NuMI Target Status
and
Design Study for Proton Driver

Outline:

- NuMI target: 1 m long graphite water-cooled target

- Current target is designed for 0.4 MW
  - what beam power has been achieved, and how is the target operating ?

- Is the concept of graphite target workable for FNAL 2 MW beam ?
  - stress from 1.5e14 protons/spill ?
  - radiation damage lifetime ?
  - cooling ?
  - difference between using 40 GeV or 120 GeV protons?

Calculations done by V. Garkusha et.al, IHEP, Protvino, Russia

NuMI Target design drivers

For maximal neutrino production with horn system, target should be

- ~ 2 interaction lengths long (to interact most protons)
- narrow (so pions can exit out sides before re-interacting in target)

For lower energy neutrinos (current MINOS experiment)

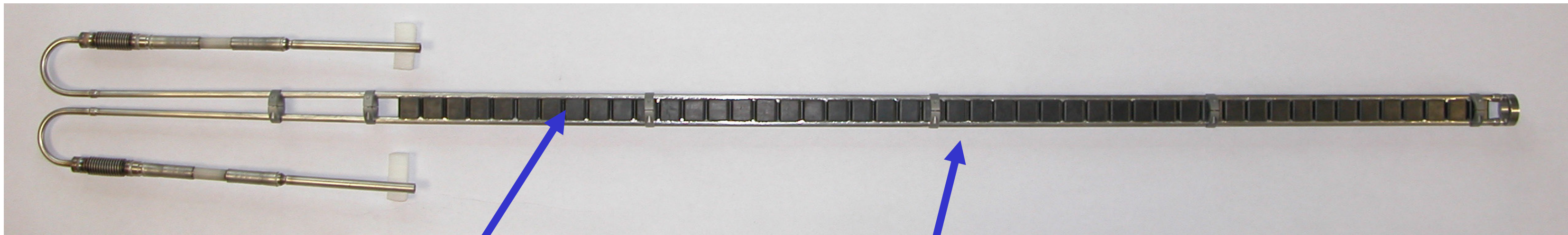
- target must stick into horn – severe design constraints

For higher energy neutrinos (future NoVA experiment)

- target can be upstream of horn

NuMI Target

long, thin, slides into horn without touching



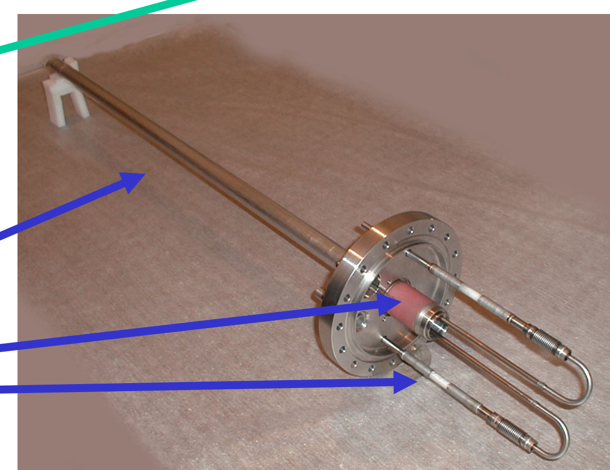
Graphite Fin Core, 2 int. len.

(6.4 mm x 15 mm x 20 mm) x 47

Water cooling tube also provides mech. support

Anodized Al spacer (electrical insulation)

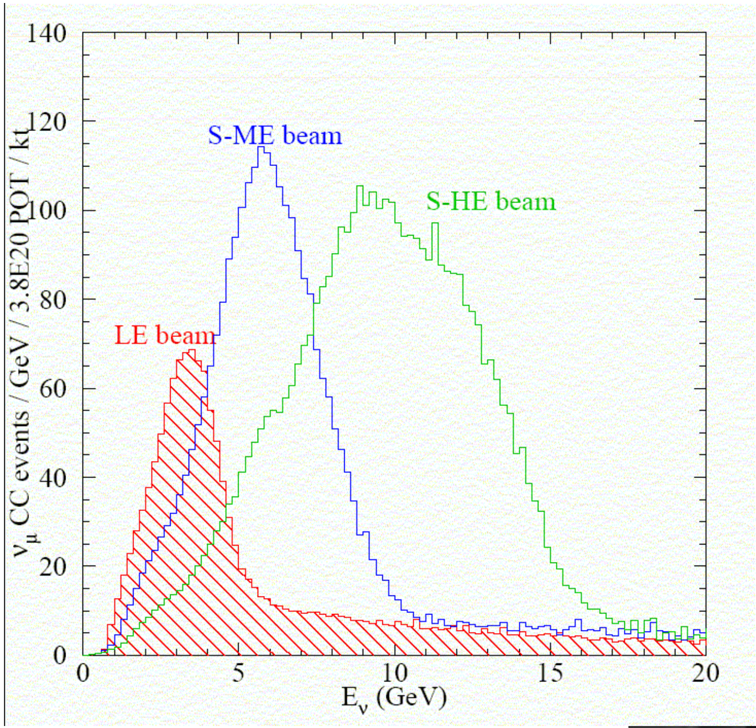
Water turn-around at end of target



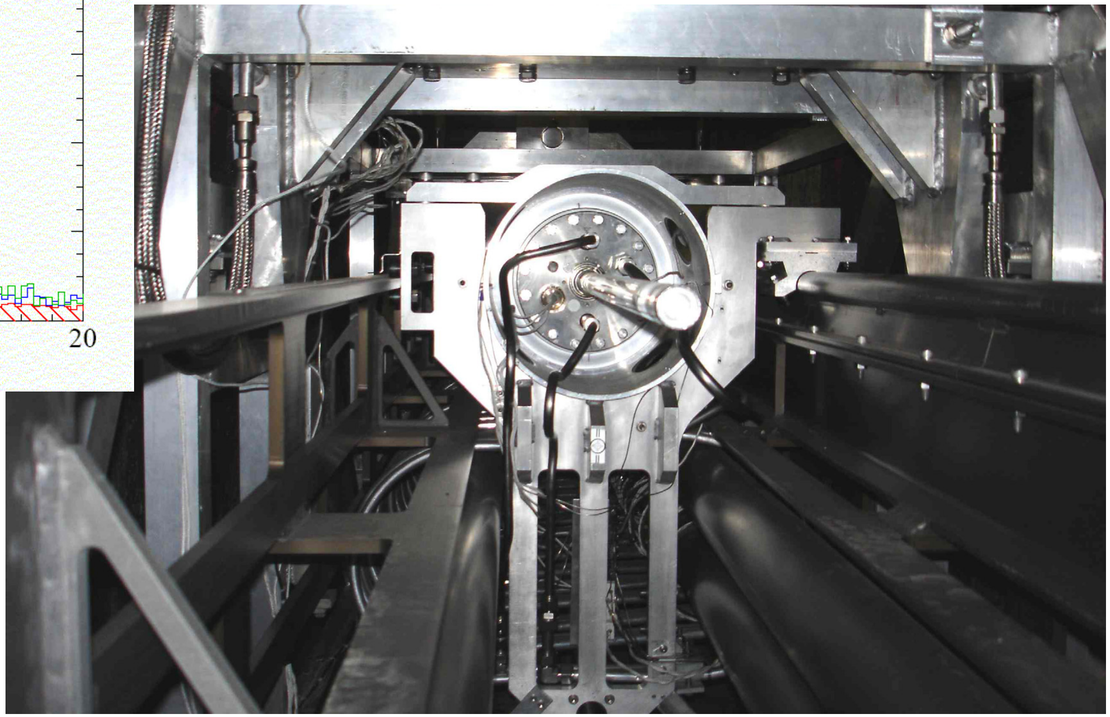
0.4 mm thick Aluminum vacuum/Helium tube

Ceramic electrical isolation

NuMI Target remotely moves 2.5 m to allow change of focus



Different neutrino spectra from moving target (Monte Carlo)



Experience with the NuMI Target

Had one major bump in the road – a water leak early in commissioning –
but now operating well !

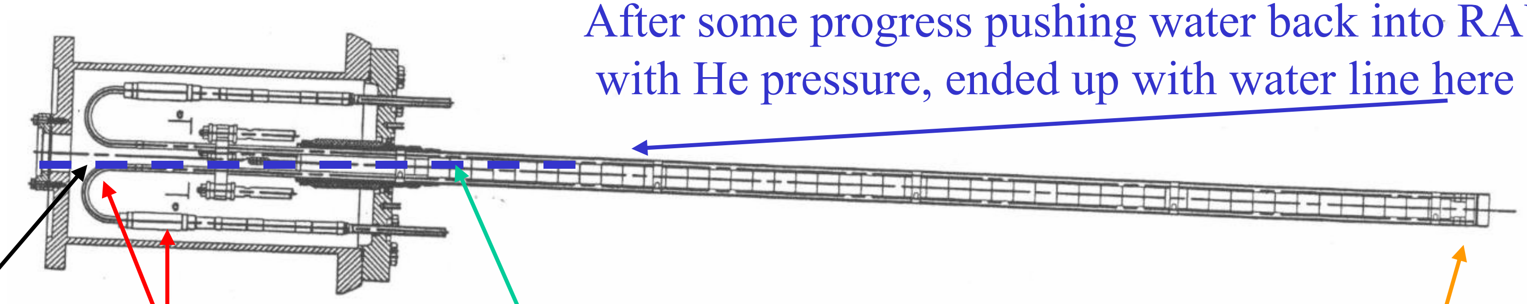
	Maximum Proton / 10μs spill	Maximum Beam Power	Integrated Protons on Target
Target Design	40e12 p.p.p.	400 kW	370 e18 p.o.t. lifetime
Goal for 2005	25e12 p.p.p.	240 kW	75 to 100 e18 p.o.t.
Achieved before leak (March '05)	25e12 p.p.p.	69 kW	0.7 e18 p.o.t.
Achieved since leak	28e12 p.p.p.	268 kW	65 e18 p.o.t. so far

1 mm RMS spot size

Target leak –
rounding up the suspects
but still don't know who did it

On March 23, water leaked from cooling line into vacuum can

After some progress pushing water back into RAW
with He pressure, ended up with water line here



(i) RAW to Vacuum delta-pressure
(0.3 MPa) overstress bellows
or overstress water line bend ?

(ii) flaw in downstream turn-around ?
complicated welds in hadron shower,
200 PSI hydraulic shock wave at design intensity

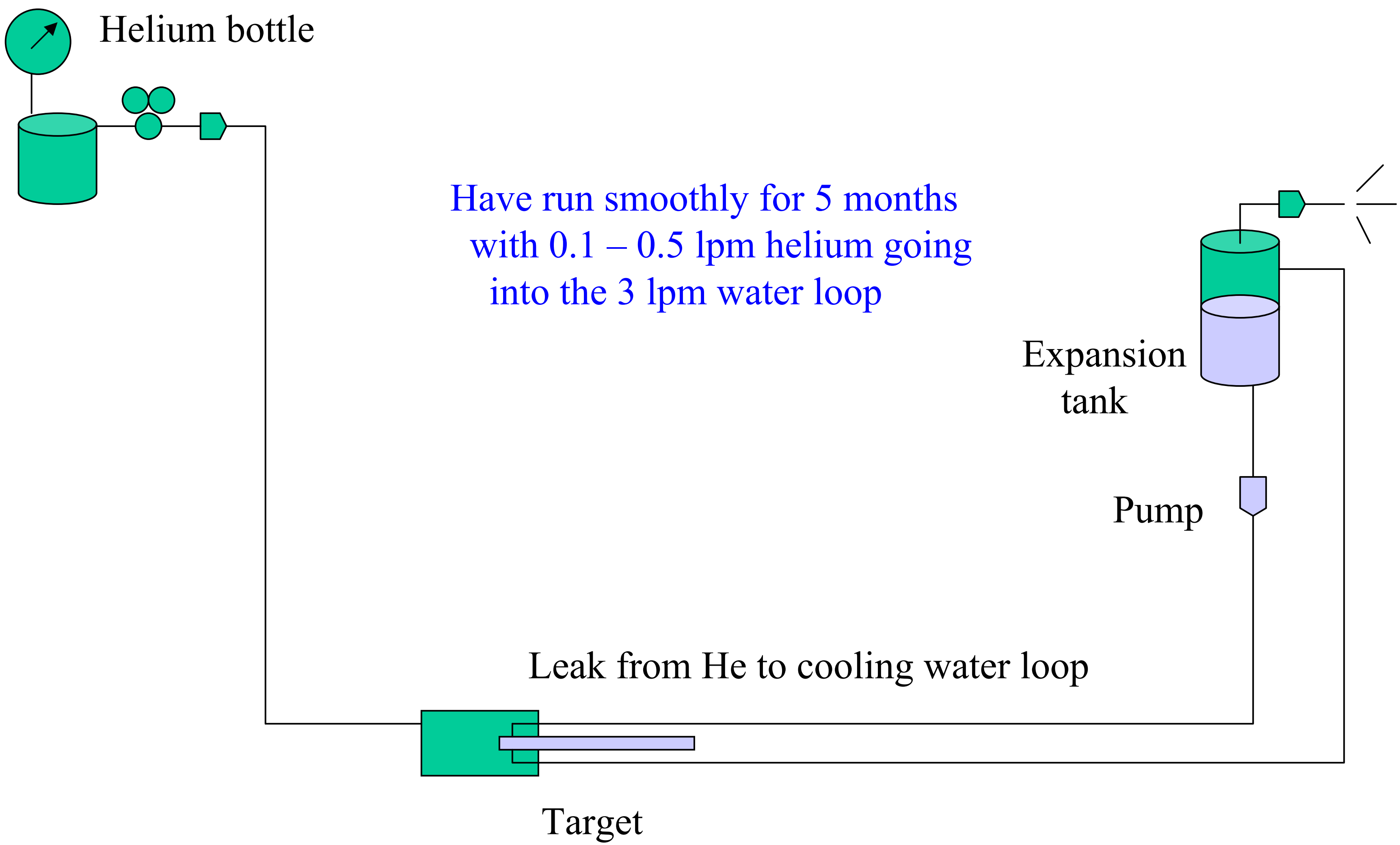
(iii) August accident overstressed tube ? Target was bent.

