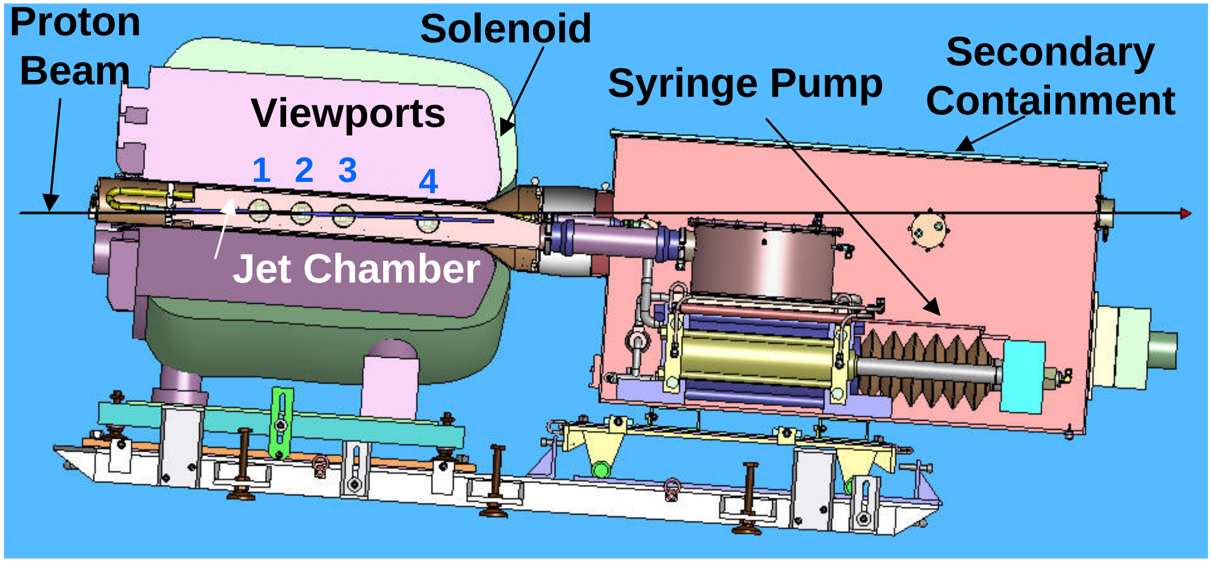
The MERIT High-Power Target Experiment

at the CERN PS



K.T. McDonald
Princeton U.

PAC'09
Vancouver, May 5, 2009

The MERIT Collaboration
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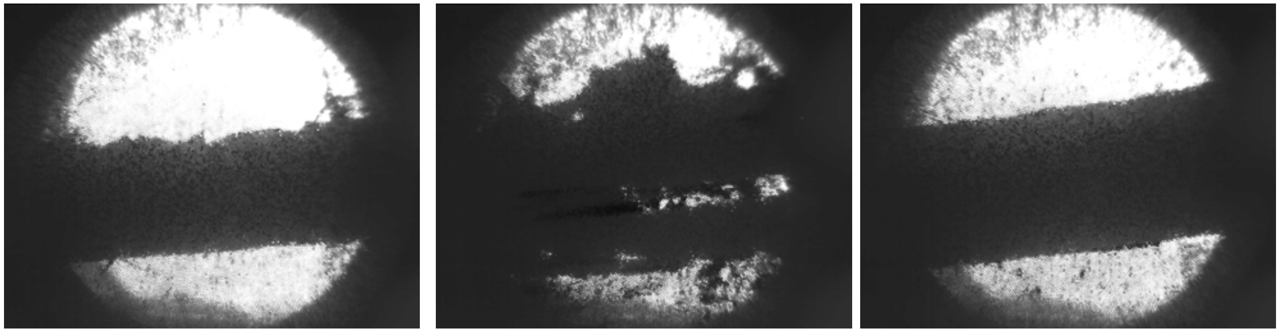
Images for 10 T*p*, 24 GeV, 10 T:



Before During After

Target Systems for a Muon Collider/Neutrino Factory

Item	Neutrino Factory Study 2	Neutrino Factory IDS / Muon Collider	Comments
Beam Power	**4 MW**	**4 MW**	No existing target system will survive at this power
E_p	**24 GeV**	**8 GeV**	π yield for fixed beam power peaks at ~ 8 GeV
Rep Rate	**50 Hz**	**50 Hz**	
Bunch width	**~ 3 ns**	**~ 3 ns**	Very challenging for proton driver
Bunches/pulse	**1**	**3**	3-ns bunches easier if 3 bunches per pulse
Bunch spacing	**-**	**~ 100 μs**	
Beam dump	**< 5 m from target**	**< 5 m from target**	Very challenging for target system
π Capture system	**20-T Solenoid**	**20-T Solenoid**	ν Superbeams use toroidal capture system
π Capture energy	**$40 < T_\pi < 180$ MeV**	**$40 < T_\pi < 180$ MeV**	Much lower energy than for ν Superbeams
Target geometry	**Free liquid jet**	**Free liquid jet**	Moving target, replaced every pulse
Target velocity	**20 m/s**	**20 m/s**	Target moves by 50 cm ~ 3 int. lengths per pulse
Target material	**Hg**	**Hg**	High-Z material favored for central, low-energy π's
Dump material	**Hg**	**Hg**	Hg pool serves as dump and jet collector
Target radius	**5 mm**	**4 mm**	Proton σ_r = 0.3 of target radius
Beam angle	**67 mrad**	**80 mrad**	Thin target at angle to capture axis maximizes π's
Jet angle	**100 mrad**	**60 mrad**	Gravity favors bringing jet in below proton beam

Solenoid Target and Capture Topology

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

Highest rate μ^+ beam to date: PSI μE4 with ≈ 10^9 μ/s from ≈ 10^{16} p/s at 600 MeV.

⇒ Some R&D needed!

R. Palmer (*BNL*, 1994) proposed a solenoidal capture system.

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

Collects both signs of π's and μ's,

⇒ Shorter data runs (with magnetic detector).

Solenoid coils can be some distance from proton beam.

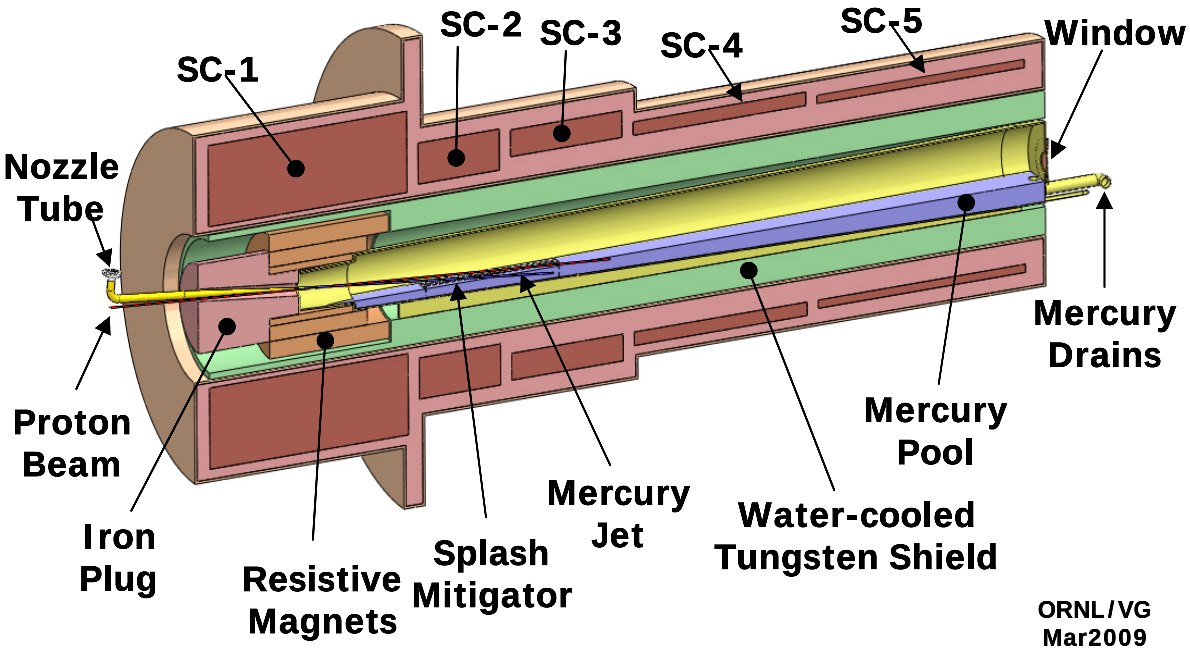
⇒ ≥ 4-year life against radiation damage at 4 MW.

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.

Neutrino Factory Study 2 Target Concept



ORNL/VG Mar2009

Remember the Beam Dump

Target of 2 interaction lengths ⇒ 1/7 of beam is passed on to the beam dump.
⇒ Energy deposited in dump by primary protons is same as in target.

Long distance from target to dump at a Superbeam,
⇒ Beam is much less focused at the dump than at the target,
⇒ Radiation damage to the dump not a critical issue (Superbeam).

Short distance from target to dump at a Neutrino Factory/Muon Collider,
⇒ Beam still tightly focused at the dump,
⇒ Frequent changes of the beam dump, or a moving dump, or a liquid dump.

A flowing liquid beam dump is the most plausible option for a Neutrino Factory, independent of the choice of target. (This is so even for a 1-MW Neutrino Factory.)

The proton beam should be tilted with respect to the axis of the capture system at a Neutrino Factory, so that the beam dump does not absorb the captured π's and μ's.

Target Options

MW energy dissipation requires liquid coolant somewhere in system

⇒ No such thing as "solid-target-only" at this power level.

The lifetime dose against radiation damage (embrittlement, cracking, ...) by protons for most solids is about $10^{22}/\mathrm{cm}^2$.

- Target lifetime of about 5-14 days at a 4-MW Neutrino Factory
- Mitigate by frequent target changes, moving target, liquid target, ...

- Static Solid Targets
  - Graphite (or carbon composite) cooled by water/gas/radiation [CNGS, NuMI, T2K]
  - Tungsten or Tantalum (discs/rods/beads) cooled by water/gas [PSI, LANL]

- Moving Solid Targets
  - Rotating wheels/cylinders cooled (or heated!) off to side [SLD, FNAL, SNS]
  - Continuous or discrete belts/chains [King]
  - Flowing powder [Densham]

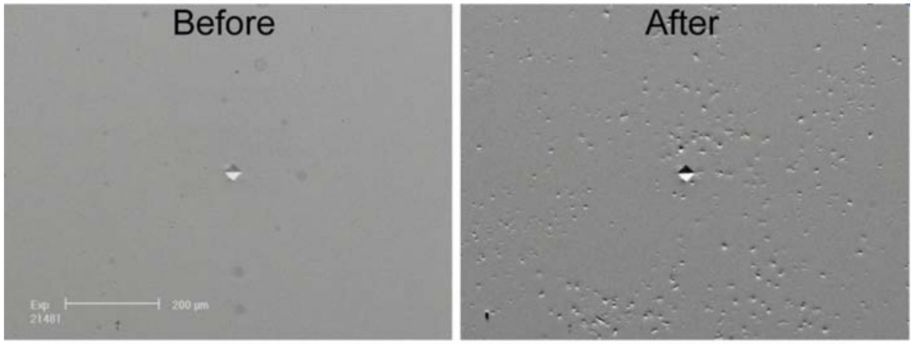
- Flowing liquid in a vessel with beam windows [SNS, ESS]
  - But, cavitation induced by short beam pulses cracks pipes!

