Hydrodynamic Tunneling and Machine Protection Problem in Future Circular Collider

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Energy Comparison for FCC

Parameters	LHC	FCC
Proton Energy	7 TeV	50 TeV
Bunch Intensity	$1.15x10^{11}$	10^{11}
Bunches / Beam	2808	10600
Bunch Length	0.5 ns	0.5 ns
Bunch Separation	25 ns	25 ns
Beam Duration	89 μs	265 μs
Focal Spot σ	0.2 mm	0.2 mm
Energy / Bunch	128.8 kJ	800 kJ
Energy / beam	362 MJ	8.5 GJ
Tunnel	28 km	100 km

Equivalent to: A 380 (560 t) at speed of 850 km/h

- **An accidental release of even a small fraction of the beam energy can cause considerable damage to the equipment.**
- **A very serious scenario could be the loss of the entire beam at a single point.**
- **Chances of happening of such an accident are remote.**
- **The consequences of such an accident needs to be estimated. The risk must remain acceptable. Depending on the consequences the probability for such failure has to be adequate to keep the risk acceptable.**
- **For this purpose we carried out numerical simulations of the full impact of the LHC beam and the FCC beam with solid targets.**

What is Hydrodynamic Tunneling?

- **In case of a long bunched beam, energy deposited by a certain number of bunches [few tens in case of LHC and a few in case of FCC] launches an outgoing radial shock wave that depletes the density along and around the axis.**
- **Protons that are delivered in subsequent bunches together with their hadronic shower penetrate deeper into the target. This is called hydrodynamic tunneling of the ultra-relativistic protons**
- **Continuation of this process leads to <u>very substantial range lengthening</u> of the protons and their hadronic shower.**

Simulations Strategy

The simulations are carried out using the energy deposition code FLUKA and a 2D hydrodynamic code BIG2, iteratively.

- **First, the FLUKA code is runs to calculate the energy deposition distribution considering solid target density.**
- **Second, This energy deposition data is used as energy input to BIG2 and thermodynamic and the hydrodynamic response of the material is simulated.**
- **The BIG2 code is stopped when the density along the target axis is reduced by 15 % due to the outgoing radial shock wave.**
- **The modified target density distribution is then used in FLUKA to calculate new energy deposition table that is then used in BUG2. The process is continued till the end.**
- **Iteration step is determined by the beam parameters**

FLUKA: is a fully integrated particle physics and multi-purpose Monte Carlo simulation package, capable of simulating all components of the particle cascades in matter from as low as a few MeV/u up to 10000 TeV/u.

More details about the applied models and their performances, as well as a vast amount of benchmarking can be found in

[*Fasso A et al 2005 FLUKA: a multi-particle transport code CERN-2005-10 , INFN/TC-05/11, SLAC-R-773*]

BIG2 Computer Code

- Two-dimensional hydrodynamic code based on an ALE scheme, but can also be run in a fully Lagrangian as well as fully Eulerian mode.
- It can handle simple and very complicated geometries and can deal with simple as well as multi-layered targets. Sophisticated, very versatile and stable mesh.
- It includes heat conduction.
- It includes ion beam energy deposition (SRIM for heavy ions and FLUKA for protons from LHC or SPS).
- It includes elastic and plastic effects using ideal plasticity model basically Hook's law complemented with von Mises yield criterien. (important for solid targets).
- Different phases of matter are treated using a sophisticated semi-empirical EOS model.

Beam-Target Coupling Parameters

[Solid Density]

	Energy (TeV)	E_P(GeV/g/p) [FLUKA]	I_{bunch}	E_S(kJ/g) [BIG2]	T(K)
SPS	0.44	3.6	1.50×10^{11}	0.08	515
LHC	7	134	1.15×10^{11}	2.4	5019
FCC	40	920	10^{11}	14.4	27440

