γ

UCRL -76881
**PREPRINT**
CONF-750723--12

LAWRENCE LIVERMORE LABORATORY
*University of California/Livermore, California*

# THE MIRROR FERF

R. W. Moir, C. E. Taylor and J. N. Doggett

August 11, 1975

This paper was prepared for submission to
the Proceedings of the International Conference on
Radiation Test Facilities for the CTR Surface and Materials Program,
Argonne National Laboratory, Argonne, Illinois, July 15-18, 1975.

# THE MIRROR FERF

R. W. Moir, C. E. Taylor and J. N. Doggett

Lawrence Livermore Laboratory
University of California
Livermore, California 94550, U.S.A.

## ABSTRACT

This paper describes an up-dated version of the small mirror reactor for a Fusion Engineering Research Facility (FERF) and describes the present status of technology development and the goals required for the magnet, neutral beam injectors, plasma start-up, and remote handling operations.

The conventional mirror FERF design has a "Yin-Yang" minimum $|B|$ magnetic well with plasma end-losses sustained by continuous injection of up to 500 A of neutral particles. Injection energy is 65 keV ($D^0$) and 97.5 keV ($T^0$). A "low-field" version, 3.75 T central vacuum field, produces 3.4 MW of fusion power and about $10^{14}$ n/cm$^2$·s uncollided 14-MeV neutron current emanating from the plasma.

## MIRROR REACTOR CONCEPT FOR A FERF

We have designed an advanced non-power-producing reactor for testing and evaluating the materials and components that will be used in early magnetic-confinement fusion power reactors. The design of this Fusion Engineering Research Facility (FERF) reactor is based on extrapolations of present mirror experiments. Scheduled for operation by 1985, FERF will be large enough to accommodate many engineering-scale test specimens, yet small enough to be acceptable in cost. FERF will provide for 1 m$^2$ of sample exposure area at a flux of $10^{18}$ n/m$^2$·s. It will have an injected neutral beam power of 13 MW and produce a fusion power of 3.4 MW.

The production of power by magnetic-confinement approaches to thermonuclear fusion is now thought to be possible within this century. This optimistic prediction is based on the substantial experimental progress made in the last few years toward understanding the physics of thermonuclear plasmas. However, the step from present magnetic-confinement experiments [2XIIB and Baseball II at Lawrence Livermore Laboratory (LLL)] to a fusion power reactor will be a large one. The many engineering and technology problems to be solved may require a research program much larger than exists today. Based on fission-reactor experience, we can expect that the engineering phase of fusion-reactor development will be many times more costly than the physics research.

One major problem that must be investigated in detail as early as possible is the extent of damage that materials will suffer in the anticipated severe reactor environment. The level of damage and expected lifetime of materials in an intense 14-MeV neutron flux is not known because there is very little applicable experience. However, we do know that the neutron radiation damage in metals caused by each 14-MeV fusion neutron will be several times greater than that caused by the lower-energy fission neutron with which there is more experience. It is also possible that this damage may be of a different nature; for example, $(n,\alpha)$ reactions caused by the 14-MeV neutrons can produce enough $He^4$ in materials to cause damage. In addition, surfaces close to the fusion plasma will suffer bombardment by energetic hydrogen ions, energetic neutral atoms, alpha particles from the D-T reaction, and intense electromagnetic radiation. The effects of this kind of exposure are also not well characterized.

Some materials testing on small samples can be done using the 14-MeV neutrons produced by bombarding a tritium target with a deuteron beam from an accelerator. However, it is difficult to achieve the 14-MeV neutron flux of $10^{18}/m^2 \cdot s$ expected in a fusion reactor, and impossible to do so over large surface areas. Some aspects of particle damage can be simulated using focused beams from particle accelerators, but again not on a large scale.

The most satisfactory method of testing reactor materials is exposure in an actual reactor environment. This painful lesson was learned by the fission-power-reactor industry when serious material problems developed (for example, swelling of core materials and fuel-pellet densification) that were not recognized until high-power-density reactors were built. Unfortunately, fission reactors do not simulate fusion-reactor conditions very well.