- Free liquid jet [Neutrino Factory Study 2]

Beam-Induced Cavitation in Liquids Can Break Pipes

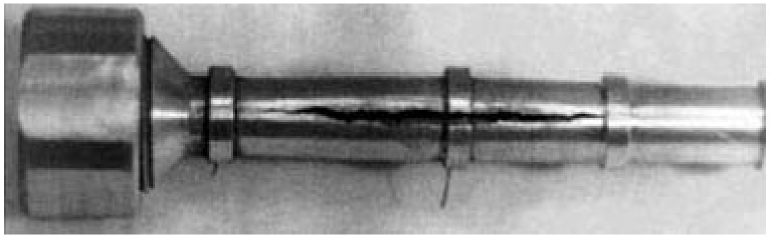
ISOLDE:

Cavitation pitting of SS wall surrounding Hg target
after 100 pulses (SNS):

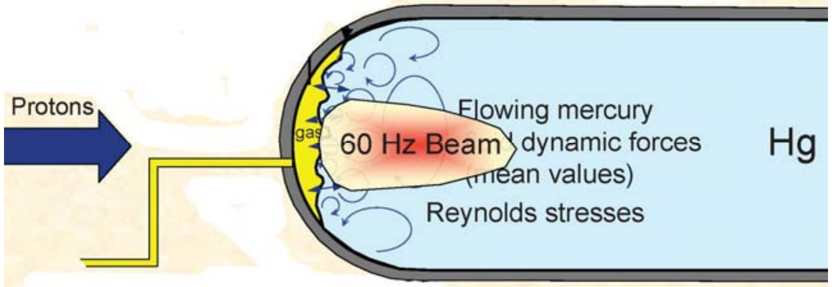


TL - High Power Target
Specimen # 29754
Equivalent SNS Power Level = 2.5

Hg in a pipe (BINP):



Mitigate(?) by gas buffer ⇒ free Hg surface:



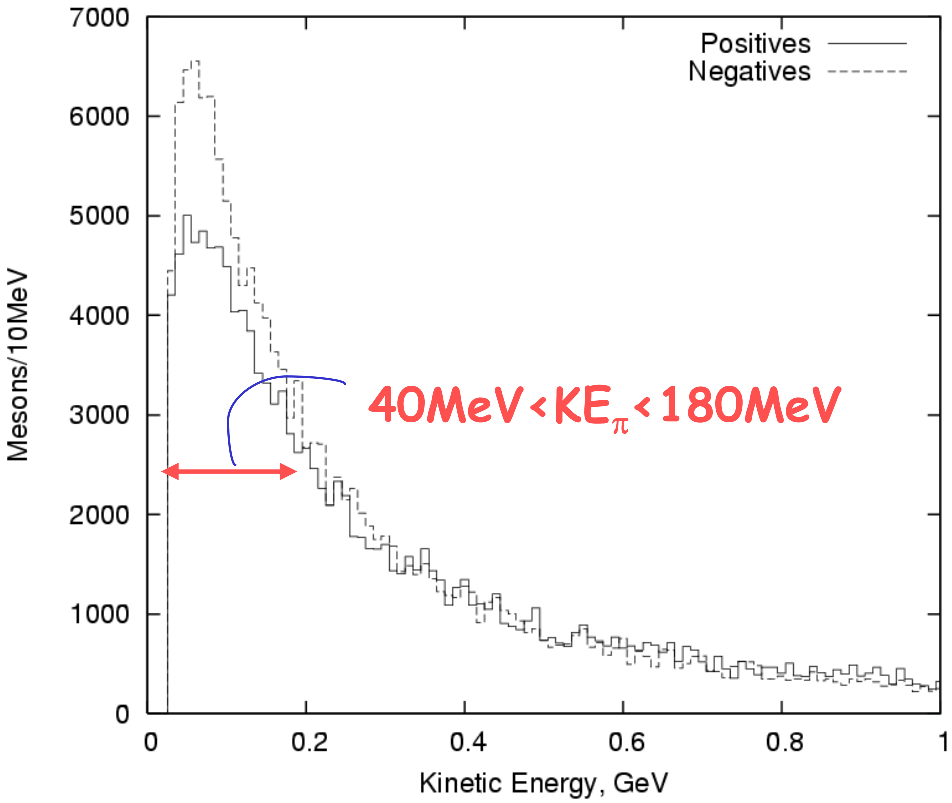
⇒ Use **free liquid jet target** when possible.

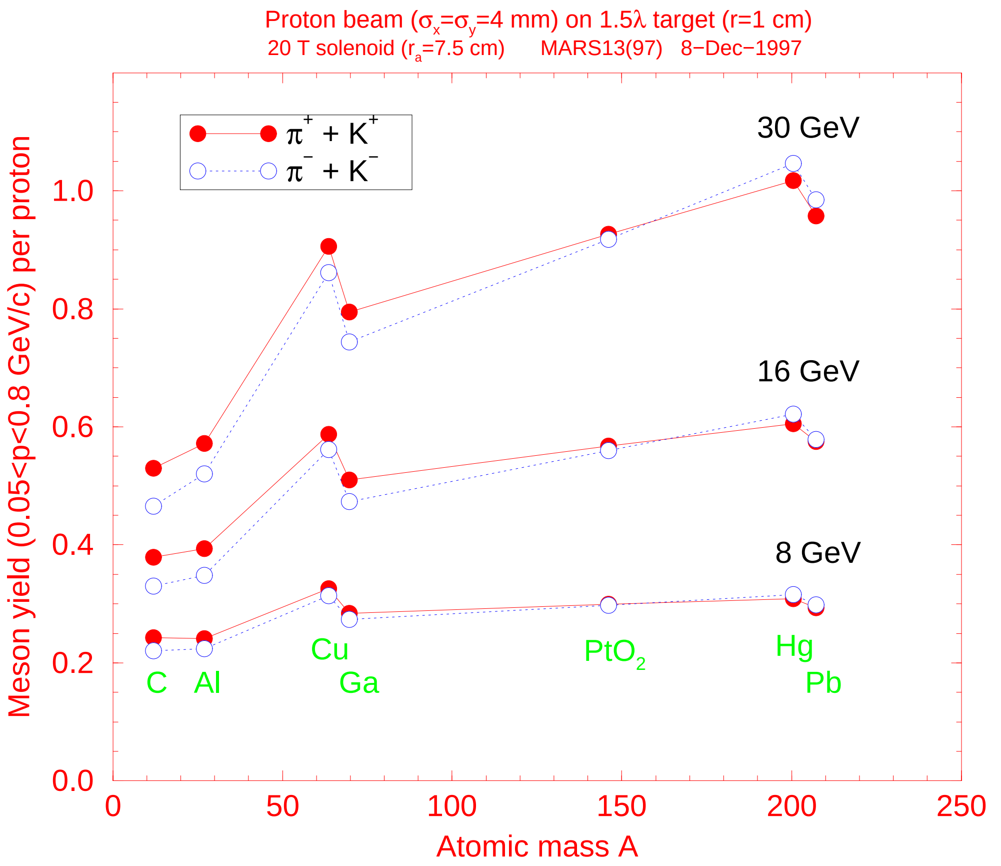
Pion Production Issues for ν Factory/Muon Collider, I

MARS simulations: N. Mohkov, H. Kirk, X. Ding

Only pions with $40 < KE_\pi < 180$ MeV are useful for later RF bunching/acceleration of their decay muons.

Hg better than graphite in producing low-energy pions (graphite is better for higher energy pions as for a Superbeam).



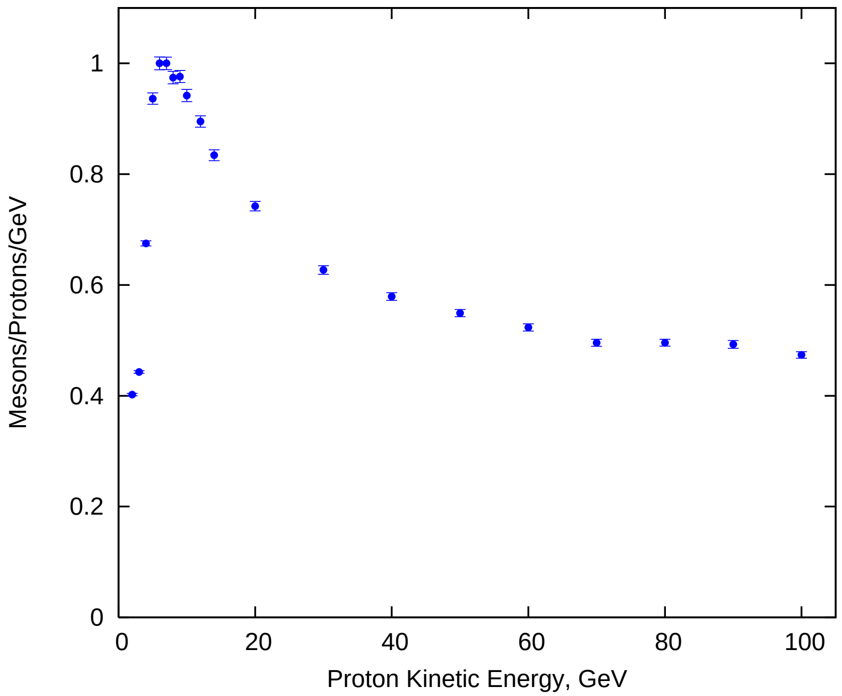


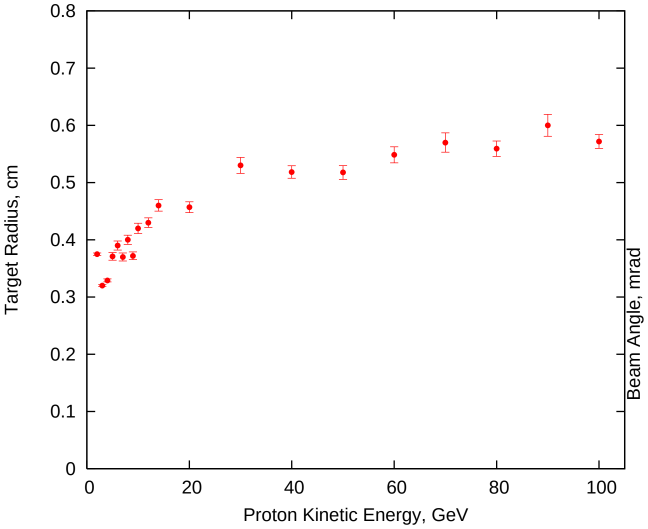
Pion Production Issues for ν Factory/Muon Collider, II

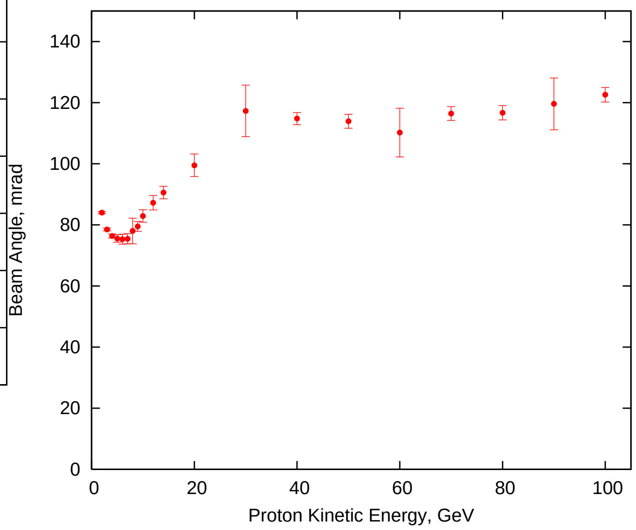
Study soft pion production as a function of 4 parameters:

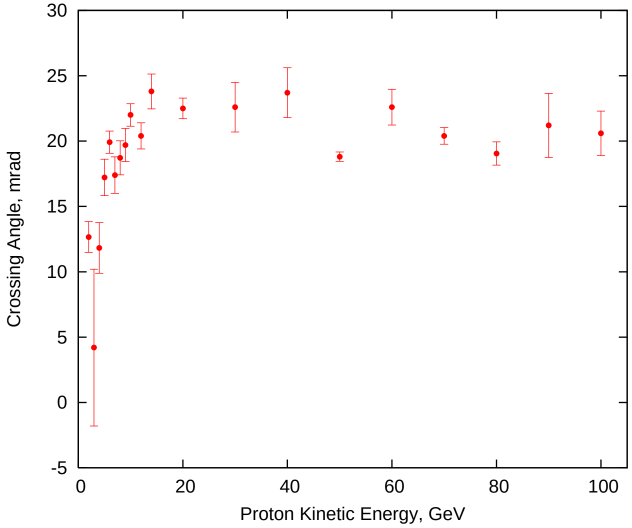
- E_{proton}
- Target radius, assuming proton $\sigma_r = 0.3 \times$ target radius
- Angle of proton beam to magnetic axis
- Angle of mercury jet to magnetic axis

Production of soft pions is optimized for a Hg target at $E_p \sim$ 6-8 GeV, according to a MARS15 simulation. [Confirmation of low-energy dropoff by FLUKA highly desirable.]


