GENERAL PURPOSE STORAGE RING AS POST ACCELERATOR FOR THE ILEC CYCLOTRON

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Summary

At the Eindhoven University of Technology a small storage ring of momentum 400 MeV/c is under construction, which will be fed by the 3 MeV ILEC cyclotron in one specific operation mode. In this paper general aspects of the storage ring will be given as well as injection requirements from the cyclotron. By suitable RF manipulations pulses with less than 10^{-4} relative energy spread can be provided. Applications of synchrotron radiation in the electron storage mode will also be given. Results of measurements of the magnet prototypes are reported.

Introduction

In the cyclotron laboratory of the Eindhoven University of Technology preparations are made for a storage ring injected by the ILEC cyclotron (1) as a tool for experimental accelerator research such as RF gymnastics for phase figure rotations in longitudinal phase space, cooling mechanisms and the setting of various optical modes. Also the storage of electrons has been considered. Because of potential synchrotron radiation applications the magnetic rigidity was increased to 1.35 Tm, corresponding to a momentum of 400 MeV/c, which still allows the project to be small scale. The EUTERPE ring, Eindhoven University of TEchnology Ring of Protons and Electrons in fact combines both options. The main parameters are given in table 1, a lay-out is given in Fig. 1, and the siting in the existing cyclotron experimental hall is given in Fig. 2.

The ring with a circumference of 40 m has four superperiods with each three dipoles and eight quadrupoles, with four straight sections 2.5 m long. These can be used for accelerating cavities, special magnets such as undulators and wigglers and injection and extraction equipment. The sectors can be operated as double achromats, leaving zero dispersion in the straights. Several optical modes may be set with the quadrupoles; Fig. 3 gives the lattice function in the Chasman-Green mode for minimum size of the electron beam. Alternatively in a doubet (FODO) mode many values of tunes can be realized, with many electron beam sizes. The top proton energy of 80 MeV is suitable for eye tumor therapy, where the beam penetrates about 40 mm in normal tissue. The intensi-

