High-Power Targets for Neutrino Factories and Muon Colliders

Including Lessons from the MERIT Experiment

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MUTAC Meeting

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Target System Specifications

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_π < 180 MeV**	**40 < T_π < 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 $\approx 10^{14}$ μ/s from $\approx 10^{15}$ p/s ($\approx$ 4 MW proton beam).

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

$\Rightarrow$ 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,

$\Rightarrow$ Shorter data runs (with magnetic detector).

Solenoid coils can be some distance from proton beam.

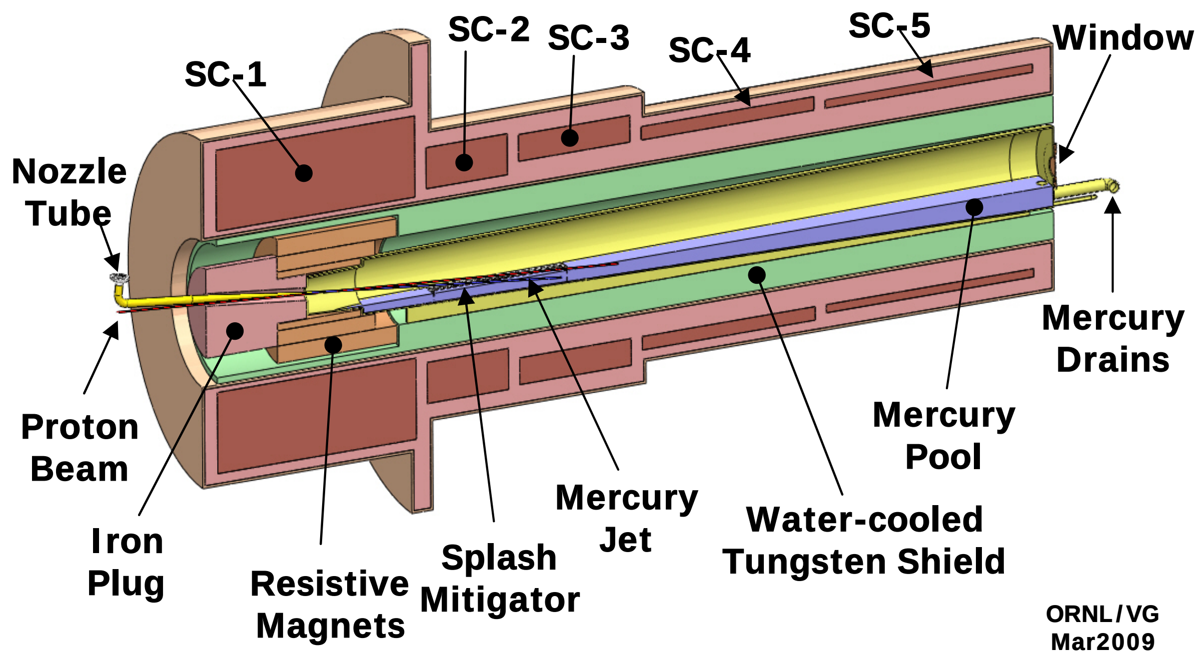
$\Rightarrow$ $\geq$ 4-year life against radiation damage at 4 MW.

Liquid mercury jet target replaced every pulse.

Proton beam readily tilted with respect to magnetic axis.

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

Neutrino Factory Study 2 Target Concept



Remember the Beam Dump

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

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

Short distance from target to dump at a Neutrino Factory/Muon Collider,
$\Rightarrow$ Beam still tightly focused at the dump,
$\Rightarrow$ 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 $10^{22}/cm^2$.

- 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!

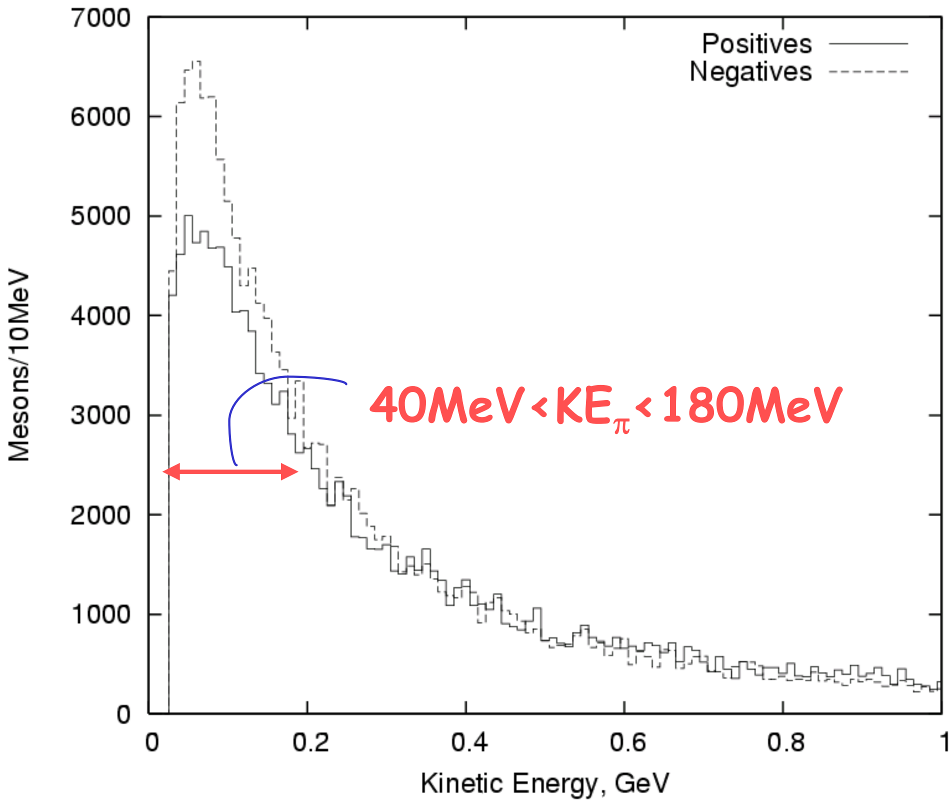
• Free liquid jet [Neutrino Factory Study 2]

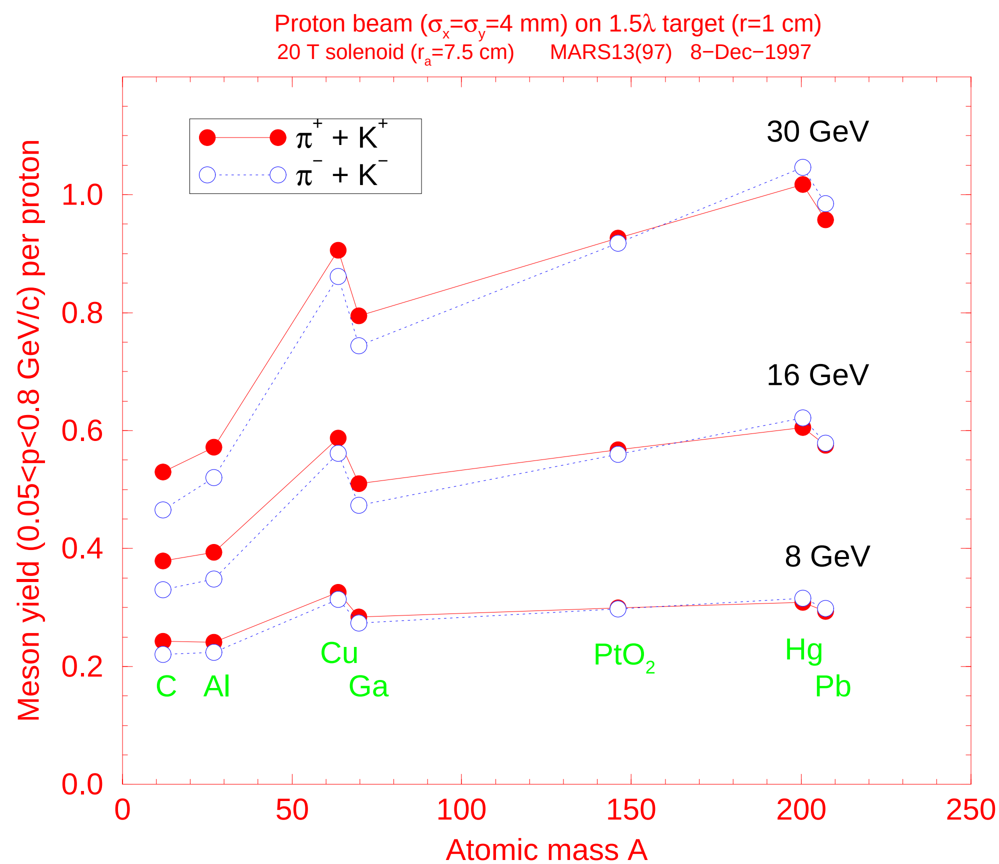
Pion Production Issues for ν Factory/Muon Collider, I

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

Only pions with 40 < KE_π < 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).



