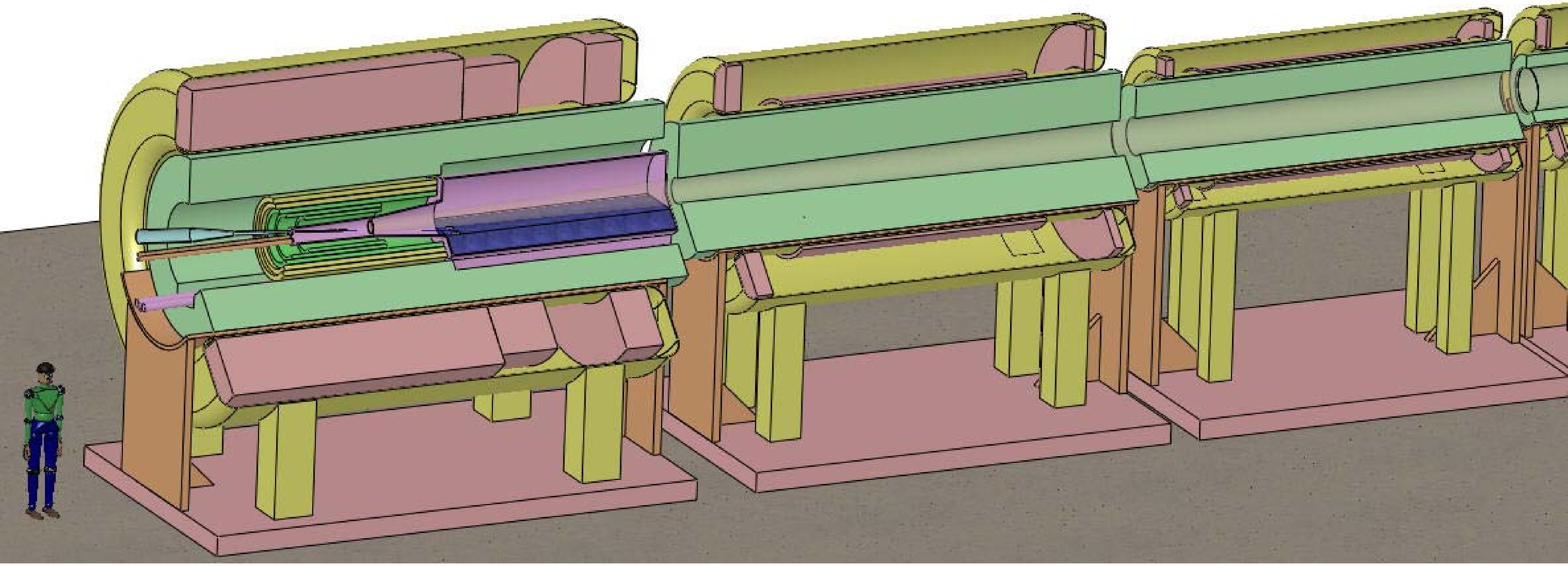
The High-Power-Target System of a Muon Collider or Neutrino Factory



K. McDonald

Princeton U.

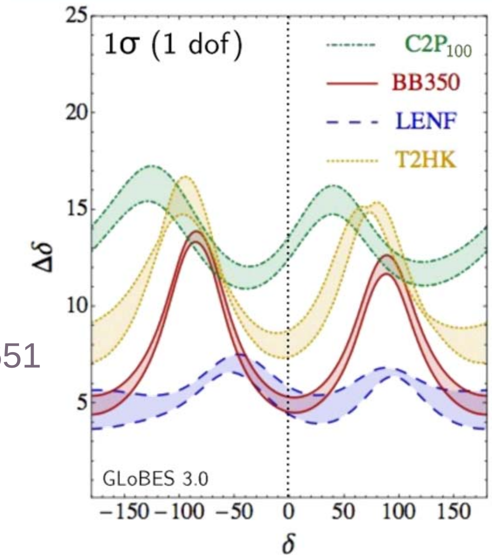
(April 19, 2013)

Snowmass Workshop on Frontier Capability

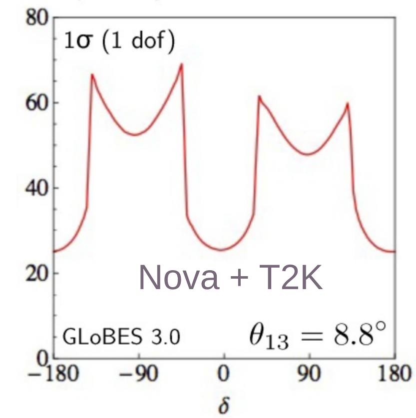
Brookhaven National Laboratory

Frontier Physics with Muon-Based Accelerators

CP Violation in the neutrino sector:
The best measurements would be made at a Neutrino Factory base on decays of stored muons.

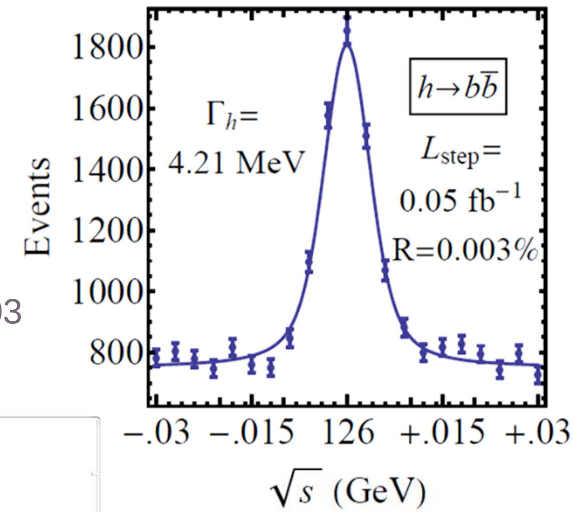


Coloma et al, 1203.5651

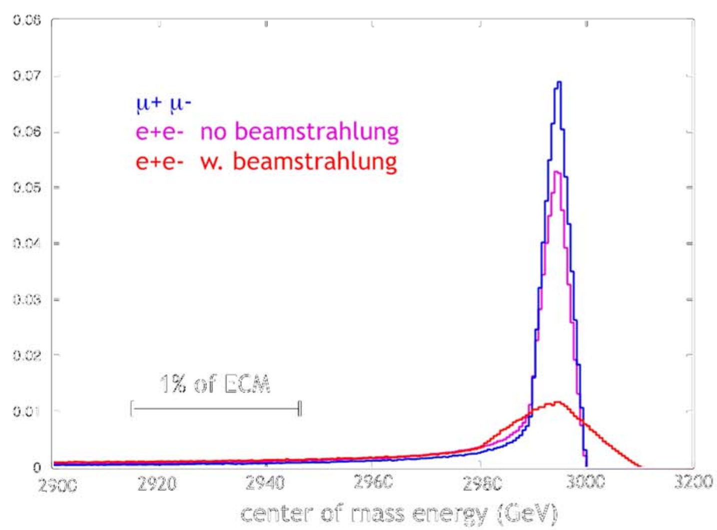


Width of Higgs boson:
Expected width of ~ 4 MeV could only be confirmed at a Higgs Factory based on colliding beams of muons.

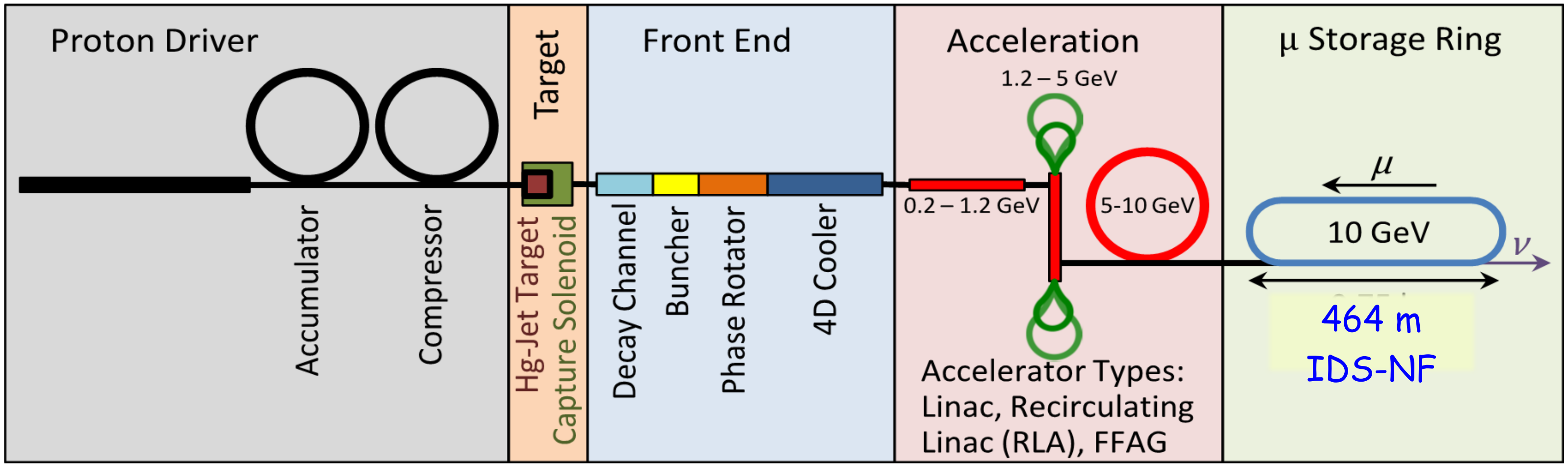
Han and Liu, 1210.7803



High-energy physics with precision initial state with fundamental particles only possible with colliding beams of muons.



