Muon Production and Capture for a Neutrino Factory

European Strategy for Future Neutrino Physics

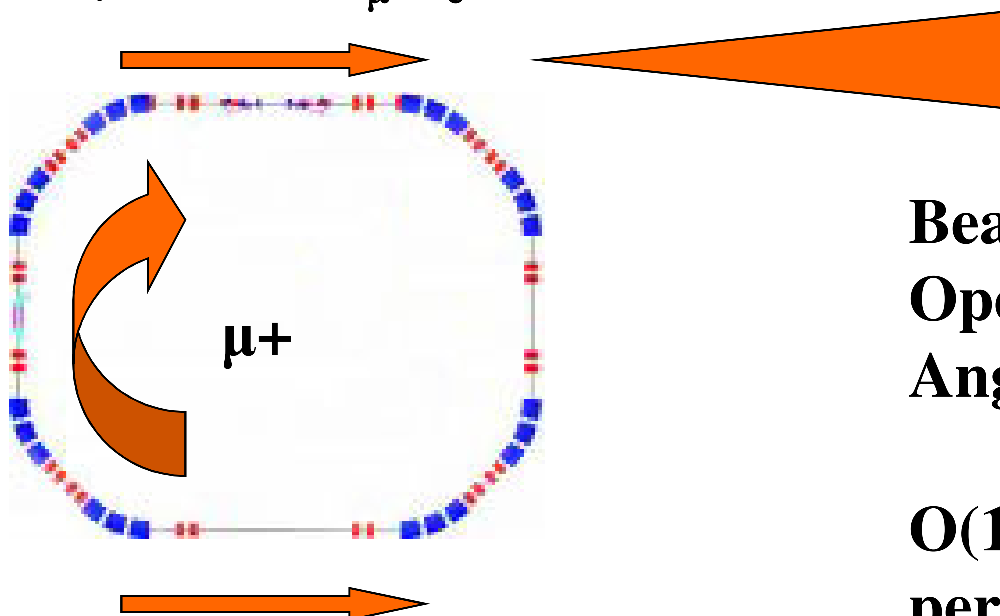
CERN

October 1-3, 2009

Harold G. Kirk
Brookhaven National Laboratory

The Neutrino Factory Concept

$\mu^+ \dashrightarrow e^+ \bar{\nu}_\mu \; \nu_e$



$\bar{\nu}_\mu , \nu_e$

$\mu^- \dashrightarrow e^- \nu_\mu \; \bar{\nu}_e$

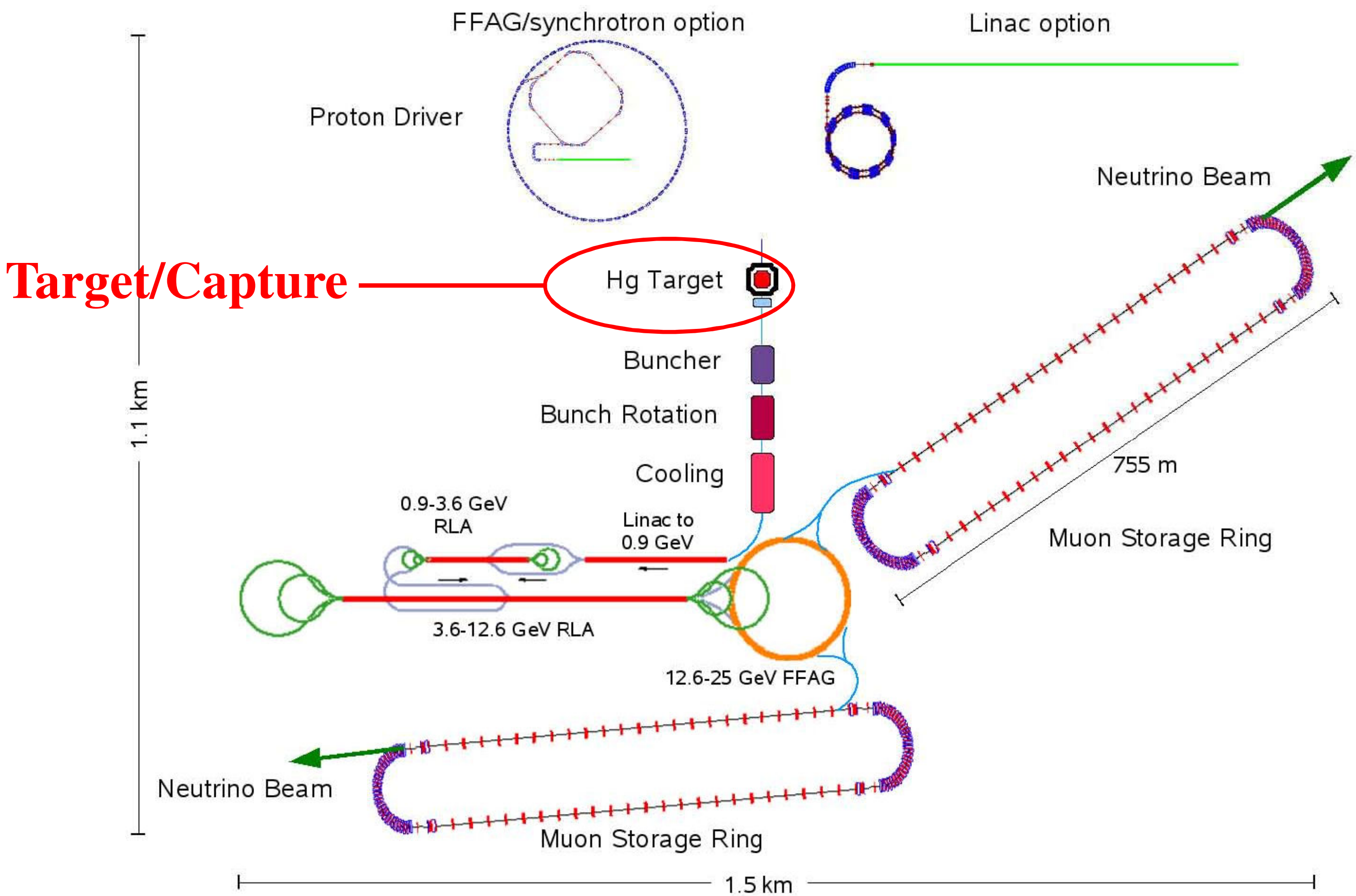
Beam Cone Opening Angle ~ $1/\gamma$

O(10^{21}) μ's per year

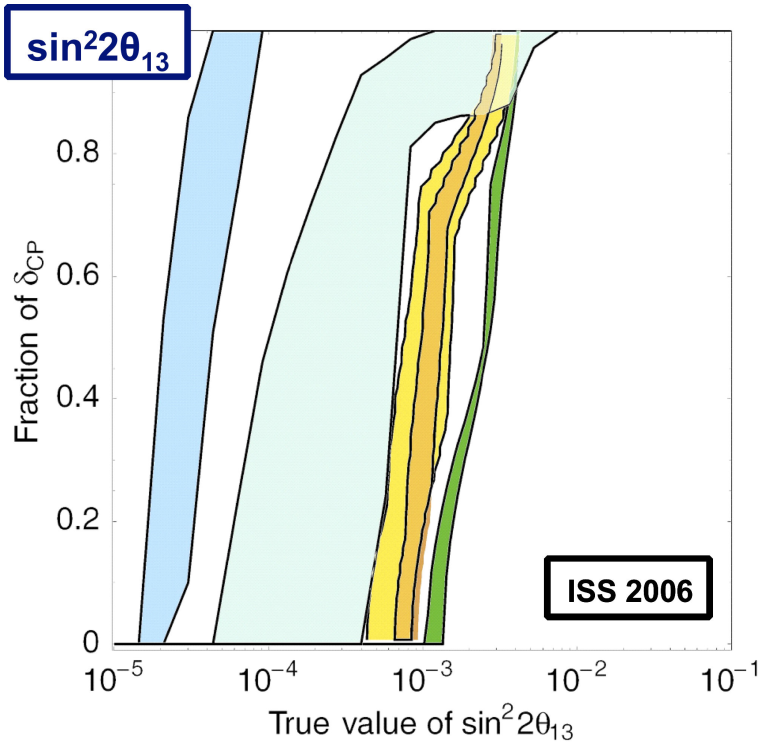
The Key Technical Challenges

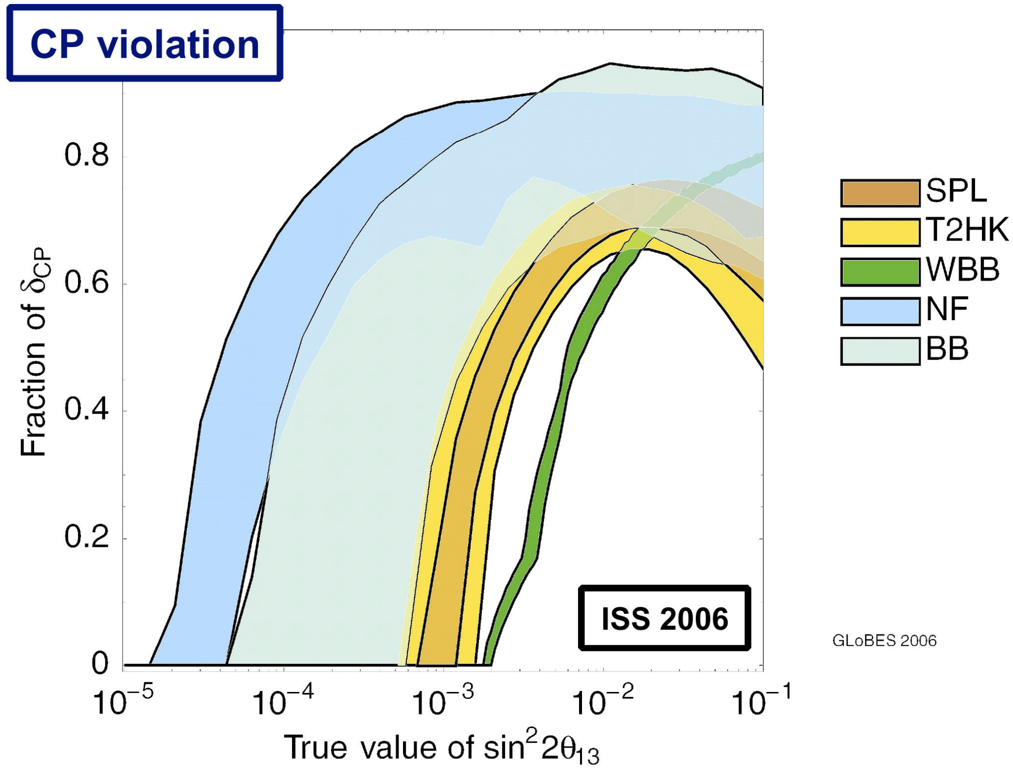
- Production of the muons
  - Require a MW-class proton driver
  - Pulsed beam on a high-Z target
  - Capture in a 20-T Solenoidal field
- Production of a muon beam
  - Reduction of dE
  - Phase Space Reduction (Cooling)
- Acceleration of the muon beam
  - Must be rapid (τ_μ = 2.2μs at rest)

