Workshop on High-power Targetry for Future Accelerators

Summary

Solid Targets

Roger Bennett

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- There were many presentations with useful information concerning solid targets even if not specifically about solid targets.

- It is not possible to cover every presentation - pick out the important points as I see it.

Crucial information for designing a target (and surroundings):

- the energy density distribution
- the radioactivity inventory
- materials and irradiation properties
- safety issues

Nikoli Mokhov

Very detailed presentation on target interactions, energy depositions etc and accuracy of the various codes and their areas of strength and weakness.

Lauri Waters

MCNPX and TRAC codes

Richard Werbeck

Safety issues - some real life examples

John Haines

Safety issues at SNS

Eric Pitcher

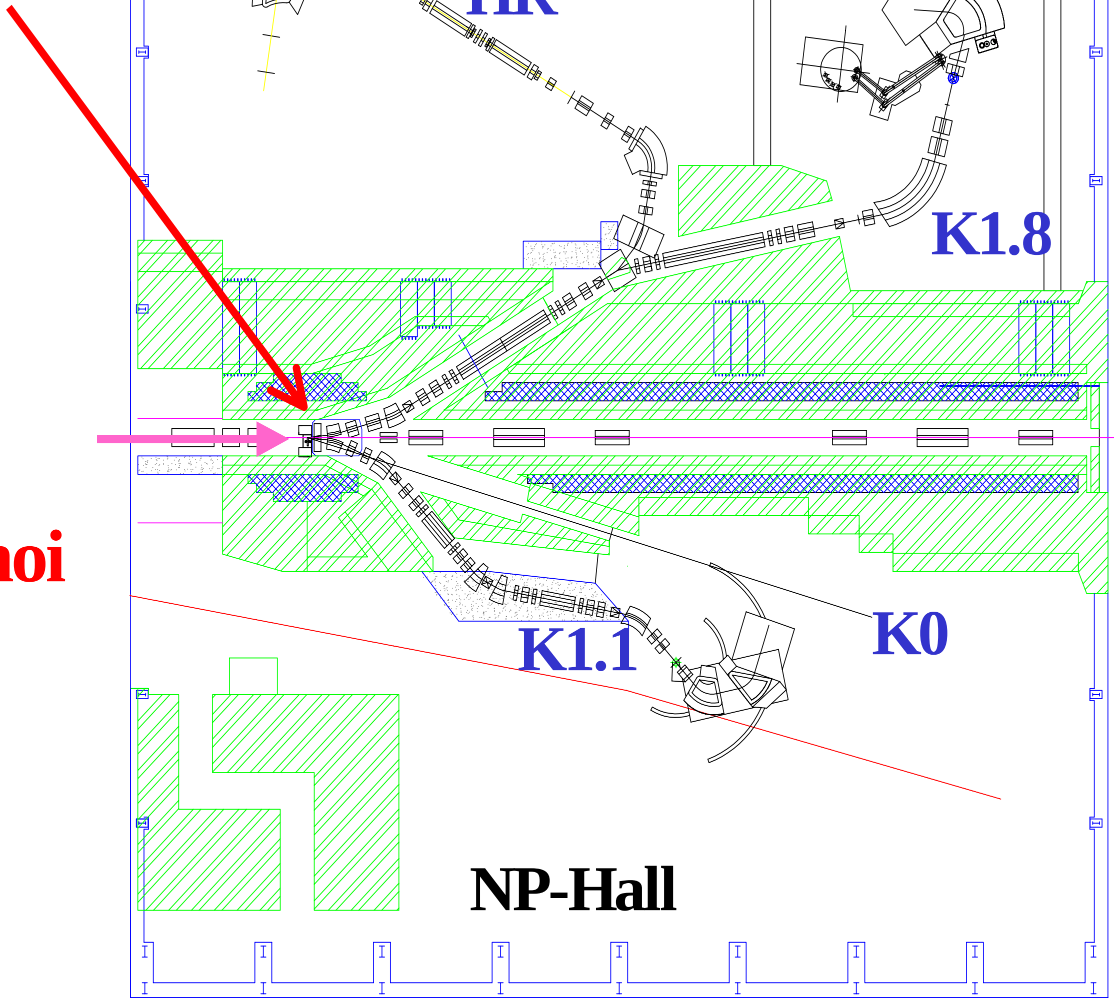
Fuels and materials test station.

Yoshikazu Yamada, (KEK) JPARC Main Ring Targets

Rotating nickel target for kaons with an energy density of 5300 Jcm^{-3}. Water cooled (gas cooling also considered). Novel design - simple water cooling. Consideration of total design, windows, containment, activation, shielding and remote handling.

Possible problems due to corrosion.

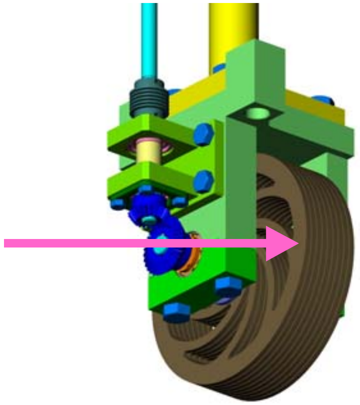
Target and secondary beam lines



Production target : T1

Rotating Nickel disks

- thickness: ~54 mm
- radius: ~24 cm
- cooled by water
- developed by **Y.Yamanoi** et. al.



Design of T1

1.3x10^{21} protons/year on Target (4000 hours/year)

- Radiation shielding
- Max. yield of secondary beam

} ⇒ 30% interaction

- Temperature rise
- Point source for secondary beam

} ⇒ Ni target

no rotation

	length of 30% interaction (cm)	max. heat density (J/cm^3)	density (g/cm^3)	specific heat (J/g/K)	temperature rise by a pulse (K)
Pt	3.15	25000	21.5	0.14	8590
Ni	5.31	5280	8.9	0.44	1340
Al	14.06	1940	2.7	0.87	820

Water cooling of T1

- **Rotating Ni disks**
  - Diameter : 48cm, Thickness : 54 mm (9mm-t×6disks)
  - 1 rotation per 0.7s (slow extraction period) : 85 RPM
- **Partially cooled by water**

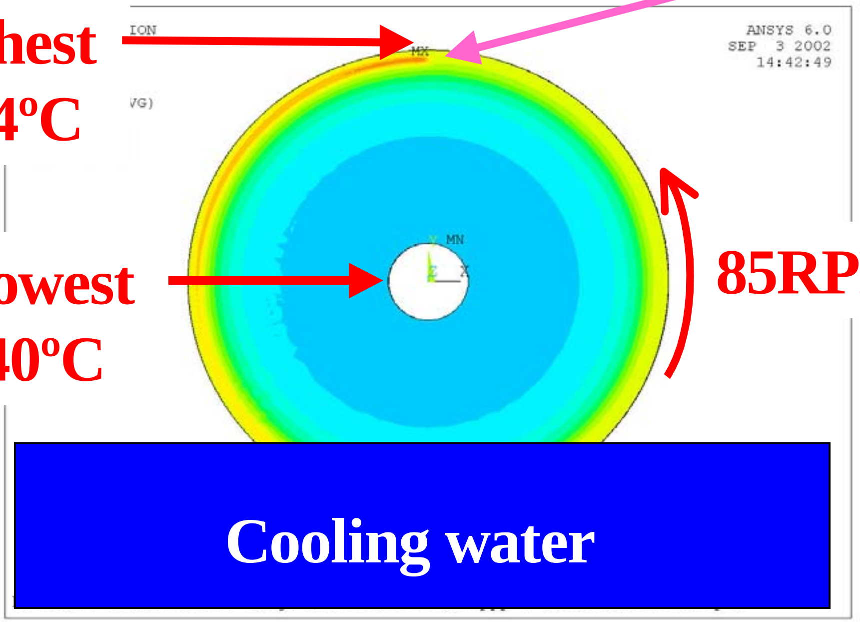
ϕ48cm x 54mm^t

beam

Highest ~94°C

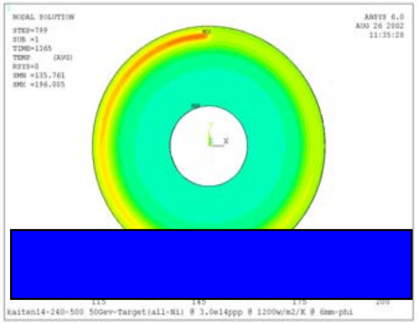
Lowest ~40°C

85RPM



ANSYS:
- After 0.7s exposure
- 1200 W/m^{2}K assumed

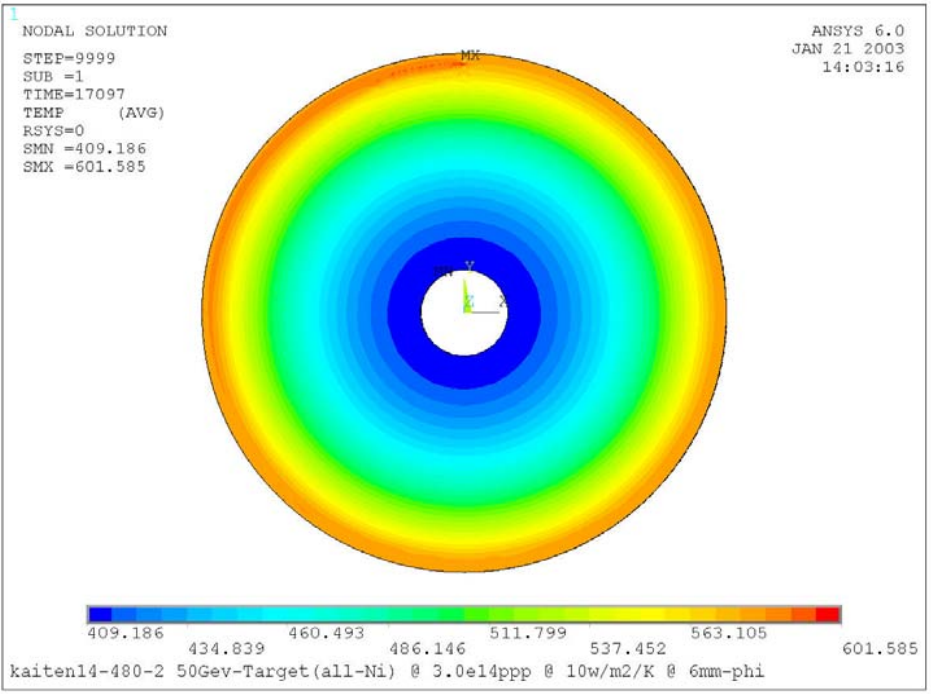
ϕ24cm x 54mm^t



Highest ~196°C
Lowest ~136°C

Gas cooling of T1

ϕ48cm x 54mm^t



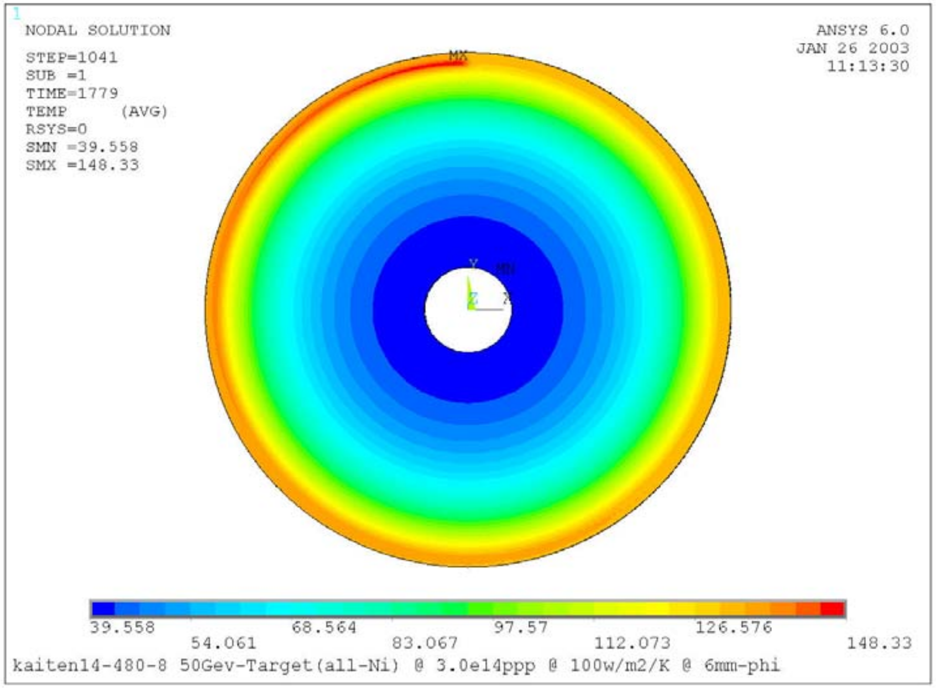
Natural convection

10 W/m^{2}K assumed

⇒ Highest ~ 602°C: too high

Lowest ~ 409°C

ϕ48cm x 54mm^t



Forced convection

100 W/m^{2}K assumed

⇒ Highest ~ 148°C: still high

Lowest ~ 40°C

R&D for T1

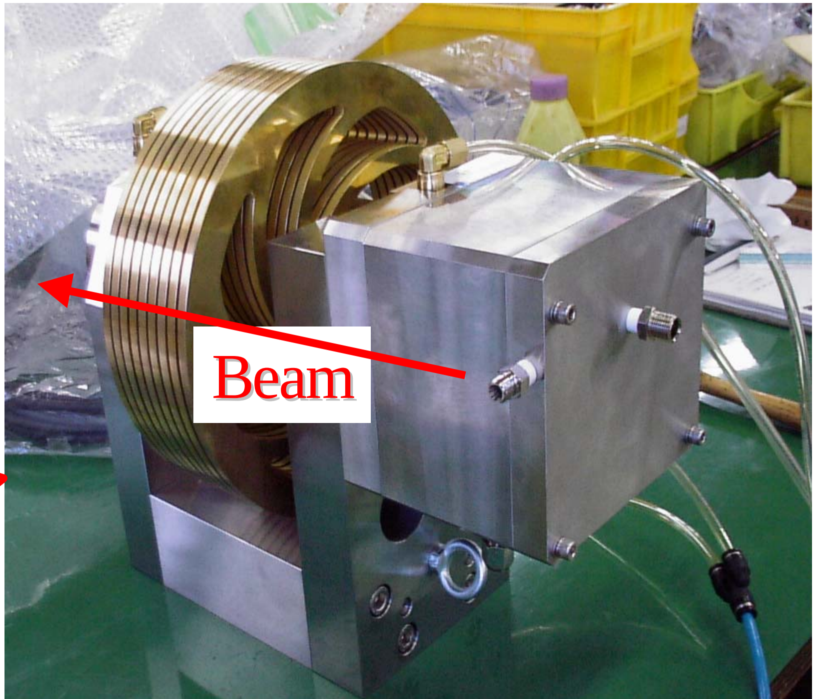
Items

- Optimization of diameter, thickness, # of disks(gaps)
- Rotation speed, Method of rotation
- Durability
- Container & shielding
- Cooling system
- Beam window & vacuum sealing
- Maintenance method

