Target concepts for future high power proton beams

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Outline

- Demand for “human made” neutrino beams
  - A neutrino factory
  - A high power proton driver
  - Target station
    - Secondary particle production
- Target concepts
  - Solid targets
  - Liquid targets
    - Jet target
  - Worldwide R&D

CNGS graphite target assembly (2005, D.Grenier et al.)

Neutrino oscillations

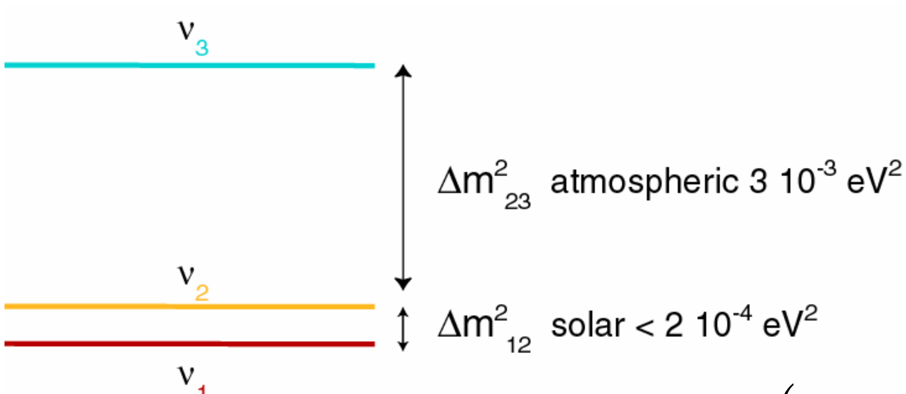
Observation: ν into another ν of different flavour

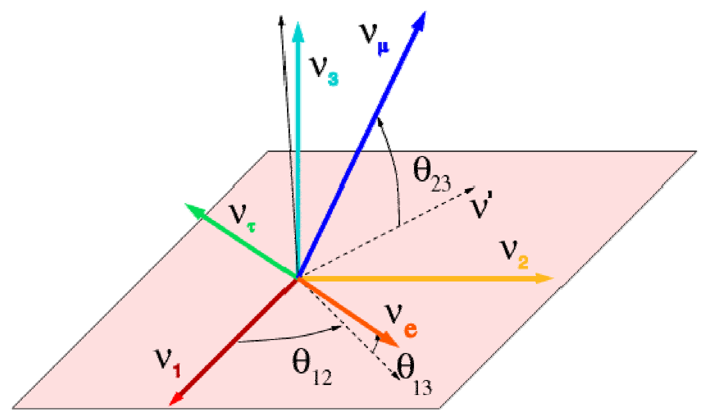
Results: NEUTRINOS HAVE MASS
MASS STATES $\neq$ FLAVOUR STATES

6 Parameters:

- Three mixing angles
- Two Δm^2 differences
  - 3 masses
- One delta phase (CP-violation angle)

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

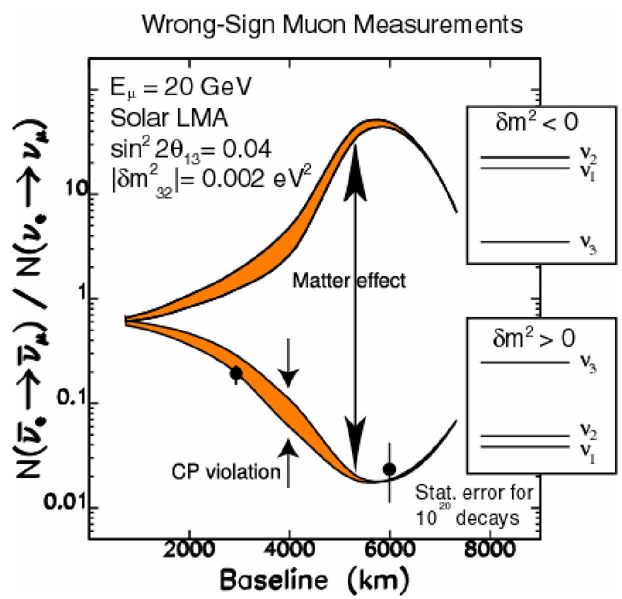




Transition probability: $$P(\nu_e \to \nu_\mu) = \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2\left(\frac{\Delta m_{23}^2 L}{4E_\nu}\right)$$

Neutrino parameters to measure

- Measure θ_{13} via $P(\nu_e \to \nu_\mu)$ with a precision of 10^{-3} or setting a limit to 10^{-6}
- Determine the sign of Δm^2_{23}
- Discover and measure the CP violation in the leptonic sector



$$P(\nu_e \to \nu_\mu) \neq P(\bar{\nu}_e \to \bar{\nu}_\mu)$$

Need of high energy ν_e:

$$\mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu$$

neutrino beams/experiments

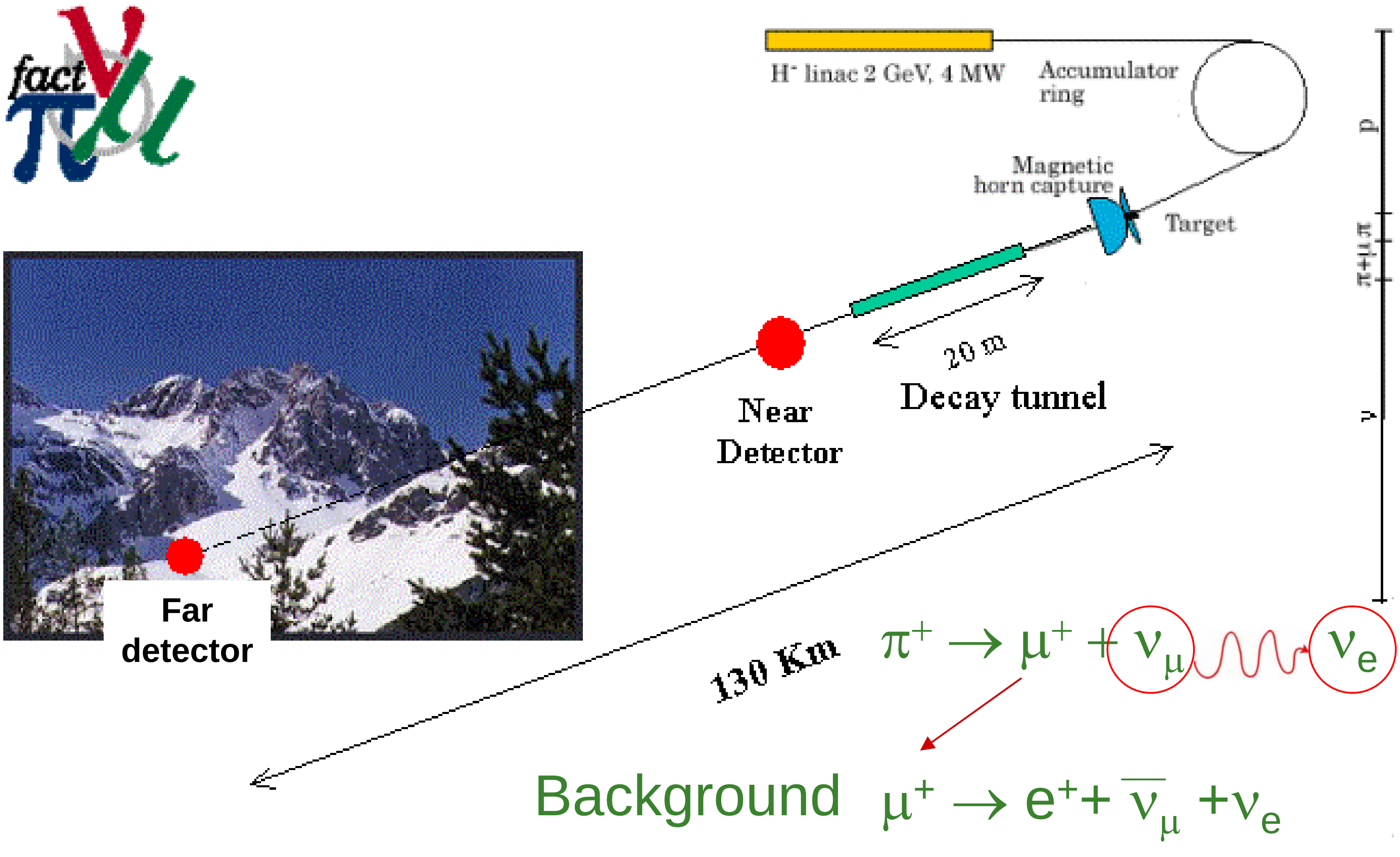
"Human made" neutrino beams provide advantage of

- pure neutrino flavour
- with known parameters (E, intensity, direction, …)
- Switching the helicity by switching the parental sign
- *A stage towards a muon collider …*

Future installation (constructed or considered)

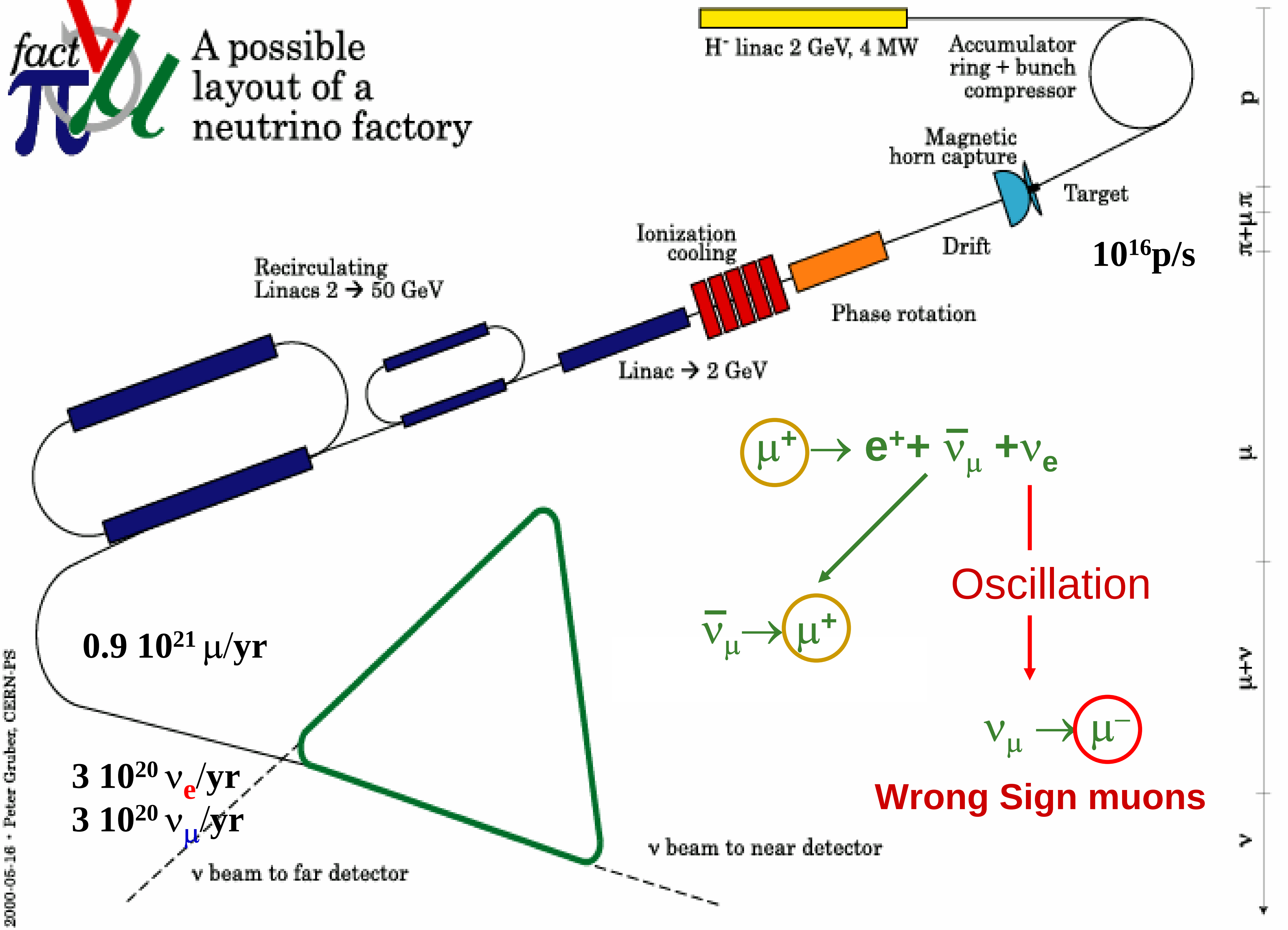
- to look for θ_{13}
  - Look for $\nu_\mu \rightarrow \nu_e$ in ν_μ beam (CNGS,ICARUS, MINOS)
  - Off-axis beam (JHF-SK, off axis NUMI)
  - Low energy SuperBeam
- to look for CP/T violation or for θ_{13} (if too small)
  - Beta-beams (combined with SuperBeam)
    - Beta-beam: neutrinos from beta-decay of boosted isotopes
  - Neutrino Factory: high energy $\nu_e \rightarrow \nu_\mu$ oscillation

Proposal for a CERN - Super Beam



A possible layout of a Low Energy Neutrino Super Beam

A possible layout of a neutrino factory



High Power Proton Beam

ν-factory:

$p + p \rightarrow \pi^+, K^+ \quad + \ldots$ — 2nd generation

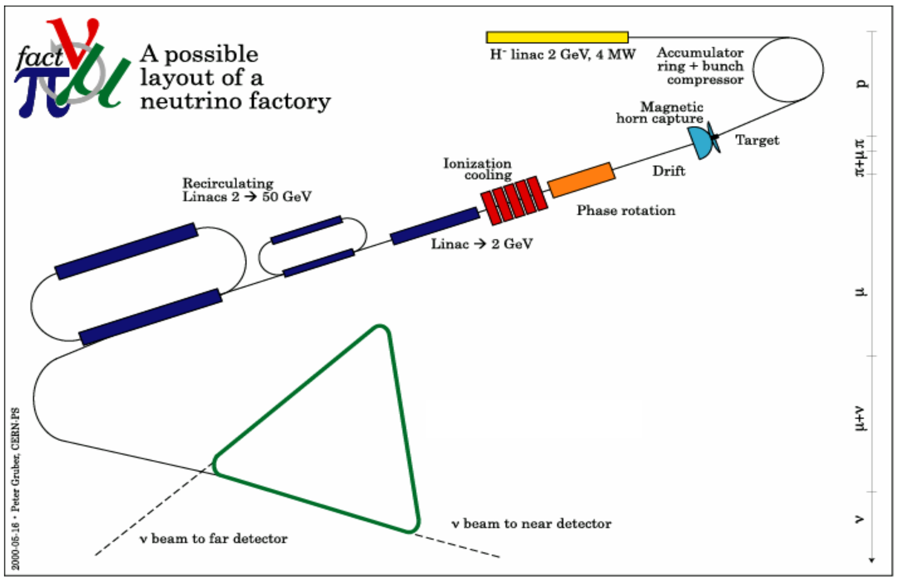
$\pi^+ \rightarrow \mu^+ + \nu_\mu$ — 3rd generation

$\mu^+ \rightarrow e^+ + \underline{\nu}_\mu + \nu_e$ — 4th generation

flux of 10^{21} neutrinos/year requested by physics

→ high power primary proton beam (average 4 MW) required

with losses assumed in production chain



→ new challenge

- not only for proton driver

  e.g. BNL/AGS, CERN/SPL

- esp. for production targets

"Secondary" particle generation

- Produce unstable daughter particles of interest:
  - Neutrons, radio-isotopes, pions, kaons, muons, neutrinos, …
- with highest flux possible

  achieve high statistics and/or background suppression
  - Collider luminosity: $\mathcal{L} = N^2 f / A$
  - sometimes (e.g. neutrino factory) the particle flux is relevant only, beam size A is not of high importance
- Primary proton beam strikes target
  - Today typical proton beam power: average 10 to 100 kW
  - Target materials: mainly solids from beryllium to lead

Target failure

- Increasing proton beam power without paying attention leads to uncontrolled energy deposition
- Causes excessive heating
- structural failure

- Above 20 % of the primary beam power are deposited in the target!

