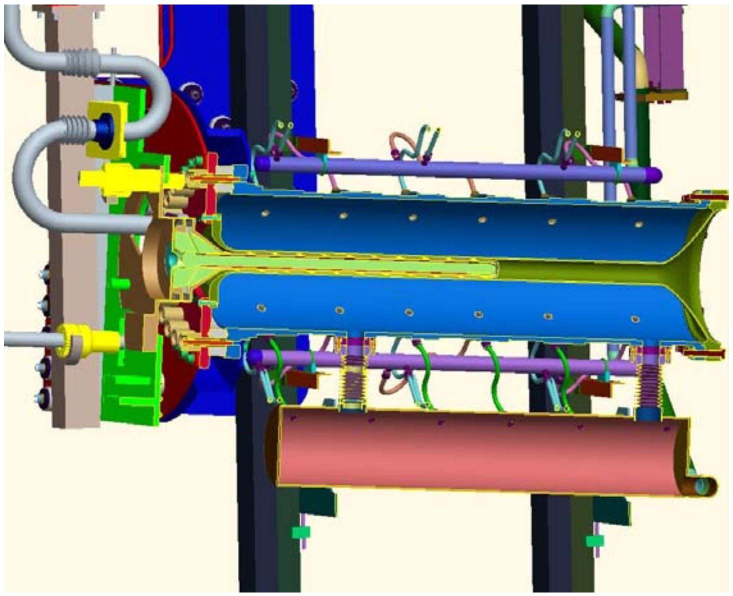
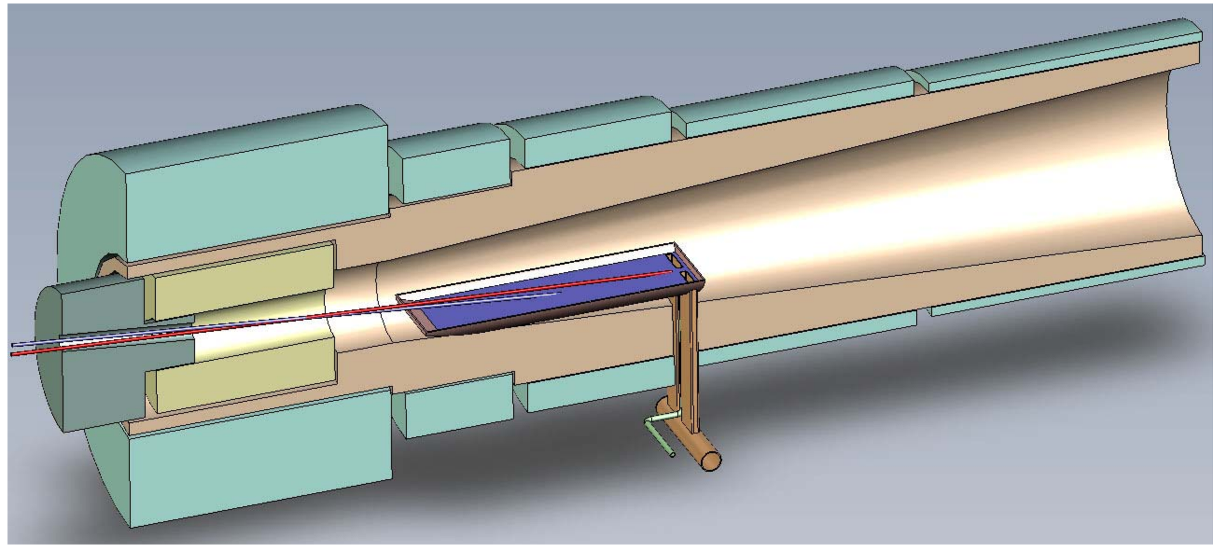
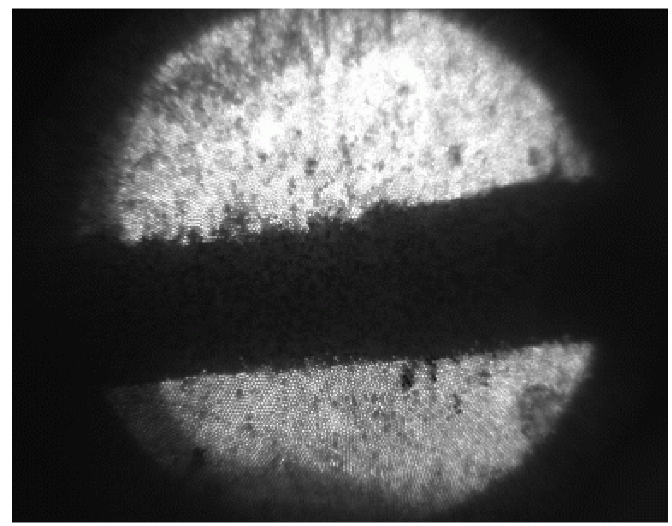
High-Power Targets for Superbeams and Neutrino Factories

(and Muon Colliders)







K.T. McDonald
Princeton U.

NuFact08
Valencia, July 3, 2008

Targetry Web Page:
http://puhep1.princeton.edu/mumu/target/

Topics Covered (as per NuFact08 Organizers)

Can solid target vs. liquid target survive Superbeam and/or Neutrino Factory beam structure at 2-4 MW?

What additional experimental results are needed to make a choice of Superbeam and Neutrino Factory target?

Presentation:

- Introduction
- Comments
- 51 backup slides for discussion

The Context

- Physics: Nature presents us with the opportunity to explore the richness of the mixing of massive neutrinos using neutrino beams: Mass hierarchy, $\sin^2\theta_{13}$, *CP* violation.

- Neutrino Beams:
  - Superbeam neutrinos from $\pi^\pm \to \mu^\pm \nu_\mu (\bar{\nu}_\mu)$ (Pions from $pA \to \pi^\pm X$.)
  - Factory neutrinos from $\mu^\pm \to e^\pm \bar{\nu}_\mu \nu_e (\nu_\mu \bar{\nu}_e)$ (Muons from $\pi^\pm \to \mu^\pm \nu_\mu (\bar{\nu}_\mu)$.)
  - β-beam neutrinos from $^6\mathrm{He} \to {}^6\mathrm{Li}\, e^- \nu_e$, $^{18}\mathrm{Ne} \to {}^{18}\mathrm{F}\, e^+ \nu_e$ (not discussed here).

- Detectors: Cheapest large detectors are calorimeters with no magnetic field.
  - $\Rightarrow$ Cheapest to study $\nu_\mu \to \nu_e$ oscillations with a sign-selected source.
  - $\Rightarrow$ Long time to study both neutrino and antineutrino oscillations.

Alternatives to permit simultaneous studies of neutrinos and antineutrinos:

- Magnetized iron calorimeter with Neutrino Factory ($\mu^\pm$ only).
- Magnetized liquid argon detector with Superbeam and/or Neutrino Factory.

(Only magnetized fine-grain detector {LAr, TASD, …] can distinguish $e^\pm$.)

(Neutrino Factory needs magnetized detector even if sign-selected beam.)

Targetry

The exciting results from atmospheric, solar and reactor neutrino programs (Super-K, SNO, Borexino, KamLAND, …) reinforce the opportunity for neutrino physics with intense accelerator neutrino beams, where targetry is a major challenge.

Targetry = the task of producing and capturing π's and μ's from proton interactions with a nuclear target.

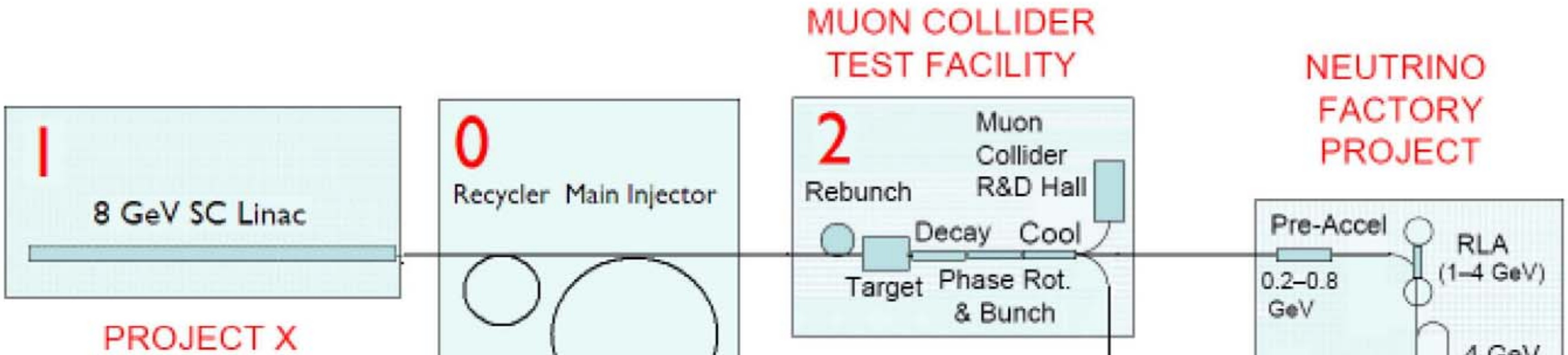
At a muon collider the key parameter is luminosity: $\mathcal{L} = \frac{N_1 N_2 f}{A} \mathrm{s}^{-1}\mathrm{cm}^{-2}$,

$\Rightarrow$ Gain as square of source strength (targetry) [but small beam area (cooling) is also critical].

At a neutrino superbeam and a neutrino factory the key parameter is neutrino flux,
$\Rightarrow$ Source strength (targetry) is of pre-eminent concern.

[Beam cooling important mainly to be sure the beam fits in the pipe.]

The Target is Pivotal between a Proton Driver and ν or μ Beams



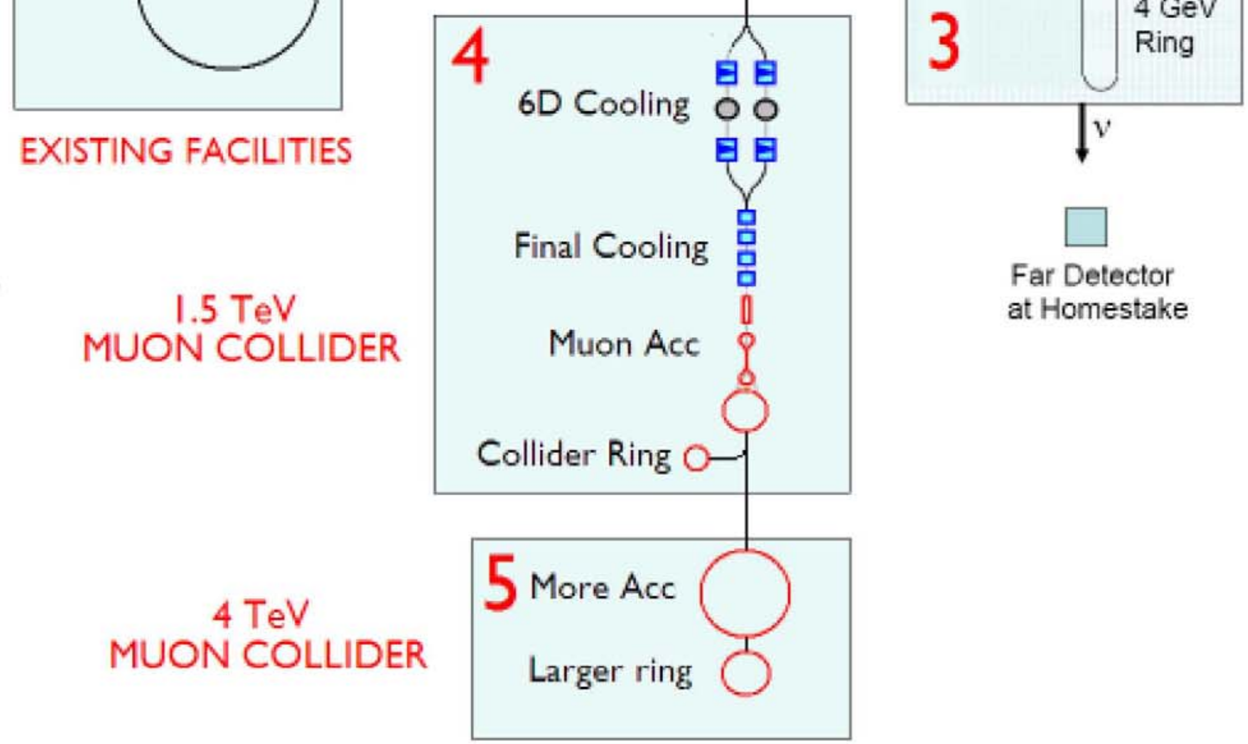
A Muon Collider is an energy-frontier particle-physics facility (that also produces lots of high-energy ν's).

Higher mass of muon
$\Rightarrow$ Better defined initial state than e^+e^- at high energy.

A muon lives $\approx$ 1000 turns.

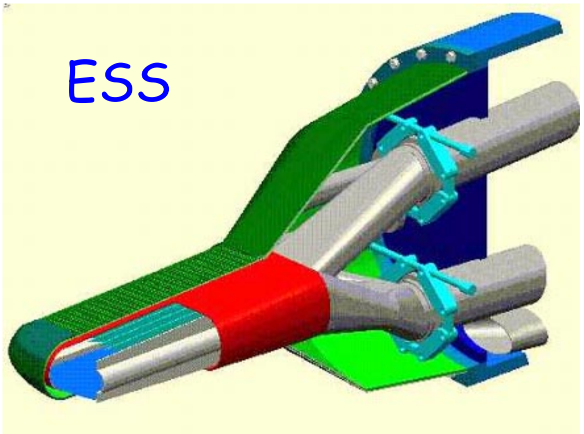
Need lots of muons to have enough luminosity for physics.

Need a production target that can survive multmegawatt proton beams.

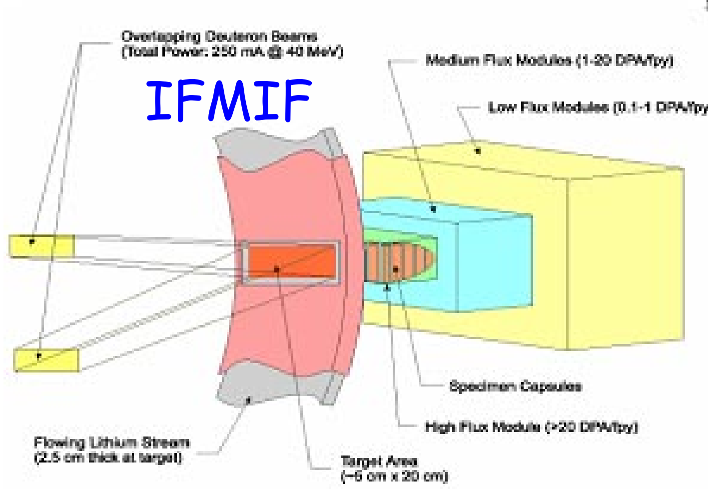


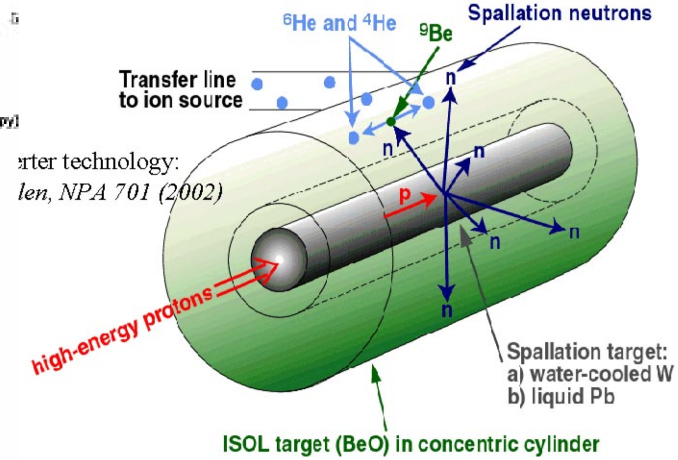
High-Power Targets Essential for Many Future Facilities

ESS



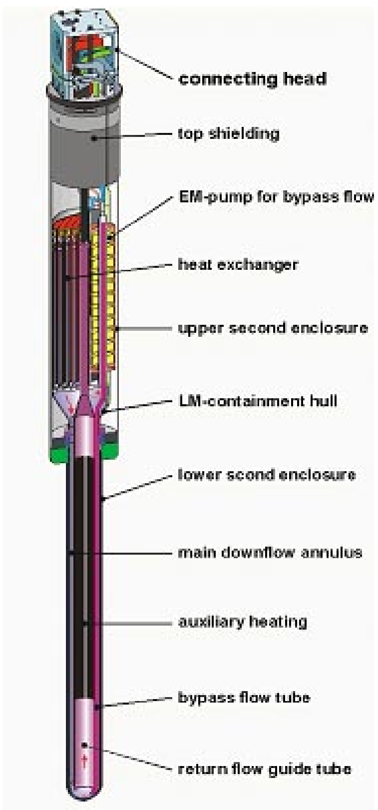
IFMIF



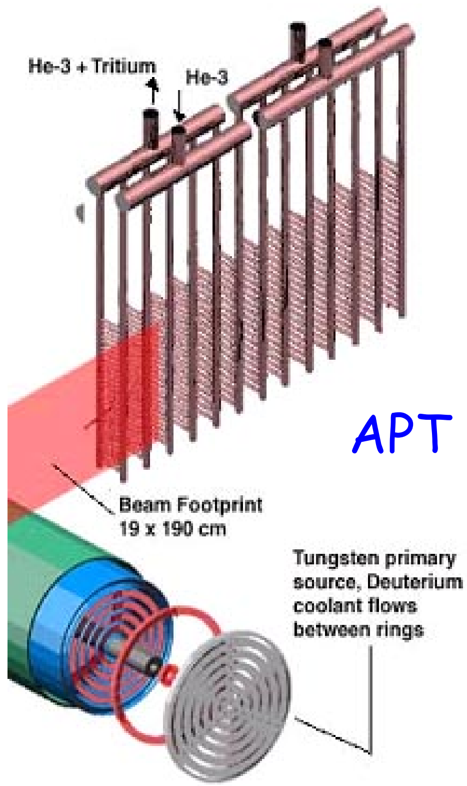


ISOL/β Beams

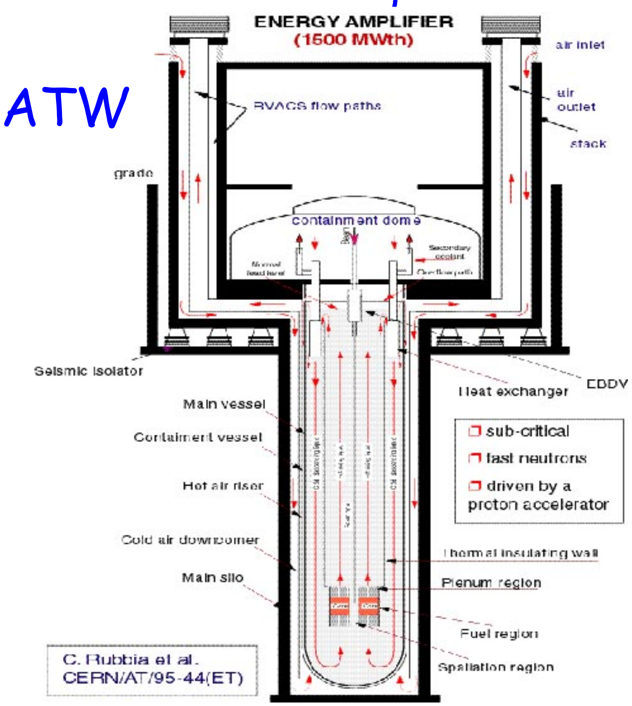
PSI



APT



ATW



2-4 MW Proton Beams

- 10-50 GeV beam energy appropriate for Superbeams, Neutrino Factories and Muon Colliders.
  - ⇒ 0.8-2.5 $\times$ 10^{15} pps; 0.8-2.5 $\times$ 10^{22} protons per year of 10^{7} s.

- Rep rate 15-50 Hz at Neutrino Factory/Muon Collider, as low as $\approx$ 2 Hz for Superbeam.
  - $\Rightarrow$ Protons per pulse from 1.6 $\times$ 10^{13} to 1.25 $\times$ 10^{15}.
  - $\Rightarrow$ Energy per pulse from 80 kJ to 2 MJ.

- Small beam size preferred:
  - $\approx$ 0.1 cm^2 for Neutrino Factory/Muon Collider, $\approx$ 0.2 cm^2 for Superbeam.

- Pulse width $\approx$ 1 μs OK for Superbeam, but $\approx$ 1 ns desired for Neutrino Factory/Muon Collider.

$\Rightarrow$ Severe materials issues for target AND beam dump.

- Radiation Damage.
- Melting.
- Cracking (due to single-pulse "thermal shock").

- MW energy dissipation requires liquid coolant somewhere in system!
  - $\Rightarrow$ No such thing as "solid target only option" at this power level.

Radiation Damage

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 (and 9-28 days at a 2-MW Superbeam).

⇒ Mitigate by frequent target changes, moving target, liquid target, ...
[Mitigated in some materials by annealing/operation at elevated temperature.]

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 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.)

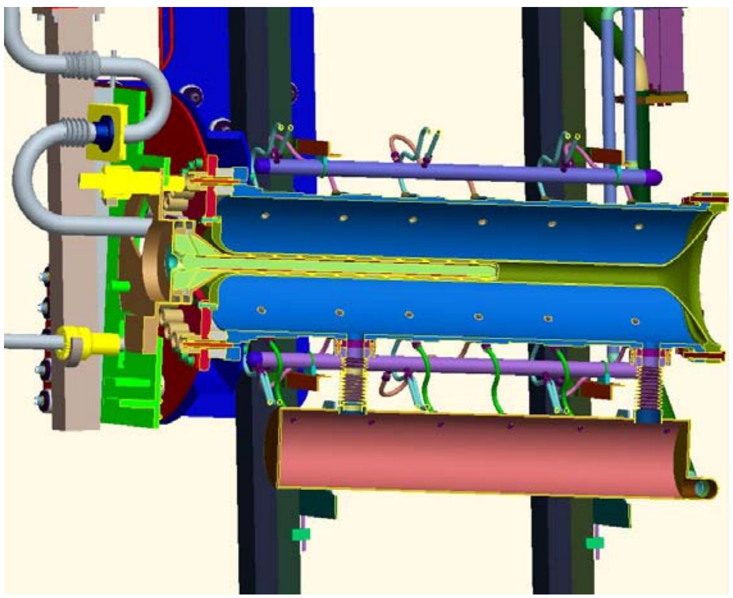
The proton beam should be tilted with respect to the axis of the capture system at a Neutrino Factory, so that the beam dump does not absorb the captured π's and μ's.

Target and Capture Topologies: Toroidal Horn

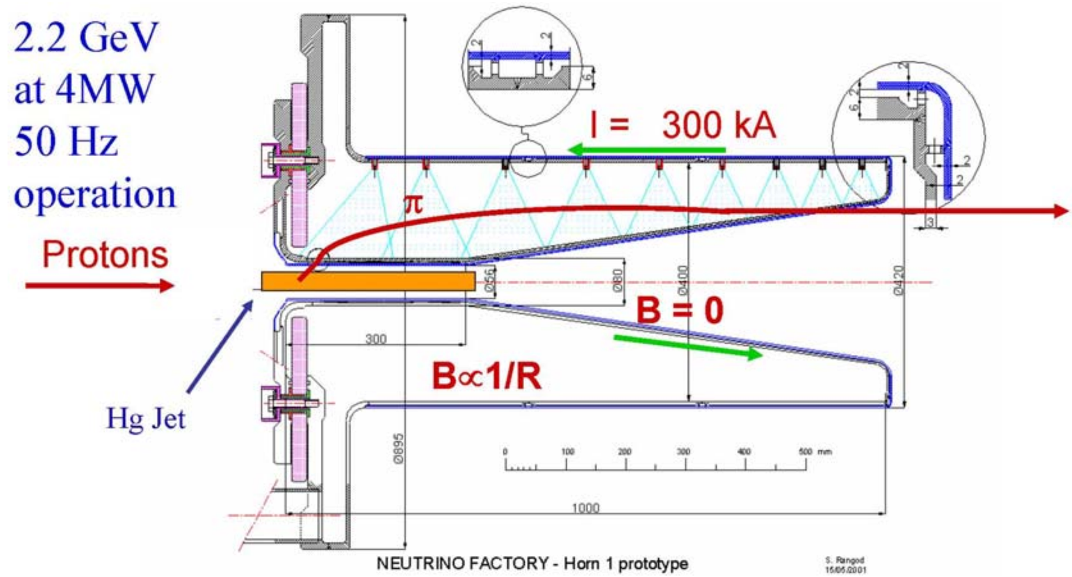
The traditional topology for efficient capture of secondary pions is a toroidal "horn" (Van der Meer, 1961).

- Collects only one sign, $\Rightarrow$ Longer data runs, but nonmagnetic detector (Superbeam).
- Inner conductor of toroid very close to proton beam.
  - $\Rightarrow$ Limited life due to radiation damage at 4 MW.
  - $\Rightarrow$ Beam, and beam dump, along magnetic axis.
  - $\Rightarrow$ More compatible with Superbeam than with Neutrino Factory/Muon Collider.

0.75-MW Graphite target with He gas cooling (T2K):



Mercury jet target (CERN SPL study):



If desire secondary pions with $E_\pi \leq 5$ GeV (Neutrino Factory), a high-Z target is favored, but for $E_\pi \geq 10$ GeV (some Superbeams), low Z is preferred.

Target and Capture Topologies: Solenoid

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)
Neutrino Factory Study 2

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).

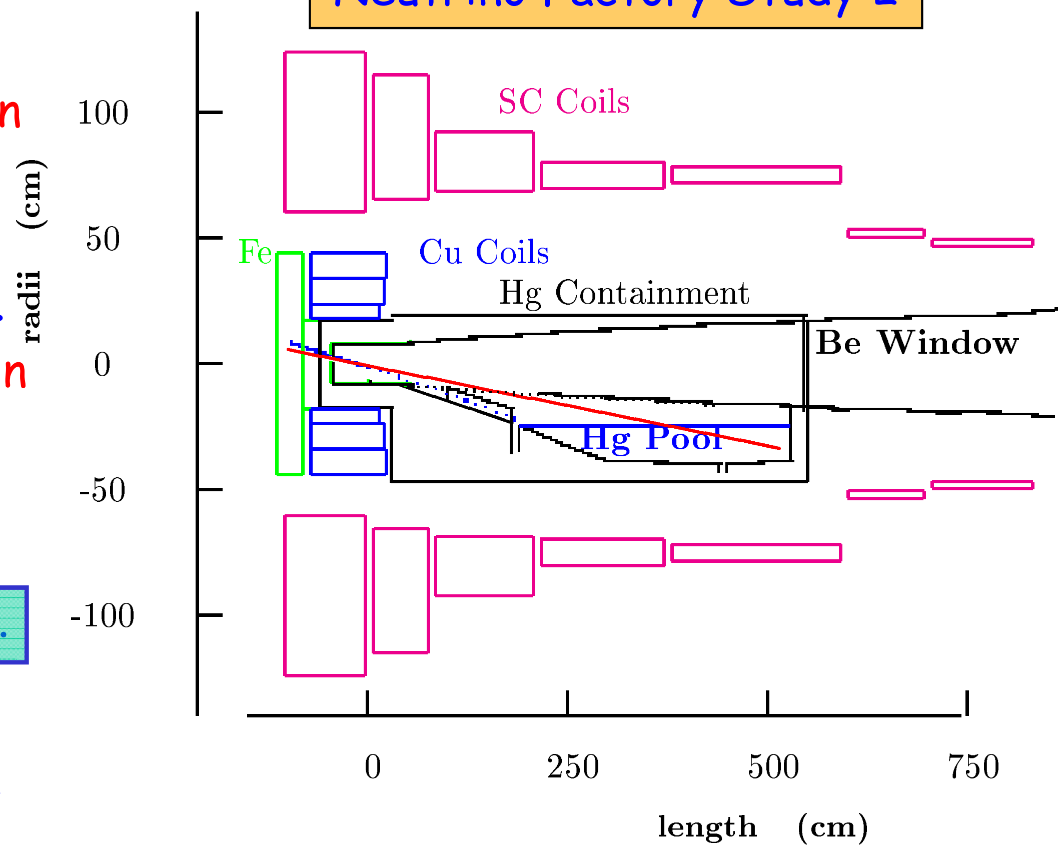
Solenoid coils can be some distance from proton beam.

⇒ ≥ 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.



Solenoid Capture System for a Superbeam

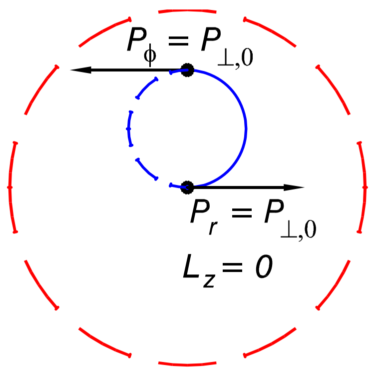
- Pions produced on axis inside the (uniform) solenoid have zero canonical angular momentum, $L_z = r(P_\varphi + eA_\varphi / c) = 0, \;\Rightarrow\; P_\varphi = 0$ on exiting the solenoid.
- If the pion has made exactly 1/2 turn on its helix when it reaches the end of the solenoid, then its initial P_r has been rotated into a pure P_φ, $\Rightarrow P_r = 0$ on exiting the solenoid.

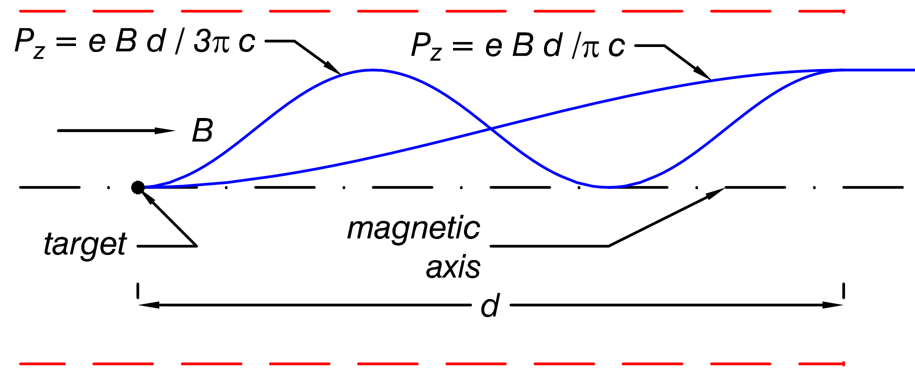
$\Rightarrow$ Point-to-parallel focusing for

$$P_\pi = eBd / (2n+1)\,\pi c.$$

$\Rightarrow$ Narrowband (less background) neutrino beams of energies

$$E_\nu \approx \frac{P_\pi}{2} = \frac{eBd}{(2n+1)2\pi c}.$$





(KTM, physics/0312022)

$\Rightarrow$ Can study several neutrino oscillation peaks at once,

$$\frac{1.27 M_{23}^2[\mathrm{eV}^2]\; L[\mathrm{km}]}{E_\nu[\mathrm{GeV}]} = \frac{(2n+1)\pi}{2}.$$

(Marciano, hep-ph/0108181)

Study both ν and $\bar{\nu}$ at the same time.

