Numerical simulation of proton-boron fusion via Micro Bubble Implosion

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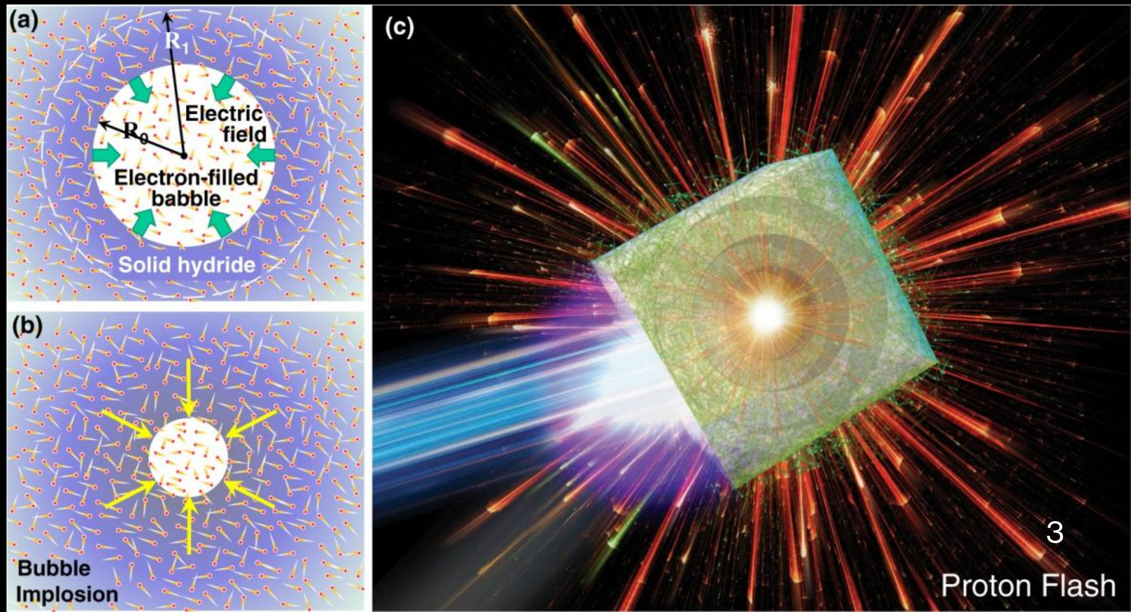
Outline

- Intro to Microbubble Implosion
- Recap of the last workshop
- EPOCH simulation setup
- EPOCH simulation results
- Pre pulse effect via FLASH
- Conclusion

The Microbubble Implosion (MBI)

- In Microbubble Implosion, a target with a spherical cavity is irradiated by an intense laser which heats the electrons. Once the electrons are heated, they start to fill the cavity and initiate the implosion of ions close to the cavity wall
- The laser intensity: $I \geq 10^{18} W/cm^2$
- The dimension of the target radius: $R \leq 1\mu m$
- The ion density at maximum compression: $\rho > 10^{30}\ ions/m^3$

[1]: M. Murakami et al, https://doi.org/10.1063/1.5093043
[2]: M.A.H. Zosa et al, Optimization of micro and nanoscale targets for ultra-high field generation and ion acceleration, Ph.D. dissertation
[3]: M.A.H. Zosa et al, https://doi.org/10.1063/5.0068815



Features of the MBI approach

- Since it's required to heat just electrons with a fs laser it is not required the adoption of high energy lasers;
- The system is intrisically highly symmetric allowing for an isotropic implosion;
- The working principle of MBI may reduce Bremmsstrhalung losses;

Potential challenges and aspects to enlighten

- It's still a theorical phenomenon which needs to be confirmed experimentally;
- The plasma regime under consideration has been investigated for astrophysical research;
- The conditions for the existence of this plasma can be maintained for a very limited time window$\rightarrow$ $tens\ of\ fs$;

Proton-Boron fusion via MBI: A preliminary study

Preliminar modeling: a 1D code

1. $\nabla^2\phi = 4\pi e\left(n_{e0}\left[1+\left(\frac{\gamma-1}{\gamma}\right)\left(\frac{e\phi}{Te0}\right)\right]^{\frac{1}{\gamma-1}} - n_{p0} - 5n_{B0} - Z_{Au}n_{Au0}\right)$
2. $\nabla\phi_e = 4\pi e n_e(\phi)$
3. $E = -\nabla\phi_e$
4. $\frac{dp_i}{dt} = \sum_{\{r_j<r_i\}}\left(\frac{Q_iQ_j}{r_j^2}\right) + \frac{Q_i^2}{2r_i^2} + Q_iE(r_i)$

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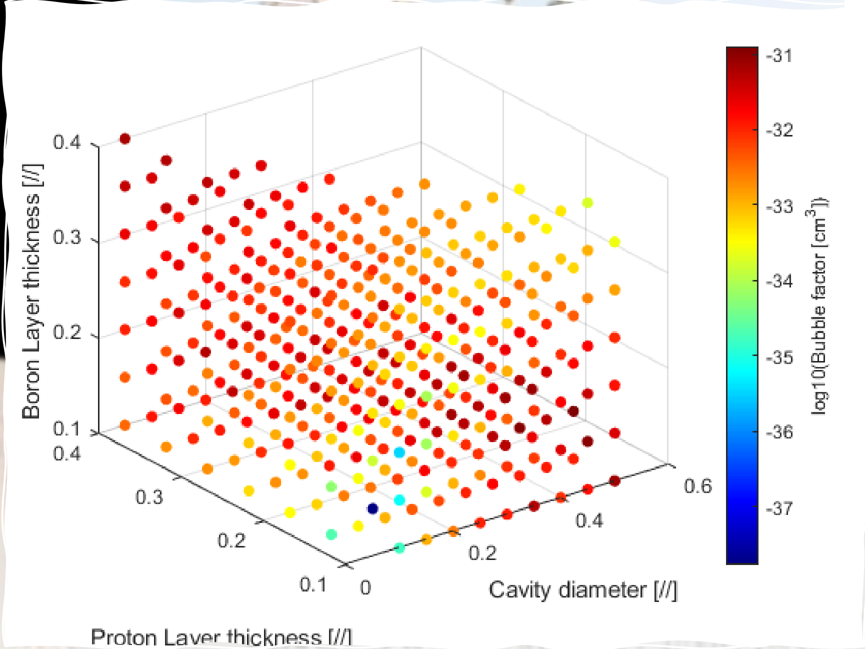
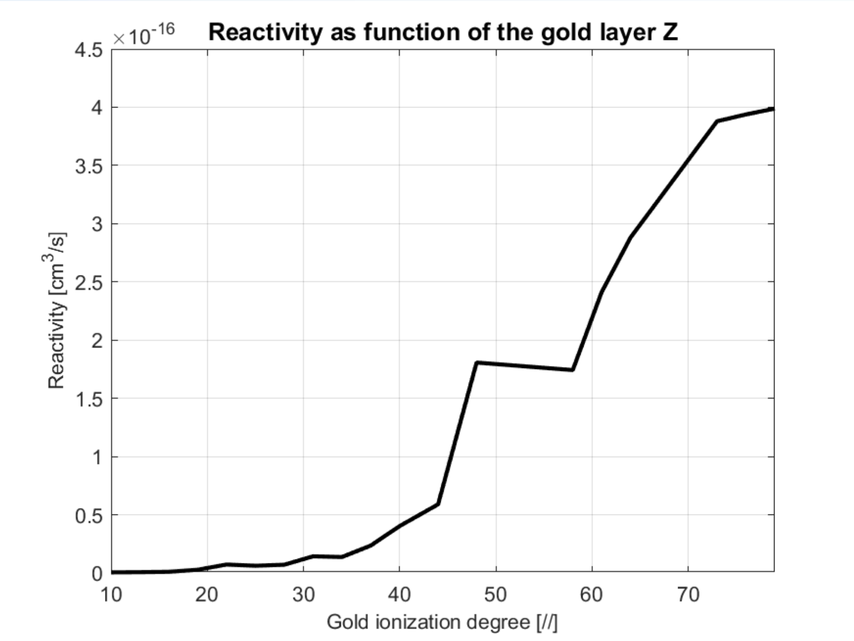




