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MULTIMEGAWATT NEUTRAL BEAMS FOR TOKAMAKS[*]

Wulf B. Kunkel[**]

Abstract

Most of the large magnetic confinement experiments today and in the near future use high-power neutral-beam injectors to heat the plasma. This review briefly describes this remarkable technique and summarises recent results as well as near term expectationa. Progress has been so encouraging that it seems probable that tokamaks will achieve "scientific" breakeven before 1990.

I. Introduction

All the major large magnetic confinement fusion experiments operating today or planned for the near future use powerful atomic-beam injection to heat and to sustain the plasma. The technique was originally developed for mirror-confinement where the particle life-time is only one scattering time, thus requiring fuel injection at or near operating energy.[1] The injection method turned out to be so effective, however, that it has also become the most popular supplemental heating technique for the large tokamaks in the United States, as well as abroad. The trend is not likely to change, at least until other schemes under development, such as high-frequency electric heating, have demonstrated similar capabilities.

There are two reasons why fast neutral atoms are particularly well suited for the heating of confined low-density controlled-fusion plasmas: They are easily trapped after passing undeflected through the surrounding magnetic field, and they tend to share all their energy with the target plasma. In addition, there are at least two "fringe benefits" worth mentioning: If the injected particles are themselves nuclear fusion reactants, such as deuterium, tritium of ^{3}He atoms, they may significantly increase the energy release rate above the thermonuclear level corresponding to the bulk plasma temperature by undergoing nuclear reactions before they have shared all their energy with the background. The so-called Two-Component-Tokamak (TCT) for example, is based on this feature.[2] On the other hand, if the injected particles are different and distinguishable from those making up the bulk plasma, new information concerning details of the energy transfer and particle transport processes can become available, affording us improved insight into the physics of magnetic confinement.

There are several problems associated with large-scale neutral-beam injection into confined high temperature plasmas, however:

1. It is not yet completely assured that massive injection of essentially monoenergetic suprathermal particles is not going to cause dangereous instabilities or anomalies incompatible with good confinement.
2. Before they are completely ionized streams of neutral atoms represent sources for electron capture by energetic plasma ions. This inevitably results in enhanced transport and possibly particle escape across the magnetic field that must be taken into consideration.
3. Most importantly, it should be noted that the production, and the transport into the confinement chamber, of beams of energetic neutral atoms at power levels of interest, i.e., in the megawatt region, are by no means trivial matters.

At the time of this writing it appears that none of the above have turned into unsurmountable obstacles.[2] On the contrary, indications to day are very encouraging[3], and it seems indeed probable that tokamaks with neutral injection will achieve "scientific breakeven" (fusion power released = beam power injected) before the year 1990.

This paper is a report on the status of problem #3 above, the solution of which called for the development of new technology. It begins with a brief discussion of the principles of and basic requirements for neutral-beam injection. The state of the art is illustrated by descriptions of existing injectors, particularly those developed at the Lawrence Berkeley Laboratory and at the Oak Ridge National Laboratory, and by a concise review of recent results. A short summary of expected near-term needs and required developments is also included.

II. Requirements

For a successful application to nuclear fusion neutral-beam injectors must meet a number or requirements and criteria. Not all of these can be considered present day state-of-the-art, although it will be seen that impressive progress has been made. A listing of all the major considerations is presumably self-explanatory:

1. Total injected power	(primary criteria)
2. Energy per particle	
3. Number of beams	(i.e. power beam lines)
4. Beam intensity	(i.e. apertures, length of beam lines)
5. Beam optics	
6. Particles species	(plasma considerations)
7. Species mix	
8. Impurity level	
9. Pulse length	
10. Repetition rate	(cost and operational considerations)
11. Gas efficiency	
12. Electrical efficiency	
13. Power recovery	
14. Reliability	
15. Source conditioning	
16. Ease of operation	
17. Maintenance	

Obviously this list is not complete; nor is it necessarily in any systematic order, such as priority, difficulty, or state of advancement. But it gives an idea of the scope of the subject. Inasmuch as this review is meant primarily as a report to the scientific community not directly engaged in fusion research, the emphasis will here be limited to the first half of the items listed, the others being considered of more restricted interest to the specialists only.

