FUTURE FACTORY TYPE ACCELERATORS

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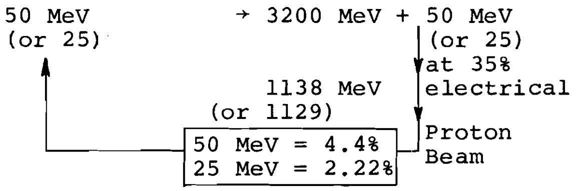
A current objective of a study in Canada is to produce a 65 mA beam of protons at 1 GeV that amounts to a continuous power of 65 MW. The purpose of the machine would be to produce neutrons at high intensity and at the same time π and μ mesons. The neutrons are produced by letting the beam plunge into a deep target of flowing lead bismuth eutectic. Excited to high energies > 100 MeV such heavy nuclei produce a copious yield of neutrons by the spallation reactions. The neutrons are slowed down in a tank of heavy water and in their turn produce radio-isotopes. Being a factory on a large scale it is important that the capital and operating costs should be low, which means that the accelerator must have a high efficiency and be not too large or complex. There are quite a number of factory-type accelerators in operation, I suppose the range should include all electron beam and radiation generators used for processing plastic sheet, mouldings and fabrics as well as those for mecial X-ray therapy. None, however, approach a continuous power rating as high as 65 megawatts. Even for the long term future it seems that power in the range of 100 MW would suffice. There is glamour and romance about building the first but looking beyond that the factory type accelerator is seen to become under strong economic pressure. That pressure can, of course, be turned to advantage as it gives zest to meet the technical challenge and at the same time provides the means. Let us see what this pressure is for the neutron generator; 100 MW of power delivered at 5 mill/kWh for 7000 hr/yr or $35/kWyr amounts to $3.5 million. We shall see that it could produce about a gram of neutrons per day so the power bill alone would add about $10,000/gm of neutrons. The price of neutrons has quite a range but this is not the lowest. Those in the nuclear power business are familiar with a reference price such as $10/g plutonium and since 1g of neutrons can produce 239g of plutonium this allows $2390/g of neutrons. Similarly $13/g of uranium-233 allows $3029/g of neutrons. So we turn back to that estimate of power cost at 5 mill/kWh contributing $10,000/g of neutrons and see that we should have to get down to 1.5 mill/kWh or less. Although it may seem surprising, this by no means ends the prospect. First we can note that any such fissile material factory would naturally be integrated with a nuclear power plant and a very large one where the incremental cost of power may be only 2 mill/kWh or less. Moreover the power to the neutron factory is returned as heat to the main power cycle so taking 100 MWe but returning 30 MWe the net consumption is 70 MWe and 70 MWe at 2 mill/kWh costs less than 100 MWe at the target figure of 1.5 mill/kWh. Still the margin is too small to make this look profitable, but there is more to come.

The long term value of fissile material will be linked to the cost of separated uranium-235, and thereby to the price of natural uranium. If the price of uranium rises $10/kg then the cost of U-235 rises $2/g since 1 kgU yields about 5g separated U-235. The values for plutonium and U-233 quoted correspond to about $11.5/g U-235 so their values would also increase by about $2/g. Another factor in reserve is the possibility of almost doubling the neutron yield by introducing U-238 or thorium into the Pb-Bi target. On the other side, if the cost of power falls the cost of isotope separative work would fall.

As accelerator experts I do not imagine you were expecting the economic target to be any easier. The next question is why anyone would want to build an accelerator type factory for fissile material into a nuclear power complex. The currently popular view is that breeder reactors are going to produce all that is necessary. I suggest that the practical operation of breeder reactors and their fuel cycles will prove so complex that the accelerator assisted thorium thermal neutron reactors will compete from their sheer simplicity, provided the accelerator designers can approach what appears physically possible, as I will explain.

The power rating of the accelerator depends on the characteristics of the reactor but would be expected to be at the most 2 to 5% of the reactor or reactor complex. As such it could be termed a 2 to 5% feedback loop on the power cycle and a 5% loop on the fuel cycle. It would be designed and applied with two purposes in mind, one already indicated is to maintain the fissile inventory in the fuel cycle and the other is to exploit the advantage of having neutrons available under instantaneous control to mitigate the poison transients and other reactivity changes characteristic of the operation of such fission chain reactors. It is fairly simple to see the power required for the first purpose as follows

1000 MeV proton → 20 to 40 neutrons
50 (or 25) MeV → 1 neutron
1 neutron → 1 fissile atom
1 fissile at. → 160 MeV + 0.95 fiss.at.
1 fiss.at.lost → 3200 MeV



If the conversion ratio is higher than 0.95 less power would be needed in the feedback loop; for 0.975 it would be halved.

