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DEVELOPMENT OF SRF GUN APPLYING NEW CATHODE IDEA USING A TRANSPARENT SUPERCONDUCTING LAYER

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Abstract

KEK has been developing a superconducting RF gun for CW ERL since 2013. The SRF gun is a combination of a 1.3 GHz, 1.5-cell superconducting RF cavity and a backside excitation type photocathode. The photocathode consists of transparent substrate $MgAl_2O_4$, transparent superconductor $LiTi_2O_4$ and bi-alkali photocathode K_2CsSb. The reason for using transparent superconductor is to reflect RF by using the feature of penetration depth of superconductor, which is defined from London equation. It protects optical components from RF damage. The critical DC magnetic field of the cathode, quantum efficiency and initial emittance were measured. These show the cathode can be used for the SRF gun. The gun cavity was designed to satisfy the photocathode operation. Eight vertical tests of the gun cavity have been performed. The surface peak electric field reaches to 75 MV/m with the dummy cathode rod which was made of bulk niobium.

INTRODUCTION

The SRF gun is a key device for the future linac base electron accelerator. KEK start a SRF gun development for KEK 3 GeV ERL project [1]. We apply the backside excitation scheme. There are two advantages. One is RF and beam line structures are simpler than conventional design using metal substrate photocathode. It is not necessary to bend the excitation laser or electron beam trajectory so as not to overlap each other as compared with the front excitation. Second advantage is that the excitation laser is able to be controlled more precisely and increase the pointing stability by using short focal length lenses. It helps the space charge effect compensation.

PHOTOCATHODE IDEA

In order to develop the back side excitation photocathode, it is necessary to use a transparent substrate such as sapphire glass. However SiC and GaN substrate seems to be difficult to operate in a high RF voltage because breakdown field is 3.5 MV/cm [2]. And RF leakage to back side of the photocathode is a risk of damaging a light fibre and lens mounted at the back of the photocathode. The photocathode substrate should have the metallic properties to reflect the RF in order not to reduce the electric field on the photocathode. It increases the initial electric gradient at low beam energy and suppresses the space charge effect.

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We propose a photocathode using a transparent superconductor (Fig.1). It is suit to the superconducting technology. A transparent superconductor $LiTi_2O_4$ can block the RF leakage and transmit the excitation visible light at the same time [3]. RF penetration depth of superconductor is defined by London penetration depth. It is about several tens of nanometers. LiTi2O4 is an epitaxial thin film deposited by pulsed laser deposition on $MgAl_2O_4$ (111). The transition temperature is about 12 K. The transmittance is about 70% at a wavelength of 477 nm. The lattice constant is 0.8405 nm. It is close to the famous photocathode surface K_2CsSb (0.861 nm) [4].

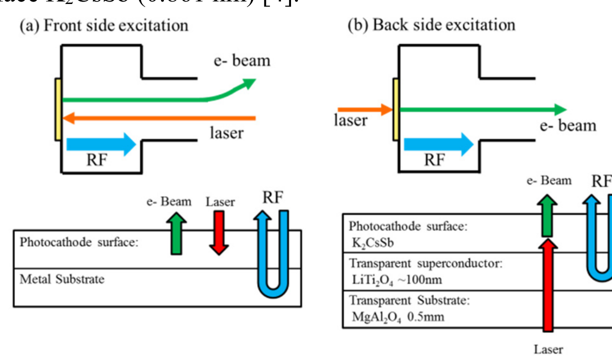

Figure 1: Front and back side excitation type photocathode structure. (a) Conventional method using metal substrate. (b) Transparent photocathode using a transparent superconductor.

SRF GUN CAVITY PERFORMANCE

The superconductor used in the photocathode needs to be cooled down. The SRF gun cavity also operates at 2 K. an effective cathode cooling system could be designed. MHI and KEK designed the KEK SRF gun #1 to test the maximum electric field and Q value [5]. It consists of 1.5 accelerating elliptical cells, choke cell and cathode plug. First cells are designed with the cathode cell to test. The accelerating cell shape was designed to minimize the energy spread and emittance by adjusting the cell taper angle. Table 1 shows the parameters of the KEK SRF gun #1. Target Q values are estimated from ILC target. Peak electric and magnetic field located on accelerating cell. On the photocathode, maximum electric field is 70% of the peak electric field of the accelerating cell and maximum magnetic field is 3.3 mT.

Figure 2 shows the KEK SRF gun #1. High gradient tests were done with dummy cathode plug, which was shaved out from bulk niobium and doesn't have the cathode mount structure. The cathode plug cleaning is important to

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INVESTIGATION OF K_2CsSb PHOTOCATHODES *

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Abstract

The interest in multi alkali antimonide photocathodes, e.g. K_2CsSb, for future ERL projects like BERlinPRO (Berlin Energy Recovery Linac Prototype) and MESA (Mainz Energy-Recovering Superconducting Accelerator) has grown in recent years. In particular for the case of RF-sources the investigation of the time response is of great importance.

In Mainz we are able to synthesize these kinds of photocathodes and investigate their pulse response at 1 picosecond level using a radio frequency streak method. We present on the one hand the cathode plant which is used for synthesizing the multi alkali antimonide photocathodes and on the other hand first measurements showing pulse responses of K_2CsSb at $\lambda = 400$ nm laser wavelength. Furthermore, an analyzing chamber has been installed, which allows investigation of lifetime under laser heating and in-situ measurements of the work function using a UHV Kelvin Probe.

INTRODUCTION

High average brightness beam applications all need a photocathode with high QE, long lifetime, low emittance and fast response. If no spin polarization is needed, these figures of merit all may be fulfilled by the group of (multi) alkali antimonide cathodes [1].

Having PEA (Positive Electron Affinity) conditions, the nature of these cathodes promises to have a faster response time ($10^{-13} < \tau < 10^{-12}$ s) than NEA (Negative Electron Affinity) cathodes like Cs(O):GaAs because the average electron energy is thermalized quickly below the energy threshold for photoemission [2]. Besides the commonly investigated FWHM or RMS pulse response, we present measurements of the longitudinal tail of these cathodes. Such tails could be generated for instance by temporal trapping in localized electronic states inside the cathode, which may lead to a delayed response albeit at very low intensity levels. High current machines have to minimize this effect to be able to run without damage or high radioactivity.

Fast response for alkali antimonides has been shown to be compatible with < 1 ps response of a Cs_3Sb cathode at an instrumental resolution of $\sigma = 2$ ps [3]. Our results below will confirm this for a K_2CsSb cathode at a improved resolution of $\sigma \approx 1$ ps. Monte Carlo simulations indicate a sub-ps response [4].

Time response measurements have been carried out at the MAMI (Mainzer Mikroton) test source PKAT (Polarisierte Kanone Test) successfully for a long time [5], [6]. During the last years, we have improved the ability for measuring long tails of the initial bunch at a high dynamic range [7].

It is difficult to manage the purchase and transport of alkali antimonides under vacuum if a commercial vendor is part of the process. We have therefore decided to synthesize the cathodes in our own lab, a similar decision has also been made by others groups, e.g. [8], [9]. Therefore, a separate cathode preparation chamber, the cathode plant, has been commissioned in Mainz with the goal to qualify cathodes for our ERL project MESA.

Since the generation of 10 mA average currents needs considerable laser intensities, we have additionally investigated the effects of laser induced cathode heating.

EXPERIMENTAL SET-UP

Photocathode Plant

UHV is essential for the cathode growing process. Semiconductor photocathodes are very sensitive tow water and oxygen; therefore, we use an combination of IGP (GammaVacuum TiTan300T) and a NEG Pump (SAES CapaciTorr). Baking out is limited to 150 °C due to the used AlfaVakuo (formerly Alvatec) dispensers, which contain an indium sealing protecting the alkali alloy from handling in air. As residual gas should not contaminate the alloy during baking, the indium sealing must not melt.

An RGA (Dycor LC-D 200) and a Bayard-Alpert gauge (Vacom Atmion) control the pressure conditions. Vacuum in the low $p = 1 \times 10^{-10}$ mbar range can be achieved with H_2 as the dominating gas. During potassium evaporation the pressure rises to 5×10^{-8} mbar, $p(H_2O)$ and $p(O_2)$ are in the 5×10^{-11} mbar region. Vacuum conditions for cesium and antimony steps are even better.

Partial pressure of antimony and the alkalis cannot be detected with the RGA during evaporation. Therefore, a thickness monitor (LewVac) is essential for providing information about the metal flux.

In the present set-up, further information on the status of the growth process can only be inferred from the photo electron yield. Due to budget restrictions, equipment yielding structural information of the deposited layer like XPS has not been purchased so far.

Figure 1 shows a schematic inner view of the preparation chamber. K_2CsSb photocathodes are synthesized by sequential deposition mainly after the classical recipe of Sommer [10] beginning with a thin antimony film on a metal substrate reacting with K and Cs vapor at an elevated temperature.

The substrate is positioned in a MAMI standard cathode holder (puck). Its position can be changed by a UHV manipulator. The crystal wheel allows storage of eight different pucks, in practice up to four pucks are used.

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THE SMALL THERMALIZED ELECTRON SOURCE AT MAINZ (STEAM)

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Abstract

The Small Thermalized Electron Source at Mainz (STEAM) is a photoelectron source which will be operated using NEA GaAs excited near its band gap with an infrared laser wavelength to reach smallest emittances. CST simulations indicate that emittance growth due to vacuum space charge effects can be controlled up to bunch charges of several tens of pC. The goal of the project is to demonstrate that the intrinsic high brightness can still be achieved at such charges. The current status will be presented.

INTRODUCTION

The brightness of a particle source can be calculated by the fraction of the emitted electron current I, the transverse emittances ε_x and ε_y and the relative energy spread $\frac{\Delta E}{E}$, see Eq. 1. It is a figure of merit for an ERL accelerator source.

$$B \propto \frac{I}{\varepsilon_x\,\varepsilon_y\,\Delta E/E} \propto \frac{QE(\lambda)\,P_L}{\varepsilon_x\,\varepsilon_y\,\Delta E/E} \quad (1)$$

The current of a photoemission electron source is mainly given by the power of the laser and the quantum efficiency $QE = N_{\text{electrons}}/N_{\text{photons}}$, which depends on the laser wavelength λ. The normalized thermal residual-mean-square (rms) emittance can be derived from the exciting laser spot size σ_0 and the thermal energy $k_B T$, see Eq. 2 [1].

$$\varepsilon_{n,\text{rms}} = \frac{\sigma_0}{2}\sqrt{\frac{k_B T}{m_e c^2}} \quad (2)$$

The thermal energy decreases with increasing laser wavelength [2], therefore the smallest emittance can be achieved at the maximum possible exciting wavelength near the band gap energy E_g of the used semiconductor material, e.g. for NEA GaAs ($E_g = 1.4\,\text{eV}$) $\lambda_L \approx 800\,\text{nm}$ is only 130 meV above the band gap, which should result in high QE but still low thermal energy and corresponds to the typical wavelength of powerful semiconductor lasers. Seen from this solid state physics point of view, it is important for high current accelerators how the emittance develops with increasing bunch charges. To investigate this aspect further, a high extracting field gradient is needed to suppress space charge effects, which is above all a low energy issue.

THE DESIGN OF STEAM

STEAM was designed and optimized to operate at 200 kV with an extracting field gradient of $5\,\text{MV}\,\text{m}^{-1}$. Its vertical design was inspired by the existing photoemission electron source Polarisierte Kanone (PKA) at the Institute of Nuclear Physics in Mainz and it uses the "inverted" R30 insulator adopted by the Jefferson Laboratory [3], see Fig. 1. The simulation program Computer Simulation Technology (CST) [4] was used to find an applicable cathode and anode geometry so that the field gradient on any point of the electrode structure stays below $10\,\text{MV}\,\text{m}^{-1}$, see Fig. 2. This is to reduce the risk of field emission.

