DESIGN RECOMMENDATIONS FOR LOW-ENERGY COMPONENTS OF ESNIT AND OMEGA*

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Abstract

Conceptual designs for the low-energy components of cw proton and deuteron accelerators for neutron sources were developed for a workshop organized by the Los Alamos National Laboratory. The proposals incorporate the high-current low-emittance 2.45 GHz electron cyclotron resonance (ECR) ion source developed at Chalk River Laboratories (CRL) and radiofrequency quadrupole (RFQ) accelerators based on CRL experience with the 75 mA cw 267 MHz RFQ1 proton accelerator.

Introduction

The Los Alamos National Laboratory recently arranged a workshop to address the requirements of two projects of the Japan Atomic Energy Research Institute (JAERI) that involve neutron sources based on cw linear accelerators. The Energy Selective Neutron Irradiation Test (ESNIT) requires a 50 mA beam of deuterons while the OMEGA project calls for a 10-30 mA proton beam. The beam currents of the deuteron and the proton accelerators must be extendable to 100 mA and 200 mA respectively. This paper offers design concepts for the low-energy components of suitable machines based on dc ion source and cw linear accelerator research at Chalk River Laboratories (CRL).

The economics of a high-energy linear accelerator are dominated by the costs of the high-energy structures and rf amplifiers, and the target. Thus, the primary consideration in the choice of the injector and the radiofrequency quadrupole (RFQ) accelerator is beam quality. Proven ion sources [1-5] and rf devices [6-10] are available, or can easily be adapted, to generate the beams required for both ESNIT and OMEGA. The specifications for the two projects were used to establish the parameters for the low-energy stages of two typical accelerators for neutron sources. Then, designs were sought that maximized the symbiosis between the two projects and existing programs at other laboratories.

Ion Sources

The 2.45 GHz electron cyclotron resonance (ECR) ion source developed at CRL [1,3,4] is a proven injector for a high-current cw RFQ accelerator [2]. In addition to the long lifetime and the high efficiency common to all ECR ion sources, the CRL source features a high proton fraction ascribed to an insulating liner and a low emittance attributed to a modest magnetic induction.

The source generates a beam current density of 500 mA/cm^2 at a microwave power of less than 900 W and a hydrogen gas feed rate of 1.5 sccm (2.3 μg/s). A beam of 125 mA with a proton fraction of 90% and a normalized rms emittance of 0.14 π mm mrad was extracted from a single aperture and transported to a beam stop. The variation of the minimum normalized rms emittance with the perveance is shown in Fig. 1. A preliminary experiment with deuterium produced a 65 mA ion beam.

The injection energy of an RFQ should be minimized to reduce the complexity and increase the reliability of the ion source extraction system. The decrease of the beam capture with the injection energy imposes a lower limit. As demonstrated later, the baseline and the extended specifications for both ESNIT and OMEGA could be met at an injection energy of 50-60 keV, assuming the upgrades are achieved by funnelling [8]. The simple three electrode extraction system of the CRL ion source already operates at up to 55 kV, and an extension to 60 kV should be straightforward.

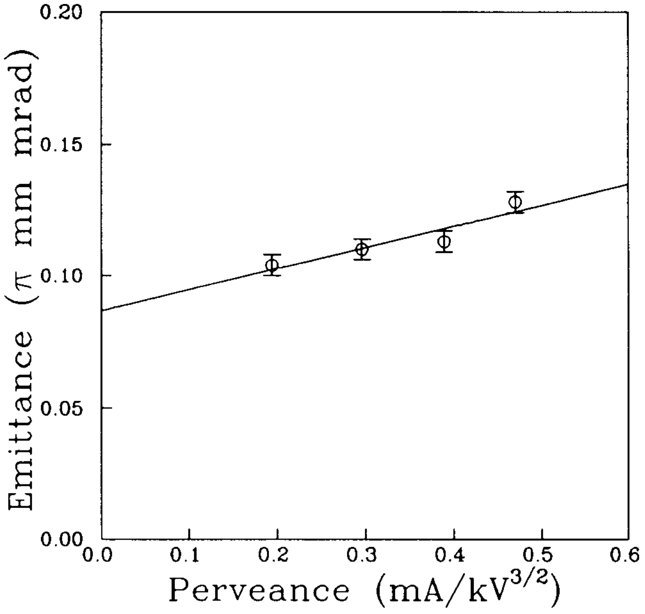

Fig. 1 Measured minimum normalized rms emittance of CRL ECR ion source as a function of perveance.

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The extended versions of both ESNIT and OMEGA would require a proton equivalent perveance of about 0.35 mA/kV$^{3/2}$, corresponding to a normalized rms emittance of approximately 0.1 π mm mrad, as indicated by Fig. 1. (In the absence of funnelling, the extensions could be achieved with a more complicated four electrode extraction system or a multiple aperture extraction system with commensurately higher emittance.)