FCC Beam on Solid Copper Cylinder

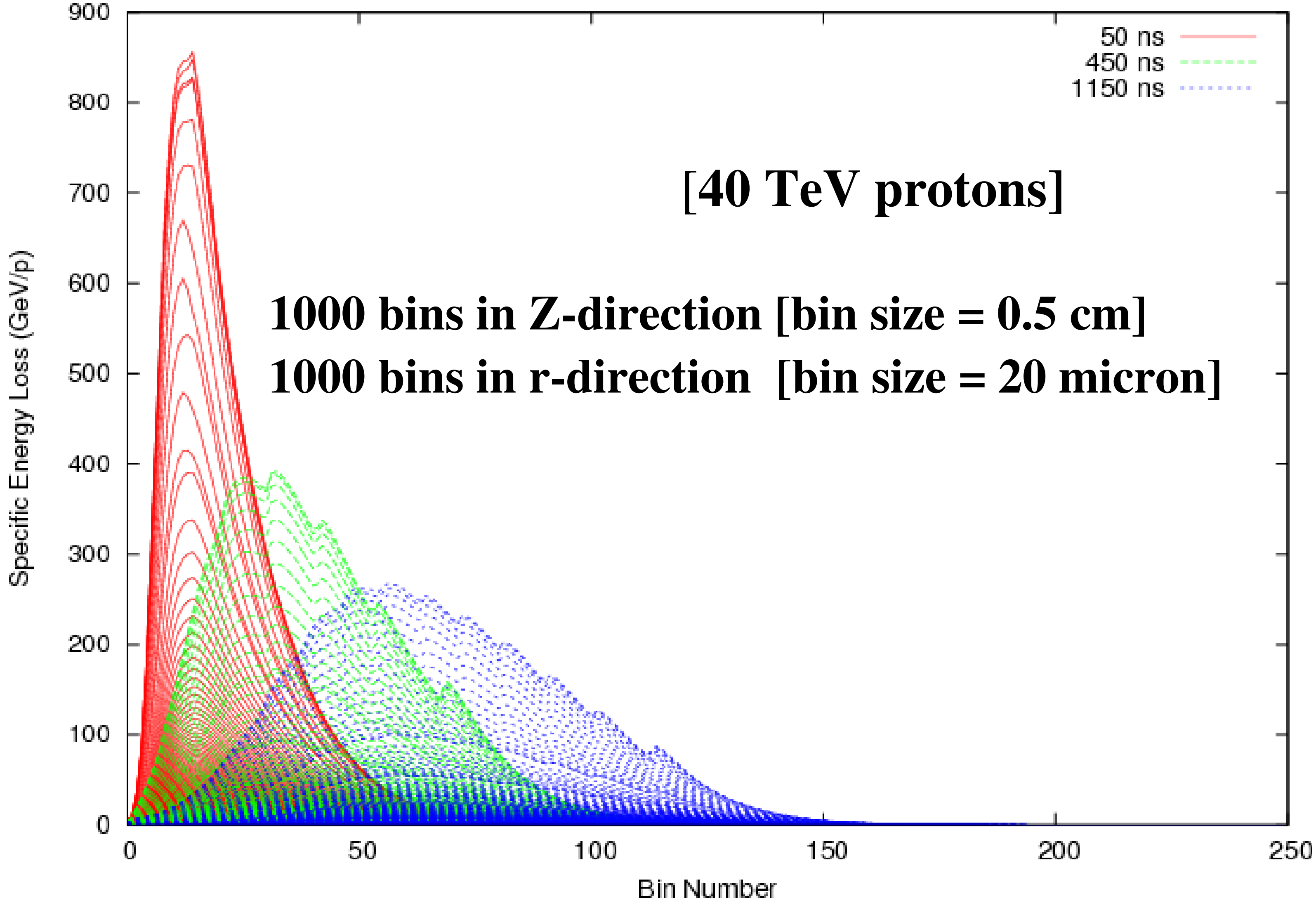
Length = 5 m **Radius = 2 cm**

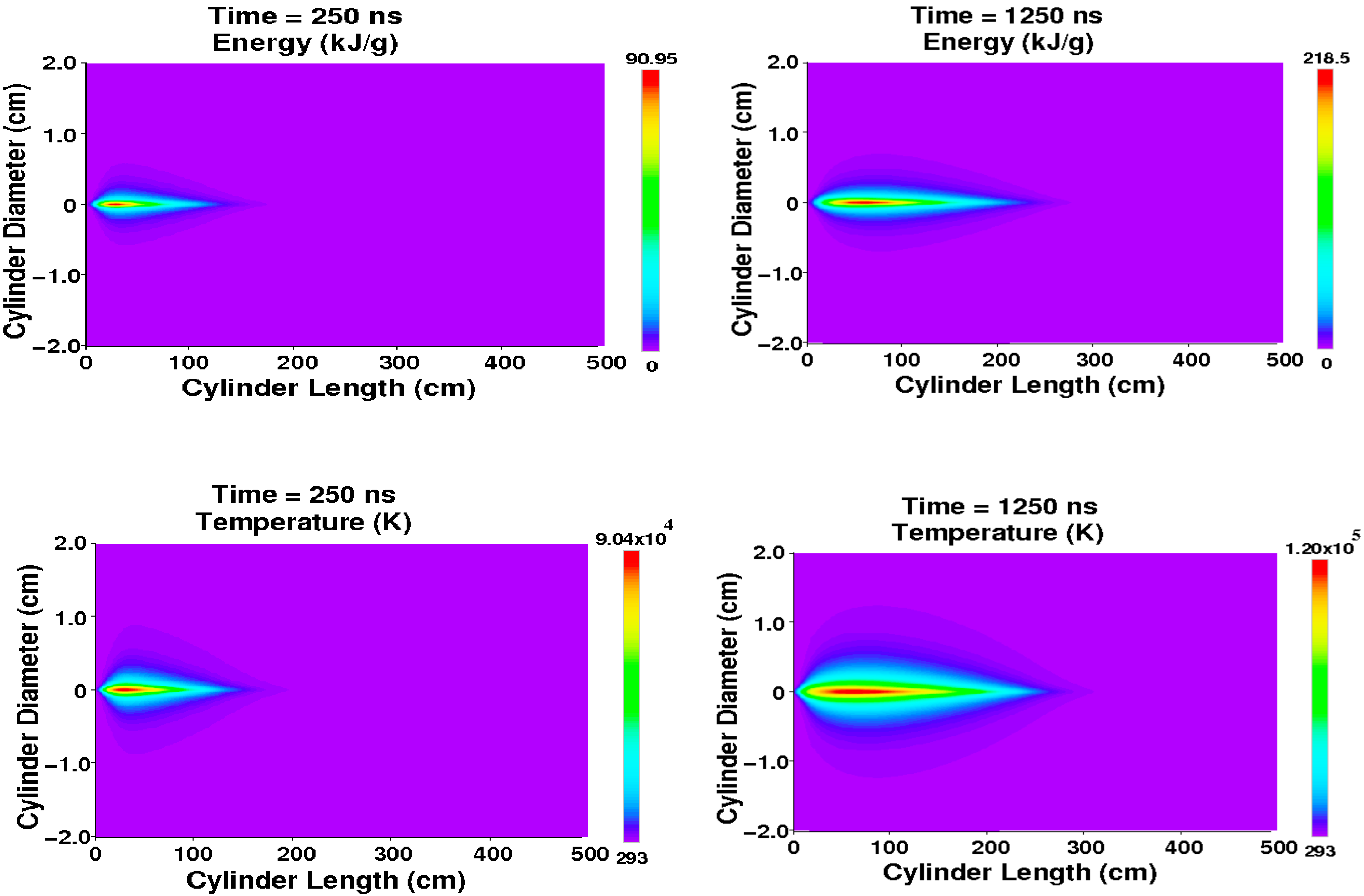
FLUKA and BIG2 used iteratively to simulate the beam-target heating.

Initially an iteration step of 25 ns was used and only after 300 ns, the step could be increased to 100 ns.

