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PERFORMANCE EVALUATION OF A HEAVY ION RF LINAC

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Abstract

In a very general prospect we have analysed the practical performances of a RF linac having in mind a double purpose : a usual heavy ion accelerator running in a large range of masses for nuclear physics and a pulsed high current heavy ion accelerator which should be a test-bed for a heavy ion driver. In this paper we describe the main parts of the linac and we analyse the space charge current limitations in the bunch. The linac should be able to run at least in the 10 MeV/AMU range and in the pulsed regime it should deliver more than 1 joule per pulse.

Introduction

In order to extend the field of interest of a new facility we have made a very preliminary study to delimit the accessible parameter ranges using quite conventional acceleration technics. We have excluded "a priori" new concepts like RFQ (Radio-Frequency Quadrupole), induction linac or accelerating gaps with magnetic insulation since these technics are still in their infancy. Clearly, considering for example the very promising results of the RFQ concept[1], a new analysis should be done, indeed this injection method can simplify the low β stage and certainly push away the space charge limitations. In our case, we have optimized the linac with respect to the following constraints :

- the accelerator should run in the low current regime for nuclear physics applications with energy in the 10 MeV/AMU range.
- in the pulsed mode, at low repetition rate, the accelerator should transport the largest current of light and heavy ions compatible with the beam radius expansion caused by space charge effects.

To reduce the shielding problem and to limit the RF power supplies, we have considered only low duty cycle accelerator. This mode of operation is related to the newest approach of inertial confinement fusion[2]. This scheme looks very promising although relatively untested; due to the large number of beam manipulations needed in a full scale heavy ion driver (at least in the RF approach), it seems necessary to start, in a first step, with a test-bed[3-4] handling 0,1 - 1 KJ bunches. Here we describe only the RF accelerator[5] at which a storage ring[6] or a longitudinal bunching system[7] should be added to obtain the required values.

- in order to simplify the cavity construction in the high energy stages, we have considered fixed frequency cavities with independant phase control at the pilot level. The gap number and the β_0 values have been optimized with respect to the energy gain per cavity in a large range of β values.

Accelerator description

A crude analysis of the accelerator cost versus

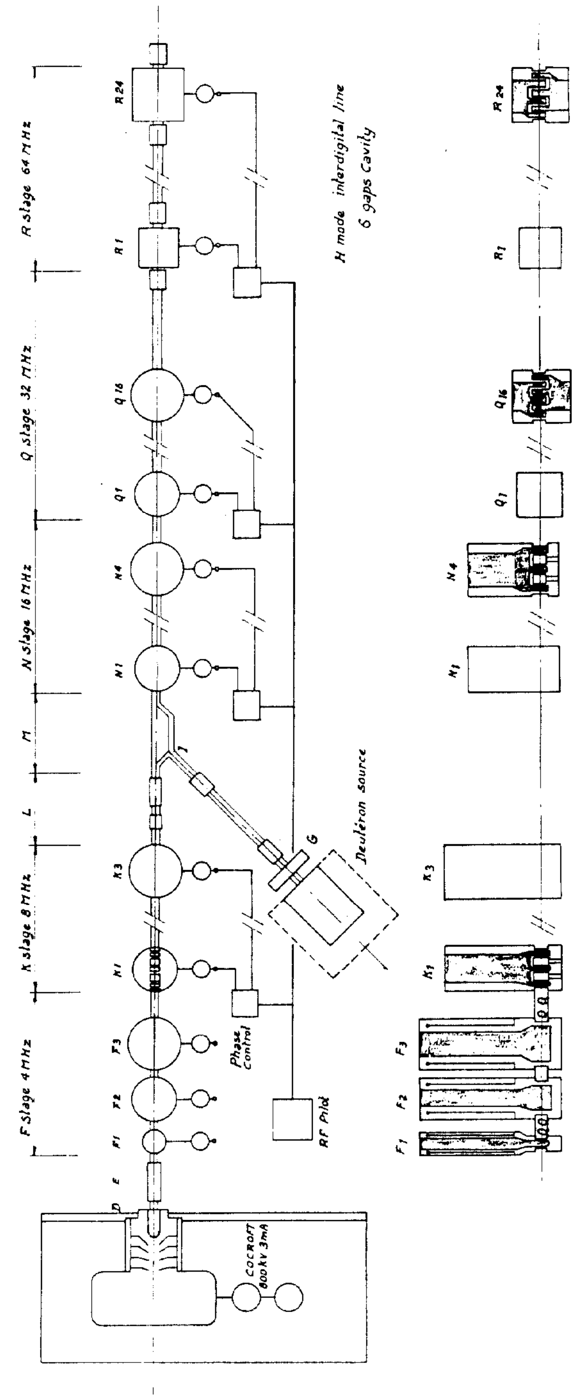

Fig.1 - Scheme of the Heavy Ion RF Accelerator

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the charge state shows that we have to consider multi-ionized ions (Z > 5-7). In the following, we have assumed that Xe^{+8}_{132} is the best compromise for the particle choice. As there is no high current multi-charged ion sources, we have to start with Xe^{+1} ou Xe^{+2} ions using a source derived from the ones developped for CTR applications (beam plasma heating).

