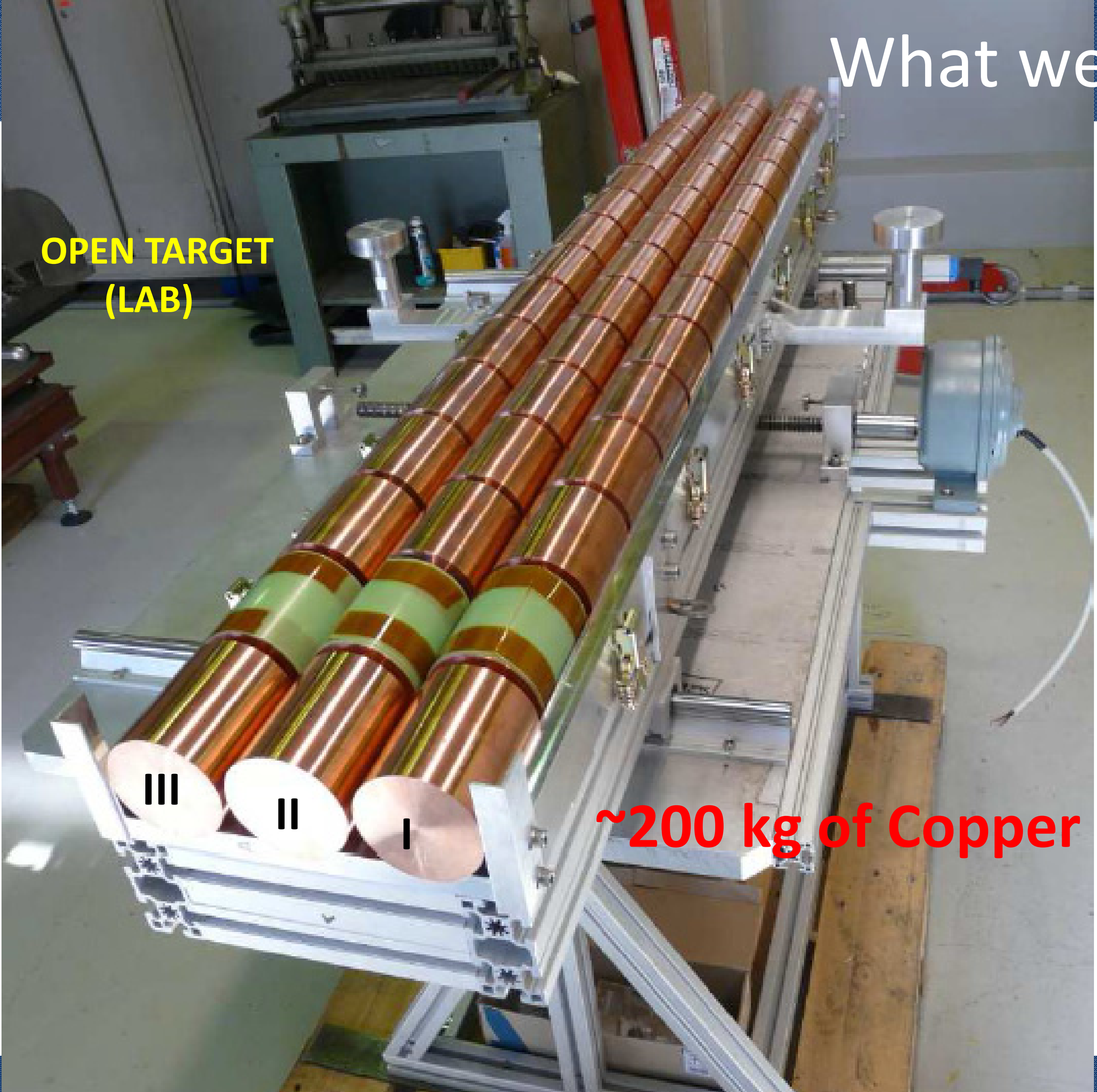
Results of an
Experiment on Hydrodynamic tunneling
at the SPS HiRadMat

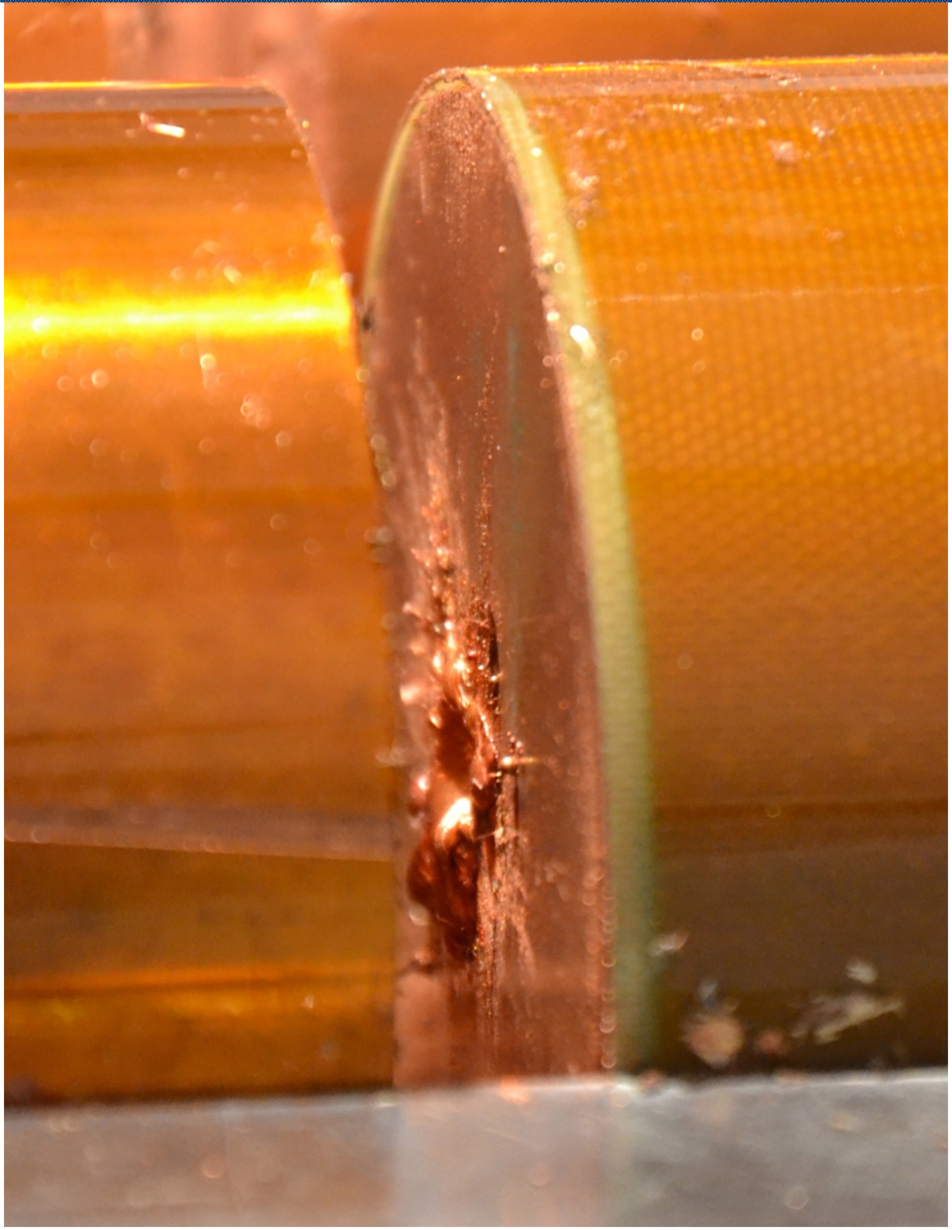
Juan Blanco
Florian Burkart
Damien Grenier
Erich Griesmayer
Rudiger Schmidt
Naeem Tahir
Daniel Wollmann

WHAT we did?

What we did?



What we did?



What we did?

σ~0.2mm , 144 bunches · 1.5E11 p+ 440 GeV

r=4cm x 150 cm length, Copper

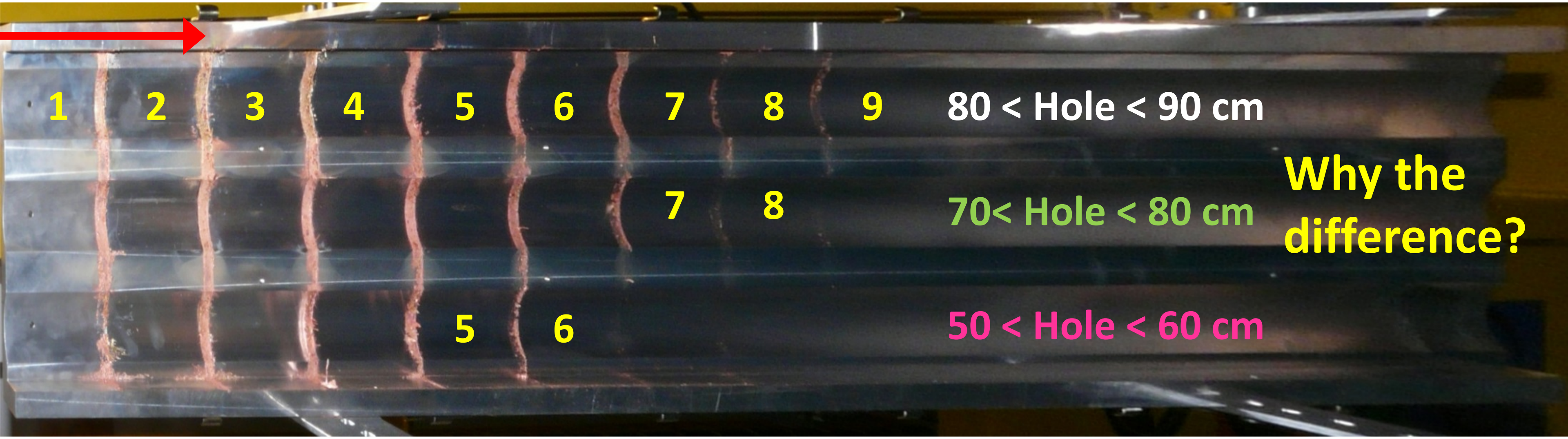
σ~0.2mm , 108 bunches · 1.5E11 p+ 440 GeV

r=4cm x 150 cm length, Copper

σ~2mm , 144 bunches · 1.5E11 p+ 440 GeV

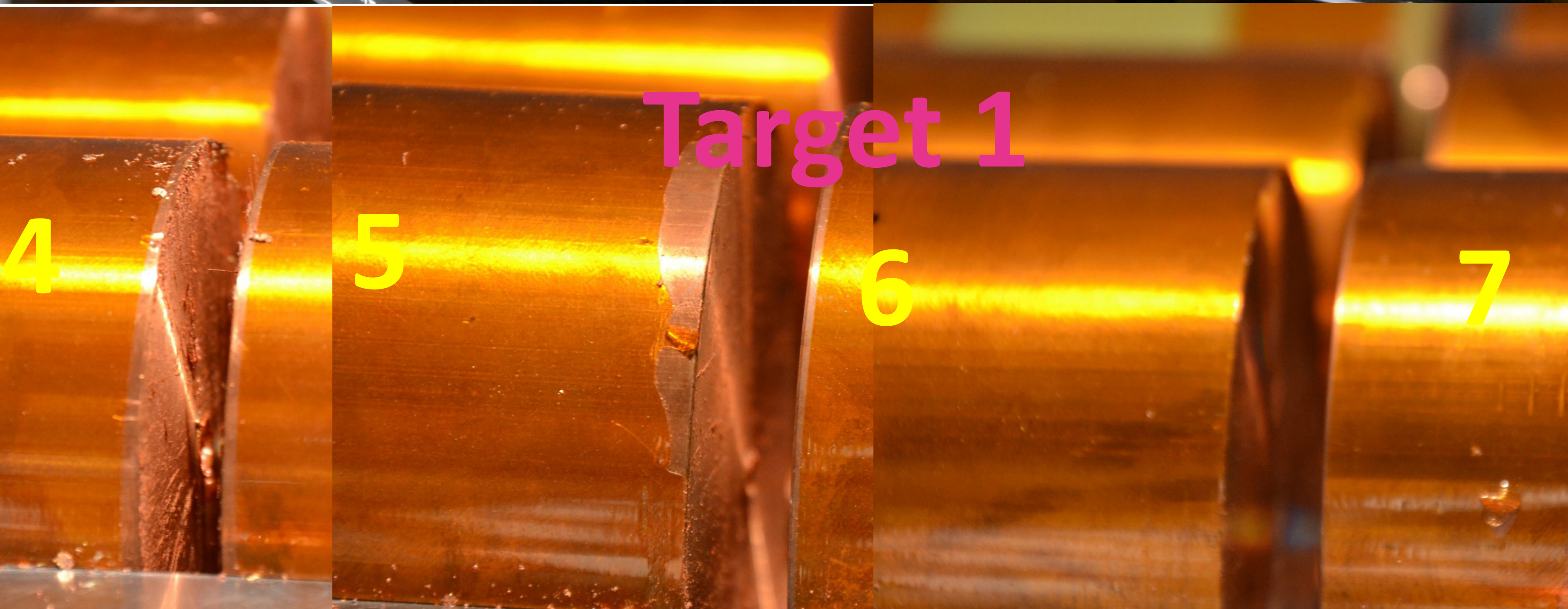
r=4cm x 150 cm length, Copper

UPPER SIDE OF TARGET's BOX

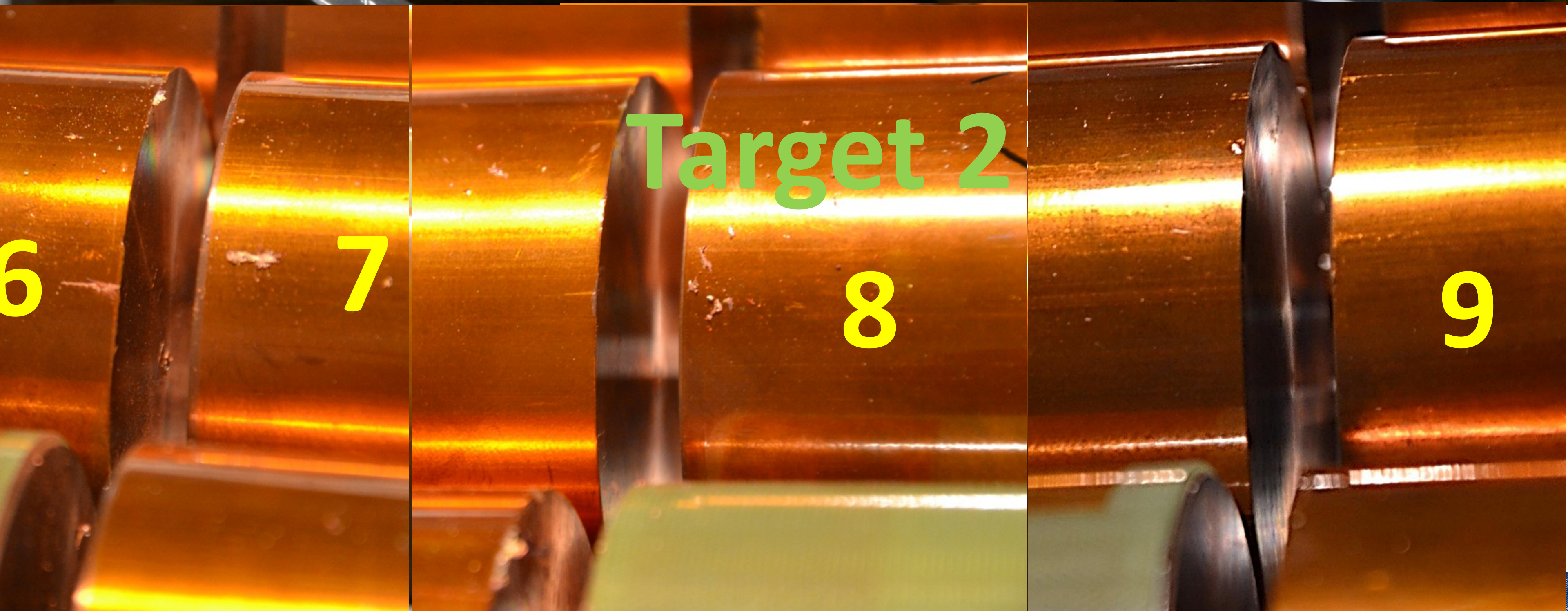


Why the difference?