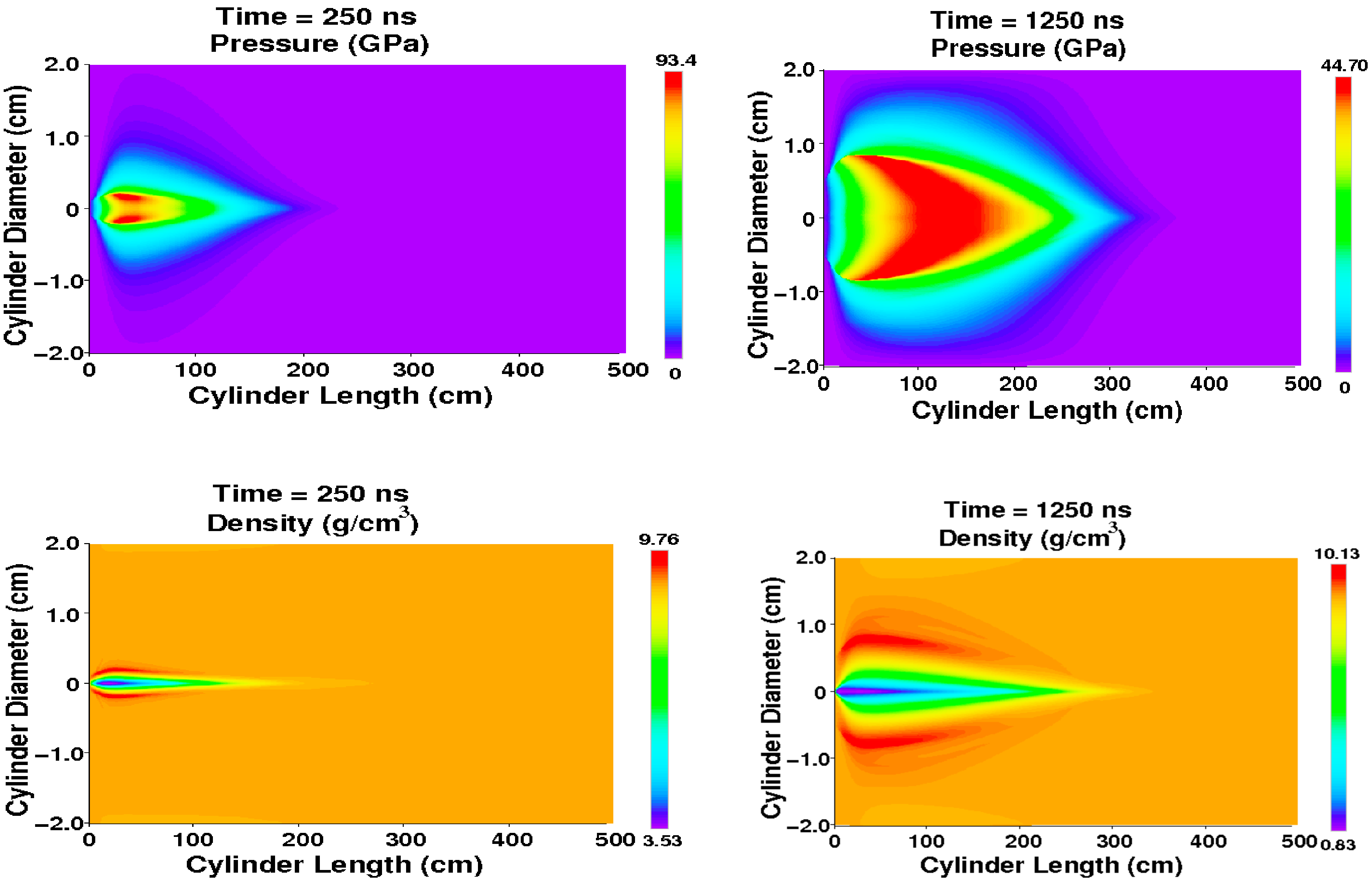
The work took about 15 months.

