# STATUS REPORT ON THE UNIVERSITY OF MARYLAND ELECTRON RING ACCELERATOR PROJECT *

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## Summary

The final concept, engineering design, and present status of the University of Maryland ERA Project is reviewed. A hollow cylindrical electron beam is produced by an injector which was designed by W. Lupton and coworkers of the Naval Research Laboratory in collaboration with members of the Maryland ERA group (design values: maximum energy 5 MeV, peak current 20 kA, pulse width 20 ns). The hollow beam is compressed into a short ring via transmission through a cusped static magnetic field configuration. The laboratory housing the facility was ready in June, 1972, construction of the injector was completed in September. Testing of the injector and assembly of the cusp and compressor coil system began in October. A first electron beam was obtained on February 22. The main results of injector, diode, and magnetic field measurements are presented. Some problems and solutions are discussed and the methods for gas loading and ring trapping are described.

## Introduction

At the 1971 Particle Accelerator Conference in Chicago the basic method and initial design concept of the University of Maryland electron ring accelerator project were described by the author in a general review paper [1]. Theoretical studies were summarized by Kalnins, Kim, and Nelson and a paper by Rhee, Zorn, Placius, and Sparrow[3] presented the results of preliminary experimental studies at the National Bureau of Standards on field emission diode characteristics and improvements. The Plasma Physics Division of the Naval Research Laboratory had decided to collaborate with the University of Maryland group and to build the injector for the ERA facility. Initial design studies for the injector were discussed in the author's review paper [1].

The basic idea of the Maryland ERA scheme is to use a hollow cylindrical electron beam pulse (emitted from an annular cathode) which is being transformed into a compressed rotating ring by passage through a changing static magnetic field. The magnetic flux enclosed by the beam has to be changed in accordance with the conservation law for the canonical angular momentum (or Busch's theorm). An important advantage of the hollow-beam approach is the axial symmetry inherent in the system which should help in avoiding some of the difficulties of nonsymmetric beam injection geometries.

Several possibilities of producing the desired flux changes were discussed in the above mentioned Chicago papers. Two alternatives were studied in great detail by Kim, Kalnins, and Nelson: a betatron-type[4] and a cusped-type[2] magnetic field configuration. In the betatron-type geometry, the magnetic field is zero at the cathode radius and the required magnetic flux is provided by a coil inside the cathode radius. The studies for the second scheme, where the cathode is located in a uniform magnetic field, showed that the use of an iron plate for the flux return and a centering coil should minimize the radial amplitudes resulting from beam passage through the cusp.

An important step in the evolution of the final design concept for the Maryland ERA facility was the second experiment by Rhee and Zorn with the Febetron 705 at the National Bureau of Standards where a hollow cylindrical beam with good quality was produced[5]. This experiment, as well as the earlier one[3], demonstrated the importance of using a strong magnetic field in the cathode region: the radial width of the hollow beam was found to be inversely proportional to the magnetic field.

On the basis of the above theoretical and experimental studies, as well as engineering considerations, (feasibility and ease of construction) the cusped-field geometry with iron plate was chosen for the final design of the facility.

The values for the basic parameters (magnetic field, etc.) were determined in a compromise between beam-focusing and ion-acceleration requirements on the one hand and existing injector technology on the other hand. Initially, we had planned to use a Febetron 705 field emission accelerator, commercially available with an electron energy of up to 2 MeV and a peak current of 5,000 A. From the point of view of ion focusing (Budker-Bennett condition) and expansion acceleration, the energy of the Febetron beam is very low, even for a first feasibility study. The Febetron plan was therefore abandoned when the Naval Research Laboratory offered to collaborate with us and to build an injector with higher energy. After careful consideration of technical know-how, engineering problems, and theoretical aspects, a design value of 5 MeV was chosen for the energy and W. Lupton and collaborators (J. Burton, J. Condon, T. O'Connell, and M. Jevnager) of NRL worked out a relatively simple and inexpensive design.

