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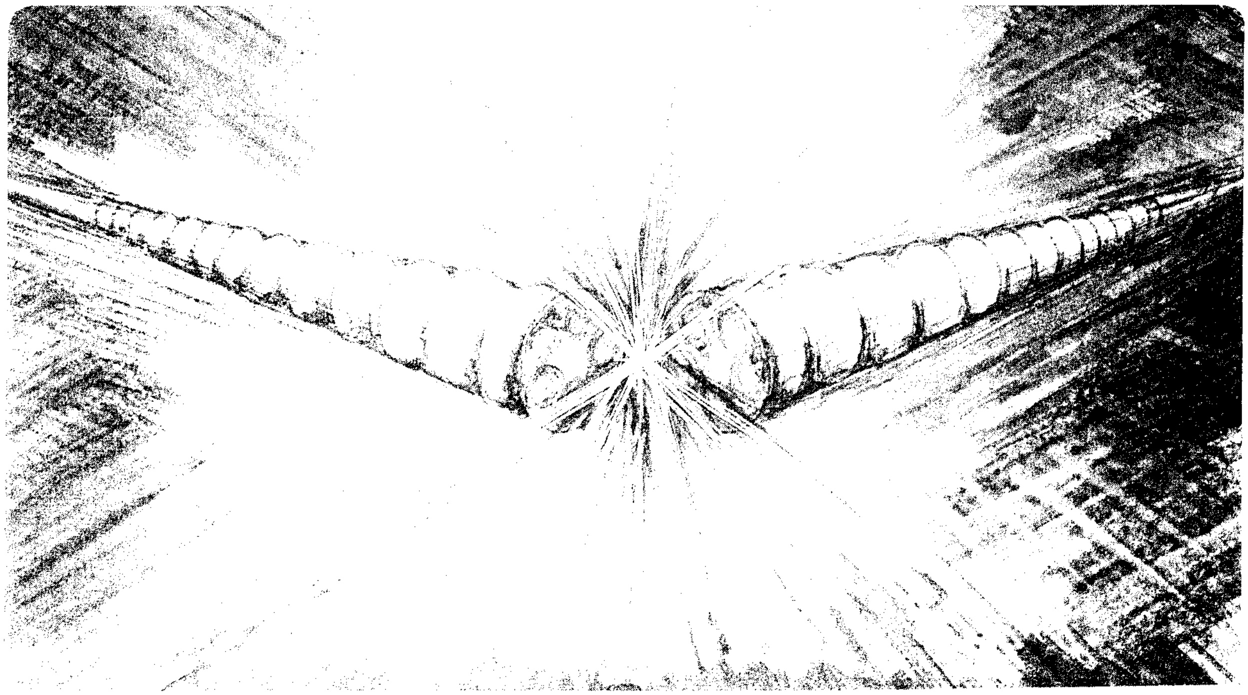

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Frontiers of Particle Beam Physics*

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ABSTRACT

First, a review is given of various highly-developed techniques for particle handling which are, nevertheless, being vigorously advanced at the present time. These include soft superconductor radio frequency cavities, hard superconductor magnets, cooling rings for ions and anti-protons, and damping rings for electrons. Second, attention is focused upon novel devices for particle generation, acceleration, and focusing. These include relativistic klystrons and free electron laser power sources, binary power multipliers, photo-cathodes, switched-power linacs, plasma beat-wave accelerators, plasma wake-field accelerators, plasma lenses, plasma adiabatic focusers and plasma compensators.

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Introduction

For the last sixty years, starting with Cockcroft and Walton's electrostatic machine and Lawrence's cyclotron, particle beam physics has matured and matured again until now it is a highly developed--and much respected--discipline. And with good reason, for modern machines are large (at CERN, LEP has a circumference of 27 km), unbelievably complicated (at Fermilab, anti-protons are produced, captured, cooled, and stored for hours while they are brought into collision with protons), and reliable (at Berkeley, the Bevatron--over 30 years old--worked last year for 90% of scheduled operating time).

The incredible capability and performance of sources, accelerators, storage rings, and beam lines--various particle handling devices--is the result of an orderly development of the field of beam physics. An understanding has been arrived at, and the technology to implement it has been developed, with results which--surely--are beyond the wildest dreams which early accelerator builders ever had. The field of particle beam physics has made possible whole areas of research, such as elementary particle physics and nuclear physics, and it has had major impact upon other fields with its synchrotron light sources, its neutral beam heaters, and its ion and electron traps.

