A CYCLOTRON-BASED ACCELERATOR FOR DRIVING THE ENERGY AMPLIFIER

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This paper presents the results of the preliminary studies of an high energy (1 GeV), high intensity (12.5 mA) accelerator complex to drive the proposed Energy Amplifier (EA) for nuclear energy production. After describing the new concept of the EA based on nuclear cascades induced by high energy protons, a solution producing a continuous beam accelerated by a three-stage cyclotron complex is presented.

1 Introduction

Scenarii presented by various experts anticipate that the world energy consumption will increase from about 9 Gtoe to 11-16 Gtoe by the year 2020. Most of the increase is expected to occur in the developing countries. To meet these needs, the classical solutions will only give a partial answer :

- The contribution from non-renewable energies will remain large but is potentially limited
- The increase in consumption of fossil fuels will induce a raising emission of carbon dioxide and greenhouse-induced global warming
- The present nuclear plants (Pressurised Water Reactors) encounter considerable social acceptance difficulties, waste reprocessing and plutonium proliferation problems
- The technological challenge of energy produced by fusion require a long effort of research and development

Therefore, the need for new concepts for clean energy production is a major concern for the society. The criteria for a nuclear revival are :

(1) An extremely high level of inherent safety
(2) A minimal production of long-lived waste and elimination of the need of the geologic repositories
(3) A strong hindrance to latent proliferation of products that can be used for nuclear weapons
(4) A more efficient use of a widely available natural fuel, without the need of isotopic separation
(5) A lower cost of the heat produced and a higher operating temperature than conventional PWRs in order to permit competitive generation of substitutes to fossil fuels.

The Energy Amplifier (EA) proposed by C. Rubbia could help in solving these problems and complement the present sources of energy. Its concept based on nuclear cascades induced by high energy protons is described in section 2 [1],[2],[3]. The last part of the paper is devoted to the design status of accelerator complex driving the EA. More specific aspects like the beam dynamics with space-charge and RF system are treated in more details in companion papers [4], [5].

2 The Energy Amplifier Concept

This concept of energy amplification to extract nuclear energy with the help of accelerator-induced nuclear cascades extends to practical energy production the calorimeter technique, widely used in High Energy Physics. A schematical view of the Energy Amplifier can be seen in Fig. 1.

As a consequence of the large number of nuclear collisions initiated by the beam, energy is released at the expense of the breaking-up of heavy nuclei inside the target. Energy (in the form of heat) is produced inside the block in an amount which largely exceeds the energy delivered by the beam. The calorimeter is designed in order to extract easily the heat produced and to optimise the development of the cascade in order to bring the overcompensation to its largest possible value, by creating physical conditions which are optimal for the break-up of heavy nuclei. A fraction of such energy in turn is transformed into electricity used to run the accelerator, with the remaining larger fraction delivered for external utilisation either in the form of heat or of electricity or both. The main energy production mechanism is based on fission. When compared to a classic calorimeter used in elementary particle physics, the incident beam flux is much larger. It is therefore possible to enhance greatly the energy amplification by breeding through nuclear transformations the content of readily fissionable materials as in the case with thorium which will easily breed ^{233}U.

The energy is produced from a nuclear fuel material disposed in a moderator medium through a process of breeding of a fissile element from a fertile element of the fuel material. After an initial phase, the rate between the concentrations of fissile and fertile elements reaches a substantial stability, resulting in a stable long term energy production. The device must operate at relatively low neutron flux, in the 10^{14} $cm^{-2}s^{-1}$ range, to ensure the correct performance of the breeding cycle and to prevent the risk of criticality. Thorium as breeding fuel has considerable advantages when compared with uranium.

Thorium is more abundant than uranium. It generates much less transuranic actinides among the radioactive waste. This primary fuel is completely burnt after a number of fuel cycles through the Energy Amplifier. Actinides present in the fuel discharge at the end of a fuel cycle are reinjected in the Energy Amplifier and become the seeds for the subsequent cycle. This ensure a very efficient use of the primary fuel element.

