DESIGN AND CONSTRAINTS FOR THE ZEBRA INJECTOR, RFQ AND DTL

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Summary

ZEBRA (Zero Energy Breeder Accelerator) is a proposed laboratory test accelerator designed to produce the full accelerator-breeder beam current of 300 mA at only 1% of the final energy of 1 GeV. Being an experimental prototype, it will be heavily instrumented to diagnose performance under conditions typical of the low energy portion of an accelerator breeder. It will consist of 3 sections - a dc injector, an RFQ buncher-preaccelerator, and a drift tube Alvarez linac. Several constraints are introduced by its eventual application as an injector for an accelerator breeder including variable beam current, economic accelerating gradients that will result in reliable operation, frequency choice and frequency multiplication between the RFQ and Alvarez linacs. This paper will discuss the constraints and present the rationale for the current reference design.

Introduction

The first stage of the accelerator breeder development program at CRNL is the ZEBRA accelerator[1]. It is intended to establish the feasibility of a linac to meet high average current requirements and develop the necessary expertise.

It will consist of four components as shown in Table 1.

Table 1

ZEBRA Components

Injector	0.075 MeV	
RFQ	0.075 - 2.0 MeV	108 MHz
DTL	2.0 - 10.0 MeV	216 MHz
Beam Dump	3 MW	

The principal requirement of ZEBRA is to deliver an output current of 300 mA at 10 MeV but the frequency choice is restricted by consideration of the entire accelerator system and by the availability of high power tubes. Preferred values are 108 MHz in the radiofrequency quadrupole (RFQ), 216 MHz in the drift-tube linac (DTL), and 432 MHz in the high β linac. The higher frequency would enable the use of klystrons as the rf source, a more efficient amplifier than gridded tubes required for the lower frequency stages. The output energy of the injector was fixed at 0.075 MeV for two reasons. Above this energy the cost of the injector would increase rapidly and its reliability at high current would decrease rapidly, while below this energy emittance growth and beam loss in the RFQ due to space charge effects become excessive. The output energy of the RFQ was fixed at 2 MeV which is below the copper (p,n) threshold to avoid activation in the RFQ and transport line and yet high enough to give satisfactory acceptance of the RFQ output beam by the DTL and to permit an efficient single tank DTL.

Injector

The ZEBRA injector poses a number of design problems not encountered in other accelerators. The most obvious is the high continuous current requirement - 375 mA of protons, but based on ion source development presently underway, this seems readily achievable. The major problem is the requirement for variable current with a restricted range of beam energy. The present reference design calls for a current variation from 0 to 375 mA at 75 keV. A two stage injector could be considered, but it would be expensive and beam transport elements that would likely be required lead to emittance growth as seen at KfK[2,3] and GSI[4]. A proposed approach is to have the injector current variable down to 40 mA and spill the remainder in the RFQ. This uses a single stage injector that can operate at variable current by changing gas pressure (to spoil the proton fraction) and a neutralizer tube to convert some of the protons to neutrals[5].

Preliminary experiments at Chalk River indicate that a reduction in the proton current by a factor of 4 is readily achievable by a 12% voltage reduction and by varying gas pressure. The remaining factor of 2.5 reduction can be achieved by the neutralizer tube.

Emittance requirements are not overly stringent but require that the phase space volume be filled uniformly to minimize beam loss in the RFQ. Calculations using the beam simulation code BEAM[6], and measurements made at Chalk River indicate that this can be achieved, provided no unexpected beam transport problems arise. The proposed design is summarized in Table 2.

Table 2

Proposed Injector Design

Injection Energy Range	60 keV - 75 keV
Proton Current Range (fixed source geometry)	40 mA - 375 mA
Normalized Emittance (at full current)	6 π mm·mrad $\pm$ 10%
Plasma Source Type	orthogonal cusp duoPIGatron
Extraction Column	tetrode, multi-aperture
Maximum Extracted Current	850 mA
Mass Separation	90°, n=1/2 double focusing magnet
Vacuum Pumps	turbo-molecular cryopumps

RFQ

The basic requirements of the RFQ are listed in Table 3. The output current of the DTL must be 300 mA of 10 MeV protons which requires slightly higher current output from the RFQ. The maximum gradient at which a cw device can be operated reliably is not known with any precision. The value in the table is our best estimate for a system with some margin of safety.