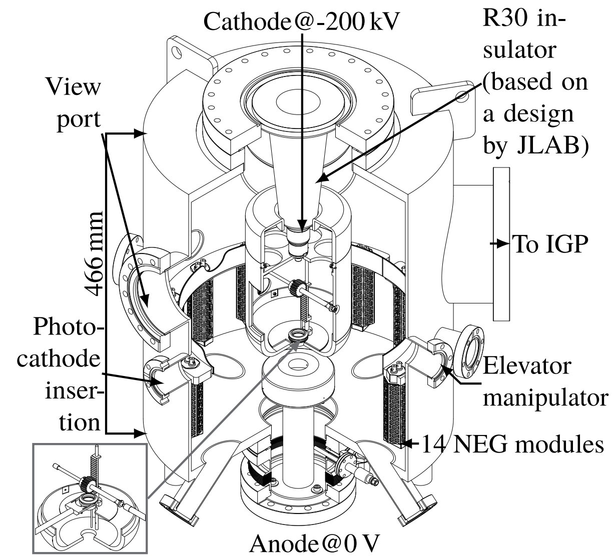

Figure 1: STEAM chamber, cathode and anode design. A working sketch of the elevator is shown in the lower left corner.

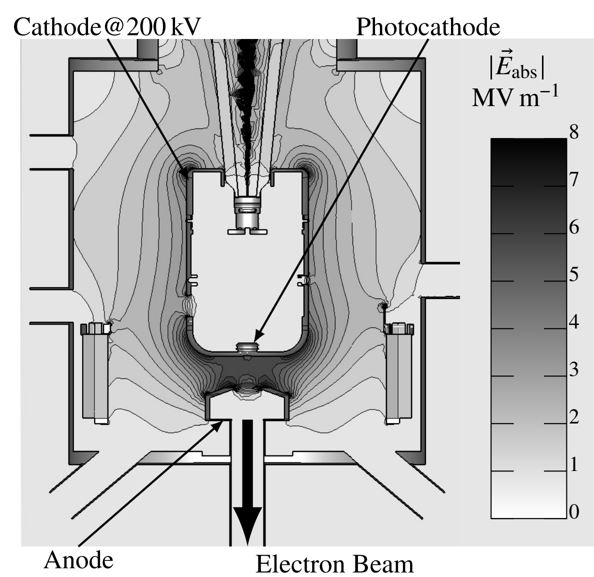

Figure 2: Electrostatic simulation using CST. The absolute field gradient in STEAM @ $U = 200\,\text{kV}$ stays below $10\,\text{MV}\,\text{m}^{-1}$, while an extracting field gradient of $|\vec{E}|_{\text{acc}} \approx 5\,\text{MV}\,\text{m}^{-1}$ is achieved. The HV cable is also simulated.

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SPOCK - A TRIODE DC ELECTRON GUN WITH VARIABLE EXTRACTION GRADIENT

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Abstract

The electron source concept SPOCK (**S**hort **P**ulse **S**ource at **K**PH) is a 100kV DC source design with variable extraction gradient. Due to its triode inspired design the extraction gradient can be reduced for e.g. investigations of cathode physics, but also enhanced to mitigate space charge effects. In the framework of the MESA-Project (**M**ainz **E**nergy-Recovering **S**uperconducting **A**ccelerator) [1] its design has been further optimized to cope with space charge dominated electron beams. Although it injects its electron beams directly into the LEBT (**L**ow **E**nergy **B**eam **T**ransport) matching section, which excludes any adjustments of the electron spin, the source SPOCK will allow higher bunch charges than the MESA standard source.

CONCEPT

The concept of the horizontal DC electron gun SPOCK [2] is based on the design of triodes developed beginning 20th century. By means of an additional control plate in-between anode and cathode the extraction voltage can be altered, see Fig. 1.

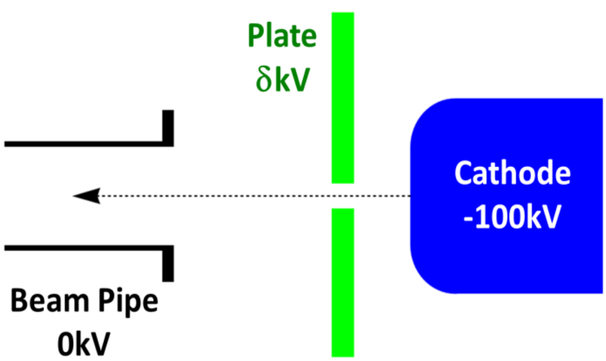

Figure 1: Concept of SPOCK

The basic design idea has been developed [3] in order to clarify the contribution of photocathode energy spread to the time response [4] of photocathodes. Due to variations of the extraction field gradient its contribution can be isolated from other effects and separately investigated. Further details to this subject will be recapitulated in e.g. [4]. Simultaneously, this layout possesses a potential for high brilliance electron beams. A major challenge is the preservation of the transverse emittance in presence of space charge. By setting the control plate at a high potential the extraction field at the cathode surface is significantly amplified. Hence the electron acceleration is considerably enhanced mitigating the space charge impacts on the beam qualities such as the transverse emittance and the energy spread.

Design and Dimensions

The design of the source is based on the design of the JLAB source [5]. It features electrode supporting insulators extending into the interior of the grounded vacuum vessel. This is known as an "inverted" source. An overview of the specific features and technical advantages of such a design is given in [5]. The main components of the source are the cathode, the anode and the control plate. By means of two ceramic isolators the cathode and plate are electrically separated. Anode and beam pipe are grounded. As in case of high intensity beam operations an early transverse focusing is beneficial, a plug-in vacuum vessel is designed containing space for a double-solenoid. This double solenoid will be placed approximately s=220mm downstream the cathode. In order to ensure the vacuum condition of $p \approx 10^{-11}$ mbar ten NEG (Non Evaporable Getter) modules grouped in two half circles are surrounding this plug-in vessel. Two additional IGP (ion getter pumps) will be attached to the main chamber. A scheme of the source design is given in Fig 2.

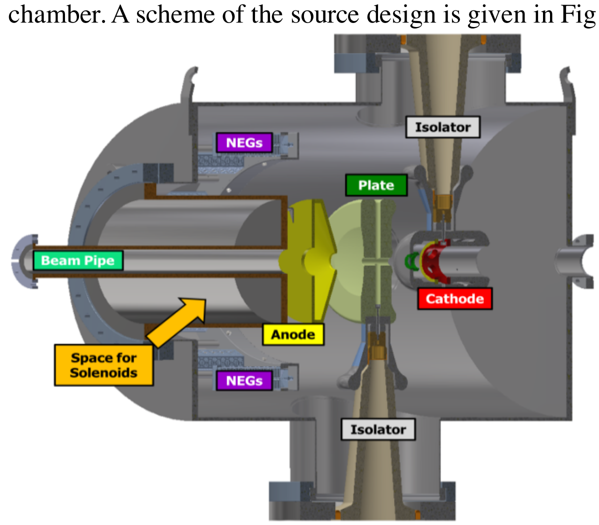

Figure 2: Design SPOCK

The dimensions of the main source vessel are length L=620mm and diameter D=410mm. A CF200 flange connects the main source chamber with the plug-in vessel. In the design phase the diameter of the plug-in vessel is set to d=170mm. Apart from hosting the double solenoid and the CF40 beam pipe the plug-in vessel also serves as a support for the extraction anode, whose shape is adapted from the source STEAM (**S**mall **T**hermalized **E**lectron Source **A**t **M**ainz) [6]. The isolators are type R30 isolators with a height of h≈240mm. Numerous minor variations in the design of the control plate and the cathode were required to mitigate potential field emissions and to allow a

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BEAM DYNAMICS AND COLLIMATION FOLLOWING MAGIX AT MESA

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Abstract

The Mainz Energy-recovering Superconducting Accelerator (MESA) will be an electron accelerator allowing operation in energy-recovery linac (ERL) mode. After the beam hits the target at the MESA Internal Gas Target Experiment (MAGIX), the beam is phase shifted and recirculated back into the linac sections. These will transfer the kinetic beam energy back to the RF-field by deceleration of the beam and allow for high beam power with low RF-power input. Since most of the beam does not interact with the target, the beam will mostly just pass the target untouched. However, a fraction of the scattered electrons may be in the range outside the accelerator and detector acceptances and therefore cause malicious beam dynamical behavior in the linac sections or even damage to the machine. The goal of this work is to determine the beam behavior upon target passage by simulation and experiment and to protect the machine with a suitable collimation system. The present status of the investigations is presented.

MESA

An overview of MESA is given in [1]. MESA will supply the P2 experiment in external beam (EB) mode with a beam current of 150 µA at 155 MeV [1,2]. In EB mode, the whole beam is dumped after interaction with the target. A second beamline is set up for the ERL mode, where the beam passes the MAGIX target and is then phase shifted 180° to the RF and recirculated through the cryomodules for energy recovery. MESA will maintain a 1 mA beam current in the first stage and 10 mA after upgrade at 105 MeV.

MAGIX

ERL operation is possible since MAGIX provides a low density target and only a small fraction of the beam actually interacts with the gas. The target is designed as a gas jet of nearly homogenous density and allows to reach luminosities in the region of $10^{35}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ [3]. The jet is of cylindrical shape with 4 mm in height and diameter [4]. The jet is produced by accelerating gas to supersonic speeds in a Laval nozzle perpendicular to the beam axis. A gas catcher is set up opposite to the Laval nozzle to collect the major part of the injected gas in order to keep vacuum conditions at a tolerable level. MAGIX is designed to operate with various elementary gases for fundamental physics experiments, e.g. the search for the dark photon as well as investigations on the proton form- and astrophysical S-factor [5]. The setup is shown in Fig. 1.

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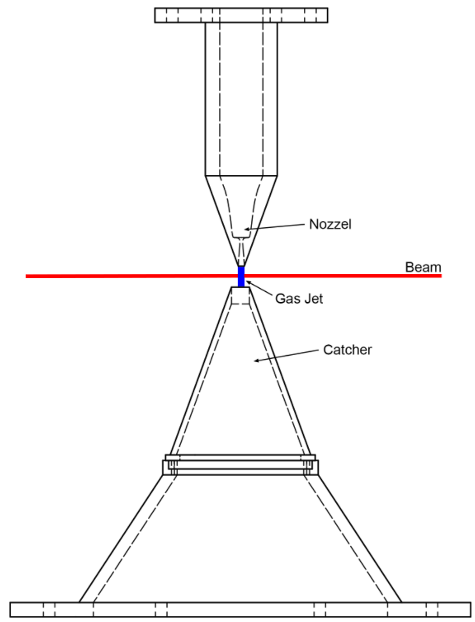

Figure 1: Schematic drawing of the MAGIX gas target [6].

Luminosity Limit Estimation

Target scattering and beam optics limit the luminosity of targets in ERL operation. Luminosity and target density limits for MAGIX can be estimated as presented in [7]. The luminosity limit then depends on beam and target properties as well as the beam power lost in the accelerator. It is therefore important to examine these parameters to ensure reliable ERL operation.

TARGET INDUCED HALO

Scattering on the gas target widens the angle and energy distribution of the electron beam in a way that a halo forms around the original beam cross-sectional area as shown in Fig. 2. The halo is therefore called "Target Induced Halo" (TAIL). TAIL might cause malicious beam dynamical behavior when passing the cryomodules, such as inducing Higher Order Modes (HOMs) in the cavity, or directly damage machine parts when electrons get dumped in the cavities and beam pipes. Radiation produced by dumping electrons may further lead to damage especially to electronic components and generate background noise in the detectors of the experiments reducing measurement precision. It is therefore crucial to carefully investigate on the effects originating from the beam passage of MAGIX and formulate a collimation approach downstream the target to encounter impacts on machine operation safety and reliability. The collimation contributes to power losses as described above and have to be minimized in order to maximize luminosity available for the experiment.

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LOW-ENERGY BEAM TRANSPORT SYSTEM FOR MESA*

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Abstract

An important part of the new accelerator MESA (Mainz energy-recovering superconducting accelerator) is the low-energy beam transport system connecting the 100 keV electron source with the injector accelerator. Here the spin manipulation and the bunch preparation for the injector accelerator take place. Due to the low energy, space charge will be an challenging issue in this part. Therefore, start-to-end simulations were done with a combination of the two particle dynamics codes PARMELA [1] and CST [2]. At the moment, a test setup is being built up to check the functionality of devices and compare the beam parameters with the simulation. Here the focus lies on the bunch preparation system because at this part we expect high impact of the space charge by reason of the necessary bunch compression. The advance of the test setup, the simulations and measurements done so far will be shown.