The purpose of the accelerator is the one of producing most efficiently the largest number of secondary neutrons by collisions between the beam and a solid target. There is a large independence of the energy gain on the energy of the incoming beam above a certain level (~1 GeV) as this has been predicted by simulations and checked experimentally [6]. Unlike a conventional reactor, the Energy Amplifier's fission reaction is not self-sustaining and subcritical and needs a continuous supply of neutrons. If the accelerator stops, the reaction stops as well.

The possibility of building an EA that operates in analogy to a Fast Breeder Reactor in the region of fast neutrons, namely well above the resonance region, with an average neutron energy of 10^5-10^6 eV has been deeply explored [2],[3]. It offers a high gain, a large maximum power density and an extended burn-up well in excess of 100 GW*day/ton corresponding to about five years at full power operation with no intervention on the fuel core. The radiotoxicity emitted in the environment for unit produced energy is largely inferior to the one of a PWR. The necessity of geological storage of radioactive waste is strongly reduced. The problem of a criticality accident is suppressed since the device operates far below the critical threshold at all times. Spontaneous convective cooling by the surrounding air makes a melt-down leak impossible.

Each module consists of a 1500 MW_{th} unit with its dedicated accelerators. A plant may be made of several such modules with accelerators in parallel. This parallel concept similar to the cyclotron-driven transmutor [7], as opposed to a series concept based on several linac stages, enables to ensure a continuous operating mode. Maintenance would be carried out separately for each accelerator without stopping the whole accelerator complex. For instance, a cluster of three such modular units will produce about 2000 MW of primary electrical power. This corresponds to a thermodynamical efficiency of about 45%. The nominal energetic gain, which is defined as the thermal energy produced by the EA divided by the energy deposited by the proton beam , is set to G=120 corresponding to a multiplication coefficient k=0.98. The nominal beam power for 1500 MW_{th} is then 12.5 mA*GeV. The delivered power is controlled exclusively by the current of the accelerator. The fuel needs no change during the whole burn-up and it may be kept sealed up as a non-proliferation safeguard measure.

The coolant medium is molten natural lead operated at a maximum temperature of 600-650 C.

A most relevant feature of this design is the possibility of using natural convection alone to remove all the heat produced inside the core. Because of the unique properties of lead, namely high density, large dilatation coefficient and large heat capacity, the "swimming pool" technique used in reactors at small power levels can be extended very safely to the large power of the EA. No pumps are needed in the primary loop. Heat is transferred by convection involving a large mass of lead from the top of the core to four 375 MW_{th} heat exchangers located some 20 meters above. Then the "cooled" liquid lead returns at a lower temperature from the heat exchangers to the bottom of the core.

