DEVELOPMENTS IN ACCELERATORS FOR HEAVY ION FUSION*

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Abstract

The long term goal of Heavy Ion Fusion (HIF) is the development of an accelerator with the large beam power, large beam stored-energy, and high brightness needed to implode small deuterium-tritium capsules for fusion power. While studies of an rf linac/storage ring combination as an inertial fusion driver continue in Japan and Europe, the US program in recent times has concentrated on the study of the suitability of linear induction acceleration of ions for this purpose. Novel features required include use of multiple beams, beam current amplification in the linac, and manipulation of long beam bunches with a large velocity difference between head and tail.

Recent experiments with an intense bright beam of cesium ions have established that much higher currents can be transported in a long quadrupole system than was believed possible a few years ago.

A proof-of-principle ion induction linac to demonstrate beam current amplification with multiple beams is at present being fabricated at LBL.

1. Introduction

Utilizing a heavy ion accelerator to deliver the large beam energy and power to drive a deuterium-tritium capsule to thermonuclear burn still continues, in my mind, to be the most promising approach to inertial fusion for civilian electricity production. Since the beam power needed is very great (200 TW) and the particle kinetic energy (or "beam voltage") is constrained to be modest -- 50 MeV/amu for an ion of mass A = 200 -- the final beam current required is consequently enormous (20 kA) compared with that which we are used to in conventional accelerators. The second key challenge to the accelerator scientist is ensuring that the low emittance delivered by the highest quality ion sources available can be preserved with insignificant dilution throughout the accelerator. Emittance is important at the final focussing lenses which must produce a small focal spot of order 5 mm diameter. (Curiously, the value of the emittance is unimportant throughout the accelerator; for instance the beam size in the transport lenses will be determined by space-charge.) Contending with enormous beam currents and simultaneously minimizing emittance dilution lie at the heart of all accelerator driver systems. Other problems arise when we focus on a specific choice of accelerator strategy, e.g., either a rf linac with storage rings for current amplification, or a multiple-beam induction linac with simultaneous current and voltage amplification.

Driver systems based on the rf linac/storage ring combination are under study in West Germany, Japan and the United Kingdom. In the U.S., the heavy ion fusion (HIF) program, formerly under DoE's Defense Programs, was transferred in October 1983 to the DoE Energy Research Office and re-titled HIF Accelerator Research (HIFAR). The HIFAR program has the restricted goal of exploring the potential of multiple-beam induction linacs for fusion and of developing the necessary research results to allow a proper evaluation of that potential. This narrowing of emphasis came about for a combination of reasons -- funds were inadequate to pursue parallel approaches, the rf linac studies were anyway being continued in other countries and, finally, the main physics issues for induction linacs can be tackled in relatively low-energy experiments, namely with accelerators of moderate size and cost [1].

The HIFAR program plan informally adopted by DoE originally envisaged a two stage research program over a six-year period (1984-89) with the goal of developing a data-base to allow in-depth evaluation of the prospects of accelerators for fusion. Stage 2 of the program would be the construction of a significant (100 MeV) induction linac, HTE, with 16 beams of sodium ions that could produce a solid-density high temperature plasma (50-100 eV) [2]. Stage 1 is defined as the research leading up to this large experiment. Because of inadequate funding, however, the six-year goal cannot be maintained; nonetheless, the broad definition of the two-stage approach is being adhered to.

2. Driver Studies

Two years ago, at Santa Fe, Bock gave a status report on Heavy Ion Fusion and described the important HIBALL overall fusion power plant study by a consortium of efforts from Darmstadt, Garching, Giessen, Karlsruhe, and Wisconsin [3]. As result of a critical examination of the physics of the driver, certain improvements in design were developed and have recently been published [4]. The earliest design, which used doubly-charged bismuth ions, seemed to be risky because of microwave instabilities in the storage rings used for current amplification. The present scheme calls for the following features:

i) Eight ion sources of singly-charged bismuth deliver their beams to RFQ's operating at 10 MHz;

ii) Stepwise funnelling of pairs of beams brings the bunch frequency to 80 MHz in the main linac, which is operated at sequentially higher harmonics up to 320 MHz. The average linac current is 165 mA, the final energy, 10 GeV.

iii) Five cascaded transfer rings, each 236 m in radius, followed by 10 storage rings and 10 bunching rings (118 m. in radius) are used to accomplish the final current amplification (by multiturn injection) to about 1 kA in each of 20 beam lines to the combustion chamber.

iv) The final induction linac bunchers proposed earlier have been eliminated.

