Proceedings of the Eighth Meeting of the International Collaboration on Advanced Neutron Sources (ICANS-VIII)
8-12 July 1985, Rutherford Appleton Laboratory Report RAL-85-110

E U R A C

THE JRC PROPOSAL FOR A EUROPEAN FUSION REACTOR MATERIALS TEST AND DEVELOPMENT FACILITY

W. Kley and G.R. Bishop
Commission of the European Communities
Joint Research Centre - Ispra Establishment
21020 Ispra (Va) - Italy

SUMMARY

The United States Department of Energy has spent in the last 10 years more than 100 Mill U.S.$ for the development of intense neutron sources for a fusion reactor material test and development programme based on the D^+-T and D^+-Li stripping reactions. The final design parameters for the large Fusion Materials Irradiator Test (FMIT) facility are:

- Linear Accelerator: . 35 MeV, 100 mA-deuteron-beam on a liquid lithium target
- Irradiation parameters: . 83 dpa/year* in 10 cm^3
  . 11 He appm/dpa*.

*dpa is displacements per atom; appm is atoms parts per million.

**A value of 6.4 is obtained if all neutrons above 30 MeV are collected in the energy group between 29.95 - 30 MeV and their He-production estimated with $\sigma_{n,\alpha}$ (30 MeV). A value of 13 is obtained if the He-production is calculated with estimated $\sigma_{n,\alpha}$-cross sections for neutrons up to 400 MeV and measured neutron spectrum in excellent agreement with Fusion Reactor First Wall conditions.

For the last 6 years we examined the use of a Spallation Neutron Source (SNS) as an alternative European Option to FMIT. For an optimized spallation neutron source design we find now for the same beam power as FMIT the following design parameters:

- Linear Accelerator: . 600 MeV, 6 m-A-proton beam on liquid lead target
- Irradiation parameters: . 320 dpa/year in 20 cm^3 or 274 dpa/year in 31.5 cm^3
  . $6 < \text{He appm/dpa} \leq 13^{**}$

For a Tokamak Experimental Power Reactor such as INTOR (1.3 $MWatt/m^2$ wall loading) the design parameters are:

15 dpa/year and 11 He appl/dpa.

If we compare FMIT with an optimized spallation neutron source of equal beam-power or neutron production cost, we arrive at the following Figure of Merit:

$$FM = \frac{(\text{dpa.volume})^{SNS}}{(\text{dpa.volume})^{FMIT}} - \frac{274\text{x}31.5}{83\text{x}10} \approx 10.4.$$

The present conceptual spallation neutron source target would allow us to use a 1200 MeV, 24 mA-proton beam, if required. The Ispra SNS-Target Station will be designed for these parameters.

For synergetic experiments concerning fatigue and radiation damage the continuous proton beam will be periodically deflected on the target:

$$\Delta t = 9 \text{ sec}, \qquad f = 10^{-1} \text{ sec}^{-1}$$

in order to simulate the Pulsed Mode of Tokamak Power Reactors. The deflected beam can be used for other experiments.

1. INTRODUCTION

The plasma physicists may realize Lawson's break-even condition in their large Tokamak fusion test facilities, such as JET, towards the end of the 1980s. This situation indicates that after 30 years of plasma physics research, the design and construction of future fusion power reactors may be considered now more realistically. However, the technical and economic success of fusion power reactors will depend on the endurance and availability of materials suitable for the radiation environment of a fusion reactor. For the evaluation of the technical and economic feasibility, predictions are needed concerning the evolution of the mechanical properties of materials being exposed to the complex radiation field of a future fusion reactor.

It is now the general understanding of the fusion materials research community that the end-of-life of the first wall or blanket materials is determined by a considerable number of complex and competing phenomena. Due to non-linear effects in the evolution towards end-of-life conditions and due to the absence of a synergetic theory on how damage energy is being stored in a material, one cannot extrapolate from low dose irradiations to end-of-life conditions. Neutron induced radiation damage can be simulated to a certain extent by energetic charged particle beam experiments. However, they have limited reliability if the primary recoil energy spectrum, the production of transmutation products (impurity atoms), dpa-rate effects and typical bulk properties are important parameters in the evolution of the mechanical properties towards end-of-life (e.g. if niobium is exposed to a fluence of 10^{23} n/cm^2, 20 percent (!) of the niobium atoms will be transformed into impurity atoms). Therefore, we need neutron irradiations up to the end-of-life that may occur between 20 and 100 dpa (displacements per atom) or at the respective fluences between 10^{22} to 10^{23} n/cm^2 (fluence = neutron flux · time: $\varphi = \phi \cdot t$ (n/cm^2)). Since one year has about $\pi \cdot 10^7$ sec, we need at least a fast neutron flux of 10^{15} n/cm^2 sec in order to reach in one year irradiation time end-of-life conditions for a typical material.

It can be shown [1-4] that only accelerator based neutron sources can provide the necessary source strength with the required neutron energy distribution. Irradiations in high flux reactors and fast reactors are not valid for fusion reactor conditions with one exception: the nickel based alloys, which are of very limited value and interest for fusion reactors because of the residual radioactivity and Helium production. Therefore, the availability of an accelerator based neutron source is mandatory for a reliable prediction of the technical and economic feasibility of fusion power reactors.

There are essentially only two competing nuclear reactions that might be used for the production of an intense neutron source: they are based either on the D^+-Li stripping, or on the spallation reaction. 35 MeV deuterons, impinging on a lithium target, produce a considerably harder neutron spectrum (average neutron energy: $\bar{E}_n \approx 9$ MeV) than in a first wall fusion reactor ($\bar{E}_n \approx 4$ MeV). On the contrary, spallation neutrons, produced by 600 MeV protons impinging on a lead target, have a somewhat softer spectrum ($\bar{E}_n \approx 6$ MeV) than the D^+-Li neutrons. Therefore, both neutron spectra deviate strongly from the one in the first wall of a fusion reactor. However, for simulating first wall conditions, it is sufficient to show that the ratio of the spectrum averaged properties:

$$\langle\sigma\phi\rangle_{n,p} : \langle\sigma\phi\rangle_{n,d} : \langle\sigma\phi\rangle_{n,t} : \langle\sigma\phi\rangle_{n,\alpha} : \langle\sigma\phi\rangle_{n,2n} : \ldots : \langle\sigma\phi\rangle_{n,\text{rest nuclei}} : P(T)$$

are similar to the one in the fusion reactor. σ stands for $\sigma(E)$, the energy dependent production cross section; $\phi \equiv \phi(E)$, the neutron spectrum; and P(T) stands for the primary recoil energy spectrum; and T for the recoil energy in the laboratory system.

For the evaluation of the spectrum averaged parameters for five neutron sources (fission, 14 MeV, Fusion Reactor First Wall, D^+-Li and spallation neutron source), we need the associated cross sections up to 30 and 40 MeV, often not available for the elements of interest to material scientists. For that reason, cross section calculations have been performed for such a programme up to 30 MeV and are now being extended up to 40 MeV for ^{52}Cr, ^{56}Fe, ^{55}Mn, ^{58}Ni and ^{60}Ni by the "Institut für Radiumforschung und Kernphysik" of the University of Viennw [5], including the production of transmutation products as well as the Primary Recoil Energy Spectrum P(T) for elastic and inelastic events, and the effects of the transmutation products. A study programme at the Swiss Institute for Nuclear Research (SIN) at Villigen has been completed for various spallation neutron source configurations, for the Fusion First Wall, the 14 MeV, the fission and the D^+-Li neutron spectrum, the spectrum averaged cross sections for chromium, iron, manganese and nickel, the main constituent of 316 stainless steel and the corresponding Primary Recoil Energy spectra. The results from F. Atchison et al. [6] show that the dimensionless ratio

$$\psi_i = \frac{<\sigma\phi>^{\text{spallation neutron source}}}{<\sigma\phi>^{\text{fusion first wall}}} = 1 \pm 0.3$$

for hydrogen, helium, the transmutation products, the damage energy cross section and dpa; in excellent agreement considering the very different neutron spectra.

Traditionally ψ_i-values have not been used for the intercomparison of different neutron sources but rather the corresponding He to dpa ratio. F. Atchison et al. [6] and V. Herrnberger et al. [7] obtained for stainless steel

$$6 < \frac{\text{He appm}}{\text{dpa}} \leq 13.$$

A value of 6.4 is obtained if all neutrons above 30 MeV are put in the last energy group from 29.75 to 30 MeV and weighted with $\sigma_{n,\alpha}$ (30 MeV). For estimated $\sigma_{n,\alpha}$-cross sections up to 400 MeV and measured spallation neutron spectrum [8] Herrnberger et al. obtained a value of 13. For the INTOR-Tokamak Concept a value of 11 is found for the first wall.

We conclude that spallation neutrons are simulating the Fusion Reactor First Wall conditions as well as the D^+-Li or the 14 MeV neutron sources.

Therefore, we propose the construction of a spallation neutron source based on a 600 MeV, 6 mA linear proton accelerator. If we compare the U.S. Fusion Materials Irradiation Test (FMIT) facility with an optimized spallation neutron source of equal beam power or neutron production cost, we arrive at the following Figure of Merit:

$$FM = \frac{(\text{dpa.volume})^{SNS}}{(\text{dpa.volume})^{FMIT}} = \frac{274 \times 31.5}{83 \times 10} \approx 10.4.$$

The present conceptual spallation neutron source target, described in the following, would allow us to use a beam energy up to 1200 MeV and a beam current up to 24 mA, equivalent to a beam power of 29 MWatt, if required.

2. SPALLATION NEUTRONS - A TOOL TO SIMULATE FIRST WALL CONDITIONS

2.1 The 1978 Hypothesis

The number of neutrons produced per second in a target is a limited criterion for an irradiation test facility. What counts is the highest accessible neutron density or neutron flux and the corresponding energy distributions of these neutrons. In a large water-cooled target such as the beam dump of LAMPF (Los Alamos Meson Physics Factory), the average neutron energy tends to be $\lesssim$ 2 MeV, while in an unperturbed spallation neutron spectrum, at 90^o to the impinging proton beam and at the point of the highest neutron density, the mean neutron energy is about 6 - 7 MeV, for 600 MeV protons, well above the mean neutron energy ($\approx$ 4 MeV) of the first wall. Therefore, we have to get as close as possible to an impinging proton beam that has the highest tolerable proton beam density. At this position we have even in a totally reflected system a mean neutron energy of about 4 MeV as in the first wall. In our 1978 hypothesis we assumed that the H, D, T, He^3, He^4, ..., the rest nuclei and the dpa-production is hopefully proportional to the mean neutron energy since the $\sigma_{n,p}(E)$ and $\sigma_{n,\alpha}(E)$ cross sections have their thresholds around 2 - 4 MeV and their maximum around 13 - 16 MeV, depending on the nuclei considered.

F. Atchison et al. [6] proved that for 20 different neutron spectra with mean neutron energies lying between 1 and 14 MeV, the spectrum averaged He to dpa ratio and the spectrum averaged displacement cross sections are really proportional to the mean neutron energy. Hence, spallation neutrons are a tool to simulate first wall conditions!

2.2 Results of the Theoretical Program and Conclusions

The guiding principle has been outlined above. However, for a well founded decision we needed more precise information on high energy cross sections not available at that time. For that reason we signed a first contract in 1979 with Prof. Dr. H. Vonach, Director of the "Institut für Radiumforschung und Kernphysik" of the University of Vienna. Cross section calculations have been performed by W. Reiter, B. Strohmaier and M. Uhl [5] for such a program between 10 and 30 MeV and are now being extended in a second contract (1984-1985) up to 40 MeV for ^{52}Cr, ^{56}Fe, ^{55}Mn, ^{58}Ni and ^{60}Ni, including the production of transmutation products as well as the Primary Recoil Energy Spectrum P(T) for elastic and inelastic events, and the effects of the transmutation products. In 1982 a contract was signed with the Swiss Institute for Nuclear Research (SIN) at Villigen, in order to obtain, for various spallation neutron source configurations, for the Fusion First Wall, the 14 MeV, the fission and the D^+-Li neutron spectrum, the spectrum averaged production cross sections for chromium, iron, manganese and nickel, the main constituent of 316 stainless steel and the corresponding Primary Recoil Energy Spectra. The geometry and parameters of the theoretical program are given in Fig. 1. The most relevant results of the First and Second Interim and of the Final Report from F. Atchison, W.E. Fischer and M. Pepin [6] are reproduced in Figs. 2 to 9. The results from F. Atchison et al. [6] show that for a spallation neutron source, based on 600 MeV protons, the dimensionless ratio

$$\psi_i = \frac{\langle\sigma_i\phi\rangle_{\text{spallation neutron source}}}{\langle\sigma_i\phi\rangle_{\text{fusion first wall}}} = 1 \pm 0.3$$

for hydrogen, helium, the transmutation products, the damage energy cross section, dpa and the mean neutron energy; in excellent agreement considering the very different neutron spectra.

