INTERACTION OF HIGH INTENSITY LASER WITH STRUCTURED SNOW TARGETS

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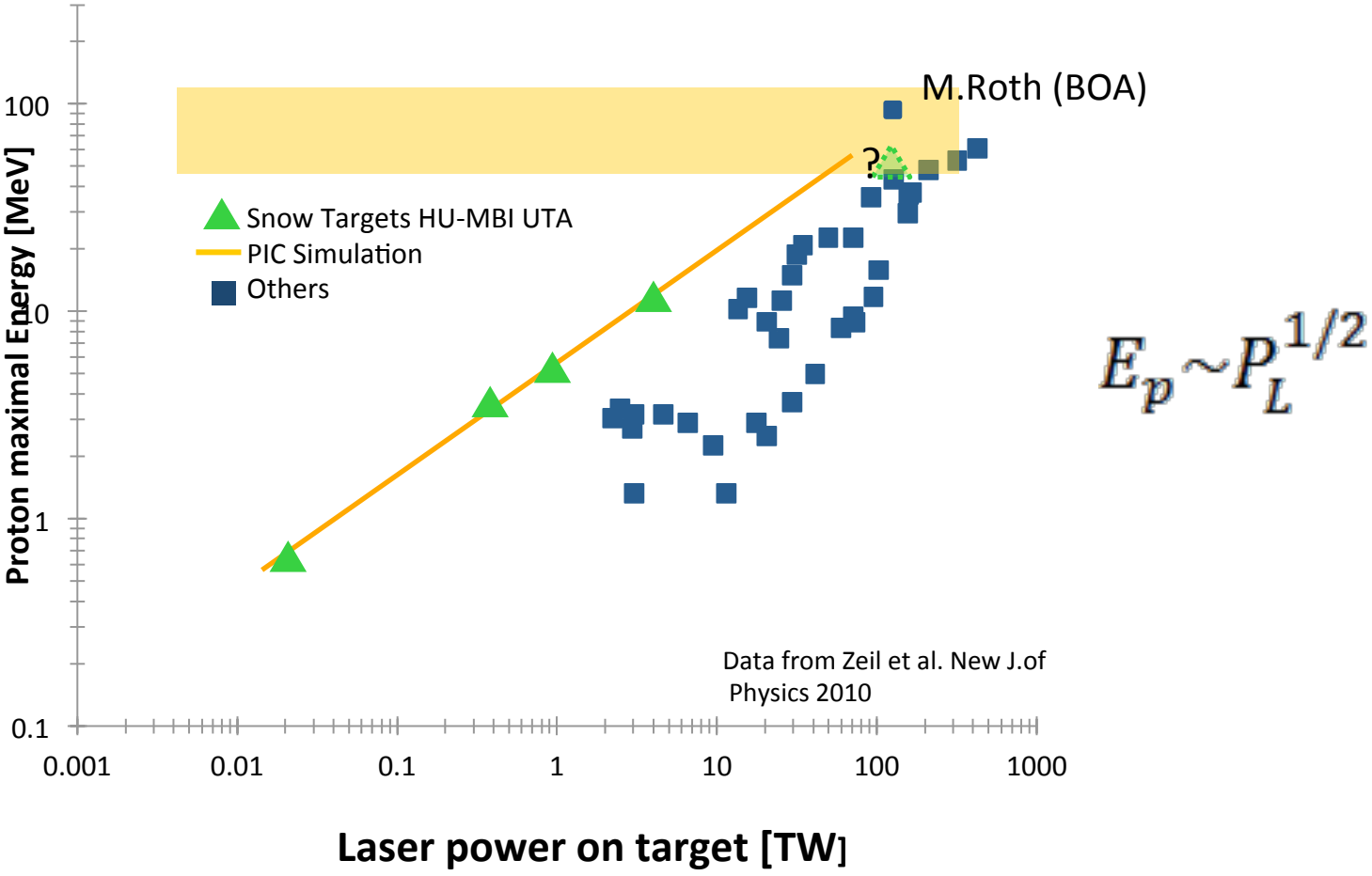
Proton energy vs. laser power (current status)



$$E_p \sim P_L^{1/2}$$

Enhanced proton acceleration from snow (microwire) targets

The high proton energy can be attributed to several effects:

- **The density gradient generated by the laser prepulse.**
- **Mass limited phenomenon.**
- **Localized field enhancement by the local plasma density near the tip of snow needle.**
- **Coulomb explosion of the positively charged snow needle, adding longtime acceleration of the protons.**
- **Aspect ratio of the needle.**

Highly structured snow surface

The snow is growing as pillars in the" normal" direction to the substrate.

The size of the snow pillars is highly non uniform and changes in the range of 30 -200 μm.

The aspect ratio of the pillars decreases as the scale size decreases. The smallest features, spatially resolved, are with diameter about 0.5 - 2 μm