The new design seems a lot safer than the old one. One question that seems still unresolved concerns vapor evolution from septa by quite small beam losses during multiturn injection.

At the HIF symposium in Tokyo in January 1984, an impressive amount of work was revealed by the Japanese fusion groups on a corresponding power plant study, culminating in the HIBLIC design [5]. The driver design was based on an rf linac with current-amplification by means of storage rings; while the details are different the general physics issues are similar to those pertaining to HIBALL.

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In practical support of ingredients of these driver systems research is in progress on RFQ's for heavy ions with low charge/mass ratio in Japan and Germany [6], on energy loss of heavy ions in a plasma target (z-pinch) at Darmstadt, and on an important storage ring experiment at Darmstadt.

Designs for induction linac drivers with a variety of parameters were studied intensively some years ago with the aid of a computer program LIACEP (Linear Induction Accelerator Cost Evaluation Program) which contains many detailed cost and engineering algorithms [7]. This program was developed not primarily as a cost-estimating tool for a preconceived design, but to generate a design using cost-minimization as a constraint to an otherwise unconstrained design problem. Had some other constraint been set -- for example, maximum efficiency -- both the derived design and cost would have been different. LIACEP was not developed to the point where it could handle the low velocity section (< 50 MeV), or the final transport/bunching lines. Several tedious point designs of the front and back ends of specific drivers indicated, however, that these sections accounted for only 20% of the total driver cost. An important conclusion from LIACEP was that use of multiple beams -- up to 4 or 8, but not much more -- could reduce cost and increase efficiency [8]. A reference driver with 4 beams is given in Ref. 9.

In the past year new studies of driver systems have begun again, and Lee has developed formulas in fairly simple form that describe the transport and acceleration of multiple beams through the accelerator and final transport lines all the way from source to target -- thus avoiding the awkward interface problem between stages inherent in the older LIACEP approach. (An example of one aspect of this work is in Ref. 10.)

Faltens, Hovingh and Lee are developing a modernized, extended version of LIACEP to provide constraints based on cost, efficiency, or other factors that will allow generation of specific designs. Their work is part of a broad driver assessment study rather than an attempt to generate a single point design such as HIBALL or HIBLIC.

3. Stage II of the HIFAR Plan: The High Temperature Experiment (HTE)

A conceptual design for an accelerator experiment that can test, within a factor of three, almost all of the questions pertaining to a full scale driver has been developed at a hardware scale of only 10% of a driver [2]. Parameters for HTE, and an accelerating "schedule" showing how the beam voltage and current increase along the length have been described by Fessenden [11]. While the goal of the experiment is often stated as demonstrating production of a solid-density plasma of high-temperature (50-100 eV) in a slab target, this is just a short-hand method of judging a much larger set of issues. Basically, HTE, is an accelerator experiment to see if we can control in practice the 16 beams with current amplification and insignificant emittance growth and focus them to a small focal spot. The plasma temperature is not of itself the main end; it is, instead, a diagnostic indicator that integrates over the entire system performance. Also, the HTE offers an experimental facility in which a broad range of experiments can be done, for example, on neutralized beam propagation to the target, on plasma effects (e.g. two-stream instability) in the target corona, on plasma-lens final focussing, and on many other effects. The general scale of the experiment (e.g. multiplicity of components) and the parameters (e.g. beam plasma frequency and target plasma frequency), are close enough to actual driver needs that, if HTE were successful, one would feel considerable confidence in extrapolating to a much larger device.

Examination of the scaling laws shows that light ions (A ~ 30) are best suited for HTE [2]. This question has been explored in detail by Lee, and the most suitable choices of mass and energy for different temperatures (see Fig. 1) have been mapped [12].