In this review, attention is focused upon some of the present frontiers of particle beam physics. Clearly, the choice of topics is somewhat arbitrary, but I have tried to call attention to the physics, as contrasted with technology or engineering, frontiers; the emphasis on plasma applications seems appropriate to the audience. I have chosen an even dozen "frontiers". First we survey the limits of various highly-developed technologies (Sections I-IV), and then describe some novel devices which may--in the future--become "stand-bys" of beam physicists. (The subjects of Sections V-VIII are a bit more near-term, those of Sections IX-XII require more development.)

I. Superconducting RF Cavities[1]

The progress in the superconducting RF cavities is very impressive. Firstly there has been significant improvement in the properties of the cavities themselves, and secondly, there has been practical experience gained in the use of such cavities in real accelerators.

The major "breakthrough" in the field was understanding multipactoring and making spherical cavities that reduce it. Recently, working with niobium producers has resulted in higher purity material; hence higher thermal conductivity and higher fields. Ultra high vacuum heating, with deoxidation, has enabled preservation of the purity of the sample. As a result, manufacturers, using solid niobium, routinely obtain cavities with accelerating gradients of 5 MeV/m . The Q values obtained are greater than 10^9. In sample cavities, accelerating gradients in the range from 17 to 27 MeV/m, with $Q \approx 3x10^{10}$ have been achieved.

The design of cavities to reduce higher order modes is very important, especially in the use of cavities in storage rings, and this has been done with great success. That is, the higher order modes have Qs in the same range as room temperature cavities, while the fundamental mode has a Q which is 10^4 times larger than that of a room temperature cavity.

The possible use of high temperature superconductors has been investigated and at present the new materials are nowhere near as good as niobium (surface resistance of $Y_1Ba_2Cu_3O_7$ is 3×10^{-3} ohms vs. a few nano-ohms for niobium at 1.5^o K).

The theoretical limit of RF superconductors is not known; it is likely to be an accelerating field of close to 100 MeV/m. The best field achieved so far is a surface field of 140 MeV/m (hence an accelerating field of maybe 1/2 that) at 6 GHz.

II. Superconducting Magnets[2]

Superconducting magnets are made with specially cabled wires made up of A-15 materials. Amongst these is the very ductile material NbTi, which is the material from which all accelerator magnets, to date, have been made. Other materials, such as V_3Ga and Nb_3Sn, which have a considerably higher H_{c2} than NbTi, and are formed in the solid state. Lead molysulfide has a very high H_{c2}, but it requires powder technology. Considerable work has been put into Nb_3Sn, which is formed by placing wires of Nb in CuSn (bronze) surroundings and then heating, to less than the Cu melting point

(700^0K). A small annulus of superconducting material forms around the Nb. In summary, on superconducting wire, one should note that there are a lot of possibilities for future development; the field is far from finished, it seems to have only just begun.

Focusing upon NbTi wire, we can examine the variation of critical current as a function of time and note that there has been an improvement from 2500 A/cm^2 to 3800 A/cm^2 in just the last five years. The variation is due to improved homogeneity of the alloy. The flux lines are pined by non-superconducting areas in the lattice. These are precipitated by many steps of heating, followed by cold working, and it is control of this process that has resulted in the improvement.

Wire used in the outer layer of the SSC magnets, which have two layers, is one example. It is made up of 30 strands of 25 1/2 mil od. Each strand is made up of about 4000 filaments. Each filament is 6μm of solid Nb Ti. (The filaments are made that small so as to reduce persistent currents.) Copper surrounds the filaments and the ratio of Cu to superconductor is 1.8.

The technology is in use throughout the world, with the HERA magnet typical of the current state of the art. For the next generation, the SSC, the field will be 6.6 T and each magnet will be 17 m long. For the LHC, the CERN people are developing a 10T dipole. (Such a field has already been achieved in laboratory magnets at CERN and at LBL.)

III. Cooling Rings[3]

Cooling of particle beams has become an important aspect of accelerator physics ever since the method was developed in the 70's. It is used in the Tevatron, the SPS, and in LEAR. A different cooling method (electron cooling) is used in ion rings for nuclear physics.

