THE ZEBRA PROJECT - PAST AND PRESENT

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Summary

The 300 mA 10 MeV proton accelerator designed for the ZEBRA (Zero Energy BReeder Accelerator) Project is a test accelerator to demonstrate construction and operation techniques required for the cw injector of an accelerator breeder that could produce fissile material for nuclear power stations. The technology development program underway at CRNL is described in the context of the overall goals of the program. Developments in ion sources, radiofrequency quadrupole structures, drift-tube structures, beam transport, diagnostics, controls and modeling will be highlighted. Status of the ZEBRA project and the high power pre-ZEBRA experiments is given with a projection on future ZEBRA related activities.

Introduction

The ZEBRA (Zero Energy BReeder Accelerator) project is the first stage of a four stage development program[1] leading to an accelerator breeder based on 300 MW of proton beam power. A four stage program was proposed because of the high cost of a full power facility and because of the opportunity presented between stages for a review of the overall program taking into account technological developments and economic changes. Each stage provided a facility that could be justified on its own merits. For example, the second stage, based on a 70 mA 200 MeV accelerator, would be an excellent facility[2] for fundamental materials and basic neutron physics research using ample neutron fluxes generated in a liquid metal target. This paper focuses on activities leading to the first stage and the first stage project itself. More information on the different stages can be found in reference 1.

The ZEBRA project included the design, construction and testing of a 300 mA 10 MeV proton accelerator operating continuous wave. Five years ago, it was felt necessary to begin launching the first stage of an accelerator breeder program in order that a 300 mA 1000 MeV accelerator breeder could be commissioned at a time when additional fissile material would be required (in about 30 to 40 years). Over the past five years, more uranium has been discovered in Canada and elsewhere, and at the same time the nuclear industry has suffered a slump worldwide. Although electronuclear breeding remains a long term goal of AECL, it was decided that the ZEBRA project would be postponed; however, generic work and some pre-ZEBRA activities would continue.

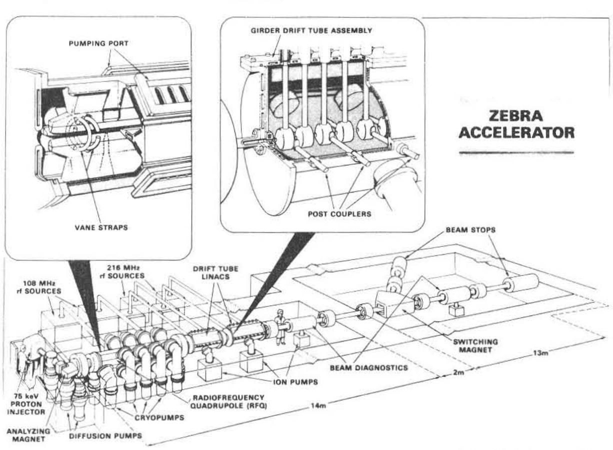

Fig. 1 Layout of ZEBRA - a 300 mA 10 MeV proton linac.

The ZEBRA project, when it was being planned, was to be the focus of a new laboratory located in the province of Quebec. In addition to the cw 300 mA 10 MeV proton linac, other related activities were being planned to give the new laboratory a well rounded research and development program. With the focus postponed, the new laboratory has also been postponed.

The ZEBRA project was estimated to cost $150 M including manpower and overhead for the first ten year operating period with a staff level reaching about 170 by the end of the period. The ZEBRA accelerator was estimated to cost $20 M for hardware and installation with the laboratory and office building estimated at an additional $25 M.

ZEBRA

Figure 1 shows a layout of the proposed ZEBRA accelerator[3]. A 75 kV dc proton injector would have delivered 375 mA of analyzed proton beam with required beam properties to a 108 MHz radiofrequency quadrupole (RFQ) structure. The ion source-injector would have to operate from zero to full current with the output beam always matching the RFQ acceptance. In addition, the injector was to operate dc with appropriate beam dumps for unwanted species and with suitable diagnostics. The ion source was to be based on successful work with multi-aperture duoPIGatron plasma generators. The 3.7 m RFQ, requiring about 1 MW of rf power, would have bunched and accelerated 305 mA of protons to 2 MeV for transport to a 216 MHz drift tube linac (DTL). The 70 mA of lost cw beam in the RFQ would have represented a significant gas load, a factor dictating the large number of cryopumps at this location. The lost beam could have led to possible vane erosion, a problem which would have been investigated in other devices before beginning ZEBRA design. The post coupler stabilized DTL would have accelerated the 2 MeV beam to 10 MeV in two tanks, delivering 300 mA to an appropriate beam stop. Each 4 m length DTL tank would have required a total rf power of 1.5 MW for structure losses and beam. One of the 3 MW proton beam stops would have been liquid metal to gain experience with liquid metal curtains prior to launching work on the second stage of the accelerator breeder program.

