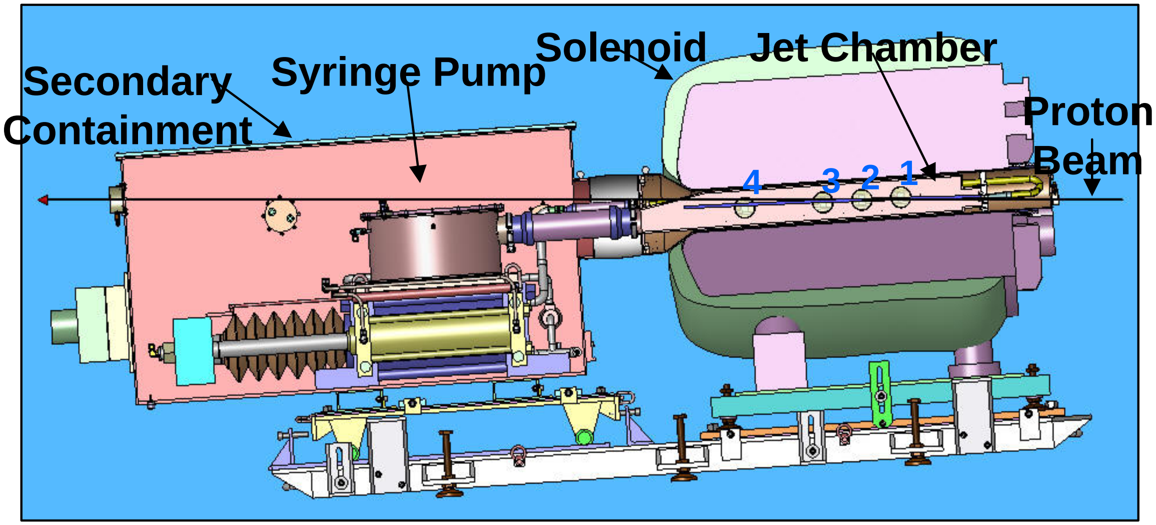
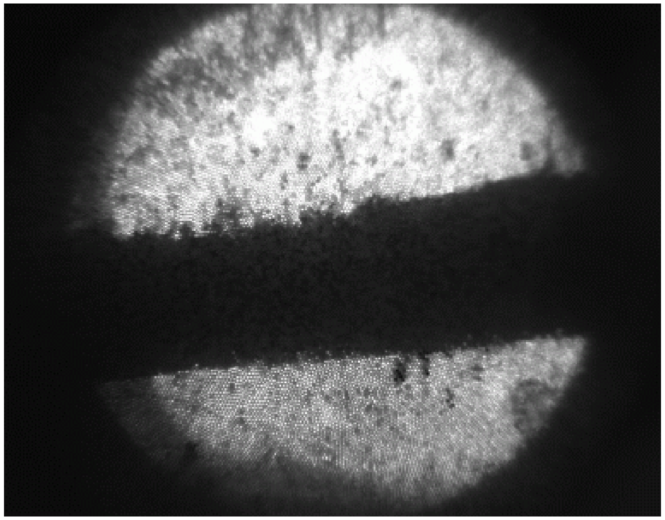
The MERIT Experiment at CERN

A Proof-of-Principle Demonstration of a Mercury Jet Target for Megawatt Proton Beams



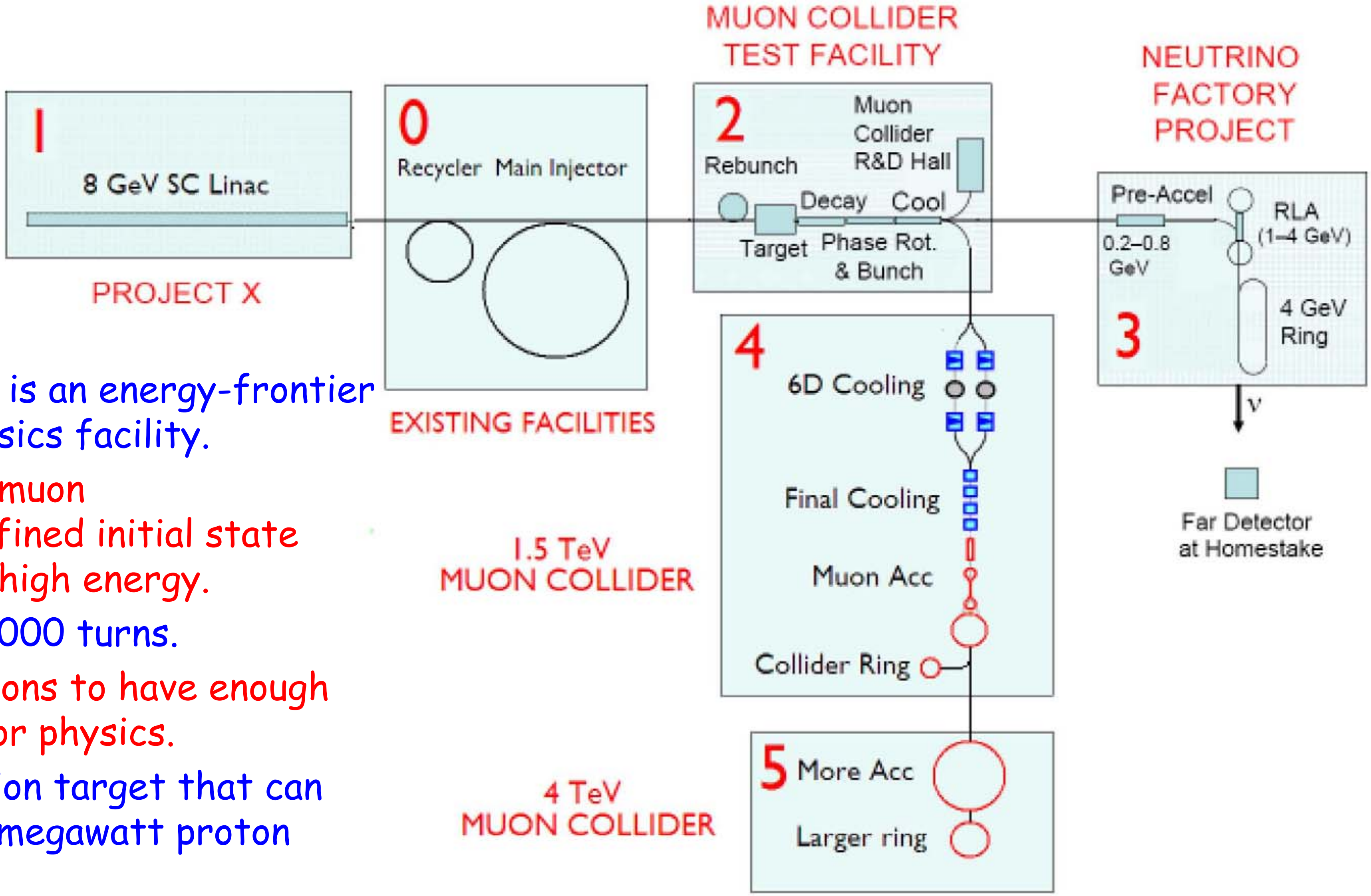


K.T. McDonald
Princeton U.

Accelerator Physics and Technology Seminar
Fermilab, April 24, 2008

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

The Target is Pivotal between a Proton Driver and a Muon Collider



A Muon Collider is an energy-frontier particle-physics facility.

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

A muon lives ≈ 1000 turns.

Need lots of muons to have enough luminosity for physics.

Need a production target that can survive multmegawatt proton beams.

Targetry Challenges of a Muon Collider

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 (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).

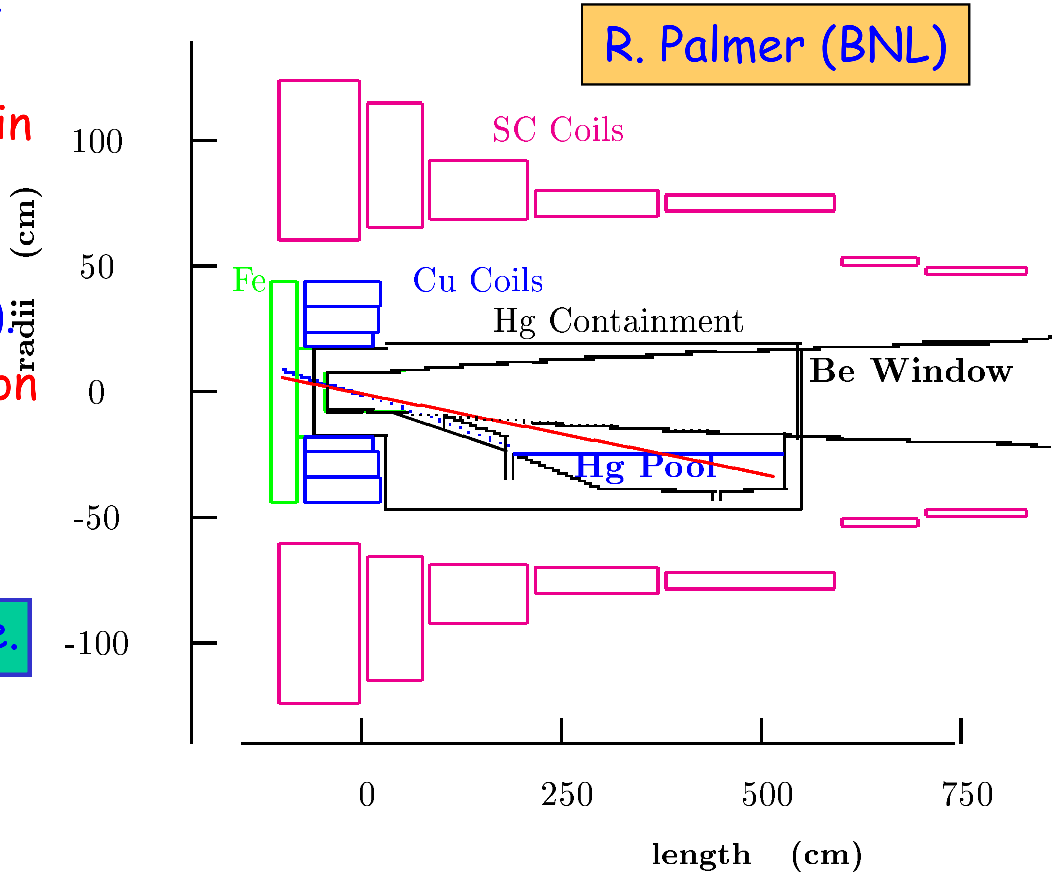
Solenoid coils can be some distance from proton beam.

$\Rightarrow$ $\geq$ 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.

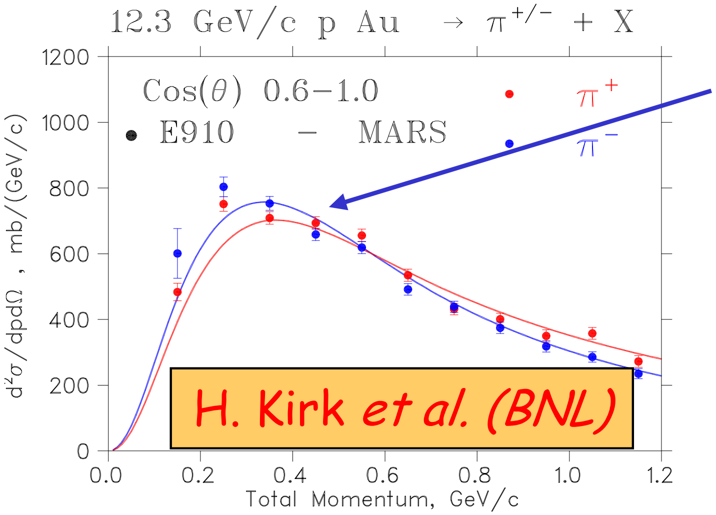
$\Rightarrow$Beam dump (mercury pool) out of the way of secondary π's and μ's.


R. Palmer (BNL)

Pion Production Facts from Experiment and Simulation

proton Au Interactions

BNL E910:

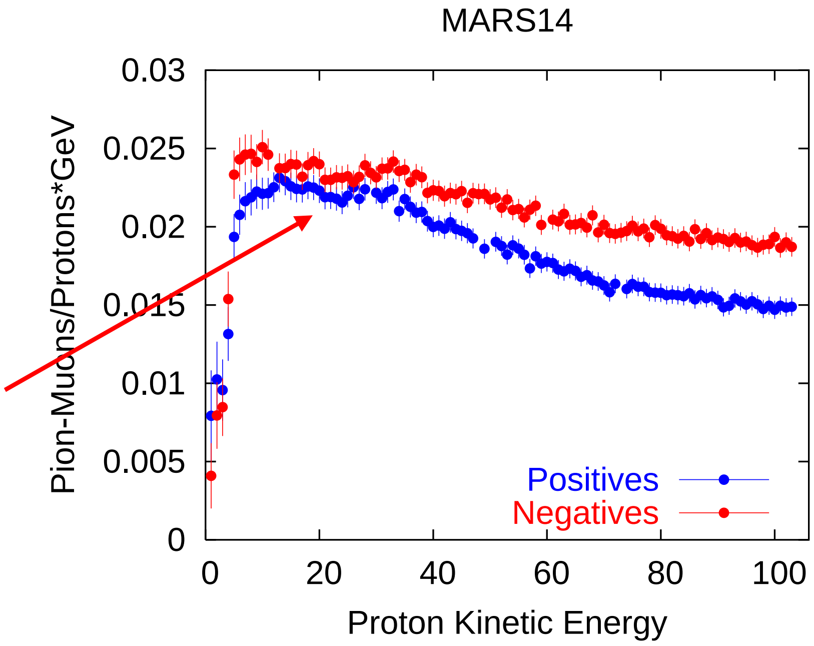


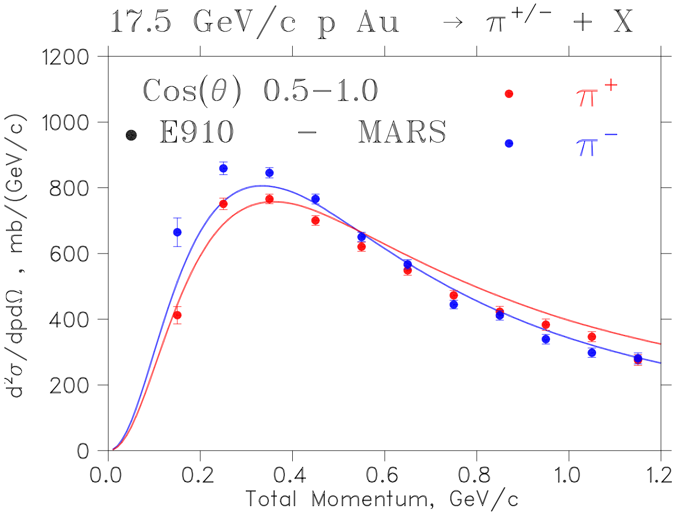
H. Kirk *et al.* (BNL)

Pion production peaks at around 300 MeV/c.

Pion production per megawatt of protons has a broad maximum from 8 to 30 GeV.

H. Kirk (BNL)

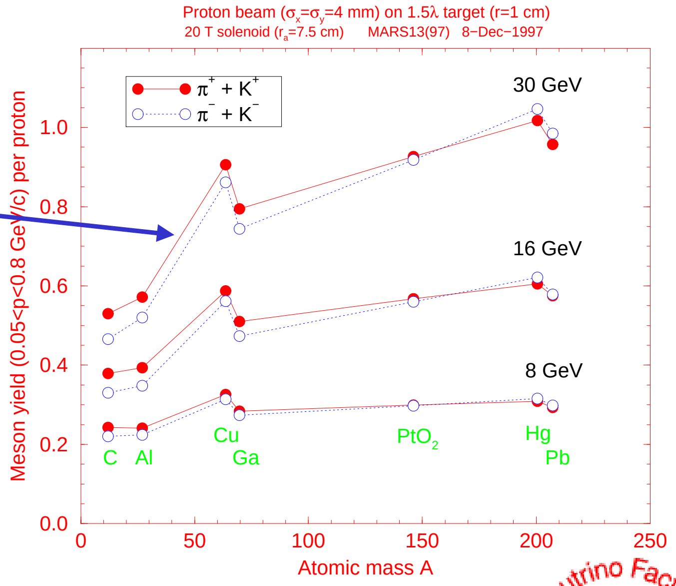




Pion production per megawatt of protons increases with atomic number of target (for E_p 8-30 GeV).

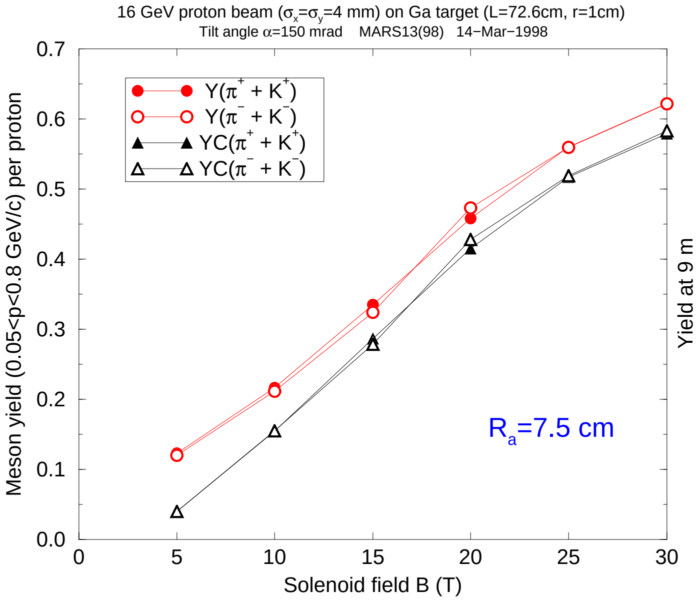
⇒ Hg or Pb-Bi target.

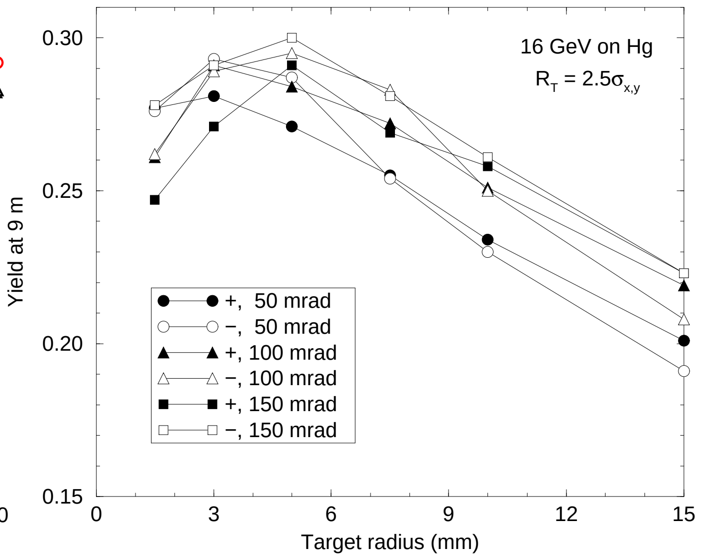
N. Mokhov (FNAL)

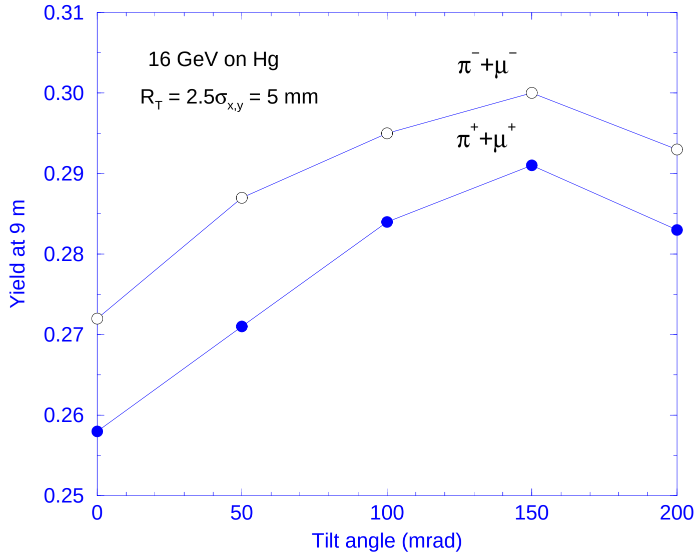


Maximizing Pion Production

MARS: N. Mokhov (FNAL)







Pion capture improved by use of high-field solenoid magnet.

Pion capture maximized by use of target of ≈ 5 mm radius.

Pion capture maximized by tilting beam/target by ≈ 150 mrad to magnetic axis.

Target Survival

Plausible that a new “conventional” graphite target could survive pulsed-beam-induced stresses at 2 MW.

Graphite target should be in helium atmosphere to avoid rapid destruction by sublimation, $\Rightarrow$ Cool target by helium gas flow.

Radiation damage will require target replacement $\approx$ monthly(?).

Graphite target less and less plausible beyond 2 MW.

Secondary particle collection favors shorter target, $\Rightarrow$ High-Z material.

High-Z targets for > 2 MW should be replaced every pulse!

$\Rightarrow$ Flowing liquid target: mercury, lead-bismuth, ...}

Pulsed beam + liquid in pipe $\Rightarrow$ Destruction of pipe by cavitation bubbles, $\Rightarrow$ Use free liquid jet.}

Free liquid metal jets are stabilized by a strong longitudinal magnetic field.

Strong solenoid field around target favorable for collection of low-energy secondaries, as needed for ν Factory and Muon Collider.}

$\Rightarrow$ High-power liquid jet target R&D over last 10 years, sponsored by the Neutrino Factory and Muon Collider Collaboration.

