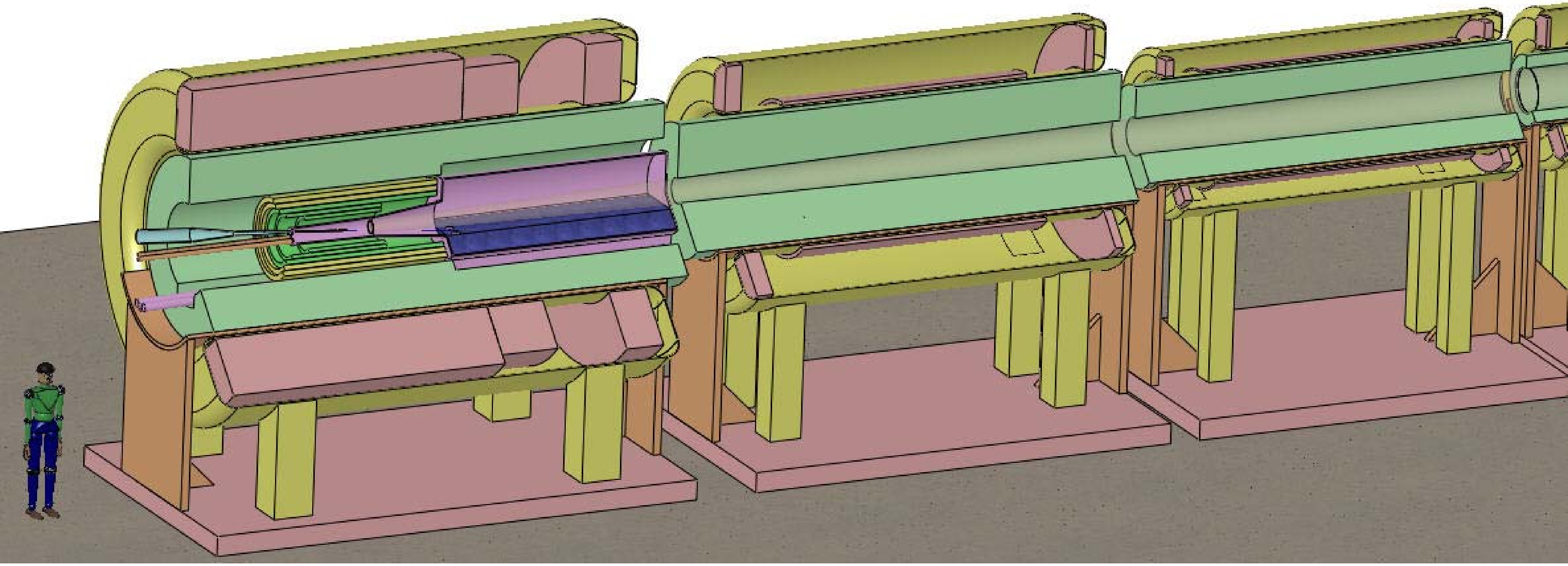
The High-Power-Target System of a Neutrino Factory



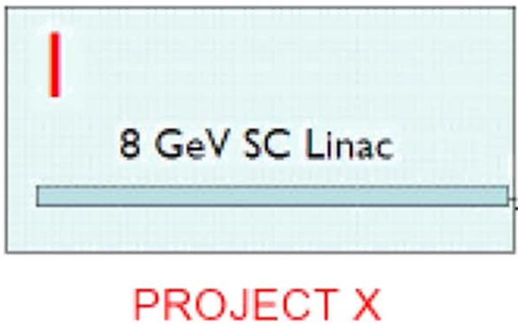
K. McDonald
Princeton U.

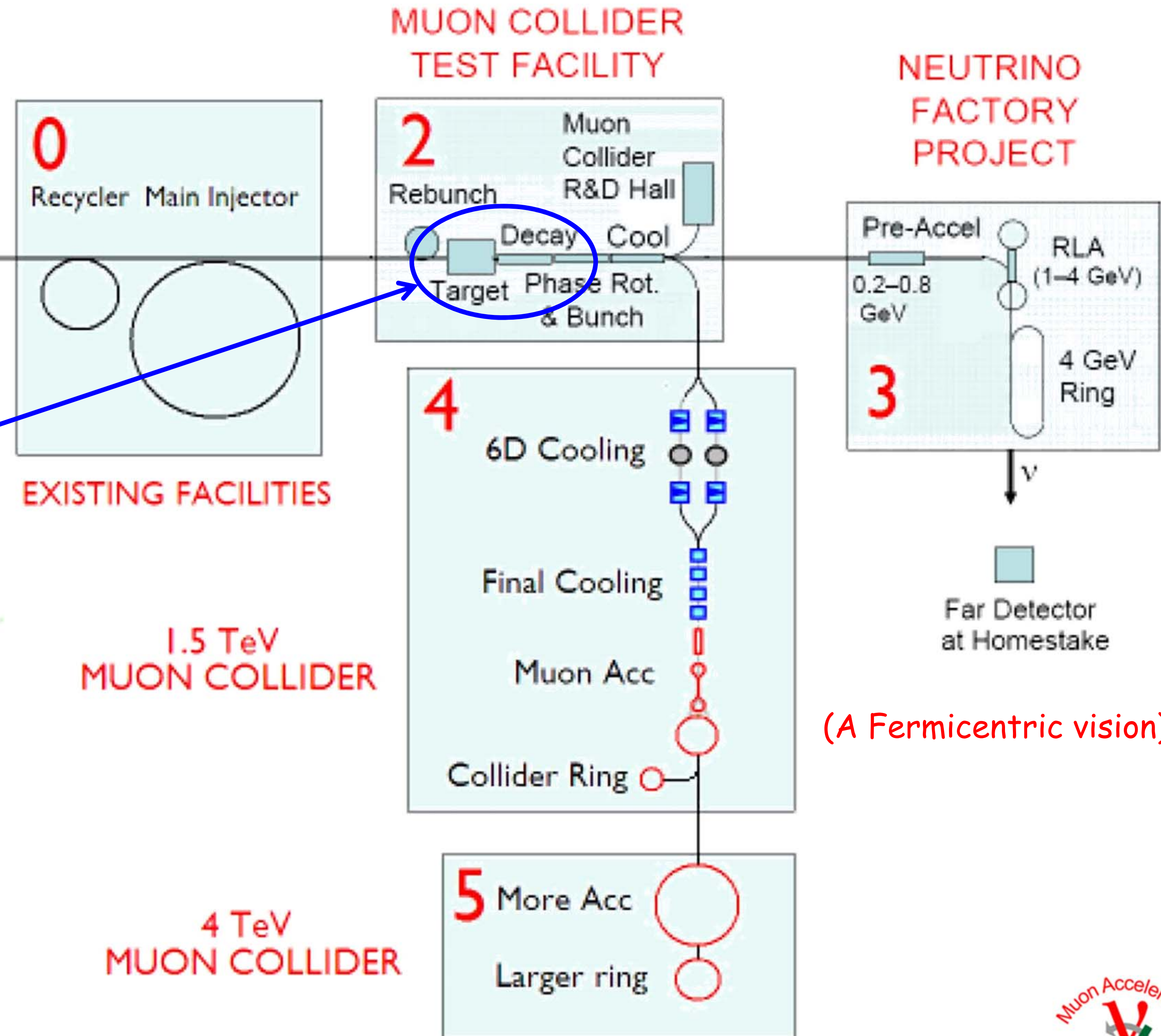
(April 6, 2013)

10th IDS-NF Plenary Meeting

Rutherford Appleton Laboratory

The Target System of a Muon-Collider or Neutrino Factory





In the IDS-NF costing scenario, the Target System includes the production target and the magnetized pion-decay channel.