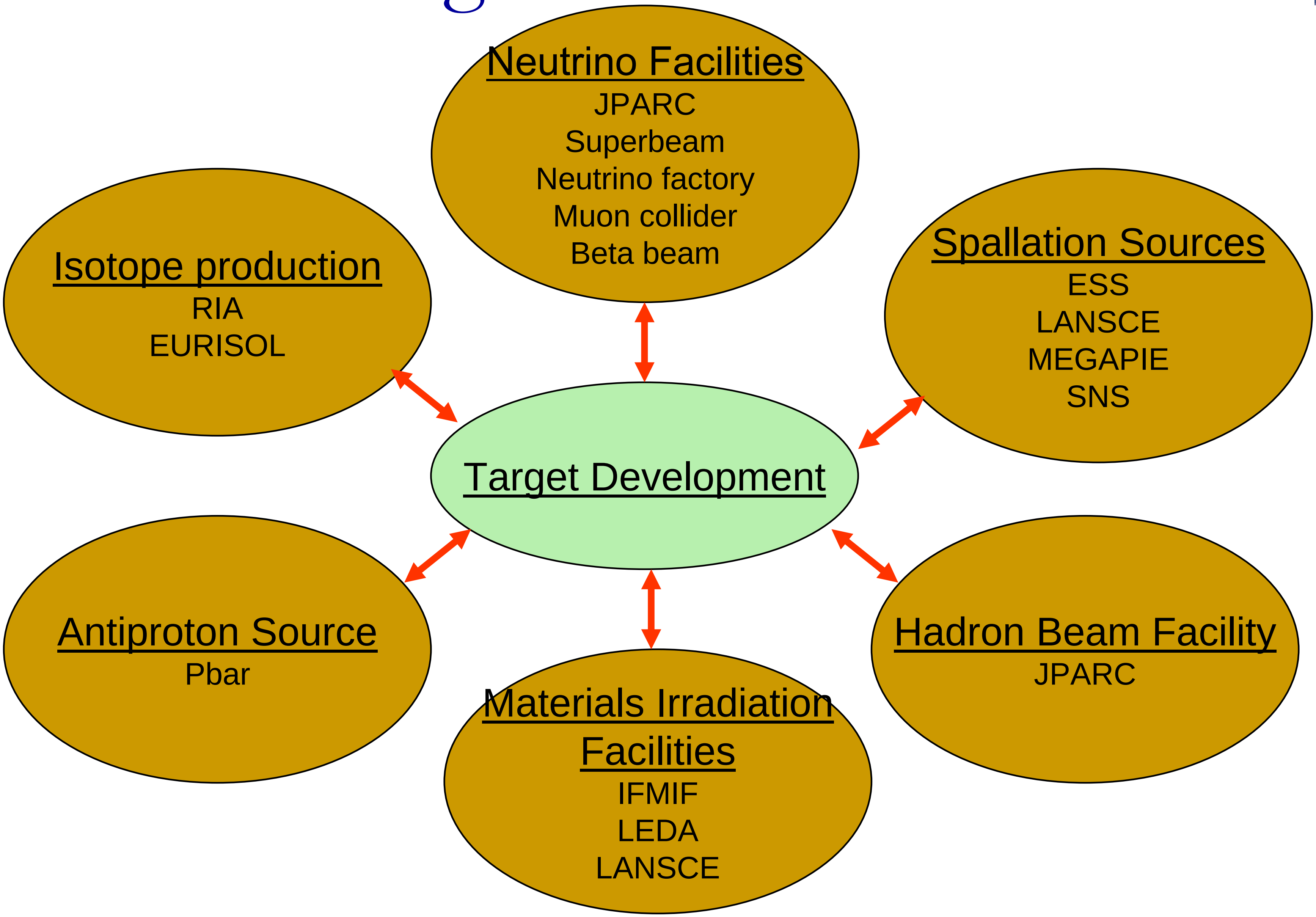
No quotation on purpose

Hot issues for a target

induced by the proton beam

- Thermal management (heat removal)
  - Target melting
  - Target vaporization
- Radiation damage
  - change of material properties
- Thermal shock
  - Beam-induced pressure waves

Future target stations



Solid targets

Numerous applications today:

but proton beam power < 100 kW

- Common materials: Beryllium, carbon, tantalum, …
  - low coefficient of thermal expansion
  - High melting point
  - High production yield
  - …

Studies

- BNL for a 1 MW proton beam (average)
- ISOLDE with a 10 kW -”-
- CNGS with a 700 kW -”-
- …

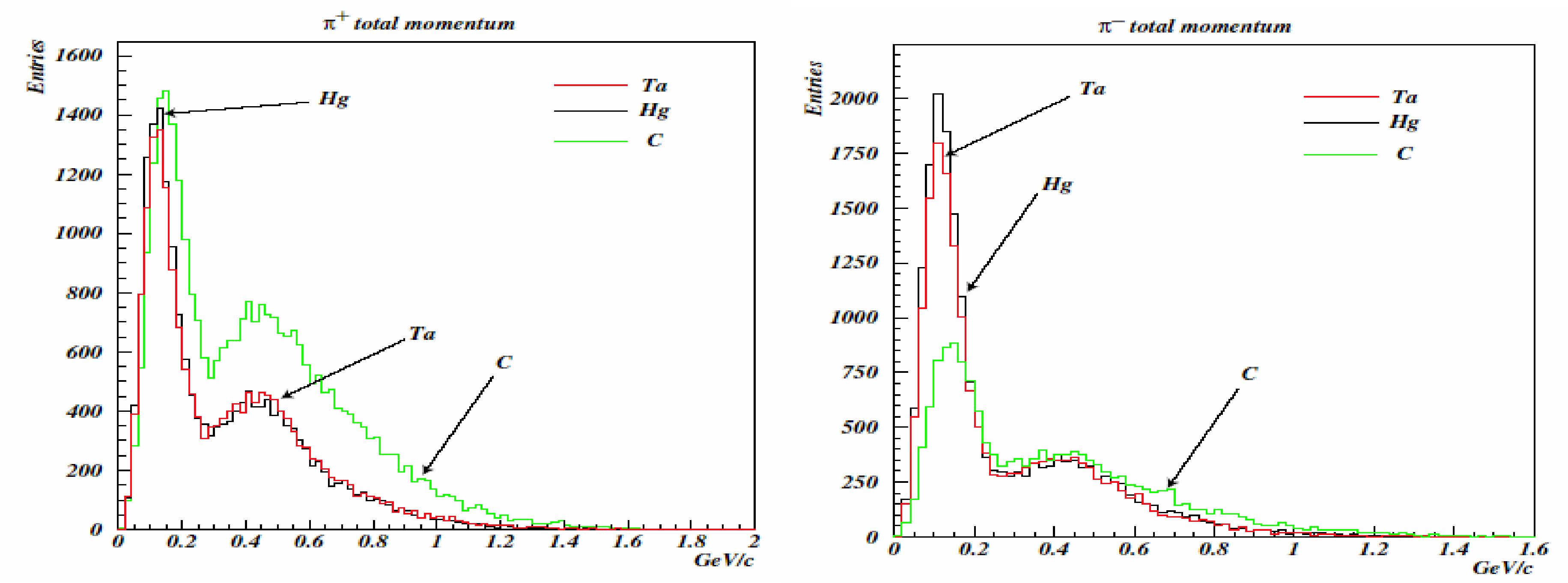
Pion yield optimisation

- fixed proton energy (2.2 GeV)
- as a function of the target material

S.Gilardoni

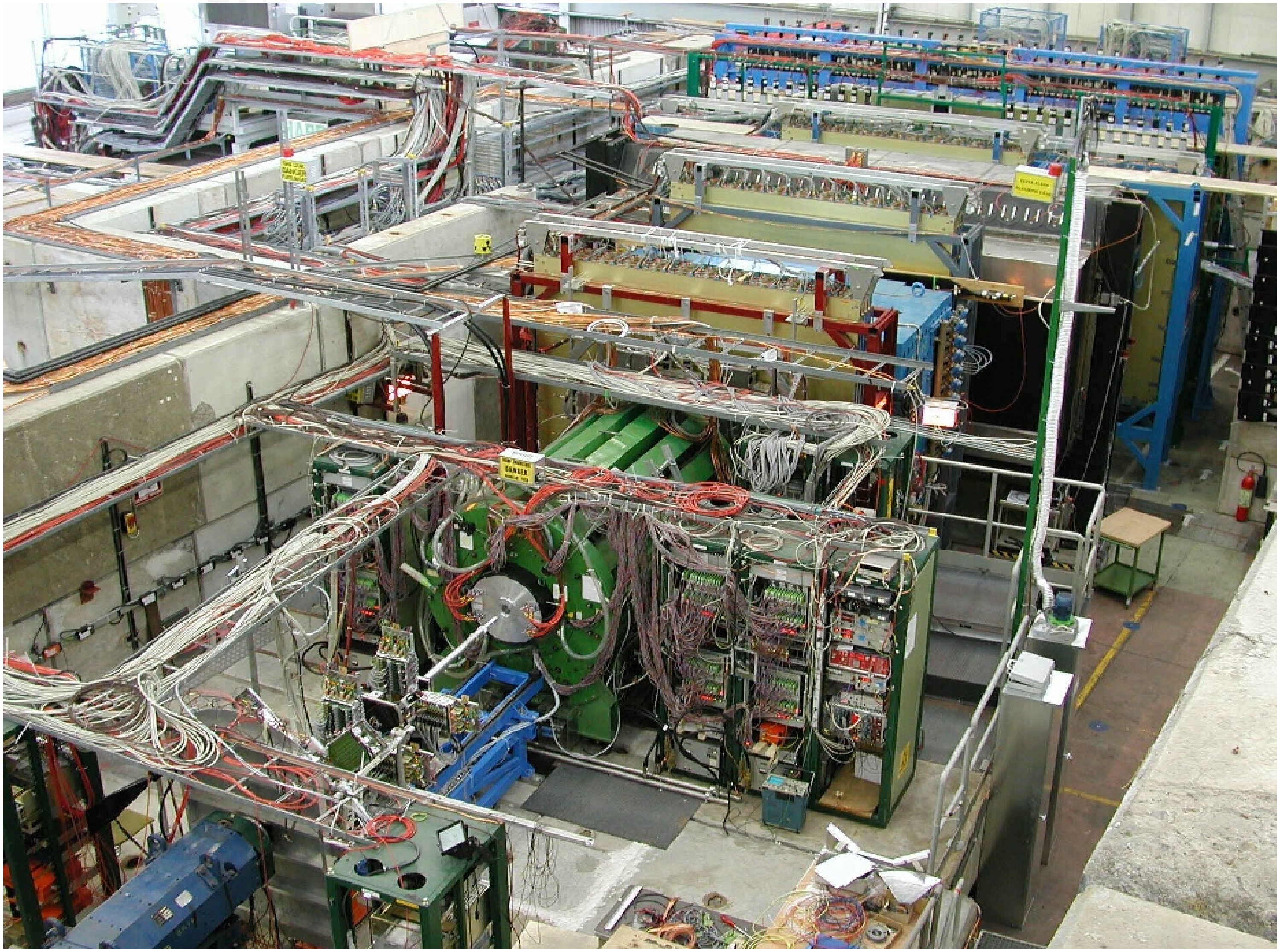
capture losses not included in figure

Material	π^+ per p.o.t.	π^- per p.o.t.
C	0.30	0.153
Ta	0.183	0.174
Hg	0.185	0.186



The Harp experiment

Hadron production cross section measurement



Towards 1 MW on target

- CNGS: CERN neutrinos to Gran Sasso, start 2006
- 750 km neutrino beam line
- 0.75 MW proton beam power

- Target: graphite
  - high pion production
  - small α
  - good tensile strength
- 10x rods
  - l=10 cm, d=5 mm
  - Helium cooled

CNGS graphite target assembly (2005, D.Grenier et al.)

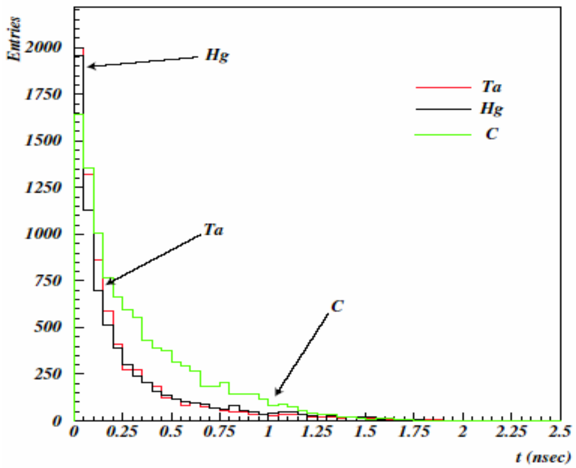
- Major concerns for target failure in case of abnormal operation of not centered beam

Carbon an ultimate candidate?

Very good material properties like thermal expansion, but …

- For Carbon 2 λ_I = 80 cm → target not point-like
  - difficult to find an efficient horn design
  - cost of the solenoid capture
- Pion time spread too large for subsequent phase rotation
  - Carbon would add > 0.5 nsec

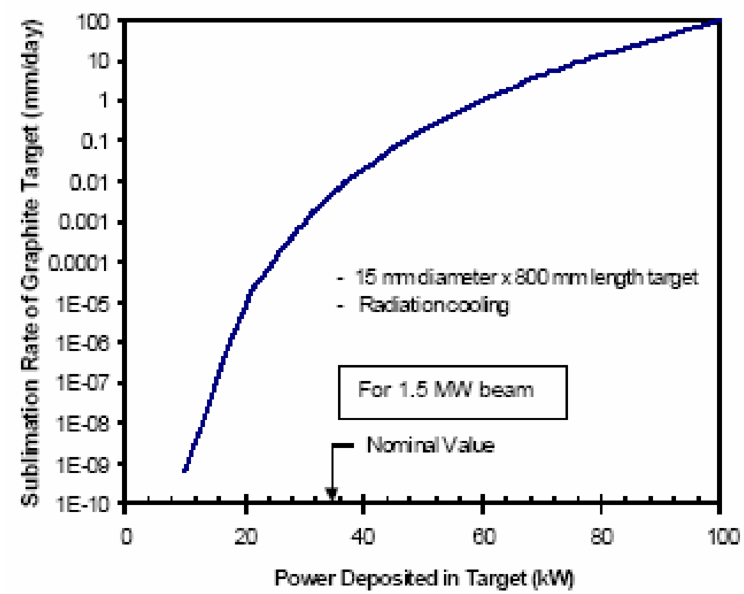
Pion time spread



Limit of carbon target lifetime

K.T.McDonald

- A Carbon target in vacuum sublimates away in one day at 4MW.

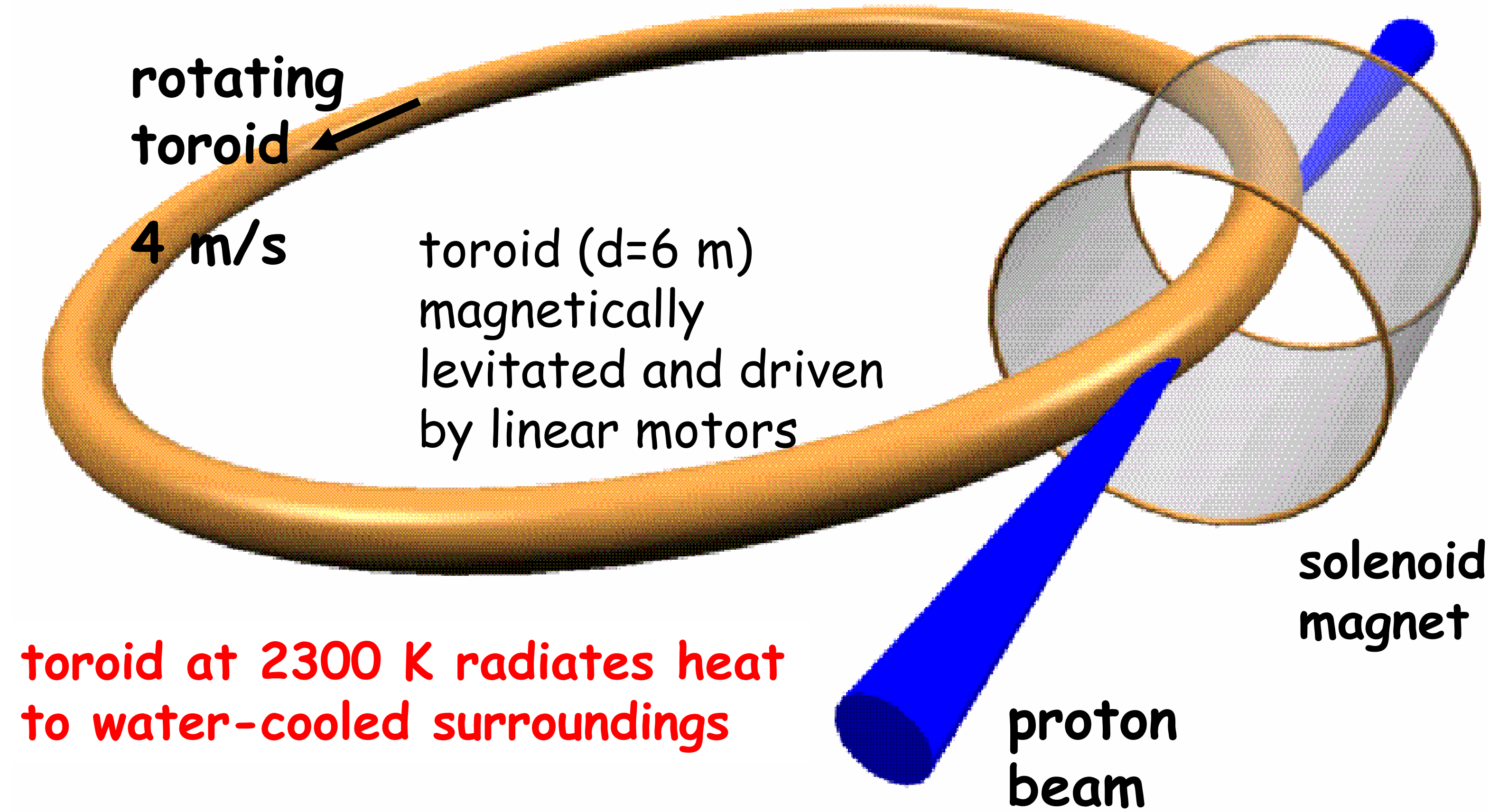


- In an helium atmosphere: sublimation negligible?
- Radiation damage limits lifetime to about 12 weeks