Thermal Issues for Solid Targets, I

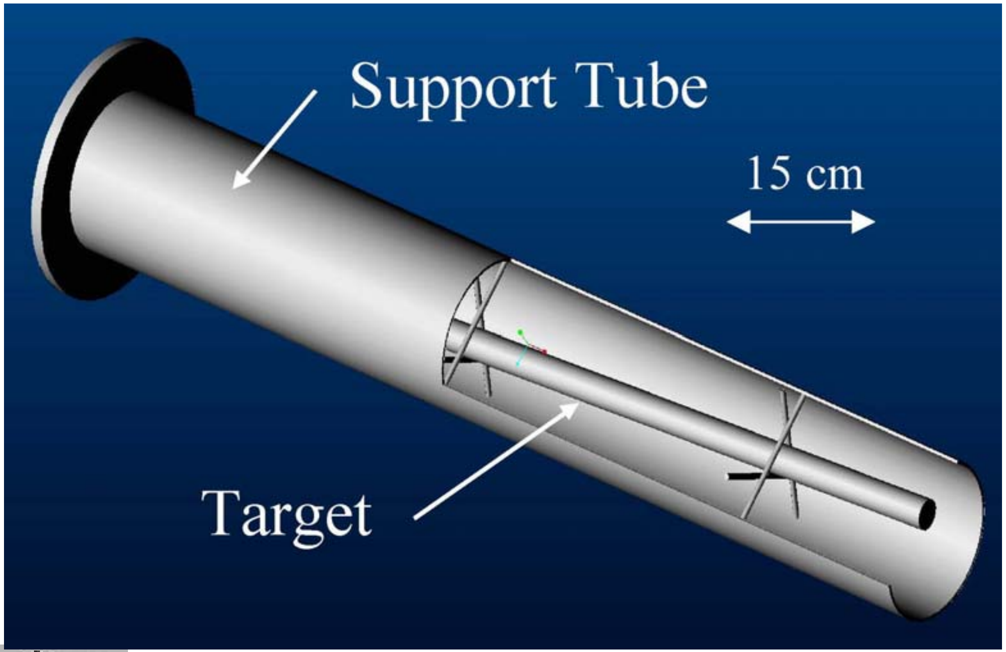
The quest for efficient capture of secondary pions precludes traditional schemes to cool a solid target by a liquid. (Absorption by plumbing; cavitation of liquid.)

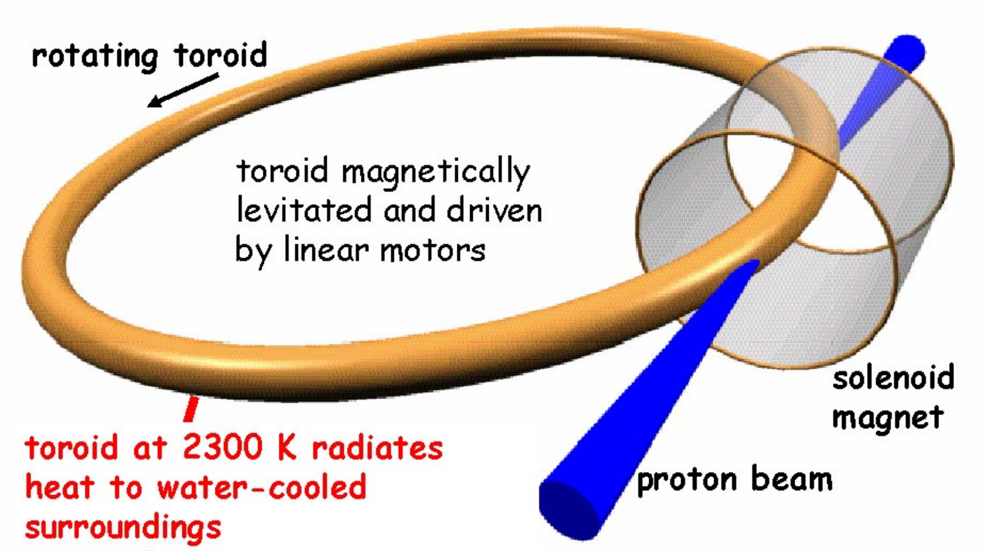
A solid, radiation-cooled stationary target in a 4-MW beam will equilibrate at about 2500 C.
⇒ Carbon is only candidate for this type of target.

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

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

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

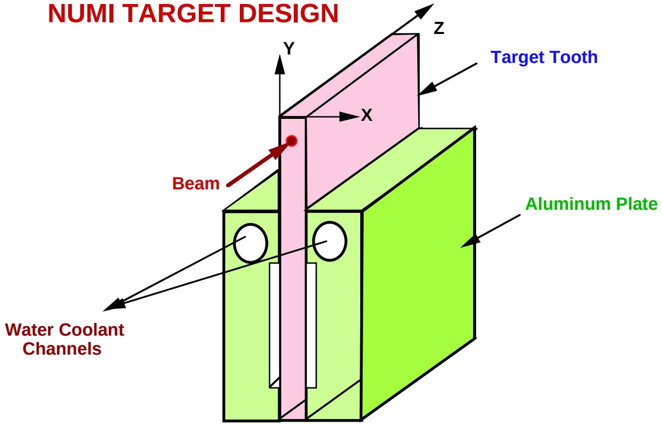
If solid targets crack under singles pulses of 60 J/g, then safe up to only 0.4 MW beam power!

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

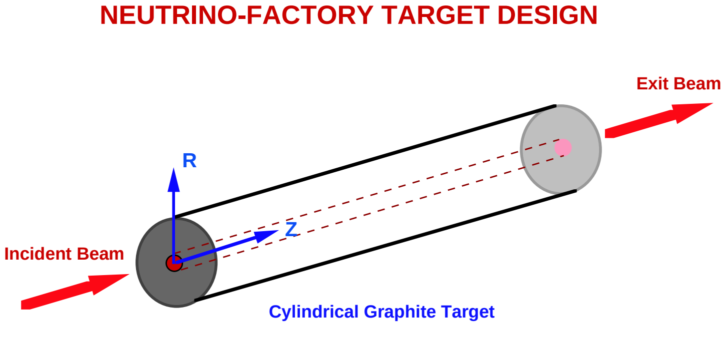
Ni target in FNAL $\overline{p}$ source: "damaged but not failed" peak energy deposition of 1500 J/g.

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

NUMI TARGET DESIGN



NEUTRINO-FACTORY TARGET DESIGN



HASSANEIN (ANL)

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: ≈ 12 weeks (?) at 1 MW.

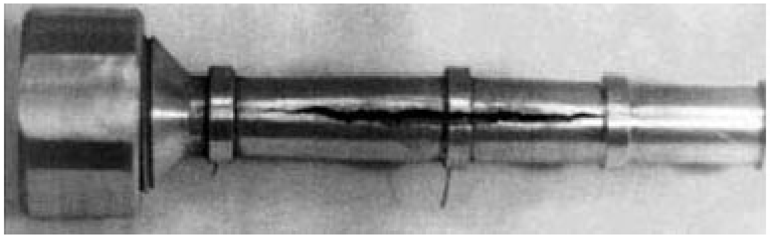
⇒ Carbon target is baseline design for most neutrino superbeams.}

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

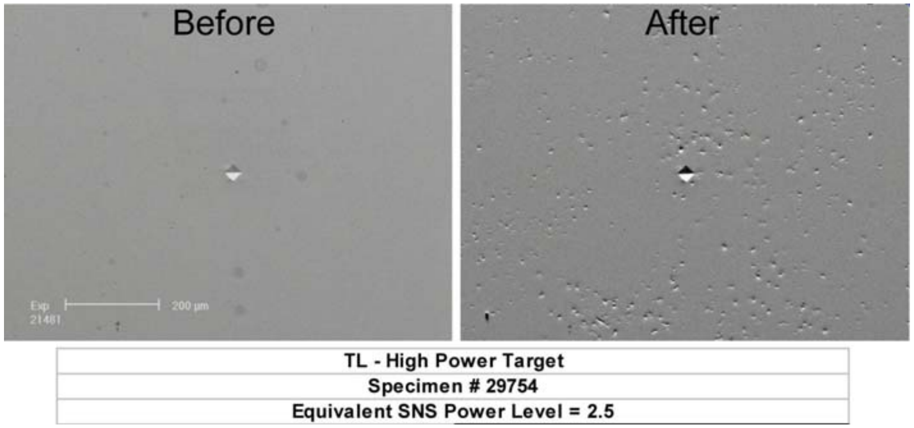
Beam-Induced Cavitation in Liquids Can Break Pipes

ISOLDE:

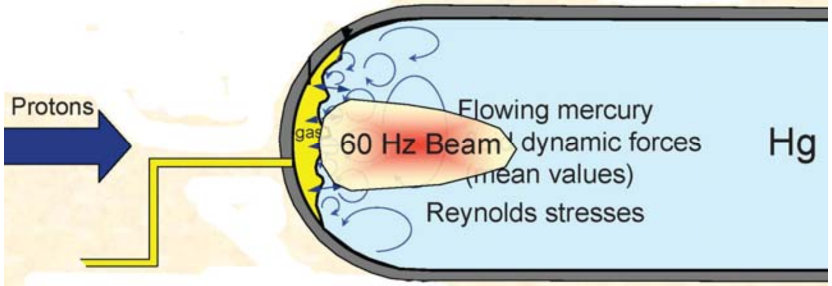
Hg in a pipe (BINP):



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



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



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.)

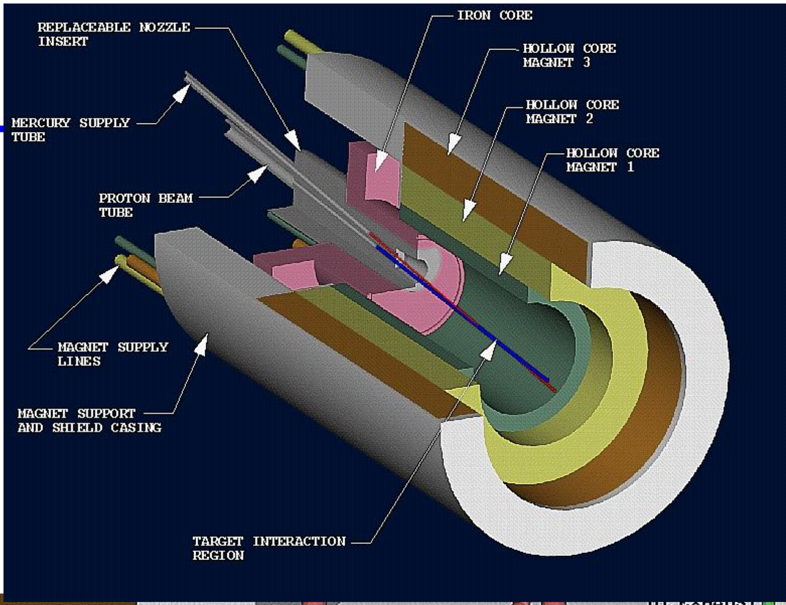
⇒ Use free liquid jet if possible.

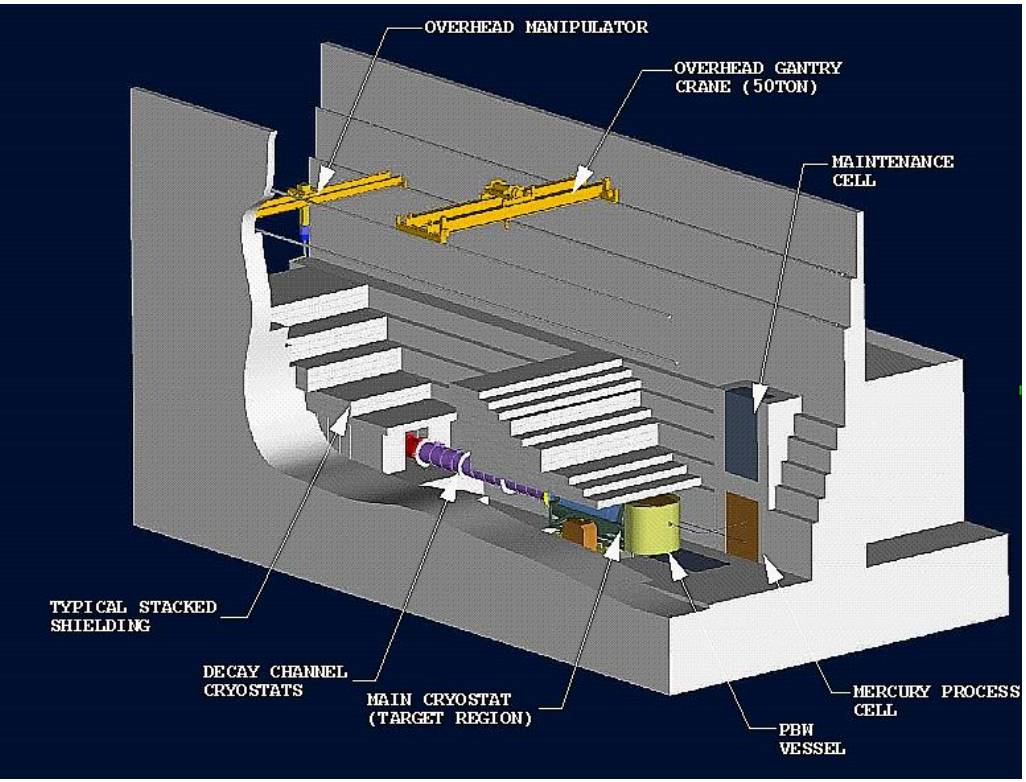
Neutrino Factory Feasibility Study 2

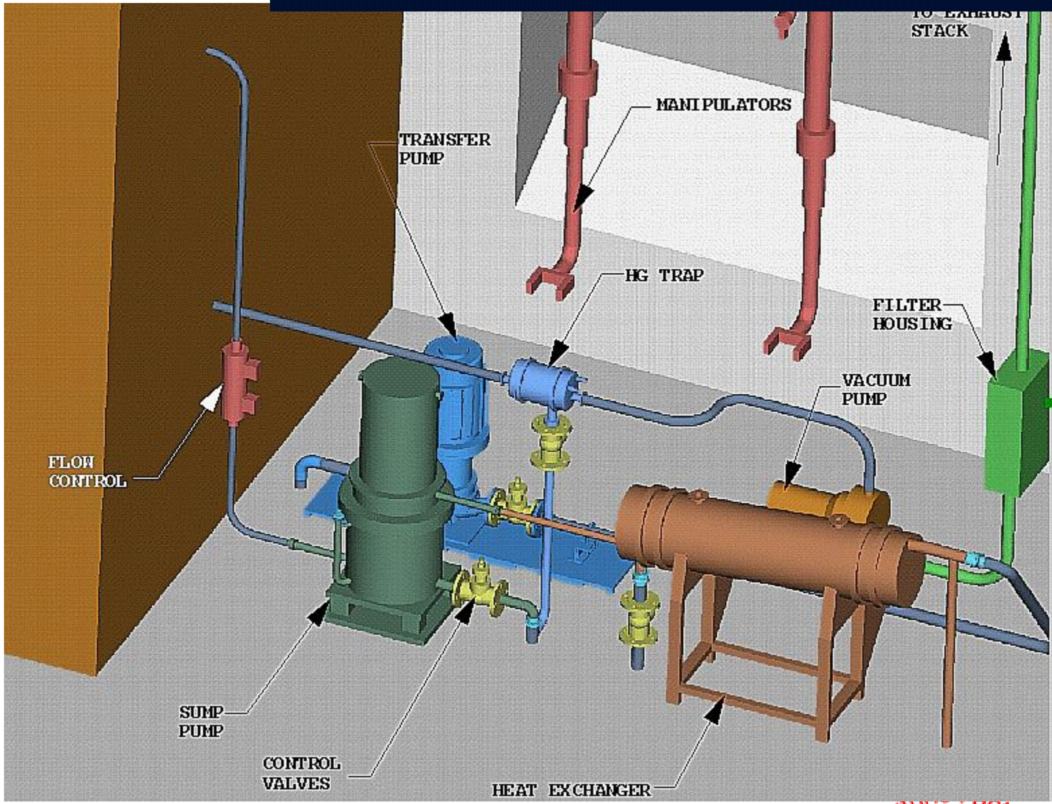
Infrastructure studies based on SNS mercury target experience.

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.

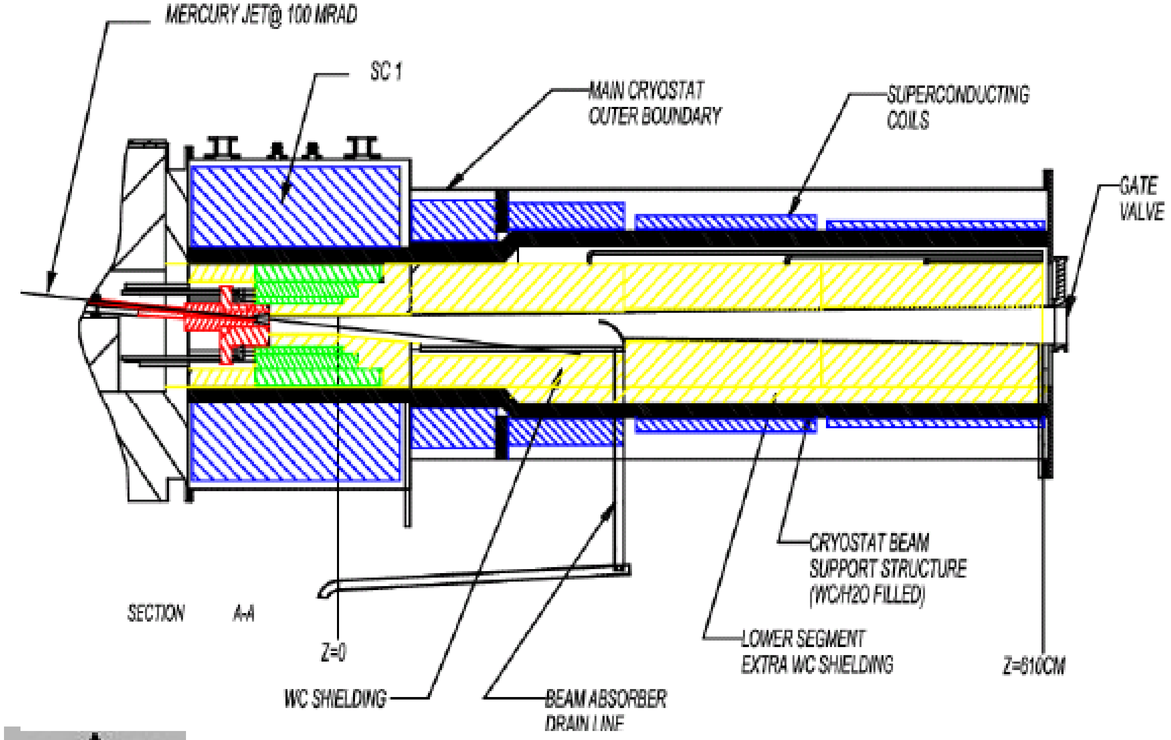
4-MW, 24-GeV, 50-Hz proton beam (2×10^{13} *p*/pulse) at 67 mrad to magnetic axis.

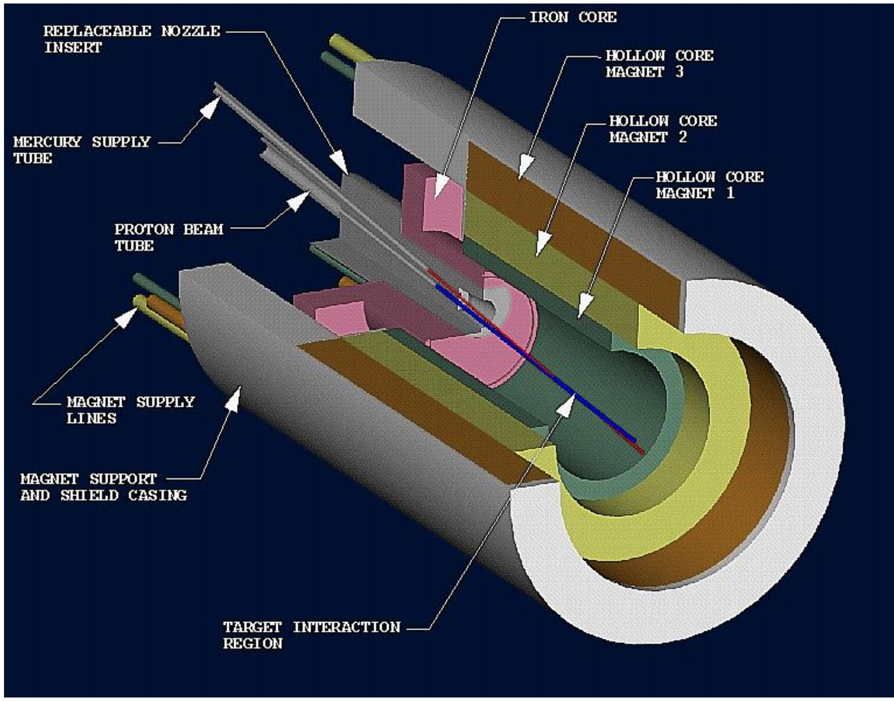
Iron plug at upstream end of capture solenoid to reduce fringe-field effect on shape of free jet.

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

Issues: Distortion of jet by magnetic field.

Disruption of jet by proton beam.



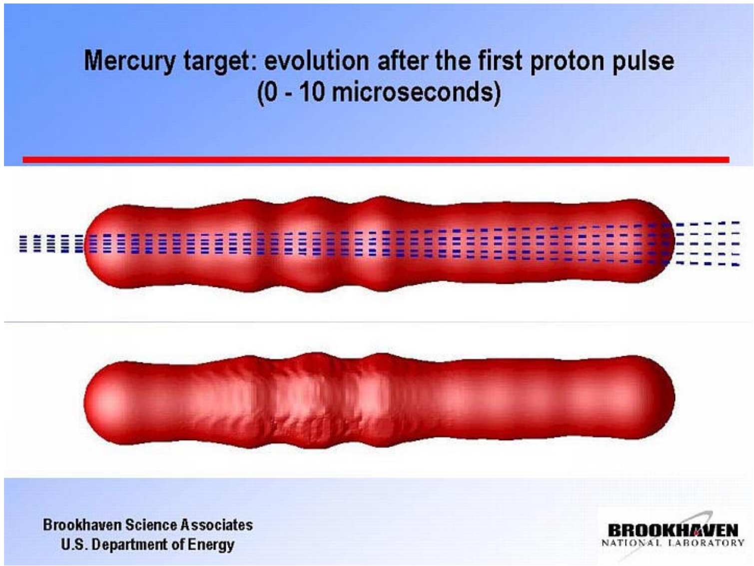


Beam-Induced Effects on a Free Liquid Jet

Beam energy deposition may disperse the jet.