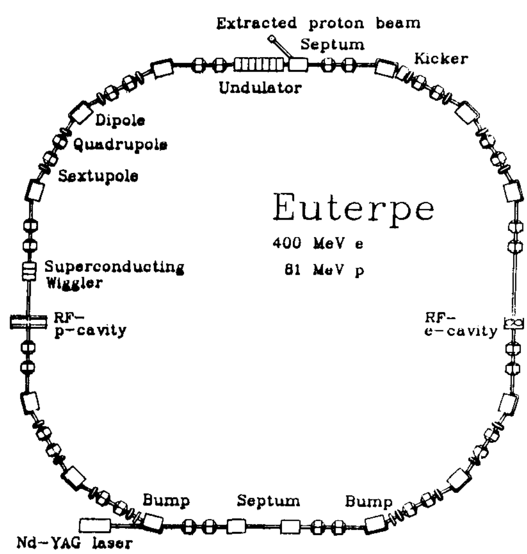


Fig. 1: Lay-out of the storage ring EUTERPE

Table 1. EUTERPE parameters

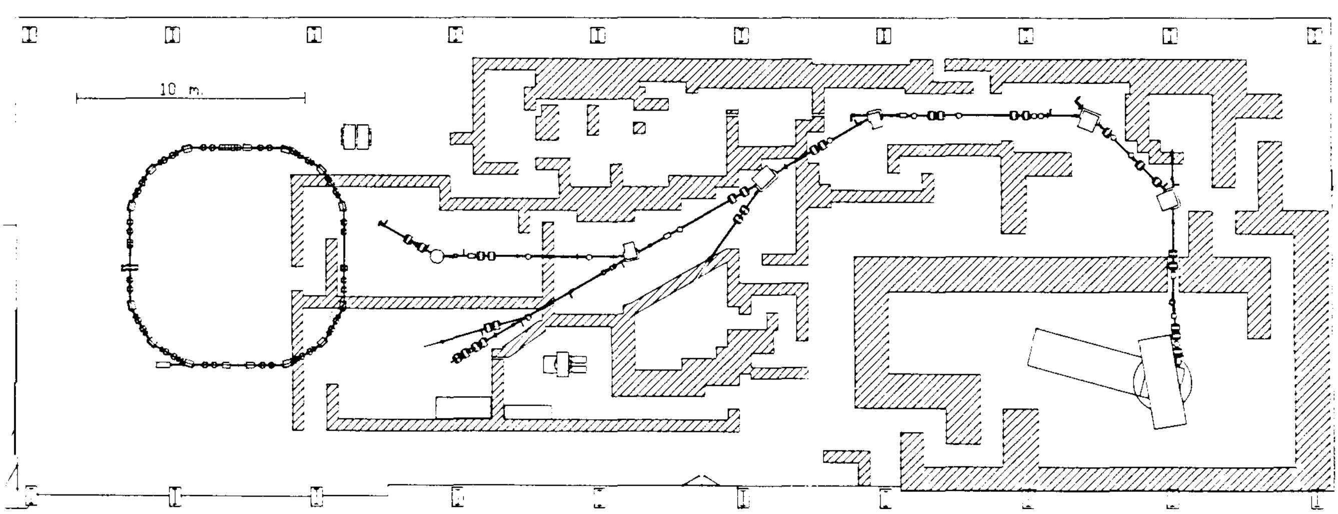
Circumference		40 m
Proton energy		3-81 MeV
Electron energy		70-400 MeV
No of superperiods		4
Proton revolution frequency		0.6-2.9 MHz
RF electron/harmonic number		75 MHz/10
Electron cavity voltage		20 kV
Dipoles	length	0.46 m
	radius	0.955 m
	B_{max}/B_{min}	1.4 T/0.25 T
Quadrupoles	length	0.30 m
	aperture radius	2.5 cm
	max poletip field	0.3 T
Sextupoles	length	0.05 m
	aperture radius	2.5 cm
	max poletip field	0.2 T
Electrons	400 MeV, CG mode	
	current	200 mA
	critical wavelength	8.3 nm
	energy loss/turn	2.4 keV
	energy spread $\Delta E/E$	3.5 10^{-4}
	pulse length	3.4 cm
	hor emittance	3.5 10^{-9} m
	max hor beam size	50 μm
	damping times	23, 22, 44 ms

ties required for this purpose are 10 to 100 nA. This can be obtained in EUTERPE by 6 turn injection from ILEC, operating ILEC in a pulsed mode with 1 mA beam current in the pulse and 5 Hz ramping of the ring: then the average current is 50 nA corresponding to $3 \cdot 10^{11}$ particles per second. The lamination thickness of the magnets allows ramping with high frequency (e.g. 50 Hz), however the dipole coils with an inductance of $1 \cdot 2\ 10^{-2}$ H and a resistance of 0.07 Ohm have a time constant of 0.17 s. The horizontal injection from ILEC in the ring is done with an electrostatic septum and four fast bump magnets. These magnets shift the closed orbit towards the septum in a typical time scale of one revolution period, i.e. 1.67 μs. A 5 cm long bump magnet of 500 gauss gives a kick of 10 mrad for the 3 MeV beam. This is sufficient for shifting the beam at the septum by 2 cm. The septum with 25 kV/cm and 25 cm long kicks the beam by 100 mrad. The acceptance of the ring (60 mm mrad) is large with respect to the horizontal emittance of the cyclotron (~ 5 mm mrad) which allows multiturn injection through painting of the horizontal phase space by a controlled closed orbit shift. A pulsing system in the ILEC central region will provide the required macropulse length from the cyclotron.

Bunch rotation

The energy definition of the ILEC beam can be increased by rotating the bunches in longitudinal phase space. With slits in the cyclotron central region, and with the flattop system in action bunches emerge with a relative energy spread of $\pm 2 \cdot 10^{-4}$ and phase width $\pm 5^{o}$ of the 42 MHz fundamental accelerating frequency. A long drift length is required and a buncher operation at 42 MHz at the end for reducing the energy spread. This can be achieved with the EUTERPE ring, see Fig. 4. The buncher effect can be described by a lense action: $\begin{pmatrix}\phi \\ \delta\end{pmatrix}_f = \begin{pmatrix}1 & 0 \\ \delta_o & 1\end{pmatrix} \begin{pmatrix}\phi \\ \delta\end{pmatrix}_i$ where ϕ is the phase w.r.t. the zero crossing of the buncher frequency, δ is is the momentum deviation $\Delta p/p$, and $\delta_o = eV_o/2T$, with e the electric charge,

