Feasibility Study of a Synchrotron for the European Light Ion Medical Accelerator

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Abstract

In the framework of the EULIMA project, a feasibility study has been undertaken at CERN for a light ion medical synchrotron. It delivers a beam in the energy range of 140 - 400 MeV/u . Two approaches have been explored, one with the emphasis on full flexibility, the other aiming at maximal compactness. Cycling schemes corresponding to different therapeutic needs are presented.

1. INTRODUCTION

The European Light Ion Medical Accelerator (EULIMA) is a prototype accelerator for cancer therapy to be built in Europe [1]. Its installation should allow the treatment of a few thousand patients per year with fully stripped ions ranging from carbon to neon and energies from 140 to 400 MeV/u, yielding a maximum penetration of about 20 cm in biological tissue (Oxygen case). Irradiation doses of 10^{10} to 10^{11} ions are distributed over the tumor by dividing it in several slices (typically 10) which correspond to different energies. The transverse scanning method is supposed to be a raster scanning.

All these characteristics fit very well with an accelerator of the synchrotron type. Moreover, the reliability of the machine is ensured by using well proven techniques. The careful design of the control system using an ample amount of local memory in the function generators, local intelligence, and an alarm system related to any failure of the timing structure, guarantees a high degree of safety. Therefore this feasibility study has been undertaken. Its detailed description can be found in [2].

The required top energy corresponds to a maximum magnetic rigidity of $B\rho_{max} = 6.34$ Tm. The injection energy of 5 MeV/u can be obtained from an industrially available injector, consisting of an ECR ion source, a standard RFQ (accelerating to 1 MeV/u) and a LINAC operating at 1 Hz repetition rate.

The performance requirements of the synchrotron are very close to the characteristics of LEAR [3] (Low Energy Antiproton Ring) at CERN, which has a maximum Bρ of 6.6 Tm, and thus its design could be used directly. However, the LEAR circumference of 78.5 m is optimized for physics purposes and is considered as too large for a medical accelerator.

2. CHARACTERISTICS OF THE SYNCHROTRON: THE SFM AND CFM

Two approaches have been explored to design a more compact medical accelerator. In the first one the LEAR principle of separated functions (pure dipole bending magnets, focussing and defocussing quadrupoles, discrete sextupoles) is maintained, but the adoption of a weaker focussing (Qh = 1.66, Qv = 1.75) allows to reduce the size by 25%. The result is a separated function machine (SFM) 59.08 m in circumference in a slight racetrack geometry (Fig. 1, Table 1).

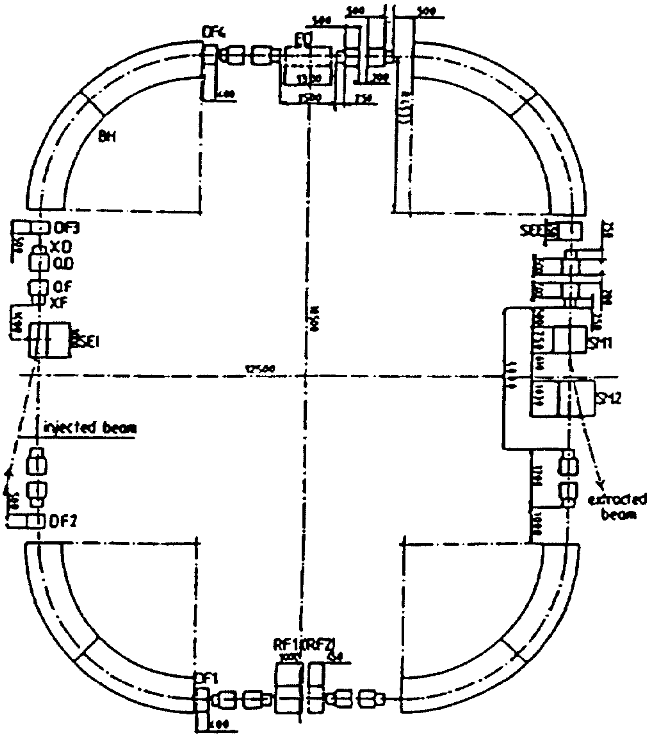

Figure. 1: General layout of the SFM. BH bending magnet, QF focussing quadrupole, QD defocussing quadrupole, XF focussing sextupole, XD defocussing sextupole, RF radio frequency, SEI electrostatic injection septum, SEE electrostatic ejection septum, SM magnetic septum, DF fast dipole, EC electron cooling.

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In this design the flexibility needed for a multipurpose machine is maintained, and the design of the LEAR magnets could be adopted.