(iv) hit tube with beam ? Post-leak survey does not show tube sticking into beam,
although right on edge of baffle protection

(v) Ceramics ? Just because people always suspect the ceramics

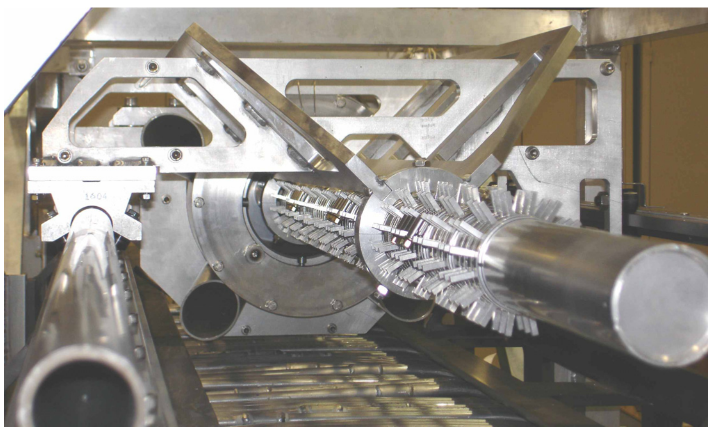
(vi) Micro flaw in weld anywhere in tube?

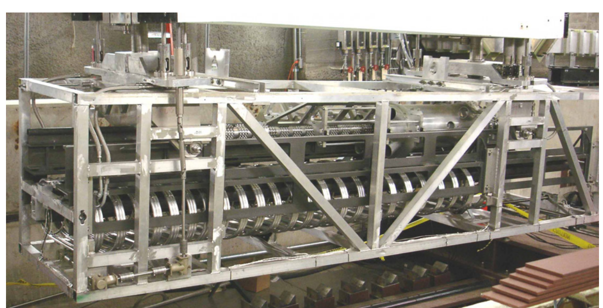
Didn't plug leak, but changed pressures, so helium leaks into water system instead of water into target

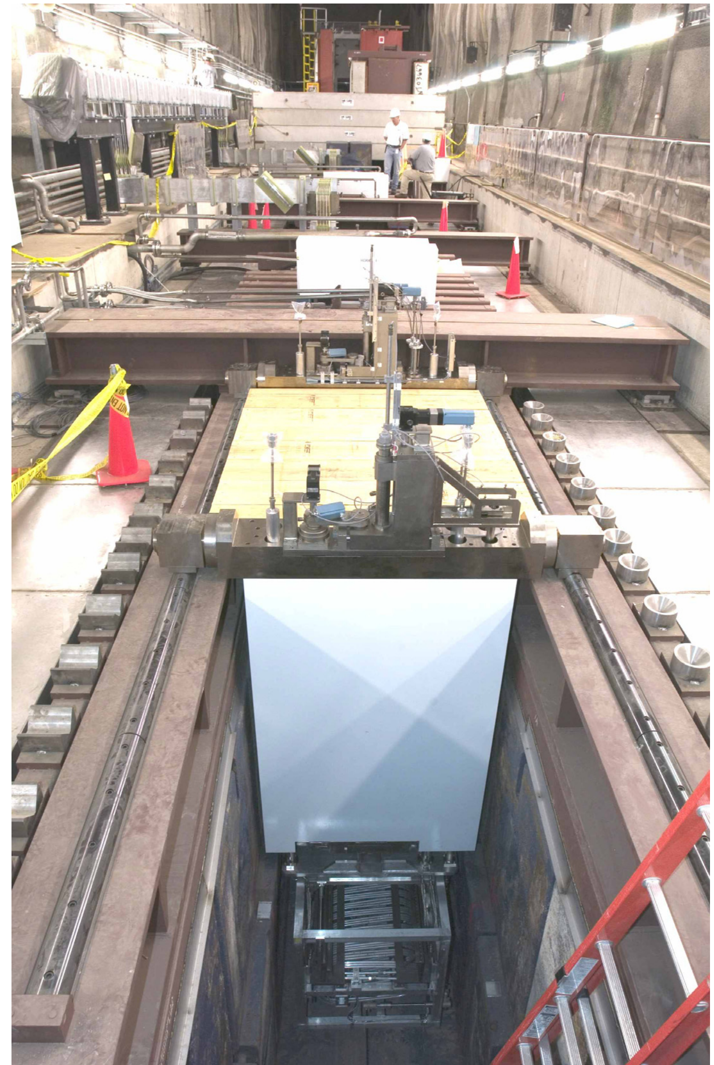


Conclusion of target status:

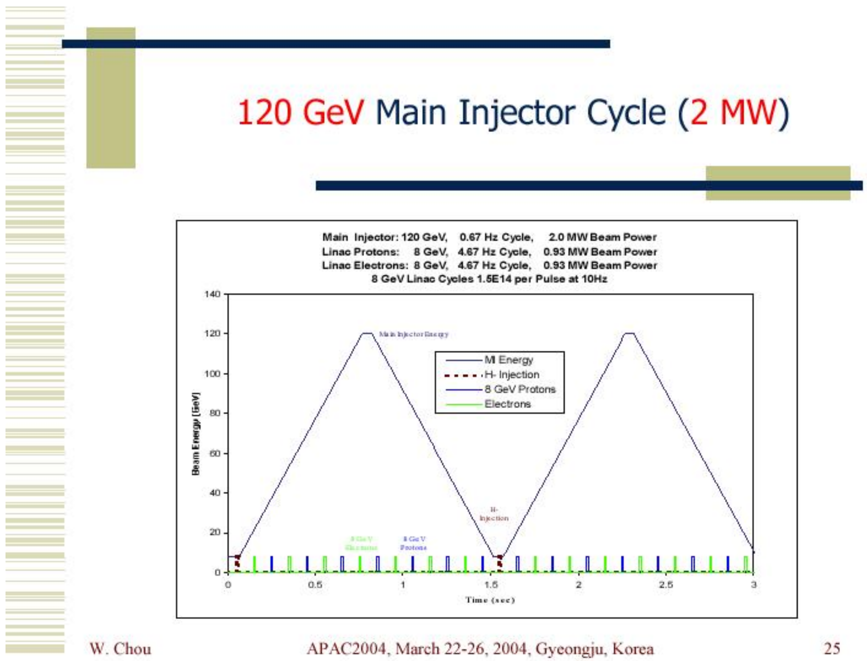
NuMI target has overcome one major problem; now looking forward to lots more beam !

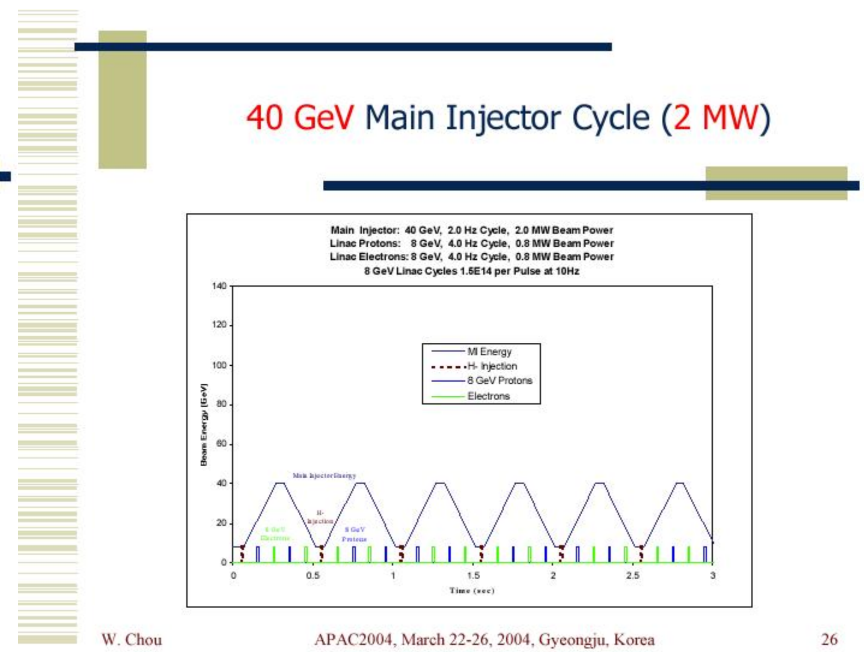






Proton Driver study - compare 2 MW at 120 GeV versus 40 GeV





0.67 Hz cycle

2.0 Hz cycle

1.5×10^{14} protons per pulse !

vs. 4×10^{13} ppp at 0.53 Hz cycle for the current FNAL accelerator complex

Target Working Group:

V.Garkusha, A.Ryabov, T.Ryabova,
F.Novoskoltsev, V.Zarucheisky…….(IHEP, Protvino)

A.Mikheyev, I.Ponimash……………..(IPPE, Obninsk)

J.Hylen…………………………………..(FNAL)

Target Design (1)

Encapsulation of graphite cylinders (segments) with a prestress of about 10 MPa into stainless steel or aluminum thin-walled pipe:

- Provides an integrity of the target core and keeps it even in the case of thermo-mechanical or radiation damages of some segments
- Prevents a direct contact of the cooling water with the heated surface of graphite
- Provides a good thermal contact between graphite and metal pipe

See NuMI notes 0501 and 0543 (1999)

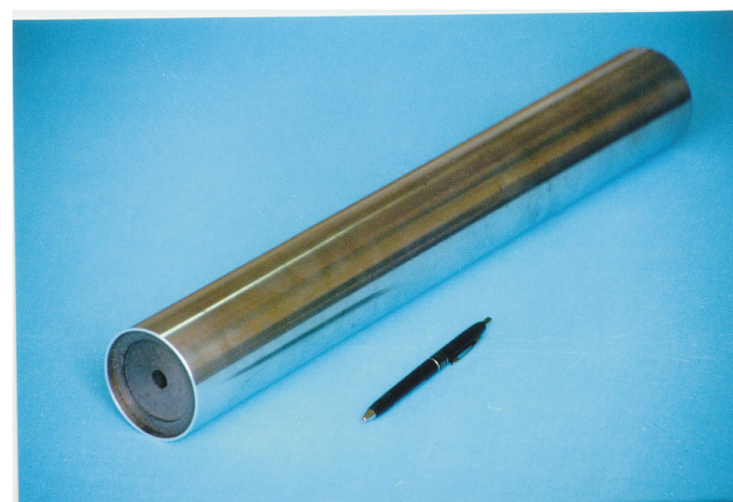
Target Design (2)

Prototype of the beam plug (1999):

∅30 mm graphite cylinders are encapsulated into 0.3 mm thick *stainless steel pipe*

Prototype of the baffle collimator (2002):

∅58 mm graphite cylinders are encapsulated into 1.5 mm thick *aluminum pipe*



Target Design (3)

Target core: ~32 graphite cylinders, each ∅15 mm and 30 mm length, with 0.2 mm gaps (~1 m length)

Metal pipe: 0.2÷0.3 mm thick stainless steel pipe or ~1 mm thick aluminum pipe

Apparent density	1.8 g/cm^3
Particle size	1 micron
Modulus of elasticity	14.5 GPa
Compressive strength	195 MPa
Tensile strength	90 MPa
Thermal conductivity	70 W/m K
Coefficient of thermal expansion	8.1×10^{-6} 1/K
Specific heat	710 J/kg K
Oxcidation threshold	450 ^{0}C

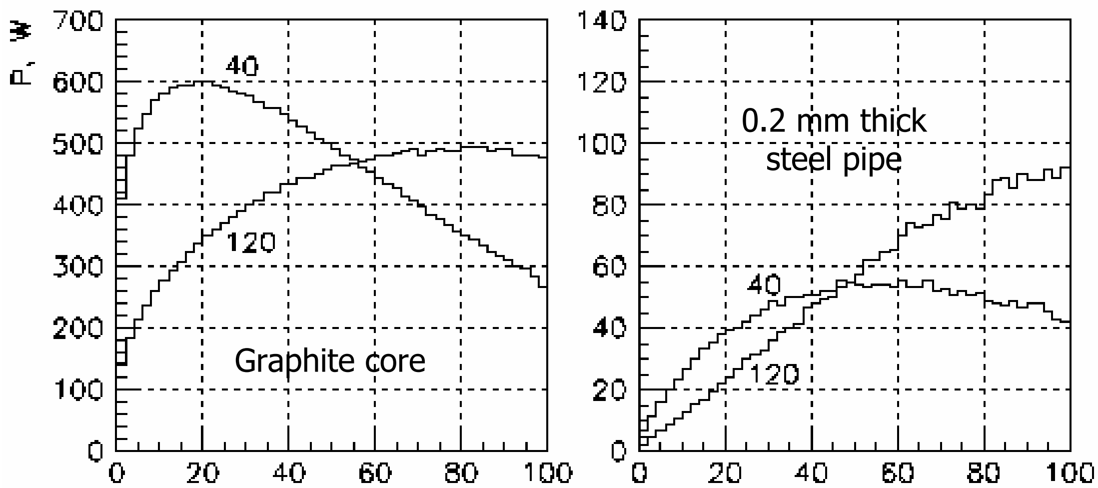
ZXF-5Q graphite grade of Poco Inc.

Properties at 20 ^{0}C

Other materials ?