$\Rightarrow$ Detector must identify sign of μ and e.

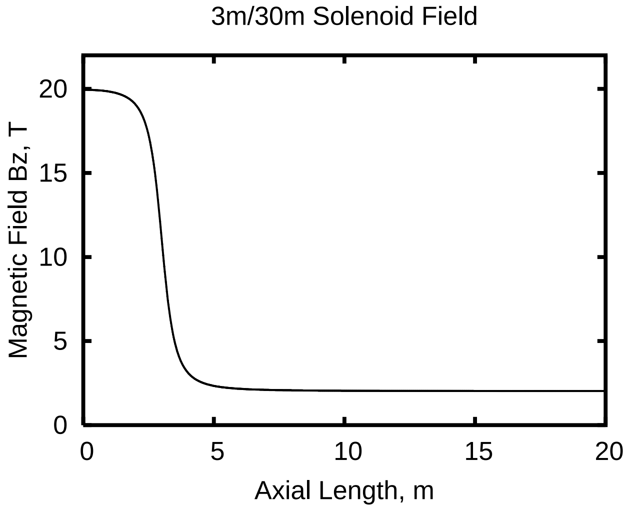
$\Rightarrow$ Magnetized liquid argon TPC [TASD?].

(astro-ph/0105442).

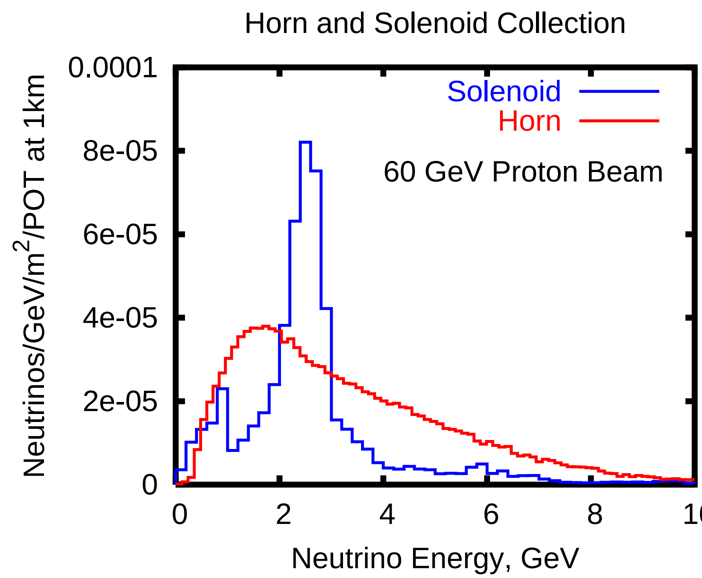
Simulation of Solenoid Horn

(H. Kirk and R. Palmer, NuFACT06)

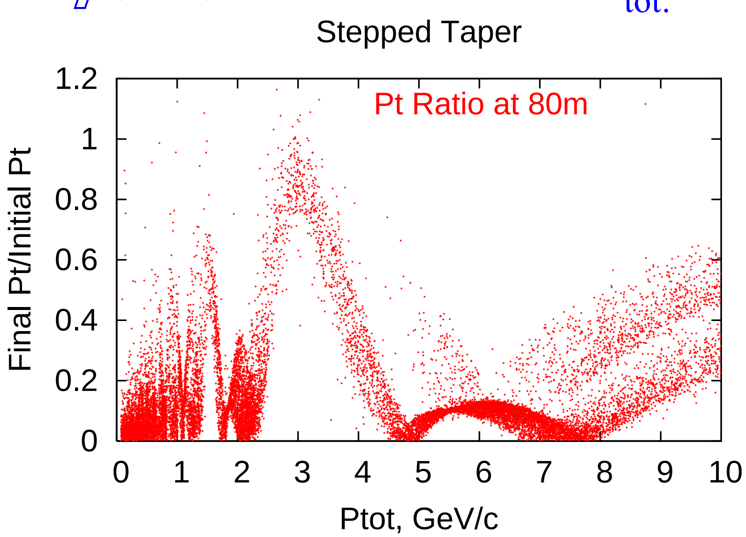
B *vs.* z for 3 + 30 m solenoid:



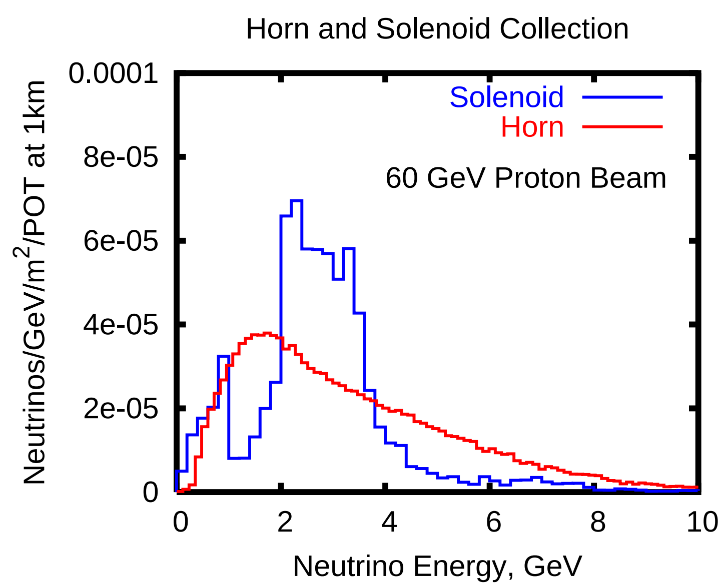
3-m solenoid gives 2 narrow peaks in ν spectrum:



$P_{\perp}$ minimized at selected $P_{tot:}$



3+30-m solenoid broadens the higher energy peak:



Results very encouraging, but comparison with toroid horn needs confirmation.

Target Options

- 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 $\overline{p}$, Bennett]
  - Continuous or discrete belts/chains [King]
  - Flowing powder [Densham]

- Flowing liquid in a vessel with beam windows [SNS, ESS]

- Free liquid jet [Neutrino Factory Study 2]

Static Solid Targets

Pros:

- Tried and true – for low power beams.
- Will likely survive "thermal shock" of long beam pulses at 2 MW (Superbeam).

Cons:

- Radiation damage will lead to reduced particle production/mechanical failure on the scale of a few weeks at 2 MW.
- If liquid cooled, leakage of radioactive coolant anywhere in the system is potentially more troublesome than breakup of a radioactive solid.

$\Rightarrow$ Must consider a "moving target" later if not sooner.

R&D: Test targets to failure in high-power beams to determine actual operational limits.

Moving Solid Targets

Pros:

- Can avoid radiation damage limit of static solid targets.
- Will likely survive "thermal shock" of long beam pulses at 2 MW (Superbeam).

Cons:

- Target geometry not very compatible with neutrino "horns" except when target is upstream of horn (high energy ν's: CNGS, NuMI).
- If liquid cooled, leakage of radioactive coolant anywhere in the system is potentially more troublesome than breakup of a radioactive solid.

R&D:

- Engineering to clarify compatibility with a target station for Superbeams.
- Lab studies of erosion of nozzle by powders.

Personal view: this option is incompatible with Neutrino Factories.

Flowing Liquids in Vessels

Pros:

- The liquid flows through well-defined pipes.
- Radiation damage to the liquid is not an issue.

Cons:

- The vessel must include static solid beam windows, whose lifetime will be very short in the small proton spot sizes needed at Superbeams and Neutrino Factories.
- Cavitation in the liquid next to the beam windows is extremely destructive.
- Leakage of radioactive liquid anywhere in the system is potentially more troublesome than breakup of a radioactive solid.

R&D: This option is not very plausible for Superbeams and Neutrino Factories, and no R&D is advocated.

Free Liquid Jet Targets

Pros:

- No static solid window in the intense proton beam.
- Radiation damage to the liquid is not an issue.

Cons:

- Never used before as a production target.
- Leakage of radioactive liquid anywhere in the system is potentially more troublesome than breakup of a radioactive solid.

R&D: Proof of principle of a free liquid jet target has been established by the CERN MERIT Experiment. R&D would be useful to improve the jet quality, and to advance our understanding of systems design issues.

Personal view: This option deserves its status as the baseline for Neutrino Factories and Muon Colliders. For Superbeams that will be limited to less than 2 MW, static solid targets continue to be appealing.

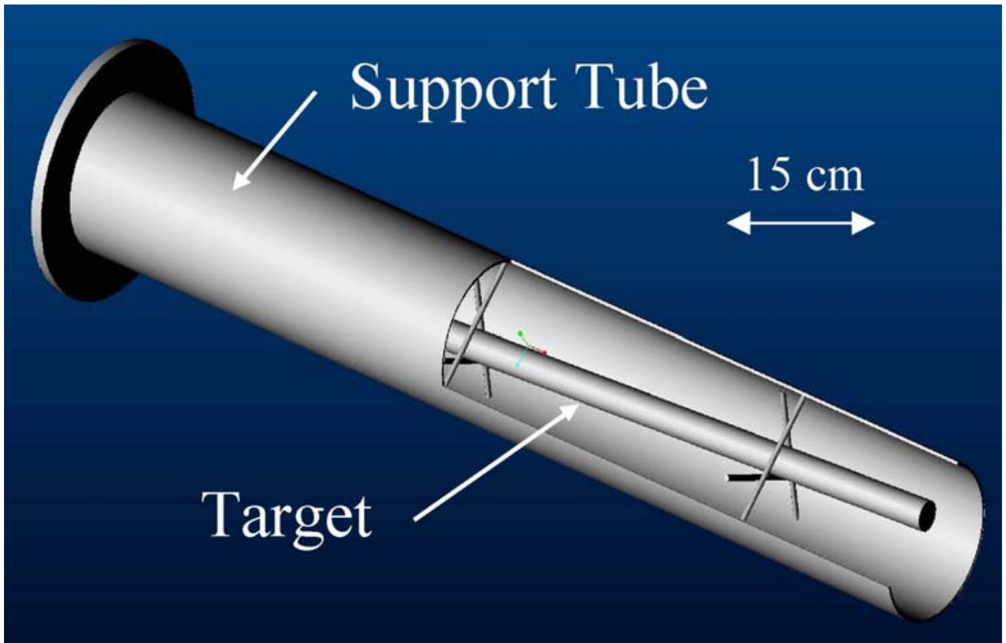
Thermal Issues for Solid Targets, I

The quest for efficient capture of secondary pions precludes traditional schemes to cool a solid target by a liquid. (Absorption by plumbing; cavitation of liquid.)

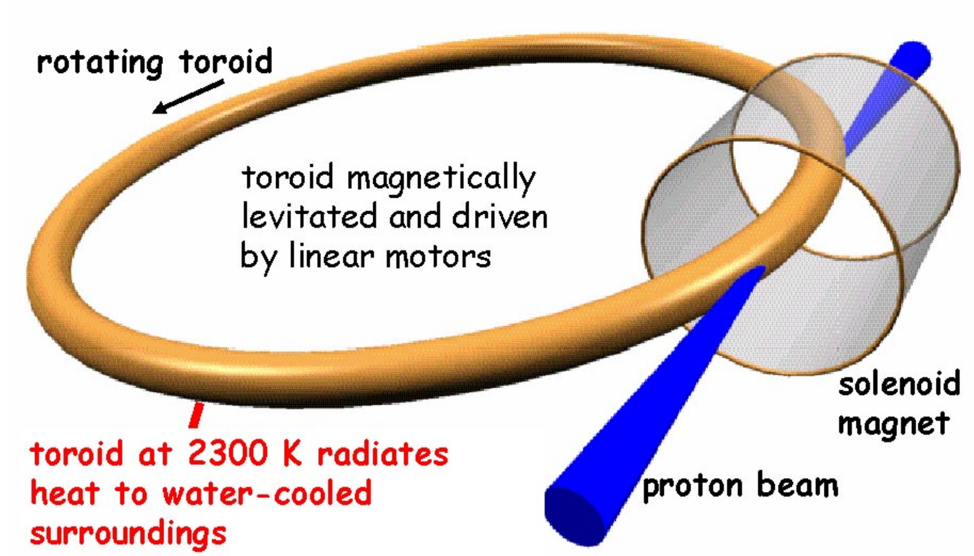
A solid, radiation-cooled stationary target in a 4-MW beam will equilibrate at about 2500 C.
$\Rightarrow$ Carbon is only candidate for this type of target.

Carbon target must be in He atmosphere to suppress sublimation.

(Neutrino Factory Study 1)



A moving band target (Ta, W, ...) could be considered (if capture system is toroidal).



B. King (BNL), R. Bennett (RAL)

Thermal Issues for Solid Targets, II

When beam pulse length t is less than target radius r divided by speed of sound v_{sound}, beam-induced pressure waves (thermal shock) are a major issue.

Simple model: if U = beam energy deposition in, say, Joules/g, then the instantaneous temperature rise ΔT is given by

$$\Delta T = \frac{U}{C},$$ where C = heat\ capacity in Joules/g/K.

The temperature rise leads to a strain $\Delta r / r$ given by

$$\frac{\Delta r}{r} = \alpha \Delta T = \frac{\alpha U}{C},$$ where α = thermal expansion coefficient.

The strain leads to a stress P (= force/area) given by

$$P = E \frac{\Delta r}{r} = \frac{E \alpha U}{C},$$ where E = modulus of elasticity.

In many metals, the tensile strength obeys $P \approx 0.002\, E$, $\alpha \approx 10^{-5}$, and $C \approx 0.3$ J/g/K, in which case

$$U_{\max} \approx \frac{PC}{E\alpha} \approx \frac{0.002 \cdot 0.3}{10^{-5}} \approx 60 \text{ J/g}.$$

$\Rightarrow$ Best candidates for solid targets have high strength (Vascomax, Inconel, TiAl6V4) and/or low thermal expansion (Superinvar, Toyota "gum metal", carbon-carbon composite).

How Much Beam Power Can a Solid Target Stand?

How many protons are required to deposit 60 J/g in a material?

What is the maximum beam power P this material can withstand without cracking, for a 10-GeV beam at 10 Hz with area 0.1 cm^2.

Ans: If we ignore "showers" in the material, we still have dE/dx ionization loss, of about 1.5 MeV/g/cm^2.

Now, 1.5 MeV = 2.46×10^{-13} J, so 60 J/g requires a proton beam intensity of $60 /(2.4 \times 10^{-13}) = 2.4 \times 10^{14}$/cm^2.

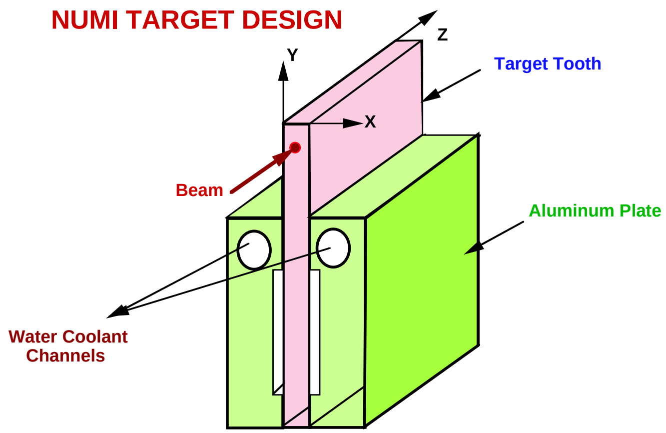
So, $P_{max} \approx 10 \text{ Hz} \cdot 10^{10} \text{ eV} \cdot 1.6 \times 10^{-19} \text{ J/eV} \cdot 2.4 \times 10^{14} \text{ /cm}^2 \cdot 0.1 \text{ cm}^2 \approx 4 \times 10^5 \text{ J/s} = 0.4$ MW.

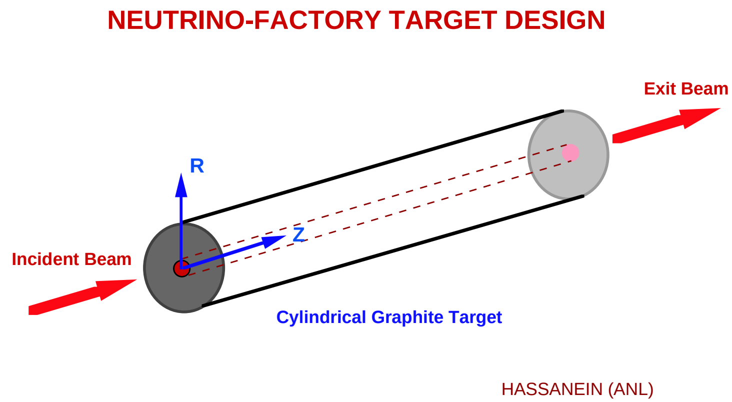
If solid targets crack under singles pulses of 60 J/g, then safe up to only 0.4 MW beam power!

Empirical evidence is that some materials survive 500-1000 J/g $\Rightarrow$ May survive 4 MW if rep rate $\geq$ 10 Hz.

Ni target in FNAL $\bar{p}$ source: "damaged but not failed" peak energy deposition of 1500 J/g.

A Carbon Target is Feasible at 1-2 MW Beam Power





Low energy deposition per gram and low thermal-expansion coefficient reduce thermal “shock” in carbon.

Operating temperature > 2000 C if use only radiation cooling.

A carbon target in vacuum would sublimate away in 1 day at 4 MW, but sublimation of carbon is negligible in a helium atmosphere.

Radiation damage is limiting factor: $\approx$ 12 weeks (?) at 1 MW.

$\Rightarrow$ Carbon target is baseline design for most neutrino superbeams.}

Useful pion capture increased by compact, high-Z target, $\Rightarrow$ Continued R&D on solid targets.

Material Irradiation Studies

ATJ graphite and a 3-D weave of carbon carbon fibers instrumented with fiberoptic strain sensors, and exposed to pulses of 4×10^{12} protons @ 24 GeV.

Thermal-expansion coefficient of engineered materials is affected by radiation.

Super-Invar: CTE \vs\ dose:

Activation Measurements

The samples were placed individually into an ATOM-LAB 100 dose calibrator in order to measure the integrated activation levels. The first (entrance) plane (Fig. 1) consisted of unnecked-down rods and wire positioned in a horizontal orientation, while the the fourth (exit) plane had a similar arrangement but with a vertical orientation. The activation levels of the front plane could then be used to extract information as to the vertical profile of the incident proton beam, while the exit plane could be used for obtaining the horizontal profile of the proton beam (Fig. 2). The nickel wire and Invar rods have different volumes as well as composition, hence overall normalization for each data set differ. However, the beam rms widths extracted from each set of material agree well.

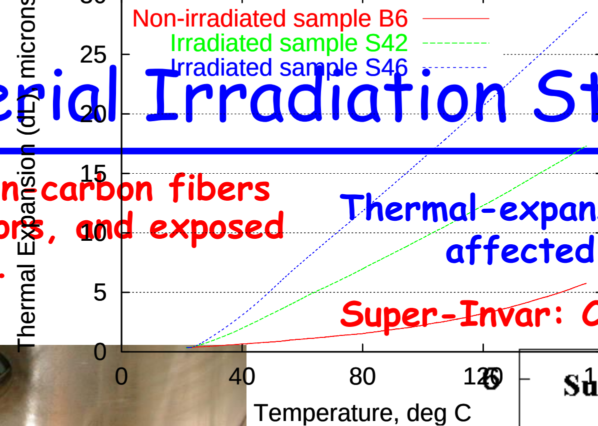
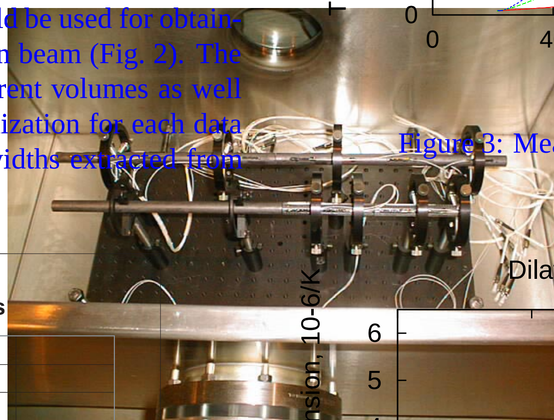
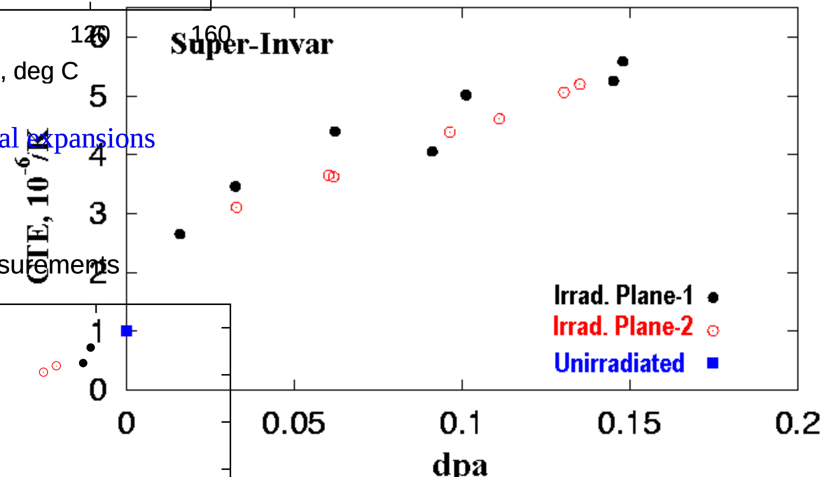


Figure 3: Measured thermal expansions





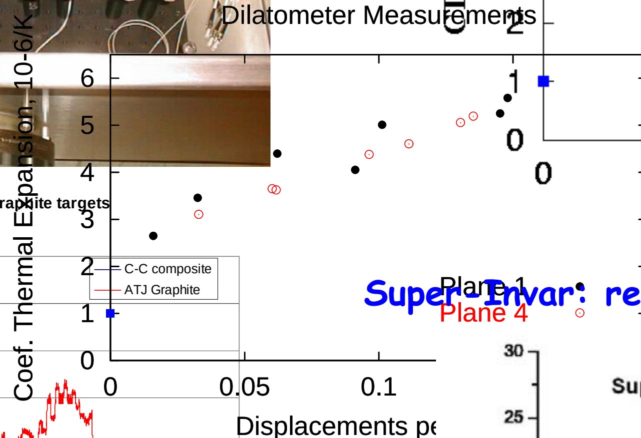


Figure 4: Measured coefficients of th function of calculated atomic displace

We also measured the CTE of the

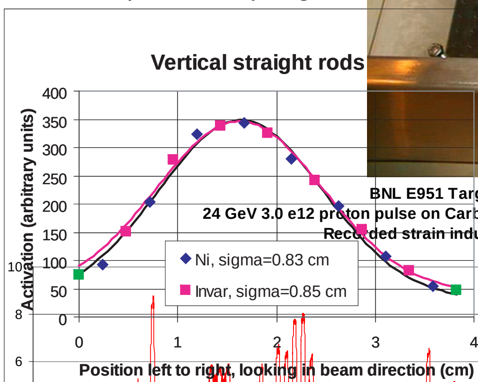
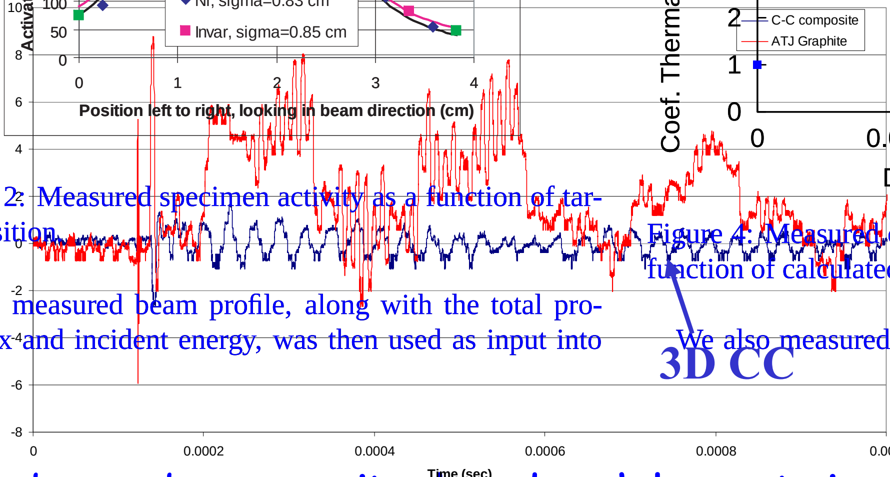
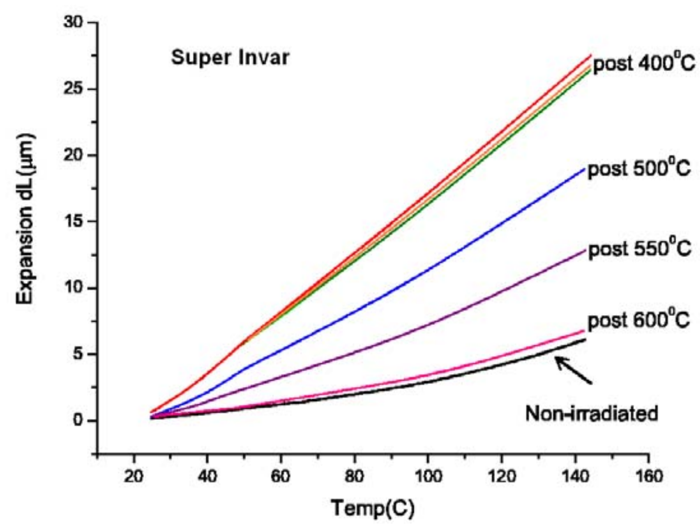


Figure 2: Measured specimen activity as a function of target position.



This measured beam profile, along with the total proton flux and incident energy, was then used as input into

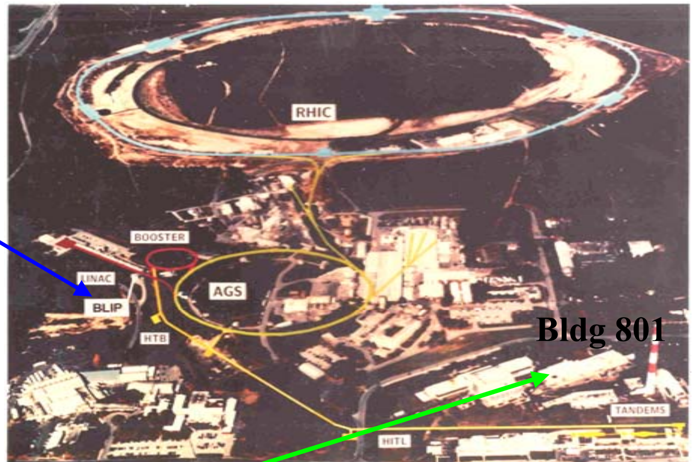
Super-Invar: recovery of the CTE by thermal annealing:



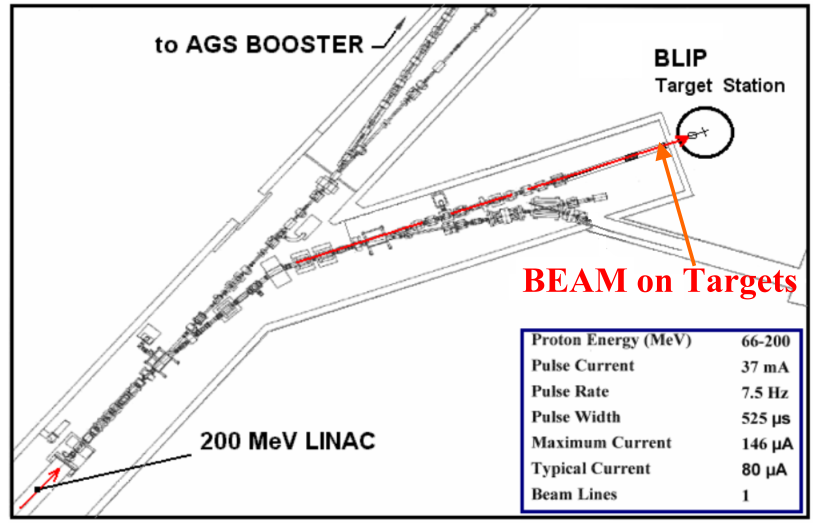
Carbon-carbon composite showed much lower strains than in the ordinary graphite -- but readily damaged by radiation!

Radiation Damage Studies at BNL (Simos)

Irradiation takes place at BLIP using 200 MeV or 117 MeV protons at the end of Linac

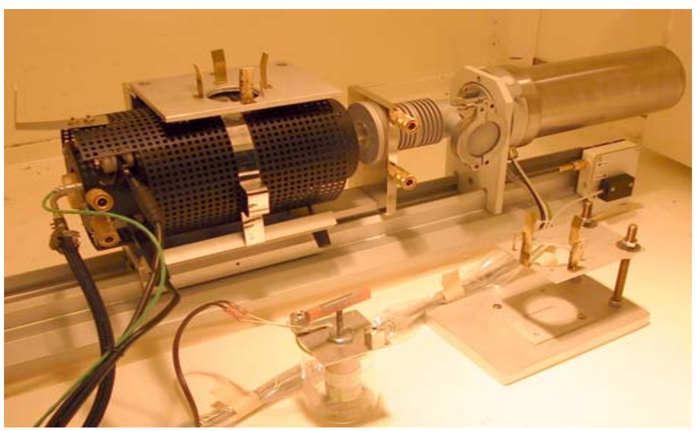


Bldg 801



Proton Energy (MeV)	66-200
Pulse Current	37 mA
Pulse Rate	7.5 Hz
Pulse Width	525 μs
Maximum Current	146 μA
Typical Current	80 μA
Beam Lines	1

Post-irradiation analysis at BNL Hot Labs



Remotely operated mechanical testing system

Thermal Expansion/Heat Capacity Measuring System

Recent/Ongoing Solid Target Projects

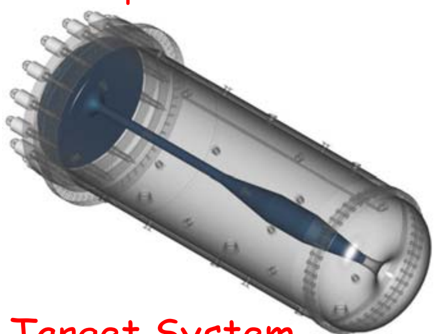
MiniBooNE Horn Target

Up to 5 × 10^{12} 8-GeV protons.

Survived 10^8 pulses.

Gas-cooled Be target.

