(Magnetized) collisionless ion- gas/plasma interactions - modelling the streaming instability in the laboratory?

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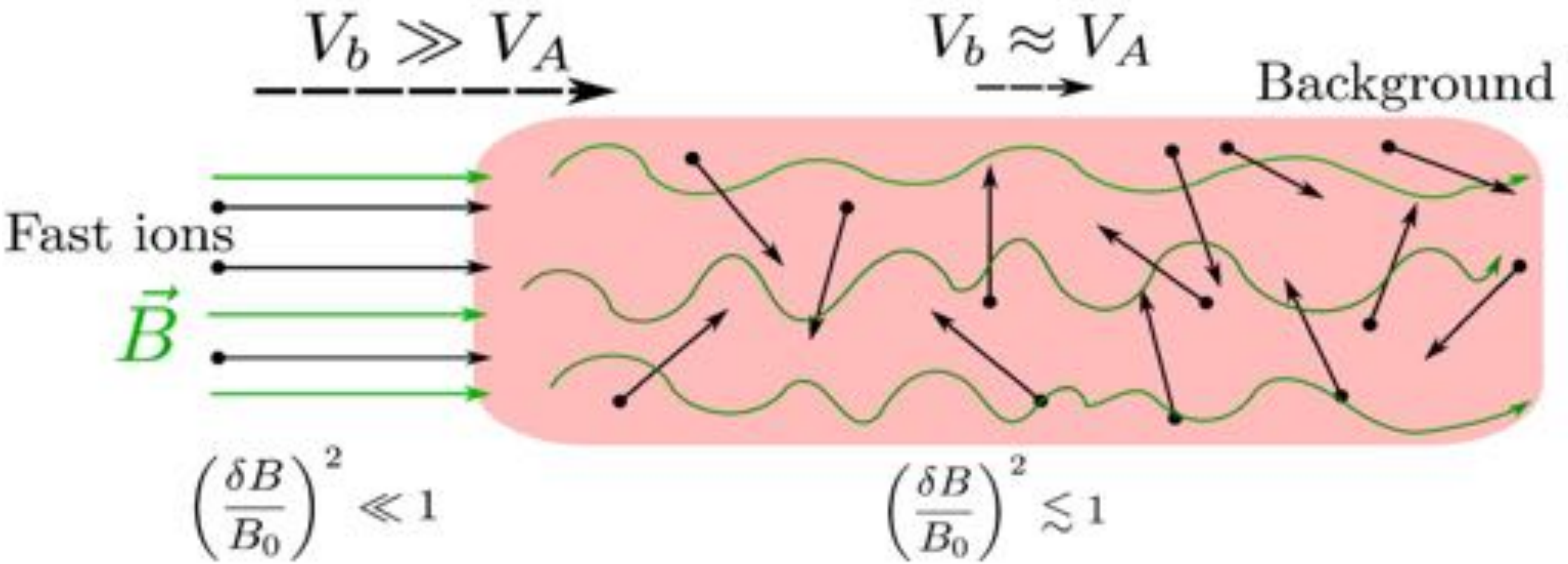
Schematic of the streaming instability

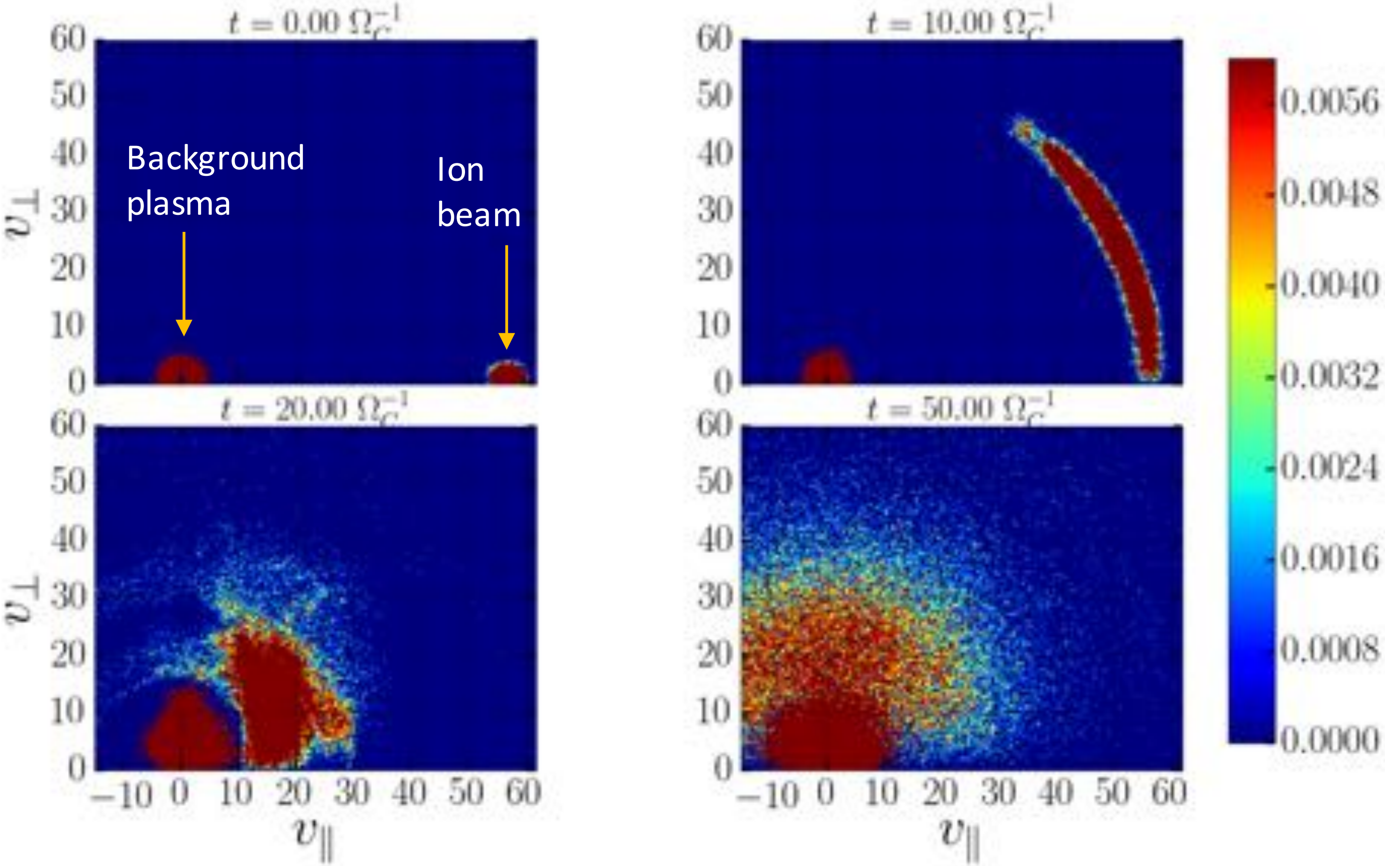
- EM ion instability ubiquitous in space plasmas
- Generates MHD waves & turbulence
- Suspected to play a key role in “anomalous” ionization of ISM, particle acceleration at shocks, …

