Review of CW Electron Machines

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Abstract

The basic principles how to obtain continuous electron beams for fixed target experiments in Nuclear Physics are described. A few operating machines are presented with their actual performance and upgrading programs.

1. Introduction

Accelerators providing continuous electron beams for experiments on internal or external fixed targets have been proposed since the late sixties already. Up to now two general schemes proved to be successful to achieve the goal: the pulse stretcher ring and the recirculating linac [1]. The latter one appears in two different versions.

The pulse stretcher ring is the natural method to convert an already existing pulsed accelerator, linac or synchrotron, into a continuous particle source. The recirculating linac, in contrary, is designed from the beginning to produce a continuous beam.

In the following the conceptual design of both schemes together with their characteristic properties is treated. Important operating machines of both types are presented.

2. Pulse Stretcher Rings

2.1 General

The basic idea of this scheme is to add an electron storage ring to the existing pulsed accelerator. The short particle bursts from the bad duty factor machine are injected into the storage ring. In the time between two bursts the circulating electrons are slowly extracted from it or used to hit an internal target. Since some time is necessary for injection and for turning on the extraction, the user beam is not really continuous, but near to it. The macroscopic duty factor is given as the ratio of the time τ of the beam on the target and the period time τ_0 of the injection. The overall duty factor is determined by further parameters. The stretcher ring has to be filled with electrons completely and homogeneously. Therefore the beam pulse duration of the primary accelerator has to be equal to the revolution time of the electrons in the ring, at least. In the case of a linac booster with a beam pulse length of one microsecond or even more a multi-turn injection is required to match pulse length and stretcher circumference. In the case of a synchrotron booster it might happen that the stretcher circumference exceeds that of the booster. Then it becomes difficult to fill the stretcher completely and homogeneously with one burst. To overcome this problem the extraction from the booster synchrotron has to be executed over more than one turn, f. i. by a shaving method which, however, suffers from lower efficiency.

At high energies the radiation losses of the circulating electrons in the stretcher ring have to be compensated by a RF accelerating system. The RF defines a microscopic time structure which in principle lowers the duty cycle of the beam. But for all the known stretcher rings the RF frequency is near to 500 MHz or higher. The corresponding bunch structure of the beam does not bother the experiments.

At the expense of the duty cycle the energy of the electrons in the stretcher ring may also be raised prior to extraction if the ring components - magnets, accelerating system - are designed for higher energy, of course.

The most crucial problem of a stretcher ring is the beam extraction. The method usually being applied is resonance extraction which makes use of slowly exciting a betatron resonance. A nonlinearity in the ring is switched on to obtain a finite phase space area and by slowly tuning the ring optics towards the betatron resonance the particles are squeezed out of the shrinking phase space area. A properly positioned septum magnet defines the narrowest place of the ring aperture. It peels off the particles with the largest oscillation amplitudes and deflects them into the external beam channel. The method of resonance extraction will be treated further in an extra chapter.

Another way to extract electrons from a stretcher ring is to make use of multiple-scattering of the particles on a thin vertical wire target. The increasing angle causes larger betatron amplitudes of the scattered electron. If the wire target position is properly chosen the large oscillation amplitude appears in front of the extraction septum magnet. With a growing number of scattering processes of an individual electron the displacement in front of the septum increases until the particle penetrates into the active field of it and is extracted. The scattering process is stochastic and a high microscopic duty factor is achieved. This method has been studied in detail at Saskatoon [2] and is used at ELSA in Bonn for low energies and intensities.

2.2 *Resonance Extraction* ([3], [4])

The betatron oscillation instability being applied for this method of extraction might be a half-integer or a third-integer resonance. In former times the half-integer resonance, which is a strong instability, was used to extract electrons from the rapid cycling synchrotrons with a high efficiency. For stretcher rings working at high repetition rate, f. i. 1 KHz in the case of the Bates SHR, the half-integer resonance still is applied. For slowly cycling machines with repetition rates of 50 Hz or even less the soft third-integer resonance is preferred. The spill is under better control and might be extended to some ten milliseconds or even seconds, as will be shown afterwards.