Traditionally [1-4,7] ψ_i-values have not been used for the intercomparison of different neutron sources but rather the corresponding He to dpa ratio. F. Atchison et al. [6] and V. Herrnberger et al. [7] obtained for stainless steel

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A value of 6.4 is obtained if all neutrons above 30 MeV are put in the last energy group from 29.75 to 30 MeV and weighted with $\sigma_{n,\alpha}$ (30 MeV). For estimated $\sigma_{n,\alpha}$ cross sections up to 400 MeV and measured spallation neutron spectrum [8] Herrnberger et al. obtained a value of 13.

For the INTOR-Tokamak Concept a value of 11 is found for the first wall. However, we do not believe that the He to dpa ratio is a very sensitive parameter for the intercomparison. A He appm to dpa ratio of 10 means that we have one helium atom for 10^5 vacancies as initial conditions. In addition, "dpa" is used here as a measure for the deposited damage energy that is certainly not only stored in point defects but also in cascades, voids, interstitial and vacancy loops, as well as in precipitates and in the microchemical evolution in general. Any slowing down helium atom is going to be trapped in its own damaged zone that does not necessarily "feel" all the other far away damaged zones which do not contain helium. Therefore, it seems to us that the total helium content or the corresponding ψ_i-value is more important than the actual He to dpa ratio. Since the He-atoms carry a certain fraction of the total damage energy, a certain lower limit of the He to dpa ratio must be respected by the neutron source designer.

We have not yet received any definite answer from material scientists if the mechanical properties of an irradiated material are the same at different dose but the same helium content. There is some speculation that the He:dpa ratio may vary by a factor of 5 without having any considerable influence on the mechanical properties as a function of the total helium content. In other words, the helium content is the more sensitive parameter in respect to DPA. Furthermore, we could not get an answer for the upper limit of the dpa-rate in a neutron source. In our present proposal we are already 20 times higher than in the first wall. What is the lower and upper limit for the He:dpa and dpa-rate, respectively?

Fig. 6 shows that the spectrum averaged <dpa> and <He:dpa> values are really proportional to the mean neutron energy, as assumed in our 1978 hypothesis.
Figs. 7 and 8 display the Primary Recoil Energy Spectra in SS-316 and iron, respectively, for neutron sources based on 600 and 1200 MeV protons, in the Fusion First Wall and FMIT (perturbed). It demonstrates clearly that spallation neutrons are simulating the Fusion First Wall conditions as well as the D^+-Li or the 14 MeV neutron sources.
Fig. 9 shows the neutron spectra for 600 and 1200 MeV protons. Increasing the proton energy does not change the neutron spectrum below 10 MeV, where the evaporation neutrons play a dominant part, while the cascade neutrons are considerably enhanced. Therefore, the spectrum averaged helium production cross sections increases from 9.655 mbarns for 600 MeV protons to 15.061 mbarns for 1200 MeV protons. Most of the damage is produced by the evaporation neutrons while the cascade and knock-on neutrons are predominantly producing helium.

In spite of the close fit of the Primary Recoil Energy Spectrum for 600 and 1200 MeV protons, as shown in Figs. 7 and 8, with the one in the Fusion First Wall, many scientists argue that the very high energy spallation neutrons, even if few in number, will produce very large damage cascades which will give rise to unpredictable problems. To disprove this argument we calculated the Lindhard Efficiency Factor and the corresponding Damage Energy up to 40 MeV recoil energy which corresponds to an elastic scattering process of a 600 MeV neutron on an iron atom. Fig. 10 shows that the damage energy g(T) of a 100 MeV neutron is only a factor 2 higher than of a 14 MeV neutron; the corresponding recoil energies are 7 and 1 MeV, respectively. Therefore, we have the paradox that the damage energy density, or subcascade density, is smaller for high than for low energy recoils. This is even more true for 600 MeV neutrons since g(T) is saturating; most of the recoil energy is transformed into heat and not into damage. Therefore, we have no problem with high energy neutrons. Mr. W. Matthes from Ispra is working on a detailed analysis of the primary damage energy deposition, to prove quantitatively our qualitative argument.

From the above follows that we can use without any difficulty also 1200 MeV protons. Using 1200 instead of 600 MeV protons the peak neutron flux increases by 37%, the mean neutron energy by 33%, the He production density by a factor 2.13 and the total helium production by a factor 3,5; see Table 1. Therefore, optimum conditions are being achieved at 1200 MeV with an increase in heat deposition density only of 40%, important for the target design.

3. THE CONCEPTUAL DESIGN OF THE SNS FACILITY

3.1 The Target

In Fig. 11 the vertical cross section of a liquid lead target is shown which can tolerate a beam power density of 15 $MWatt/cm^2$ and more. The fins are guiding the liquid lead in such a way that along the beam axis the centrifugal forces are generating an increasing pressure in the liquid lead suppressing any violent boiling of the lead. But, in contrast to the FMIT target, explosive boiling is not dangerous since the target can be made long enough and consequently the proton beam does not hit a solid wall.

3.2 The Irradiation Test Section

Figs. 12 and 13 show the horizontal and vertical cross section of the irradiation test section. The first three rows of Li or $Li_{17}Pb_{83}$ cooled channels are the fusion reactor materials test zone. In the first row along the beam, 320 dpa per year are generated in a volume of 20 cm^3, allowing 50 percent coolant volume, excluding the structural material of target and test section, which have an even higher dpa-rate. The neutrons leaking from the test zone are driving a subcritical booster ($\lesssim$ 10 MWatt) which provides a thermal neutron flux trap with a liquid hydrogen moderator in the centre. The ZrH_2-thermal neutron moderator will be gas cooled in order to avoid any light or heavy water in the liquid metal cooled target station. Close to the booster target large irradiation test sections (for the development of fast breeder construction materials) and isotope producing rigs can be installed (not shown in Figs. 11 and 12). Thermal and cold neutrons are leaking from the moderator into bent neutron guide tubes, providing intense neutron beams to the neutron scattering spectrometers, used as analytical instruments for the non-destructive testing of highly radioactive samples.

3.3 The Target Station

Fig. 14 shows the lay-out of the Neutron Target Station. The large iron shield will have a diameter $\leq$ 14 metres, depending on the desired maximum beam power in the future. Six thermal and cold neutron beam ports are foreseen for the analytical instruments, designed particularly for highly radioactive samples.

3.4 The Fusion Reactor Materials Test and Development Facility

Fig. 15 shows the lay-out of the facility. H^+- and H^--ion sources are 1200 metres distant from the target station. The 600 MeV proton linear accelerator occupies the first 600 metres. A beam transport system guides the proton beam to the target station. Hence, at a later time, if desired, the proton beam can be brought to an energy of 1200 MeV. For synergetic experiments concerning fatigue and radiation damage the continuous proton beam will be periodically deflected on the target:

$$\Delta t = 9 \text{ sec}, \qquad f = 10^{-1} \text{ Herz}$$

in order to simulate the Pulsed Mode of Tokamak Power Reactors. The deflected beam will be used for a:

- Nuclear Physics Programme;
- Solid State Physics and a Bio-Medical Research Programme;
- Health Physics Research Programme;
- Special Isotope Production for medical, biological, agricultural and industrial application;
- μ-meson Fusion Programme;
- Breeding or Incineration with neutrons.

3.5 EURAC: The European Accelerator Neutron Source

Drs. R.A. Jameson and S.O. Schriber [10] informed us that for reasons of efficiency and economy, a pulsed proton linear accelerator feeding a pulse stretcher ring must be considered instead of a continuous wave accelerator, at least for the average proton current of 6 to 24 mA, which is our case. An optimalization study will have to be performed to find the crossing point at what beam current the continuous wave accelerator is more economic than the pulsed proton linear accelerator with a pulse stretcher ring. For a number of very important reasons we believe now that we must consider a 12 (24) mA, 1200 MeV pulsed proton linear accelerator, delivering 100 pps of 250 μsec pulse width, as the basis for the future European Neutron Sources. A conceptual scheme of EURAC is given in Fig. 16. EURAC can provide simultaneously a pulsed thermal and cold neutron source, as pioneered by the SNQ-Project Group at Jülich, FRG, and a continuous fast neutron beam for a Fusion Reactor Materials Test and Development programme, as pioneered at the JRC-Ispra, Italy. It can serve many other areas of research from particle physics to medical, biological, agricultural and industrial application, to energy strategies including μ-meson - Fusion, Electrobreeding and Incineration of very long-living radioisotopes.

It may be remarked that muon - Fusion is making remarkable progress [11-15] and it has to be considered seriously as a possible solution to our future energy requirements. To produce one μ-meson an energy of about 5 GeV is necessary, therefore "break even" would be reached at around 300 catalytic D-T muon reactions. Recently at LANL [16], 200 muon catalytic reactions have been measured per μ-meson. This is more than expected from the theoretical sticking factor, describing the probability of attachment of the μ-meson to the α-particle in the D-T muon catalytic fusion process, that predicts about 100 reactions per muon. Two hundred reactions would be sufficient for a Hybrid-Fusion Reactor. However, the problem remains how to collect the muons efficiently from a target and to transfer them to a reaction chamber. It seems a difficult but solveable problem. Therefore, more theoretical and experimental work must be devoted to the collection of μ-mesons.

Fig. 17 shows the artistic view of a Material Science Spectrometer [17] of which a 90 metre long version was designed for the SNS Rutherford Appleton Laboratory, UK, and a 150 metre long version for the SNQ Jülich. The foundations and the beam port insert have been constructed at RAL and a considerable part of the detectors have been purchased. The spectrometer is capable to measure simultaneously Small Angle Scattering (SAS), Elastic Diffuse Scattering (EDS), Quasi Elastic Scattering (QES) and Bragg Scattering (BS). Therefore, the spectrometer is capable to measure simultaneously the density of point defects, the density and size distribution of precipitates, damage cascades and voids, the texture, the stress and strain distributions, the mobility of hydrogen as well as the microchemical evolution of candidate materials irradiated to end-of-life conditions. The high resolution neutron spectrometer will complement the conventional analytical instruments.

Fig. 18 gives an outlook why fusion-fission hybrid power stations might be more economic than pure fusion reactors. The SNS-Ispra is a miniaturized form of a fusion-fission hybrid reactor system. In Table 2 the various neutron source parameters, of interest in our context, are listed.

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TABLE 1 - Neutron source performance data for 600 and 1200 MeV protons

Proton energy : 600 Mev Sample position: Z = 3.75 cm			Proton energy : 1200 MeV Sample position: Z = 3.75 cm		
Flux/proton (n/cm^2)	$\bar{E}n$ MeV	<He> mbarns	Flux/proton (n/cm^2)	$\bar{E}n$ MeV	<He> mbarns
0.065	4.75	9.655	0.089	6.31	15.061

Conclusion:

Switching from 600 to 1200 MeV protons increases:

1. (dpa.volume) by a factor 2,64
2. Peak neutron flux by 37%
3. Mean neutron energy by 33%
4. He-production density by a factor 2.13
5. Total helium production by a factor 3,5

