Wir schaffen Wissen – heute für morgen

Paul Scherrer Institut

M. Wohlmuther

Targets and Beam Dumps

CERN ACCELERATOR SCHOOL

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Outline

- **General remarks**
- **Repetition of physics**
- **MC Simulations**
- **Spallation targets**
  - Solid targets
    - *SINQ target*
    - *ISIS TS1 target*
  - Liquid metal Targets
    - *SNS Hg-Target*
    - *JSNS Hg-Target*
- **Meson production targets**
  - Target E @ PSI
  - NuMi Neutrino production target
- **Beam Dumps**
  - 3 GeV Injector beam dump @ JSNS
  - 590 MeV beam dump @ PSI

A trial of a definition

TARGET

A target is an assembly of material(s) that intercept accelerated particle beams to produce secondary particles (in large amounts). Created secondary particles are either used as probes to investigate other object(s) for their (physical) properties (behavior under irradiation) or themselves (or their decay products) are objects of interest. In some cases produced secondary particles are again used to create other species at so called secondary targets.

Aim of Targets

Particle Production

Boundary conditions/constraints:

❖ Geometrical situation
❖ Thermo-mechanical stability
❖ Material damage (Lifetime)
❖ Compactness (→ conflicting with dissipation of energy)
❖ Availability
❖ Safety
❖ Handling

Information for Target Design

Crucial information for Target Design

❖ Particle production performance
❖ Energy density distribution → Energy density Limits of Material(s)
❖ Radioactive inventory → Handling of used Targets and Beam Dumps
❖ Material and irradiation properties → Radiation damage Limits, Erosion/Corrosion Limits, Fatigue …
❖ Safety issues → Accident scenarios (Licensing)

Target Design

Design is a complex and iterative process which has to satisfy multiple requirements with usually incomplete data

Frequent sources of problems include:

- Incomplete or unknown requirements at the start
  - Performance
  - Safety
  - Reliability/Maintainability/ Inspectability

- Initial cost and schedule estimates used to get project approval overly optimistic

Beam parameters

Most key design parameters for the target scale with the peak intensity (protons/unit area).

For the same total number of protons, the peak can vary significantly depending on the profile.

Initial scoping calculations frequently use **Gaussian**,

I= I_0 *exp{-($x^2/2\sigma_x^2$+ $y^2/2\sigma_y^2$)}

- I_0= $N_p/(2\pi\sigma_x\sigma_y)$

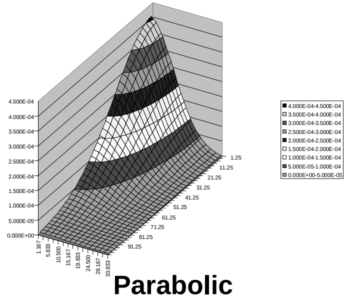
Parabolic,

- I= I_0 *(1-$(x/a)^2$)*(1-$(y/b)^2$)
- I_0= 9 $N_p/(16ab)$

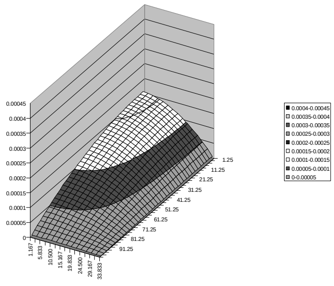
or **Flat** beam profiles (beam painting)

- I= I_0
- I_0= $N_p/(4ab)$
  - N_p= number of protons per pulse, I_0= peak number of protons per unit area per pulse

Gaussian



Parabolic



Beam Parameters

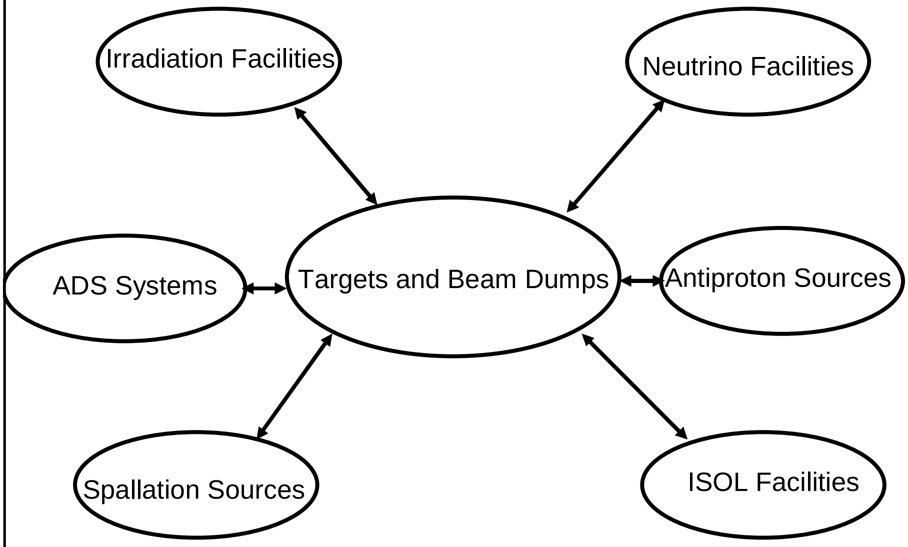
Power = N_p*f*E*1.6021x10^{-13} = I[µA]*f*E [MeV] [W]
Where N_p= protons per pulse, f= frequency (Hz), E = beam energy in MeV
Current (A) = N_p *f*1.6021x10^{-19}
Peak current density(A/mm²) = I_0(p/mm^2)*f*1.6021x10^{-19}

For a proton energy loss of C [eV/mm] the volumetric heating would be
Q’’’(MW/m^3)= I(p/mm^2)*f*C(MeV/mm)*10^9*1.6021x10^{-19}
for thin windows at ~ 1GeV

C= .7 MeV/mm – aluminum
C= 1.85 MeV/mm – Inconel

Example 2.9x10^{10} p/mm^2 @ 60 hz, 1 GeV Inconel window
Current density = .28 A/m^2 Q’’’= 515 MW/m^3

Targets and Beam Dumps


Irradiation Facilities
Neutrino Facilities
ADS Systems
Targets and Beam Dumps
Antiproton Sources
Spallation Sources
ISOL Facilities

And many more applications

Repetition of some physics

Energy loss in a medium

By Ionization/excitation - Bethe Bloch formula

$$-{}^{dE}\!\!\diagup_{dx} = 4\cdot\pi\cdot N_A\cdot r_e^2\cdot m_e\cdot c^2\cdot z^2\cdot(Z/A)(1/\beta^2)$$
$$\times\left[\ln\left(\frac{2\cdot m_e\cdot c^2\cdot\gamma^2\cdot\beta^2}{I}\right)-\beta^2-\frac{\delta}{2}\right]$$

$$I = 16\cdot Z^{0.9}\ [\mathrm{eV}]\ \text{for Z} > 1$$

I=15 eV for atomic hydrogen, I=19.2 eV for molecular hydrogen and I=21.8 eV for liquid hydrogen

N_A - Avogadro const. (= $6.023\cdot10^{23}$ mol^{-1})
r_e - classical electron radius (= $2.82\cdot10^{-13}$ cm)
m_e - electron rest mass (= 0.511 MeV/c^2)
z - projectile charge
Z - atomic number of medium
A - atomic weight of medium (g/mole)
γ - Lorentz factor (= $\frac{E}{m_0c^2}$)
β - (= v/c)
I - average ionization potential of medium
δ - density correction (shielding effects of electrons)

Energy loss in a medium

Bremsstrahlung

Interaction of charges particles with the Coulomb field of nuclei of the medium → de-acceleration → part of kinetic energy emitted in form of photons → Bremsstrahlung

$$-dE\Big/dx = 4 \cdot \alpha \cdot N_A \cdot \frac{Z^2}{A} \cdot z^2 \left(\frac{1}{4\pi\varepsilon_0} \frac{e}{mc^2} \right) \cdot E \cdot \ln\left(\frac{183}{Z^{1/3}} \right)$$

In addition, at high energies, pair production as well as energy loss due to photonuclear effects also contribute to the total energy loss of a particle. These losses are ~ to the incident particle energy (E) and become important at sufficient high energies.

α - fine structure constant $(= \frac{1}{137.035})$

N_A - Avogadro const. $(= 6.023 \cdot 10^{23}\ \mathrm{mol}^{-1})$

Z - atomic number of medium

A - atomic weight of medium (g/mole)

z - atomic number of projectile

m - mass of projectile

E - energy of projectile

Range of particles

The range (R) of particles is defined as the mean free distance that a particle travels before it comes to rest:

$$R \equiv \int_0^{x_{\max}} dx(\beta) = \int_0^{\beta_{initial}} \left[-\frac{dE}{dx} \right]^{-1} \frac{dE}{d\beta} d\beta$$

Semi-empirical approximation by Carpenter for spallation source materials (Z > 10 and 0.1 ≤E≤1 GeV) – incident particle is a proton

$$R = (1/\rho) \cdot 233 \cdot Z^{0.23} (E - 0.032)^{1.4} \ \ [\mathrm{cm}]$$

Temperature rise

The instantanuous temperature rise in a material – hit by a Gaussian beam – can be written as:

$$\Delta T = \frac{dE}{dx} \cdot \frac{N_p}{(2 \cdot \pi \cdot \sigma_x \cdot \sigma_y) \cdot \rho \cdot c_p}$$

The instantanuous temperature rise will be small if $\rho \cdot c_p$ is large.

The resulting cyclic thermal stress is proportinal to: $\sigma_{cyclic} \propto \Delta T \alpha E$

ΔT ... Temperature difference [K]

$\frac{dE}{dx}$ ... Energy loss $\left[\frac{\mathrm{J}}{\mathrm{cm}}\right]$

N_p ... number of particles per pulse

$\sigma_{x/y}$ ... beam width (Gaussian beam assumed) [cm]

ρ ... Density $\left[\frac{\mathrm{g}}{\mathrm{cm}^3}\right]$

c_p ... Heat capacity $\left[\frac{\mathrm{J}}{\mathrm{g} \cdot \mathrm{K}}\right]$

Material	**Aluminium**	**Berylium**	**Copper**	**Graphite**	**Iron**	**Lead**	**Tantalum**	**Tungsten**	**Uranium**	**Mercury**	**Zirconium**
density [g/cm^3]	2.7	1.85	8.79	2.3	7.87	11.35	16.6	19.2	19.1	13.58	6.57
c_p [J/(gK)]	0.91	1.83	0.39	0.17	0.46	0.13	0.14	0.13	0.12	0.139	0.27
$\rho \cdot c_p$ [J/(cm^{3}K)]	2.46	3.39	3.43	0.39	3.62	1.48	2.32	2.50	2.29	1.89	1.77

Coulomb scattering

The differential cross section for a charges particle scattered into the solid angle interval dΩ, Ω+dΩ can be written as

$$\frac{d\sigma}{d\Omega} = \frac{1}{4} \cdot \left(\frac{Z \cdot z \cdot e^2}{\beta \cdot c \cdot p} \right) \cdot \frac{1}{\sin^4(\Theta/2)}$$

In general scattering at different scattering samples → stochastic → only statistical distribution can be given

$$\Theta_{rms} = \sqrt{\langle \Theta^2 \rangle} = \frac{13.6\,\mathrm{MeV}}{\beta \cdot \mathrm{c} \cdot \mathrm{p}} \cdot z \sqrt{\frac{x}{X_0}} \cdot \left[1 + 0.038 \cdot \ln(x / X_0)\right]$$

With X_0 the radiation length

$$X_0 = \frac{A}{4 \cdot \alpha \cdot N_A \cdot Z^2 \cdot r_e^2 \cdot \ln(183 \cdot Z^{-1/3})} \, (\mathrm{g/cm}^2)$$

MC Simulation codes

Targetry and MC simulation codes

Targetry issues

- To get adequate „parameters“ for targets at any accelerator facility it is necessary to produce and collect a (very) large number of particle tracks/histories. For instance, at a spallation neutron source neutronic behavior has to be studied, for neutrino target the production of pions and kaons is necessary, rare isotope accelerators need information about the formation of residual nuclei in targets …

Informations of interest:

- Production of particle of interests and their behavior inside complex geometries.
- Behavior of „unwanted“ particles which could create background → Adequate suppression in beam lines can be tailored.
- Information on the survivability and life time of the target and beam windows. Strongly depends on fatigue, stress limits, radiation damage, erosion….
- Activation of components → planning of remote handling and exchange procedures, radioactive waste issues …
- Heat loads, activation and radiation damage in targets and surrounding structures; for instance in superconducting focusing devices at v-beam lines, moderators at spallation neutron sources and so on.
- Shielding issues for radiation protection, „spent“ beam handling, ground water activation …

Targetry and MC simulation codes

Most of these issues can be addressed by Monte-Carlo particle transport codes. Therefore, the predictive power and reliability of these computer codes is of crucial importance. This leads to requirements of the physics implemented in such code systems:

- ❖Reliable description of cross-sections, particle production modes, particle yields in a large energy regime from (sub-)eV to several GeV even TeV, for hadrons, photons, composite particles and even nuclei.
- ❖Adequate π^0 and K^0 production (v_e) and correct the modeling of electromagnetic showers ($\pi^0 \rightarrow \gamma\ \gamma \ldots$), photoproduction of hadrons, muons.
- ❖Description of energy loss processes, e.g. charged hadrons, neutrons, muons …(ionization losses, knock-on electrons, and at high energies Bremsstrahlung, Pair production).
- ❖Correct transport and moderation of neutrons at meV energies.
- ❖Predictive powers for nuclide inventories, dpa, Helium and Hydrogen production.
- ❖Accurate transport of all particle species from microns to meters.
- ❖Inclusion of effects of magnetic fields, gravity (cold and ultra-cold neutrons).
- ❖User interface.