The facility at Fermilab uses this technique to cool and stack anti-protons. It consists of two rings. The first, the Debuncher, is primarily a bunch rotator. It takes a big energy spread and reduces it by a factor of 10 (while increasing the time spread by a factor of 10). It then adiabatically de-bunches. It also has a fast transverse cooling system that in 2 seconds reduces the emittance in each plane by a factor of 4.

The Accumulator is a cooling and stacking ring. Every 2 seconds a transfer is made into the ring and the bunches are de-accelerated (stacked) and cooled in longitudinal space. As a result the phase density is increased by a factor of 10^4.

In the future, there will be improvement of the signal transmission cables (from the present superconducting cables to optical fibers) which should result in the cooling of more particles per second. Also there will be an effort to develop the ability to cool bunched beams; i.e. to cool beams while they collide.

IV. Damping Rings[4]

Damping rings are a vital part of linear colliders. They provide the small emittance beams which are essential for obtaining high luminosity. The new storage rings for providing synchotron radiation, "third generation rings", all have exceedingly small emittance beams, for this is what is required in order to make bright sources. Thus the problems of damping rings are very similar to those of synchrotron rings. In both cases one is talking about GeV energies, transverse normalized emittances ($\gamma\sigma\sigma'$) of 1×10^{-8} m-rad vertically and 1×10^{-6} m-rad horizontally, or smaller, and longitudinal brightnesses ($I/\Delta\gamma$) of 50-200 Amp.

A major issue is the choice of energy of the beam. If the energy is low, then the damping time is very long (and the rate at which damped particles are produced, for a collider application, is very low). Furthermore, the emittance is dominated by intra-beam scattering and is rather high, and in addition the Touschek lifetime is small and the threshold for various collective instabilities is low. If the energy is high, then intra-beam scattering is unimportant (Coulomb cross section is reduced) but quantum fluctuations in the radiation are large and cause a large emittance. The optimal energy is about 1 GeV.

A second major issue is the choice of lattice. People have considered FODO lattices, Chasman-Green lattices, wiggler lattices, Vignola lattices, and even rings operating on the transition energy (so that particles of slightly different energies have the same circulation frequency). Issues include, besides the rate of damping and the equilibrium value of the emittance, the effect of wigglers on dynamic aperture and alignment tolerances for the flat beams.

The only damping ring so-far built is the SLAC damping ring for the SLC. It has a circumfrence of 35 m, operates at an energy of 1.2 GeV with two bunches each of 4 X 10^{10} particles. It produces a normalized emittance, in each plane, of 1.5 X 10^{-5} m-rad in a damping time of 3.4 msec.

Damping rings can be designed which meet the stringent requirements of TeV colliders; in particular they appear able to produce normalized emittances of 2.7 X 10^{-6} m-rad and 3 X 10^{-8} m-rad in the horizontal and vertical planes, respectively. The damping time is about 4 msec.

V. Binary Power Multipliers[5]

Binary power multipliers are devices which take the relatively long pulse ($\approx$ 1μs) of low power ($\approx$100 MW), typical of ordinary klystrons, and turn them into short pulses (tens of ns) and high peak power (500 MW) as is required for a linear collider.

Work has been done, at SLAC, on a low-power two stage binary energy compressor, working at 11.4 GHz. Using an overmoded delay line and 3dB hybrid couplers, a 312 ns pulse was compressed to 78 ns giving a power multiplication of about 3.2 and an efficiency of 81%. The circular waveguide (WC 281) has 0.004 dB/m loss while the standard rectangular guide (WR 90) has a loss of 20 times that; for this reason the circular waveguide is employed for the long delay lines.

SLAC is now making an X-Band klystron, 11.4 GHz, to operate at 100 MW. The device, which has been tested as a diode, but not with klystron cavities, operates at 450 kV and 400 A. As a diode it transmitted 98% of the current. It is expected to be more than 50% efficient and give a pulse of 1μsec duration. With 3 stages of pulse compression; i.e., a factor of 8 compression, they expect to get a 70 nsec pulse of more than 500 MW (factor of 6) and an efficiency of 71%.

