Large
SOLID TARGETS
for a
Neutrino Factory

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Note.

- In all cases I will refer to the power in the target rather than the beam.

Thus, in the case of the neutrino factory, a 1 MW target has 1 MW dissipation and the beam power is 4 MW.

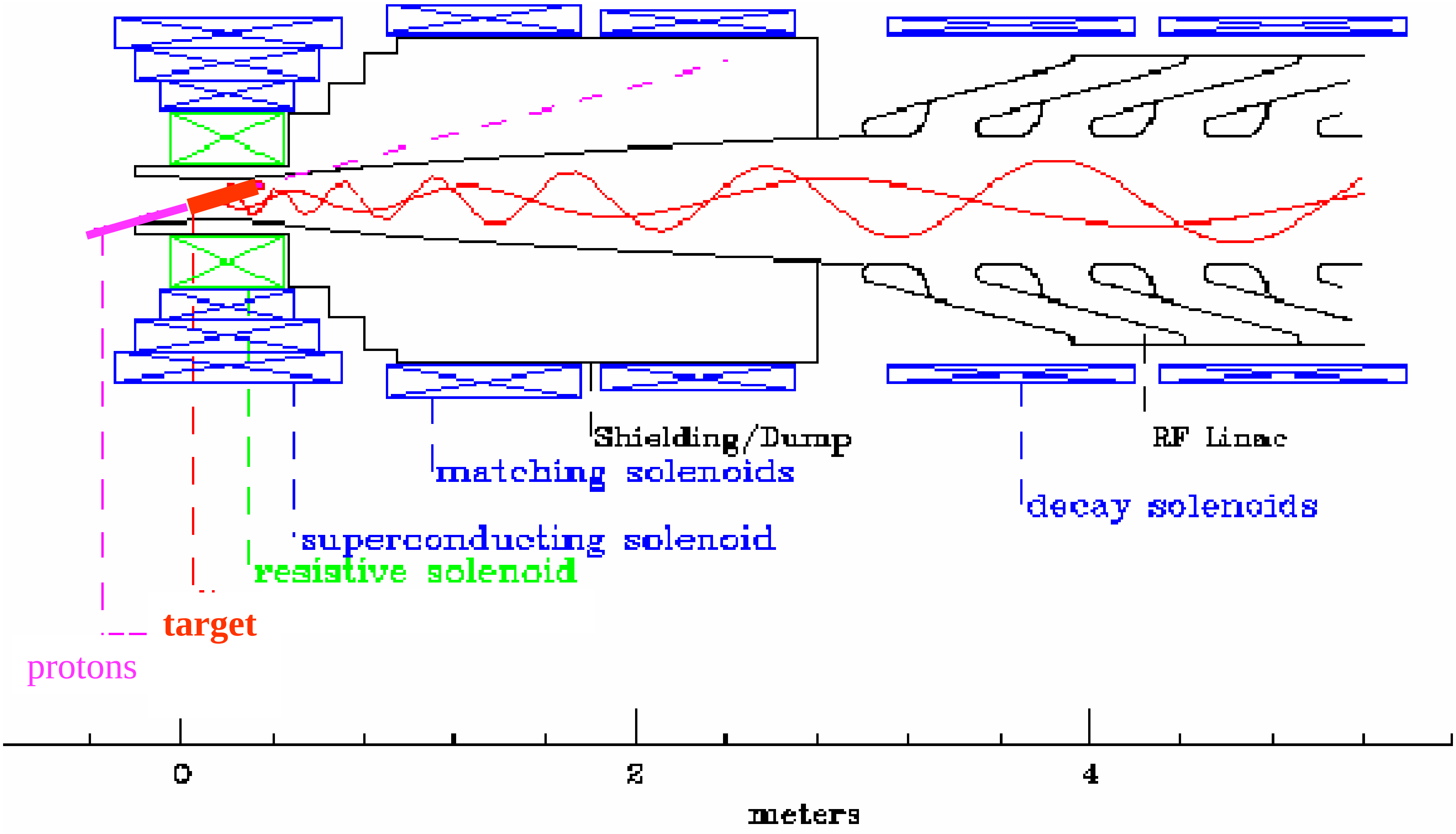
- I will not talk about liquid metal targets.

Contents

1. Solid target review -- or

Why are we afraid of solid targets?

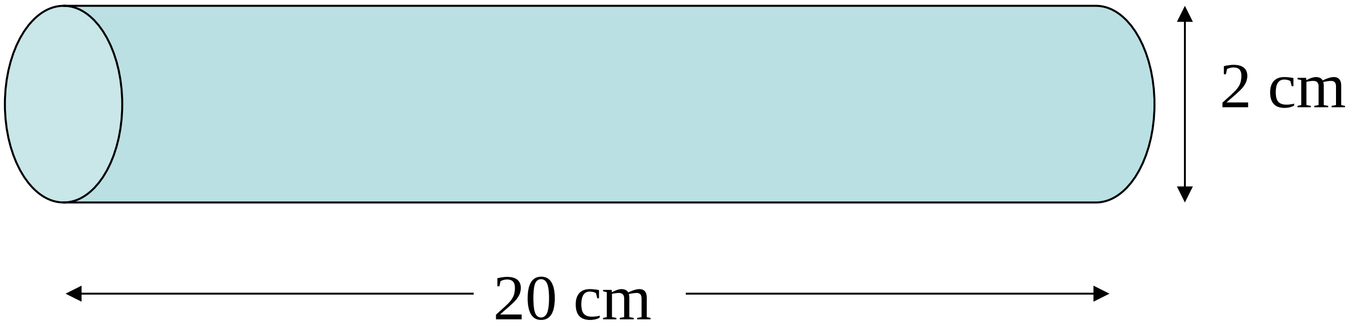
2. Proposed R&D in the UK



Typical Schematic Arrangement of a Neutrino Factory Target

Target

Heavy metal - Tantalum



Beam hits the whole target

Not a stopping target

SOLID Targets

Need to remove the heat - 1 MW

BUT

The PERCIEVED problem is

SHOCK WAVES

Shock

Shock processes are encountered when material bodies are subjected to rapid impulse loading, whose time of load application is short compared to the time for the body to respond inertially.

R A Graham in *High-Pressure Shock Compression of Solids*. Ed. J R Asay & M Shahinpoor, Springer-Verlag, 1992

The processes are all non linear so mathematical description is complex. Further, discontinuities complicate solution. Thus specialised techniques have been constructed to render the problem mathematically tractable.