Normalized Distribution


Optimized Target Radius


Optimized Beam Angle


Optimized Crossing Angle

WE6PFP102

Pion Production Issues for ν Factory/Muon Collider, III

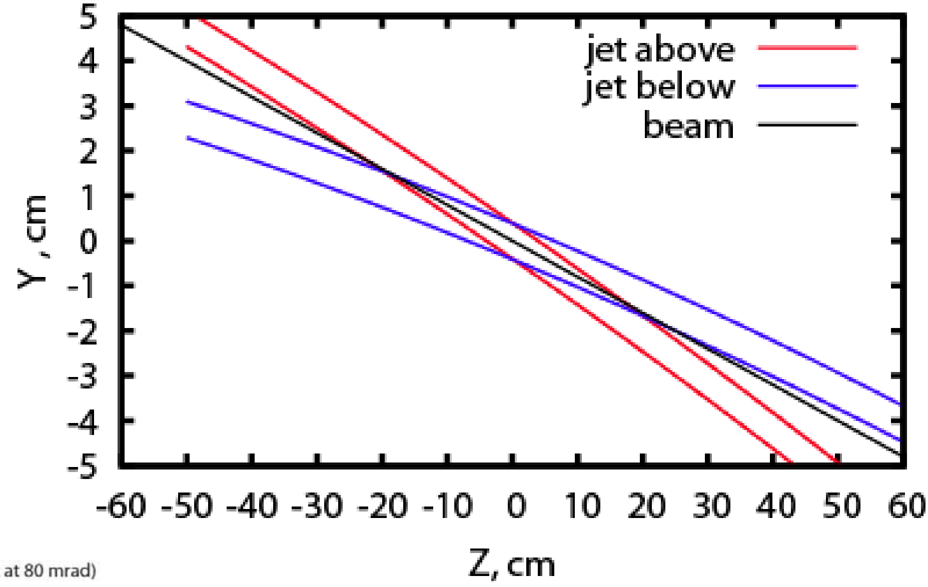
For E_p = 8 GeV, optimal target radius = 4 mm,
optimal proton beam angle = 80 mrad,
optimal jet-beam crossing angle = 20 mrad.

Gravity deflects a 20-m/s jet by 20 mrad in 50 cm,

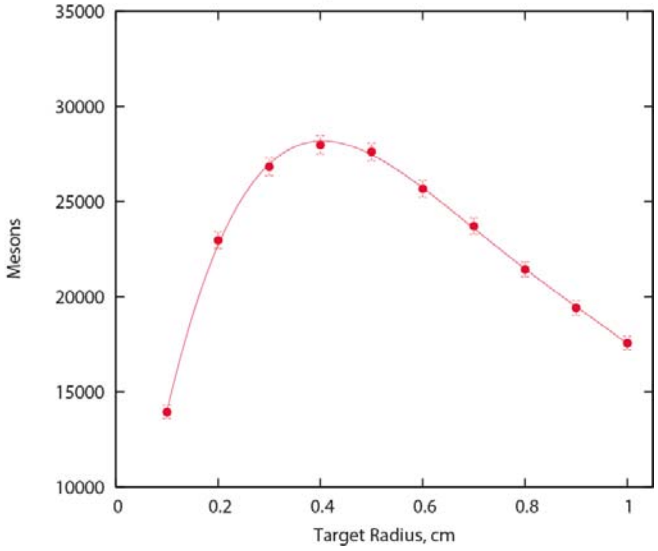
⇒ Bring jet in from below proton beam for larger clearance between nozzle and beam.

[Jet recrosses proton beam at z = 160 cm, y = -12 cm, i.e., close to surface of mercury pool.]

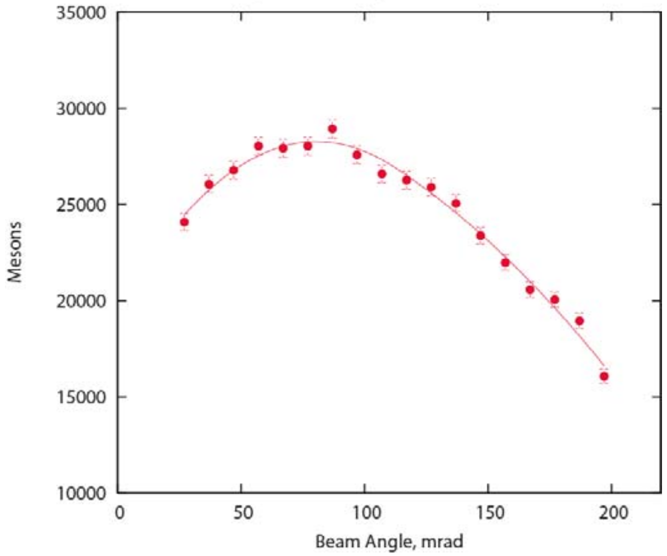
Hg Jet/Proton Beam Trajectories



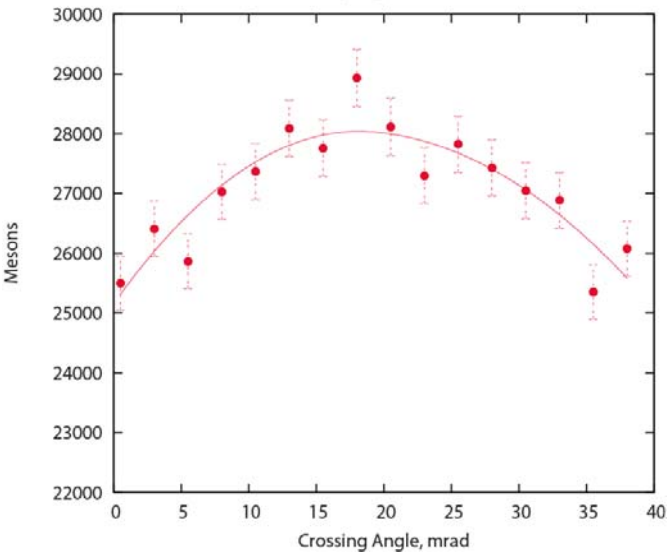
Vary the Target Radius (Peak at 0.4 cm)



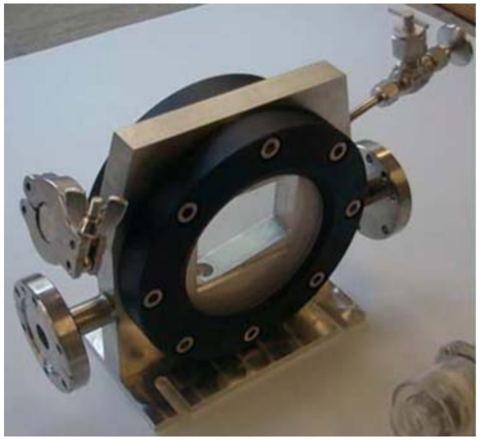
Vary the Beam Angle (Peak at 80 mrad)

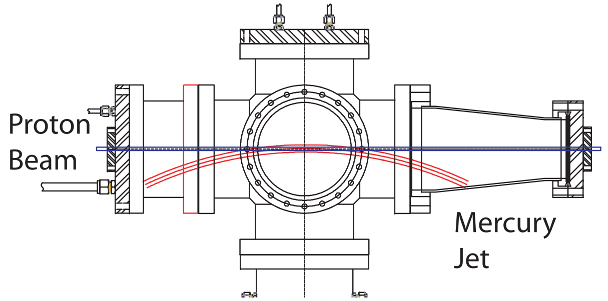


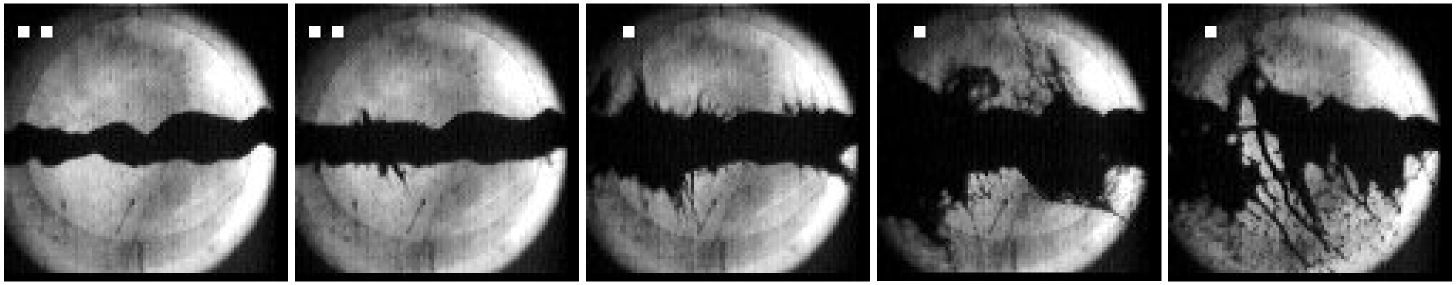
Vary the Crossing Angle (Peak at 18.2 mrad)

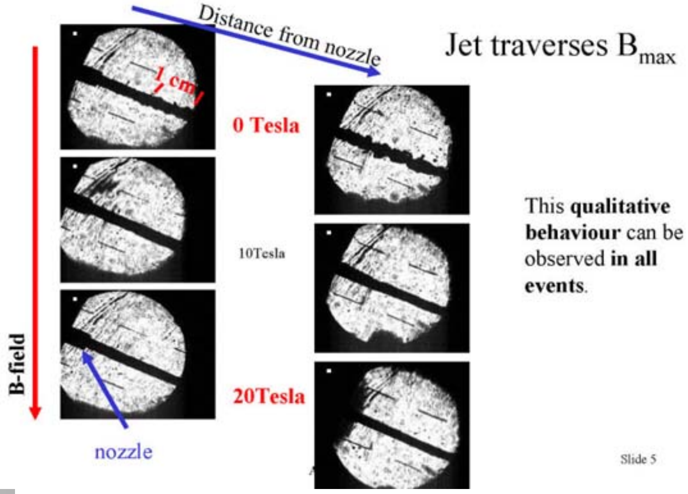


Mercury Target Tests (BNL-CERN, 2001-2002)









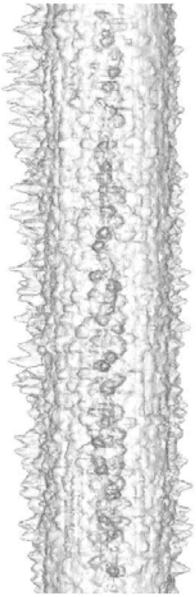
This **qualitative behaviour** can be observed **in all events**.

Data: $v_{dispersal} \approx$ 10 m/s for $U \approx$ J/g.
$v_{dispersal}$ appears to scale with proton intensity.
The dispersal is not destructive.
Filaments appear only ≈ 40 μs after beam,
⇒ After several bounces of waves, OR v_{sound} very low.
Rayleigh surface instability damped by high magnetic field.

