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ACCELERATOR TECHNOLOGY IN TOKAMAKS*

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Introduction

The technology required for development of accelerators is, to a great extent, quite similar to that required for tokamak plasma confinement devices. These similarities are dramatized in the cartoon versions of an accelerator and a tokamak, shown in Figs. 1 and 2.

The major subsystems of both devices include magnets, normal or superconducting; power supplies and energy storage units; cryogenic equipment; vacuum liners, ducts, valves, and pumps; ion sources and high voltage accelerating structures; and RF amplifiers, transmission lines and waveguides.

Presumably, this being an accelerator conference, those participants present at this session are completely familiar with the role played by these subsystems in the operation of accelerators. Since the same might not be true for tokamak systems, a short description of tokamak operation and the role of major subsystems is appropriate.

Hydrogen, or deuterium and tritium, gas is injected into the vacuum tank and ionized with a magnetic field in the ohmic heating (OH) coils. The OH coil field is either discharged or reversed in a relatively short time, up to tens of milliseconds on present day experiments and longer on future experiments, to produce a toroidal forcing field, which creates a toroidal current. At the outset of the OH current pulse, the plasma is relatively cool and a considerable amount of joule heating occurs in the plasma. As the plasma heats up to about 1 to 2 keV, joule heating becomes insignificant and the changing OH field simply drives the toroidal current to higher values.

The toroidal field (TF) coils provide a toroidal magnetic field for confinement of the plasma. Typically, the TF is not varied during plasma confinement. However, in most present-day experiments, the TF coils are constructed with normal conducting, water-cooled copper operated in a pulsed mode to keep average power levels low. The normal evolution in the size and pulse duration of tokamaks will ultimately require superconducting TF coils.

Temperatures in the range of 5 to 10 keV are required for fusion to occur at a reasonable rate. Since OH heating is insufficient, supplemental heating must be provided. Two basic schemes, neutral beams and RF heating, are actively being studied for this function. A neutral beam injector is composed of an ion source, an accelerating column, a neutralizer, and other ancillary equipment. Many amperes of current in the energy range of 15 to 60 kV are developed prior to neutralization in present-day neutral beam injectors. Once neutralized, the particles pass undeflected across the TF and deposit their energy into the plasma. The frequency of RF heating modes tends to be on the order of tens of megahertz for ion-cyclotron heating, L-band for lower hybrid heating, and many tens to hundreds of gigahertz for electron cyclotron heating. Coupling between the RF power transmission system and the plasma and the physical processes of heating the plasma with RF waves are quite complicated; and as a result, RF heating is not as well advanced or understood as is neutral beam heating.

The equilibrium field (EF) coils provide a magnetic field for shaping the plasma. The equilibrium field increases with plasma current and plasma temperature and, as a result, increases rapidly during the OH pulse and auxiliary heating period.

The length of time over which the plasma can be confined and kept pure is limited; so that evacuation of the chamber and replenishment of fresh gas is repeated periodically. Most present-day experiments operate with a fairly low duty cycle, one pulse every few minutes. Ultimately, however, high duty cycle, long pulse operation will be necessary if fusion power plants are to be economically feasible.

The similarity in the technology required for the two types of devices naturally leads to a considerable amount of cross-fertilization. A fair number of accelerator physicists and engineers have been attracted to fusion research and tokamak programs because of this close relationship. Paul Reardon, who left the Fermi Laboratory to become project manager of the Tokamak Fusion Test Reactor (TFTR) at the Princeton Plasma Physics Laboratory (PPPL), represents one example of a typical desertion in the accelerator ranks. Many other names which have long been familiar in accelerator circles can now be found on the staff of fusion laboratories.

The close similarity in technology between accelerator and fusion devices has also stimulated some of the accelerator laboratories to develop fusion-related programs. Examples of such programs currently in progress at the Brookhaven National Laboratory, Lawrence Berkeley Laboratory, and Argonne National Laboratory are presented later in this paper.

Description of Typical Tokamak Projects

A rough description of two tokamak devices under construction will be given in this section in order to present conference participants a more definitive perspective of the field.

