A High Intensity Accelerator For Driving The Energy Amplifier For Nuclear Energy Production

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Abstract

This paper presents the results of the preliminary studies of an high energy [1GeV], high intensity [10mA] accelerator complex to drive the recently proposed Energy Amplifier for nuclear energy production. After describing shortly this new concept of energy amplification based on nuclear cascades induced by high energy protons, the design criteria of the accelerator complex are discussed. A solution producing a continuous beam accelerated by a three stage ring cyclotron complex is presented.

1. INTRODUCTION

The need for new concepts for clean energy production is a major concern for the society. The present civilian nuclear energy system creates radioactive wastes of variable life-time. It also opens the possibility of highly dangerous proliferation of fissile material such as Plutonium. Moreover the need for energy in developing countries increases dramatically. Based on the present accelerator technology the proposed Energy Amplifier which has been developed by a team led by C. Rubbia [1] could help solving these problems and complement other sources of energy. The Figure 1 shows a schematic layout of the Energy Amplifier.

2. THE ENERGY AMPLIFIER CONCEPT

The concept is based on the use of a particle accelerator producing a proton beam in the 900-1000 MeV energy range which induces nuclear cascades and acts as a source of a relatively low neutron flux in the 10^{14} $cm^{-2}s^{-1}$ range. 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. Thorium, as a breeding fuel, is more abundant than Uranium and generates less transuranic actinides among the radioactive waste.On the basis of computer simulations, energy will be amplified by a factor of 40 ,i.e. the 10 MW input beam controls 400 MW thermal output. This system is composed of two main elements: the accelerator and the tank. A system for the transmutation of radiotoxic reaction products is also under study.

This concept, if validated by the experimental programme to be made in the coming few months at CERN [2] using a low intensity beam from the Proton Synchrotron , could lead to the construction of a prototype .

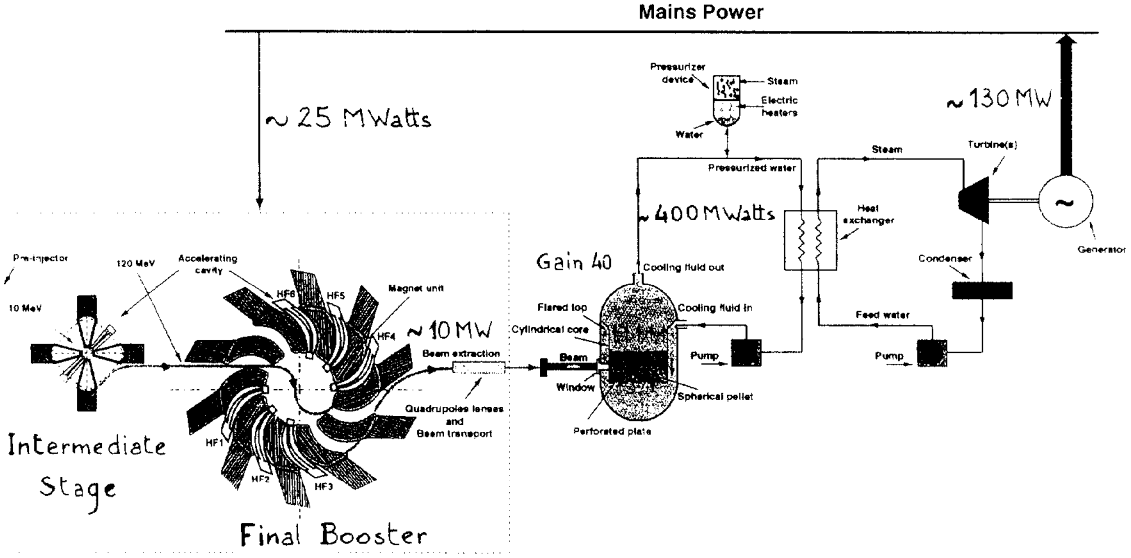

Fig 1. Scheme of the Energy Amplifier

3. A CYCLOTRON-BASED ACCELERATOR COMPLEX

3.1 A three stage cyclotron

The goal of the accelerator is to provide a 9 to 10 MWatt proton beam which is one order of magnitude less than the requirements of the Los Alamos Accelerator Transmutation of Waste [3]. 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 [4] producing a cw beam. Based on the outstanding results obtained at PSI [5], a 3 stage cyclotron accelerator is a possible solution:

- **the pre-injector** which should be able to deliver a 10 mA beam in a given phase width
- **the intermediate stage:** 2 possible designs are being investigated either a 4 separated sector cyclotron accelerating the pre-injected beam up to 120 MeV or a 6 separated sector cyclotron accelerating the pre-injected beam up tp 300 MeV.
- **the final booster** which is a 10 sectors-6 cavities machine raising the energy to the 900 to 1000 MeV kinetic energy range.