Figure 1 shows a general view of the accelerator.

To reduce the space charge expansion in the low β region we have to start at low frequency (4 MHz) and a strong magnetic focusing has to be introduced between each two gaps acceleration stage. After bunching, the beam is injected in a two gaps coaxial cavity (F_1 in Fig.1) and then in a two π/3 - 2 π/3 wideroe six gaps cavity (F_2, F_3). After a frequency doubling, the beam is accelerated by three magnetically focused wideroe linacs (K_1 - K_3). The charge changing from 1 - 2 to 8 is realized by stripping at 28 MeV in the M region. At the end of the N stages (wideroe linac at 16 MHz) the particle energy is 0.8 MeV/AMU. For the high energy stages (regions Q at 32 MHz and R at 64 MHz) we have chosen six or eight gaps cavities with magnetic focusing between the cavities. The H mode interdigital line developped by J. Pottier[8] appears to be the best structure for heavy ion acceleration since the shunt impedance is high for reduced sizes. Figure 2 shows one of the final stage cavity.

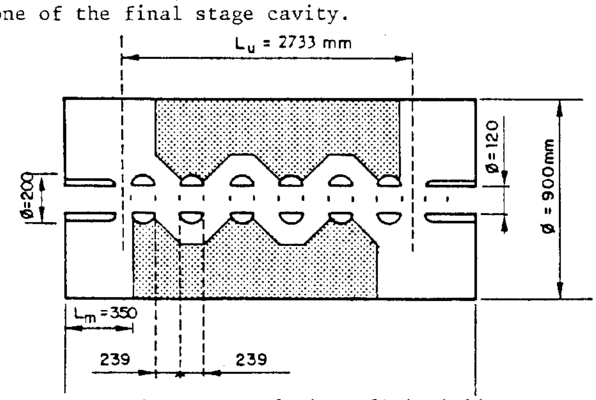

Fig.2 - H Mode interdigital line

We use a π-π mode, the gap length is of the order of the drift tube length ($\ell \simeq \beta\, \lambda/4$). The drift tube internal diameter is 7 to 10 cm. The mean electric field in the useful part of the cavity will be of the order of 4 MV/m. The shunt impedance[9] of such a structure scales as $Z_o = 20\beta^{-2}\, C^{-3/2}\, f^{1/2}$ where C is the line capacity (≃ 50 pF/m). In the high frequency stages the shunt impedance may be as large as 30 - 50 MΩ/m.

During the acceleration process, the beam will pump a part of the energy stored in the cavity ; this stored energy is given by :

$$W = \frac{1}{2}\,\varepsilon \iiint E^2\, dv$$

Taking into account the frequency dependances of the cavity sizes and of the electric field limit, the frequency has to be significantly lower than 100 MHz to reduce the beam pumping at a few per cent of the stored energy.

The final kinetic energy will depend on the cavity number ; a good choice seems to be 30 cavities with 8 gaps or 50 cavities with 6 gaps to obtain a X^{+8} output energy in the 1.4 to 1.6 GeV range.

Space charge limitations

We have analysed the beam expansion by space charge and RF defocusing effects. A strong periodic magnetic quadrupole focusing counteracts this expansion. Figure 3 shows some examples of beam envelopes in the high energy stages. The different curves refer to different strengths of focusing forces. The simplified beam envelope equation is written in the bunch frame as :

$$\frac{d^2\xi}{du^2} = \frac{a}{\xi^2} + \xi b \cos 2u$$

where $\xi = r/r_o$, $u = \pi\beta\, ct/\ell$, a characterizes the space charge effect $a \sim NZ^2/f^2$ and b the focusing effect $b \sim Z/f$; N being the number of particles in the bunch. By adjusting correctly the focusing forces, one can suppress the large wave-length oscillations even for bunches containing up to 5 10^{10} to 10^{11} particles.

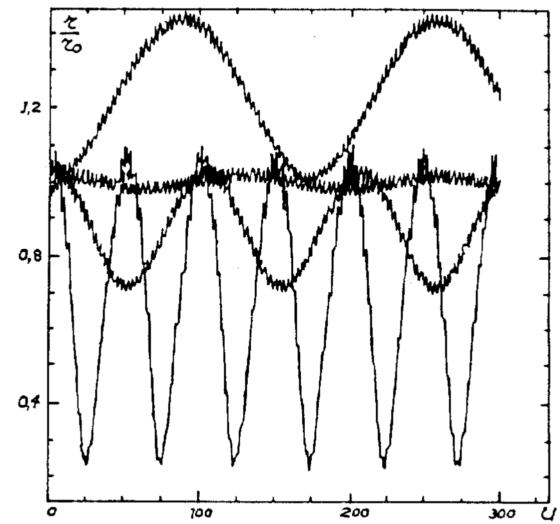

Fig.3 - Beam envelope for different focusing forces

The phases of each high energy cavity are optimized with respect to the energy gain, therefore we have to compute the RF defocusing effect with these optimized phases ; this is shown on Figure 4.

