# THE ZEBRA (ZERO ENERGY BREEDER ACCELERATOR) PROGRAM AT CRNL - 300 mA-10 MeV PROTON LINAC

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## Summary

ZEBRA is being designed as a test accelerator at CRNL to demonstrate operation of an injector for an electronuclear breeder that could produce fissile fuel for nuclear power reactors. Problems and characteristics of launching a high-current beam will be investigated by the 100% duty cycle 300 mA-10 MeV proton linac. The program of work including design and testing of 100% duty cycle intermediate steps prior to ZEBRA construction are described. These steps include a 270 MHz RFQ for field breakdown measurements, a 100 mA-1 MeV RFQ at 270 MHz, a 20 mA-3 MeV drift tube linac at 270 MHz, a 270 MHz high power resonant load and various low power experiments. Extension of the program in the long term is described to give a basis for the injector program.

## Introduction

A high-current, low-energy, 100% duty-cycle (cw) proton linear accelerator called ZEBRA (Zero Energy BReeder Accelerator) will be the first stage of a Canadian development program that could lead to a full-scale accelerator breeder. The rationale for the 300 mA-10 MeV ZEBRA project and its associated research and development program was developed in context of the Canadian nuclear power program.

Four important fields of study (other than economics) that must be addressed are a) launching of the required beam current with characteristics dictated in part by high-energy linac sections, b) activation of the accelerating structure from lost beam, c) run-up, control and operation of the facility and d) design, control and operation of the target-blanket system. The last item, although significant, will not be discussed in this paper. Obviously, design and operational characteristics of the target-blanket have to be considered in the overall facility economics and optimization.

ZEBRA will provide information on the first three study areas. Estimates of breeder activation will be determined not only from accelerator performance but from beam dynamics predictions. These predictions will be made after agreement is achieved, in fine detail, between experimental beam measurements and calculated results using improved computer beam dynamics codes.

## Accelerator Breeder

In the early part of the twenty-first century it will probably be necessary[1] to produce some of the fissile fuel for nuclear electrical-generating stations by electronuclear methods. One method, the accelerator breeder, is promising not only in an economic sense but also in most aspects of the technology required to produce beams geared to the target-blanket system. What needs to be demonstrated is the reliability, controllability and operation of all aspects of an accelerator in a facility designed for this purpose and under the constraints required of an industrial facility, i.e. > 80% availability. To do this, it is necessary to study in detail the first 10 MeV of beam acceleration where most of the significant beam effects and limitations occur. ZEBRA operation is considered an important link in obtaining the necessary background data to establish the fundamental feasibility of an accelerator breeder.

Economic studies on the production of $^{239}$Pu or $^{233}$U, to be used as topping enrichment for nuclear power reactors operating on an advanced CANDU (CANadian Deuterium Uranium) thorium cycle, have demonstrated that the proton beam energy impinging on a high Z target should be at least 1 GeV. For calculational purposes a 80 mm radius liquid Pb-Bi target was surrounded by a 2.1 m radius blanket with a 0.9 m void separating the target from the sodium-cooled carbide fuel.

Beam power incident on the Pb-Bi target should be at least 300 MW to produce sufficient fuel (1 Mg per year at 80% availability) for support of a 10 GWe electrical system. Figure 1 shows fissile fuel costs in 1981 Canadian dollars to produce $^{239}$Pu as a function of the proton energy for three beam powers. The curves show that the optimum beam energy is ∿ 1 GeV. Fuel costs have been determined using realistic cost estimates, 20% engineering and management charges, 20% contingency and an 11% capital charge rate that includes operating and maintenance charges.

Currents significantly higher than 300 mA would be more difficult to produce because beam funneling[2] would have to be considered. Higher energy at the same power offers the advantage of reduced current at only a slight economic penalty (fuel from a 150 mA-2 GeV facility is only 11% more expensive than that from a 300 mA-1 GeV facility). In the future an energy higher than 1 GeV may be necessary for various reasons including increased fuel production, lower beam loss and better target penetration.

Figure 2 shows schematically an energy self-sufficient 300 mA-1 GeV accelerator breeder facility, including some of the optimized parameters and estimated costs that used assumptions listed in Table 1. If the equilibrium plutonium concentration were increased to 2% from the 1.3% case illustrated in the figure, ∿ 110 MWe could be delivered to the electrical grid. The optimized accelerating gradient of 2.1 MeV/m results in a linac that is 80% beam-loaded and that requires ∿ 375 MW of rf power.

A program, with major review stages, that leads to an operating accelerator breeder facility is illustrated in Fig. 3. Although the first stage is only 1% of the breeder energy, ZEBRA will investigate the important area of launching the full 300 mA beam current. Other features of ZEBRA are described in the following section.