TABLE 2 - Intercomparison of existing and projected neutron sources

Neutron-Sources	RTNS-II LLL-USA	FMIT HEDL-USA	SNS-RAL Rutherford App. Lab. GB	SNS-LASL WNR USA	LAMPF-Beam-Stop USA	SNS-CH Villigen Switzerland	SNQ-Jülich FRG	SNS-JRC-Ispra	Fusion' 1. Wall "INTOR"
Nuclear Reaction	D^+-T Fusion Reaction	D^+-Li- Stripping-Reaction	800 MeV-Protons; U-238-Target spallation	800 MeV-Protons; U-238 Target spallation	500 - 800 MeV Protons on Cu spallation	590 Mev-Protons on liquid Pb spallation	1100 MeV-Protons on solid W, Pb, U-238 spallation	600 MeV-Protons on liquid Pb spallation	D^+-T^+ Fusion
Beam Energy	400 keV	35 MeV	800 MeV	800 MeV	800 MeV	590 MeV	1100 MeV	600 MeV	
Beam Current	D^+: 150 mA	D^+: 100 mA	$\overline{P^+}$: 0.2 mA	P^+: 0.1 mA	$\overline{P^+}$: 1 mA	$\overline{P^+}$: 2 mA	$\overline{P^+}$: 5 mA	$\overline{P^+}$: 6 mA	
Beam Power	60 kWatt	3.5 MWatt	160 kWatt	80 kWatt	800 kWatt	1.18 MWatt	5.5 MWatt	3.6 MWatt	1.3 MW/m²
Estimated Beam Power Density	$\frac{60\ kWatt}{cm^2}$	$\frac{1.2\ MWatt}{cm^2}$	$\approx \frac{6.4\ kWatt}{cm^2}$	$\approx \frac{3.2\ kWatt}{cm^2}$	$\approx \frac{8\ kWatt}{cm^2}$	$\lesssim \frac{50\ kWatt}{cm^2}$	$\approx \frac{250\ kWatt}{cm^2}$	$\frac{15\ MWatt}{cm^2}$	$\approx \frac{130\ Watt}{cm^2}$
Mode of Operation	Continuous	Quasi-continuous	Pulsed $\Delta t \approx 0.4\ \mu sec$ f = 50 Herz $\Delta t \cdot f = 2 \cdot 10^{-5}$	Pulsed $\Delta t \approx 0.4\ \mu sec$ f = 12 Herz $\Delta t \cdot f = 4.8 \cdot 10^{-6}$	Pulsed $\Delta t = 500\ \mu sec$ f = 120 Herz $\Delta t \cdot f = 6 \cdot 10^{-2}$	Continuous	Pulsed $\Delta t = 250\ \mu sec$ $f \leqslant 100$ Herz $\Delta t \cdot f = 2.5 \cdot 10^{-2}$	Quasi-continuous; $\Delta t = 9$ sec, f = 0.1 Herz $\Delta t \cdot f = 0.9$	Quasi-continuous; $\Delta t \leqslant$ 3000 sec, $f \leqslant 10^4$ per year
Number of Neutrons produced per sec in Target	$4 \cdot 10^{13}$ n/sec TiT	10^{16} n/sec Li	$4 \cdot 10^{16}$ n/sec U-238	$2 \cdot 10^{16}$ n/sec U-238	$\lesssim 10^{17}$ n/sec Cu/U-238	$1.2 \cdot 10^{17}$ n/sec Pb	$1.4 \cdot 10^{18}$ n/sec U-238	$9 \cdot 10^{17}$ *n/sec Pb -reflected Pb-target	$5.5 \cdot 10^{14}$ n/cm².sec
Estimated accessible average fast neutron-energy	14 MeV $E_n^{max} = 14.1$ MeV	9 MeV $E_n^{max} \lesssim 40$ MeV	$\lesssim 0.5$ MeV $E_n^{max} \leq 800$ MeV	$\lesssim 0.5$ MeV $E_n^{max} \lesssim 800$ MeV	$\lesssim 1$ MeV $E_n^{max} \lesssim 800$ MeV	$\lesssim 0.5$ MeV $E_n^{max} \lesssim 590$ MeV	$\lesssim 0.5$ MeV $E_n^{max} \lesssim 1100$ MeV	6 - 7 MeV unrefl. 4 MeV Pb-refl. $E_n^{max} \lesssim 600$ MeV	4 MeV
Accessible Fast Neutron Flux	$1.5 \cdot 10^{13}$ n/cm².sec	$1.4 \cdot 10^{15}$ n/cm².sec			$\lesssim 10^{13}$ n/cm².sec			$\approx 2 \cdot 10^{16}$ n/cm².sec	$5.5 \cdot 10^{14}$ n/cm².sec
dpa/year	0.2	83 (10 cm³)			≈ 0.2			320 (20 cm³)	15
He appm/dpa	15	11			< 1			$6 < \frac{He\ appm}{dpa} \leqslant 13^{**}$	11

* The apparent source strength of the Pb reflected Pb-target. A uranium-238 bare target would deliver $9 \cdot 10^{17}$ n/sec. A 10 MW-Booster target will deliver $1.7 \cdot 10^{18}$ n/sec.

Note: D^+-Li produces: $2,85 \cdot 10^{15}$ n/sec.MWatt; P^+–Spallation prod.: $2.5 \cdot 10^{17}$ n/sec.MWatt in U-238.

For an irradiation damage program the beam power density is the decisive parameter that is translated to fast neutron flux and correspondingly to dpa and He appm/dpa, the important parameters.

SNS–LASL, SNS–RAL, SNS–CH and SNQ–Jülich are designed for thermal and cold neutron production. They cannot be compared with SNS–Ispra, designed primarily for radiation damage, including thermal and cold neutron production.

** A value of 6.4 is obtained if all neutrons above 30 MeV are collected in the energy group between 29.75-30 MeV and their He production estimated with $\sigma_{n,\alpha}$ (30 MeV). A value of 13 is obtained if the He-production is calculated with estimated $\sigma_{n,\alpha}$ cross sections for neutrons up to 400 MeV and measured spallation neutron spectrum, in excellent agreement with Fusion Reactor First Wall conditions.

FIGURE CAPTIONS

Fig. 1 Geometry and parameters of the theoretical program.

Fig. 2 ψ_i-values in SS-316 as a function of sample position for an iron shielded neutron source: E_p = 600 MeV.

Fig. 3 ψ_i-values for transmutation products in SS-316 as a function of sample position for an iron shielded neutron. Source: E_p = 600 MeV.

Fig. 4 ψ_i-values in SS-316 as a function of sample position for an iron shielded neutron source: E_p = 1200 MeV.

Fig. 5 ψ_i-values for transmutation products in SS-316 as a function of sample position for an iron shielded neutron source: E_p = 1200 MeV.

Fig. 6 Spectrum averaged <dpa>- and <He:dpa>-values as a function of mean neutron energy.

Fig. 7 Primary recoil energy spectra for SS-316 for neutron sources based on 600 and 1200 MeV protons, fusion first wall and FMIT (perturbed).

Fig. 8 Primary recoil energy spectra for iron for neutron sources based on 600 MeV and 1200 MeV protons, fusion first wall and FMIT (perturbed).

Fig. 9 Neutron spectra at 3.75 cm for iron shielded neutron sources based on 600 and 1200 MeV protons.

Fig. 10 Damage efficiency in iron.

Fig. 11 The conceptional design of the liquid lead target; vertical cross section.

Fig. 12 Conceptional design of target-station; 1/2 horizontal cross section.

Fig. 13 Vertical cross section of conceptual SNS target station.

Fig. 14 Lay-out of the neutron target station.

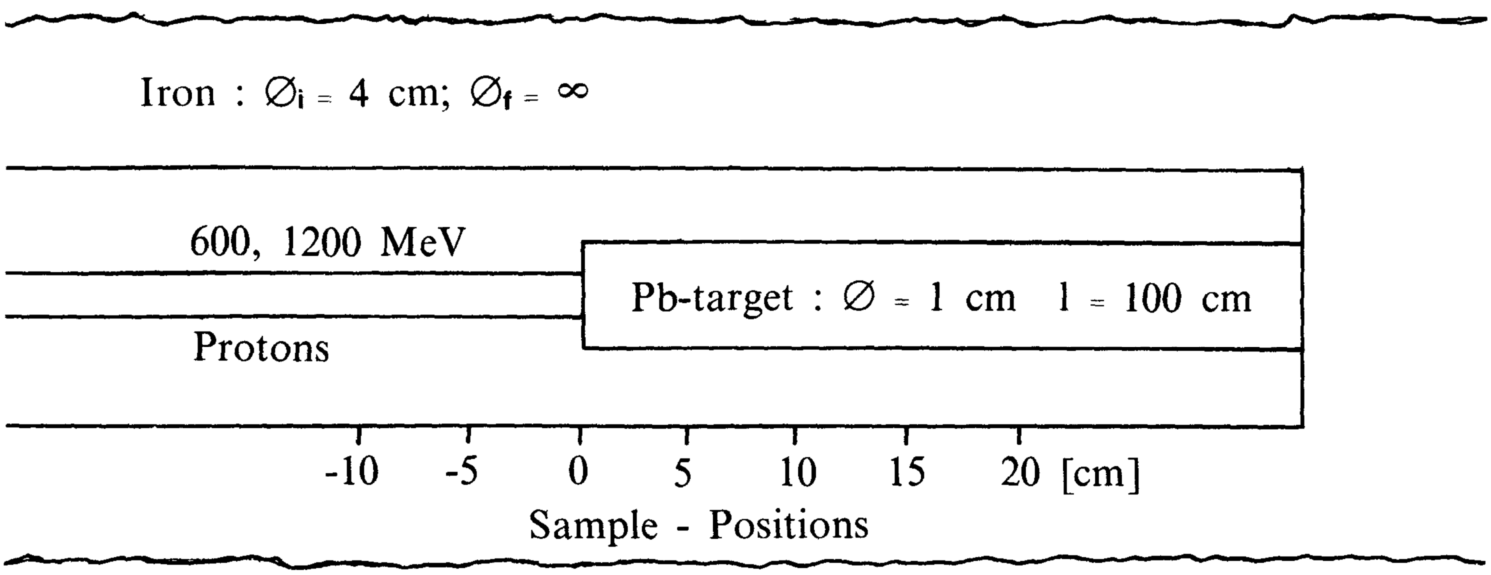
Fig. 15 Lay-out of the fusion reactor materials test and development facility, based on a continuous wave 600 MeV, 6 mA proton linear accelerator.

Fig. 16 EURAC: a European solution to future needs of neutrons.

Fig. 17 The material science spectrometer.

Fig. 18 Fusion hybrid energy strategy.

Fig. 19 Time schedule for EURAC.



$$\Psi_i = \frac{\langle \sigma\ (E)\ \varnothing\ (E) \rangle\ \text{Neutron Source}}{\langle \sigma\ (E)\ \varnothing\ (E) \rangle\ \text{Fusion 1. Wall}}$$

P(T) : Primary Recoil Energy Spectrum

Damage Energy : $g(T) = T - U = T\ L(T)$

$L(T)$ = Lindhard's Damage Efficiency Factor

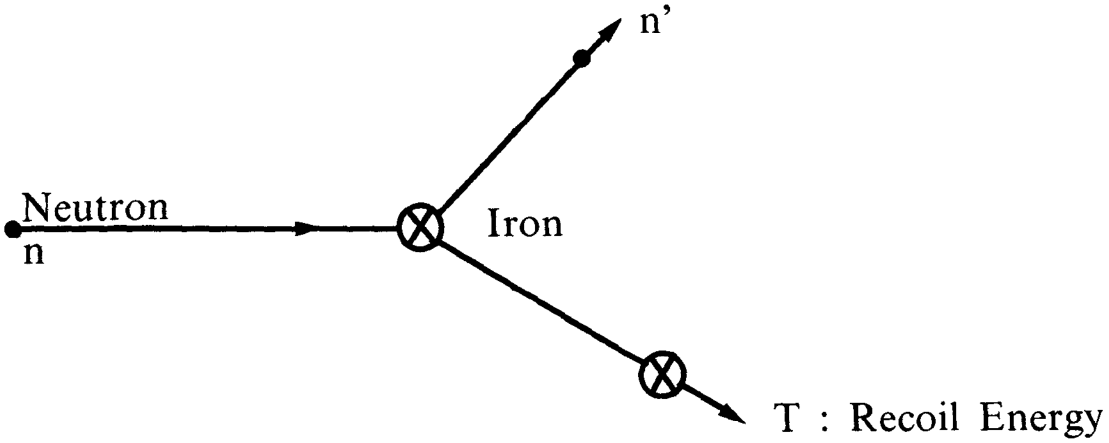


Fig. 1 : Geometry and Parameters of the Theoretical Program.

