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Effects of Initial Target Inhomogeneity and Projectile Energy Ramping in Ion-Driven Warm Dense Matter Experiments

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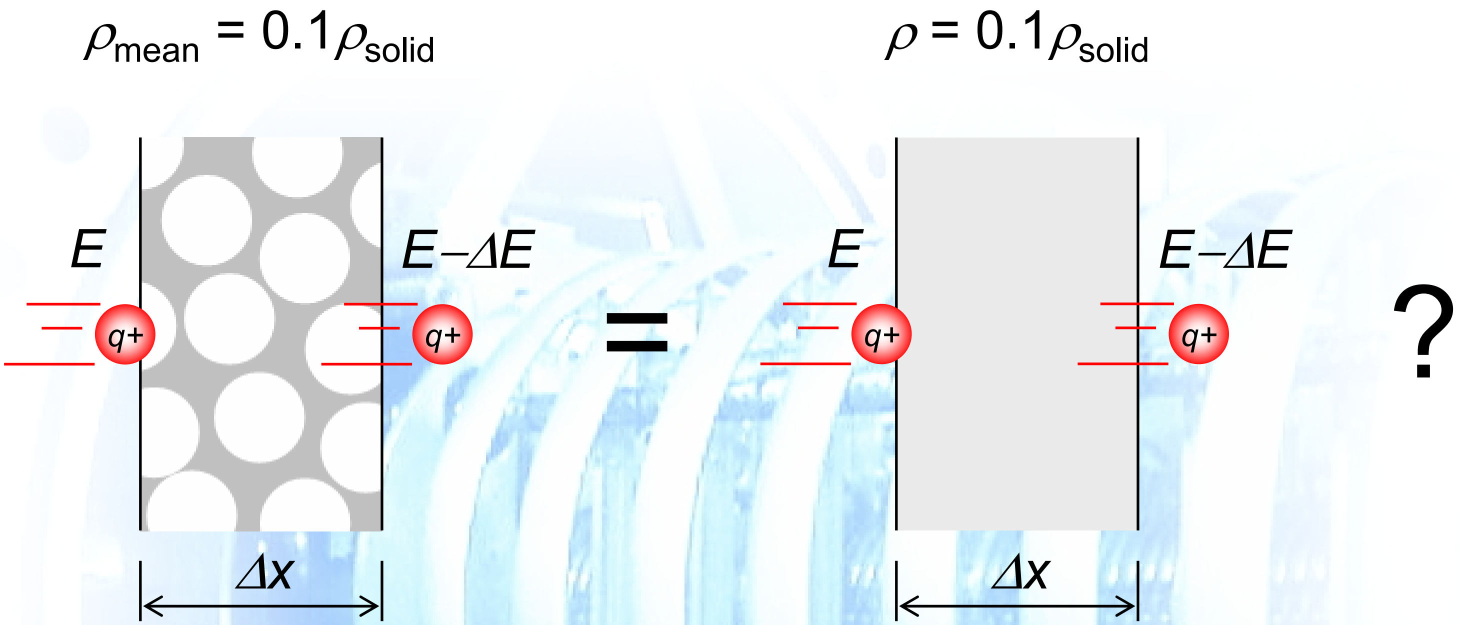
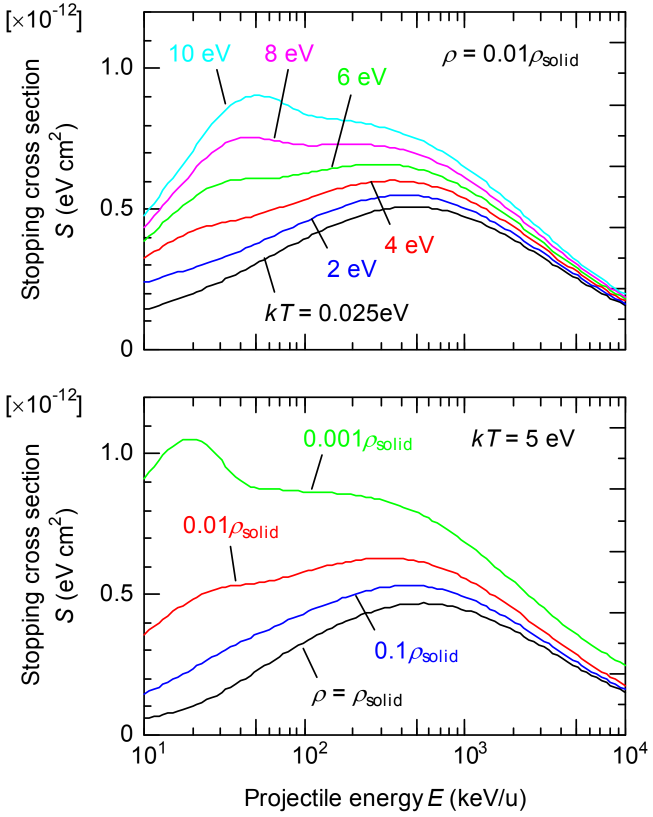


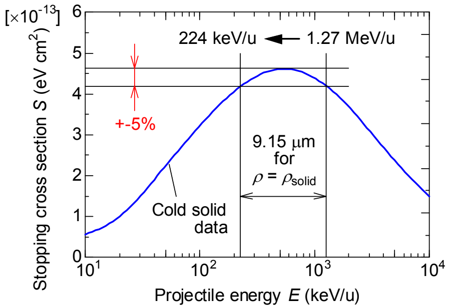
1. Effects of Initial Target Inhomogeneity

In hydrodynamic calculation on the WDM experiments, foam targets are so far assumed to be homogeneous.

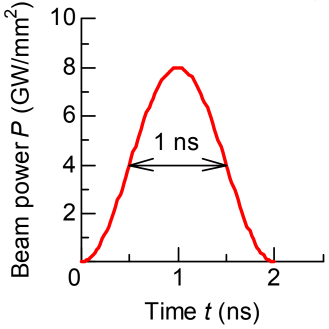
- ρ / kT-dependent Bragg curves:

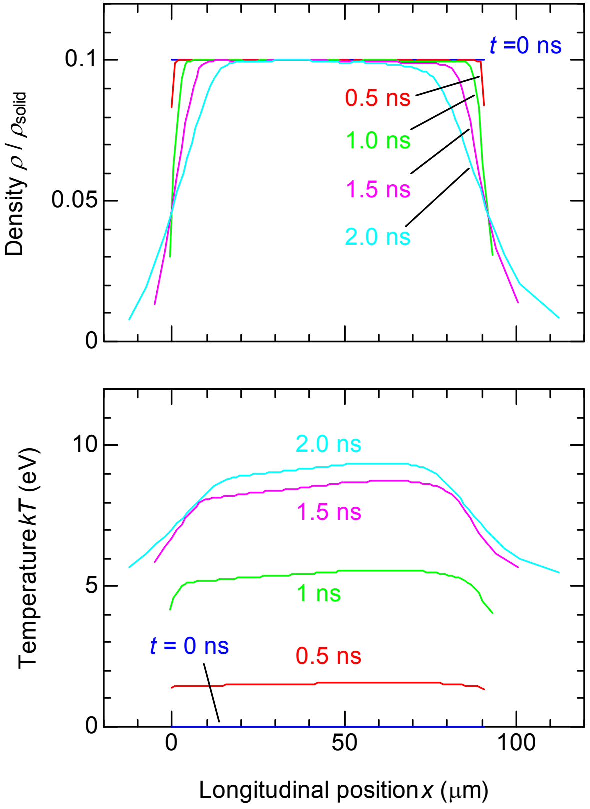


- Hydro motion of a $\rho = 0.1\rho_{\text{solid}}$ "foam" target:



Hydro code "MULTI"

