HIGH ENERGY (1-2 MeV) BEAMS FOR MAGNETIC FUSION - TOKAMAK PLASMA HEATING AND CURRENT DRIVE*

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The next-generation fusion devices based on the tokamak confinement concept are expected to emphasize steady-state operation. Such future reactors may include designs like the International Thermonuclear Experimental Reactor (ITER) and that of the recent International Tokamak Reactor (INTOR) program. Effective means of non-inductive plasma current drive would therefore be necessary.

This paper describes a concept for a current drive system based on negative ions with beam energy > 1 MeV. Preliminary physics calculations[1] show that the core current necessary for stability enhancement can best be achieved in these future reactor-like machines with beams having energies ranging from 1 to 4 MeV. Further study and experiments will better define the optimum energy. In particular, within the last year, the plasma theorists have shown that the required energy for optimum neutral beam current drive (NBCD) efficiency is, for a machine with the parameters of ITER, approximately 1.5 MeV (US ITER Team selected 1.6 MeV). Additional calculations by Houlberg, et al,[2] have also shown that a vertical column of parallel beams injected tangentially into the tokamaks and inside the magnetic axis can provide a beneficial contribution to the plasma current profile control. Studies of how to accomplish beams of this energy led to the system described in this paper.

DC accelerated beam systems were first considered and have been studied in the past for positive ion beams.[3-8] The biggest difficulty in this development is the presence of electrons due to beam gas interaction and their acceleration down the column reducing the system efficiency, and reliability by creating x-rays, and causing breakdown of insulators and further ionization. However, for negative ion based dc accelerators there are several differences: (1) the relative low gas efficiency of the negative ion sources (1% that of positive ion sources) that cause higher quantities of gas to exit at the extraction apertures; (2) the stripping cross section is five times higher; (3) about 20-200 times more electrons want to be extracted from the negative ion source for every negative ion. Some negative ion source concepts attempt to trap these electrons possibly to the 90% level. A result of the processes (1) and (3) is the presence of an abundant supply of electrons in the negative ion source exit. This results in some efficiency degradation, since they can be accelerated along with the negative ions. Any additional electrons born along the beam in the accelerator column will also be accelerated. Examples of such accelerators intended for ITER application are shown in Figs. 1 and 2 for the EC and USSR proposal, respectively. These accelerators apparently do not take the precaution of using x-ray and ultraviolet shields that are present in the developments of the similar systems described in Refs. 2-7 (see, for example, Fig. 3 from Ref. 3).

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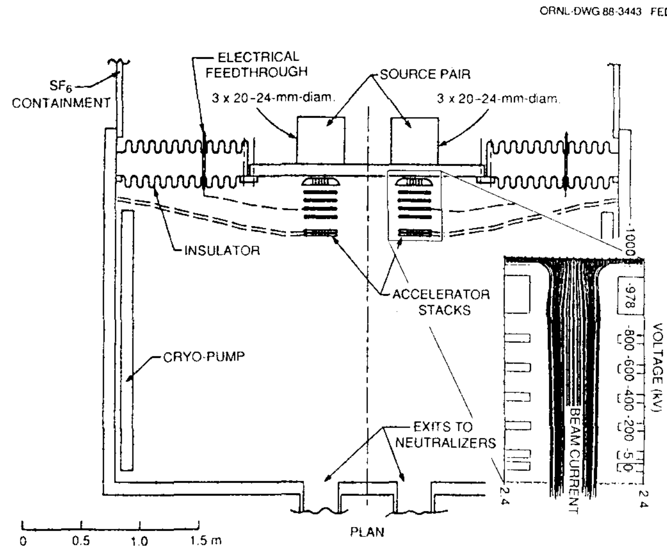