Fig. 2: Experimental hall



V_o the top voltage and T the kinetic energy of the particle. Similarly a single passage of the the storage ring can be described by:

$$\binom{\phi}{\delta}_f = \begin{pmatrix} 1 & (\alpha-1)\phi_R \\ 0 & 1 \end{pmatrix} \binom{\phi}{\delta}_i$$

where α is the momentum compaction factor and $\phi_R = \omega T_R$ with ω the ILEC angular RF frequency and T_R the storage ring revolution time. For EUTERPE α ranges from 0.0075 to 0.05 in three different optical modes, which means that the storage ring can be considered as a pure drift length. The condition for rotating the bunch over 90 deg is then: $\phi_R\ \delta_o = 1$. Inserting numbers: a particle with $\delta = 10^{-4}$ uses 480 m in EUTERPE for a phase change of 30 deg and a peak buncher voltage is required of 1.2 kV for reducing the momentum spread. The final momentum spread of the ILEC bunch then is determined by the particles with ± 5 deg phase deviation and is $\pm\ 1.65 \cdot 10^{-5}$. It is seen that a normal drift would be unpractically long. Alternatively bunches can rotate for short pulse time by first applying a buncher voltage and then a drift space.

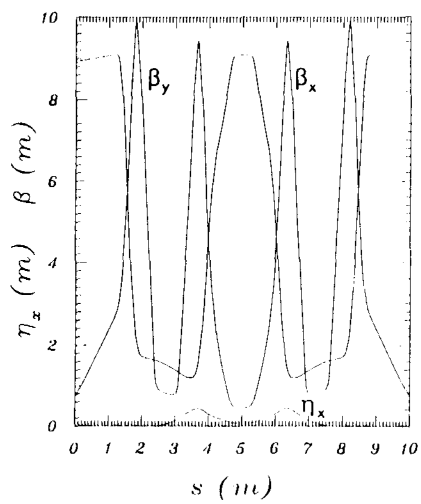


Fig. 3: Lattice functions in the Chasman-Green mode

The electron option/synchrotron radiation

There is a broad range of applications of synchrotron radiation generated in electron storage rings. In Fig. 5 one can see the spectrum of EUTERPE extending from the infrared to the XUV-region. The characteristic wavelength of the synchrotron radiation spectrum is 8.3 nm for the regular dipole magnets. A later extension with a 10 T wiggler magnet shifts the spectrum towards the X-ray-region which can be interesting e.g. for lithography. Then the characteristic wavelength is 1.2 nm, providing useful radiation for e.g. XRF up to 3.2 KeV. The various options of applications need corresponding electron beam sizes in the ring. These depend on the optics of the quadrupole structure. In this respect for EUTERPE there is a large flexibility.

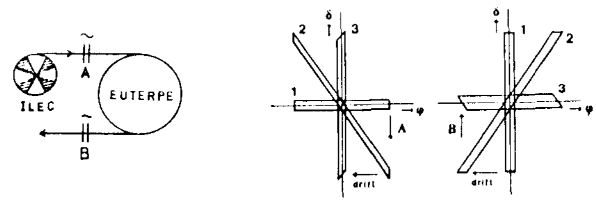


Fig. 4: Bunch rotation with EUTERPE

For very detailed spectroscopy one can realize a low intensity narrow beam of 50 µm times 15 µm in the Chasman-Green optical mode. Alternatively in the FODO mode the beam size can be enlarged to one tenth of the dimensions of the vacuum chamber (3-5 cm) which is useful for the storage of a large electron current for e.g. lithographic applications. In a single bunch mode time resolved spectroscopic experiments can be performed on the nanosecond time scale (2). Because of the lack of lasers in the 200-400 nm, synchrotron radiation can be of great help here, e.g. for biophysics regarding the study of molecular movement in complex biologic systems. Other applications of the electron option include FOCON (foton conversion) on 0.124 eV laser light from a high power CO_2-laser for generation of 100 keV for e.g. XRF. In a collaboration with the Twente University two racetrack microtrons will be built: one of 25 MeV as electron source for a free electron laser (3), and one of 70 MeV as injector for EUTERPE. The last one has equal size and equal orbit pattern as the 25 MeV machine, however the magnet gap is smaller and the acceleration voltage is higher by factor 2.8. The microtrons exhibit focusing properties comparable to cyclotrons, i.e. the axial focusing is realized by a modulated field in the two sector magnets. The injector for the injector microtron of EUTERPE will be 10 MeV medical linac, arriving in our lab in july of this year. The construction of the racetrack bodies has just started.