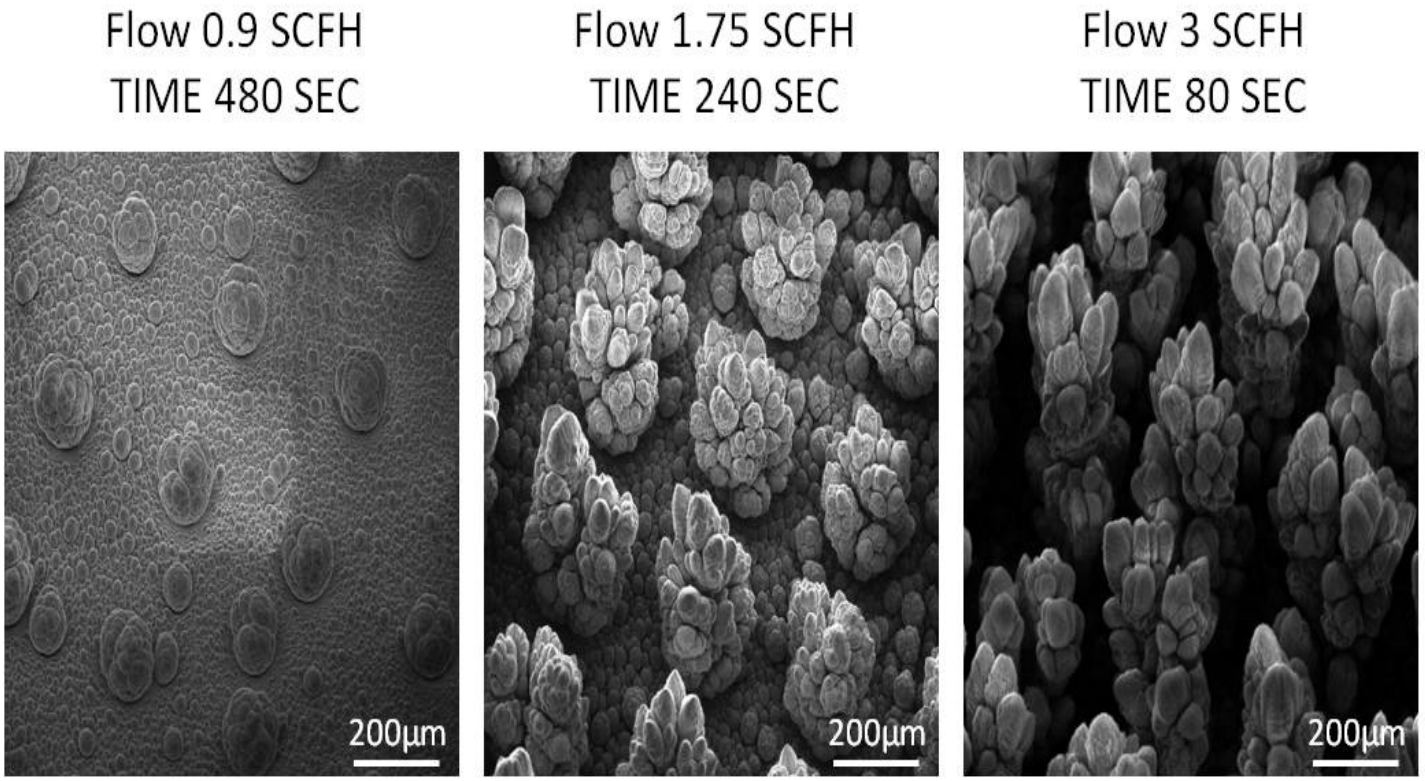
The surface can be characterized by three roughness scales:

a) pillars of about 100 μm

b) spikes of about 10 μm on top of them

c) whiskers of about 1 μm on the spikes.

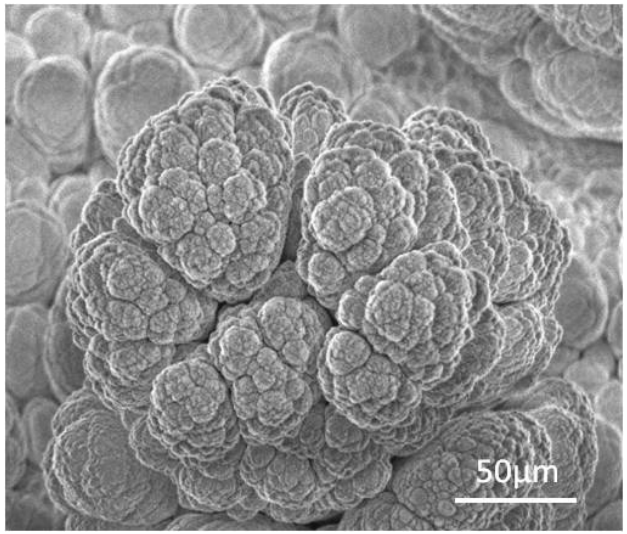
Control of the structured snow target by changing the flow rate and varying the nucleation centers



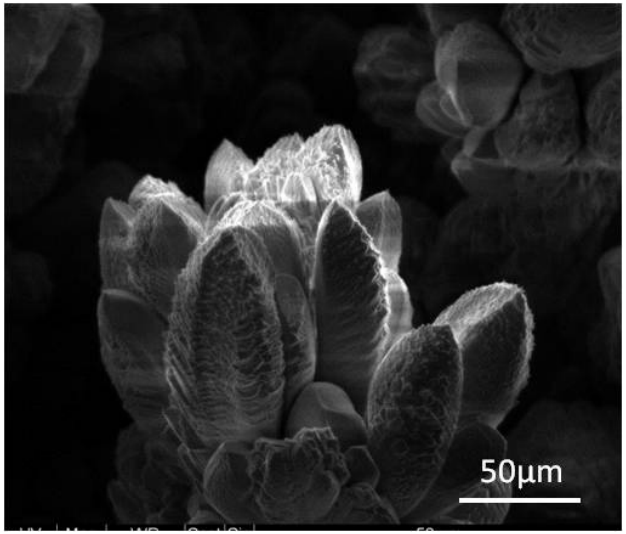
SEM images of snow pillars that were grown over artificial Aluminum nucleation centers on Sapphire substrate at various growth conditions.