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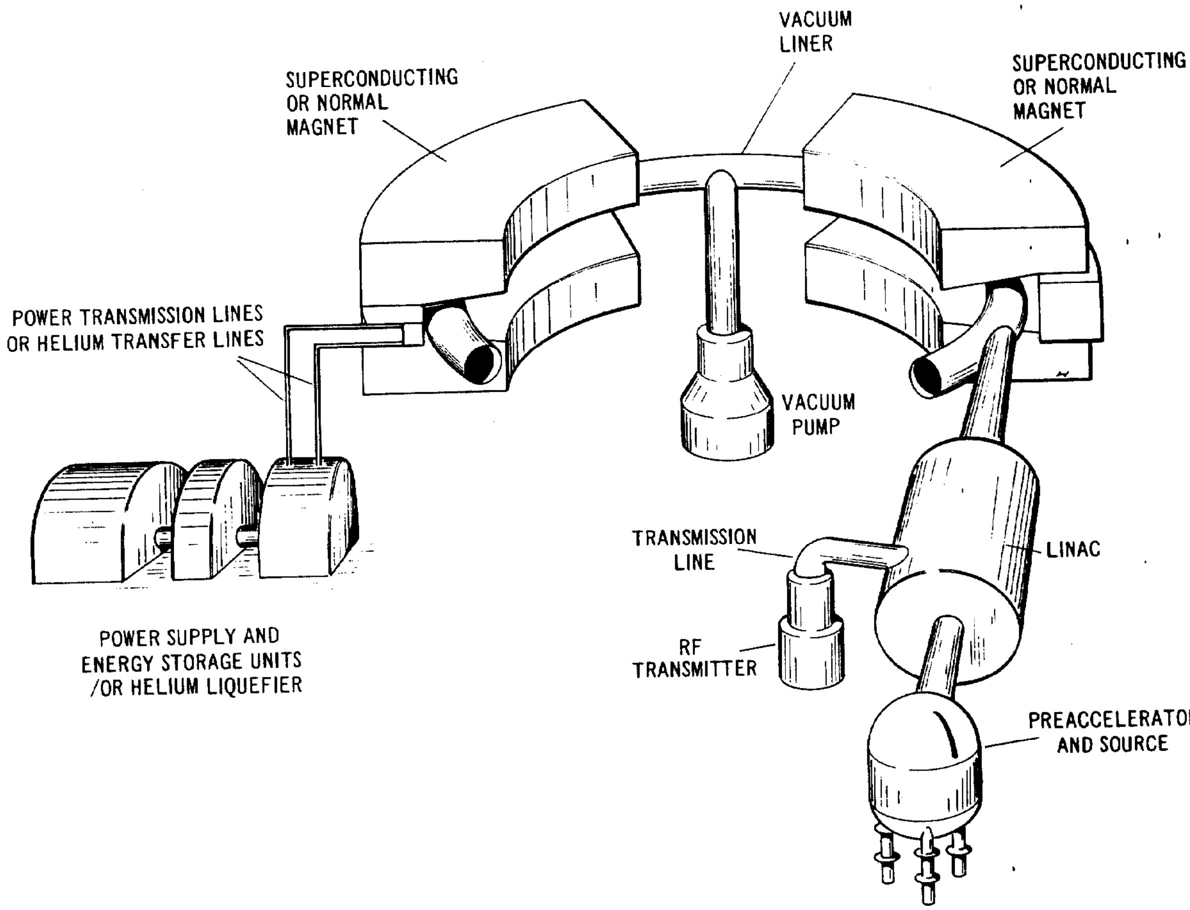

