PLANS FOR AN ERL TEST FACILITY AT CERN

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Abstract

The baseline electron accelerator for LHeC and one option for FCC-he is an Energy Recovery Linac. To prepare and study the necessary key technologies, CERN has started – in collaboration with JLAB and Mainz University – the conceptual design of an ERL Test Facility (ERL-TF). Staged construction will allow the study under different conditions with up to 3 passes, beam energies of up to about 1 GeV and currents of up to 50 mA. The design and development of superconducting cavity modules, including coupler and HOM damper designs, are also of central importance for other existing and future accelerators and their tests are at the heart of the current ERL-TF goals. However, the ERL-TF could also provide a unique infrastructure for several applications that go beyond developing and testing the ERL technology at CERN. In addition to experimental studies of beam dynamics, operational and reliability issues in an ERL, it could equally serve for quench tests of superconducting magnets, as physics experimental facility on its own right or as test stand for detector developments. This contribution will describe the goals and the concept of the facility and the status of the R&D.

INTRODUCTION

Coupled to a vigorous R&D program on high-field magnets and high-gradient accelerating structures, CERN has started Design Studies to prepare the technologies that will be in demand for a future "ambitious post-LHC accelerator project"[1]. Since normal-conducting RF is limited to pulsed operation at high gradients, superconducting RF (SRF) clearly is a key technology for future large particle accelerators.

SRF has made remarkable progress over the last decades, notably towards the ILC, but recently interesting new ideas indicate further potential (nitrogen doping, Nb_3Sn coating …). R&D to fully exploit this potential requires facilities to fabricate and test prototypes, ultimately probing also the interaction with a particle beam. The planned ERL-TF could serve this purpose.

The Large Hadron electron Collider (LHeC) is a proposed electron proton collider that uses one of the LHC 7 TeV proton beams and collides it with a 60 GeV electron beam [2]. The LHeC may potentially be an interesting intermediate project for bridging the transition from the LHC and HL-LHC era to a future 'ambitious post LHC accelerator project', allowing for interesting complementary physics including DIS to probe the inner structure of protons and Higgs production via vector boson fusion, and would in particular fully develop the interesting technology of ERLs at large. At the same time, it employs the same SRF technology that takes centre stage of the R&D program for an "ambitious post-LHC accelerator project" and could eventually even serve as a lepton pre-injector for a post-LHC machine.

GOALS OF THE ERL-TF

Test Facility for SRF Cavities and Cryomodules

As mandated by the European Strategy, CERN has started strengthening its know-how, facilities and competencies in SRF technology. This will be needed to maintain the existing LHC systems (401 MHz), to upgrade it to HL-LHC (401 MHz crab cavities and 802 MHz harmonic system study), to design, fabricate and operate new SRF systems (e.g. HIE-ISOLDE at 101 MHz) and to further develop the technology for future applications. One of these R&D directions concerns the SPL and ESS. In this framework short 704 MHz, 4-cavity cryomodules with 5-cell cavities were designed and built – they are presently under test. Another direction is the initial design phase for the FCC [3], for which again 401 MHz and 802 MHz systems are considered. Primarily for reasons of compatibility with LHC, HL-LHC and FCC, the LHeC study has opted for the same frequency, 802 MHz.

For most of these projects and studies, the proposed ERL-TF would serve as training ground for scientists, engineers and technicians; it would have relevant parameters, including the possibility to study operational aspects with full power and beam interaction, but without perturbing the important physics exploitation of the LHC and its injector chain. Under conditions described below, the facility may be reconfigured to test cavities/cryomodules at other frequencies, notably 704.4 MHz (SPL, ESS) and 1,300 MHz (ILC, European XFEL).

Study of a High-Energy, Multi-Pass ERL

Another important goal of the proposed ERL-TF is to study fundamental questions in the behaviour of an ERL itself. Important beam dynamics aspects will require experimental verification simultaneous acceleration and deceleration, acceptable spent beam quality or the limits of energy recovery, just to name a few.

Study Injector and Electron Gun

An important part of the study is the injector and the electron gun, which should provide 350 pC bunches at a rate of 36 MHz. The preferred option would be a photo injector, but other options are currently also considered. A booster would accelerate the electron beam to at least 5 MeV (66 kW beam power) – ongoing simulations will indicate whether this energy has to be increased to better cope with space charge effects. Note that the frequency is

ISBN 978-3-95450-142-7

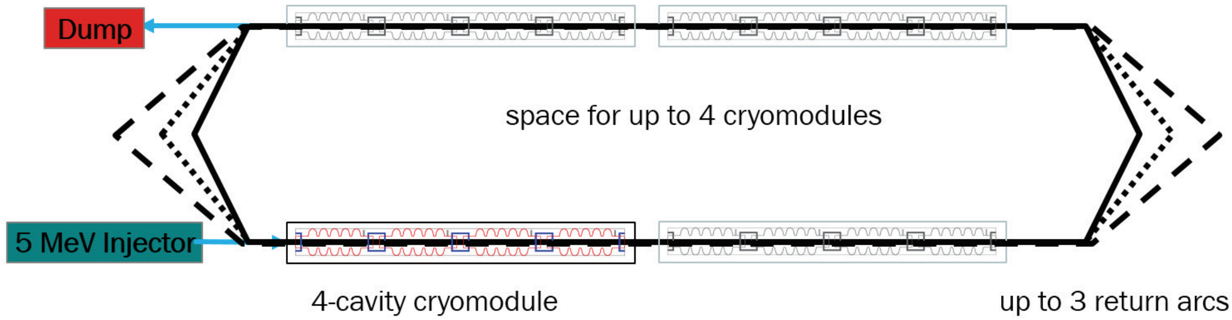

Figure 1: A possible layout of the ERL-TF

chosen different from the LHeC injector frequency (40.1 MHz) in order to stay compatible with the operation at different frequencies as described below.