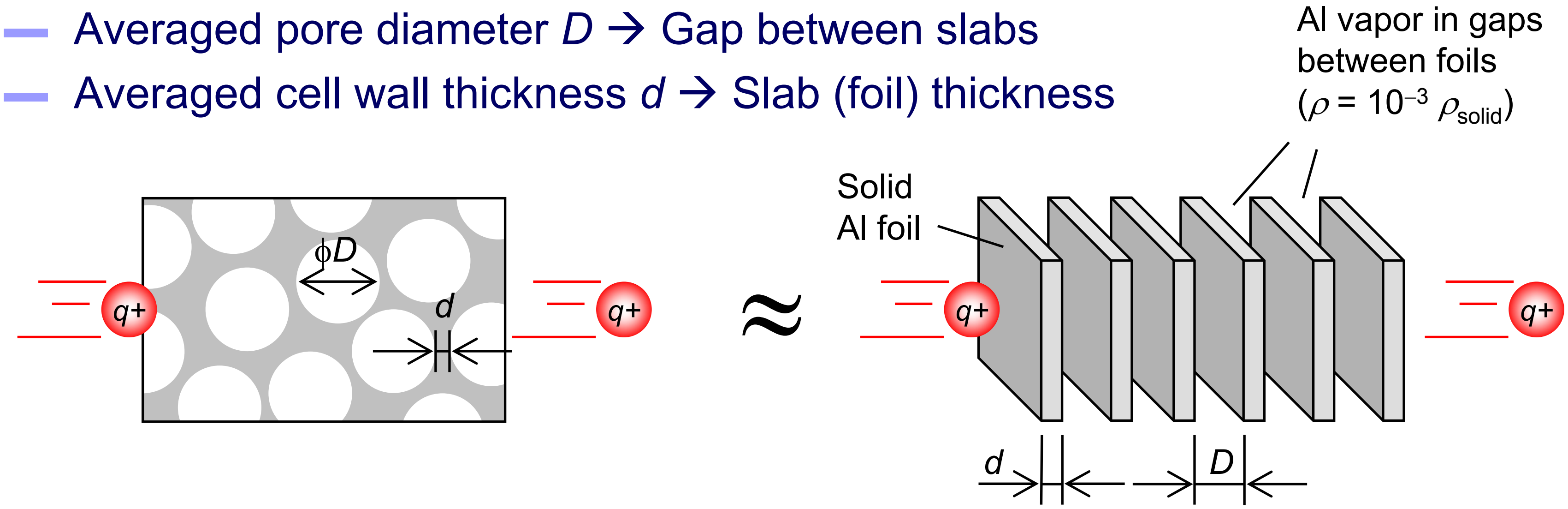




- For detailed analysis, however, initial inhomogeneity (porous structure) of the foam target should be taken into account.

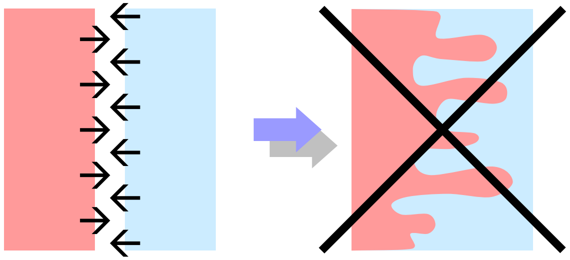
To simulate inhomogeneous porous foam targets, a 1D multilayer structure was applied.

- Modeling of the inhomogeneous 3D porous structure for calculation with a 1D hydrodynamic code (MULTI, ver. 7):
  - Averaged pore diameter *D* → Gap between slabs
  - Averaged cell wall thickness *d* → Slab (foil) thickness



- Limitations of the analysis:
  - Homogenization by multidimensional mixing (instability) cannot be treated.
    → Homogenization is underestimated!
  - Projectile effective charge is always at equilibrium.

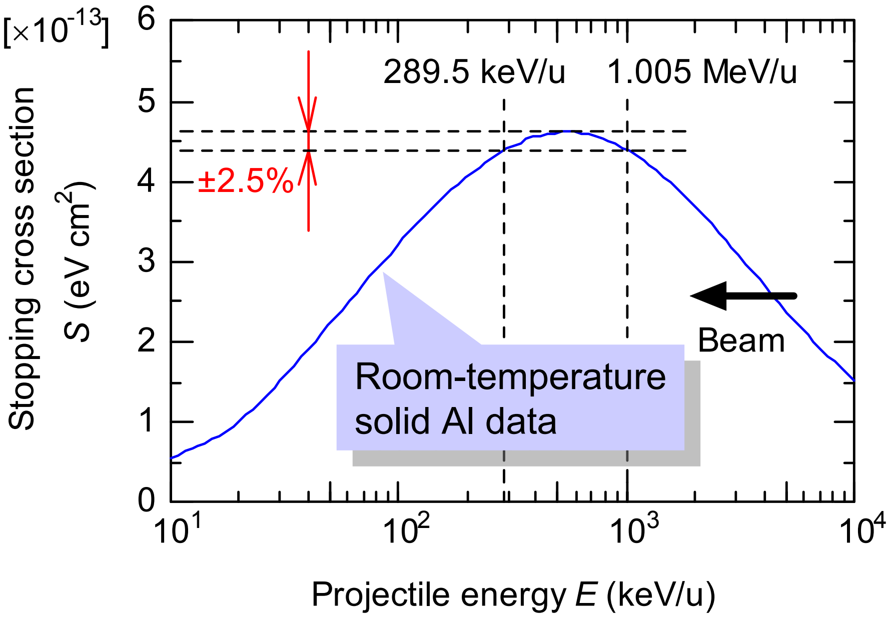
→ Only the upper limit of the effect is obtained.



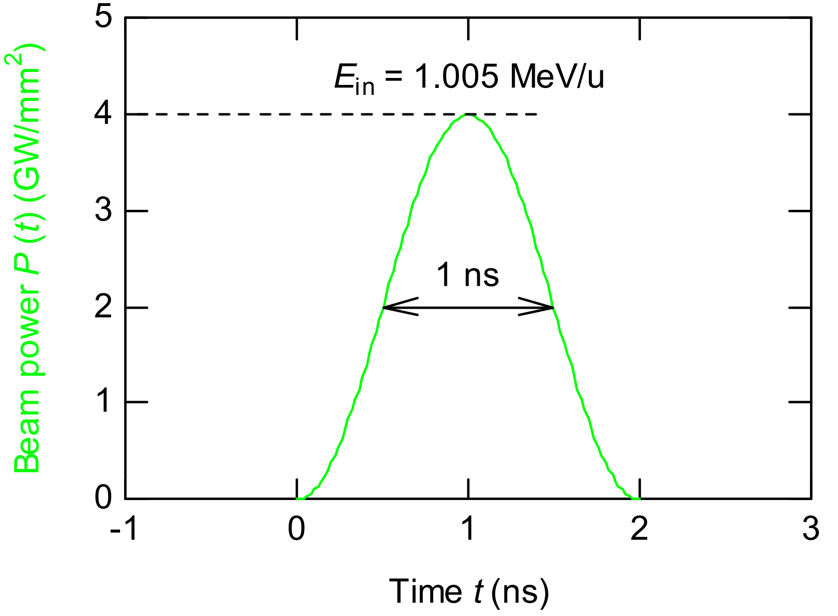
Beam- and target parameters were adjusted so that the Bragg peak is located at the center of the target.

- Beam- and target parameters:
  - Projectile: 23.1-MeV $^{23}\mathrm{Na}^{+}$ (1.005 MeV/u), 4 GW/mm^2 (peak) × 1 ns
    $\rightarrow$ Energy per pulse W = 4 J/mm^2 (1.7×10^{13} ions/mm^2)
  - Target: $_{13}$Al-foam, $\rho_{\mathrm{mean}} = 0.1\rho_{\mathrm{solid}}$, gross thickness = 61.7 μm

→ $dE/d(\rho x)$-inhomogeneity = ± 2.5%, if cold solid Al data are used.