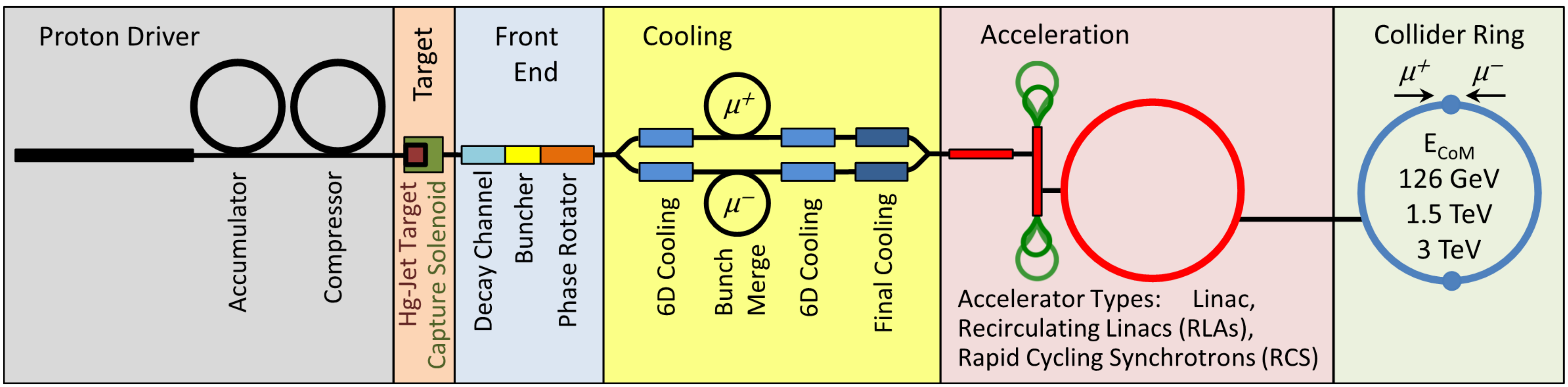
Neutrino Factory



Neutrino beam to large magnetized detector @ 2500 km

Muon Collider

could be Neutrino Factory + 6-D cooling + final acceleration and collider ring



The Target System is Challenging

Simultaneous capture of both signs of μ's (from decays of charged π's) requires use of solenoidal beam transport (in contrast to toroidal magnetic horns)

High capture efficiency of low energy π/μ favors use of a magnetic bottle with initial field of 15-20 T, followed by an adiabatic "taper" down to 1.5-2 T. This performs an emittance exchange which "cools" the transverse size of beam, while "heating" it longitudinally.

Economically favorable to use superconducting magnets in the beam transport, but then the 4-MW proton beam power must be dissipated inside the magnets,
$\Rightarrow$ Massive internal shielding, and large stored magnetic field energy.

Need for further "cooling" of the muons favors use of very short proton beam pulses (~ 2 ns)
$\Rightarrow$ Very high peak thermal stresses in target
$\Rightarrow$ Favorable to use liquid jet target that is replaced every beam pulse (~ 50 Hz).

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.

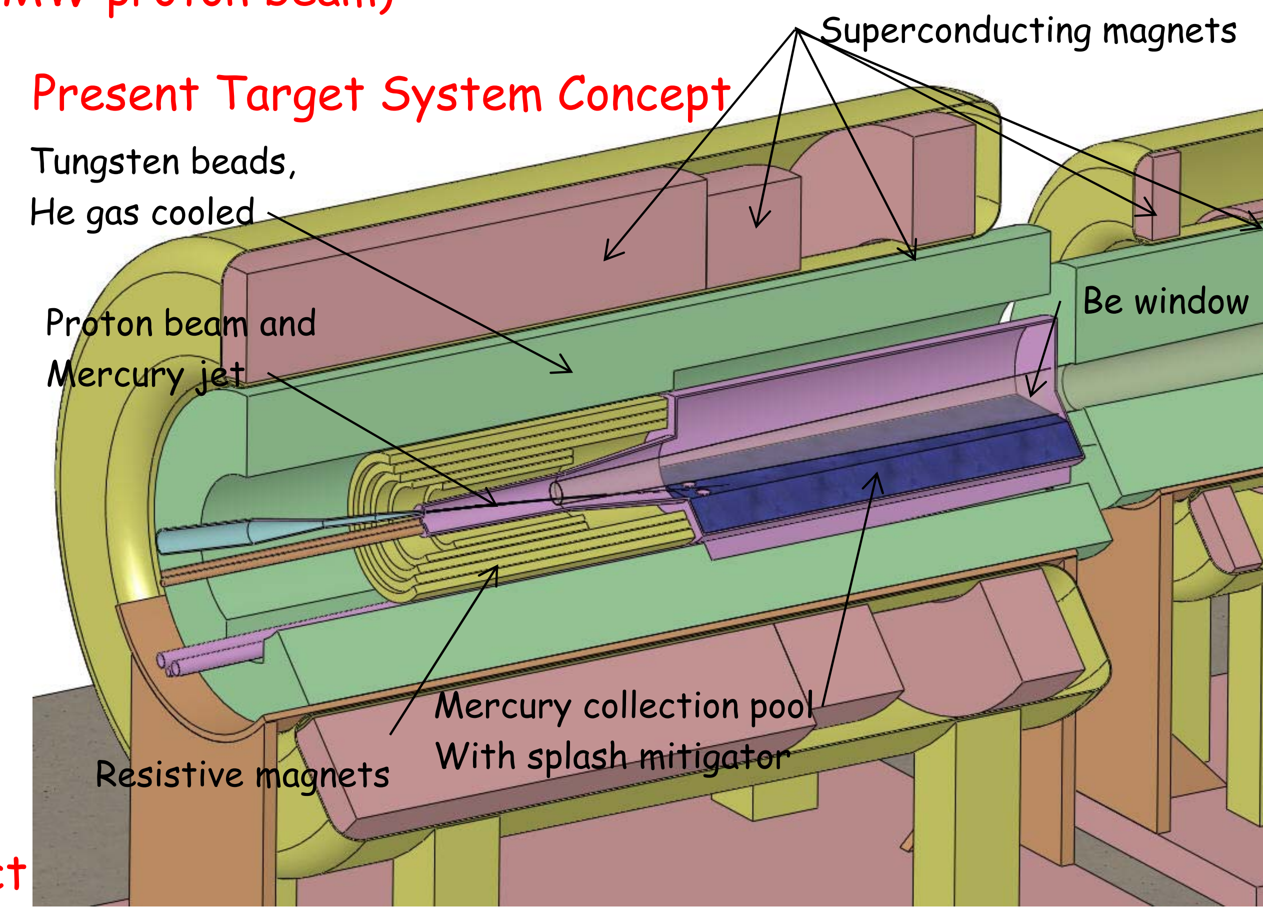
Solenoid coils can be some distance from proton beam.

⇒ ≥ 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.