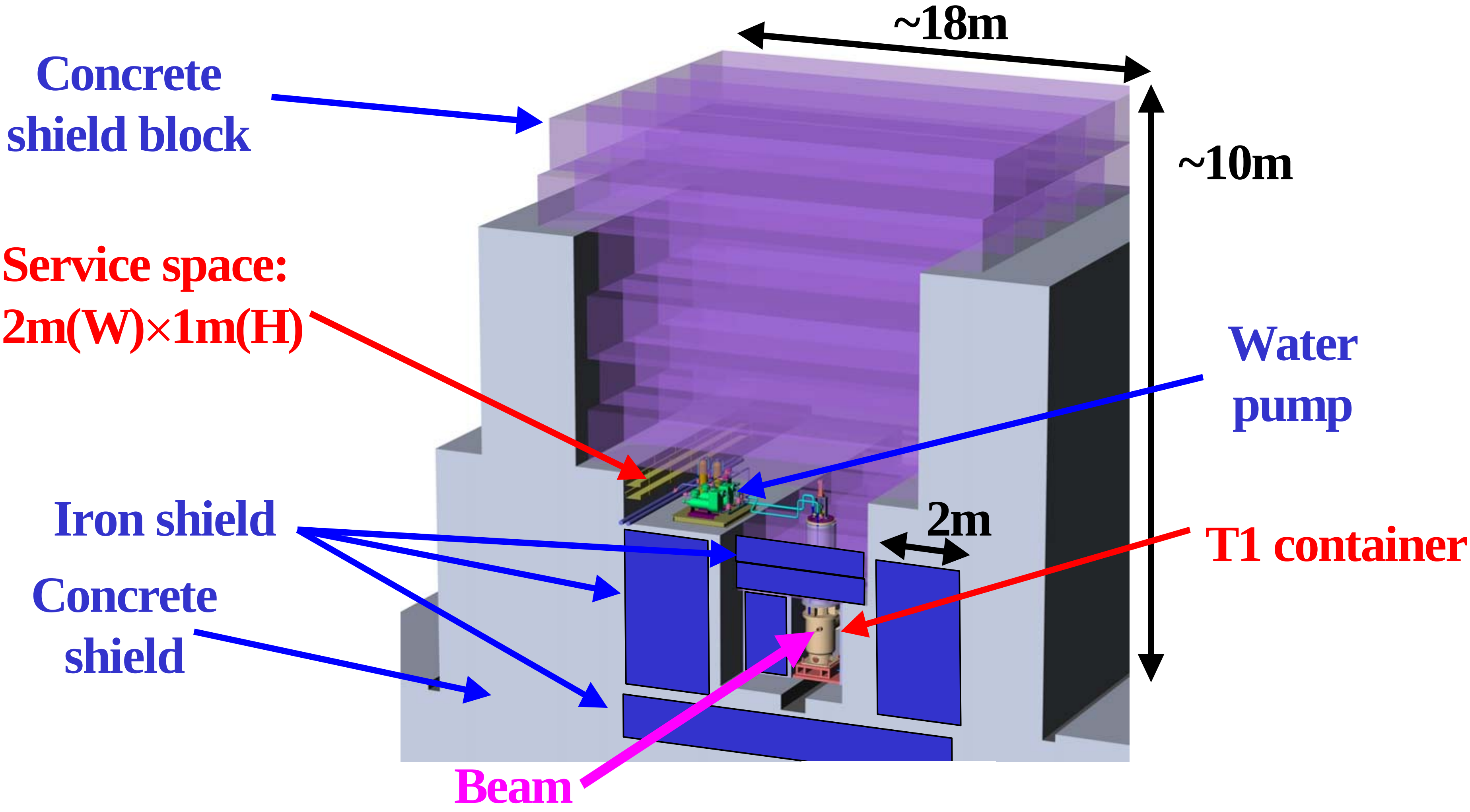
⇒

- **Prototypes**
- **Mockup**

Nickel disks (ϕ24cm x 6mm^t x 9, 24kg)



Shield around T1

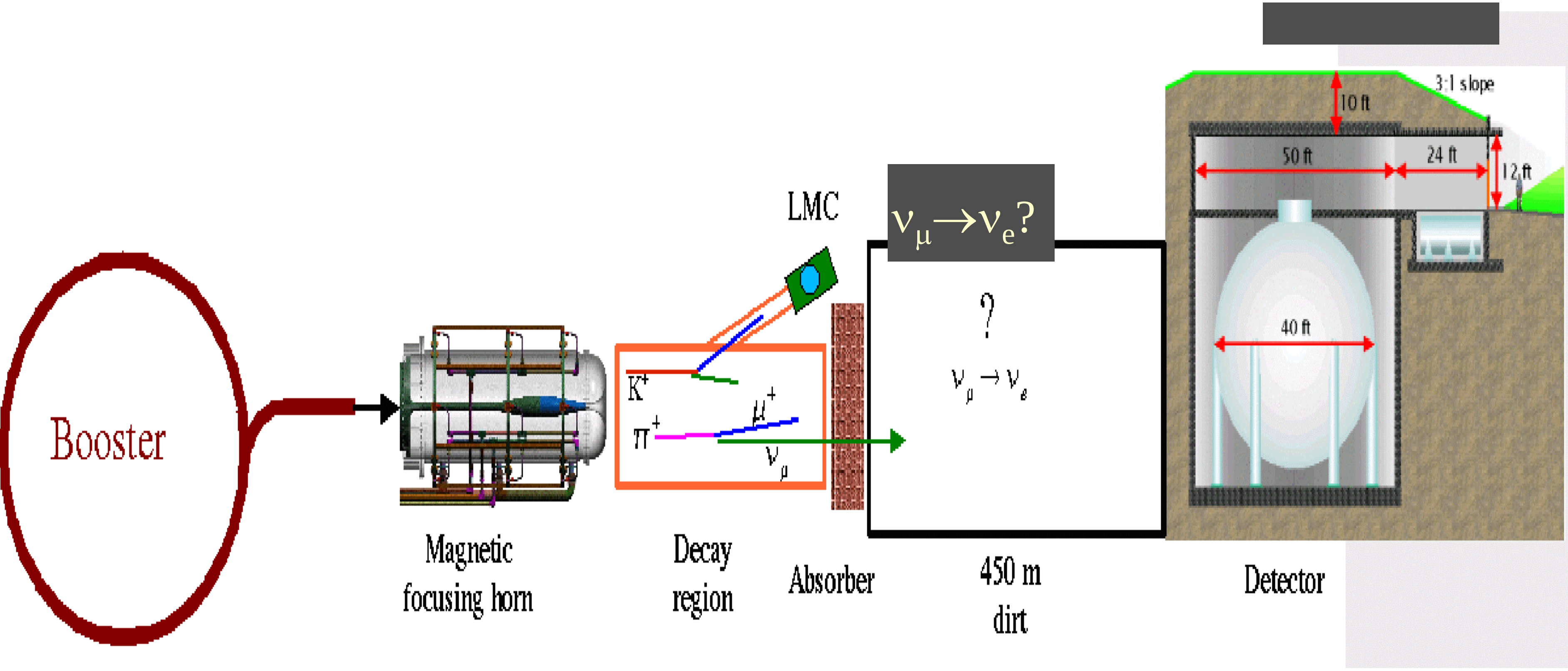


The whole system will be tested by the T1 mockup.

Geoff Mills - The MiniBoone Proton Target (FNAL)

Fully constructed and operational beryllium target for pion production with magnetic horn. Air cooled. Segmented to avoid any possible shock problems. 600 W at 5 Hz. Energy density 35 J cm^{-3}.

The MiniBooNE Neutrino Beam



MiniBooNE Target Requirements

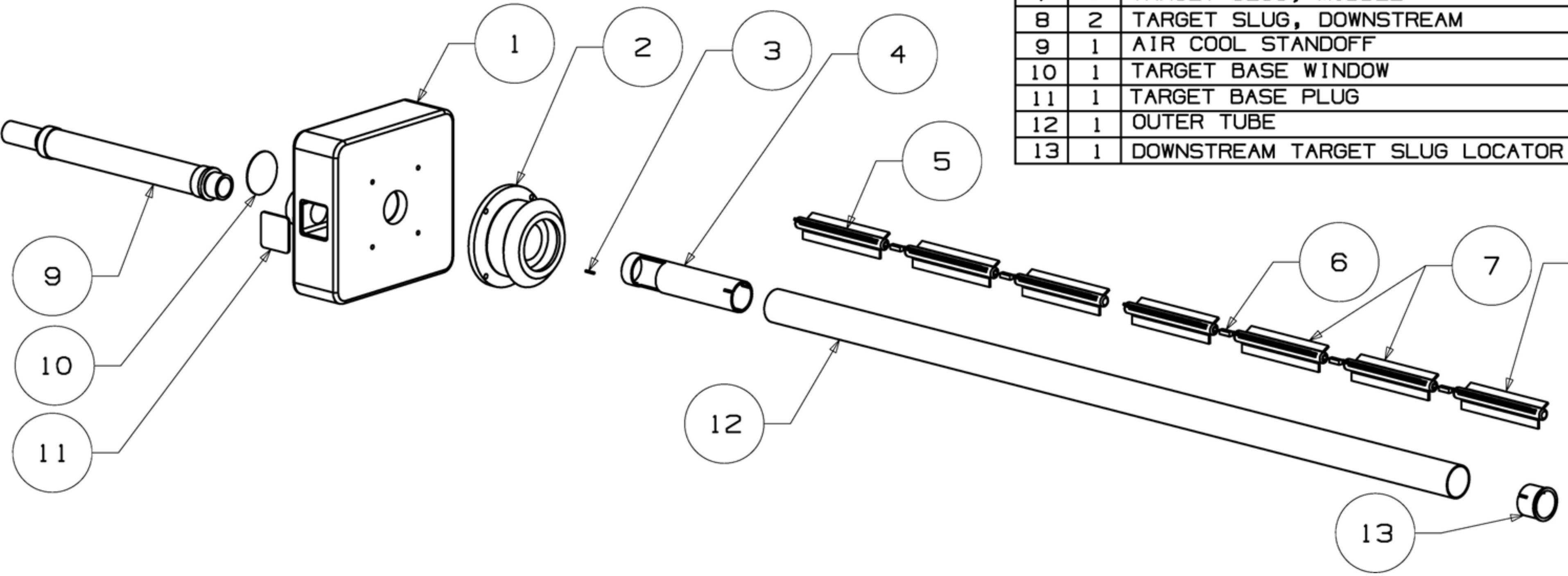
- Maximize pion yield
- Long lifetime (~10^{22} p.o.t.)
- 5×10^{12} p.o.t. @ 5 Hz and 8 GeV/c
- Separately removable from horn
- Fit inside 3 cm horn inner conductor
- Low residual activity

Design

- 3/8 inch diameter segmented Be target material
- 1.5mm beam spot sigma
- 1.75 interaction length target material
- Longitudinal air-flow for cooling