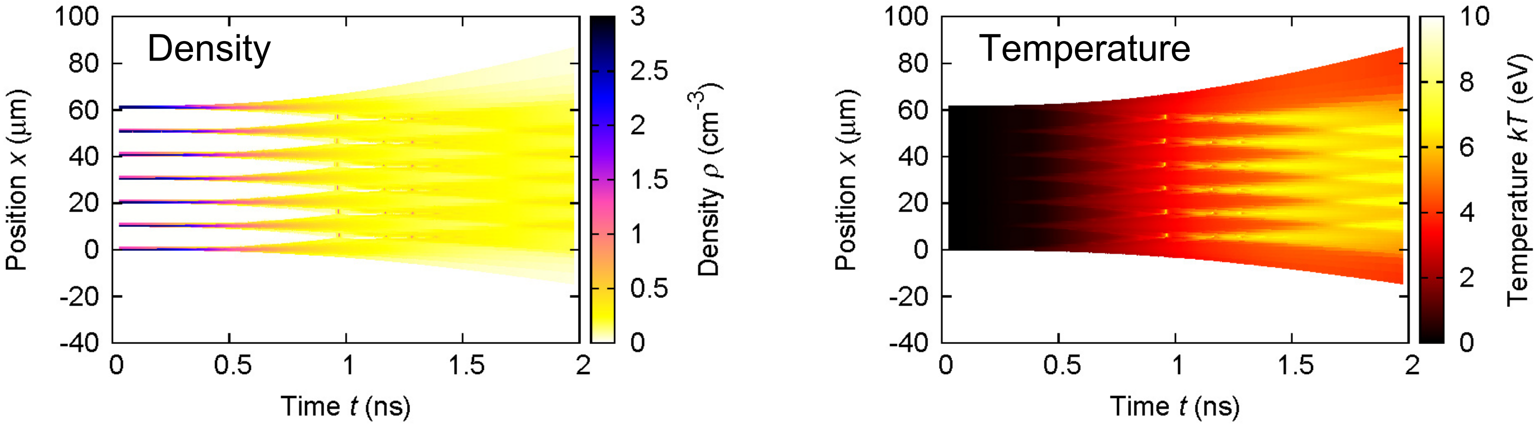


Room-temperature solid Al data

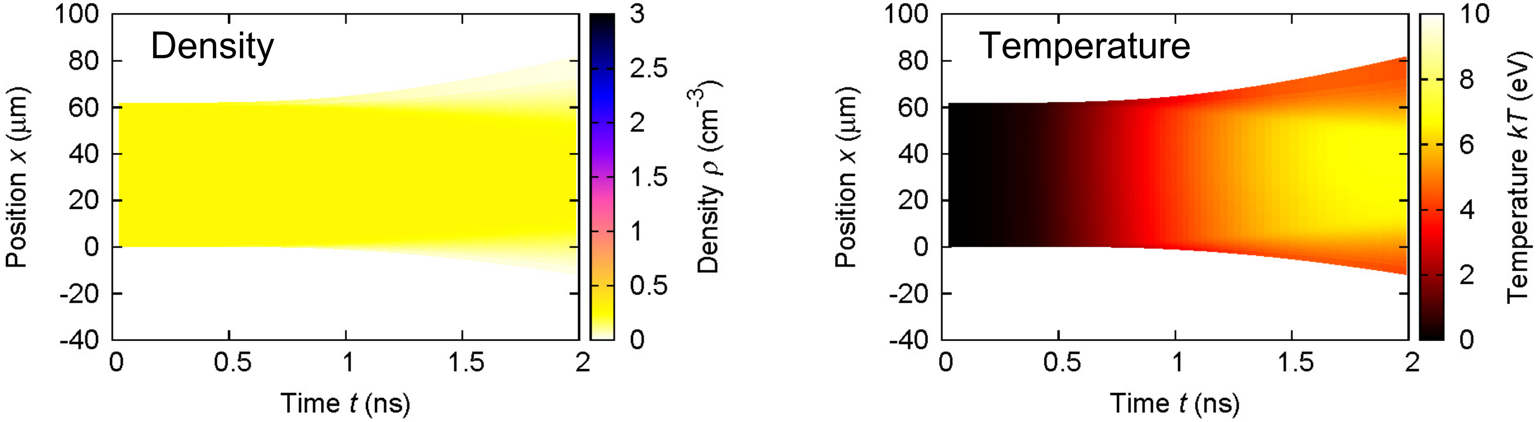


Macroscopic responses of the inhomogeneous (foam) and the homogeneous target are similar each other.

- Streak images of the density- and the temperature profiles:
  - Foam target (7 layers, D = 9 µm, d = 0.9 µm):



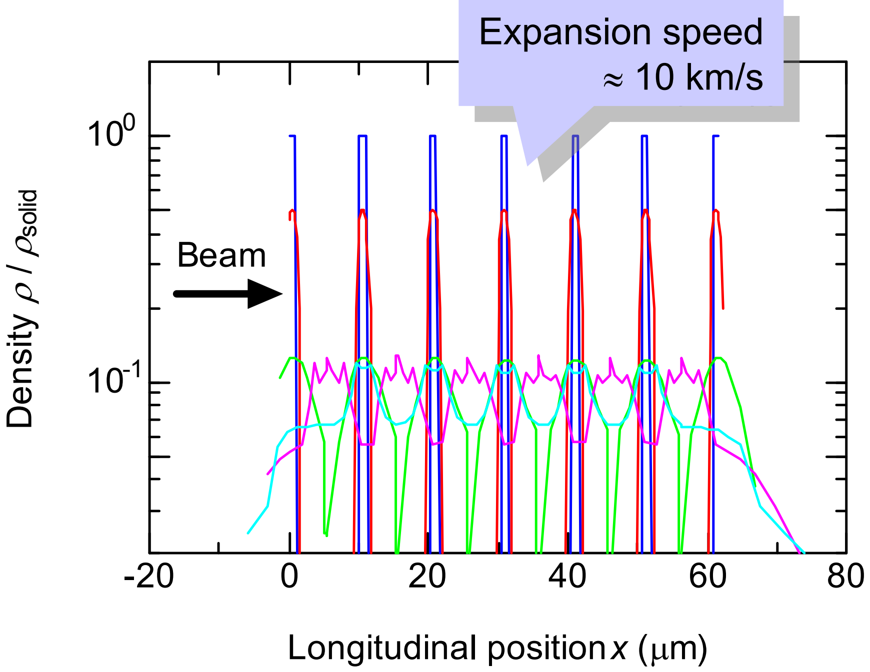
  - Homogeneous equivalent ($\rho_0 = 0.1\rho_{solid}$):



Inhomogeneity of the density is not smeared out even after gaps were filled with blow-off materials.

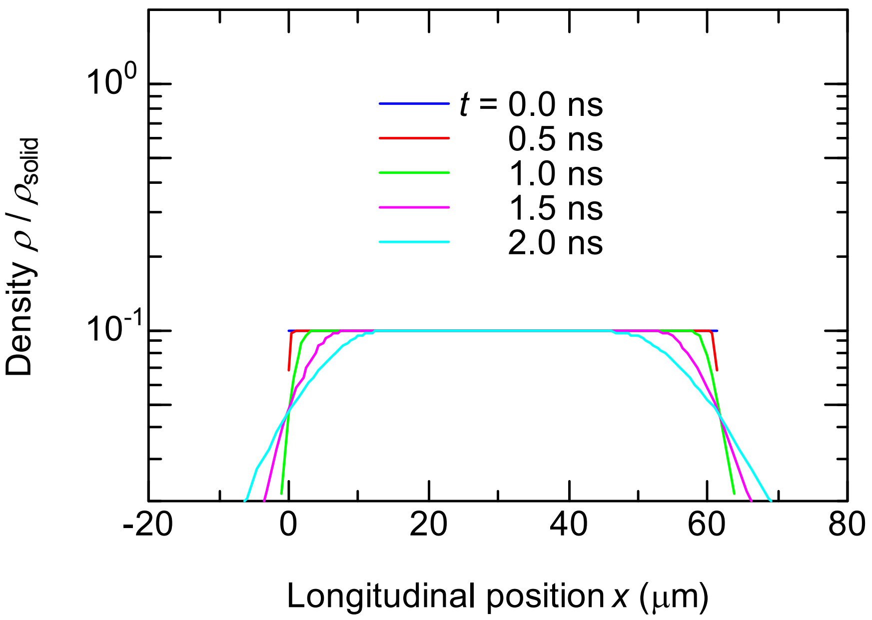
- Snapshots of the density profile up to the end of the pulse duration:
  - Dense spots appear at the original position of pores (gaps) due to stagnation of blow-off materials. (cf. t =1.5 ns).
  - "Macroscopic" rarefaction waves do not reach the central part, even at the end of the pulse (t = 2 ns), as in the case of the homogeneous equivalent.