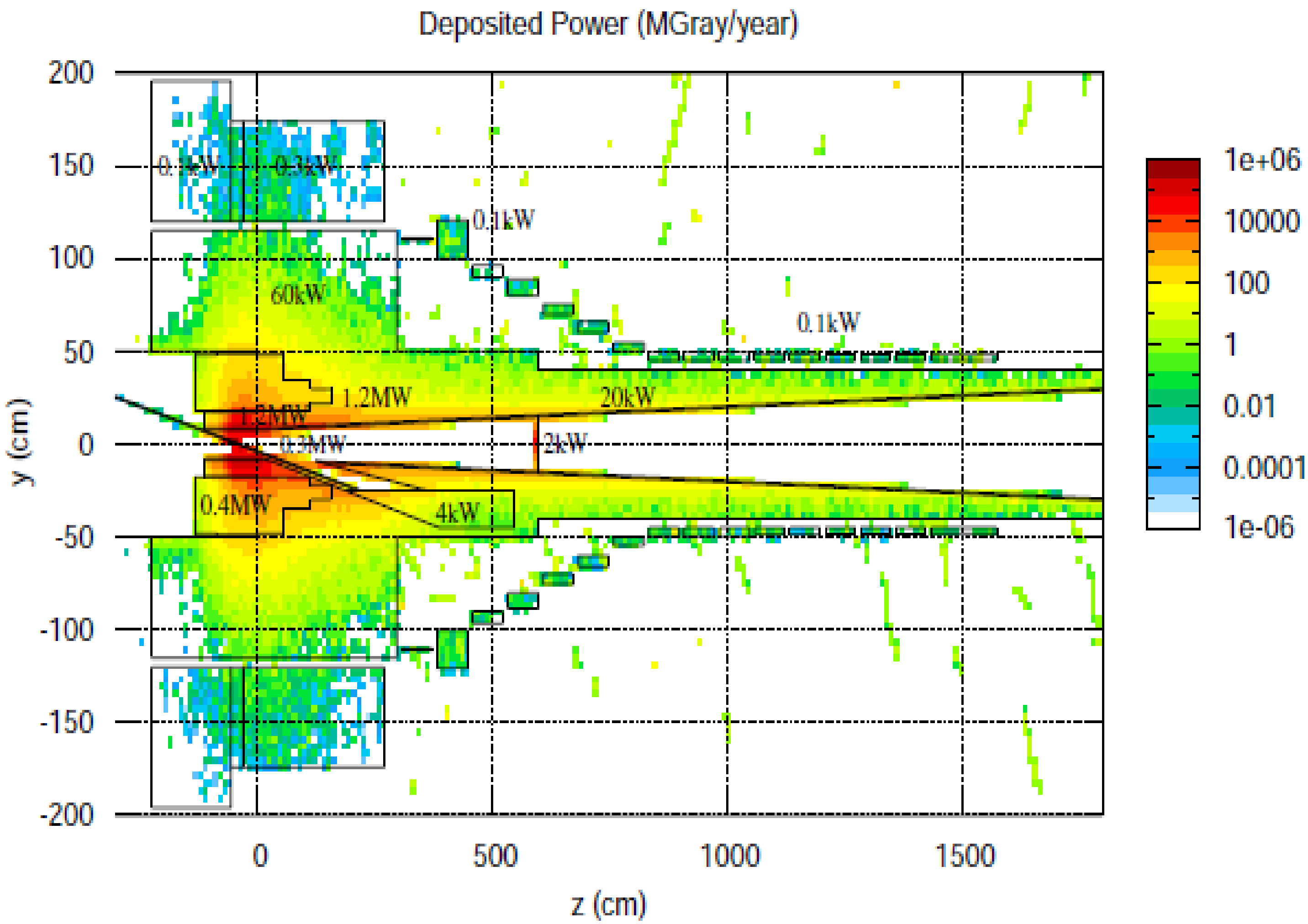
Shielding of the superconducting magnets from radiation is a major issue.

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.

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 0.1 mW/g = limit for ~ 10 year lifetime against radiation damage ("ITER limit").

(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, CMS magnet).

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

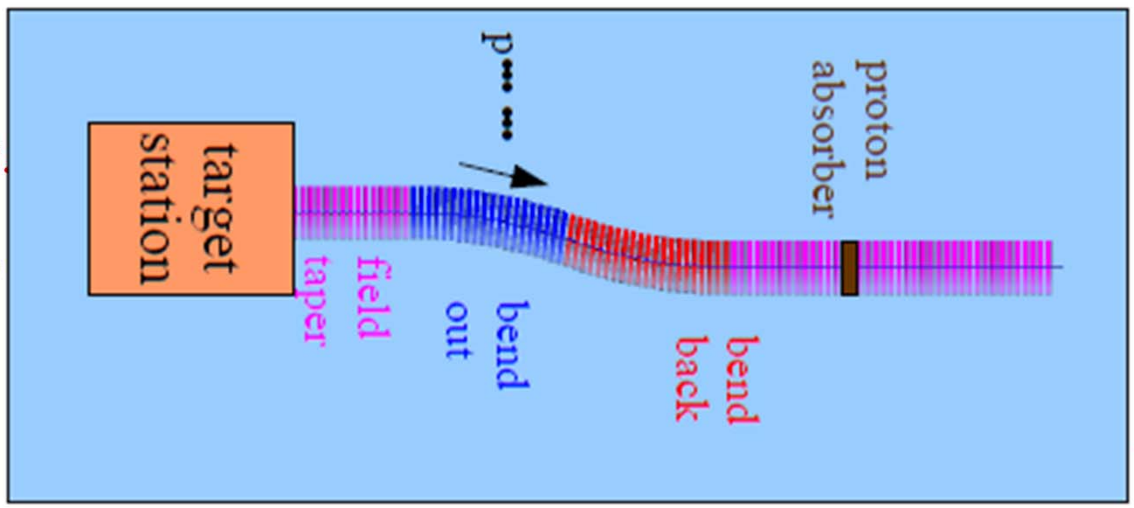
Of the 4-MW proton beam power, some 500 kW continues down the 30-cm-radius beam pipe beyond z = 15 m (= end of taper); mostly in the form of GeV scattered protons.

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

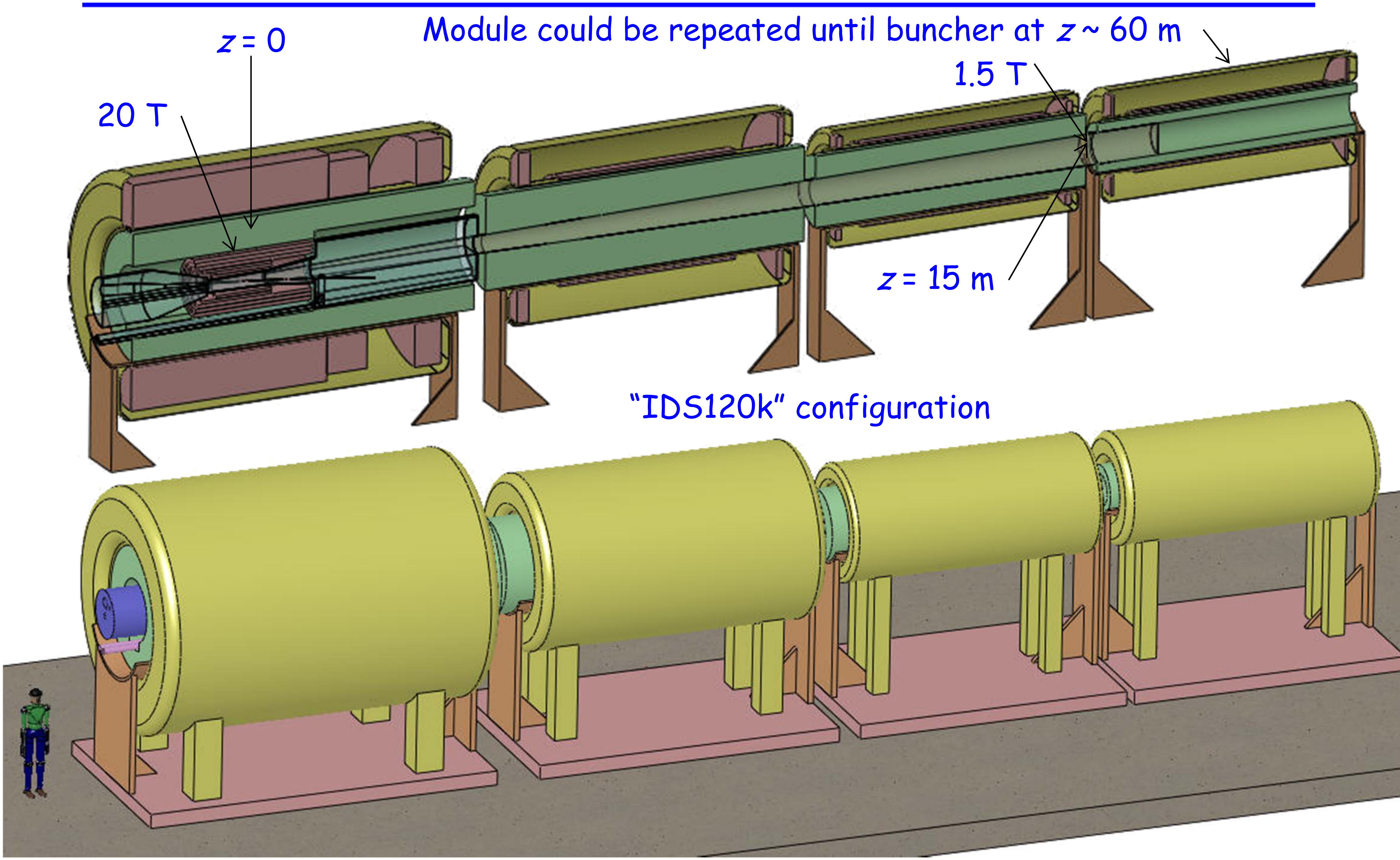
A chicane + proton absorber in the decay channel (15 < z < 60 m) will mitigate this issue.