Growth rate $\sim \Omega_{ci}$

Length scales$\sim c/\omega_{pi}$



Hybrid (Heckle code) illustrative simulation

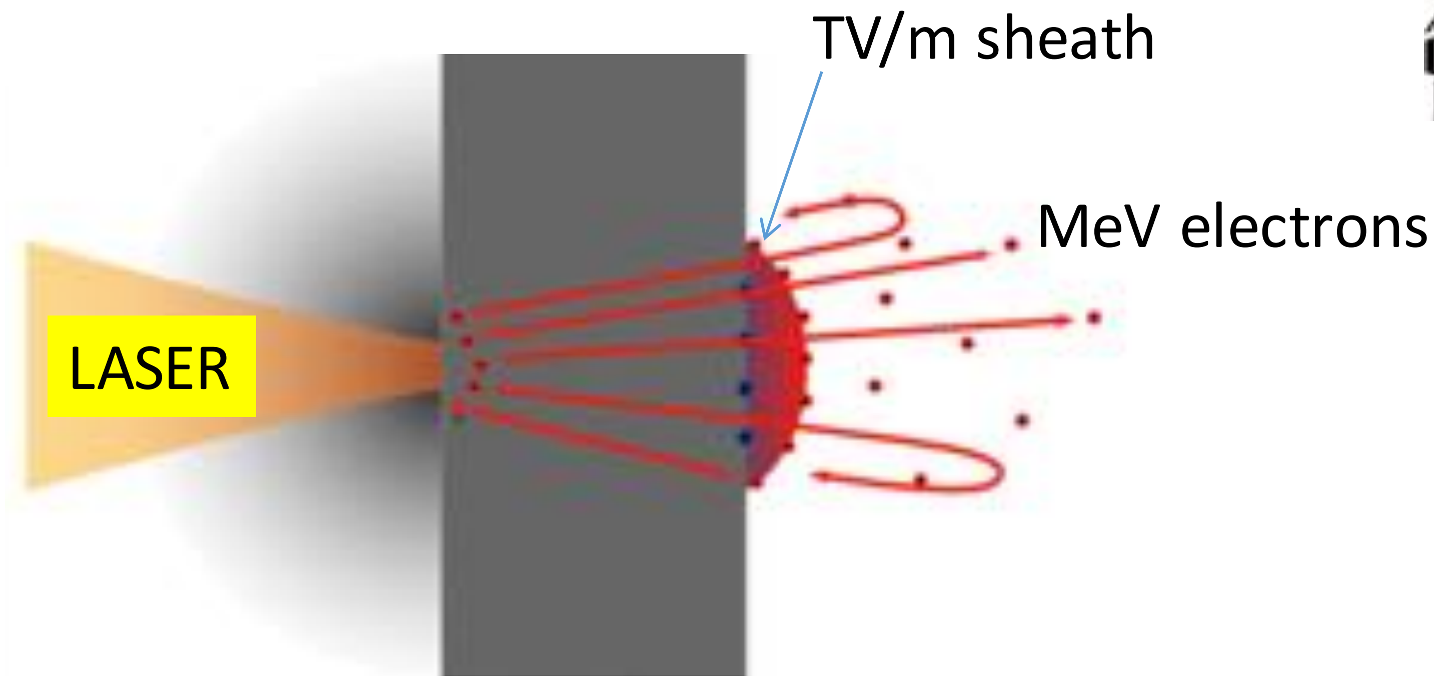


- initial streaming proton at $v_{//}$=55 (in units of Alfven speed, i.e. 300 keV)
- 20 T magnetized plasma

→ **progressive thermalization of the directed ion beam**

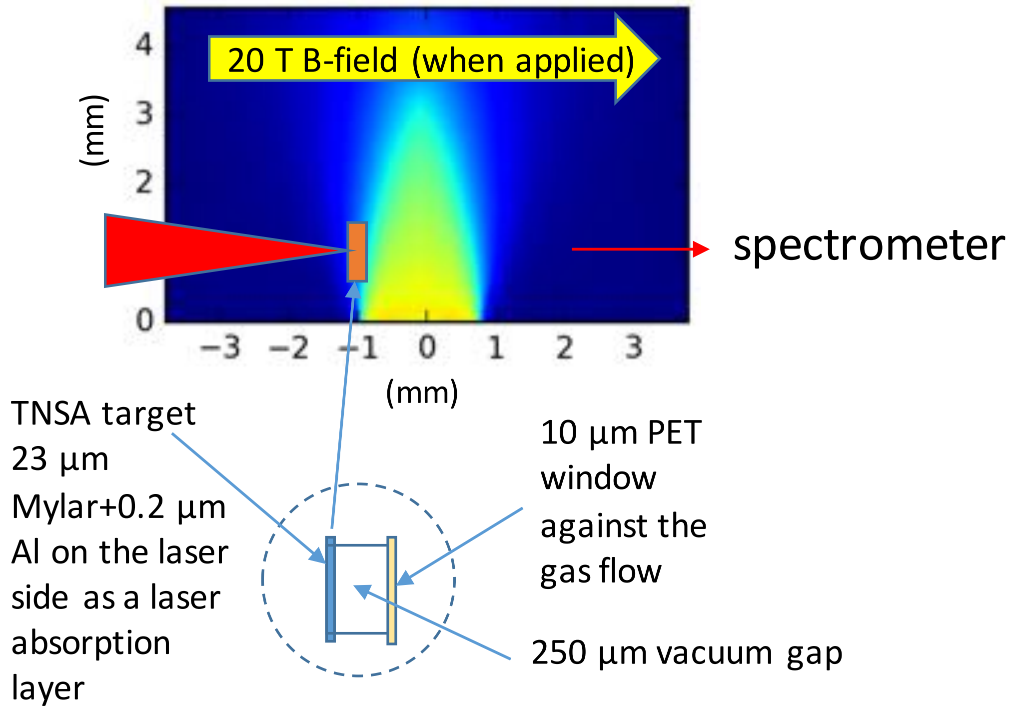
We exploit ultra-intense lasers electrostatic acceleration on solids ("TNSA") to generate the fast ions