When these cycles were first recognized in 1952 their application seemed so far off that they were put on the shelf. Several happenings since then have brought us to some detailed studies. Already such a market for cobalt-60 has developed that we are producing 2 megacuries a year in the NRU reactor and deliberately destroying separated uranium-235 to do so, because it pays. That only accounts for about 30g of neutrons/year but even at 20 ¢/curie of Co-60 that amounts to $400,000/year or $13,000/g neutrons. The demand for other radioisotopes such as Pu-238, Sb-124, Cm-242, Cm-244 is expected to grow and also afford a higher price for neutrons at high intensity. Now that is just what an accelerator neutron factory can offer. Over the same time interval since 1952, as you know, there have been major advances in accelerators and especially in prospective accelerators. Thirdly the uses of neutron beams as research tools have achieved importance in the development and understanding of materials and everyone looks for higher intensities.

Accelerator Prospects

My personal world-line as related to accelerators can serve as introduction. The first accelerator I came to nurse in 1934 was the original Cockcroft-Walton H.T. set at the Cavendish Laboratory. A 750 kV Cockcroft-Walton accelerator remains very popular for the initial acceleration of proton beams up to 200 mA or more. Higher D.C. potentials require screening in special enclosures, high-pressure gas or under oil where the ion source is less readily accessible. Having brought the beam down to ground potential, only tandem type accelerators and the "staticelerator" can thereafter conveniently apply D.C. and acquire the advantage of approaching 100% efficiency, or so it had been thought until the recent emergence of ion drag accelerators, to which I shall return.

The next accelerator on my personal world-line was the cyclotron we built at the Cavendish in 1936-39. This introduced one important principle concerning efficiency that had not up till then been a feature of cyclotrons, namely to design the radiofrequency system so that the large r.f. currents flowed over wide surfaces of high conductivity copper in a non-radiating resonant assembly. This principle has ever since been an essential feature of r.f. accelerators whether cyclic or linear, and also of the magnetrons, klystrons and other high power microwave generators.

My next accelerator was the very first synchrotron of Fry and Goward. In the meantime I had acquired a large and high-powered team of radio-frequency designers and the ending of the war allowed some of them to see whether they could beat their radar swords into accelerator plowshares. The synchrotron was a relatively simple exercise but it was perhaps not a winner until coupled up with the alternating-gradient magnetic field, as here at Brookhaven, but off my world-line. It has a place in the family of factory type accelerators because the beam passes many times through the same accelerating cavity and as a result the radiofrequency losses from the currents in all the cavities can be kept reasonably low. These principles were extended in the separated orbit cyclotron design of F.M. Russell that reached us in 1963 and.

seemed then the most promising design for the intense neutron generator. The study of the S.O.C. has been carried on at Oak Ridge for a similar purpose.

Back in 1945-6, however, there were ideas for linear accelerator for electrons and for protons that would exploit the techniques of high power microwave pulses and waveguide techniques and, on my world-line, Fry, Walkinshaw, Harvie, Harvey, Mullett and others turned their attention to these. The idea was simply that by correct design of a waveguide the velocity of a wave could be controlled so that the charged particle riding ahead of the wave crest could be kept there in stable phase as it was accelerated. It was quickly found that an extremely high degree of precision was required in the construction of the disc-loaded waveguide, especially for protons. This led to a preference for the Alvarez type of accelerator for protons up to 100 MeV, that is still in favour but undergoing intensive design improvement at the present time.

