High-Power Targets

H.G. Kirk

Applications of High-Intensity Proton Accelerators

FNAL

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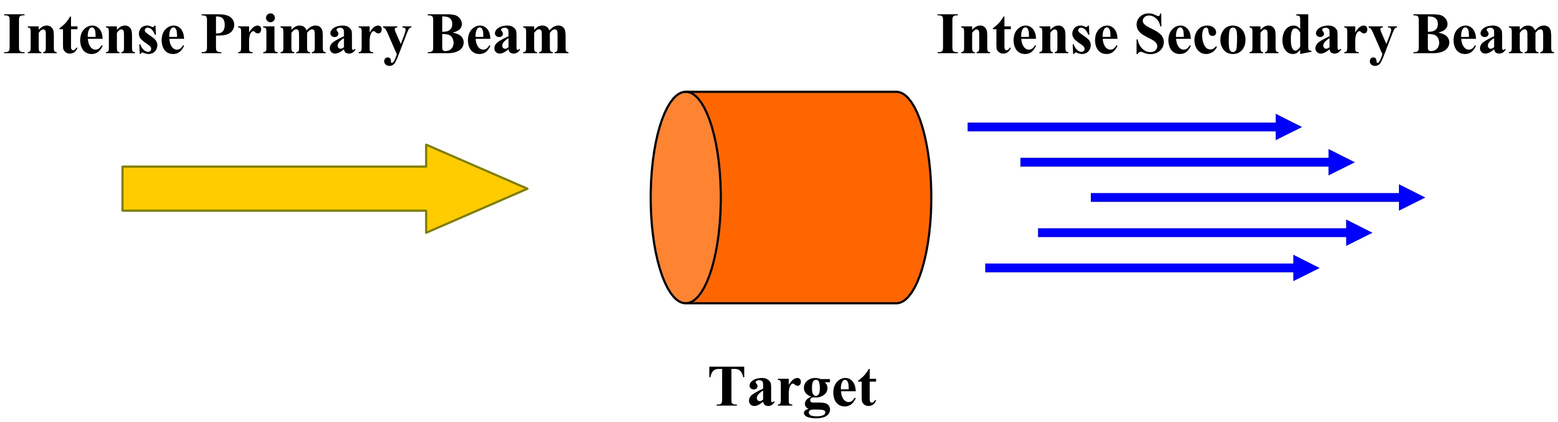
Subject Matter Covered Here

WG1 High-Power Target Issues

WG2 Target Station Design and Requirements for Muon Colliders and Neutrino Factories

The Challenge: Convert to Secondaries



Secondary Beams for New Phyisics

- **Neutrons (e.g. for neutron sources)**
- **π's (e.g. for Super ν Beams)**
- **μ's (e.g. for Muon Colliders, Neutrino Factories)**
- **Kaons (e.g. for rare physics processes)**
- **γ's (e.g. for positron production)**
- **Ion Beams (e.g. RIA, EURISOL, β-Beams)**

High-power Targetry Challenges

High-average power and high-peak power issues

- Thermal management
  - Target melting
  - Target vaporization
- Radiation
  - Radiation protection
  - Radioactivity inventory
  - Remote handling
- Thermal shock
  - Beam-induced pressure waves
- Material properties

Choices of Target Material

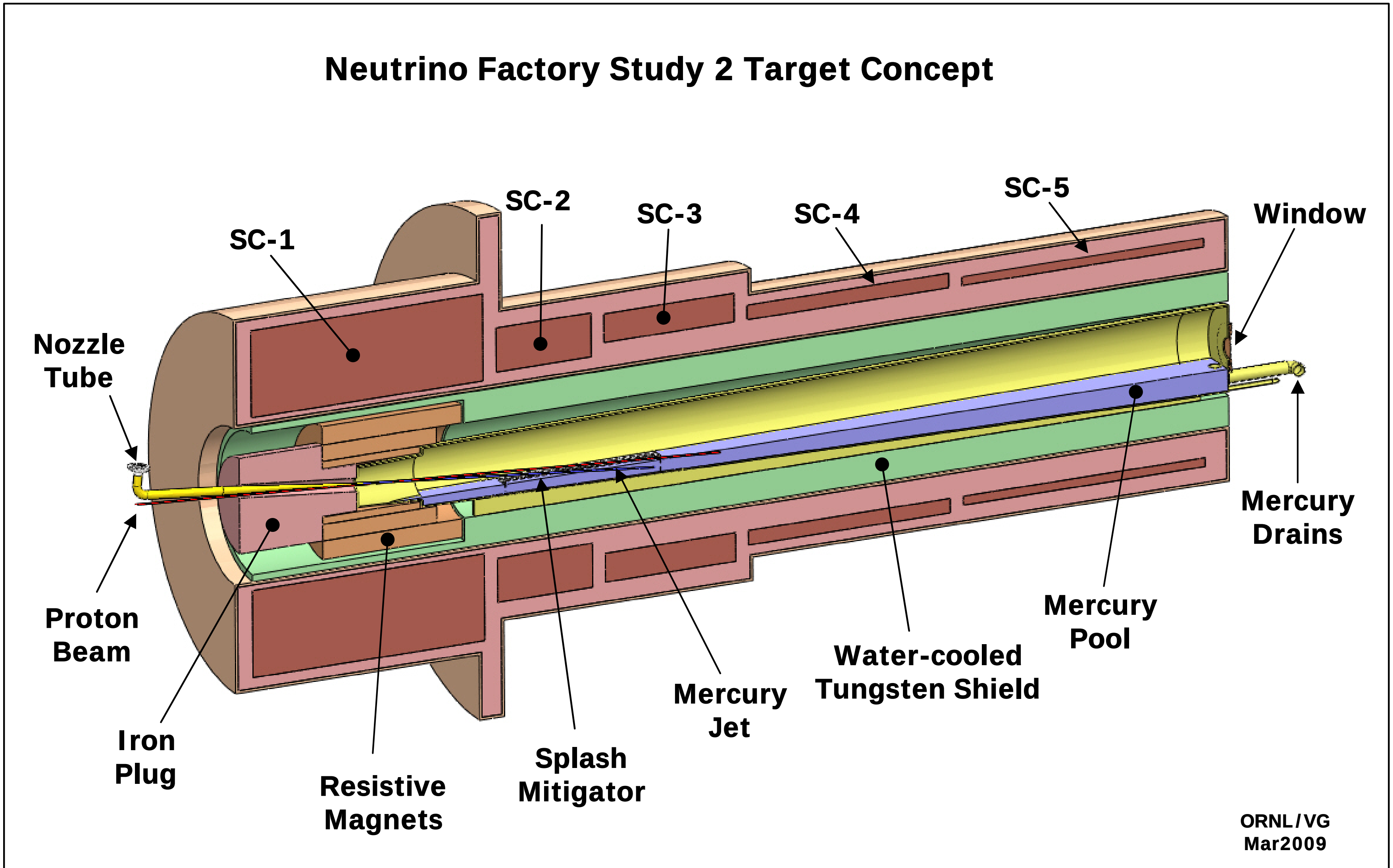
- **Solid**
  - Fixed
  - Moving
  - Particle Beds
- **Liquid**
- **Hybrid**
  - Particle Beds in Liquids
  - Pneumatically driven Particles

High-Power Targetry R&D

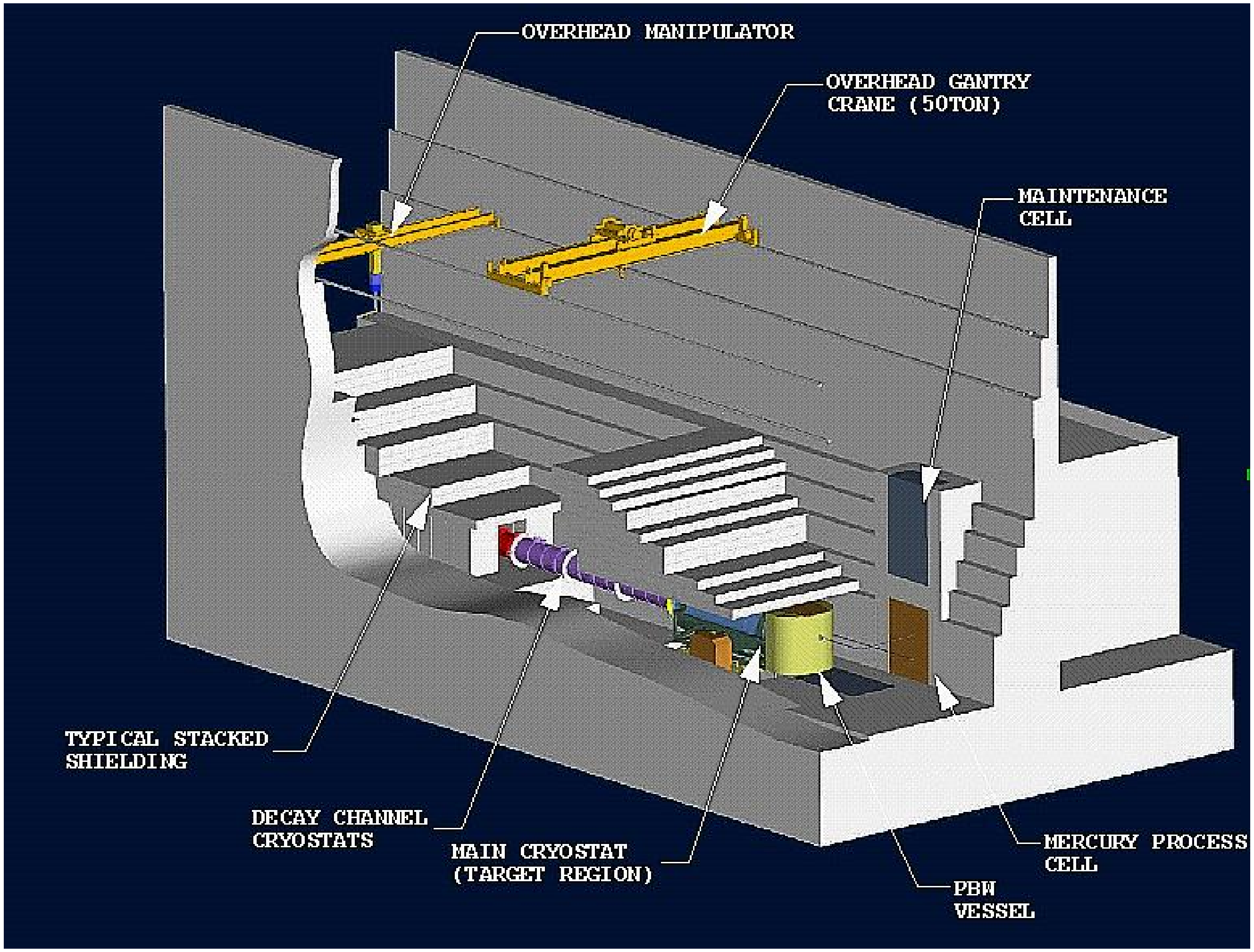
Key Target Issues for high-power targets

- What are the power limits for solid targets?
- Search for suitable target materials (solid and liquid) for primary beams > 1MW
- Optimal configurations for solid and liquid targets
- Effects of radiation on material properties
    - Target materials
    - Target infrastructure
- Material limits due to fatigue
- Design of reliable remote control systems

NF/MC Target System



A 4MW Target Hall



Phil Spampanato, ORNL

High-peak Power Issues

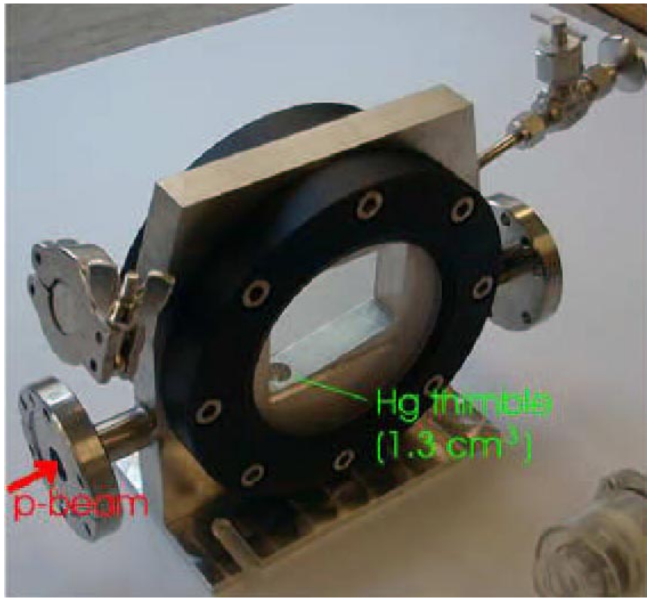
When the energy deposition time frame is on the order off or less than the energy deposition dimensions divided by the speed of sound then <u>pressure waves generation</u> can be an important issue.

Time frame = beam spot size/speed of sound

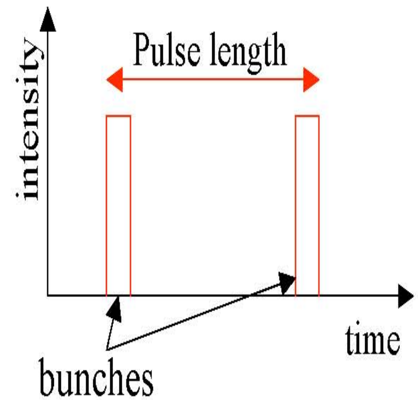
Illustration

Time frame = 1cm / 5×10^3 m/s = 2 μs

CERN ISOLDE Hg Target Tests



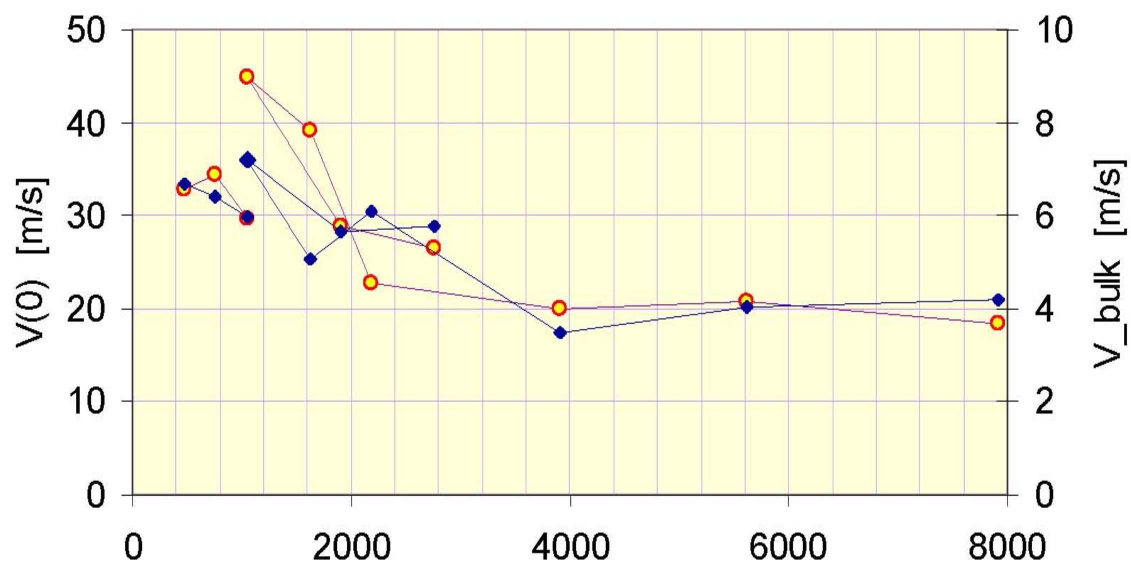
A. Fabich, J. Lettry



Pulse length

Proton beam 5.5 Tp per Bunch.