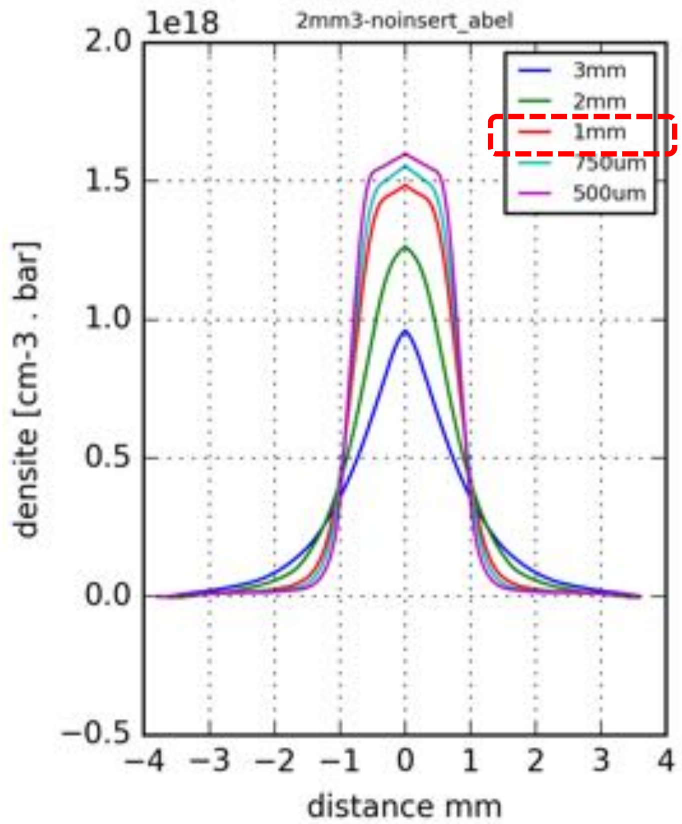
10 J, 300 fs



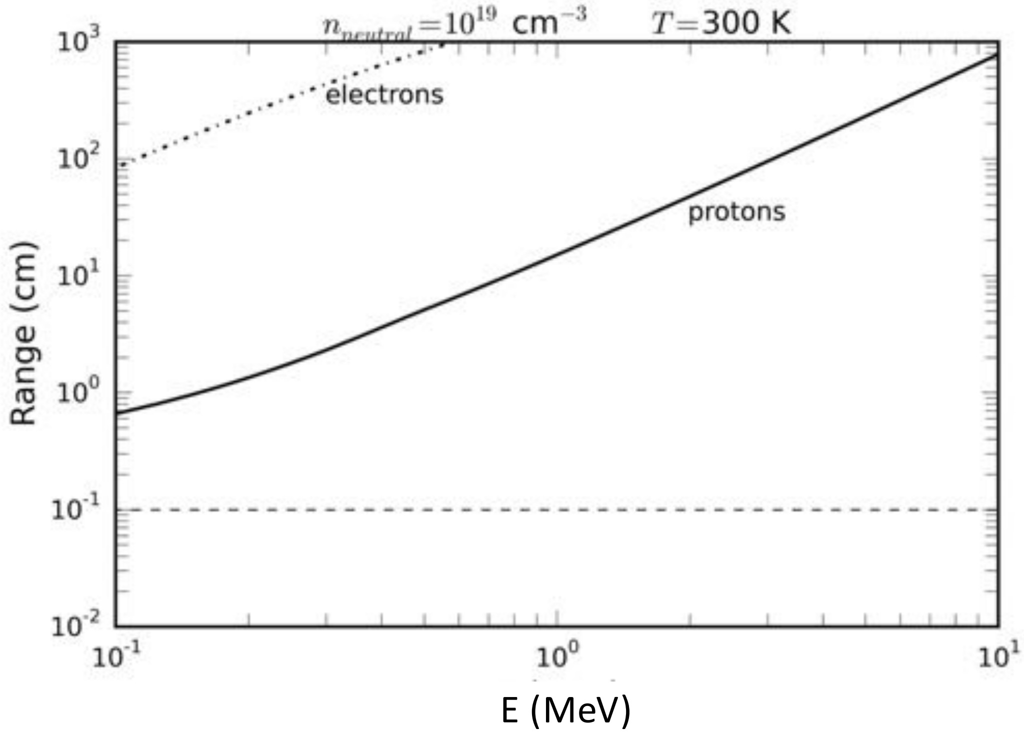
- Maximum proton energy is near 10 MeV.
- Divergent beam.