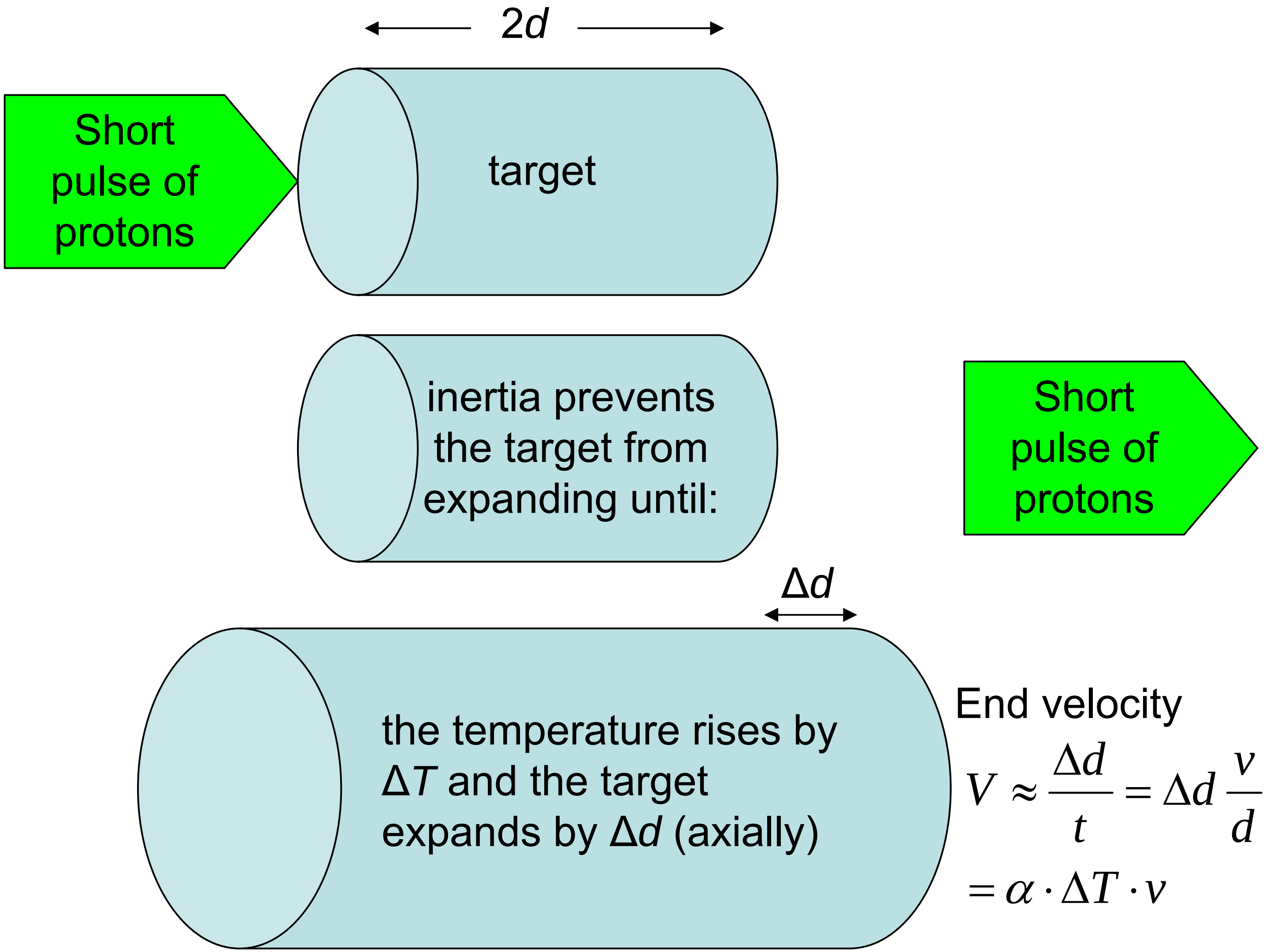
Neil Bourne, RMCS, Shrivenham

private communication

Examples of Shock Events:

- Explosions
- Bullets Impacting
- Volcanic Eruptions
- Meteor Collisions
- Aircraft Sonic Boom

Simple explanation of shock waves



Time

$t = 0$

$t > 0$

$t \approx v \cdot d$

the temperature rises by Δ*T* and the target expands by Δ*d* (axially)

End velocity

$$V \approx \frac{\Delta d}{t} = \Delta d \, \frac{v}{d}$$

$$= \alpha \cdot \Delta T \cdot v$$

v is the velocity of sound in the target material; α is the coefficient of linear expansion

End velocity

$$V \approx \frac{\Delta d}{t} = \frac{\Delta d \cdot v}{d} = \alpha \cdot \Delta T \cdot v = \alpha \frac{q}{C} v$$

Where:

v is the velocity of sound in the target material

α is the coefficient of linear expansion

q is the energy density dissipated (J g^{-1})

C is the specific heat (J g^{-1})

The velocity of sound is given by,

$$v = \sqrt{\frac{E}{\rho}}$$

where E is the modulus of elasticity and ρ the density

Thus the end velocity becomes,

$$V \approx \alpha \frac{q}{C} \sqrt{\frac{E}{\rho}}$$

To minimise V, for a given q, select a material with:

α & E small; C & ρ large. (Super-Invar has a very small α but losses this property under irradiation)

Expressing the energy density in terms of J cm^{-3},

$$V \approx \alpha \frac{q}{C}\sqrt{\frac{E}{\rho}} = \alpha \frac{e}{C \cdot \rho}\sqrt{\frac{E}{\rho}}$$

Hence the momentum of the end of the target can be found.

Since the force is equal to the rate of change of momentum it is possible to calculate the stress in the material.

In the case of the Neutrino factory target the stress exceeds the strength – ***disaster.***

- Can make a better analysis - Peter Sievers, under ideal elastic conditions, CERN Note LAB.II/BT/74-2, 1974.
- There are modern stress analysis packages available commercially to deal with dynamic situations.
- Chris Densham has calculated (ANSYS) that a solid tantalum target for the neutrino factory will probably show signs of shock fracture after a few pulses.

Shock, Pulse Length and Target Size

If we heat a target uniformly and slowly – there is no shock!

Or,

when the pulse length τ is long compared to the time t taken for the wave to travel across the target – no shock effect!

So,

if we make the target *small* compared to the pulse length there is no shock problem.

If $$t = \frac{d}{V} < \tau$$ No problem!

Assume $\tau = 2\ \mu\text{s}$, $V = 3.3\text{x}10^5\ \text{cm s}^{-1}$, then $d = 0.7$ cm

Also need sufficient pulsed energy input.

This principle has been used in the target designed by Peter Seivers (CERN).

Solid Metal Spheres in Flowing Coolant

- Small spheres (2 mm dia.) of heavy metal are cooled by the flowing water, liquid metal or helium gas coolant.
- The small spheres can be shown not to suffer from shock stress (pulses longer than ~3 μs) and therefore be mechanically stable.

