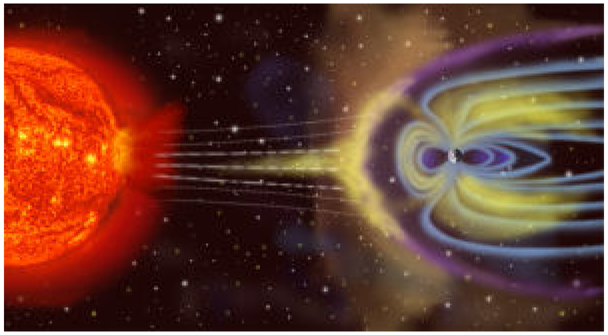
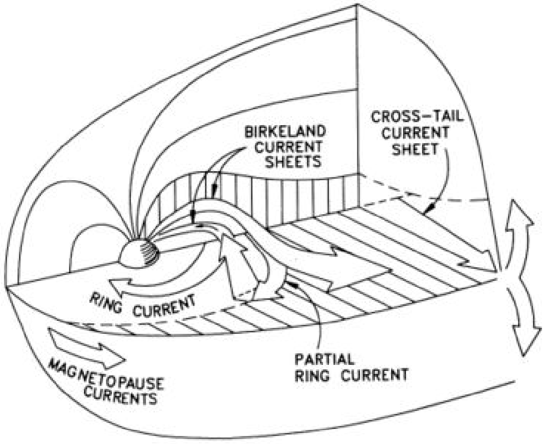
MagnetoHydroDynamics (MHD)

- MHD consists in solving Maxwell's and fluid dynamics equations for conducting fluids.
- Every day's examples of MHD
  - Earth's magnetic field, the Riga dynamo experiment
  - Plasma physics, magnetosphere, stars (sun's spots)
  - Metallurgy (flow control and steering of molten metals)

Forces on charged particles:

Electrostatic	q **E**
Electrodynamics	q d**B**/dt
Lorentz	q **V**×**B**





Hannes Alfvén, received the Nobel Prize in Physics in 1970 for his contribution to MHD

The Riga Dynamo Experiment

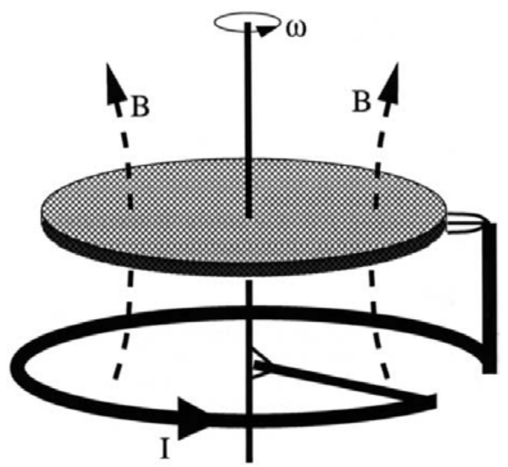
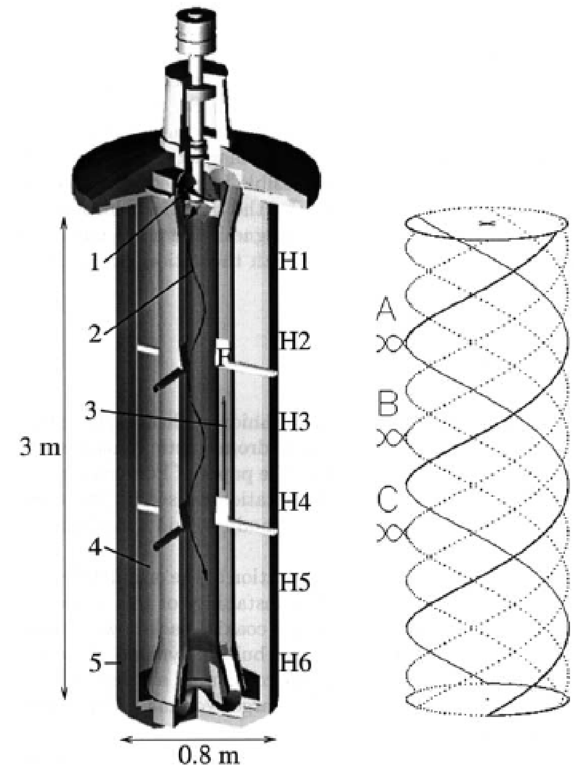
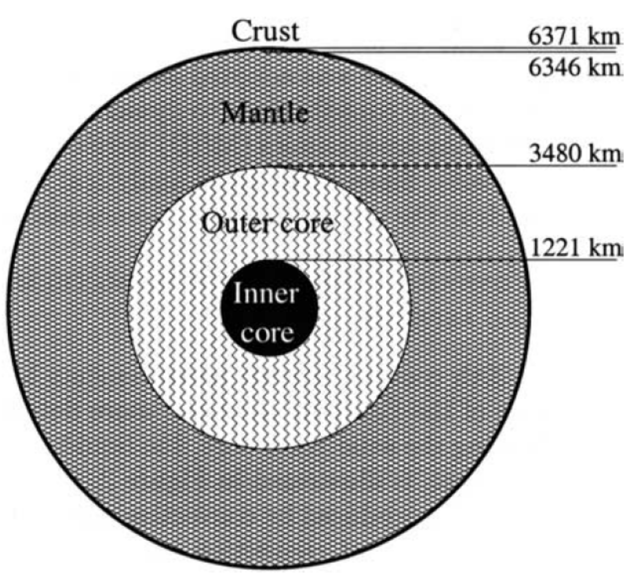


Figure 1. Bullard's disk dynamo. The rotation of the disk in a given magnetic field B induces a current in the wire that amplifies the magnetic field. At a certain critical value of the rotation rate ω, self-excitation occurs.





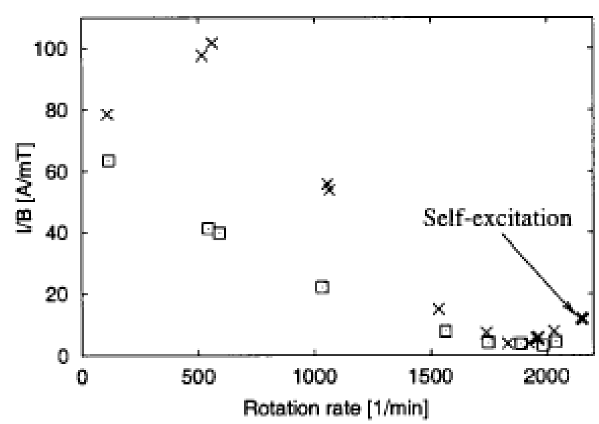


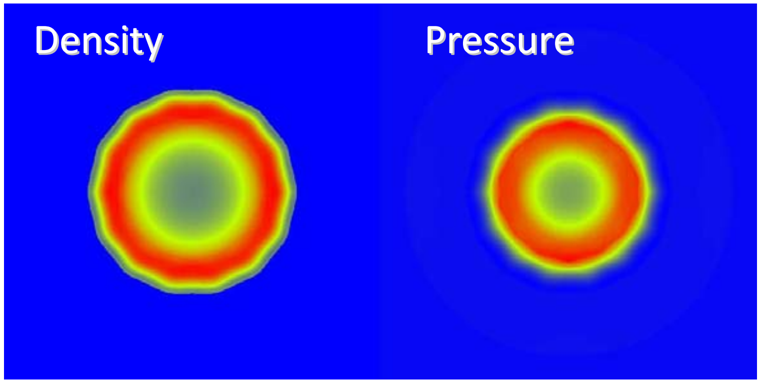
Figure 5. Magnetic field amplification depending on the propeller rotation rate for a seed field frequency $f = 1$ Hz. The ordinate axis shows the inverse relation of the measured magnetic field to the current in the seed field coils. Squares and crosses correspond to two different settings of the 3-phase current in the seed field coils with respect to the propeller rotation. At the highest rotation rate of 2150 rpm, self-excitation occurred, in addition to the amplification of the seed field.

References, further reading

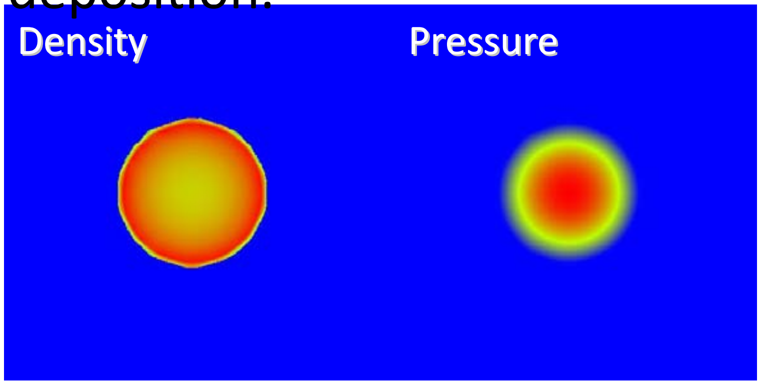
- Alfvén, H., "Existence of electromagnetic-hydrodynamic waves" (1942) Nature, Vol. 150, pp. 405.
- The Riga Dynamo Experiment, A. Gailitis et.al, Surveys in Geophysics 24: 247–267, 2003.
- An Introduction to Magntohydrodynamics, P.A. Davidson, Cambridge 2001.

Numerical example: propagation of shock waves due to external energy deposition

Evolution of a hydro shock.



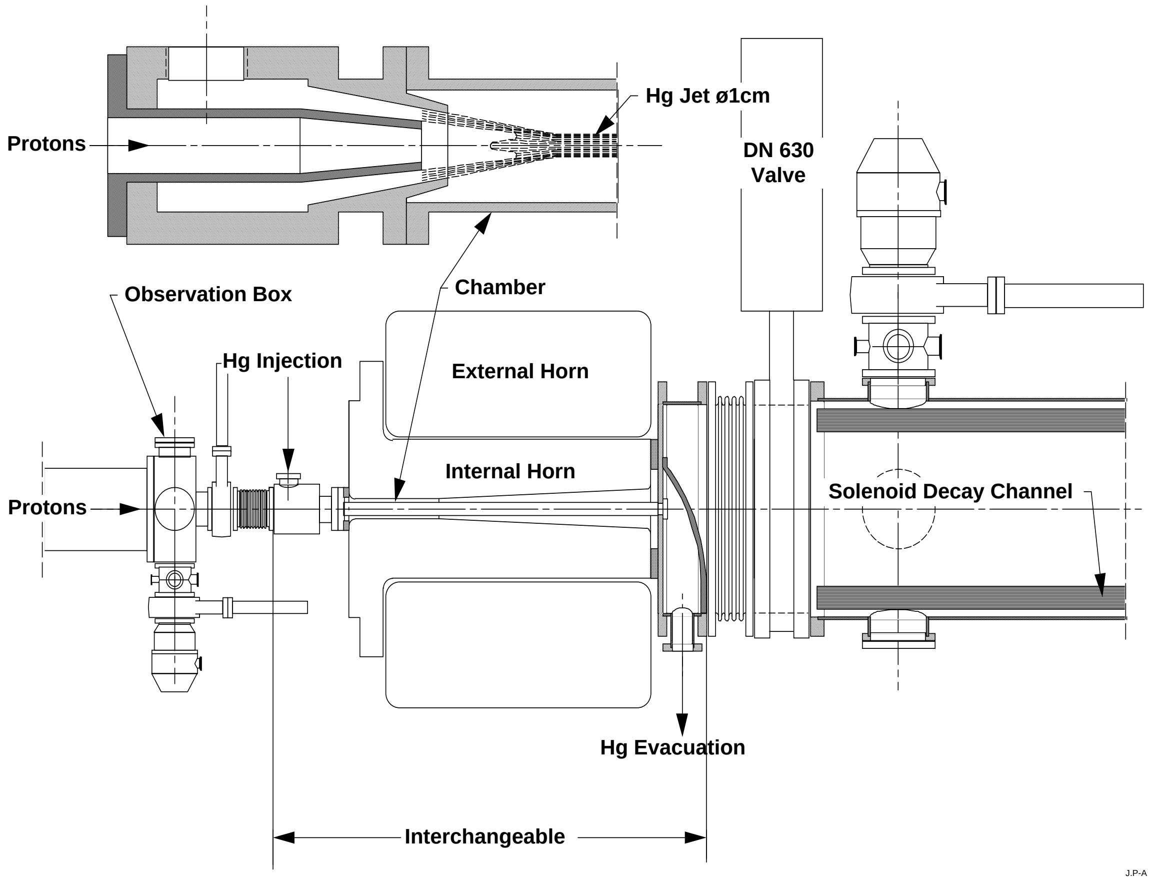
MHD effects reduce the velocity of the shock and the impact of the energy deposition.



R. Samulyak

MHD in Nufact targetry

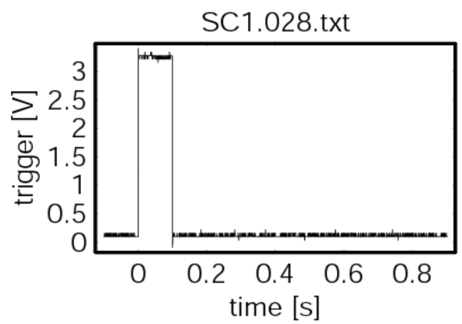
- Injection of the High velocity Hg jet into a 20 T dc-magnetic field
- Nozzle, MHD enhanced corrosion (Hartmann Layer)



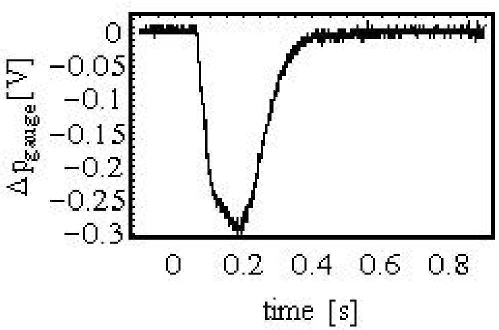
J. Pier Amaury
CERN Nufact team

Setup of the observation chamber in the M9 magnet

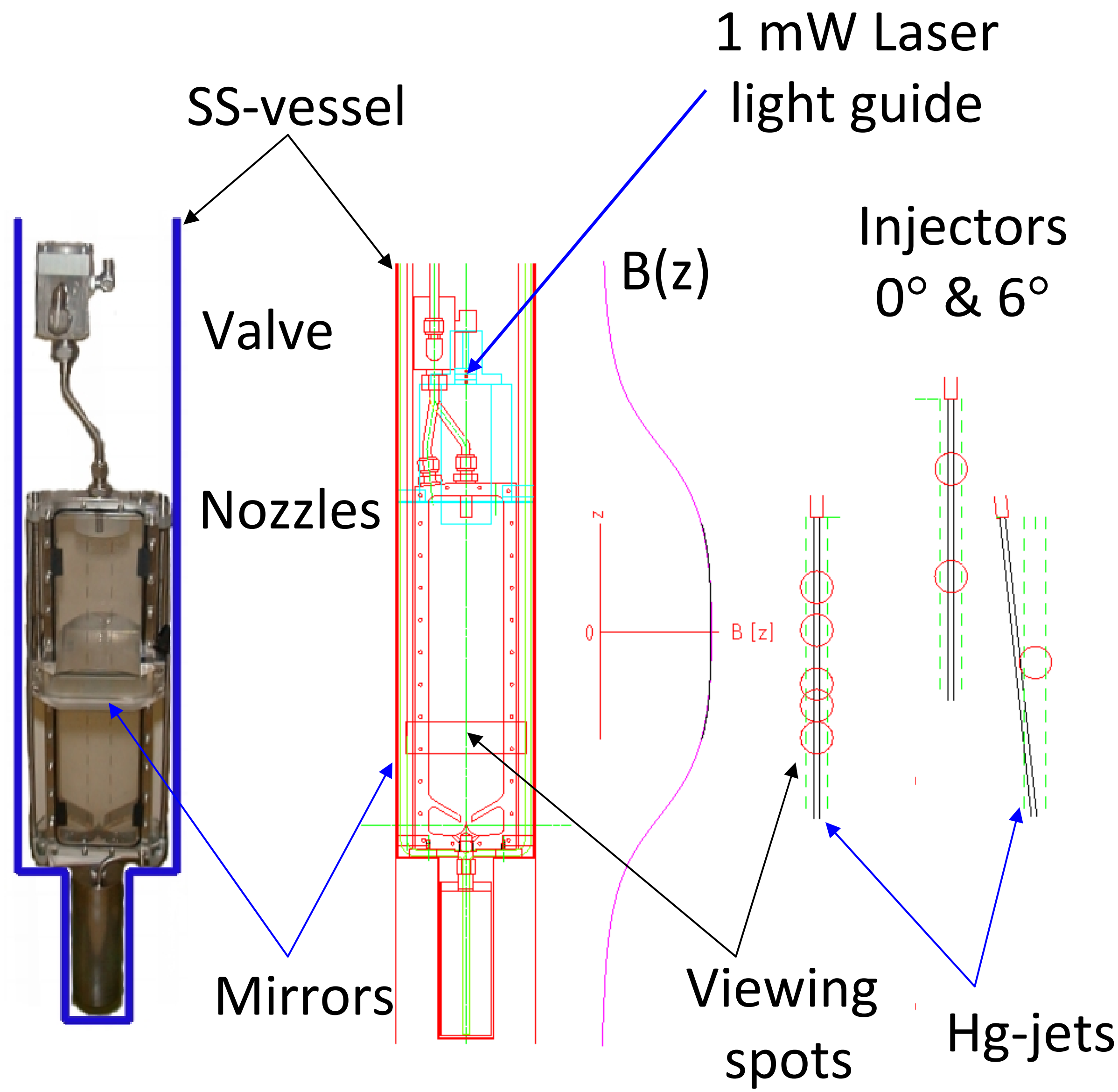
Air activated Hg-pump



Pneumatic valve trigger signal

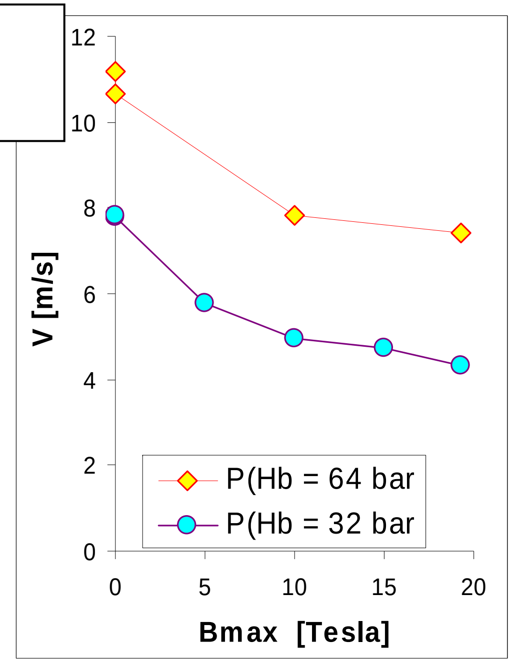


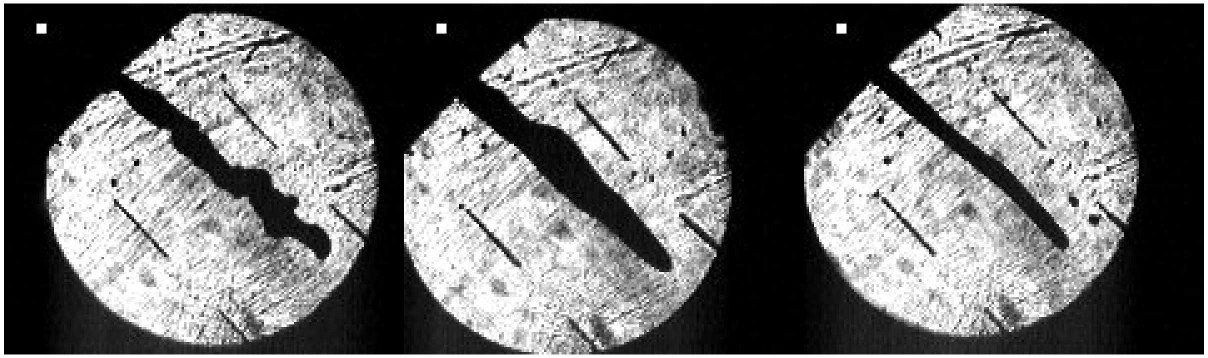
Hg-dynamic pressure in the pipe between pump and valve



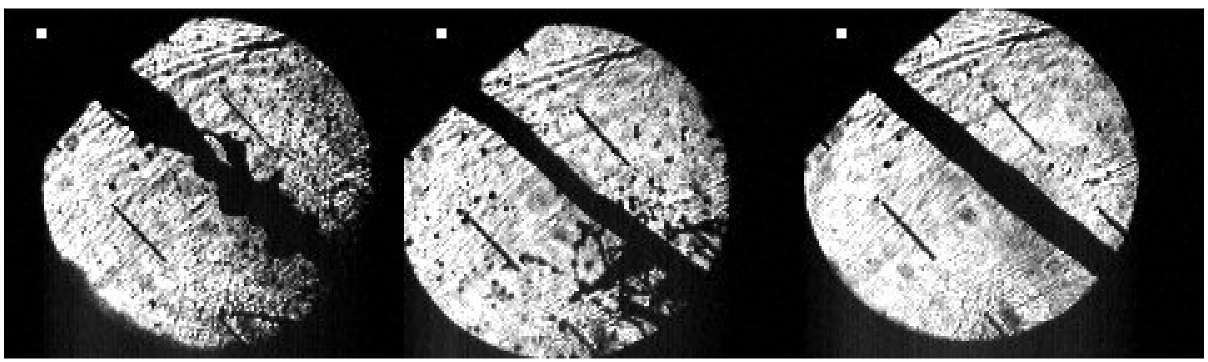
Jet velocities and shapes, injection at 6°, P(Hg) = 64 bar

Ref: A. Fabich
PhD. thesis TUV

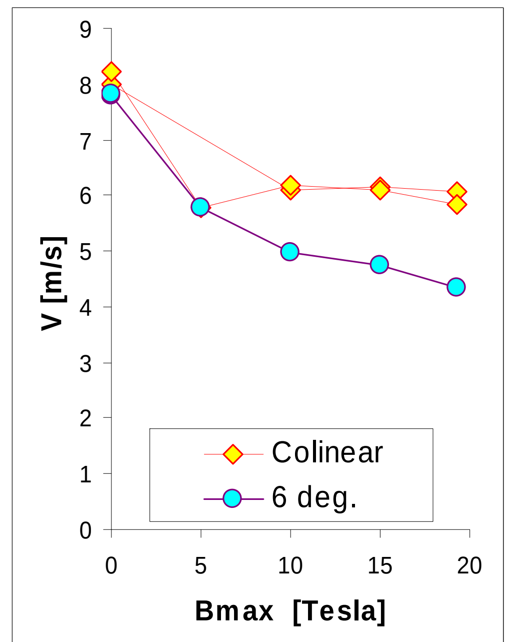




0 T **10 T** **19.3 T**

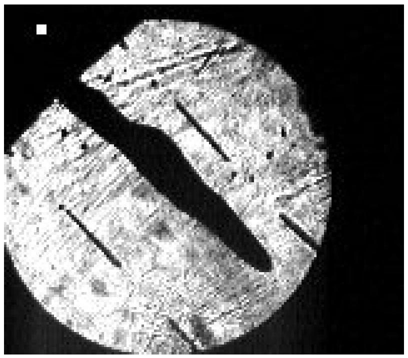


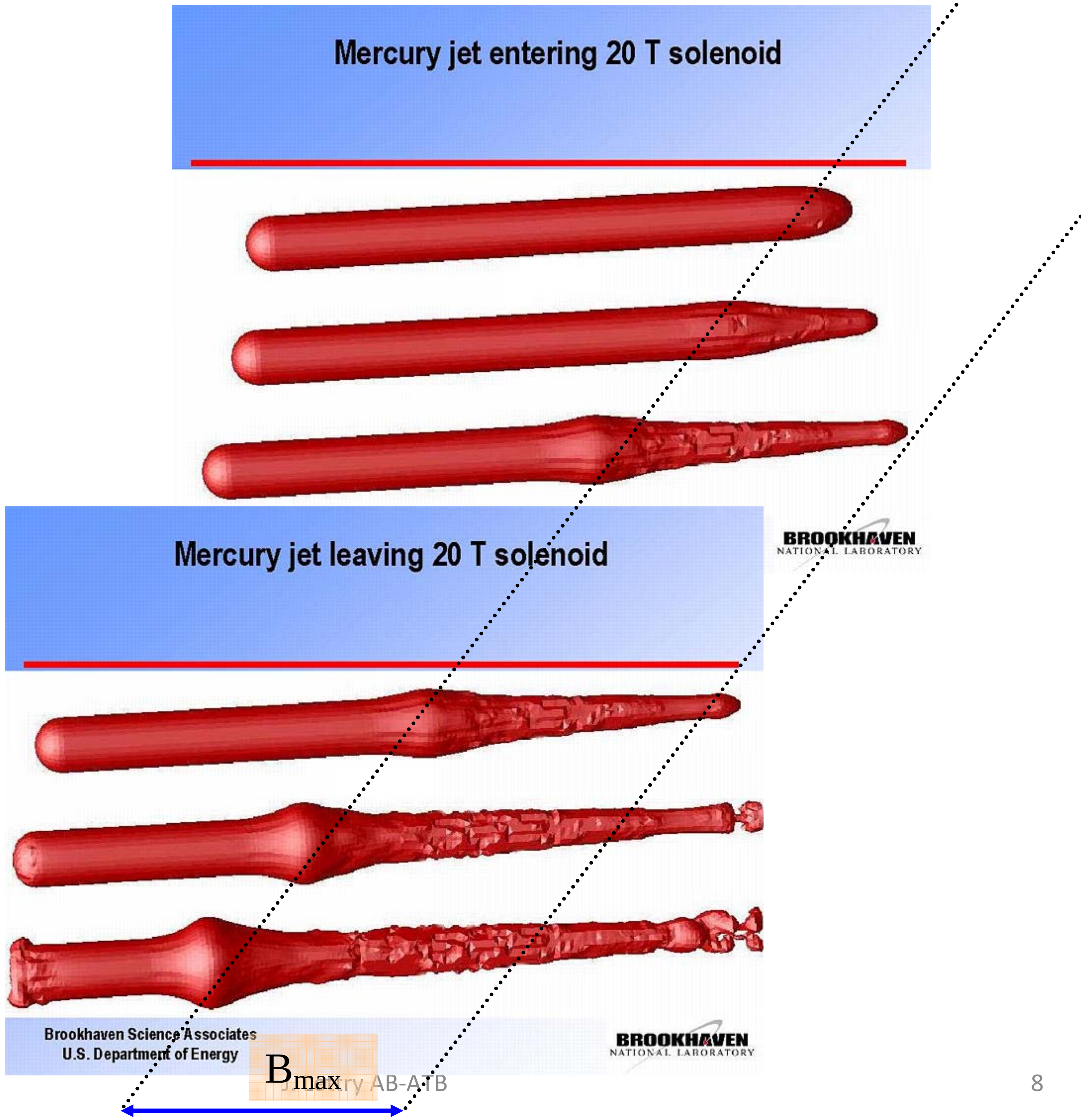
~10ms after the tip of the Hg-jet



Simulation:
R. Samulyak BNL

10 T

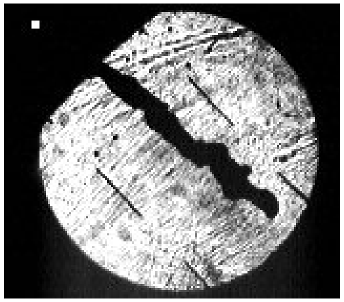


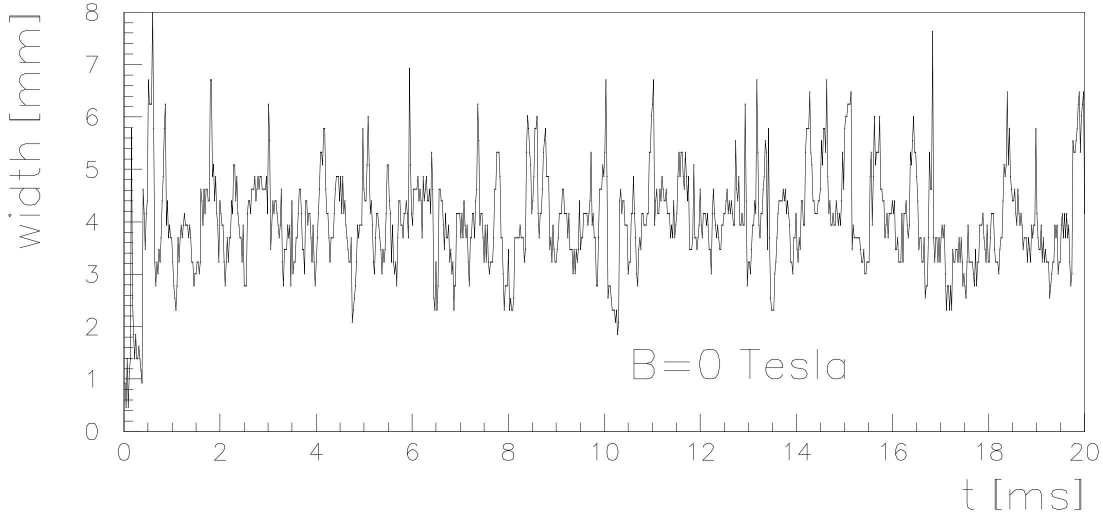


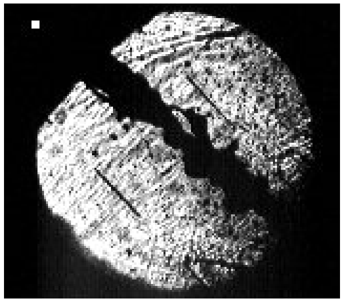
MHD damping of the instabilities of a 11 m/s Hg-jet successfully injected into a 19.3 T magnetic field