For the plasma medium, we use a gas jet





For these densities (~10^{19} cm^{-3}), we are in a collisionless configuration



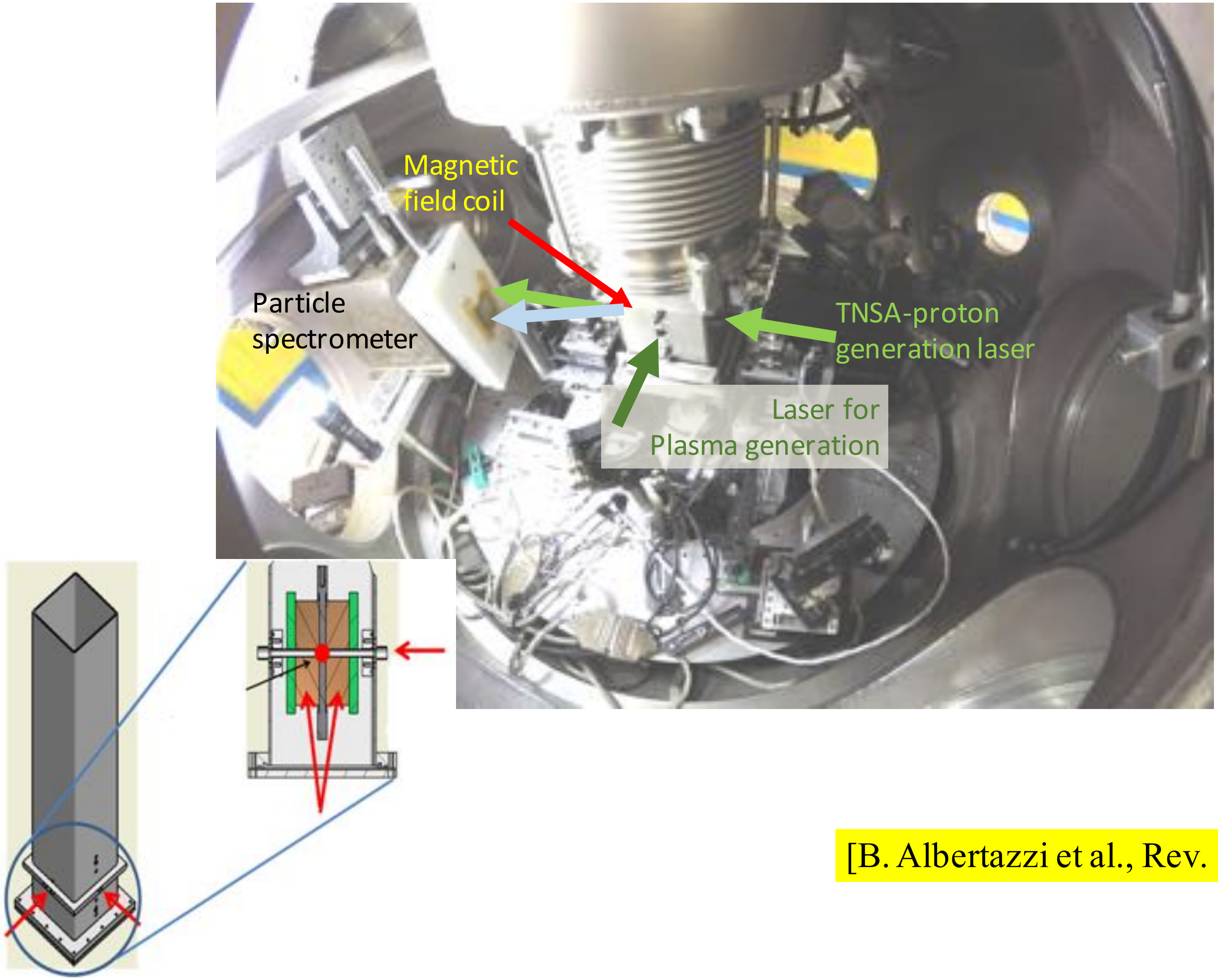
For a 1 MeV proton:

Gyro-period ~ 0.5 ns

Mean free path > system size (few mm)

