DESIGN OF AN RFQ-BASED, H^- INJECTOR FOR THE BNL/FNAL 200 MeV PROTON LINACS*

R. A. Gough, J. Staples, J. Tanabe, D. Yee, and D. Howard
Lawrence Berkeley Laboratory

C. Curtis
Fermi National Accelerator Laboratory

and

K. Prelec
Brookhaven National Laboratory

Summary

AN LBL/BNL/FNAL collaboration has been formed to design an RFQ-based Cockcroft-Walton replacement, suitable for use at the Brookhaven and Fermilab 200 MeV proton linacs. A common design for the ion source and the RFQ will result in an economical construction and testing program compatible with both applications. The technical requirements have been evaluated and it appears that they can be satisfied with identical RFQs, capable of accelerating 50 mA of H^- from 35 to 750 keV, at a nominal frequency of 200 MHz.

Introduction

In recent years, the many advantages of RFQ-DTL linac combinations have been realized with a number of devices now in routine operation and several others either planned or under construction. The RFQ offers a compact and low-maintenance alternative to the traditional Cockcroft-Waltons with a number of additional benefits. It has a low input energy requirement, typically a few tens of keV, placing the ion source on a low voltage platform with easy access. A high capture and transmission efficiency through the RFQ can be achieved, approaching 100 percent, and the output beam is well matched to the input requirements of the DTL. These and other considerations have led to the successful implementation of RFQs at several injectors worldwide including those at Brookhaven (1), Saclay (2), Berkeley (3), and CERN (4). These installations are all in accelerator operations environments where high reliability is essential, and the collective experience of over 12 years of operations has been extremely good.

At Brookhaven, where a low-current polarized proton RFQ has been in successful operation for several years, plans were developed for a second RFQ, a high-current, H^- device to be independent of the polarized proton line and to eliminate the need for the Cockcroft-Waltons. Plans for an RFQ were also under consideration at Fermilab. Because of the similarity of the 200-MeV injectors, a joint design study was undertaken among LBL, BNL and FNAL, to evaluate a common design option for a possible front-end upgrade of both injectors. In this report we discuss the current status of these activities.

Ion Source Development

A program has been initiated at BNL to develop an H^- source whose parameters are well matched to the requirements of the RFQ (5). The goal is to provide a 50 mA beam at 35 keV with approximate rotational symmetry. Among the several source options under study are the magnetron, a cesiated Penning source, and a multicusp, cesium-free, volume source.

The source now in use at the AGS is a single slit magnetron with a grooved cathode. It is presently capable of delivering the required 50 mA current, but at 20 kV and with normalized emittances of 0.14 by 0.035π cm-mrad in the directions parallel and perpendicular to the extraction slit respectively. This asymmetry is due in large measure to the extraction through a 1 by 10 mm^2 slit oriented perpendicularly to the source magnetic field. Geometrical modifications to the anode slit and to the cathode groove of this source will be made to achieve a more symmetric beam.

In order to avoid beam losses and emittance degradation in the low energy beam transport line, it is desirable to mount the source as close to the RFQ as possible. Both magnetron and Penning sources require a continuous injection of cesium vapor to achieve high extracted H^- current density, and diffusion of cesium vapor may limit the attainable voltage gradients required in the RFQ. In recent years, a substantial effort has been devoted in several laboratories to the development of a cesium-free H^- ion source, and the best candidate seems to be a multicusp volume source. As an additional advantage, this type of source produces a rotationally-symmetric beam and it should have a lower emittance. Sources of this type are already within a factor of three of the required current and current density, and efforts are planned at BNL over the next two years to develop a cesium-free volume source suitable for RFQ injection. This source-type is also under development at LBL and LANL to demonstrate beam parameters that would meet (or exceed) the requirements of this application (6).