Resonant extraction requires that the betatron tune of the individual particle is changed from its initial tune $Q_{x\,inj}$ at injection to a tune close to the resonant tune $Q_{x\,res}$:

$$Q_{x\,inj} + \Delta Q_x = Q_{x\,res} = n/3. \qquad (1)$$

Because of the fact that the stretcher ring has a natural chromaticity CH_x particles with an energy deviation $\Delta p/p_o$ undergo a tune shift ΔQ_x:

$$\Delta Q_x = CH_x \cdot \Delta p/p_o. \qquad (2)$$

In this connection two extraction methods are defined according to how the necessary tune shift is achieved: achromatic and monochromatic extraction.

In the first method the extraction probability of a particle depends only on its phase space co-ordinates and not on its energy. This condition is obtained by cancelling the natural chromaticity of the ring with appropriate sextupole fields. The tune shift ΔQ_x is created by changing the current of the main ring quadrupoles, or more suitable, by the current of special extraction quadrupoles.

For monochromatic extraction the ring chromaticity must not vanish and the tune shift is connected to the energy deviation of the particles. Therefore the electrons, by losing energy through synchrotron radiation, are individually outside the stability triangle some time and are extracted. Appropriate settings of the chromaticity and the excitation sextupoles allow to optimize the extraction process in respect to efficiency as well as to smoothness and duration of the spill. Because of synchrotron radiation emission being a stochastic phenomenon the electron extraction occurs at a high microscopic duty factor. The only problem is that at high energies it is necessary to use an accelerating system to obtain the needed lifetime of the circulating beam. However, the monochromatic extraction scheme may also be applied with a bunched beam. The RF bucket size is kept at a minimum width and by reducing the RF amplitude with decreasing internal current the overvoltage factor stays constant or even goes down.

2.3 Operating Stretcher Rings

2.3.1 EROS, Saskatoon ([5], [6], [7], [8], [9])

The pulse stretcher ring (PSR), EROS, was designed to stretch the pulsed beam of the Saskatchewan University Electron Linac into a continuous beam. Concept and design of EROS were published for the first time in 1971 [7]. A lot of pioneering theoretical work on stretcher rings was carried out by the Saskatoon group. Technical data of EROS are not repeated here because a lot of papers on this machine exist (see references in the heading).

Since years the machine is routinely used for nuclear physics. The latest news of it follow below [9]:

Until now the maximum electron energy is 300 MeV, but it will be 320 MeV soon. Low energy operation of the PSR is difficult, the lowest external beam energy has been 118 MeV until recently. For operation at 106 MeV a new closed orbit had to be established which needed to move the extraction septum 10 cm closer to the PSR axis.

To date, up to 150 mA of beam have been injected into the PSR, but the available ring RF power limits the maximum stored beam to about 50 mA and the maximum extracted beam to 10 μA. To store and extract higher currents the ring RF power will be upgraded to 2 kW from the present 1 kW. With beam loading, this should be sufficient for 200 mA at 250 MeV and 50 mA at 300 MeV.

To achieve extracted beams at lower emittance PSR chromaticity adjusting is needed. The sextupoles to provide this are installed and tested, but they have not been used in the routine operation.

During the past year 1992/93 2600 hours of beam time were available for seven different experiments and various detector tests.

2.3.2 ELSA, Bonn ([5], [6], [10], [11])

The Electron Stretcher and Accelerator ELSA at Bonn University was designed to improve the duty factor and to raise the energy of the 2.5 GeV Electron Synchrotron. Since October 1987 ELSA has been operated in three different modes: (1) pure stretcher, (2) post accelerator and stretcher, (3) synchrotron radiation source.

The stretcher mode is applied for energies up to 1.6 GeV. In this operation mode high energy electrons from the synchrotron are injected at a repetition rate of 50 Hz. Extraction of the circulating electrons is done between the injections over a time of almost 20 ms. Two different methods are exercised: resonant extraction at a tune of 14/3, multiple-scattering on an internal wire target.

The resonant extraction produces external beam intensities up to 100 nA at a duty factor of 50 %. The current limit is set by radiation background reasons in the experimental hall. The duty factor is limited due to an imperfect filling of the ring circumference which again is due to the ratio of 2.35 between the circumferences of the stretcher and of the synchrotron.

