BEAM DYNAMICS STUDIES OF HIGH CURRENT RFQ AND DTL TANKS

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Summary

An accelerator for spallation breeding of fissile fuel must have low beam loss and high acceleration efficiency. An extensive investigation using the PARMTEQ and PARMILA computer beam dynamics codes has been undertaken to obtain a reference design for a 100% duty cycle 300 mA 10 MeV proton linac called ZEBRA (Zero Energy BReeder Accelerator) that could serve as the first stage of an accelerator-breeder. This paper discusses results of this investigation, showing how current carrying capacity and accelerating efficiency in both RFQ's and DTL's is affected by accelerator and injector parameters.

Introduction

The Zero Energy BReeder Accelerator (ZEBRA)[1] is being designed as a demonstration injector for an accelerator breeder. A 300 mA cw proton beam at 10 MeV is required that is of sufficiently high quality to be further accelerated to 1 GeV with very low beam loss. In ZEBRA, beam spill on copper surfaces above 2.2 MeV (the neutron activation threshold for protons on copper) must be minimized. Below this energy, appreciable loss can be tolerated in the radiofrequency quadrupole structure (RFQ), medium energy beam transport line (MEBT) and drift tube linac structure (DTL) with limits being determined by sputtering and energy deposition. The ZEBRA reference design is summarized in Table 1.

Table 1: ZEBRA Reference Design

Injector	Column voltage	75 kV dc
	Proton Current	375 mA
	Normalized Emittance	0.6 π cm-mrad
RFQ	108 MHz,	
	Shaper Output Energy	0.1 MeV
	Gentle Buncher Output Energy	0.6 MeV
	Accelerating Section	
	Output Energy	2 MeV
	ϕ_s	-35°
MEBT	216 MHz Buncher	
	Gap Voltage	165 kV
	Quadrupoles	same as DTL
DTL	216 MHz	
	Bore Radius	2 cm
	Axial Electric Field	3.5 - 3.0 MV/m
	ϕ_s	-42.4 - -30°
	Quadrupoles	
	Length	5 cm
	Gradient	50 T/m (5 kG/cm)
	Sequence	+-+-

The constraint associated with frequency doubling between the RFQ and DTL tanks puts stringent limits on beam phase and energy spread at the RFQ output. The computer codes RFQUIK, PARMTEQ and PARMILA were used to search for a reference design that would meet the constraints described by Chidley et al.[2]. Briefly summarized, accelerator constraints used in the investigation of beam characteristics for different designs were as follows: frequencies of the RFQ and DTL were fixed at 108 and 216 MHz respectively and the RFQ output energy was fixed at 2 MeV. A current capability of 400 mA was used to provide a safety factor for the required 300 mA operating value. Peak surface electric fields in the RFQ and DTL structures were required to be less than 1.75 and 1.25 times the Kilpatrick breakdown limit, respectively. Other parameters such as the beam bore hole radii in the two tanks, and transition energies between the regions in the RFQ (shaper, gentle buncher, etc.) were freely varied to find a design that maximized RFQ transmission and efficiency while minimizing dc injection voltage and beam spill in the DTL.

RFQ Beam Dynamics

In designing the RFQ for ZEBRA, the additional constraints proposed by Crandall, Stokes and Wangler[3] were imposed. They are discussed in a companion paper by Chidley et al.[2]. These constraints may not give the optimum RFQ design for high current and low injection energy, but they represent a conservative choice because the structure can be built and the required field pattern can be achieved[4]. For the selected design, a 2000 particle PARMTEQ run with 460 mA of injected current gives a 375 mA, nominal 2 MeV beam with output characteristics shown in Fig. 1.

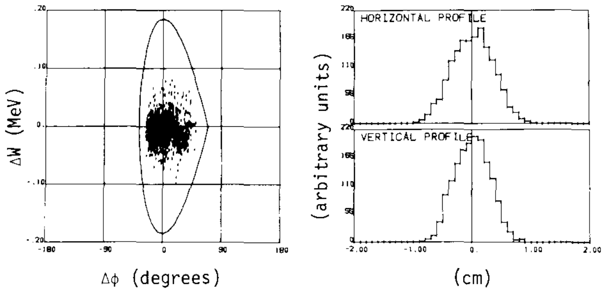


Fig. 1 RFQ output beam.