Fig. 1.
Cartoon Version of an Accelerator Highlighting Major Subsystems

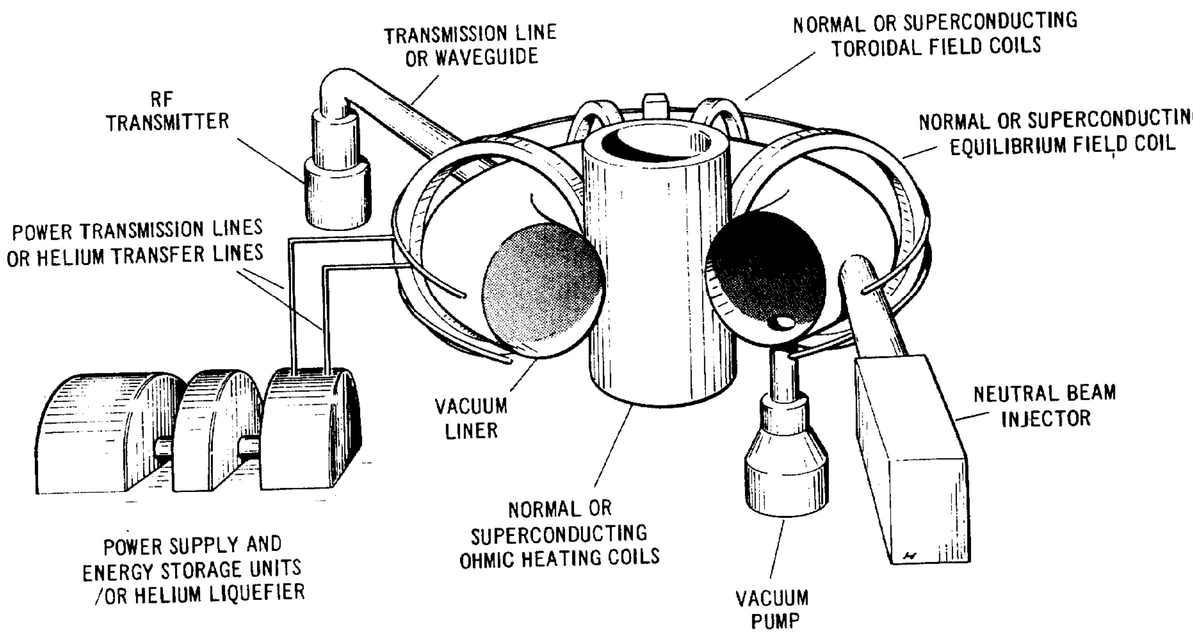

Fig. 2. Cartoon Version of a Tokamak Highlighting Major Subsystems

Tokamak Fusion Test Reactor

The Tokamak Fusion Test Reactor (TFTR)[1] is under construction at the Princeton Plasma Physics Laboratory--with Princeton the project manager; and Ebasco Services, Inc., and Grumman Aerospace Corporation--the industrial participants. The goal of TFTR is to achieve reactor grade plasmas and produce significant deuterium and tritium reaction rates. An artist's drawing of the TFTR device is shown in Fig. 3. Some of the basic machine parameters are listed in Table 1.

Table 1. Major TFTR Parameters

Plasma Radius	0.85 m
Plasma Density	$10^{20}/m^3$
Vacuum Vessel Major Radius	2.65 m
Vacuum Vessel Inner Minor Radius	1.1 m
Number of Toroidal Field Coils	20
TF Coil Bore, Major Radius	2.8 m
TF at 2.48 m Radius	5.2 T
OH System Flux Swing	10.88 V-s
EF at 2.48 m Radius	0.3 T
Plasma Current Capability	2.5 MA
EF and OH Flattop Time	1 s
Pulse Repetition Period	300 s
D° Neutral Beam Power to Plasma	20-24 MW
Power Efficiency in Neutralization	25-30%
Total Power in Accelerated Beam	80 MW
Energy of Neutral Beam	120 keV
Main Power Supply Rating (AC Motor Generator Flywheel)	4500 MJ, 950 MVA
Vacuum Pumping System-- 8 Turbomolecular Pumps	28 000 ℓ/s

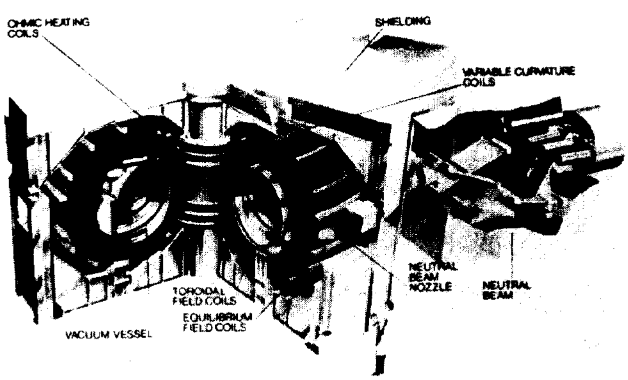

Fig. 3. Artist's Conception of the Tokamak Fusion Test Reactor Under Construction at the Princeton Plasma Physics Laboratory. (Courtesy of Dr. Paul Reardon, PPPL)

TFTR is expected to have a circular plasma, roughly 1.7 m in diameter; a plasma density of about $10^{20}/m^3$; and a plasma temperature between 5 and 10 keV. The machine is designed to be pulsed for about 1 s every 300 s. The main torus pumping system is to consist of eight 3500 ℓ/s turbomolecular pumps capable of evacuating the main chamber from 1.3×10^{-3} Torr to 1.5×10^{-5} Torr in the roughly 300 s dwell time between plasma pulses.