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

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



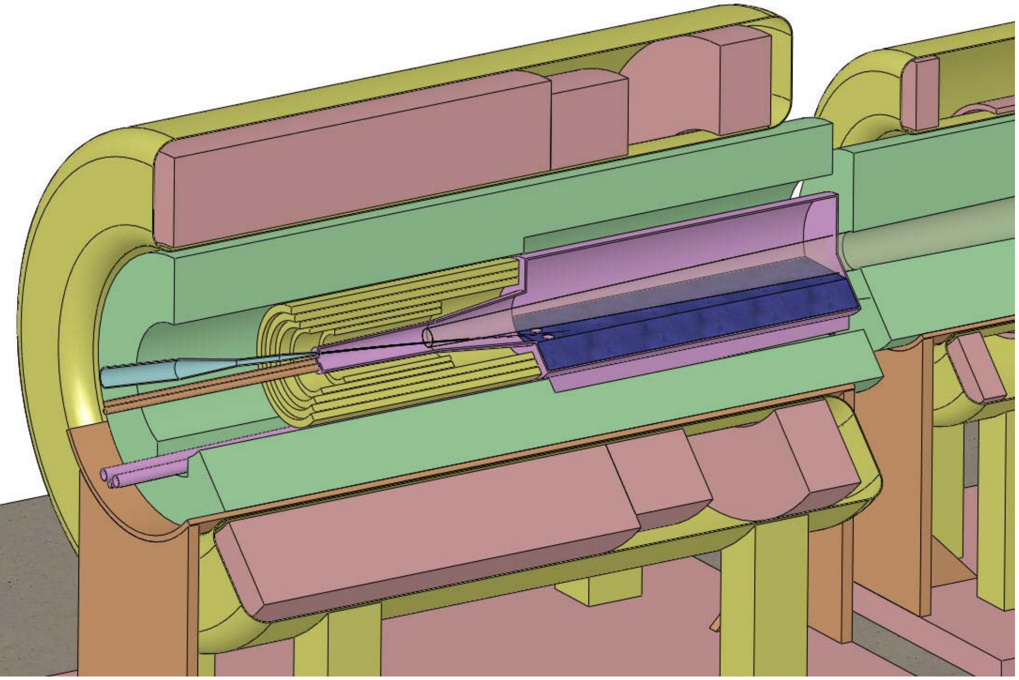
20-T Field on Target "Tapers" in 15 m to 1.5 T in Decay Channel



The taper exchanges longitudinal and transverse phase space.

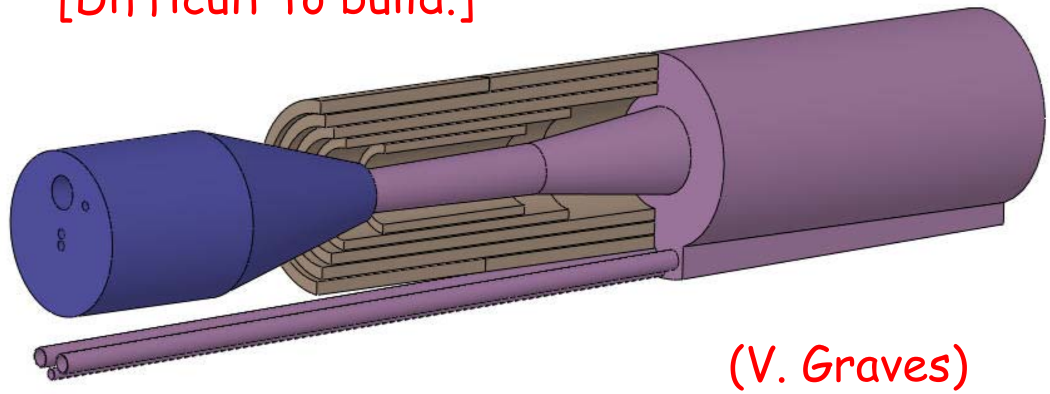
May be advantageous to use shorter taper, and higher field in decay channel.

Mercury Target Module with Beam Dump/Collection Pool

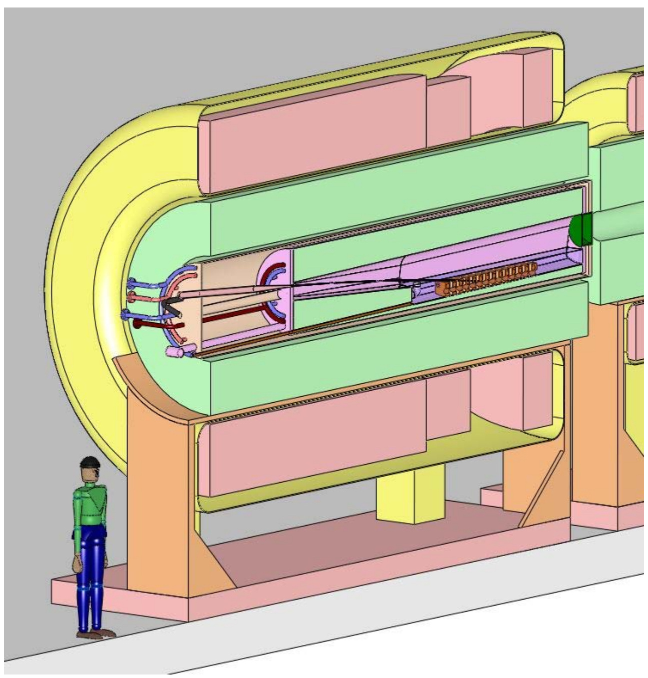


Baseline: Mercury target module (double containment vessel) is surrounded by the 5-T copper magnet (all within the 15-T SC magnet.

[Difficult to build.]

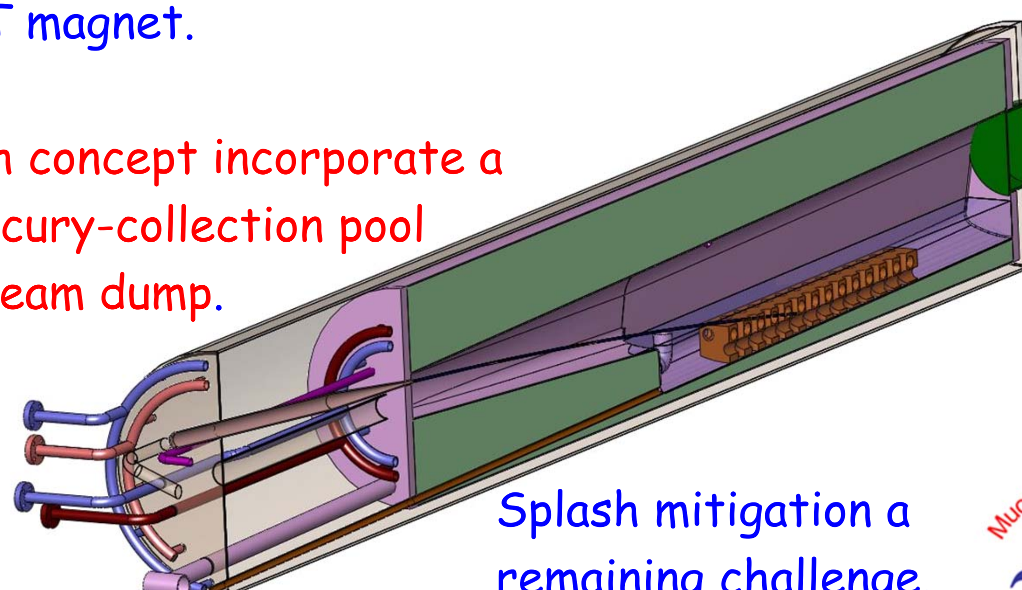


(V. Graves)