Sensitivity to Source Emittance

The matched input beam for the RFQ, as given by the code IMS, is identical in both planes and is: $\gamma = 0.62$, $\alpha = 7.5$, $\beta = 92.5$, $\varepsilon = 0.0475$, where $\gamma x^2 + 2\alpha x x' + \beta x'^2 = \varepsilon/\pi$ is the equation of transverse phase space occupied by the input beam with ε having dimensions of cm-radians. Transmission of the RFQ as a function of input beam emittance ε for a 460 mA input beam is shown in Fig. 2.

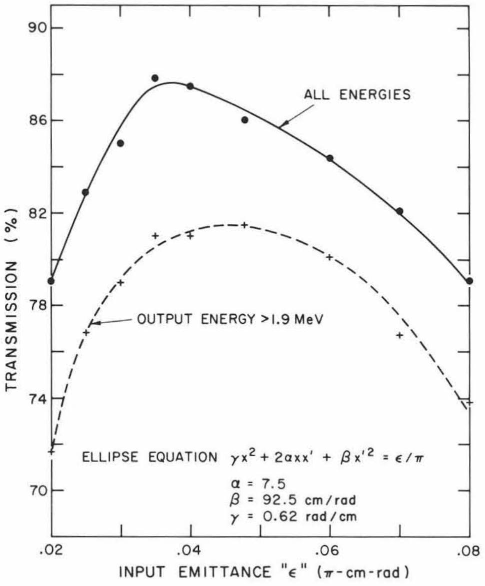


Fig. 2 RFQ transmission versus input beam emittance.

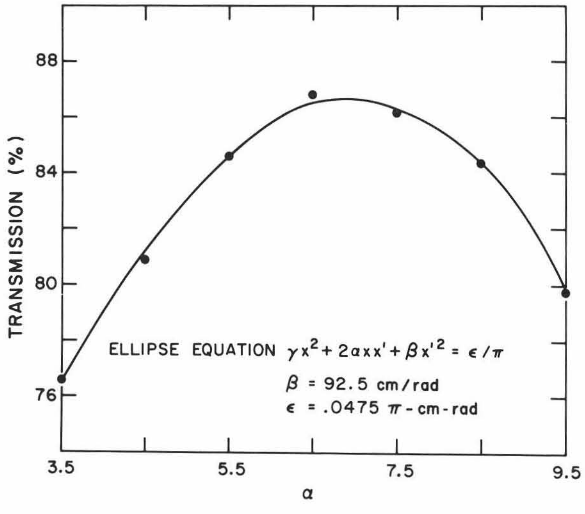


Fig. 3 RFQ transmission versus input beam "α".

At the optimum ε value of 0.0475 π cm-rad, 81.5% or 375 mA is accelerated to > 1.9 MeV with an additional 23 mA of lower energy beam being transmitted. Most of the lower energy beam is < 0.6 MeV and does not get through the quadrupoles in the MEBT. Notice in Fig. 2 that the percentage of low energy beam does not change over the range of ε studied. Figures 3 and 4 show how the total transmission of the RFQ depends on the input beam transverse emittance shape parameters "α" and "β". Further studies on variable current effects are necessary to understand accelerator operation and matching conditions.

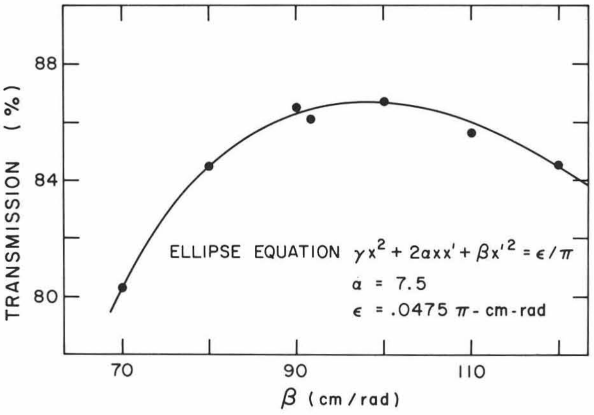


Fig. 4 RFQ transmission versus input beam "β".

Variable Current Operation

RFQ output current and transmission (for particles > 1.9 MeV) are shown as a function of input current in Fig. 5. These PARMTEQ runs indicate a current limit for this RFQ design of $\approx$ 430 mA. To check that the ZEBRA design is suitable for an injector for a high energy linac, PARMILA runs with the DTL were taken to 100 MeV. These runs predict that > 98% of the beam exiting the RFQ at > 1.9 MeV can be captured and accelerated to 100 MeV. We should achieve the design 300 mA with $\approx$ 360 mA into the RFQ.