4th International Workshop on Proton-Boron Fusion

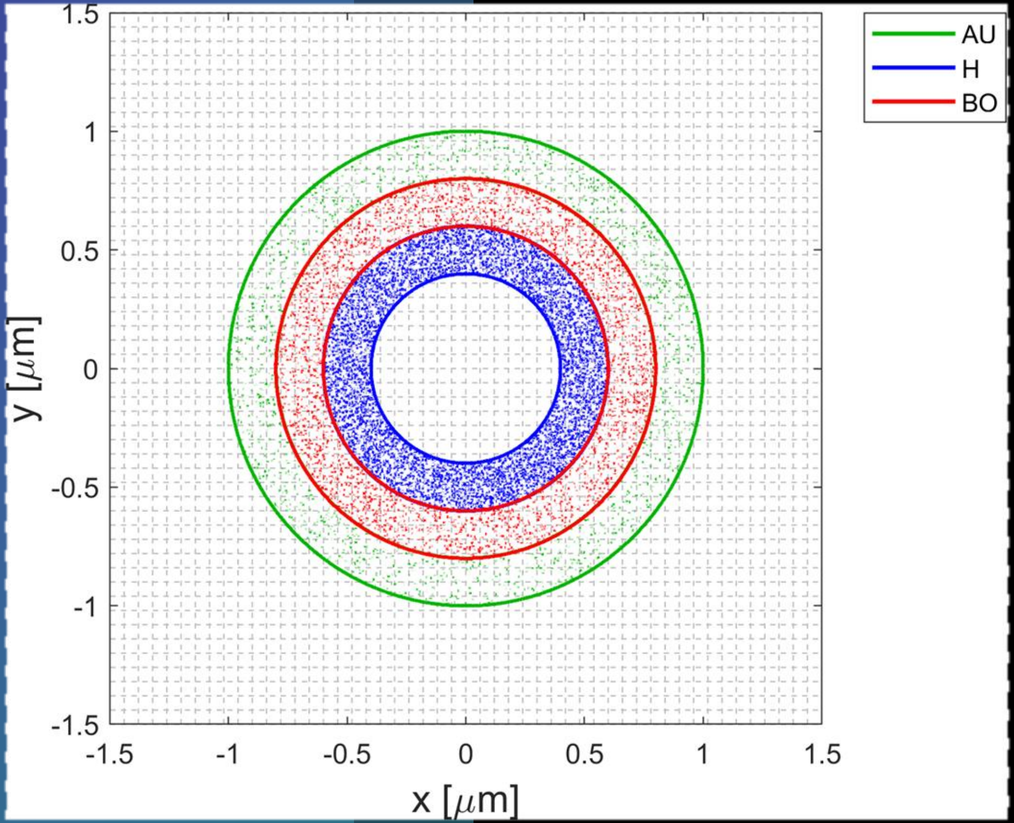
30th September – 3rd October 2024

FRASCATI, ITALY

Laser-Matter interaction via EPOCH

EPOCH 2D simulations setup

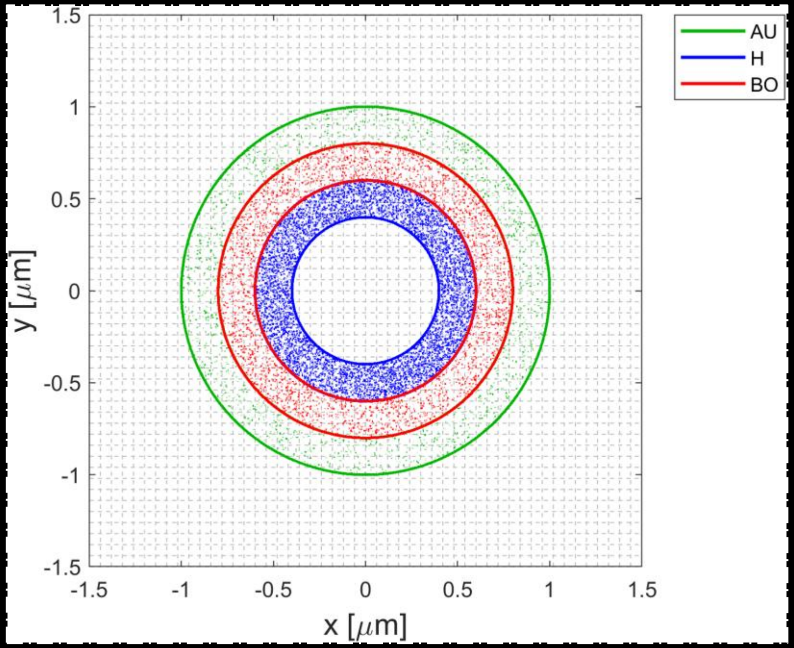
- Domain: 3 µm x 3 µm
- Mesh: 200x200

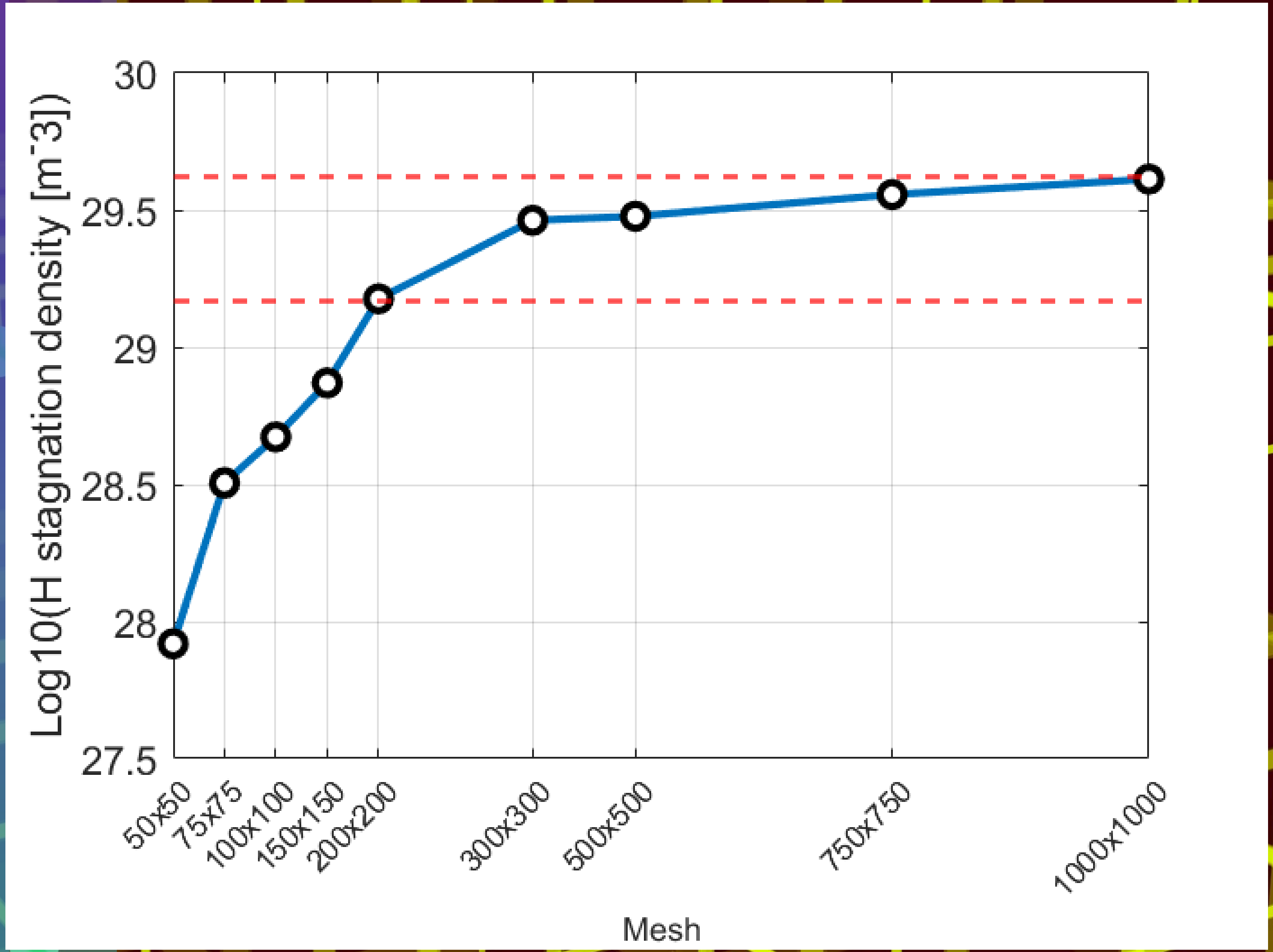


- Wavelength: 0.854 µm
- Spot size: 3 µm
- FWHM: 30 fs
- Intensity: 10^{17} to 10^{22} W/cm^2

- Outer radius: 1 µm
- Gold thickness: 0.2 μm
- Boron thickness: 0.2 μm
- Hydrogen thickness: 0.2 μm
- Cavity radius: 0.4 μm