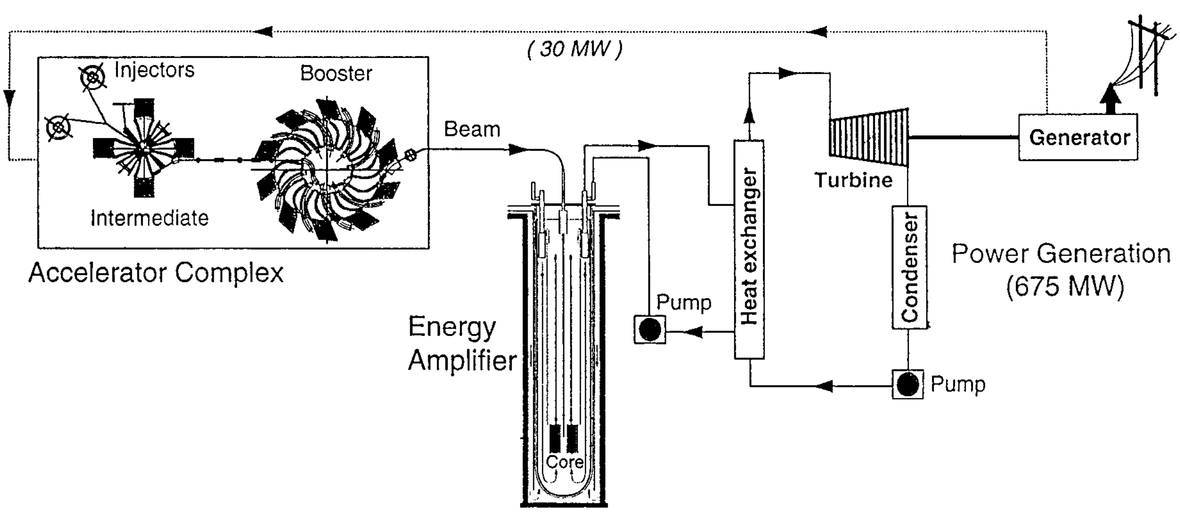

Fig. 1: Schematics of the Energy Amplifier complex

The main EA vessel is therefore relatively slim (6.0m diameter) and very tall (30m). It is housed below floor level in a very robust cylindrical silo geometry lined with thick concrete, which acts also as ultimate container for the liquid lead in case of the highly hypothetical rupture of the main vessel. It is supported at the top by antiseismic absorbers.

Thermal run-off is prevented through a certain number of additional volumes that would take care of the subsequent dilatation of the liquid lead. A liquid lead beam stopper sufficiently massive as to completely absorb the beam some 20 meters away form the core would bring the EA safely to a stop. In addition, absorbers would be pushed into the core and anchor the device firmly away from criticality.

The penetration of the beam in the Energy Amplifier vessel is achieved through an evacuated tube and a special tungsten window, which is designed to sustain safely both radiation damage and the thermal stress due to the beam heating.

3 The Cyclotron-Based Accelerator Complex

3.1 General considerations and design criteria

As this has been presented in the previous section, the goal of the accelerator is to provide a 12.5 MW proton beam, which is one order of magnitude less than the requirements of planned facilities for transmutation of waste [8]. Therefore, the requirements for the Energy Amplifier open different technical solutions for the accelerator, either an accelerator chain based on linacs or circular machines as ring cyclotrons producing a cw beam. Based on the outstanding results obtained at the Paul Scherrer Institute [9], a three-stage cyclotron accelerator is a possible solution. Its features have been described in a preliminary report [10]. It consists of:

- two injectors, which are compact isochronous cyclotrons (CIC) able to deliver a 6.25 mA beam in a given phase width (typically 30 deg. RF) up to 10 MeV
- an intermediate separated-sector cyclotron (ISSC), which is a four sector ring cyclotron accelerating the beam up to 120 MeV
- a final booster separated-sector cyclotron (BSSC), which is a ten sector six cavity ring cyclotron raising the energy up to 1000 MeV.

An alternative to this solution based on two 5.2 mA injectors , a 10-200 MeV ISSC and a 200-1200 GeV BSSC (with twelve sectors and eight accelerating cavities) is being investigated to produce the required 12.5 mA*GeV beam power

Acceleration of intense beams requires a very efficient extraction process with low beam loss. They must be reduced to a few μA in order not to hinder the safe operation and maintenance of the cyclotrons according to the experience gained at PSI [9] provided adequate shielding and handling devices are present.

The main parameters of the various cyclotrons are presented in Table 1 for both alternatives.