The International Design Study Baseline



The Neutrino Factory Payoff

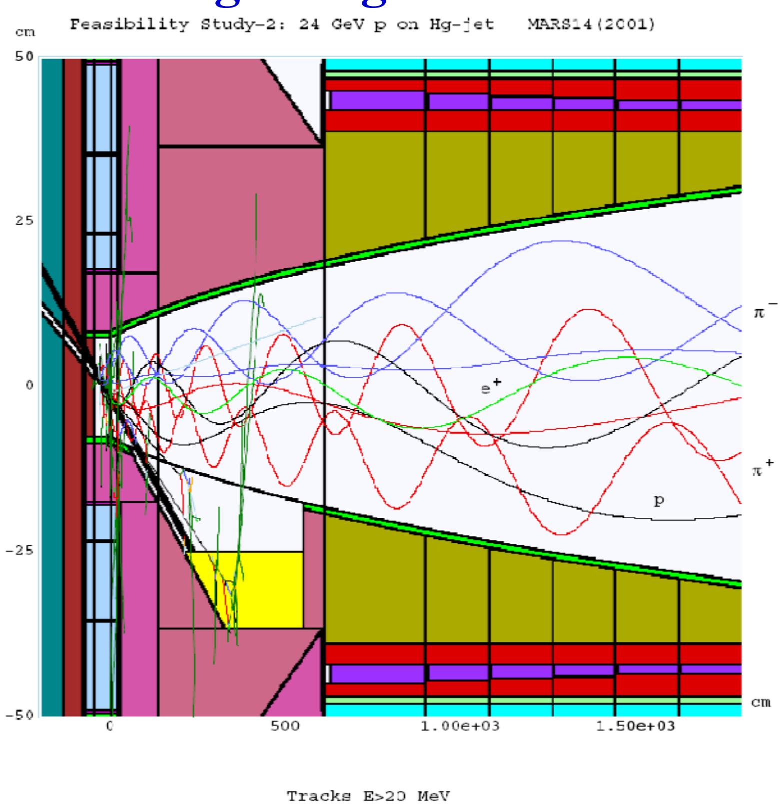


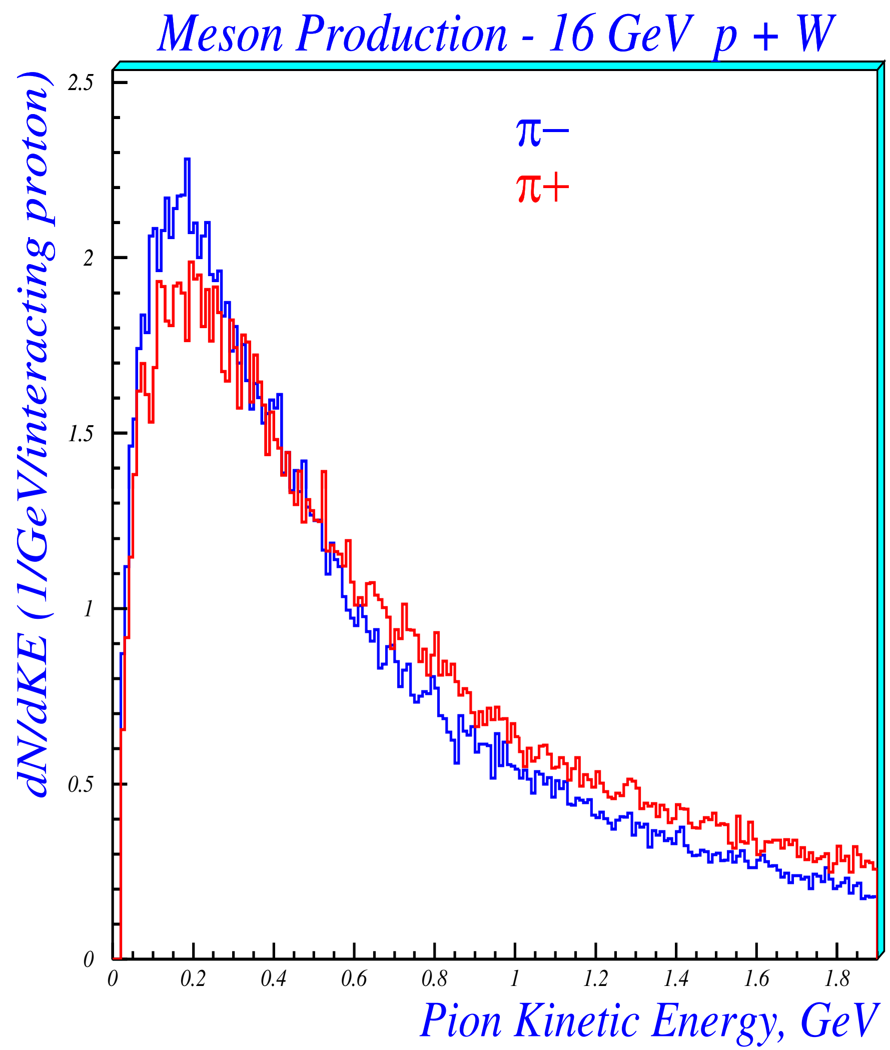


The Neutrino Factory Target Concept

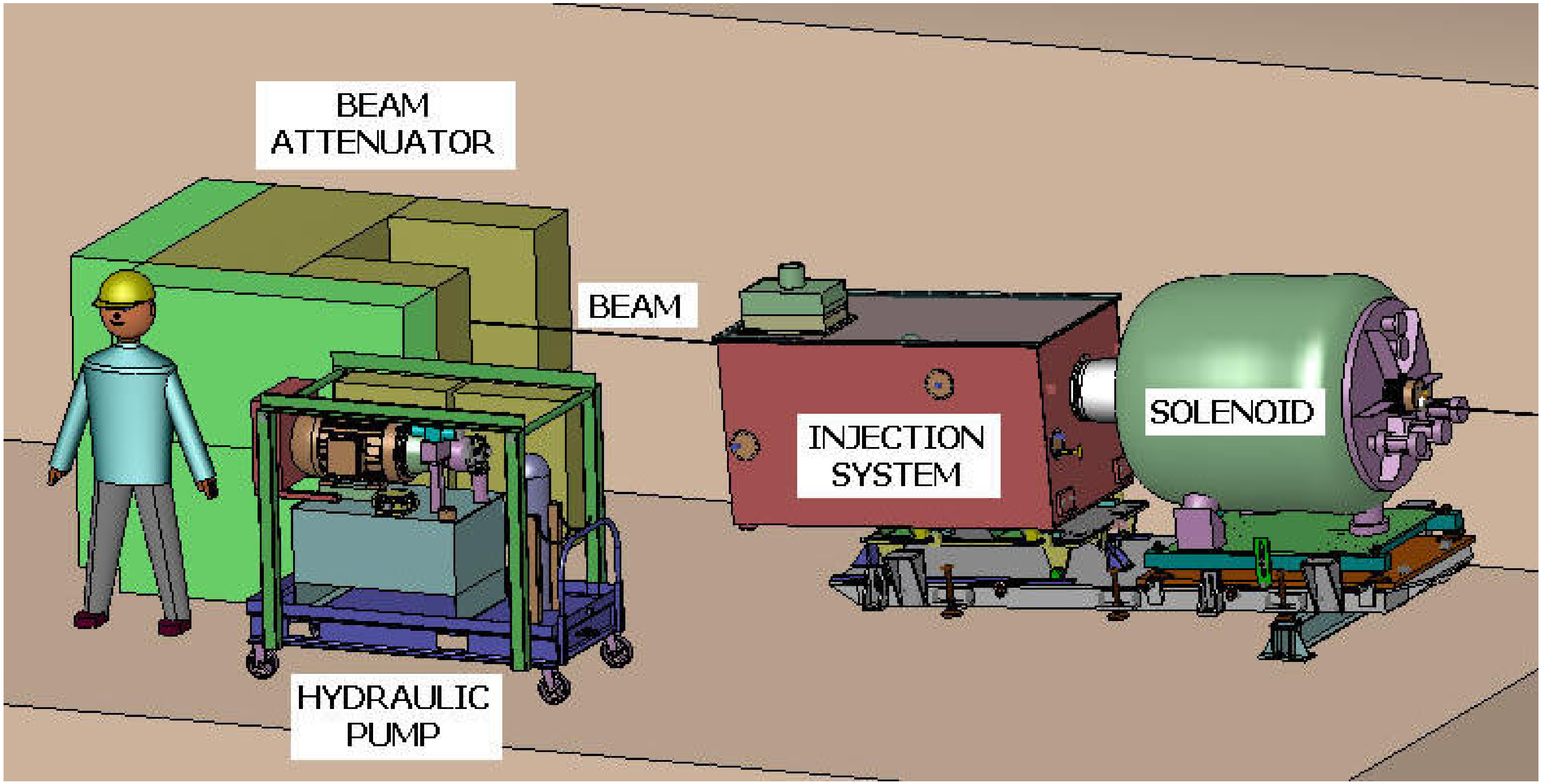
Maximize Pion/Muon Production

- Soft-pion Production
- High-Z materials
- High Magnetic Field





The MERIT Experiment at CERN



MERcury Intense Target

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Profile of the Experiment

- 14 and 24 GeV proton beam
- Up to 30 x 10^{12} protons (TP) per 2.5μs spill
- 1cm diameter Hg Jet
- Hg Jet/proton beam off solenoid axis
  - Hg Jet 33 mrad to solenoid axis
  - Proton beam 67 mrad to solenoid axis
- Test 50 Hz operations
  - 20 m/s Hg Jet

Installed in the CERN TT2a Line

← **Before Mating**

After Mating and Tilting →

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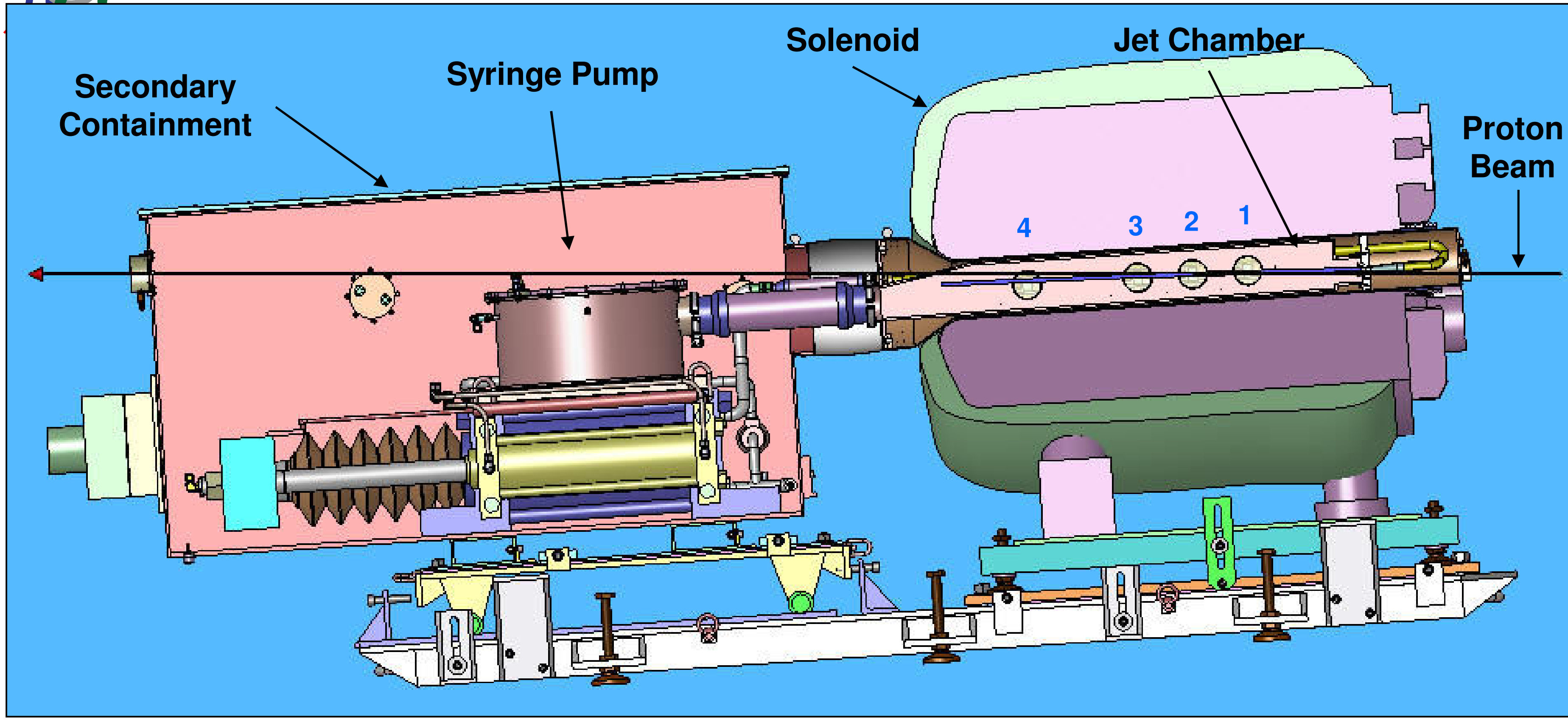
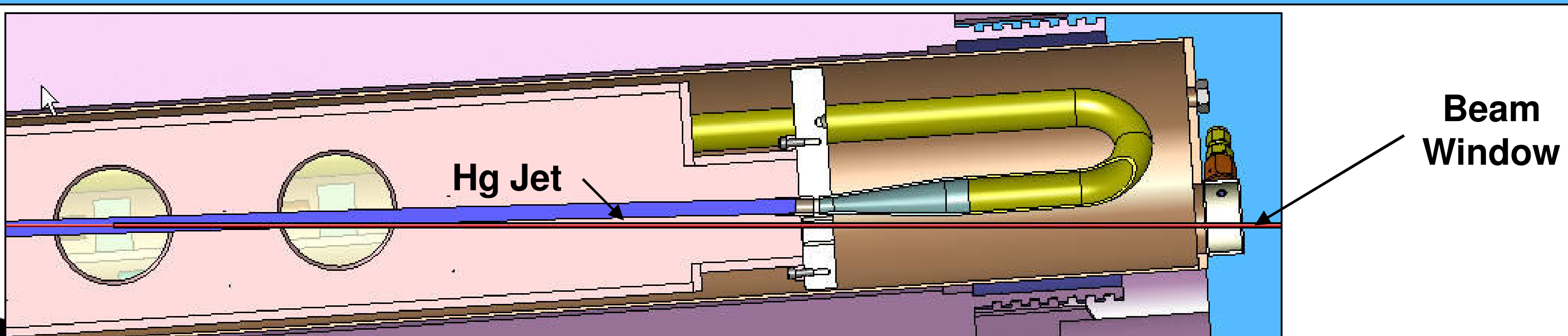
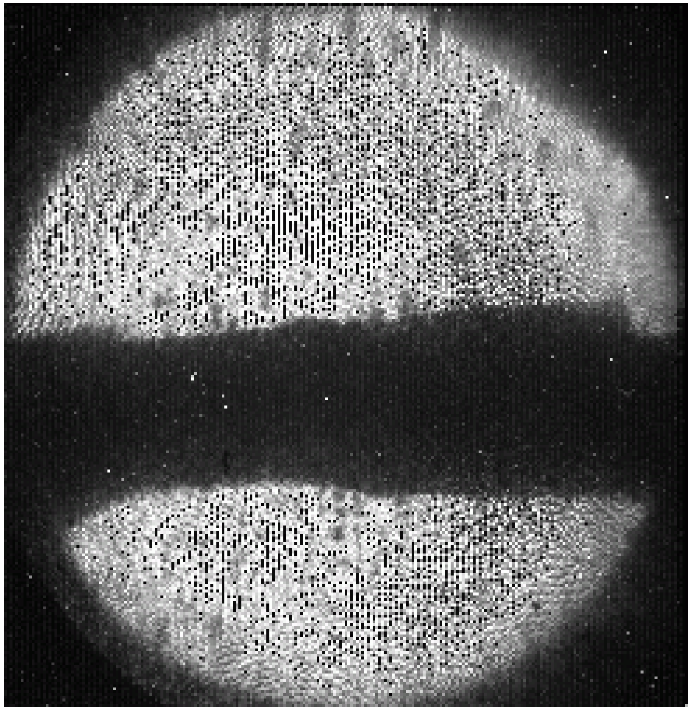
Sectional view of the MERIT Experiment

