GA-A16130

TRIP REPORT ON TRAVEL TO KFA, JULICH, GERMANY
OCTOBER 5-10, 1980

by
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I. INTRODUCTION

The purpose of my visit to the Kernforschungsanlage in Jülich, Federal Republic of Germany, was to participate in the Sixth Meeting of the TEXTOR Executive Committee and to discuss further the pulsed gas injection system that GA is supplying for TEXTOR. (TEXTOR is the European tokamak that will specialize in plasma-wall interaction and impurity problems.) The Executive Committee Meetings consumed most of October 7 and 8, 1980; gas injector discussions took the rest of October 6 and 9.

II. TEXTOR STATUS

TEXTOR was in the assembly phase at the time of the meeting. All toroidal field coils were in place, the poloidal field system was partially assembled, and work had begun on the initial assembly of the vacuum vessel. As part of the presentation to the Executive Committee, Dr. H. Conrads, TEXTOR Project Manager, discussed the schedule for final machine assembly and check out. His presentation is summarized in Fig. 1. Final assembly should be completed by September, 1981, with final check out completed by July, 1982. The goal of the check out phase is to obtain reproducible plasma operation with plasma currents up to 500 kA, toroidal field of 2 T and Z_{eff} near one.

During the initial check out phase, the TEXTOR group plans to implement the discharge cleaning methods that they have previously explored in laboratory simulations. Their receipe calls for use of a combined DC glow and RF discharge in hydrogen at a pressure of about 10^{-3} torr at a wall temperature of about 350°C. (TEXTOR's liner is designed for baking at temperatures up to 600°C.) Extensive laboratory simulations have been

IPP/22. Sept. 80/Co/He
Planungsstand Sept. 80

Commissioning and first operation of TEXTOR

Commissioning of all magnets (coils, power supplies, cooling system)	Mapping of the magnetic field	System integration-test of the vacuum system (pumps, heating- and cooling systems, cleaning systems)	Measuring of the response of the BM-, BKZ-, BKR-systems	Measuring of the response of the poloidal field systems with open feed back control circuit for plasma position control
Ip = 0	Ip = 0		Ip = 50 kA	iP = 100 kA

5.81 7.81 8.81 9.81 10.81 12.81

Determing of the response of the poloidal field system with closed feed back control circuit for plasma pos. control	Response of the poloidal field system driving power-supplies into inversion	Determination of Z_{eff} and pulse-length	Operation of TEXTOR at the full rated parameters
Ip = 100 kA	Ip = 200 kA	200 kA $\leq$ Ip $\leq$ 500 kA	

1~~2~~.82 2.82 3.82 5.82 7.82

done to try to optimize the cleaning efficiency of this method using a test chamber with the same ratio of wall area to pump speed as that in the TEXTOR vessel.

Installation of most of the basic plasma diagnostics is scheduled for this check-out phase. A summary of the presentation of Professor J. Schluter is provided in Fig. 2. According to some private discussions that I had, there are 8 to 10 physicists available for all of these diagnostics. This seems like quite a small number to design, construct, and check-out such a large set of diagnostics.

Advanced tokamak edge diagnostics are also under development, based primarily on optical resonance fluorescence or resonance scattering for analysis of hydrogen atoms and impurity atoms and ions in the plasma edge. A summary of the techniques discussed by Prof. E. Hintz is given in Fig. 3. No definite completion schedule was given for these. Some of them (e.g., thermal arc source for Lyman-α radiation, flashlamp-pumped dye lasers) are operational in the laboratory while others (e.g., infra-red camera and time of flight neutral analysis) are still under development. It appears to me that more effort is going into various sorts of advanced diagnostics than into the standard diagnostics.

Surface diagnostics are being developed at present. Although the KFA has considerable expertise in surface physics measurements, their plans for a TEXTOR surface station suffered a set back when an anticipated cooperation with the Canadians fell through. The TEXTOR group is now rethinking their plans and has requested help in this area from any other groups that are interested.

III. EXPERIMENTAL PROPOSALS

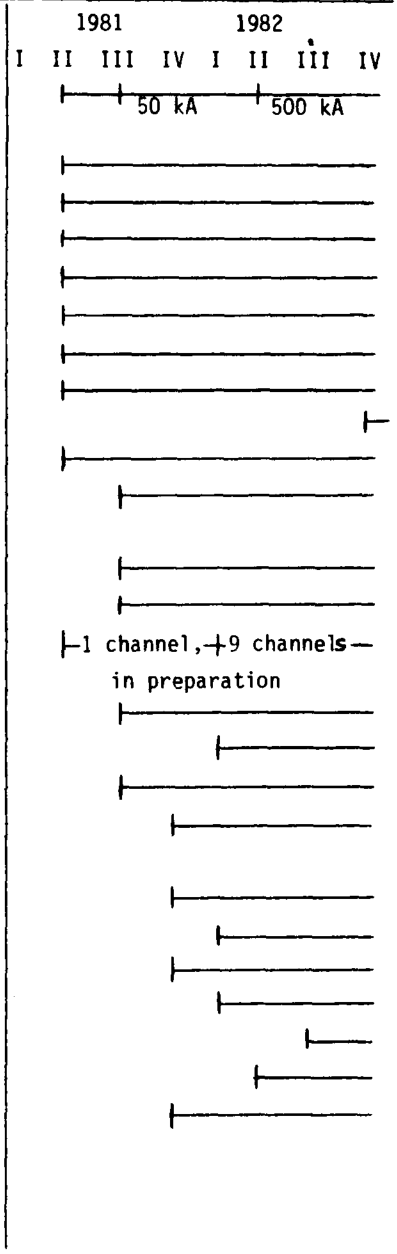
Preliminary proposals for experiments on TEXTOR were given by representatives of several of the nations that are participants in the

6.10.1980
Dr. J. Schlüter

Foreseen Implementation of Diagnostics for the Plasma Core

	device	energy or wavelength	physical quantity
	TEXTOR		
el.-mgt. configuration	voltage loop		U
	Rogowski coil		I_p
	Hall probes		B_{Vac}
	saddle coils		Φ_r, Φ_v
	ext. magn. probes		ΔR_0, Δz
	sin-cos-coils	(m=1)	ΔR_0, Δz
	Mirnov coils		A_m(modes)
	x-ray mode analyzer		A_m(modes)
	diamagnetic loop		beta
parameter of plasma core	HCN-polarimeter (like on ISX-B) 9 channels	337 µm	B_p, j_T
	µ-wave interferometer	2 + 4 mm	n_e
	HCN-interferometer	337 µm	n_e
	Thomson scattering device	694,3 nm	n_e, T_e
	Fouriertransform spectrometer	1 - 6 mm	T_e
	NaI-IHA (pulse height analysis)	0,1 - 20 MeV	E_{raw}
	neutral particle analyzer	1 - 55 keV	T_i
	ionization chamber	0,5 - 3 MeV	$\Phi_{neutron}$
	proportional counter	0,5 - 3 MeV	$\Phi_{neutron}$
H^0 + impurities	(like Suckewer's) Czerny-Turner + rot.mirror	656 or 486 nm	n_0, τ_p
	normal incidence spectrometer	30 - 300 nm	n_0, n_C
	graz. inc. + rot. mirror	1 - 50 nm	n_{metal}
	flat crystal spectrometer	2 - 9 nm	n_{metal}
	curved crystal spectrometer	0,15 - 0,27 nm	$n_{met.}$ T_i
	Si(Li)-IHA	0,8 - 20 keV	$n_{met.}$ T_e
	metal resistor bolometer	0,1 - 200 nm	Φ_{rad}

operation



	Measurement	Technique	Estimated Limiting Sensitivity
1.	H° Density	Optical fluorescence using arc as light source	10^8 cm^{-3}
2.	H_2 Density	Optical fluorescence using arc as light source	10^9 cm^{-3}
3.	H° Velocity Distribution	Arc source plus laser tuned to H_{α}	10^5 cm^{-3} H° (n=2)
4.	H° Flux	1. plus 3.	10^{15} cm^{-2} sec^{-1}
5.	H° Velocity Distribution $30\ eV \leq E \leq 200\ eV$	Time of flight	
6.	Metallic Impurity Density	Laser fluorescence	10^5 cm^{-3}
7.	Metallic Impurity Velocity Distribution	Laser fluorescence	
8.	Surface Coverage	Laser-Induced thermal desorption plus laser fluorescence	10^{-3} monolayer
9.	n_e, T_e	Langmuir probes, Thomson scattering	
10.	Impurity Ion Density	Emission spectroscopy	
11.	Limiter Temperature	Infra-red camera	

Fig. 3. Edge plasma diagnostics

International Energy Agency Agreement on TEXTOR: Prof. A. Miyahara and Prof. Matsura from Japan, Dr. K. H. Burrell and Dr. J. Roberto from the United States and Prof. S. Vepcek from Switzerland. These proposals are quite preliminary, in some cases, and msut be acted upon by national decision making bodies as well as by the Executive Committee before they can be considered as approved.

The Japanese apparently wish to use TEXTOR primarily as a materials test bed. Consequently, they want to see the machine attain reliable, reproducible plasma operation as soon as possible. To this end, they are sending people experienced with plasma position feedback control on JIPP T-II to participate in the check out phase on TEXTOR. In addition, they would like to see TEXTOR move on to the actively heated phase as soon as possible. Prof. Miyahara's summary is reproduced as Appendix A.

The proposals from the United States fell in three general areas: tests of hot wall recycling, limiter pumping systems and a method of pumping impurities out of the plasma by throwing lithium pellets through the edge. The first presentation was by J. Roberto, the later two by me.

The TEXTOR device is the only machine that, in the near future, will be able to confront the question of particle recycling in a machine with wall temperatures in the range anticipated for a reactor. Roberto discussed a joint Sandia Laboratories/Oak Ridge collaborative effort directed towards understanding recycling in this environment.

The limiter pumping proposal was suggested by a joint Sandia Laboratories/UCLA collaboration. The goal would be to test a pumping limiter similar to those proposed for STARFIRE [1] or INTOR [2] on TEXTOR. The presentation is summarized in Appendix B. Both this proposal and the hot wall recycling are similar to ideas that the TEXTOR group had planned to try; they were excited about the possibility that a collaborative effort in this area would allow more work to be done than they could accomplish by themselves.

