Spallation Target Design for the EUROTRANS Accelerator-Driven Sub-critical System Project

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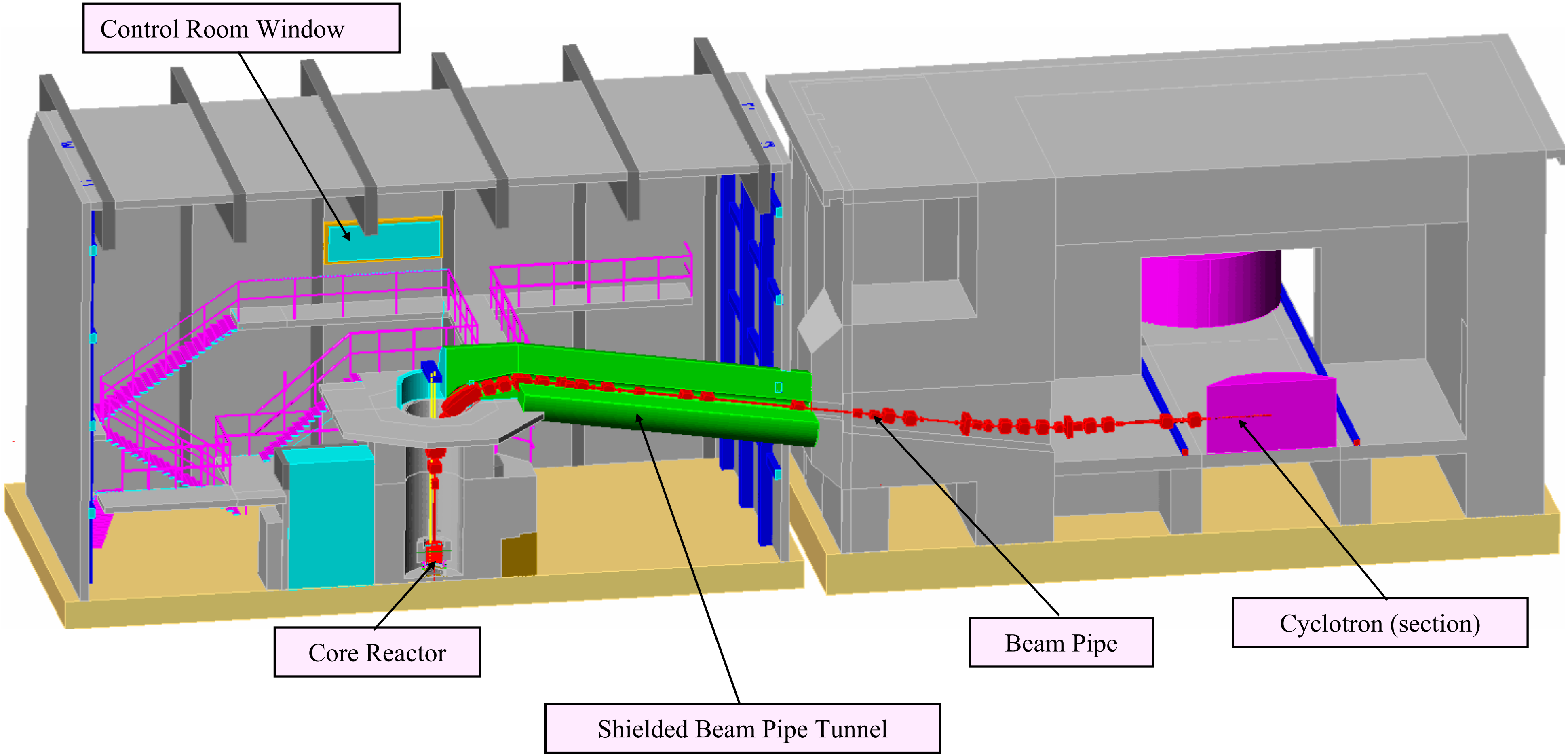
TRADE Project

- The TRADE experiment suggested by C. Rubbia, first worked-out in an ENEA/CEA/CERN feasibility study and presently assessed by a wider international group (lead: ENEA, CEA, DOE, FZK), is a significant step towards the ADS demonstration
- Coupling of a proton accelerator to a power TRIGA Reactor via a spallation target, inserted at the centre of the core.

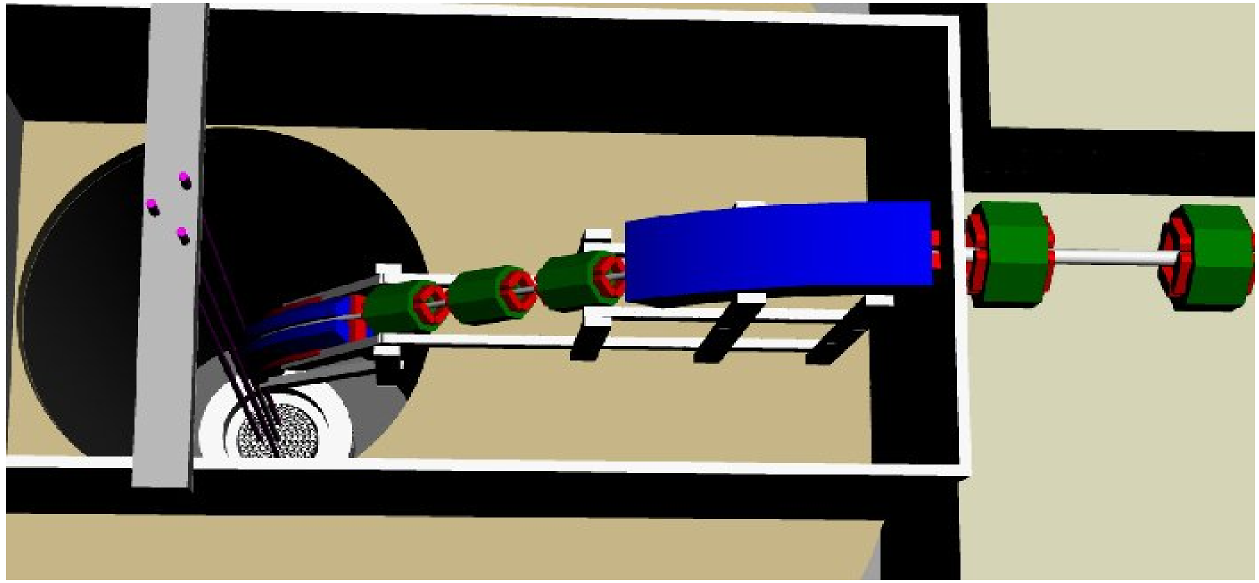
- Range of power :
  - in the core : 200 - 1000 KW,
  - in the target : 20 - 100 KW.

- The main interest of TRADE, as compared to previous experiments, is the ability of incorporating the power feedback effects into the dynamics measurements in ADS and to address ADS **operational**, **safety** and **licensing issues**.

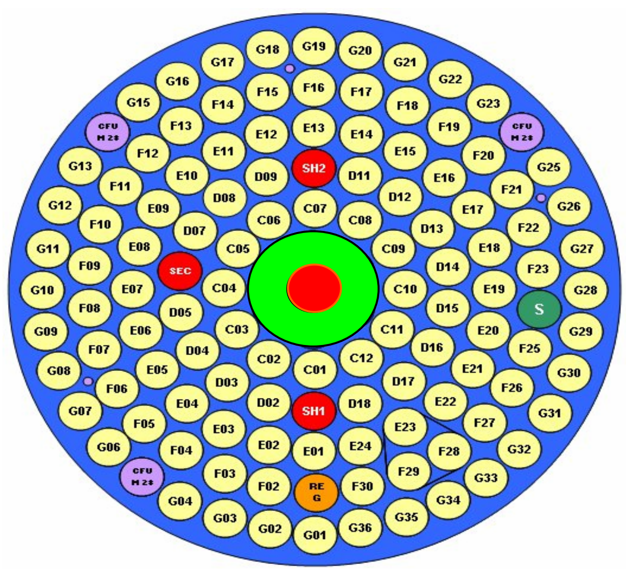
The TRADE Facility - Reactor and Accelerator Buildings



