The Abdus Salam
International Centre for Theoretical Physics

United Nations
Educational, Scientific
and Cultural Organization

International Atomic
Energy Agency

Workshop on
"Technology and Applications of Accelerator Driven Systems (ADS)"

17 - 28 October 2005

1677/6

Examples of ADS Design I:
Spallation Target for TRADE

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LECTURES OUTLINE

- ✓ LECTURE 1: Physics of Spallation and Sub-critical Cores, Fundamentals
  (Monday 17/10/05, 16:00 – 17:30)
- ✓ LECTURE 2: Nuclear Data & Methods for ADS Design I
  (Tuesday 18/10/03, 08:30 – 10:00)
- ✓ LECTURE 3: Nuclear Data & Methods for ADS Design II
  (Tuesday 18/10/03, 10:30 – 12:00)
- ✓ LECTURE 4: ADS Design Exercises I & II
  (Tuesday 18/10/03, 14:00 – 17:30)
- ✓ **LECTURE 5: Examples of ADS Design I**
  (Thursday 20/10/03, 08:30 – 10:00)
- ✓ LECTURE 6: Examples of ADS Design II
  (Thursday 20/10/03, 10:30 – 12:00)
- ✓ LECTURE 7: ADS Design Exercises III & IV
  (Thursday 20/10/03, 14:00 – 17:30)

Examples of ADS Design I : Spallation Target for TRADE

Y. Kadi
CERN, Switzerland

20 October 2005, ICTP, Trieste, Italy

TRADE - TRIGA Accelerator Driven Experiment: A Pilot Experiment for the Global Demonstration of the ADS Concept

- Motivations
- Reference Configuration
- Experimental Programme
- Global Neutronic Parameters
- Spallation Target Studies

The Three Levels of ADS Validation

Three different levels of validation of an ADS can be specified:

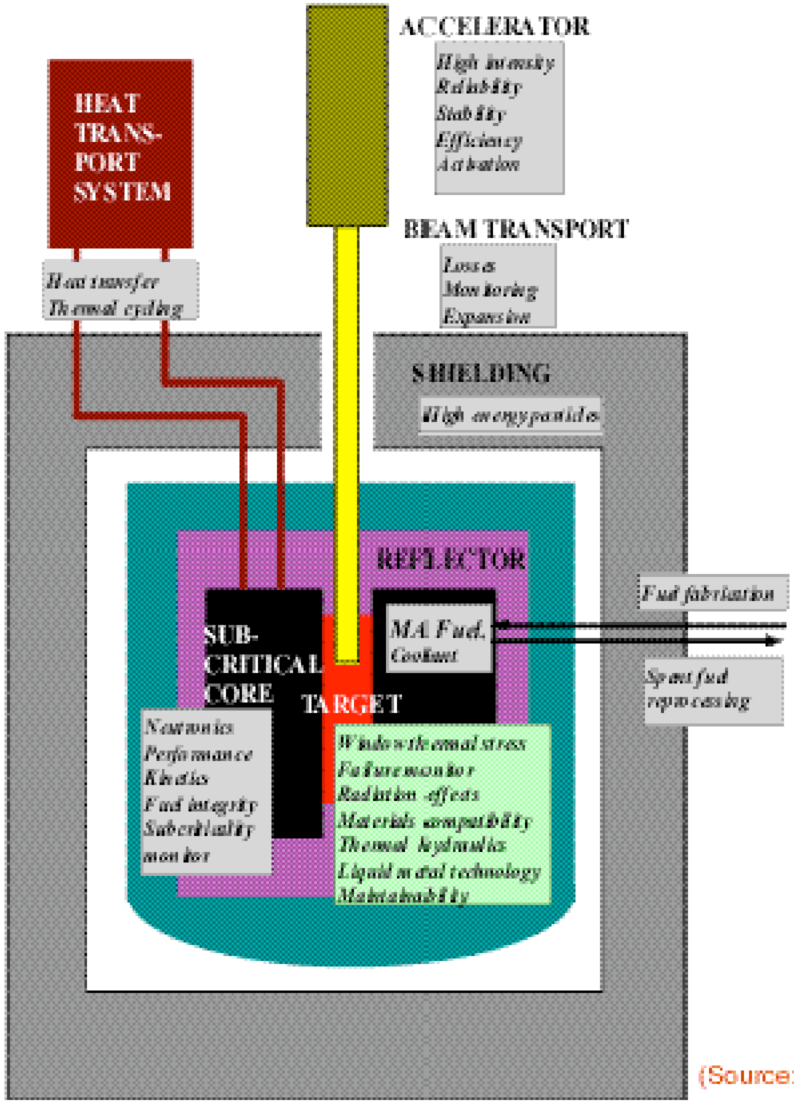
- **First**, validation of the different component concepts, taken separately (accelerator, target, subcritical core, dedicated fuels and fuel processing methods). In Europe: The FEAT, TARC, MUSE & YALINA experimental programs and the MEGAPIE project are significant examples.

- **Second, validation of the coupling of the different components in a significant environment, e.g. in terms of power of the global installation, using as far as possible existing critical reactors, to be adapted to the objectives.**

- **Third**, validation in an installation explicitly designed for demonstration (e.g. the ADS installation described in the **European roadmap** established by the Technical Working Group, chaired by prof. Rubbia). This third step should evolve to a **demonstration of transmutation fuels**, after a first phase in which the subcritical core could be loaded with "standard" fuel.

ADS Programs Worldwide

Project	Neutron Source	Core	Purpose
MUSE (France)	DT ($\sim 10^{10}$n/s)	Fast (< 1 kW)	Reactor physics of fast subcritical system
TRADE (Italy)	Proton (140 MeV) + Ta (40 kW)	Thermal (200 kW)	Demonstration of ADS with thermal feedback
TEF-P (Japan)	**Proton (600 MeV) + Pb-Bi (10W, $\sim 10^{12}$n/s)**	**Fast (< 1 kW)**	**Coupling of fast subcritical system with spallation source including MA fueled configuration**
SAD (Russia)	Proton (660 MeV) + Pb-Bi (1 kW)	Fast (20 kW)	Coupling of fast subcritical system with spallation source
MYRRHA (Belgium)	Proton (350 MeV) + Pb-Bi (1.75 MW)	Fast (35 MW)	Experimental ADS
MEGAPIE (Switzerland)	Proton (600 MeV) + Pb-Bi (1MW)	-----	Demonstration of 1MW target for short period
TEF-T (Japan)	**Proton (600 MeV) + Pb-Bi (200 kW)**	-----	**Dedicated facility for demonstration and accumulation of material data base for long term**
Reference ADS	Proton (≈ 1 GeV) + Pb-Bi (≈ 10 MW)	Fast (1500 MW)	Transmutation of MA and LLFP



(Source:PSI)

Vast R&D activity in Europe over last 10 years: 12 countries, 43 institutions

EU ➠ 31 MEuros

Member States ➠100 MEuros

TRADE Project

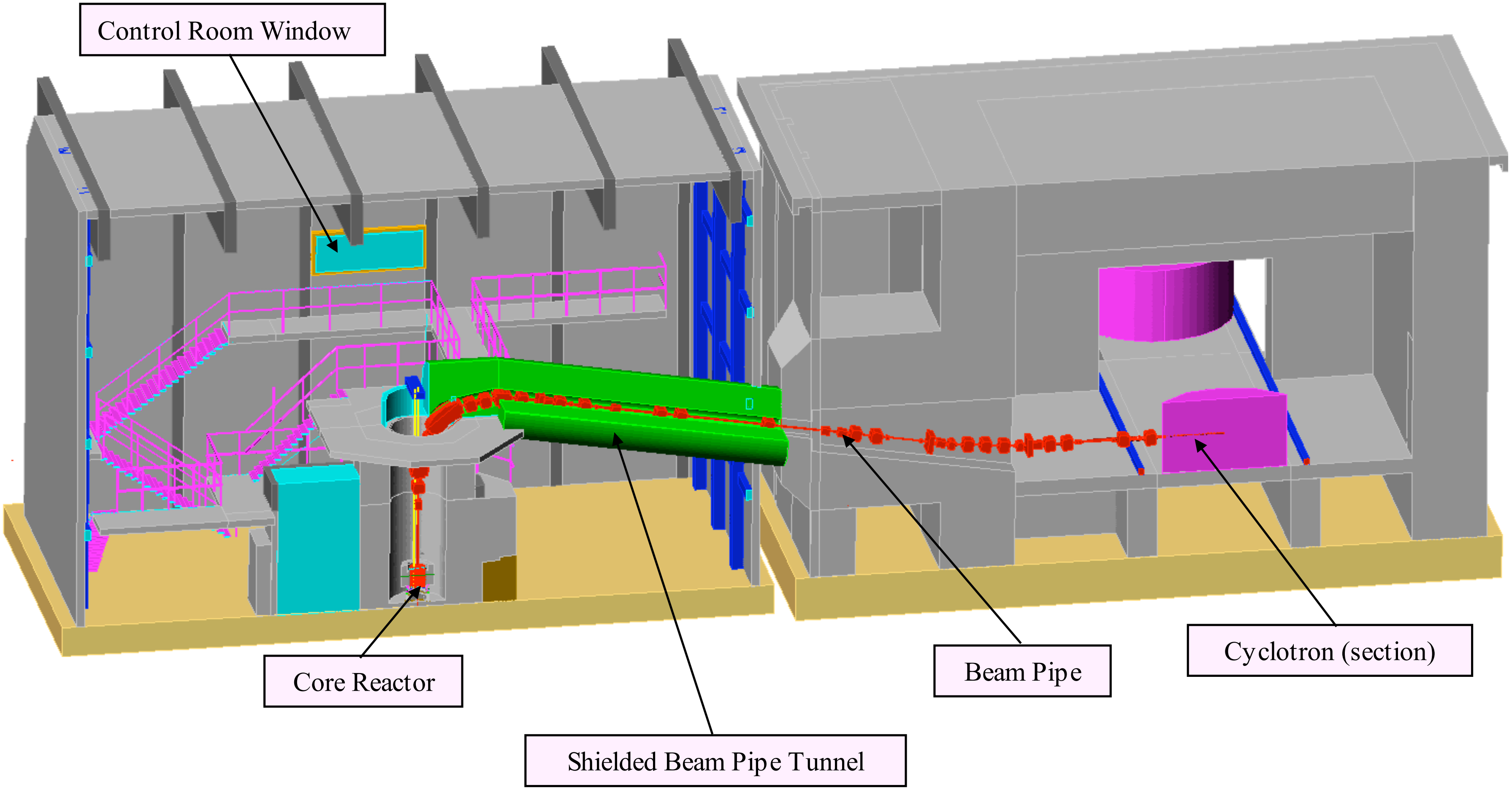
- The TRADE experiment suggested by C. Rubbia, first worked-out in an ENEA/CEA/CERN feasibility study and presently assessed by a wider international group (lead: ENEA, CEA, DOE, FZK), is a significant step towards the ADS demonstration, i.e. within the second phase of ADS validation

- Coupling of a proton accelerator to a power TRIGA Reactor via a spallation target, inserted at the centre of the core.

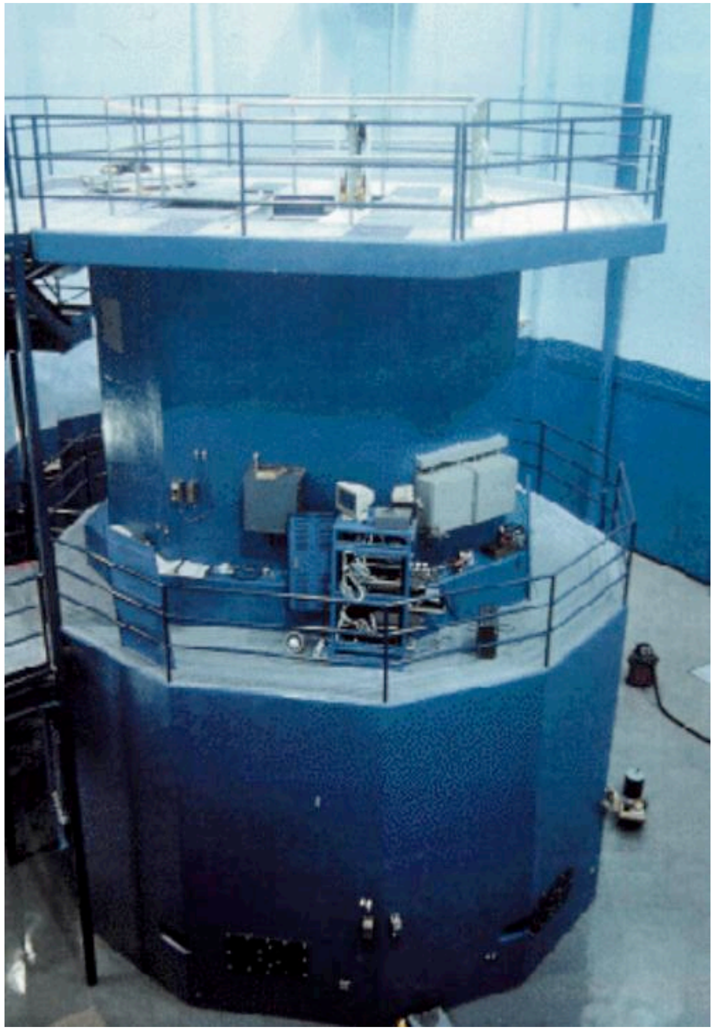
- Range of power :
  - in the core : 200 - 1000 KW,
  - in the target : 20 - 100 KW.

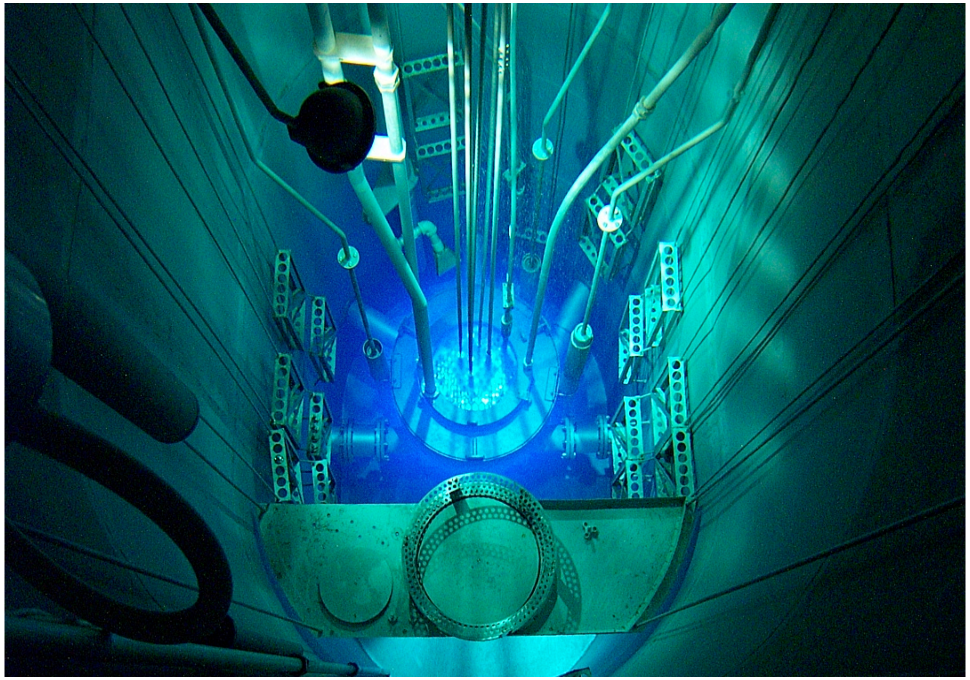
- The main interest of TRADE, as compared to the MUSE experiments, is the ability of incorporating the power feedback effects into the dynamics measurements in ADS and to address ADS **operational**, **safety** and **licensing issues**.