The pellet pump proposal had as a goal an in plasma test of the erosion of small pellets. It is crucial that this be low enough if this pumping method [3] is not to contaminate the plasma. TEXTOR is an ideal place to test this, since its excellent diagnostic access allows implementation of the idea without any machine modification. A summary of this presentation is in Appendix C.

The Swiss presentation set forth some ideas for testing wall coatings that could be deposited in situ. There was considerable discussion over whether these tests could be done in a way that would not jeopardize the machine.

IV. GAS INJECTION SYSTEM

General Atomic is providing the pulsed hydrogen gas injection system for TEXTOR. Since mechanical design had just been finished at the time of this trip, we used this opportunity to hold a final design review. The design was approved without any changes.

The design of the electrical control system has already begun, and its capabilities were also reviewed. They expressed concern with the initial pulse rise time during the pre-fill phase. I pointed out that this could be decreased substantially, if they would specify what flow rate they wanted during pre-fill, because the initial pulse height could be set to give that flow rate. I will show them how to make this adjustment at installation time.

Overall schedule was discussed with a meeting with Dr. Conrads and Dr. Dipple. The present contract calls for GA to ship the units in April, 1981. Dr. Conrads requested a copy of a bar chart schedule for fabrication and check out, so that he can judge if we remain on schedule. This will be provided. In addition, he suggested that Dr. Dipple come to GA to witness the final tests.

The schedule for the final installation of the gas injecctors on TEXTOR is not yet certain. Delays in fabrication of the hot liner have forced a re-examination of the schedule for the vacuum vessel. After that schedule is firm, Dr. Dipple and I will decide the gas injector schedule.

This work was supported by the Department of Energy under Contract DE-AT03-76ET51011.

REFERENCES

1. Brooks, J.N., C.C. Baker, D.L. Smith, and R. Prater, "Impurity Control System for the STARFIRE Commercial Fusion Reactor," *Proceedinsg of the Eighth Symposium on Engineering Problems of Fusion Research*, (IEEE, 1979), p. 1634.
2. Ulrickson, M., R.W. Conn, S.P. Grotz and R.J. Taylor, "Limiter Pumping Considerations for ETF/INTOR," ETF-R-80-PS-024 (July 1980).
3. Burrell, K.H., "A Method for Removing Helium Ash and Impurities from Fusion Reactors," General Atomic Report GA-A15731 (January 1980).

APPENDIX A

Japanese Proposals on International Co-operation of TEXTOR Project

presented by Akira Miyahara
Institute of Plasma Physics, Nagoya
University, Nagoya 464, Japan

§1. Introduction

It is very delightful that the assembly of TEXTOR systems is expected to be completed by May of 1981, and the experiment with plasma will begin shortly after this accomplishment. I think, it is effective to consider the next stage co-operation now, because it is necessary to have a long time to prepare for the meaningful experiment.

In Japan, we have discussed the proposal having made by a number of plasma researchers and surface scientists at the Domestic Technical Committee Meeting on TEXTOR co-operation held on both Aug.25 and Sep. 11. As a summary at the meeting, we could find ourselves headed to three directions; the first is towards to realize reproducible plasma, the second to realize the upgraded plasma parameter and the third to achieve the irradiation test with this plasma. I would like to make detailed description about these problems.

In a sense of the realization close to reactor grade plasma parameter, TEXTOR can apparently succeed in accelerating the magnetic fields to 2.6 T earlier than we expected first and going a step farther in additional heating by NBI or RF, being accompanied with diverter. On the other hand, however, we must not forget that the principle of TEXTOR's mission should be a technology oriented research. In this point, I would rather take the meaning "Technology Oriented Research" strictly to my own view, and pursue the possibility to produce reproducible tokamak discharges. Furthermore, we would like to challenge to realize the plasma parameters, which are preset at machine system before discharge. It makes an important sense not only on the surface irradiation studies but also plasma physics itself(Engineering feasibility study). It is the exact reason why we have repeated our comments on this point and contributed ourselves to these problems. As the first step, we will continue this line further, especially for the contributions between phase I and II, in order to achieve reproducible plasma production in TEXTOR operation.

As the next step, we are considering the contributions to upgrade the TEXTOR. Additional heating, helical diverter and the improvement of other plasma parameters are essential features, but in this case it is also necessary to achieve reproducible experiment with these upgrade plasma parameters.

Finally, we have to focus on the wall materials. Irradiation studies of candidate surface materials can be performed after solving the above mentioned problems. We must irradiate the surface with any preset plasma parameter and number of shots, so as to study erosion and modified surface problems. With these procedure, we can compare the test sample irradiated with well-defined beams to the irradiated surface with numbers of tokamak discharges.

§2. Co-operation of TEXTOR plasma production

When the assembly of TEXTOR is finished, the plasma production work will begin. First of all, discharge cleaning must be applied to remove light impurities from the limiter and wall, although TEXTOR can be baked up sufficiently high temperature. Several methods have been proposed from TEXTOR team such as TDC and glow discharge cleaning, but we have also proposed the application of ECR technique with the experience of JFT-II experiment. This method will be performed by using two sets of 2.45 GHz, 5 kW microwave transmitters with the troidal magnetic field of Bt=0.0725T, and allow us to remove 100 atomic layer of oxides in six hours.

In parallel to the discharge cleaning method, certain surface diagonostics must be developed so as to check the surface condition. Low energy ion scattering spectroscopy(ISS) is perhaps the most suitable one because the sensitivity of top layer atoms of this instrument is excellent.

When the surface cleaning is sufficiently done, we can enter upon the plasma experiment. As I already described in the previous section, the production of impurity free ohmic heated plasma with sufficiently good reproducibility is the first object. ECR preionization will improve the breakdown property of initial plasma, and is effective to suppress the arcing and the other origin of impurity release. For 1.3 T operation of TEXTOR, 10~50 kW 36 GHz klystron is sufficient for this purpose. Plasma position, plasma current and gas puffing controls are inevitably necessary to realize the reproducible plasma operation.

In addition to these problems, in order to study the plasma wall interaction in TEXTOR, estimation of boundary layer plasma which contacts with the wall is one of the key roles. With the various experience of JIPP-T-II, JFT-II and DIVA in production of tokamak discharge and also diagonostics of boundary layer plasma, we would like to join TEXTOR co-operation from the view point of estimation on plasma behaviours, especially scrape-off plasma.

§3. Upgrading of TEXTOR plasma parameter

To produce upgraded plasma of TEXTOR and optimization of tokamak plasma with additional heating such as NBI and/or ICRF are very important object because plasma parameters close to reactor plasma is necessary to obtain realistic irradiation condition. Also in this case, reproducible operation is necessary, but this problem is really challenging one. Plasma control with NBI injection and ICRF is important subject, but at the same time to increase the reliability of NBI hardwares is also not forgetable.

§4. Proposal for TEXTOR co-operation of the first wall material research

(a) The aim and plan of the project

The plasma-wall interaction study is an urgent and most important scientific and technological issue for the development of near-term nuclear fusion technology. TEXTOR is a very timely project from this point of view, and we all greatly appreciate, and hope that the TEXTOR project will take the initiaive in the world wide study in the field of plasma-wall interactions.

In the plasma-wall interaction of tokamak devices, the recycling coefficient r, which is the ratio between the outgoing, from the wall into the plasma, and in-coming, from the plasma into the wall, particles, and, at the same time, for the impurity issue in the plasma, as well. In the tokamak devices so far worked out, PLT for example, a condition r=0 was artificially set up by Ti coating on the wall surface. However, as it is usually believed that this artificial modification of the wall surface will not be realistic in future devices, we shall inevitably have to take the coefficient into the account for the design of future tokamak.

From physical point of view, this coefficient is a very complicated quantity and contains several elementary processes in it. It is presumed that these elementary processes work in a synergistic way at one time, and/or in a successive way at the other time, depending on the history of plasma discharge. The aim of this project is to clarify the effect of the number of shot of the plasma discharge on the recycling and inventry of hydrogen at the surface and in the sub-surface layer of wall materials, and consequently to determine the physical meaning of the recycling coefficient r.

Firstly, we will concern with the modification and roughening on the surface on plasma particle bombardment, and associated change in the desorption, adsorption, and inventry of the plasma particles, and further with the surface segregation, using probe specimens exposed to the plasma discharge. Each of these processes plays an important role in determining the recycling characteristics, and at the same time, contains fundamental scientific problems which must be clarified for the development of future first wall materials. Experimental techniques such as Surface Roughening Factor(SRF) measurement, Ion Surface Scattering(ISS), Auger Election Spectroscopy(AES), Scanning Electron Microscopy(SEM), and Secondary Ion Mass Spectroscopy (SIMS) will be utilized.

Secondly, since the particle energy(ion temperature) under the NBI operation of the TEXTOR is expected to be rather high (1.5-4 keV), ion implantation into the wall will take place, and it will be detected by an ion beam analysis technique. In this project, Elastic Recoil Detection(ERD) measurement using high energy heavy ion accelerator is planning. This kind of measurement will be of benefit for the inventry study, and for the recycling study as well.

Finally, topographic observations of the surface erosion after the plasma exposure of a probe specimen will be carried out. For this purpose, both of Scanning Electron Microscope (SEM) and Transmission Electron Microscope(TEM) are requisite.

All of these experiments will be carried out as functions of number of shot of the plasma discharge.

(b) Materials expected in the project

Materials which are expected as probe specimens in this project will be various candidate materials for the first wall, including Al, Ti, V, Ni, Cu, Mo, SUS, INCONEL, low-z materials such as graphite, B_4C, SiC, TiC, TiB_2, and their composite materials.

