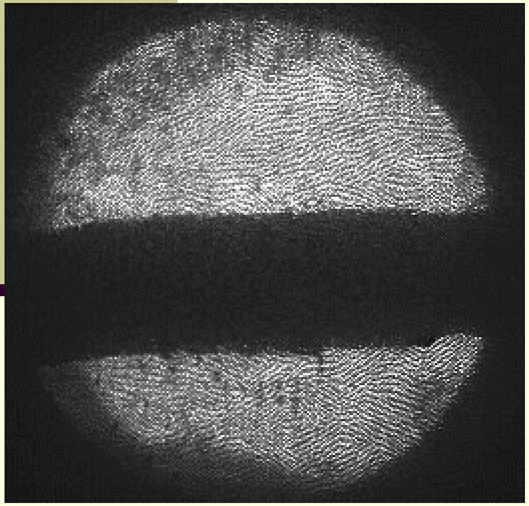
The MERcury Intense Target Experiment – or nTOF11



Beam jet interaction @ MERIT
14 GeV/c beam, 12TP, 10T field

I. Efthymiopoulos – CERN, AB Dept.

(for the MERIT collaboration)

MUTAC Review
LNBL – April 9, 2008

Outline

- Reminder: scientific goals & layout of the experiment
- The experiment's sub-systems
  - Solenoid & Hg-loop
  - Cryogenics
  - Beam diagnostics & particle detectors
  - Safety
- Installation at CERN
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- Summary - outlook

The MERIT experiment

*A **proof-of-principle test of a target station** suitable for a Neutrino Factory or Muon Collider source using a 24-GeV proton beam incident on a target consisting of a **free mercury jet** that is inside a **15-T capture solenoid magnet**.*

Proposal submitted to CERN – May 2004

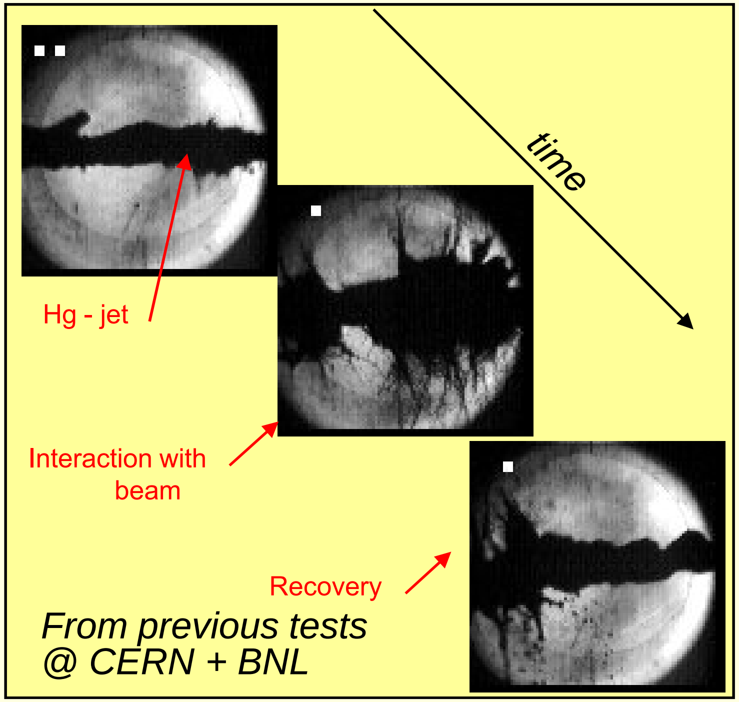
Experiment approved as **nTOF11**

Participating Institutes

- BNL, MIT, ORNL, Princeton University
- CERN, RAL

Spokespersons

- H. Kirk (BNL), K. McDonald (Princeton Univ.)



MERIT Experiment – Profile

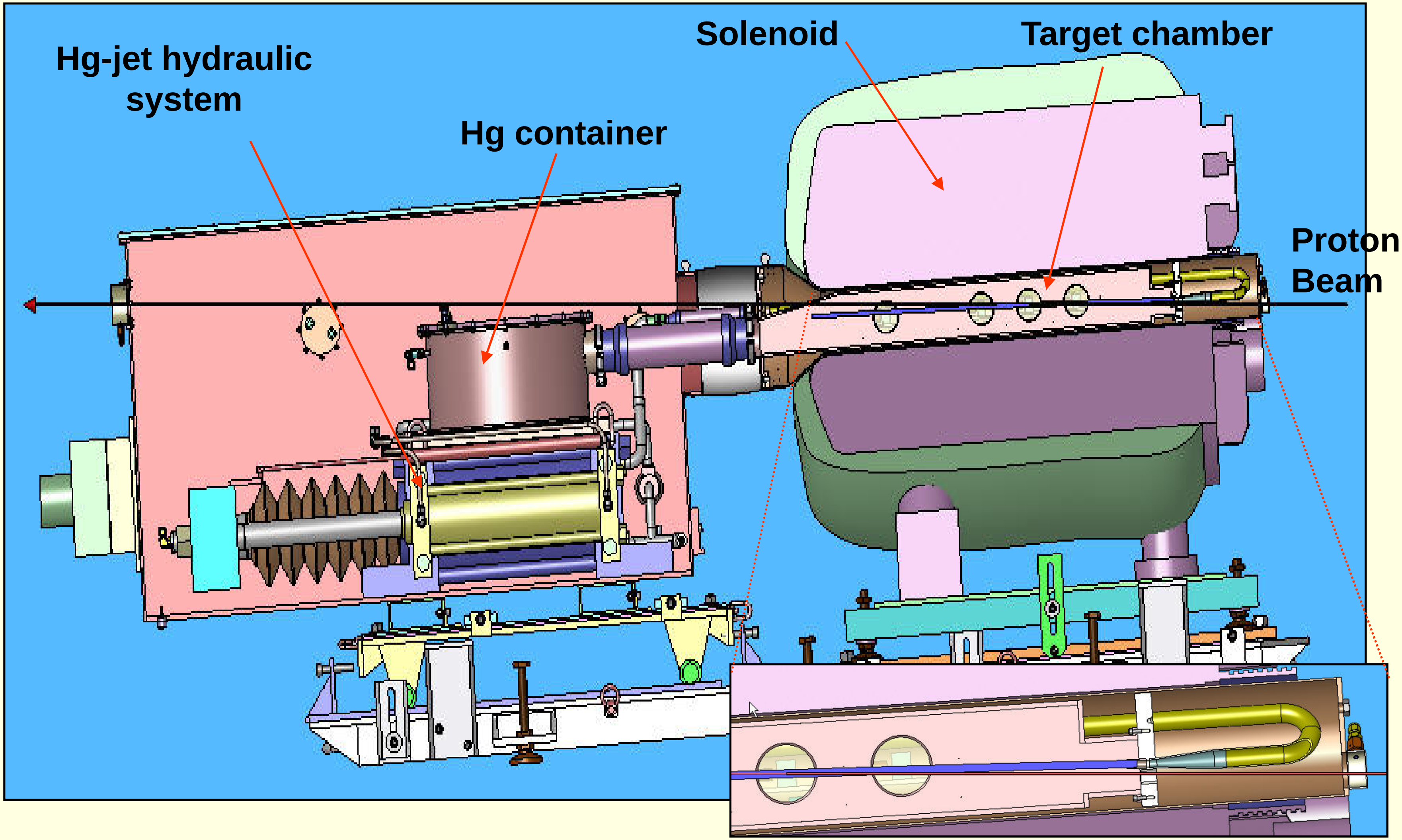
Target

- 1-cm diameter **Hg jet,** jet velocity ≅ **20m/s**
- Hg jet/proton beam configuration:
  - Hg-jet ↔ solenoid axis = 33 mrad
  - proton beam ↔ Hg-jet axis = 67 mrad
  - beam ↔ Hg-jet interaction length = ~30cm (2.1 λ_I)

Proton beam

- 24(14) GeV/c extracted from PS
  - Max. intensity **3 × 10^{13} protons/pulse**
  - Beam spot r≤ 1.2 mm rms
  - Variable pulse length 0.134 ÷ 700 μsec
  - **~100** high-intensity pulses
  - 3 × 10^{15} protons on target in total (radiation limit)

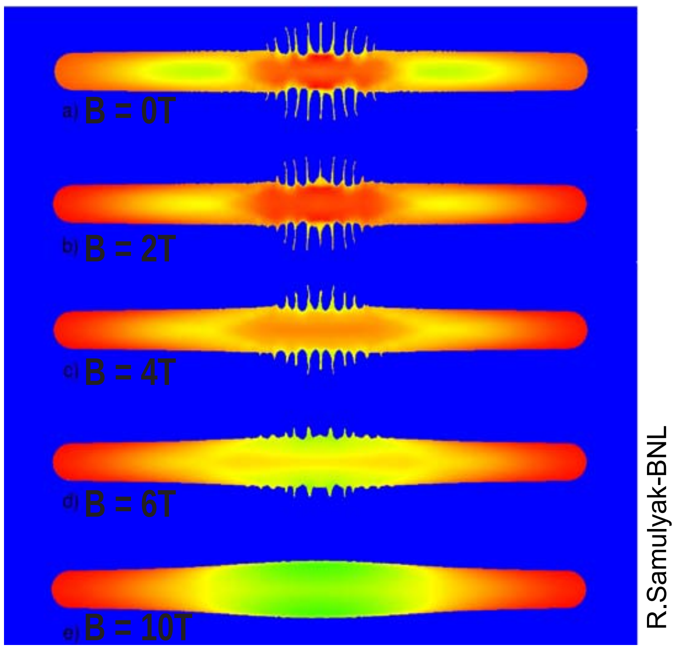
MERIT Experiment – The apparatus



MERIT Experiment – Scientific Goals

Important milestone towards the production of 1-4MW pion production targets

1. Study MHD effects on Hg-jet with

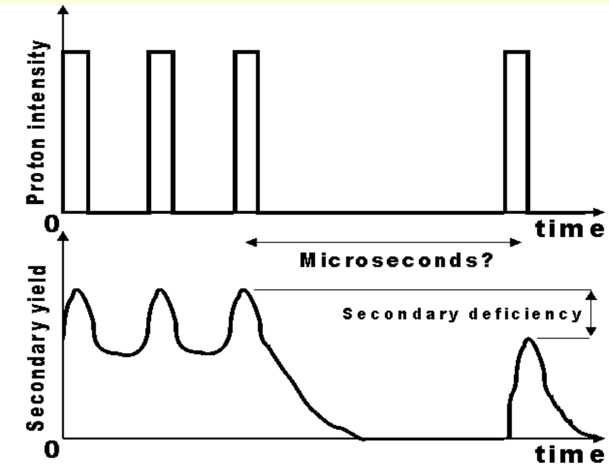


Jet dispersal at t=100μs with magnetic field varying from 0 to 10 Tesla

2. Study jet disruption (cavitation?) by varying the PS spill structure

MERIT: 180 J/g

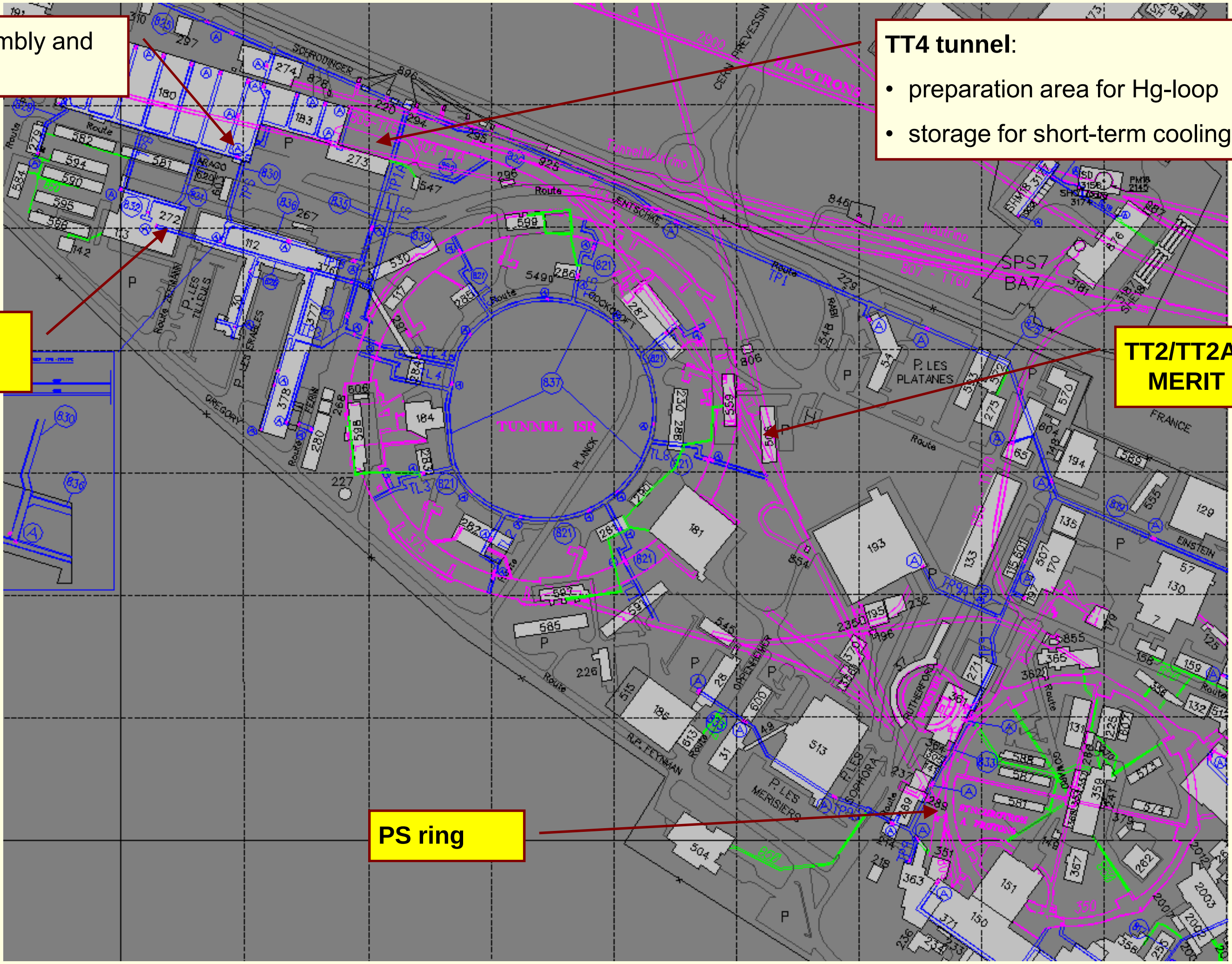
- 28TP@24GeV protons
- 1cm diam. Hg-jet
- 1.2×1.2 mm^2 beam size rms