Possible use as Beam Facility

In addition to the use as a R&D facility for SRF and ERLs themselves, the finished ERL-TF could become a beam facility with interesting parameters for other applications, including controlled beam-induced quenches of superconducting cables, magnets and cavities or Free Electron Lasers, for more examples please refer to [4].

CONCEPTUAL DESIGN OF THE ERL-TF

Layout

A possible layout and its optics is described in detail in [5]. In its full energy version, the ERL-TF will consist of two anti-parallel linacs with two 4-cavity cryomodules in each (cf. Fig.1) – in its minimal configuration it allows testing a single cryomodule with beam and with or without recirculation. No focussing elements are foreseen in the linac(s). Vertical spreaders/combiners (not shown in Fig. 1) separate the beams into up to 3 vertically separated arcs, each of which is optimized for its nominal energy but flexible enough to work at different energies. The highest energy arc is adjusted in length to assure arrival in the decelerating phase when entering the linac again for subsequent deceleration.

Without precluding the use at other frequencies and different cavity/cryomodule parameters, some baseline parameters have been chosen for the ERL-TF and are presented in Table 1.

Frequency choice

Several frequencies were considered in discussion for the test facility, e.g. 704 MHz (SPL) and 1.3 GHz (X-FEL, ILC). A frequency of 802 MHz was eventually chosen (it has to be a harmonic of 40.1 MHz) for the LHeC and as baseline for the ERL-TF since it is identical to the CERN SPS harmonic system, the LHC harmonic system presently under discussion and one of the frequencies envisaged for the FCC study.

Table 1: Basic Parameters of the ERL-TF

Parameter	*Value*	
injection energy	5 MeV	
RF frequency	801.59 MHz	
acc. voltage per cavity	18.7 MV	
# cells per cavity	5	
cavity length	≈ 1.2 m	
# cavities per cryomodule	4	
RF power per cryomodule	≤ 50 kW	
# cryomodules	4	
max. acceleration per pass	300 MeV	
bunch repetition f	36.4395 MHz*	
injected beam current	< 13 mA	
nominal bunch charge	$350\ \text{pC} = 2.2 \cdot 10^9\ e$	
number of passes	2	3
top energy	604 MeV	903 MeV
duty factor	CW	

Cavity and Cryomodule Concepts

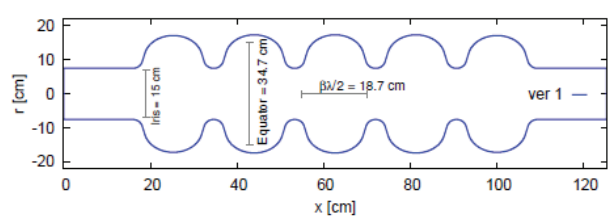

Figure 2: 5-cell cavity envelope for 802 MHz, version 1 with 150 mm aperture.

The initial cavity design is based on existing SPL, JLAB and BNL experience; the considered 802 MHz cavity shape is sketched in Fig. 2; it is derived from an earlier 704 MHz design, keeping the beam aperture at constant 150 mm. The cavities should be optimized for Q_0 while the accelerating gradient is kept at about 15 MV/m. Scans of the parameter space around this starting point (varying iris aperture, iris width and cavity wall angle) revealed that this first guess was acceptable in terms of R/Q and peak surface fields.

Due to the high currents (at least some tens of mA) foreseen in the ERL cavity, the higher order mode (HOM)

* assuming $f_0 = 12.145$ MHz. For LHeC, a bunch frequency of $f_0 = 40.079$ MHz will be used.

spectrum and damping plays an equally important role in the final geometry. The ultimate goal is to reach a single mode cavity with all HOMs freely propagating into the beam pipe, even though this seems very challenging in multi-cell cavities.