ZEBRA serves as the injector for an accelerator breeder with full current but only 1% of the final breeder energy. The 10 MeV output energy was selected as a compromise between being low enough to keep facility cost reasonable and being high enough to study aspects of launching a satisfactory beam for an accelerator breeder. ZEBRA was being designed as an experimental facility that would investigate multi-tank operation, high beam loading of different rf structures, overall beam control, engineering techniques, remote-handling methods, and suitable non-destructive and non-intercepting beam diagnostics. Although the 108 MHz rf sources would have been triodes, discussions with manufacturers indicated that the 216 MHz rf sources could have been klystrons. Vacuum would have been provided by diffusion pumps in the injector area, cryopumps in the RFQ area and ion pumps in the DTL area. A possible additional area for study was funneling of two beams from two 108 MHz RFQ's into the 216 MHz DTL (an obvious overlap of interest with a heavy ion fusion rf accelerator).

Pre-ZEBRA

A number of experiments were planned as pre-ZEBRA work to develop the technology necessary to ensure that the 300 mA 10 MeV proton linac could be built. The activities shown in Fig. 2, which all operate 100% duty factor, have been underway at CRNL for the past four years. Details are provided in following sections. The activities were organized into three main thrusts - the ion source-injector, the RFQ and the DTL. Early work on ion sources and injectors showed that a two stage injector and the biased RFQ had more disadvantages than advantages and that a single stage injector should provide the required beam emittance and current variability in a reliable and controllable manner.

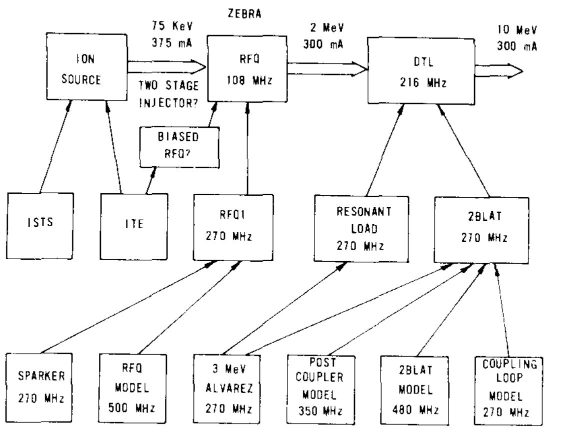

Fig. 2 Pre-ZEBRA activities and their relationship to ZEBRA.

Ion Source and Injector

Figure 3 shows a schematic of the Injector Test Experiment at CRNL. This facility and the Ion Source Test Stand[4] have been used to demonstrate technology and the operating and assembly procedures necessary for ion sources that would be suitable for an accelerator breeder (and ZEBRA). Aspects of the necessary stable current variation from 0 to 375 mA have been demonstrated but at reduced (50 kV) voltage. Proton current variation with acceptably small variations of emittance was possible by neutralization and combining heavy ion (Ar) beams with the main beam. Work has been concentrating on multi-apertures, beamlet stacking[5], various cusp geometries[6], species dumps and diagnostic equipment as well as on improving performance, efficiency and plasma uniformity. Work on dc duoPIGatron ion sources with multiple apertures has been successfully extended to other high current beams such as oxygen, argon and xenon. Optimization studies completed for duoplasmatron and duoPIGatron sources, including materials selection and close attention to cooling, have provided a good background on which to proceed with future experiments.

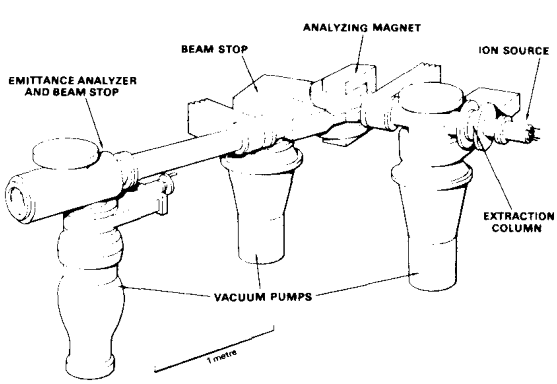

Fig. 3 Injector test experiment for injector development.