INTRODUCTION

A layout of the lattice of MELBA (MESA low-energy beam apparatus) can be seen in Figure 1. The electrons will be focused by quadrupoles and solenoids. Two times the beam will be bended by 270° by two alpha magnets. Several steerer magnets will correct the orbit of the electrons if it deviates from the reference orbit. Misalignment of the devices and magnetic stray fields will lead to such a deviation. One important part of MELBA is the spin manipulation consisting of two Wien filters and one solenoid. After the electrons are produced in the source, their spin is oriented in the longitudinal direction. The first Wien filter and the solenoid will align the spin in the horizontal direction. Compensation of further precession in the accelerator will be done by the second Wien filter. In principle the spin can be aligned in any direction with this arrangement. The reason for manipulation of the spin in this section is that the rotation angle of the Wien filter $\phi_{\text{spin, Wien}} \propto \frac{1}{\beta\gamma^2}$ and that of the solenoid $\phi_{\text{spin, sole}} \propto \frac{1}{\beta\gamma}$ [3]. So the required fields for spin rotation are small in this section. A challenging issue in this low-energy region is the transport of moderate bunch charges ($\mathcal{O}(1\,\text{pC})$) demanded by the experiment MAGIX (MESA gas internal target experiment). This is due to the fact that the space charge forces scale with $\frac{1}{\gamma^3}$. For offline characterisation of the beam, there are scanners installed, whereas for the online characterisation, there will be a xy monitor and a phase monitor. The second big part is the chopper and the buncher system responsible for matching the beam with the longitudinal acceptance of the injector where the beam will accelerated to an energy of 5 MeV. The chopper system consists of two circular deflecting cavities with a resonance frequency of 1.3 GHz, a solenoid ,and a collimator. For longitudinal bunching also two cavities are used, the first one with a resonance frequency of 1.3 GHz and the second one with double the frequency.

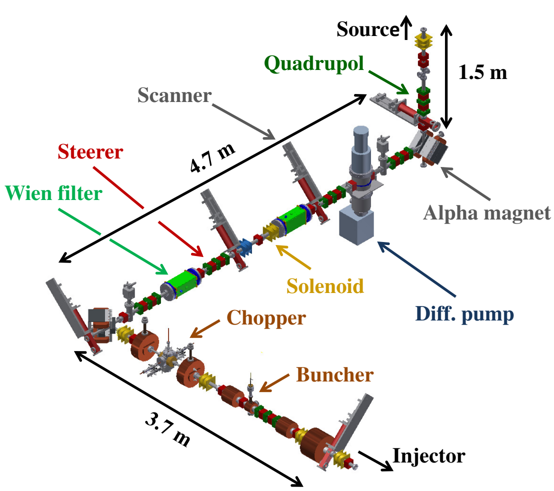

Figure 1: Layout of the low energy beam transport system for MESA.

* Work supported by the DFG within the GRK 2128; Cluster of exellence PRISMA

SIMULATIONS

Alpha magnet

First the alpha magnet was modelled and simulated with CST (Computer simulation technology) to calculate the elements of the transport matrix. In Figure 2, the results are shown and compared with old simulations of Ref. [4]. The simulated magnet deflects the electrons by 270° in the horizontal plane. The discrepancy between the two results may explained by the fact that different algorithms are used. Furthermore the position of the beginning and the end of the alpha magnet can be different. The operating point will be chosen between 300 and 400 G to have little focusing in the x-direction and little dispersion. Furthermore the optical properties in both planes are quite similar.

Start-to-end

Simulation of the whole beamline is done successively with PARMELA (Phase and radial motion in electron linear accelerators) and CST. Both are particle in cell (PIC) codes. The resulting particle distribution of one program is used as a start distribution for the other one. In a first simulation, the source was simulated with CST [5] followed by a simulation with PARMELA of the beamline from the source to the first alpha magnet, which again is simulated with CST. The beamline downstream to the second alpha magnet, which is also simulated with CST, is simulated with PARMELA. The last part from the second alpha magnet to the injector

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BEAM BREAKUP SIMULATIONS FOR THE MESA ACCELERATOR

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Abstract

MESA is a recirculating superconducting accelerator under construction at Johannes Gutenberg-Universität Mainz. It will be operated in two different modes: the first is the external beam (EB) mode, where the beam is dumped after being used at the experiment. The required beam current in EB mode is 150 µA with polarized electrons at 155 MeV.

In the second operation mode MESA will be run as an energy recovery linac (ERL) with an unpolarized beam of 1 mA at 105 MeV. In a later construction stage of MESA the achievable beam current in ERL-mode shall be upgraded to 10 mA. To understand the behaviour of the superconducting cavities under recirculating operation with high beam currents simulations of beam breakup have to be performed. Current results for transverse beam break up calculations and simulations with Beam Instability (bi) [1] code are presented.

INTRODUCTION

The Mainz Energy-recovering Superconducting Accelerator (MESA) is currently being built at Johannes Gutenberg-Universität Mainz. The accelerator will be constructed in a double sided layout with two linacs and vertically stacked recirculation arcs. It will be operated in either an external beam mode (EB) with three recirculations or in an ERL mode with up to two recirculations.

Within this contribution we focus on the ERL operation mode which is planned to provide electron beams of 1 mA and later 10 mA at a beam energy of 105 MeV. With an injection energy of 5 MeV up to 100 MeV of beam energy can be recovered from the beam in ERL mode.

Further information on the MESA facility can be found in [2] and in [3]. A sketch of the lattice configuration can be seen in Fig. 1. As there are no SRF multiturn ERLs existing so far, investigations on beam stability in such an operation mode are accessible by simulations or theory only. A thorough understanding of beam stability is necessary for optimizing the layout of the accelerator before construction.

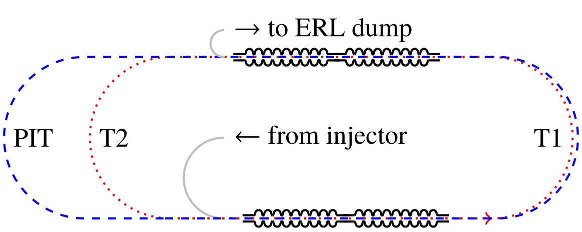

Figure 1: Lattice configuration for the ERL-mode of MESA. T1 to T3 are the return arcs for the different energies while the Pseudo Internal Target (PIT) arc contains the experiment and the 180° phase shift for the energy recovery mode.

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SRF Cavities and Cryomodules

For MESA main accelerators two modified ELBE-type cryomodules were chosen [4], which each consist of two 9-cell superconducting radio frequency (SRF) cavities of the TESLA/XFEL-type. The modifications aim on the improved cw-operation of the cryomodules and include the integration of fast piezo tuners as well as an improved cooling of the HOM-coupler antennas [4].

The accelerating cavities will provide a gradient of 12.5 MeV at $Q_0 = 1.25 \times 10^{10}$ while being operated at 1.8 K and 1.3 GHz. A CAD model of the full cavity string is provided in Fig. 2. Besides the wanted accelerating π-mode, also unwanted HOMs with high quality factors can exist in the cavity. For the first calculations presented here the transverse BBU induced by dipole HOMs was investigated as quadrupole and higher order HOMs have weaker influence on the beam unless they are very strong with respect to the dipole HOMs.

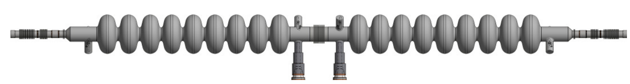

Figure 2: CAD Model of the MESA cavity string. In the bottom center the two HF power couplers can be seen, the four other visible ports (bottom left and right, top center) are the HOM couplers.

TRANSVERSE BBU

Electron bunches that enter a SRF cavity with a small deviation from the reference orbit excite dipole HOMs in said cavity. Due to their naturally high Q_L, these modes can persist until the next bunch arrives at the cavity. The magnetic field of an excited mode deflects the following bunches that do not travel on the reference orbit. The deflection angle produced by the mode translates into a transverse displacement at the cavity after recirculation. The recirculated beam induces a HOM voltage, depending on the magnitude and direction of the beam displacement.

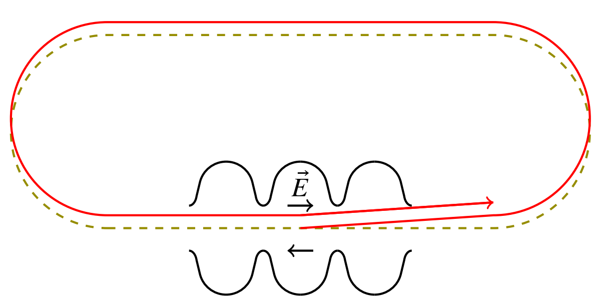

Figure 3: Orbit deviation (red) from the reference orbit (green) induced by dipole HOMs.

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DEVELOPMENT OF A MULTIALKALI PHOTOCATHODE DC GUN FOR HIGH CURRENT OPERATION

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Abstract

We have developed a DC gun test stand at National Institutes for Quantum Radiological Science and Technology (QST) for high current electron beam generation. The gun test stand consists of an alkali antimonide photocathode preparation chamber, a DC gun with a 250kV-50mA Cockcroft Walton high voltage power supply, and beam line with a water cooled beam dump to accommodate 1.5 kW beam power. We successfully fabricated a Cs_3Sb photocathode with quantum efficiency of 5.8 % at 532 nm wavelength and generated 150 keV beam with current up to 4.3 mA with 500 mW laser at 532 nm wavelength. Unfortunately, we encountered a vacuum incident during beam transport of high current beam and the development has been halted. We will fix the vacuum problem and restart the gun development as soon as possible.

INTRODUCTION

A high-brightness and high-current electron gun has been developed worldwide for the next generation light sources such as a high power EUV FEL for semiconductor lithography based on an energy recovery linac (ERL) [1]. Such a gun can also be used as a compact and high-power THz light source based on coherent Smith Purcell radiation technique in combination with an appropriate grating [2].

We have developed a photoemission DC gun test stand at National Institutes for Quantum Radiological Science and Technology (QST) for generation of high-brightness and high-current electron beam [3]. An alkali antimonide photocathode preparation system was added to the gun test stand, because electron beam generation with current up to 75 mA was demonstrated at the Cornell photoinjector and the charge lifetime of the multialkali photocathode was measured to be greater than 15 kC [4].

In this paper, fabrication result of a Cs_3Sb photocahode is reported. The preparation chamber for Cs_3Sb photocahode has been developed since 2013 [3]. The quantum efficiency (QE) in our latest fabrication reached 5 %, which was more than 15 times greater than our previous value [3]. A photoemission gun system has been prepared for beam generation. A cathode electrode was replaced to accommodate a photocathode puck compatible with the compact ERL (cERL) at KEK as well as to reduce the surface electric field [3]. High voltage at 210 kV has been successfully applied with cathode electrode in place for more than eight hours without any discharge. A beamline for high current beam generation has also been prepared. We have generated electron beam from the Cs_3Sb photocathode with current up to 4.3 mA at 150 kV. The results of beam generation are described.

FABRICATION OF CAESIUM ANTIMONIDE PHOTOCATHODE

Details of our alkali antimonide photocathode preparation chamber are described elsewhere [3]. The QE obtained in the first fabrication in March 2015 was 0.37 % at 532 nm. The QE decreased to almost zero one year later, though the puck had been kept under vacuum pressure of 2×10^{-9} Pa. A silicon wafer of 0.5 mm thickness is used as the substrate. We decided to reactivate the Si wafer with similar way with our previous procedure. The wafer was heat cleaned at 550-degree C for two hours. The evaporation of antimony and caesium was performed another day.