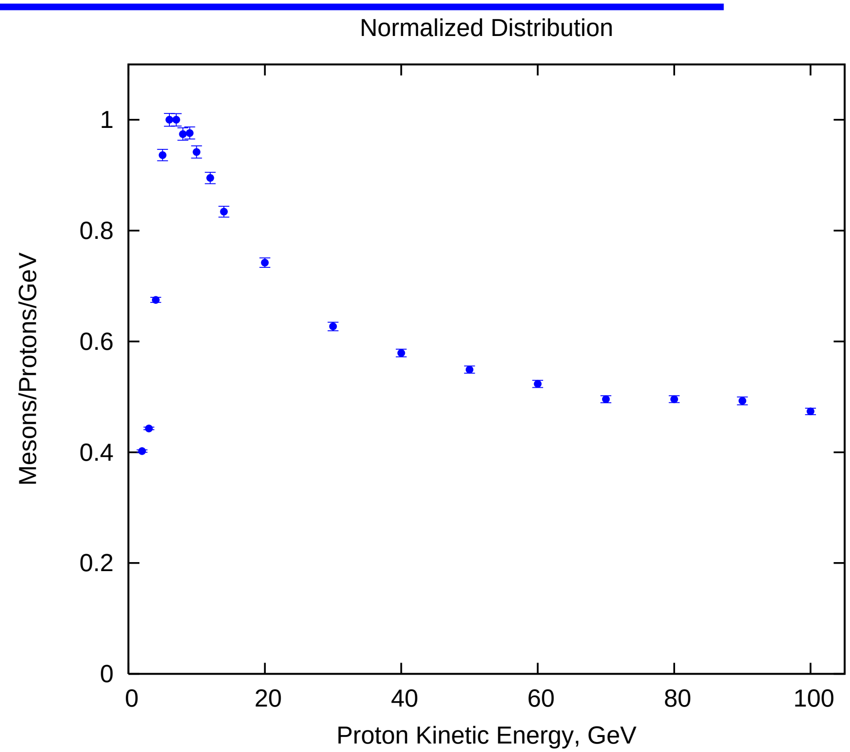


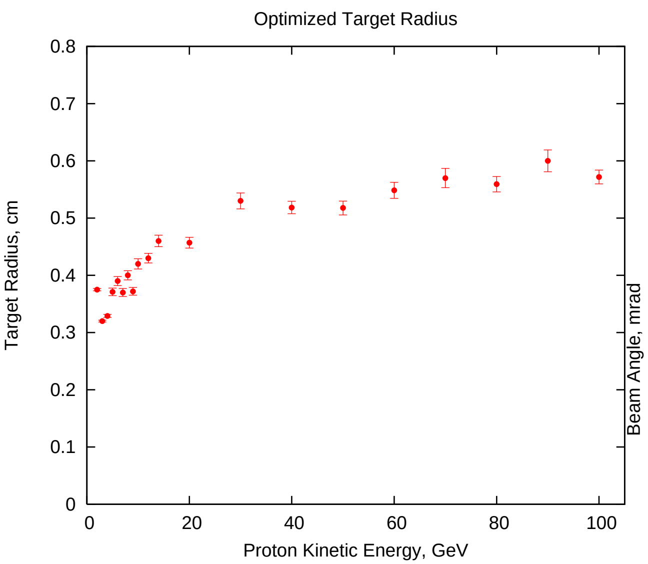
Pion Production Issues for ν Factory/Muon Collider, II

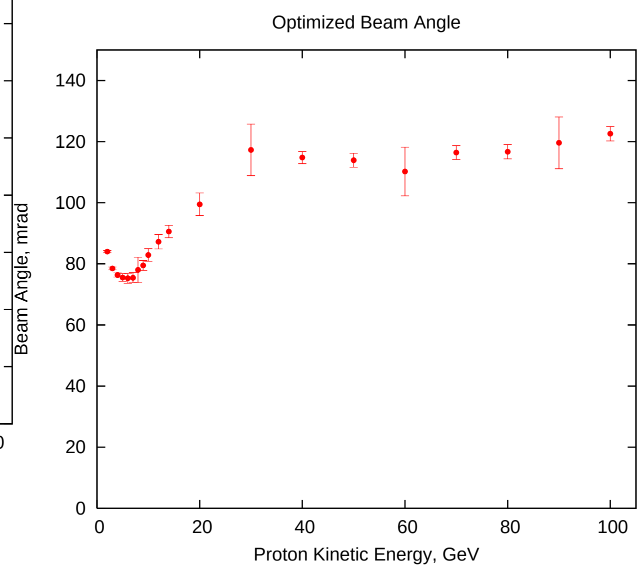
Study soft pion production as a function of 4 parameters:

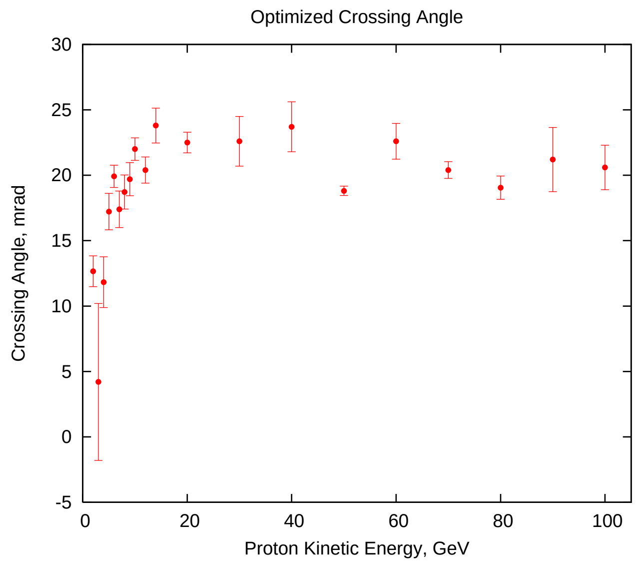
- E_{proton}
- Target radius, assuming proton σ_r = 0.3 × target radius
- Angle of proton beam to magnetic axis
- Angle of mercury jet to magnetic axis

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









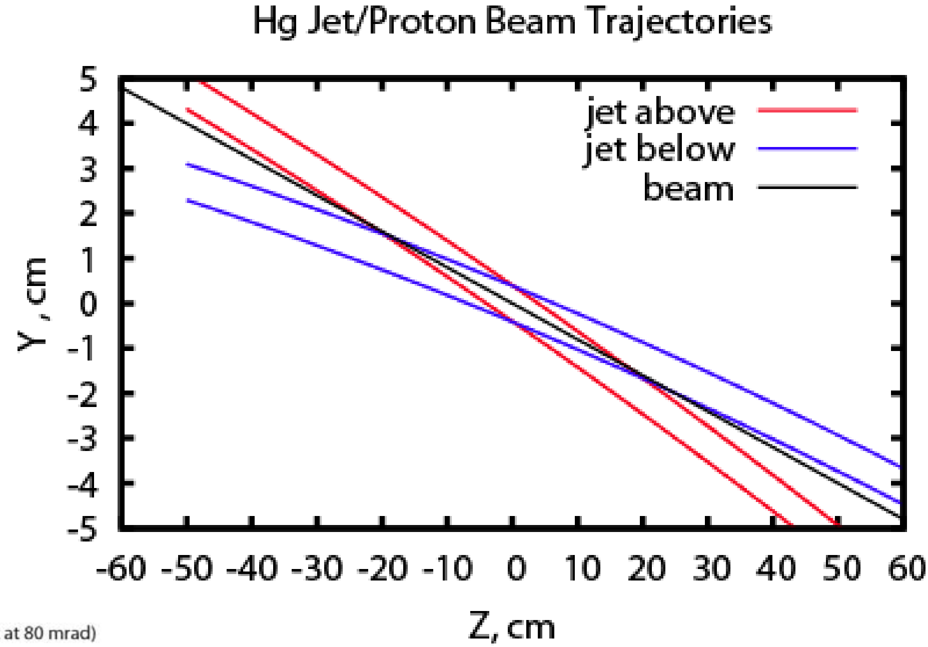
Pion Production Issues for ν Factory/Muon Collider, III

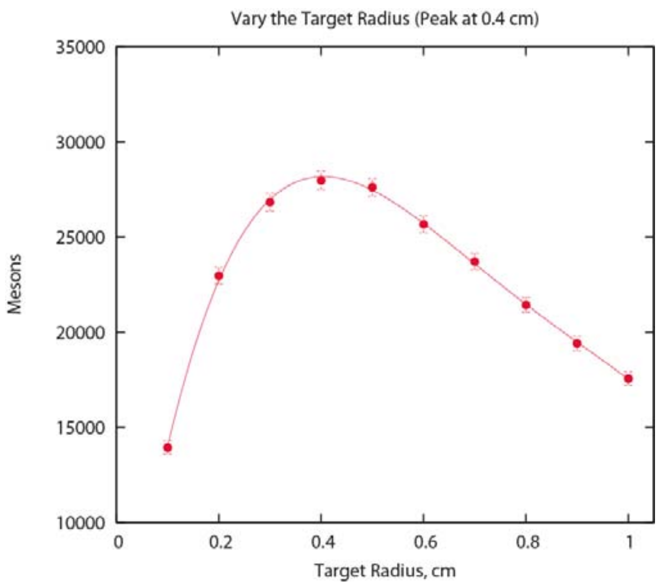
For E_p = 8 GeV, optimal target radius = 4 mm,
optimal proton beam angle = 80 mrad,
optimal jet-beam crossing angle = 20 mrad.

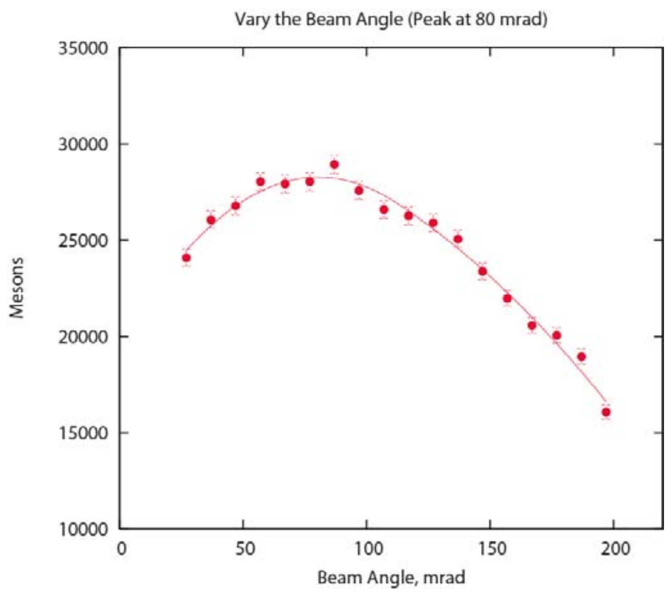
Gravity deflects a 20-m/s jet by 20 mrad in 50 cm,

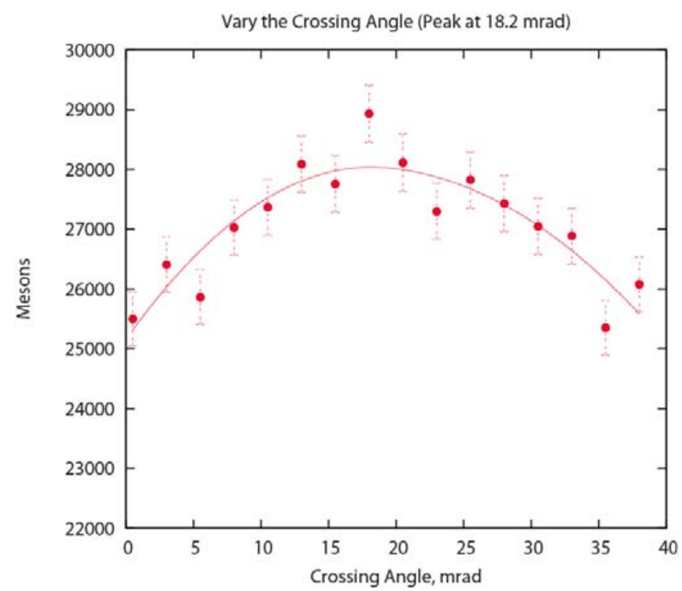
⇒ Bring jet in from below proton beam for larger clearance between nozzle and beam.