FRONTIER simulation predicts breakup via filamentation on mm scale:

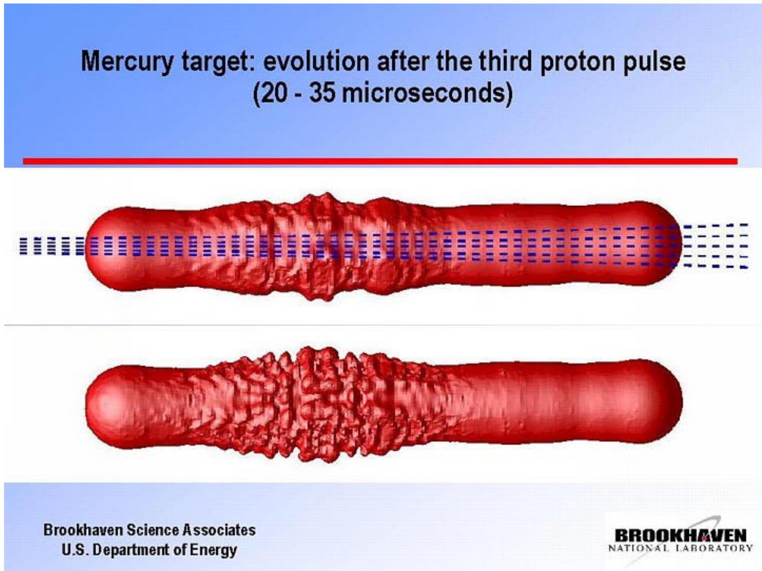
R. Samulyak (BNL)



Mercury target: evolution after the first proton pulse
(0 - 10 microseconds)

Brookhaven Science Associates
U.S. Department of Energy

BROOKHAVEN NATIONAL LABORATORY



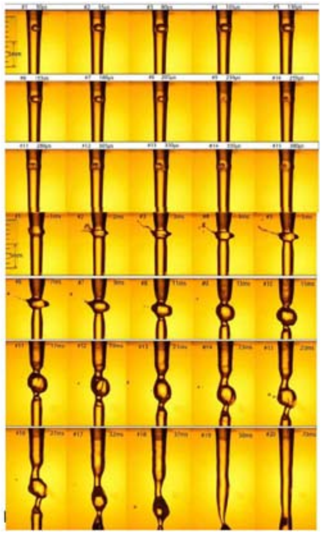
Mercury target: evolution after the third proton pulse
(20 - 35 microseconds)

Brookhaven Science Associates
U.S. Department of Energy

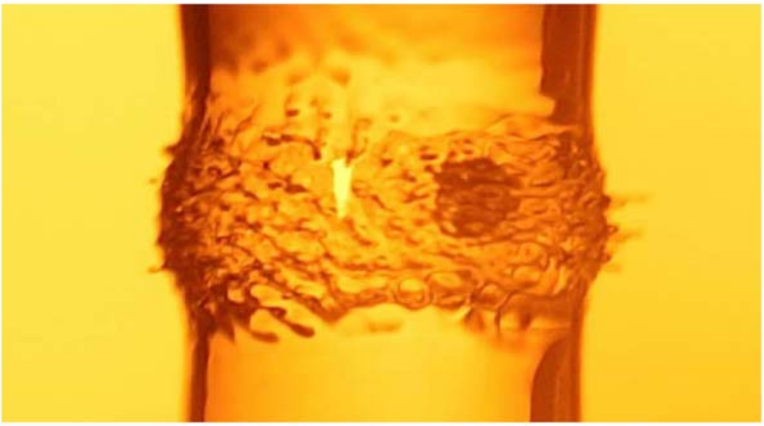
BROOKHAVEN NATIONAL LABORATORY

Laser-induced breakup of a water jet:

J. Lettry (CERN)

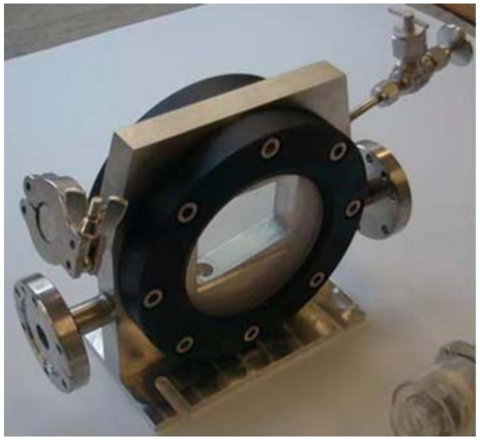


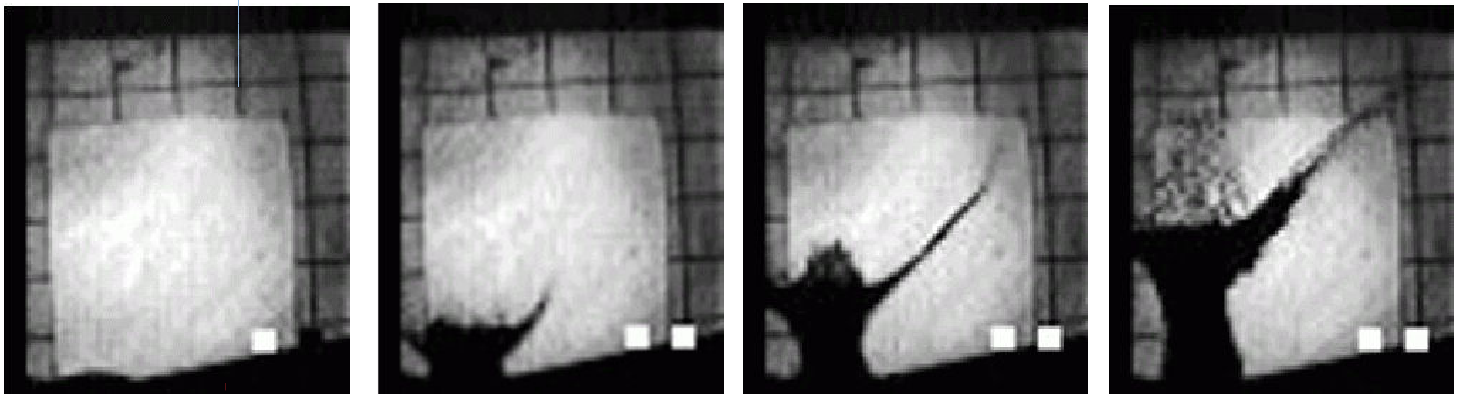
Water jet ripples generated by a 8 mJ Laser cavitation bubble



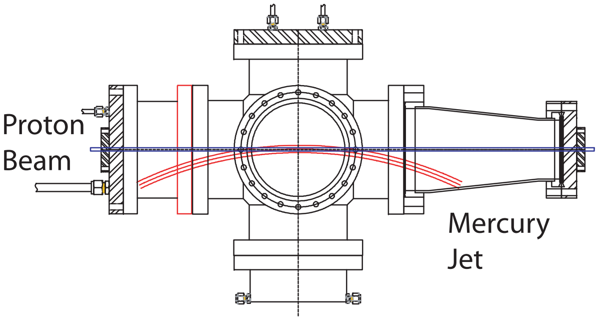
Mercury Target Tests (BNL-CERN, 2001-2002)

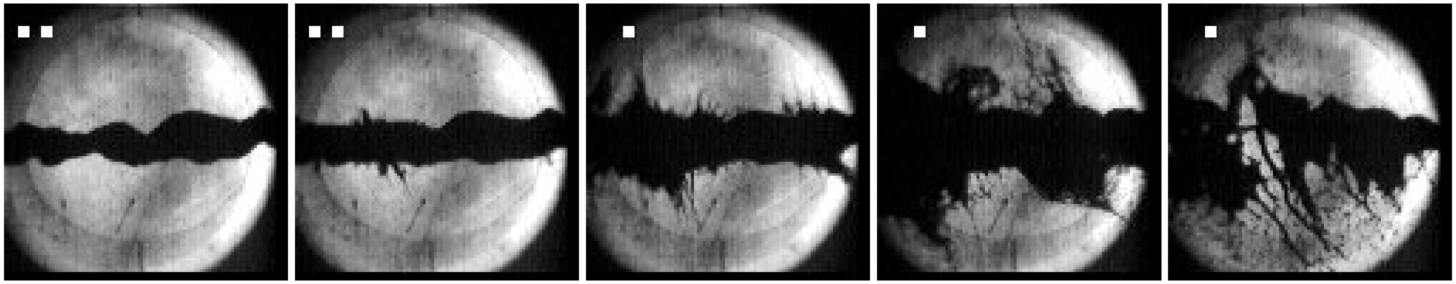
Mercury thimble:





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 ≈ 40 μs after beam,

⇒ After several bounces of waves, OR v_{sound} very low.

Model:

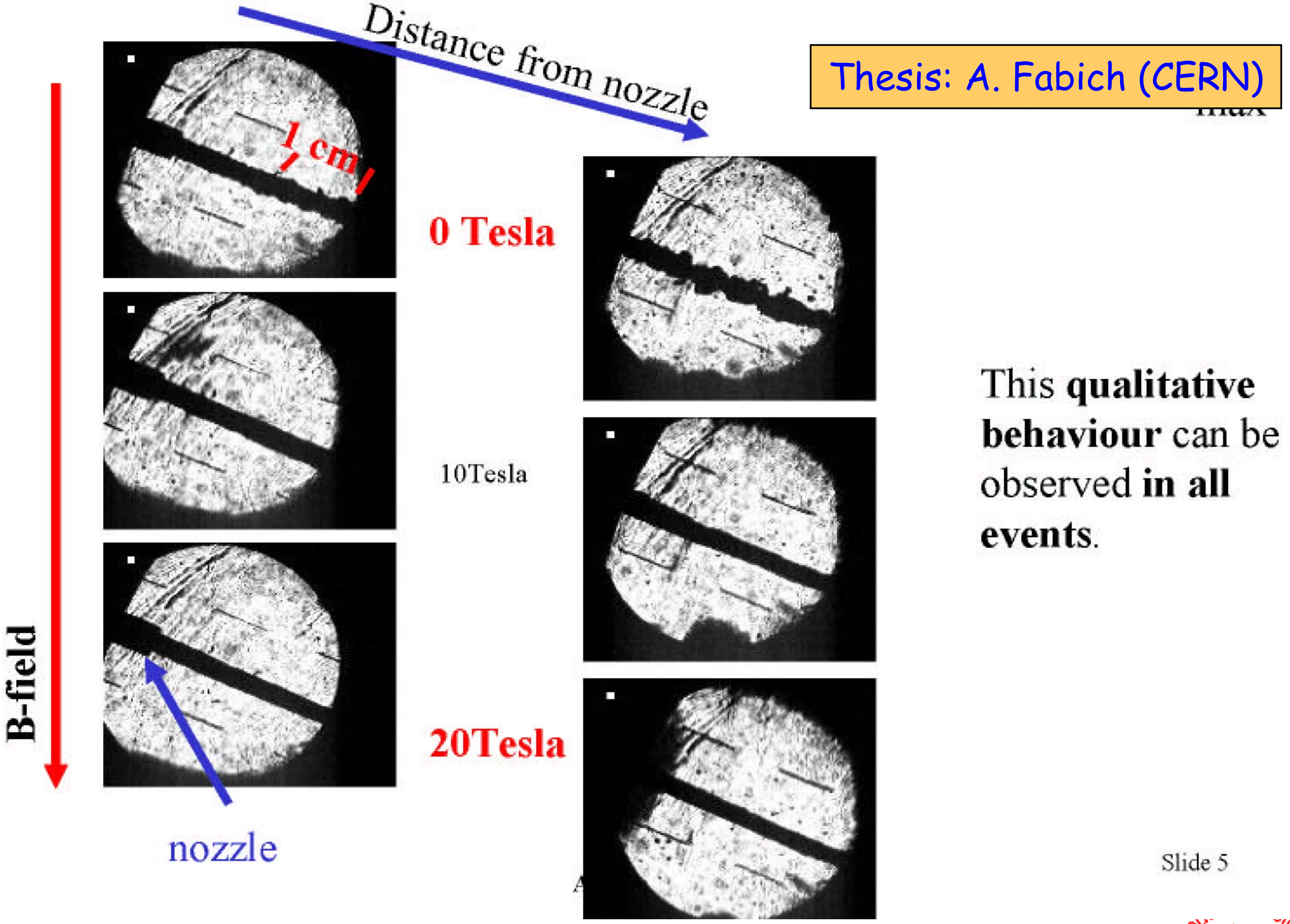
$$v_{\text{dispersal}} = \frac{\Delta r}{\Delta t} = \frac{r\alpha\Delta T}{r / v_{\text{sound}}} = \frac{\alpha U}{C} v_{\text{sound}} \approx 50\ m/s$$

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**.

Magnetic Damping of Jet Filamentation

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

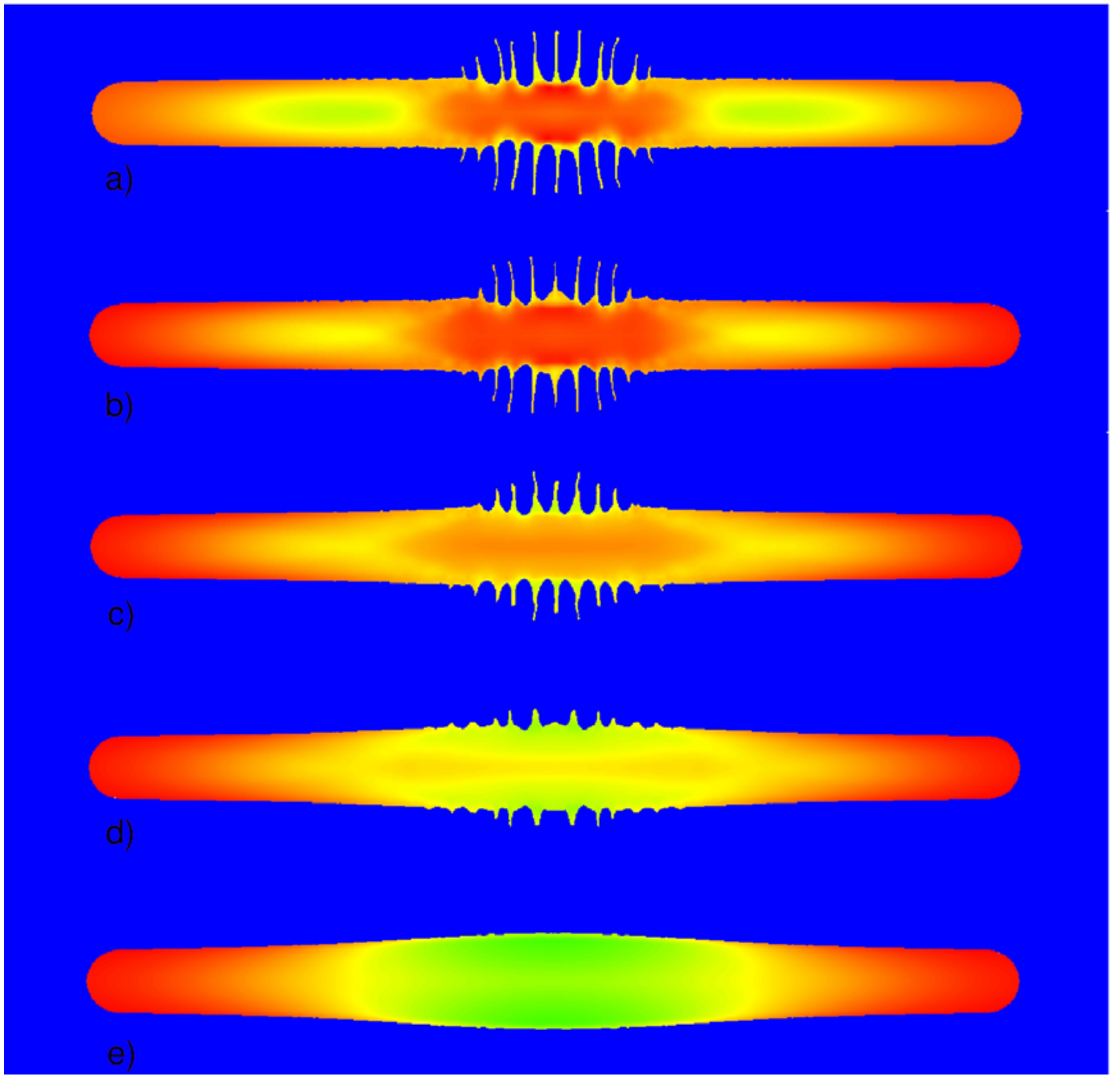
0 T

2 T

4 T

6 T

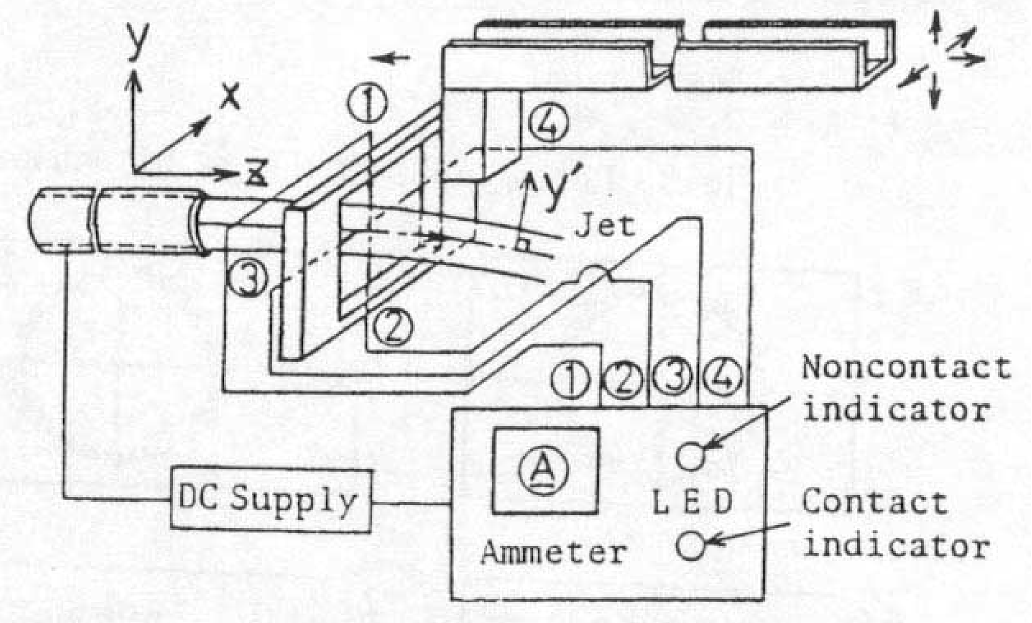
10 T

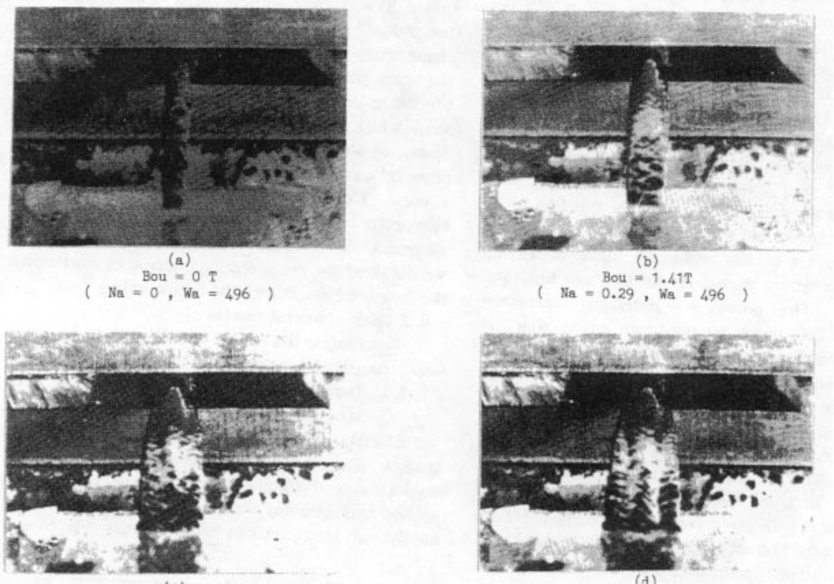


R. Samulyak (BNL)

Distortion of a Mercury Jet by a Transverse Magnetic Field

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





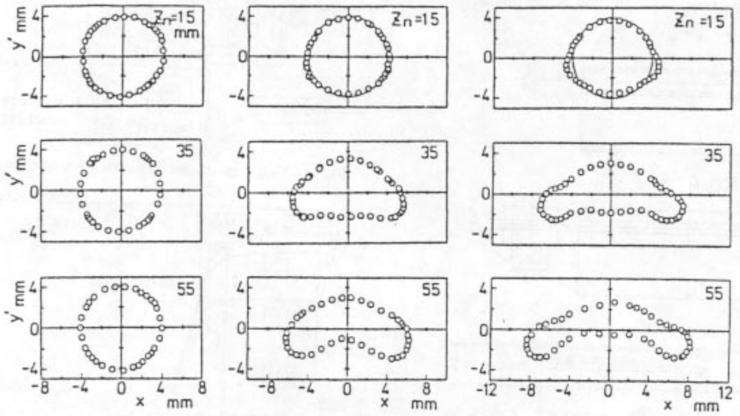
(a)
Bou = 0 T
(Na = 0 , Wa = 496)

(b)
Bou = 1.41T
(Na = 0.29 , Wa = 496)

(c)
Bou = 1.88T
(Na = 0.57 , Wa = 496)

(d)
Bou = 2.02T
(Na = 0.60 , Wa = 496)

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



(a)
Bou = 0 T
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Bou = 1.41 T
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(c)
Bou = 1.88 T
(Na = 0.57 , Wa = 496)

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

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.

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).