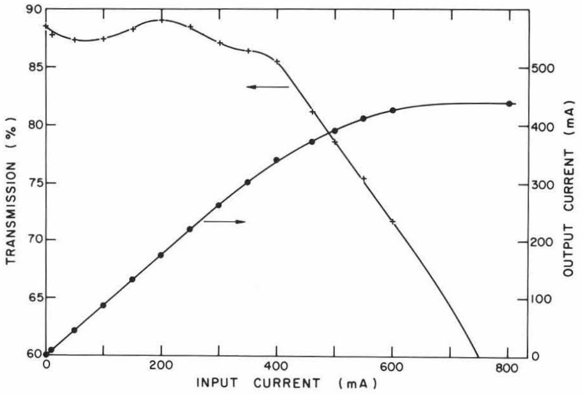


Fig. 5 RFQ output versus input current (W_{out} > 1.9 MeV).

A further requirement for ZEBRA is that the output (10 MeV) current should be variable from 300 mA down to 0 mA. A difficulty in achieving this current range is that a single stage injector has limited current variability at fixed voltage. The reference design calls for a two stage injector to provide variable current at constant injection energy but it may be preferable to use a single stage injector. At design current (360 mA input), ≈ 40 mA of low energy beam will be spilled on the RFQ vanes and it is assumed that the RFQ will be constructed to tolerate this. Therefore at lower input currents, a higher percentage spill should be tolerable provided that the total spill remains less than 40 mA and spill in the DTL is not increased. Beam spill in the RFQ as a function of input beam energy (injector voltage) is shown in Fig. 6.

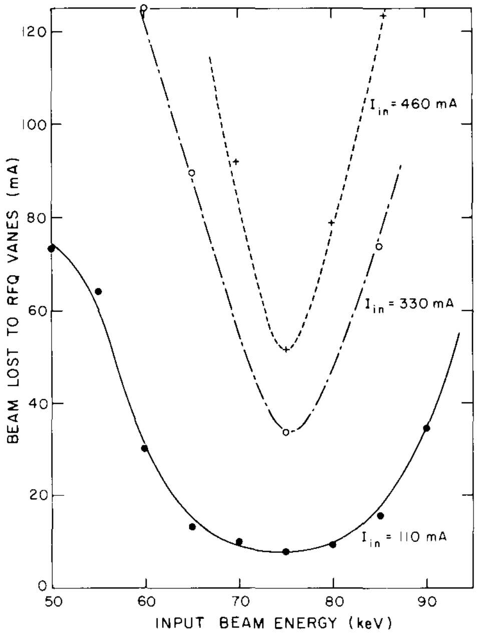


Fig. 6 Beam loss in RFQ versus input beam energy.

Figure 6 shows that it should be possible to operate with an injector voltage of 60 kV when the input current is 110 mA and still have tolerable beam spill. Under these conditions, PARMTEQ predicts 40% transmission of output energy > 1.9 MeV (i.e. ≈ 45 mA out). As with the design current case, there is little output beam in the energy range from 0.6 to 1.9 MeV so spill in the DTL should not be markedly different. By further reducing the injector voltage, the high energy output beam transmission continues to decrease, reaching zero at ≈ 53 kV. Therefore, if by reducing the injector voltage to 60 kV the current can be decreased to ≈ 50 mA (Shubaly[5] discusses how this can be achieved), further small reductions in injector voltage should permit any desired remaining fraction of the beam to be dumped in the RFQ. By this means it should be possible to vary the current that will be accelerated by the DTL from the design operating value to zero with a single stage injector. More tests and detailed beam dynamics calculations are required to confirm or reject this proposal.