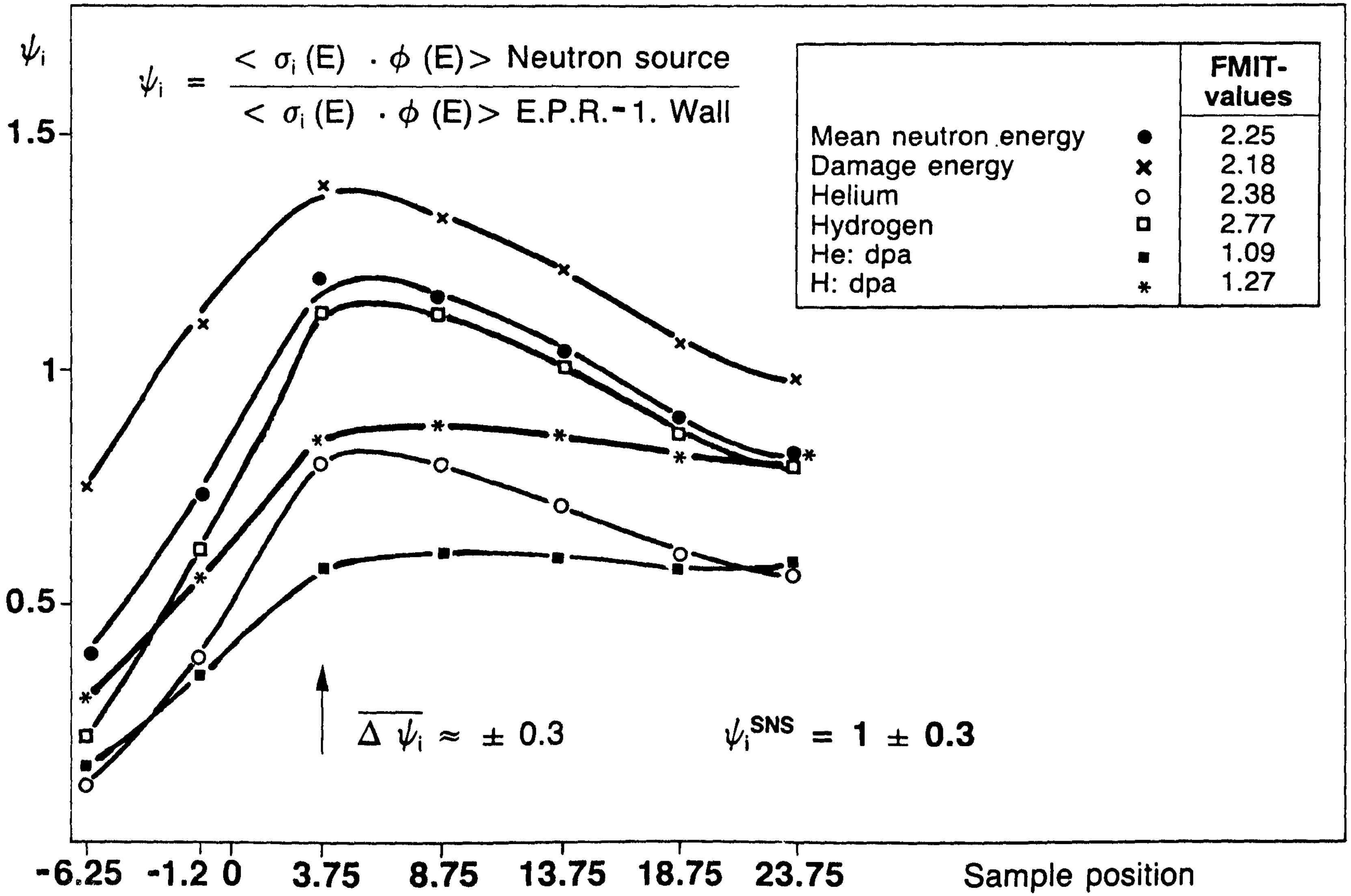


Fig. 2 : Ψ_i -Values in SS-316 as a Function of Sample Position for an Iron Shielded Neutron Source : Ep = 600 MeV.

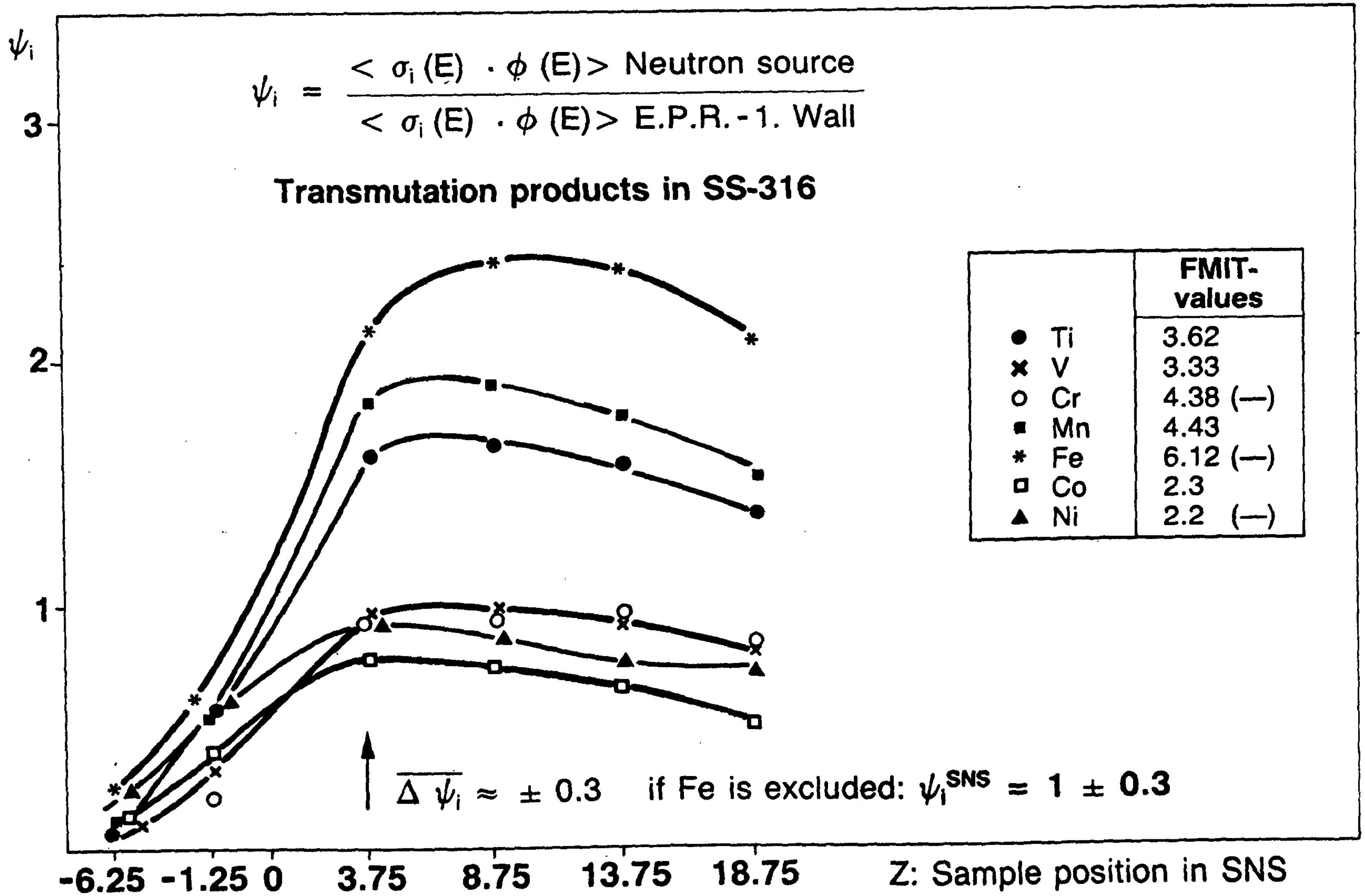


Fig. 3 : Ψ_i -Values for Transmutation Products in SS-316 as a Function of Sample Position for an Iron Shielded Neutron Source : Ep = 600 MeV.

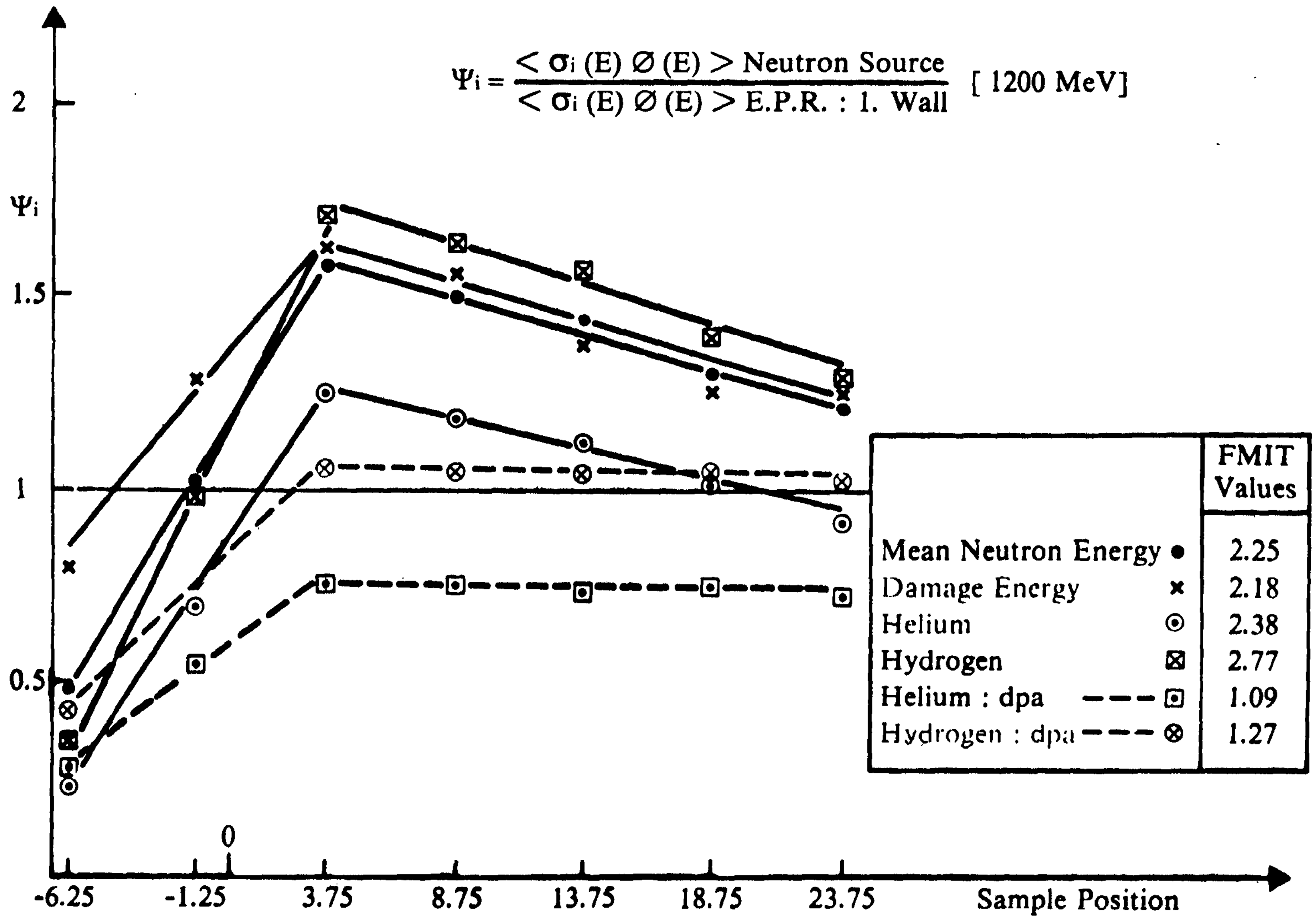


Fig. 4 : Ψ_i -Values in SS-316 as a Function of Sample Position for an Iron Shielded Neutron Source : Ep = 1200 MeV.