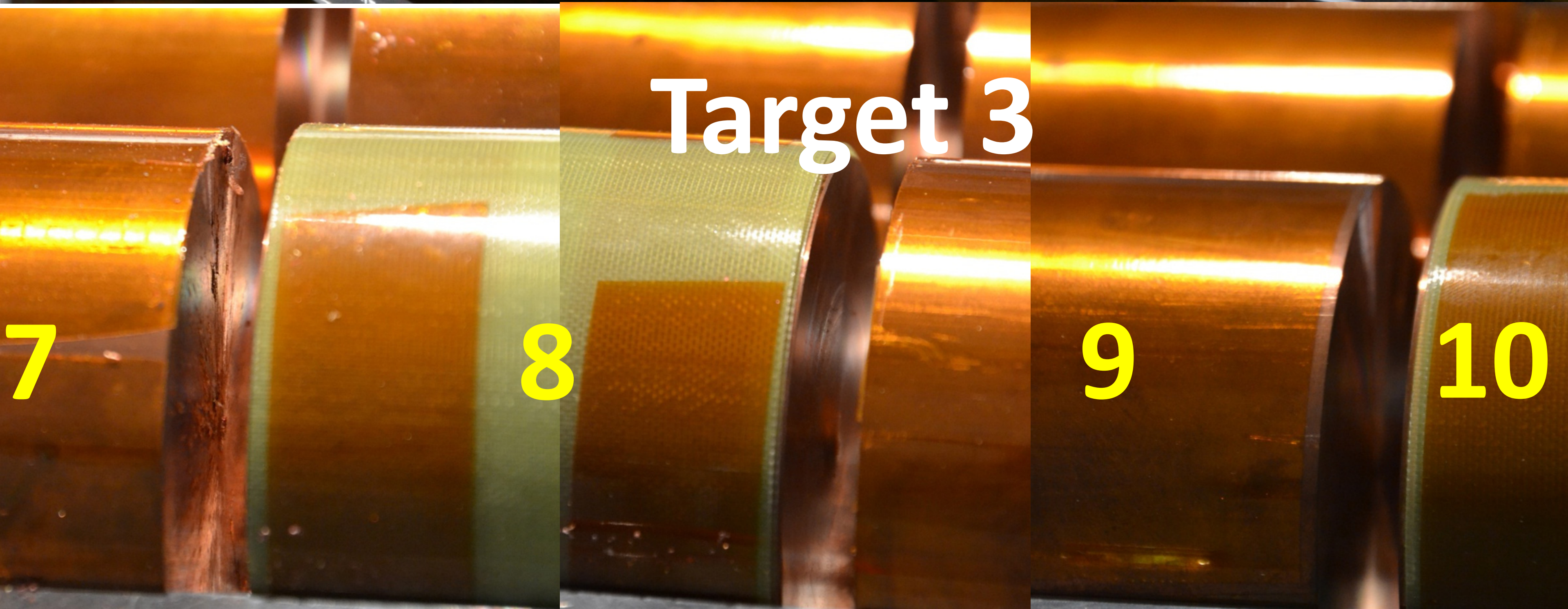
UPPER SIDE OF TARGET's BOX



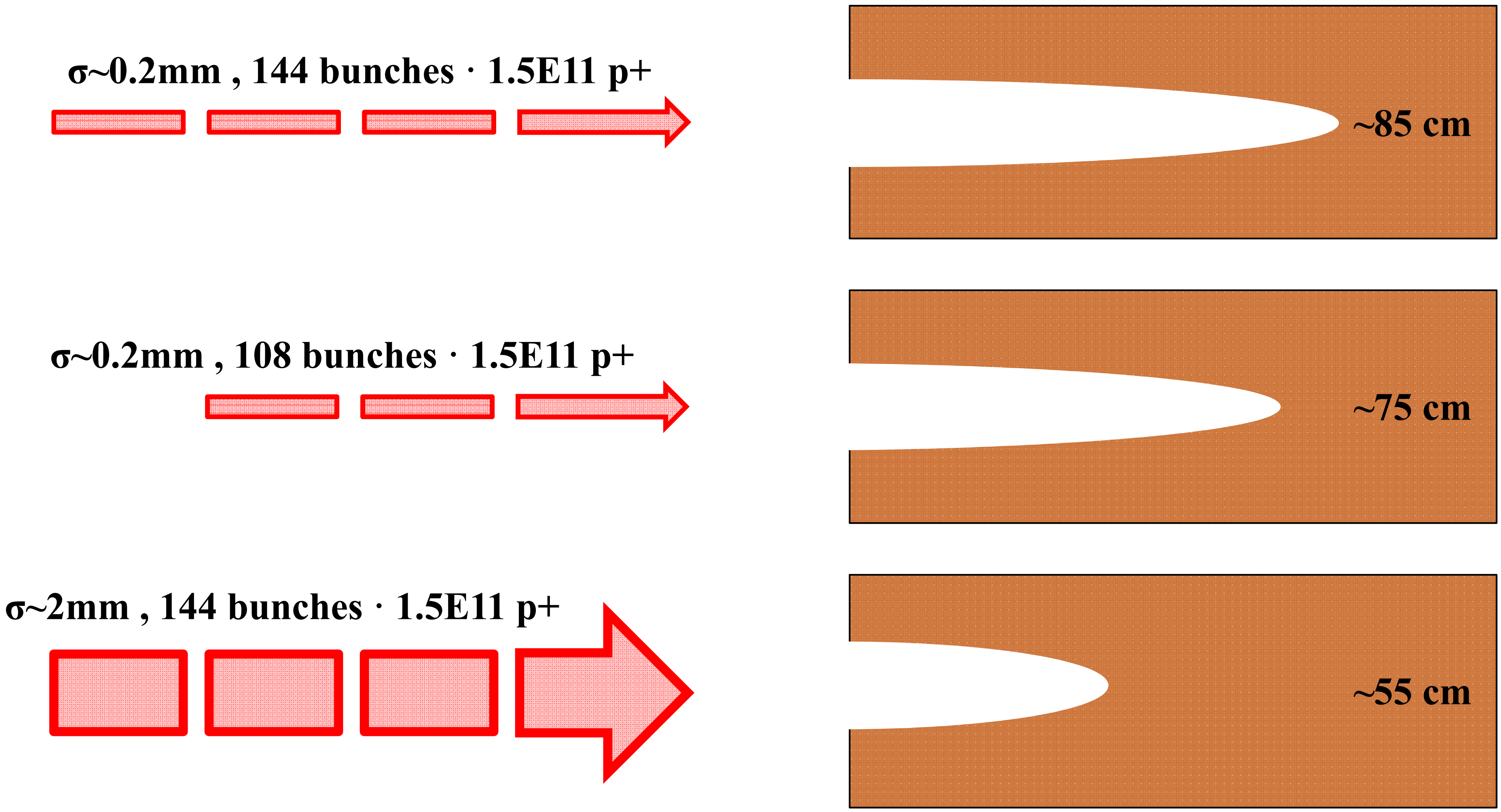
UPPER SIDE OF TARGET's BOX



UPPER SIDE OF TARGET's BOX

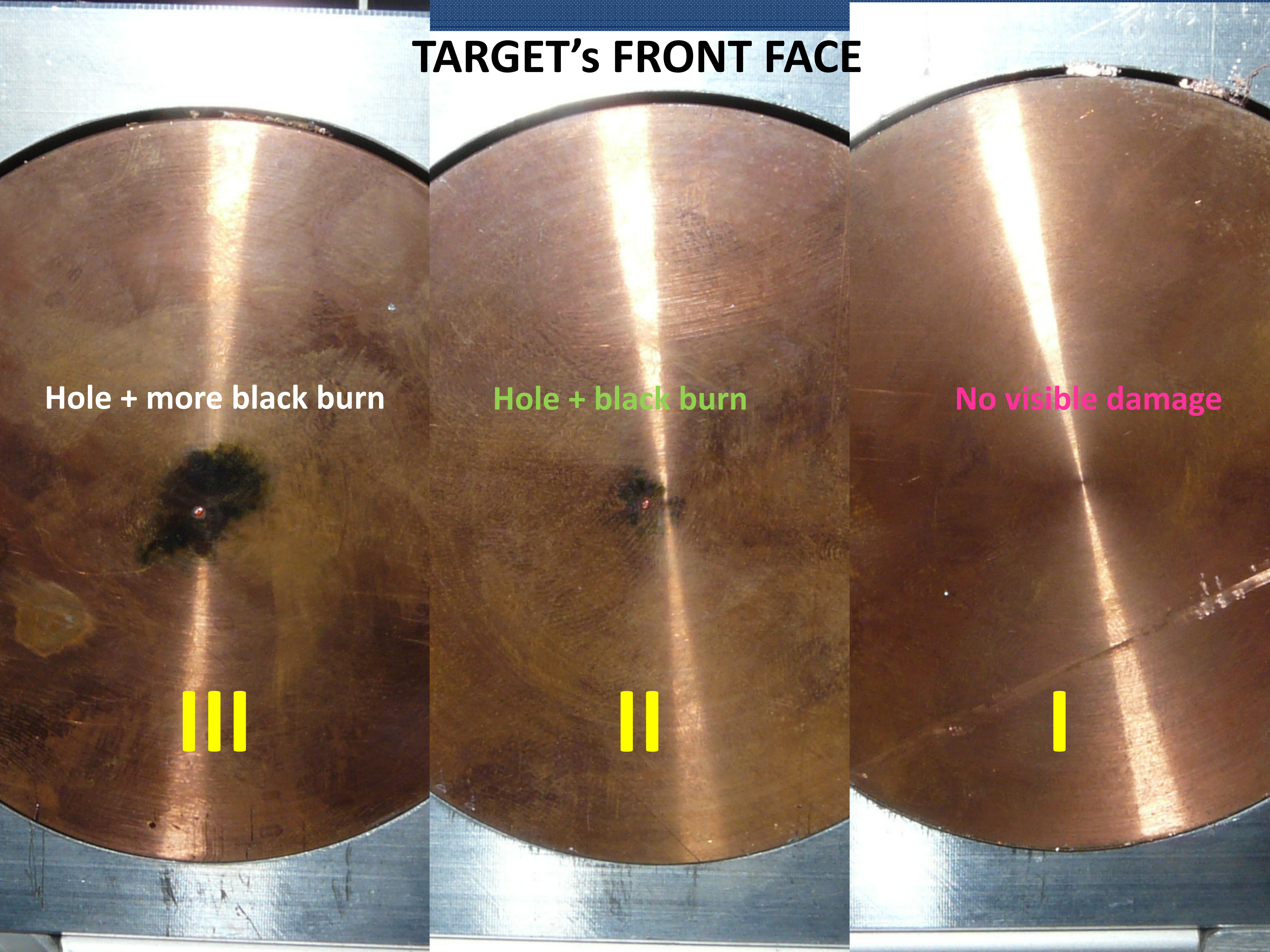


What we did?

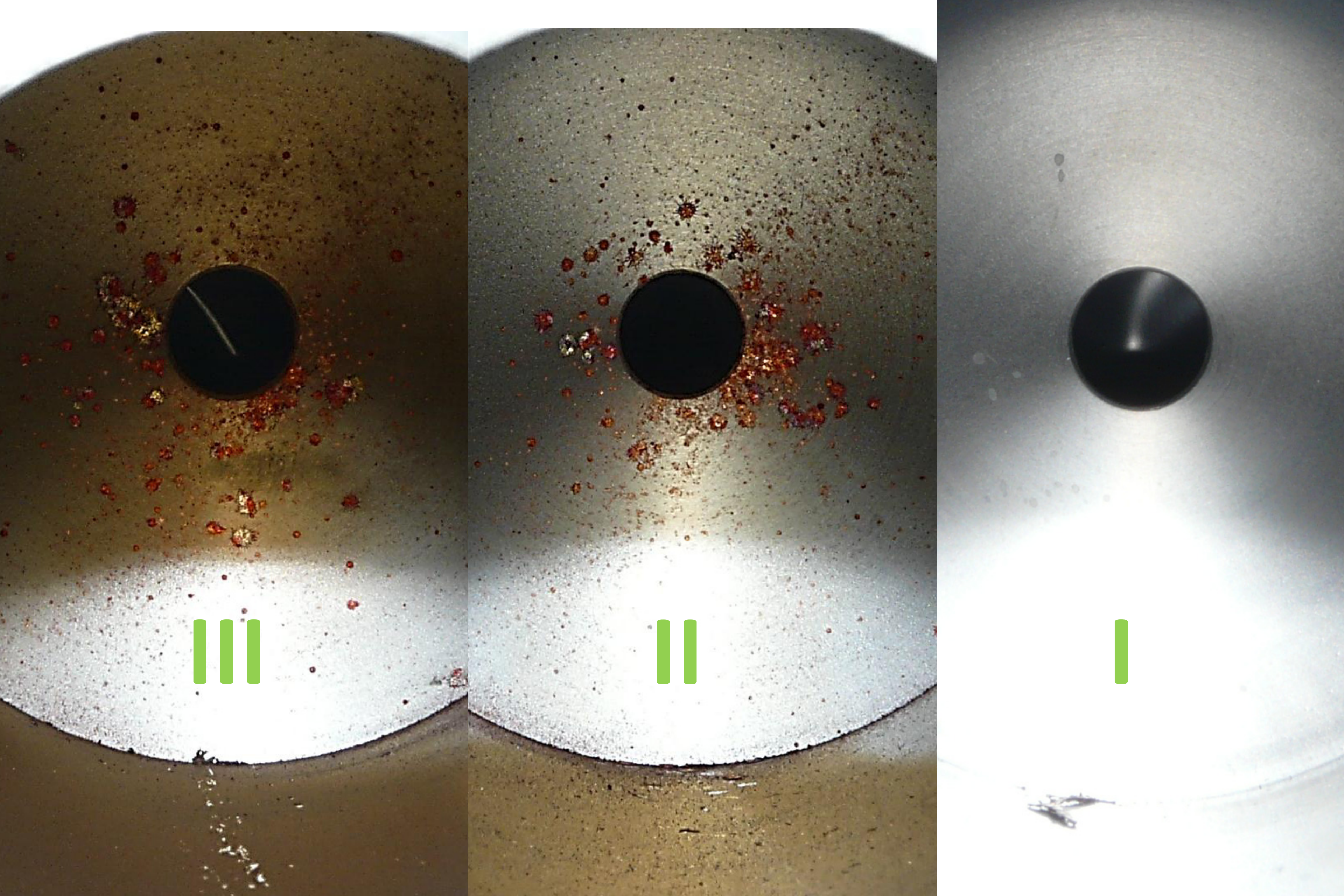


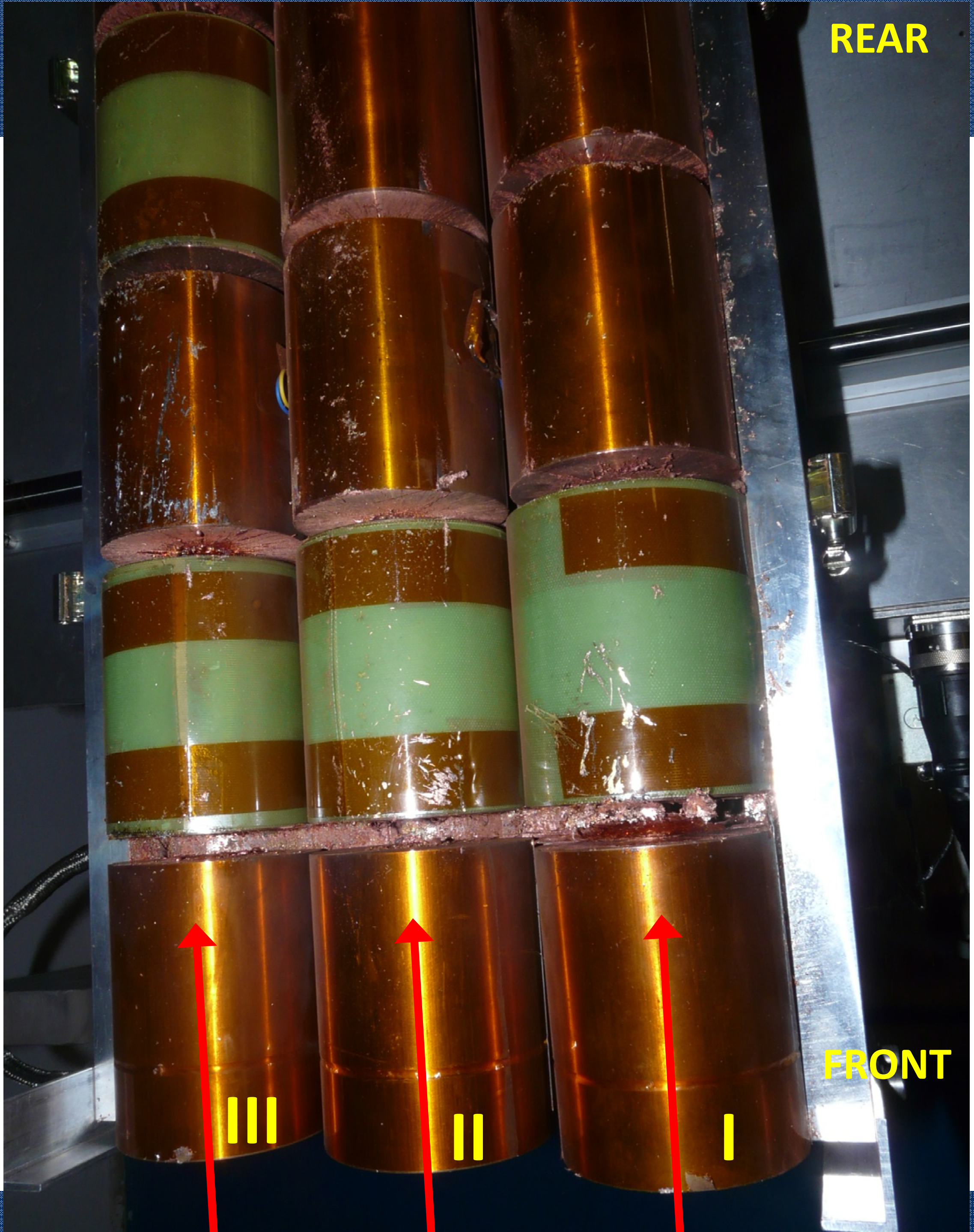
σ~0.2mm , 144 bunches · 1.5E11 p+
~85 cm
σ~0.2mm , 108 bunches · 1.5E11 p+
~75 cm
σ~2mm , 144 bunches · 1.5E11 p+
~55 cm

TARGET's FRONT FACE



OPOSITE SIDE OF TARGET's FRONT FACE




REAR
FRONT
III
II
I

Ok, but WHY we did it?

Accelerators operate with…

… higher energy …

… higher intensity…

… smaller size…

… beams

LHC beam has an energy of **362 MJ** per beam

sufficient to melt **500 kg** of copper or equivalent to

WHY?

Accelerators operate with…

… higher energy …

… higher intensity…

… smaller size…

… beams

Kinetic Energy of a 200m train at 155 km/h ≈ 360 MJoule

WHY?

Machine Protection systems are **essential** to safely operate high-energy high-density accelerators.

Machine protection systems are **not 100% safe.**
(accidents can occur)

It is important to understand the **consequences** of all possible accidents; specially a **full beam loss.**

(catastrophic scenario)

WHY?

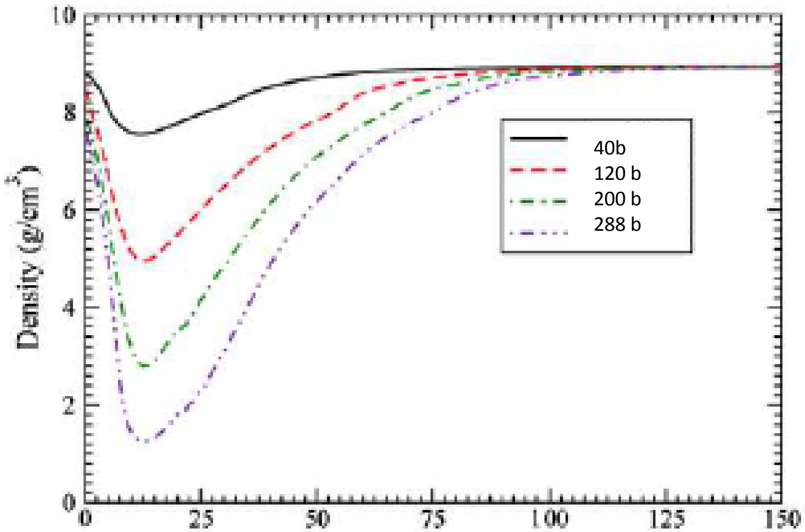
Possible LHC full beam impact scenarios:

Injection kicker failure: injection beam not deflected OR circulating beam is deflected

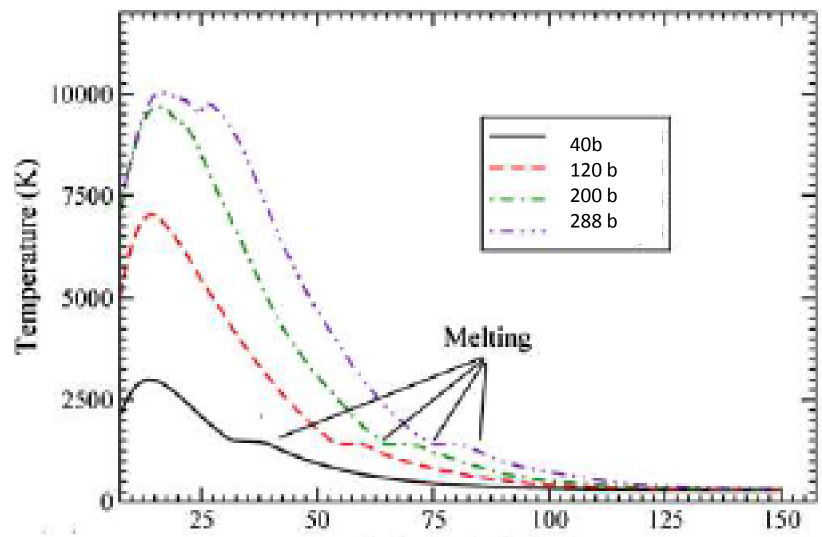
Extraction kickers failure: kicker misfire OR wrong deflection angle OR beam dump system not working OR etc

Previous work (simulations)

Simulations

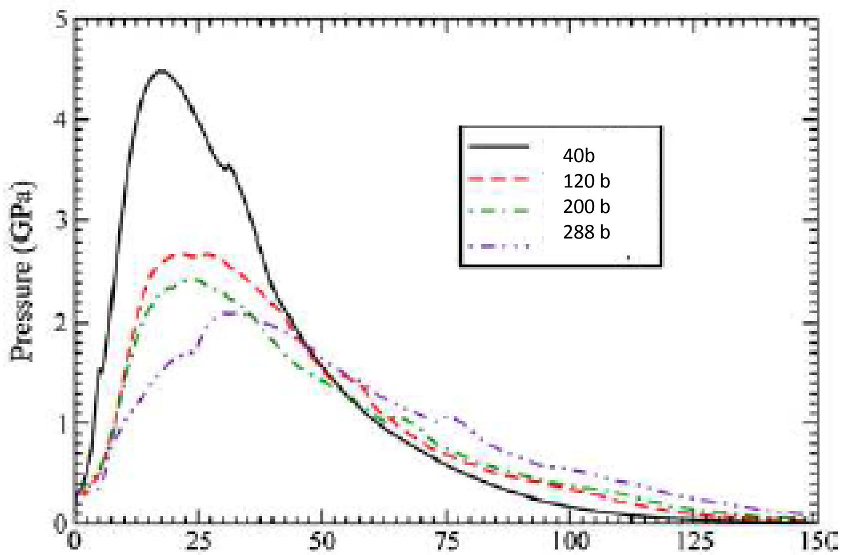


Density (g/cc)



Temperature (K)

Si
(e
ge
m
be

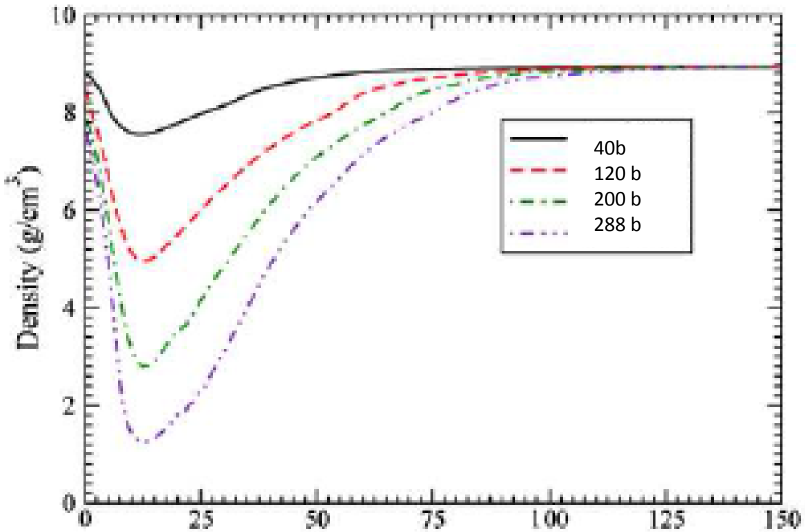


Pressure (GPa)

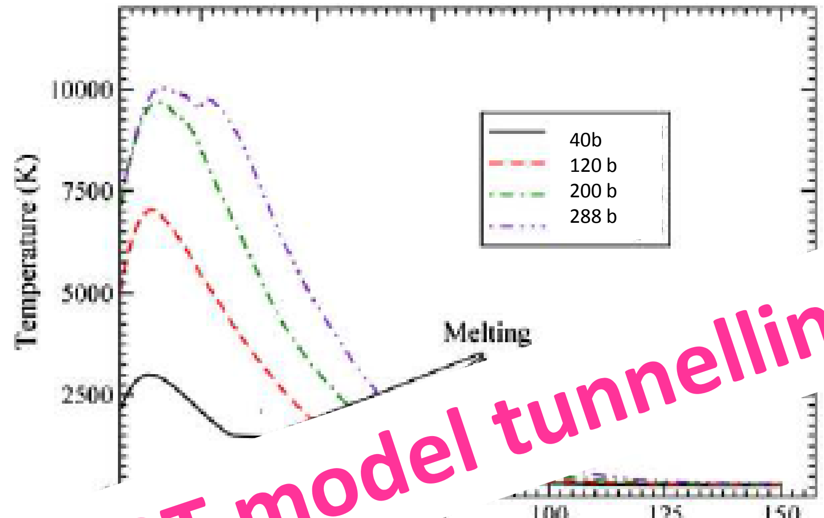
0.5 mm
440 GeV
288*1.15E11 protons
25ns

- * **Phys, Rev. Special Topics Accel. Beams, vol, 15, p. 051003, 2012. N. Tahir et al.**
- **J. Appl, Phys. Vol 97, p, 083532, 2005. N. Tahir et al.**

Simulations



Density (g/cc)