$v \sim 3 \times v_{Alfven}$

Our method for large-scale, uniform external magnetization

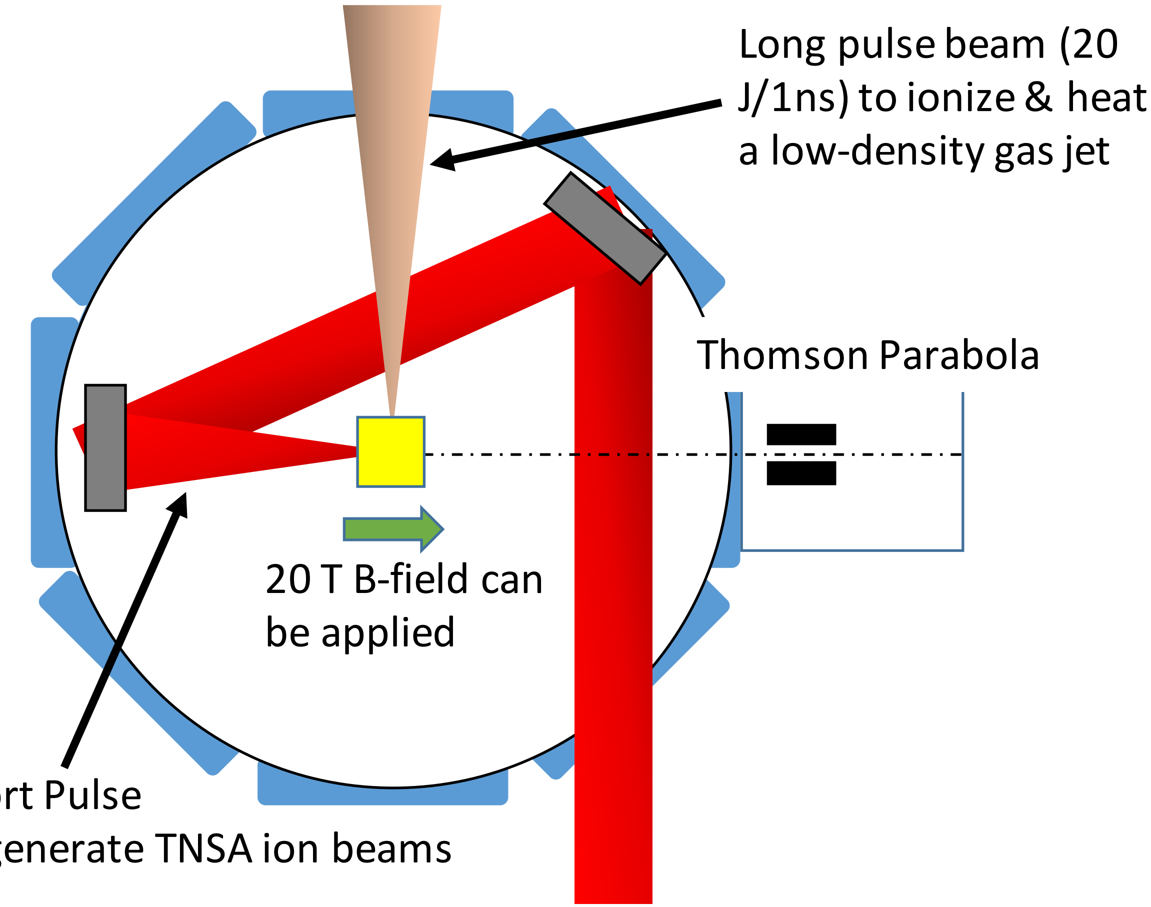


Typical plasma scales
mm, ps

B-field scales
cm, µs

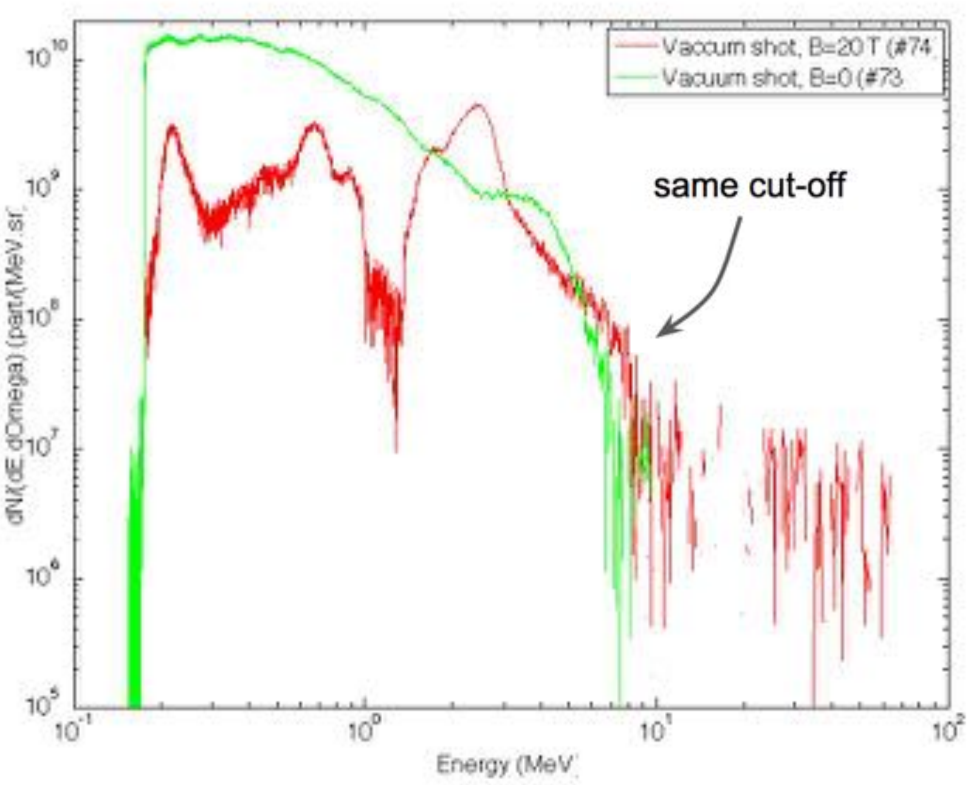
[B. Albertazzi et al., Rev. Sci. Instru 84, 043505 (2013)]

Overall set-up



First vacuum test shots : Immersing the setup in 20 T B-field

→ does not affect the proton maximum energy from the TNSA target, but modulates the spectrum

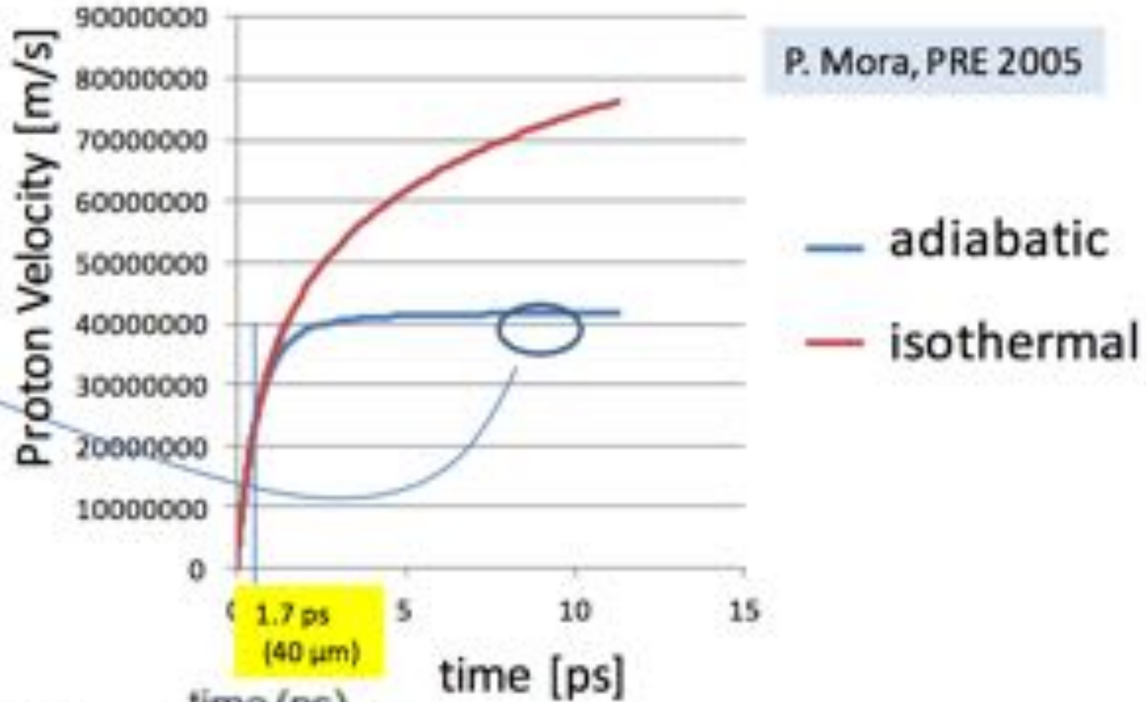


Magnetization would impact the protons if the B-field magnetizes the electrons before acceleration is saturated

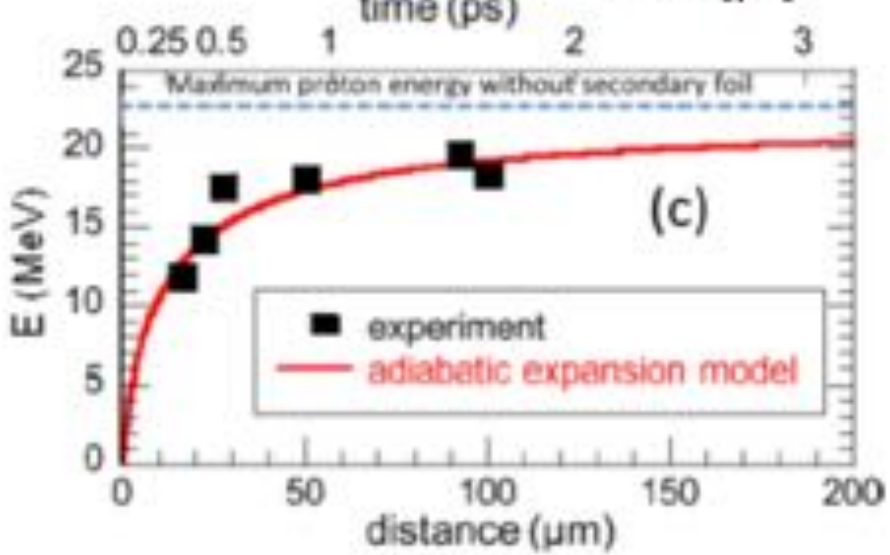
Two phases in TNSA:

1) Isothermal
2) Adiabatic cooling of the electrons

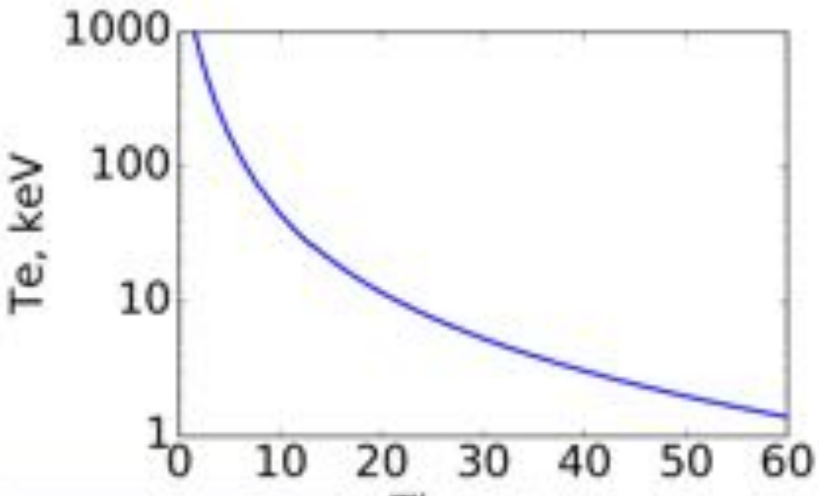
$$v_{final} \cong 2c_s \ln(0.32\, x_L/\lambda_D + 4.2)$$



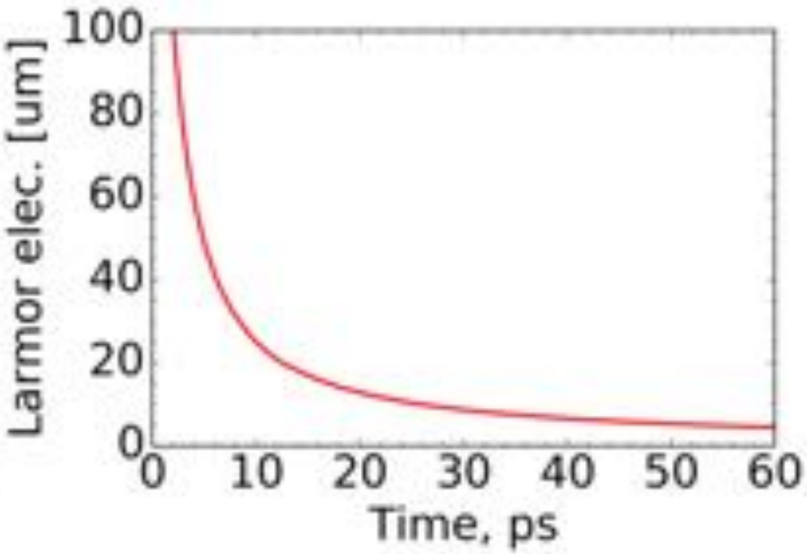
Corroborated by our measurement of proton energy saturation using similar parameters [S.N. Chen, PoP 2014]



Before 2 ps, the electrons are indeed not magnetized, hence no impact of the B-field on acceleration



P. Mora, PRE 2005



$$\text{For}: \ t < \tau_{x_L}$$
$$\rightarrow T_e \sim T_{e0}$$

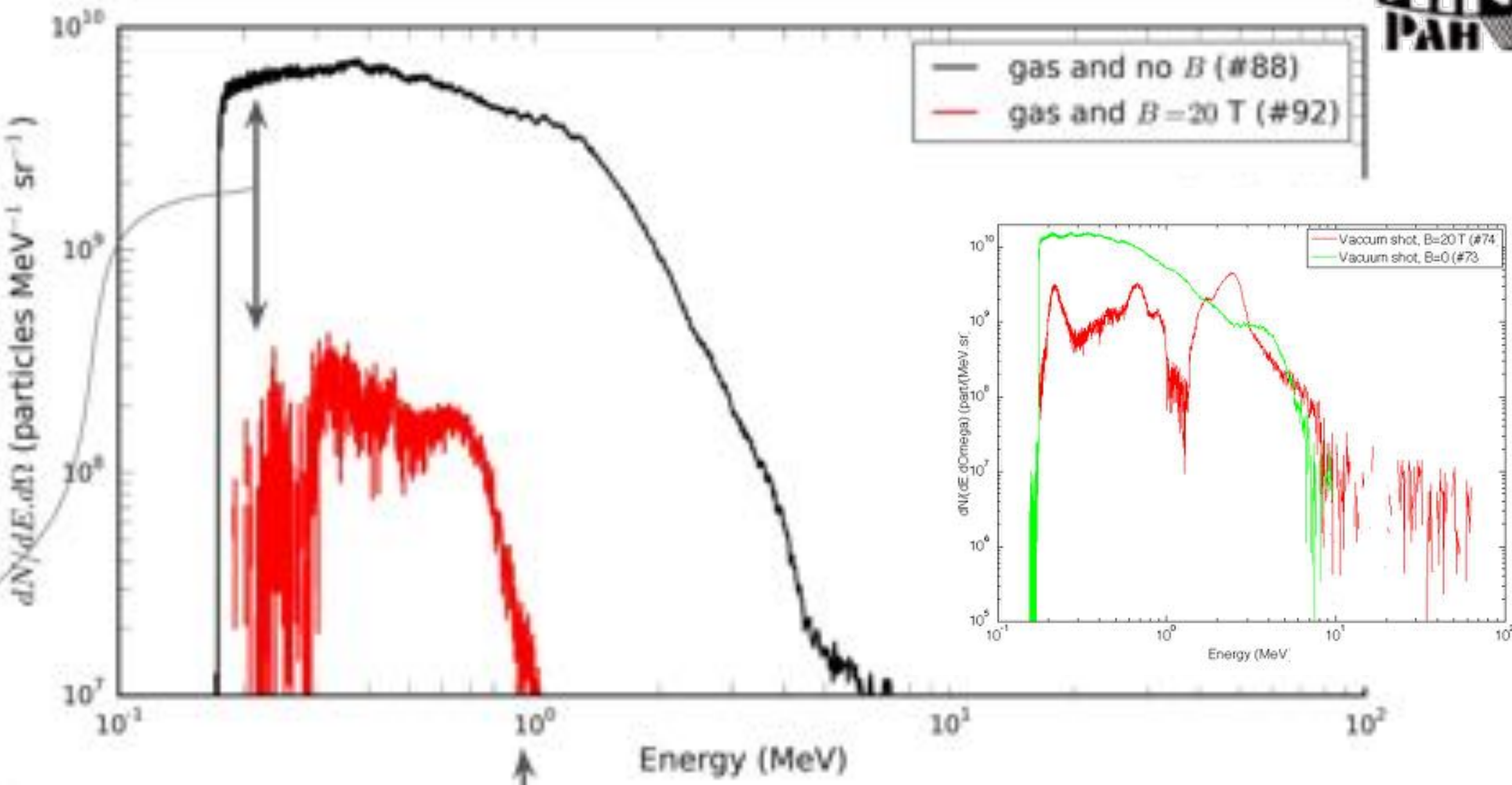
$$\text{For}: \ t > \tau_{x_L}$$
$$\rightarrow T_e(t) \propto T_{e0} \left(\frac{\tau_{x_L}}{t} \right)^2$$

- When the TNSA beam reaches > 100 µm, the electrons have fully cooled down.
- By this time their gyroradii are small compared to the system size.