EPOCH 2D mesh scaling

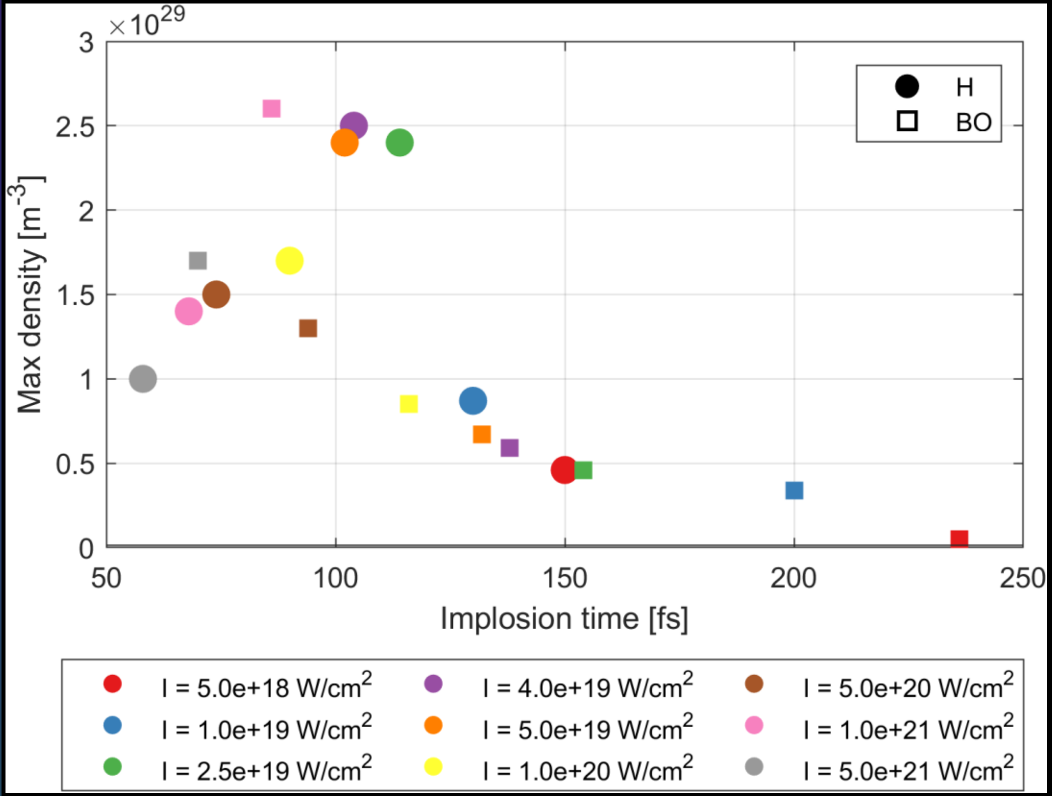


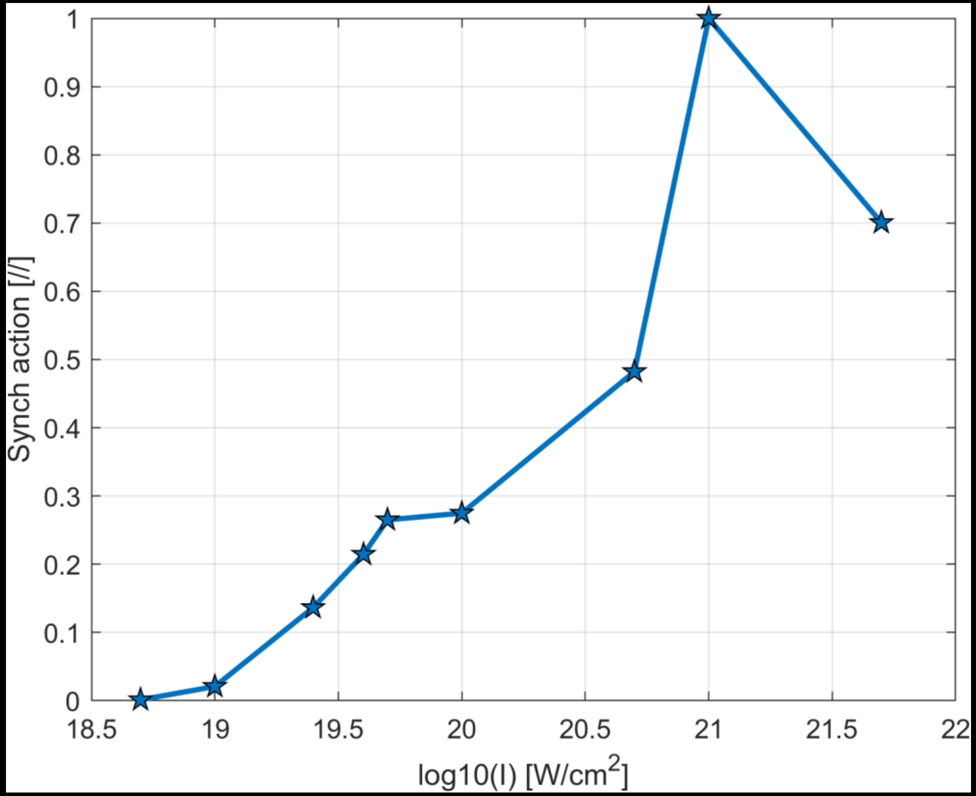


- Wavelength: 0.854 µm
- FWHM: 30 fs
- Spot size: 3 µm
- I: 5e20 W/cm^2

EPOCH results

LASER INTENSITY SCALING



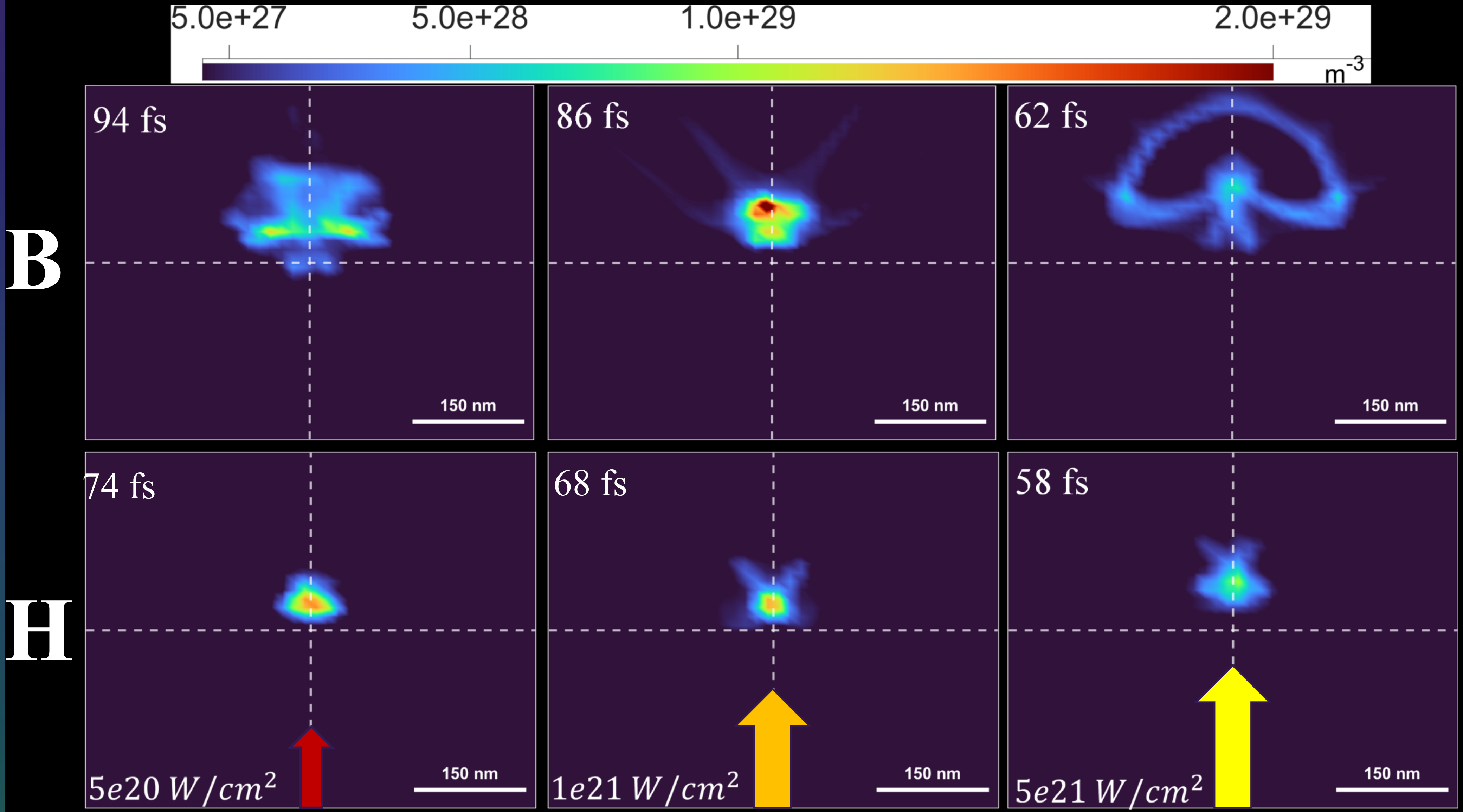


- A parametric analysis with respect to the laser intensity has been carried out