Before a large number of fusion power reactors are built, it will be necessary to do substantial materials testing in a fusion reactor designed to test materials - i.e., one that delivers an intense-enough neutron flux over a large-enough area. To this end, we have developed a conceptual design for a FERF based on the principle of plasma confinement in a magnetic mirror [1]. The design is an extrapolation of the two current LLL mirror experiments, 2XIIB and Baseball II; it will have a density-confinement time product similar to that of our proposed MX mirror experiment, scheduled for operation in 1980, but, unlike MX, will produce the high neutron flux required for materials testing. The total cost of FERF is estimated to be about $300 million; it is scheduled for operation in the mid 1980's. A model of the FERF reactor separated at midplane is shown in Fig. 1.

In a magnetic mirror, charged particles spiraling around the magnetic field lines experience a repelling force as they move into regions of increasing magnetic field. The high-magnetic-field region serves as a "mirror" to reflect charged particles, which can be trapped in a magnetic "well" between two appropriately-shaped, high-magnetic-field regions. A charged particle remains trapped in a magnetic well until its helical orbit is deflected (by collision) into an angle too closely parallel to the magnetic field lines, in which case the particle is promptly lost through one of the mirrors.

To achieve a stable magnetic well for confining the plasma, one needs a magnetic field that increases in every direction from the center of the well; such fields are produced by the baseball-seam-like windings of the Baseball II experiment and by the Yin-Yang coils of 2XIIB. Because the Baseball II and 2XIIB plasmas as a whole are stable, they should decay relatively slowly by the loss of particles through the mirrors. (Actually, microinstabilities exist that increase the losses through the mirrors; a major goal of present experimental and theoretical efforts is to understand and control these losses.) We belive that particle losses in mirror experiments can be minimized and that a stable mirror-confined plasma can be maintained.

Figure 2 shows the general layout of the FERF reactor (Table I gives some parameters of the design). The coil shape, illustrated in Fig. 3, will be the conventional Yin-Yang configuration similar to that in the 2XIIB experiment. In addition to producing a stable magnetic well, this type of magnet allows good access for injection of the neutral beams used to maintain the plasma. The magnetic field strength must be as high as possible because, for a given machine size, the total neutron production is proportional to the fourth power of the magnetic field strength. The superconducting magnets, if wound with Nb-Ti conductors, will provide a central field of 3.7 T; if $Nb_3Sn$ is used, the central field will be 5.0 T, which would provide a maximum neutron flux three times greater than the 3.7-T field. The entire coil and structure will be operated at liquid-helium temperature and must be well shielded from the plasma, because each joule of heat deposited in the coils requires 500 J of energy to remove.

Startup of the reactor will likely be done by neutral-beam bombardment of a small target plasma created by heating a small pellet with a $CO_2$ laser. The plasma will then be continuously maintained against end losses out the mirrors by the injection of neutral beams of deuterium and tritium. Because deuterium is lost more rapidly than tritium, a deuterium beam current of 365 A with a tritium beam current of 135 A will give the desired equimolar D-T mixture in the plasma. The deuterium will be injected at an energy of 65 keV and the tritium at 97.5 keV - near the optimum injection energies for neutron production but well below the energies appropriate for a power reactor.

The fan-shaped plasma (see Fig. 2) will be 0.5 m in diameter at its center and 4.2 m long mirror-to-mirror. At a plasma density of $3 \times 10^{20}$ ions/$m^3$, the thermonuclear power produced will be 3.4 MW, which requires an injected neutral-beam power of 13 MW. (FERF will be capable of injecting 37 MW of beam power should end losses be greater than expected.) The nearest walls will be only 10 cm away from the edge of this plasma and thus will be subject to heat loads of several hundred watts per square centimetre. This heat will be carried away by fast-flowing water in thin-walled tubes that form the first wall. We expect that the damage to the first wall will be severe, so the reactor is designed for periodic replacement of the first wall, perhaps as often as several times a year.

The large amount of gas produced by the neutral-beam injectors in the process of generating the neutral beam must be pumped away to prevent it from reaching the plasma. This gas and the particles leaving the mirrors will be pumped by liquid-helium-cooled cryopanels. These cryopanels "freeze out" the gases impinging on them and must on occasion be shut off from the system, warmed up to release the trapped gas, and then returned to the system. (Development of the cryopumping system will in itself be a major engineering effort.) The deuterium and tritium that are pumped out must be recovered, purified, isotopically separated, and reinjected. Tritium handling will be a major problem, but we feel that all aspects of tritium handling and safety can be managed using techniques and hardware that, in most cases, are known today.