The travelling wave linear accelerator for electrons went ahead into several applications, quite a few were made for 15 MeV for high energy X-rays for medical purposes. A number of relatively new ones have come into use in Canada as research tools, and of course the 2 mile 20-40 GeV Stanford Linear Accelerator, SLAC, is a record holder. Along the way it has become recognised that the original idea had some bad features. First there was the extreme sensitivity to dimensions and frequency and second it was wasteful to transmit power down the length of the waveguide to give energy to the beam at the far end. In recent years all designs arrange both to be less frequency sensitive and to feed the power into separate lengths or tanks. Especially in the Los Alamos Meson Physics Facility design, a proton accelerator, these principles have been applied so that the machine has merited a new description as a standing-wave coupled-cavity accelerator. Power is fed into each cavity through resonant side-cavities that also serve as the main coupling between successive accelerating cavities. By these means it has been possible to double the shunt impedance and so halve the losses. Moreover by careful design and construction it became possible to realize in practice the expected conductivity of copper instead of only 50 to 60% of it, which had been characteristic of accelerators built ten years previously. These improvements were published in 1965.

It should also be remembered that when building an accelerator for a given particle energy the losses are almost inversely proportional to the length, for the loss per unit length is proportional to the square of the electric field gradient.

Taking advantage of these improvements and an increased length suggested that at 800 MHz the r.f. copper losses for a 1 GeV 65 mA proton beam could be brought down to 20 to 30 MW leading to the current reference specification for the Intense Neutron Generator shown in the Table below.

ING REFERENCE ACCELERATOR, MARCH 1968

Output energy	1 GeV	
Current	- positive ions	65 mA
	- negative ions	0.5 mA
Length	1540 m	
Injection		
Current	- positive ions	120 mA
	- negative ions	1 mA
D.C. Acc. Voltage	750 kV	

	Alvarez Sections	Coupled Cavity Sections
Output energy	106 MeV	1000 MeV
Frequency	268.3 MHz	805 MHz
Length	110 m	1430 m
No. of tanks	9	322
Total R.F. power	10 MW	80.5 MW
Total R.F. losses	3.5 MW	22.4 MW

The table indicates that a subsidiary beam of negative ions is also to be accelerated. This trick was proposed by C.H. Westcott as being simpler than schemes for deflecting pulses out of the beam for some of the experimental work, particularly with mesons. It is because of the dual beams that the ratio of the radio-frequencies in the Alvarez and Coupled Cavity sections of the accelerator is an odd number and different from the Los Alamos linac.

In an Alvarez type accelerator the beam passes from an accelerating gap into a drift tube where it is shielded from all external fields. It emerges one or more full periods later to be repelled from the resonant tube into which it had previously been attracted. When the velocity of the beam is low the wavelength $\beta\lambda$ is short and it becomes geometrically more efficient to make the drift tube more than one beam wavelength long. I referred earlier to improvements in the design of the Alvarez section. By introducing resonant stubs in the main cavity it becomes possible to flatten the response to any local change of characteristic. By these means greater ease of operation over a range of beam current and therefore of power transfer is expected.

Basic Energy Transfers in Ion Accelerators

The main power supply for the beam goes to the coupled-cavity accelerator where the beam is accelerated from 106 to 1000 MeV. This power is basically supplied as D.C. power to the anodes of the r.f. generator tubes which may be magnetrons or klystrons. The power is transferred to become kinetic energy of the electrons and is passed by them to become oscillating radiofrequency currents on the inner surfaces of the resonant cavities of the r.f. tubes. It is then transmitted by waveguide and the coupling cavities to maintain large oscillating r.f. currents in the accelerating cavities and these pass the power to the proton beam.

For the longer term future many suggestions have been made to obviate the complexity and the losses inherent in these processes. I have time only to touch on a few. Perhaps the nearest to practical application is to make the cavities of superconducting material. The resulting big reduction of the losses should allow the accelerator to be shortened until limited by sparking or flashover. What this limit would be in practice is not yet clear but a reduction in length by a factor of four to ten has a strong appeal and may be attainable.

Beam transport and confinement is achieved by quadrupole focussing magnets and if superconducting cavities are used these magnets would be either permanent or superconducting to minimize the refrigeration power load.

It should be mentioned that with the high current beams of factory type accelerators the fraction that can be allowed to spill becomes very small. We hope to keep it to less than 0.5 μA which is only 1 in 10^5 of the 65 mA beam of ING. If not, then the artificial radioactivity that would build up in the structure would not only make maintenance more difficult but also perhaps more frequent, until all components such as magnet windings and coolant systems can be made sufficiently radiation resistant.

