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LIMITATIONS AND IMPROVEMENTS OF HEAVY ION ACCELERATION WITH A 20-MEV PROTON LINAC

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Summary

CRYEBIS will be the next heavy ion source to be installed in the 20-MeV proton linac injector for the strong focusing synchrotron SATURNE II. The possibilities offered in running the linac in the 2βλ-mode and the limitations to accelerate heavy ions characterized by $\varepsilon < 0.5$ (where $\varepsilon = z/A$) were studied. Other proposed improvements to increase the efficiency of this injector are described.

Introduction

Early in 1980 a new preinjector terminal having a heavy ion source will be put into operation. The new ion source, using cryogenic techniques and high electron-beam density is able to yield either polarized particles (protons and deuterons) or completely stripped heavy ions, up to iron. It is intended to run the 20-MeV Alvarez linac in the 2βλ-mode, as was done for deuterium and helium,[1] but the efficiency is lower since ε is less than 0.5. Several improvements, such as increasing the linac duty factor, modifying the first cells of the existing linac, or increasing the trapping efficiency, are discussed.

The CRYEBIS Source

The ion source[2] (Fig. 1) is essentially constructed of a cryogenic solenoid and an electron gun, delivering a high-density electron beam ($j > 1000$ A/cm^2). The potential is defined by a set of cylindrical electrostatic electrodes. The potential distribution is shown in Fig. 2a during the containment time, where the ions are trapped by the radial space charge potential of the electrons, and the longitudinal potential well. They are completely stripped step-by-step. During this process the positive charge fills up the radial potential of electrons. Ions are then extracted by the potential configuration of Fig. 2b. At this time their energy is about 5 keV/A.

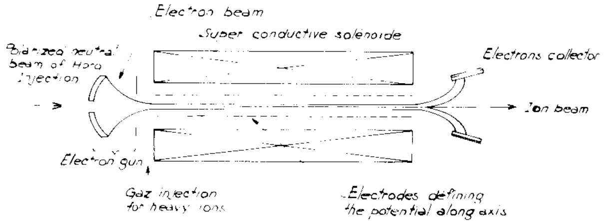

Fig. 1 CRYEBIS ion source

Ions are transported to the accelerating column through the very low-energy beam transport system (VLEBT) and accelerated to the nominal energy of 187.5 keV/A before being injected into the linac (Fig. 3)

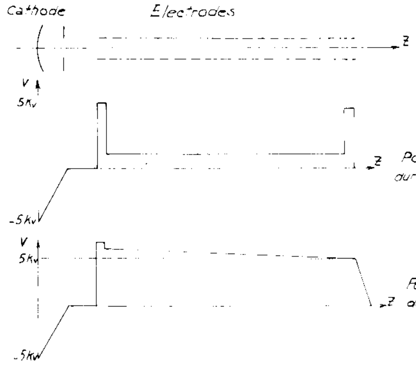

FIG 2A Potential distribution during Containment time

FIG 2B Potential distribution during ejection time

Beam characteristics are:

Max. no. Ions:	$N_i = 10^{11}/Z$
Extraction Pulse Width:	50-300 μsec
Transverse Emittance: (normalized)	5×10^{-7} m-rad
Energy Spread:	< ± 50 eV

The containment time depends upon ion species but is typically of the order of 10 ms allowing the source to operate at 10 Hz.

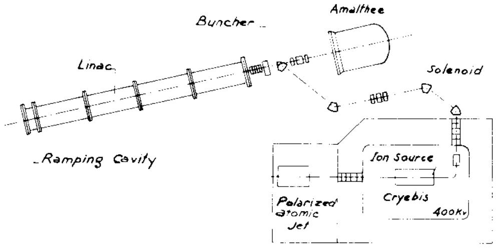

Fig. 3 New injector system

Linac Behavior for Ions with $\varepsilon < 0.5$

The linac will operate in the $2\beta\lambda$-mode, where the ion velocity is half that of protons in the normal $\beta\lambda$-mode. Thus ions travel through one unit-cell in two rf cycles, and the energy gain per gap and per nuclei is:

$$\Delta W_i/A = z\, e\, \overline{E}\, L\, T \cos \phi_i$$

where z, $\overline{E}$, L, T and ϕ_i represent the charge state, mean accelerating field, cell length, transit-time factor and synchronous phase, respectively.