At a fusion power level of 3.4 MW, about $2 \times 10^{18}$ 14-MeV neutrons are produced each second. A radiation shield will protect the superconducting coils from excessive heat and radiation damage from these neutrons. This shield is designed to be as thin as possible so that the magnet size and thus its cost can be minimized. The present shield design consists of stainless steel with circulating borated water, which absorbs neutrons and provides cooling. High radiation fields - on the order of $10^6$ R/h - will exist outside the reactor while it is operating; and, immediately after shutdown, the dose rate 6 m from the center of the reactor will be about $10^3$ R/h. These radiation levels require a 3-m-thick concrete biological shield and the use of remote maintenance techniques.

For the experimenter who wishes to use the reactor, there will be available in the space surrounding the plasma an experimental area of about 1 $m^2$ in which samples can be exposed to 14-MeV neutron fluxes of about $10^{18}$ $n/m^2 \cdot s$. This is to be compared with the best available source of $1 \times 10^{16}$ $n/m^2 \cdot s$ over 1 $cm^2$ - available in the present LLL rotating-target neutron source (RTNS). In addition, FERF will serve as a proving ground for engineering a complete tritium-handling system, large superconducting magnets, and high power, neutral-beam injectors.

## DESIGN MODIFICATIONS

The FERF, as described in Ref. 1, has undergone two design revisions aimed at overcoming certain operational problems.

The first revision improved the maintenance characteristics of the reactor [2]. The results were a vertical rather than horizontal orientation of the reactor axis, and the simplification of major, interior components in order to minimize the problem of replacement.

The second revision added facilities for testing materials and systems [3]. The coil assembly was further simplified into a self-supporting structure, and facilities for inserting and removing fully-instrumented, experimental capsules were added to the design.

In addition, the radial magnetic well, which prevents gross sideways movement of the plasma, was deepened considerably by increasing the arc lengths of the Yin-Yang coils. More theoretical and experimental work will be needed to determine how deep a magnetic well is needed.

The development of a high-field, multifilamentary superconductor, $Nb_3Sn$, appears very promising for fields of 12 T. The design using NbTi is limited to 9 T at the conductor. Since the neutron flux is proportional to density squared or magnetic field to the fourth power, there is a strong incentive to employ the high-field conductor. The neutron flux at the plasma surface and at test samples 35 cm from the center (10 cm from the plasma edge) is given in Table II.

Reference 1 describes a self-consistent design for the low-field case; however, several provisions of "over-design" were made. For example, we estimated the size and cost of a magnet structure appropriate for the forces resulting from the high field. The designed injector current is more than three times that required for the low-field case and just slightly more than that for the high-field case.

## RELATIONSHIP OF FERF TO THE MIRROR PROGRAM

FERF is based on an extrapolation of present-day mirror confinement machines. The key scaling index is the $n\tau$ or Lawson number; $n\tau$ is theoretically proportional to ion energy to the three-halves power, as shown in Fig. 4. The experimental results from LITE, Baseball II, and 2XII fall on a straight line (dashed) whose scaling is more than adequate if the extrapolation holds to 70 keV for FERF operation. As indicated by the solid line, the fusion-fission reactor and pure fusion reactor require a high mirror ratio (R = 7 for the fusion-fission reactor, R = 10 for the pure fusion reactor, R = 2 for FERF).

In conclusion, we think the prospects to be quite good for realization of a small-sized mirror reactor designed for materials and component testing.

## ACKNOWLEDGMENTS

This work was performed under the auspices of the U.S. Energy Research and Development Administration.

## REFERENCES

1. The FERF design is described in greater detail in T. BATZER et al, "Conceptual Design of a Mirror Reactor for a Fusion Engineering Research Facility (FERF)," Lawrence Livermore Laboratory Rep. UCRL-51617 (1974).

2. J. N. DOGGETT, "Remote Operations in a Fusion Engineering Research Facility," Lawrence Livermore Laboratory Rep. UCRL-51778 (1975).

3. J. N. DOGGETT, R. R. VANDERVOORT and W. L. BARMORE, "A User's View of FERF," Lawrence Livermore Laboratory Rep. UCRL-76890 (1975).

