MERIT and Target Plans

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Muon Accelerator Program Review
(Fermilab, August 25, 2010)

Prior efforts on the target system for a Muon Collider/Neutrino Factory have emphasized proof-of-principle demonstration of a free mercury jet target inside a solenoid magnet.

Future effort should emphasize integration of target, beam dump and **internal shield** into the capture magnet system.

Key challenges (H. Kirk, Front End Talk):

- Shielding of the superconducting coils against heat and radiation damage
- Thermal management of the 4-MW beam power deposited in the target system.
- Delivery of stable 20-m/s Hg jet
- Containment/recirculation of Hg (whose collection pool serves as beam dump).

Addressed by simulation and engineering design, with some hardware studies of

- The mercury nozzle.
- Splash mitigation in the mercury collection pool/beam dump.
- Coolant flow in the internal shield.

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 (NF) / 15 Hz (MC)	Collider L $\propto n^2 f \propto (nf)^2/f$ favors lower f at fixed nf
Bunch width	1-3 ns	1-3 ns	Very challenging for proton driver
Bunches/pulse	1	3 (NF) / 1 (MC)	1-3-ns bunches easier if 3 bunches per pulse
Bunch spacing	-	~ 160 μs (NF)	
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 40 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
Jet angle	100 mrad	96 mrad (V)	Thin target at angle to capture axis maximizes π's
Beam angle	67 mrad	96 mrad (V), 27 mrad (H)	Optimum with beam out of plane of jet

Solenoid Target and Capture Topology

Desire ≈ 10^{14} μ/s from ≈ 10^{15} p/s (≈ 4 MW proton beam) in 15-50 pulses/sec.

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

Highest power on target at present is ~ 1 MW, and for ~ CW beams with "large" spot.

R. Palmer (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.

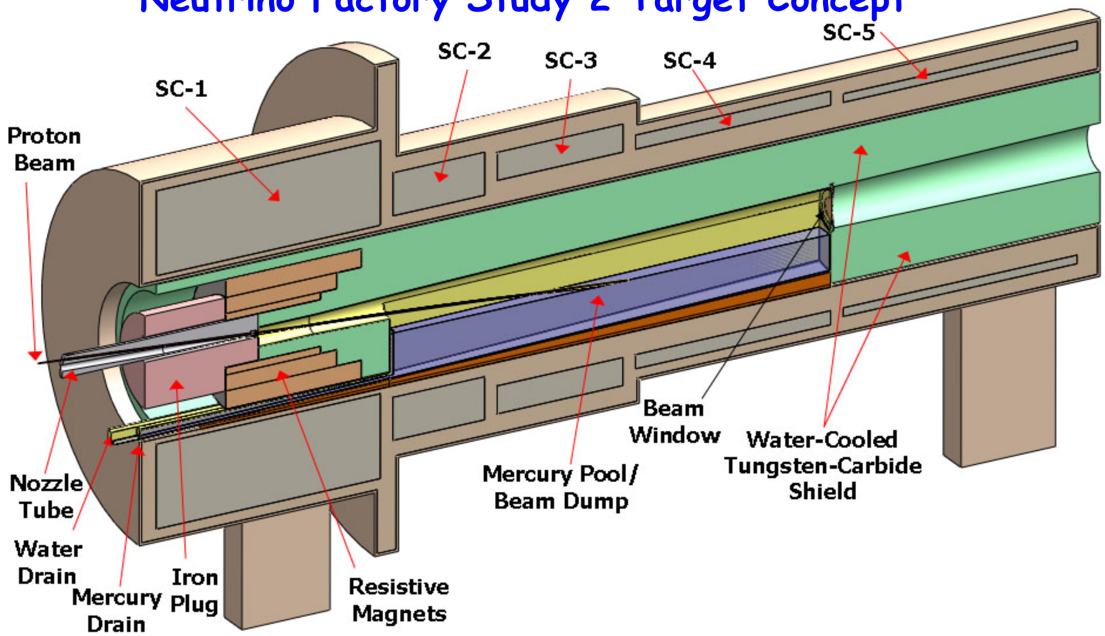
⇒ ≥ 4-year life against radiation damage at 4 MW.

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



Major issue: internal shield of the superconducting Magnets.

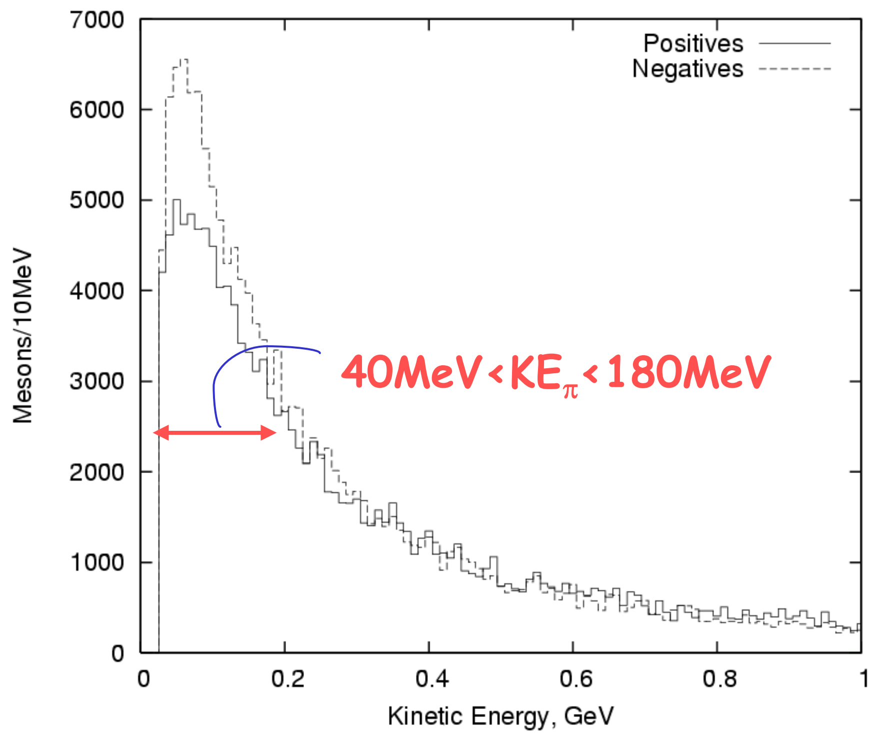
Study 2 baseline: water-cooled tungsten-carbide beads (only 20% water by volume).

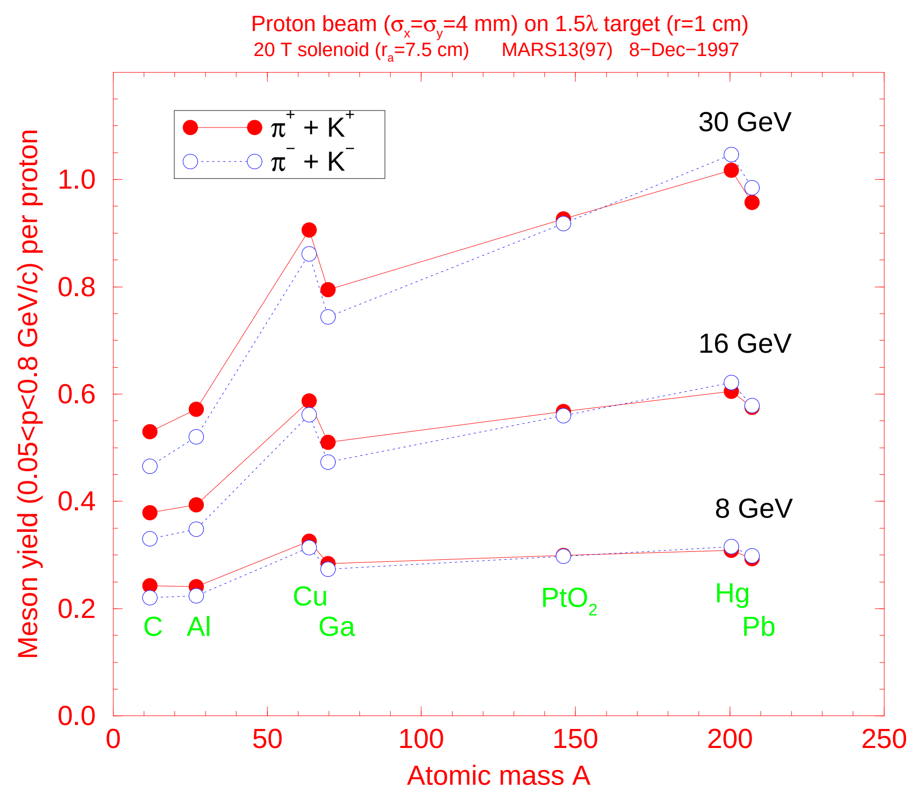
Pion Production Issues for ν Factory/Muon Collider, I

MARS simulations: N. Mokkov, 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).