30 kW beam power.



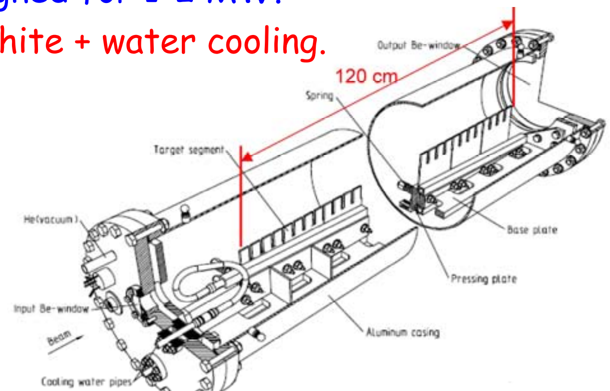
NUMI Target Upgrade

Up to 1.5 × 10^{14} 120-GeV protons every 1.4 s.

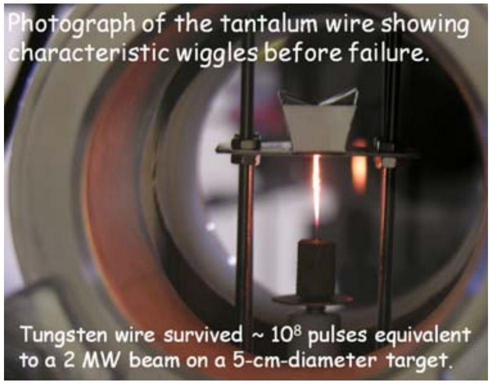
Beam σ = 1.5 mm.

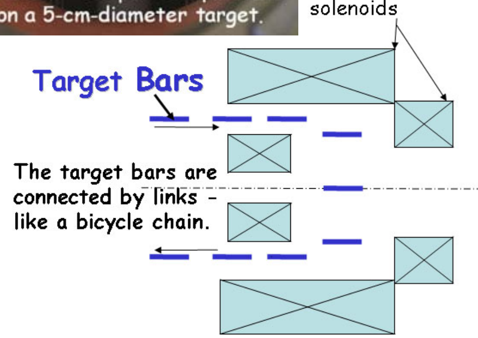
Designed for 1-2 MW.

Graphite + water cooling.



Pulsed-Current Studies of Ta & W Wires at RAL (R.Bennett *et al.*)





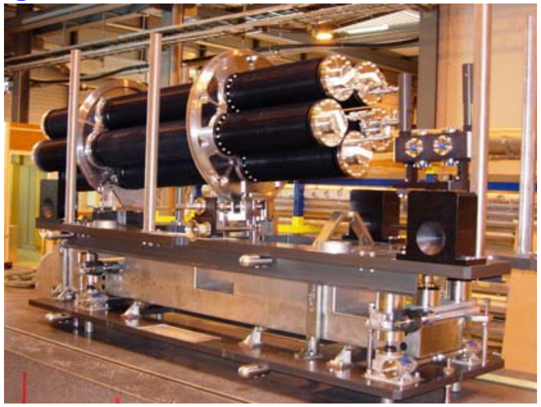
CNGS Target System

Up to 7 × 10^{13} 400-GeV protons every 6 s.

Beam σ = 0.5 mm.

5 interchangeable graphite targets.

Designed for 0.75 MW.



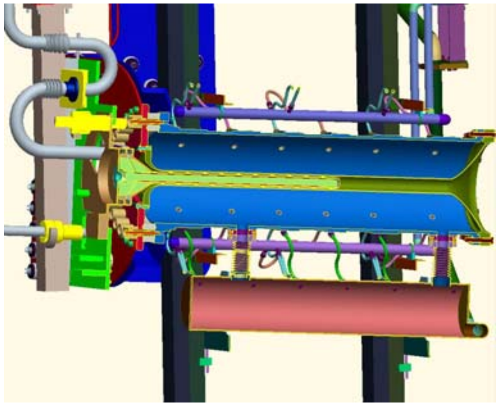
JPARC ν Horn Target

Up to 4 × 10^{14} 50-GeV protons every 4 s.

Beam σ = 4 mm.

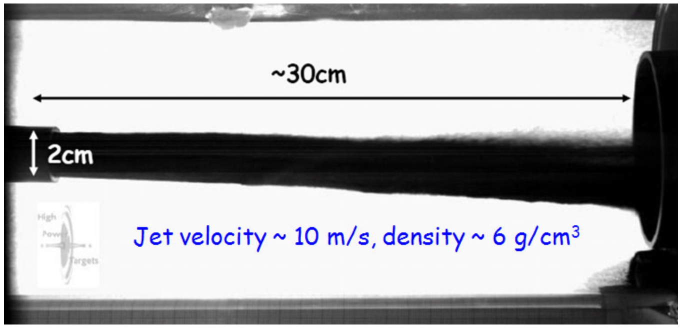
Designed for 0.75 MW.

Graphite + He gas cooling.

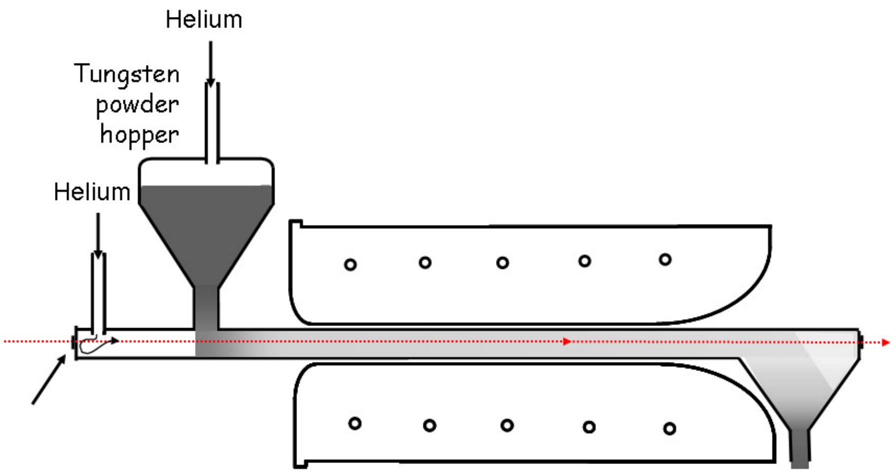


Flowing Tungsten Powder Targets

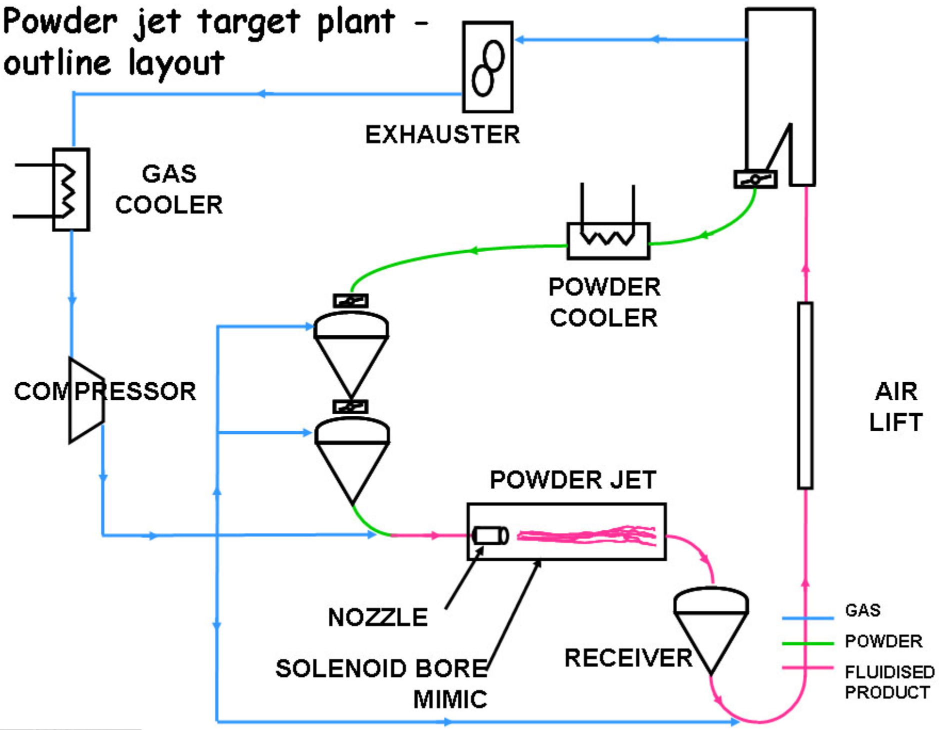
(C.Densham *et al.*, RAL)

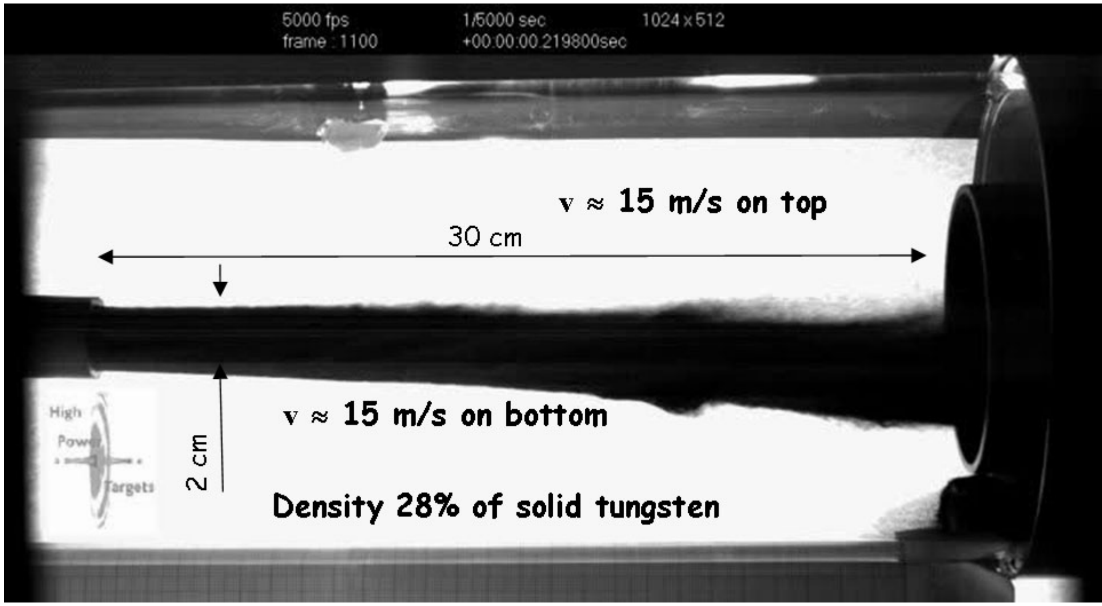


Tungsten Powder Jet R&D at RAL (Densham et al.)



Powder jet target plant – outline layout

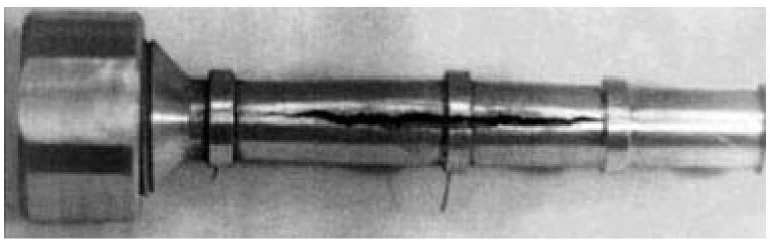




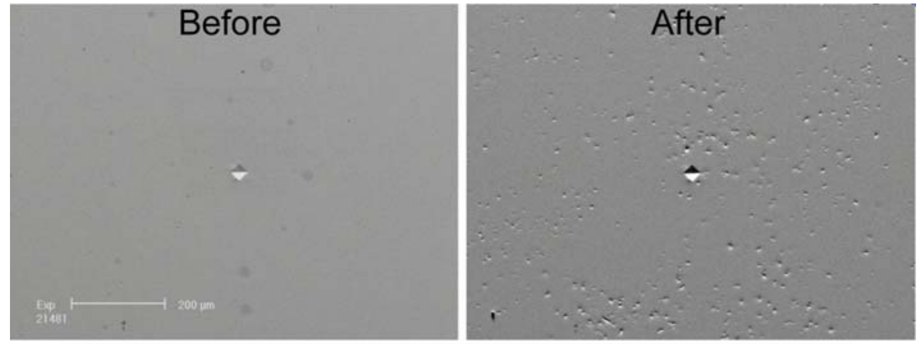
Beam-Induced Cavitation in Liquids Can Break Pipes

ISOLDE:

Hg in a pipe (BINP):

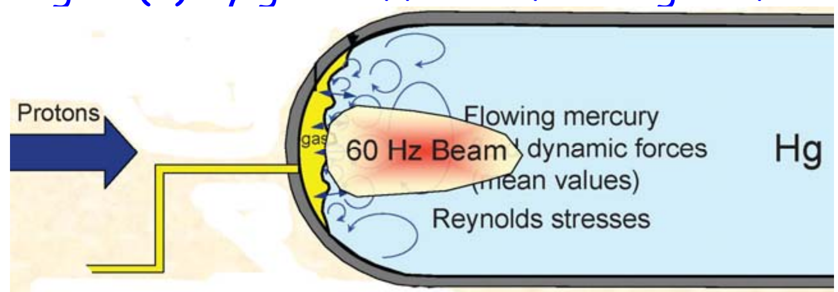


Cavitation pitting of SS wall surrounding Hg target after 100 pulses (SNS):



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

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



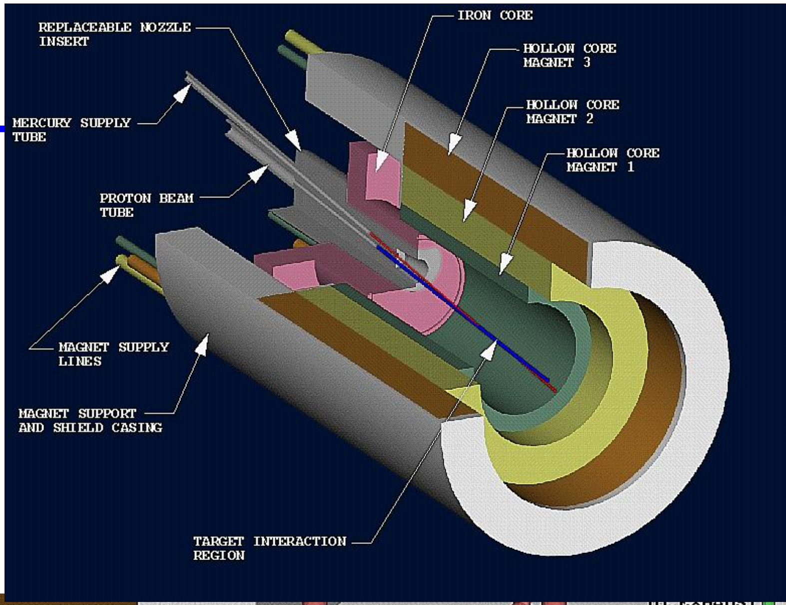
Water jacket of NuMI target developed a leak after ≈ 1 month.

Perhaps due to beam-induced cavitation.

Ceramic drainpipe/voltage standoff of water cooling system of CNGS horn failed after 2 days operation at high beam power. (Not directly a beam-induced failure.)

⇒ Use free liquid jet if possible.

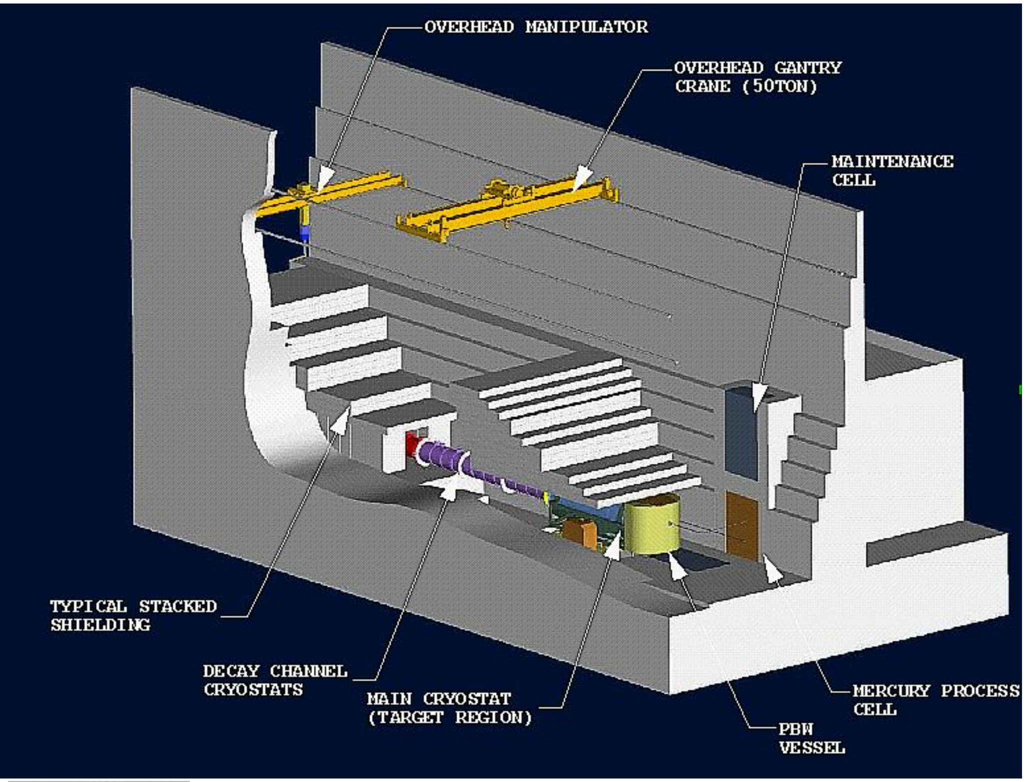
Neutrino Factory Feasibility Study 2

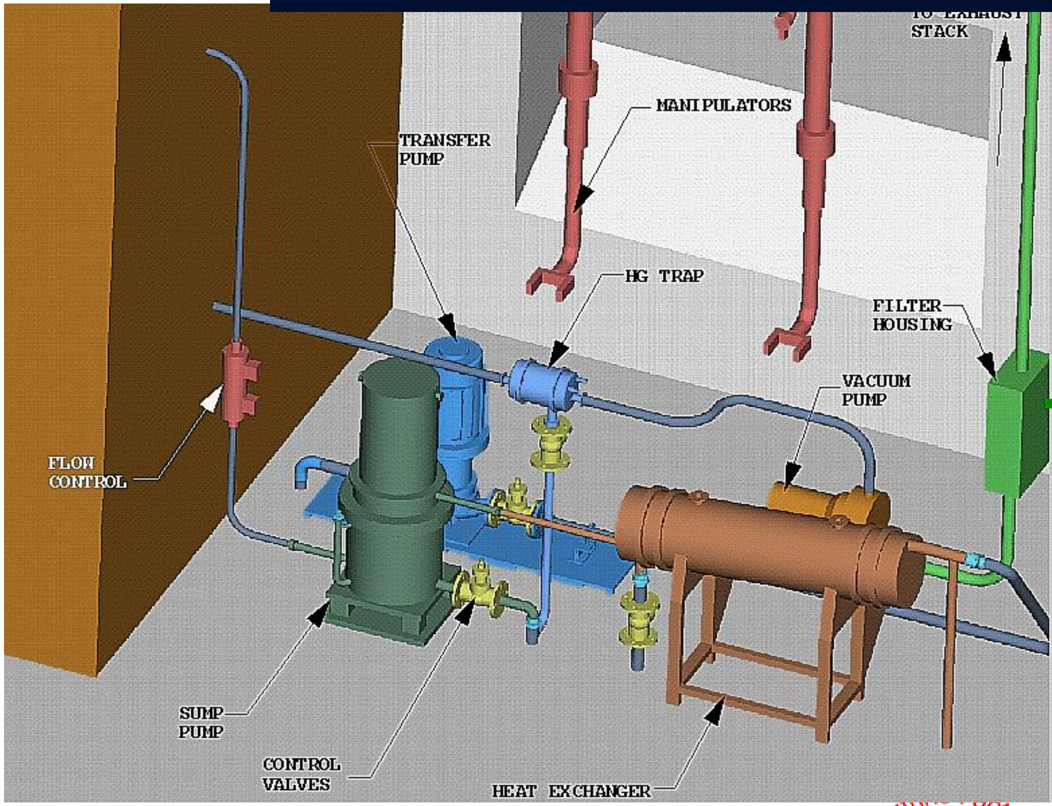


Infrastructure studies based on SNS mercury target experience.

ORNL/TM-2001/124, P. Spampinato et al.
http://www.hep.princeton.edu/~mcdonald/mumu/target/tm-2001-124.pdf

Should be extended during the Muon Collider Feasibility Study.





Features of the Study 2 Target Design

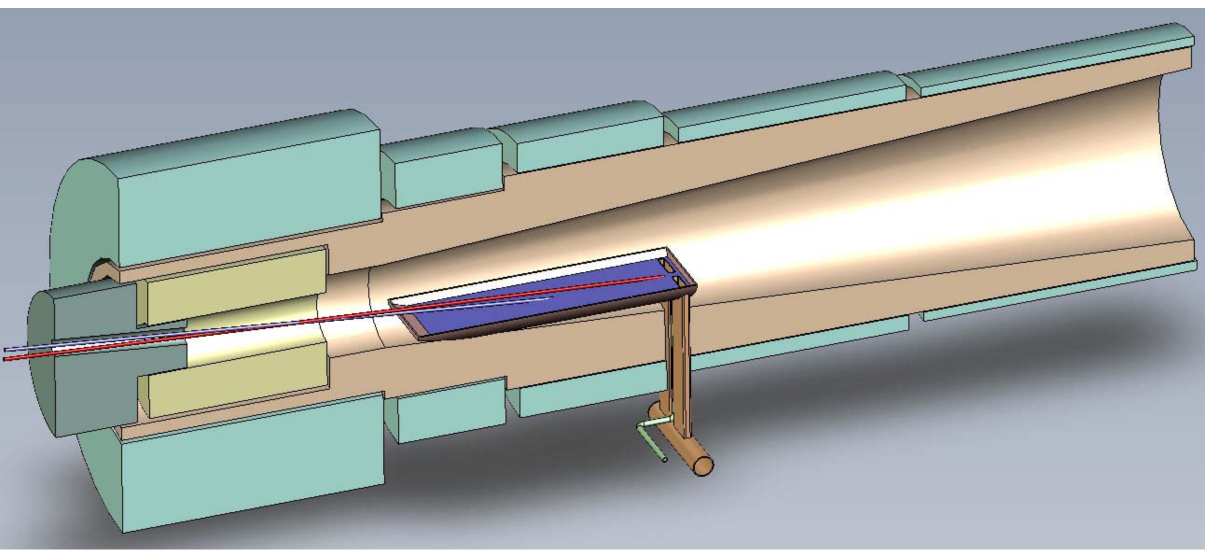
Mercury jet with 1-cm diameter, 20 m/s velocity, at 100 mrad to magnetic axis.

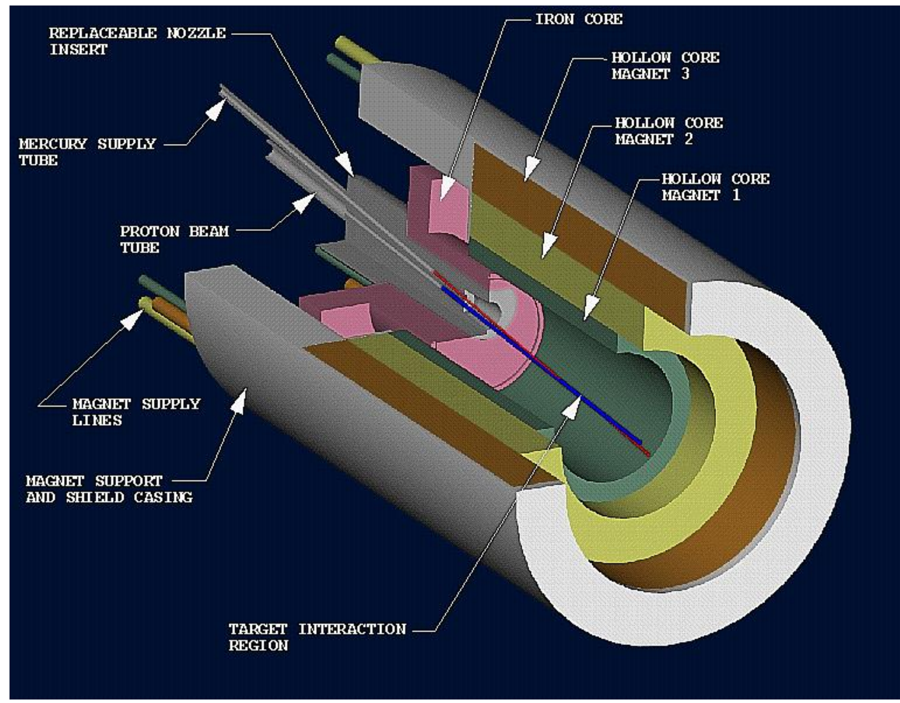
4-MW, 24-GeV, 50-Hz proton beam (2×10^{13} p/pulse) at 67 mrad to magnetic axis.

Iron plug at upstream end of capture solenoid to reduce fringe-field effect on shape of free jet.

Mercury collected in a pool in ~ 4 T magnetic field.

Issues: Distortion of jet by magnetic field.
Disruption of jet by proton beam.



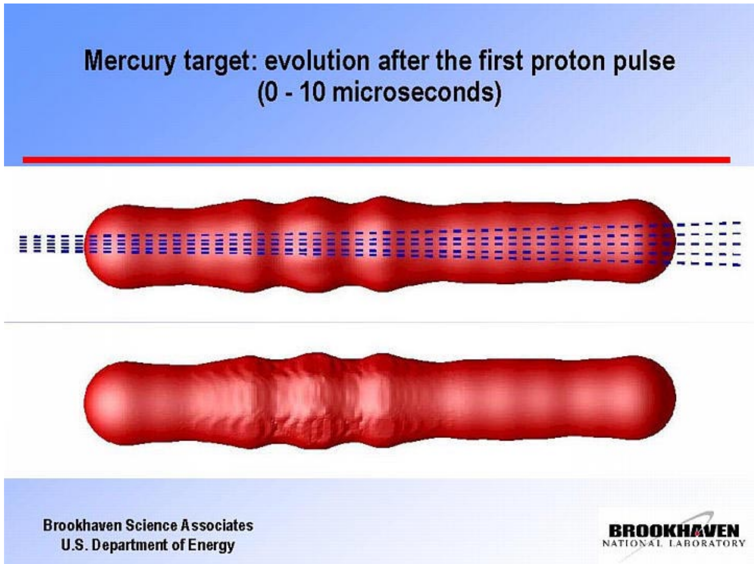


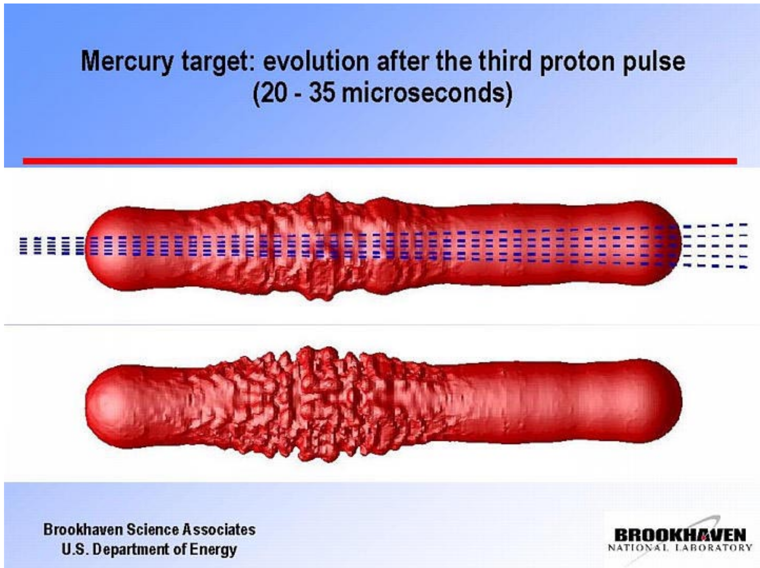
Beam-Induced Effects on a Free Liquid Jet

Beam energy deposition may disperse the jet.