Fig. 1
Accelerator Concept, EC Proposal for ITER

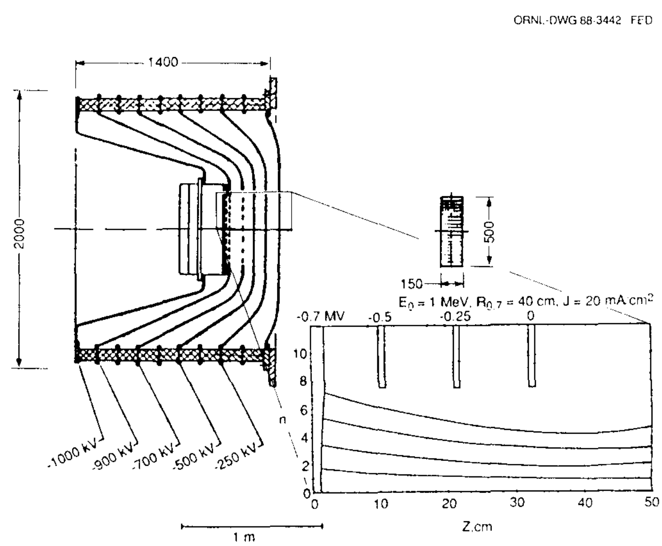


Fig. 2
Accelerator Concept, USSR Proposal for ITER
Soviet Proposal

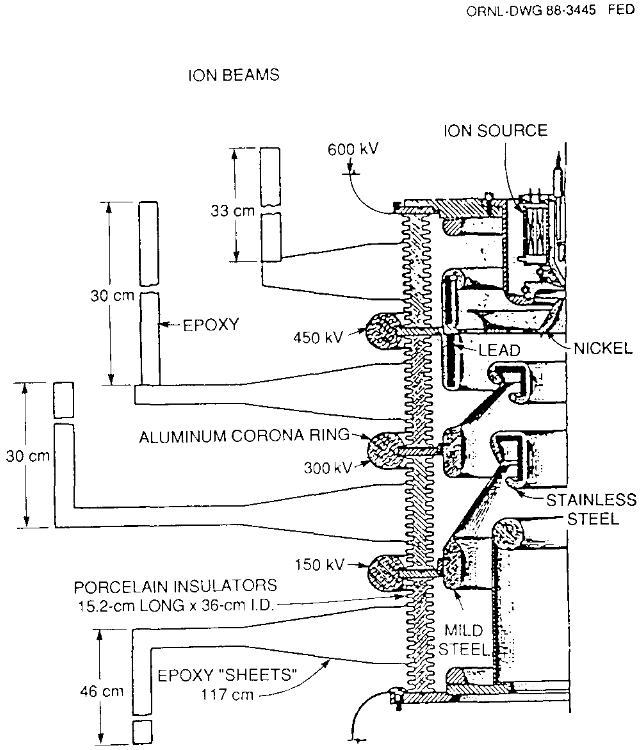


Fig. 3
600 kV Beam Accelerator Design, ORNL

Consideration has been given to some means of efficiently filtering out the electrons so none would be available to be accelerated along with the ions. However there is no dc system that has been proposed that does not allow a large portion of the electrons to accompany the negative ions. Some attempts have been made to apply transverse fields to prevent electrons from being accelerated down the gap. For example, the LBL-ESQ accelerator shown in Fig. 4 has transverse fields which were claimed to trap the

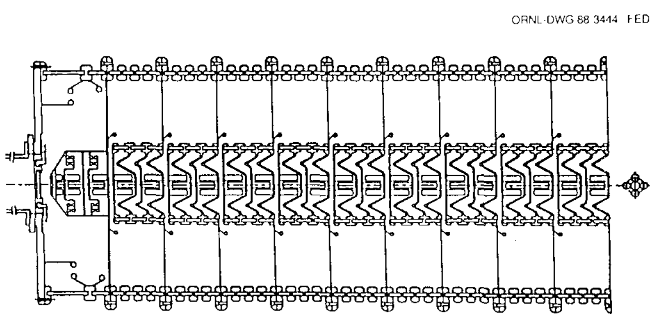


Fig. 4
LBL-ESQ Accelerator Concept Proposed for ITER

electrons. A typical ESQ accelerator section is shown in Fig. 5, showing these transverse fields through a 3-D solution to the Vlasov-Poisson equations.[9] A closer look at Fig. 4 shows the asymmetric ESQ termination which is shown heuristically in Fig. 6. There are significant longitudinal electric fields which result in about half of the volume produced electrons being accelerated down the column (calculated in Fig. 7).