Room temperature properties + temperature dependencies of main properties are needed for correct comparison of materials

Energy Deposition



$$\sigma_{BEAM} = \frac{1}{5} R_{TARGET}$$

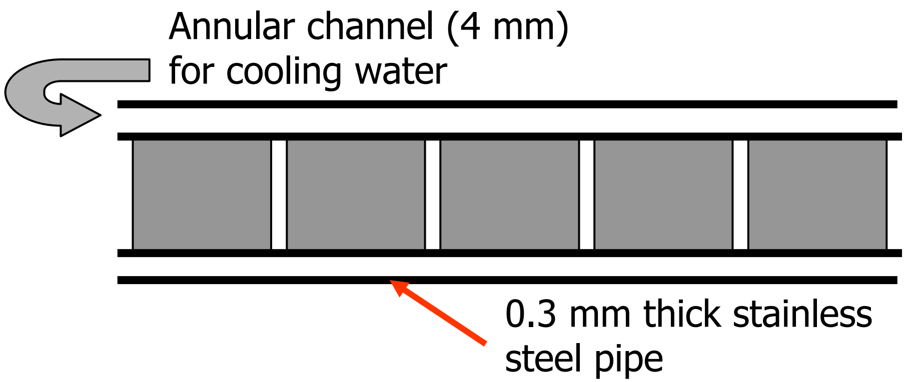
Approx. the same distributions take place in case of graphite, encapsulated in the 1mm aluminum pipe

Energy deposition (kW) in different parts of the 1 m length target

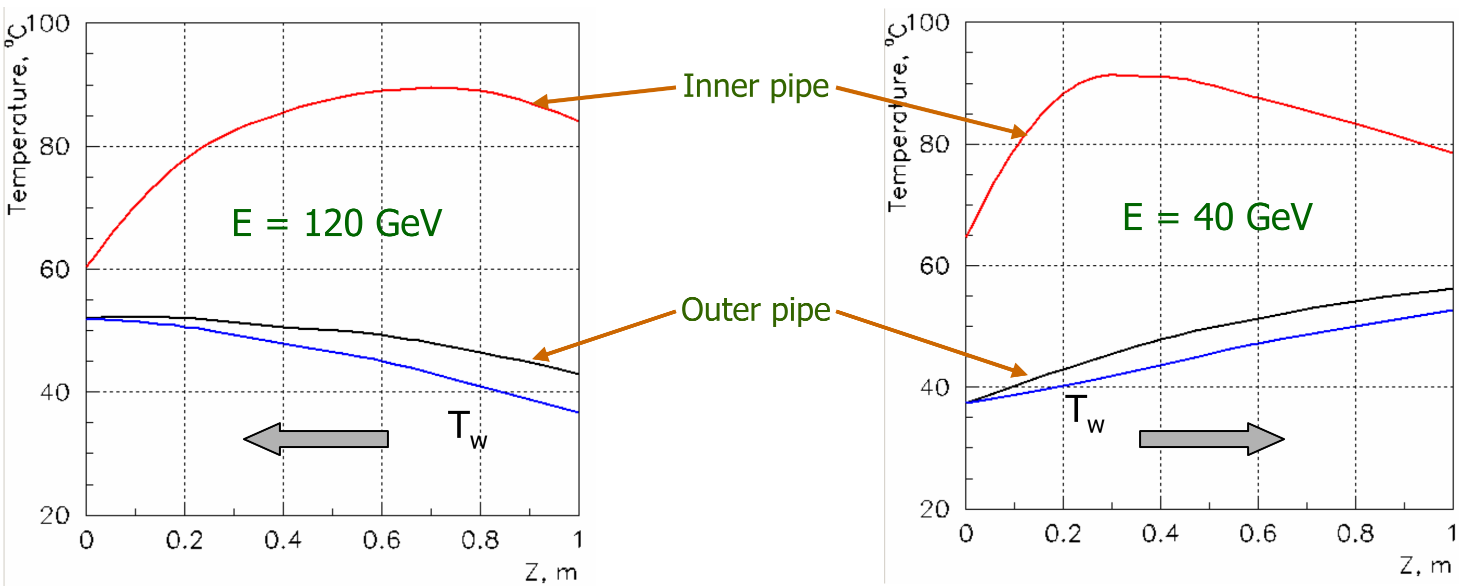
Proton beam energy	40 GeV		120 GeV	
Graphite core	23.3	22.7	20.8	19.7
Steel pipe (0.2 mm)	2.2		2.7	
Aluminum pipe (1 mm)		3.4		3.7
The whole target	25.5	26.1	23.5	23.4

The power flux through the lateral surface of target reaches 700 kW/m^2

Cooling of Target (1)



Velocity of a cooling water	2.2 m/sec
Water flow rate	30 l/min
Heat transfer coefficient	15 kW/m² K
Pressure drop	0.008 MPa
Input pressure of water	>0.11 MPa
Input temperature of water	37 ⁰C



Cooling of Target (2)

Instantaneous pressure rise in a cooling water:

$$\Delta P = \frac{\beta \Delta T_{water}}{\kappa}$$

$\beta(T = 20^0 C) = 0.2 \times 10^{-3}$ - coeff. of volume change

$\kappa = 0.46 \times 10^{-9}$ - volume compressibility

$\downarrow T_{water} \rightarrow \downarrow \beta \rightarrow \downarrow \Delta P$

For 120 GeV proton beam ΔT_{water} reaches 20 ^{0}C → $\Delta P \sim 90$ atm !

(hydraulic shock)

Next steps of a cooling system study:

1. Estimation of the hydraulic shock impact on the cooling system
2. Use of <u>the two-phase flow</u> for shock absorption:

   Loading of a cooling water with He or Ar bubbles (10-15%)

   Phase transfer (boiling of water)
3. Use of <u>the heat pipe technology</u> (evaporating cooling) for target cooling

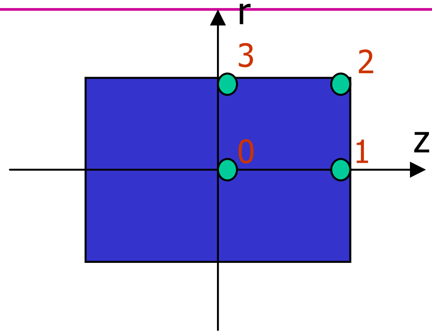
Temperature and Stresses (1)

Were calculated by ANSYS for target segments with highest energy deposition density (EDD) under following conditions:

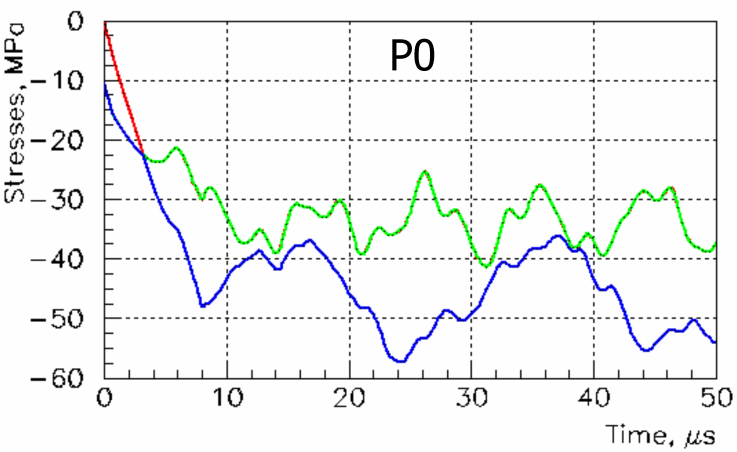
- prestress to graphite segments is equal to 10 MPa
- zero thermal resistance between target segments and steel pipe
- heat transfer coefficient to a cooling water is equal to 15 $kW/m^2/K$

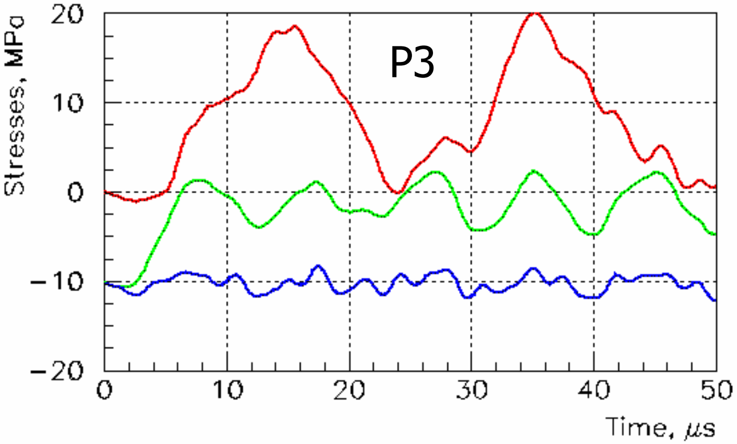
Beam energy	40 GeV	120 GeV
Segment number	2	6
EDD, GeV/cm^3/proton	0.025	0.033
Temperature of water, ^0C	37	50
Temperature at beam axis, ^0C		
before beam spill	120	80
after beam spill	380	430
Temperature rise at beam axis, ^0C	260	350

Temperature and Stresses (2)



E = 120 GeV





Safety factors for different point of segments with the highest EDD

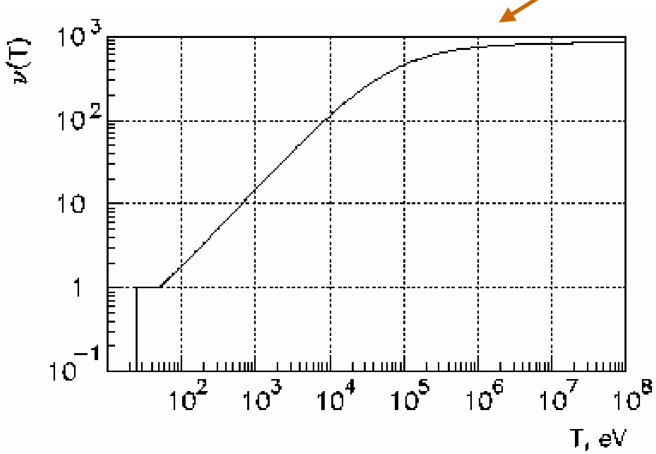
Beam energy	40 GeV	120 GeV
P0	2.3	1.9
P1	7.5	5.5
P2	2.7	2.3
P3	2.8	2.0

- Mohr-Coulomb Stress Criterion (used for brittle materials with different tensile and compressive properties)
- 10^7 cycle fatigue endurance limit of graphite ~0.5÷0.6

Radiation Damage Estimate (1)

1. Approximate calculations of DPA in graphite segments, irradiated by multi-GeV proton beam
2. Comparison of obtained results with the data on the irradiation damage of graphite due to reactor neutrons (in the absence of data for high-energy protons)

$$N = \int_{E_{\min}}^{E_{\max}} f(E)dE \int_{T_{\min}}^{T_{\max}} \sigma(E,T)\nu(T)dT < \int_{E_{\min}}^{E_{\max}} f(E)\sigma_t(E)\nu(E)dE$$



120 GeV beam with 1.9×10^{21} protons/year:

1-st segment — proton beam, $f(E)dE=1.3\times10^{22}$ cm^{-2}

N < 4.0 DPA per year

9-th segment — f(E) was calculated by GEANT for each kind of particles

N < 5.0 DPA per year

Radiation Damage Estimate (2)

J.Hylen/N.Mokhov presentation in 2003:

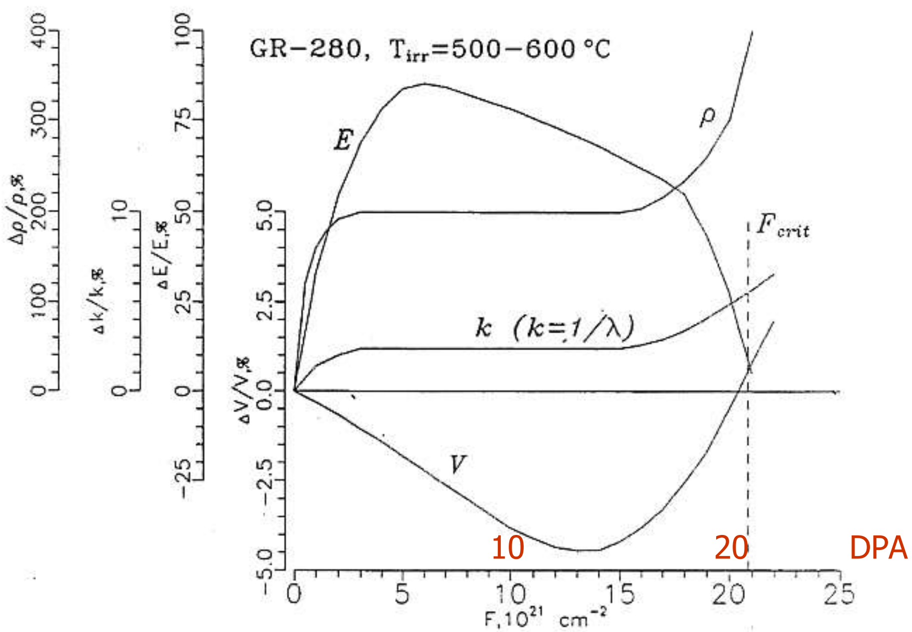


Fig.1. Determination of critical value of neutron fluence for graphite and changing of its physical properties under irradiation.
V – volume changing; E – elastic modulus; k – thermal resistance;
ρ – electrical resistance.

Radiation Damage and Life-time Evaluation of RBMK Graphite Stack, *XA9642904*,

P.A.Platonov, O.K.Chugunov, V.N.Manevsky, V.I.Karpukhin, Russian Research Center Kurchatov Institute

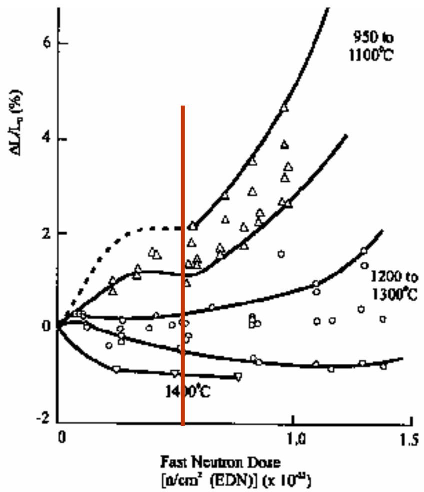
<u>2 MW NuMI Target (upper estimate)</u>

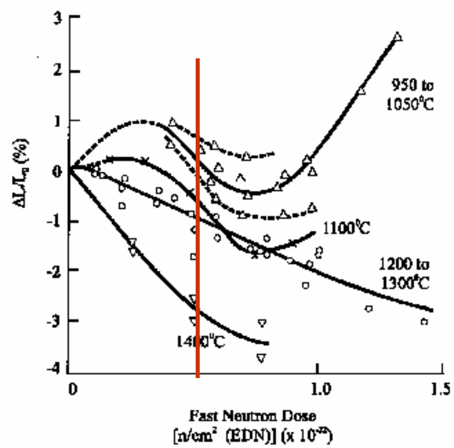
120 GeV beam → 5 DPA per year

40 GeV beam → 15 DPA per year

Irradiation Damage data for ZXF-5Q graphite of Poco ???