Figure 1 shows our fabrication procedure. The distance between the wafer and alkali and antimony sources is 3 cm. The temperature during the fabrication was monitored with a thermocouple connected to the puck holder. The antimony was evaporated at monitor temperature of 140-degree C. The duration of evaporation time which

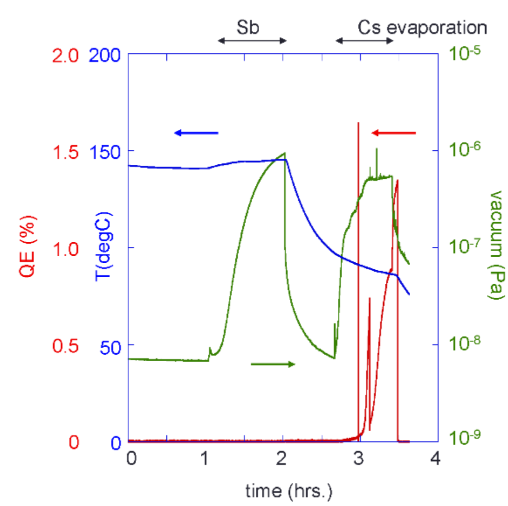

Figure 1: The Cs_3Sb photocathode fabrication procedure. The blue curve shows temperature of puck holder measured with a thermocouple. The green curve shows the vacuum pressure in the fabrication chamber. The antimony is evaporated at the monitor temperature of 140-degree C and caesium is evaporated at 90-degree C. The QE (red curve) is derived from photo current measured with a charge collector in front of a Cs_3Sb photocathode and laser power at 532 nm.

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NOVOSIBIRSK ERL FACILITY*

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Abstract

The first project of the four turn ERL for Novosibirsk FELs (NovoFEL) was proposed at FEL'90 Conference. Later the project was modified, but the base lines kept: a four turn normal conductance linac with energy recovery, low RF cavities (180 MHz), grid controlled DC gun (Q~1nC, τ=1 nsec, f_{rep} = 10 kHz–50 MHz). The ERL can operate in the three modes, providing an electron beam for the three different FELs (from 300 μm up to 5 μm). Construction and commissioning four-track ERL was divided on three stage: the first stage NovoFEL working in spectral range (90–240) μm, based on one track energy recovery linac (ERL) with energy 12 MeV and current 30 mA, was commissioned in 2003. The second stage of NovoFEL working in spectral range (35–80) μm, based on two track energy recovery linac with energy 22 MeV and current 7 mA, was commissioned in 2009. The third stage of NovoFEL working in spectral range (8–15) μm, based on four track energy recovery linac with energy 42 MeV and current 5 mA was commissioned in 2015.

INTRODUCTION - ERL ACTIVITY IN BUDKER INP

The Energy Recovery Linac (ERL) concept for the free electron laser (FEL) was proposed at Budker INP by N. Vinokurov and A. Skrinsky in 1978 [1]. The first project of the four-turn race-track microtron-recuperator for the FEL was proposed at the FEL'90 Conference (1990) [2].

Later the project was modified, but the base line kept: a four-turn normal conductance linac with energy recovery; normal conducting RF cavities (180 MHz); a grid-controlled DC gun with bunch charge about 1nC, duration 1 nsec, and bunch frequency 10kHz–50 MHz.

Advantages of the low frequency (180 MHz) RF system: high threshold currents for instabilities; operation with long electron bunches (for narrow FEL linewidth); large longitudinal acceptance (good for operation with large energy spread of used beam); relaxed tolerances for orbit lengths and longitudinal dispersion.

Today, the ERL can operate in three modes, providing an electron beam for the three different FELs, from 300 μm up to 5 μm [3,4].

The first stage of the Novosibirsk FEL (NovoFEL) works in the spectral range (90–240) μm, based on a one track Energy Recovery Linac (ERL) with energy 12 MeV, was commissioned in 2003 [5]. It is the most powerful radiation source in terahertz region.

The second stage works in infrared spectral range (35–80) μm, based on two track Energy Recovery Linac with energy 22 MeV, was commissioned in 2009 [6].

The third stage working in spectral range (8–15) μm, based on four track energy recovery linac with energy 42 MeV, was commissioned in 2015 [7].

From 1997 the using an ERL for a fully spatially coherent X-ray source has been discussed at BINP [8]. The feasibility study of the 5.6 GeV machine with two split super-conducting accelerating sections (similar to CEBAF accelerator [9]) was presented at ERL-11 conference in 2011 [10]. The same accelerating scheme was supposed for the project of compact 13.5 nm FEL based on 800 MeV ERL facility for extreme ultraviolet lithography in 2010 [11, 12].

NOVOFEL ACCELERATOR

The NovoFEL facility includes three FELs. All the FELs use the electron beam of the same electron accelerator, a multi-turn energy recovery linac. A simplified scheme of the four-turn ERL is shown in Fig. 1. Starting from low-energy injector 1, electrons pass four times through accelerating radio frequency (RF) structure 2. After that, they lose part of their energy in FEL undulator 4. The used electron beam is decelerated in the same RF structure, and the low-energy electrons are absorbed in beam dump 5.

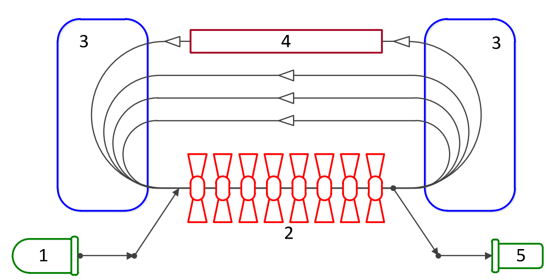

Figure 1: Simplified multi-turn ERL scheme:
1 – injector, 2 – linac, 3 – bending magnets,
4 – undulator, 5 – dump.

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ERL MODE OF S-DALINAC: DESIGN AND STATUS*

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Abstract

Recently, the S-DALINAC was extended by an additional recirculation beam line to a thrice-recirculating linear accelerator. This upgrade enables an increase of the maximum achievable energy close to its design value of 130 MeV as well as an operation as an ERL. The new beam line features a path-length adjustment system which is capable of changing the phase of the beam by a full RF phase and, thus, allowing to shift the timing of the electron bunches to the decelerating phase. The project comprises different aspects concerning the design (magnets, beam dynamics, lattice, etc.) and the construction work including the alignment done at the accelerator. This contribution presents a rough overview on the design, installation and status.

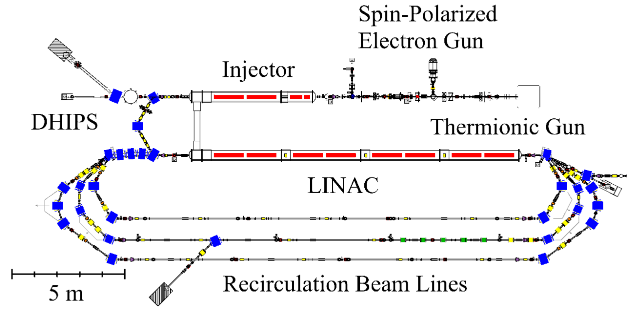

Figure 1: Floor plan of the S-DALINAC with three recirculations in the final set-up.

INTRODUCTION

The S-DALINAC is a superconducting electron accelerator of TU Darmstadt. It was operated from its first commissioning as a recirculating LINAC in 1991 [1] until autumn of 2015 in a twice-recirculating set-up. The decision was made to add an additional recirculation beam line to increase the final beam energy and to enable an ERL operation. In 2015/2016 this major upgrade of the S-DALINAC was performed. The new beam line was installed in between the two existing recirculation beam lines. An upgrade of the final beam energy was necessary as in the past the final design energy of 130 MeV could not be reached due to a lower quality factor of the superconducting (sc) cavities [2] than originally anticipated and, thus, a higher dissipated power to the helium bath. Adding a main LINAC passage by installing an additional recirculation beam line allows the operation of the sc cavities on a decreased gradient while keeping the overall design beam energy constant. In this operation the dissipated power to the helium bath is adapted to the cooling power of the cryo plant. Figure 1 shows the floor plan of the thrice-recirculating S-DALINAC. In case of a thrice-recirculating operation an energy gain of up to 7.6 MeV for the injector LINAC and up to 30.4 MeV for the main LINAC are used. A maximum beam current of 20 μA can be accelerated in the recirculating operation.

ERL MODE

The upgrade of the S-DALINAC features an Energy-Recovery LINAC (ERL) mode in its new beam line. The path-length adjustment system of this newly installed section is capable of an adjustment range of 360° of the RF phase. Thus also a phase shift of 180° is possible so that the beam re-enters the main LINAC on the decelerating phase. Figure 2 shows the area of the first arcs with one out of two path-length adjustment systems of the new beam line, the separation dipole magnet as well as the dump for the decelerated beam. The beam, coming from the main accelerator, can directly be guided into the second recirculation. In this beam line the phase shift of 180° is conducted so that the beam is dumped at injection energy after being decelerated in the main LINAC (once-recirculating ERL mode, see Fig. 3). Alternatively, the beam can be deflected into the first recirculation followed by an additional acceleration in the main LINAC. During the passage through the second recirculation beam line the necessary phase shift is performed so that the beam then passes a second time through the first recirculation. After a second deceleration the beam is finally dumped at injection energy (twice-recirculating ERL mode, see Fig. 4). The purpose of the ERL mode of S-DALINAC is to serve as a test bed for principle investigations concerning the RF controlling [3] or the beam dynamics (e.g. the effect of (transversal) beam break-up (BBU) [4]).

DESIGN OF A THIRD RECIRCULATION INCLUDING ERL MODE

Figure 5 shows a view into the accelerator hall after the installation of the new beam line was finished. Long time in advance, before this installation could start, a complex design and detailed planning of this modification was done [5, 6]. Not only the design aspects considered in the following sections have been taken into account but also the design of other magnetic elements or more general aspects like the vacuum system.

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LERF – NEW LIFE FOR THE JEFFERSON LABORATORY FEL*

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Abstract

In 2012 Jefferson Laboratory's energy recovery linac (ERL) driven Free Electron Laser successfully completed a transmission test in which high current CW beam (4.3 mA at 100 MeV) was transported through a 2 mm aperture for 7 hours with beam losses as low as 3 ppm. The purpose of the run was to mimic an internal gas target for DarkLight [1] – an experiment designed to search for a dark matter particle. The ERL was not run again until late 2015 for a brief re-commissioning in preparation for the next phase of DarkLight. In the intervening years, the FEL was rebranded as the Low Energy Recirculator Facility. In 2016 several weeks of operation were allocated to configure the machine for DarkLight with the purpose of exercising – for the first time – an internal gas target in an ERL. Despite a number of challenges, including the inability to energy recover without losses (precluding CW operation), beam was delivered to a target of thickness 10^{18} cm^{-2} which represents a three order of magnitude increase in thickness from previous internal target experiments. Details of the machine configuration and operational experience will be discussed.

BACKGROUND

After 15 years of consistent operation and upgrades Jefferson Laboratory's energy recovery linac (ERL) driven Free Electron Laser (FEL) ceased operation in 2012. Missing a steady funding for operations, the LERF has only been operational for a combined few weeks over the last five years. The common thread in all those run periods was the DarkLight experiment. This innovative experiment is searching for a dark matter particle by studying e^-p scattering using a high power (1 MW) electron beam and a gaseous hydrogen internal target [2].

2012: APERTURE TEST

The DarkLight physics run requires continuously running a 1 MW beam into an internal target for 60 days. To address the technical challenges several different experiments were run at the LERF. One foundational question that needed to be answered is whether a high power, CW beam could be transmitted through an aperture consistent with that of an internal target with sufficiently low beam loss.

To mimic an internal target, apertures of (2, 4 and 6) mm diameter were drilled in a 127 mm long block of aluminum and the whole apparatus installed in the 3F region of the FEL (see Figs. 1 and 2). Though the target and detector package were ultimately located downstream in the 4F region, the 3F region was a natural choice for the initial test since it is well instrumented with BPMs, correctors and viewers, the beamline is well characterized (90° FODO cells) and it provides enough focusing to achieve the desired match with additional knobs available for halo control [3].