(a) Beam Energy

The energy of the neutral atoms is primarily determined by the need to deposit the particles well inside the plasma, preferably near the axis of the column. After entering the plasma a beam of fast neutrals attenuates by charge exchange collisions and by ionizing collisions with plasma ions and electrons: $dI = -\alpha I dx$. The probability of electron loss per centimeter of propagation in the beam direction, x, has been thoroughly discussed by Riviere[4], and useful simplified expressions for design estimates have been given by Sweetman.[5] For hydrogen atoms with energies $E<40$ keV (or deuterium atoms with $E<80$ keV) the attenuation is primarily caused by charge exchange. At higher energies the dominant process is ionization by plasma ions (see Fig. 1).

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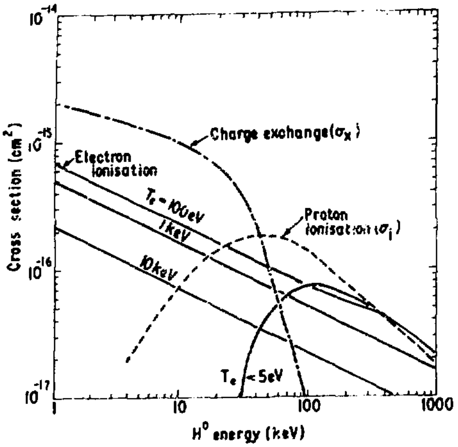

Fig. 1. Cross sections for charge exchange and for ionization of injected neutral hydrogen atoms versus energy (from Ref. 5). For injected deuterium atoms the energy scale should be multiplied by 2.

According to Sweetman for $E > 40$ keV the rate can be approximated by

$$\alpha(\mathrm{cm}^{-1}) \approx 1.8 \times 10^{-14}\ A\ Z_{eff}\ n\ (\mathrm{cm}^{-3})/E(\mathrm{keV})$$

where A is the mass of the neutral particle (in atomic units) and E is its energy (in keV)[5]. Z_{eff} is the usual effective charge per plasma ion.

The length $\lambda \equiv \alpha^{-1}$ can be looked upon as a mean-free-path for ionization and must be comparable to the desired depth of penetration. Thus we see here that for large fusion experiments with plasma diameters of the order of 1m and densities $n \approx 10^{14}$ cm^{-3} penetration to the axis calls for 200 keV deuterium atoms, even if the plasma is pure and has $Z_{eff} \approx 1$.

(b) Beam Power and "Current" (Flux)

The standard method of producing the required neutral beam consists of first generating and accelerating ions to the desired energy and then converting a fraction of them into neutral atoms. For the usual positive ions (e.g. protons and deuterons) we can use the process of electron capture (charge exchange). The latter is accomplished simply by passing the ion beam through a gas-containing "neutralizer" region. [The beam flux is therefore usually expressed as a "current" in equivalent amperes, as if the particles were singly charged]. The electron capture cross section σ_x is quite large for ion energies in the keV range. But as seen in Fig. 1, it is a decreasing function of the particle velocity. The charge exchange neutralizer target thickness therefore has to be larger for higher energy beams. Unfortunately, the probability of reionization decreases less rapidly with increasing energy than the probability of electron capture, so that the net conversion efficiency for positive ions into neutrals by thick neutralizer targets is still a rapidly decreasing function of energy (see Fig. 2), and at a given energy is lower for hydrogen than for deuterium.[6]

The situation is a little more favorable if we start with diatomic, or better yet with triatomic ions since these have lower velocities. But these ions are not as readily produced in large quantities and, moreover, they result in neutral atoms with fractional energies only. It turns out to be much more promising, as far as net conversion to neutrals is concerned, to start with negative hydrogen (or deuterium) ions and produce neutral atoms by electron detachment in a stripping cell after acceleration if energies well above 50 keV (100 keV for deuterium) are needed. Therefore efforts are under way to develop intense sources of negative hydrogen ions[7], and perhaps some day these will be considered standard equipment. At present, however, for the near term, we have to rely on relatively inefficient positive-ion-based beams.