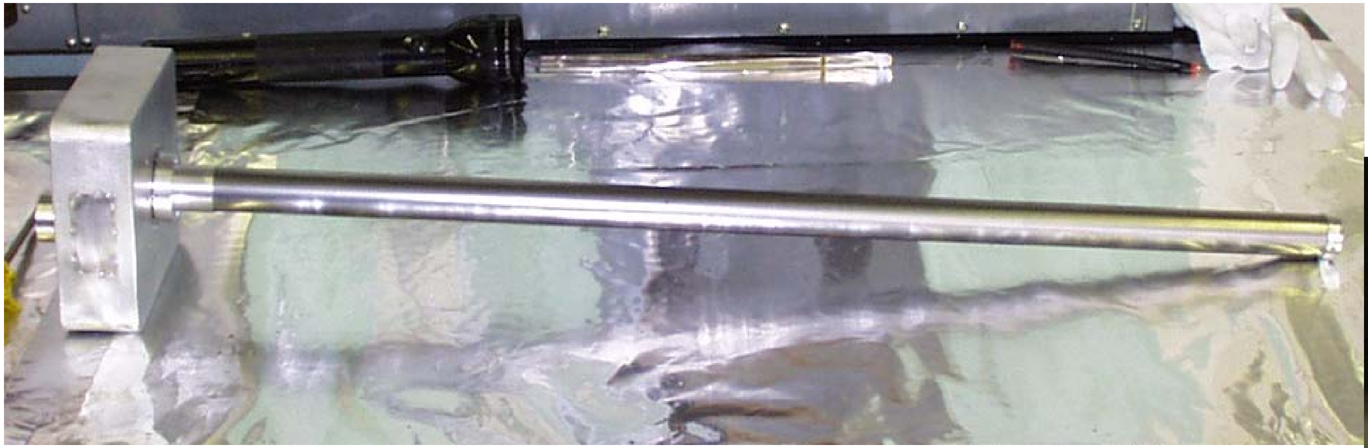
Target Assembly

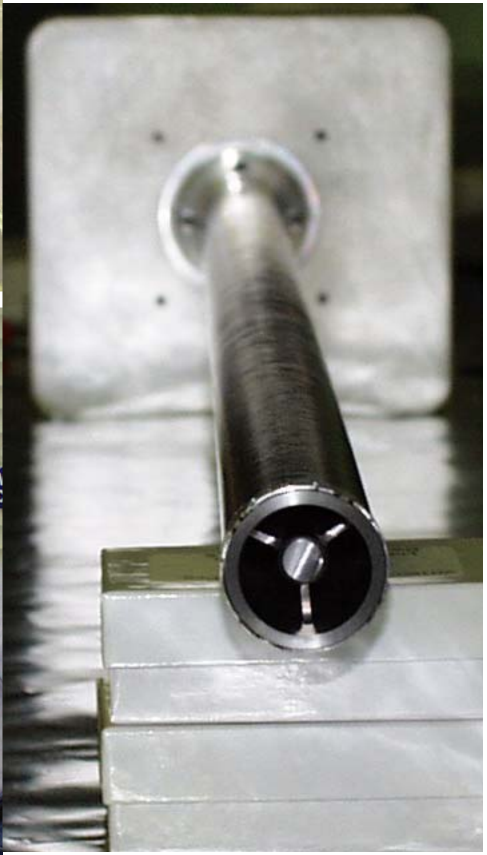
1	1	TARGET BASE BLOCK
2	1	BELLOWS CONTACT ASSEMBLY
3	1	UPSTREAM TARGET SLUG LOCATOR P
4	1	UPSTREAM TARGET SLUG LOCATOR
5	2	TARGET SLUG, UPSTREAM
6	5	TARGET SLUG PIN
7	3	TARGET SLUG, MIDDLE
8	2	TARGET SLUG, DOWNSTREAM
9	1	AIR COOL STANDOFF
10	1	TARGET BASE WINDOW
11	1	TARGET BASE PLUG
12	1	OUTER TUBE
13	1	DOWNSTREAM TARGET SLUG LOCATOR



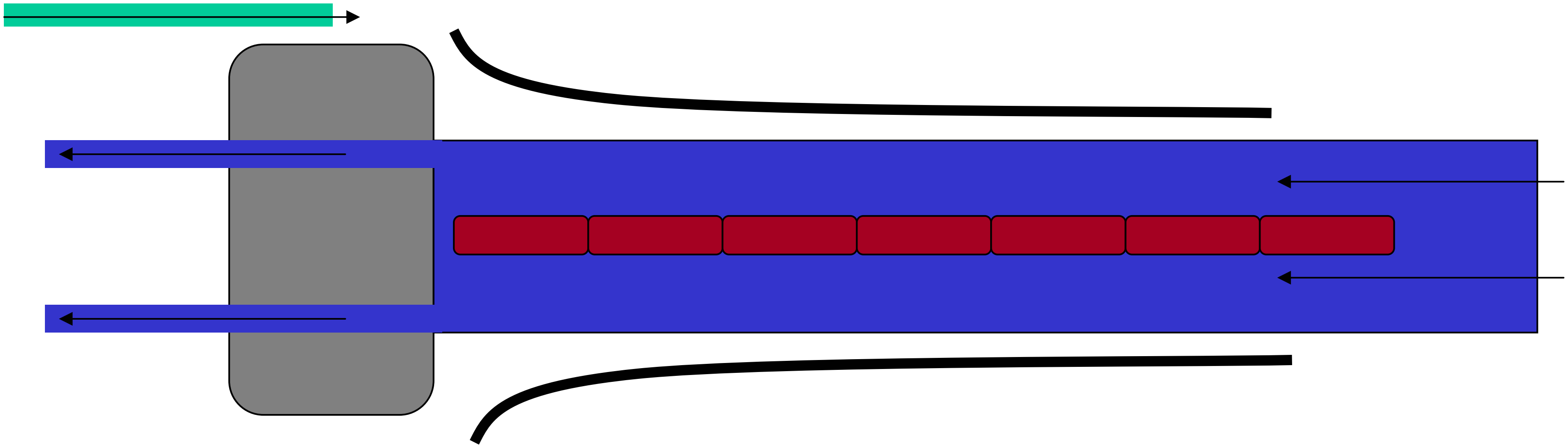
Beryllium Parts

Assembled Target



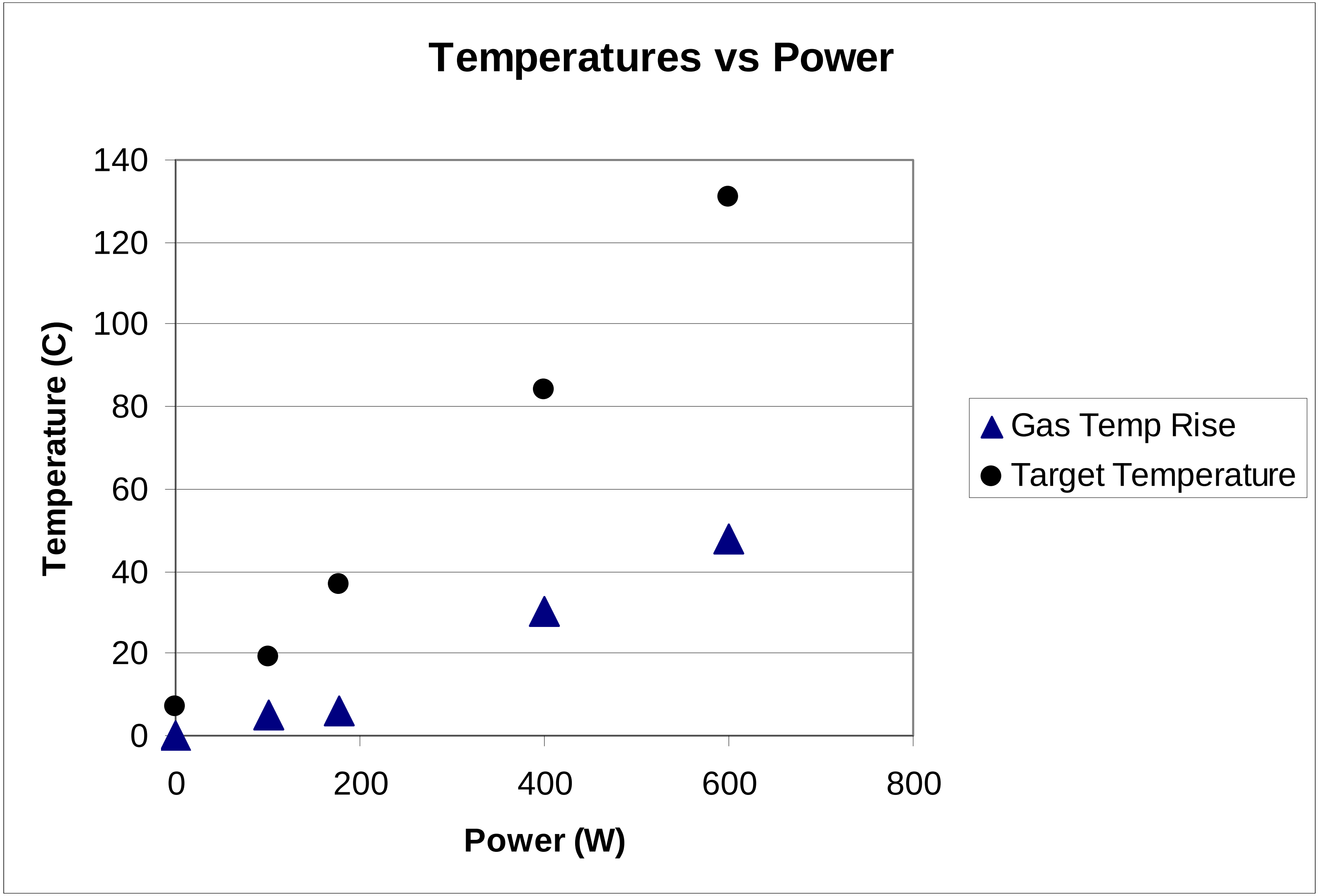


Target Cooling



Beam heating: 610 W
Operating temperature ~100 C
Air temperature rise   ~25 C
(depends on flow…)

Measured Temperatures



Summary of Cooling Tests

- Achieved flow rates of > 20 liters/second
- 131 °C target temperature rise @ 600 W
- 55 °C gas temperature rise @ 600 W

Operation

- First beam delivered September 1, 2002
- Typical rates ~4-4.5x10^{12}p.o.t. @ ~3 Hz
- > 35 million horn pulses
- > 10^{20} protons on target
- Still going…

Richard Werbeck - Performance of a Clad Tungsten-rod Spallation-Neutron-Source Target -LANCE

Tests on SS clad Tantalum rods

Conclusions

- The success of the irradiation of slip clad tungsten rods as a spallation neutron target is based on the following observations:
  - The spallation target performed without incident at a peak power density of 2.25 kW/cm ^{3} and a peak heat flux of 148 W/ cm ^{2} . Peak fluence reached 4 x 10 ^{21} particles/cm ^{2} .
  - The target design produced very low stress and post irradiation testing showed that the properties of the target materials far exceeded design requirements throughout the irradiation.
  - Target geometry is not restricted, especially with further verification that the hydrogen gas created by spallation will not overpressure the volume between the tungsten rod and the clad.
- These observations, coupled with the extensive use of slip clad technology other nuclear applications, demonstrate that future spallation neutron sources should seriously consider using water cooled, slip clad tungsten rod bundles in the target assembly.

Roger Bennett (RAL) Large Solid Targets for a Neutrino Factory

Table placing existing high power targets in relation to the neutrino factory. Pbar target over 20 times the energy density of neutrino factory target.

Rotating toroidal target thermal radiation of over 10 MW capability depending on size etc.

Possible problems with shock or thermal non-uniform heating - seen in other solid targets e.g. ISOLDE.

Could make target from small pieces “shot” through the beam and recirculated.

Target programme in the UK based on solid targets - applying to PPARC funding agency.

Need a high power target test facility.

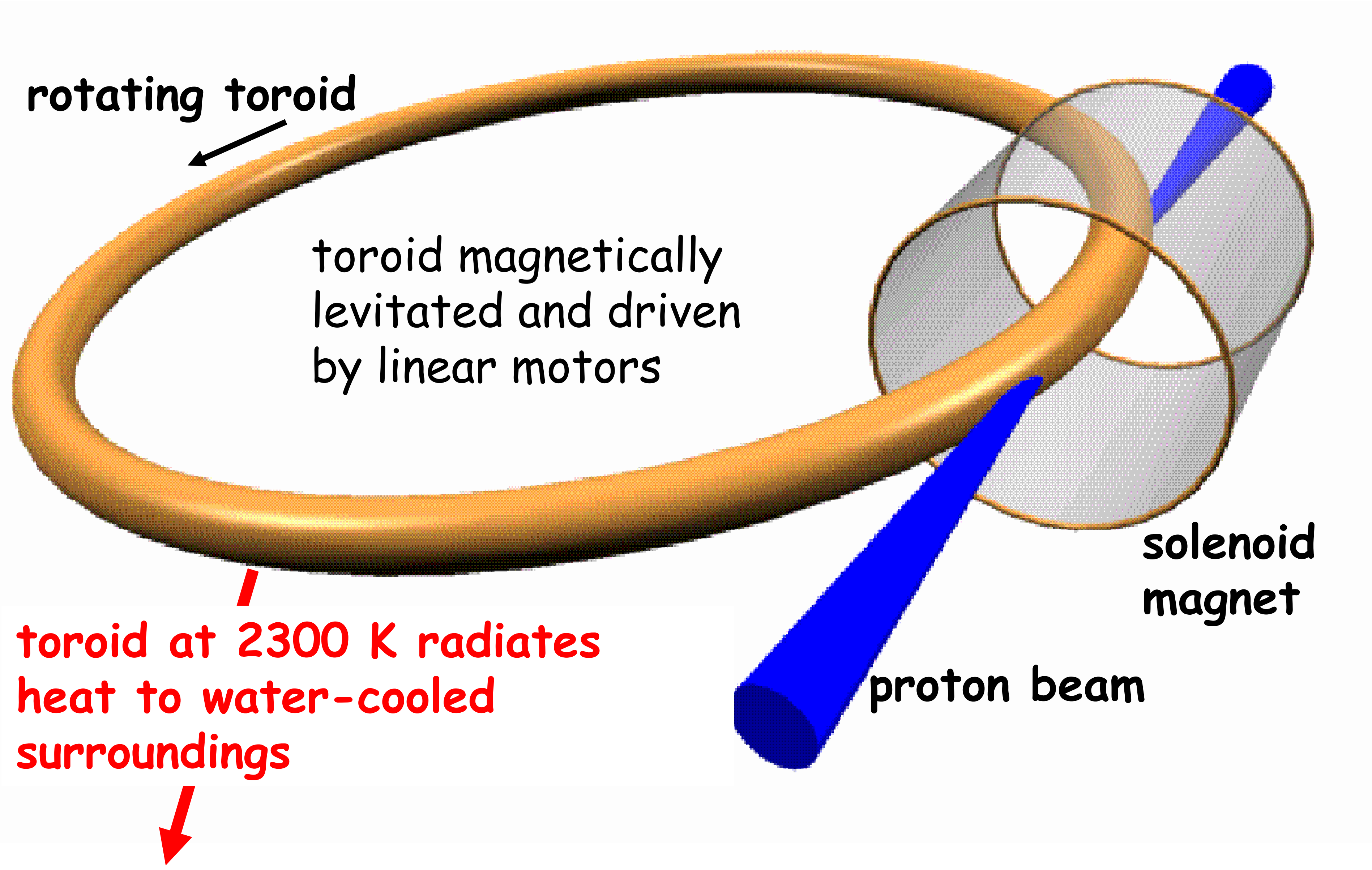
Table comparing some high power pulsed proton targets