This system is about 50 m long.

Very preliminary cost estimate now exists.

(A Fermicentric vision)

Target and Capture Topology: Solenoid

Desire ≈ 10^{14} μ/s from ≈ 10^{15} p/s (≈ 4 MW proton beam)

R.B. Palmer (*BNL*, 1994) proposed a 20-T solenoidal capture system.

Low-energy π's collected from side of long, thin cylindrical target.

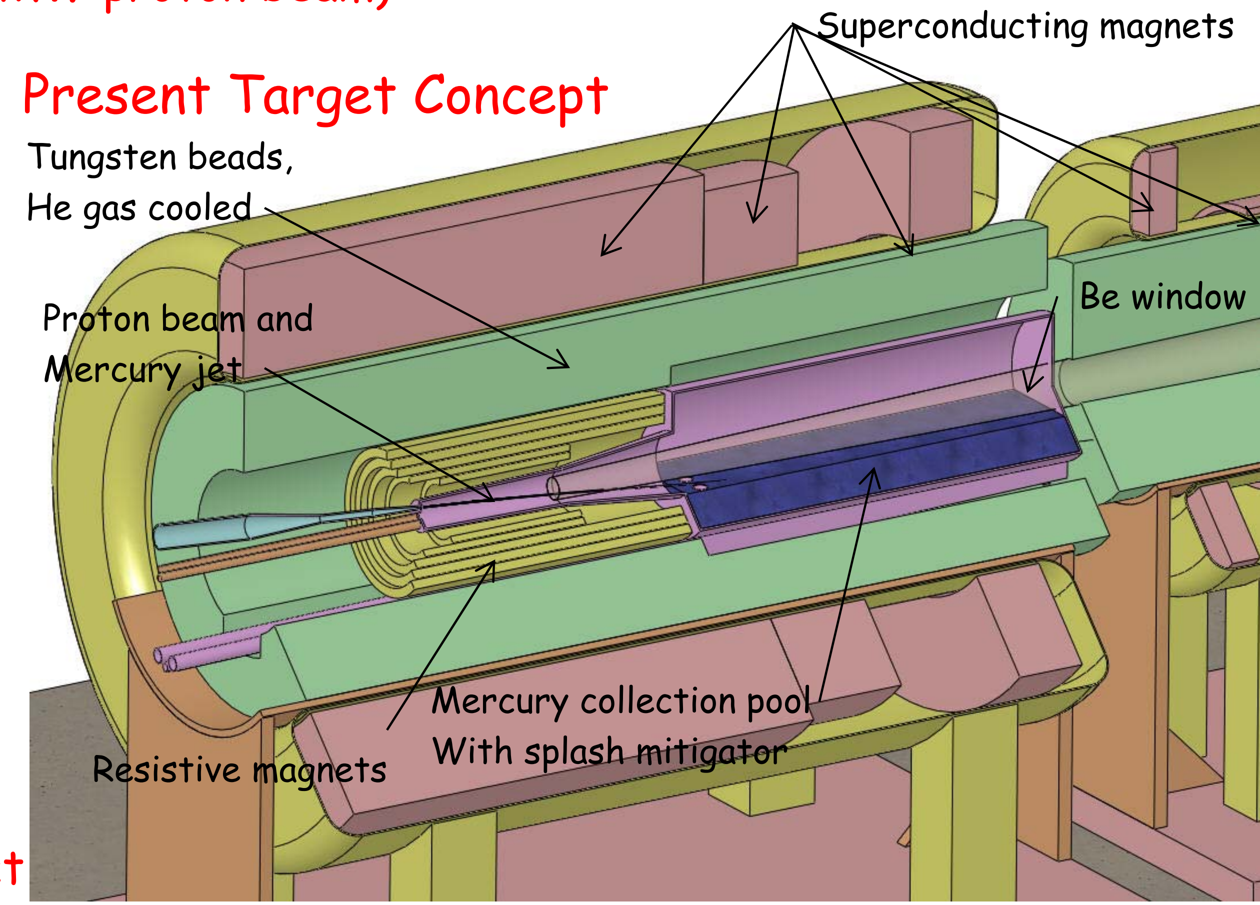
Solenoid coils can be some distance from proton beam.

⇒ ≥ 10-year life against radiation damage at 4 MW.

Liquid mercury jet target replaced every pulse.

Proton beam readily tilted with respect to magnetic axis.

⇒ Beam dump (mercury pool) out of the way of secondary π's and μ's.



Shielding of the superconducting magnets from radiation is a major issue.

Magnet stored energy ~ 3 GJ!

5-T copper magnet insert; 15-T Nb_3Sn coil + 5-T NbTi outsert.

Desirable to replace the copper magnet by a 20-T HTC insert.