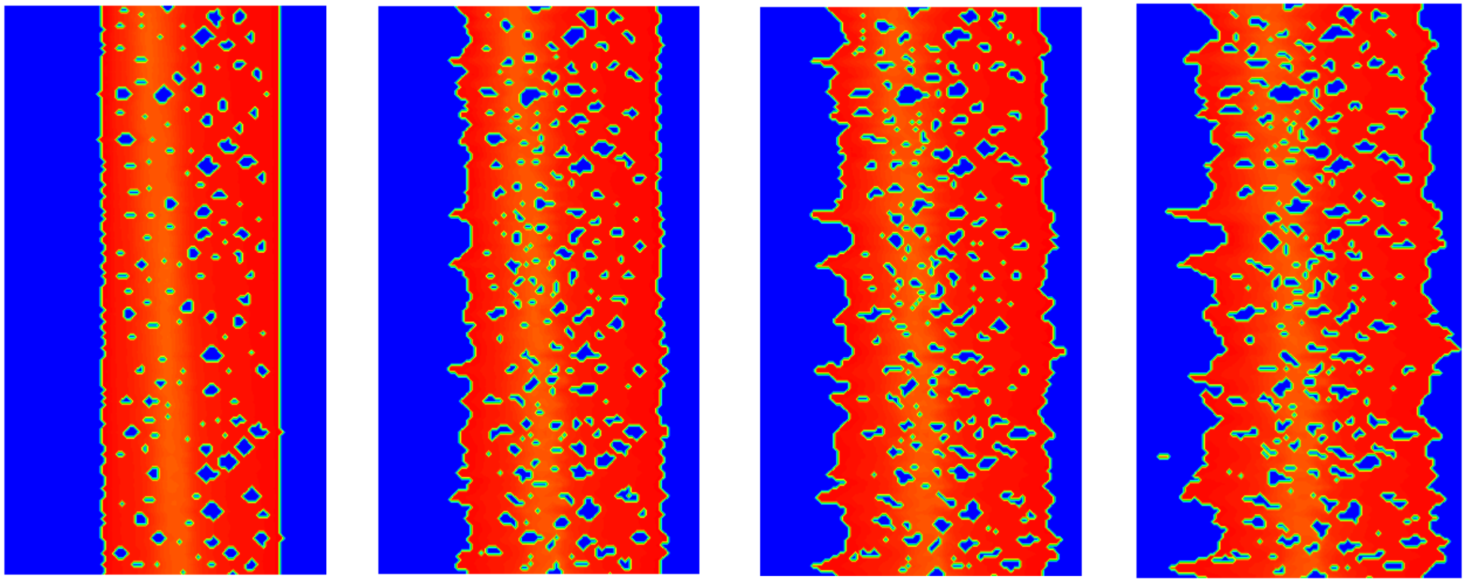
(PhD thesis: A. Fabich)

Magnetohydrodynamic Simulations (R. Samulyak, W. Bo)

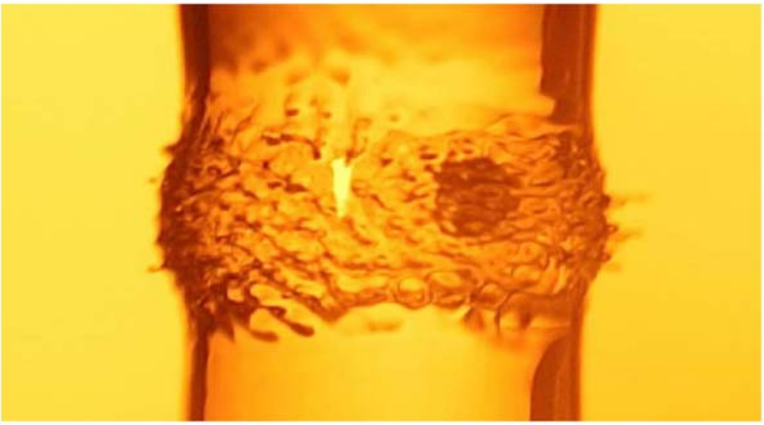
FRONTIER simulations, with cavitation, of effects of energy deposited by an intense proton pulse.



Surface filaments at 160 μs



Water jet ripples generated by a 8 mJ Laser cavitation bubble



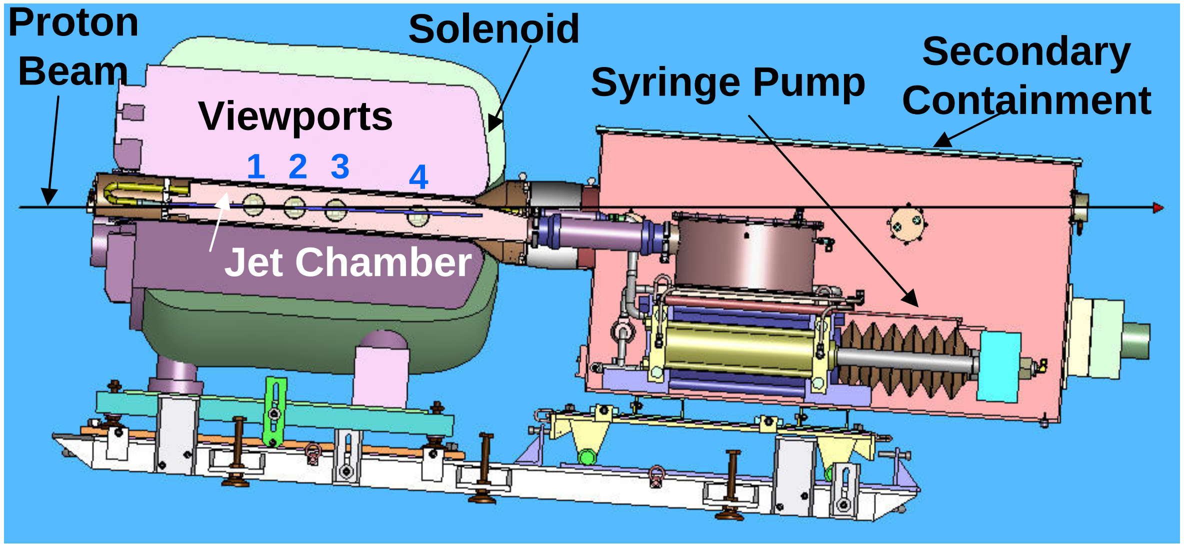
Laser-induced breakup of a water jet:

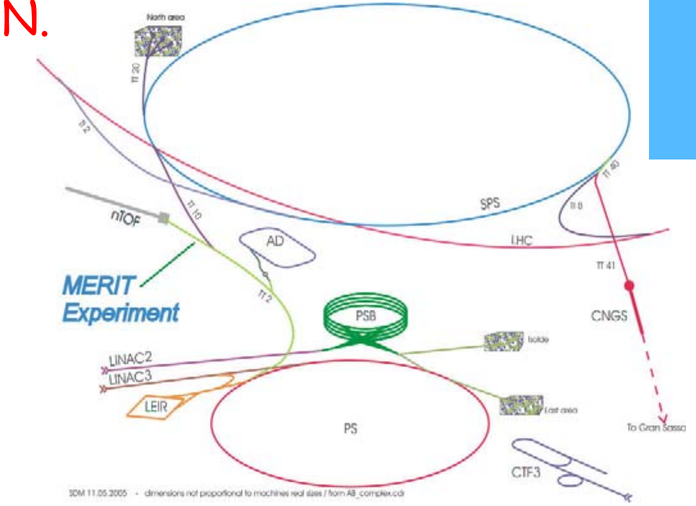
(J. Lettry, CERN)

CERN MERIT Experiment (Nov 2007)

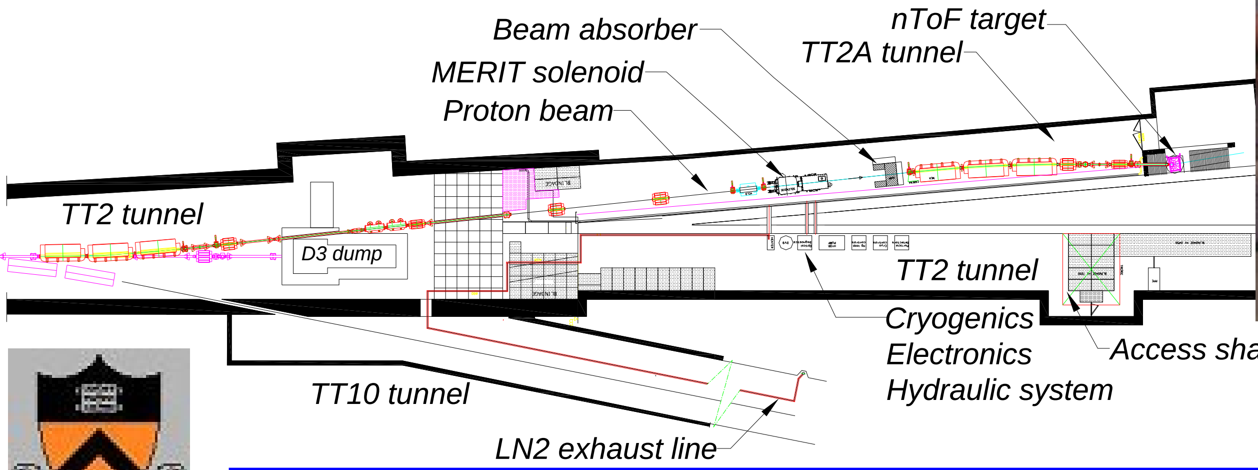
Proof-of-principle demonstration of a mercury jet target in a strong magnetic field, with proton bunches of intensity equivalent to a 4 MW beam.

Performed in the TT2A/TT2 tunnels at CERN.





SDM 11.05.2005 - dimensions not proportional to machines real sizes / from AB_complex.cdr



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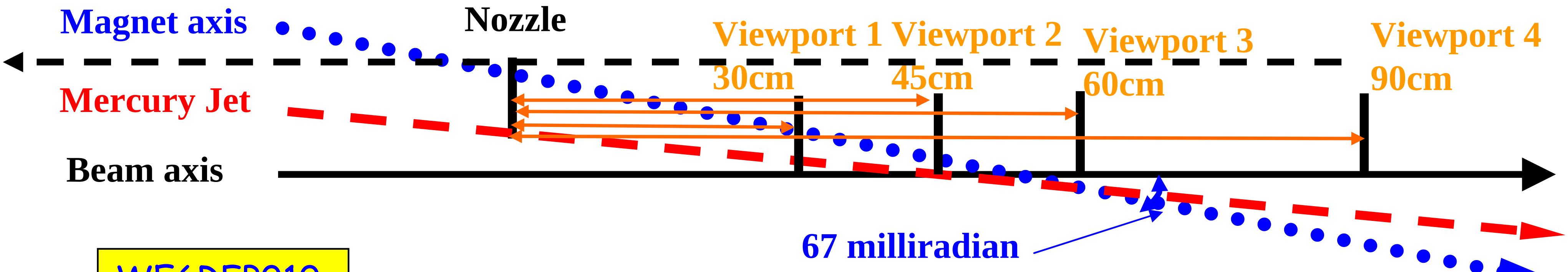
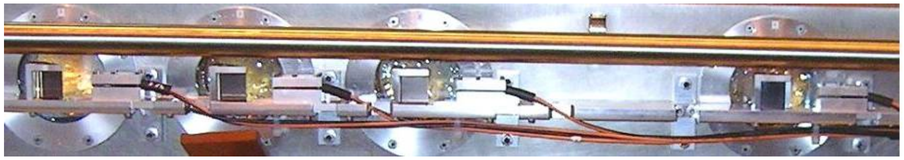
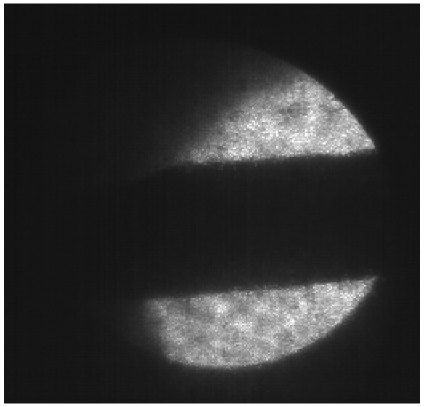
Optical Diagnostics of the Mercury Jet (T. Tsang)


