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Benchmarking simulation of hydrodynamic tunneling against HiRadMat-12 coupling FLUKA and Autodyn

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Acknowledgments:

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J. Blanco Sancho, R. Schmidt, N. Tahir, F. Burkart, D. Wollmann, etc

Outline

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II. Benchmarking study: beam and target parameters

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IV. Results and comparisons

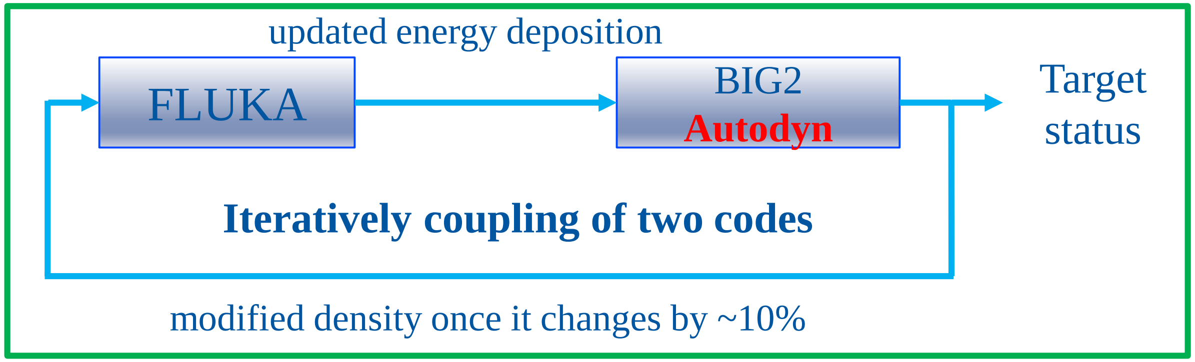
V. Summary

I. Motivation: comparison between codes

HiRadMat-12 experiment at SPS

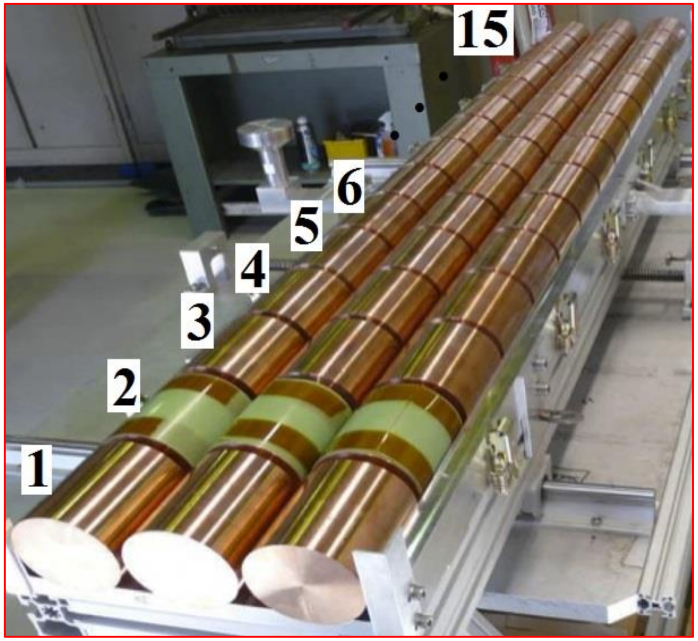
Damage of a beam (144b) with an energy of 1.5 MJ **(Hydrodynamic tunneling)**

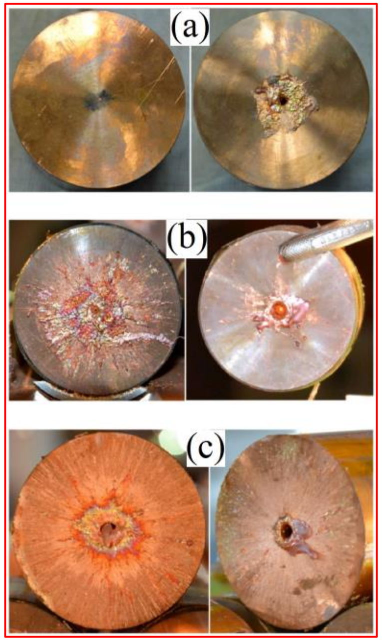
[N.A. Tahir, et al., ***Phys. Rev. E*** 2014; F. Burkart, et al., ***J. Appl. Phys.*** 2015]



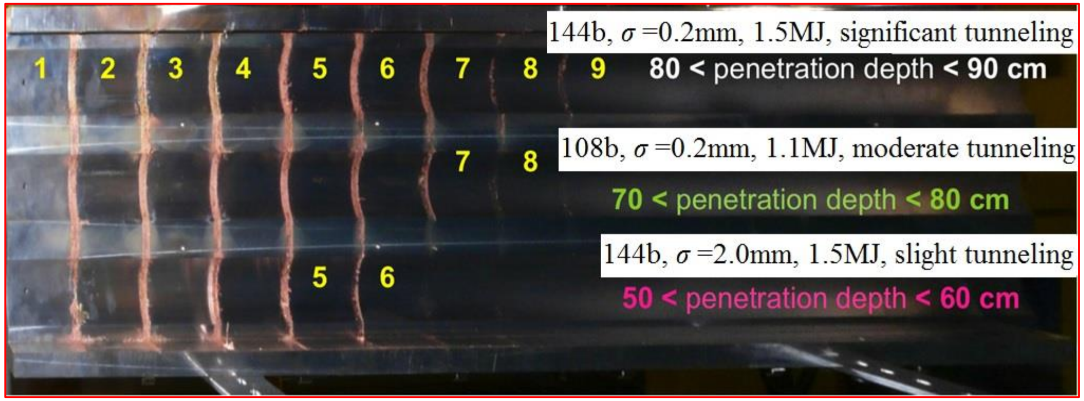
[**Y. Nie**, et al., ***IPAC*** 2018; ***Phys. Rev. Accel. Beams***, under review]