Table 1: Main parameters of the cyclotrons

Accelerator	CIC	ISSC	BSSC
Inj. energy. (MeV)	0.1	10	120/200
Ext. energy. (MeV)	10	120/200	1000/ 1200
Frequency (MHz)	42	42	42
Harmonic	4	6	6
Magnet gap (cm)	6	5	5
Nb of sectors	4	4	10
sector angle at inj.	15 deg.	26/25 deg.	10/8 deg.
sector angle at ext.	32 deg.	31/34 deg.	20/15 deg.
sector spiral at ext.	0 deg.	0/0 deg.	12/14 deg.
Nb of acc. cavities	2	2	6/8
Inj. voltage (kV)	110	170/190	550
Ext. voltage (kV)	110	340/380	1100
Nb of flat-top cav.	2	2	2
Flat-top harmonic	3	3	5
Inj. voltage (kV)	12	20/22	(1)
Ext. voltage (kV)	12	40/44	(1)
Radial gain ext. (mm)	16	12/10	10/12
acc. cav. losses (total) (MW)	0.05	0.44/ 0.63	2.4/3.2
Beam power (total) (MW)	0.062/ 0.052	1.38/ 1.98	11/10.4

(1) This voltage depends on the type of flat-topping that will be used (local or global) and that has not been fixed yet.

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. a high energy gain per turn, in order to get an efficient 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 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.
- Matching the three stages : In order to avoid any beam loss, matching conditions must be satisfied between

the various 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. This frequency has been selected because it enabled to obtain good focussing frequencies and high enough field levels in the sector magnets (to reduce the machine size).

The efficiency of the accelerator complex, i.e the power provided to the beam divided by the electrical power needed to run the accelerators, has been estimated to be equal to about 40 %, considering a 70% DC to RF conversion efficiency in the RF amplifiers and including losses in the magnets of the cyclotron and beam lines.

The injection energy in the ISSC is certainly one of the most important parameters, which influences the overall performances of the cyclotron complex [12]. Approximation formulae and beam dynamics simulations in the beam tranfer line between the injector cyclotrons and the intermediate ring and in the ISSC itself [4] indicate that 10 MeV should be an acceptable value of this parameter.

3.2 The injector cyclotrons

A solution based on two compact cyclotrons is proposed. An axial injection system is needed for each cyclotron with the following characteristics :

- A high extraction voltage i.e. about 100 kV.
- Based on the recent development of high intensity sources [13], an external multicusp ion source for the production of H^- ions has been selected.
- Getting a high brightness beam accelerated by the cyclotron requires a careful matching in transversal and longitudinal phase-space. In particular, it is necessary to use a buncher in a way to avoid too strong effects of the space charge [14].
- A high enough vacuum quality, which enables the use of high RF voltages.

This compact cyclotron solution implies the combination of the output beams of the two injectors, each of them delivering a 6.25 mA current and being operated at the same frequency than the following stages. It is then necessary to superpose the bunches of the two 6.25 mA beams produced by each injector in order to obtain a single 12.5 mA beam in the intermediate ring. So as to reduce the space-charge effects, it could be attractive to combine an H^+ beam (extracted by H^- ion stripping) and an H^- beam (extracted by a conventional channel). These two beams are synchronized so that the bunches are combined in a straight section 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 "pure" H^+ beam.

A general view of one of the injector cyclotron is shown in Fig. 2. A closed version (as opposed to a separated sector one) is presently studied in details. The computations carried out up to now show that a separated-sector version of the 10 MeV injector is probably not necessary to reach the 5-6 mA design goal. Nevertheless the final decision concerning the injector type will be taken before the end of this year.