GRANULAR TARGET COOLED BY LIQUID

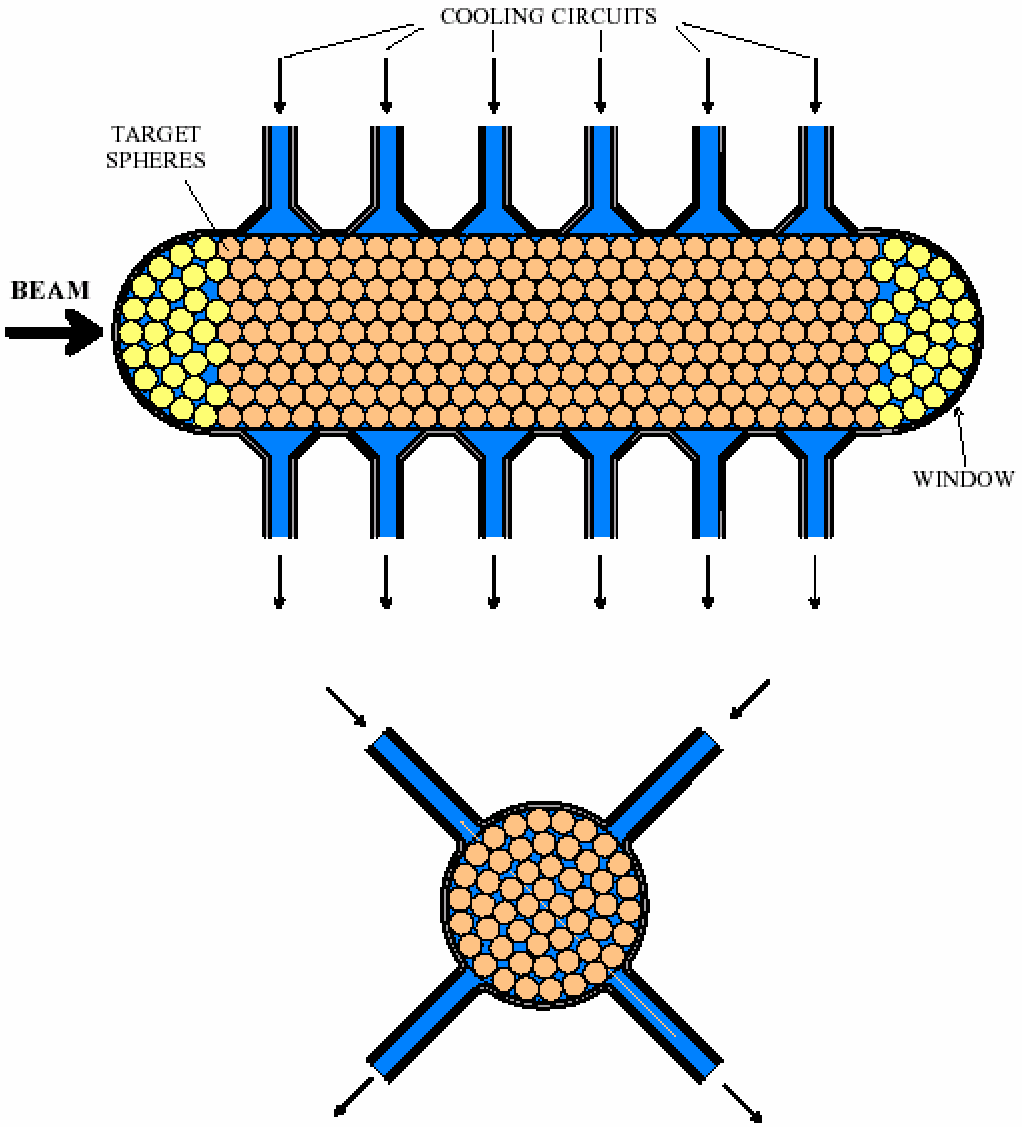


Fig. 1 : Principle lay-out of a liquid cooled, granular target. Tantalum spheres with a diameter of about 2mm are confined in a Titanium container and cooled by water (or possibly liquid metal) traversing the voids between the spheres.

Looks like we have a problem for large targets!

(2 cm diameter, 20 cm long)

BUT!

Have we seen shock wave damage in solid targets?

What do we know?

There are a few pulsed ($\leq$~1μs) high power density targets in existence:

Pbar - FNAL

NuMI

SLAC (electrons)