Code packages

Monte Carlo Codes	**Event Generators**	**Developed at**	**Available through**	**Main developer**
FLUKA	PEANUT / DPMJET	INFN (Italy)	http://www.fluka.org/fluka.php	Alfredo Ferrari
GEANT4	QMD	CERN (Switzerland / France)	http://www.geant4.org/geant4/	Collaboration
MARS	CEM /LAQGSM/DPMJET	Fermi National Lab (USA)	http://www-ap.fnal.gov/MARS/	Nikolai Mokhov
MCNPX	BERTINI, CEM, FLUKA89, INCL, ISABEL, LAQGSM	Los Alamos National Lab (USA)	https://mcnpx.lanl.gov/ official versions OECD/NEA or RSICC	MCNP(X) team
PHITS	JAM / QMD	JAERI (Japan)	http://phits.jaea.go.jp/ OECD/NEA or RSICC	Koji Niita

IAEA benchmark for different codes and event generators where Results as well as experimental data are provided:

http://nds121.iaea.org/alberto/mediawiki-1.6.10/index.php/Main_Page

Spallation Targets

Spallation Sources - operating or shut down

Facility	Status	Time Structure			Coolant			Target Material	Power	Notes
		Steady State	Long Pulse	Short Pulse	Water	Mercury	Pb-Bi			
IPNS	De-commissioned			X	X			Depleted U	7kW	short life
IPNS	De-commissioned			X	X			Tungsten	7kW	
ISIS 1	Operated			X	X			Depleted U	~100 kW	short life
ISIS 1	Operated			X	X			Tantalum	~150 kW	high decay heat
ISIS 1	Running			X	X			W-Ta clad	~150 kW	
LANSCE	Running			X	X			Bare Tungsten	~100 kW	
KENS	De-commissioned			X	X			W-Ta clad	3 kW	
SINQ	Operated	X			X			Zircalloy rods		
SINQ	Operated	X			X			Pb in SS rods	~800 kW	
SINQ	Test run completed	X					X	Pb-Bi	~800 kW	Target removed
SINQ	Operated	X			X			Pb in Zr rods	0.9 MW	optimized target
ISIS 2	Running			X	X			W-Ta clad	~40 kW	Very optimized
SNS	Running			X		X		Mercury	1 MW	1.4 MW design
JSNS	Running			X		X		Mercury		1 MW design

Selected Design Studies

Design studies – not (yet) built

Conceptual or Preliminary Design										
Facility	**Status**	**Time Structure**			**Coolant**			**Target Material**	**Power**	**Notes**
		Steady State	**Long Pulse**	**Short Pulse**	**Water**	**Mercury**	**Pb-Bi**			
CSNS	Preliminary Design			X	X			W-Ta clad	250 kW	
ESS (2003)	Conceptual Design			X		X		Mercury	5 MW	
SNS-STS	Pre Conceptual Design		X			X		Mercury	1-3 MW	
SNS-STS	Pre Conceptual Design		X		X			W-Ta clad	1-3 MW	Rotating Target
IPNS Upgrade	Conceptual Design			X	X			W-Ta clad	1 MW	
Los Alamos - Next Generation	Conceptual Design			X	X			W- with clad	1 MW	
JSNS	Conceptual Design			X	X			W- SS clad	1 MW	
SNS	Conceptual Design			X	X			W- with clad	1 MW	
Eurisol	Conceptual Design	X				X		Mercury	4 MW	
MTS	Conceptual Design		X				X	W	1 MW	Los Alamos Material Test Station

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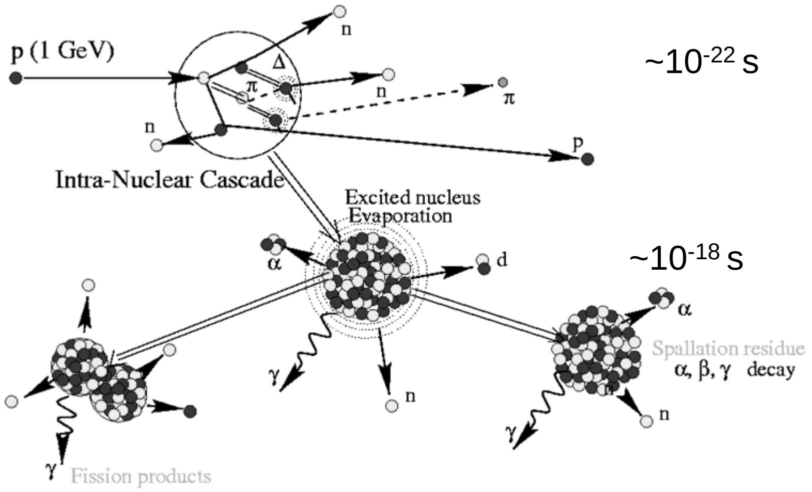
Physics

time

$\sim 10^{-22}$ s

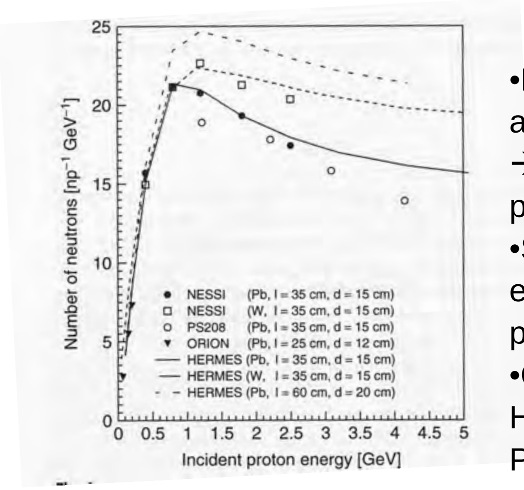


$\sim 10^{-18}$ s

Evaporation competing with high energy Fission

Physics

Existing spallation neutron sources are driven by proton accelerators operating in an energy regime from 0.5 – 3 GeV.



•Minimum ionisation approached at 0.8 – 1.0 GeV → more energy into neutron production

•Slow fall off towards higher energies due to increasing production of π

•Other high-Z materials (e.g. Hg) show similar behavior as Pb

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Target material choice for Spallation Sources

❖High Z → high neutron production rate

❖High density → high luminosity

❖Radiation stability → long lifetime, availability

❖Low neutron absorption → high neutron intensities (for pulsed sources not so much of an issue)

❖Low activity & after-heat → service and decommisioning

Target Materials for Spallation Sources

	Pb	Bi	LME	LBE	Hg	W	Ta
Composition	elemental	elemental	97.5%Pb+ 2.5% Mg	45% Pb + 55% Bi	elemental	elemental	elemental
Atomic # Z	82	83		~82.5	80	74	73
Density (g/cm^3) solid(20^{0}C)	11.35	9.75				19.3	16.65
Density (g/cm^3) liquid	10.7	10.07	10.6	10.5	13.55		
Coeff. of thermal expansion (K^{-1})	2.91*10^{-5}	1.75*10^{-5}			6.1*10^{-5}	4.4*10^{-6}	6.6*10^{-6}
Contraction on solidification (%)	3.32	-3.35	~3.6	~0			
Melting Point. (^{0}C)	327.5	271.3	250	125	-38.87	3370	2996
Specific heat capacity (c_p)(J/g/K)	.14	.15	.15	.15	.12	.134	.134
Thermal neutron absorption (barn)	.17	.034	.17	.11	389	18.5	21

Comparison of n production

Nuclear Process	Neutron Production yield (neutrons/reaction)	Energy deposition (MeV/neutron)
400 keV D on T in Ti-matrix	4•10^{-5} (neutrons/D)	10^4 MeV/n
35 MeV D on liquid Li (stripping)	3•10^{-3} (neutrons/D)	10^4 MeV/n
100 MeV e$^-$ on ^{238}U	5•10^{-2} (neutrons/e)	2•10^3 MeV/n
^{235}U(n,f) (thermal fission)	3 neutrons/fission	1.9•10^2 MeV/n
1 GeV protons on thick Hg target	~ 30 neutrons/proton	5.5•10^1 MeV/n
CTR (controlled thermonuclear reaction) (D,T) fusion by laser beam	1 neutron/fusion	3 MeV/n

SINQ – Schweizer Intensive Neutronen Quelle

SINQ

- ❖SINQ is the only existing CW spallation source
- → Medium size reactor
- ❖Advantage compared to reactor
  - ❖No chain reaction
  - ❖Energy deposition
- ❖ Low neutron absorbing materials
  - ❖Coolant/Moderator D_2O
  - ❖Cold Moderator D_2 @25 K
- ❖Optimum Target Materials (low σ_{abs})
  - ❖Lead Bismuth Eutectic (LBE), Pb, Zr, Al

Proton beam:
- **CW**
- **575 MeV**
- **~ 1.5 mA ⇒ 0.9 MW**
- **Gaussian beam shape (σ_x=2.14 cm σ_y=2.96cm)**
- **Peak current density 25 µA/cm²/mA**

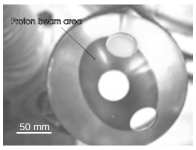
- ❖ Vertical alignment → Proton beam from below
- ❖ 360° access → cylindrical shape of the target
- ❖ Fully coupled system
- ❖ Beam Energy E_p=575 MeV
- ❖ Beam current 1.5mA
- ❖ 2/3 of beam power deposited in target
- ❖ SINQ Target lifetime 2 years → limit: embrittlement of AlMg3 BEW

Lifetime Limiting Component

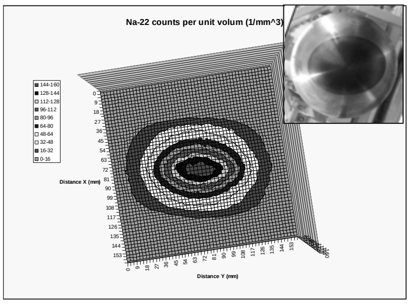
AlMg3 proton beam window (integrated into the Safety Hull of the SINQ targets)

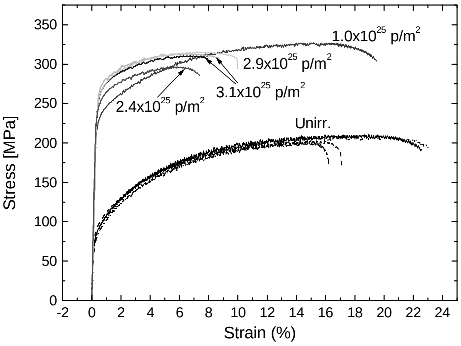
SINQ Target Safety Hull:

Tensile tests after one year of irradiation



γ-mapping of the beam footprint

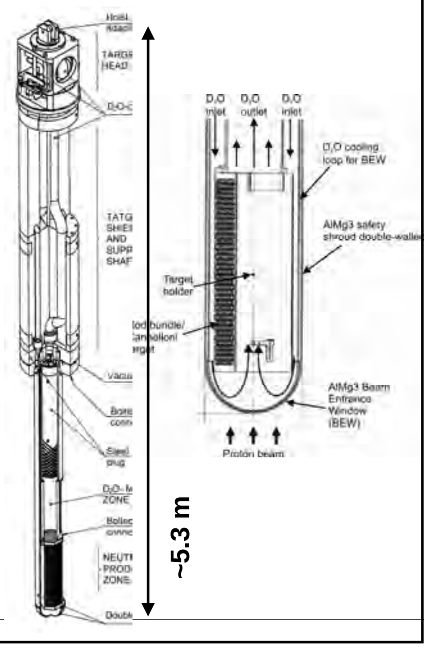




Target Development History

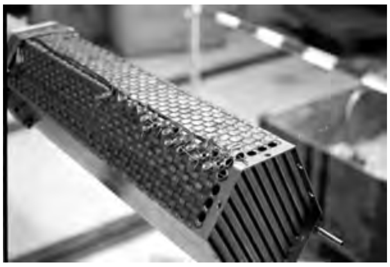
Target Development History – a very short overview

- ❖ 1996/97: Start-up of SINQ with a **solid Zircalloy rod target** (Target 1, Mark II)
- ❖ 1998/99: Operation with a **solid Zircalloy rod target** (Target 3, Mark II)
- ❖ 2000/01: Use of Steel-cladded Lead rods **„Cannelloni Target“** (Target 4, Mark III)
- ❖ 2002/03: **„Cannelloni Target“** as in previous operation cycle (Target 5, Mark III)
- ❖ 2004/05: Again Lead-filled Steel tubes **„Cannelloni Target“** (Target 6, Mark III)
- ❖ 2006: Liquid Lead Bismuth Eutectic Target – **MEGAPIE**
- ❖ 2007/08: Mix of Lead-filled Steel and Zircaloy tubes - **„Cannelloni Target“** (Target 7, Mark III)
- ❖ 2009/10: **Improved** solid target, still **„Cannelloni Target“**, only Zircaloy used as cladding material (Target 8, Mark IV)
- ❖ 2011 Slightly modified Mark IV **„Cannelloni Target**“; start of operation April 2011 (Target 9, Mark IV)