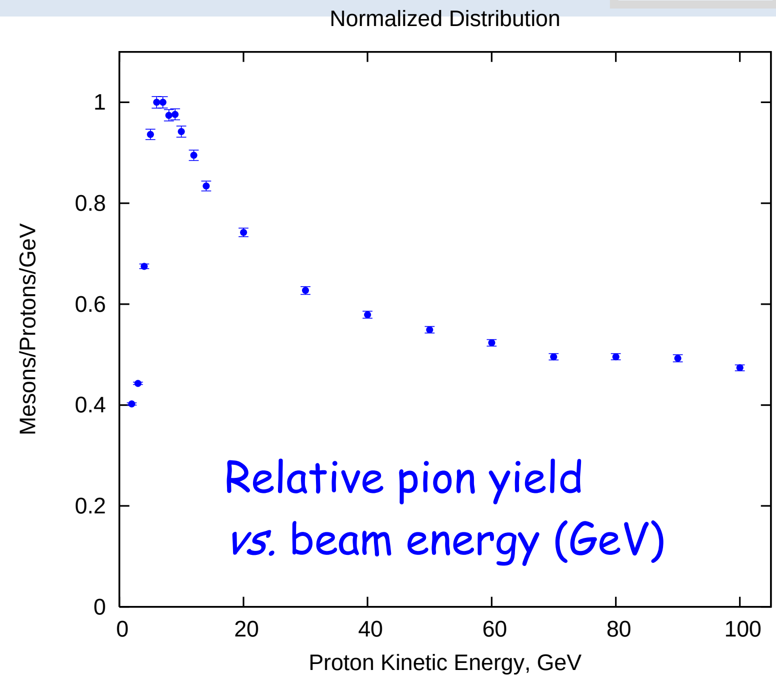
Advantage of mercury is less for lower beam energy.

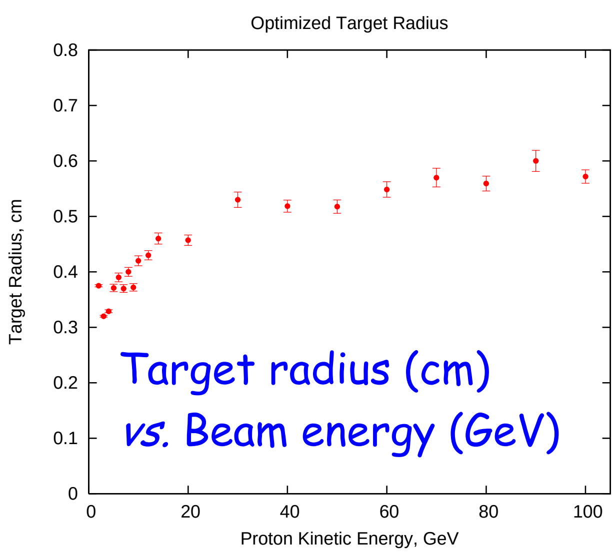
Pion Production Issues for ν Factory/Muon Collider, II

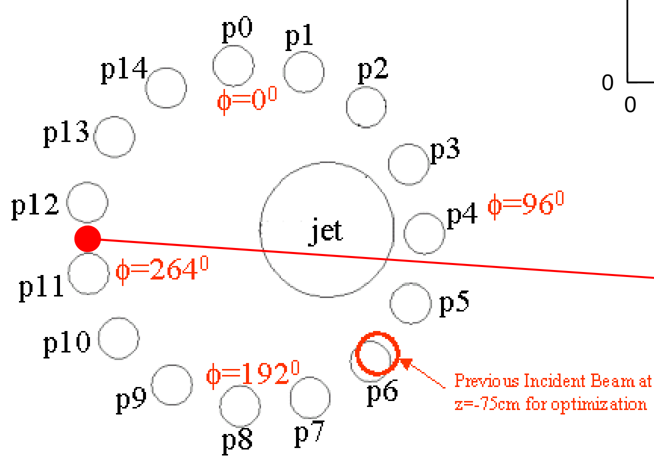
Study soft pion production as a function of 4 parameters:

- 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. More experimental data may be needed.]







Best production with proton beam coming into jet from the left (for present sign of B).

Vertical angle of both beam and jet to solenoid axis = 96 mrad.

Horizontal angle of jet = 0 mrad.

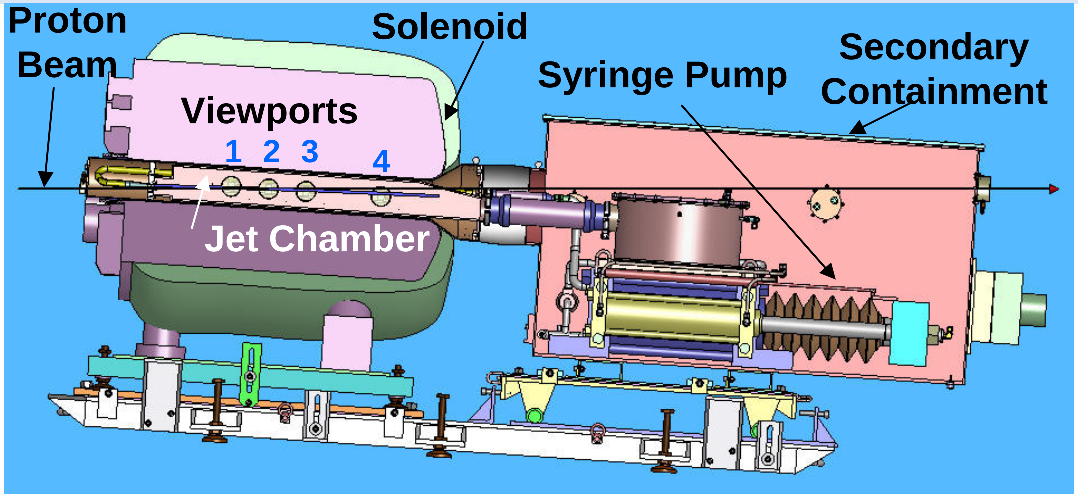
Horizontal angle of beam = 27 mrad.

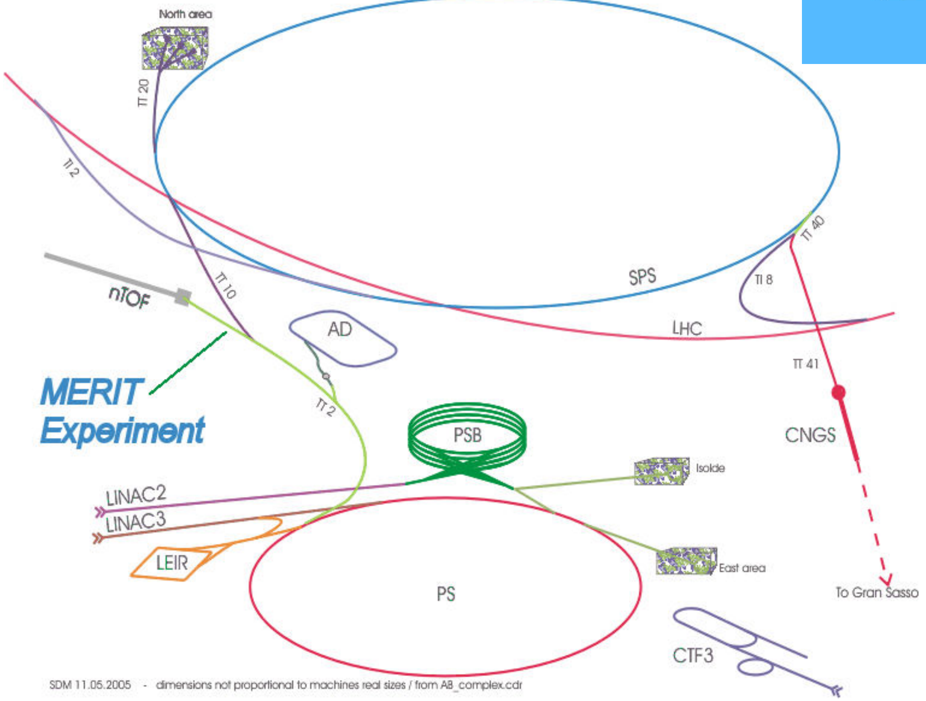
http://www.hep.princeton.edu/~mcdonald/mumu/target/Ding/ding_082509b.pdf

CERN MERIT Experiment (Nov 2007)

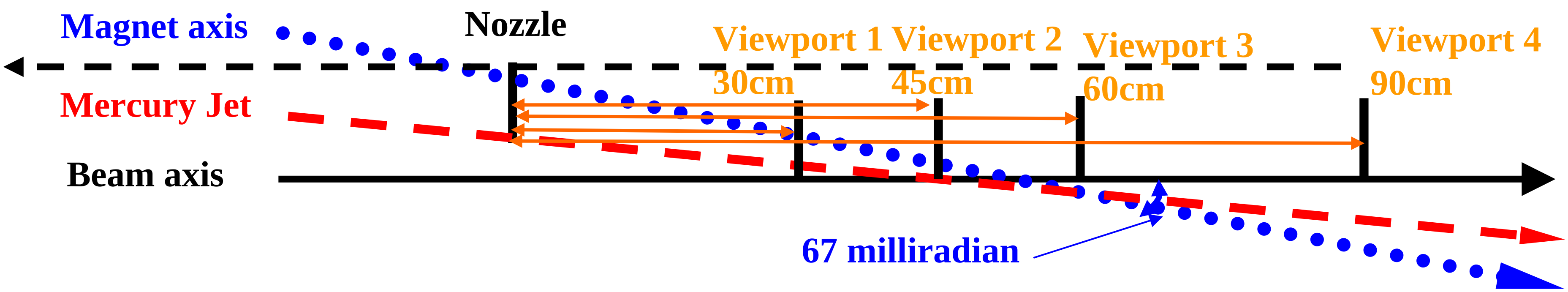
Proof-of-principle demonstration of a mercury jet target in a strong magnetic field, with proton bunches of intensity equivalent to a 4 MW beam.