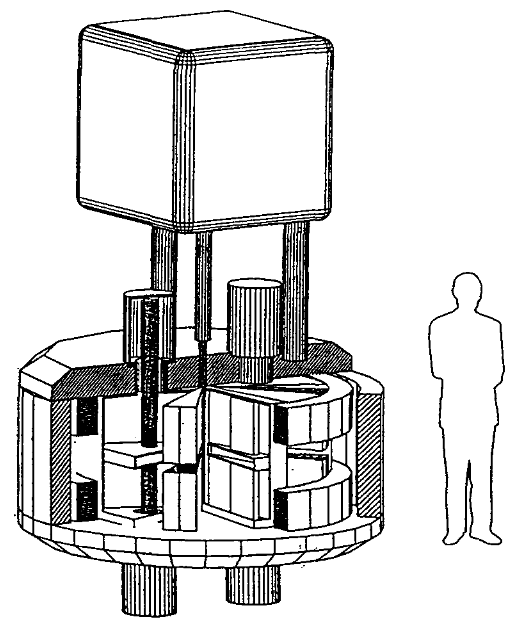

Fig. 2: General view of one injector cyclotron CIC

At the end of the injection line, it is planned to use a spiral inflector in order to steer the beam from its axial direction into the horizontal median plane of the cyclotron. Strong coupling between the various phase space components in the inflector in addition to space-charge and gap effects in the first turns in the cyclotron require collimation before efficient beam acceleration can be achieved in order to obtain clean and compact bunches at the exit of the injector cyclotrons.

The RF system consists of two accelerating and two flat-topping cavities. So as not to worsen space-charge effects by phase compression a constant voltage distribution along the cavity gaps is desired. The cavities have been designed with the CAD code MAFIA [15]. Due to room available between the sectors and coil, a classical $\lambda/2$ coaxial-type accelerating cavity with a single circular stem has been selected. The stem and liner must break through the return yoke according to the design frequency

[5]. As far as the flat-topping cavities are concerned, they would also operate according to a coax-like fundamental mode but the stem geometry is rather different. Long stem extension along the dee is necessary in order to meet the frequency and voltage requirements. The whole cavities can be housed below the cyclotron return yoke.

Another possibility based on a superconducting separated-orbit cyclotron has been studied by U. Trinks [10], [11]. Its main characteristics are summarized in Table 2. This type of injector might be used in the future once its reliability is assessed, specially in the presence of large currents.

Table 2: Main parameters of the SOC injector

Injection energy	2 MeV
Extraction energy	12.3 MeV
Revolution frequency	6 MHz
Cell structure	OFODO
Turn separation (in cav.)	60 mm
Number of cavities	4
RF frequency	168 MHz
Acc. voltage at inj.	180 kV
Acc. voltage at extr.	450 kV
Number of sectors	12
Number of channel/sect.	13 (12)
Magnetic field	1.3 T
Cryostat Diameter	3.6 m

3.3 The intermediate stage

A four-separated sector cyclotron shown in Fig. 3 has been retained because of the following features :

- The acceleration up 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 and a good turn separation at extraction..
- The cavities can be easily inserted in the valleys.
- An efficient extraction channel can be located in the field-free valleys.
- This type of cyclotron has good focussing properties.

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 [16]. In a second step, magnetic maps have been generated with a program that enabled to extrapolate smooth azimuthal profiles form data measured on models used for other cyclotrons and introduced in a equilibrium orbit code. Transverse space-charge effects have been taken into account by mutiplying the focussing frequencies by correction factors as suggested by Joho [17]. The sector width and field level (about 1.45T) have been selected so that the radial and vertical focussing frequencies remain in the intervals 1.2-1.4 and 1.3-1.4 over the acceleration range [4].

Double-gap cavities for both acceleration and flat-topping purposes have been selected (as opposed to single-gap ones) because their radial extension is much smaller, thus leaving more space in the centre of the machine for the bending and injection magnets and the beam diagnostics. Low-level models of the main and flat-topping cavities have been respectively built at 1:3 and 1:1 scales in oder to check the predictions made with the code MAFIA [5]. For voltages respectively equal to 170 and 340 kV at injection and extraction, the estimated losses in one accelerating cavity are 220 kW.