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								

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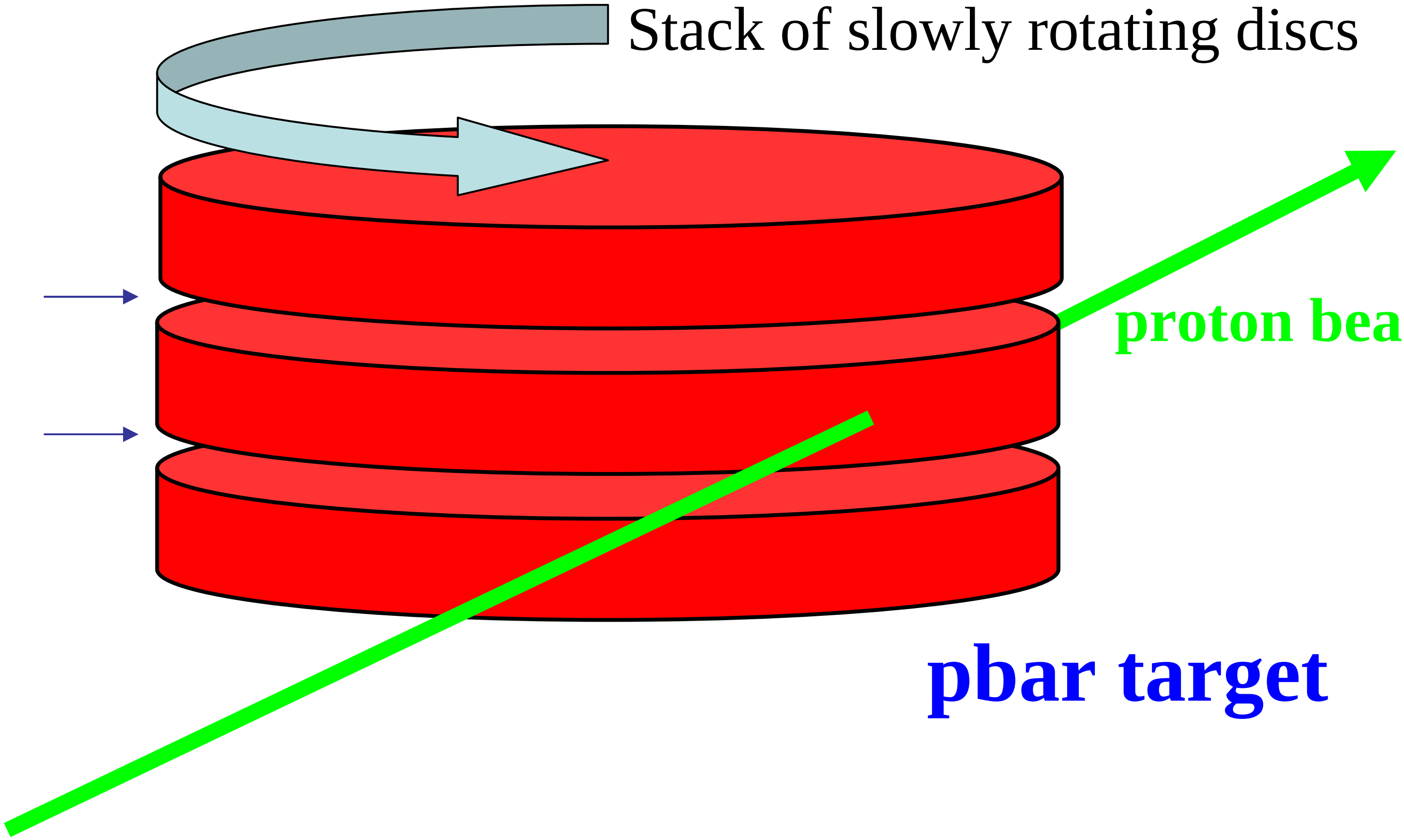
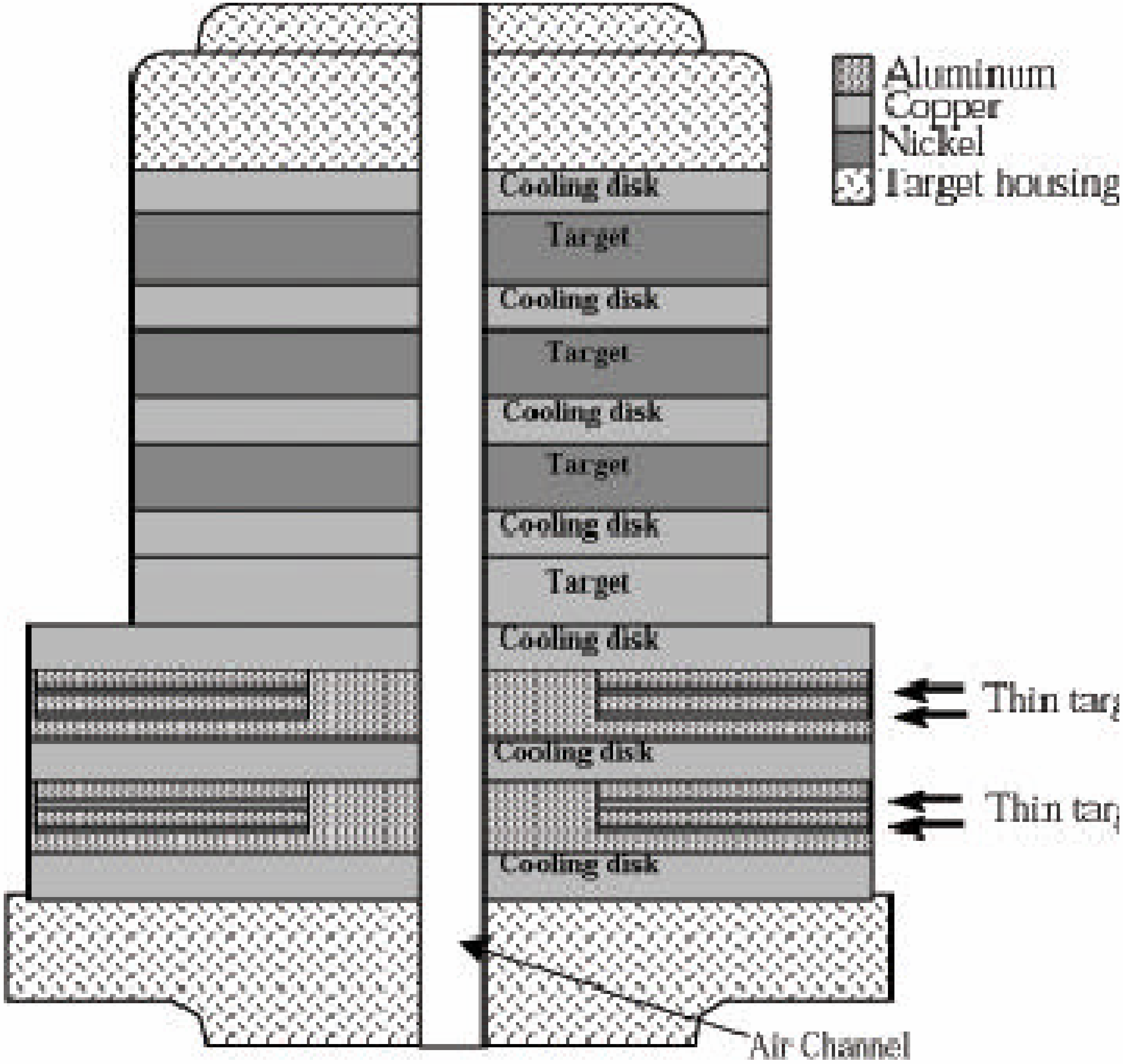
		f	P	Q	height	width	length	volume	thick	material	q		N
		Hz	W	J	cm	cm	cm	cm^3	cm		J cm^{-3}	days	
NuFact	**protons**	**50**	**1E+06**	**20000**	**2**	**2**	**20**	**63**	**20**	**Ta**	**318**	**279**	**1.E+09**
				Number of pulses on any one section of the toroid									**7.E+06**
SLC	**e**	**120**	**5.E+03**	**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							