II. Benchmarking study: beam and target parameters (HiRadMat-12)



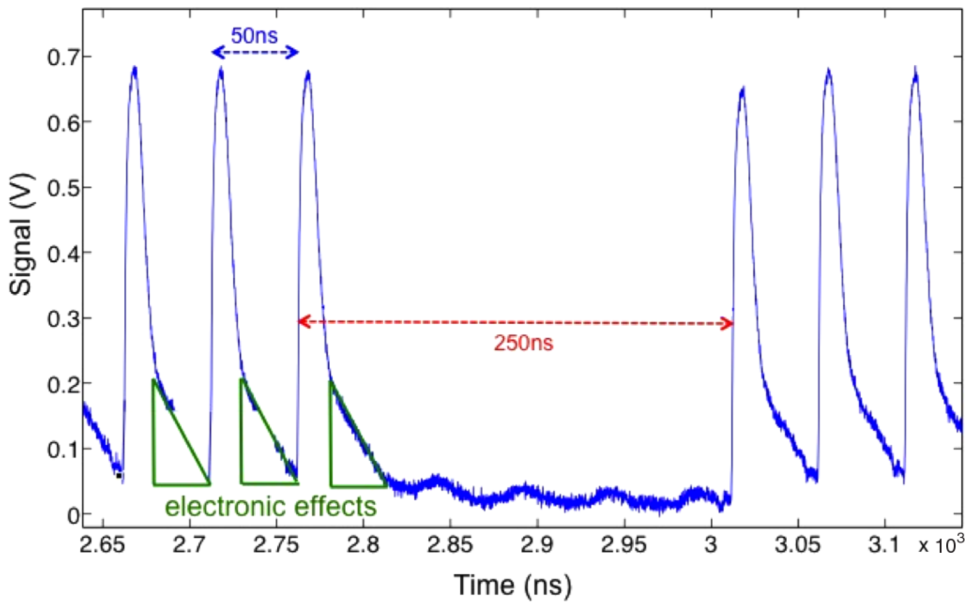


Upper left: three Cu targets (cylinder R=4 cm, L=150 cm)
Upper right: front and back faces of cylinders 1-3 (a-c) of target 3
Lower: top cover of the three targets (up to down: target 3, 2, 1)



R. Schmidt, et al., *Phys. Plasmas* 2014
http://dx.doi.org/10.1063/1.4892960
N.A. Tahir, et al., *PRE* 2014
https://doi.org/10.1103/PhysRevE.90.063112
F. Burkart, et al., *J. Appl. Phys.* 2015
http://dx.doi.org/10.1063/1.4927721

II. Benchmarking study: beam and target parameters (HiRadMat-12)



Proton energy: 440 GeV
Transverse beam size: 0.2 mm
Bunch intensity: 1.5×10^{11}
Bunch length: 0.5 ns
Bunch spacing: 50 ns

- For Target 3, the protons were delivered in sets of **36** bunches each, separation between two neighboring bunch packets was **250 ns**, total (36×4=144 bunches) beam length ~7750.5 ns
- The time structure was considered in the simulation

III. Simulation procedure: workflow

First FLUKA simulation using nominal density (8.93g/cm^3) of the (copper) target

Predict beam heated area composed of fine regions (cylinders) that are supposed to undergo density changes

Autodyn: dynamic response of material to certain number of bunches

physical state of the target

modified density map once the density changes by 10-15%

Construction of new FLUKA model (assign densities to regions, possible extension of fine regions, merge/split regions to assure the total number of regions <20000 and density gradient within a few percent.)

Predefine ~100 density levels (materials) from 0.1 g/cm^3 to 10.0 g/cm^3. (in maximum 700 materials handled by FLUKA)

New FLUKA simulation for the following bunch/bunches

updated energy deposition distribution

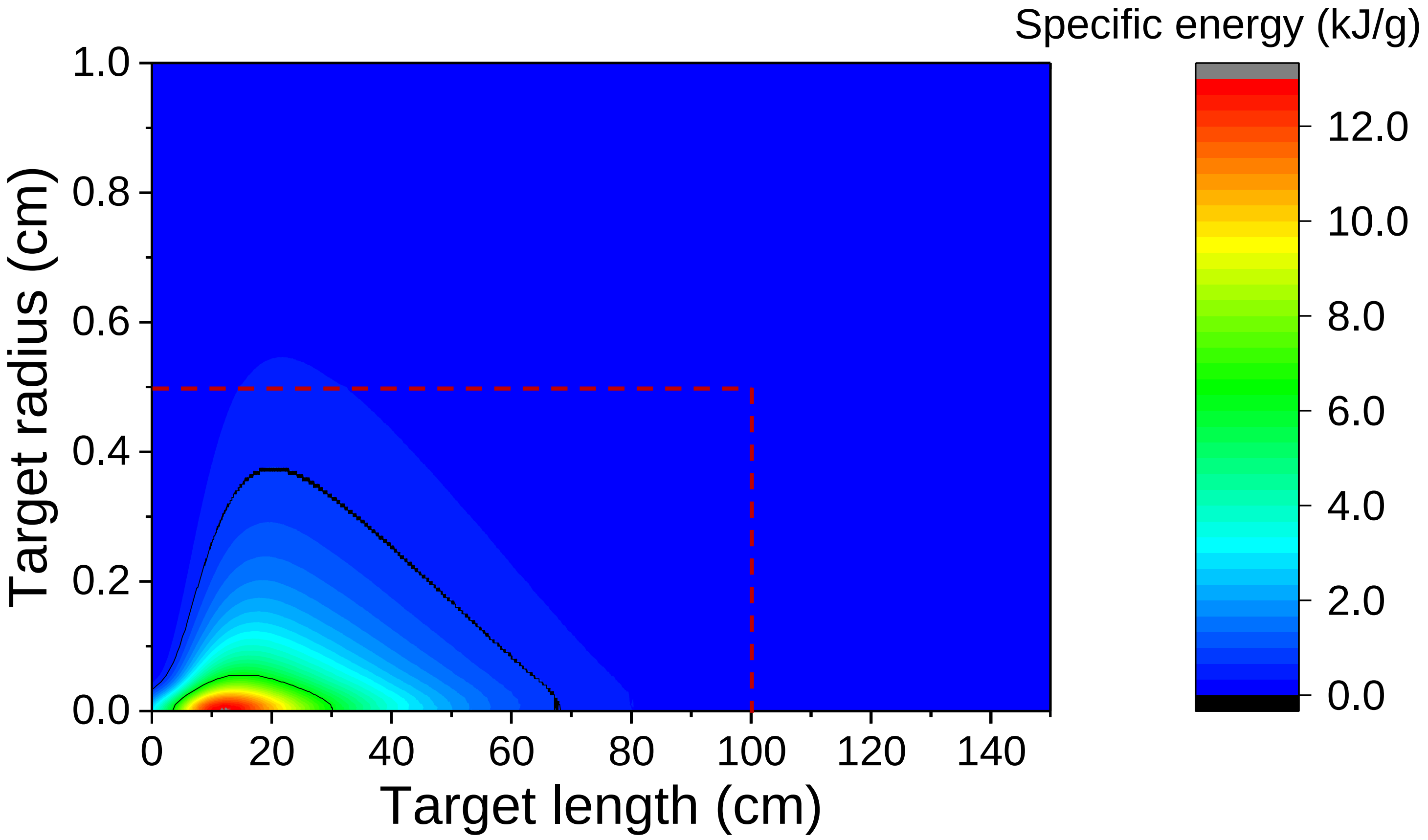
iterative run till the end of beam impact

III. Simulation procedure: comparison

Hydrocode	EOS	Strength model	Failure model	Mesh
BIG2	Semi-empirical	Prandtl-Reuss model		Eulerian
Autodyn	SESAME (LANL)	Empirical J-C	Empirical J-C	Lagrangian

- For Autodyn, analytical or tabular EOS/other models/other mesh can be adopted on a case-by-case basis, according to beams and materials.