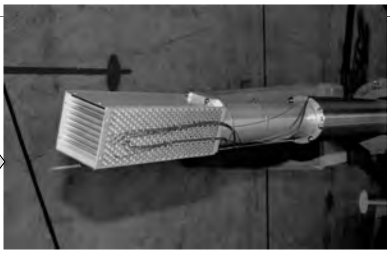


Target Evolution at SINQ

1997-1999: SINQ Target Mark 2
Water-cooled Zircaloy rods



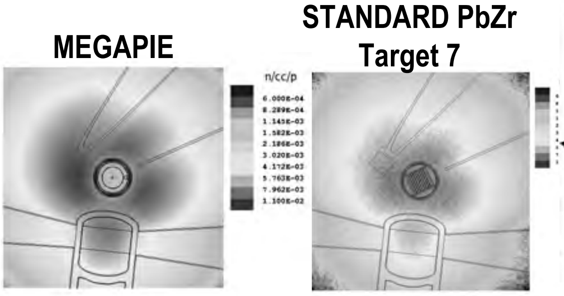
2000 - 2009:SINQ-Target Mark 3:
Lead rods, with steel clad
42% increase in neutron yield

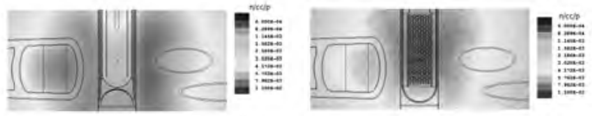


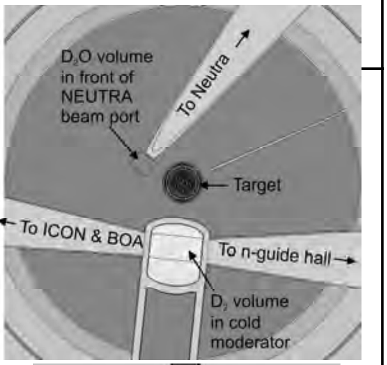
2010 – present: SINQ-Target Mark 4:
Lead rods, with Zr clad, blanket

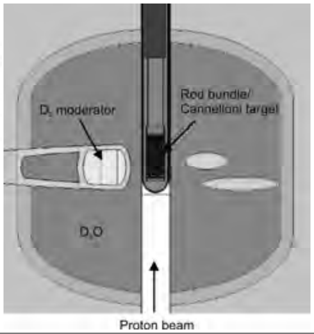
Aug- Dec 2006: MEGAwatt Pilot Experiment:
- **Joint international initiative to design, build, licence, operate and explore a liquid metal spallation target for 1 MW beam power**

Validation of MC-model





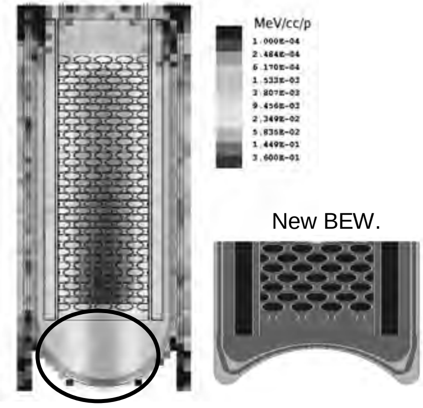




Calculated flux maps of MEGAPIE, Target 7 and the improved SINQ target (target 8).
Simulated differences to Target 6 are: MEGAPIE (~1.80), Target 7 (1.20*), Target 8 (~ 1.60).
*if STIP samples are included (1.10)
Good agreement with measured data!

Calculation of energy depositions for stress analysis

Original Beam Entrance Window



New BEW.

Inversion of the Beam Entrance Window (BEW)

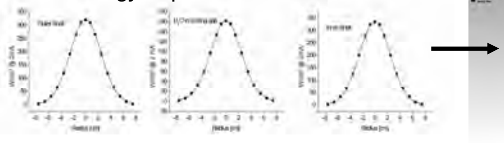
❖ Original BEW designed for minimum mechanical stress → hemispherical shape

❖ Water head between BEW and Target Array ~ 10cm → ~ 10 MeV energy loss & only spallation on light nuclei (Oxygen of D_2O), see circle

❖ Inversion of BEW: energy loss minimized, mechanical stress slightly higher. Neutron Flux gain → 10 %

❖ Temperatures of safety shroud between 65 – 75℃

Energy deposition from MC-model



Von Mises Stresses.

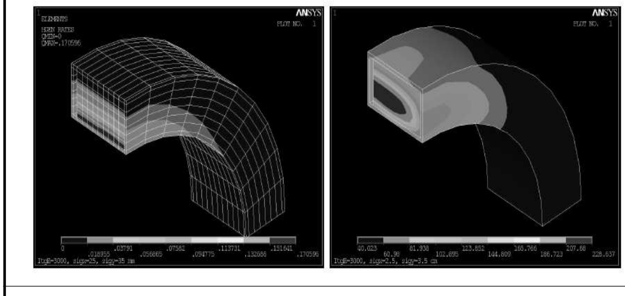
D_2O flow.

Mis-Steering of the beam

Stresses in the beam entrance window due to off center beam

Stresses found in this abnormal conditions are between 1.7 and 4.2 MPa, which are well below the yield strength of AlMg3 → maximum deformation 0.1mm

Temperatures in Blanket/Reflector

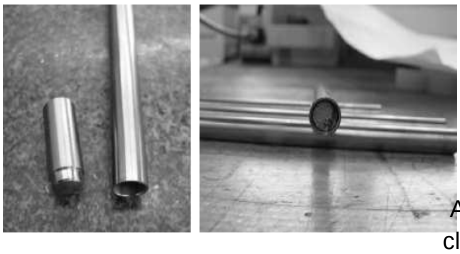


Also in the new Blanket/Reflector temperatures and resulting stresses are found to be in a regime were no damage is to be expected.

The SINQ Mark 4 Target

Increasing the Lead content in the Cannelloni target:

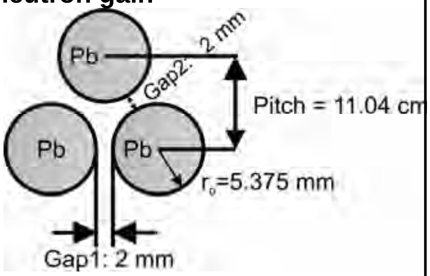
- ❖ Compact the Target array
- ❖ Decreasing the cladding thickness



Cooling vs. n-Production

Compact the Target array

The outlet gap (gap2) was reduced to 1.2 mm → Pitch 10.11 mm → **5 % neutron gain**

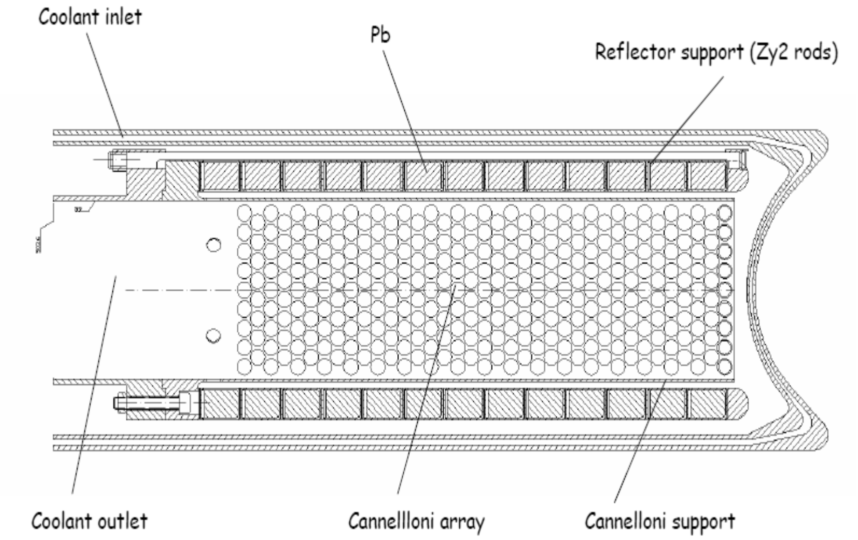


Decreasing the cladding thickness

Attempts have been made to decrease the Zr cladding thickness from 0.75 mm to 0.5 mm by drilling. However, during fabrication temperatures are high, so that Zr crystal structure might have changed. Moreover, quality not always the same.

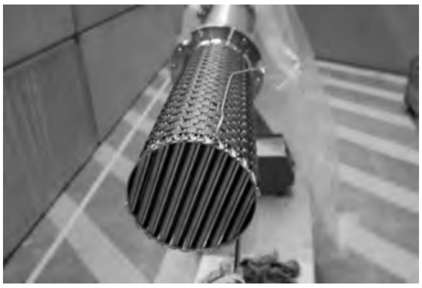
Conceptual design of SINQ Mark 4 Target

Optimization between coolant and spallation material



SINQ Mark4 Target

The new Zr-Pb cannelloni target for SINQ

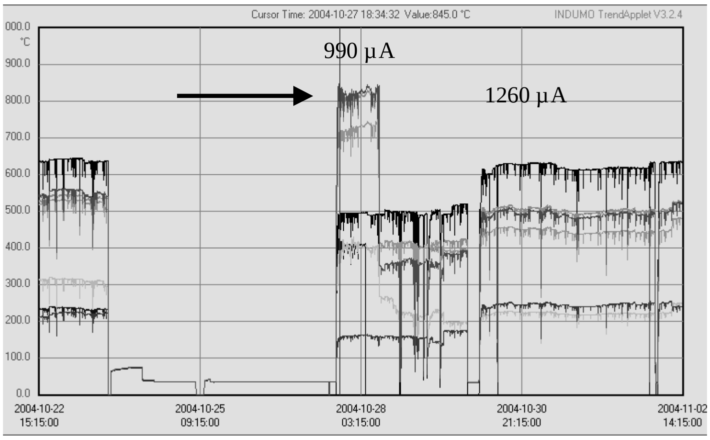


Status:
Operated @ 0.9 MW
April 2009 – Dec. 2010

Neutron flux gain:
54% compared to Target Mark 3
(2004 / 2005)

Accident – beam focus: Target temperature recording

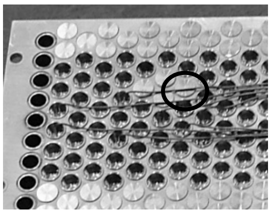
Temperatures during an unintended beam focussing, October 2004



Accident: Searching for the object of failure

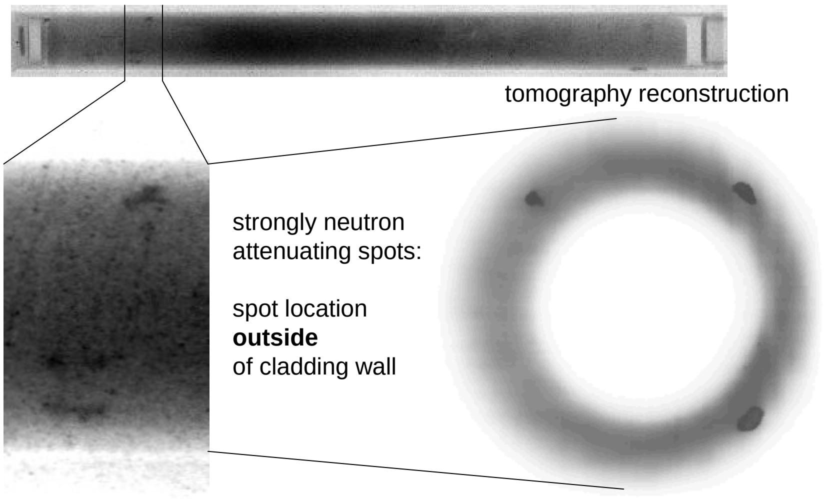
Zr-clad rod:

visual inspection after 2 years in SINQ (>10Ah of accumulated proton charge):



Searching for the object of failure

Neutron tomography: Zr-clad test rod

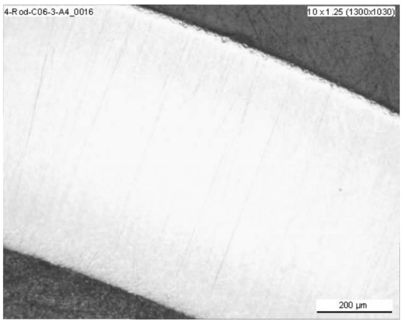


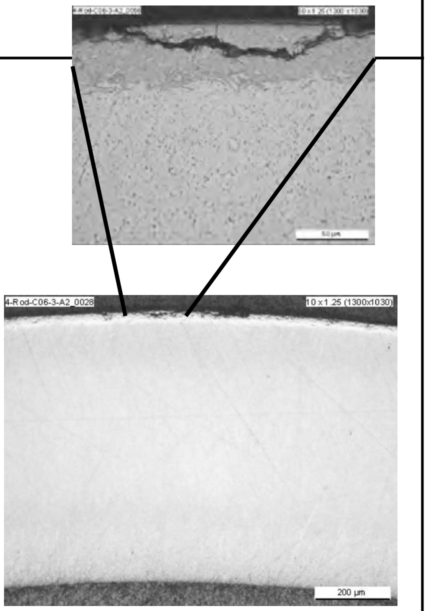
tomography reconstruction

strongly neutron attenuating spots:

spot location **outside** of cladding wall

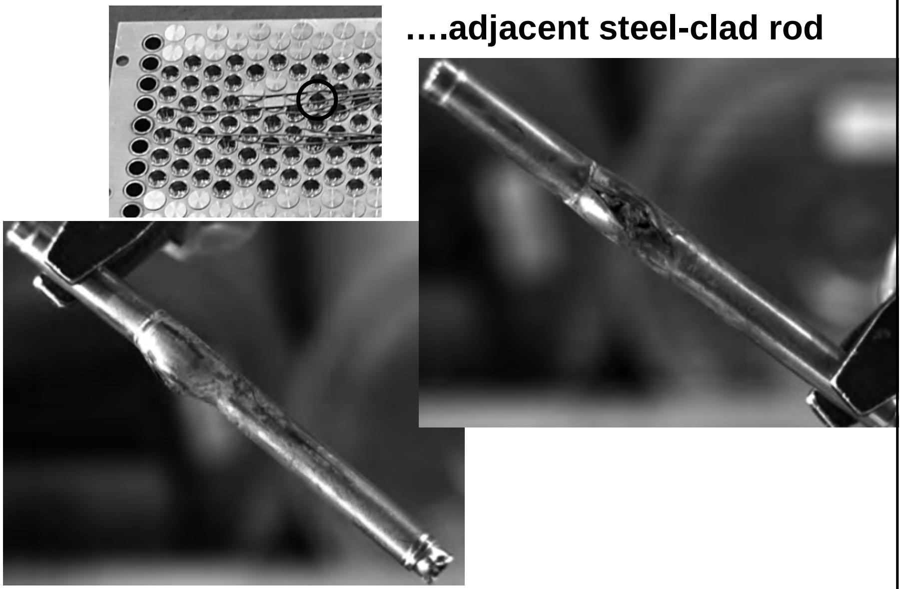
Metallographic investigation:
Zr-rod 06-3