The injection energy is 375 keV for deuterons having $\varepsilon = 0.5$, but for heavier ions ε may be less than 0.5 and to satisfy the velocity requirement the accelerating column must be set at a higher voltage according to the formula:

$$V_i = V_p/\varepsilon h^2 = V_d/\varepsilon \quad .$$

This is shown in Fig. 4.

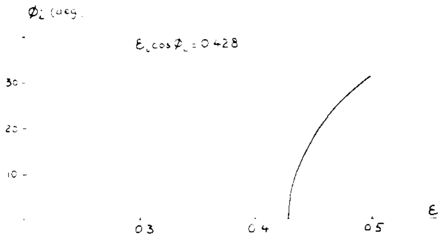

Fig. 4 Preaccelerator voltage requirements versus ε

Taking deuteron acceleration as reference, fixes the harmonic number h, accelerating field and transit-time factor, which are identical for any heavy ion. It turns out that the following relationship must be satisfied:

$$\varepsilon_i \cos \phi_i = \varepsilon_d \cos \phi_d \qquad \begin{array}{l} i \to \text{any ion} \\ d \to \text{deuteron} \end{array}$$

This means that the phase acceptance depends upon the charge-to-mass ratio and sets a lower limit for ε_i. Thus, linac efficiencies decrease with small ε values. Specifically, with $\varepsilon_d = 0.5$ and $\phi_d = 31°$, the experimental results give a measured energy acceptance of ± 10 keV/A. The lowest acceptable ε_i, equal to 0.428, corresponds to the smallest phase acceptance, $\phi_i = 0$, for zero longitudinal acceptance (Fig. 5).

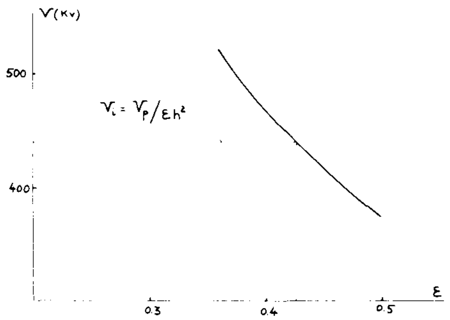

Fig. 5 Stable phase versus ε

Energy acceptances were calculated using the following formula:

$$\Delta W_i/A = \Delta W_d/A \sqrt{2\varepsilon_i} \sqrt{\frac{(\phi \cos \phi - \sin \phi)_i}{(\phi \cos \phi - \sin \phi)_d}}$$

Trapping efficiences for different ε values were computed, using the existing buncher and optimizing its rf field requirement. It was found that this buncher was too far from the linac entrance and cannot completely fill the energy acceptance (Fig. 6). Table 1 gives the final efficiencies versus ε.

ε_i	ϕ_i (°)	$\Delta W_i/A$ (keV)	ρ
0.5	31	10	0.66
0.49	29	8.9	0.65
0.48	27	7.9	0.65
0.47	24	6.8	0.63
0.46	21	5.5	0.62
0.45	18	4.1	0.58
0.44	13	2.6	0.52
0.43	5	0.6	0.39
0.428	0	0	0

Table 1

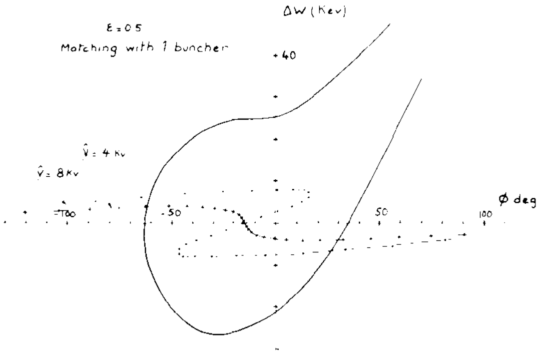

Fig. 6 Bunching schemes with the present buncher

Possible Improvements

It is clear that the linac was not designed for the purpose of accelerating heavy ions in the $2\beta\lambda$-mode. As already seen, the longitudinal acceptance is small due to the low transit-time factor in the first cells, and the buncher position is not correct for particles other than protons. It is proposed first, to put a second 200-MHz buncher operating at low rf level, which, together with the existing buncher, will provide a much better trapping efficiency; second, to install either a diaphragm inside the linac cavity to increase the longitudinal acceptance, or to operate the present linac at the higher duty cycle allowed by the 10-Hz repetition rate of the CRYEBIS source.