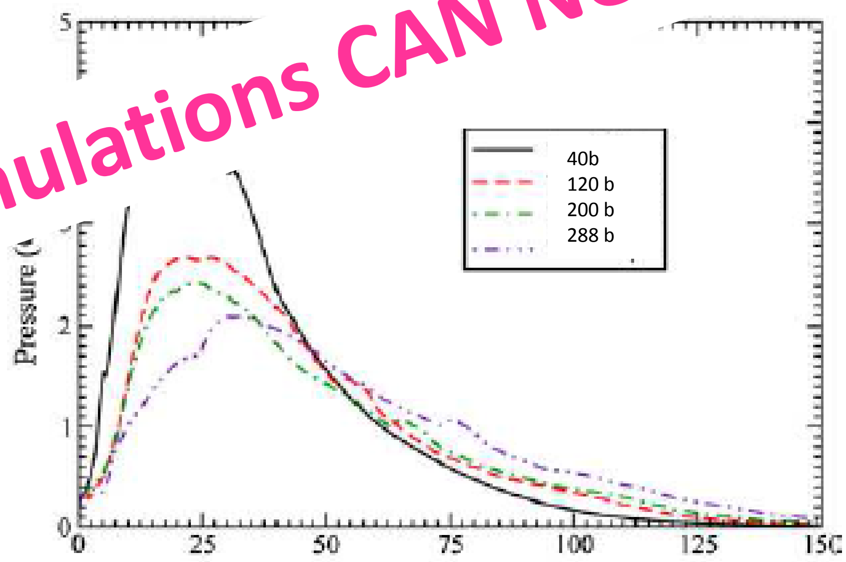


Static simulations CAN NOT model tunnelling

ge

ma

be



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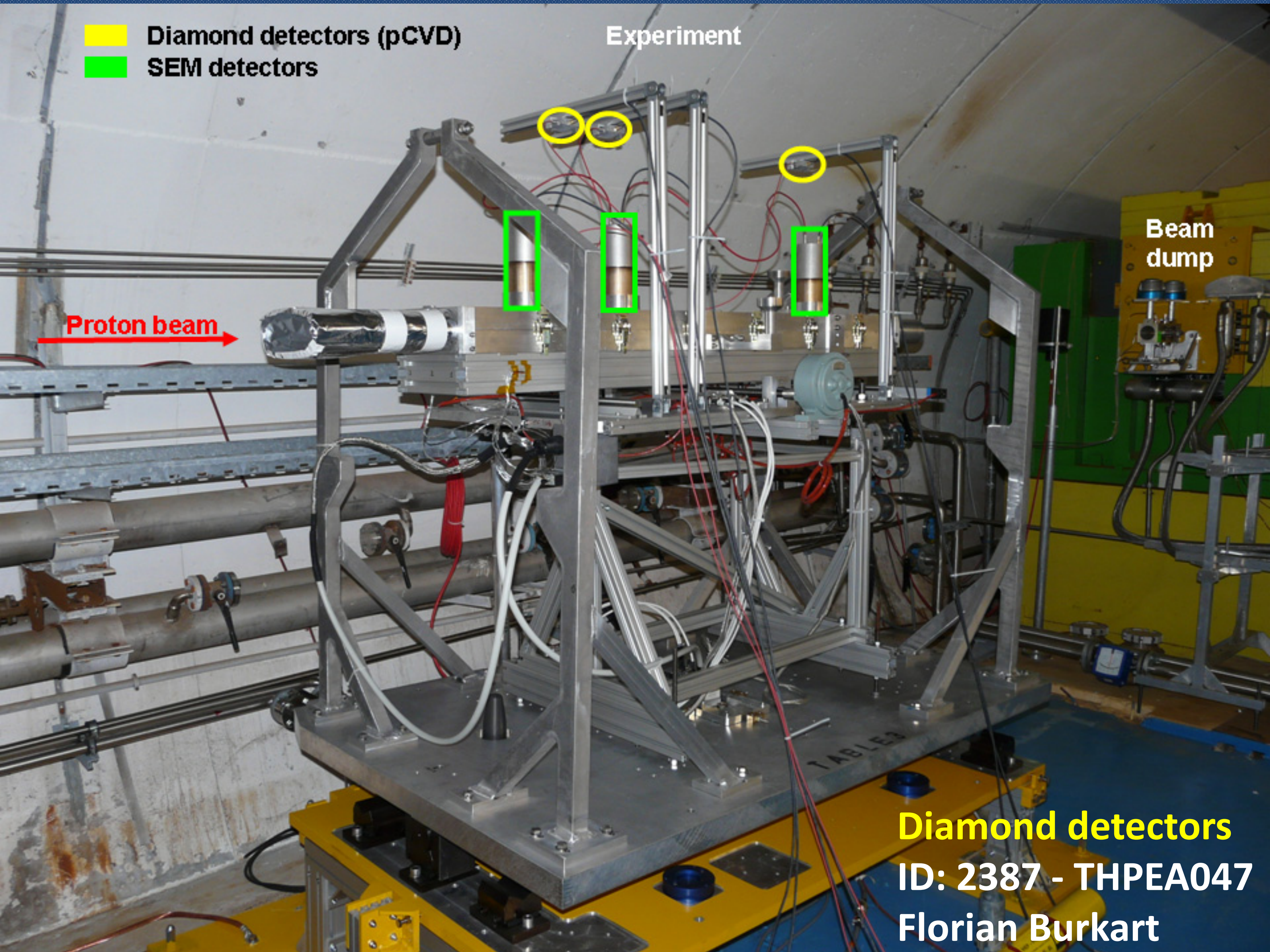
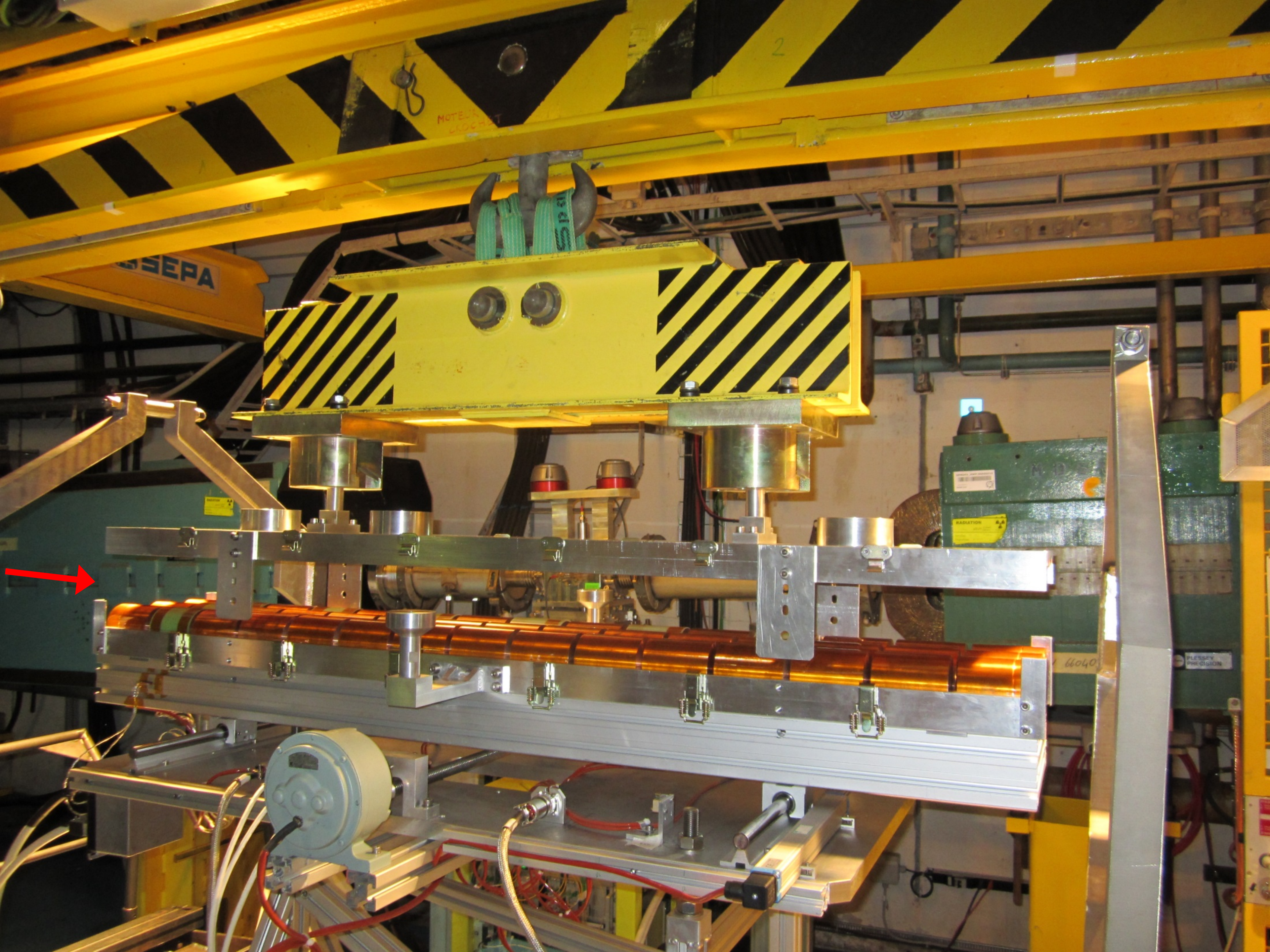
- * Phys, Rev. Special Topics Accel. Beams, vol, 15, p. 051003, 2012. N. Tahir et al.
- J. Appl, Phys. Vol 97, p, 083532, 2005. N. Tahir et al.

Design


Diamond detectors (pCVD)
SEM detectors
Experiment
Beam dump
Proton beam
TABLES
Diamond detectors
ID: 2387 - THPEA047
Florian Burkart


SEPA
PLESSEY PRECISION

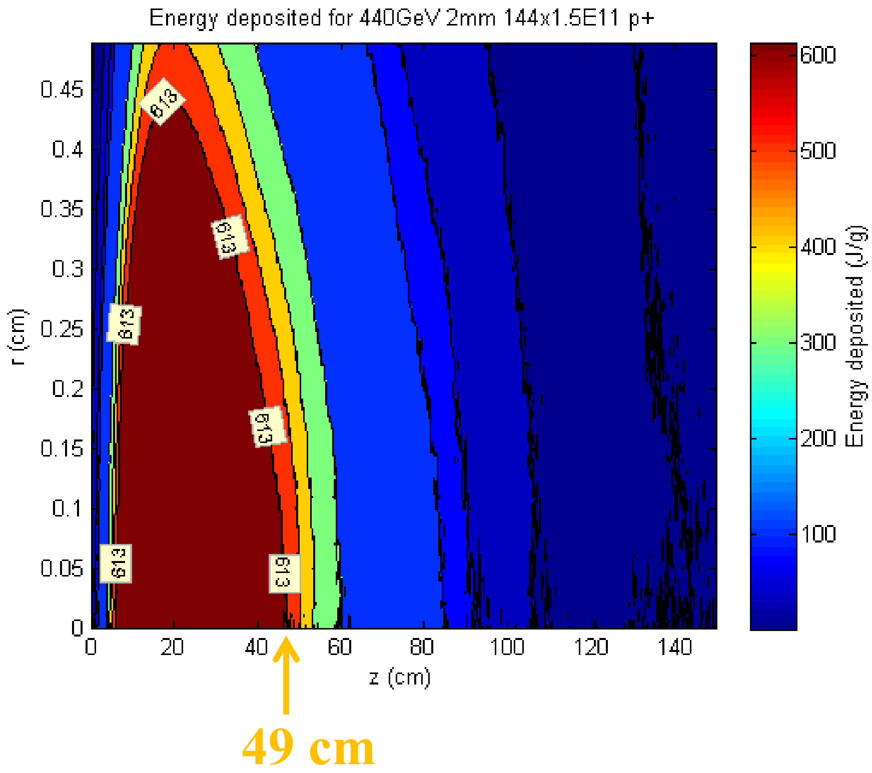
Results

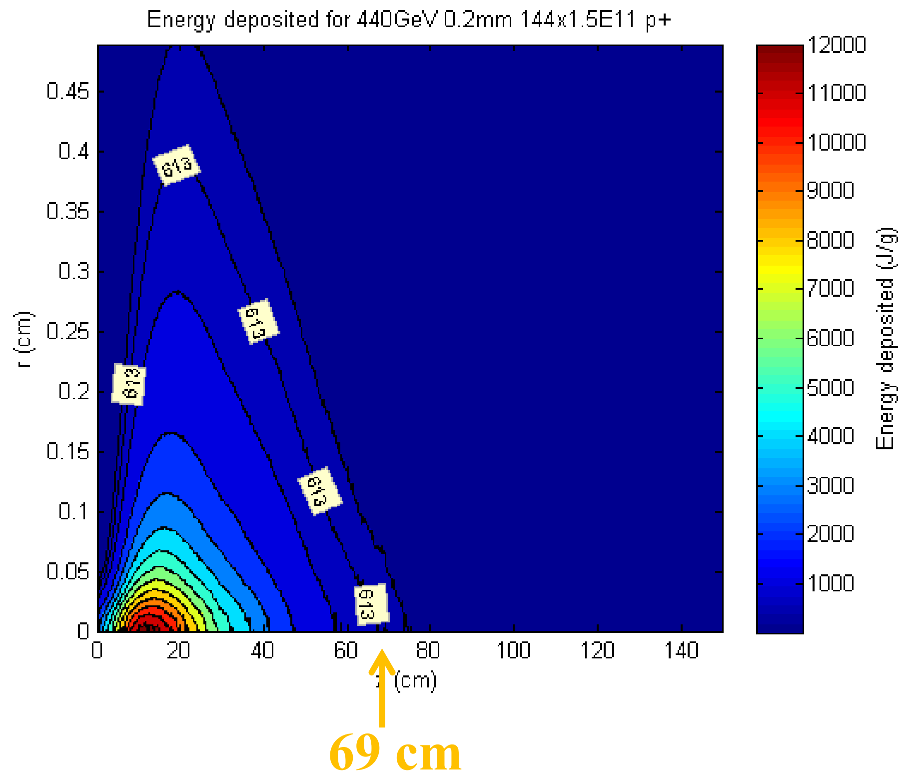
SPS beam type @ 440 GeV

Relevant parameters of the experiment's high intensity beam phase

Target	Nbunches	Ibunch	total I	Spacing	Size	Expectation
III	144	1.50E+11	2.16E+13	50 ns	0.2 mm	**more tunnelling**
II	108	1.50E+11	1.62E+13	50 ns	0.2 mm	**tunnelling**
I	144	1.50E+11	2.16E+13	50 ns	2 mm	**NO** tunnelling expected

Results

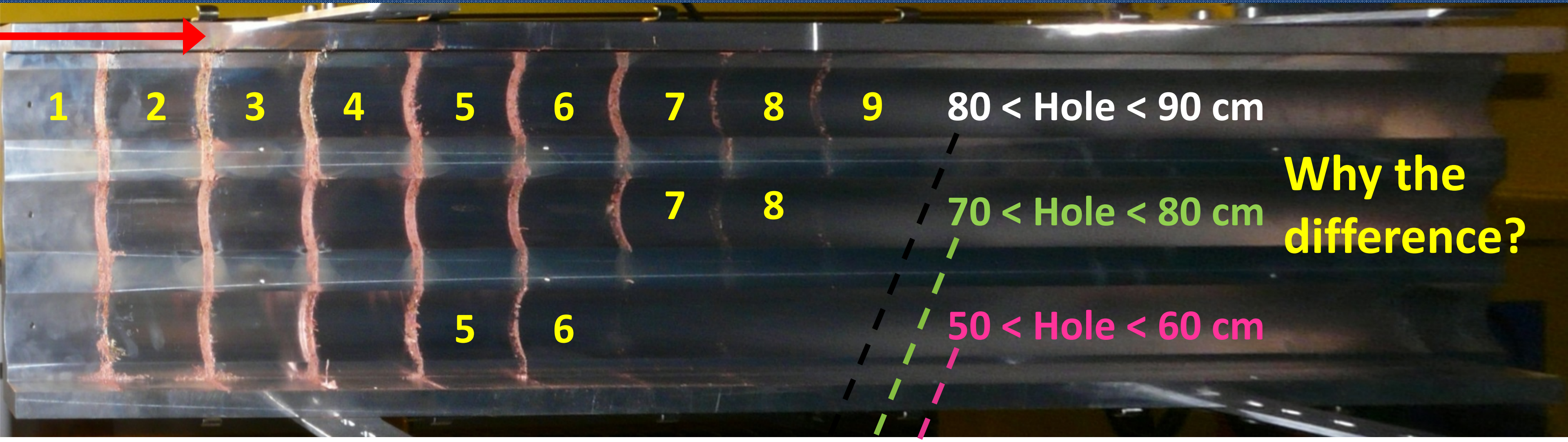




Static simulations ONLY with FLUKA give a penetration distance of:

(if no tunnelling)

T1 = 49 cm , T2 = 65 cm , T3 = 69 cm



Evidence of tunnelling !!!

Target	Nbunbes	p+ per bunch	beam sigma [mm]	Measured Melting Distance [cm]	Δ to target 2 [cm]	Simulation (no tunneling) [cm]	Δ to measured [cm]
3	144	1.5E11	0.2	85 ± 5	10	~69	16±5
2	108	1.5E11	0.2	75 ± 5		~65	10±5
1	144	1.5E11	2	55 ± 5	-	~49	6±5

Comparison between experiment and hydro- simulations (with slightly different parameters)

Experiment Hydrodynamic tunnelling speed: D3-D2 / Δt = 10 cm / 1.8us = 5.5 cm/us

Hydrodynamic simulations (σ=0.1 mm, 288*1.15 E11 protons, 440GeV, 25 ns) 8 cm/us

Hydrodynamic simulations (σ=0.5 mm, 288*1.15 E11 protons, 440GeV, 25 ns) 5 cm/us

Conclusions

Conclusions

- Evidence of **hydrodynamic tunneling** has been **observed** in the experiment (target 3 w.r.t Target 2). **SUCCESS**.

- **Results** are **compatible** with **simulations** however better measurements (e.g. ultrasounds) are required to reduce uncertainty.

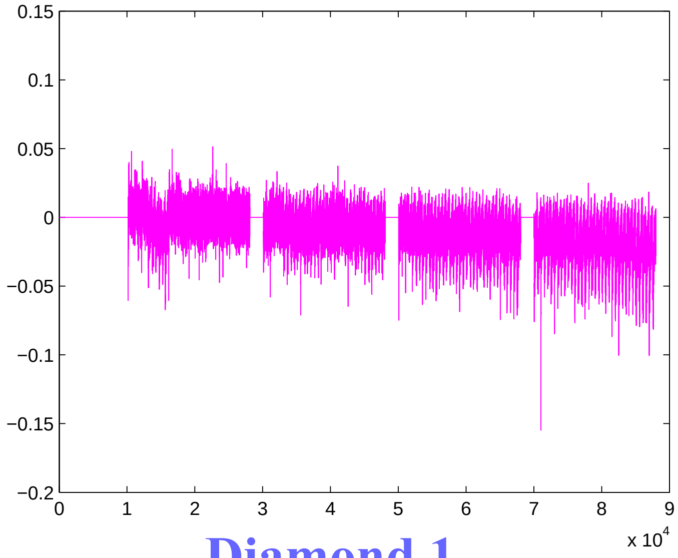
- Hydrodynamic simulations with the same parameters as the experiment are needed to fully confirm tunnelling and validate simulations.

- To continue studying these effects and simulation results **new experiments** are suggested.

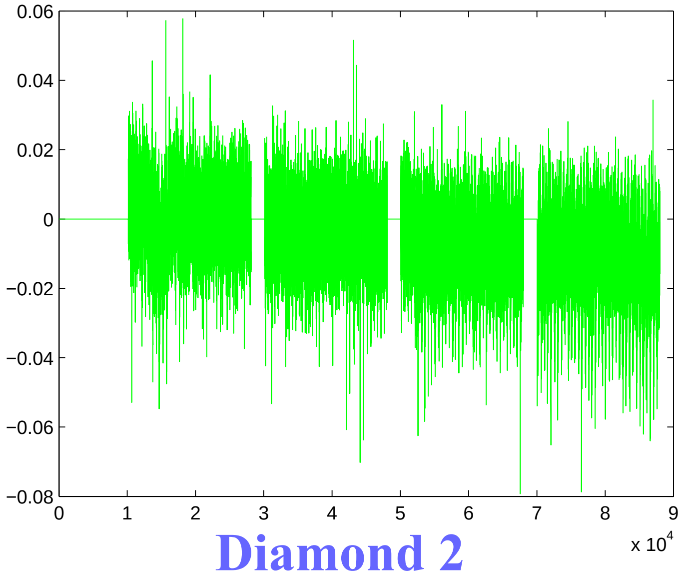
- New **diamond** detectors **performed well** under high radiation environment. Although, an improved version with more HV capacitance is suggested. (ID: 2387 - THPEA047 - F. Burkart et. al)

END

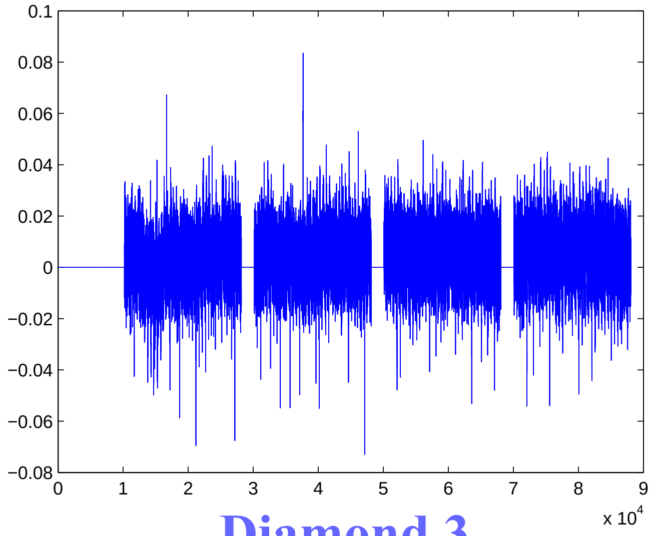
Target III diamond signal – Target I diamond signal



Diamond 1



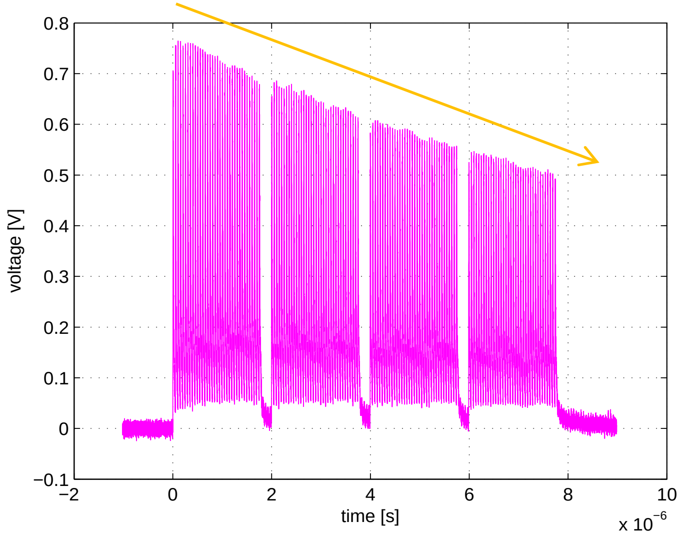
Diamond 2

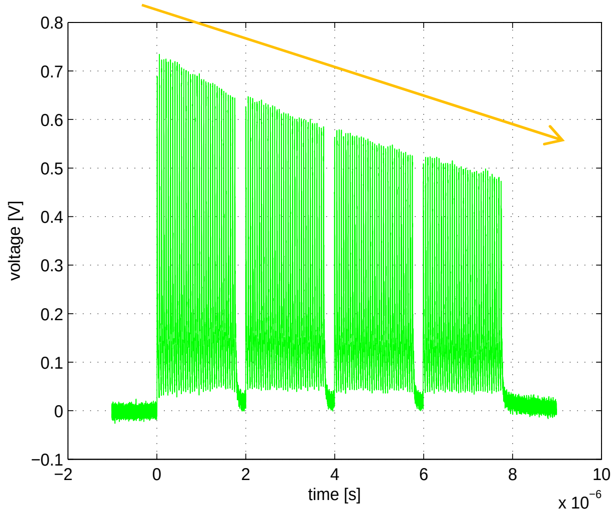


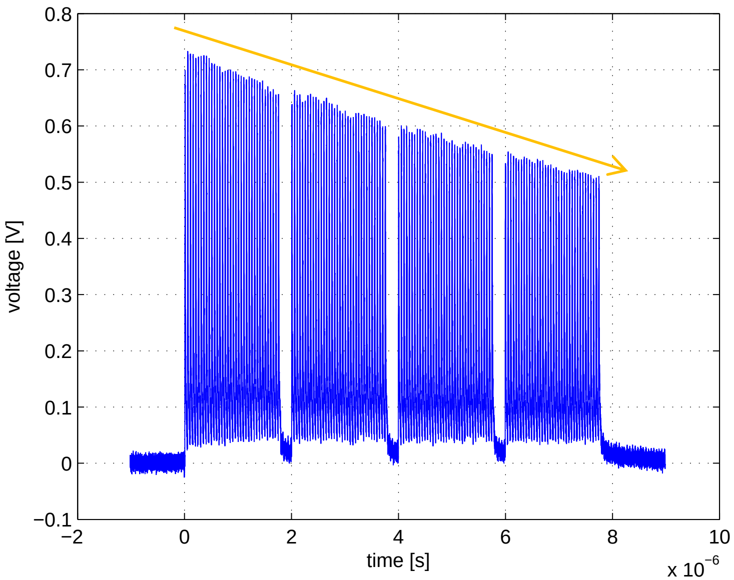
Diamond 3

Signal difference from diamond 1 and 2 show that the third target signal decreases more rapidly than for target I. Diamond 3 signal increase is barely noticeable.