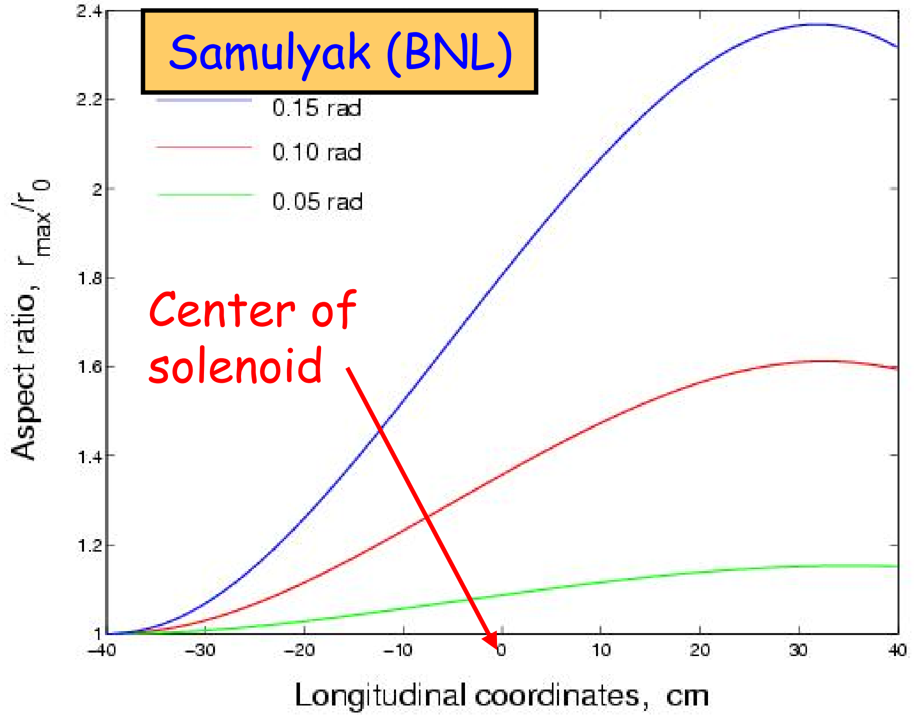
Simulations by Samulyak and by Morley confirm this behavior.

⇒Reduce angle of jet to magnetic axis.

⇒Place nozzle close to peak field region.

⇒Reduce field nonuniformity.

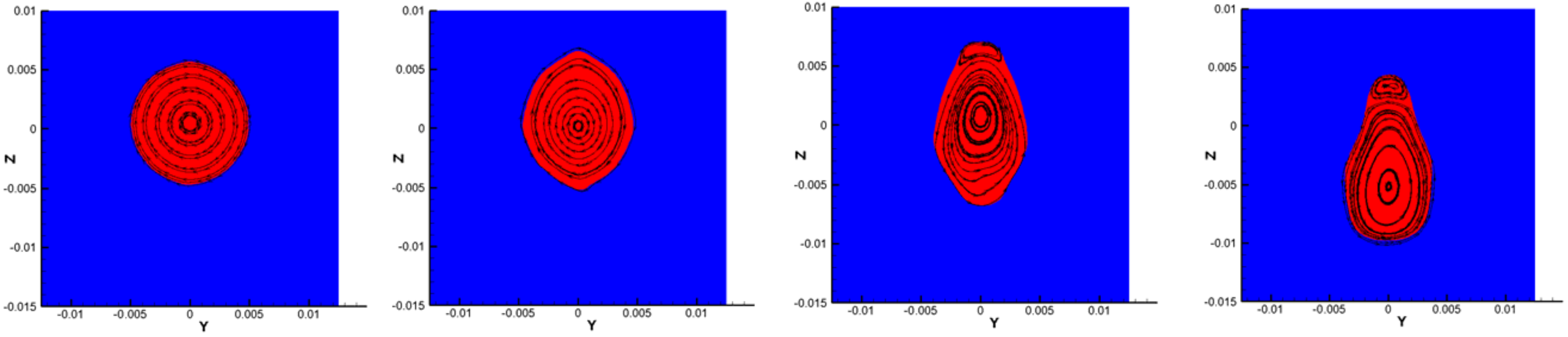
Study 2: Nozzle in iron plug that smoothes upstream field.



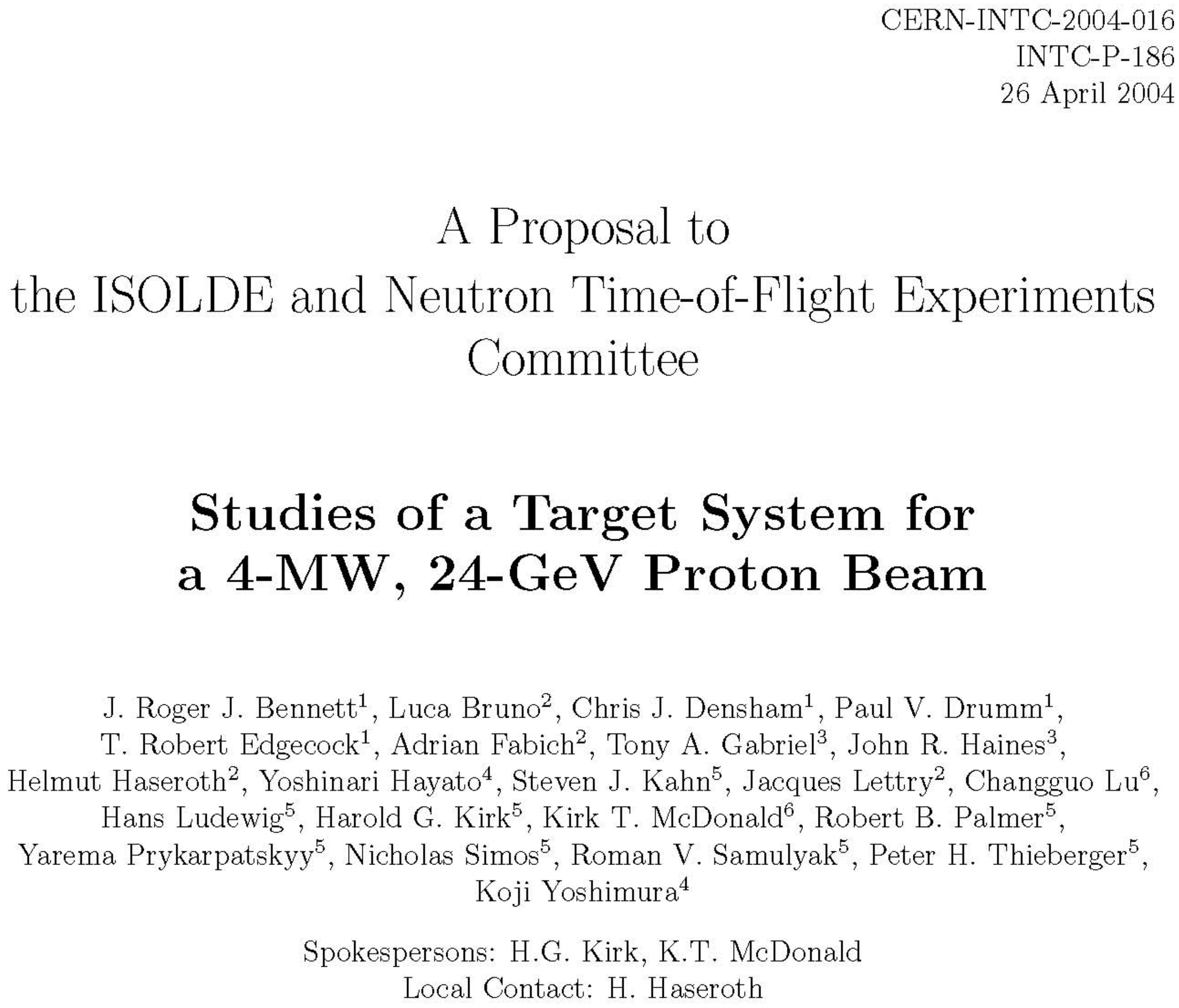
Samulyak (BNL)

Center of solenoid

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

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

Proposed: April 2004

Approved: April 2005

Formal name nToF11

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:

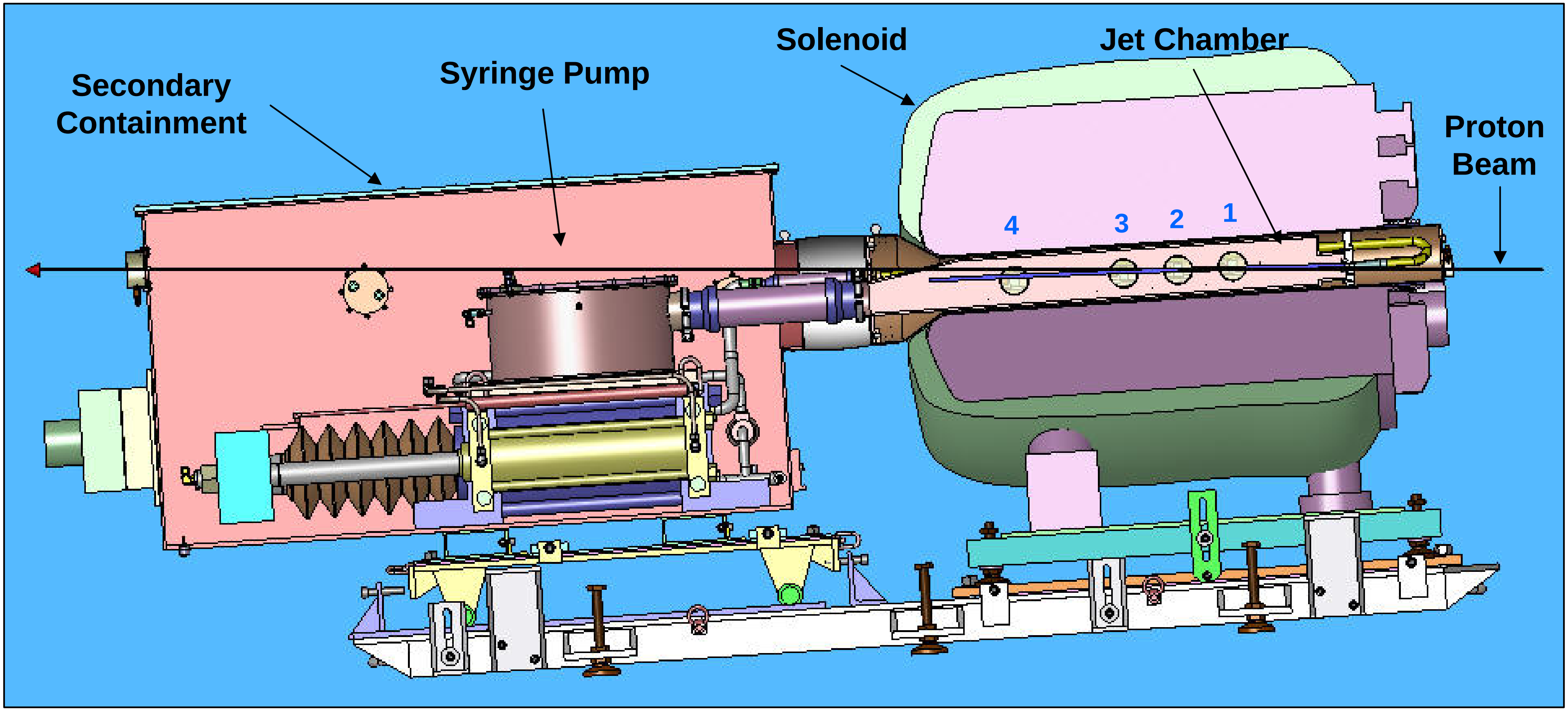
- 14 and 24-GeV Proton beam pulses, up to 16 bunches/pulse, up to 3.5×10^{12} p/bunch.
- σ_r of proton bunch = 1.2 mm, proton beam axis at 67 mrad to magnet axis.
- Mercury jet of 1 cm diameter, v = 20 m/s, jet axis at 33 mrad to magnet axis.
- ⇒ Each proton intercepted the Hg jet over 30 cm = 2 interaction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

Every beam pulse is a separate experiment.

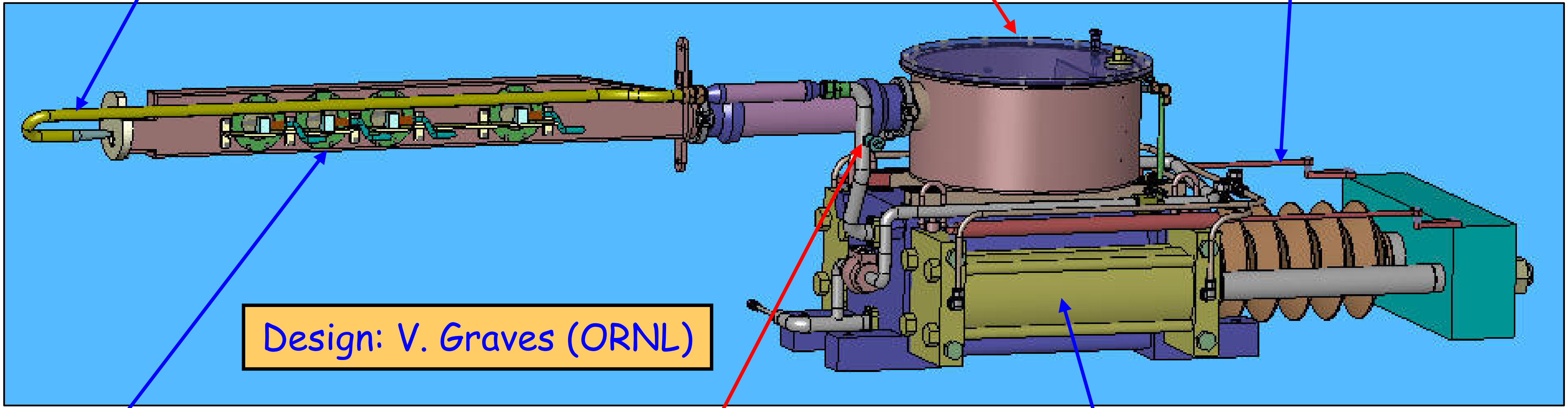
- ≈ 360 Beam pulses in total.
- Vary bunch intensity, bunch spacing, no. of bunches.
- Vary magnetic field strength.
- Vary beam-jet alignment, beam spot size.

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.

Design: V. Graves (ORNL)

Optical diagnostics mounted on outside of the primary vessel.

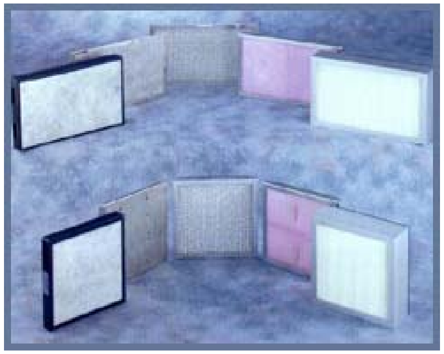
Pressure monitor of mercury supply pipe.

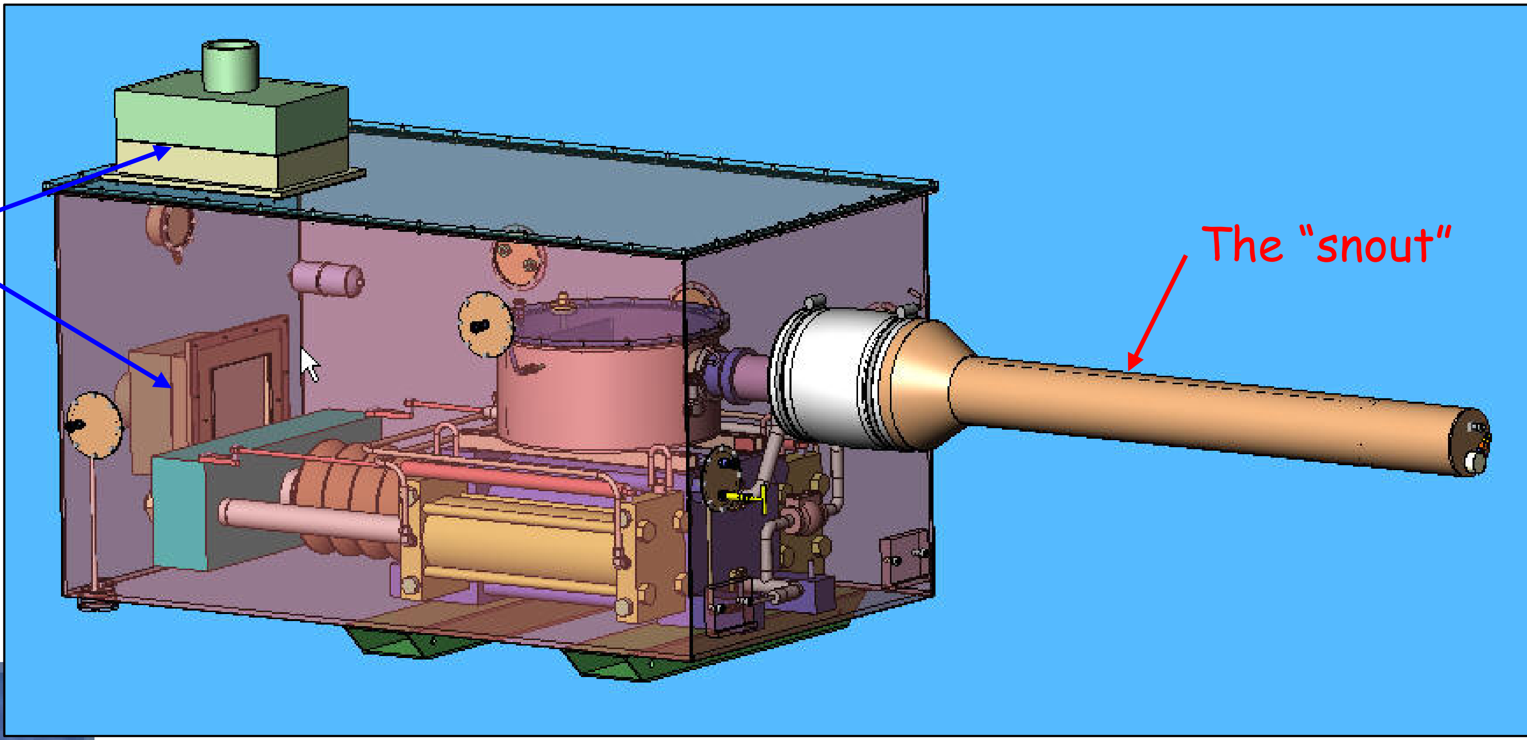
Giant syringe can produce a mercury jet for 15 s.

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

Secondary Containment of Mercury

Charcoal filters

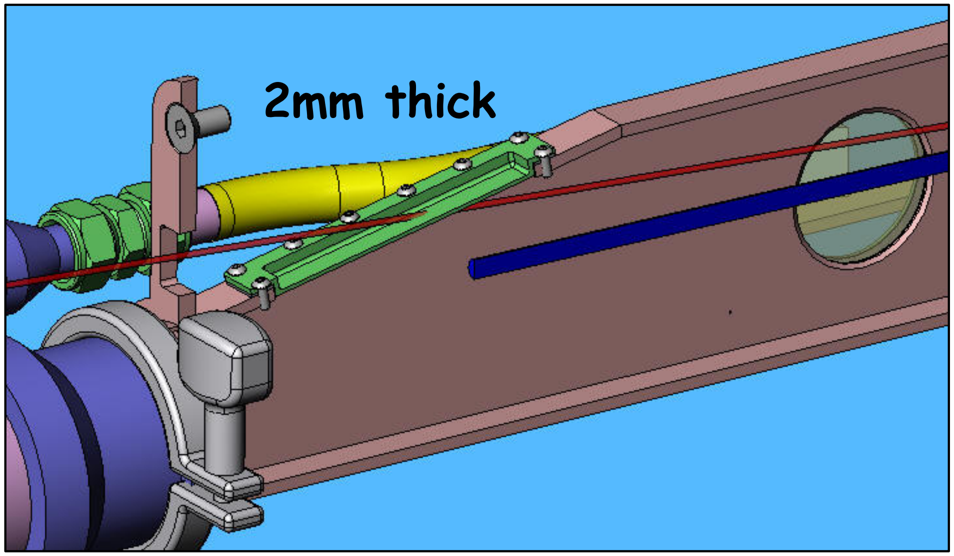


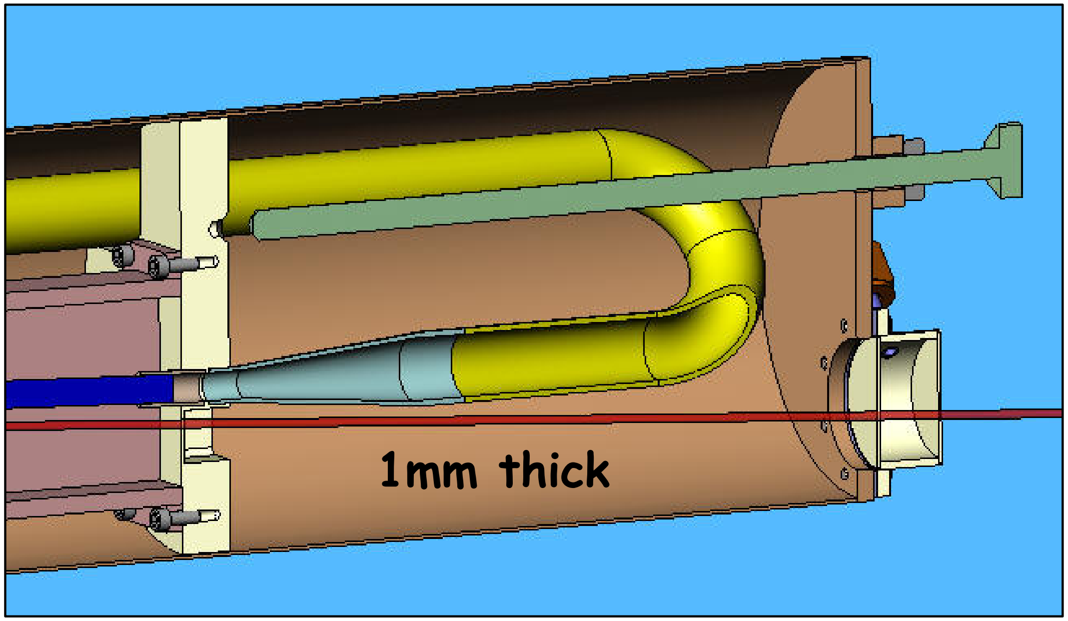


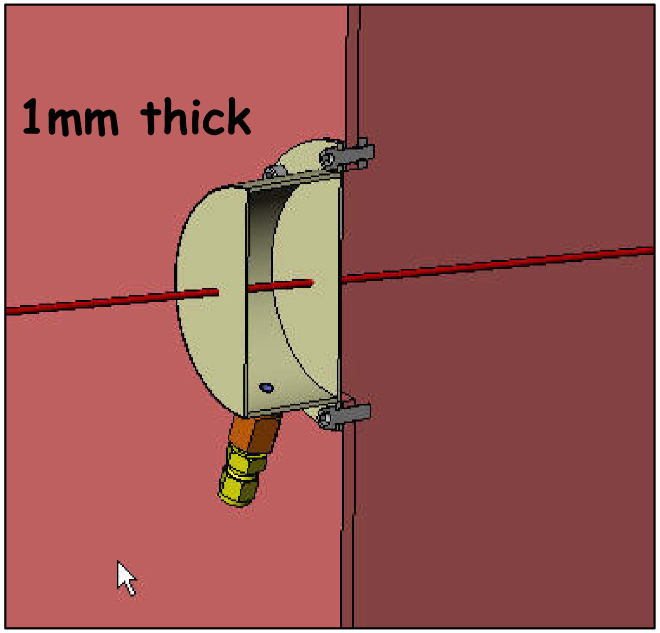
The secondary containment vessel was monitored for mercury vapor at all times with a VM3000 vapor monitor.