RFQ Accelerators

The optimum frequency for a given rf accelerator is determined by many factors. The availability of rf amplifiers is a major consideration, keeping in mind that multiple frequencies will be required, if funnelling is contemplated. While higher frequencies can introduce problems with miniaturization, they increase tolerable field gradients [11] and acceptable surface power densities. A lower frequency, on the other hand, leads to a larger aperture ratio, thereby reducing beam spill and easing hands-on maintenance of the high-energy components. The beam current limit is generally higher at a lower frequency, and, for a given beam current, the minimum injection energy tends to increase with the frequency.

If a single stage of funnelling were used for future extensions to higher beam currents, then a single frequency could be used for the low-energy stages of both accelerators. The frequency should be at least 200 MHz, to ensure a practical beam size and an acceptable emittance growth. For a realizable field gradient and an acceptable injection energy, the frequency should be 400 MHz at most. The extensive operating experience and experimental data acquired at CRL [6,9] suggest that 267 MHz is a plausible choice.

The klystrode, which is more efficient than a klystron of comparable cost, is a good candidate for an rf power supply for cw accelerator applications. A 250 kW cw klystrode operating at 267 MHz is being developed for CRL [12]. At least one additional high-power rf amplifier would have to be developed at a higher frequency to satisfy the requirements of funnelling.

The accelerating and focusing fields of an RFQ are limited primarily by the maximum field gradient. The cw RFQ1-1250 accelerator at CRL was designed [13] to operate at 1.8 times the Kilpatrick limit [11]. Field gradients as high as 2.1 times the Kilpatrick limit were demonstrated with this accelerator [10]. The conceptual designs for both ESNIT and OMEGA, presented below, assume 1.8 times the Kilpatrick limit, corresponding to a peak field gradient of 30 MV/m at 267 MHz.

The four-vane RFQ is preferred over the four-rod RFQ because, at 267 MHz cw, the cooling requirements of the latter complicate the fabrication and compromise the efficiency.

While the RFQ1 vanes are demountable and adjustable, the correct frequency and flat fields could be achieved with fixed vanes. The electroforming procedure, pioneered for the BEAR (Beam Experiments Aboard a Rocket) RFQ [14], should be considered. Whereas RFQ1 employs a single 250 kW cw rf drive loop at the mid-plane of one segment, multiple drive loops would be required for ESNIT and OMEGA. Power combining, a common practice in pulsed linear accelerator structures, should be equally appropriate for cw cavities. Three rf systems operating at two thirds of their maximum power could provide redundancy for servicing.

In a 50 mA deuteron RFQ, beam losses of less than 10% are difficult to achieve. Calculations with the PARMTEQ [15] computer code show that, although more than half of the lost particles are accelerated to less than twice the injection energy, the energy of the remainder can extend up to the output energy of the RFQ. The threshold for the ^{65}Cu(p,n)^{65}Zn reaction is 2.13 MeV. The decay of the resultant ^{65}Zn, with a 244 day half-life, generates 1.11 MeV gamma rays. Thus, a maximum output energy of 2 MeV is suggested for the proton RFQ. Deuterons are less of a problem at low energy because the ^{63,65}Cu(d,n)^{64,66}Zn reactions lead to stable isotopes. Although a detailed analysis of the beam-dynamics of the subsequent structures may favour a slightly higher output energy for the deuteron RFQ, 2 MeV was adopted as the reference value.

The codes CURLI, RFQUIK and PARMTEQ were used to design deuteron and proton RFQ accelerators [16] with beam currents of 50 and 100 mA respectively. The transmission was virtually constant for an input emittance of 0.5 to 3.0 times the anticipated value. Emittance growth in the deuteron RFQ was less than 20%, except for unrealistically small input emittances. The parameters of both accelerators are given in Table I. The transmission of the deuteron and the proton accelerators versus the input beam current is shown in Fig. 2. At the required beam currents, the transmission exceeds 90%.

Table I Parameters for deuteron and proton cw RFQ accelerators.

	D^+	H^+
Input Energy (MeV)	0.06	0.05
Input Emittance (π mm mrad)	0.13	0.13
Output Current (mA)	50	100
Output Energy (MeV)	2.0	2.0
Length (m)	4.32	3.12
Bore Radius (mm)	3.5	4.6