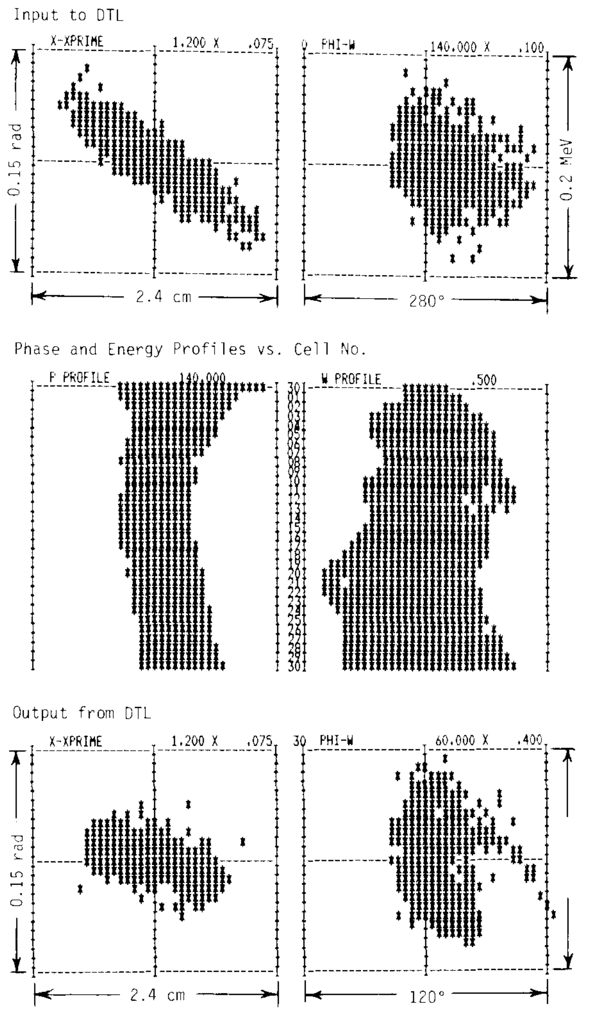
DTL Beam Dynamics

Transverse Acceptance

The calculated normalized acceptance of the DTL (3 π cm-mrad) is approximately 4 times the 90% normalized emittance of the RFQ output beam. Detailed matching between the RFQ and DTL will be done, but a simple MEBT comprising 6 drift tube quadrupoles at $\beta\lambda$ spacing and a 216 MHz buncher is sufficient to provide 100% capture by the DTL in the transverse planes. Increasing the transverse emittance of the RFQ output beam by a factor of 2 reduces the capture to 96% according to PARMILA calculations with a 400 mA input beam to the DTL. Transverse matching and acceptance does not therefore appear to be a restriction for the ZEBRA DTL and MEBT assuming misalignment errors do not significantly degrade the acceptance. The misalignment errors that seem to present the most potential problems are longitudinal rotation errors in the quadrupoles. Calculations with quadrupole rotations show that if the uncertainties are less than ±1° there should be no problems. However if the uncertainties are ± 5°, emittance growth by an additional factor of 2 and beam loss up to 30% is possible.

Longitudinal Acceptance

Total phase spread for the output beam from the RFQ is approximately 85° at the 108 MHz RFQ frequency. Thus at the 216 MHz DTL frequency, the phase width is 170° - too broad to be completely captured by the DTL. The capture percentage in the DTL was improved by operating the first ten cells at a higher gradient and larger synchronous phase than the remaining 20 cells where the gradient and phase are closer to the optimum for accelerator efficiency. Calculations demonstrated that capture was still inadequate and a buncher was included in the MEBT. PARMILA calculations with this configuration predict that ≈ 99% of the beam from the RFQ with energy > 1.9 MeV can be captured with most of the lower energy particles being spilled into the MEBT beam line.


Input to DTL

Phase and Energy Profiles vs. Cell No.

Output from DTL

Fig. 7 DTL phase, energy and emittance plots.

Phase-energy profiles and emittance plots for the ZEBRA reference design are shown in Fig. 7. Of particular concern is the tail on the PHI-W plot (lower right) at the output of the ZEBRA tank. These are particles that have not been captured longitudinally and would be lost in a longer DTL at energies sufficient to cause activation problems. It appears therefore that better discrimination and longitudinal matching in the MEBT will be necessary.

Conclusions

Beam dynamics calculations show that the ZEBRA reference design meets most of the requirements for an accelerator breeder injector. Improvement is required, in the longitudinal phase space capture of the RFQ output beam by the DTL operating at twice the RFQ frequency, to reduce high energy beam spill in the DTL. Possible means of improving the capture, including modifying the RFQ design recipe, alternate bunching schemes such as incorporating a drift plus kick into a lengthened RFQ, and different ϕ_s and field gradients in the DTL, will be investigated.

References

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3. K.R. Crandall, R.H. Stokes and T.P. Wangler, "RF Quadrupole Beam Dynamics Design Studies", Proc. 1979 Linear Accel. Conf., Montauk, NY, BNL-51134, 205.
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5. M.R. Shubaly, "Ion Source Development and Injector Design for ZEBRA", Proc. 11th Linear Accel. Conf., Santa Fe, NM, 1981 October 19-23.