Target Baseline: Proton Beam Assumptions

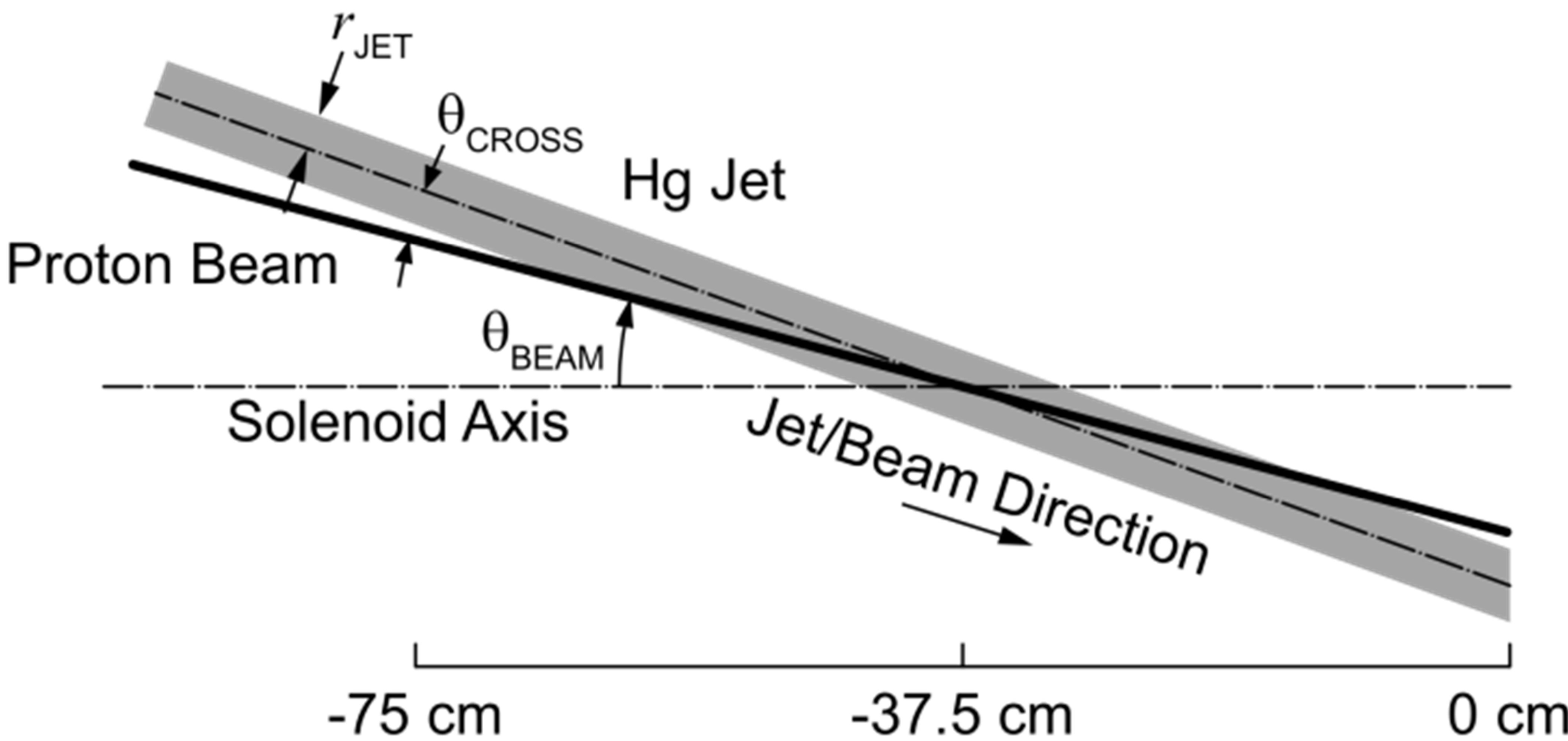
Proton Beam Energy	8 GeV
Rep Rate	50 Hz
Bunch Structure	3 bunches, 240 μsec total
Bunch Width	2 ± 1 ns
Beam Radius	1.2 mm (rms)
Beam β^*	$\geq$ 30 cm
$\varepsilon_\perp$	$\leq$ 5 (π) μm
Beam Power	4 MW (3.125×10^{15} protons/sec)

http://www.hep.princeton.edu/~mcdonald/mumu/target/hkirk/hkirk_101811.pdf
IDS Plenary Meeting, Oct. 18, 2011

Target System Baseline

Target type	Free mercury jet
Jet diameter	8 mm
Jet velocity	20 m/s
Jet/Solenoid Axis Angle	96 mrad
Proton Beam/Solenoid Axis Angle	96 mrad
Proton Beam/Jet Angle	27 mrad
Capture Solenoid Field Strength	20 T

Jet/Solenoid/Proton-Beam Geometry



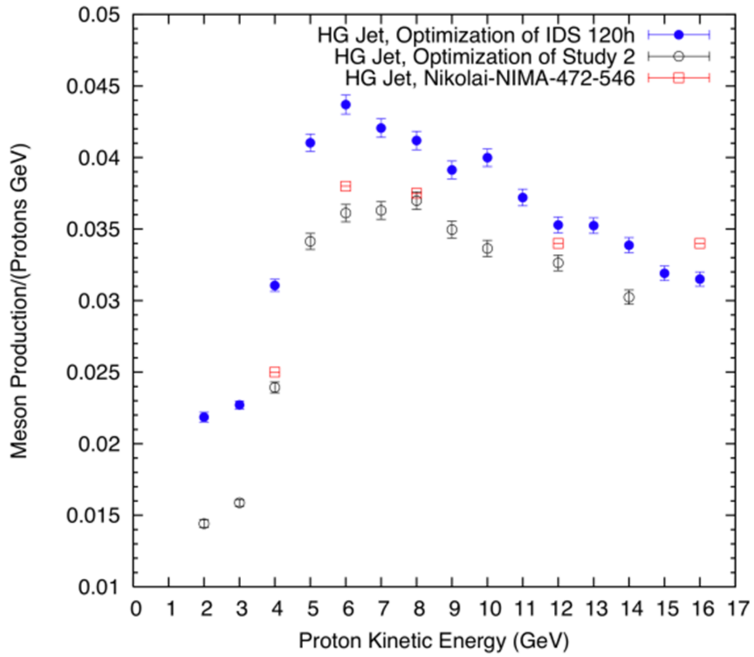
All "useful" pions for the Neutrino Factory produced at $z < 0$,

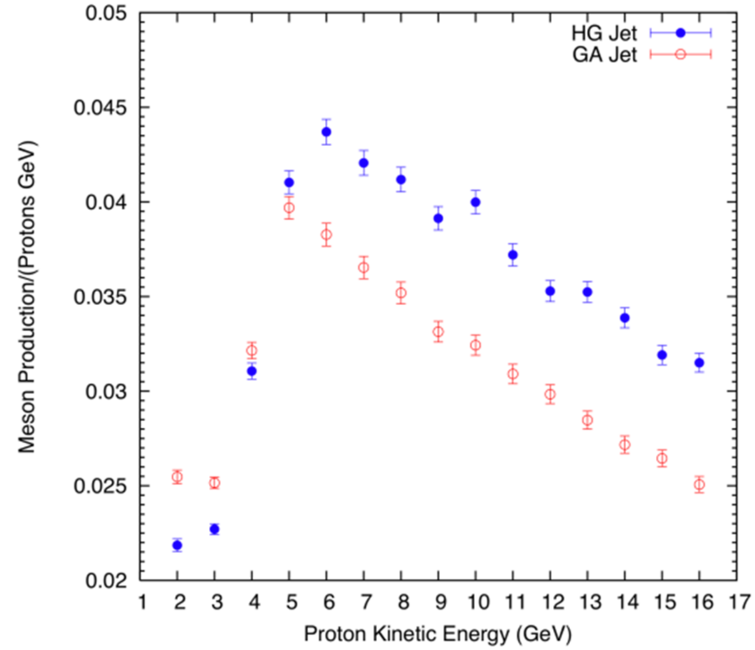
⇒ Center of beam-jet interaction is at $z = -37.5$ cm.