Solid Density Value: 920 GeV/g/p

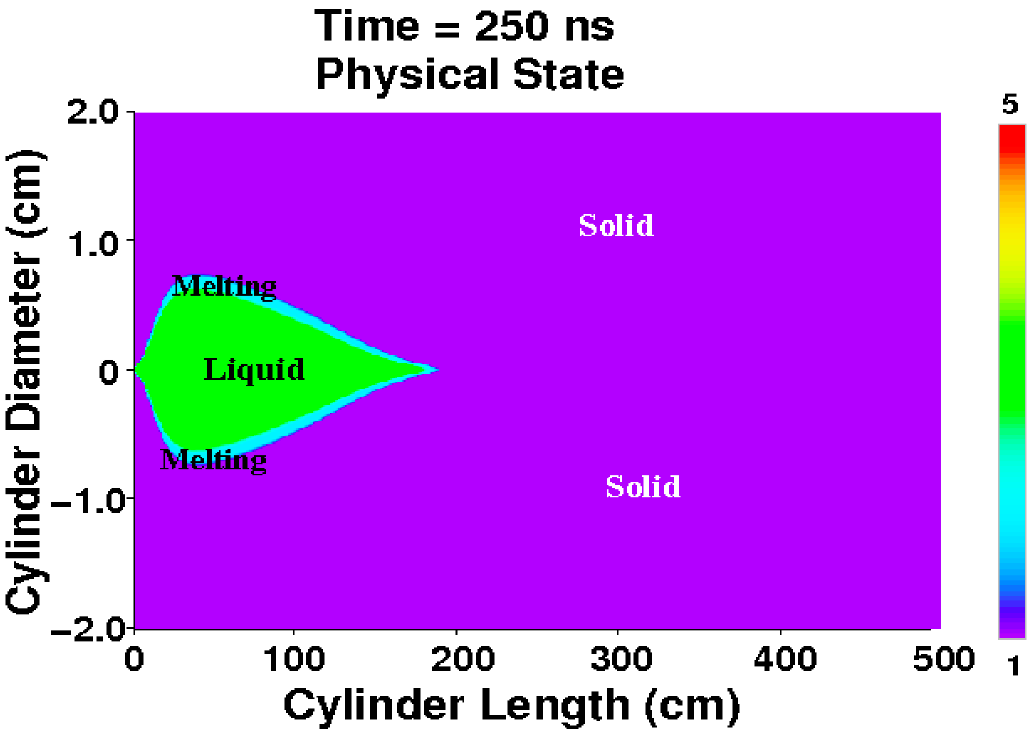


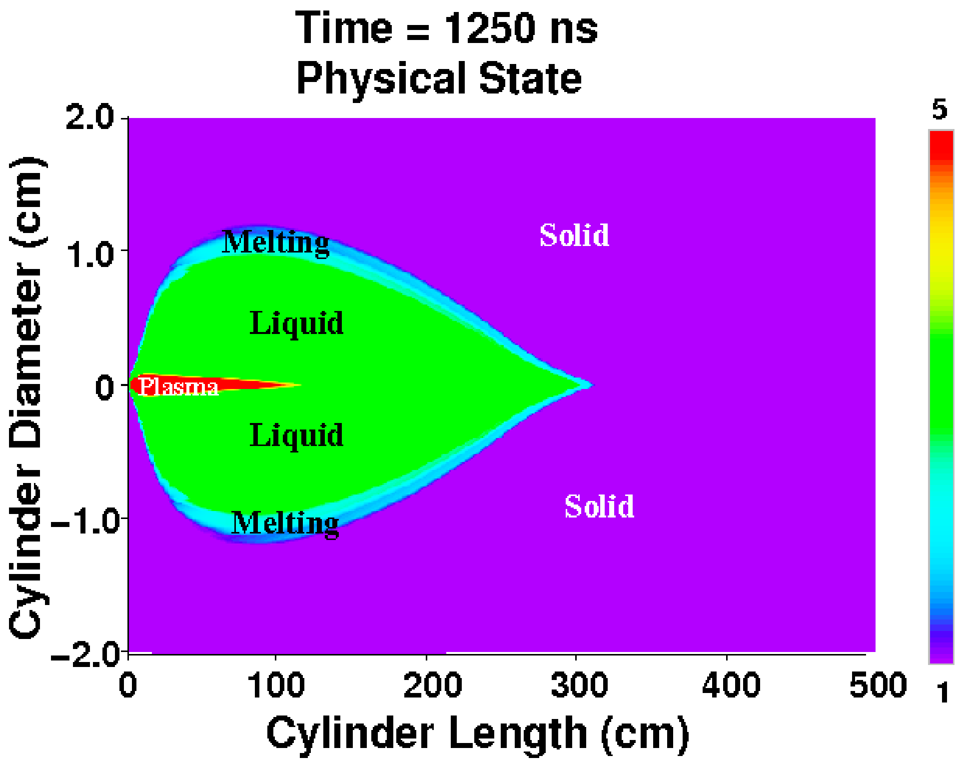


Time = 250 ns
Energy (kJ/g)
90.95
0
Time = 1250 ns
Energy (kJ/g)
218.5
0
Time = 250 ns
Temperature (K)
9.04x10^4
293
Time = 1250 ns
Temperature (K)
1.20x10^5
293
Cylinder Diameter (cm)
2.0
1.0
0
−1.0
−2.0
Cylinder Length (cm)
0
100
200
300
400
500


Time = 250 ns
Pressure (GPa)
93.4
0
2.0
1.0
0
−1.0
−2.0
0
100
200
300
400
500
Cylinder Diameter (cm)
Cylinder Length (cm)
Time = 1250 ns
Pressure (GPa)
44.70
0
Cylinder Diameter (cm)
Cylinder Length (cm)
Time = 250 ns
Density (g/cm3)
9.76
3.53
Cylinder Diameter (cm)
Cylinder Length (cm)
Time = 1250 ns
Density (g/cm3)
10.13
0.83
Cylinder Diameter (cm)
Cylinder Length (cm)

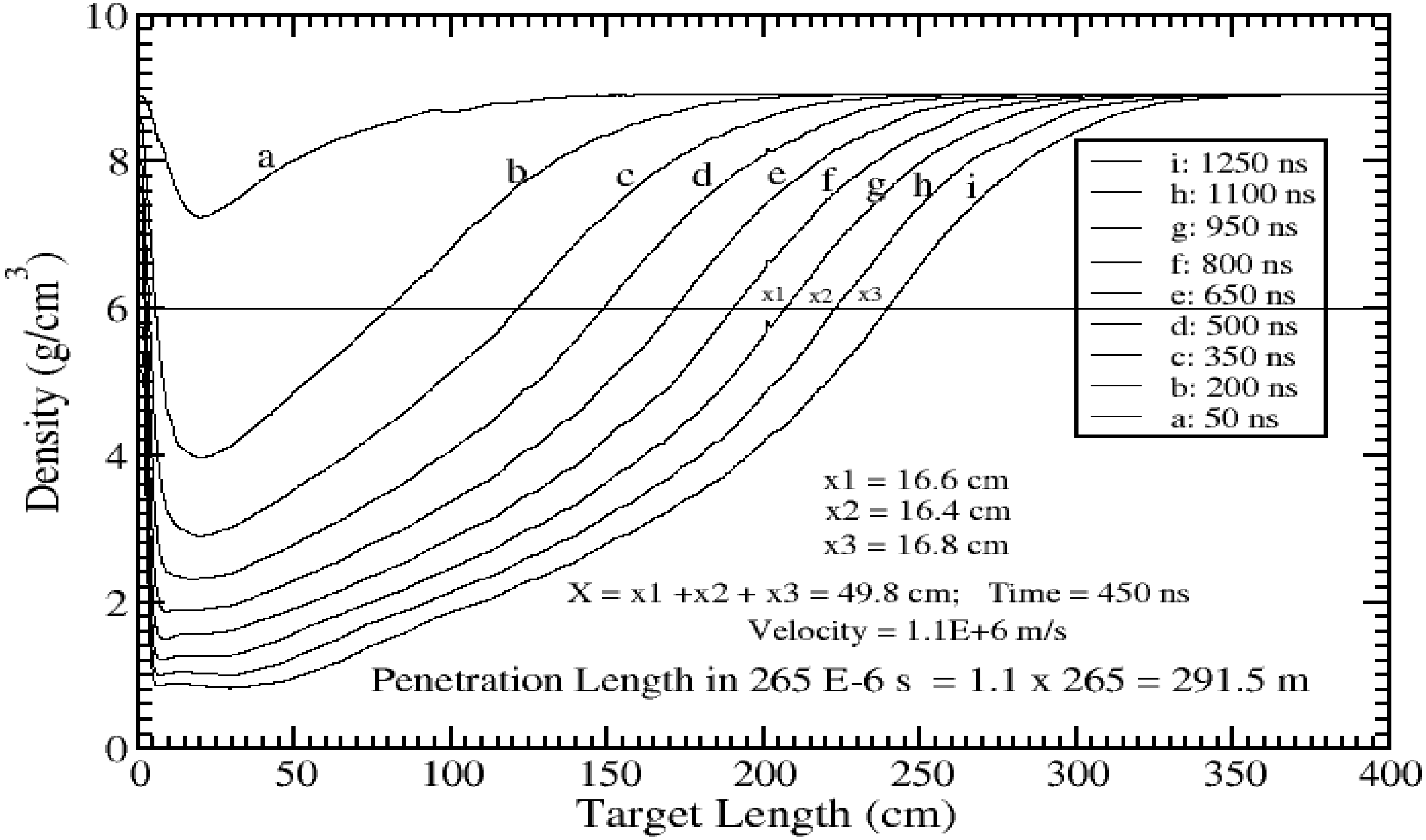
Target Physical State





Calculation of Penetration Distance

Penetration Length is some 100's of m



Hydrodynamic Tunneling in LHC

[Reference: N.A. Tahir, J. Blanco Sancho, A. Shutov, R. Schmidt and A.R. Piriz, Phys. Rev. Special Topics Accel. Beams 15 (2012) 511003.]

Nominal LHC beam parameters (except σ = 0.5 mm), full impact of the LHC beam on a solid carbon cylinder was simulated using full hydrodynamic model. Although the static range of the protons and shower in solid carbon is about 3 m, but dynamic calculations showed that due to the hydrodynamic tunneling the range becomes 25 m!!