VI. Relativistic Klystrons, FEL Power Sources, and The Two-Beam Accelerator[6]

For five years now, the concept of a Two-Beam Accelerator (TBA) has been receiving attention by accelerator physicists. The idea is simply to use one relativistic (a few MeV), intense (a few kilo-amps) beam of electrons to generate the required power for a linear collider. It has been shown that the beam can be treated as a "working fluid"; i.e. energy can be removed from the beam in the form of microwaves and put back into the beam by superconducting cavities or induction units, and this process can be repeated many times. Efforts have focused on theoretical analysis of the idea and experimental realization of components of the system.

Energy is extracted from the beam either with a free electron laser (FEL) or with extraction cavities; i.e. a relativistic version of an ordinary klystron (RK). Experimental work has been done on both. An LLNL/LBL group has shown that an FEL can give more than 1 GW of peak power from a 3.5 MeV beam of 1 kA going through a wiggler, of length 3 m, having a peak field of 3.8 kG. The efficiency of power transfer from the beam to microwaves was 45%. A LLNL/SLAC/LBL group has shown that the RK can give 300 MW peak power from a 1.4 MeV beam of 700 A. The efficiency of beam-to-microwave conversion was 28%.

Experimental work is currently underway at KEK with a plasma guided FEL. Work is in progress at CERN on creating the drive beam and on developing suitable RK cavities. Work is also being done, in the US, on re-acceleration as well as on alternative bunching schemes for the RK. Paper studies have been made of a 17 GHz FEL.

It is possible to greatly reduce the complexity of the TBA concept so that only a few re-accelerations are made. (Thus one would have [say] a 13 beam accelerator.) Paper studies have shown that some re-acceleration is advantageous in terms of both capital costs and operating costs. Many re-accelerations may not be particularly advantageous (the returns are diminishing); the trade-off in a TBA is between more injectors vs. complexity of operation.

VII. Photo-Cathodes[7]

Motivated by the need for high peak current beams ($I_p \approx$ few hundred amps) and low emittance beams for an FEL, the Los Alamos group has led the development of photo-cathodes in an RF gun. At present there is photo-cathode work going on in many laboratories around the world.

The balance is between space charge forces (which are reduced if the bunch is long in time) and RF non-linearities (which are small if the bunch is short in phase). Clearly, the larger the applied RF field the better, but there are breakdown limits. (The use of switched power for this application holds the promise of a major breakthrough.) Magnetic bunching is usually used subsequent to the RF gun.

The cathode could either be a metal, and hence have low quantum efficiency (about 10^{-4}) or a substance like Cs_3Sb (where the quantum efficiency is about 10^{-2}, but the vacuum requirement is 10^{-10} torr). The smaller the laser spot size, the smaller the emittance, but the larger the space charge forces and the less current emitted. Making various pulse trains is relatively easy, for one only needs to program the laser light.

The Los Alamos group has achieved a current of 590 Amps from a spot of less than 1 cm^2 (13.2 nC from the cathode in 16 ps which expands to 22 ps by the end of the first cavity) and an emittance of about 1.3×10^{-5} m-rad at an energy of 3 MeV. The extracted charge for a 108 MHz train of 75 ps pulses was 27 nC per micropulse or 2.9 A averaged over the pulse period.

Designs have been made of a compact FEL, operating at 20 MeV, with 10 μsec macro-pulse, 350 A and an emittance of 5×10^{-6} m-rad. This device has a peak field of 60 MV/m at the cathode, but people are talking of using switched power, getting higher surface fields, and hence reducing even further the beam emittance.

VIII. Switched Power[8]

The switched power linac (SPL) concept exploits fast-switched high voltage technology to produce short, single (or a few) pulses in an electron gun, or an accelerating structure.

The basic idea is that an outer wire is negatively pulsed to 200 - 1000 kV with a risetime of $\leq$ 1–2 ns. Its surface is a good photo-emitting material (i.e. has a high quantum efficiency). Before normal electrical breakdown can occur, the ring is illuminated around its periphery by a UV laser pulse of a few psec, whose energy is in the mJ range. In the pulsed electric field of $\approx$0.5 GV/m, a current density of $\approx$200 kA/cm^2 flows to the nearest disk which is $\approx$1 mm away. The short electric field pulse thus produced propagates toward the center of the disks, increasing in magnitude as it travels. At the center, a pulse of less than 10 ps, and about 1.5-5 GV/m is created.