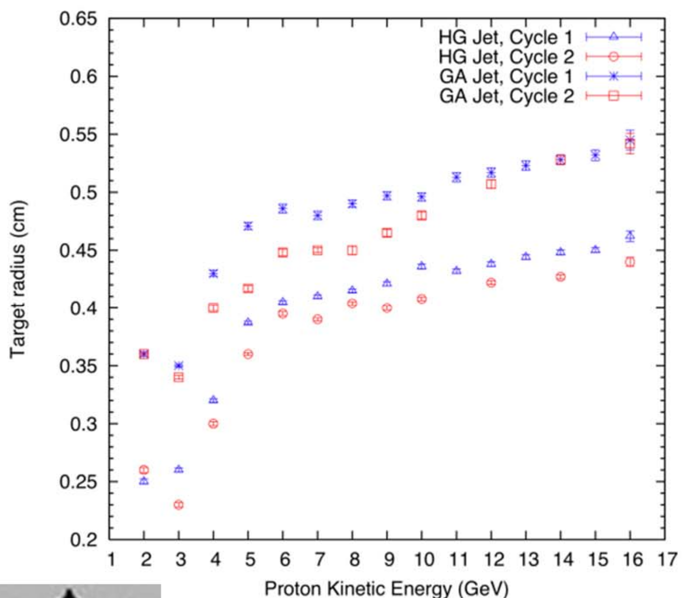
Optimization of Pion Production via MARS1512

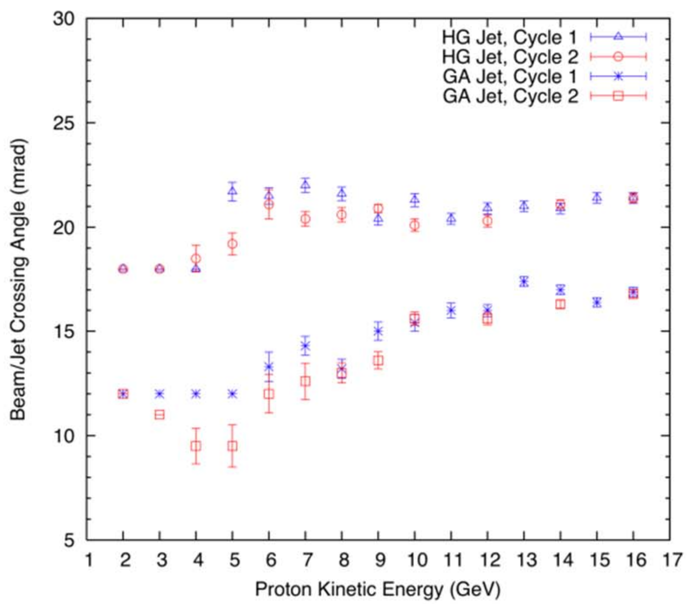
Optimization of beam energy, radius, angle, as well as jet radius and angle, for both Hg and Ga.

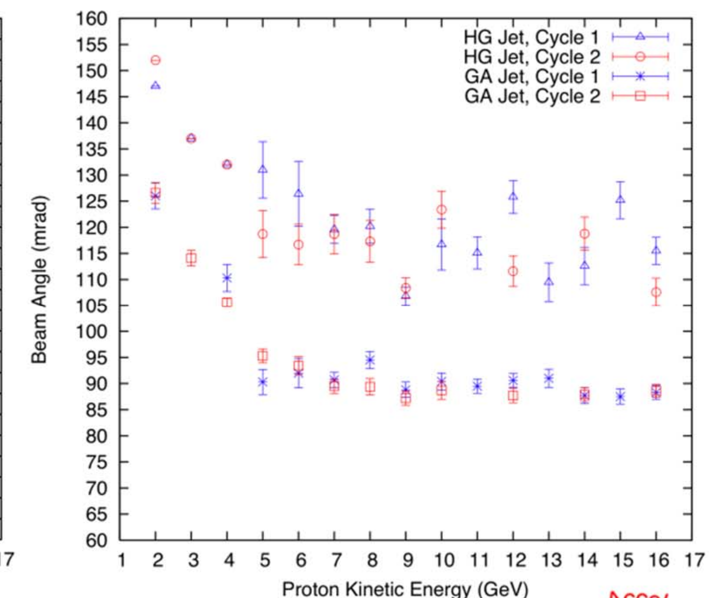
X. Ding et al., MOPPC044, IPAC12





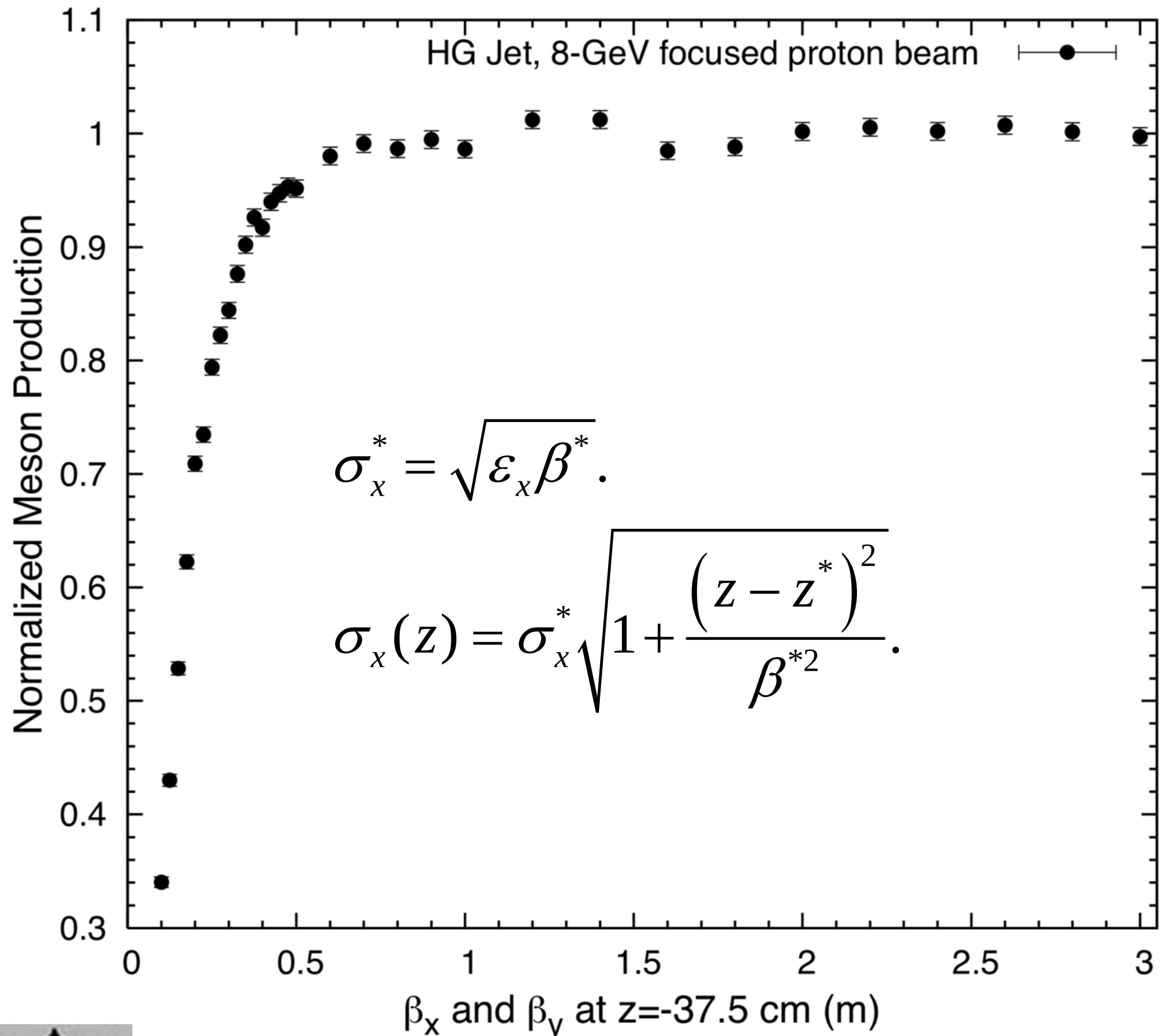






http://www.hep.princeton.edu/~mcdonald/mumu/target/ipac12/MOPPC044.pdf

Proton Beam Emittance and β*



$$\sigma_x^* = \sqrt{\varepsilon_x \beta^*}.$$

$$\sigma_x(z) = \sigma_x^* \sqrt{1 + \frac{(z - z^*)^2}{\beta^{*2}}}.$$

Beam radius is fixed at 0.12 cm at z = -37.5 cm.