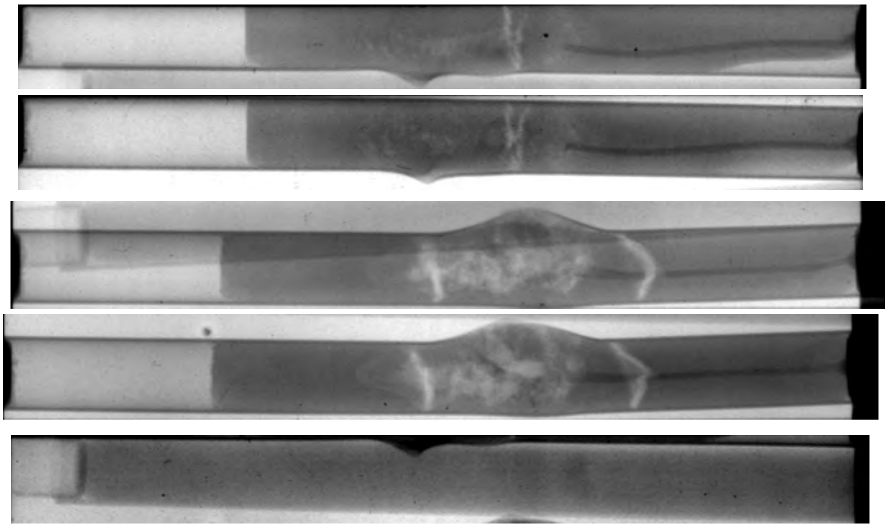


Accident: Searching for the object of failure

….adjacent steel-clad rod



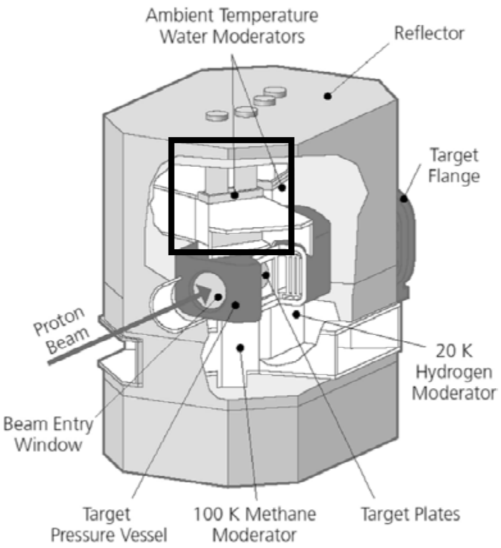
Neutron radiographs from damaged (steel-clad) target rods

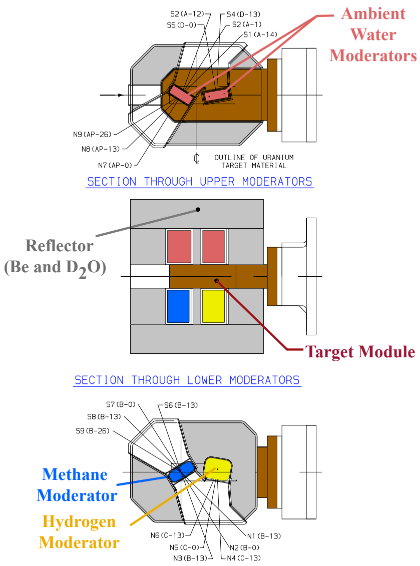


PAUL SCHERRER INSTITUT

ISIS TS1 Targets

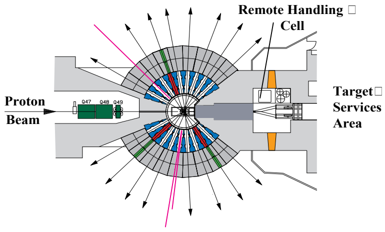
ISIS Target moderator and Reflector Assembly





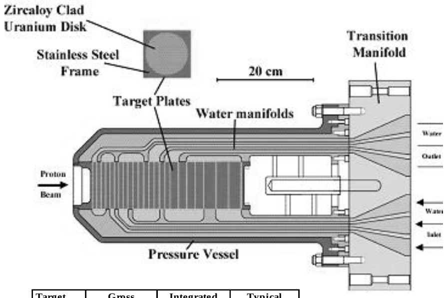
ISIS TS1 Targets

Beam Parameters
800 MeV
50 Hz – short pulse (< 10^{-6} s)
200 mA → ~ 160 kW



- ISIS started with Uranium (depleted) plate Targets → additional neutrons due to fission
- Target plates thickness inversely proportional to energy deposition (7.7 – 26.5 mm)
- U-plates clad with Zircalloy to prevent corrosion (similar materials as in reactors)
- D_2O cooled

ISIS TS1 Targets



Target	Gross Thermal cycles	Integrated protons MWd	Typical current µA
U#1	Unknown	3.1	30
U#2	40000	1.8	45
U#3	10389	5.8	65
U#4	4147	4.6	75
U#5	5074	9.9	90
U#6	2628	4.2	110
U#7	1805	3.6	125
U#8	Not	Used	
U#9	815	3.8	150
Ta#1	73378	58.4	170
Ta#2	37734	40.8	180
Ta#3	45860	58.8	180
Ta#4	23000	45.8	180
W#1		87.0	180

Radiation Damage Failures

Instrumentation failures

ISIS TS1 Uranium Target

•U (depleted) plates (thickness 7.7 -26.5 mm, Ø 90mm) cladded with Zircalloy (by isostatic pressing @850℃) cooling channels 1.75 mm

•High neutron output

•Higher heat production due to fissioning (max. 0.77 kW/cm^3)

•Surface cooled with D_2O

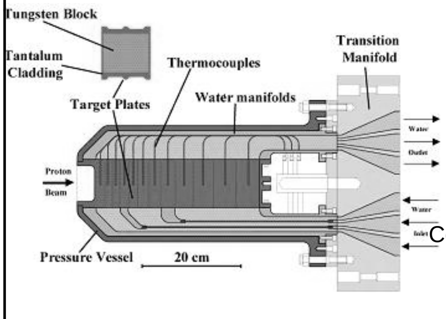
•All U-Targets failed ~250 mAh

•Reason for failure unclear (thermal cycling, phase transition, H-,He-production …)

•Failure mode: Crack in the cladding Zr → release of FP to D_2O

ISIS Targets

•**Ta-Target** used as a replacement for U-targets
•Change in HTC as fct. of protons on target
  ❖Peak temp. of target 320℃ in last run period, peak temp. 180℃ in first run period
  ❖High afterheat →significant release of Tritium in storage (500 MBq/day)!!



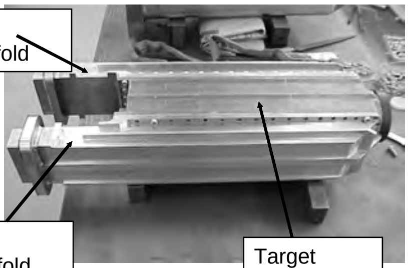
ISIS TS1 Tungsten Target

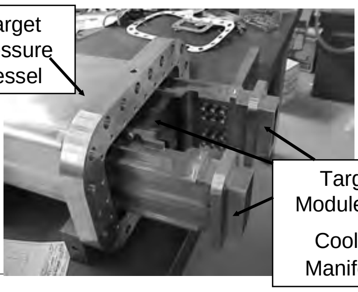
•12 Ta cladded W plates (high corosion of W in water, APT experience)
•Surface cooled with D_2O

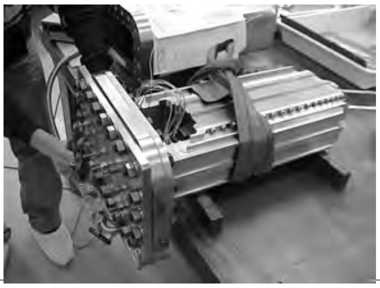
Proton beam power	160 kW
Total heat deposited	95 kW
Peak power deposited	0.25 MW/l

Cooling system	D_2O cooled
• Inlet pressure	6.2 bar
• Pressure drop	0.25 bar
• Inlet temperature	35 C
• Temperature rise	4 C
• Flow rate	350 l/min
• Peak plate temperature	380 C

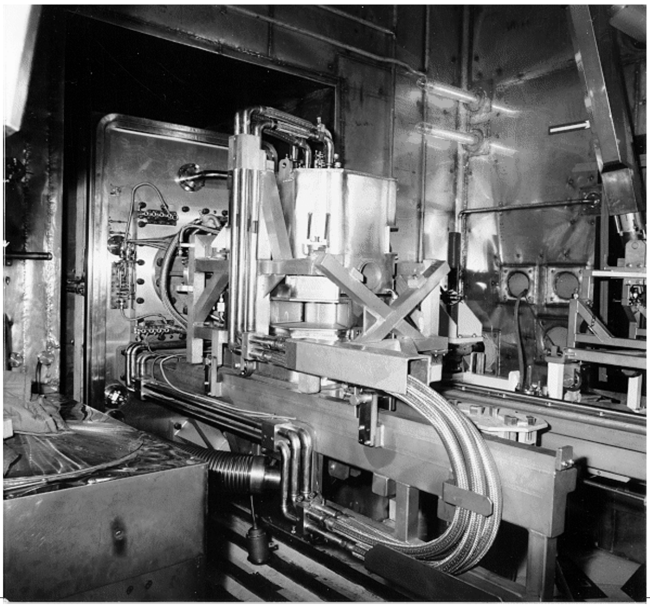
The ISIS Tungsten Target Construction





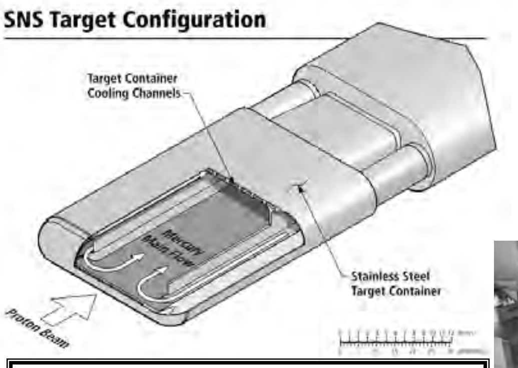


ISIS Target moderator and Reflector Assembly



SNS mercury target

SNS Mercury Target



SNS Ultimate Parameters
- 1 GeV protons
- 2 MW average beam power
- Pulse duration ~ 0.7 μs
- 60 Hz rep rate

Pulsed spallation Source
- Shape of target rather thin and broad → allows for moderators near to target
- Target material Hg → liquid at room temperture (no heating for liquification)
- Hg is target material and coolant

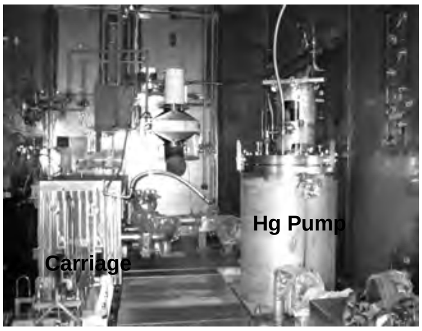
Mercury Loop Parameters @ 2 MW

Power absorbed in Hg	1.2 MW
Nom Op Pressure	0.3 MPa
Flow Rate	340 kg/s
V_{max} (In Window)	3.5 m/s
Temperature	
• Inlet to target	60ºC
• Exit from target	90ºC
Total Hg Inventory	1.4 m^3
Centrifugal Pump Power	30 kW