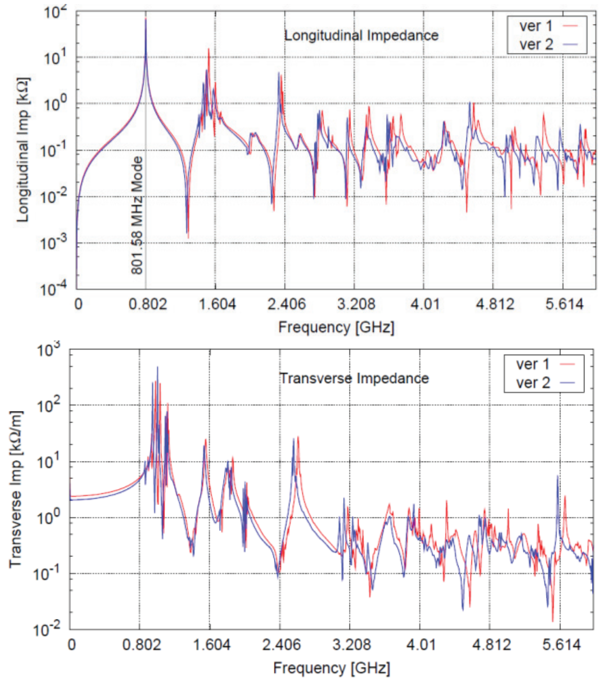

Figure 3: Longitudinal (top) and transverse impedance spectrum of initial 5-cell, 802 MHz cavities. ver 1: 150 mm aperture, ver 2: 160 mm iris aperture.

Fig. 3 shows the mode spectra for longitudinal and transverse modes for different iris apertures. The larger aperture gives a smaller longitudinal loss factor, but the optimization of the cavity shape is not yet conclusive.

JLAB had designed an 805 MHz cryomodule for SNS, which is a good starting point for the 802 MHz design; the concept is indicated in Fig.4.

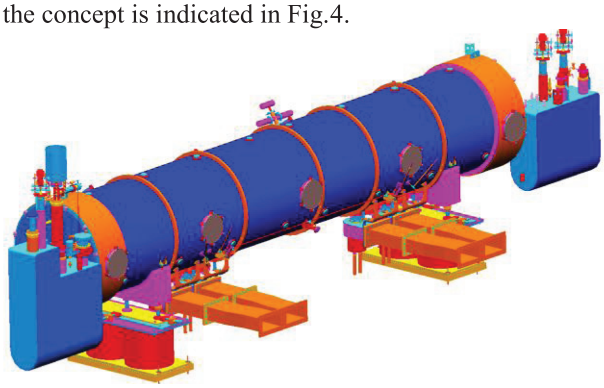

Figure 4: Conceptual design of the 802 MHz CM, SNS style [6].

Operation at different frequencies

Since the main purpose of the ERL-TF is testing of SRF cavities and cryomodules, one should not preclude by design operation at other frequencies, notably at 704 MHz and 1.3 GHz. This flexibility could be built in under two conditions: 1) If the injector pulses at $f_0 =$ 12.1453 MHz, the facility would in fact allow operation at 704 MHz ($h = 58$), 802 MHz ($h = 66$) and 1.3 GHz ($h = 107$). This requires the injector RF system also to operate on an arbitrary harmonic of f_0. 2) the arc lengths must be adjustable such that subsequent passes are in phase in the cavities (except for the highest energy passage, where phase inversion is introduced). This can be done e.g. allowing one entire arc to be axially adjustable by about 10 cm. Thus the ERL-TF could be re-configured to test cavities/cryomodules at all three considered frequencies.

Lattice

An example arc layout is shown in Fig. 5 by example of the lowest energy arc. It includes a two-step achromat spreader and a mirror symmetric combiner. The vertical dispersion introduced by the first step bend is suppressed by the quadrupoles located appropriately between the two stages. The switchyards separate all 3 arcs into a 90 cm high vertical stack with the highest energy arc remaining at the linac-level. A horizontal dogleg, used for path length adjustment, is placed downstream of each spreader. The recirculating arc at 155 MeV is composed of four 90 cm long dipoles to bend the beam by 180° and of a series of quadrupoles (2 triplets and 1 singlet).

INTERNATIONAL COLLABORATIONS

Strong synergy exists with the MESA project at Mainz University [7]; help with the design and construction of the 802 MHz cavities and cryomodules will result from

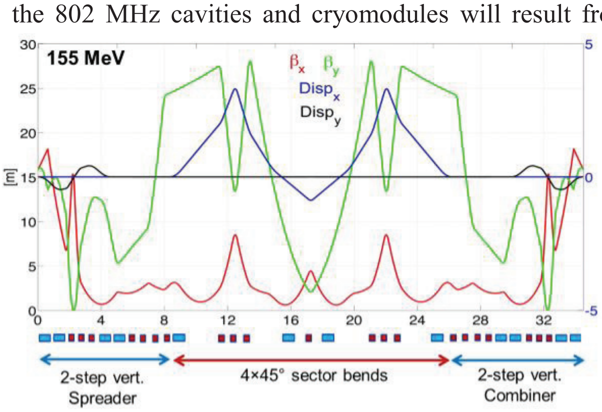

Figure 5: Optics based on an FMC cell of the lowest energy return arc at 155 MeV. Horizontal (red) and vertical (green) β-functions are shown. Blue and black curves show horizontal and vertical dispersion, respectively.

collaboration with JLAB, who have already contributed significantly to the lattice and with their relevant experience operating CEBAF and the FEL in ERL mode, Cornell University has studied an injector with similar characteristics. CERN invites further collaborations, e.g. for the injector, magnets and other subsystems.

The authors wish to thank H. Schopper for his encouragement and support.

ISBN 978-3-95450-142-7

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