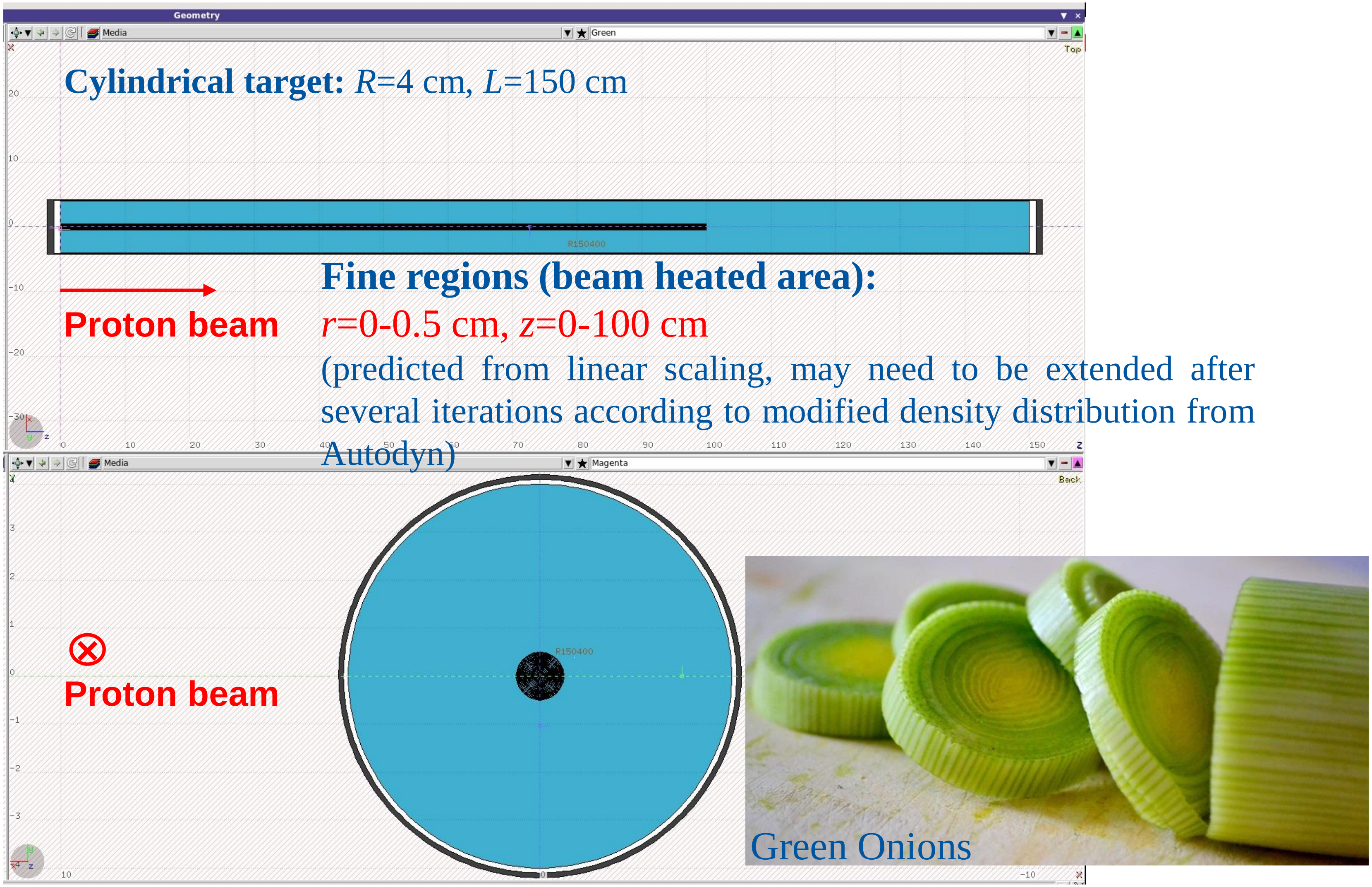
III. Simulation procedure: beam heated area (predicted by FLUKA)



- Static approximation: linear scaling from one proton (GeV/g/p) to 144 bunches (kJ/g)
- Two black curves, upper: melting contour line; down: boiling contour line

III. Simulation procedure: target modelling in FLUKA

Cylindrical target: *R*=4 cm, *L*=150 cm



Proton beam

Fine regions (beam heated area):