Magnet axis
Nozzle
Viewport 1
30cm
Viewport 2
45cm
Viewport 3
60cm
Viewport 4
90cm
Mercury Jet
Beam axis
67 milliradian

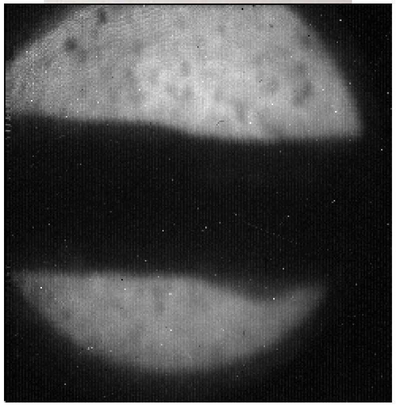
WE6RFP010



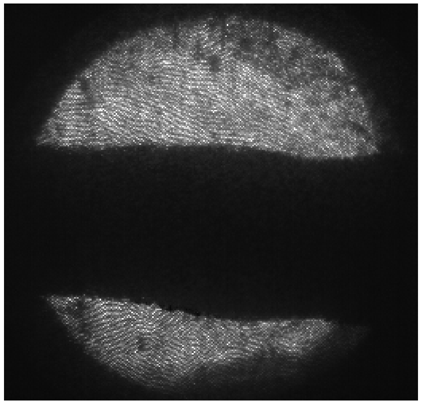
Viewport 1, FV Camera
6 μs exposure
260x250 pixels



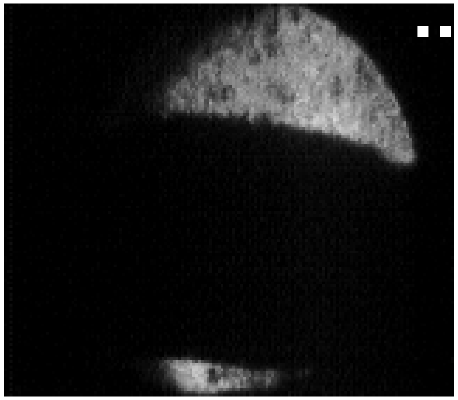
Viewport 2, SMD Camera
0.15 μs exposure
245x252 pixels



Viewport 3, FV Camera
6 μs exposure
260x250 pixels



Viewport 4, Olympus
33 μs exposure
160x140 pixels



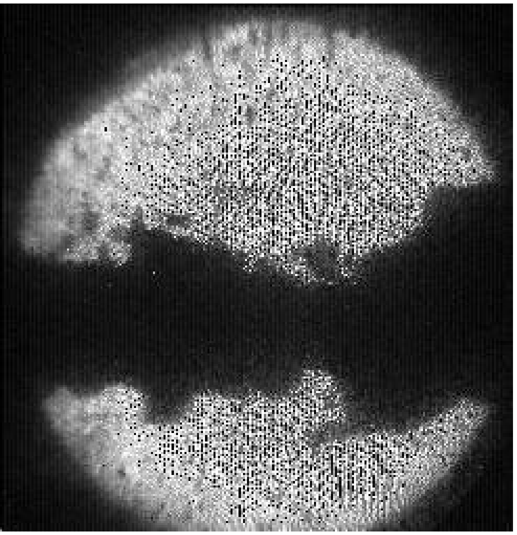
7 T,
no beam

Stabilization of Jet Velocity by High Magnet Field

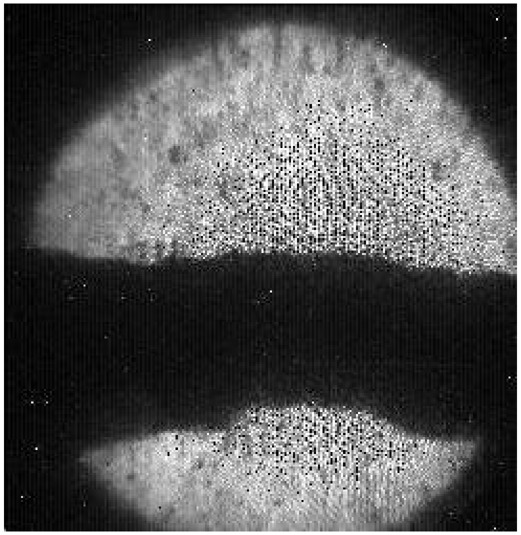
The mercury jet showed substantial surface perturbations in zero magnetic field.

These were suppressed, but not eliminated in high magnetic fields.

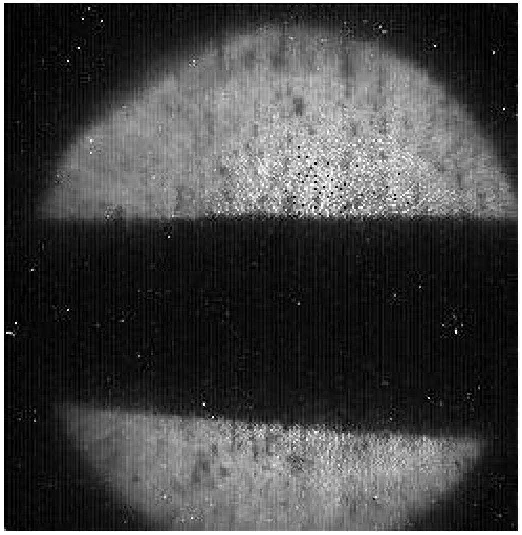
Jets with velocity 15 m/s:



0T



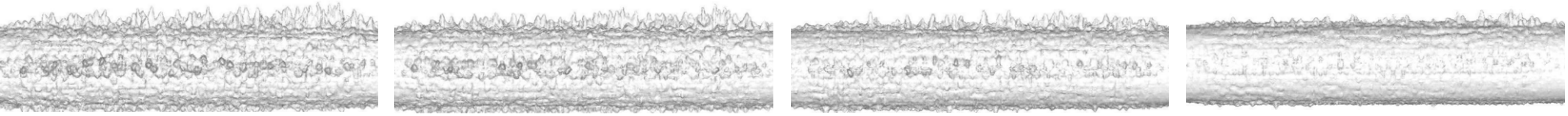
5 T



10 T

15 T

MHD simulations:



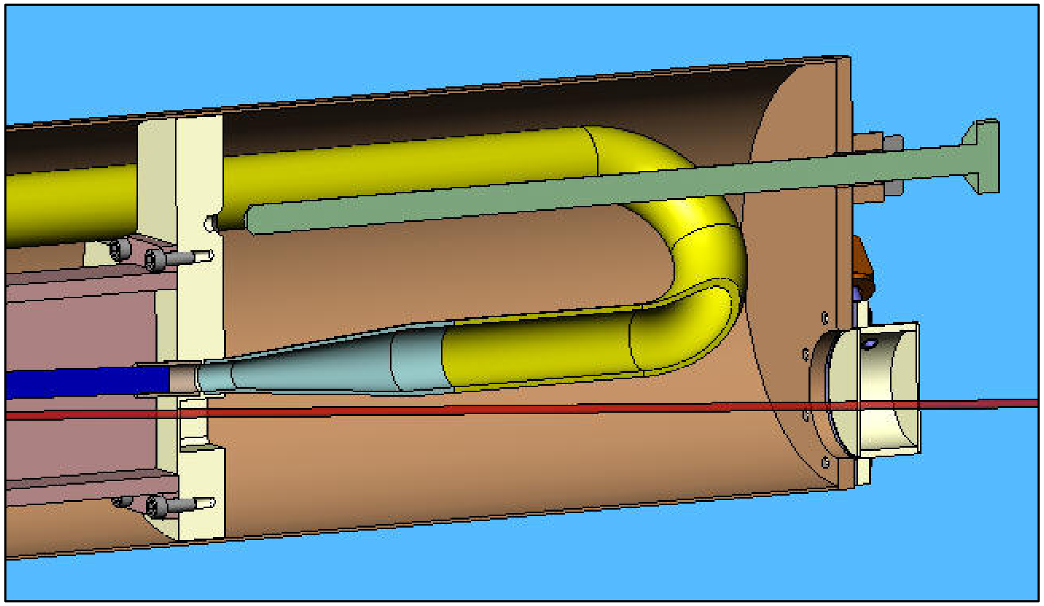
Jet Height

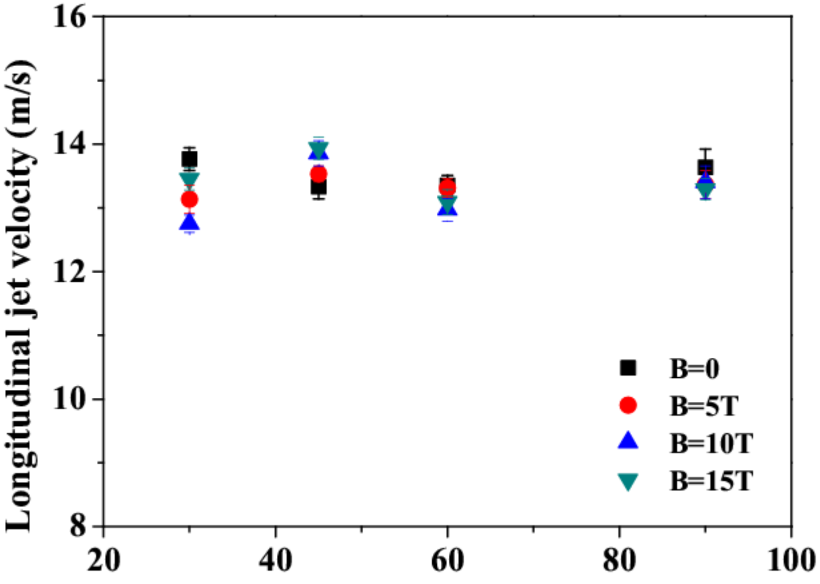
The velocity of surface perturbations on the jet was measured at all 4 viewports to be about 13.5 m/s, independent of magnetic field.

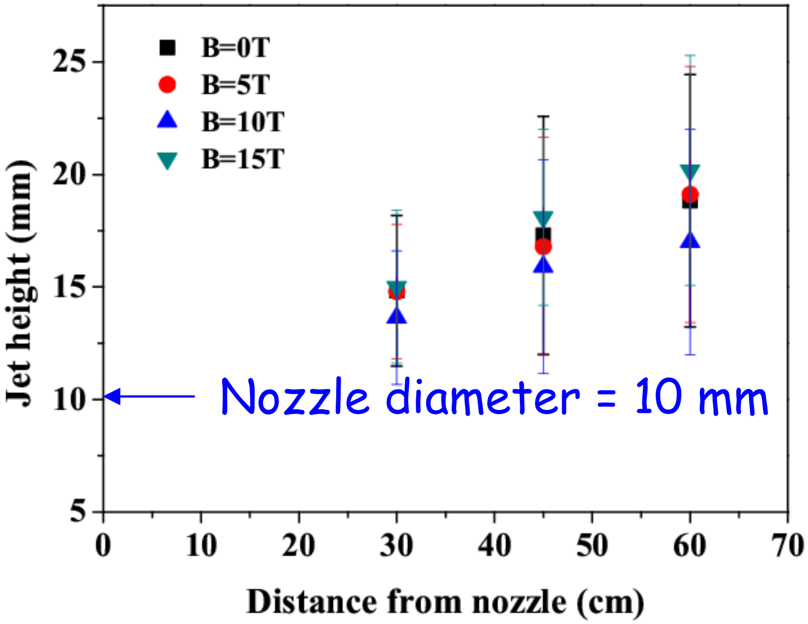
The vertical height of the jet grew ~ linearly with position to ~ double its initial value of 1 cm after 60 cm, almost independent of magnetic field.