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PERLE – BEAM OPTICS DESIGN*

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Abstract

PERLE (Powerful ERL for Experiments) [1] is a novel ERL test facility, initially proposed to validate design choices for a 60 GeV ERL needed for a future extension of the LHC towards a hadron-electron collider, the LHeC [2]. Its main goal is to test the limits of a high current, CW, multi-pass operation with superconducting cavities at 802 MHz (and perhaps exploring other frequencies of interest). PERLE optics features Flexible Momentum Compaction (FMC) lattice architecture for six vertically stacked return arcs and a high current, 5 MeV photo-injector. With only one pair of 4-cavity cryomodules, 400 MeV beam energy can be reached in three re-circulation passes, with beam currents in excess of 15 mA. This unique quality beam is intended to perform a number of experiments in different fields reaching from uncharted tests of accelerator components via elastic ep scattering to laser-Compton backscattering for photon physics [3]. Following the experiment, the CW beam is decelerated in three consecutive passes back to the injection energy, transferring virtually stored energy back to the RF.

LAYOUT AND ENERGY

PERLE accelerator complex is arranged in a racetrack configuration; hosting two cryomodules (containing four, 5-cell, cavities operating at 802 MHz), each located in one of two parallel straights, completed with a vertical stack of three recirculating arcs on each side. The straights are about 10 meter long and the 180° arcs are 5.5 meter across. Additional space is taken by 4 meter long spreaders / recombiners, including matching sections. As illustrated in Fig. 1, the total 'footprint' of PERLE is: 24 m × 5.5 m × 0.8 m; the last dimension reflecting 40 cm vertical separation between the arcs. Each of the two cryomodules provides 65.5 MeV energy boost. Therefore, in three turns, a 393 MeV energy increase is achieved. Adding initial injection energy of 5 MeV yields the total energy of 398 MeV – call it '400 MeV'.

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MULTI-PASS LINAC OPTICS WITH ENERGY RECOVERY

Multi-pass energy recovery in a racetrack topology explicitly requires that both the accelerating and the decelerating beams share the individual return arcs. This in turn, imposes specific requirements for the TWISS function at the linacs ends: the TWISS functions have to be identical for both the accelerating and decelerating linac passes converging to the same energy and therefore entering the same arc.

To represent beta functions for multiple accelerating and decelerating passes through a given linac, it is convenient to reverse the linac direction for all decelerating passes and string them together with the interleaved accelerating passes, as illustrated in Fig. 2. This way, the corresponding

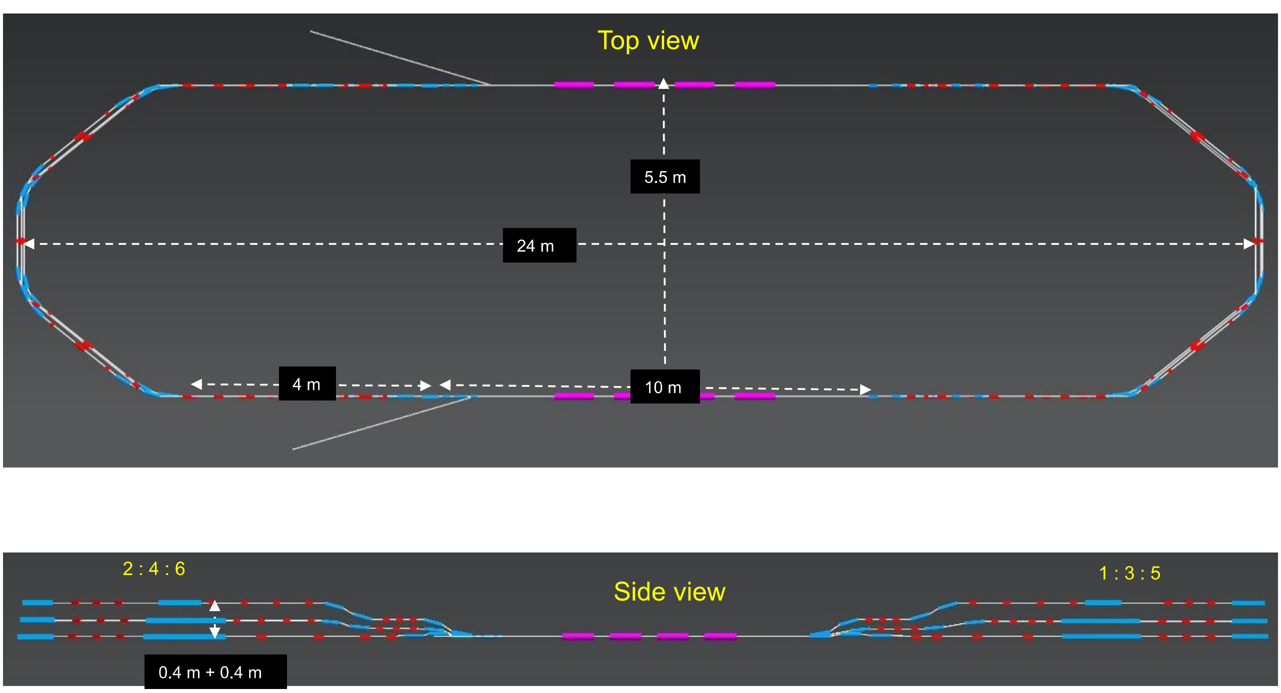

Figure 1: PERLE layout featuring two parallel linacs each hosting a 65.5 MeV cryomodule, achieving 400 MeV in three passes.

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CBETA FFAG BEAM OPTICS DESIGN*

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Abstract

CBETA is an Energy Recovery Linac (ERL) accelerating an electron beam to 150 MeV in four linac passes. Instead of having four separate return loops to the linac, it instead has a single fixed field alternating gradient (FFAG) beamline with nearly a factor of 4 energy acceptance. While ideally the FFAG would be circular with identical cells all around, space and cost considerations dictate that small radius of curvature FFAGs should be used near the linac, connected by a straight beamline. To ensure good orbit matching over the entire energy range, adiabatic transitions are inserted between the arcs and the straight. After briefly introducing basic principles of FFAG optics, we describe how we choose the parameters of the arc cell, the basic building block of the lattice. We then describe how the straight cell is chosen to work well with the arc. Finally we describe the design process for the transition that ensures orbits over the entire energy range end up very close to the axis of the straight. We discuss how the realization of this lattice design with physical magnets impacts the design process.

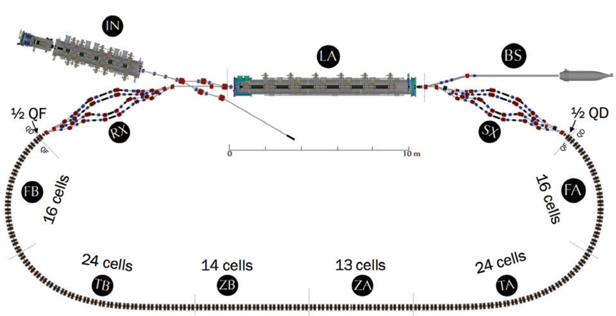

Figure 1: The CBETA energy recovery linac, with sections labeled. The FFAG beamline, discussed in this paper, consists of the sections labeled FA, TA, ZA, ZB, TB, and FB.

THE BASIC PARAMETERS

CBETA [1], illustrated in Fig. 1, is an energy recovery linac that will make 4 accelerating passes through the linac, and return the beam to the linac using a single fixed field alternating gradient (FFAG) return line, which must simultaneously transport beams from all passes, ranging in energy from 42 MeV to 150 MeV. At the ends of the linac are 4 spreader/combiner lines, each of which transports a single energy from the linac to the FFAG line or from the FFAG line back to the linac.

Table 1: Basic parameters for the FFAG return line.

Total energy, pass 1 (MeV)	42
Total energy, pass 2 (MeV)	78
Total energy, pass 3 (MeV)	114
Total energy, pass 4 (MeV)	150
Focusing quadrupole length (mm)	133
Defocusing magnet length (mm)	122
Minimum short drift length (mm)	66
Minimum long drift length (mm)	123
Arc radius of curvature, approximate (m)	5.1
Arc cell bend angle (deg.)	5
Cells per arc	16
Cells per transition section	24

The FFAG return line has arcs at its ends (FA and FB in Fig. 1) with a relatively small bending radius to keep the machine compact. Completing the return to the linac requires a section that is straight (ZA and ZB in Fig. 1) to connect the two arcs. We connect the arcs to the straights with adiabatic transition sections (TA and TB in Fig. 1).

Table 1 describes the basic requirements for the FFAG line design. The energies correspond to a four-pass energy recovery linac with a 6 MeV injection energy. The minimum drift lengths result from allowing space for various devices (the short drift allows for a button beam position monitor (BPM), the long drift will allow for a wide variety of devices) and any overhang of magnet hardware. The radius of curvature is a result of a space limitation. The magnet lengths and maximum energy are parameters related to an earlier design using an iron-dominated magnet design, but are reasonable choices that were retained.

Each arc has 16 cells, giving 80 degrees of bend. The transition will be designed with a symmetry such that the average bend per cell is half the arc cell bend angle. Thus each transition section supplies 60 degrees of bend. Thus each spreader/combiner supplies the remaining 40 degrees of bend for half the machine.

Every focusing quadrupole will have a horizontal corrector (vertical dipole field), while every defocusing magnet will have a vertical corrector.

ARC CELL

The arc cell is the basic building block for the FFAG beam line. An illustration is given in Fig. 2. The basic cell is a doublet, consisting of a focusing quadrupole and a combined function magnet with a dipole and defocusing

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ER@CEBAF - A 7 GeV, 5-PASS, ENERGY RECOVERY EXPERIMENT*†

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Abstract

A multiple-pass, high-energy ERL experiment at the JLab CEBAF will be instrumental in providing necessary information and technology testing for a number of possible future applications and facilities such as Linac-Ring based colliders, which have been designed at BNL (eRHIC) and CERN (LHeC), and also drivers for high-energy FELs and 4th GLS.

ER@CEBAF is aimed at investigating 6D optics and beam dynamics issues in ERLs, such as synchrotron radiation effects, emittance preservation, stability, beam losses, multiple-pass orbit control/correction, multiple-pass beam dynamics in the presence of cavity HOMs, BBU and other halo studies, handling of large (SR induced) momentum spread bunches, and development of multiple-beam diagnostics instrumentation.

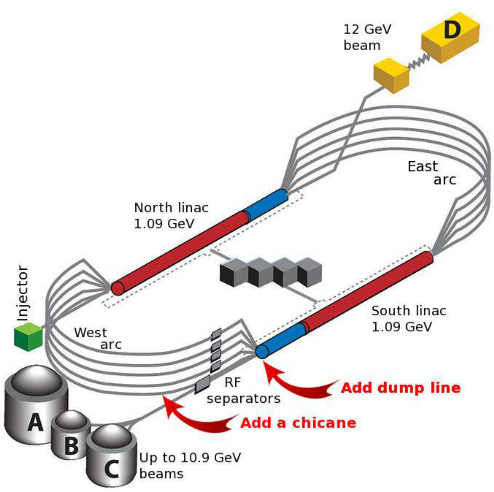

Figure 1: 12 GeV CEBAF recirculating linac. Location of chicane and dump line for ER@CEBAF.

Since it was launched 2+ years ago, the project has progressed in defining the necessary modifications to CEBAF (Fig. 1, Tab. 1, 2), including a 4-dipole phase chicane in recirculation Arc A, beam extraction and a dump line at the end of the south linac, and additional dedicated multiple-beam diagnostics. This equipment can remain in place to

Table 1: Machine/Lattice Parameters of ER@CEBAF

f_{RF}	1497	MHz	RF frequency
E_{linac}	700	MeV	Gain per linac (baseline)
E_{inj}	79	MeV	= $E_{\mathrm{linac}} \times 123/1090$
ϕ_{FODO}	60	deg	Per cell, at first NL pass and last SL pass
M_{56}	<90	cm	Compression, Arc A
Extraction	8	deg	Angle to dump line
Dump power	20	kW	
$\Delta\phi_{\mathrm{tol}}$	0.25	deg	Req$^{\mathrm{ed}}$ path-length control

Table 2: Beam Parameters

f_{beam}	31 - 499	MHz	Bunch rep. freq., CW
	7.485	MHz	Bunch rep. freq., tune mode
I_{beam}	100	μA	Max. CW beam current
q_{bunch}	0.2	pC	Bunch charge at 100 μA
σ_l	90 - 150	μm	Bunch length, high energy
σ_t	0.3 - 0.5	ps	
$\epsilon_{\mathrm{x,y}}$	$\sim 10^{-8}$	m	Geom. emitt. at injection
dp/p	$< 10^{-4}$		Energy spread at injection
$\epsilon_{\mathrm{x,y}}$	$\mathcal{O}(10^{-8})$	m	Geom. emitt., after ER
dp/p	2-3	%	At extraction

permit ER@CEBAF tests without hardware reconfiguration. Dedicated optics settings are required in the linacs (60^o phase advance), in arcs 1 and 2 (low dispersion), as well as *ad hoc* spreader and combiner tunings for linac to arc matching. Longitudinal match will require specific settings (arc M_{56}, RF phasing). These evolutions make ER@CEBAF an expansion of CEBAF capability to a 5-pass ERL, with modest switch over time and minor impact to the CEBAF physics program.