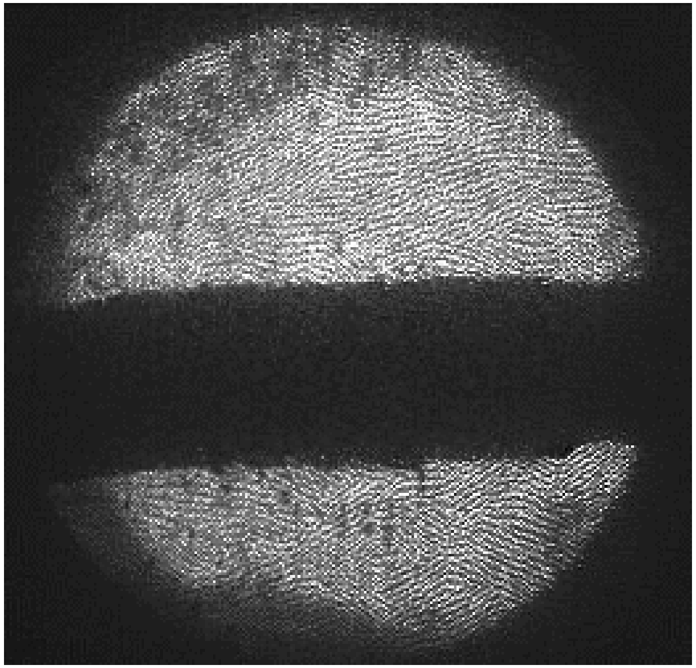




Optical Diagnostics



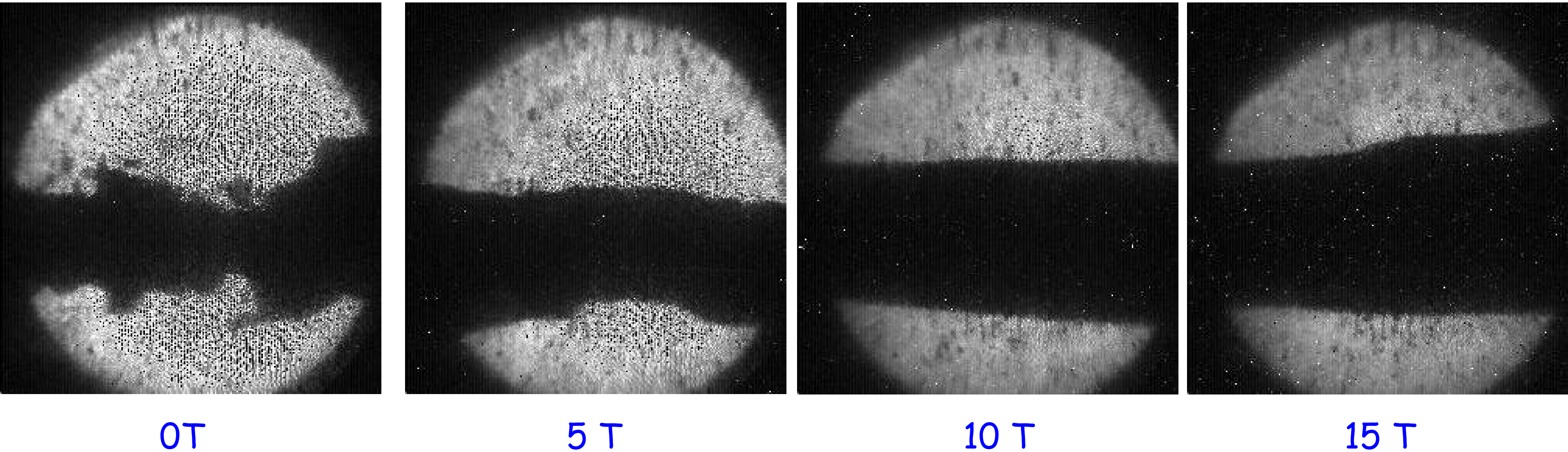
1 cm



Viewport 2
100μs/fras
Velocity Analysis

Viewport 3
500μs/fras
Disruption Analysis

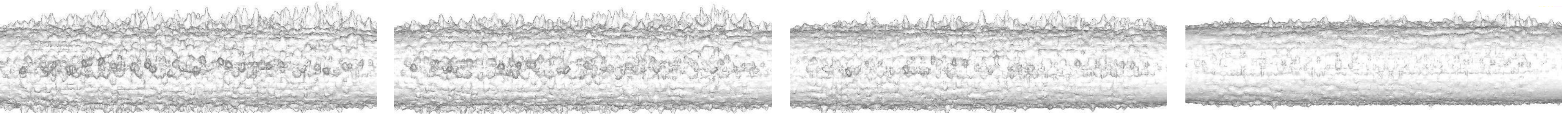
Stabilization of Jet by High Magnet Field



Jet velocities: 15 m/s

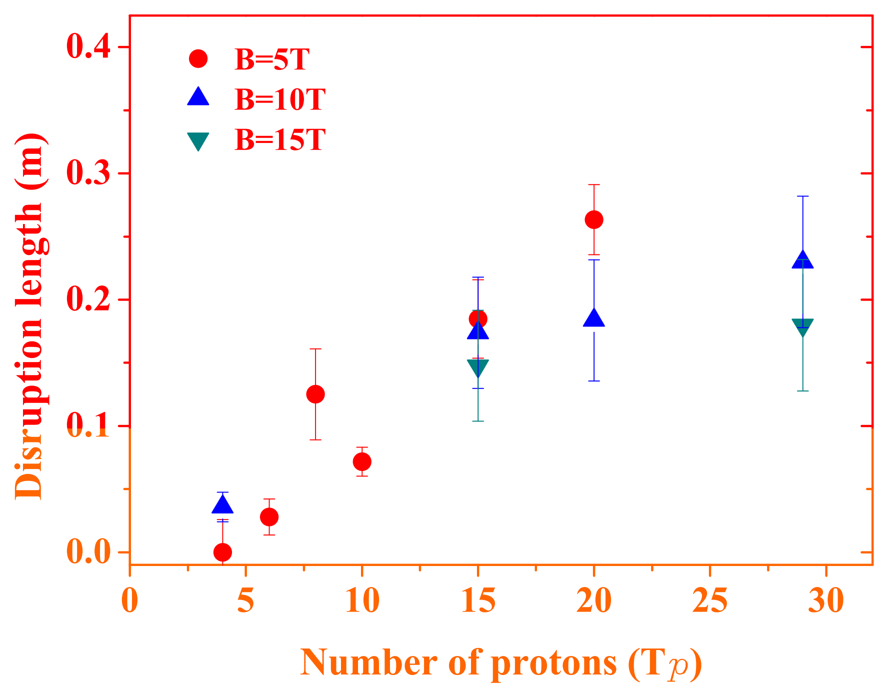
Substantial surface perturbations mitigated by high-magnetic field.

MHD simulations (W. Bo, SUNYSB):

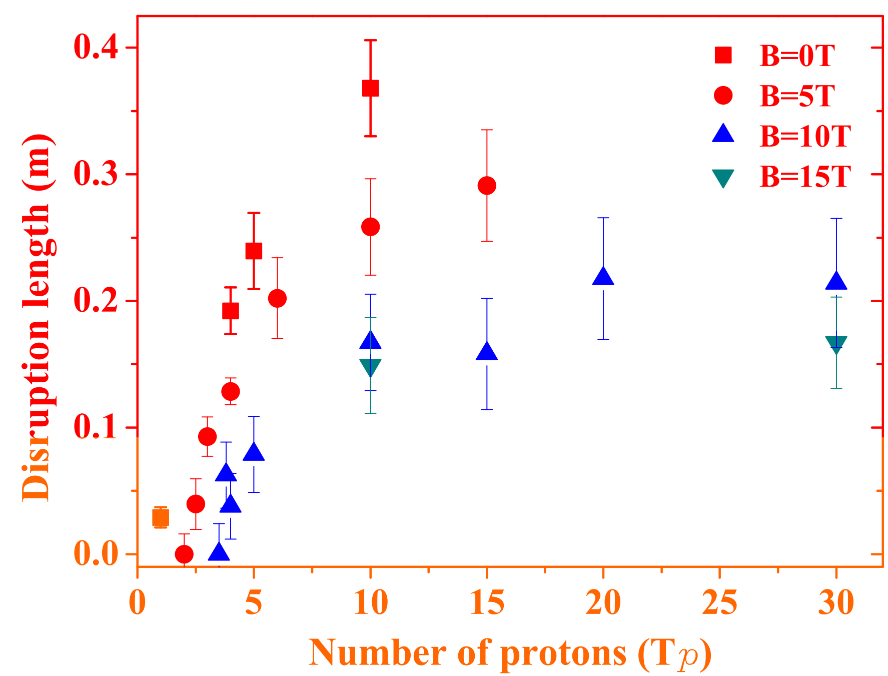


Disruption Analysis

14 GeV



24 GeV

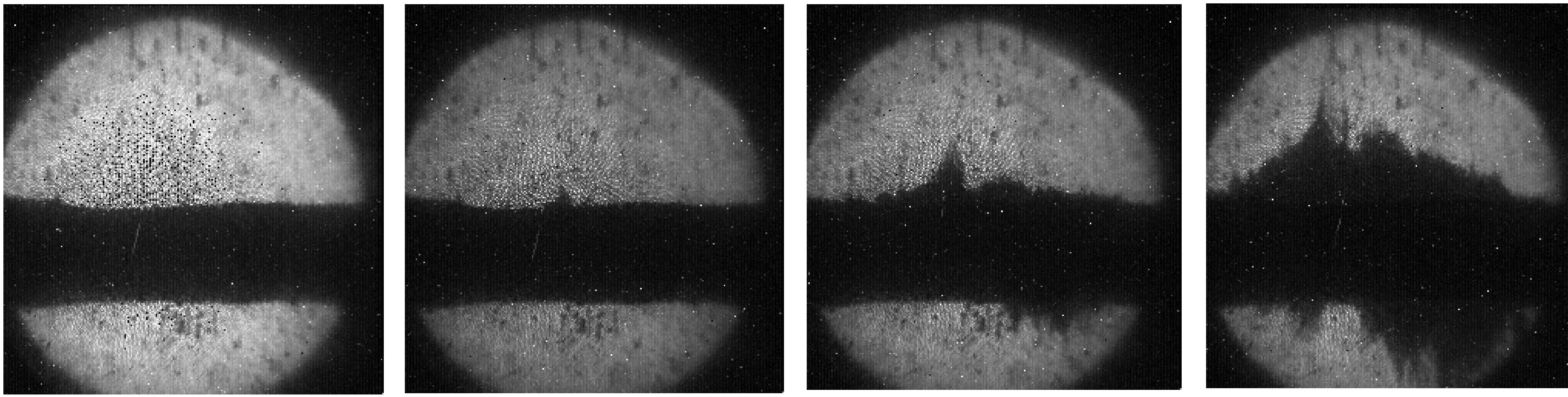


Disruption lengths reduced with higher magnetic fields

Disruption thresholds increased with higher magnetic fields

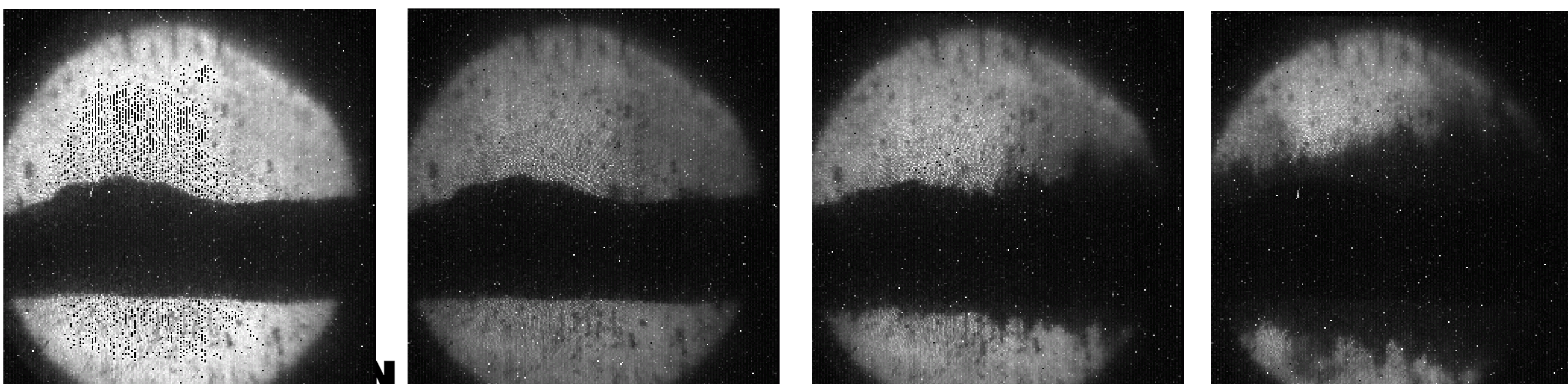
Velocity of Splash: Measurements at 24GeV