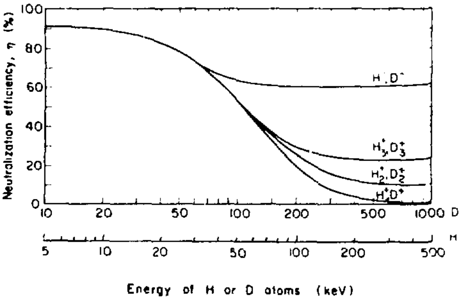

Fig. 2. Maximum efficiency of converting ions of hydrogen (deuterium) into neutral atoms in a collision chamber.

The electric discharges which are used to produce the positive ions generally yield a mixture of the three species shown in Fig. 2. The exact proportions are not readily predictable, but in high-power discharges at low filling pressure the atomic fraction tends to dominate. Whatever the ion mixture turns out to be, the neutralizer converts almost all particles into monatomic species, if it is sufficiently "thick". The original ion mix is then reflected primarily in an energy mix.

The relevant cross sections for these hydrogen ion interactions with hydrogen gas target molecules are fairly well known[8]. Hence neutralizer output yields have been calculated as a function of target thickness for low density beams (i.e. for beams that do not modify the target by their presence), for different input species and for a variety of beam energies.[6,8] A representative graph from Ref. 8 is shown in Fig. 3. The total neutral yield in this case (typical for a TFTR deuterium beam) is about 50% of the ion beam power. But only 1/3 of the original power is in full energy neutral atoms. For the lighter hydrogen, or for higher energies, the situation is worse.

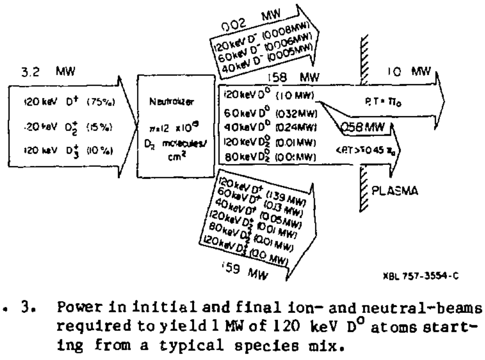

Fig. 3. Power in initial and final ion- and neutral-beams required to yield 1 MW of 120 keV D^0 atoms starting from a typical species mix.

While the desired particle energy is readily obtained with conventional ion sources in the milliampere range, the power levels generally required for meaningful fusion experiments call for new technological development. The power needed to sustain a plasma volume V m^3 with a mean density of n ions/cm^3, ion and electron "temperatures" of T_i and T_e resp. (in keV/particle) and energy confinement time τ expressed in milliseconds is given by

$$P(MW) \approx 2.4 \times 10^{-13}\, \bar{n}(cm^{-3})(T_i + T_e)(keV)V(m^3)/\tau(ms).$$

For large experiments in the thermonuclear regime this means injected power in the multi-megawatt range is indeed required. For injection energies of the order of 100 keV this implies neutral currents in the neighborhood of 100 ampere, i.e. ion currents from the ion sources of several hundred ampere. Fortunately, these currents tend to be divided up among a number of sources. But each source must be capable of delivering some tens of amperes of ions to be useful in such an application.

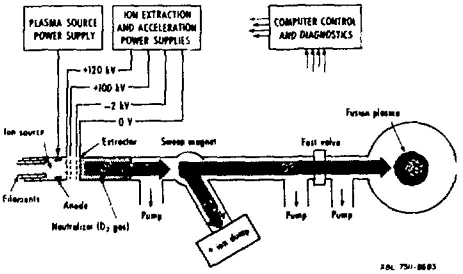

Fig. 4. Schematic of a typical neutral beam injection system.