A costing of these changes to CEBAF has been performed, amounting to below $1M. Nine months will be required to have the ER installation ready for operation.

Hardware commissioning will include 3 different recirculation regimes, namely 1 linac up/1 linac down, 1-pass up/1-pass down starting with reduced energy (400~500 MeV/linac), and eventually 5-pass up/5-pass down, to be concluded with completion of ER at 7 GeV.

The project has been submitted to, and has received approval from, JLab Program Advisory Committee (PAC 44) in July 2016 [1]. A next major objective in demonstrating readiness is a technical review as mandated by PAC 44.

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[1] S.A. Bogacz et al., ER@CEBAF: A Test of 5-Pass Energy Recovery at CEBAF, JLab Tech. Note, June 6, 2016, eRHIC Tech. Note 54, BNL, June 2016.

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STUDIES OF CSR AND MICROBUNCHING AT THE JEFFERSON LABORATORY ERLS*

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Abstract

One attractive feature of energy recovery linacs (ERLs) is they are source limited. However as beam brightness increases so too do the effects of coherent synchrotron radiation (CSR) and the microbunching instability. The Low Energy Recirculator Facility at Jefferson Laboratory provides a test bed to characterize aspects of CSR's effect on the beam by measuring the energy extraction via CSR as a function of bunch compression. Data was recorded with acceleration occurring on the rising part of the RF waveform while the full compression point was moved along the backleg of the machine and the response of the beam measured. Acceleration was moved to the falling part of the RF waveform and the experiment repeated. Initial start-to-end simulations using a 1D CSR model show good agreement with measurements. The experiment motivated the design of a modified Continuous Electron Beam Accelerator Facility-style arc with control of CSR and the microbunching gain. Insights gained from that study informed designs for recirculation arcs in an ERL-driven electron cooler for Jefferson Laboratory's Electron Ion Collider. Progress on the design and outstanding challenges of the cooler are discussed.

INTRODUCTION

Coherent synchrotron radiation (CSR) poses a significant challenge for accelerators utilizing high brightness beams. When a bunch travels along a curved orbit, fields radiated from the tail of the bunch can overtake and interact with the head. Rather than the more conventional class of head-tail instabilities where the tail is affected by the actions of the head, CSR is a tail-head instability. The net result is that the tail loses energy while the head gains energy leading to an undesirable redistribution of particles in the bunch. Because the interaction takes place in a region of dispersion, the energy redistribution is correlated with the transverse positions in the bend plane and can lead to projected emittance growth. The following section describes experiments at the Low Energy Recirculator Facility (LERF, formerly the Jefferson Laboratory FEL [1]) to quantify these bulk effects on the bunch distribution. However, in addition to the potential for emittance and energy spread growth, CSR can also drive the microbunching instability. This aspect is addressed later in the context of the Jefferson Laboratory Electron-Ion Collider (JLEIC).

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MEASURED EFFECT OF CSR

Studies at the LERF (see Fig. 1) focused on characterizing the impact of CSR with the goal of benchmarking measurements with simulation . The LERF was designed as an energy recovery based linear accelerator used to condition an electron beam for high average power lasing. Electrons are generated in a DC photocathode gun (135 pC), accelerated to 9 MeV and injected into the linac where they are further accelerated up to 130 MeV through three cryomodules. Acceleration nominally occurs 10° ahead of the crest of the RF waveform, to impart a phase-energy correlation across the bunch. The first- and second-order momentum compactions of the first Bates-style recirculation arc are set so that, in conjunction with the downstream chicane, the bunch is rotated upright at the wiggler and phase space curvature is eliminated. Following the wiggler, the longitudinal phase space must be rotated back by 90° to energy compress the beam as it arrives at the dump. The experimental program consisted of characterizing the effects of CSR for two different longitudinal matches: accelerating on the rising (falling) side of RF waveform together with a negative (positive) momentum compaction – from the combined arc and chicane system – for compression.

Accelerating 10° Before Crest

Measurements were made to quantify the effect of parasitic compressions (i.e. when the bunch goes through a full compression) on beam quality through linac-to-wiggler transport. With the nominal energy chirp the beam experiences three such parasitic compressions. Quadrupole scans to measure emittance and Twiss parameters were performed at several locations around the machine and repeated with the linac cross-phased. Cross-phasing refers to switching the accelerating phase of only the middle cryomodule (which has the same gradient as the two outboard cryomodules combined) to the falling side of the RF waveform. Upon exiting the linac the energy chirp is removed and the nearly mono-energetic distribution avoids parasitic compressions. Results of the measurements are summarized in Table 1. The small horizontal emittance growth through the machine for cross-phased measurements is not unexpected, while the effect of parasitic compressions is more dramatic. These measurements together with simulations suggest that while parasitic compressions do not lead to copious CSR-

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FIRST RESULTS OF COMMISSIONING DC PHOTO-GUN FOR RHIC LOW ENERGY ELECTRON COOLER (LEReC)*

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Abstract

Non-magnetized bunched electron cooling of ion beams during low energy RHIC operation requires electron beam energy in the range of 1.6-2.6 MeV, with an average current up to 45 mA, very small energy spread, and low emittance [1]. A 400 kV DC gun equipped with a photocathode and laser system will provide a source of high-quality electron beams. During DC gun test critical elements of LEReC such as laser beam system, cathode exchange system, cathode QE lifetime, DC gun stability, beam instrumentation, the high-power beam dump system, machine protection system and controls has been tested under near- operational conditions [2]. We present the status, experimental results and experience learned during the LEReC DC gun beam testing.

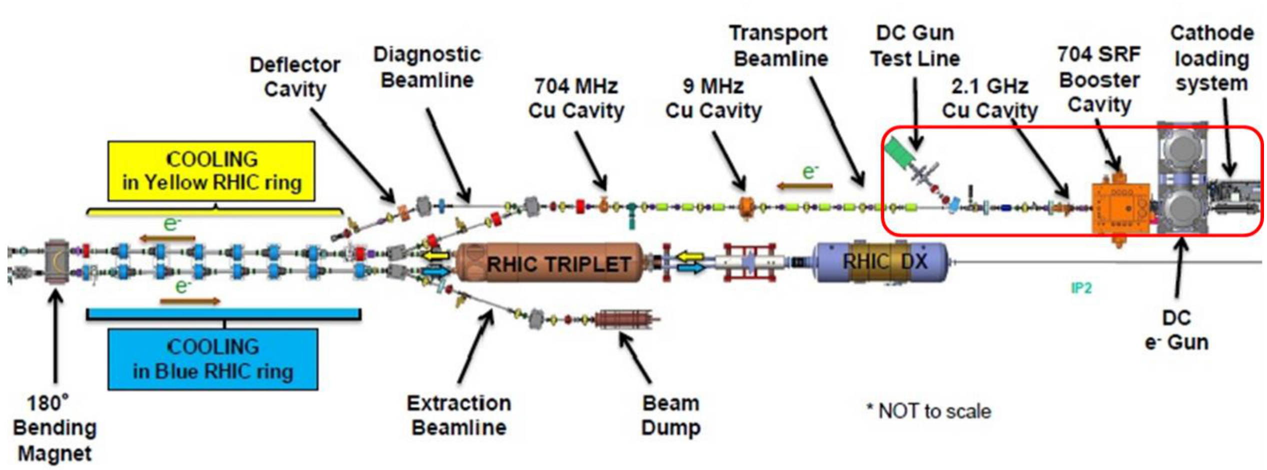
INTRODUCTION

The LEReC uses a replica of the DC photocathode gun used in the Cornell University prototype injector, which has already been producing record high-brightness, high average current electron beams [3]. The gun has been built by Cornell University. DC Gun is required to operate with more than 30 mA 24/7. Gun will use multi-alkali NaK2Sb (or CsK2Sb) photocathode, which will be illuminated with green (532 nm) laser light with an oscillator frequency of 704 MHz. We expect that lifetime of such cathodes should be 10s hours. In order to optimized operation time and minimized the cathode exchange time multi cathodes carrier has been built. It's designed to hold up to 12 pucks of photocathodes attached to the gun in 11 scale vacuum [4]. The 400 keV electron beam from the gun is transported via a 704 MHz SRF booster cavity and 2.1 GHz 3rd harmonic linearizer normal conductive cavity. Electron beam is accelerated to maximum kinetic energy of 2.6 MeV. In drift space electron bunch is stretched to required bunch length. Before entering the cooling section accumulated energy chirp is compensated by normal conductive 704 MHz cavity. Two dogleg-like mergers and mirror dipole are used to combine and to separate electron cooler electron beam with/from RHIC ion beams. The layout of LEReC is shown in Fig. 1. The optics of entire transport line has been designed and optimized to delivery electron bunches for different operation energies with quality satisfied electron cooling requirement summarized in Table 1 [5].

Table 1: LEReC electron beam requirements

Kinetic energy, MeV	**1.6**	**2.0**	**2.6**
Bunch Charge, pC	130	160	200
Bunches per train	30	27	24
Macro bunch charge, nC	3.9	4.3	4.8
Macro bunch rep. f, MHz	9.3	9.3	9.3
Total beam Current, mA	36	40	45
Normalized Emittance, μm	< 2.5	< 2.5	< 2.5
Energy spread, 10^{-4}	< 5	< 5	< 5

Figure 1: Layout of LEReC accelerator. Red contour box indicates DC gun test area.



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DEVELOPMENT OF AN ERL RF CONTROL SYSTEM*

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Abstract

The Mainz Energy-recovering Superconducting Accelerator (MESA), currently under construction at Johannes Gutenberg-Universität Mainz, requires a newly designed digital low-level radio frequency (LLRF) system. Challenging requirements have to be fulfilled to ensure high beam quality and beam parameter stability. First, the layout with two recirculations and the requirements will be shown from an LLRF point of view. Afterwards, different options for the control system are presented. This includes the generator-driven system, the self-excited loop and classical PID controller as well as more sophisticated solutions.

OVERVIEW AND REQUIREMENTS OF MESA

At Johannes Gutenberg-Universität Mainz a new accelerator will be built: The Mainz Energy-recovering Superconducting Accelerator (MESA). This accelerator will not only feature high current beams, feasible by means of energy recovery, but will also be operated as conventional multi-turn linac with a polarized electron beam. A part of the building is yet to be constructed and civil works will begin in 2018. The accelerator itself is scheduled to be constructed in 2020, but some parts can already be tested in existing halls [1].

Figure 1 shows a (preliminary) lattice [2]. The source

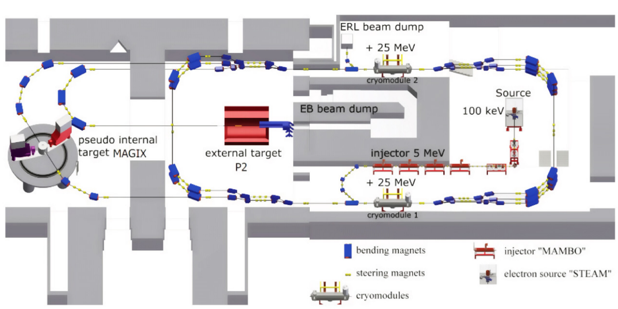

Figure 1: MESA lattice as of 2016.

called STEAM [1] ("Small Thermalized Electron-source At Mainz") will deliver a beam of polarized electrons which are pre-accelerated up to 5 MeV in the injector MAMBO ("Milli Ampere Booster") before they enter the main linac. MESA uses a double-sided layout with two cryomodules, providing an energy gain of up to 25 MeV each. After passing the cryomodules the beam is guided through the arcs for multi-turn operation. Separator magnets split the beams of different energies and recombine them before entering the cryomodules again or before experimental use.