Table 3

RFQ Requirements and Constraints

Frequency	108 MHz
Input Energy	0.075 MeV
Output Energy	2.0 MeV
Output Current	306 mA (2 MeV H^+)
Maximum Gradient	1.75 x Kilpatrick limit

Difficult Requirements: High Current

The reference design given in Table 4 was generated according to the procedure of Crandall et al.[7]. Although acceptable, the design has an output phase spread that is larger than desired. High current is the most difficult design requirement to be met and because experience with operating RFQ's is limited[8], a detailed analysis of the factors affecting current limits was made.

Table 4

RFQ Reference Design

Frequency	108 MHz
Input Energy W_{in}	0.075 MeV
Buncher Energy W_g	0.600 MeV
Final Energy W_f	2.0 MeV
Final Synchronous Phase ϕ_s	-35°
Maximum Gradient	20.3 MV/m
Gradient on axis V/r_0	15.0 MV/m
Focusing Parameter B	7.07
Vane Voltage V	0.261 MV
Outer Diameter	660 mm
Vane Length	3.70 m
Excitation Power	830 kW
Beam Power	590 kW
Total Power	1420 kW
Design Current	
I_{in}	360 mA
I_{out}	306 mA (2 MeV protons)
Normalized Emittance	
Input (90%)	6.0 π mm·mrad
Output (90%)	7.5 π mm·mrad
Input (RMS)	1.0 π mm·mrad
Output (RMS)	1.7 π mm·mrad
Current Limit	430 mA (2 MeV protons)

The transverse and longitudinal current limits in an RFQ are given by Wangler[9] as

$$I_t = \frac{8}{3Z_0}\,\mu_t\,\frac{m_0c^2}{eq}\,\frac{1}{1-f}\,\frac{r^2b}{\lambda^3}\,\sigma_t^2$$

$$I_\ell = \frac{4\pi}{3Z_0}\,\mu_\ell\,\frac{m_0c^2}{eq}\,\frac{1}{f}\,\frac{r^2b}{\lambda^3}\,\sigma_\ell^2$$

Z_0 = 376.73 Ω

μ_t,μ_ℓ ratio of space charge to focusing forces, maximum value 0.84

m_0c^2/eq = 938.952 x 10^6 volts

f space charge form factor (= 1/3 if r=b)

r beam average radius

b beam bunch half-length

σ_t,σ_ℓ zero current phase advance per period.

For high current σ_t should equal σ_ℓ and be as large as possible (up to a maximum of $\pi/2$)

$$\sigma_\ell^2 = -\pi^2\,\frac{eq}{m_0c^2}\,\frac{A\,V}{\beta^2}\sin\phi_s$$

$$\sigma_t^2 = \frac{B^2}{8\pi^2} + \Delta rf$$

where $B = \dfrac{eq}{m_0c^2}\,\dfrac{\lambda^2}{r_0^2}\,V$

$\Delta rf = -\sigma_\ell^2/2$

A acceleration efficiency

V vane voltage

r_0 mean radial aperture

To obtain maximum current we require a design with $\sigma_t = \sigma_\ell = \pi/2$

$$\text{i.e., } A\,V\sin\phi_s = \frac{-\beta^2}{4}\,\frac{m_0c^2}{eq}$$

$$B = \sqrt{3}\,\pi^2$$

In practice V/r_0 is limited by the sparking limit so at small values of λ it may not be possible to reach the optimum value of B. In this region the condition to be met is

$$\sigma_t = \sigma_\ell = \frac{B}{2\sqrt{3}\,\pi}$$

or $$\frac{r_0^2\,A\sin\phi_s}{\beta^2} = -\left(\frac{V}{r_0}\right)\frac{eq}{m_0c^2}\,\frac{\lambda^4}{12\pi^4}$$

At a specified frequency, V/r_0 is at the sparking limit so the right hand side is a constant. The procedure of Crandall et al. preserves this relation in the bunching section but not in the accelerating section.