pCVD

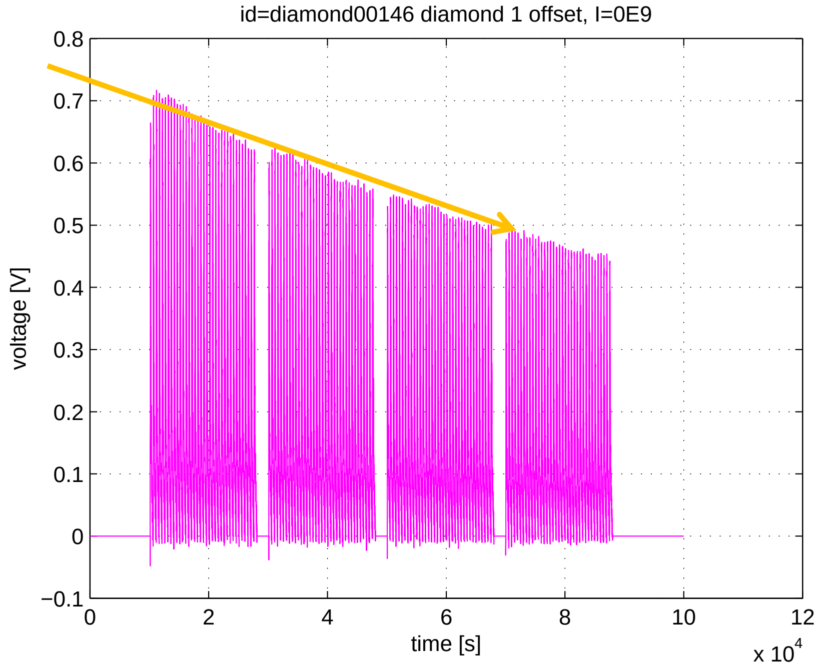


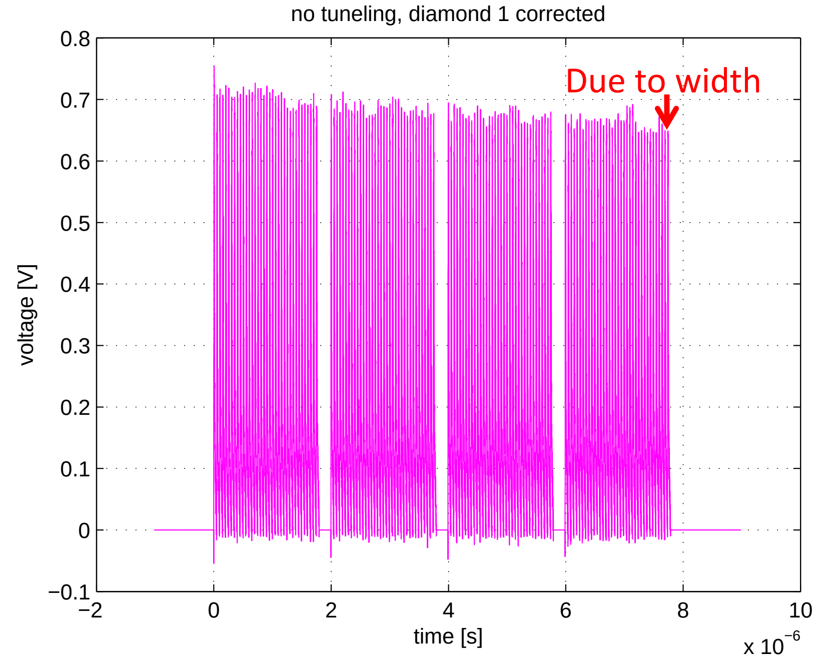




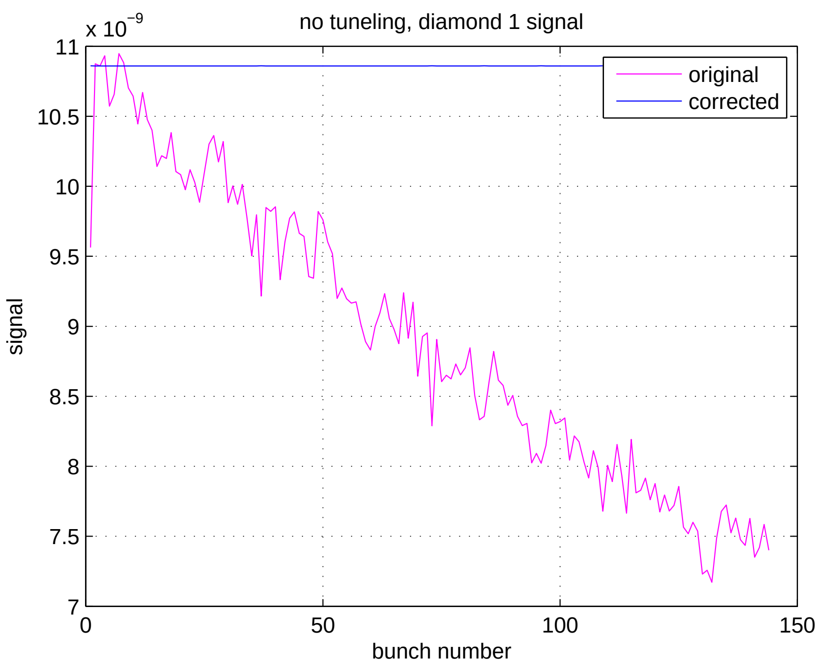
The signal from the first target is used to calculate the relation between voltage drop across the diamond with the decrease of efficiency.

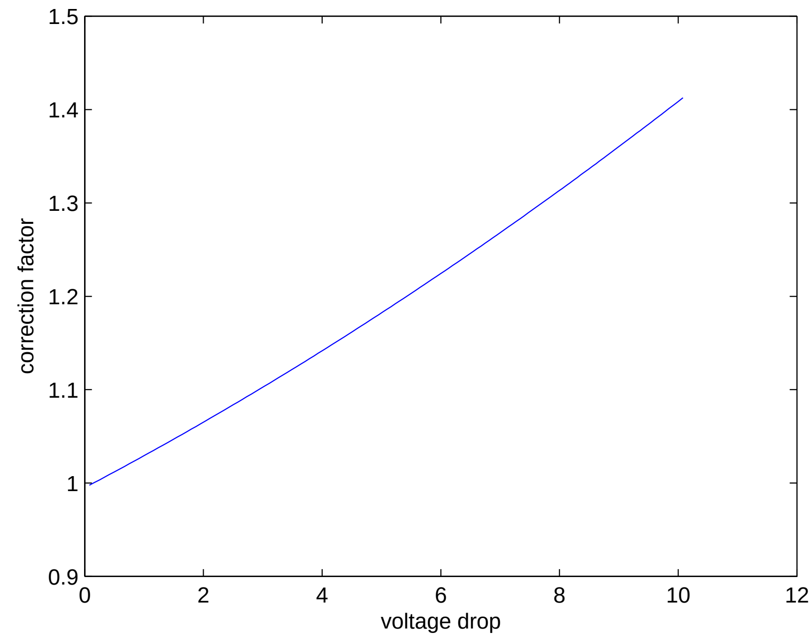
The calibration V-eff is used to correct target's III signal





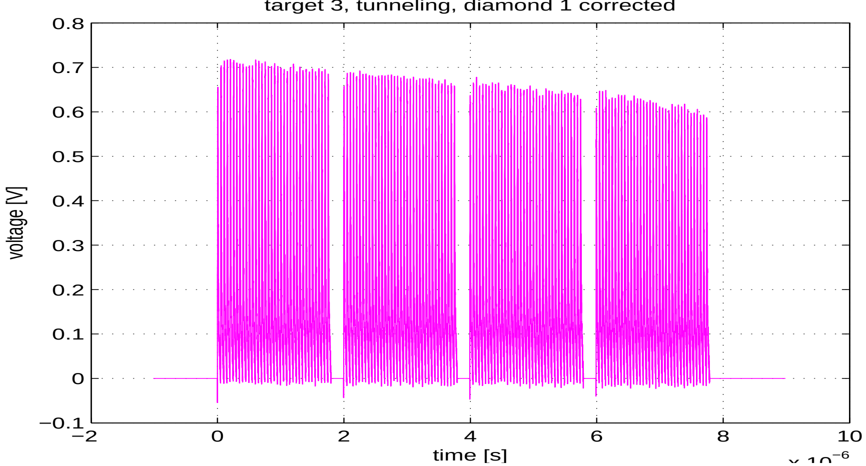
Target I calibrates Voltage-Charge for target III



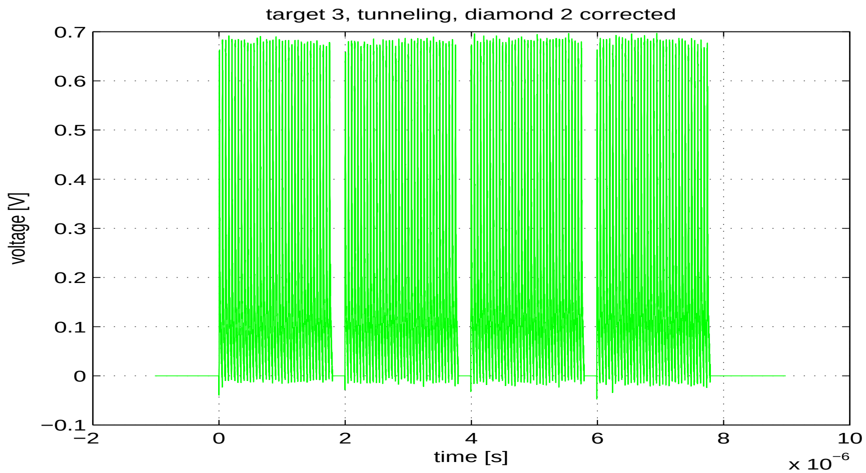


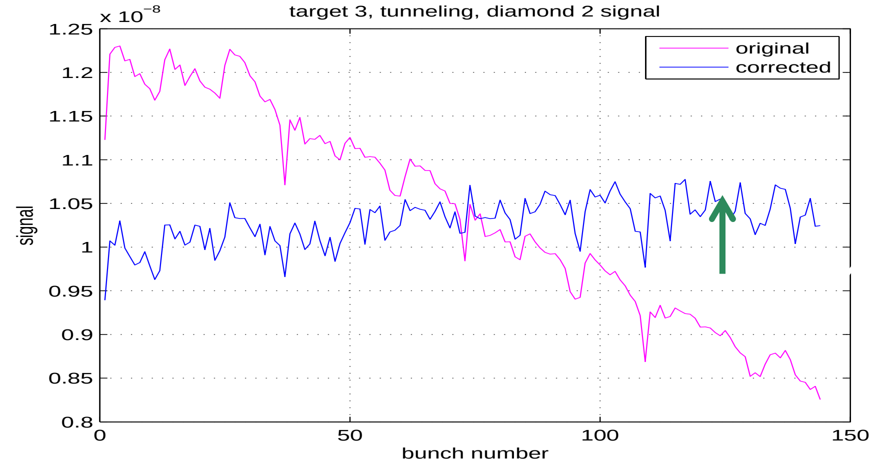
Corrected signals
for target 3

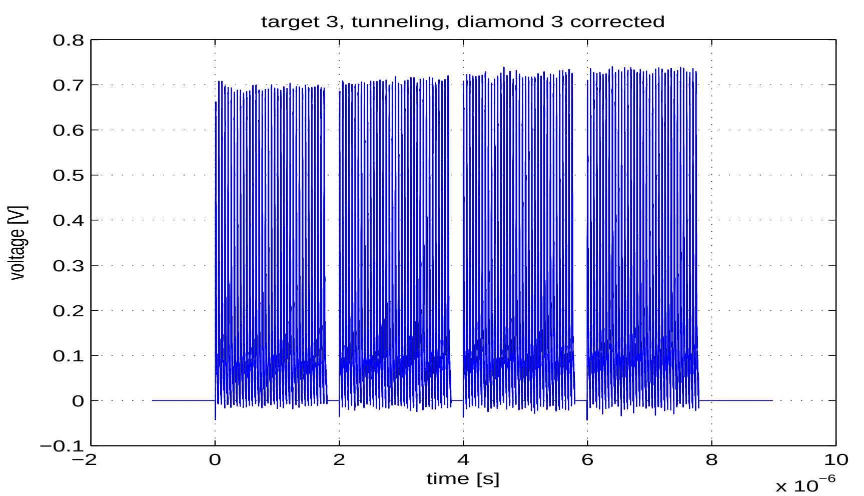
(144 bunches, 50ns, 0.2 mm sigma)

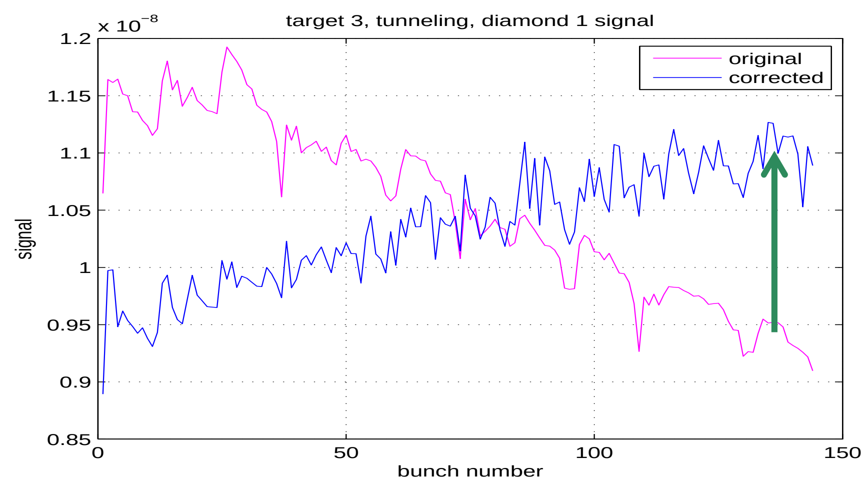

target 3, tunneling, diamond 1 corrected
voltage [V]
time [s]


target 3, tunneling, diamond 1 signal
× 10⁻⁹
signal
bunch number
original
corrected
-16.3%


target 3, tunneling, diamond 2 corrected
voltage [V]
time [s]
× 10⁻⁶

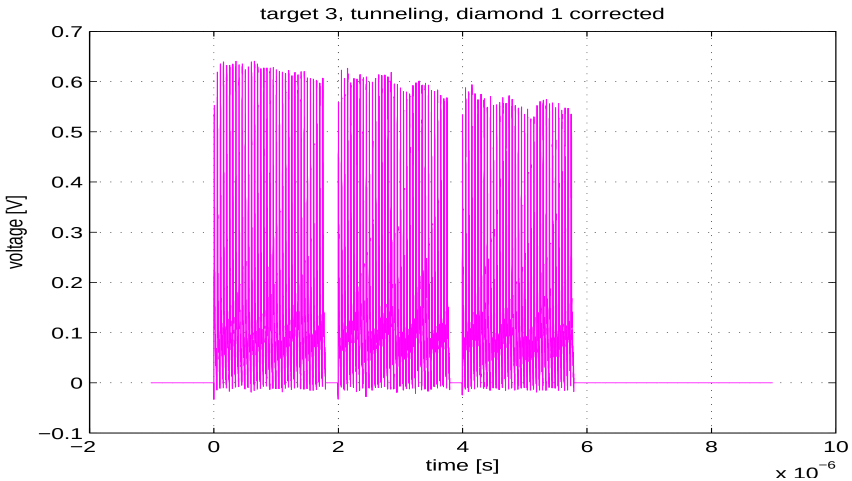

target 3, tunneling, diamond 2 signal
× 10⁻⁸
signal
bunch number
original
corrected

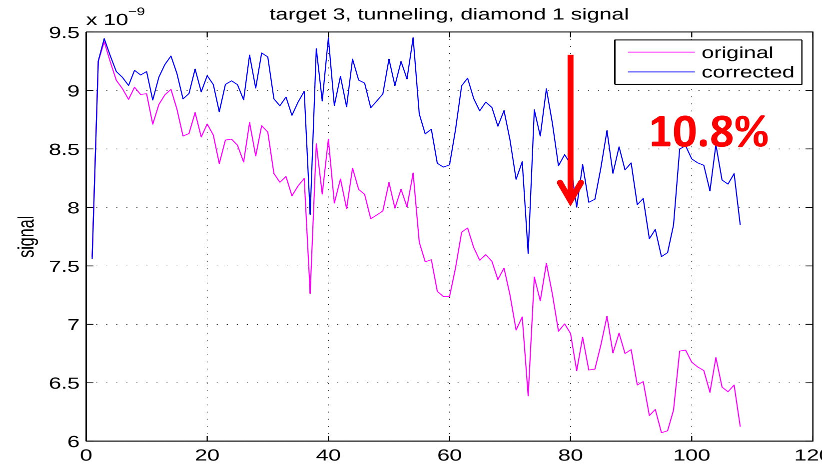

target 3, tunneling, diamond 3 corrected
voltage [V]
time [s]
× 10⁻⁶

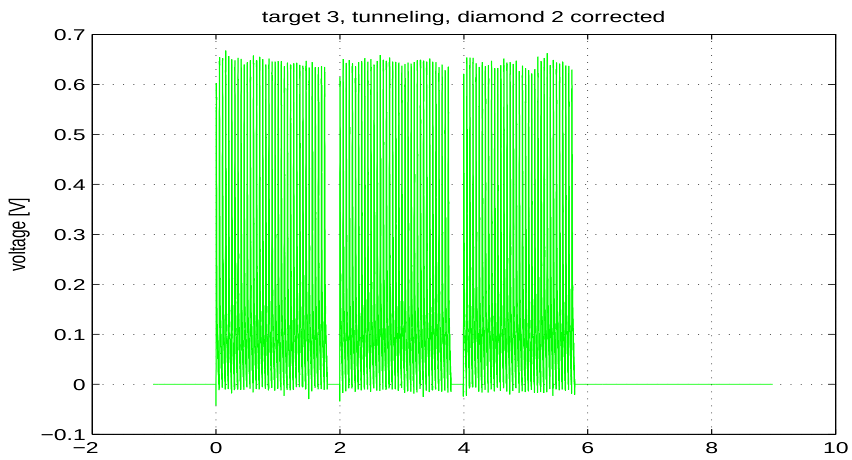

target 3, tunneling, diamond 1 signal
× 10⁻⁸
signal
bunch number
original
corrected