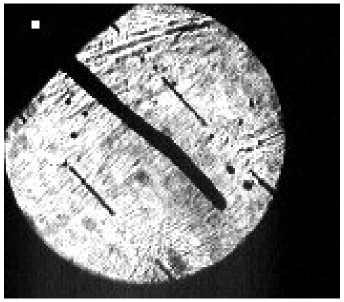
Ref: A. Fabich
PhD. thesis TUV

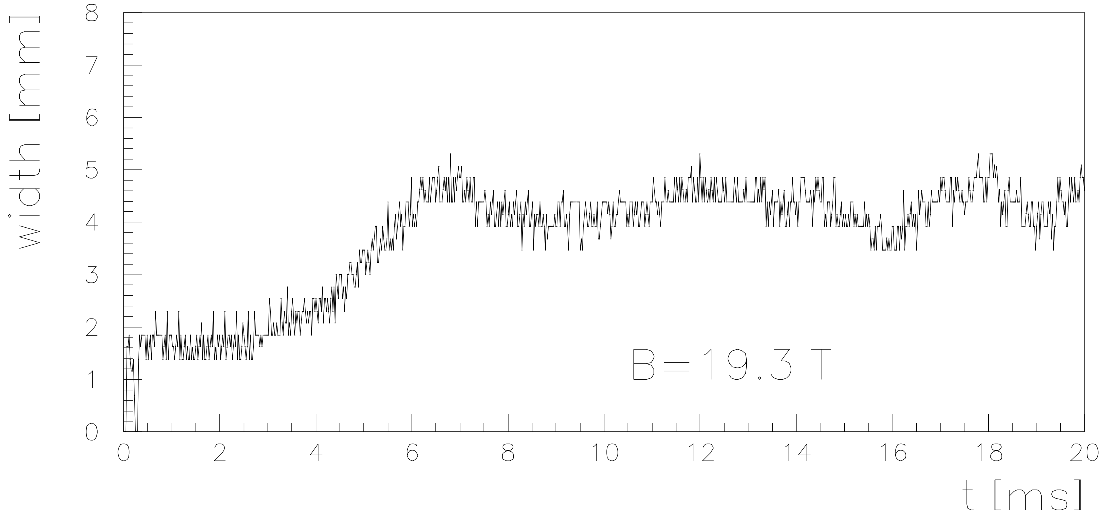
The radius is measured at a fixed position

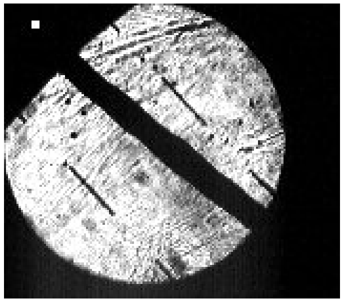












Materials properties

- Fatigue,
- Embrittlement
- Heat conductivity
- Modulus of elasticity
- Rupture
- Corrosion, metals compatibility

Fatigue.

- Fatigue behavior is described by Wöler (S-N) diagram and Manson–Coffin law for low-cycle fatigue
- The curve depends on
  - Material, state, surface, environment, …
- It is an statistical phenomenon, with considerable scattering
- It follows initiation – propagation – final fracture

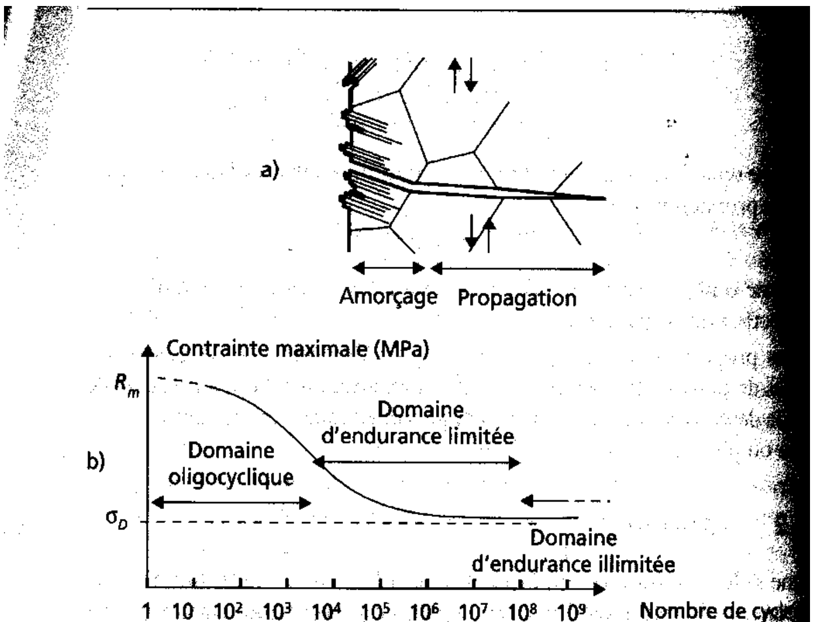
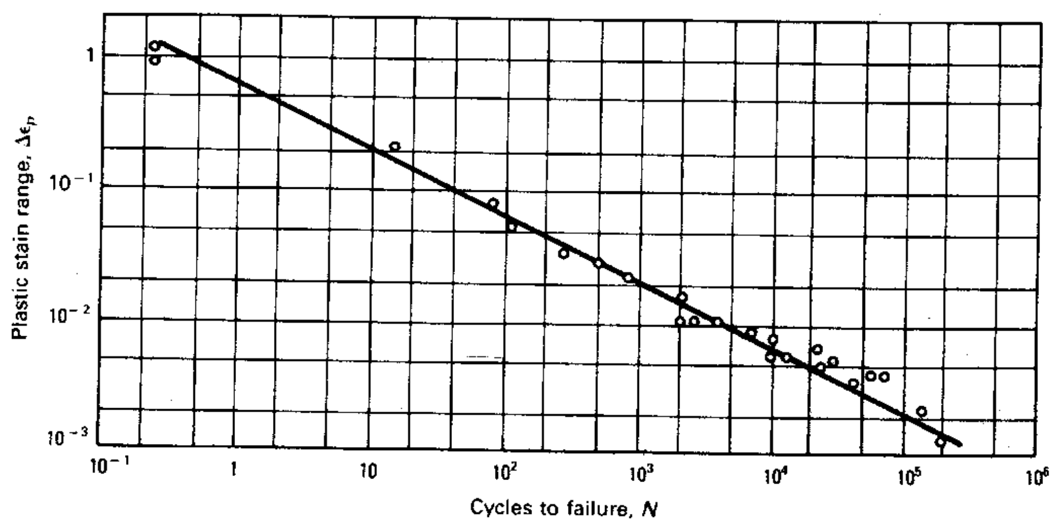


Figure 6.32
a) Amorçage et propagation des fissures de fatigue dans un polycristal métallique. b) Courbe de Wöhler.

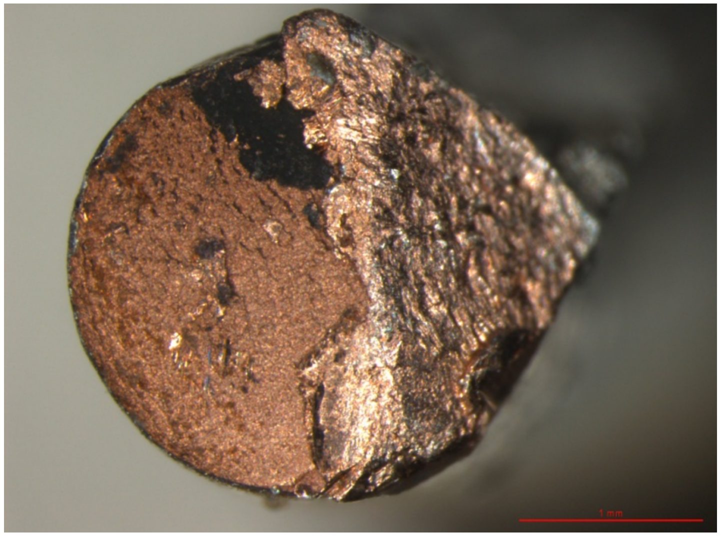
Fig. 2 Low-cycle fatigue curve ($\Delta\epsilon_p$ versus N) for type 347 stainless steel
Source: Ref 1

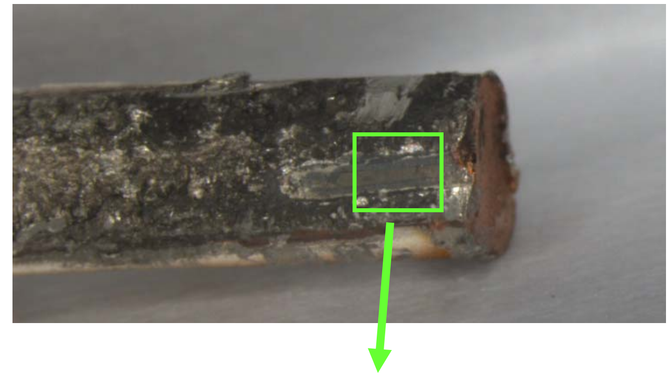


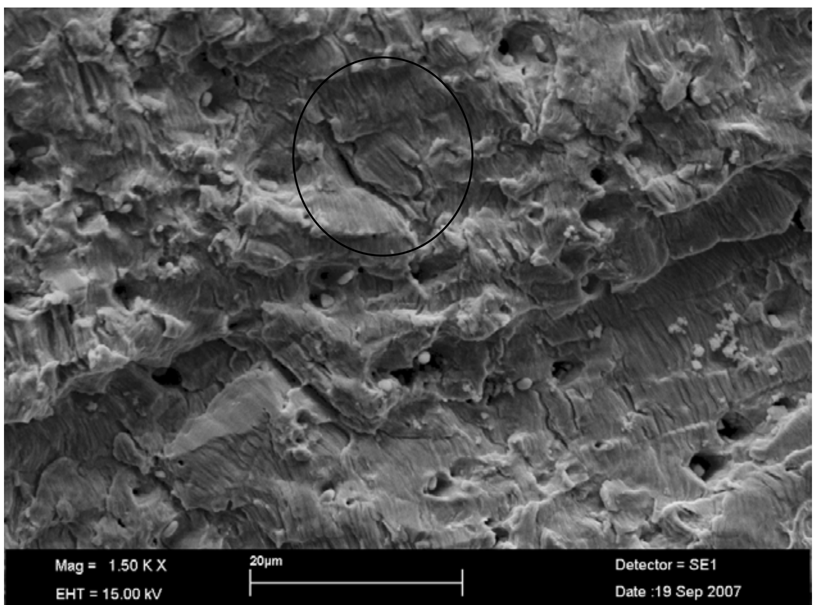
S. Sgobba, JM Dalin, A. Gonzalo

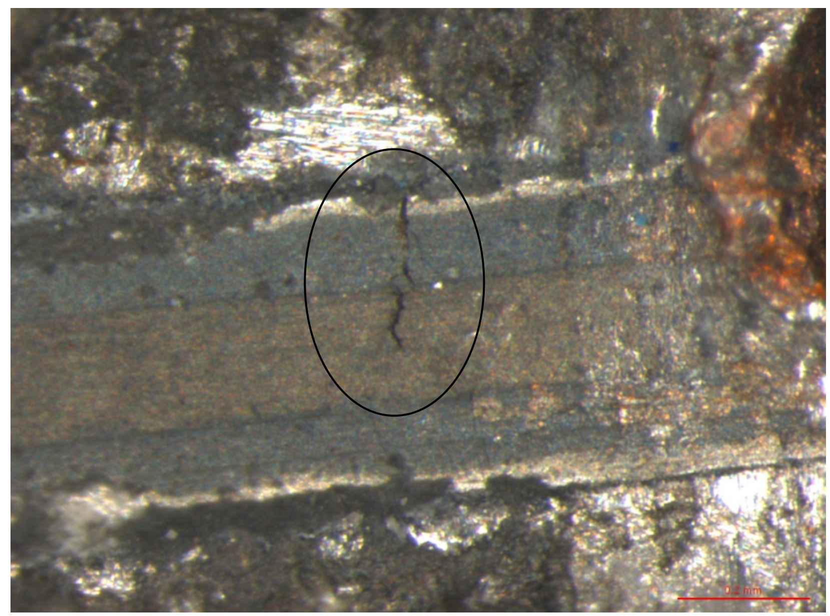
Fatigue failure

- Beach marks
- Striations
- Secondary cracks

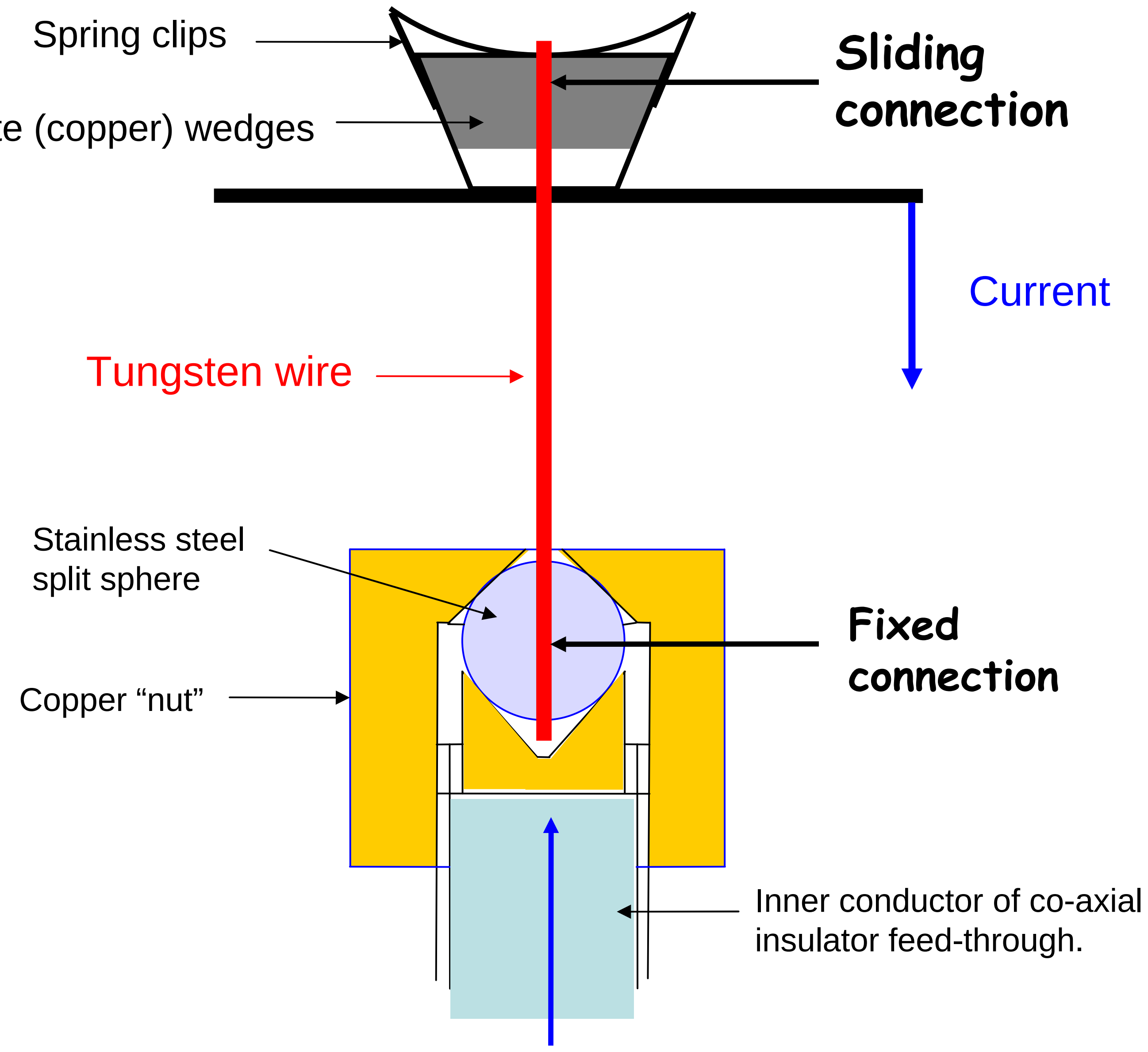




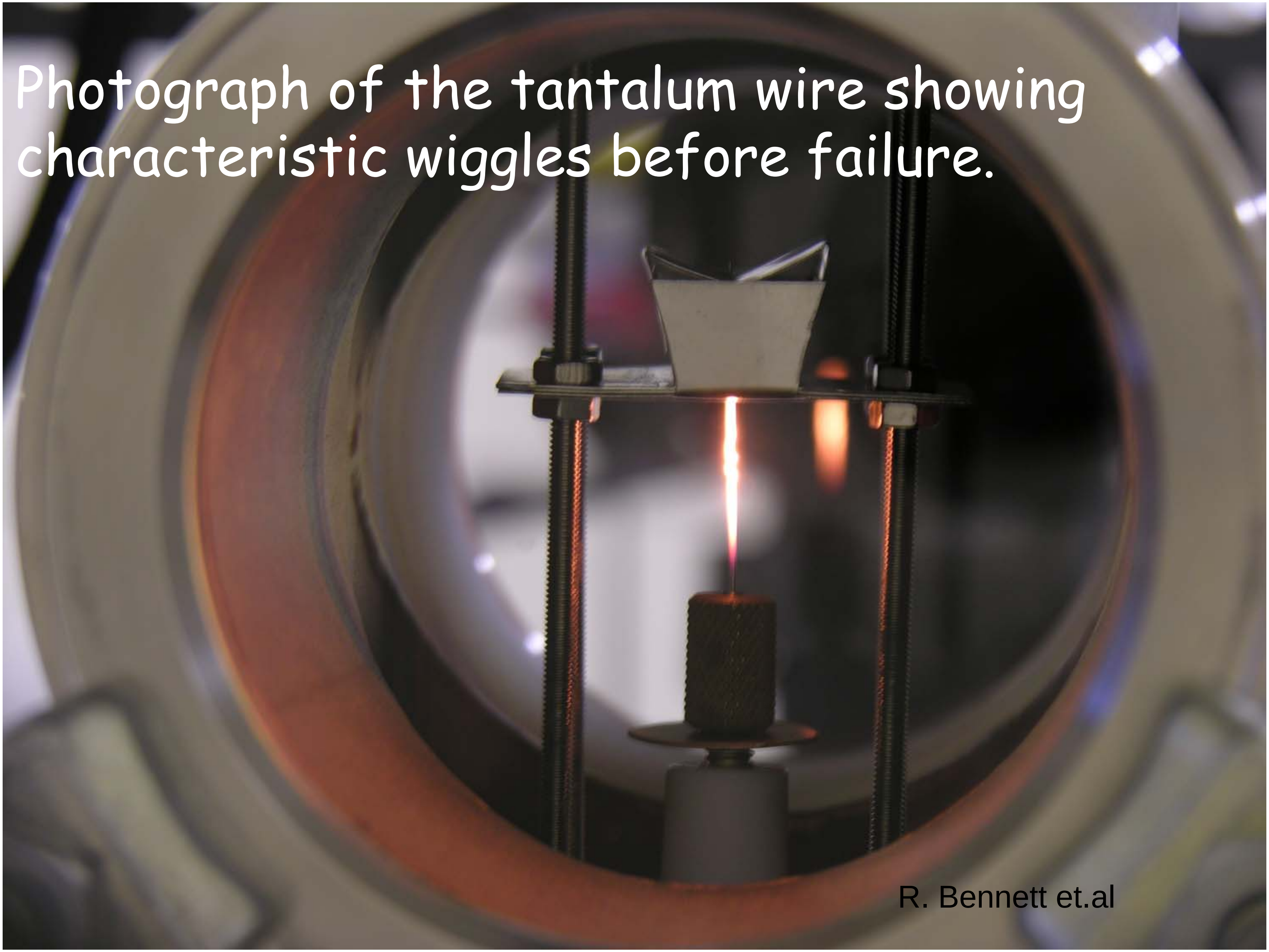




Vertical Section through the Wire Test Apparatus



R. Bennett et.al



Photograph of the tantalum wire showing characteristic wiggles before failure.

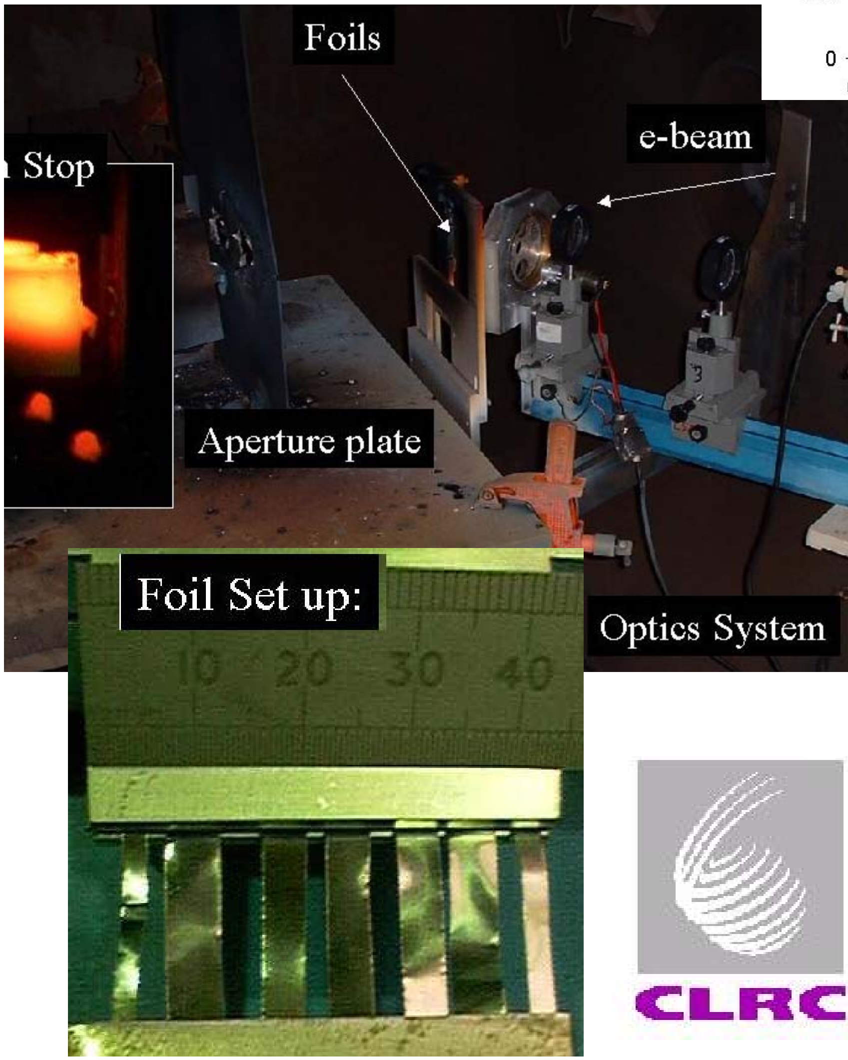
W3 Tungsten Wire, after operating at 4900 A, peak temperature 1800 K, for 3.3×10^6 pulses and then a few pulses at 7200 A at >2000 K.

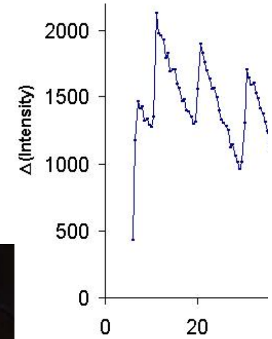
W5 Tungsten Wire showing "wiggles": 6200 A, >2000 K peak temperature, 5625 pulses.