Velocities (pulse length)



Bunch Separation [ns]

Pressure Wave Amplitude

$$\text{Stress} = Y\,\alpha_T\,U / C_V$$

Where Y = Material modulus

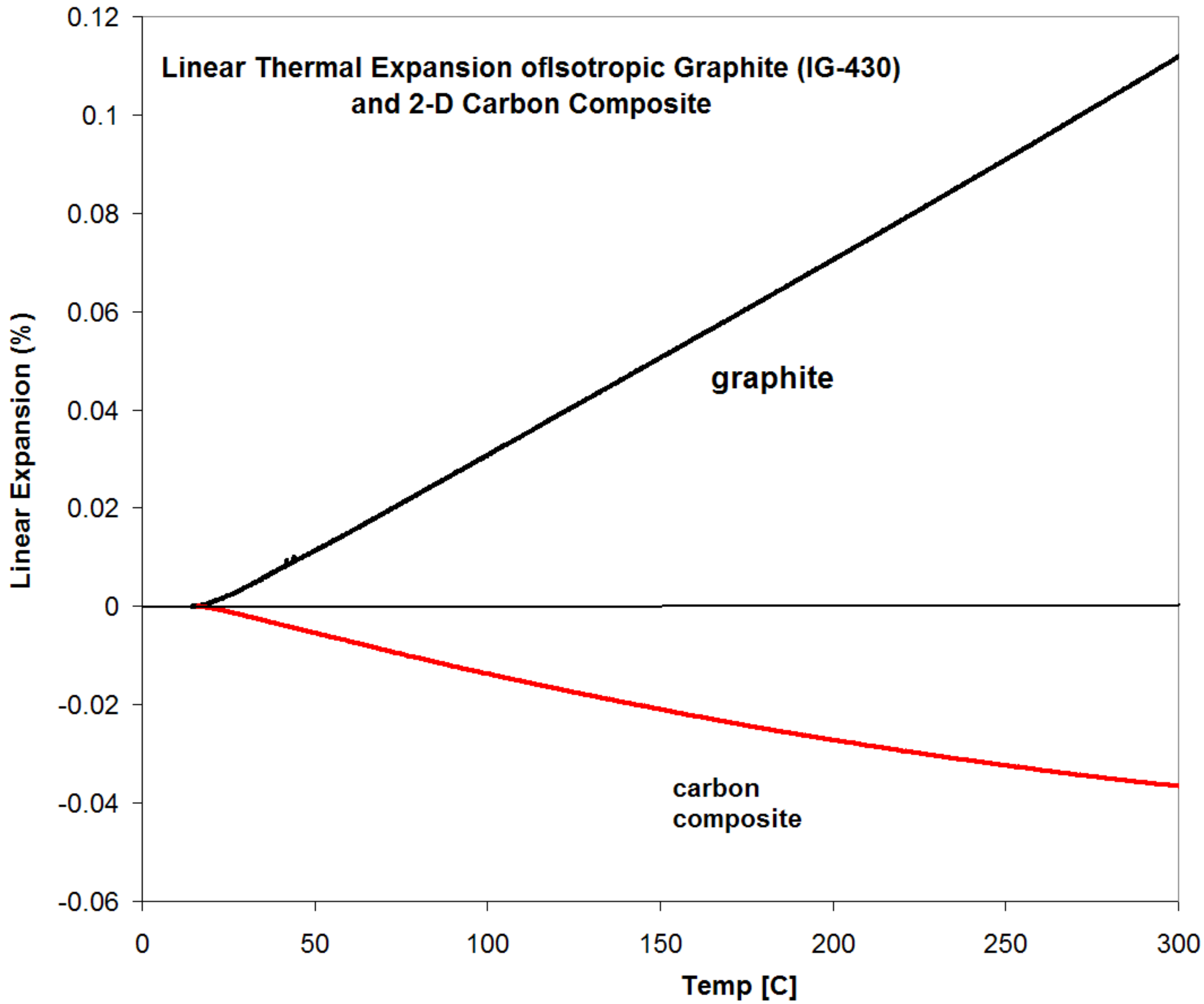
α_T = Coefficient of Thermal Expansion

U = Energy deposition

C_V = Material heat capacity

When the pressure wave amplitude exceeds material tensile strength then target rupture can occur. This limit is material dependant.

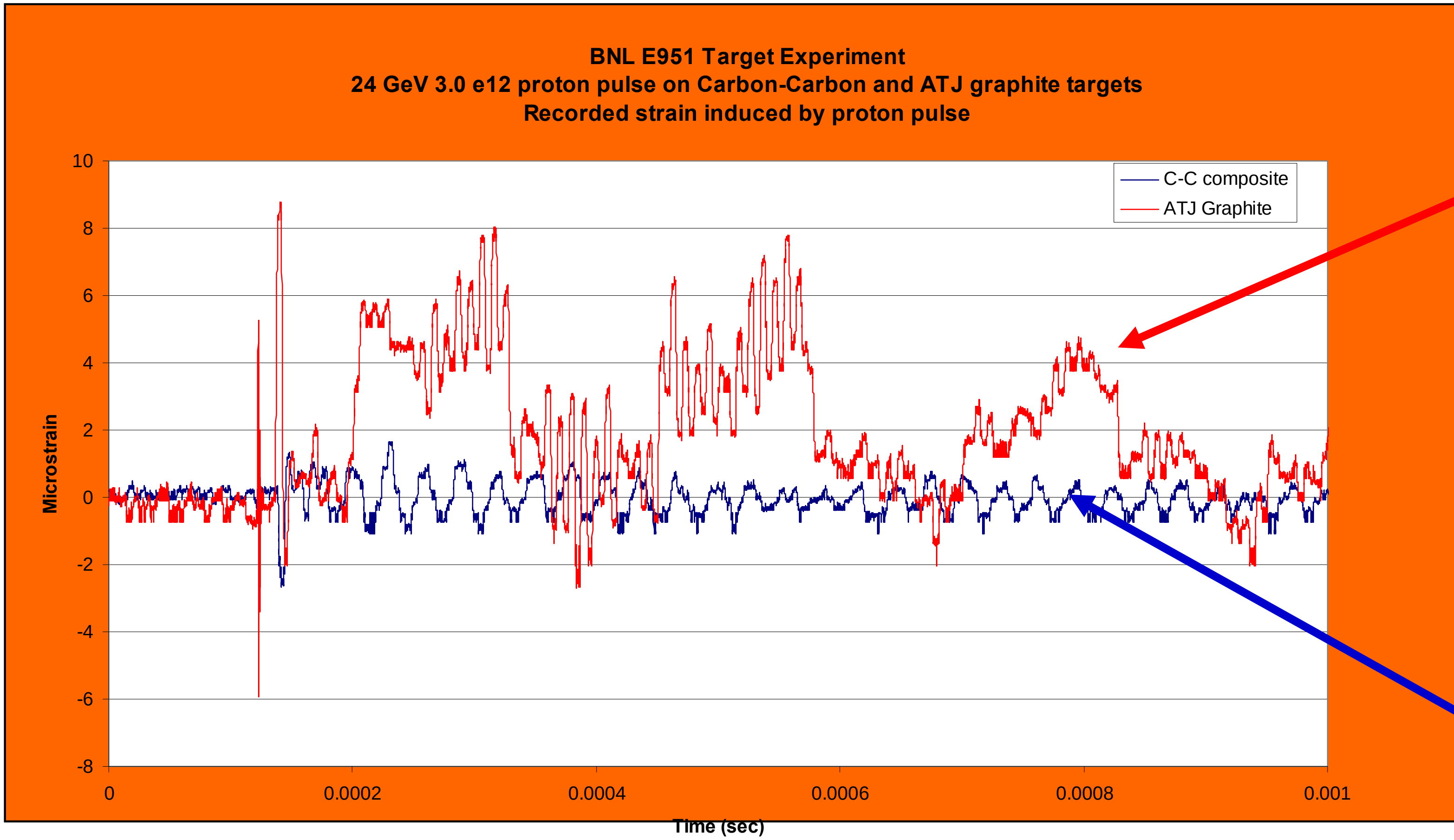
Example: Graphite vs Carbon Composit



Strain Gauge Measurements

BNL E951: 24 GeV, 3 x 10^{12} protons/pulse

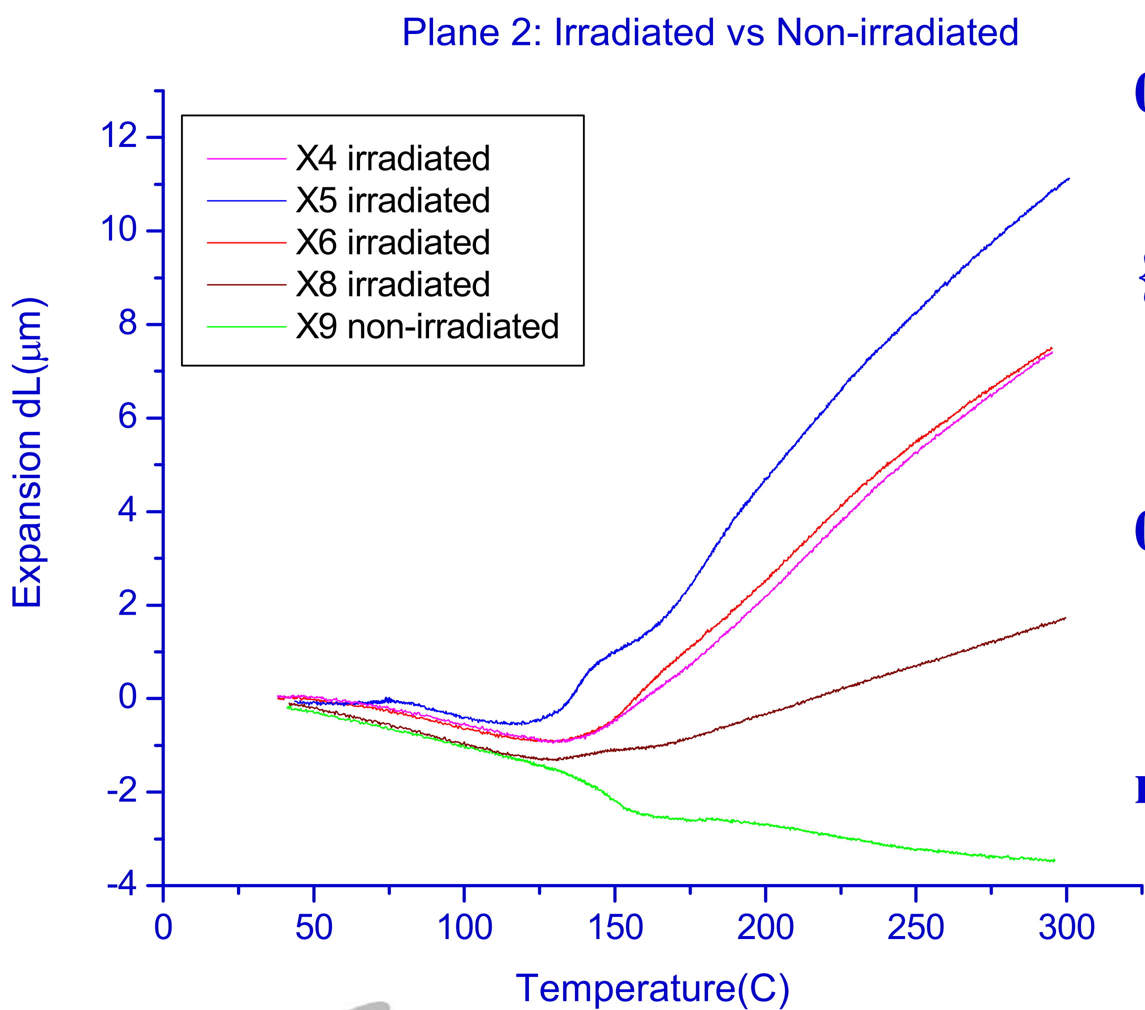
Stress = $Y \alpha_T U / C_V$



ATJ Graphite

Carbon-Carbon Composite

Carbon-Carbon Composite



Average Proton Fluence
(10^{20} protons/cm^2)