Corrected signals
target 2

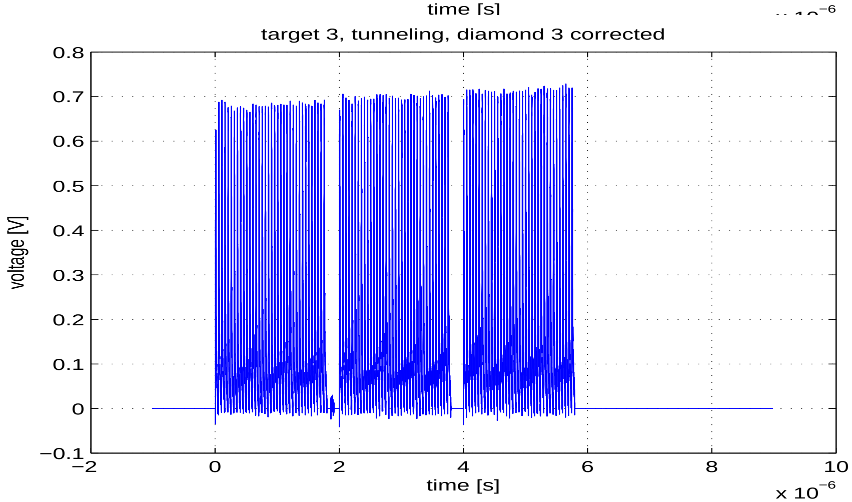
(108 bunches, 50ns, 0.2 mm sigma)


target 3, tunneling, diamond 1 corrected
voltage [V]
time [s]
x 10^-6


target 3, tunneling, diamond 1 signal
x 10^-9
signal
original
corrected
10.8%

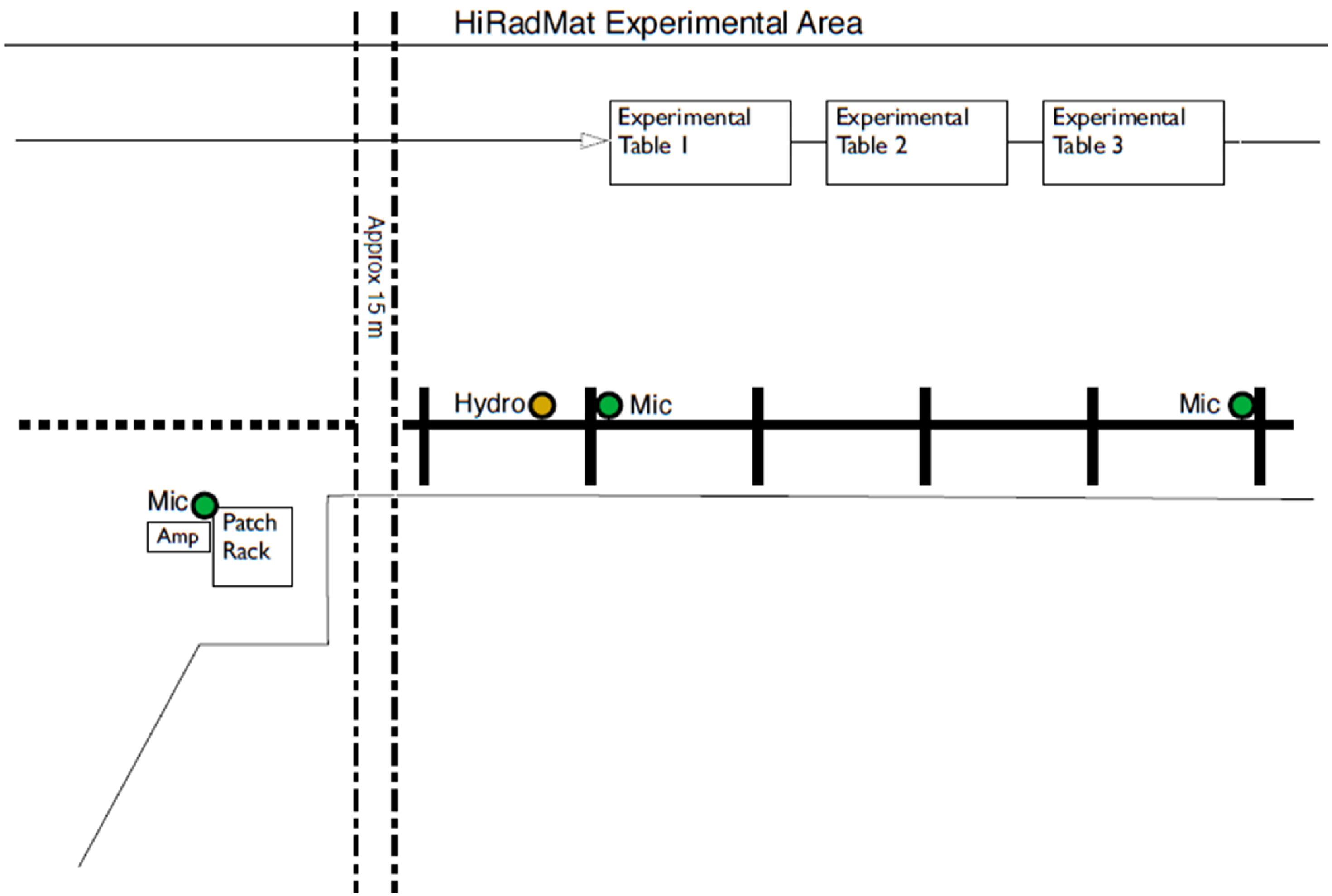

target 3, tunneling, diamond 2 corrected
voltage [V]
time [s]


target 3, tunneling, diamond 2 signal
x 10^-9
signal
original
corrected
bunch number

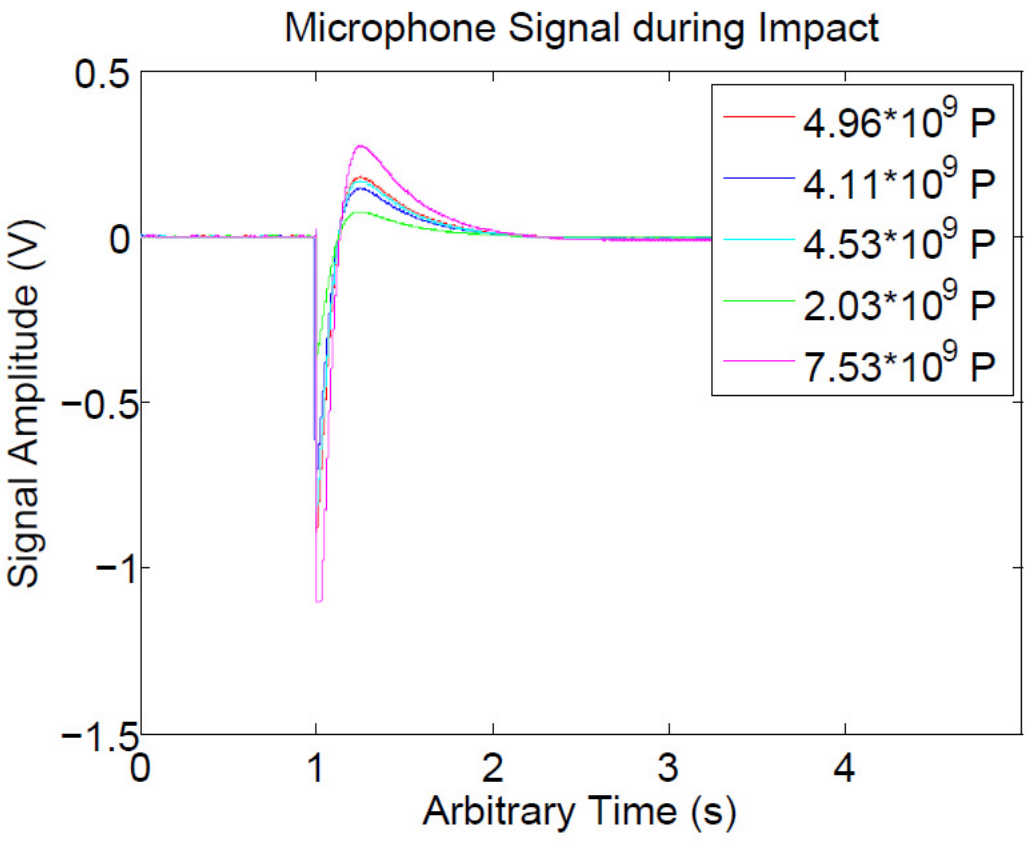

target 3, tunneling, diamond 3 corrected
voltage [V]
time [s]
x 10^-6


target 3, tunneling, diamond 1 signal
x 10^-8
signal
original
corrected
bunch number

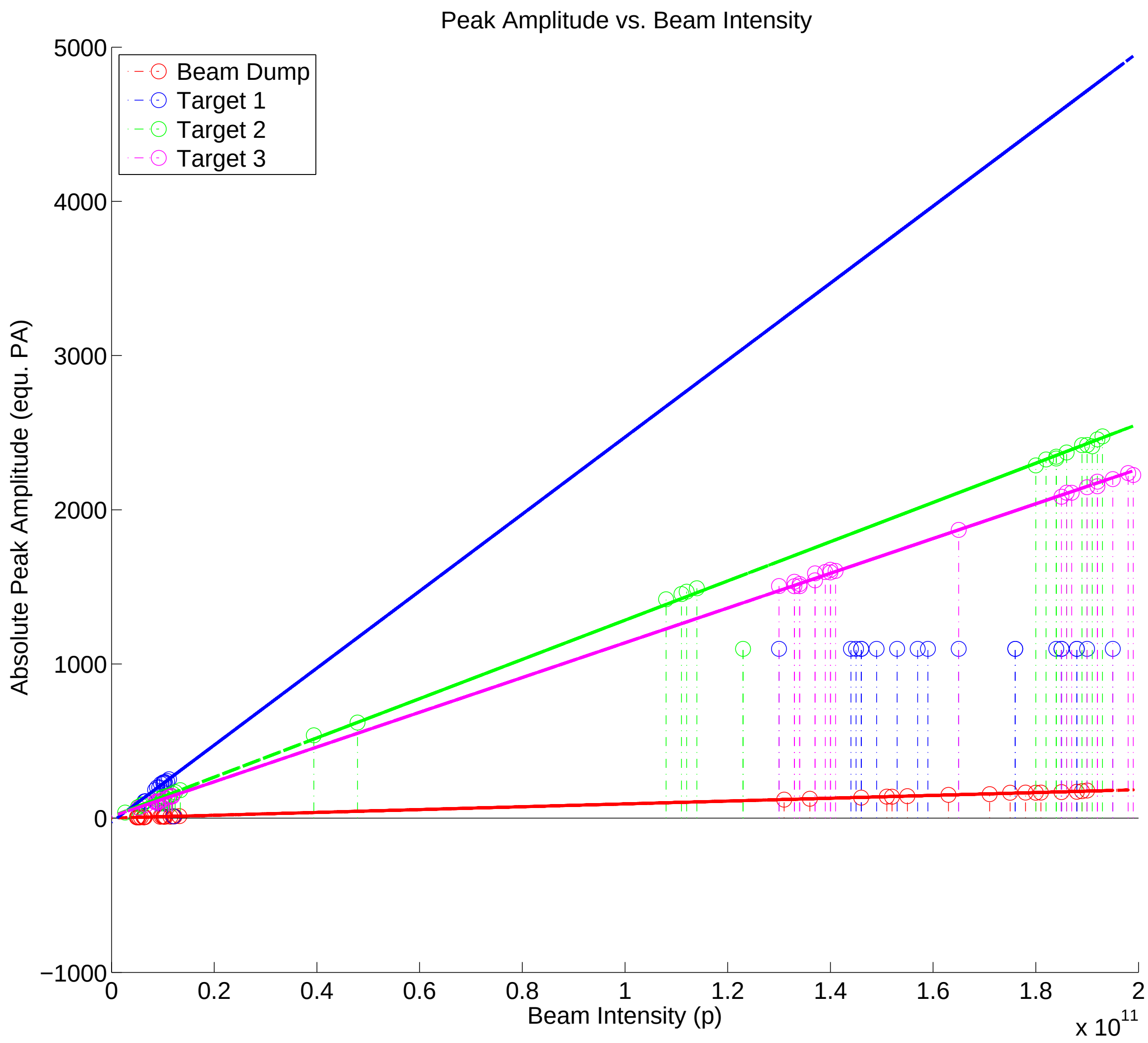
Microphones



Microphones



Microphones

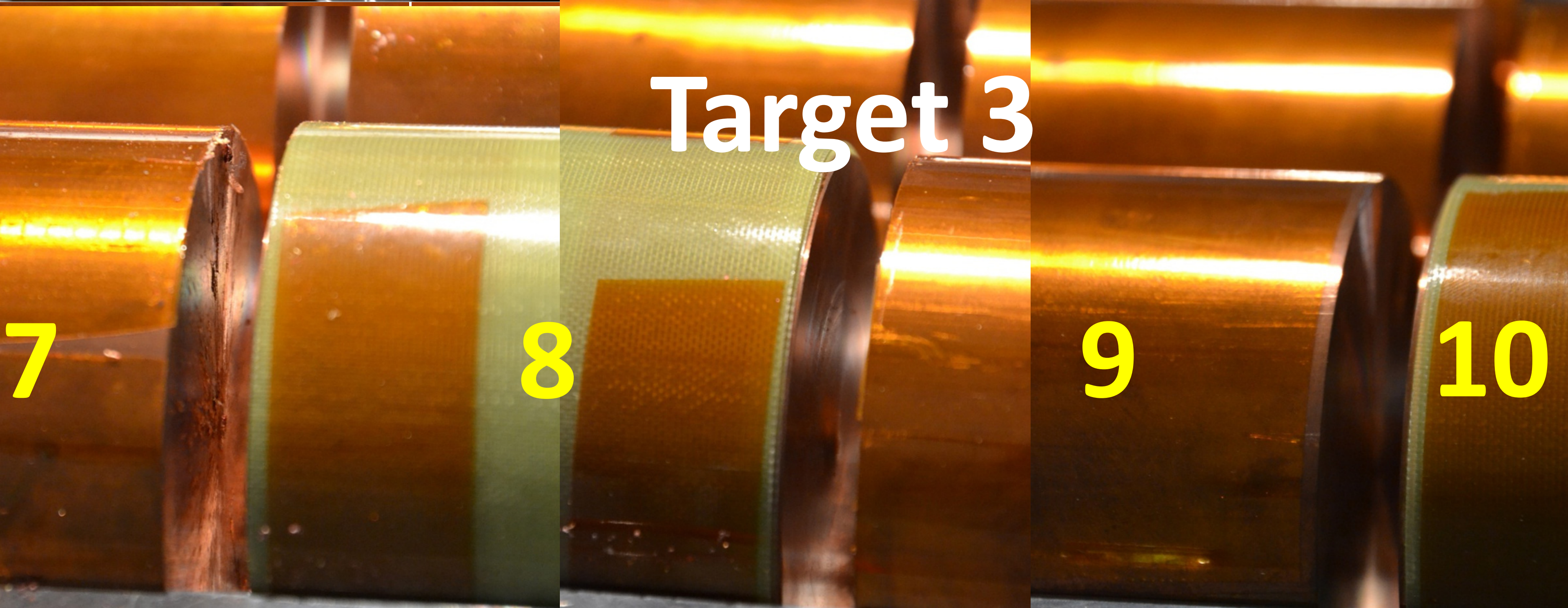


Microphones

Target 3
Single bunch 4.5E10 protons
Beam sound

Target 3
Full beam 144 bunches
1.5E11 protons/bunch
Beam sound

UPPER SIDE OF TARGET's BOX



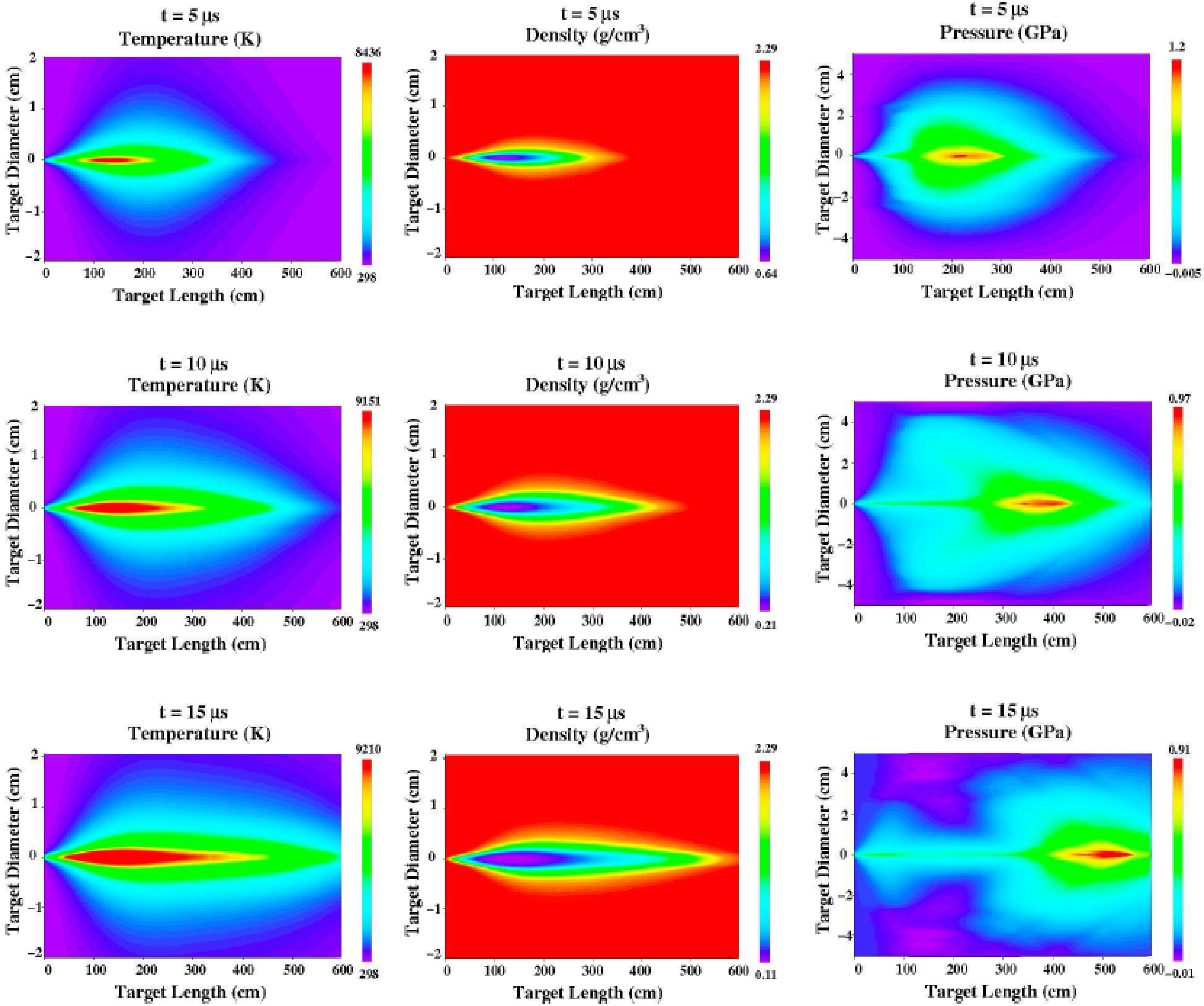
Simulations

LHC beam into Graphite:

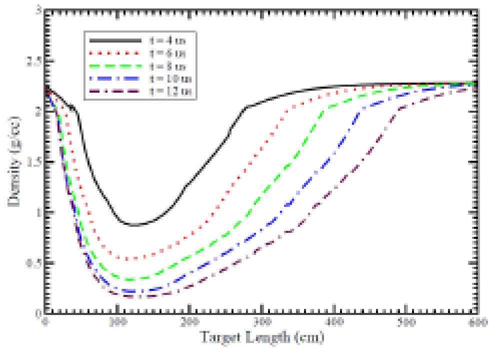
- **7 TeV**
- **2808 bunches 1.15E11 p+**
- **σ beam = 0.5 mm**
- **25 ns bunch to bunch space**
- **5 cm radius x 6 m length graphite target**
- **beam collinear with target's axis**
- **front face irradiation**

Real Scenario:

Wrong deflection angle at LHC extraction. Beam impacts the 6 m TCDQ carbon fiber collimator at point 6.

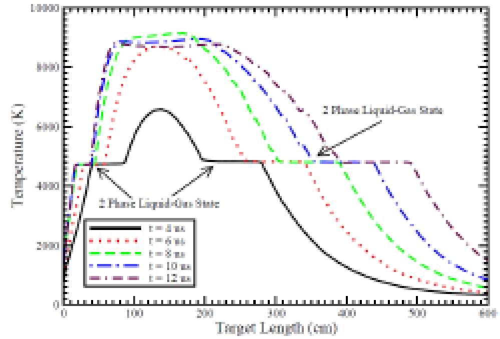

t = 5 μs
Temperature (K)
8436
298
t = 5 μs
Density (g/cm³)
2.29
0.64
t = 5 μs
Pressure (GPa)
1.2
−0.005
t = 10 μs
Temperature (K)
9151
298
t = 10 μs
Density (g/cm³)
2.29
0.21
t = 10 μs
Pressure (GPa)
0.97
−0.02
t = 15 μs
Temperature (K)
9210
298
t = 15 μs
Density (g/cm³)
2.29
0.11
t = 15 μs
Pressure (GPa)
0.91
−0.01
Target Diameter (cm)
Target Length (cm)

Simulations



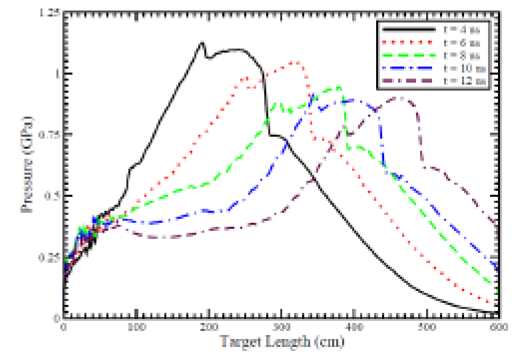
Density (g/cc)

Along beam axis



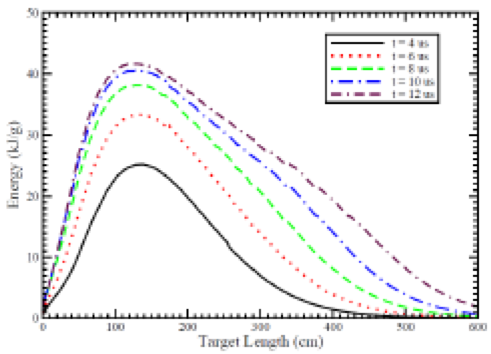
Temperature (K)

Along beam axis



Pressure (GPa)

Along beam axis



Spec. Energy (g/cc)

Along beam axis

The high energy density deposited by the beam vaporizes the material and also creates a pressure wave that transports material outwards in the radial direction further decreasing the density along the axis.

Following bunches will interact with the target further inside. The energy deposition region will move further inside.

Simulations show:

After **15us** the temperature reaches ~**9100 K** and pressure is **7 kbar** -> **W**arm **D**ense **M**atter (WDM)

The density depletion region moves at **~25 cm/us, after 89us** the beam will melt **21 m** of copper

TCDQ collimator **will not stop** the whole **LHC beam** however a part of the beam energy will be dissipated on the collimator and the remaining energy will be highly diluted.

Simulations need to be verified with an experiment

LHC beam type experiment is infeasible

For this reason, SPS beam type simulations were done. Using the same methodology and codes.