Did the jet stay round, but have reduced density (a spray) or did the jet deform into an elliptical cross section while remaining at nominal density?

This issue may have been caused by the 180° bend in the mercury delivery pipe just upstream of the nozzle.

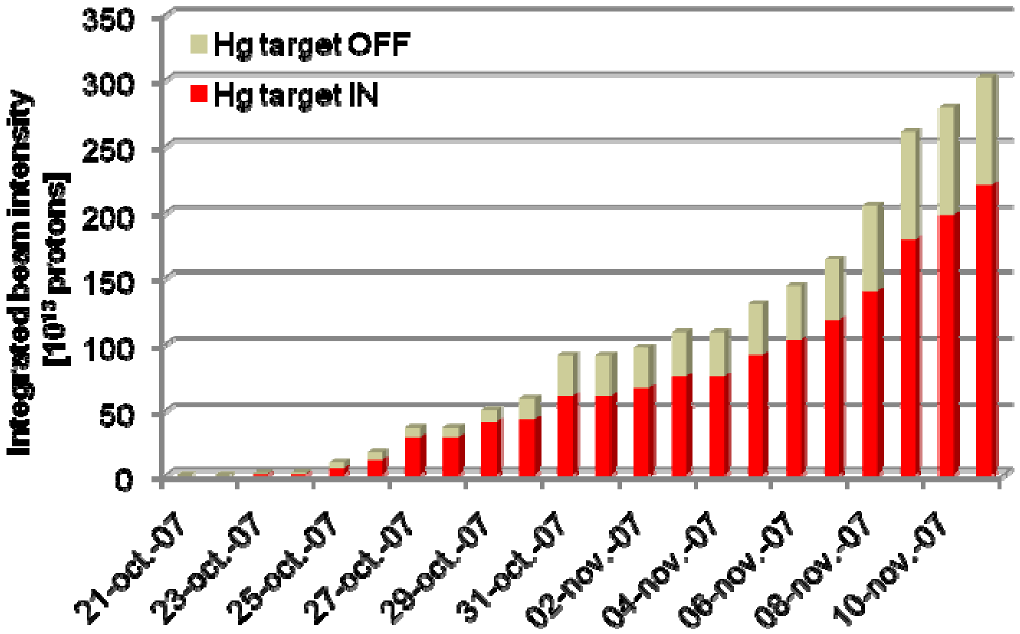






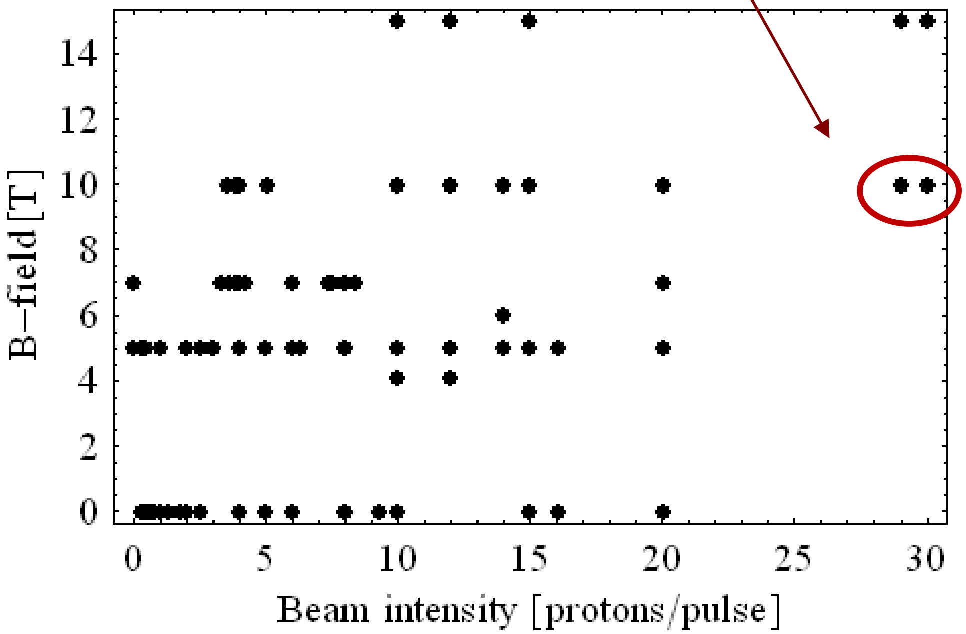
Nozzle diameter = 10 mm

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 !

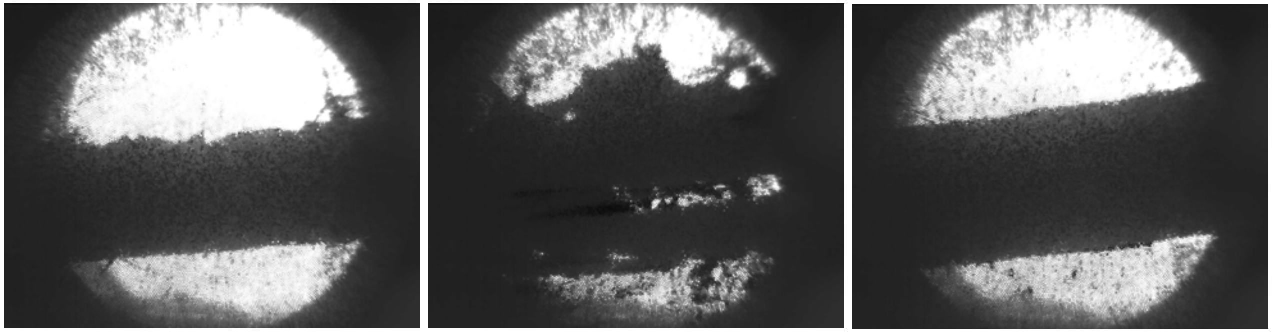


1 T*p* = 10^{12} protons

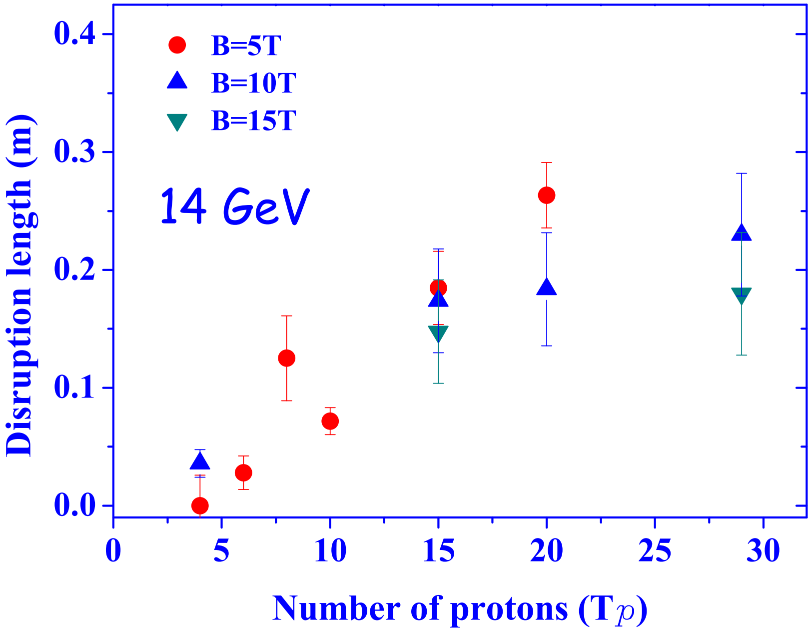
Disruption Length Analysis (H. Park)

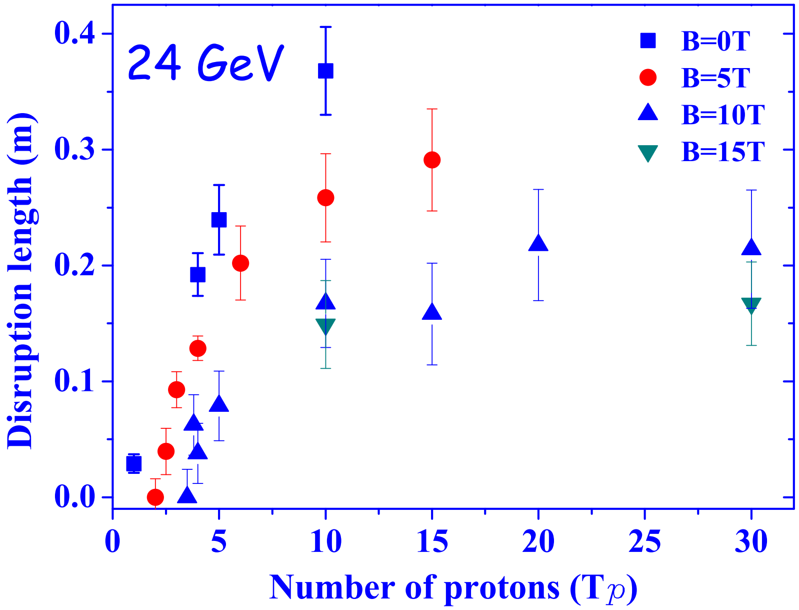
Observe jet at viewport 3 at 500 frames/sec to measure total length of disruption of the mercury jet by the proton beam.

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



Before | During | After





Disruption length never longer than region of overlap of jet with proton beam.

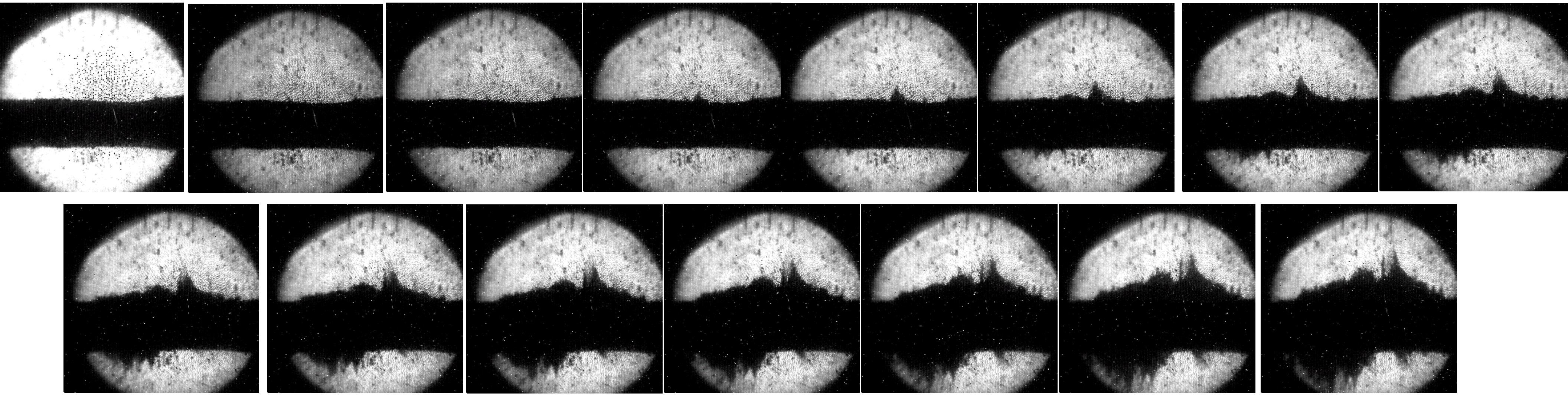
No disruption for pulses of < 2 T*p* in 0 T (< 4 T*p* in 10 T).

Disruption length smaller at higher magnetic field.