Experimental work has been done on a 240-cm diameter model. The disks were pulsed at 64 equally spaced points on the circumference. The pulse risetime was 210 ps. The central field enhancement, i.e. gain, approaches 10 when there is no central hole, but falls to $\approx$4.5 with a 4-cm diameter hole. For an actual accelerator with a 5 ps switch risetime, the gain might approach 15. For reproducible central fields, it is important that the switch risetime be very reproducible.

In order to avoid dipole and higher multipole central electric fields, it is important that the inwardly propagating wave be very uniform when it arrives at the center of the disks. Results were obtained on the 240-cm diameter model where 1/8 of the feeds were disconnected. Rather surprisingly, even though the missing feeds cause a corresponding power loss near the center, the resulting field distribution near the axis becomes uniform and well-centered, with the resulting dipole and quadrupole excitation at a 1-cm radius of only about 2% and 1%, respectively.

Current challenges at the forefront of technology are:

(1) fast risetime (1–2 ns) 0.2-1.0 MV pulsers; i.e. creating the voltage to be photo-switched.

(2) fast risetime ($\leq$10 ps) high voltage switch; i.e. development of the laser system (or even solid state) switching.

(3) voltage-holding for $T_p \approx 2$ ns; i.e. holding the high voltage for even this long.

IX. Plasma Beat-Wave Accelerator[9]

Interest in plasma accelerators stems from the realization that it is not possible in conventional accelerators to operate with a very high gradient because of breakdown of the structure. A plasma, on the other hand, is fully ionized and can't break down. It can support ultra-high longitudinal fields, $eE_{max}=mc\omega_p=n_p^{1/2}$ (eV/cm). In this expression, the electron has charge e and mass m; the plasma density is n_p, and ω_p is the plasma frequency. For a plasma of $n_p= 10^{18}$ cm^{-3} the gradient is 1 GeV/cm.

Considerable analytic work has been done on the excitation of plasma waves by a resonant interaction resulting from two laser beams whose beat frequency is the plasma frequency. Two dimensional particle simulations support the analytic work.

Experimental work has been done by groups at NRC (Canada), RAL (England), and UCLA. UCLA achieved an accelerating gradient of 1-3 GeV/m, corresponding to 3-9% bunching of the plasma over a length of 2 mm (similar results were achieved in Canada).

Presently, UCLA is constructing an experiment whose goal is 1 GeV/m over 2 cm; i.e. 10-20 MeV electrons. They plan to use a powerful CO_2 laser giving 20 Joules in a 200 psec pulse, and have injected electrons at 1.5 MeV. The present status is that the CO_2 laser and the electron beam injector are operational, and the plasma source is operational, but density uniformity is still a question. Diagnostics for the electron beam is in hand, that for the laser is being implemented. Key issues are production and stability of the plasma.

X. Plasma Wake-Field Accelerator[10]

The basic idea of a wake field accelerator is to use an intense beam to "leave behind" fields in a structure and then use these fields to accelerate a second (smaller) group of particles. This approach thus entails shock excitation of a structure, rather than periodic excitation.

The process is subject to a theorem, however, which states that if the two groups of particles are co-linear, can be described by delta functions (i.e. are point-like), and pass through a passive structure, then a particle in the second group can gain energy which is at most twice the energy of a particle in the first group.

A way to "get around the theorem" is the wake-field transformer, or radial transmission line concept which puts the two groups of particles through different paths in the same structure. This idea has been developed, and experimental work performed, by the DESY group. However, it is not one of the topics considered here. Rather I want to focus attention upon the possibility of using a plasma as the "structure", rather than a copper structure.

Theoretical analysis has been done by a number of groups, and an experiment has been performed at the Argonne National Lab Accelerator Test Facility. They used a drive beam of 21 MeV, 2-6 nC, 15-20 psec full width, and a witness beam of 15 MeV. The plasma had a length L=20-35 cm, a density $n_p = (0.5\text{-}7.0) \times 10^{13}$ cm^{-3}, and a temperature T_p=2-8 eV. The results achieved was a gradient of a few MeV/m corresponding to 30% bunching. Pinching was observed by noting that the wake didn't scale with driver charge.

In the future they plan to increase the driver beam, shape the driver pulse (so as to "get around the theorem"), and study and control non-linear effects (which have already been seen and may be advantageous).