Experimental Evidence of Hydrodynamic Tunneling is Established Using 440 GeV SPS Proton Beam at the CERN HiRadMat Facility

[Reference: *R. Schmidt, J. Blanco Sancho, F. Burkart, D. Grenier, D. Wollmann, N.A. Tahir, A. Shutov and A.R. Piriz, Physics of Plasmas 21 (2014) 080701.]*

Conclusions:

- **Iterative calculations have been done using FLUKA and BIG2 codes to study the consequences of the full impact of one FCC beam on a solid copper cylindrical target.**

- **A penetration length of about 350 m has been predicted for the full FCC beam of 50 TeV protons in solid copper.**

- **A significant part of the target material undergoes phase transitions which means that an accident can cause serious pollution of the accelerator environment.**

- **The machine protection system need to be designed with high dependability to avoid such accidents.**

Recent Publications

1. **N.A. Tahir, J. Blanco, A. Shutov, R. Schmidt and A.R. Piriz, *PRSTAB* 15 (2012) 051003.**

2. **N.A. Tahir, J. Blanco, R. Schmidt, A. Shutov and A.R. Piriz, *High Energy Density Physics* 9 (2013) 269.**

3. **N.A. Tahir, F. Burkart, A. Shutov, R. Schmidt, D. Wollmann and A.R. Piriz, *Phys. Rev. E* 90 (2014) 063112.**

4. **R. Schmidt, J. Blanco, F. Burkart, D. Grenier, D. Wollmann, N.A. Tahir, A. Shutov and A.R. Piriz, *Phys. Plasmas* 21 (2014) 080701.**

5. **F. Burkart, R. Schmidt, V. Raginel, D. Wollmann, N.A. Tahir, A. Shutov and A.R. Piriz, *J. Appl. Phys.* 118 (2015) 055902.**

6. **N.A. Tahir, F. Burkart, R. Schmidt, D. Wollmann, A. Shutov and A.R. Piriz *on FCC calculations* (2016) in press.**

Ref: R. Schmidt, J. Blanco Sancho, F. Burkart, D. Grenier, D. Wollmann, N.A. Tahir, A. Shutov and A.R. Piriz, Phys. Plasmas ***21*** *(2014) 080701.*