MERIT Experiment – Installation & CERN

Build.180: Cryogenics assembly and surface tests

TT4 tunnel:
- preparation area for Hg-loop
- storage for short-term cooling

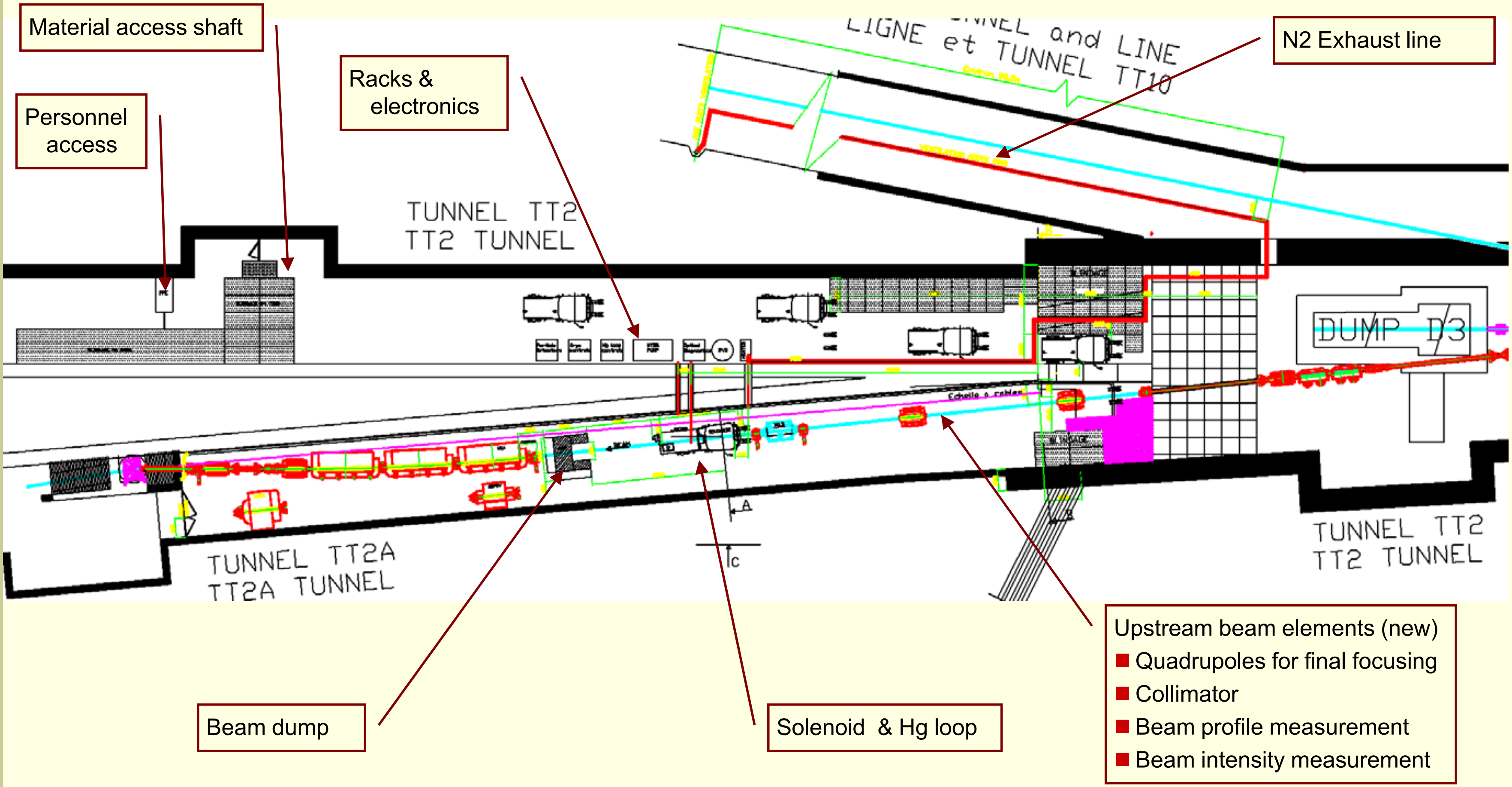


Build.272: Offices & Control Room

TT2/TT2A: MERIT

PS ring

MERIT Experiment – Layout



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Hg loop system

- Required flow: 1.57 lt/s
- Mercury inventory: **~23 lt**
- Piston velocity : 3.0 cm/s
- Hg jet duration of 12s
- Drive cylinders:
  - 15-cm diam
  - 45 lt/min
  - 20 MPa (200 bar)

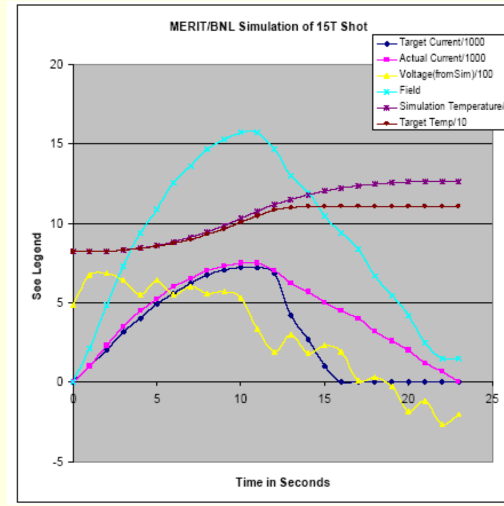
Geneva's jet d'eau

Hg-loop assembled – during water tests & ORNL

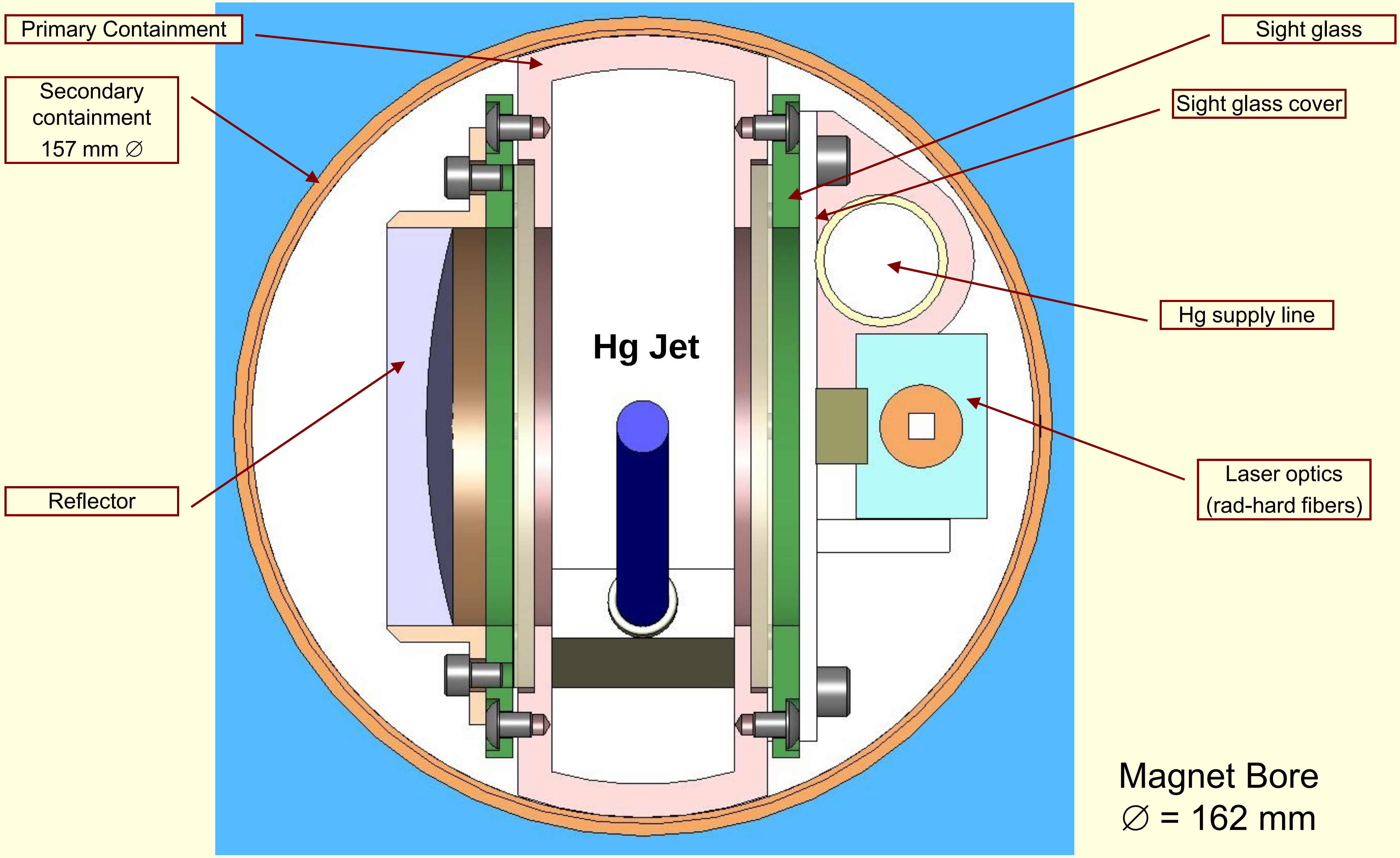
Solenoid

- Cu conductor solenoid,15T field
- cooled at LN temperature
- 1m long, 15cm inner diameter