When injected in the *magnetized* (non pre-ionized) gas, a huge downshift in proton energy is observed

Ne gas @ 15 bars
→ ~2 10^{20} at/cc

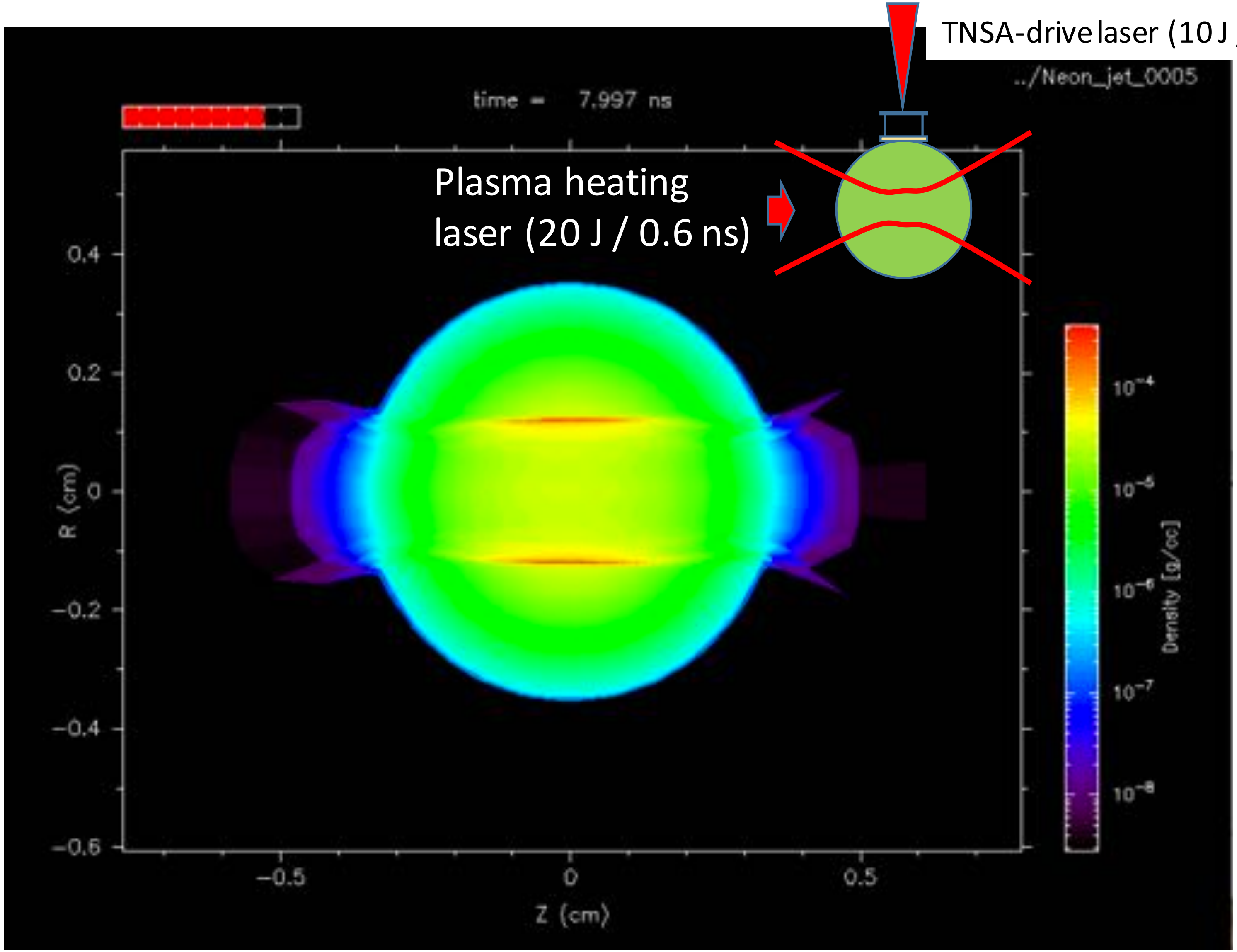
nanosecond-laser OFF



Shift cannot be due to magnetic field modulation only. Extra scattering?