r=0-0.5 cm, *z*=0-100 cm

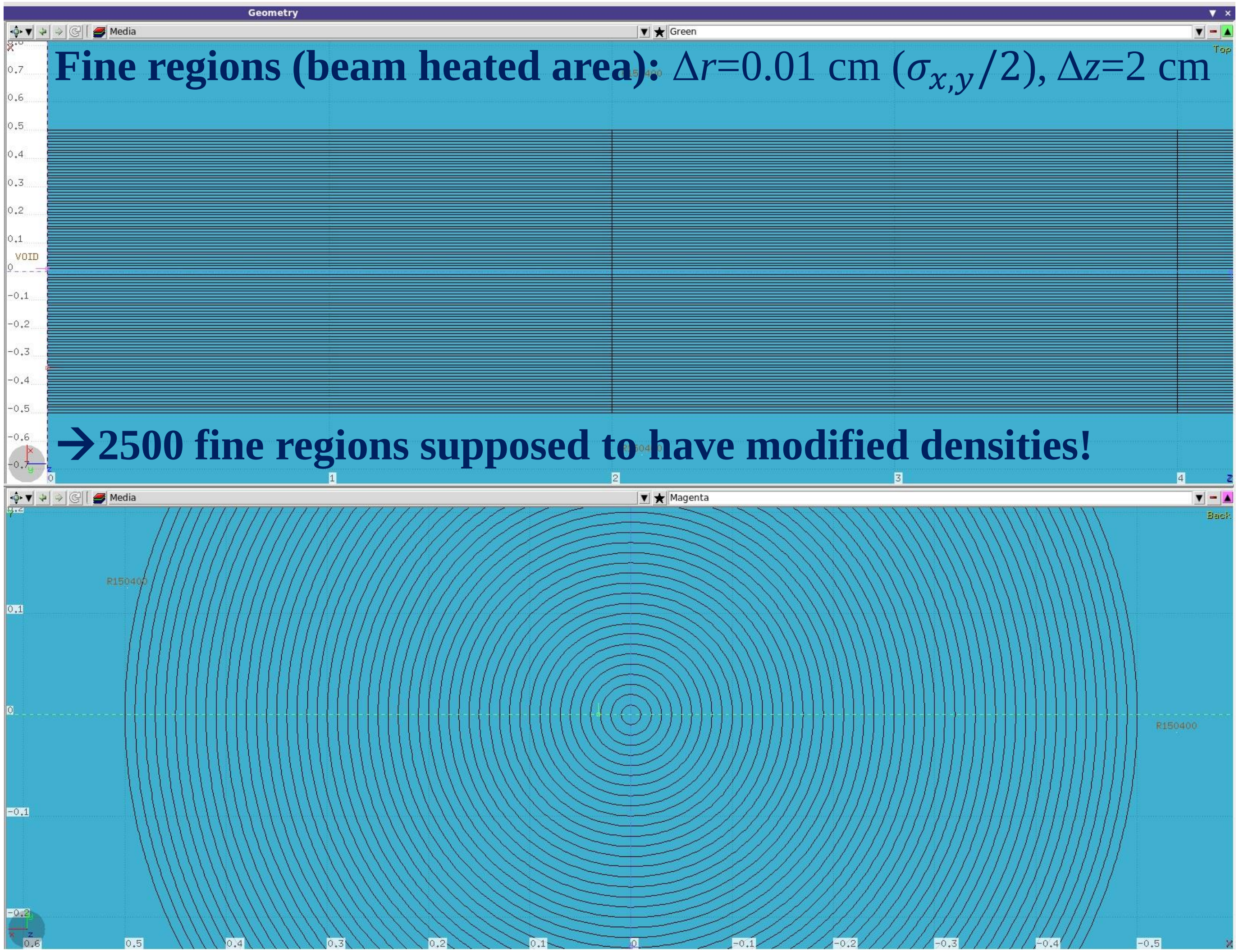
(predicted from linear scaling, may need to be extended after several iterations according to modified density distribution from Autodyn)

⊗

Proton beam

III. Simulation procedure: target modelling in FLUKA

Fine regions (beam heated area): Δr=0.01 cm ($\sigma_{x,y}/2$), Δz=2 cm

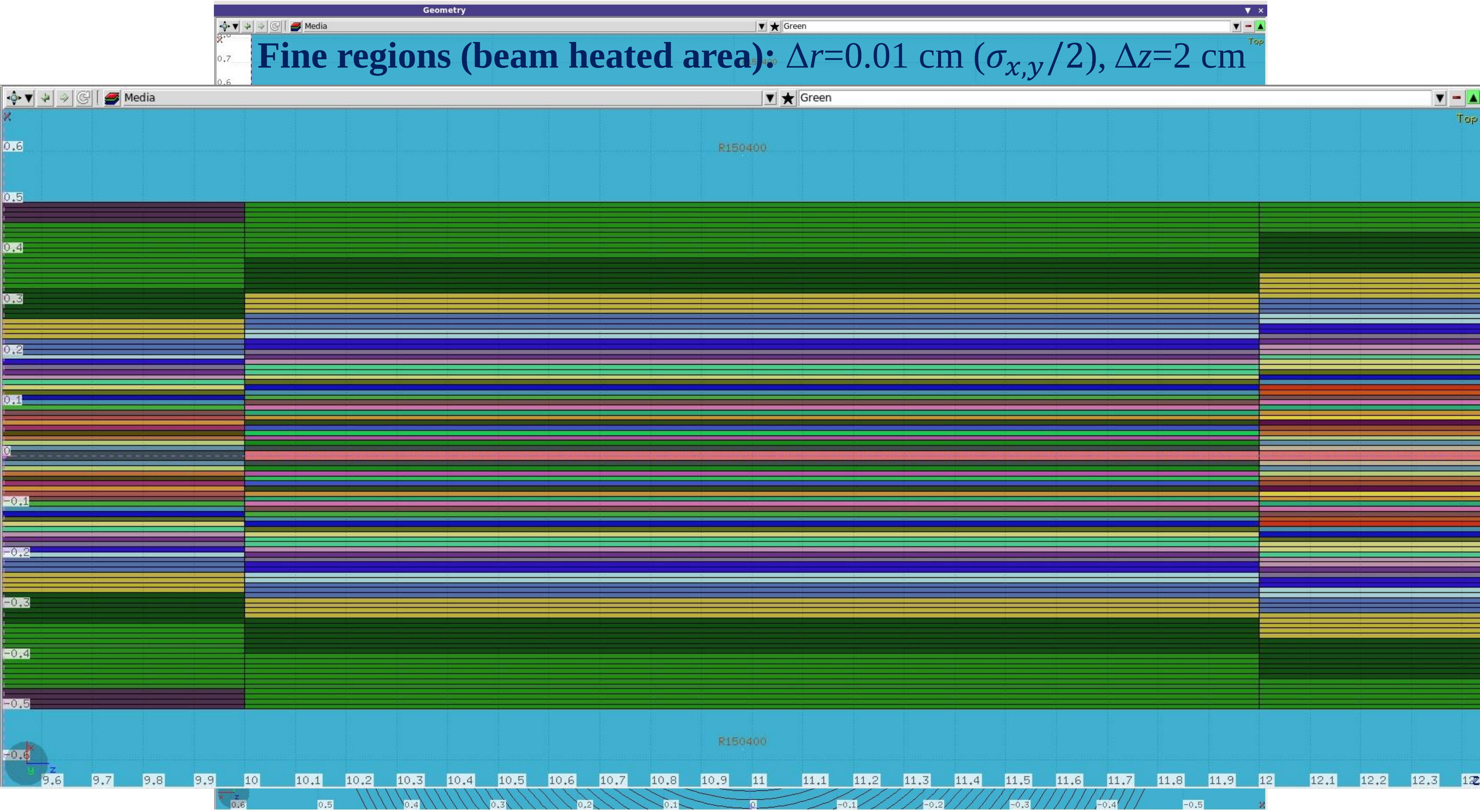


→2500 fine regions supposed to have modified densities!