Solenoid at its test stand at MIT



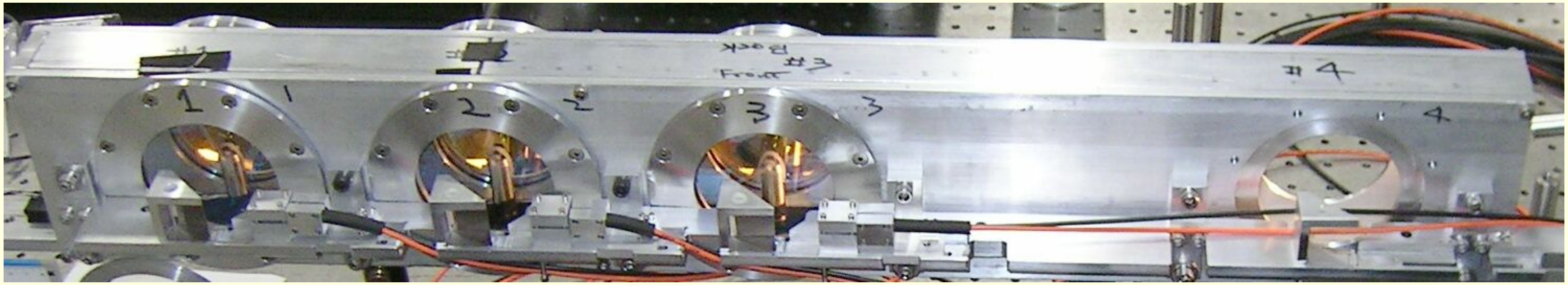
Optical diagnostics



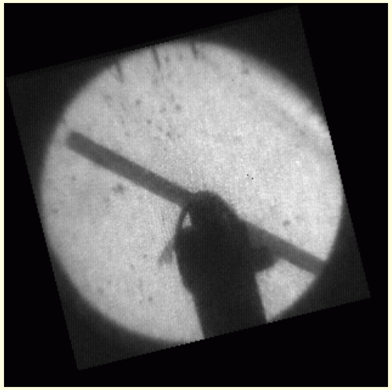
Magnet Bore
∅ = 162 mm

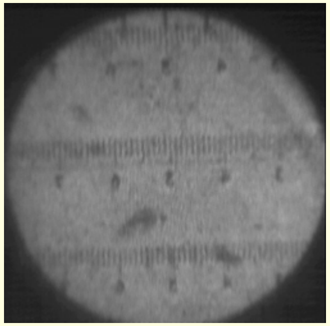
Optical diagnostics

- 4 viewports along the primary container

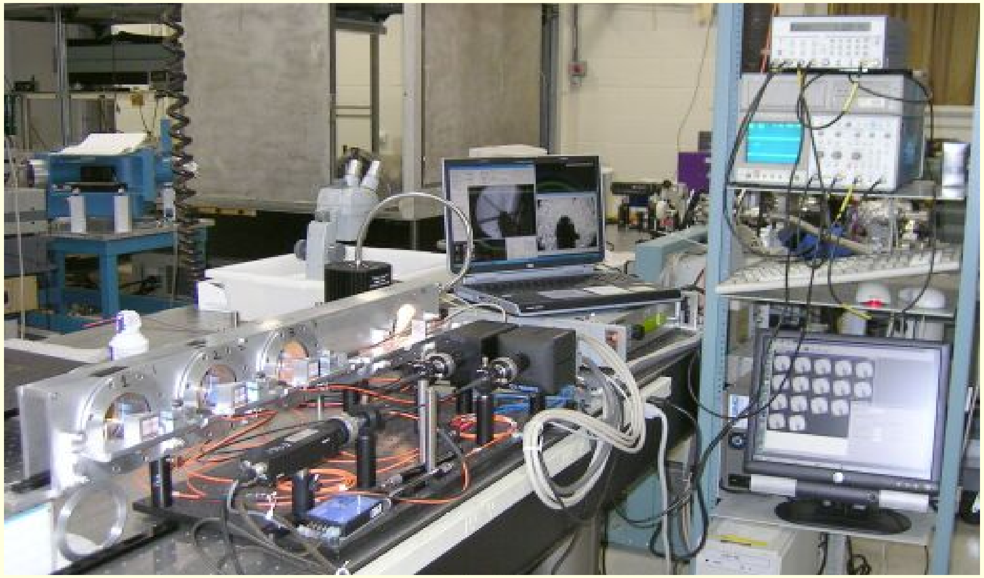


80us/frame, 16 frames pulsed NIR light SMD camera

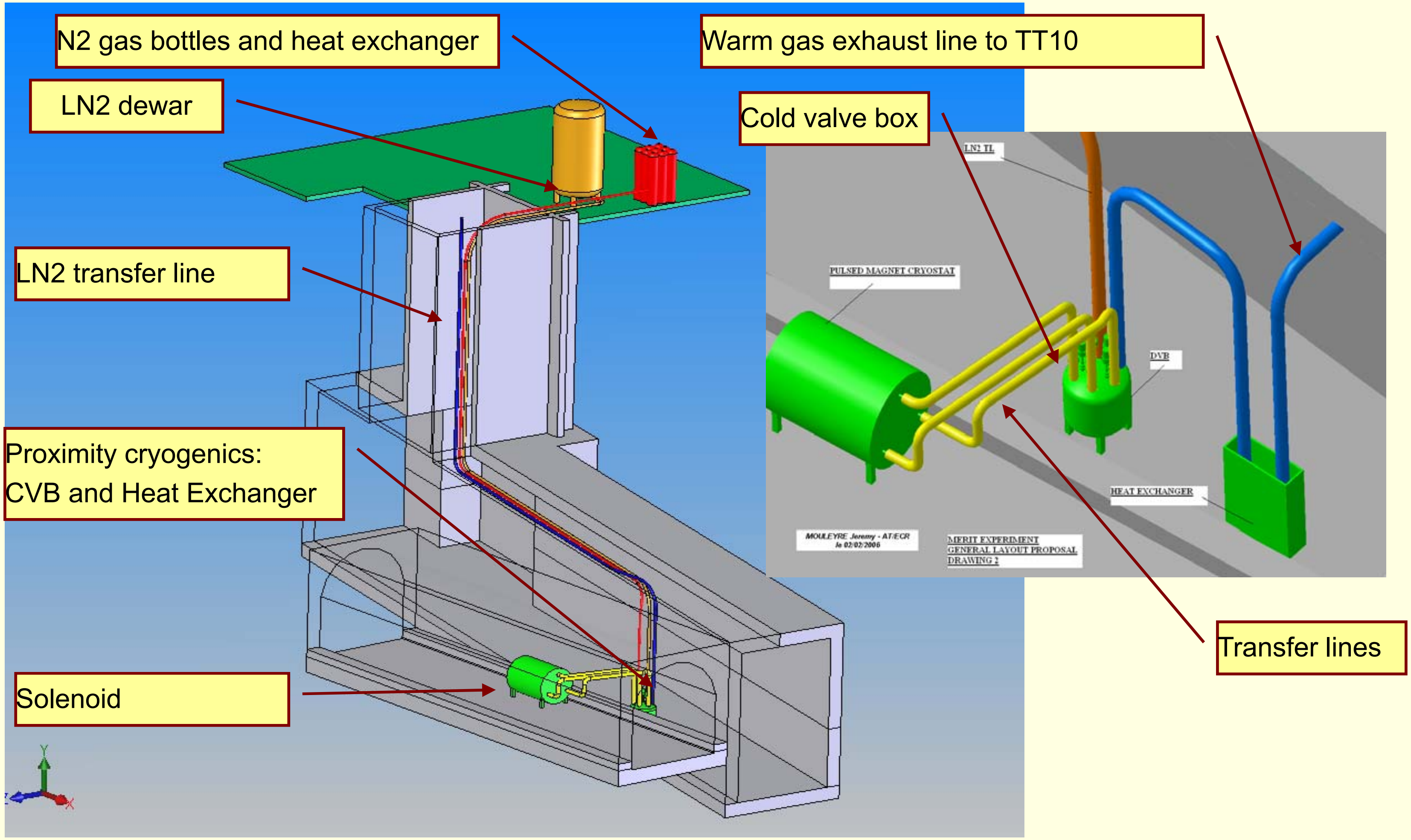




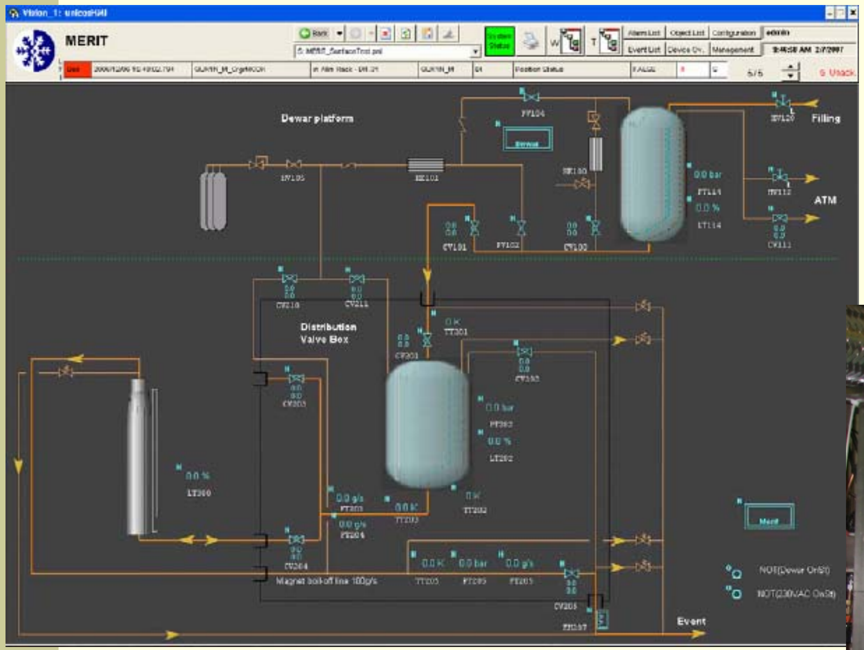
Test setup lab @ BNL



Cryogenics – Layout



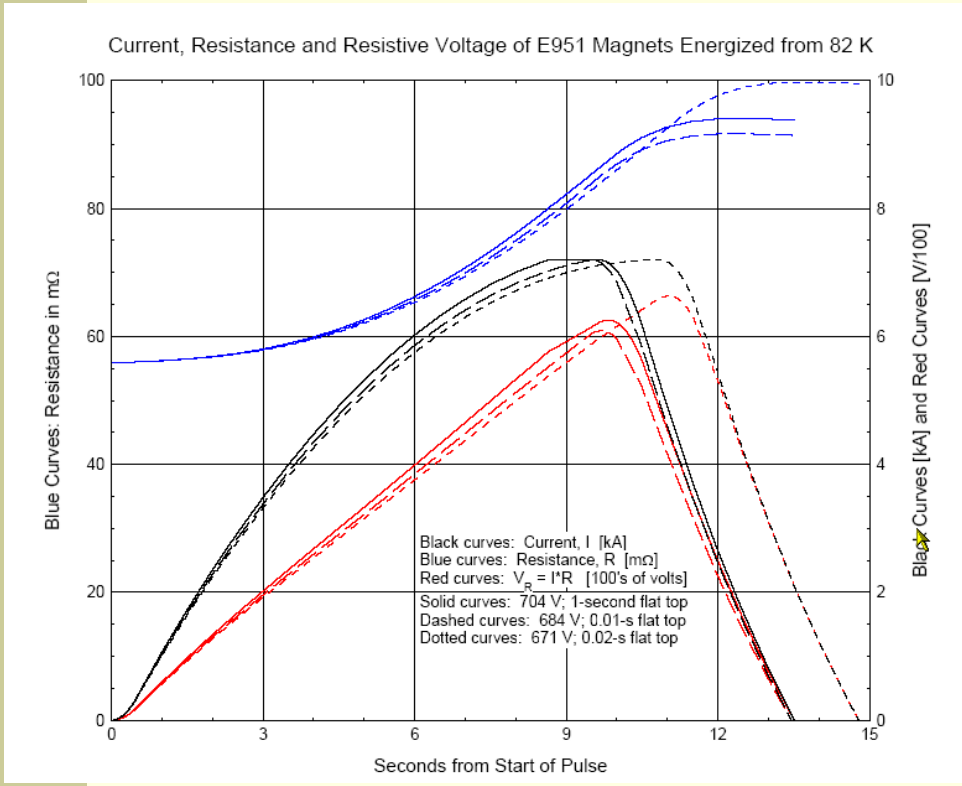
Cryogenics



- System design @ CERN
- P&I diagram according to CERN standards (safety & operation)
- Fully remote control

- DVB designed @CERN and constructed at RAL

Power supply



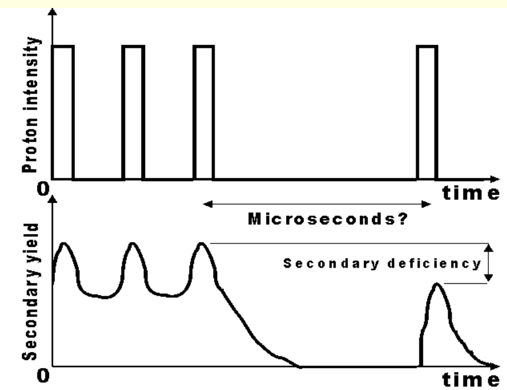
AC transfo outside build. 193

PS unit inside build. 193

- Recuperated from the old SPS West Area extraction
- "pulsed" mode: **7kA / 30 min** ; 5MW

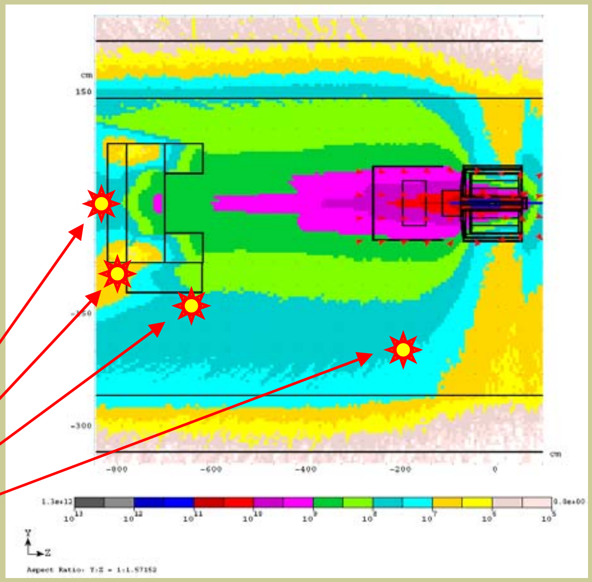
Particle Detectors

- Measure particle production per bunch in “pump-probe” runs for cavitation studies
- Place detectors around the target at various locations
  - Detectors: pCVD diamonds, pin diodes, ACEM detectors
- Monitor the beam-target interaction



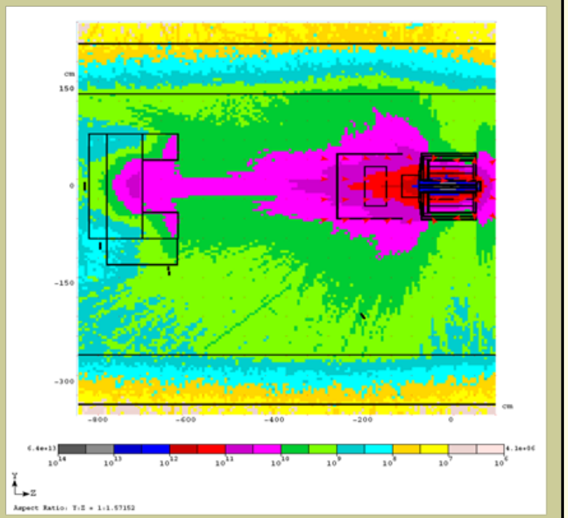
Particle Detectors

Particle fluxes - 3×10^{13} protons (MARS Simulation)



charged hadrons (E>200 KeV)

neutrons (E>100 KeV)



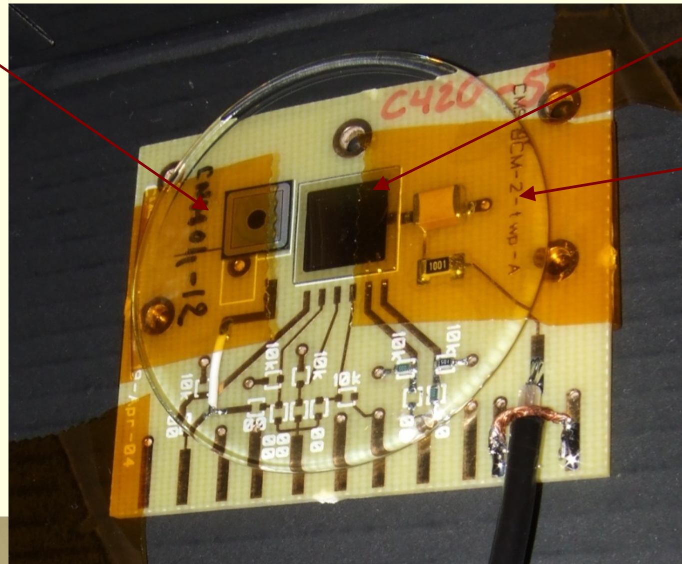
S.Striganov - FNAL

Particle Detectors

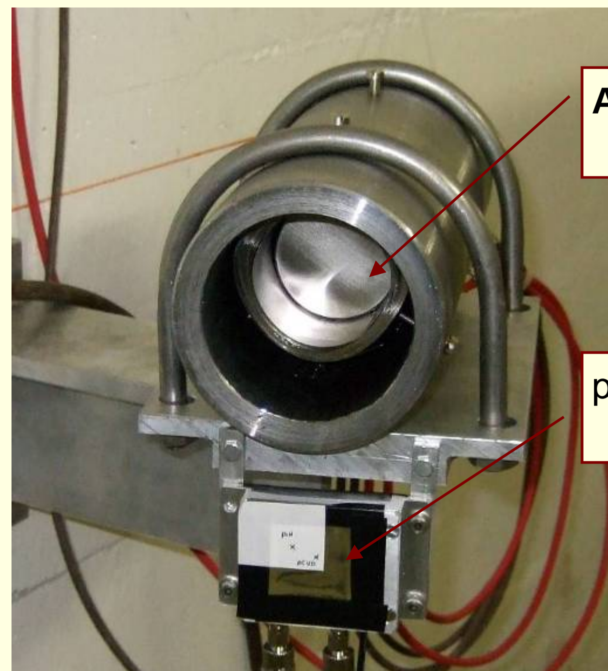
PIN diode
- ~1cm^2 active area, 200 um thick

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

bypass capacitor: 100 nF/500V

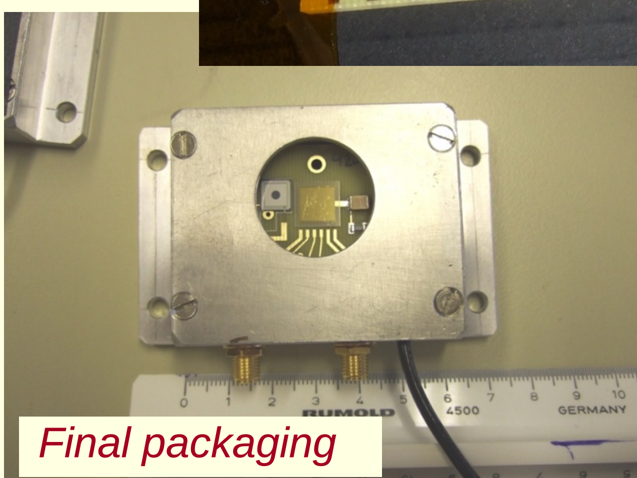


Detector assembly unit



ACEM detector

pCVD diamond + PIN diode



Final packaging

Safety for MERIT experiment

1. Preliminary hearings with safety officials at CERN before the proposal submission and approval of the experiment
2. Safety reviews of the major sub-systems of the experiment, in time with their production
   - Cryostat and cryogenics – **February 3, 2006**
   - Hg-system – **June 20, 2006**
3. Safety pre-installation review **March 30, 2007**
   - Experience from the combined tests & MIT
4. Safety inspections in-situ
   - Transport, installation, Hg-handling, cryogenics, electrical safety, etc.
   - Access, interlocks, monitoring systems, etc.