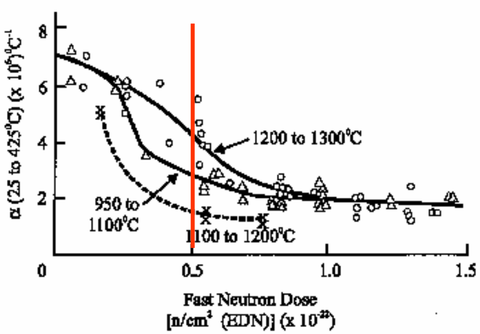
Radiation Damage Estimate (3)

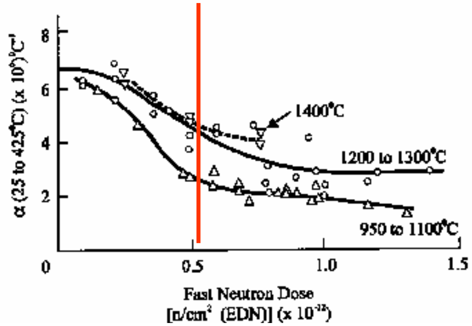




Dimensional changes of AXF-8Q (left) and AXZ-5Q (right) Poco graphite grades

Red vertical lines show ~5 DPA level



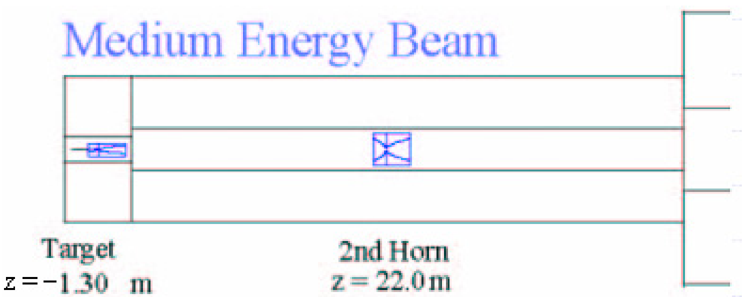


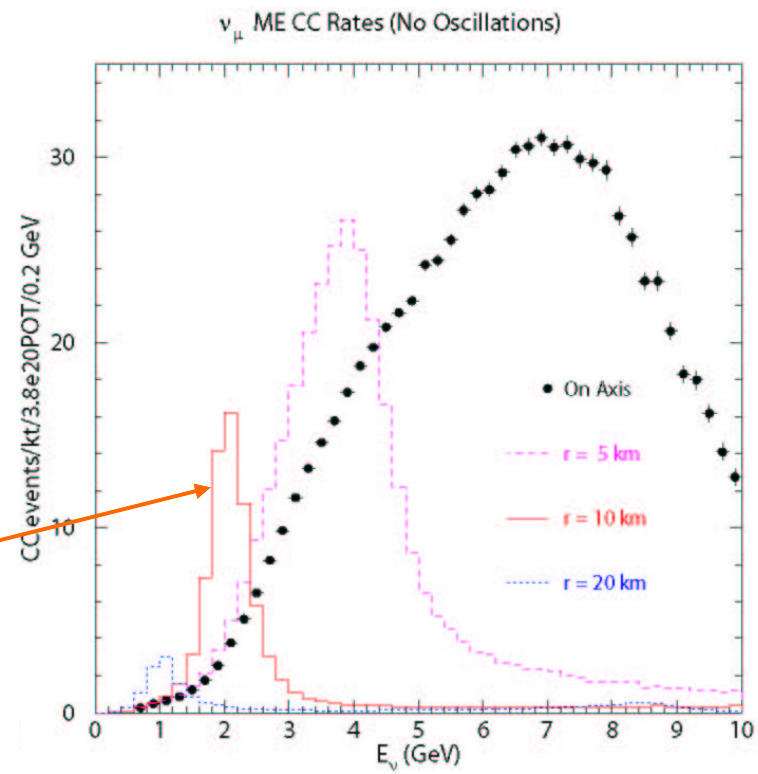
Thermal expansion coefficients of AXF-8Q (left) and AXZ-5Q (right) Poco graphite grades

Stress ~ $\alpha E \Delta T$ is invariable, because of 2 times decrease of α at approx. the same increase of E

CC ν_μ Event Rates (1)

Calculations were carried out for the 14 mrad off-axis NuMI beam in its medium energy configuration



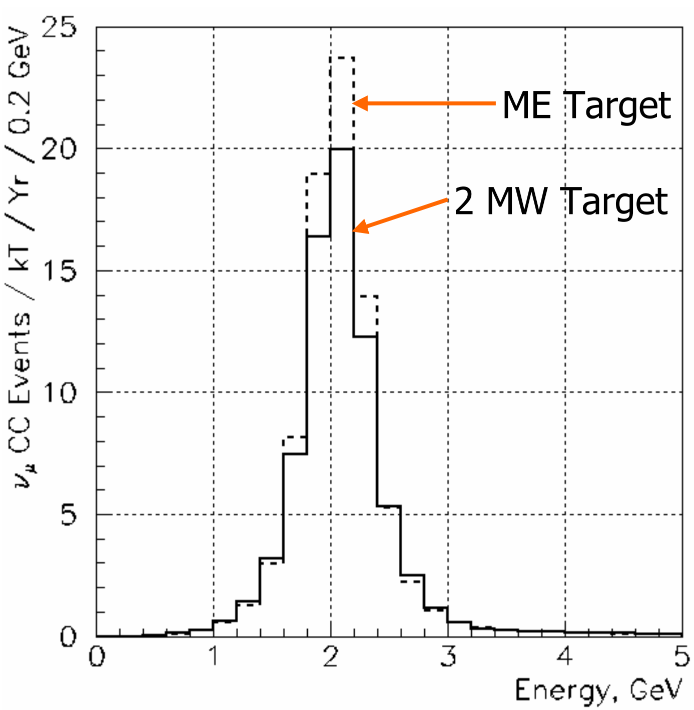


"… the medium energy NuMI beam gives the optimum spectrum for the $\nu_\mu \rightarrow \nu_e$ oscillation experiment."

(NOνA proposal, March 21, 2005)

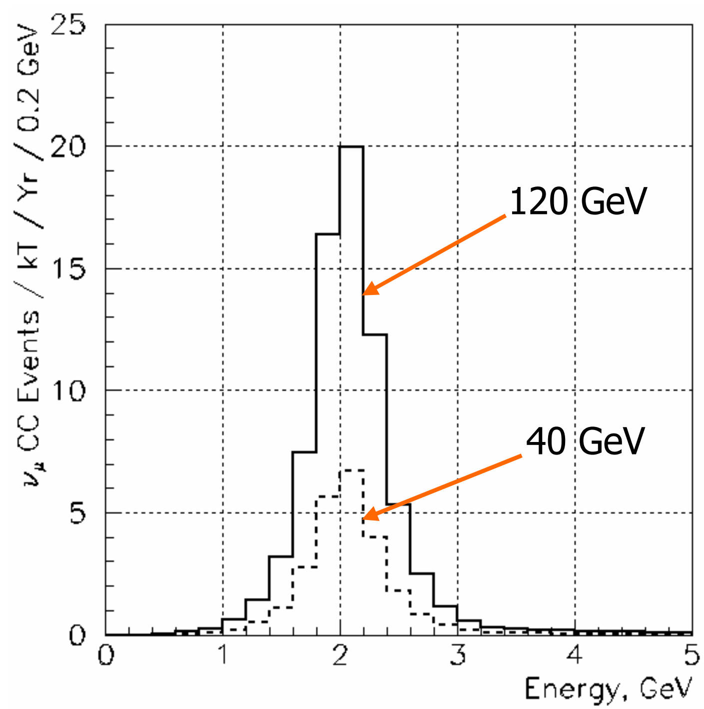
CC ν_μ Event Rates (2)

E = 120 GeV



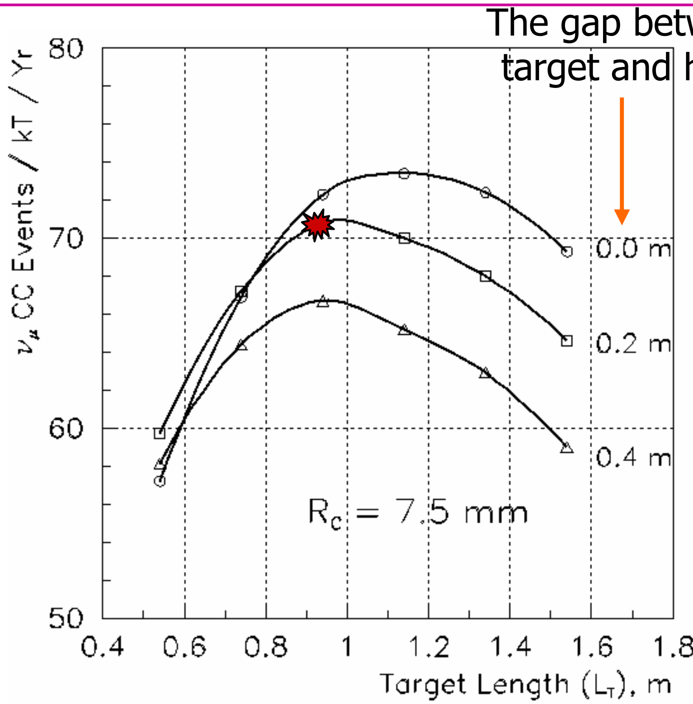
1 year = 3.8×10^{20} pot

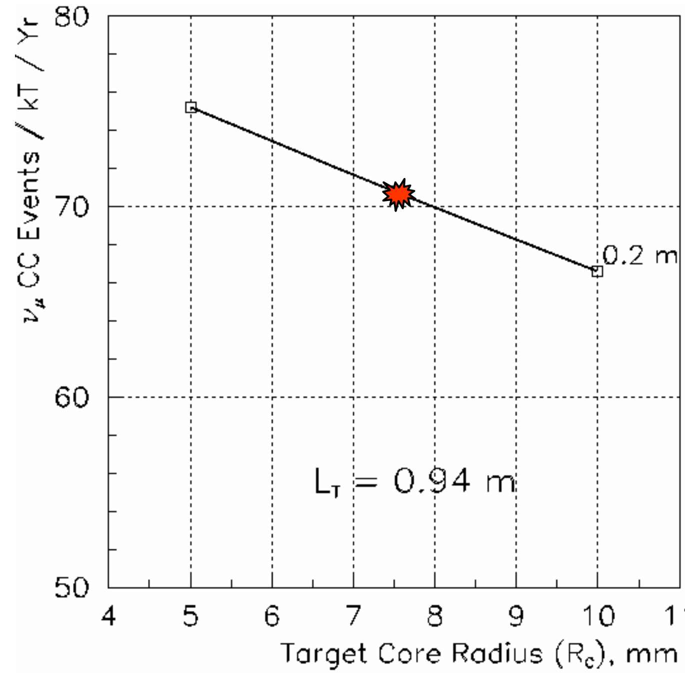
2 MW Target



- There is no difference in the event rate between 40 GeV and 120 GeV beam options
- New target, irradiated by the 2 MW proton beam gives 4.5 times increase of the total neutrino event rate, as compared with the ME target, irradiated by the 0.4 MW beam

CC ν_μ Event Rates (3)





- The length of target about 1 m is quite optimal for neutrino production. The gap between target and 1-st horn should be as small as possible
- Decrease of graphite radius gives no way for substantial increase of the event rate

Conclusions of NuMI target proton driver study

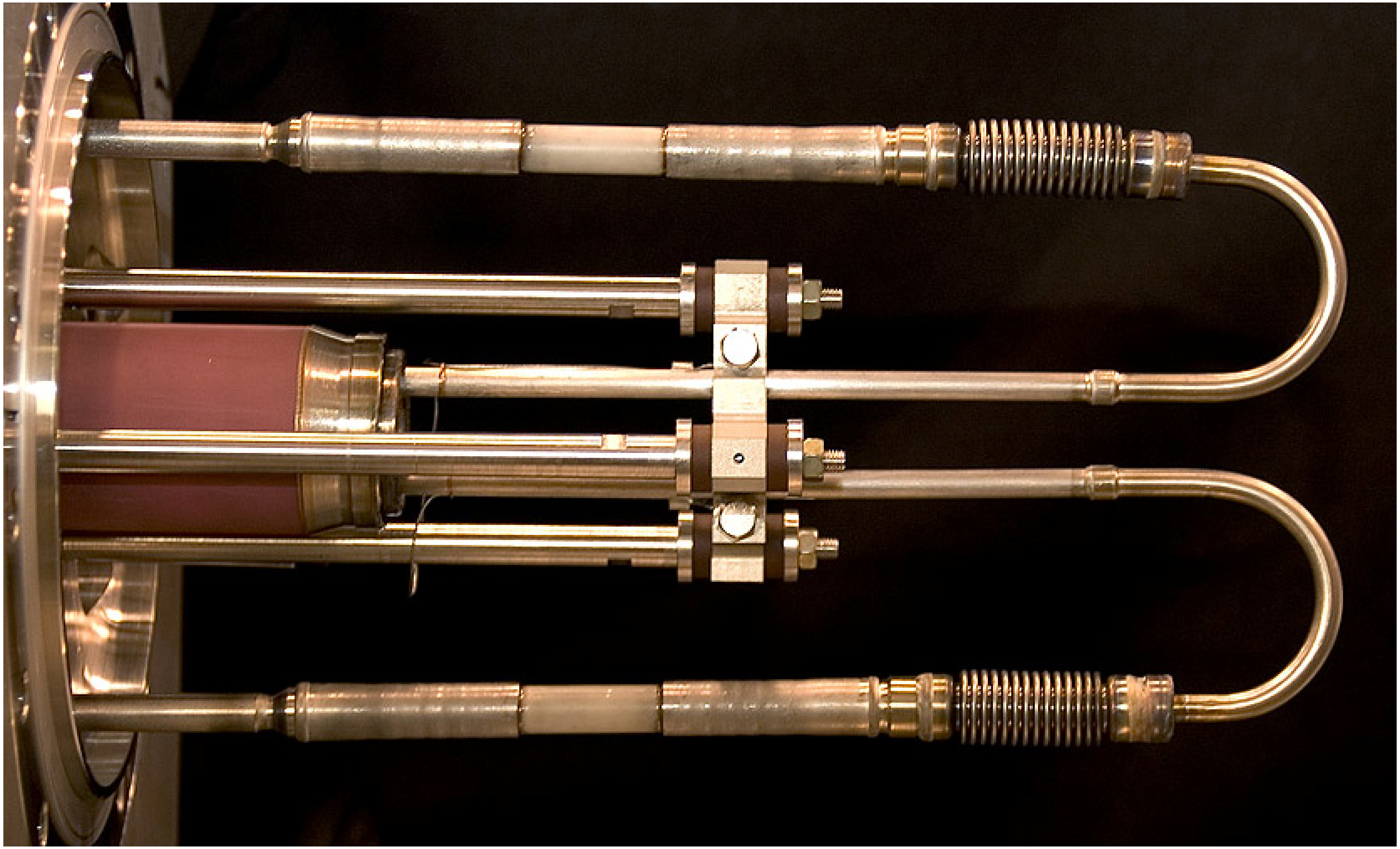
1) The proposed target provides 4.5 times increase of neutrino events, as the beam power increases from 0.4 up to 2 MW

2) 120 GeV beam option appears more preferable than 40 GeV one, since at
   - approx. equal total energy deposition in the target
   - exactly equal number of neutrino events

   in case of the 40 GeV beam we will have
   - ~3 times more radiation-induced effects
   - 3 times higher power consumption for the horns supply
   - ~2 times higher power deposition in horns (resistance & beam heat)

3) Next steps of the design study should include
   - Further (advanced) study of the cooling system
   - Examination of other graphite grades as a target core material
   - Prototyping of some components of the target ?