10TP, 10T V = 54 m/s



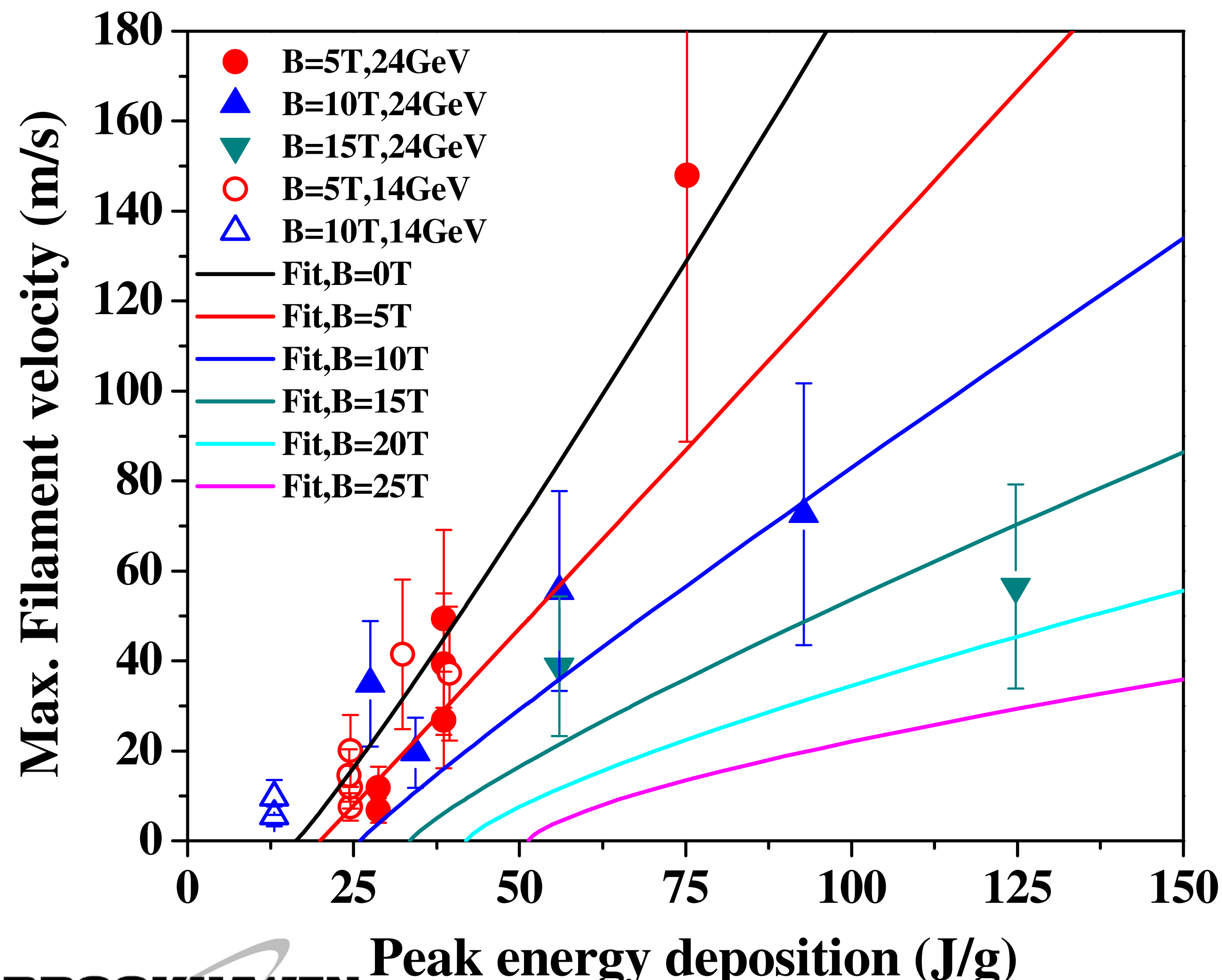
t=0 t=0.075 ms t=0.175 ms t=0.375 ms

20TP, 10T V = 65 m/s



t=0 t=0.050 ms t=0.175 ms t=0.375 ms

Filament Velocities



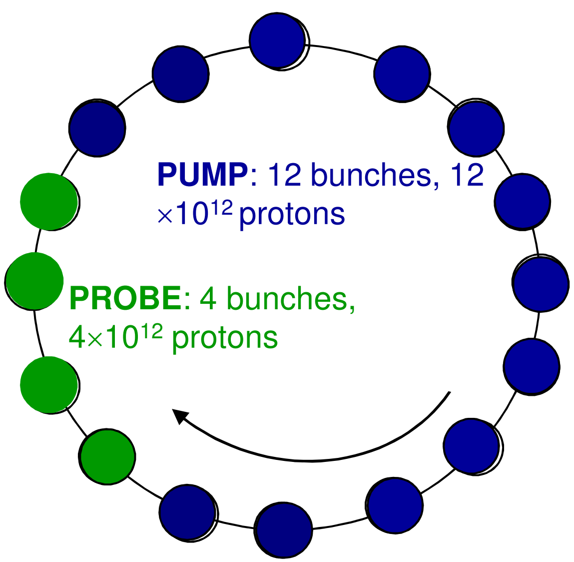
Ejection velocities are suppressed by magnetic field

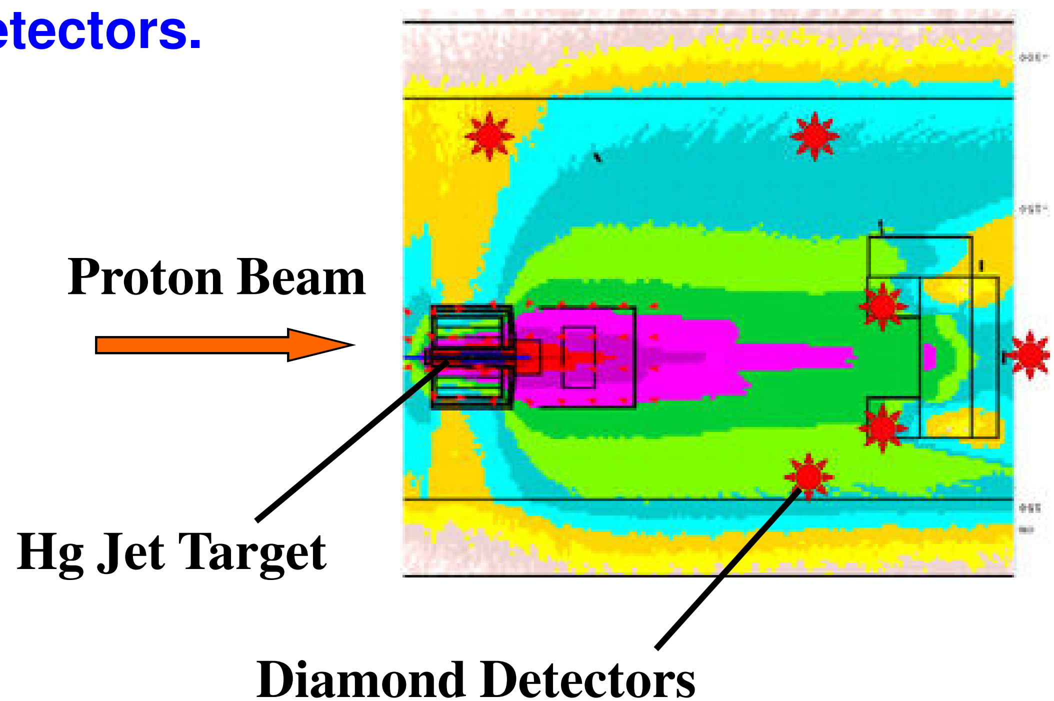
Pump-Probe Studies

Test pion production by trailing bunches after disruption of the mercury jet due to earlier bunches

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

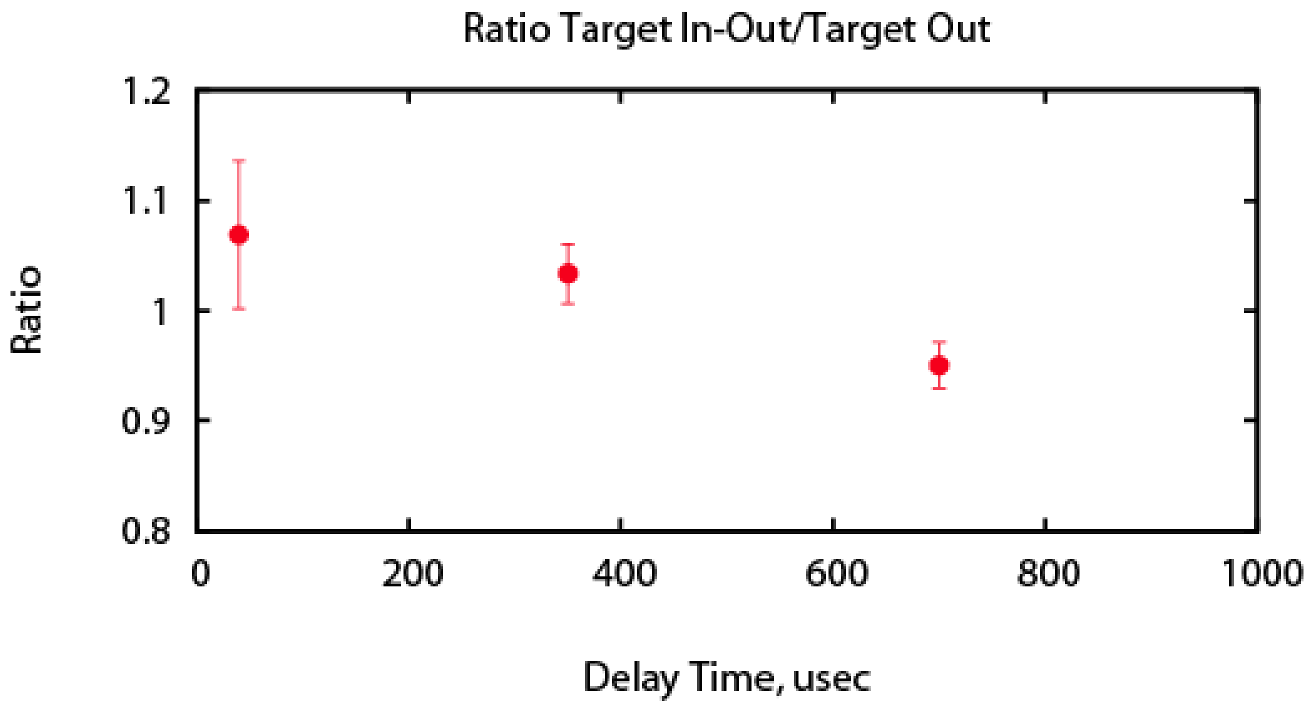
Pion production was monitored for both target-in and target-out events by a set of diamond diode detectors.





Pump-Probe Data Analysis

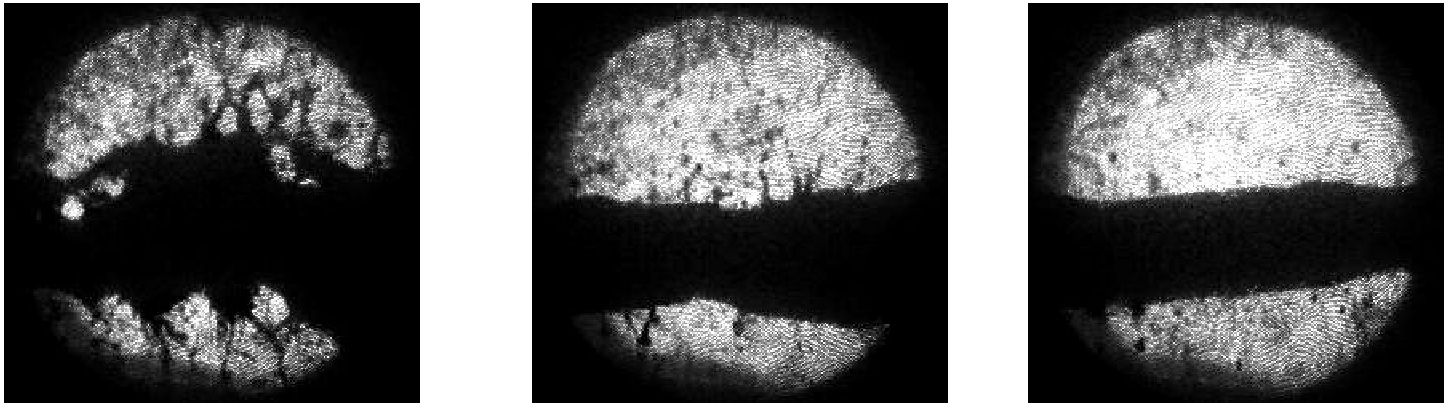
Production Efficiency: **Normalized Probe / Normalized Pump**



No loss of pion production for bunch delays of 40 and 350 μs,

A 5% loss (2.5-σ effect) of pion production for bunches delayed by 700 μs.