After successful ZEBRA operation, the second stage would begin in the early 1990's, with construction of a 70 mA-200 MeV accelerator facility, EMTF (Electronuclear Materials Test Facility). The cw accelerator parameters are optimized to provide users with a useful flux of $10^{15}$ n/s/cm$^2$ from a Pb-Bi target. This facility would be used for materials and fundamental research as well as for accelerator development. The energy of the facility determines the point at which a change to more efficient coupled-cavity structures would occur. EMTF would be designed so that beam current could be increased to 300 mA at a later date by adding rf power. Higher current operation would permit beam splitting, part of the beam could be used for investigating beam-loaded operation of the higher frequency coupled-cavity tanks while not reducing average flux from the materials test facility target. In parallel with developments in accelerator technology there is a need for a good deal of development work on the 14 MW target.

Initial EMTF design was for 300 mA at 100 MeV but subsequent studies showed that the target would perform much better with a higher energy beam. The 70 mA current was determined from an optimization of parameters and economics and is considered adequate to study characteristics of the drift-tube portion of an accelerator breeder.

The third stage of the development program, to commence in the early 2000's after successful operation of EMTF, is designed to test a target-blanket assembly at as low a power as will give meaningful target engineering results. Fortuitously, the 1 GeV proton current required is $\sim$ 70 mA (similar to EMTF) for 70 MW input to a 150 MWe target-blanket assembly. This upgrade of EMTF to full energy would be designed so that in the future 300 mA of protons could be accelerated by adding more rf power.

The fourth and final stage would be a full-scale breeder facility with electrical generation from the target-blanket system. Costs for this facility are given in Fig. 2. The determination of accelerator parameters that are suitable begin with ZEBRA tests, a facility that is being designed on limited information available for cw structures.

## ZEBRA

For proper determination of accelerator breeder parameters, accelerating structures have to be operated cw under conditions similar to those of the breeder. ZEBRA models the first stage of such an accelerator and results will not only be useful for the future breeder program but also for other high current cw linacs. In addition, ZEBRA will be used to study high beam loading, to develop diagnostics for monitoring and understanding accelerator operation, to investigate engineering techniques, to check shielding and activation estimates, to study emittance growth, multi-tank control and beam start-up and to test remote-handling methods. An energy of 10 MeV is high enough to fully exploit the accelerator in tests of the concepts listed above but is barely high enough to adequately investigate beam loss. Higher energies, such as 20 MeV, would result in a more expensive facility that would yield very little extra information.

Parameters for ZEBRA are shown in Fig. 4. Detailed design and construction are expected to begin in 1984. Reasons for parameter choices other than the current and energy are given in reference 3. Leading up to ZEBRA is a set of activities depicted in Fig. 4 that will test some of the ZEBRA requirements. Three main components of this experimental program are the ion source and injector, the radiofrequency quadrupole (RFQ) structure and the drift-tube linac (DTL) structure. Not shown in this figure are the important developments required in beam diagnostics and control systems.

Reference 4 describes development work underway on ISTS and ITE for a suitable ion source and injector that will not only provide required current at the correct emittance but will produce variable current over a fixed voltage range. A biased RFQ is no longer a consideration, because combining high voltage and rf problems in one structure completely overshadows the small savings possible for the injector power supply.

A copper 270 MHz RFQ "sparker" is under construction to determine cw field breakdown levels and associated consequences. A frequency of 270 MHz is being used for all pre-ZEBRA tests because of the availability of a > 400 kW rf source. The 360 mm long vanes are not modulated and have the same 5 mm bore radius as the 270 MHz RFQ1.

RFQ1 has been designed using low power measurements on a 500 MHz RFQ model and beam dynamics calculations. Detailed design and construction awaits "sparker" measurements this winter. The 2.5 m RFQ will accelerate 100 mA of 50 keV protons to 800 keV to test space-charge limits and beam loss. Design rf power is 260 kW with RFQ vane fields limited to the Kilpatrick limit[5]. A 40-60 kV injector will provide variable currents up to 135 mA.

The present 3 MeV DTL[6] has provided very useful information on drift-tube stem to outer wall joints, engineering techniques, vacuum manifolds, cooling, windows, beam monitors and rf system operation. An improved replacement tank, 2BLAT[6], will be used to verify techniques and components to be employed on ZEBRA. Prior to 2BLAT construction, rf coupling studies[7] and post-coupler model studies[8] will be completed to provide necessary details. At most, 20 mA of protons will be accelerated by this structure because of injector and transport line limitations.

An important component for pre- and post-ZEBRA tests is the 270 MHz resonant load[9] under construction. This aluminum structure has been designed to test many types of joints and rf devices including drift-tubes, post-couplers, tuners and windows with a variety of ports. Extra ports were included for future experiments and for viewing cw operation.

## Conclusions

Prior to construction of an accelerator breeder, information is required on cw operation of structures under similar conditions. The 300 mA-10 MeV ZEBRA facility being investigated at CRNL will provide much data related to launching the beam for a breeder accelerator. In addition, control system requirements, beam diagnostic devices and beam loss estimates will be determined. Construction of this accelerator, the first stage of a four stage program, should begin in 1984 and cost about $13 M (1981).