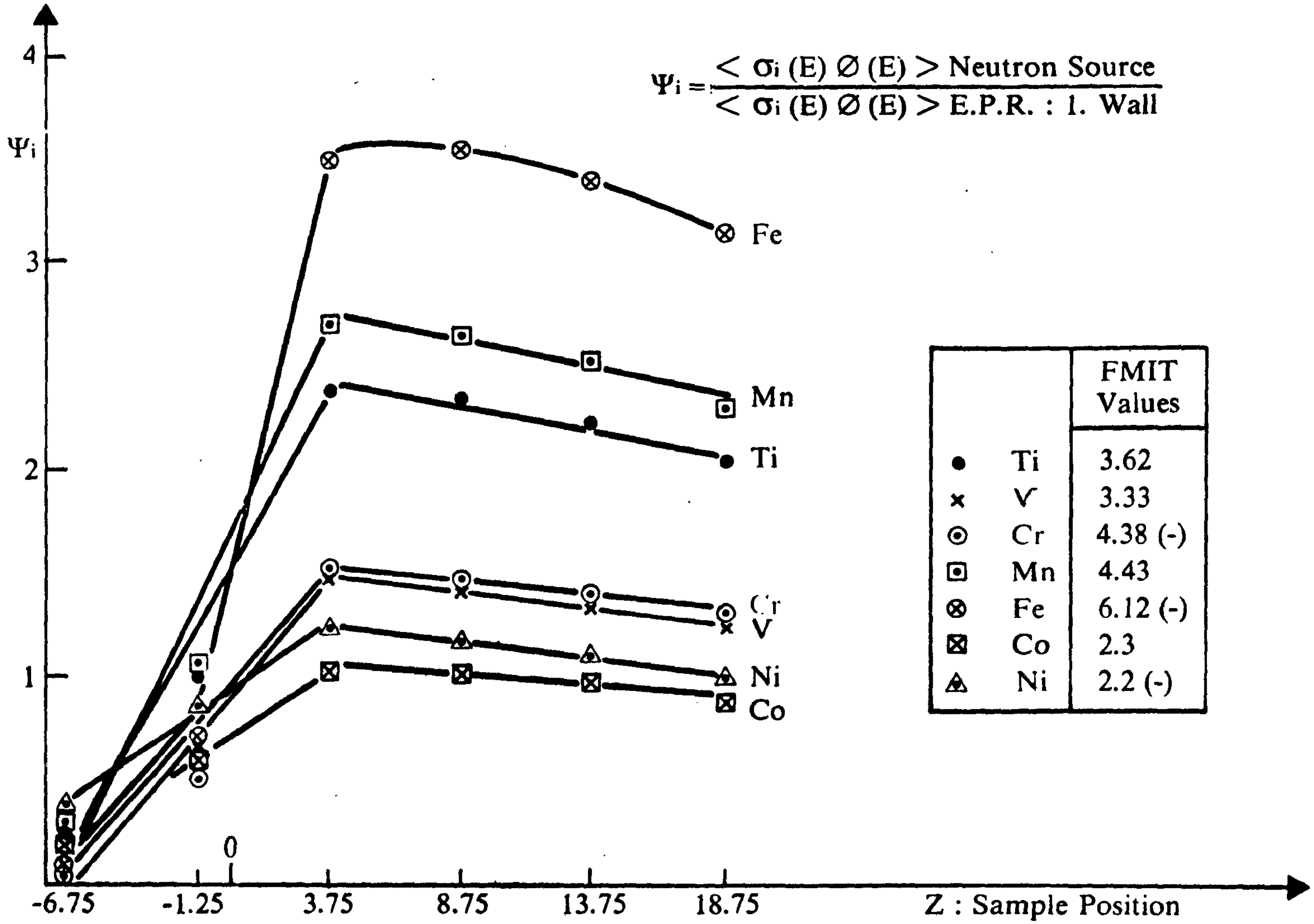
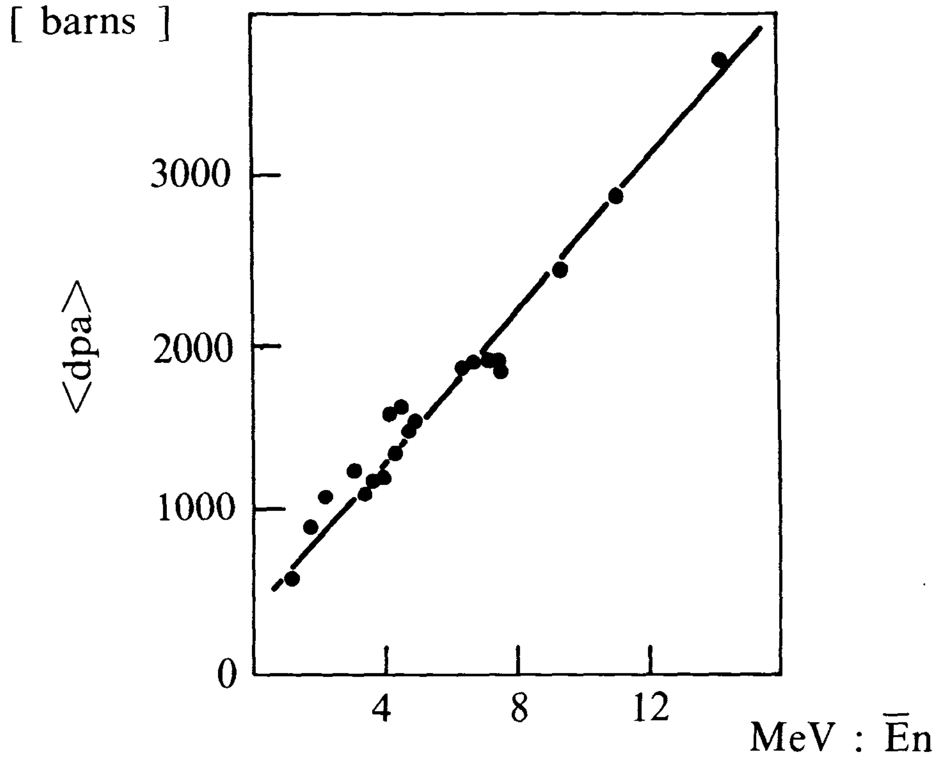


Fig. 5 : Ψ_i -Values for Transmutation Products in SS-316 as a Function of Sample Position for an Iron Shielded Neutron Source : Ep = 1200 MeV.



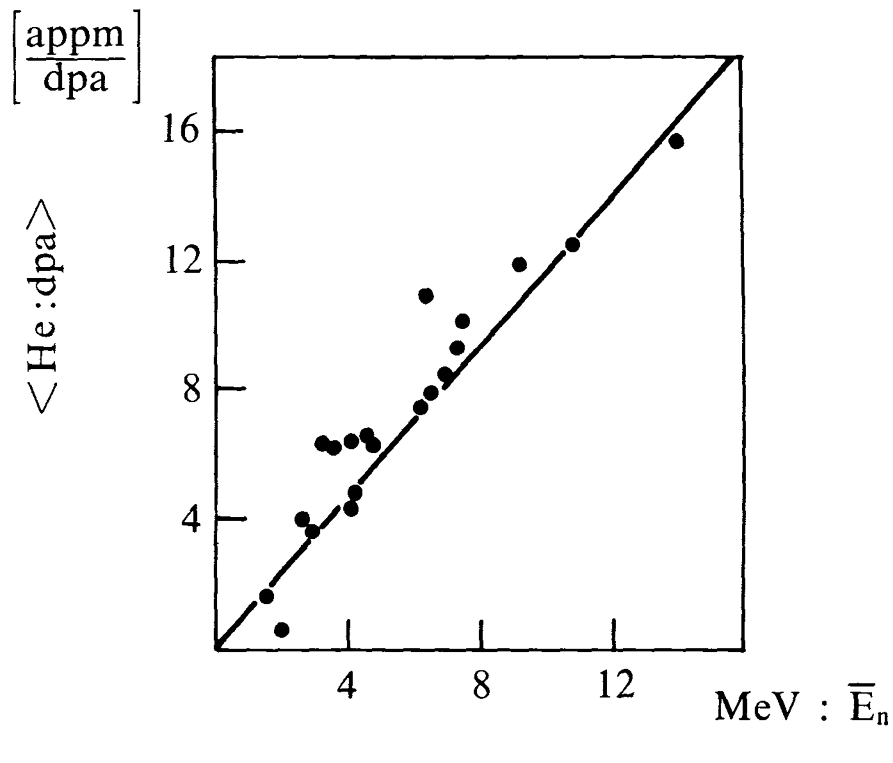


Fig. 6 : Spectrum Averaged <dpa> and <He : dpa> Values as a Function of Mean Neutron Energy.

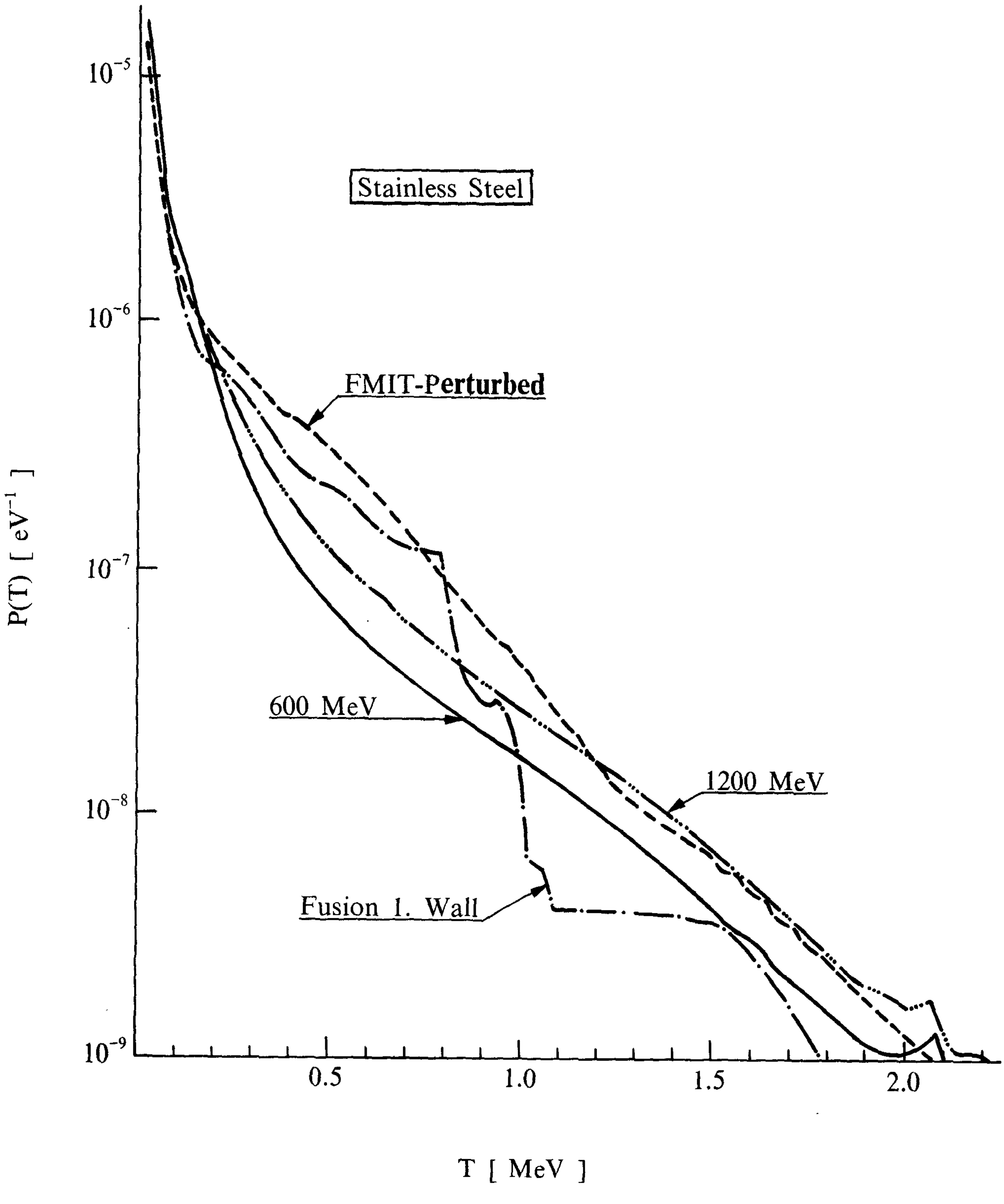


Fig. 7 : Primary Recoil Energy Spectra for SS-316 for Neutron Sources Based on 600 and 1200 MeV Protons, Fusion 1. Wall and FMIT (perturbed).

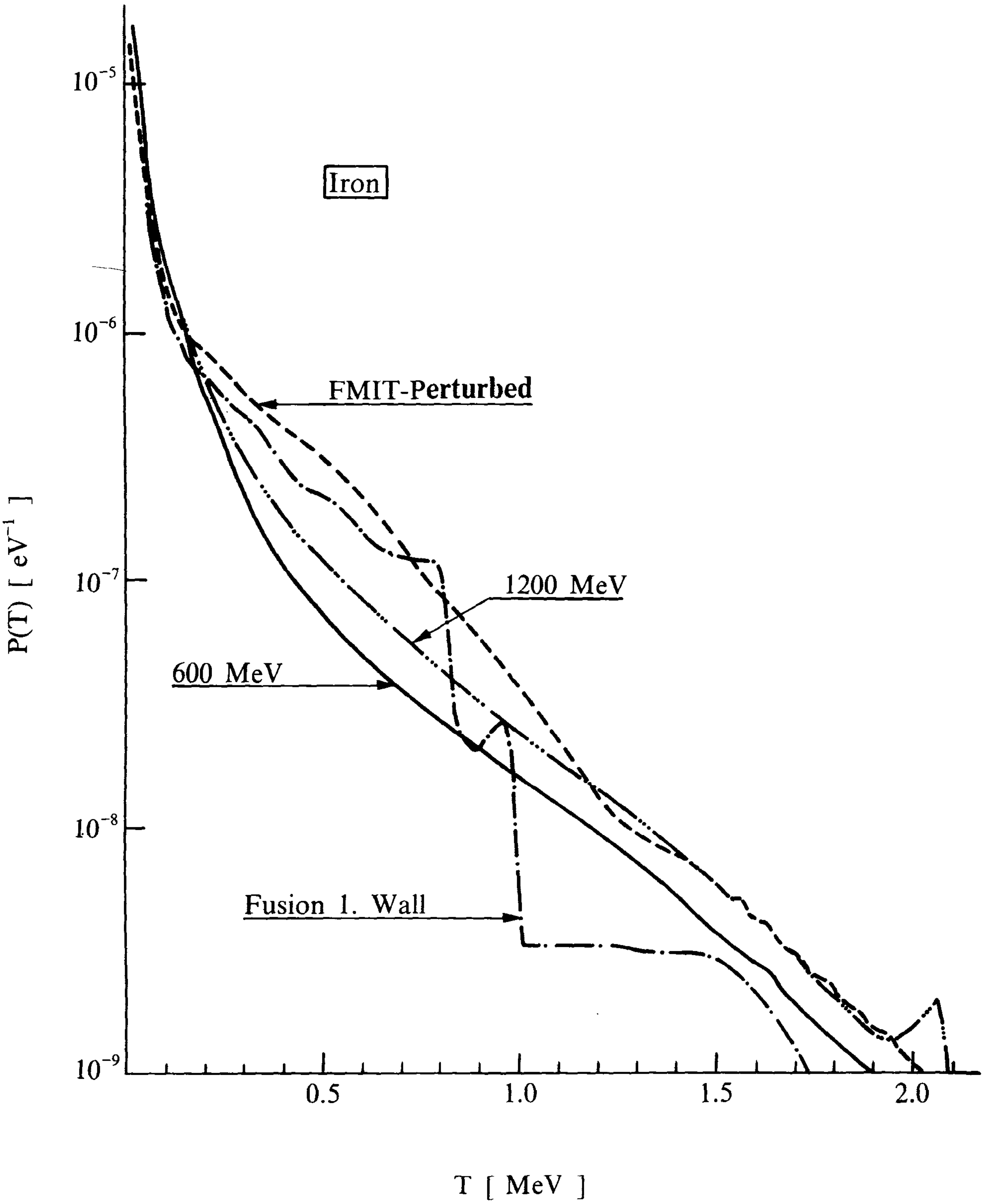


Fig. 8 : Primary Recoil Energy Spectra for Iron for Neutron Sources Based on 600 MeV and 1200 MeV Protons, Fusion 1. Wall and FMIT (perturbed).