0.76

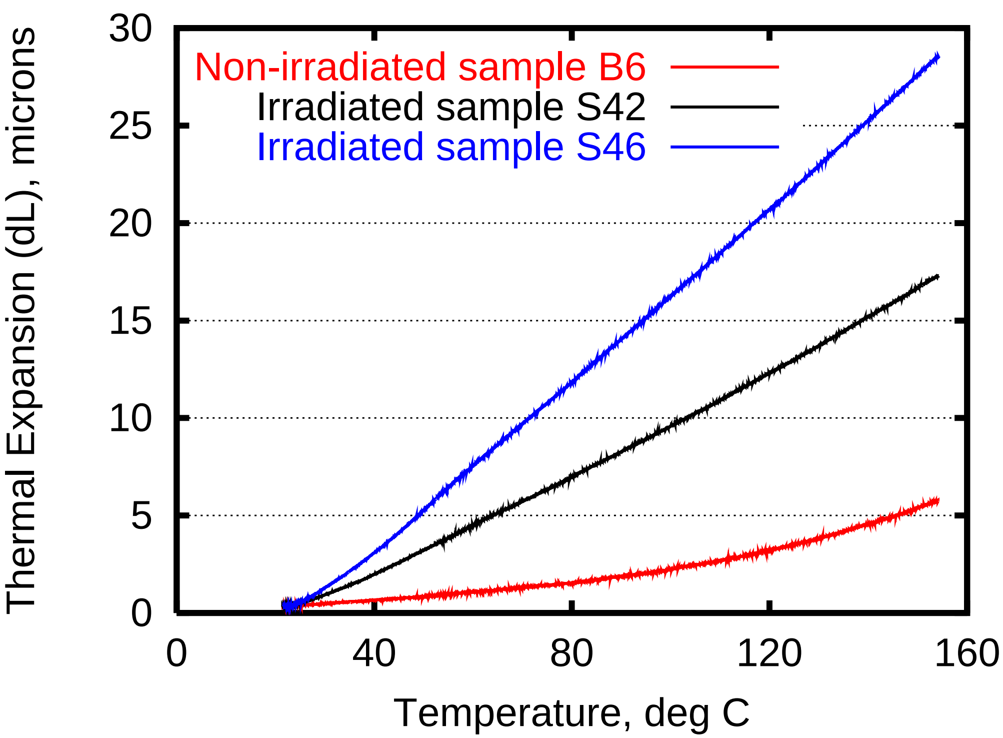
{ 0.52 and 0.36

0.13

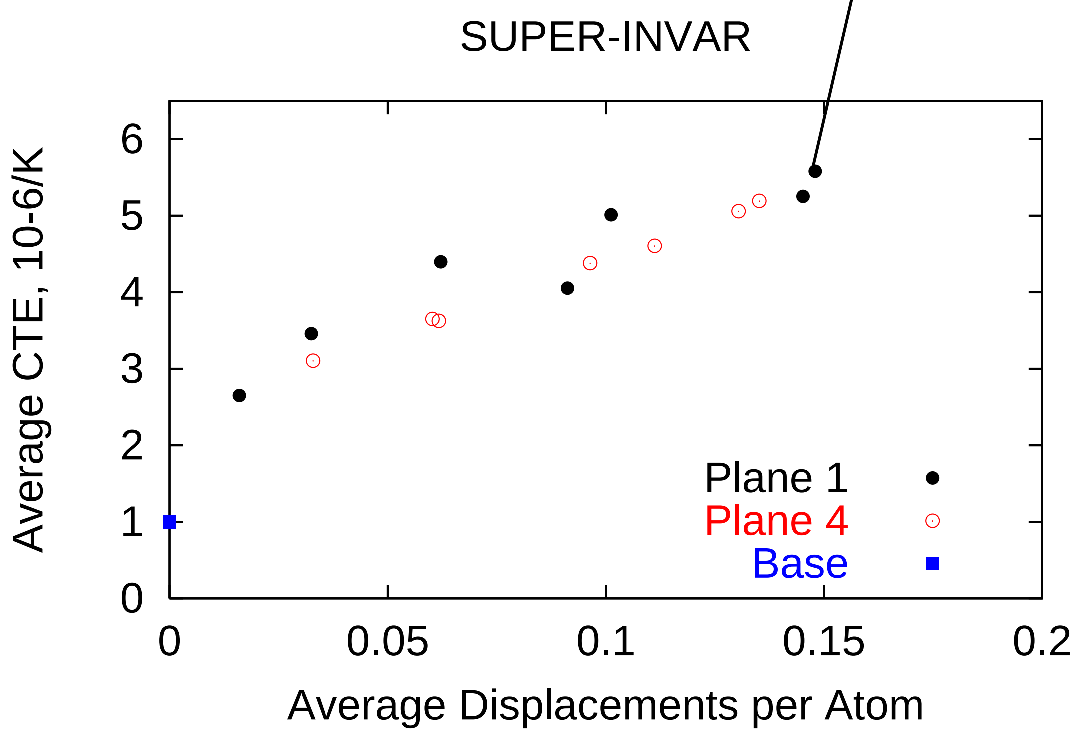
none

Super-Invar CTE measurements

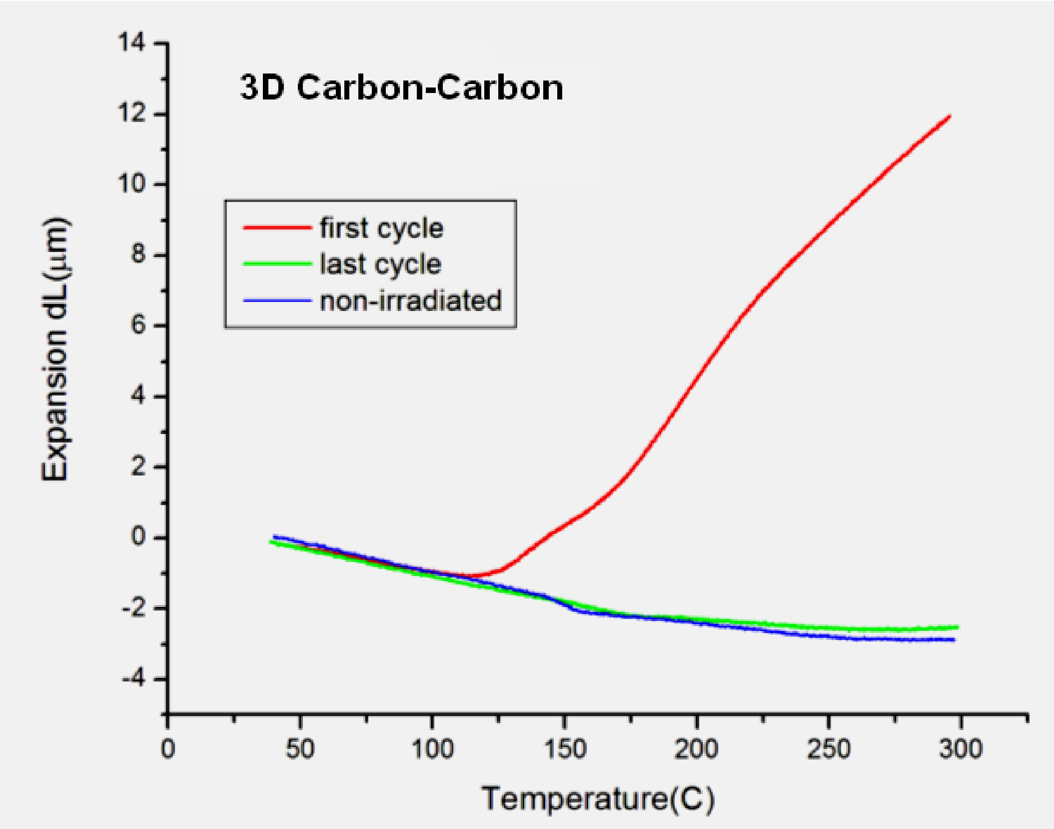
BNL BLIP

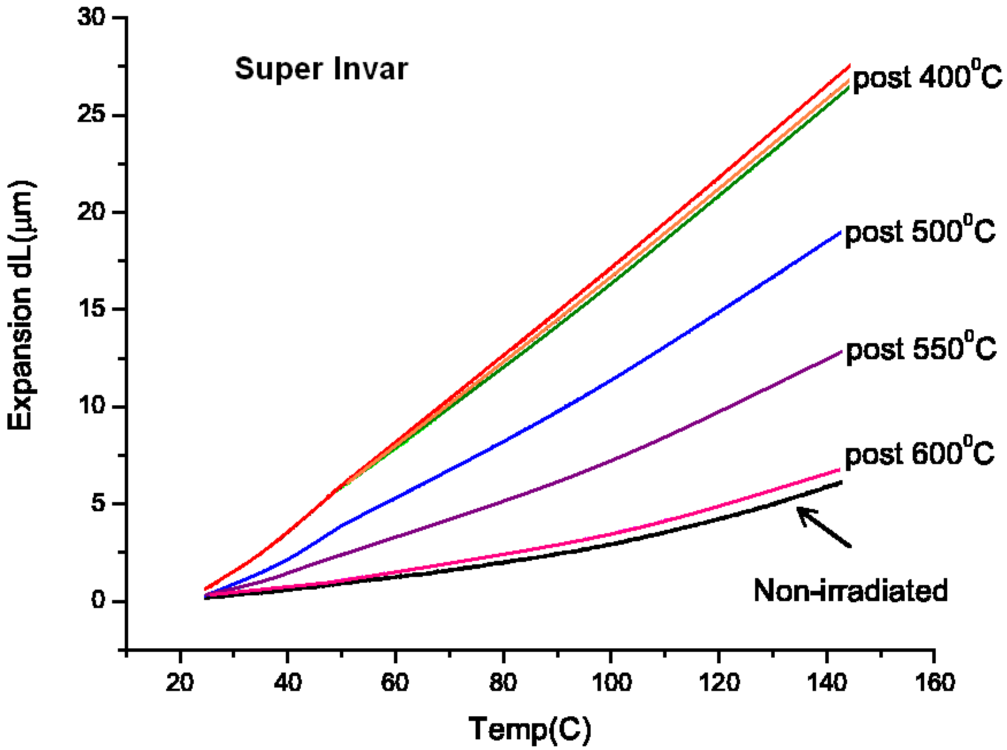


Peak Proton fluence
1.3 x 10^{20} protons/cm^2



Recovery of low α_T

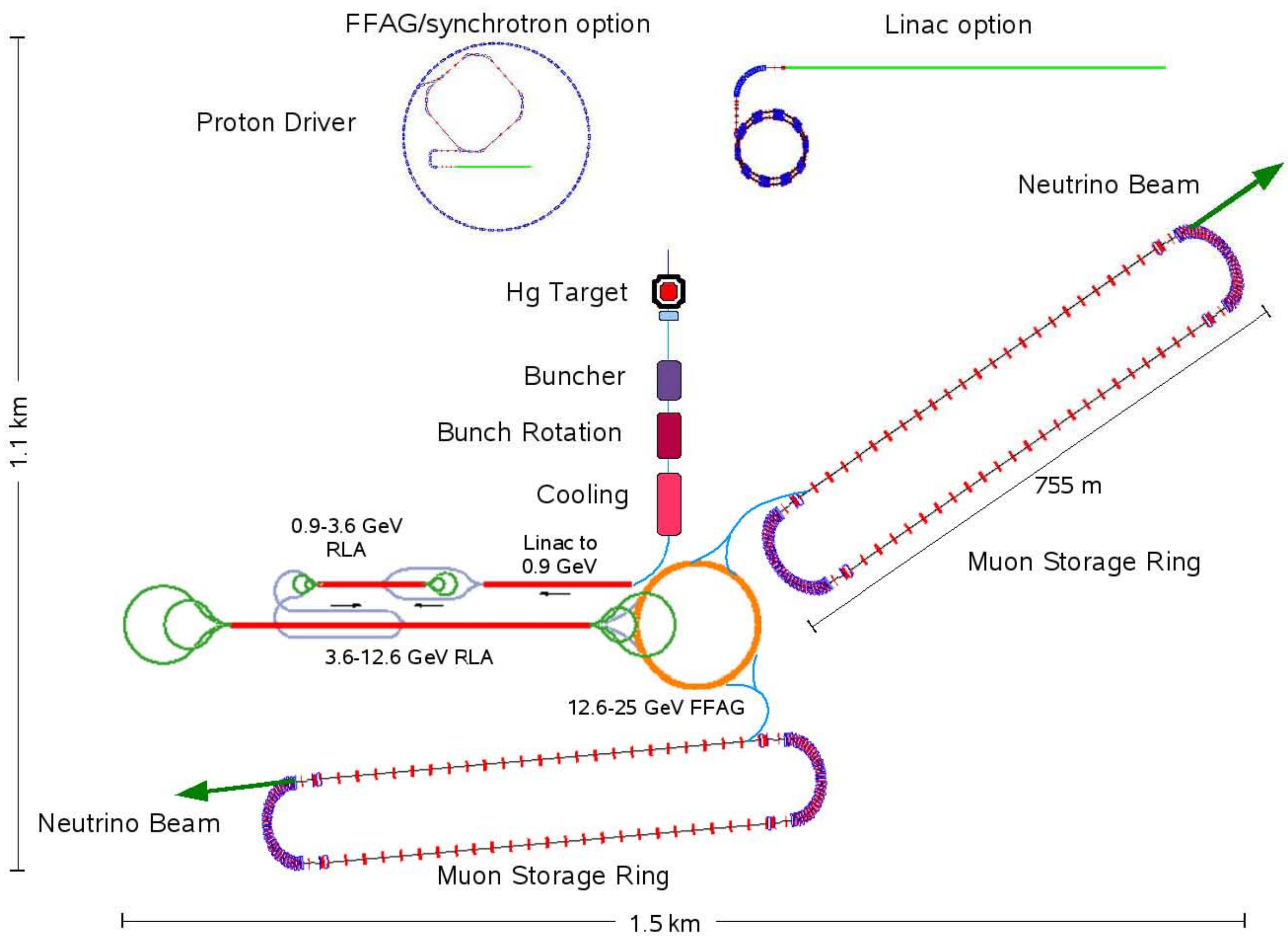




Carbon-Carbon anneals at ~300^{0}C

Super-Invar anneals at ~600^{0}C

The International Design Study Baseline

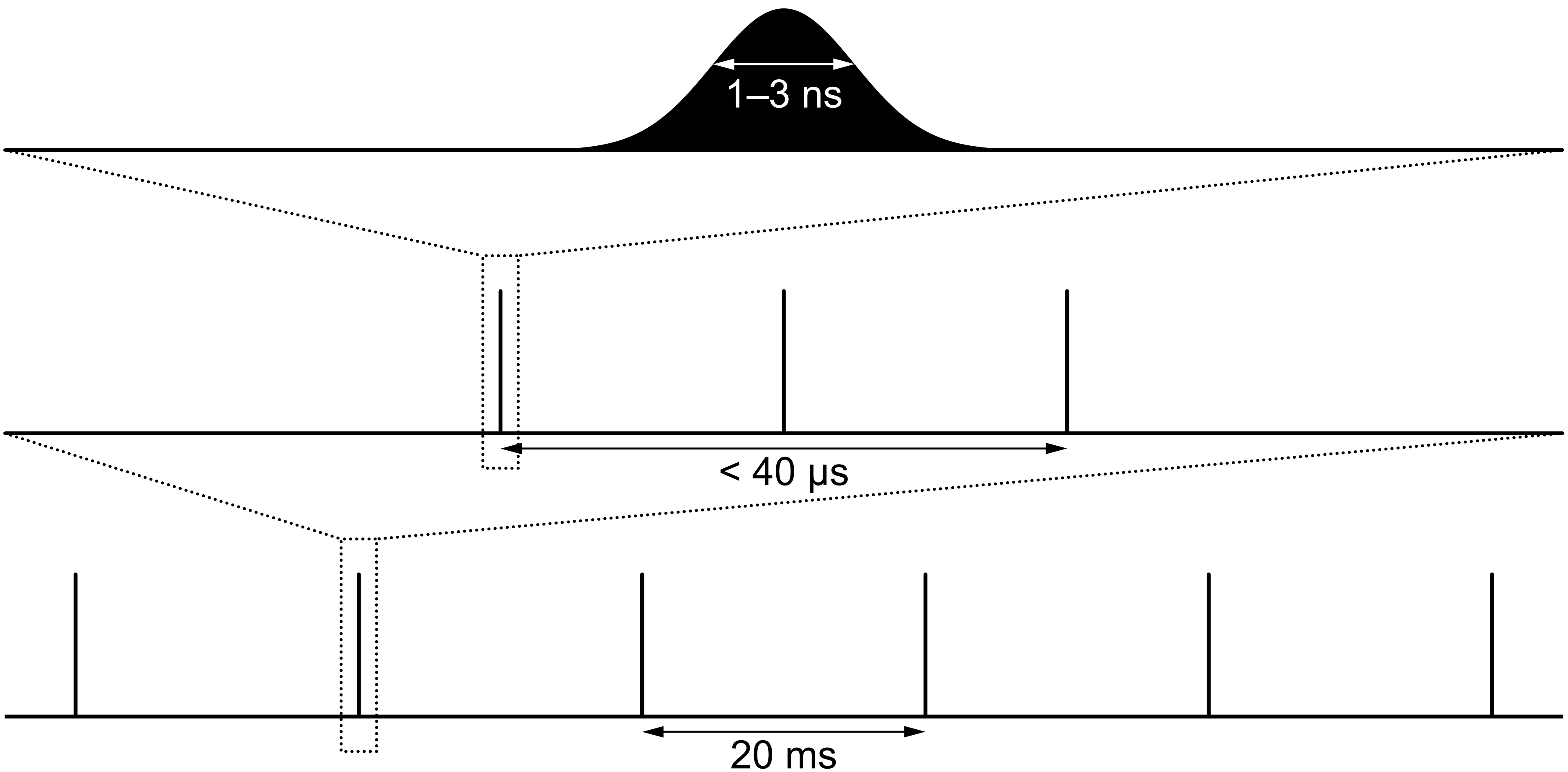


The IDS Neutrino Factory Baseline

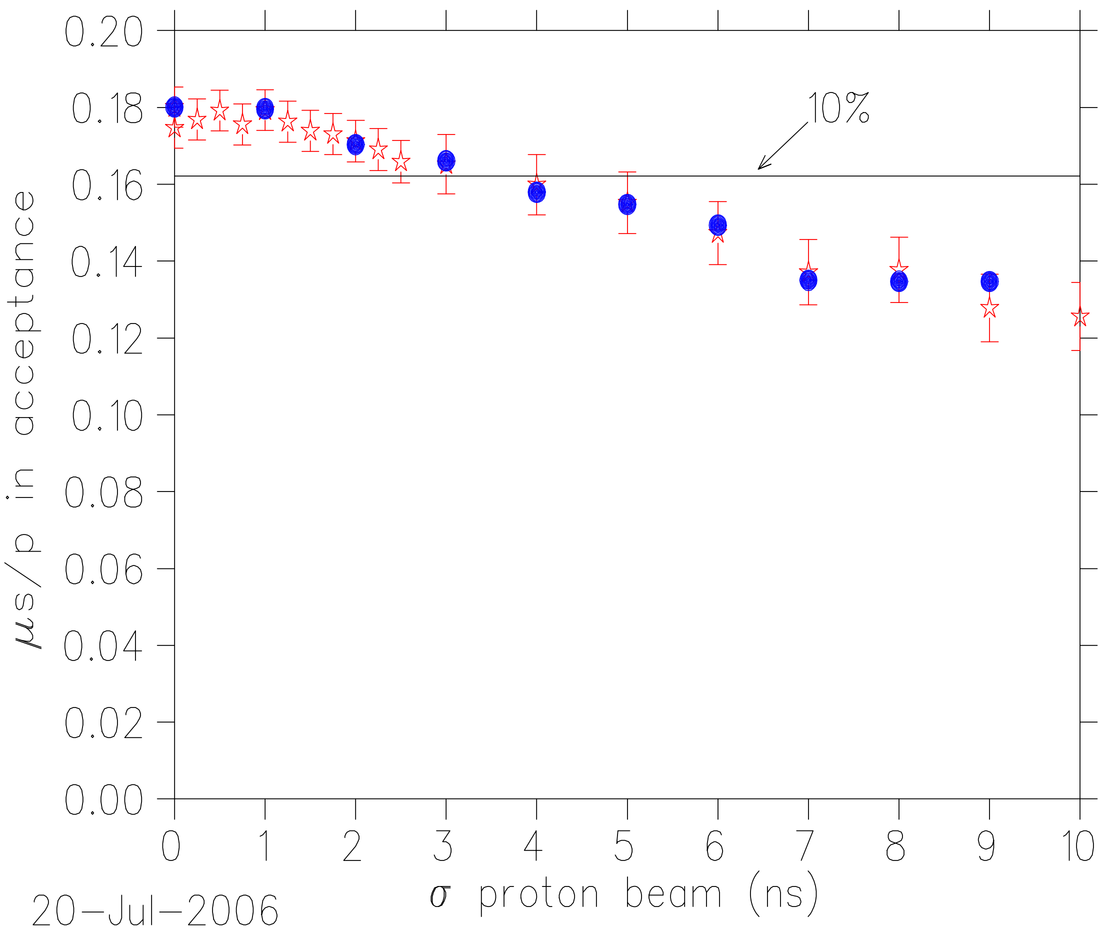
Mean beam power	**4 MW**
Pulse repetition rate	**50 Hz**
Proton kinetic energy	**5-10-15 GeV**
Bunch duration at target	**1-3 ns rms**
Number of bunches per pulse	**1-3**
Separated bunch extraction delay	**≥ 17 μs**
Pulse duration:	**≤ 40 μs**

The IDS Proton Driver Baseline Parameters

The Neutrino Factory Bunch Structure



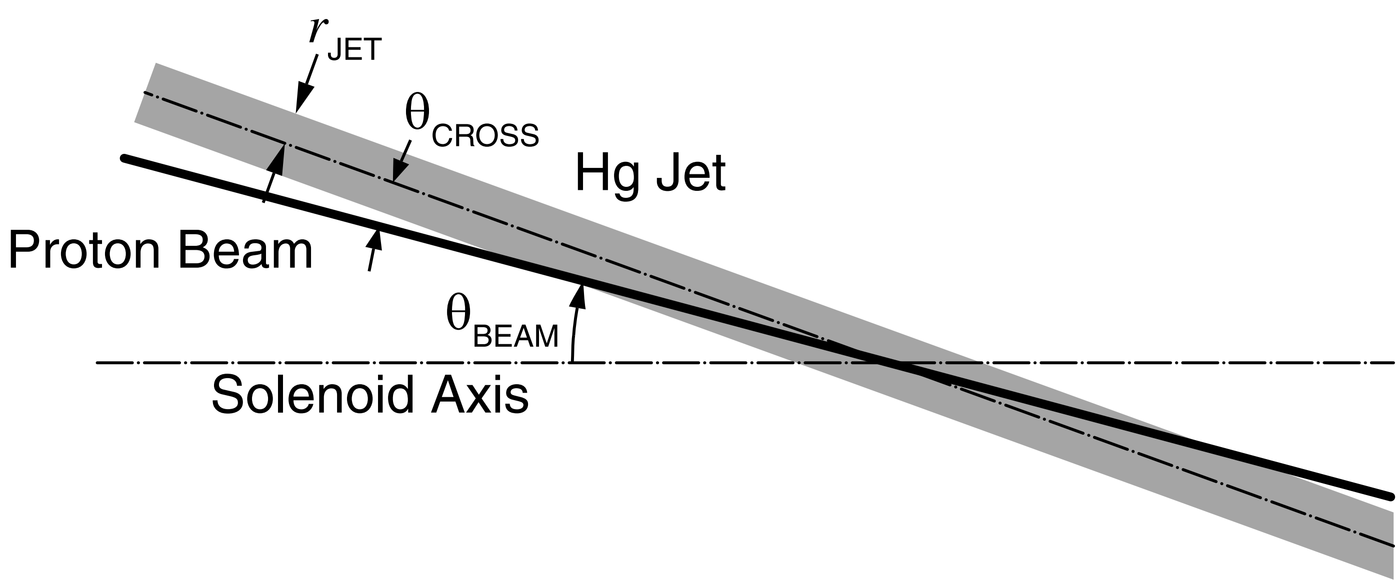
Driver Beam Bunch Requirement



Proton beam bunch length requirements due to rf incorporated in the downstream phase rotation and transverse cooling sections.