A number of techniques and principles were also developed for column design[7] and diagnostic units. For example, an emittance measuring unit that can accommodate power densities of 3 kW/cm^2 is being fabricated on the basis of previous units that have operated at high power densities. Experiments on beam transport and diagnostics are being planned for the existing facilities.

Radiofrequency Quadrupole

Besides generic work on modeling and determining the overall RFQ parameter space, our main effort has been directed towards two projects - the RFQ Sparker and RFQ1. The 270 MHz RFQ Sparker[8] (Fig. 4) was built to provide information on 100% duty factor operation with the four vane RFQ geometry. Results from this experiment have led to a redesign of our RFQ1 experiment[9] because cw surface fields approaching 2.3 times the Kilpatrick limit (Kp) can be achieved with copper surfaces that have not been treated to improve surface characteristics. The experiment has provided useful information on microdischarge and breakdown effects in rf structures. Differences between pulsed (< 1 ms pulse time) and cw operation were apparent in the experiments undertaken. Further work will cover surface treatment for the four vane geometry and a study of breakdown characteristics for the four rod geometry[10] at 108 MHz. Work on the four rod geometry was initiated because of construction simplifications possible for the ZEBRA RFQ. High power tests at 108 MHz are being planned in association with the University of Frankfurt.

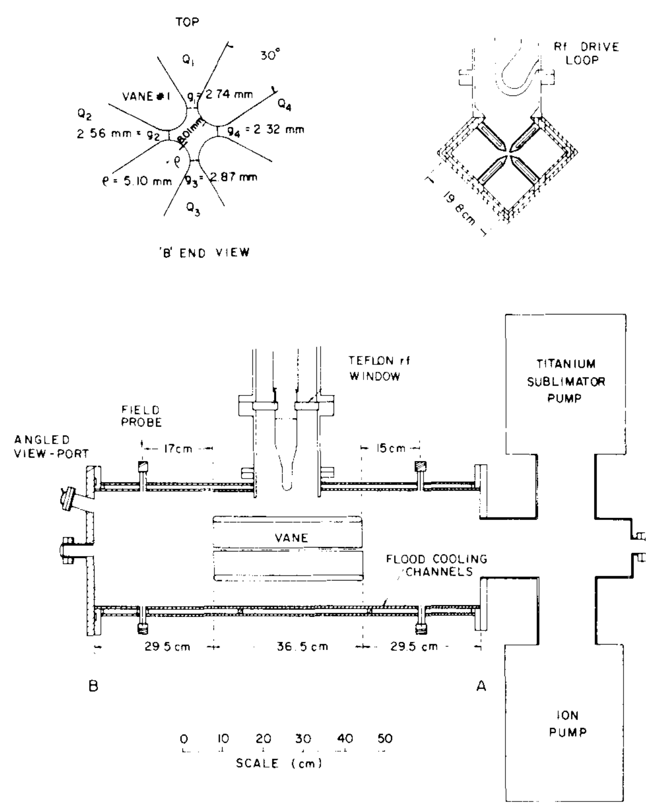

Fig. 4 The RFQ Sparker experiment.

The understanding of design constraints and operational characteristics for RFQ structures has been improved by the development of a computer code[11] that represents the RFQ by an equivalent circuit. Recent additions to the code have made it possible to study the four rod geometry.

RFQ1 is our major pre-ZEBRA high current proton linac project. Hardware and installation costs are estimated at about $1.5 M (not including professional and technical salaries) over the three year development and construction period. Beam from the 75 mA 600 keV cw linac is expected in the fall of 1986. Work is progressing well on this schedule with injector components being built, cryopumps and diffusion pumps on hand, and RFQ mechanical and rf tests well underway. Construction of the high power RFQ structure with 1.47 m vanes is expected to begin this fall following a final design review. Present design[12] employs removable vanes that make a knife edge rf joint with the outer wall. Construction is almost complete on a full scale aluminum model designed to determine frequency perturbations from pumping slots, tuners, end caps, straps and coupling loop ports. A layout of the RFQ1 injector is shown in Fig. 5.