No damage with ISOLDE (foil) or ISIS targets; but some damage with Pbar targets.

In 2 tests on solid tantalum bars (20 cm long 1 cm diameter) at ISOLDE Jacques Lettry has observed severe distortion. He considers this is due to shock.

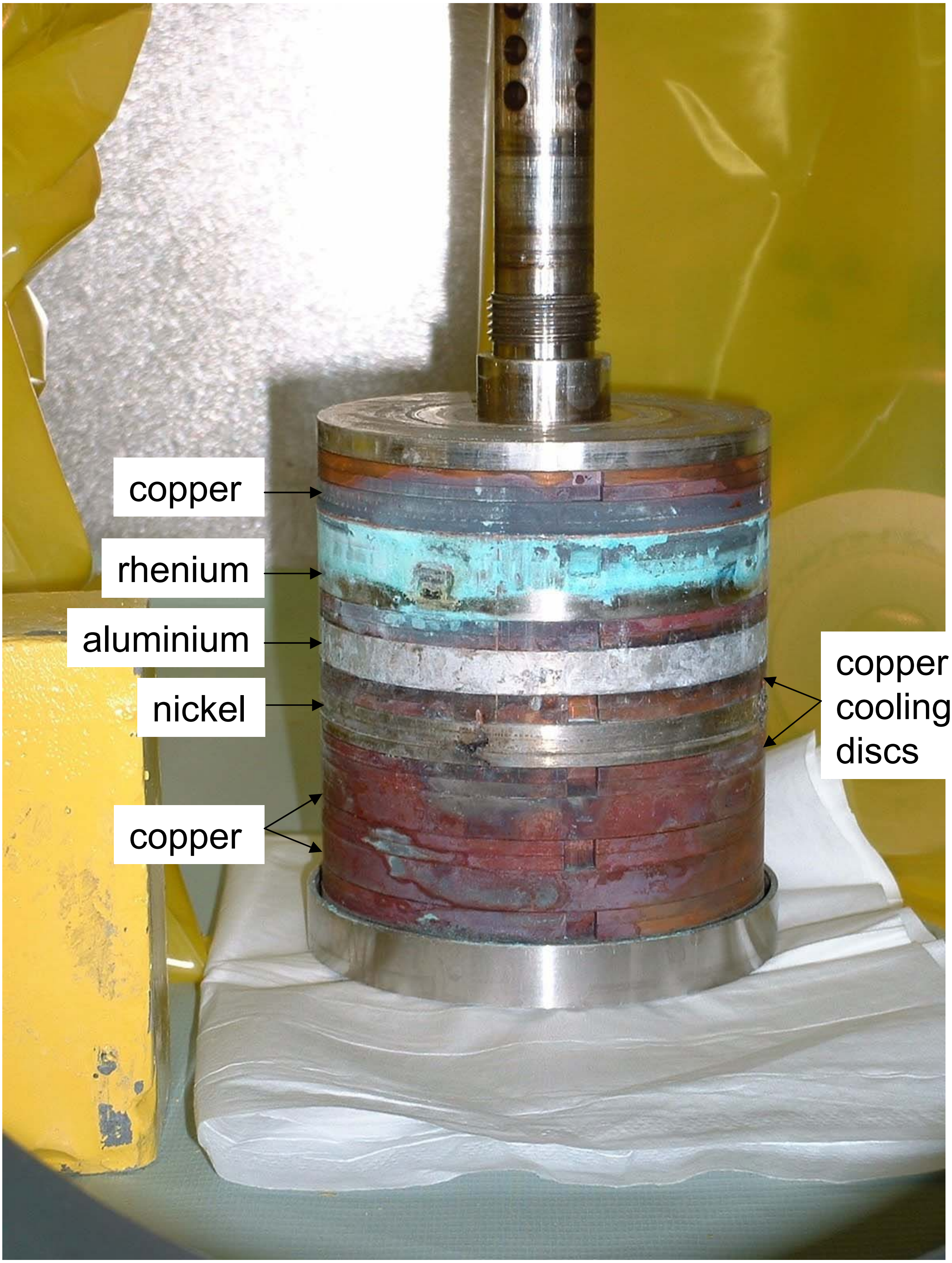
Schematic Diagram of the Pbar target





Section through the pbar target assembly

Vinod Bharadwaj / Jim Morgan



Pbar Target (Jim Morgan)