XI. Plasma Lens and Adiabatic Focuser[11]

Plasma focusing is based upon the observation that if the plasma density is less than the high energy beam density (under dense) then the beam (here taken to be electrons) will eject electrons from the beam region and be focused by the remaining ions. (Clearly, a beam of positive particles will be focused in an analogous manner.) The focussing strength is $F_r/r \approx 3 \times (n_p/10^{18}\ cm^{-3})$ Gigagauss/cm; i.e. a very large number for most plasmas.

Ion focusing has been employed, in recent years, on a number of machines. In particular, at Livermore the ATA normally operates with ion focusing. The focusing is very large, and highly non-linear, and both of these effests are good for preventing transverse coherent instabilities (BBU).

It seems possible to employ ion focusing in linear colliders. So far, only paper studies have been made of this concept, but the results look interesting. Using SLAC-type beam parameters one can focus the beam in only 10 cm, as contrasted with the present final focus system which extends over hundreds of meters. Of course there is a background problem (unwanted events) associated with the use of a plasma.

Tailoring the focus system, so as to have a continuous focus, the adiabatic focuser has distinct advantages. In particular, for discrete focusing there is a limit to the smallness of the spot size which can be created at the final focus. This comes about because in going through the final focus a beam particle radiates, and the radiation is random, to some degree, due to quantum fluctuations. Hence the particle is subject to the chromatic aberration of the system and the final beam spot is not perfect. In the continuous focusser this restriction is greatly relaxed.

It has been shown that if the beam emittance is less than a critical value, which is proportional to λ_c/α^3 (λ_c the Compton wavelength and α the fine stucture constant), and has the numerical value of 6.2 X 10^{-6} m-rad, then the focus can be made very sharp indeed. Notice that the critical emittance only involves fundamental constants and notice, also, that the it is quite attainable in practice.

For the adiabatic focuser tailoring of the plasma density is required. There are also background considerations. Nevertheless the concept seems worthy of further study.

XII. Plasma Compensator[12]

Still another way in which plasmas may be of value to particle beam physicists is in the plasma compensator. In a linear collider the very fine, and intense, beams which are brought into collision create, just because they are so fine and intense, very large magnetic fields. The magnetic field is B (Mgauss) $\approx$ 2 X I (kA)/a (μm).

The large field affects the other beam. It pinches it, which increases the luminosity and hence is a "good effect", but also causes it to disrupt and hit the detector and hence is a "bad effect". The field also causes the other beam to radiate, a phenomena known as beamstrahlung, which due to quantum fluctuations causes the particles to have a spread in energies and hence is a “bad effect”. To aleviate this last effect, which is very serious in practice, one must design linear colliders with very flat beams; i.e., a very small emittance in the vertical plane.

The influence of one beam on the other can be eliminated if the charge and current of the beam is “compensated”. This is exactly what a dense enough plasma will do. In fact it is easy to show that good compensation requires an overdense plasma, $n_b/n_p<<1$, a short plasma period $\omega_p\tau_r>>1$, and a small current skin depth $k_pa>>1$. In these expressions appear the beam radius, a, the beam rise time, τ_r, the beam and plasma densities, the plasma frequency, ω_p, and the plasma wave number, k_p. In addition the magnetic diffusion time must be long, which requires a collisionless plasma (to some degree).

Examples, on paper, have shown that compensation can occur. There are problems of making the plasma and, as with all plasma devices, questions of background.

Conclusion

It is hoped that after surveying these dozen frontiers, the reader will have obtained an appreciation of the vitality of particle beam physics. The range is wide, progress significant, and the demand for physicists large. The need is across the board and the work is broad enough to encompass those with all kinds of interests and with all kinds of personal likes.

Some developments, such as those covered in Sections I-IV, are vitally important for existing machines. These developments are “very real”; i.e., they are already in everyday use. These activities involve many people; in fact most accelerator physicists work on things like this.

The second group, Sections V-VIII, are small activities, involving in each case less than 20 physicists. These activities are vital to the near-term health of the field. The projects have all experienced a certain measure of success and appear likely to result in practical additions to the roster of beam handling devices.

The third group, Sections IX-XII, are all plasma-based devices. They are, just because of this, more "far-out". Generally, the effort on these devices is very small. Nevertheless, I believe they need to be explored (just as some equally "far-out", non-plasma devices need to be explored), for they are the small experiments out of which will grow the large machines of the far future.

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