3.2 Design criteria

Acceleration of intense beams requires a very efficient extraction process: in order to get an extraction free of beam loss the main parameters of the intermediate stage and the final booster should satisfy the following design criteria:

- **magnet:** use of separated sector magnets and small gap [5cm] to achieve a good vertical focussing and for inserting accelerating structures with a high energy gain per turn in order to keep a low number of turns to reach the extraction radius.The number of sectors is mainly determined by the number of RF cavities and space considerations to install the injection and extraction elements.
- **injection energy:** it should be high enough in order to reduce the longitudinal space charge effects at low radii .
- **Flat-top RF cavities** to reduce the radial spread due to the phase width of the beam at extraction. These cavities work on a 3rd harmonic mode with a peak voltage between 12 and 14 % of the main RF cavities.
- **Isochronous field trimming:** in order to avoid difficulties in the magnetic field trimming one should keep the number of turns less than 200.
- **Single turn extraction:** the radial gain per turn d is given by the following expression:

$$d = \frac{RNV}{E_0} \frac{\gamma}{(\gamma^2 - 1)} \frac{1}{\nu_r^2}$$

R=average extraction radius,V=RF peak voltage,

N=number of cavities, $\gamma=[T+E_0]/E_0$, E_0=proton rest mass

T=kinetic energy at radius R,ν_r=radial betatron frequency at extraction. Therefore to get an high extraction efficiency it is necessary:

1] to choose a large extraction radius

2] to use an high energy gain per turn [N large, V high]

3] to try to accelerate in the fringe field where ν_r decreases while controlling the subsequent phase slip

- the **effective turn separation** is given by the following expression

$$\delta = d(1 - ng(\varphi)) - \Delta_i(R)$$

where n=number of turns, 2ϕ=phase width of the beam at extraction, g[ϕ]=characteristic of the RF voltage wave form which takes into account the third harmonic component given by the flat-top cavitiy, Δ_i[R]=intrinsic radial width of the beam at the extraction radius R

3.3 Main parameters

Various possible designs for a 9 MWatt beam power have been compared on the basis of a similar radial turn separation at extraction. The main parameters of the intermediate stage and the final booster are presented in the Tables 1 and 2. The equilibrium orbits and their properties have been calculated numerically using realistic computed magnetic field maps.

Table 1
Main parameters for the 120/900 MeV design

Acceleretor type	Intermediate	Final booster
Injection	10 MeV	120 MeV
Extraction	120 MeV	900 MeV
Frequency	42 MHz	42 MHz
Harmonic	6	6
Magnet gap	5 cm	5 cm
nb. sectors	4	10
sector angle (inj/ext)	26/31 deg	10/19 deg
sector spiral extraction	0 deg	22 deg
nb.cavities	2	6
Peak Voltage injection	300 KVolt	500 KVolt
Peak Voltage extractio	700 KVolt	900 KVolt
Radial gain per turn	12 mm	10 mm

Table 2
Main parameters for the 300/900 MeV design

	Intermediate	Final booster
Injection	20/30MeV	300 MeV
Extraction	300 MeV	900 MeV
Frequency	42 MHz	42 MHz
Harmonic	6	6
Magnet gap	5 cm	5 cm
nb. sectors	6	10
sector angle (inj/ext)	15/20 deg	10/19 deg
sector spiral extraction	0 deg	22 deg
nb.cavities	3	6
Peak Voltage injection	300 KVolt	500 KVolt
Peak Voltage extractio	600 KVolt	1000 KVolt
Radial gain per turn	12 mm	10 mm

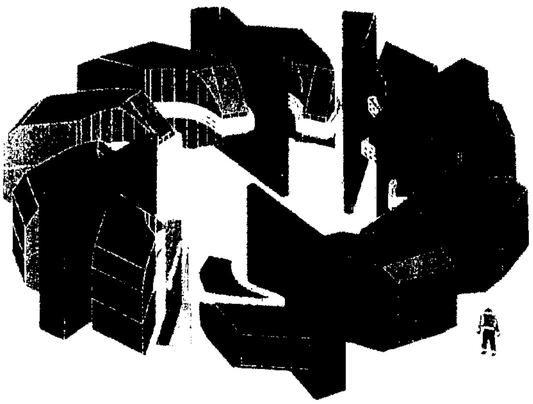

Figure 2. View of the 10 sectors final booster

3.4 Computational methods

To study the general characteristics of the beam dynamics in the cyclotron the focusing properties are computed first using classical matrix methods including soft-edges effects by using a linear fringe field approximation for the magnetic field produced by the sectors. This gives a preliminary estimate of the sector angle. Then a more sophisticated programme, EUQUIL, is used to calculate these characteristics more accurately. EUQUIL includes the transversal space charge effects on the focussing frequencies ν_r and ν_z as suggested by W.Joho [7].

More refined beam dynamics computations are being carried out with a specific code, BDWAASC, to study the beam evolution under space charge during the acceleration process. Different space charge models are needed, depending on the beam energy, as mentionned by S.Adam [8]. At low energies a rather refined model is needed : two multiparticle methods derived from models used in high intensity linacs have been adopted. The first one is based on a model used at GANIL for cyclotrons [9] using an equivalent global gaussian distribution of which parameters are updated at each gap crossing. The second one has been derived from concepts proposed by M.Berz and H.Wollnik [10]. The beam is divided into gaussian subbeams whose relative motions and interactions are computed at periodic azimuths. At higher energies, a simpler model can be used [8], the beam being approximated as a set of thin disks.

A dedicated transport code INJLINSC has been developed in order to study the injection process with linear space-charge effects.It is based on the usual methodology for designing beam lines with space charge effects [11]. A more accurate code using multiparticle should be used to take into account non linear effects of the space charge.

4. CONCLUSION

An important aspect of the accelerator chain is the overall efficiency which depends mainly on the RF performances. Power estimates have been made under the following assumptions:

- A 60% yield of the RF power amplifiers.

- RF losses have been estimated by analytical calculations. The cavity shape should be further optimised using more sophisticated tools and measurements on a reduced-scale model.

The goal is to reach a global efficiency slightly greater than 40%

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