Control of morphology by growth kinetics

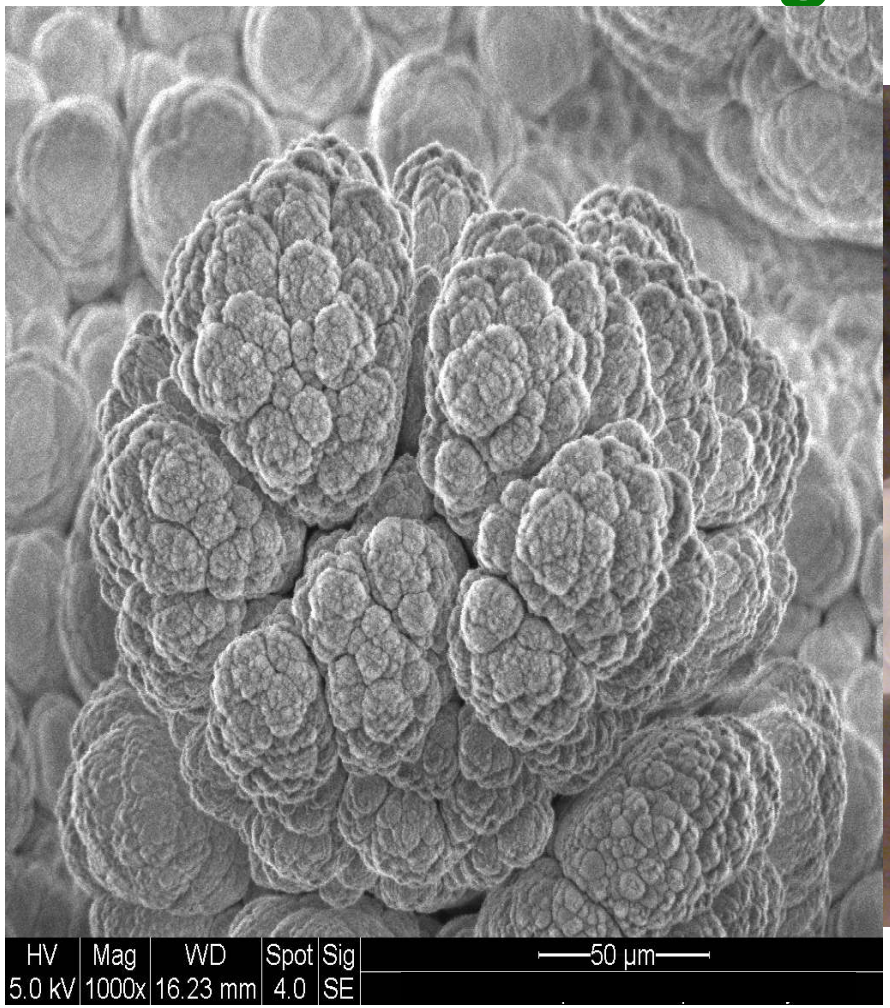
0.9 SCFH, 480 sec

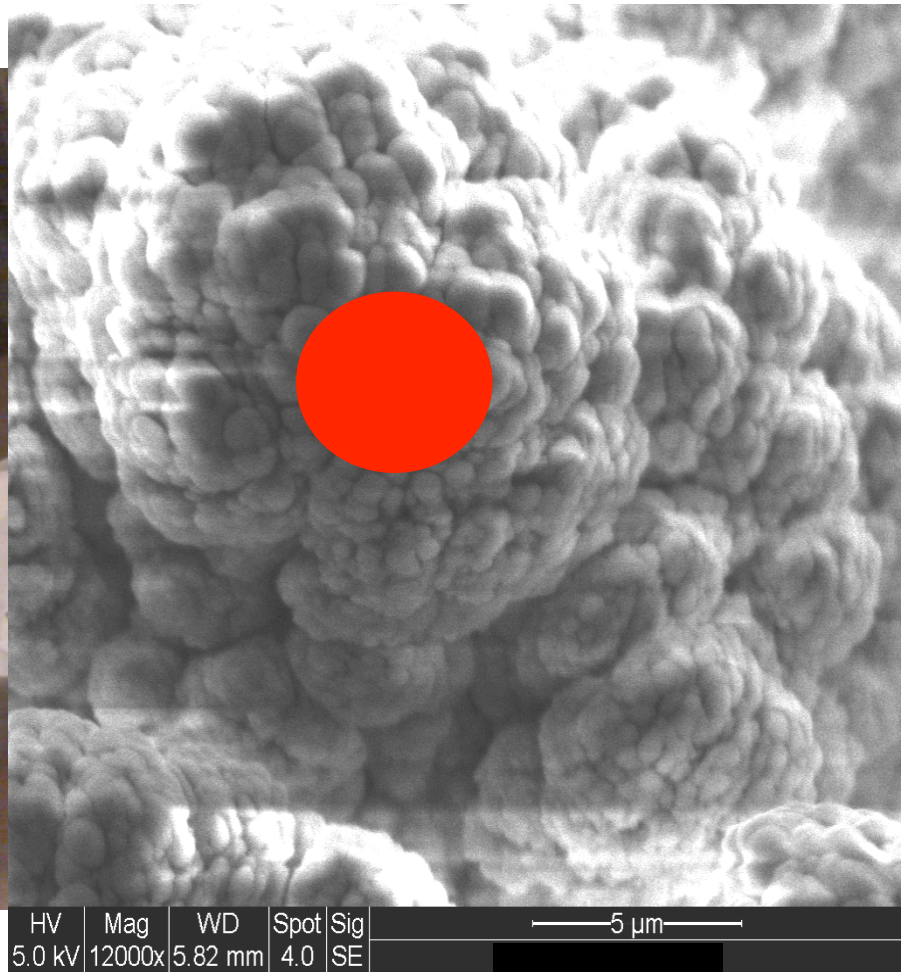


3 SCFH, 80 sec