The TRADE Facility - Reactor and Accelerator Buildings

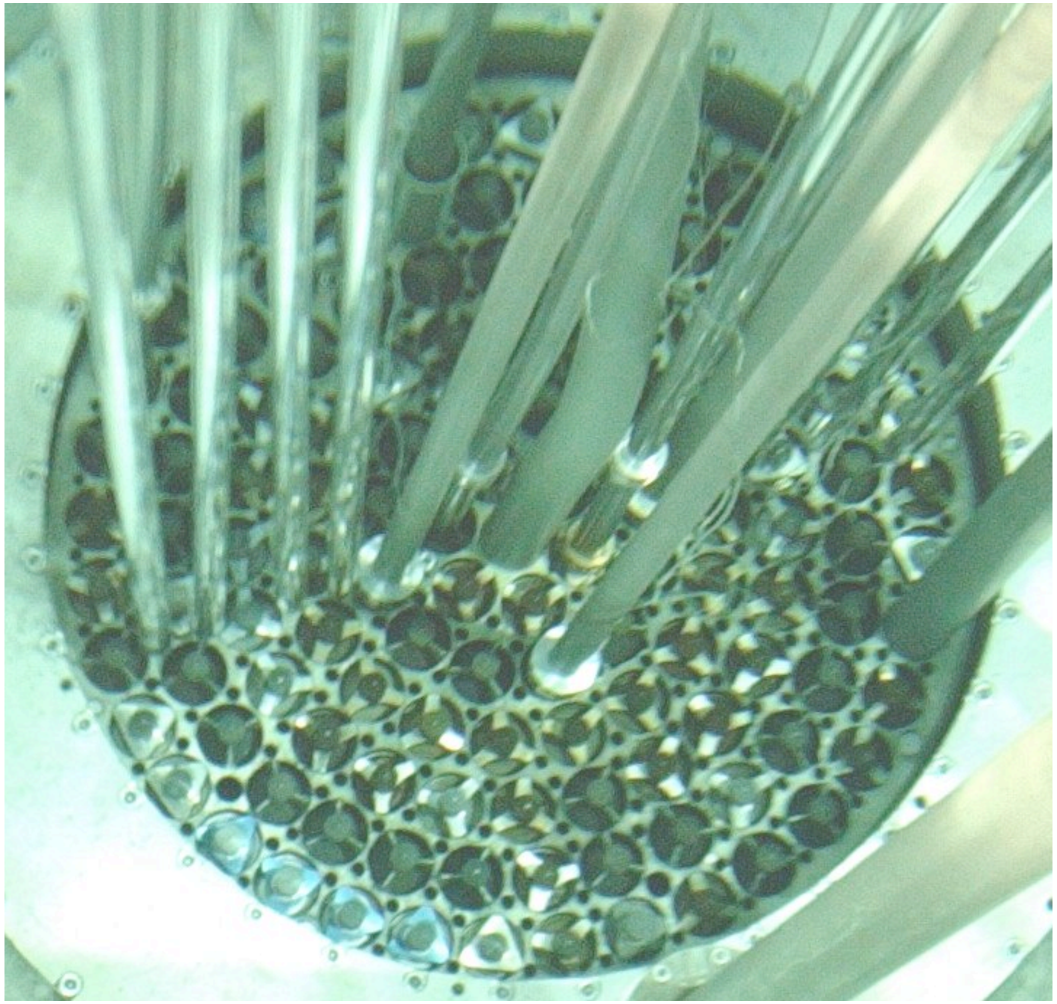


TRIGA MARK II REACTOR

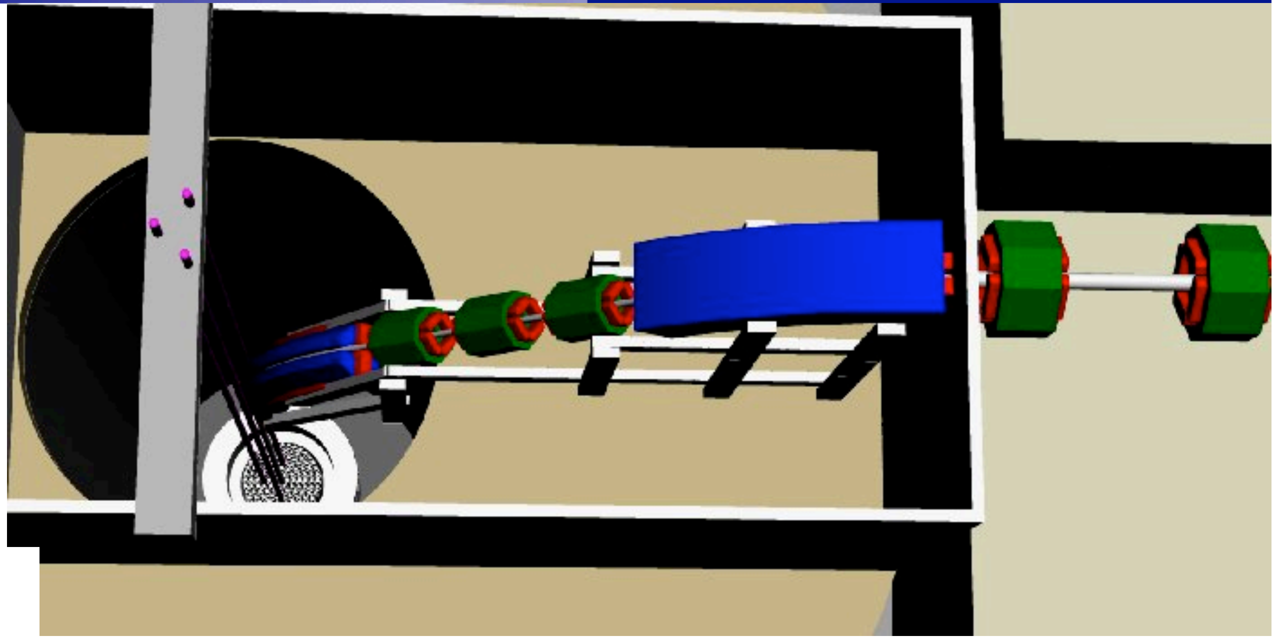




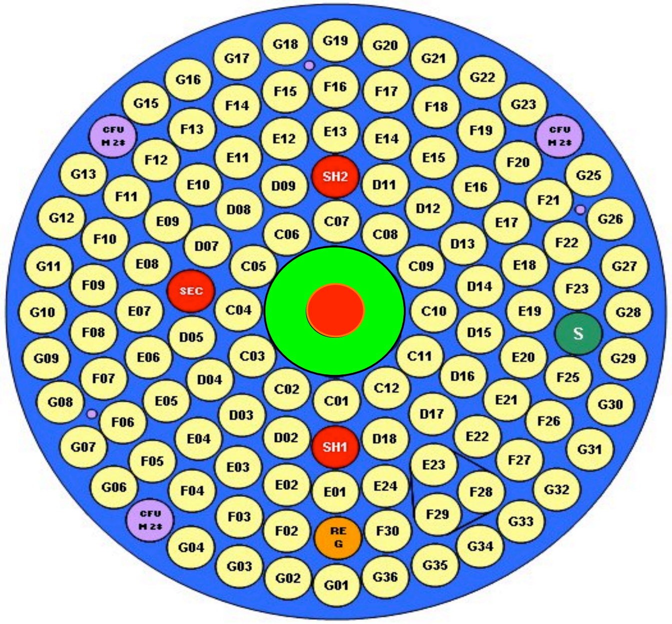
TRIGA MARK II REACTOR



Overall Lay-out of the TRADE Facility



Top view with
bending magnets



Core cross-section

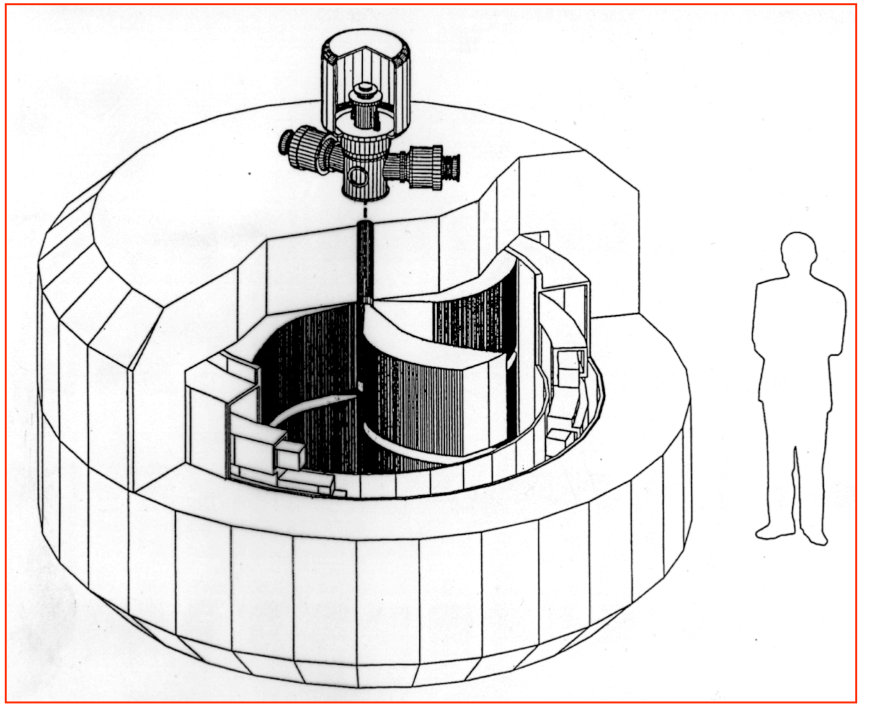
The accelerator

220 MeV-H2$^+$ Superconducting Cyclotron

Based on the concepts developed in the Cyclotron Laboratory of CAL for compact superconducting fixed-frequency cyclotrons for hadrontherapy (EULIMA for fully stripped Carbon of 340 MeV/nucleon and PRIAM for 230 MeV protons) a 220 MeV H2+ superconducting cyclotron is being investigated to produce 110 MeV protons by stripping.

The following Table gives a list of the preliminary parameters of the proposed superconducting cyclotron.

Injection energy	50/60 KeV
Extraction energy for protons after stripping	110 MeV
Accelerated Beam intensity of H2+	2 mA
RF frequency	70.4 MHz
Harmonic	4
External diameter	4.44 m
Number of sectors	4
Magnet vertical gap	0.06 m
Sector angle at smaller/larger pole radius	31/23 deg.
Sector spiral angle at pole maximal radius	30 deg.
Inner/outer coil radius	1.38/1.52 m
Average current density	4464 A/cm2
Total iron weight	200 tons
Number of cavities	4
Type of cavity	delta, 2 gaps
Peak voltage (Injection/Extraction)	70/200 kV
Extraction	Stripping
RF Power Losses per cavity	70 KWatt
Total electric power for the cavities (2 mA-H2+ beam+wall losses)	1.0MWatt
Estimated Total Power required for extracting 4 mA-110 MeVprotons (beam power 440 KWatt)	1.10/1.15 MWatt



≈ 200 ton

Types of Experiments

- The planned experiments would have allowed to validate different operational modes of a full power ADS:
  - start-up and shut down procedures,
  - operation and monitoring of the system at steady state,
  - monitoring of the time evolution of the reactivity, and
  - practical coupling of an accelerator, a spallation target and the subcritical core.

- Most of these features are largely independent on the type of neutron spectrum in the core and on the type of proton accelerator.

- Of course, no significant demonstration of waste transmutation in a fast neutron spectrum was foreseen.

Monitoring of the Time Evolution of the Reactivity

- **Steady state** measurements of the reactivity by the Modified Source Multiplication method (MSM). The core was equipped with several in-core and ex-core detectors. First measurements already performed in Nov. 2002 in a critical configuration.

- **Dynamic** measurements:
  - Pulsed Neutron Source.
  - Noise measurement.

- These methods enable the response of the system to flux perturbations and to the intrinsic neutron fluctuations to be evaluated

- These methods will allow to measure simultaneously ρ (reactivity), β(effective delayed neutron fraction) and Λ (neutron generation time).

Monitoring of the Time Evolution of the Reactivity

- Specifically, it would have been possible to experimentally validate theoretical models in the cases where :
  - core dynamics regulates the system's response to external perturbations,
  - core power levels are high enough for core dynamics feedback to be important, and
  - external source behaviour determines the core dynamics behaviour.

- This type of behaviour and the transition between the **source dominated** and the **core dominated** modes, can happen in the same core during the irradiation cycle due to burn-up reactivity swing and should be carefully investigated, in order to develop appropriate **monitoring and control systems** for the power distribution in the core and in order to choose appropriate reference sub-criticality levels.

- ADS-oriented simplified dynamics methods are being developed at FZK, ENEA and ANL.

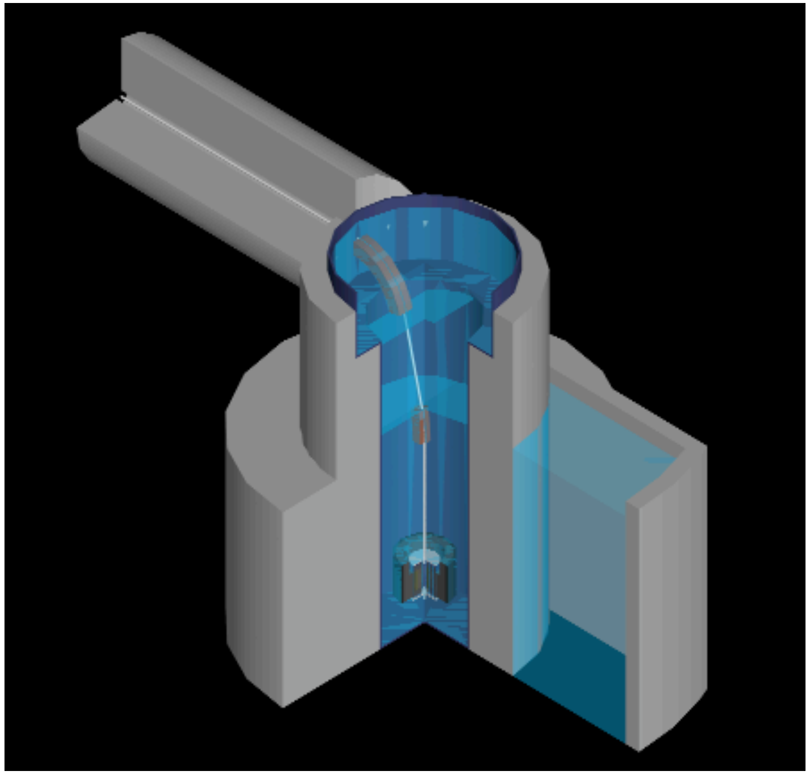
- Also, use of well established, but adapted, tools like RELAP-5.

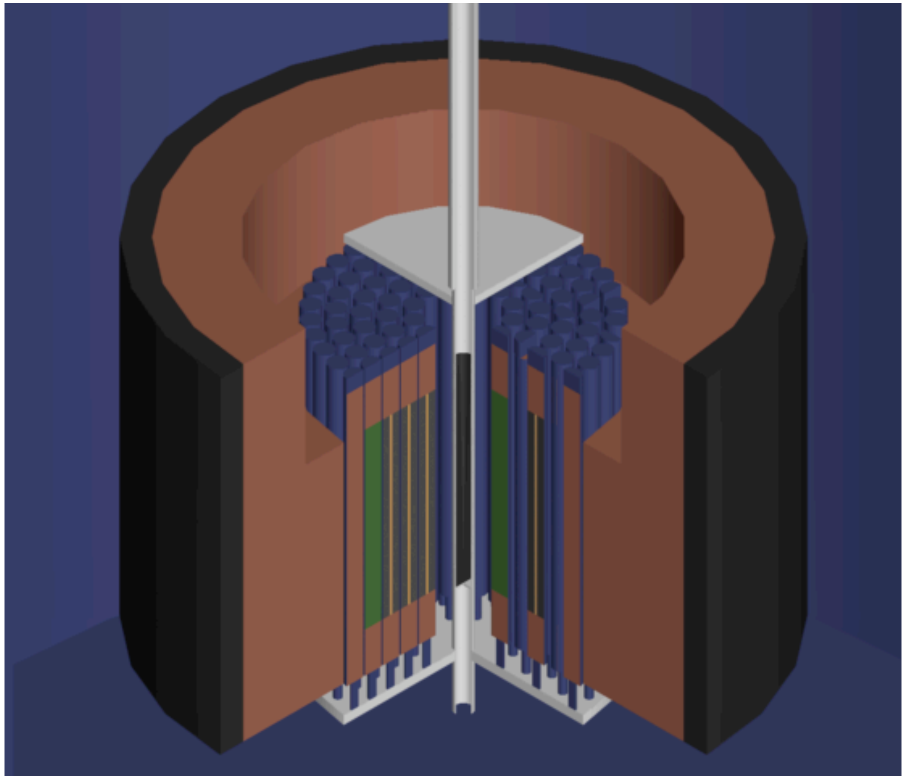
- Start of the Phase IA Experimental Programme in TRIGA aimed at characterizing the TRADE core reference configuration → winter 2003
  - Chamber check-out → detectors for estimating subcritical reactivity by source multiplication
  - Neutron flux measures
  - Reactivity worths of fuel elements → help in the decision regarding purchase of fresh fuel
  - Control rod calibrations
  - Temperature feedback measurements → evaluation of reactivity temperature coefficients

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 sub-criticality levels : k = 0.90 ÷ 0.99

FLUKA and EA-MC Monte Carlo codes were used to perform these studies





Sub-criticality Levels and main Reactor Parameters: 200 kW

Global Parameters	Symbol	**Reference case**	Critical	High K_s	**Low K_s**
Proton Beam Energy	E_p (MeV)	110	—	110	
Spallation Neutr. Yield	$N_{(n/p)}$ (n/p)	**0.451**	-	0.451	
Multiplic. Coefficient	K_s	0.977	1.000	0.988	0.903
Energetic Gain	G	15.1	—	28.1	4.0
Accelerator Current	I_p (mA)	0.13	—	0.07	0.61
Beam Power	P_{beam} (kW)	14.2	—	7.4	66.9
Core Power Distributions					
Av. fuel power density	$\mathbf{P_{th}/V_{fuel}}$ **(W/cm³)**	4.9	4.8	4.7	6.5
Max. linear power	P_l (W/cm)	75.6	70.2	70.5	118.2
Radial peaking factor	P_{max}/P_{ave}	1.48	1.45	1.46	1.76
Linear peaking factor	P_{max}/P_{ave}	1.51	1.45	1.48	1.78

Core Neutronic Analysis at 200 kW

Table 2. Integrated flux, heating and damage in the reactor internal structures due to neutrons with energy below 20 MeV as computed by EA-MC.

gion	Flux ($n/cm^2.s$)	Heat (W/cm^3)	DPA/yr
Reactor vessel	$6.6x10^{7}$	–	–
Neutronic protection	$1.3x10^{12}$	$6.4x10^{-3}$	$4.3x10^{-4}$
Graphite reflector	$1.0x10^{13}$	$1.0x10^{-2}$	$1.5x10^{-2}$
Water coolant	$1.2x10^{11}$	$8.8x10^{-4}$	$2.3x10^{-5}$
Top support grid	$3.9x10^{11}$	–	–
Bottom support grid	$3.7x10^{11}$	–	–
Unfuelled ring B	$2.5x10^{13}$	0.224	$2.9x10^{-2}$
Fuel ring C	$2.6x10^{13}$	38.44	$5.9x10^{-2}$
Fuel ring D	$2.6x10^{13}$	34.71	$5.7x10^{-2}$
Fuel ring E	$2.4x10^{13}$	33.28	$5.3x10^{-2}$
Fuel ring F	$1.9x10^{13}$	29.25	$4.2x10^{-3}$
Unfuelled ring G	$1.1x10^{13}$	$1.5x10^{-2}$	$2.3x10^{-2}$
Av. AISI-304 cladding	$1.4x10^{12}$	0.215	$2.7x10^{-3}$
B4C absorber rods	$7.6x10^{12}$	1.356	0.180

Core Neutron Balance at 200 kW

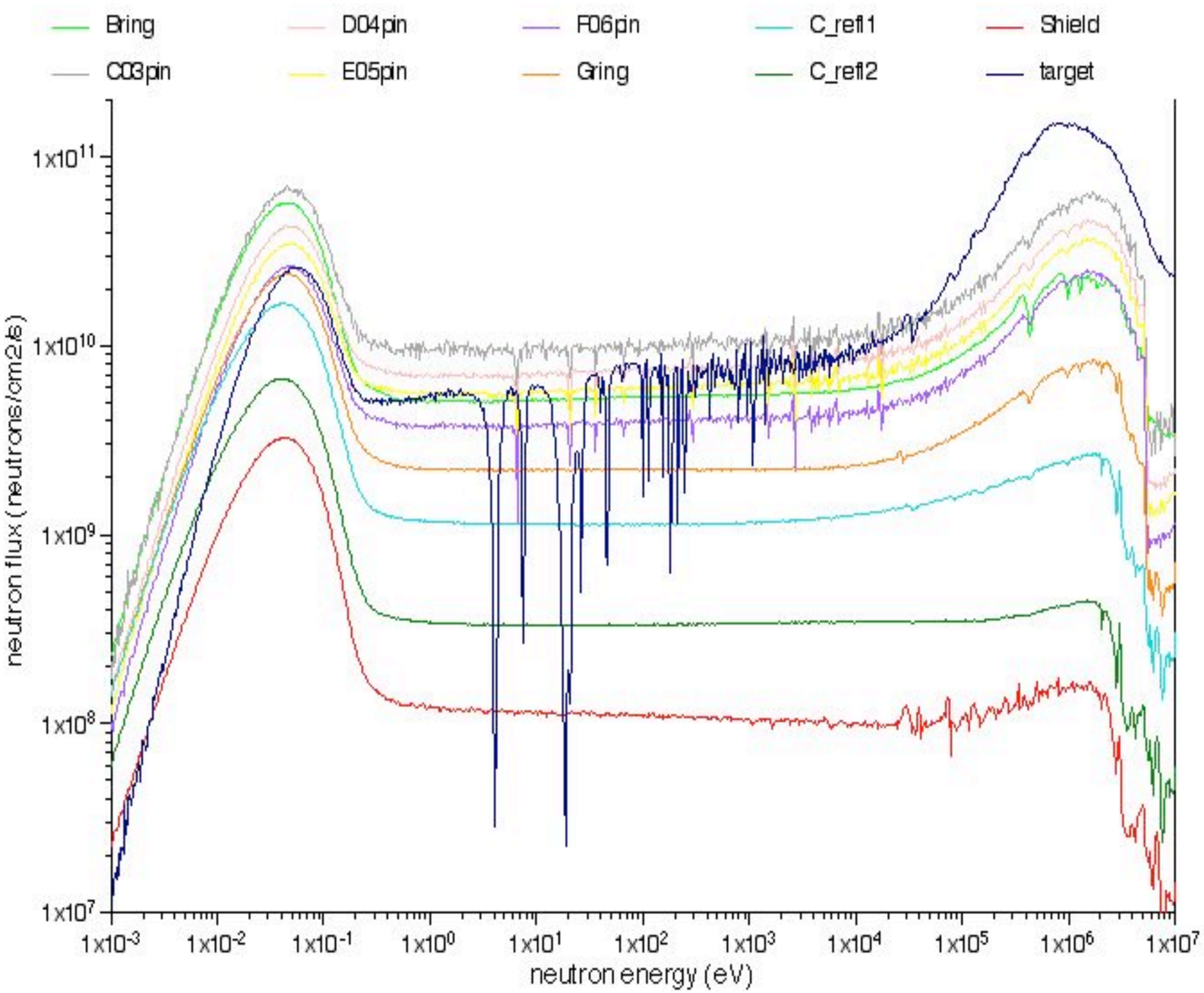
Table 3. Neutron reaction inventory at several locations of the TRIGA reactor.

utron Absorption Inventory		Neutron Absorption Inventory	
Reactor vessel	.002 %	Absorber rods	6.44 %
Neutron shield	1.04 %	Cladding	10.47 %
Aluminiun lining	1.46 %	Fuel ring C	7.91 %
Upper grid	0.05 %	Fuel ring D	14.55 %
Lower grid	0.08 %	Fuel ring E	18.45 %
Spallation target	0.18 %	Fuel ring F	18.64 %
Primary coolant	19.82 %	Fuel total	59.55 %
Core radial reflector	0.79 %	Escapes	0.05 %
Core axial reflector	0.07 %	Total	100 %
in Nuclear Reactions		Main Nuclear Reactions	
Capture	53.06 %	Others	7.00 %
Fission	38.85 %	Escapes	0.05 %
n,Xn	1.04 %	Total	100 %

Table 4. Neutron reaction inventory in the fuel core of the TRIGA reactor.