Entry Damage (Jim Morgan)

Exit Damage (Jim Morgan)

Proposed R&D in the UK

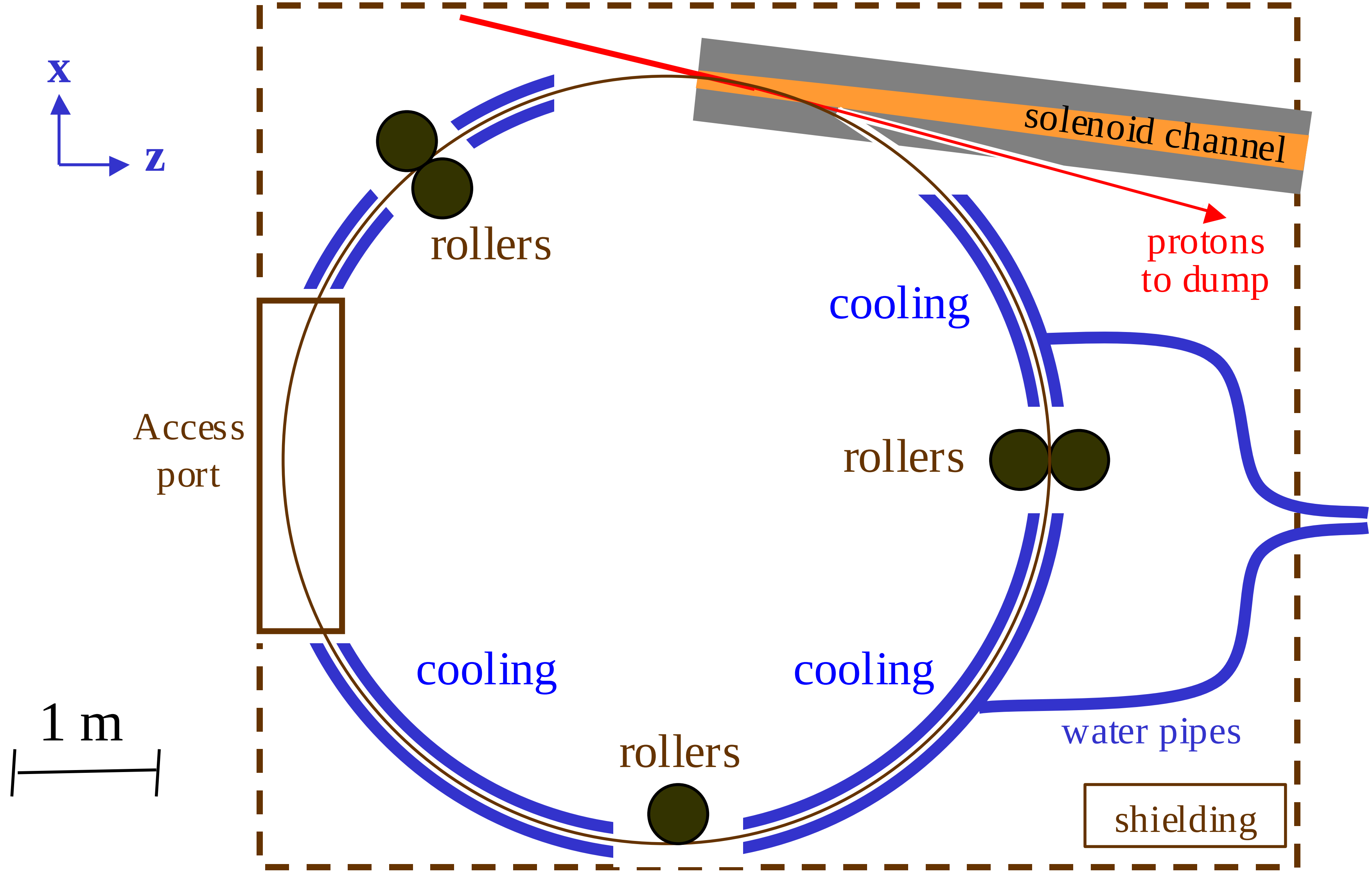
1. Radiation cooled rotating toroid
    a) Calcuate levitation drive and stabilisation system
    b) Build a model of the levitation system
2. Individual bars
    a) Calculate mechanics of the system
    b) Model system
3. Calculate the energy deposition, radio-activity for the target, solenoid magnet and beam dump.

Calculate the pion production (using results from HARP experiment) and calculate trajectories through the solenoid magnet.

Proposed R&D, Continued

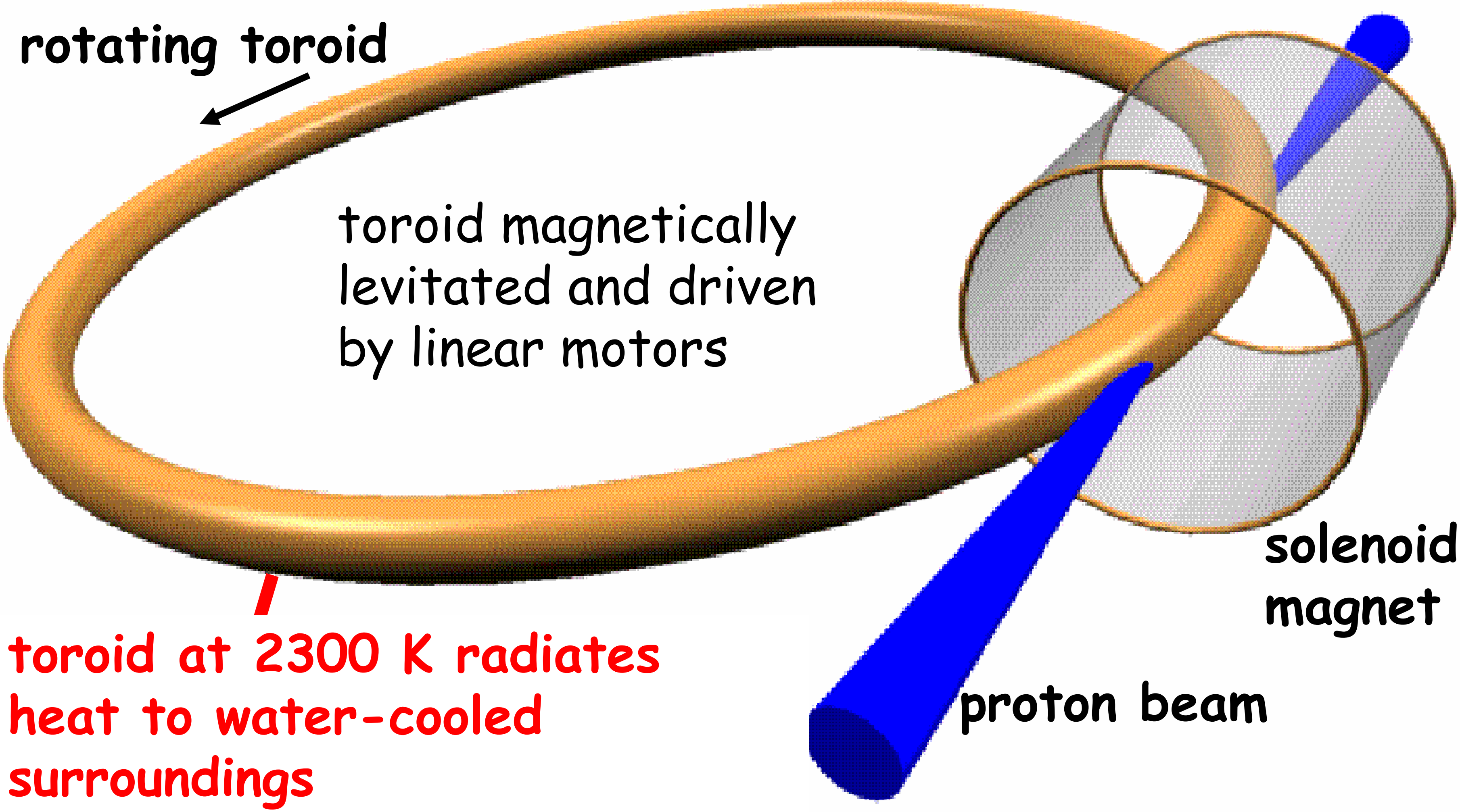
4. Model the shock
   - a) Measure properties of tantalum at 2300 K
     - b) Model using hydrocodes developed for explosive applications at LANL, LLNL, AWE etc.
     - c) Model using dynamic codes developed by ANSYS
5. Continue electron beam tests on thin foils, improving the vacuum
6. In-beam test at ISOLDE - 10^6 pulses
7. In-beam tests at ISIS – 10^9 pulses

