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PRELIMINARY HARDWARE CONCEPTS FOR A HIGH-ENERGY ELECTRON-RING ACCELERATOR

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PRELIMINARY HARDWARE CONCEPTS FOR A HIGH-ENERGY ELECTRON-RING ACCELERATOR*

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Summary

Results of the first study of the conceptual design of a collective-effect proton accelerator of substantial energy (65-100 GeV) are described. Basic theoretical considerations are outlined and components and their arrangement for a conceptual accelerator are discussed. This first study shows that the promise of ERA principle to produce remarkably compact accelerators can be achieved by use of single-pulse surge-excited acceleration cavities. The example single-pass machine provides accelerating gradients of 250 MeV/meter overall where conventional synchrotrons yield 40-80 MeV/meter. The relaxed tolerances of the surge-excited cavities and their associated components allow great advantage to be taken of mass-production techniques with ensuing low cost ($\lesssim$ M\$ 0.24/GeV).

Introduction

This paper describes the principal features of a conceptual study by the Berkeley-LRL ERA Staff[1]. Collective-effect accelerators will entail a radical departure from traditional accelerator technology. In order to gain some feeling for the promise to be anticipated from such a departure, and to establish the nature of the most productive development work for the future, we chose to study in some detail a proton accelerator capable of a top energy of 100 GeV. Study of this example included rough optimization, proposal of a credible hardware concept, and approximate cost estimating.

The study was based on certain assumptions about untried concepts and systems. Subsequently, the construction and operation of the high-current electron source[2] allowed us to test analogous systems, with the welcome outcome that high reliability and very small jitter were obtained more simply and more rapidly than anticipated. While this report incorporates several changes from the original study (1) we still believe that some of the elements described below may be too conservative.

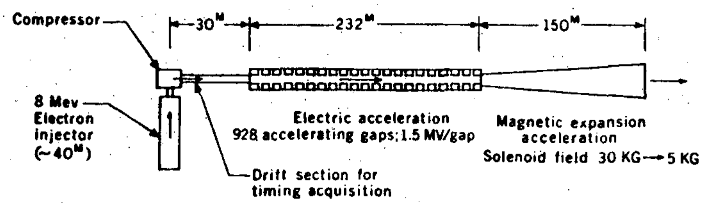
General Considerations and Parametric Constraints

Because of the wide variety and novelty of design possibilities for the ERA, some of the background considerations will be briefly summarized. Later, one specific example of an ERA will be described in more detail and a satisfactory engineering solution for its construction shown to exist.

For an ERA composed of an electric accelerating column followed by a magnetic "expansion" column (Fig. 1), one can show[3]:

$$\text{Final proton energy} = \frac{e\, M\, V_{eff}}{m(\gamma_f^* + G)} = \eta\, e\, V_{eff}$$

where M and m are the proton and electron masses; $m\,\gamma_f^*$ is the transverse energy of the electrons in the ring rest-system at the end of the accelerator; G is the ratio (mass of protons/mass of electrons) in the ring = $N_p M / N_e m = \frac{M}{m} f$; V_{eff} is the effective potential drop experienced by the ring in passing through the electric column. The advantage of using collective-effects for acceleration is usually described in terms of an energy-gain that is enhanced by a mass-ratio factor, η, over that appropriate to a bare proton in the same field.



65 - 100 Gev Electron Ring Proton Accelerator

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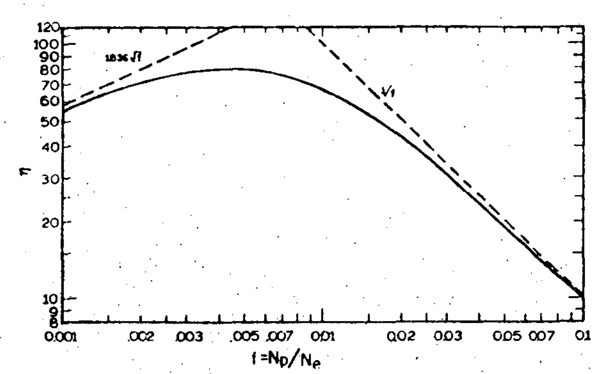
Figure 1