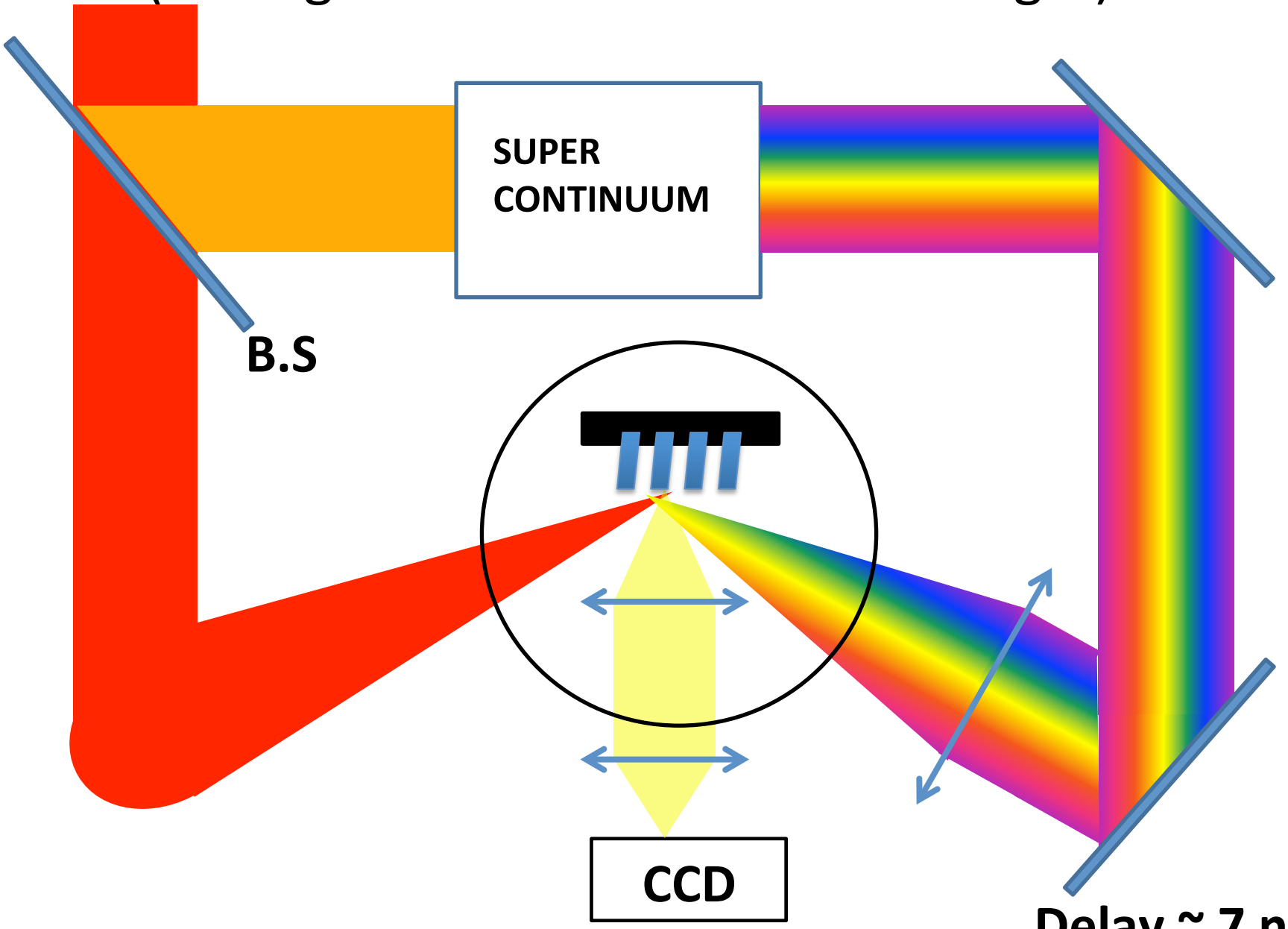


Snow target In the ESEM

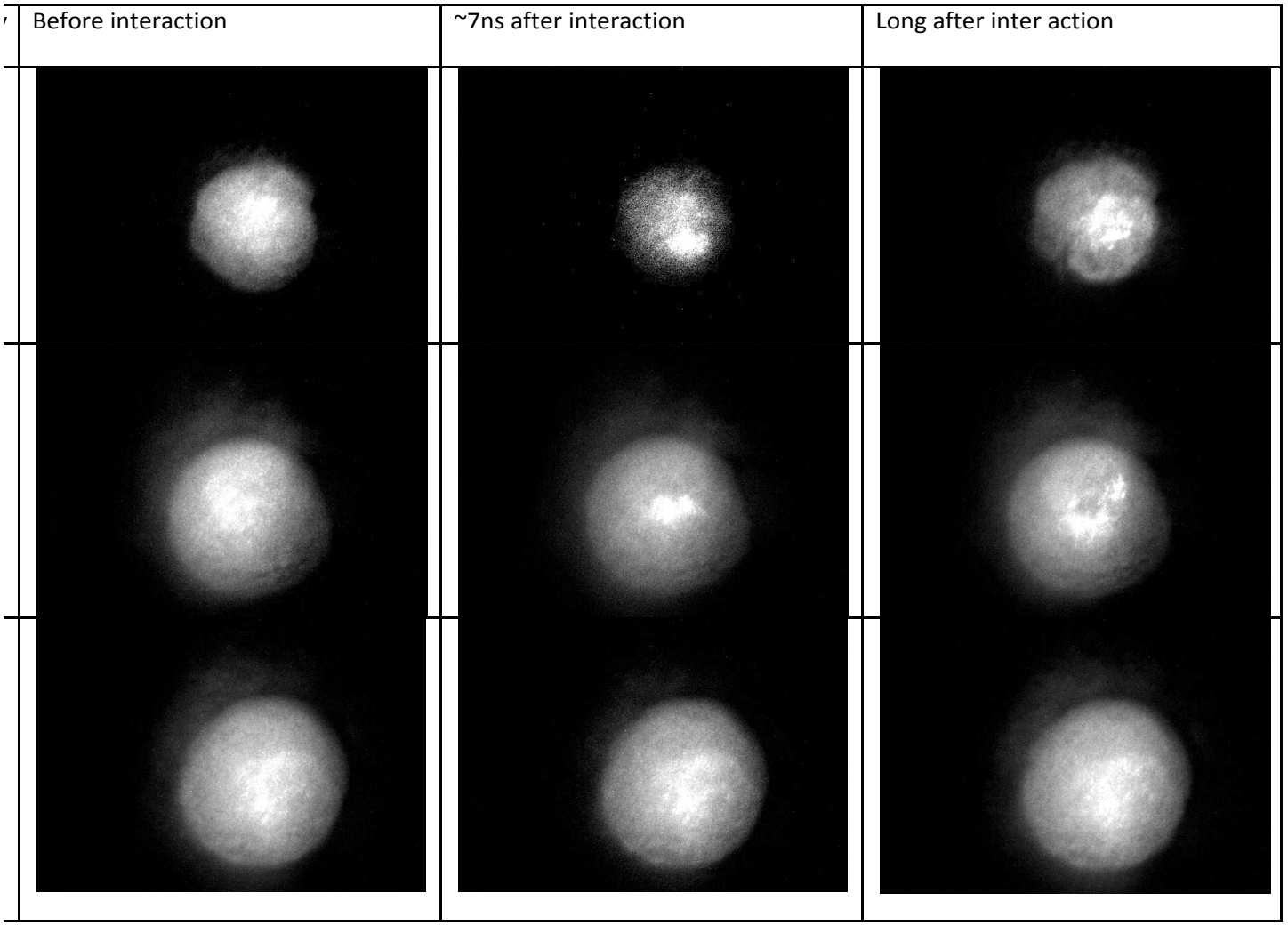




Influence of the pre pulse
(damage threshold of the snow target)