(Maximum number of regions: 20 000)

III. Simulation procedure: target modelling in FLUKA

Fine regions (beam heated area): Δr=0.01 cm ($\sigma_{x,y}/2$), Δz=2 cm



(Maximum number of regions: 20 000)

III. Simulation procedure: difference

- Compared to previous coupling between FLUKA and BIG2 [J. Blanco Sancho, Ph.D thesis, EPFL Lausanne, 2014], the basic principle is similar, but the implementation is different.

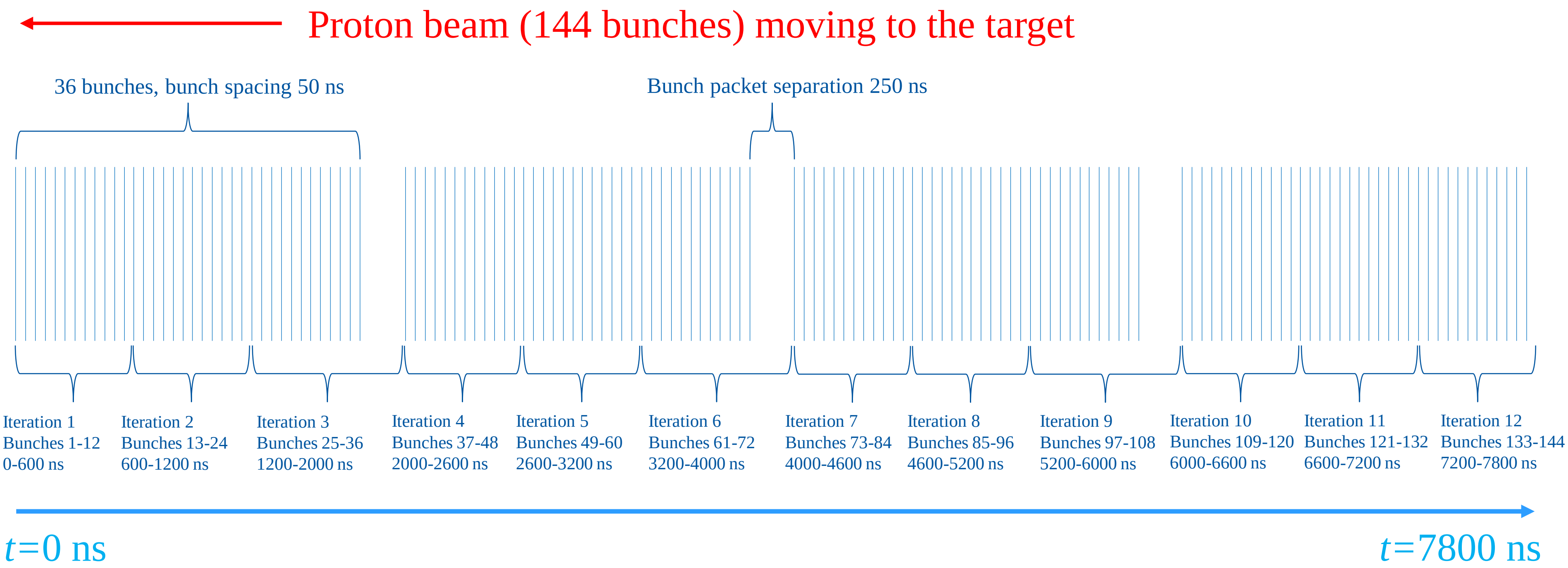
  a) We don't define discrete density levels in each iteration. From the accuracy point of view, 100-200 predefined (fixed) densities are sufficient.

  - Data analysis and FLUKA modelling are hence simplified, since for each density, different kinds of material & compound have to be defined.

  b) Previous scripts assign one material to one region, so the total number of regions is limited to be less than ~700. We are able to assign one material to different regions, so that the region number could be up to 20 000 (by default).

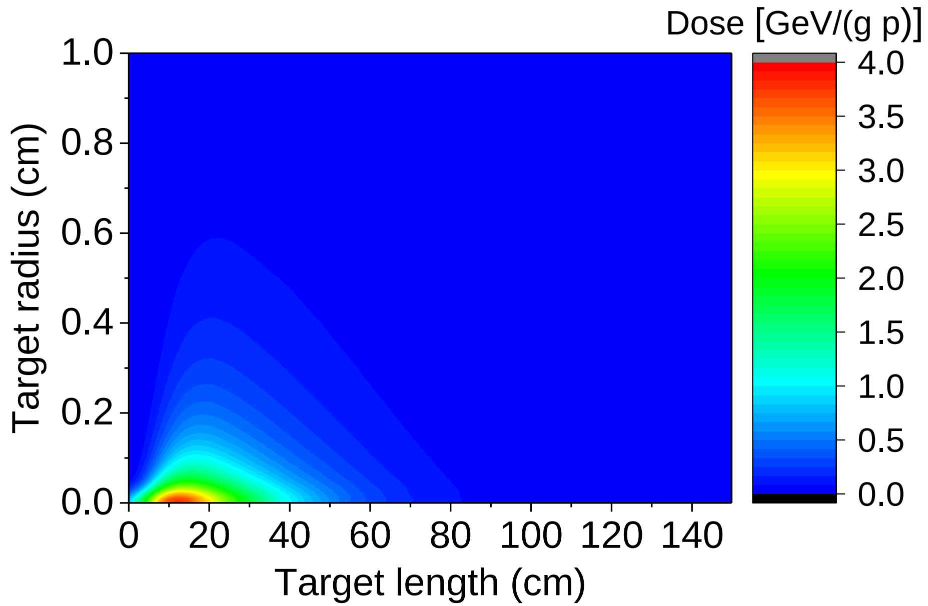
  - Regions with same/close density may be merged **(Boolean Calculation)** to save simulation time, but we are more flexible (merging regions takes time as well).