Simulations

SPS beam into Copper:

450 GeV

288 bunches 1.15E11 p+

σ beam = 0.5/0.2/0.1 mm

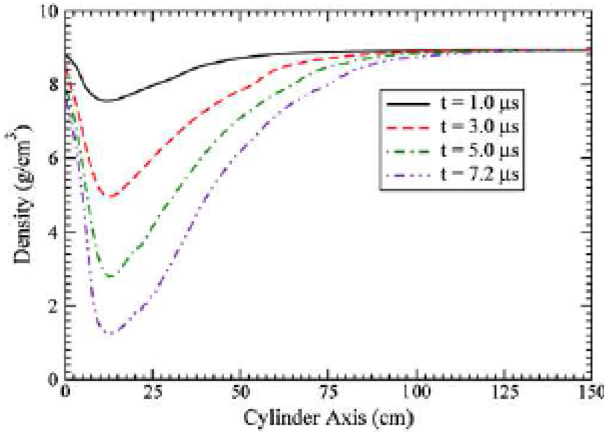
25 ns bunch to bunch space

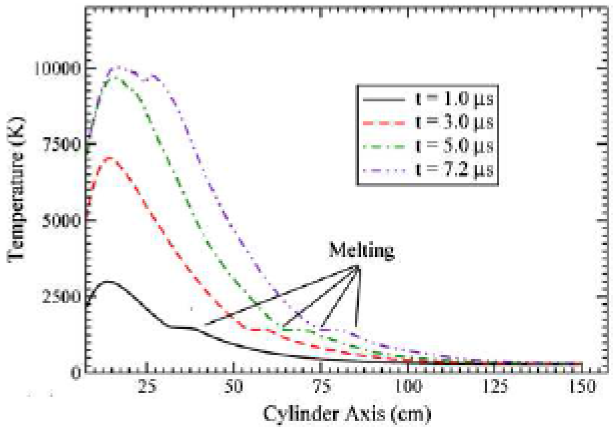
5 cm radius x 1.5 m length copper target

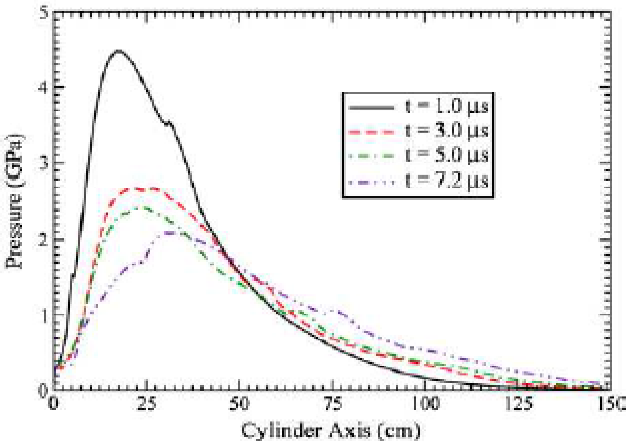
beam collinear with target's axis

front face irradiation

Simulations







Density (g/cc)
Along beam axis

Temperature (K)
Along beam axis

Pressure (GPa)
Along beam axis

Tunneling effect also **present** with a velocity of **5cm/us**

Peak temperature **10.000 K**

Peak pressure **~4 GPa**

Simulations

Main Objectives:

Reproduce the hydrodynamic tunneling observed

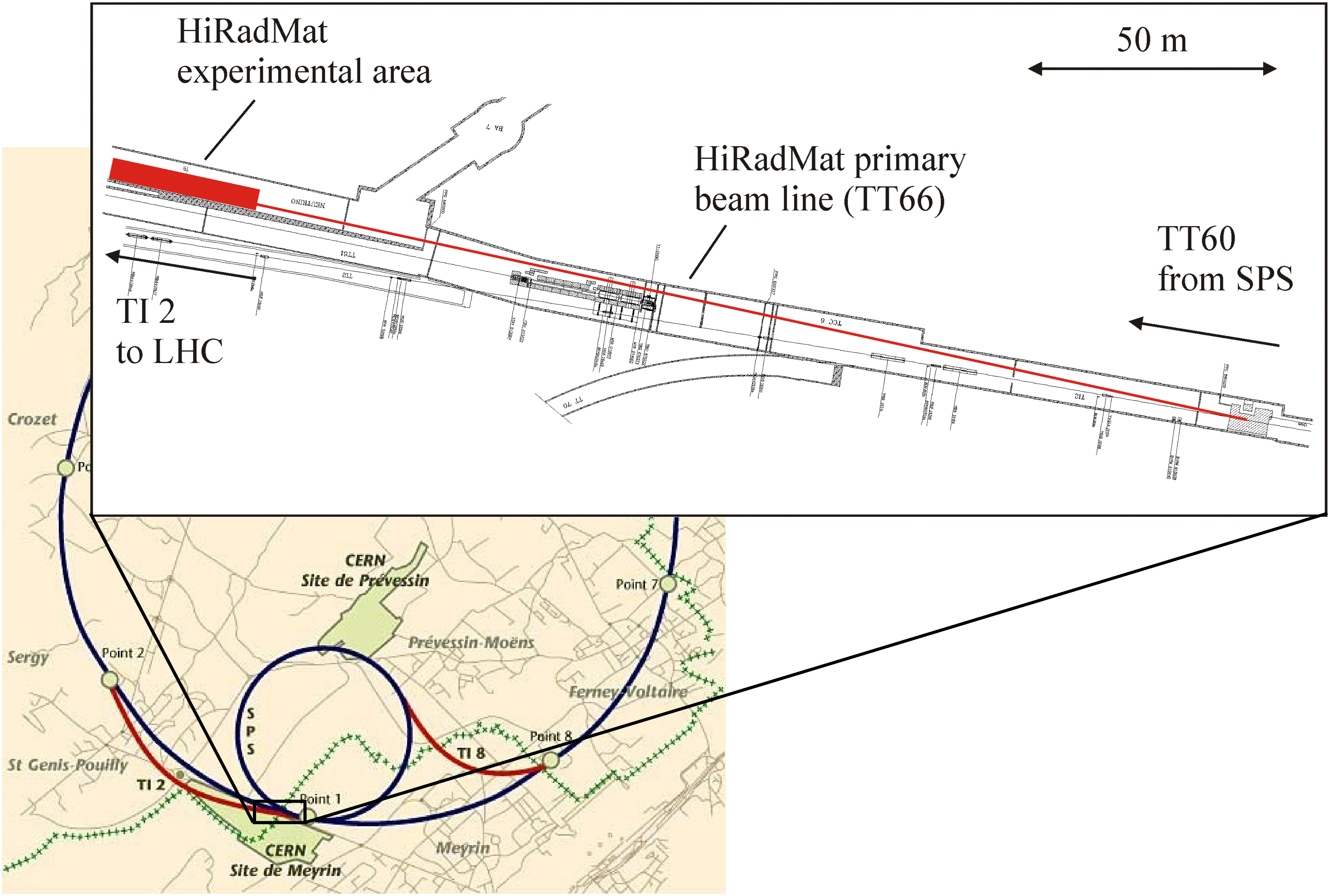
Measure hydrodynamic tunneling (opening target)

Validate SPS simulations -> gain confidence with LHC simulations

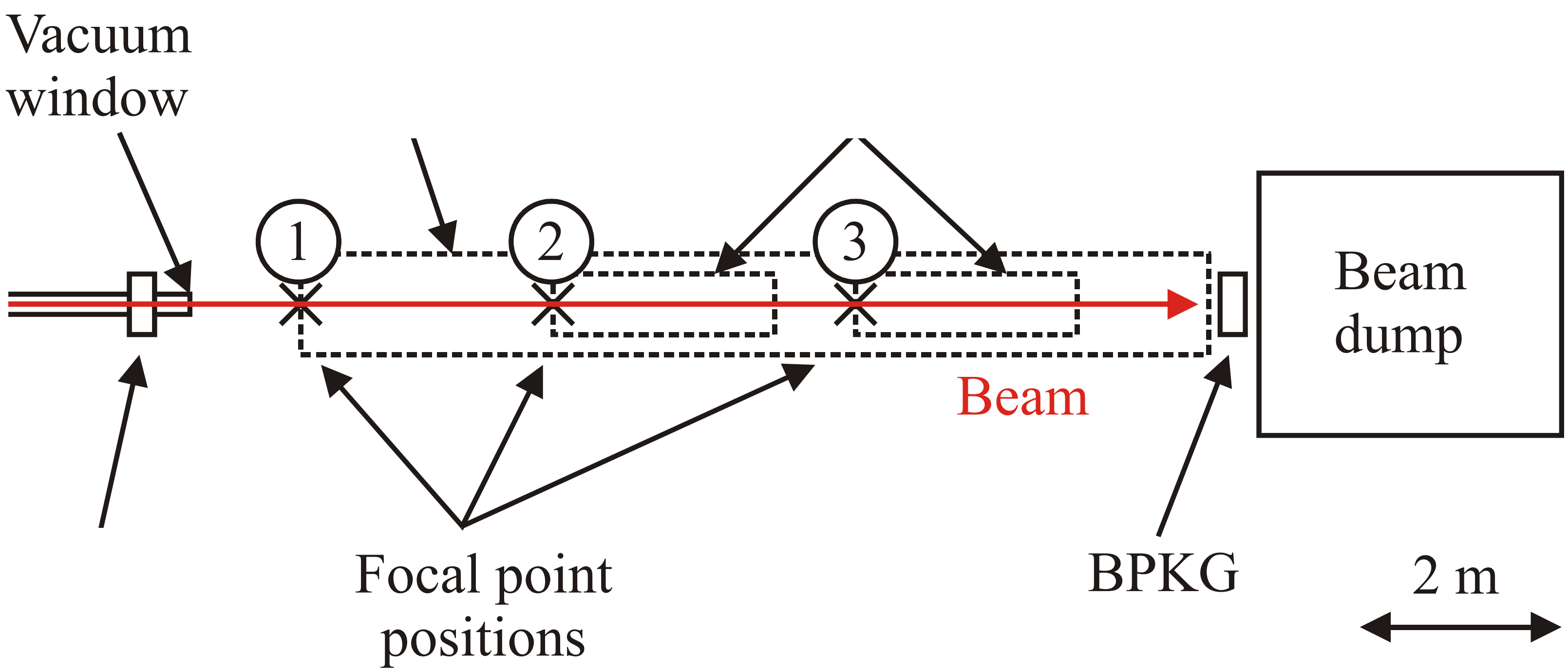
Other Objectives:

Capture hydrodynamic tunneling evolution with detectors

Location of HiRadMat



Layout of Experimental Area



- Flexible optics to provide beam radii of σ = 0.1 to 2.0 mm at the focal points.
- Focal point longitudinal location continuously variable between positions 1 and 3.
- Predefined optics for 3 focal points and 6 beam sizes.

HiRadMat

Design

3 copper targets , 4 cm radius 150 cm length

each target is composed of 15 blocks of 10 cm

1 cm block to block separation

aluminum box enclosures targets (except front and rear faces)

box can be open in two parts, exposing the targets

front and rear faces are covered with an aluminum cylinder with a 1 cm hole (d)

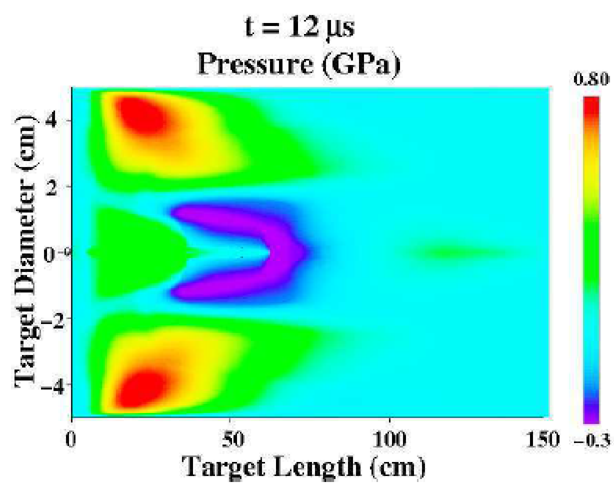
Constrains

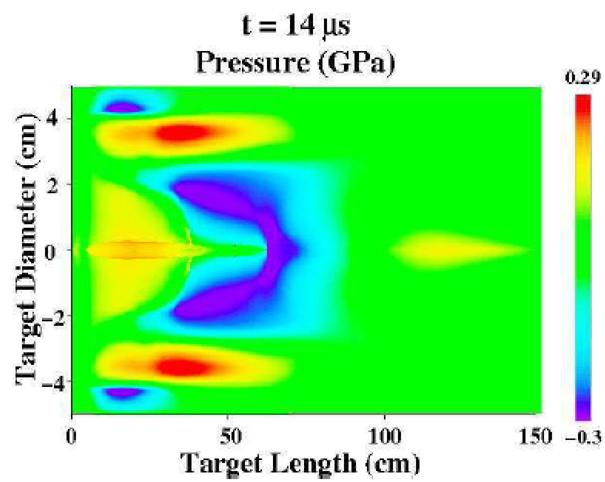
Avoid damage to surroundings. Copper blocks may not explode or crack.

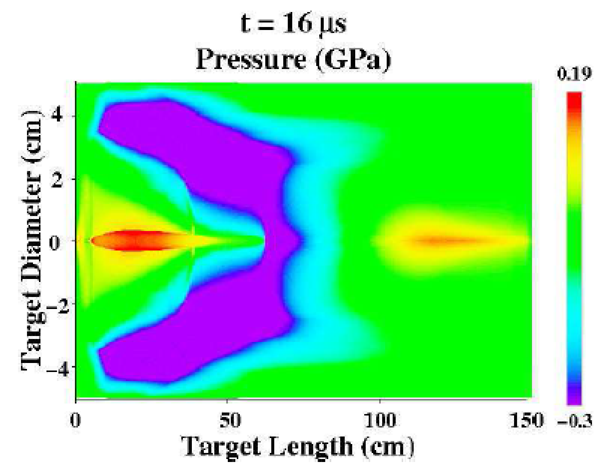
Avoid contamination. Aluminum box and front cylinders may confine all ejected material.

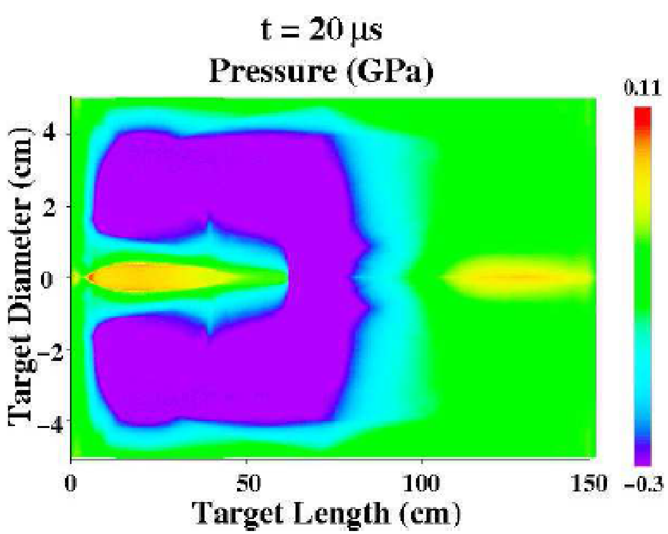
Allow visual inspection. Experiment needs to be opened after irradiation and cool-down time.

SPS simulation (0.5mm)

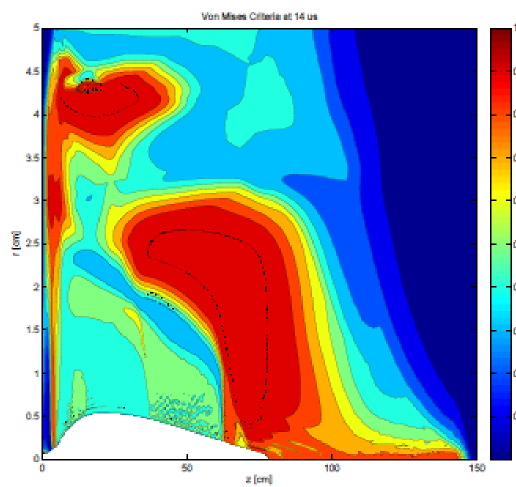


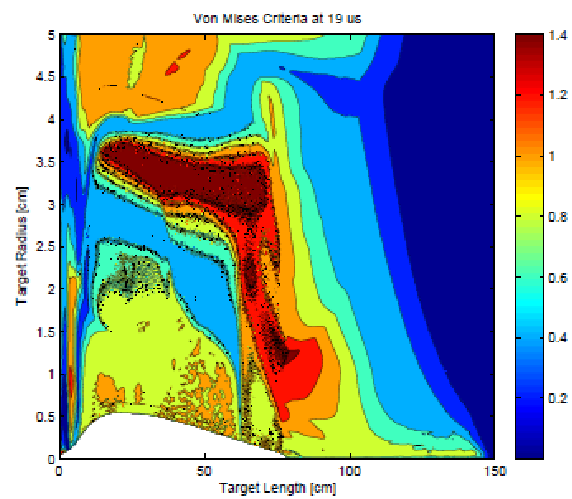






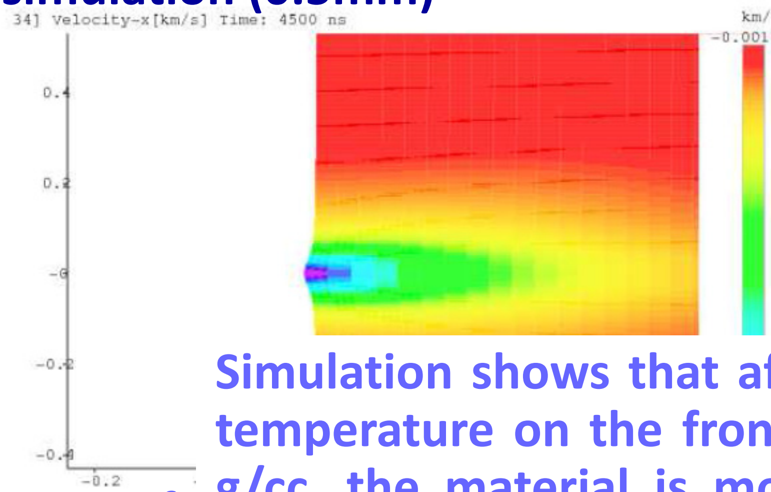
Lateral face remains in elastic regime

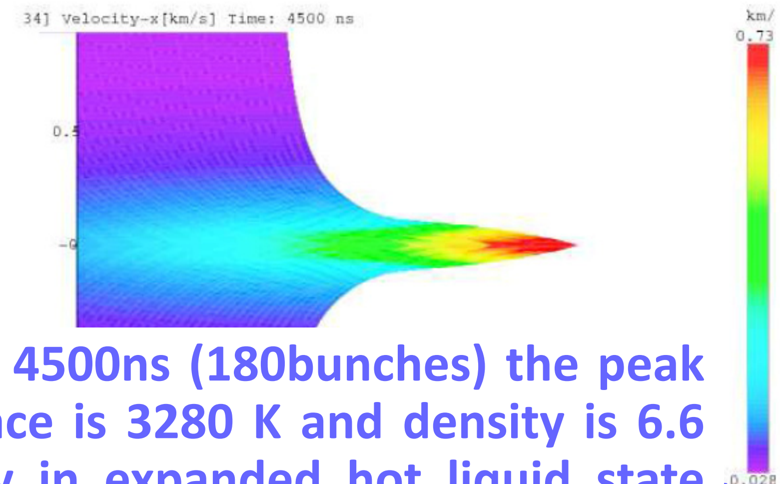




Avoid contamination

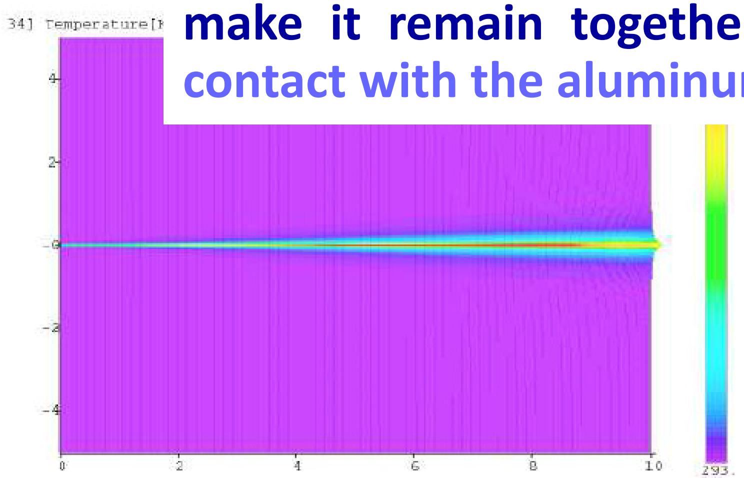
SPS simulation (0.5mm)



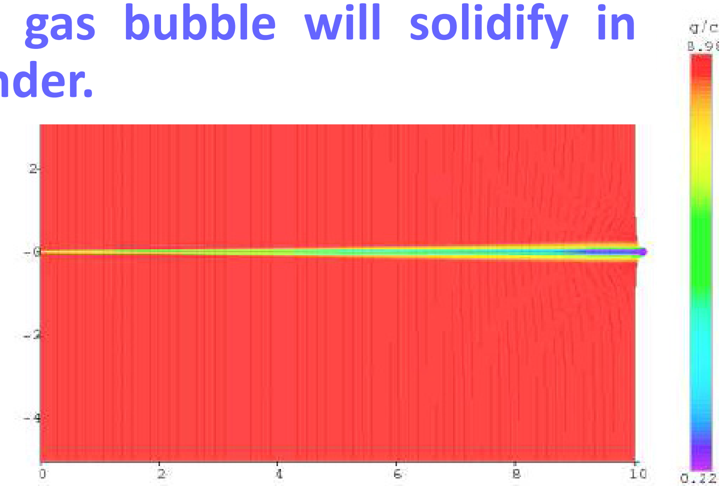


Surfa ... k

Simulation shows that after 4500ns (180bunches) the peak temperature on the front face is 3280 K and density is 6.6 g/cc, the material is mostly in expanded hot liquid state with little gas bubbles. **The cohesion forces of the liquid will make it remain together.** Any gas bubble will solidify in contact with the aluminum cylinder.