III. Neutral Beam Injection Systems

It is best to start with a brief description of an entire neutral-beam injection system. A schematic diagram of such a system is shown in Fig. 4. The basic elements are:

1. Ion source (an electric gas discharge or plasma generator).
2. Accelerating structure (a set of grids with aligned apertures).
3. Neutralizer (a beam-transport region containing low density gas).
4. Ion separator (a sweep magnet and divertor tube).
5. Ion dump (possibly an energy recovery system).
6. Neutral-beam transport tube (possibly with beam scrapers).
7. Pumping system (preferably using cryogenic panels).
8. Source and beam power supplies (well regulated).
9. Control system (computerized and fully automated).
10. Various automatic diagnostic devices (current and temperature sensors and spectroscopic monitors).

The principal functions of the various components are obvious and need little explanation. The system operation is as follows: A hydrogen or deuterium plasma is created in the plasma generator by means of a high-current discharge. Ions from this plasma are accelerated in a carefully designed multi-electrode structure. The ions then pass through a neutralizer containing deuterium gas, and a fraction becomes neutralized by charge-exchange collisions. Remaining ions are removed from the beam by the sweep magnet; otherwise, the various reactor magnetic fields would bend the ions into surfaces near the entrance port, possibly releasing gas bursts or melting the surfaces. The considerable power in this ion beam must be handled by the ion-beam dump. The vacuum pumps distributed along the beam line remove most of the gas emerging from the neutralizer and the ion-beam dump and must maintain the pressure between the sweep magnet and the entrance port at a sufficiently low value that very little of the neutral beam is reionized. Well-regulated power supplies are required to assure good beam optics; to minimize accelerator damage when a spark occurs, the power supplies must also be capable of rapid turn-off with a minimum of stored energy (e.g. in cable capacitance). Optical, mechanical, and electrical sensors determine the condition and performance of the neutral-beam system and permit the control system to adjust the power-supply voltages and to shut down the system if a malfunction occurs.

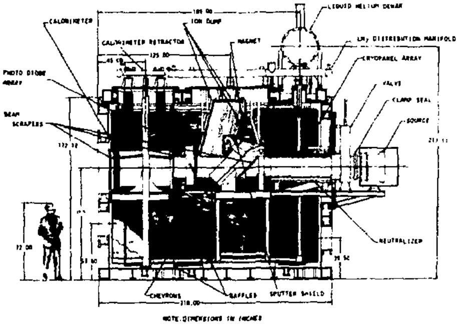

Fig. 5. Design for the TFTR prototype beam line.

Actual beamlines for multimegawatt injection become very bulky, mainly because of the large gas pumping requirements. It is likely that the injectors will always take up more space than the confinement device itself. For example the prototype beamline for the Tokamak Fusion Test Reactor (TFTR) had to be set up in the 184" cyclotron building at the Lawrence Berkeley Laboratory; no other building at LBL was spacious enough. A design sketch is shown in Fig. 5, to give an impression, with the canonical six foot person at the left.[9] The pumping in this case is seen to be accomplished with large "cryopanels" at liquid helium temperature.

The TFTR at the Princeton Plasma Physics Laboratory has been designed to operate eventually with four or at least three such beamlines, each containing three individual beams from three sources delivering 60 A of deuterium ion current per source for 0.5 sec. The accelerator voltage is 120 kV so that a species mix as indicated in Fig. 3 will deliver about 2 MW of full energy neutrals per beam plus an additional 1.2 MW of neutrals at fractional energies.

IV. High Current Ion Sources

The most critical items in these injection systems are the large ion sources. They have to generate and deliver tens of amperes of ions essentially in a steady state in such a manner that well collimated (low divergence) beams can be formed in simple electorstatic accelarating structures. Space charge and electric breakdown considerations limit the deuteron current density in this energy range (20 to 150 keV) generally to 0.5A/cm^2 or less. This means that the beams, and thus the sources, must have cross sectional areas of many tens of square centimeters. The latter, in turn, implies that the beams must be formed in multiple-aperture accelerating structures.

Large area ion sources and multiple aperture beam-forming electrodes are familar components in space technology as electrostatic ion "thrustors" for advanced propulsion systems.[10] The "propellant" in that case is usually mercury instead of our isotopes of hydrogen, and the current densities are very much lower.