The TF coil is designed to achieve a field of 4.6 T at the coil center with a peak field of 9.54 T in the coil, a stored energy of 1.37 GJ, and a peak I^2R power of 295 MW. The TF coil design has 20 coils with 96 turns per coil and a coil current of about 33 500 A.

The neutral beam injector design for TFTR requires the ability to deliver 20 MW of power to the plasma for a period of 0.5 s.

The main energy storage and transfer system is to consist of two motor-generator-flywheel sets capable of delivering a total of 950 MVA and 4500 MJ.

TFTR is in the early stages of construction. Procurement of the copper for the coil systems has begun and procurement of other long-lead items is expected to start shortly. Complete assembly of the tokamak is scheduled for July 1980.

Doublet III

Doublet III (DIII)[2,3] is under construction at the General Atomic Co. in San Diego. An important objective of the DIII program is to test the confinement of noncircular cross section toroidal plasmas. An artist's conception of DIII is shown in Fig. 4 and the major parameters are listed in Table 2.

Table 2. Major Doublet III Parameters

	Half V-s	Full V-s
Plasma Density	$1\times10^{20}/m^3$	2×10^{20}
Ion Temperature	2 keV	5.0 keV
Major Radius	1.43 m	1.43 m
Width of Vacuum Chamber-min.	0.8 m	0.8 m
-max.	1.04 m	1.04 m
Height of Vacuum Chamber	3.02 m	3.02 m
Number of Toroidal Field Coils	24	24
Toroidal Magnetic Field (nominal) @ 1.43 m Radius	2.6 T	2.6 T
OH System Flux Swing	5.2 V-s	10.4 V-s
Plasma Current Capability	2 MA	5.0 MA
Experimental Time	0.6 s	1.0 s
Pulse Repetition Rate	5.5 min	5.5 min
Neutral Beam Power to Plasma	4.0 MW	4.0 MW
Main Power Supply Rating (Motor-Generator-Flywheel)	794 MJ/ 260 MVA	1588 MJ/ 520 MVA

The vacuum chamber cross section is a centrally pinched rectangular which can accommodate a vertically elongated plasma with a waist on the midplane of the machine. Field-shaping coils are located inside the TF coils at close proximity to the vacuum chamber. The flux swing in the OH coil is 10.4 V/s in the DIII design.

Four megawatts of neutral beam are planned for DIII and, with extended power supply capabilities, plasma temperatures as high as 5 keV and nτ values of 10^{20} s/cm^3 may ultimately be reached. The nominal plasma current is expected to be 2.0 MA, although 5.0 MA will be possible with the extended capacity of the motor-generator (M-G) set.

The present design for the M-G set provides 260 MVA peak output and extractable stored energy of 794 MJ. Ultimately, the possibility exists of doubling the capacity.

The present state of the DIII construction is shown in Fig. 5.

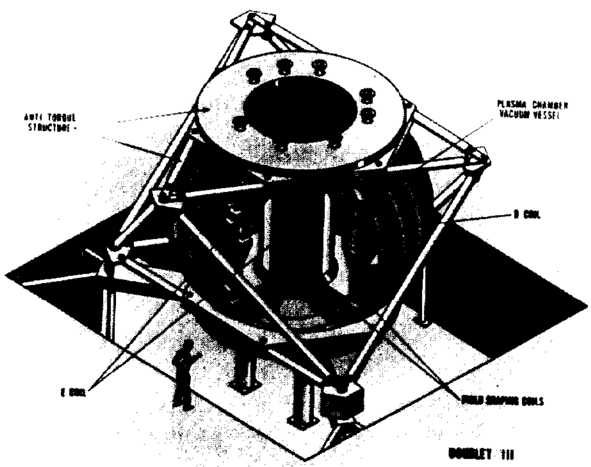

Fig. 4. Artist's Conception of Doublet III Under Construction at the General Atomic Co. (Courtesy of Dr. C. Ross Harder, GA)