It seems apparent from a cursory consideration of power supply technology, that the high voltage dc power supply and controls needed for such a steady state system would be a formidable design challenge and, even if it could be made to perform reliably, would have losses in such elements as the required voltage dividers and control elements that the ac to dc efficiency would be seriously reduced.

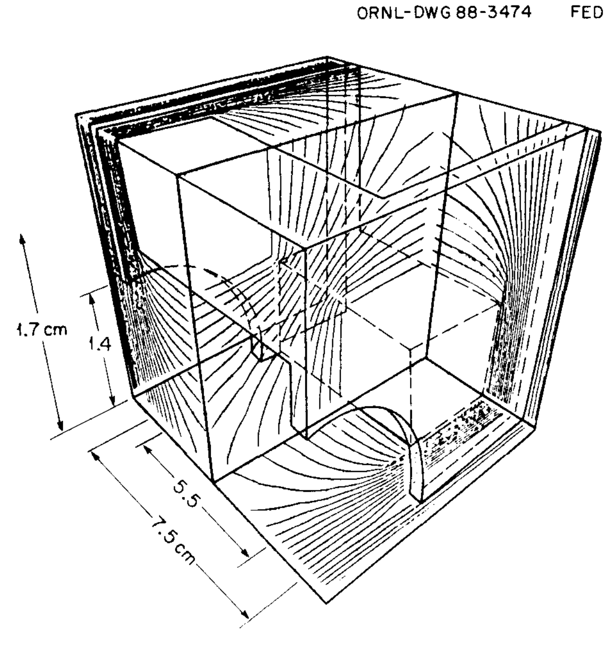


Fig. 5
Transverse Fields, ESQ Section

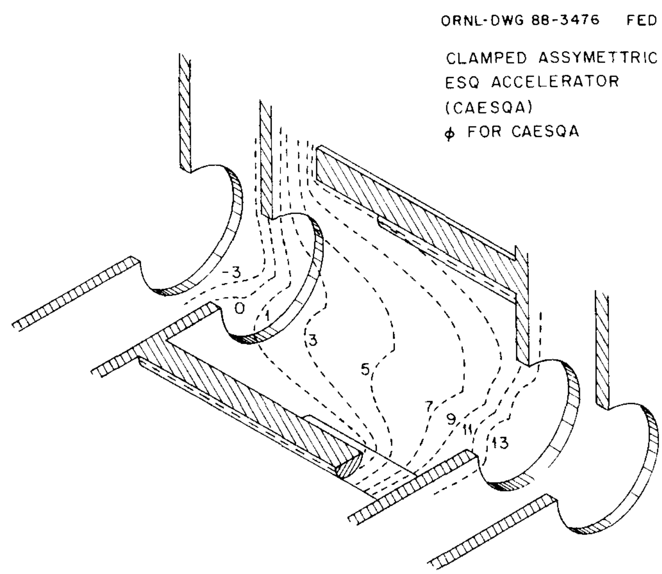


Fig. 6
Longitudinal Fields Shown Heuristically for ESQ Section
Clamped Assymetric ESQ Accelerator
(CA ESQA) Ø for CAESQA