The University of Maryland ERA project is supported by the National Science Foundation. Initial funds for the facility were received in January 1972. A temporary building was modified by the University to house the facility and the associated laboratory; construction work on this building started in April 1972 and was completed by July 1972. The injector without diode section was built during the summer last year and initial testing began in October. The magnetic coil system with iron plate and d.c. power supply for Phase I of the planned experimental program had been completed by December. The diode section (with cathode, anode, and vacuum system) was installed in February and the first electron beam shot was fired on February 22. Further details on the status of the project are given in the following sections of this paper.

The initial objectives of our project are threefold; firstly, we want to find out whether our ERA

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method works in principle; secondly, if it works, we want to determine the design parameters for a heavy-ion accelerator with ion energies in the range of 10 MeV/nucleon; thirdly, the program serves an educational purpose by training engineering and physics students in this new field of applied physics.

The number of technical personnel involved in the project at the University of Maryland is relatively small. Collaborating with me at present are the following people (some of them only part time): H. Kim (co-principal investigator, theory), G. Zorn (co-principal investigator, experiment), M.J. Rhee (experiment), D. LeVine (theory), F. Desrosier (mechanical engineering), J. Henness (electrical engineering); two technicians (C. Meese and R. Hendron), and five graduate research assistants (A. Greenwald, D. Hudgings, G. Kalnins, A. Kehs, and P.K. Misra).

## Description of Facility

### Principle of Operation

The initial magnetic field system and the operating principle of the Maryland ERA facility is schematically illustrated in Fig. 1. A hollow electron beam pulse (design values: peak energy 5 MeV, peak current 20 kA, pulse width 20 ns) is generated by the field emission diode of the injector. The annular cathode (diameter 12 cm) and the entire diode region are located in a uniform magnetic field between 2.5 and 4.0 kG depending on electron energy and the type of experiment to be performed. The beam propagates with $v_z \sim c$ in z direction and passes through an annular opening in the iron plate which is 2 cm thick at that radius and 8 cm further out. On the downstream side of the iron plate the magnetic field is again approximately uniform but is in the opposite direction to the field on the diode side. The iron plate serves as a radial return path for the flux and reduces the transition width of this cusp field geometry. The $v_z B_r$ force turns the electrons into a circular path about the z axis thereby slowing down the motion in z direction and thus compressing the beam axially as depicted in the figure. In the initial experiments the magnetic field is more or less symmetric having the same magnitude (but opposite direction) on either side of the iron plate. The z-velocity of the electrons after passage through the iron plate is controlled by adjusting the field intensity. Only seven coils are being used in this initial phase on the "compressor" side of the iron plate. Later on more coils will be added to the compressor system and the field will be shaped as shown on the bottom of Fig. 2. For a beam with 5 MeV peak energy the field intensity will be approximately 2.5 kG in the diode region and -2.5 kG at the compressor side of the iron plate. The z-velocity of the 5 MeV electrons will still be very high at that point. Further downstream the magnetic field increases gradually to 3.6 kG. This results in a quasi-adiabatic radial compression of the hollow beam from 12 cm to 10 cm diameter and a simultaneous slowing down of the z motion to almost zero velocity at the peak of this "compression" field. During this compression phase the beam passes through a gas cloud (injected from a puff valve) where ion loading takes place. The loaded ring then emerges from the gas with small z velocity and may then be accelerated by expansion or electrical fields or both, as in the Dubna ERA scheme. This entire compression and ion-loading process is relatively short - between 10 and 50 ns - and the pressure requirements not very critical ($10^{-3}$ to $10^{-4}$ torr in the ion-loading region, $10^{-5}$ torr or better outside). We also intend to perform trapping experiments, as will be described in the next section. In these experiments, the ring will be completely stopped and trapped for a longer period of time; the pressure required for ion loading must then be correspondingly lower.