Performed in the TT2A/TT2 tunnels at CERN.



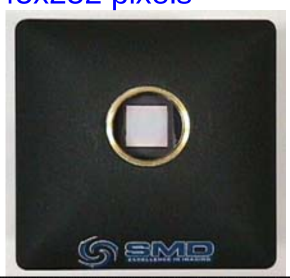


Optical Diagnostics of the Mercury Jet (T. Tsang)



Viewport 1, FV Camera
6 μs exposure
260x250 pixels

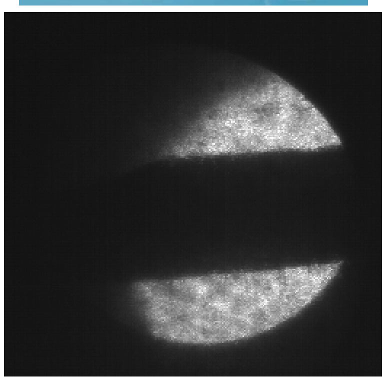
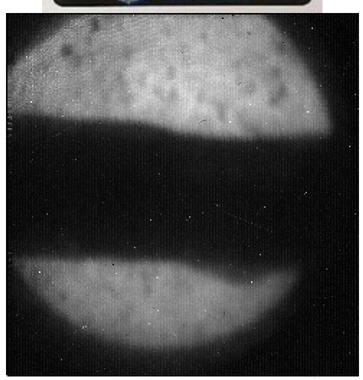
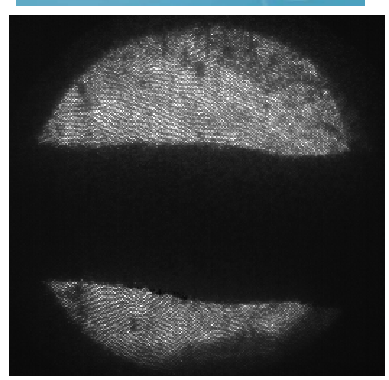
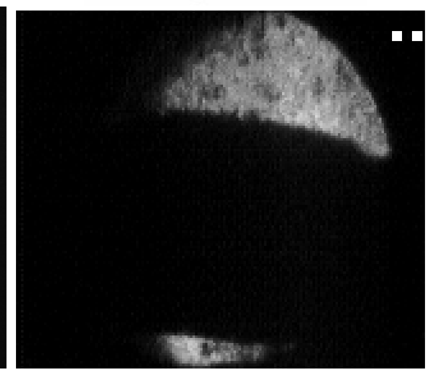
Viewport 2, SMD Camera
0.15 μs exposure
245x252 pixels



Viewport 3, FV Camera
6 μs exposure
260x250 pixels

Viewport 4, Olympus
33 μs exposure
160x140 pixels

7 T,
no beam

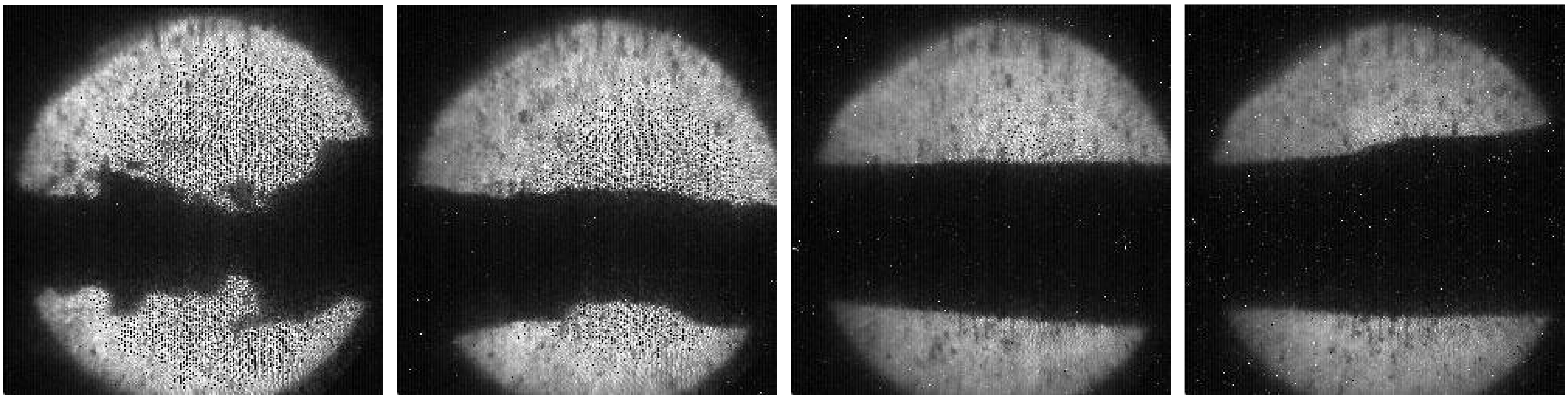





Stabilization of Jet Velocity by High Magnet Field

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

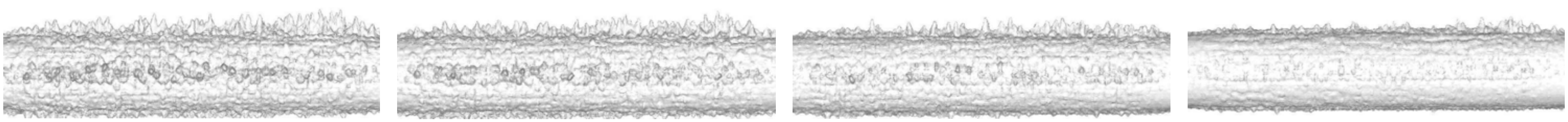
These were suppressed, but not eliminated in high magnetic fields.

Jets with velocity 15 m/s:



0T | 5 T | 10 T | 15 T

MHD simulations (R. Samulyak, W. Bo):



Mercury jet surface at 150 μs after the interaction with pulse of 1.2×10^{13} protons.

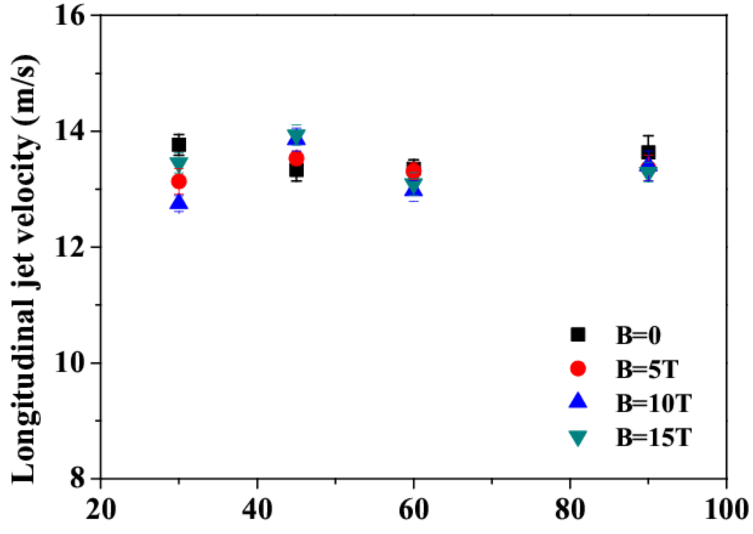
Jet Height

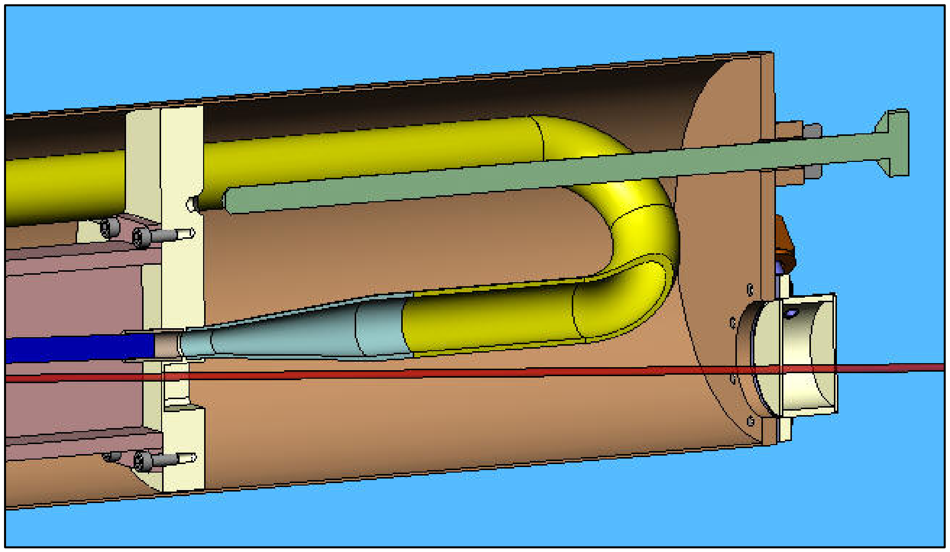
The velocity of surface perturbations on the jet was measured at all 4 viewports to be about 13.5 m/s, independent of magnetic field.