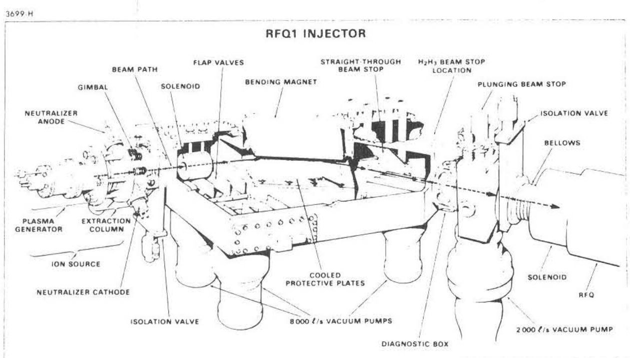

Fig. 5 The RFQ1 injector.

The RFQ1 experiment should demonstrate all aspects of RFQ acceleration including beam current limits. The experiment has been designed to cover a full range of operating conditions, from 1.25 Kp to 2 Kp surface electric fields in the RFQ, using a 50 kV injector that could supply up to 125 mA of analyzed beam. Tests will include comparisons of single and multiple aperture beamlet acceleration with beam dynamics predictions. Considerable effort is being invested to ensure reliable control and long term reliability for the entire experiment. An output beam energy of 600 keV was selected to make it possible to transport the output RFQ beam to a 270 MHz $2\beta\lambda$ drift tube linac that was being designed for 10 mA proton acceleration. With the addition of the new DTL, all facets of the ZEBRA accelerator would have been investigated, but not necessarily under the proper parameter regime.

Extensive beam dynamics calculations[12-14] and computer code developments have aided in the design of RFQ and DTL structures. Developments have been reported on vane electric field enhancement factors[15,16], image charge forces[17] and space charge forces with beam transport[18].

Drift Tube Linac

Previous work[19,20] showed the parameter space restrictions for obtaining field stabilization with post couplers in drift tube linacs. Although there is an incentive for improving rf efficiency by reducing the drift tube diameter, there is a practical limit for the ratio of the drift tube diameter to outer tank diameter. For standard post coupler design, the ratio should not be less than 0.1, nor should it be greater than 0.3 (at which point there is no gap between the post coupler and drift tube). One possible explanation for field stabilization with post couplers in a DTL is that the passband of an interdigital line (the post couplers) is being overlapped with that of the Alvarez structure to provide some stability or feedback in the on-axis field distributions. This interpretation may help explain why it is possible to stabilize a DTL with post couplers opposite every seventh drift tube rather than each drift tube.

Measurements on stem currents (Fig. 6) demonstrated the importance of making the geometry as symmetric as possible. By adding a dummy half drift tube to each end flange of the tank, it was possible to reduce stem currents by at least three orders of magnitude.

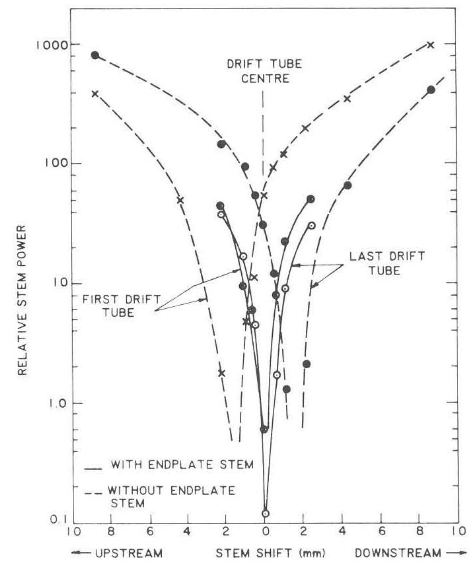

Fig. 6 Stem current versus drift tube support.

A 3 MeV DTL[21] (see Fig. 7) has been operated cw at high power 270 MHz to accelerate several mA of protons. This facility demonstrated ways to improve 100% duty factor DTL design. Based on these studies a new DTL, 2BLAT[21], was being designed to accelerate 0.6 MeV protons from RFQ1 to 2.5 MeV. The $2\beta\lambda$ linac would have mocked the first cavities of the ZEBRA DTL and should have provided important information relevant to initial acceleration of low energy beams. Work is underway for testing girder suspensions for the 2BLAT drift tubes and for copper plating various DTL components.

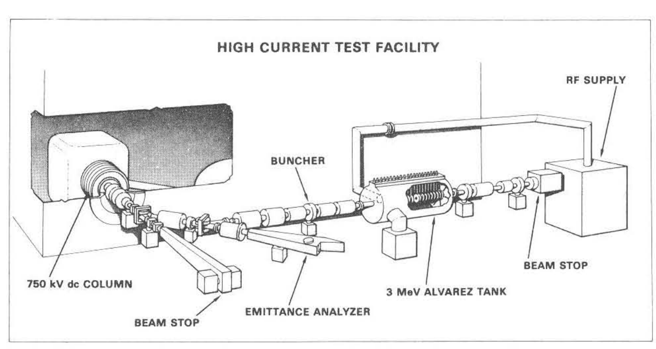

Fig. 7 Schematic of the High Current Test Facility.