The magnetic field configuration acts as an energy selector; only electrons with energy above a given threshold (which can be defined by varying the field) pass through the peak field. Those with lower energies are being reflected. It is therefore important that the current and energy peak of the electron pulse coincide in time as much as possible. Preliminary experiments indicated that this should be feasible[5]. In addition, we are interested in a very sharp peak; a slice of only 1 ns length with current of 1.6 kA from the center of the pulse would be sufficient to obtain $10^{13}$ electrons.

It should be noted that the radial $v_\theta B_z$ force in the cusp field tends to increase the radial width of the beam. However, this effect can be fully compensated by use of the iron plate and a centering coil (not shown in Figures 1 and 2), as was mentioned previously.

### The Injector

Fig. 2 shows a schematic of the entire facility. The injector has a total length of approximately 7.8 m and the full compression coil system will be about 3.7 m long; the seven compressor coils employed in the initial studies, however, have a length of only about 0.7 m.

The 1.0 MV Marx generator charges a 8 Ω water Blumlein system. Six switches symmetrically arranged around the Blumlein, are fired via a pulse from a small trigger Blumlein. The resulting high-voltage pulse then travels down the coaxial oil transformer whose inner conductor is shaped conically to change the impedance from 30 Ω to 73 Ω. The electron beam from the cathode has an impedance of about 300 Ω. The impedance mismatches from water to oil, in the transformer, and between transformer and diode are designed to increase the voltage amplitude to 5 MV. In order to insure a 20 ns "clean" pulse, the Blumlein and transformer were built long enough that reflections arrive at the diode at a later time.

The diameter of the transformer tank is about 1.15 m. A radial insulator 7.5 cm thick, separates the oil section and the vacuum of the diode. This radial disk insulator is a departure from the coaxial insulators commonly used in electron beam machines. Its design, as well as that of the entire diode, was a collaboration effort between NRL and the University of Maryland workers. Main considerations in the design were electrical breakdown, mechanical stability, and prevention of electron current emitted from the cathode stem to flow backward into the insulator. The diode coil played an important part in the solution finally arrived at. It has three functions, namely (a) to provide the uniform magnetic field needed in our scheme between cathode and iron plate, (b) to prevent radial spread of the beam due to space charge forces, and (c) to prevent electrical breakdown at the insulator. The $\vec{E}$ and $\vec{B}$ field in the diode were shaped in such a way that $\vec{E} \times \vec{B}$ drift forces accelerate electrons from the stem towards the anode rather than towards the insulator.

A photo of the injector with Marx generator in the foreground and the transformer section pointing backward is shown in Fig. 3. The Blumlein section with some of the switches is shown in a close-up view on Fig. 4. Initial performance characteristics of the injector will be briefly discussed in the next chapter. A more detailed description of the injector system and results of the tests are presented in paper E-15 of this conference[6].

The Compressor System

The compressor coil system is separated from the diode region by an iron plate (see Figs. 1 and 2) which is used for guiding the magnet return flux thereby providing as short a transition width as possible for the field reversal. This plate consists of two parts: the inner disk, with diameter of 12 cm and thickness of 2 cm and the main plate which has an outer diameter of 180 cm and a width which increases conically from 2 cm to 8.2 cm. A small gap, 5 mm wide, separates the disk from the main plate. The disk is connected with the outer plate by three radial spikes on the diode side.

Following the iron plate are a series of double-layered coil pancakes. They are separated spatially such that the field - in the final phase - increases from 2.5 kG at the iron plate to 3.6 kG, remains at that level for a short distance, and then falls off gradually (as required by expansion acceleration). For initial experiments only seven coils will be used, as was mentioned previously. All of the coils, including the diode coil, are driven by a dual output, 170 V, 1800 A dc power supply with $< 10^{-4}$ current regulation. If needed, a second power supply will be added for the expansion acceleration section. The coils are wound of copper conductors with a 0.73" x 0.73" rectangular cross section and a 0.4" diameter hole for cooling water. Inner diameter of each pancake in the compressor section is 40 cm, outer diameter is 61 cm; the pancakes of the diode coil are larger (see Figs. 1 and 2). The compressor coil system including the pump section at the end will have a total length of about 3.7 m when all coils are assembled as presently planned. Each individual coil is mechanically adjustable to correct for errors and to achieve a desired field variation along the path of the beam.