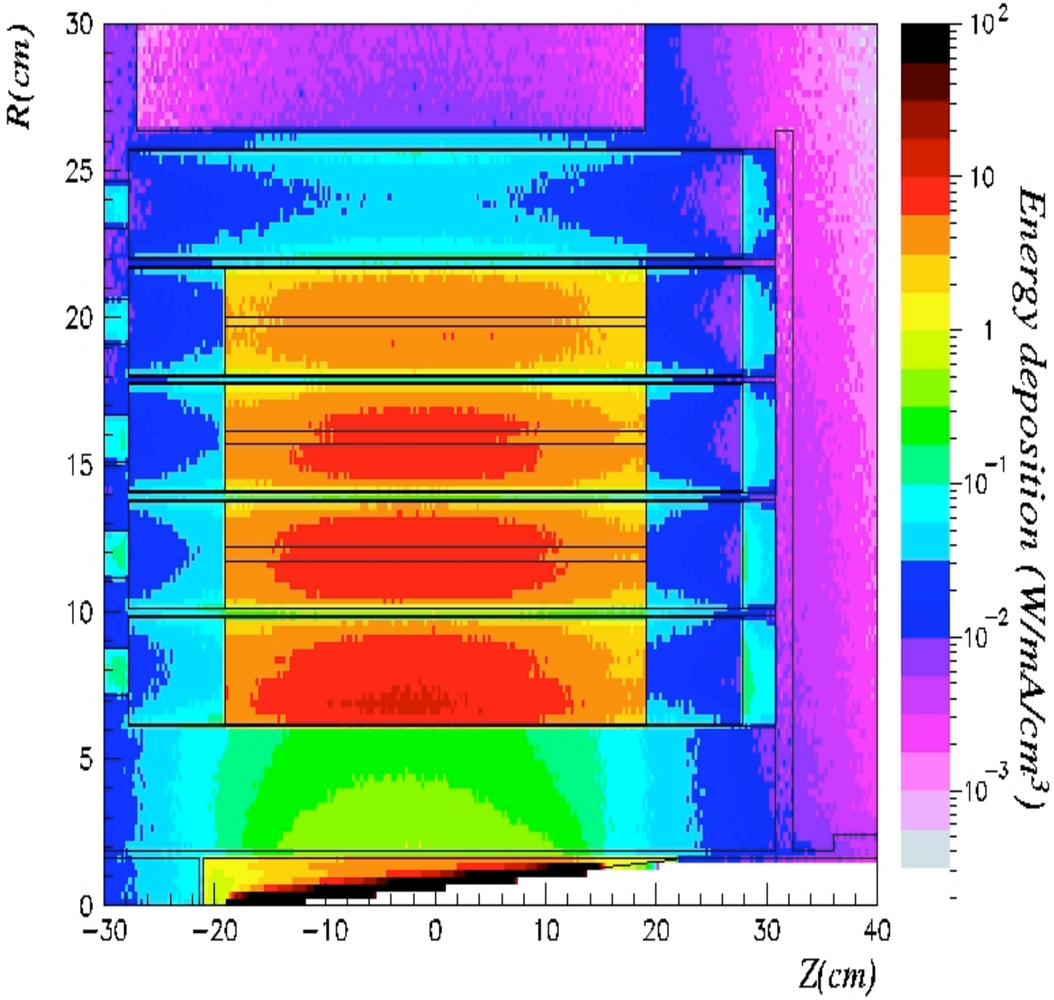
utron Absorption Inventory		Neutron Absorption Inventory	
LEUZrH fuel	68.85 %	Central Zr bar	0.09 %
AISI-304 cladding	12.01 %	Coolant	19.05 %
in Nuclear Reactions		Main Nuclear Reactions	
Capture	53.48 %	n,Xn	1.16 %
Fission	44.91 %	Others	0.45 %

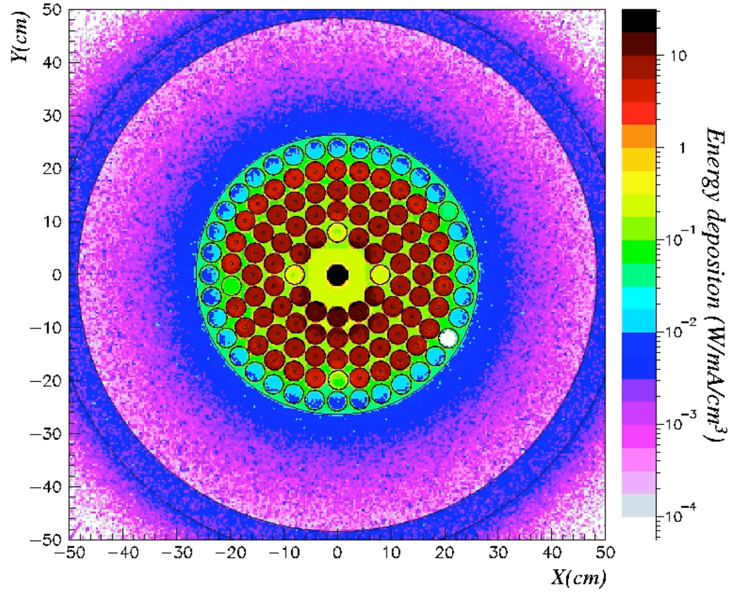
Neutron Energy Spectra



- High-energy peak in the Ta spallation target where capture resonances can be clearly seen
- Thermal spectrum, reaching highest values for sub-critical modes in ring C (except for low k's where the flux in higher in the target)
- Fast thermalisation process beyond the target; spallation neutron reach ~5 cm
- Clear domination of fission neutron vs spallation neutrons in all the core, even for k_{src}=0.90

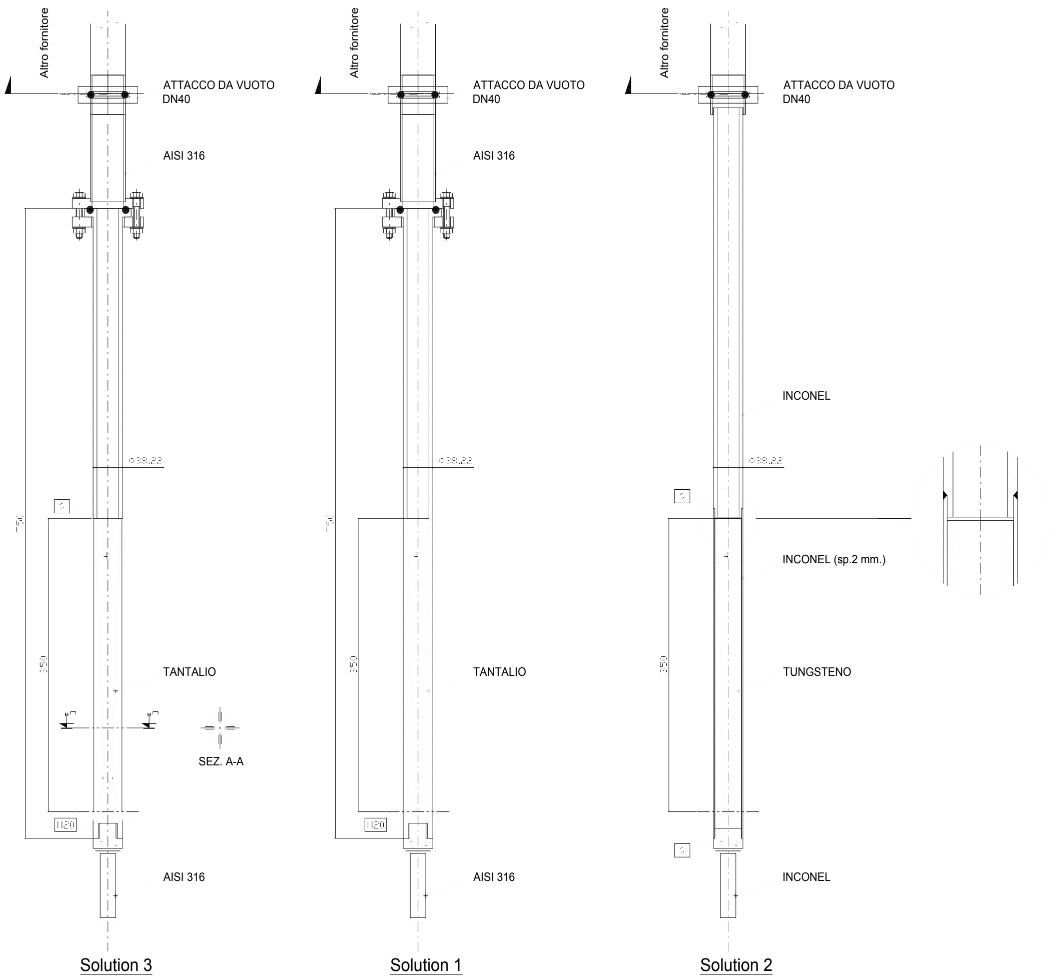
Power Distribution





- Maximum energy deposition at the tip of the conical spallation target where 12 kW/cm^3 per mA of proton beam current can be reached
- Maximum working temperature of the target 760 ºC
- Energy deposition in the hottest fuel pin: ~25 W/cm^3 for 200 kW

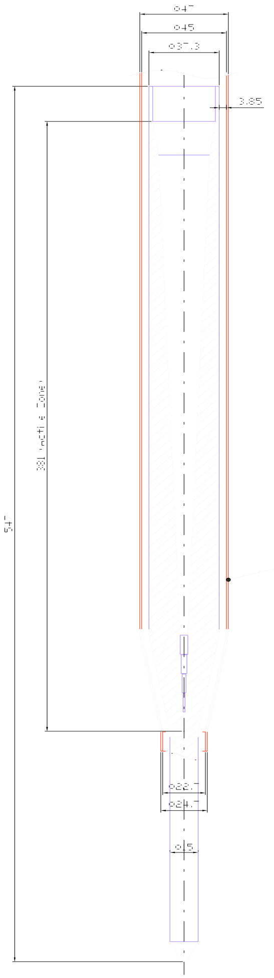
Three alternative concepts for the target



Some preliminary target concepts were designed under the geometrical constraint of the central fuel space. A conical cavity was envisaged as the most promising solution. Apart from the material choice, three different solutions are presented: thin walls, thick walls and thick walls with cladding.

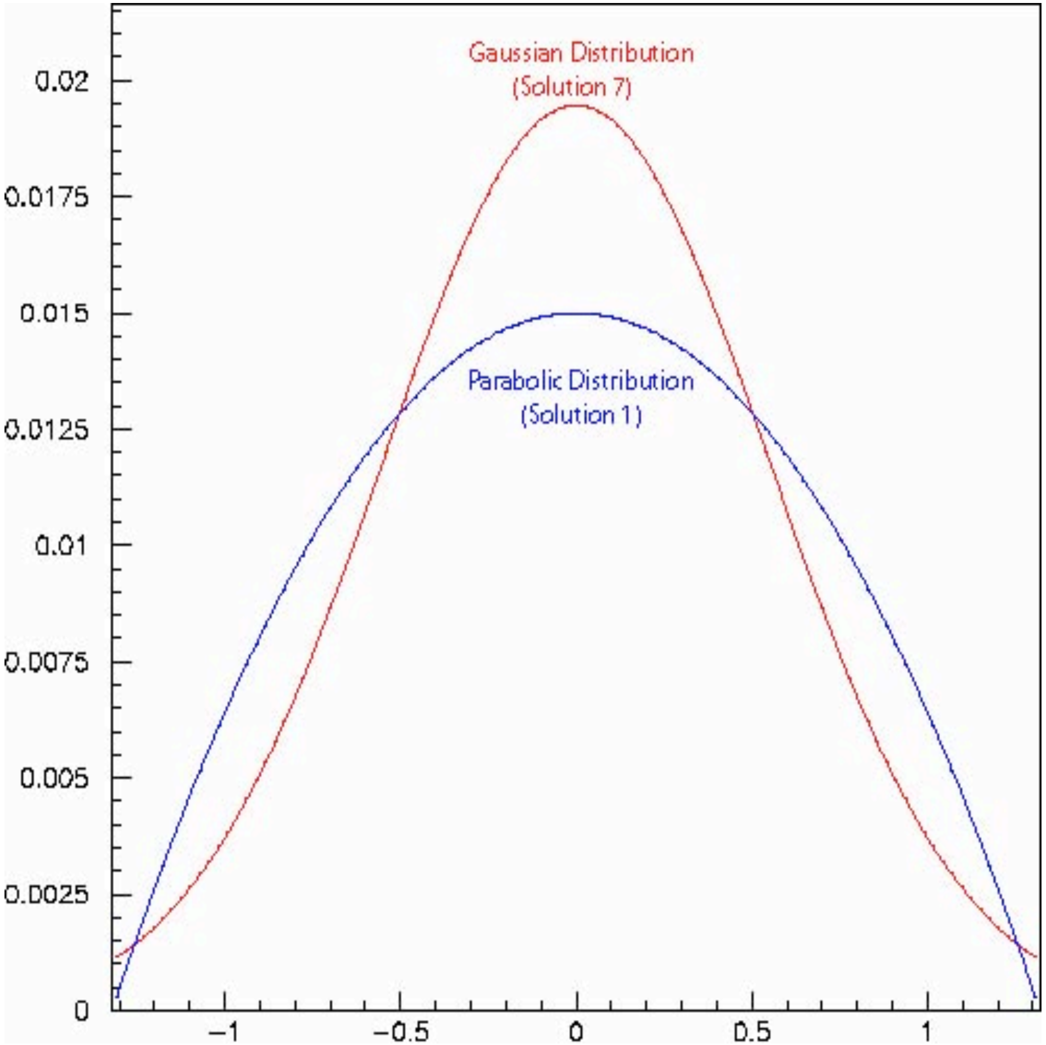
A reference design of a Ta Target and its cooling system has been selected on the basis of deep in-house neutronic, thermal-hydraulic thermo-mechanical, beam characteristics and safety analyses, as well as extensive interactions with the LANL and ISIS communities.

Further studies on fabricability, target lifetime and needed qualification tests are in progress



Solution 7

The annular channel has a constant gap to improve the cooling flow in the bottom region


Gaussian Distribution
(Solution 7)
Parabolic Distribution
(Solution 1)
0.02
0.0175
0.015
0.0125
0.01
0.0075
0.005
0.0025
0
−1
−0.5
0
0.5
1

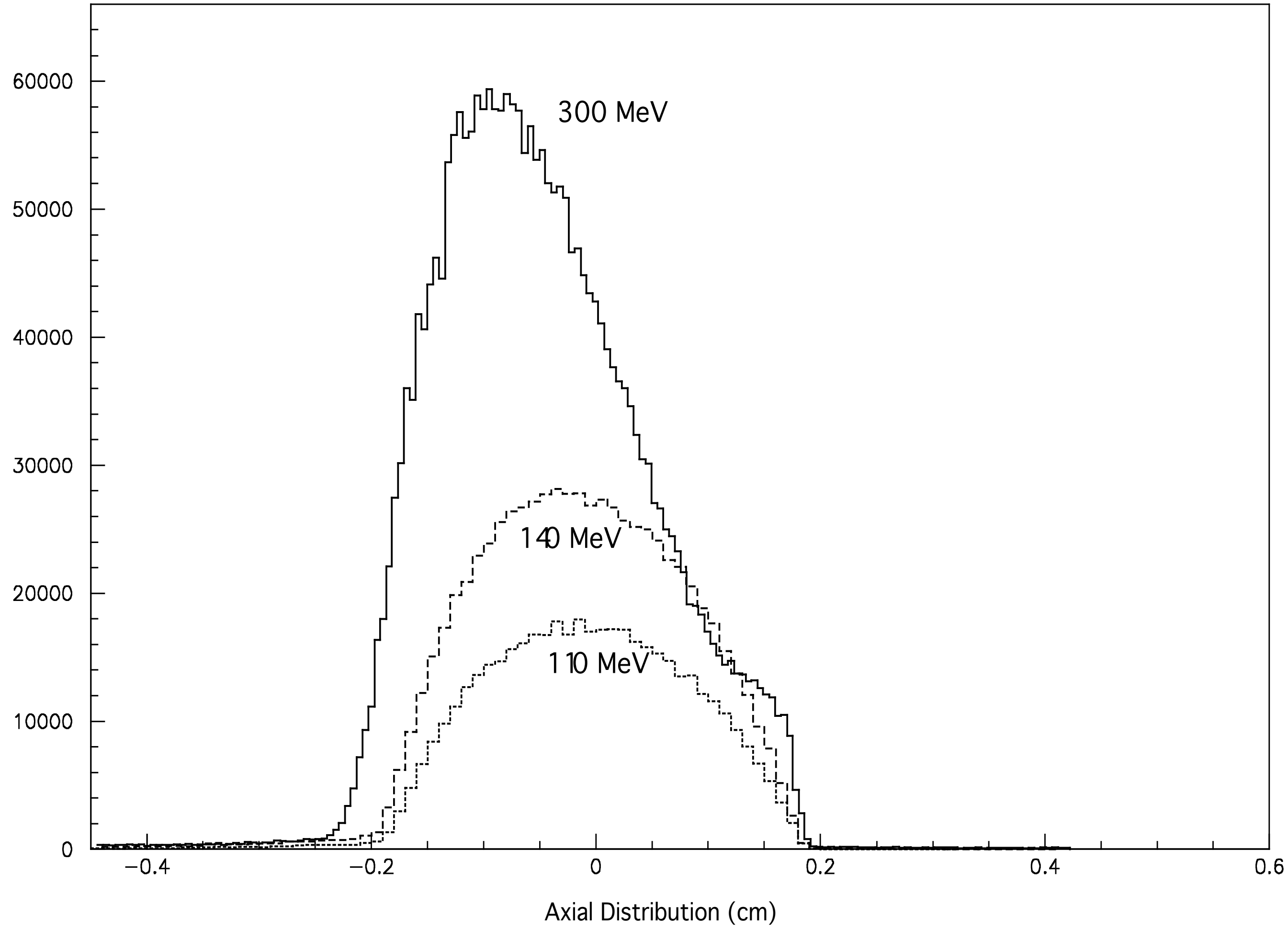
Spallation Neutron Axial Distribution

Axial distribution spallation neutron source centered around core mid-plane @ low proton energies

- Distribution widens with energy of incident protons

- Strong forward shift of the centre of production at 300 MeV (-10 cm)

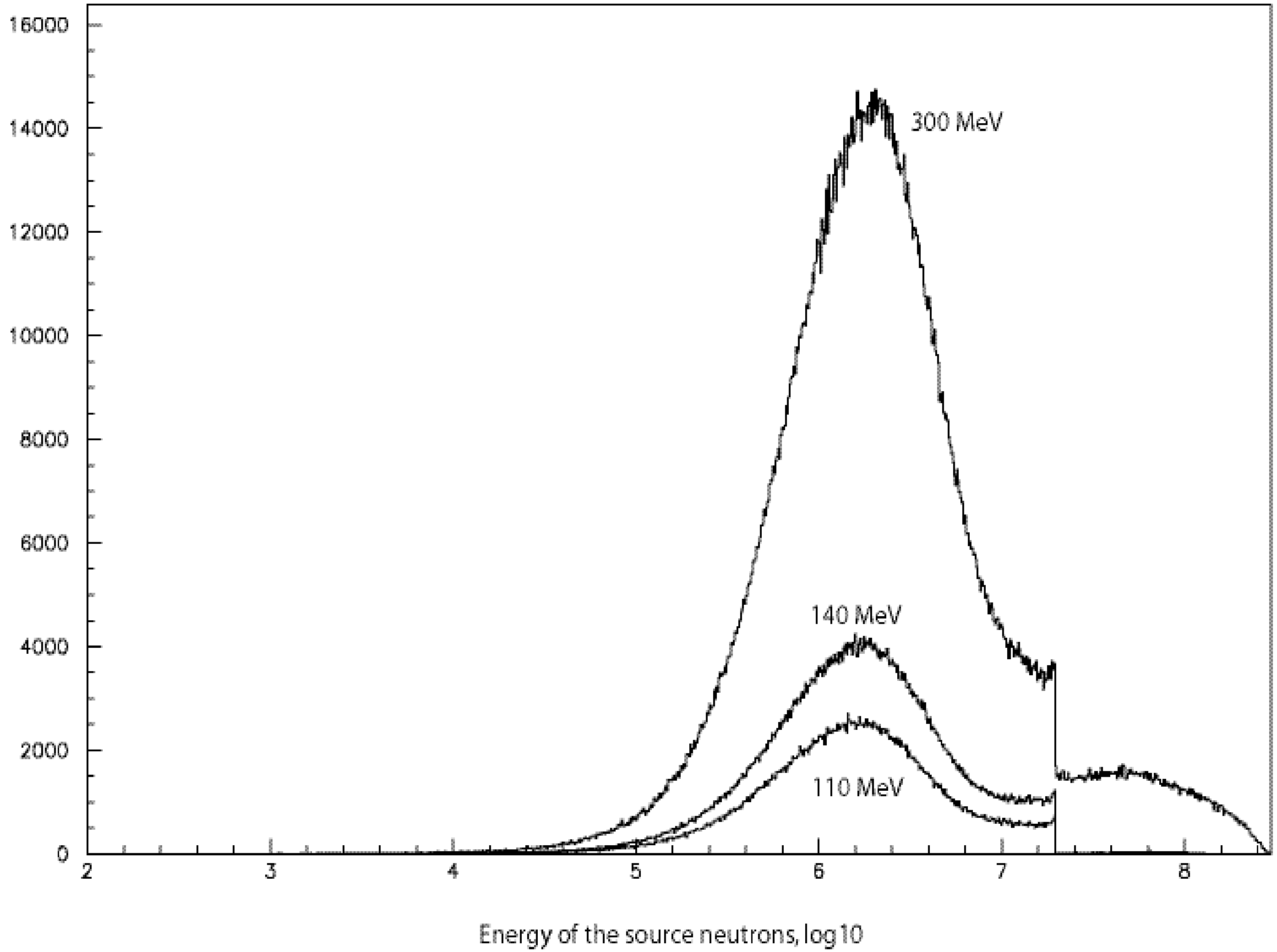
==> Lorentz Boost



Energy Distribution of Spallation Neutrons

Energy distribution is affected:

- En ≈ 1.5 MeV for 110 MeV p
- En ≈ 1.6 MeV for 140 MeV p
- En ≈ 2.3 MeV for 300 MeV p
- Large component of high-energy neutrons (En > 50 MeV) is escaping from the target

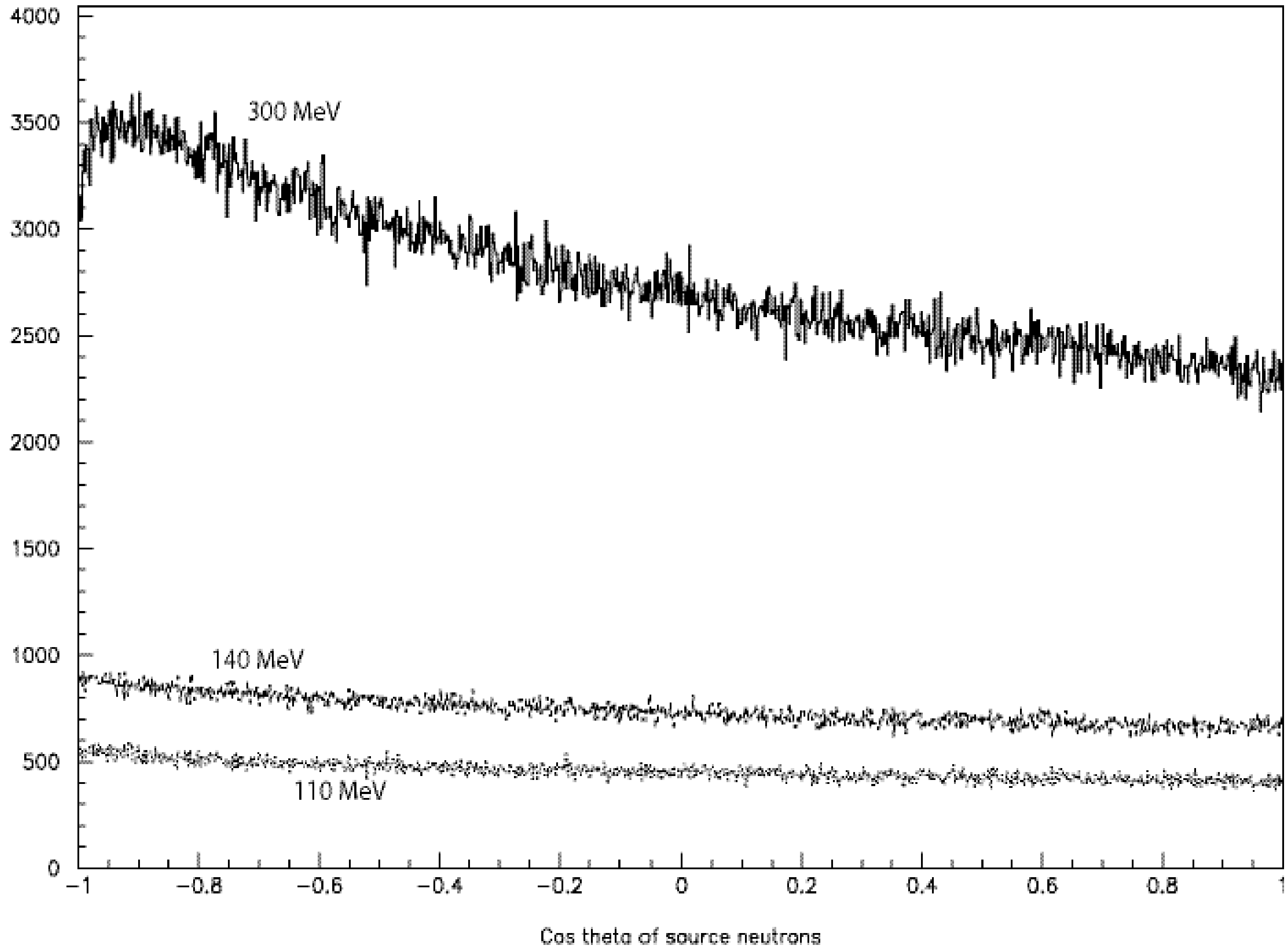


Angular Distribution of Spallation Neutrons

Angular distribution is highly affected at 300 MeV:

Large component of neutrons which are forward peaked (travelling at large angles > 130º)

==> probably high-energy neutrons escaping the target



Yield of Spallation Neutrons

The neutron yield n/p is very sensitive to the proton incident energy 2.90 vs 0.74 vs 0.45 n/p for 300, 140 and 110 MeV respectively

x6.5 in the spallation yield while proton energy increased by x2.7

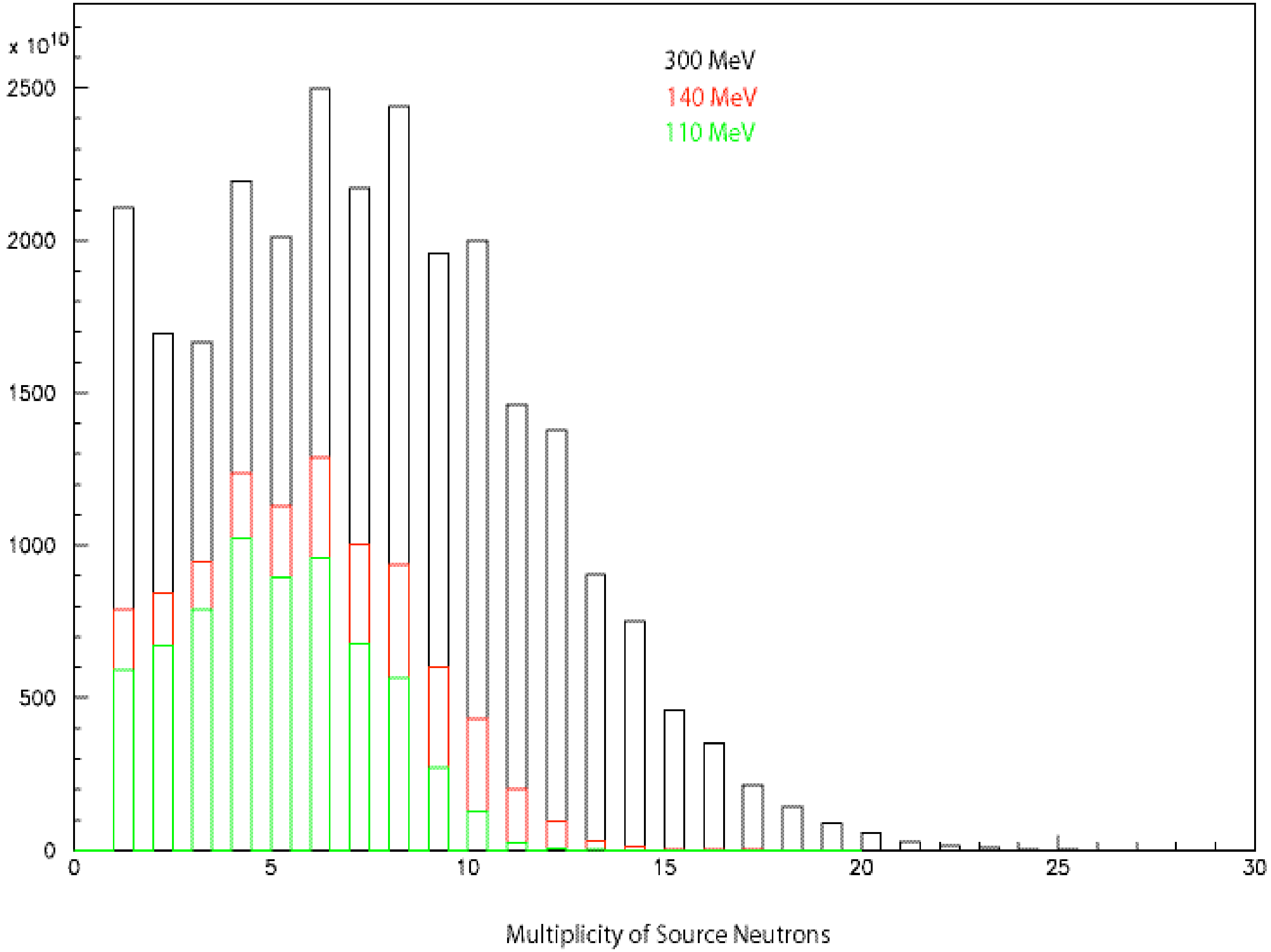
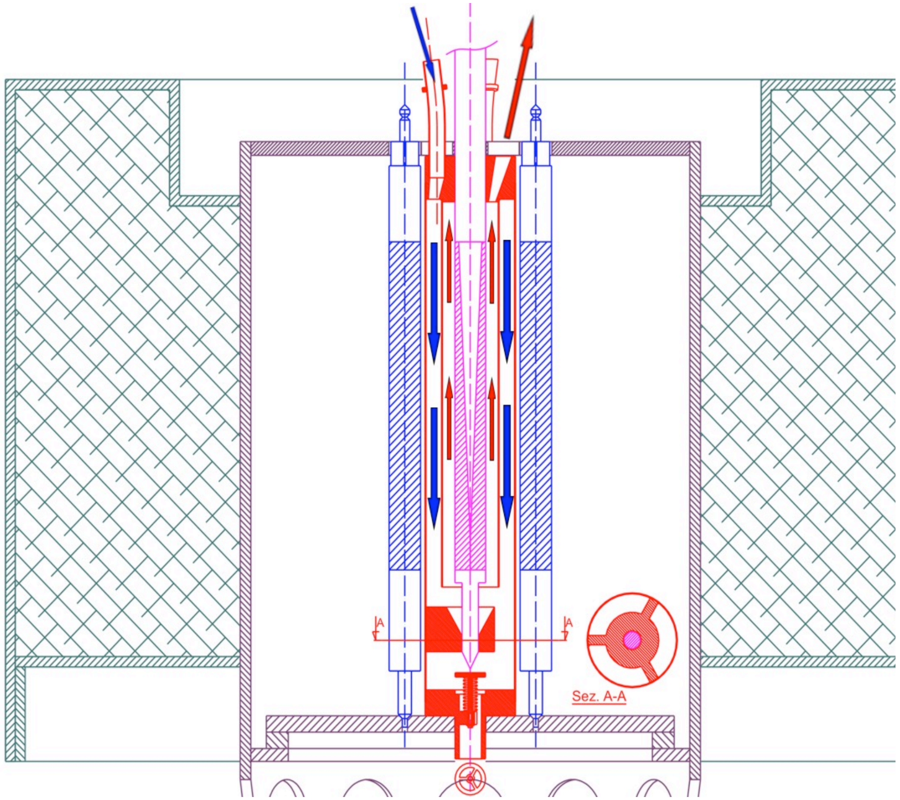
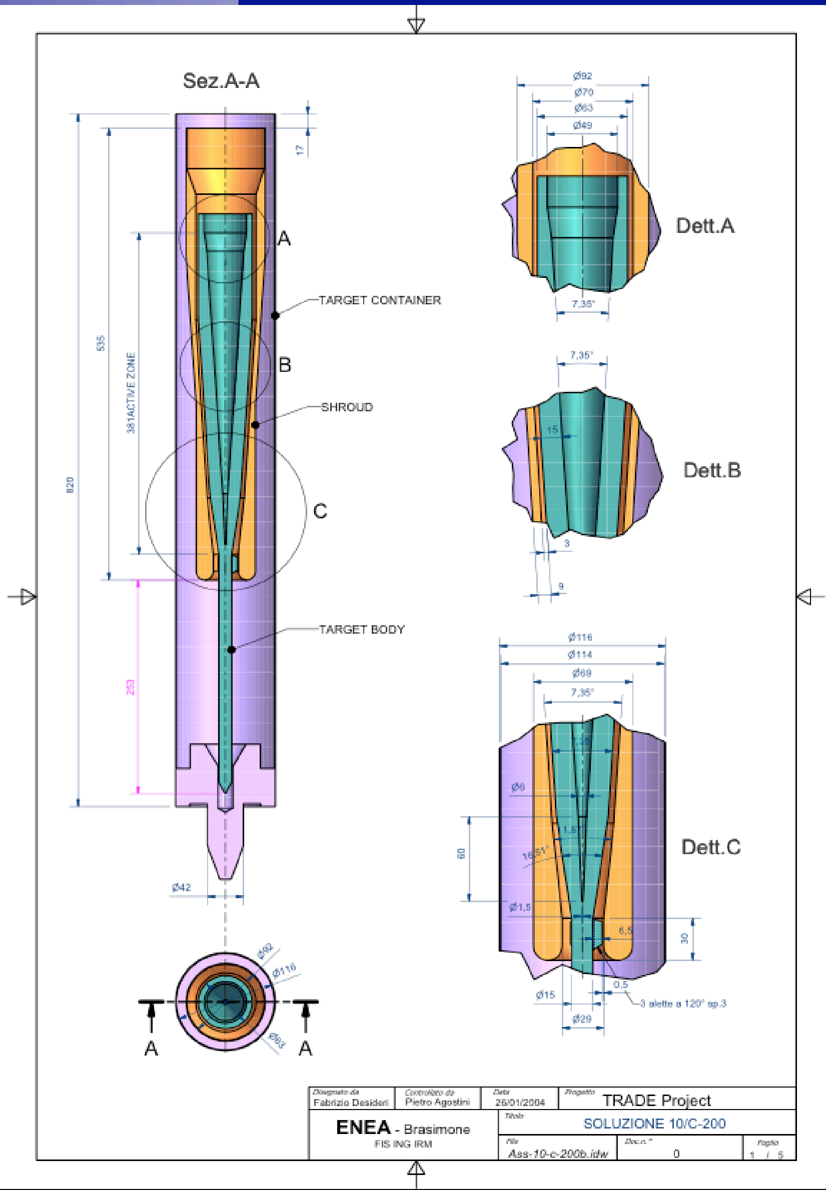


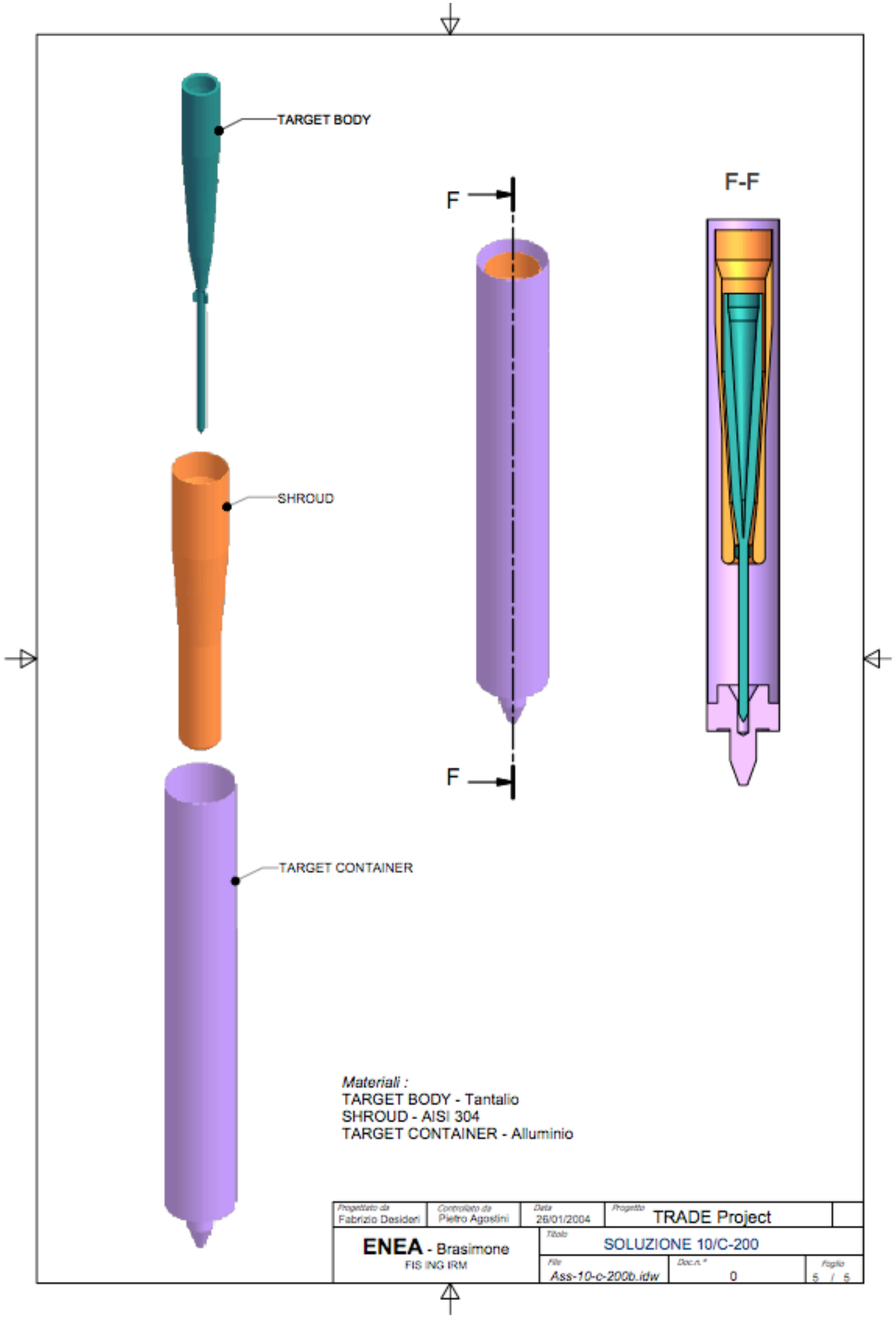
Table 1 - *Main parameters of the TRIGA sub-critical configurations*

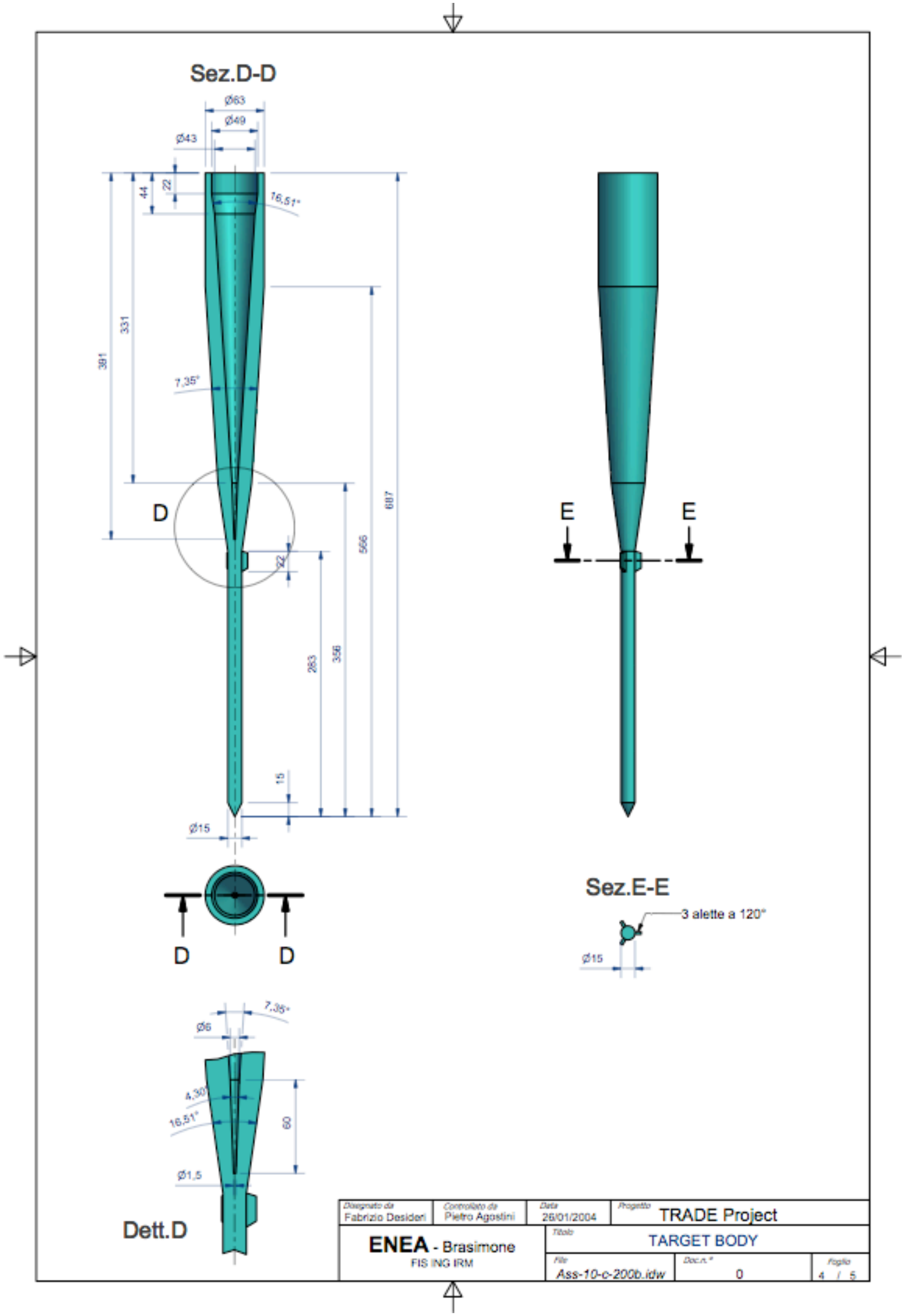
Global Parameters	Symbol	Reference Case		
Initial fuel mixture	LEU	UZrH		
Initial fuel mass	m_{fuel} (kg)	235.2		
Initial U concentration	m_U/m_{fuel} (wt.%)	8.5		
Initial Fissile enrichment	U^{235}/U (at.%)	20		
Thermal Power Output	P_{th} (kWatt)	200		
Spallation target		**Tantalum**		
Proton Beam Energy	E_p (MeV)	110	140	300
Spallation Neutron Yield	$N_{(n/p)}$ (n/p)	0.451	0.74	3.11
Net neutron multiplication	M	44.1	43.4	28.7
Multiplication Coefficient	k=(M-1)/M	0.977	0.977	0.965
Energetic Gain	G	15.1	18.8	23.8
Gain coefficient	G_0	0.34	0.44	0.83
Accelerator Current	I_p (mA)	0.13	0.08	0.03
Beam Power	P_{beam} (kWatt)	14.2	11.2	8.8
Escapes	%	0.01	0.02	0.06
Core Power Distributions				
Av. fuel power density	P_{th}/V_{fuel} (W/cm^3)	4.9		
Spec. fuel power density	P_{th}/m_U (W/g HM)	10.0		
Max. heat flux	P_h (W/cm^2)	9.3	6.0	5.9
Max. linear power	P_l (W/cm)	75.5	68.0	67.5
Radial peaking factor	P_{max}/P_{ave}	1.51	1.30	1.40
Linear peaking factor	P_{max}/P_{ave}	1.28	-	-