Rotating toroidal target

- Distribute the energy deposition over a larger volume
  - Similar a rotating anode of a X-ray tube

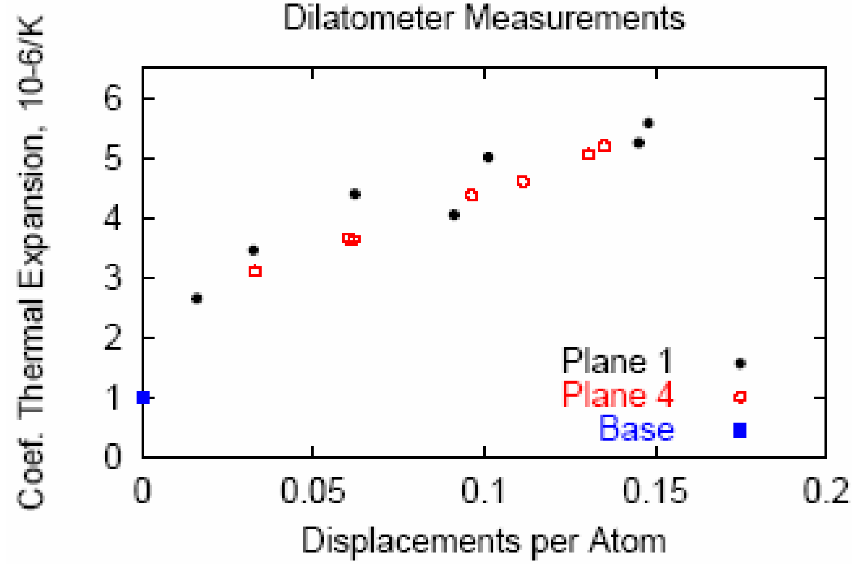
R.Bennett, B.King *et al.*

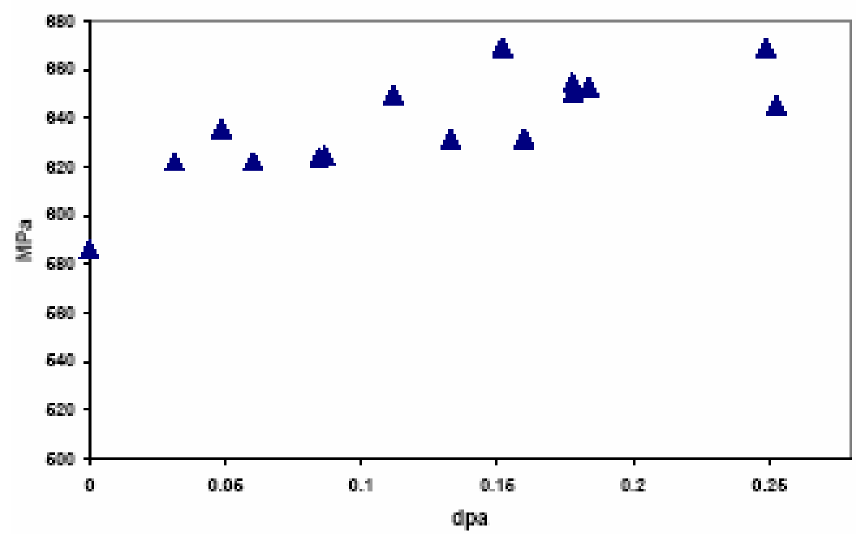


- Tensile strength of many metals is reached with stresses induced by the equivalent of a 1.5 MW proton beam → structural failure

Target material studies

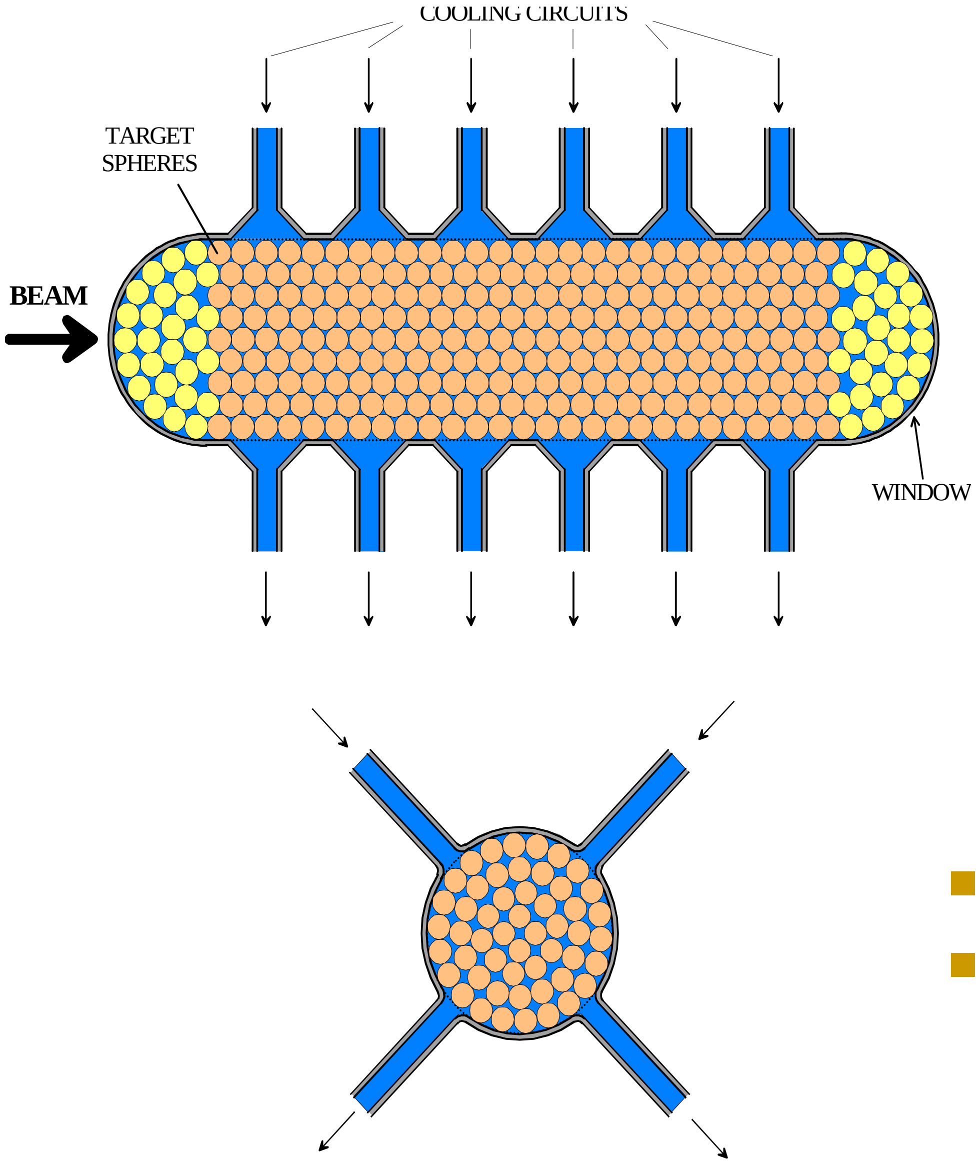
- Radiation induced change of material properties:
  - CTA
  - Tensile strength
  - …
- Studies ongoing at BNL



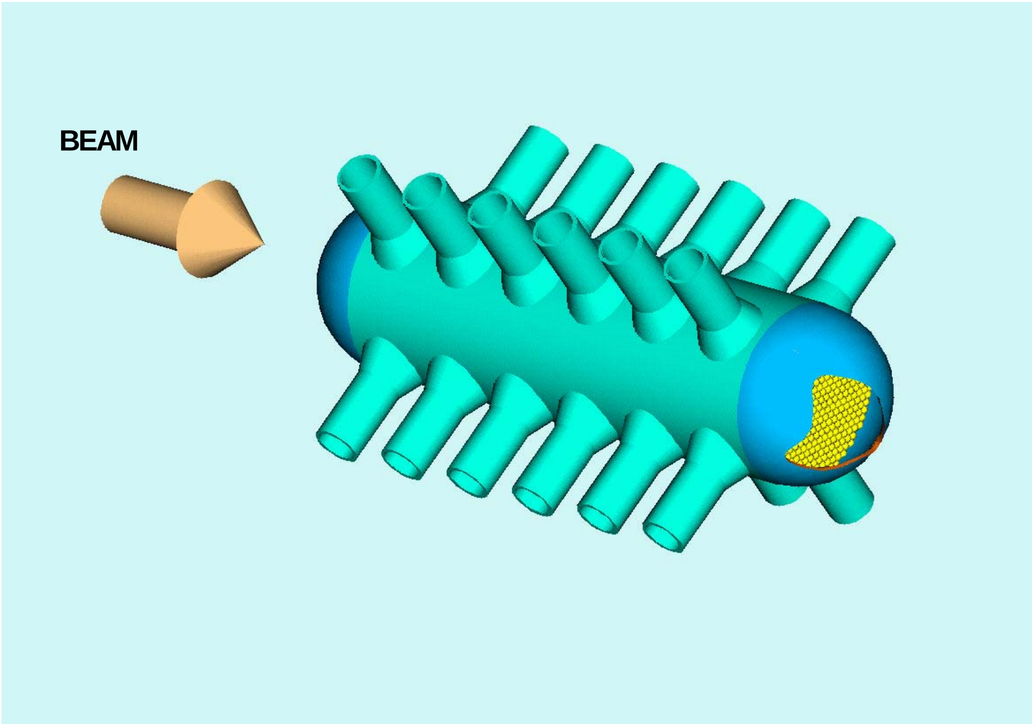


H.Kirk, N.Simos et al.

Granular target



Granular Target Cooled by Liquid or Gas



Peter Sievers

G. Laurent, Project Engineer

- Volume of Tabtalum beads, d~2mm
- Cooled by liquid or gas

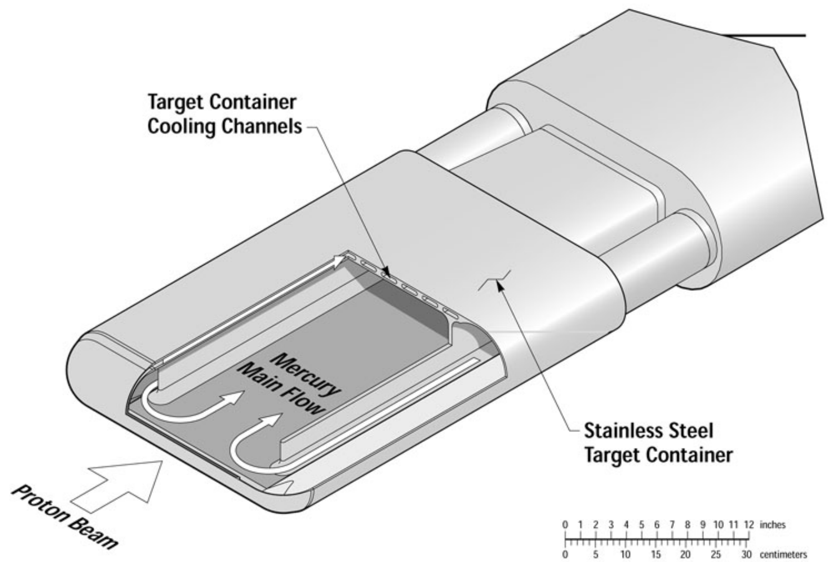
Granular target

P.Sievers et al.

- Tantalum Spheres: **$\varnothing$ = 2 mm, ρ = 0.6 x 16.8 $\approx$ 10 g / cm^3**
- Small static thermal stress: **Each sphere heated uniformly.**
- Small thermal shock waves: **Resonance period of a sphere is small relative to the heating time**
- Large Surface / Volume: **Heat removed where deposited.**
- Radiation/structural damage of spheres, container and windows:
- Lifetime of Target > Horn to be expected ?
- R&D not pursued

Contained liquid target

- SNS, ESS: high power spallation neutron sources
- 1m/s mercury flow
- Liquid immune to stresses
- passive heat removal
- No water cooling



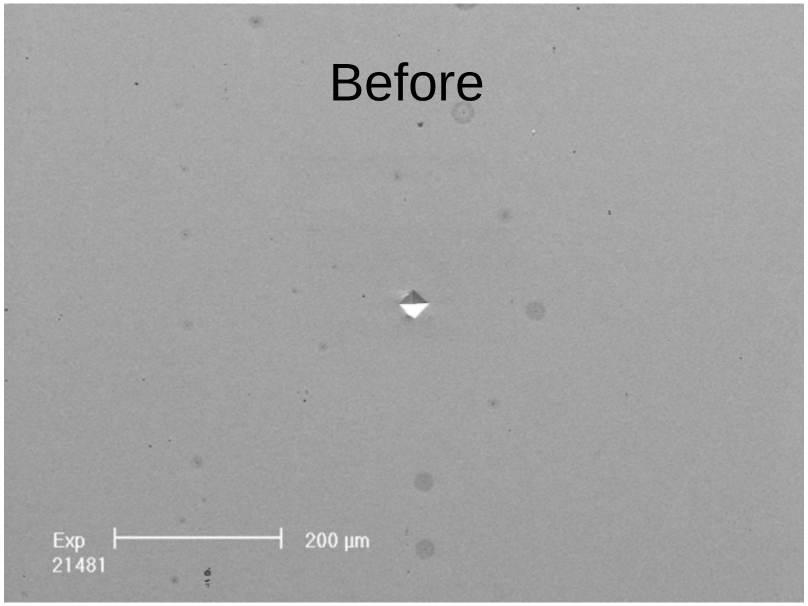
- Not an option for charged particles

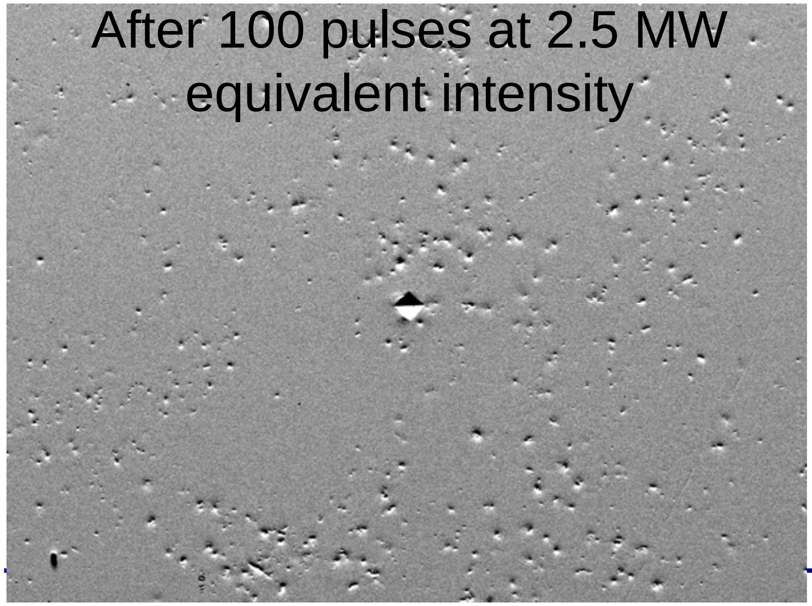
!!! Beam window:

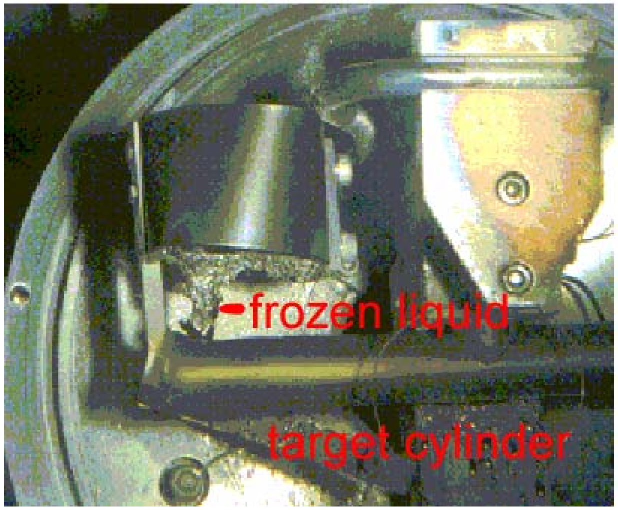
- Beam induced stresses
- Cavitation induced erosion (pitting)

T.Gabriel et al.