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Two experimental sides are foreseen: If MESA works as a 3-turn linac without energy recovery, the beam will be used in the so-called "external target P2" for high precision measurements of the Electro-Weak mixing angle [1]. In this mode, a 0.15 mA polarized electron beam will be accelerated to 155 MeV. Since there will be no energy recovery after P2 the beam will be dumped at high energy. This makes heavier shielding for radiation protection necessary.

The other operation mode will be the energy-recovery mode. In this mode, the beam will interact with the pseudo internal target called MAGIX which is a windowless gas target [1]. There will only be two passes, since this experiment only needs lower energies—but ideally, the available energies range from quite as low as 25 MeV up to a maximum of 105 MeV. The use of energy recovery makes higher currents feasible. In the first stage, a current of 1 mA is planned which shall be upgraded to 10 mA in the second stage. Currently, discussions are ongoing whether this mode will also make use of polarized electrons [1]. There are many possible experiments in MAGIX' portfolio, from nuclear physics to the search for dark matter [1].

All the experiments will require high accuracy and stability of the accelerating RF field while a wide variety of parameters (e. g. beam current and energy) has to be dealt with. The RF control system will have to handle this on demand.

Multi-Turn ERL Layout

In this paper, the focus is set to the energy-recovery mode. The path a beam takes is sketched in Fig. 2, starting from the injector through the main linac to the internal experiment and back on the decelerating phase ending in the beam dump. The beam re-enters the cavities 180° out of phase

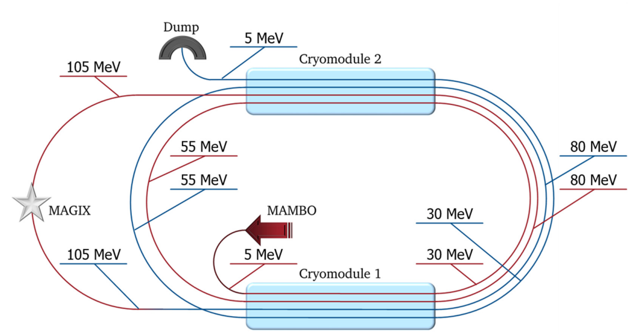

Figure 2: Sketch of the way a beam travels through MESA in the energy-recovery mode. Red: accelerating phase. Blue: decelerating phase. Note that the spatial separation is meant to clarify the different ways—in reality, the bunches are interleaved and those with the same energy share also the same beampipes in the arcs.

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STUDY OF MICROBUNCHING INSTABILITY IN MESA*

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Abstract

The Institute for Nuclear Physics (KPH) at Mainz is building a multi-turn energy recovery linear accelerator, the Mainz Energy-recovering Superconducting Accelerator (MESA), to deliver a CW beam at 105 MeV with short pulses, high current and small emittance for physics experiments with an internal target. Space charge effects potentially cause beam quality degradation for medium energy beams in smaller machines like MESA. As beam quality preservation is a major concern in an ERL during recirculation. We present a study on Microbunching Instability (MBI) caused by Longitudinal Space Charge (LSC) in MESA. Our results demonstrate the impact of the MESA arc lattice design on the development of Microbunching Instability.

INTRODUCTION

Energy recovery linacs (ERLs) provide electron beams of high current, high intensity with short pulses, facilitating their use as apparatus for various physics experiments and as free electron laser (FEL) drivers. ERLs were first proposed in 1965 and have gained tremendous interest since the 21st century [1]. At present, there are three operating ERLs: the JLab IR FEL Upgrade, the Japan Atomic Energy Agency (JAEA) FEL, and the Novosibirsk High Power THz FEL. While ERLs such as these three have been used largely for applications as FEL drivers, a large amount of research is focused on alternative applications such as dark photon detection and scattering experiments. Currently, upcoming ERL facilities include cERL at KEK, BerlinPro, and the Mainz Energy-recovering Superconducting Accelerator (MESA).

A detailed understanding of the physics of high current and high intensity beams in ERLs is of fundamental importance to preserve beam quality. While rapid advances have been made in the field of ERLs through investigations using particle tracking, the effect of space charge has received less attention. Space charge will be important in smaller machines and for medium energy and might, for example also affect the transport matrix in the arcs for recirculation [2]. It is important to develop an effective methodology to optimize the effect of space charge on lattice arcs. There is a need to explore measures to circumvent beam mismatch and corresponding emittance growth. Such studies rely on accurate predictions of the 3D beam envelope in the presence of space charge [3]. Longitudinal space charge (LSC) together dispersion can lead to the amplification of the initial shot noise, which is the well-known microbunching instability (MI). The linear microbunching gain process due to LSC can be depicted as follows [4]:

$$G \simeq 4\pi \frac{I_0}{I_A} L_s \frac{|Z(k)|}{Z_0} k |R_{56}| \tag{1}$$

where $Z(k)$ is longitudinal space charge impedance, R_{56} is the longitudinal dispersion, the bunch peak current I_0 and the Alfven's current I_A.

We adopt the LSC impedance derived in Ref. [5]. The beam is assumed transversely uniform with a circular cross section of radius r_b [5],

$$Z(k) = \frac{iZ_0}{\pi\gamma\, r_b}\left[1 - \frac{kr_b}{\gamma} K_1\left(\frac{kr_b}{\gamma}\right)\right] \tag{2}$$

where $r_b \approx 1.7(\sigma_x + \sigma_y)/2$.

The goal of our study is to predict the microbunching instability due to LSC, for the specific MESA lattice and beam parameters which we will describe below. Further, as a first step, we analyze the MESA lattice parameter in the presence of 3D space charge.

BRIEF OVERVIEW OF MESA

MESA is a small-scale, multi-turn, double-sided recirculating linac with vertical stacking of the return arcs operating in cw mode. Currently there are two planned experiments in MESA [6]:

(I) Fixed target experiment for precise measurement of the Weinberg angle with the beam extracted to the experiment in the external beam (EB) mode at 155 MeV.

(II) Pseudo Internal Target (PIT) experiment in search for dark photons with high luminosity as compared to storage rings due to low emittance life time.

A 3D sketch of MESA is shown in Fig. 1. It consists of a 100 keV polarized photo-cathode electron gun [7] with a normal conducting injector linac with an extraction energy of 5 MeV. The photo-cathode electron gun produces very short electron bunches. There are two superconducting linac modules with an energy gain of 25 MeV for each pass with four spreader sections for separating and recombining the beam and two chicanes for injection and extraction of the 5 MeV beam [8]. For beam recirculation there are five arcs to support the beam corresponding to five different energy levels: 55 MeV, 80 MeV, 105 MeV,130 MeV and 155 MeV. The proposed beam parameters for MESA are in Table. 1. After the PIT experiment, the beam re-enters the main module with a 180^0 phase shift and starts to decelerate. The decelerated beam is dumped at 5 MeV [8].

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ERL17 WORKSHOP, WG1 SUMMARY: INJECTORS

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Abstract

The 59th ICFA Advance Beam Dynamics Workshop on Energy Recovery Linacs, hosted by the CERN was held on CERN campus. The working group (WG) 1 ERL injectors focused on high-brightness, high-power CW electron gun and high QE long lifetime semiconductor photocathode. The working group 1 was separated into two sessions: One is electron gun session, which has eight invited talks; another is photocathode session, which has six invited talks and one contributed talk. This report summarizes the state of the art of electron guns and photocathodes discussed in the ERL workshop WG1.

INTRODUCTION

Energy Recovery Linacs (ERL) enable the generation of high current high brightness electrons beam with high energy and cost saving. The high current, low emittance electron sources are always one of the challenges of ERL. So far, there are several facilities successfully commissioned and operated the electron guns in last a few years. Also, several labs are capable of preparing high QE semiconductor photocathodes for electron guns. These experiences provide an opportunities to push to even higher quality electron source. However, the challenges are still existed such as long lifetime operation cathode, stable operation SRF gun as well as high current operation.

There are total 14 talks in WG1. A large variety of interesting and important topics have been presented in the WG1 sessions. From the number of talks, we identified 4 topics with two separated sessions: Session1 photocathode: i. High QE, long lifetime photocathode: CeC, LEReC (BNL), SHXFEL (SHLS),Mainz Univ. HZB, HZRD. ii. Cryogenic cathode: Cornell, HZB, HZRD Session 2: iii. DC gun: BNL, JAEA/KEK, Mainz Univ.,Cornell Univ., KEK,ALICE iv. SRF gun: BNL, HZDR, PKU DCSC, HZB.

This report concludes with the discussions of cathode and gun operation/commissioning results, concerns, technical issues related to electron source realization and interesting concepts.

SUMMARY OF PHOTOCATHODE SESSION

The photocathode session has seven talks. All talks are discussed alkali antimony based photocathode including CsK2Sb, KNa2Sb, and Cs3Sb. Alkali antimony photocathodes have advantages on visible light sensitive (Green prefer), high QE, low thermal emittance and long lifetime. It could use in DC gun, RF gun, and SRF gun. The presenter Dr. Taro Konomi from KEK, Dr. Triveni Rao from BNL, and Dr. Julius Kuhn from HZD showed the prepared antimony based photocathode can reach 10% QE with the green laser. More discussions brought up in these talks: 1) Using ITO as a substrate to generates transparent photocathode for RF sealing. The cathode QE is almost equalized using reflection mode and transparent mode by a green laser. Transparent photocathode has advantages on simplified the laser transport system and obtaining the low emittance electrons. 2) The cathode routing production system requires very high capacities of alkali source. Conventional SAES sources are not sufficient for continuous cathode preparation. So J-bend effusion cells are developed and used in routing alkali antimony cathode preparation. 3) Using the cathode in cryogenic environments is an open discussion issue for many years. Measure the cathode QE evolution in temperature reducing helps to understand the cathode performance in SRF gun. Besides on high current operation, obtain low transverse and longitudinal emittance electrons beam are very important directions for electron source development. Dr. Monika Dehn From Univ. Mainz compared the multialkali PEA material's longitudinal temporal response with GaAs NEA material and found that the PEA material has significantly short bunch tail. Prof. Ivan Bazarov from Cornell Univ. discussed the cathode in a cryogenic environment and combining with transparent mode operation will generate orders of magnitude lower mean transverse energy electrons. More labs involve the alkali antimony photocathode development. Some labs switch from GaAs photocathode to alkali antimony photocathode for either DC gun or RF gun. The presenter Zhenggong Jiang from SHLS and Dr. Nishimori from KEK presented their new developed alkali antimony deposition systems.

In open discussion, we have two major opening discussion topics, which were recommended to future R&D.

1) Several labs tested the cathode performance in cryogenic temperature. For the HZB case, the cathode QE at long wavelength side is increased once cathode cool down to LN2 temperature. It is possible caused by the phonon scattering domination in cathode crystal. In the cryogenic environment, the phonon-electron scattering rate decreased, then the QE increase. This may be related to the cathode lattice structure, defects or surface states. The advantage is possible to cool the cathode, generate low thermal emittance electron beams with high QE.

2) Recently, The challenge will be using the alkali semiconductor cathode inside the SRF gun, either caused multipacting or lifetime concerns. It is possible to develop advanced cathodes without any alkali metals or say with superconducting prefered materials such as hydrogen, nitrogen? The diamond amplifier was studied at BNL in a few years before. This is only H_2 terminated on emission source. Recently, the SRF gun has tested with alkali antimony cathode. Test diamond amplifier may solve the issues found in SRF gun test.