Backup slide -
Target water line and clamp



AP-0 Target Hall Experience

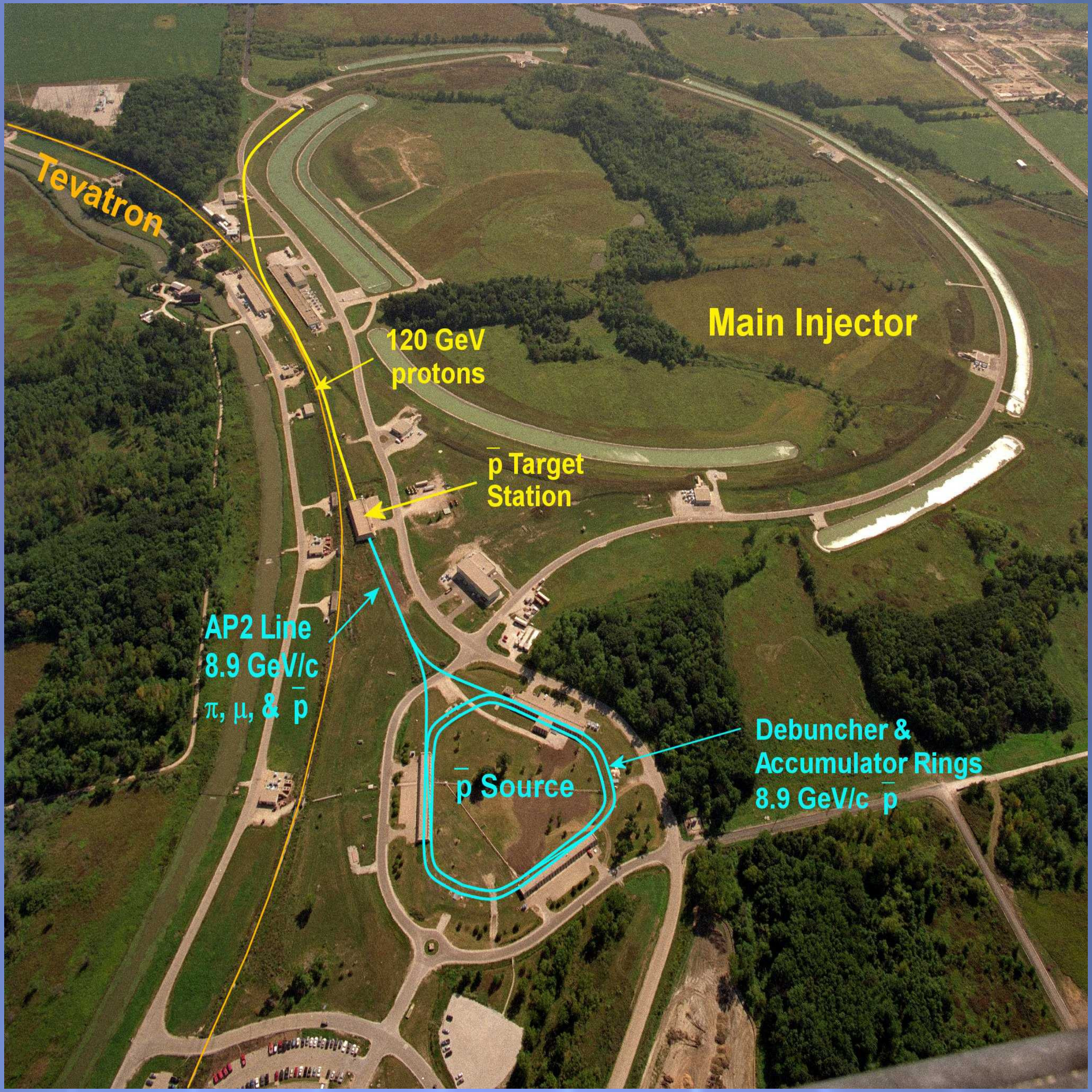
Fermilab Anti-Proton Source

P. Hurh (10-7-05)
Mechanical Support Dept.

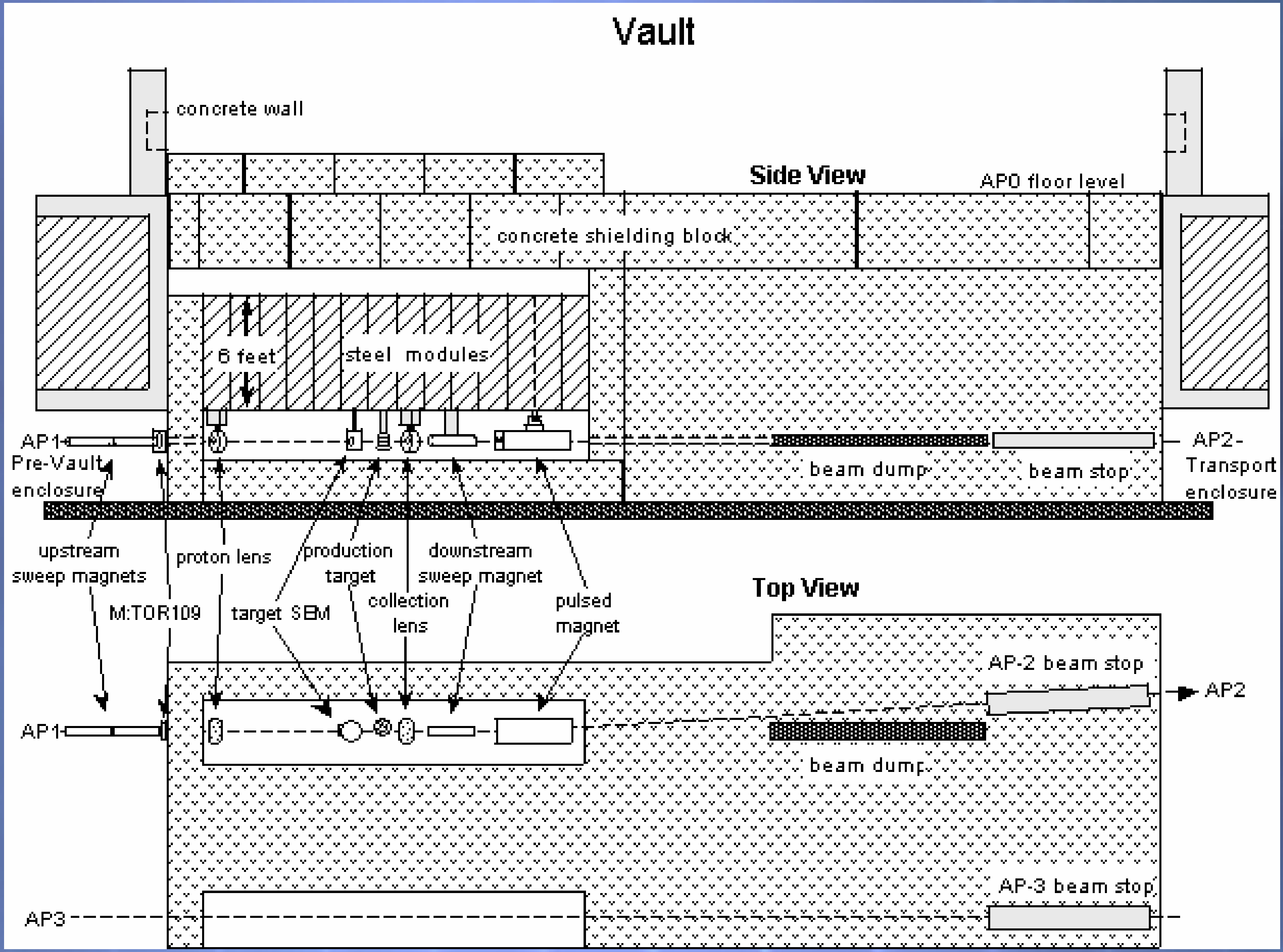
Recent Events

- New Target and Target Module installed to restore Target rotation
- High Gradient Lens (8 mm) installed and operating
- High Gradient Lens (10 mm) almost complete
- Failures of electrical insulators (radiation damage?)