The centering coil, which is not shown in Fig. 2 will be located in the transition region between iron plate and maximum compression field. It is fed by a separate small power supply.

## Present Status and Test Results

Injector

During the past three months the injector was tested rather extensively without the diode section installed to determine pulse shape, rise time, switch performance and synchronization, voltage amplification by impedance mismatch, etc. It should be pointed out that the injector itself, like the rest of the Maryland ERA facility, represents a new developmental project for which no prototype model existed. Its design was based on extrapolation and application of available knowledge and experience with machines of lower voltage and diode impedance. The results of the initial tests may be summarized as follows:[6]

1. The rise time of the voltage pulses is of the order of 30 to 35 ns, total pulse width between 50 and 60 ns. The pulses are thus by a factor of 3 longer than was expected, but they do have a sharp peak (no flat top) which is desired for energy-time selection.

2. The amplification of the voltage peak is less than theoretically expected, partly as a result of the longer rise time, partly due to other factors such as Blumlein geometry, etc.

3. After a few initial difficulties, all six Blumlein switches could be fired in synchronism with good reproducibility.

4. The blue-nylon radial insulator at the diode end of the transformer was damaged by electrical breakdown. It was temporarily replaced by lucite; later an epoxy disk will be installed.

5. Similar breakdown problems exist with the Blumlein switches where two failures have occured so far. The switch casings are also made of blue nylon. Possibilities to change the design and to use some other material are being investigated.

Beam Tests

The diode section was installed in February and the first shots with an electron beam from an annular knife-edge cathode were made on February 22. In these experiments the beam was confined to the diode side of the iron plate, i.e., no cusp transition was attempted. The diode coils produced a magnetic field in the range of 2 kG. The beam current was measured with a Faraday cup mounted right behind the anode. Cathode-anode spacing was approximately 3 inches. The measured current pulse had a width of about 45 ns and a sharp peak of about 6 kA. The peak of the voltage pulse was approximately 2.1 MV. (To avoid possible breakdown problems we deliberately stayed below the maximum voltage capability of the Marx generator). In subsequent experiments film was placed on the inside of the anode. The traces left by the annular beam showed a remarkably good circular shape and indicated a sharp radial density profile with a typical radial width of about 3 mm. Fig. 5 shows a picture of the diode section with the cathode stem protruding outward from the radial insulator and the inner conductor of the transformer. The ribbon-like cathode emitter made from 1-mil tantalum foil is mounted on the disk, but was not installed when this picture was taken.

Magnetic Field

One of the major problems in our project is the design of the magnetic field, in particular, the shape of the iron plate and the positioning of the coil pancakes on both diode and compressor side to achieve a desired field configuration. The initial setup was determined with the aid of a computer program that calculates coil-produced magnetic fields in the absence of magnetic materials. The iron plate was taken into account by considering it as an ideal plane surface which images the coil fields on each side. In the actual plate the width increases with radius (see Fig. 1) to stay below saturation level for the flux density. The coil system for the initial experiment is schematically indicated in Fig. 1 and a photograph of the coil and iron-plate assembly at the diode end of the injector is shown in Fig. 6.