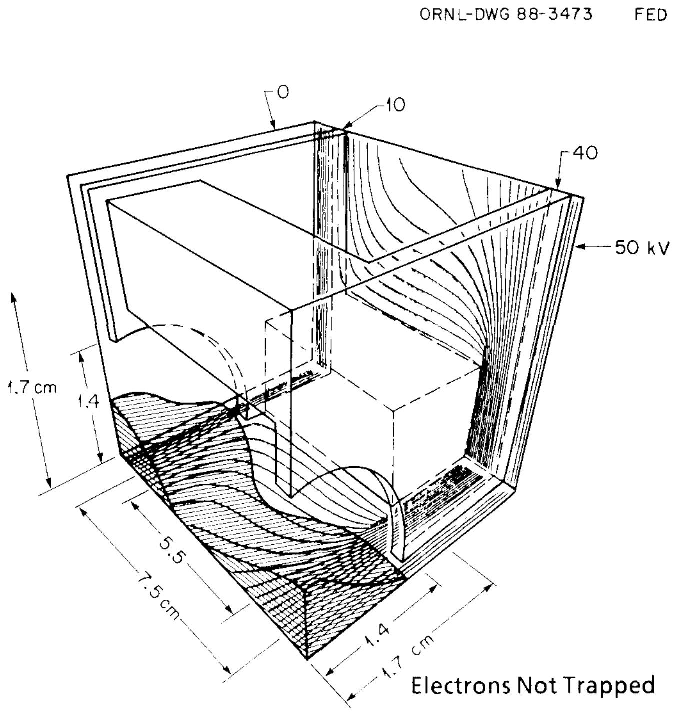


Fig. 7
ESQ Calculations Showing Electrons Not Trapped

The approach that was taken to obtain a system that could avoid the above dc system issues of efficiency and reliability was to use rf beam acceleration based on the radio frequency quadrupole (RFQ). This was first considered because the RFQ has been universally accepted by the accelerator institutes around the world to provide intense ion beam acceleration up to a few MeV, similar to the task required for fusion. Work under way on this approach at Oak Ridge National Laboratory (ORNL) and at collaborating institutes in the USA, Canada and the Federal Republic of Germany is defining such a system for fusion application. The beam system under study comprises a negative ion source (similar to the JAERI development source), a low-energy beam transport (LEBT), a radio-frequency quadrupole (RFQ) accelerator (4-rod concept), a plasma neutralizer, ion dumps for non-neutralized particles, and the necessary auxiliary elements such as a vacuum system. The system concept to be described was developed for the ITER application and has two 40MW (20 A, 2 MeV) beamline units.

Such an RFQ device was first tested in 1975 and today there are over 60 in operation worldwide. The critical disadvantages with a dc approach as enumerated above are eliminated or significantly reduced by using an RFQ. The RFQ acts somewhat as a "mass filter" and will not accelerate electrons to full energy along with the ion beam. It therefore does not suffer from the same efficiency loss that a dc system would inherently have from accelerating these electrons. Also there are no insulators in the RFQ to be affected by any X-rays that may occur.

Design concepts for neutral beam current drive systems have been developed at ORNL, in collaboration with the above groups, using the rf accelerator technology base that has expanded so rapidly in recent years. In addition to the substantial and growing operating database for the RFQ accelerator, a significant advantage accrues from the fact that its driving power is rf in the ion cyclotron range of frequencies (ICRF) (10-120 MHz) for tokamaks, a very available and economical power source. The rf frequency of the RFQ's can be selected so that it is within the ion cyclotron resonance frequency (ICRF) range. This could facilitate power sharing between programmatic phasing of ICRH and NBCD if both systems were to be used. Present accelerator theory appears adequate to design such RFQs, and experience at various laboratories with heavy ion accelerators at similar frequencies, and light ion accelerators operating near their space-charge limits, lends confidence to the predictions of rf properties and accelerator efficiencies calculated for the system described below.

The RFQ design selected is based on the 4-rod RFQ concept, advanced by Schempp,[10] along with McMichael, Hutcheon, et al., which is particularly suitable for high-current designs. Conceptual designs for RFQs with an output currents up to 3.7 A per column have already been done and are under further study.[11] Calculated energy efficiencies (rf to beam coupling) exceed 70% for such room-temperature RFQs, even though the designs are yet to be optimized for efficiency. A program has been initiated to study the potential of raising the RFQ room-temperature efficiency to as much over 80% as seems feasible from a cost payoff basis.