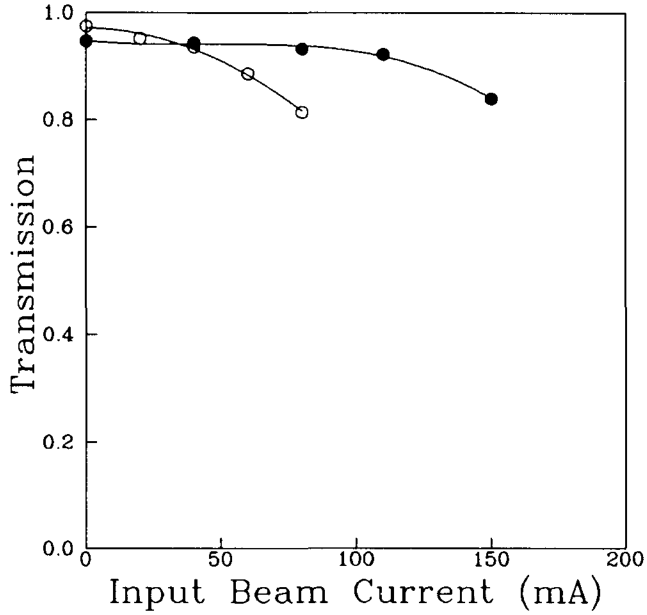

Fig. 2 Calculated transmission versus input ion beam current for RFQ accelerators proposed for ESNIT (open symbols) and OMEGA (closed symbols).

The RFQ designs are preliminary. The calculations ignore the higher harmonics that can affect the transmission of an RFQ accelerator, although the deleterious effects can probably be kept small by minor changes [13].

Conclusions

The CRL ECR ion source already produces the deuteron and the proton beam currents required for both the baseline and, assuming funnelling, the extended versions of the ESNIT and the OMEGA accelerators. The measured emittance of the proton beam is well within the requirements and similar results are expected for the deuteron beam. The ion source operates readily at the 50 keV input energy of the proton accelerator, and the upgrade to the 60 keV required for the deuteron accelerator should be straightforward.

Adopting a frequency of 267 MHz for both RFQ accelerators would provide commonality between the deuteron and the proton projects, and, with a single stage of funnelling, could accommodate the highest necessary beam currents (100 mA of deuterons and 200 mA of protons) with little additional prototyping. The proposed RFQ designs are similar to the 75 mA cw RFQ1 designs that operated successfully at CRL. Confidence in the beam physics is accordingly high. The major challenge is the engineering required to ensure the necessary reliability.

References

[1] T. Taylor and J.S.C. Wills, Nucl. Instr. and Meth. **A309** (1991) 37.

[2] G.M. Arbique, T. Taylor, M.H. Thrasher and J.S.C. Wills, 1991 IEEE Particle Accelerator Conference, IEEE Conference Record 91CH3038-7, pp. 842-844.

[3] T. Taylor and J.S.C. Wills, "Enhanced High-Current ECR Proton Source", these proceedings.

[4] T. Taylor and J.S.C. Wills, "Extraction of High-Current Low-Emittance Proton Beams from an ECR Plasma Generator", these proceedings.

[5] G.M. Arbique, T. Taylor, A.D. Davidson and J.S.C. Wills, "High-Current Direct Injection to a CW RFQ Using an ECR Proton Source", these proceedings.

[6] G.M. Arbique, B.G. Chidley, W.L. Michel, G.E. McMichael and J.Y. Sheikh, 1991 IEEE Particle Accelerator Conference, IEEE Conference Record 91CH3038-7, pp. 845-847.

[7] T. Tran-Ngoc, G.E. McMichael, G.M. Arbique and F.P. Adams, Proc. 1990 Linear Accel. Conf., LANL Rept. LA-12004-C (1991) 48.

[8] K.F. Johnson, O.R. Sander, G.O. Bolme, J.D. Gilpatrick, F.W. Guy, J.H. Marquardt, K. Saadatmand, D. Dandoval and V. Yuan, Proc. 1990 Linear Accel. Conf., LANL Rept. LA-12004-C (1991) 701.

[9] G.M. Arbique, B.G. Chidley, G.E. McMichael and J.Y. Sheikh, "Beam Parameter Measurements on the CW RFQ1-1250 Accelerator", these proceedings.

[10] J.Y. Sheikh and R.J. Burton, "Tuning and Conditioning of RFQ1-1250 Cavity", these proceedings.

[11] W.D. Kilpatrick, Rev. Sci. Instr. **28** (1957) 824.

[12] J.Y. Sheikh and J.C. Brown, Chalk River Laboratories Accelerator Physics Branch Annual Technical Report 1989, AECL Research Co. Rept. AECL-10235 (1990) 8.

[13] B.G. Chidley, F.P. Adams, G.E. McMichael and T. Tran-Ngoc, Proc. 1990 Linear Accel. Conf., LANL Rept. LA-12004-C (1991) 42.

[14] D. Schrage, L. Young, B. Campbell, J.H. Billen, J. Stovall, F. Martinez, W. Clark, G. Bolme, S. Gibbs, D. King, P.G. O'Shea, T. Butler, J. Rathke, R. Micich, J. Rose, R. Richter and G. Rosato, Nucl. Instr. and Meth. **B40/41** (1989) 949.

[15] K.R. Crandall and T.P. Wangler, Linear Accelerator and Beam Optics Codes, AIP Conference Proceedings 177, 1988, pp. 22-28.

[16] T.P. Wangler, "Space-Charge Limits for Linear Accelerators", LANL Rept. LA-8388 (1980).