The Spallation Target System






TARGET BODY
SHROUD
TARGET CONTAINER
F
F
F-F
Materiali :
TARGET BODY - Tantalio
SHROUD - AISI 304
TARGET CONTAINER - Alluminio
Progettato da Fabrizio Desideri
Controllato da Pietro Agostini
Data 26/01/2004
Progetto TRADE Project
ENEA - Brasimone
FIS ING IRM
Titolo SOLUZIONE 10/C-200
File Ass-10-c-200b.idw
Doc.n.° 0
Foglio 5 / 5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Disegnato da Fabrizio Desideri
Controllato da Pietro Agostini
Data 26/01/2004
Progetto TRADE Project
ENEA - Brasimone
FIS ING IRM
Titolo TARGET BODY
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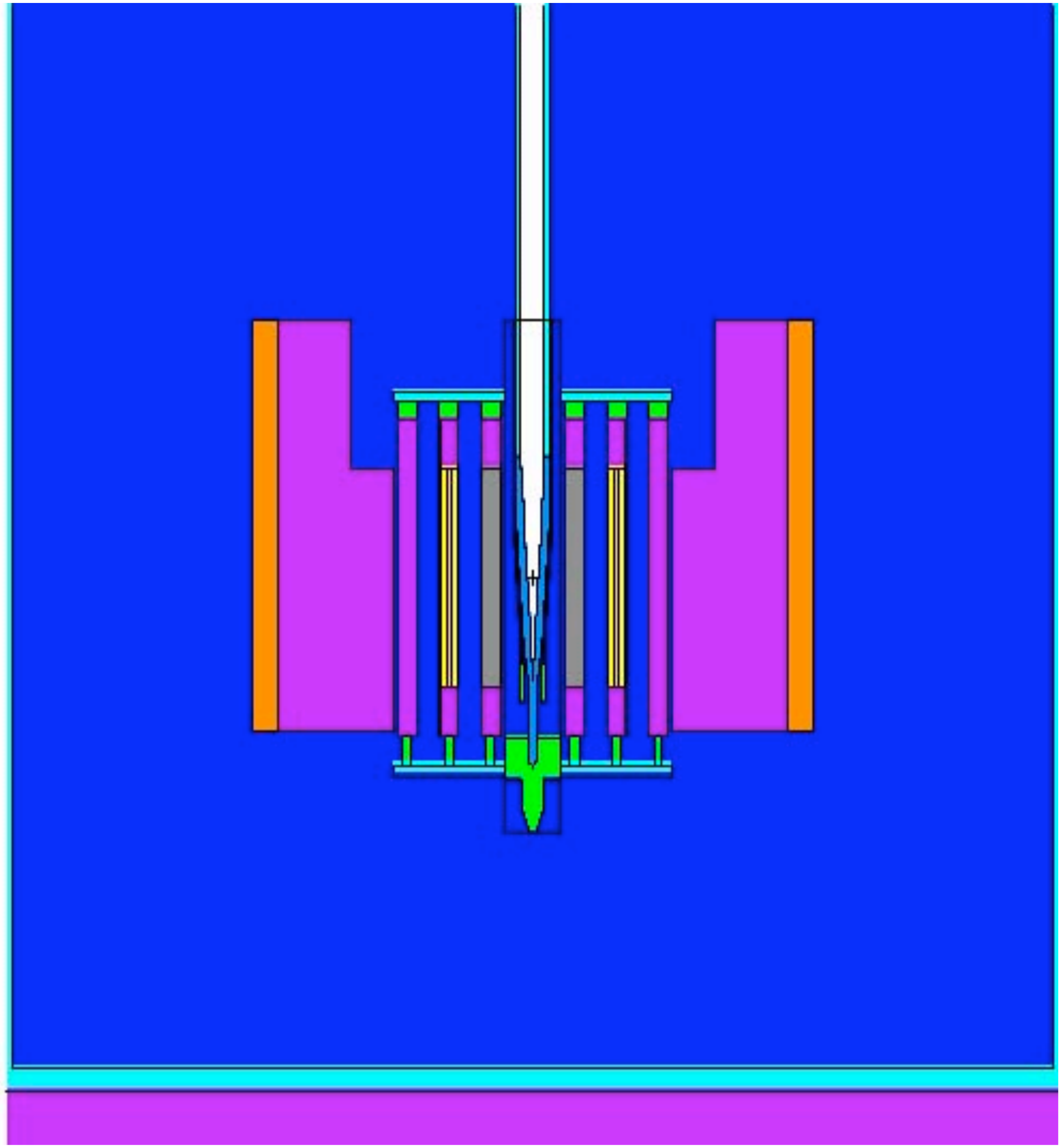
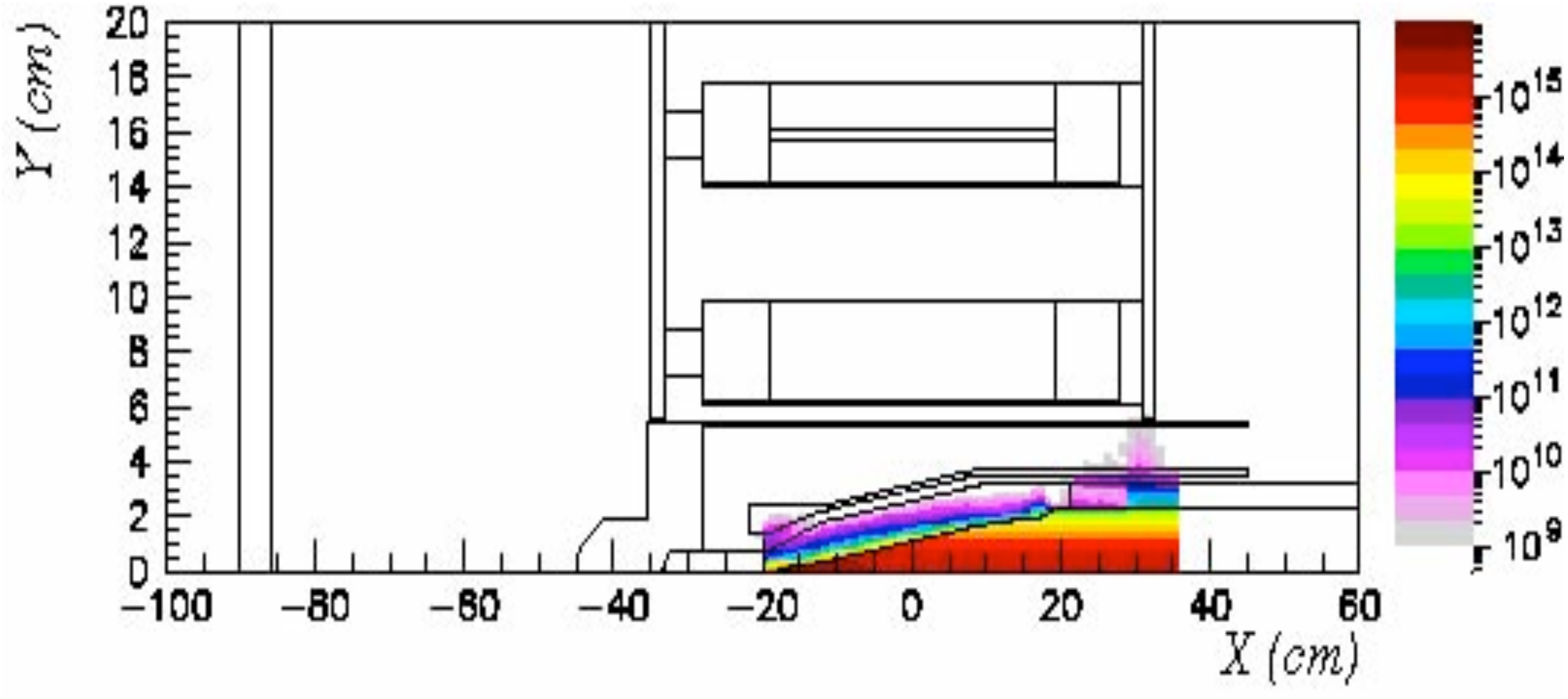
Foglio 4 / 5