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





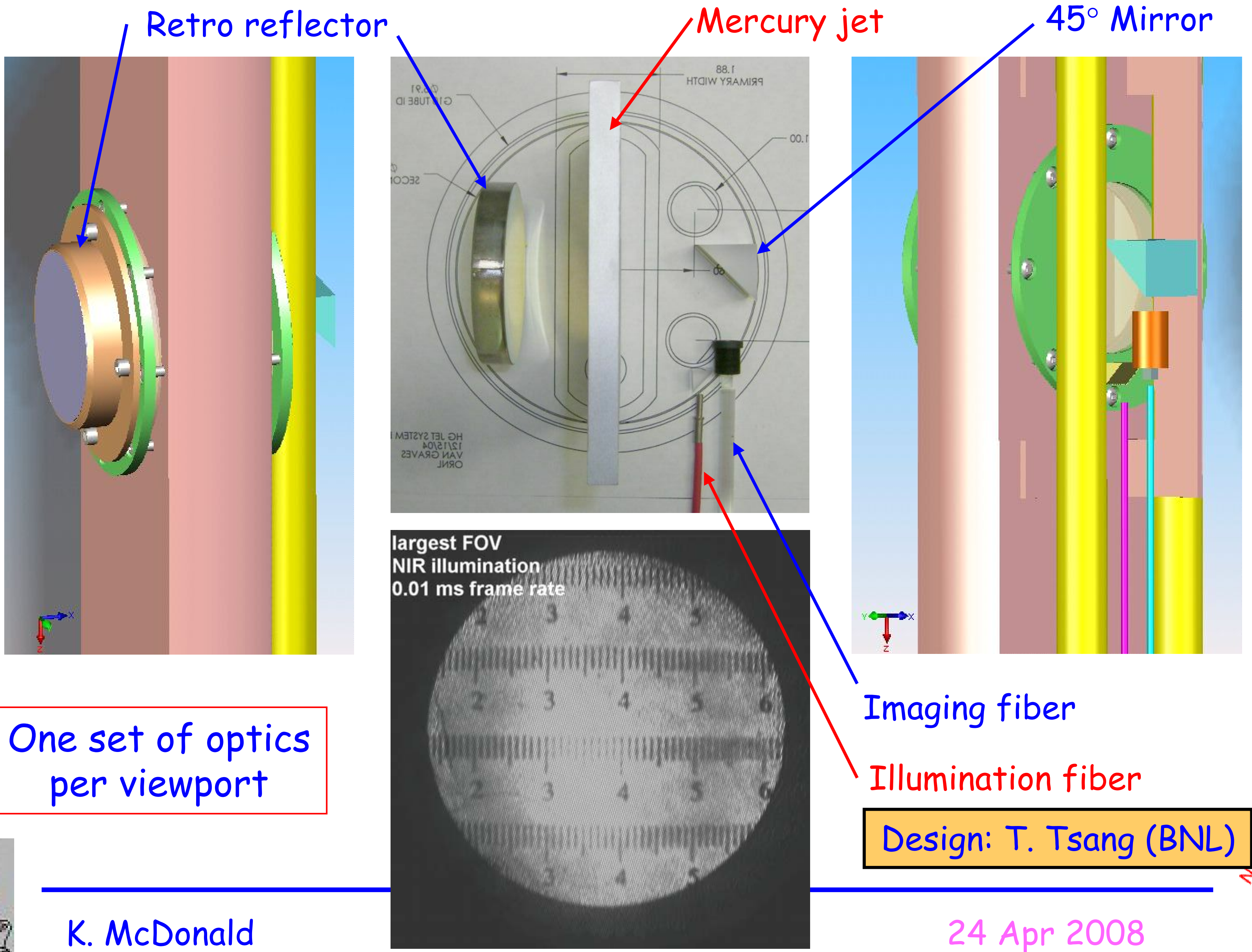


Windows made of Ti6Al4V alloy.

Single windows for primary containment, double windows for secondary.

Pressurize secondary windows, monitor to detect failure.

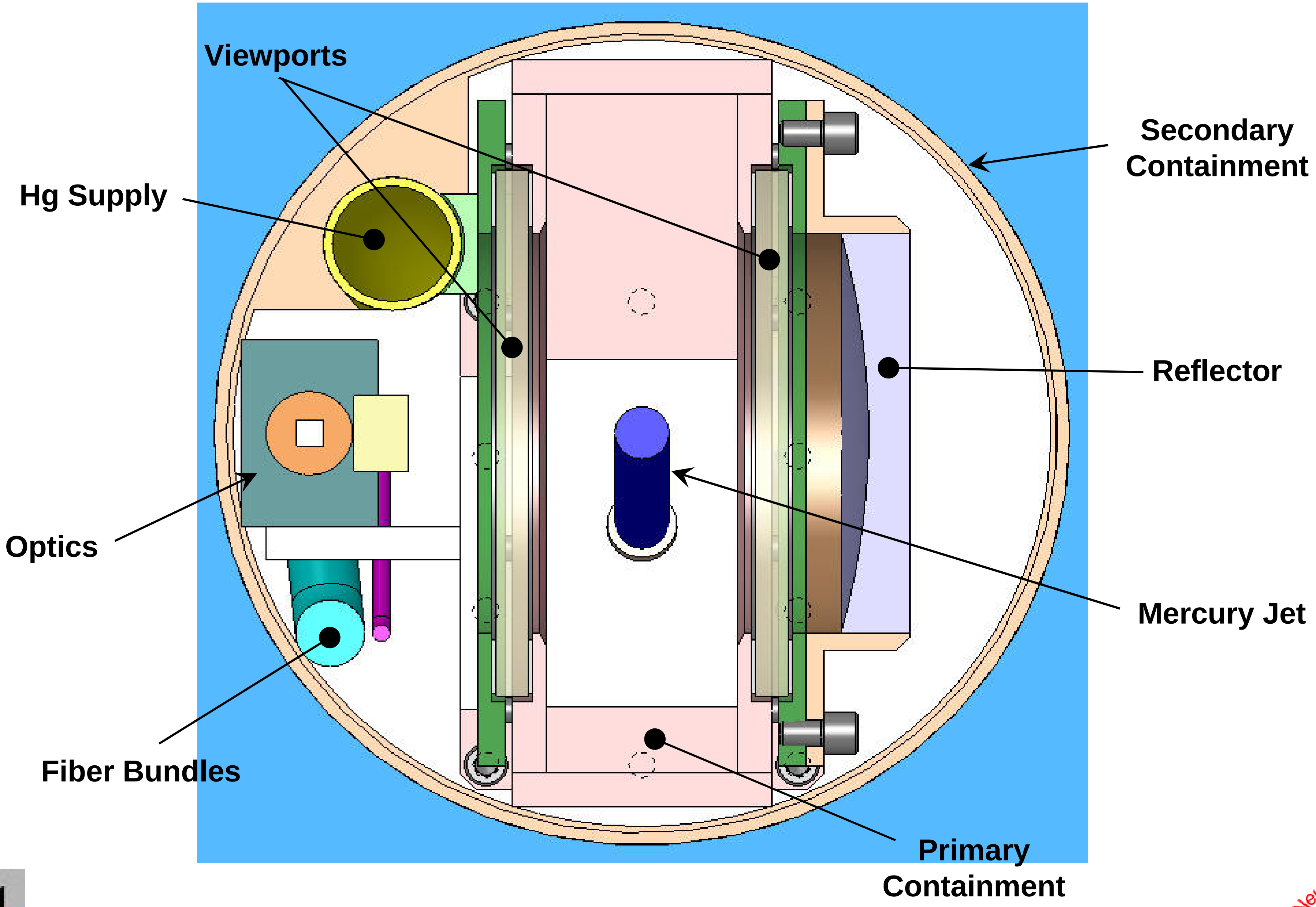
Optical Diagnostics via Fiberoptic Imaging



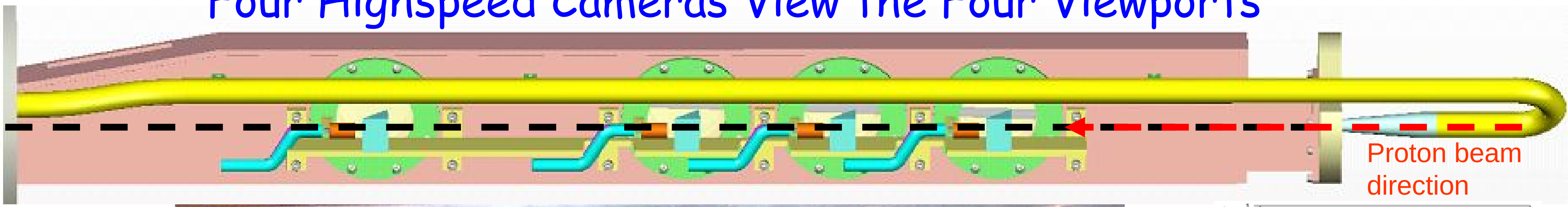
One set of optics per viewport

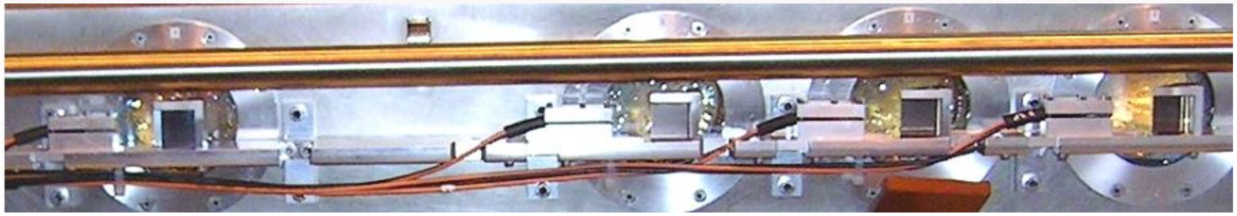
Design: T. Tsang (BNL)

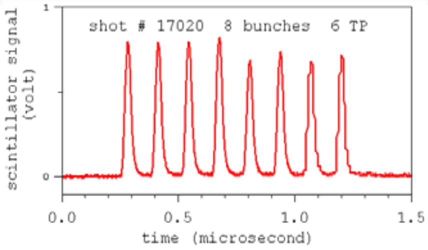
Section through the Primary Vessel at the Magnet Center



Four Highspeed Cameras View the Four Viewports



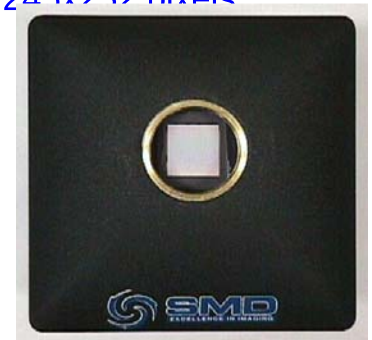




Viewport 4, Olympus
33 μs exposure
160x140 pixels

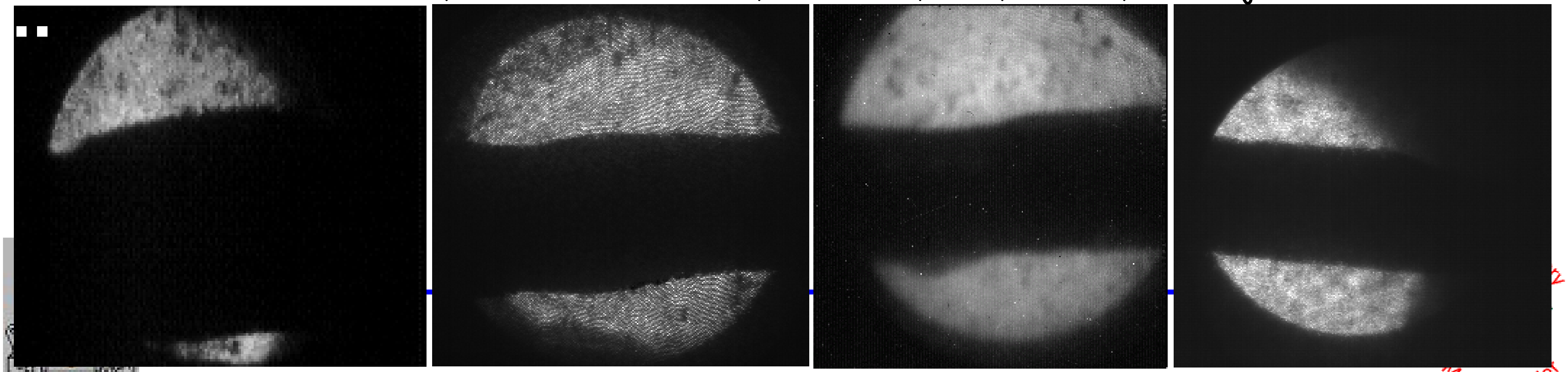
Viewport 3, FV Camera
6 μs exposure
260x250 pixels

Viewport 2, SMD Camera
0.15 μs exposure
245x252 pixels



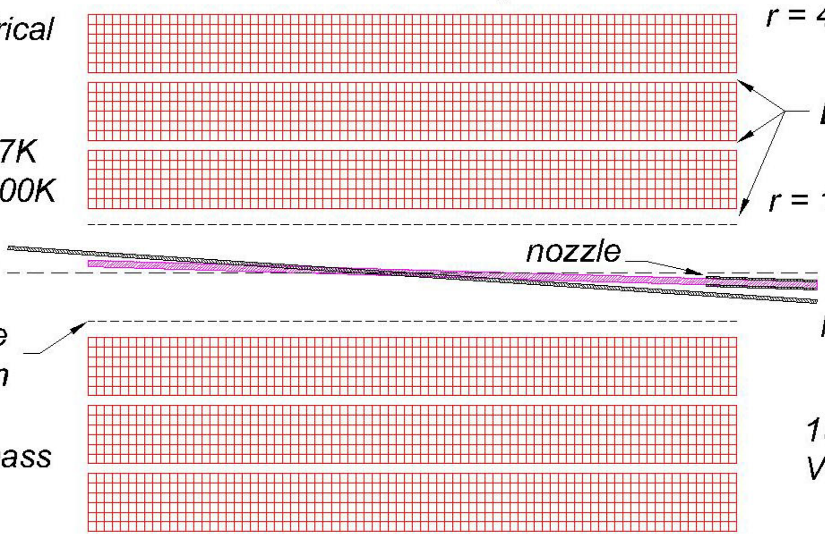
Viewport 1, FV Camera
6 μs exposure
260x250 pixels

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 = 0.06Ω@ 77K
R = 0.45Ω@ 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

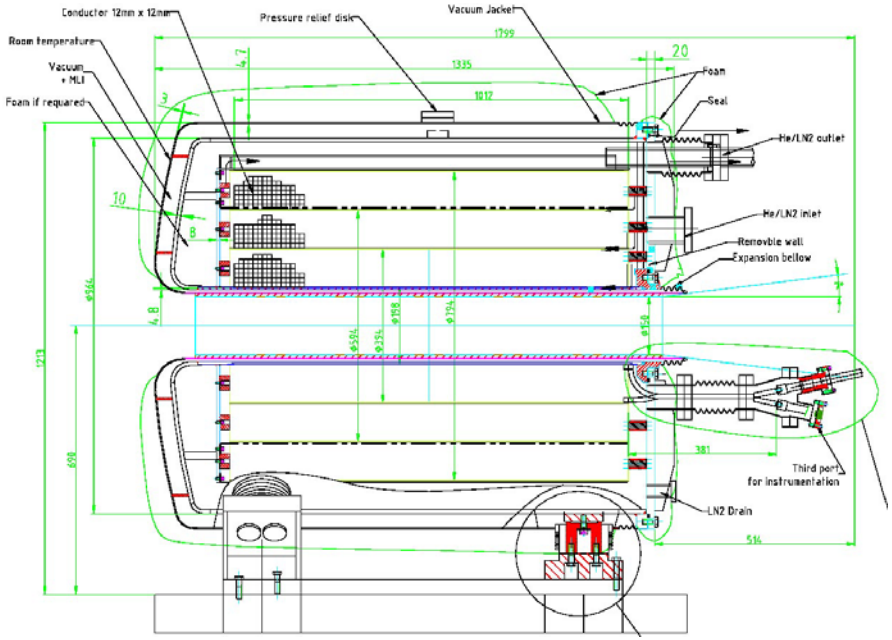
z = - 50 cm

z = 50 cm

Design: R. Weggel (BNL)

Engineering: P. Titus (MIT)

Fabrication: CVIP, Everson-Tesla

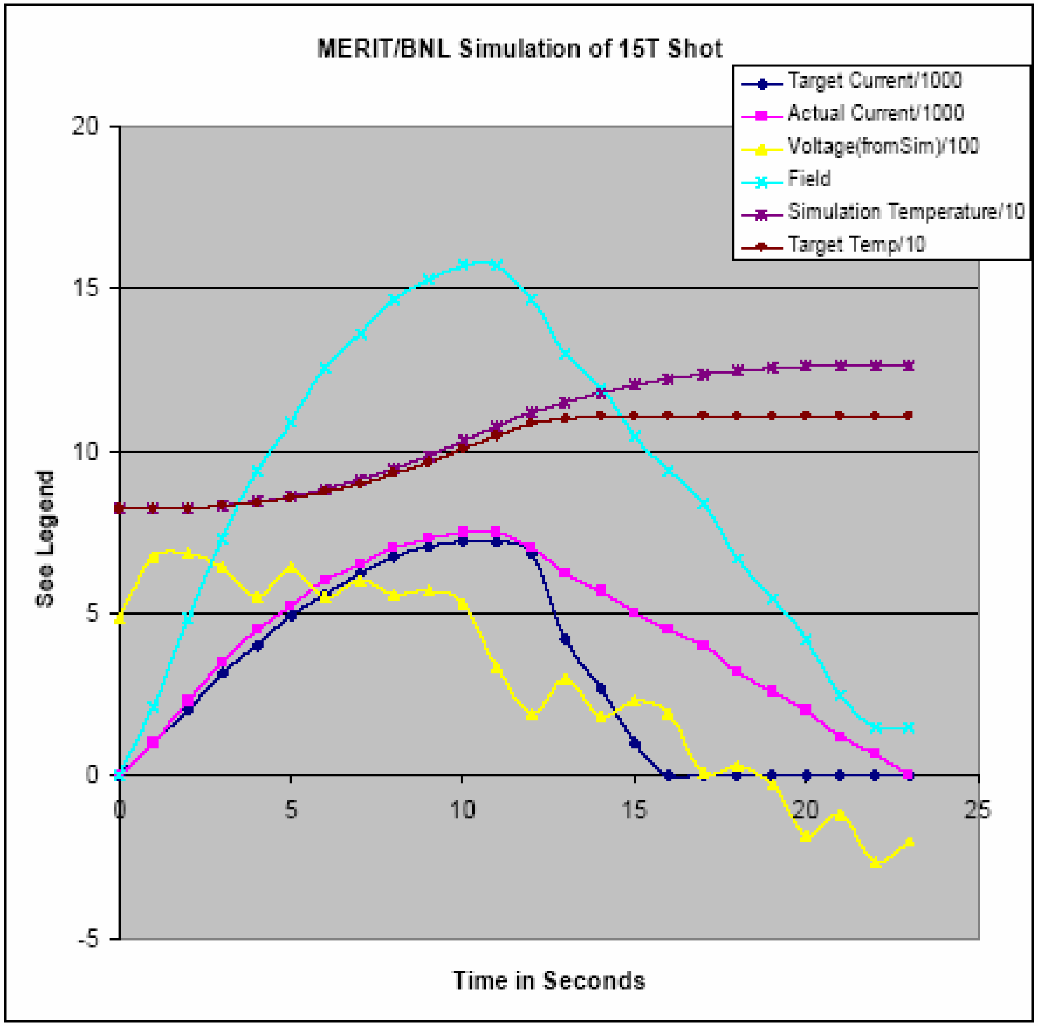


5 MW Power Supply

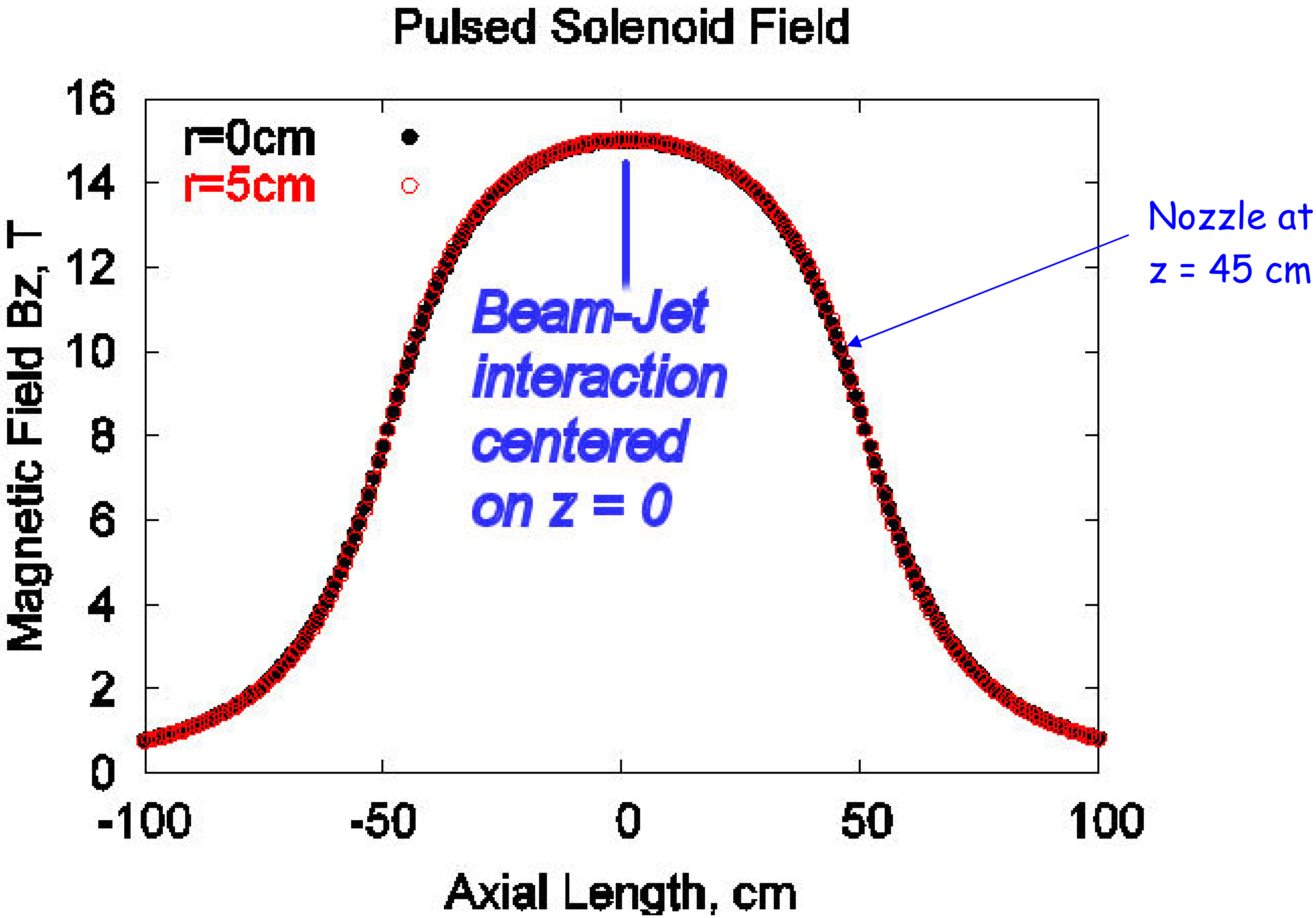
Recycled from the old SPS West Area extraction line.