III. Simulation procedure: iteration steps



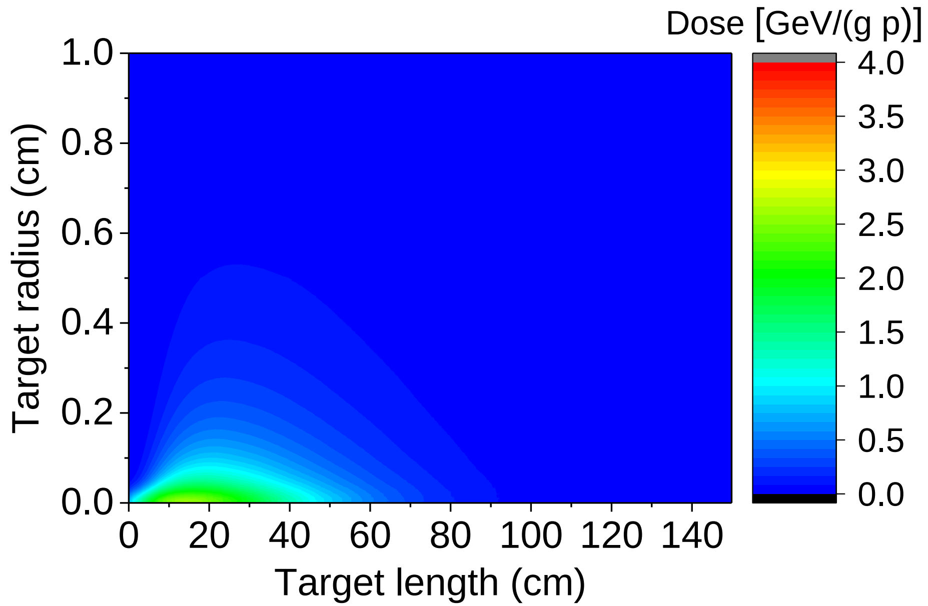
- Bunch length 0.5 ns is not shown in the picture
- In total, 4 packets, each consists of 36 bunches
- The beam pulse length is 35*50*4+250*3=7750 ns for 144 bunches (target 3)
- The density drops 13% in max. after the first 12 bunches → **12*12** bunches

IV. Results and comparisons: FLUKA maps [GeV/(g p)]



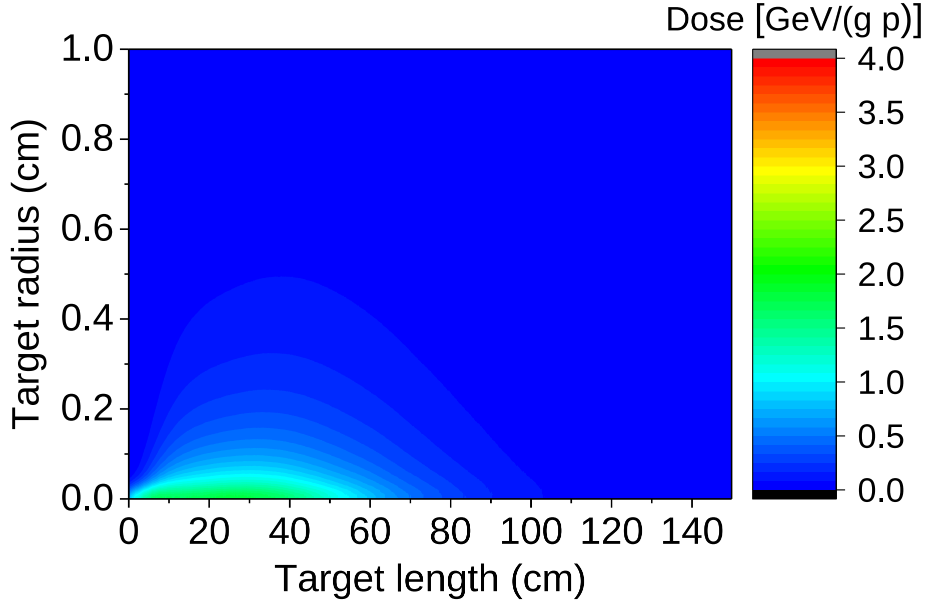
- 2D dose distribution for bunches 1-12, using density at *t* = 0 ns

IV. Results and comparisons: FLUKA maps [GeV/(g p)]



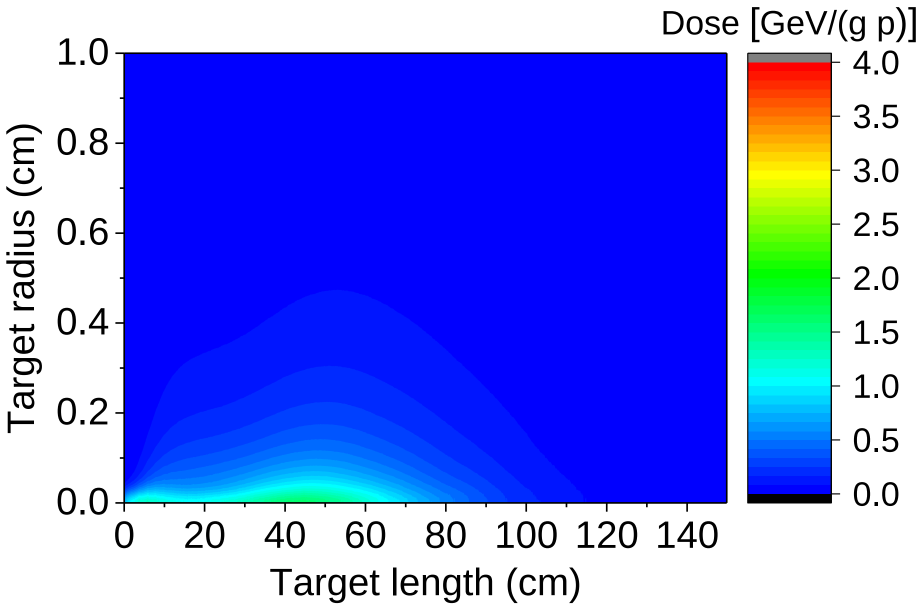
- 2D dose distribution for bunches 37-48, using density at *t* = 2000 ns