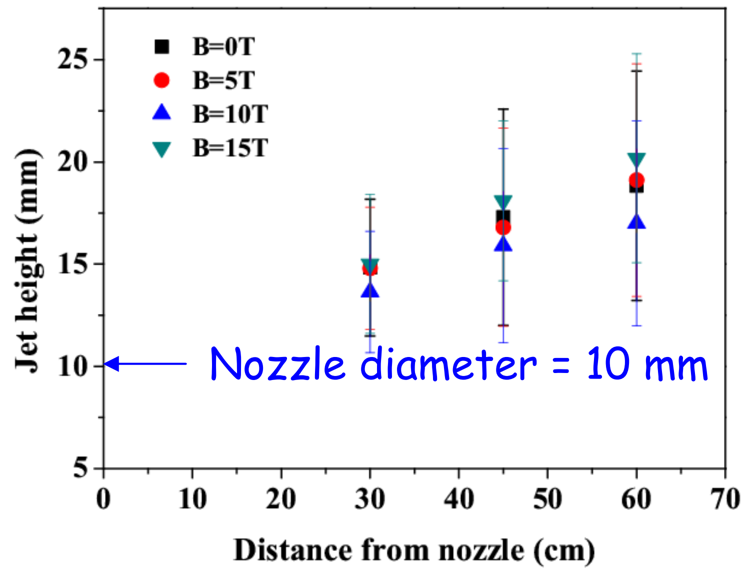
The vertical height of the jet grew ~ linearly with position to ~ double its initial value of 1 cm after 60 cm, almost independent of magnetic field.

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?

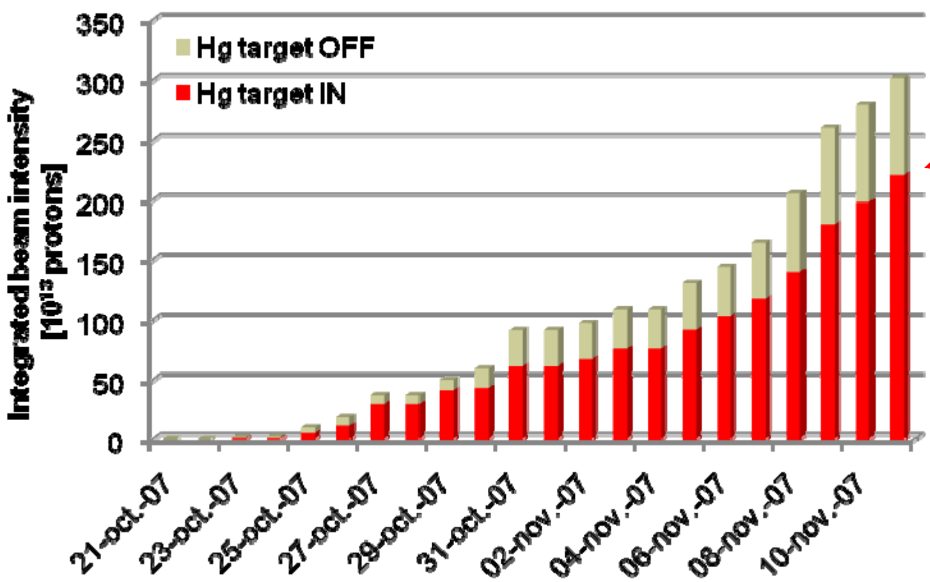
This issue may have been caused by the 180° bend in the mercury delivery pipe just upstream of the nozzle.







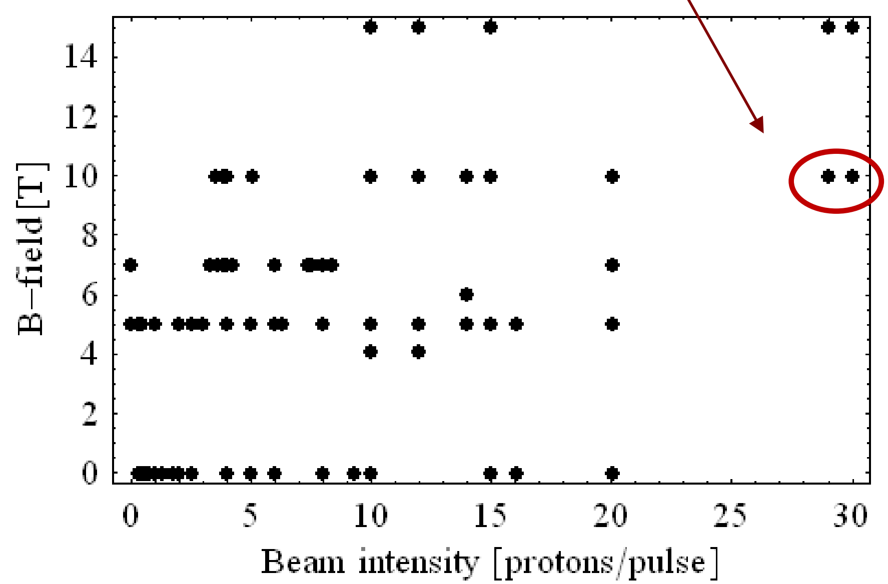
MERIT Beam Pulse Summary



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 !

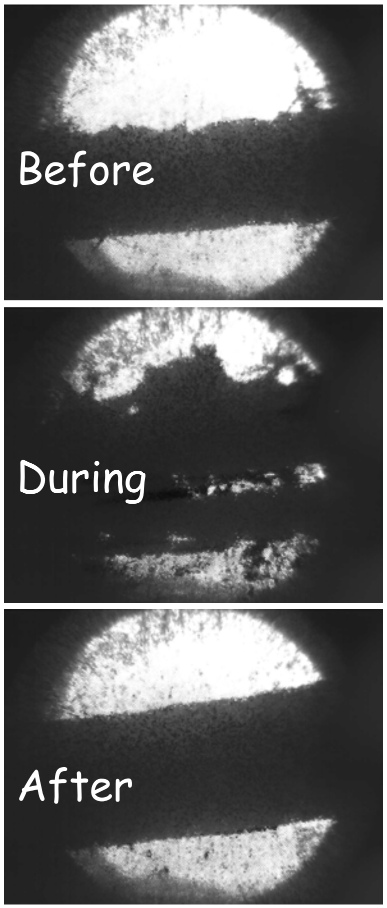
1 T*p* = 10^{12} protons

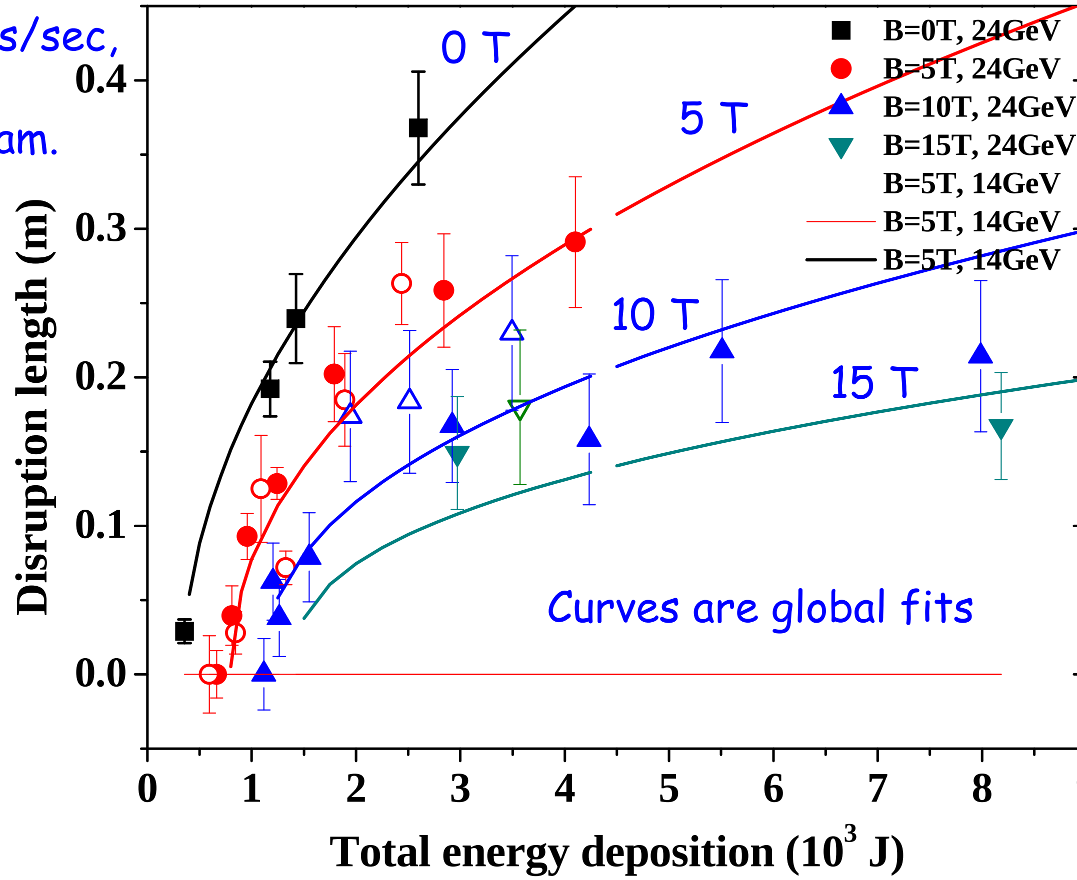


Disruption Length Analysis (H. Park, PhD Thesis)

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:



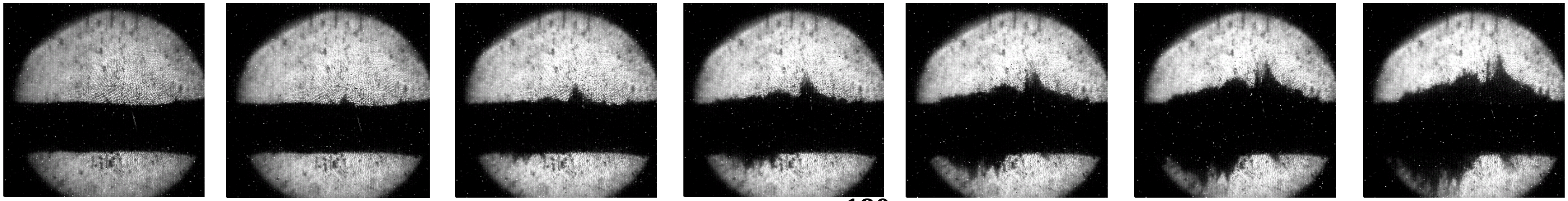


Disruption length never longer than region of overlap of jet with proton beam.

