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THE ION BEAM COMPRESSOR FOR PELLET FUSION*

Ronald L. Martin
Argonne National Laboratory
Argonne, Illinois

Summary

Intense ion beams of short duration can be created by charge exchange injection into a number of small, high field storage rings. If the beams are extracted and focussed from many directions simultaneously onto a DT pellet, a beam of protons or α particles of 15,000-30,000 A for a duration of 1-2 ns can result. Such beams have possibilities for compressing and heating to fusion temperatures submillimeter pellets of a DT mixture. The potential of this method is discussed.

Introduction

Protons and heavier ions have attractive properties for heating materials to very high temperatures. These properties include: (a) penetration with increasing rate of energy loss as the ions slow down, (b) a well defined range with little straggling and a high percentage of their energy deposition in a small amount of material at the end of their range, and (c) they carry a large amount of momentum per unit of energy, also mostly transferred near the end of their range. The latter property may be important for density compression of a compressible material such as a DT mixture in a small pellet.

Proton beams of 100 mA for 300-500 μs duration at energies of 50-200 MeV are achievable today with proton linacs. Such beams carry a few kJ of energy. If one can compress these beams in time to the order of ns durations, they become interesting, though perhaps marginal, for heating submillimeter pellets of a DT mixture to fusion temperatures.

Multiturn injection into an accelerator or storage ring quite naturally compresses an injected beam in time to give higher circulating currents. It normally does this compression, however, with no increase in brightness of the circulating beam over that of the injected beam. Since brightness is a critical factor in one's ability to concentrate the energy into a small volume, the compression achievable does not appear to be adequate for the present purpose. With charge exchange injection, on the other hand, gains in brightness of a factor of 100 have been demonstrated. By this technique, compression of an ion beam of several kJ to ns time duration appears feasible and pellet fusion by intense ion beams becomes interesting. One would store the 300-500 μs beam into a number of small, high field storage rings by charge exchange injection and extract and focus the beams from many directions simultaneously onto a DT pellet.

Proton Beams

As a first example, one might consider the possibilities of intense proton beams. An H^- beam of 100 mA for 300 μs duration at 50 MeV appears feasible with existing technology. The beam would have the microstructure, imposed by the linac RF, that is, bursts of 1-2 ns duration each 5 ns (for a 200 MHz linac). A total of 600 turns would be injected (by stripping to protons) into a small, high field superconducting storage ring with a revolution period of 5 ns. Therefore, 3 μs of injected beam, or 2×10^{12} protons, would be stored in a single ring. To store the entire 300 μs beam would require 100 such storage rings with a proton orbit radius of 7.5 cm at a field of 14 T. RF fields at 200 MHz would maintain the 1 ns bunch structure of the circulating proton beam giving a peak circulating current of 300 A in each ring. Because the weakly bound electron of an H^- ion would be stripped by the fringe field of such a strong magnet, charge exchange injection here would be a two-stage process with stripping to neutrals occurring before the storage ring.

In order that 2×10^{12} protons not exceed the space charge limit of the storage ring, the emittance of the circulating beam should be 11 π cm mrad in both the horizontal and vertical directions. The emittance of the linac beam is assumed to be that of our existing 50 MeV proton beam, namely, 2.5 π cm mrad. Thus, there is adequate allowance for emittance growth due to scattering in the injection stripping foil. In the space charge calculations, I have assumed a Q value of 0.7 for the storage rings.

The smallest diameter onto which one can focus such a beam will depend upon the size and strength of the optical elements and on the emittance of the proton beam. With 100 beams, the total solid angle available to each is 4 π/100 sr, giving maximum convergence angles of 350 mrad for each beam. Assuming that one can make use of about 80% of this in a practical way, then convergence angles of 280 mrad seem feasible. The minimum diameter onto which a beam with an emittance of 11 π cm mrad can be focussed with this system is 1.6 mm.

Space charge effects will tend to enlarge on this minimum diameter if the angles of convergence are too small. However in the case assumed, the effects are negligible.

The range of a 50 MeV proton is about 2.2 g/cm^2, and the range straggling is about 1.2% of this or ± 0.026 g/cm^2. To stop the protons in the center of a small pellet, therefore, requires an outer shell of heavy material of a thickness of nearly the proton range, or somewhat more than 1 mm for a gold shell. The shell would be vaporized by this energy loss leading to a pressure of about 10^8 atmospheres to

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compress an inner DT pellet. About 10% of the total proton energy is deposited in the Bragg peak at the end of its range and available for direct heating of the pellet.