The other extraction method being applied in the pure stretcher mode at low energies (1.2 GeV) is multiple-scattering. The ring is operated in a topping-up mode, that means: at a frequency of 50 Hz electrons are injected on top of an already circulating current of 10 to 15 mA. The internal target is a 50 μm thick beryllium wire being stretched vertically near to the closed orbit. The electrons have to be scattered about a hundred times until they are extracted by a septum magnet. External current is provided up to 1 nA at duty factors around 80 %, measured by accidental coincidences at the experiment.

Exercising post acceleration and stretching some ten pulses at 50 Hz and 1.2 GeV are injected into the stretcher ring. The accumulated current of about 50 mA then is ramped up to the wanted energy within a time of 1 second. Having arrived at the flat top the ring is prepared for extraction within 0.1 s: extraction sextupoles are activated, betatron tune and RF amplitude are adjusted. Monochromatic extraction then starts and continues for 50 s or more. The macroscopic duty factor of this mode arises to 92 %. Due to the stochastic behaviour of the monochromatic extraction and the homogeneous filling of the ring the overall duty factor amounts to 90 %. The scheme has been tested successfully up to 3 GeV. It is routinely exercised up to 2.2 GeV. However, this mode of operation suffers from low external beam intensity. Therefore it is applied for operating a photon tagging facility, only.

The third operation mode of ELSA is to accumulate an internal current of up to 100 mA at 1.2 GeV, then ramp up to 2.3 or 2.7 GeV and store the beam for producing synchrotron radiation. The ring is filled every 2 hours.

The main actual improvement project at ELSA is the acceleration of polarized electron beams.

ELSA is operated for 5000 hours per year in the average. Synchrotron radiation users participate about 20 % of this time.

2.3.3 AmPS, Amsterdam ([5], [6], [12], [13], [14], [15])

The Amsterdam Pulse Stretcher improves the MEA linac (500 MeV, 1 % duty cycle) of NIKHEF. The main objectives of the project are to increase the duty cycle to close to 100 % and the electron energy to a level of 700 MeV at a circulating current of 80 mA (zero current energy: 900 MeV). To obtain higher energies without post acceleration in the stretcher ring the linac has been upgraded to the wanted level.

In 1993 AmPS moved to the operational phase. Major goals were achieved as listed below:

Linac MEA:	670 MeV,	30 mA,	0,01 % d.f.,
AmPS (Storage):	550 MeV,	100 mA,	100 % d.f.,
AmPS (Stretcher):	490 MeV,	3 μA,	50 % d.f..

In the storage mode the particle energy is limited to 550 MeV by the available RF voltage of the 2856 MHz accelerating system. Therefore in 1994 a 476 MHz system using a modified DORIS cavity will be installed. The stored current of 100 mA has been obtained after switching on clearing electrodes and by a proper choice of the betatron tune.

In the stretcher mode the electrons have been extracted by energy loss due to synchrotron radiation at a tune of 25/3. Above 350 MeV RF acceleration is required to prevent that the electrons are extracted too fast.

For future a facility with a polarized electron beam and a polarized internal target is proposed for AmPS (SPITFIRE project [15]).

2.3.4 BATES SHR, MIT ([5], [6], [16])

At the Bates Linear Accelerator Center the so-called "South Hall Ring" (SHR) has been completed recently. The SHR was designed to provide high duty factor external electron beams and an internal target capability for nuclear physics. It takes advantage of the existing pulsed linac recirculator machine. The ring will operate in the energy range of 0.3 to 1.0 GeV. The circumference has been chosen carefully allowing a two-turn injection. With a peak current of 40 mA and a repetition rate of 1 KHz of the injector machine a circulating current of 80 mA and an average current of 50 μA in the extracted beam will be provided if there are no beam losses on the way.

For resonant beam extraction a half-integer resonance is foreseen. The initial tune of 7.46 is slowly adjusted towards 7.50 by means of ramped air-core quadrupoles. Three octupoles, operating at a constant strength, separate particle motion in phase space into stable and unstable regions.

A low power (50 kW) RF system working cw at 2856 MHz will be used to maintain the injected energy spread and the mean energy.