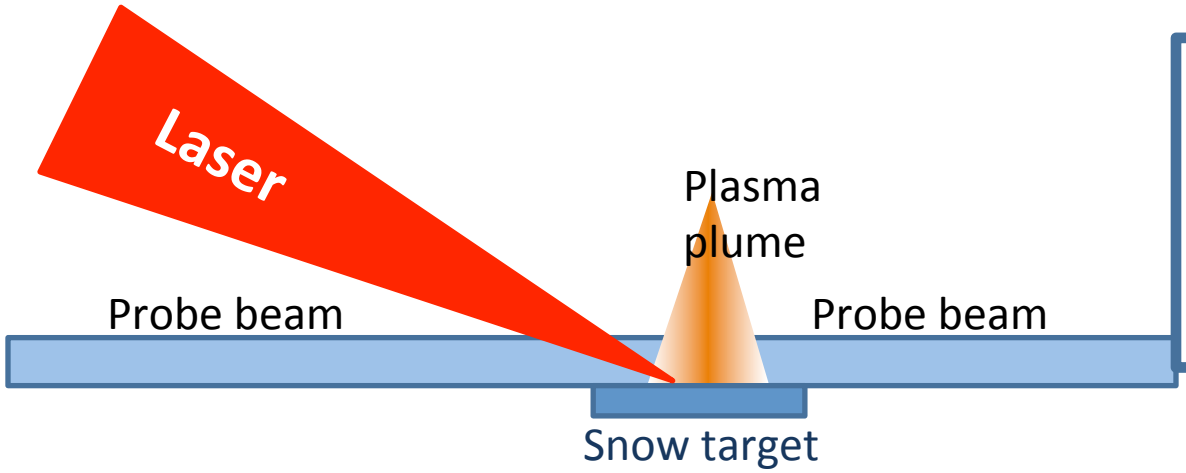
LASER @ ~70 fsec. Field of view 400x300 µm. Just Strobe images.



The damage threshold – 0.3j/cm^2

Less than 1 microjoule for tight (<10 micron) focusing !

Pre-plasma density spatial profile

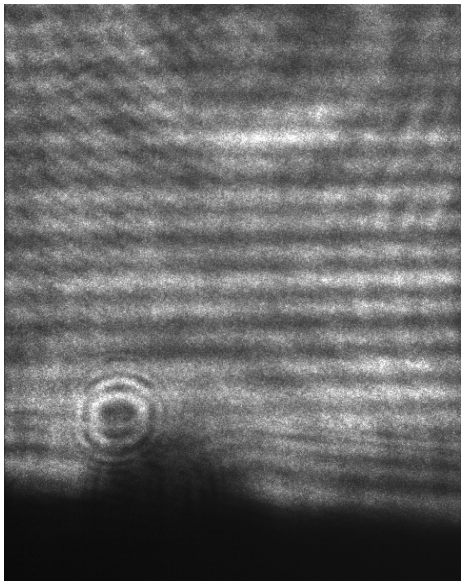


Loyd mirror interferometry and schlieren shadowgraphy

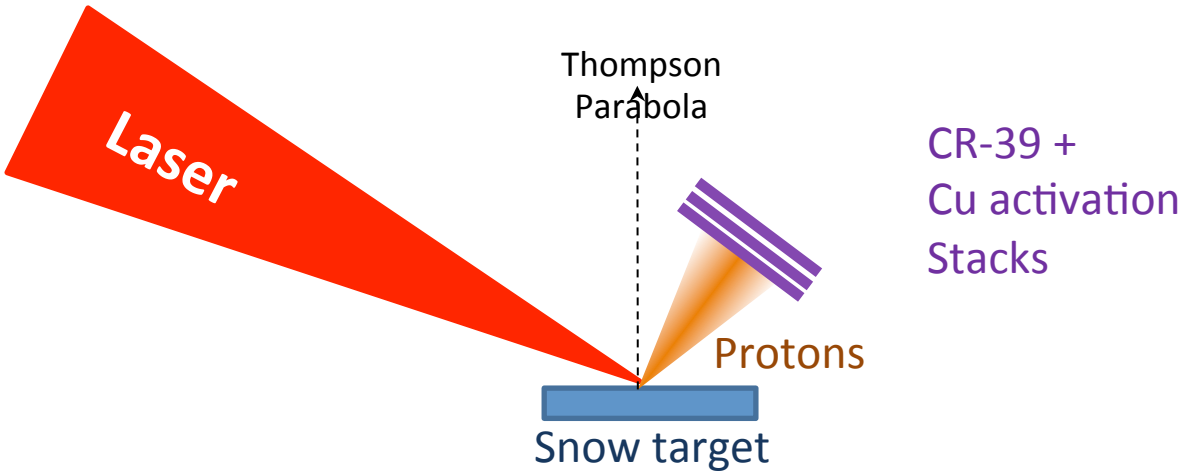
Interferometry Measurements:

Electron density up to $N_e \sim 10^{20}\ cm^{-3}$

Spatial resolution up to 1-3 microns

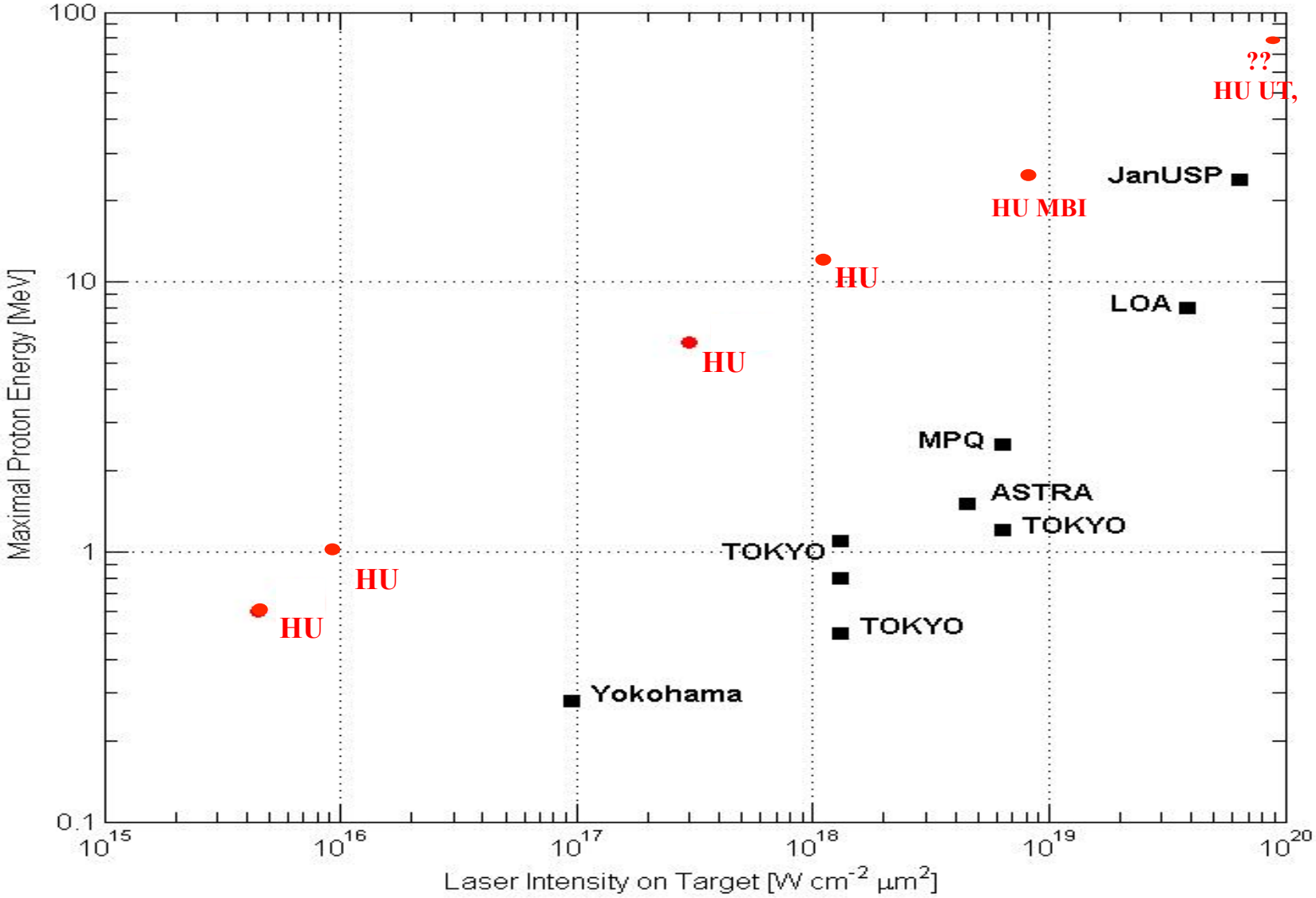


Experimental Setup



Laser Parameters	HU	MBI (up to 10TW on target in or exper.)	Texas PTW (40TW on target in our experiment)
Energy (on target)	50 mJ	400 mJ	100 J
Pulse Duration	50 fsec	65 fsec	150fsec
Spot Size	10 um^2	10 um^2	10 um^2 (multi spots)
Contrast Ratio	10^{-4} (10 nsec)	10^{-5} (6 nsec) (artificial pre-pulse)	10^{-6} (100 nsec ,many prepulses) 10^{-8} (with plasma mirror)

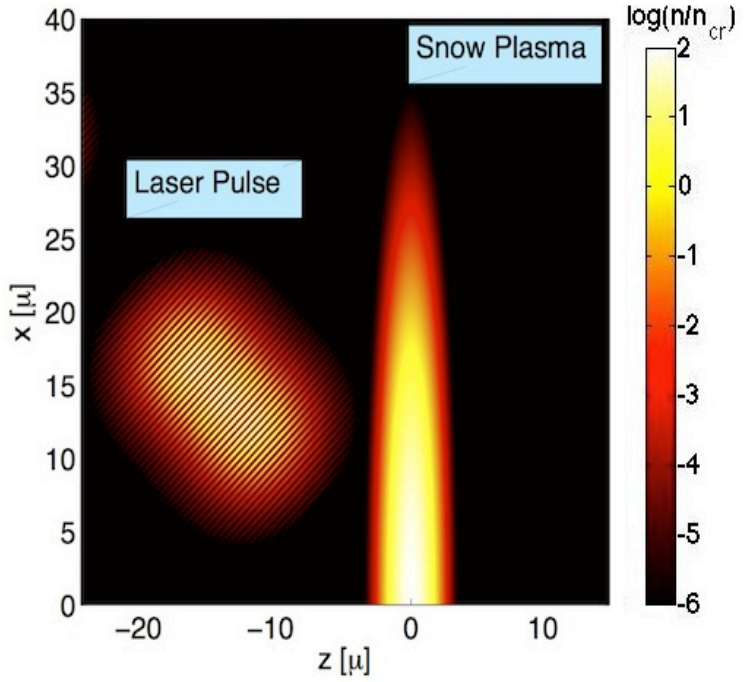
Max Proton Energy vs. Intensity



Model of laser whisker interaction

- Interaction of the laser with a single wire.
- The prepulse with the same time duration as the main pulse generates plasma with temperature of 2–5 eV.
- During the 10 ns interval between the prepulse and the main pulse the plasma expands forming a cylindrical plasma column.
- The main pulse interacts with a proper density scale length plasma.

Laser – snow wire interaction by 2D PIC simulations with TURBOWAVE



Laser: 88 fs (32 + 24 + 32), 0.8 μm, 4-5 μm spot size, $2.5 \cdot 10^{17} – 2.5 \cdot 10^{19}$ W/cm^2

The core of $100 \cdot n_{cr}$, : ellipsoid ~ 0.1-0.2μm x 1-2μm .
The critical density contour: ellipsoid ~ 1-2μm x 10μm .

TURBOWAVE, Gordon et al., IEEE Trans. Plasma Sci. 35, 1486 (2007).