One stability criterion for choosing the final transverse energy of the electrons is that the space charge defocussing is allowed to become equal to the ion-focussing strength, i.e. $1/\gamma_f^{*\,2} = f$. (This is a conservative assumption because extra focussing by image-forces is possible in the magnetic column). Then

$$\eta = \frac{1836}{1/\sqrt{f} + 1836 f}$$

and this quantity is plotted in Figure 2. It has a maximum near $f \doteq 0.4\%$ and the peak enhancement is about 80; thus provision of an electric accelerating column with $V_{eff} = 1.25$ GV could provide 100 GeV protons.



The enhancement, η, as a function of the fractional ion-loading, f.

Figure 2

* Work supported by the U.S. Atomic Energy Commission.

Apart from kinematics there are several physical constraints that limit the choice of parameters.

(a) Cavity Radiation occurs when the intense ring of charge passes through the periodic structure of the electric column, and results in loss of energy by the electrons, making V_{eff} somewhat less than the applied potential V_o.

(b) The axial integrity of the ring during electric acceleration must be ensured by Ion-focussing.

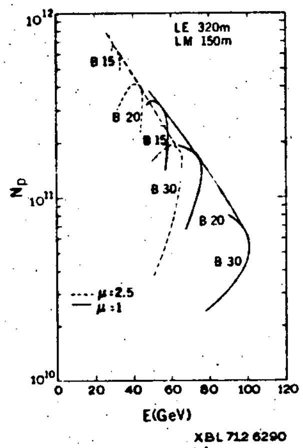
(c) While undergoing acceleration, electric Polarization occurs in which the mean position of positive charge lags spatially behind that of the electrons. This reduces both the ion-focussing action and also the effective peak holding-field of the ring.

(d) The attainment of high holding-fields in the ring requires the number of electrons, N_e, to be large, and the major and minor ring dimensions to be small, which can lead to Collective Limits and Instabilities. The most important are (i) Space Charge effect, (ii) Resistive-wall effect, (iii) Negative mass effect. An extensive study of how these instabilities can be avoided in ring-formation was made by Bovet and Pellegrini.[4]

In addition, they have mapped the range of suitable ring parameters needed for successful acceleration in the electric and magnetic columns described below and derived the corresponding requirements for compressor operation. They discuss two types of compressor with different properties. Type A is a straightforward extension of present pulsed-compressor designs in which the ring compression takes place by the action of a sequence of nested coils. A repetition rate of 20 Hz is possible. Type B utilizes emission of synchrotron radiation from the compressed ring to obtain further reduction in the major and minor dimensions. The phenomenology of pulsed-compressor design can bear much more study before an optimum detailed design is reached.

In considering stability limits for rings accelerated in the electric and magnetic columns, Bovet and Pellegrini have used a factor, μ, to describe how far one is below threshold for the Resistive Wall instability (generally the most restrictive instability). Rings that are comfortably far below the resistive-wall limit ($\mu \geq 2.5$) can be formed in a Type A compressor. If operation closer to the limit (which allows higher energy for the protons) is desired, it can be accomplished by proceeding to a Type B compressor. The most reasonable approach at this time is to consider initial operation with a compressor of Type A and later develop and add a compressor of Type B. Another highly promising solution would be a static-field compressor[5] operating with superconducting coils, which could operate at a repetition rate of a few hundred hertz.

It is difficult to characterize an ERA by quoting a design energy and intensity; and it depends on how one chooses to trade between energy and intensity. These options are illustrated in Figure 3.



Energy-intensity relationship for an electron ring accelerator

Figure 3

Arrangement and Description of Components

A high-energy collective-effect accelerator would consist of five principal components: 1) an injector to supply electrons, 2) a compressor to form the electron stream into a compact ring, 3) a drift section where the guide field makes the transition from pulsed to steady-state, and where electric acceleration timing signals are acquired, 4) an electric acceleration section where approximately two-thirds of the final energy is added to the protons and 5) a magnetic expansion section where the protons receive the last third of their energy. Figure 1 shows the arrangement and proposed lengths for these components.