IV. Results and comparisons: FLUKA maps [GeV/(g p)]



- 2D dose distribution for bunches 73-84, using density at t = 4000 ns

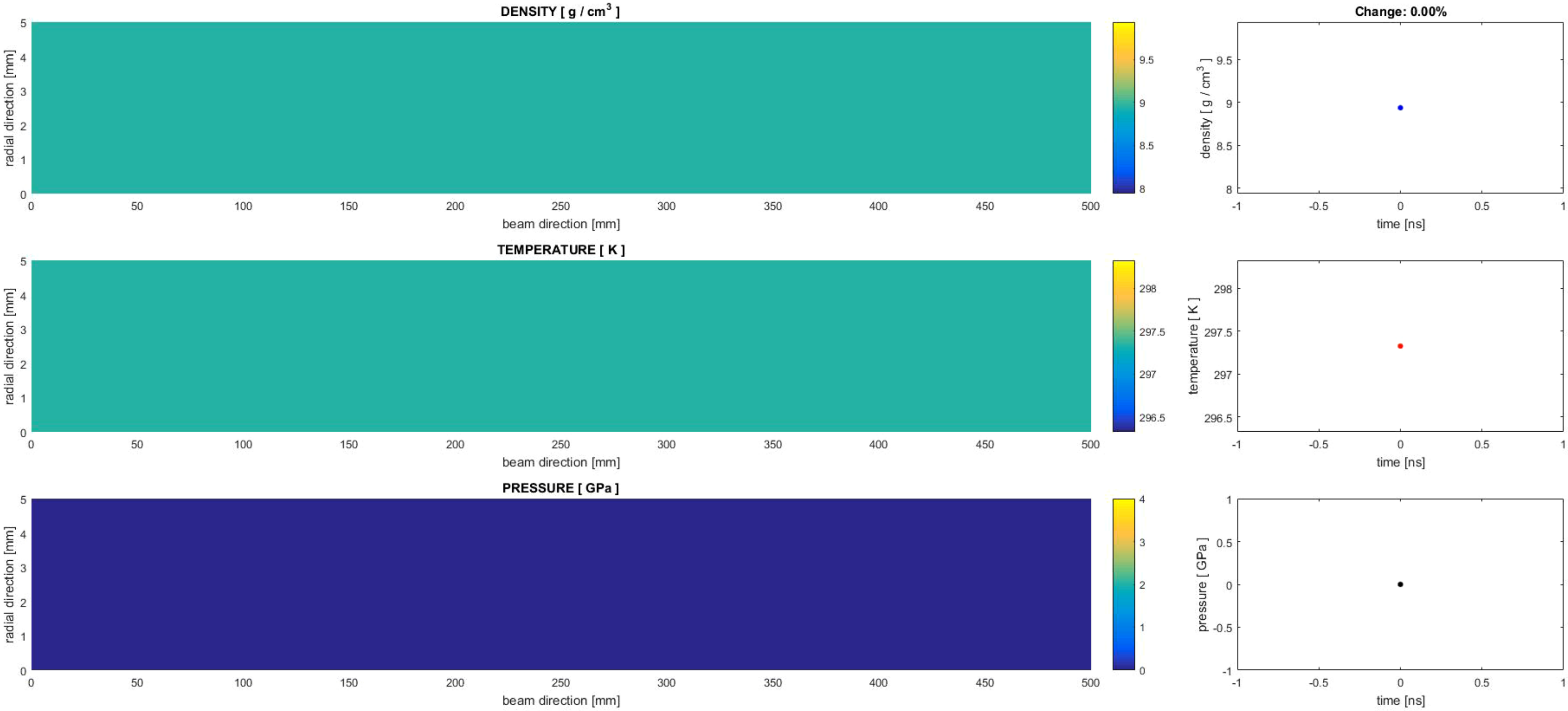
IV. Results and comparisons: FLUKA maps [GeV/(g p)]



- 2D dose distribution for bunches 109-120, using density at *t* = 6000 ns

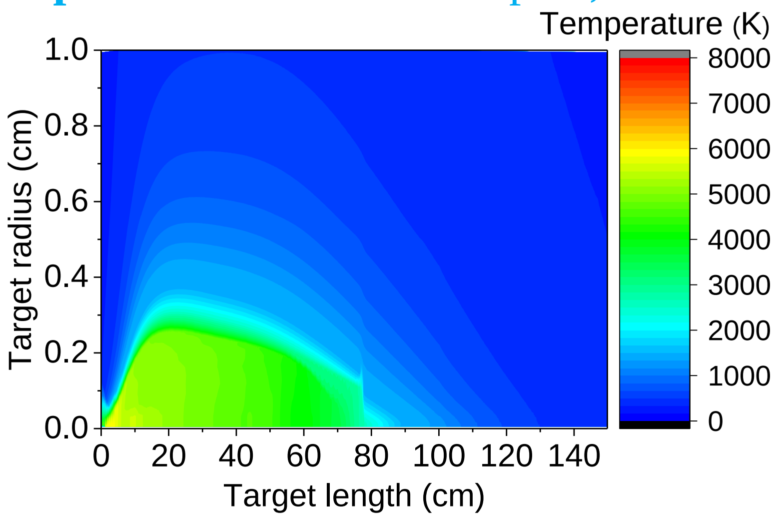
IV. Results and comparisons: mechanical responses to the first 36 bunches