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ERL17 WORKSHOP, WG2 SUMMARY: OPTICS, BEAM DYNAMICS AND INSTRUMENTATION

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During the workshop a number of interesting projects were discussed: ERL at KEK, ALICE, PERLE, LHeC, eRHIC, CBETA, ERL for MESA and bERLinPro; a nice mixture of future, existing and past facilities. As a message for future ERL facilities, past operational experience and optimization efforts from ALICE were highlighted (P. Williams/Daresbury). Importance of implementing separate diagnostics for the lattice and the beam was emphasized along with a need for simulations aimed at step-by-step modeling of procedures one needs to exercise to establish the beam conditions defined by milestones of the project. Valuable experience of high charge per bunch operation of compact ERL at KEK was also presented (T. Miyajima/KEK).

Three talks were devoted to beam dynamics challenges of CBETA (G. Hoffstaetter/Cornell, C. Mayes/SLAC, S. Berg/BNL); covering lattice design, magnet technology and orbit control. With four different energies CBETA becomes a test-bed for multi-pass beam dynamics issues, such as: time of flight control for beams with energy spread and the recirculative BBU (addressed by cavity design with strong damping).

Extending the quest for more passes in a racetrack ERL, optimized linac optics for 5-pass ER@CEBAF was presented. Multi-pass energy recovery in a racetrack topology explicitly requires that both the accelerating and the decelerating beams share the individual return arcs. This in turn, imposes specific requirements for the TWISS function at the linacs ends.

As an ultimate application of multi-pass ERLs the FFAG, 6-pass e-RHIC ring was highlighted (V. Ptitsyn/BNL). Here, CBETA will provide an important synergistic input. Even so, recently the Ring-Ring option has become more in the focus for the eRHIC design, there are still efforts on ERL-Ring option for eRHIC.

A comprehensive review of beam dynamics driven design of the LHeC, 60 GeV ERL was presented (D. Pellegrini/CERN), which is probing the longitudinal acceptance limits in high energy ERLs. Extreme synchrotron radiation effects (almost 2 GeV energy loss around a 3-pass racetrack) were simulated to assure that the SR induced energy spread and corresponding emittance dilution due to quantum excitations will not impede the energy recovery process on the decelerating passes. These effects along with beam-beam, short and long range wake-fields and imperfections were simulated with PLACET2 and ELEGANT. The resulting End-to–End simulation showed acceptable levels of energy spread and emittances all the way to the dump, vastly dominated by the synchrotron radiation effects.

Probing the limits of virtual power vs RF power in high current ERLs, two presentations on rapidly developing bERLinPro highlighted the overall design and project commissioning status (A. Jankowiak/HZB), as well as the beam dynamics challenges of the extreme high current (100 mAmp) operation (M. Abo-Bakr/HZB). In the same category of high power ERLs, PERLE – the newly proposed ERL Test Facility at Orsay – was introduced (W. Kaabi/LAL) along with its current layout and optics design (A. Bogacz/JLAB). A future R&D program was presented to fully develop a Technical Design Report, which will require work in the following areas:

- Liner lattice optimization and initial magnet specs
- Momentum acceptance and longitudinal matching
- End-to-End simulations with synchrotron radiation, CSR micro-bunching (ELEGANT)
- Correction of nonlinear aberrations (geometric & chromatic) with multipole magnets (sextupoles and possibly octupoles)
- RF cavity design, HOM content BBU studies (TDBBU)
- Injection line/chicane design space-charge studies at injection
- Diagnostics & Instrumentation
- Multi-particle tracking studies of halo formation
- Final magnet specs
- Engineering design

Operational experience of another superconducting linac based nuclear physics user facility – MESA – was described (F. Hug/U. of Mainz). This two-pass, high current (10 mAmp) ERL truly excels in versatility providing highly polarized beams to large number of experiments.

Finally, a clever lattice mitigation scheme for CSR/micro-bunching suppression was presented (C. Tennant/JLAB). As the lattice figure of merit, a variation of M_{56} (max value of M_{56} across the lattice) was chosen. Two lattices with diverse values of M_{56} variation were simulated with ELEGANT, introducing initial density fluctuation 'seed' and looking for the onset of micro-bunching instability. The results revealed striking suppression of instability growth for the case of minimum M_{56} variation.

In summary, we witness a rather vigorous development of new ERLs, aggressively pushing the limits:

- Maximizing number of passes
- Maximizing virtual beam power
- Opening longitudinal acceptance
- Mitigation of limiting factors: BBU, CSR/micro-bunching
- Diagnostics & Instrumentation for multiple beams
- Multi-particle tracking studies of dark current and halo formation (M. McAteer/HZB).

A bright future can be expected for the field.

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ERL17 WORKSHOP, WG3 SUMMARY: TEST FACILITIES AROUND THE WORLD

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This contribution has not been submitted.

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ERL17 WORKSHOP, WG4 SUMMARY: SUPERCONDUCTING RF

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F. Gerigk, CERN, Geneva, Switzerland

Abstract

Working Group 4 consisted of 10 talks (see References), which were split into three sessions around four main themes. These themes will be listed and summarized in the following along with a summary of the discussion session.

HIGHER ORDER MODE DAMPING AND FUNDAMENTAL POWER COUPLERS

ERL power couplers need to be able to provide 10's of kWs in Continuous Wave (CW) operation. While CW power transmission has been demonstrated up to levels of 500 kW (standing wave) or even 750 kW in travelling wave, e.g. at CERN [1], it became clear that a successful coupler development is a multi-year effort, which is only mastered by a few experts worldwide. For lower frequencies, which are often favoured by ERLs, coaxial couplers are typically preferred [2] with a new development of TE11 coaxial couplers showing particular promise to handle high average CW power. High-pass filters in Higher Order Mode Suppressors (HOMS) are relatively new and require further development.

ADVANCES IN SRF SURFACE PERFORMANCE

In CW ERLs, RF surface losses often determine the maximum gradients at which the SRF cavities can be used. Lowering surface losses therefore has a significant impact on the facility footprint, initial cost, and running costs of the RF stations and cryogenic installations. Recent advances in the field of nitrogen doping flattened out the Q-slopes (in 1.3 GHz cavities) up to gradients of around 25 MV/m. Nitrogen infusion, which is still being optimized shows high Q values even at high gradients up to 40/45 MV/m. The nitrogen infusion method offers the possibility to tailor cavities to specific applications [3]. The effort of Niobium on Copper coatings has re-started and first samples show that it is possible to flatten the Q-slope, which was typically observed on coated cavities up until today [4]. Further effort is needed to unblock the full potential of this technique, which is used at CERN for LEP, LHC, and recently the HIE-ISOLDE cavities.

MICROPHONICS AND RESONANCE CONTROL

Issues of microphonics and cavity resonance stability continue to challenge new SRF installations, especially in view of the recent advances with nitrogen doping/infusion, which substantially increases the cavity Q but which equally decreases the cavity bandwidth. In case of the LCLS-II cryo module this translates into a cavity half-bandwidth of 16 Hz and a peak detuning requirement of 10 Hz, which means that active resonance control is becoming mandatory for operation [5]. First beam has just been seen in the Main Linac Cryomodule (MLC) at the CBETA facility (Cornell), which also faces the challenge of operating with a very small bandwidth (10 Hz) [6].

As part of the Low-Level Control System (LLRF) [7] active resonance control typically consists of Lorentz Force detuning compensation via fast piezo tuners and adaptive feedforward algorithms. In order to achieve the small detuning levels, which are necessary for the active resonance control to work, the cavities [8], the cryo module design and the cryogenic supply system all have to be optimised for very low vibrations/microphonics [9].

CAVITY DESIGNS AND CRYOMODULE PERFORMANCE

Dual axis cavities [10] can offer significant advantages as they: i) allow to have a straight trajectory for the injection of low-energy beams, ii) allow dumping of beams with large energy spread (no dispersion in the dumped beam as there is no bend between the decelerating cavity and the dump), iii) have the potential of improved BBU suppression. Despite these advantages, there are very few proposals today to actually use this type of cavities in a machine (see discussion session).

DISCUSSION SESSION

Coated versus bulk Niobium cavities

The question of which fabrication technique to choose depends on the desired beam characteristics. For high-current applications lower frequency cavities are often chosen because of the lower excitation and easier extraction of HOM power. Due to their larger size, low-frequency cavities are mechanically more stable if made out of copper, as it was done for instance for the 350 MHz LEP cavities or the 400 MHz LHC cavities. For lower-current applications, higher frequency (> 650 MHz) multi-cell cavities out of bulk Nb are typically chosen, as they are easier to fabricate and require small cryostats. Recent progress in nitrogen doping/infusion have dramatically reduced the surface resistance of bulk Nb cavities and this technique is already being applied to the series production of LCLS-II cavities [3]. One can argue that nitrogen doping is in fact a thin film/coating technique as the ensuing physics takes place only in the top surface layer.

Nb/Cu has lower residual resistance at low fields than bulk Nb but has traditionally suffered from a strong Q-slope at higher fields. Recent work has related the Q-slope to small defects at the Nb/Cu interface. Moving

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ERL17 WORKSHOP, WG5 SUMMARY: APPLICATIONS

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Abstract

For the ERL17 Applications Working Group (WG5), a focus was identified for Photon science and Particle and Nuclear Physics application areas. For the Photon applications; THz, FEL and Compton drivers were most relevant and for the Particle and Nuclear Physics field, Compton, Polarised and Cooled beams were most prominent. The following then highlights the key performance needs, challenges and anticipated future demands for each of these application areas as reviewed and discussed at the workshop.

PHOTON APPLICATIONS

THz

For optimum THz user delivery, there is a fundamental need for high power and broad spectral range (ideally upto 3THz). It was noted that broadband, short-pulse, high repetition rate THz is inconsistent with competing demands for highly monochromatic and coherent THz delivery, which ideally should be accomplished using the same ERL platform. Good pulse-pulse THz stability is also a key operational requirement. The challenges to achieve such requirements are driven by the stability of the energy recovered beam in terms of bunch charge, beam energy, bunch length and RF stability. Careful and repeatable machine optimisation is therefore required, however it was noted that the use of a THz cavity could provide a more consistent THz beam for user exploitation. In addition, the transport of THz radiation across long distances is difficult and it was reported that Jlab have a precision HeNe laser alignment system which includes source-point tracking for their THz distribution line in order to minimise transmission losses from the ERL to their exploitation area. THz utilisation is most definitely a growing field of scientific research and with advent of diffraction-limited performance from synchrotrons, the scope for THz research is expected to expand even further.

FEL

For effective ERL delivery for FEL applications, the stability of the entire machine was cited as the fundamental requirement, in particular the beam energy and pulse-pulse stability in order to achieve the required FEL wavelength and output power. Utilisation of complex, fast feedback across the ERL laser, RF and FEL systems are identified as the most effective direct mitigation mechanism, however achieving higher repetition rates with equivalent stability performance is a fundamental target for ERLs in comparison with single pass linac topologies.

EUV

Industrial demands for achieving high power EUV radiation at <13.5nm wavelengths for X-ray lithography applications drive the FEL output performance to way beyond current state-of-the-art. Such an ERL platform requires >10kW EUV power at >98% machine availability with an extremely high degree of beam stability throughout the entire accelerator chain. In order to achieve such demanding requirements, necessitates a considerable level of inherent system redundancy and relaxation (wherever possible) of the sub-system complexity and operational demands, to the extent whereby even complete system replication can be incorporated, which will facilitate rapid change-over should a system failure occur. Such consumer demand is driving technologies to shorter and shorter wavelength regimes and whilst commercial commitment is not yet at the stage to formally launch a complete ERL platform delivery, this is likely to change in the near future as competing demand continues to strive towards higher integrated circuit transistor densities.

Compton

Laser Compton Scattering (LCS) techniques for both X-ray and γ-ray beam generation, with X-rays being used for medical imaging and γ-rays being used for nuclear material security interrogation. The demand for such capabilities requires high energy beams to enable reduced exposure times for imaging/interrogation; for X-rays, typically need 50MeV, 10mA and >100kW laser power to achieve ~40keV X-ray energy and for γ-rays utilising various Nuclear Resonance Fluorescence (NRF) techniques. For both, the key challenge is the provision of a suitable high power laser source which can be accommodated in a small footprint. A laser enhancement cavity which can store dual-beams with a fast polarisation switch appears to be a suitable solution for providing both X and γ-ray beam generation. Compact ERL platform demands for implementation into a hospital environment is an overriding challenge for medical imaging.

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