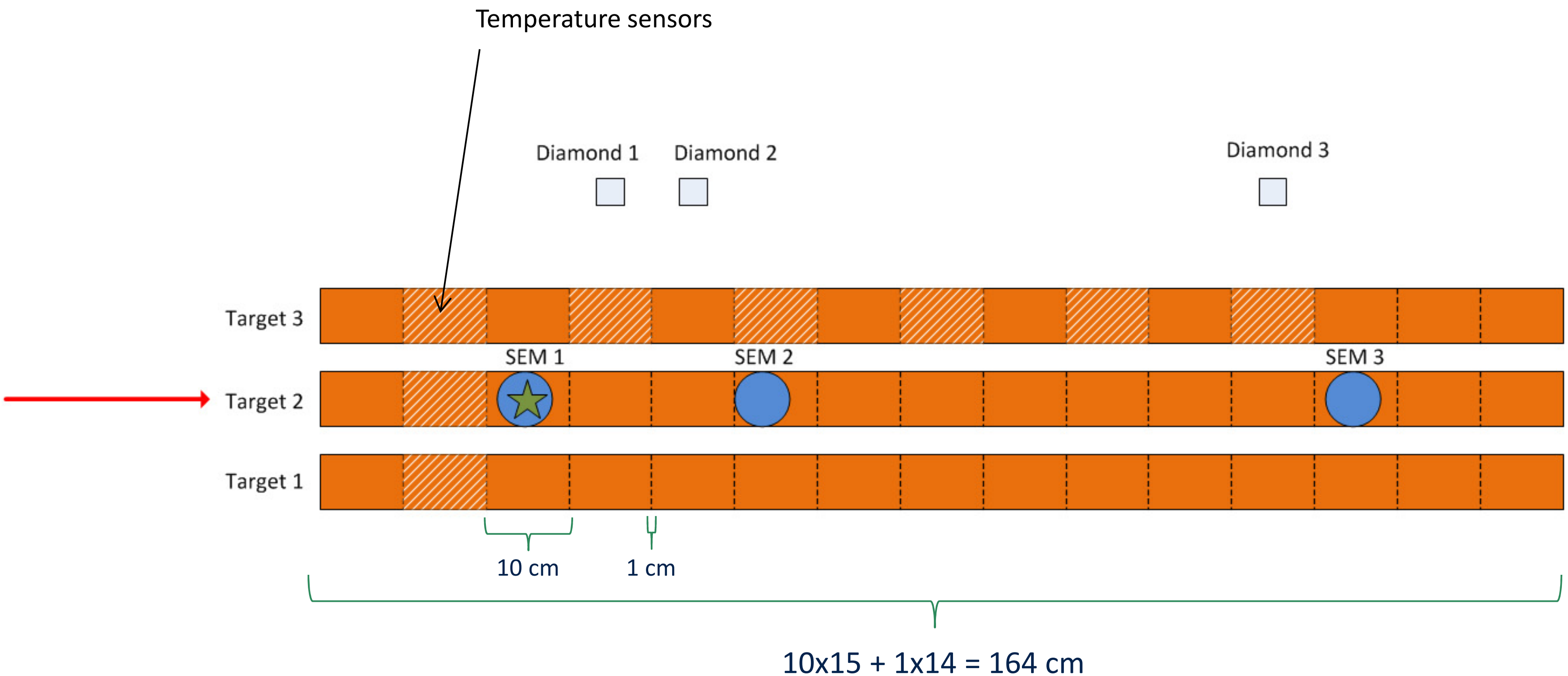
Temperature (K)



Density (g/cc)

Detectors:

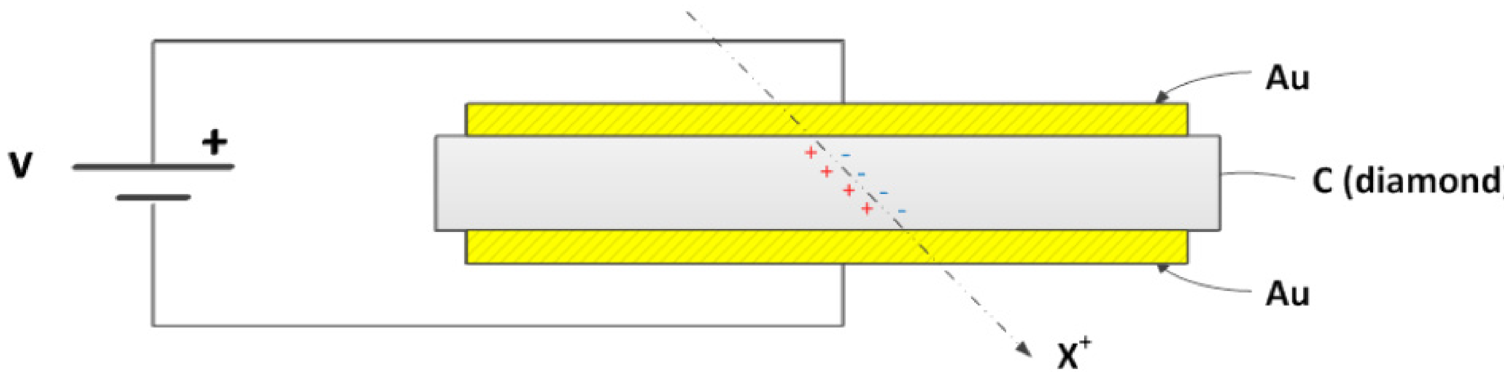
- **3 pCVD diamond detectors**
- **3 LHC Secondary Electron Emission Monitors**
- **8 PT100 temperature sensors**
- **4 strain gauges**

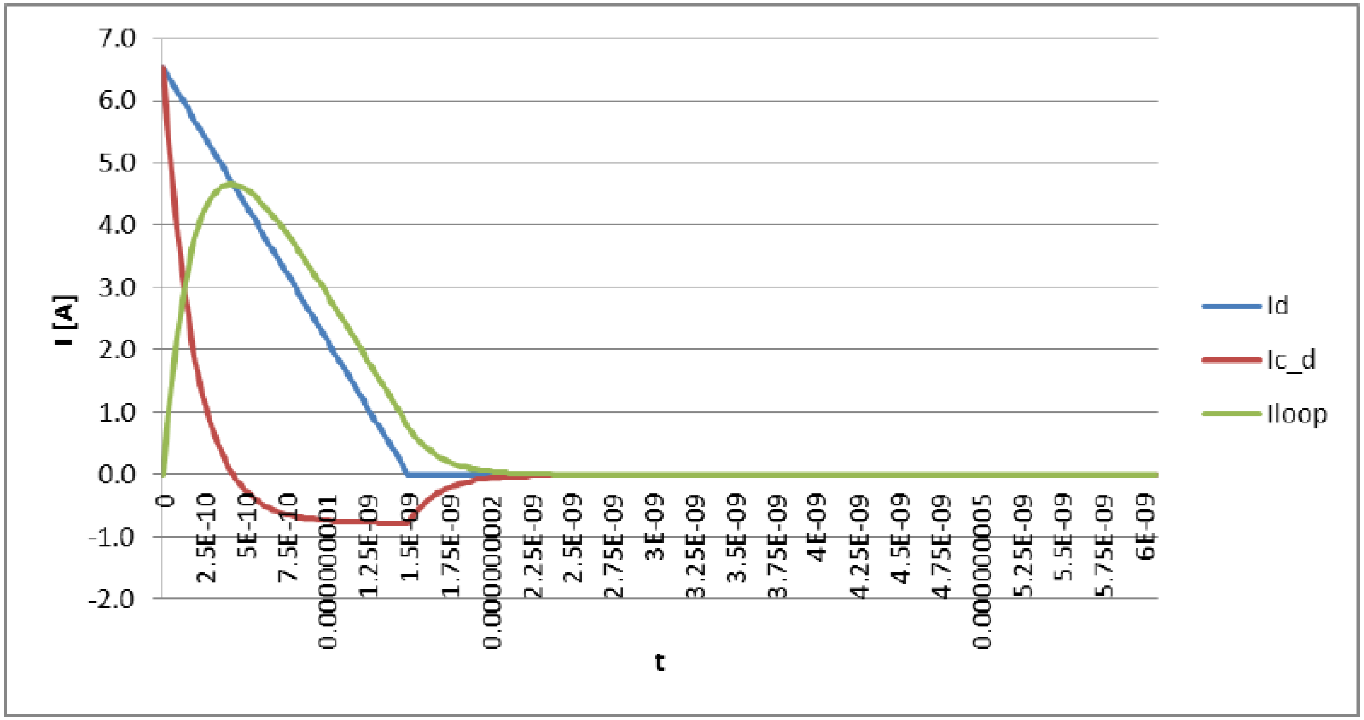


Avoid damage to surroundings. Copper blocks may not explode or crack.

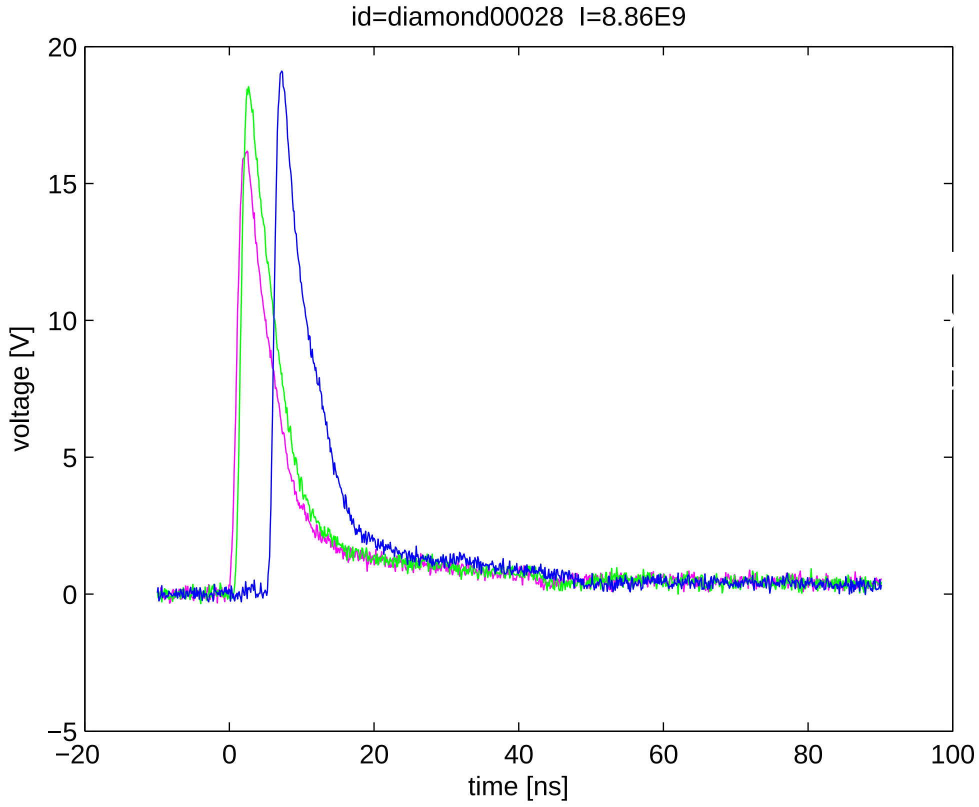
Avoid contamination. Aluminum box and front cylinders may confine all ejected material.

Allow visual inspection. Experiment needs to be opened after irradiation and cool-down time.


V
+
Au
C (diamond)
Au
X+

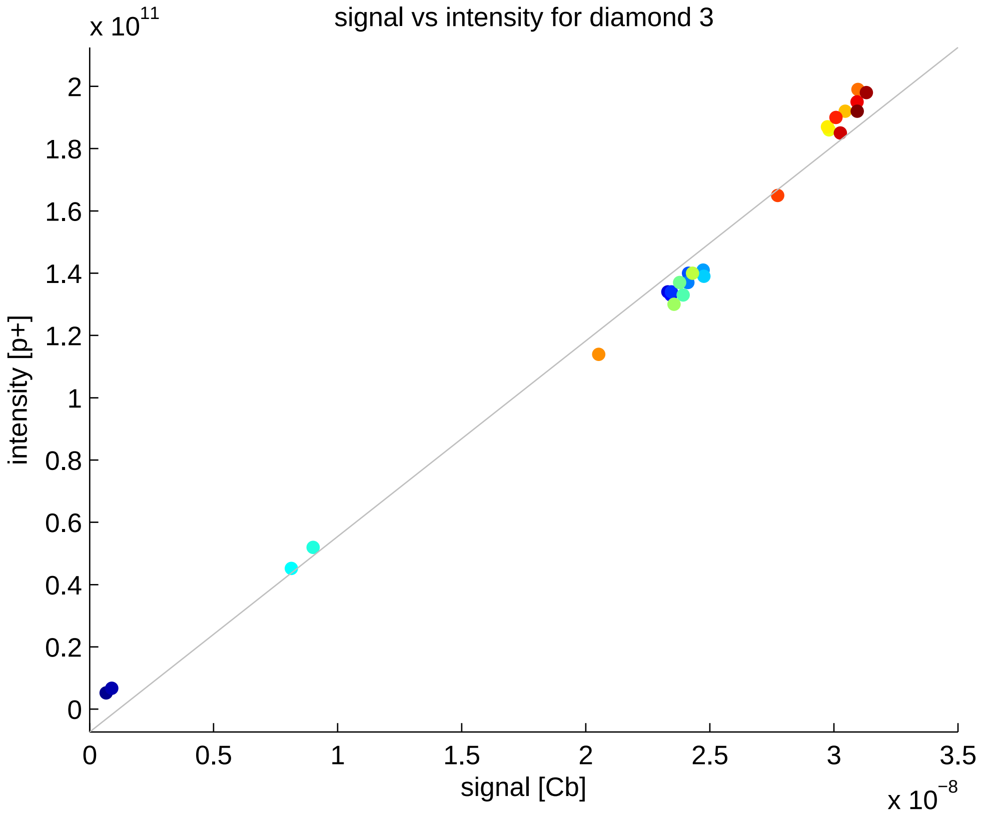

7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
-1.0
-2.0
I [A]
0
2.5E-10
5E-10
7.5E-10
0.000000001
1.25E-09
1.5E-09
1.75E-09
0.000000002
2.25E-09
2.5E-09
2.75E-09
3E-09
3.25E-09
3.5E-09
3.75E-09
4E-09
4.25E-09
4.5E-09
4.75E-09
0.000000005
5.25E-09
5.5E-09
5.75E-09
6E-09
t
Id
Ic_d
Iloop

Diamond detector signal

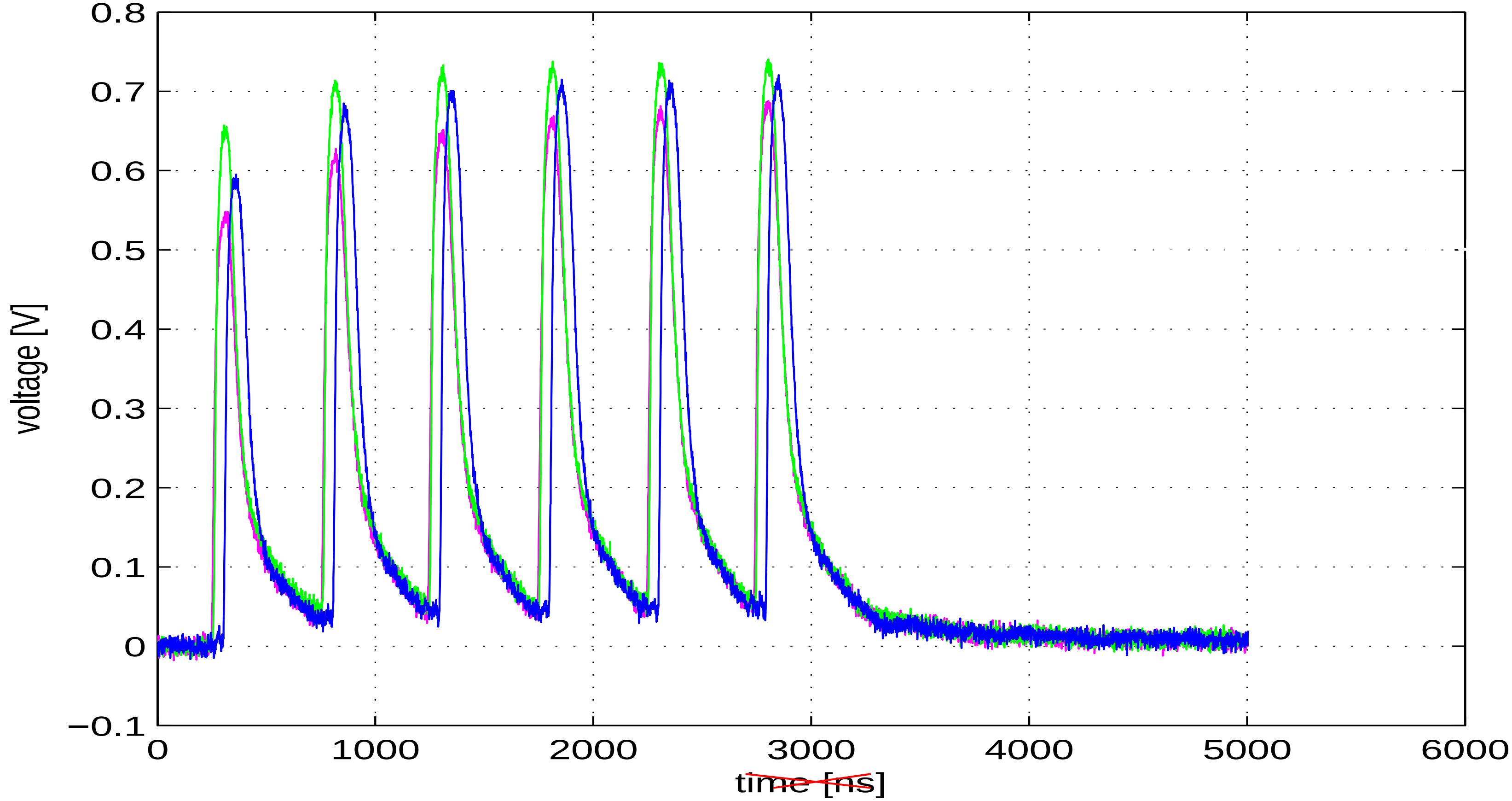


Diamond detector linearity

- Diamond detectors have a good linearity for a wide intensity range.
- Tested different bias voltage across the detectors and its influence on the signal.

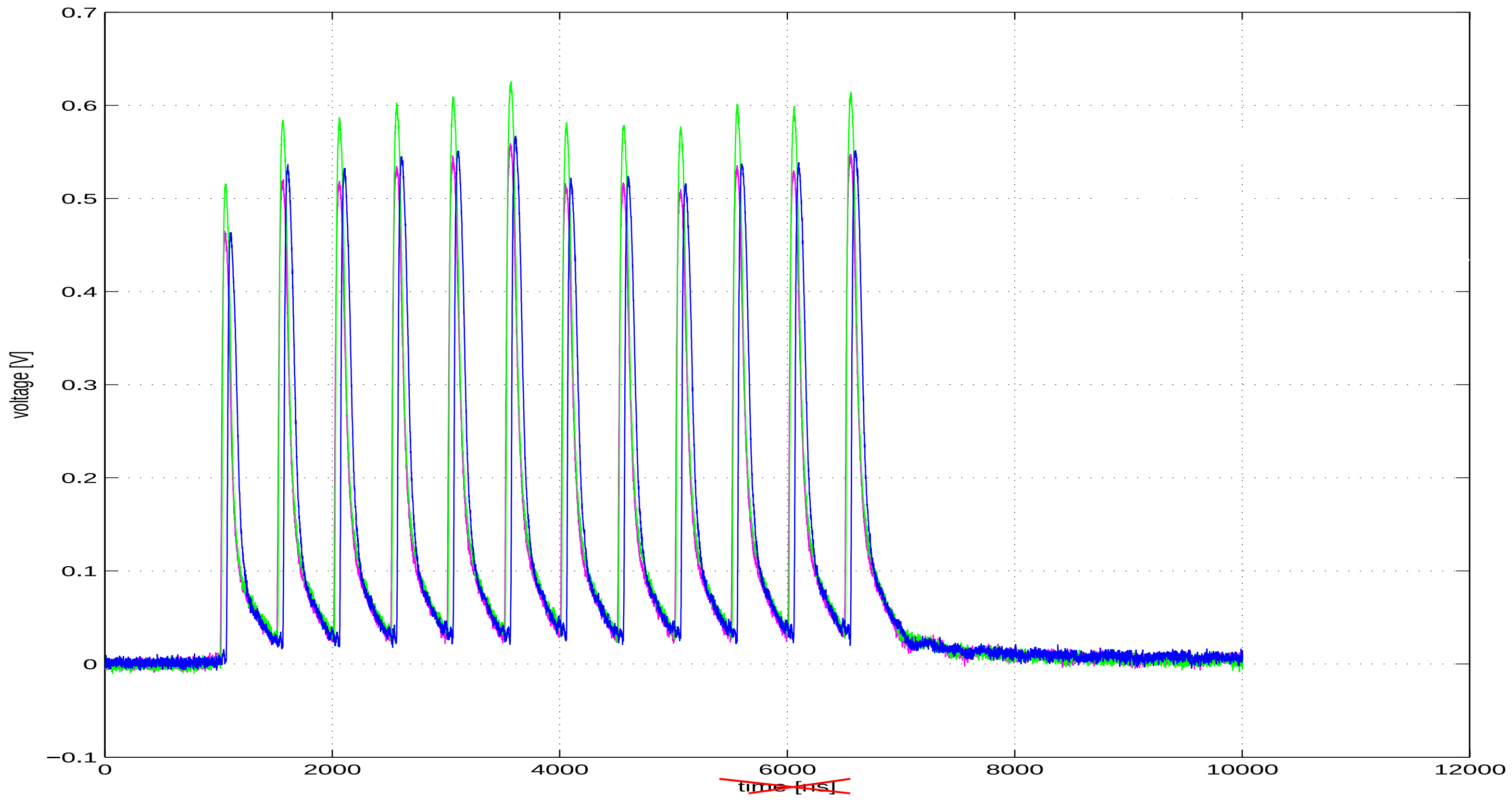


Multi-bunch



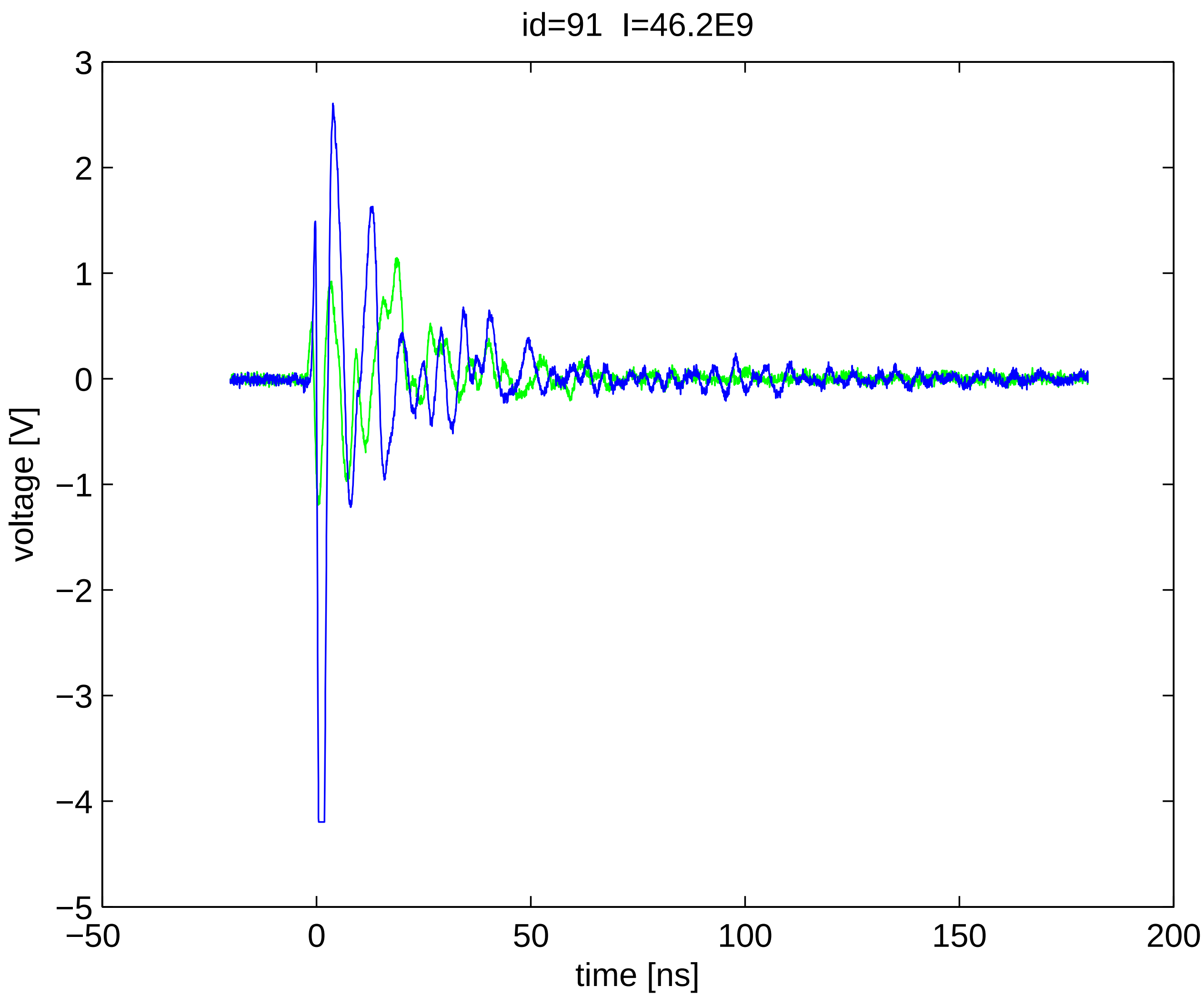
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
−0.1
voltage [V]
0
1000
2000
3000
4000
5000
6000
time [~~ns~~]