Several different forms of rf accelerators have been considered: in particular, the MEQALAC, drift tube linear accelerators (DTL), and RFQs. Only the RFQ can simultaneously provide continuous adiabatic bunching and strong focusing. It is an ideal matching device between a continuously operating ion source and the discrete beam bunches needed for rf accelerators. It is this development that makes possible the efficient acceleration of very intense beams from low energies. Only four electrodes are required for each beam throughout the entire RFQ system, which consists of a matching section, an adiabatic buncher, and the accelerator with continuous radial focusing throughout.

The system proposed for ITER by ORNL and its collaborators is shown conceptually in block diagram in Fig. 8. It comprises the negative ion source, a low-energy beam transport system to match the beam to the RFQ, the RFQ, a plasma neutralizer, and an ion dump. The neutralization fraction of 0.85 for the 2 MeV beam plasma neutralizer is used in the design.

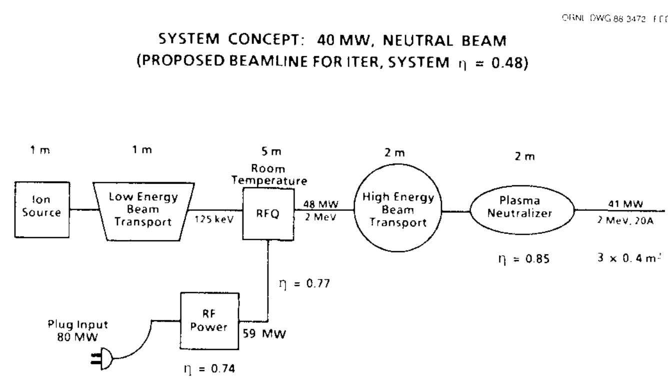
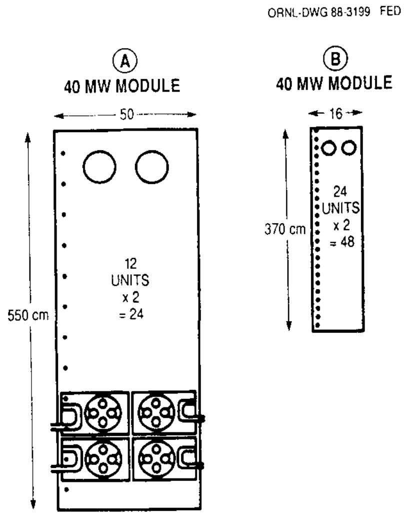


Fig. 8

The reliability, availability, and maintainability requirements of ITER indicate a per-module or per-port need of 40 MW (either 40 amps at 1 MeV or 20 amps of neutral beams at 2 MeV appears preferable). The RFQ is shown in two variations in Fig. 9. The RFQ variations are shown for two options, one (Option A) was designed to have a current of 1 A per channel in the RFQ and, assuming a 2-MeV system, would consist of 24 channels in a 2×12 matrix to provide 24 A of ions (20 A of neutrals) to achieve the needed 40 MW per beamline. The second case (option B) has a current of 0.5A per channel in the RFQ where there would be 48 channels in a 2×24 matrix. The system trades of these two options have been considered in some detail with respect to rf efficiency, emittance growth, beam size, and beam divergence. In particular, the divergence of the 23 MHz, 1 A per RFQ module is approximately 10 milliradians. In the case of the 65 MHz, 0.5 A per RFQ module, the beam divergence would be about 3 milliradians, corresponding to a significantly smaller emittance growth. The ac line to ion



CURRENT	1A	1/2A
ENERGY	2 MeV	2 MeV
FREQUENCY	23 MHz	65 MHz
POWER	80 MW	80 MW
BEAM AREA	2.8 M2	0.6 M2
NEUTRAL BEAM DIVERGENCE (NO TELESCOPE)	10 mr	3 mr