The philosophy for the low-Z coating study is as follows: low-Z ceramics, such as B_4C, SiC, TiC and graphite materials have attractive characters to be used as fusion reactor materials, and screening tests are extensively being carried out to obtain the optimum combination of low-Z material/graphite systems. The important factor to be evaluated are adherence of coatings, resistance to thermal shock, erosion by hydrogen ions and changes in surface morphology. It is reported that coatings of TiB_2, TiC and B_4C onto graphite exhibited favorable characters. However, some of these materials produce helium atoms by $^{10}B(n,\alpha)$ reaction and are highly anisotropic in nature, thus the problems are anticipated to occur. In our country, high density isotropic graphite materials are commercially available and technology of SiC coating onto graphite materials have been well established. Since the material is considered to be favorable from stand point of radiation damage, we study feasibility of SiC/isotropic-graphite systems as a liner material. We intend to measure adherence of coatings, thermal shock resistance, weight loss and changes in surface morphology by irradiation in TEXTOR. In particular, changes in surface morphology will be measured with scanning electron microscopy and BET method using xenon gas.

(c) Requisite facilities for this project are as follows:

(1) Surface station:

Must be connected to the tokamak, and must be equipped with a manipulator, which transfers probe specimen into the tokamak, and with ISS, SIMS, AES and SRF systems as well.

Size;

diameter	600mmϕ,
height	500mm,
base pressure	5×10^{-10}Torr,
material	SUS304,
vessel temperature	up to 300°c,

(2) Vacuum chamber for ion beam analysis:

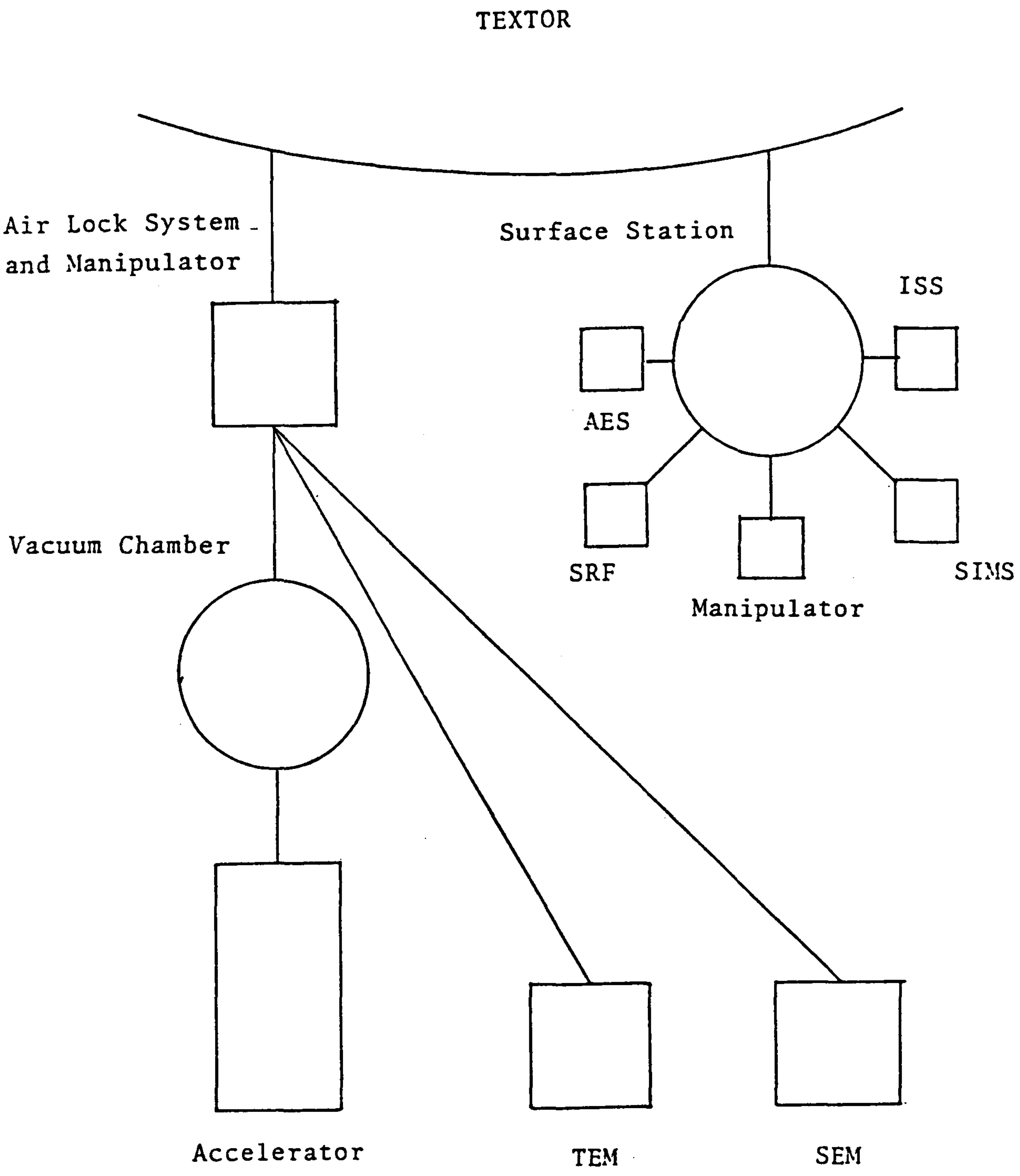
Must be connected to high energy heavy ion accelerator, and must be equipped with three axes goniometer and beam detection system.

Size;

diameter	600mmϕ,
height	500mm,
base pressure	5×10^{-10}Torr,
material	SUS304,
vessel temperature	up to 300°c.

(3) Scanning electron microscope.

(4) Transmission electron microscope.


TEXTOR
Air Lock System and Manipulator
Surface Station
ISS
AES
Vacuum Chamber
SRF
Manipulator
SIMS
Accelerator
TEM
SEM

§5. Conclusion

As a conclusion of this presentation, I would like to summarize some questions which was made by Japanese team.

The first one is the time schedule of co-operation, namely the time when we are to utilize TEXTOR as an irradiation source. Of course the problem of the plasma wall interaction study contains a lot of subjects besides material studies but because of essentially no tokamak which can be used as irradiation study, many Japanese surface scientists are waiting for TEXTOR.

The second question is whether you could give us a plasma irradiation with well-defined parameter.

The third one is what is the problem definition of plasma wall interaction for upgraded plasma.

The last question is concerning about CSAS. What kind of surface diagonostics will be prepared at CSAS, and is it close enough to TEXTOR so as to mount the sample piece at the wall with good reproducibility?

Japanese domestic technical committee members want to know the real feature of international co-operation at TEXTOR. However, I believe that this will be accomplished through experience of co-operation, and that it is also one of the subjects for international co-operation.

APPENDIX B

ADVANCED LIMITER DEVELOPMENT FOR TEXTOR

Participants:

• Sandia National Laboratories, Albuquerque and Livermore	M. J. Davis W. Bauer R. S. Blewer W. B. Gauster
• University of California, Los Angeles	R. W. Conn

Objectives:

- to design and construct a prototype limiter to be installed in TEXTOR in fiscal years 1983-85;
- to evaluate limiter designs in terms of plasma performance under TEXTOR's experimental conditions.