Cavitation induced erosion (pitting)





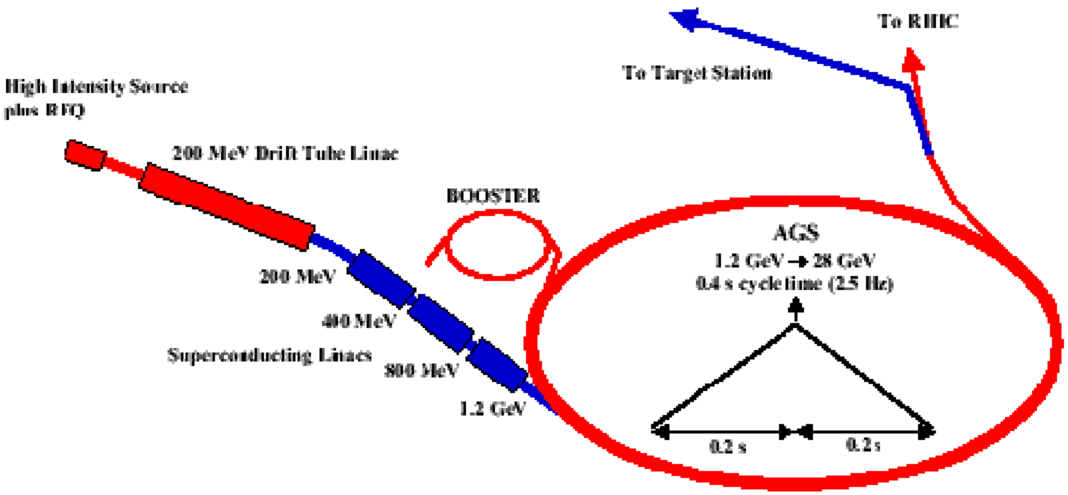


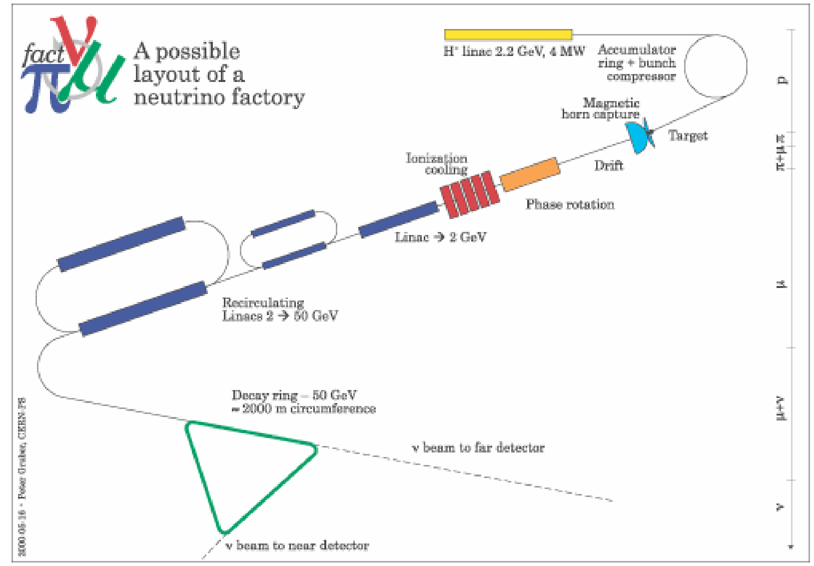
Containment failure

"solved by":

- surface treatment
- Bubble injection

4MW Proton driver

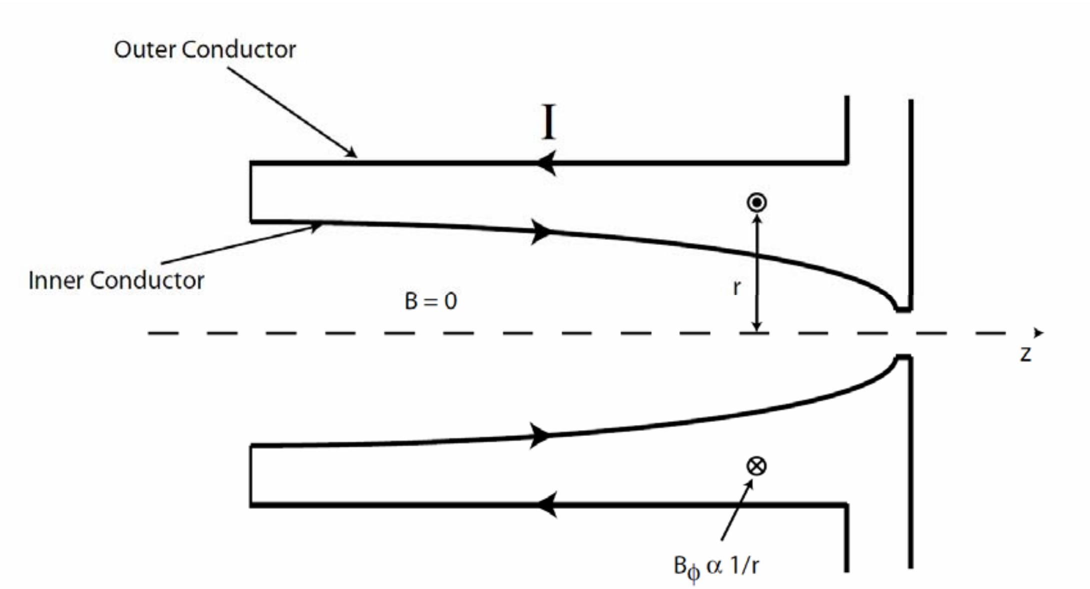


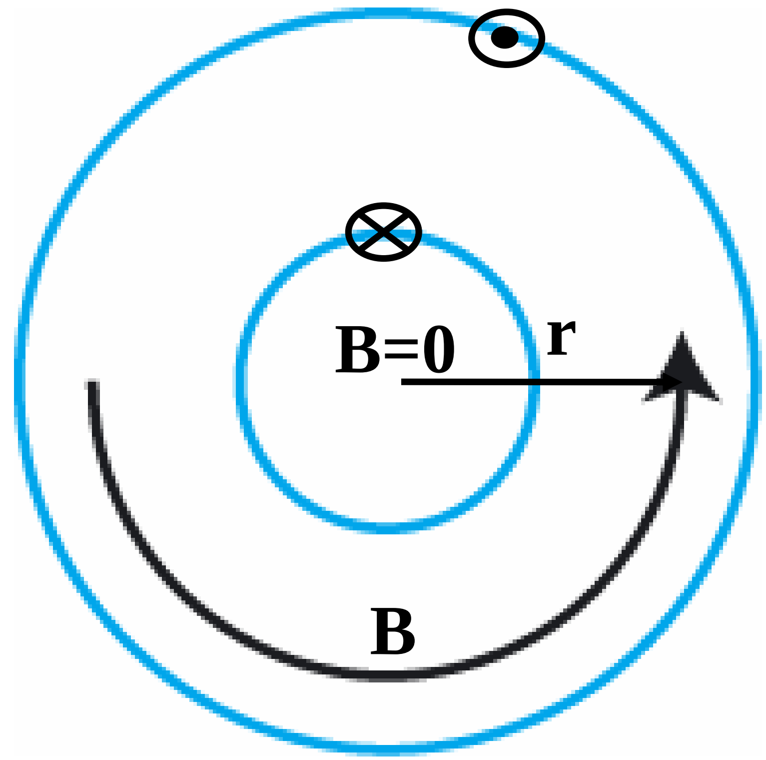


	BNL	CERN
Energy [GeV]	24	2.2
Proton intensity/pulse	$3\ 10^{13}$	$24\ 10^{13}$
Rep.rate [Hz]	32	50
Pulse length [ns]	5	3200
Focusing element	20 T solenoid	Magnetic horn

Magnetic Horn

Magnetic volume according to the Ampere law:





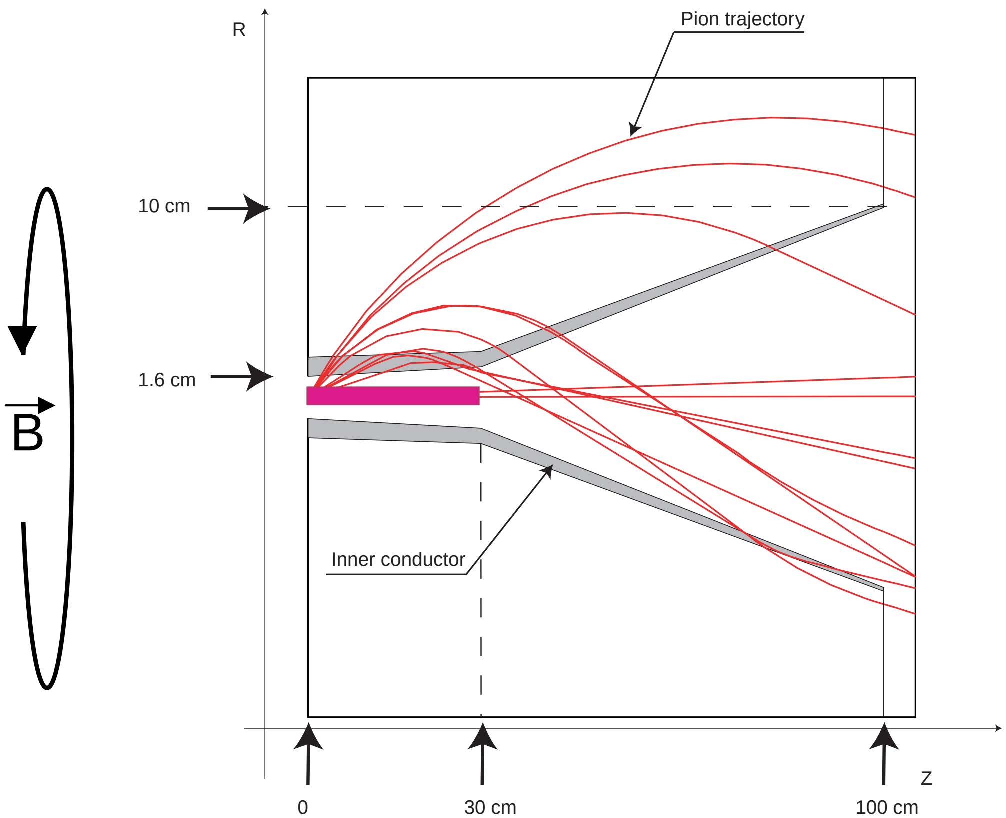
$$\oint B \cdot dl = 2\pi r B = \mu_0 I$$

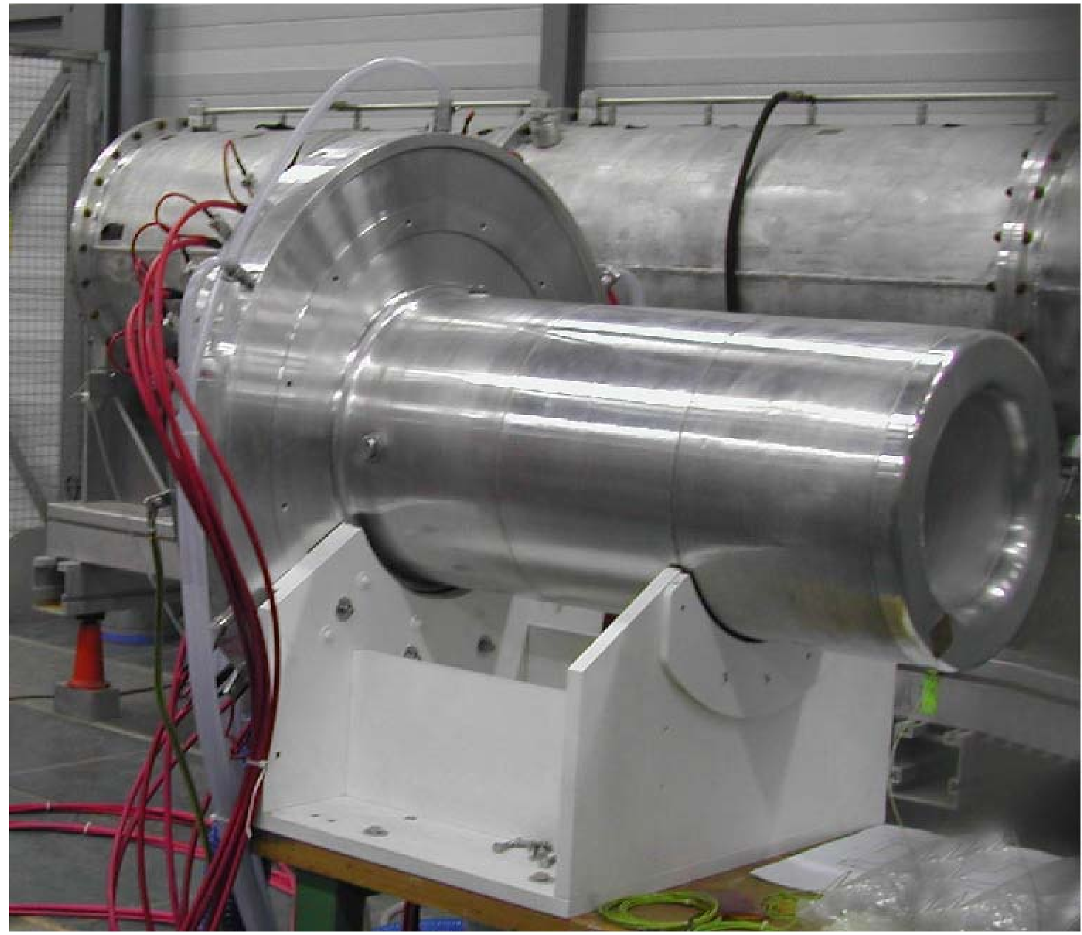
$$B = \frac{\mu_0 I}{2\pi r}$$

⊗ Current OUT

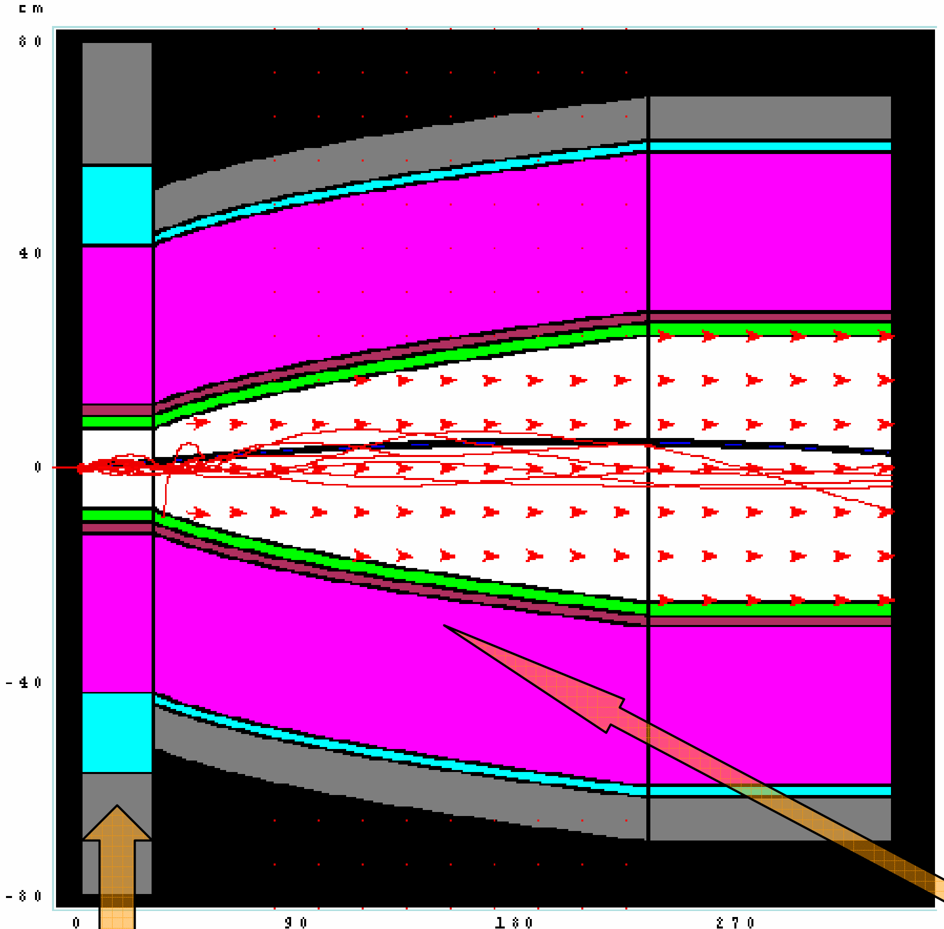
⊙ Current IN

First piece of Nufact





US-NuFact: 20 T Solenoid



Capture B=20 T

Φ = 15 cm, L=30 cm

•Focusing:

Tapered field 20 T → 1.25 T

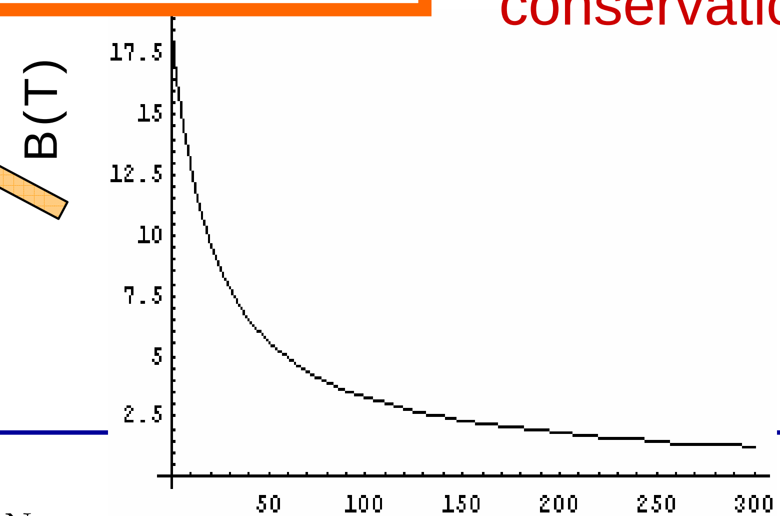
$$B_z(z) = \frac{B_0}{1 + \alpha * z}$$

$$B\rho^2 = const$$

•Magnetic flux conservation

$$\frac{B}{p_\perp 2} = const$$

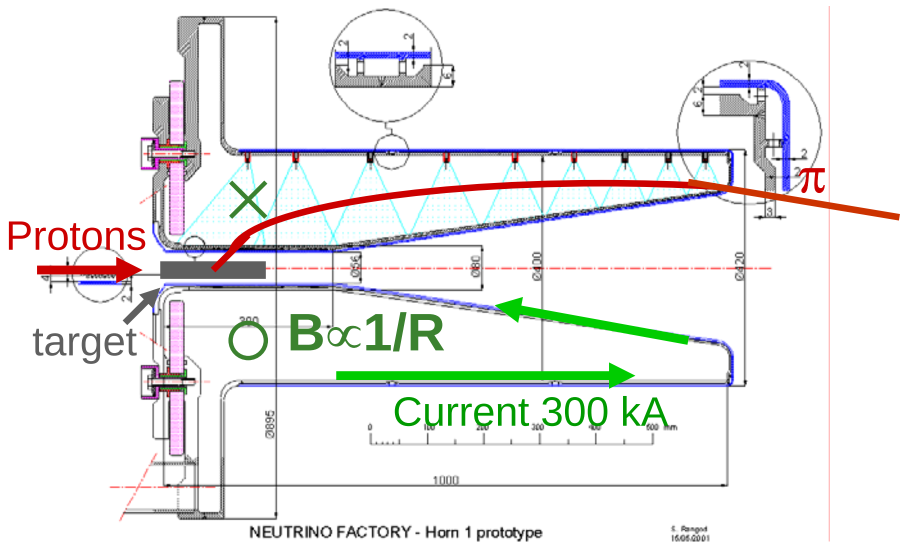
•Angular momentum conservation



Focusing options

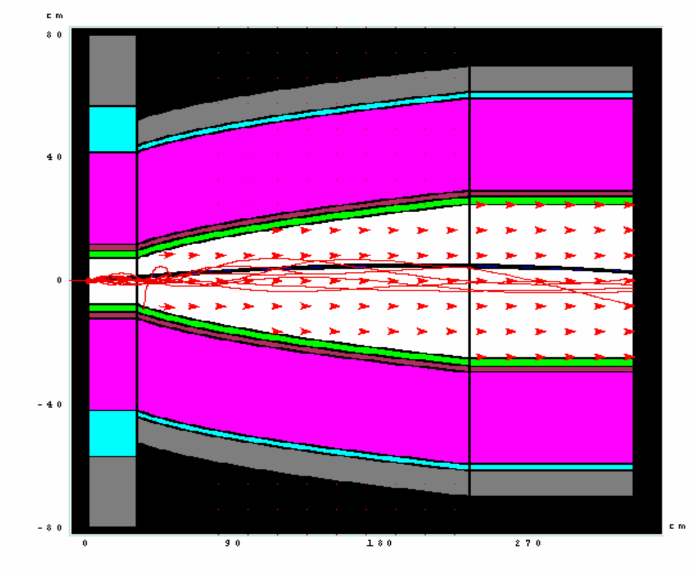
Increase secondary acceptance

- Magnetic Horn (CERN)



- B=0 T at target
- Focuses only one charge state, which is required for super-beam
- highly restricted space

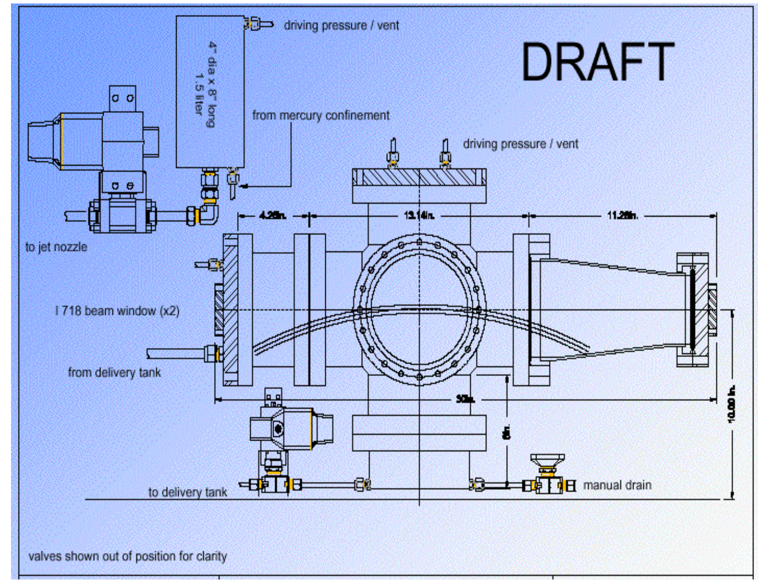
- Solenoid (US)

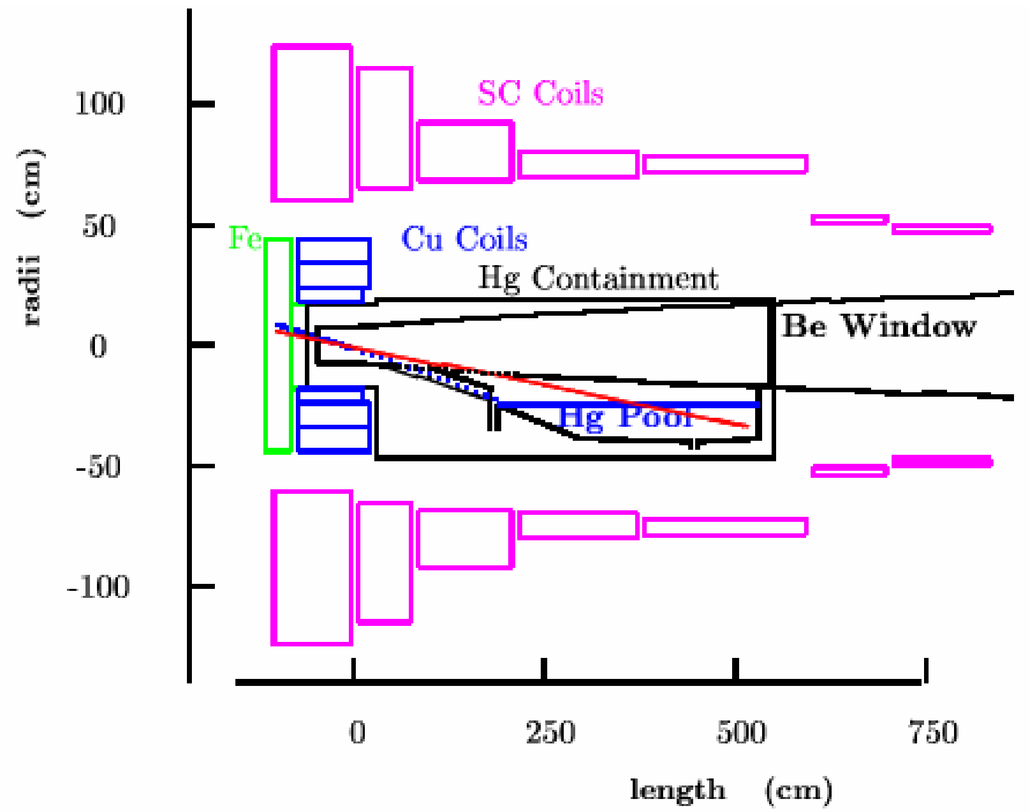


- B = 20 T at target
- Adiabatic focusing channel
- Two charges collected can be separated by RF

Liquid target with free surface

- jet avoid beam window
- v~20 m/s Replace target at 50 Hz
  each proton pulse sees new target volume
- Cooling passively by removing liquid
  - no water-radiolysis



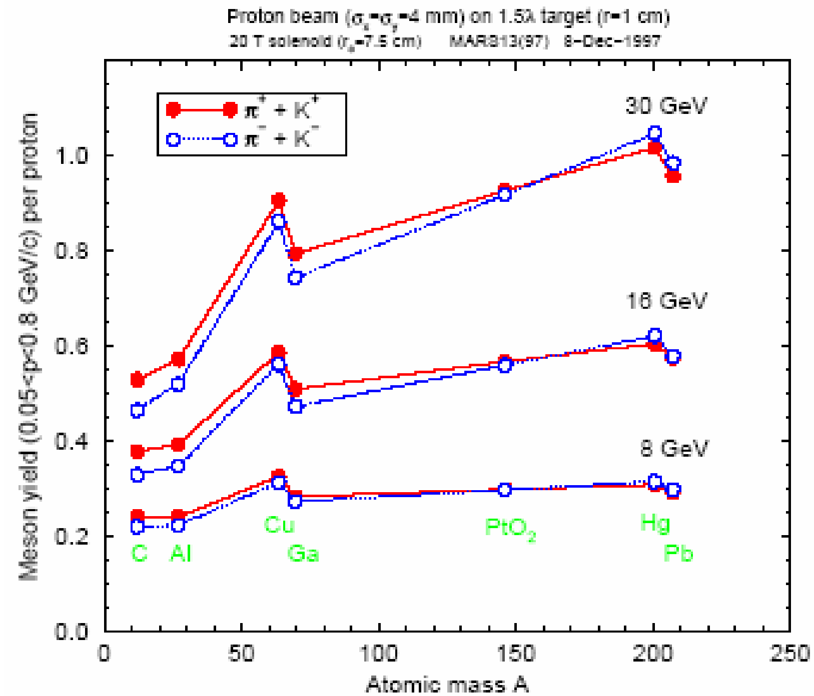


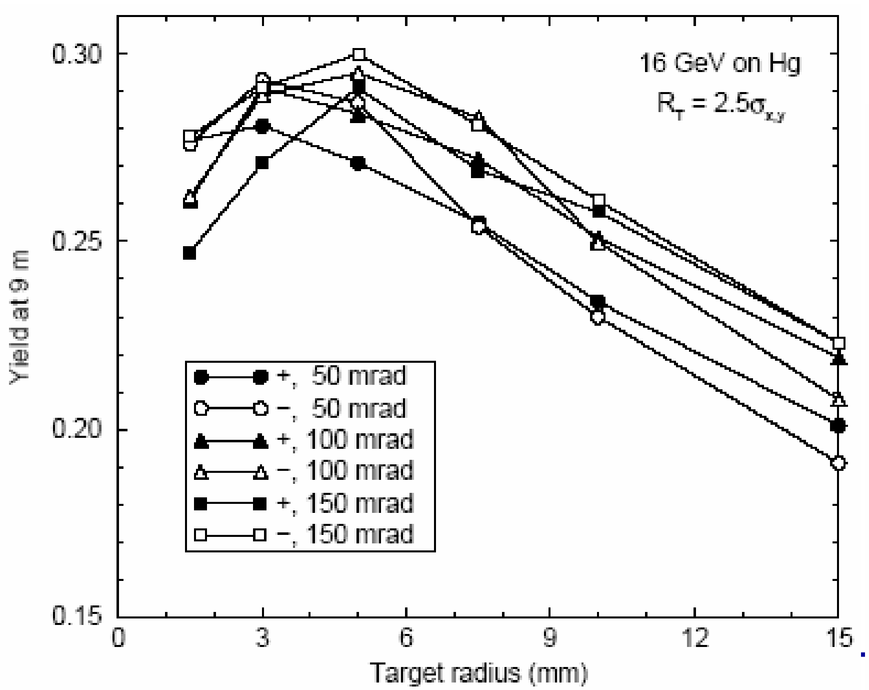
??? What is the impact on the jet by

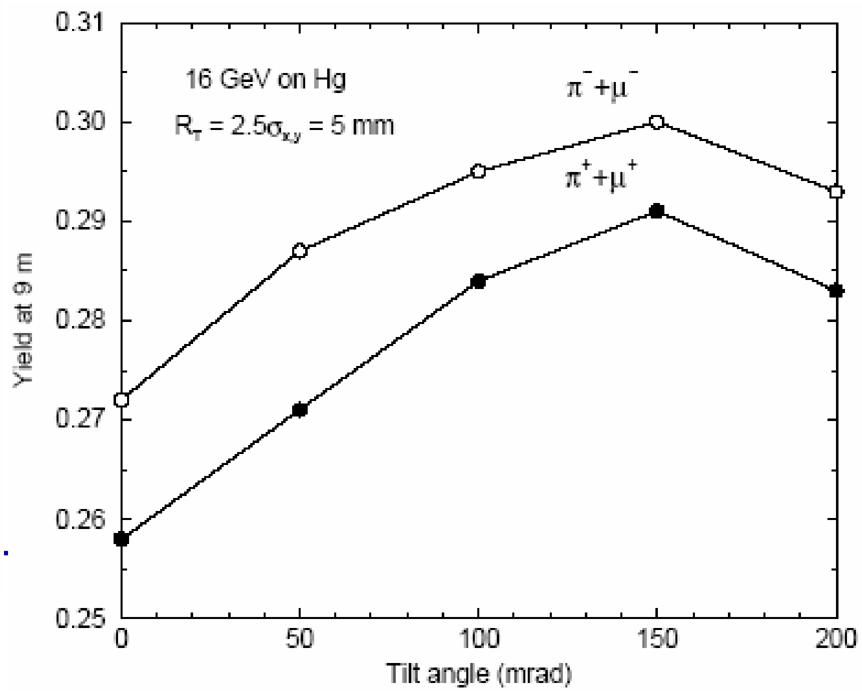
- **4 MW proton beam**
- **20 T solenoidal field**

Target properties

- E_p>10 GeV: high Z
  - point-like source
- L = 2 nuclear interaction length
- R= 5 mm
- Tilt: 100 (150) mrad
  - Limited by bore





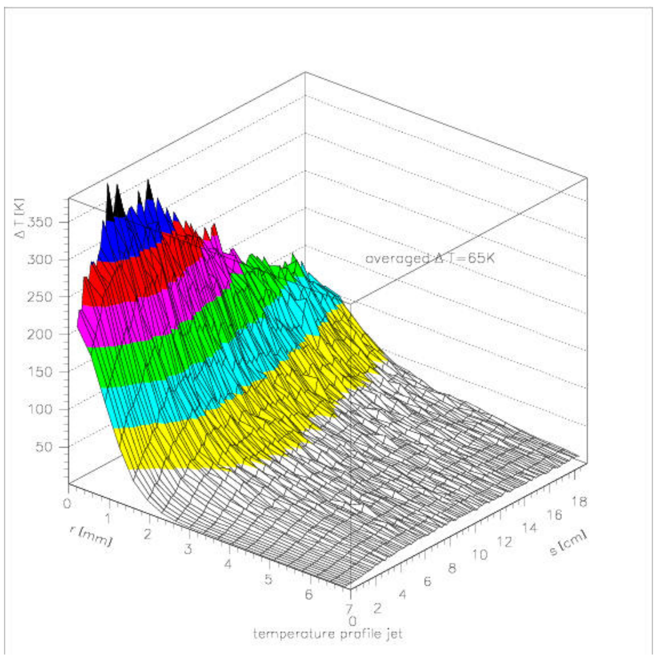


Mercury

- Advantages
  - High Z
  - Liquid at ambient temperature
    - Highly convenient for R&D
  - Easily available
- Disadvantages
  - Toxic
  - “only” compatible with very few materials
    - Stainless steel, Titanium, EPDM, …
  - High thermal expansion coefficient

Proton induced shock(s)