Al foam target (ϕD = 9 μm, d = 0.9 μm)



Expansion speed ≈ 10 km/s

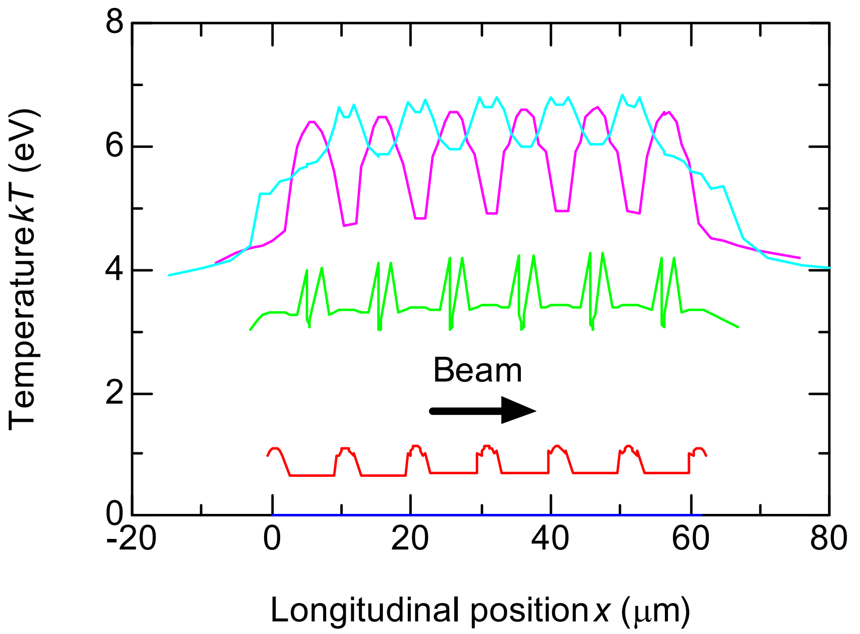
Homogeneous equivalent ($\rho_0 = 0.1\rho_{solid}$)



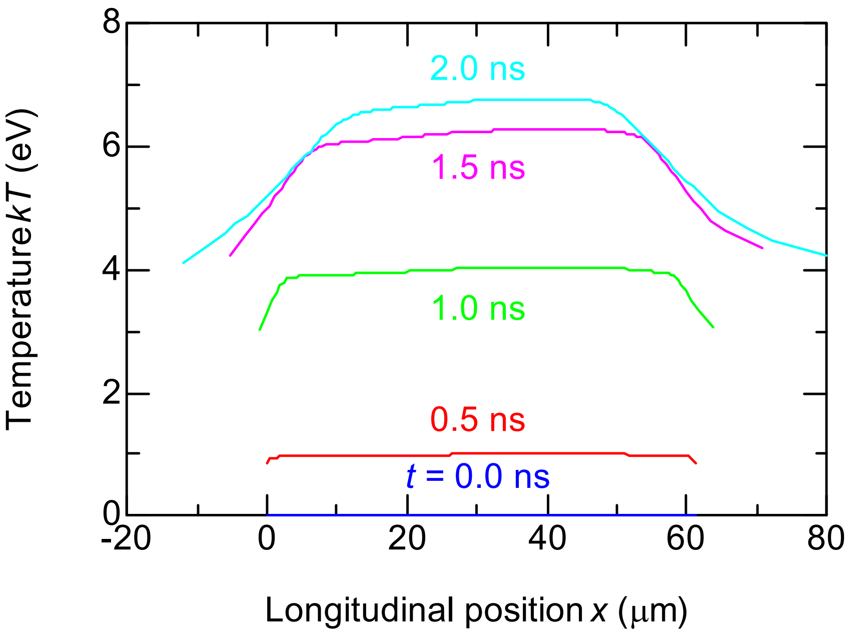
The inhomogeneity persists by the periodic exchange between the kinetic and the thermal energy.

- Snapshots of the temperature profile up to the end of the pulse duration:
  - "Hot spots" appear at the original position of pores by collisions of blow-off materials from each foil[1]. (cf. *t* = 1.5 ns)
  - Averaged temperature of the inhomogeneous target is always lower than that of homogeneous equivalent.

Al foam target (ϕ*D* = 9 μm, *d* = 0.9 μm)



Homogeneous equivalent ($\rho_0 = 0.1\rho_{solid}$)



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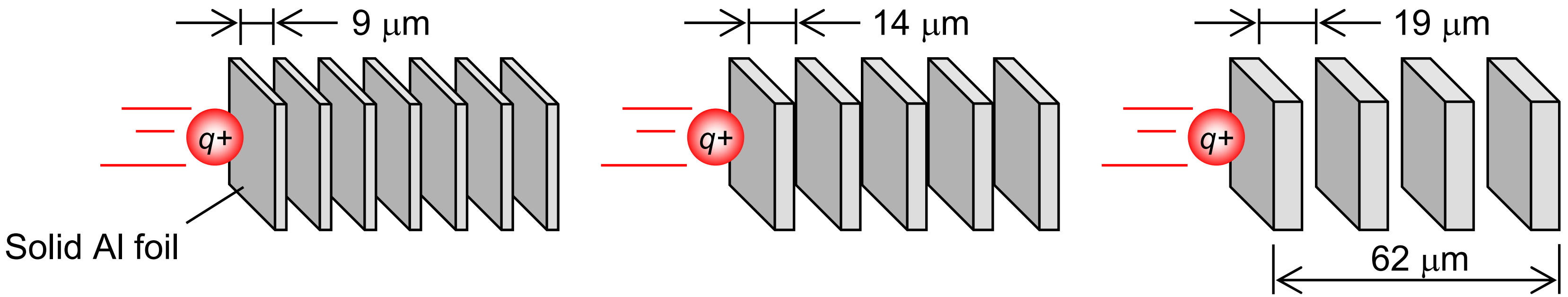
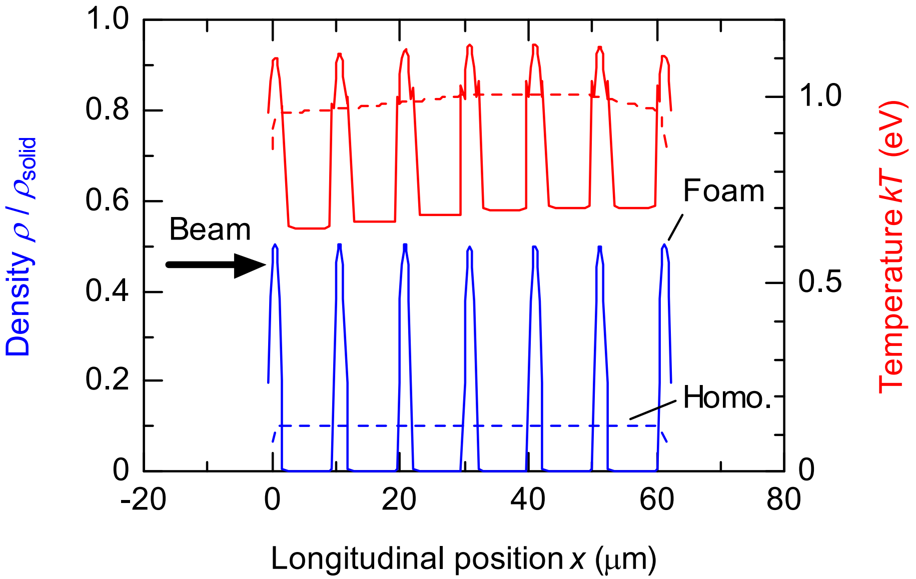
[1] V. Eremov et al., *Nucl. Instr. and Meth.* A **577** (2007) 324.