FRONTIER simulation predicts breakup via filamentation on mm scale:

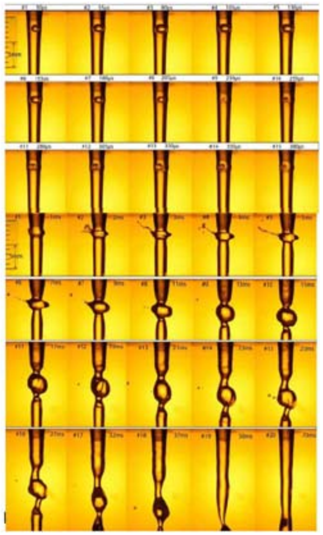
R. Samulyak (BNL)



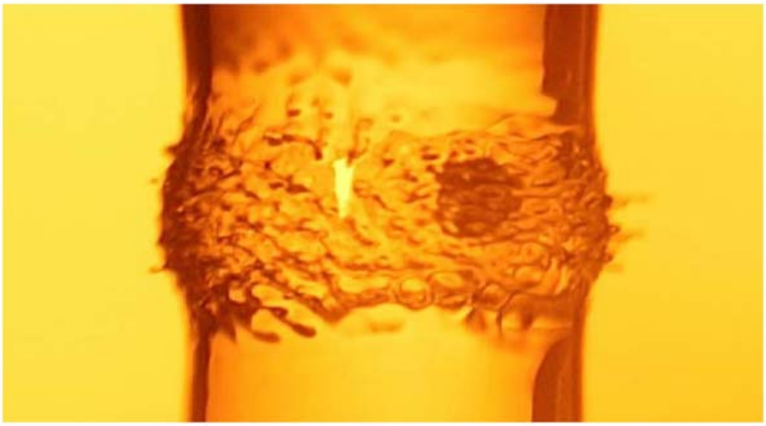


Laser-induced breakup of a water jet:

J. Lettry (CERN)

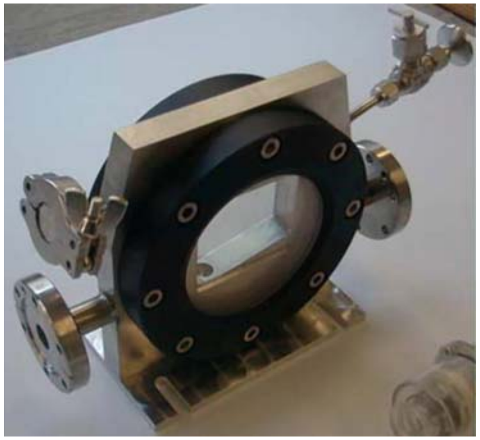


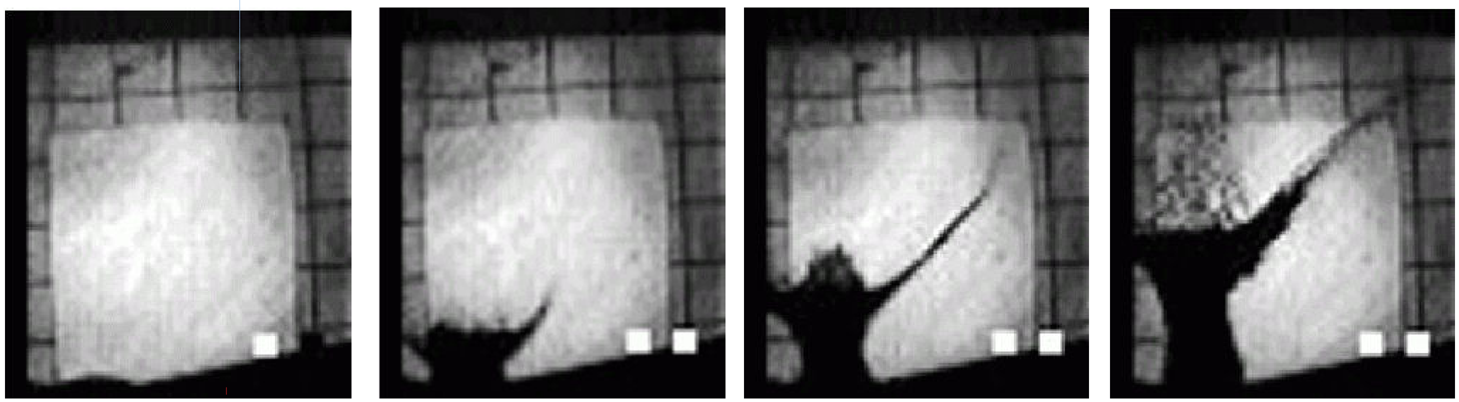
Water jet ripples generated by a 8 mJ Laser cavitation bubble



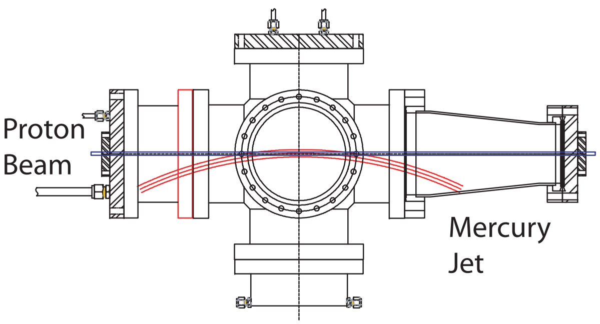
Mercury Target Tests (BNL-CERN, 2001-2002)

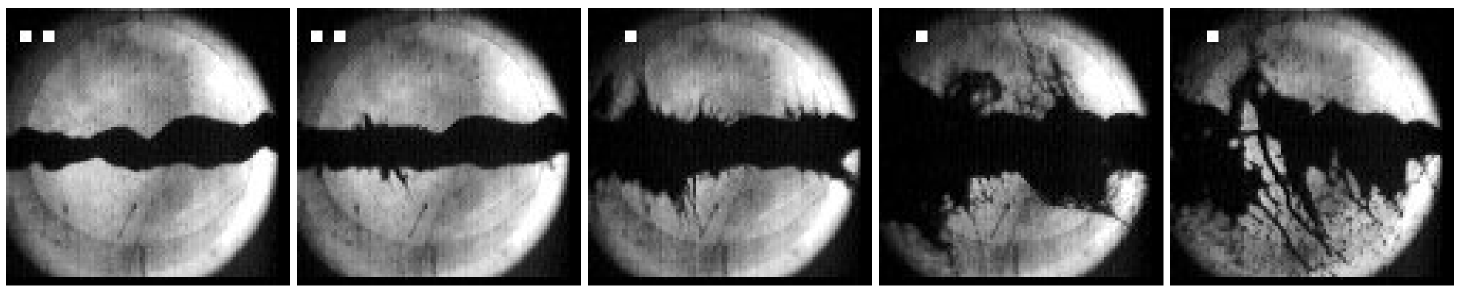
Mercury thimble:





2-m.s free mercury jet:





Data: $v_{\text{dispersal}} \approx$ 10 m/s for $U \approx$ 25 J/g.

$v_{\text{dispersal}}$ 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.

Model:

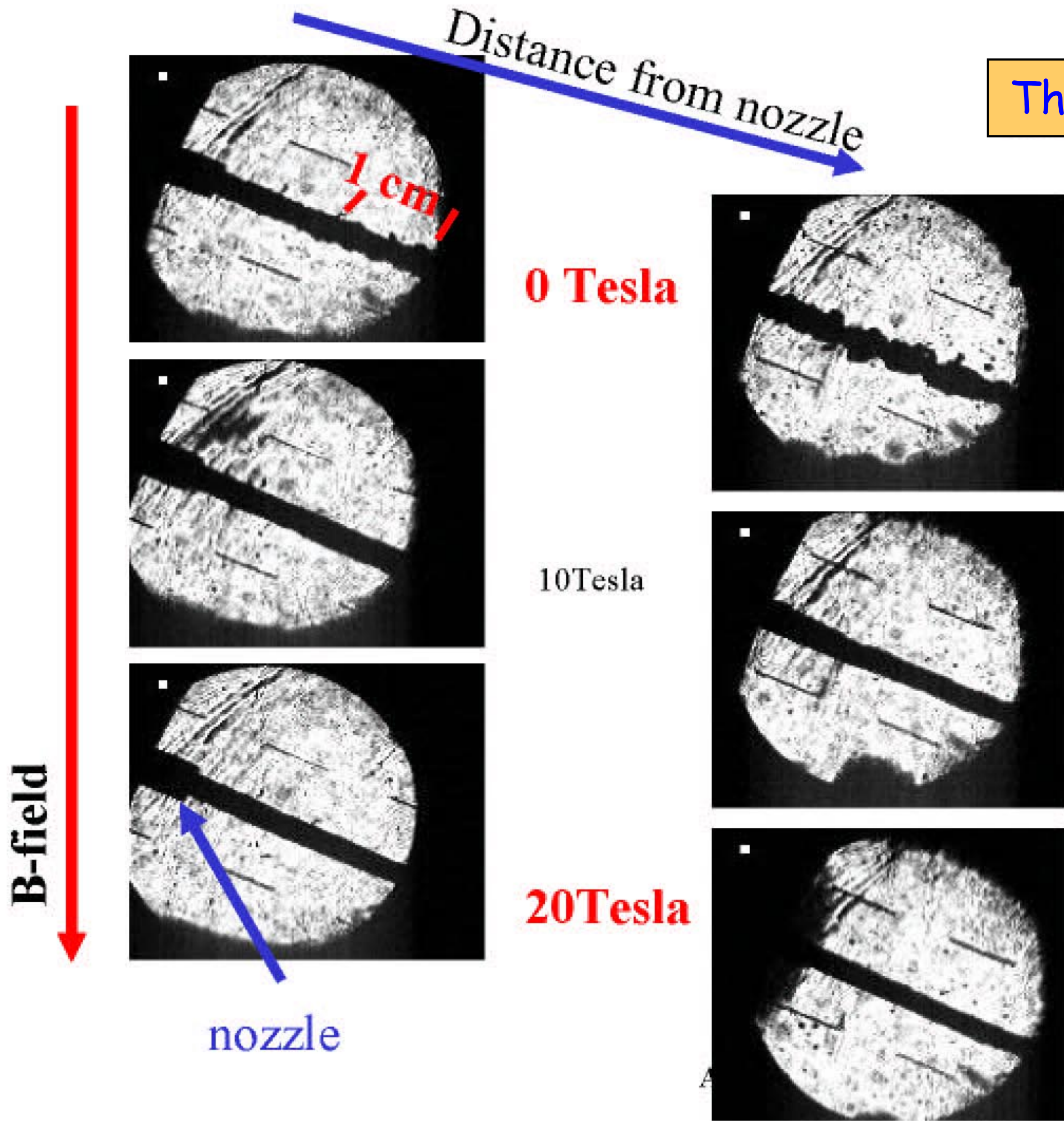
$$v_{\text{dispersal}} = \frac{\Delta r}{\Delta t} = \frac{r\alpha\Delta T}{r / v_{\text{sound}}} = \frac{\alpha U}{C} v_{\text{sound}} \approx 50\ m/s$$

for $U = 25$ J/g.

Mercury Jet Studies at Grenoble High Field Magnet Lab (2002)

Rayleigh surface instability damped by high magnetic field.

Thesis: A. Fabich (CERN)



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

Slide 5

Magnetic Damping of Jet Filamentation

Magnetic pressure suppresses (but does not eliminate) breakup of the Hg jet by the proton beam.

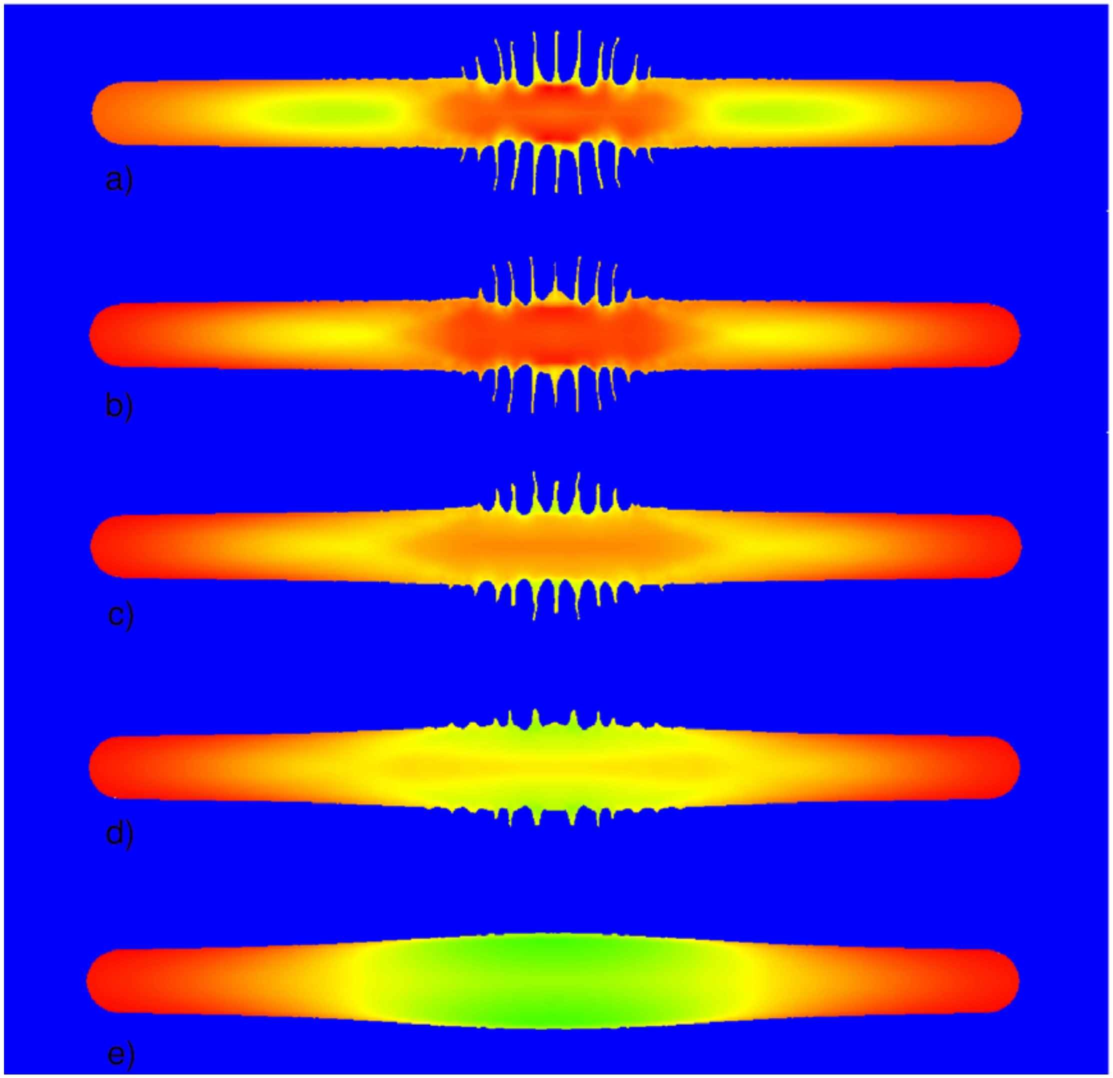
0 T

2 T

4 T

6 T

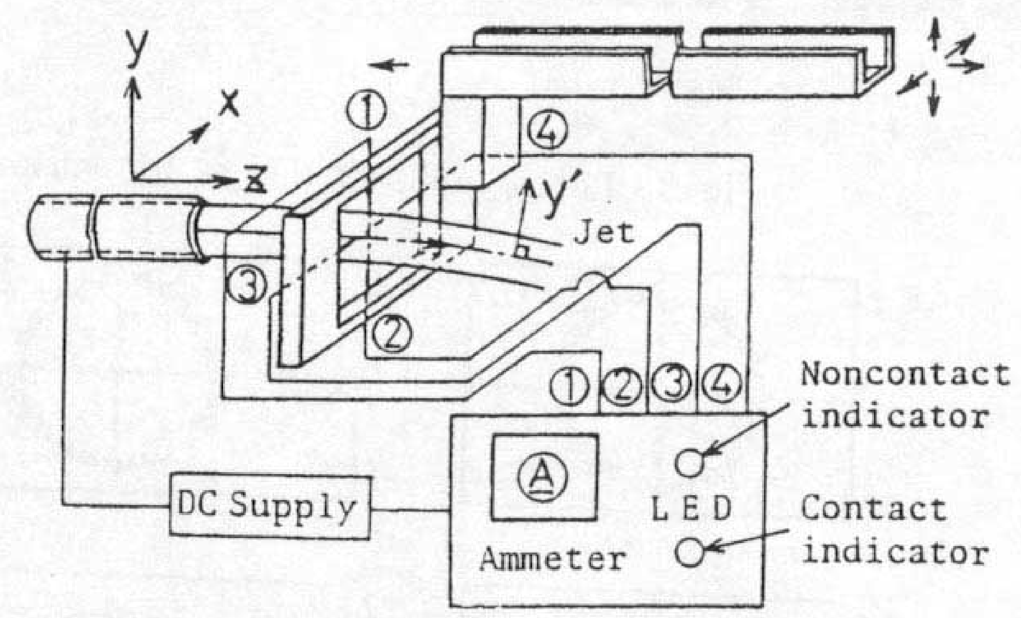
10 T



R. Samulyak (BNL)

Distortion of a Mercury Jet by a Transverse Magnetic Field

S. Oshima *et al.*, JSME Int. J. **30**, 437 (1987).



A 1-T transverse magnetic field caused severe quadrupole distortion of a 1-cm-diameter mercury jet.

Along a line at 100 mrad to a 20 T field the transverse field is 2 T.

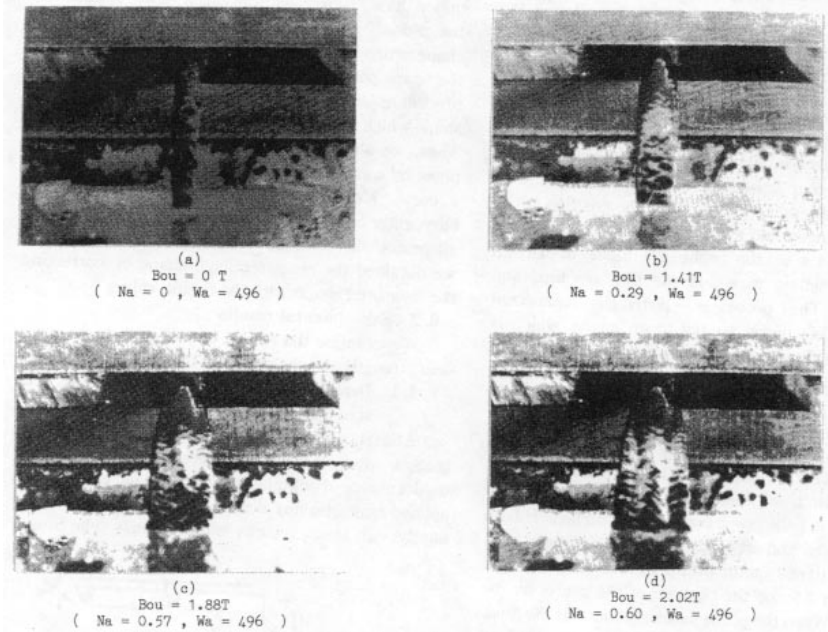


Fig. 9 Photographs of the jet for various applied mag- netic field strengths

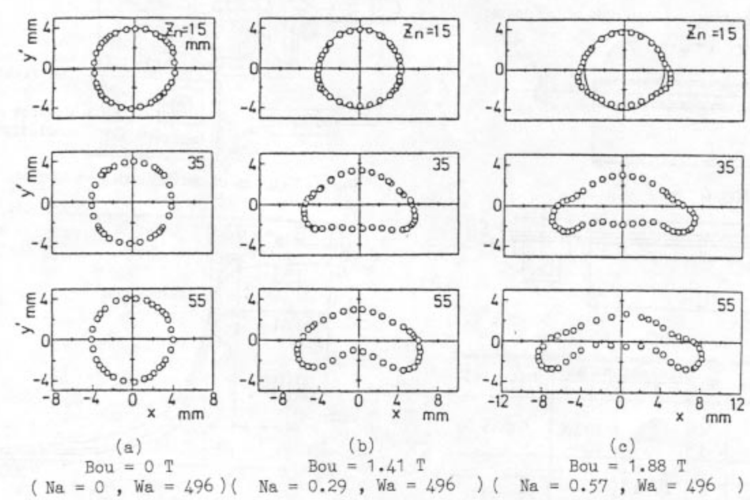


Fig. 10 Cross-sectional shape of the jet obtained by spot a electrode probe

Modeling of the Distortion of a Mercury Jet by a Magnetic Field

Quadruple distortion depends on nonuniformity of the transverse field (Gallardo *et al.*, 2002).

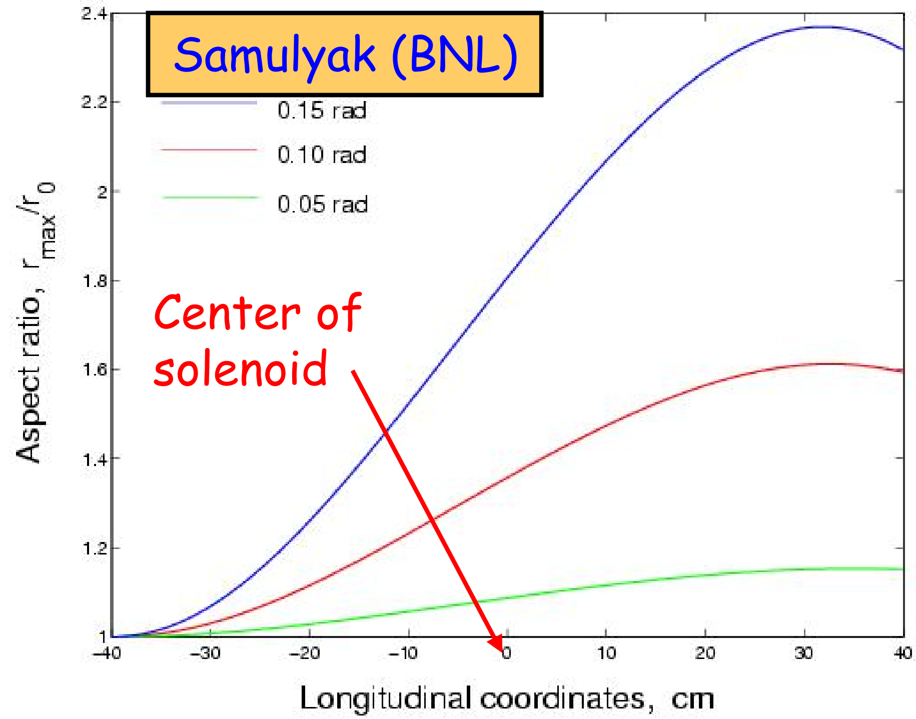
Simulations by Samulyak and by Morley confirm this behavior.

⇒Reduce angle of jet to magnetic axis.

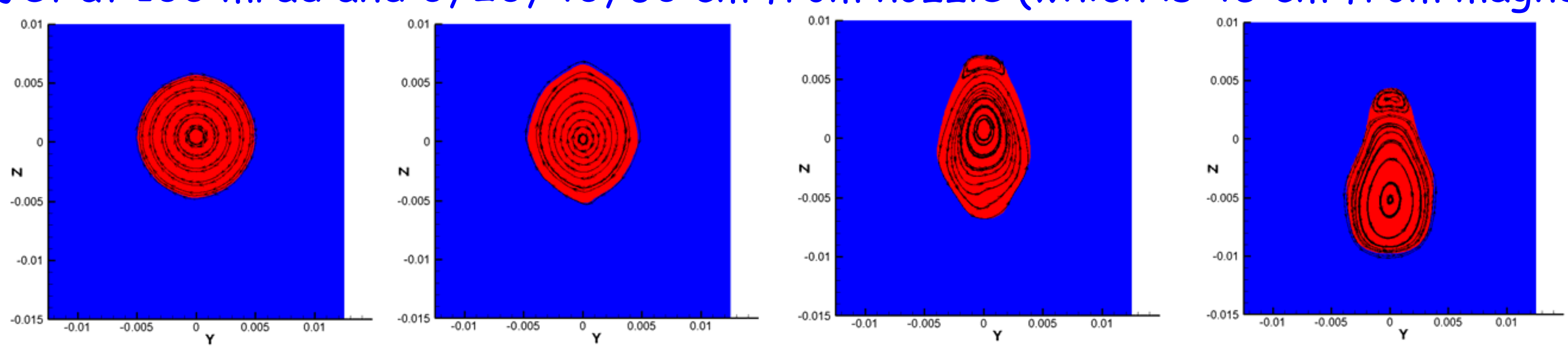
⇒Place nozzle close to peak field region.

⇒Reduce field nonuniformity.

Study 2: Nozzle in iron plug that smoothes upstream field.



Morley: (UCLA) Jet at 100 mrad and 0, 20, 40, 60 cm from nozzle (which is 45 cm from magnet center).



The MERcury Intense Target Experiment

CERN-INTC-2004-016
INTC-P-186
26 April 2004

Proposed: April 2004

Approved: April 2005

Formal name nToF11

A Proposal to
the ISOLDE and Neutron Time-of-Flight Experiments Committee

Studies of a Target System for a 4-MW, 24-GeV Proton Beam

J. Roger J. Bennett[1], Luca Bruno[2], Chris J. Densham[1], Paul V. Drumm[1], T. Robert Edgecock[1], Adrian Fabich[2], Tony A. Gabriel[3], John R. Haines[3], Helmut Haseroth[2], Yoshinari Hayato[4], Steven J. Kahn[5], Jacques Lettry[2], Changguo Lu[6], Hans Ludewig[5], Harold G. Kirk[5], Kirk T. McDonald[6], Robert B. Palmer[5], Yarema Prykarpatskyy[5], Nicholas Simos[5], Roman V. Samulyak[5], Peter H. Thieberger[5], Koji Yoshimura[4]

Spokespersons: H.G. Kirk, K.T. McDonald
Local Contact: H. Haseroth

CERN nToF11 Experiment (MERIT)

The MERIT experiment is a proof-of-principle demonstration of a free mercury jet target for a 4-megawatt proton beam, contained in a 15-T solenoid for maximal collection of soft secondary pions.

MERIT = MERcury Intense Target.

Key parameters:

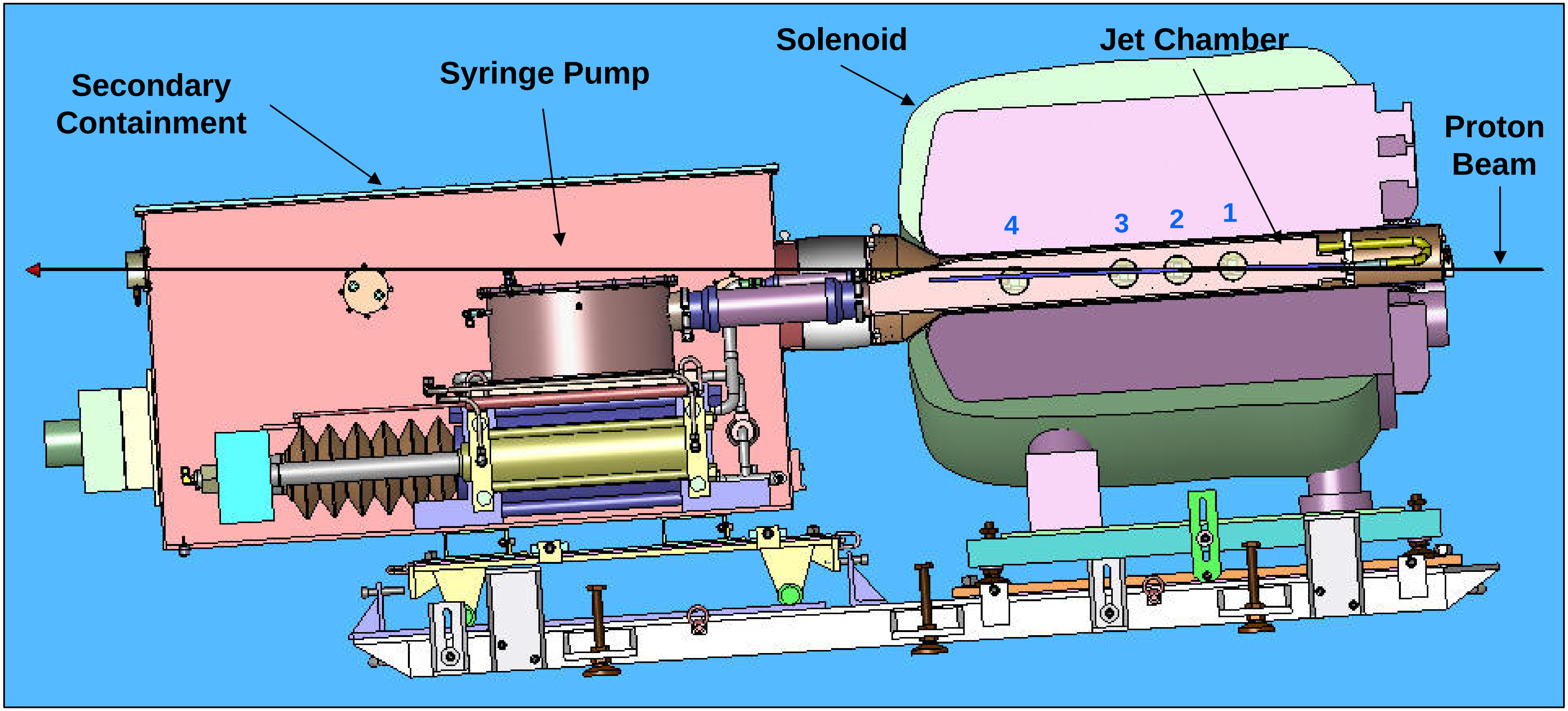
- 14 and 24-GeV Proton beam pulses, up to 16 bunches/pulse, up to 3.5×10^{12} p/bunch.
- σ_r of proton bunch = 1.2 mm, proton beam axis at 67 mrad to magnet axis.
- Mercury jet of 1 cm diameter, v = 20 m/s, jet axis at 33 mrad to magnet axis.
- $\Rightarrow$ Each proton intercepted the Hg jet over 30 cm = 2 interaction lengths.

Every beam pulse is a separate experiment.

- $\approx$ 360 Beam pulses in total.
- Vary bunch intensity, bunch spacing, no. of bunches.
- Vary magnetic field strength.
- Vary beam-jet alignment, beam spot size.

MERIT @ CERN is Proof of Principle not Prototype

MERIT @ CERN used a 180° bend in the mercury delivery path because CERN would not permit any mercury-wetted connections to be made onsite.

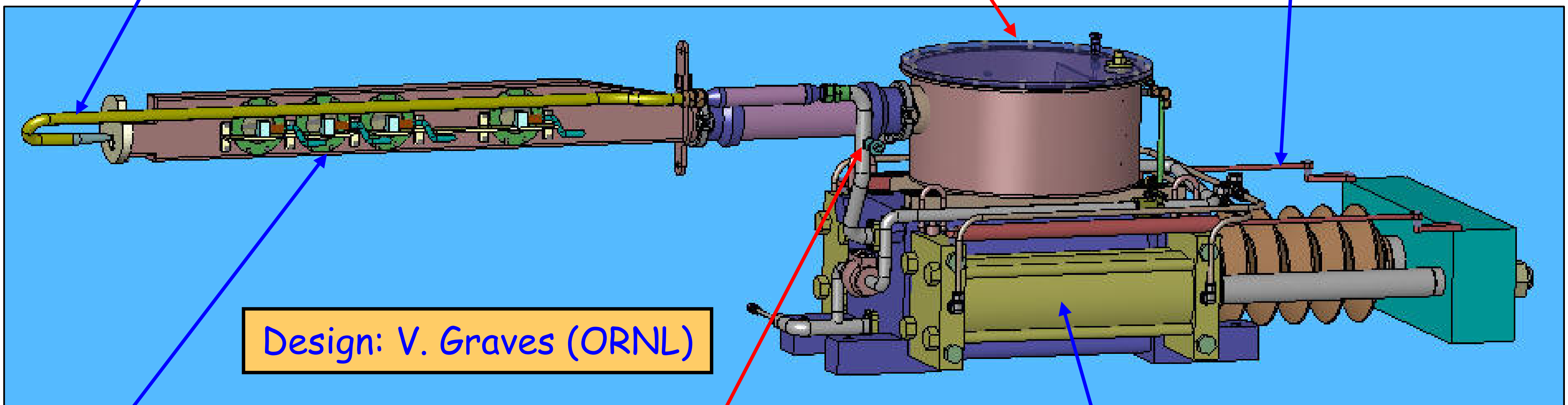


All Mercury Contained in the Primary Vessel

1″ pipe to transport mercury to nozzle at upstream end of primary vessel

Reservoir to collect mercury returning from a jet.

Electronic scales monitor piston velocity.



Optical diagnostics mounted on outside of the primary vessel.

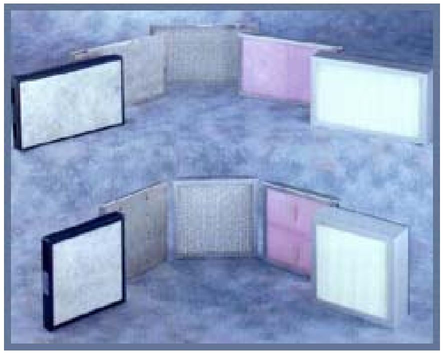
Pressure monitor of mercury supply pipe.