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

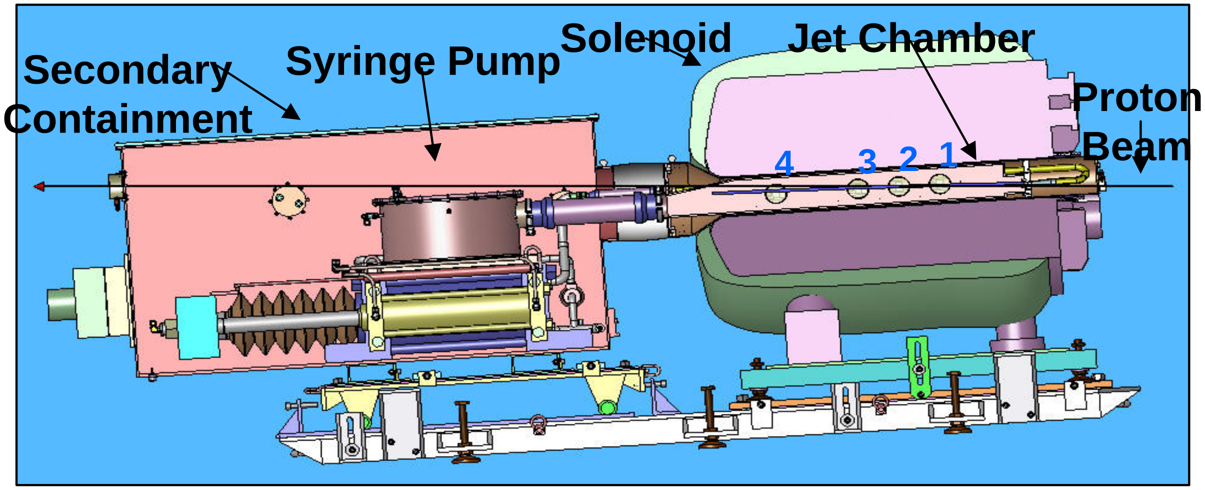


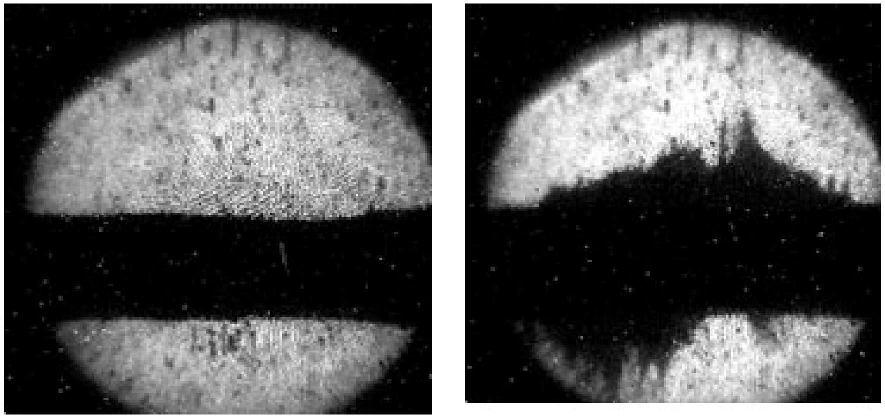






CERN MERIT Experiment (Nov 2007)





Proof-of-principle demonstration of a mercury jet target at 20 m/s in a strong magnetic field, with proton bunches of intensity equivalent to a 4 MW beam.

Most data collected with jet velocity of 15 m/s.

Pion production remains nominal for several hundred μs after first proton bunch of a train.

Jet disruption suppressed (but not eliminated) by high magnetic field.

Region of disruption of the mercury jet is shorter than its overlap with the proton beam.

Filament velocity < 100 m/s.

The mercury jet showed a vertical growth to double its original height at 50 cm from the nozzle, largely independent of magnetic field.

Pump-Probe Data

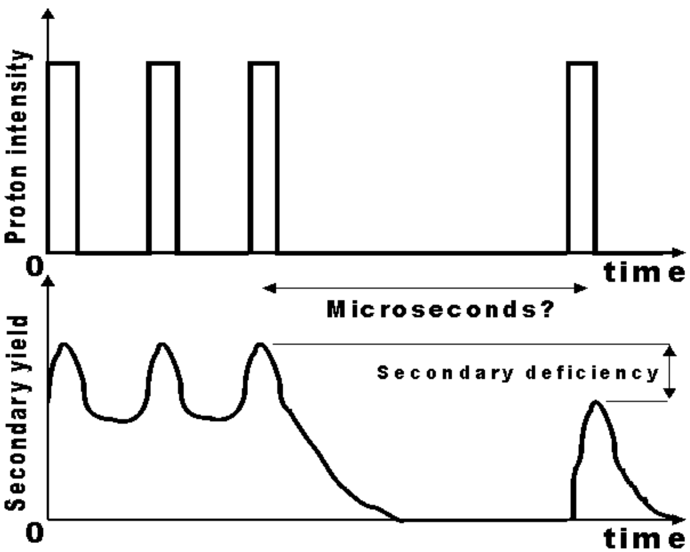
? Is pion production reduced during later bunches due to disruption of the mercury jet by the earlier bunches?

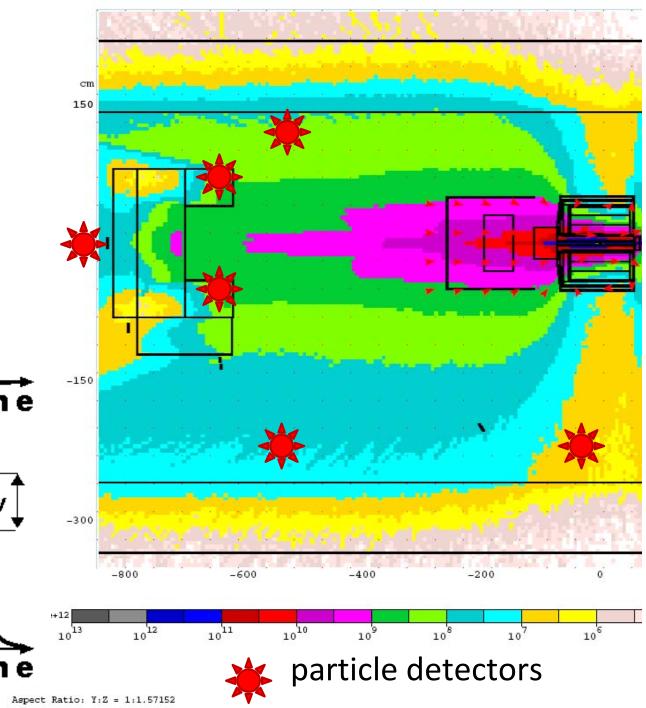
At 14 GeV, the CERN PS could extract several bunches during one turn (pump), and then the remaining bunches at a later time (probe).

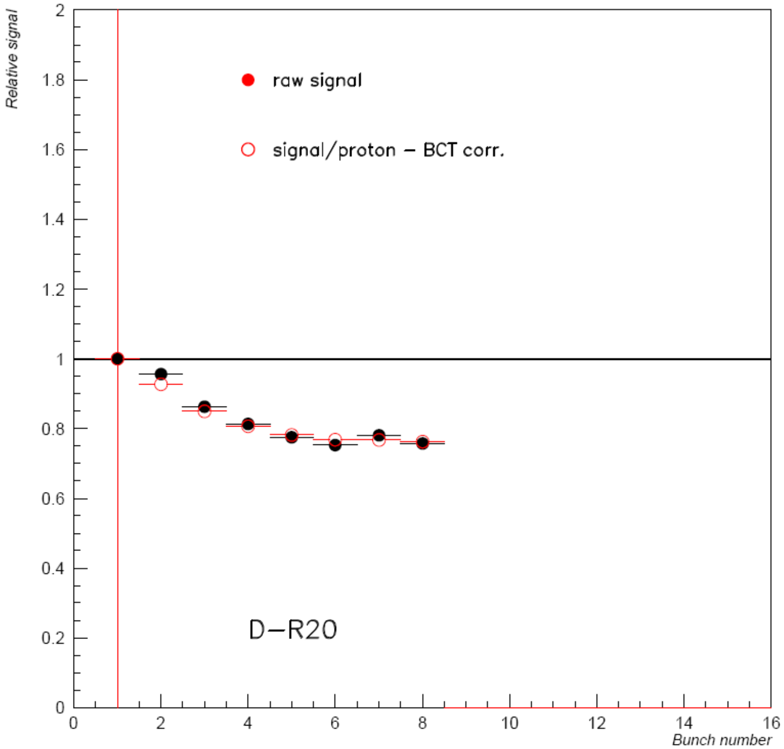
Pion production was monitored for both target-in and target-out events by a set of diamond diode detectors.

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.