MERIT Safety Reviews

Chairman

- **Ghislain Roy (CERN-AB/DSO)**

Mercury experts & Chemical Safety

- Friedrich Groeschel (PSI)
- Bernie Riemer (ORNL)
- Jonathan Gulley (CERN/SC)

Radiation protection (CERN-SC/RP)

- Marco Silari
- Thomas Otto
- Pierre Carbonez

Mechanical safety (CERN-SC/GS)

- Benoit Delille
- Andrea Astone

General Safety (CERN-SC/GS)

- Bruno Pichler
- Karl Gunnar Lindell
- Ralf Trant

Fire protection (CERN-SC/GS)

- Fabio Corsanego

Safety issues

- MERIT Presentations in:
  - **AB Installation Committee (ABIC)**
    - interface with PS/SPS and CERN services teams
      - → permission to work in TT2/TT2A tunnel during PS/SPS operation
  - **AB Safety Committee (ABSC)**
    - Presented safety structure of the experiment and proposal for review program of various components
  - **AB Technical Committee (ATC)**
    - discussed status of the experiment, schedule, AB & CERN resources, safety…
  - **Radiation Protection Committee (RPC)**
    - Presentation to French and Swiss authorities; authorization to run obtained

- **ISIEC form** for the experiment submitted
  - Ardian Fabich (CERN) nominated as GLIMOS (**G**roup **L**iaison **I**n **M**atters **O**f **S**afety)

A very good and continuous contact with the CERN safety officials has been established throughout the experiment's lifetime

The "**safety file**" for MERIT sets the example on how safety should be handled for experiments at CERN

Dismantling

- At the end of the run the experiment will remain in place for a **cool-down time** until the machine shutdown (November ’07)
  - The Hg will be emptied and stored in the flasks in TT2 tunnel

- During the **2008 shutdown** the experiment will be removed from the tunnel
  - All equipment will be stored at CERN for **one year cool down**
  - At the end of that period radioactivity will be minimal for all components which allows classifying them as **“exempted” packages** for shipment

- Transport back to US is defined & agreed with CERN officials
  - <u>Hg volume</u> : transported by air-cargo using the existing packaging
    - radioactivity will be minimal and chemical hazards precede
  - <u>Hg loop</u>: transported by air-cargo or sealand container
    - Classified as “mercury wet” material (< 1lt of Hg)
  - <u>Solenoid & other heavy material</u> : transported by air-cargo or seland container as separate packages

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Transport to CERN

- Leaving MIT on **Wednesday March 14th**
- {solenoid, Hg-loop, optical diagnostics}

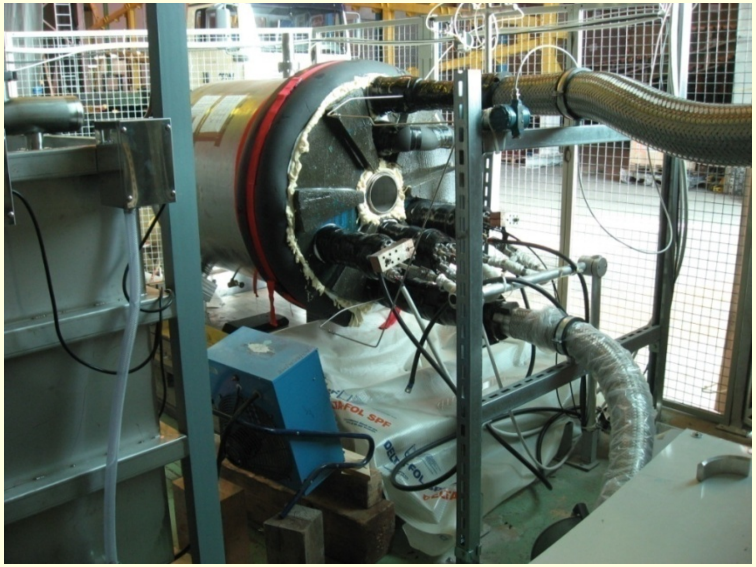
- Arrival at CERN on **Monday March 19th**

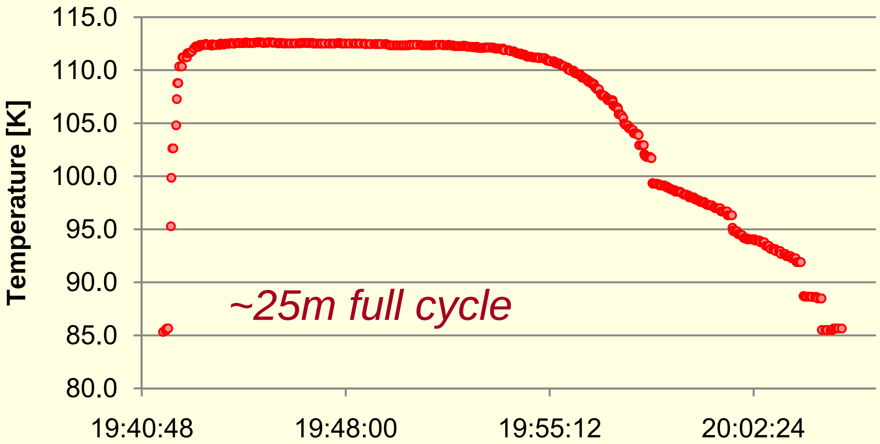
Transport to CERN

- The Hg volume was send to CERN separately
  - 23-lt in 11 drums transported according to safety rules for chemically hazardous material
    - Only **~13lt** were finally used in the experiment

Cryogenics – Surface tests

- Commissioning tests of the cryogenics system with the solenoid at surface

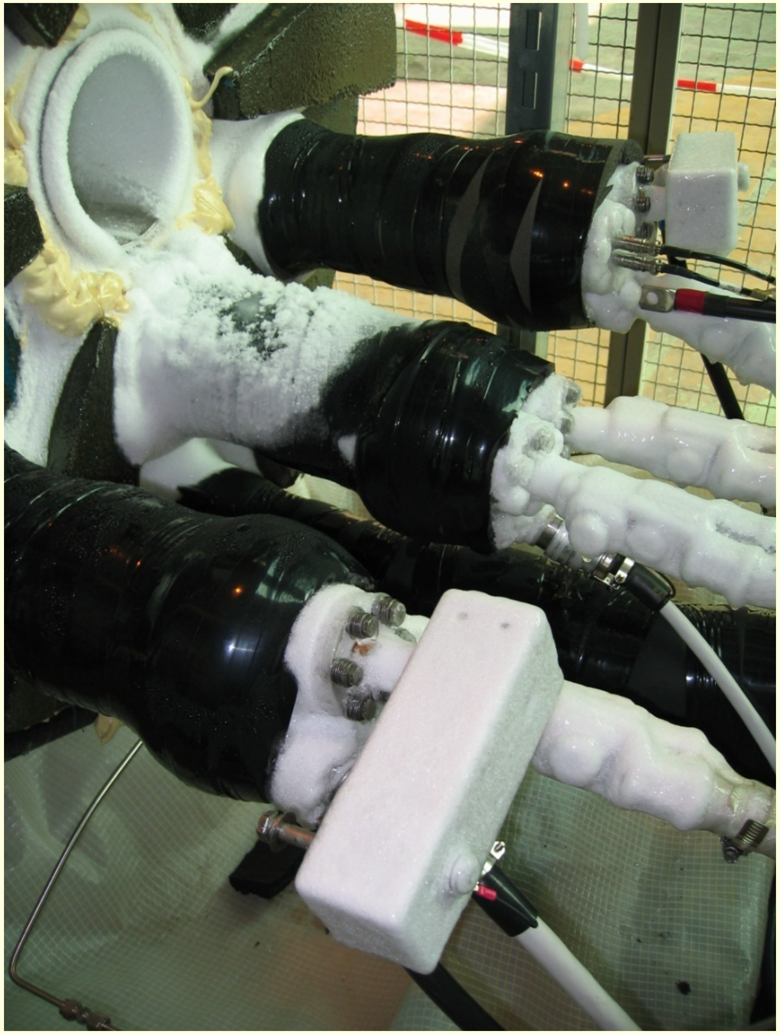




Cryogenics – Surface tests

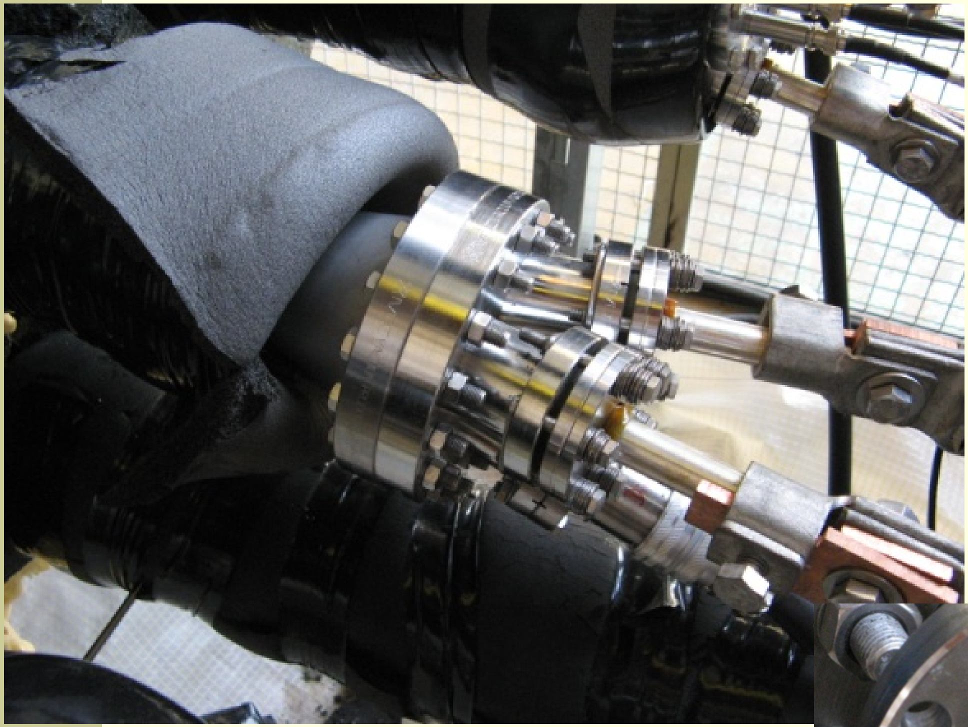
- After first cool-down leaks at cold observed when filled with LN
  - Already observed at MIT but not fully corrected due to lack of time
- In addition, icing due to insufficient insulation was also observed in the front face of the solenoid

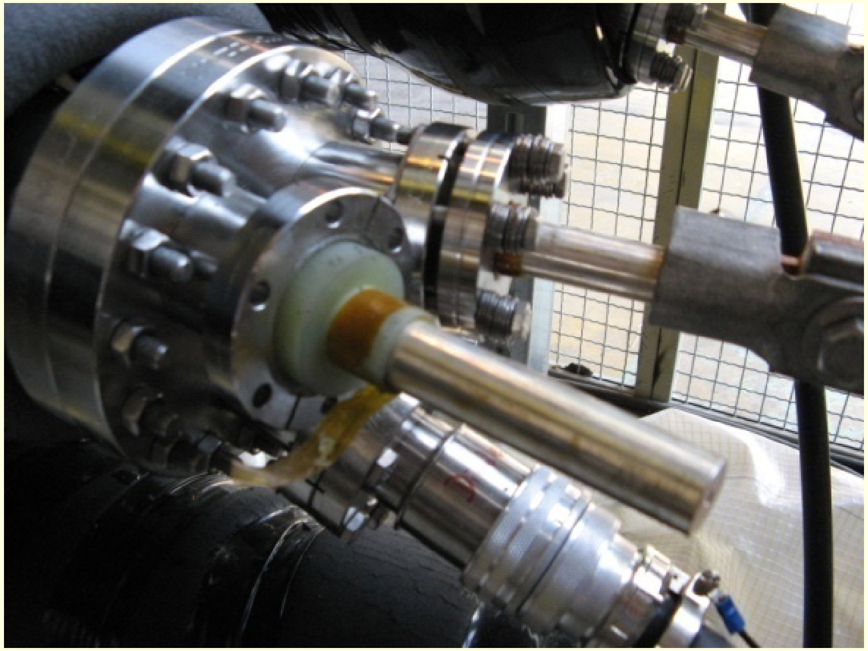
- **First challenge:** repair the magnet!
- CERN safety officials blocked installation underground until the solenoid was repaired: no leaks, minimum icing

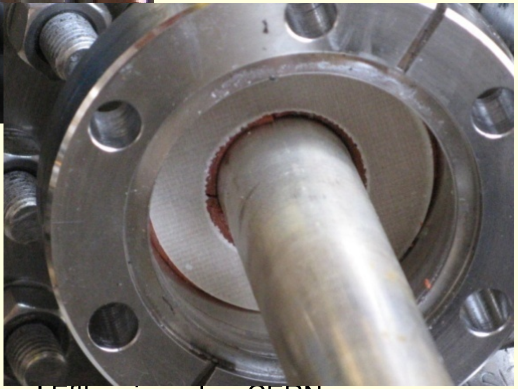


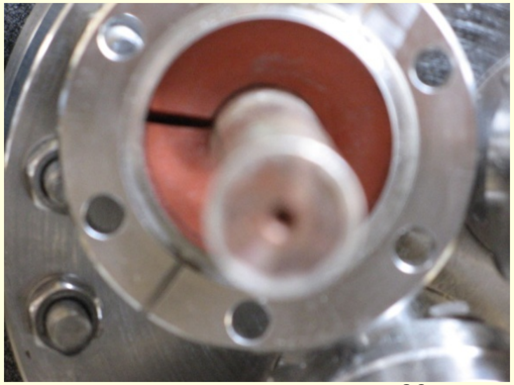
Solenoid repair work

- Fix the solenoid current feedthroughs!









Solenoid repair work

- Replace rubber material….

- Solution finally worked well – no leaks after several cooling cycles!

Installation

- The green light for installation was finally given on June, unfortunately beyond the end of the accelerator shutdown.
- Measurements in the nTOF/MERIT tunnels while beam was ejected to PS→ SPS showed radiation levels beyond the allowed limits.
- As a result access to MERIT for installation was conditioned with no beam to PS & SPS → major impact on the physics program of the lab
- Additional **double challenge**:
  - Find/inject slots in the CERN accelerator schedule without beam to the PS, SPS and AD experiments
  - Make a crash program to install the experiment AND the beam line to shortest time possible
- Delaying the experiment to 2008 was not considered in view of the even more complicated situation with CNGS and nTOF running and LHC startup.

Installation

- The access shaft was opened on **November 22, 2006**
- All preparatory work for the reception of the experiment was done during the machine shutdown

- Installation of the experiment on **June 14**
- Major effort from CERN transport team to do the installation in two days:
  - One day for the experiment
  - One day for the beam line

Installation

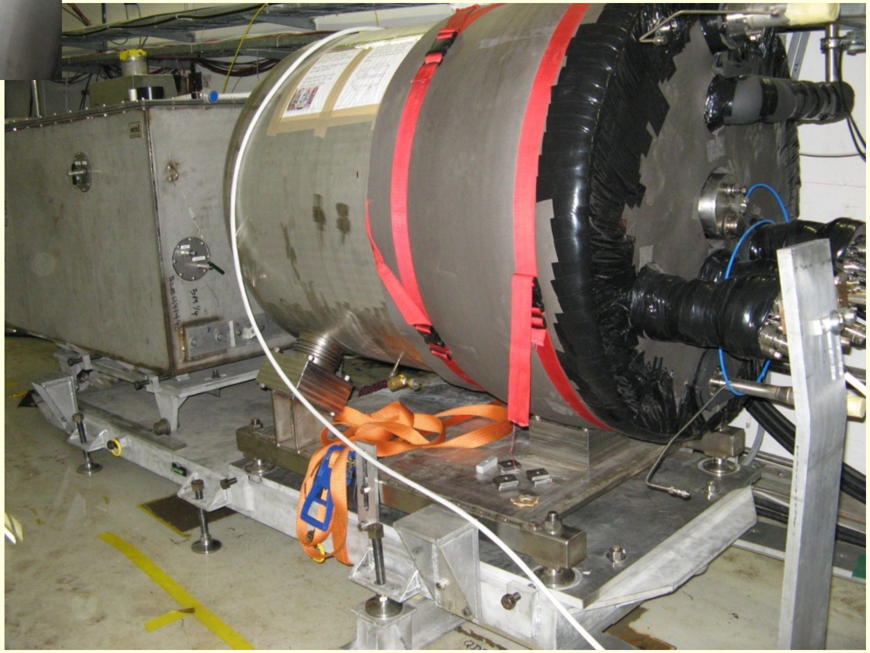
Lowering of the solenoid into the shaft

… down the TT2 tunnel (6% slope, 6T object)

… getting around the narrow turn between TT2/TT2A tunnels

Installation

Sophisticated alignment equipment !!