The injector would be similar to that now operating at LRL. Approximately 25 surge-excited cavities would provide 45 nanosecond pulses to produce an electron beam of 500 amperes at 8 MeV. The best 20 nanoseconds is selected and delivered to the compressor. This stream of electrons is formed into a ring and compressed to a 3.5 cm major radius and minor radius $\approx$ 1 mm. It is then loaded with protons by injecting a puff of hydrogen gas near the ring. Next the compressor coils are asymmetrically excited to extract the ring and launch it into the drift section after which it enters the electric accelerating column.

Electric acceleration would be accomplished by 928 surge-excited cavities. Accelerating gaps of 2-1/2" - 3" would be included in an axial repeat length of approximately 8", and the voltage per gap would be 1500 KV for a few nanoseconds duration. Each interval is really two cavities back-to-back, one side excited with a positive, the other with a negative voltage pulse - a feature aiding axial compactness and allowing insertion of a ground plane between cavities for introduction of superconducting solenoid leads and cryogenics. Although one Blumlein line feeds two cavities, the need for both positive and negative drives leads to a system-average of one Blumlein line per cavity. The electrical length of 15 ns is now considered to be overly conservative in light of our recent experience.

The spark gaps are fired by a cascading trigger system wherein each stage involves a fan-out of a factor of 10. Jitter is thus determined by the fluctuations in firing times of 3 stages in series, and is expected to be approximately 2 nanoseconds. One Marx generator is needed to charge 4 Blumlein lines or to supply power for 10 triggering gaps. Thus, a total of 232 + 12 or 244 Marx units are required, each with a stored energy of 320 joules.

Each side of a cavity is provided with its own ferrite disc to suppress that part of the electric field which would impede electron ring acceleration if it reached the accelerating gap. These are large pieces of ferrite, perhaps 32" OD x 20" bore and weigh approximately 180 lbs. - 170 tons total; to supply this quantity would strain the present capabilities of ferrite manufacturers.

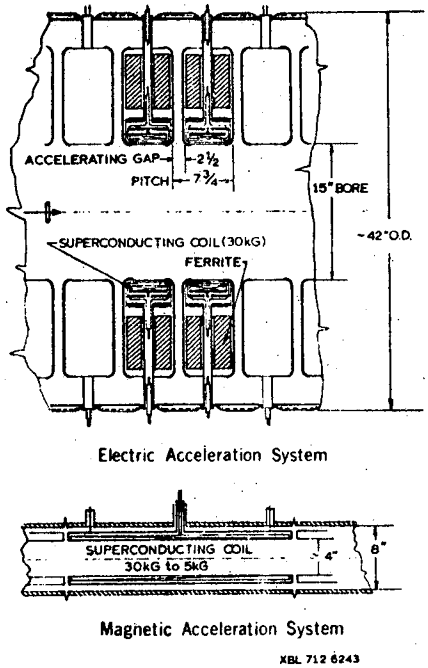


Figure 4

Cavity radial size and the quantity of ferrite required are functions of the degree to which radiated energy losses must be minimized. With the 15" bore shown, approximately 10% of the accelerating energy would be radiated into the gap structure as the ring passes by ($V_{eff} = .9\ V_o$). Calculations indicate this loss would increase to perhaps 18% if the bore were reduced to 11" ($V_{eff} = .82\ V_o$). An increase in ferrite quality would require less total ferrite volume, which would reduce the size and cost.

For this example the guide field for the electron ring is provided by steady-state magnetic fields of at most 30 kG, provided by superconducting solenoids. Such coils are well within the scope of present superconducting technology. Conventional fast-pulsed coils would be another approach to the guide-field, but the large stored energy (> 100 MJ) would pose substantial problems.