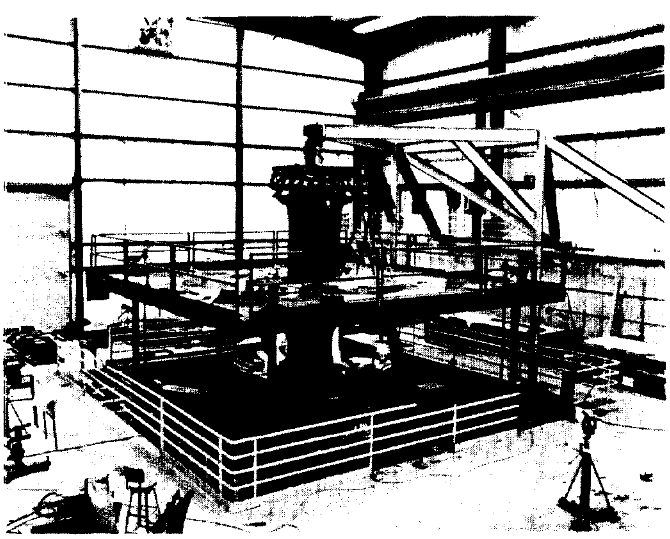

Fig. 5. Recent Photograph of Progress of Construction on Doublet III. (Courtesy of Dr. C. Ross Harder, GA)

Examples of Tokamak Technology Programs at High Energy Accelerator Laboratories

The technology programs described in this section were selected to give a perspective of tokamak problems which are well suited to investigation at high energy laboratories. Similar programs can well exist, and often do, in plasma physics laboratories throughout the country.

High Current Negative Ion Beam Development - Brookhaven National Laboratory (BNL)

Unless some dramatic reversal occurs in the magnetic fusion energy program, power producing tokamaks are going to be huge machines requiring neutral beam energies in the range of hundreds of kilovolts. The present neutral beam injectors start with H^+ ions which are neutralized after they are accelerated to full energy. Beyond 100 kV, the efficiency of neutralizing an ion starts to decrease rapidly. The high level of power which has to be delivered to the plasma quickly becomes a heavy burden on the power system as the ion voltages approach 200 kV. The vacuum system is similarly burdened.

The efficiency of stripping negative ions to neutrals exceeds 50% for most voltage ranges of interest. Thus, if a sufficiently intense negative ion source could be developed, the problem of extending neutral beam injectors to hundreds of kilovolts would be overcome. High current negative ion sources for this purpose are under development at Brookhaven National Laboratory under the direction of Krsto Prelec and Theo Sluyters.[4, 5]

A far more complete description of this program will be given by the BNL group at this conference[5] than will be presented here. Only a short summary of their work is presented here, since it is not the intent of this paper, nor within the ability of this author, to divest the subtlety of source technology. Interested parties are referred to paper I-7 presented by Theo Sluyters at this conference.

Three different types of sources are under investigation at BNL: the hollow discharge duoplasmatron, the magnetron, and the Penning discharge source. A cross section of the magnetron source is shown in Fig. 6. A magnetic field is applied perpendicular to the plane of the picture. Hydrogen gas passes through a slit in the anode. A discharge is created in the annular racetrack region, developing a dense plasma. The molybdenum cathode has a small cavity containing cesium bichromate. A discharge is created in the hydrogen-cesium mode by leaking cesium through small holes in the cavity. The combination of hydrogen discharge, cesium gas, and cathode temperature leads to H^- production.

The BNL source has reached 0.9 A in 10 ms pulses. H^- current densities were 0.7 A/cm^2. The gas flow rate was 3.3 Torr-ℓ/s cm^2. Thus far, experimental results with existing sources have shown that multiampere and/or longer pulse lengths require cooling of the cathode. Long pulse operation will be necessary for any practical application of negative ion sources for neutral beam injectors.