Measurements of the magnetic field were made in January and indicated substantial discrepancies with regard to the ideal shape predicted by the computer studies. At that point it was decided to employ the more accurate computer program TRIM[7] at the Argonne National Laboratory which takes into account magnetic materials. The problem in our system is that iron is present only in a small but critical region between the two coil sections. In accelerator-magnet and other applications where TRIM has been successfully employed, the magnetic circuit, by contrast, is dominated by the iron, and usually one wants to know the field in a small air gap between poleshoes. For our purpose it was therefore necessary to start with a relatively large "universe" with artificial boundaries at large distance from the coils and a coarse grid of meshpoints. The series of computer runs carried out with TRIM so far produced results that are closer to the measurements, but there are still significant differences both in shape as well as in field magnitude. Fig. 1 shows typical magnetic flux lines as calculated by the TRIM program for the coil geometry indicated in the figure. The computed curve $B_z$ versus distance along the orbit radius of r = 6 cm for this particular geometry, however, deviates from the desired "ideal" curve plotted on the bottom of the figure. Further refinements in the program calculations are necessary to achieve better accuracy and we hope to get errors down into the 1% range or better. Despite the discrepancies which still exist between the numerical and experimental data we have gained already a great deal of very valuable information concerning the field design from the TRIM studies. Thus, it appears that the thickness of the central part of the iron plate has to be increased somewhat and that correction coils have to be placed on either side of the plate with small radii close to the beam in order to achieve the desired short transition from negative to positive magnetic field.

## Future Work

A puff-valve gas system in which the valve is opened for a short time interval by a current pulse from a discharging capacitor bank is being developed. All of the hardware for this system has been assembled and measurements have begun. Main objectives of these measurements with fast ionization gauges are to determine pressure and expansion of the gas cloud as a function of time.

Initial experiments of beam transmission through the cusp and compression will be performed with static pressure in the vacuum tank. The puff-valve system will be added later in the second phase of the experimental program (latter part of 1973).

Possibilities of trapping the ring for a certain period of time prior to acceleration are under investigation. Two schemes are being studied at the present time: 1. Trapping by a resistive-wire scheme[8] similar to the Astron experiment. Here the beam is stopped by the interaction with a specially designed coil. 2. Trapping by two mirror coils. In this scheme a small coil generates a bump in the uniform region of the compressor field whose mirror action reflects all electrons. Before they can escape a second coil is triggered upstream which generates a second bump. This bump increases until a desired level is reached. The beam then remains trapped while ion loading takes place. A further increase of the upstream bump (or a decrease of the downstream bump) opens the "bottle" and kicks the loaded ring out into the acceleration region.

At present, we have not yet decided which of the two schemes will be tried first. Theoretical studies are still in progress and it is too early to assess the relative merits of each. Perhaps the optimum solution might be a suitable combination of both methods.

## References


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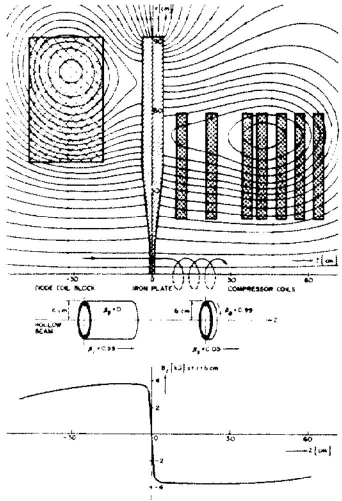