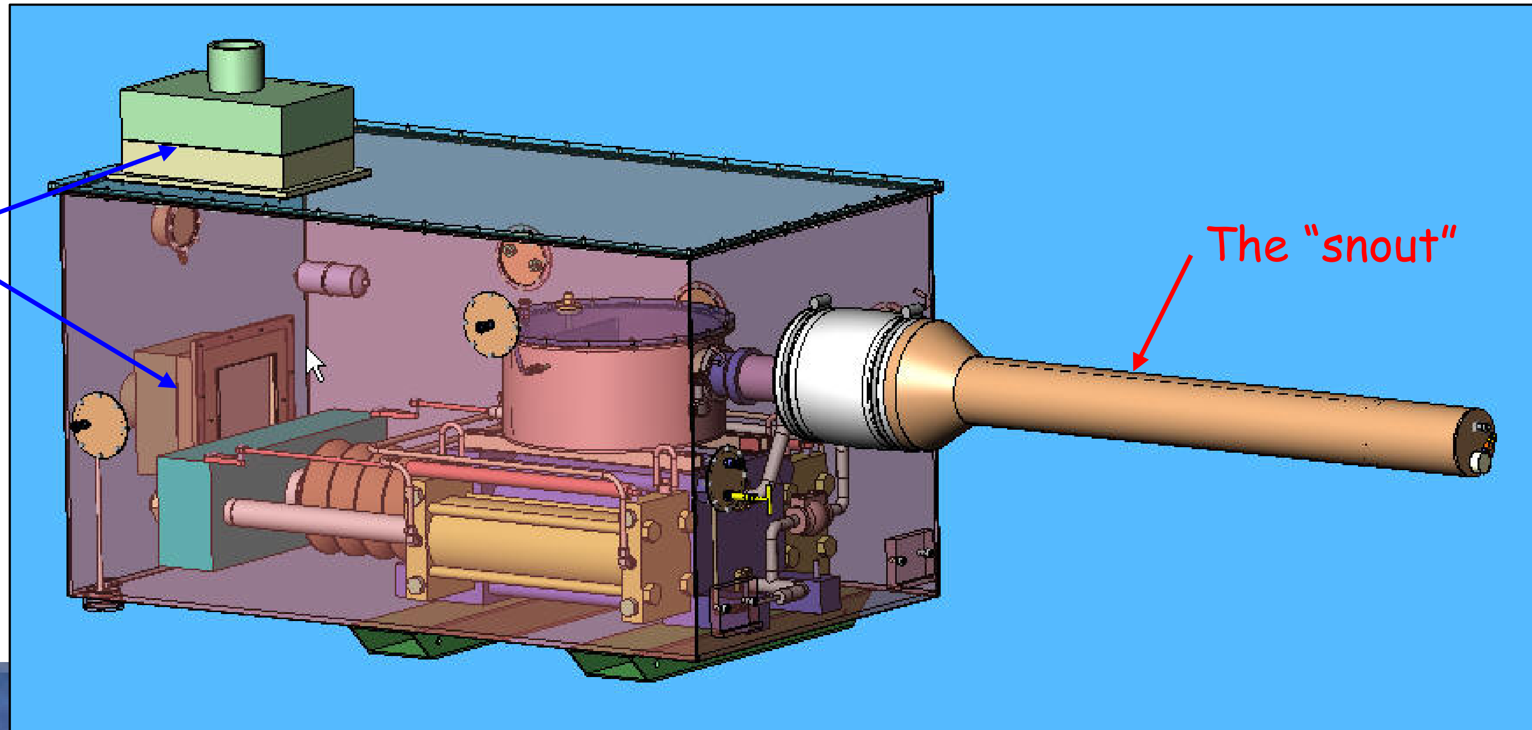
Giant syringe can produce a mercury jet for 15 s.

The primary vessel was not opened at CERN, other than for filling and emptying the mercury.

Secondary Containment of Mercury

Charcoal filters

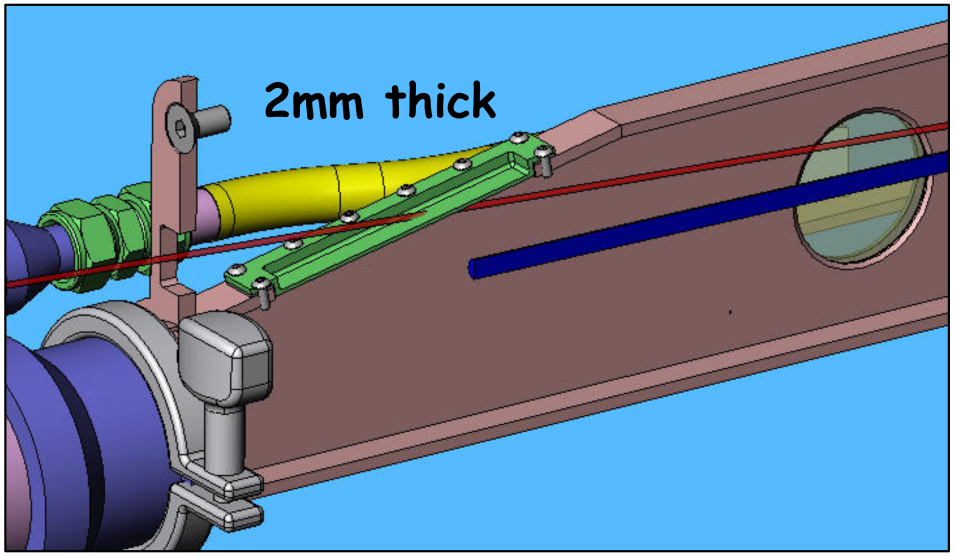


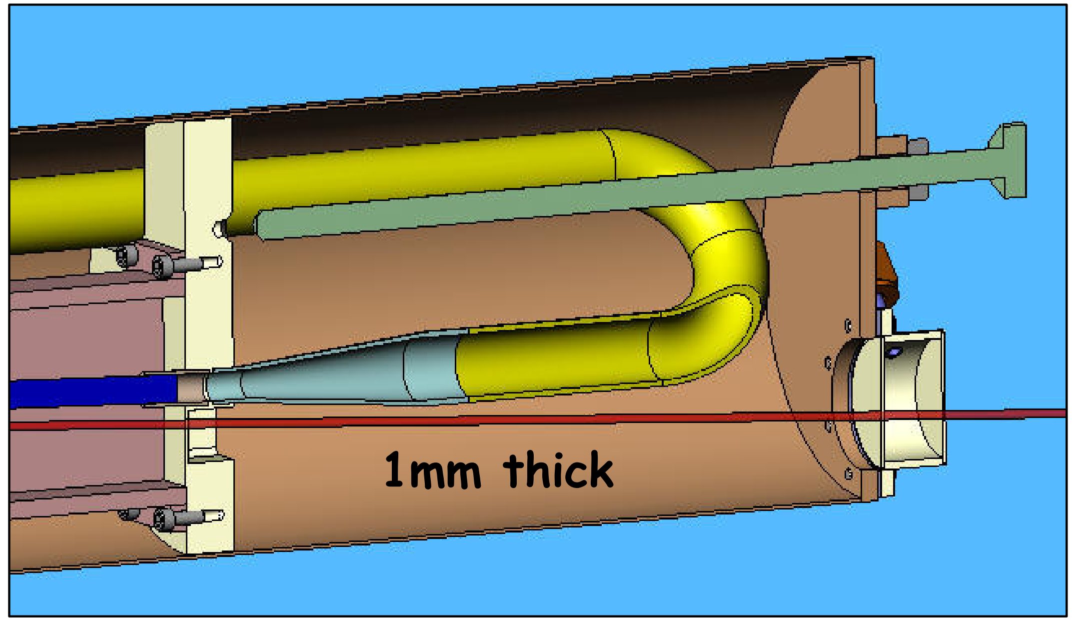


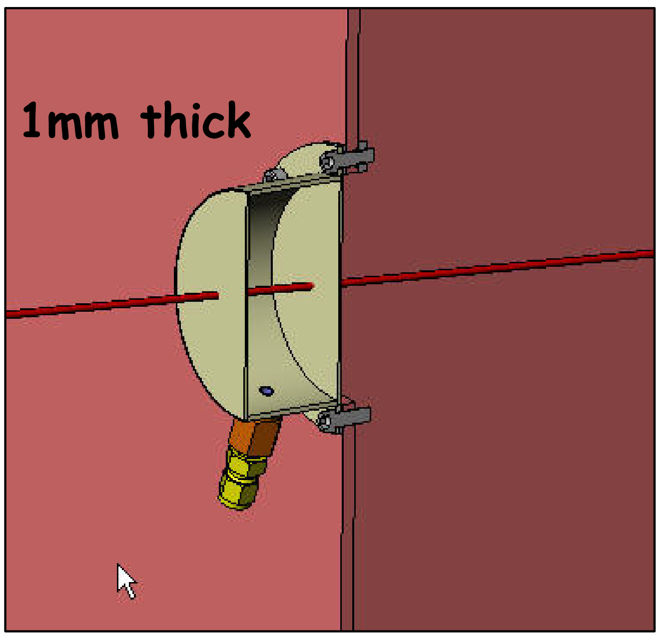
The secondary containment vessel was monitored for mercury vapor at all times with a VM3000 vapor monitor.

When the secondary containment vessel was opened for maintenance, a "Scavenger" with charcoal filters was used to capture any mercury vapors in the work area.

Beam Windows







Windows made of Ti6Al4V alloy.

Single windows for primary containment, double windows for secondary.

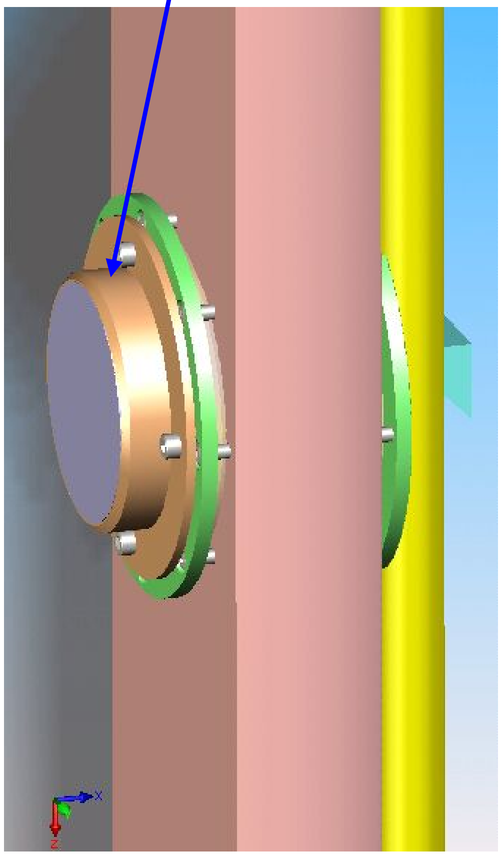
Pressurize secondary windows, monitor to detect failure.

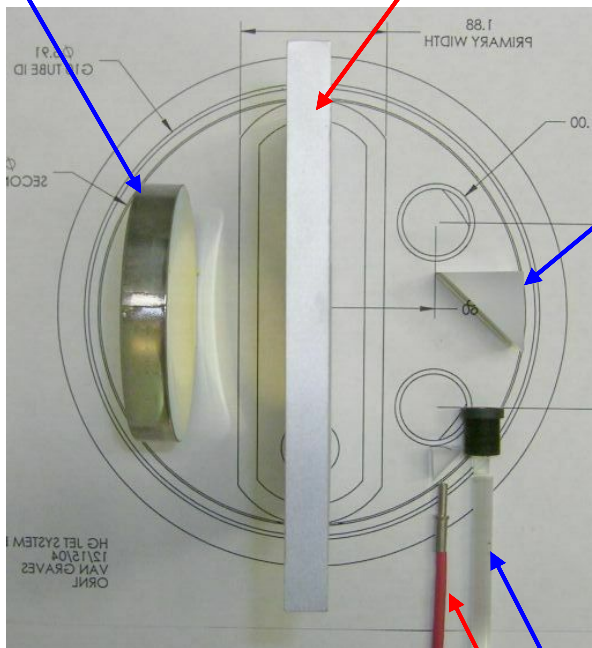
Optical Diagnostics via Fiberoptic Imaging

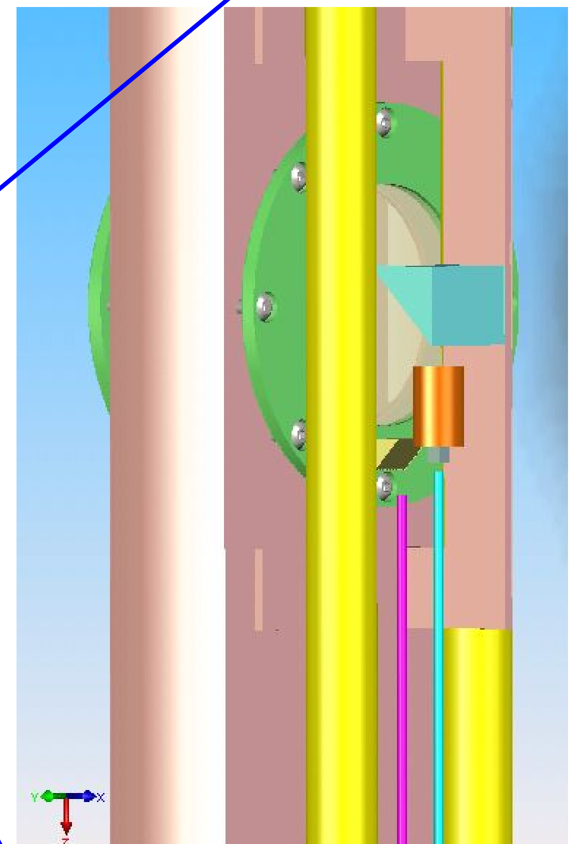
Retro reflector

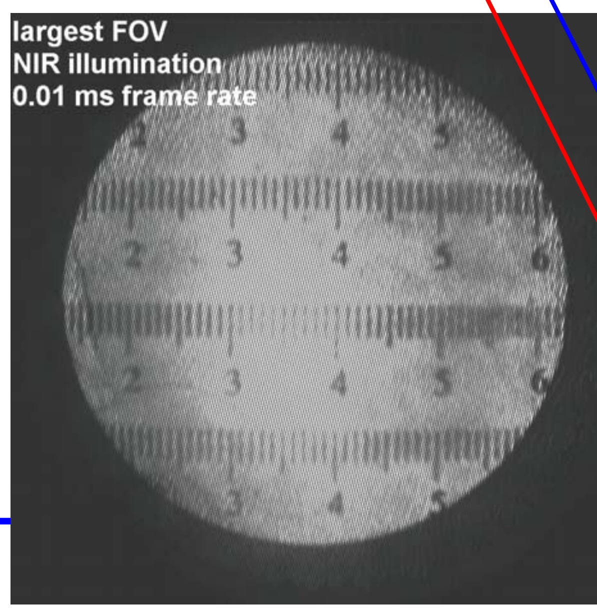
Mercury jet

45° Mirror









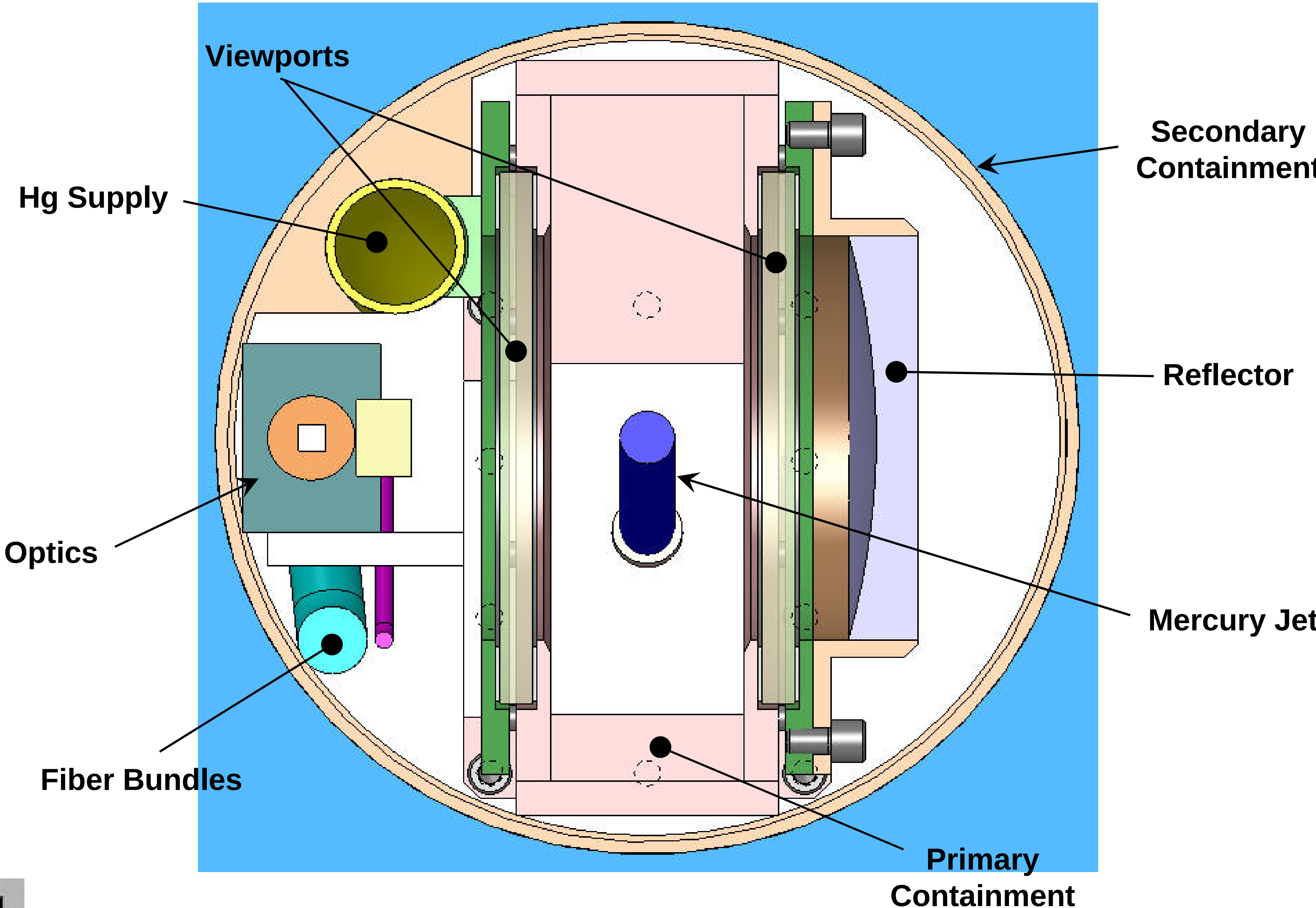
Imaging fiber

Illumination fiber

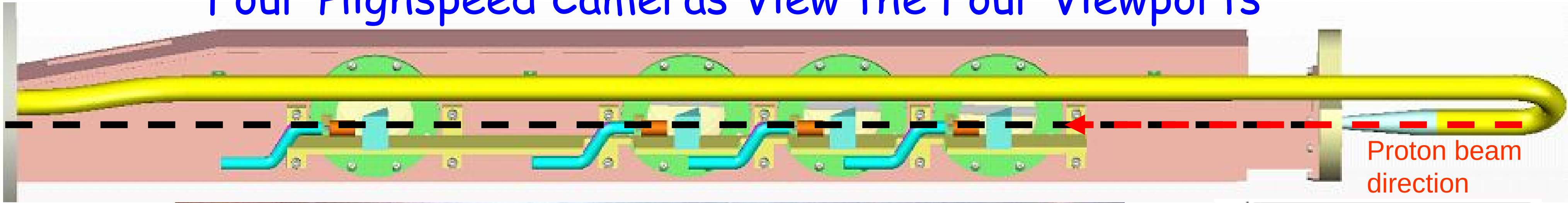
One set of optics per viewport

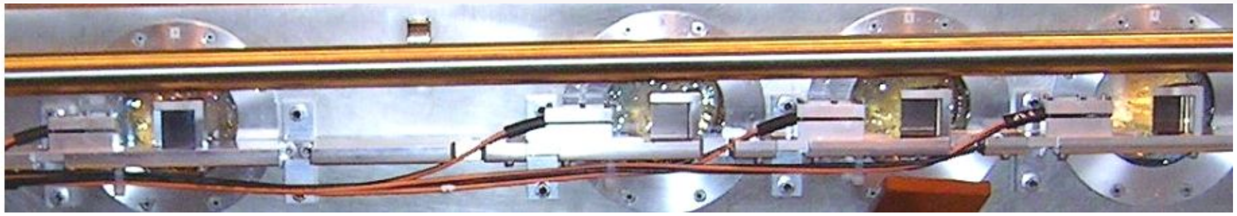
Design: T. Tsang (BNL)

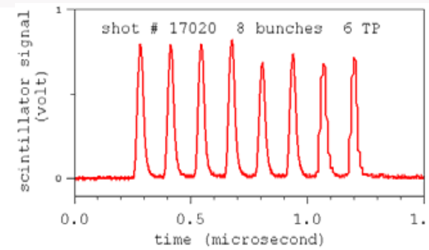
Section through the Primary Vessel at the Magnet Center



Four Highspeed Cameras View the Four Viewports







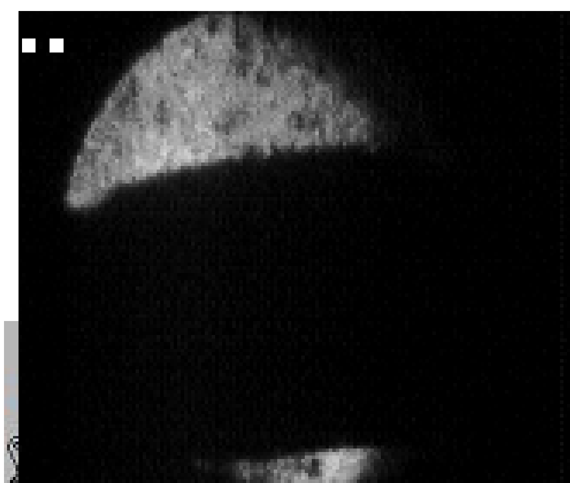
Viewport 4, Olympus
33 µs exposure
160x140 pixels

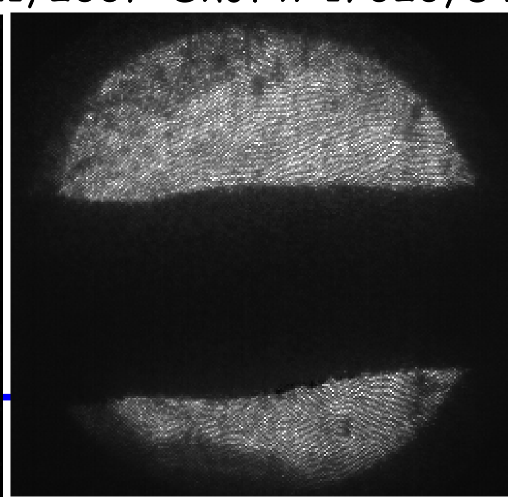
Viewport 3, FV Camera
6 µs exposure
260x250 pixels

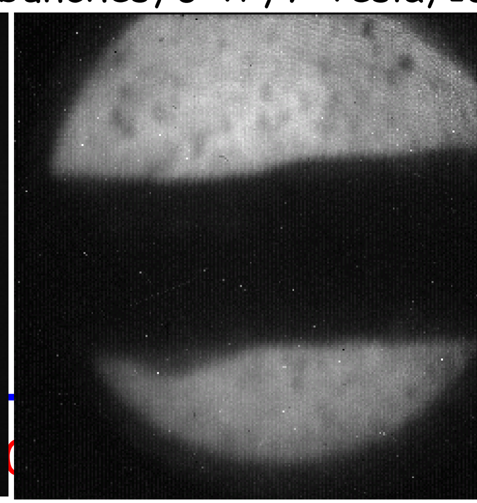
Viewport 2, SMD Camera
0.15 µs exposure
245x252 pixels

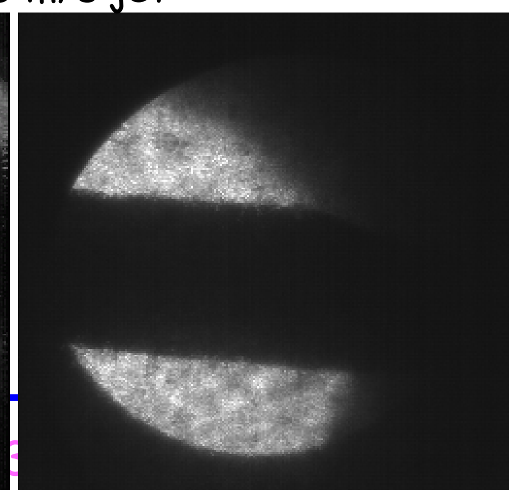
Viewport 1, FV Camera
6 µs exposure
260x250 pixels

Nov. 11, 2007 Shot # 17020, 8 bunches, 6 TP, 7 Tesla, 15 m/s jet





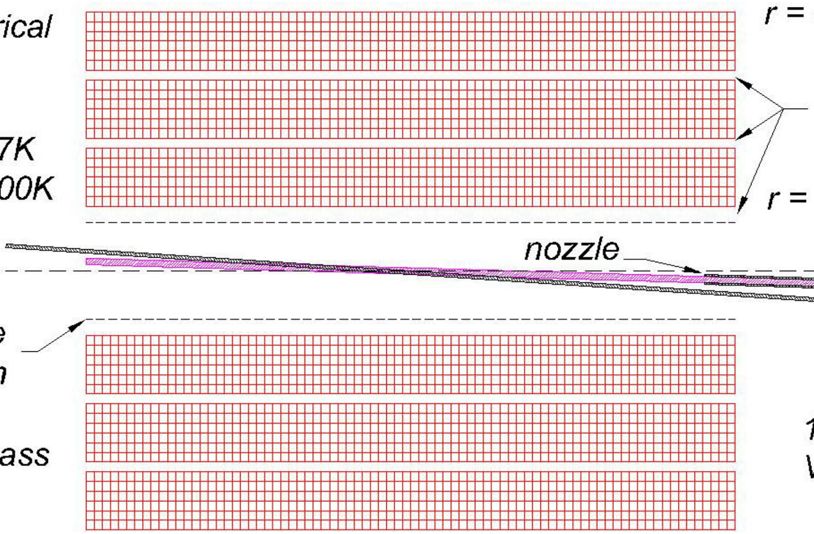




15-T LN_2-Precooled Pulsed Solenoid Magnet

15-T Pulsed Magnet

3 nested cylindrical copper coils
$L = 0.48$ H
$R = 0.06\,\Omega$ @ 77K
$R = 0.45\,\Omega$ @ 300K



r = 40 cm

LN_2 coolant channels

r = 10 cm

magnet axis

nozzle

mercury jet (22 mrad)
proton beam (67 mrad)

warm bore
r = 7.5 cm

total magnet mass
~ 6000 kg

15-T field @ 7200A
V = 700 @ 77K

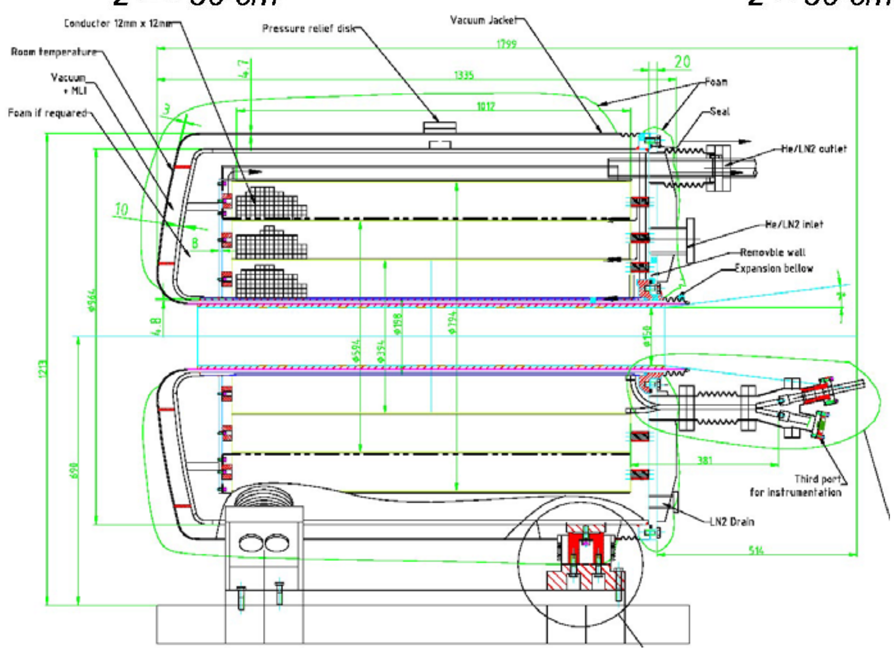
z = - 50 cm

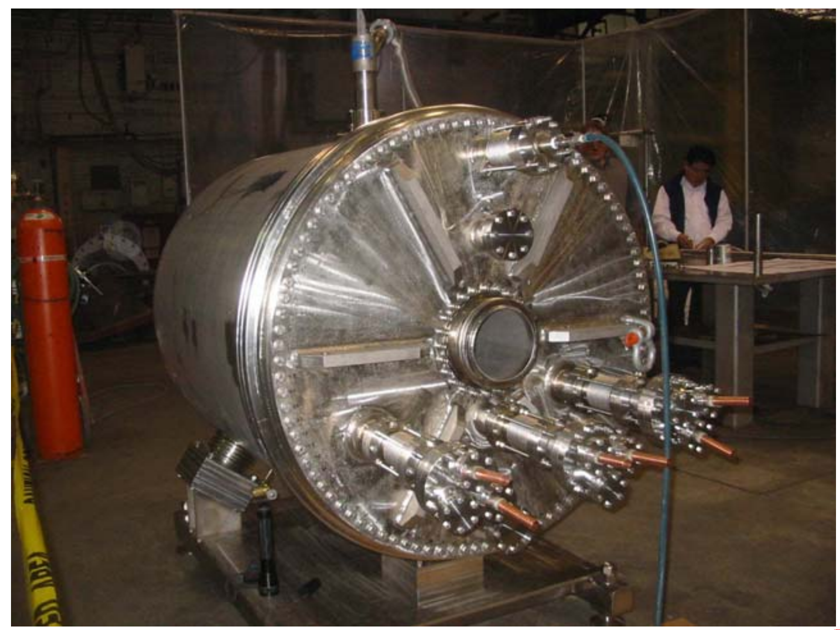
z = 50 cm

Design: R. Weggel (BNL)