Overall Lay-out of the TRADE Facility

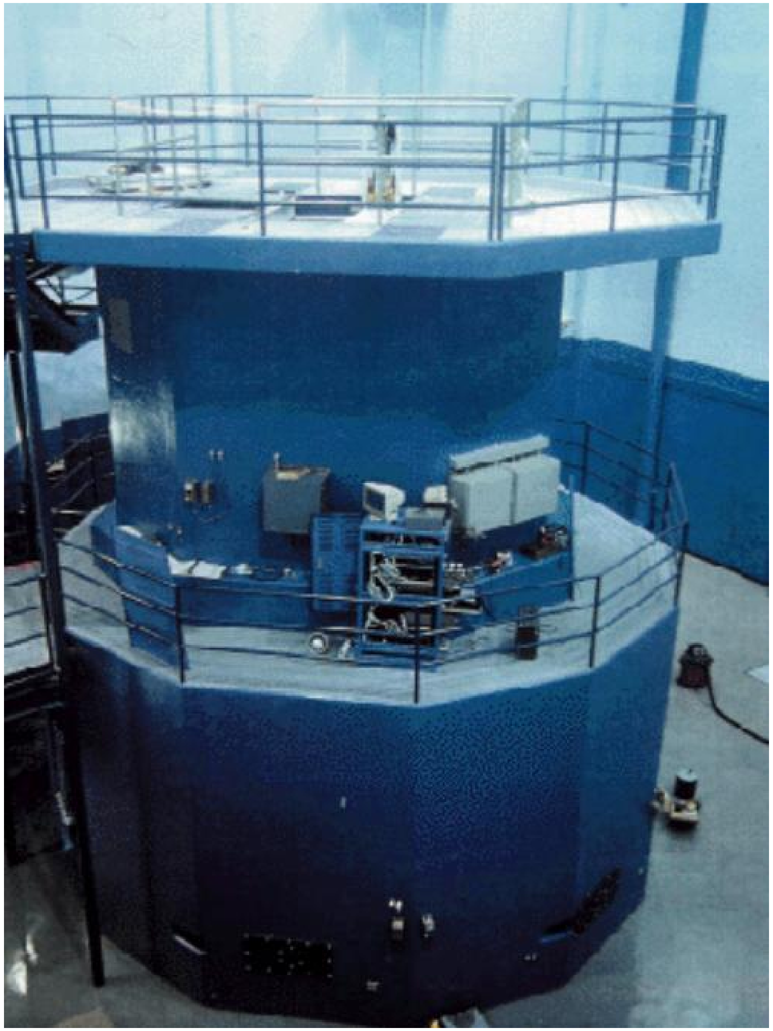


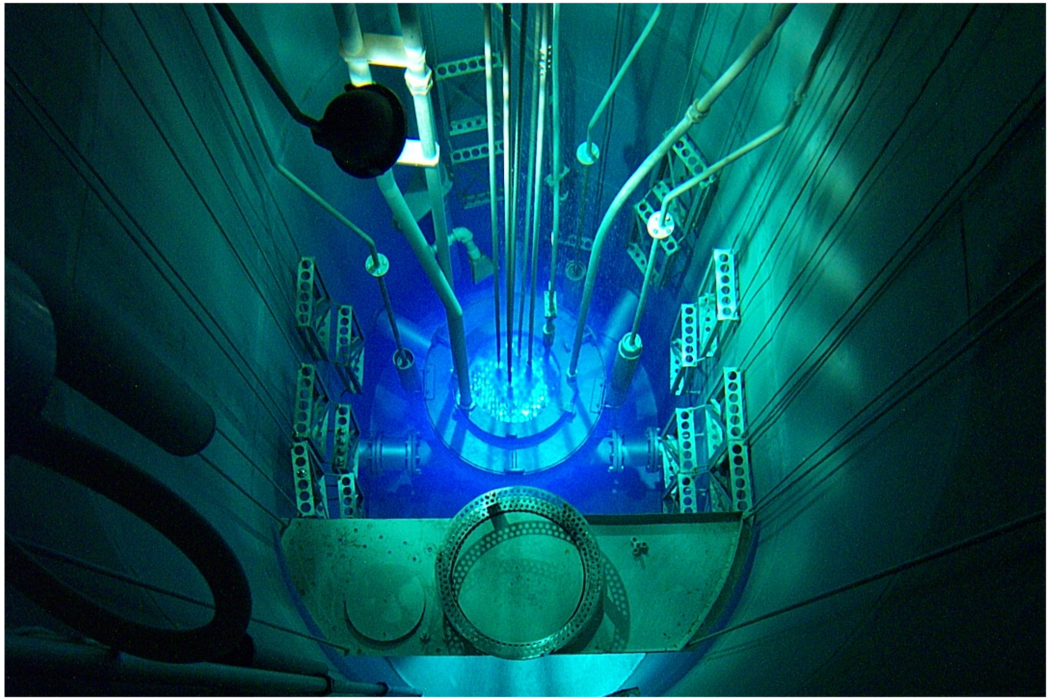
Top view & bending magnets



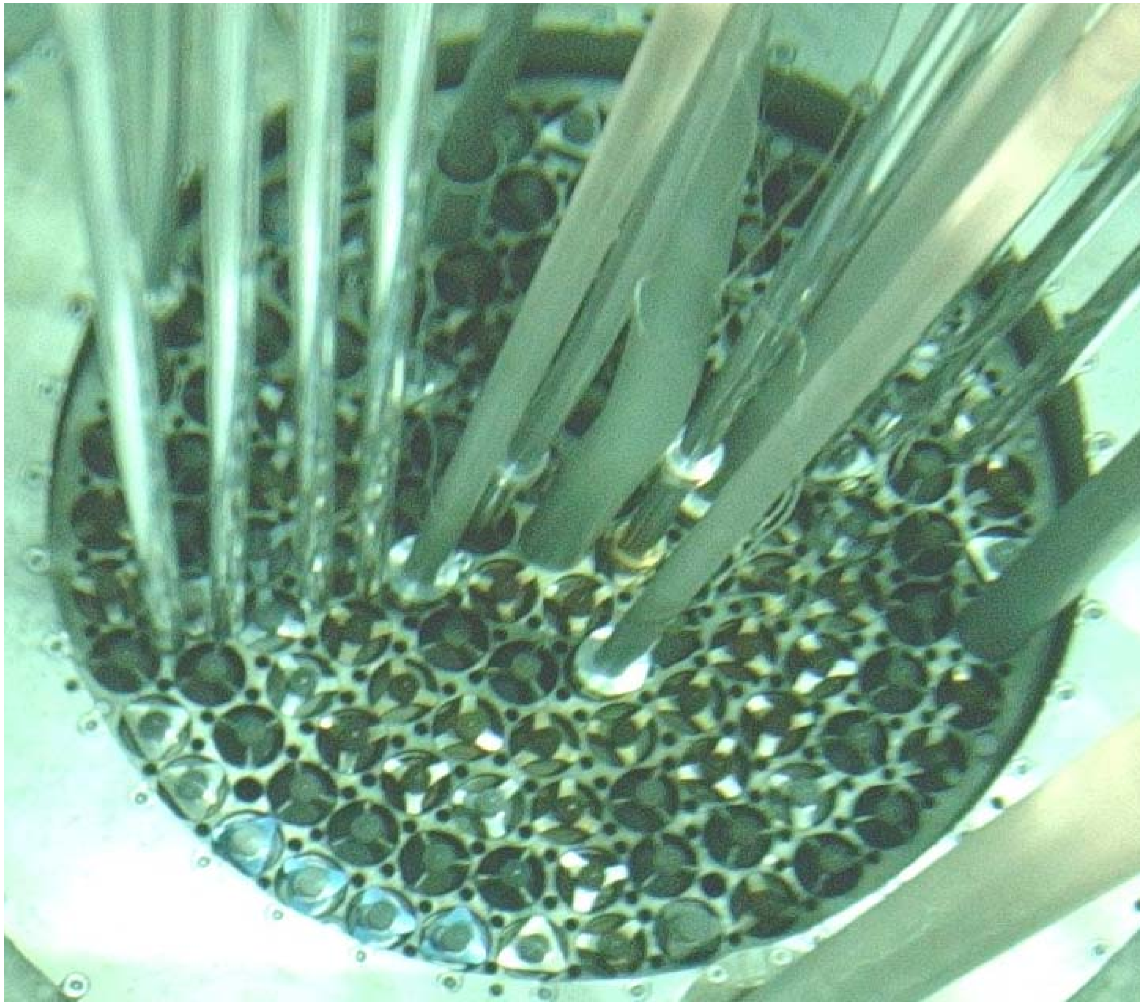
Core cross-section

TRIGA MARK II REACTOR





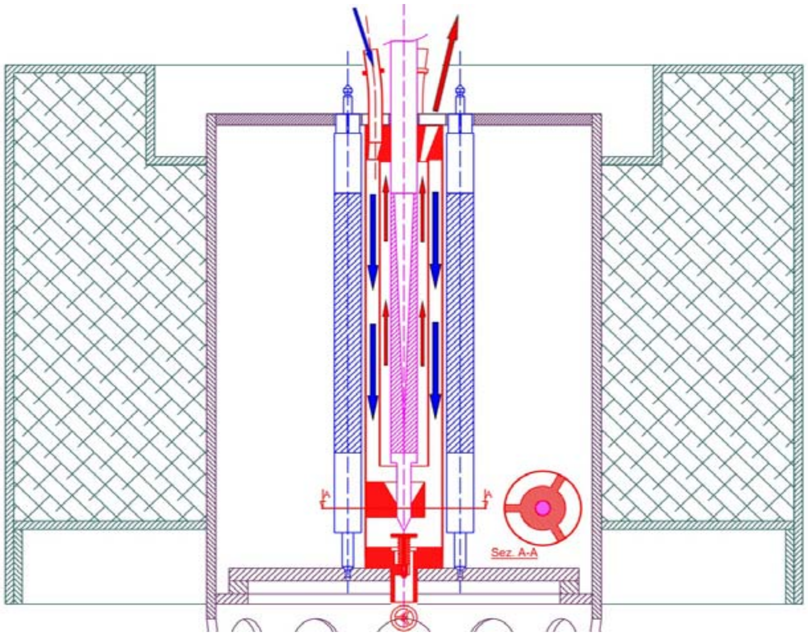
TRIGA MARK II REACTOR

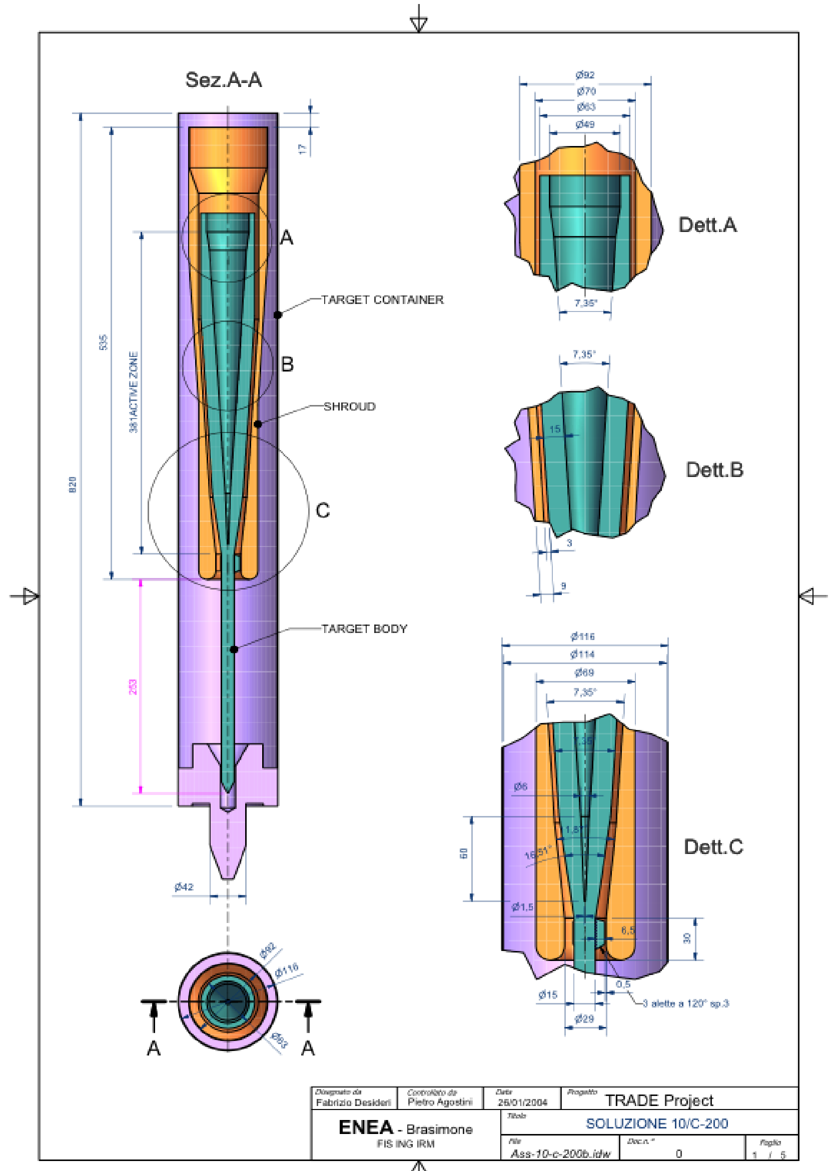


The main characteristics of TRADE

- A proton cyclotron delivering a beam of 140 MeV protons (option investigated → 300 MeV).
- A three sections beam transport line: Matching section/Straight transfer line/Final bending line.
- A solid Ta target (back-up : W clad in Ta).
- Forced convection of the target cooling with a separate loop.
- Natural convection for the core cooling.
- Range of subcritical levels : $k = 0.90 \div 0.99$

