HIGH INTENSITY CYCLOTRONS FOR DRIVING HYBRID NUCLEAR SYSTEMS

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Several cyclotron-based high intensity accelerators have been studied in the framework of the Energy Amplifier (EA) project proposed by Prof. C. Rubbia [1]. Among them, two basic designs are presented: a 380 MeV separated sector cyclotron delivering a high intensity proton beam to a target or to a booster accelerator and a low injection energy stand-alone H_2^+ cyclotron producing 110 MeV protons, extracted by stripping, available for further acceleration in a cyclotron or a superconducting linac structure. Specific aspects in the methods used for the design of these cyclotrons are also briefly described.

1 Introduction

The goal of an accelerator-driven hybrid nuclear system [2] such as the Energy Amplifier (EA) [1] is to provide a few MW proton beam at high energy (about 1 GeV). These requirements open various technical options for the driving accelerator:

- a full linac solution similar to the various Los Alamos [3] or JAERI proposals [4]. A structure using superconducting cells operating at 352 MHz similar to those designed and developped at CERN [5] is being studied.

- a full cyclotron solution, namely a three-stage cyclotron accelerator, has been studied for driving a 12.5 MW EA. Its features have been described in the last conference [6]. It consists of two injectors, which are compact isochronous cyclotrons able to deliver a 6.25 mA beam at 15 MeV, an intermediate cyclotron with four separated sectors accelerating the beam up to 120 MeV and a final booster cyclotron ring with ten separated sectors and six cavities raising the energy up to 1000 MeV.

- an hybrid linac-cyclotron system, where a linac could be used either as an injector or as a booster (e.g. operating at 352 MHz). In order to avoid any beam loss, matching conditions must be satisfied between the various stages for further acceleration. In particular, the ratio of the injector and booster RF frequencies must be an integer. Two cyclotron designs for this kind of hybrid solutions are presented in this paper.

2 Criteria for a cyclotron-based design

For the acceleration of intense beams a very efficient extraction process with low beam loss is mandatory. Two different concepts are possible:

- single turn extraction: In order to get an efficient peak to peak turn separation i.e a high extraction efficiency, it is necessary:
1) to choose a large extraction radius i.e. a relatively low average magnetic field.
2) to use a high energy gain per turn (separated sectors, high voltage, large number of cavities)

The internal accelerated current is limited by longitudinal space charge forces, which tilt the bunch radially.

- stripping or overlapping turn extraction : At high energy, the extraction efficiency is very close to 100%. It is no longer necessary to separate the turns if the next acceleration stage can accept the energy spread due to the overlap, which is true for a linac. The maximum current is, in this case, limited by vertical space charge forces:

$$I_{lim}=\Delta z.\nu_z^2.\omega_{RF}.\varepsilon_0.E_g.\Delta\phi/(2.\pi)$$

where Δz is the vertical beam size, ω_{RF} the RF frequency, ν_z the focussing frequency, E_g the energy gain per turn and $\Delta\phi$ the beam longitudinal width.

An interest for a relatively low energy (about 100 MeV) proton accelerator which could be operated in a stand-alone mode or as an injector for a cyclotron booster or a 352 MHz linac using superconducting cells has been developped [7]. Preliminary studies for a high intensity H^- cyclotron have shown that the electromagnetic stripping is a strong limitation, which lead to use low magnetic fields for energies larger than 100 MeV and thus to design large machines. Using H_2^+ ions seems to be a promising alternative to H^- ions because the stripping process by electromagnetic fields is much less stringent. Moreover, they can be produced with high production rates in any ion source. In addition, space-charge effects are reduced since only half (2.5 mA) of the equivalent proton current is needed. The main drawback is their higher magnetic rigidity. Particular interest is being developped for this possibility in the accelerator community (e.g. [8,9,10]).

3 Two examples

3.1 A 380 MeV booster cyclotron

The main incentive to study a 10 mA 380 MeV proton cyclotron has been to obtain a beam of which characteristics were suitable for a 250 MW(thermal) energy production demonstration unit [7].

This type of cyclotron is rather classical and close to existing designs. Promising results obtained at the PSI facility [11], where considerable experience with high intensity beams has been acquired, has lead us to propose such a ring cyclotron.

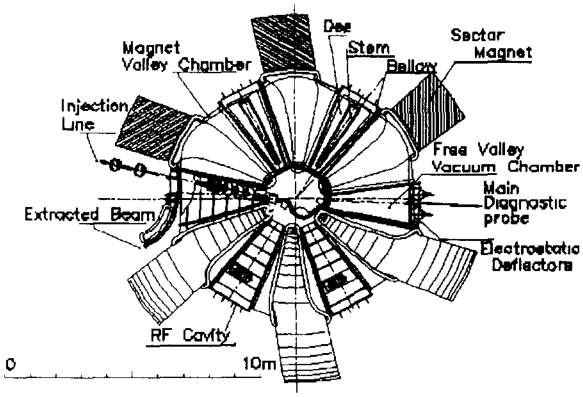

Fig.1 View of the 380 MeV ring cyclotron

Table 1: Main parameters of the 380 MeV cyclotron

Beam intensity (mA)	10
Inj./ext. energy (MeV)	20/380
RF frequency (MHz), harmonic	70.4, 10
Nb of sectors	6
Sector angle at inj. / ext.	14/22 deg.
Sector spiral at extraction	3.6 deg.
Total magnet weight (tons)	1920
Magnet power (total) (MW)	0.48
Nb of acc. cavities	4
Inj./ext. voltage (kV)	200/600
Losses/cavity (kW)	320
Radial gain at ext. (mm)	18
Beam power (MW)	3.6
RF power (total) (MW)	4.9