LIMITER PUMPING SCHEME

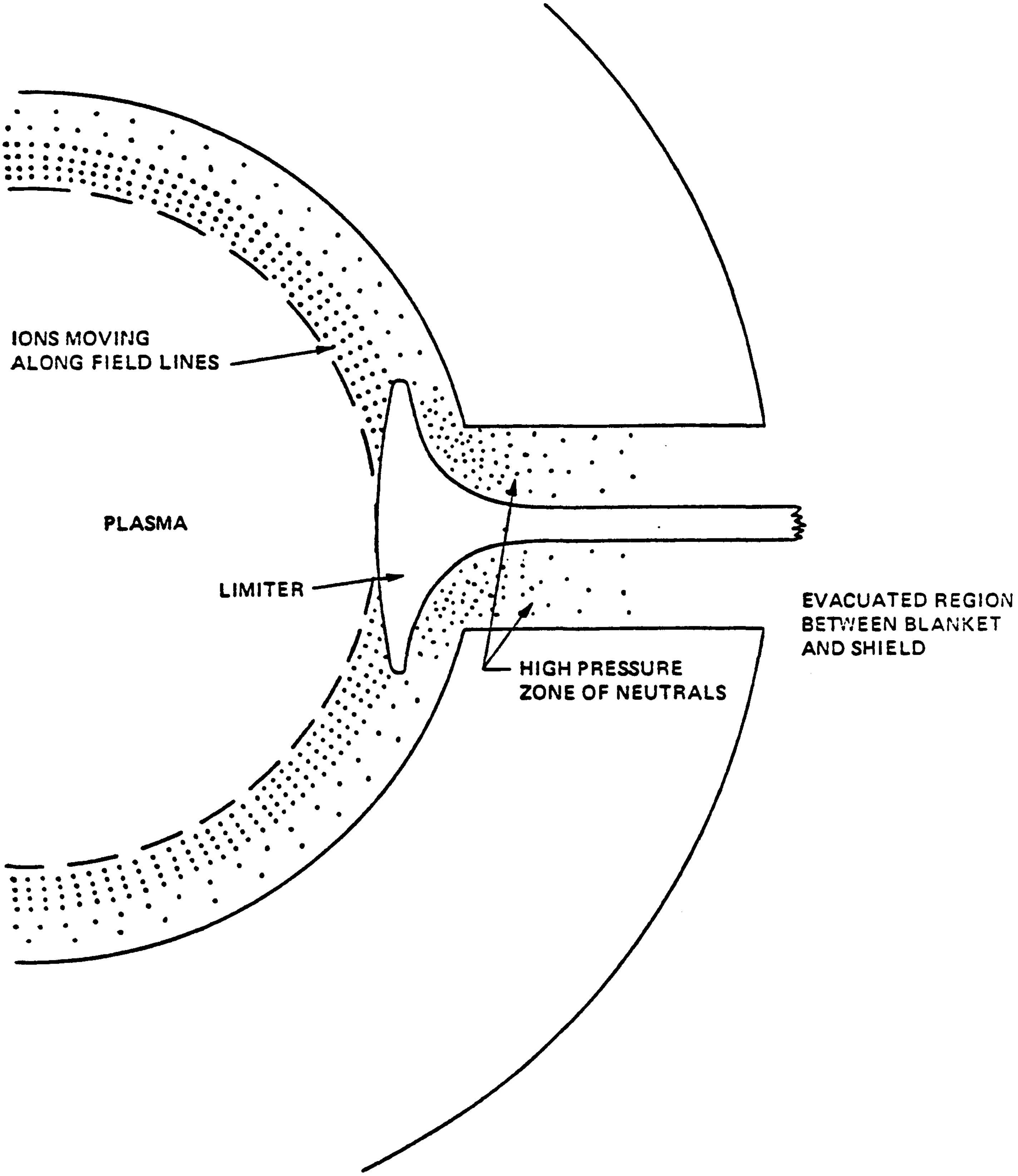


Fig. 1

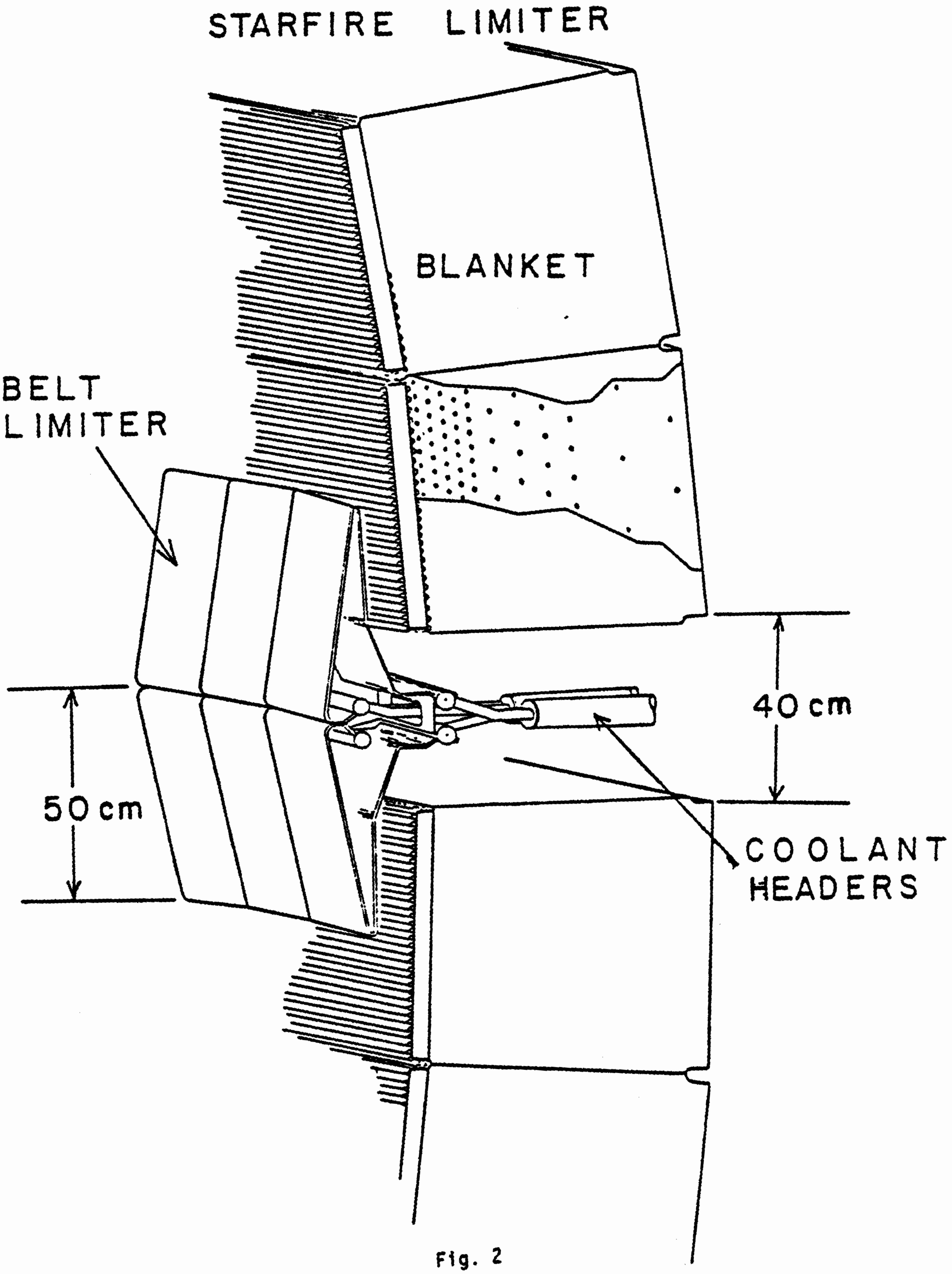
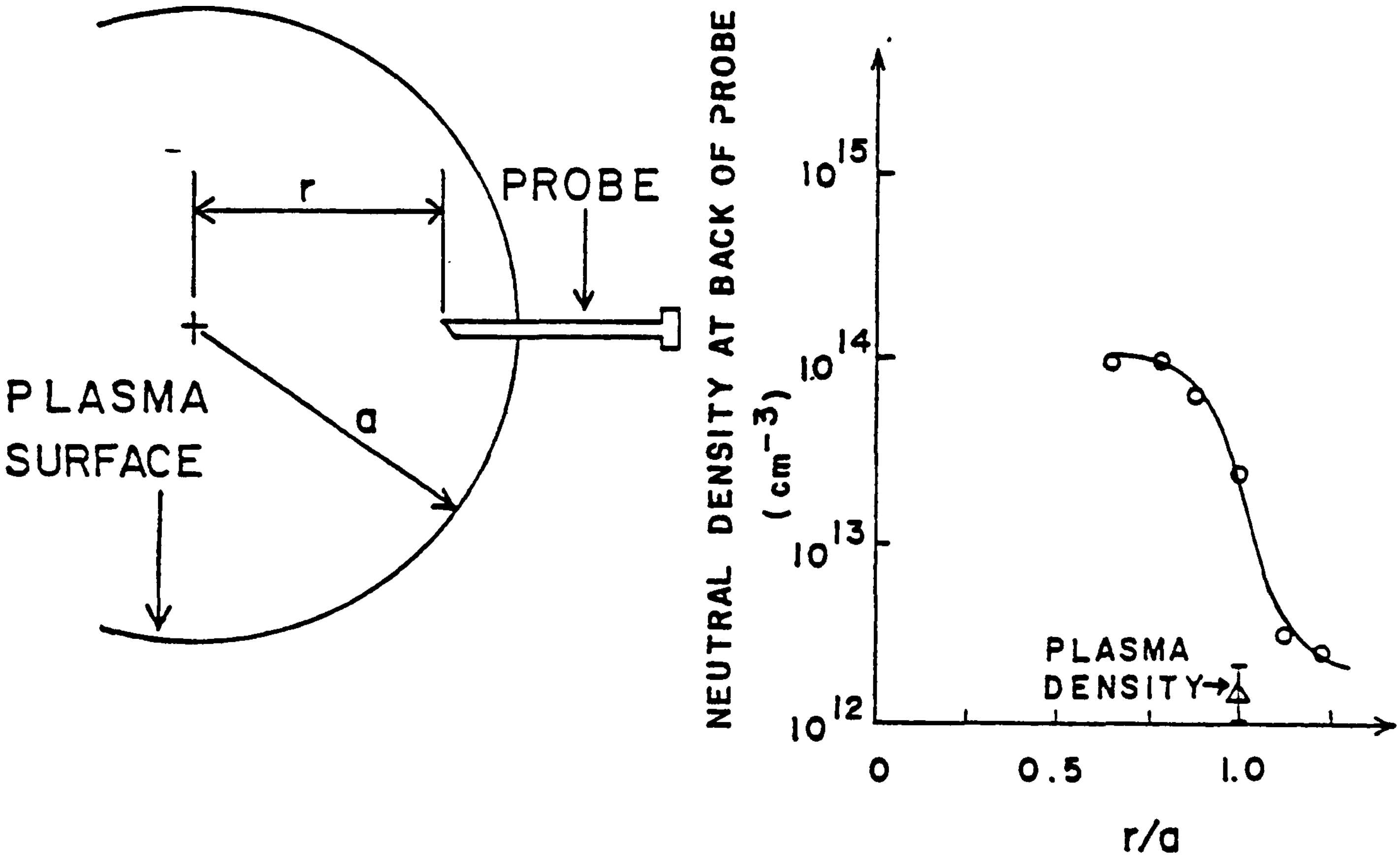

STARFIRE LIMITER
BLANKET
BELT LIMITER
40 cm
50 cm
COOLANT HEADERS

Fig. 2

Program Elements

- evaluation of advanced limiter concepts, leading to prototype limiter design;
- evaluation of steady state heat removal over large areas as part of limiter design studies;
- development of low-Z materials systems with increased erosion life (e.g. thick coatings, in-situ regenerated coatings, composites, extended area concepts);
- investigation of hydrogen recycle properties for relevant materials at elevated temperatures in plasmas;
- study of the effect of recycling rate on plasma parameters by systematic variation of materials, temperatures and procedures.

