IMPORTANT DESIGN ISSUES OF A HIGH EFFICIENCY CYCLOTRON COMPLEX TO DRIVE THE ENERGY AMPLIFIER

P. Mandrillon 2), S. Besançon 1) , N. Fietier 2), A. Giusto 2), S. Michel 1), S. Ponnelle 1),
C. Rubbia 1),
1) EET-Group -CERN-LHC-1211 Geneva 23
2) Laboratoire du cyclotron, 227 Avenue de la Lanterne, 06200-Nice (France)

Abstract

A high efficiency 3 stage cyclotron has been proposed [1] to provide a 10 MWatts proton beam in the 1 GeV kinetic energy range for driving the Energy Amplifier. This accelerator complex consists of the following chain : two 15 MeV compact isochronous cyclotron (CIC) feeding a 4 separated sector ring cyclotron (ISSC) raising the energy up to 120 MeV. A final stage made of 10 spiral separated sectors boosts the energy in the 1 GeV range. This paper presents some critical design issues.

1 INJECTOR CYCLOTRON

A 4 sectors compact isochronous cyclotron (CIC) has been chosen. The main features of this injector are summarized in Table 1. Fig 1 shows a general view of the cyclotron, its source and axial injection line.

Table 1: Main parameters of the injector

Injection energy (keV)	100
Extraction energy (MeV)	15
Sector maximum radius (mm)	900
Sector gap (mm)	60
Total iron weight (ton)	40
Number of main RF cavities	2
RF peak voltage (kV)	100
Number of auxilliary RF cavities	2

1.1 Source and LEBT

A source delivering a high-brightness H^- beam (about 50 mA at 100 keV) for DC operation is required. A RF driven (2 MHz) volume-produced, low temperature H^- multicusp plasma source has been selected whose characteristics are close to that developped by K.Leung[2].

A 2-D code called SLAC has been adapted to define the configuration of the electrodes of the Low energy beam transport system (LEBT). It was developped by W.Hermannsfeldt [3], and adapted by J.Pamela [4] for the design of high intensity sources in fusion research. A Poisson solver is used interactively together with an ion tracking routine until a satisfactory convergence on the position of the beam at the final electrode exit is obtained. It includes the effects of space-charge due to H-, electrons and gas stripping. The electrons must be deflected because they contribute to increase the space-charge effects on the H^- beam since the electron current is several times (3-10) larger than the H^- current and would produce radiations if accelerated further. It is planned to carry out more sophisticated calculations using a 3D code integrating the Poisson Vlasov's equations.

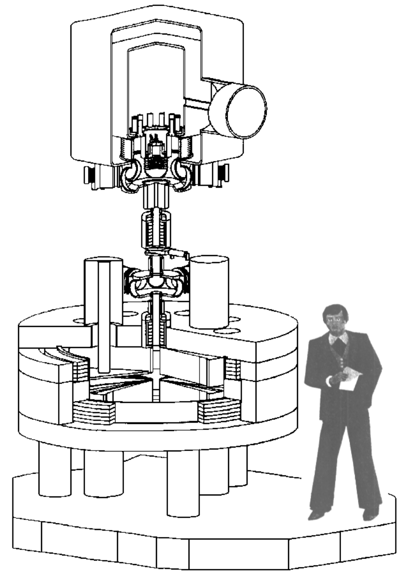

Figure 1 :View of the injector

A multi-stage design with six electrodes provides enough flexibility to handle high currents allowing to adjust independently the beam radius and divergence at the matching point of the beam line.The layout of the LEBT for a 100 keV and 50 mA design is shown in Fig 2.

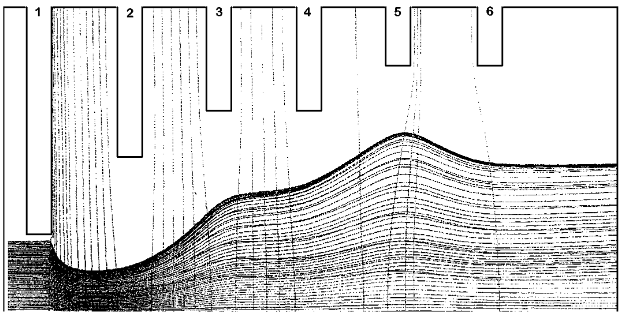

Figure 2 : LEBT layout and beam enveloppe

1.2 Axial injection line

Two solenoids are used to focus the beam. Preliminary studies have shown that a buncher might slightly enable to reduce the source current needed to reach the design current level in the cyclotron. The second solenoid is needed to focus the beam at the entrance of the inflector.Several diagnostics stations have to be inserted before the beam is deflected from its axial direction into the median plane.