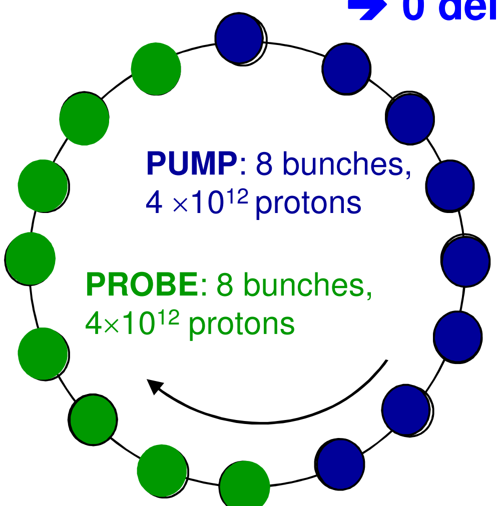
Study with 4 T*p* + 4 T*p* at 14 GeV, 10 T



Single-turn extraction
➔ 0 delay, 8 T*p*

4-T*p* probe extracted on subsequent turn
➔ 3.2 μs delay

4-T*p* probe extracted after 2nd full turn
➔ 5.8 μs Delay



Threshold of disruption is > 4 T*p* at 14 Gev, 10 T.

⇒**Target supports a 14-GeV, 4-T*p* beam at 172 kHz rep rate without disruption.**

Key MERIT Results

- Jet surface instabilities reduced by high-magnetic fields
- Hg jet disruption mitigated by magnetic field
  - 20 m/s operations allows for up to 70Hz operations
- 115kJ pulse containment demonstrated

  → 8 MW capability demonstrated
- Hg ejection velocities reduced by magnetic field
- Pion production remains viable upto 350μs after previous beam impact
- 170kHz operations possible for sub-disruption threshold beam intensities

The MERIT Bottom Line

The Neutrino Factory/Muon Collider target concept has been validated for 4MW, 50Hz operations.

BUT

We must now develop a target system which will support 4MW operations

MERIT and the IDS Baseline

		NERIT
Mean beam power	4 MW	OK
Pulse repetition rate	50 Hz	OK
Proton kinetic energy	5-10-15 GeV	
Bunch duration at target	1-3 ns rms	
Number of bunches per pulse	1-3	
Separated bunch extraction delay	$\geq$ 17 μs	$\geq$ 6 μs
Pulse duration:	$\leq$ 40 μs	$\leq$ 350 μs

The IDS Proton Driver Baseline Parameters

IDS-NF Target Studies

Follow-up: Engineering study of a CW mercury loop + 20-T capture magnet

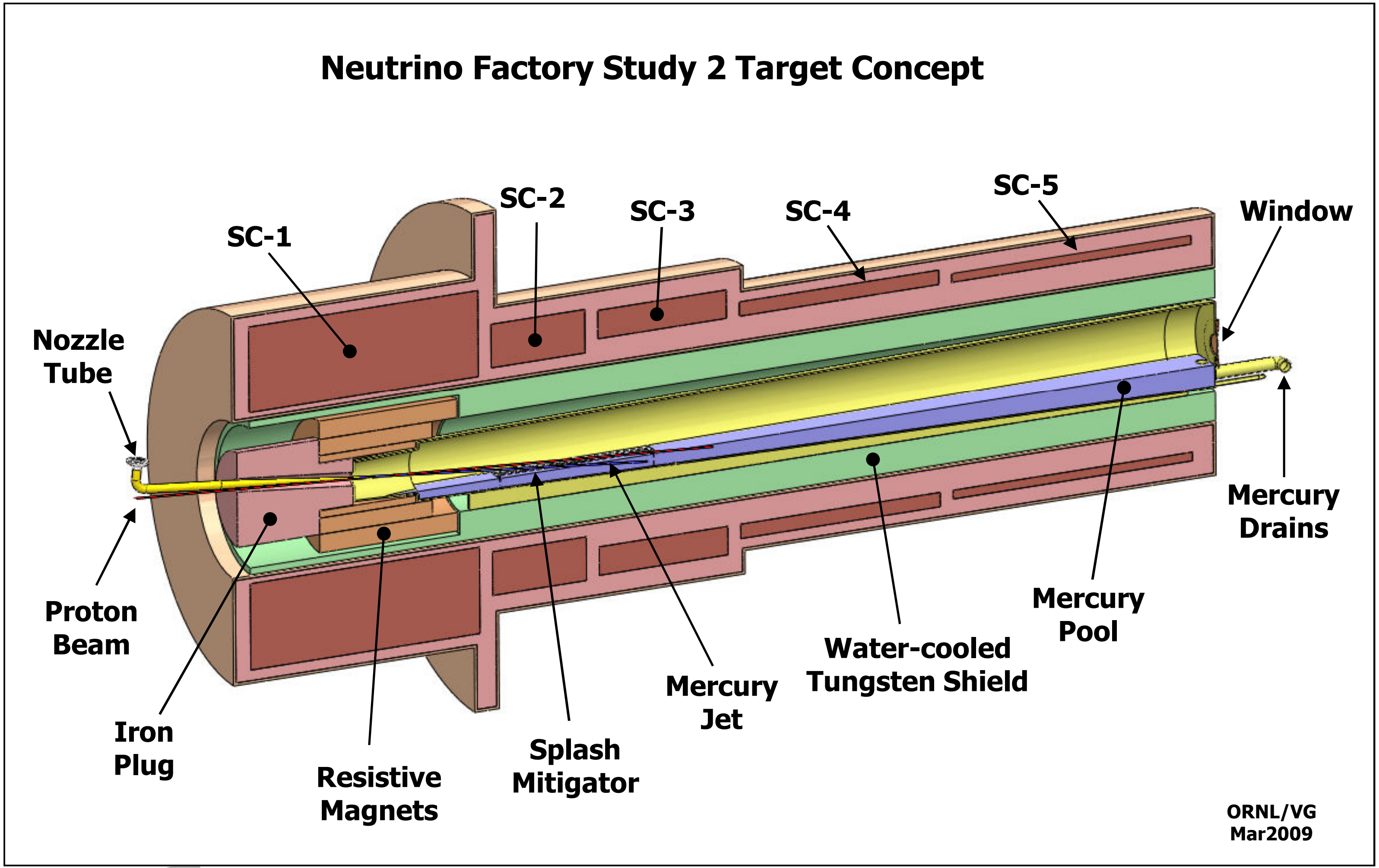
- Splash mitigation in the mercury beam dump.
- Possible drain of mercury out upstream end of magnets.
- Downstream beam window.
- Water-cooled tungsten-carbide shield of superconducting magnets.
- HTS fabrication of the superconducting magnets.
- Improved nozzle for delivery of Hg jet

Possible Future Role for CERN

A natural CERN contribution would be participation in the design and testing of a prototypical neutrino factory target system with an intense proton beam.

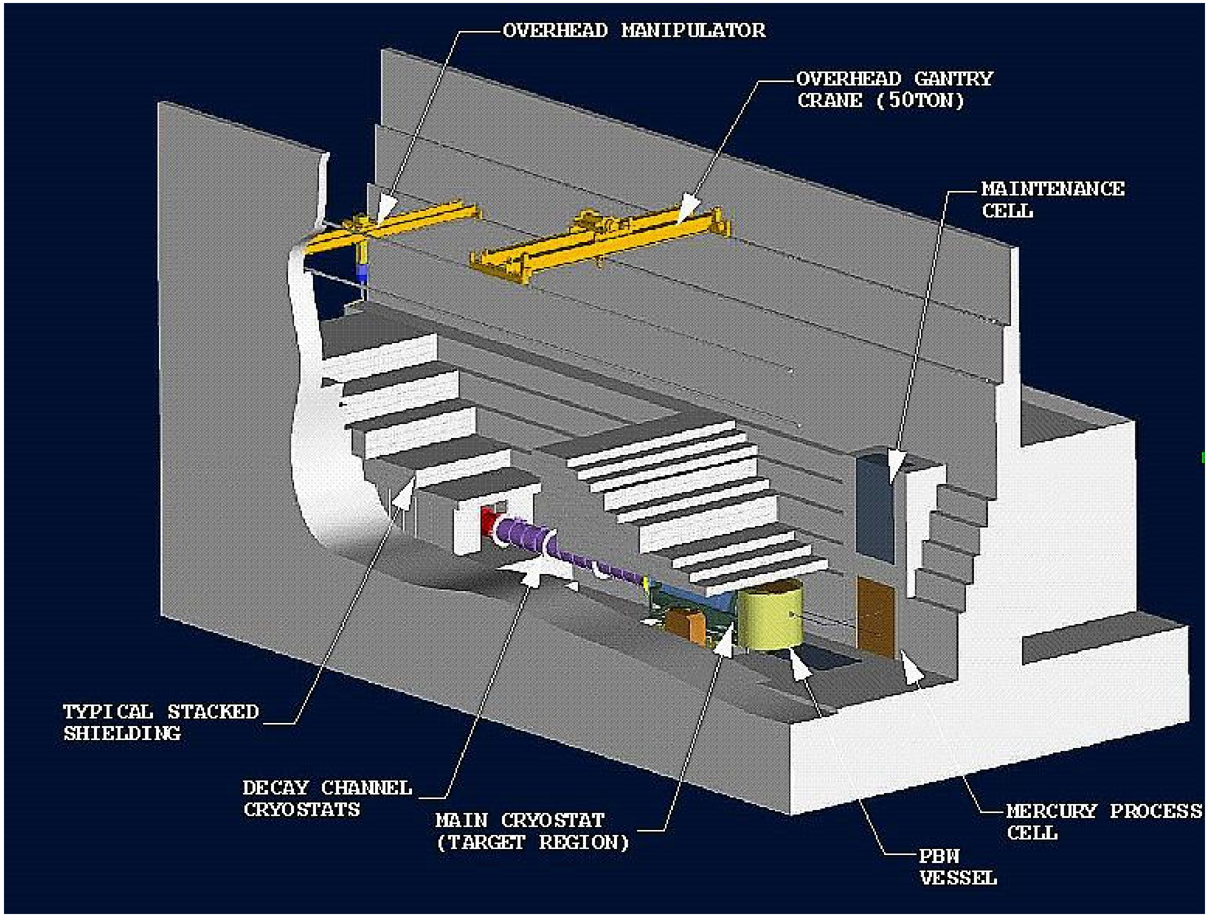
This would take explicit advantage of CERN's expertise, capabilities and facilities