30 MJ delivered during 15-s pulse.

⇒Magnet temperature rises from 80 to 110K.



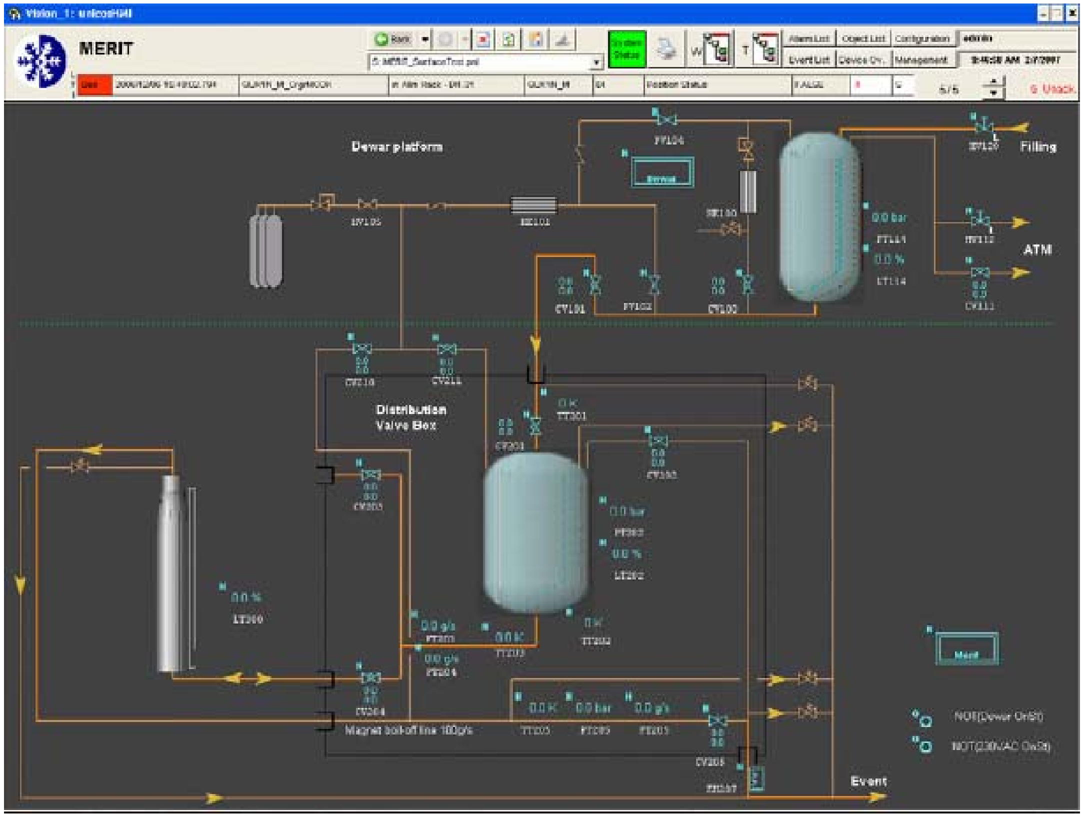
Magnetic Field Profile



Beam-Jet interaction centered on z = 0

Nozzle at z = 45 cm

LN_2 Cryogenic System



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

Fabrication: AES (UK)

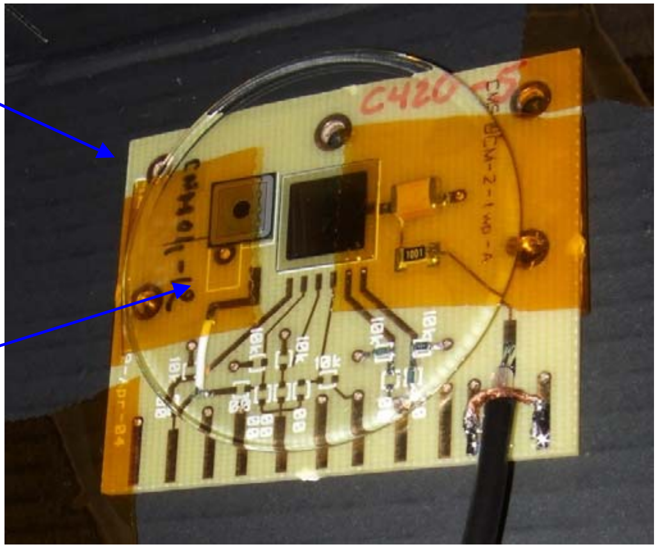
A 15-T pulse of the magnet deposited ≈ 30 MJ,
⇒ 30K increase in magnet temperature.

≈ 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

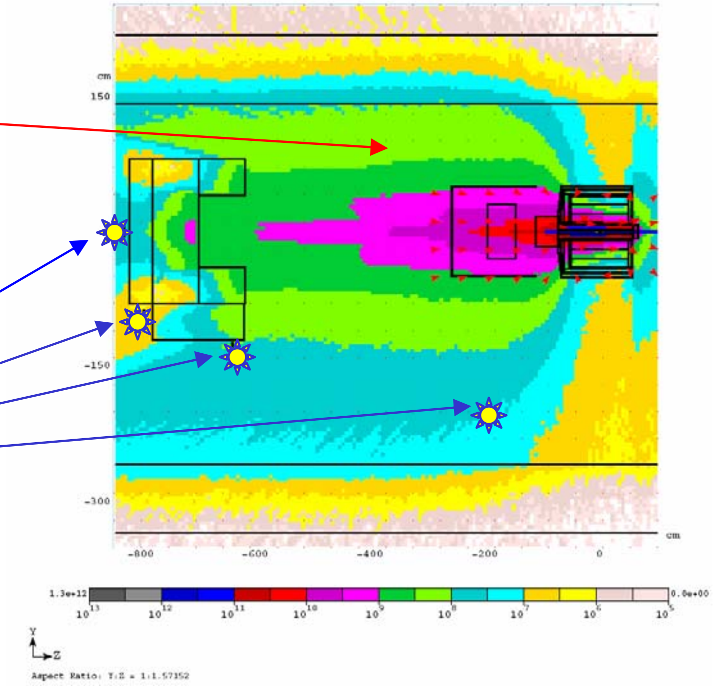
pCVD Diamond

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

ACEM detector

pCVD diamond
+ PIN diode

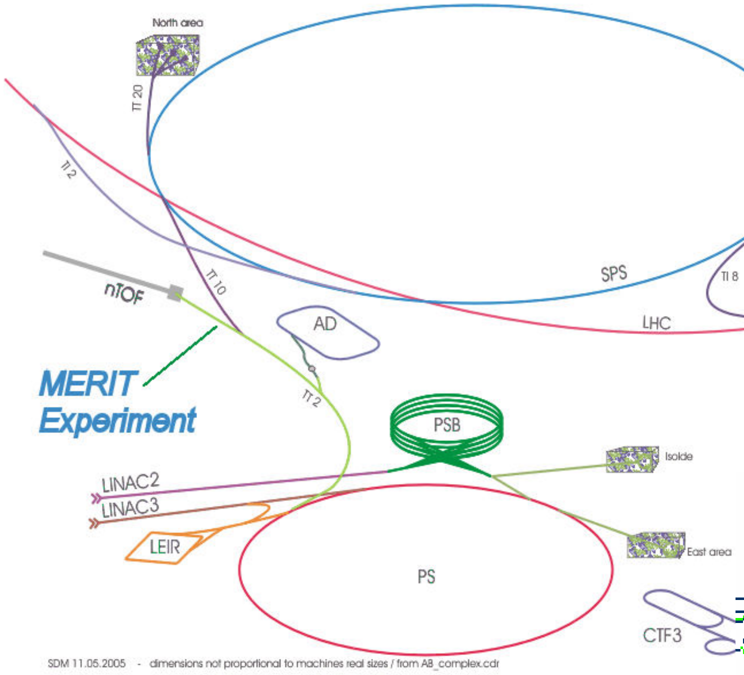
Particle fluxes - 3×10^{13} protons
charged hadrons (E > 200 KeV)
(MARS Simulation: S. Striganov)

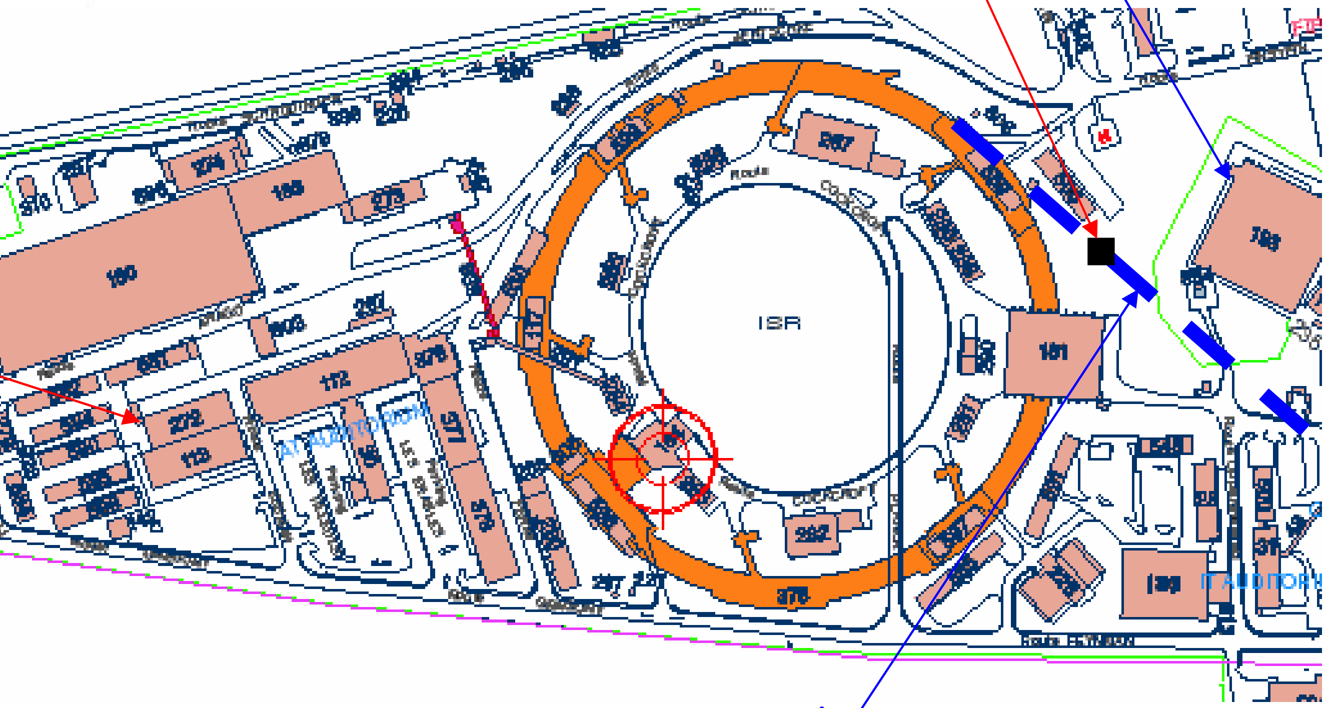


Particle
Detectors

I.Efthymiopoulos
M. Palm (CERN)

MERIT Locations at CERN





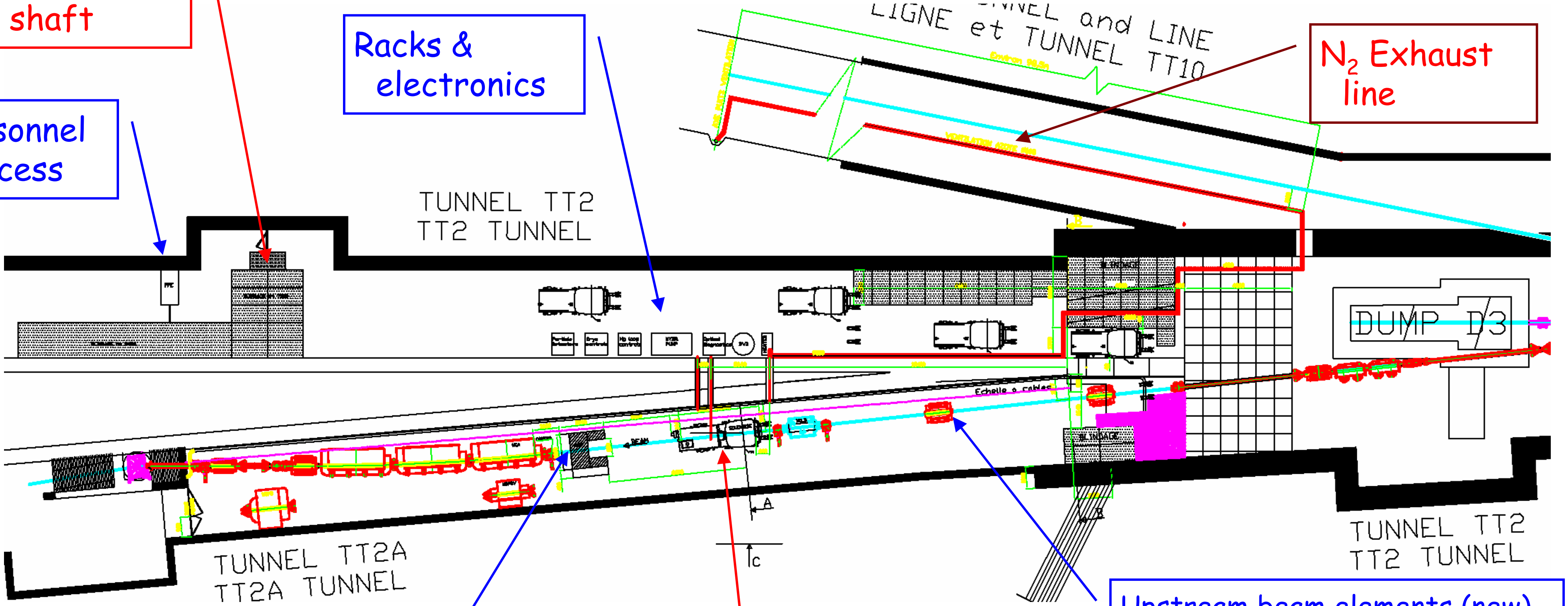
Power supply building

MERIT

Build.272: Offices & Control Room

TT2A tunnel

MERIT Layout in the TT2 and TT2A Tunnels



Material access shaft

Racks & electronics

Personnel access

N_2 Exhaust line

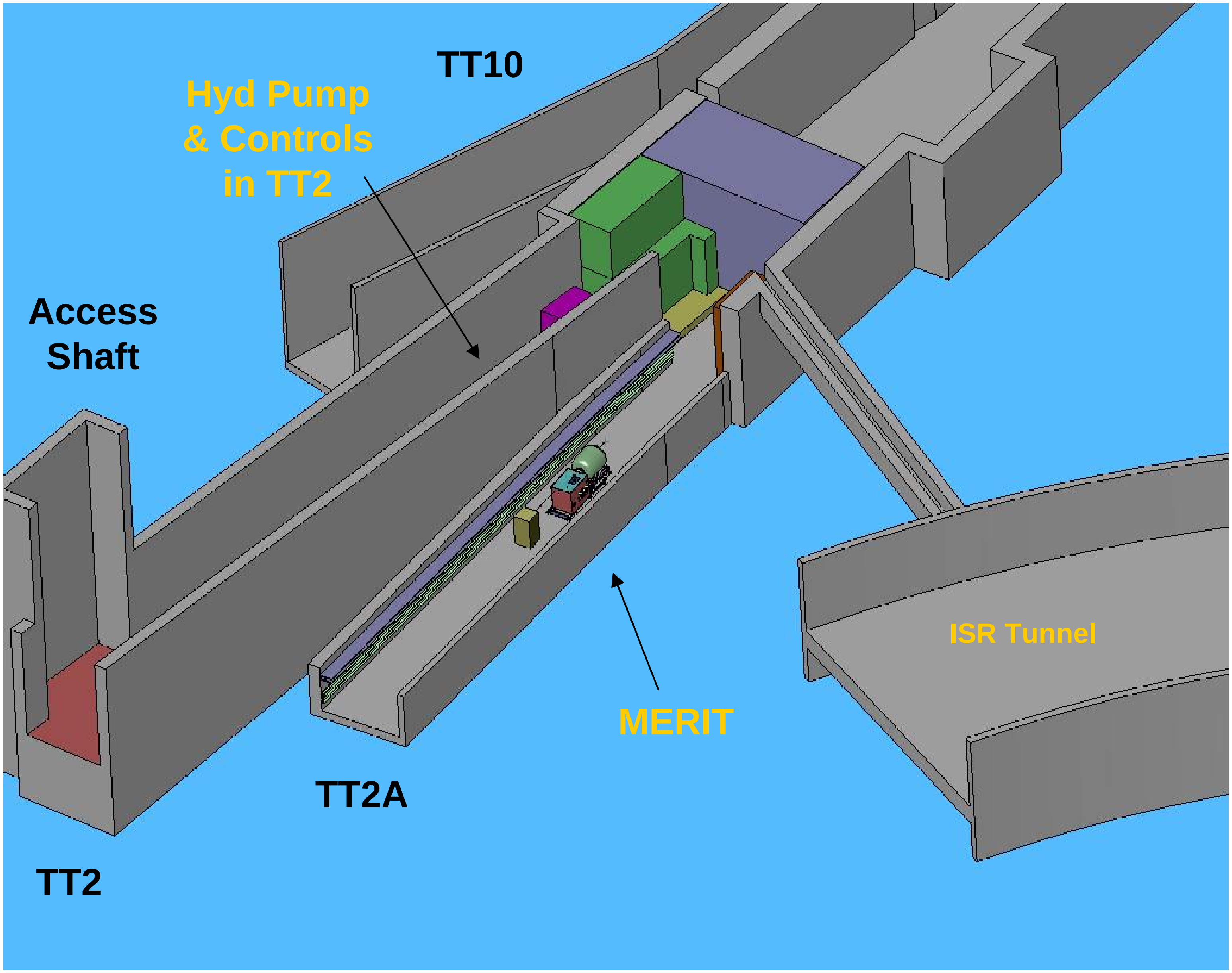
Solenoid & Hg loop

Beam dump

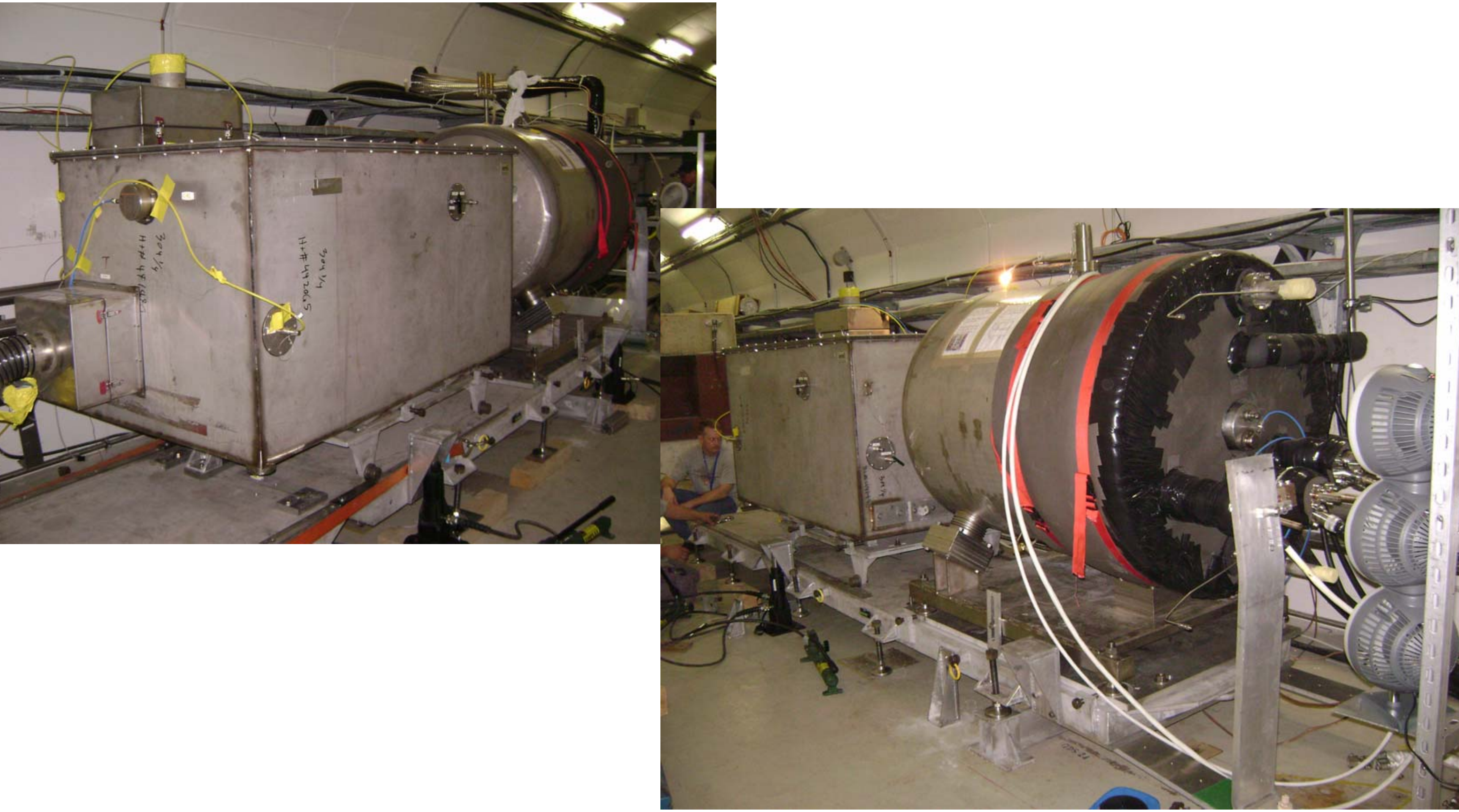
Upstream beam elements (new)