For geometrical rms emittance 5 π μm, need $\beta^* = \beta_x = \beta_y = 0.3$ m.

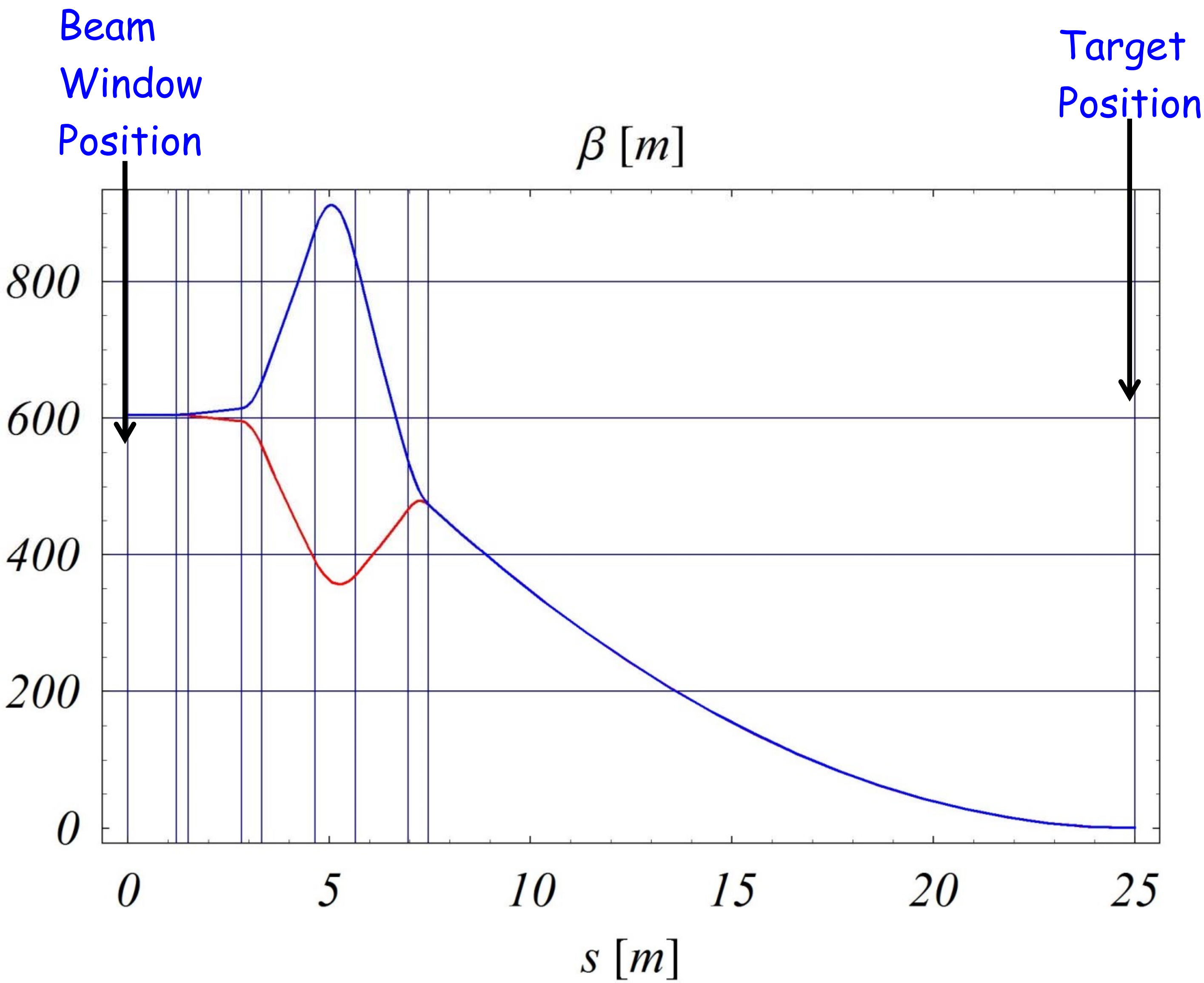
But, prefer $\beta^* = \beta_x = \beta_y = 0.65$ m.

(X. Ding)

http://www.hep.princeton.edu/~mcdonald/mumu/target/Ding/ding_100412.pdf

Proton Beam Final Focus with β^* of 0.65 m

Final focus consists of 4 room-temperature quads.

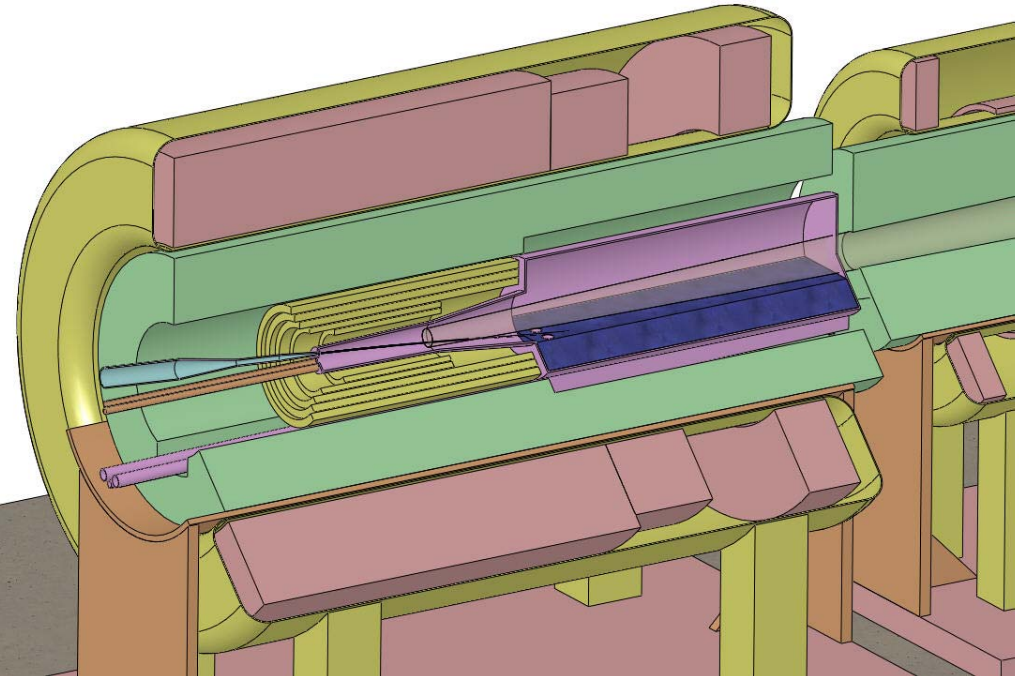


To do: Move last quad to z ~ - 4 m, and determine largest $\varepsilon_\perp$ for which σ_r = 1.2 mm at target.