The Spallation Target System



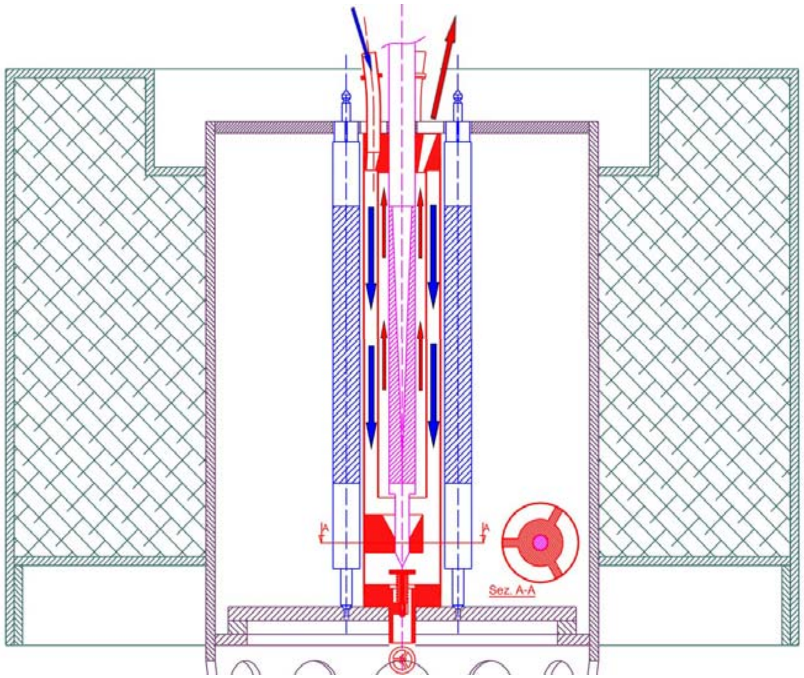


The inner geometry is characterized by three conical cavities having different angles and total length equal to the active height of the TRIGA core. The cone tip (lowest cone) is exposed to the highest power density for two reasons:

• the relevant proton current at the centre of the Gaussian distribution,

• the forward scattering of protons as a consequence of the conical angle steepness.

Target cooling system operating conditions



Coarse Dimensioning of the circuit:

- Thermal power = 40kW
- Design ΔT ~ 5 - 20°C

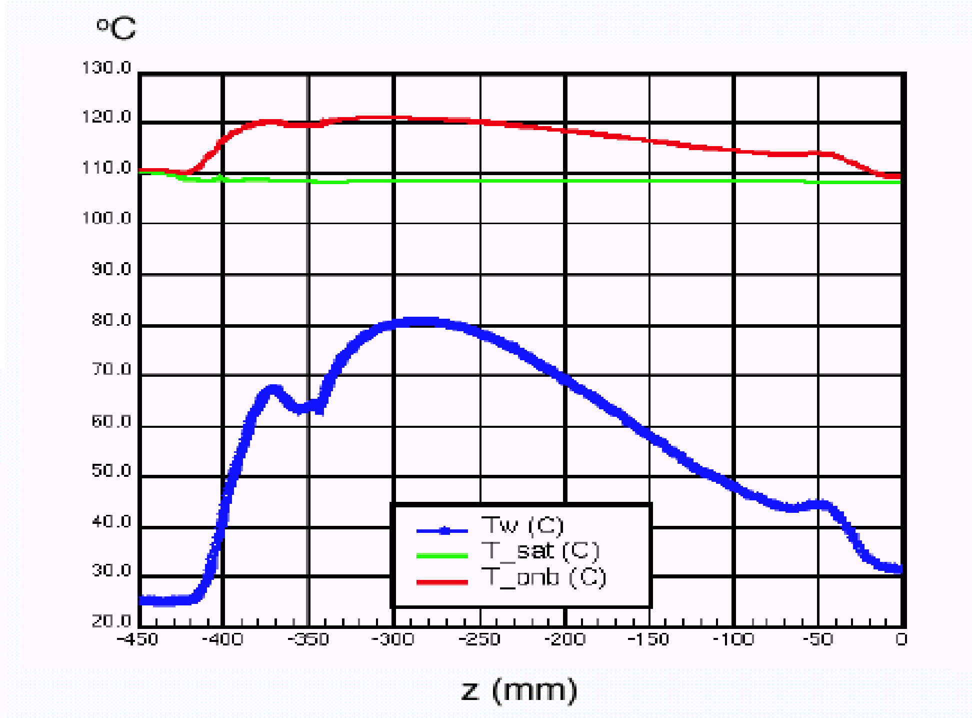
Pumps and circuit characteristics:

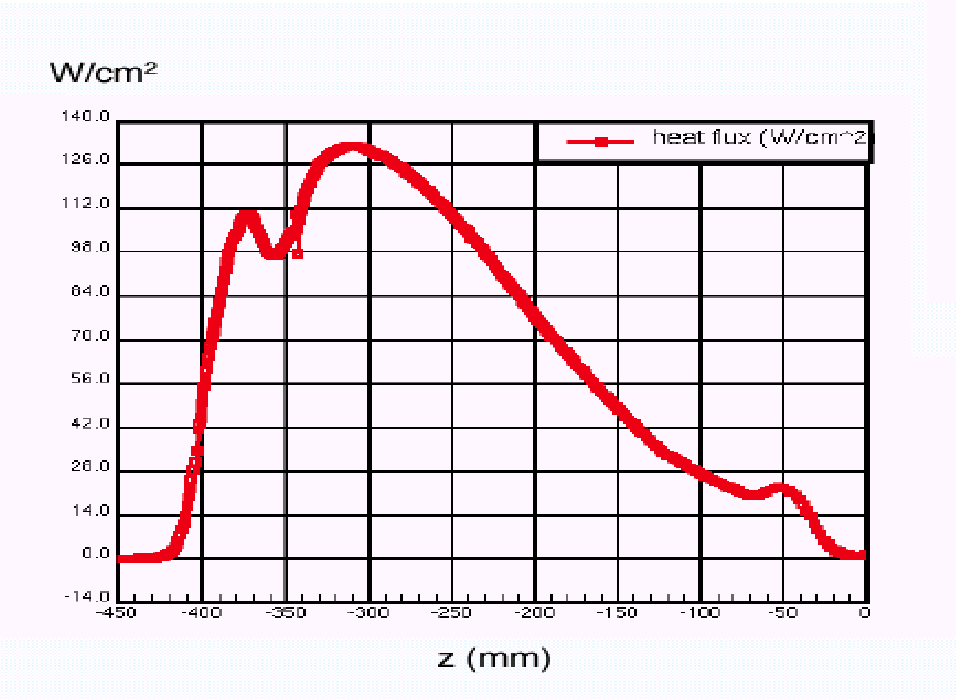
- Pumps flow-rate ~ 8 - 2 m^3/h
- Water max speed (3 holes of Φ = 18 mm) ~ 3 - 1 m/s