Tunneling effect during proton-copper interactions for the first 36 bunches

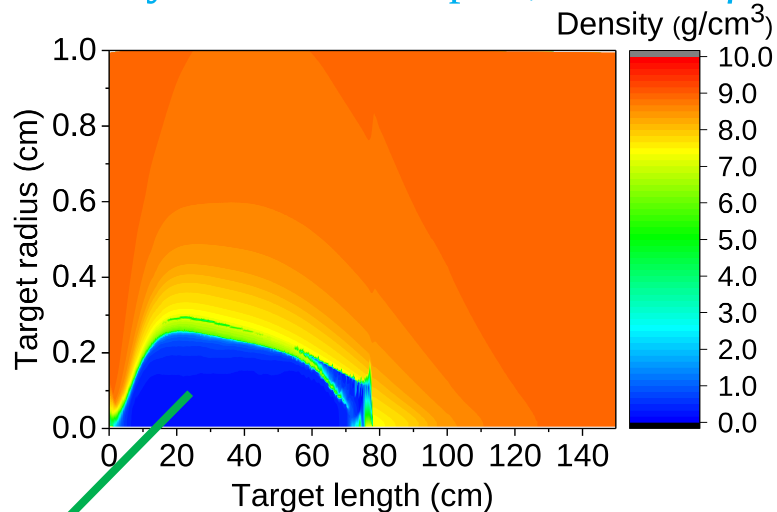


IV. Results and comparisons: temperature and density after beam impact

Temperature after beam impact, at t = 20 μs

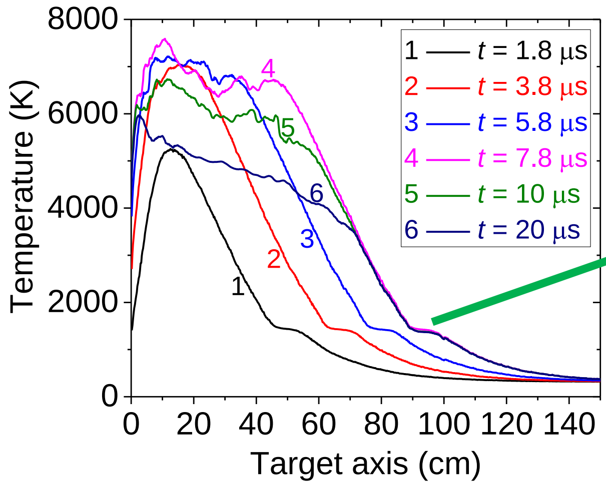


Density after beam impact, at t = 20 μs

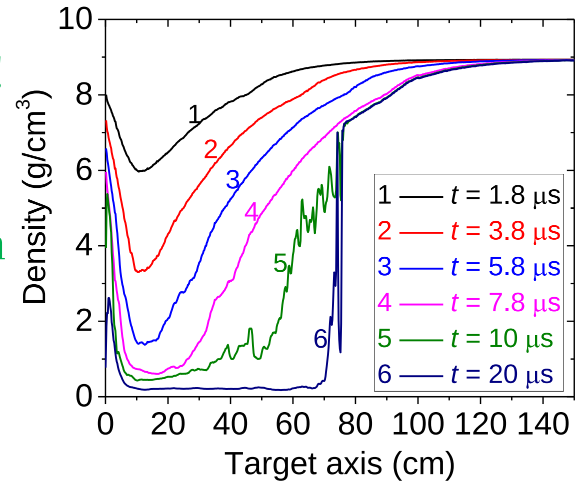


Hollow cavity!

Melting platform

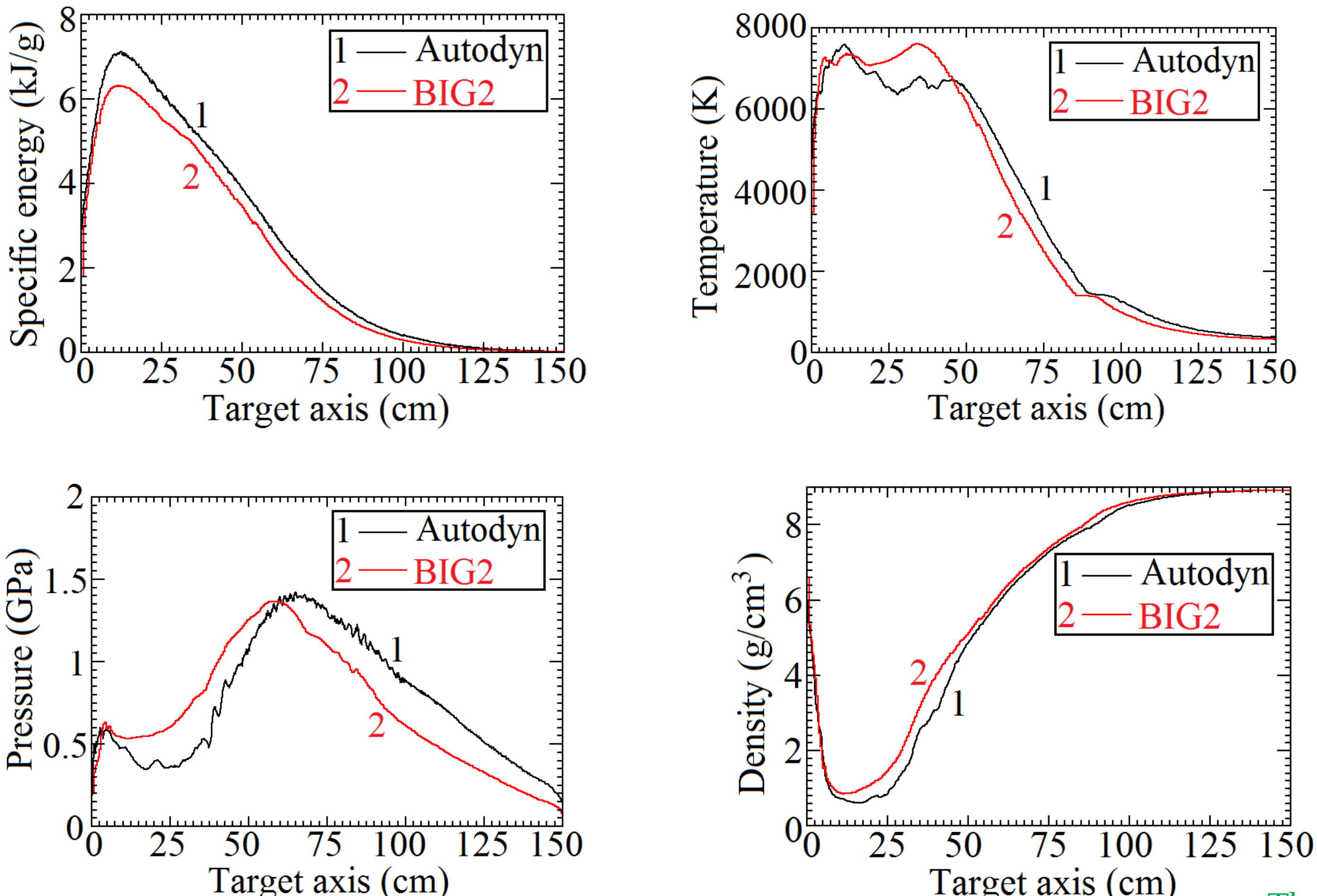


Temperature vs. target axis at different times



Density vs. target axis at different times

IV. Results and comparisons: comparison after 144 bunches



Thanks to Naeem

- Difference of the order of 10%, which is acceptable, considering different:
  1) FLUKA scoring; 2) Iteration step; 3) EOS; 4) Strength/Failure model; 5) Mesh type and size

IV. Results and comparisons: comparison of melting depth

Bunch number	FLUKA (static)	Measurement	Coupling BIG2 (melting platform)	Coupling Autodyn (melting platform)
108	63.5 cm	79.5 cm	74-81 cm	77-83 cm
144	67.5 cm	85 cm	85-92 cm	89-95 cm

- FLUKA-Autodyn results agree with that of FLUKA-BIG2 and test (difference ~10%)
- A numerical error of 20-30% should be considered, arising from:
  1) **FLUKA statistic error: <5%**
  2) **Limited iteration step (#bunch): defined by a density drop of 10-15% (not e.g. 1%...)**
  3) **Error from EOS, Strength/Failure model: order of 10% (or more?)**
  4) **Simulation accuracy of hydrocodes (mesh size, time step, …): order of 5%**
- Reference for machine protection: a margin of 20-30% is suggested

V. Summary

- For the simulation of hydrodynamic tunnelling, a different implementation coupling FLUKA and Autodyn has been benchmarked against HiRadMat-12 experiment and previous study coupling FLUKA and BIG2.
- Other case studies are foreseen, see Christoph's talk this afternoon.

Thank you!

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