Facility	Particle	Rep. Rate	Power	Energy /pulse	Beam and Target size						Energy density /pulse	Life	Number of pulses
		f	P	Q	height	width	length	volume	thick	material	q		N
		Hz	W	J	cm	cm	cm	cm^3	cm		$J\ cm^{-3}$	days	
NuFact	protons	50	1E+06	20000	2	2	20	63	20	Ta	318	279	1.E+09
				Number of pulses on any one section of the toroid									7.E+06
ISOLDE	protons	1		3675	0.6	1.4	20	13	0.05 to 0.0002	Ta	279	21	2.E+06
ISIS	protons	50	180000	3600	7	7	30	1155	0.7	Ta	3	450	2.E+09
Pbar	protons	0.3		1797	0.19	0.19	7	0.25	~6	Ni	7112	186	5.E+06
Run I	3E12 ppp									(Cu, SS, Inconel)			Damage
Run II	5.E+12			Damage in one or a few pulses							13335		
Future	1.E+13				0.15	0.15					30000		
NuMI	protons	0.53			0.1	0.1	95		2	C	600		
	120 GeV				Radiation Damage - No visible damage at 2.3E20 p/cm^2								
	4E13 ppp				Shock - no problem up to 0.4 MW (4E13 at 1 Hz)								
	8.6 μs				Sublimation -OK								
					Reactor tests show disintegration of graphite at 2E22 n/cm^2								
					NuMI will receive a max of 5E21 p/cm^2/year								

Table comparing some high power pulsed electron targets

Facility	**Particle**	**Rep. Rate**	**Power**	**Energy /pulse**	**Beam and Target size**						**Energy density /pulse**	**Life**	**Number of pulses**
		f	P	Q	height	width	length	volume	thick	material	q		N
		Hz	**W**	**J**	**cm**	**cm**	**cm**	**cm^3**	**cm**		**$J\ cm^{-3}$**	**days**	
NuFact	**protons**	**50**	**1E+06**	**20000**	**2**	**2**	**20**	**63**	**20**	**Ta**	**318**	**279**	**1.E+09**
				Number of pulses on any one section of the toroid									**7.E+06**
SLC	**e**	**120**	**5.E+03**	**42**	**0.08**	**0.08**			**2**	**W/Re**	**591**	**1500**	**6.E+05**
SLAC	33 GeV			Rotating disc, 6.35 cm diameter, 2cm thick						26% Re			
				Target designed to withstand shock									
		Radiation damage leading to loss of strength and failure when subjected to shock											
FXR	**e**									**Ta**	**160**		**100**
LLNL	17 MeV									**Ta**	**267**		**10**
												No damage	
RAL/TWI	**e**	**100**	**4.E+04**			**0.2**			**25 μm**	**Ta**	**500**		**up to 1E+06**
	150 keV					Thin foil 0.4 cm wide			Range ~10 μm				
						Failures probably due to oxidation in poor vacuum							

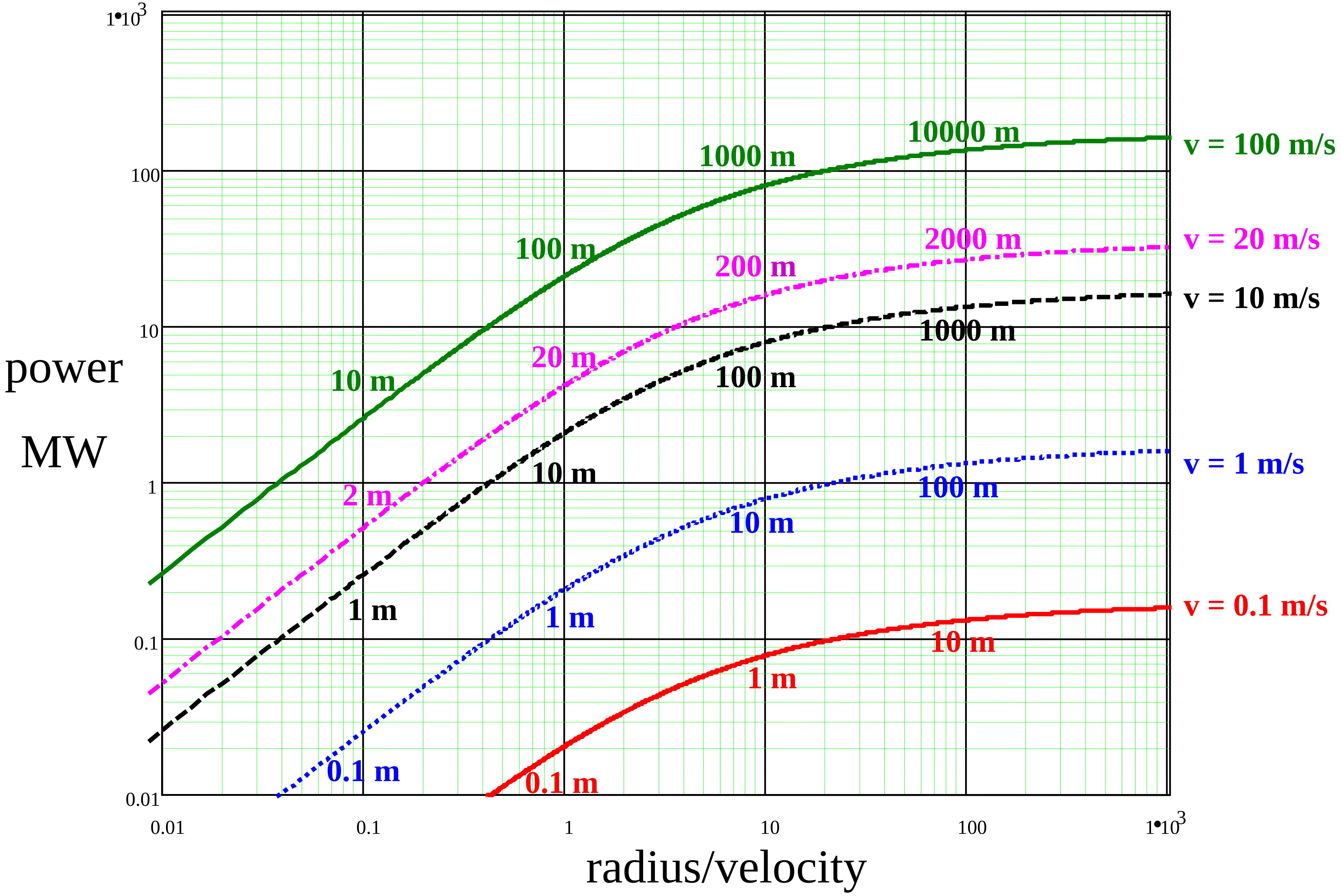
Schematic diagram of the rotating toroidal target



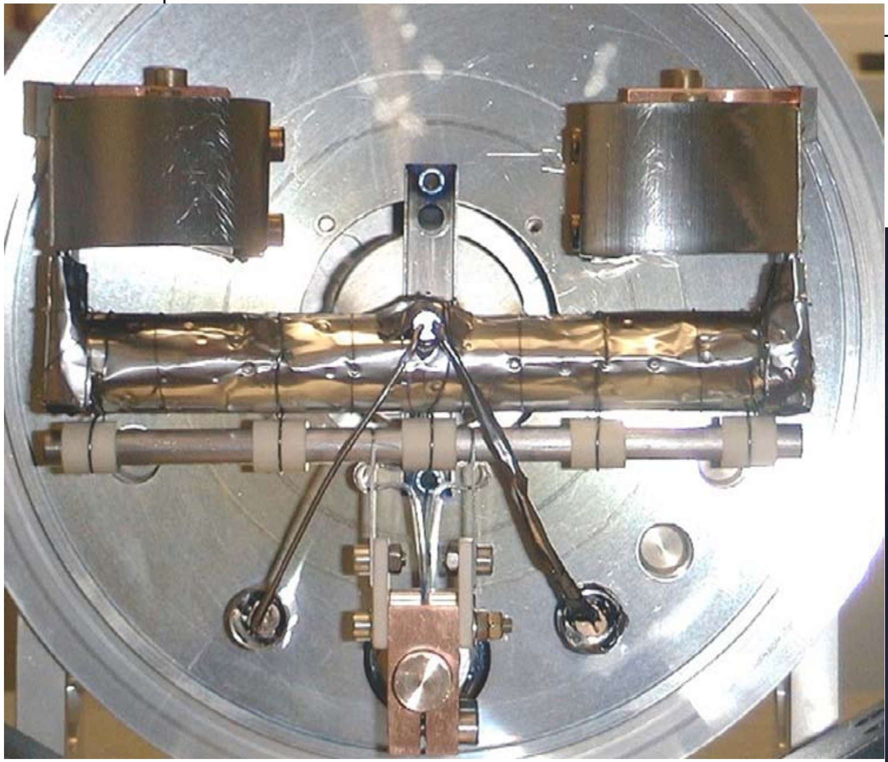
toroid magnetically
levitated and driven
by linear motors

toroid at 2300 K radiates
heat to water-cooled
surroundings

POWER DISSIPATION



ISOLDE converter targets

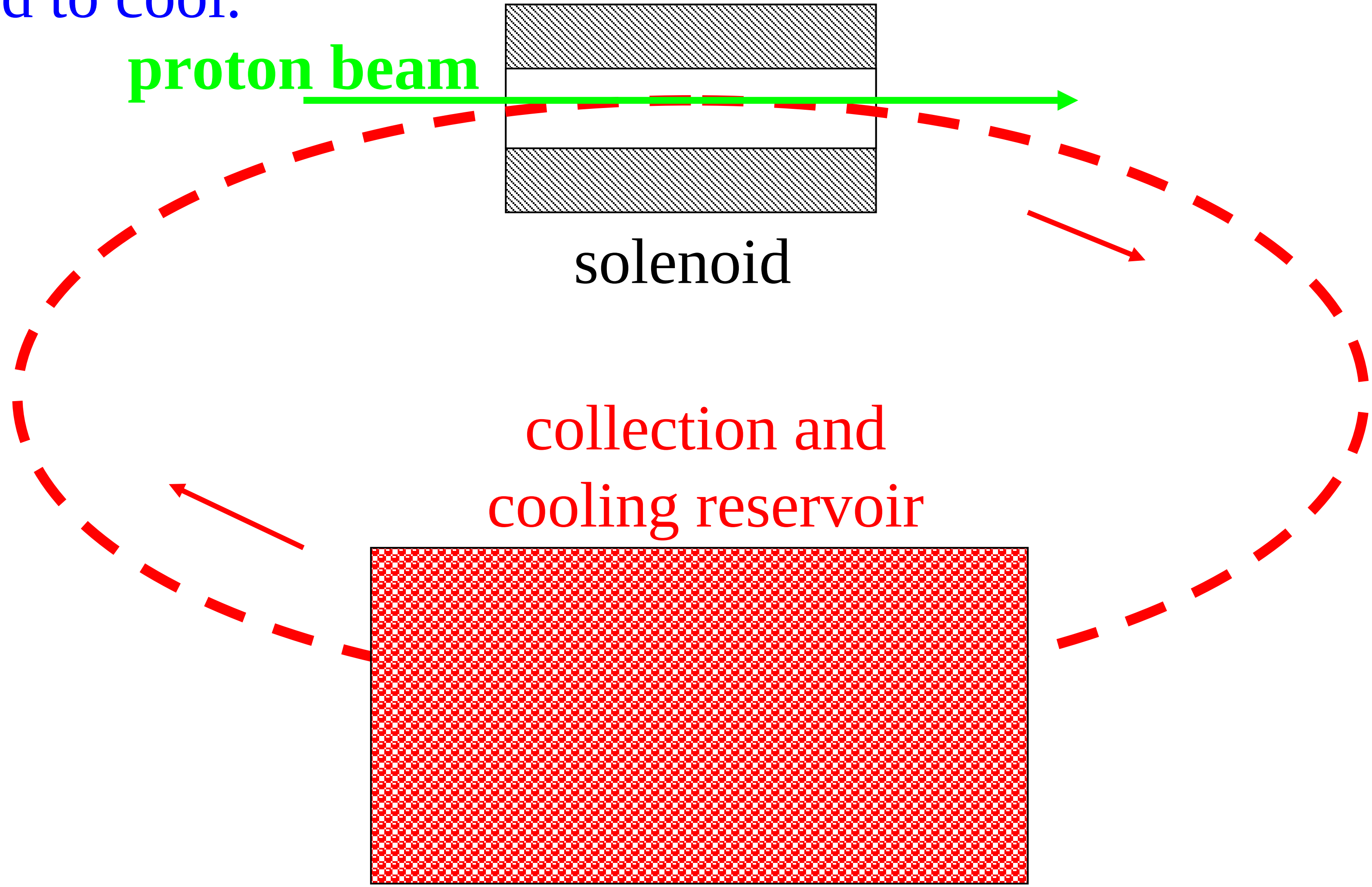


Ta-converter mounted below the UC target before irradiation

Ta-rod after irradiation with 6E18 protons in 2.4 µs pulses of 3E13

Individual free targets

Levitated target bars are projected through the solenoid and guided to and from the holding reservoir where they are allowed to cool.