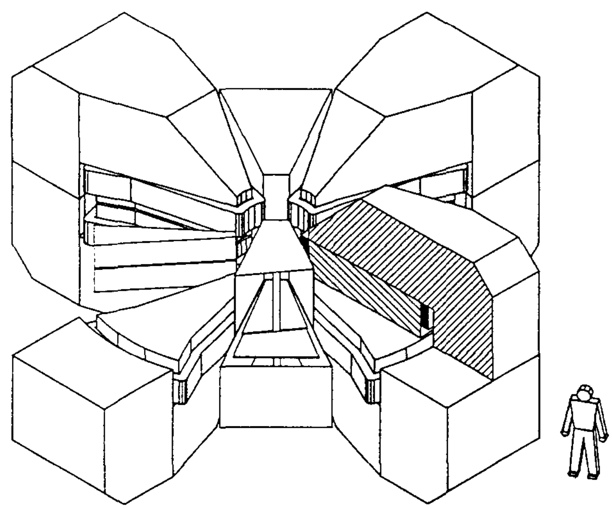

Fig. 3 : The intermediate stage ISSC

A preliminary design of the injection and extraction systems is shown in Fig. 4. At the end of the beam line that transports the combined H^+/H^- beam from the injectors, a final stripper produces a pure H^+ beam, which is injected in the cyclotron through a valley along a flat-topping RF cavity in order not to be affected by the fringe field of the magnet sectors. The beam is deflected by two bending magnets BMI1 and BMI2 before entering an electromagnetic channel EMDI located in one of the cyclotron sector gap so that it reaches the first RF cavity gap where acceleration starts. Injecting at 10 MeV enables to take benefit of enough room to locate the deflecting magnets and use a simple set of deflecting elements with moderate magnetic field requirements. An electrostatic deflector located in one of the valleys where a flat-topping cavity is installed should be used for slightly steering the beam position radially so that the first internal orbit is sufficiently separated from the injected orbit and impose optimized injection conditions for the accelerated orbit in the ISSC.

In order to extract the beam with a very high efficient way (very little beam loss is allowed in order to reduce radioactivity), a simple system consisting of an electrostatic deflector ESDE, an electromagnetic deflector EMDE and a bending magnet is proposed. The three channel components are located in two successive valleys. After the beam is kicked outwards from the last internal orbit by the ESDE located at the exit of a main RF cavity, it passes through a magnet sector and is further deflected to the entrance of the next valley by the EMDE. The last section is a conventional bending magnet, which is located in the valley behind a RF flat-topping cavity as shown in Fig. 4.

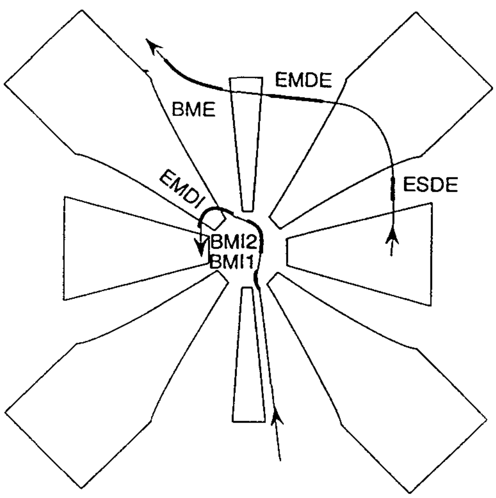

Fig. 4: Injection and extraction system of the ISSC

3.4 The booster stage

This section presents the main characteristics of the booster ring cyclotron. the design method and technology that would be used for all the elements of this machine are the same as the ones that have been presented in the previous section. For the sake of avoiding redundancy, only peculiar characteristics of the BSSC will be presented. A general view of the booster cyclotron can be seen in Fig. 5.

The methodology used for the design of the booster cyclotron as far as the magnets are concerned is quite similar to the one presented in the previous section. In order to obtain sufficient vertical focussing at high energies, a spiral is needed on the edges of the magnet sectors. The sector angular width and magnetic field level (1.8T) have been selected so that the radial and axial focussing frequencies remain in the intervals 1.1-1.95 and 1.1-1.2 over the acceleration range [4].