The stringent requirements on ion optics for our application make it imperative that the current density is steady and uniform to within a few percent over the entire extraction area. As is well known, ionizing discharges in gases do not usually have these characteristics. In particular, plasma densities and hence current densities tend to be higher in the center of the enclosure and decrease monotonically with decreasing distance from the walls.

Special measures have to be taken, therefore, to produce sources in which the available ion current density is sufficiently flat over an extended large extractor area. The first successful megawatt beam sources solved this problem with a large number of hot tungsten filaments as cathodes distributed along the perimeter of the extractor area.[11] In a way these can be regarded as high-power versions of the quiescent plasma generators that have been pioneered at UCLA.[12] Because of the large required electron emission these 75A, 20-40 kV sources (good for 1 MW of neutral deuterium) are limited to pulse durations of 30-50 msec. This turns out to be good enough for many experiments with mirror confinement, in progress at the Lawrence Livermore Laboratory where a fair number of such sources have been in operation for some time and have proved quite reliable.[13]

For the heating in tokamaks, however, longer pulses are needed, and the multifilament sources developed at LBL do not necessairly represent the most practical solution. Very successful, and currently in operation at the Princeton Plasma Physics Laboratory as well as at the Oak Ridge National Laboratory, are the so-called modified "DuoPIGatrons" developed at ORNL.[14] A sketch of the 22 cm diameter model is shown in Fig. 6. It is rated for 60A proton currrent extraction at 40 kV for 300 ms pulses, for injection into the Princeton Large Torus (PLT). Larger versions, good for 100 A per source, are getting ready for the Poloidal Divertor Experiment (PDX) at Princeton and the Impurity Study Experiment (ISX) at ORNL.

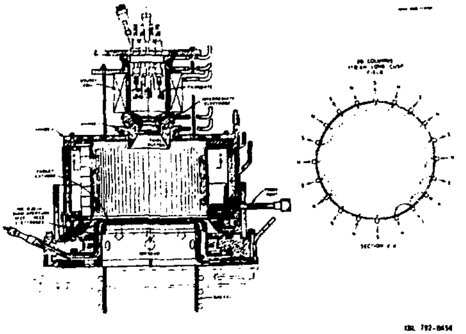

Fig. 6. ORNL 22-cm modified dup PIGatron ion source with magnetic bucket, as developed for PLT.

These sources are essentiallly expanded DuoPIGatrons[15] i.e. they are powerful duoplasmatrons (magnetically focused double discharges) in which the second section is operating as a reflex arc (PIC discharge). Such devices are known to be efficient plasma producers, but they also tend to be "noisy", that is, they suffer from

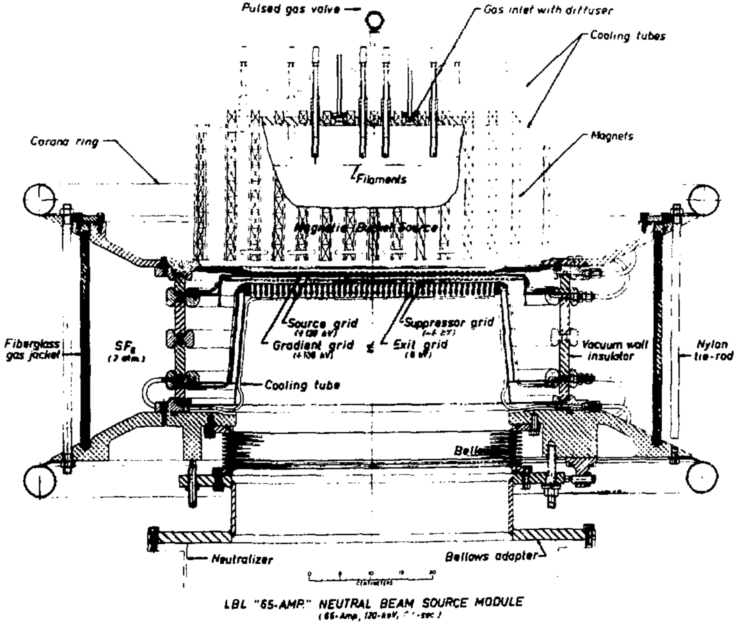

Fig. 7. Cross section of a 120 keV 65A source for TFTR, with magnetic bucket.