Bunch length = 2± 1 ns

MARS15 Study of the Hg Jet Target Geometry

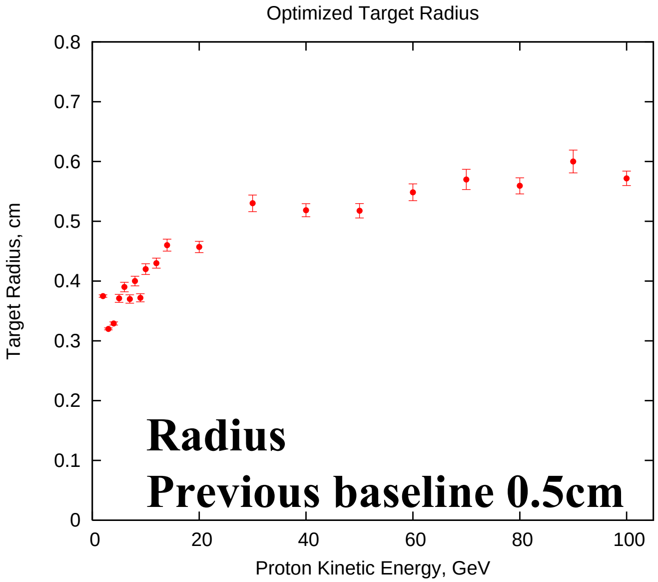


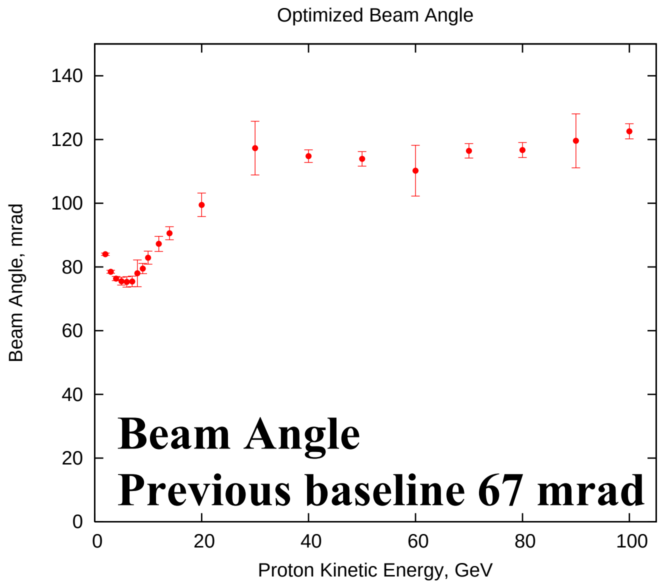
Previous results: Radius 5mm, θ_{beam} =67mrad

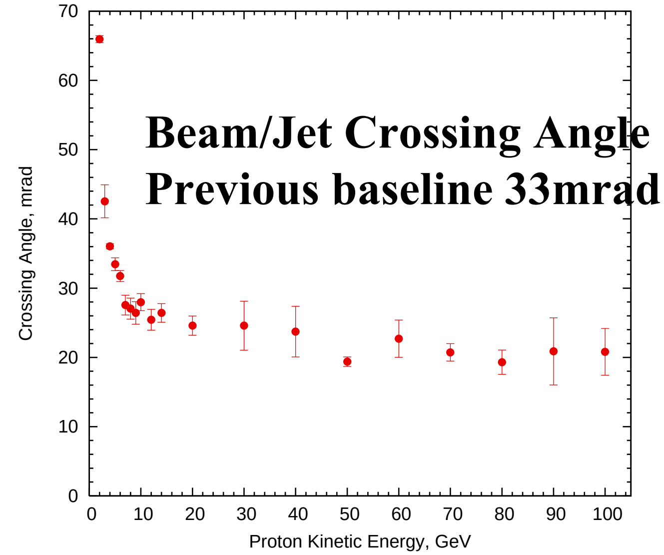
$\Theta_{crossing}$ = 33mrad

Optimized Meson Production

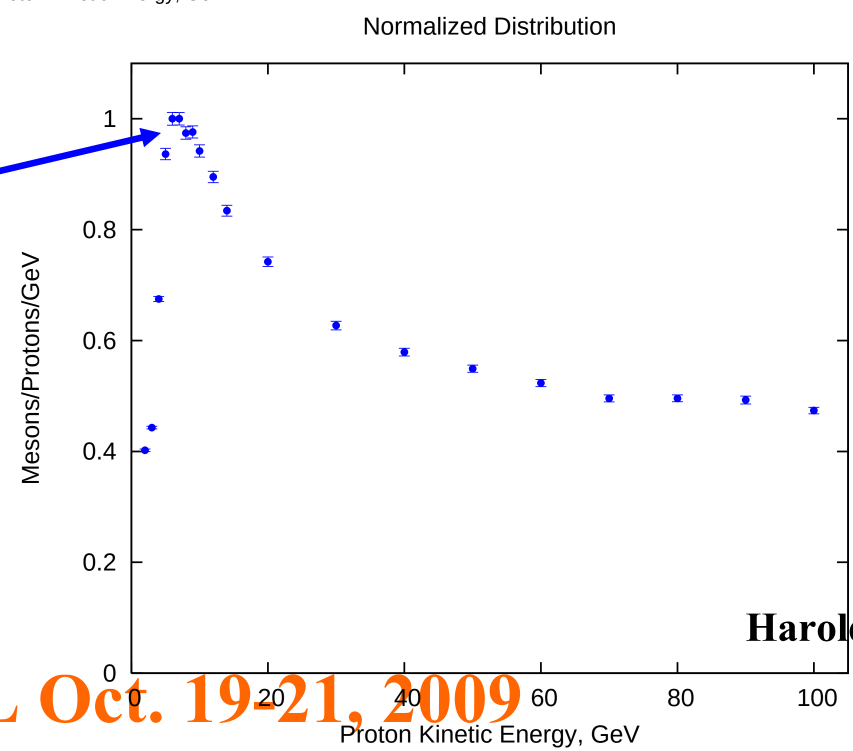
X. Ding, UCLA







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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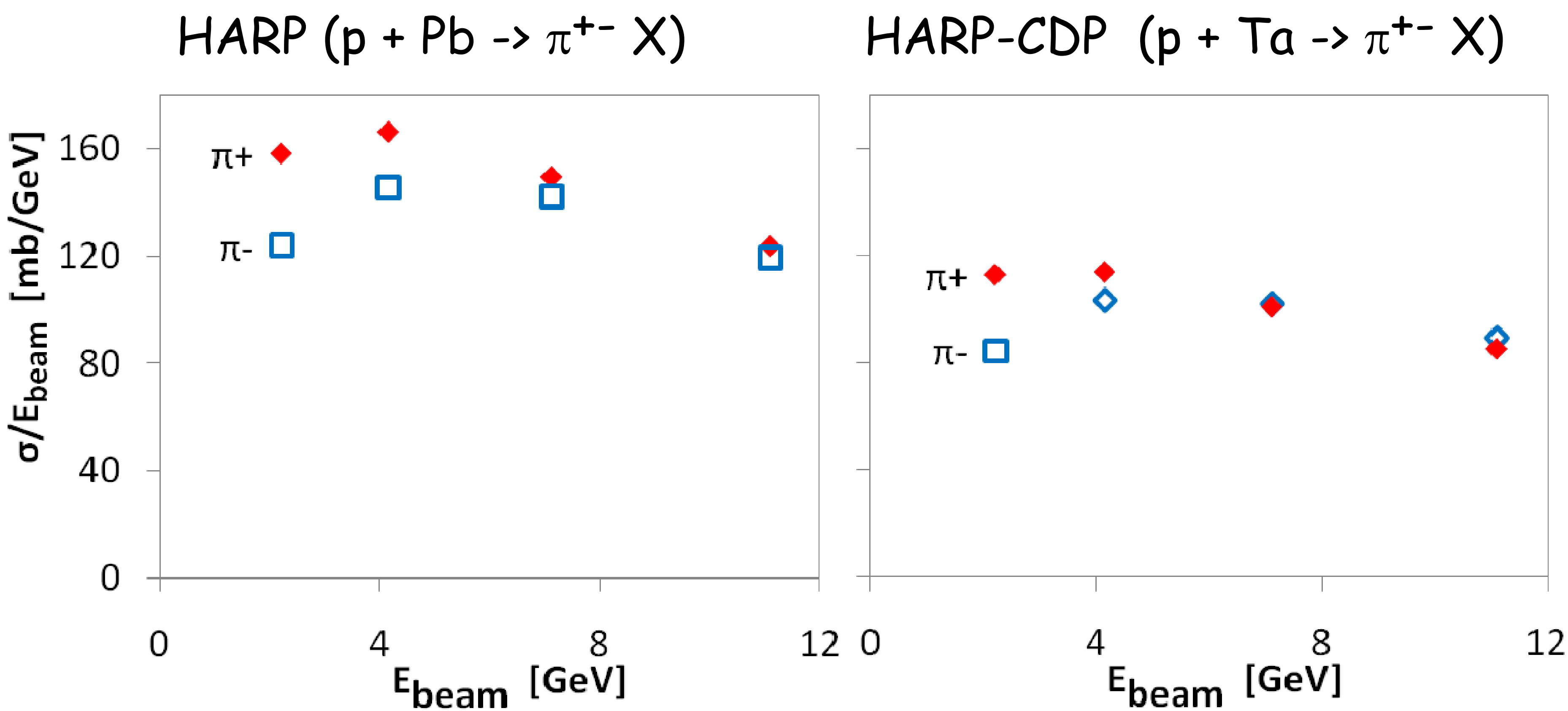
Jim Strait – NUFACT09

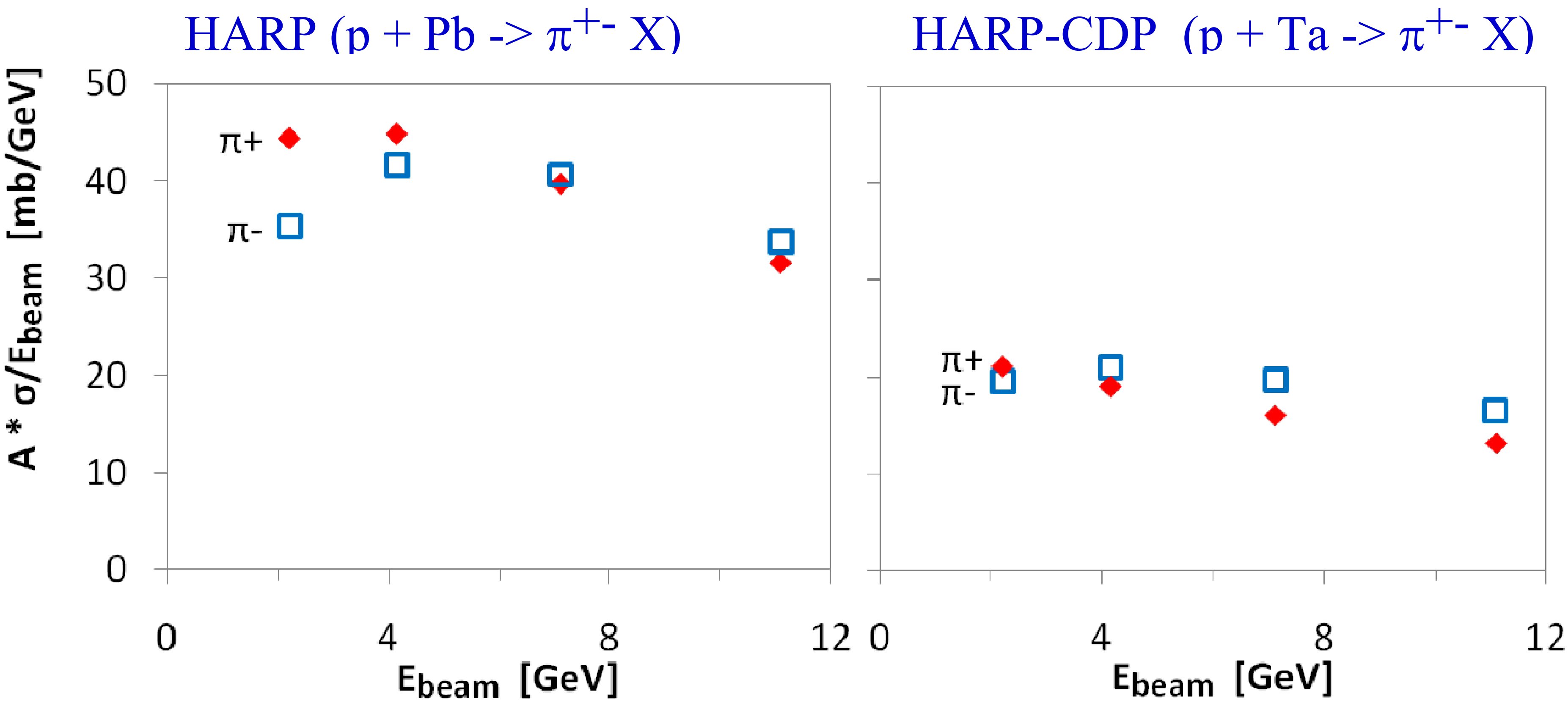
$\sigma(\pi^{+-})$ $/E_{beam}$, integrated over the measured phase space

(*different for the two groups*).