TARGET LAYOUT



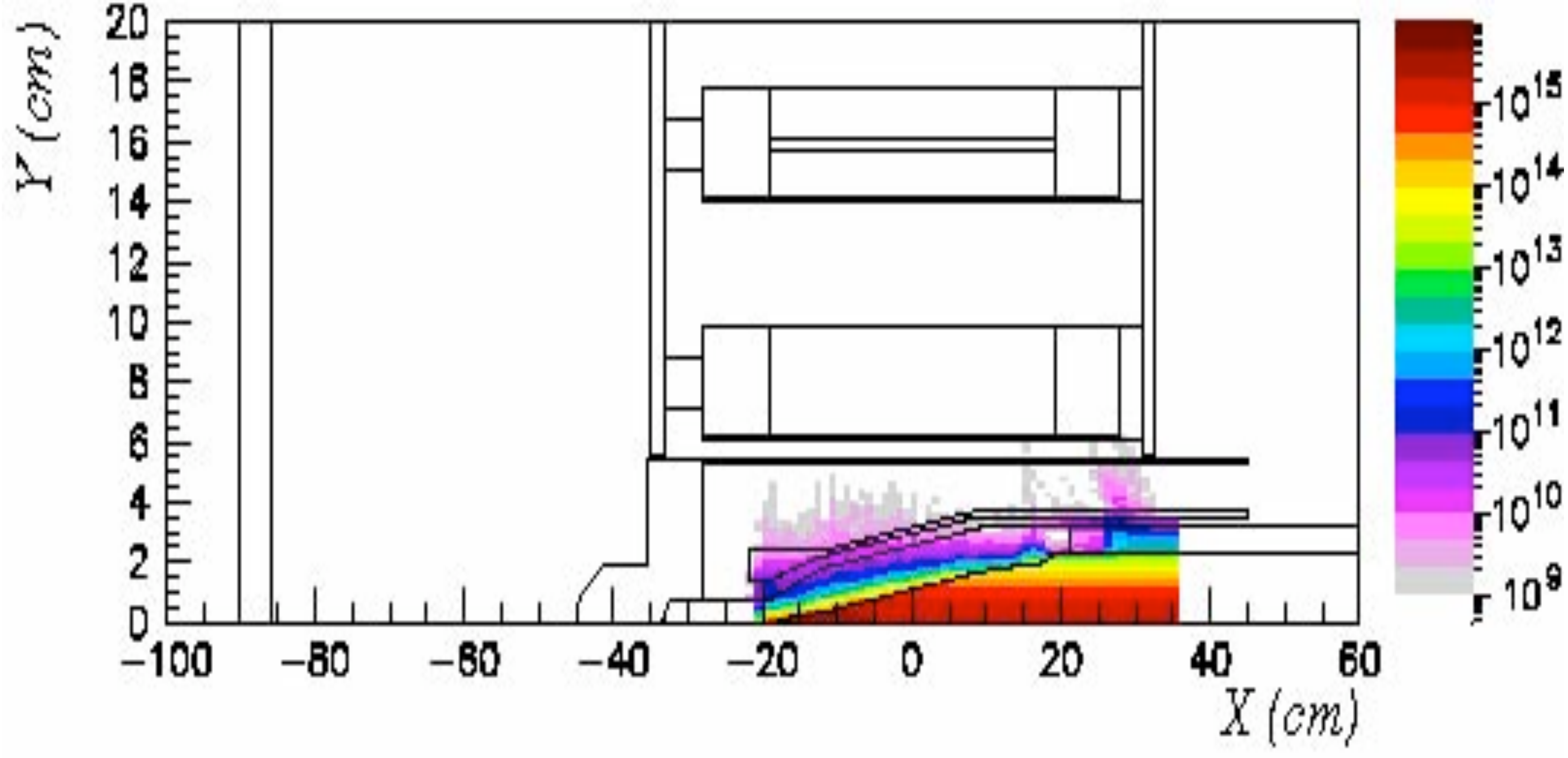
Thick Ta Target (protons/cm2/s) per mA

- 140 MeV -



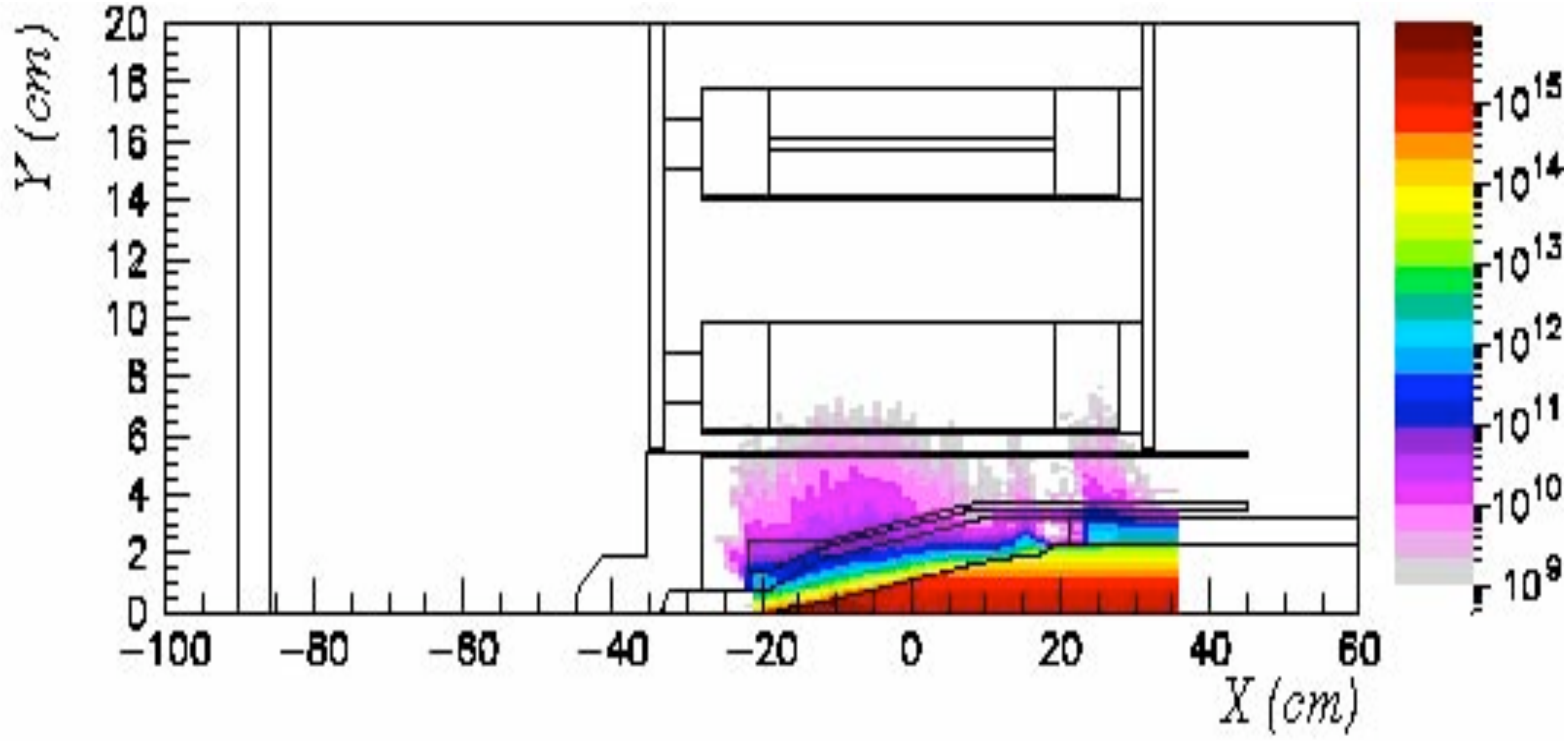
Thick Ta Target (protons/cm2/s) per mA

- 170 MeV -



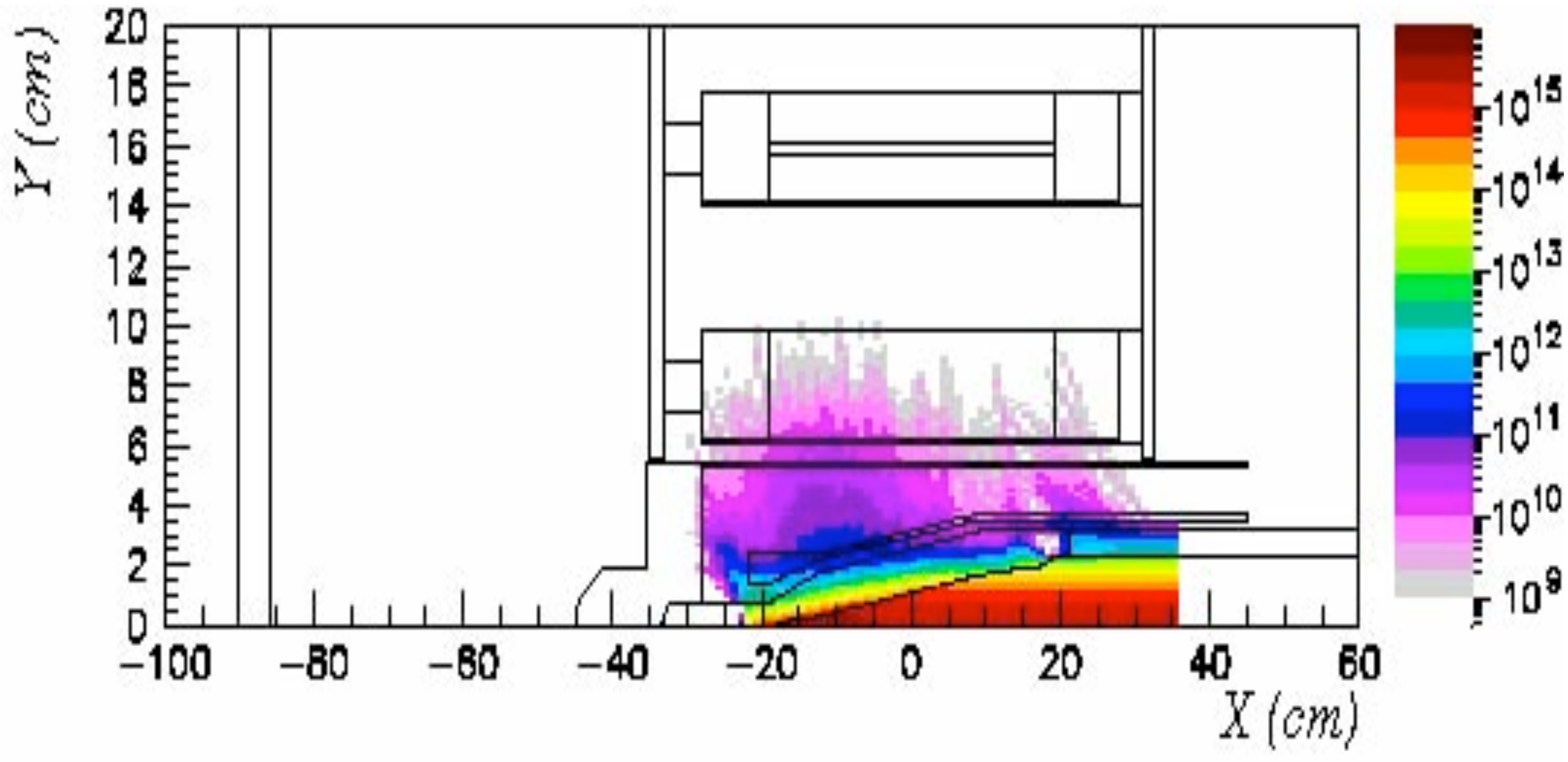
Thick Ta Target (protons/cm2/s) per mA

- 200 MeV -



Thick Ta Target (protons/cm2/s) per
mA

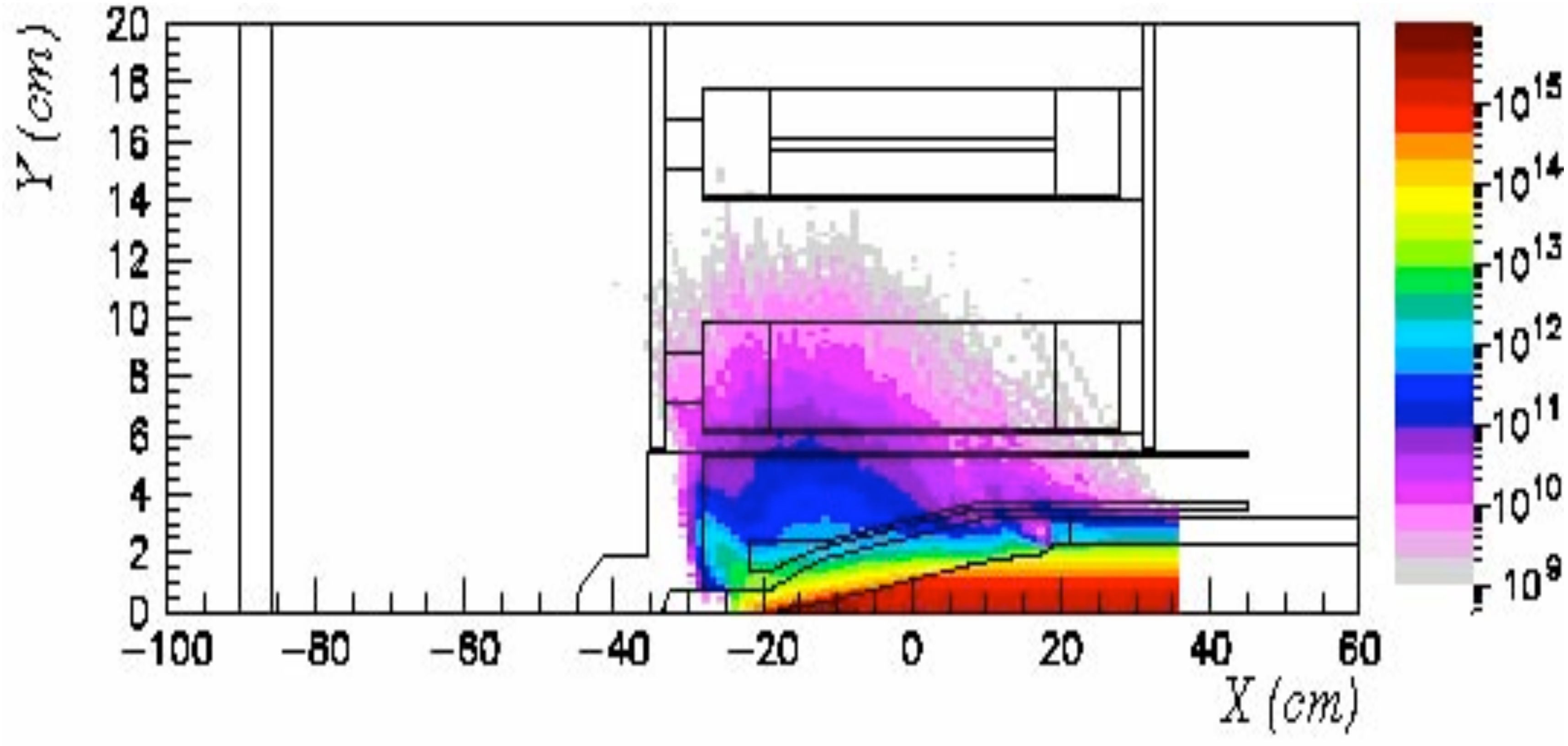
- 240 MeV -



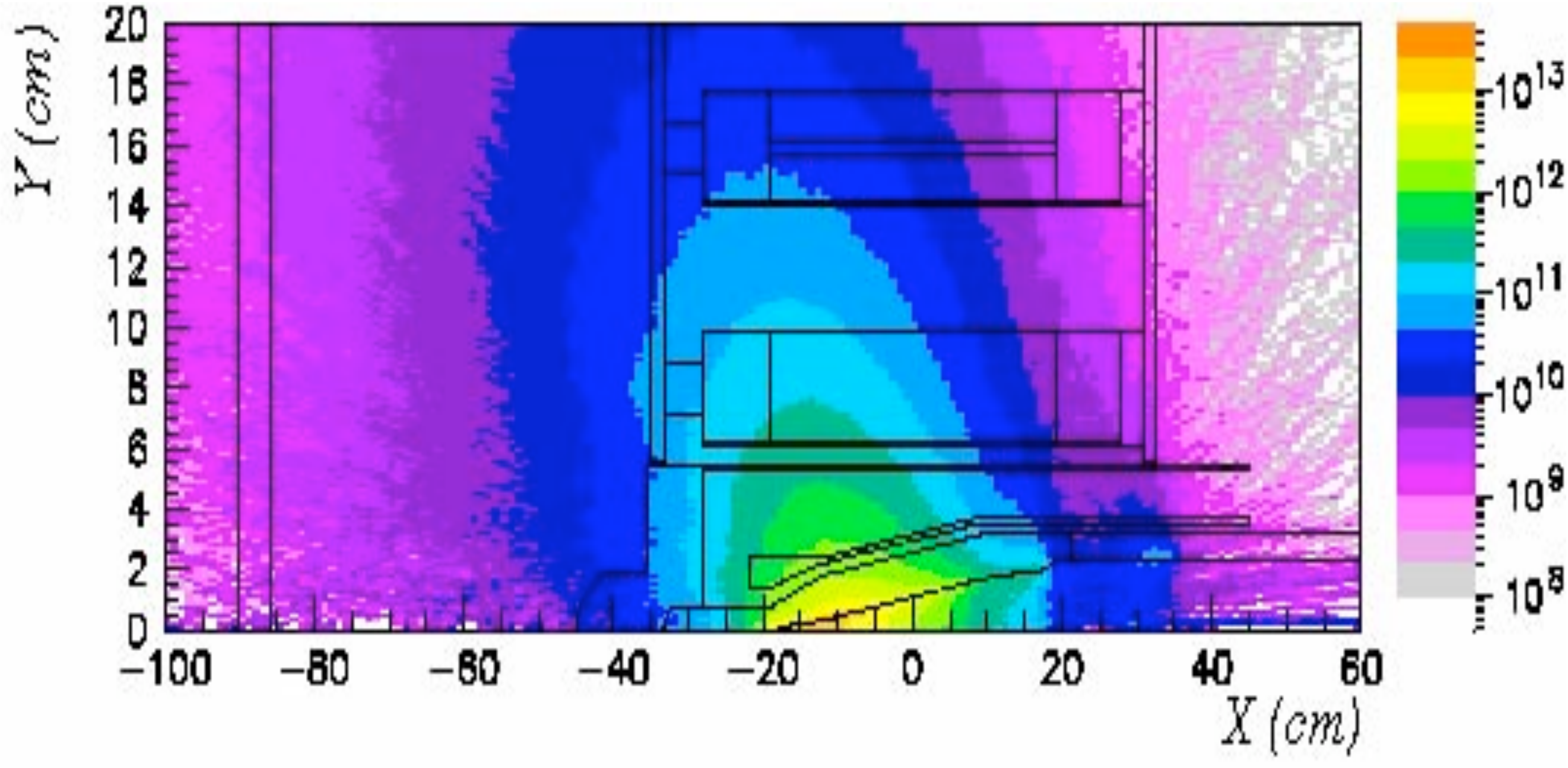
Primary Flux

Thick Ta Target (protons/cm2/s) per mA

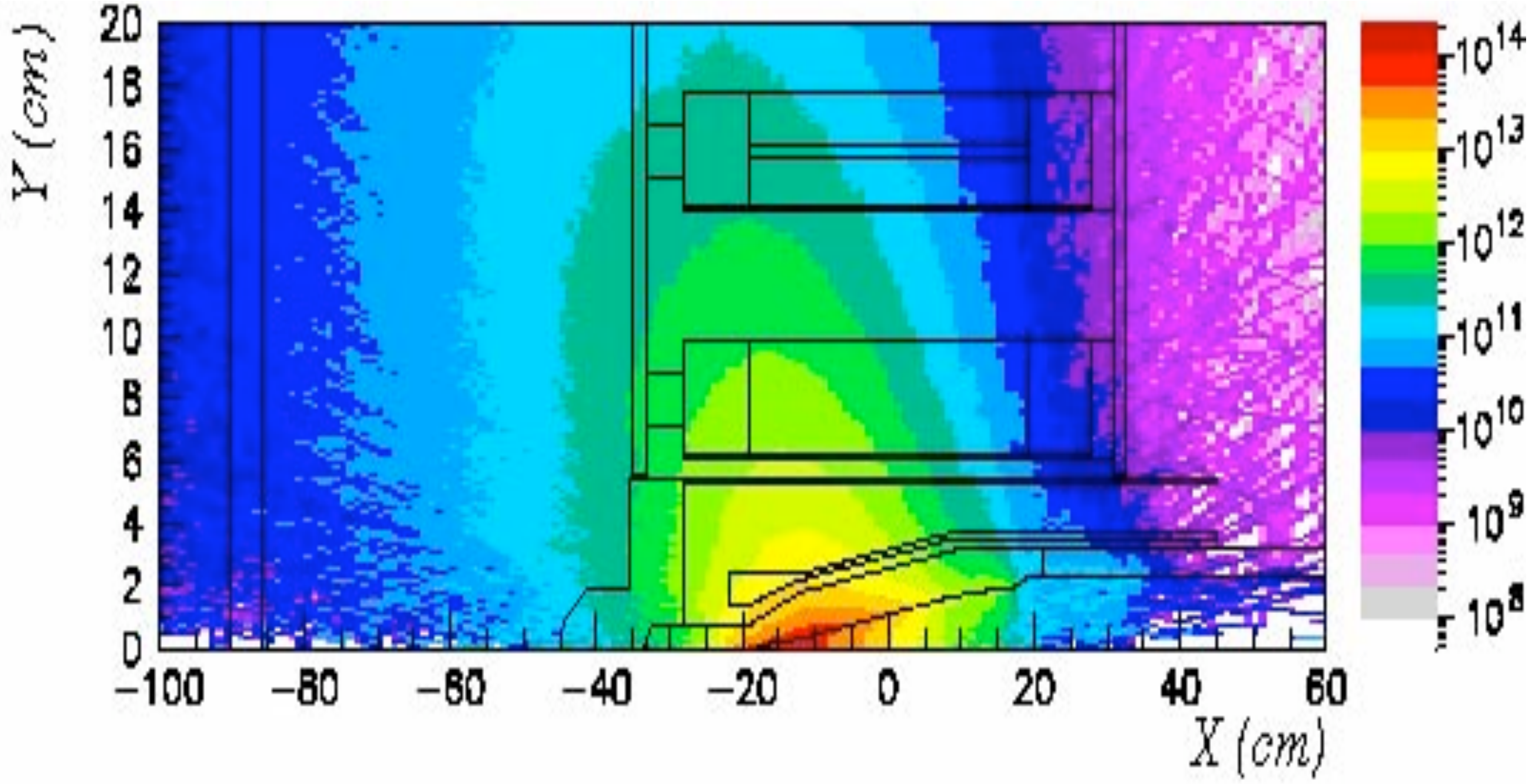
- 300 MeV -



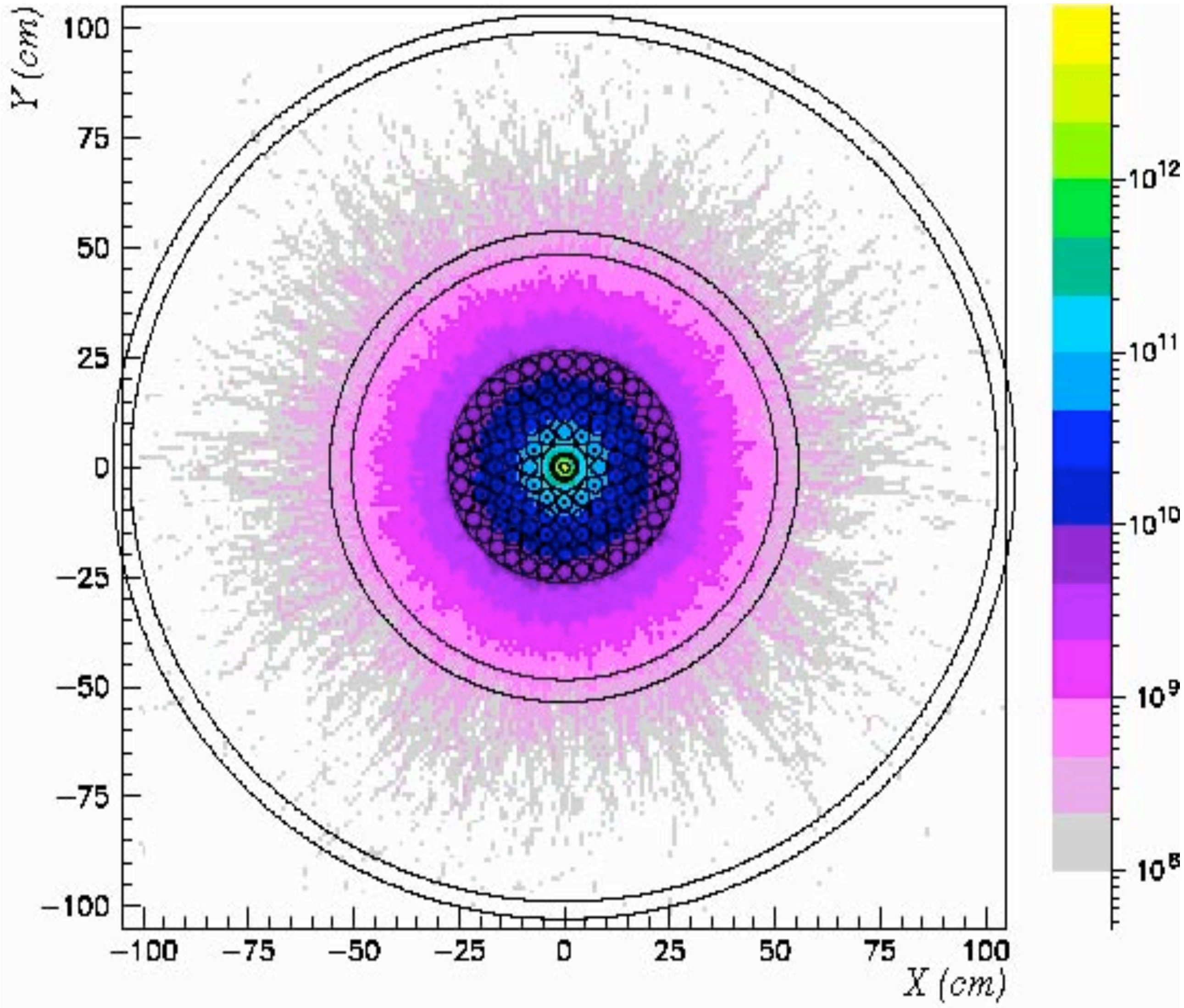
Neutron Flux Distribution at 140 MeV



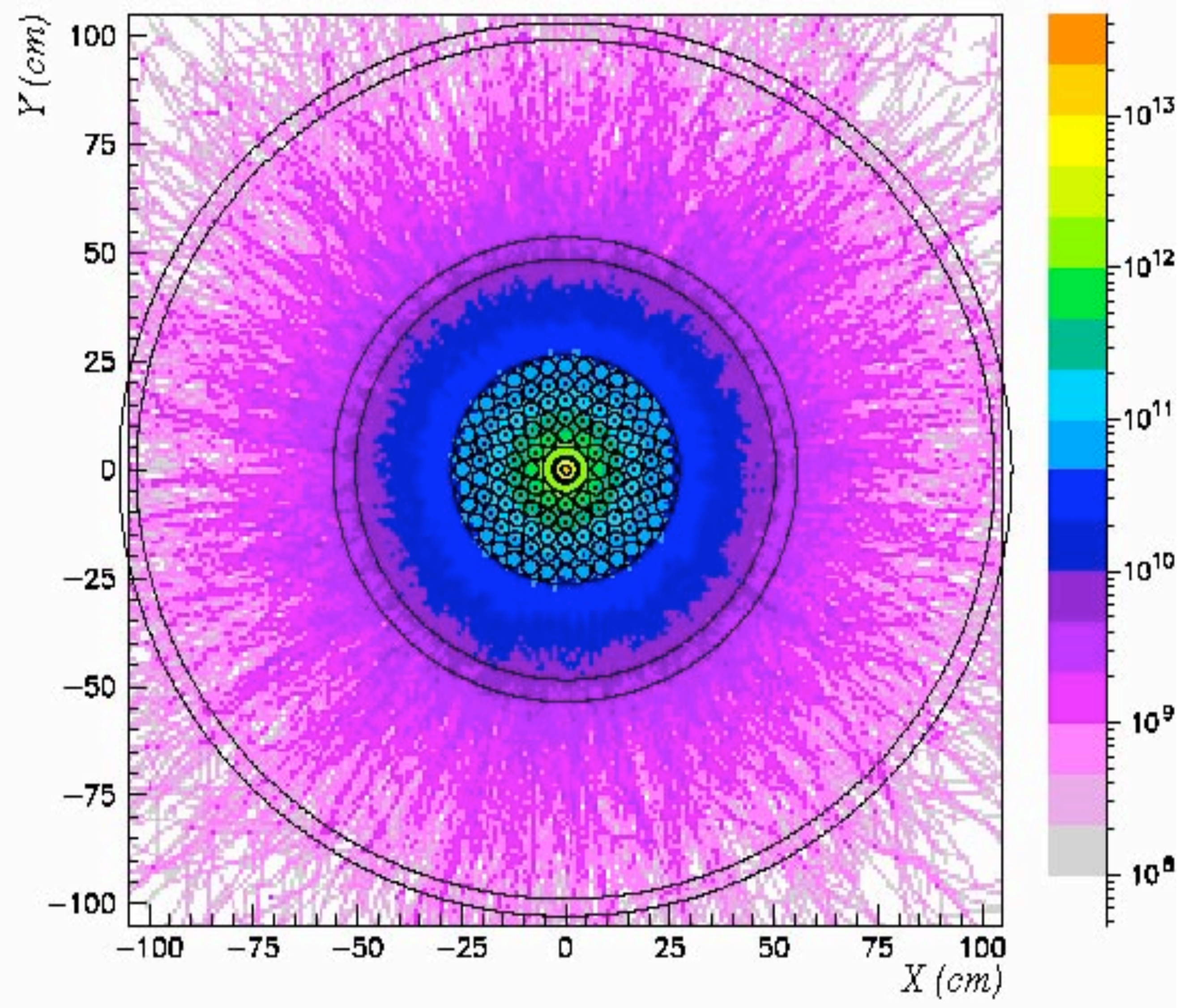
Neutron Flux Distribution at 300 MeV



H-E Neutron Flux @ 140 MeV

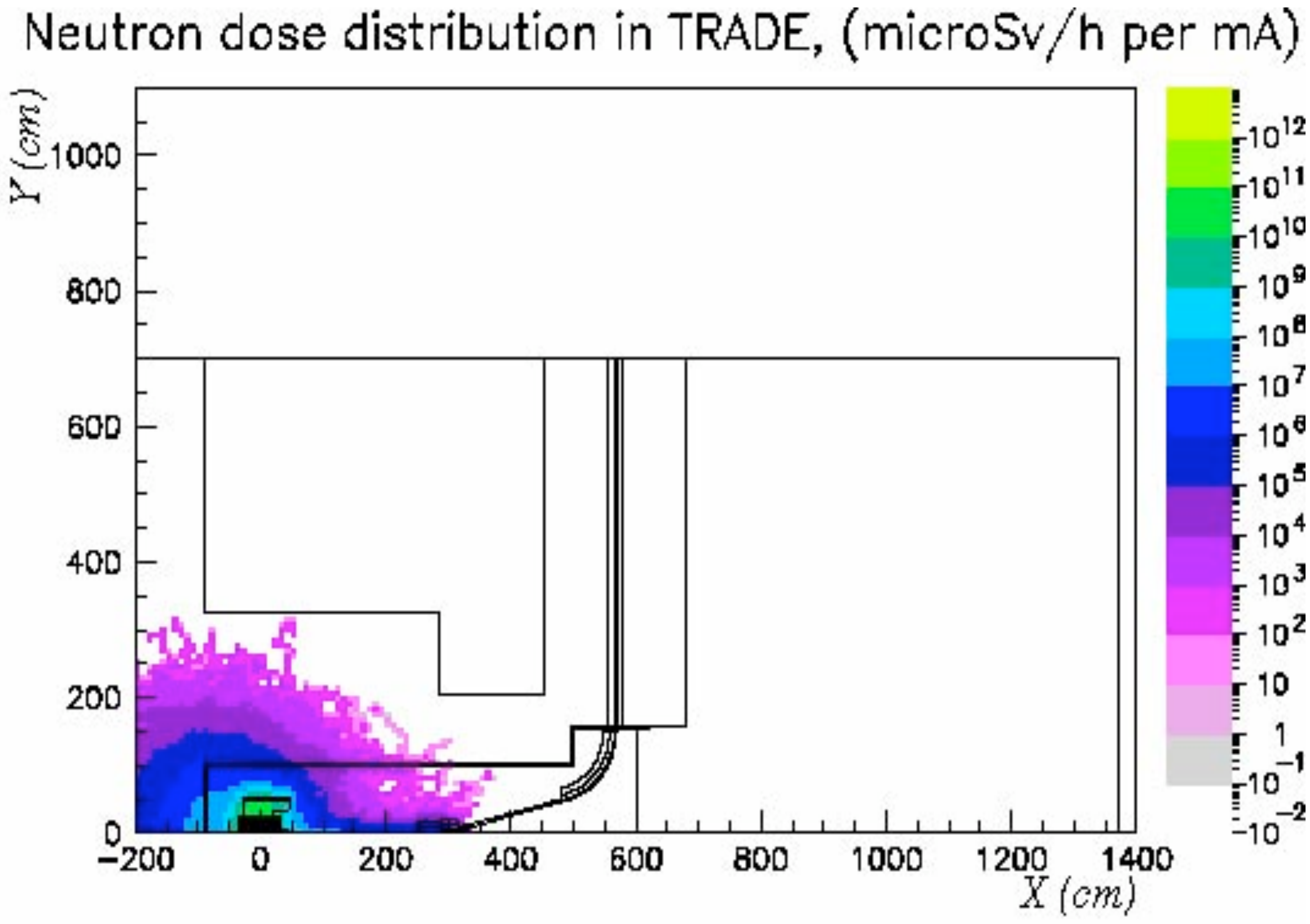


H-E Neutron Flux @ 300 MeV

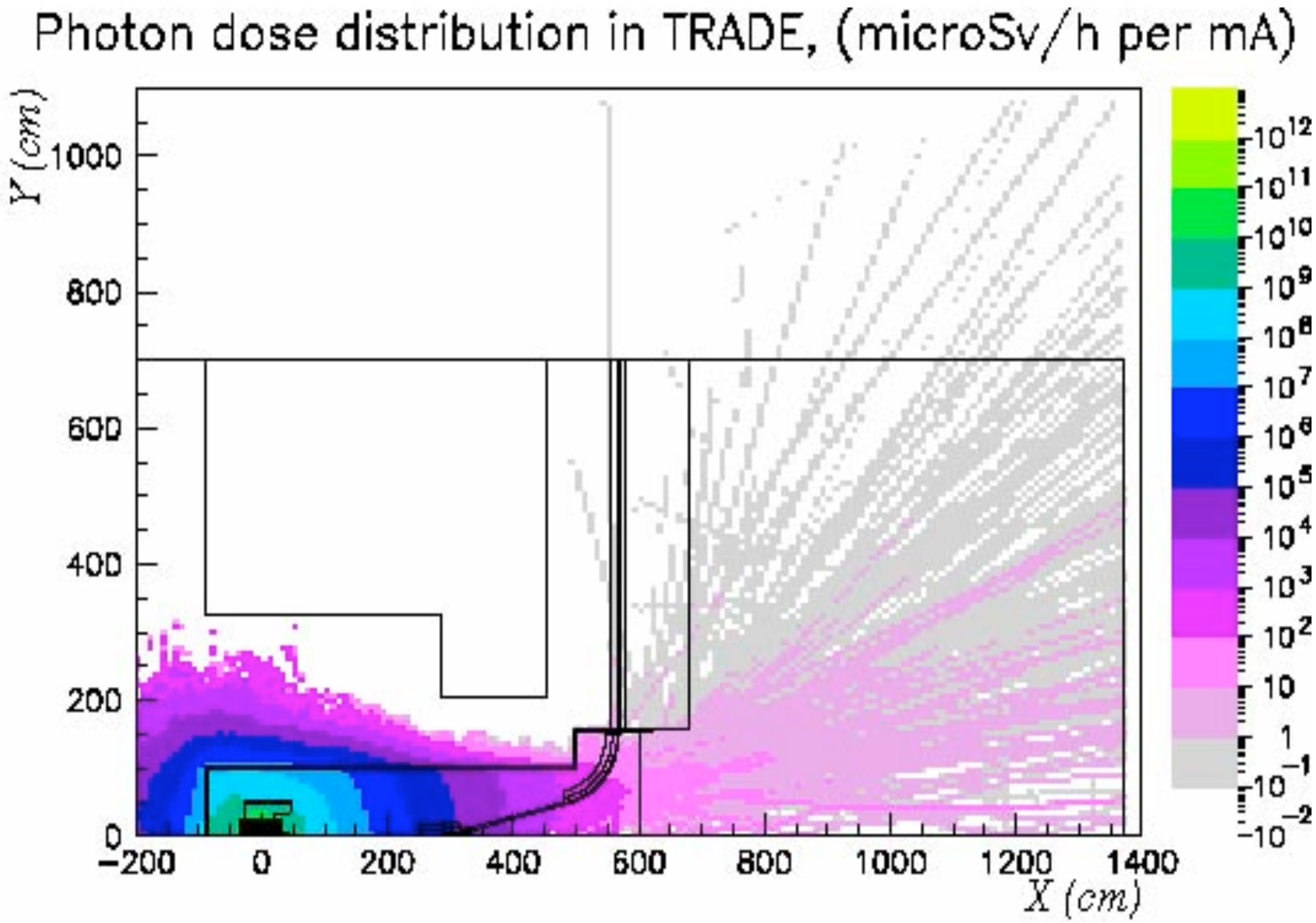


Gas production and the displacement rates per kW of beam

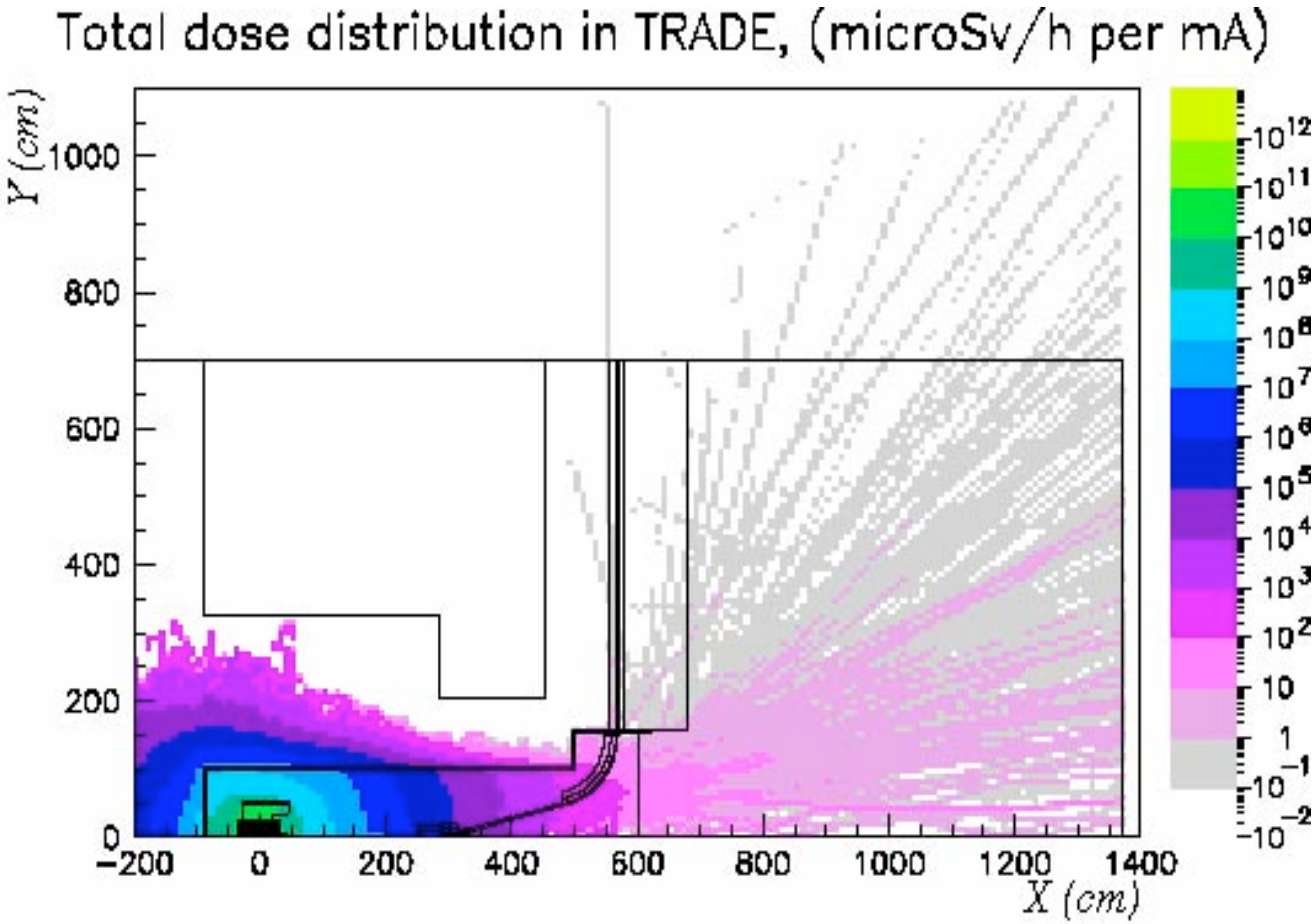