Engineering: P. Titus (MIT)

Fabrication: CVIP,
Everson-Tesla



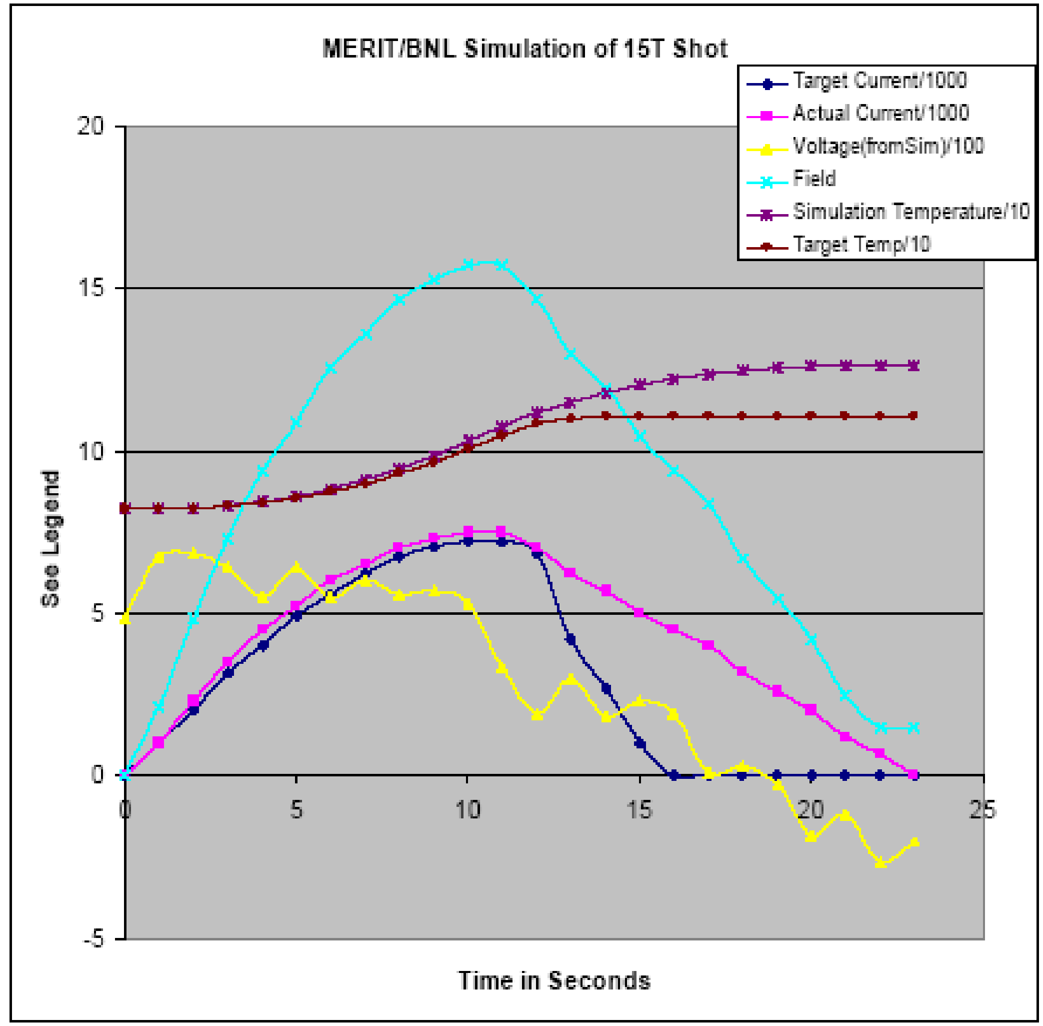


5 MW Power Supply

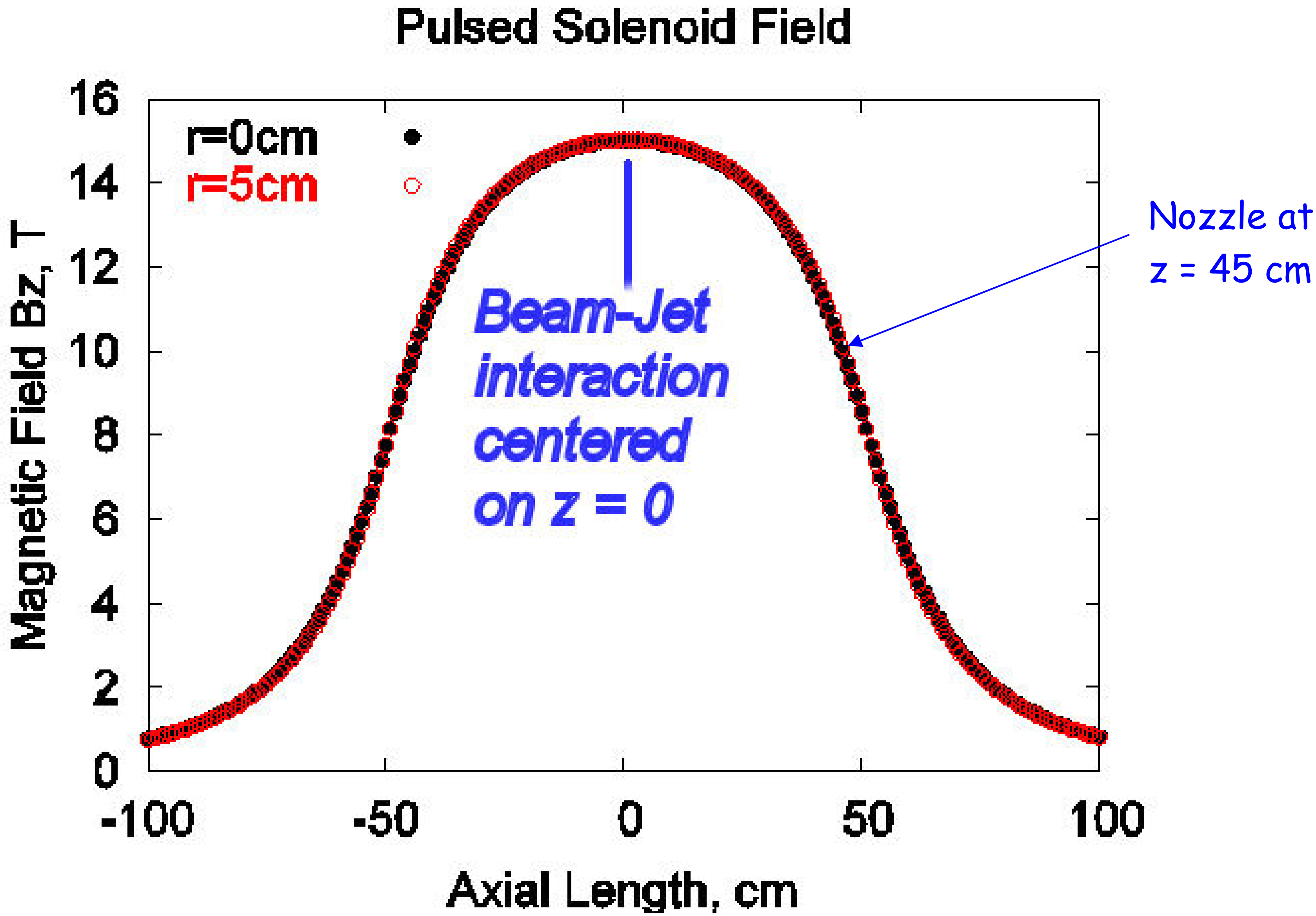
Recycled from the old SPS West Area extraction line.

30 MJ delivered during 15-s pulse.

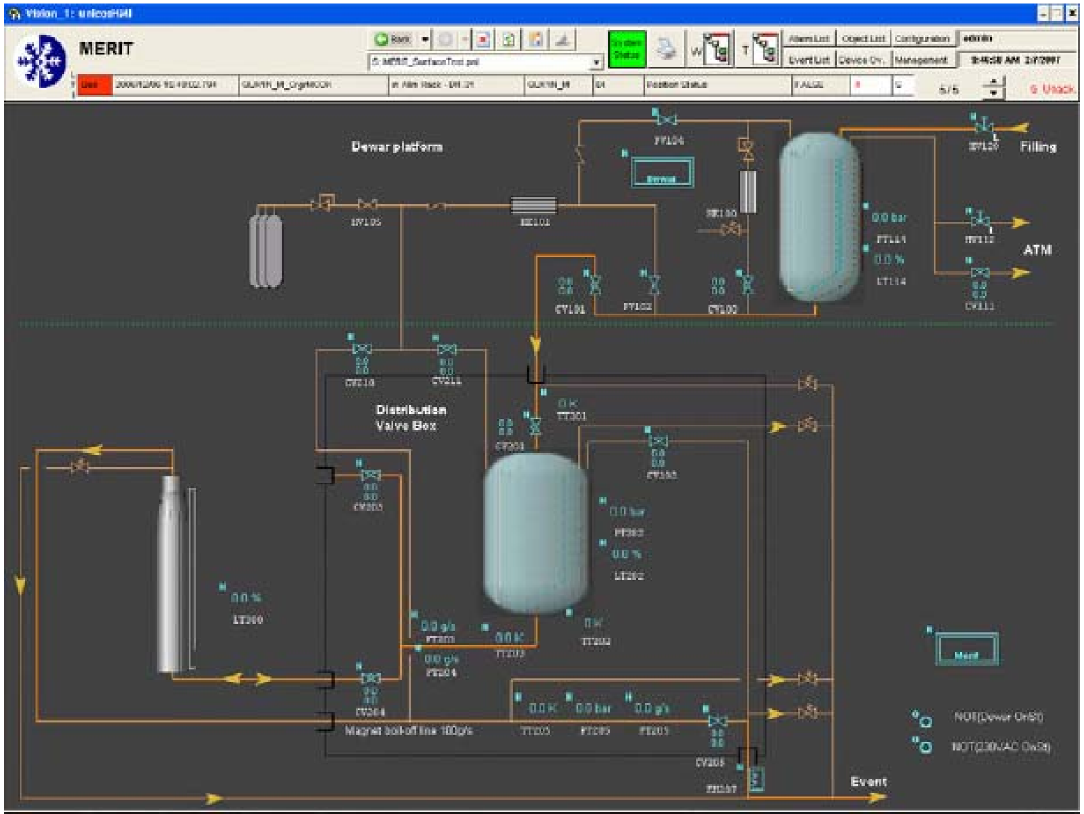
⇒Magnet temperature rises from 80 to 110K.



Magnetic Field Profile



LN_2 Cryogenic System



Design: F. Haug, O. Pirotte (CERN)

Fabrication: AES (UK)

A 15-T pulse of the magnet deposited ≈ 30 MJ,
$\Rightarrow$ 30K increase in magnet temperature.

≈ 100 l of LN_2 needed to cool magnet back to 80K.

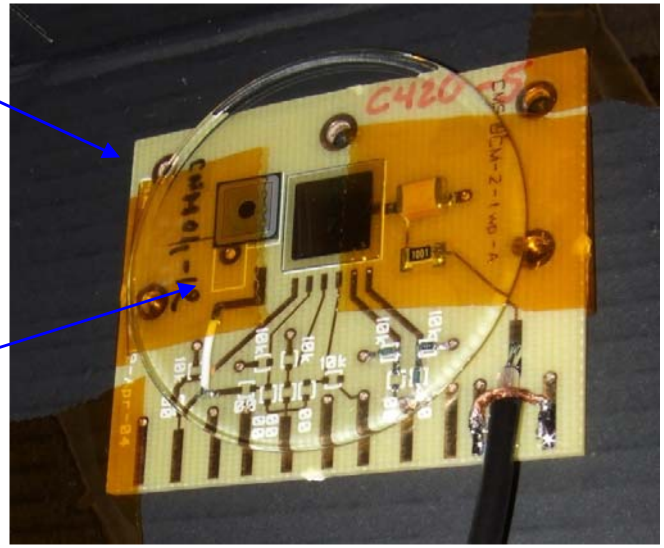
This took ≈ 40 min, which set the cycle time of the experiment.

LN_2 flushed from magnet during beam pulses to minimize activation of N2 exhausted to room air.

Secondary Particle Detectors

PIN diode
~1-cm^2 active area,
200 μm thick

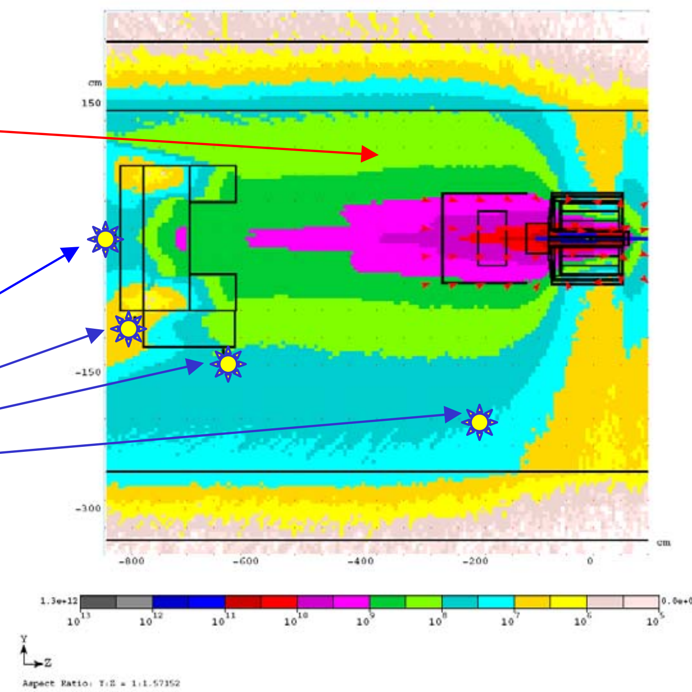
pCVD Diamond
7.5×7.5 mm^2 active area,
300 μm thick



ACEM detector

pCVD diamond
+ PIN diode

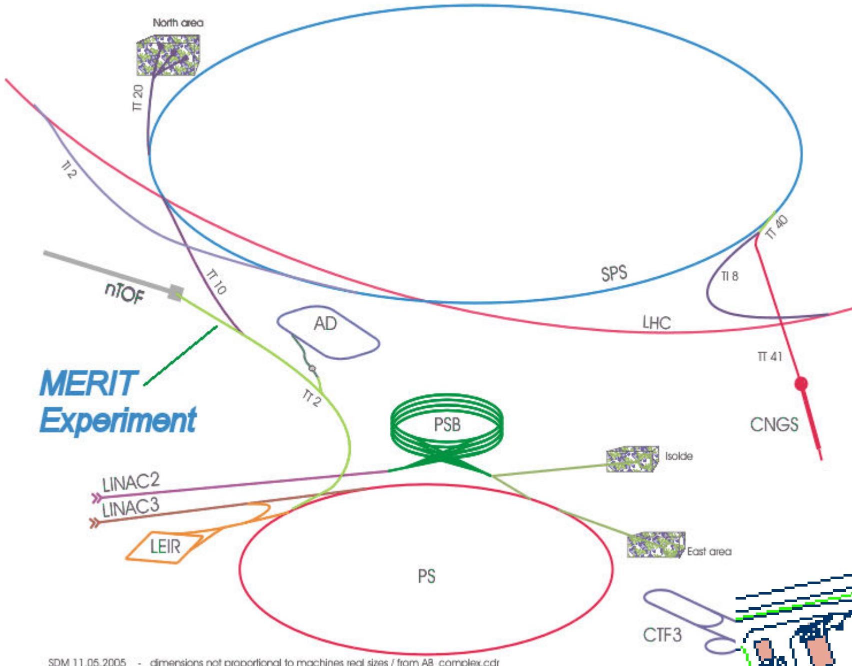
Particle fluxes - 3×10^{13} protons
charged hadrons (E > 200 KeV)
(MARS Simulation: S. Striganov)



Particle Detectors

I.Efthymiopoulos
M. Palm (CERN)

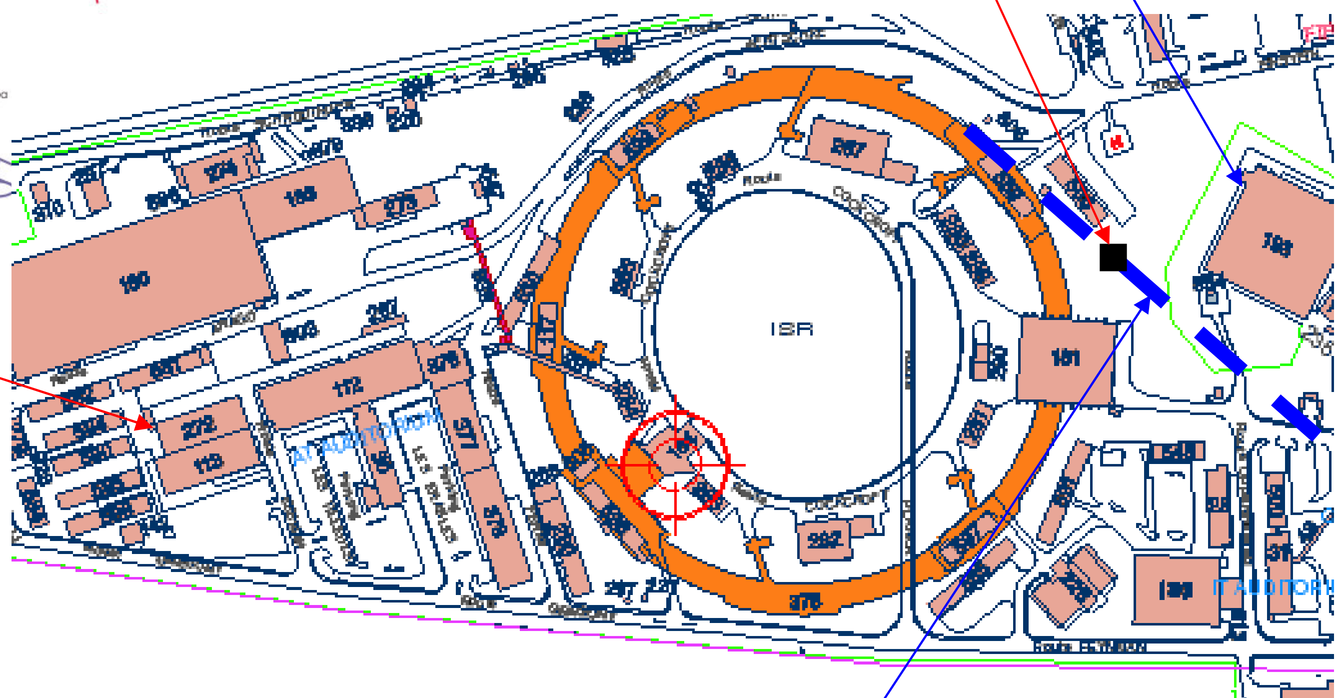
MERIT Locations at CERN



Power supply building

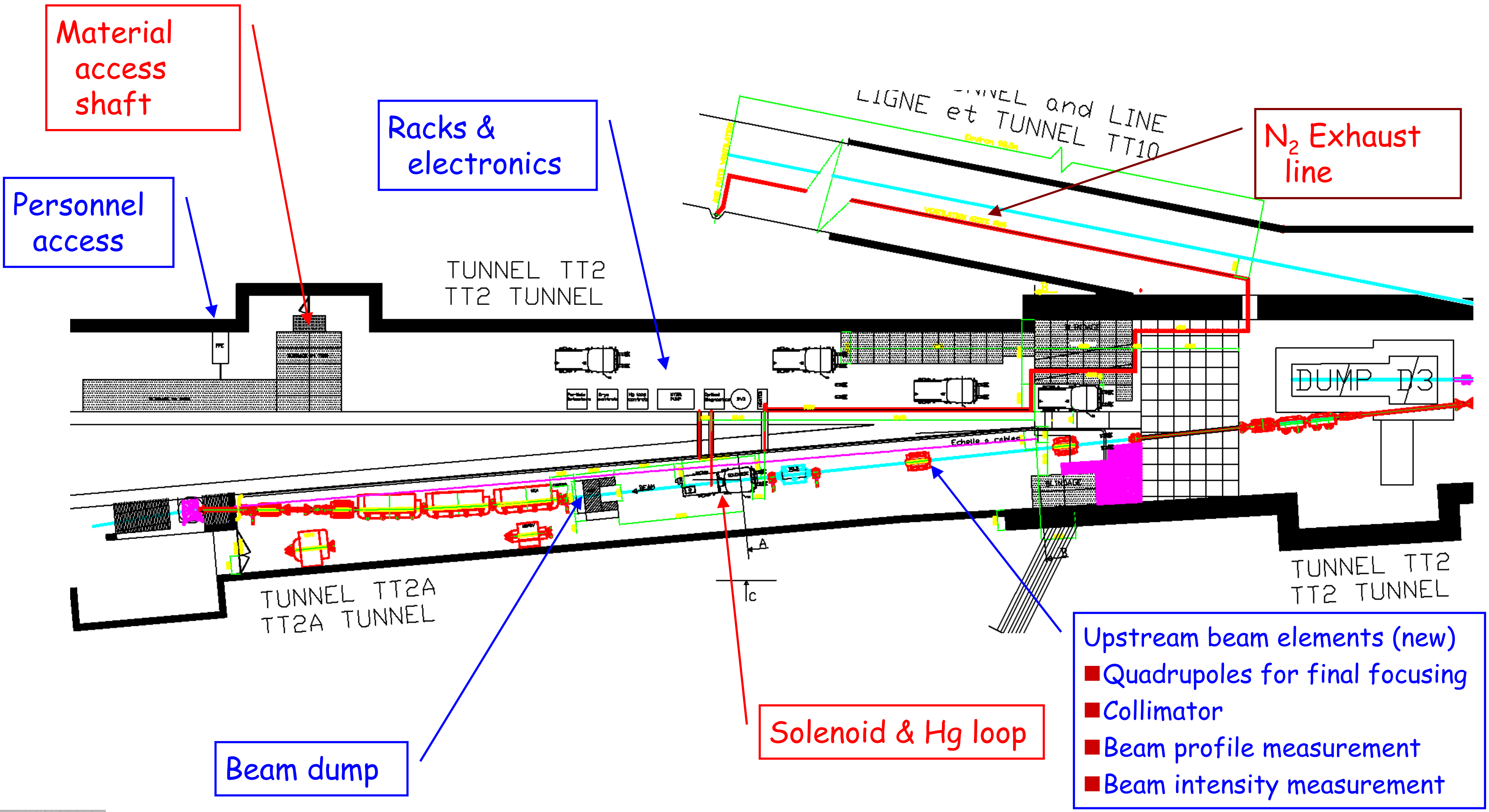
MERIT

Build.272: Offices & Control Room

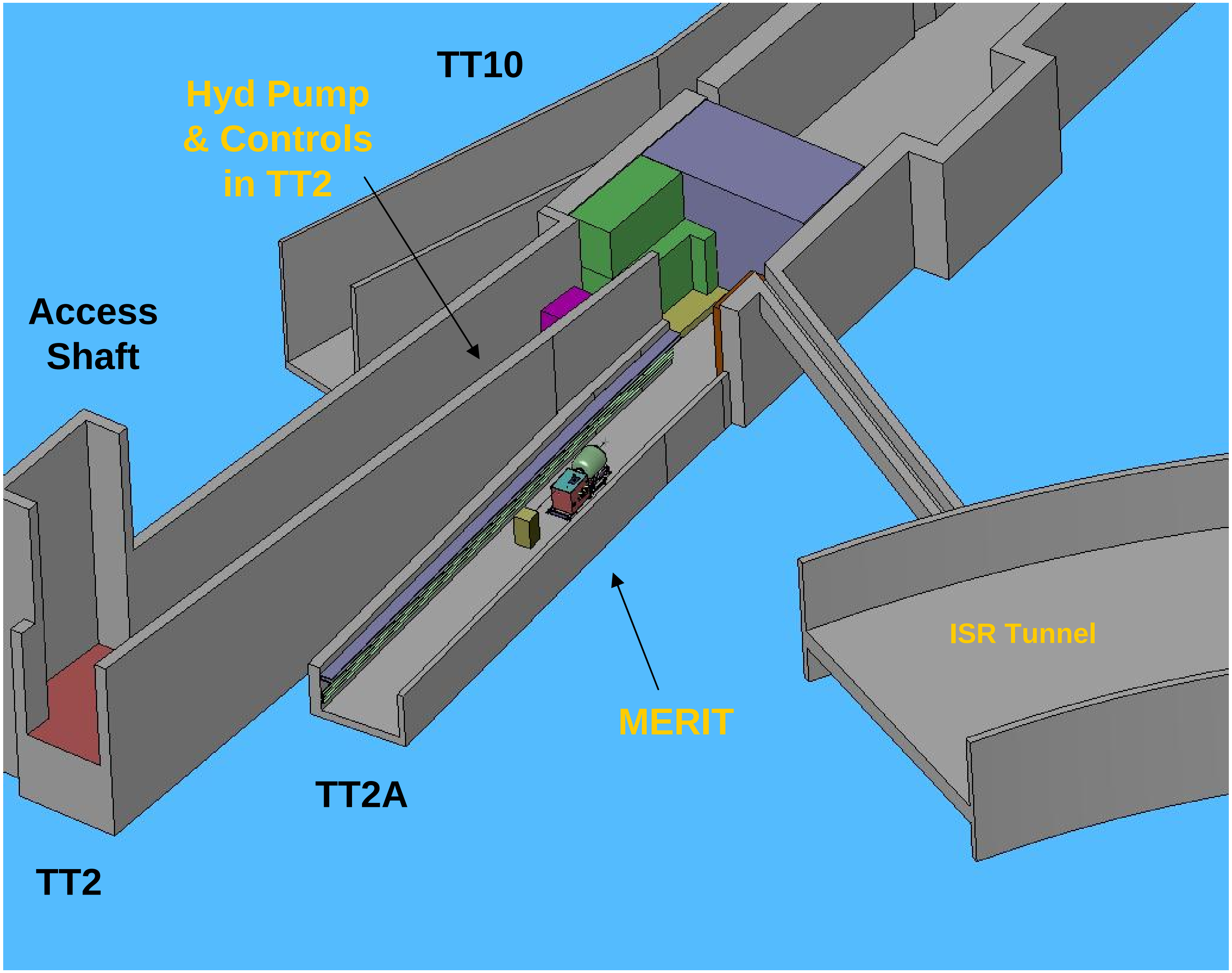


TT2A tunnel

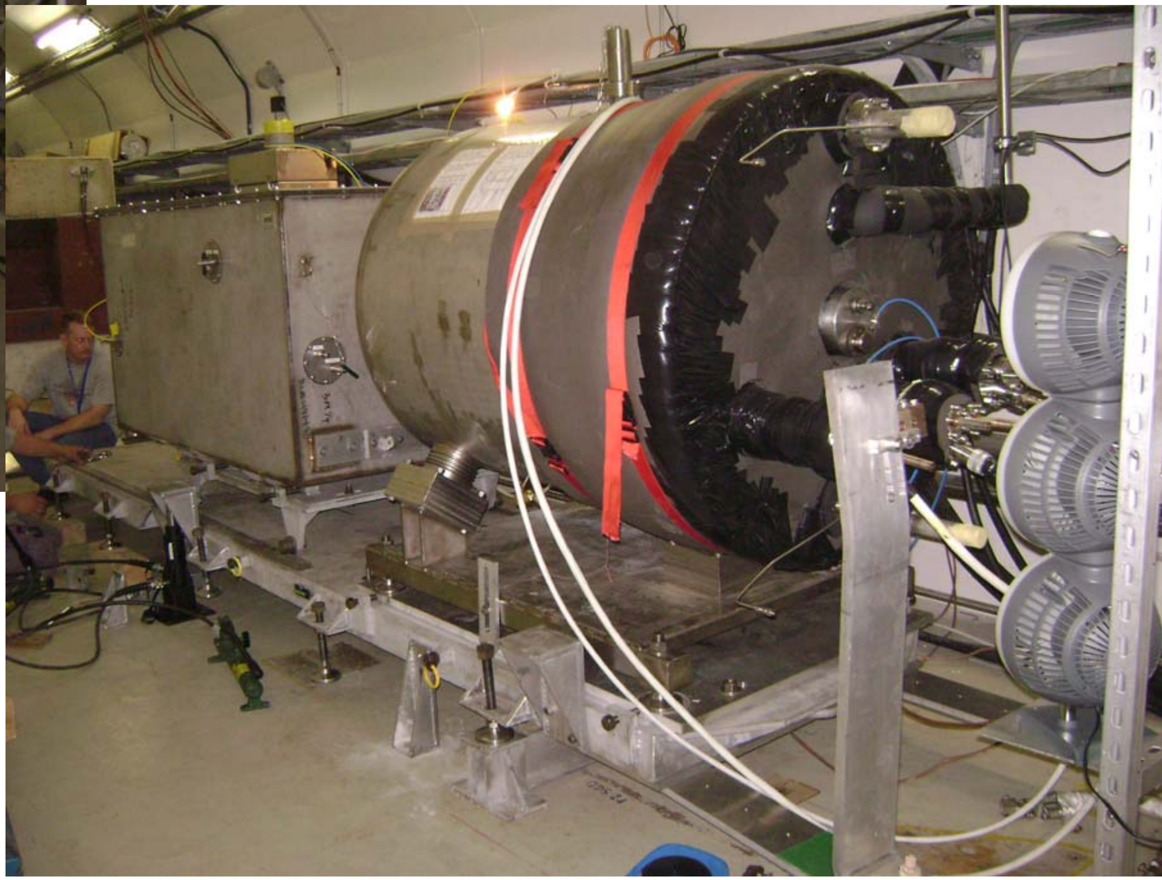
MERIT Layout in the TT2 and TT2A Tunnels



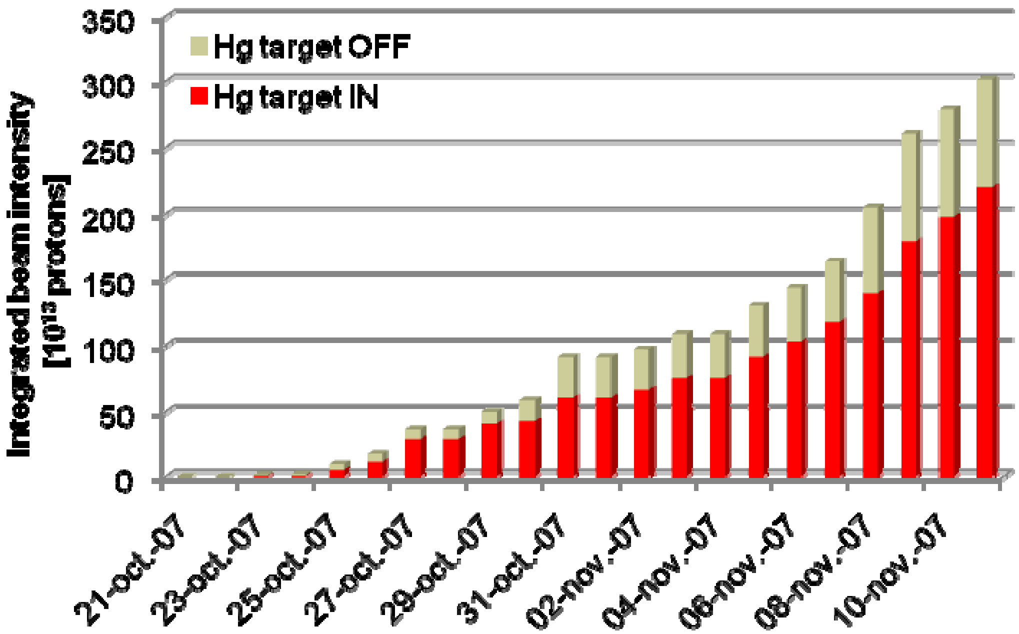
MERIT Layout in the TT2 and TT2A Tunnels



MERIT Installed in the TT2A Tunnel



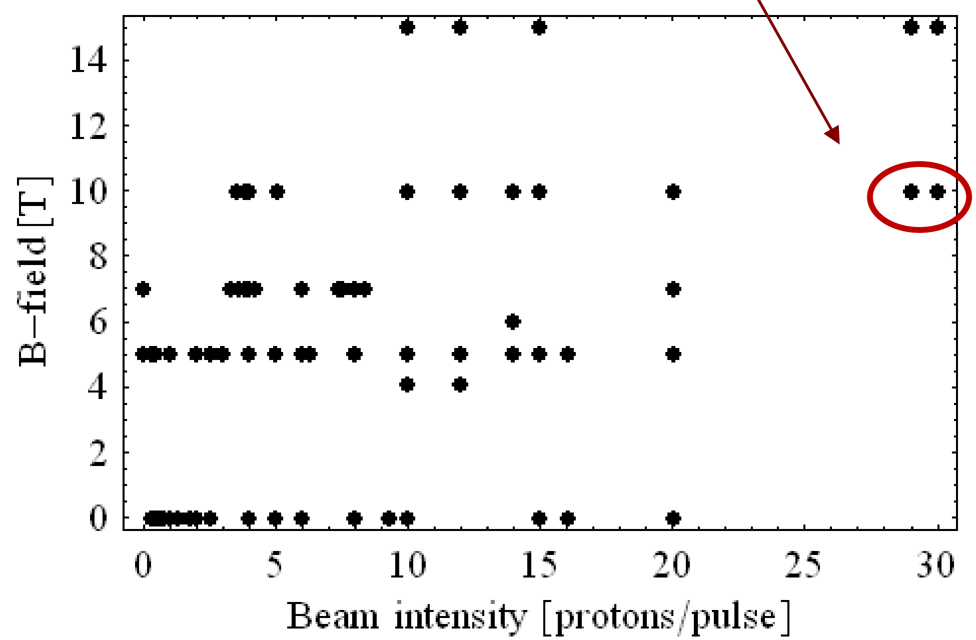
MERIT Beam Pulse Summary



MERIT was not to exceed 3×10^{15} protons on Hg to limit activation.