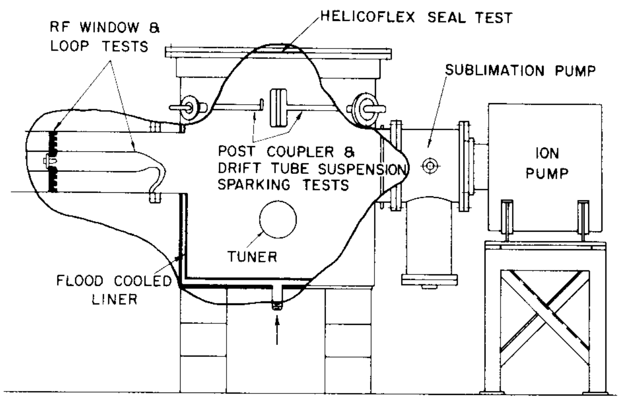

Fig. 8 Schematic of the resonant load facility.

Resonant Load

Because various devices should be high power tested prior to large component construction, a 270 MHz resonant load[22] was fabricated. It is a pillbox cavity (Fig. 8) with ports and holes for mounting components to be tested and for visual observation. The test facility has been extremely useful for demonstrating high power characteristics of a redesigned tuning plunger that has performed well at high power (up to 170 kW) and for new coupling loop[23] and rf window designs. Tuner measurements showed that on-power movement had no visible breakdown if the plunger was within the cavity - unlike the situation when it was withdrawn into the tuner port. The resonant load will be used to test RFQ joint capabilities, helicoflex rf joints and windows made from either ceramic disks or cylinders.

Diagnostics and Control

Work has been underway for some time on non-destructive and non-intercepting diagnostics using beam light monitors not only for beam profile measurements but for momentum analysis by use of the Doppler shifted light from the fast hydrogen atoms formed by charge exchange on the background gas (transverse momentum from the Doppler broadening of the lines). Preliminary measurements using Doppler broadened light techniques have indicated that average energies of background gas atoms were several eV, a value used in preliminary calculations for estimating background gas effects[24]. The preliminary estimates led to the more rigorous treatment presented in reference 24. Further work on diagnostics will include beam phase monitors, dc beam current monitors and the use of beam light to investigate emittance characteristics.

Work on distributed control systems with "smart" instruments and local computing power is underway for the RFQ1 experiment and for the ion source injector development areas. Good results have been achieved with the fibre optic telemetry links[25] which should provide noise-free data transfer. The RFQ1 control system[26] will be based on an intelligent crate with interchangeable modules that make the system simple and relatively inexpensive. An 8085-based microcomputer will link to a bus designed for easy interfacing with the plug-in modules. Items to be monitored include temperatures, coolant flows, voltages, currents, rf parameters and status signals.

Comments

Pre-ZEBRA activities have made contributions to the development of low beta structures and ion source injector systems. The work is not only applicable to ZEBRA but to any low beta device - whether it be cw or pulsed. Although the ZEBRA project itself has been postponed, development work on high current cw proton accelerators will continue at CRNL and include RFQ1, beam transport, ion injectors, and diagnostics.