Yoshinari Haito (KEK) The JPARC neutrino Target

Water cooled carbon target, 300 Jcm^{-3}. 3 cm diameter 90 cm long. Thermal stress evaluated by ANSYS - OK - but need to use dynamic analysis. Radiation damage lifetime unknown.

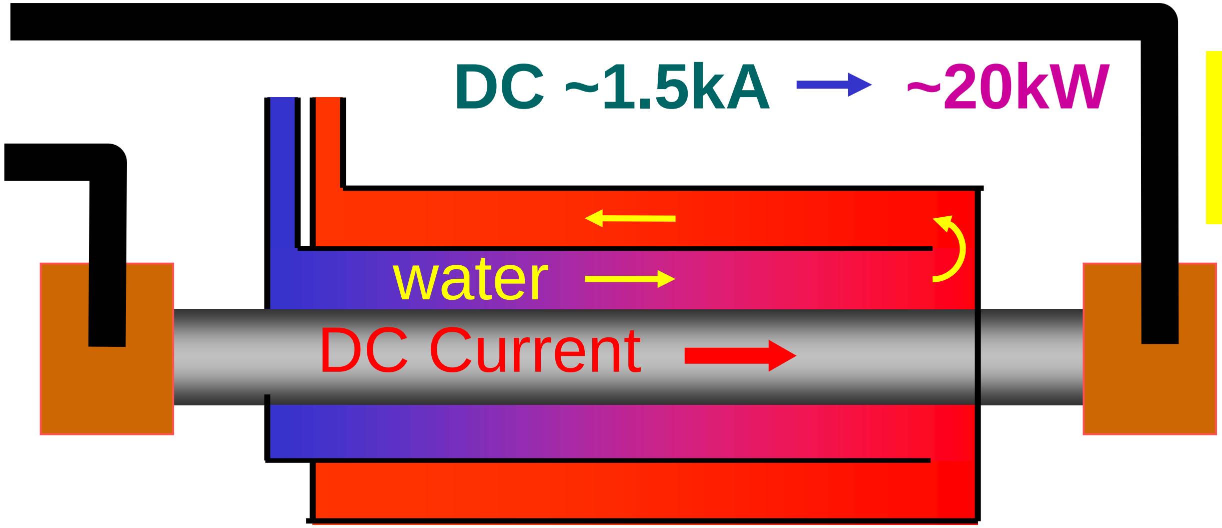
Cooling test

According to the results from the calculations,

heat transfer rate → larger than ~6kW/m^2/k.

→ Heat up the target with DC current

and try to cool by the flowing water.



Could clad the target

measure water flow rate and temperature at various points

→ estimate the heat transfer rate.

Summary (I)

For the JPARC ν experiment,
solid target R&D is now ongoing.

material	Graphite (or C/C composite ?)
dimensions	diameter ~30mm length 900mm (2 interaction length)
cooling	Water (direct or put in the case?) Heat transfer rate > ~ 6kW/m^2/K
cooling method	Direct cooling → seems to work Water flow rate ~20l/min.
temperature rise	~ 175 ^{o}C (center) ~ 25^{o}C (surface)
thermal stress	~ 9MPa (for G347) [Tensile strength (G347) ~ 31MPa]

Summary (II)

R&D Items (We want to test/check the following items.)

- Cooling test

  Set the water flow rate at 20l/min. and confirm the method.

  Measure the heat transfer rates with a target container.

- Stress test

  Beam test (with same energy concentration) Where?

- Irradiation effects other than the thermal conductivity
- Search for the best material

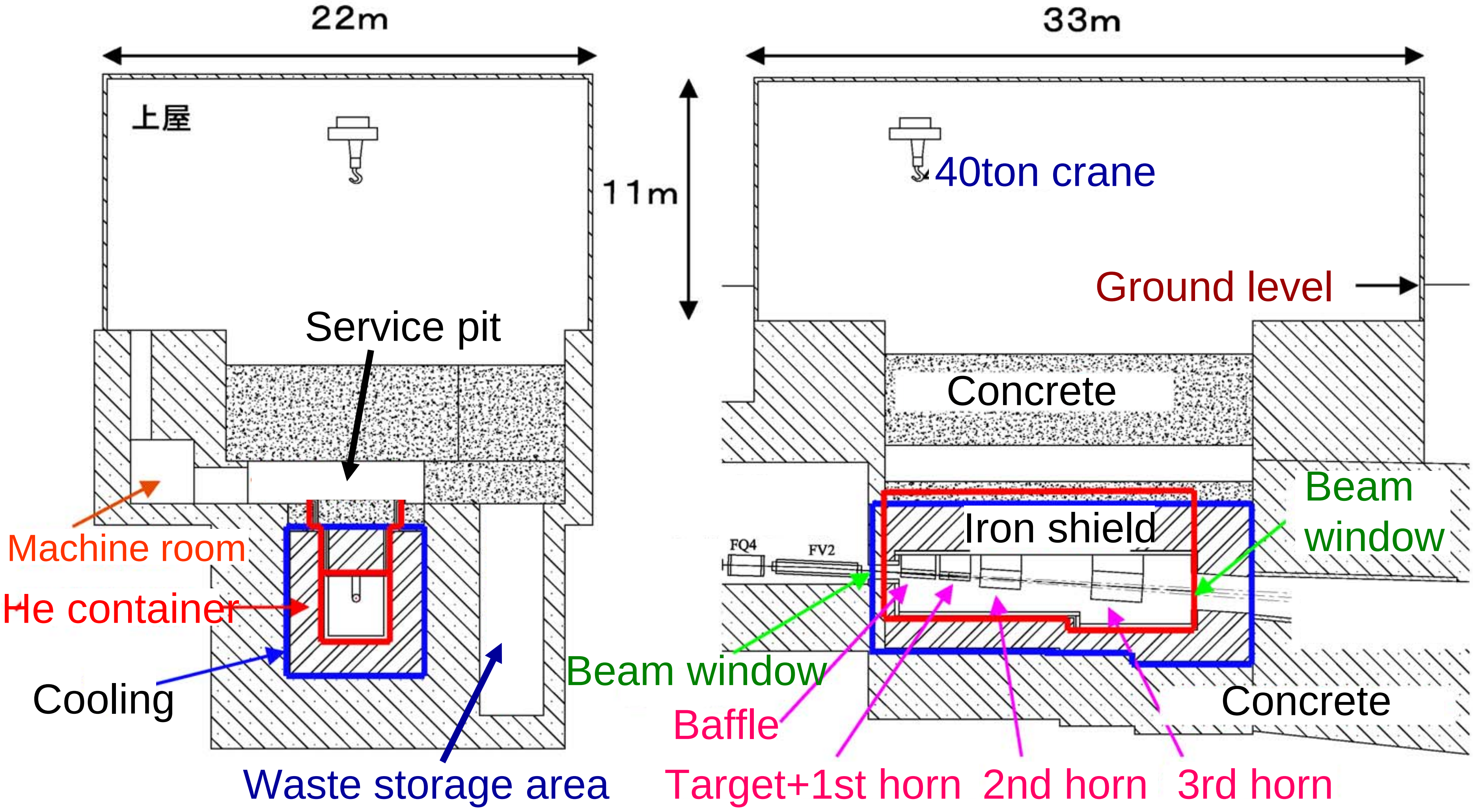
  (Usually, graphite, whose tensile strength is large,
  has large Young's modulus.
  → the thermal stress is also getting larger.)

  Temperature dependences of the material properties.

Summary (III)

- Design of the entire system has to be fixed.

  How to fix (support) the target, alignments etc...

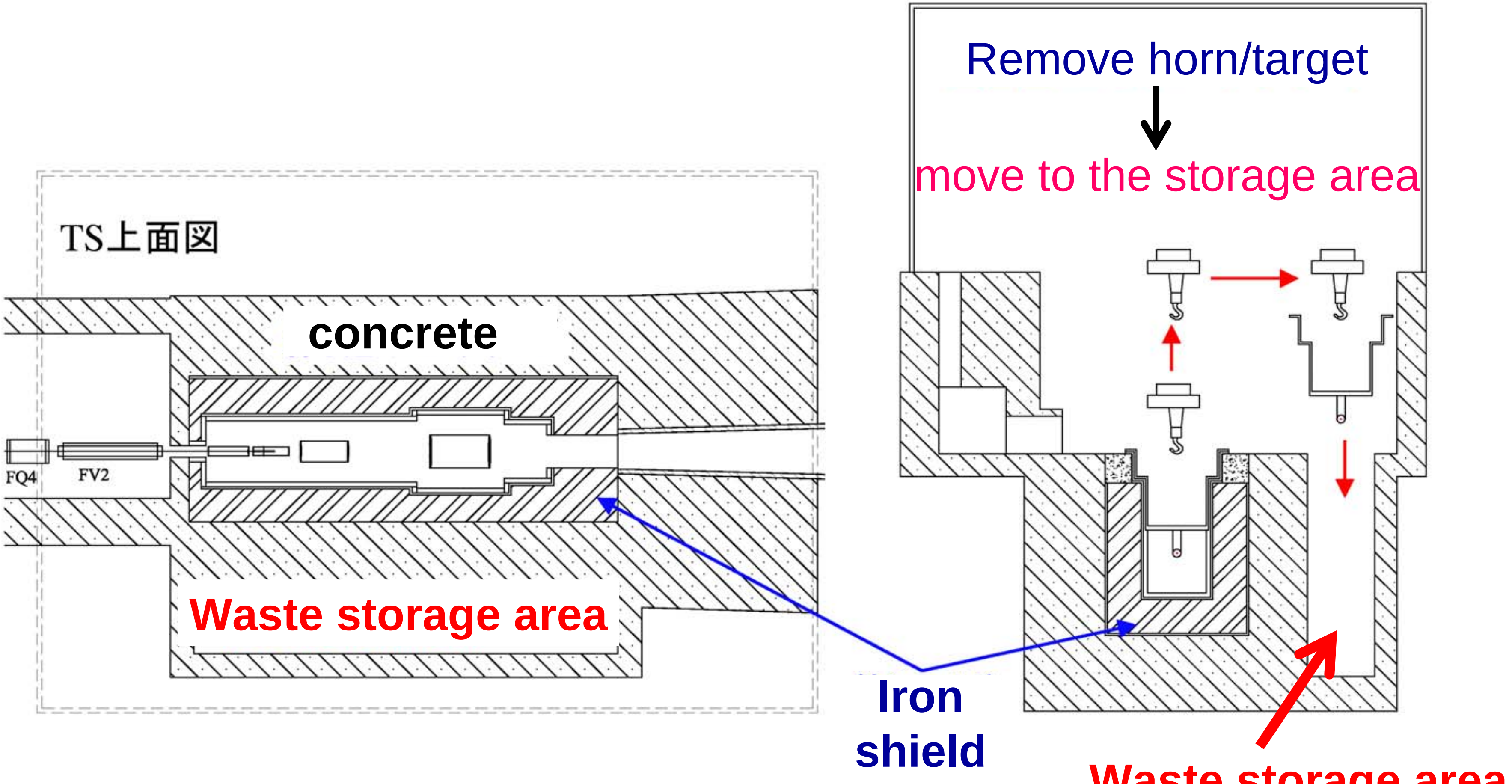


Summary (IV)

- Target handling

How to remove the target from the horn remotely?

(It may be necessary to remove the target from the horn when the target part is broken.)



Remove horn/target

↓

move to the storage area

Nikoli Mokhov (FNAL) NuMI Target (Jim Hylen & Jim Morgan)

Water-cooled graphite, segmented. Energy density 640 Jcm^{-3}. Shock limit in graphite ~ 2000 Jcm^{-3}. Radiation damage lifetime unknown. Proton beam.

Vinod Bharadwaj (SLAC) NLC Positron Production Target

Tungsten/25Re rotating target disc, water-cooled.