Super Proton Synchrotron Beam Parameter

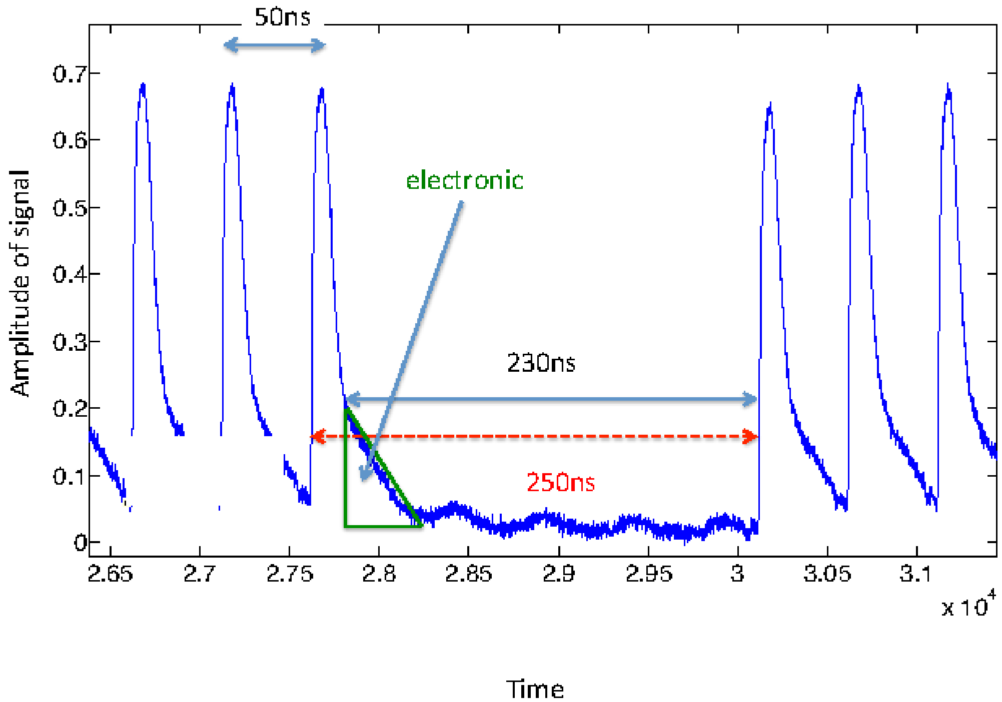
440 GeV protons

Bunch length : 0.5 ns

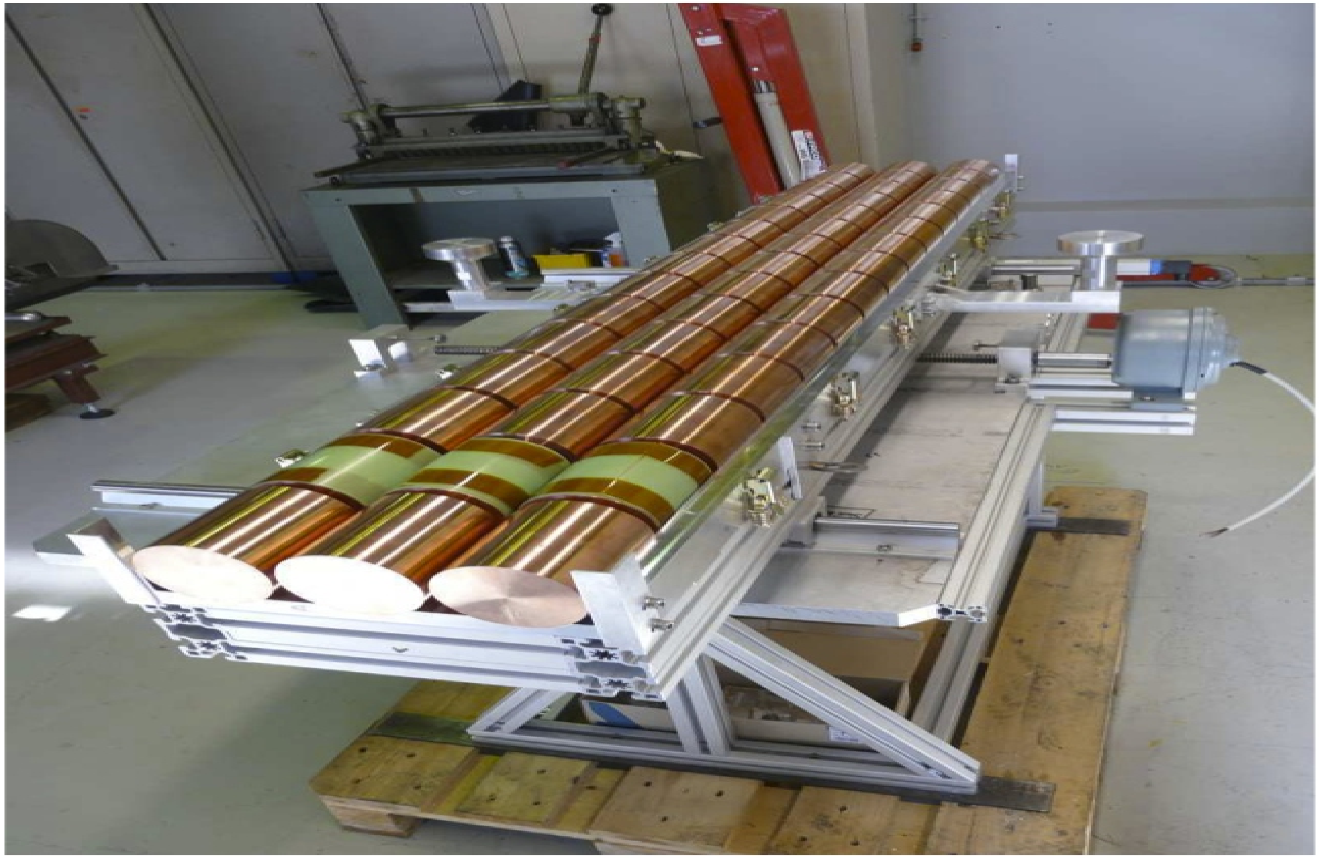
Bunch Separation: 50 ns

Bunch Intensity : 1.5×10^{11}

σ : 0.2 mm



Packets of 36 Bunches and Gap of 250 ns



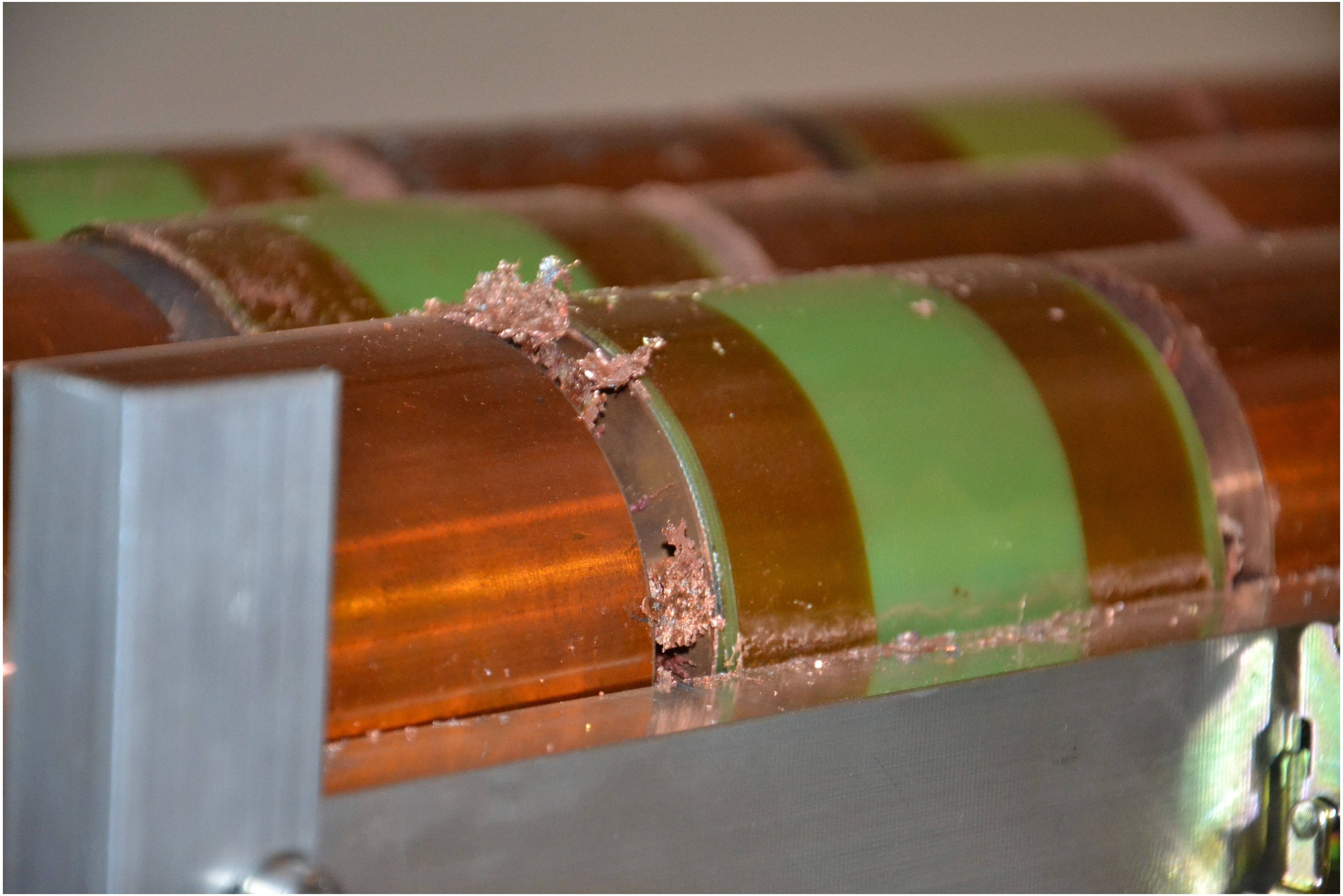
- **Three sets of targets**
- **Each comprises of 15 solid Cu cylinders L = 10 cm, r = 4 cm.**
- **Gap of 1 cm between between neighbouring cylinders**
- **Al cover on on the top**
- **Al caps around first & last cylinder**