MACROTOR EXPERIMENTAL RESULTS



- NEUTRAL DENSITY ENHANCEMENT FACTORS OF 100 HAVE BEEN MEASURED AT PLASMA EDGE USING A HYDROGEN PLASMA
- INITIAL HELIUM EXPERIMENTS INDICATE THAT HELIUM CONDUCTANCE THROUGH PROBE IS GREATER THAN HYDROGEN CONDUCTANCE

Fig. 3

UCLA BELT LIMITER

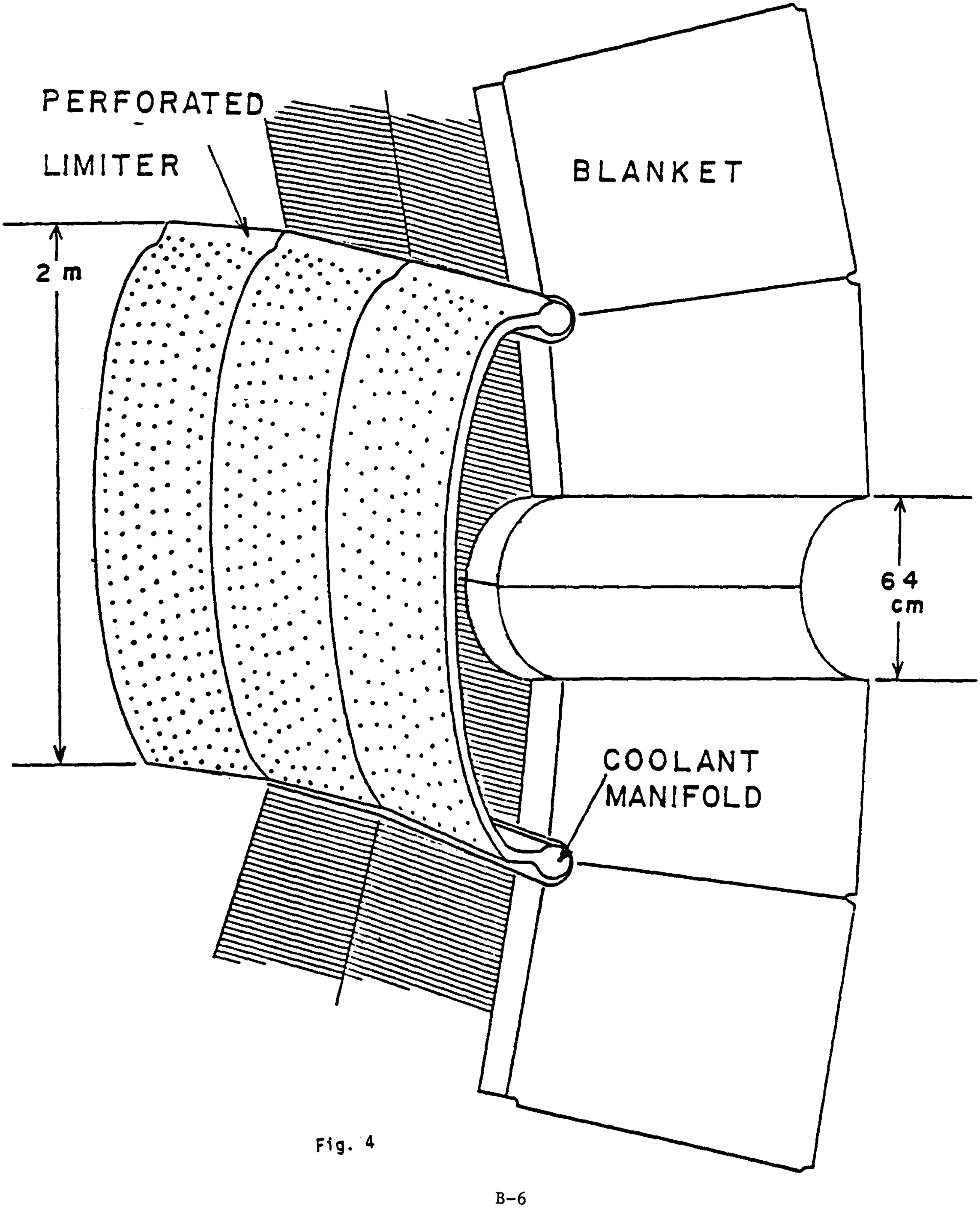
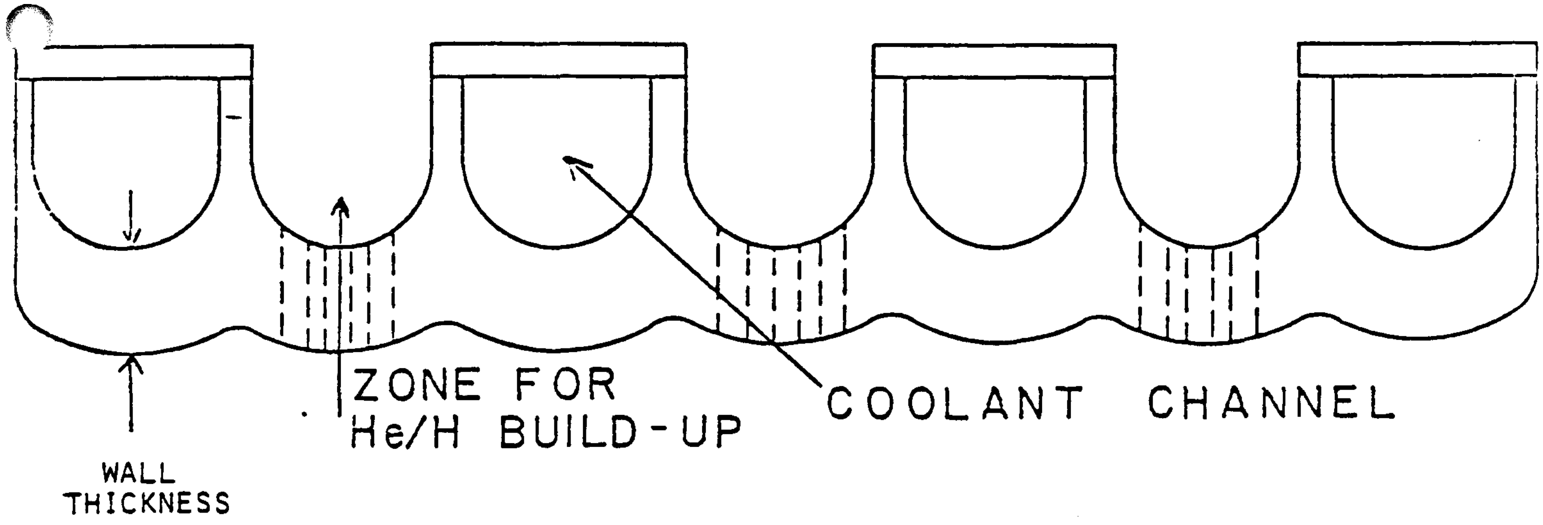


Fig. 4

UCLA PERFORATED LIMITER CROSS SECTION



LIMITER SURFACE

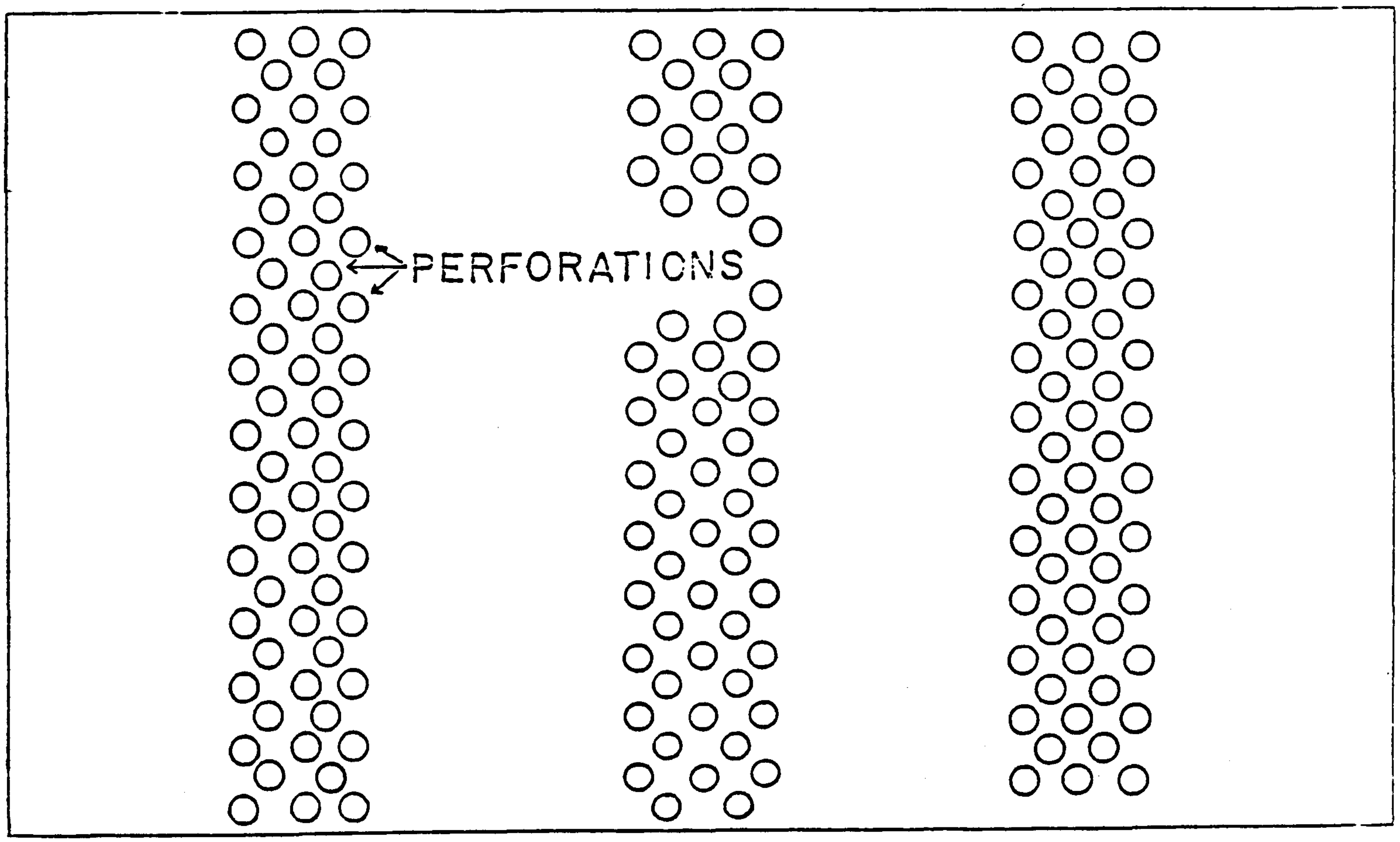
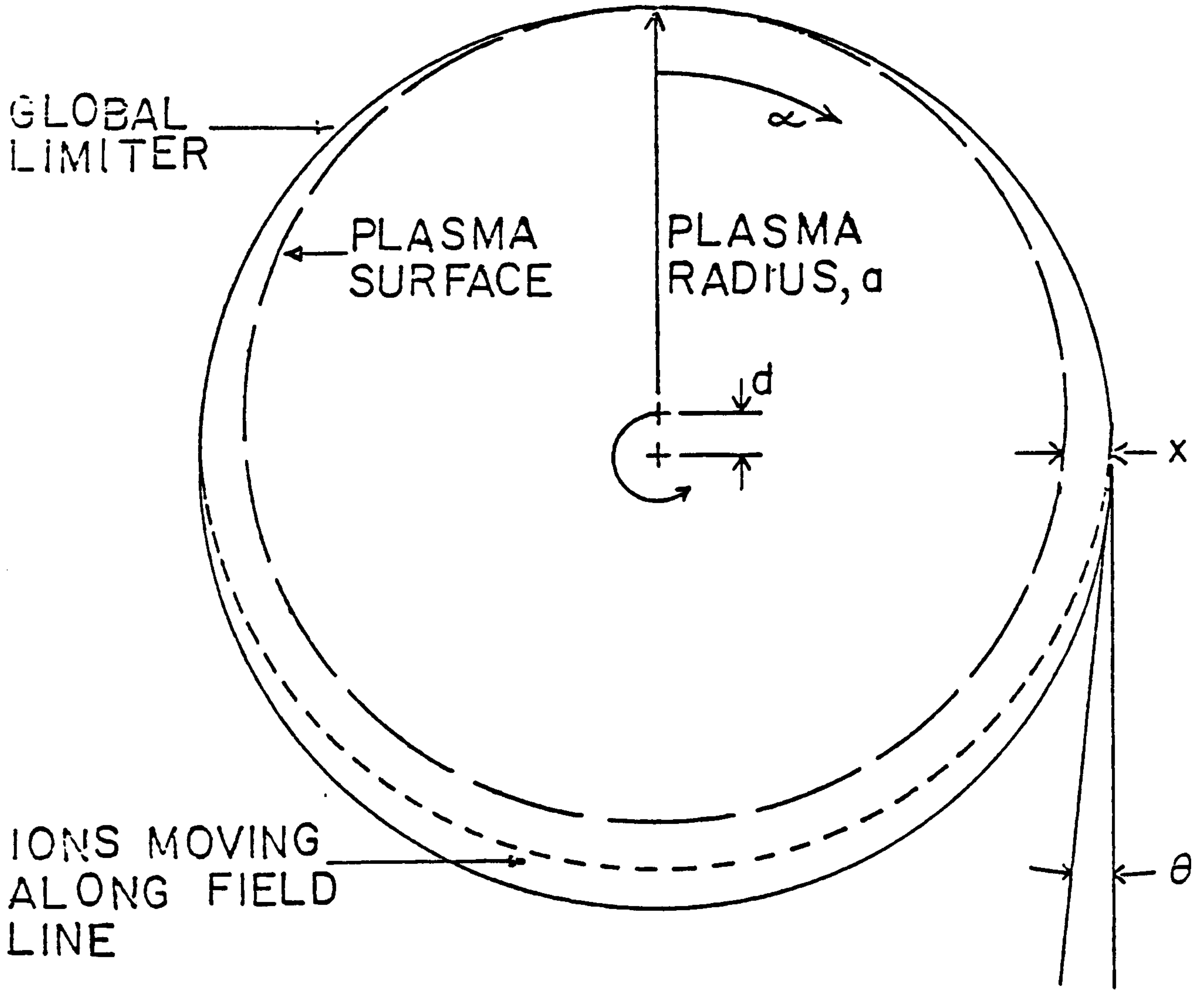