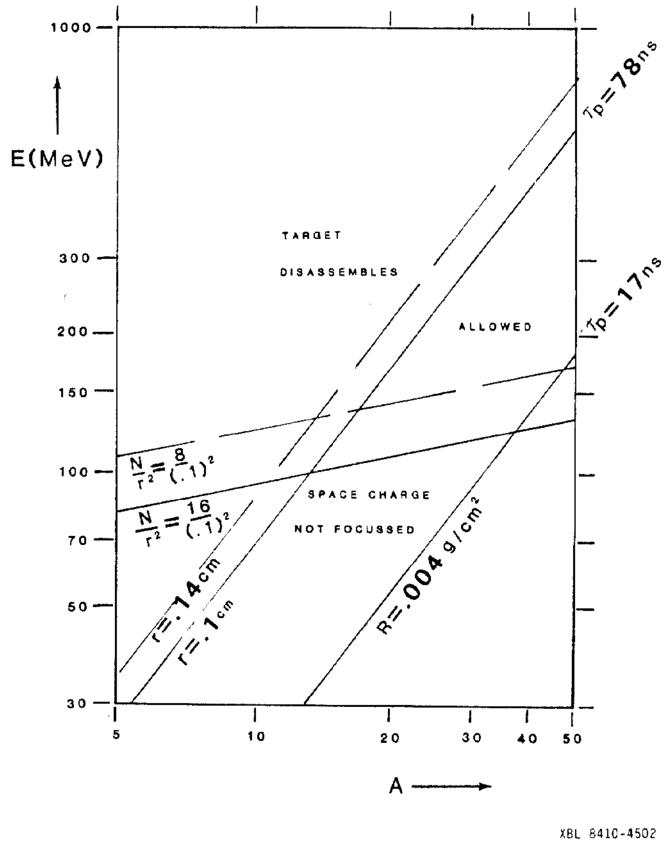

Fig. 1. Allowed energy and ion mass for T = 80 eV [12]

4. Stage I of the HIFAR Plan: Present Experiments

In his review paper, Reiser discussed several recent beam transport experiments to study the propagation of high current beams [13]. Widespread interest in this topic has been mainly stimulated by the two challenges presented by HIF, the need to handle extremely high currents and the need to ensure that virtually no dilution in emittance takes place.

4.1 Single Beam Transport Experiment (SBTE)

In the past three years, the mainstay of our experimental efforts at LBL has been the Single Beam Transport Experiment (SBTE) [14]. The apparatus consists of a long transport channel comprising 82 electrostatic quadrupoles in a FODO lattice arrangement, i.e. 41 focussing periods. For other details of the SBTE see Ref. 4.

The principal motivation of the experiment was to find the limits for the stable transport of a high-current beam in a long quadrupole transport array. Nearly ten years ago, Maschke conjectured that troubles might be encountered if the space-charge defocussing force became as large as one-half of the quadrupole restoring force. Later analytical work based on the K-V envelope equation by Hofmann et al. indicated that a space-charge depressed phase advance per lattice period, σ, as low as 24° might be safely attained for a lattice set for a low-current phase advance of < 60° [15]. Still later, particle-in-cell (PIC) simulation results by Hofmann and Haber suggested that the depressed phase-advance could be still lower [16]. (These PIC simulations were for on-axis beams without images and hence did not contain all the physical effects that we now know to be important.)

The experimental procedure adopted was to measure the current (I) and emittance (ε) at the beginning of the transport system and again at the end; if both I and ε are unchanged within the resolution (a few percent) the transport of the beam is empirically defined as "stable". Next, the emittance and the current are used in the K-V envelope equation to derive a space-charge depressed phase-advance, σ.

As reported at the Tokyo HIF Symposium, no sign of any instabilities was found if σ_0 was kept below 90° [14]. We reported then that for $\sigma_0 = 60°$ we had achieved a depressed phase advance of $\sigma = 12°$. Since that time, Tiefenback has demonstrated beam stability for σ depressed from 60° to 8°; lower values of σ cannot be explored until the injector current can be increased or the emittance reduced. For such a low value of σ, the beam in the focussing quadrupoles has a dimension of two thirds of the ideal aperture (more, when misalignments are included) so that, in seeking to explore still lower values we are nearing yet another limit of the apparatus.

While the idealized results from the K-V stability analysis suggested that, for design purposes, it might be prudent to keep σ_0 less than 60° to avoid third-order modes growing, we find no difference in behavior whether σ_0 is greater than or less than 60°.