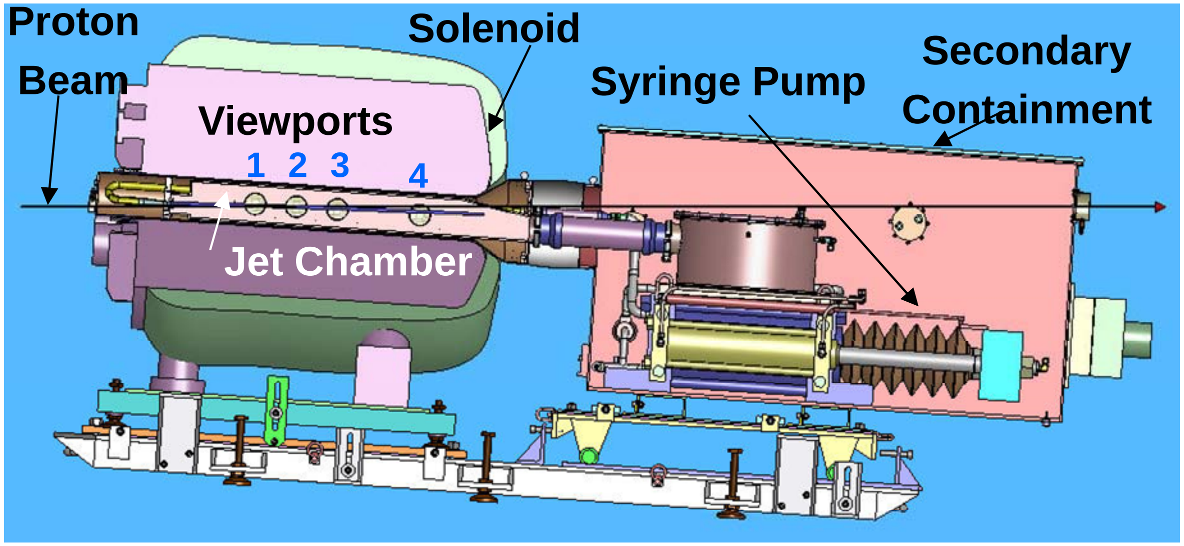
Alternative concept has no 5-T copper magnet (only 15-T magnet.

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



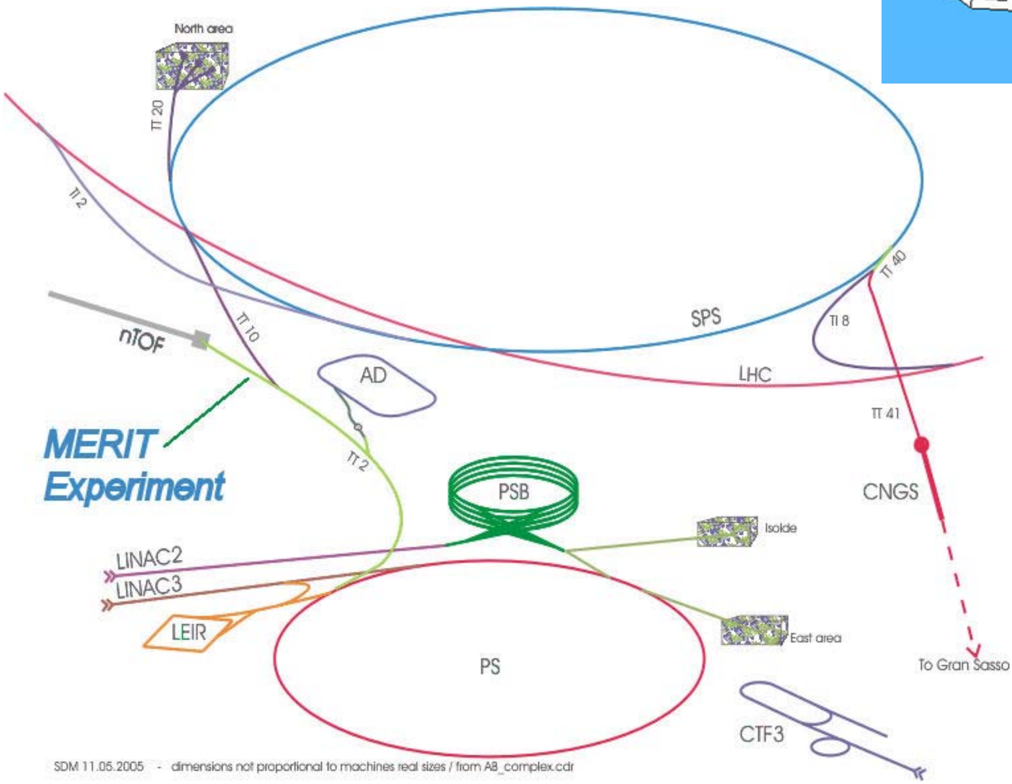
Splash mitigation a remaining challenge.

CERN MERIT Experiment (Nov 2007)

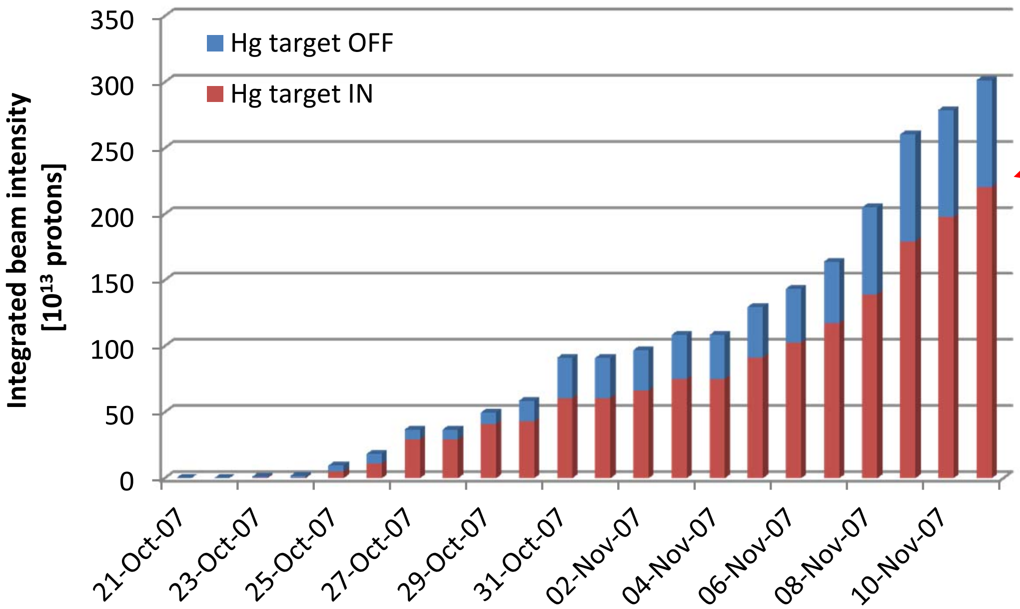


Proof-of-principle demonstration of a mercury jet target in a strong magnetic field, with proton bunches of intensity equivalent to a 4-MW beam.

Performed in the TT2A/TT2 tunnels at CERN.