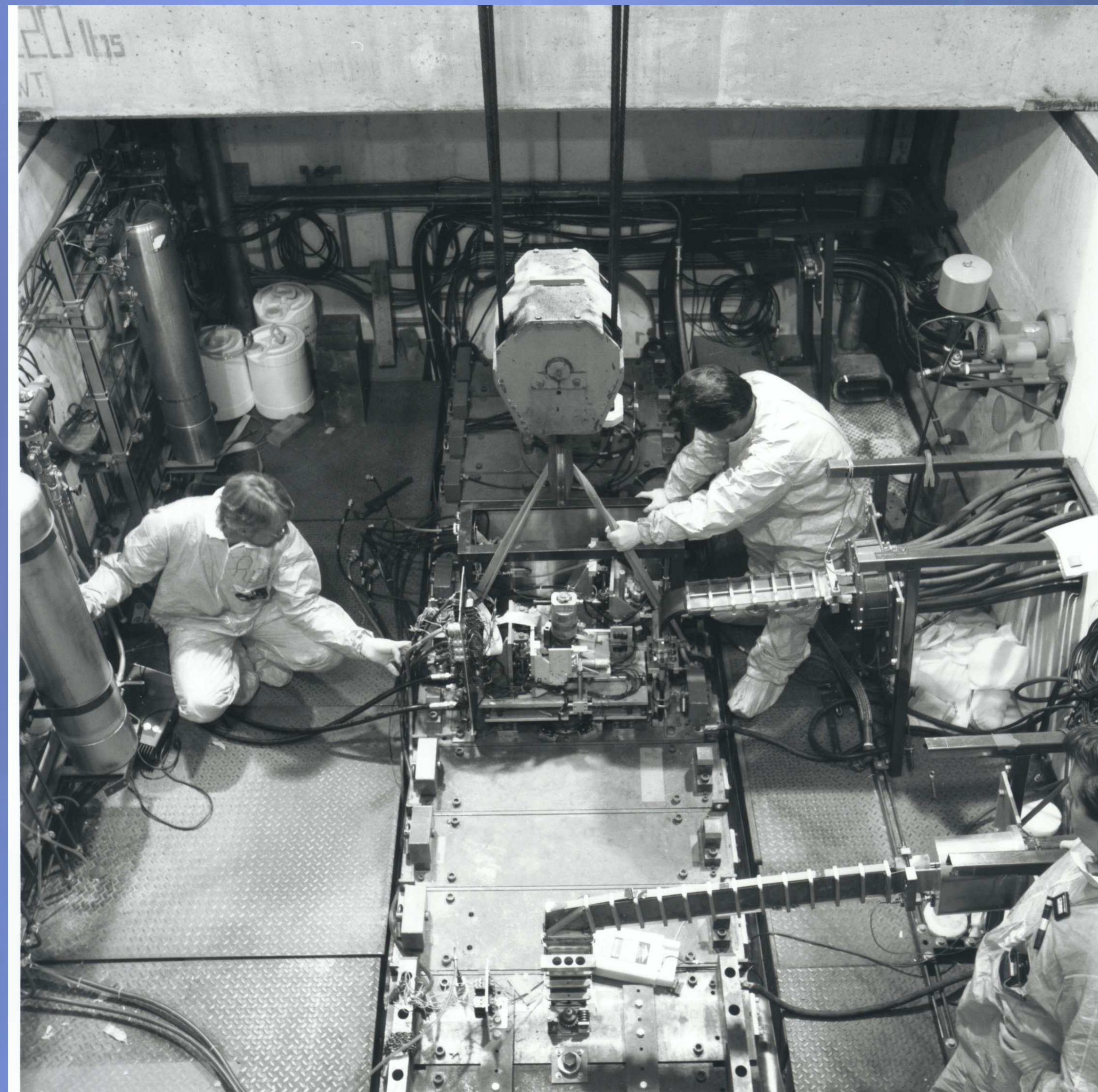
P-Bar Source Overview



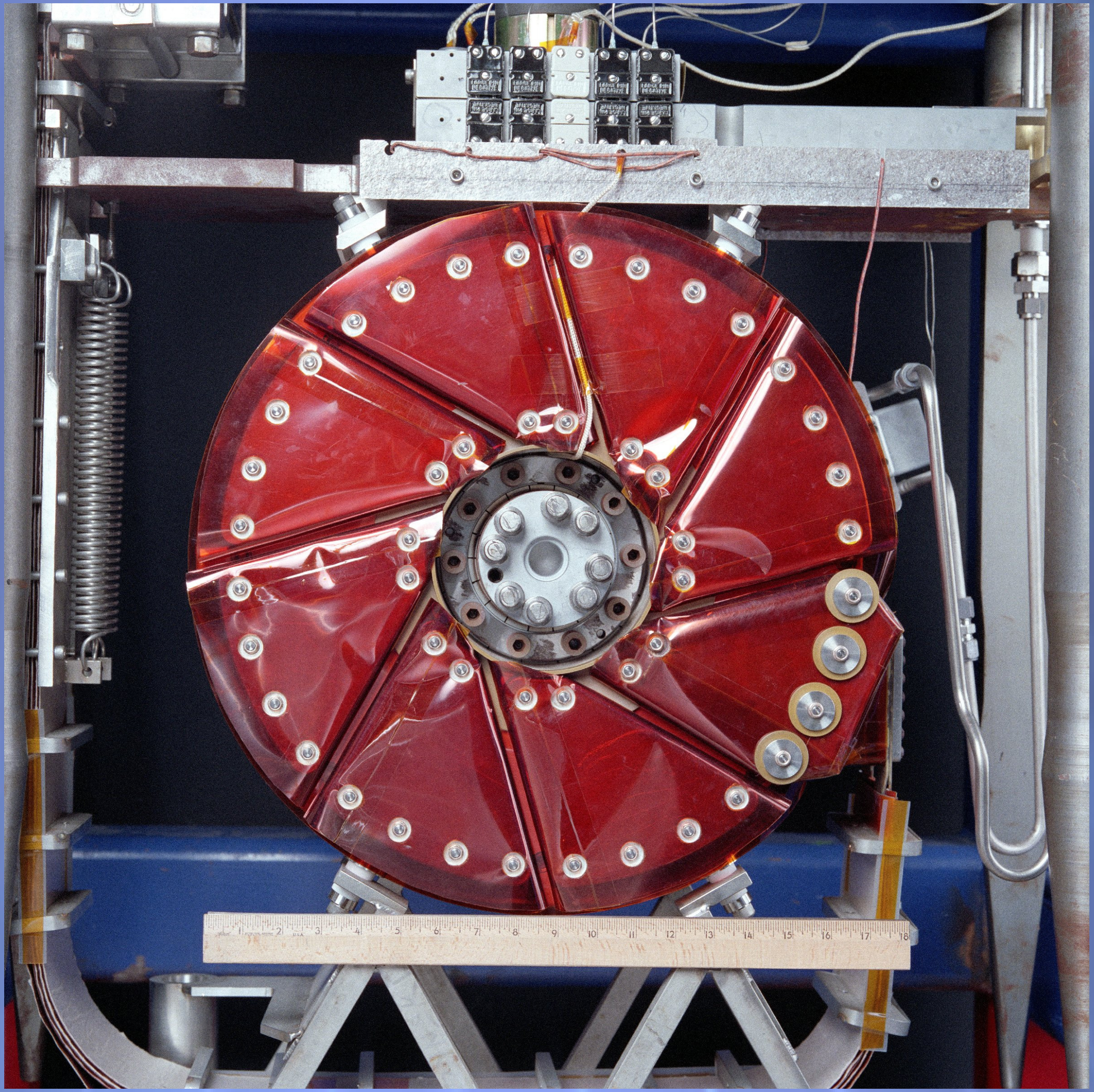
P-bar (AP-0) Target Vault



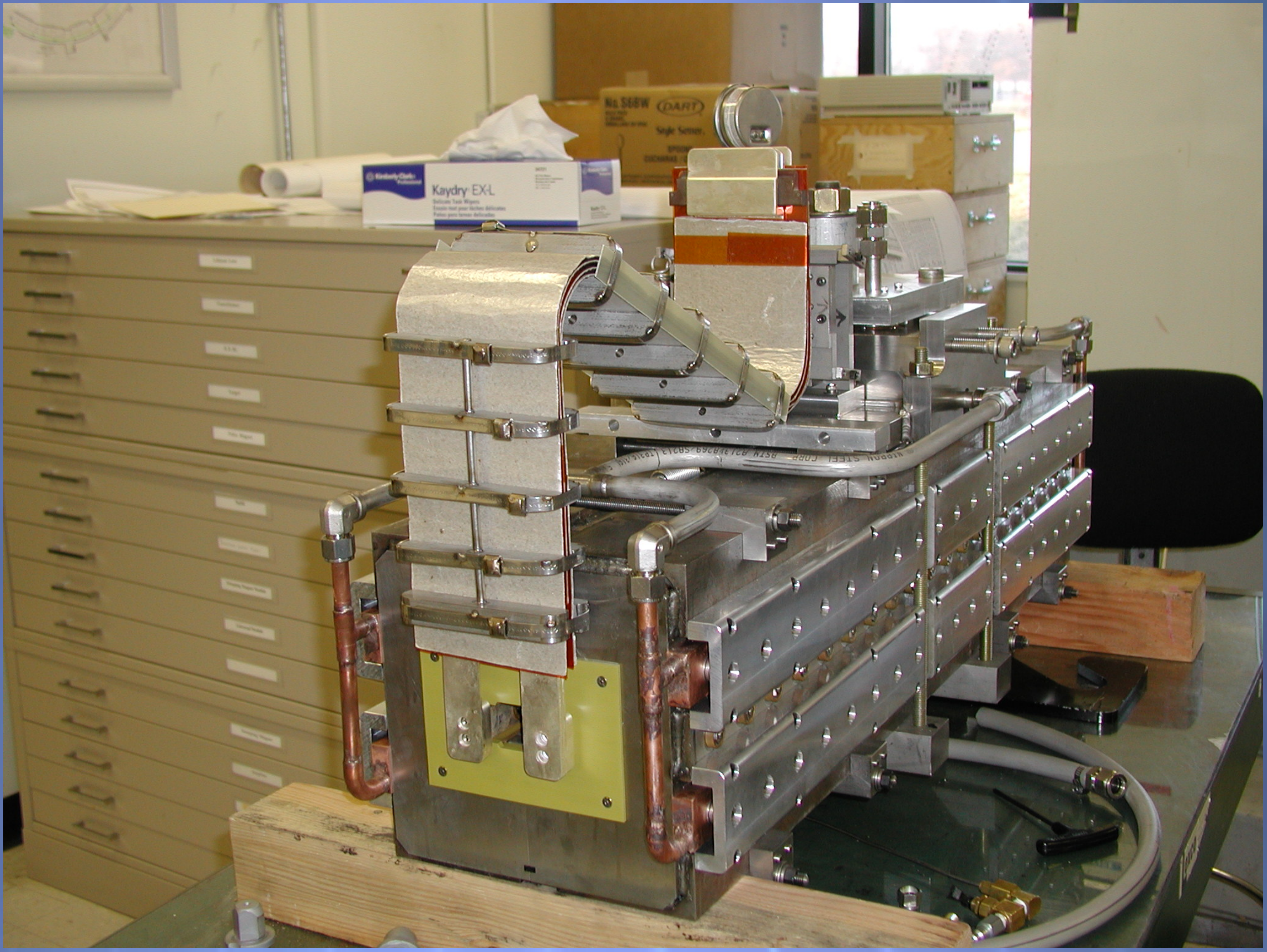
Workers in Vault



Lithium Lens



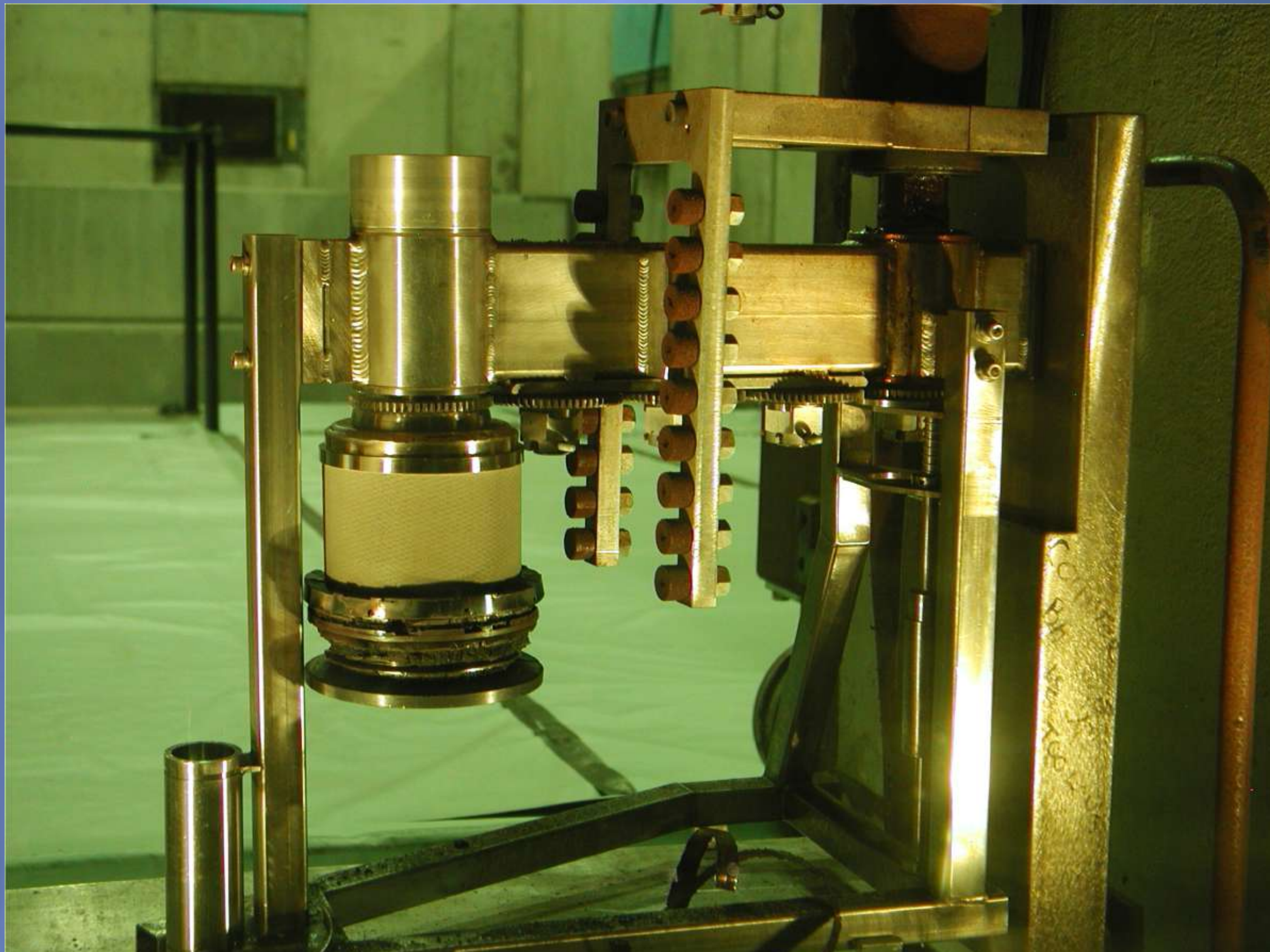
Pulsed Magnet



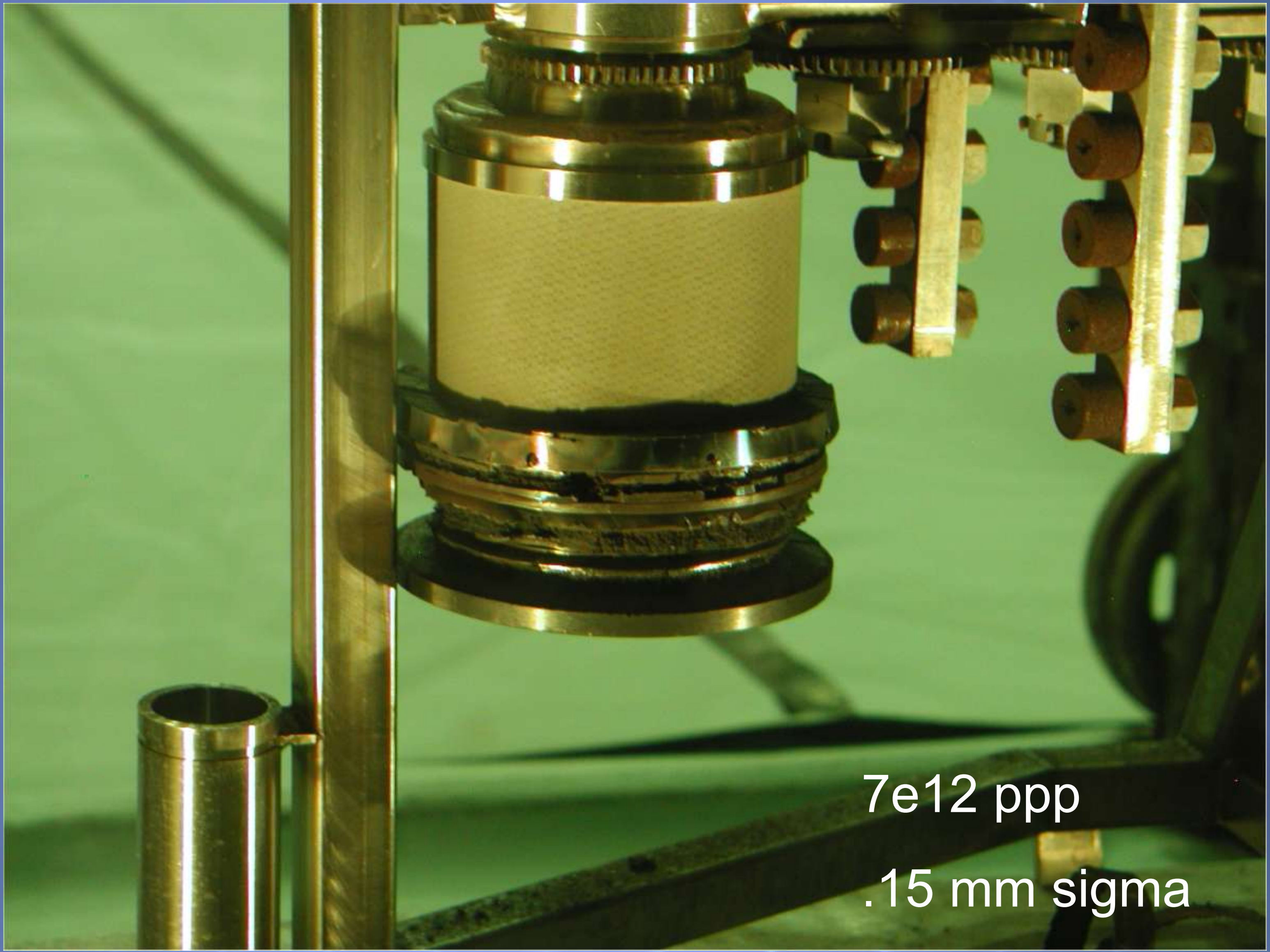
Target on Frame

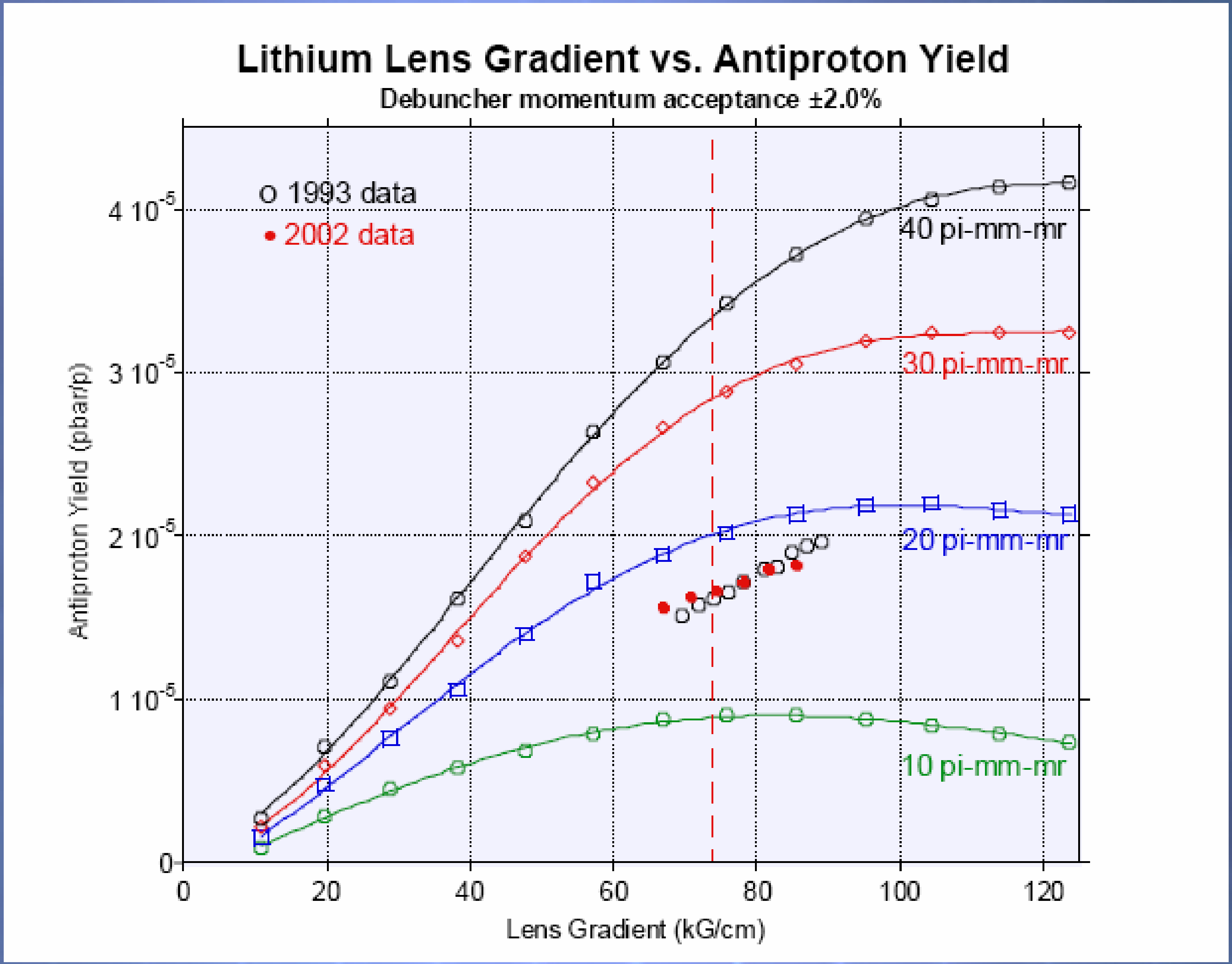
Target Stack

Target R2-T3

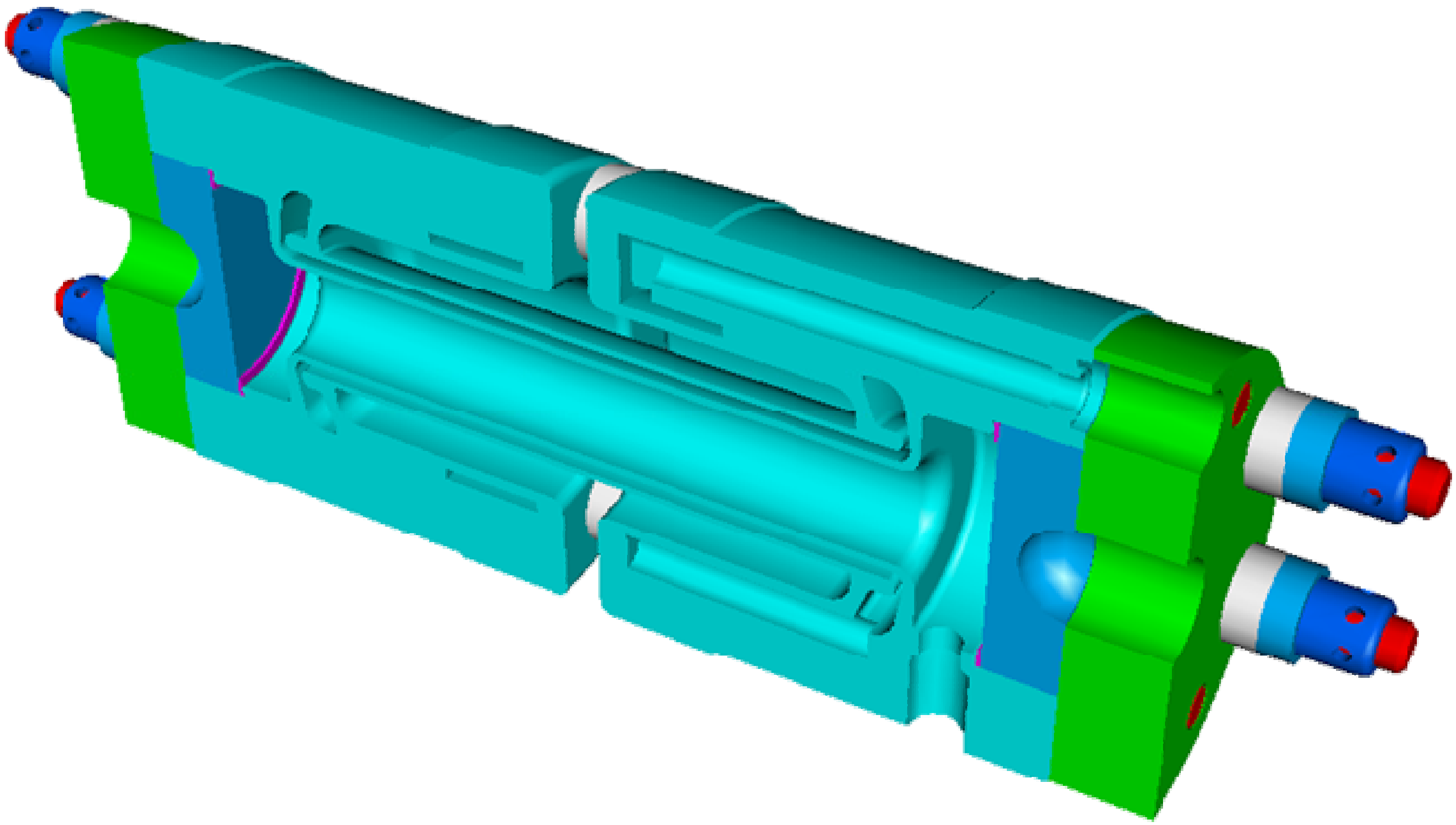


Target R2-T3




Lithium Lens Gradient vs. Antiproton Yield
Debuncher momentum acceptance ±2.0%
o 1993 data