General Layout:		
Total Length	m	59.080
Length of Short Straight Sections	m	1.500
Length of Long Straight Sections	m	4.000
Bending Radius	m	4.533
Lattice:		
Q_h	-	1.670
Q_v	-	1.755
β_h^{max}	m	11.41
β_v^{max}	m	10.97
D^{max}	m	5.40
ξ_h (1)	-	- 0.80
ξ_v	-	- 1.03
γ_{tr}	-	1.96
Magnets - Normalized Strengths:		
Bending Horizontal ($1/\rho$)	m^{-1}	0.221
Quadrupole Focussing (2)	m^{-2}	0.10
Quadrupole Defocussing	m^{-2}	-1.17

Table 1: Lattice parameters of the SFM. (1) Natural chromaticity $\xi = (\Delta Q/Q)/(\Delta p/p)$, (2) $k_1=(1/B\rho)\ \partial B_y/\partial x$

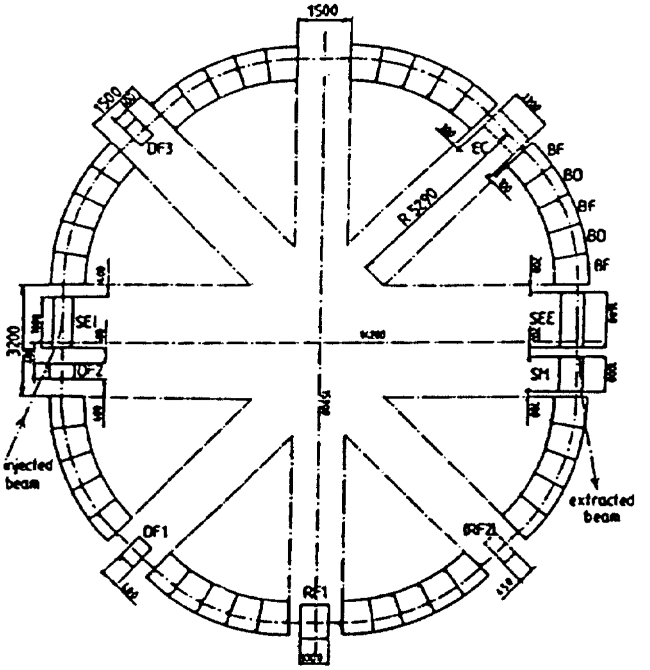

Figure 2: General Layout of the CFM. BF focussing bending magnet, BD defocussing bending magnets, RF radio frequency, SEI electrostatic injection septum, SEE electrostatic ejection septum, SM magnetic septum, DF fast dipole, EC electron cooling.

A further reduction in size can be achieved with a combined function machine (CFM). In this case focussing or defocussing gradient is added to the dipole component of the bending magnets. Also the correcting elements for Q tuning and the sextupoles for the excitation of the extraction resonance are integrated in the bending magnets. The sextupolar component to adjust the chromaticity will be produced by shimming the magnet poles. A very compact machine with a circumference of 48.6 m is obtained (Fig 2, Table 2). This design is less flexible than the SFM, but has advantages in terms of simplicity, compactness, and also for injection and ejection.

The transition energy of both machines lies above the maximum design energy.

General Layout:		
Total Length	m	48.638
Length of Short Straight Sections	m	1.500
Length of Long Straight Sections	m	3.200
Bending Radius	m	5.239
Lattice:		
Q_h	-	1.660
Q_v	-	1.800
β_h^{max}	m	7.104
β_v^{max}	m	9.443
D^{max}	m	3.16
ξ_h	-	-0.60
ξ_v	-	~ 0
γ_{tr}	-	1.72
Magnets - Normalized Strengths:		
Bending Horizontal ($1/\rho$)	m^{-1}	0.189
Quadrupole Focussing Component	m^{-2}	0.528
Quadrupole Defocussing Component	m^{-2}	-0.826

Table 2: Lattice parameters of the CFM.

For both the SFM and CFM the injection is a standard horizontal, multi-turn process in which one batch is injected per machine cycle. Fast electrostatic bumpers make a variable orbit deformation in the horizontal plane at the exit of a DC electrostatic injection septum, permitting injection on the successive turns. The number of injected turns is limited to ~ 20, with an overall injection efficiency of 40 to 50 %. The injected intensity is in the order of 2.0 10^9 ions.

The extraction is an ultraslow third order resonance extraction with alignment of separatrices [4]. Phase and amplitude of the resonance are controlled by a set of sextupolar lenses (SFM) or coils (CFM). The first element of the extraction channel is a thin electrostatic septum. The particles having jumped the electrostatic septum are further deflected by one or two thicker magnetic septa. The instantaneous intensity of the extracted beam will be regulated by applying RF - noise. This technique has been successfully implemented at LEAR [3].