- It appears clear that the relative distance between pB implosion time increases as the intensity decreases

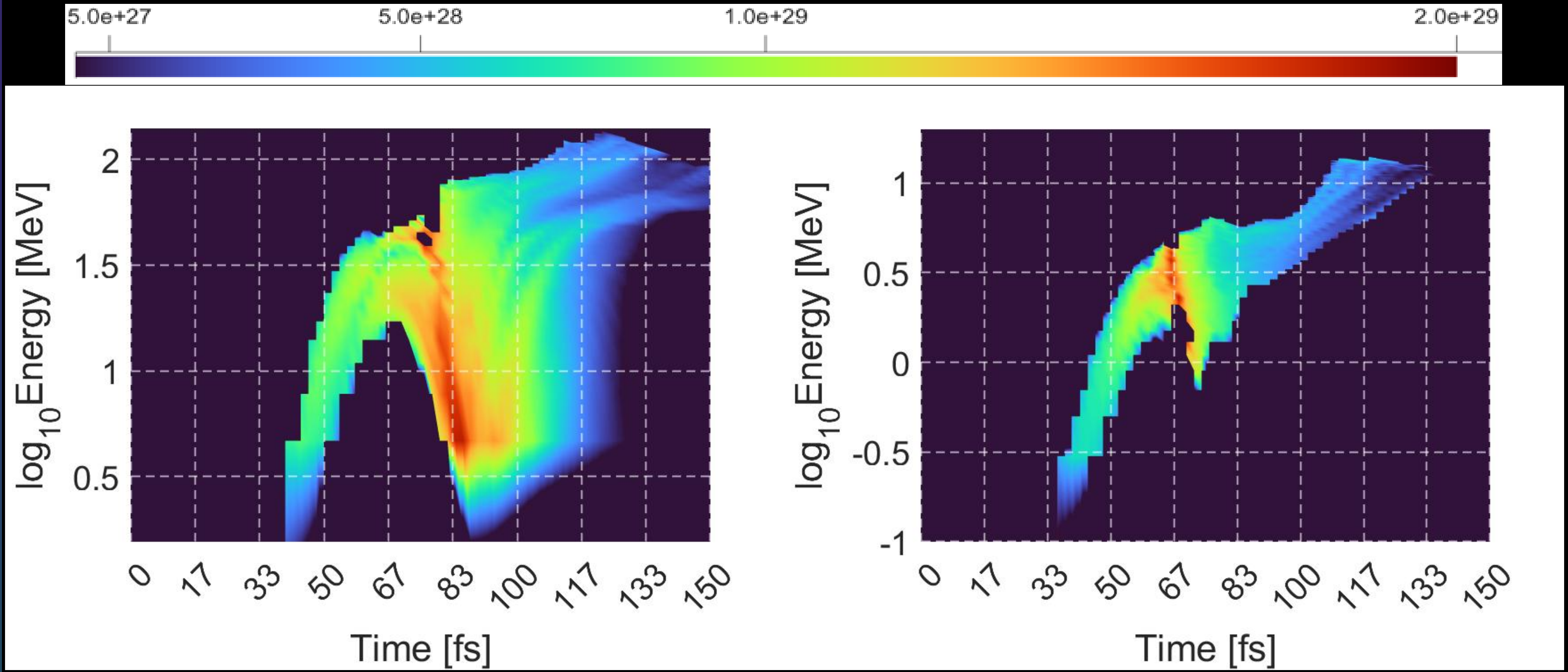
A figure of merit called Synch Action has been introduced:

$$S_A(I) \equiv \frac{\max\big(\rho_H(I)\big)\max\big(\rho_{BO}(I)\big)}{abs\big(t_{imp}^{H}(I) - t_{imp}^{BO}(I)\big)}$$