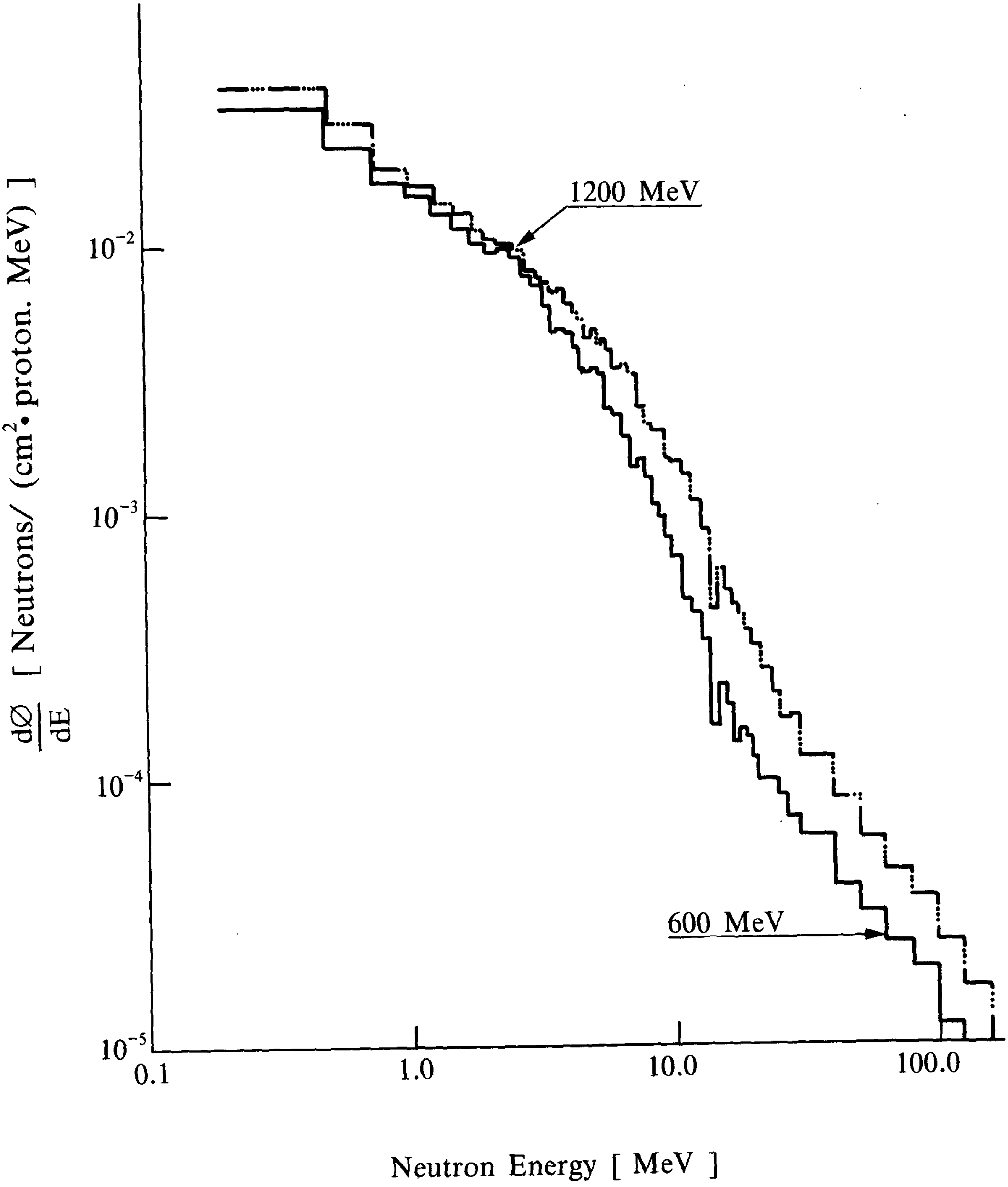


Fig. 9 : Neutron Spectra at 3.75 cm for Iron Shielded Neutron Source Based on 600 and 1200 MeV Protons.

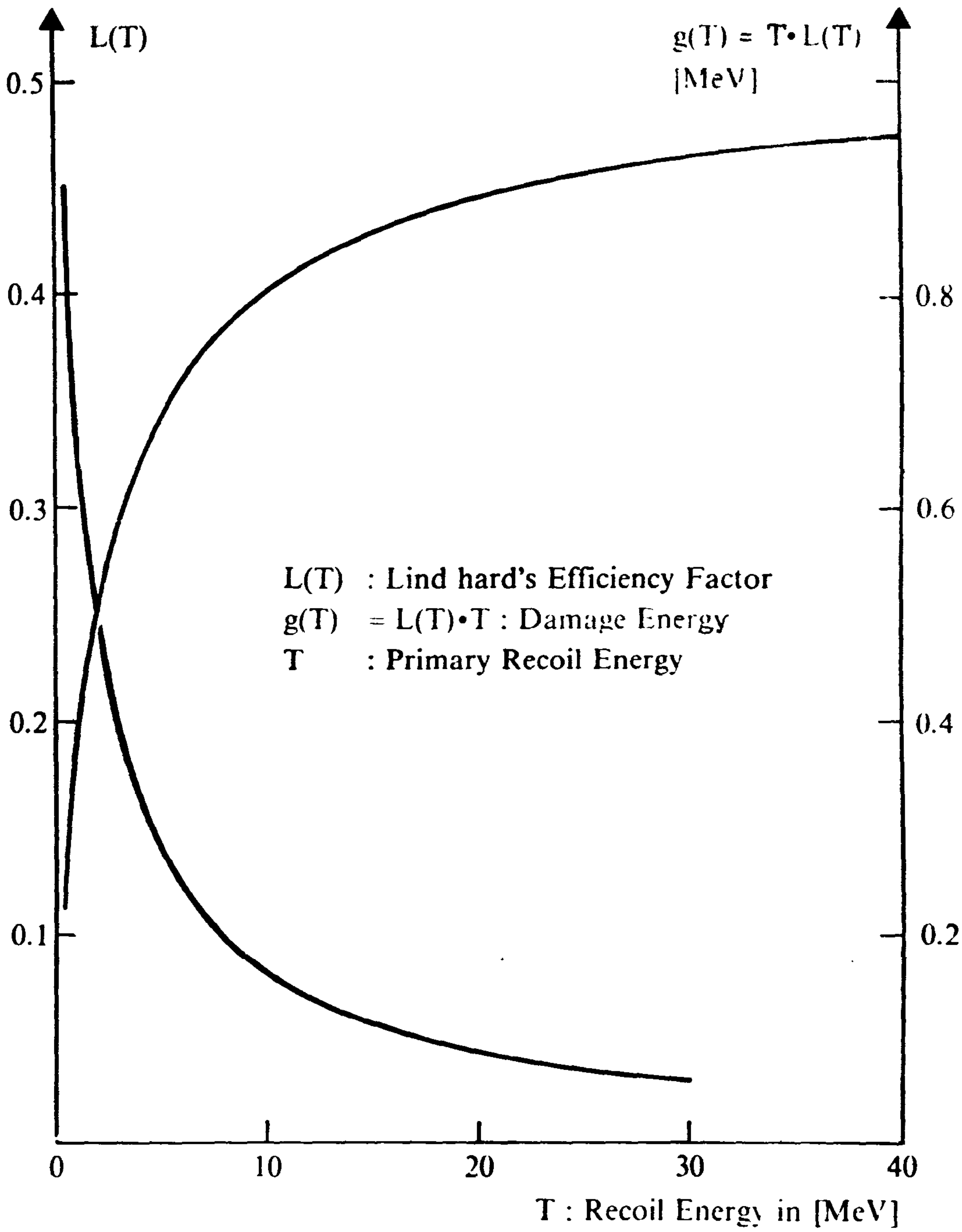


Fig.10 Damage Efficiency in Iron

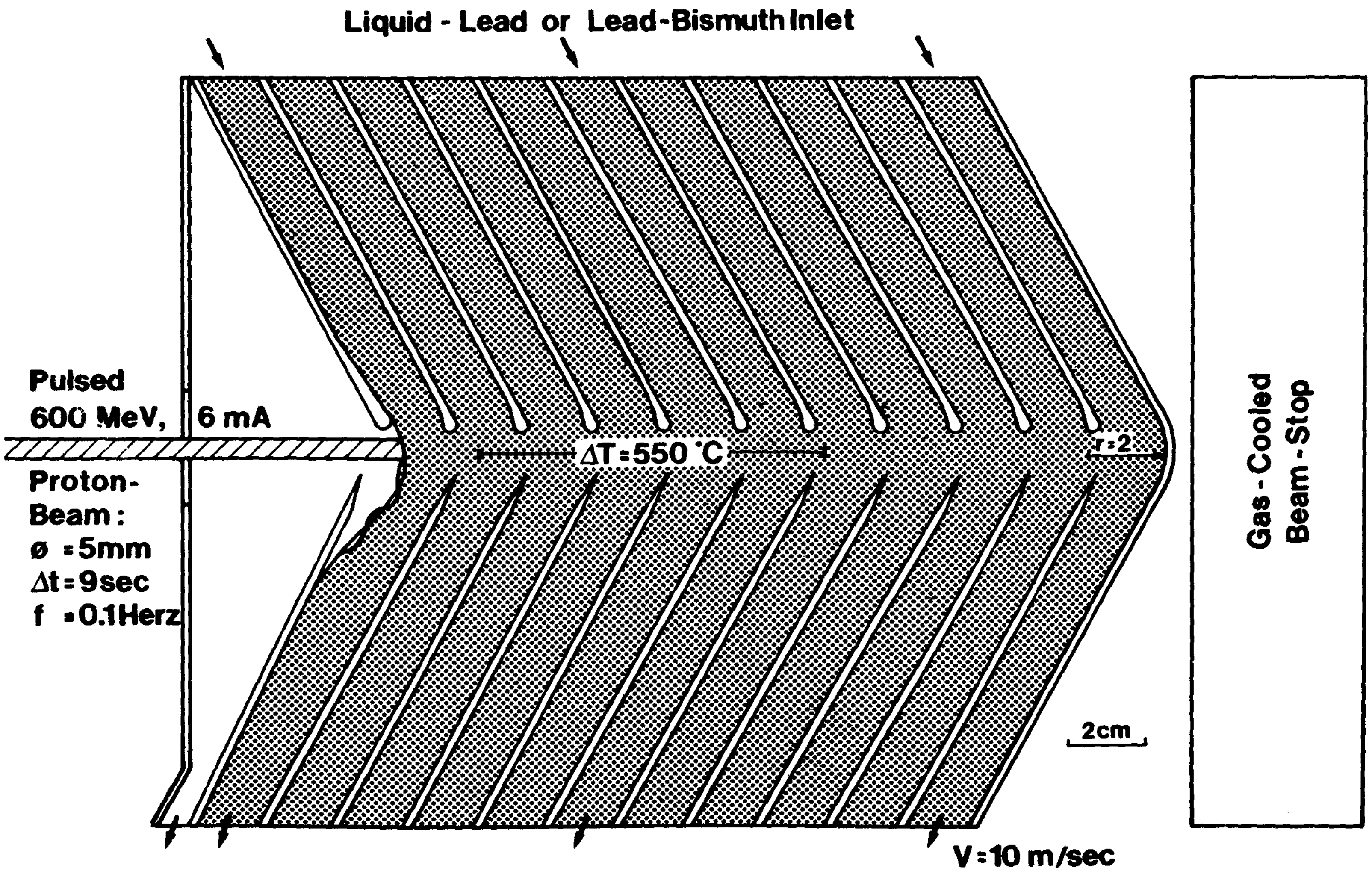


Fig. 11 : The Conceptional Design of the Liquid Lead Target; Vertical Cross Section.