Proximity cryogenics: DVB and heater

End of the day: experiment installed and tilted to position

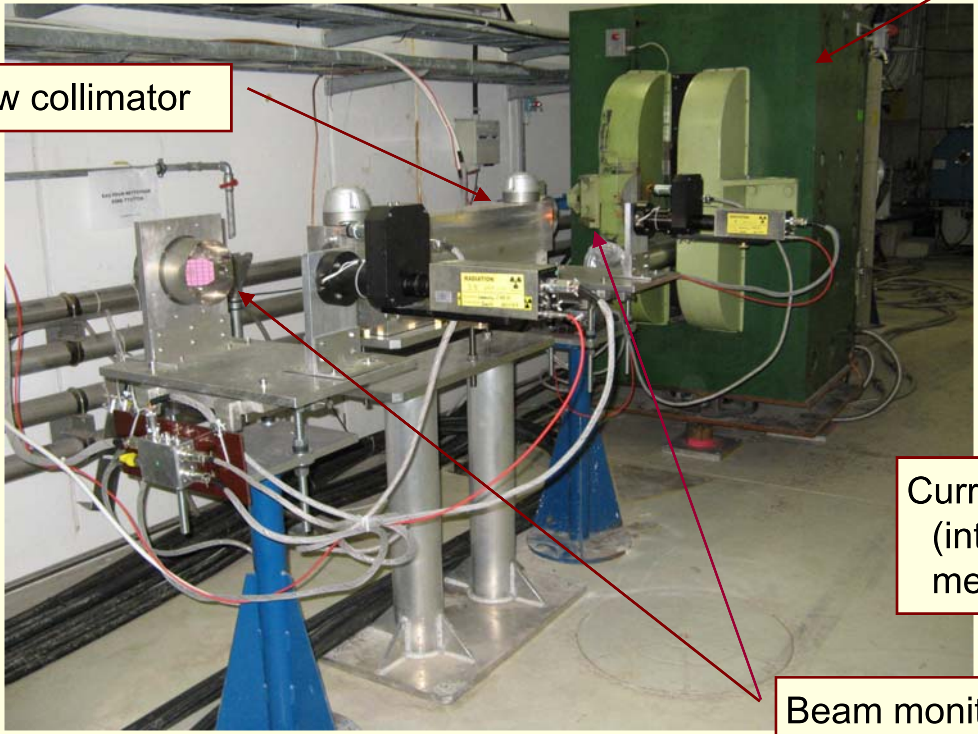
Installation

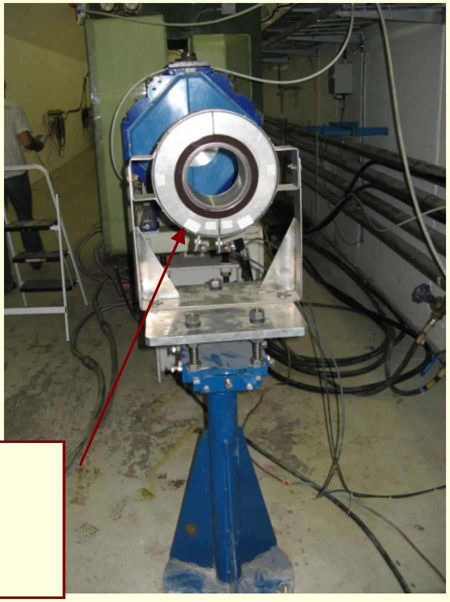
LN2 Dewar at the surface

Final adjustment of the optics in the primary container

Installation

- Upstream beam instrumentation





Vertical steering dipole

Fixed jaw collimator

Current transformer (intensity measurement)

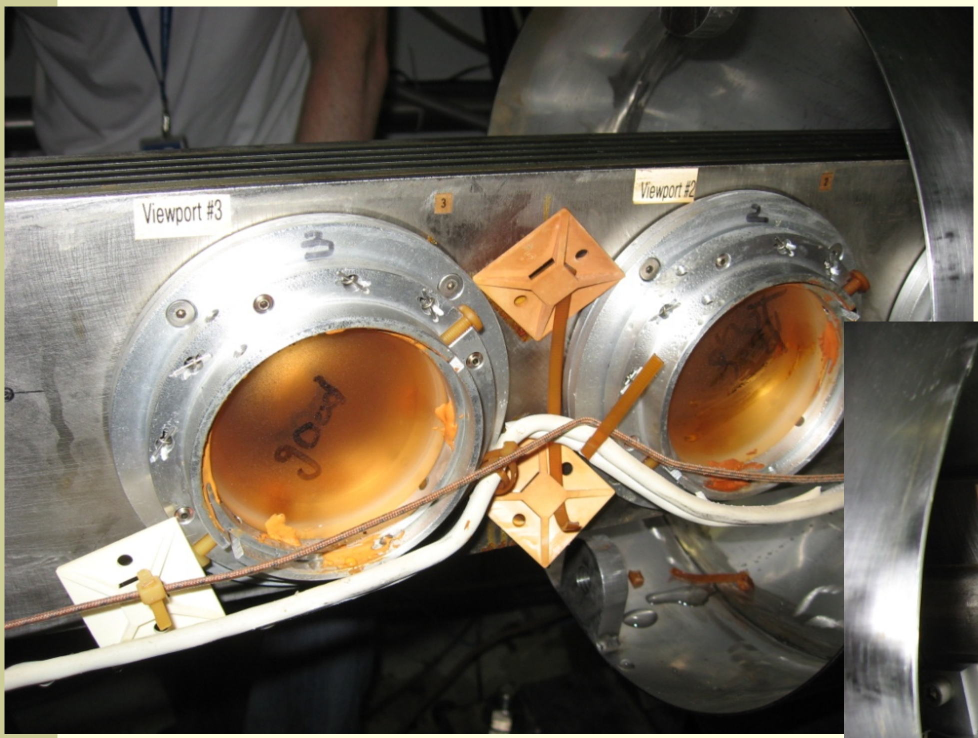
Beam monitors (profile)

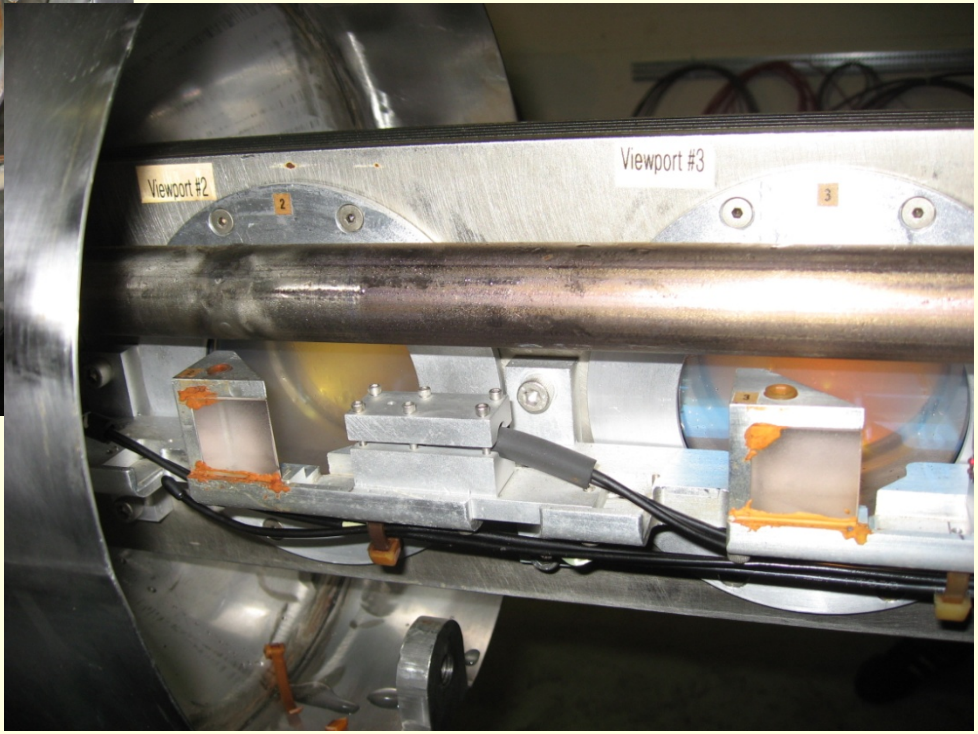
Installation completed!

Commissioning

- The installation of the experiment was finally completed on **August 28th**.
- Commissioning of the beam line, setting up of the PS machine and of the experiment started soon after.
- Unfortunately due to an operational error, the power supply of the solenoid was left in standby mode for ~18h, injecting a DC current of 60A to the solenoid.
- When discovered, the solenoid had reach ~170 deg-C and the optics diagnostics were severely damaged
- **Two new challenges:**
  - *negotiate new accesses to the experiment to check the magnet status*
  - *open the snout and repair whatever possible of the optics system*

Commissioning





Optical diagnostics viewports after the magnet heat-up incident

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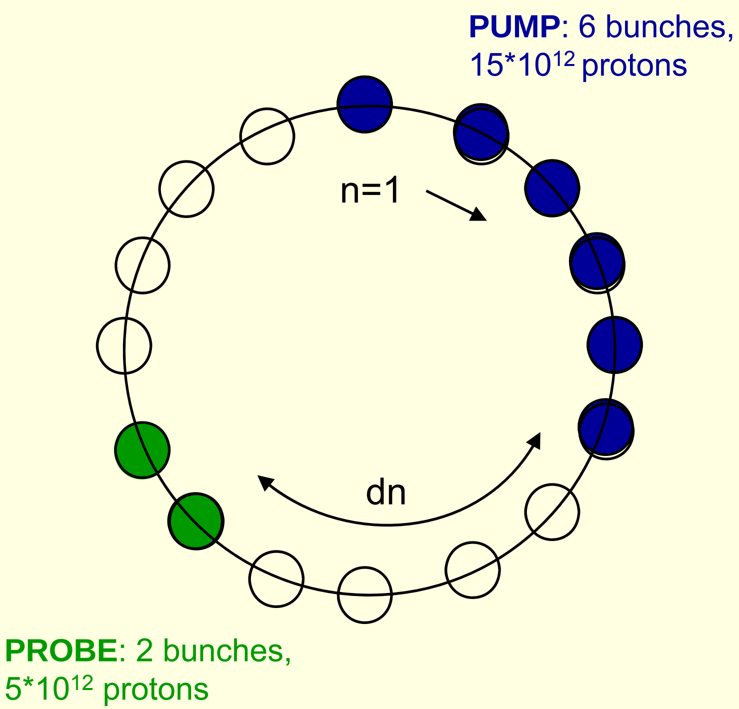
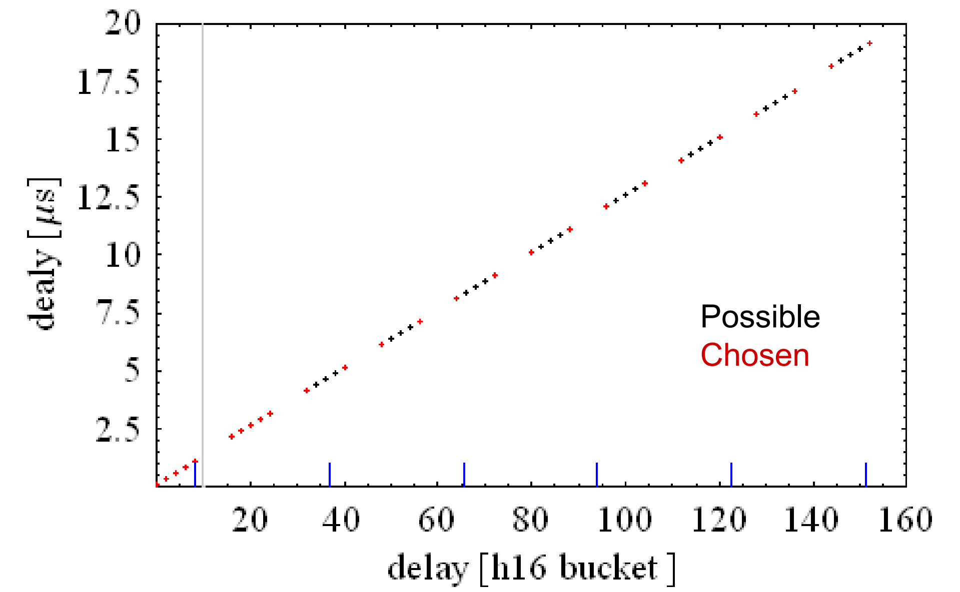
Operation with beam

- The repair work was finally made on **October 5th**
- At the end of the intervention three of the four viewports were operational although with some compromised image quality
- Since then, the rest of the run was very smooth without major issues.
- The run took place between **October 22nd** to **November 12th** (21 days)
- We managed to fully exploit the capabilities of the PS machine: 14 and 24 GeV/c of extracted beam, variable bunch structure and timing.

Beam setup for cavitation studies

- Setup the PS machine in harmonic-16
  - fill the machine in bunch pairs

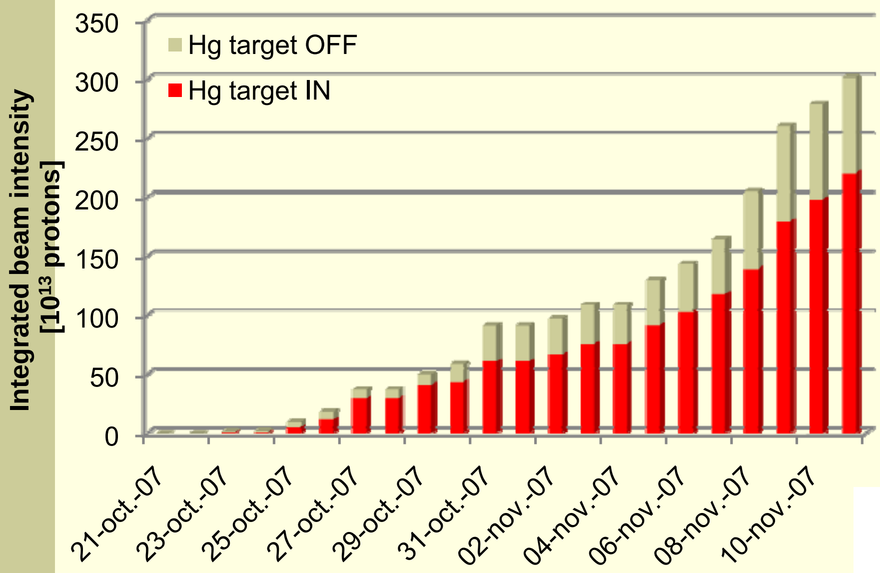




- $dn_{experiment}$ = 0,2,4,6,8, 16,18,20,22,24, 32,40, 48,56, …

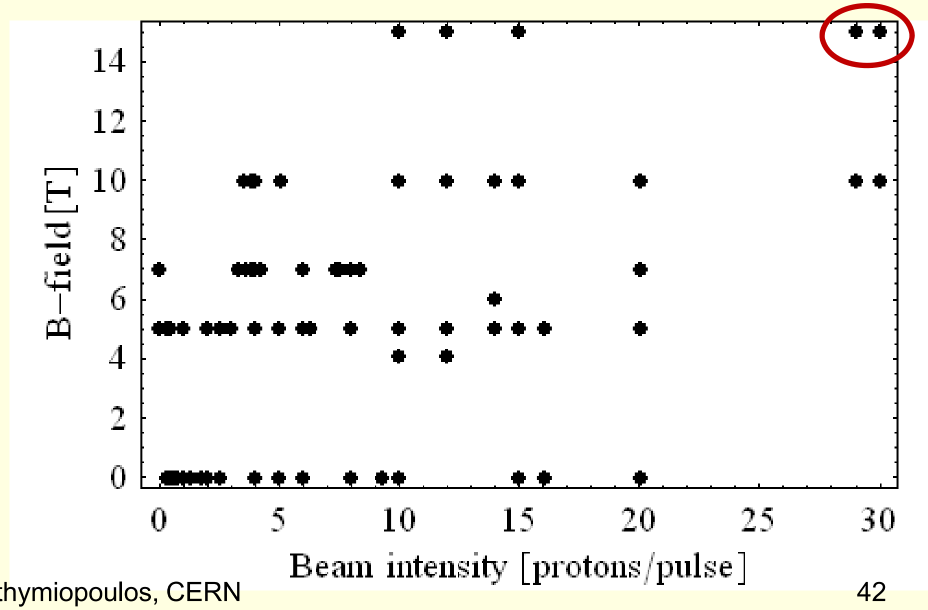
- switching between harmonic-8 and harmonic-16 was possible
- allowed us to study the target disruption length vs beam structure

Beam shots summary



30 TP shot @ 24 GeV/c

- **115 kJ** of beam power
- a PS machine record !