### TABLE I

### FERF Plasma Parameters

$n = 3 \times 10^{14}\ \mathrm{cm}^{-3}$

$W_i = 80\ \mathrm{keV}$

$\tau = 15\ \mathrm{ms}$

$n\tau = 2 \times 10^{12}\ \mathrm{cm}^{-3}\cdot\mathrm{s}$

$Q = 0.1$

$B = 3.8\ \mathrm{T}$

$\beta = 0.65$

$P/V = 60\ \mathrm{W}\cdot\mathrm{cm}^{-3}$

$W_{\mathrm{inj}} = 70\ \mathrm{keV}$

$I_{\mathrm{inj}} = 500\ \mathrm{A}$ (136 A classical)

$P_{\mathrm{inj}} = 40\ \mathrm{MW}$

$\dfrac{n\tau}{n\tau_{\mathrm{classical}}} \approx 0.3$

Radial Well
Depth:

$\dfrac{B(r = R) - B(0)}{B(0)} = 0.014$

### TABLE II

### 14-MeV Neutron Flux

| | Low Field (9 T, NbTi) ($\times 10^{14}$ n/cm$^{-2}\cdot$s$^{-1}$) | High Field (12 T, $Nb_3Sn$) ($\times 10^{14}$ n/cm$^{-2}\cdot$s$^{-1}$) |
|---|---|---|
| $\phi_{\mathrm{plasma}}$ | 1.1 | 3.5 |
| $\phi_{\mathrm{test\ area}}$ | 0.6 | 1.9 |

## Figure Captions

Fig. 1. Model of the mirror reactor for the Fusion Engineering Research Facility (FERF) showing half of the Yin-Yang magnet system and magnet support structure. Behind the magnet system are the main plasma chamber, shown partly disassembled, and the lower half of the neutron shields. This is our conceptual design of a 3.4-MW fusion reactor to produce neutrons for CTR materials testing.

Fig. 2. Vertical cross section through the FERF reactor.

Fig. 3. Perspective view of FERF coils and plasma.

Fig. 4. Lifetime versus mean ion energy.