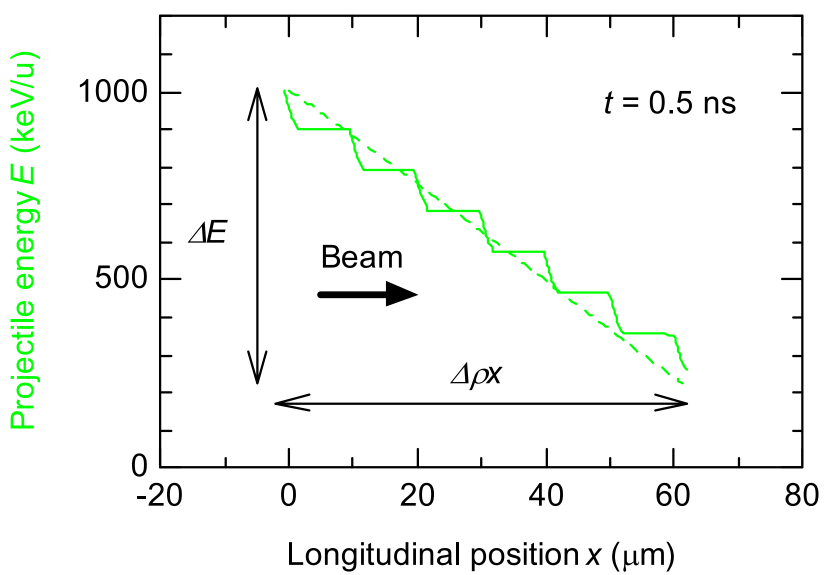
Averaged "macroscopic" $-dE/d(\rho x)$ was evaluated using the total energy loss through the target.

- Effect of pore size was investigated by changing the gap between slabs:
  - The gross density was kept constant at $\rho_{\mathrm{mean}} = 0.1\rho_{\mathrm{solid}}$.



  - Example: Profiles of ρ , kT and E for D = 9-μm target at t = 0.5 ns:

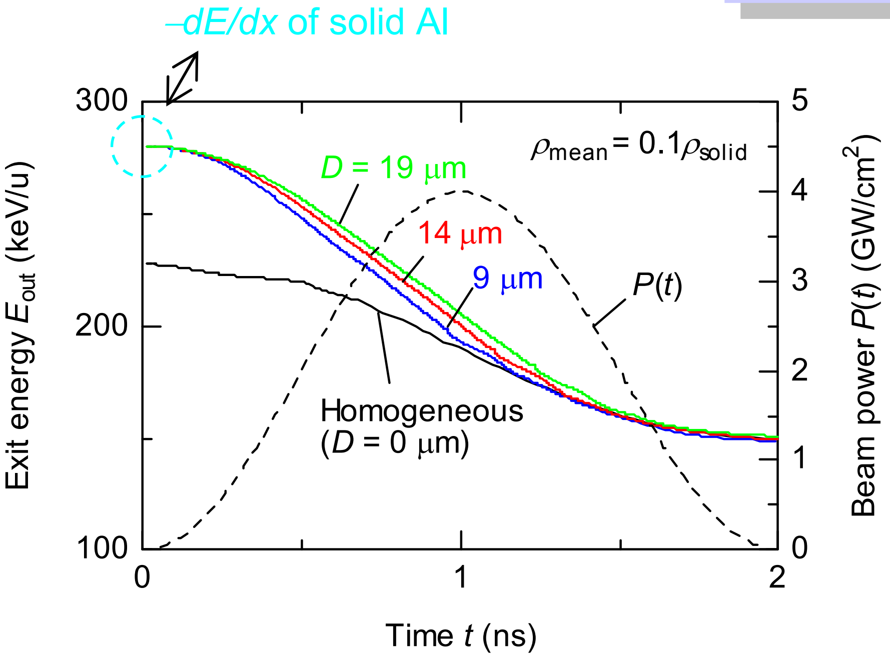


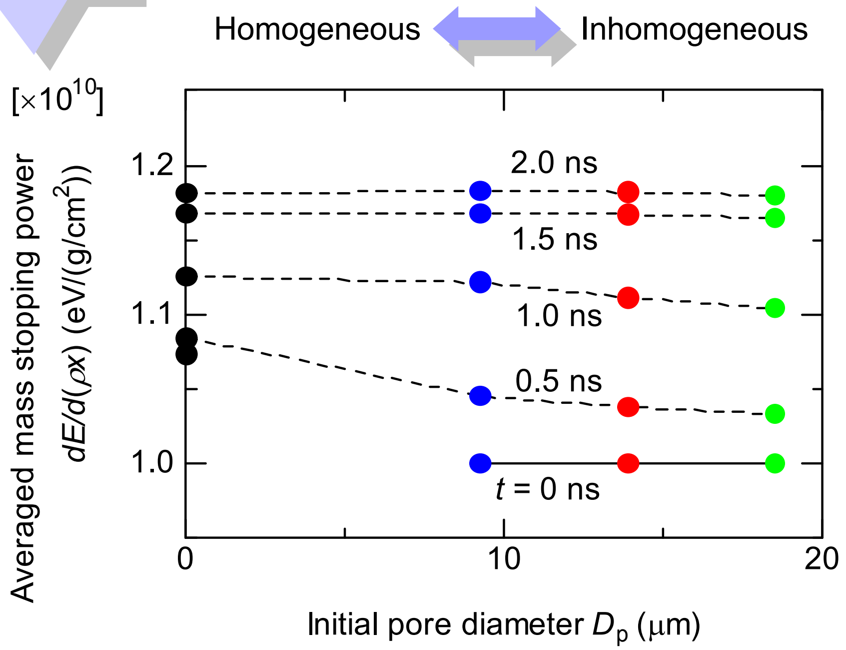


Macroscopic stopping power decreases with increasing the pore size of the foam target.

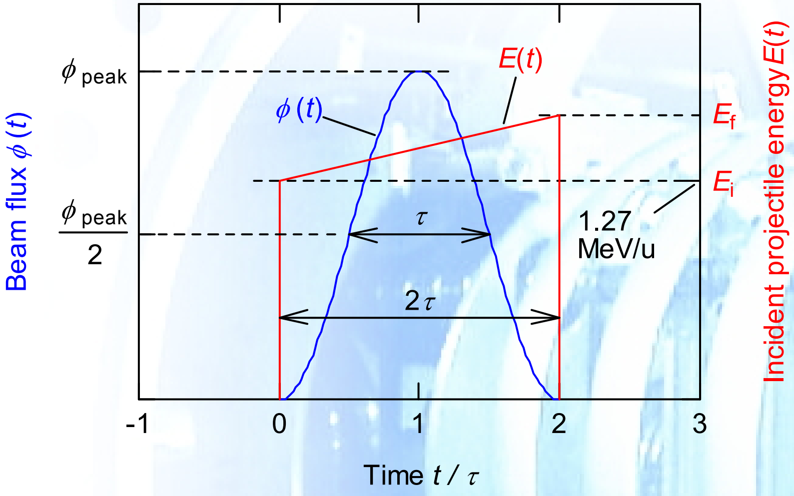
- Temporal evolution of the "macroscopic" stopping power as a function of initial pore radius:
  - Before homogenization ($t < \approx 1$ ns), the energy deposition in the foam targets are smaller than in the homogeneous target. → Low target temperature!
  - After homogenization at the end of pulse duration, energy loss by every target is roughly equal.