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

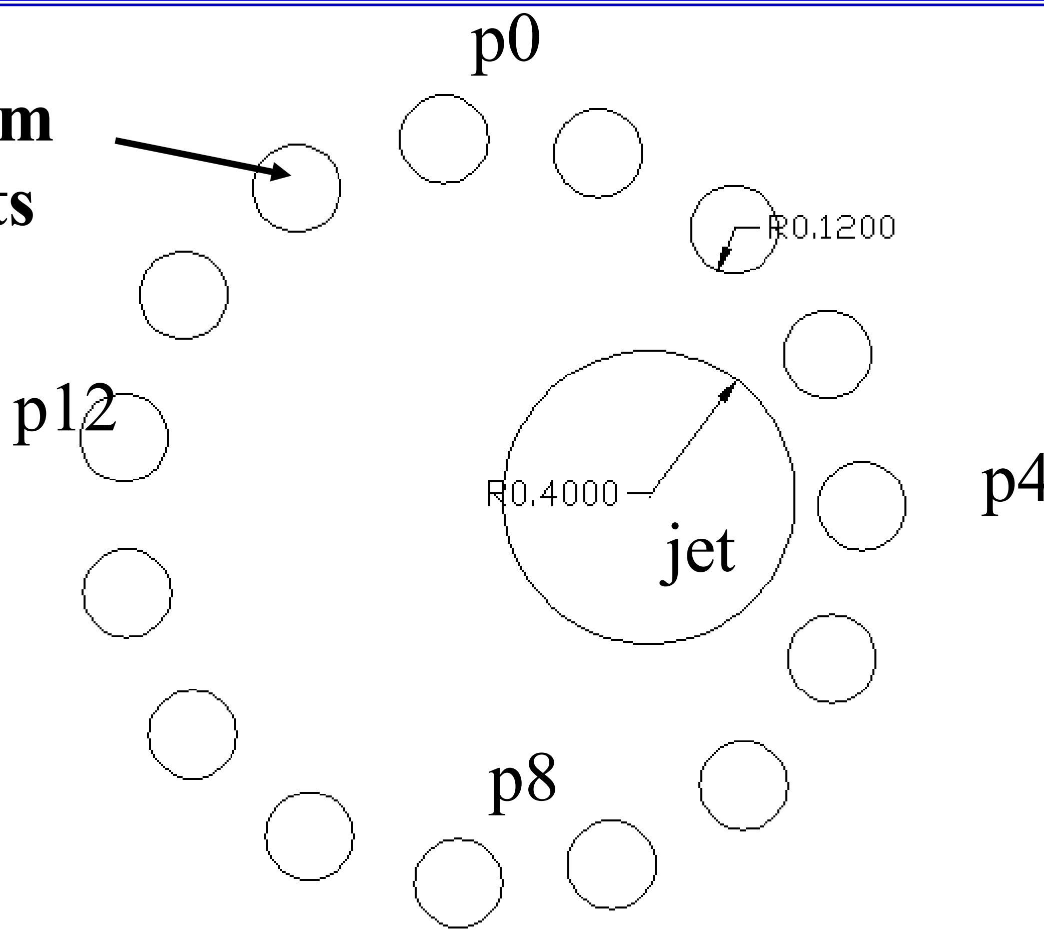
HARP Cross-Sections x NF Capture Acceptance



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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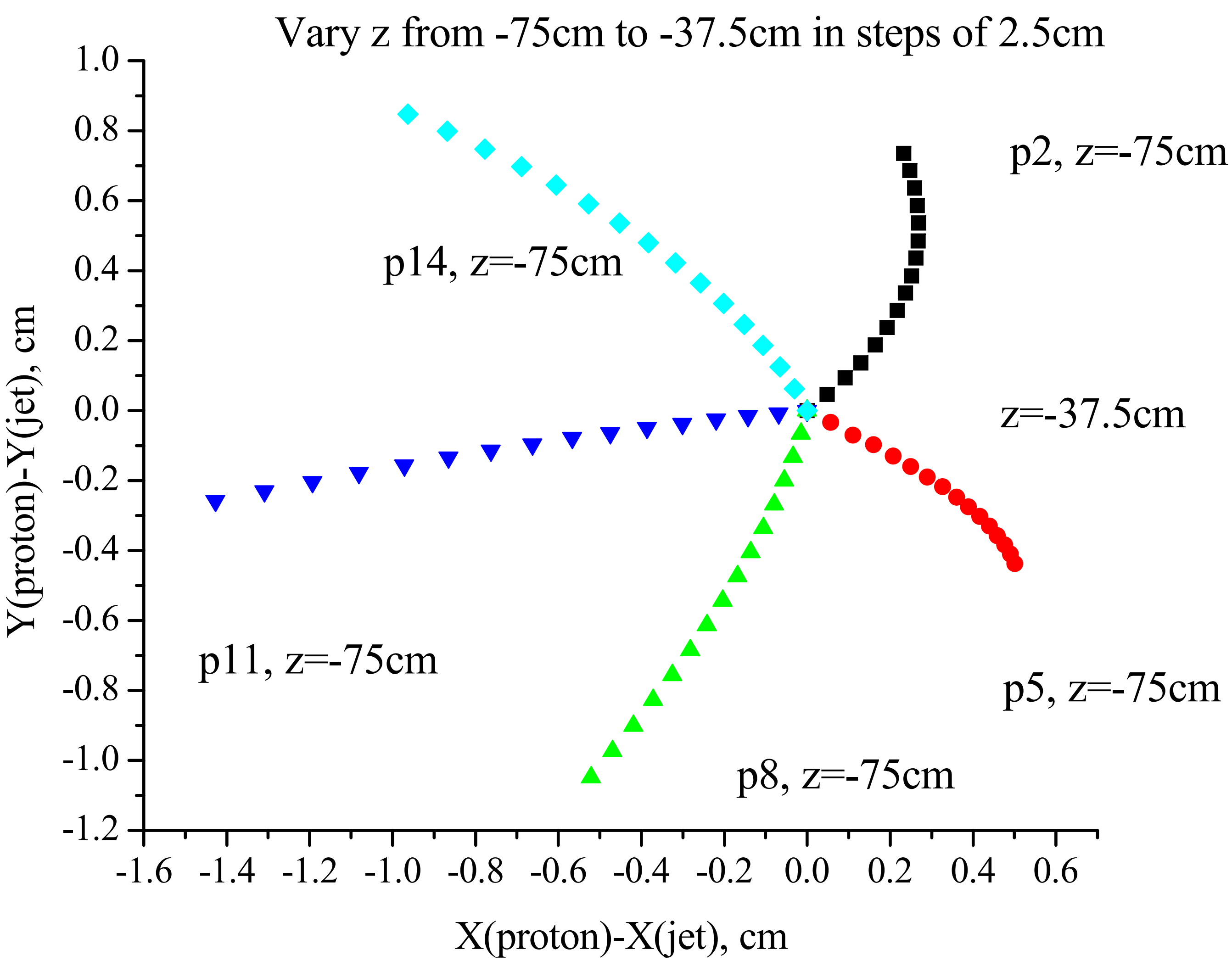
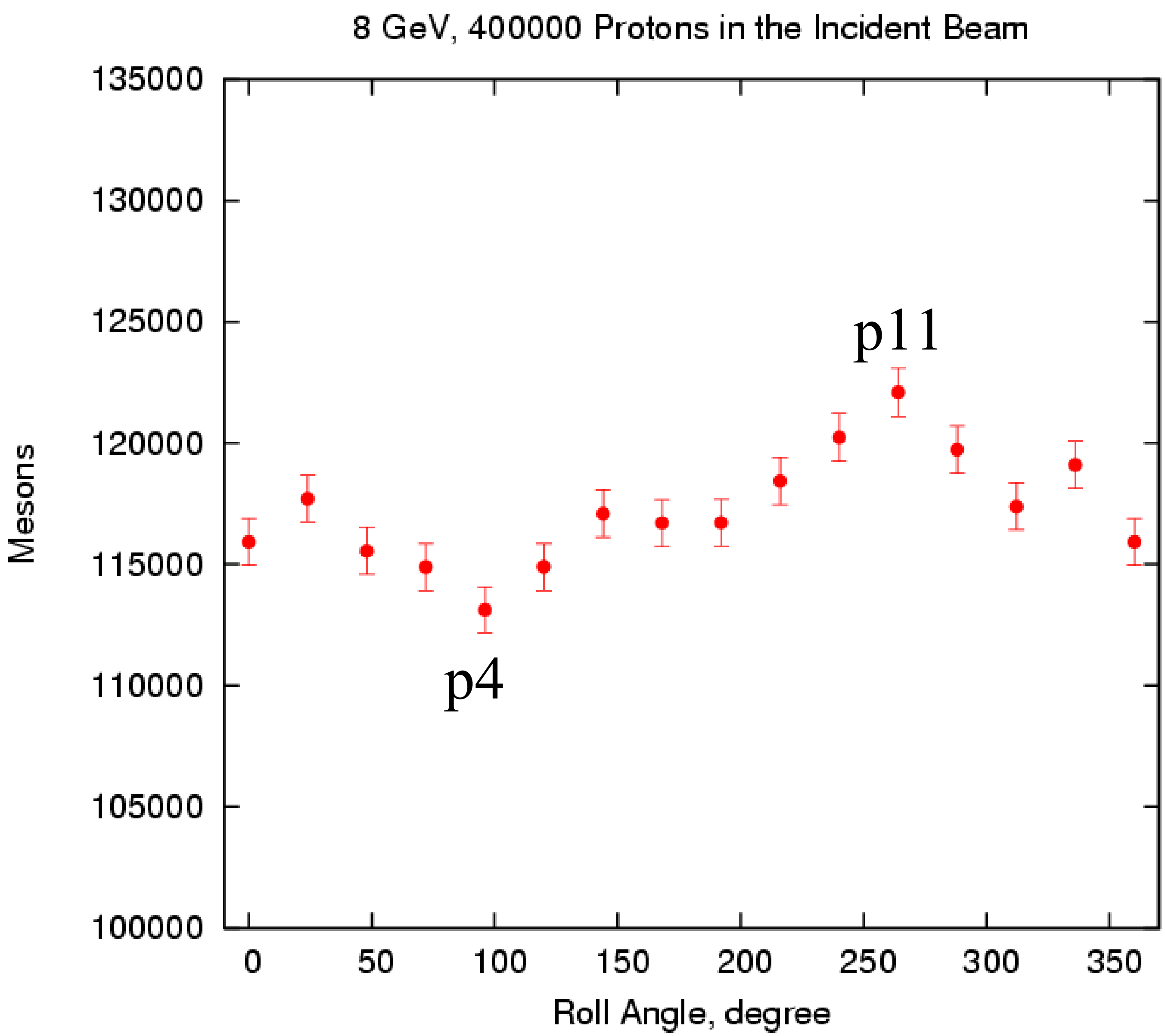
Proton beam entry points upstream of jet/beam crossing

Trajectory of the Proton Beam



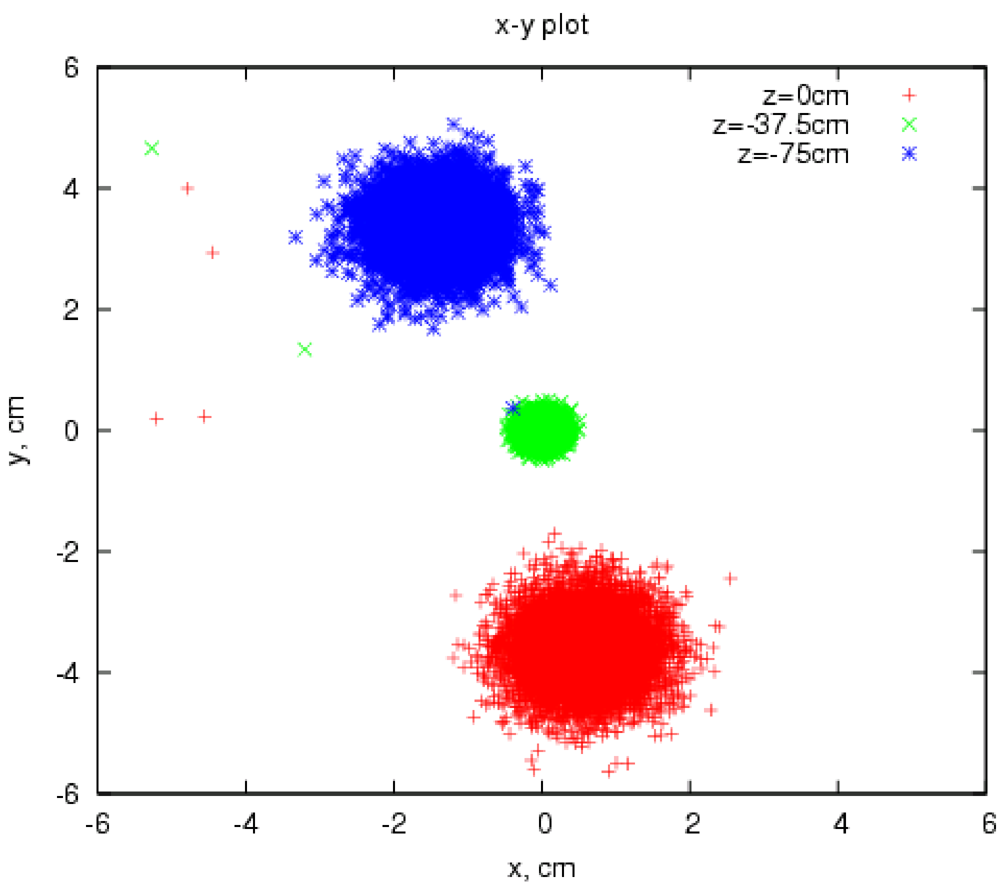
Selected proton beam transverse trajectories relative to the Hg Jet.