The Target System



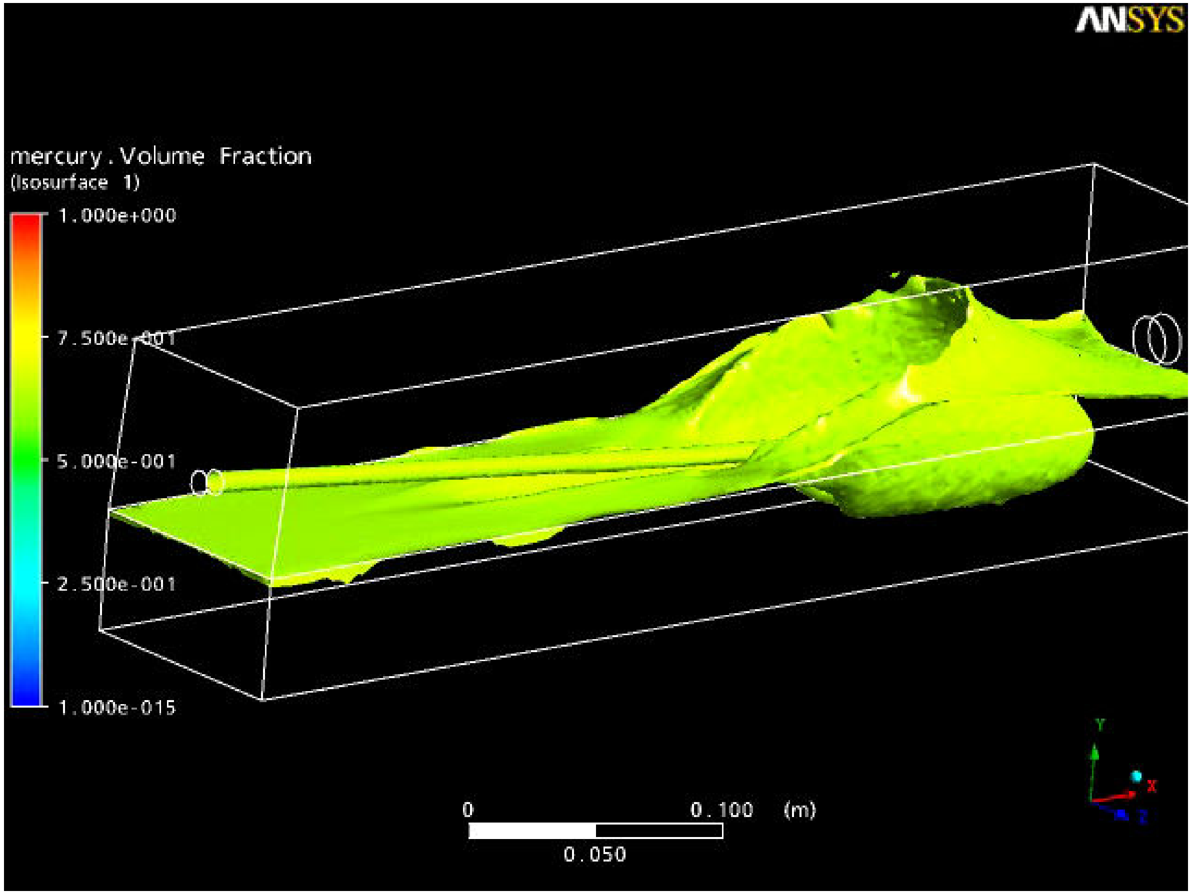
Van Graves, ORNL

A 4MW Target Hall



Phil Spampanato, ORNL

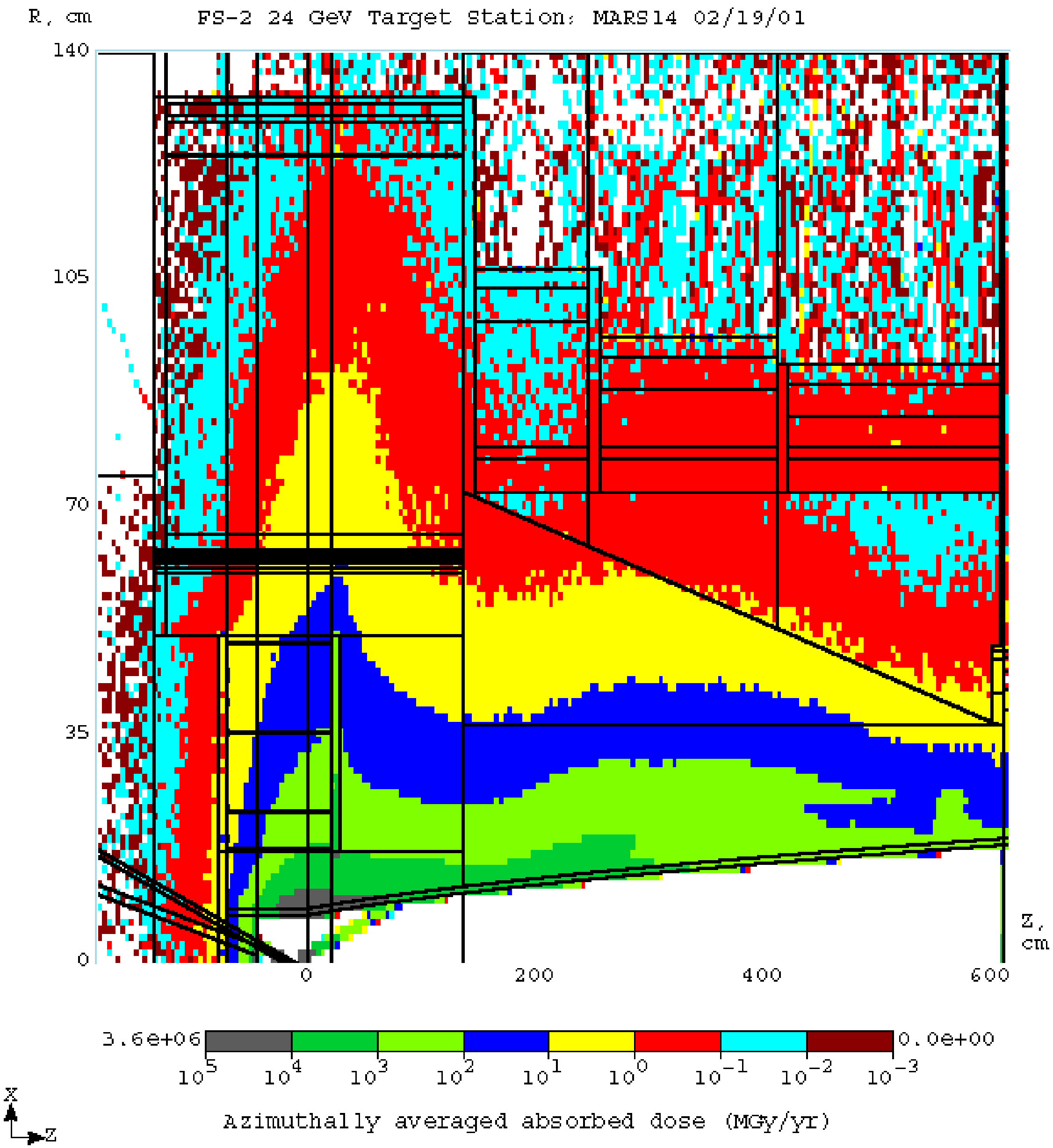
The Jet/Beam Dump Interaction



T. Davonne, RAL

Shielding the Superconducting Coils

MARS
Dose
Rate
calculations



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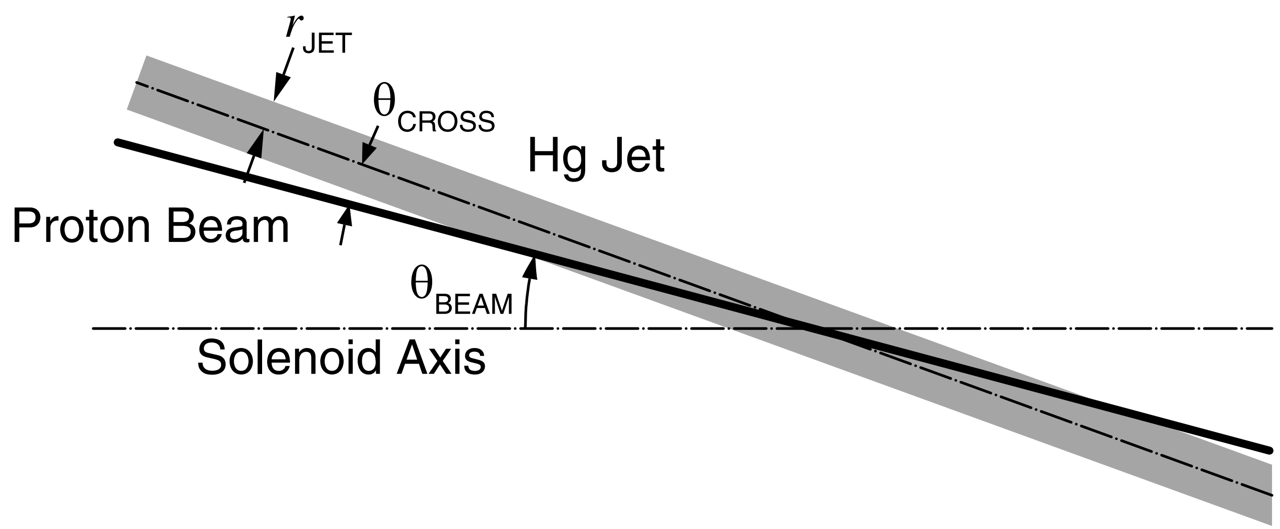
MARS15 Study of the Hg Jet Target Geometry

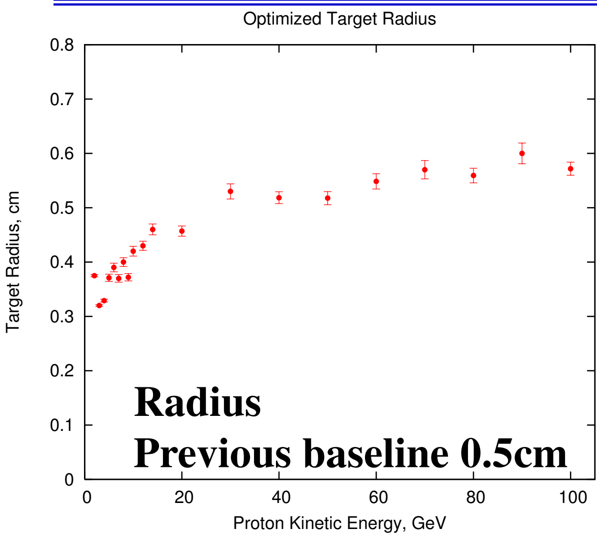


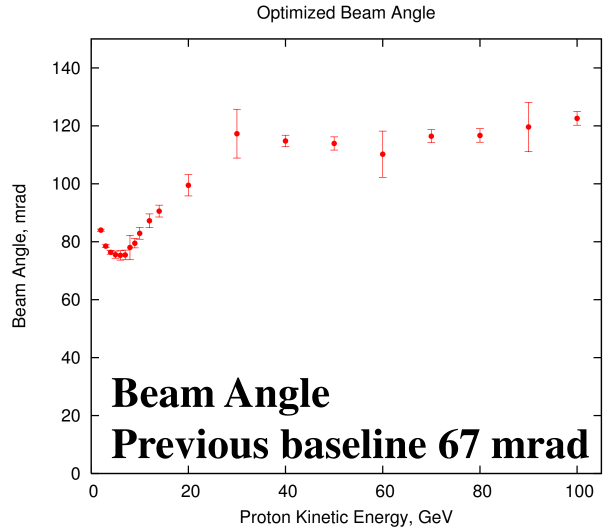
Previous results: Radius 5mm, θ_{beam} =67mrad

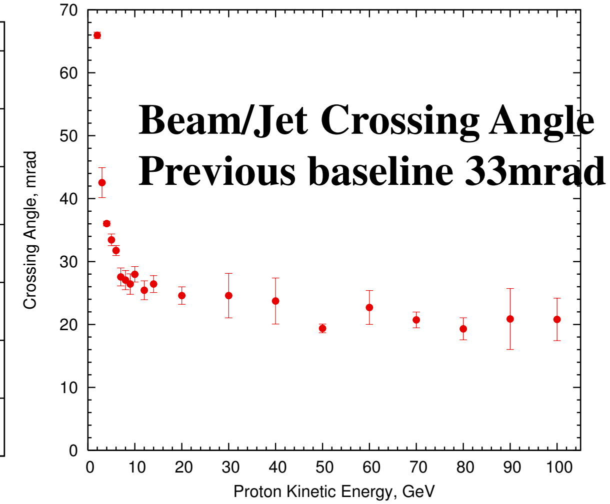
$\Theta_{crossing}$ = 33mrad

Optimized Meson Production

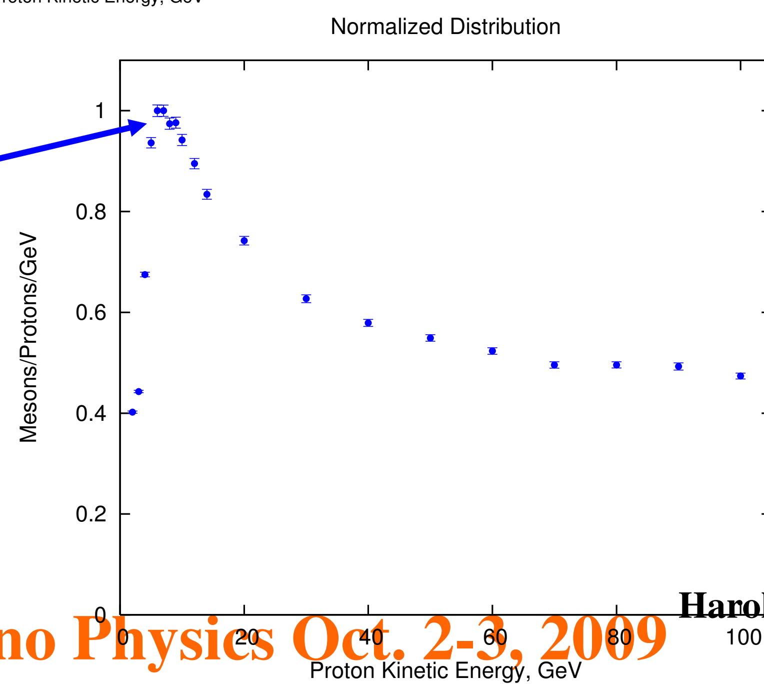
X. Ding, UCLA







Production of soft pions is most efficient for a Hg target at $E_p \sim$ 6-8 GeV,