Multi-bunch

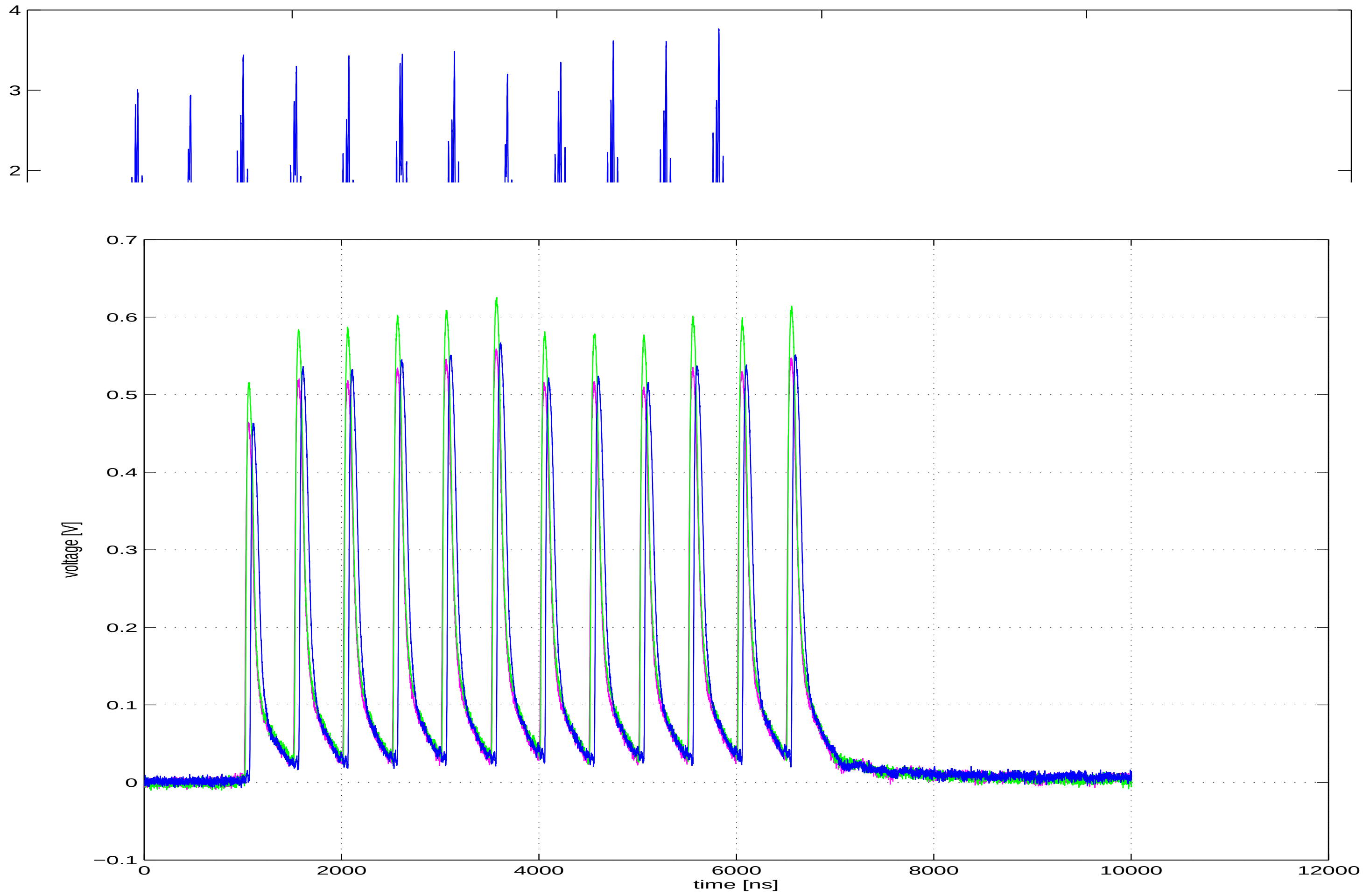


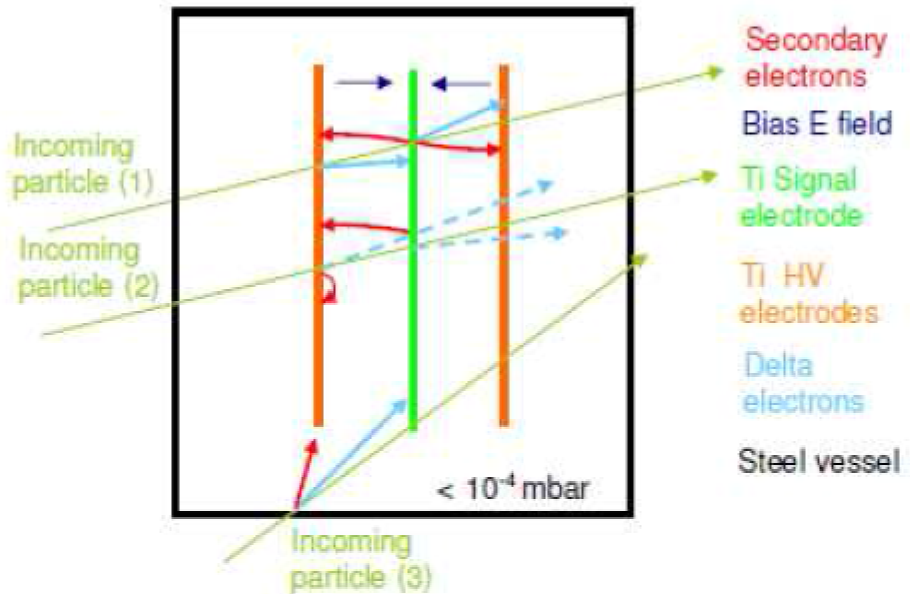
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
−0.1
voltage [V]
0
2000
4000
6000
8000
10000
12000
~~time [ns]~~

SEM detectors



SEM detectors




Incoming
particle (1)
Incoming
particle (2)
Incoming
particle (3)
< 10⁻⁴ mbar
Secondary
electrons
Bias E field
Ti Signal
electrode
Ti HV
electrodes
Delta
electrons
Steel vessel

Allow inspection

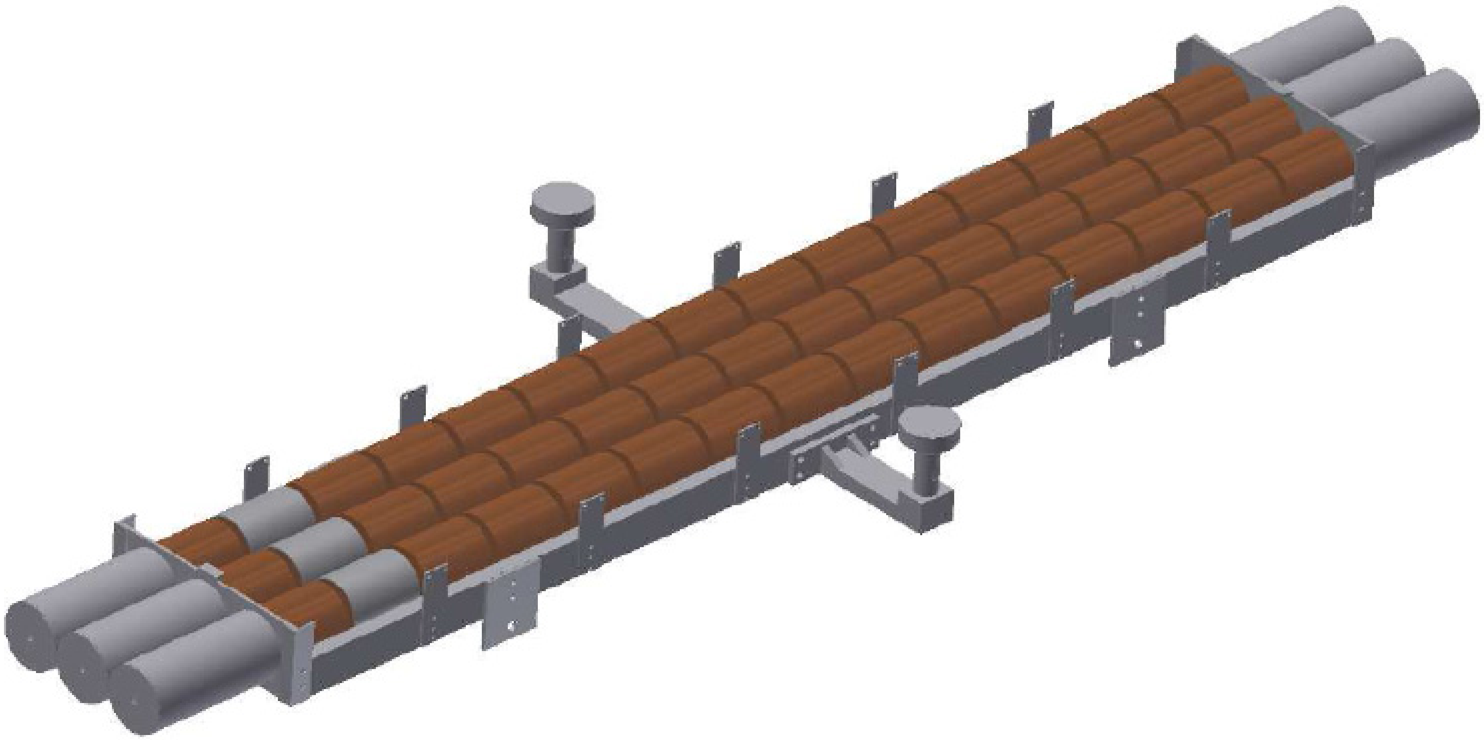
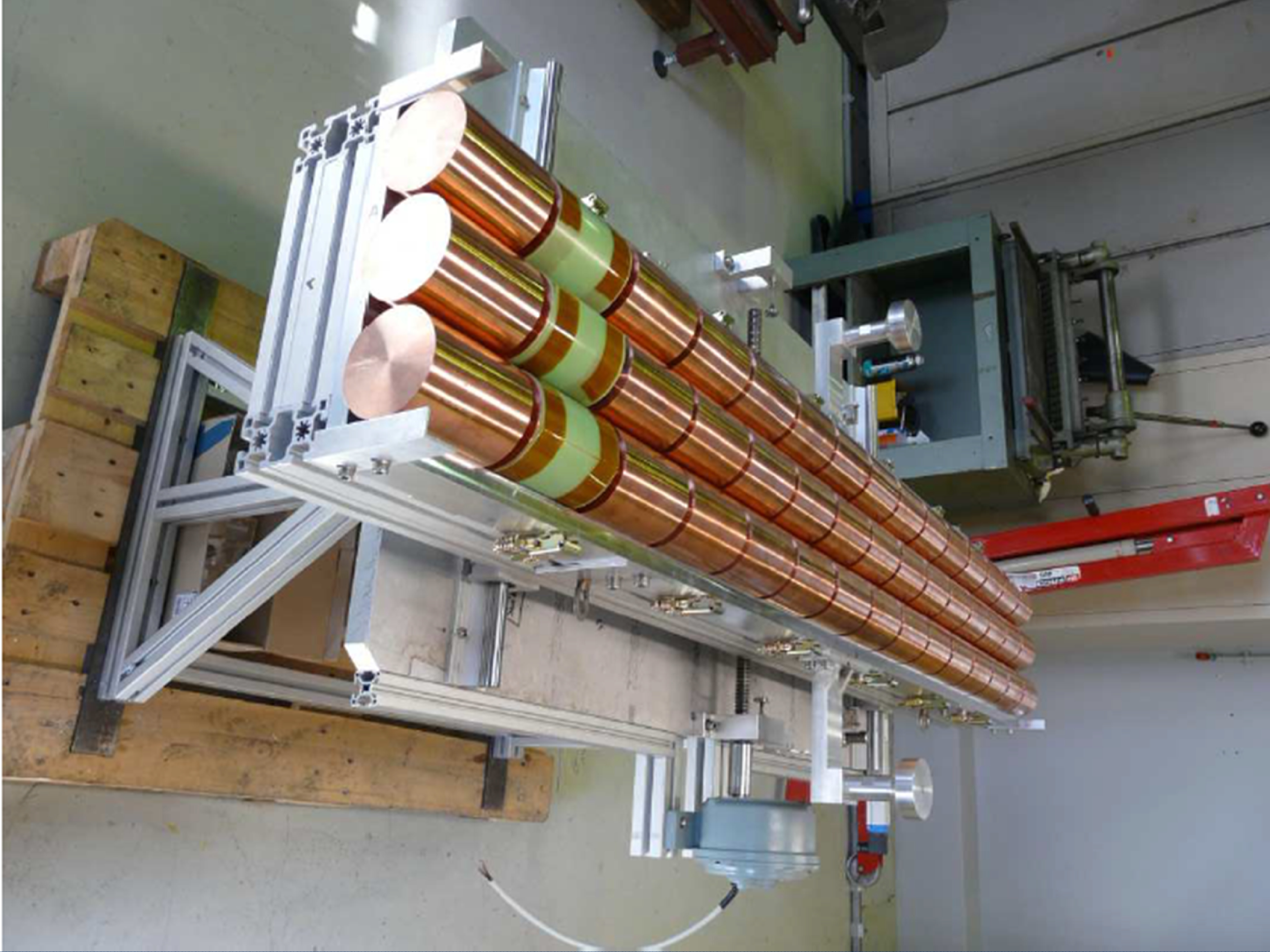


Figure 8.11: Target design



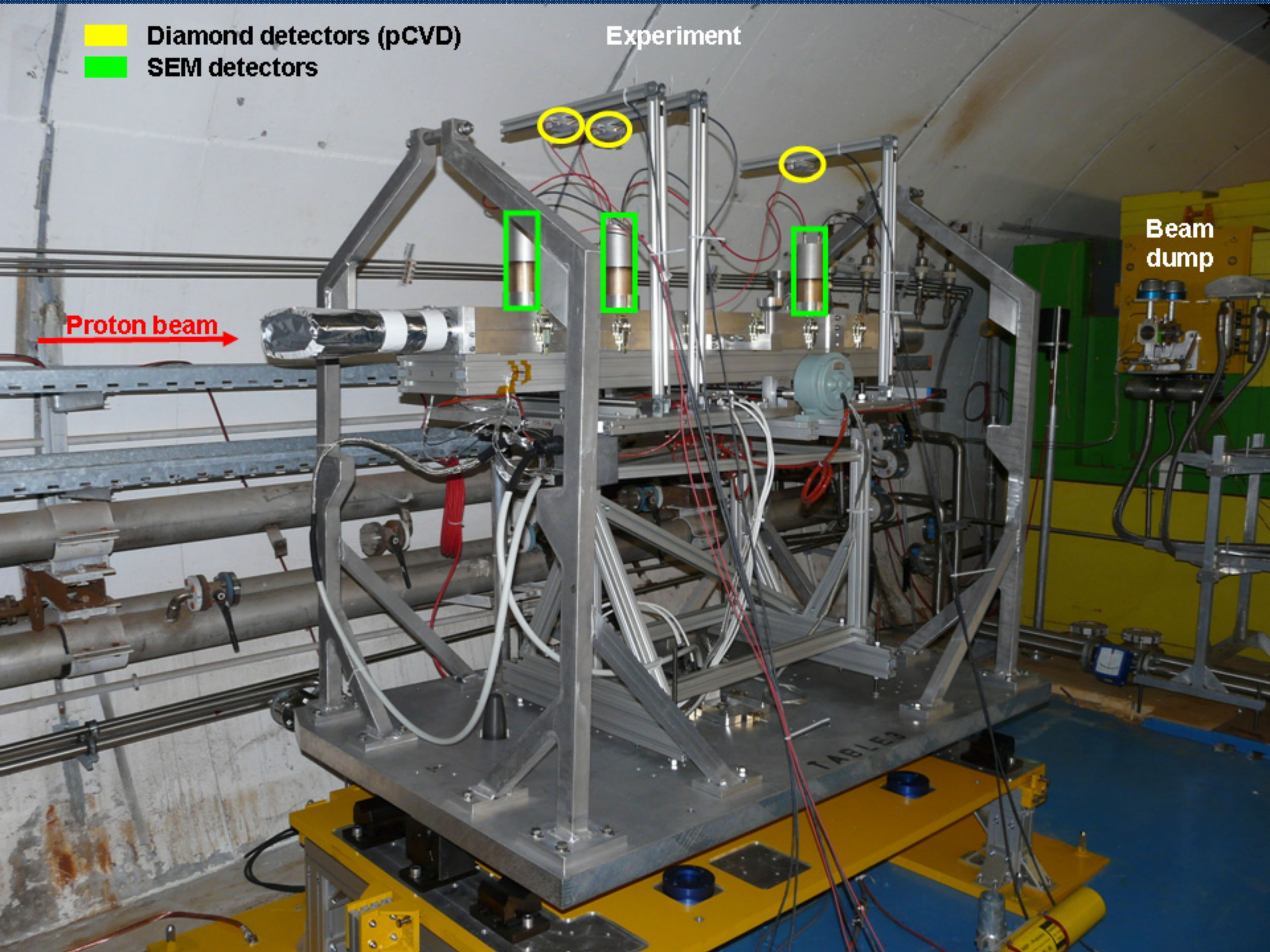
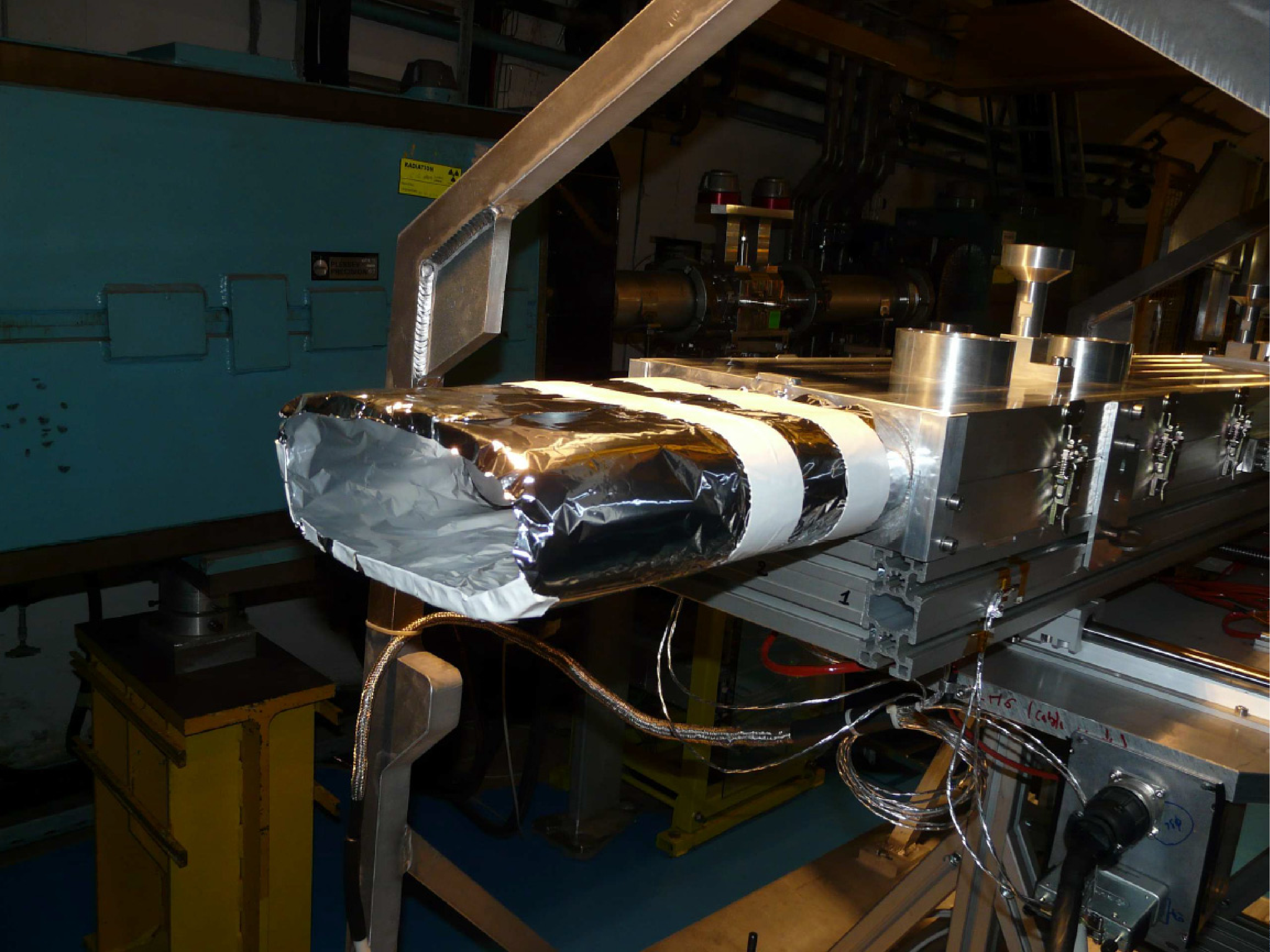

Diamond detectors (pCVD)
SEM detectors
Experiment
Proton beam
Beam
dump


TABLE3
500KG


RADIATION
1