- Proton intensity: $3\ 10^{13(14)}$ p+/pulse
- dE/dx causes “instantaneously” dT of Gaussian shape within pulse duration



pressure gradient accelerates …

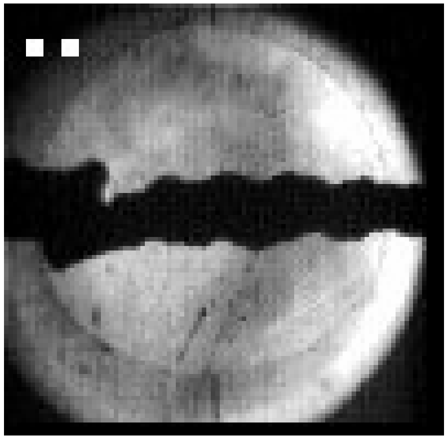
$$dP/dr = -dv/dt$$

$$v_{dipersal} \sim \alpha\ dE/dm\ 1/cp\ v_{sound}$$

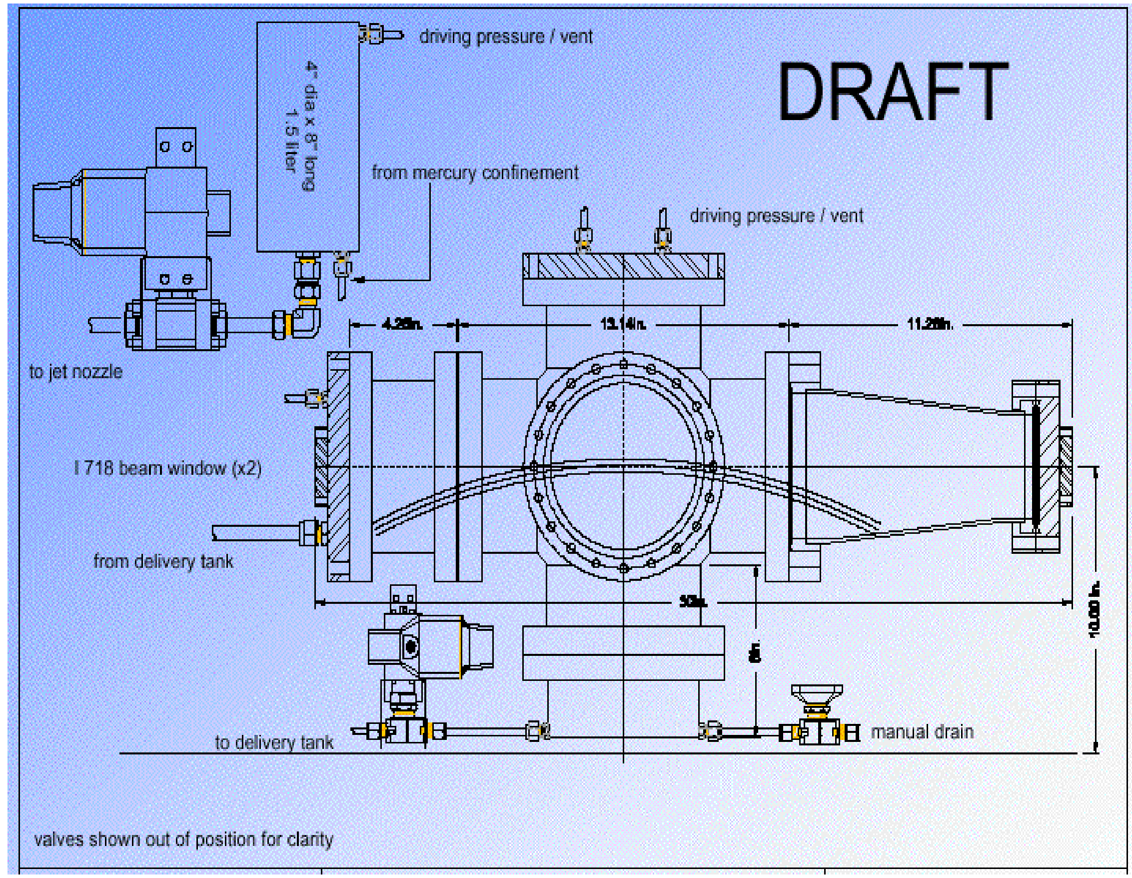
$$v_{dipersal} \sim 50\ m/s$$

for dE/dm=100J/g

Hg Jet test a BNL E-951



Protons



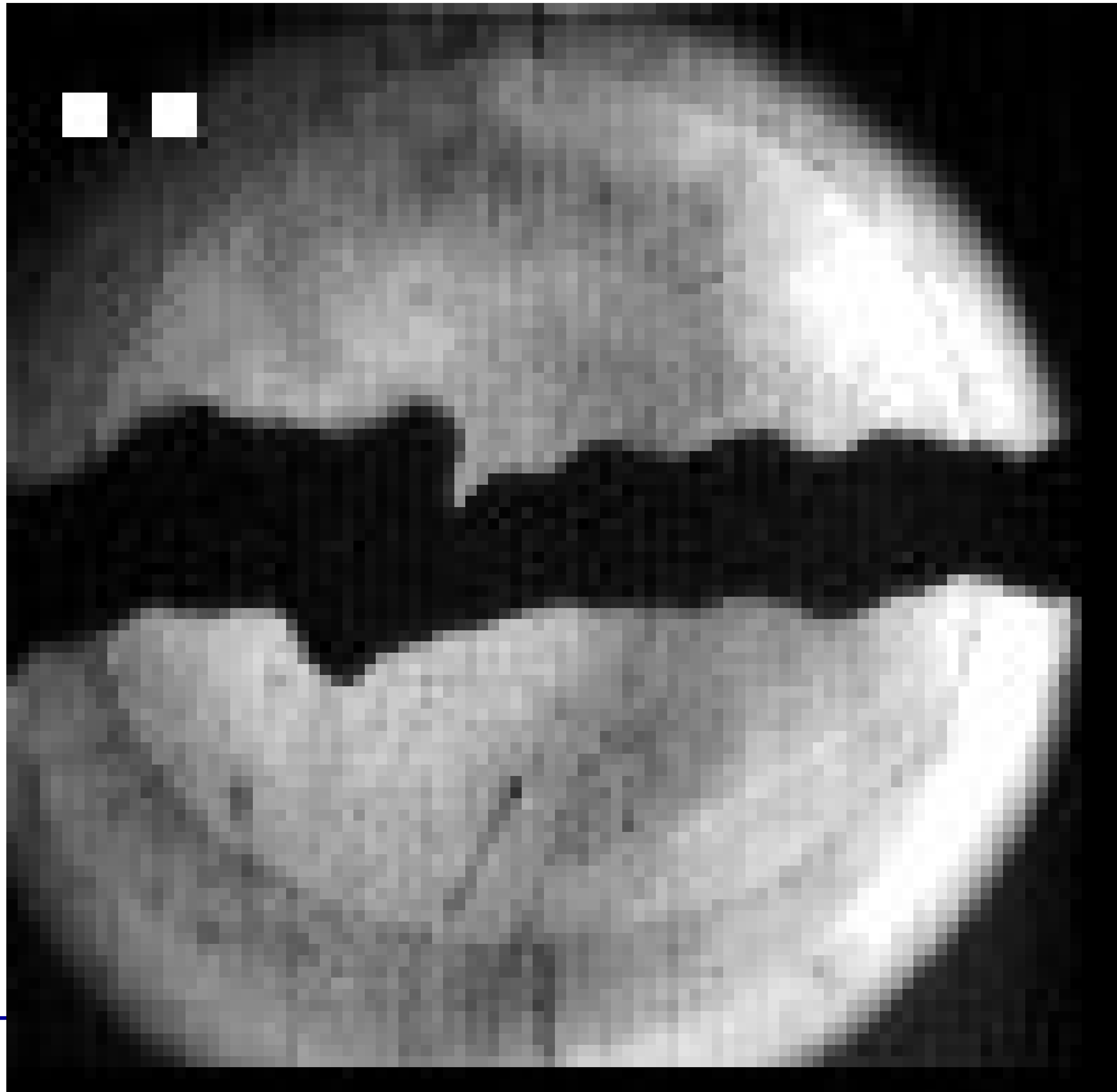
P-bunch: 2.7×10^{12} ppb
100 ns
t_o = ~ 0.45 ms