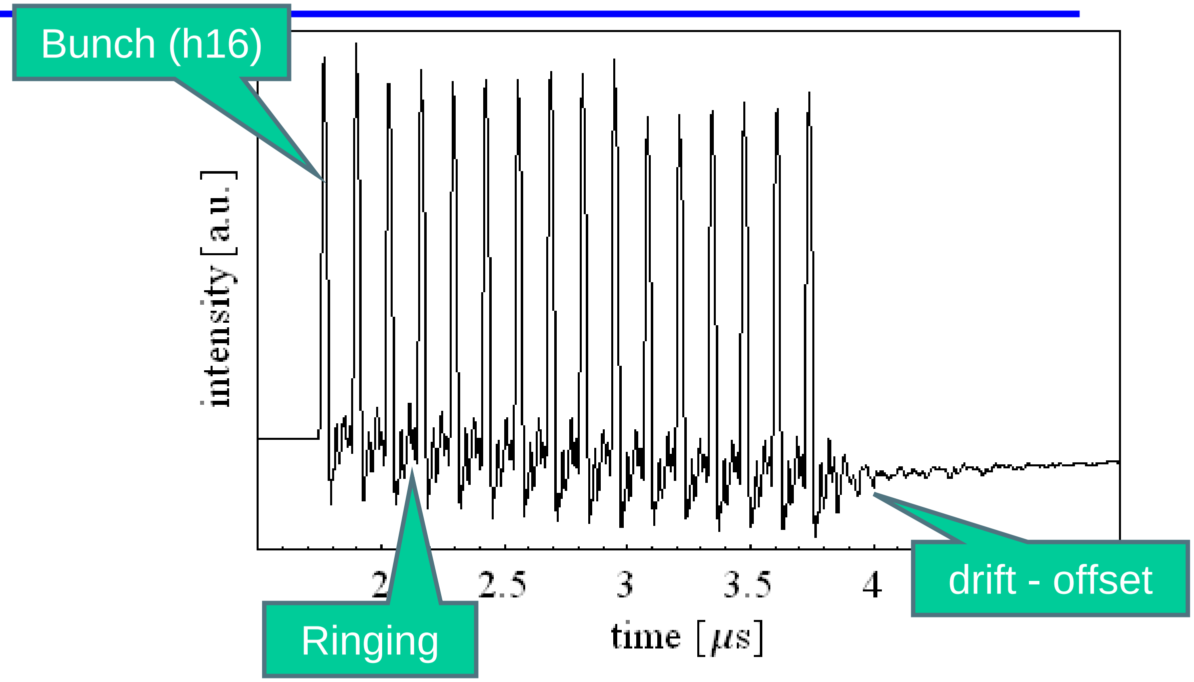
Beam-Current Transformer Corrections (A. Fabich)

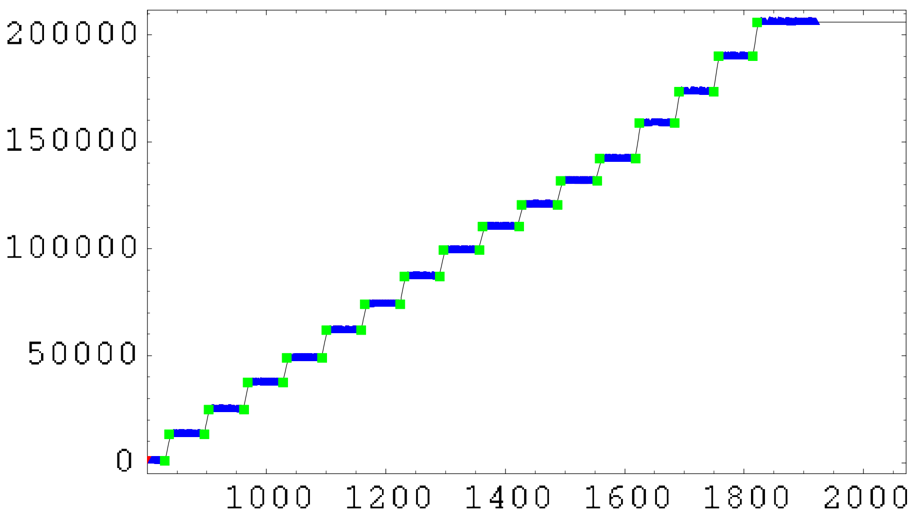
The signal from the beam-current transformer "rang" for longer than the time between bunches.

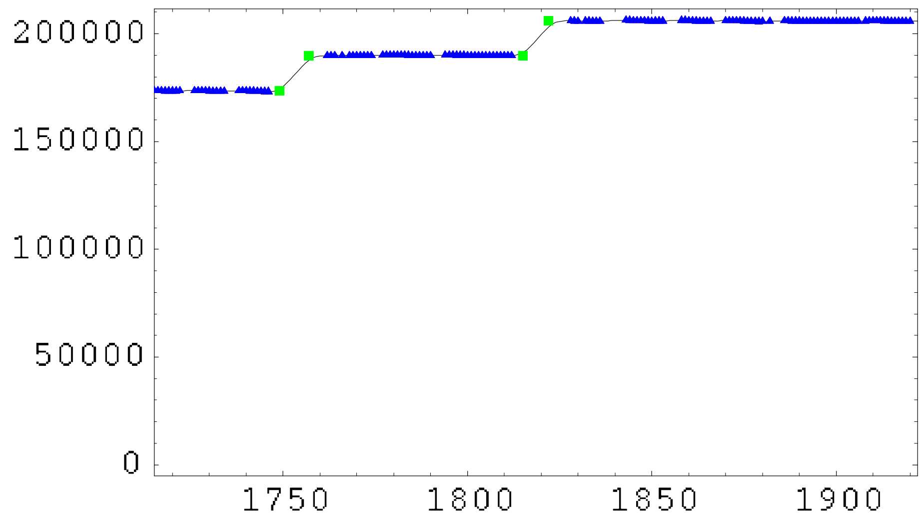
A small baseline drift occurred over a full-turn extraction.

A correction to each bunch of a multibunch event was made using waveforms from single-bunch events.

The integral of the corrected signal was flat between the short steps, showing the the drift and ringing have been well corrected.



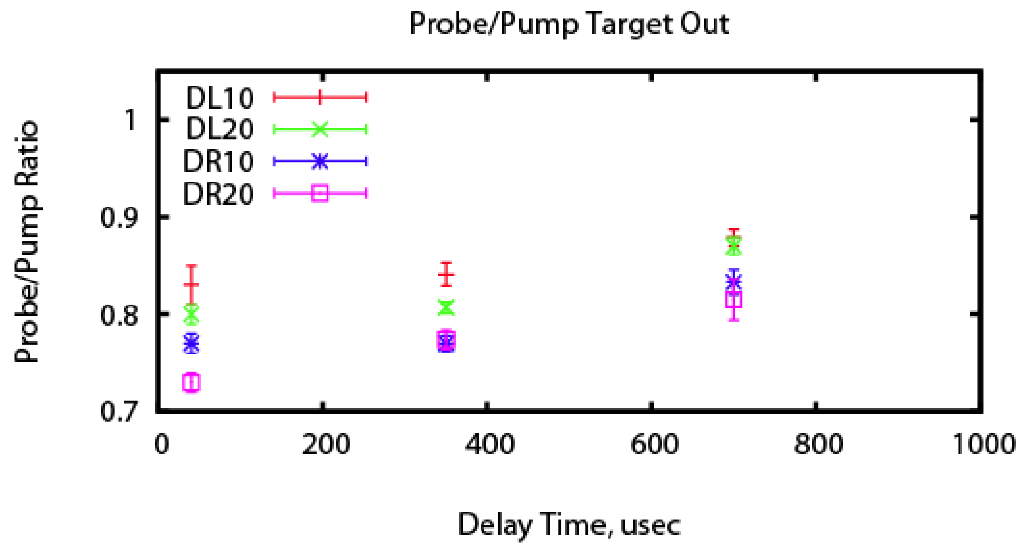




Preliminary Pump-Probe Data Analysis (I. Efthymiopoulos, H. Kirk)

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.

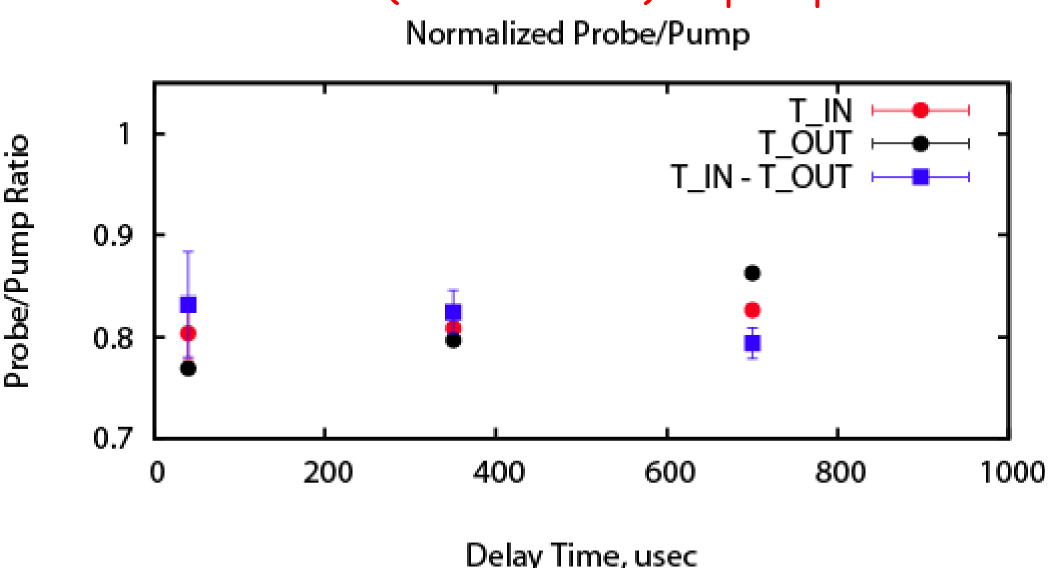
Similar behavior seen in all 4 usable diamond detectors:

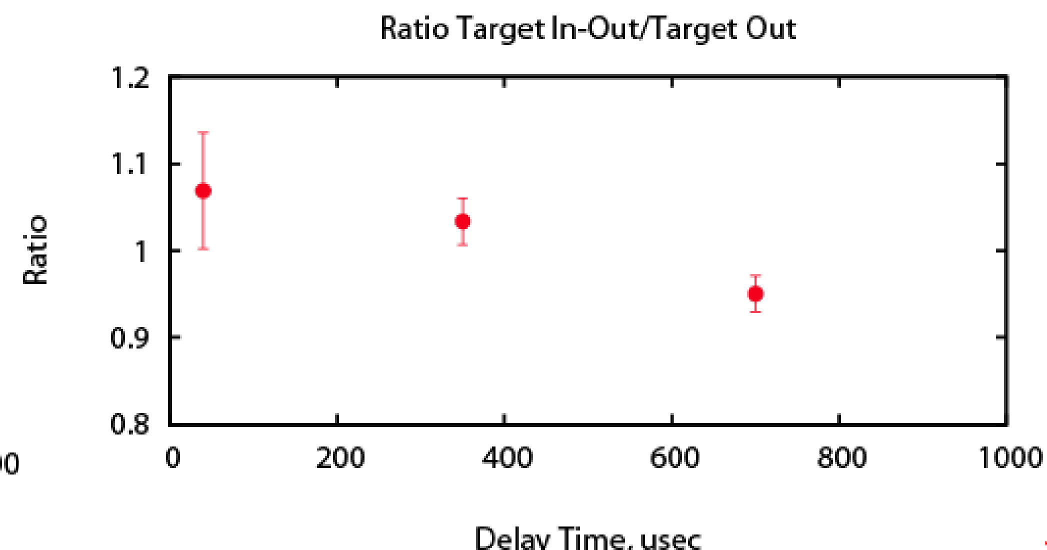


We therefore report a corrected probe/pump ratio:

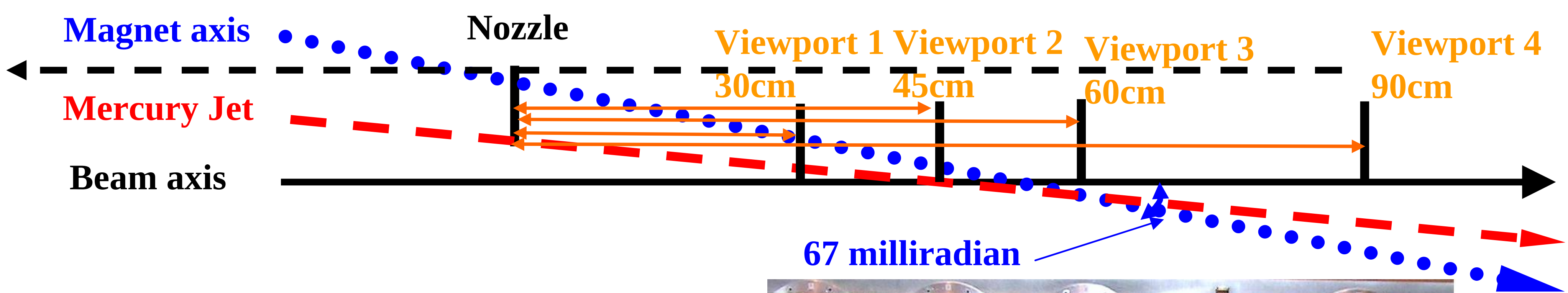
$$\text{Ratio} = \frac{\dfrac{\text{Probe}_{\text{target in}} - \text{Probe}_{\text{target out}}}{\text{Pump}_{\text{target in}} - \text{Pump}_{\text{target out}}}}{\dfrac{\text{Probe}_{\text{target out}}}{\text{Pump}_{\text{target out}}}}$$

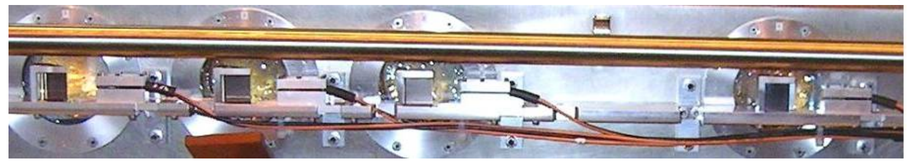
The preliminary results are consistent with no loss of pion production for bunch delays of 40 and 350 μs, and a 5% loss (2.5-σ effect) of pion production for bunches delayed by 700 μs.





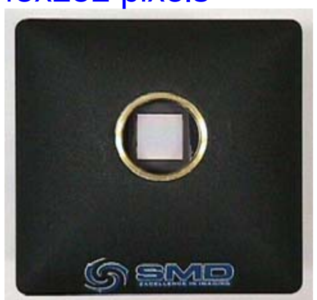
Optical Diagnostics of the Mercury Jet (T. Tsang)





Viewport 1, FV Camera
6 μs exposure
260x250 pixels

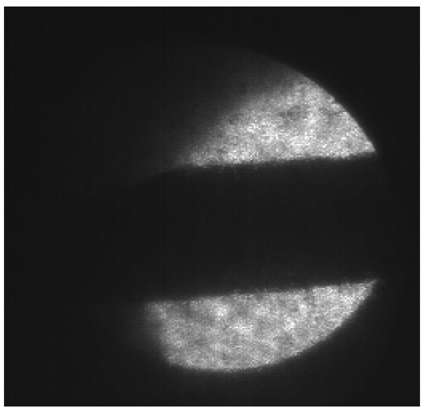
Viewport 2, SMD Camera
0.15 μs exposure
245x252 pixels

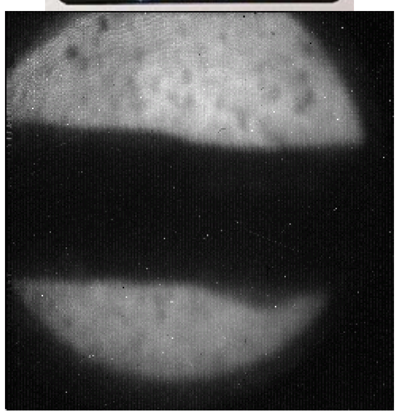


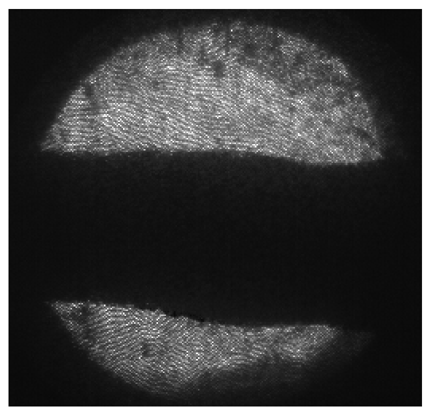
Viewport 3, FV Camera
6 μs exposure
260x250 pixels

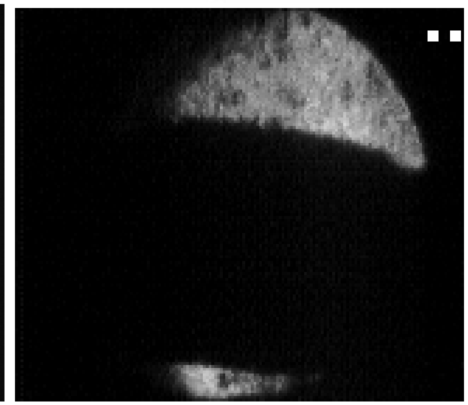
Viewport 4, Olympus
33 μs exposure
160x140 pixels

7 T,
no beam





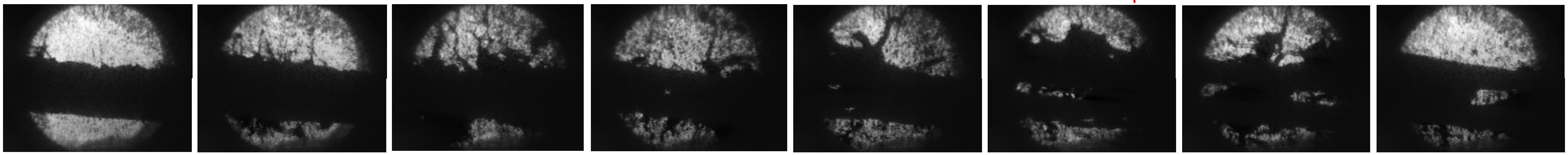




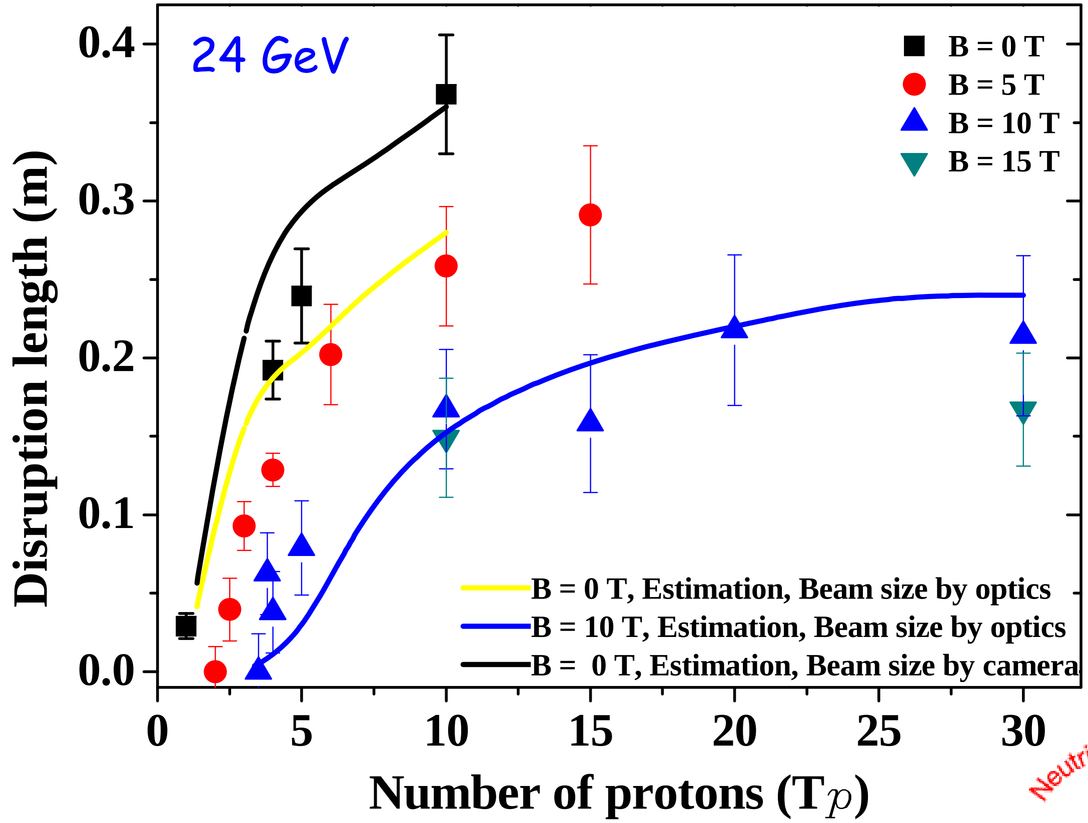
Disruption Length Analysis (H. Park)

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

Images of Jet Flow at Viewport 3, B = 10 T, N = 10 Tp, 2 ms/frame, ⇒ $L_{disruption}$ = 17 cm.



t = 6, 8, 10, 12, 14, 16, 18, 20 ms



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

No disruption for pulses of < 2 Tp.