IMPLOSION DISPLACEMENT



MBI HEATMAPS



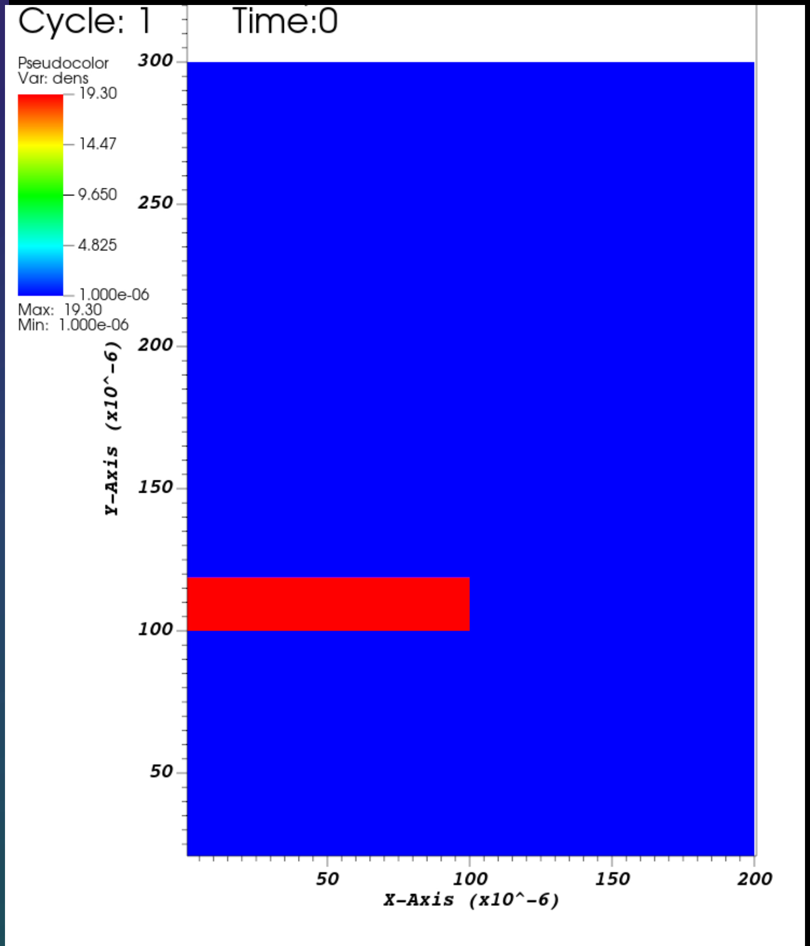
Boron

Hydrogen

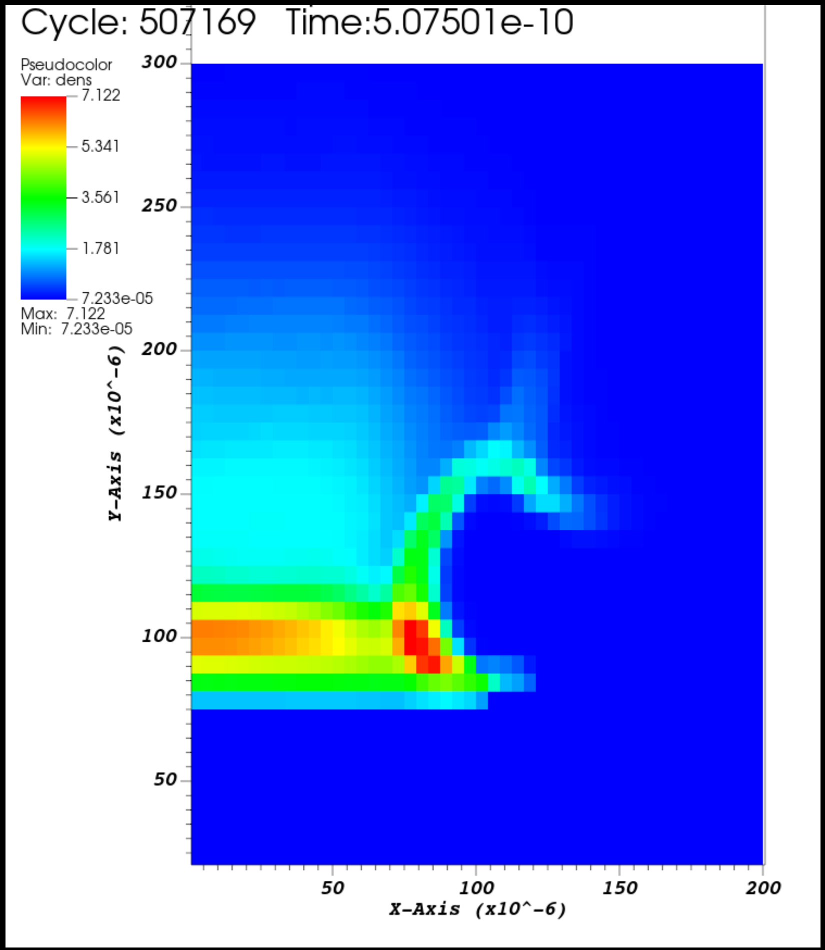
$I = 10^{21} W/cm^2$

Hydrodynamic simulations via FLASH

Pre-pulse effect via FLASH



- 2D cylindrical
- 200 nm thick slab
- Gold (ideal EoS)
- cgs units
- 0.5 ns irradiation
- I: $10^{21} W/cm^2$
- C: 10^9
- Flat-top profile



Conclusions

The EPOCH code results for MBI needs to be interpreted as general trend behaviour

In the near future the best would be to use the EPOCH outputs after the laser irradiation as inputs of a 3D MD code

THANK YOU FOR THE ATTENTION!

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"PROton BOron Nuclear fusion: from energy production to medical applications",
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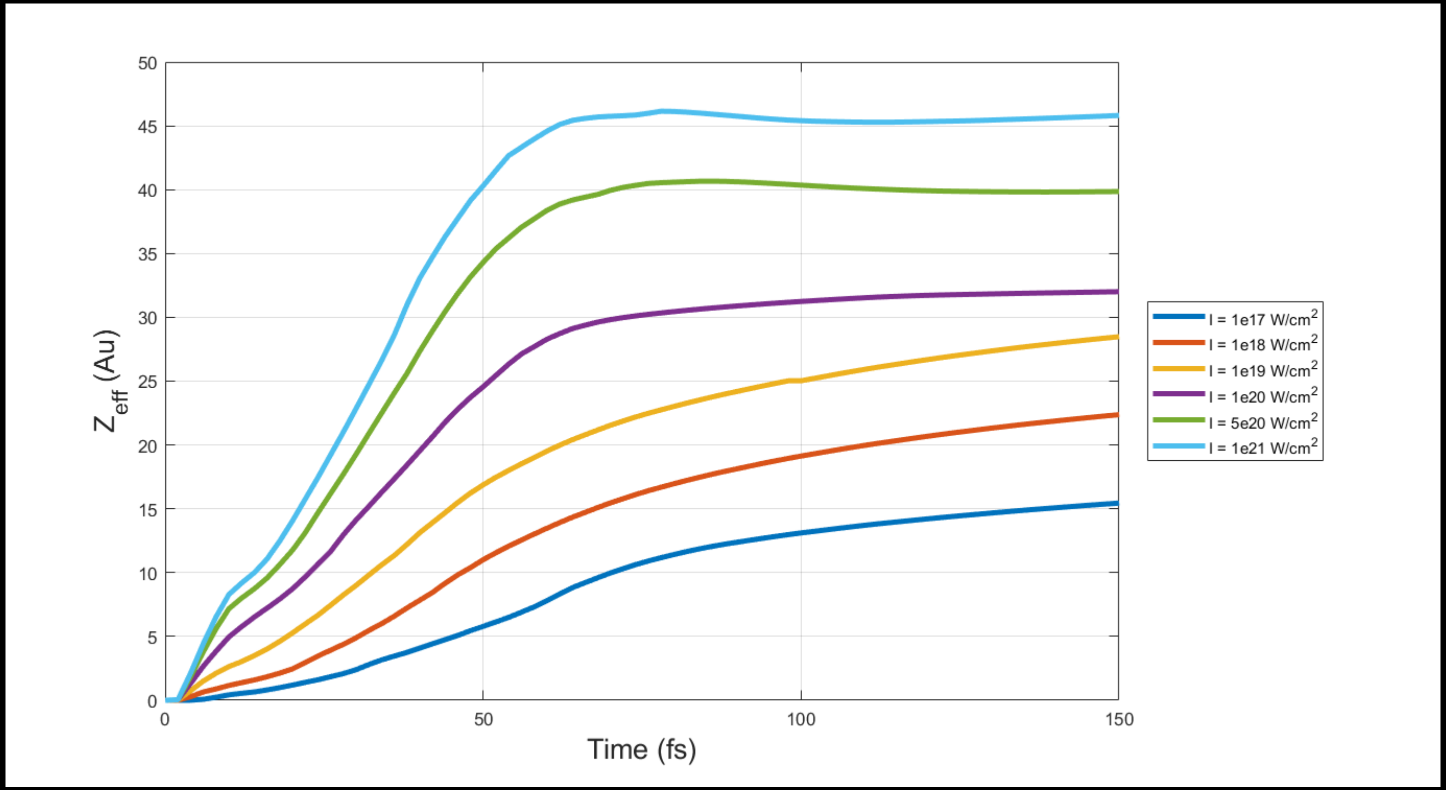
Backup slides