Comparison of low-energy result with HARP data ongoing

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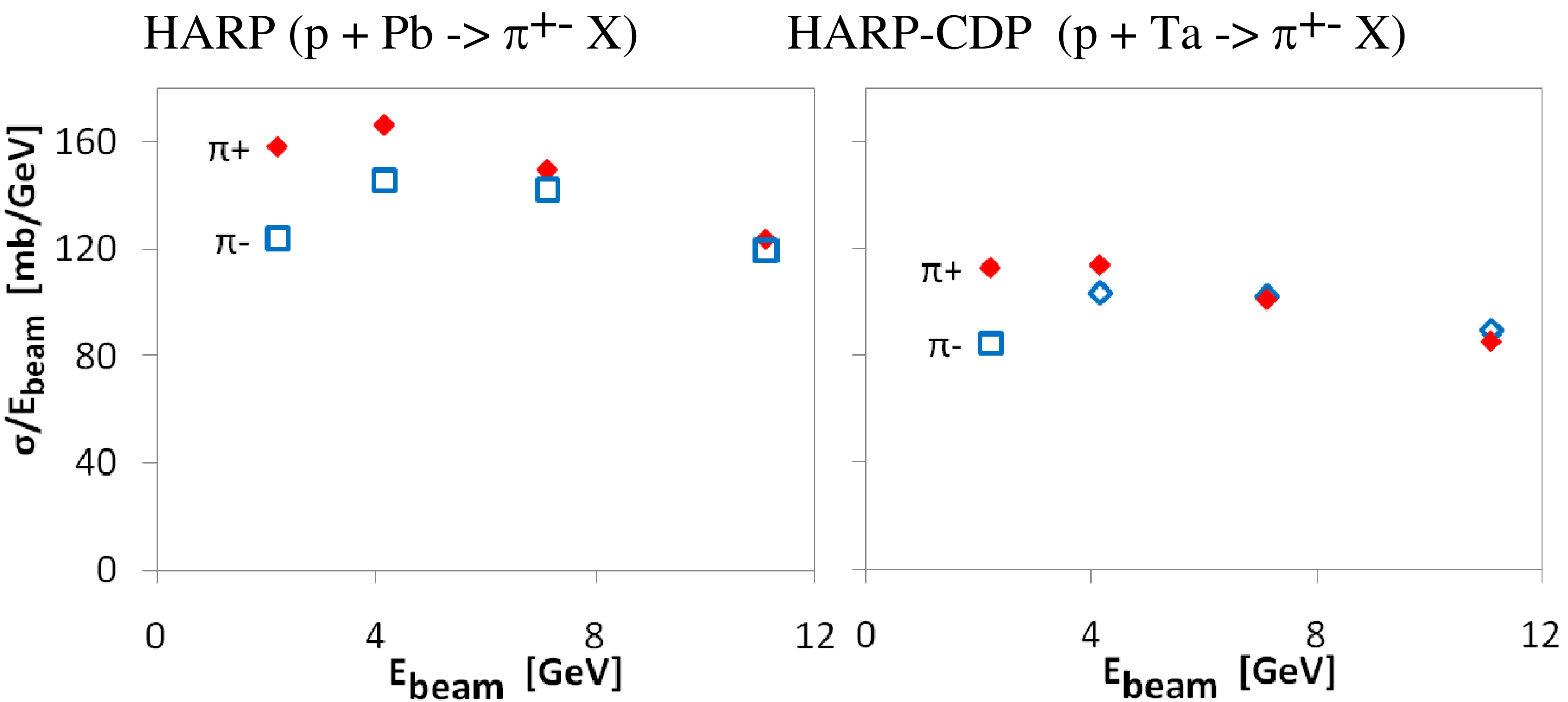
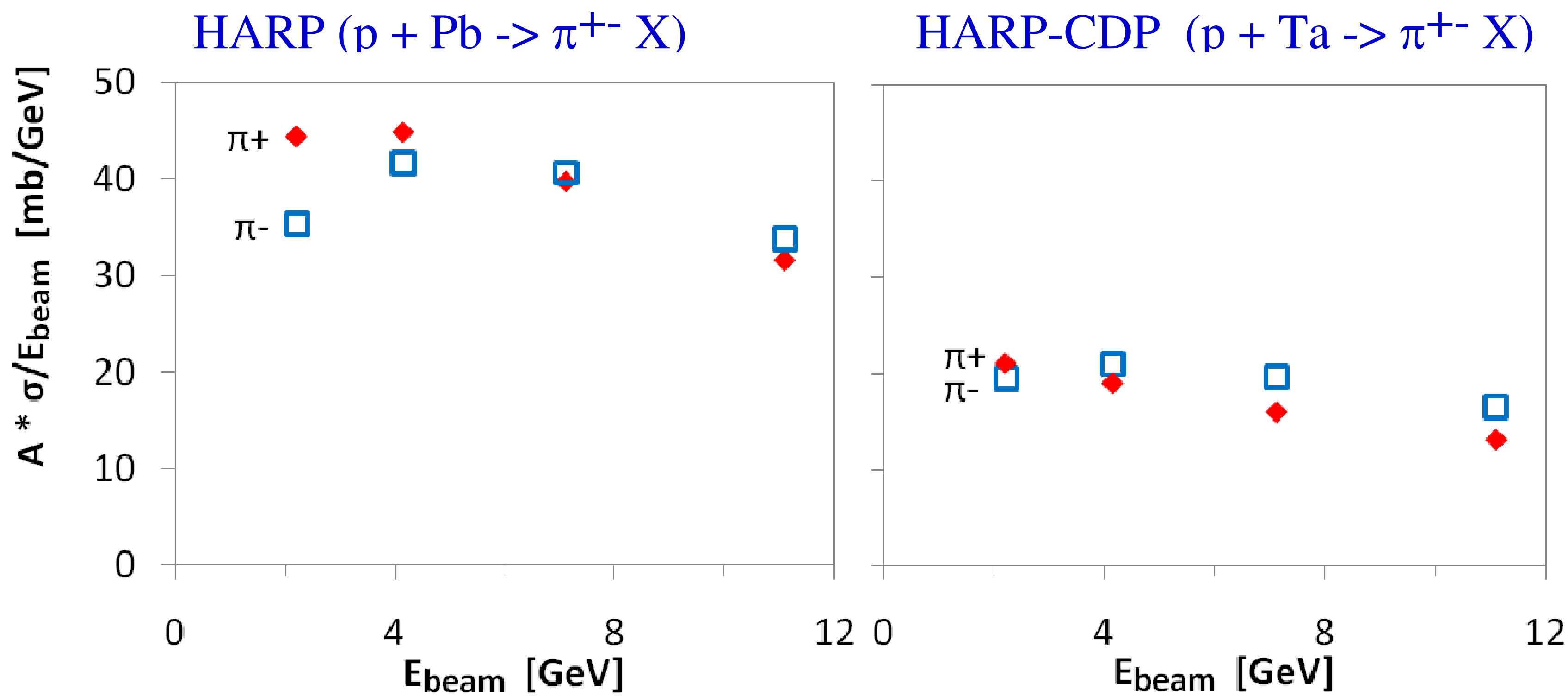
Jim Strait – NUFACT09

$\sigma(\pi^{+-})$ / E_{beam}, integrated over the measured phase space
(*different for the two groups*).



σ peaks in range 4~7 GeV => no dramatic low E drop-off

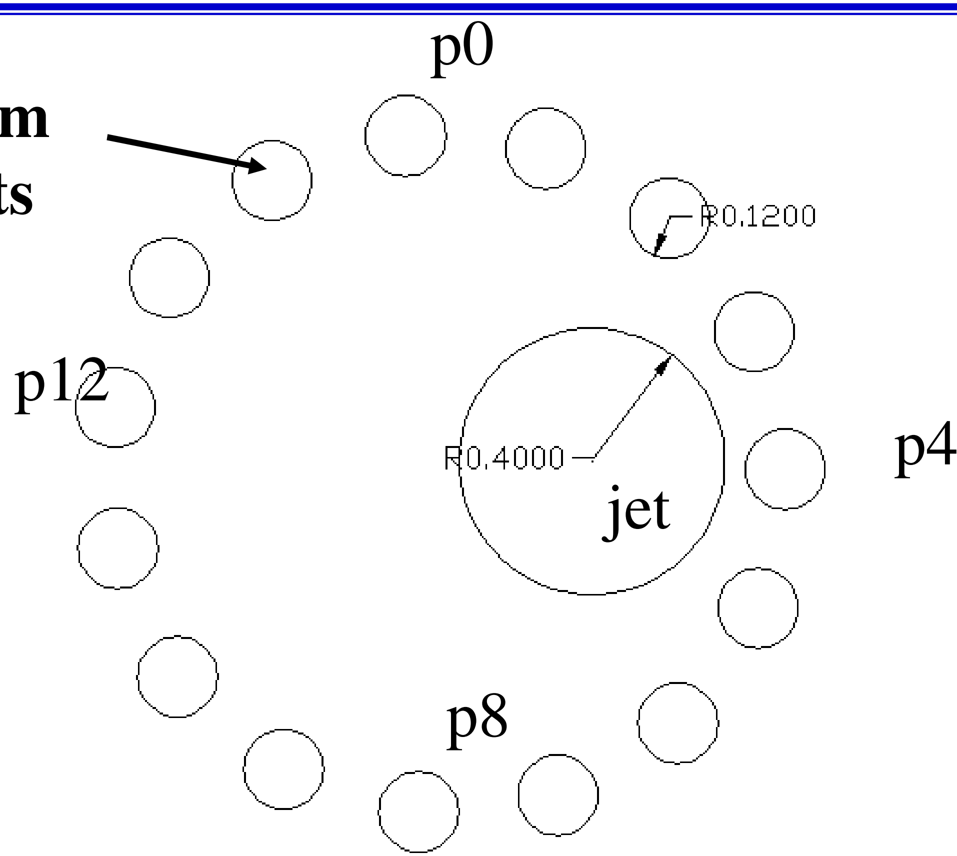
HARP Cross-Sections x NF Capture Acceptance



HARP pion production cross-sections, weighted by the acceptance of the front-end channel, and normalized to equal incident beam power, are relatively independent of beam energy.