Multiple Entry Entries

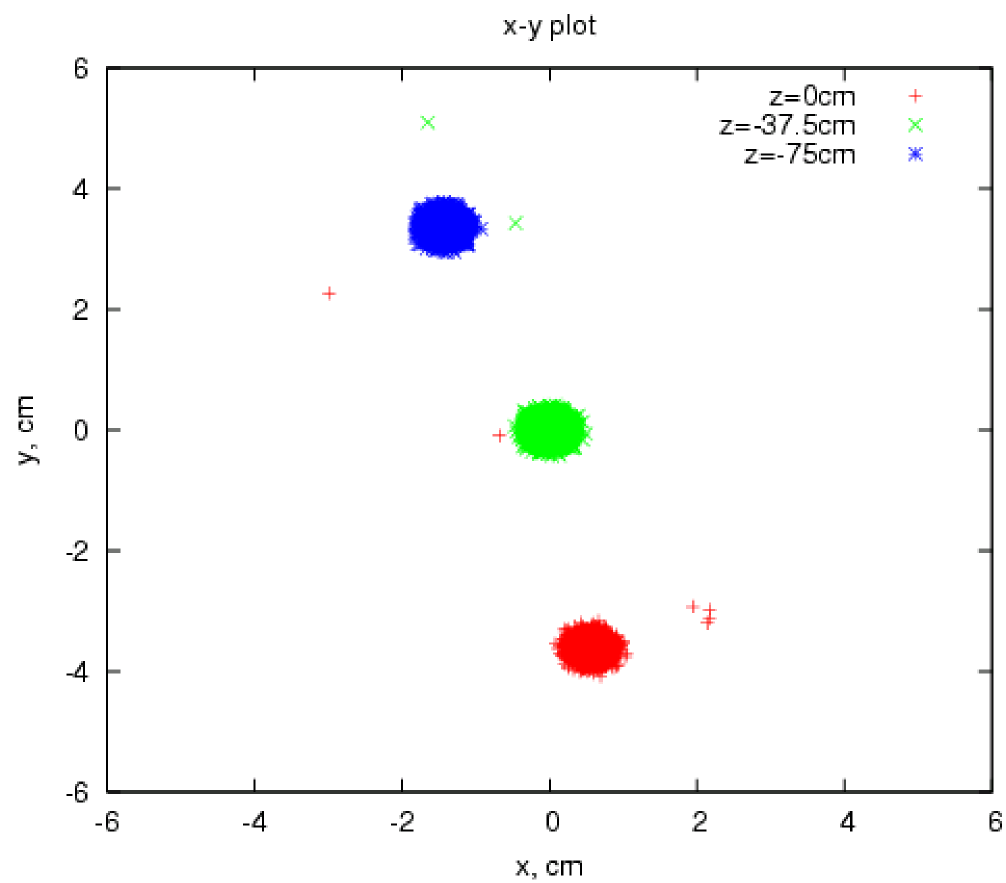


A 10% swing in meson production efficiency

Influence of β* of the Proton Beam



β* = 10cm



β* = 300cm

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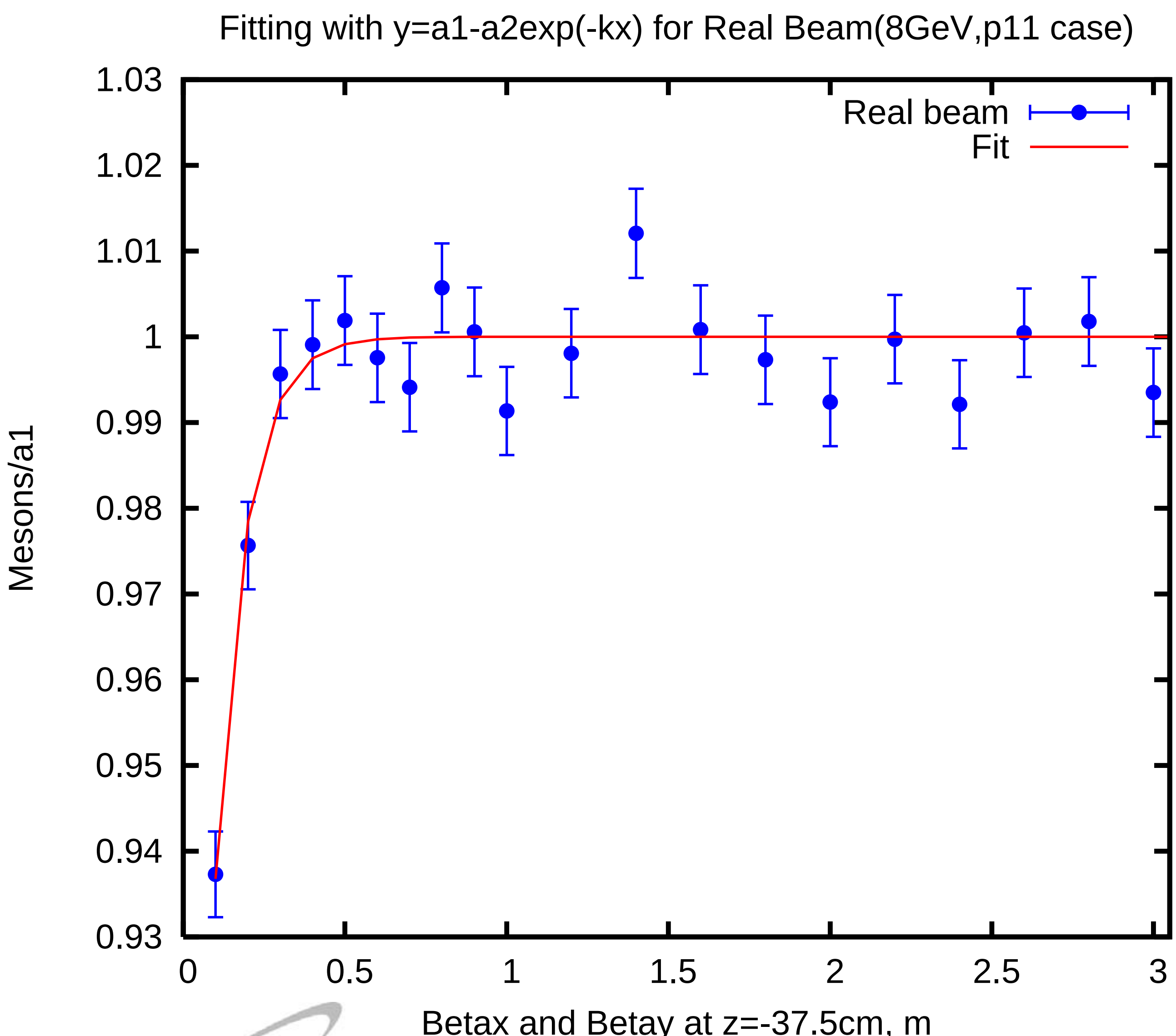
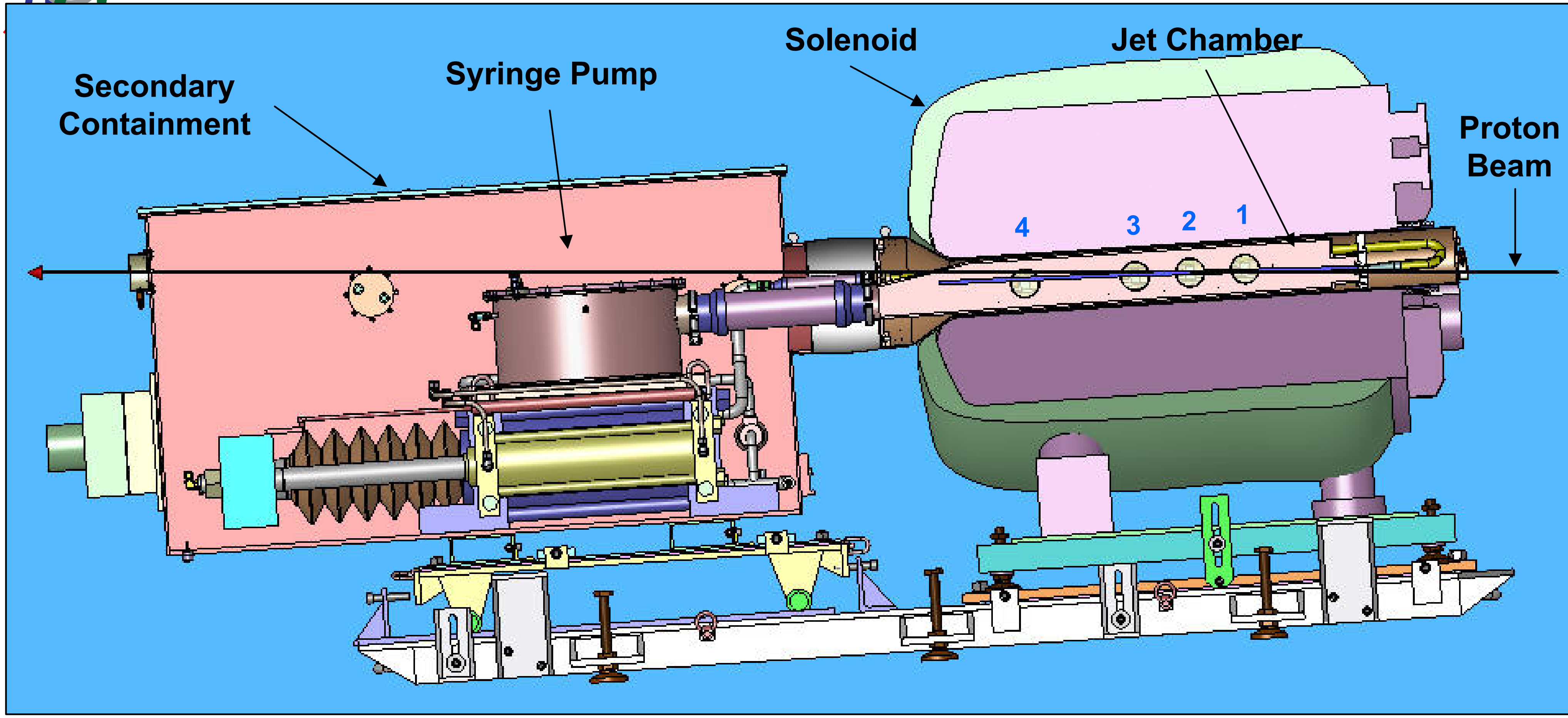
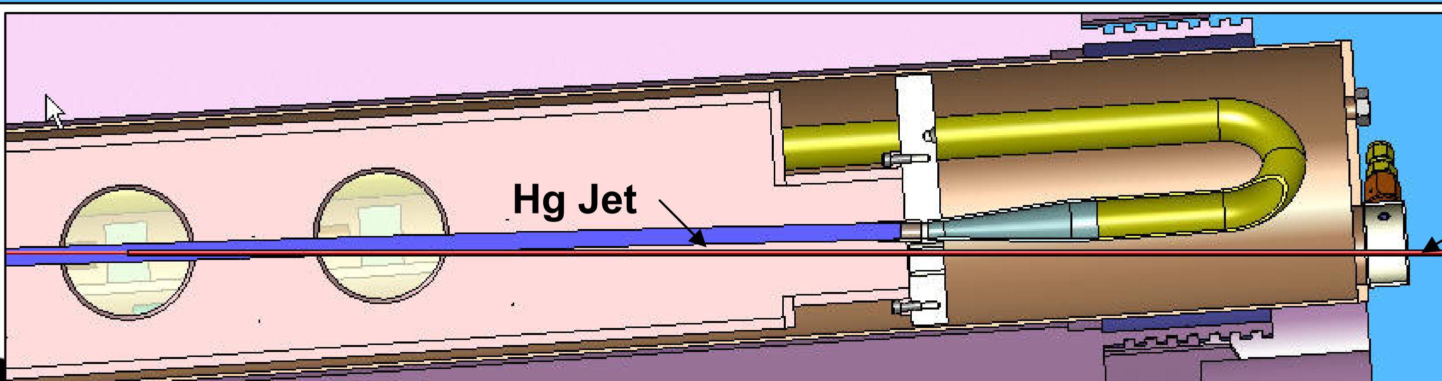
Meson Production vs β*