Fig. 5

GLOBAL LIMITER WITH ROTATING PLASMA



FOR INTOR

$$q'' = 20 \sin\theta \exp-\left(\frac{x}{\lambda}\right)$$

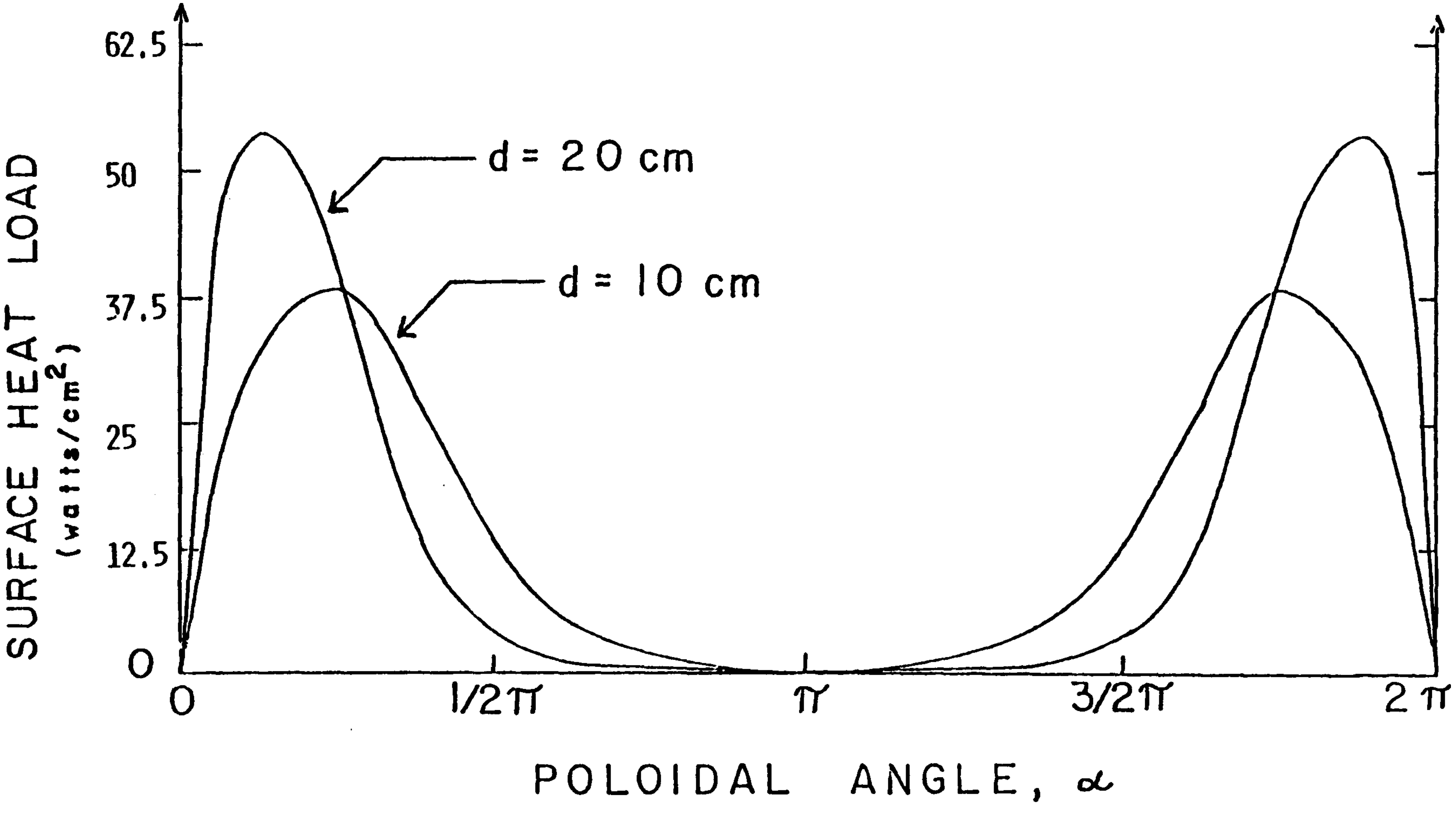
USING THE GEOMETRY SHOWN:

$$q''(\alpha) = 20 \sin\left(\frac{d}{a+d} \sin\alpha\right) \exp-\left(\frac{2d}{\lambda} \sin^2 \frac{\alpha}{2}\right)$$

Fig. 6

Fig. 7

SURFACE HEAT LOAD ALONG GLOBAL LIMITER VERSUS POLOIDAL POSITION



UCLA GLOBAL LIMITER DESIGN

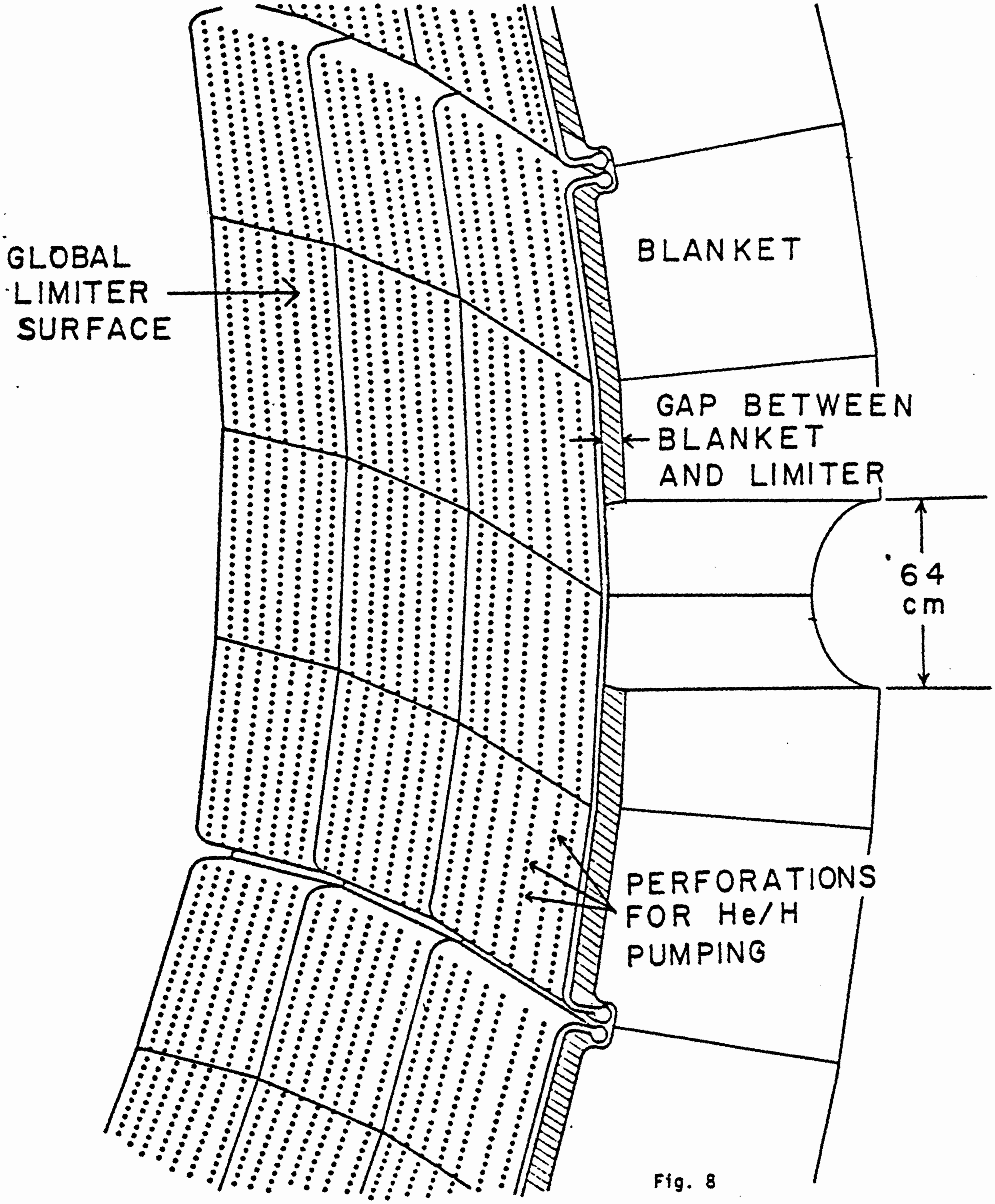


Fig. 8

Milestones

- FY81: tests of design concepts in MACROTOR (e.g. neutral density enhancement effects for perforated limiter scheme);