The shape of the sectors has been determined in a first step with a dedicated program enabling to estimate the properties of the equilibrium orbits (position and focussing frequencies) of separated sector cyclotrons from analytical formulae taking into account soft-edge effects. Transverse space-charge effects have been taken into account by mutiplying the focussing frequencies by correction factors as suggested by W. Joho [12]. The sector width and field level (1.6 T) have been selected so that the vertical focussing frequency ν_z remain above 1.0 with a sufficient margin over the acceleration range. The magnet shape has been optimised with the computer code MAFIA [13] in a second iterative step.

Acceleration of the beam is provided by four cavities located in opposite valleys, increasing the beam energy from 20 to 380 MeV. Double-gap RF cavities have been selected because their radial extension is smaller than single-gap cavities of the PSI-type, thus leaving more space in the centre of the machine for the bending and injection magnets and the beam diagnostics. The design of the cavities have been carried out with MAFIA. Measurements on a half-scale model made of copper and wood, have been carried out in order to check the predictions. An excellent agreement was found with an error of the order of 0.5% on the frequency and 3% on the voltage.

In addition, these cavities will have to handle about 3.6 MW of beam power for a 10 mA beam. Therefore, about 1.22 MW RF power must be transmitted to each cavity, which makes the coupling an uneasy task. According to the PSI experts, one RF window can handle up to 600-700 kW. This means that two such windows would be needed per cavity.

A preliminary design of the injection line can be seen in fig. 1. The beam is injected in the cyclotron through a free valley 1.30 m above the median plane. Two 30 degree dipoles enable to bring the beam in the median plane. It is further deflected by three bending magnets before entering an electromagnetic inflector located in one of the cyclotron sector gaps. It reaches then the first RF cavity gap where acceleration starts. Injecting at 20 MeV enables to take benefit of enough room to locate the deflecting and diagnostics elements. Quadrupoles are inserted along the line to provide the necessary focussing strength. It is planned to use an electrostatic element to correct a possible small beam off-centering in the first turn.

In order to extract the beam in a very high efficient way, a simple system consisting of three channel components is proposed. After the beam is kicked outwards from the last internal orbit by the electrostatic deflectors set in a free valley, it passes through three magnet sectors and is further deflected in the next free valley by an electromagnetic deflector. The last section is a conventional bending magnet located in the same valley. The extraction system is also shown in fig. 1.

3.2 A H_2^+ injector

In order to reduce the overall size, we have investigated a superconducting solution similar to the one studied for the EULIMA feasibility studies [14]. No refined design of the low energy injection line has been carried out yet but this will be done in the near future.

The magnetic field of the superconducting cyclotron has been determined with the usual method consisting of adding three parts, respectively the contributions due to the yoke (computed with the CERN 2-D code POISSON), the sectors (home-made code EUBSAT assuming a uniform magnetization) and the coil (analytical expression). The sector spiral has been adjusted so that a high value of the vertical focussing frequency (above 0.3) is obtained over most of the acceleration range. The magnetic field characteristics have been checked with the 3-D CAD software MAFIA. The maximum field in the sector is 3.8T.

The RF cavities have been designed with the same code. Their design has been carried out so that the whole cavity can be inserted in the valley. The stem shape has been determined in order to comply with this constraint and provide the required gap voltage law.