Parameter	Value
Power deposited in the target	38.7 kW (0.2857 mA)
Mass flow rate	2.24 Kg/s
Inlet mean velocity	0.728 m/s
Inlet mean temperature	25 °C
Outlet mean velocity	2.78 m/s
Outlet mean temperature	29 °C
Mass-averaged h×mfr i/o diff.	39.1 kW
Total-pressure loss	0.08 bar
Static-pressure loss	0.12 bar

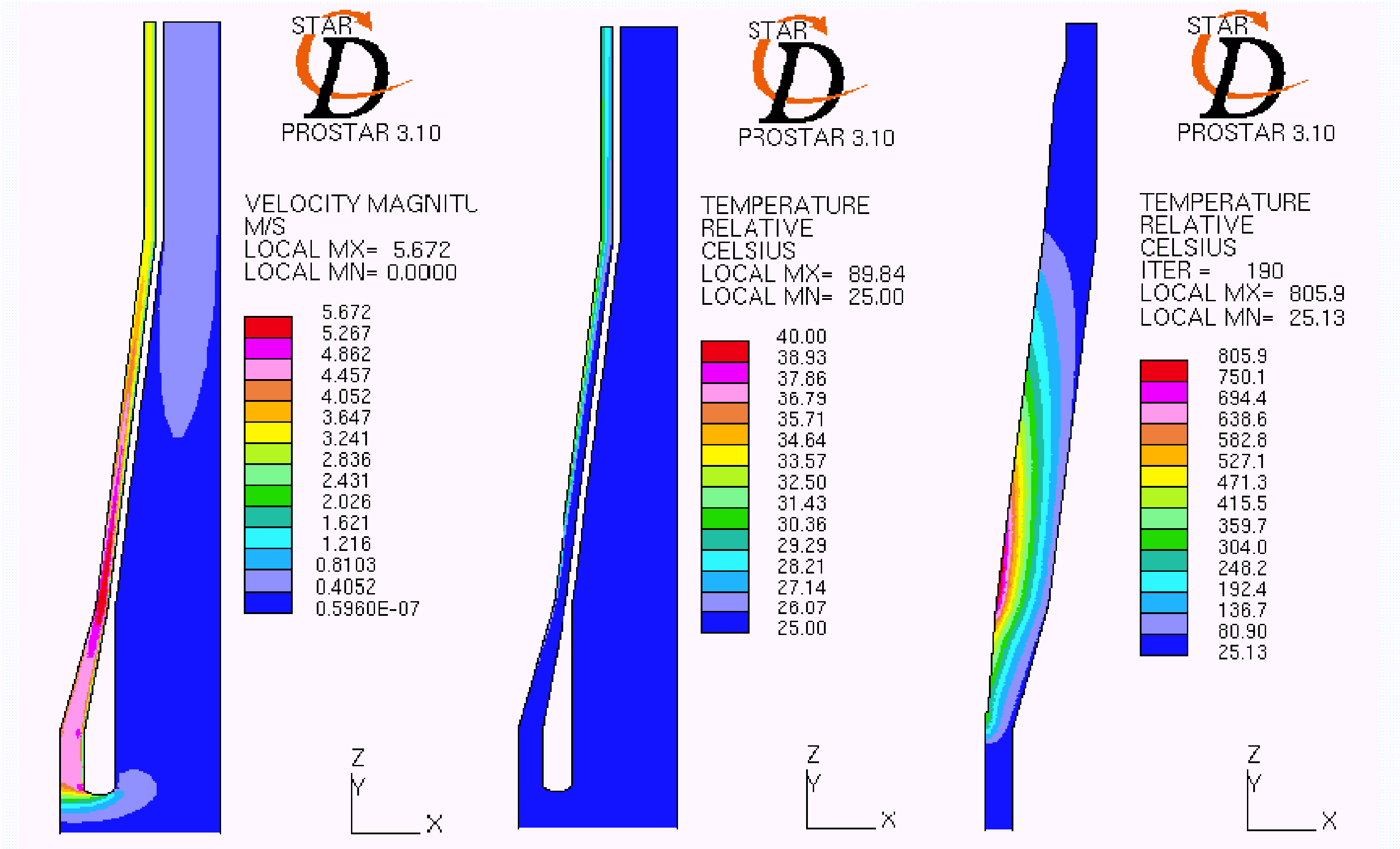
Thermal performances of the target

In presence of the design mass flow-rate of water (2.24 Kg/s), the maximum thermal flux at the outer wall of the target is 135 w/cm2 thus assuring a margin large enough to prevent the occurrence of Critical Heat Flux. Moreover the maximum temperature is 80°C which is significantly lower than the TRIGA saturation temperature

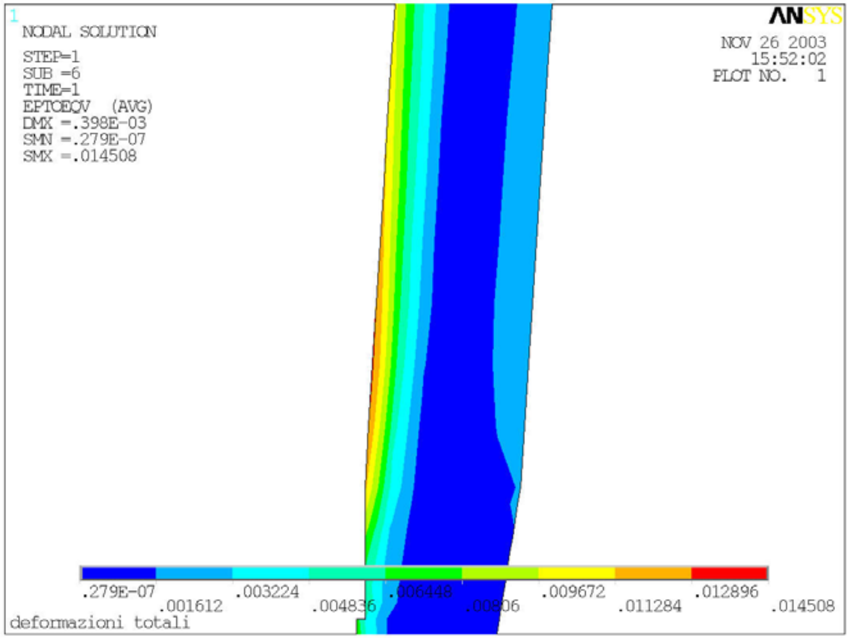


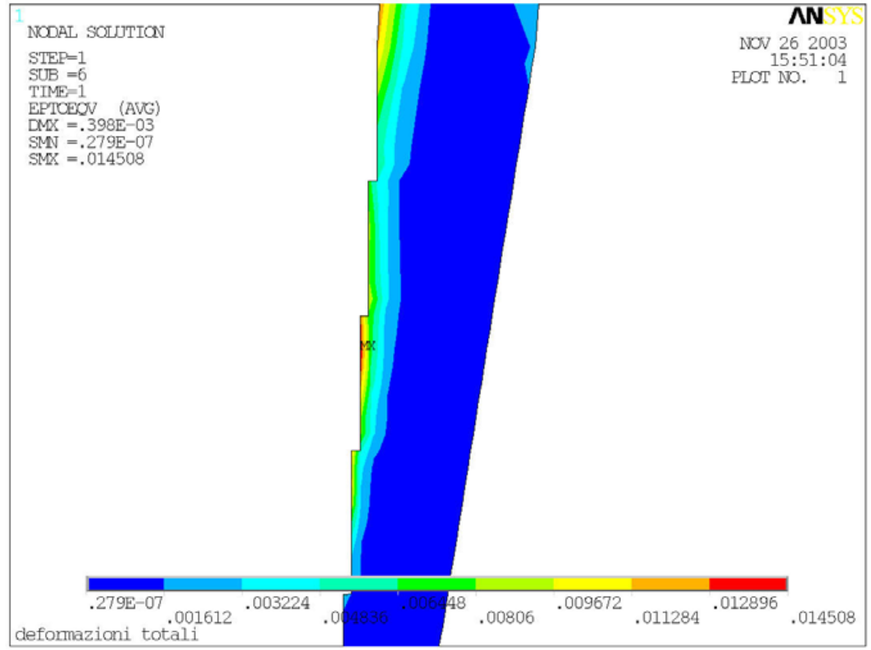


Thermal performances of the target



Mechanical performances of the target





Calculations of total strain on the target when exposed to 40 kW beam power, by 140 MeV protons, are reported:

- The maximum strain (1.45 %) is located in the stepped region while a lower local maximum (1.12 %) corresponds with the region of maximum temperature
- It seems that Tantalum can survive a total strain range of 1.4 % after 1000 cycles.