R. Bennett et.al

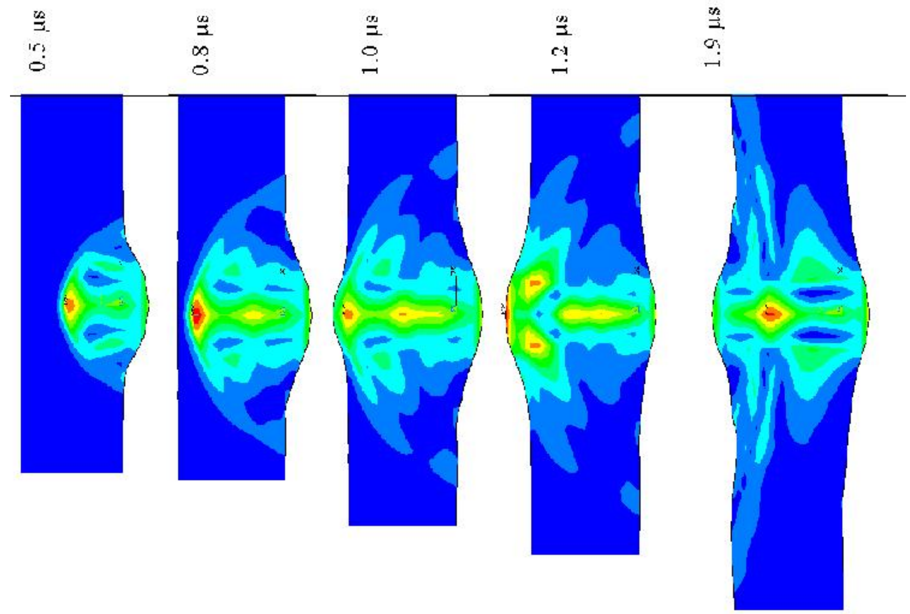
Solid target tests

Paul Drumm & Chris Densham



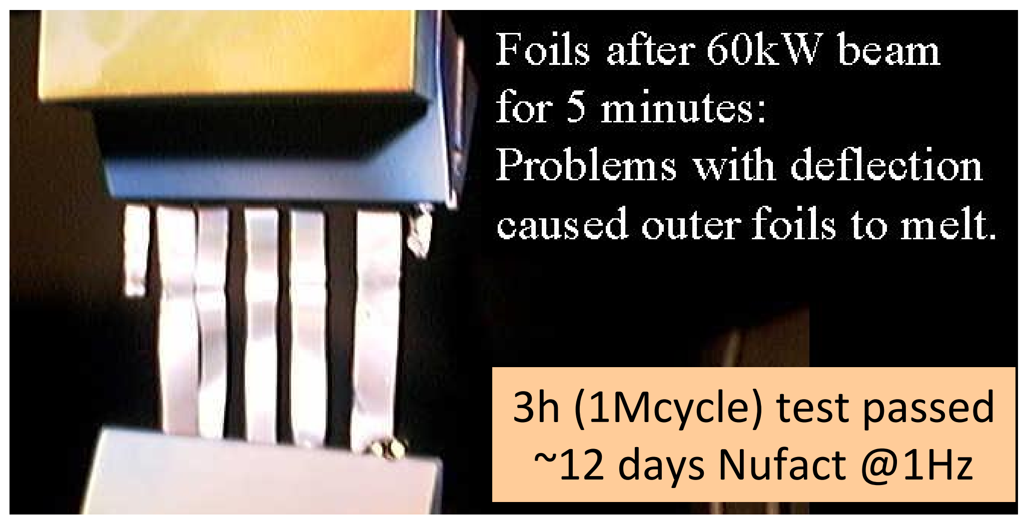


2100°



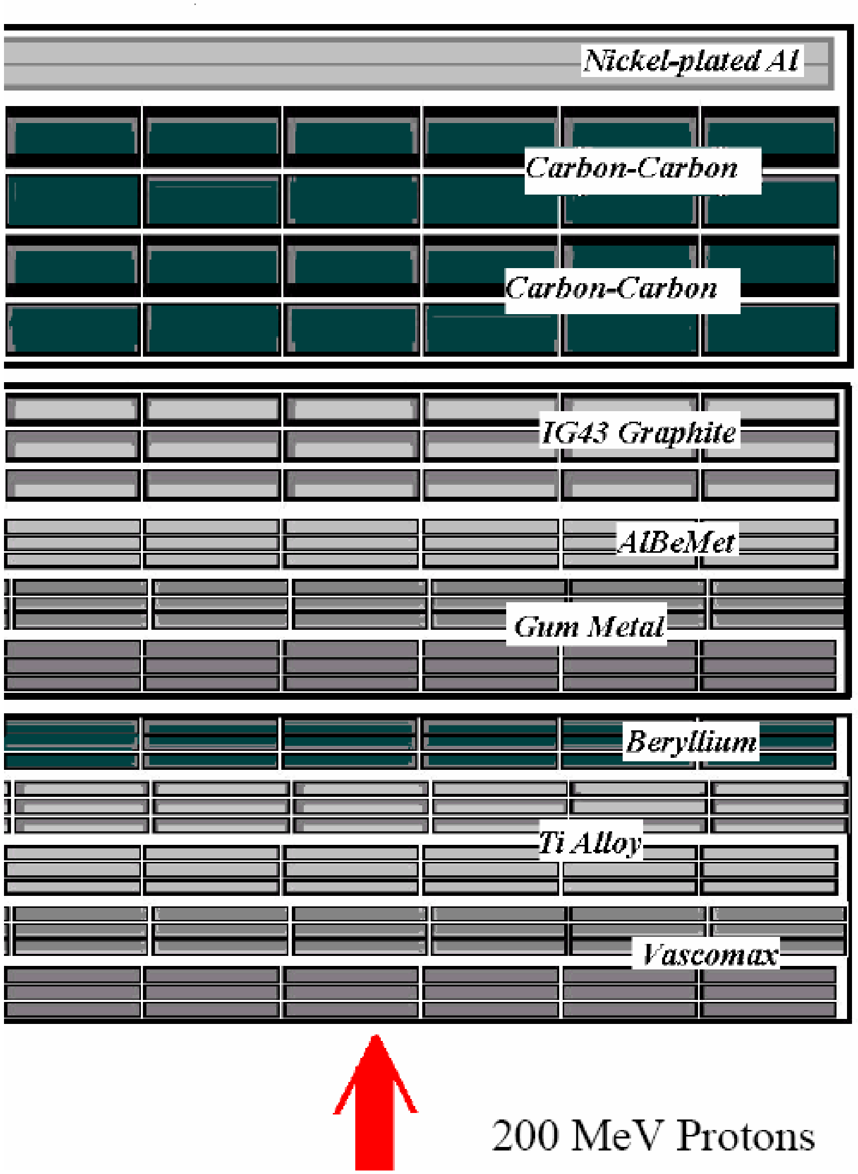
Shock Wave moving in foil

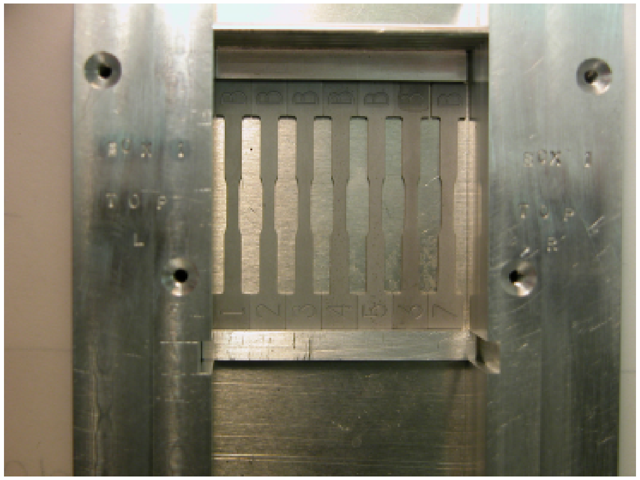
3d-code for shock propagation ?



Material tests after irradiation

Ref: N.Simos et.at BNL



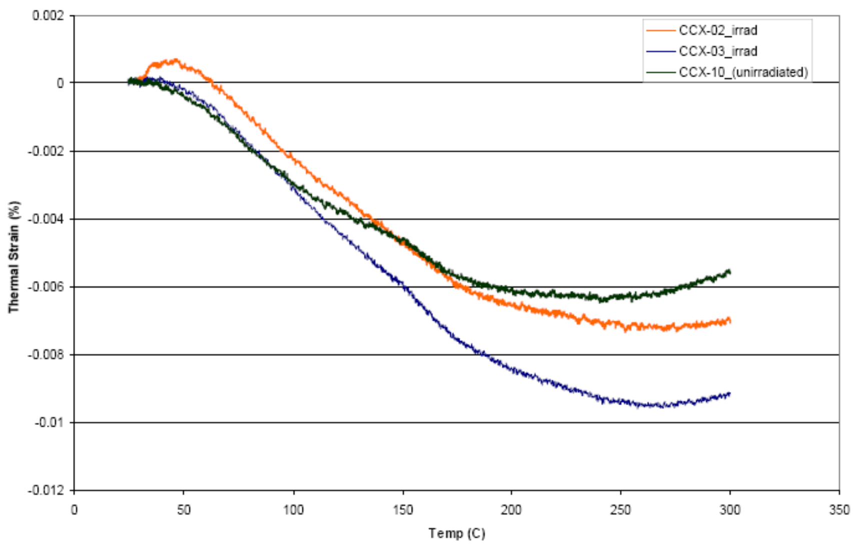


Few dpas (displacement per atom) expected in materials surrounding the target

C-composite

Th-expansion

Ref: N.Simos et.at BNL



Th-conductivity

Ref: J.P. Bonal et C.H. Wu
Nucl. Mat. 277 (2000)

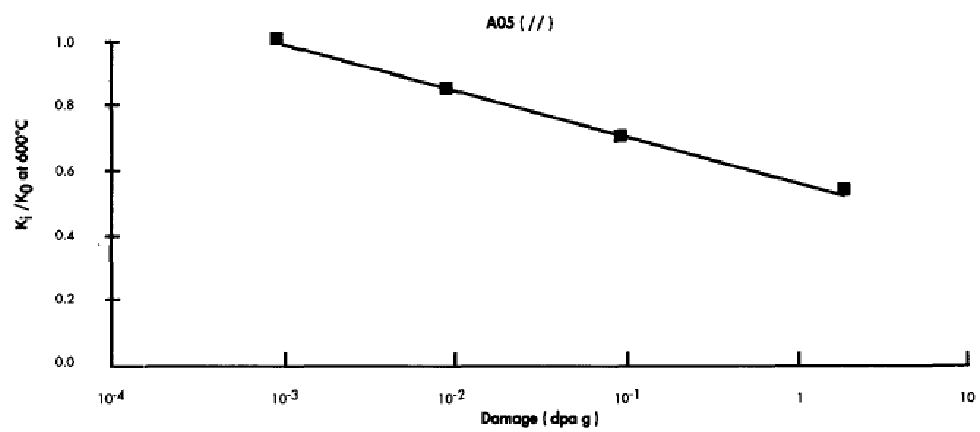


Fig. 4. Thermal conductivity A 05(||) normalized at 600°C as a function of neutron damage.

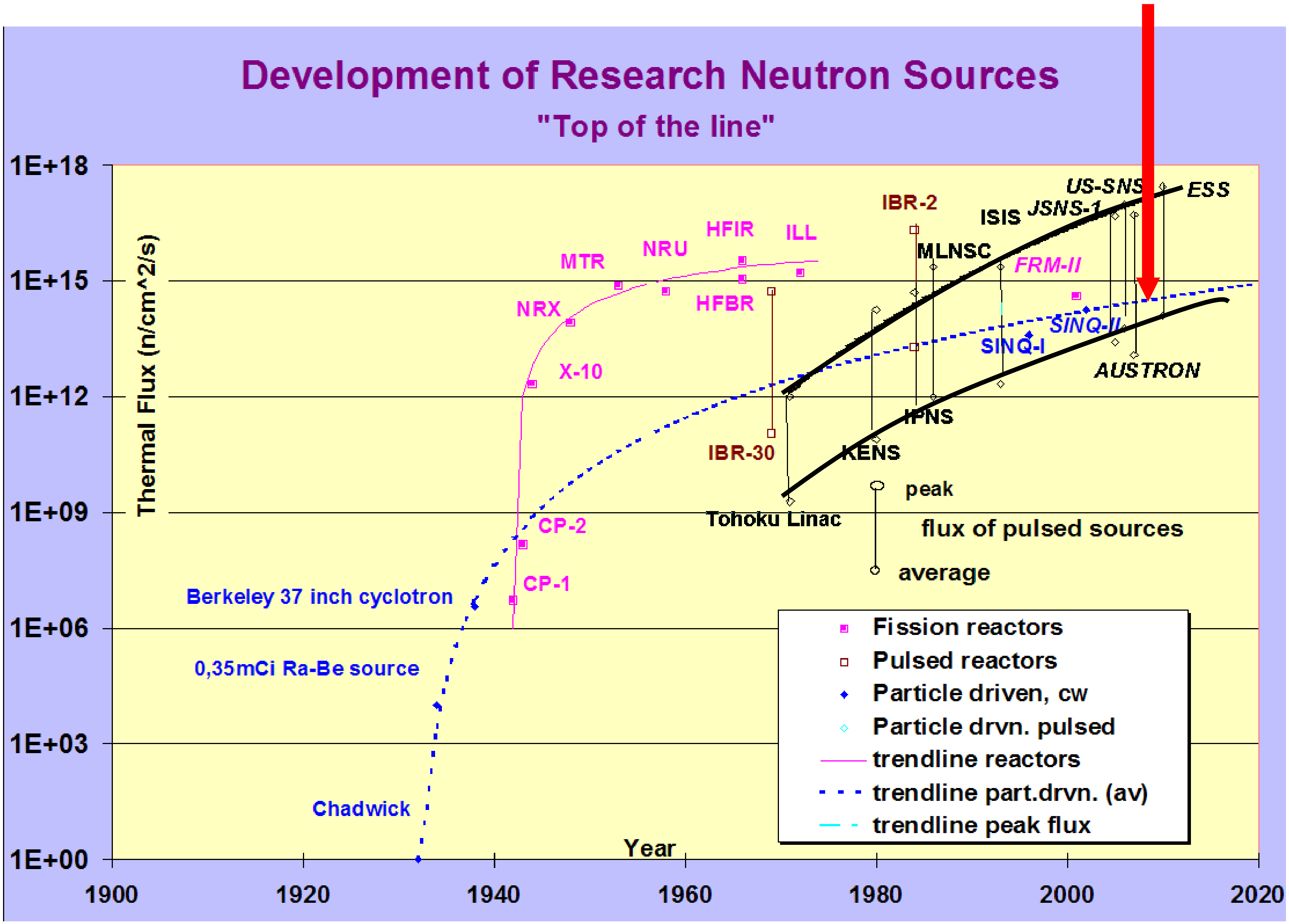
SINQ-Target Mark 4:

⇨ **Solid target: Lead clad in steel tubes, partly clad in Zircaloy**

ZrPb-Canneloni

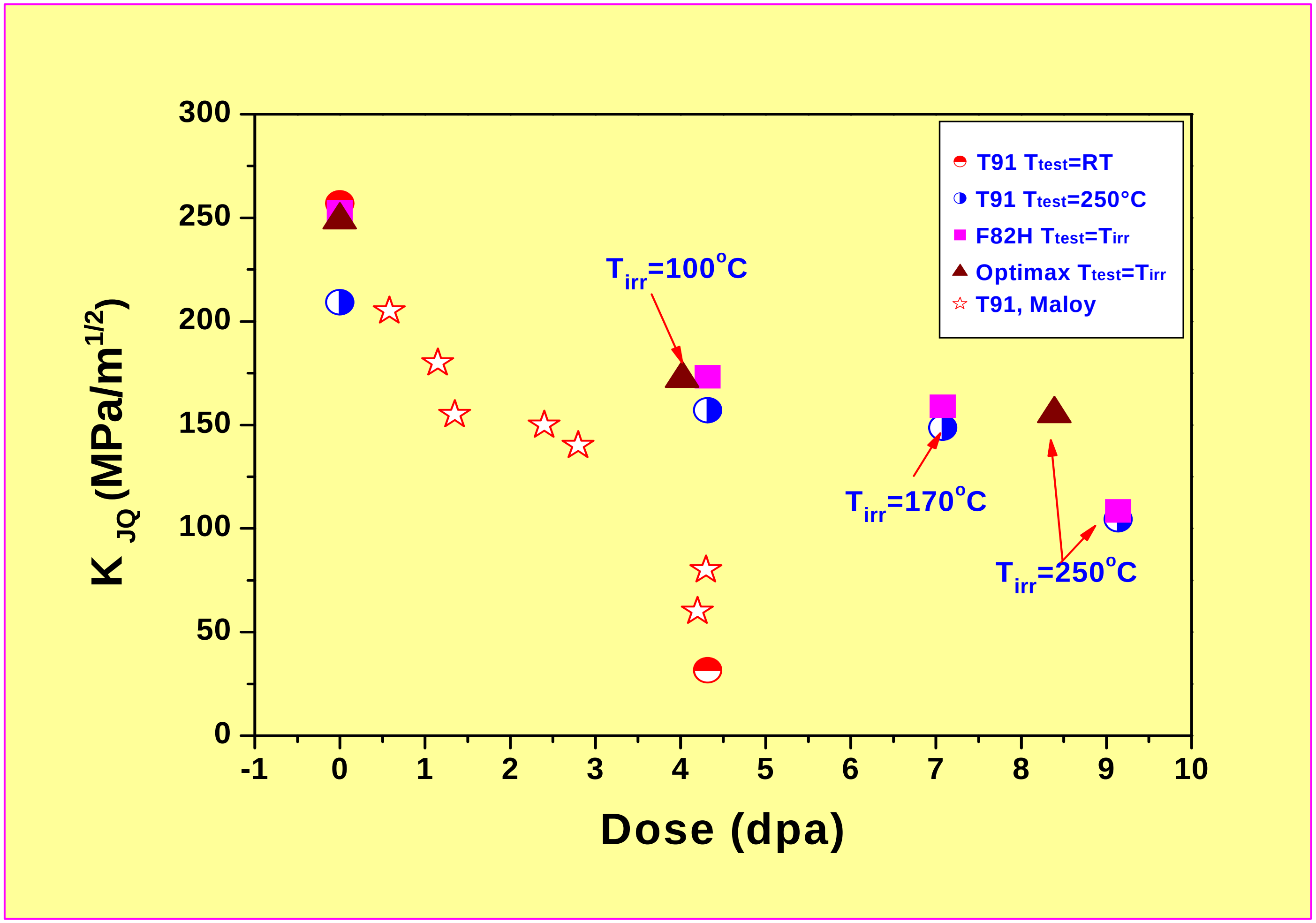
in service since end of April 2004

Next step for SINQ along the development curve



Few results

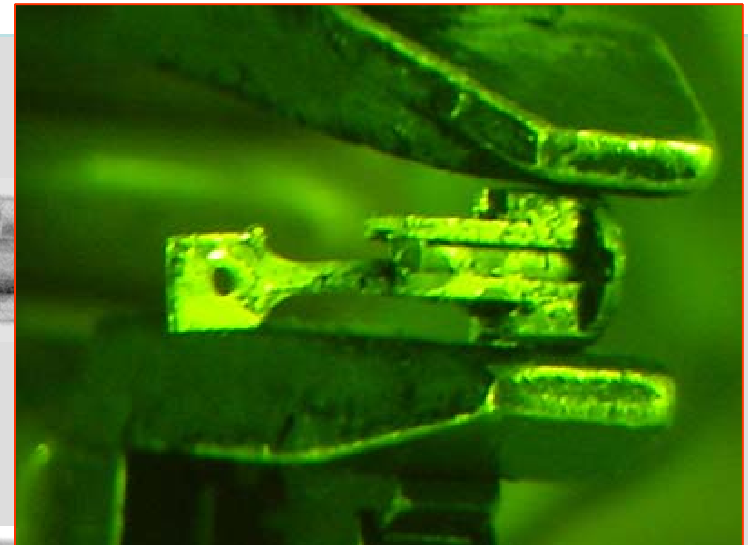
Fracture toughness of FM steels irradiated in STIP-I



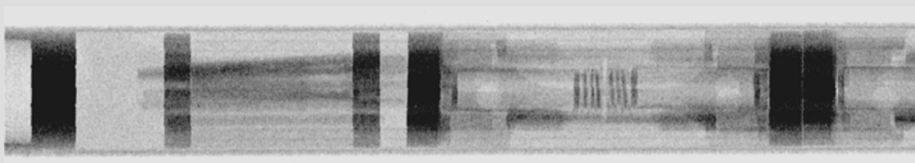
Jia & Dai, IWSMT-7, Thun, 2005, to be published in JNM.

Few results

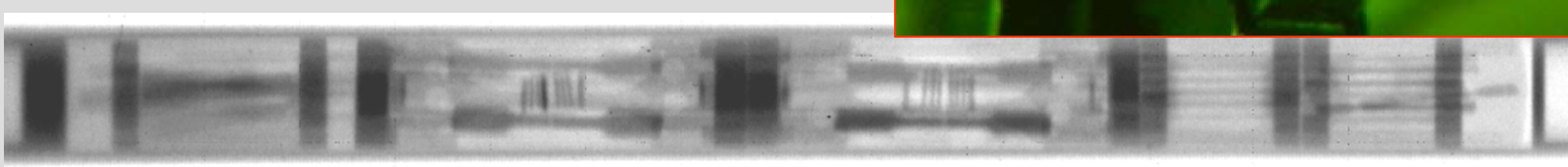
Inspection on STIP-II Pb-Bi Rod



Before irradiation



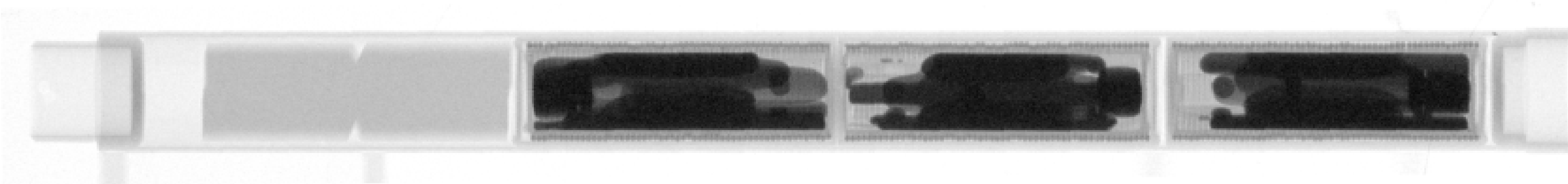
After irradiation (max dose: 19 dpa)



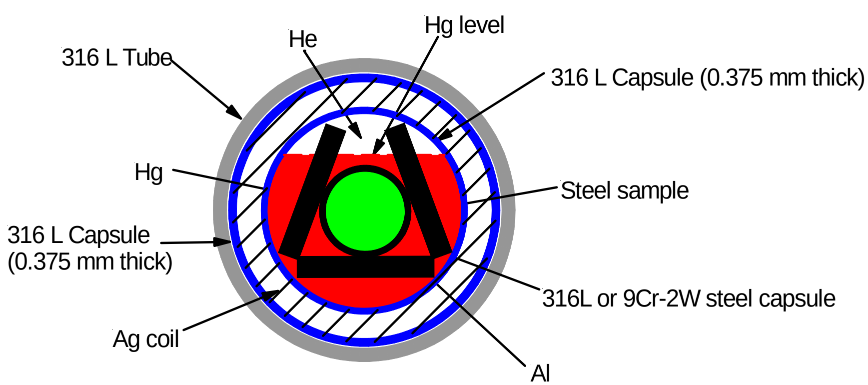
Target Rod B:
It contains a PbBi (about 38 g) filled T91 capsule. Inside PbBi there are about 50 test samples for studying irradiation assisted corrosion effects of PbBi on different kinds of materials.

STIP-II Hg Rod

Before irradiation



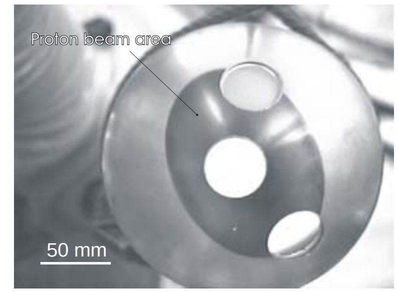
After irradiation (max dose: 20 dpa)



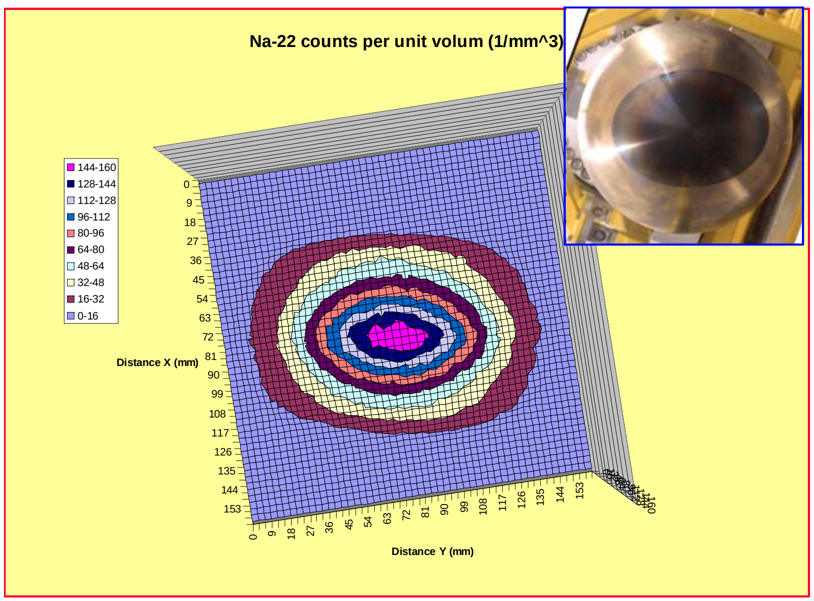
Target Rod A:
It contains three Hg (about 19 g in total) filled capsules and one steel sample package. There is about 25% free space in each Hg filled capsule.