Experiments are being made on superconducting linacs at Stanford University and elsewhere. Results appear promising but there is still a long way to go.

Touching on another family of ideas, we may note that the operation by which D.C. power becomes r.f. power efficiently in an ordinary r.f. generator tube is for the electrons to deliver current to the anode at a phase when the r.f. and d.c. fields are in opposition, so the electron arrives with little kinetic energy. If a proton took the same path at the same time it would transfer power from the r.f. to the d.c. system and also would suffer little change in kinetic energy. Since over this part of their paths neither the protons nor the electrons are accelerated, I suggested the name "staticelerator" to describe it. The proton, it may be noted, would have reached a point of high potential, the anode, and passing on would be accelerated to a zero potential electrode. By repeating the process many times the proton could in principle be taken to any desired voltage many times that of the d.c. supply. Ideally the only transfer of power to the r.f. system is that to make up for the conductor losses. On the one hand such a system may be compared with the tandem d.c. accelerator, on the other it may be regarded as an ultimate in collapsing together the r.f. generator and accelerator of the conventional linac. Nevertheless it is still complex and still limited by the electric potential gradients that can be maintained between conductors and I have introduced it here only as a lead towards simpler ideas. I know of no actual embodiment.

Much higher electric fields, even 10^9 volts per meter or more can be experienced in finite electron clouds or bunches and by charged particles moving in magnetic fields. Most directly

the field $E = v \times B$

$= 10^9$ V/m if $v \approx c = 3 \times 10^8$ m/s

and $B = 3.3$ Weber/m^2

$= 33$ kG.

Electrons with nearly the velocity of light and magnetic fields of 30 to 40 kilogauss are readily available.

The field at the edge of a cylindrical electron bunch of radius r and uniform electron density ρ is $E_r = \rho e r / 2\varepsilon_o$

$$= 10^{9}\ \text{V/m for } r = 1\ \text{cm and}$$

$$\rho = 2 \times 8.854 \times 10^{-12} \times 10^{9}/1.602 \times 10^{-19} \times 10^{-2} = 10^{19}\ \text{electrons/m}^3 = 10^{13}\ \text{electrons/cm}^3$$

Since the cross-section $\pi r^2 = \pi \text{cm}^2$ the current for $v = c$ is $3\pi \times 10^{23}$ electrons/s = 15100 amperes

If we enquire where such large fields exist in laboratory experience, attention is drawn to the relatively recent development of Electron Pulse Generators. These machines deliver single pulses of tens or even hundreds of thousands of amperes of electrons typically at 2 to 4 MeV of 20 to 50 nanosecond duration.

The remarkable characteristic of these intense and intensely energetic electron pulses is that in practical applications they are not simply explosive. The published literature on the stabilizing mechanisms is still very sparse. The first, and still perhaps the most detailed, publication was that of Graybill and Nablo in Applied Physics Letters, January 1966, entitled "Observation of Magnetically Self-Focussing Electron Streams" the evidence supported the focussing expected from the theory of Willard H. Bennett published in 1934. The stability is essentially due to the relativistic velocity of the electrons relative to positive ions they produce in a gas at low pressure ~ 0.2 torr. This Bennett pinch phenomenon was very neatly described by Budker in a paper to the 1956 CERN accelerator conference. It is,of course, the same as is applied in the proposed electron ring accelerators, the subject of the paper that follows this, so I will restrict my remarks. The range relevant to future factory type accelerators seems wide. Budker's description seems relevant, he notes that given the presence of the positive ions the electron beam can be a potential well for electrons in their frame of reference, while the presence of the electrons makes it also a potential well for the positive ions in their frame of reference. Quantitatively if γ is the familiar relativistic mass multiplier, $1/\sqrt{1-\beta^2}$ and $\beta = v/c$ and the particle densities are defined as follows:

	Laboratory system ions at rest	Moving system electrons at rest
Density of electrons	n_e	n'_e
Density of ions	n_i	n'_i

$$n'_e = (1/\gamma) n_e$$

$$n'_i = \gamma n_i$$

If $n_e > n_i$ there is a potential well for ions in the laboratory system

If $n'_i > n'_e$

i.e. $\gamma n_i > (1/\gamma) n_e$

or $n_i > (1/\gamma^2) n_e$ there is a potential well for electrons in the moving system.