The results have to be confirmed by more direct experiments at operational temperature and are presently considered only a reference indication. In order to enhance the target duration a lower level of proton beam power must be envisaged.

Nuclear performances of the target

1. The main neutron physic parameters of the target such as neutron yield and energy spectra, power deposition, material damages and spallation product distributions are evaluated by probabilistic transport codes (FLUKA/EA-MC and MCNPX).

2. The impact of different target parameters (material choice, geometry of the proton beam, energy of the protons) has been studied extensively. While the neutron yield and spectra are mainly related to the nuclear behavior of the system, energy deposition is directly related to the thermo-mechanics of the target and its cooling capabilities, which determine its lifetime in the core.

Neutron Production

The main goal of the spallation target is the neutron production.

Target type	Neutron yield
Thick target (SOL-1)	0.80 n/p
Thin target 3 mm thick (SOL-4)	0.79 n/p
Thick target (SOL-7)	0.75 n/p

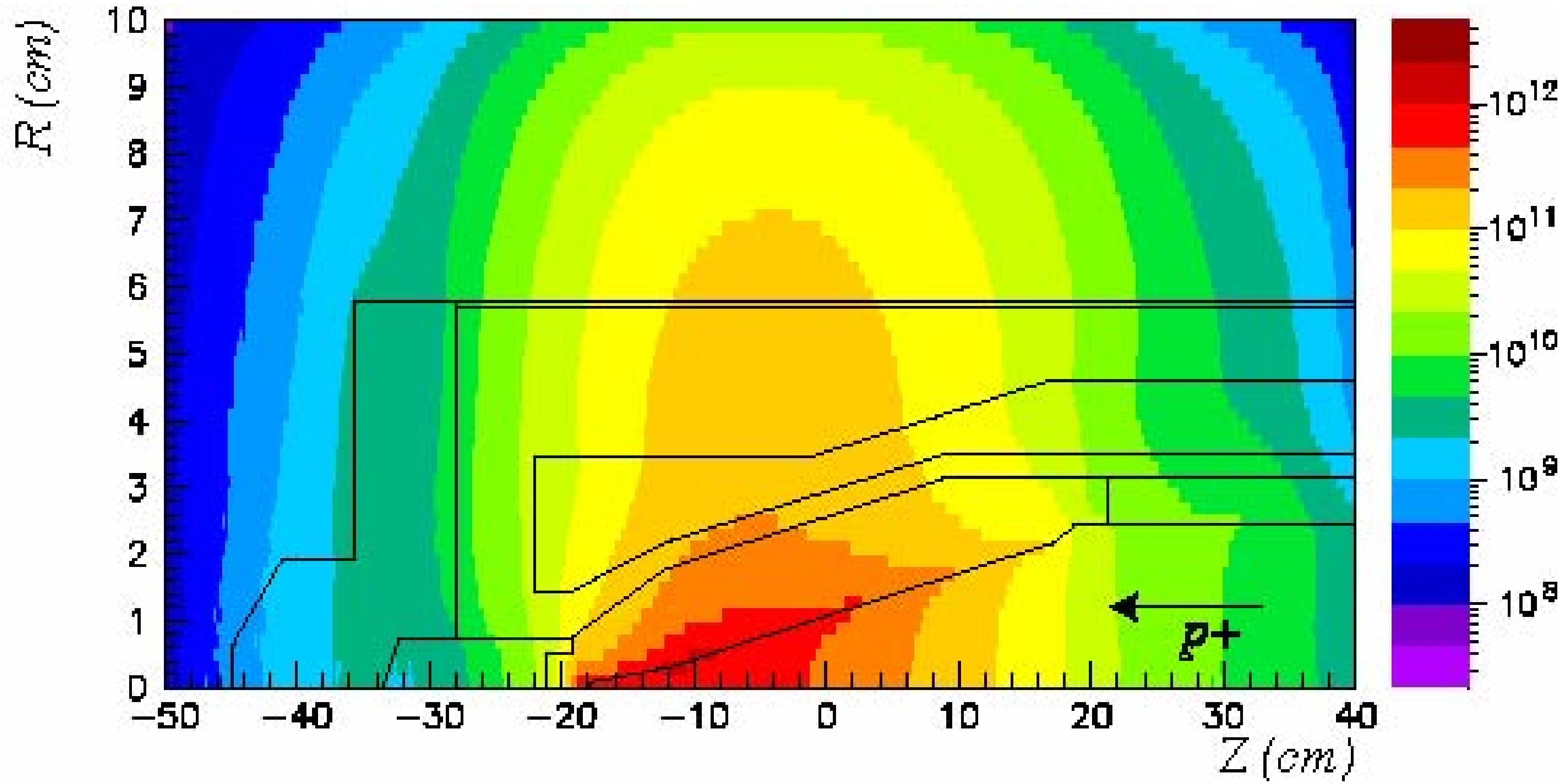
Calculations performed for 140 MeV protons distributed according to a Gaussian profile on thick and thin geometries of the Tantalum target show that:

1. the neutron yield is not affected significantly by the target geometry since the protons are almost at the end of their range when they leave the target
2. Even in the "thin" geometry, the material thickness (3 mm in the radial direction) is sufficient to allow the whole spallation reactions to take place inside the target's material.

Spallation Neutron Flux

Neutron flux distribution in (n/cm^2/s) per kW of beam

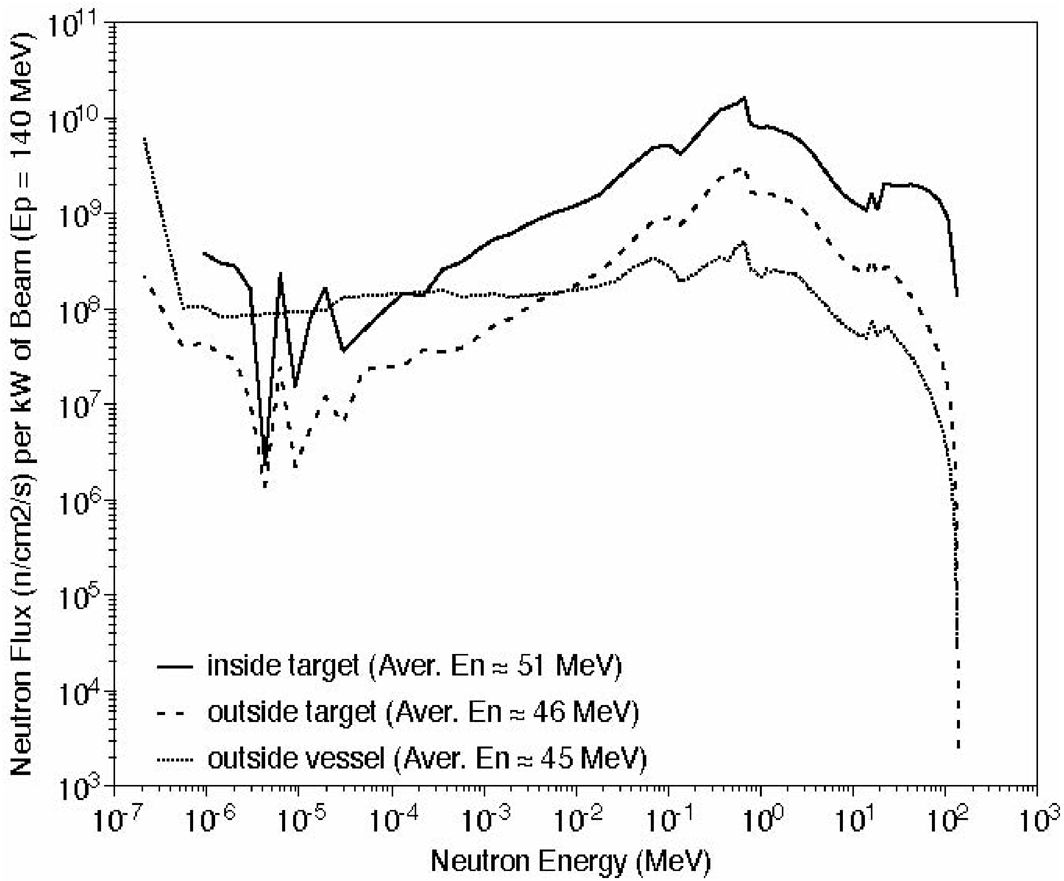
140 MeV protons on thick Ta target



Spallation Neutron Flux

Neutron flux spectra at several locations inside the spallation target vessel in ($n/cm^2/s$) per kW of beam

140 MeV protons on thick Ta target



For high energies, it is possible to distinguish the well-known peak at 1 MeV related to evaporation phase of the spallation process. A second broader peak is clearly distinguishable at higher energies (above a few tens of MeV), which is related to the INC phase (Intra-Nuclear Cascade) of the spallation process.

Overall, the integrated flux of neutrons escaping the target (i.e. entering the core) is reduced by a factor 10 as a result of the successive attenuation in the target body but also in the thick shroud surrounding it. For neutrons above a few 100 keV's, the attenuation reaches almost a factor 100.