Gold effective ionization



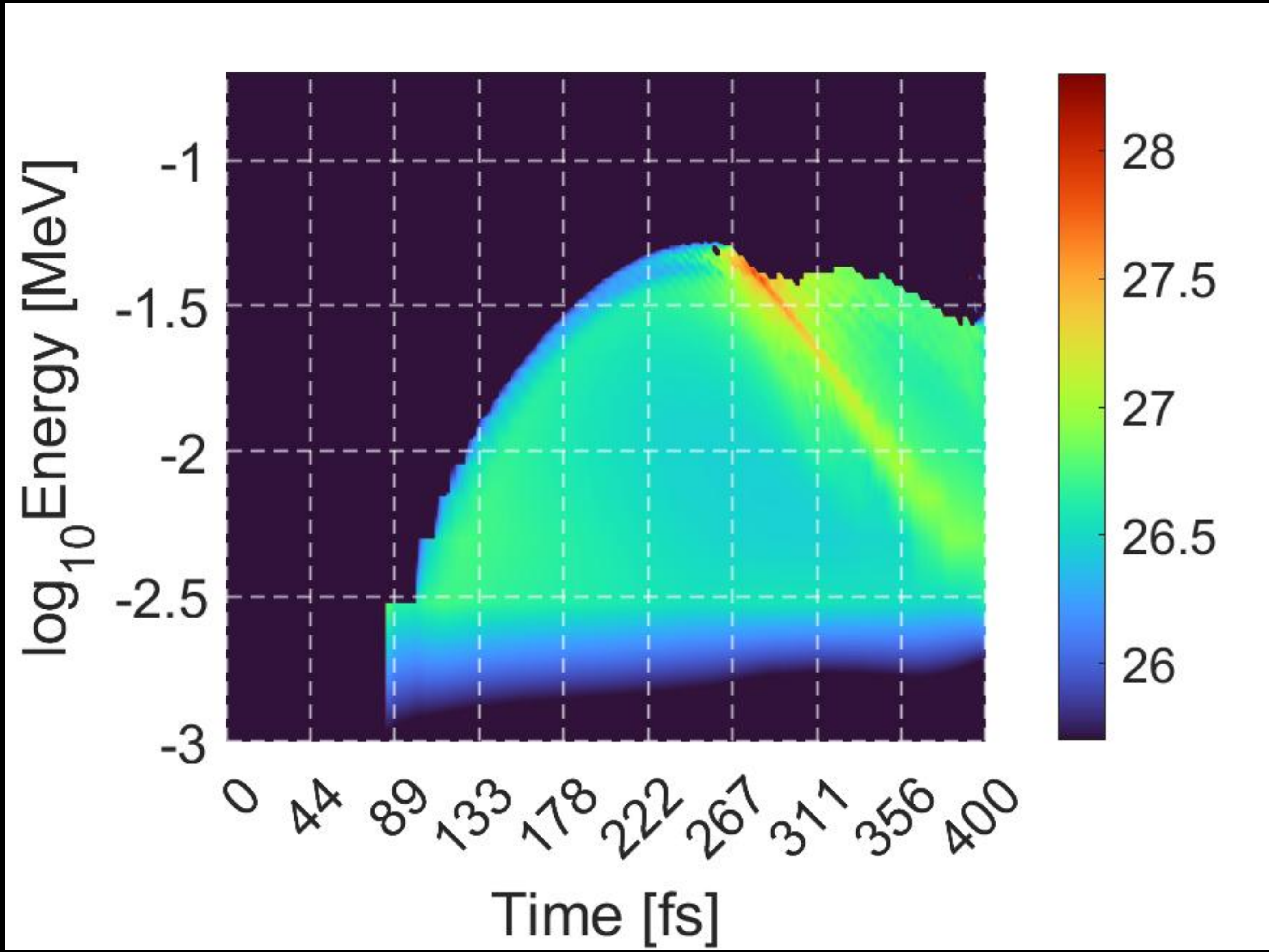
$$Z_{eff}(t) = \sum_{k=1}^{79} k\, AU_k\,(t)$$