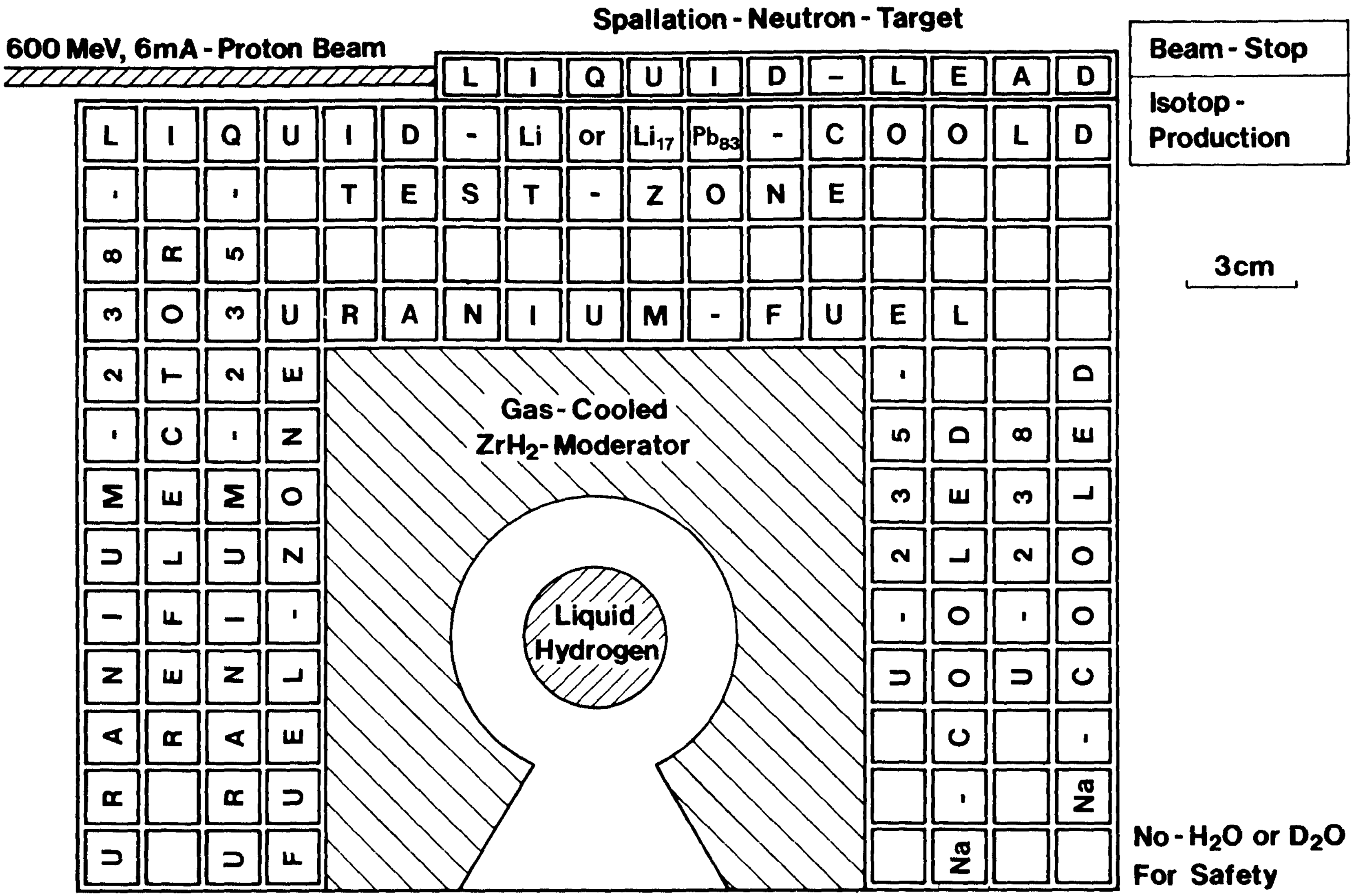


Fig. 12 : Conceptional Design of Target-Station; 1/2-Horizontal Cross Section.

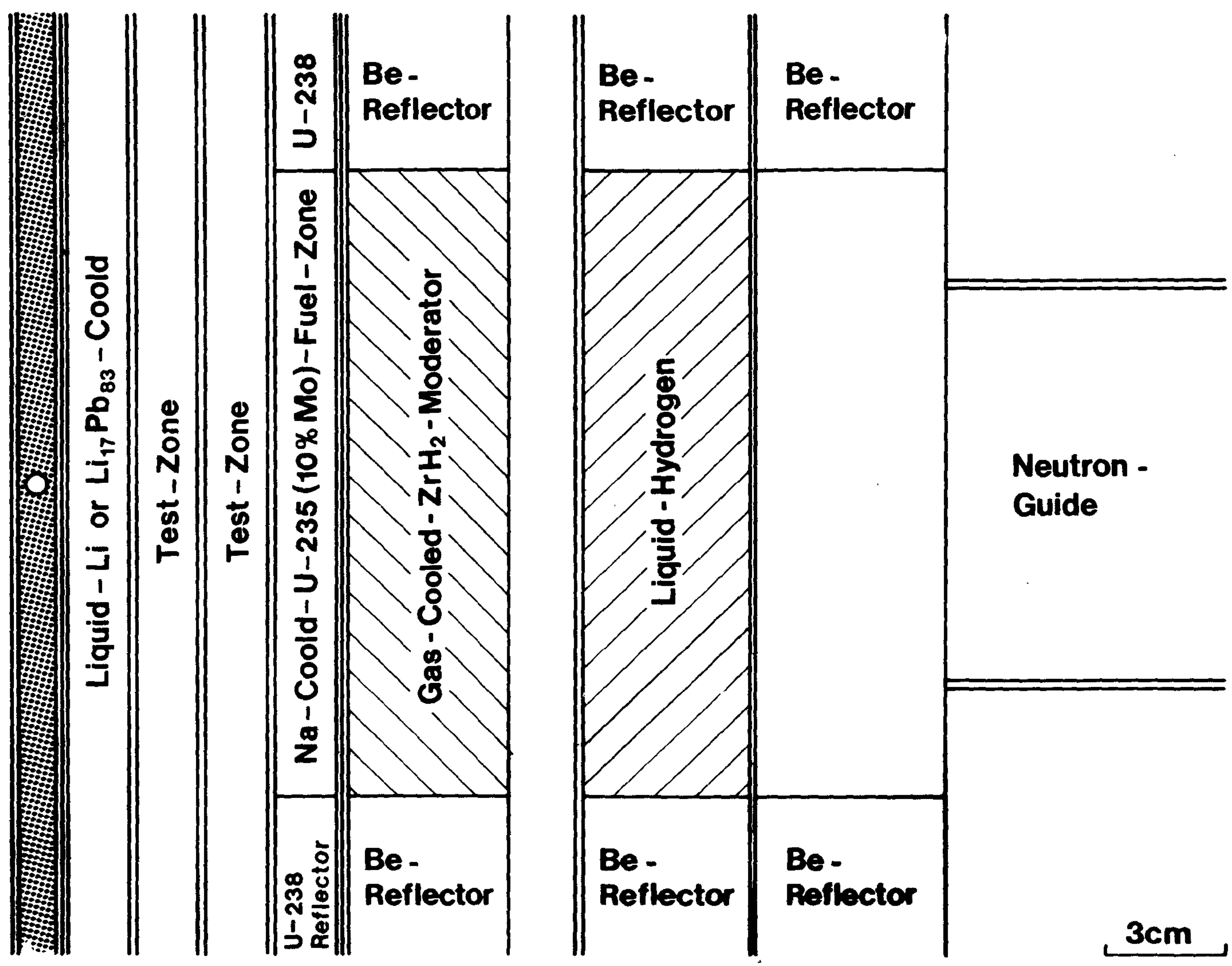


Fig. 13 : Vertical Cross Section of Conceptional SNS Target Station.

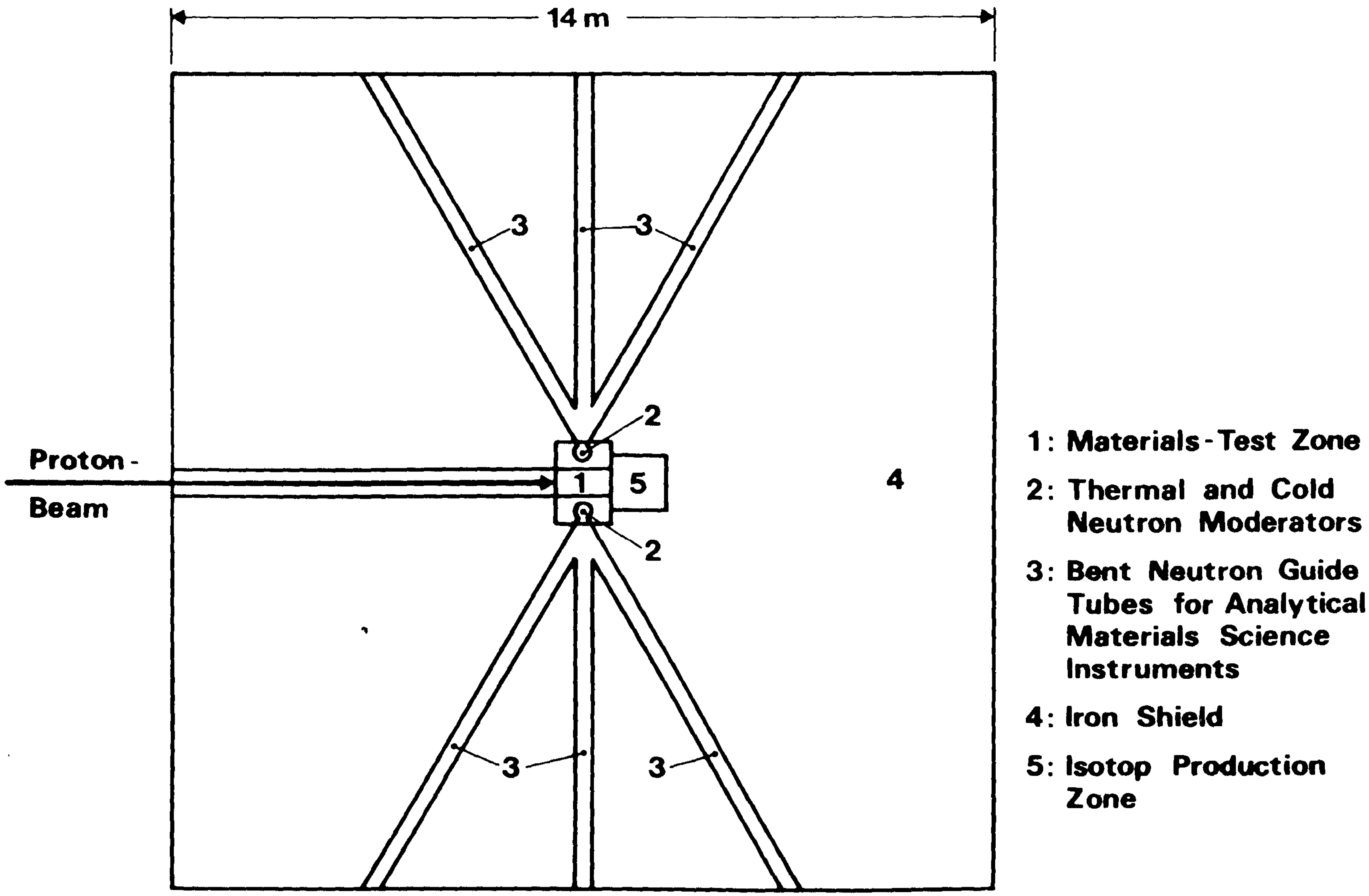


Fig. 14 : Lay-Out of the Neutron Target Station.