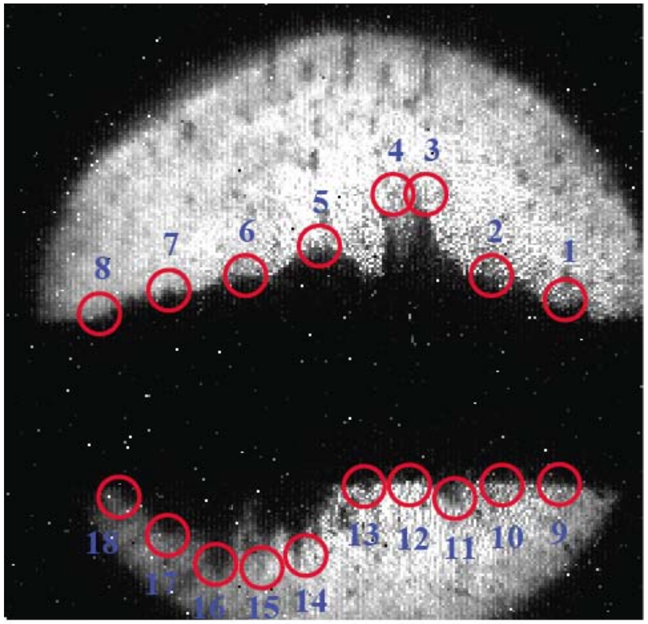
Filament Velocity Analysis (H. Park)

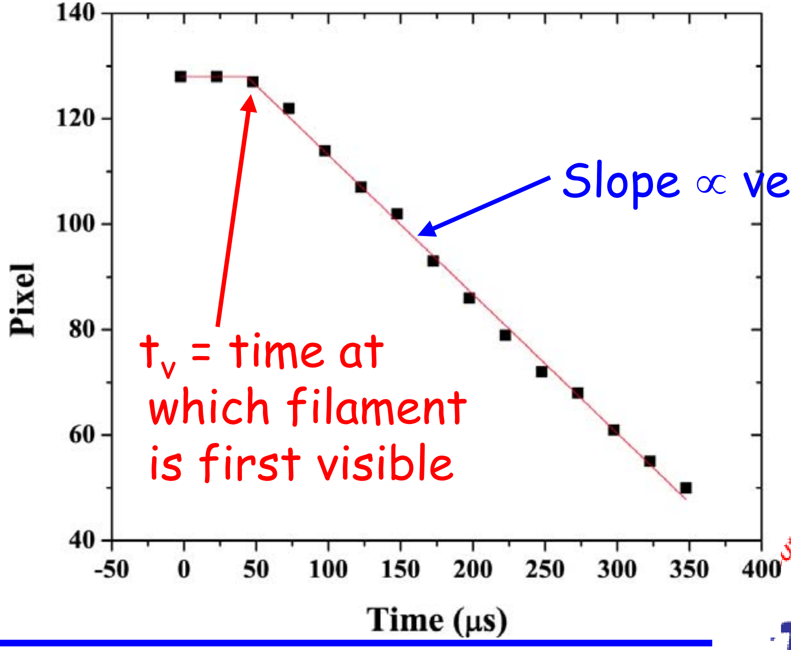
Study velocity of filaments of disrupted mercury using the highest-speed camera, at viewport 2, at frame periods of 25, 100 or 500 μs

Shot 11019: 24-GeV, 10-Tp Beam, 10-T Field, 25μs/frame:



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





Slope ∝ velocity

t_v = time at which filament is first visible

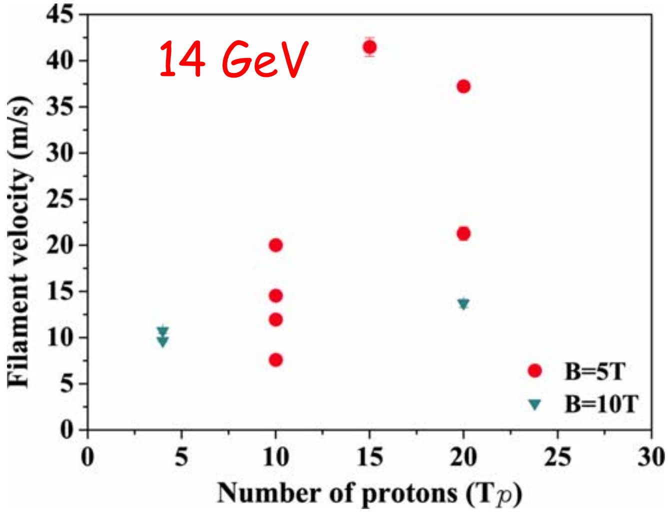
Filament Velocities and Start Times

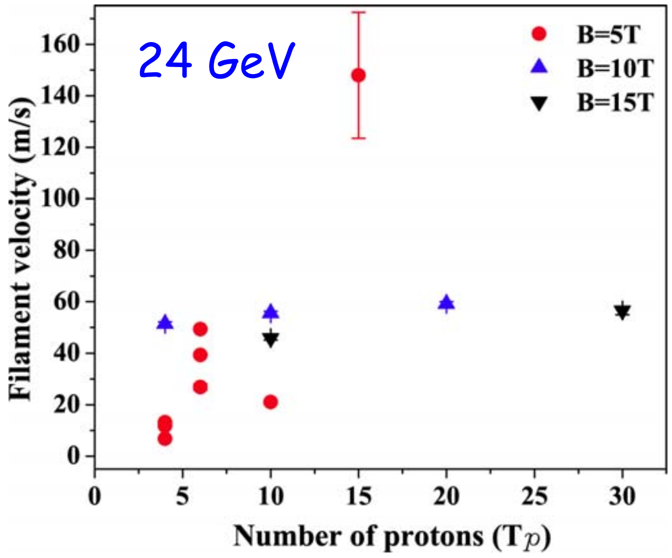
For our projected data, take the characteristic filament velocity to be the largest velocity observed in a shot, and take the associated filament start time to be that of the largest velocity filament.

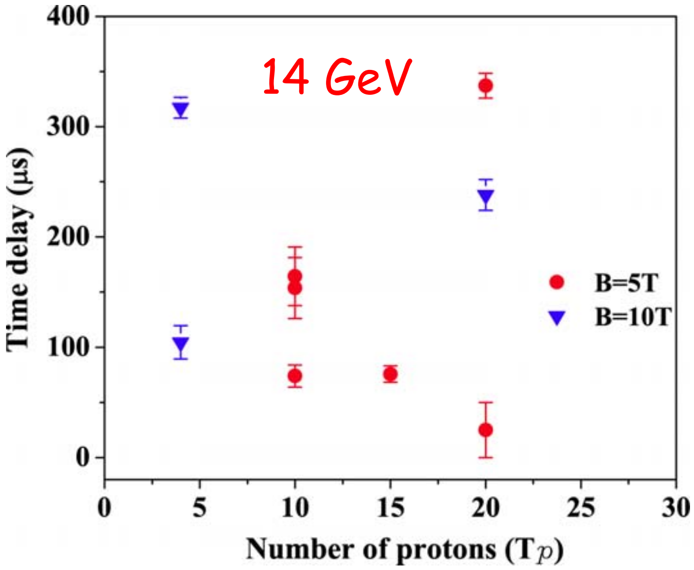
⇒ Filament velocity observed to be ~ linear in number of protons, and somewhat suppressed at higher magnetic fields.

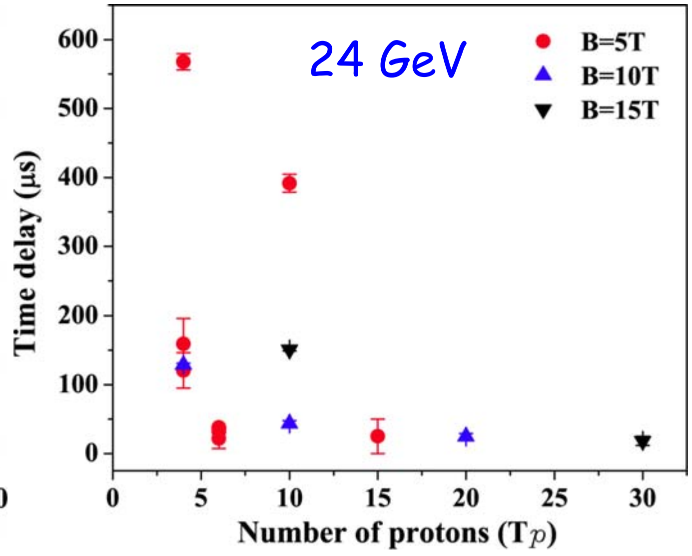
Filament start time is typically much longer than 2 μs = transit time of sound (pressure) wave across the jet.

The start time depends on number of protons, and on magnetic field, but more study needed.









Pump-Probe Studies

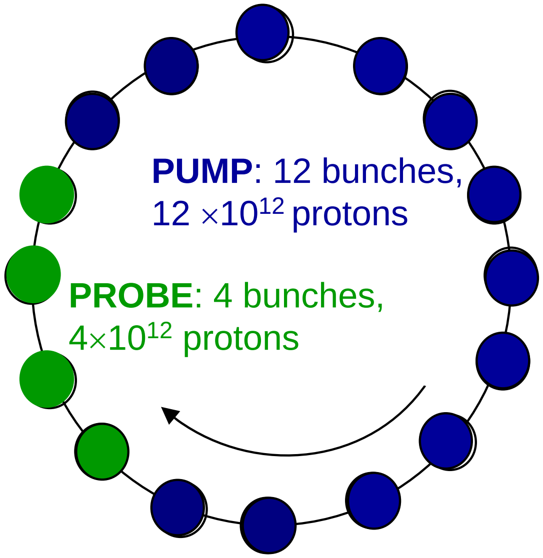
? Is pion production reduced during later bunches due to disruption of the mercury jet by the earlier bunches?

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.

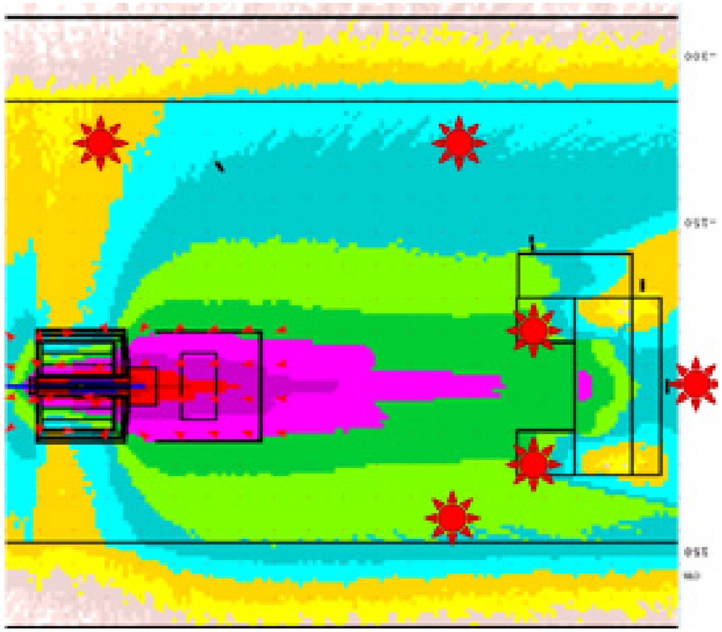
These detectors showed effects of rapid depletion of the charge stored on the detector electrodes, followed by a slow RC recovery of the charge/voltage.