  heat transfer tests in the laboratory for design verification;

  coatings development, emphasizing plasma spraying (50 to 250 μm coating thickness) and CVD impregnation of felts;

  laboratory studies of heat removal, thermal fatigue, material erosion and hydrogen recycle.

- FY82: installation and testing of scaled limiter in a U.S. device; power deposition studies.

- FY83 and Beyond: installation and testing of limiter in TEXTOR.

Diagnostics Required at TEXTOR

- Plasma edge diagnostics (near the limiter):

  laser-induced fluorescence detection of impurity densities;

  infrared radiometry, thermocouples;

  determination of plasma-Z;

  (Limiter will be calibrated for use as heat flux monitor.)

APPENDIX C

SIMPLE METHOD OF REMOVING HELIUM ASH AND IMPURITIES FROM FUSION REACTORS

KEITH H. BURRELL

GENERAL ATOMIC COMPANY

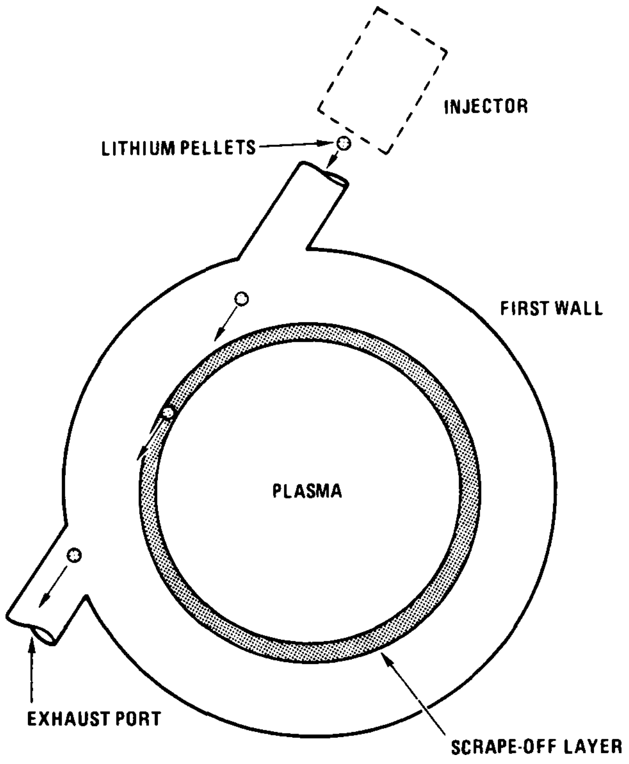
REACTOR REQUIREMENTS

- A KEY REQUIREMENT FOR LONG BURNS IN TOKAMAK FUSION REACTORS IS A MEANS OF REMOVING IMPURITIES AND HELIUM ASH FROM THE PLASMA.
- SUGGESTED METHODS INCLUDE DIVERTORS OR CONVENTIONAL VACUUM PUMPING.
- THESE METHODS ARE COSTLY OWING TO THEIR VARIOUS ENGINEERING REQUIREMENTS.

BASIC CONCEPT

- THE PRESENT CONCEPT CALLS FOR INJECTING A STREAM OF SMALL, LOW VELOCITY PELLETS (1 mm RADIUS, 5-20 m/sec SPEED) THROUGH THE OUTER EDGE OF THE PLASMA.
- THE PELLETS COLLECT HELIUM, IMPURITIES AND HYDROGEN AND REMOVE THEM FROM THE SYSTEM.
- THE CONCEPT IS SIMILAR TO THE METHODS PROPOSED TO REMOVE PARTICLES FROM DIVERTOR CHAMBERS, BUT, IF OUR CALCULATIONS ARE CORRECT, ONE NEED NOT SURROUND SUCH A PARTICLE PUMP WITH A DIVERTOR TO REMOVE IMPURITIES EFFECTIVELY.

LITHIUM PELLET ABSORBER



PELLET MATERIAL

- LITHIUM IS THE BEST MATERIAL FOR THE PELLETS.
- ITS LOW ATOMIC NUMBER MEANS THAT TOLERABLE CONCENTRATIONS IN THE PLASMA ARE QUITE HIGH.
- ITS HYDROGEN SPUTTERING AND SELF-SPUTTERING YIELDS ARE LOW.
- IT HAS A HIGH HELIUM PUMPING CAPACITY DUE TO THE LONG RANGE OF HELIUM IONS IN LITHIUM.
- LITHIUM IS A LIQUID ABOVE 454^{o}K, FACILITATING THE FORMATION OF PELLET STREAMS BY THE CONTROLLED BREAK-UP OF LIQUID JETS.

EROSION PROBLEMS

- PELLET SPEED IS SUFFICIENT THAT TEMPERATURE RISE IS SMALL (300^{o}K) AND VAPORIZATION IS INSIGNIFICANT.
- PELLETS ARE TOO SMALL TO SUPPORT UNIPOLAR ARCS.
- SPUTTERING APPEARS TO BE TOLERABLE.
- IF EROSION IS A PROBLEM, ONE CAN USE IMPURITY FLOW REVERSAL TO HOLD THE PELLET MATERIAL IN THE OUTER EDGE OF THE PLASMA.

HEAT LOAD

- TREAT ENERGY AND PARTICLE DEPOSITION VIA ONE DIMENSIONAL LANGMUIR PROBE THEORY

$$\Gamma_i = \frac{n_i v_i}{2\pi^{1/2}}$$

$$Q = \frac{n_i v_i}{\pi^{1/2}} \left[T_i + T_e \left(1 + \frac{1}{4} \ln \frac{m_i T_e}{m_e T_i} \right) \right]$$

- IF THE PELLET REMAINS IN THE PLASMA FOR A TIME t GREATER THAN SEVERAL THERMAL DIFFUSION TIMES, SURFACE TEMPERATURE IS

$$T_s = \frac{3\,Q\,t}{2\,c_v\,a}$$

- EXAMPLE: $n_i = 10^{13}\ \mathrm{cm}^{-3}$, $T_e = T_i = 20\ \mathrm{eV}$,

  $T_s = 300^{o}\mathrm{K}$ IN 140 msec

- LITHIUM VAPOR PRESSURE IS 3×10^{-6} TORR AT 600 ^{o}K, THIS GIVES AN EROSION RATE OF ONLY A FEW PERCENT OF THE SPUTTERING RATE.

NUMBER REQUIRED FOR PUMPING

- IF 1-3 keV α-PARTICLES HIT A NICKEL SURFACE, IT CAN RETAIN 3-5 x 10^{16} He/cm^2.

- SCALING BY THE RATIO OF THE PARTICLE RANGES, LITHIUM SHOULD BE ABLE TO RETAIN 4-6 x 10^{17} He/cm^2. TAKE 4 x 10^{16} He/cm^2 AS A SAFE ESTIMATE.

- NUMBER REQUIRED IS

$$\dot{N}_p = \frac{\dot{N}_\alpha}{4\pi a^2}\ \mathrm{MAX}\left((\Gamma_\alpha t_p)^{-1}, F_p^{-1} \right)$$

- FOR A D-T PLASMA WITH $T_e = T_i = T$,

$$\Gamma_\alpha t_p = f_\alpha \frac{c_v\, a\, T_s}{15.6\, T}$$

PELLET PRODUCTION RATE

- MINIMUM NUMBER OF PELLETS IS OBTAINED FOR $\Gamma_{\alpha} t_p = F_p$, WHICH GIVES $f_{\alpha} = 3\%$ AND

$$\dot{N}_p = 2 \times 10^4 \text{ sec}^{-1} \text{ (INTOR)}$$

$$2 \times 10^5 \text{ sec}^{-1} \text{ (STARFIRE)}$$

- ALPHA PARTICLE PRODUCTION RATES ($10^{20} - 10^{21}$ sec^{-1}) ARE MUCH WORSE THAN OTHER IMPURITY PRODUCTION RATES; HENCE, LITHIUM PELLETS SHOULD BE ABLE TO HANDLE ALL OTHER IMPURITIES IN THE PLASMA.

METHOD OF PELLET GENERATION

- USE CONTROLLED BREAK-UP OF LIQUID JETS, AS IN INK JET PRINTERS AND SOME HYDROGEN PELLET SYSTEMS.
- THESE GIVE 100 μm PELLETS AT RATES OF 10^5 sec^{-1} AND SPEEDS OF 20 m/sec.
- WE MIGHT LIVE WITH 100 μm SIZE OR TRY TO EXTEND PERFORMANCE TO 1 mm.

EROSION RATES

- THERE ARE THREE MAIN SOURCES OF EROSION: VAPORIZATION, ARCING AND SPUTTERING.
- PELLET SPEED CAN BE MADE HIGH ENOUGH TO PREVENT SIGNIFICANT VAPORIZATION.
- UNIPOLAR ARCS CANNOT OCCUR IF

$$n e v_e a^2 \lesssim 3 \text{ A}$$

- SPUTTERING PRODUCES THE WORST EROSION.