Hg- jet : diameter 1.2 cm
jet-velocity 2.5 m/s
perp. velocity ~ 5 m/s

Proton beam on mercury Jet

Recorded at
4kHz
Replay at
20 Hz

1 cm

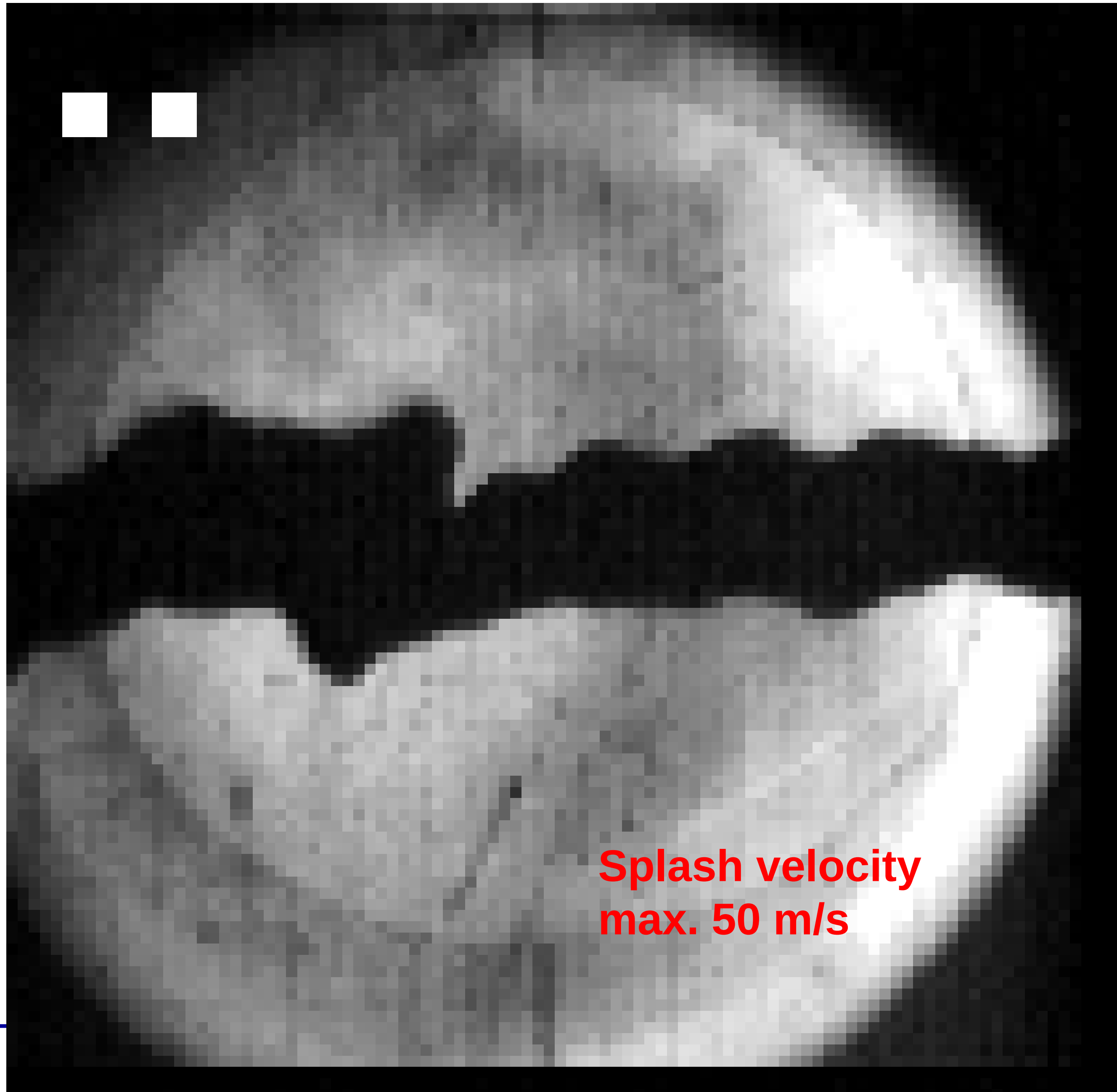


BNL AGS
Proton beam

Hg jet
v=2 m/s

Proton beam on mercury Jet

Recorded at 4kHz
Replay at 20 Hz

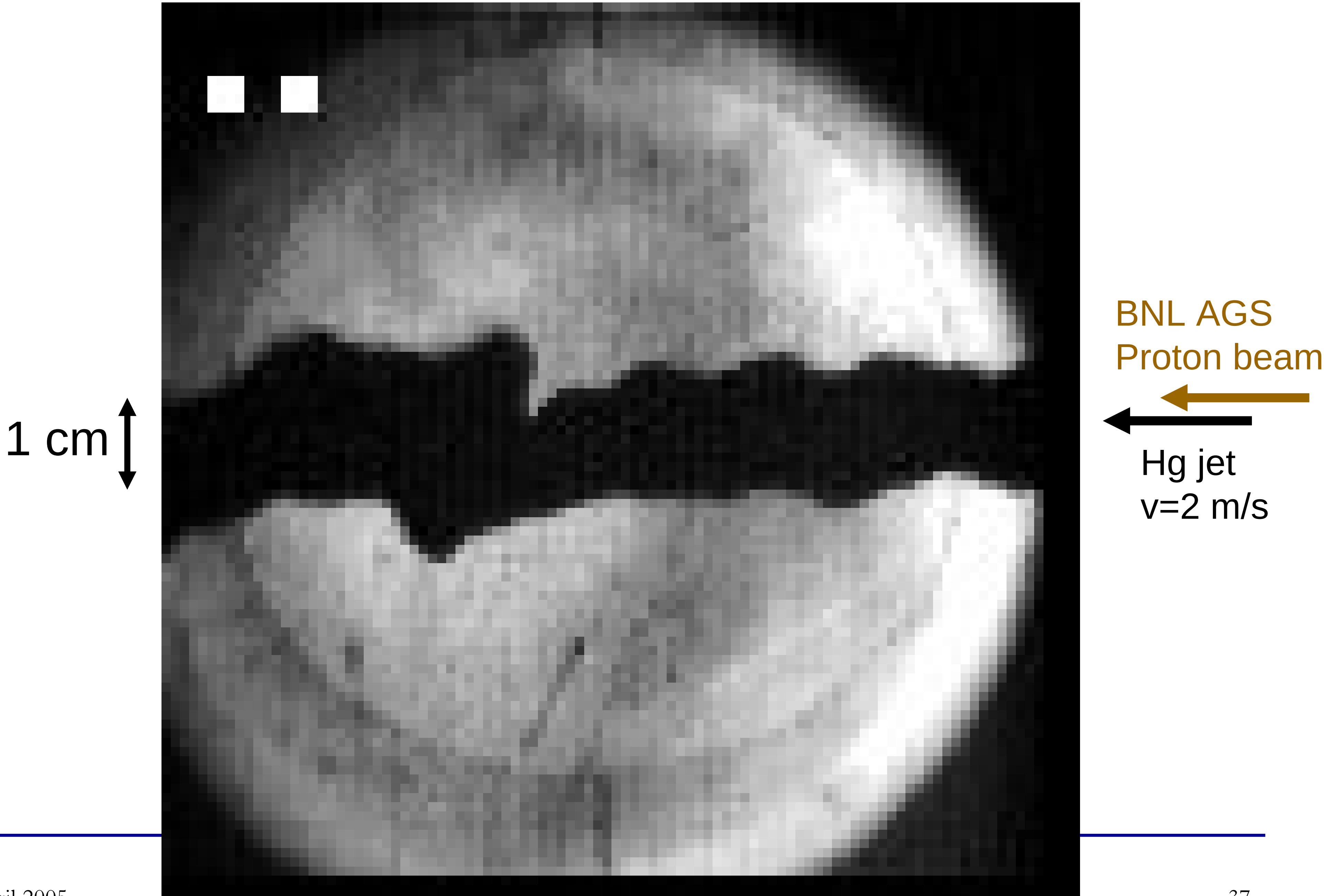


1 cm

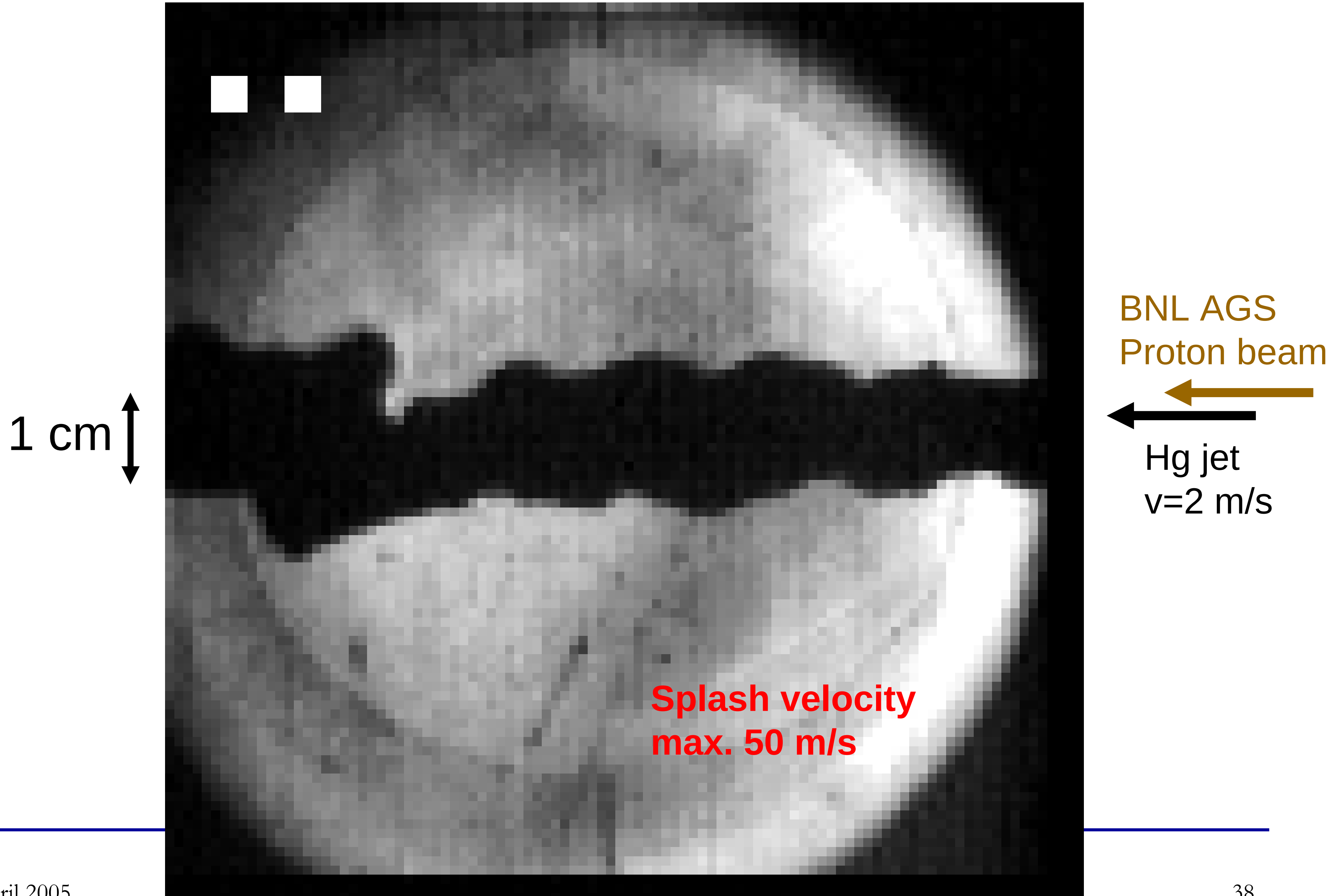
BNL AGS Proton beam

Hg jet
v=2 m/s

Proton beam on mercury Jet

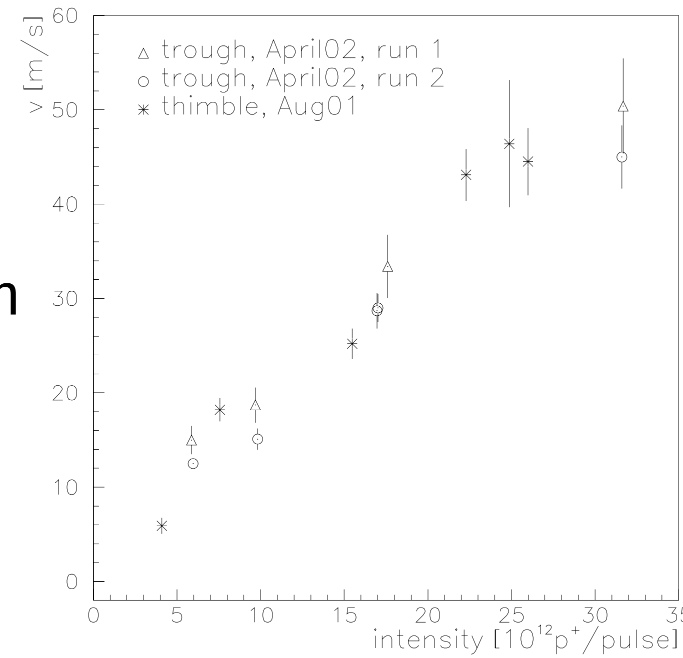


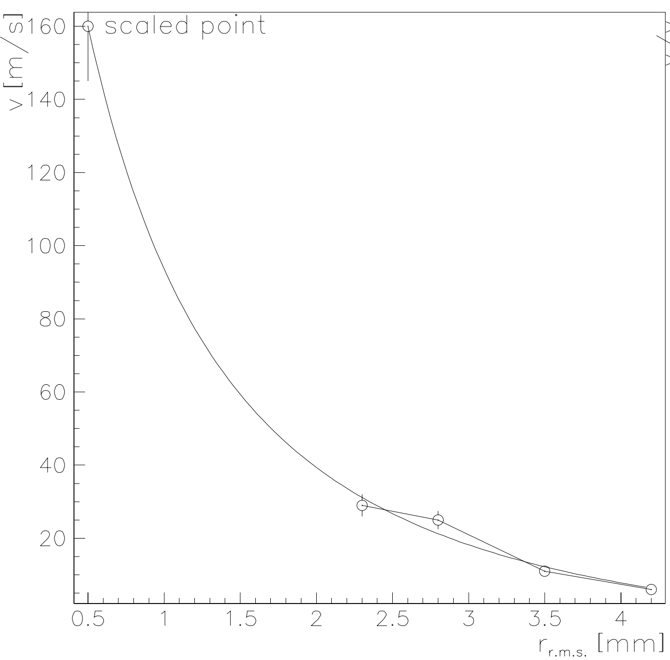
Proton beam on mercury Jet

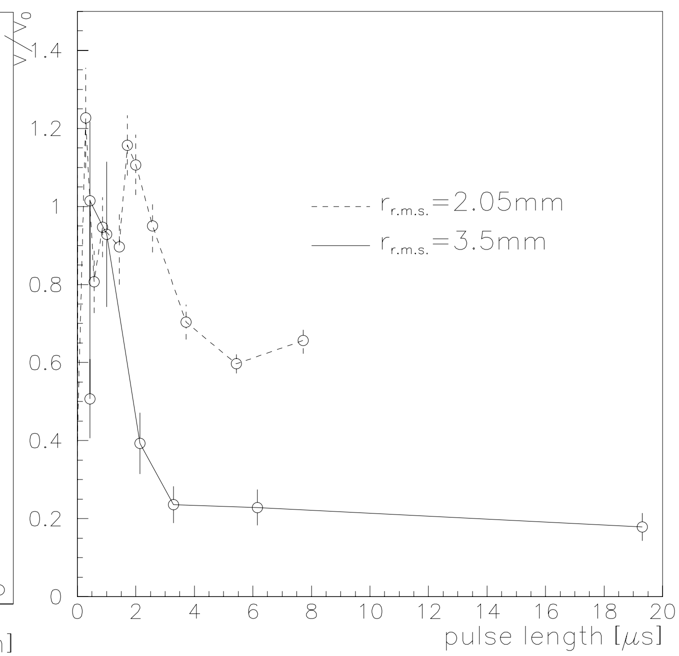


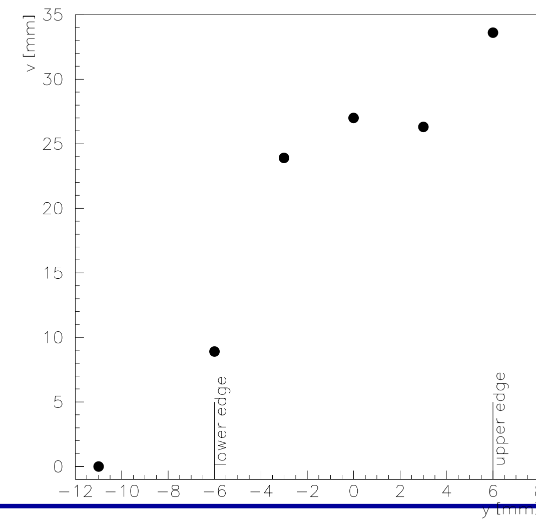
Experimental results

- **Scaling laws for splash velocity in order to extrapolate to nominal case**
  - Beam variables: pulse intensity, spot size, pulse length, pulse structure, beam position





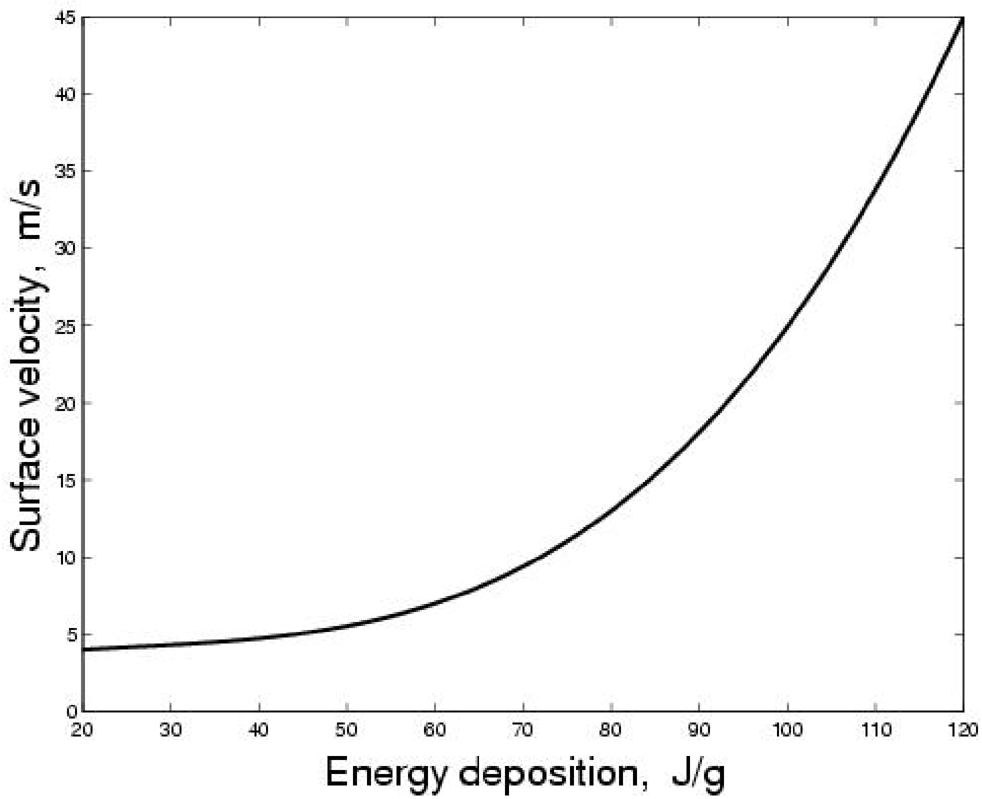


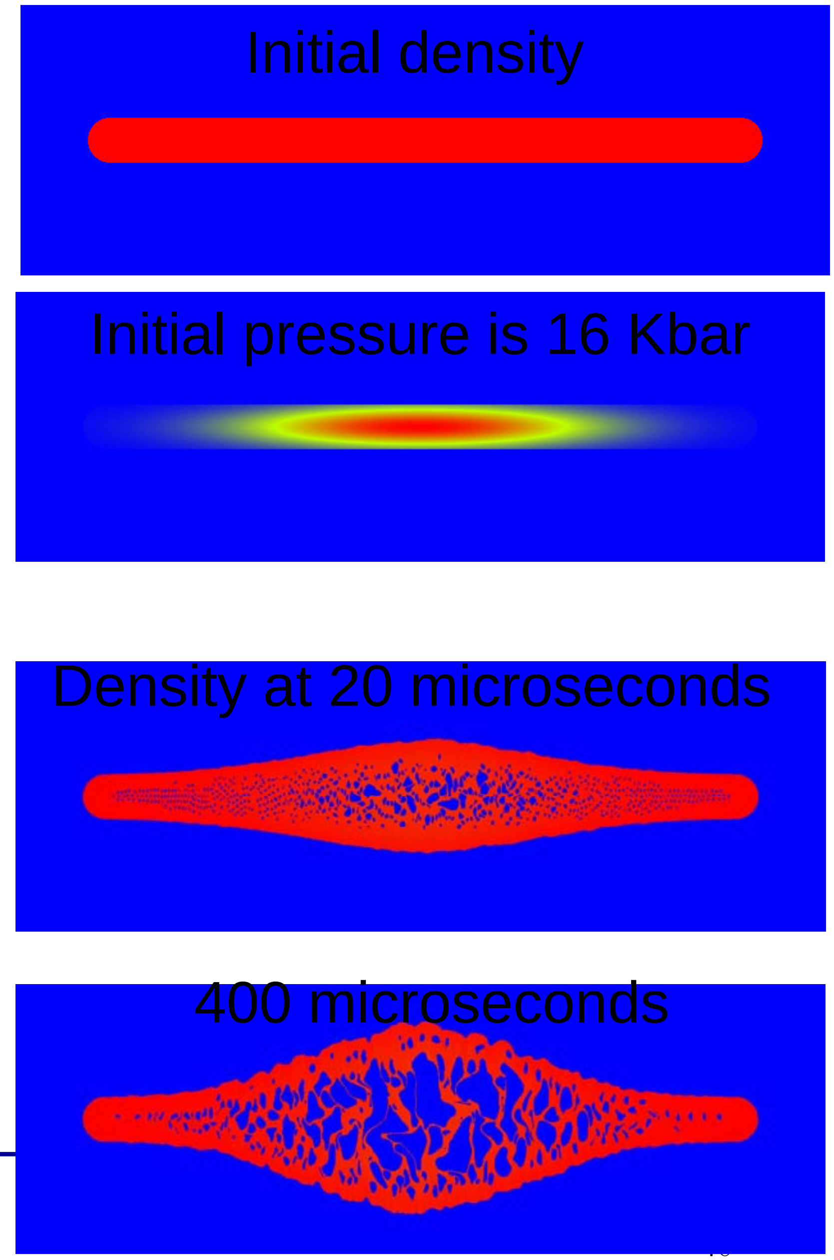


- **Benchmark for simulation codes**

Simulation: Shocks

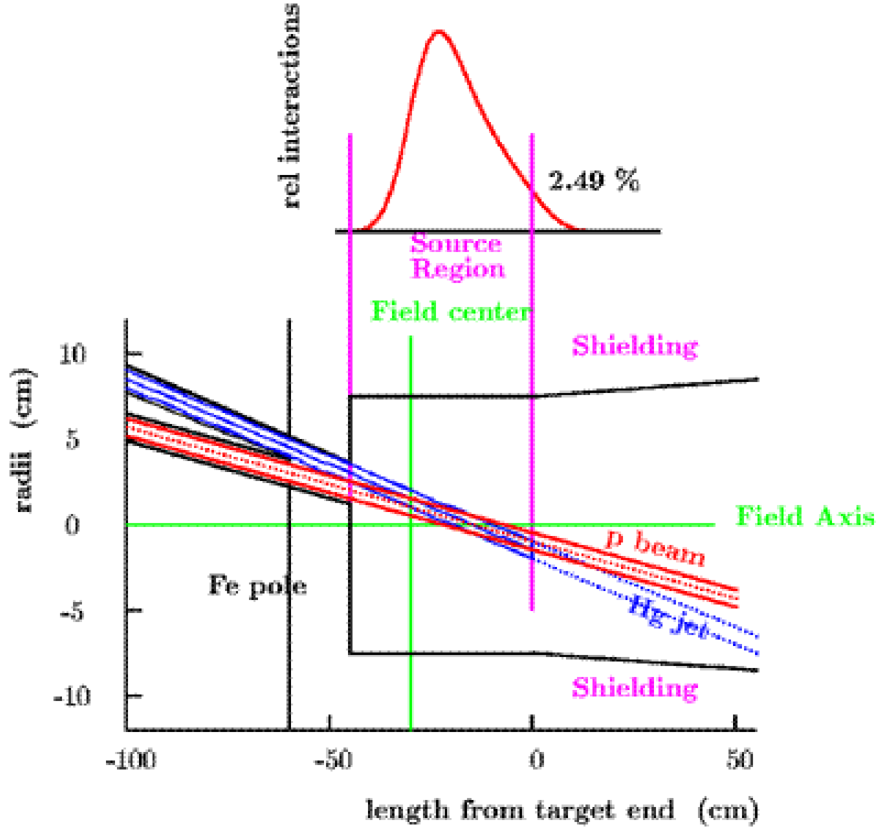
Frontier code,
R.Samulyak et al.