Target (Ta)	**Average** Prot. Ener (MeV)	**Average** Neut. Ener (MeV)	**H_3** Production (appm/dpa)	**He** Production (appm/dpa)	HE proton (dpa/yr)	HE neutron (dpa/yr)
					Max	Ave
140 MeV	90	51	0.99	54.8	0.6	0.07
200 MeV	115	65	2.92	130.	0.5	0.05
300 MeV	155	88	6.93	275.	0.4	0.04


Neutron dose distribution in TRADE, (microSv/h per mA)
Y (cm)
1000
800
600
400
200
0
−200
0
200
400
600
800
1000
1200
1400
X (cm)
10^{12}
10^{11}
10^{10}
10^{9}
10^{8}
10^{7}
10^{6}
10^{5}
10^{4}
10^{3}
10^{2}
10
1
10^{-1}
10^{-2}

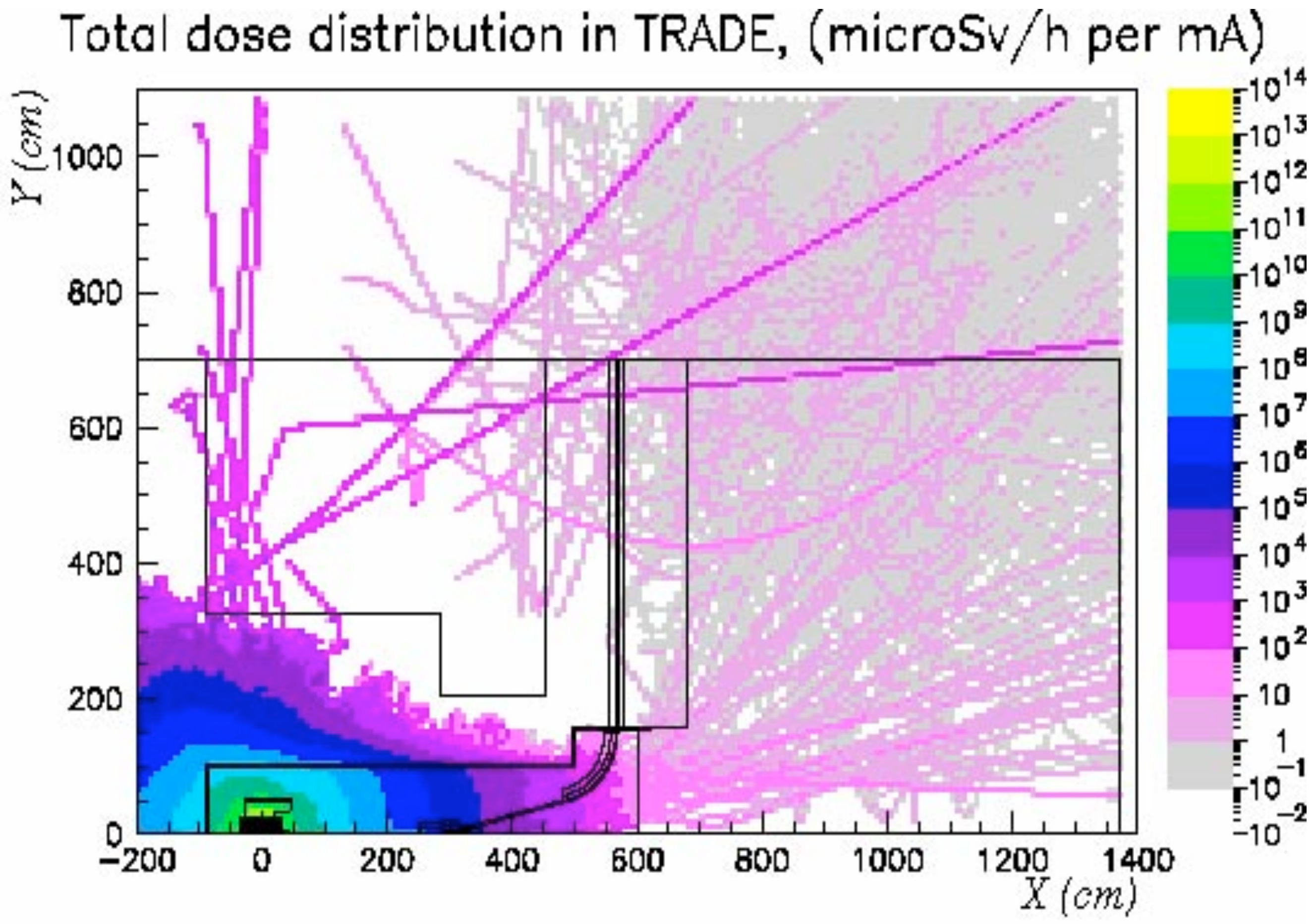
Dose in TRIGA @ 140 MeV



Dose in TRIGA @ 140 MeV



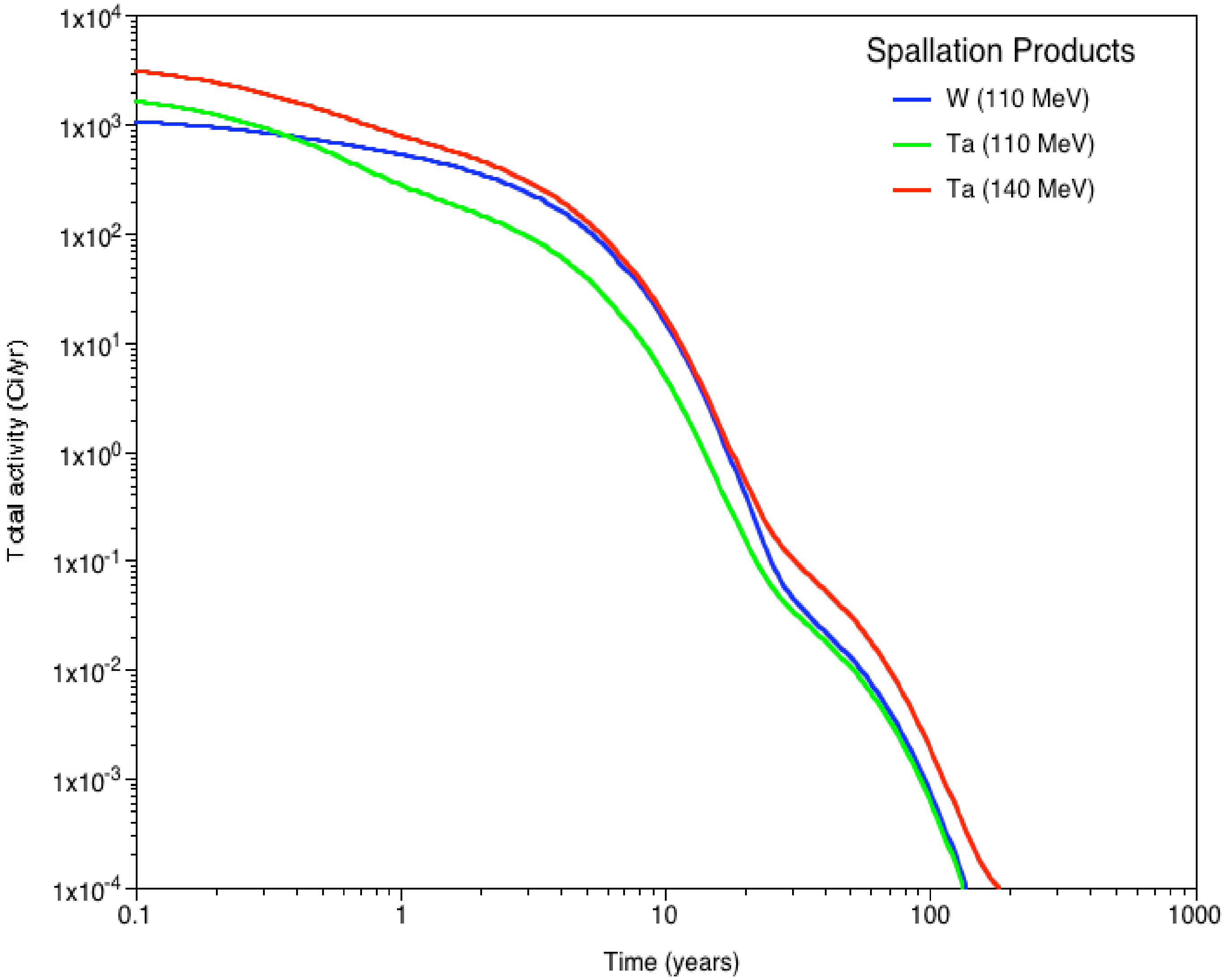
Dose in TRIGA @ 300 MeV



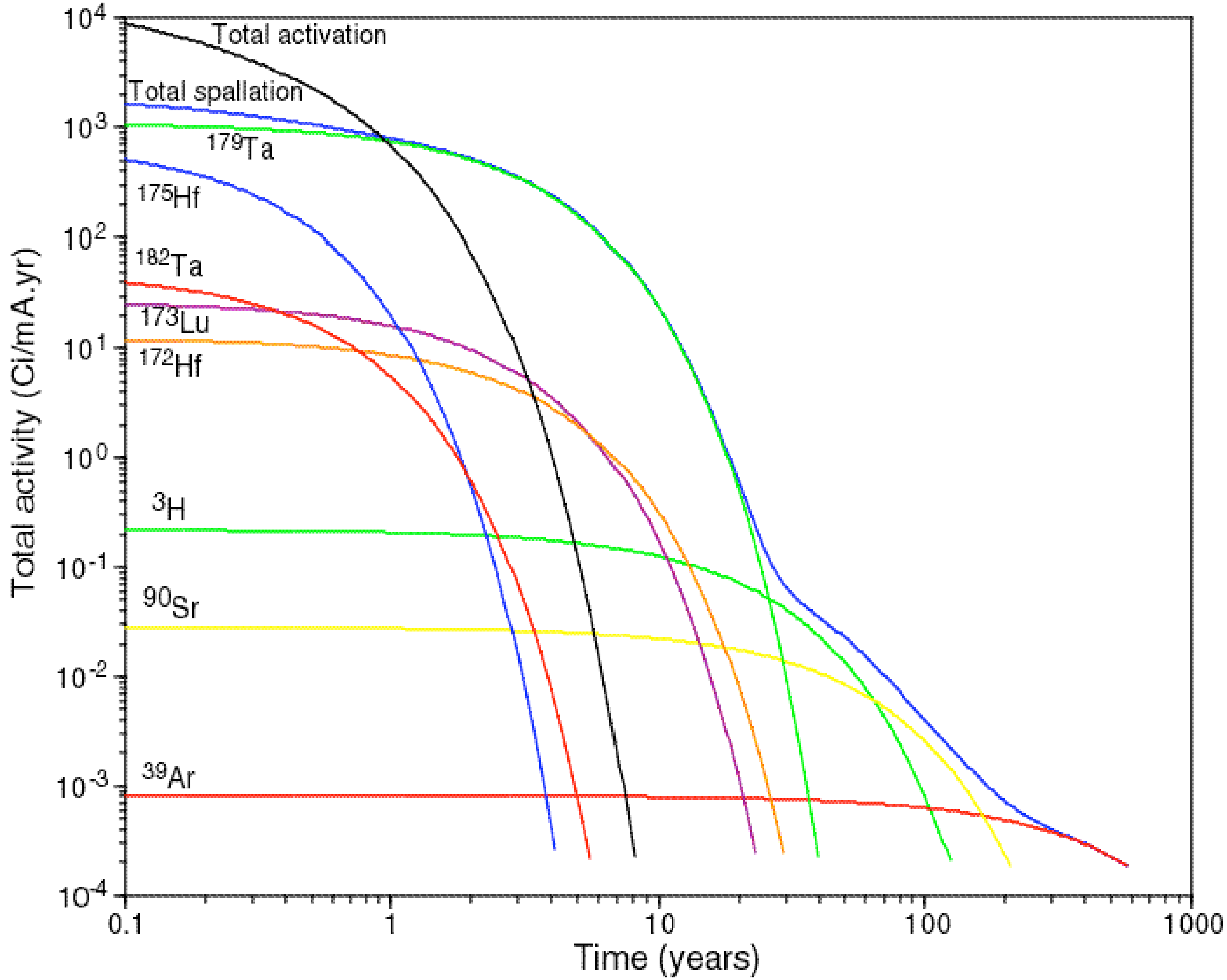
Activation calculations still in progress but first indication:

x10 increase in gas production per proton (H-3, He-3 and He-4)

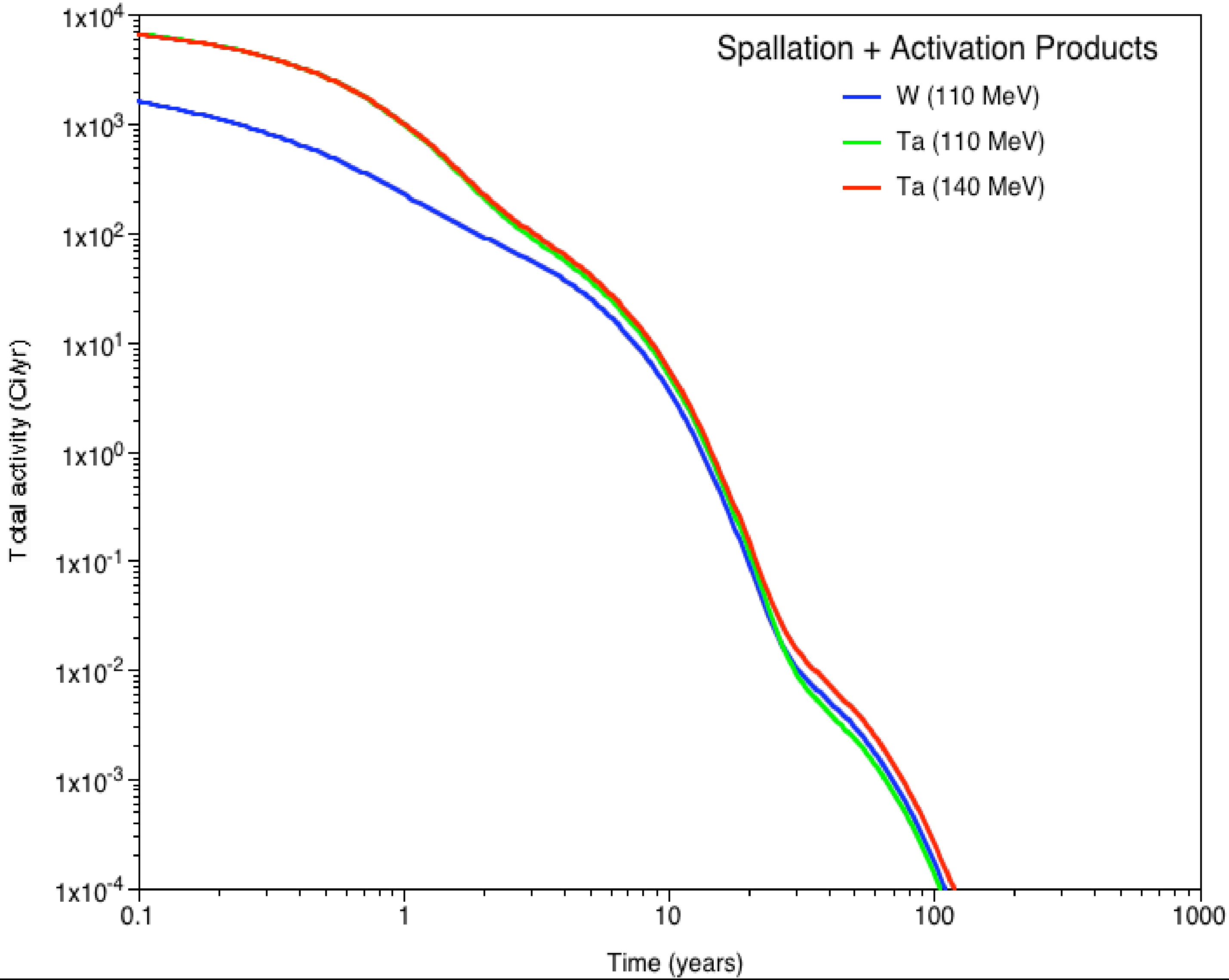
H-3 ≈ 0.004 at./p
He-3 ≈ 0.002 at./p
He-4 ≈ 0.2 at./p