The so-called "second phase" of SHR construction, including the injection septa, one injection kicker and the entire lattice and control system, was completed in February 1993. Commissioning of this incomplete stretcher ring was successfully carried through at an energy of 33 MeV in mainly two runs. Finally, a peak current of 40 mA has been stored for 20 ms, a limit dictated by synchrotron radiation losses.

Completion of the third phase of construction, including the second injection kicker, the cw accelerating system, the extraction octupoles, the ramped quadrupoles and extraction septa and the external beam line have been planned for the third quarter of FY 93.

In future the Bates SHR will also be operated with internal and external polarized electron beams.

3. Accelerators based on CW Linacs

3.1 General

The second scheme to produce continuous electron beams for fixed target application uses a relativistic ($\beta_P = 1$) cw linear accelerator as the basic component. It can be a straight multi-section machine through which the beam passes only once. Or it can be a machine of only a few sections, even one, but with two 180° bends on both ends which allow repetitive passes through it [1].

Depending on the technical lay-out of the bending sections two types of machine are defined: (1) If the particles of different energies are bent around by independent magnetic channels the accelerator is called a recirculating linac or shortly "recirculator". (2) In the case of using only one big bending magnet for all the trajectories of different energy, this is a race-track microtron (RTM). The latter one is a non-isochronous machine. The electrons undergo phase oscillations which generally result in a beneficial final energy stabilisation.

The bending sections of recirculators may be tuned to either isochronous or non-isochronous behaviour. In the first case a great expense has to be spent for stabilisation of phase and amplitude of the accelerating fields. However, some RF power is saved because the electrons are accelerated on the crest of the wave.

The linear accelerator for both machines, the RTM as well as the recirculator, must work continuously (cw), and may be either normal conducting or superconducting. The warm linac structure needs a high amount of RF power for creating the electrical field. Thus, warm structures are used at low fields (1 MV/m) which implies that particles have to pass through it a lot of times. This leads to the concept of the RTM using a copper structure, f. i. MAMI of Mainz University. The recirculator with only a few passes needs a high gradient ($\geq$ 10 MV/m) which nowadays can be achieved with superconducting waveguides at a low power expense. The great advantage of the recirculating linac scheme compared to the simple straight linac is the saving of RF power. The shunt impedance of the n-fold recirculating machine is n times smaller than that of the corresponding straight linac. The recirculating machine RF power P_R is smaller by a factor n^2 than the straight linac power P_L:

$$P_R = 1/n^2 \cdot P_L. \quad (3)$$

For an increasing number of recirculations in a machine with superconducting waveguides the danger of multipass beam blowup (BBU) arises which is less dangerous in a normal conducting structure because of the much lower Q value.

In the case of the race-track microtron which uses one bending magnet on either end of the accelerating section the ratio of the output and input energy is limited to about 10. Furthermore, there is an absolute limit of energy for the classical RTM because of emittance growth due to synchrotron radiation and because of rapidly increasing magnet weight with energy.

3.2 Operating Machines based on Linacs

3.2.1 MAMI, Mainz ([5], [6], [17], [18])

The "Mainz Microtron" (MAMI) of Mainz University is a cascaded scheme of three race-track microtrons (RTM). The machine is mainly used for nuclear physics. It provides one external electron beam which is guided to several target places. The maximum beam energy amounts to 855 MeV. Lower energies are possible at certain steps. The stability of the maximum energy is 3 x 10^{-5} (or better) if an operator permanently controls the machine. Otherwise it drops down to ± 60 KeV.

The three MAMI RTMs use normal conducting linacs. They are operated at low gradients of about 0.9 MeV/m. Further technical information is available in a lot of papers, f. i. in the references given in the heading.

The maximum cw electron current so far is 107 μA at full energy. Nuclear physics experiments are performed at intensities up to 60 μA, so far. The beam emittance (4 σ-value) is below $0.1 \cdot \pi \cdot$ mm$\cdot$ mrad at a current of 20 μA and full energy. A polarized electron beam was used for nuclear physics experiments in 1992 and 1993 already. The total operation times were 5460 h and 4300 h in 1992 and 1993, respectively, nuclear physics experiments participating 4180 h and 2920 h [18].