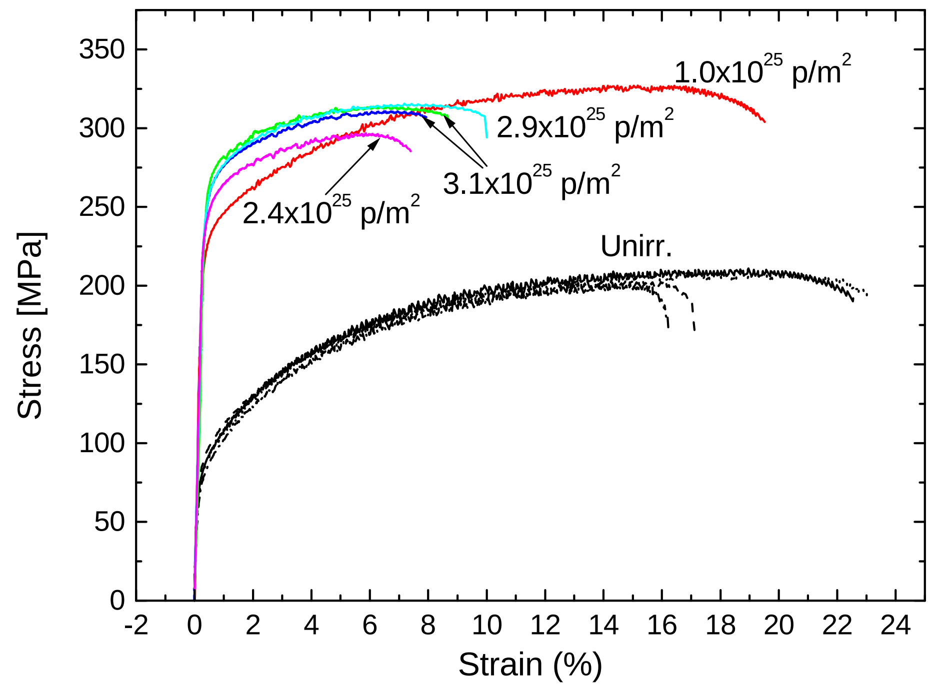
SINQ Target Safety Hull:

Tensile tests after one year of irradiation



γ-mapping of the beam footprint





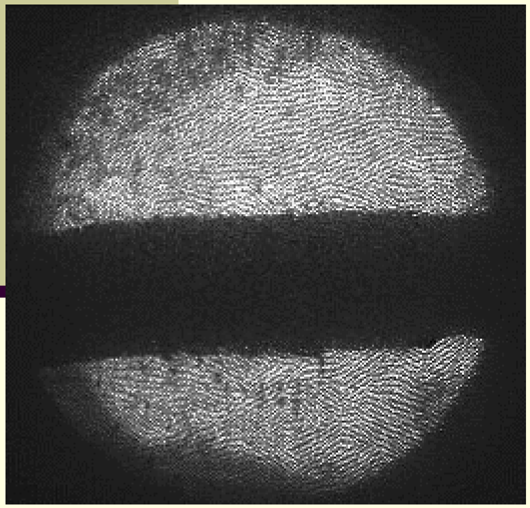
Conclusion

- The materials of the target area will evolve along with the irradiation time
  - The Displacement per atom (dpa) is the (time) scale to measure this evolution
  - This evolution shall be included in the engineering design.
- Metal chemistry under high dpas is starting, radiogenic H and He trapped in metals will affect their properties.
- Fatigue is a key element that is not yet fully investigated (experimental challenge) under irradiation
  - Annealing of the parts kept at elevated temperature may be beneficial.

MERIT will:

- **Produce benchmarks for Neutrino Factory targetry design tools**
  - Study MHD of the Hg jet with nominal size and velocity
  - Study the origin of jet disruption by varying PS spill structure *"Pump / Probe"*
- **Validate the Neutrino Factory targetry concept**
  - Effects of single beam pulses with realistic proton energy, timing, intensity and energy density
  - Influence of solenoid field strength on Hg jet dispersal (MHD shock damping)
  - Information on the 50 Hz operations scenario by recording 2 pulses at 20 ms interval.
- **Define potential issues and open the path to engineering study**
- ***Set a milestone towards 1-4 MW pion production target***

The MERcury Intense Target Experiment – or nTOF11



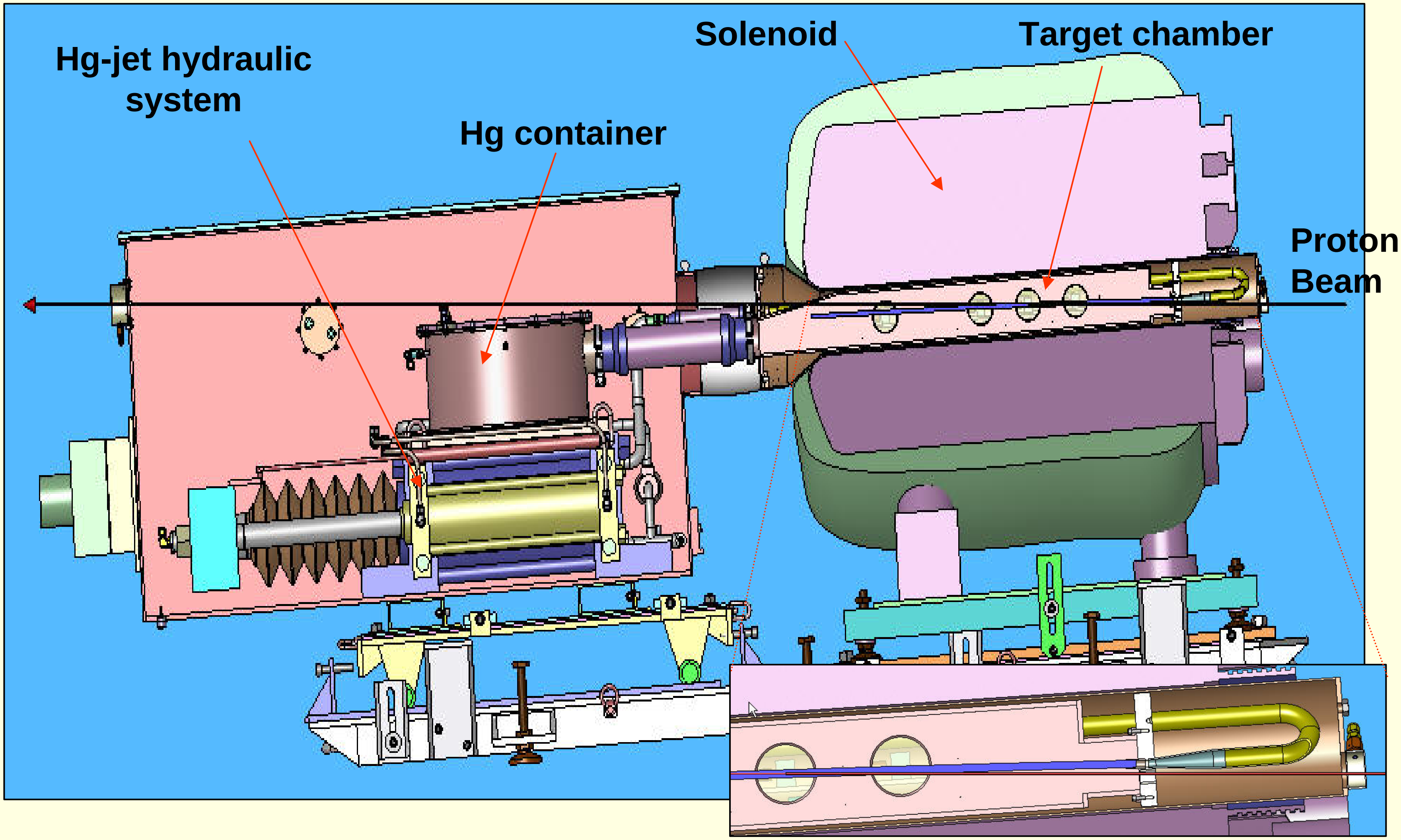
Beam jet interaction @ MERIT
14 GeV/c beam, 12TP, 10T field
April 2008

I. Efthymiopoulos – CERN, AB Dept.

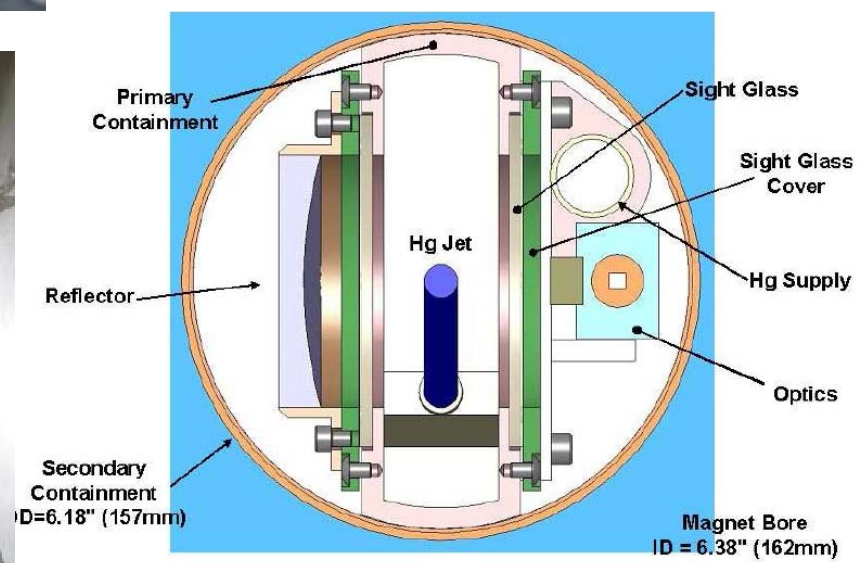
(for the MERIT collaboration)

MUTAC Review
LNBL – April 9, 2008

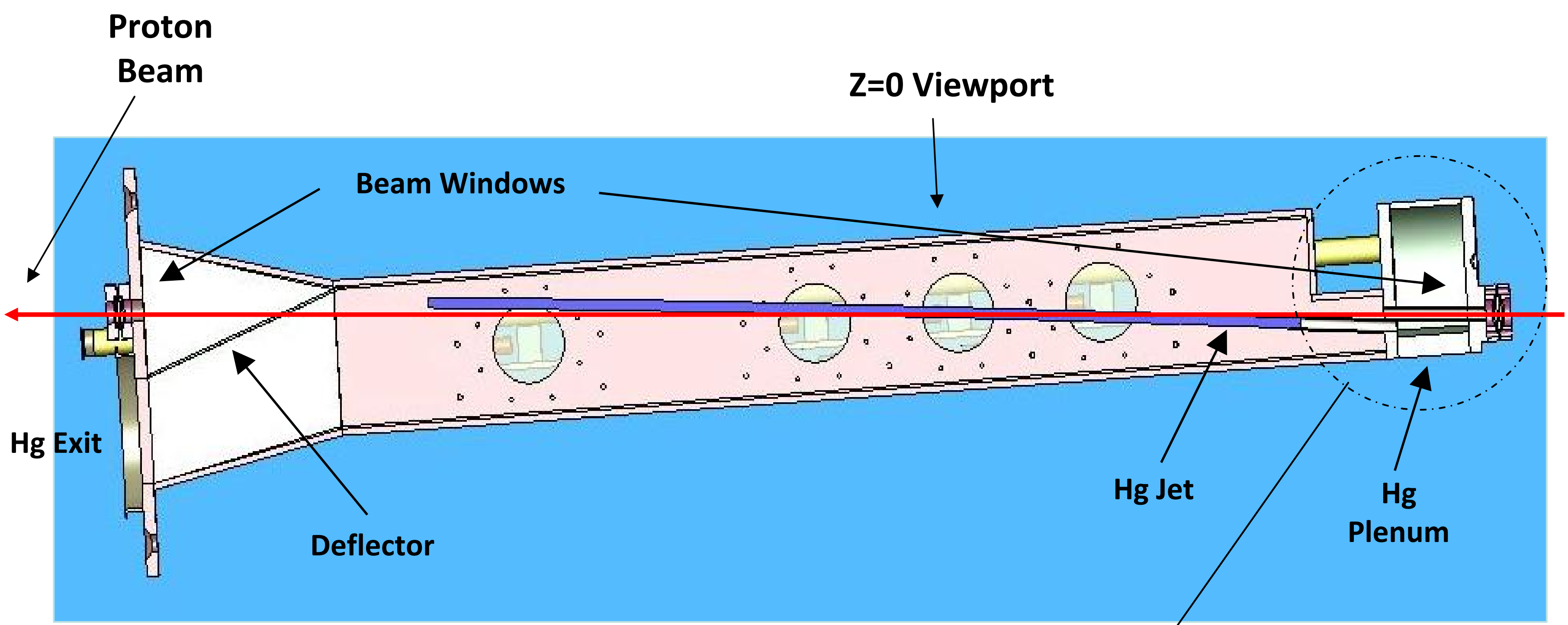
MERIT Experiment – The apparatus

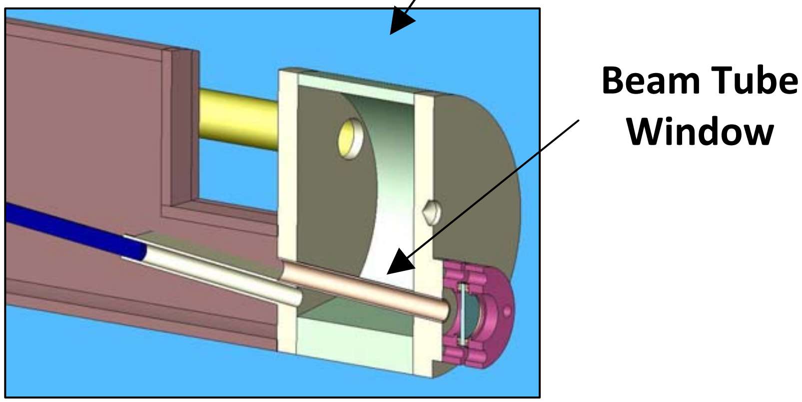


Optical diagnostics



Observation chamber



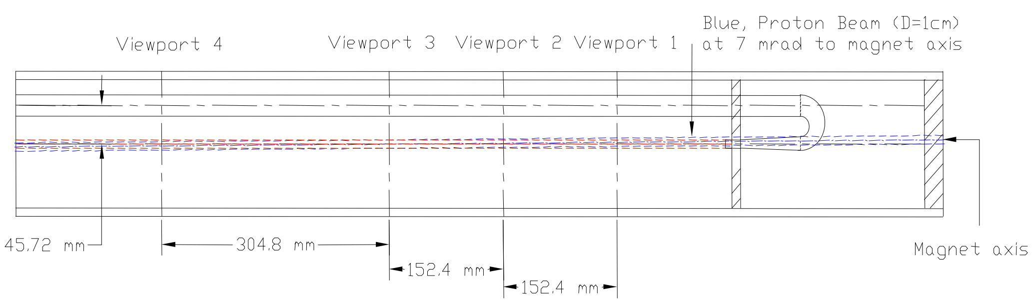


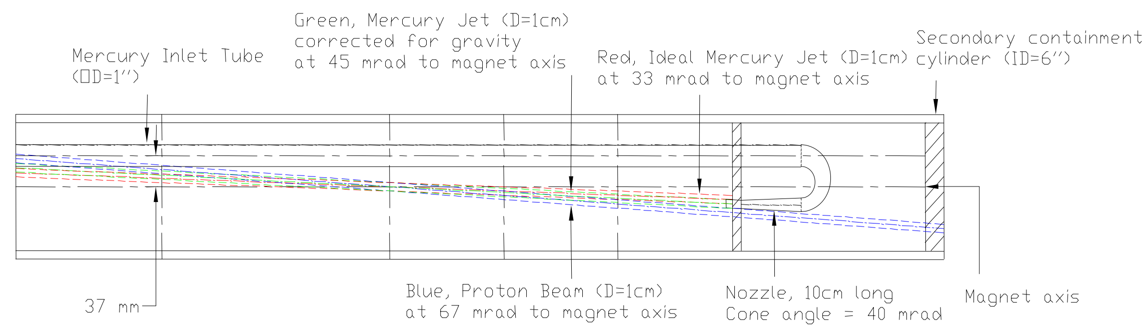
Nozzle under R&D

Nozzle Configuration

A : Reduction after 180 degree bend with 44 mrad angle
with respect to magnet axis.
B : Reduction before 180 degree bend with 44 mrad angle
with respect to magnet axis.
C : Reduction after 180 degree bend, but straight nozzle with
no tilted angle with respect to magnet axis.
D : Nozzle A is reamed through the nozzle flange.

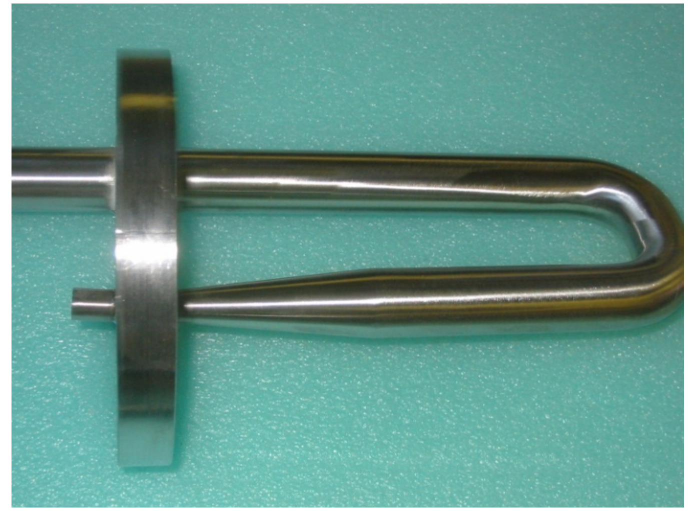
Top View



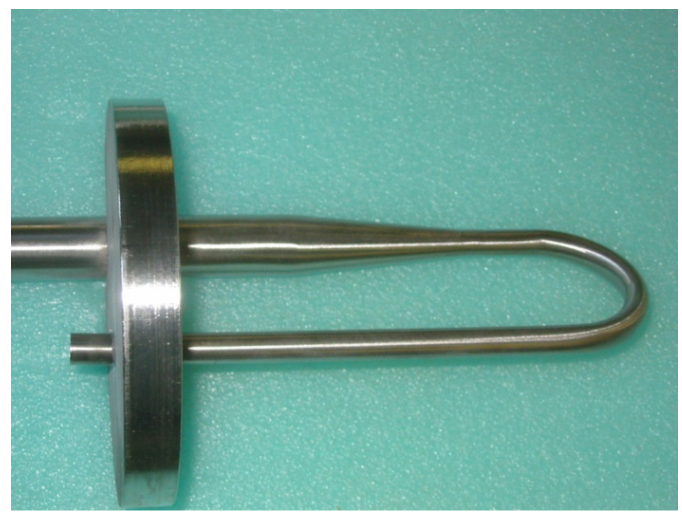


Side View

Nozzle A

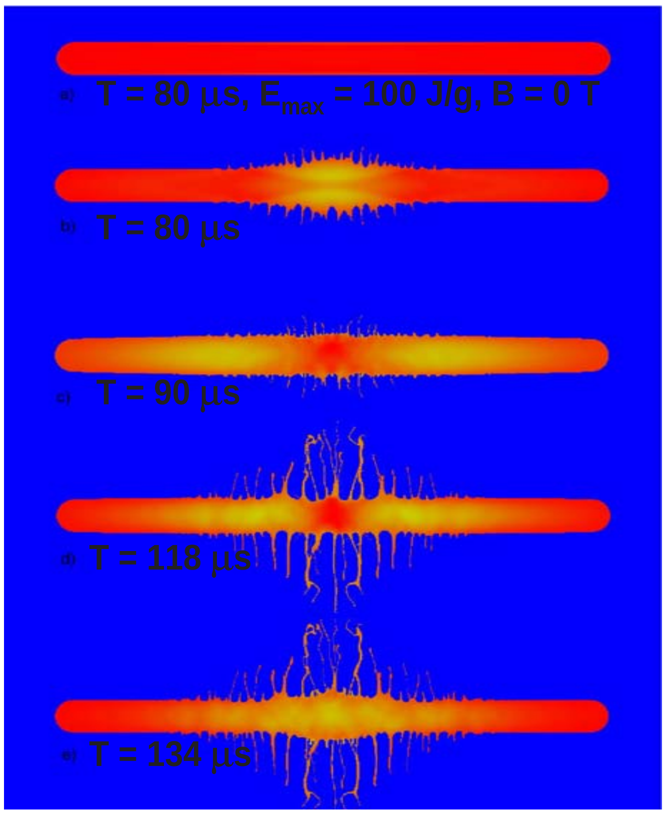


Nozzle B

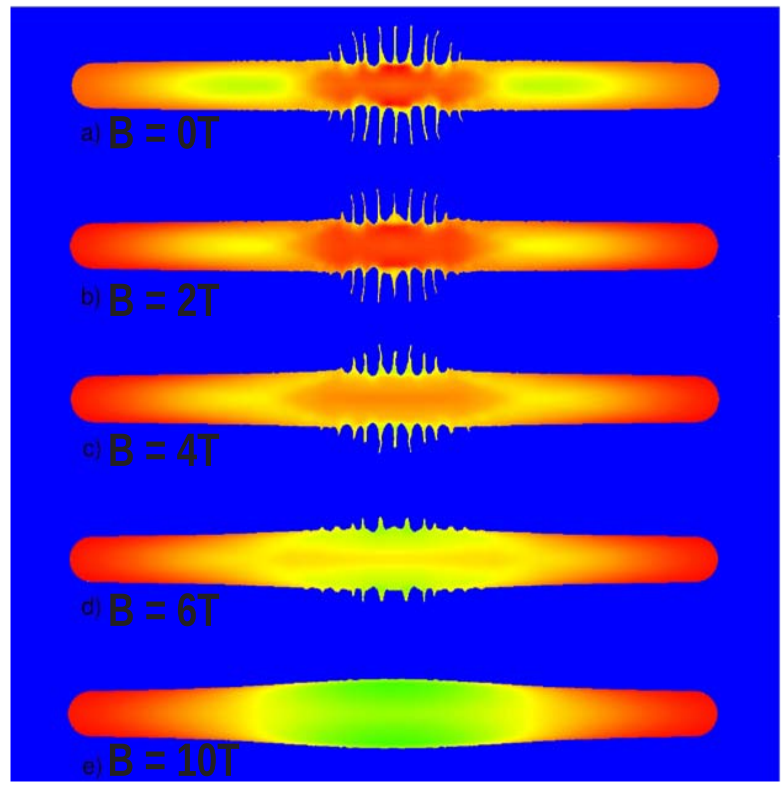


MHD + shock Simulations
BNL (Samulyak)

Gaussian energy deposition profile
Peaked at 100 J/g. Times run from
0 to 124 μs, B = 0 T



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



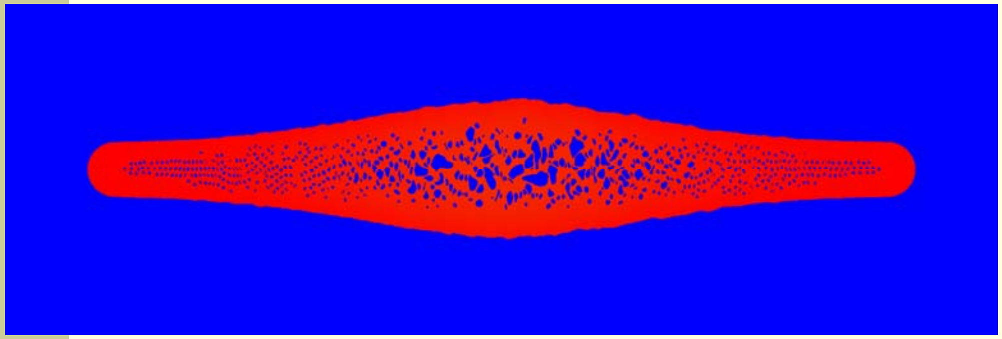
Axial symmetric splashes amped by MHD forces

MERIT Experiment – Scientific Goals

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

1. Study MHD effects on Hg-jet with normal target size and velocity

R.Samulyak-BNL

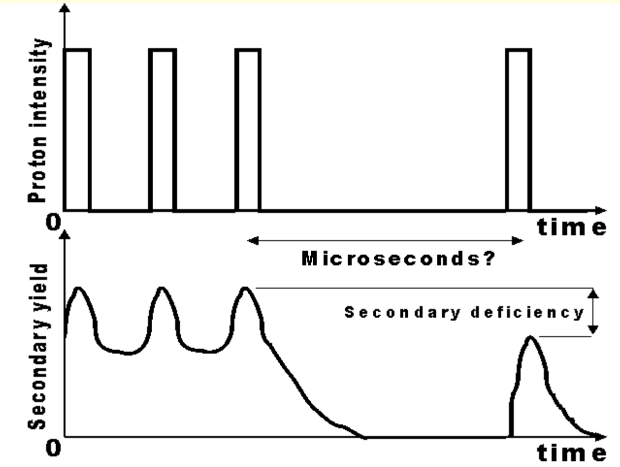


Jet dispersed by 3 bunches, existence of cavitation bubble reducing the nominal density probed by the 4th bunch

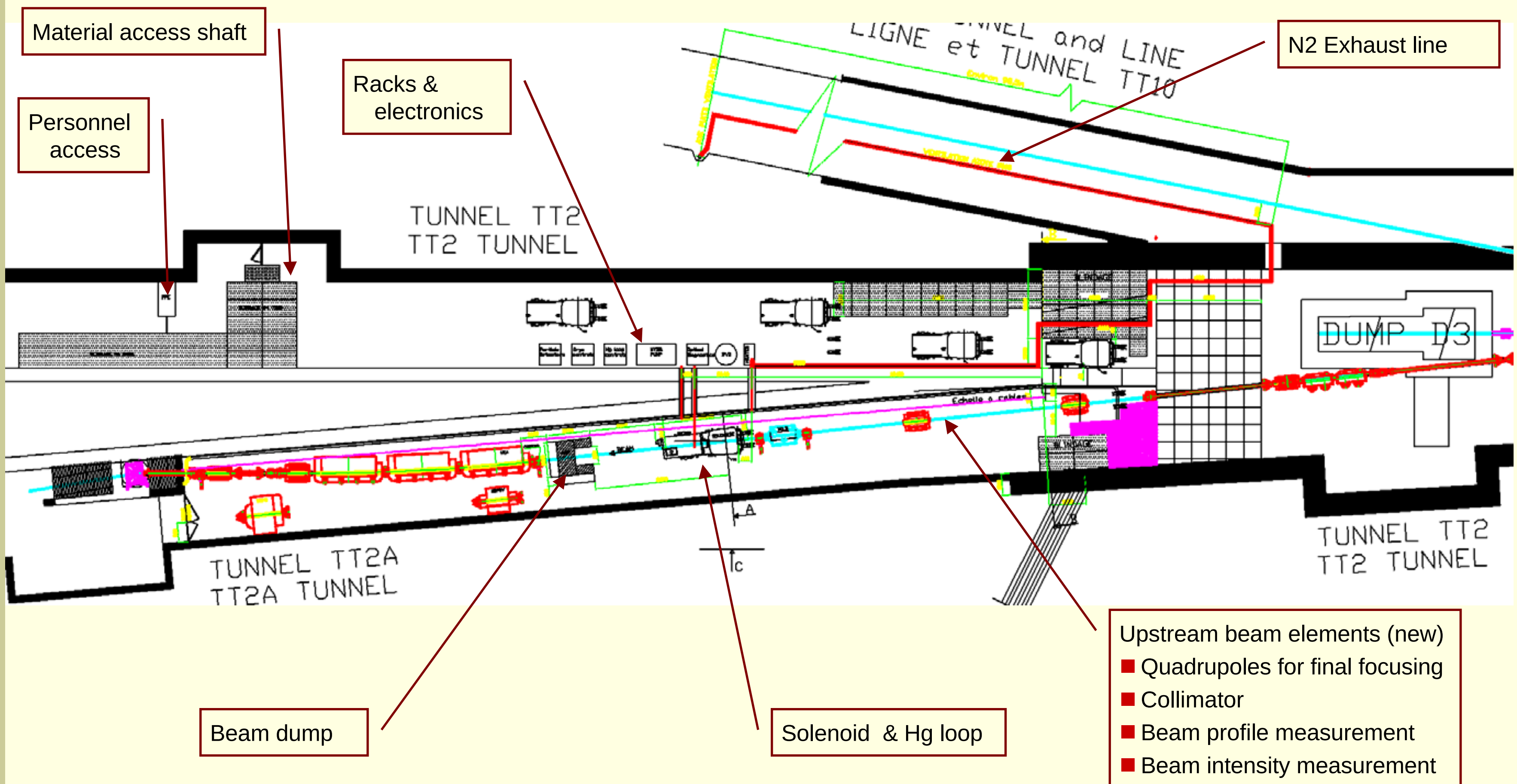
2. Study jet disruption (cavitation?) by varying the PS spill structure