Multiple Proton Beam Entry Points

Proton Beam Entry points



Entry points are asymmetric due to the beam tilt in a strong magnetic field

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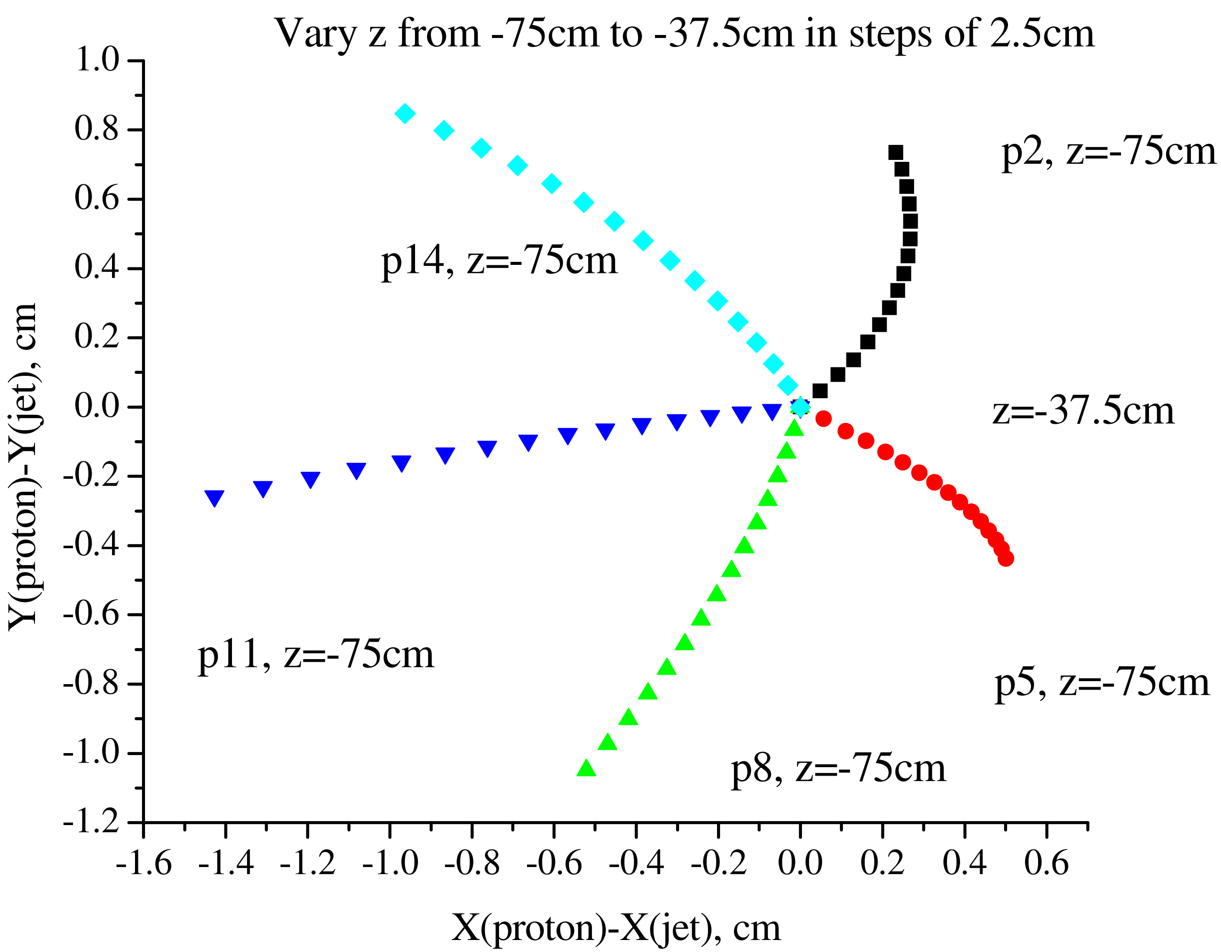
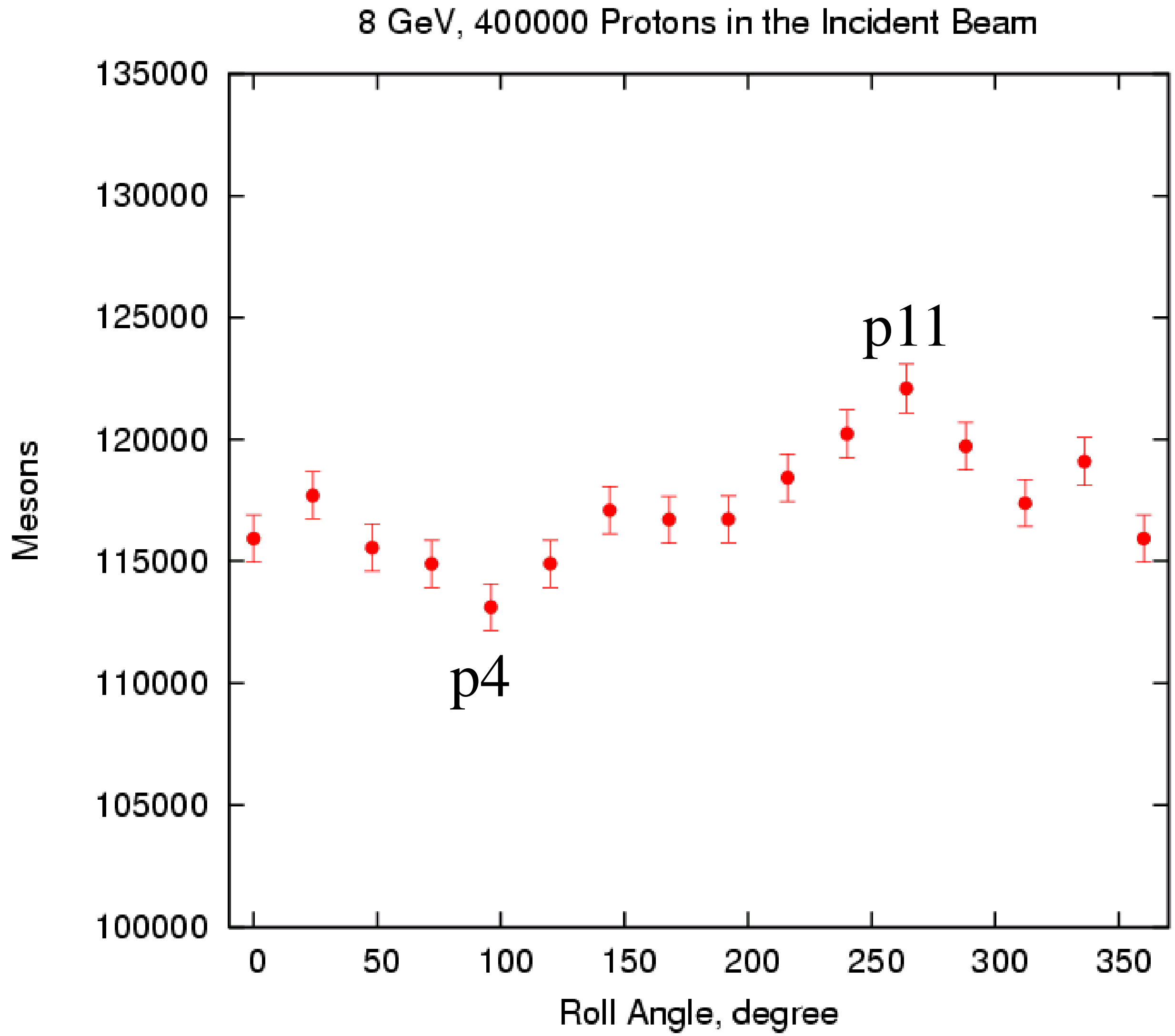
Proton beam entry points upstream of jet/beam crossing

Trajectory of the Proton Beam



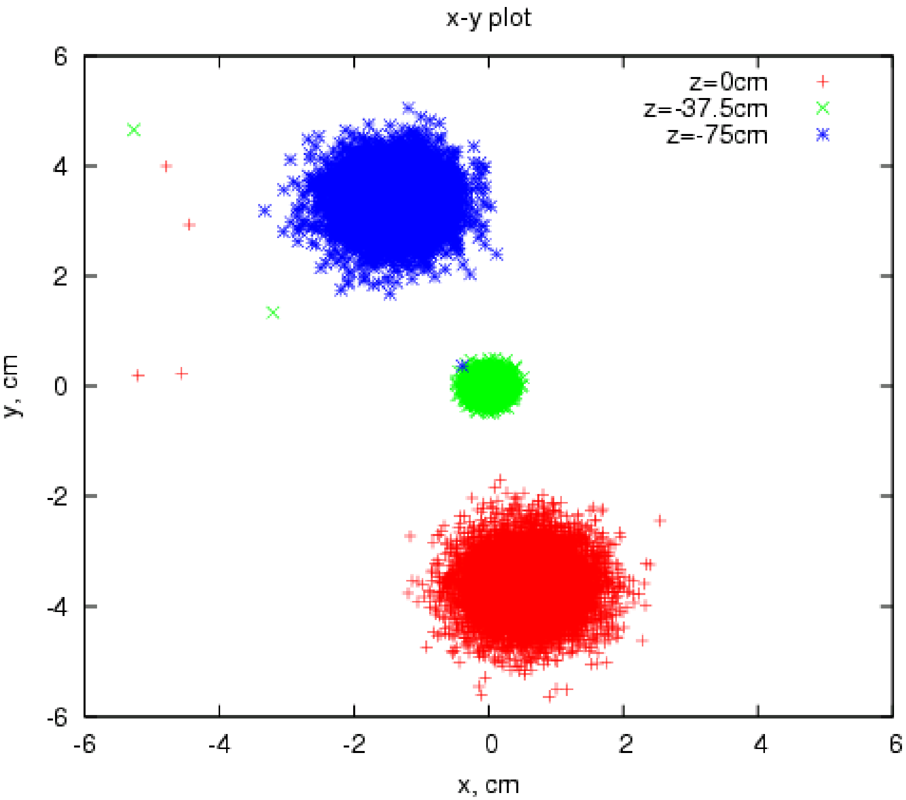
Selected Proton Beam transverse trajectories relative to the Hg Jet.

Multiple Proton Beam Entries

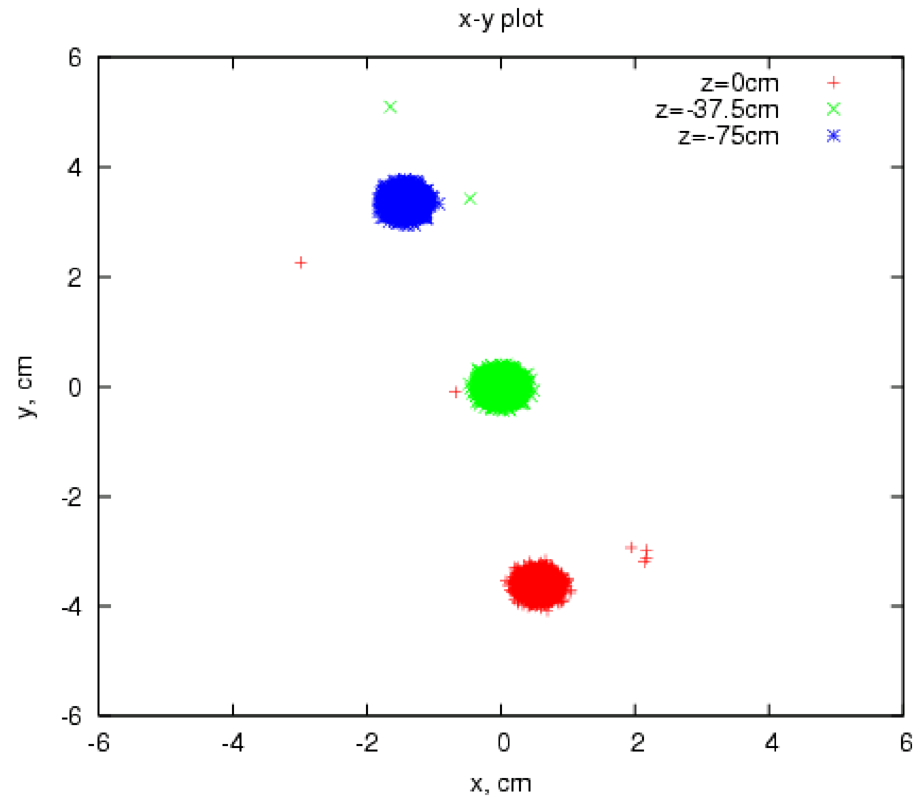


A 10% swing in meson production efficiency

Influence of β* of the Proton Beam

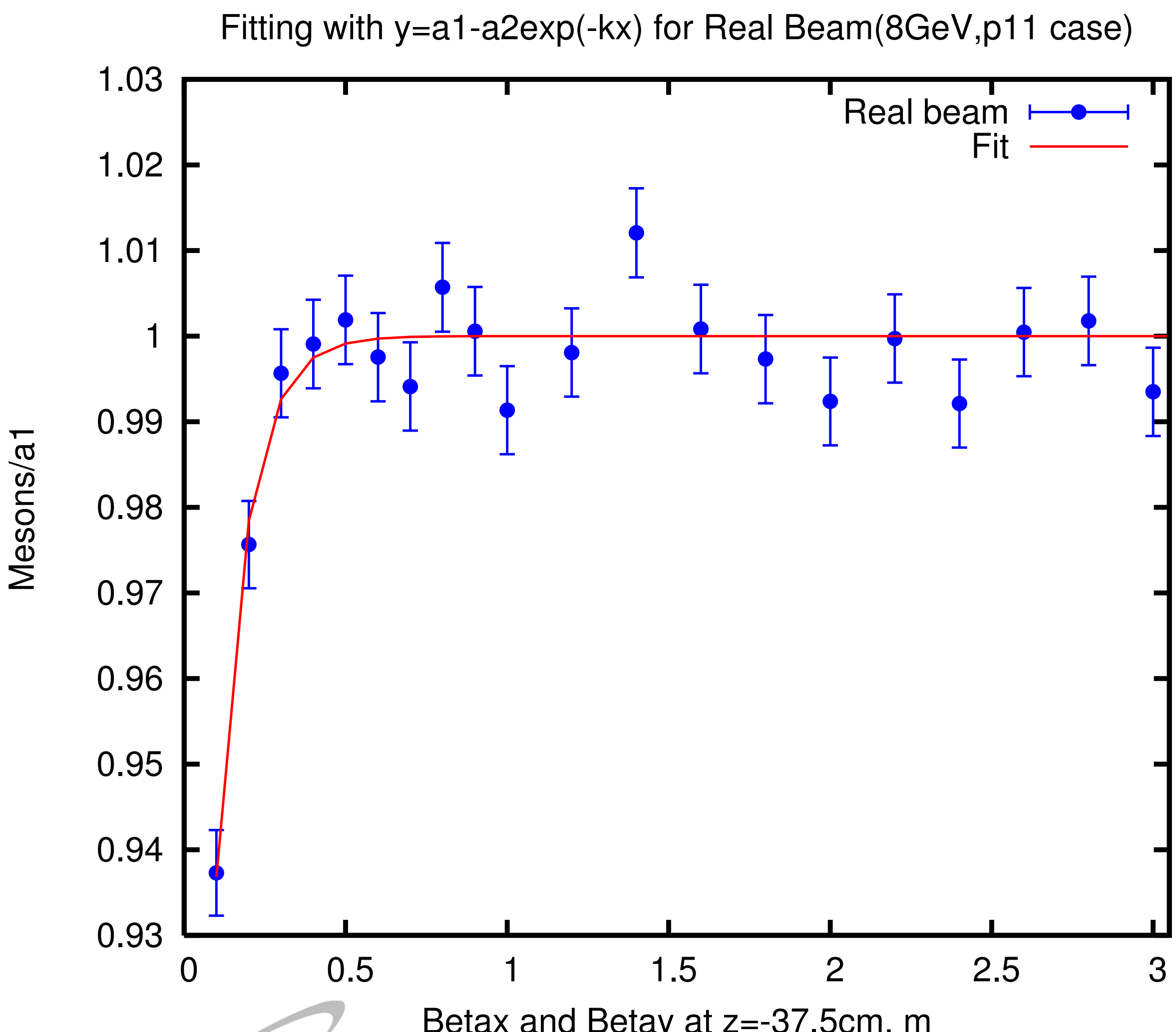


$\beta^* = 10$cm



$\beta^* = 300$cm

Meson Production vs β^*



Meson Production loss $\leq$ 1% for $\beta^* \geq$ 30cm

Summary

- MERIT has successfully demonstrated the Neutrino Factory/Muon Collider target concept
- Target studies are continuing within IDS-NF framework
- The infrastructure for a 4MW target system needs to be designed/engineered (this has generic value beyond a Neutrino Factory specific target station)
- CERN participation in MERIT was crucial to its success. CERN participation in the development of a 4MW target system would be both welcome and beneficial to the entire accelerator physics community