$\Rightarrow$ Smaller β^*

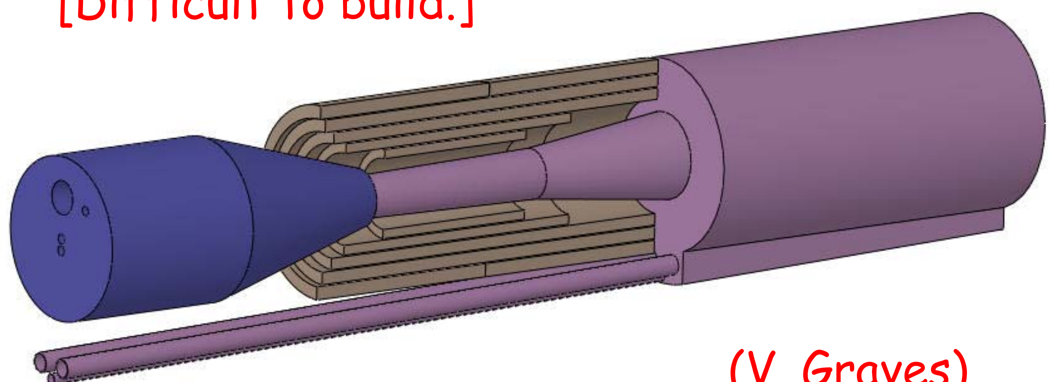
J. Pasternak, Aug 7, 2012
http://www.hep.princeton.edu/~mcdonald/mumu/target/Pasternak/pasternak_080712.pdf

Mercury Target Module with Beam Dump/Collection Pool

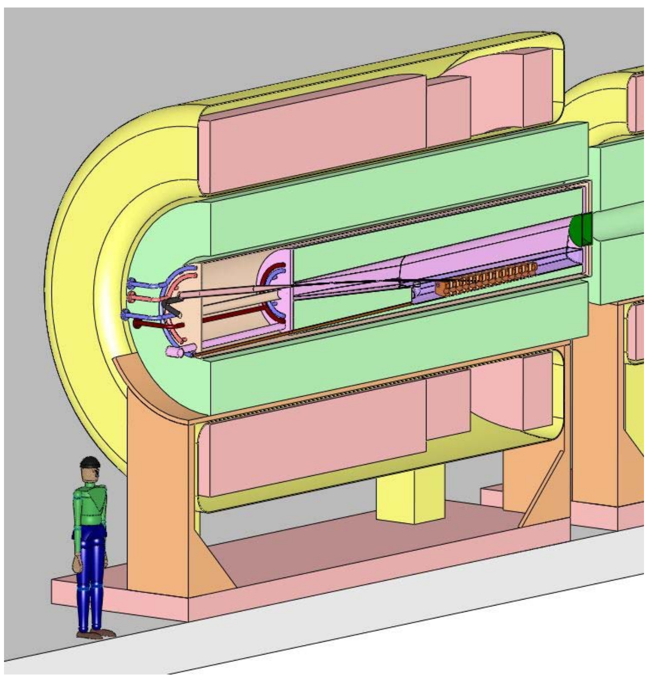


Baseline: Mercury target module (double containment vessel) is surrounded by the 5-T copper magnet (all within the 15-T SC magnet.

[Difficult to build.]

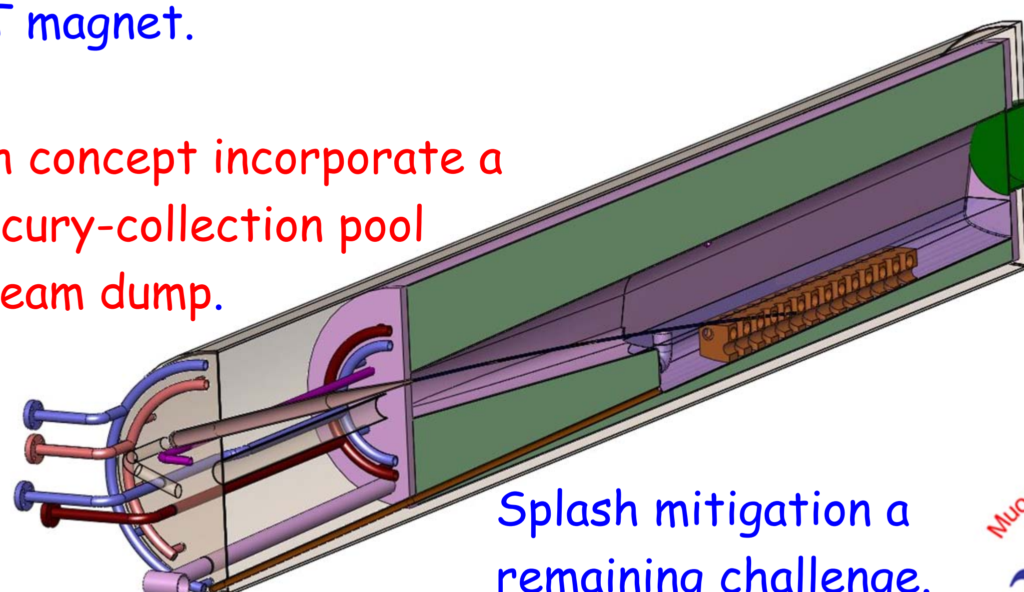


(V. Graves)