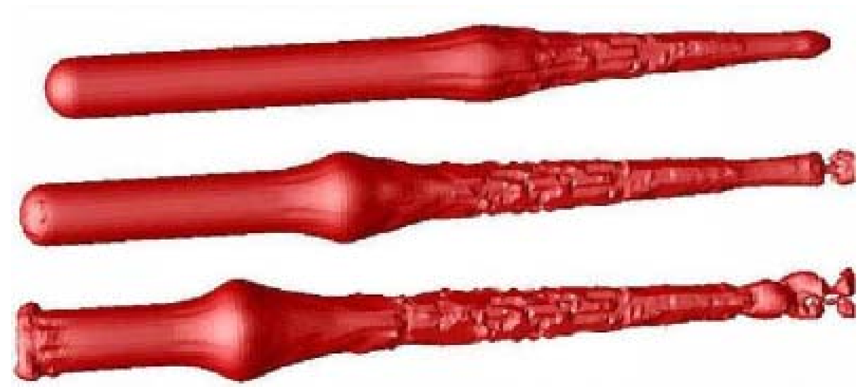




Magneto-hydro-dynamics (MHD)

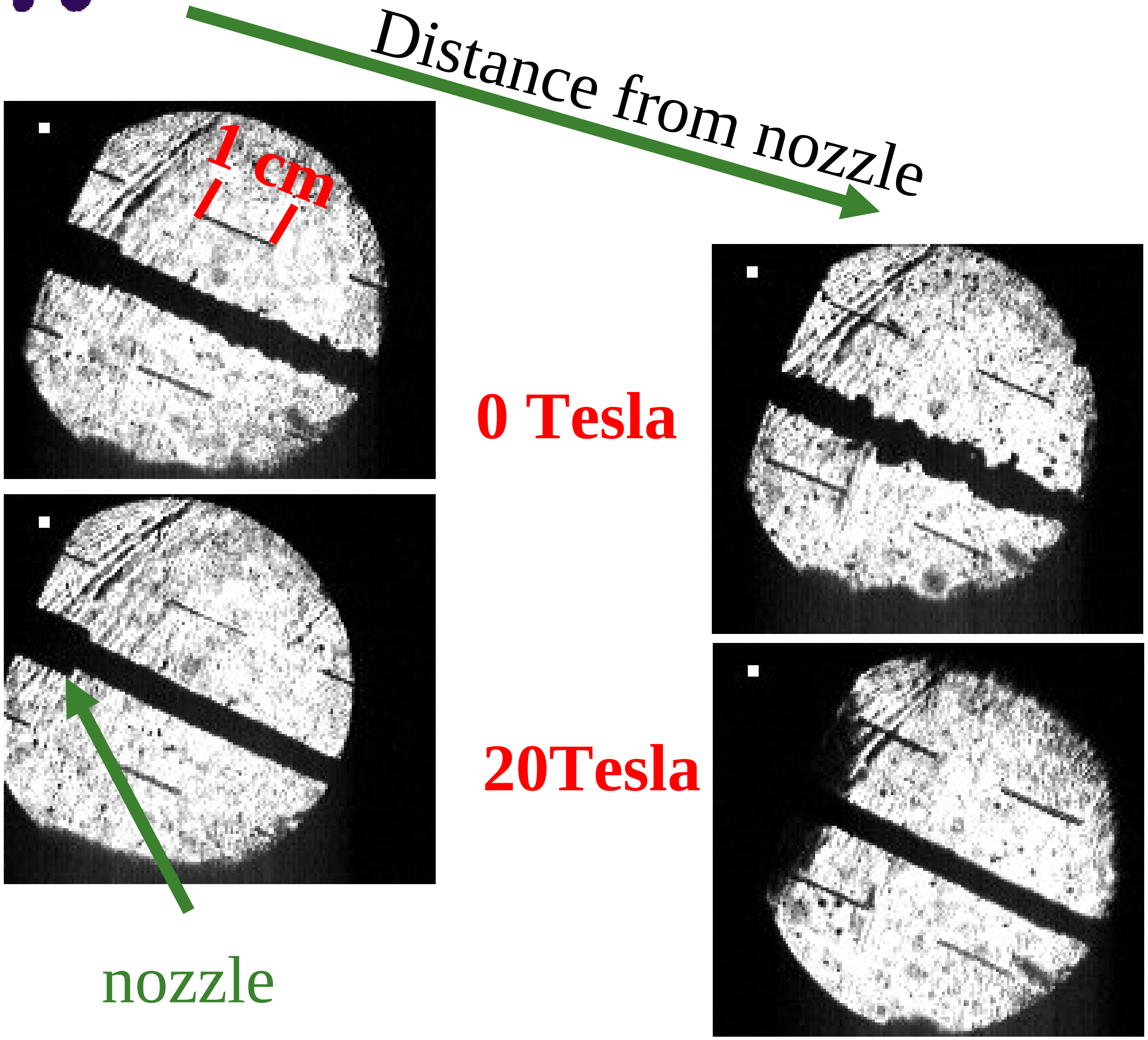
- 20-T solenoid DC-field for sec. particle capture
- Moving mercury target sees dB/dt
- Farady's law → eddy currents induced
- Magnetic field acts back on current and mercury jet
- Forces: repulsive, deflecting, quadrupole deformation, …

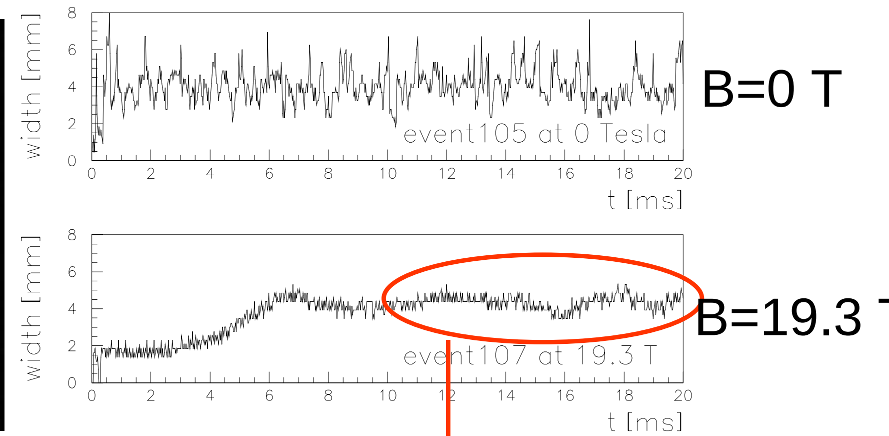




J.Gallardo et al., PAC01, p.627

Previous experimental results



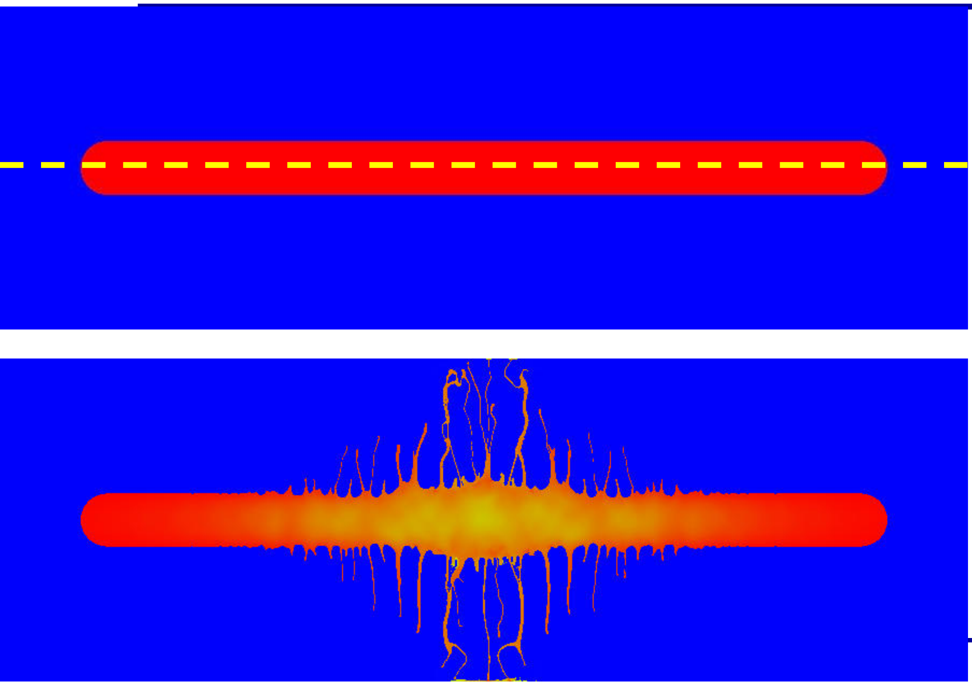


Jet smoothing

(damping of Rayleigh surface instability)

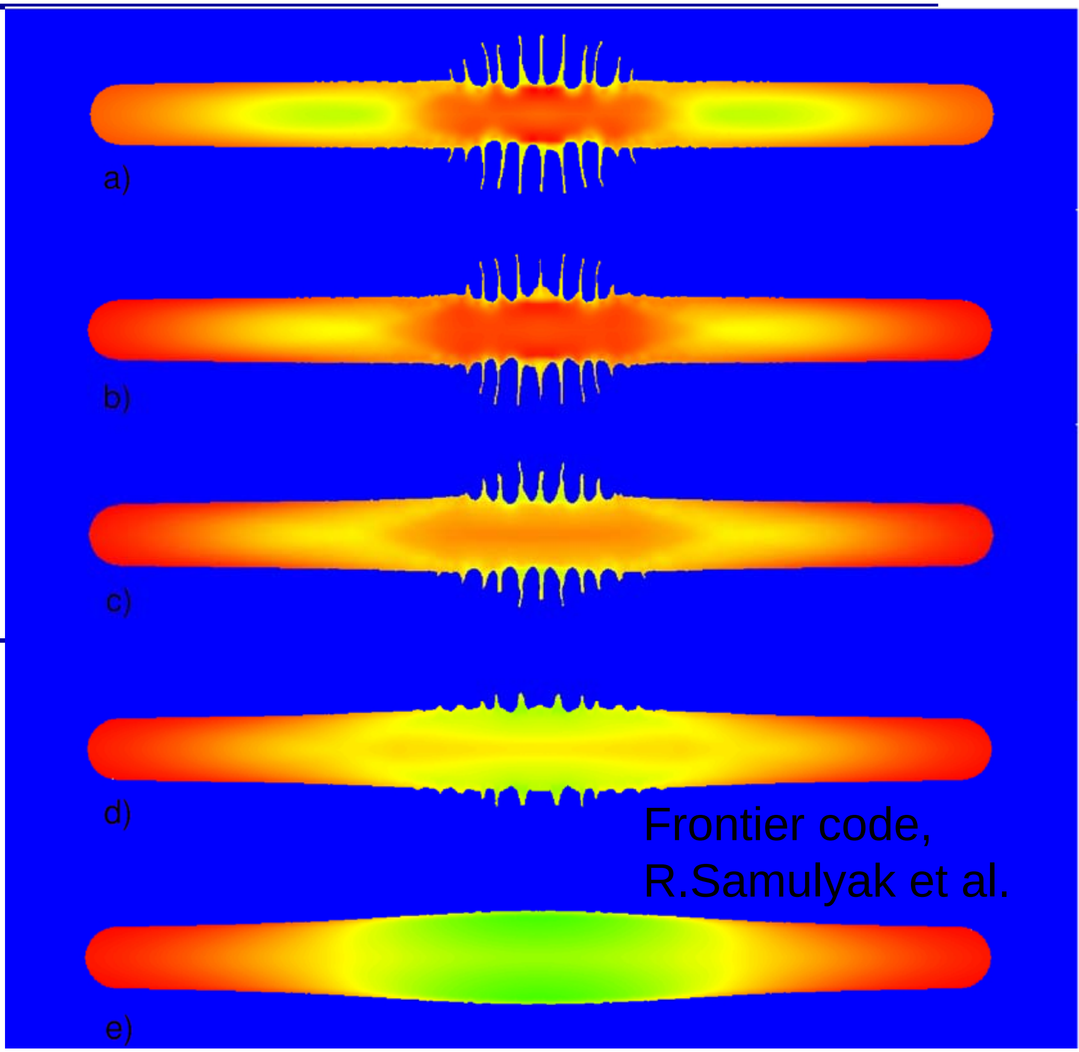
15 m/s mercury jet injected into 20 T field.

MHD stabilization



Simulation of the mercury jet – proton pulse interaction during 100 microseconds, B = 0

damping of the explosion induced by the proton beam



a) B = 0 b) B = 2T c) B = 4T
d) B = 6T e) B = 10T

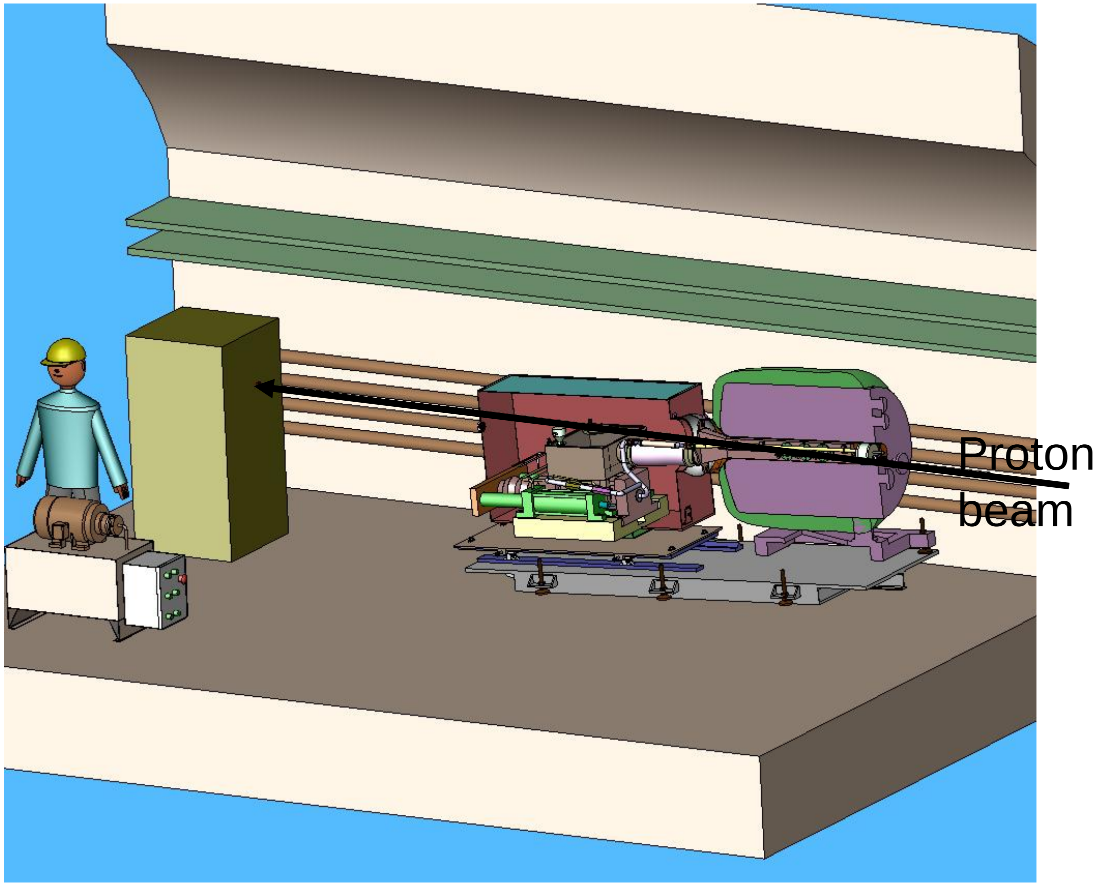
Experimental history

	ISOLDE	GHMFL	BNL	TT2A	NuFact
p+/pulse	3 10^{13}	----	0.4 10^{13}	2.5 10^{13}	3 10^{13}
B [T]	---	20	---	15	20
Hg target	static	15 m/s jet (d=4mm)	2 m/s jet	20 m/s/ jet	20 m/s jet (d=10mm)
	DONE	DONE	DONE	2007	DESIGN

- proof-of-principle test proposed at TT2A @ CERN
- Experimental setup: 15 T solenoid + Mercury Jet + proton beam
- Completion of the target R&D for final design of the Hg-Jet

Nominal mercury jet target test in TT2A at CERN

- Approved CERN experiment nToF11
- Setup:
  - Proton beam
    - 24 GeV, nominal intensity
  - 15 T solenoid
  - 20 m/s mercury jet
- Collaboration:
  - BNL,ORNL, Princeton University, MIT, RAL, CERN, KEK
- Beam time in spring 2007



Conclusion

- (Mercury) jet target a viable solution as a production target for a 4MW proton beam and beyond!
- Target R&D on target concepts different than jet are alive, but comparable small.
- Synergies of target development for a large variety of applications.