A dedicated transport code BEAMLINSC has been developed in order to design beam lines with linear space-charge effects. In addition to the usual optics elements bunchers and spiral inflectors can be included. In a first step the influence of the cyclotron magnetic field along its axis has been approximated by a solenoidal field where strength varies along the axis. A more accurate code using multiparticle is being developped in order to take into account non-linear effects due to space charge. These effects are present in the spiral inflector, where a strong coupling between the various beam coordinates is encountered. The magnetic field in the center of the cyclotron being rather non-uniform, analytical expressions for the particle trajectories can not be used reliably and must be replaced by numerical integration in 3-D static magnetic and electric field maps. Knowing the particle positions without space charge effects, the electric field due to space charge is computed via FFT for solving Poisson's equation [5]. After smoothing procedures particle trajectories are computed again and so on until a satisfactory convergence (a few iterations) is obtained on the particle position at the inflector exit.

1.3 Magnet design

After some preliminary 2-D and hard edge calculations the 3-D code MAFIA [6] has been used to design the magnet circuit. It turned out that preliminary geometrical sector shape was close enough so that only very few iterations with MAFIA have been needed. Starting from the map generated with the computer code MAFIA the equilibrium orbit code EUQUIL, indicates how far the generated field is from isochronism.

A mechanical study of the magnet deformations under the effect of the magnetic forces and own weight, has been carried out allowing to fix the final thickness of the yoke.

2 BEAM DYNAMICS

A dedicated code based on the micro-gap concept [7] computes the accelerated reference particle trajectory in the injector cyclotron median plane and check that the isochronism condition is satisfied. A 3-D multiparticle code TRACKSC3D using the potential maps in the gaps generated with MAFIA takes into account the various effects that occur in the injector cyclotron particularly in the central region where the beam quality is defined. This is a full 3-D PIC code using FFT technique to compute the beam-induced potential by solving Poisson's equation. This model could also be applied to study the dynamics in the ISSC and compared to the more crude one where space-charge effects have been taken into account by introducing a simple model [8]: at regular locations along the accelerated path, energy and momentum increments are computed from the analytical expression providing the electric field generated by an ellipsoidal beam. At low energies, the beam is far from this kind of shape, its size is overestimated and the lectric field values are underestimated.

Preliminary simulations of the beam bunch behaviour under space-charge effects at various beam energy in the transfer line between the injector and ISSC have determined that 15 MeV would be an acceptable value of this parameter. In order to reduce the longitudinal debunching of the beam in the transfer lines, it is planned to combine an H^+ beam and an H^- beam These two beams are synchronized so that the bunches are superposed in a straight portion of the ISSC injection line. A stripper is installed at the end of this line before the beam enters the ISSC magnetic field in order to get a "pure" H^+ beam. The beam bunches have been approximated in a first rough model as a set of cylinders.A more detailed study of the "bunch mixing" needs to be undertaken to get an accurate description of the injection conditions in the ISSC.

3 THE 200/1200 MEV OPTION

In order to increase the beam power requirements from 10 mA.GeV to 12.5 mA.GeV the intensity has to be increased by 25 %. Keeping the same RF frequency (42 MHz) it might be interesting to increase the booster energy from 1 GeV to 1.2 and the number of sectors form 10 to 12 thus alllowing to use 2 additional RF cavities (8 instead of 6). In order not to increase too strongly the spiral of the sector edges of the booster cyclotron, it is advisable to increase the final energy of the ISSC from 120 to about 200 MeV. The main parameters of the ISSC and BSSC are presented in Table 2.

Table 2 : Parameters of the 2 options

	Inter (A)	Booster (A)	Inter (B)	Booster (B)
Inject. energy (MeV)	15	120	15	200
Ext.energy (MeV)	120	1000	200	1200
current (mA)	12.5	12.5	10.4	10.4
Rad. gain extr.(mm)	12	10	10	12
Number of sectors	4	10	4	12
Sector span in/ex(dg)	26/31	10/20	25/34	8/15
Sector spir. ext.(dg)	0	12	0	14
Number of cavities	2	6	2	8
Injec voltage (kV)	170	550	190	550
Extr. voltage (kV)	340	1100	380	1100
Total losses (MW)	0.44	1.8	0.63	2.4
Flat-top harmonic	3	5	3	5

The upper limit to increase the energy in the ISSC comes from the focussing point of view and is close to 200 MeV with a four sector machine operating without coils for providing an additional field gradient to the contribution obtained by the radial increase of the sector angular width and without spiraling the sectors.

