

A 3-stage Cyclotron complex for driving the Energy Amplifier

P.Mandrillon, N.Fietier, Laboratoire du Cyclotron, Nice, France, C.Rubbia, CERN, Switzerland

I. INTRODUCTION

The goal of this accelerator complex is to provide a 10 MWatt proton beam for driving the Energy Amplifier recently proposed by C.Rubbia [1]. It is lower (by one order of magnitude) than the requirements of most of the accelerator-driven projects based on c-w linacs [2]. Therefore, the requirements for the Energy Amplifier open an alternative solution based on ring cyclotrons [3] [4] producing a continuous beam. Thus taking into account the present development of high-intensity cyclotrons (cf. PSI [5]), a three-stage cyclotron accelerator is a possible solution. It comprises:

- **the injector(s)** which should be able to deliver a 10 mA beam in a given phase width. a solution based on two 5mA compact isochronous cyclotrons (CIC) working in parallel is proposed.
- **the intermediate stage (ISSC)** which is a four-separated-sector cyclotron accelerating the injected beam up to 120 MeV.
- **the final booster (BSSC)** which has ten separated sectors and six cavities raising the kinetic energy up to about 1000 MeV.

II. DESIGN CONSIDERATIONS

Acceleration of intense beams requires an very efficient extraction process free of beam loss. The main parameters of the intermediate stage and the final booster should satisfy the following design criteria :

- **Single turn extraction** : A large radial gain per turn is requested, i.e. an high energy gain per turn, in order to get an effective turn separation on the extraction radius.

- **Flat-topping RF cavities** : In this multi-stage cyclotron complex, the extraction efficiency and the energy spread of a given accelerator stage depends on the pulse length and energy spread of the beam extracted from the previous stage. Therefore the only way of decreasing the energy spread for a given longitudinal particle density and phase width, is to use flat-topping accelerating cavities, namely, two additional RF resonators working on a harmonic of the main RF cavity frequency in order to obtain an "as flat as possible" accelerating voltage wave form. Usually these cavities work on a third harmonic mode.

- **Matching the three stages** : In order to avoid any beam loss, matching conditions must be satisfied between the different stages for further acceleration : in particular the RF frequency of the booster should be a multiple of that of the injector. In order to simplify the overall design of the RF system, a good choice is to operate all the machines with the same RF frequency, i.e. 42 MHz in the proposed design.

The main parameters of the intermediate stage and the final booster of the 42 MHz option are presented in Table 1. The equilibrium orbits and their properties have been calculated numerically using realistic computed magnetic field maps.

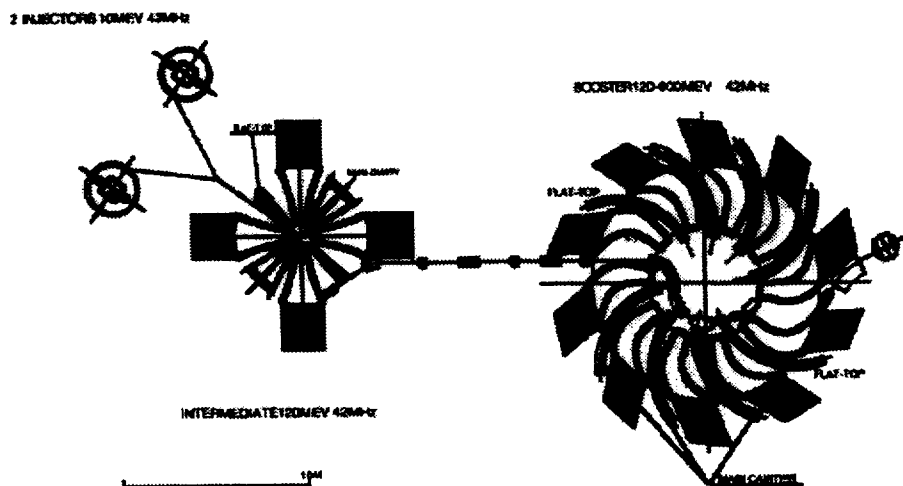


Figure 1 : General lay-out of the accelerator complex

Table 1 : Main parameters for the 42 MHz design

Accelerator type	ICC	ISSC	BSSC
Injection (MeV)	0.1	10	120
Extraction (MeV)	10	120	990
Frequency (MHz)	42	42	42
Harmonic	4	6	6
Magnet gap (cm)	6	5	5
nb. sectors	4	4	10
sector (inj/ext)(deg)	15/32	26/31	10/20
sector spiral ext. (deg)	0	0	12
nbr. cavities	2	2	6
Peak Volt. injection (kV)	110	170	550
Peak Volt. extraction (kV)	110	340	1100
nbr. flat-top cavities	2	2	2
Flat-top frequency	126	126	210
FT Volt. injection (kV)	13	20	22
FT Volt. extraction (kV)	13	40	44
Radial gain ext.(mm)	16	12	10