Where

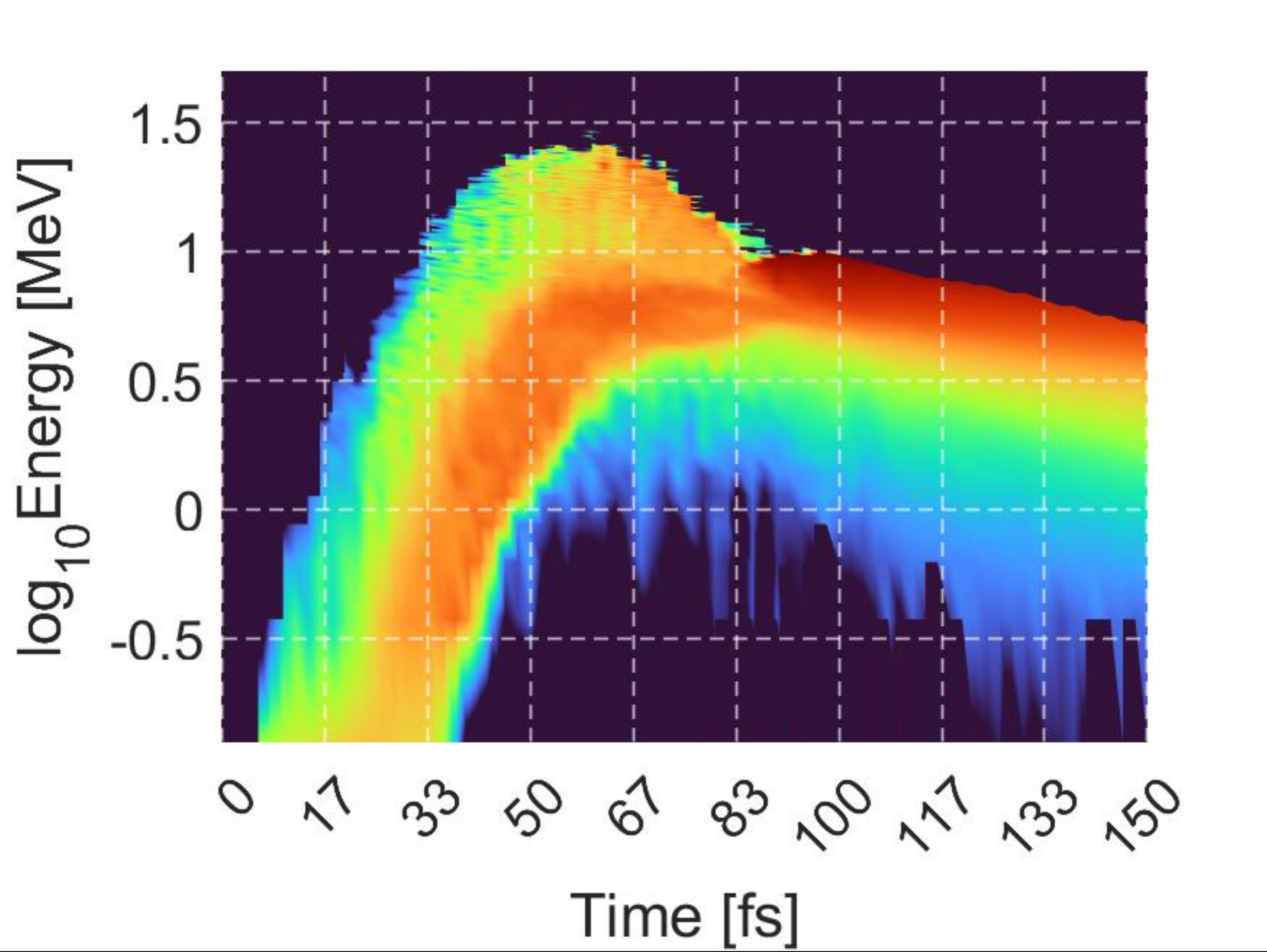
$$AU_k(t) = \frac{N_{AU_k}(t)}{N_{AU_0}}$$

Which is the lower limit for the intensity?

$I = 10^{17} W/cm^2$



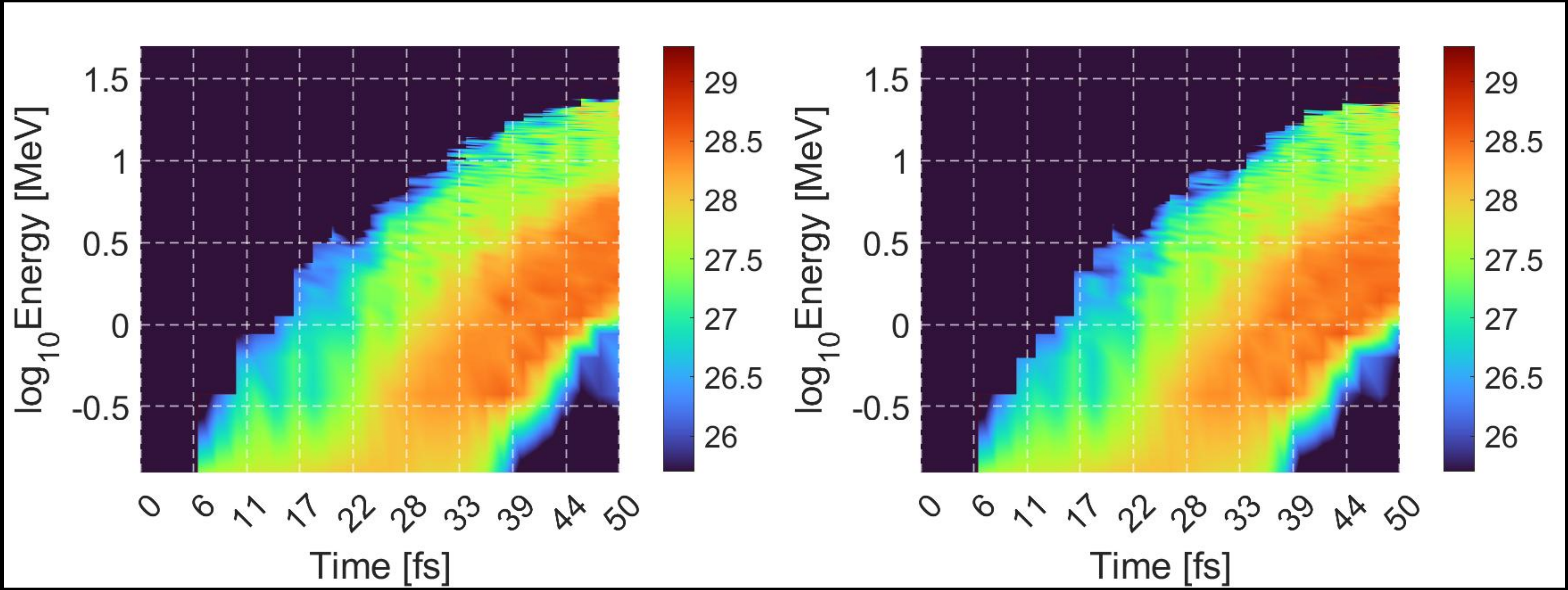
Electrons heatmap



$I = 10^{21} W/cm^2$

Bremmstrhalung losses

$$I = 10^{21} W/cm^2$$



Bremmstrhalung off

Bremmstrhalung on

Why MBI is interesting in the case of pB nuclear fusion(1)

One of the most problematic aspect of pB11 fusion is about Bremmstrhalung losses;