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

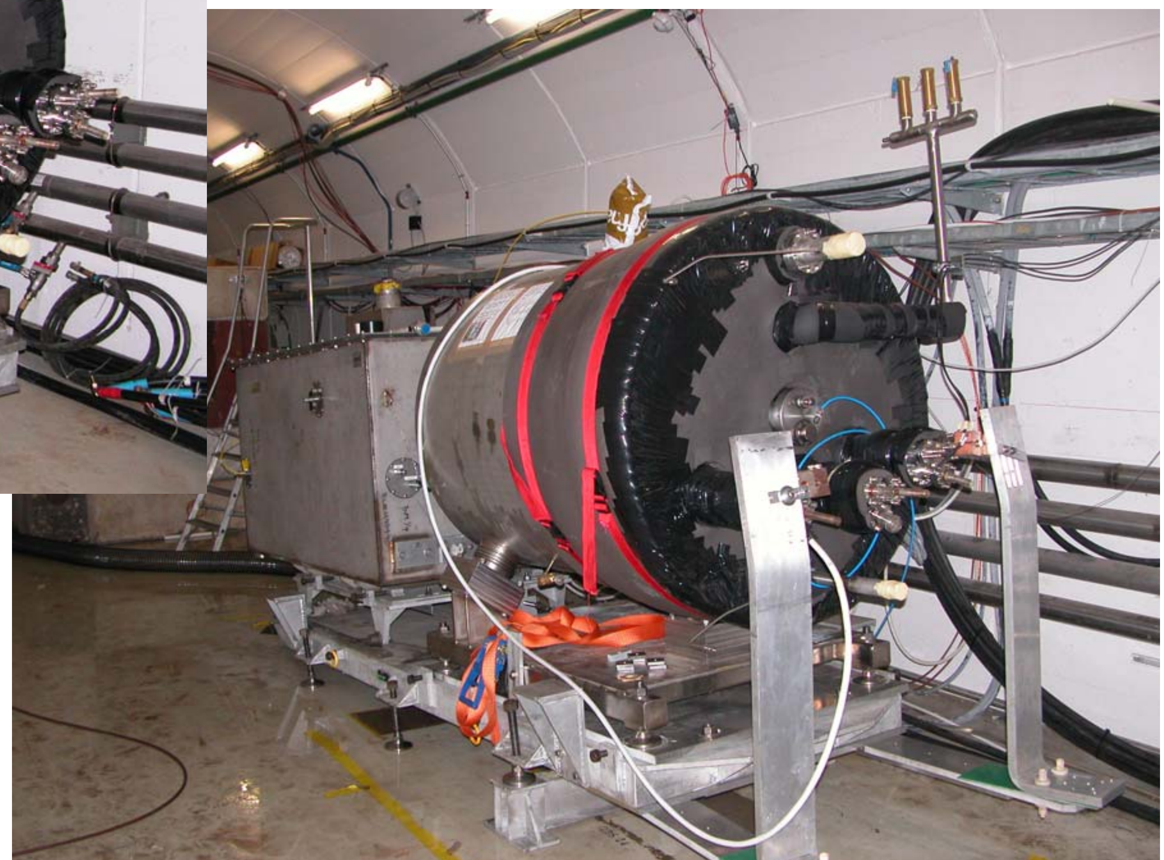
The MERIT Experiment at CERN





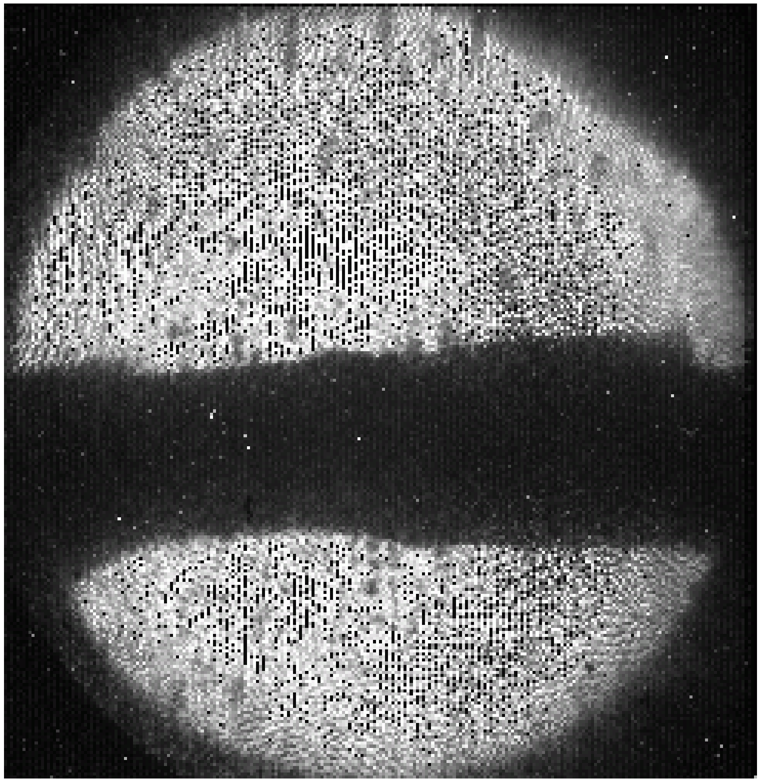
Installed in the CERN TT2a Line

Before Mating

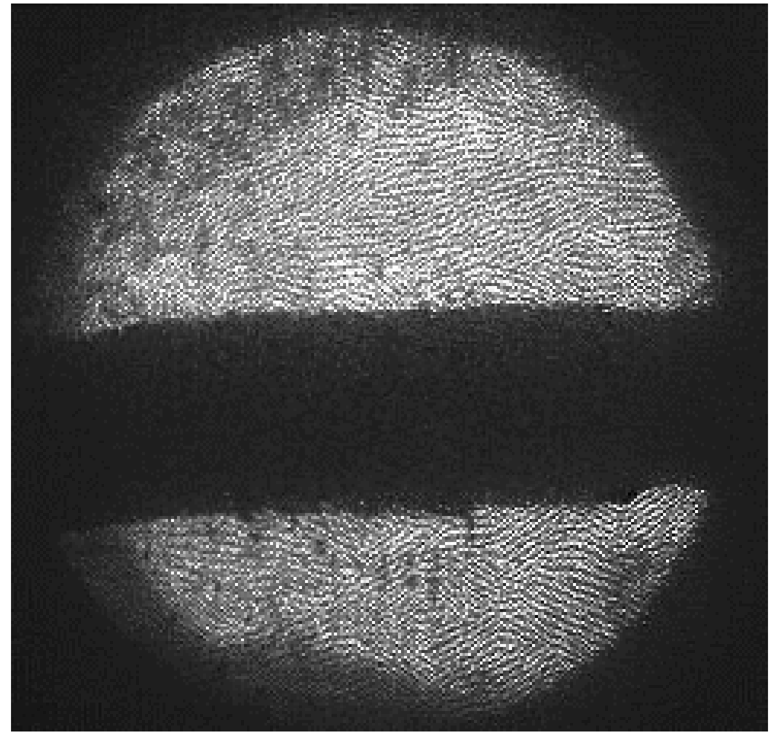


After Mating and Tilting

Optical Diagnostics



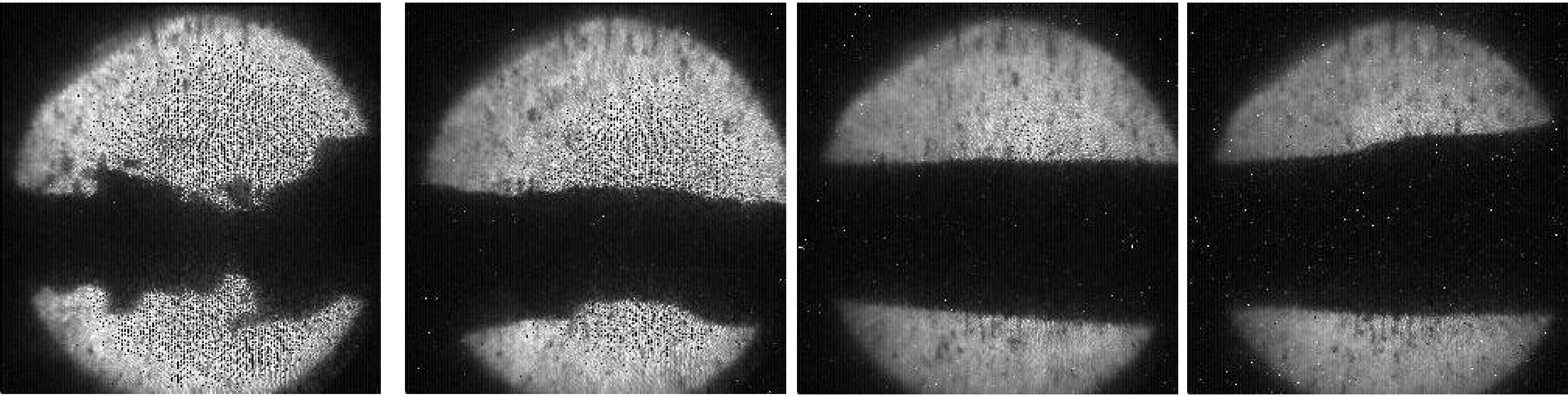
1 cm



Viewport 2
100μs/fras
Velocity Analysis

Viewport 3
500μs/fras
Disruption Analysis

Stabilization of Jet by High Magnet Field

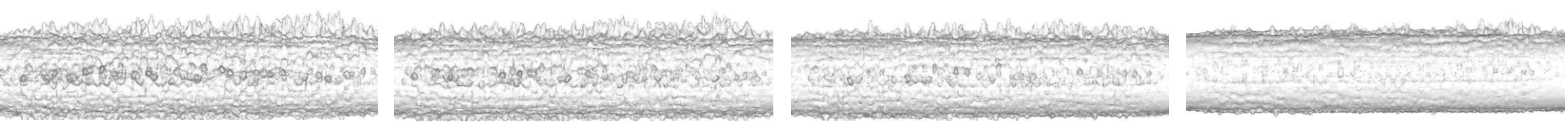


0T 5 T 10 T 15 T

Jet velocities: 15 m/s

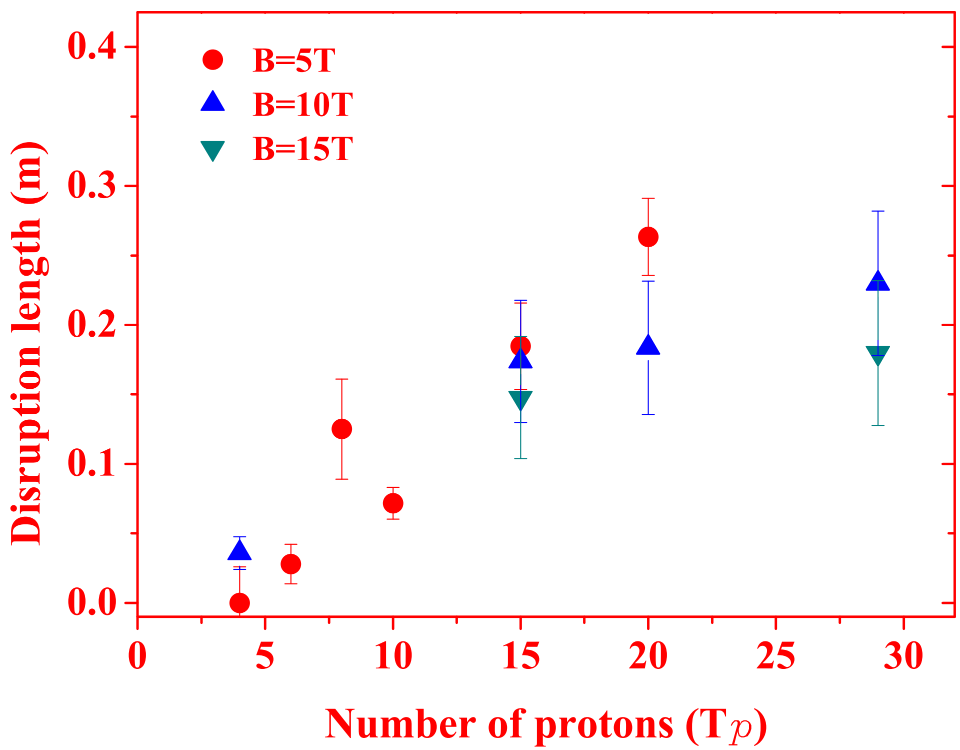
Substantial surface perturbations mitigated by high-magnetic field.

MHD simulations (W. Bo, SUNYSB):

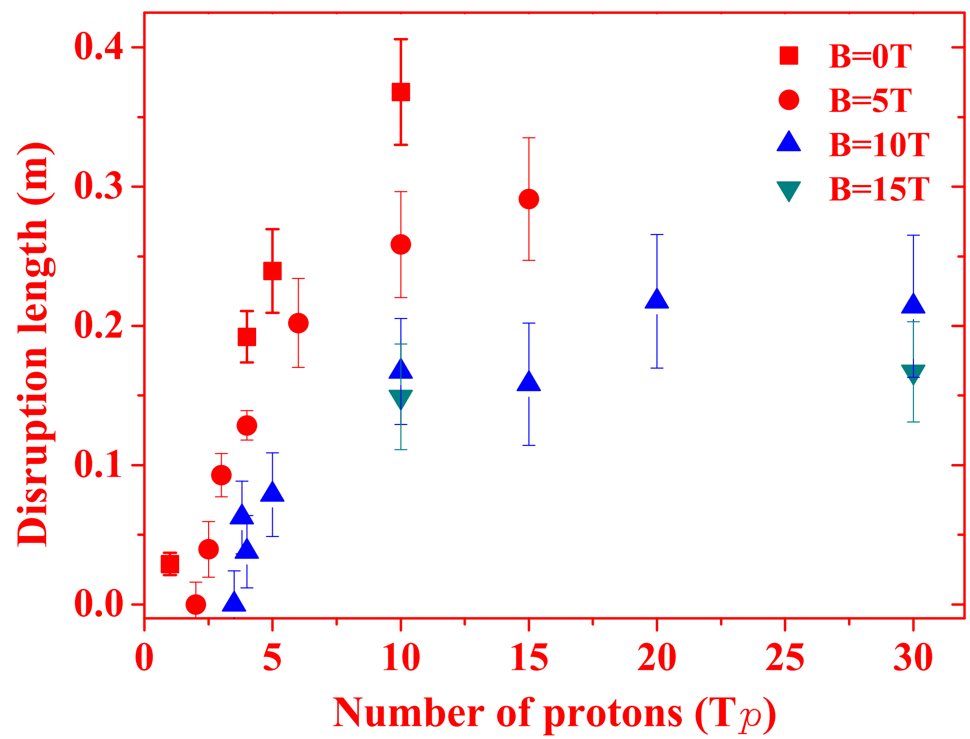


Disruption Analysis

14 GeV



24 GeV

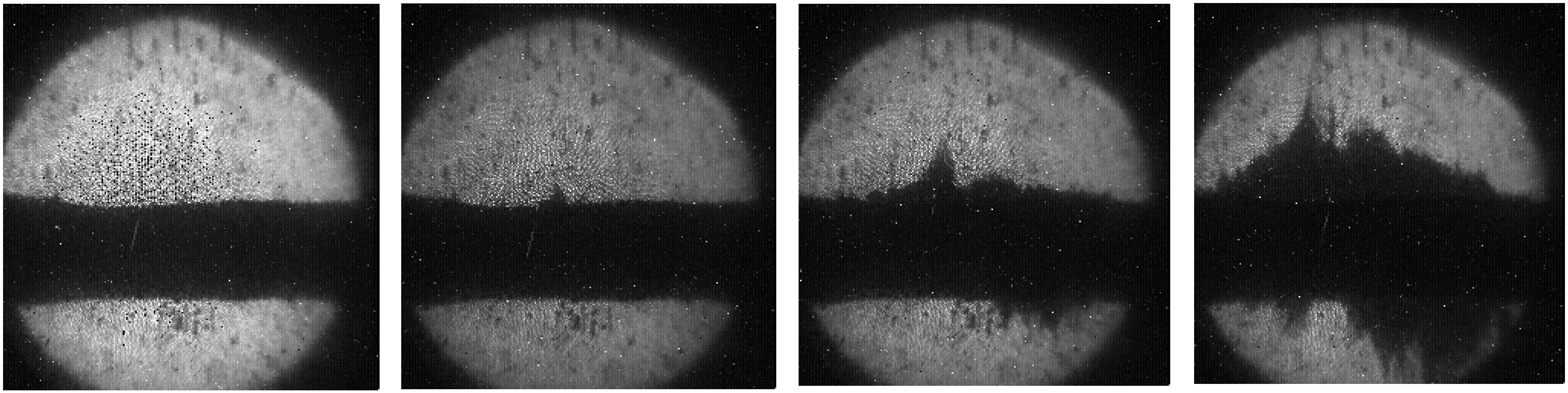


Disruption lengths reduced with higher magnetic fields

Disruption thresholds increased with higher magnetic fields

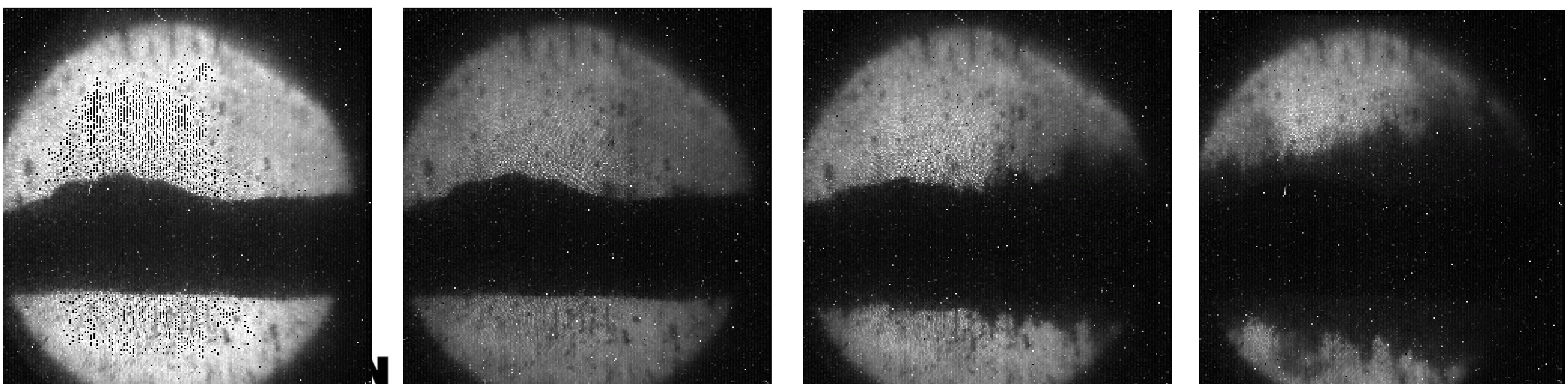
Velocity of Splash: Measurements at 24GeV

10TP, 10T   V = 54 m/s



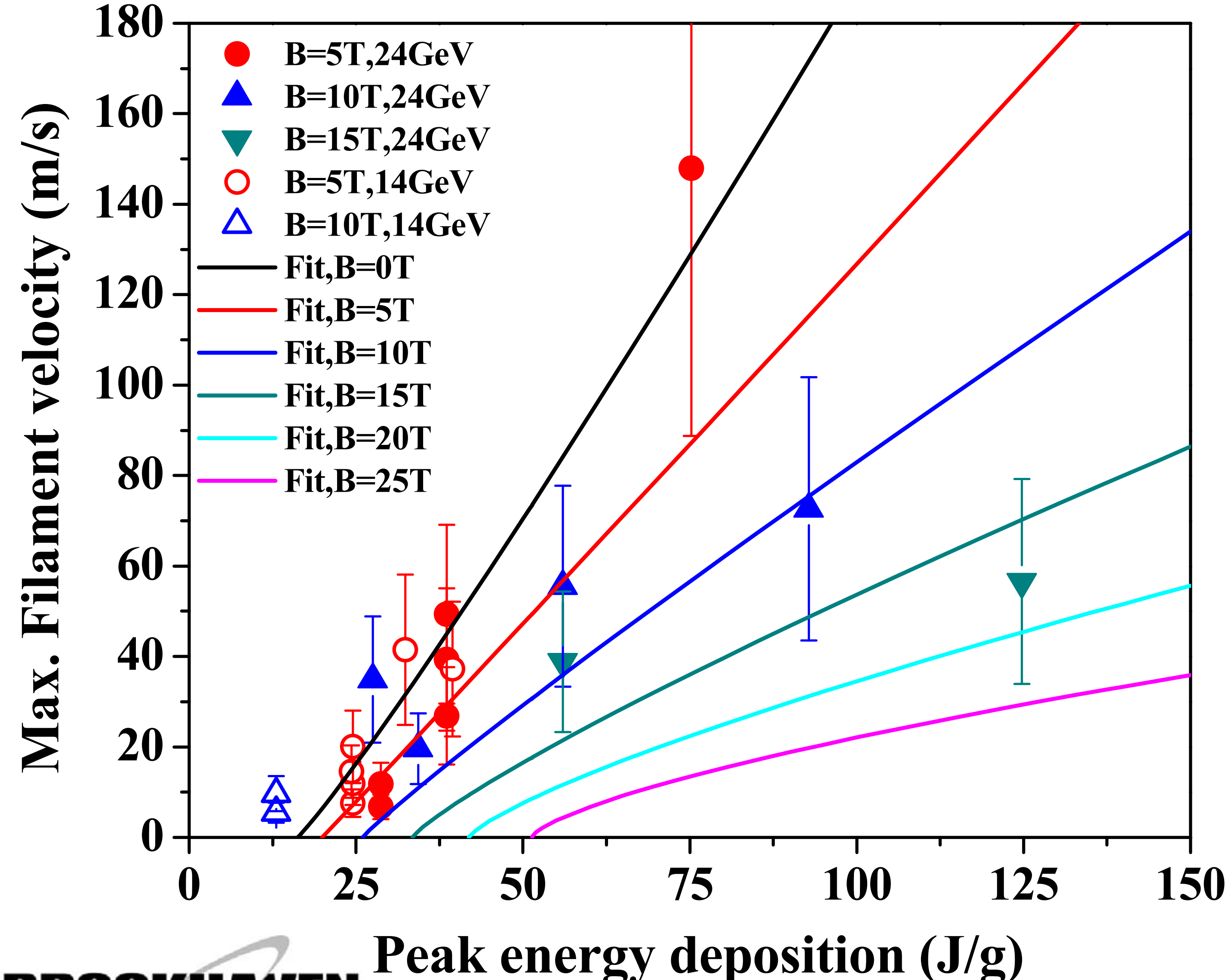
t=0   t=0.075 ms   t=0.175 ms   t=0.375 ms

20TP, 10T   V = 65 m/s



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

Filament Velocities



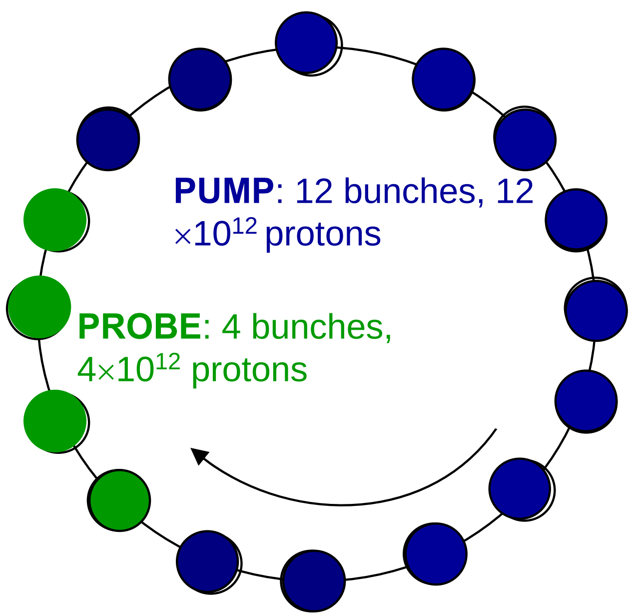
Ejection velocities are suppressed by magnetic field

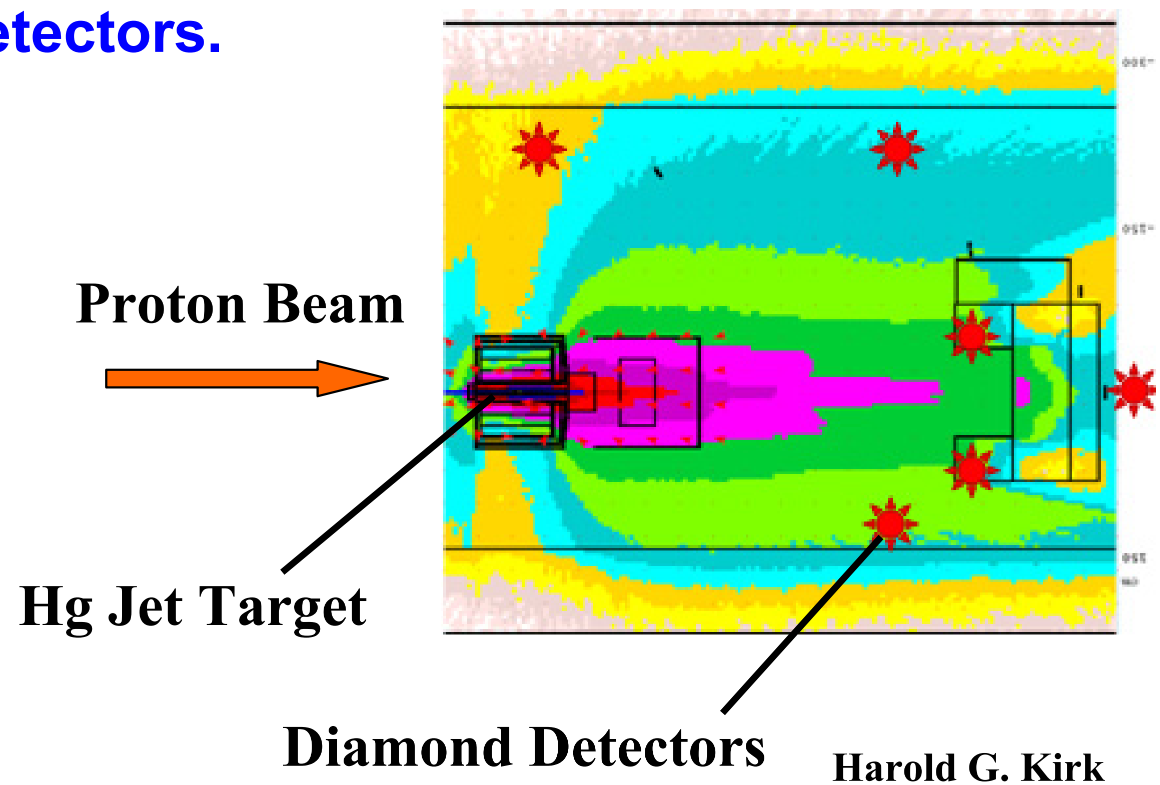
Pump-Probe Studies

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).