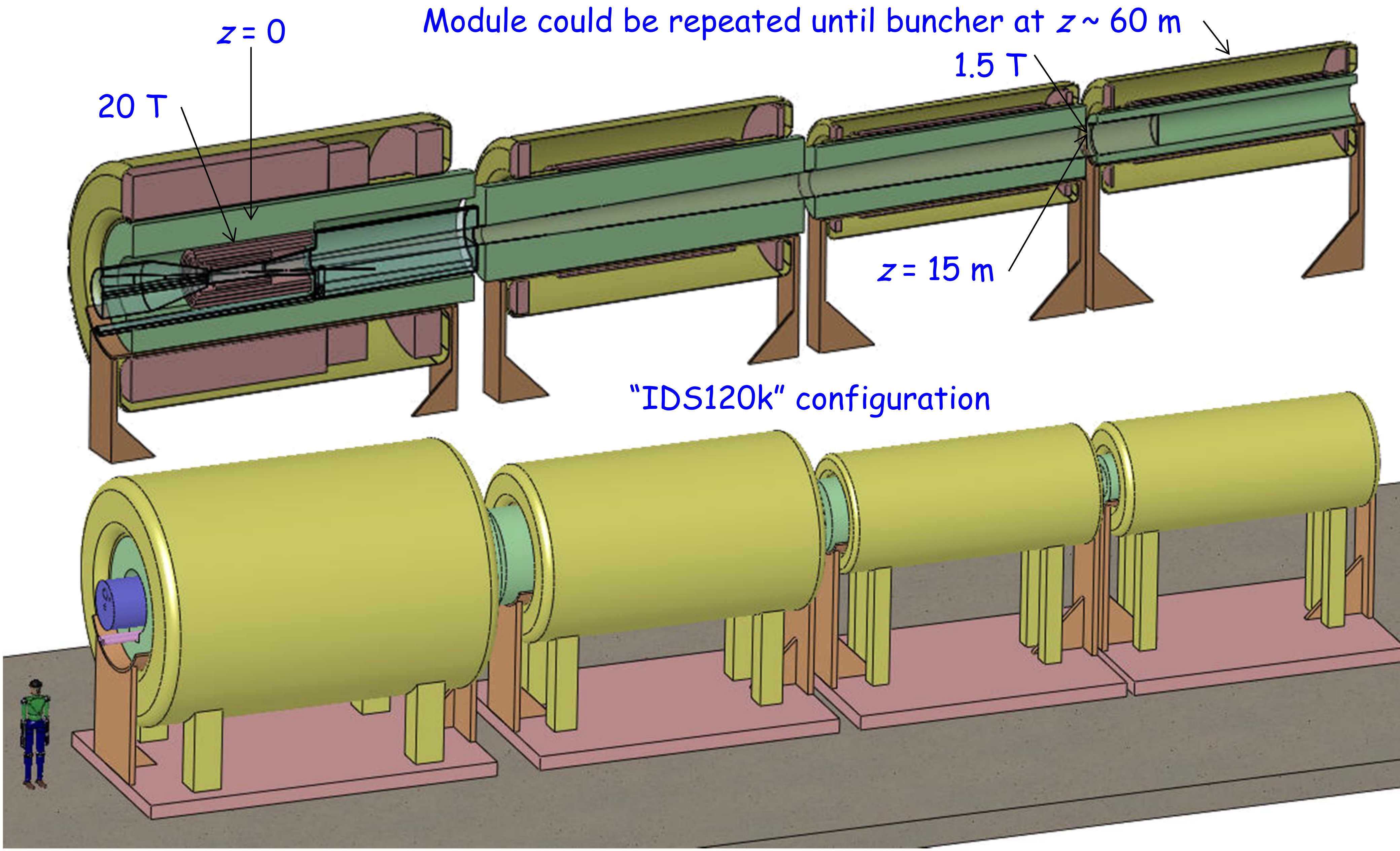
Alternative concept has no 5-T copper magnet (only 15-T magnet.

Both concept incorporate a Mercury-collection pool as beam dump.



Splash mitigation a remaining challenge.

20-T Field on Target "Tapers" in 15 m to 1.5 T in Decay Channel



The taper exchanges longitudinal and transverse phase space.

May be advantageous to use shorter taper, and higher field in decay channel.

Radiation Damage to Nb Superconductor

The ITER project quotes the lifetime radiation dose to the superconducting magnets as 10^{22} *n*/m^2 for reactor neutrons with E > 0.1 MeV. This is also 10^7 Gray = 10^4 J/g accumulated energy deposition.

For a lifetime of 10 "years" of 10^7 s each, the peak rate of energy deposition would be 10^4 J/g / 10^8 s = 10^{-4} W/g = 0.1 mW/g (= 1 MGray/year of 10^7 s).

The ITER Design Requirements document, http://puhep1.princeton.edu/~mcdonald/examples/magnets/iter_fdr_DRG1.pdf reports this as 1 mW/cm^3 of peak energy deposition (which seems to imply $\rho_{magnet} \approx 10$ g/cm^3).

Table 1.17-1 Maximum Nuclear Load Limits to the Magnet

Parameters	Unit	H	DT	TBA
Local nuclear heat in the conductor	kW/m^3	0	1	
Local nuclear heat in the case and structures	kW/m^3	0	2	
Peak radiation dose to coil insulator	Gray	0	10x10^6	
Total neutron flux to coil insulator	N/m^2	0	10^{22}	
Total nuclear heat in the magnets	kW	See Table 1.15-5		

Damage to Nb-based superconductors appears to become significant at doses of 2-3 × 10^{22} *n*/m^2 :

A. Nishimura *et al.*, Fusion Eng. & Design **84**, 1425 (2009)

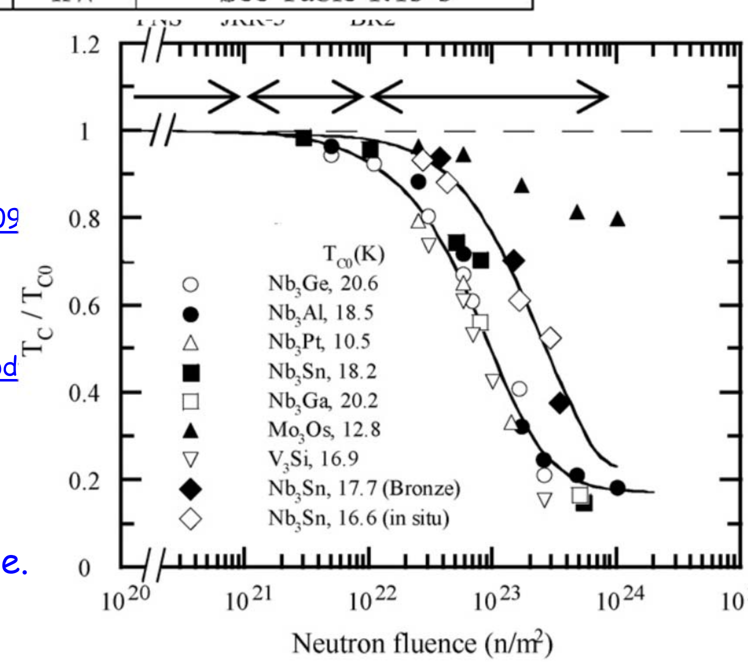
http://puhep1.princeton.edu/~mcdonald/examples/magnets/nishimura_fed_84_1425_09

Reviews of these considerations for ITER:

J.H. Schultz, IEEE Symp. Fusion Eng. 423 (2003)