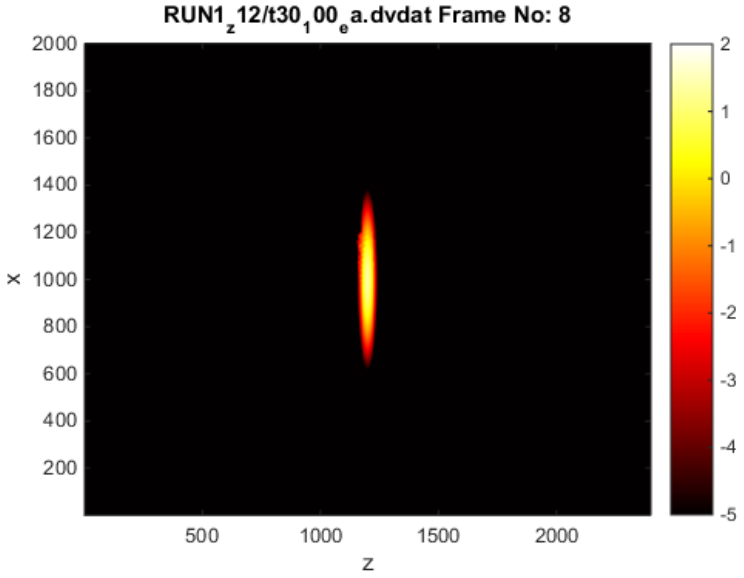
Acceleration process

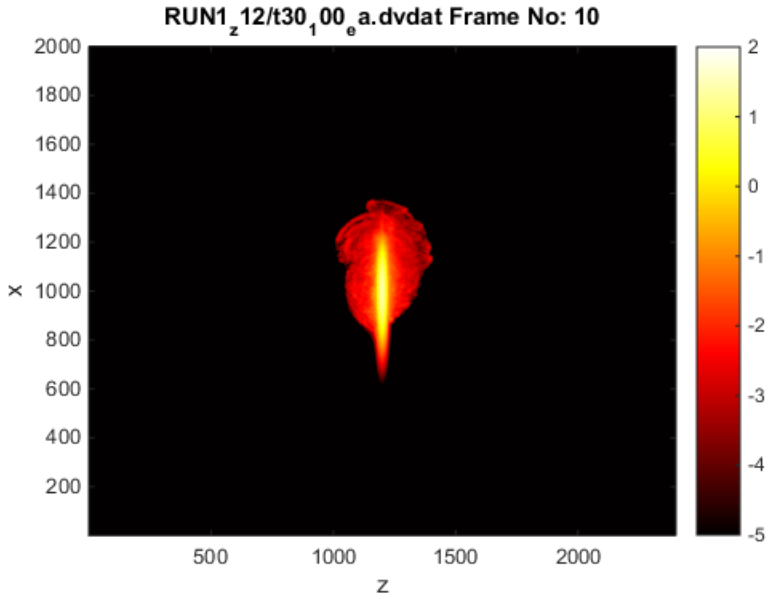
- Electrons are driven out of the plasma ellipsoid, starting charge separation ~ τ_L . Unlike TNSA, no difference between front and rear surface.
- After passage of the laser, electrons accumulate near the tip, the protons start to react, ~ (2 -3) τ_L.
- The electrons accumulation near the tip is reduced, charge separation still maintained, (3 – 6) τ_L. Oxygen ions add a pushing field.
- Late times, acceleration ceases, the protons move at constant velocity.

Zigler et al. PRL 110, 2013.