To summarize the concept of an intense proton beam: It would be 100 separate beams of 300 A each with a duration of 1 ns, all focussed simultaneously onto a small DT pellet with an outer shell from all directions. The total proton current would then be 30,000 A with a total energy of 1500 J. For the purposes of energy release from the fusion process, a repetition rate of 30-60 Hz would seem feasible.

He^{++} Beam

α particles with the same energy/nucleon as the proton beam have distinct advantages over protons for energy deposition in a small volume. They have four times the energy and four times the beam momentum for the same number of particles, have the same space charge limits ($\sim A/q^2$) in the storage rings, and have the same range with about one-half of the range straggling.

The requirement for charge exchange injection (from α^+ to α^{++}) into the storage rings means that singly charged α particles of 200 MeV have to be produced. To do so, however, appears quite straightforward, possibly even easier than the comparable H^- beam. Single charged α particles will be the predominant charge state to emerge from a duoplasmatron filled with helium gas. Source intensities approach those achieved with protons from the same type of source. A 3 MeV preaccelerator of high current is required for linac injection at 750 kV/nucleon. A 200 MeV α^+ linac at 100 mA would be comparable to the proton linacs at Brookhaven National Laboratory and Fermi National Accelerator Laboratory but with different drift tube structure.

The $H\rho$ of the storage ring to contain 200 MeV α^{++} is double that for 50 MeV protons. Since a 28 T storage ring is beyond the capability of existing superconductors, it appears that one must retain the limitation of 14 T fields and double the radius of curvature to 14.8 cm. The revolution period now becomes 10 ns, and one has the option of a single circulating bunch from a 100 MHz linac or two bunches from the more common 200 MHz linac. The latter could have some advantages in producing two beam pulses 5 ns apart, the first for compression of the cold pellet and the second for heating. In fact, the flexibility of dividing the total energy of the linac beam into any number of intense beam pulses at regular intervals exists with protons as well as α particles with proper design of linac and storage rings. In any case, it appears feasible to inject into any one storage ring for 3 μs and of the order of 100 storage rings will be required.

An α particle beam that might be produced would be two bursts of 300 A each (because of the double charge) from each storage ring at 200 MeV with a duration of 1 ns separated by an interval of 5 ns. The total current of 100 such beams would then be two 30,000 A pulses containing a total energy of 6000 J. Their range would be 2.2 g/cm^2 and the range straggling ± 0.013 g/cm^2. Their focussing properties would be identical to that discussed for protons, that is, able to be focussed onto a sphere of 1.6 mm diameter.

Remarks

Several accelerator type questions have not been discussed. Most significant of these is the problem of extraction from the storage rings. This problem appears to be formidable, and no conceptual solution presently exists. Its solution will have a strong impact on the design of the storage rings. I have not considered the problems associated with storing circulating currents an order of magnitude higher than any which exist. Fortunately, the required storage time is less than 1 ms. The layout of the injection lines, storage rings, and extraction lines is difficult to visualize because of the three-dimensional geometry. The requirements on the final focussing elements may be severe, particularly for the α beam with its high momentum of 1.2 GeV/c.

The information to resolve other questions does not presently exist. One of these is the optimum energy of the particles. Energies lower than 50 MeV for protons and 200 MeV for α particles would reduce the total energy of the beam, reduce the number of particles attainable in the beam because of space charge limits, and have a larger emittance. The range and range straggling would be less, however. The situation for higher particle energies is just the reverse. An optimization of the particle energy clearly depends on the details of the beam interaction with the pellet. The latter subject is most complex, not well understood, and beyond the scope of this paper.

Ions heavier than He could also have advantages at the same energy/nucleon. The higher energy per particle, however, is offset by the lower space charge limit of the storage rings. Their main advantage seems to lie in their reduced range straggling so that the rate of energy deposition at the end of range is high. The main drawback is the many competing charge states and the difficulty of attaining adequate current from the source and linac. On the surface, tritium appears to be an optimum ion species because of the A/q^2 term in the space charge equation. I do not regard this as a serious suggestion, however.

One interesting effect for which a simple solution exists is the electrostatic voltage the pellet would acquire with 2×10^{14} charges deposited in such a small diameter. Without compensation, it would reach hundreds of MeV potential! Electron emission from many sharp points connected to ground potential would guarantee near neutrality of the pellet, however.

Conclusions

The possibilities of producing short, intense ion beams by charge exchange injection is most promising although not all technical details are resolved. The potential of such beams for pellet fusion is not clearly understood. The total beam energies that can be foreseen are in a range that continued investigation seems justified.