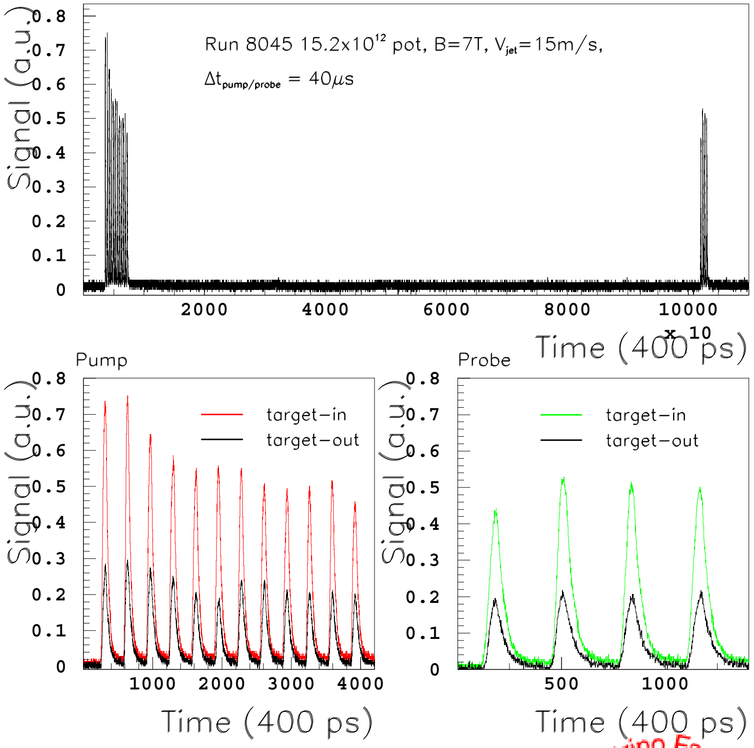
The beam-current transformer data was used to correct for fluctuations in the number of protons per bunch.



PUMP: 12 bunches, 12×10^{12} protons

PROBE: 4 bunches, 4×10^{12} protons





pCVD Diamond, beam-right 20deg, PS in h=16

TU6PFP085

Preliminary Pump-Probe Data Analysis (I. Efthymiopoulos, H. Kirk)

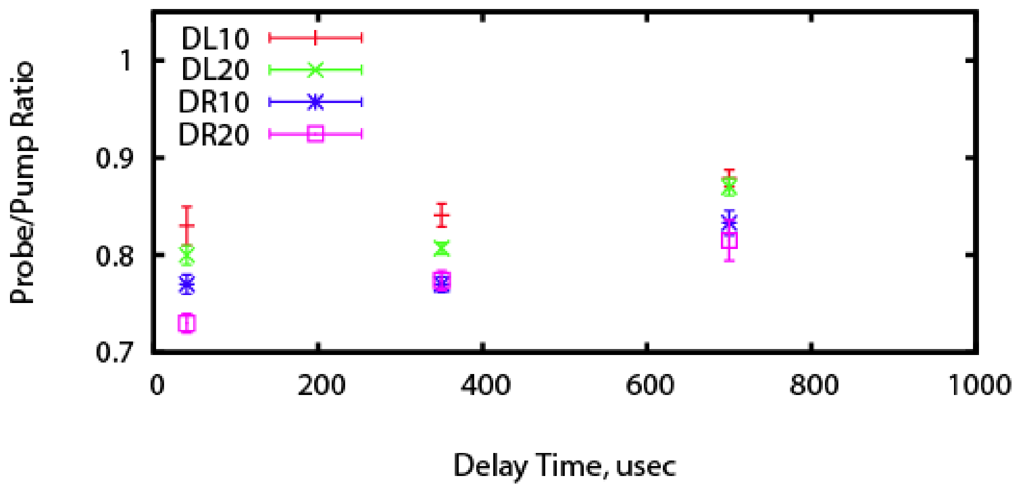
Both target-in and target-out data showed smaller signals, relative to the pump bunches, for probe bunches delayed by 40, 350 and 700 μs.

Similar behavior seen in all 4 usable diamond detectors:

We therefore report a corrected probe/pump ratio:

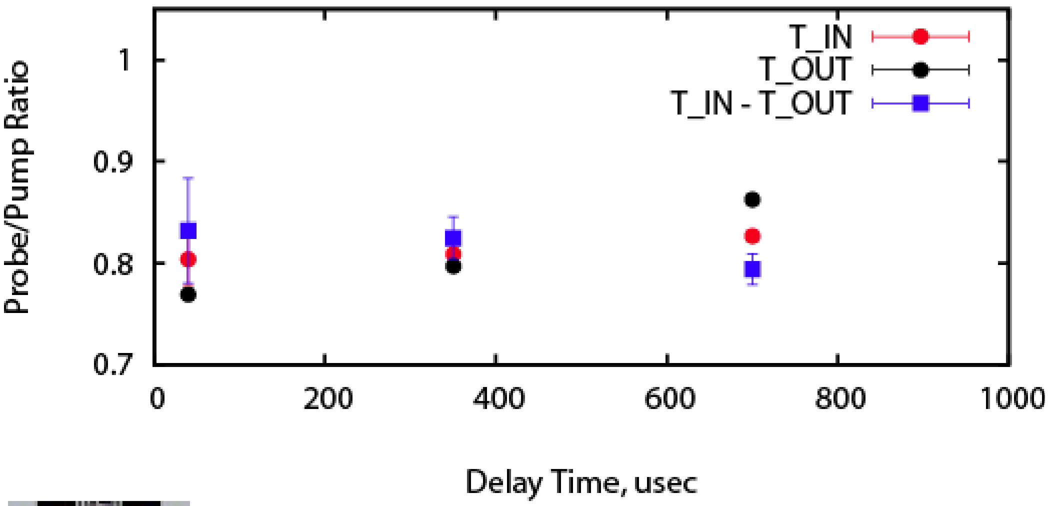
$$\text{Ratio} = \frac{\dfrac{\text{Probe}_{\text{target in}} - \text{Probe}_{\text{target out}}}{\text{Pump}_{\text{target in}} - \text{Pump}_{\text{target out}}}}{\dfrac{\text{Probe}_{\text{target out}}}{\text{Pump}_{\text{target out}}}}$$

Probe/Pump Target Out

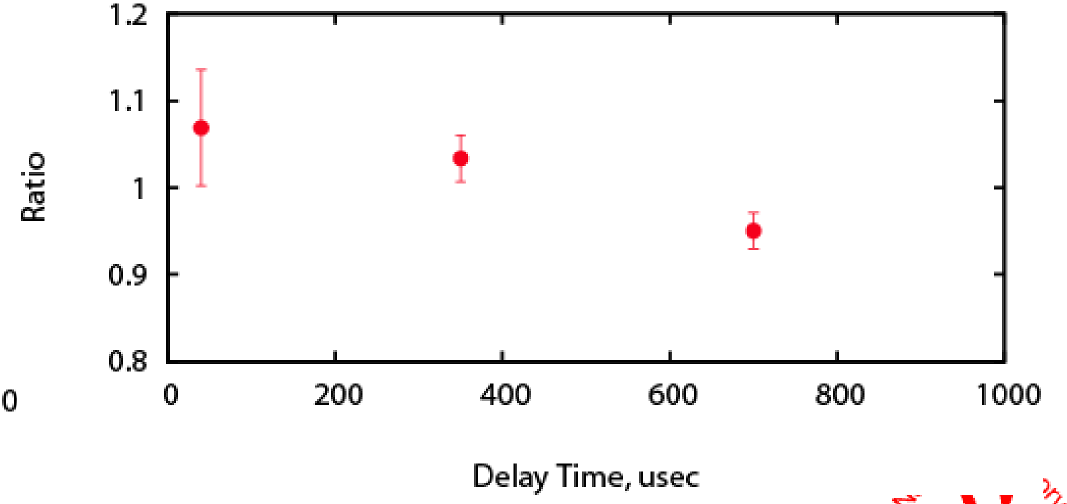


The preliminary results are consistent with no loss of pion production for bunch delays of 40 and 350 μs, and a 5% loss (2.5-σ effect) of pion production for bunches delayed by 700 μs.

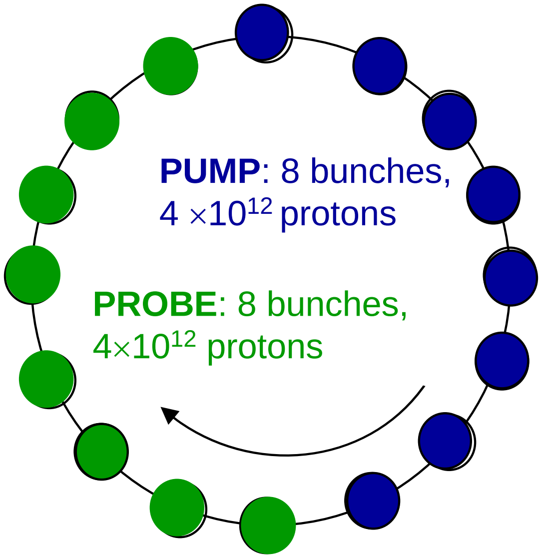
Normalized Probe/Pump



Ratio Target In-Out/Target Out

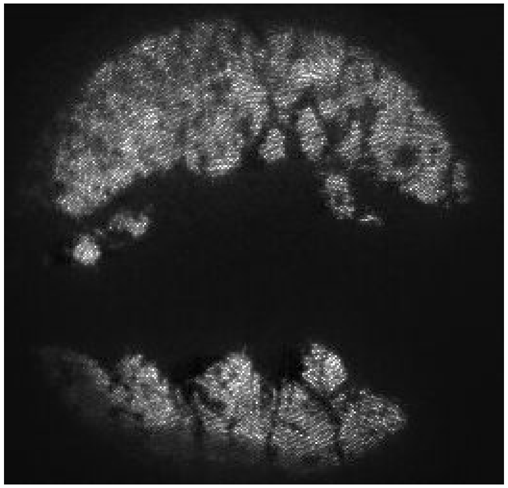


Pump-Probe Study with 4 T*p* + 4 T*p* at 14 GeV, 10 T

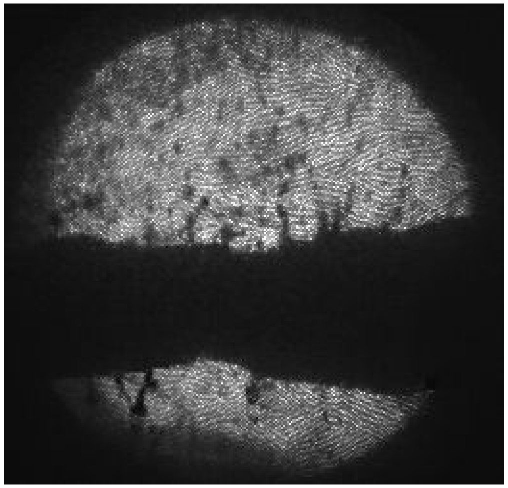


PUMP: 8 bunches, 4 ×10^{12} protons

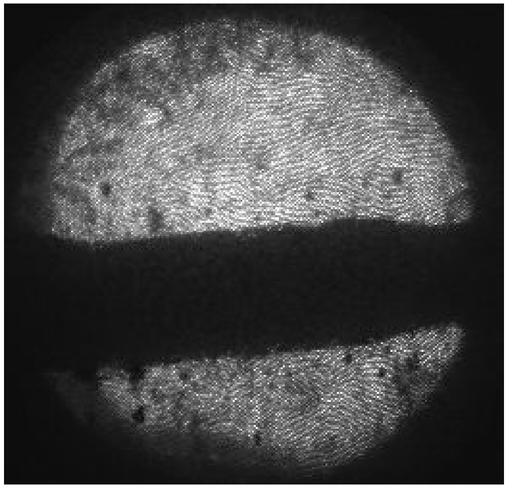
PROBE: 8 bunches, 4×10^{12} protons



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.

Summary

The MERIT experiments 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 that the length of the beam-target interaction,
  ⇒ 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 × 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 ≈ 300 μs, permitting use of short bunch trains at high power.

•Followup: Engineering study of a mercury loop + 20-T capture magnet, begun in ν Factory Study 2, in the context of the International Design Study for a Neutrino Factory.

- 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.
- High-TC fabrication of the superconducting magnets.