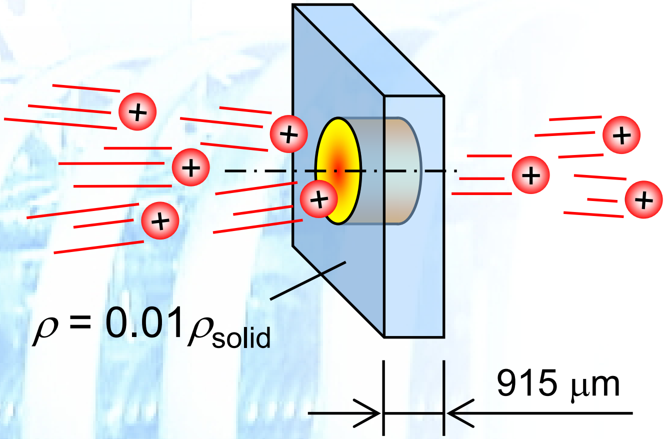
Interaction energy not well-defined!





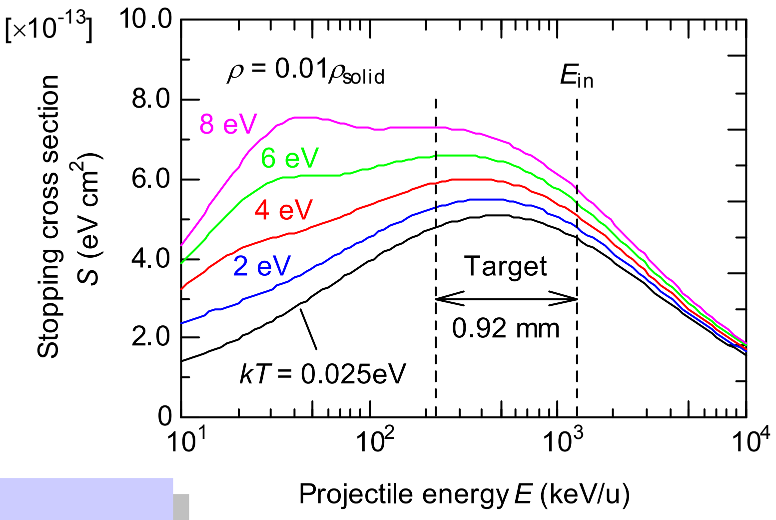
2. Effects of Projectile Energy Ramping



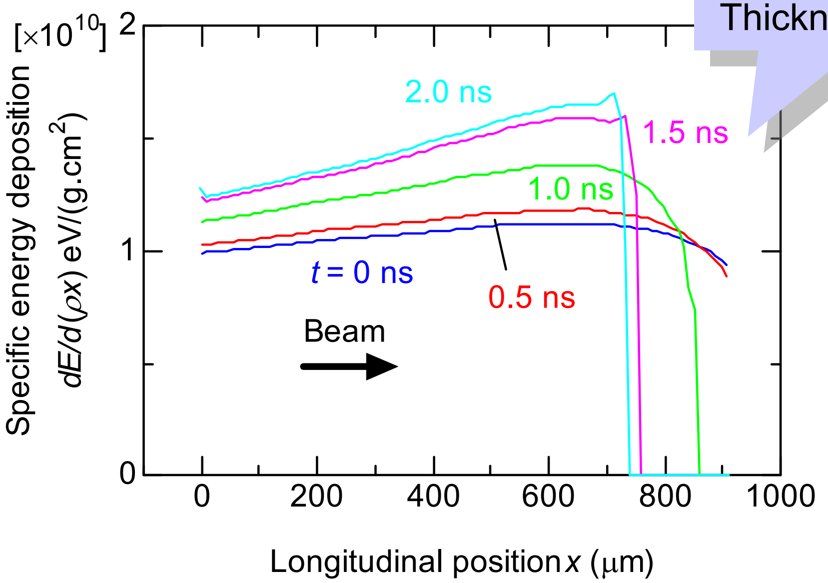


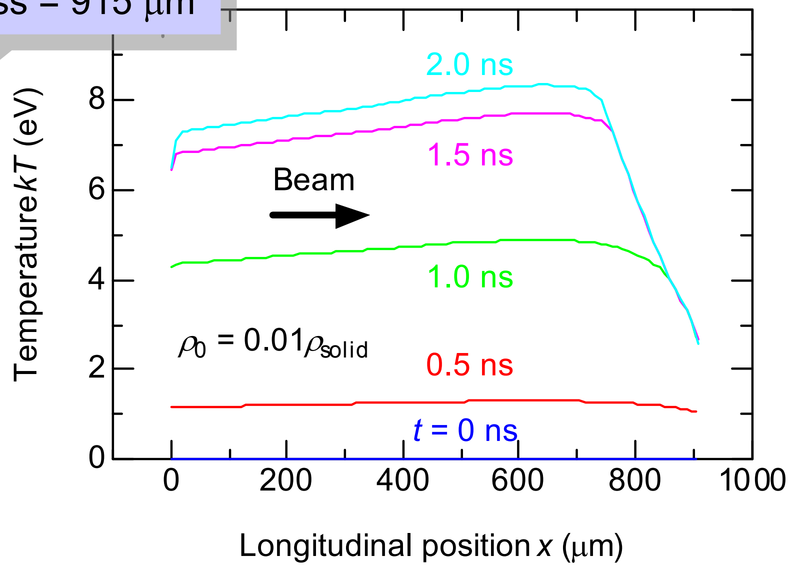
Due to the increase of $-dE/d(\rho x)$ with kT, the rear side of the target cannot effectively be heated.

- Change of the Bragg curve with kT for low-density Al target:
  - $-dE/d(\rho x)$ increases with kT at fixed ρ.
- Energy-deposition and kT profile at the end of the pulse duration:
  - Projectiles can stop in the target at high kT! (range shortening)



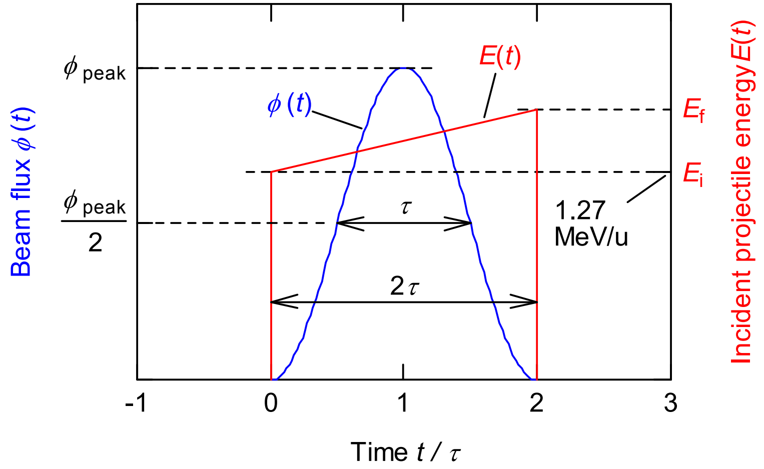
$\rho_0 = 0.01\rho_{solid}$
Thickness = 915 μm