Fig. 9
A Geometric Arrangement:
Two RFQ Options

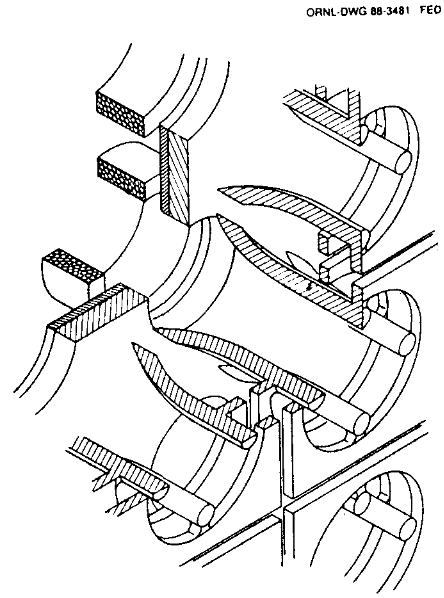
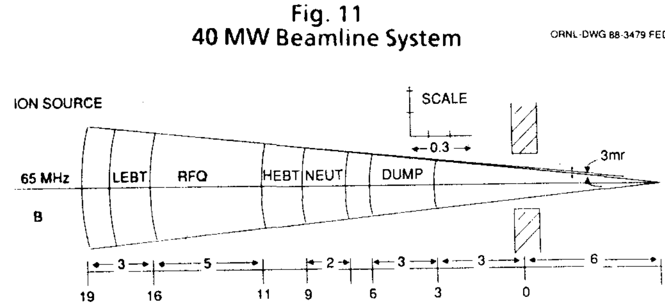


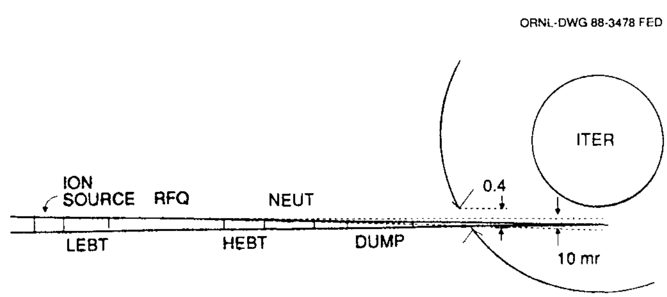
Fig. 10
4 Rods for One Column
RFQ Entrance

Fig. 11
40 MW Beamline System



Option B

PLAN VIEW
40 MW SYSTEM



Option A

beam efficiency for the 23-MHz system has two elements: (1) the efficiency of the wall plug to the rf power, using 2.5 MW transmitters, which is estimated from a nonoptimized system database to be 74%, and (2) the coupling efficiency of the rf power to the beam exiting from the RFQ which, for a configuration that also has not been optimized, is calculated to be 76%.

The efficiency of the rf transmitter (wall plug to 23 MHz) is extrapolated based on test data. A measurement was done on a variable frequency, 40-80 MHz, 1.5 MW cw unit, operating in a near-class B mode, and the resulting efficiency was 65.2%, wall plug to outlet power. However, by converting to a 2.5 MW tube vs a 1.5 MW tube, having only single frequency of 23 MHz, and operating at hard-class C, the projected output is 73.9%. This calculation uses plate efficiencies of 79.4%. EIMAC and BBC's tube specifications show plate efficiencies of over 80%. This efficiency combines with that of the RFQ above to yield a total "plug to ions" efficiency of 57%.

A view of a section of the RFQ entrance showing the arrangement of the four rods per beam column is shown in Fig. 10. The rf technology issues here, and the balancing and phasing requirements of the RFQ, appear tractable and solutions are underway that will enable a rather compact design with a high transparency.

The elevation view of the option B beamline shown in Fig. 11. The ion sources would be 19 m from the port. The beamline subsystems are shown approximately to scale. The most notable difference between options A and B would be the 10-milliradian, 3-milliradian beam divergences respectively. A plan view of option A is also shown in Fig. 11, and includes the approximate dimensions of the ITER tokamak. The divergence angles of 10-milliradions for option A is shown in this particular view. The 3-milliradian beam (option B) would be more convenient with respect to machine interface.