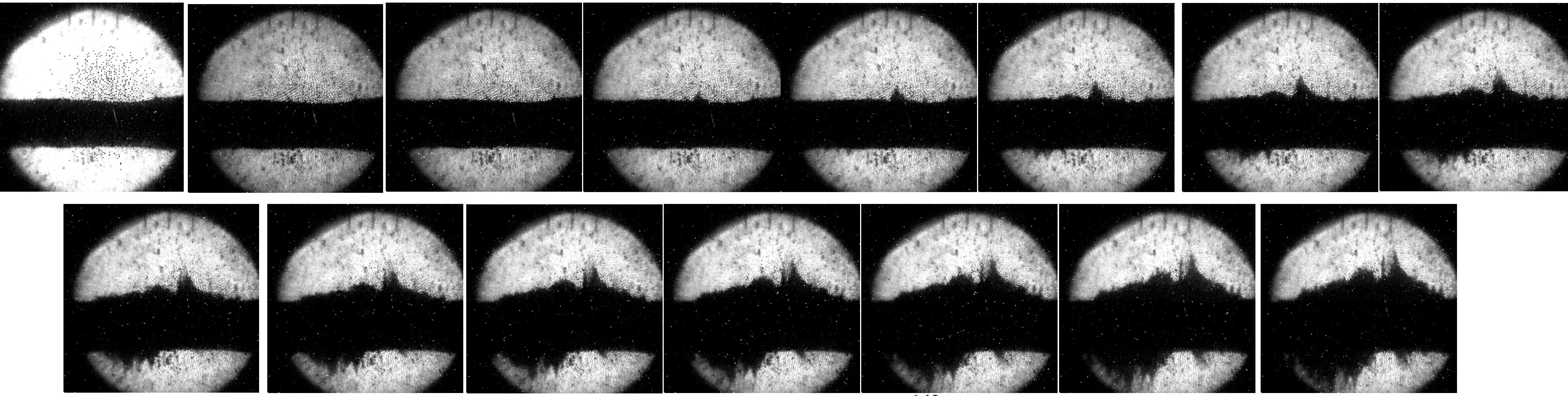
Disruption length smaller at higher magnetic field.

Model: disruption occurs wherever the energy deposition exceeds a minimu value (that depends on B).

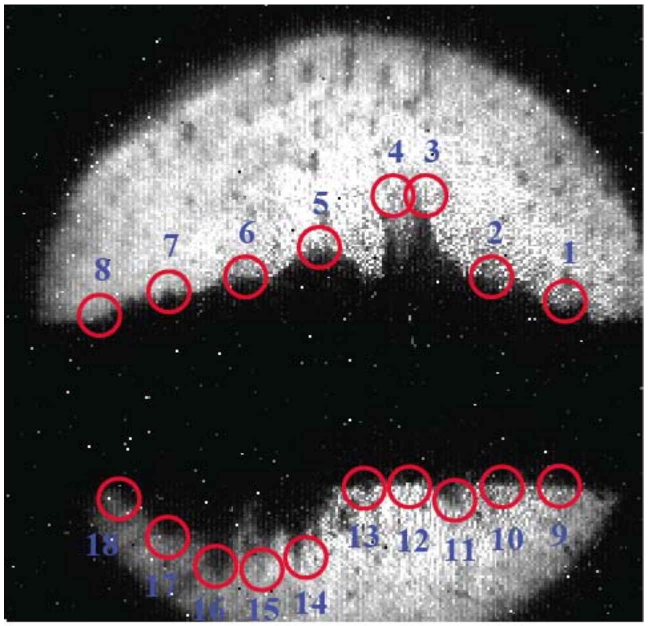
Filament Velocity Analysis (H. Park)

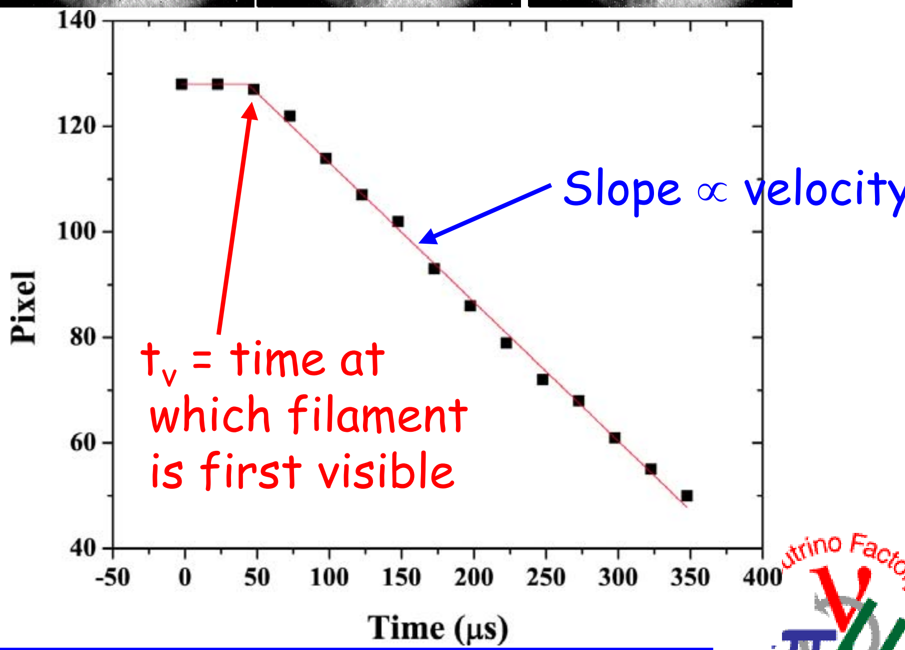
Study velocity of filaments of disrupted mercury using the highest-speed camera, at viewport 2, at frame periods of 25, 100 or 500 μs

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

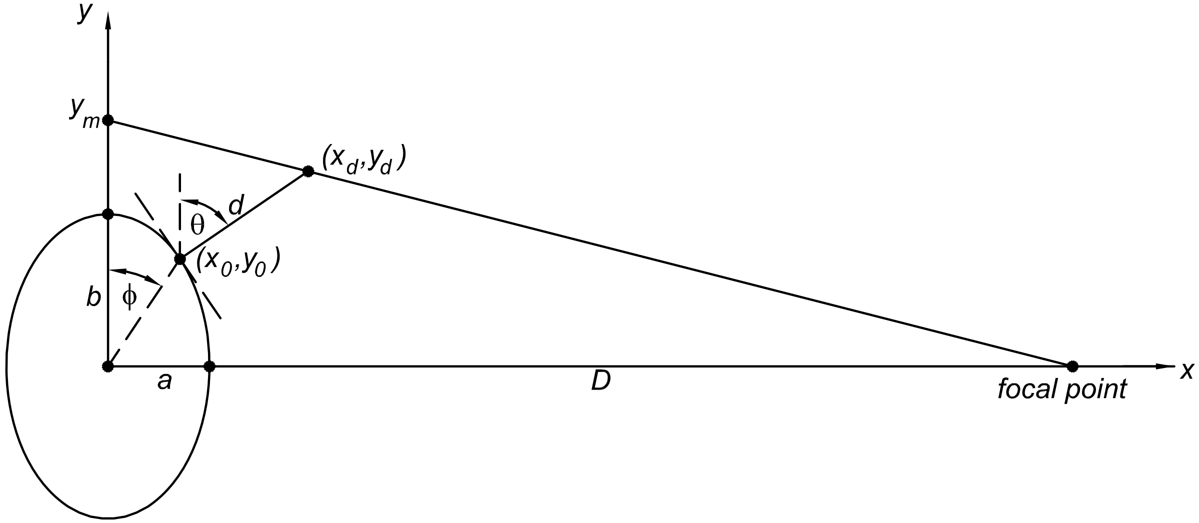


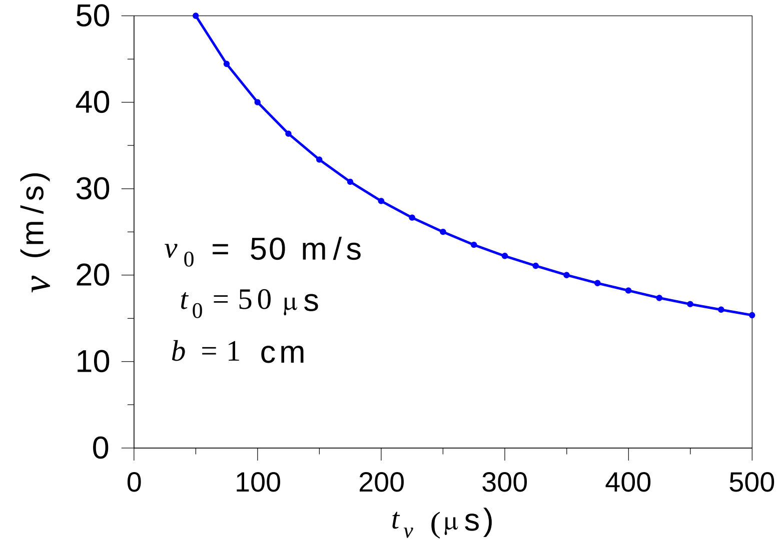
Measure position of tip of filament in each frame, and fit for t_v and v.





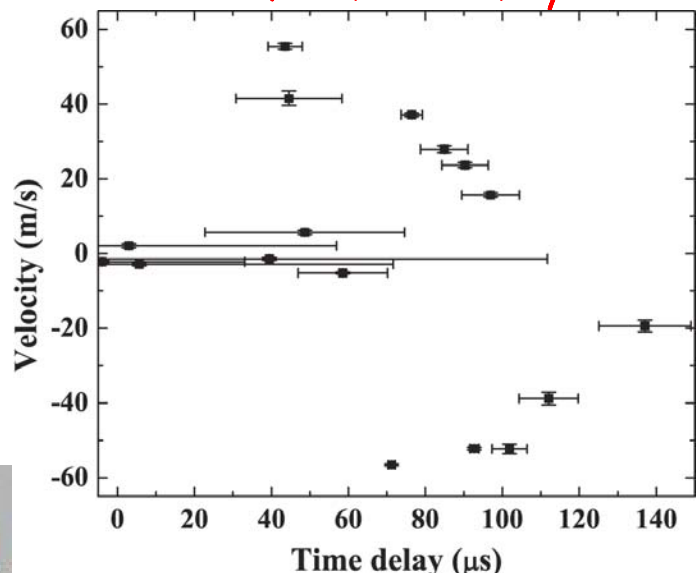
Shadow Photography ⇒ Observe Projection on Vertical Plane





If all filaments had the same velocity v_0 and same starting time t_0, but differing azimuthal angle ϕ, then observe filaments with larger start times t_v and smaller velocities v.

Data from shot 11019 are consistent with upwards filaments having v_0 ~ 60 m/s and t_0 ~ 40 μs, but downwards filaments may have started later, t'_0 ~ 70-80 μs.



Challenge: use projected data to extract information as to the size a of the jet in the horizontal plane.