The solenoids would be wound from conventional Nb-Ti wire in units 4.25 ins. long. Because oil vapor which could collect on cryogenic surfaces is expected in the accelerator vacuum system because of the oil-vacuum interfaces at the top of the Blumlein lines, each unit would have its own LN-LHe dewar in a separate vacuum chamber between cavities. The outer circumferences of this chamber would be a heavy steel flux ring which, with a short additional space to the ferrite keeps the solenoid return field in the ferrite to the 200-300 gauss range. The 3 KW cryogenic system heat load would require a refrigeration plant assumed to be located in the injector building.

At the conclusion of electric acceleration the ring enters a region of decreasing solenoidal field. The field drops in a prescribed manner from 30 to 5 KG over 150 meters. A small radial component of the magnetic field in the solenoid continues to accelerate the electron ring. This magnetic acceleration system can be quite compact, a 4" bore through the dewar being adequate. Coil assemblies can be conveniently long, perhaps a meter or more, since interruptions for accelerating gaps are not needed (Fig. 4). The LN component of the superconducting coil dewar can be exposed for vacuum pumping, minimizing the number of actual vacuum pump stations required along the 150 meters.

Advantages of an ERA System

Single-pulse surge-excited cavities display remarkably friendly aspects compared to the stringent requirements usual in accelerator technology. Attributes include:

1) Insensitive to material choice - cavity walls must be reasonably conducting, but the high conductivities of copper or aluminum are not essential. The material can be ferromagnetic, such as mild steel which is inexpensive.

2) Insensitive to rather large dimensional variations - cavities do not operate in a tuned mode. Therefore quite large dimensional variations (to 1/4") would be tolerable.

3) Suitable for Mass Production - the attributes mentioned above suggest fabrication techniques similar to auto body production - die-pressings of sheet steel assembled in fixtures of rather ordinary precision. Variable deflections due to vacuum loading would be tolerable.

4) Compact - the very short pulse length (a few nanoseconds) allows remarkably high voltages on accelerating gaps. Voltages of 1500 KV on 2-1/2" - 3" gaps are intended, and the limit is not yet known. Averaged over the entire length of the accelerating structure, the accelerating gradient for protons would be 270 MeV/meter (compare with ~ 1 to 2 MeV/meter for linacs, 40 to 80 MeV/meter for large conventional synchrotrons). A shorter machine means less real estate and fewer conventional facilities and, hence, less cost.

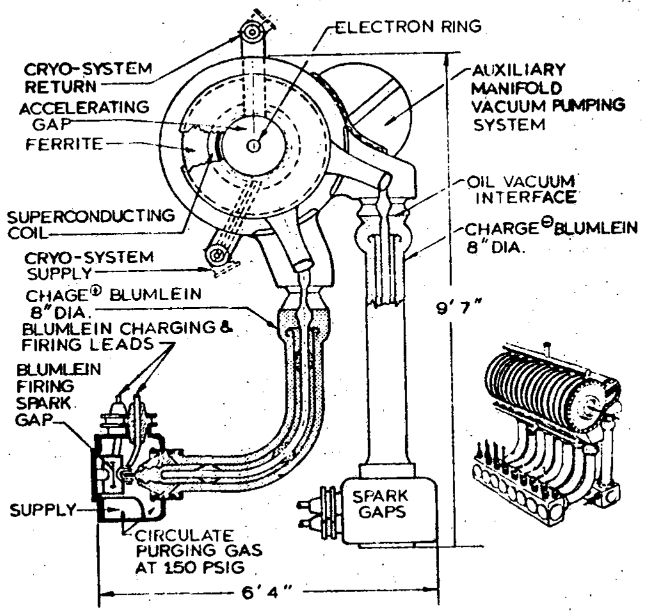
5) Power Economy - electric acceleration requires 244 Marx units each storing 320 joules; at 20 Hz this would draw 1.9 MW from the line. The only other major power load would be 1 MW required by the cryogenic refrigeration system.

6) Operational Simplicity - a precision alignment is not required, variations of millimeters can be tolerated. Surge-excited cavities at present in use are proving reliable in operation. D.C. superconducting solenoids should be simple and reliable. Spark gaps are the only component forseen to need periodic replacement and their design would allow quick change on a routine maintenance basis.