SNS Hg Target operates at low temperature and pressure

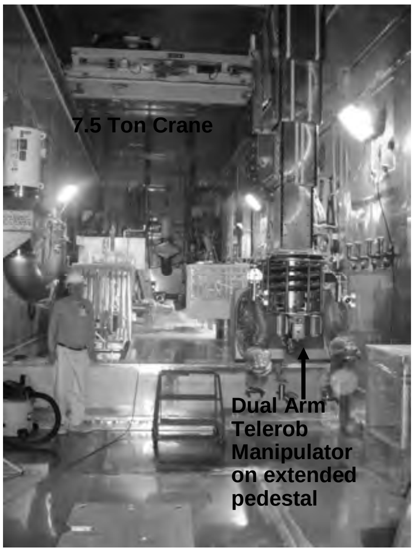
Peak power density in mercury ~ 800 MW/m^3 @ 2 MW

Target Service Bay



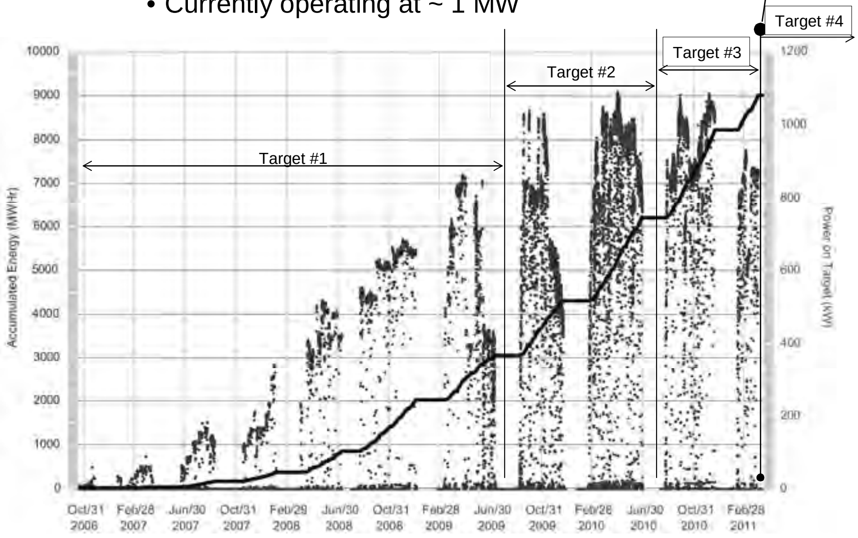
Target Service Bay

- **Stainless-steel lined**
- **4 window workstations**
- **8 through-the-wall manipulators**
- **7.5 ton crane**
- **Pedestal mounted manipulator**
- **Shielded transfer bay**



SNS Power Ramp-Up

- Currently operating at ~ 1 MW



April 3:
End of life
reached!

Target #4

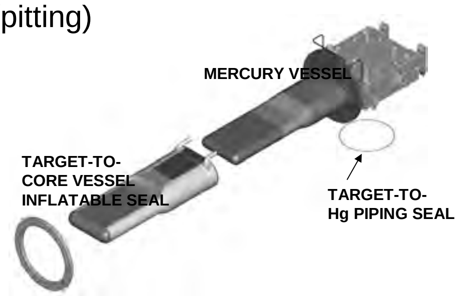
Target #3

Target #2

Target #1

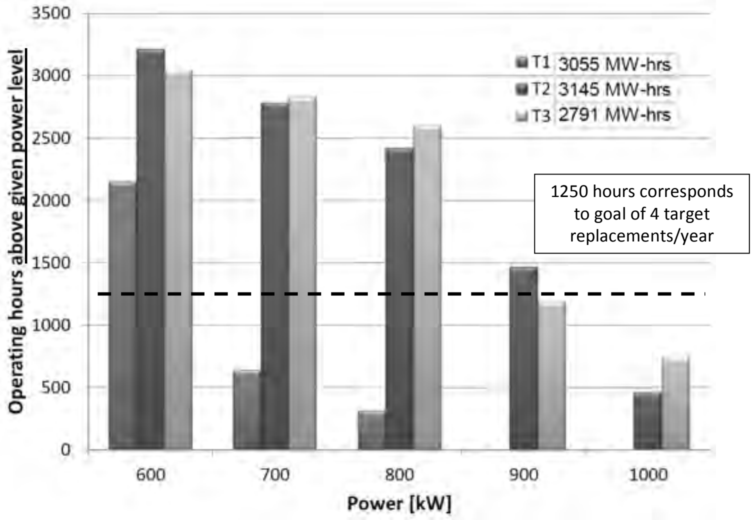
Target Status @ SNS

- 1st Target ran until July 2009 (more than 5 dpa – the design goal)
- 2nd Target replaced July 2010
- Plan: Run Targets till end-of-life, i.e. mercury leaks from primary container to its water-cooled shroud (or 10 dpa)
- 3rd Target reached end-of-life on April 3rd 2011(10 dpa reached in summer) → replaced in 14 days → PIE on Target 3 → location and characterization of leak → confirmation for cavitation erosion (pitting)



Three spare target modules on-site; five more by 2012

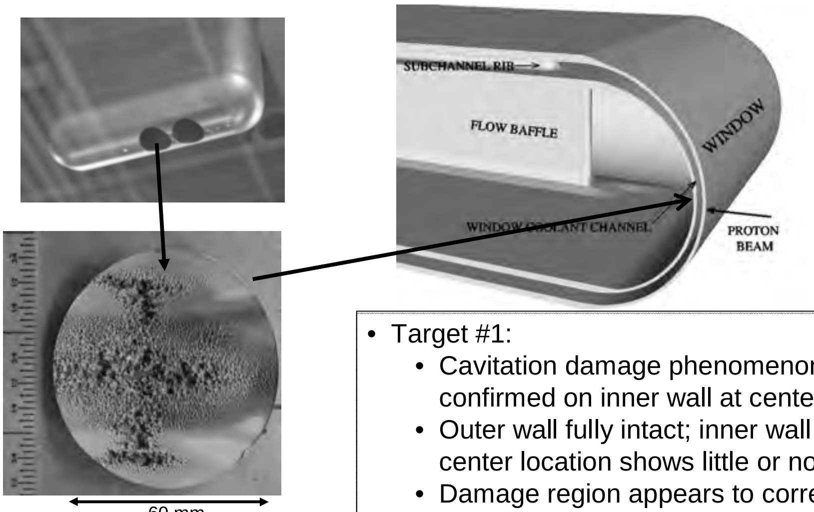
Mercury target module lifetime remains uncertain



1250 hours corresponds to goal of 4 target replacements/year

Demonstrated power limit is now > 900 kW

Results Post-Irradiation Examination Target Module #1

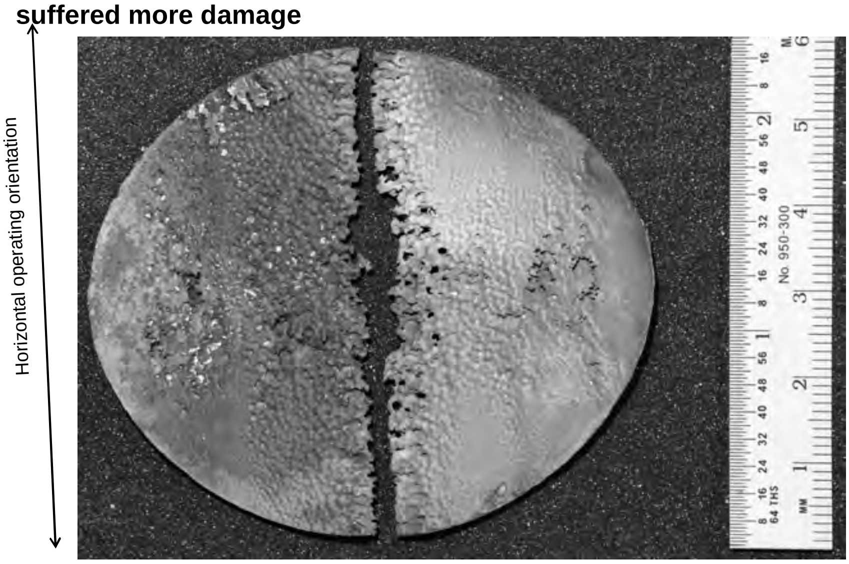


60 mm

Inner surface of wall between bulk Hg and small channel

- Target #1:
  - Cavitation damage phenomenon confirmed on inner wall at center of target
  - Outer wall fully intact; inner wall at off-center location shows little or no damage
  - Damage region appears to correlate with regions of low Hg velocity, but not such a clear distinction on Target #2

Target #2 survived through planned operating period but inner wall suffered more damage

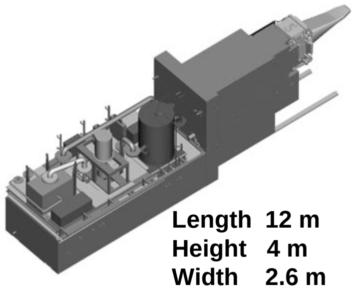


Bulk Hg Flow Surface - UNCLEANED

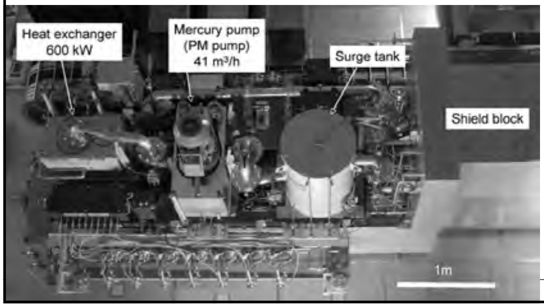
JSNS mercury target

JSNS Hg Target

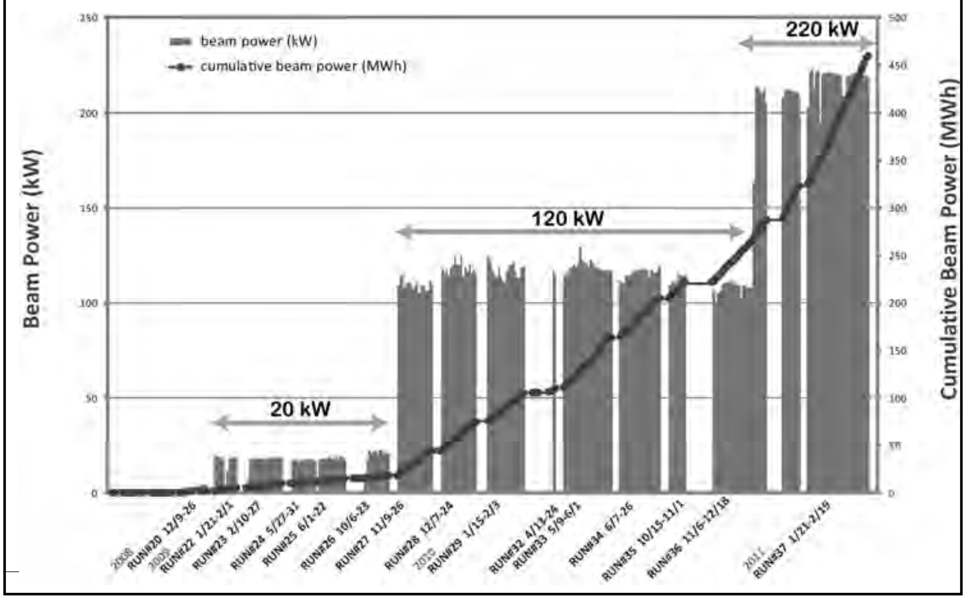
- Proton Beam (design parameters):
  - 3 GeV, 25 Hz rep rate, 0.33 mA ⇒ 1 MW
- Hg Target:
  - Cross-flow type, with multi wall vessel
  - Hg leak detectors between walls
  - All components of circulation system on trolley
  - Hot cell : Hands-on maintenance
  - Vibration measuring system to diagnose pressure wave effects



Length	12 m
Height	4 m
Width	2.6 m
Weight	315 ton

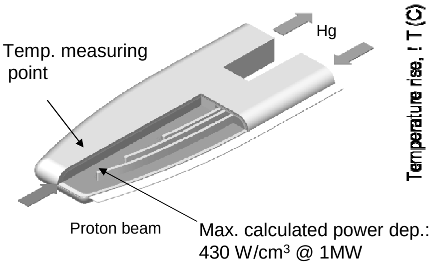


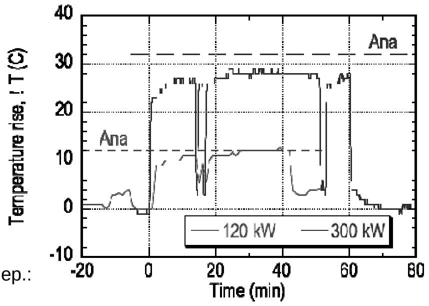
Beam power on JSNS target



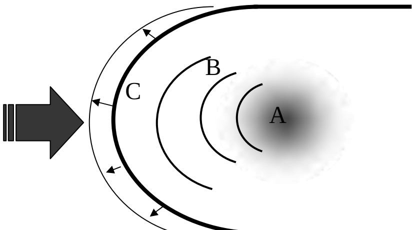
Confirmation of target system design

- Temperature rise of mercury vessel for 120 kW & 300 kW beam power agreed with estimates
  - Confirmed operation of the mercury circulation system EM pump, heat exchanger, etc.