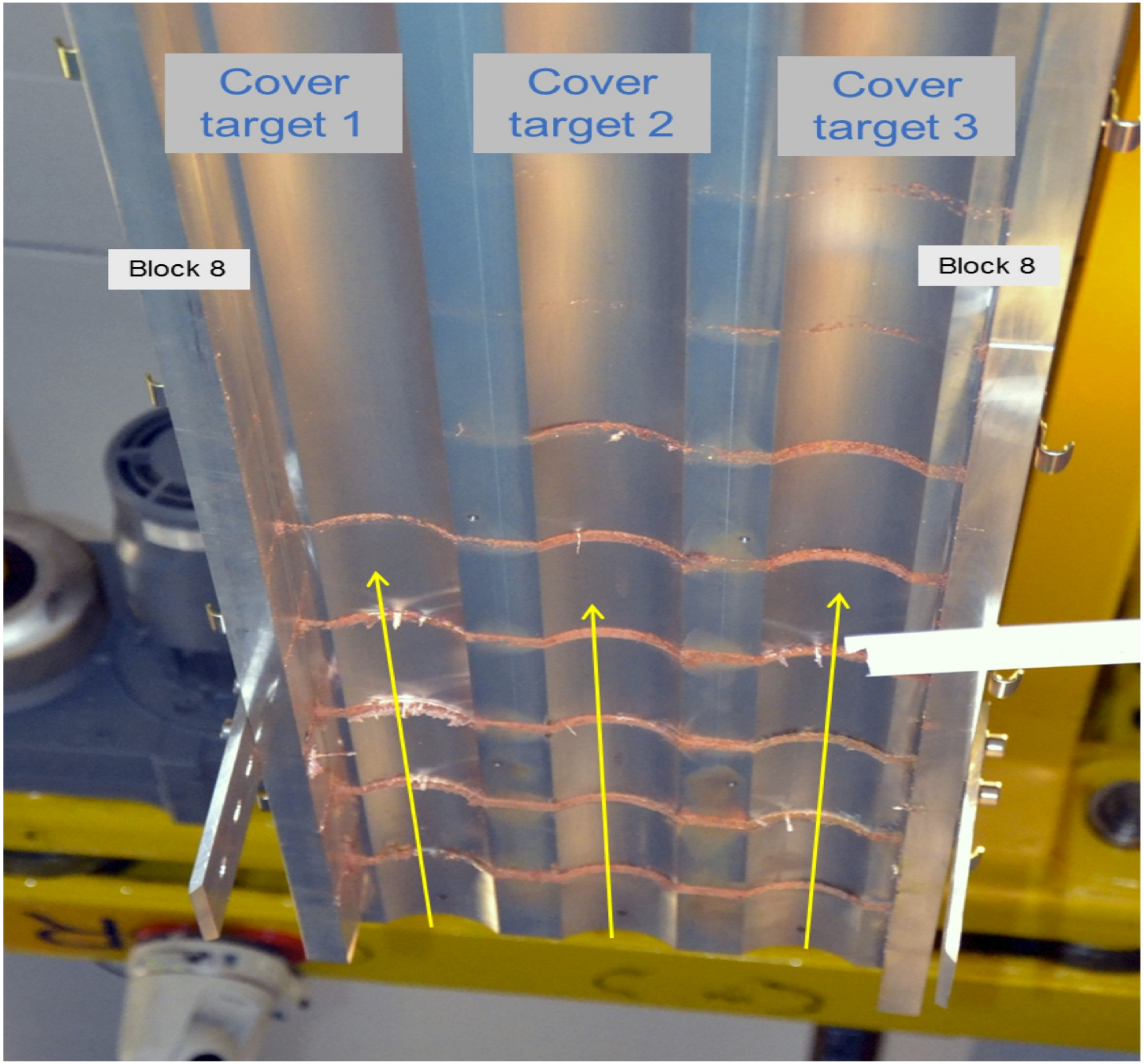
to avoid contamination

1. **First target is irradiated with 144 bunches with beam σ = 2 mm.**

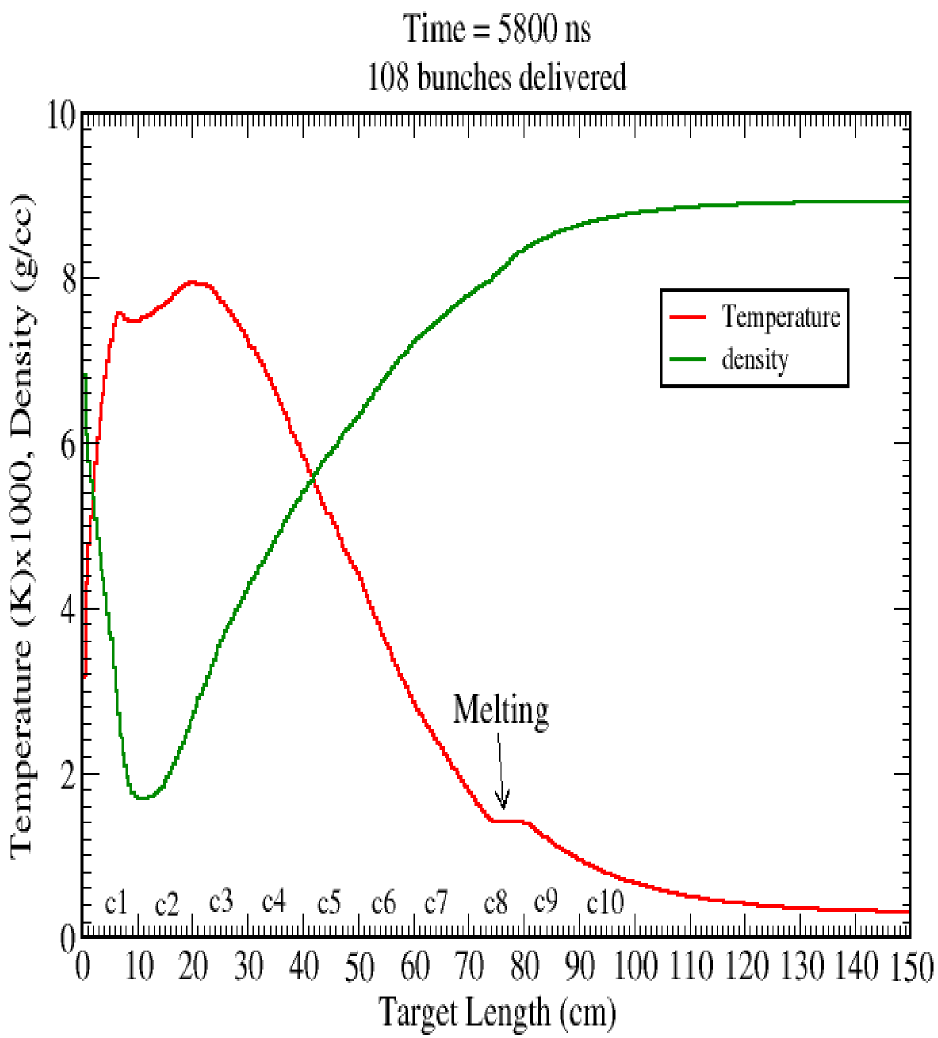
2. **Second target is irradiated with 108 bunches with beam σ = 0.2 mm.**