Mechanical Features

Cost will be an ever more important design parameter for future accelerators. Three mechanical features proposed here would make significant impact on cost. First, parting planes can be joined by standing-edge welds, which can be "can-opened" for re-entry. Such joinery will be less than one-quarter the cost of traditional gasketed, bolted flanges. Second, the oil-vacuum transition is simplified by eliminating a plastic insulator and allowing a free oil surface at the top of the blumlein. Tests indicate this approach will be viable. Third, replicated production can be employed and should yield great economies.

For reasons already stated this last factor is unusually applicable to ERA machines. Accelerating cavities, blumleins, spark gaps, Marx generators, solenoids are all suitable for "mass production", in the sense that investment in tooling will return its price many times over in lower unit costs. For example, this study envisions fabricating the 928 accelerating gaps in 16 unit sub-assemblies (Fig. 5). Parts would be die-formed from light (14 gauge) mild steel, stiffening ribs being pressed in along with the major forming. They would then be welded into 3140 lb. units (197 lbs/gap) in two large assembly fixtures. Preliminary analysis indicates $254,000 of tooling would be required and 16-gap sub-assemblies would cost $4,500 thereafter.



ERA Electric Acceleration Cavities

XBL 712 6240

Figure 5

This represents a unit cost of $555 per gap, which is a very substantial gain over the $3,300/gap cost for a bolted-flange assembly with plastic insulator, such as was used for the present Berkeley electron source. Likewise there is also a substantial reduction in weight per gap (to approximately one-third).

This study includes conventional facilities for housing and operating the accelerator - a tunnel (Fig. 6), electric sub-station (4MW), cooling tower (4 MW) and distribution. These facilities are estimated to be 20% of overall cost. If cut-and-cover methods were used in making the accelerator enclosure, conventional facilities would be only 16% of overall costs. Traditional values for EDIA and contingency (25% and 25%) and A & E and contingency (12-1/2% and 15%) have been incorporated. This first look suggests cost (1971) for the accelerator only (no experimental area) will range downward from $.24 million/GeV.

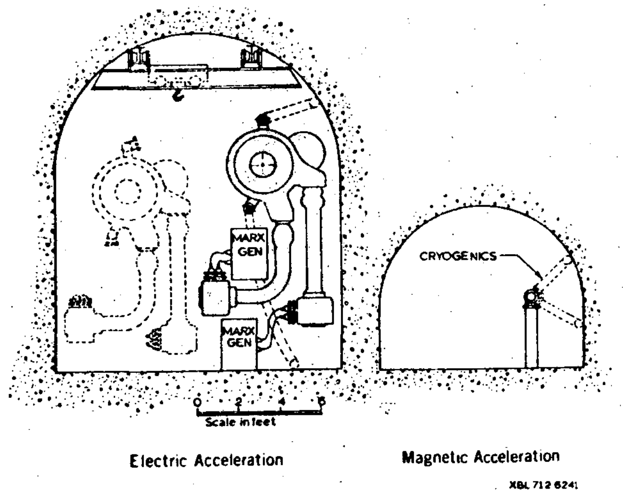
65 - 100 GeV Electron Ring Proton Accelerator

Proportionate Cost of Components

1) Injector		9.0%
2) Compressor		6.5%
3) 30 Meter Drift Section		1.3%
4) Elec. Acceleration		53.0%
a) Cavities blumleins, spark gaps	= 8.3%	
b) Ferrite	= 8.8%	
c) Superconducting coils	= 9.2%	
d) Marx gen., power supplies & triggering	= 11.4%	
e) Vacuum pumping system	= 4.0%	
f) Misc. (supports, tooling, controls)	= 11.3%	
	53.0%	
5) Magnet Expansion		2.7%
6) Cryogenic Refrigeration and Distribution		7.5%
7) Conventional Facilities		20.0%
		100 %

* Note - if cut and cover enclosure used conventional

$$\text{facilities} = \frac{3.5}{22.3} = 15.7\% \text{ of system cost}$$



Arrangement within the enclosure

Figure 6

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