Spallation Neutron Flux

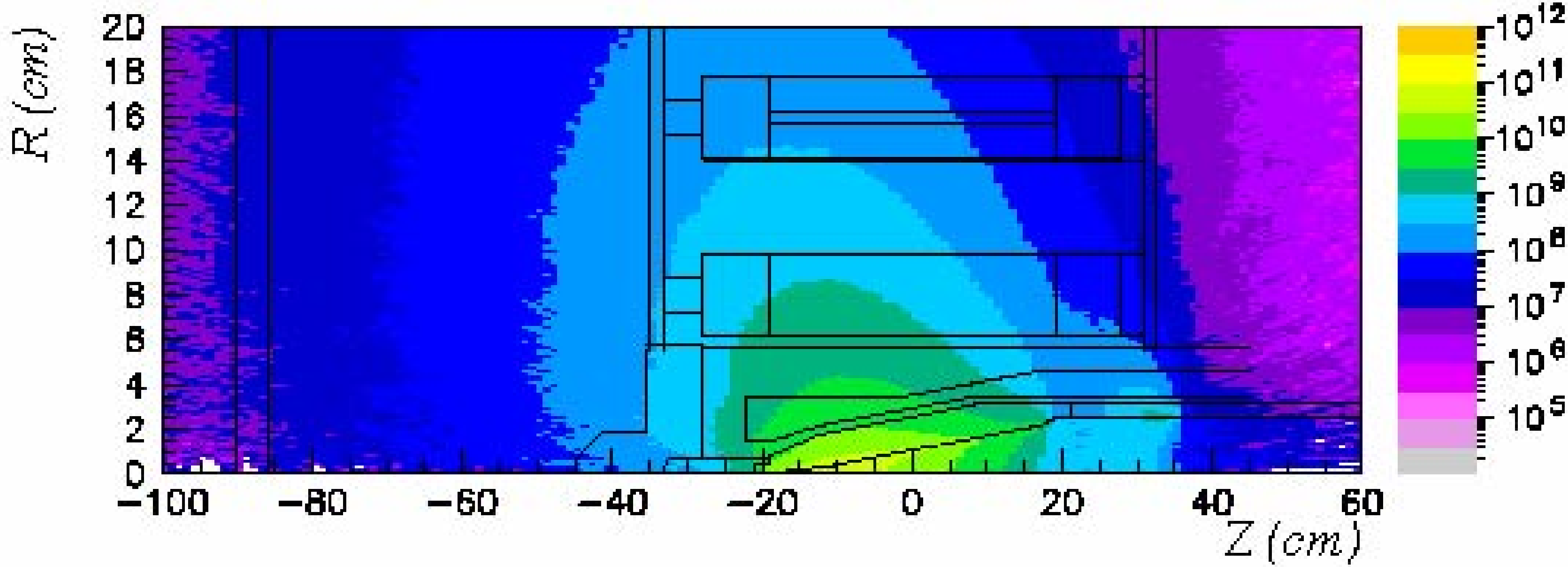
Energy groups	Neutrons escaping from vessel (% of flux)	Neutrons escaping from target (% of flux)
0. Š 1. eV	34.0	0.6
1. eV Š 1. keV	10.5	0.8
1. keV Š 1. MeV	31.5	51.9
1. MeV Š 10. MeV	19.5	39.7
> 10. MeV	4.5	7.0

The high-energy neutrons (> 10 MeV) are only slightly moderated, they represent 4.5% of the spallation neutron population with an average energy of about 45 MeV. This fraction is of the order of 7 % inside the spallation target with an average energy of 51 MeV

These high-energy neutrons are very hard to shield, and contribute to a certain extent to the radiation damage of the inner structure of the target station but also to the ambient dose should they leak out. Moreover, they will most probably react with the core coolant and produce N^{16} through (n,p) reactions on O^{16} which has a threshold at ~ 10 MeV and which cross section peaks at 0.15 barn compared to the 0.2 barn total cross section of H.

Spallation Neutron Flux

Neutron flux distribution > 20 MeV in ($n/cm^2/s$) per kW of beam



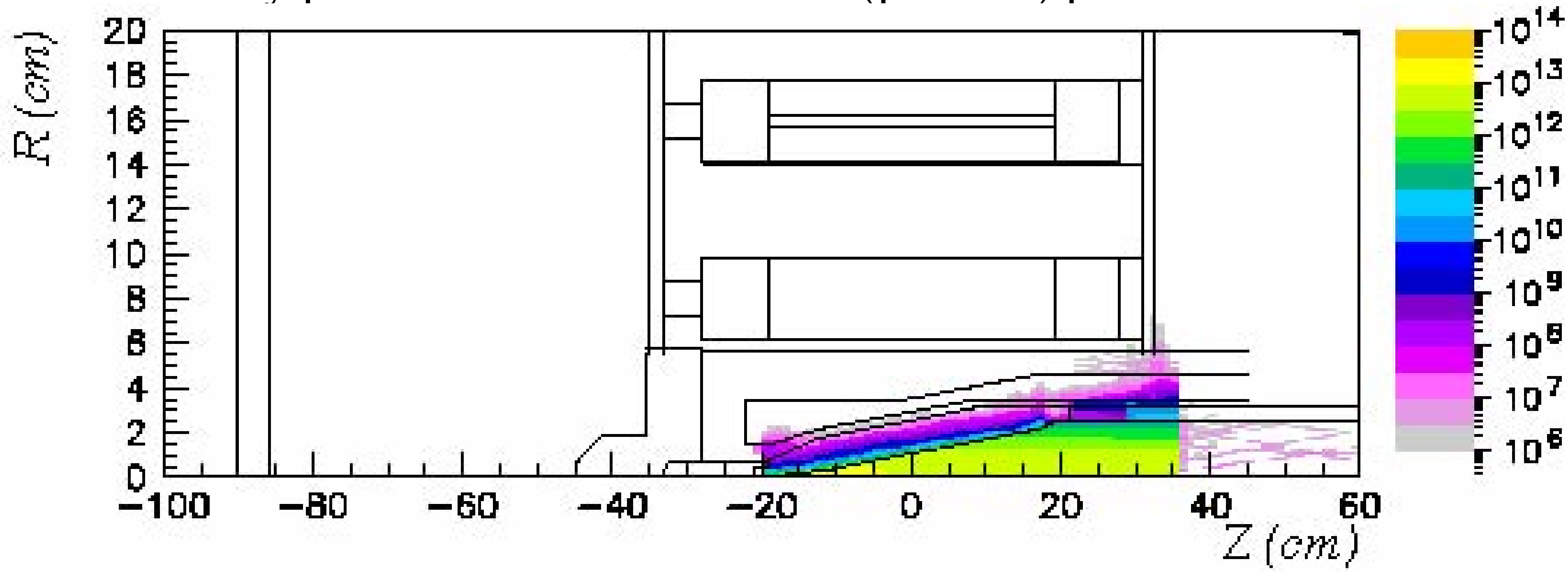
The flux of neutrons > 20 MeV reaching the inner most fuel elements is of the order of a few 10^9 $n/cm^2/s$ per kW of beam.

These neutrons tend to be forward peaked (> 130º), contrary to the low-energy neutrons which are more or less centred along the core mid-plane.

On the other hand, any beam offset will produce an axial shift of the high-energy neutron distribution that can be easily monitored by placing at several locations along the height of the target a series of detectors sensitive to the recoils generated by the high-energy component of the neutron flux (> 1 MeV).

Primary Flux

Primary proton flux distribution in $(p/cm^2/s)$ per kW of beam

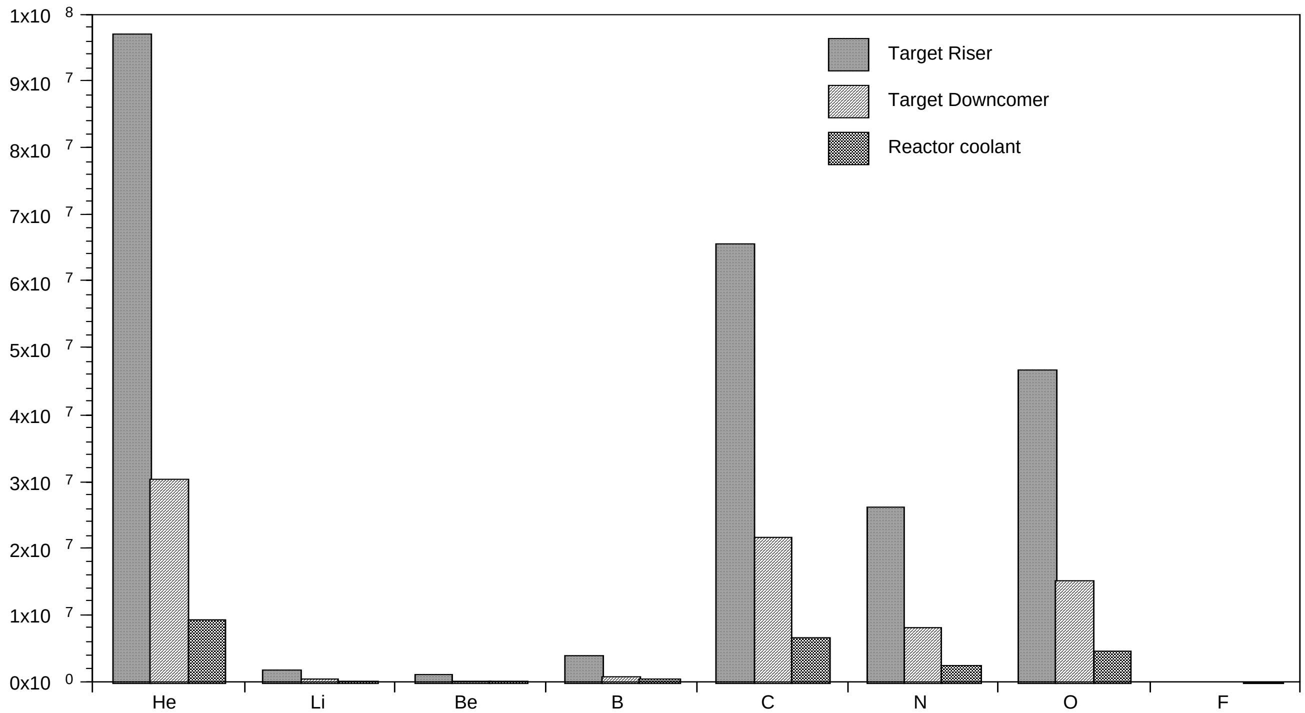


The release of protons out of the spallation target causes the production of unwanted radionuclides in the cooling water, therefore it has to be taken into account to identify the target acceptability and if possible minimized.