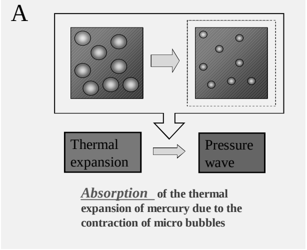
Bubble Injection to Mitigate Cavitation Damage



3 mechanisms for each region

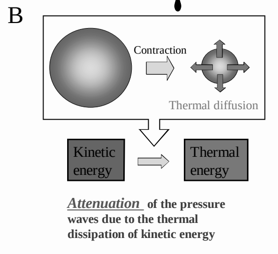
Center of thermal shock : A
Absorption
Propagation path : B
Attenuation
Negative pressure field : C
Suppression

Bubble<50 μm



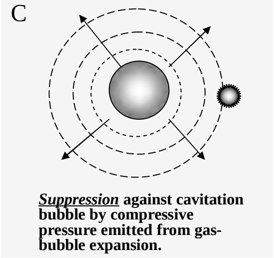
Absorption **of the thermal expansion of mercury due to the contraction of micro bubbles**

Absorption



Attenuation **of the pressure waves due to the thermal dissipation of kinetic energy**

Attenuation



Suppression **against cavitation bubble by compressive pressure emitted from gas-bubble expansion.**

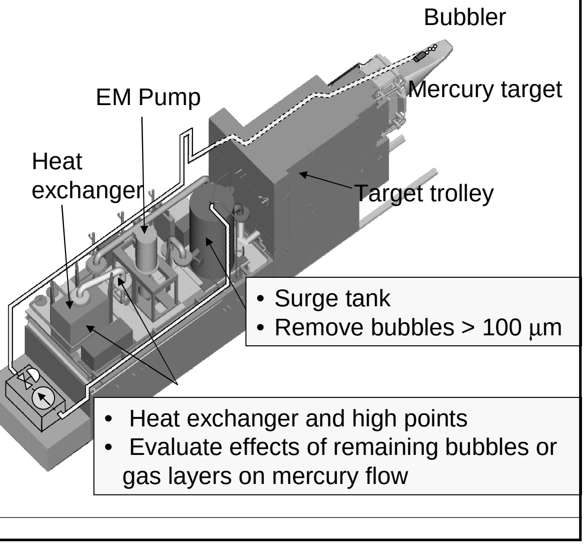
Suppression

Gas supply system for bubblers

Component tests are being carried out in water and mercury loops

Conceptual design is being made by a company

Mercury loop



- Surge tank
- Remove bubbles > 100 μm

- Gas supply system
- Control gas pressure and flow rate

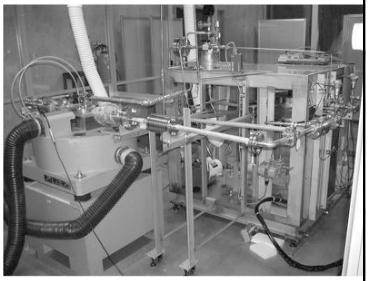
- Heat exchanger and high points
- Evaluate effects of remaining bubbles or gas layers on mercury flow

Strong Collaboration Between JSNS and SNS

Facilities for cavitation damage characterization and mitigation tests:

- Off-line tests
  - JAEAs impact testing apparatus (MIMTM)
  - ORNLs full-scale Hg loop (TTF)
- In-Beam Tests at LANLs WNR facility

Characterize bubbles, measure mitigation effects, etc.



MIMTM

WNR

TTF

Conclusion Spallation Targets

- ❖High power targets (solid and liquid) are operated in the 1 MW regime.

- ❖Target lifetime is mostly limited by following effects
  - ❖Radiation damage → Embrittlement, fatigue or more general change of material properties due to irradiation
  - ❖Cavitation Erosion (Pitting) in case of LMT

- ❖All laboratories do extensive Post Irradiation Examination (PIE) of spent Targets → knowledge data base growing

- ❖At power levels > 1 MW the biggest problems are:
  - ❖Dissipation of energy densities (liquid targets, rotating targets …)
  - ❖Shock waves → search for new structural materials,mitigation

- ❖**Personal opinion**: In the regime of 1 MW it is not clear which target concept (Liquid Metal Target or Solid Target) is advantageous.

- ❖**New projects aiming for higher beam powers (2 MW+) need know-how from existing sources → intensive collaborations**

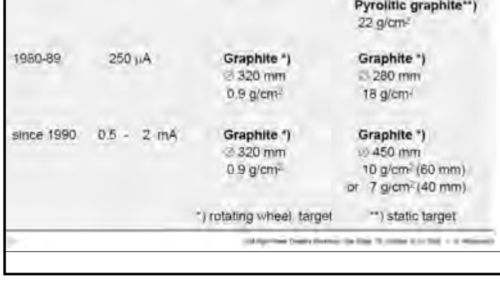
Meson and Neutrino targets

„Target E“ @ PSI

Meson Production Targets at PSI

Basic parameters

- ❖590 MeV proton cyclotron with maximum current of 2.2 mA (~1.3 MW)
- ❖2 meson production targets:
  - ❖Target „M“ (mince, 5 mm graphite)
  - ❖Target „E“ (epaisse, 4 cm graphite)



		Target M	Target E
1974-80	< 100 μA	**Be, Graphite *)** ⌀ 190 mm 0.9 g/cm^2	**Be, Graphite *)** ⌀ 190 mm 22 g/cm^2 **Pyrolitic graphite**)** 22 g/cm^2
1980-89	250 μA	**Graphite *)** ⌀ 320 mm 0.9 g/cm^2	**Graphite *)** ⌀ 280 mm 18 g/cm^2
since 1990	0.5 - 2 mA	**Graphite *)** ⌀ 320 mm 0.9 g/cm^2	**Graphite *)** ⌀ 450 mm 10 g/cm^2 (60 mm) or 7 g/cm^2 (40 mm)

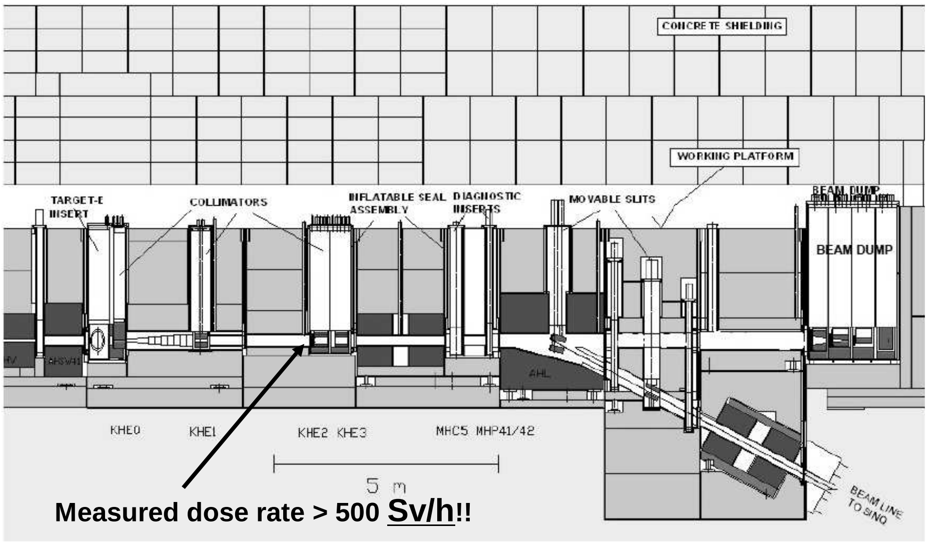
*) rotating wheel target **) static target

History of meson targets at PSI

- Mainly graphite targets
- Targets radiation cooled
- Operated in continuous mode (no pulses)
- Target M: σ_x=0.8 mm σ_y=0.9 mm
- Target E: σ_x=0.75 mm σ_y=1.3 mm

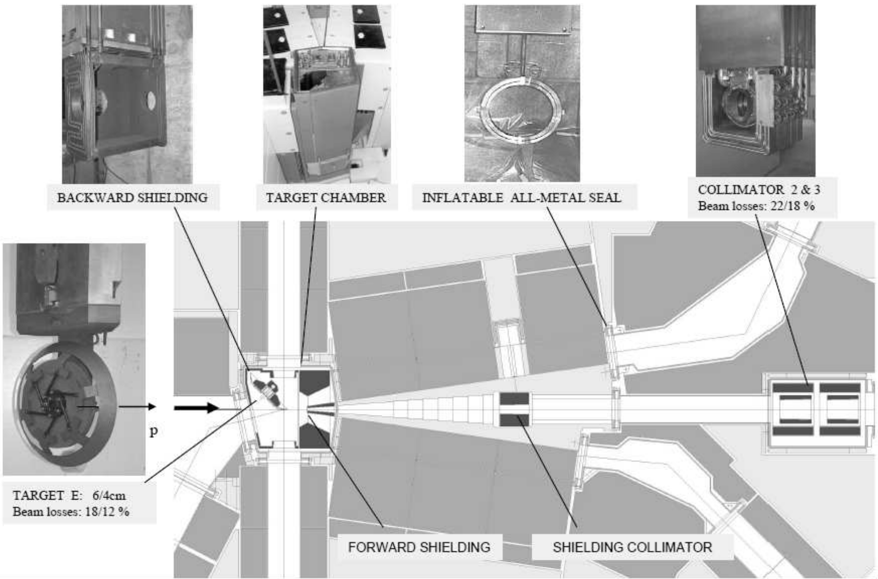
Design of „p-Kanal“, Target E, collimators & beam dump

High dose rates at beam level shielded → working platform moderate dose

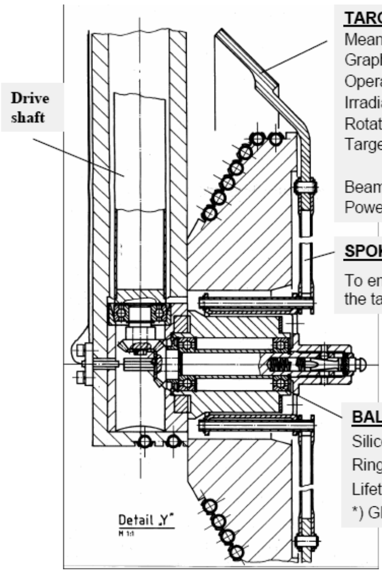


Measured dose rate > 500 Sv/h!!

Meson production Target E



Meson production Target E



TARGET CONE

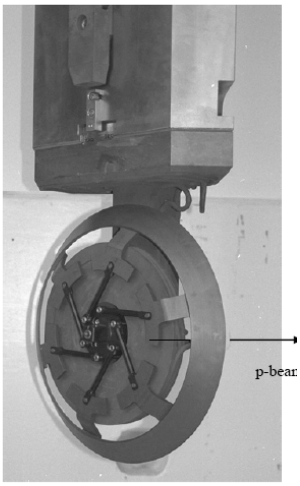
Mean diameter: 450 mm
Graphite density: 1.8 g/cm³
Operating Temperature: 1700 K
Irradiation damage rate: 0.1 dpa/Ah
Rotational Speed: 1 Turn/s
Target thickness: 60 / 40 mm
10 / 7 g/cm²
Beam loss: 18 / 12 %
Power deposition: 30 / 20 kW/mA

SPOKES

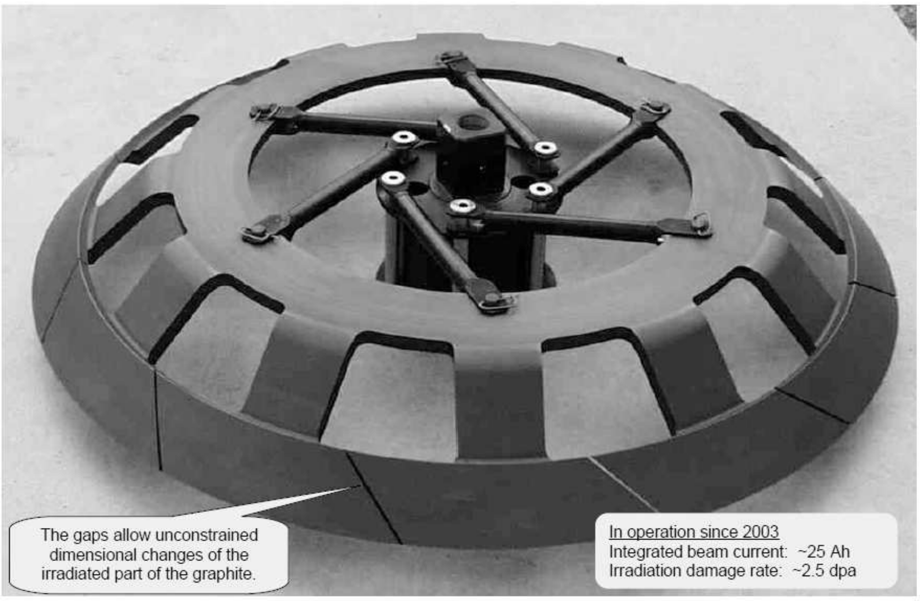
To enable the thermal expansion of the target cone

BALL BEARINGS *)

Silicon nitride balls
Rings and cage silver coated
Lifetime 2 y
*) GMN, Nürnberg, Germany



Target E – latest design



The gaps allow unconstrained dimensional changes of the irradiated part of the graphite.