large amplitude fluctuations. The addition of the large expansion chamber with multipole magnetic fields isolating the essentially field-free plasma from the walls (see Fig. 6) seems to damp out the fluctuations and simultaneously permits the plasma to spread uniformly over the end face which carries the beam forming grids. Moreover, impressive yields in excess of 80% atomic ions have been reported for this source. Multipolar magnetic surface fields have also been used successfully before in ion-propulsion engines,[16] and the technique has been perfected and extensively applied to the production of large quiescent plasma for basic studies.[17] The configuration is rapidly gaining popularity under the name "magnetic bucket", although some plasma always leaks out along the magnetic cusps so that the term "magentic basket" would be more appropriate.

The 120 kV source that is being developed at LBL for Princeton's TFTR is sketched in Fig. 7, It is rectangular in shape with an ion extraction grid that measures 10 cm x 40 cm, as seen in the photograph of the accelerator structure in Fig. 8.[18] Rectangular shapes are more difficult to work with than axisymmetric arrangements which can be assembled from a variety of cylindrical sections and hence can more easily be repaired or modified. However, an elongated cross section is advantageous for TFTR beamlines which have to accommodate three such sources side by side. In Fig. 8 it is also seen that the apertures here are parallel slots instead of circular holes, as are used in most other beam sources. In other words, the grids are made up of sets of rails that are carefully aligned and cooled at the ends, rather than of plates with a large number of holes drilled through them. Long slender slots are well suited to our rectangular geometry, and in this respect this TFTR source has been patterned after the short-pulse 2XIIB source mentioned before." In the first version the discharge is operated without magnetic field but with a large number of filaments, as before. In Fig. 7 we show a modified version incorporating the magnetic-bucket feature and using fewer filaments. Improved efficiency and a higher atomic ion yield has indeed been demonstrated for this configuration.

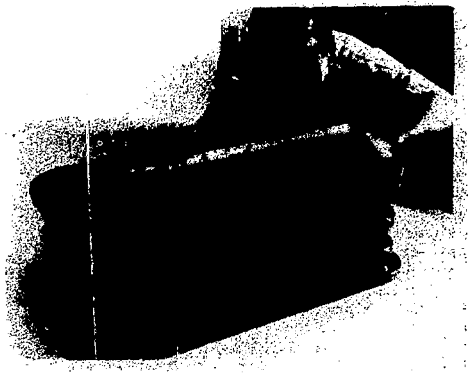

Fig. 8. 120 keV 65A accelerator module.

In an effort to optimize the ion optics an iterating computer code was developed that calculates conditions for minimized beam divergence in the presence of space charge and temperature effects.[19] Figure 9 shows as an example the TFTR accelerator structure designed with the help of this code for a current density of 0.3 A/cm^2. The wedge angle in the first grid, a so-called "Pierce configuration", is particularly important for good beam formation. Multiple-aperture structures with circular holes have usually not been able to accomodate anything but straight edges because any funnel-like shape, such as that in Fig. 9, would reduce the net transparency of the grid to an intolarably low level. In this respect long slots have a distinct advantage over circular holes. On the other hand, the actual price paid for the imperfect optics of simple straight holes, in the form of fringing beam edges and resulting beam interception has not yet been fully assessed.

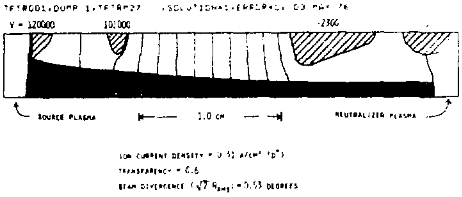

Fig. 9. Computer-designed 4-electrode accelerator structure with 120 keV ion beam.

The large tokamak with noncircular cross section, Doublet III, at General Atomic in San Diego calls for 4 80 keV sources. These are also being developed at LBL, and are very similar in design to the TFTR sources. Other large tori that are being set up abroad, in England, Japan and the Soviet Union, will have multimegawatt injectors that may differ in detail but the gross features will all be similar to those shown in Fig. 4.