RFQ Design

The design for a Cockcroft-Walton replacement must not only provide enough beam at the right energy, but also enhance the existing injection linac system. In this design, the longitudinal phase space at the DTL entrance is small compared to the linac bucket that is usually filled with a conventional buncher. This will result in a more linear longitudinal motion and less longitudinal-transverse coupling. One hundred percent capture of the RFQ beam in the DTL is expected, leading to a more satisfactory operation of the first DTL tank. If the DTL is followed by a high frequency structure, the frequency jump and matching the beam into the smaller bucket of the following structure will be enhanced by the brighter beam.

A detailed RFQ design has been developed using a new approach to the beam dynamics design that reduces the RF power requirement and the output energy spread,

*Work supported by the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

while raising the space charge limit over previous proton preinjector RFQ designs. This allows the injection energy and RF amplifier power to be reduced while still retaining the desirable characteristics of the RFQ accelerator. The mechanical design is based upon the LBL concepts that were developed and implemented on two earlier machines, one now in service at the Bevatron in Berkeley (3), and the other operational at Linac I at CERN (7). The general characteristics of the RFQ are summarized in Table 1.

Table 1: Summary of RFQ Parameters

Ion	$H^{\pm}$	
Frequency	201.25	MHz
Energy	35 - 753	keV
Current limit	> 100	mA
Normalized emittance	0.1π	cm-mrad
Vane Length	161.89	cm
Mean radius (r_0)	0.418	cm
Surface field	20.3	MV/m
Peak cavity power	100.5	kW
Max duty factor	0.007	
Stored energy	0.5	Joules

Beam Dynamics

A new beam dynamics approach has been taken in this design, using (and extending) an idea first developed by Wangler (8), where the linear shaper section is extended and the tapered gentle buncher is shortened. The beam is accelerated from 35 keV at injection to a relatively high value of 68 keV at the end of the shaper where the stable phase is -76 degrees. At the end of the gentle buncher, the energy is only 180 keV and the stable phase is -50 degrees. The large bucket at the end of the buncher reduces the bunch compression and the charge density. The bunch remains small compared to the bucket area, linearizing the phase motion. This linearized motion in the bunch is responsible for the very low energy spread of ±14 keV (at 50 mA) with a phase spread of ± 33 degrees. For a design normalized input emittance of 0.1π cm-mrad, the emittance blowup is about 12%.

The accelerating section is 71 cm in length, almost one-half the 162 cm total length of the RFQ. The accelerating parameter (A) varies from 0.344 to 0.597 along the accelerating section with a constant focusing parameter (B) of 9.08. The large fraction of the machine devoted to acceleration increases the average shunt impedance. With an estimated Q of 57% of the theoretical value, the cavity power for full excitation is 100 kW at a vane voltage of 67 kV. The design surface field is 1.48 Kilpatrick. The capture efficiency is 97% for a 50 mA beam, gently degrading to 81% at 100 mA.

Mechanical Design

The mechanical design is based on the concept first conceived for the Bevatron RFQ (9) and later used for the O^{+6} RFQ (10) built by LBL for use at the CERN Linac I. It is a design optimized for low duty factor applications. It is a four-vane, loop-driven structure, stabilized azimuthally with vane coupling rings (VCRs) (11), with an easily-adjustable end geometry to flatten the axial field distribution. The cavity and vanes are made of copper-plated mild steel. Thermal stabilization of the structure is maintained by circulating temperature-controlled water through a tube that makes good thermal contact with the outside of the cylinder. Heat generated on the vanes is removed by conduction to the cavity through the RF spring contacts used along the base of the vane, and through the vane mounts located periodically along the structure. Precise vane positioning is achieved by referencing the vanetips to accurately ground flats on the outside of the cavity cylinder. Copper bars are introduced along the sides of the vanes to trim the final frequency. These devices are readily inserted and removed without disturbing the precise vane alignment. In the present design, each bar shifts the frequency 0.94 MHz per square centimeter of cross-sectional area. The natural frequency of the structure is controlled with a single auto-tracking tuner, in this case a shorted rotating loop.