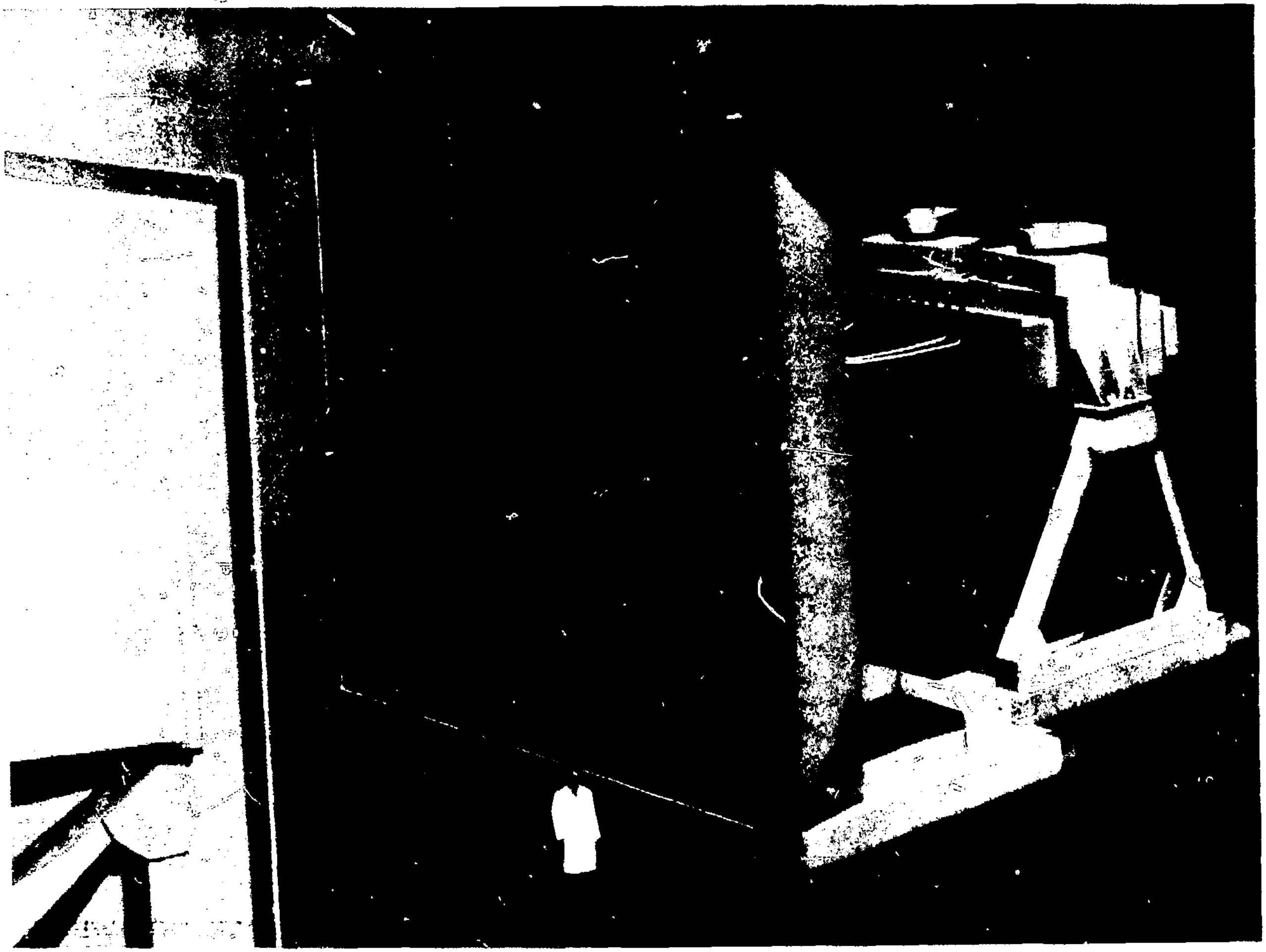


Fig. 1.

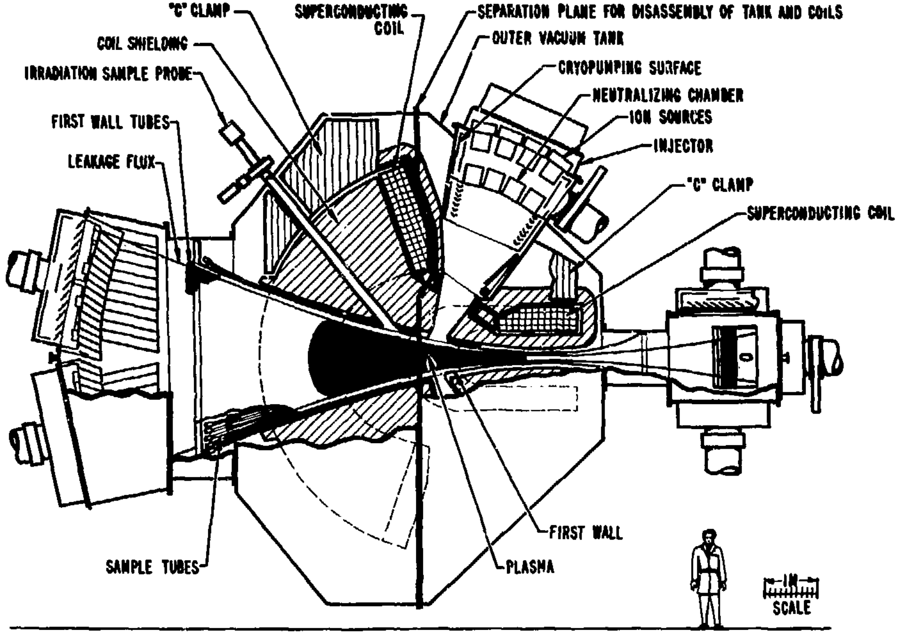

"C" CLAMP
SUPERCONDUCTING COIL
SEPARATION PLANE FOR DISASSEMBLY OF TANK AND COILS
OUTER VACUUM TANK
COIL SHIELDING
IRRADIATION SAMPLE PROBE
CRYOPUMPING SURFACE
NEUTRALIZING CHAMBER
FIRST WALL TUBES
ION SOURCES
INJECTOR
LEAKAGE FLUX
"C" CLAMP
SUPERCONDUCTING COIL
FIRST WALL
SAMPLE TUBES
PLASMA
1M
SCALE

Fig. 2.