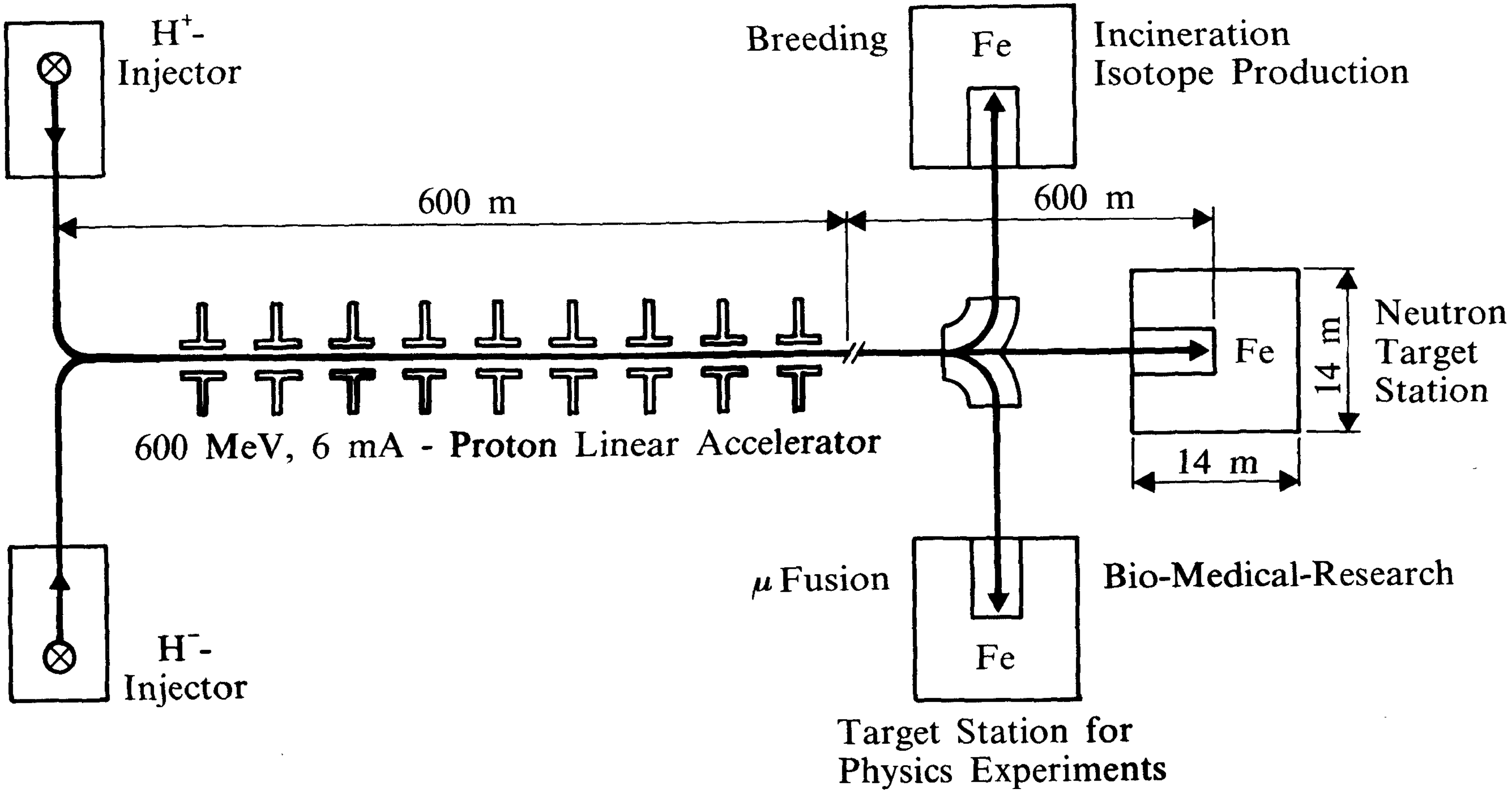


Fig. 15 : Lay-Out of the Fusion Reactor Materials Test and Development Facility, Based on a Continuous Wave 600 MeV, 6 mA Proton Linear Accelerator.

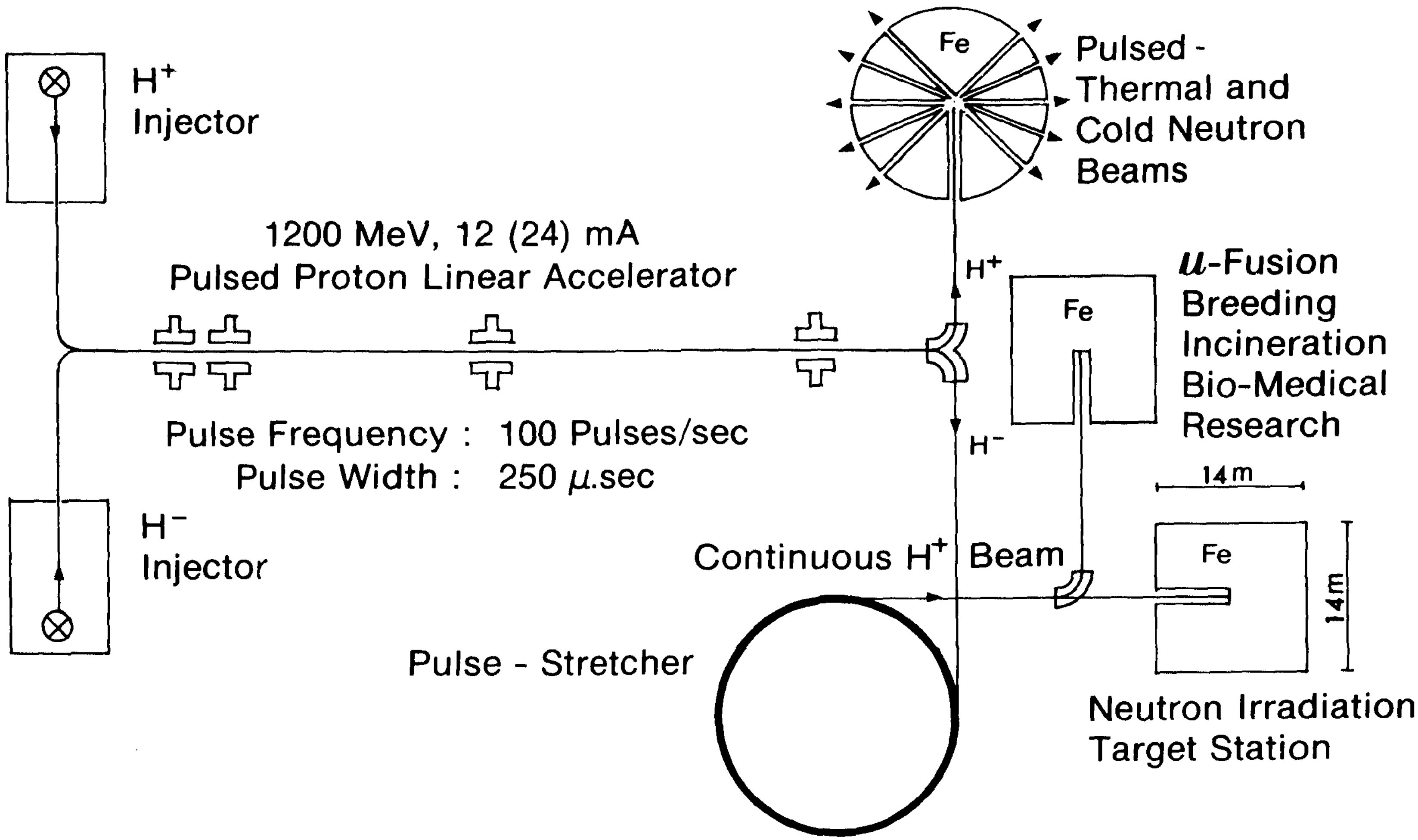


Fig. 16 : EURAC : A European Solution to Future Needs of Neutrons

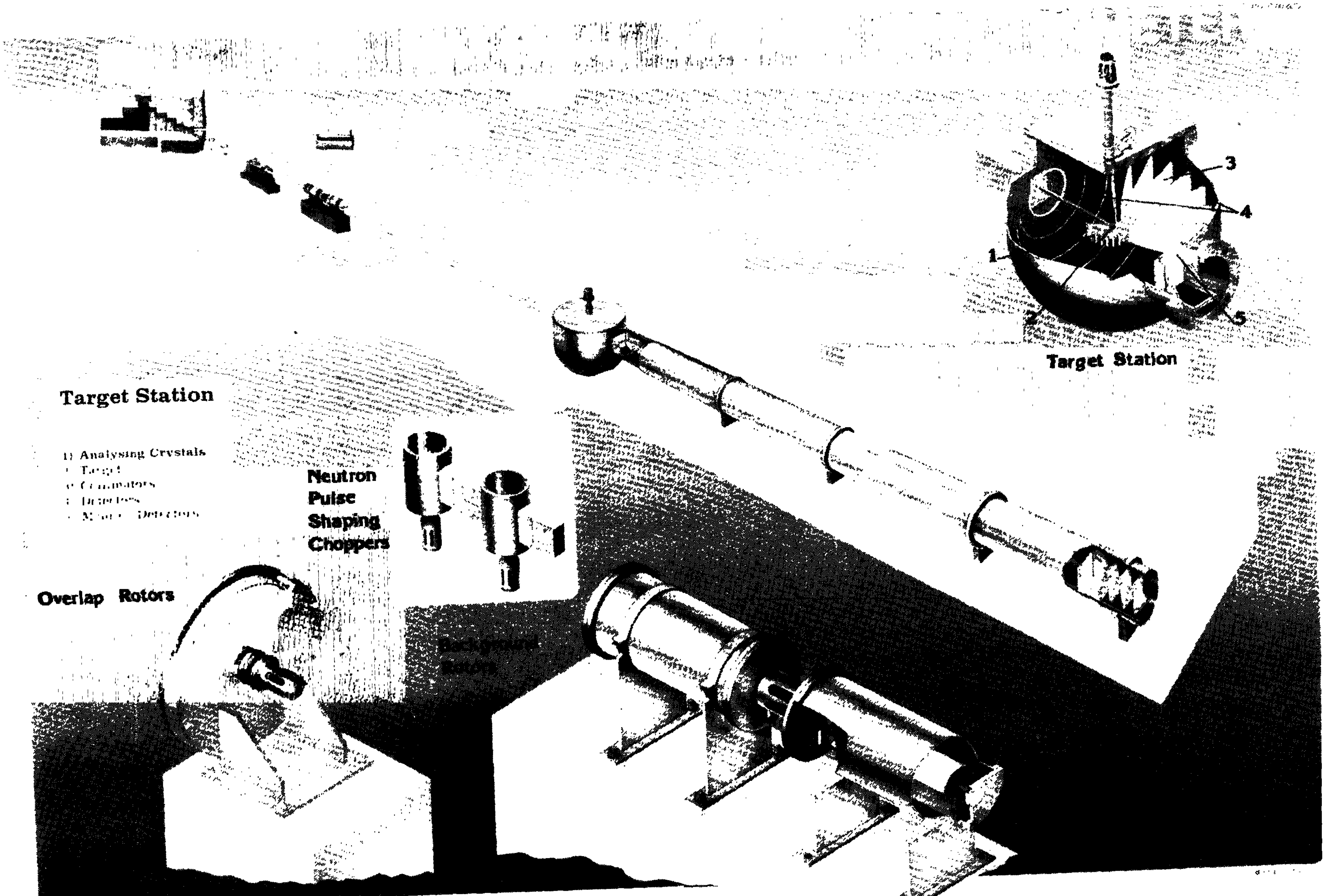


Fig. 17 : The Material Science Spectrometer.

Future Power Stations ?

The physicist's answer :

Subcritical Fast Fission Reactors driven by Fusion Neutrons !

Why ?

$D^+(E \geqslant 10\ \text{KeV}) + T^+(E \geqslant 10\ \text{keV}) \rightarrow \text{He}\ (3.5\ \text{MeV}) + n(14.1\ \text{MeV})$

Pure Fusion : 1 n(14.1 MeV) → Energy
→ Tritium (n,2n)

does it breed ?

Hybrid Fusion : 1 n(14.1 MeV) → U^{238} (Th^{232}) + 2.5 n
200 MeV fast fission

energy and neutron multiplier

SNS-Ispra a miniaturized form of the subcritical Fast Fission Power Reactor driven by Fusion-Neutrons

Fig. 18 : Fusion-Hybrid Energy Strategy.

Time Schedule
for
EURAC*

1986	: Final Layout Design
1987-88	: Industrial Design
1989	: Improve Industrial Design - Decision - Procedure by Council of Ministers
1990-93	: 4 year Construction Period
1994-95	: Start up Period to Full Power
1996	: Start of Routine Operation [LAMPF has now an availability of 85%]

*__Eur__opean __Ac__celerator Neutron Source : __EURAC__

Fig. 19 : Time Schedule for EURAC