• 2002 data
40 pi-mm-mr
30 pi-mm-mr
20 pi-mm-mr
10 pi-mm-mr
4 10-5
3 10-5
2 10-5
1 10-5
0
Antiproton Yield (pbar/p)
0
20
40
60
80
100
120
Lens Gradient (kG/cm)

High Gradient Prototype 2 (10 mm) Lens



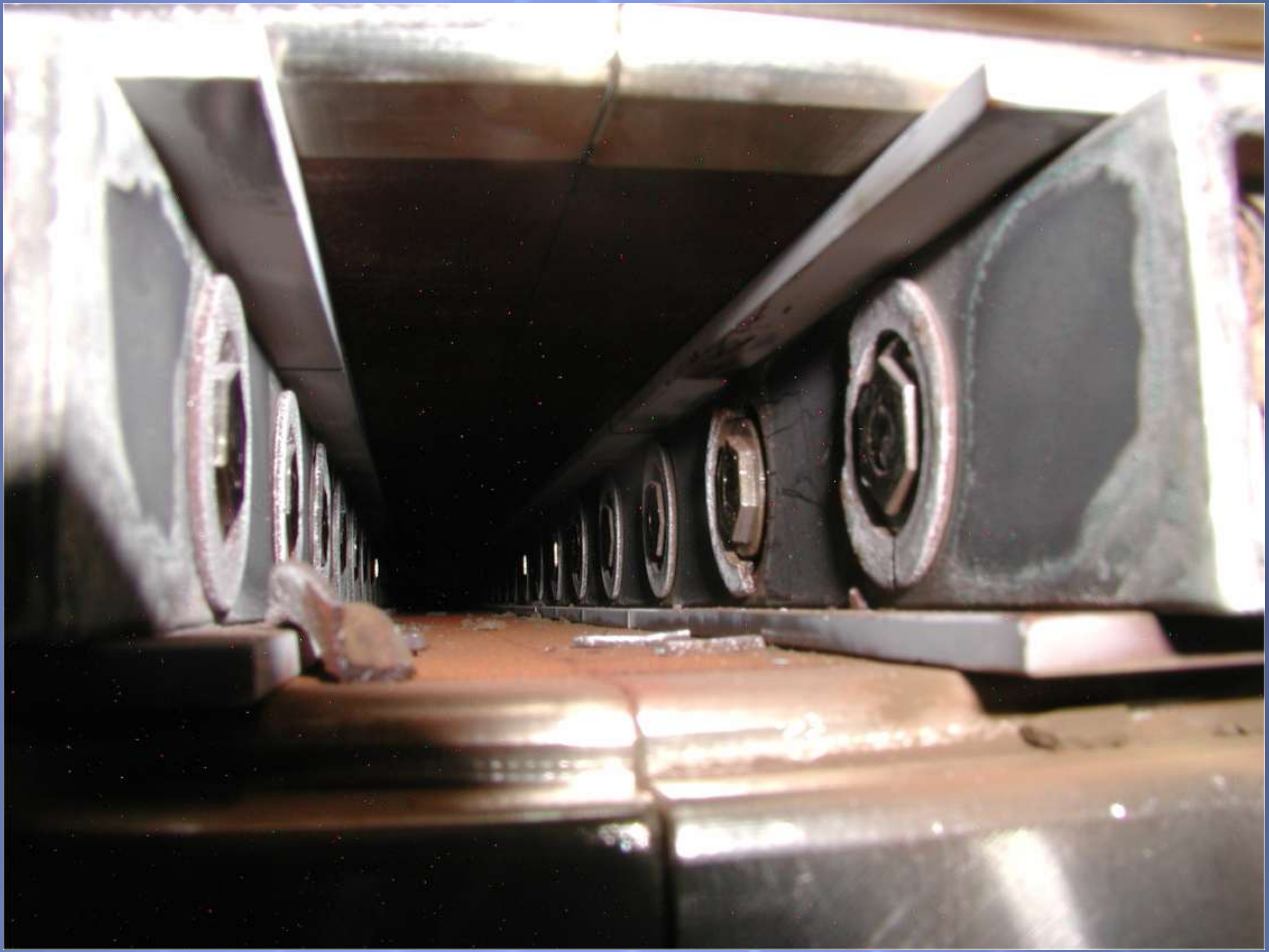
Prototype 1 Lens Diffusion Bonding

High Gradient Li Lens Current Status

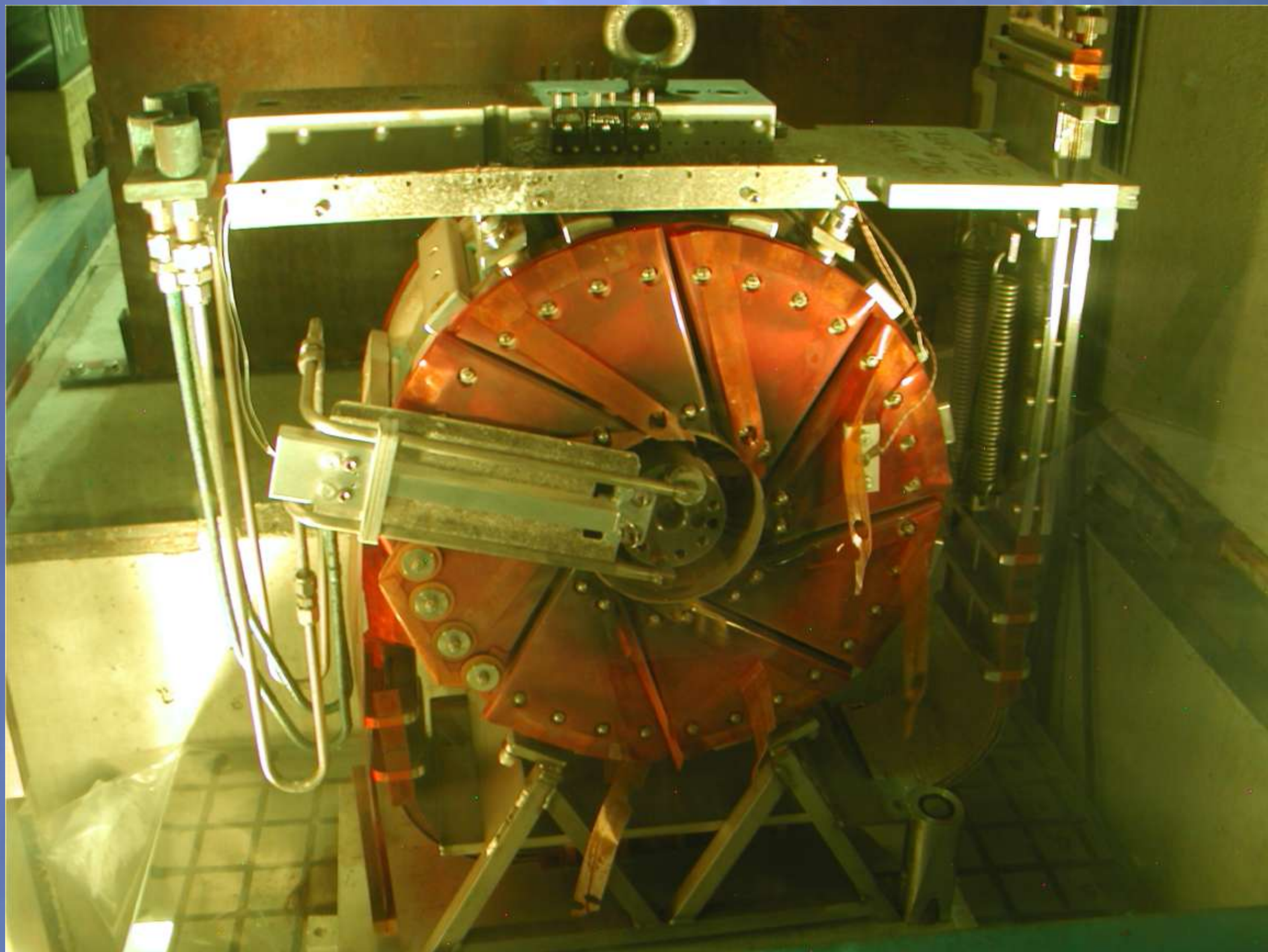
- Prototype 1 tested to failure and autopsied.
- 2 lenses of proto 1 (8 mm) design constructed, 1 currently operational
- Prototype 2 (10 mm) currently being filled with lithium