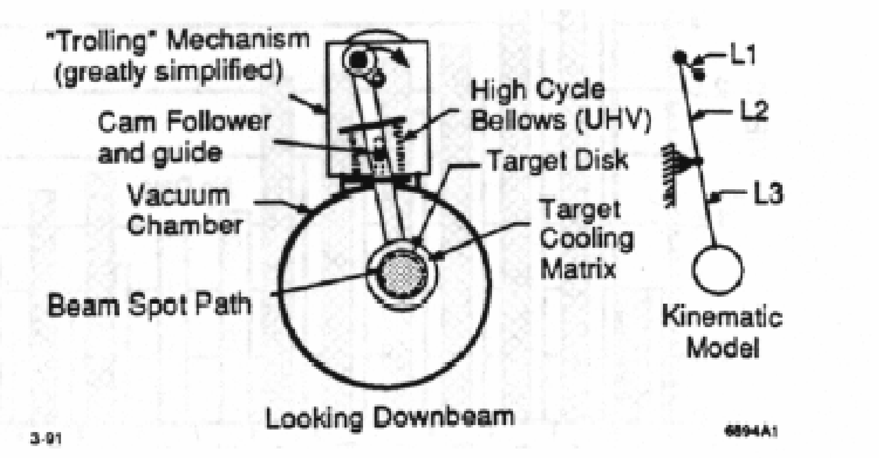
Energy density 600 Jcm^{-3}. Electron beam.

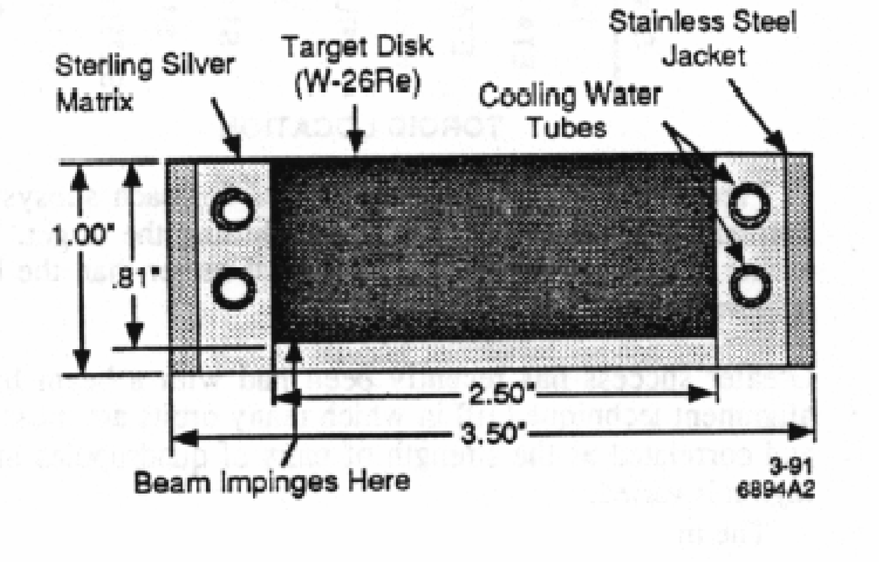
Damage caused failure after 5 years. Damage thought to be due to radiation deterioration of strength and pulse stress failure.

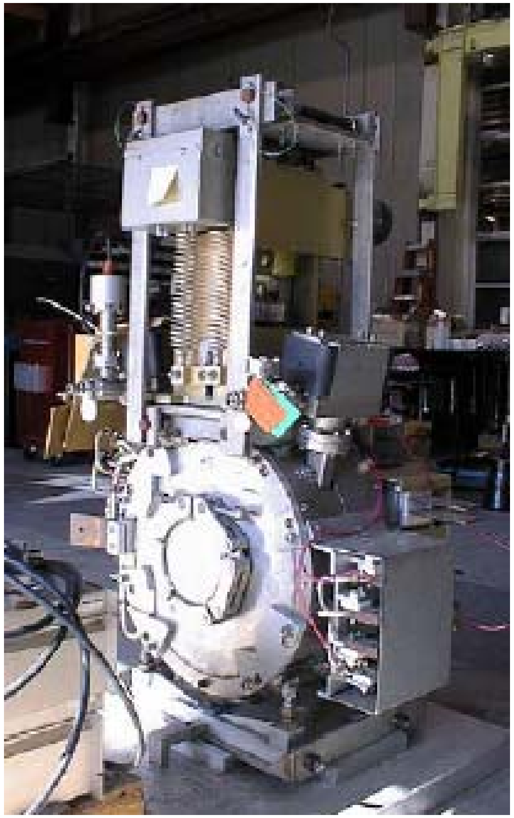
HIGHLY SUCCESSFUL TARGET!!

NLC target - to have multiple targets to reduce stress in target to acceptable level.

SLC Positron Target







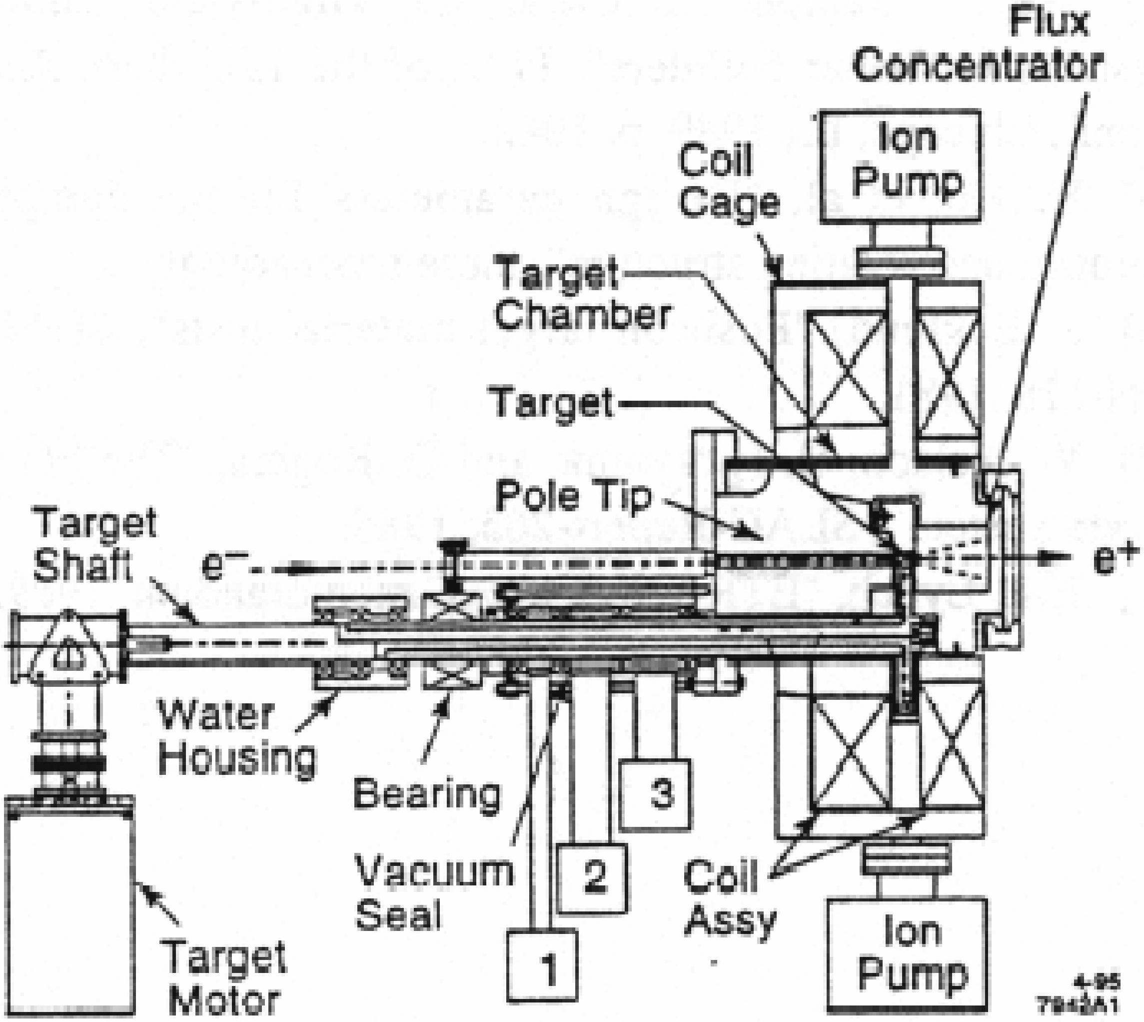
The NLC target design uses the operational experience gained from the SLC.

SLC positron target made of 6 r.l. W-Re. “Trolling target”. Was made so that average heating would not damage the target

SLC drive beam is 30 GeV, 4 x 10^{10} e^-/bunch,
1 bunch/pulse, 120 pulses/sec, 24 kW

NLC Positron Target

NLC positron target design – extrapolated from the SLC positron target



NLC spinning target design.

20 cm. dia. W Re target ring. 23 kW deposited

Oscillating at 1/2 Hz.

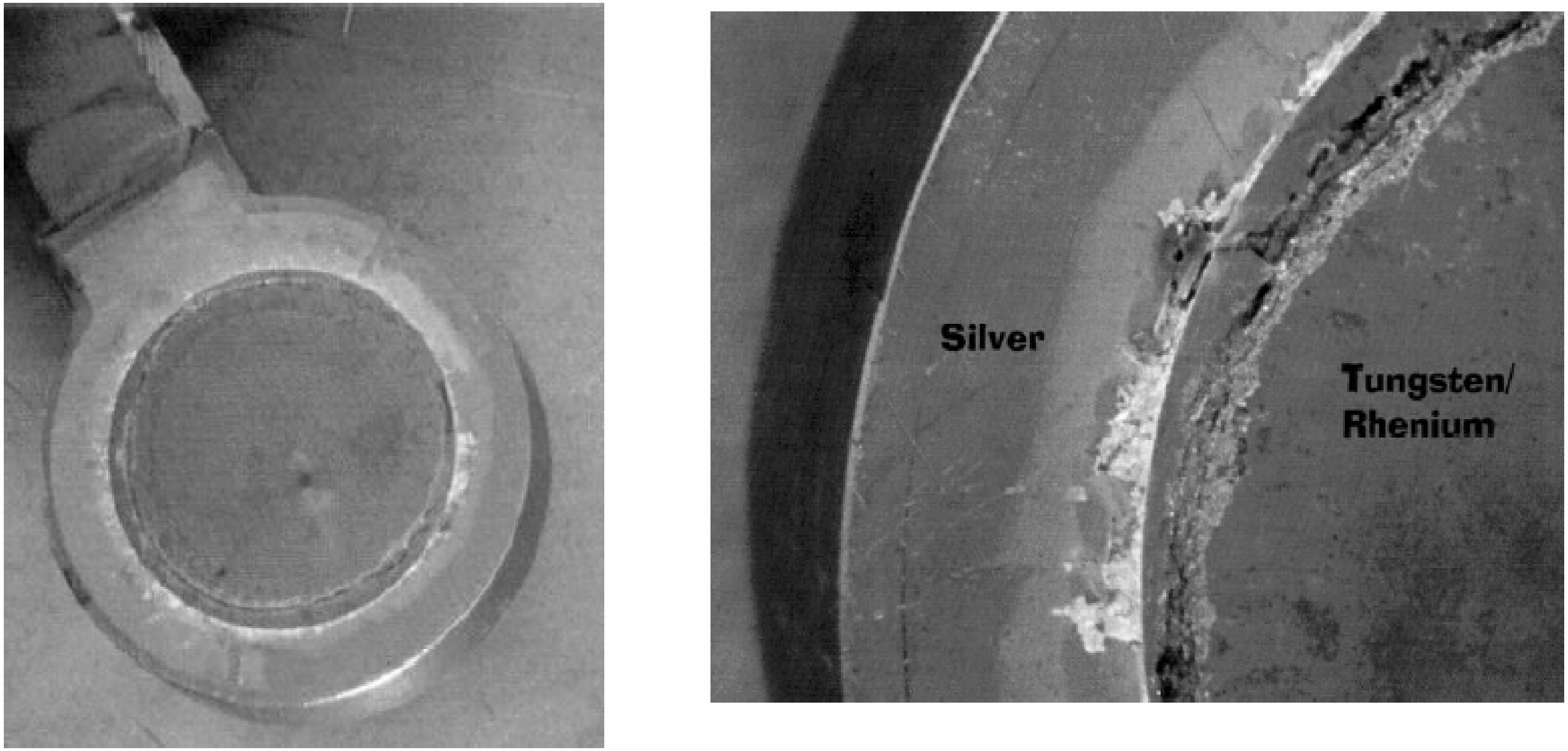
Beam rate is 120 Hz.

Spinning shaft with water and vacuum seals.

Extrapolation to NLC Drive Beam Power

- NLC target made bigger to allow for greater average beam power (340 kW as compared with 24 kW)
- The energy deposition for a single pulse in the NLC target is calculated to be below the level that will damage the target material.
- The SLC was thought to be a factor of two below damage threshold
- BUT
  - The SLC positron target failed (after 5 years of operation)
  - Failure lead to a detailed analysis of materials properties: radiation damage, shock and stress, fatigue, etc.

SLAC Target Damage



SLC target damage studies were done at LANL. Results show evidence of cracks, spalling of target material and ageing effects.

Peter Sievers (CERN) Moving and Stationary High-Power Targets for Neutrino Factories.

Multiple (4) granular targets (Ta, WC, Pt) to alleviate thermal shock (4MW proton beam). Cooled by helium gas. Can be used with horns and the beams combined.