- Beam envelop – (1σ)

Beam [GeV/c]	Horiz. [mm]	Vert. [mm]	Spot [mm2]	Beam Density [J/gr @ 30 TP]
14	4.45	0.87	12.18	80.4
24	2.94	0.66	6.13	160

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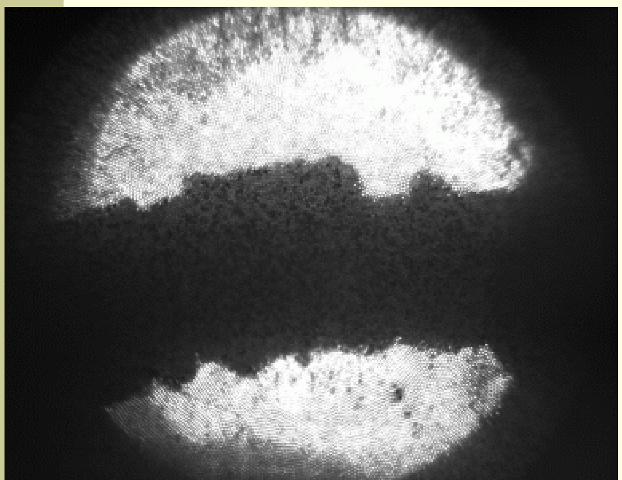
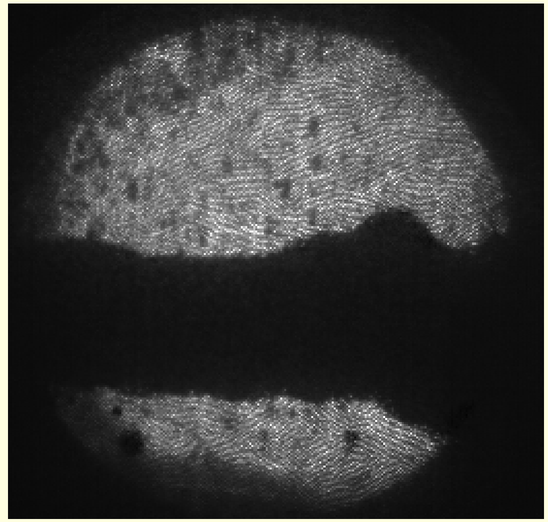
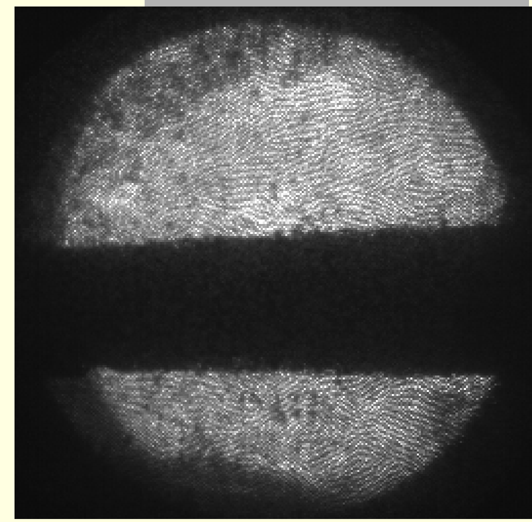
Interaction examples – 14 GeV/c



8 Tp beam, 0T field

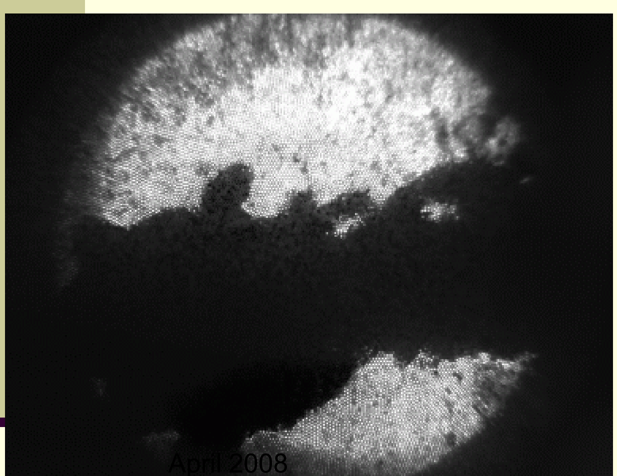


8Tp beam, 5T field

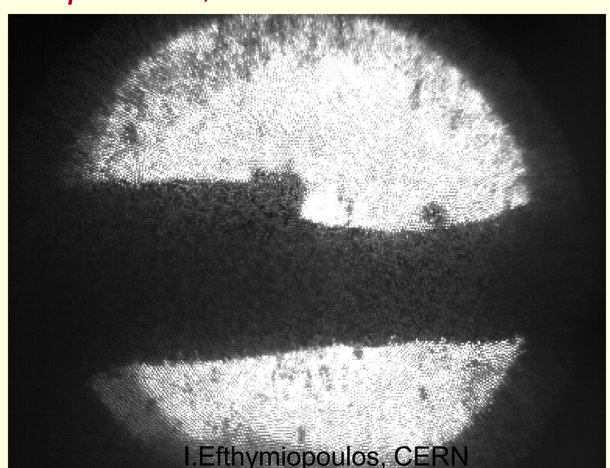


12 Tp beam, 10T field

4Tp beam, 0T field

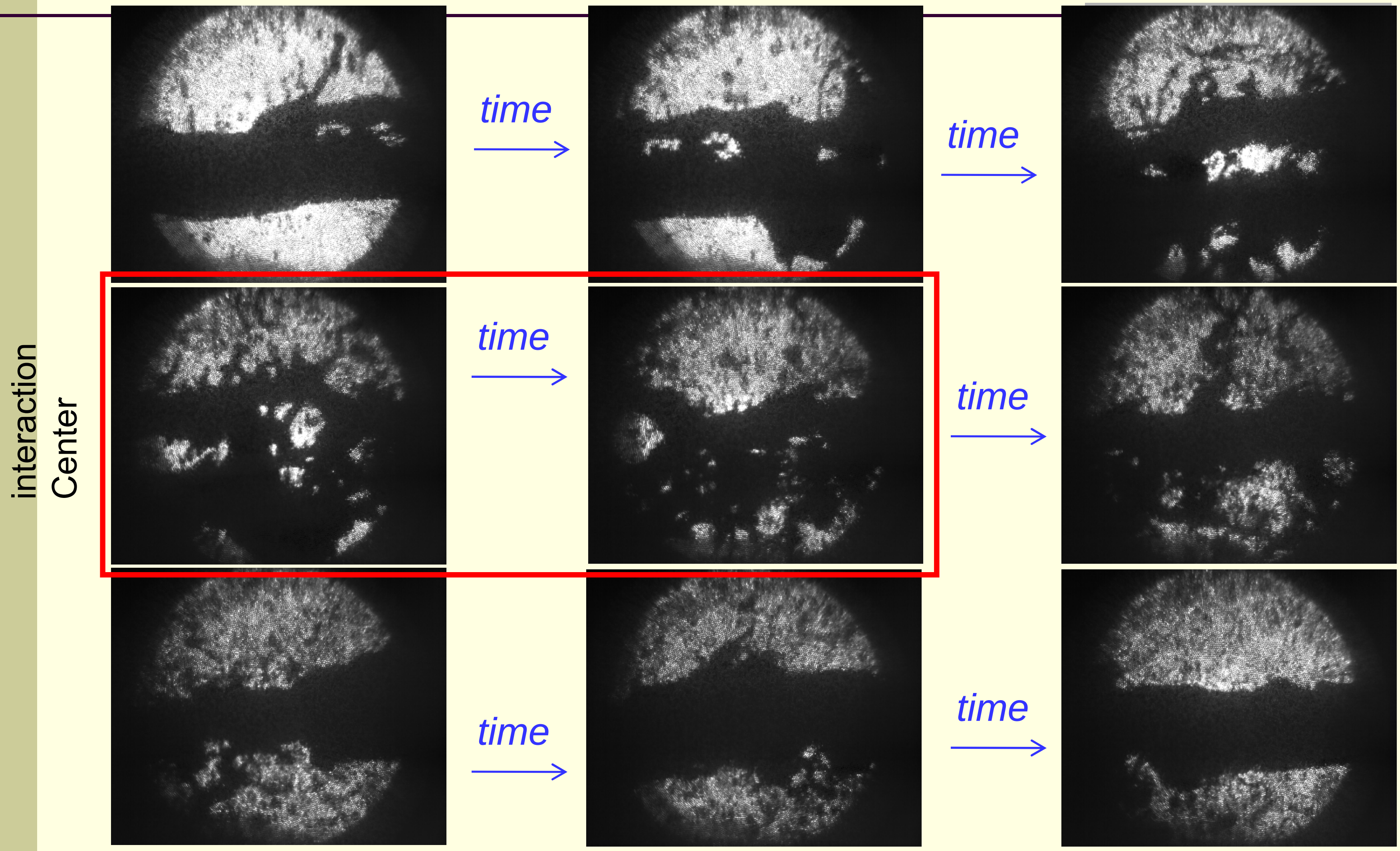


16Tp beam, 5T field



20Tp beam, 10T field

Interaction example - 16Tp, 5T, 14 GeV/c



Jet observations

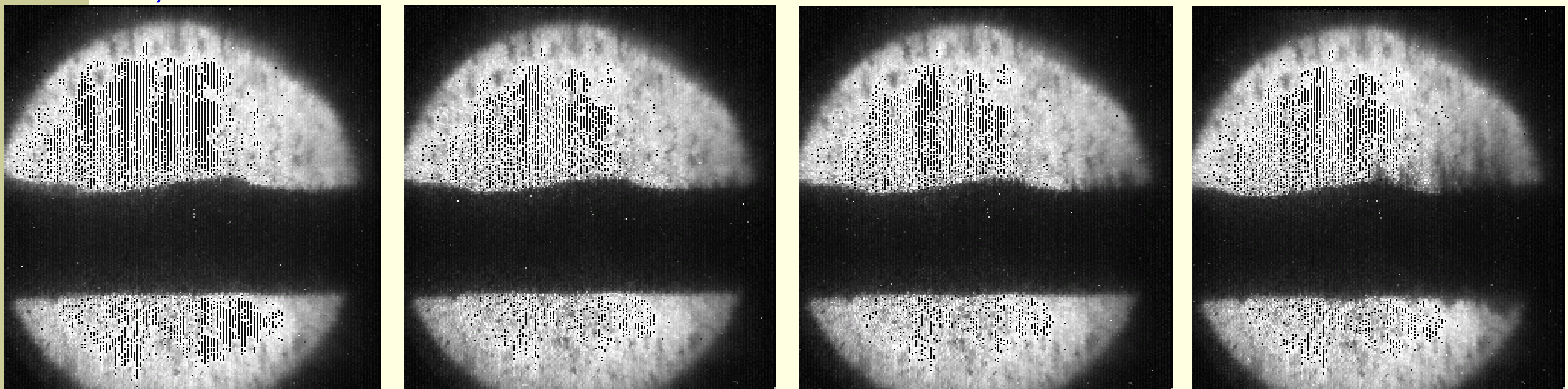
Summary-I

- The splash begins at the bottom of jet and ends at the top, which seems to be consistent with the beam trajectory.

- The breakup is consistent with the beam trajectory and could be the by-product of cavitation caused by the energy deposition of the proton beam.