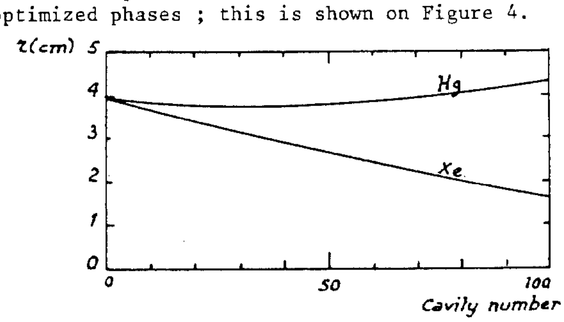

Fig.4 - Beam envelope with the optimized phases

where one can see that the Xe or Hg beam radii do not increase all along the linac. From our first order analysis one can conclude that bunches of 5$10^{10}$ particles (Xe^{+8}) can be accelerated and transported.

In fact the problem is more severe in the low energy stages and it seems difficult, when using conventional methods, to transport beams having more than a few 10^{10} particles per pulse. Figure 5 shows examples of beam radius envelopes in the first 3 acceleration stages (F_1 - F_3 see Fig.1). To push away this limit, one should consider pulsed high magnetic field quadrupoles and/or RFQ lines. Due to the stripping efficiency the number of particles will be reduced by a factor of

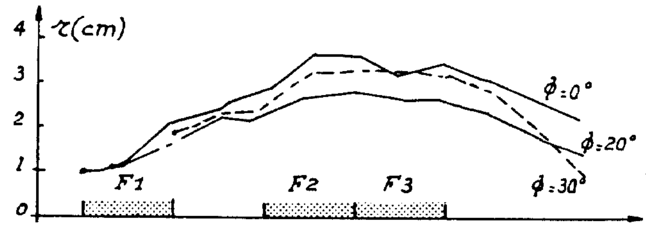

Fig.5 - Beam radius in the first 3 acceleration stages

the order of 5, therefore the number of particles in the high energy stages will be restricted to $5 10^9$-10^{10}. The energy per bunch will then be of the order of 1 - 2 J (at 1.5 GeV for Xe^{+8}). Hundred to thousand bunches should be stored in a storage ring and then time compressed to obtain 0.1 to 1 KJ on a target.

The space charge longitudinal expansion has also been analysed[7] and the mean electric current can be expressed by :

$$\bar{I}_{(A)} = 4.86\ 10^{-4}\ E_{(V/m)}\ \beta^2\lambda\ \phi_s^4$$

where ϕ_s is the synchroneous phase : $\phi_s \simeq \pi/5$. Here we have assumed that all the RF periods are filled up by using multi-injection systems. Applying this formula one has $N \sim 5 10^{10} - 10^{11}$ particles per bunch which is well above the space charge radial limitations.

Accelerator performances

In the pulsed mode regime, with conventional technics, the energy per bunch should be of the order of 1 - 2 J for 1.5 GeV Xe^{+8}. The high energy part of the linac should be able to accelerate up to 10 - 15 J per bunch but in this case the low energy stages have to be modified. It is not yet clear that the use of RFQ[1] will solve the problem.

In the low current regime, for nuclear physics applications, the energy per nucleon depends weakly on the mass number (see Fig.6) and the accelerator can also accept light ions (protons and deuterons).

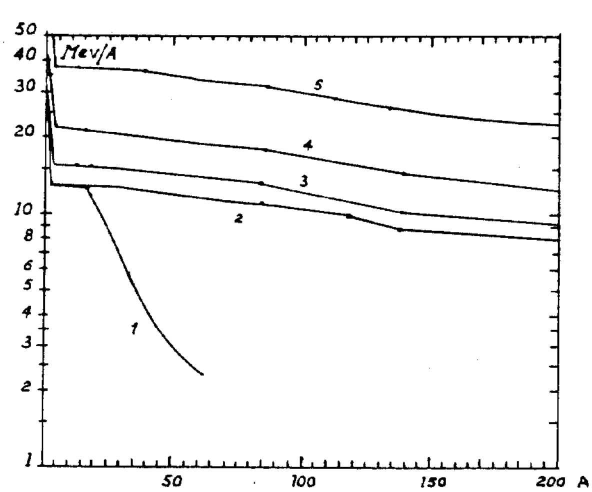

Fig.6 - Energy in MeV/A versus A for different 8 gaps cavity number

1 - 20 cavities in series with a 7 MV tandem
2 - Fig.1 accelerator with 25 cavities
3 - 33 cavities
4 - 50 cavities
5 - 100 cavities

Conclusions

The main pecularities of this proposal in comparison to the one described in reference 4 are the followings :

- two modes of operation; a low current conventional mode and a high current mode in the pulsed regime
- low frequency (4 MHz) resonators with $\pi/3$ - $2\ \pi/3$ modes are used in the first stages
- high RF gap voltage (0.5 - 0.8 MV/gap)
- small length cavities with phase control and periodic magnetic focusing by using doublet of quadrupoles
- H mode interdigital lines for the high energy cavities
- free beam diameter of the order of 10 cm
- modular RF power supplies
- higher final energy ($\sim$ 1.5 GeV for Xe^{+8}).

Acknowledgements

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