Pulsed magnet just removed from Vault

Pulsed magnet Torlon Damage



Li Lens just removed from Vault (Transformer Damage)



Ceramic Coating at BINP

- Gas detonation method (melted alumina ceramic at 1500 m/s)
- Up to 1 mm thickness
- Not great corona stand-off, but can flex (up to 3° bend tests without cracking)
- Tested on transformer (over 5 million test pulses, over 0.5 million in beam conditions)

Gas Detonation Studies

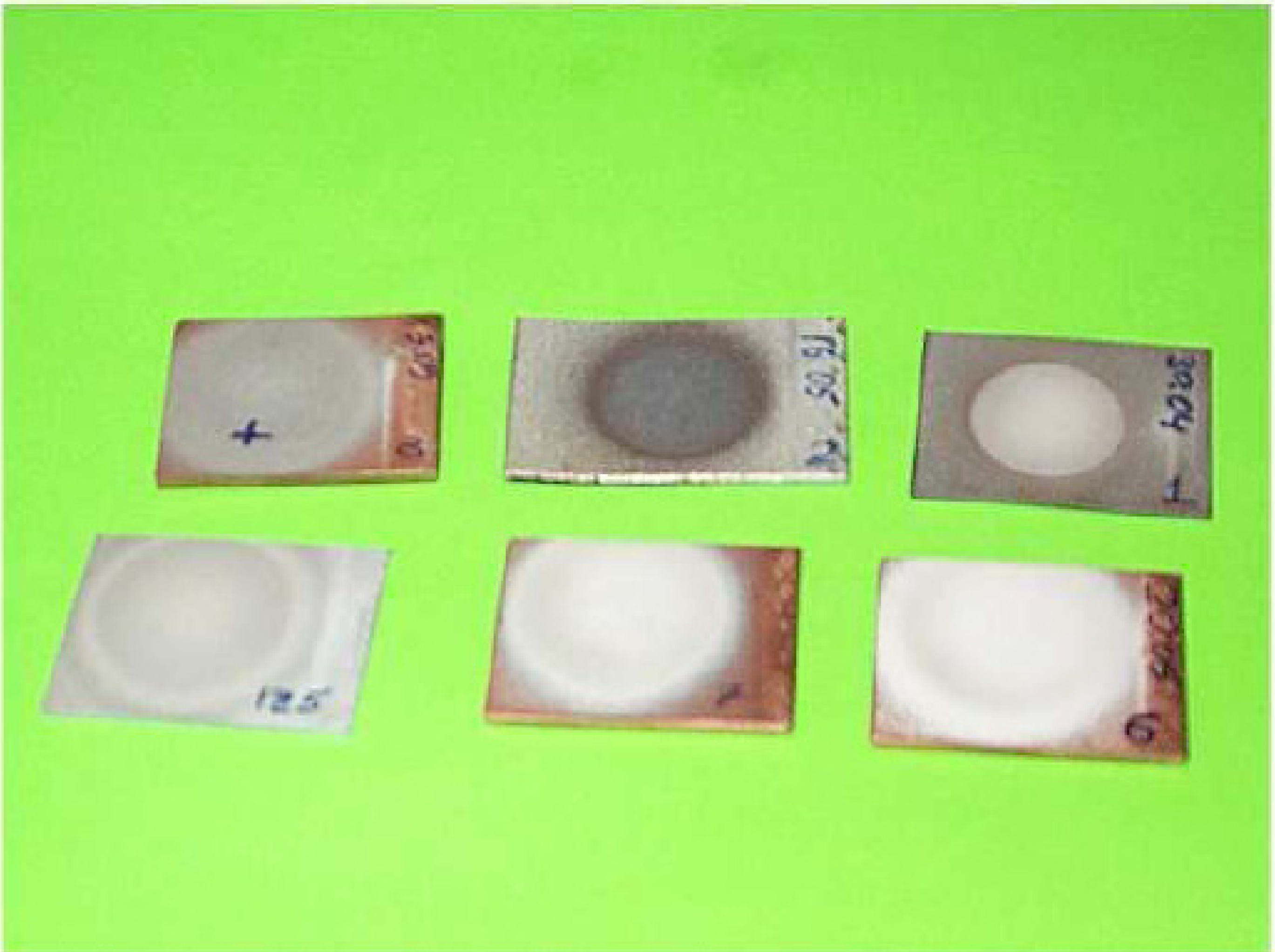
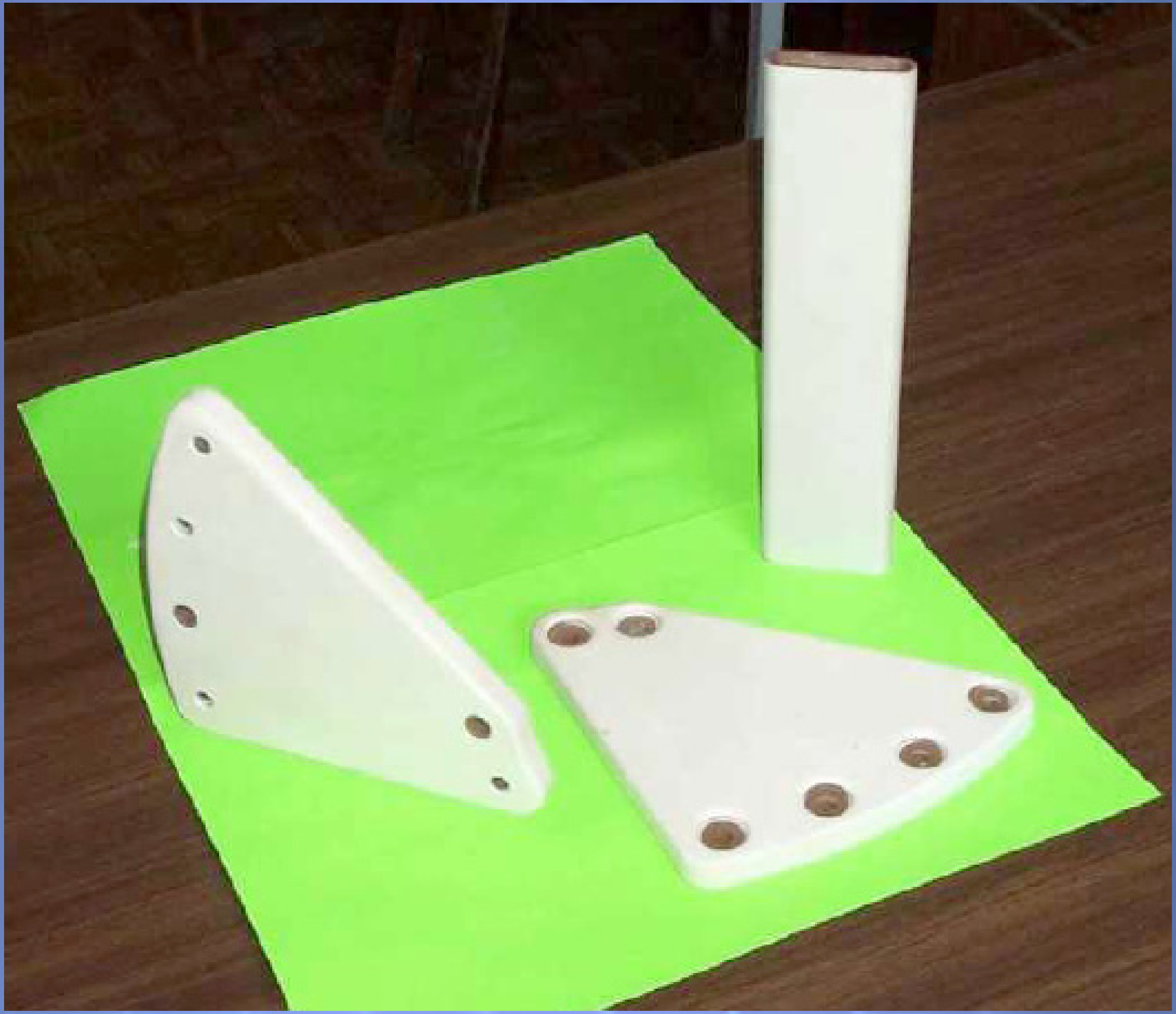
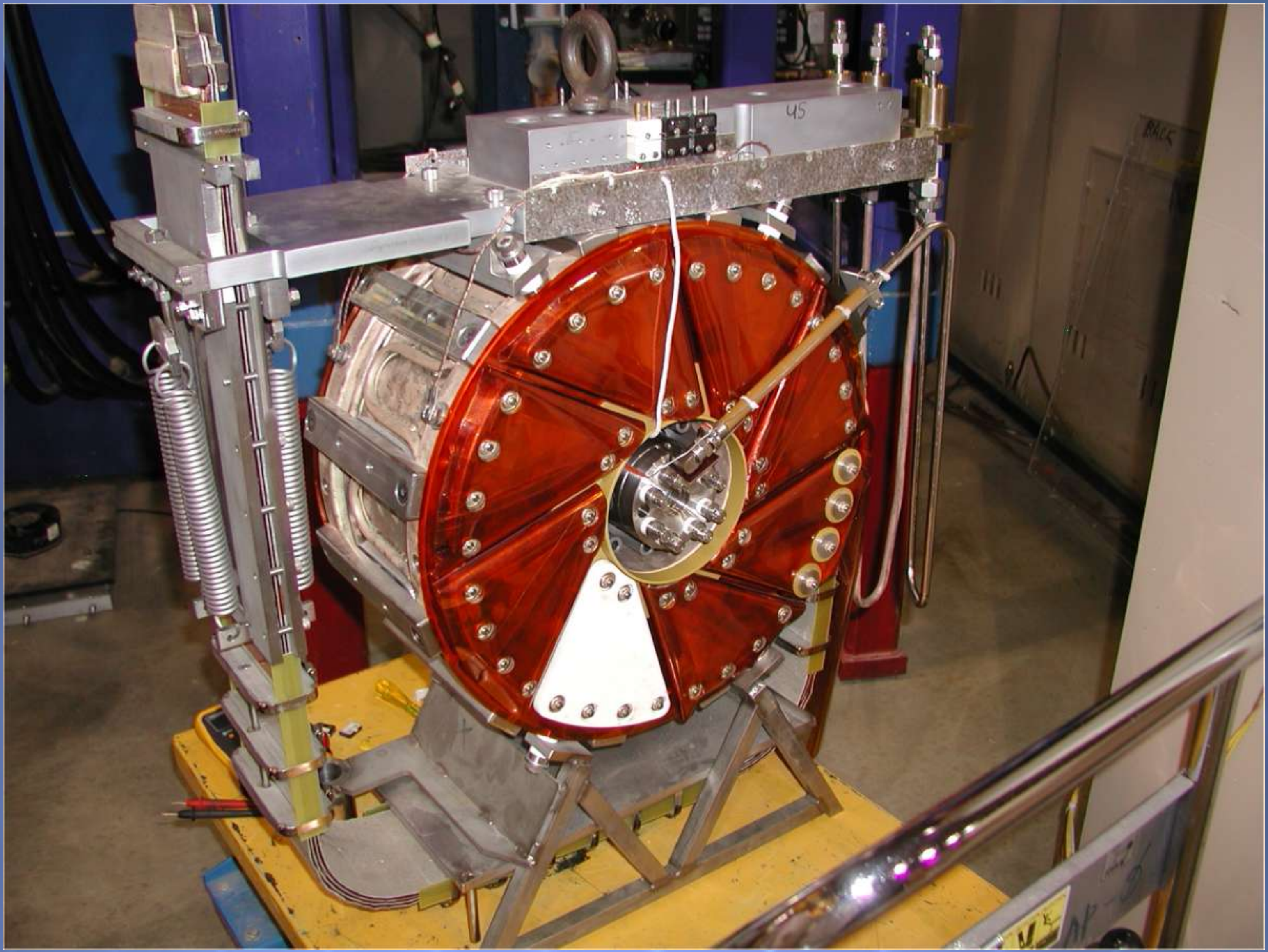


Photo 1b Samples with coating by different oxides

Ceramic Coated Li Lens Transformer Parts



Coated Primary Plate



Conclusion

- We’ve had our ups and downs, but overall running with higher intensities than ever (7.5 e 12 ppp, 0.5 Hz, sigma of 0.15 mm).
- Recent Target experience shows rotation crucial. May need to install beam sweeping.
- High gradient 10 mm lens progress made. Should be testing by end of this year.
- Focus is now on overcoming radiation damage problems in pulsed magnet and lens transformer.
- Looking to use of AP-0 as Target Test Facility after Run II

AP-0 Target Test Facility

- After Collider Run II ends, AP-0 could be converted into Target Test Facility (2009)
- Some minor kicker changes could allow full NuMI beam to be delivered to tests at AP-0 (as NuMI operations allow)
- Just after Run II:
  - 120 GeV
  - 7.5-10 e12 ppp
  - 0.5 Hz
  - Sigma 0.1 - 5 mm (2,000 - 3,000 J/g in Ni)
- After proton intensity upgrade (proton driver, proton accumulator):
  - 120 GeV
  - 2.2 MW
  - 0.75 Hz
  - Sigma ??
- Anyone interested?