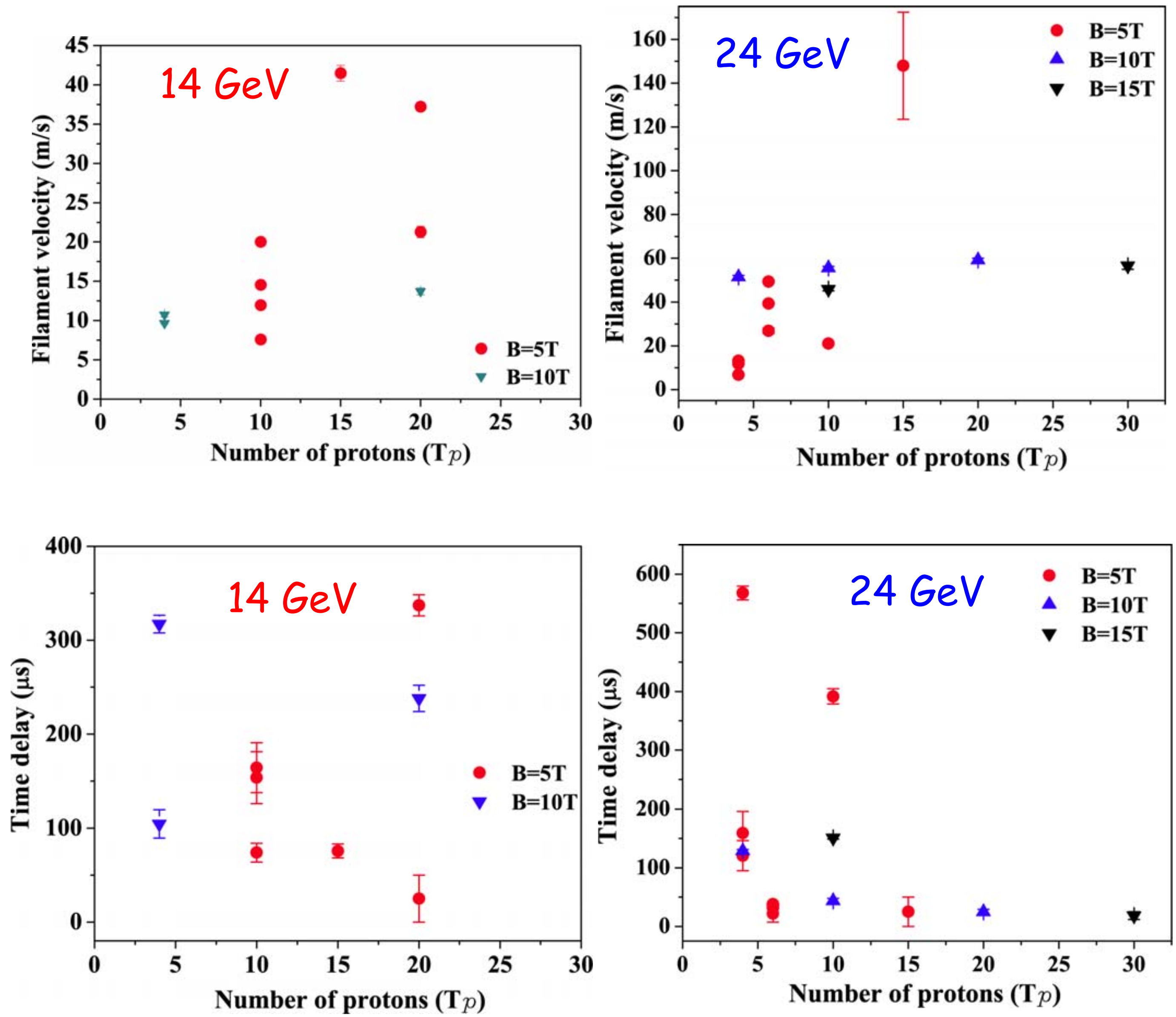
Filament Velocities and Start Times

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.



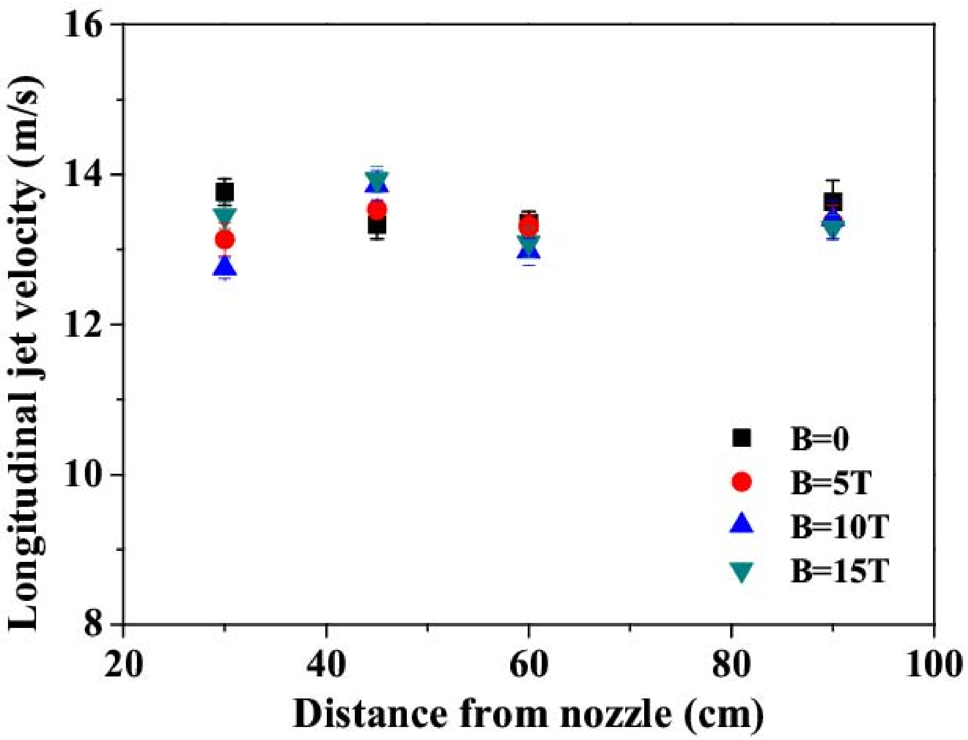
Jet Velocity Issues (with Magnet but without Beam)

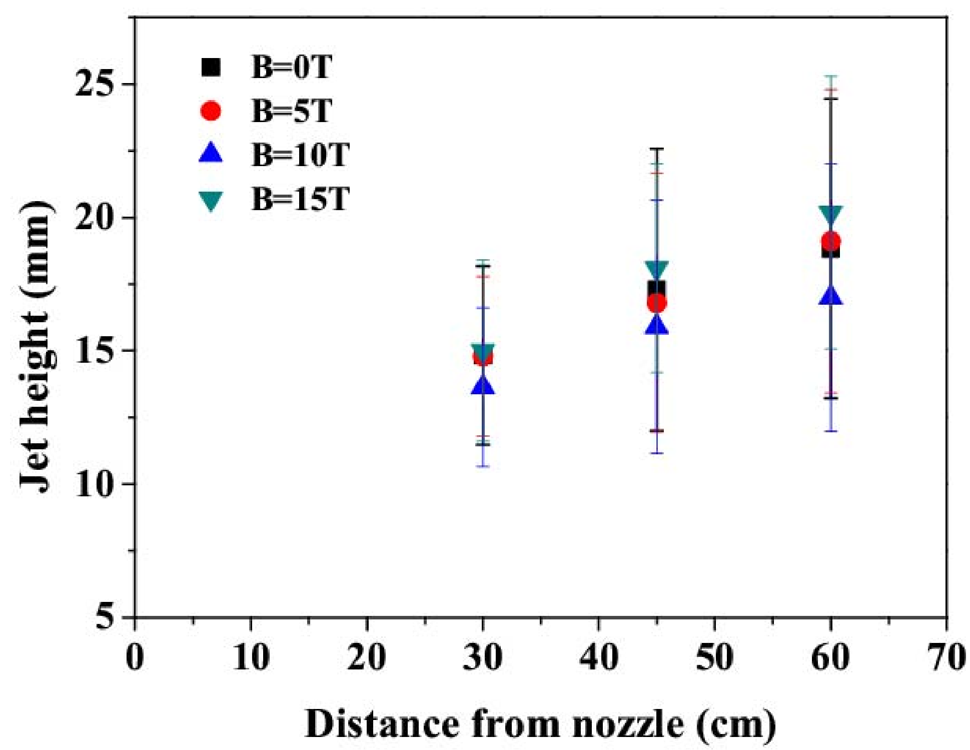
The velocity of surface perturbations on the jet was measured at all 4 viewports to be about 14 m/s, independent of magnetic field (when nominal jet velocity was 15 m/s).

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?