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References

1. S.O. Schriber, "Canadian Accelerator Breeder System Development", Atomic Energy of Canada Limited, Report AECL-7840, 1982.
2. M.A. Lone, W.N. Selander, B.M. Townes, J. Latouf, E.C. Svensson and G.A. Bartholomew, "Characteristics of a Thermal Neutron Source Based on an Intermediate Energy Proton Accelerator", Atomic Energy of Canada Limited, Report AECL-7839, 1982.
3. S.O. Schriber, "The ZEBRA (Zero Energy BReeder Accelerator) Program at CRNL - 300 mA 10 MeV Proton Linac", Proc. of 1981 Linac Conf., Los Alamos National Laboratory Report No. LA-9234-C, 363 (1981).
4. M.R. Shubaly and M.S. de Jong, "High Current DC Ion Beams", IEEE Trans. Nucl. Sci., NS-30 (2), 1399 (1982).
5. M.R. Shubaly, "Reduction of Effective Emittance by Stacking Beamlets in Phase Space", IEEE Trans. Nucl. Sci., NS-30 (4), 2621 (1983).
6. M.R. Shubaly, "A Study of a Cusp-Enhanced DuoPIGatron Ion Source," proceedings of this conference.
7. J.D. Hepburn, M.R. Shubaly and J. Ungrin, "Spark Resistant Design for High-Voltage, High-Current Accelerating Columns", Low Energy Ion Beams 1980, edited by I.H. Wilson and H.G. Stevens, Inst. of Physics, Bristol (1980).
8. R.M. Hutcheon, S.O. Schriber, J.C. Brown, D.W. Clements, H.F. Campbell, G.E. McMichael and M.S. de Jong, "Operation of a CW High Power RFQ Test Cavity", proceedings of this conference.
9. M.R. Shubaly, J.C. Brown, B.G. Chidley, M.S. de Jong, L.D. Hansborough, R.M. Hutcheon, G.E. McMichael, S.O. Schriber, R.B. Turner and J. Ungrin, "RFQ1: A 600 keV, 75 mA CW Proton Accelerator", IEEE Trans. Nucl. Sci., NS-30 (2), 1428 (1982).
10. R.M. Hutcheon, "A Modeling Study of the Four-Rod RFQ", proceedings of this conference.
11. R.M. Hutcheon, "An Equivalent Circuit Model of the General 3-Dimensional RFQ", IEEE Trans. Nucl. Sci., NS-30 (4), 3524 (1983).
12. B.G. Chidley and G.E. McMichael, "RFQ1 Design Parameters", proceedings of this conference.
13. B.G. Chidley, J.C. Brown, G.E. McMichael, S.O. Schriber, M.R. Shubaly and J. Ungrin, "Design and Constraints for the ZEBRA Injector, RFQ and DTL", Proc. of 1981 Linac Conf., Los Alamos National Laboratory Report No. LA-9234-C, 49 (1981).
14. G.E. McMichael and B.G. Chidley, "Beam Dynamics Studies of High Current RFQ and DTL Tanks", ibid., 149.
15. B.G. Chidley, G.E. McMichael and G.E. Lee-Whiting, "Design of RFQ Vane Tip to Minimize Sparking Problems", IEEE Trans. Nucl. Sci., NS-30 (4), 3560 (1983).
16. N.J. Diserens, "RFQCOEF, A Package for Extracting the Harmonic Coefficients for the Potential Function in an RF Quadrupole Cell", proceedings of this conference.
17. N.J. Diserens, "Investigation of the Effects of Space Charge and Image Charge Forces on Beam Loss in an RF Quadrupole", proceedings of this conference.
18. M.S. de Jong and E.A. Heighway, "A First Order Space Charge Option for TRANSOPTR", IEEE Trans. Nucl. Sci., NS-30 (4), 2666 (1983).
19. J. Ungrin, S.O. Schriber and R.A. Vokes, "Post Coupler Studies for Alvarez Tanks to be used for High Power or Variable Energy", Proc. of 1981 Linac Conf., Los Alamos National Laboratory Report No. LA-9234-C, 183 (1981).
20. J. Ungrin, S.O. Schriber and R.A. Vokes, "Post-Coupler and Stem Current Measurements for High Current CW Drift-Tube Linacs", IEEE Trans. Nucl. Sci., NS-30 (4), 3013 (1983).
21. J. Ungrin, J.C. Brown, B.G. Chidley, R.M. Hutcheon, G.E. McMichael and S.O. Schriber, "Low Energy 100% Duty Factor Alvarez Linacs at Chalk River", Proc. of 1981 Linac Conf., Los Alamos National Laboratory Report No. LA-9234-C, 12 (1981).
22. J. Ungrin, J.C. Brown, B.G. Chidley, S.B. Hodge, G.E. McMichael, S.O. Schriber and R.B. Turner, "Construction of a High-Power RF Resonant Test Load", ibid., 68.
23. J.C. Brown and R.M. Hutcheon, "Design Considerations for a Developmental High Power Coupling Loop to Drive a Resonant Load", ibid., 180.
24. M.S. de Jong, "Background Ion Trapping in RFQs", proceedings of this conference.
25. M.R. Shubaly and J.G. Plato, "A Multi-Channel Fibre-Optic Link for Analog Telemetry", IEEE Trans. Nucl. Sci., NS-30 (4), 2296 (1983).
26. M.R. Shubaly, J.G. Plato and R.W. Davis, "A Low Cost Modular Control and Instrumentation System for Accelerators", proceedings of this conference.