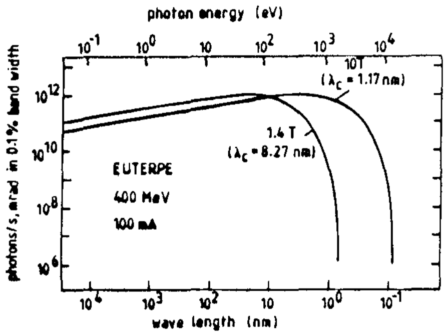


Fig. 5: Synchrotron radiation spectrum of EUTERPE

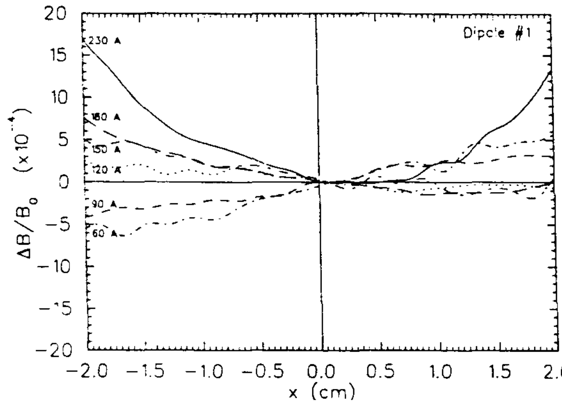


Fig 6: Dipole field homogeneity perpendicular to the optical axis

Components

The design of EUTERPE is based on simple low-cost magnets, which still provide sufficiently good field properties. The dimensions of the magnets that will be needed have been specified with the aid of POISSON calculations. As a result prototypes (three dipoles and three quadrupoles) were manufactured by a transformer company, and equiped with coils and the necessary power supplies by the university workshops. They consist of laminated rectangular blocks of iron, fixed together by drawbolds or screws. The prototypes differ in the type of iron and the lamination width 0.35 mm and 0.5 mm, used. Four types of measurement have been performed for the dipoles: the excitation curve, line measurements of the magnetic field along the length direction of the dipoles and perpendicular to the optical axis, and the measurements of a complete field map.
The line measurements revealed some saturation effects at the highest excitation at the edges of the poles. For the length line measurement this lead to reduced field levels at the entrance and exit of the magnet and to a reduced effective magnetic length of up to one percent. Fig. 6 shows a measurement of the field perpendicular to the optical axis, displaying a sextupole component of up to 1.86 10^{-2} T cm^{-2}. In this figure 230 A corresponds to 1.4 T. For the quadrupole the good field radius, the fraction of the aperture radius for which the relative gradient error is within 1%, is 0.7, mainly restricted by a 20-pole term being 0.6% of the quadrupole term. This is in agreement with the POISSON calculations on the predicted pole shape.

A rotating coil device (4) was also built for determining the higher order content of the quadrupole field. Signal analysis will be performd by an on-line computer. The 32 quadrupoles of the ring will be measured in this way.
The complete field maps of dipoles and quadrupoles were used as input for a particle tracking code. As an example, in this way the double achromatic behaviour of one superperiod of the ring was confirmed. In a first phase the ring material cost will be limited to MDF 1, half of which is for ultra high vacuum equipment. First beam tests will be with protons, for which less severe vacuum requirements are called for. Dipoles will be larger than the test types: block-length 46 cm, height 36 cm, width 33.5 cm, pole width 12 cm, gap 2.5 cm, block weight 368 kg. Quads have rectangular outer shape with size 30x21x21 cm^3.The complete magnet system has an estimated cost of kDF70. Hollow copper conductor of 5 km length and cross section 6x6 mm^2 with bore 3.5 mm has been ordered. The assembly and coil winding will be done in the own workshop. The dipoles and eight families of quadrupoles will be powered by separate power supplies, with which many optical modes can be set. The dipole power supply has a 300 V, 300 A capacity.

References

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