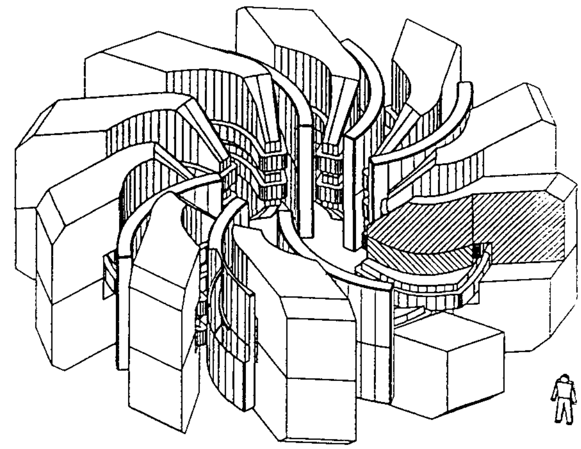

Fig. 5: The booster stage BSSC

Acceleration of the beam is provided by 6 main resonators located in the valleys. They should provide an energy gain per turn of 3.3 MeV at injection and 6.6 MeV at extraction, increasing the beam energy from 120 to 1000 MeV. In order to compensate the effects of space charge forces, two flat-topping cavities are needed. They would operate on the fifth harmonic of the main cavities i.e 210 MHz. Single-gap cavities are the most suitable canddates because azimuthal space is restricted between the sectors [5]. In addition, this type of cavity has an inherent high quality factor. In order to reduce the number of turn in the cyclotron and obtain sufficient turn separation at extraction. Accelerating voltages of 550 kV and 1100 kV are required at injection and extraction. If cavities with simple cylindrical walls are slected, the corresponding wall losses have been estimated to be 600 kW per cavity, which makes the design of the cooling circuit rather complicated. The shape of the cavities is being optimized and depart from the simple cylindrical one in order to reduce this losses below 400 kW In addition these cavities, will have to handle about 1.84 MW of beam power. Therefore about 2.24 MW RF power must be transmitted to each cavity, which makes the coupling an uneasy task. According to the PSI experience, one RF window can handle up to 600-700 kW, which means that four such windows would be needed per cavity.

Fig. 6 shows the injection and extraction channels of the BSSC. The location of the deflecting elements of the injection channel have been defined with a dedicated code tracking the beam from the first RF cavity gap backwards outside the ring. The beam is injected through one of the empty valleys, deflected clockwise towards the machine center by the first bending element BMI1. After a straight section, it is successively bent counter-clockwise by the four following bending magnet BMI2 to BMI5, of which location and magnetic field has been adjusted to clear out both neighbouring cavity and sector magnet. An additional electromagnetic deflector should be used in the following sector nose in order to bring the beam in the first RF cavity gap with conditions appropriate for efficient beam acceleration and transport in the cyclotron.