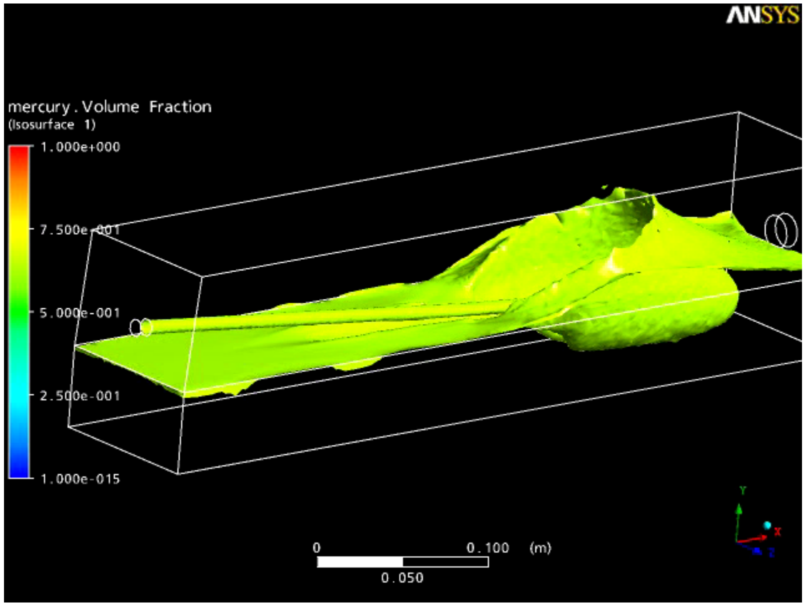


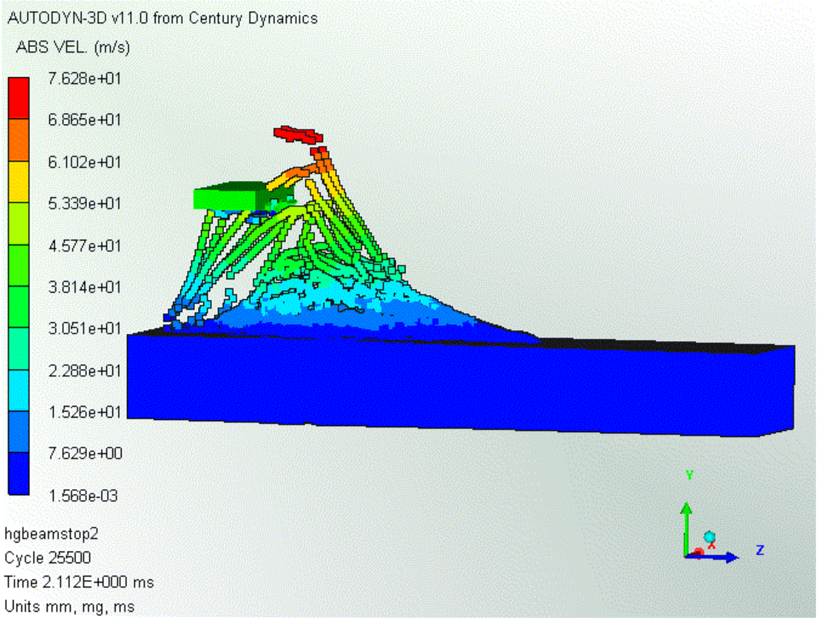
R&D Issues for Hg Jet Target Option

- Continue and extend simulations of mercury flow in and out of the nozzle.
    - Can we understand/mitigate the observed transverse growth of the jet out of the nozzle, which was largely independent of magnetic field.
- Examine the MERIT primary containment vessel for pitting by mercury droplets ejected from the jet by the proton beam.
- Extend the engineering study of a mercury loop + 20-T capture magnet, begun in ν Factory Study 2, in the context of the International Design Study.
    - 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.
- Hardware prototype of a continuous mercury jet with improved nozzle.

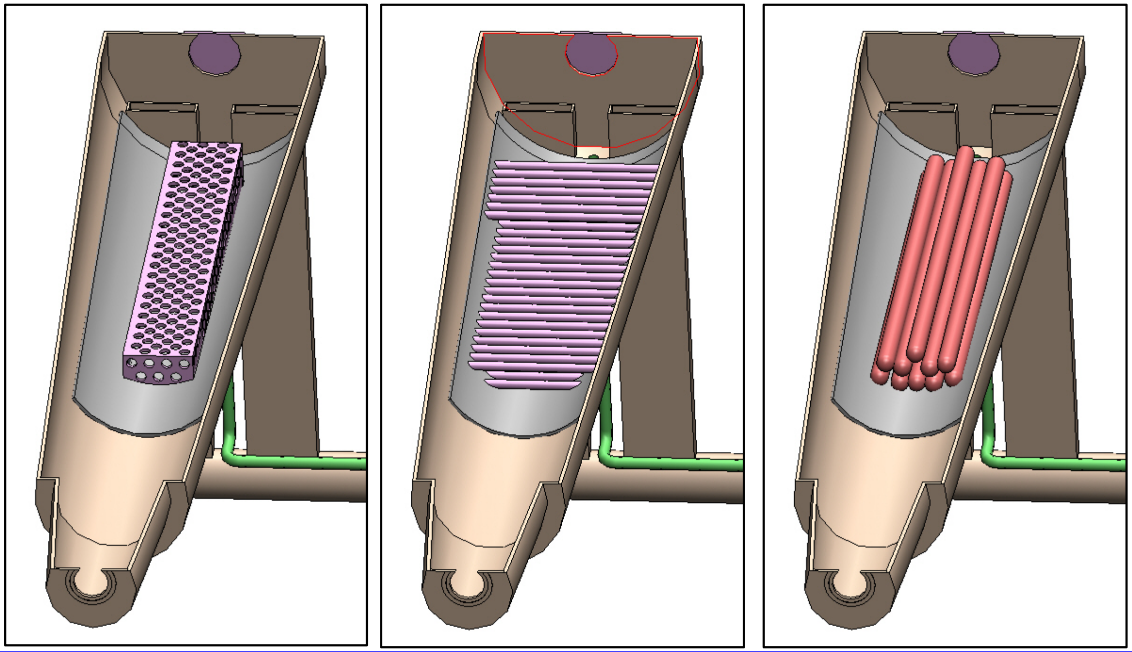
Mercury Pool Issues

Both the jet and the proton beam will disrupt the mercury pool (T. Davenne)



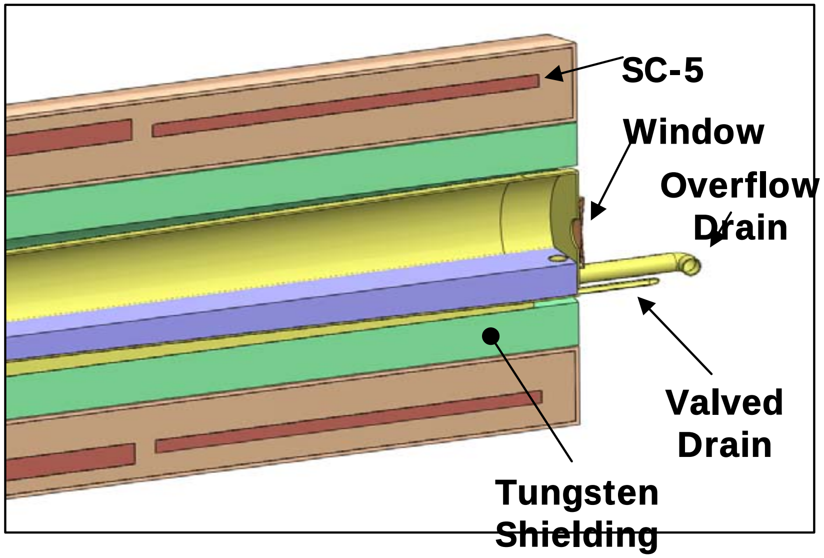


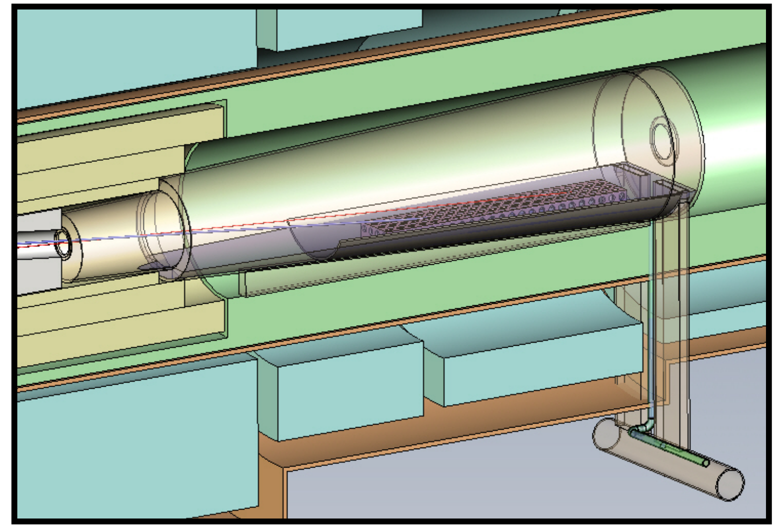
$\Rightarrow$ Need splash mitigation (V. Graves)

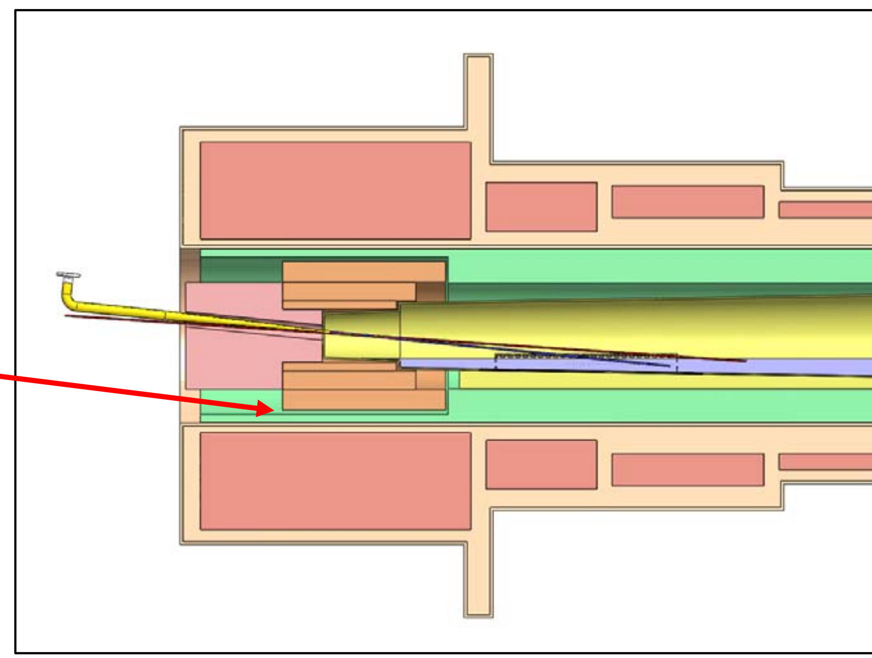


Mercury Drain, Downstream Beam Window

Mercury drain at downstream end of containment vessel is awkward – and may interfere with the pion-beam window.







⇒ May be better to drain mercury between the resistive magnets and SC1.

Summary

MUTAC08 Recommendations:

- Complete the analysis of the data from the MERIT experiment and compare with hydrodynamic calculations and benchmark particle production simulations.
- Determine what further targetry studies are required to establish the feasibility of a muon collider.

Status of NFMCC high-power target studies:

- Analysis of MERIT data not quite complete, but major qualitative trends have emerged.
  - Jet disruption by the beam is limited in extent, and somewhat suppressed by the strong pion-capture solenoid field.
  - Pion production remains nominal if use a bunch train of length up to several hundred μs.
- 3-D magnetohydrodynamic simulations with beam-induced cavitation are well advanced and in good agreement with most features of the MERIT data.
- The MERIT experiment has established the feasibility of a mercury jet target in a 20-T magnetic field with parameters suitable for a Neutrino Factory or Muon Collider.
  - The infrastructure for such a target system is substantial, and deserves additional study in the context of the Neutrino Factory International Design Study and the Muon Collider Feasibility Design Study.
  - The proton beam dump remains a very challenging issue.