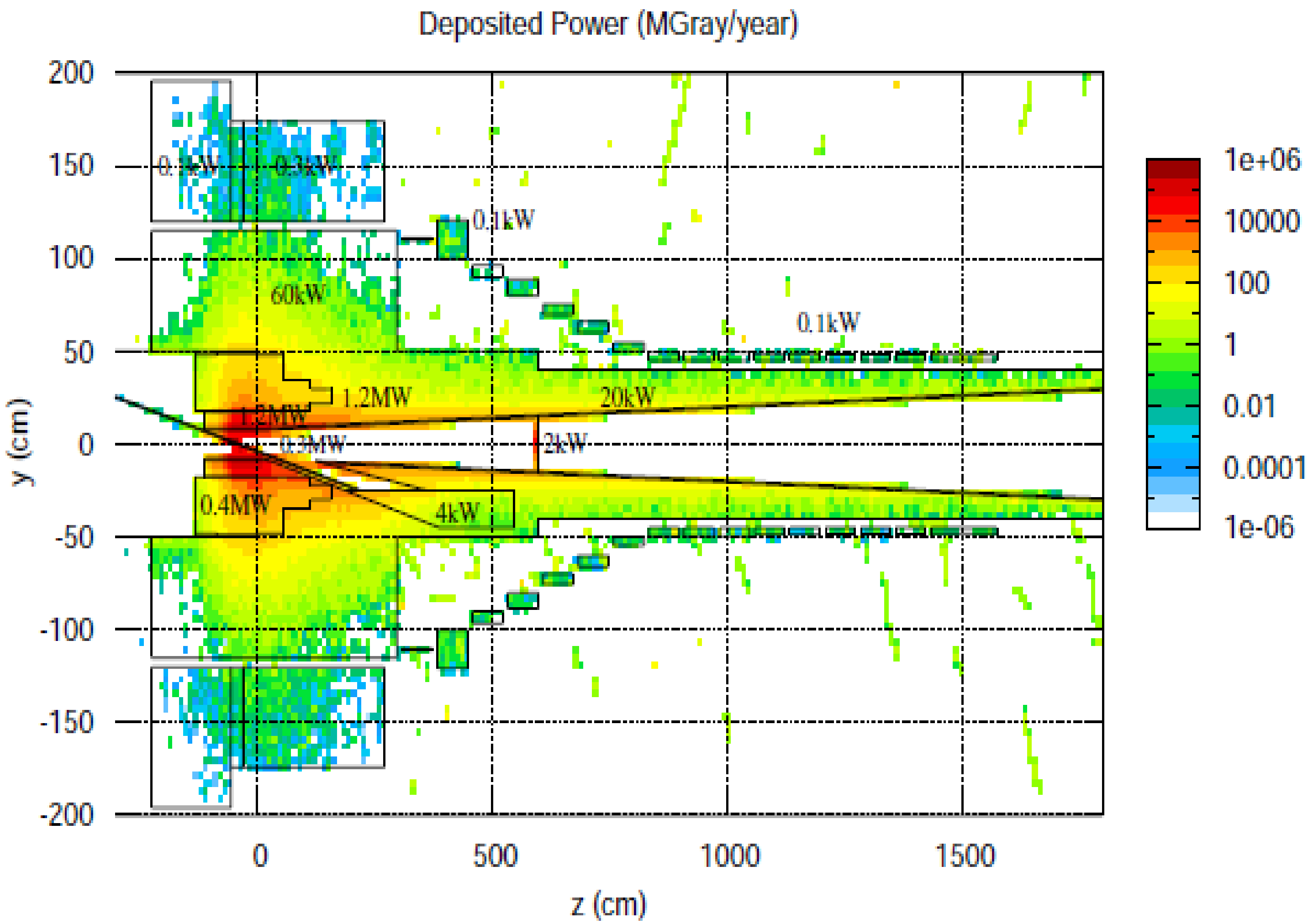
http://puhep1.princeton.edu/~mcdonald/examples/magnets/schultz_ieeesfe_423_03.pd

http://puhep1.princeton.edu/~mcdonald/examples/magnets/schultz_cern_032205.pdf



Reduction of critical current of various Nb-based Conductors as a function of reactor neutron fluence. From Nishimura *et al.*

High Levels of Energy Deposition in the Target System



Power deposition in the superconducting magnets and the He-gas-cooled tungsten shield inside them, according to a FLUKA simulation.

Approximately 2.4 MW must be dissipated in the shield.

Some 800 kW flows out of the target system into the downstream beam-transport elements.

Total energy deposition in the target magnet string is ~ 1 kW @ 4k.

Peak energy deposition is about 0.03 mW/g.

(J. Back, N. Souchlas)

Shielding of the Superconducting Solenoids Drives the Design

MARS15 simulations (with MCNP data for very low particle energies) indicate that use of He-gas-cooled, tungsten-bead shielding

⇒ Inner radius of the 15-T solenoid around the target must be 120 cm;

⇒ Stored energy in target magnet system ~ 3 GJ (same as LHC octant).

⇒ Target-magnet module weighs ~ 200 tons ⇒ Need big crane for assembly.

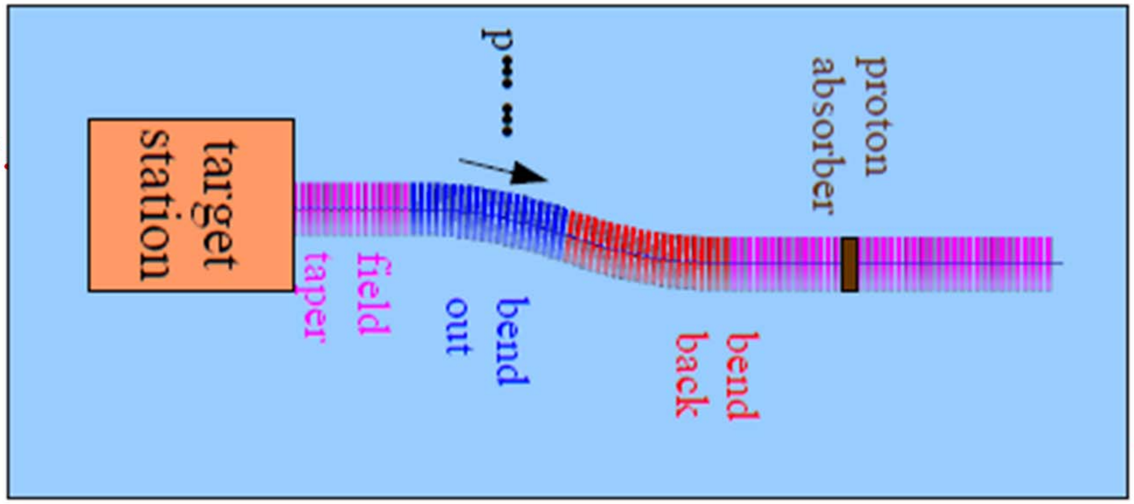
Of the 4-MW proton beam power, some 500 kW continues down the 30-cm-radius beam pipe beyond z = 15 m (= end of taper); mostly in the form of GeV scattered protons.

This energy would eventually be deposited in the rf cavities and low-Z absorbers of the cooling section, if not removed earlier.

A chicane + proton absorber in the decay channel (15 < z < 60 m) will mitigate this issue.

May be favorable to use HTS for the decay region/chicane magnets.

(C. Rogers, P. Snopok, D. Neuffer, R. Weggel)



RDR Readiness

Blue = "ready", Red = "not so ready"

Target System Overview (-3 < z < 65 m, including "chicane")

Alternatives: Ga or C targets; shorter taper; 15-T peak field; 2-2.5/T min field

Particle Production Simulations

Beam-Jet Interaction (data from MERIT expt. + simulations)

Energy Deposition simulations for 0 < z < 15 m

Energy Deposition simulations for 15 < z < 65 m

Magnet configuration for 0 < z < 15 m

Magnet configuration for 15 < z < 65 m

Mercury handling system

Magnet power supplies

Cooling systems

Civil engineering

Utilities

Safety