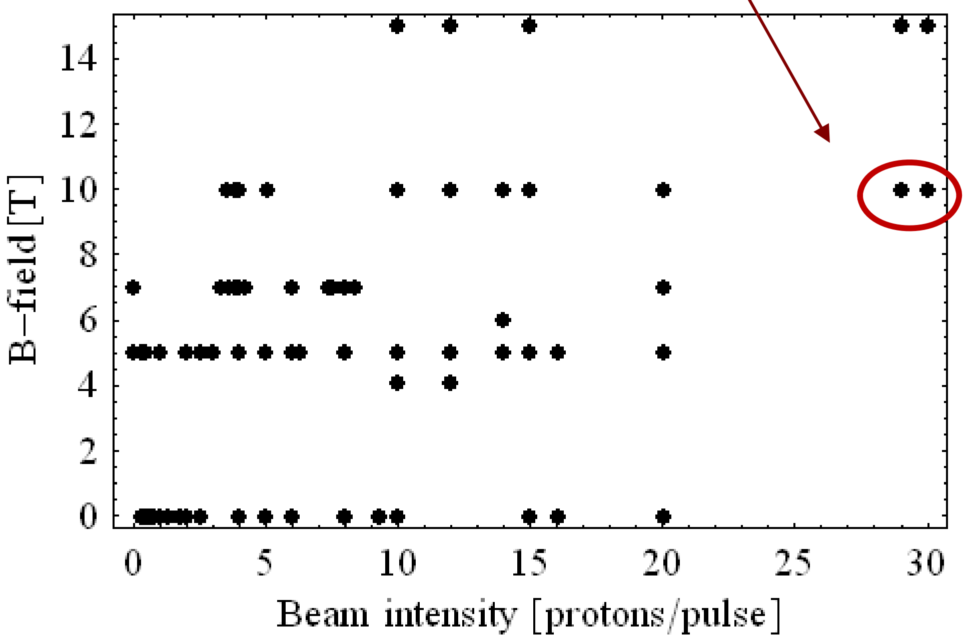


MERIT Beam Pulse Summary



MERIT was not to exceed 3×10^{15} protons on Hg to limit activation.

30 T*p* shot @ 24 GeV/c
- **115 kJ** of beam power
- a PS machine record !

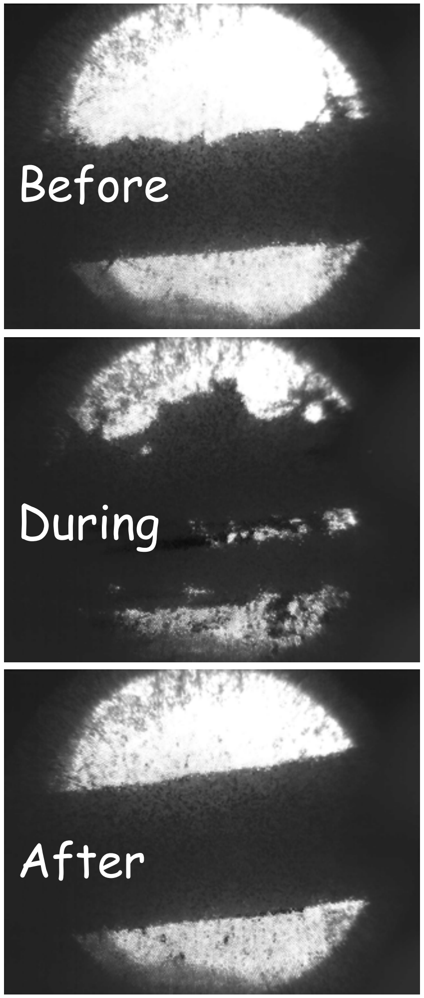


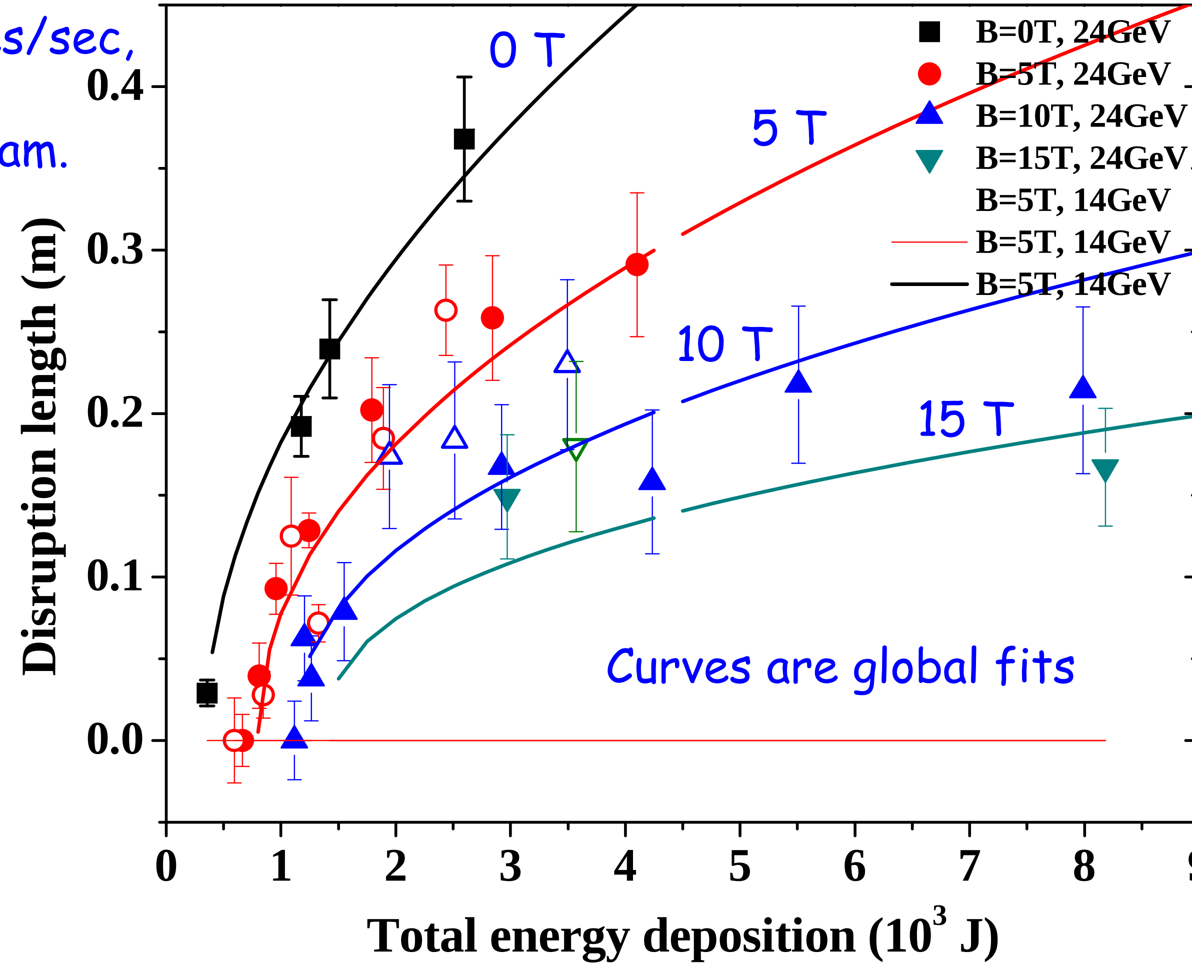
1 T*p* = 10^{12} protons

Disruption Length Analysis (H. Park, PhD Thesis)

Observe jet at viewport 3 at 500 frames/sec,
measure total length of disruption
of the mercury jet by the proton beam.

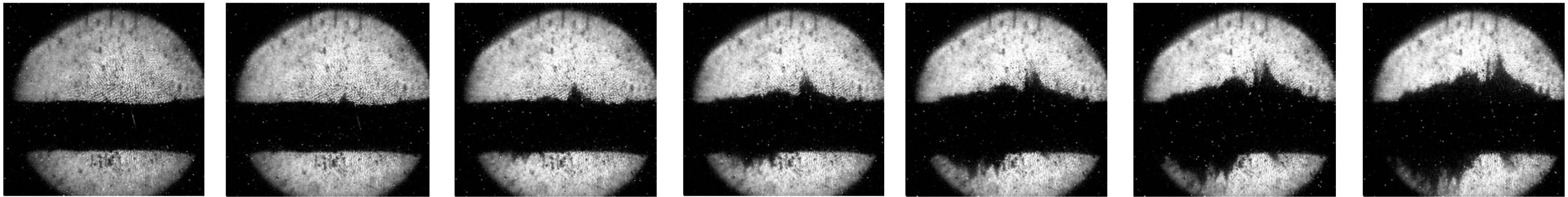
Images for 10 T*p*, 24 GeV, 10 T:



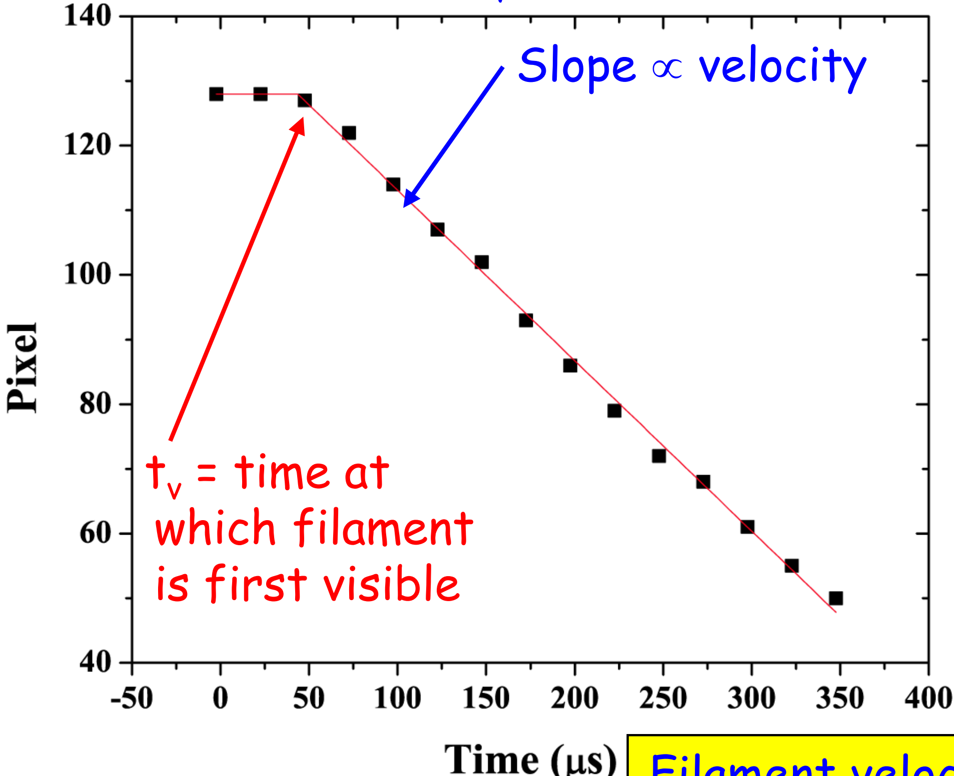


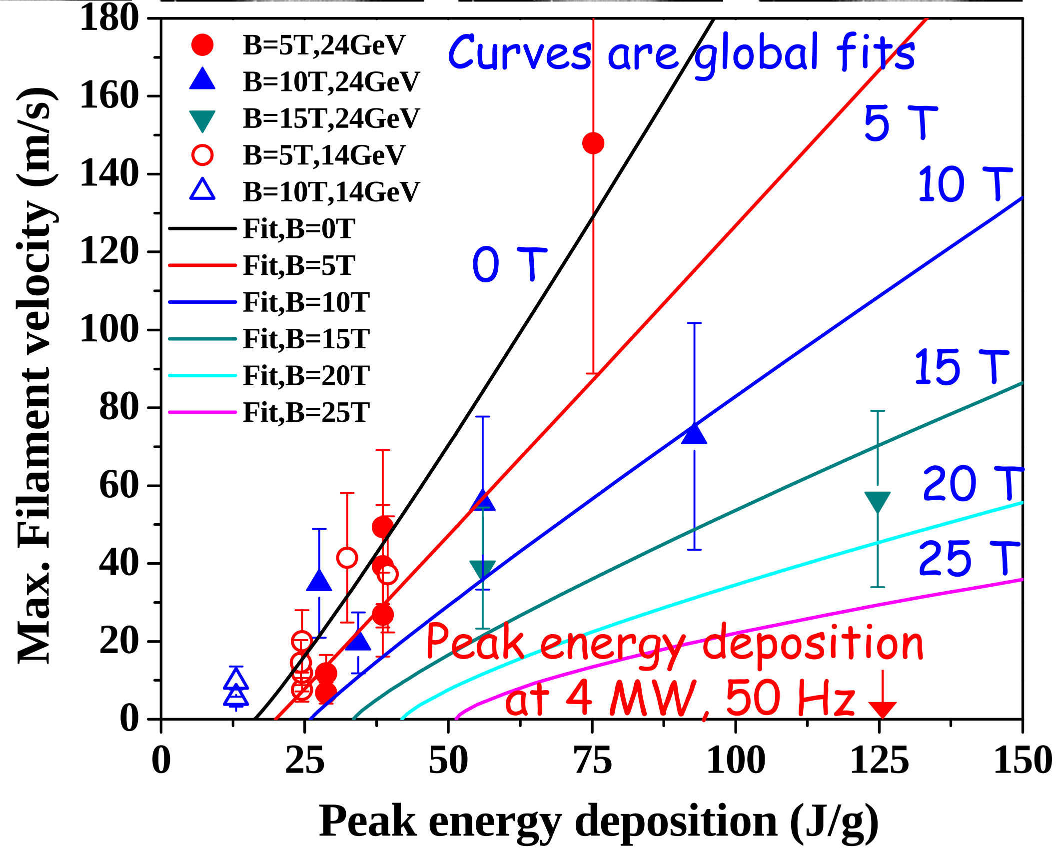
- Disruption length never longer than region of overlap of jet with proton beam.
- No disruption for pulses of < 2 T*p* in 0 T (< 4 T*p* in 10 T).
- Disruption length shorter at higher magnetic field.

Filament Velocity Analysis (H. Park)



Measure position of tip of filament in each frame, and fit for t_v and v.





Filament velocity suppressed by high magnetic field.

Filament start time >> transit time of sound across the jet.

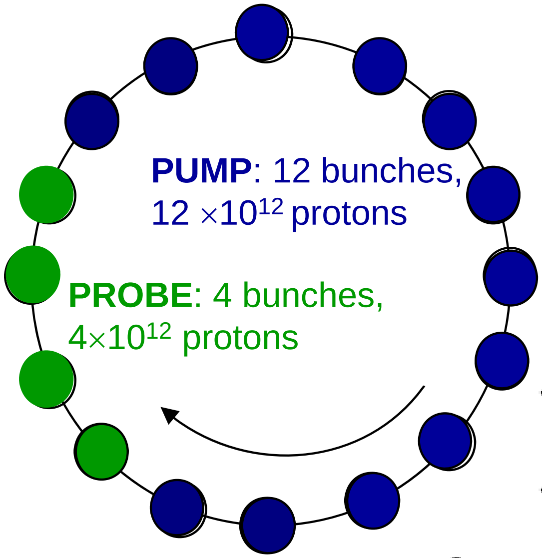
⇒ New transient state of matter???

Pump-Probe Studies

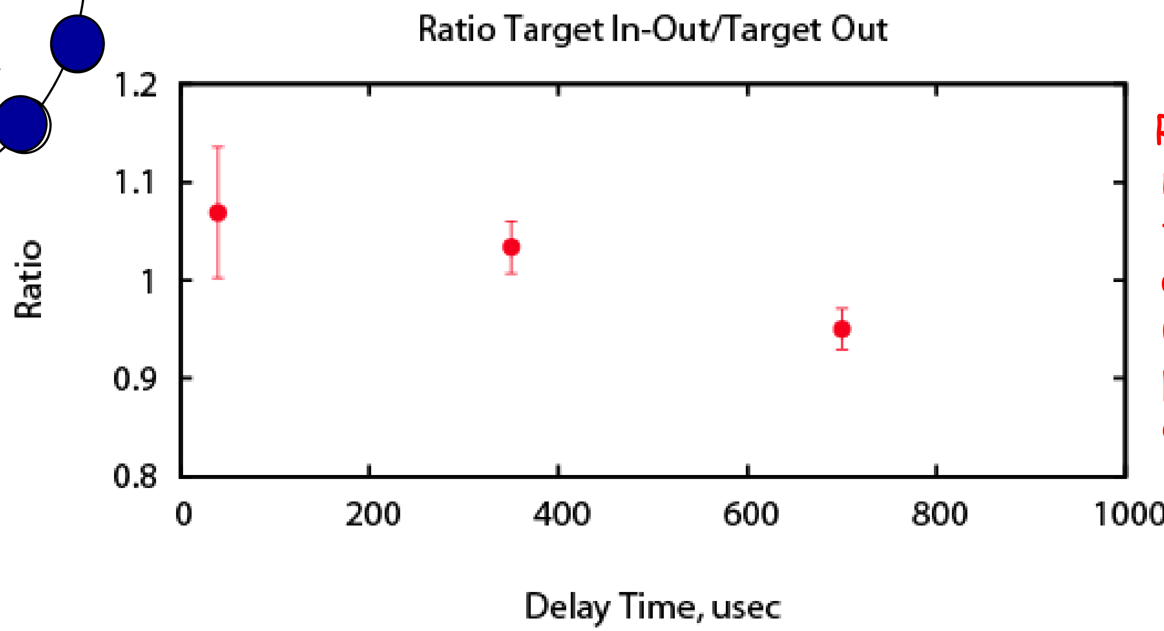
? Is pion production reduced during later bunches due to disruption of the mercury jet by the earlier bunches?