In operation since 2003
Integrated beam current: ~25 Ah
Irradiation damage rate: ~2.5 dpa

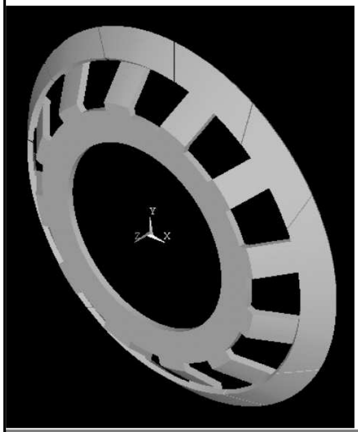
Target E – Temperatures & Stresses

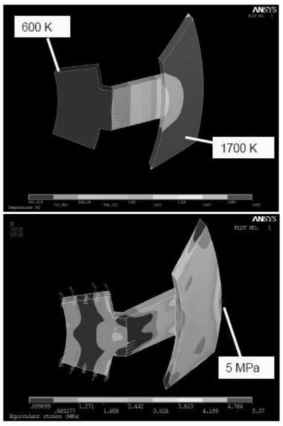
$$Q\left[\frac{\mathrm{W}}{\mathrm{m}^2}\right]=\varepsilon\cdot\sigma_{SB}\cdot T^4$$

ε ... emissivity

σ_{SB} ... Stefan - Boltzmann Konstante $(=5.67\cdot10^{-8}\frac{W}{m^2K^4})$

T ... Temperature [K]





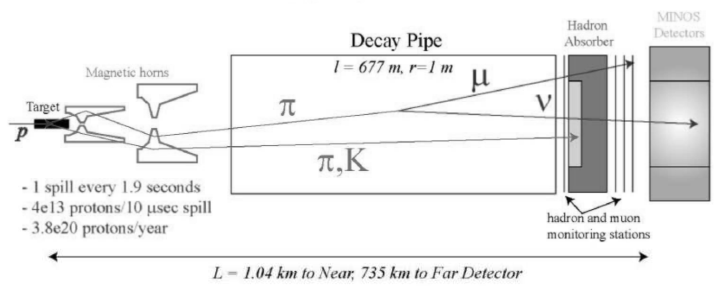
Radiation cooling

- Very effective at high temperatures.
- Cool surrounding instead of target.
- High emissivity necessary.

Neutrino Production Targets

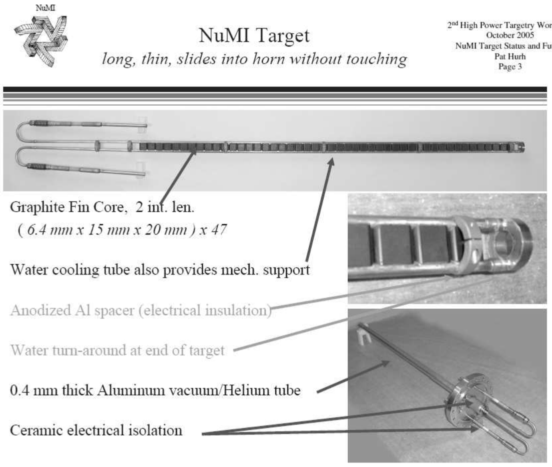
Production principle

Production scheme of Neutrino beam



NuMi Target (LE option)

~1 meter long graphite target, water cooled
120 GeV proton beam N_p=4 10^{13} (f=0.53 Hz, pulse length 10 µs, gaussian shape σ_x=0.7 mm σ_y=1.4 mm)
p+A → π (T=2.6033·10^{-8} s) emerge from target → decay in long tunnel → π → µ +ν_μ (99.987%)
Intense ν_μ neutrino beam (contamination due to µ → e + ν_e + ν_μ)



NuMI Target
long, thin, slides into horn without touching

2nd High Power Targetry Workshop
October 2005
NuMI Target Status and Future
Pat Hurh
Page 3

Graphite Fin Core, 2 int. len.
(*6.4 mm x 15 mm x 20 mm*) x 47

Water cooling tube also provides mech. support

Anodized Al spacer (electrical insulation)

Water turn-around at end of target

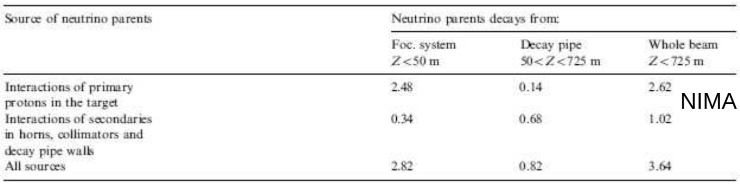
0.4 mm thick Aluminum vacuum/Helium tube

Ceramic electrical isolation

Neutrino Target

- Long (2 -3 interaction lengths), thin sturctures → fast escape of mesons (π,K..)
- Shape governed by magnetic focusing system (horns) → inside horns
- Highly focussed beam → large energy densities
- Current targets → low Z materials (C, Be)
- Future targets → high Z foreseen (Hg, W …)

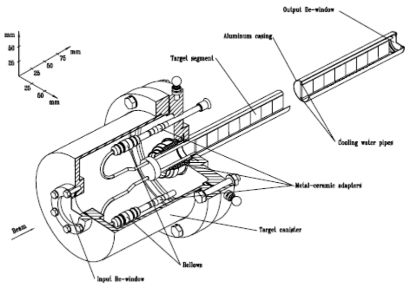
NuMi Target (LE option)



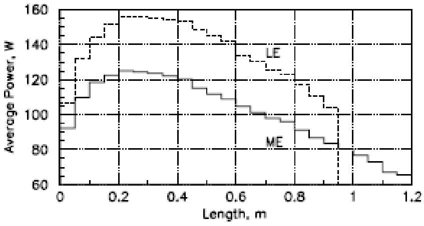
Source of neutrino parents	Neutrino parents decays from:		
	Foc. system $Z < 50$ m	Decay pipe $50 < Z < 725$ m	Whole beam $Z < 725$ m
Interactions of primary protons in the target	2.48	0.14	2.62
Interactions of secondaries in horns, collimators and decay pipe walls	0.34	0.68	1.02
All sources	2.82	0.82	3.64

NIMA 485, p. 209, 2002

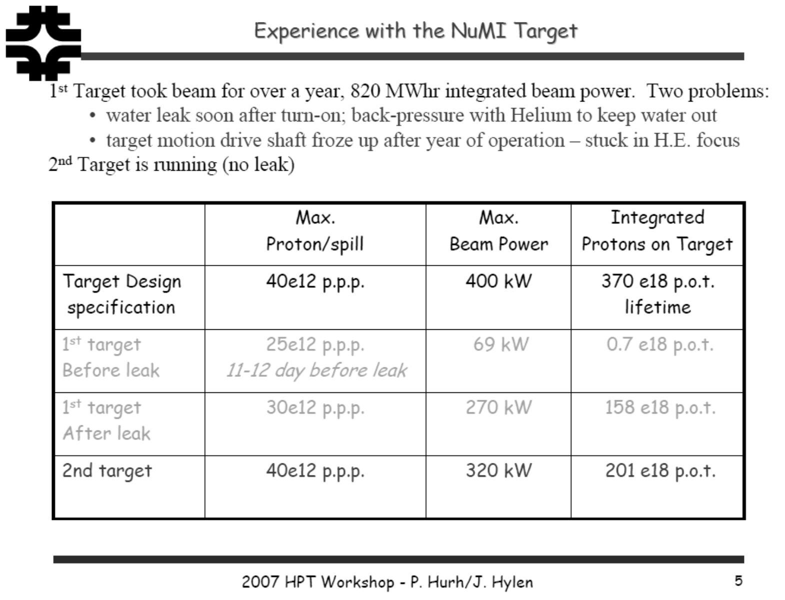
NIMA 485, p. 209, 2002



Power deposition along LE (low energy) and ME (medium energy targets → energy density (0.092 GeV/cm^3)



NuMi Target (LE option)



Experience with the NuMI Target

1st Target took beam for over a year, 820 MWhr integrated beam power. Two problems:

- water leak soon after turn-on; back-pressure with Helium to keep water out
- target motion drive shaft froze up after year of operation – stuck in H.E. focus

2nd Target is running (no leak)

	Max. Proton/spill	Max. Beam Power	Integrated Protons on Target
Target Design specification	40e12 p.p.p.	400 kW	370 e18 p.o.t. lifetime
1st target Before leak	25e12 p.p.p. *11-12 day before leak*	69 kW	0.7 e18 p.o.t.
1st target After leak	30e12 p.p.p.	270 kW	158 e18 p.o.t.
2nd target	40e12 p.p.p.	320 kW	201 e18 p.o.t.

Neutrino Targets

Neutrino targets	Laboratory	Energy/momentum		Target material	
CNGS	CERN	400 GeV/c protons $2.4\cdot10^{13}$ ppp 512 kW		Carbon	L=2.2 m Air Cooling
NuMi	Fermi National Laboratory	120 GeV/c protons f=0.53 Hz		Carbon	L = 1 m Water cooling
MiniBoone	Fermi National Laboratory	8 GeV protons $5\cdot10^{12}$ ppp f=5 Hz		Beryllium	L = Air Cooling
T2K	J-Parc				

Conclusion Neutrino Targets

•High energy densities and resulting thermal shocks currently set limit for (solid) neutrino targets → cyclic stresses → fatigue limits

•New target concepts for v-Production targets address following issues:

- Dissipation of energy due to rotating/moving targets
- Liquid metal targets (as e.g. MERIT)
- High Z materials → higher neutrino production
- Extensive tests of materials

Beam Dumps

Beam Dumps

- Used during beam development and set-up of accelerators
  - Generally not used during normal operation (except for colliders)
- Parts of accelerators can be optimized → other parts do not see beam
- Have to absorb and stop primary beam particles → secondary particles in general shielded by a so-called biological shield (concrete, earth …)
- Essentially the same requirements as targets (not for particle production) → same assessment
  - Beam often defocussed to reduce peak current densities → reduction of power densities
- High Z materials favored
  - Often medium Z materials such as Steel or Copper used

3 GeV Extraction Beam Dump JSNS

Y. Kasugai and H. Kogawa
JAERI

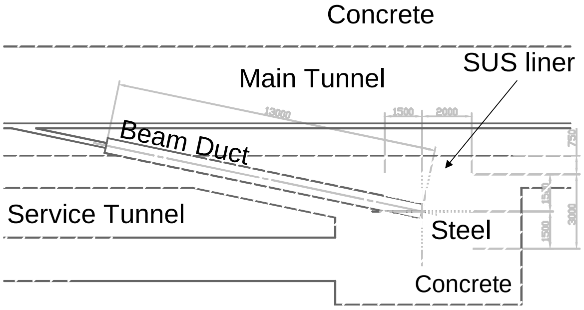
Specification

Maintenance free and passive cooling

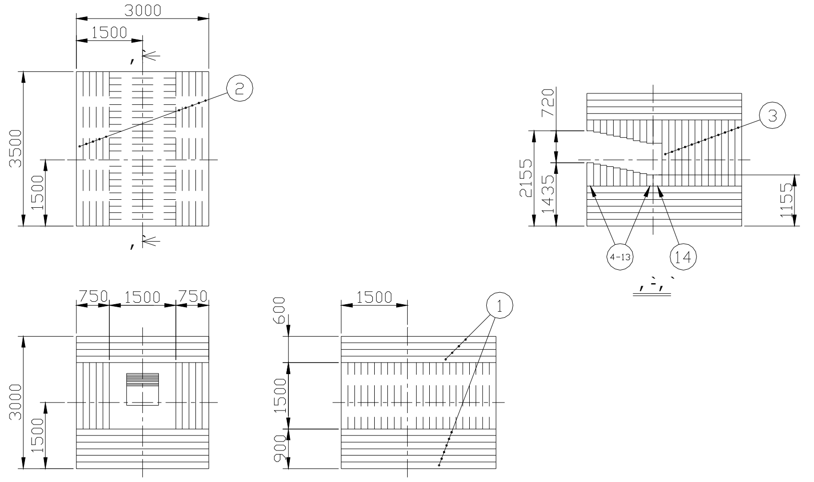
Maximum proton beam power: 4 kW

Configuration

- Steel: 3.5 m × 3.0 m × 3.0 m, type 304-SS liner.
- Concrete: 2.0 m in thickness.
- Beam duct



Configuration of Steel



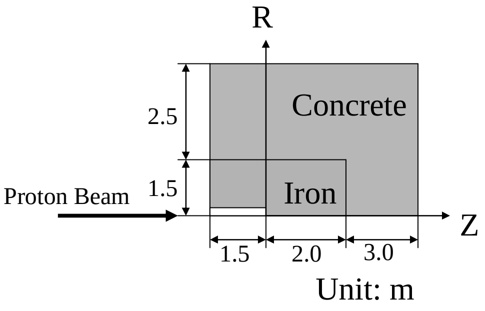
Radiation Dose

Technical requirement

- Radiation dose limit at boundary of concrete and soil is set to be less than 11 mSv/hr.
- Safety margin of factor 2 should be considered for calculation.
- That means less than 5 mSv/hr is required for shielding calculation.

Calculation

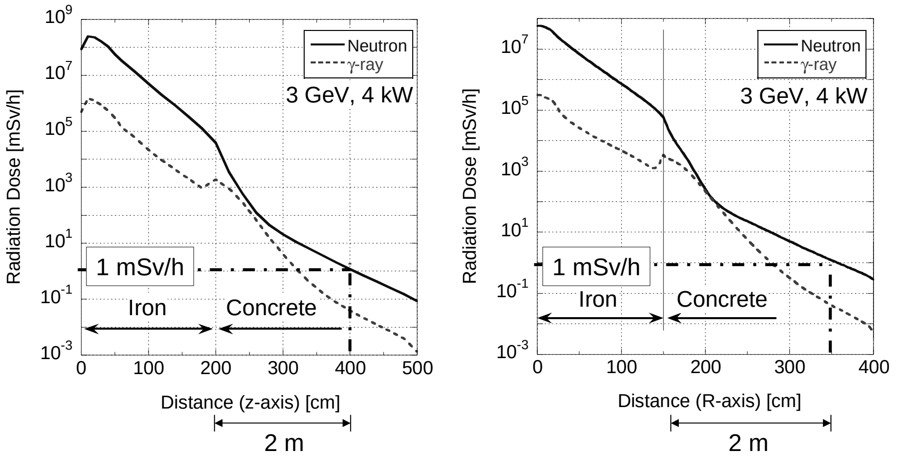
- NMTC/JAM + DORT
- Calculation Model: R-Z



Radiation Dose

Calculation results

- Concrete with 2 m thickness is sufficient.