The maximum rise of the magnetic field during acceleration $\dot{B}_{max}$ is 2.5 Ts^{-1}. One cavity of 1 m length and tunable in the range 1 to 5 MHz provides an RF voltage of 4 kV. After injection the beam is bunched on the second harmonic and accelerated to 35 MeV/u, then it is debunched and rebunched on the first harmonic on an intermediate flat top (100 ms) to be accelerated to the extraction flat top. The intermediate flat top could be avoided in view of the shortest possible cycle by using two cavities.

3. MACHINE CYCLE AND STORAGE OPTION

Basically the machine is intended to be fast cycling. The cycle duration is largely determined by the length of the extraction spill, which can be freely chosen between 100 ms and one hour. This flexibility permits a compromise between irradiation rate and irradiation time. The minimum spill time will probably be imposed by the beam delivery system and the transverse scanning method. As an illustration two cases are presented, both based on 10^9 ions extracted per cycle. A short cycle with 400 ms spill corresponds to the working hypothesis of 10^{11} particles delivered in less than 200 s at a spill rate of 2.5 10^9 ions/s, whereas a long cycle with a 10 s spill (spill rate 10^8 ions/s) needs about 1200 s for the same dose. The extraction energy can be changed from cycle to cycle. The set of cycles corresponding to the different energy slices form a periodic supercycle. It is repeated the number of times to deliver the required total dose. (Fig. 3)

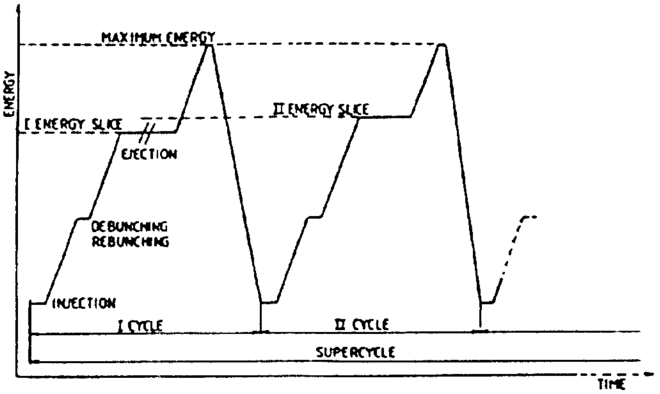

Figure 3: Machine cycle

If it is desired to decrease the number of supercycles to obtain the total irradiation dose (i.e. for faster medical treatments), one has to increase the intensity per cycle in order to deliver the same dose. This can be achieved either by using a more intense ion source (to be kept as a future possibility), or by implementing a storage mode. The latter option is based on a repetition of the multiturn injection scheme with strong electron cooling (less than 100 ms cooling time) of the circulating beam between subsequent batches. With a 10 Hz injector this method would typically allow for 10^{10} particles to be stored per cycle, and thus for a performance increase in terms of irradiation time by a factor of 10. At this point space charge limits are reached.

This storage option would also be required if the delivery of a low flux of radioactive ions were demanded [5]. For this application one can arrange a cycle with many extraction flat tops at different energies (Fig. 4).

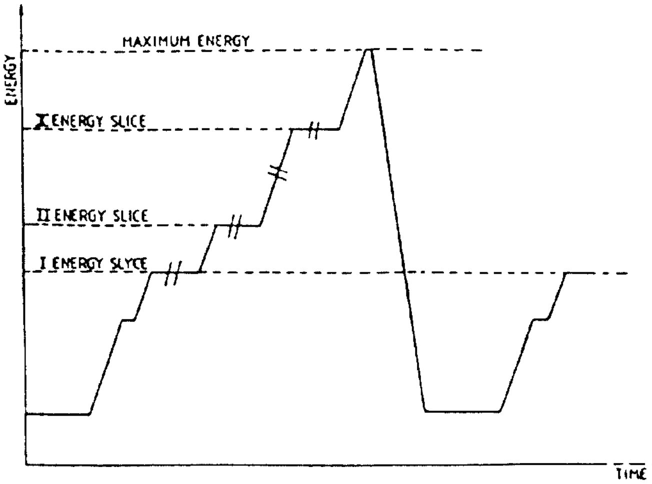

Figure 4: Multi extraction flat top cycle
(radioactive ions)

4. CONCLUSIONS

Two machines of the synchrotron type have been proposed for a medical accelerator facility and its operation mode has been investigated.

The SFM with storage mode is recommended if it is necessary to develop a general purpose tool. If the scope of the irradiation program can be limited to well defined operations with stable ions, then the recommended machine is the CFM without options. It is cheapest and easiest to operate, although more delicate for the running in. The storage option remains attractive in the perspective of radioactive ion applications.

5. ACKNOWLEDGMENTS

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6. REFERENCES

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