MERIT: 180 J/g

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

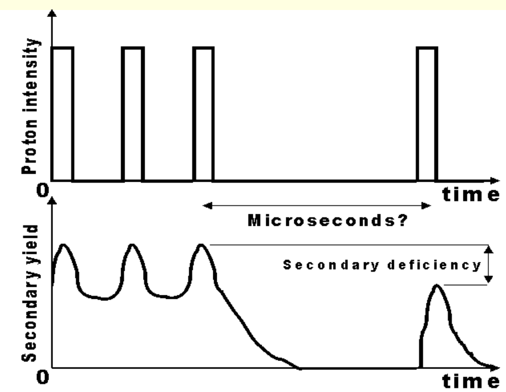


MERIT Experiment – Layout



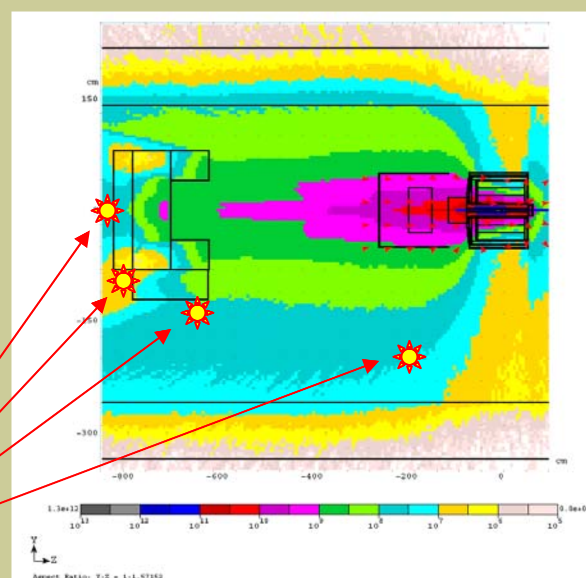
Particle Detectors

- 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



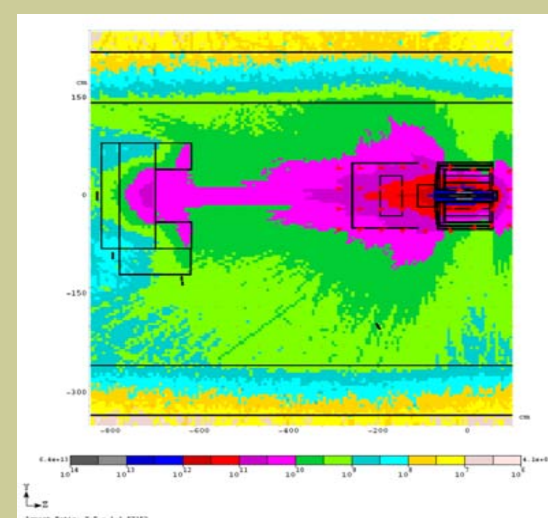
Particle Detectors

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



charged hadrons (E>200 KeV)

neutrons (E>100 KeV)

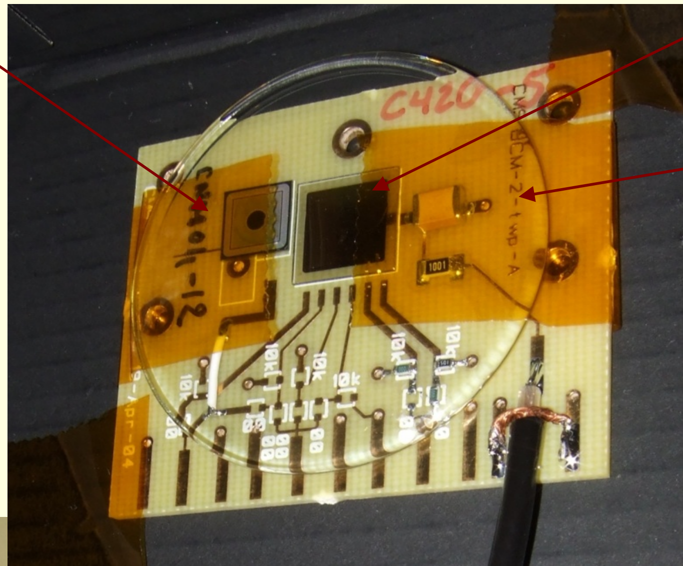


S.Striganov - FNAL

Particle Detectors

PIN diode

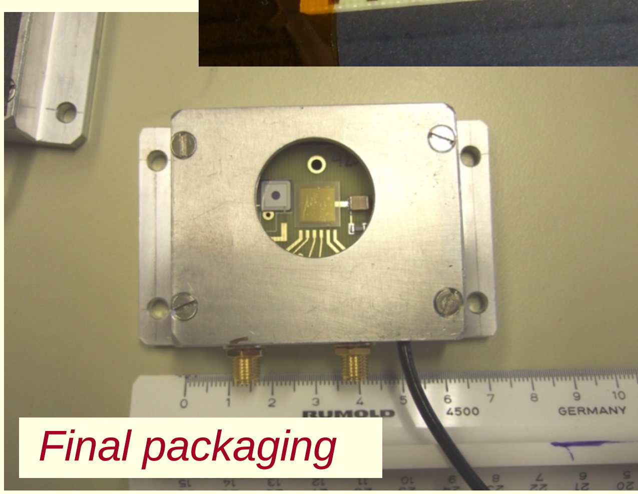
- ~1cm^2 active area, 200 um thick



pCVD Diamond

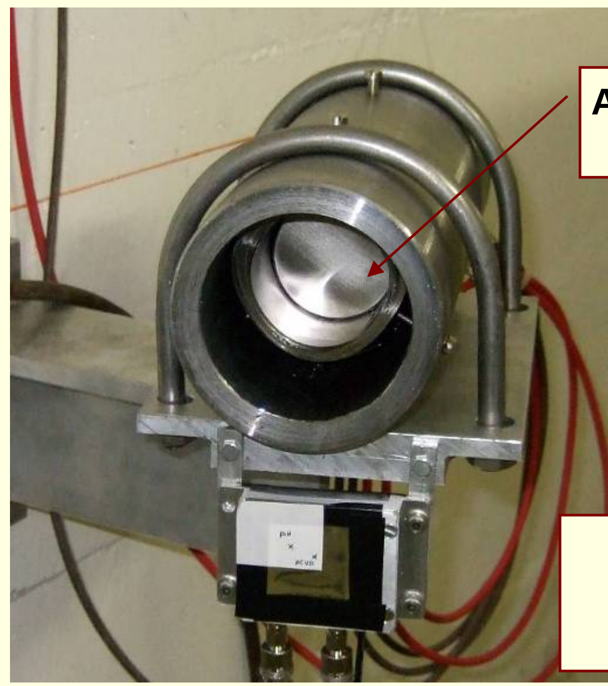
- 7.5×7.5 mm^2 active area, 300 um thick

bypass capacitor: 100 nF/500V



Final packaging

Detector assembly unit

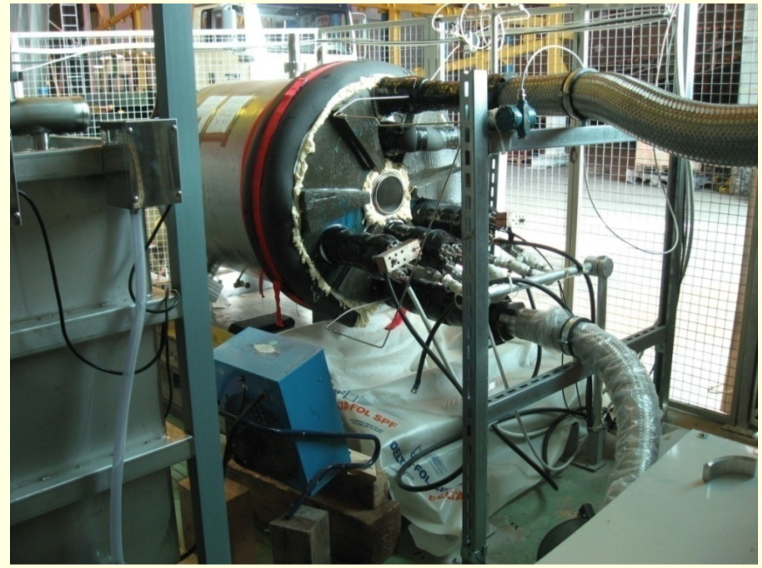


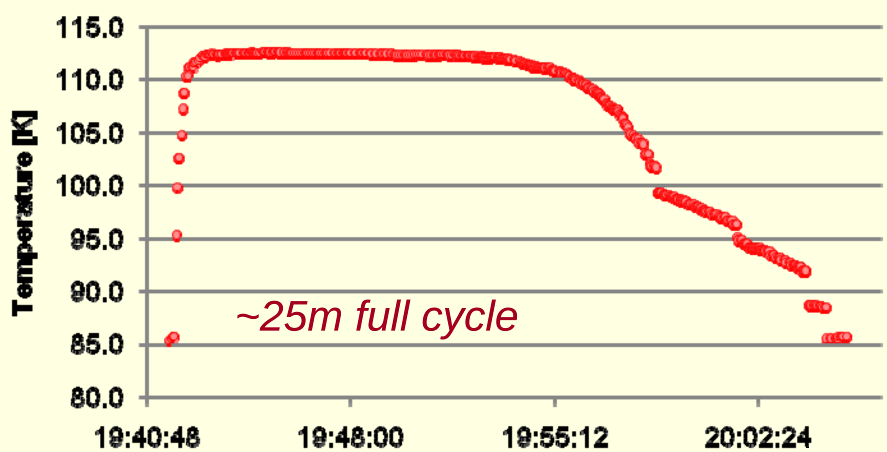
ACEM detector

pCVD diamond + PIN diode

Cryogenics – Surface tests

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



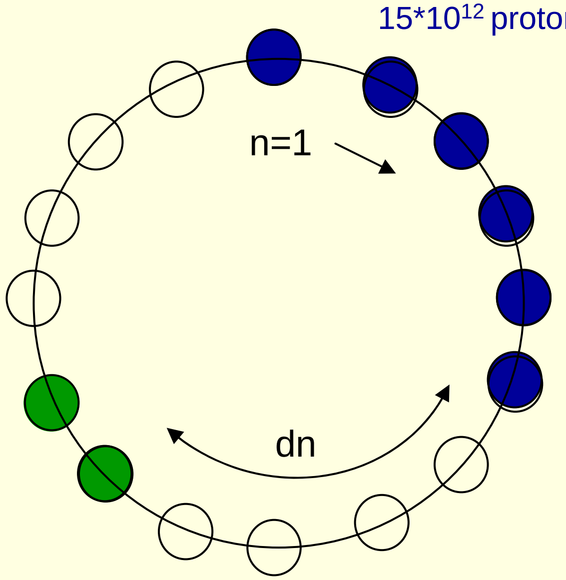


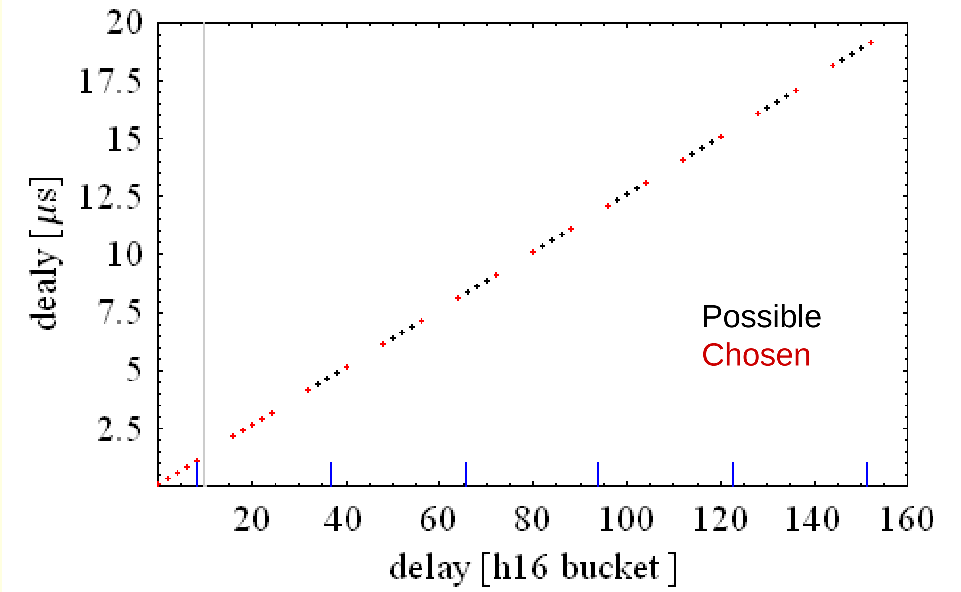
Operation with beam

- 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

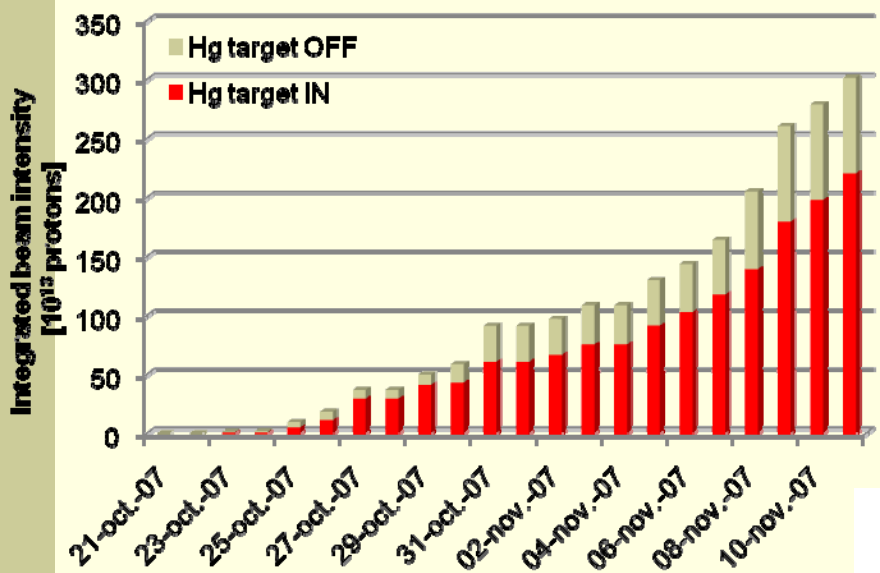




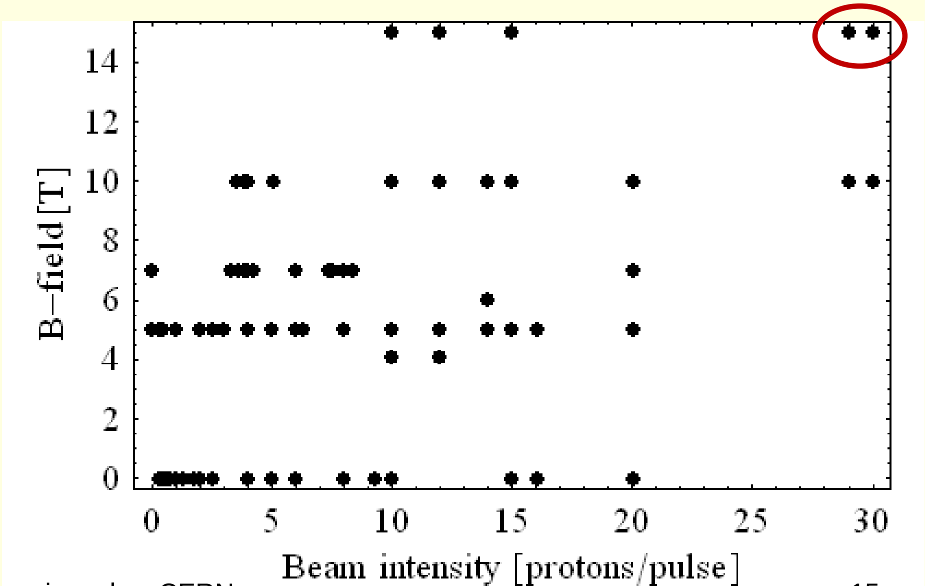
- $dn_{experiment}$ = 0,2,4,6,8, 16,18,20,22,24, 32,40, 48,56, …

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

Beam shots summary



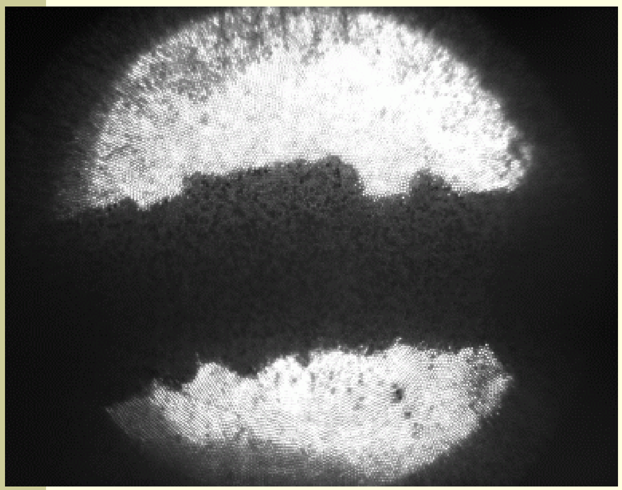
30 TP shot @ 24 GeV/c
- **115 kJ** of beam power
- a PS machine record !



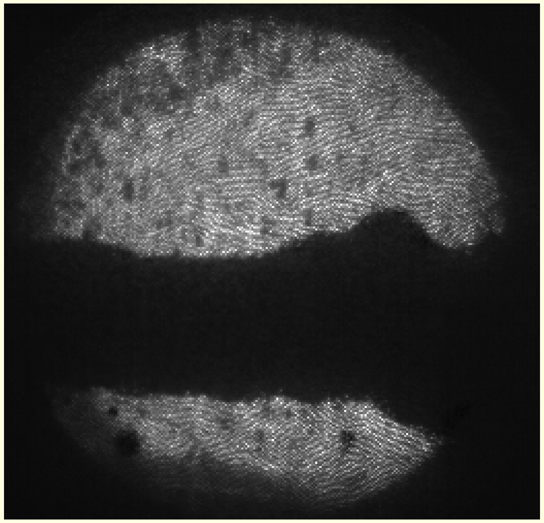
- Beam envelop – (1σ)

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

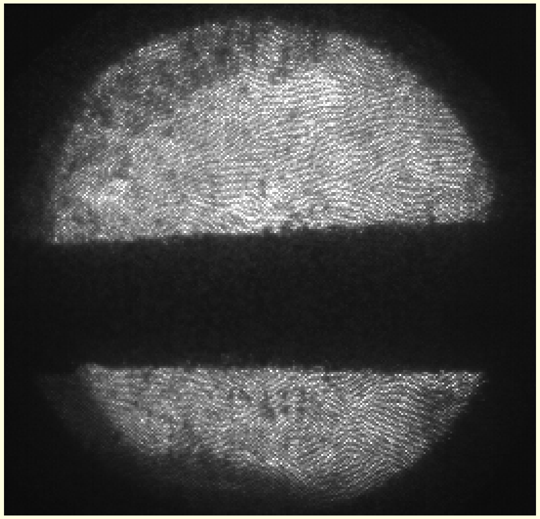
Interaction – 8,12 Tp – 14 GeV/c – 0,5,10 T



8 Tp beam, 0T field



8Tp beam, 5T field



12 Tp beam, 10T field

Jet observations

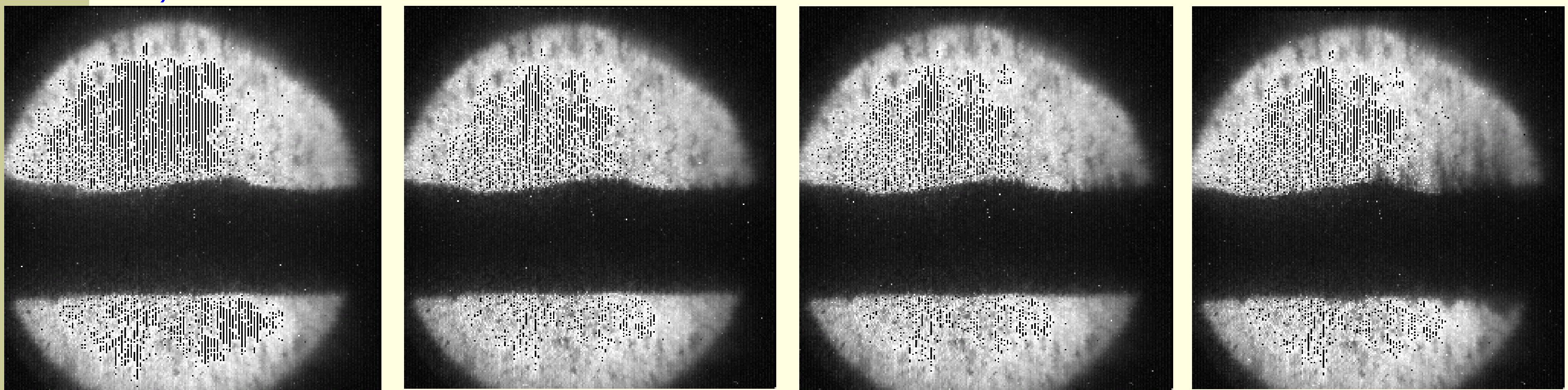
Summary-I

- 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.

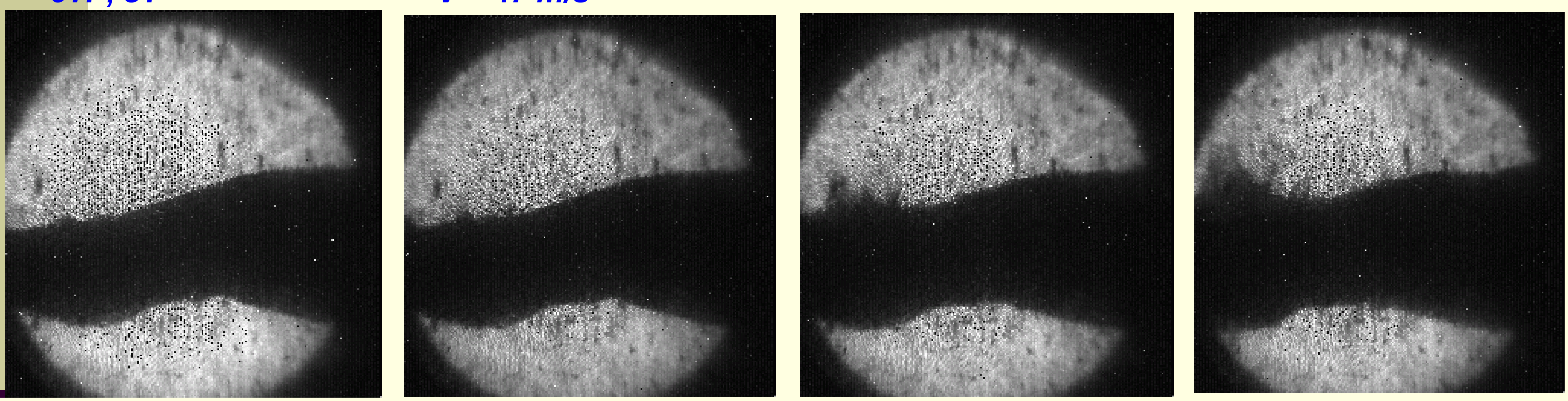
Splash velocity - 24 GeV beam: ~7 m/s/Tp

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



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

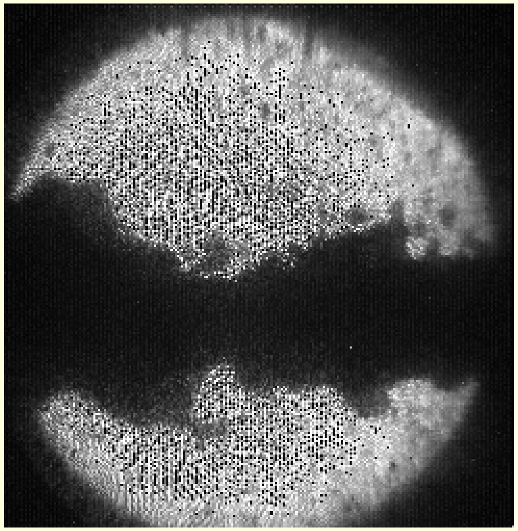
6TP, 5T ***V = 47 m/s***



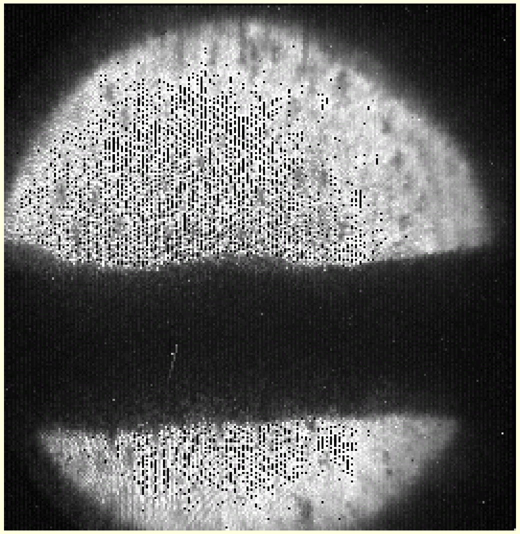
t=0 *t=0.050 ms* *t=0.175 ms* *t=0.375 ms*