For σ_0 above 90°, envelope instabilities are expected and a secondary goal of the experiment was to map out the stability boundary in this region, and to see if the data were amenable to theoretical understanding. In all cases explored for $\sigma_0 > 90°$ the experimental parameters were adequate to give rise to high current instabilities. (The change in behavior from stable to unstable was found, in fact, not to occur exactly at $\sigma_0 = 90°$, where envelope instabilities begin. Instead, onset of emittance growth could be detected at $\sigma_0 = 85°$ and above for the highest current beams; this discrepancy is not regarded as significant.) The data for σ_0 greater than 90° (or 85°, to be precise) are complicated to understand, and are discussed in greater detail by Tiefenback and Keefe [17]. Between $\sigma_0 = 120°$ and 150°, σ/σ_0 for stable transport is about 0.8 in contrast to the much lower value (still an upper limit) at $\sigma_0 < 90°$, namely $\sigma/\sigma_0 < 0.1$. There appears to be a transition region between $\sigma_0 = 100°$ and $\sigma_0 = 105°$ [17].

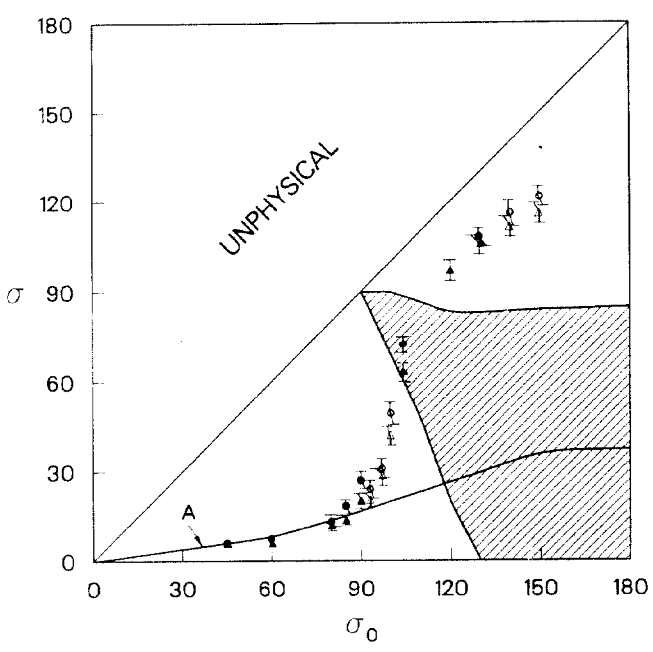

Fig. 2. Values of depressed phase advance marking limits of stable transport. Curve A marks experimental limit of apparatus..

Recently, Celata et al. have explored with PIC simulations the behavior of beams with phase advance depressed from $\sigma_0 = 60°$ to $\sigma_0 = 6°$ (close to the experimentally achieved parameters) for an off-axis beam with inclusion of image forces due to the four electrodes. In contrast to the on-axis case for which no change is observed, they observed oscillatory behavior of the r.m.s. emittance accompanied by a steady growth in emittance. For SBTE they predict small but significant emittance growth that has, indeed, been seen in the experiment when the beam is deliberately mis-steered by displacing a quadrupole lens [18].

The SBTE has proved a useful apparatus also for examining longitudinal dynamics, in particular the longitudinal focussing for the head and tail of the bunch to prevent the ends from spreading excessively. At injection the bunch in the SBTE is nearly rectangular in shape -- many microseconds long with a rise and fall time of a few hundred nanoseconds. The non-zero derivative of line-charge density at the bunch ends, however, causes acceleration of particles at the head and deceleration of particles at the tail. In the 14-meter length of SBTE, the current profile evolves to a trapezoidal shape with a rise and fall time each about 1-2 µsec. The enhanced energy at the head and decreased energy at the tail have been clearly observed by means of a 90-degree electrostatic energy analyzer. Following an idea proposed by Hartwig, who noted that the long sequence of quadrupoles could be likened to a sequence of drift tubes (and could be used as such), Faltens has applied pulsed voltages to quadrupoles at seven locations, and timed the pulses to coincide with the passage of the bunch tail [19]. He has shown that the application of occasional low-voltage kicks, appropriately timed, are highly effective at resisting spreading and energy change due to space-charge, and that a well-compacted bunch tail can be maintained.