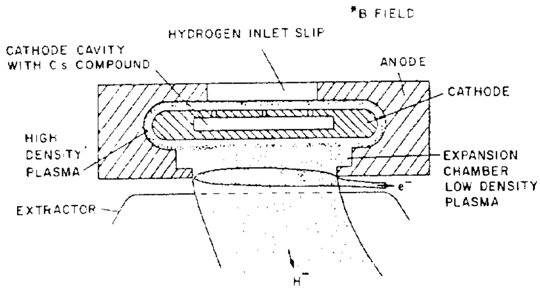

Fig. 6. Cross Section of the BNL H⁻ Magnetron Source. (Courtesy of Dr. Krsto Prelec - BNL)

BNL is continuing to explore the possibilities of achieving high current level H⁻ beams with good gas efficiency. Acceleration of the H⁻ beams to high energy is also a basic requirement. Preliminary experiments have been conducted in this area. Currents of 200 mA have been accelerated to 120 kV.

Pulsed Coil and Power Supply Program - Argonne National Laboratory (ANL)

Many of the present designs for future power-grade tokamaks incorporate superconducting coils for the OH and EF functions. A program on pulsed coils and energy storage and transfer has just started at ANL under the direction of S-T Wang and the author of this paper.

The level of energy storage required for these coils will be at least a gigajoule, and probably much greater. The rate of change of magnetic flux will probably exceed 5 T/sec. Superconducting technology has not yet reached a level of achievement to ensure that such design goals can be met. ANL has started an R&D program on cryostatically stable pulsed coils using copper stabilized Nb Ti wire. Several different conductor configurations have been studied and samples of three of these are being prepared for preliminary test. The current level is designed to operate at 10 000 A at 4 T. Within a year, a 1.5 MJ coil will be built which can operate at 5 T and be pulsed at rates of 2 to 5 T/s. The basic coil design uses the Rutherford cable, although the final selection of the conductor will be based on the short tests now in progress.

In addition to the pulsed coil program, an energy storage and power supply program is in progress. Inertial energy storage in the form of homopolar generators[6] and superconducting energy storage with SCR bridge convertors[7] are under study.

Several different types of bridge circuits are being considered for energy transfer between superconducting coils. A circuit diagram for a three-phase inductor-convertor bridge is shown in Fig. 7. The left-hand bridge commutates current through the capacitors at constant frequency so as to develop ac voltages separated by 120° between capacitors. The right-hand bridge acts as a full wave rectifier, discharging the capacitors into the right-hand inductor. Energy can be transferred from right to left, even though the current in the left-hand coil becomes small compared to the right-hand coil. The capacitor voltage waveforms are influenced by both coil currents.

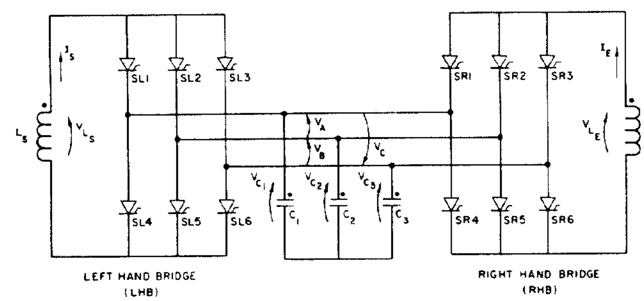

Fig. 7. Circuit Diagram for a Three-Phase Inductor-Convertor Bridge.

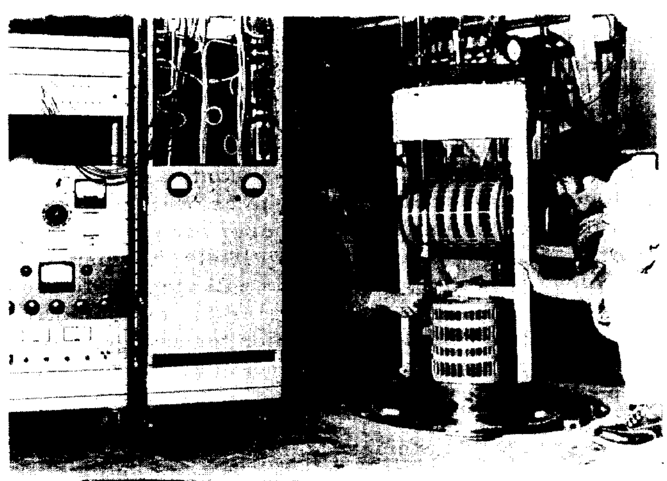

Fig. 8. Photograph of Test Model for Transferring Energy Between Two Superconducting Coils with Different SCR Bridge Circuits.