The fraction of protons escaping the target vessel is almost negligible apart from the upper part of the target (direct connection to the beam transport line) where the tails of the Gaussian profile are truncated.

In any case the majority of the protons escaping the spallation target are either stopped in the cooling channel (riser) surrounding the target or inside the thick flow guide, none reach the core internal structures and only a few are backscattered into the vacuum beam pipe

Residual Products and Activation

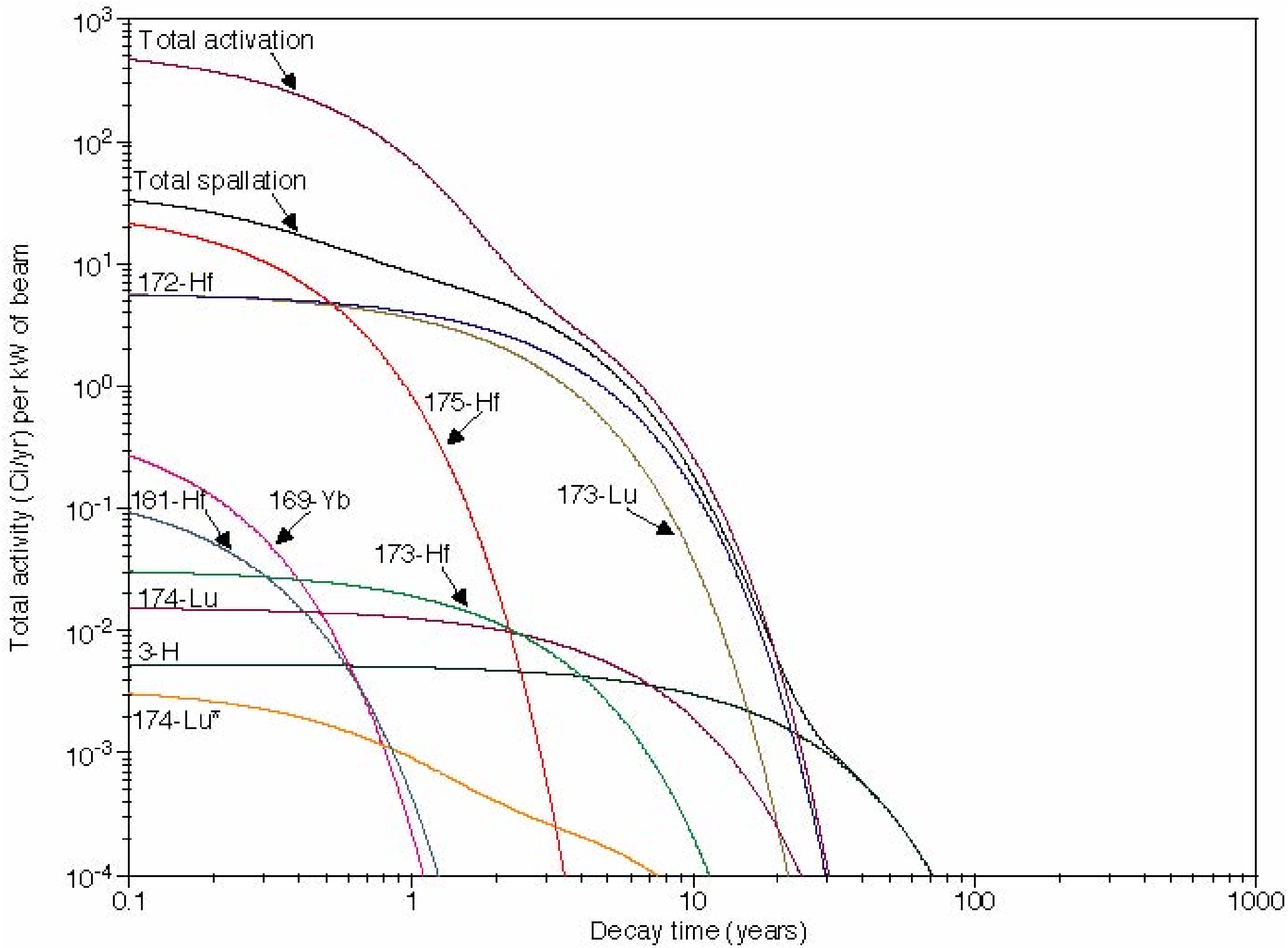


Residual yield of the most troublesome isotopes in the target cooling channel in (g/year) per kW of beam after 1 yr operation

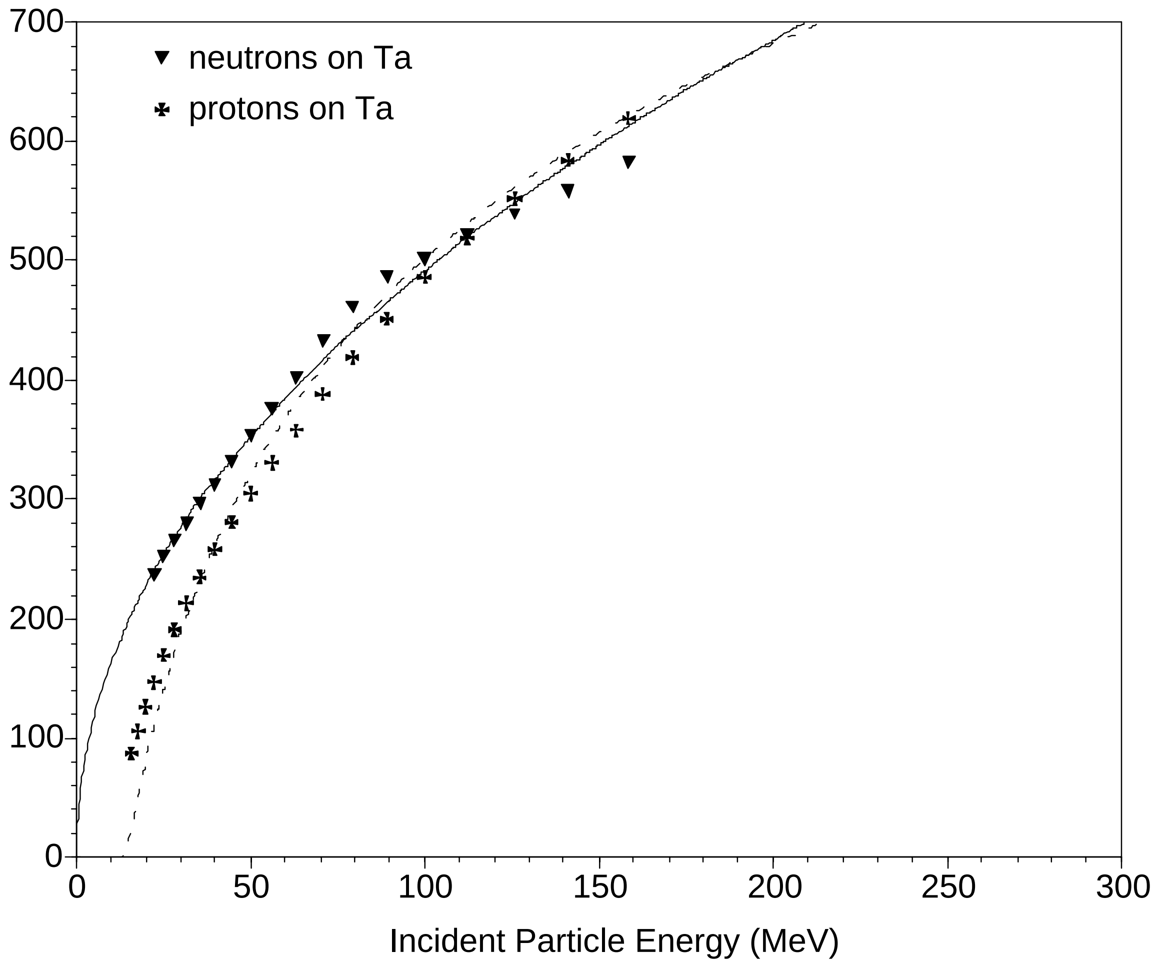
Isotopes	Riser	Down-comer
H-3	$8.70\ 10^{-9}$	$2.43\ 10^{-8}$
Be-7	$9.40\ 10^{-9}$	$2.25\ 10^{-8}$
C-14	$5.40\ 10^{-8}$	$1.72\ 10^{-7}$
N-16	$1.33\ 10^{-7}$	$6.05\ 10^{-7}$