An approximate isometric view of the system is examined in Fig. 12, showing the various components. Blowups of several regions are considered. The first is a blowup of the

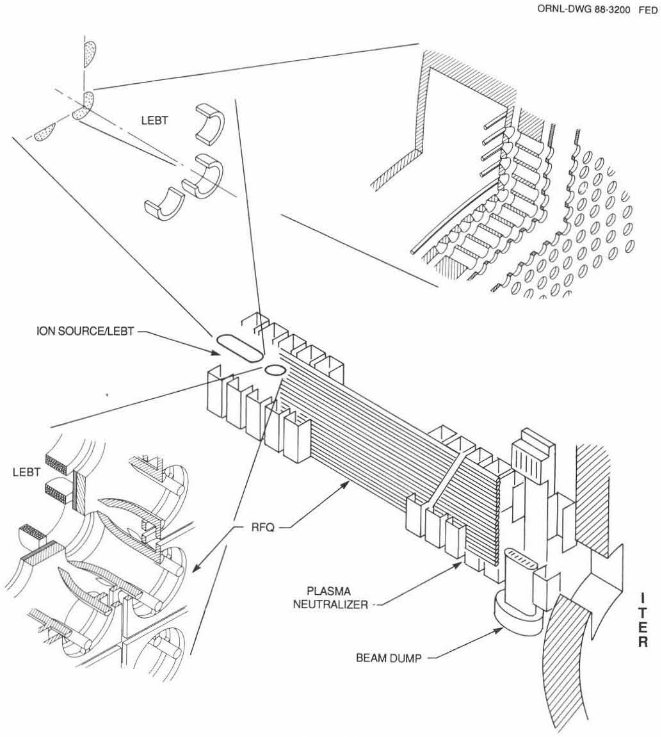


Fig. 12
Schematics of RFQ Beamline Elements
Ion Source

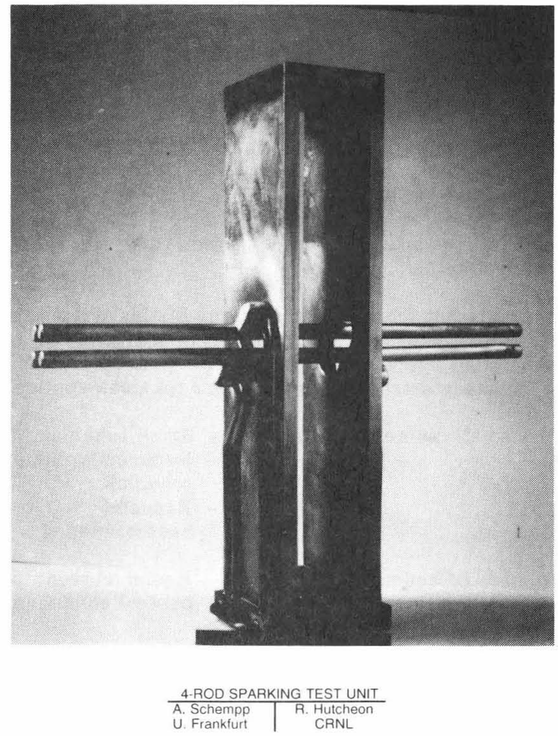


Fig. 13

ion source. Each channel of the RFQ would be fed with one such ion source. Furthermore, each ion source in the figure is further expanded to show the multi-beamlet channels as are in the configuration of the JAERI ion source. The LEBT consists of a drift region which includes a plasma, and extends from the ion source to the entrance to the RFQ. Within the LEBT, beams are directed by steering the beamlets as shown in the blowup of the ion source. A solenoidal magnetic field at the end of the LEBT matches the beam properties with the acceptance of the RFQ. Shown as another blowup in this figure is the end of the LEBT with the solenoidal fields, and the RFQ entrance (see also Fig. 10). Also in this blowup, at the RFQ entrance, the tapers of the radial matching section electrodes are shown as well as an indication of how the electrical connections are made in a multi-channel, 4-rod structure. In this example, the electrical connections are made from one set of the inductance/support structure to one diametrically opposed pair of the four rods, which provide the distributed capacitance, and then through the other leg of the inductance/support structure, thereby completing the high-Q circuit. Another example of how the rf connections into the 4-rod RFQ are made is shown in the Fig. 13, a photograph of a 4-rod single element ("sparking") unit designed and under test by Schempp, McMichaels, and Hutcheon. An approximate rod contour configuration for an RFQ, designed for 30-MHz, ~1 A is shown in Fig. 14. The emittance growth from space-charge forces is larger in low-frequency, high-current devices. This could be an important trade item in the neutral beam lines as there are significant requirements on the beam divergence.