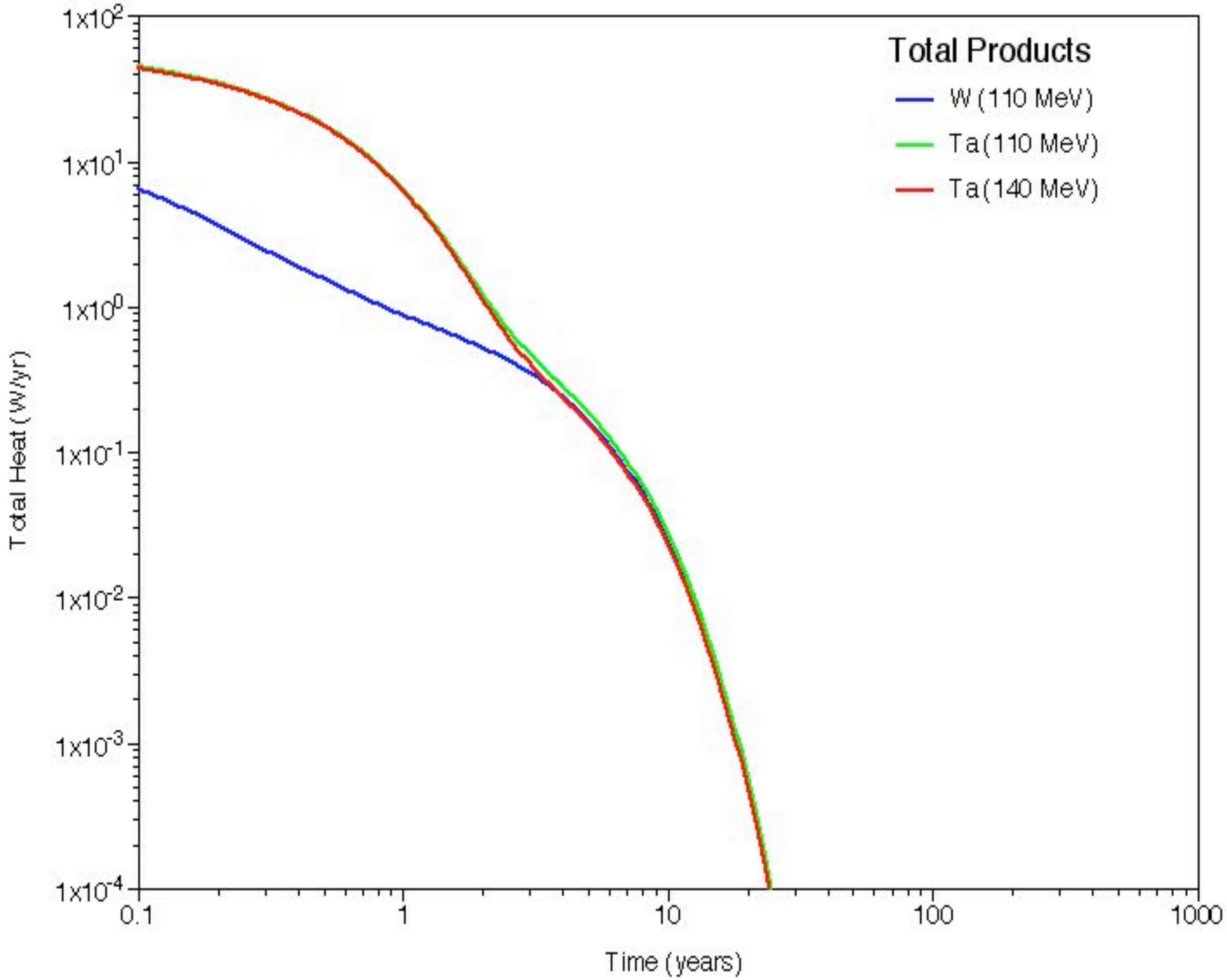
Radio-activity of the SpallationTarget: Spallation products (2)



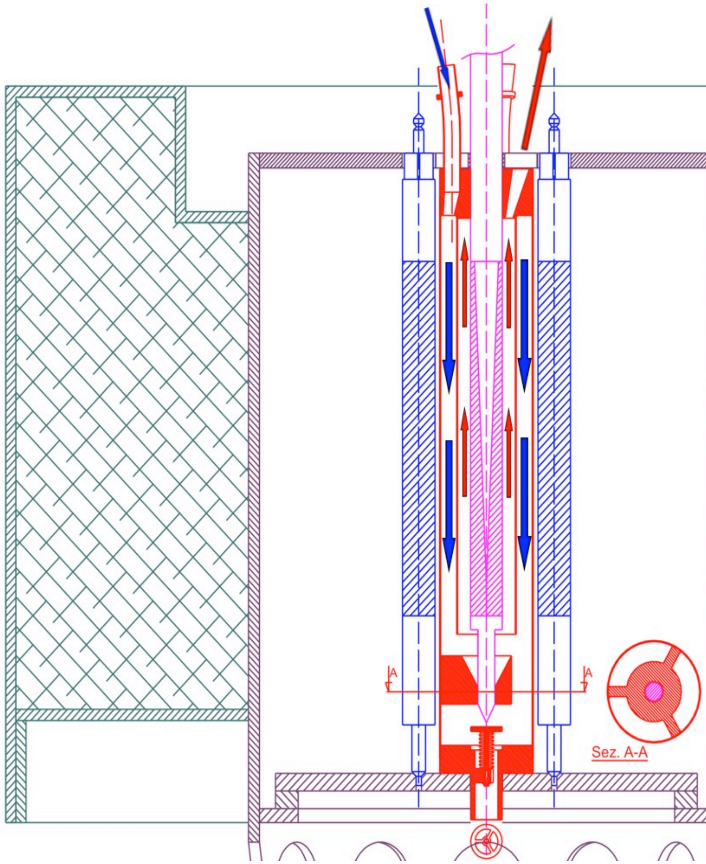
Radio-activity of the SpallationTarget: Total products (1)



Radio-activity of the SpallationTarget: Decay Power



Target cooling system in forced convection



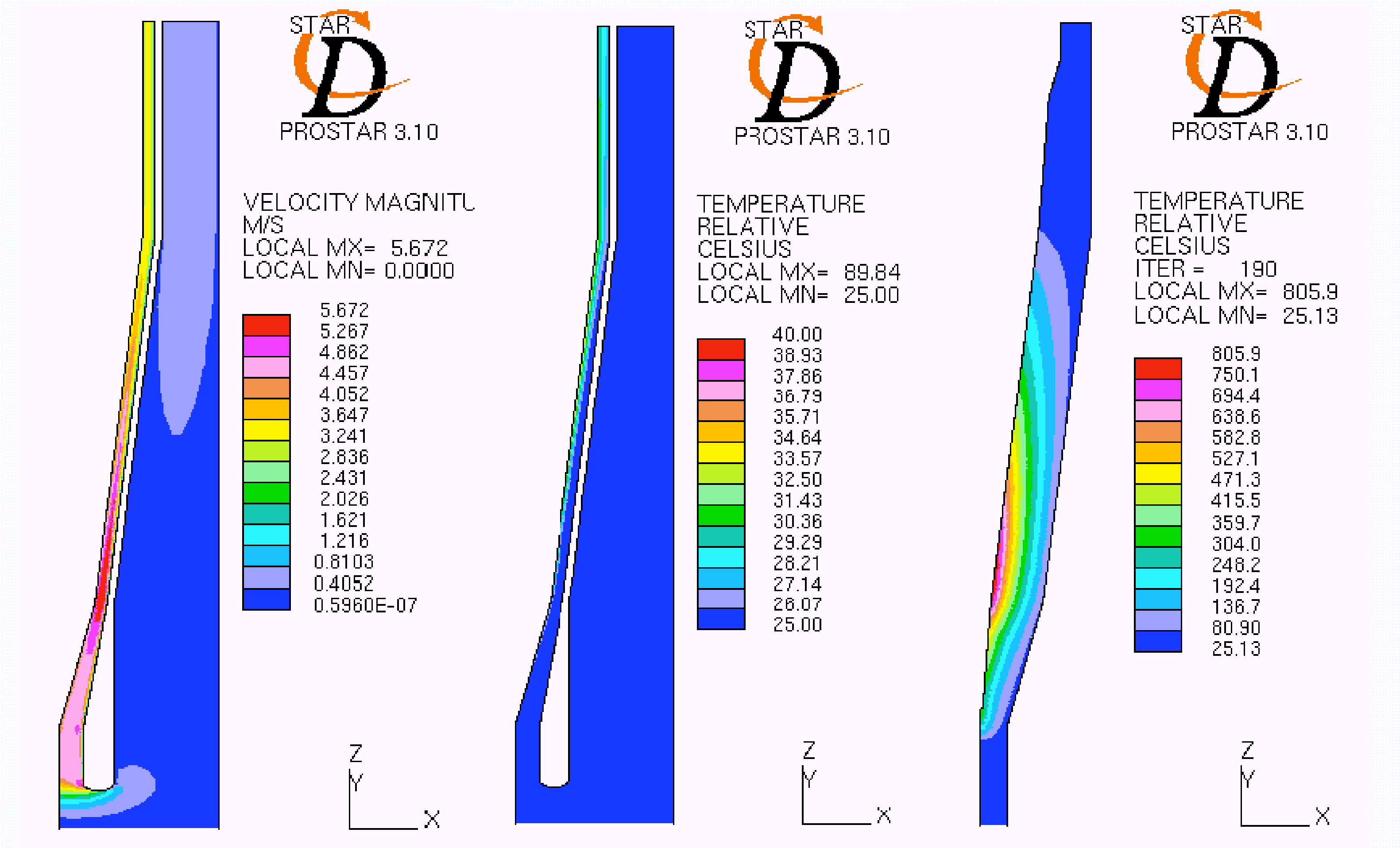
Coarse Dimensioning of the circuit:

- Thermal power = 40kW
- Design $\Delta T \sim 5 - 20°C$

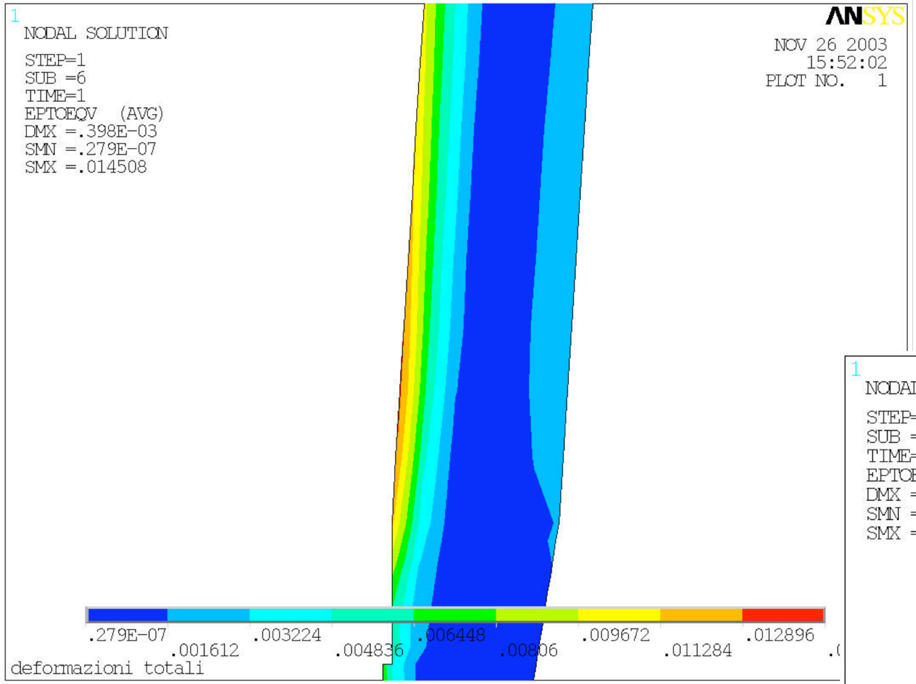
Pumps and circuit characteristics:

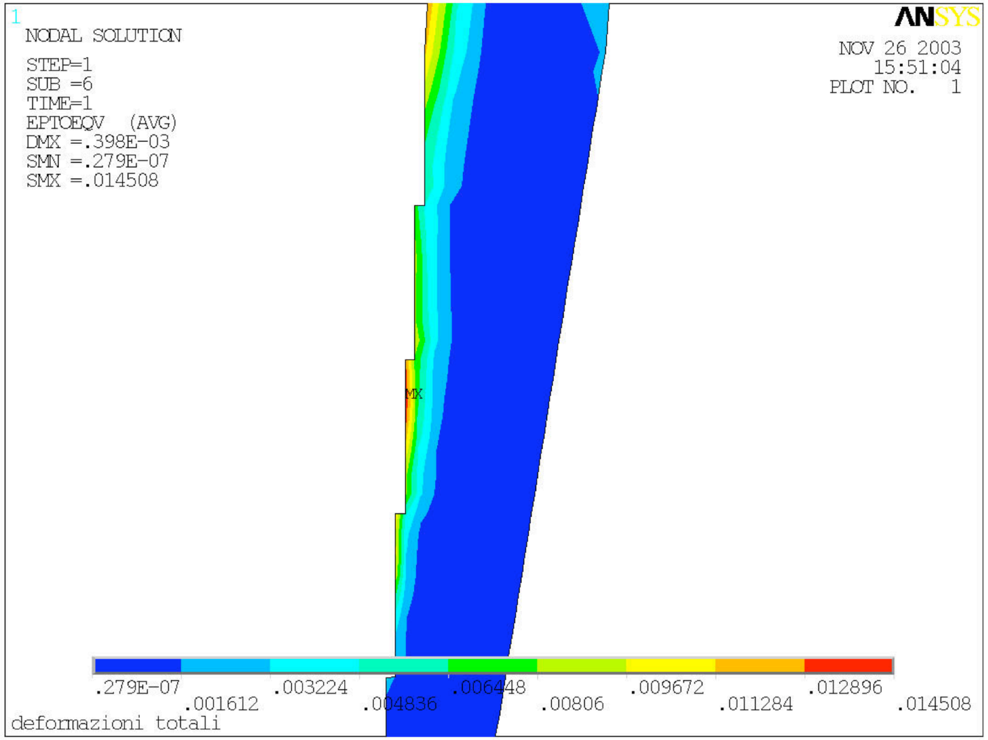
- Pumps flow-rate ~ 8 - 2 m^3/h
- Water max speed (3 holes of $\Phi = 18$ mm) ~ 3 - 1 m/s

Thermo-hydraulics Characteristics



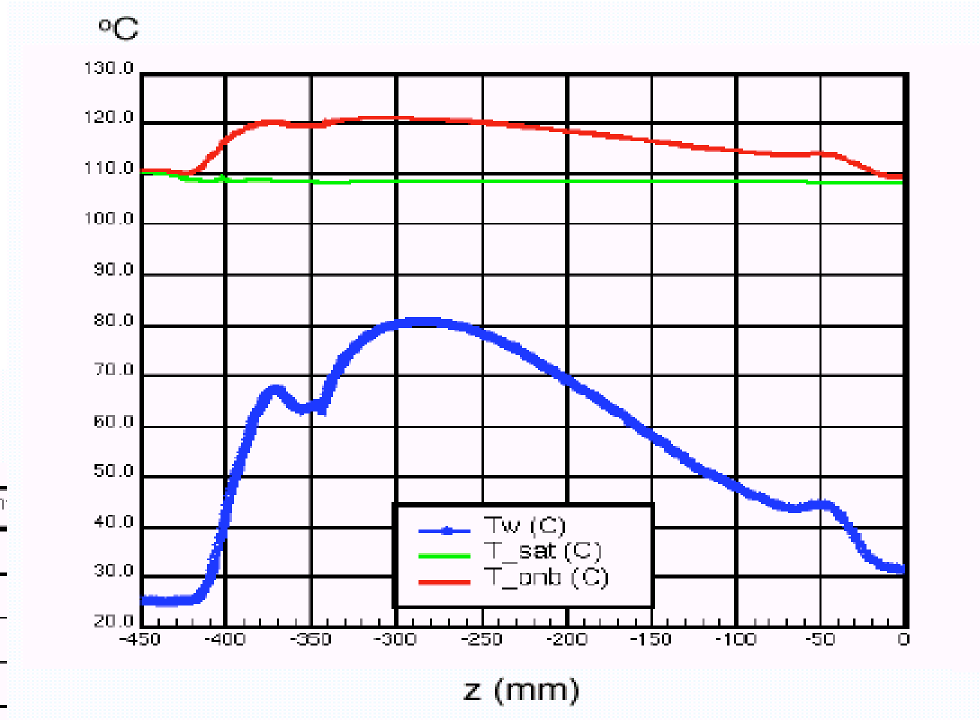
Thermo-mechanical Characteristics

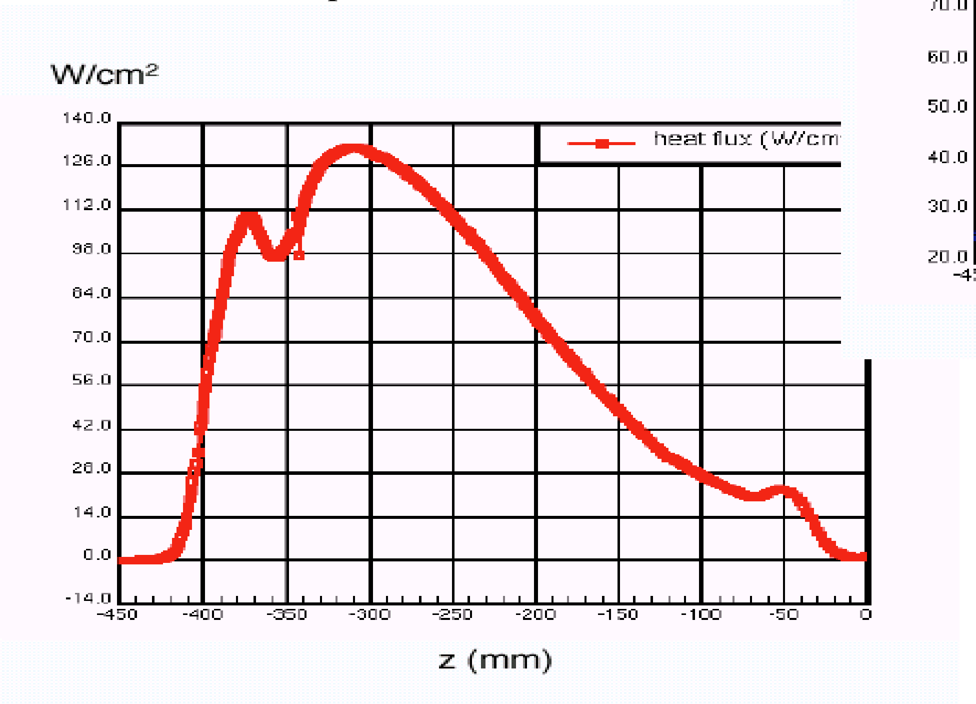




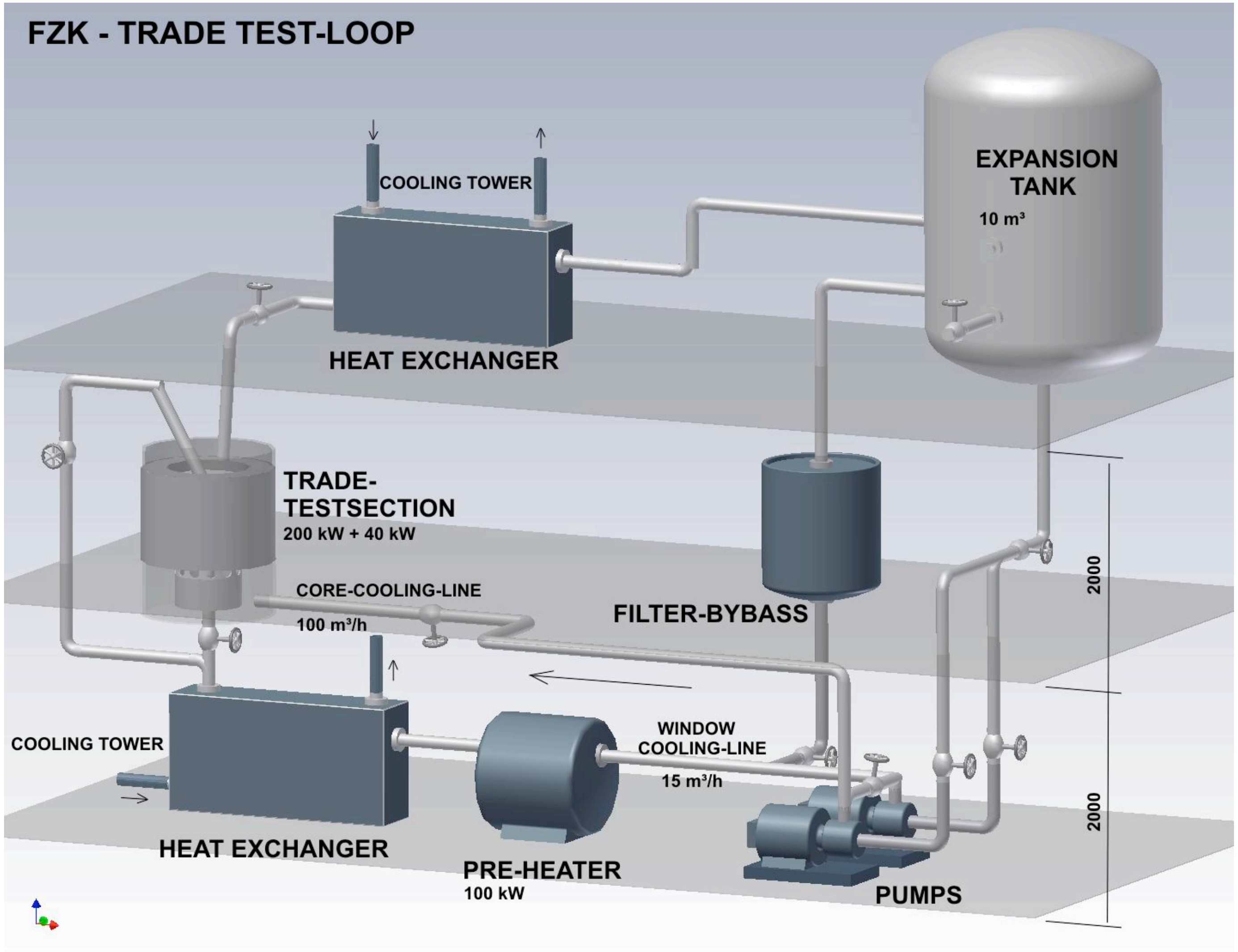
Critical Heat Flux

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





Test loop configuration to be built at FzK



High-Power issues

- Thermal management
  - Target melting
  - Target vaporization
- Radiation
  - Radiation protection
  - Radioactivity inventory
  - Remote handling
- Thermal shock
  - Beam-induced pressure waves
- Material properties

Conclusions

- Transmutation of nuclear waste is establishing the case for the development of new high-power proton drivers.
- High-power targets are necessary for the exploitation of these new machines.
- Target systems have been developed for the initial 1MW class machines, but are as yet unproven.
- No convincing solution exists as yet for the envisioned 4 MW class machines.
- A world wide R&D effort is under way to develop new high-power targets.