Residual Products and Activation

Evolution of the radioactivity of the Tantalum spallation target as a function of time in (Ci/yr) per kW of beam



Radiation Damage

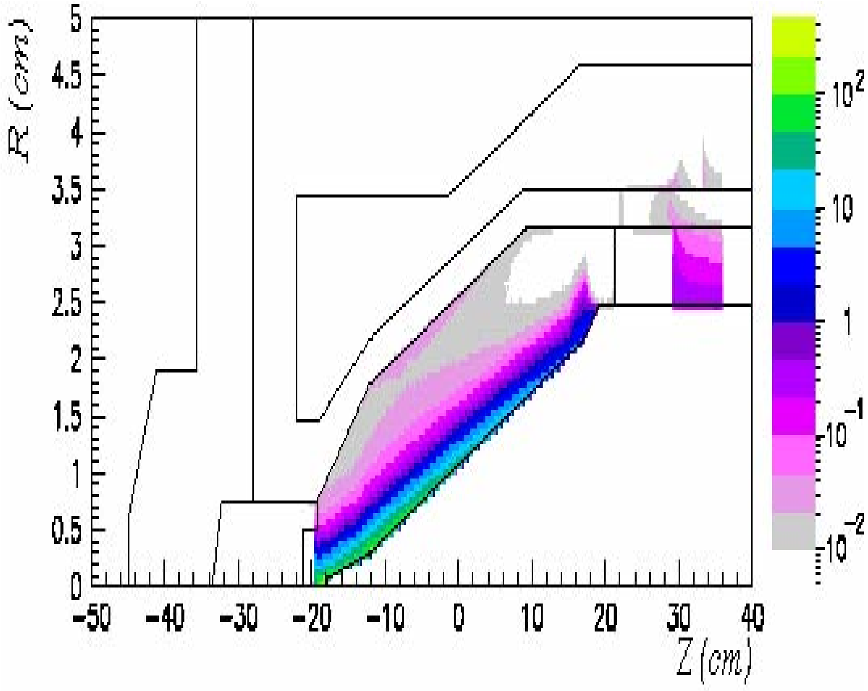


Radiation Damage

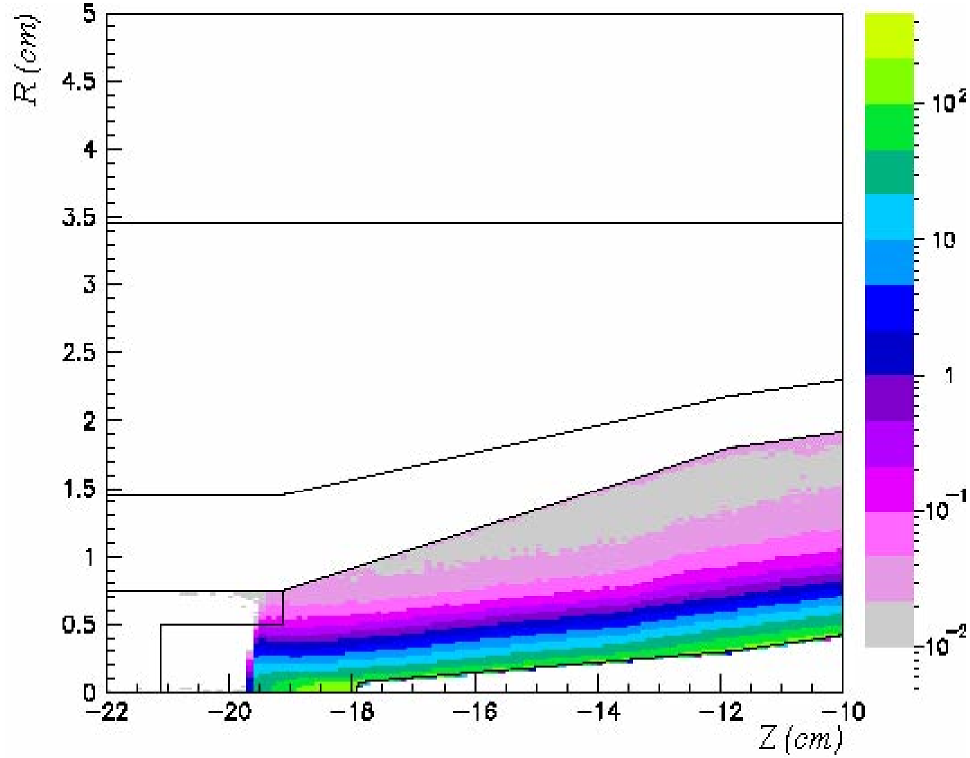
Gas production and the displacement rates per kW of beam

Target (Ta)	**Average** Prot. Ener (MeV)	**Average** Neut. Ener (MeV)	**H_3** Production (appm/dpa)	**He** Production (appm/dpa)	HE proton (dpa/yr)	HE neutron (dpa/yr)
					Max	Ave
140 MeV	90	51	0.99	54.8	0.6	0.07
200 MeV	115	65	2.92	130.	0.5	0.05
300 MeV	155	88	6.93	275.	0.4	0.04

Energy Deposition

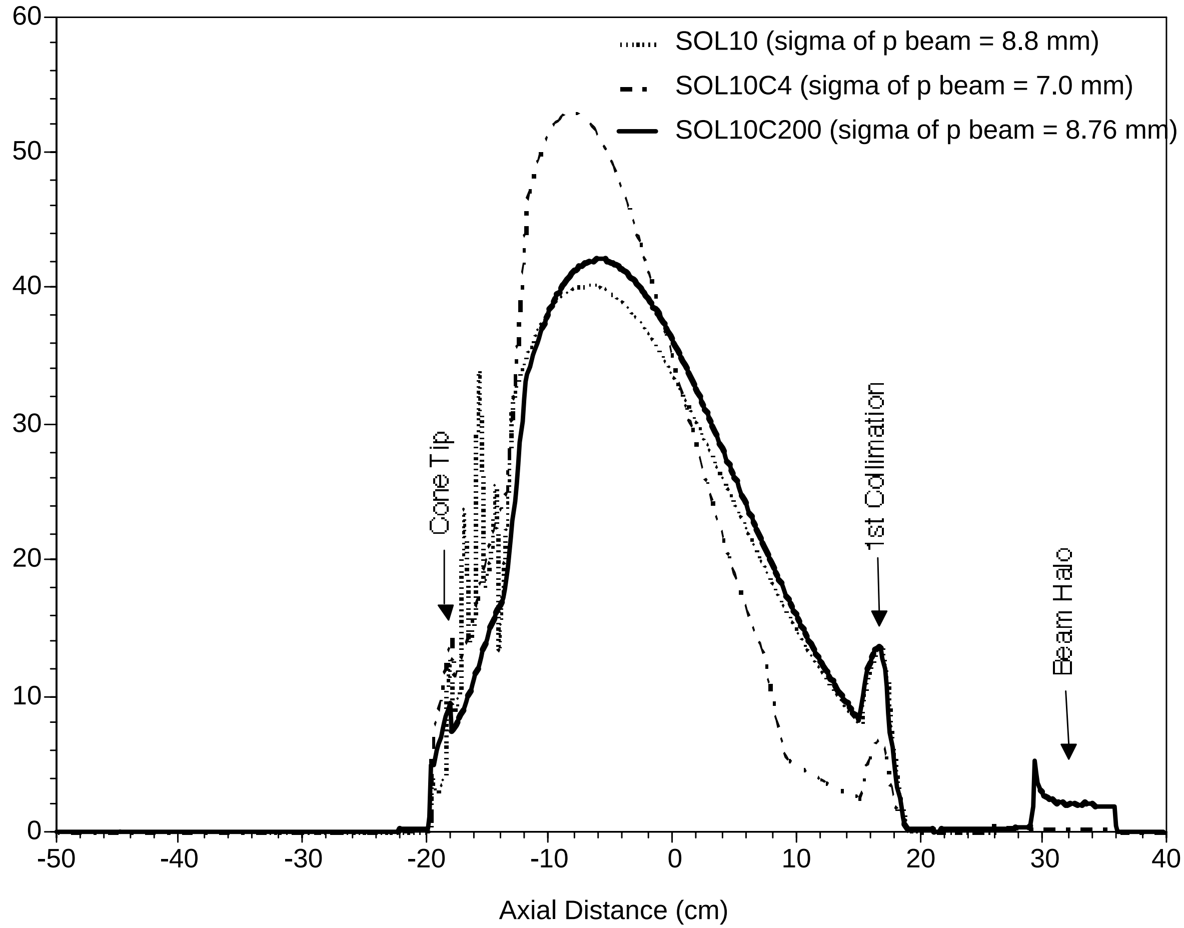


Power deposition inside the target in (W/cm^3) per kW of beam at 140 MeV



The largest value of the power density, which is equal to 175 W/cm^3 per kW of beam of 140 MeV protons, is found at the tip of the conical cavity at the bottom of the target

Energy Deposition



Main Parameters

Variation of the main neutronic parameters for configurations 10 C4 and 10 C200 at 200 MeV proton beam energies

	Solution 10 C4		Solution 10 C200
Proton Energy (MeV)	140	200	200
Neutron Yield (n/p)	0.80	1.65	1.49
Net Neutron Multiplication	11.7	11.0	11.0
k	0.9143	0.9093	0.9093
$\Delta k/k$ (pcm)	0.0	-550	-550
Scaling Factor	1.0	0.52	0.57