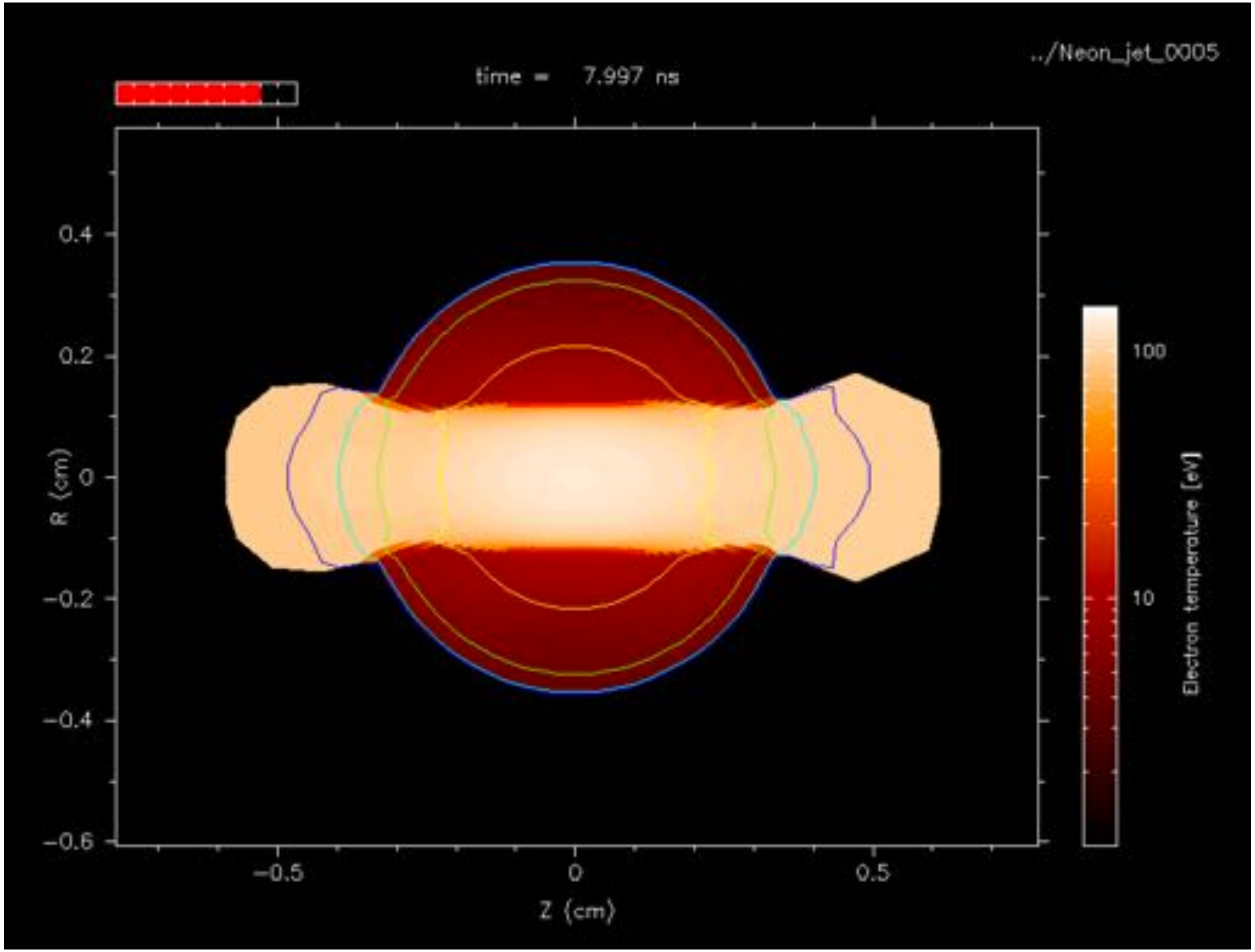
Large change in the energy cut-off

Now heating by the long-pulse, quite homogeneously



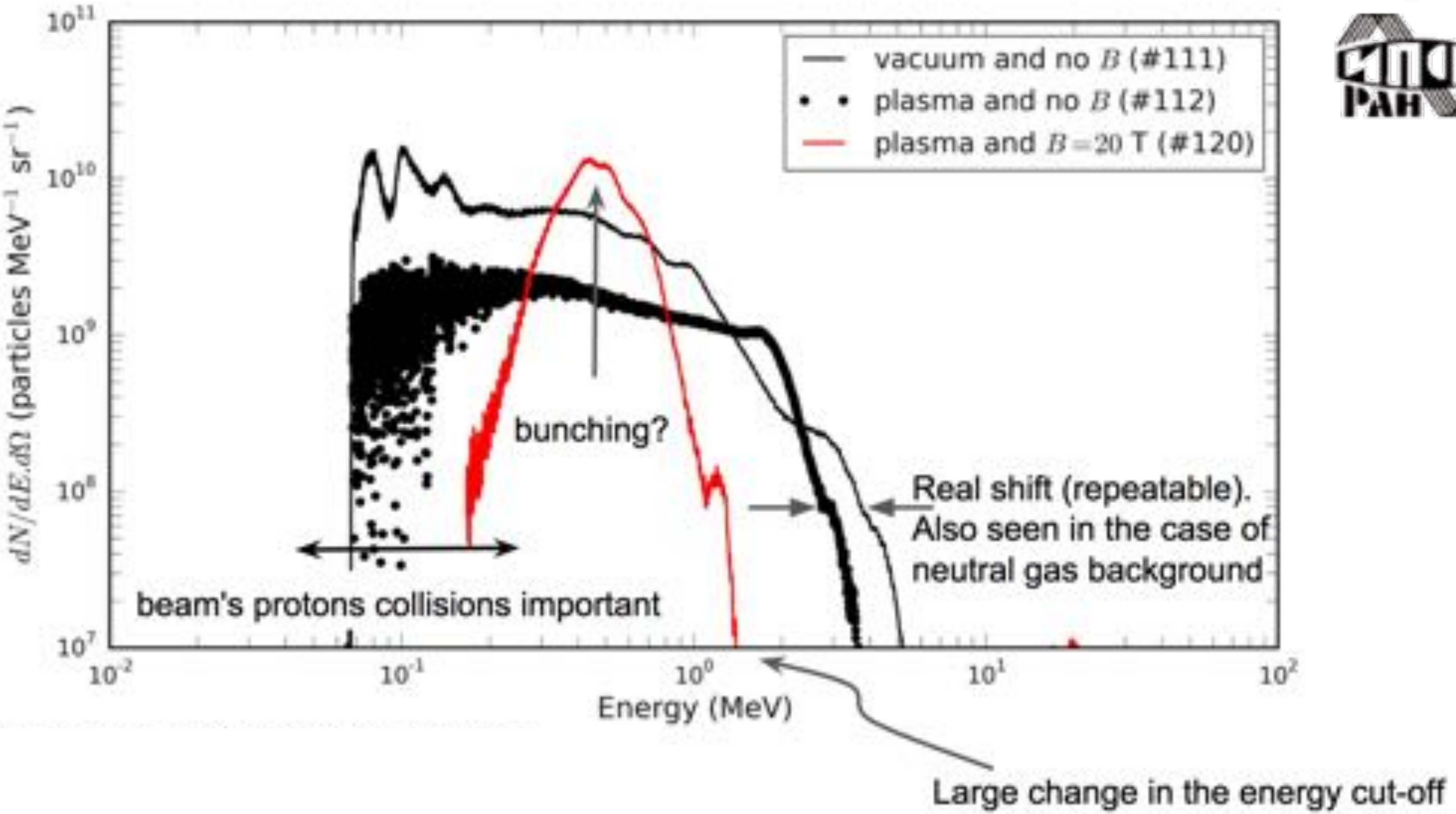
Simulations using the DUED code (S. Atzeni), Ne gas

The long-pulse induces a quite homogeneous heating



Simulations using the DUED code (S. Atzeni)

Proton beam in plasma: also large downshift



Wrap-up

Beam through

- vacuum **with** magnetic field
  - modulation of the spectrum
  - no change in cut-off energy

- "neutral" gas/plasma **without** magnetic field
  - small downshift in cut-off energy

- "neutral" gas or heated plasma **with** magnetic field
  - beam-background particle collisions mostly negligible → collective effects (?)
  - large modification of spectrum
  - much smaller energy cut-off