Fig. 1 Magnetic Field

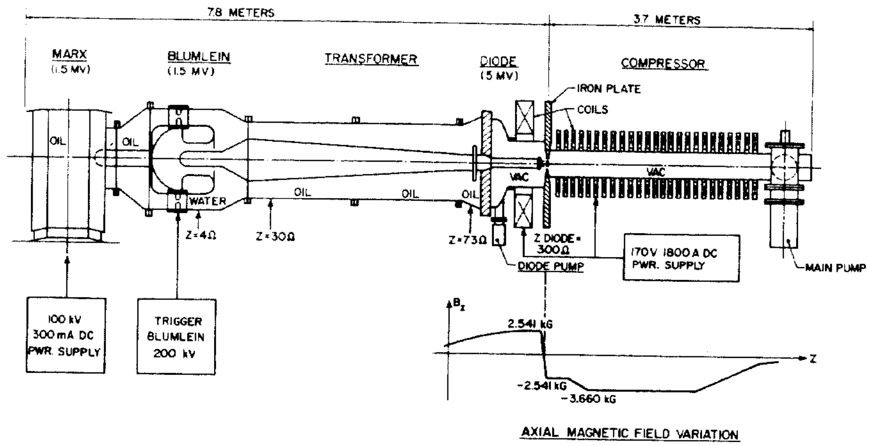


Fig. 2 Schematic of Maryland ERA Facility

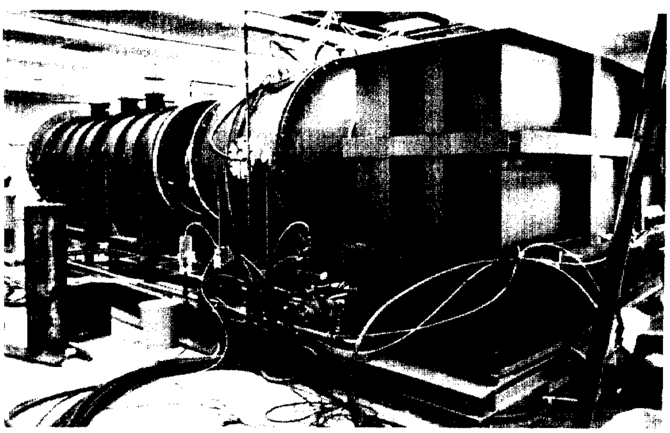

Fig. 3 Injector

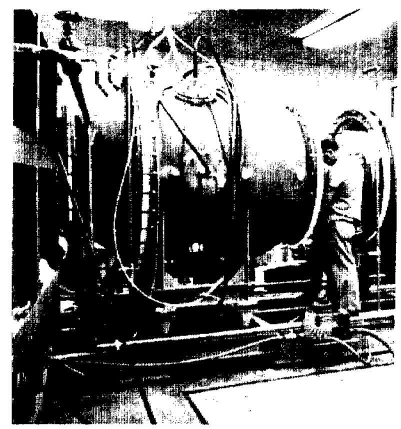

Fig. 4 Blumlein Section

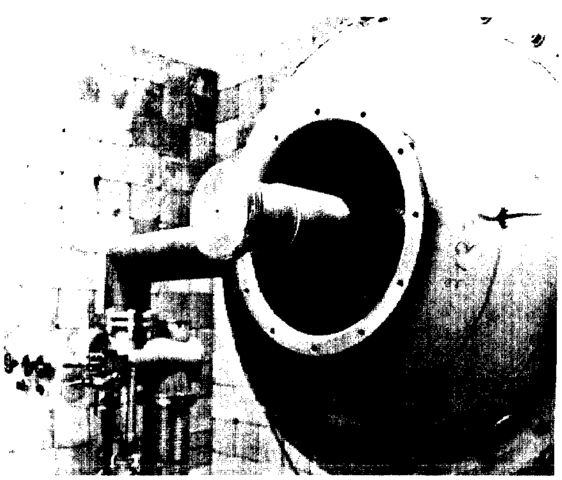

Fig. 5 Diode Section with Cathode Stem

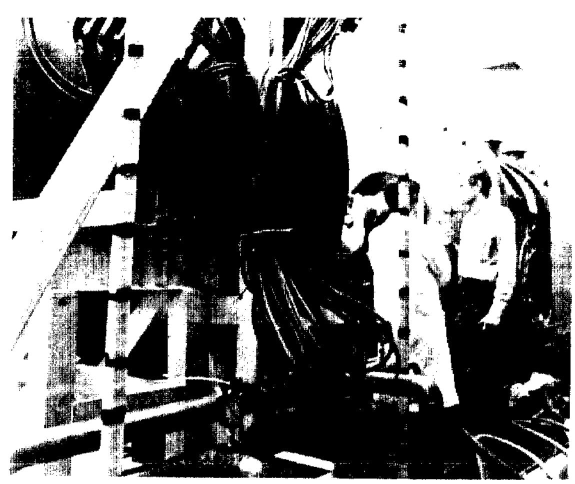

Fig. 6 Coil System