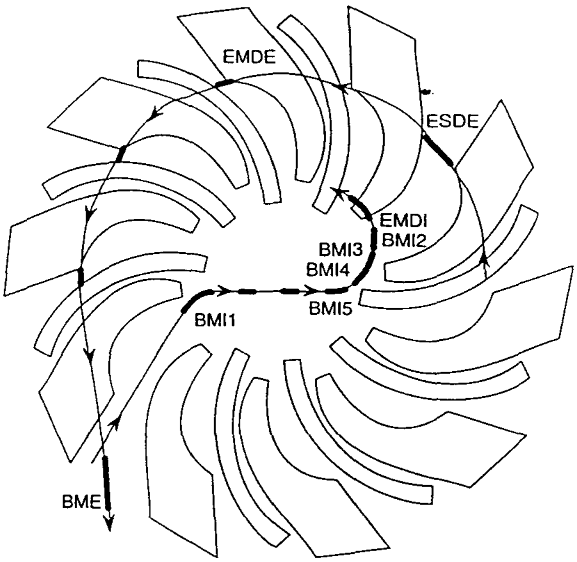

Fig. 6: Injection and extraction channels of the BSSC

An electrostatic deflector ESDE located in the free valley first deflects the beam in order to get sufficient separation from the last internal orbit so that the beam does not interfere with the electormagnetic deflector (EMDE) structure. This element further deflects the beam outwards, which goes naturally out of the magnetic field. The last element of the extraction system, the bending magnet BME, has been located far enough from the magnet yoke so that enough room is provided for the injection beam line to pass between the yoke and the bending magnet itself. The additional elements visible in Fig. 6 between EMDE and BME are radially focussing the beam when it strongly experiences the effects of the sector fringe field.

The basic features of the 1200 MeV version are the same except the followings points that must be underlined. In order to get sufficient room between the twelve sectors to locate the eight RF accelerating cavities without requiring excessive amounts of RF power, the field level must be increased to 2T. The cyclotron is operated with radial and axial focussing frequencies respectively remaining in the intervals 1.1-2.2 and 1.1-1.3 over the acceleration range.

3.5 Beam transport to the Energy Amplifier

The beam extracted from the cyclotron complex has a typical transverse invariant emittance of $\varepsilon_{inv}=2\pi$*mm*mrad and a momentum spread of the order of a few 10^{-4}. The current density is roughly uniform in the transverse phase-space. leading to an approximately parabolic current density in a focal point. Standard bending magnet and quadrupoles can be used to transport the beam to the EA. It is planned to irradiate the target with a large beam spot which is obtained naturally because of its emittance after a long drift space following a tiny focal point, which would enhance the angular divergence of the beam.

An appropriate collimator is limiting the aperture available to the beam in this point to about 10 times its nominal radial size, large enough in order to let the beam through with no loss in ordinary conditions. In case of the accidental mis-steering of the beam or of a malfunctioning of the focussing lenses, the spot will grow in size and the beam will be absorbed by the collimator. In this way, the beam window can be protected against accidental “hot spots” caused by the wrong handling of the beam. It has been verified that the defocussing forces due to the beam current do not appreciably affect the beam optics.

The beam must be transported under a reasonable level of vacuum. In our design, the last part of the beam tube is filled with Pb vapour at the pressure of about 10^{-2} Torr, the vapour tension of the coolant at the operating temperature. Differential pumping and a cold trap will remove these vapours, which may be radioactive before they reach the accelerator. There are no appreciable effects of this residual pressure on the beam propagation. The need of clearing electrodes will be further studied, but it appears unnecessary at this level.

The beam current and positions should be carefully monitored with dedicated diagnostics [18]. In case of a malfunctioning of the beam, the accelerator current can be cut-off very easily in the axial injection line of the injectors in typical times of the order of µs (the transition time from the ion source to the final focus), thus avoiding any damage of the hardware due to beam mis-steering. An alternate beam stopper should be provided to which the beam could be dumped during accelerator tuning and the like.

4 Conclusion

The preliminary studies have shown that a three-stage cyclotron facility could provide a solution a 12.5 mA*GeV beam to drive the Energy Amplifier. 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) refined computations of the beam merging (H^+ and H^-) and transfer from the injectors in order to define the beam characteristics at injection in the ISSC.

3) detailed beam dynamics evolution in the ISSC with space-charge effects taking into account the particle distribution after the final stripper.

In addition to the beam dynamics aspects, engineering studies on the three accelerators have to be started. Of particular importance are the mechanical design studies of the vacuum chamber and structure of the cavities of the BSSC.

Further design and testing work has to be carried out in order to assess a very high reliability of various components like the RF flat-topping and accelerating cavities. The shape of the BSSC cavities is being optimized so as to reduce the wall losses. It is planned to build a high power prototype of the accelerating cavity and of the high speed beam absorber of the booster cyclotron.

Finally, the preliminary features of a conceptual study aiming at increasing the energy towards 1200 MeV have been presented and more detailed investigations are in progress.

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