III. THE INJECTORS

We propose a solution based on 2 compact cyclotrons. Therefore an axial injection is needed for each cyclotron with the following advantages :

- the use of an high extraction voltage,i.e. about 100 KV.
- the choice of a multicusp ion source for the production of negatively charged ions. This source is cumbersome and could not be installed in the central region of the cyclotron.
- getting a high brightness beam accelerated by the cyclotron requires a careful 6D matching (the two transversal and the longitudinal phase space), in particular it is necessary to use a buncher in a way to avoid too strong effects of the space charge.
- better vacuum which allows to use high RF voltages.

This compact cyclotron solution implies combining the output beam of 2 injectors delivering 5 mA working at the same frequency as the intermediate stage and the final booster. It is then necessary to superpose the bunches of the two 5 mA beams produced by each injector to obtain a single 10 mA beam in the ISSC. In order to reduce the space charge effects, it could be attractive to combine an H^+ beam (extracted by stripping H^- ions) and an H^- beam (extracted by a conventional channel). These two beams are synchronised so that the bunches are superposed in a straight portion of the ISSC injection line. A stripper is installed at the end of the injection line, before the beam enters the ISSC magnetic field in order to get a H^+ beam.

The RF system consists of two accelerating and two flat-topping cavities. In order not to worsen space-charge effects

by phase compression, a constant voltage distribution along the cavity gaps is desired.

Refined 3-D computations of the magnetic field have been carried out in particular in the injection and extraction regions. As opposed to the intermediate and booster cyclotrons, a closed magnet configuration with a return yoke is used in order to make the cyclotron more compact. A general view of the injector cyclotron is visible in Figure 2.

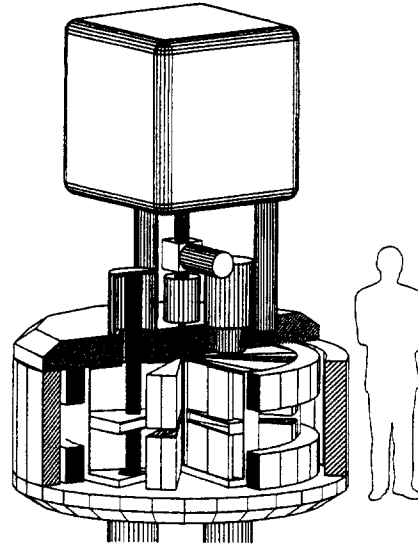


Fig. 2 : General view of the injector cyclotron

IV. THE INTERMEDIATE STAGE

A four-separated-sector cyclotron (cf. Fig. 3) has been chosen because of the following features :

- the acceleration to a sufficiently-high injection energy for the booster can be achieved in about 200 turns due to the possibility to install between the sectors cavities providing a high accelerating voltage.
- the flat-topping of the RF voltage is easy to achieve.
- the strong magnetic focusing provided by the four identical C-shaped sector with a constant small gap (5 cm).
- the possibility to install an efficient extraction channel in the field-free valleys.

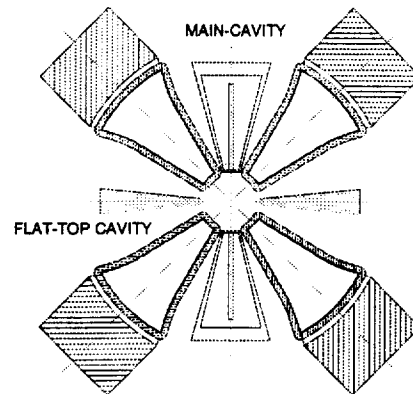


Figure 3 : Top view of the ISSC

The injection energy into the ISSC is certainly one of the most important parameters which influences the overall performances of the cyclotron complex. The space charge effects are strong at low energy. They are present in both transversal and longitudinal directions of the beam. Figure 4 shows the simulation of the evolution of a 20 mA beam in the horizontal plane during the first 16 turns in the ISSC.