Fig.3 shows a general view of the 12 sectors of the final booster and their surrounding yokes. It has been necessary to increase the field level in the sectors up to 2T in order to leave sufficient room at large radii to locate RF accelerating cavities.

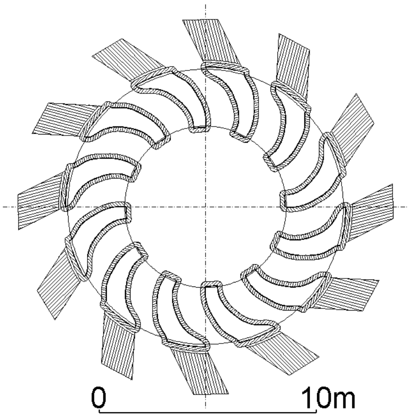

Figure 3 : The 12 sectors BSSC

4 REDUCING THE RF LOSSES

Single-gap cavities with simple cylindrical shape have been considered in a first step.However, due to the limited room available between the sectors because of the spiral, the RF losses in the walls are large (of the order of 500 kW with voltages of 550 and 1100 kV at injection and extraction), making the design of the cooling system a rather uneasy task. In order to reduce these losses, a study with MAFIA has been carried out. Three successive models have been considered.The model referenced as “#1” corresponds to the basic cylindrical box shape without lips for which an analytical solution of the electromagnetic field and losses can be determined. It has been introduced in order to check that correct results are obtained with MAFIA for this simple model. The differences are shown in the Table 3. In the “Cavity #2 lips have been symmetrically added near the cyclotron median plane in order to account for transit time effects in the gap. This induces a frequency reduction of 3.5% and an increase of the losses of 7.5% if the cavity walls are left unchanged. The cavity height must therefore be slightly increased in model “#2” in order to get the design frequency (42 MHz). Model “#3” is a modified version of model “#2” in the sense that the cavity walls have been extended in order to benefit more from the room available between the coils since the analytical model shows that the RF losses are roughly proportional to the inverse of the square of the distance between the walls (model #1). For the same design parameters the reduction of the RF losses is 44% and the total cavity height has been decreased to 3.0 m (4.56 m for model #2). The voltage distributions along the gap of the various models depart only slightly from the theoretical sinusoidal shape.

Table 3: Losses of the various cavity models

	Losses (kW)	Voltage ratio	Quality factor
Analytical	509	2.0	42200
Cavity #1	488	2.05	42170
Cavity #2	525	1.83	41680
Cavity #3	292	1.97	51420

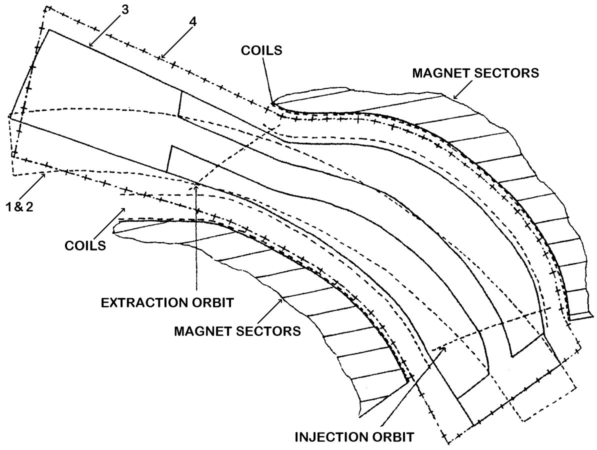

Figure 4 : Various models of the BSSC cavity

5. CONCLUSIONS

The possibility of operating the ion source under DC conditions at high current densities is certainly one of the crucial issues which should be tested rapidly. Detailed beam dynamics simulations will have to be carried out before a choice is made for the initial and final energies of the ISSC and BSSC machines. A detailed study of the tuning and power coupling system has to be completed and their performances must be checked on models. Further investigations should help in determining whether a single amplifier chain with power splitters should be allocated to each accelerating cavity or whether each loop would be associated with its own transmitter.

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