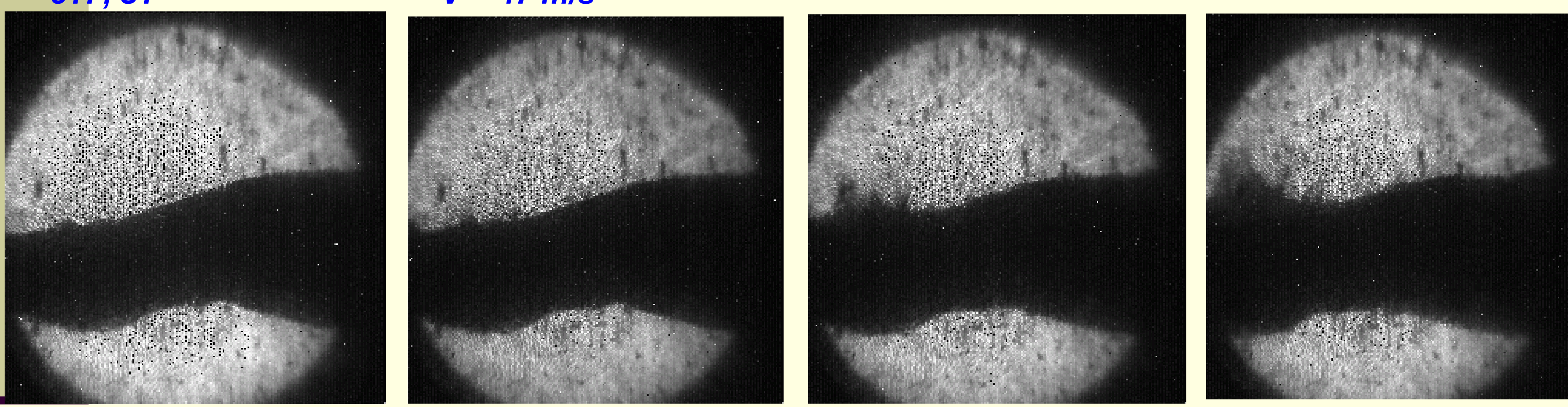
Splash velocity - 24 GeV beam

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



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

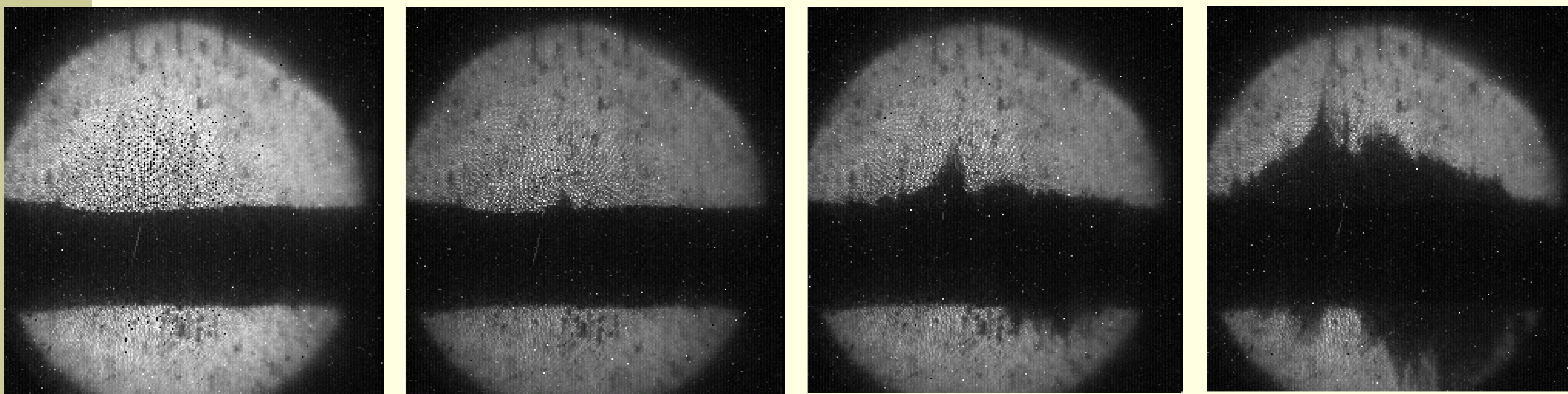
6TP, 5T **V = 47 m/s**



t=0 t=0.050 ms t=0.175 ms t=0.375 ms

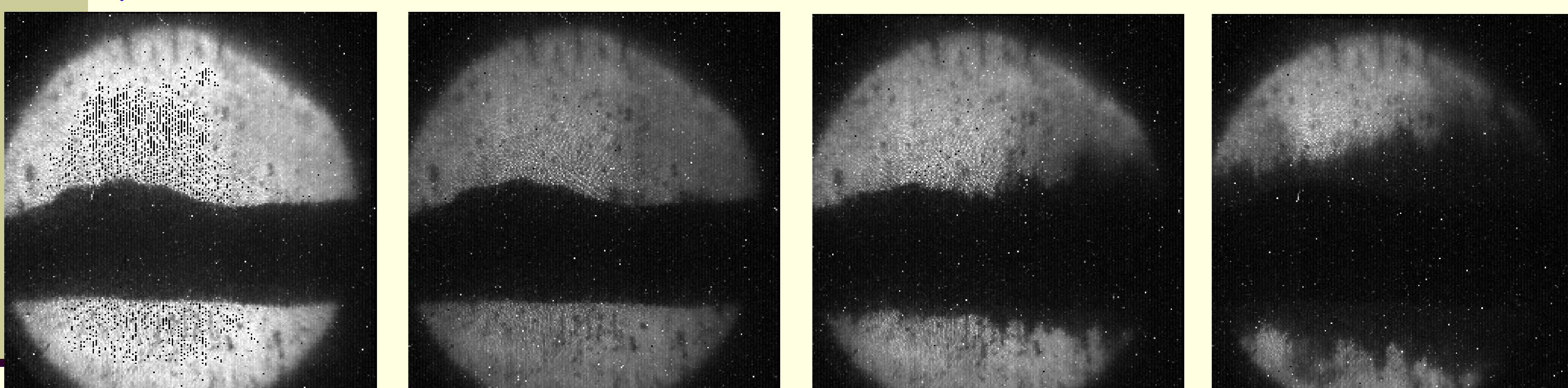
Splash velocity – 24 GeV beam

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



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

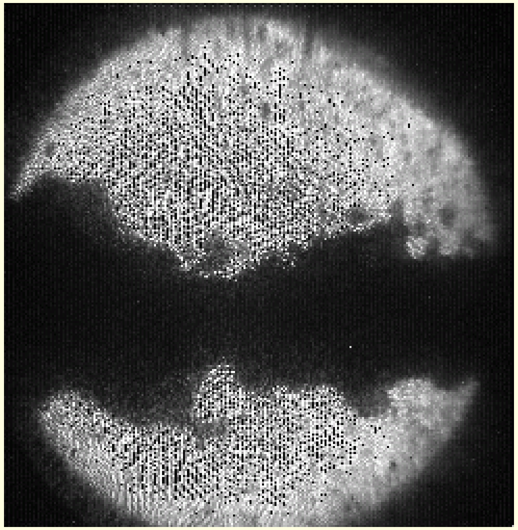
20TP, 15T **V = 65 m/s**



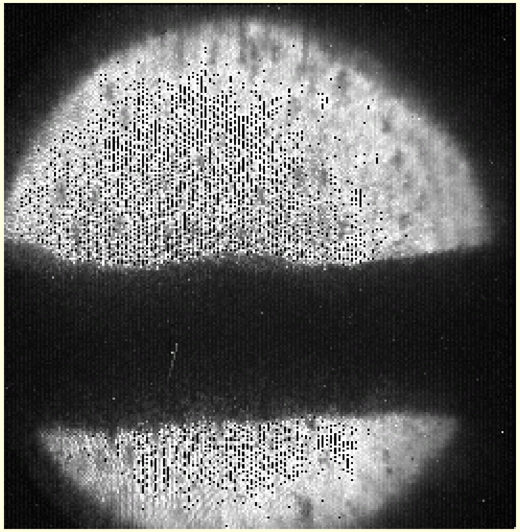
t=0 t=0.050 ms t=0.175 ms t=0.375 ms

Hg-jet vs Magnetic field

0.4 T

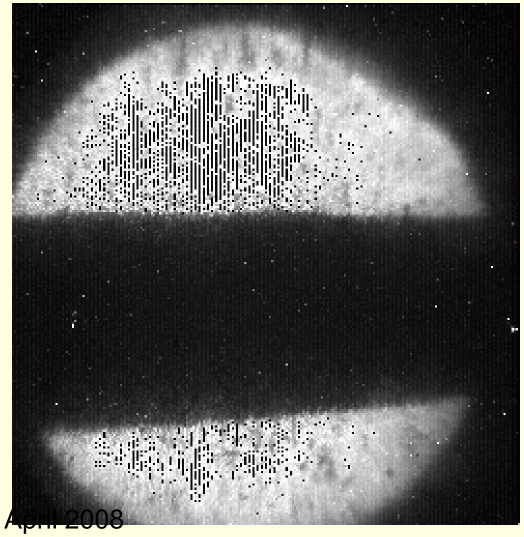


5 T

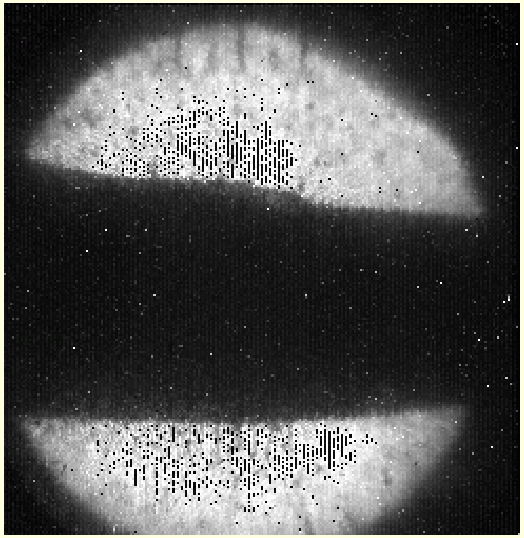


Jet velocity : 15 m/s

10 T

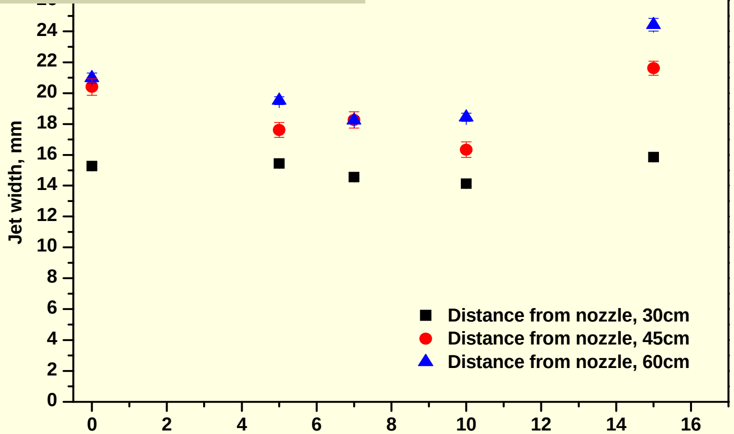


15 T

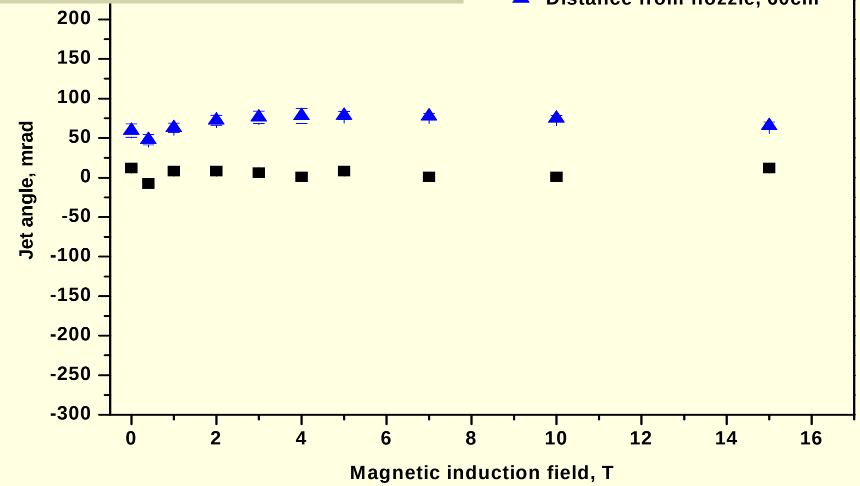


Hg-jet properties – 15m/s jet

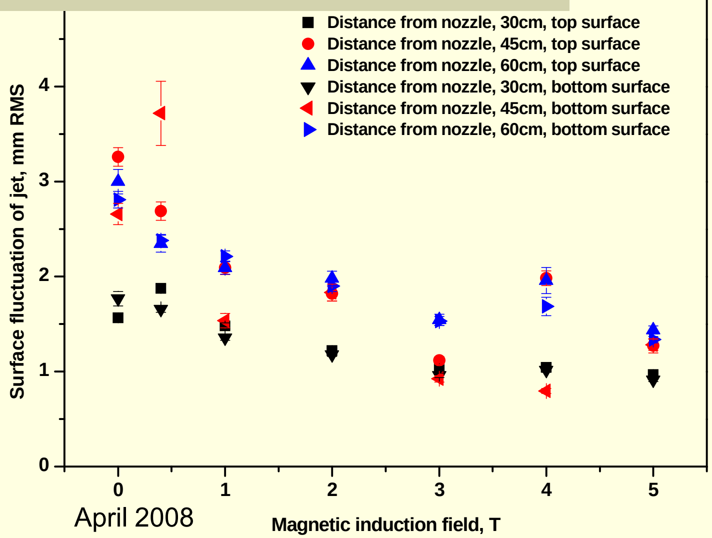
Jet width vs magnet axis



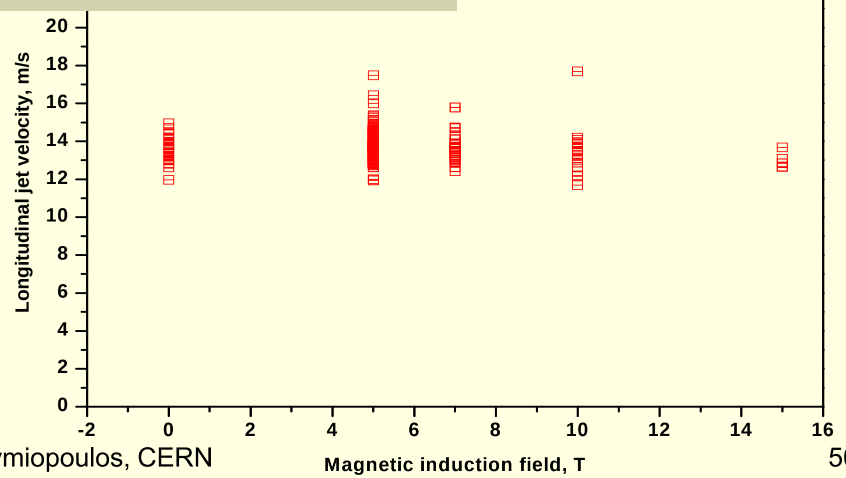
Jet angle vs magnetic field



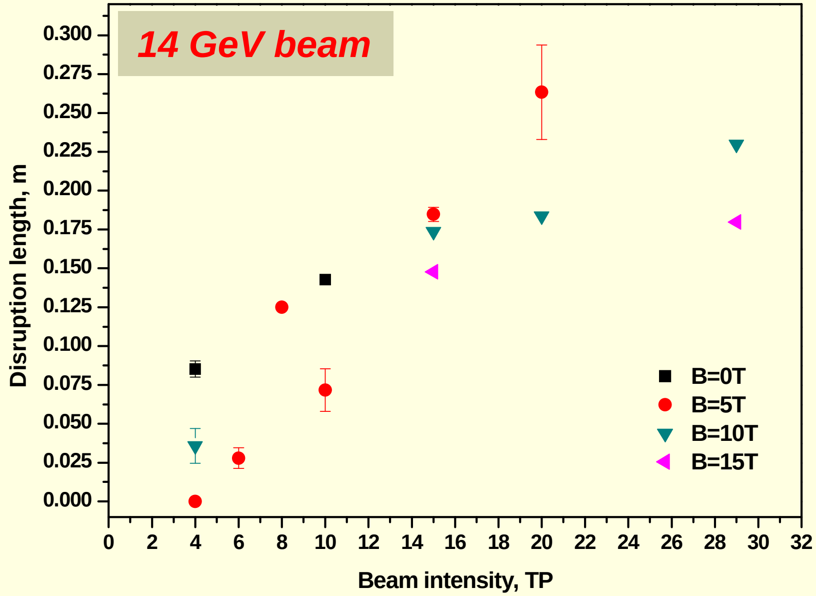
Jet width fluctuation vs magnetic field



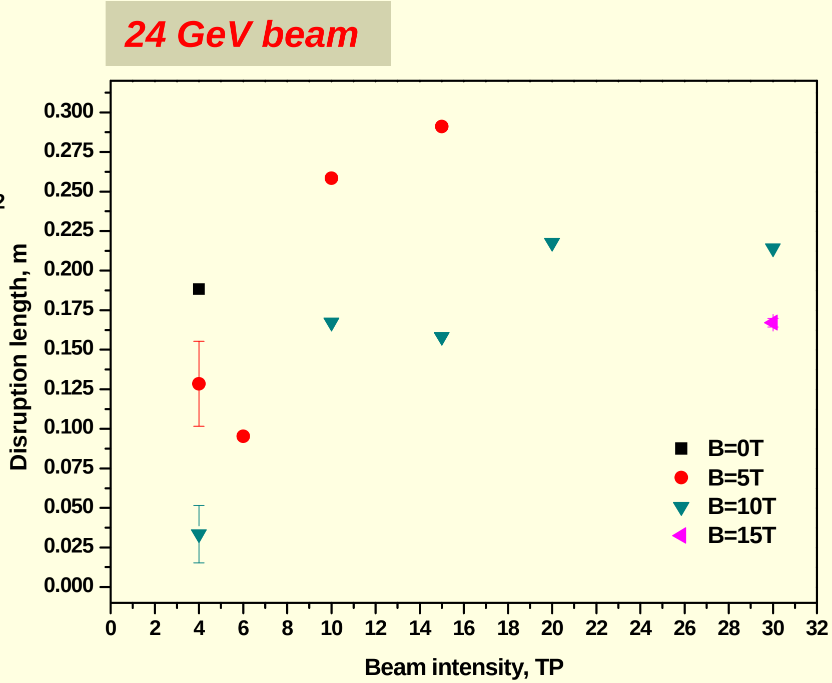
Jet speed vs magnetic field



Disruption length vs beam intensity



- Disruption length @ 24 GeV is about 20cm for 10-15T field
- In a 20m/s jet, 28cm ($2\lambda_I$) can be renewed in 14ms which means a rep rate of 70 Hz or equivalent of **8 MW** of beam power !



Jet observations

Summary-II

- The break up of the Hg jet is influenced by the magnetic field.
  - The splash velocity increases as the beam intensity increases, however, magnetic field reduces the effect
  - The Hg jet disruption length is suppressed by magnetic field.