Hg-jet vs Magnetic field

0.4 T

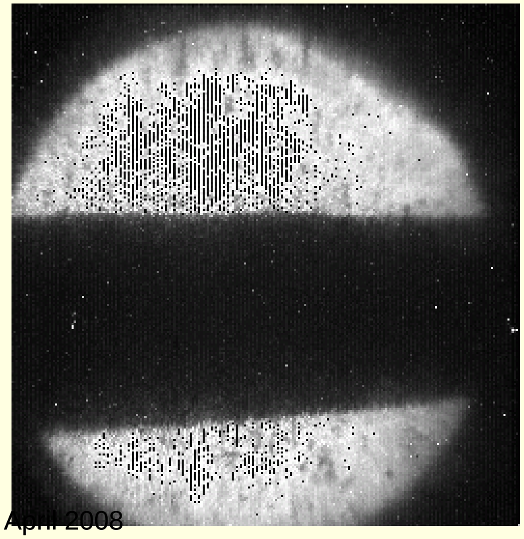


5 T

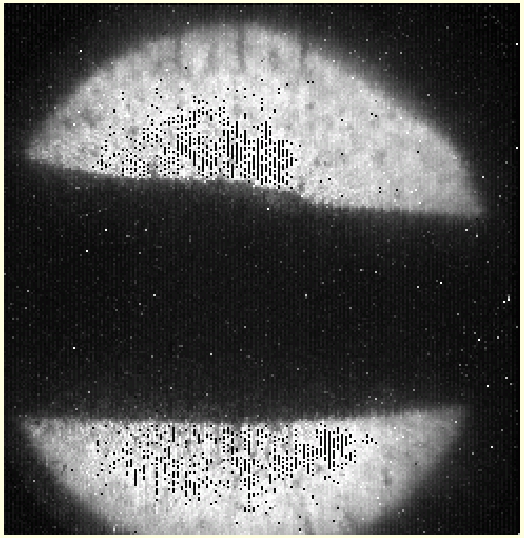


Jet velocity : 15 m/s

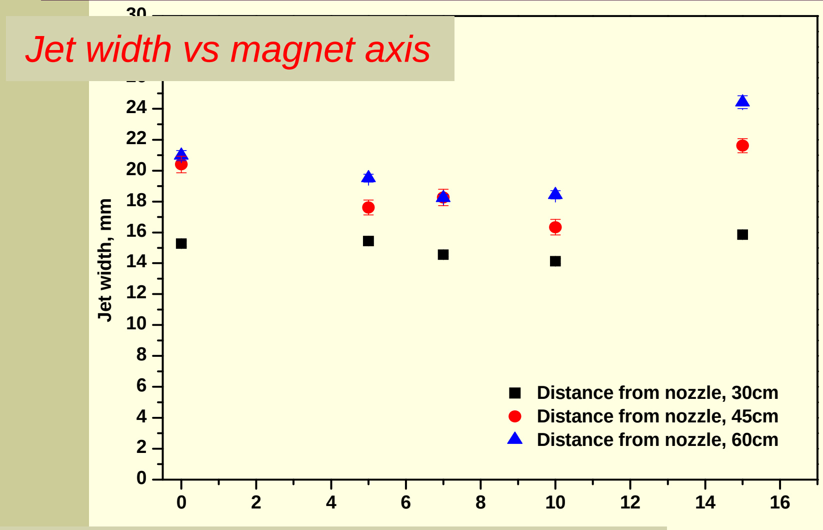
10 T

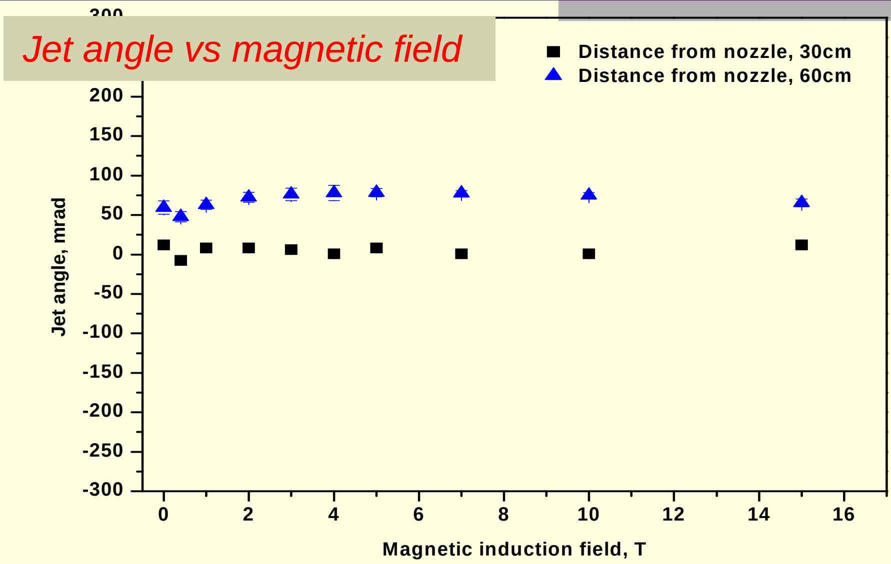


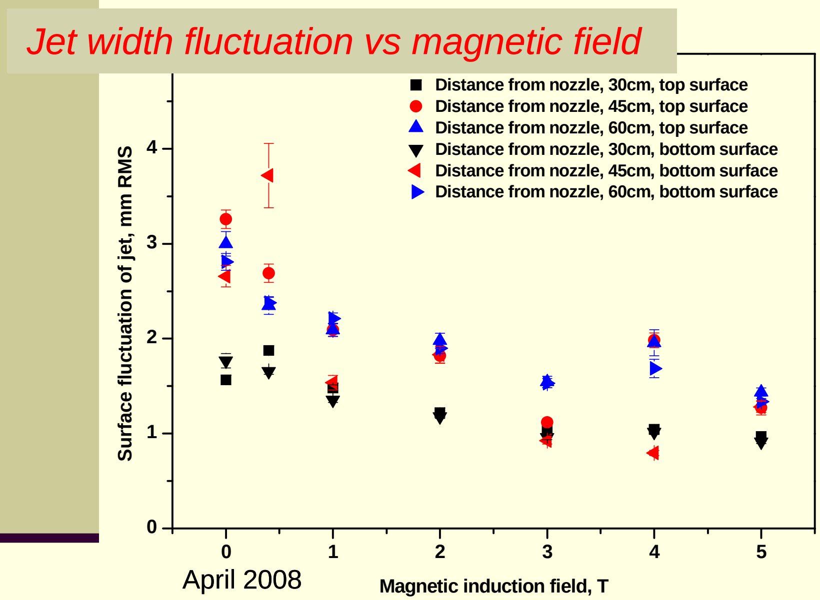
15 T

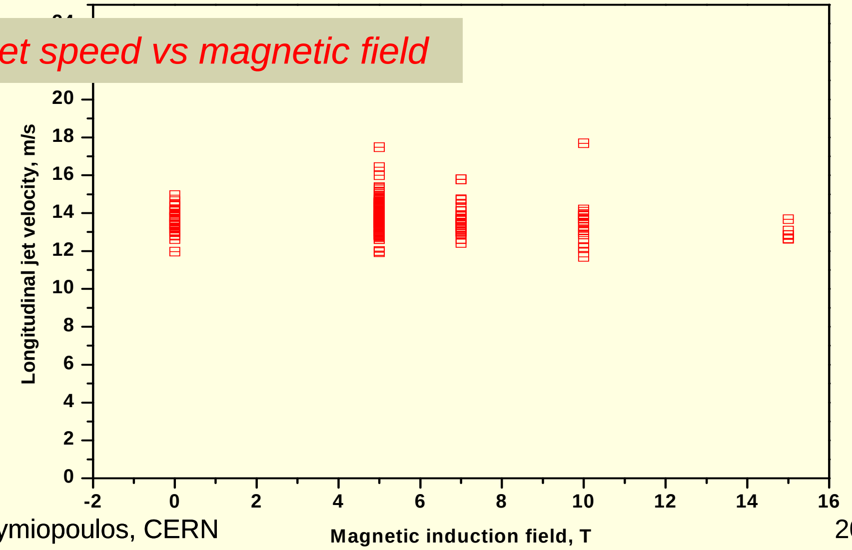


Hg-jet properties – 15m/s jet

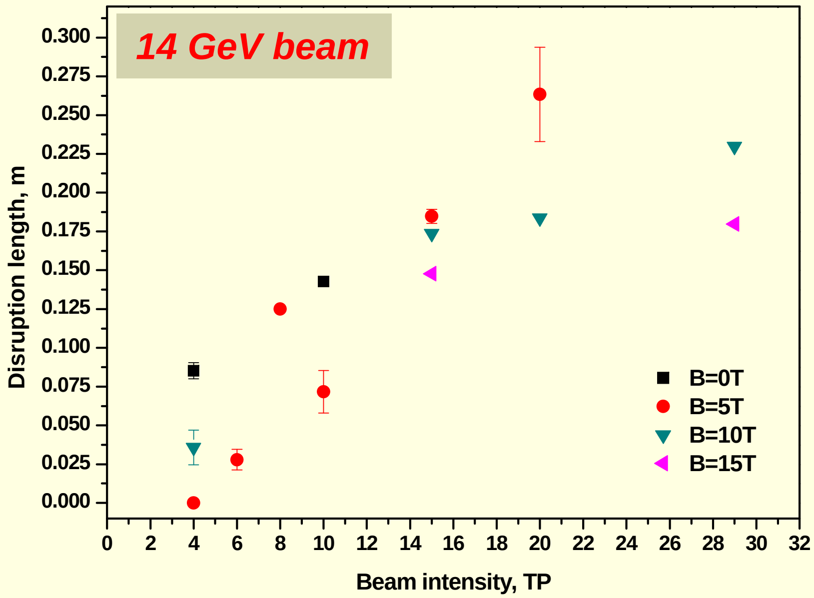




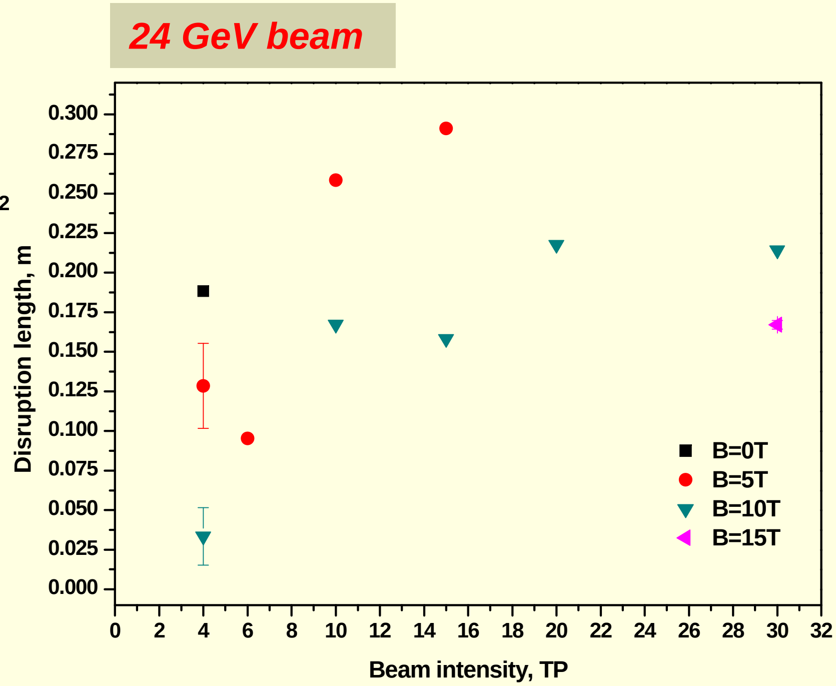




Disruption length vs beam intensity



- 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 !



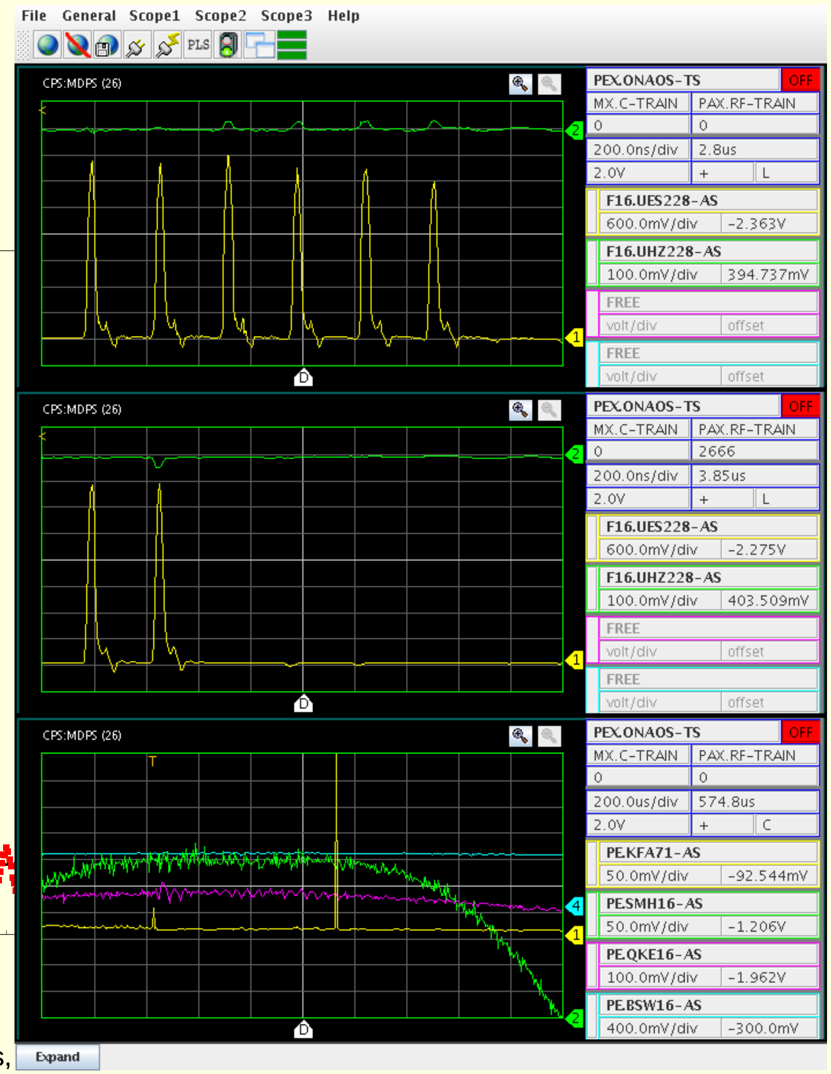
Jet observations

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.

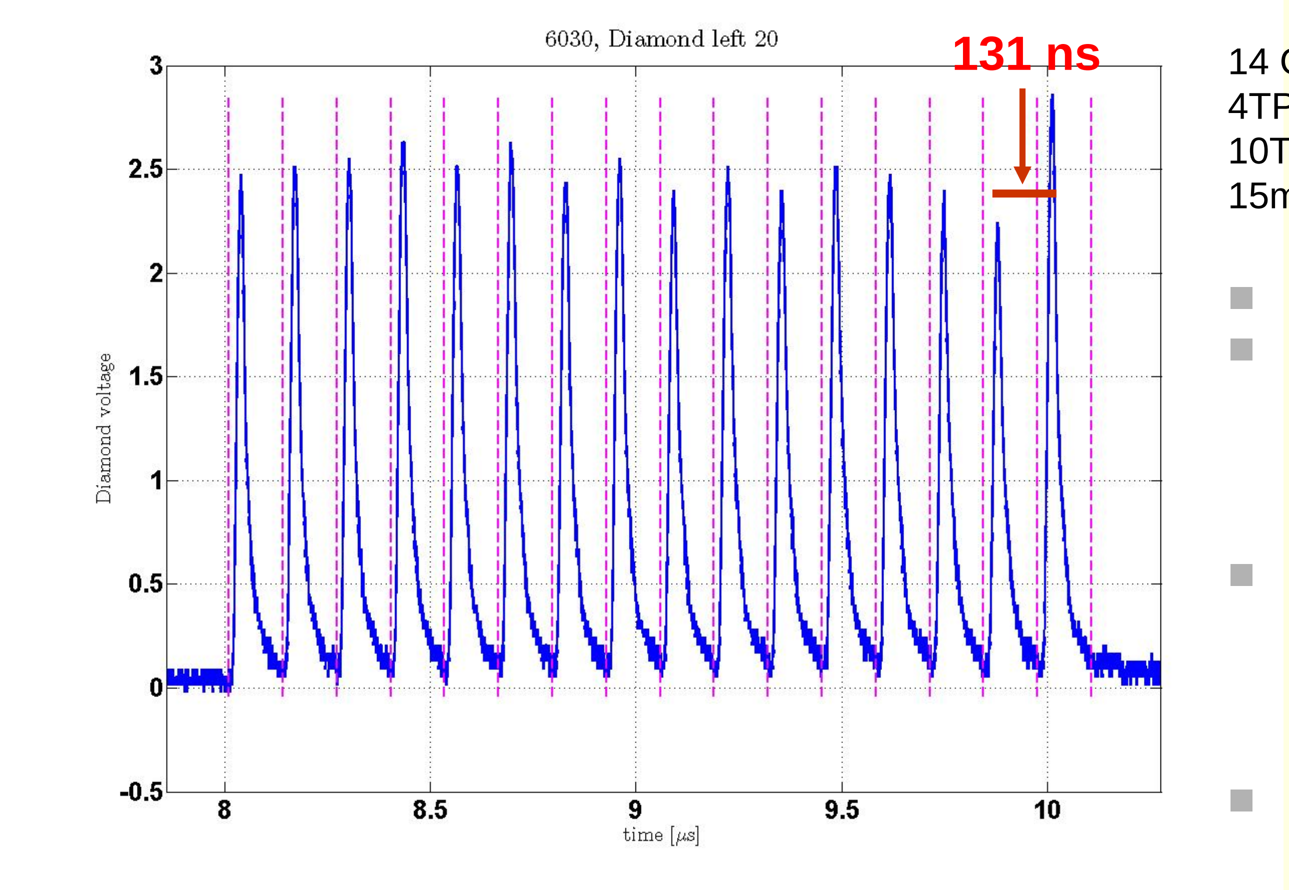
Proton beam intensity measurement

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



Particle detector data

- pCVD diamond detector (left 20-deg location)

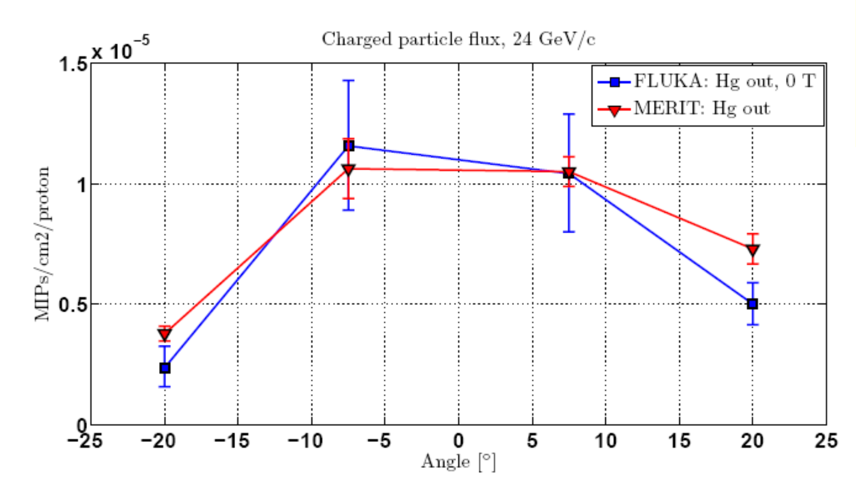


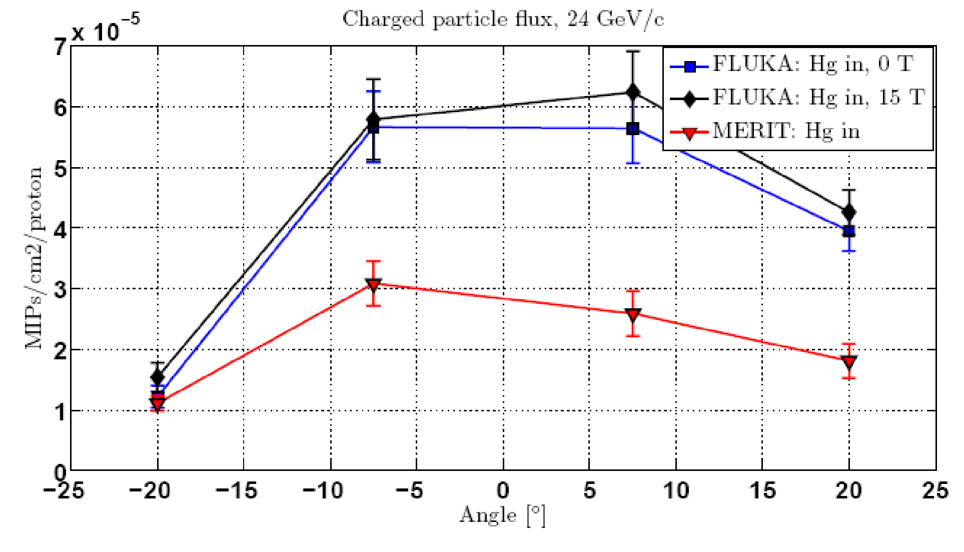
14 GeV beam
4TP
10T Field
15m/s Hg Jet

- 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





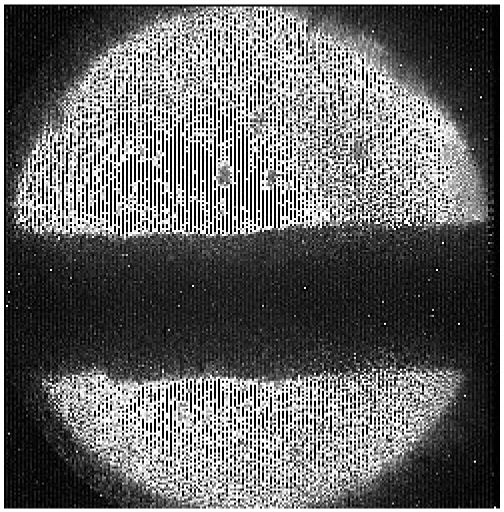
Summary

- 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.

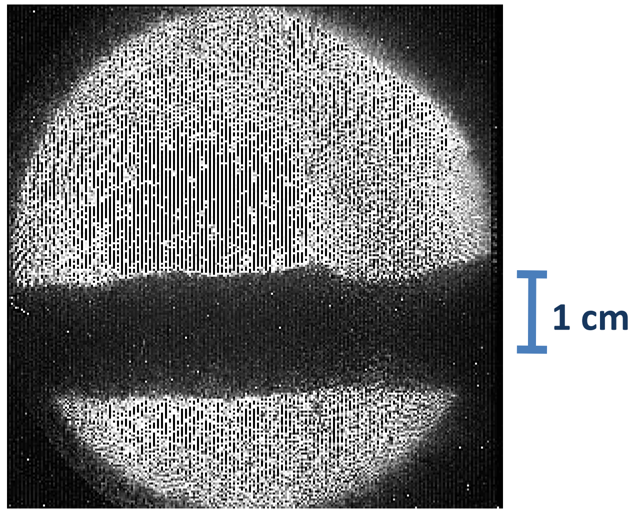
The MERIT Experiment do closely match the nominal parameters of the ν-factory

- 24 GeV Proton beam
- Up to 28 x 10^{12} Protons (TP) per 2 μs spill
- Proton beam spot with r ≤ 1.5 mm rms
- 1 cm diameter Hg Jet
- Hg Jet/Proton beam off solenoid axis
  - Hg Jet 100 mrad
  - Proton beam 67 mrad
- Test 50 Hz operations
  - 20 m/s Hg Jet
  - 2 spills separated by 20 ms

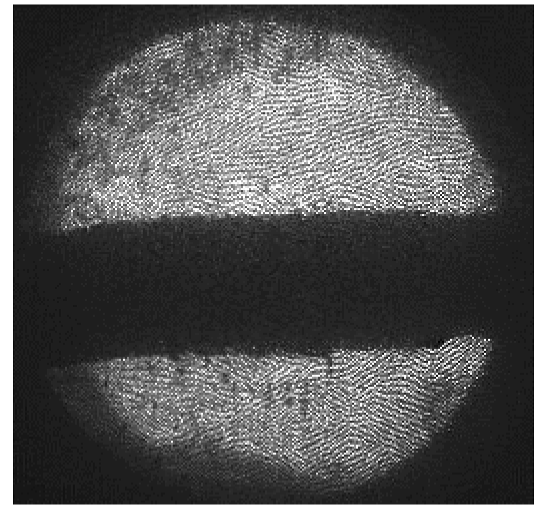
View on mercury jet



Run 103
• 14 GeV/c
• $1.6*10^{13}$ protons/pulse
• B-field 5 T



Run 119
• 14 GeV/c
• $1.6*10^{13}$ protons/pulse
• B-field 5 T



Run 214
• 14 GeV/c
• $1.2*10^{13}$ protons/pulse
• B-field 10 T

• Images were recorded at 2000 frames/second.
• Play-back is about 400 times slower.
• Splash velocities up to 60 m/s observed.

To be presented at Nufact 08

The MERIT High-Power Target Experiment at the CERN PS

H.G Kirk*, T. Tsang, *BNL, Upton, NY 11973, USA*
I. Efthymiopoulos, A. Fabich, F. Haug, J. Lettry, M. Palm, H. Pereira, *CERN, CH-1211 Genève 23, Switzerland*
A.J. Carroll, V.B. Graves, *ORNL, Oak Ridge, TN 37831, USA*
K.T. McDonald, *Princeton University, Princeton, NJ 08544, USA*
J.R.J. Bennett, O. Caretta, P. Loveridge, *CCLRC, RAL, Chilton, OX11 0QX, UK*
H. Park, *SUNY at Stony Brook, NY 11794, USA*

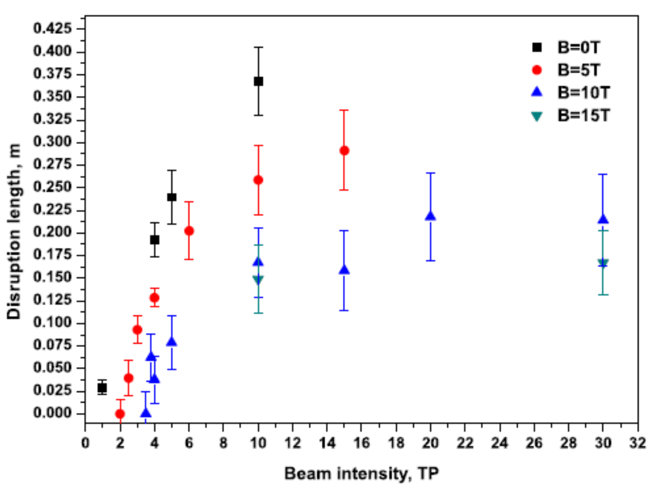


Figure 6: The observed disruption length of the Hg jet for various beam intensities and solenoid field strengths for an incoming proton beam energy of 24GeV.

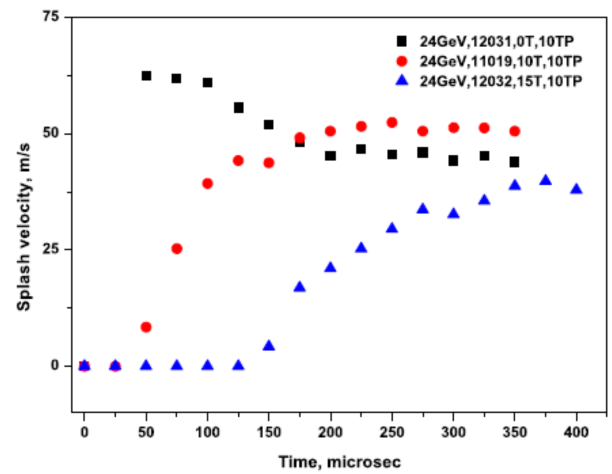


Figure 8: The observed time delay for material being ejected from the Hg jet after impact with a 24-GeV beam containing 10×10^{12} protons.