3. **Third target is irradiated with 144 bunches with beam σ = 0.2 mm.**

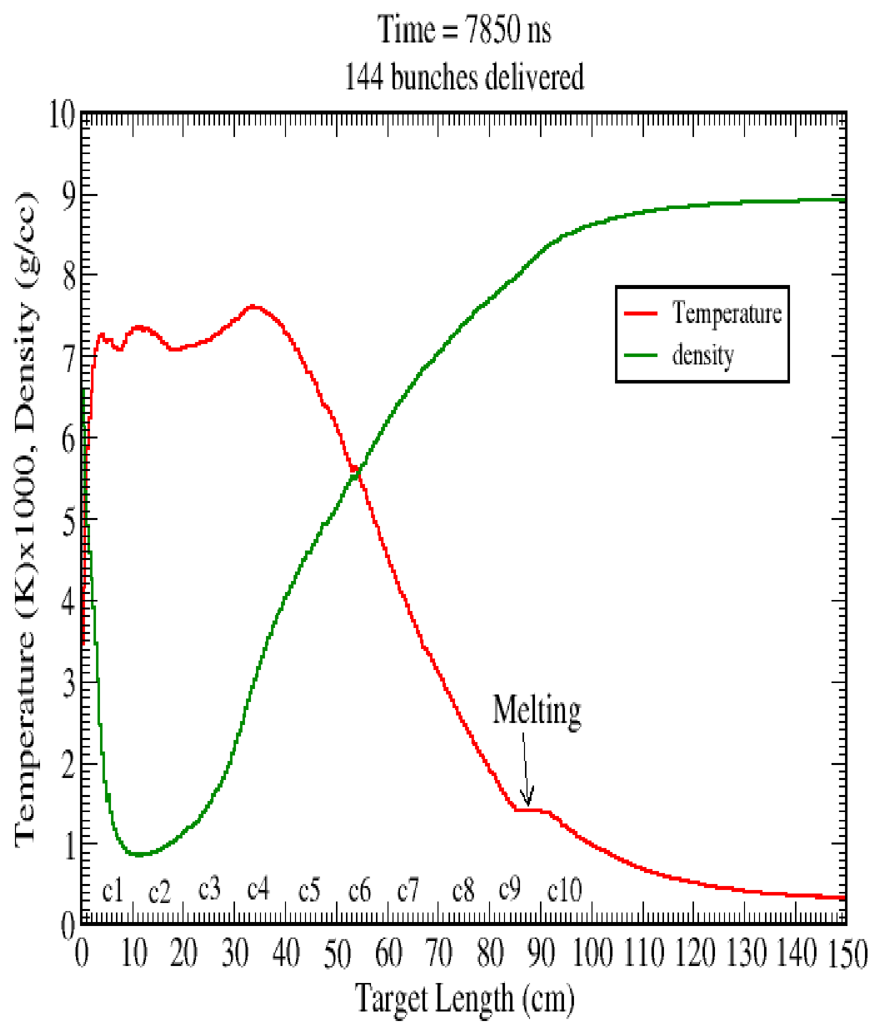



Cover target 1
Cover target 2
Cover target 3
Block 8
Block 8

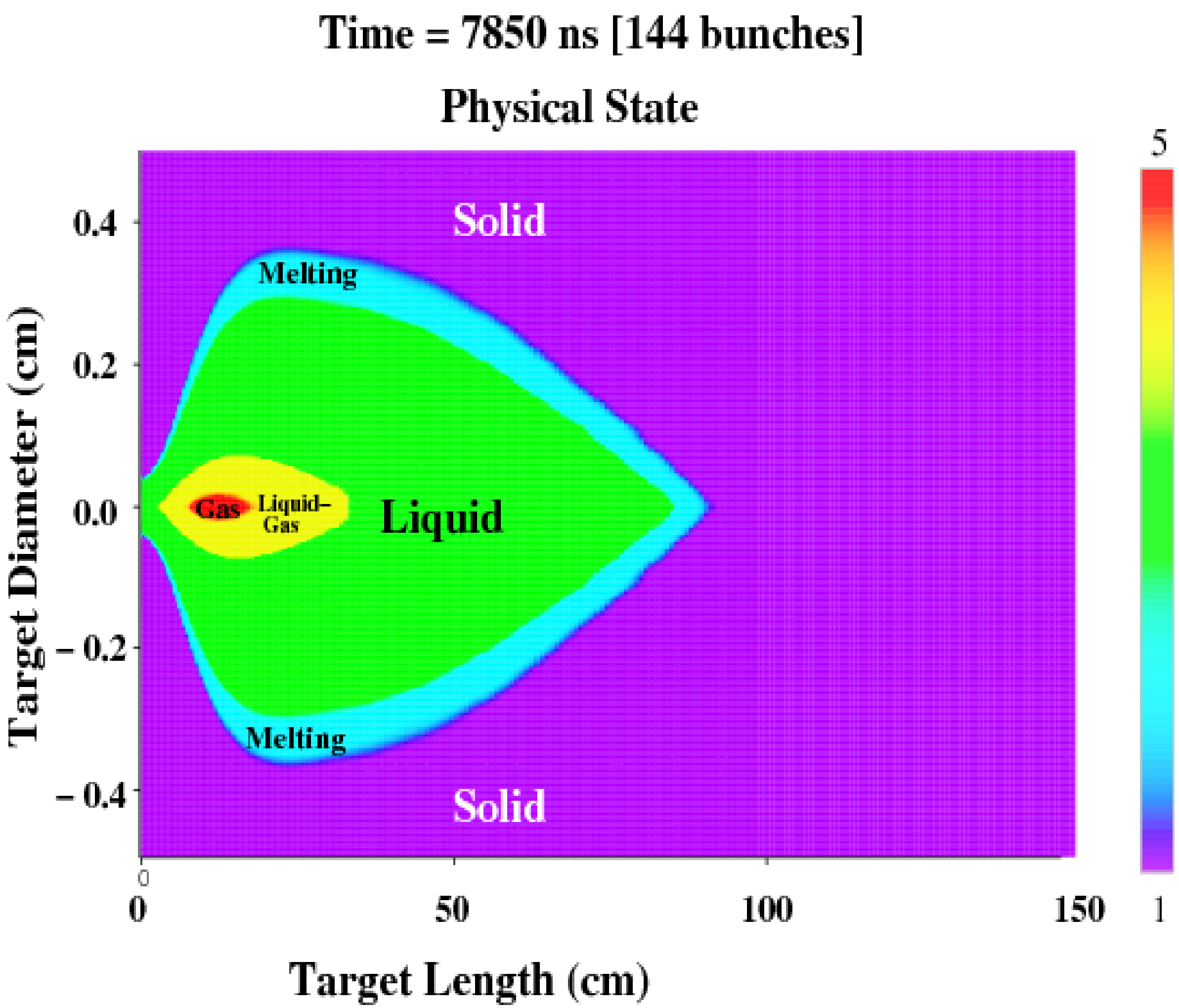
Case 2: 108 bunches



Case 3: 144 bunches



Generation of Warm Dense Matter



- **Hydrodynamic simulations using BIG2 code.**
- **Phase state of the target after delivery of 144 bunches.**
- **Based of semi-empirical EOS data from**

References:

- ***I.V. Lomonosov, LPB 25 (2007) 567.***
- ***I.V. Lomonosov, V.E.Fortov Tech. Phys. 48 (2003)727.***