Since γ can be a large number a very wide range of the relative number of ions can exist over which the electron bunch does not explode.

Before discussing the principles by which electron bunches can accelerate positive ions by ion drag, it seems appropriate to touch on some of the reported behaviour of these 20-50 nanosecond electron streams. At the velocity of light such streams are 6 to 15 metres long. S.E. Graybill and S.V. Nablo reported 20 ns pulses of 2.5 MeV electrons of 17000 A focussed to current densities over 5000 A/cm^2 propagated over 3 m in gas at 0.3 torr with a loss of one half in current density. The range of 2.5 MeV electrons is, of course, very long, about 9 m in air at N.T.P. The theory developed by J.D. Lawson and by G. Budker suggests a limiting current for such streams of several times 8500 $\beta\gamma$ amperes. Recent experiments reported by S. Graybill and J. Uglum support this. Currents of 1 mega-ampere should be stable at 10 MeV. T.G. Roberts and Willard H. Bennett reported beams of 30000 A at 3.5 MeV stabilized by a linear pinch in Argon at 0.1 torr which could be taken around a 90° turn at a radius of 15 cm and focussed at 160 cm from the source with a mean radial spread of less than 2 mm.

Ion Drag Accelerators

For effective ion drag we need to break such streams into shorter bunches. If the ions are travelling axially along a magnetic field the electrons can be constrained to travel a helical path with the same axial velocity. In this configuration there can be a very rapid and efficient transfer of energy from the electrons to the ions.

For the ions to acquire a high energy from a small bunch of electrons the bunch must move like the carrot in front of the donkey but also accelerate to keep pace with the ions. This is the mode of acceleration called ion drag. Because of the complexity of the motions and interactions I like to think of another analogy. The ion is like a marble in a saucer on a railway train. Given a sufficiently gradual acceleration the marble will stay in the saucer and acquire the velocity of the train.

Suppose we want 1 GeV protons and we have to start with 20 MeV electrons ($\gamma = 39$) and 20 MeV protons, i.e. $\beta = 0.2c$. At 1 GeV for protons $\beta = 0.875c$ and for the same velocity electrons have a kinetic energy of about 600 keV. The axial velocity of the electron bunch then has to change from 0.2c to 0.875c. Suppose the number of protons is 1% of the number of electrons, then to give the protons 1 GeV the electrons must lose 10 MeV. Everything seems quite practicable and it could all be accomplished by an axial magnetic field of say 40 kg falling off to 4 kg in a distance of perhaps 10 to 20 metres.

In these concepts we are engineering with plasma and experience warns that there exists a wide range of possible instabilities. It seems to me, however, that there are equally many tricks we can play in return and we may take heart from the experience with the relativistic electron streams. For example, to deliver the electrons to the starting point they can be guided by a linear pinch of low energy plasma without much interchange of energy. Thereafter the electron bunches are primarily stabilized by the protons travelling with them, but suppose the electrons at the head of the bunch are not feeling enough drag from the protons, other slow positive ions could drag them back, slow electrons being pushed aside. It is probably unwise to speculate further so I will only point out that the accelerated protons acquire a very special position and need not spread out to the full radius of the electron helix. Other ions and electrons while able to influence the focussing of the electrons do not necessarily acquire much energy. It will be most interesting to see how the electron ring accelerators develop. They provide the equivalent of zero power machines pointing the way to the future high power factory accelerators.

It may be noted that for a neutron factory the exact energy of the ions is not important. If there are strays all can usefully be dumped into the target.

These ideas of ion drag accelerators suggest the possible importance of delivering high power, 100 MW, to electrons at 20 MV. In the present state of electrical engineering, generators and transformers can deal efficiently with such power levels but only up to about 1 MV. Low power D.C. machines of the Van de Graaff type show promise of operating at 20 MV. The late Dr. Van de Graaf himself was interested in extending mechanical generators to these voltages and higher powers. We are supporting a study aiming at 4 MW 20 MV with power transmitted mechanically by an insulated shaft. The main problems appear to be windage drag and cooling at high D.C. potentials. Such a generator could launch the proton beam for a factory type accelerator. It is interesting to speculate on extending mechanical generators to higher powers at the same high voltage.

It is possible that steps to these higher power levels will follow other routes, possibly through other objectives such as factories for K-mesons.