3.2.2 S-DALINAC, Darmstadt ([5],[6],[19],[20],[21])

The superconducting recirculating electron linac, S-DALINAC, of the Technische Hochschule Darmstadt is designed to provide high quality beams for nuclear and radiation physics experiments, requiring electron energies in the range from a few MeV up to 130 MeV and currents of a few nA up to some tens of μA.

The machine consists of a room temperature injector (250 keV), a superconducting injector linac (10 MeV) and a superconducting main linac of 40 MeV. The recirculation system allows three passes of the beam through the main linac. Extraction of the beam is possible after each pass. Technical details may be taken from the above noted references.

The S-DALINAC came into operation at the end of 1990 when for the first time a beam was recirculated and accelerated twice. In August 1991 a maximum energy of 104 MeV at a duty factor of 50 % was achieved. In the meantime about 8000 hours of beamtime have been provided for the experimental work. Due to the different demands various combinations of energy and current are to be provided, f. i. Nucl.Res.Fluorescence: 2,5 - 10 MeV, 40 μA; LE Channeling: 3 - 10 MeV, 0.01 - 10 μA; HE Channeling: 75 MeV, 1 μA; Electron Scattering: 22 - 80 MEV, 5 μA. The energy spread has been measured to be 50 KeV at 80 MeV.

The Darmstadt Institute for Nuclear Physics (in the early phase together with the Physics Dpt. of Wuppertal University) has done a lot of pioneering work on superconducting linac structures and on the recirculating scheme. They gathered much experience on the behaviour of niobium. The present installation contains structures made from niobium of different quality classes and with different treatments of the surfaces. There are big differences in the obtained electrical field. On an average they got 5.6 MV/m, measured with an electron beam going through.

During the commissioning phase of the recirculating system the group was faced with unforeseen problems, f. i. the following: The phase of the recirculated beam has to match the phase of the injector beam exactly. Since the injector beam undergoes some phase slippage in the first main linac cavities and since this slippage depends on the injector beam energy too much, it became necessary to change the recirculation path length in both bends to more than 180° with respect to the accelerator wave-length. It is important to learn that without a path length adjustment the successful operation of the S-DALINAC as a recirculator would not have been possible.

3.2.3 CEBAF, Newport News/Virginia ([5], [6], [22], [23])

In these days the Continuous Electron Beam Accelerator Facility starts commissioning of the 4 GeV recirculating linac. The main goals are: continuous beam of 200 μA at 0.5 - 4 GeV, 2 x 10^{-9}m$\cdot$ rad and $\sigma E/E \leq 2.5 \times 10^{-5}$.

The machine consists of two antiparallel superconducting linacs linked by nine isochronous recirculation beamlines. Thus, five passes of the beam through both linacs are possible. The linacs were designed for an energy of 400 MeV each, specifying a gradient of 5 MeV/m. In tests prior to cryomodule assembly, the cavities performed in excess of specifications with a mean usable gradient of 8.5 MeV/m and an average resonance Q factor of 5.3 x 10^9 (specification: 2.4 x 10^9). During linac testing one cryomodule accelerated beam to an energy 160 % of specification showing that an energy well above the 4 GeV level may be reached.

The 45 MeV injector achieved continuous operation at full energy and 200 μA with specifications met for transverse and longitudinal emittance and momentum spread in 1992 already.

Recently, the first linac was operated with a beam up to 120 MeV. A current of 100 μA was run for extended periods. The beam was also fed into the first recirculating beamline. A precise method was demonstrated for measuring the recirculation beam transport isochronicity which turned out to be better than needed.

The goal of the now starting operation is to single-pass beam to the Experimental Hall C.

Preparations are under way to install a polarized electron beam source developed at the University of Illinois.

4. Outlook

Concerning pulse stretcher rings there are two new projects as far as I know.

The first one is that of the Tohoku University at Sendai, Japan: PSR, 250 MeV, external current of 13 μA [24].

The other new project is a 3 GeV PSR at the Kharkov Institute of Physics and Technology [25].

Concerning cw electron linacs for fixed target operation, there is the big European project ELFE ([6], [26]) which is designed for 15 GeV and a possible upgrade to 30 GeV.

At energies of some ten GeV the superconducting linac is the best way to obtain a continuous electron beam of high intensity. Only in cases where an internal target in a storage ring can be used, this is a real alternative.

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