- Quadrupoles for final focusing
- Collimator
- Beam profile measurement
- Beam intensity measurement

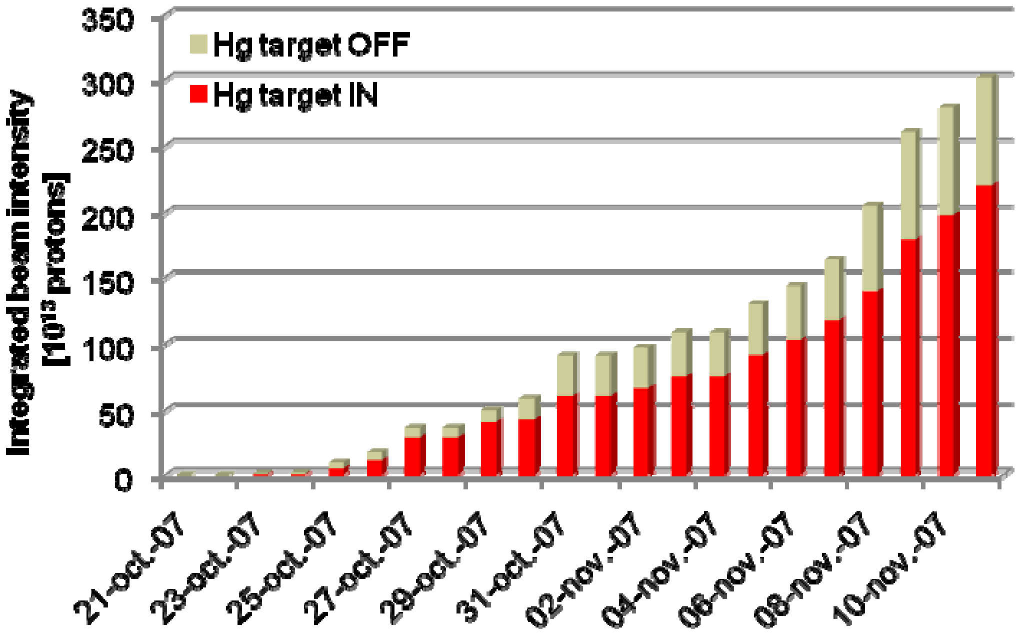
MERIT Layout in the TT2 and TT2A Tunnels



MERIT Installed in the TT2A Tunnel

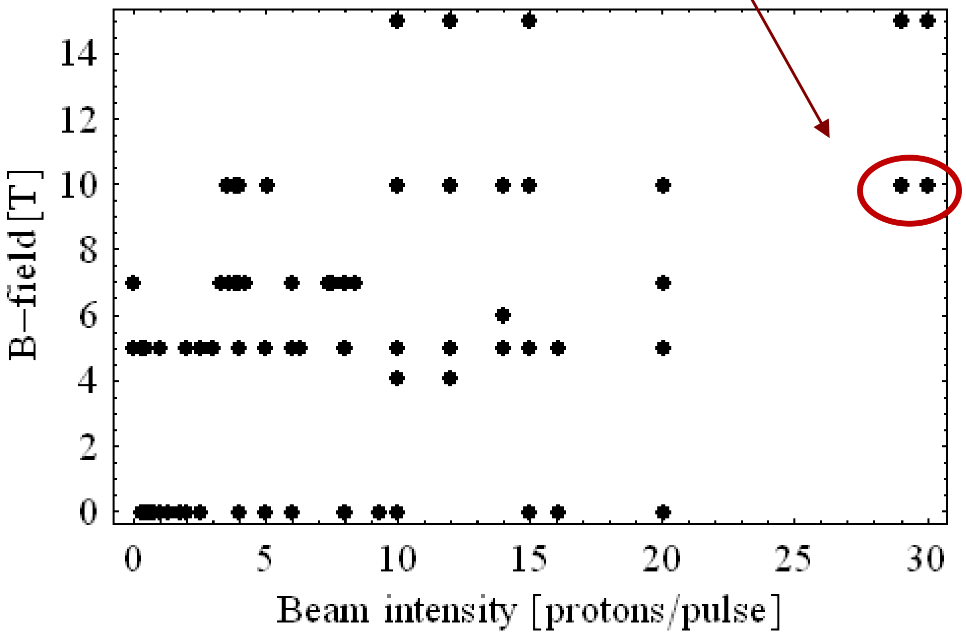


MERIT Beam Pulse Summary



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.

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

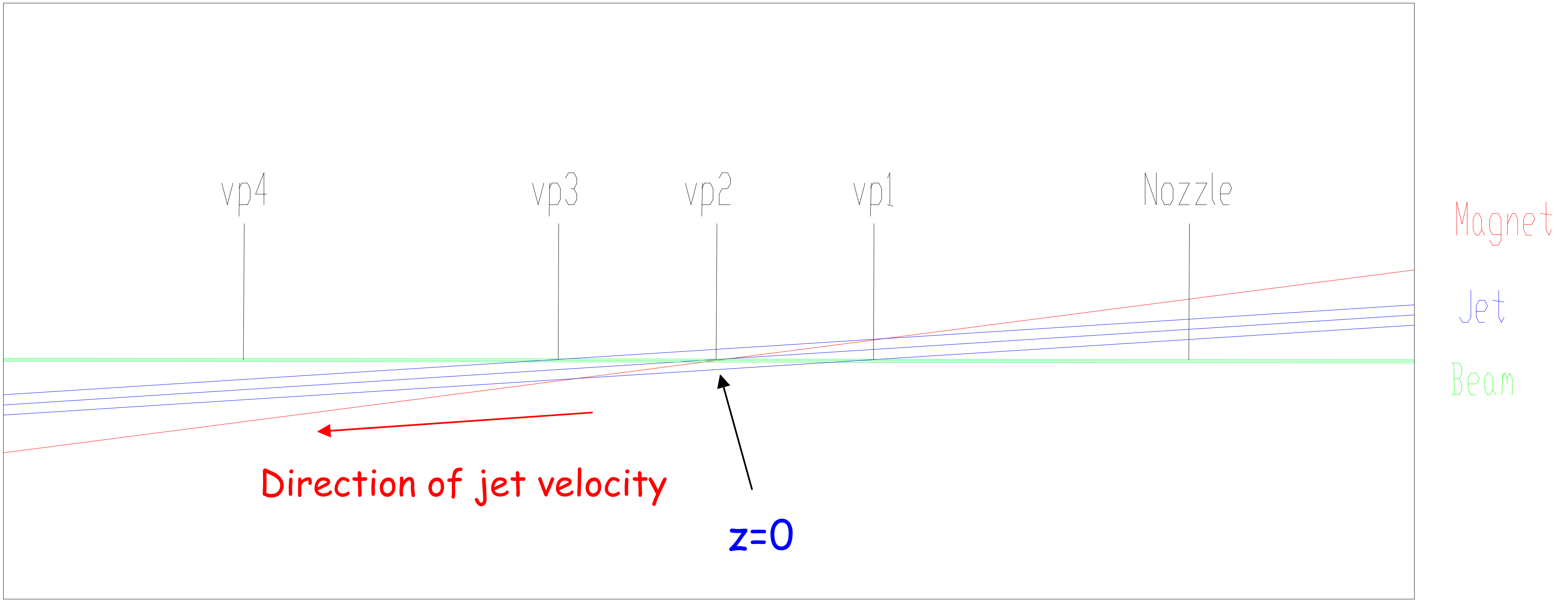
Geometry of the Beam-Jet Interaction

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.

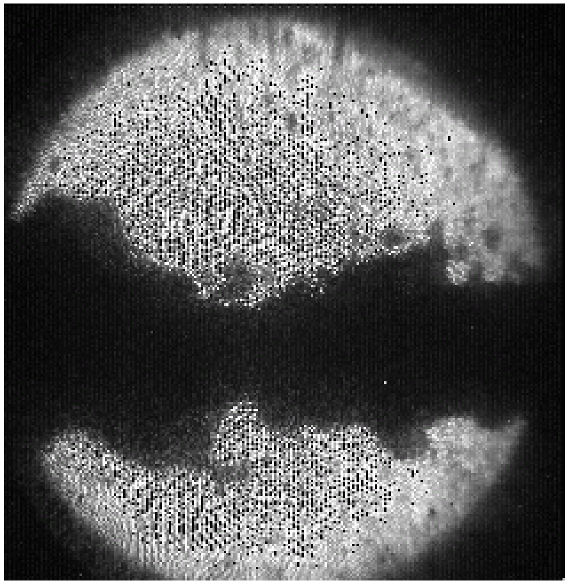
The cameras on ports 1, 3 and 4 took 200 frames at 2000 fps, ⇒ "movie" 1/10 s long.

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.

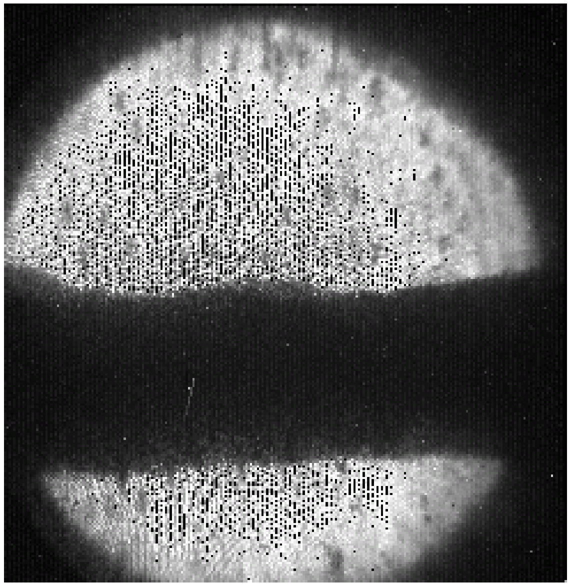


Jets of 15 m/s without Beam

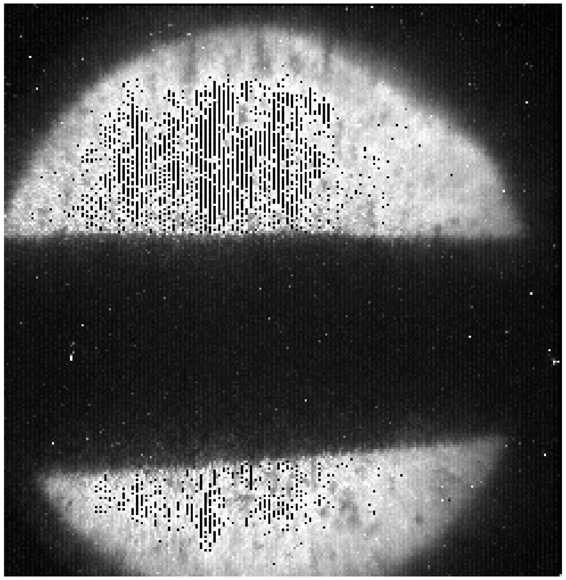
0.4T



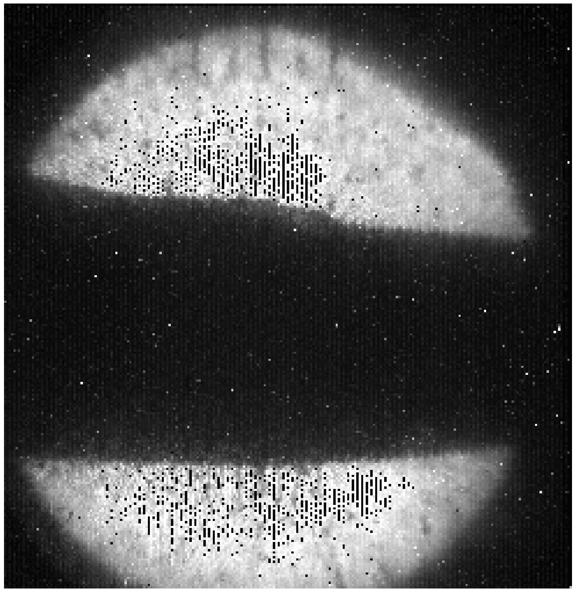
5T



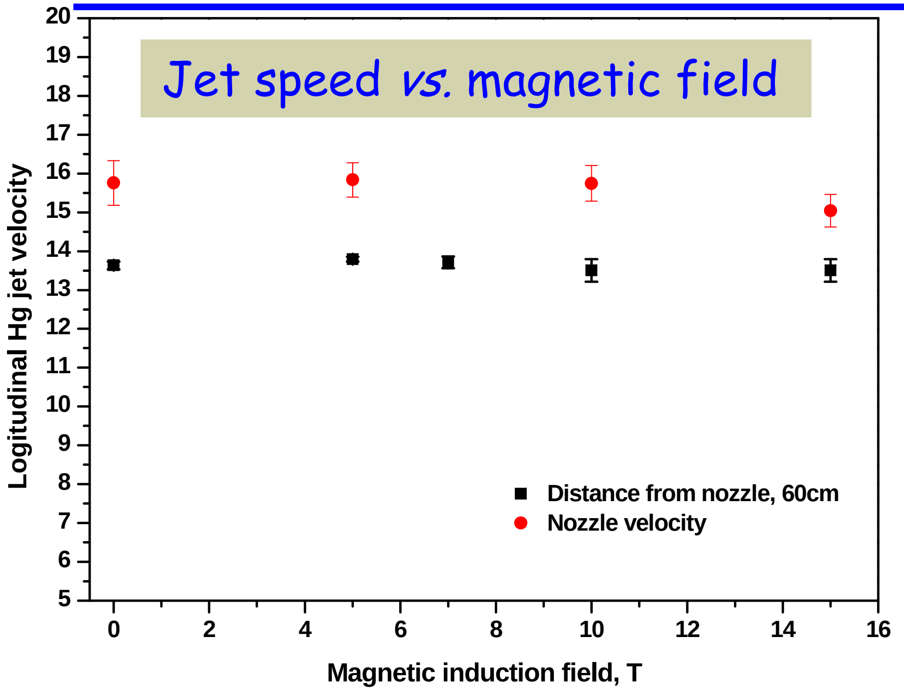
10T

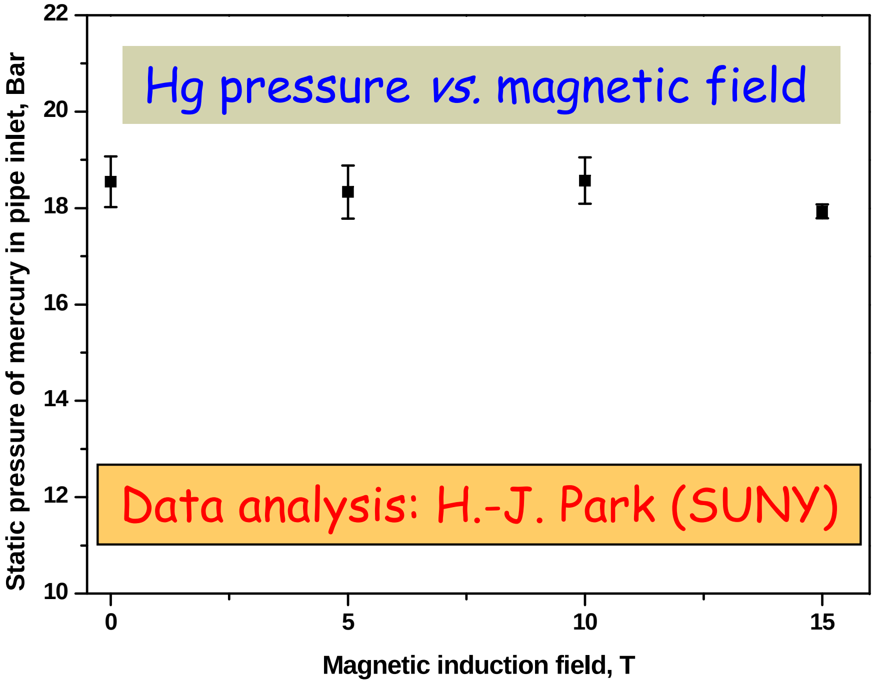


15T

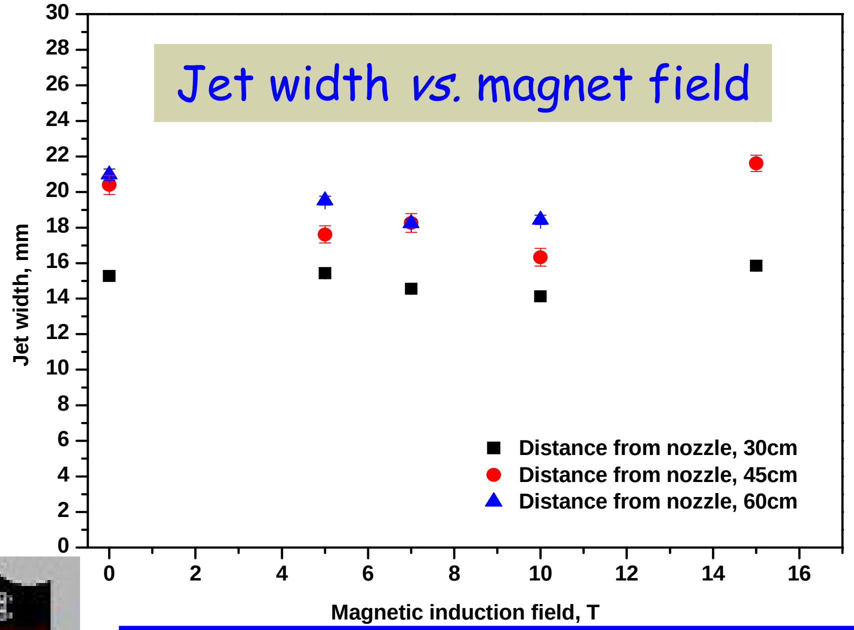


Jet Properties without Beam


Jet speed *vs.* magnetic field


Hg pressure *vs.* magnetic field

Data analysis: H.-J. Park (SUNY)

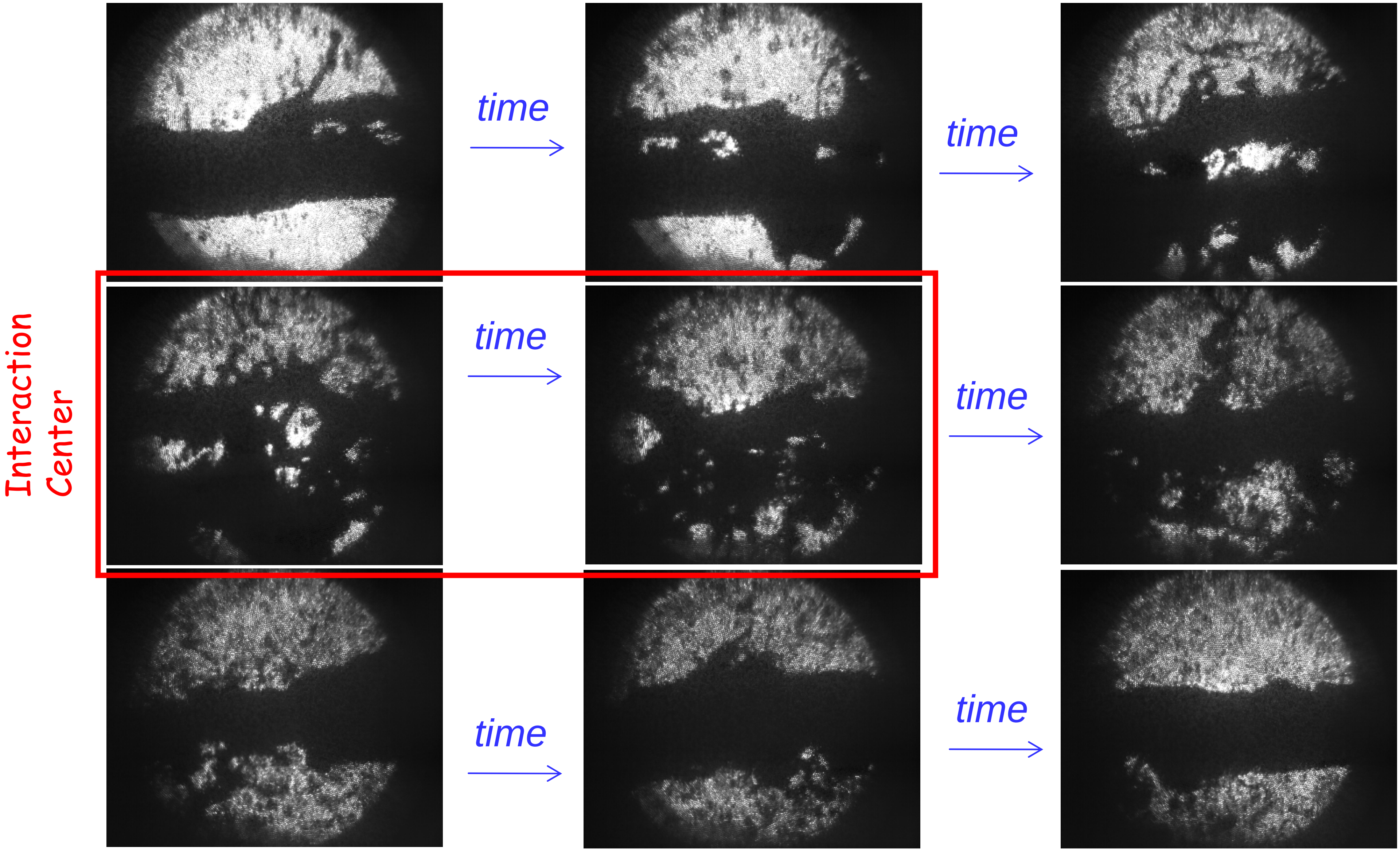

Jet width *vs.* magnet field

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.