A number of pre-ZEBRA tests have started at CRNL including an RFQ "sparker" to determine rf breakdown levels, a 100 mA-800 keV RFQ to determine current limits, a resonant load to high power test cw components and an improved drift-tube linac to test engineering techniques and permanent magnet quadrupoles. The results of these experiments will put the design of an accelerator breeder on a much firmer foundation.

Table 1

Costing Assumptions

| | |
|---|---|
| Accelerator Structure Length Costs | $[1.212/\sqrt{f(MHz)} + 0.015] \times 10^6/m$ |
| Length Cost for Cooling Services, Instrumentation and Building | $0.044 × 10⁶/m |
| Rf Costs | $0.7/W |
| Target/Blanket Complex | 1.5 M$/MWe |
| Control and Monitoring | 10% of total linac and rf costs |
| Efficiency - thermal to ac | 35% |
| - ac to dc | 95% |
| - dc to rf (gridded tubes) | 70% |
| - dc to rf (klystrons) | 75% |
| Reprocessing Charges | $17/g |

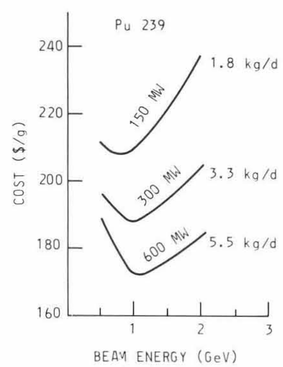


Fig. 1 Fissile fuel costs in $/g versus proton beam energy in GeV for three beam powers with fissile fuel production rate given for each curve.

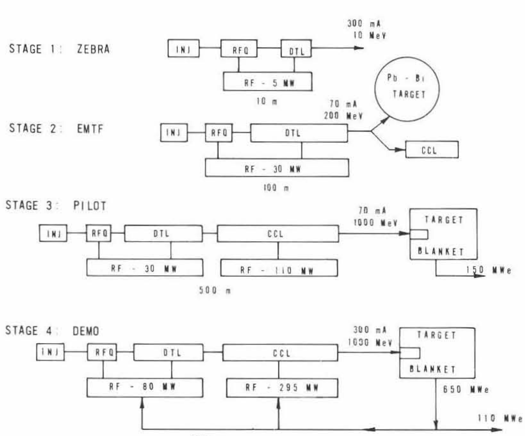


Fig. 3 Stages in the development of an accelerator breeder facility.

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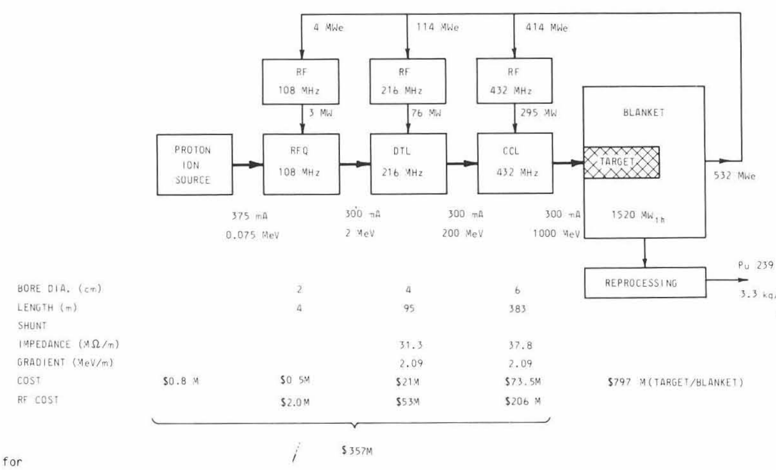


Fig. 2 Schematic layout of an accelerator breeder facility.

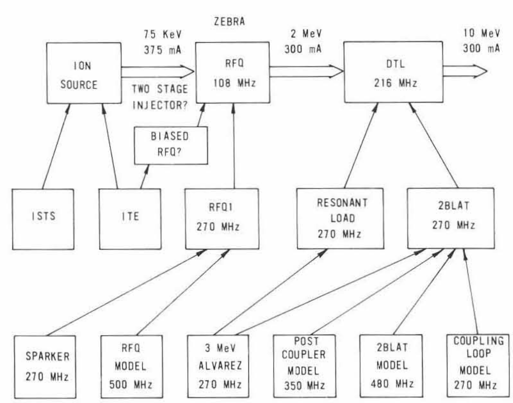


Fig. 4 Set of activities leading up to ZEBRA system.

## Discussion

We thought about a biased RFQ, but three considerations make the idea unattractive: first is the combination of rf and high-voltage problems that it is better to avoid; second, Shubaly's method for ion source operation means biasing isn't needed; and third, when the energy is taken back out, the match into the drift-tube linac isn't as good.

If you are interested in the by-products from fuel production, you should refer to the Japanese literature. The waste from electronuclear breeding compared to the breeder reactor is reduced by a factor of 5 to 10. The amount of waste produced is directly related to the thermal power of the target to first order.