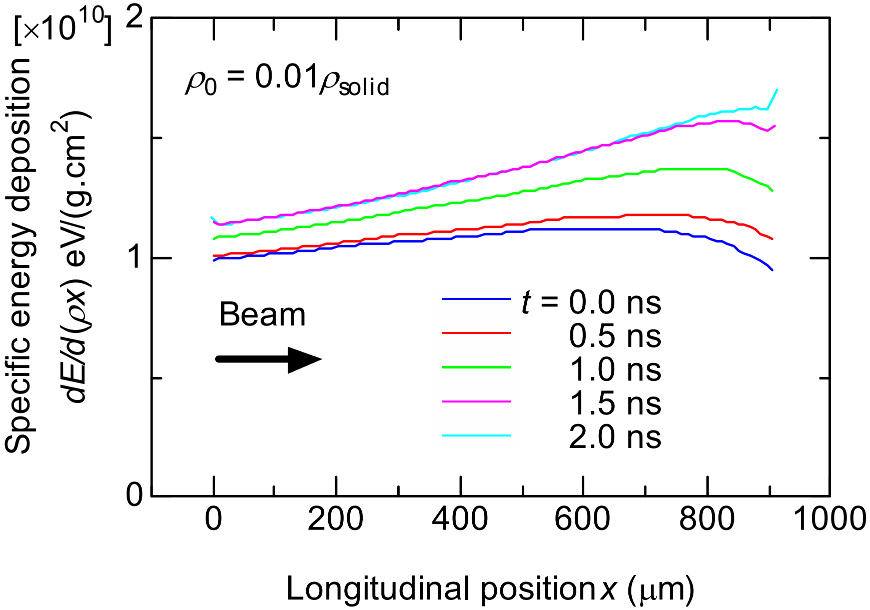


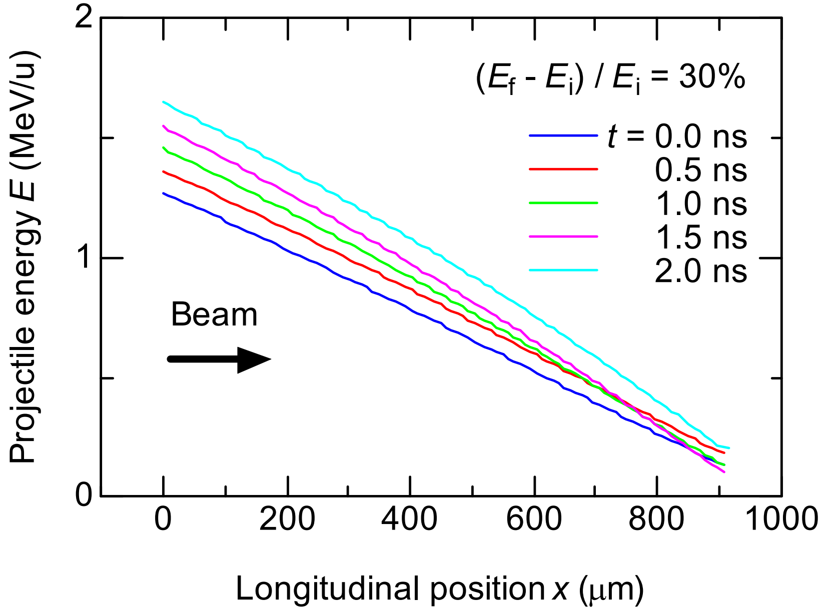


As compensation for the increased stopping, temporal ramping of the projectile incident energy was examined.

- Waveform of the incident projectile energy ramping:
  - Constant ramping during the pulse duration (t = 0-2 ns)
- e. g. History of the energy-deposition- and projectile-energy profile for $(E_f - E_i) / E_i = +30\%$

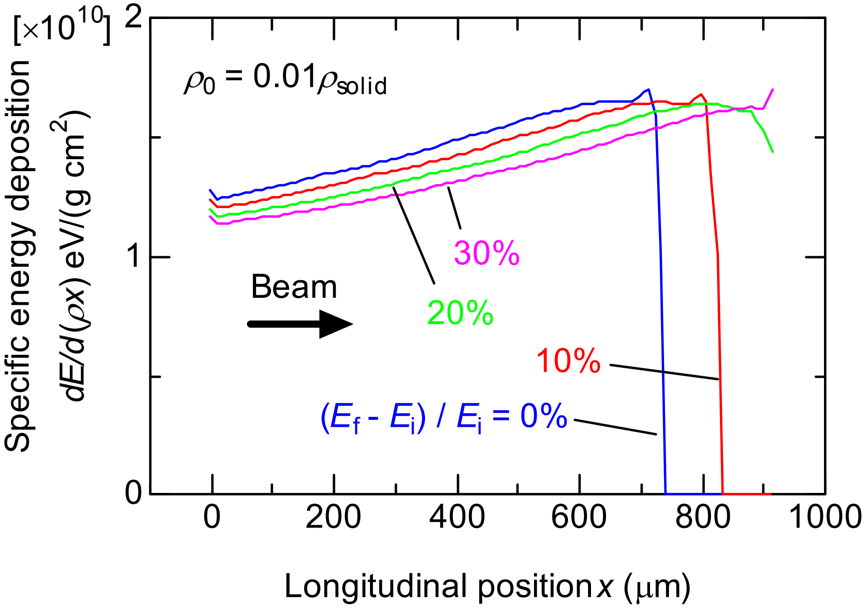


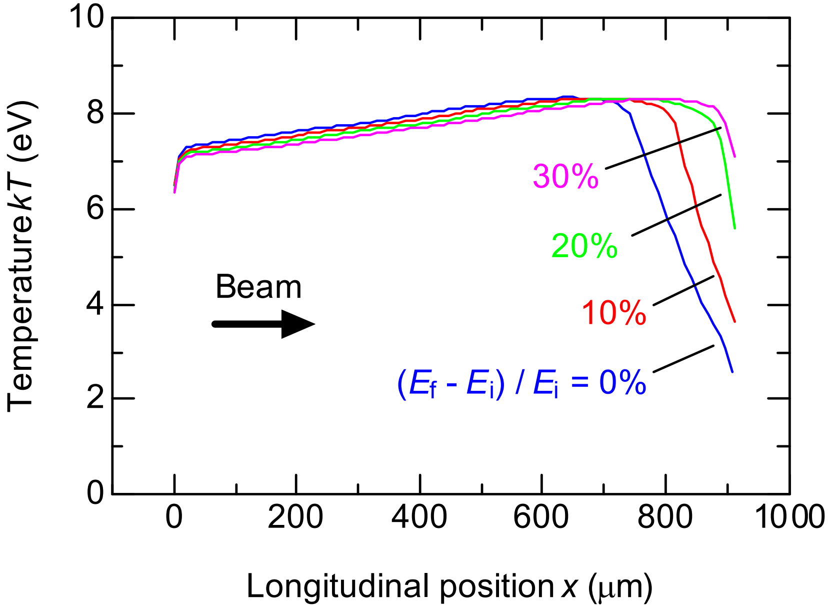




By temporal ramping of the projectile incident energy, homogeneity of heating can be improved.

- Projectile energy ramping during the pulse duration:
  - Compensation for increased stopping due to the target temperature rise
- Energy-deposition and *kT* profile at the end of the pulse duration for different ramping rate:
  - Optimum ramping rate ≈ +30% → $-dE/d(\rho x)$ inhomogeneity = ±20%
    → *kT* inhomogeneity = ±13%