Adapting the design concept to the present applications led to certain special considerations. The earlier LBL RFQs were designed for use with heavier ions (Si^{+4} and O^{+6}) and for shorter duty factors. The vacuum requirements for H^- beams and the thermal response of the structure under conditions of higher average power have been evaluated.

Vacuum Considerations

Loss cross sections for H^- on hydrogen decrease in this energy range from 8 down to 1 x 10^{-16} cm^2/molecule, fully an order of magnitude lower than for O^{+6} or Si^{+4}. (For residual air or hydrocarbons, the cross sections are approximately a factor of three higher.) Thus, negligible losses can be expected for an on-axis pressure of 1 x 10^{-6} Torr or better. Using conservative outgassing rates of 1 x 10^{-6} T-ℓ/cm^2s for organics and 1 x 10^{-9} T-ℓ/cm^2s for metal surfaces, the structure has a predicted total gas load of 1 x 10^{-3} T-l/s, dominated by organics. Even with moderate gas loads through the small end holes, adequate pressures can be achieved readily with two 1500 l/s pumps each pumping on one of the four quadrants. The pump ports consist of a matrix of holes in the cavity wall with the length to diameter ratio determined to prevent RF leakage. The net pumping speed on the cavity is 480 l/s per pump. Experience with the first two LBL RFQs demonstrates an actual base pressure after RF cleanup of 3 to 5 times lower than calculated with the above outgassing rates.

Since it is proposed to pump on only two of the four quadrants, Monte Carlo calculations were performed to determine the pressure distribution within both a pumped and unpumped quadrant. The results indicate a 20% pressure increase on-axis and a 60% increase at the highest point in the unpumped quadrant, relative to the region closest to the pump port.

Thermal Considerations

The maximum anticipated duty factor (in the Brookhaven application) is 0.007. With a peak cavity power of 100 kW, this results in an average power dissipation of 700 watts. Because of the relatively inefficient heat transfer between the vane and cavity, the structure is not isothermal, the vanes running several degrees hotter than the cavity. This leads to a net reduction in the bore aperture during RF turn-on with a resulting decrease in the natural frequency that must be compensated. The time constant for this behavior is long, requiring about 100 minutes to reach equilibrium. It is important to determine the magnitude of the frequency shift and to ensure an adequate range of the dynamic frequency tuner.

With the heat load distributions specified by SuperFish as input, a finite element analysis code (ANSYS) was used to study the thermal behavior of both the Bevatron RFQ structure and the new design. This code is capable of calculating both steady-state and transient effects. Measurements of the thermally-induced frequency shift associated with RF turn-on were made using the Bevatron RFQ. The measured shift (df) of 80 kHz at equilibrium implies a change in bore radius (dr) of 3 microns. Using this result together with the ANSYS code and the SuperFish heat distributions, a thermal contact resistance between the vanes and the cavity of 6.5 Watts/m/^{o}C was established. This result is in good agreement with independent engineering estimates. With finite element techniques, it was also possible to correctly predict the observed time constant. Using this contact resistance for the new design, the ANSYS code projects a net change in the bore radius of dr = 11.7 microns at full power with a 0.007 duty factor. For the new design, the frequency sensitivity is df/dr = 156 MHz/cm, leading to a worst-case frequency shift df = 183 kHz. This frequency shift falls comfortably within the range of a single tuner loop which can be designed to cover a total range of 300 - 400 kHz. The calculated time constant is approximately 30 minutes.