The Beam dump of a 4 MW proton beam, activation, radioactive waste and target handling issues

Examples of CNGS (doserate) and T2K (Dump)

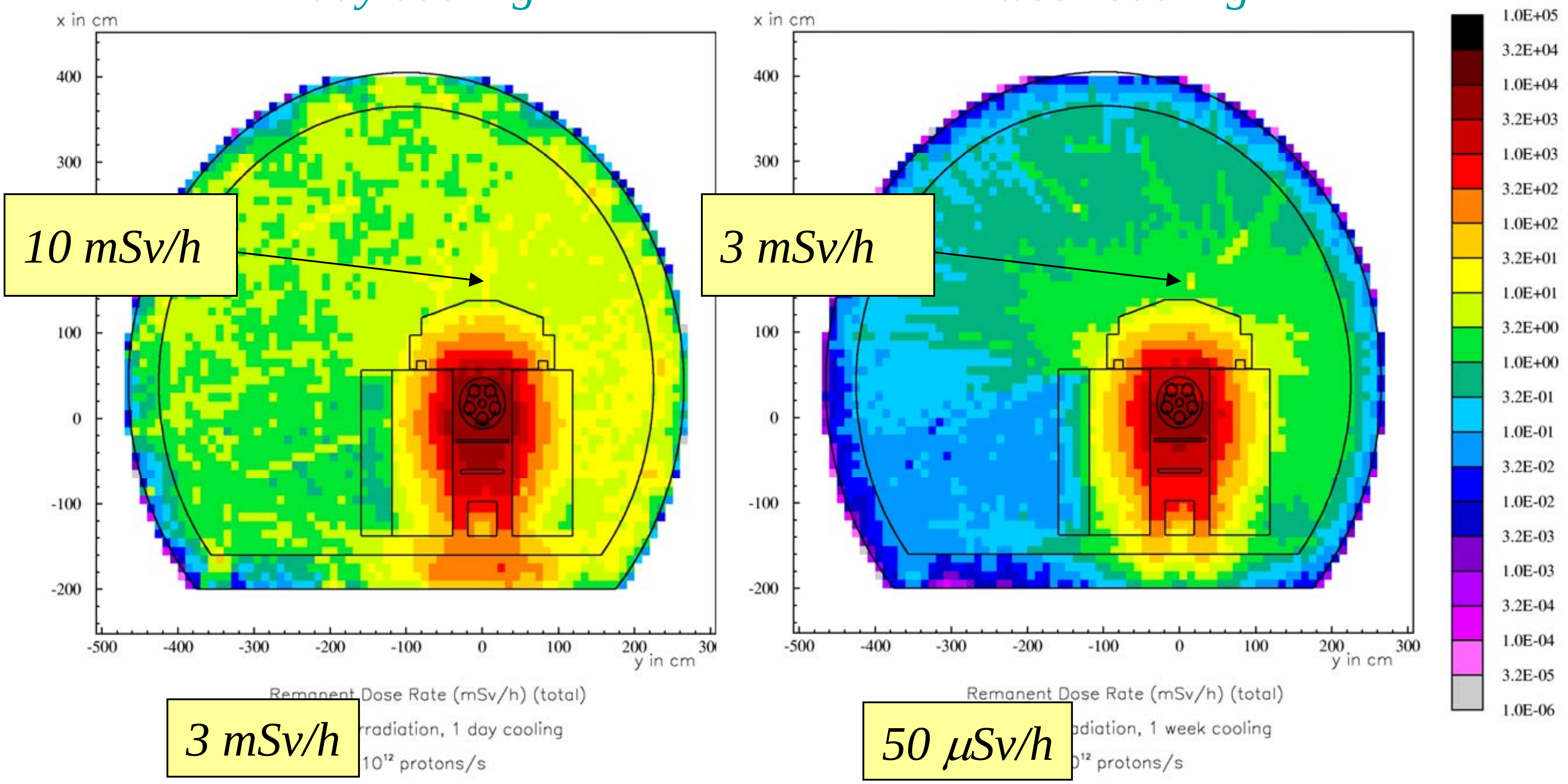
EURISOL-DS (Activation of concrete)

CNGS-Remanent dose rates … well shielded ~1/500

All possible human interventions needs description, timing and training

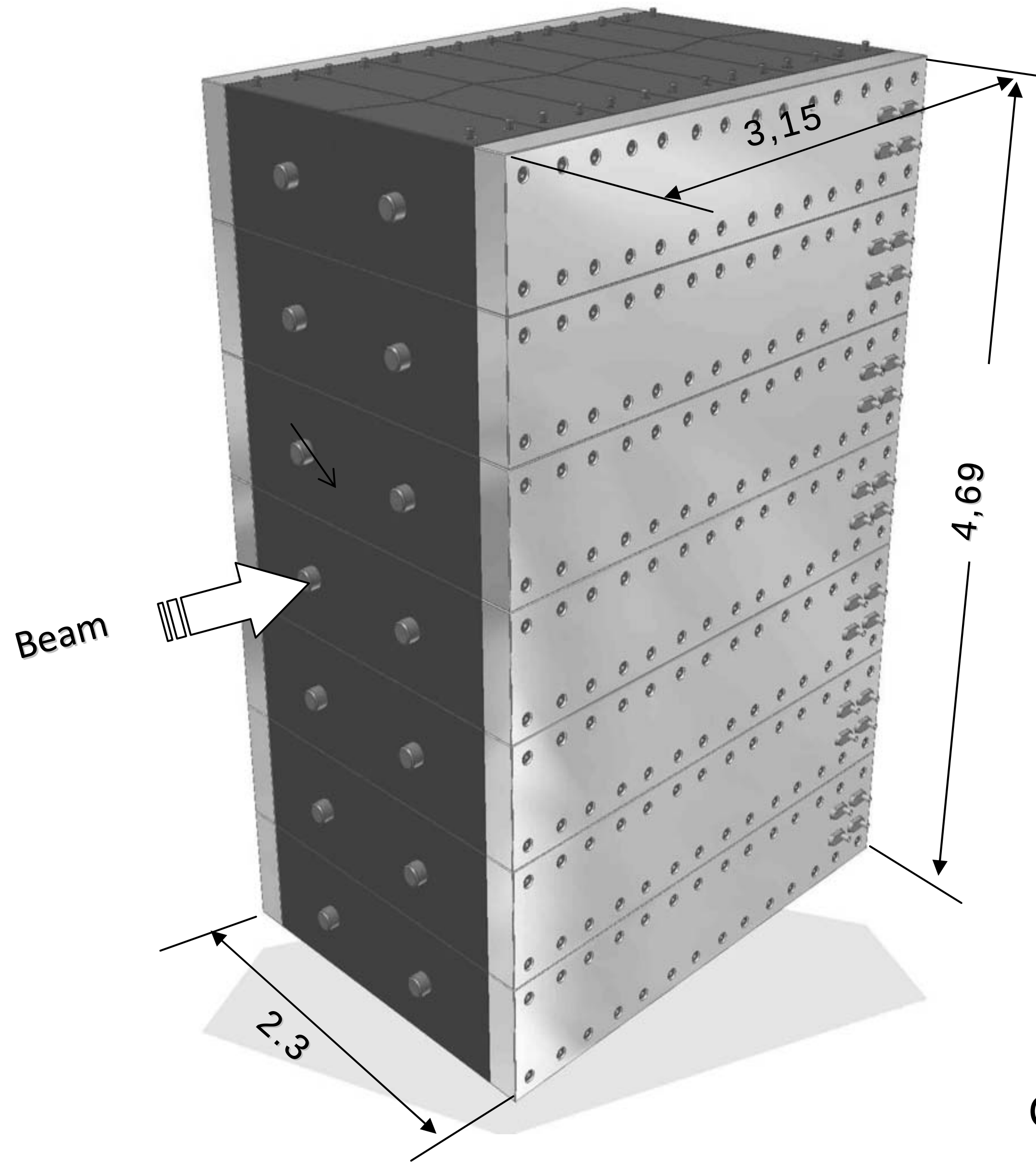
Total remanent dose rate (mSv/h) *(200 days irradiation)*

1 day cooling *1 week cooling*



T2K graphite Hadron Absorber

Graphite Blocks
+ cooling module
layout

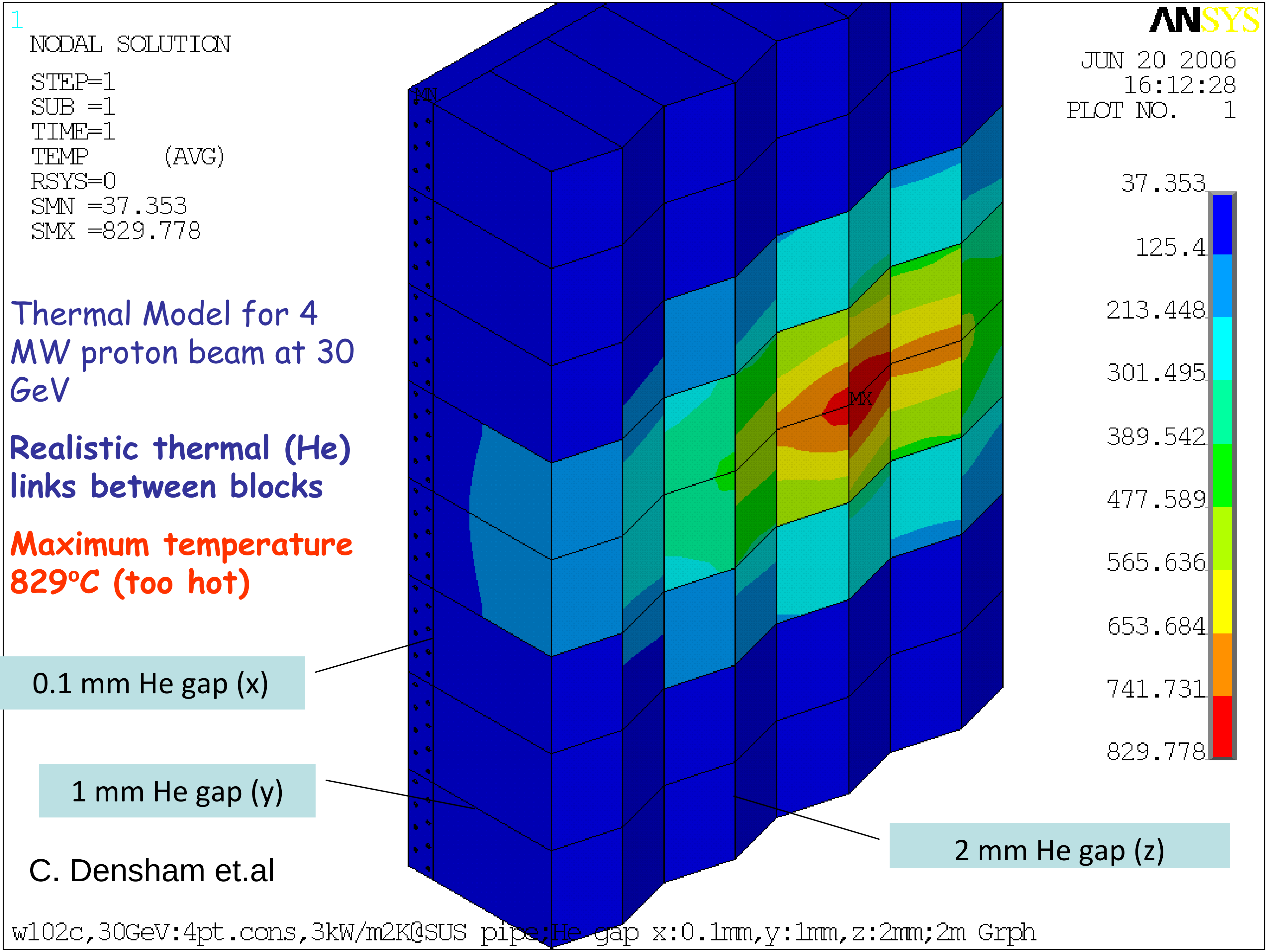


C. Densham et.al

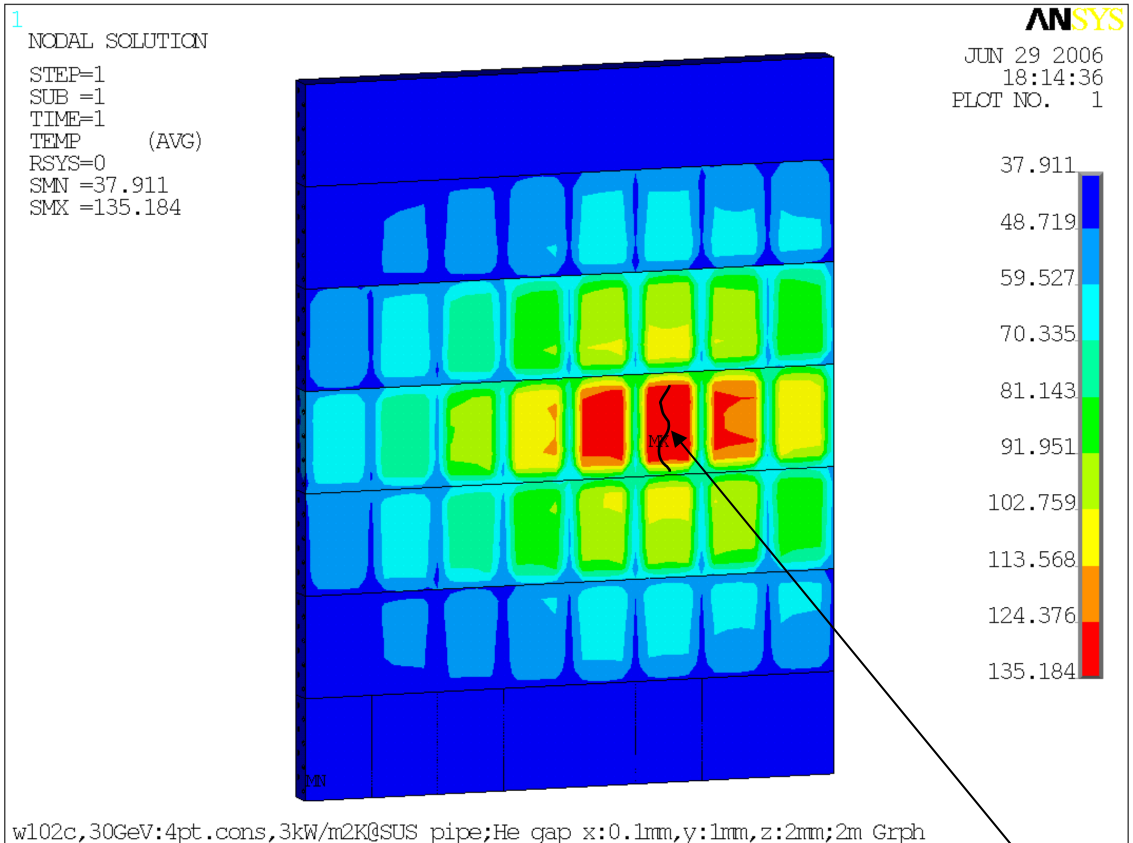
Thermal Model for 4 MW proton beam at 30 GeV

Realistic thermal (He) links between blocks

Maximum temperature 829°C (too hot)

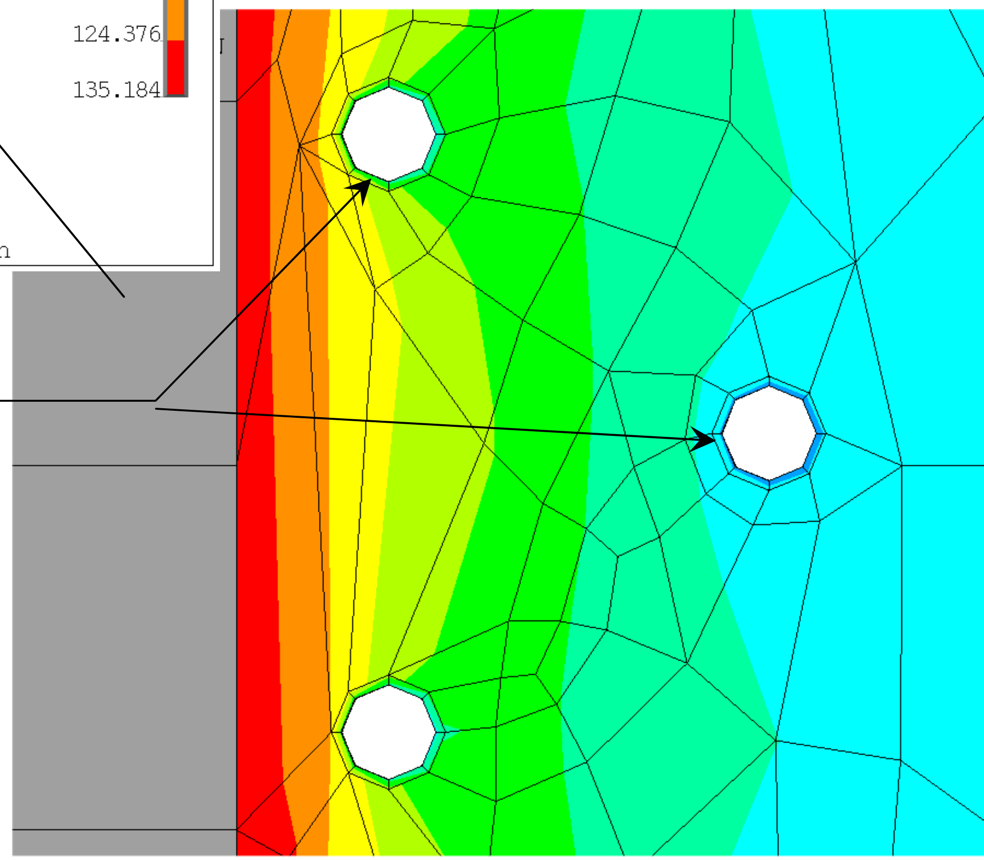


C. Densham et.al



Cooling module temperatures

Maximum temperature = 135 C



3,000 W/m2/K
Water cooling

Cross-section through cooling module at shower maximum

C. Densham et.al

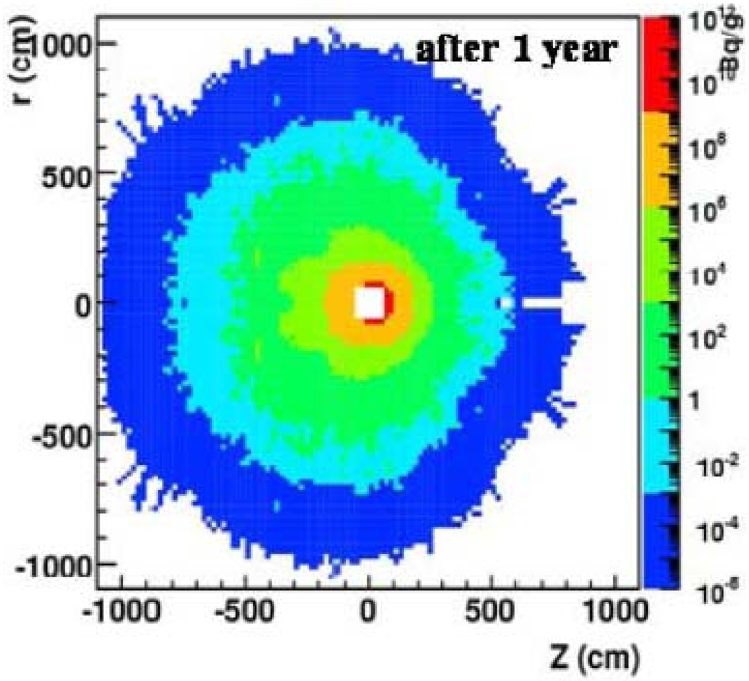
14/06/2008

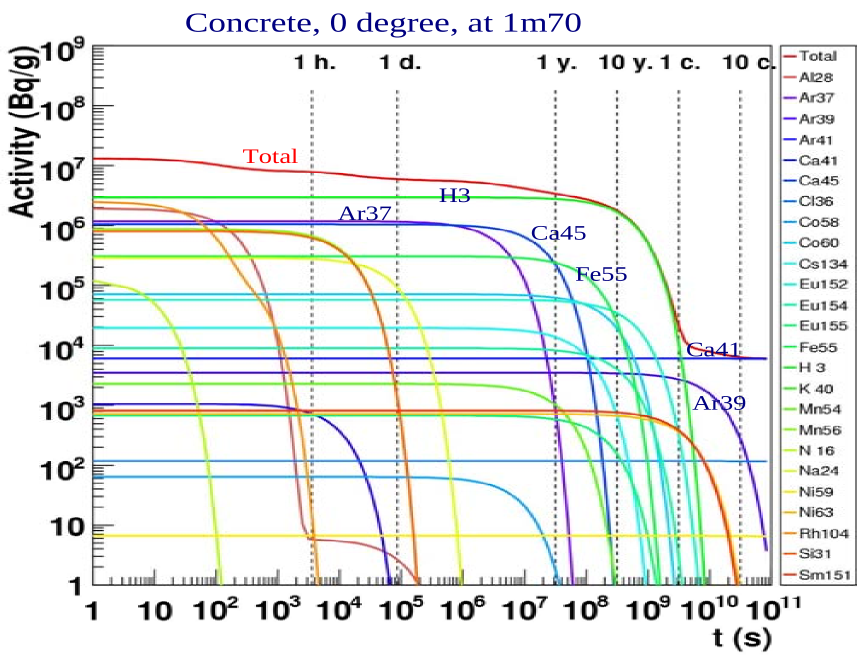
Conclusions

- Graphite temperatures acceptable for up to 3 MW beam operation
- Single point connection for each graphite block to cooling module is preferable to multi-point connections
- Splitting graphite blocks along centreline reduces stresses to acceptable level
- Downstream copper core planned to be replaced with iron and plate coil water cooling. More work needed to reduce stresses

EURISOL 4MW Hg beam dump

09-Shielding specific activity





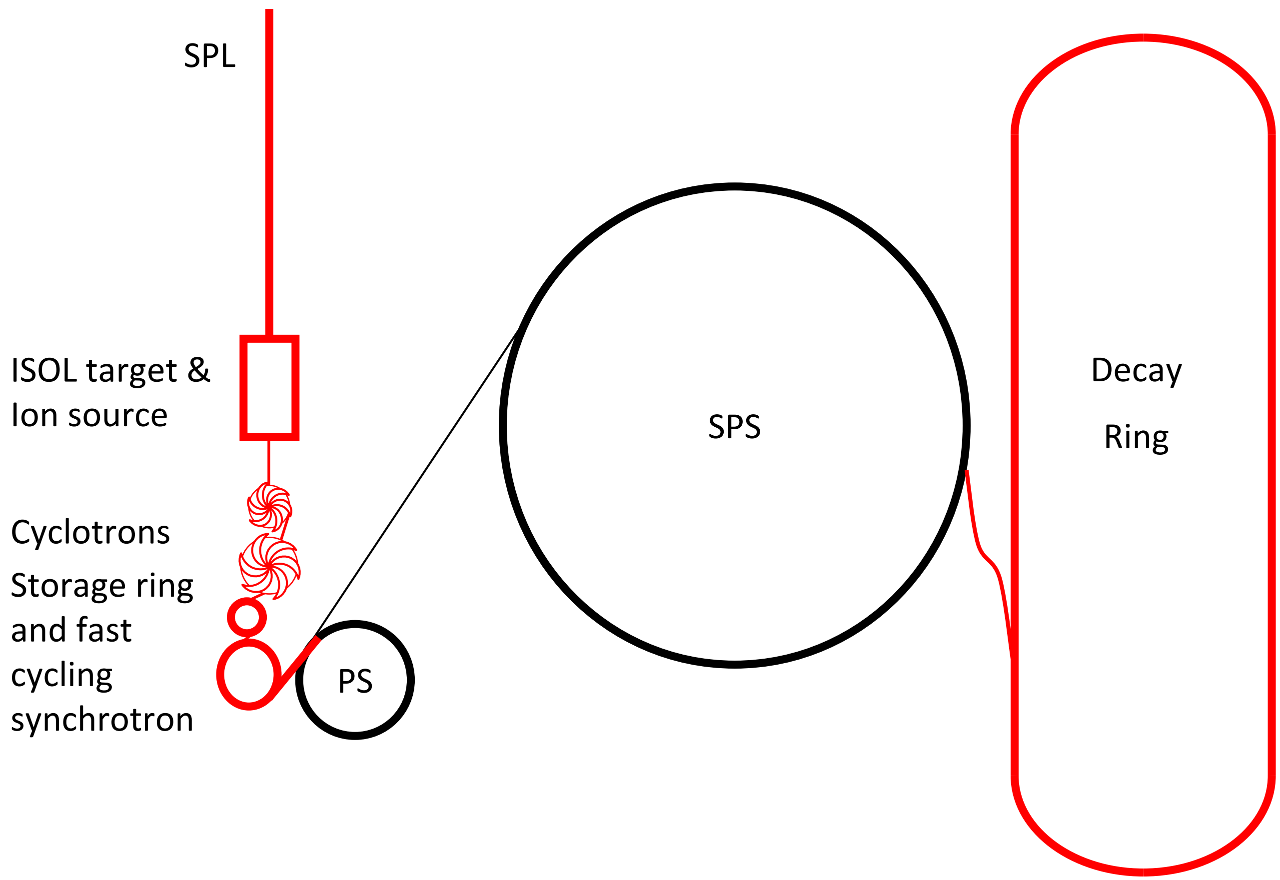
Activity profile (Bq/g) as a function of shielding coordinates (r, z) of the MMW target station, located at (0,0): on the top – after 1 year of cooling. The time evolution of the activity of the shielding concrete after forty years of operations is also shown. In this simulation, 2.3 MW are deposited in the Hg neutron spallation source out of the 4 MW average beam power.