In the accelerating section Crandall et al. keep A and ϕ_s constant, which results in a reduction in longitudinal stability. This can be prevented by increasing A or ϕ_s to keep (A sin $\phi_s)/\beta^2$ constant. The output phase energy distributions for the reference design and an alternate, which increases ϕ_s in the accelerating section, are shown in Figs. 1 and 2. Note the smaller phase spread in Fig. 2.

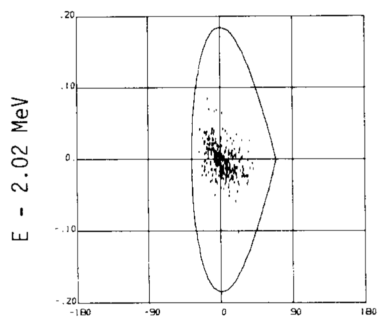

Fig. 1 Phase-energy plot of output beam for reference design.

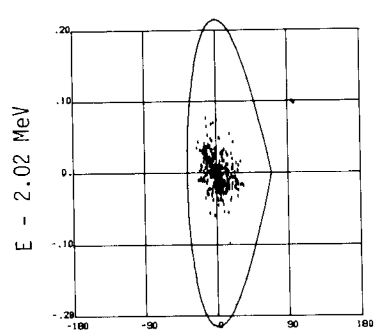

Fig. 2 Phase-energy plot of output beam for alternate design.

DTL

Basic requirements of the DTL are listed in Table 5. 300 mA transmission is not difficult to achieve even considering that only alternate buckets are loaded due to the frequency doubling, so the design is influenced more by the requirement of low beam spill than the requirement of high output current. The chief factor leading to excessive beam spill is the large phase spread (expressed for 216 MHz) in the RFQ output. To achieve acceptable capture it is necessary to add a buncher in the beam transport line - a single gap buncher operating at 216 MHz with a voltage of 145 to 165 kV. The buncher reduces the phase spread from 170° to 140°.

Table 5

DTL Requirements and Constraints

Frequency	216 MHz
Input Energy	2 MeV
Output Energy	10 MeV
Output Current	300 mA
Maximum Electric Field	1.25 x Kilpatrick limit
Maximum Magnetic Field	1.0 Tesla
Difficult Requirements:	Low Spill of Beam from RFQ

The DTL reference design parameters are listed in Table 6.

Table 6

Drift Tube Linac Reference Design

Frequency	216 MHz
W_{in}	2 MeV
W_{out}	10 MeV
Number of Drift Tubes	30
ϕ_s cells 1-10	-42.5°
cells 11-30	-30°
E_0 cells 1-10	3.5 MV/m
cells 11-30	3.0 MV/m
Drift tube, ID	40 mm
OD	167 mm
Tank Diameter	920 mm
Quadrupole Length	50 mm
Gradient	50 T/m (5 kG/cm)
Sequence	+-+-
Excitation Power	800 kW
Beam Power	2400 kW
Total Power	3200 kW
Design Current	
I_{in}	306 mA
I_{out}	300 mA
Normalized Emittance	
Output (90%)	11.1 π mm·mrad
Current Limit	700 mA

Conclusions

A preliminary design of an accelerator for the ZEBRA project has been completed based on existing technology. The design meets some of the requirements and constraints as verified by computer calculations using PARMTEQ and PARMILA[10]. Significant work remains to be completed on tolerances to machining and assembly, on reducing the amount of beam spilled in the structure (and that expected for higher energy sections of an accelerator breeder), on optimizing design parameters, on verification of injector performance, on beam diagnostics and location, on control features that influence the overall design and on suitable specifications for the rf sources.

The design, although preliminary, is not expected to change in a significant manner. Studies have shown that funneling techniques are not necessary for the currents considered. Higher vane fields in the RFQ would lead to reliability problems and would not significantly lower the injection voltage. Lower vane fields do however mean a complete redesign, probably even consideration of different frequency regimes such as 83 and 166 MHz for the RFQ and DTL. A re-examination of fabrication and construction costs may lead to small changes in accelerating gradient but not overall changes in DTL surface fields. Drift tube face angles will be determined not only from efficiency arguments but from break-down effects.

References

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