MATERIAL BALANCE DUE TO SPUTTERING

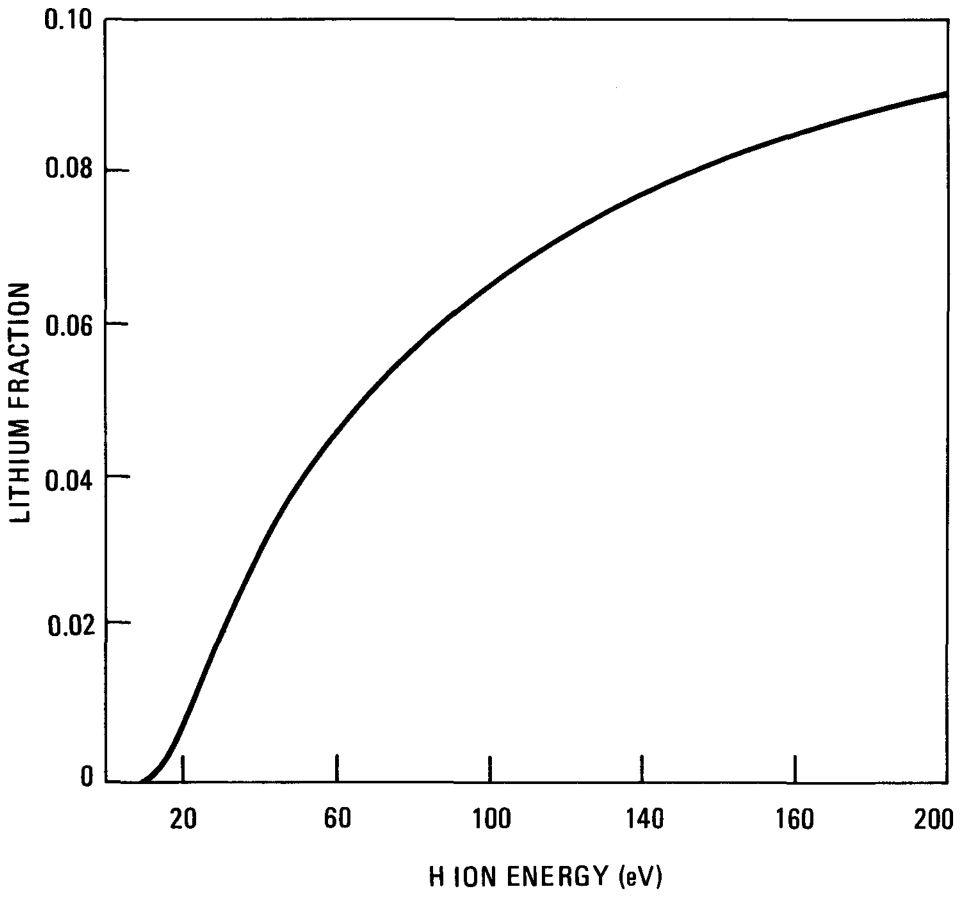
- IN STEADY STATE, WE HAVE A BALANCE OF EROSION AND REDEPOSITION

$$\sum_j S_j \Gamma_j = \Gamma_p \eta_p$$

- CONSEQUENTLY, THE LITHIUM FRACTION IS

$$f_p = \frac{\sum_{j \neq p} S_j (m_p/m_j)^{1/2} f_j}{\eta_p - S_p}$$

- SPUTTERING RATES USED ARE SEMIEMPIRICAL FORMULAS OF ROTH, BOHDANSKY AND OTTENBERGER.



UNCERTAINTIES IN EROSION CALCULATION

- **SPUTTERING YIELD FORMULA IS ONLY GOOD TO A FACTOR OF TWO.**
- **SURFACE OF THE PELLET WILL QUICKLY TURN INTO Li D & Li T, WHICH SHOULD HAVE LOWER SPUTTERING YIELDS THAN SOLID LITHIUM.**

FLOW REVERSAL ENHANCEMENT

- EXPERIMENTS ON ISX–B INDICATE THAT FLOW REVERSAL WORKS POORLY ON IMPURITIES THAT RECYCLE.
- CLEAN METAL SURFACES CAN PUMP ALL IONS IN THE PLASMA.
- PELLET PUMPING ENHANCES FLOW REVERSAL BY ALLOWING FOR LARGE, STEADY STATE HYDROGEN INJECTION AND BY PUMPING THE IMPURITIES THAT FLOW REVERSAL PUSHES OUT OF THE PLASMA.

USE OF IMPURITY FLOW REVERSAL

- IN EXPERIMENTS ON ISX–A, POLOIDALLY ASYMMETRIC HYDROGEN GAS INJECTION IN THE RANGE OF 1 – 7 x 10^{21} H_2/sec CAUSED A REDUCTION IN THE NEON INFLUX OF UP TO A FACTOR OF 3.5.
- TO SCALE TO OTHER MACHINES, USE THE FORMULA

$$\dot{N}_R = \frac{C_R}{2\pi a_I} \frac{B_I}{B_R} \dot{N}_I$$

- THEORY SAYS THAT R IS EQUAL TO EXP (– CONST · $\dot{N}$).
- EXAMPLE: B_R = 5.0 T AND a_R = 2 m, GIVES R = 0.5 AT 2 x 10^{21} sec^{-1}.
- FOR 2 x 10^4 TO 2 x 10^5 PELLETS/sec, $\dot{N}_I$ = 5 x 10^{21} TO 5 x 10^{22} sec^{-1} AND

$$R = 0.18 \text{ TO } 3.7 \times 10^{-8}$$

CONCLUSION

- IF OUR EROSION RATE CALCULATIONS ARE CORRECT, SMALL LITHIUM PELLETS CAN REMOVE HELIUM ASH AND IMPURITIES WITHOUT CONTAMINATING THE PLASMA.
- IF OUR CALCULATIONS OF EROSION ARE TOO LOW, WE CAN STILL COMBINE PELLET INJECTION WITH IMPURITY FLOW REVERSAL TO KEEP THE LITHIUM IN THE EDGE.

CALCULATIONS FOR 1981

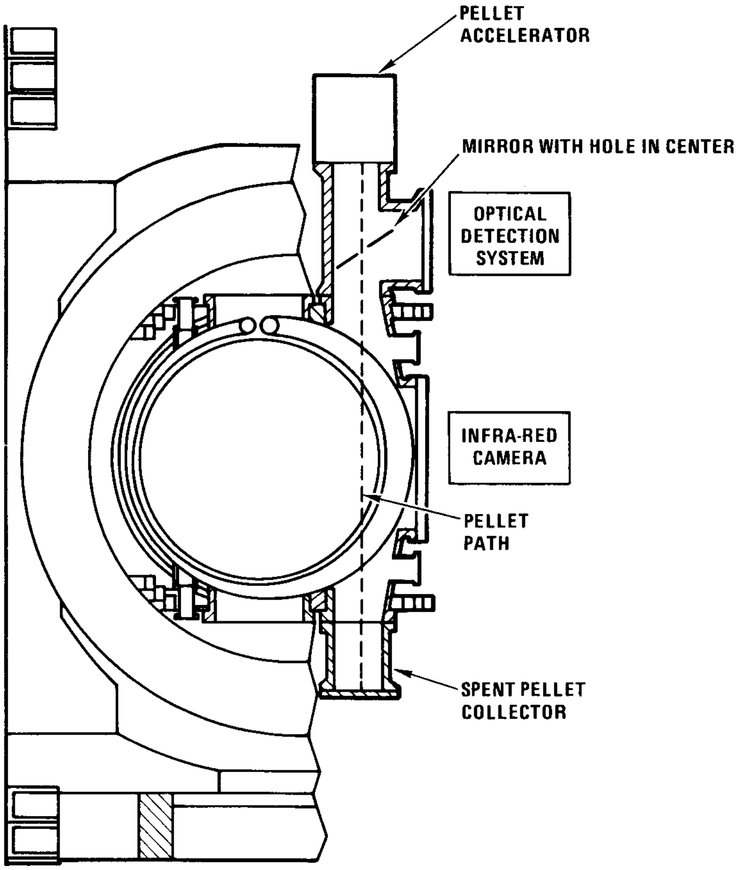
- FORCES ON THE PELLET DUE TO PLASMA PRESSURE AND NONUNIFORM MAGNETIC FIELD
- EFFECTS OF SECONDARY ELECTRON EMISSION ON HEAT FLOW THROUGH THE SHEATH AND ON SPUTTERING YIELD
- SPEED OF CHANGE OF SURFACE FROM Li TO LiH OWING TO PLASMA IMPACT

NECESSARY EXPERIMENTAL TESTS

- ACTUAL EROSION MEASUREMENTS IN A TOKAMAK PLASMA
- LABORATORY TESTS OF HELIUM RETENTION CAPABILITY
- Li AND LiH SPUTTERING COEFFICIENT MEASUREMENTS

PROPOSED TEXTOR EXPERIMENTS

- SHOOT TEST PELLETS OF VARIOUS MATERIALS THROUGH THE PLASMA EDGE (POTENTIAL MATERIALS OR COATINGS: Li, TiC, C, Al, STAINLESS STEEL)
- DETECT THE ERODED MATERIALS THROUGH LINE RADIATION PRODUCED BY ELECTRON IMPACT. DETERMINE THE AMOUNT THROUGH KNOWLEDGE OF LOCAL ELECTRON DENSITY AND TEMPERATURE AND KNOWN ATOMIC RATE COEFFICIENTS
- DETERMINE HEAT FLUX TO THE PELLET BY MEANS OF SURFACE TEMPERATURE MEASUREMENTS USING AN INFRARED CAMERA



DIAGNOSTICS REQUIRED

- PROBES FOR LOCAL ELECTRON DENSITY AND TEMPERATURE
- OPTICAL SYSTEM FOR DETECTING ERODED MATERIAL (LENSES, FILTERS, CAMERA)
- INFRA-RED CAMERA
- SPECTROMETER TO DETERMINE AMOUNT OF ERODED MATERIAL PENETRATING THE PLASMA
- MICROSCOPES FOR ANALYSIS OF PELLET SURFACE AFTER REMOVAL FROM VACUUM VESSEL

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