Plan View of Targetry Setup



Bruce King et al

Schematic diagram of the rotating toroidal target



rotating toroid

toroid magnetically
levitated and driven
by linear motors

**solenoid
magnet**

proton beam

**toroid at 2300 K radiates
heat to water-cooled
surroundings**

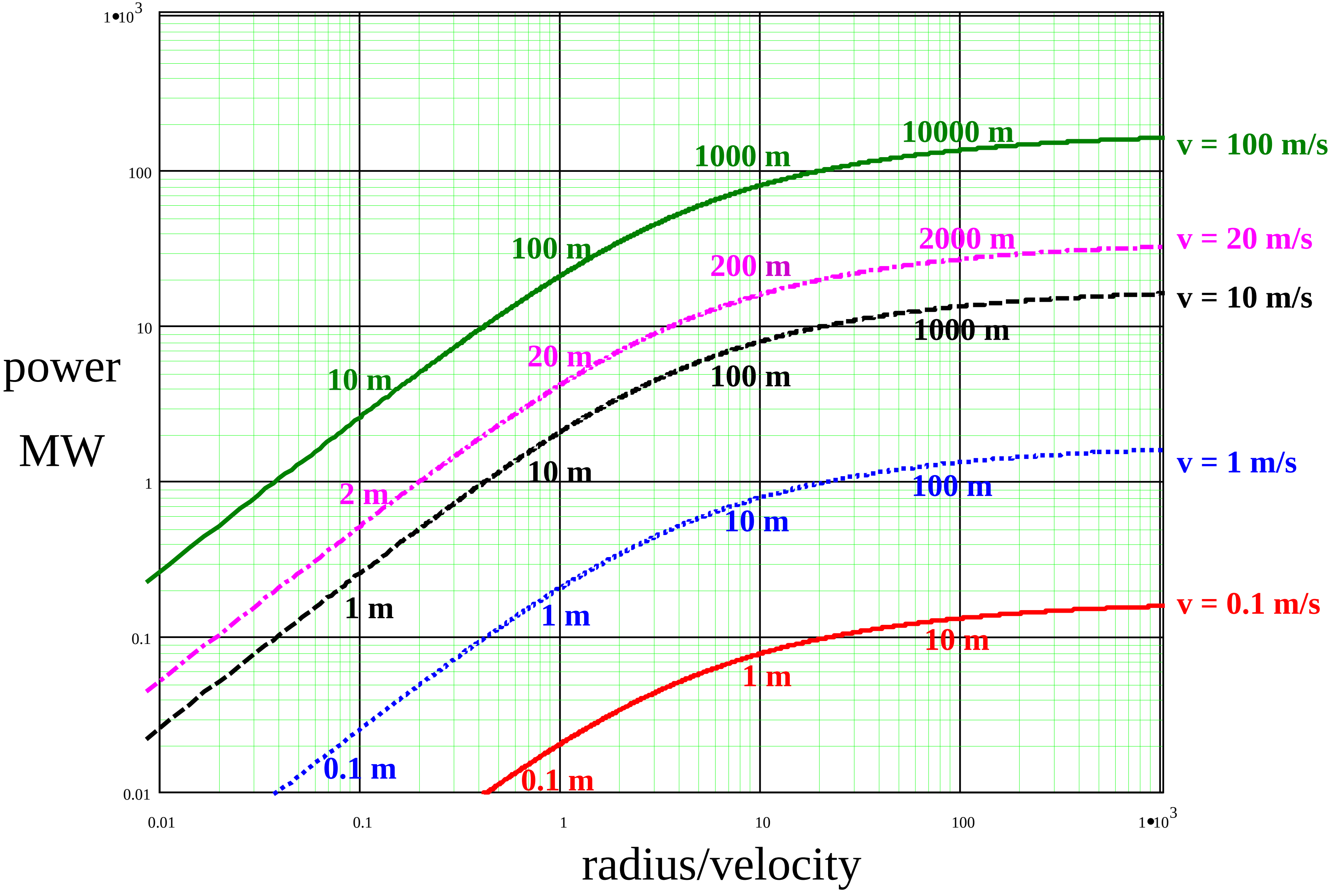
Heat Dissipation

by

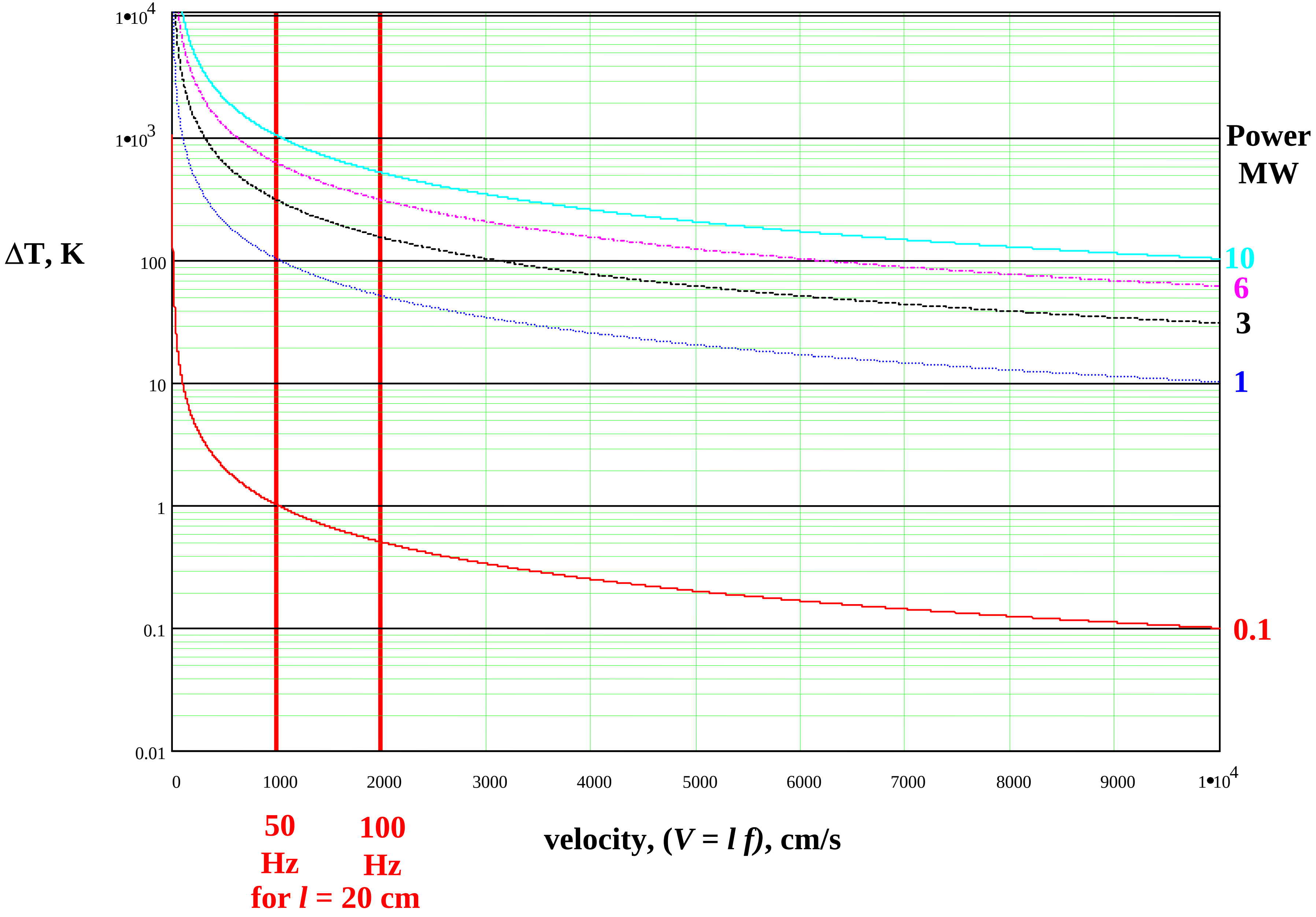
Thermal Radiation

This is very effective at high temperatures due to the T^4 relationship

POWER DISSIPATION



Temperature Rise v Velocity at Different Powers



Target Designs

1. Toroid

   If the toroid breaks there are problems.

   Individual bars are better

2. Bars on a wheel

   - Problems with the solenoid magnet

3. Free bars

Wheel Target

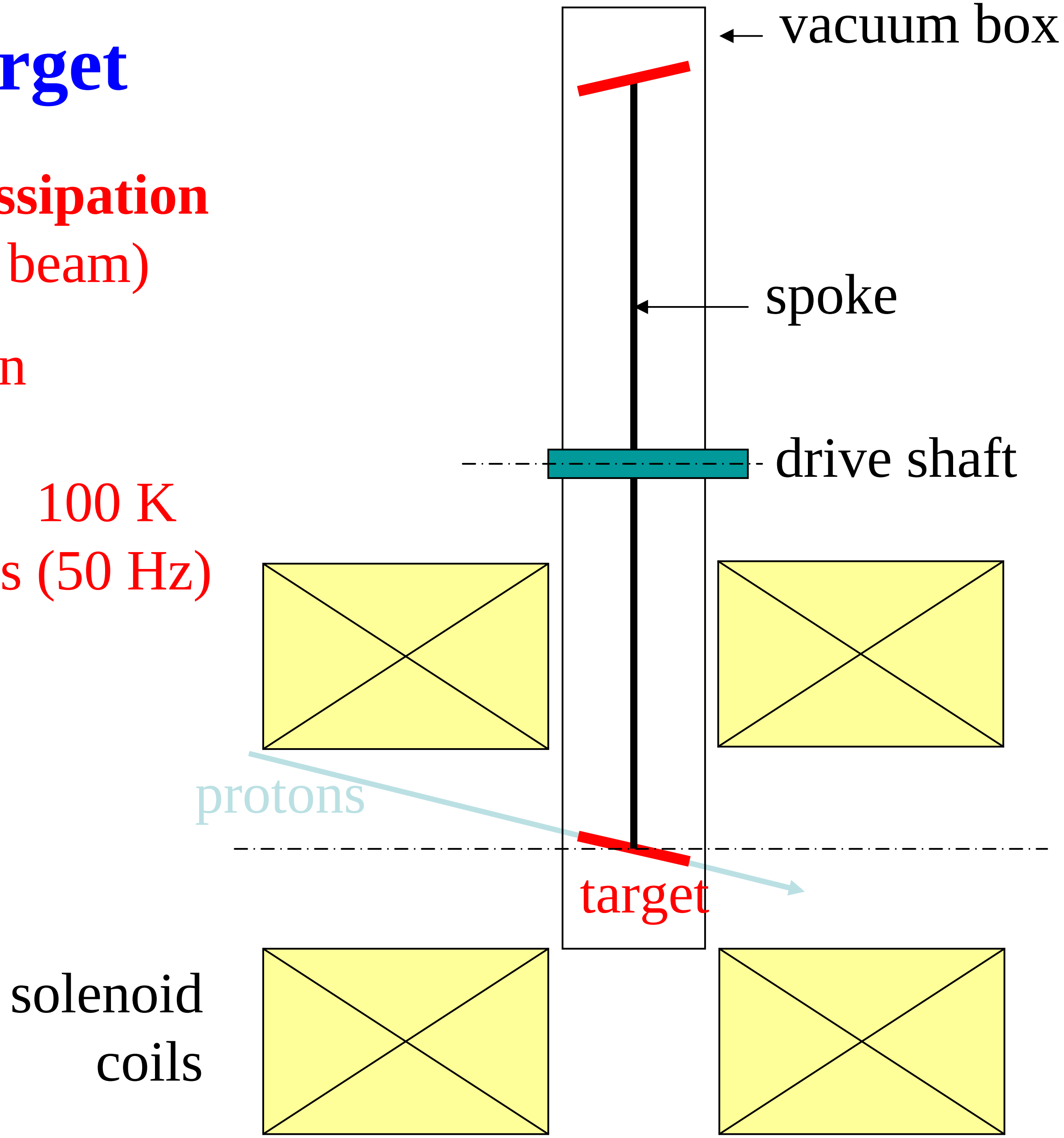
1MW Target Dissipation

(4 MW proton beam)