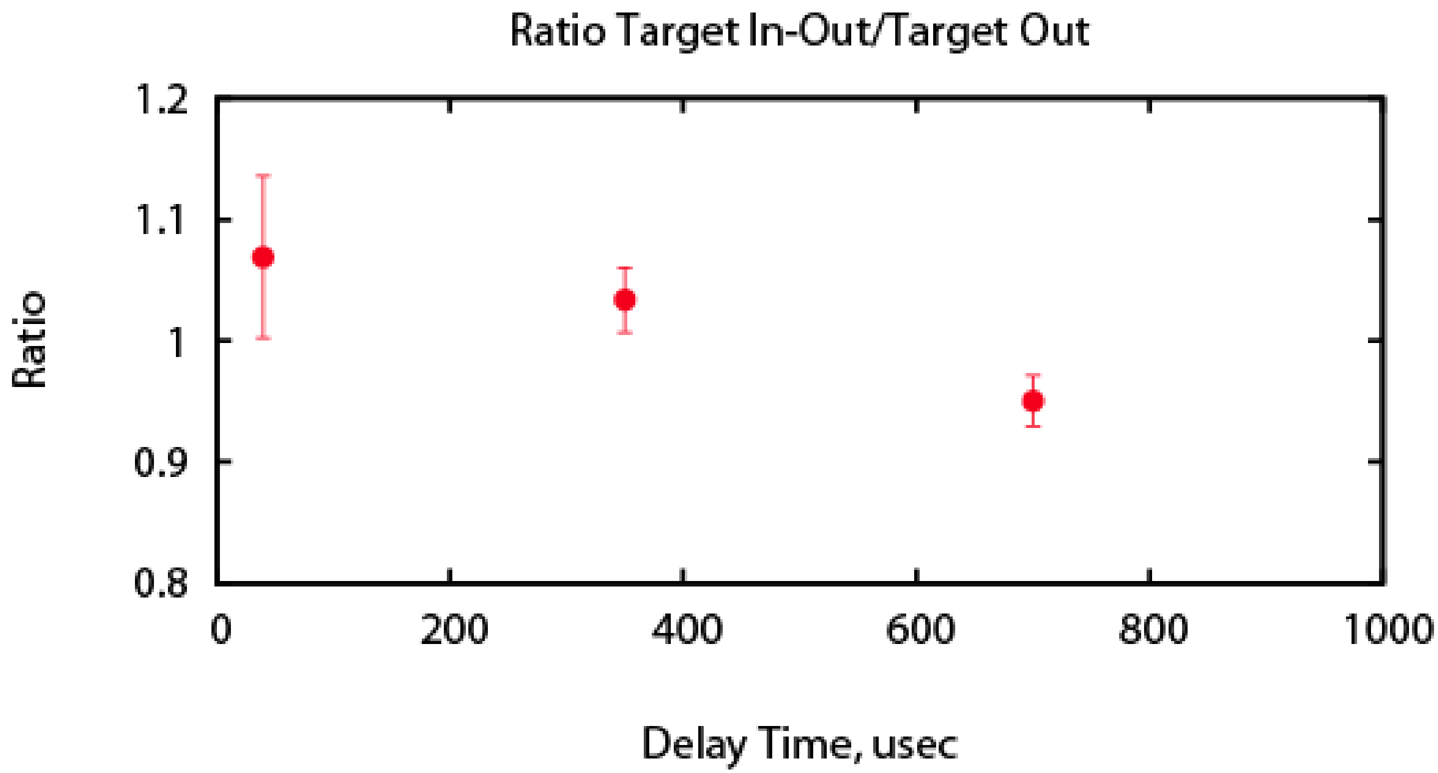
Pion production was monitored for both target-in and target-out events by a set of diamond diode detectors.





Pump-Probe Data Analysis

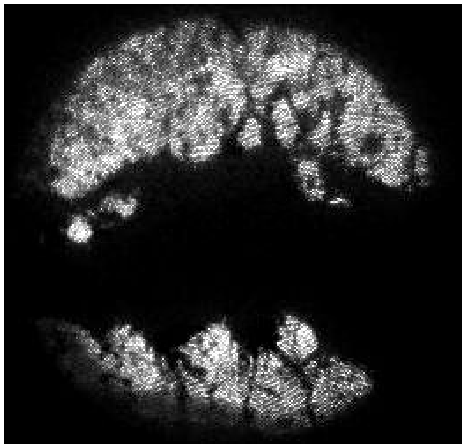
Production Efficiency: Normalized Probe / Normalized Pump



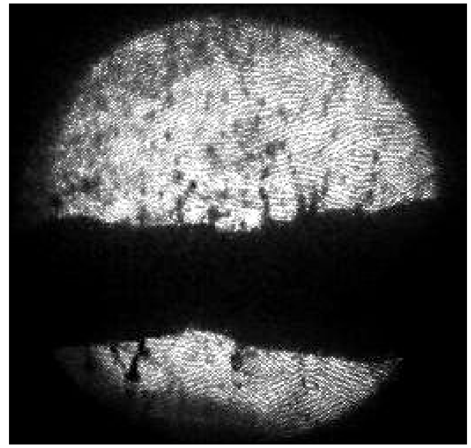
No loss of pion production for bunch delays of 40 and 350 μs,

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

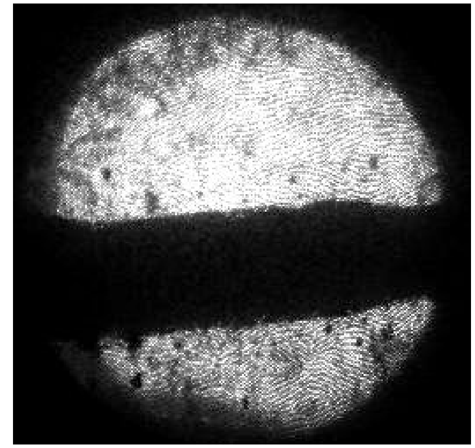
Study with 4 T*p* + 4 T*p* at 14 GeV, 10 T



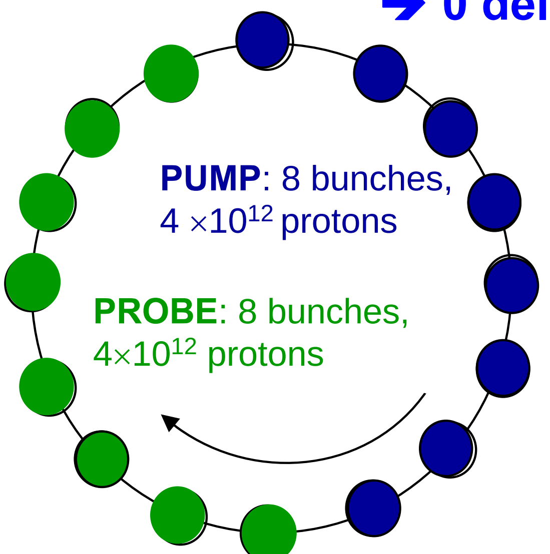
Single-turn extraction
➔ 0 delay, 8 T*p*



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 stable up to 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	≥ 17 μs	≥ 6 μs
Pulse duration:	≤ 40 μs	≤ 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

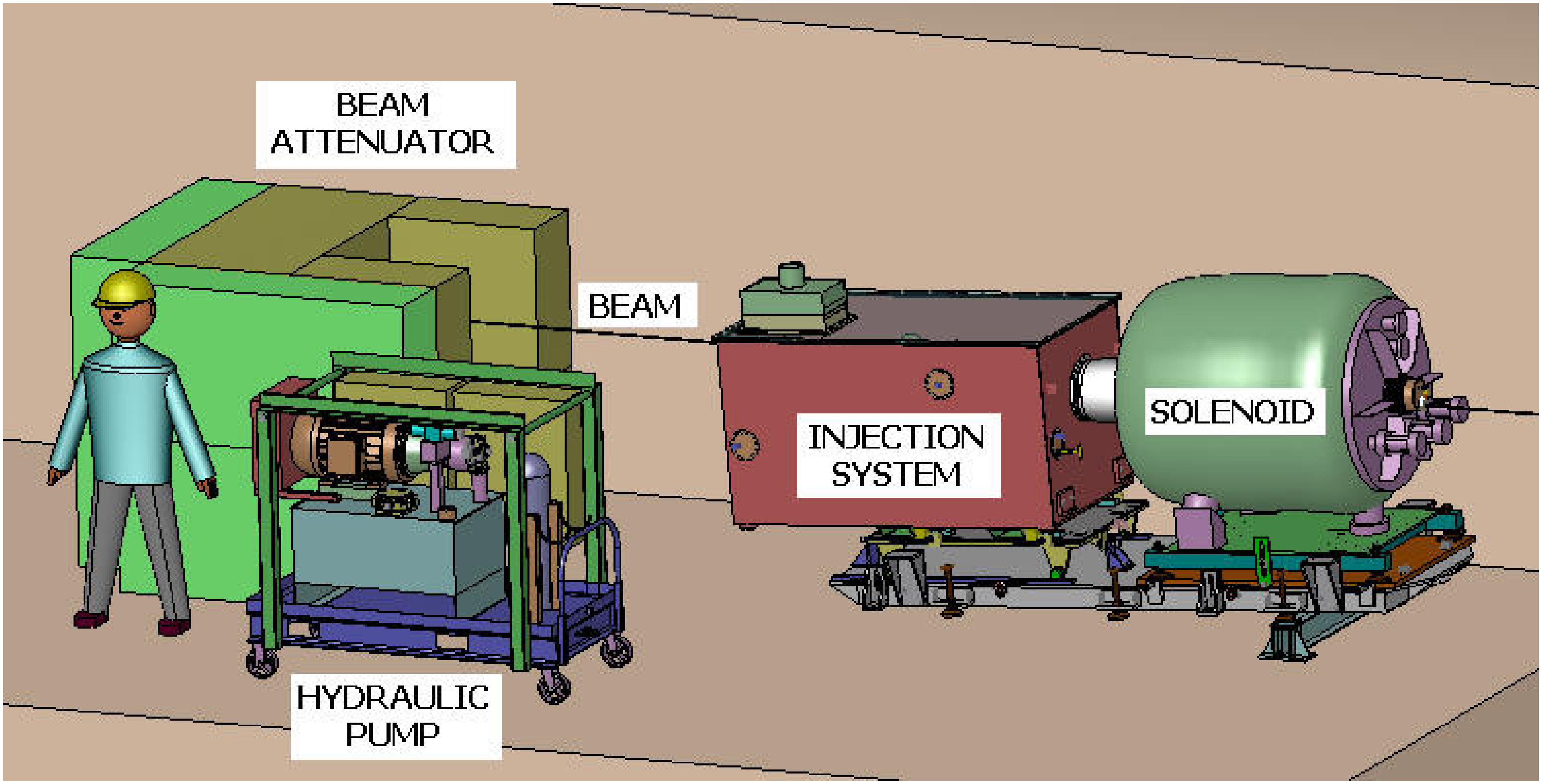
- Splash mitigation in the mercury beam dump.
- Possible drain of mercury out upstream end of magnets.
- Downstream beam window.
- Water-cooled tungsten-carbide shield of superconducting magnets.
- HTS fabrication of the superconducting magnets.
- Improved nozzle for delivery of Hg jet

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

Backup Slides

The MERIT Experiment at CERN

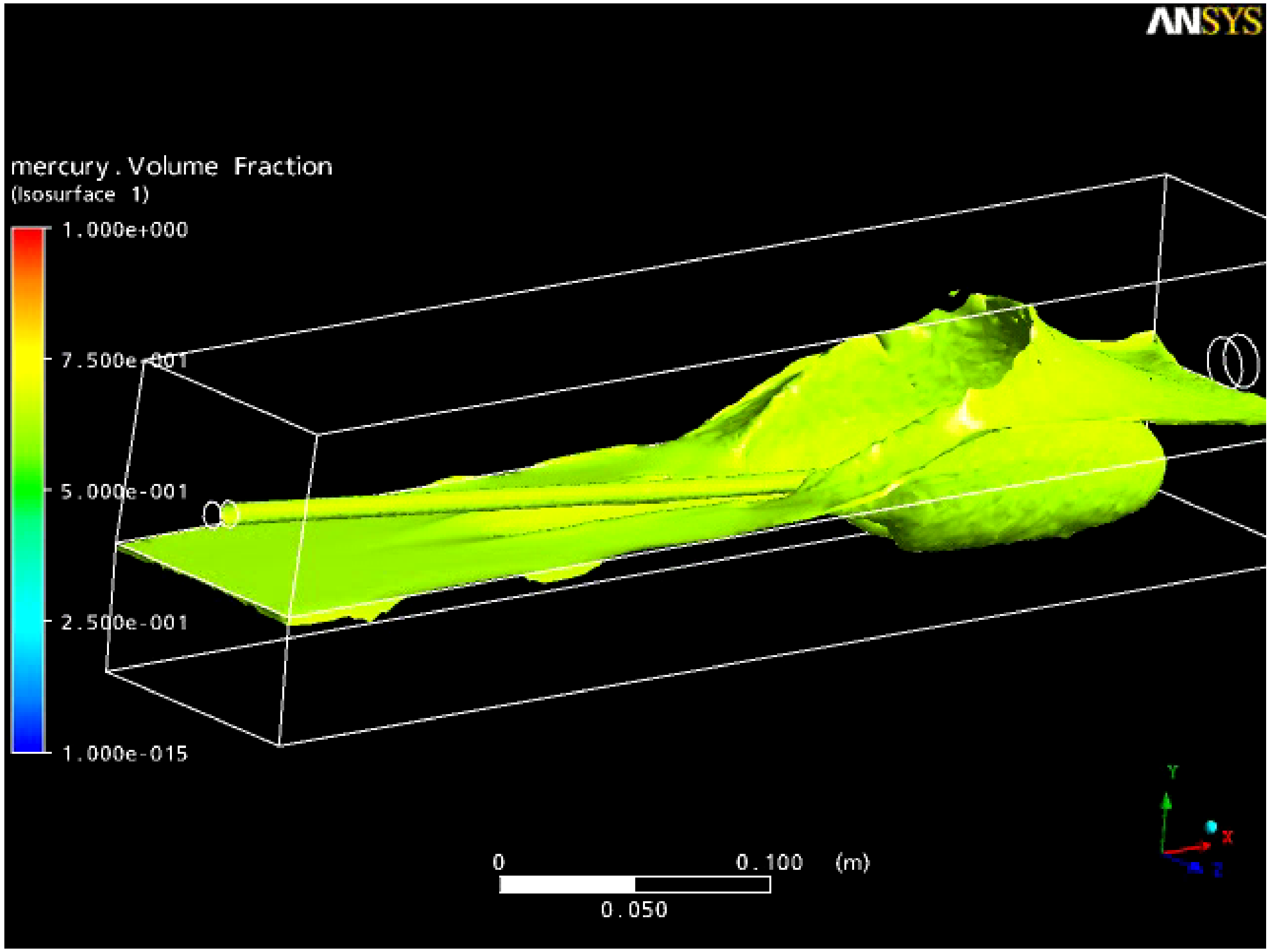


MERcury Intense Target

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

The Jet/Beam Dump Interaction



T. Davonne, RAL

Shielding the Superconducting Coils

MARS Dose Rate calculations