30 Tp shot @ 24 GeV/c
- **115 kJ** of beam power
- a PS machine record !

1 Tp = 10^{12} protons



CERN nToF11 Experiment (MERIT), II

Data taken Oct.22 -- Nov.12, 2007 with mercury jet velocities of 15 & 20 m/s, magnetic fields up to 15 T, and pulses of up to 3 $\times 10^{13}$ protons in 2.5 μs.

As expected, beam-induced jet breakup is relatively benign, and somewhat suppressed at high magnetic field.

"Pump-Probe" studies with bunches separated by up to 700 μs are still being analyzed.

$\Rightarrow$ Good success as proof-of-principle of liquid metal jet target in strong magnetic fields for use with intense pulsed proton beams.

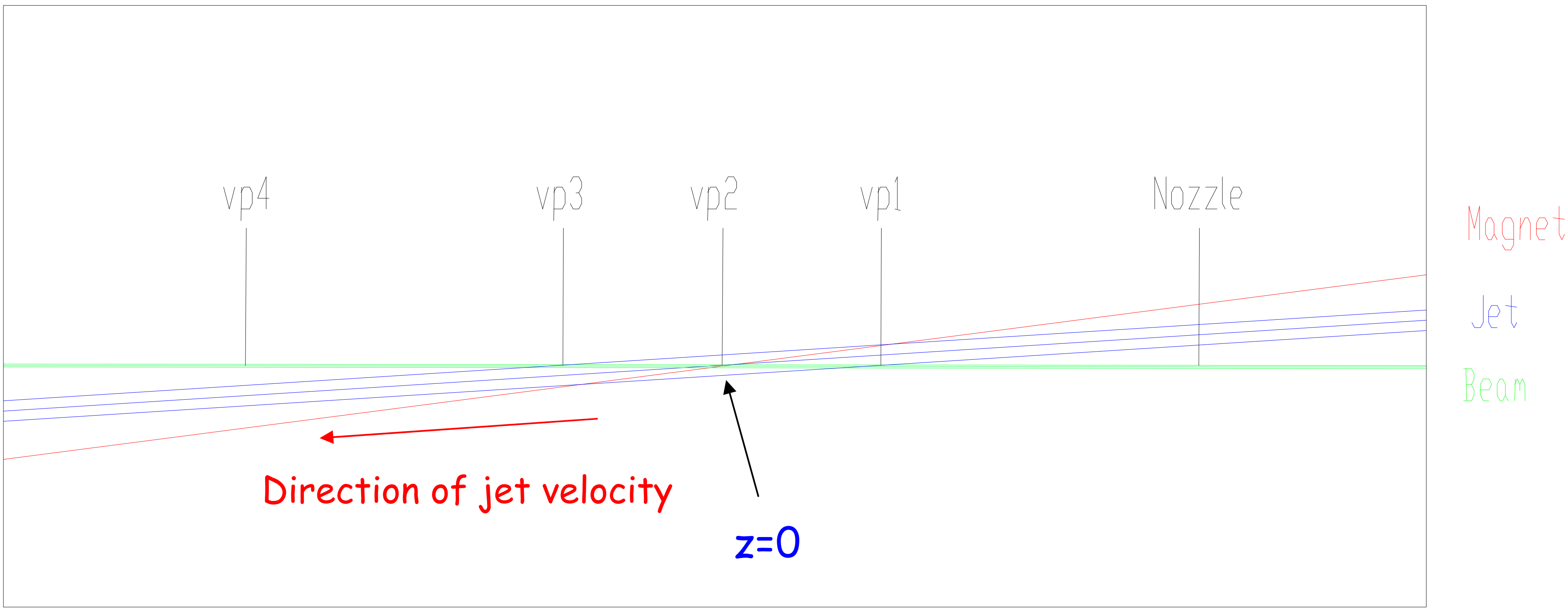
Geometry of the Beam-Jet Interaction

The proton beam enters the jet from below, and exits from above, about 30 cm downstream.

The camera on viewport 2 takes only 16 very high speed frames.

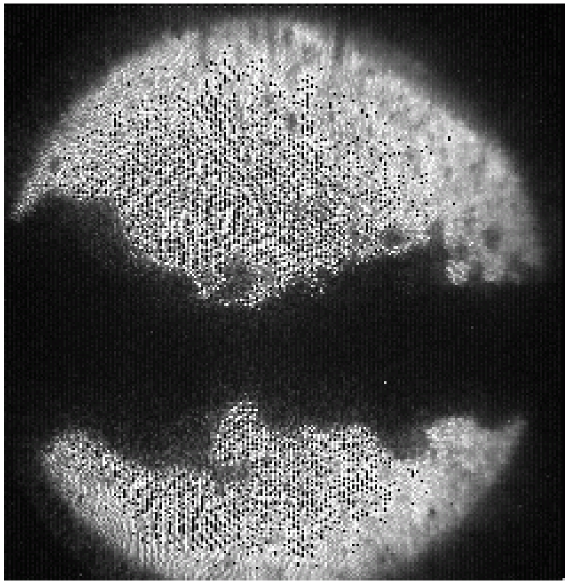
The cameras on ports 1, 3 and 4 took 200 frames at 2000 fps, ⇒ "movie" 1/10 s long.

A "movie" at viewport 3 sees the beam exiting the top of the jet first, and it entering the bottom of the jet ≈ 100 frames later.

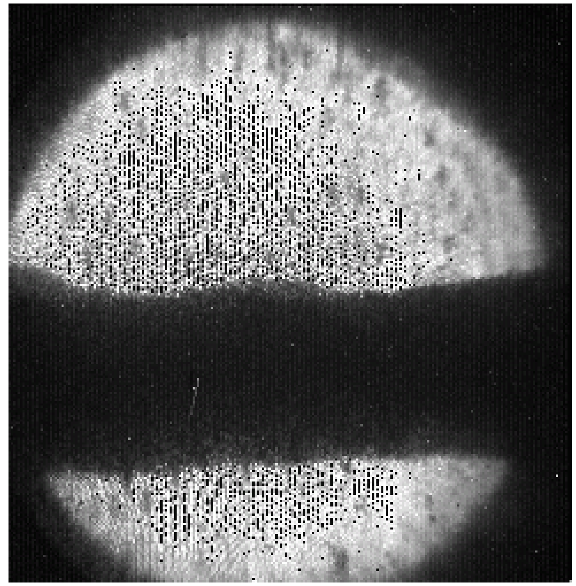


Jets of 15 m/s without Beam

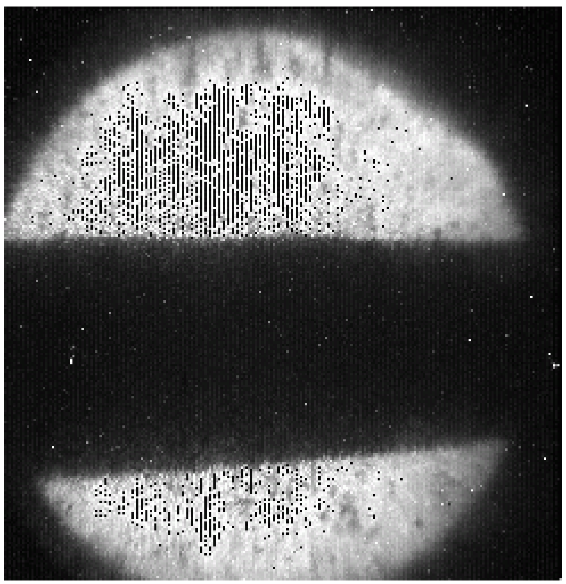
0.4T



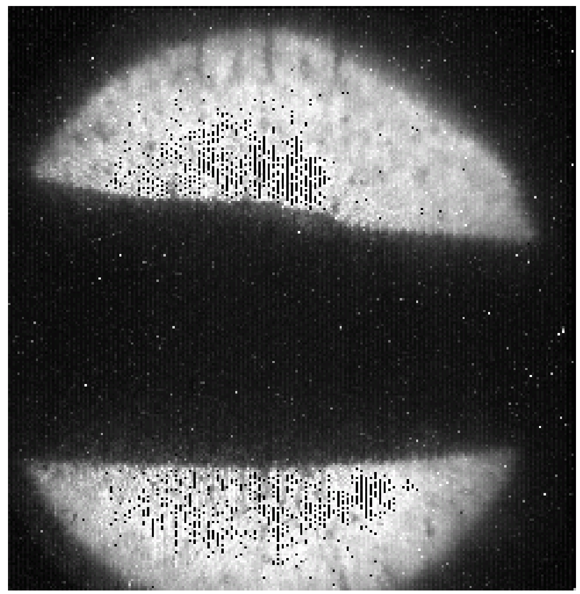
5T



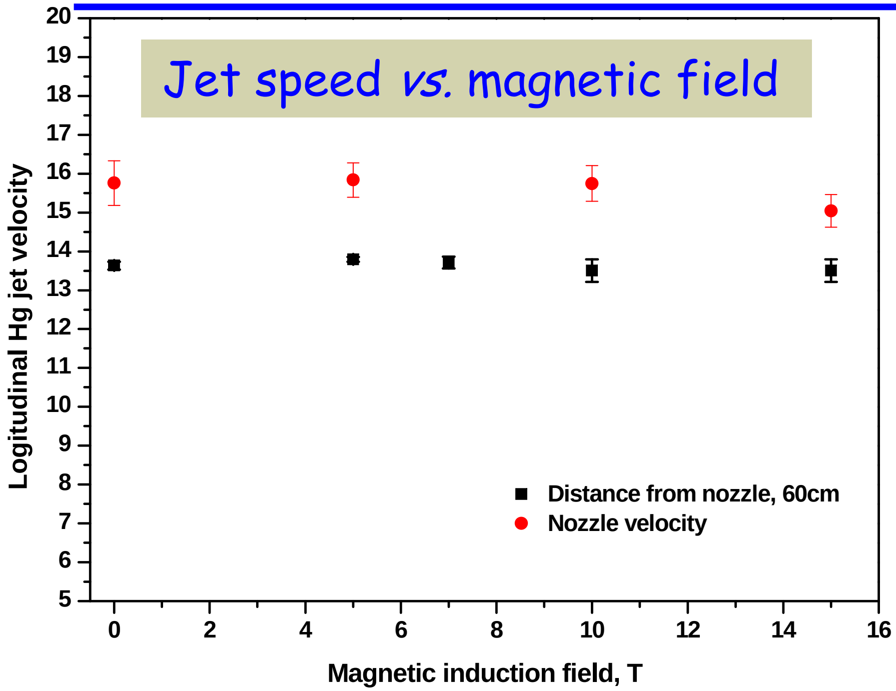
10T

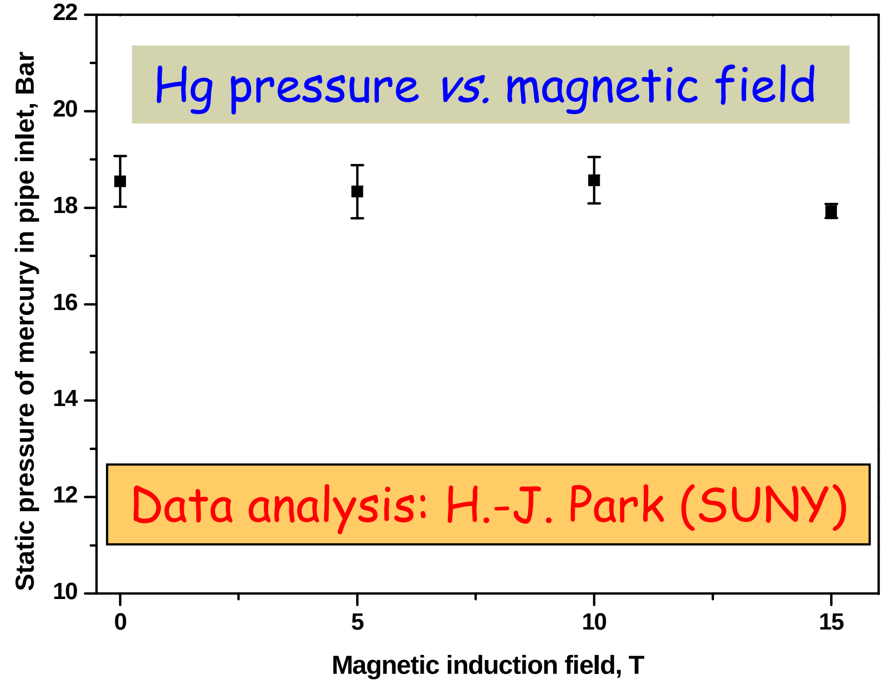


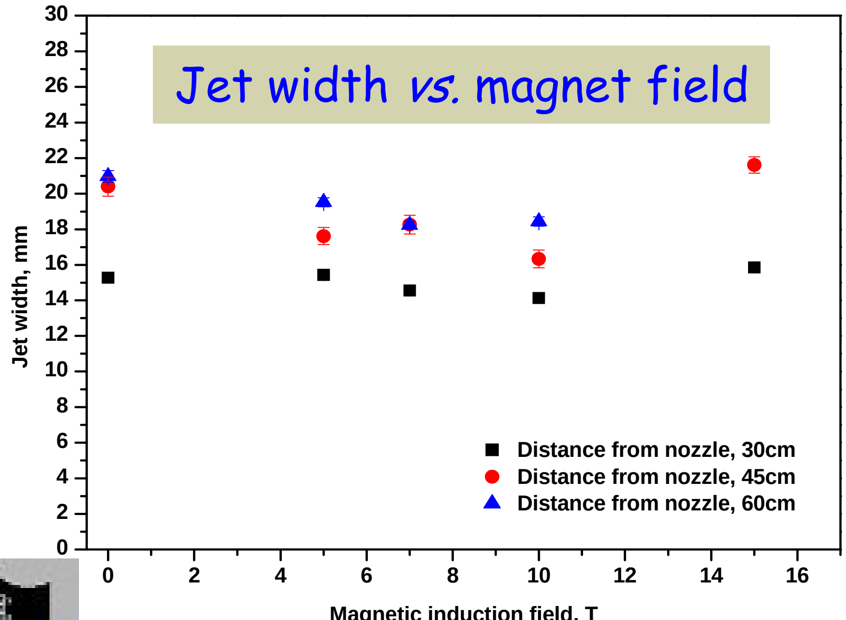
15T



Jet Properties without Beam





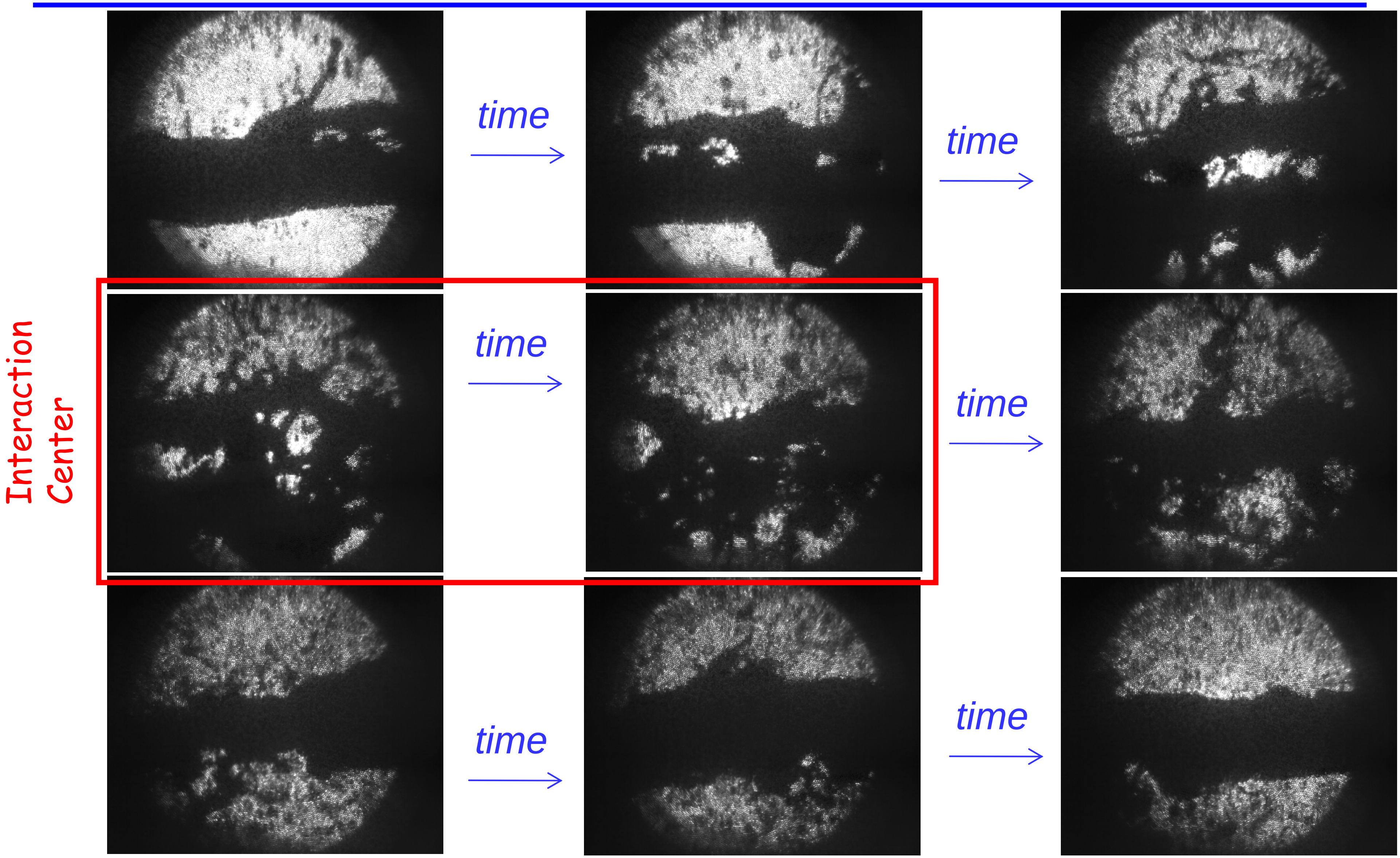


Jet velocity not noticeably reduced on entering magnetic field.

Pressure needed for v = 15 m/s does not increase with magnetic field.

Vertical height of jet not affected by magnetic field – but the height is ≈ double the nozzle diameter.

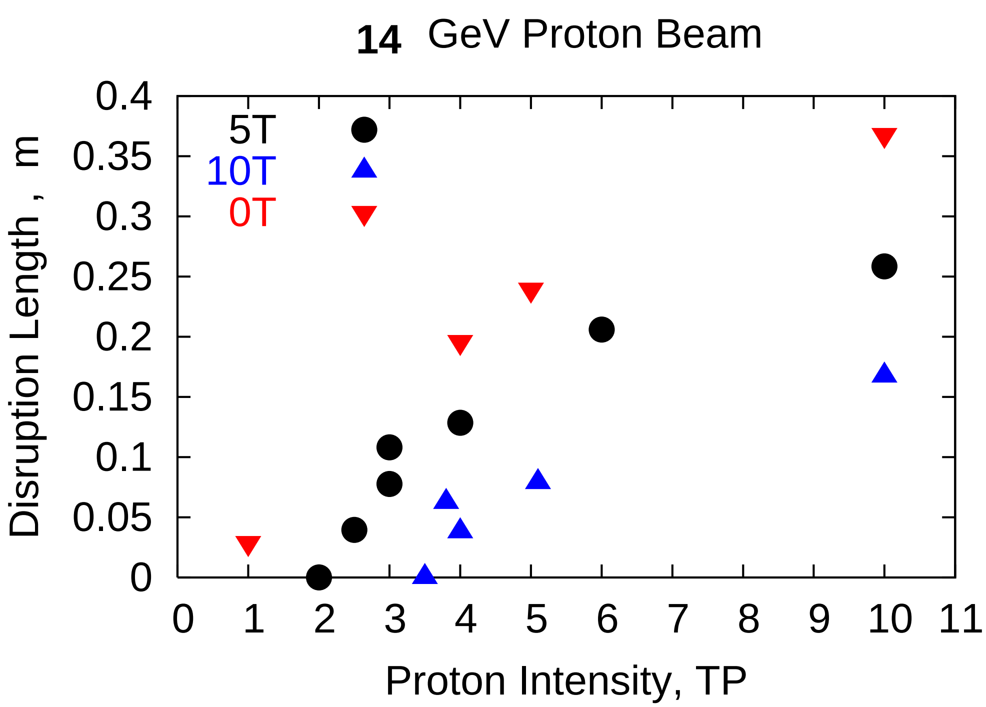
"Typical" Interaction: 16 Tp, 5 T, 14 GeV/c, 15 m/s

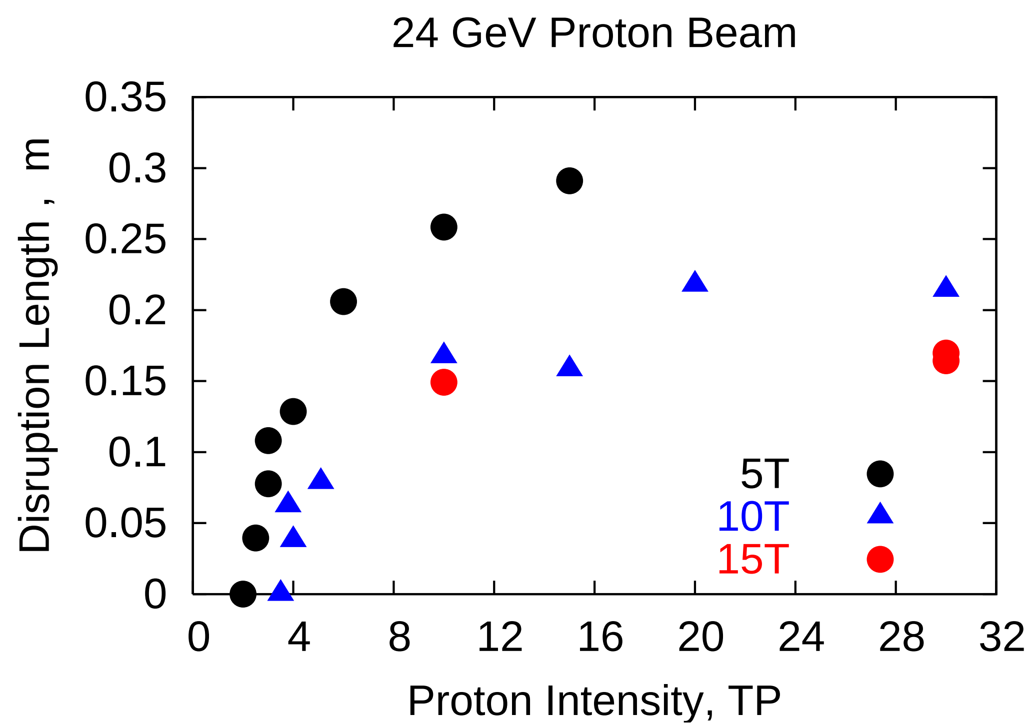


Note disruption of top of jet at early times, and of bottom at later times.

"Disruption length" inferred from number of frames the disruption lasts.

Disruption Length *vs.* Beam Intensity





Disruption length is never longer than length of overlap of beam and jet.

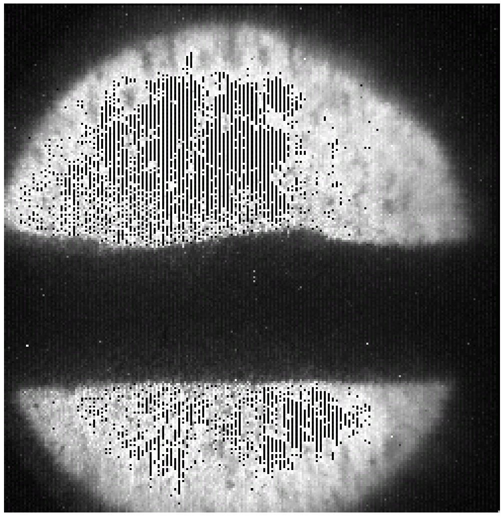
Maximum disruption length same at 14 and 25 GeV/c.

Disruption length smaller at higher magnetic field.

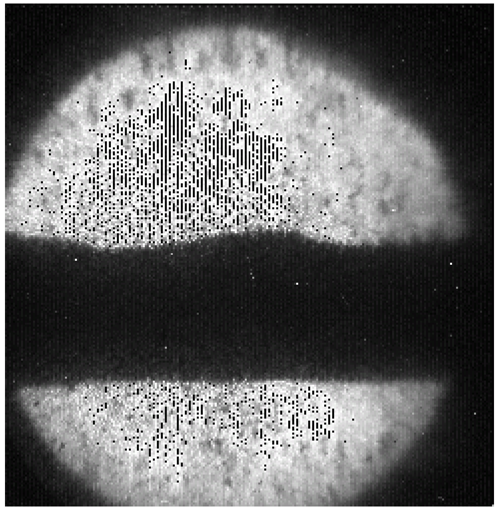
Disruption threshold increases at higher magnetic field.