4.2. Multiple Beam Experiments

A year ago, anticipating a significant increase in funding (80%) for the HIFAR program in FY85, we were hard at work designing a new experiment, MBE-16, to demonstrate the physics issues of beam control in the presence of voltage and current amplification for multiple beams and, further, to give us experience in the engineering questions related to large (2-m diameter) induction cores and large insulators, such as would be needed in the early parts of an HTE. Los Alamos National Laboratory assumed responsibility for the challenging task of developing a 16-beam, high-voltage (2MV), high-current (150-300 mA/beam) injector. This injector -- apart from its envisaged use in MBE-16 -- will represent an important benchmark in the technology needed for the HTE injector [20].

When significant increases in funding failed to materialize we were forced to abandon the engineering and cost exploration of large scale components and decided, instead, to assemble an experiment to illuminate the physics questions of simultaneous current and voltage amplification of multiple beams. To utilize components, e.g., induction cores and insulators, that were to hand or available at low cost, we chose four beams as a suitable number for the experiment called, for obvious reasons, MBE-4 [21].

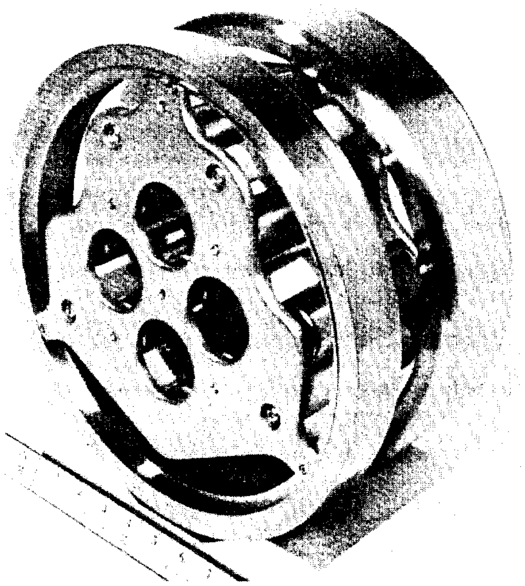

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Fig. 3. Electrostatic quadrupole array for MBE-4.

To deal with the problem of handling very large currents at low velocity the idea of subdividing a beam into a number of independently focussed beams has been an approach that has been proposed, or implemented, in the past, for example in the multiple sheet beams used for CTR neutral beam heating accelerators or multiple annular beams suggested by Herrmannsfeldt [22], both of which ideas rely on weak electrostatic focussing. The first suggestion of using strong-focussing for multiple beams, due to Maschke, has been followed by experiments with electrostatic quadrupoles by Maschke and by the F.O.M. group at Amsterdam [23]. Maschke's experiments, however, have had varying degrees of success depending on the transverse scale sizes chosen for the quadrupoles.

For high-current beams we note the following points that need quantitative consideration:

(a) For a single, monoenergetic beam, the transverse filling factor (maximum beam dimension/aperture radius) should not exceed 0.8 to avoid emittance growth even in a perfectly aligned system [Haber, 16]. For strongly depressed phase-advance ($60° \rightarrow 6°$) misalignments will lead to emittance growth.

(b) For a single beam in which current amplification is desired it is inevitable that the head and tail pass a given lens with different speed, hence with different σ. The response to misalignments, i.e., coherent betatron motion, is thus different for the bunch head and tail. Steering corrections must have a time dependence during the time of passage of the bunch; how frequently such corrections must be applied depends on the alignment tolerances of the lenses.

(c) For multiple beams within a focussing array such as shown in Fig. 3, beam-beam interactions can occur through self-electrostatic repulsion; these effects are small but represent a displacement in equilibrium orbit.

(d) In the case of multiple beams misalignment of an electrode shared between two or more beams will cause coherent responses that are different for the affected beams. Thus steering corrections must be arranged independently for each of the beams, which can be cumbersome and costly if needed frequently. If current amplification is attempted the steering corrections must be time dependent, too.

(e) Compromises in mechanical support, can introduce unwanted multipoles. The interdigital support method described in Ref. 21 creates a small but not wholly insignificant octupole term which affects the equilibrium orbit, and a dodecapole term that in principle (but probably not in practice) could cause emittance growth [24].