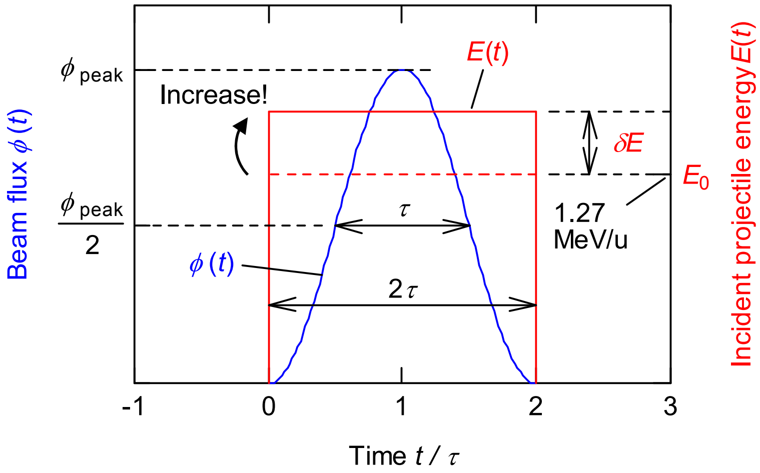


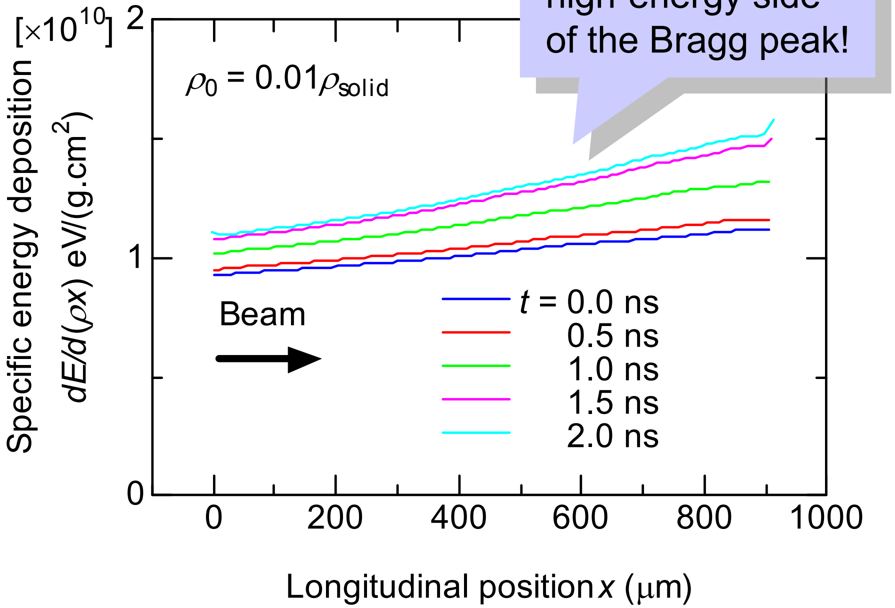


- Energy (velocity) modulation → consistent with the beam bunching scheme?

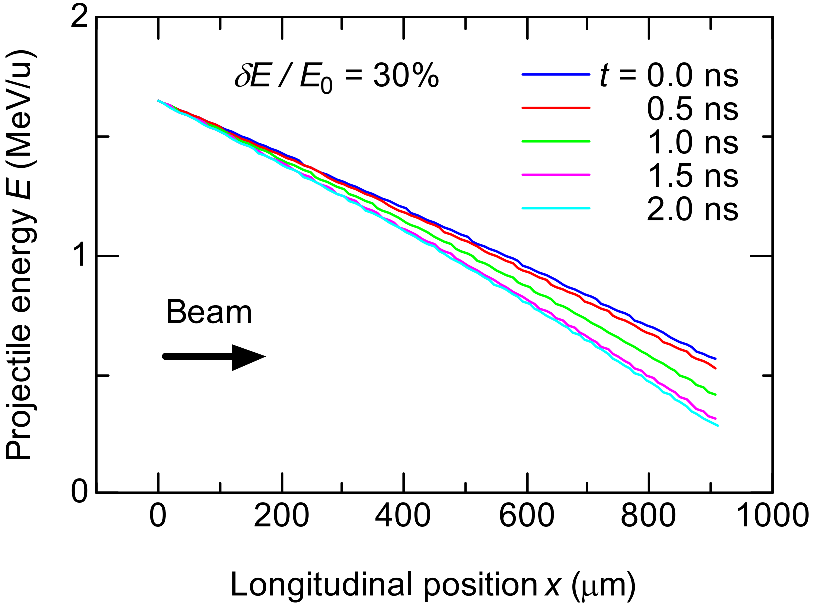
As an alternative, simple increase (without temporal change) of the incident projectile energy was tested.

- The projectile energy was increased from the beginning of the pulse duration to secure a sufficient penetrability:
  - Constant energy, no temporal ramping
- e. g. History of the energy-deposition- and projectile-energy profile for $\delta E/E_0$ = +30%:



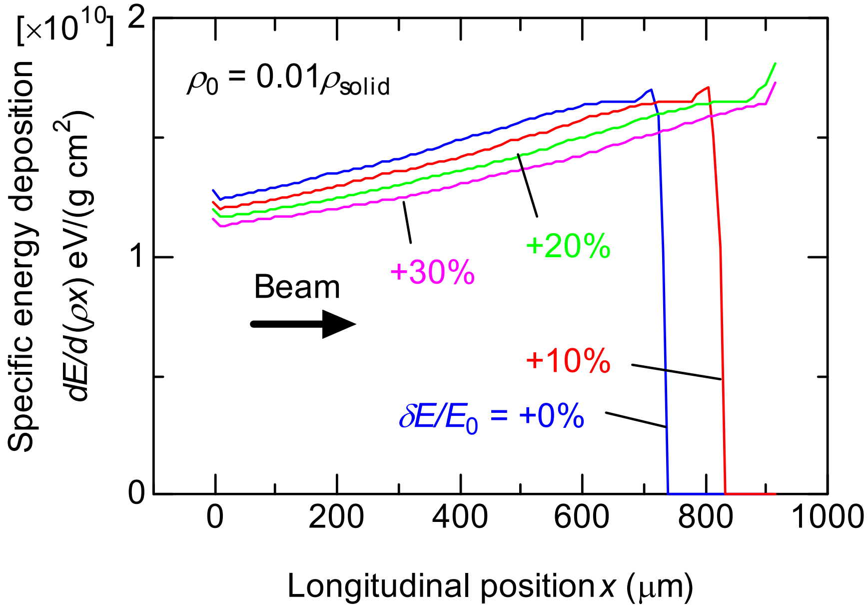


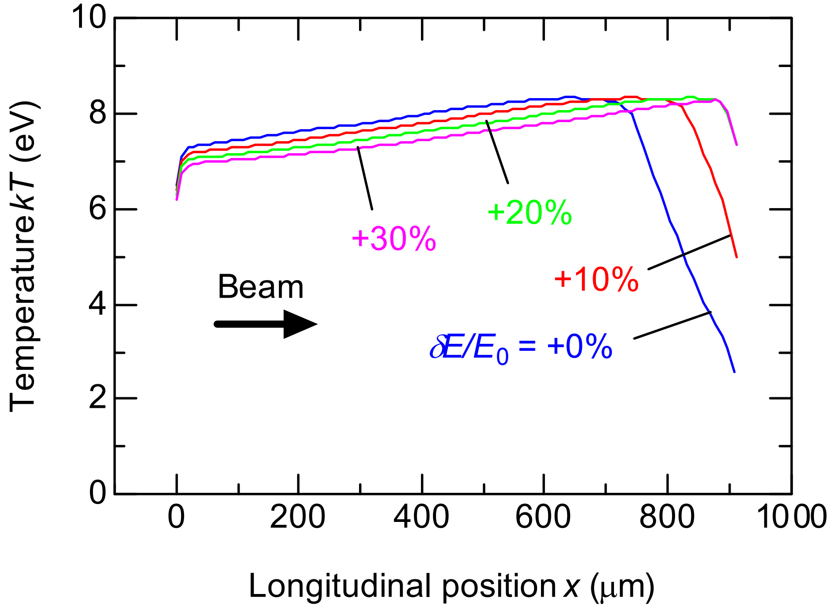
Always on the high-energy side of the Bragg peak!



Also simple increase of the incident projectile energy can improve the homogeneity of heating.

- Energy-deposition and *kT* profile at the end of the pulse duration (*t* = 2 ns) for different increment factor:
  - Comparable improvement is obtained, although the incident energy is constant during the whole pulse duration.
  - Optimum increment factor ≈ +30% → $-dE/d(\rho x)$ inhomogeneity = ±19%
    → *kT* inhomogeneity = 15%





- No projectile-velocity modulation → compatible with the bunch compression!

"Effects of Initial Target Inhomogeneity and ·····" Conclusions:

- Effects of initial target inhomogeneity analyzed by a 1D hydro code:
  - Initial inhomogeneity is not completely smeared out even after the gap (pore) is filled with the blow-off materials. (····· overestimation of the effect?)
    → Multi-dimensional calculations are needed for detailed analysis.
  - Before homogenization, the total energy deposition into the target is smaller than expected for homogeneous equivalent.
  - "Macroscopic" mass stopping power decreases with the pore size.
    → No effect is expected for small (≈ 1 μm) pore sizes.
- Effects of projectile-energy ramping:
  - Inhomogeneity of heating due to the range shortening can be reduced.
  - Similar effect is available also by simply increasing the incident energy, without temporal ramping.

Methods (Projectile energy)	Heating homogeneity	R&D needed	Interference with beam bunching	Cost
Temporal ramping	☺	☹	☹	☹
Simple increase	☺	☺	☺	☺