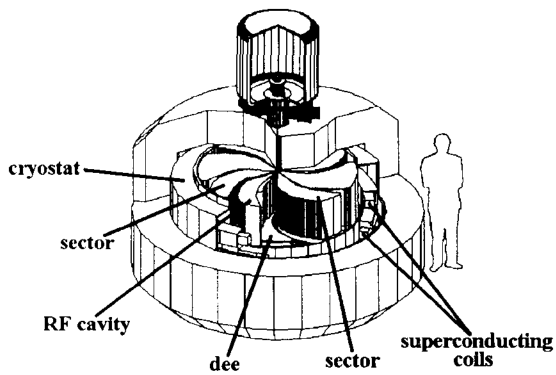

Fig. 2: General view of the s.c. H_2^+ cyclotron

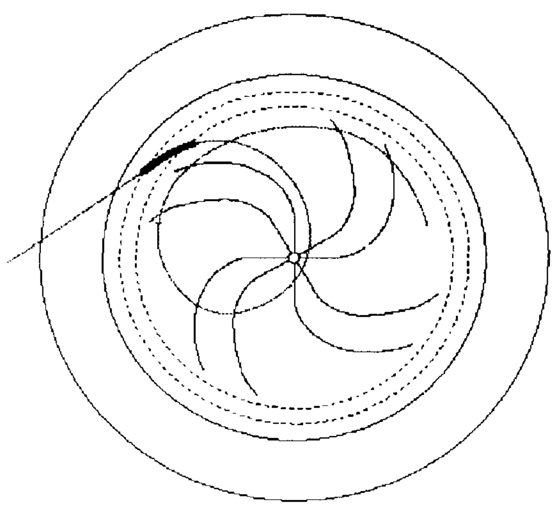

Fig. 3: Beam trajectory in the s.c. H_2^+ cyclotron

Fig. 3 shows the trajectory of the beam in the cyclotron The extraction energy is large enough so that the beam trajectory remains sufficiently far from the machine center. An optimal location of the stripper was found so that both trajectory and beam focussing are satifactory while the beam is located at a radius lower than the pole outer radius. Additional focussing elements have to be inserted as in other superconducting cyclotrons once the beam goes through the pole fringe field on his way out of the cyclotron.

Table 2: Main parameters of the s.c. H_2^+ cyclotron

Beam intensity (mA)	2.5
Inj./ext. energy. (MeV)	0.08/220
RF frequency (MHz), harmonic	70.4, 4
Nb of sectors	4
sector angle at inj. / ext. (deg.)	30/23
Sector spiral at extraction (deg.)	52
Total magnet weight (tons)	215
Coil current density (A/mm^2)	44.65
Nb of acc. Cavities	4
Inj./ext. voltage (kV)	80/160
Losses/cavity (kW)	60
Beam/RF power (total) (kW)	550/790

4 Specific aspects of the numerical methods for the design of the cyclotrons

4.1 Magnet models

In order to be able to evaluate the degree of accuracy that can be reached with a CAD code like MAFIA [13] when designing separated-sector cyclotrons, we have decided to make a computational model of one of the magnet sectors of the PSI 590 MeV cyclotron. The complex geometry of this magnet [15] has been modelled in a first step with the 3-D CAD software AUTOCAD [16]. Then, using a home-made dedicated program, the model has been decomposed into various slices in the vertical direction that could be translated directly into MAFIA commands, thus making their generation easier. An excellent agreement was found between the measured data [15] and the computed one. The field difference was found to be of the order of 200 G locally but is smaller over most of in the region where the beam acceleration takes place.

4.2 Space charge computations

In the beam intensity range that we are considering in the various designs (several mA), space charge effects play a very important role in the beam dynamics, more specially at low energies. Depending on the beam energy, various models can be used as this has been extensively described in the literature (e.g. [17,18]). Besides easy-to-implement subroutines where either a uniform or gaussian charge distribution is assumed within the beam, more complicated algorithms have been developped to compute the electromagnetic field due to space-charge using multi-particles and no peculiar assumption on the beam charge distribution. Depending on the mathematical model and geometrical approximation introduced for the beam, either Poisson's equation is solved or related convolution products are computed via FFT techniques. Charges assigned to particles are distributed over a computational mesh grid according to various schemes of which complexity can be increased (from the area-weighted method to the gaussian assignment algorithm [19]) and has been tested [20]. The number of particles to be used in a given simulation depends strongly on this charge distribution scheme, in order to obtain a reasonable noise in the results. It increases with the degree of simplicity of the algorithm. Additional smoothing has to be introduced if a simple scheme is used. Gaussian assignment was found quite attractive because it enabled to reduce the number of particles in a drastic way without need of additional smoothing. The same type of interpolation scheme (area-weighted, gaussian) is used to determine the fields or space-charge forces at any location from their values on the mesh grid points.

5 Conclusion

The studies of different solutions carried out up to now have shown that cyclotrons are good candidates to drive subcritical nuclear systems such as energy amplifiers. Detailed design studies are now being undertaken in order to clarify the essential following points from the beam dynamics point of view:

1) Simulations with refined space-charge models in the injectors in order to assess more precisely the intensity limits of this kind of accelerator.

2) In addition to the beam dynamics aspects, engineering studies have already been achieved and will be pursued. Of particular importance are the mechanical design studies of the vacuum chamber and structure of the cavities of the 380 MeV cyclotron.

Further design and testing work has to be done in order to assess a very high reliability of various components like the RF accelerating cavities. The shape of the cavities is being optimized so as to reduce the wall losses. It is planned to build a high power prototype of the accelerating cavities.

Acknowledgements

The authors wish to thank Prof. C. Rubbia for stimulating and helpful discussions. Various people have been involved in these studies and should be acknowledged: D. Molina and M. Petitot from the Institut Polytechnique de Sévenans, J. Favre-Bonvin, S. Mihele, C. Sailler and D. Totouom from the Institut National des Sciences Appliquées de Lyon, the cyclotron laboratory staff in Nice, and more particularly, A. Giusto, G.Donadey and J.F. Di Carlo for designing the various mechanical parts of the cyclotrons and achieving most of the drawings. Drs D. Brombach and W. Joho from PSI should also be thanked for providing us with the data concerning the 590 MeV cyclotron magnets.

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