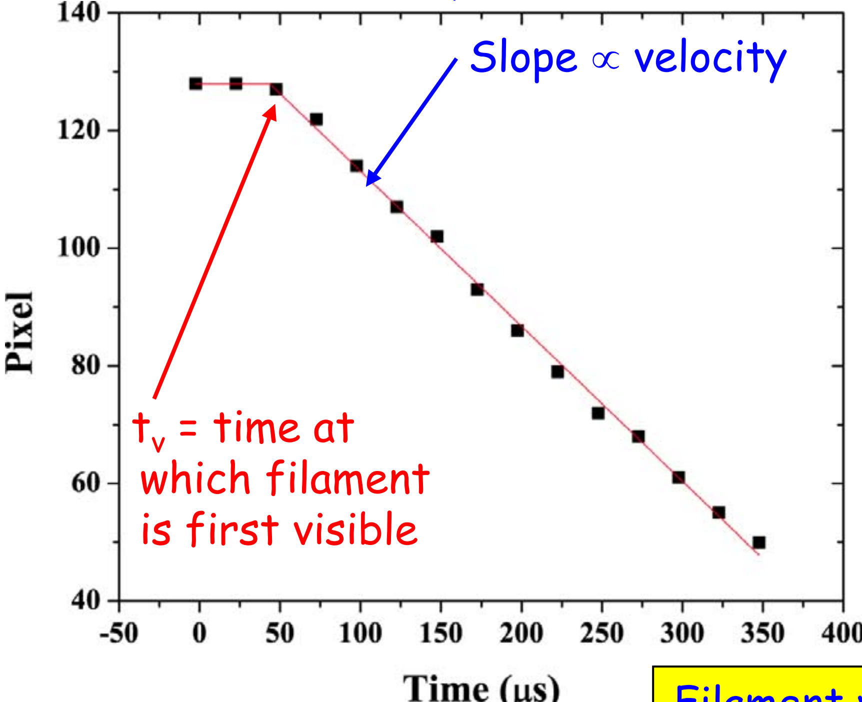
No disruption for pulses of < 2 T*p* in 0 T (< 4 T*p* in 10 T).

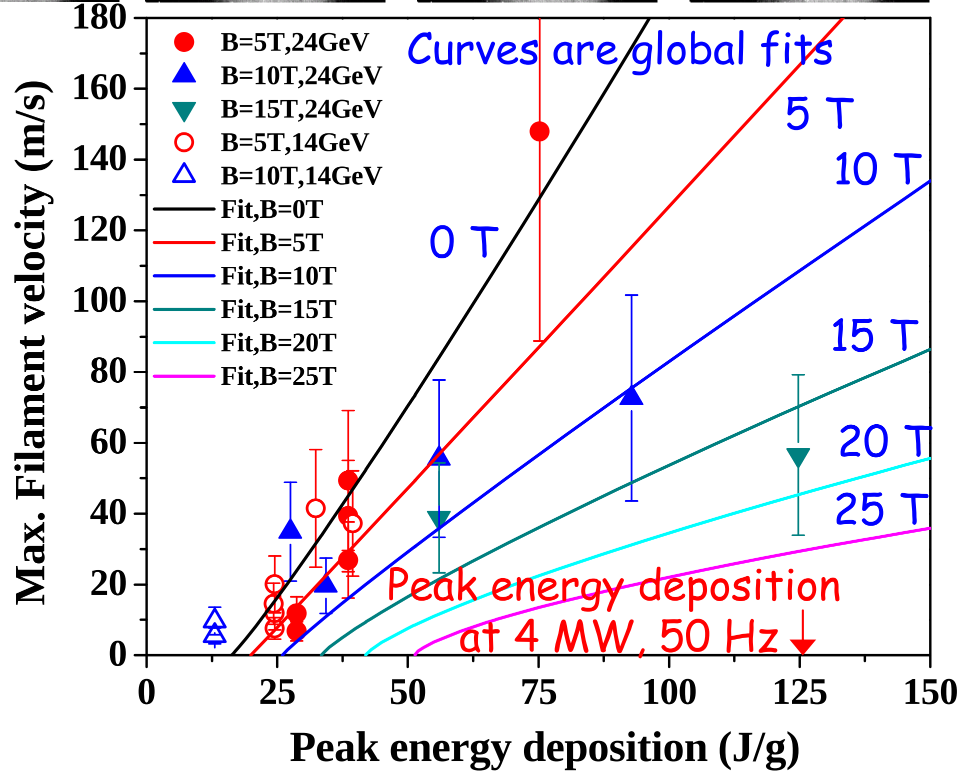
Disruption length shorter at higher magnetic field.

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.

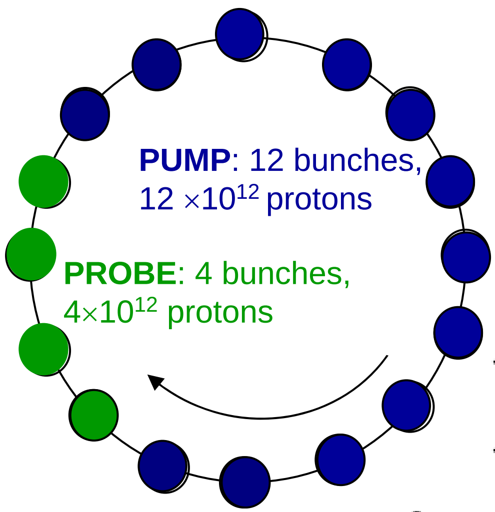
Filament start time >> transit time of sound across the jet.

Pump-Probe Studies

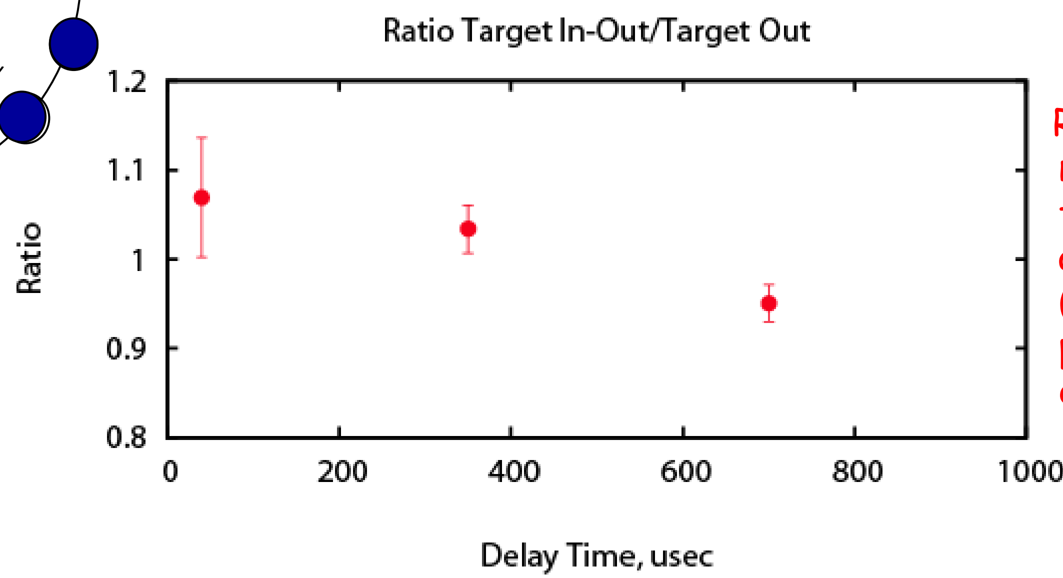
? Is pion production reduced during later bunches due to disruption of the mercury jet by the earlier bunches?

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 Mercury-Wetted Equipment Disposal

Chronology:

Description	Date(s)
MERIT Experiment at CERN	Oct/Nov 2007
Equipment removal from TT2/TT2A	8-Feb-2008
Shipment of mercury equipment from CERN	7-Oct-2009
Receipt of mercury equipment at ORNL	19-Oct-2009
Syringe pump dismantlement & Hg draining	May/June 2010
Syringe pump packed for disposal	4-Aug-2010
Syringe pump leaves ORNL for final disposal	Sept 2010 (est.)

Visual inspection of interior of 316L stainless-steel primary containment vessel showed no pitting due to "splash" of mercury.

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 μs, permitting use of short bunch trains at high power.
- No apparent damage to stainless-steel wall only 1 cm from interaction region.

Future Plans

Continued magnetohydrodynamic simulations of the beam-jet-magnet interaction.