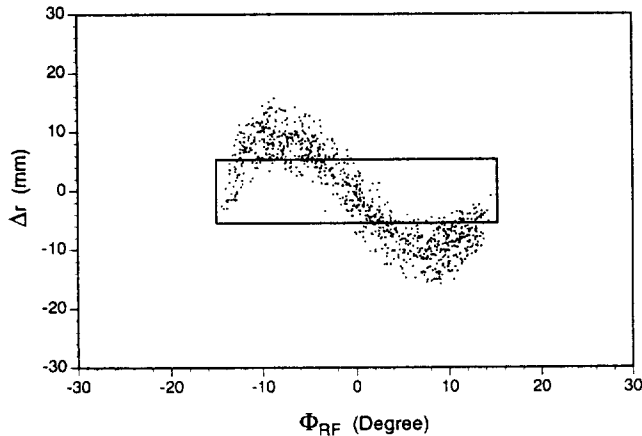


Figure 4 : Space charge effects after 16 turns (initial conditions at injection in the rectangular box).

V. THE FINAL BOOSTER

The lay-out of the booster can be seen in Figure 5. The magnet of the final booster consists of 10 identical C-shaped sector magnets with a strong spiral needed in order to obtain sufficient vertical focusing at high energy. As in the ISSC cyclotron design, no trimming coils are used for generating the radial magnetic field increase required by isochronism. This effect is obtained by increasing the sector width with radius.

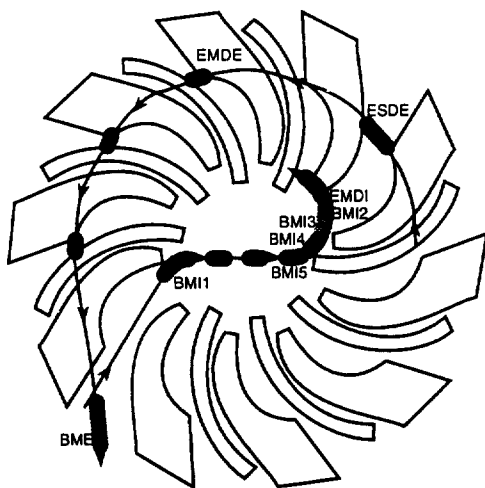


Figure 5 : Lay-out of the BSSC

Acceleration of the beam is provided by 6 main resonators located in the valleys giving an energy gain per turn of 3.0 MeV at injection and 6.0 MeV at extraction giving a voltage (or phase compression) ratio of 2.0. Single-gap

cavities are used for both accelerating and flat-topping cavities. Since the beam phase width can be reduced to 15 degrees at the intermediate cyclotron exit, fifth harmonic operation has been selected for the flat-top cavities. This enables to decrease the flat-top cavity power compared to operation on the third harmonic. Measurements on the accelerating cavity model have been carried out in order to check and determine precisely the cavity characteristics. A very good agreement has been found between theoretical and experimental results. The injection channel and extraction channels of the BSSC are shown on the Fig. 5.

VI. CONCLUSIONS

An essential aspect of this accelerator complex is the overall efficiency which depends mainly on the RF performances. For a 10 mA beam the power to be delivered to each main cavity of the BSSC is estimated to be about 2.05 MW (1.45 MW beam power and 0.60 MW cavity loss), which correspond to about 2.9 MW electrical power (assuming a 70% DC to RF conversion efficiency). Further optimisations of the cavity shape which are in progress show that a global efficiency slightly greater than 40 % is within the reach.

The authors would like to express their thanks to the members of the AT-ET Group for the many useful discussions during these studies.

VII. REFERENCES

- [1] F.Carminati et al, An Energy Amplifier for Cleaner and Inexhaustible Nuclear Energy Production Driven by a Particle Beam Accelerator, CERN/AT/93-47 (ET), 1st November 1993.
- [2] R.A.Jameson et al., Accelerator-driven transmutation technology for energy-production and nuclear-waste treatment, 3rd EPAC, Berlin 1992, pp. 230-234.
- [3] P.Bonnaure, P.Mandrillon, H.Rief, H.Takahashi, Actinide transmutation by spallation in the Light of recent cyclotron development, ICENES 86, Madrid, July 1986.
- [4] C. Rubbia, P.Mandrillon, N.Fiétier, A High Intensity Accelerator for Driving the Energy Amplifier for Nuclear Energy Production, 4th EPAC, London 1994, pp. 270-272.
- [5] Th. Stambach et al., Potential of cyclotron based accelerators for energy production and transmutation, Int. Conf. on Accelerator-driven transmutation technologies and applications, Las Vegas, July 1994.