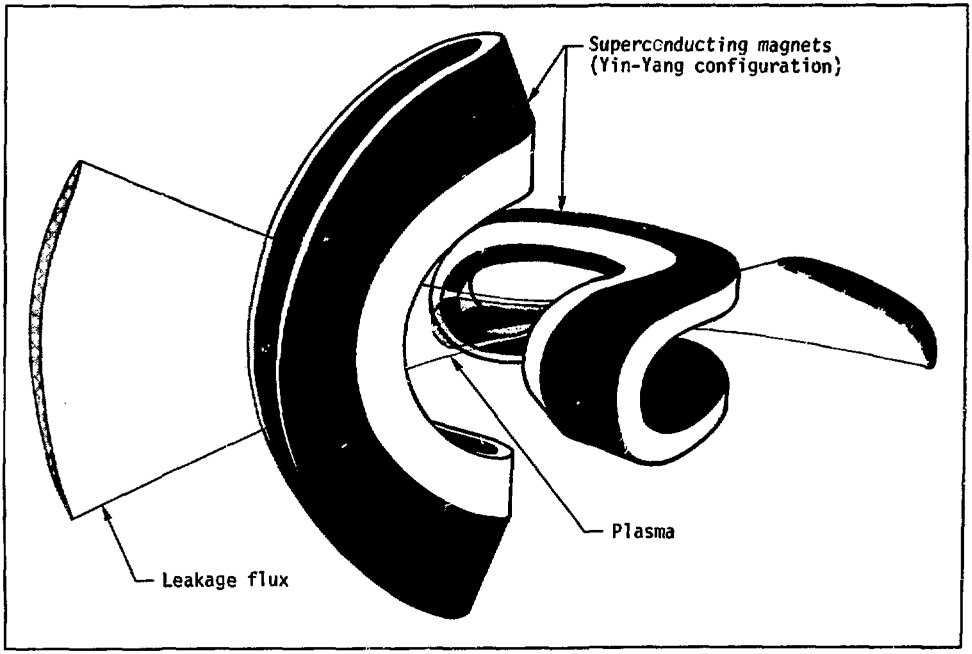
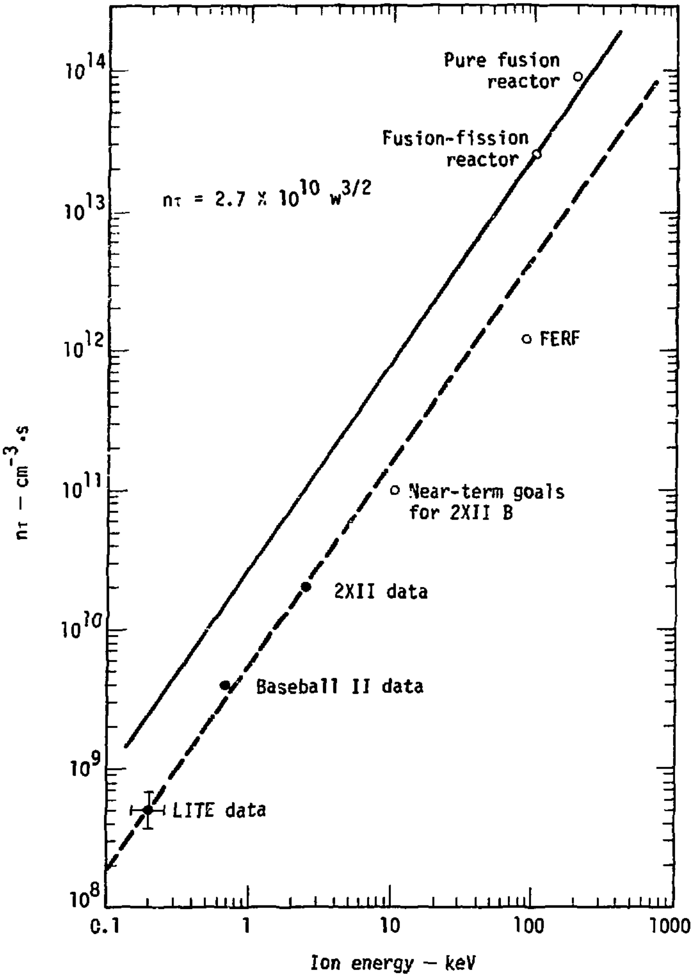

Superconducting magnets
(Yin-Yang configuration)
Plasma
Leakage flux

Fig. 3.



$10^{14}$
$10^{13}$
$10^{12}$
$10^{11}$
$10^{10}$
$10^{9}$
$10^{8}$
$n\tau$ — $cm^{-3} \cdot s$
0.1
1
10
100
1000
Ion energy — keV
$n\tau = 2.7 \times 10^{10}\ W^{3/2}$
Pure fusion reactor
Fusion-fission reactor
FERF
Near-term goals for 2XII B
2XII data
Baseball II data
LITE data

Fig. 4.