Continued simulation of pion production to optimize the target geometry, and also to optimize the emittance reduction of the π/μ beam by the target magnets.

Make use of additional pion yield measurements to validate MARS, Fluka, …, simulations.

Integrated design study of a mercury loop + 20-T capture magnet.

- Improved nozzle for mercury jet.
- Splash mitigation in the mercury beam dump.
- Downstream beam window.
- Water-cooled tungsten-carbide shield (or alternative) of superconducting magnets.
- High-T_C fabrication of the superconducting magnets. (Can we eliminate the iron plug?)

Magnetohydrodynamic Simulations

Ongoing effort led by R. Samulyak (SUNY Stony Brook).

Recent summary:

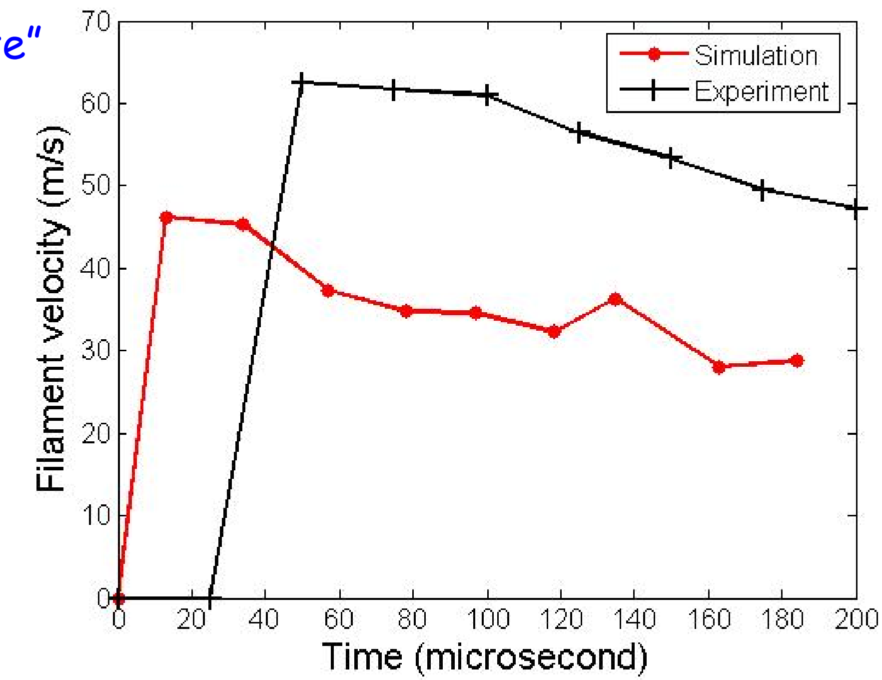
http://www.hep.princeton.edu/~mcdonald/examples/accel/samulyak_cmp_10.pdf

Outstanding issue: understanding/simulation of the delayed onset of filamentation of the mercury jet after interaction with a pulsed proton beam.

Model: rapid microcavitation of the mercury results in a reduction in the speed of sound.

Improved cavitation models can begin to address this issue numerically.

Past simulations showed "immediate" onset of filamentation:



Optimization of Target for Pion Yield

MARS simulations of pion yield for a Muon Collider/Neutrino Factory initiated by N. Mokhov (FNAL), and now pursued by X. Ding (UCLA).

Simultaneous optimization in proton beam energy, beam and target radii, beam and target angles relative to the magnetic axis, and for various target materials (Slide 5).

Must be revisited as engineering constraints on the target system design are clarified.

MARS and Fluka simulations of pion yields in the target system have notable differences, some of which are due to different interpretations of conflicting data as to pion production at 1-10 GeV.

Review by J. Strait (NuFact'09) of the HARP experiment data: http://www.hep.princeton.edu/~mcdonald/mumu/target/Strait/strait_marsvsharp.pdf

MARS and Fluka will incorporate additional experimental data at low energy and for various nuclear targets, including mercury, to be collected in the upgraded FNAL MIPP experiment (P-960): http://ppd.fnal.gov/experiments/e907/Collaboration/P960/

Optimization of Magnets for Pion Yield

If the pions are produced in a high field region, and transported to a region of low magnetic field through an adiabatic transition, the rms emittance (both longitudinal and transverse can be reduced).

This led to the baseline of a 20-T capture solenoid, and 1.5-T solenoid transport in most of the front end.

The effect of $\pi \to \mu\nu$ decay on the rms emittance of the resulting muons depends on the strength of the magnetic field in which the decay occurs.

Thorough optimization should be performed for

- Initial field
- Final field
- Length of the adiabatic taper
- Field strength and length of the decay region

Simulations should be integrated with phase-rotation/rf bunching in the front end.

Integrated Design Study of the Target System

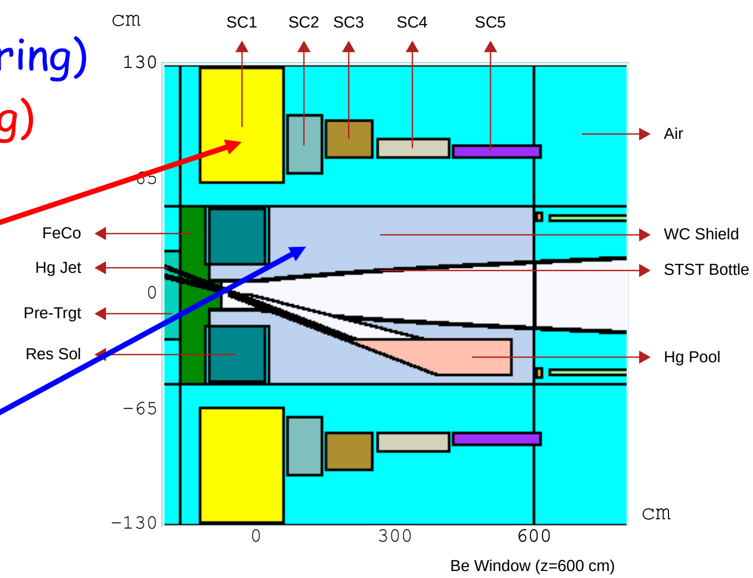
The target system has complex subsystems whose design requires a large variety of technical expertise.

- Nozzle configuration (fluid engineering at high Reynolds number)
- Solid-target alternatives (mechanical and thermal engineering)
- Mercury collection pool/beam dump (fluid, mechanical and thermal engineering)
- Internal shield of the superconducting magnets (fluid, mechanical and thermal engineering)
- Magnet design (SC-1:Nb_3Sn outsert, copper insert with option for high-T_C insert; cryogenic, fluid, mechanical engineering)
- Mercury flow loop (fluid engineering)
- Remote handling for maintenance (mechanical engineering)
- Target hall and infrastructure (mechanical engineering)

The baseline design of the internal shield does not appear sufficient to permit reliable operation of the superconducting magnets of the target system (and of much of the following front end).

25 kW of energy deposition in SC1

~ 3 MW in shielding



Future Hardware Studies

The issue of good flow of mercury at ~ 20 m/s from a nozzle of 8-10 mm diameter is ultimately empirical.

- Once the simulation effort (Ladiende group, SUNY Stony Brook) suggests an improved nozzle design, it should be tested in the lab.

The mercury jet (and the noninteracting proton beam) will cause substantial perturbations to the mercury collection pool.

- Splash mitigation by plates, rods, pebble bed, etc., can be studied by numerical simulation, but the favored solution should also be tested in the lab.

The dissipation of ~ 3 MW in the internal shield of the magnets is extremely challenging.

- Liquid coolant is required, in long, restricted flow paths due to the compact geometry of the target system.
- Numerical simulation should be used to suggest a solution, but it will be prudent to test key features of this in the lab.

The schedule of these studies depends on completion of the related simulations and engineering design, which is expected to take 1-3 years.

No hardware studies of absorbers beyond those in ongoing MICE (Coney, Snopok) are foreseen at present.

Summary

Prior efforts on the target system for a Muon Collider/Neutrino Factory have emphasized proof-of-principle demonstration of a free mercury jet target inside a solenoid magnet.

Future effort should emphasize integration of target, beam dump and **internal shield** into the capture magnet system.

Key challenges (H. Kirk, Front End Talk):

- Shielding of the superconducting coils against heat and radiation damage
- Thermal management of the 4-MW beam power deposited in the target system.
- Delivery of stable 20-m/s Hg jet
- Containment/recirculation of Hg (whose collection pool serves as beam dump).

Addressed by simulation and engineering design, with some hardware studies of

- The mercury nozzle.
- Splash mitigation in the mercury collection pool/beam dump.
- Coolant flow in the internal shield.

Backup Slides

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, ...