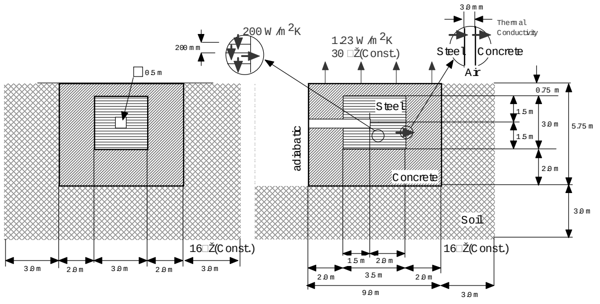
Thermal Distribution

Technical requirement

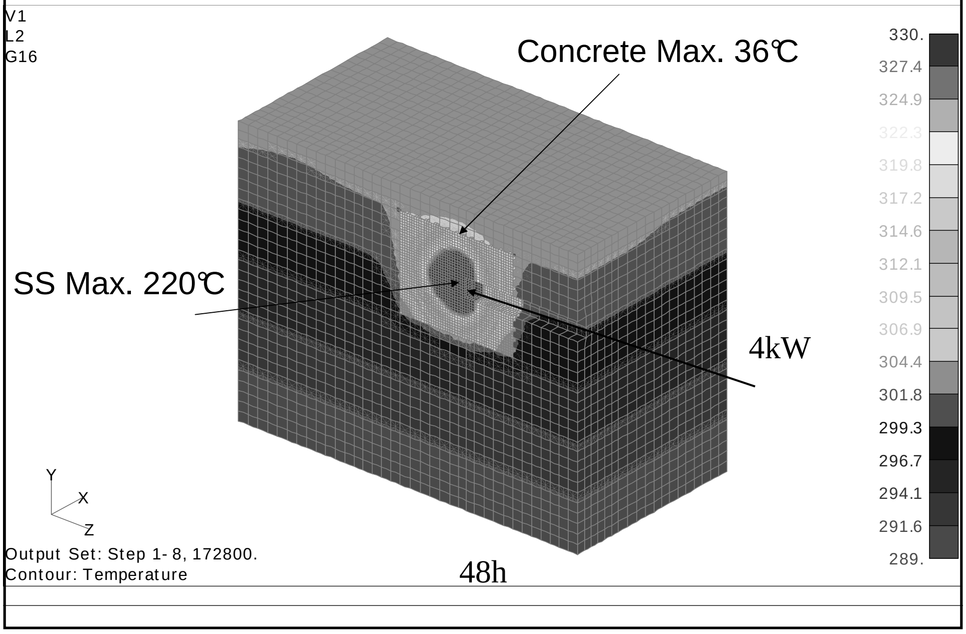
- Temperature of concrete should be kept less than 60℃ in order to keep the structural strength.

Calculation

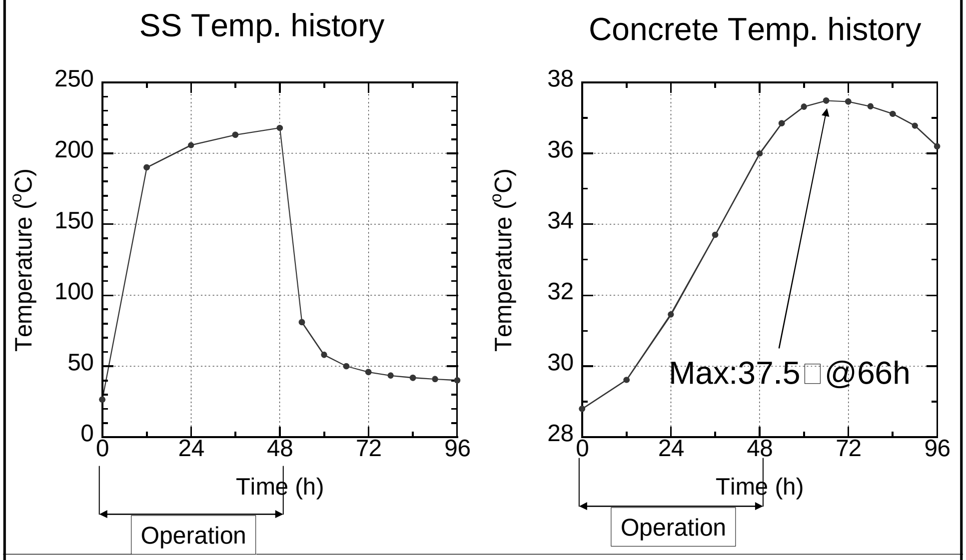
- Heat deposition: NMTC/JAM
- Thermal conduction: ABAQUS
- Continuous operation for 48 hours is assumed.



Thermal Distribution at 48 hours



Temperature History


SS Temp. history

Concrete Temp. history

PSI 590 MeV beam dump

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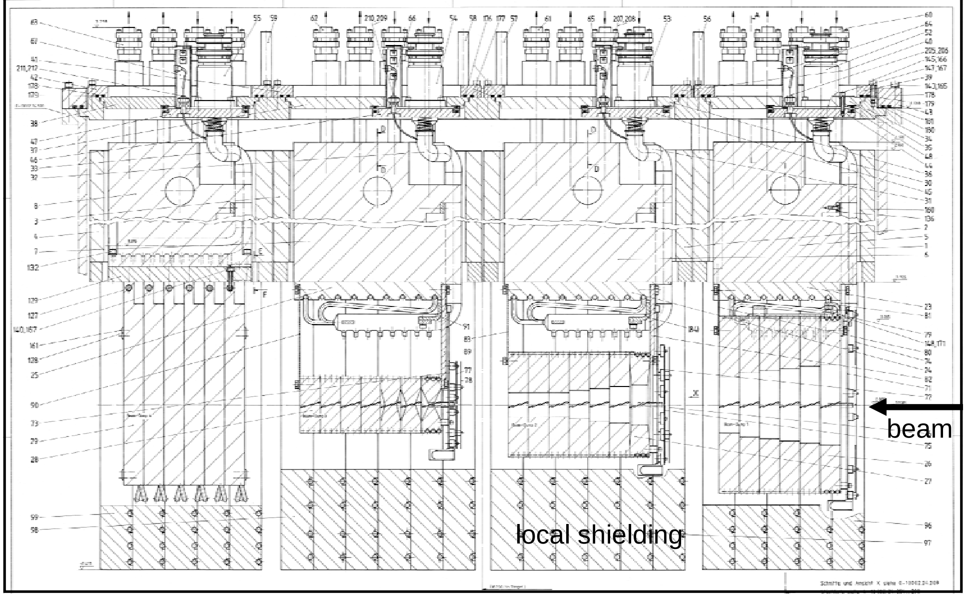
590 MeV Beam Dump: side view

Material: copper

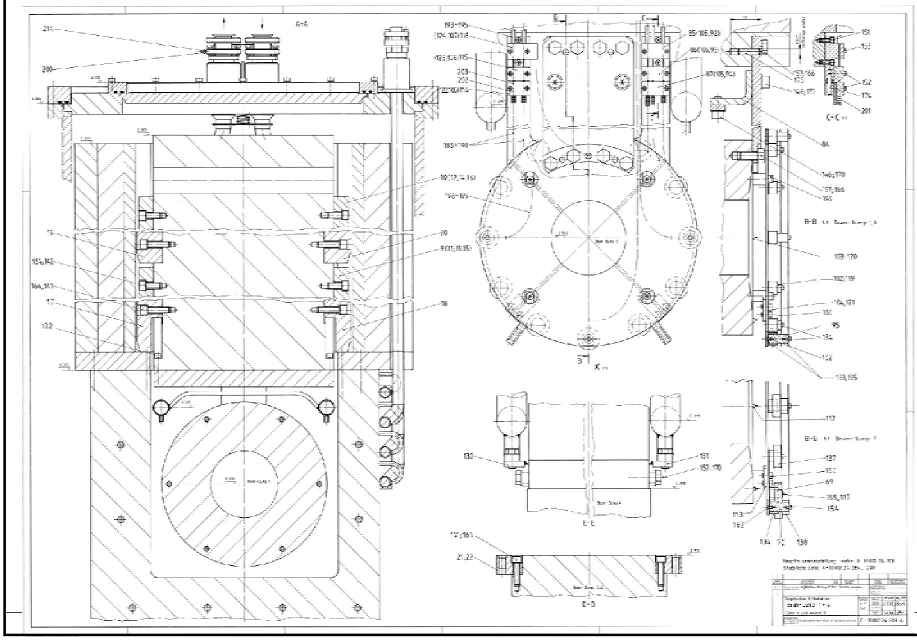
water cooled



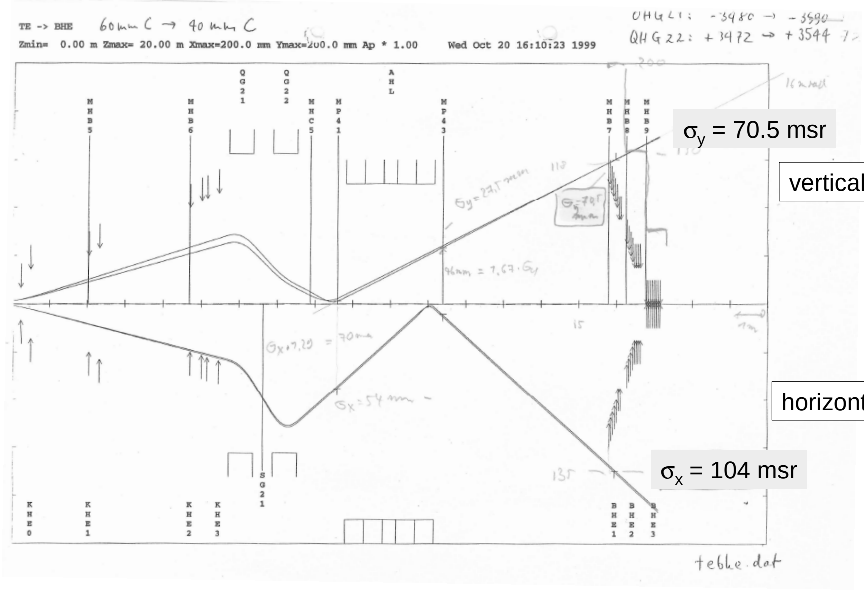
beam

local shielding

590 MeV Beam Dump: front view



Beam envelope from Target E (6 cm) to Beam Dump



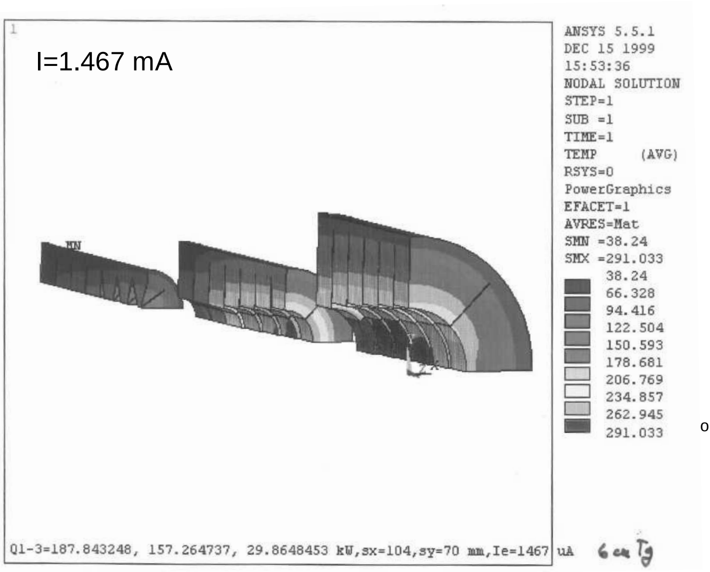
σ_y = 70.5 msr

vertical

horizontal

σ_x = 104 msr

Temperature distribution for 6 cm C-target E



I=1.467 mA

°C

Key parameters

on beam dump

	size (cm)	slices	power deposit (kW/mA)	water flux (l/s)
1.section:	30 x 44	6	220	4.2
2.section:	35 x 26	7	180	4.2
3.section:	35 x 14	7	30	4.2
4.section:	30 x 50.5	6	- (= shielding)	1.2
local shielding			30-60	1.2

designed for
2 mA with 6 cm C-Target E → 40% beam loss → 1.2 mA on beam dump
1.6 mA 4 cm → 30% → 1.12 mA

total max. power deposit: 500 kW
highest power density: 350 W/cm^3
highest temperature: 380 °C for 2mA, 6 cm C-Target E
< 405 °C (allowed limit due to recristallisation of Cu)

energy deposit: 425 MeV/mA
proton range: 23 cm

Thank you for your attention.