At the exit of the RFQs, one element shown in Fig. 15, the termination of the rods is shown by squiggly lines representing the possibility of actually terminating the rods to produce, with a rebuncher, a reduced energy spread, or to design the output beam optics to render the beam parallel.

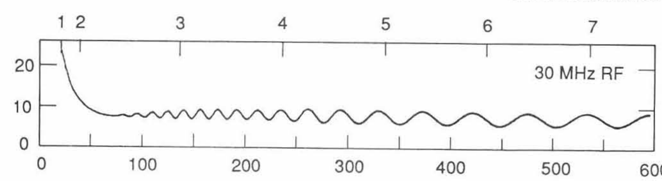


Fig. 14
RFQ Rod Contour, 30 MHz, ~1-A Beam

RFQ HE
TERMINATION

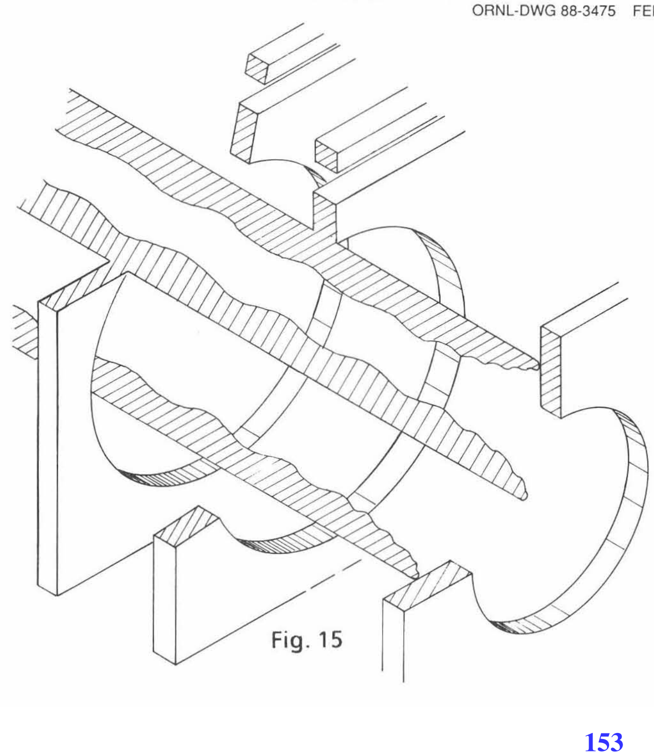


Fig. 15

Summary

- A non-inductive plasma current drive mechanism is necessary to achieve steady state operation of tokamaks
- Core plasma current drive is essential for plasma stability.
- High energy beams (1-4MeV) are able to penetrate the core to drive the required current for reactor type devices like ITER.
- RF accelerated beam systems using RFQs appear most feasible to provide these beams, and at reasonable efficiencies.

It is apparent from a cursory study of this system that, in addition to relying only on engineering scaling of presently developed and operating concepts, the rf acceleration using RFQs has many attractive features for tokamak application:

Very small diameter beam	- Small tokamak ports - Reduced volume near tokamak - Reduced neutron backstreaming
Columns of beams	- Radial current profile control enhancement
Beam bendability (inside or after RFQ)	- No neutron backstreaming to sensitive beam components, i.e. ion source - More machine interface flexibility
Low beam divergence achieveable (~3m-rad)	- Can use long drift tube after neutralizer - Can place key equipment farther from the machine, behind shield - Easier hands-on maintenance can result

The cost of the rf accelerated beam should be quite competitive with other beam concepts that may be considered for current drive.

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