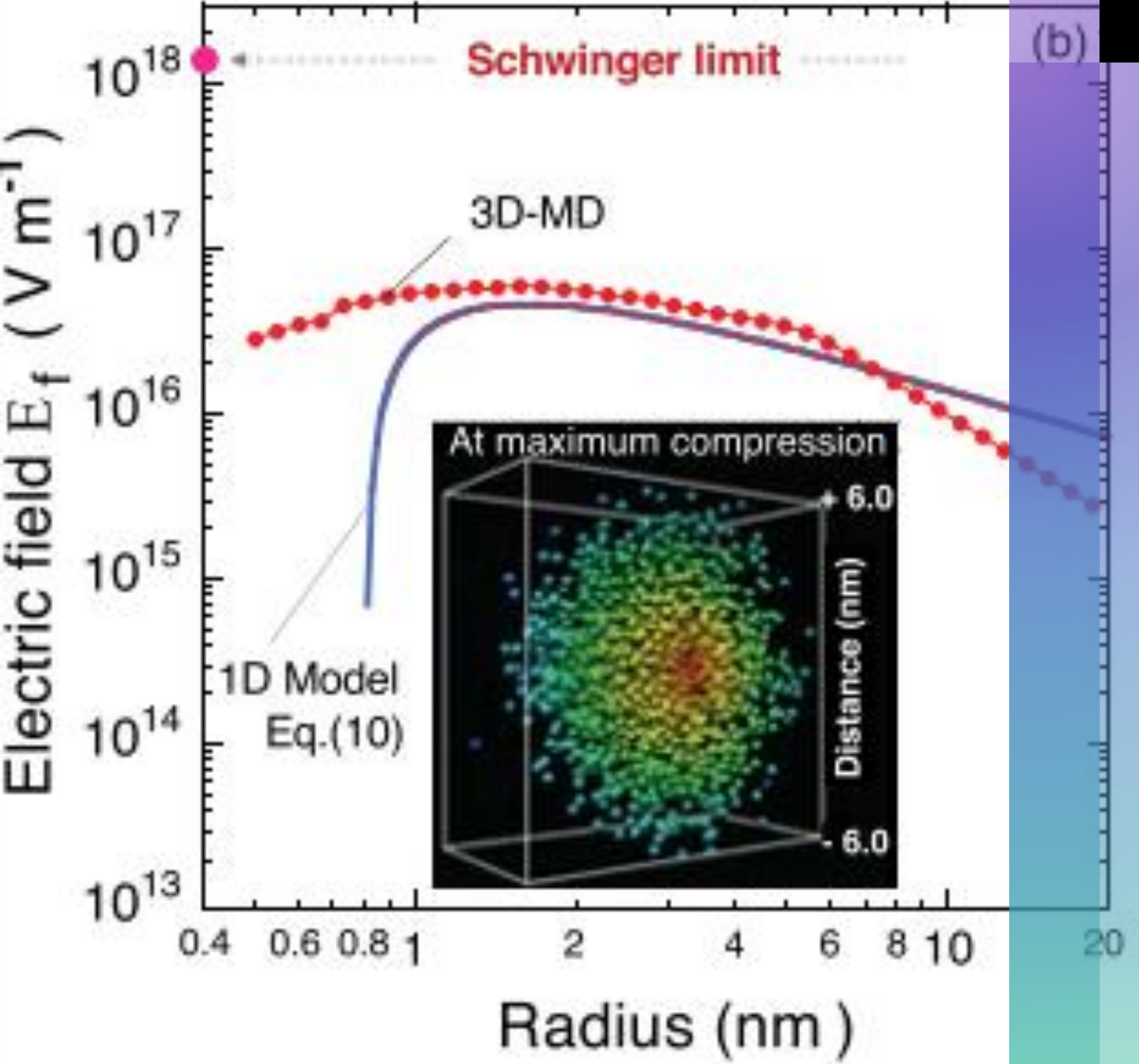
As we know these losses scales as the Z^2 of the plasma, therefore a pB11 plasma will be subject to losses which are 25 times higher than DT plasmas;

Bremmstrhalung losses are mitigated thanks to design of the target also. They may actually be beneficial for the compression and confinement;

As mentioned in [5], the possibility of having a non equilibrium burning plasma may help in this respect;

The MBI concept is founded on a non equilibrium condition between ions and electrons. The MBI is what happens to ions trying to reach the equilibrium;

[5]: T.A. Mehlhorn et all, https://doi.org/10.1155/2022/2355629



About the MBI proposition (2)

- In this picture, you can observe the effect of this compression;
- The electric field reported on the y-axis is the field generated by protons while compressed to such high densities, in the order of $10^{28} - 10^{29}\ particles/cm^3$;
- The possibility to exploit this phenomenon is very interesting for nuclear fusion too!

- [1]: M. Murakami et al, https://doi.org/10.1063/1.5093043

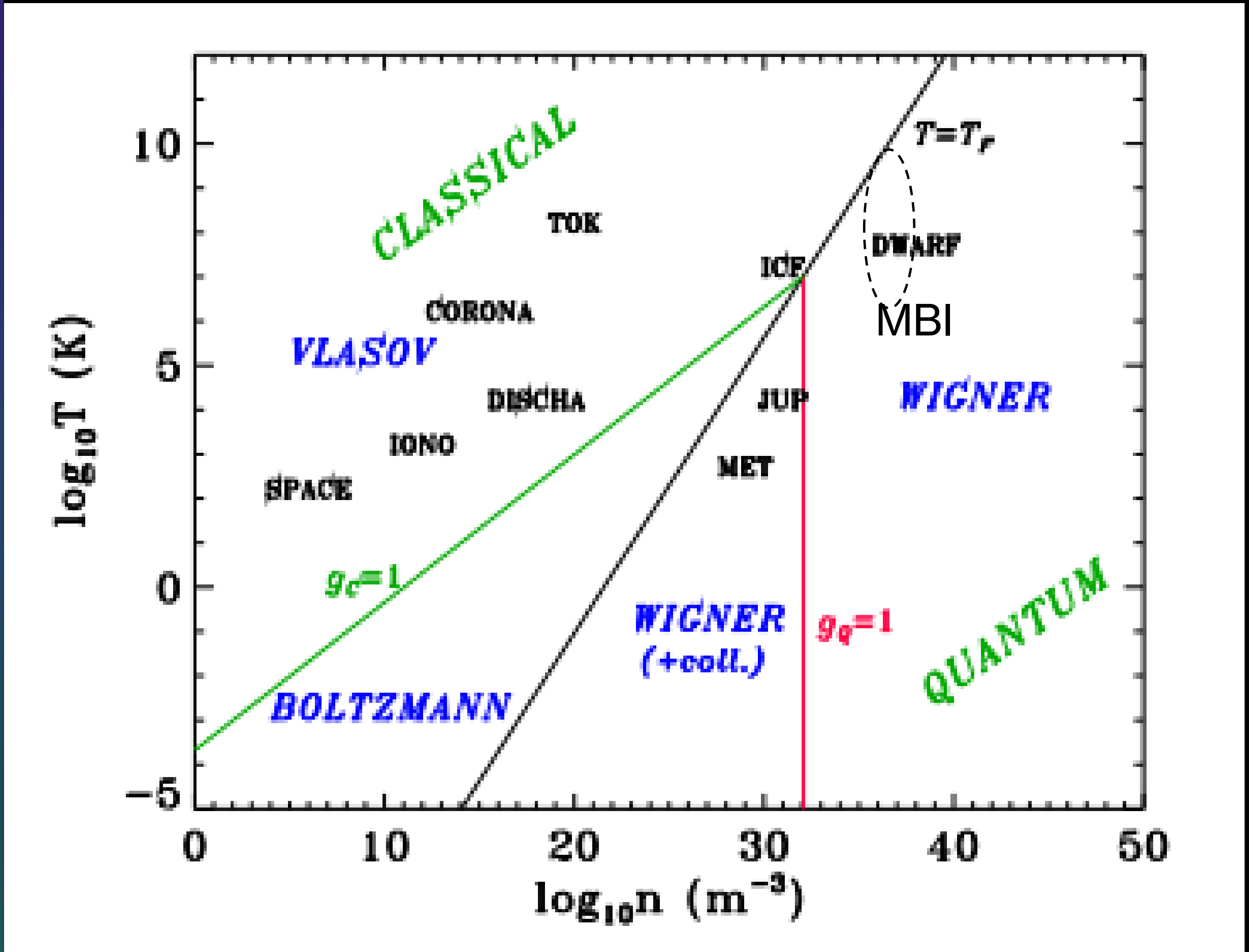
Coulomb explosion (CE) vs MBI

- CE is a phenomenon which share with MBI some basic ideas;
- Thanks to the irradiation of a solid sphere by a HIL there will be an explosion as consequence of the coulomb repulsion between ions which have been ionized
- The condition for achieving CE is:

$$\frac{I_L}{10^{18} W/cm^2}\left(\frac{\lambda_L}{1\mu m}\right)^2 \gg \frac{4Zn_{io}}{50nm}\left(\frac{R_0}{50nm}\right)^2 \quad [6]$$

[6]: M.Murakami, K. Mima, https://doi.org/10.1063/1.3256183

Quantum plasmas in nuclear fusion



- In the case of proton-boron fusion, it's required a higher energy with respect to the deuterium-tritium case.
- Moreover, protons are fermions therefore subject to the Pauli's principle.
- For what concerns the DT fusion, quantum effects may play a major role and therefore we need a more time to address this point

[7]: G.Manfredi, https://doi.org/10.1090/fic/046/10