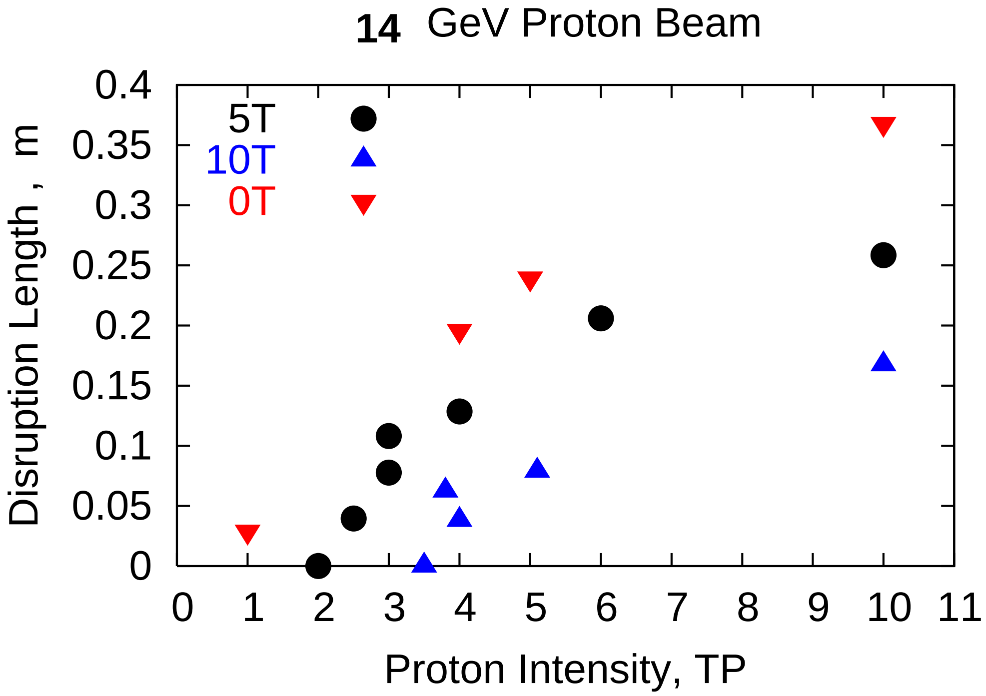
“Typical” Interaction: 16 Tp, 5 T, 14 GeV/c, 15 m/s

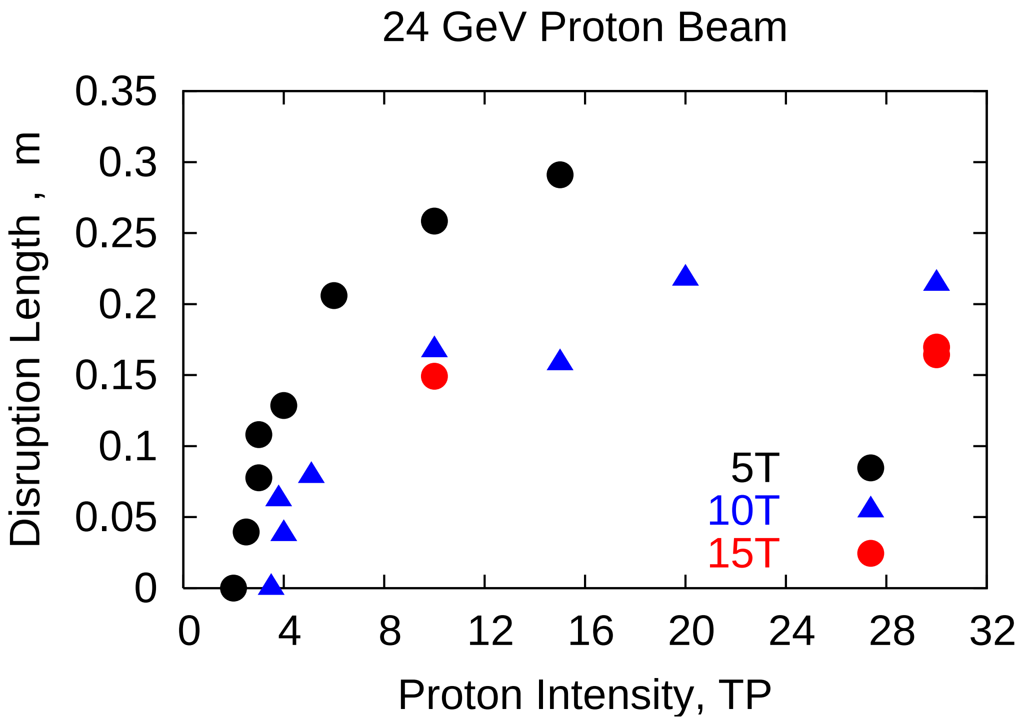


Note disruption of top of jet at early times, and of bottom at later times.

“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.

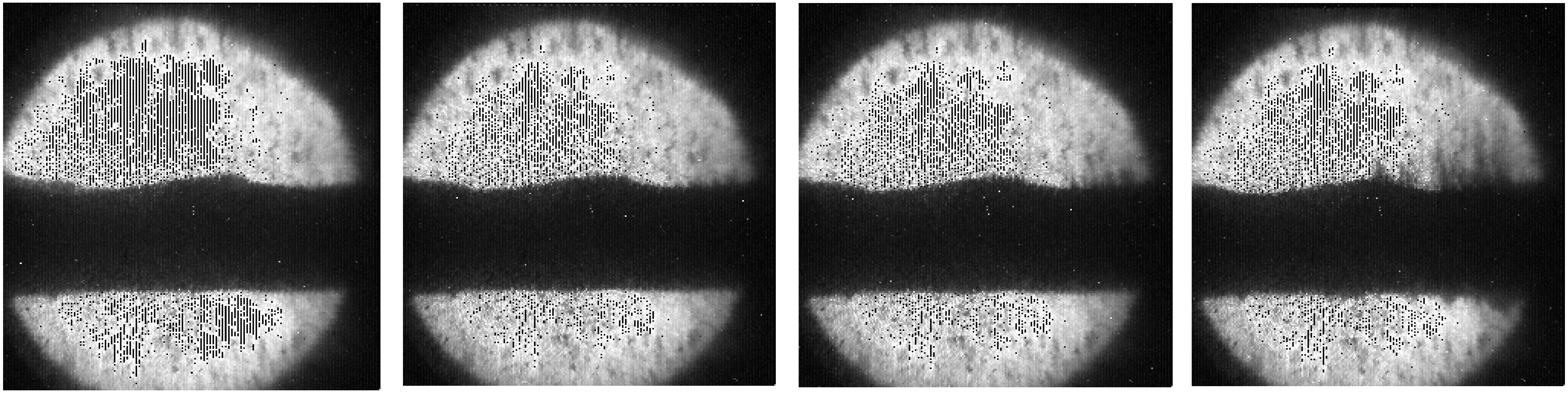
Maximum disruption length same at 14 and 25 GeV/c.

Disruption length smaller at higher magnetic field.

Disruption threshold increases at higher magnetic field.

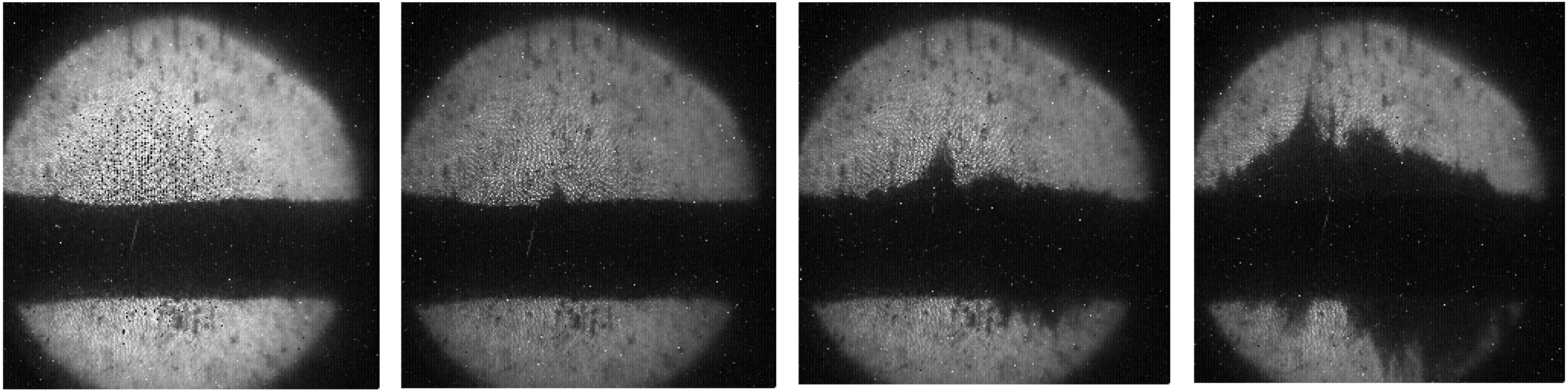
Jet Breakup Velocity Observed at Port 2 with Fast Camera

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



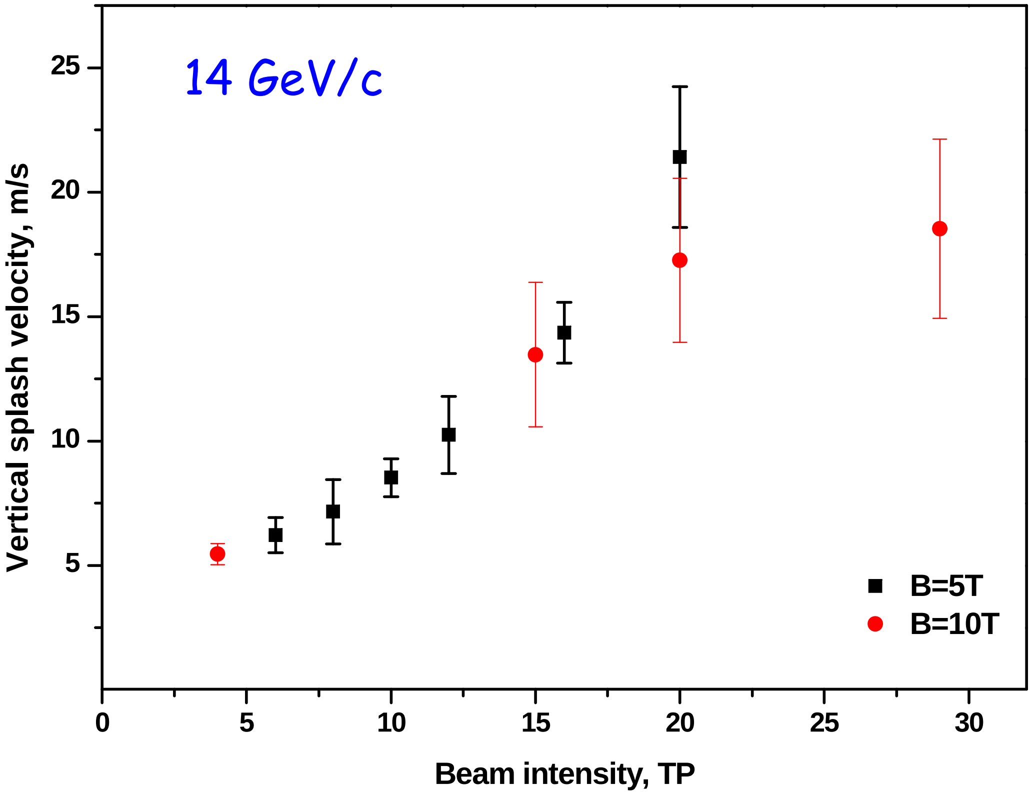
t = 0 *t* = 0.150 ms *t* = 0.175 ms *t* = 0.375 ms

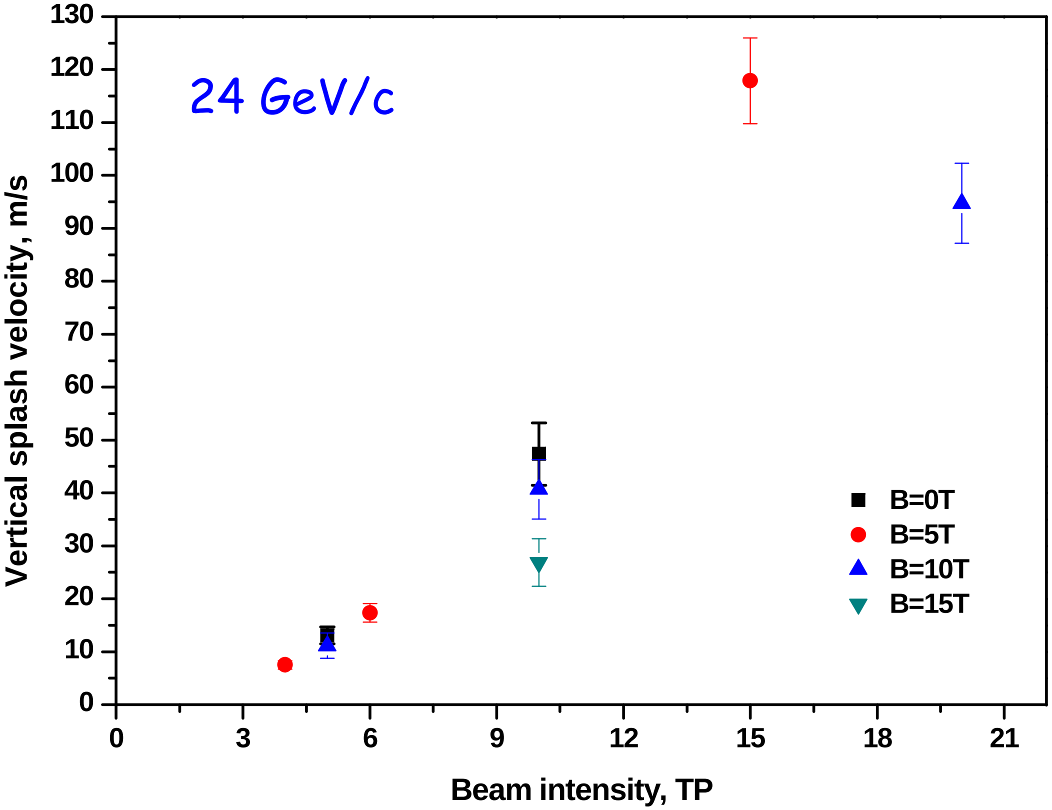
10TP, 10T **V = 54 m/s**



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

Jet Breakup Velocity Measurements





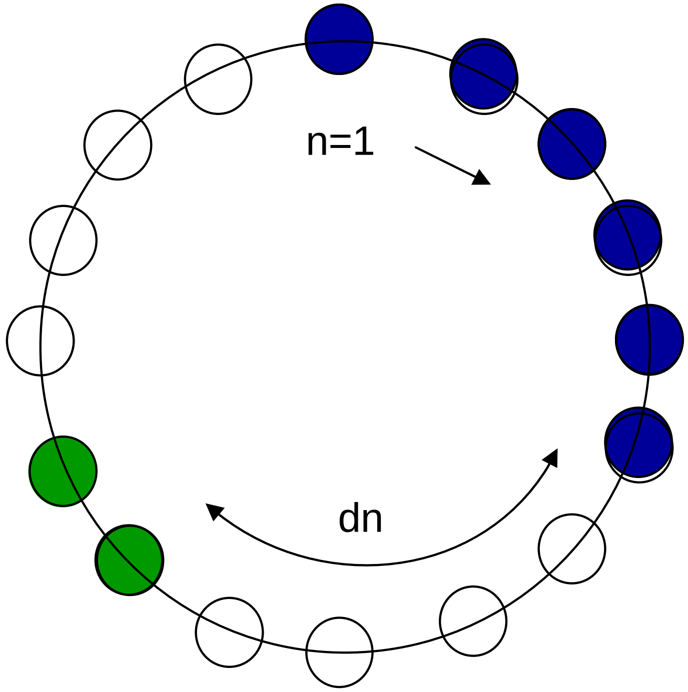
Beam spot area at 24 GeV/c is (14/24) of that at 14 GeV/c.

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.

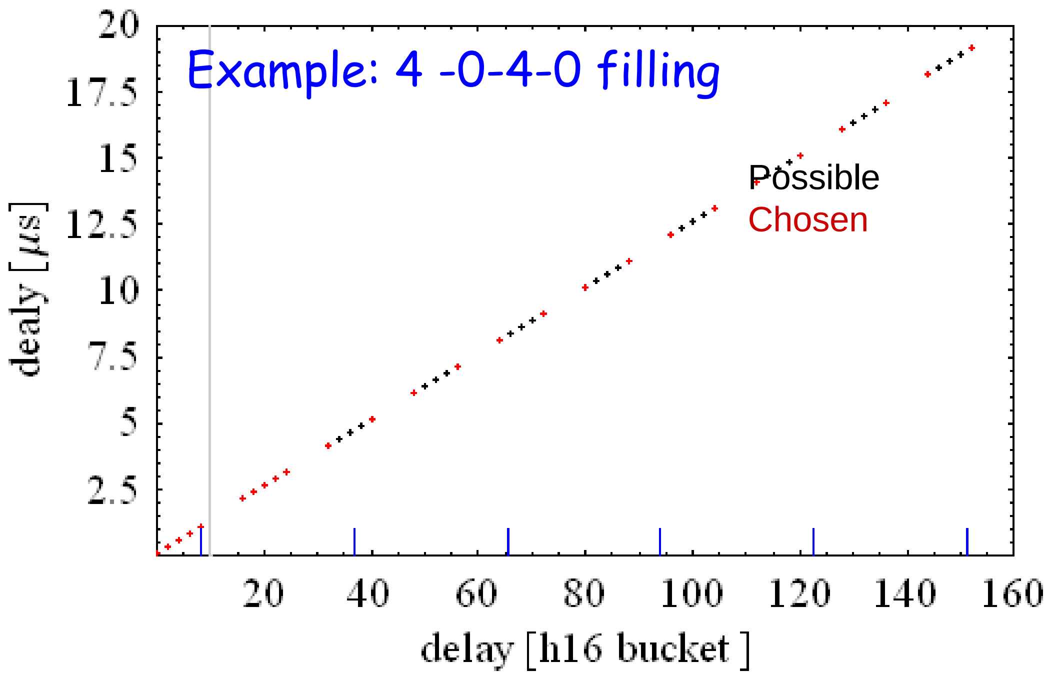
Pump-Probe Studies via Extraction Gymnastics

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.

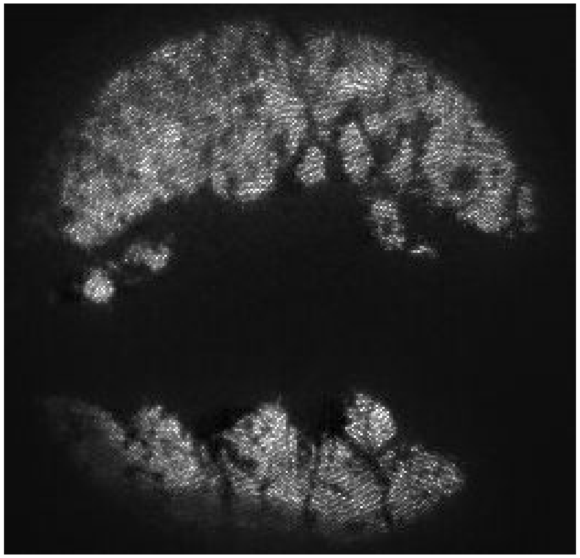


PUMP: 6 bunches, $15*10^{12}$ protons

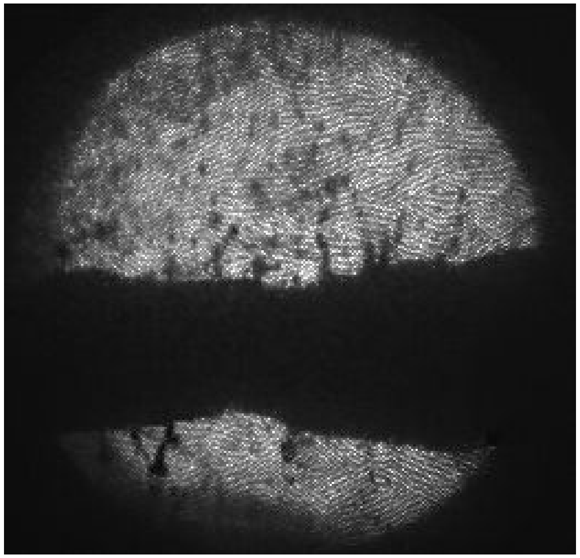
PROBE: 2 bunches, $5*10^{12}$ protons



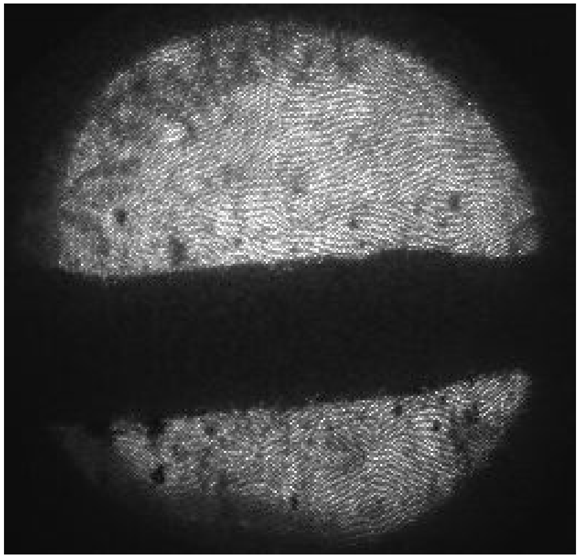
Pump-Probe Study with 4 Tp + 4 Tp at 14 GeV/c



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.