(f) Economic considerations point in the direction of minimizing the transverse dimensions of the electrodes to save aperture. How far one can go, depends on judgments about the degree of non-linearity, or reduction in beam-beam electrical screening, that can be tolerated.

Such considerations have led us to choose a quadrupole aperture radius of approximately one inch for MBE-4, with a beam radius of one-half an inch. The injector can supply more than the design current (10 mA per beam), and hence a beam of larger matched radius, so that we can test the degree of conservatism of these choices.

Voltage waveforms that must be supplied at the discrete accelerating gaps to accomplish a desired schedule for current amplification has been developed in the past year by Kim and others [25]. To accomplish current amplification, the natural distension of bunch length such as occurs, for example, in an rf linac (a constant current accelerator), must be halted by applying a higher accelerating field to the tail of the bunch than to the head. Depending on the choice of waveform, this distension can be simply slowed, or halted, or changed in sign (bunch length compression); in all cases, current amplification ensues, but to different degrees. Inspection of the results of Kim et al. reveals that example waveforms have a roughly triangular shape for the earliest accelerating gaps and approximately square waves for the latest gaps.

Thus, the overall goal of MBE-4 is to test with a significant number of hardware components how well multiply focussed beams can be controlled under circumstances where space charge plays a dominant role in

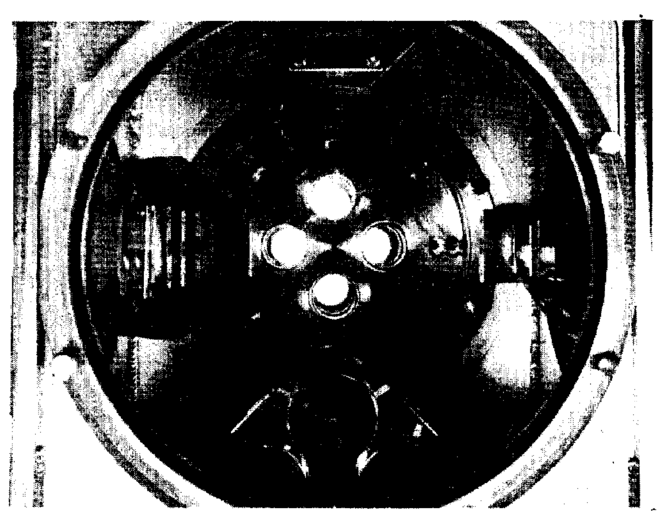

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Fig. 4. View of the four heated cesium zeolite emitters (at center). Diagnostic devices protrude from four directions (at sides).

both the transverse and longitudinal beam dynamics, and where current amplification is a crucial ingredient of operation. Results from MBE-4 can help greatly in the design of larger accelerator systems like HTE; in particular, it can help show us which may be the safe, and which the unsafe short-cuts to take in seeking to cut accelerator costs..

To date, the 4-beam injector has been operated successfully (see Fig. 4) [26]. The matching section which comprises eight independently controlled quadrupoles (and ample diagnostics) is being installed and will be ready for testing in a few weeks. Acceleration experiments with the first few induction units will take place in late summer. Completion of the apparatus is paced largely by availability of funds and is expected to occur late in 1986.

5. Other Activities

While the GSI group is planning an ambitious and important experiment on the energy loss of heavy ions in a high-density plasma target, Heckman et al. are pursuing studies of energy loss of heavy ions in cold condensed matter at the energies of interest for H.I.F. (50 MeV/amu) in low-Z and high-Z targets -- an energy range where data have not previously been taken [27]. Of special interest is the measurement of non-equilibrium behavior as the ions first enter the target material. For these studies, the Bevalac has delivered heavy ions of remarkably low charge-to-mass ratio, viz., Au^{+11}. While these measurements will help calibrate the theory on the bound-electron contribution to dE/dx, knowledge of the free-electron effects must await the plasma-target experiments.

Experiments at a modest level have been in progress at LBL on characterizing the performance of a plasma lens of the type described by Robertson, in which cold co-moving electrons are injected with the ions into a solenoid [28]. The use of such a powerful tool in the final focussing, while offering some risk, can provide enormous benefit when dealing with high-rigidity beams ($B\rho \sim 200$ Tm). Work is still in progress but further research on this approach seems indicated [28].

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