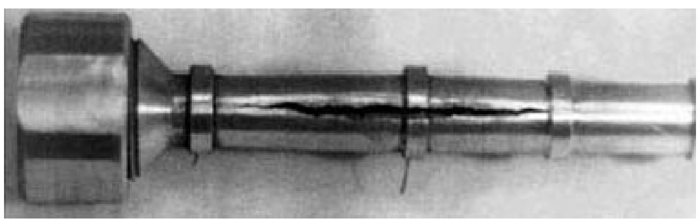
- Static Solid Targets
  - Graphite (or carbon composite) cooled by water/gas/radiation [CNGS, NuMI, T2K]
  - Tungsten or Tantalum (discs/rods/beads) cooled by water/gas [PSI, LANL]
- Moving Solid Targets
  - Rotating wheels/cylinders cooled (or heated!) off to side [SLD, FNAL, SNS]
  - Continuous or discrete belts/chains [King, Bennett]
  - 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]

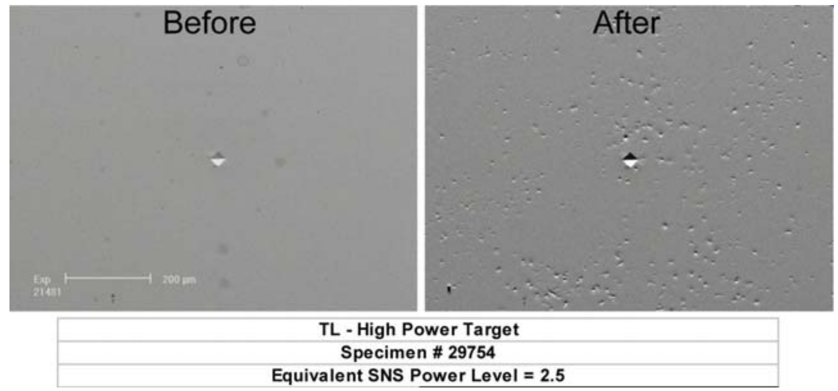
Beam-Induced Cavitation in Liquids Can Break Pipes

ISOLDE:

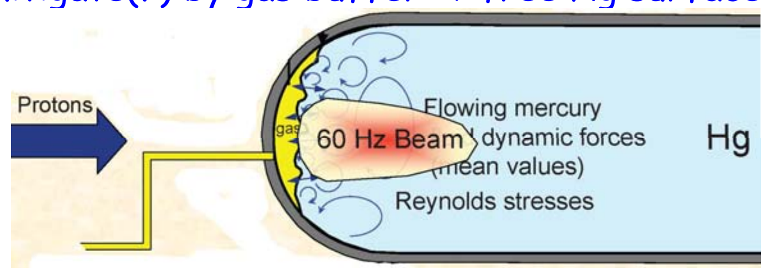
Hg in a pipe (BINP):



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

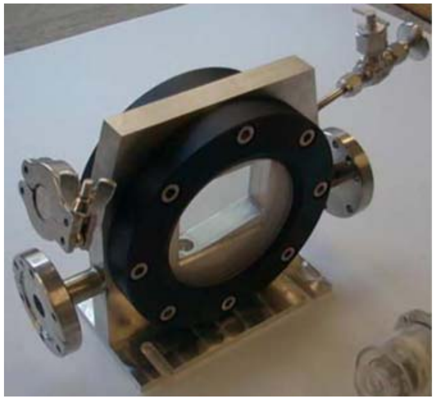


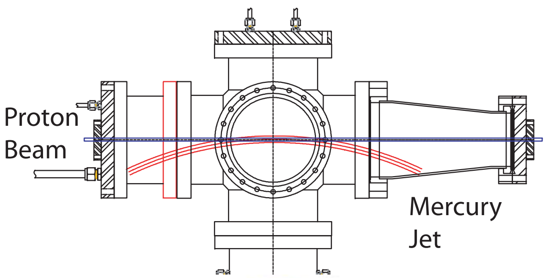
Mitigate(?) by gas buffer ⇒ free Hg surface:

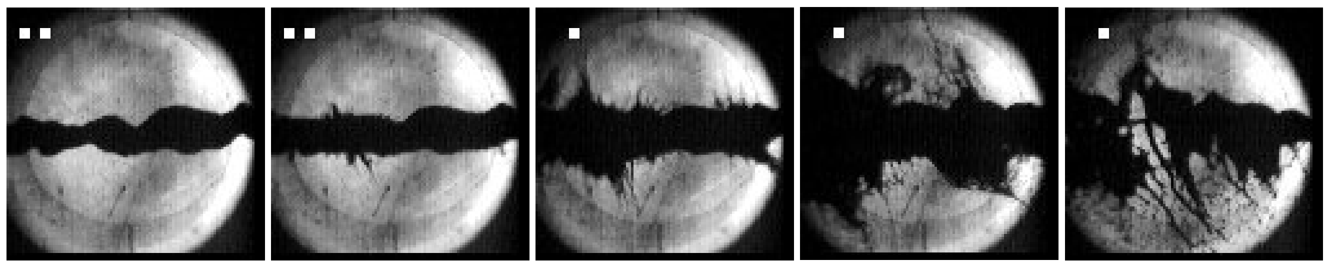


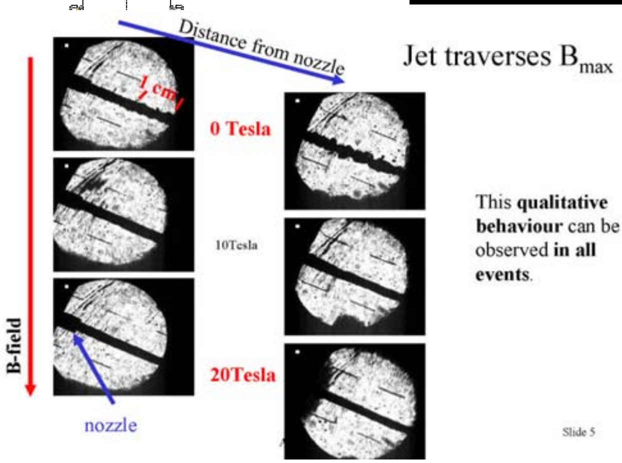
⇒ Use free liquid jet target when possible.