The ANL studies are directed towards making an actively controlled power supply by adjusting the relative switching phases between the left-hand and right-hand bridges.[8] Since the circuit is completely symmetrical, energy can be transferred in either direction. A model bridge has been built to study different transfer schemes. A photograph of the experimental apparatus is shown in Fig. 8. The two superconducting coils, the model bridge circuit, and the control system are the items shown.

Neutral Beam Injectors - Lawrence Berkeley Laboratory (LBL)

Unlike the other examples presented, the neutral beam studies at LBL have historically been closer to the fusion program, principally at LLL, rather than to the high energy program. Nonetheless, some staff members associated in one way or another with the accelerator program do work with the neutral beam program.

LBL has been at the forefront of neutral beam development, both in R&D programs and neutral beam injectors for various fusion machines.[9] A cutaway version of the "50-A LBL" source is shown in Fig. 9. Ions are extracted from a spacially uniform plasma produced by an arc drawn from 86 tungsten filaments. The plasma region is a rectangle with dimensions of 7 x 35 cm. Ions are accelerated by a gradient between the plasma surface and an acceleration grid which contains 105 slots. The source has delivered as much as 1.4 MW to a 20 x 40 cm calorimeter, 2.9 m from the source. A photograph of the source is shown in Fig. 10.

In addition to the continuing research program and other neutral beam injector programs, LBL has recently been given prime responsibility for building the 120 keV TFTR neutral beam sources.

Summary

This article is intended to present the similarities in the technology required for high energy accelerators and tokamak fusion devices. The tokamak devices and R&D programs described in the text represent only a fraction of the total fusion program. The technological barriers to producing successful, economical tokamak fusion power plants are as many as the plasma physics problems to be overcome. With the present emphasis on energy problems in this country and elsewhere, it is very likely that fusion technology related R&D programs will vigorously continue; and since high energy accelerator technology has so much in common with fusion technology, more scientists from the accelerator community are likely to be attracted to fusion problems.

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LBL "50 AMP" SOURCE

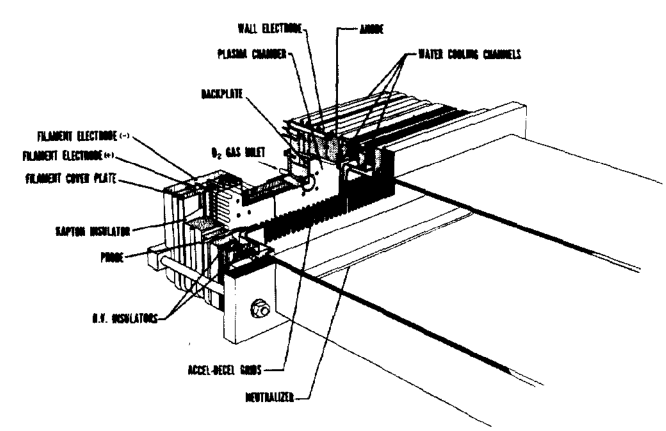

Fig. 9. Artist's Conception of an LBL "50 Ampere" Source.(Courtesy of Dr. Robert Pyle, LBL)

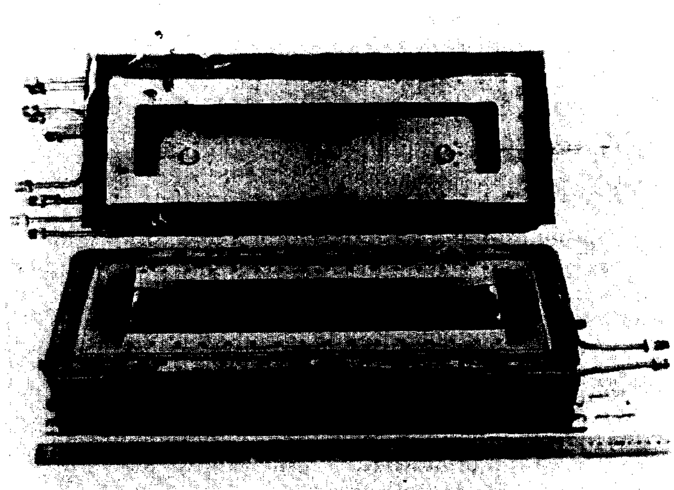

Fig. 10. Photograph of an LBL "50 Ampere" Source. (Courtesy of Dr. Robert Pyle, LBL)