tantalum or carbon

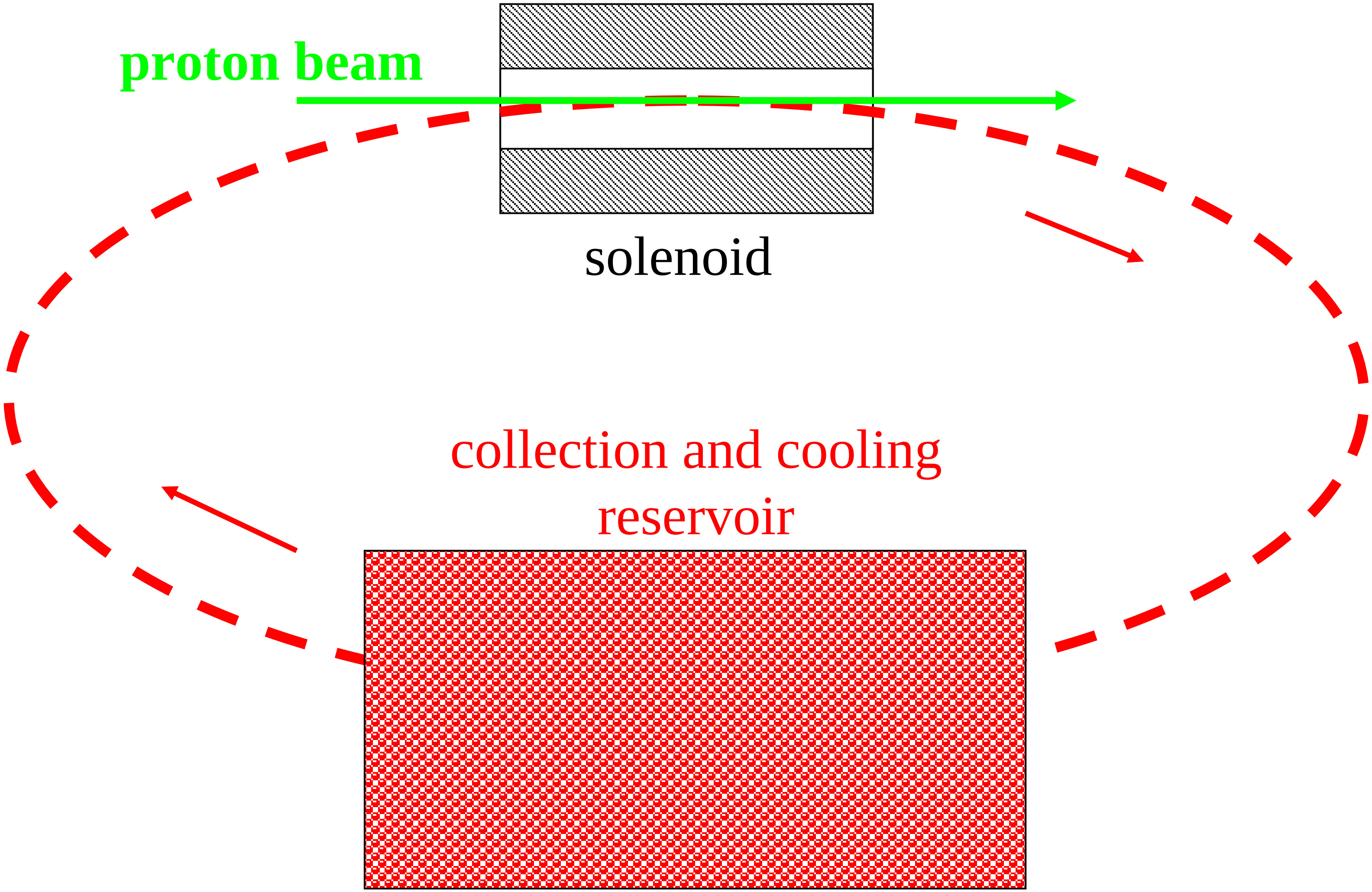
radiation cooled

temperature rise	100 K
speed	5.5 m/s (50 Hz)
diameter	11 m



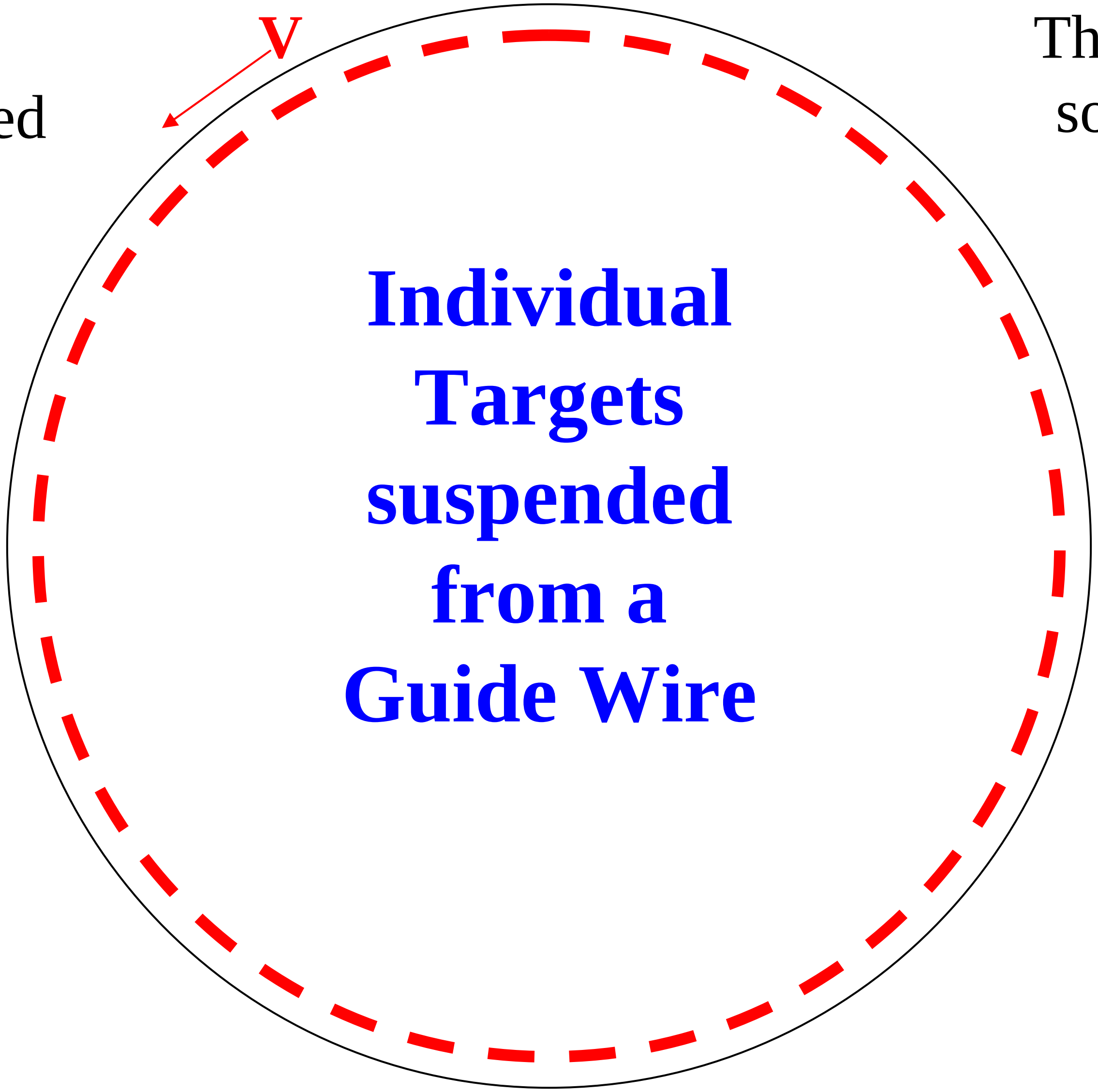
Individual free targets

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



$V = Lf$

R governed
by power



Threading
solenoid

**Individual
Targets
suspended
from a
Guide Wire**

Choice of Target Material

Tantalum

Why?

Why Tantalum?

1. Refractory. Melting point 3272 K

2. Good irradiation properties

   No damage observed with ISIS tantalum target after bombardment with 1.27×10^{21} protons/cm^2, suffered 11 dpa. No swelling. Increased yield strength. No cracking. Remains very ductile. Hardness increased by a factor <2. [J. Chen et al, J. Nucl. Mat. **298** 248-254 (2001)]

3. Relatively easy to machine and weld etc.