D. Ridikas

Beta-decay ν_e-beams

Why not solve the muon production and cooling problem by deriving neutrinos beams from stored short-lived beta emitters (*P. Zuchelli*)

β-ν-beam baseline scenario 2003



Decay ring

Brho = 1500 Tm

B = 5 T

L_{ss} = 2500 m

$${}^{6}_{2}He \rightarrow {}^{6}_{3}Li\, e^{-}\,\overline{\nu}$$

$$\text{Average } E_{cms} = 1.937 \text{ MeV}$$

$${}^{18}_{10}Ne \rightarrow {}^{18}_{9}F\, e^{+}\,\nu$$

$$\text{Average } E_{cms} = 1.86 \text{ MeV}$$

Louvain la neuve cyclotron

Typical intensities

After

post-acceleration

and

isobaric separation

on experimenter's target

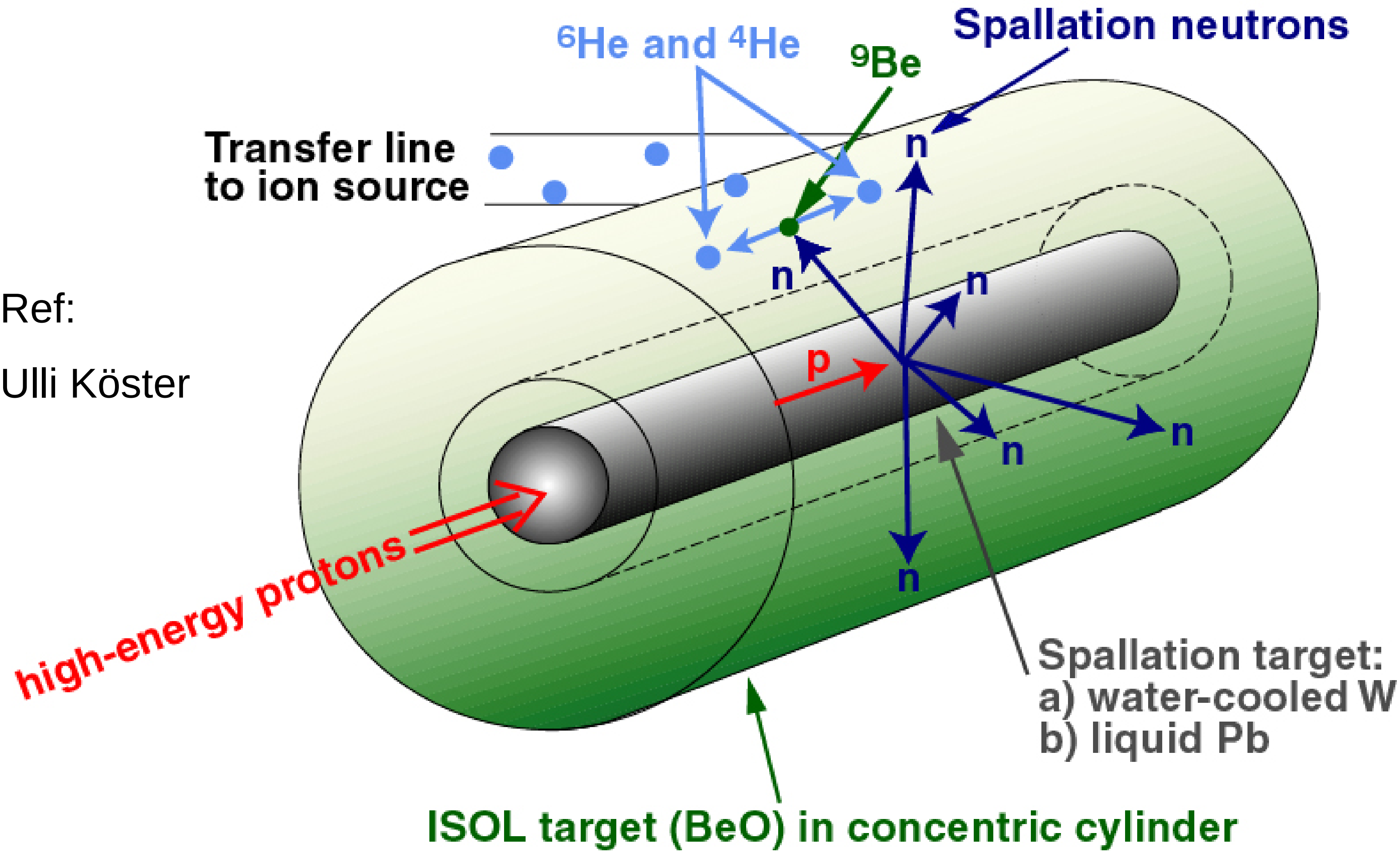
Element	$T_{1/2}$	q	Energy Range [MeV]	Intensity [pps]*
^{6}Helium	0.8 s	1+	5.3 – 18	$1 \cdot 10^{7}$
		2+	30 – 73	$3 \cdot 10^{5}$
^{7}Beryllium	53 days	1+	5.3 – 12.9	$2 \cdot 10^{7}$
		2+	25 – 62	$4 \cdot 10^{6}$
^{10}Carbon	19.3 s	1+	5.6 - 11	$2 \cdot 10^{5}$
		2+	24 - 44	$1\ 10^{4}$
^{11}Carbon	20 min	1+	6.2 – 10	$1 \cdot 10^{7}$
^{13}Nitrogen	10 min	1+	7.3 – 8.5	$4 \cdot 10^{8}$
		2+	11 – 34	$3 \cdot 10^{8}$
		3+	45 – 70	$1 \cdot 10^{8}$
^{15}Oxygen	2 min	2+	10 – 29	$6 \cdot 10^{7}$
^{18}Fluorine	110 min	2+	11 – 24	$5 \cdot 10^{6}$
^{18}Neon	1.7 s	2+	11 – 24	$1 \cdot 10^{7}$
		3+	24 – 33, 45 – 55	$4 \cdot 10^{6}$
^{19}Neon	17 s	2+	11 – 23	$2 \cdot 10^{9}$
		2+	7.5 – 9.5	$5 \cdot 10^{9}$ (CYC44)
		3+	23 – 35, 45 – 50	$1.5 \cdot 10^{9}$
		4+	60 – 93	$8 \cdot 10^{8}$
^{35}Argon	1.8 s	3+	20 – 28	$2 \cdot 10^{6}$
		5+	50 – 79	$1 \cdot 10^{5}$

M. Loiselet

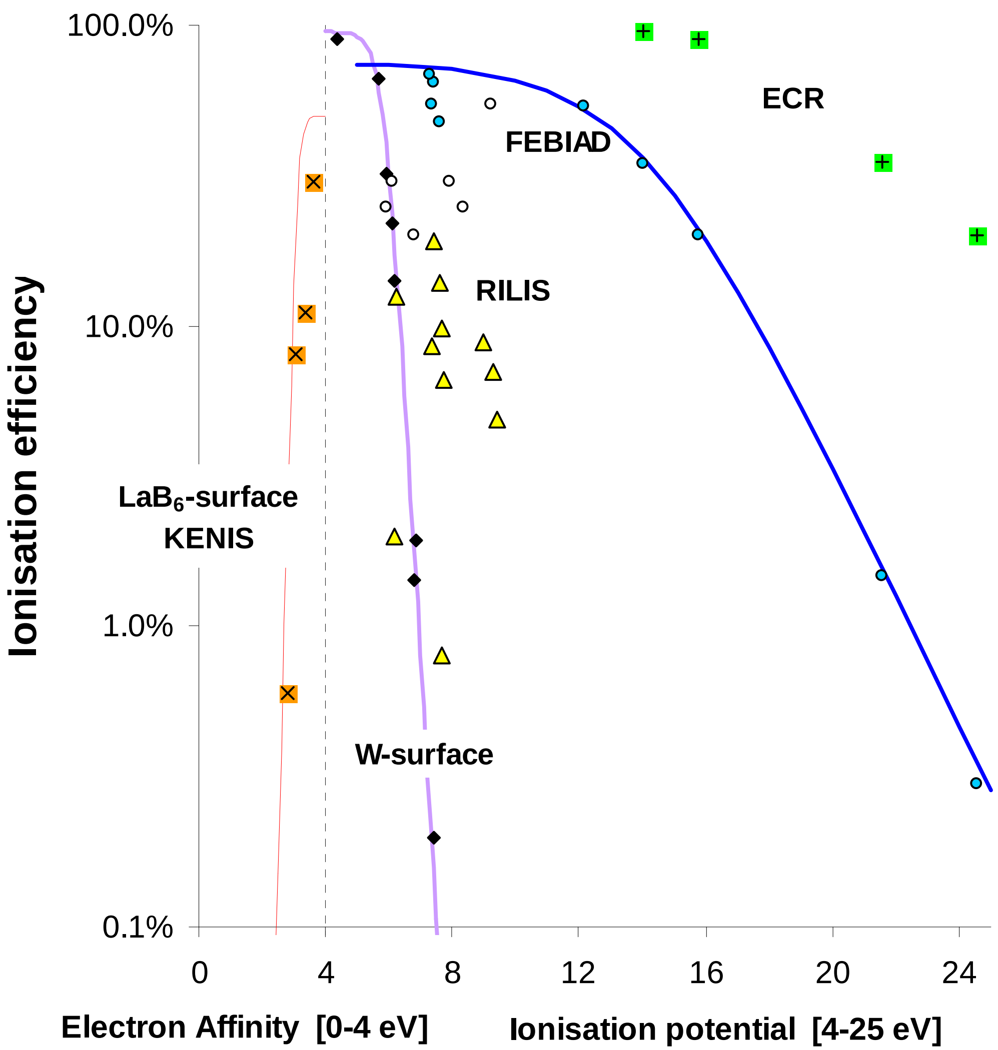
^{6}He production by $^{9}Be(n,\alpha)$

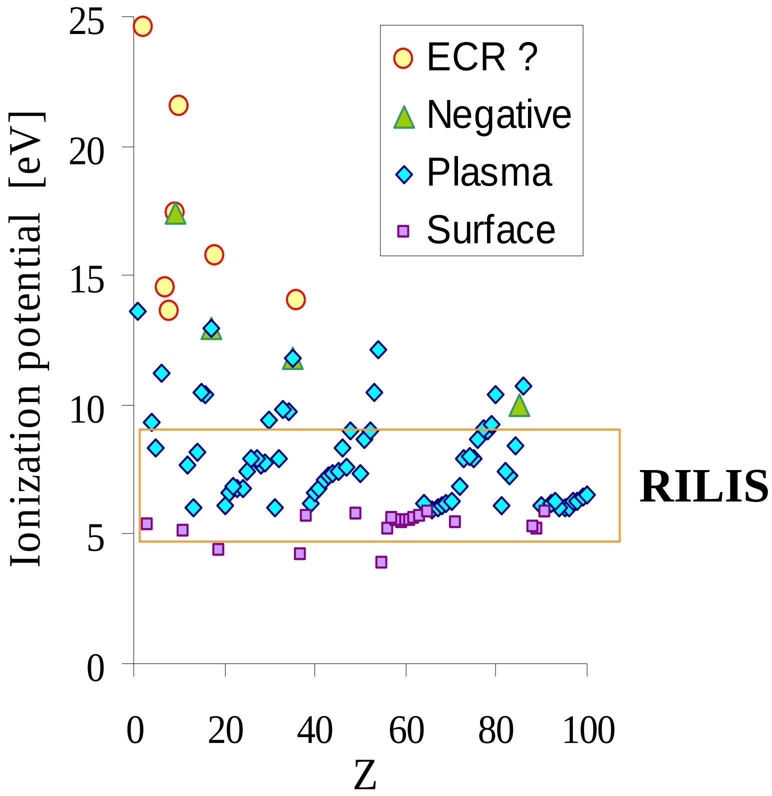
Ref:

Ulli Köster

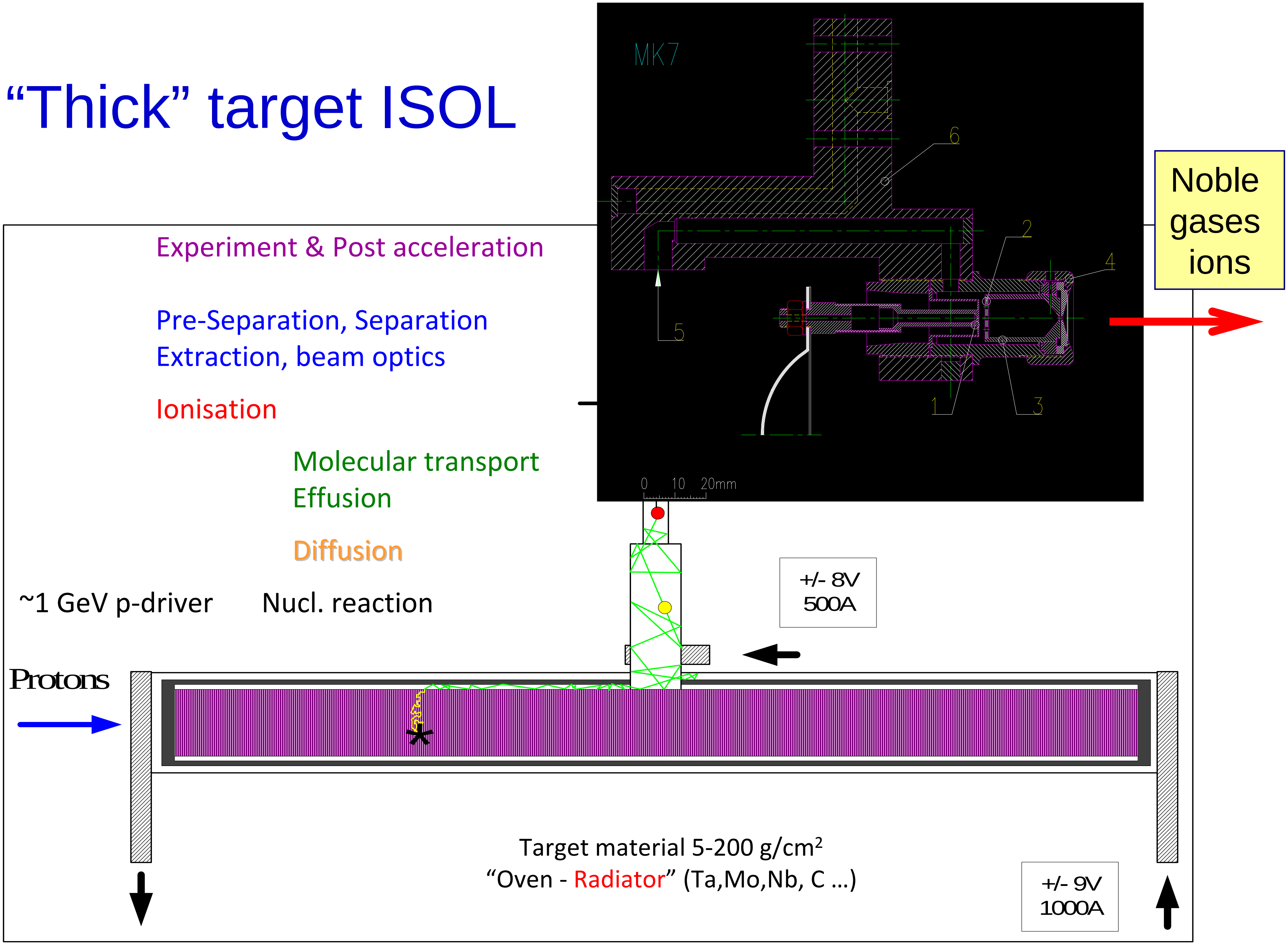


RIB-Ion-sources efficiencies
+ ARC-ECRIS charge state breeder ?

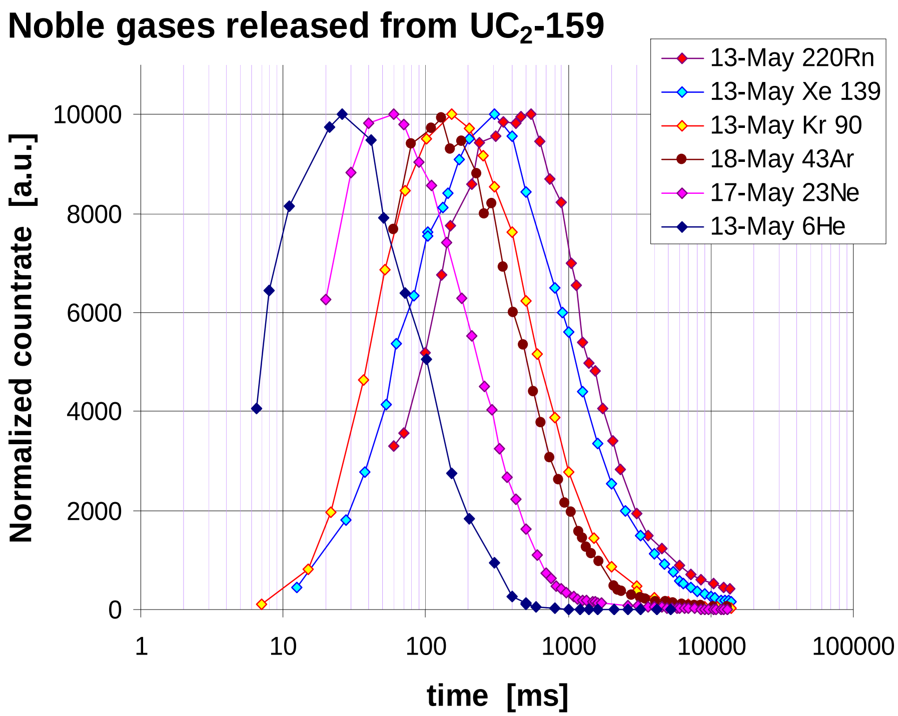


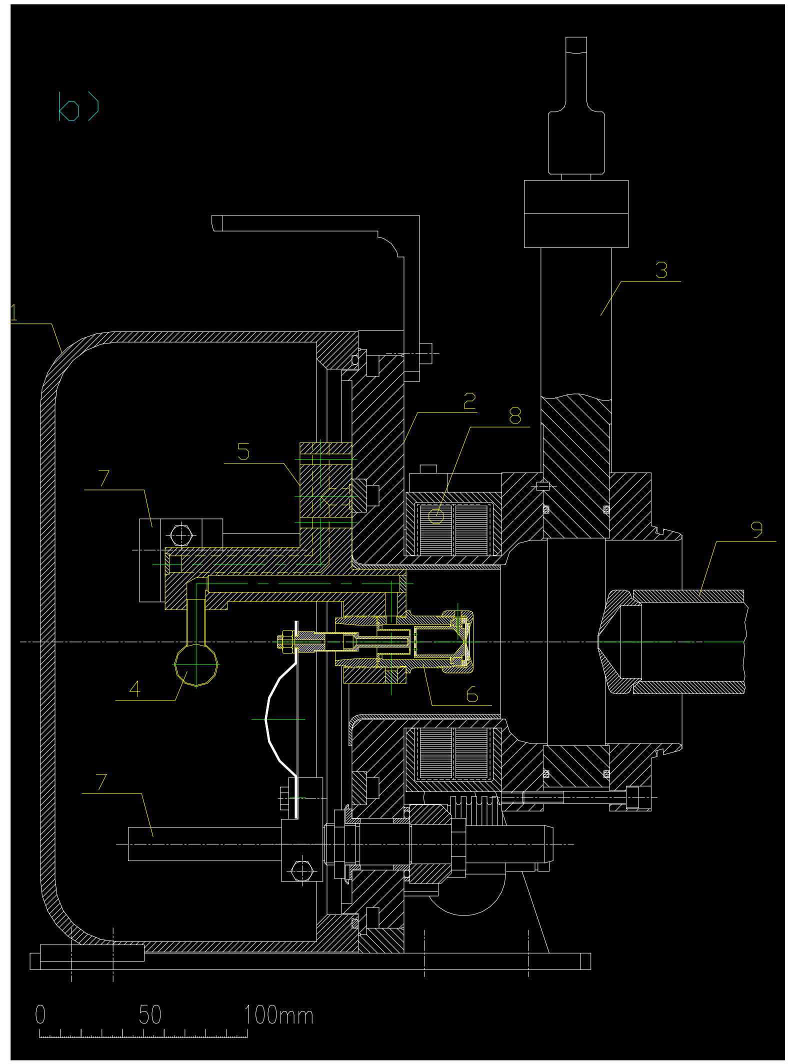


“Thick” target ISOL



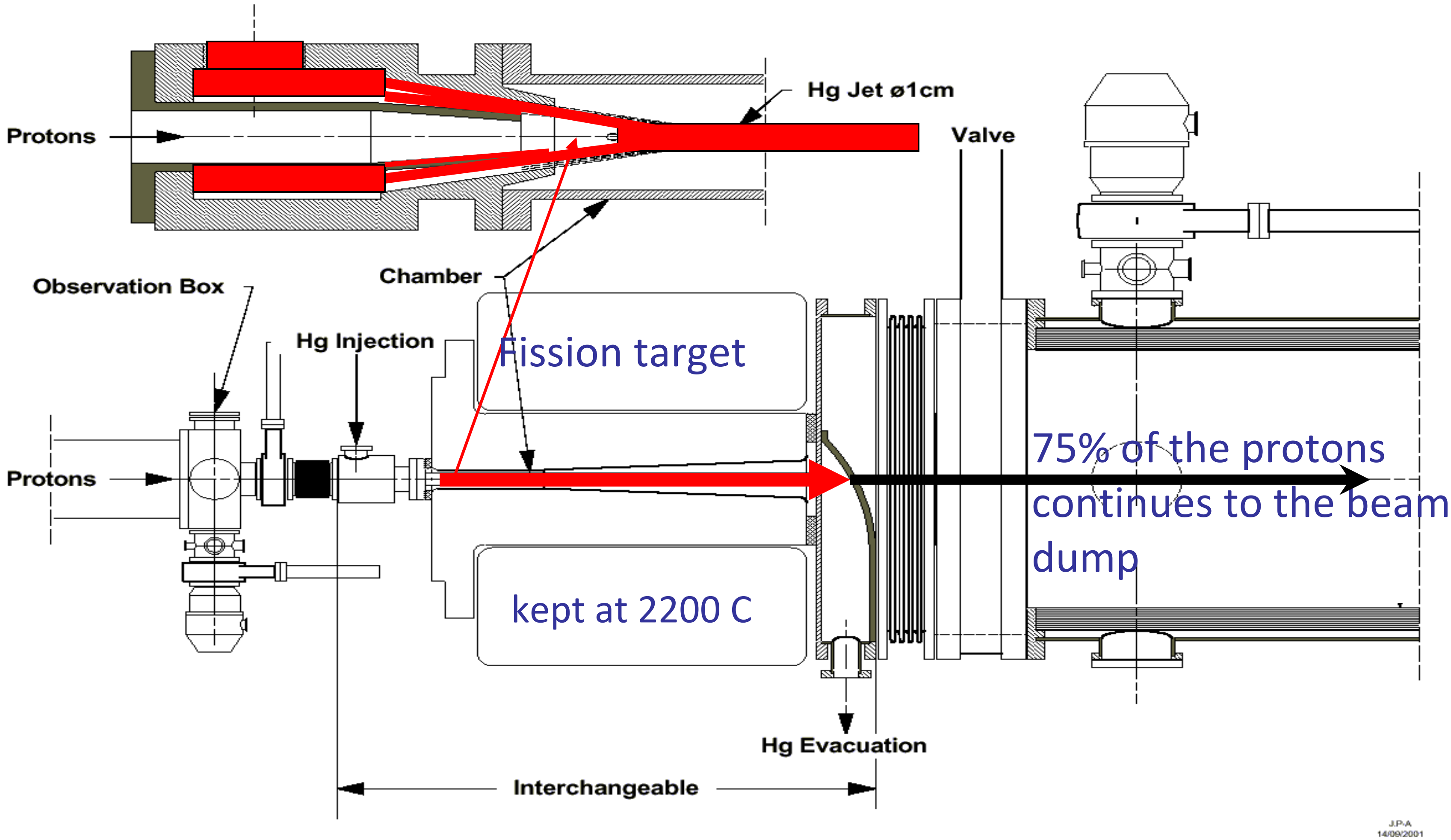
Release of noble gases from UCx target and MK7 ion-source





Scaling and parameterization of release
Vs. Temperature, masses, diffusion coefficients,
and desorption enthalpies
Trapped Mother in the target (i.e. ^{224}Ra – ^{220}Rn)

Mercury-jet p-n converter surrounded by a Uranium carbide target



^{6}He production by ^{9}Be(n,α)

^{9}Be(n,α)^{6}He reaction favorable:

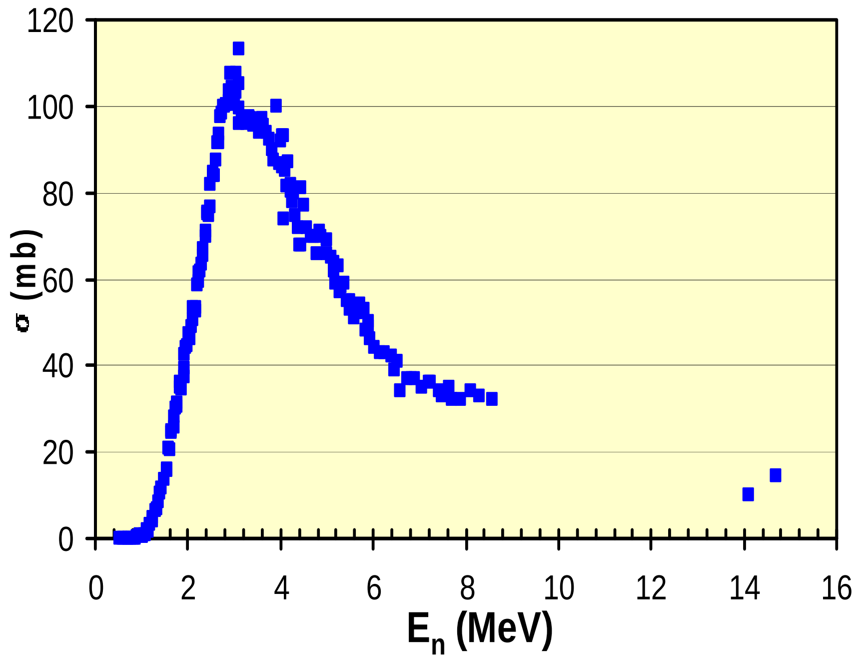
•Threshold: 0.6 MeV

•Peak cross-section 105 mb

•Good overlap with evaporation part of spallation neutron spectrum: n(E)~√E*exp(-E/E_e)

•E_e: 2.06 MeV for 2 GeV p on Pb *G.S. Bauer, NIM A463 (2001) 505*

•BeO very refractory



Targetry Challenges & tools, a Conclusion

- Proton beam
  - Energy and time structure
  - Pion-Cross sections
- Molten metal targets (cooling & transport)
  - Hight pressure high velocity molten metal fluid dynamics
    - Cavitation in the piping, Corrosion
    - Recuperation of high velocity splashes, Phase transition
  - Purification of the molten metal circuits
  - MHD of molten metal jets
- Solid targets (cooling & transport)
  - Effect of dpa and radiogenic chemical impurities on material properties
  - High velocity mechanics under vacuum
  - Compaction of Ta-beads, powders
- Component reliability or life time of pion-optics vs. exchange time
  - Horns & Solenoids
- Simulation codes
  - Detailled Energy deposition (MARS, GEANT, FLUKA)
  - Shock transport elastic-plastic (LS-Dyna, Autodyn,…)
  - 3d-Shocks in liquids with MHD
- Activation of components, inventory of specific activities vs. time
  - Radioactive waste handling
  - Internal transport, intermediate storage
  - End disposal
- *Experimental areas dedicated to target tests (highest radiotoxicity)*
  - Optical measurement techniques in high radiation environment