- The 24GeV proton beam results in a longer disruption length than the 14GeV proton beam. The intensity threshold for the 24GeV beam is lower than the 14GeV beam.

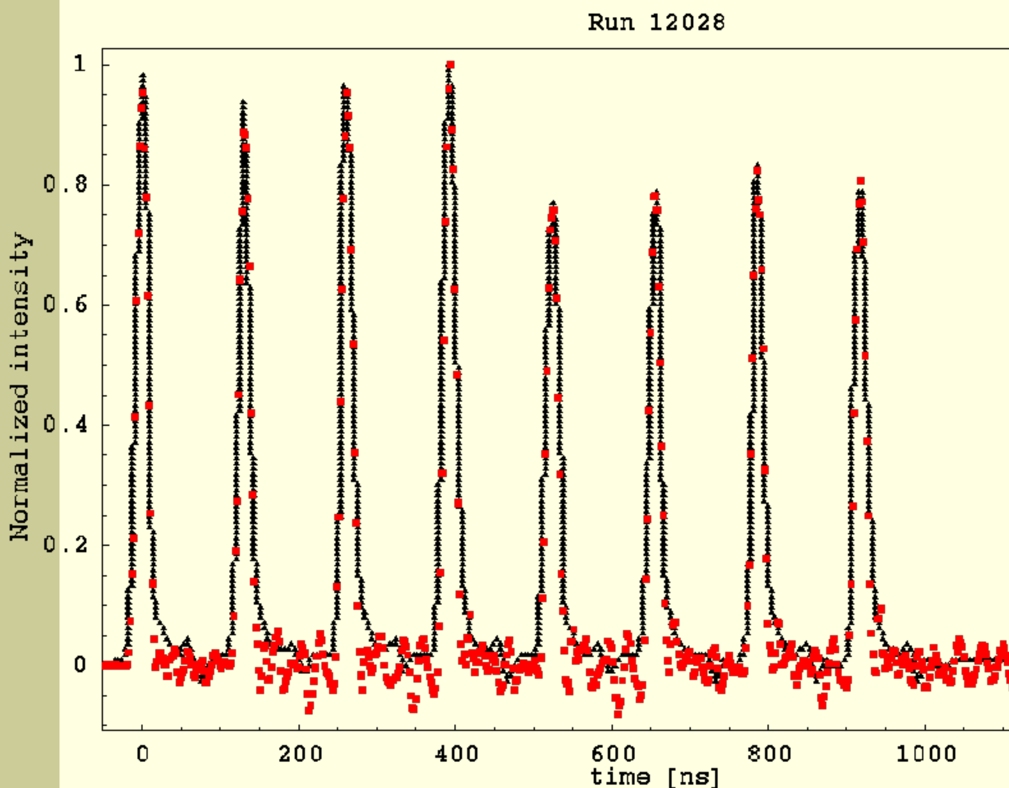
- The magnetic field stabilizes the Hg jet flow.
  - The fluctuations on the jet surface decreases as the magnetic field increases.

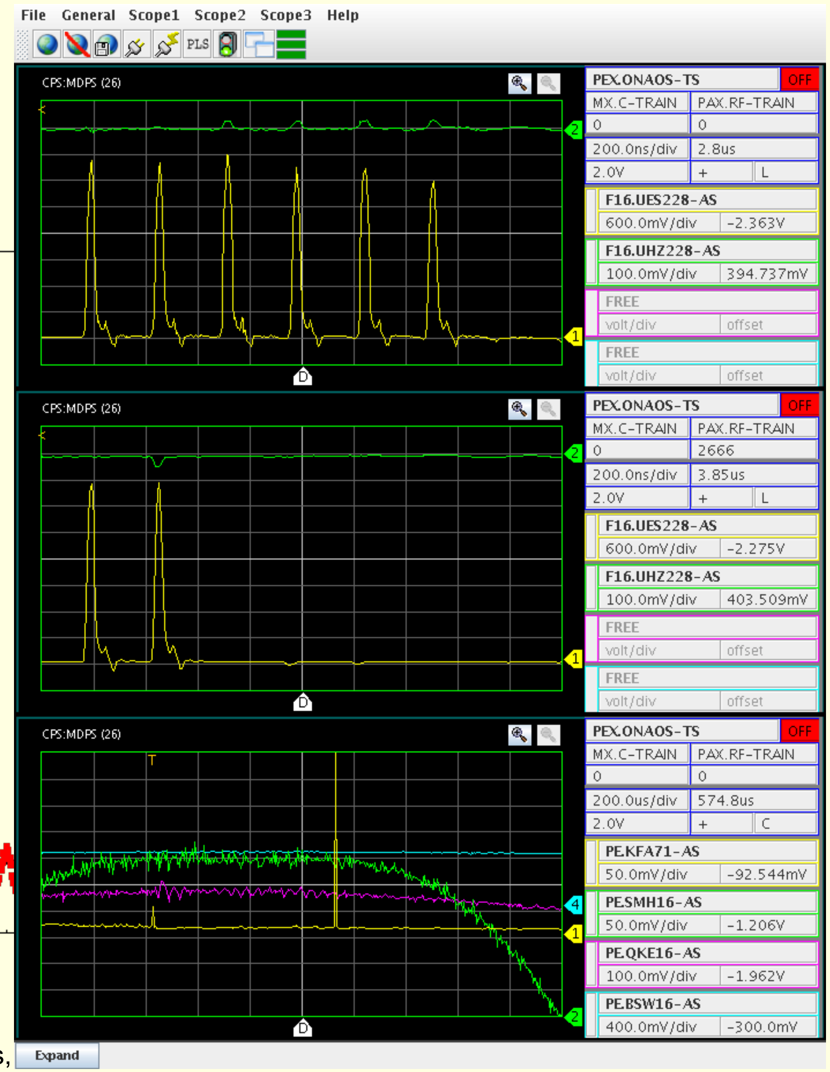
- The jet size increases as it moves to downstream and it was same up to 10T but increases at 15T.
  - The jet size at 10T was smaller than that for a 15T field, which might have varied between the major and minor axis of an elliptical core.

- The longitudinal Hg jet velocity was not affected by the magnetic field.

Proton beam intensity measurement

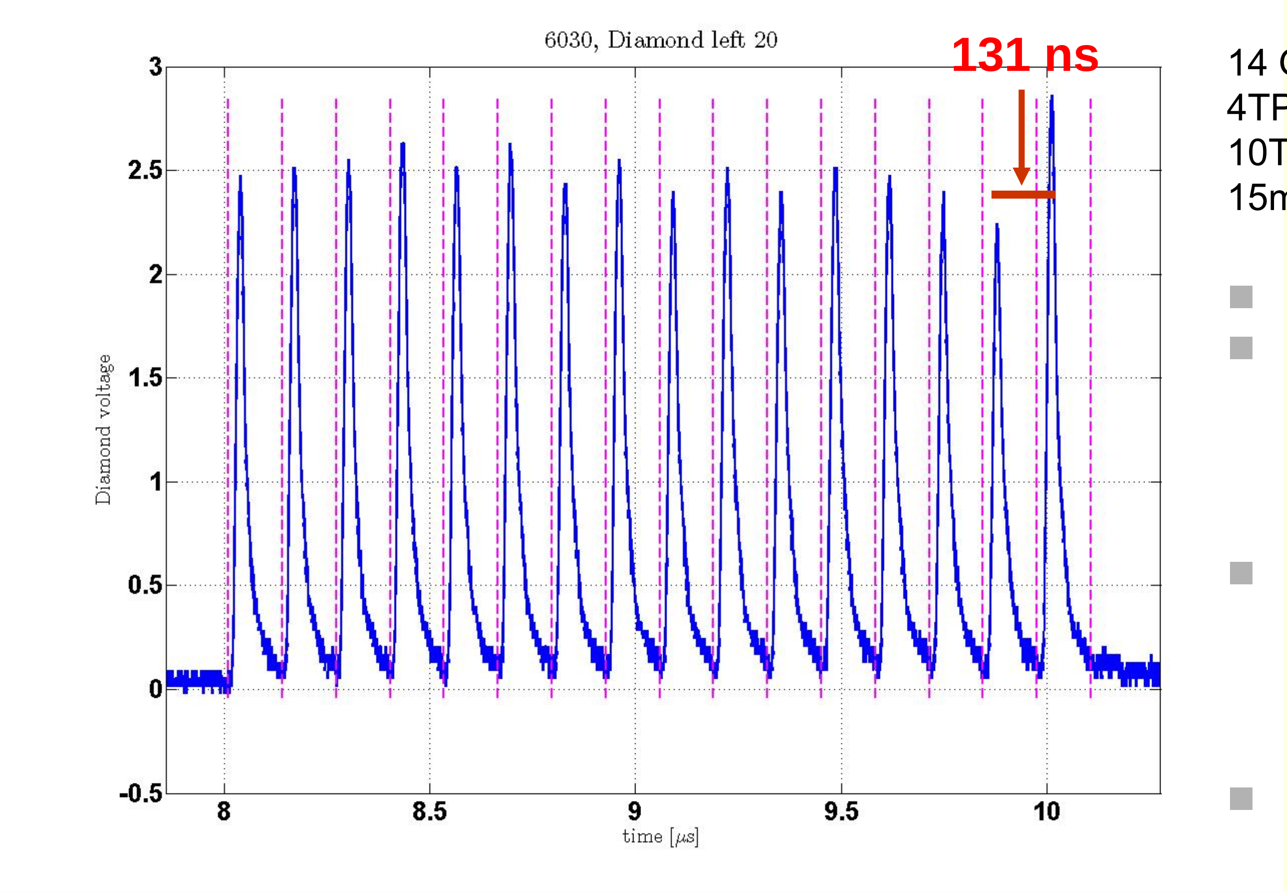
- Current transformer data analysis
- Non-trivial analysis due to internal noise in the device





Particle detector data

- pCVD diamond detector (left 20-deg location)

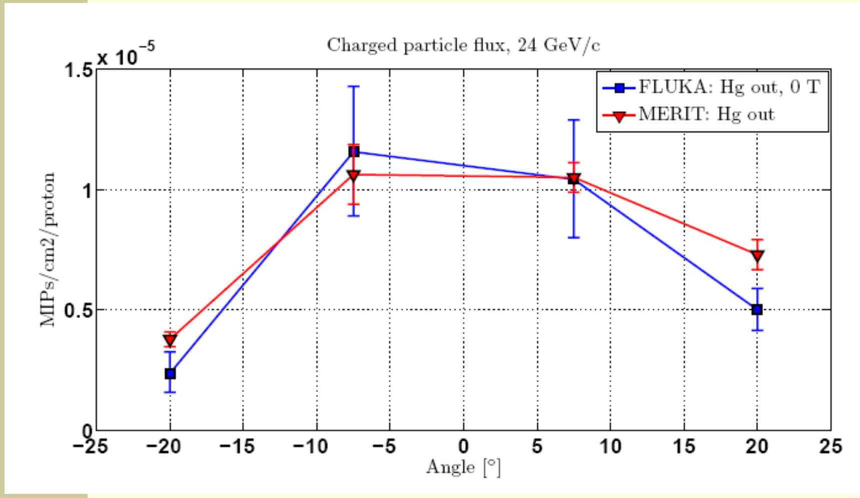


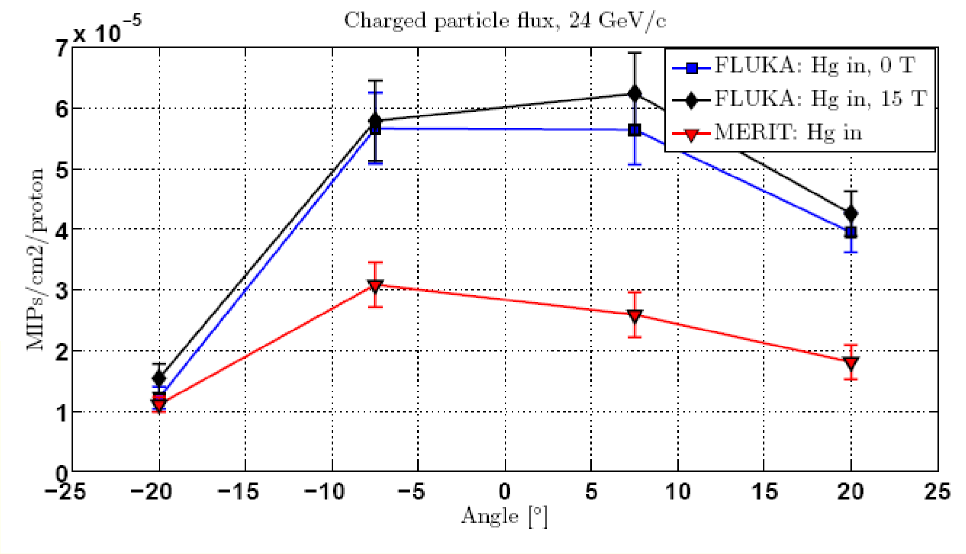
14 GeV beam
4TP
10T Field
15m/s Hg Jet

- Good performance
- Able to identify individual bunches event at the highest intensities
- Needs to be combined with the beam intensity per bunch to normalize
- Data analysis ongoing…

Particle detector - flux measurement

- Good agreement with MC simulation for target-out data
- Large discrepancy for target-in case
  - needs further understanding, along with further simulation studies and beam spot analysis





Data Analysis Pipeline

- Disruption threshold based on proton beam characteristics
  - intensity variations
  - proton beam harmonic structure
- Disruption threshold based on solenoid field strength
- Pump/probe studies
  - 15TP pump + 5TP probe with delays 2 to 700μs
  - 24 GeV pump/probe studies with delays < 2μs
- Magnetodynamic studies
  - disruption (filamentation) velocities
  - quadruple distortions
- Proton beam spot size analysis

Dismantling of the experiment

- We proceeded to the dismantling of the experiment as planned:
- Step #1:
  - At the end of the run the experiment will remain in place for a **cool-down time** until the machine shutdown (November '07)
    - The Hg will be emptied and stored in the flasks in TT2 tunnel
- The mercury emptying was done the week **February 4-8**
- Due to a last minute modification to the procedures and a human error, a mercury spill to the floor occurred
  - small quantity, mostly contained in the primary and secondary envelops
  - clean-up was very efficiently done using the available tools
  - safety inspections by CERN officials and related documentation prepared:
    - accident report and "lessons learned" documents compiled according to CERN safety rules

Dismantling of the experiment

- Step #2:
  - During the **2008 shutdown** the experiment will be removed from the tunnel
    - All equipment will be stored at CERN for **one year cool down**
- Done in several steps according to availability of CERN transport team
  - Status today: tunnel empty from all MERIT material, floor repainted, nTOF line is being re-installed
- All material stored in the temporary radioactive storage at CERN
- Discussions on the best way for the transport to US ongoing
  - Actual transport will happen early January 2009

MERIT Dismantling – March 2008

MERIT Dismantling – March 2008

Summary

- After facing successfully several challenges, the MERIT experiment took beam as scheduled for three weeks in autumn 2007 at CERN PS
- All systems performed well, the run with beam was very smooth and the whole scientific program was completed
- The experiment was dismantled in winter 2008 with its components put in temporary storage for cool-down at CERN waiting to be shipped back to US
- The primary objective to conduct a successful and safe experiment at CERN was amply fulfilled
- Important results validating the liquid metal target concept are already available, more to come as the analysis progresses
- The MERIT experiment represents a big step forward in the targetry R&D for high power targets.