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







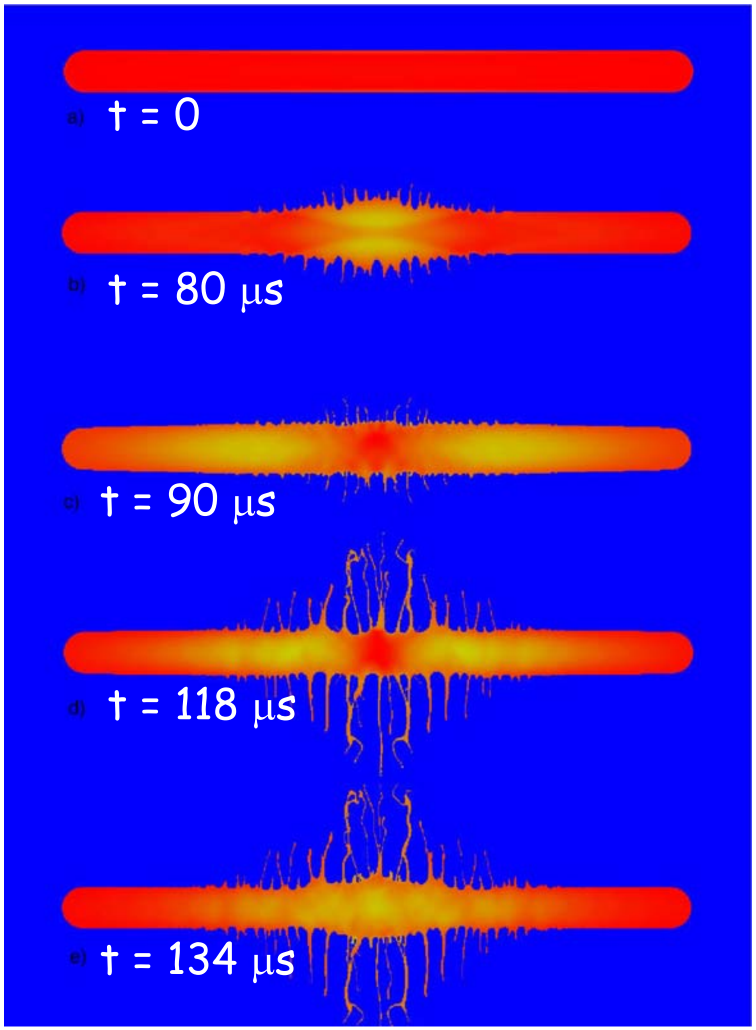


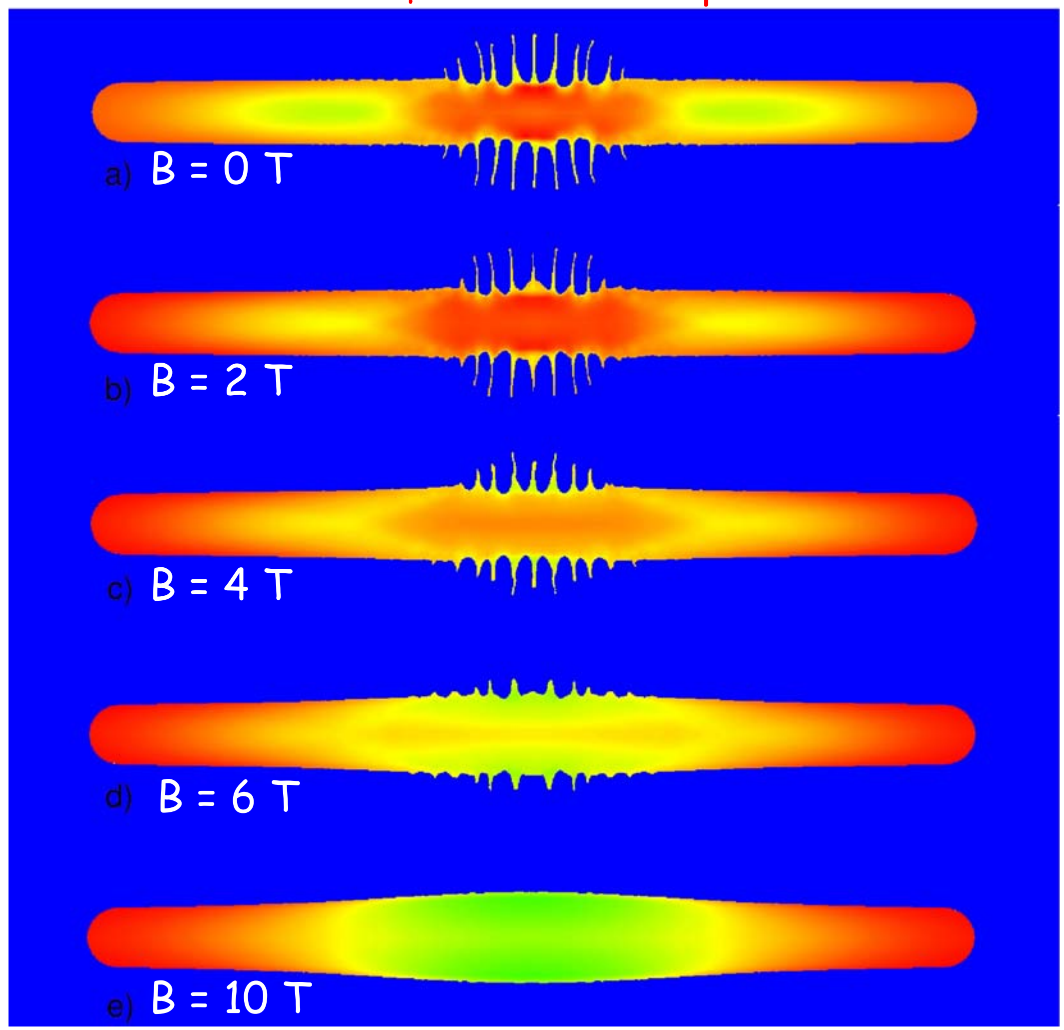
Data: $v_{dispersal} \approx$ 10 m/s for $U \approx$ J/g.
$v_{dispersal}$ appears to scale with proton intensity.
The dispersal is not destructive.
Filaments appear only $\approx$ 40 μs after beam,
$\Rightarrow$ After several bounces of waves, OR v_{sound} very low.
Rayleigh surface instability damped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

(PhD thesis: A. Fabich)
http://www.hep.princeton.edu/~mcdonald/mumu/target/thesis-2002-038.pdf

Magnetohydrodynamic Simulations (R. Samulyak)

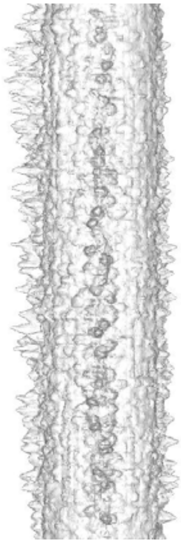
Peak energy density = 100 J/g



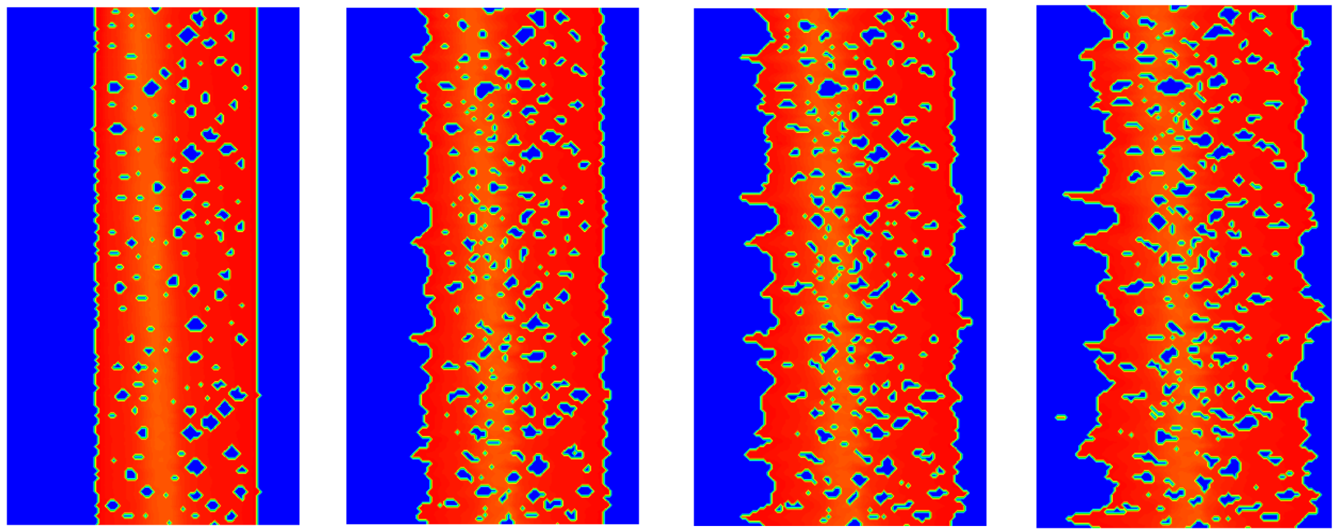


Magnetohydrodynamic Simulations (R. Samulyak, W. Bo)

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



Surface filaments at 160 μs

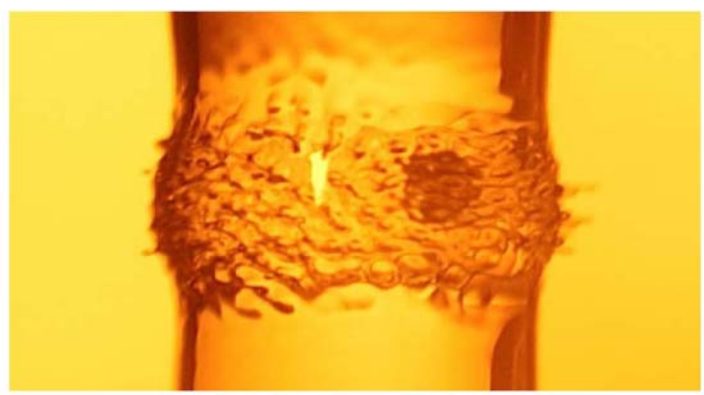


20 μs 130 μs 200 μs 250 μs

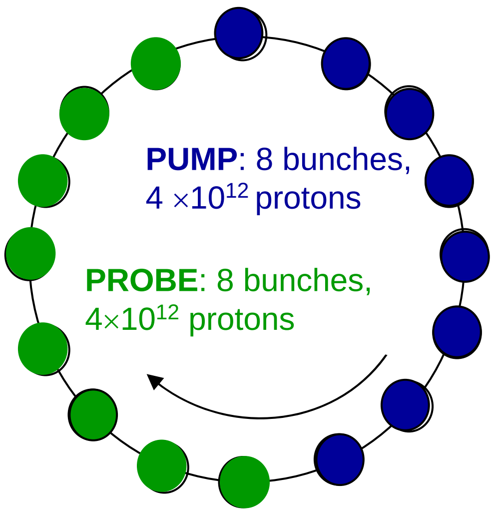
Experiment:

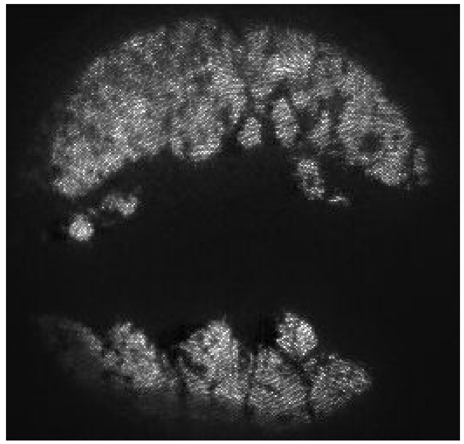
Laser-induced breakup of a water jet:

(J. Lettry, CERN)

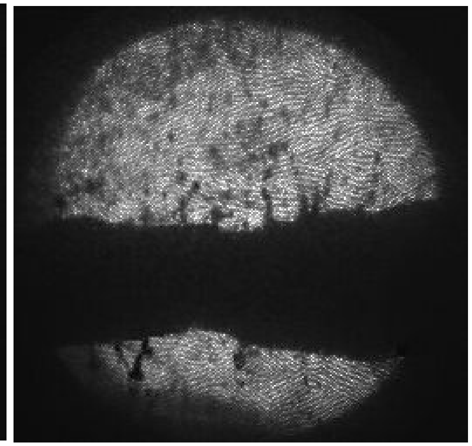


Pump-Probe Study with 4 T*p* + 4 T*p* at 14 GeV, 10 T

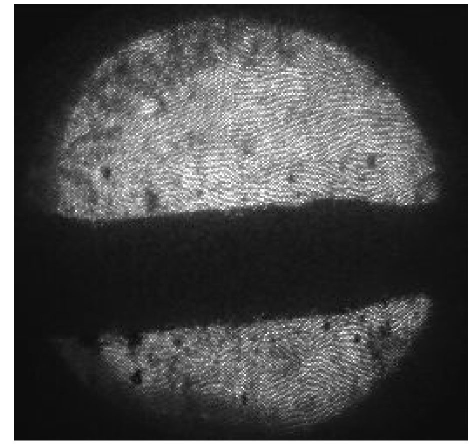




Single-turn extraction
➔ 0 delay, 8 T*p*



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.