V. Results and Prospects

The only fully operational multimegawatt injection system for tokamaks, with pulse duration in excess of 100 msec, today is built by ORNL for the PLT experiment at Princeton. A schematic plan view if the layout with its four beamlines is shown in Fig. 10. When all four beamlines are energized the total power injected into the plasma in the form of neutral beams exceeds by a large factor the ohmic heating power that initially formed the target plasma. Such operating conditions had never been achieved before in tokamaks and there was some concern that new problems would make their appearance. Fortunately, no deleterious effects were observed, which is particularly encouraging because the plasma reached high-temperature long-mean-free-path conditions similar to those required for a power producing fusion reactor.[20] A representative result of plasma ion heating by 2.5 MW neutral deuterium injection into PLT is reproduced in Fig. 11.

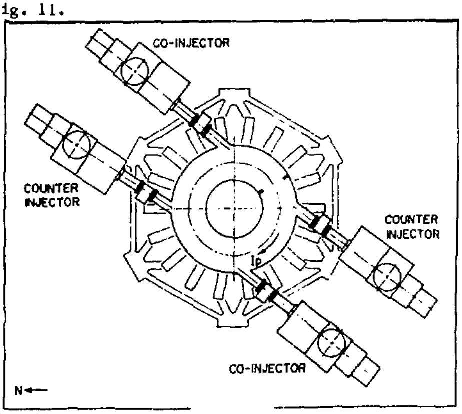

Fig. 10. PLT schematic plan view with four injectors.

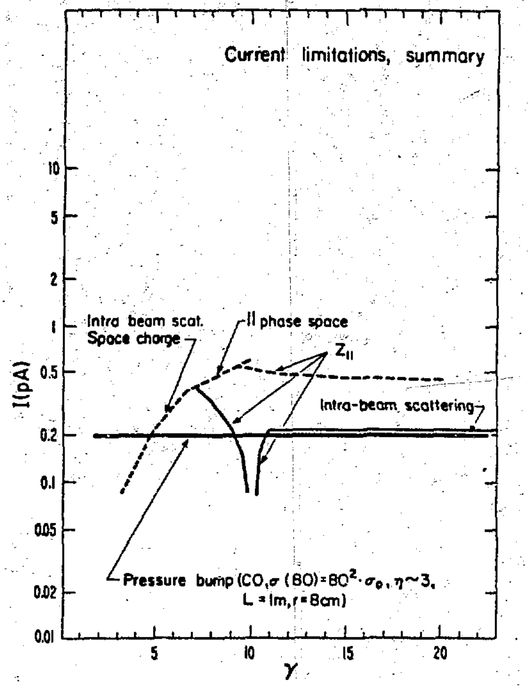

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Fig. 9 Summary of currents limitations, including estimate of limitation imposed by pressure-bump phenomenon.

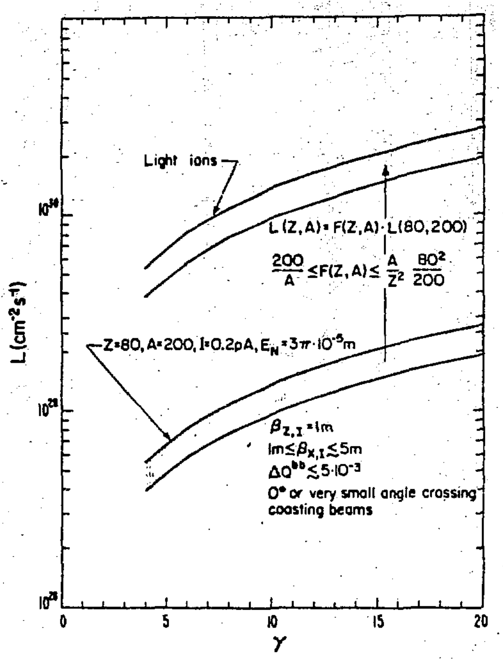

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Fig. 10 Luminosity estimates for parameters indicated in figure