GRANULAR TARGET COOLED BY LIQUID

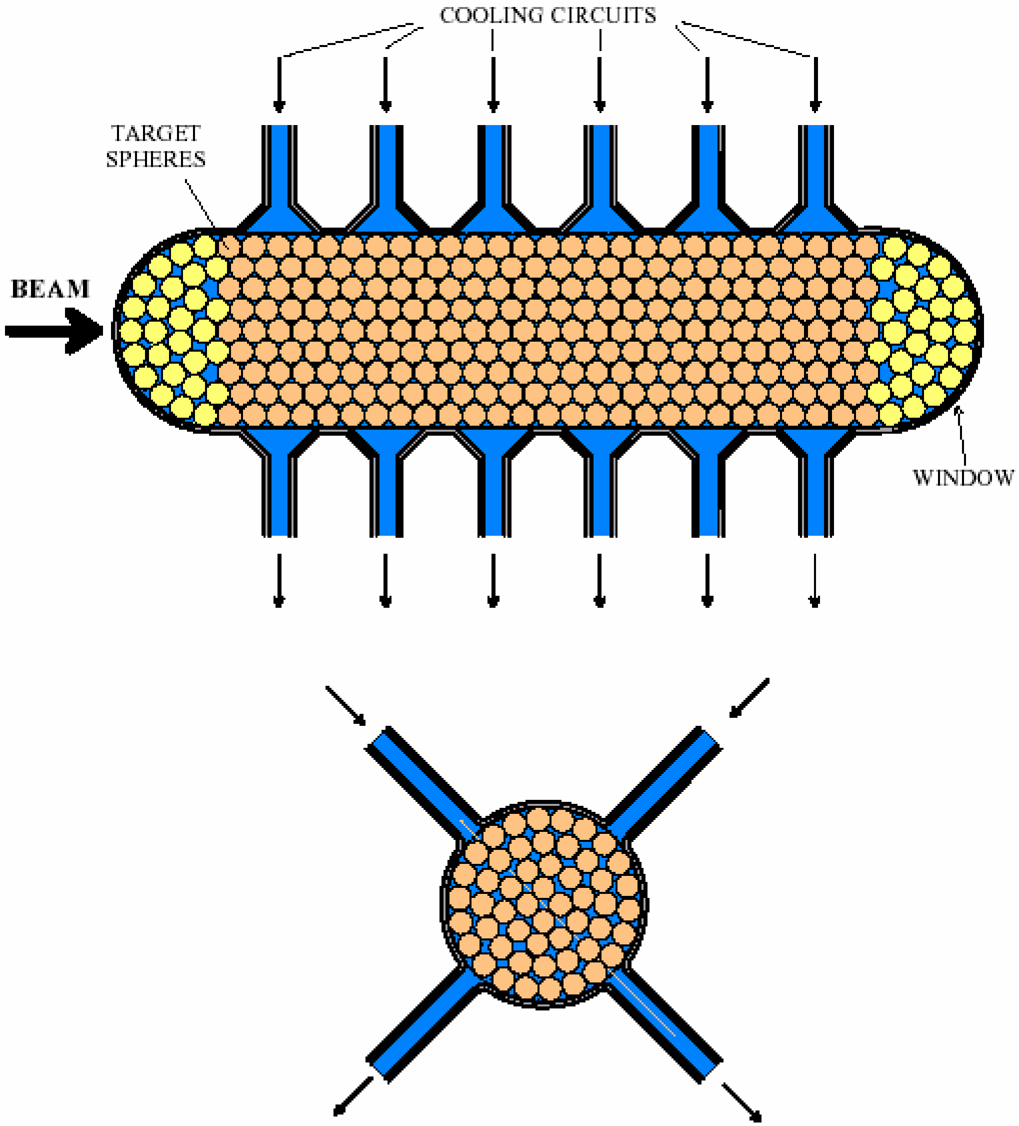


Fig. 1 : Principle lay-out of a liquid cooled, granular target. Tantalum spheres with a diameter of about 2mm are confined in a Titanium container and cooled by water (or possibly liquid metal) traversing the voids between the spheres.

Nick Simos (BNL) Simulations of Proton Beam Induced Pressure Waves

Modelling of shock in solid targets (graphite) and windows. On the whole fairly good agreement. Vital work must be continued to reduce the need for expensive in-beam tests.

Long term (many pulses) failure may not be easy to predict.

Jim Morgan (FNAL) Pbar Target

Very high energy density dissipation - 2000 $\mathrm{Jcm^{-3}}$.

Targets melt on beam centre!

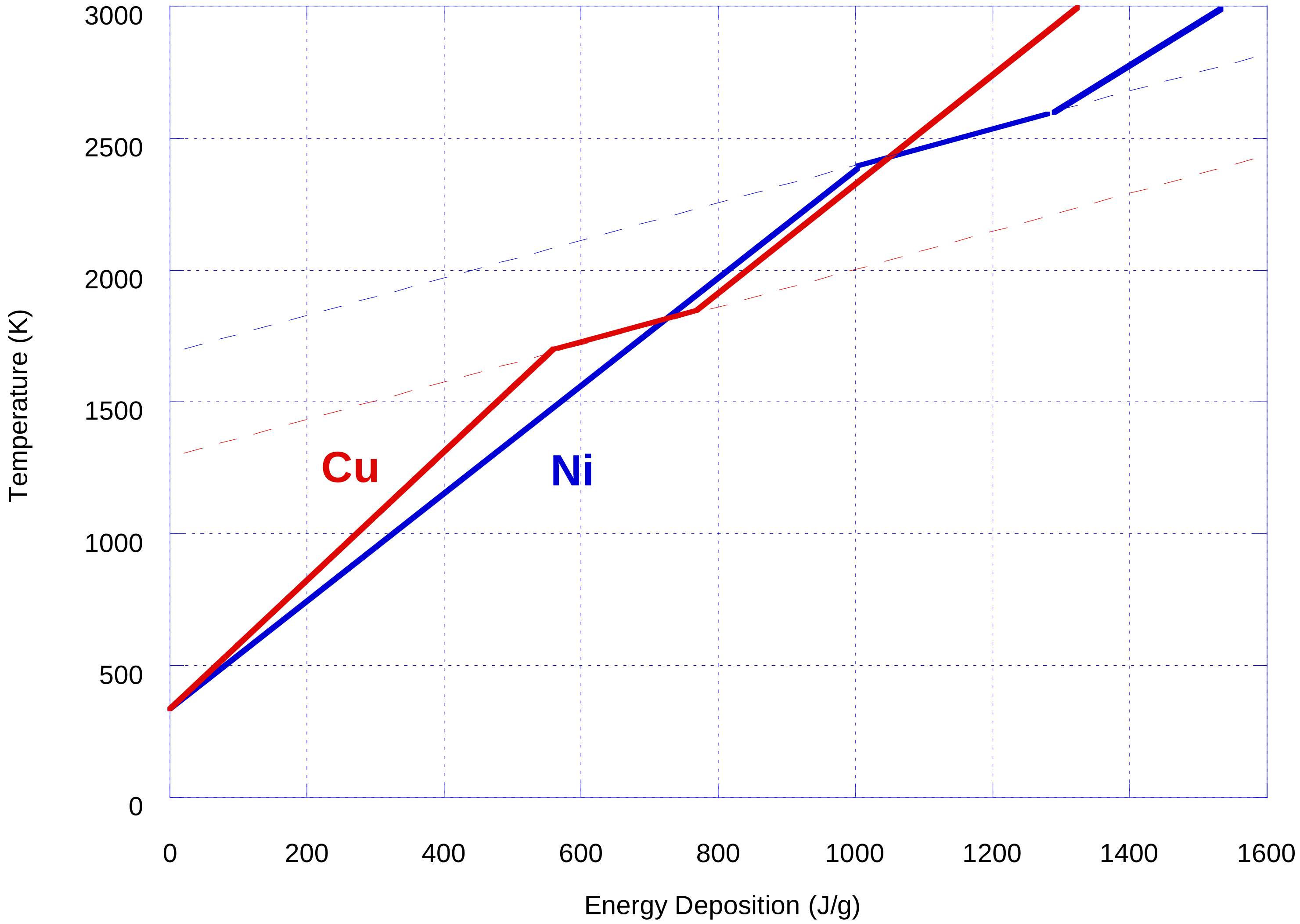
But the system works!

Some damage seen. Is it melting or shock or a combination of both?

Target material comparison

Target Material	**Iridium**	**Rhenium**	**Tungsten**	**Nickel**	**Copper**
$A^{1/3}/\rho$ (m^3/Kg)	**.255**	**.271**	**.295**	**.437**	**.445**
$A^{1/3}/\rho$ (Normalized)	**1.71**	**1.61**	**1.48**	**1**	**.98**
Observed Yield (Normalized)			**1.05**	**1**	**.99**
Melting Point Energy (J/g)	**460**	**610**	**630**	**1,250**	**770**
Yield Strength (kPa)	**160**	**270**	**500**	**230**	**72**
Gruneisen parameter (kPa Kg/J)	**80.6**	**66.0**	**31.0**	**15.8**	**17.2**

Energy deposition vs. peak target temperature



Damage to Tungsten-Rhenium target

Damage to Tungsten target

Target damage to nickel target (entry)

Helge Ravn (CERN) Eurisol and Beta Beam Target Issues.

Solid targets for ISOL targets up to ~100 kW (250 kWcm^{-3}). Radiation cooled. (I believe 500 kW max is possible.)

Experience with tantalum converter target test - not good experience!!

Kirk McDonald (Princeton) Neutrino Factory Targetry Concept

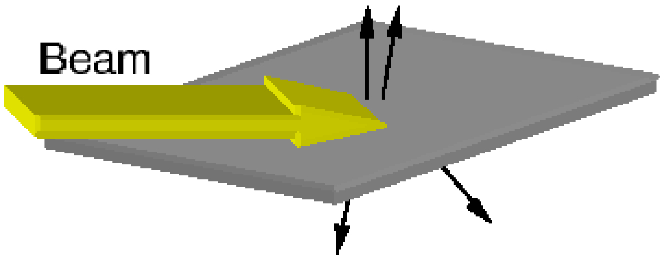
Summary of solid targets for neutrino factories.

Jerry Nolan (ANL) High Power Targets for RIA

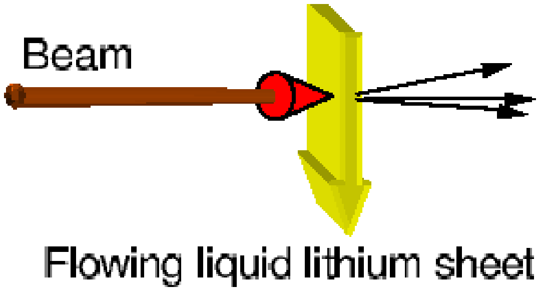
A variety of Targets for radioactive beams - some solid.

A Variety of Targets and Production Mechanisms

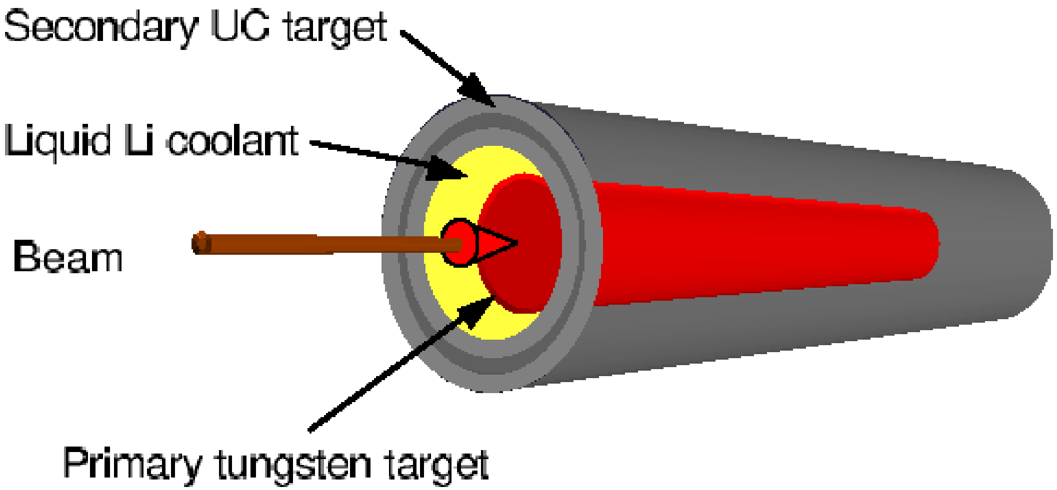
(a) Tilted spallation target



(b) Liquid lithium target



(c) Two-step neutron-induced fission target



Harold Kirk and Peter Thieberger (BNL) Moving Solid Targets in a Multi-Megawat Beam Environment

Benefit of flat beam profile over a Gaussian to reduce the peak energy density.

Metal chain link moving target design.

Selection of target material for low thermal expansion to reduce shock stress. Super Invar excellent - BUT radiation damage! Thus Super Invar no good.

Vascomax very strong - but magnetic.

Inconel 718 is a good choice.