At 14 GeV, the CERN PS could extract several bunches during one turn (pump), and then the remaining bunches at a later time (probe).

Pion production was monitored for both target-in and target-out events by a set of diamond diode detectors.



$$\text{Ratio} = \frac{\dfrac{\text{Probe}_{\text{target in}} - \text{Probe}_{\text{target out}}}{\text{Pump}_{\text{target in}} - \text{Pump}_{\text{target out}}}}{\dfrac{\text{Probe}_{\text{target out}}}{\text{Pump}_{\text{target out}}}}$$



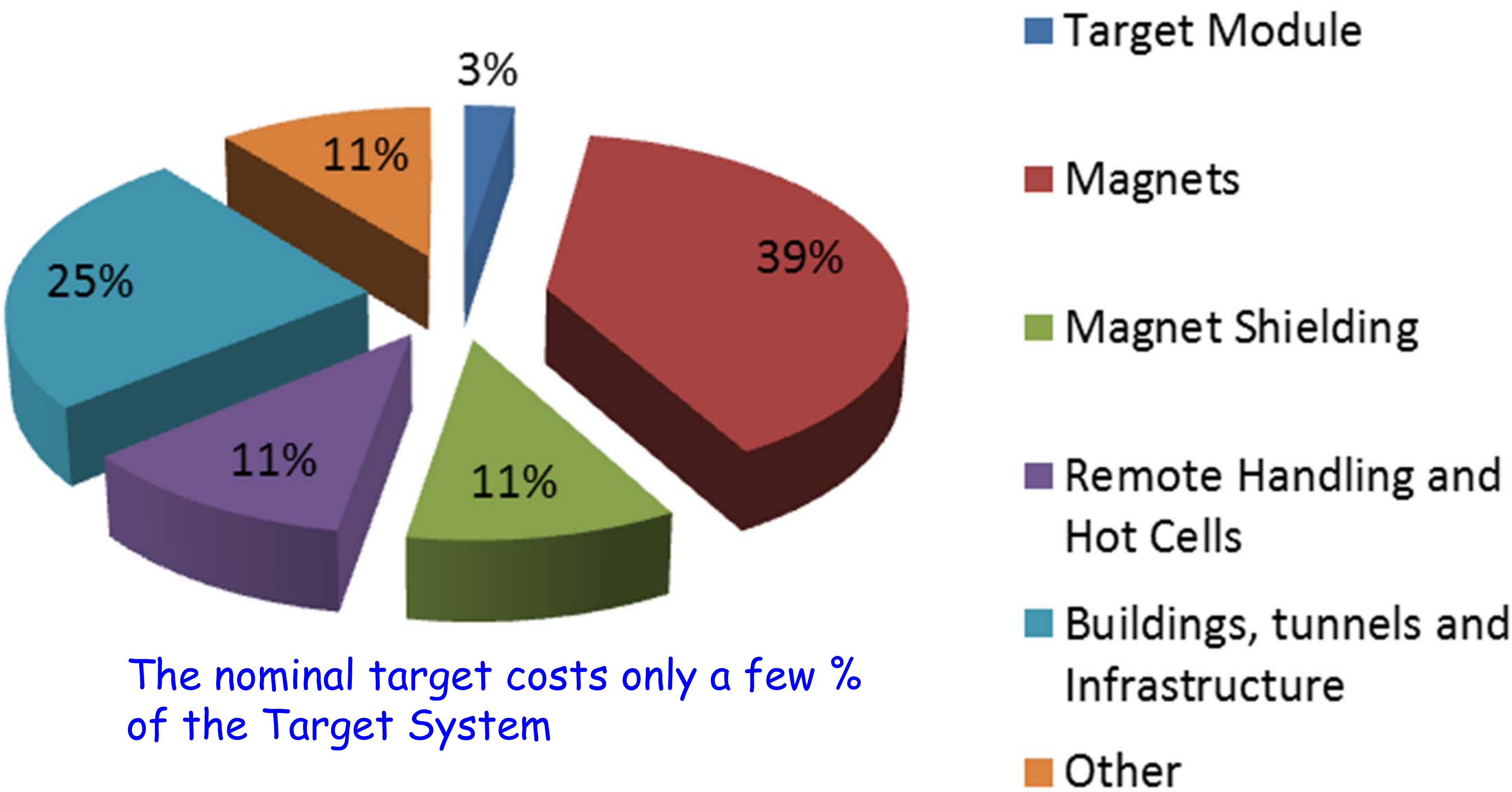
Results consistent with no loss of pion production for bunch delays of 40 and 350 μs, and a 5% loss (2.5-σ effect) of pion production for bunches delayed by 700 μs.

MERIT Experiment Summary

The MERIT experiment established proof-of-principle of a free mercury jet target in a strong magnetic field, with proton bunches of intensity equivalent to a 4 MW beam.

- The magnetic field stabilizes the liquid metal jet and reduces disruption by the beam.
- The length of disruption is less than the length of the beam-target interaction, $\Rightarrow$ Feasible to have a new target every beam pulse with a modest velocity jet.
- Velocity of droplets ejected by the beam is low enough to avoid materials damage.
- The threshold for disruption is a few $\times 10^{12}$ protons, permitting disruption-free operation at high power if can use a high-rep-rate beam.
- Even with disruption, the target remains fully useful for secondary particle production for $\approx 300\ \mu$s, permitting use of short bunch trains at high power.
- No apparent damage to stainless-steel wall only 1 cm from interaction region.

Preliminary Costing of a 4-MW Target System



The nominal target costs only a few % of the Target System

(A. Kurup, International Design Study for a Neutrino Factory)

Overall Summary

The **opportunity** for a Muon Collider/Neutrino Factory is associated with many **challenges**.

[No pain, no gain!]

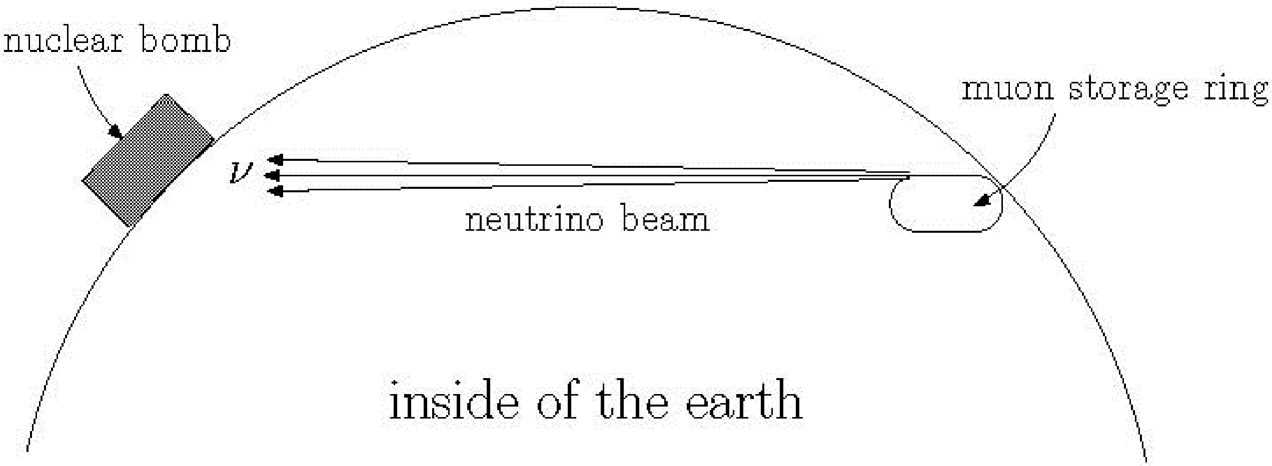
Footnote

hep-ph/0305062
revised, June 2003

Destruction of Nuclear Bombs Using Ultra-High Energy Neutrino Beam

— dedicated to Professor Masatoshi Koshiba —

Hirotaka Sugawara* Hiroyuki Hagura† Toshiya Sanami‡



Abstract

We discuss the possibility of utilizing the ultra-high energy neutrino beam ($\simeq$ 1000 TeV) to detect and destroy the nuclear bombs wherever they are and whoever possess them.