Trapping Efficiency

The deuteron case in which the existing buncher is used was found to lead to an underbunched beam. As shown in Fig. 6, the efficiency is only 30%. By decreasing the bore radius, one should get a better transit-time factor (0.15 instead of 0.05), but the efficiency only increases to 55%. A more flexible solution is to set up a second 200-MHz buncher located at a distance L = 4 m from the existing one and phase-locked to it. The respective voltages are optimized to give the best bunching efficiency. Figure 7 shows that such longitudinal matching leads to 80% efficiency for $\varepsilon = 0.5$. A great advantage of this system[3] is that it is easily tuned for particles having ε less than 0.5, where the efficiency decreases to 70% (Fig. 8). The solution, which would completely fill the energy acceptance, requires a buncher located much closer to the linac, and a higher rf field. The first is unfortunately not achievable due to lack of space. Figure 9 shows the bunch incompletely filling the bucket, as described above.

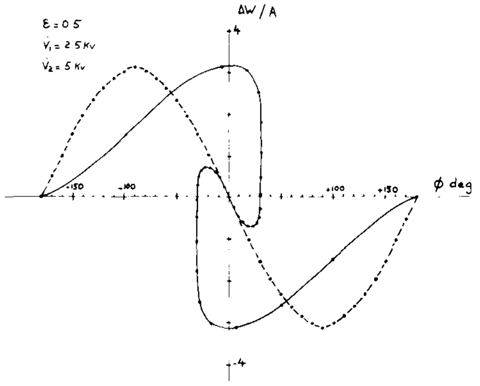

Fig. 7 Bunching scheme with two bunchers

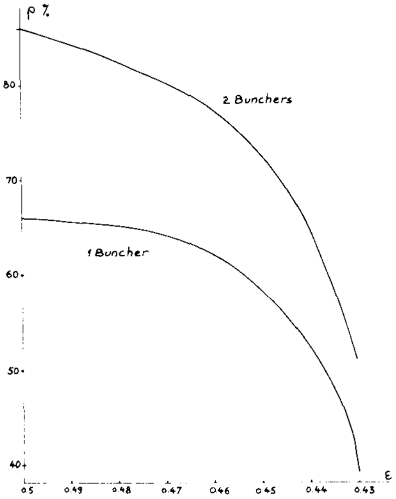

Fig. 8 Trapping efficiency versus ε

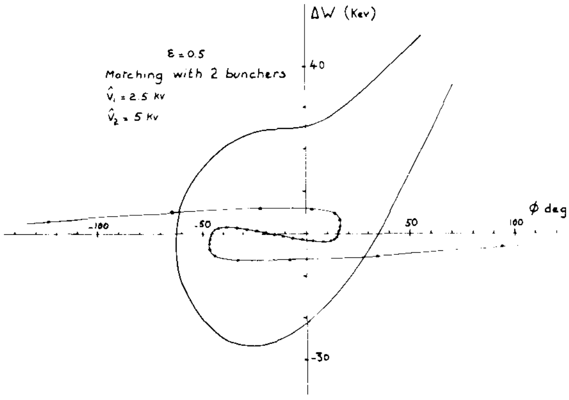

Fig. 9 Longitudinal matching with 2 bunchers

Modification of the First Cells

The solution of turning off a few accelerating gaps by installing a diaphragm in the cavity has already been investigated.[4] A serious drawback in the present case is that the preaccelerator would have to be operated at a different voltage than that for which it was designed.

An alternative is to add an accelerating cavity before entering the linac. The cavity would accelerate the ion beam to the synchronous energy corresponding to cell number 10. The most serious problem is to match the beam longitudinally between the two cavities because the drift is about 4 m and debunching will occur.

Instead of turning off the first 10 cells, it might be possible to modify them mechanically. This means that these drift tubes must be redesigned and replaced by a new optimized structure operating in either $\beta\lambda$- or $2\beta\lambda$-mode.[5] This possibility should enable the linac to accelerate ions with ε as low as 0.35.

Higher Linac Duty Cycle

A third possible means of increasing the total number of injected heavy ions to the main ring is to accumulate several linac pulses. The repetition rate of the accelerator is 1 ms. The possibility was studied of accumulating 5 pulses of 100-μs duration spaced in time by 5 ms. The improvement is a straightforward factor of 5. As mentioned previously, the CRYEBIS source is able to operate at this repetition rate.

This can be achieved without major modification of the injection system. Additional coils in the main ring magnets will provide the required $\dot{B}_i$ for stacking and usual injection process will be used for each pulse. The only hardware improvement is to increase the power of the high voltage supplies feeding the rf generator in order to maintain the same rf accelerating field on each pulse.

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