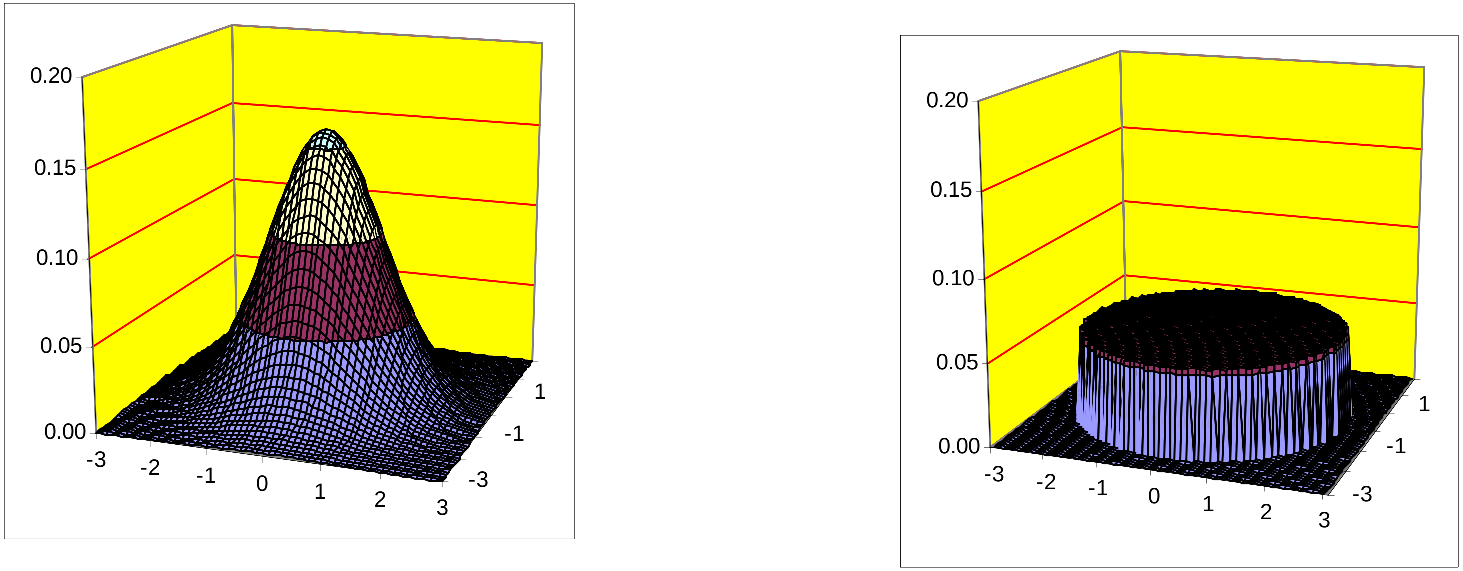
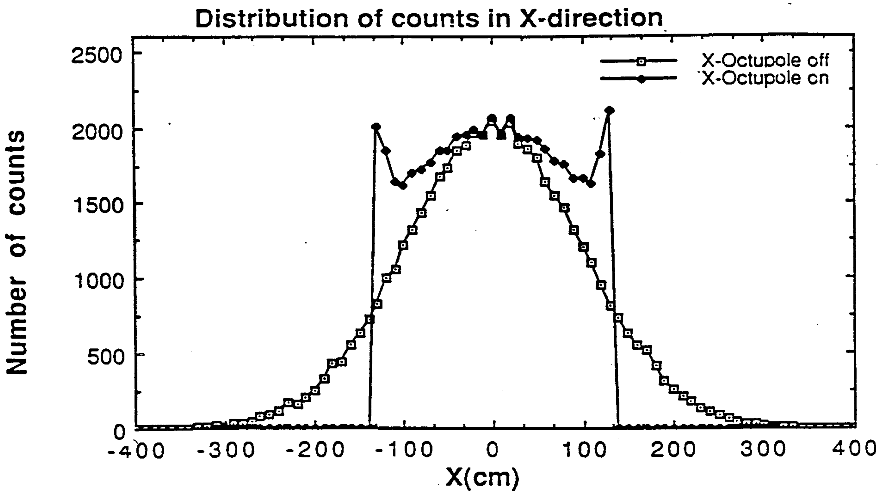


Fig 12a **Fig. 12b**

Comparison of a doubly Gaussian beam profile (a) with an ideal flat profile (b) containing the same number of particles.

A perfectly flat beam such as shown in Fig. 12b can of course not be realized, but using octupole lenses one can generate profiles which are fairly close to this goal. Fig 13 shows one of the projections of such a distribution which was calculated$^{11)}$ for larger "uniform" beams required for the irradiation of biological materials.



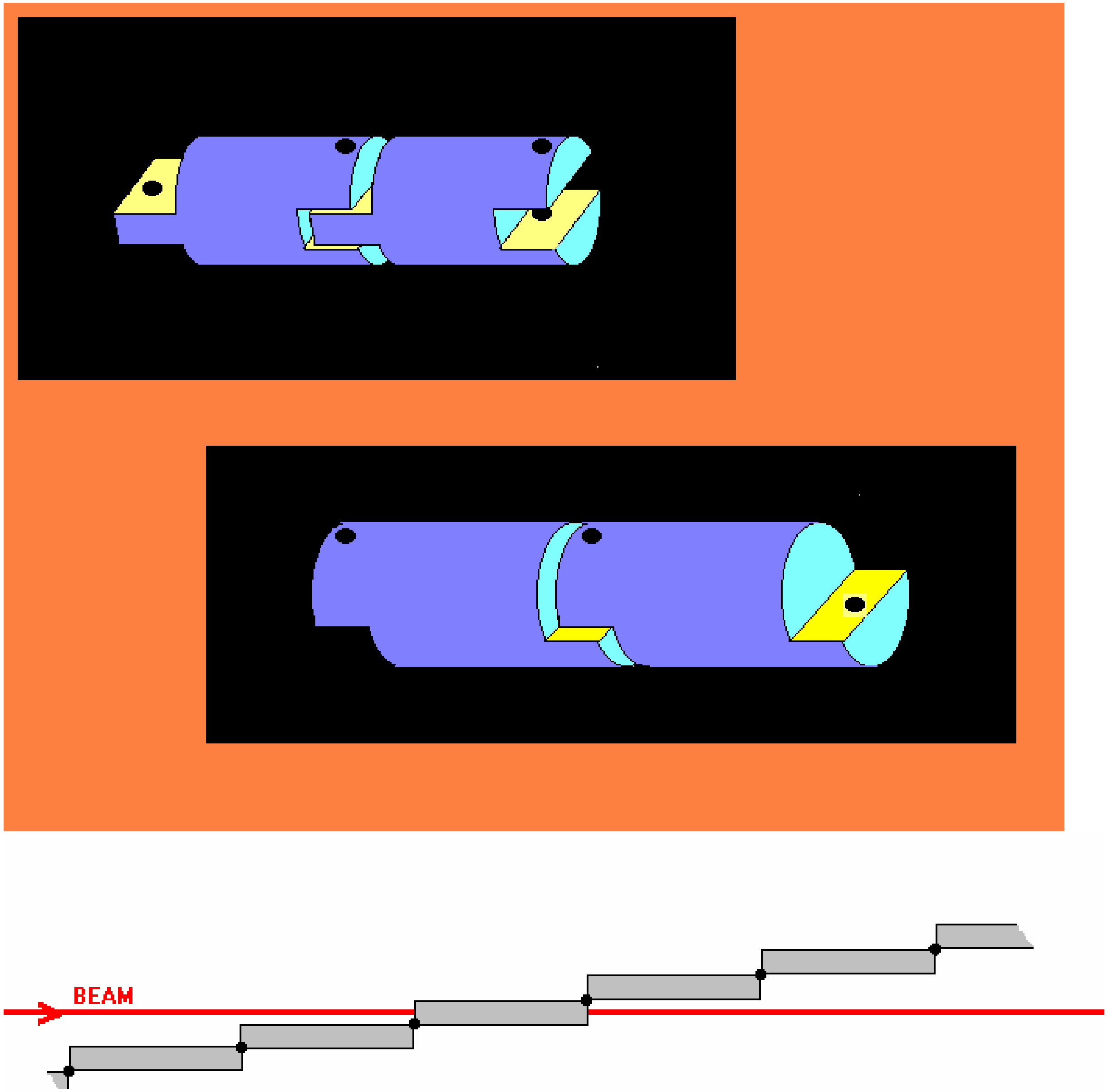
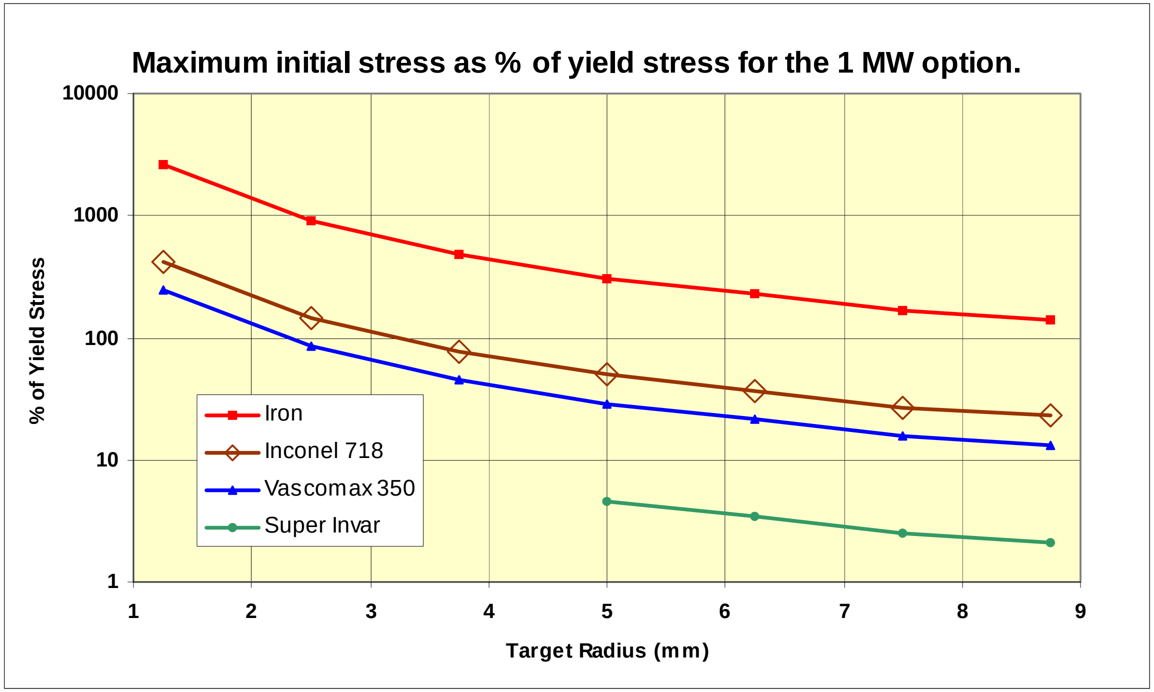
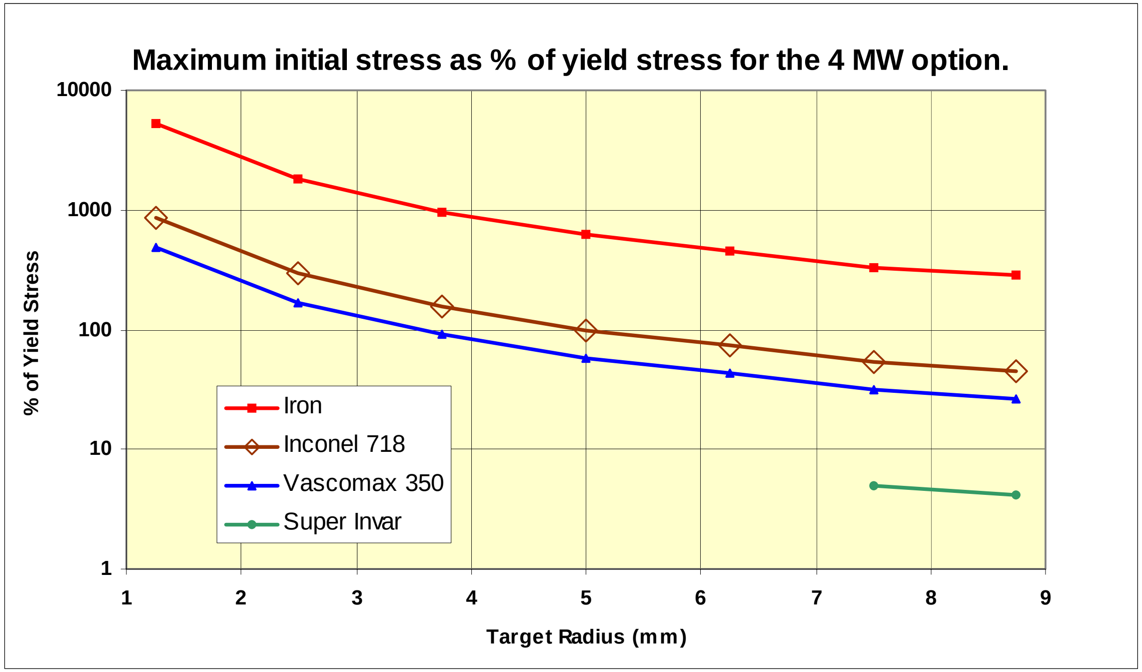


Fig.15 Schematic example of a chain with long links that would allow the beam to be coaxial with the target.


Maximum initial stress as % of yield stress for the 1 MW option.
% of Yield Stress
10000
1000
100
10
1
1
2
3
4
5
6
7
8
9
Target Radius (mm)
Iron
Inconel 718
Vascomax 350
Super Invar


Maximum initial stress as % of yield stress for the 4 MW option.
% of Yield Stress
10000
1000
100
10
1
1
2
3
4
5
6
7
8
9
Target Radius (mm)
Iron
Inconel 718
Vascomax 350
Super Invar