RF Considerations

The total length of 162 cm is just over one free space wavelength of the operating frequency of 201 MHz. Three sets of vane coupling rings (VCRs), one set near each end and one set in the center, will stabilize the field distributions azimuthally and eliminate concern about the dipole modes. They will introduce a total variation in the longitudinal field distribution of only 6%. RF power can be provided through a single drive loop; 100 kW of cavity power and 36 kW of beam power at 50 mA. In the present design, the number of tuning bars attached to the vanes has been reduced from 8 to 4, thereby reducing by one-third the number of RF joints in the current path. This reduces the number of components required for fabrication and assembly and reduces the RF joint losses. The expected Q is about 6500, or 57% of the theoretical value for pure copper with no joint losses. Twelve monitor loops are provided for phase and level control, monitoring field balance, and spark detection. The maximum surface fields in the structure never exceed 1.5 times the Kilpatrick criterion, leading to a short initial conditioning period and the promise of high operational reliability.

Conclusions

Based on the studies completed at this time, it appears that all technical requirements for an RFQ-based front-end upgrade of the 200 MeV proton linacs at either Fermilab or Brookhaven can be satisfied with a common design. The ion source options include the magnetron source, similar to those now operating at both labs, a cesiated PIG source, or a cesium-free, multicusp volume source. A development effort is underway at BNL to evaluate these options. The RFQ requirements can be satisfied with a design developed at LBL. The beam dynamics design for this machine offers several advantages over earlier proton RFQ designs, including improved longitudinal phase space and lower RF power demand. It appears that the requirements for the BNL/FNAL applications can all be satisfied with the mechanical design concept developed at LBL for low-duty-factor, heavy-ion applications.

References

1. H. Brown, T. Clifford, S. Giordano, F. Khiari, R. McKenzie-Wilson, M. Puglisi, and P Warner, Design, Fabrication and Testing of the BNL Radio Frequency Quadrupole Accelerator, Proceedings of the 1984 Linear Accelerator Conference, Seeheim, W. Germany (May 1984) p65.

2. M. Olivier, First Heavy Ion Acceleration in Saturn at 1 GeV/amu Using the CRYEBIS-RFQ Preinjector Hyperion II, Proceedings of the 1984 Linear Accelerator Conference, Seeheim, W. Germany (May 1984) p59.

3. J. Staples, R. Dwinell, R. A. Gough, J. Halliwell, D. Howard, R. Richter, G. Stover, and J. Tanabe, Initial Operation of the New Bevatron Local Injector, Proceedings of the 1985 Particle Accelerator Conference, Vancouver, Canada (May 1985) p3208.

4. E. Boltezar, H. Haseroth, Ch. Hill, F. James, W. Pirkl, G. Rossat, P. Tetu, and M. Weiss, Performance of the CERN RFQ (RFQ1 Project), Proceedings of the 1984 Linear Accelerator Conference, Seeheim, W. Germany (May 1984) p56.

5. K. Prelec, J Alessi, A. Kponou, and A. McNerney, Development of H^- Ion Sources at BNL, Second European Workshop on the Production and Application of Light Negative Ions, Palaiseau, France (March 1986).

6. K. Leung, private communication.

7. H. Haseroth et al, Ion Acceleration in the CERN Linac I, this conference.

8. T. Wangler, private communication.

9. S. Abbott, R. MacGill, and R. Yourd, Mechanical Design of a Heavy Ion RFQ, Proceedings of the 1983 Particle Accelerator Conference, Santa Fe, NM (March 1983) p3004

10. R. A. Gough, J. Staples, R. Caylor, D. Howard, and R. MacGill, A Compact Heavy Ion RFQ Preaccelerator for Use at the CERN Linac I, Proceedings of the 1985 Particle Accelerator Conference, Vancouver, Canada (May 1985) p3205.

11. D. Howard and H. Lancaster, A Simple Technique for Stabilizing a Four-Vane Radiofrequency Quadrupole Structure, Proceedings of the Seventh Conference on the Application of Accelerators in Research and Industry, Denton, TX (Nov 1982).

Acknowledgements

We gratefully acknowledge the assistance of S. Abbott, H. Brown, R. Caylor, and R. MacGill for their help on this study, and to R. Wells for his capable running of the ANSYS calculations.