Jet Breakup Velocity Observed at Port 2 with Fast Camera

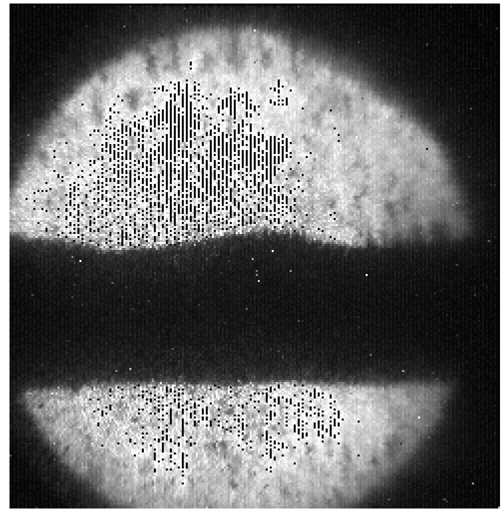
3.8TP, 10T **V = 24 m/s**



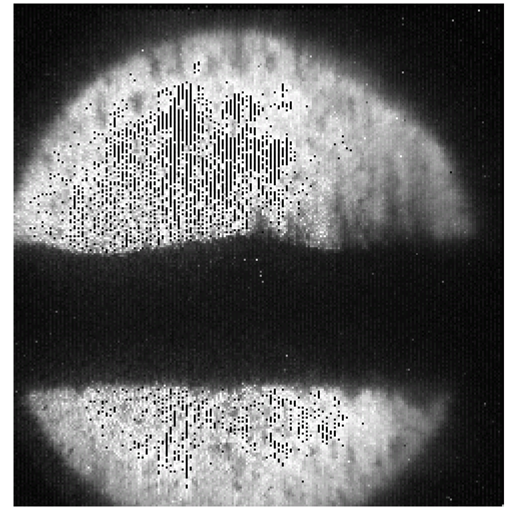
t = 0



t = 0.150 ms

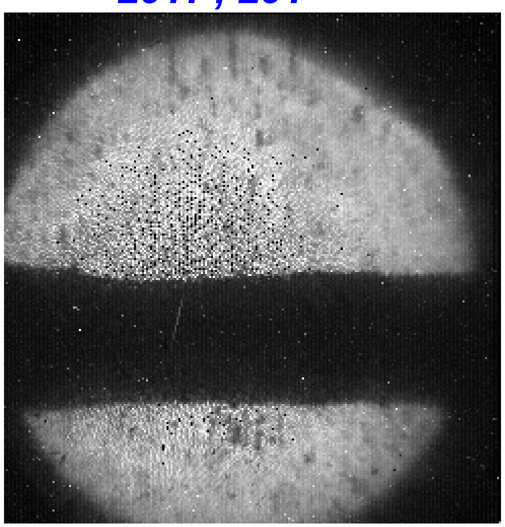


t = 0.175 ms

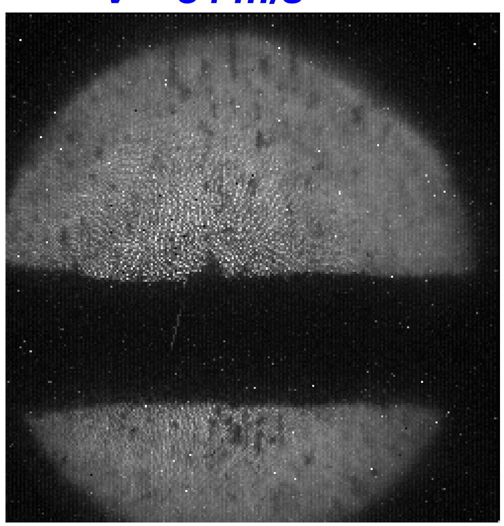


t = 0.375 ms

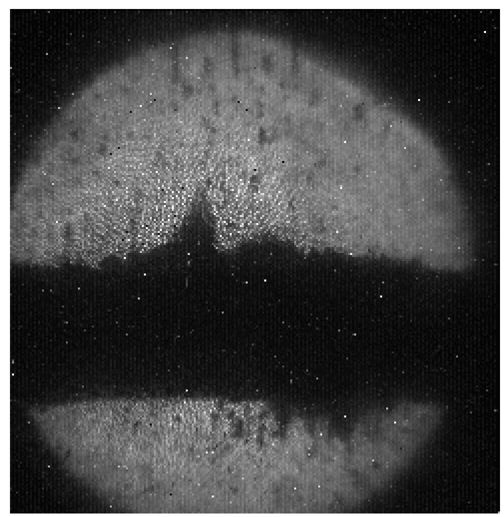
10TP, 10T **V = 54 m/s**



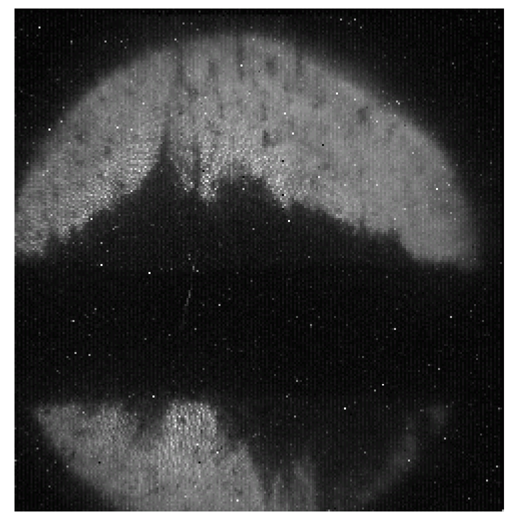
t = 0



t = 0.075 ms

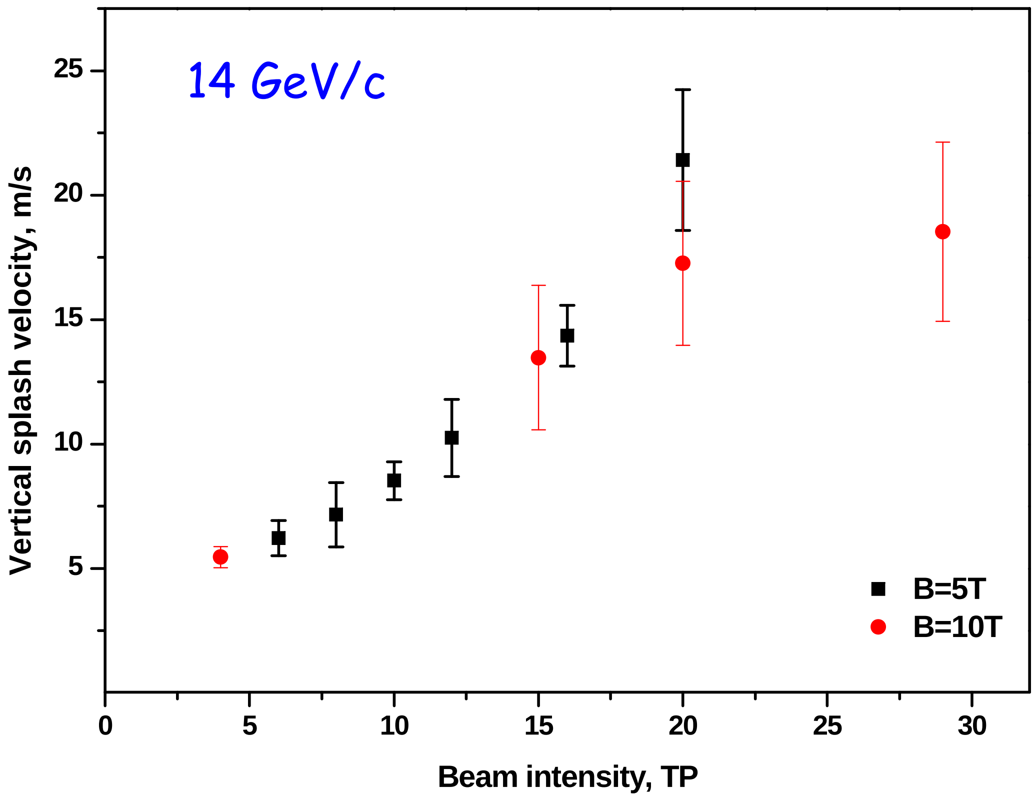


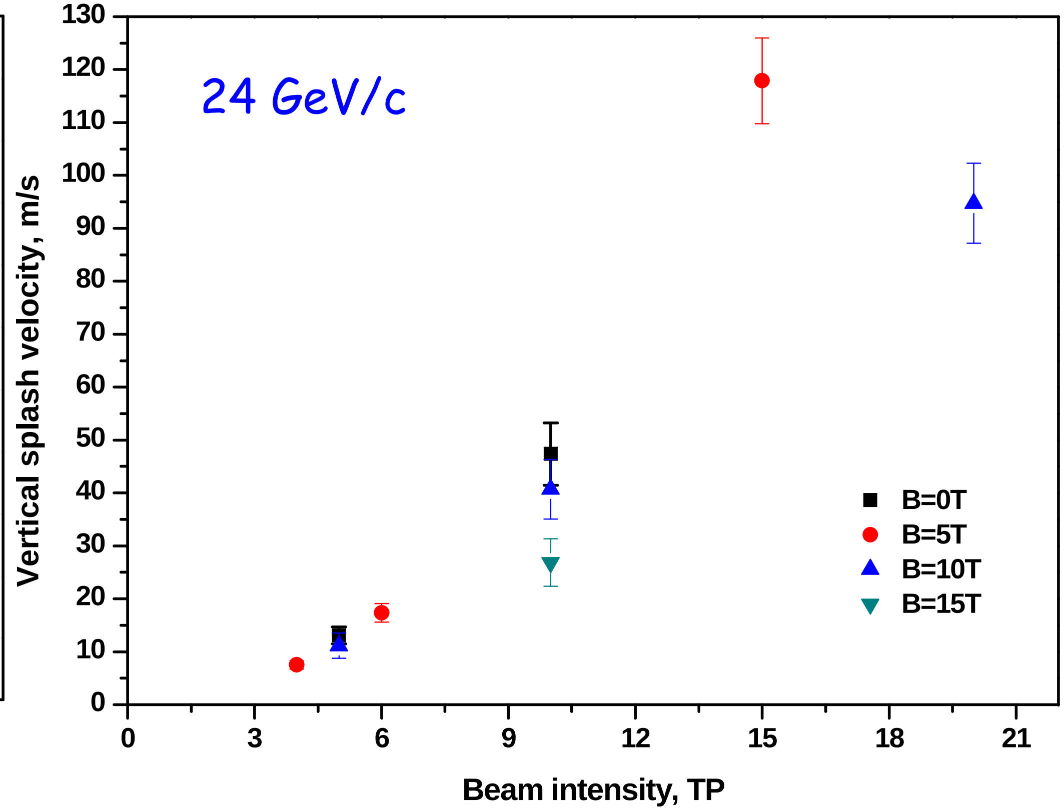
t = 0.175 ms



t = 0.375 ms

Jet Breakup Velocity Measurements





Beam spot area at 24 GeV/c is (14/24) of that at 14 GeV/c.

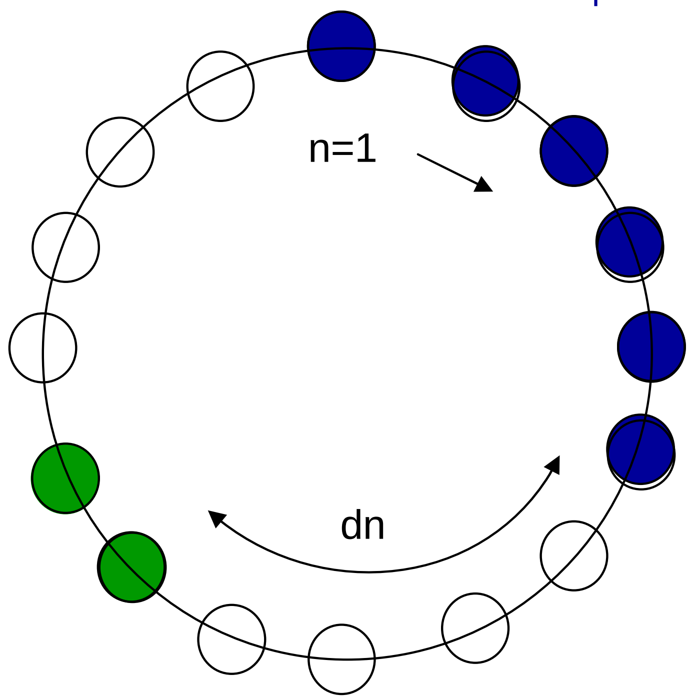
Beam intensity = energy/cm^2 is $(24/14)^2 \approx 3$ times greater at 24 than at 14 GeV/c.

Measurements are consistent with model that breakup velocity$\propto$beam intensity.

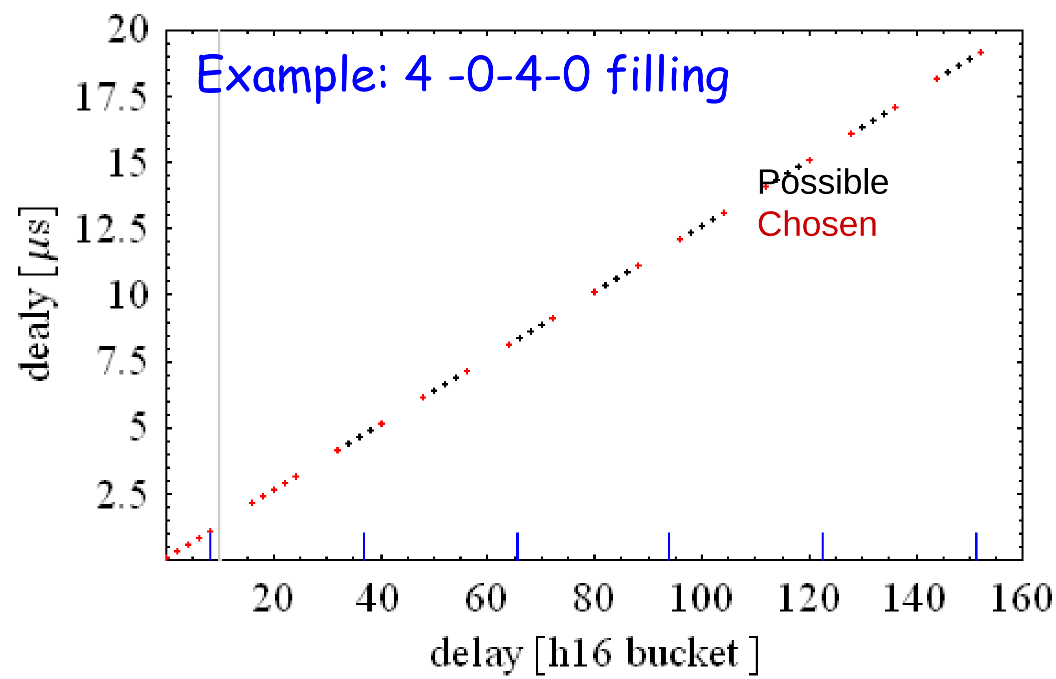
Pump-Probe Studies via Extraction Gymnastics

Example: Operate PS at harmonic 16, fill only bunches 1-6 and 11-12.
Extract bunches 1-6 first, and then bunches 11-12 N turns later.

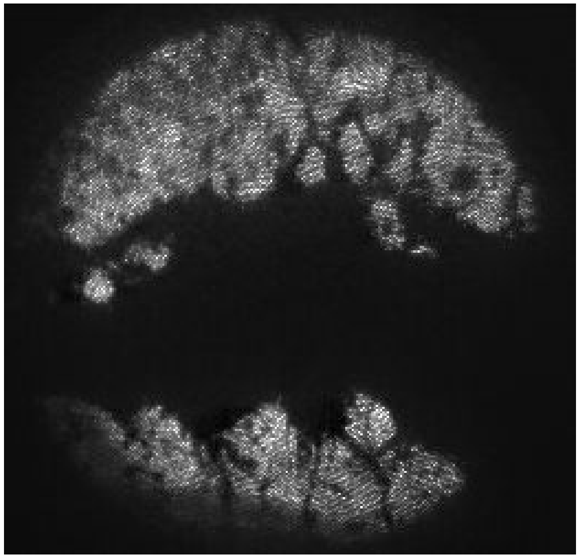
PUMP: 6 bunches, $15*10^{12}$ protons



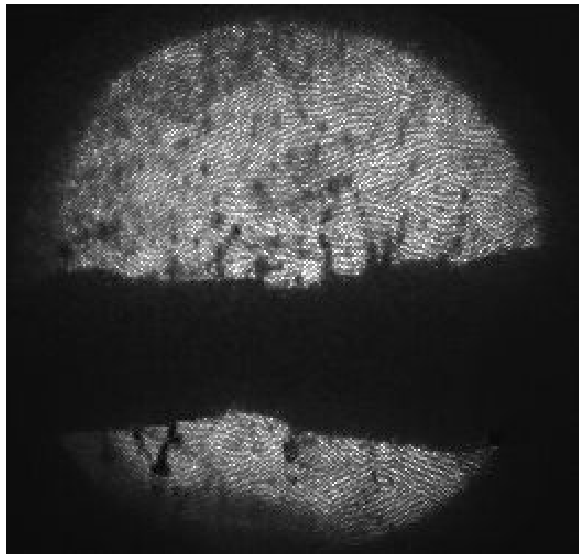
PROBE: 2 bunches, $5*10^{12}$ protons



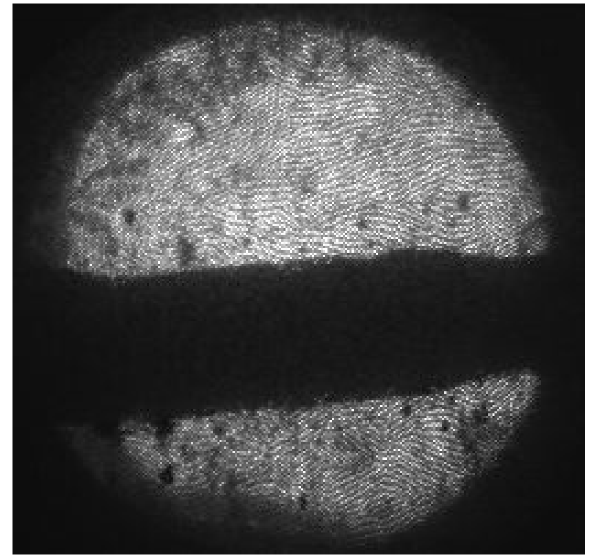
Pump-Probe Study with 4 Tp + 4 Tp at 14 GeV/c



Single-turn extraction
➔ 0 delay, 8 Tp



4 Tp probe extracted on subsequent turn
➔ 3.2 μs delay



4 Tp probe extracted after 2nd full turn
➔ 5.8 μs Delay

Target supports 14-GeV/c, 4 Tp beam at 172 kHz rep rate without disruption.

Preliminary *analysis of studies at 14 GeV/c with 15 Tp pump and 5 Tp probe with delays of 2-700 μs indicate little change in secondary particle production by probe.*
⇒ Initial breakup of jet does not reduce particle production immediately.
⇒ May be able to use bunch trains of several-hundred μs length.

Summary of MERIT Analysis to date

Jet velocity, shape and delivery pressure little affected by magnetic field.

Jet surface instabilities are reduced at higher magnetic field.

Jet height is larger than expected, perhaps an effect of the 180° bend upstream of the nozzle.

Jet disruption velocity scales with beam intensity, and is not destructive.

Jet disruption length is less than length of beam overlap with the jet.

Jet disruption length and velocity are reduced at higher magnetic field.

There is no jet disruption for pulses of less than 1 Tp (or higher in higher magnetic field).

Bunches more than 5 μs apart act separately in causing disruption.

While visible disruption begins 50 μs after a proton pulse, secondary particle production is the same for pulses that follow at several times this value.

In sum, the MERIT experiment provides a proof of principle of a mercury jet target in a high-field solenoid for multimegawatt proton beams.

Post-MERIT Liquid Target Issues

MHD simulations

Optimize performance of nozzle in Fe plug

Eliminate 180^0 bend

Splash in liquid pool beam dump

Particle production

Rep-rate delay limits

Use of a Pb-Bi alloy rather than Hg

Target station engineering

Study these issues in context of IDS/MCFS

Issues from MERIT: Jet Quality, Vertical Height

Jet quality poor in zero magnetic field, and improves (as expected) with increasing field.

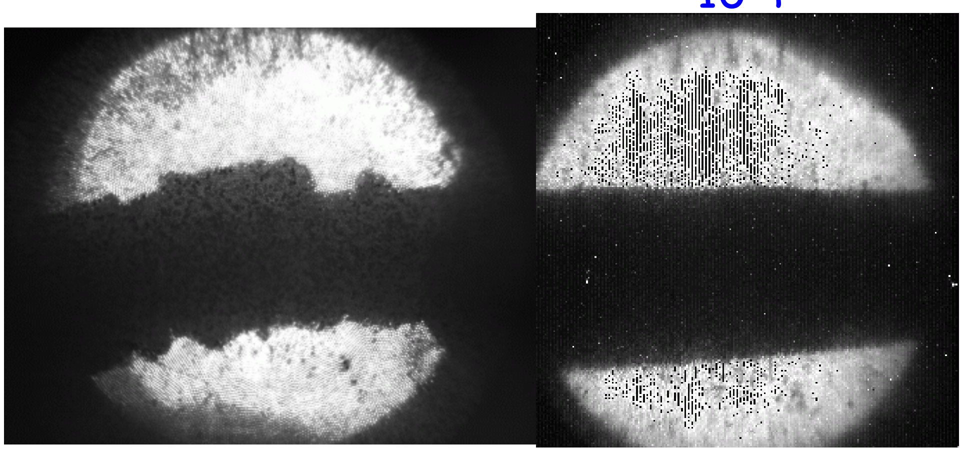
Jet vertical height 1.5-2.4 times nozzle diameter, and little affected by magnetic field.

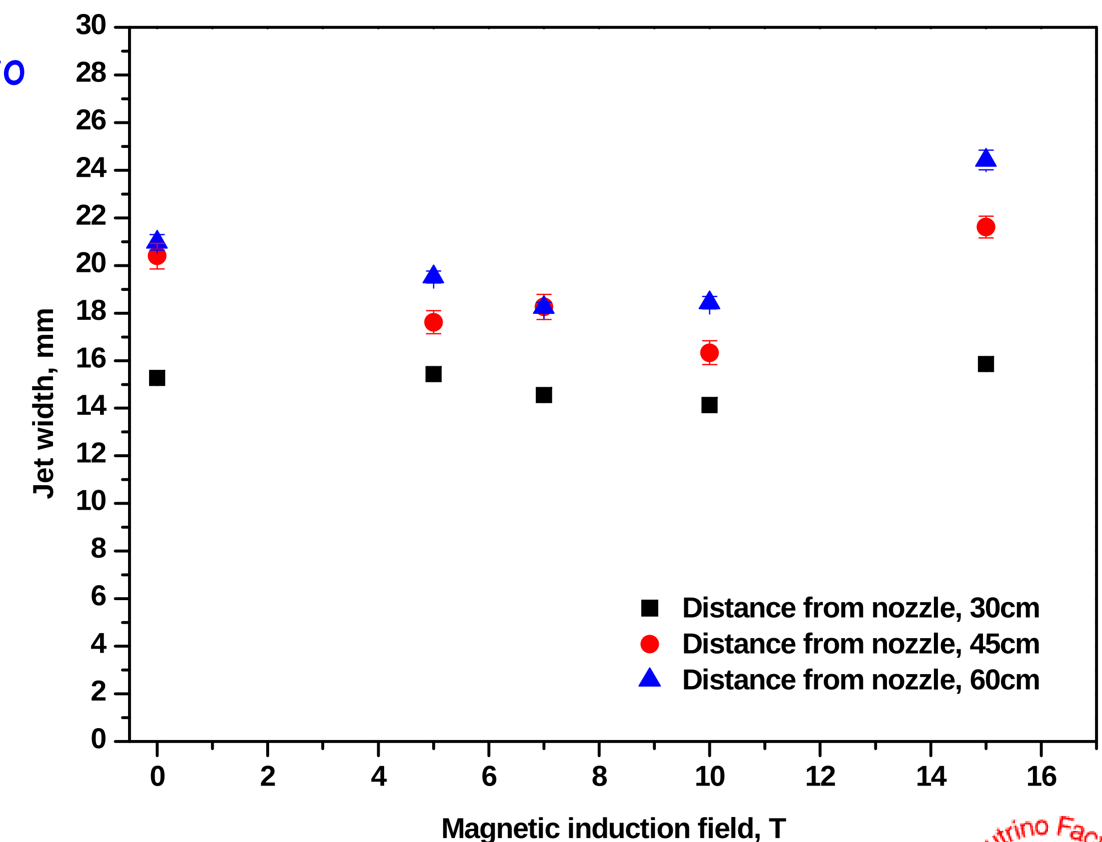
Simulations predict that vertical expansion of jet would be small, and would vary as B^2.

Suggests that 180° bend before nozzle leads to vertical expansion of jet.

Interesting hydrodynamic issues, but may be best to focus of aspects relevant to ν Factory/Muon Collider – where no 180° bend is contemplated.

0 T 10 T





Could Reuse MERIT Equipment to Study Jet Issues without Beam

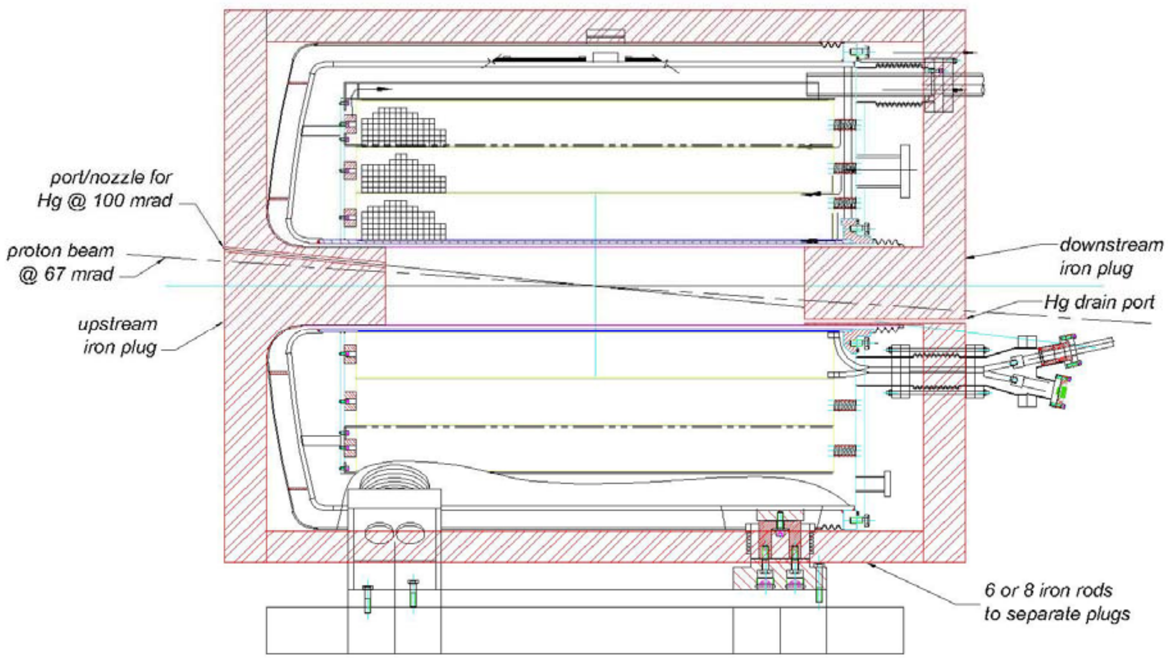
At a facility suitable for more general handling of mercury, could connect the mercury test volume to the mercury pump by hoses so that mercury enters at one end of magnet and exits at the other.

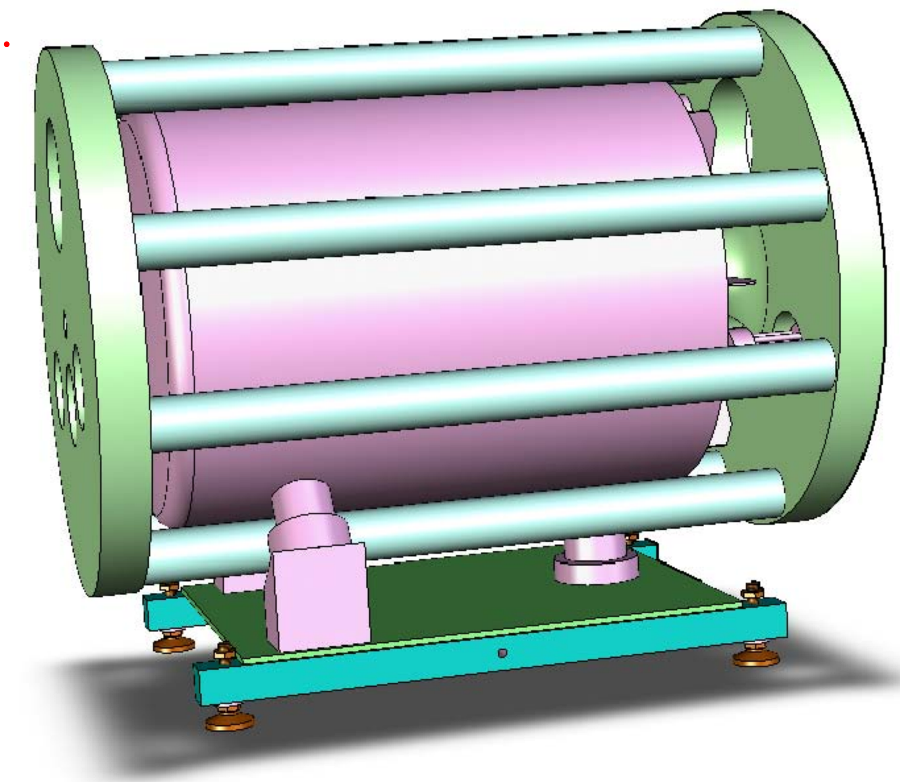
Could study jet quality in nozzles with no sharp bends.

Could use optical diagnostics with both side and top views.

Could add iron plugs to the MERIT magnet to study effect of field on a jet at 100 mrad (instead of 33 mrad as in MERIT @ CERN).

Could also study collection of the jet in a mercury pool.





Option for Follow-On Studies at ORNL

Bldg 7627

Bldg 7625

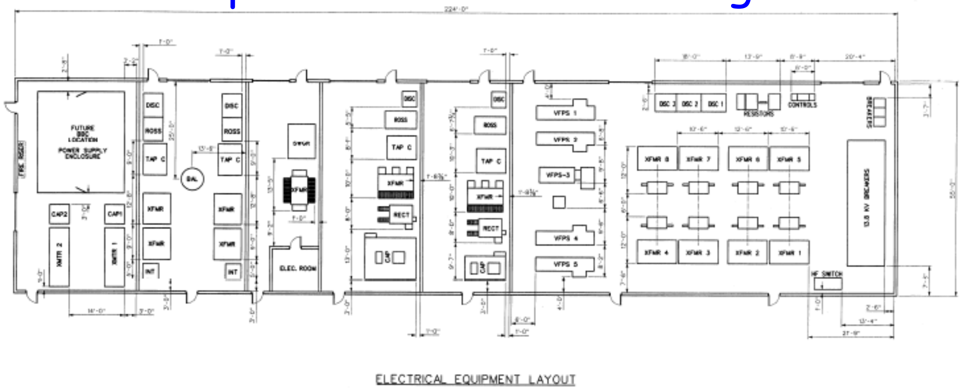
A new fusion test facility in bldgs 7625, 7627 will be completed in late 2008.

Several 10-MW power supplies available.

LN_2 dewar 20-t overhead crane, equipment pit.

Could begin with zero field studies (nozzle optimatization, Hg splash in pool,….)

Eventual option to use MERIT magnet at 15 (or 20!) T.



Vertical field power supplies (capability of each)
650V peak
15,000 A pulsed > 5 sec
Voltage and/or current can be controlled by SCR gate waveform control

Lead-Bismuth Alloys

Lead-bismuth alloys are solid are room temperature, but liquefy at 70-125°C.

Easier to contain a target "spill" if material solidifies at room temperature.

More radioisotope production with Pb-Bi than with Hg (but "trivial" compared to a reactor).

Boiling of liquid target by proton beam (> 4 MW) less of an issue than with mercury.

Design studies for MERIT-like tests mandated by the NFMCC.

Some Pb-Bi alloys wet quartz, so difficult to use with optical diagnostics.

Woods metal (Low 158) does not wet glass (Palmer), but contains cadmium.

Pb-Bi-Sn alloys melt as low as 95°C.

Lab tests will be done soon on wetting of quartz by several low melting alloys.

Type/ Approx Temp	Antimony	Bismuth	Cadmium	Lead	Tin	1-9 lb	10-49 lb	50 + lb
Low 158	0 %	50%	10%	26.7%	13.3%	17.99	16.19	14.39
Low 158-190	0 %	42.5%	8.5%	37.7%	11.3%	17.99	16.19	14.39
Low 203	0%	52.5%	0%	32%	15.5%	17.99	16.19	14.39
Low 212	0%	39.4%	0%	29.8%	30.8%	17.99	16.19	14.39
Low 217-440	9%	48%	0%	28.5%	14.5%	17.99	16.19	14.39
Low 255	0%	55.5%	0%	44.5%	0%	17.99	16.19	14.39
Low 281	0%	58%	0%	0%	42%	17.99	16.19	14.39
Low 281-338	0%	40%	0%	0%	60%	17.99	16.19	14.39