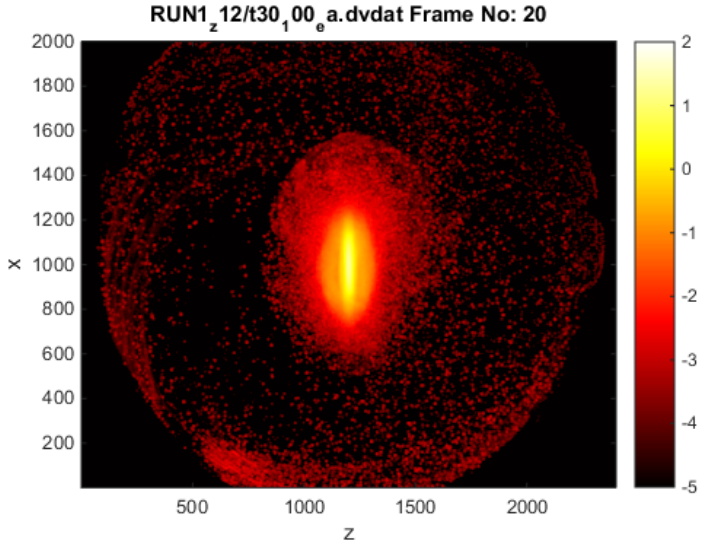
Electrons

36 fs

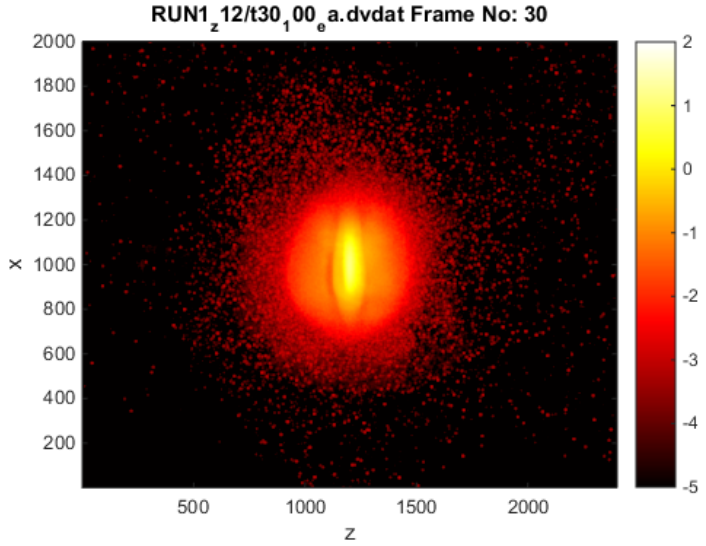




212 fs

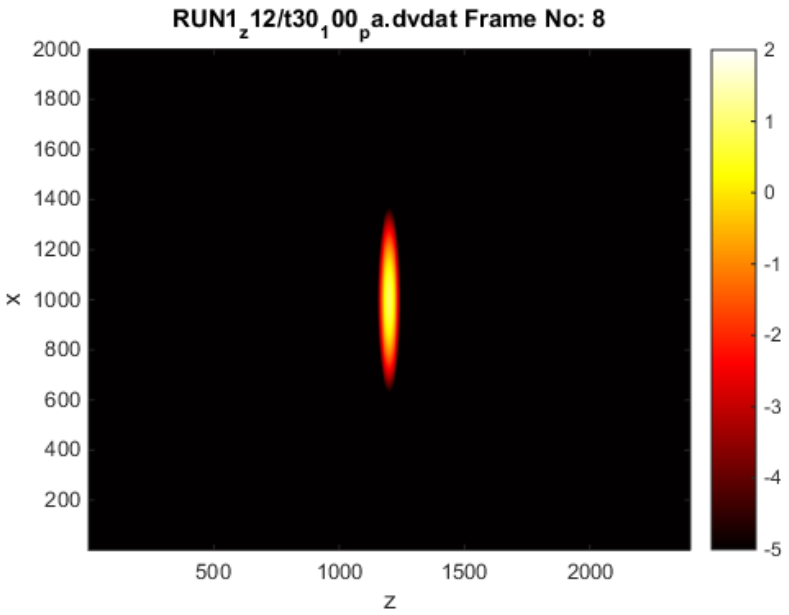


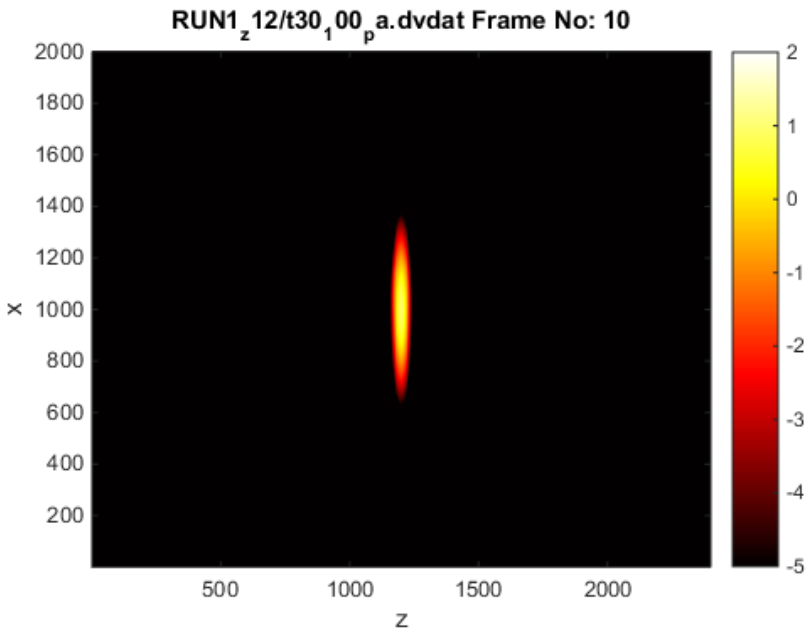
390 fs



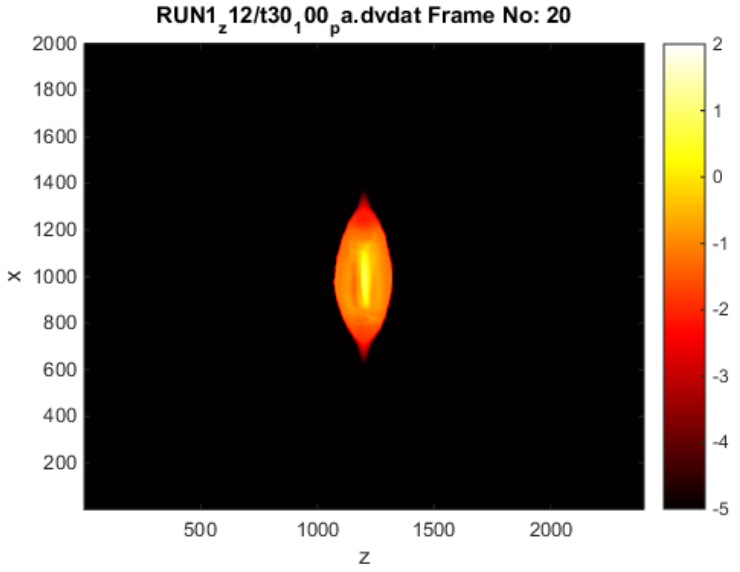
Protons

36 fs

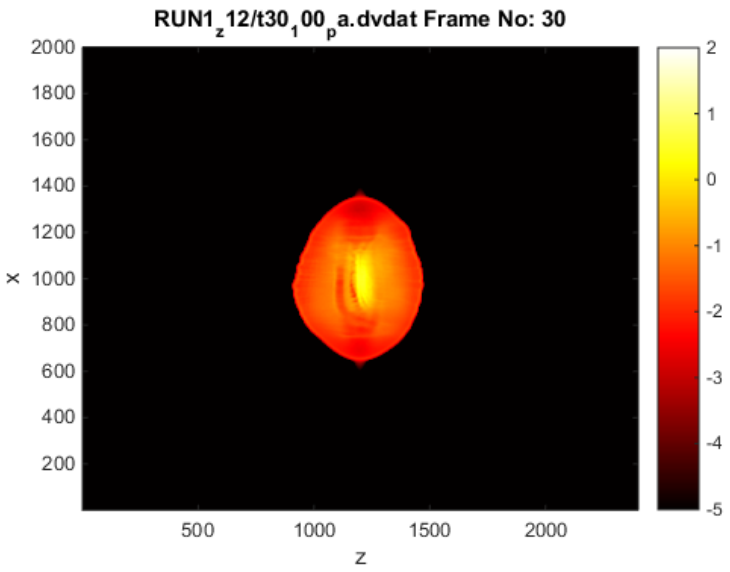




212 fs



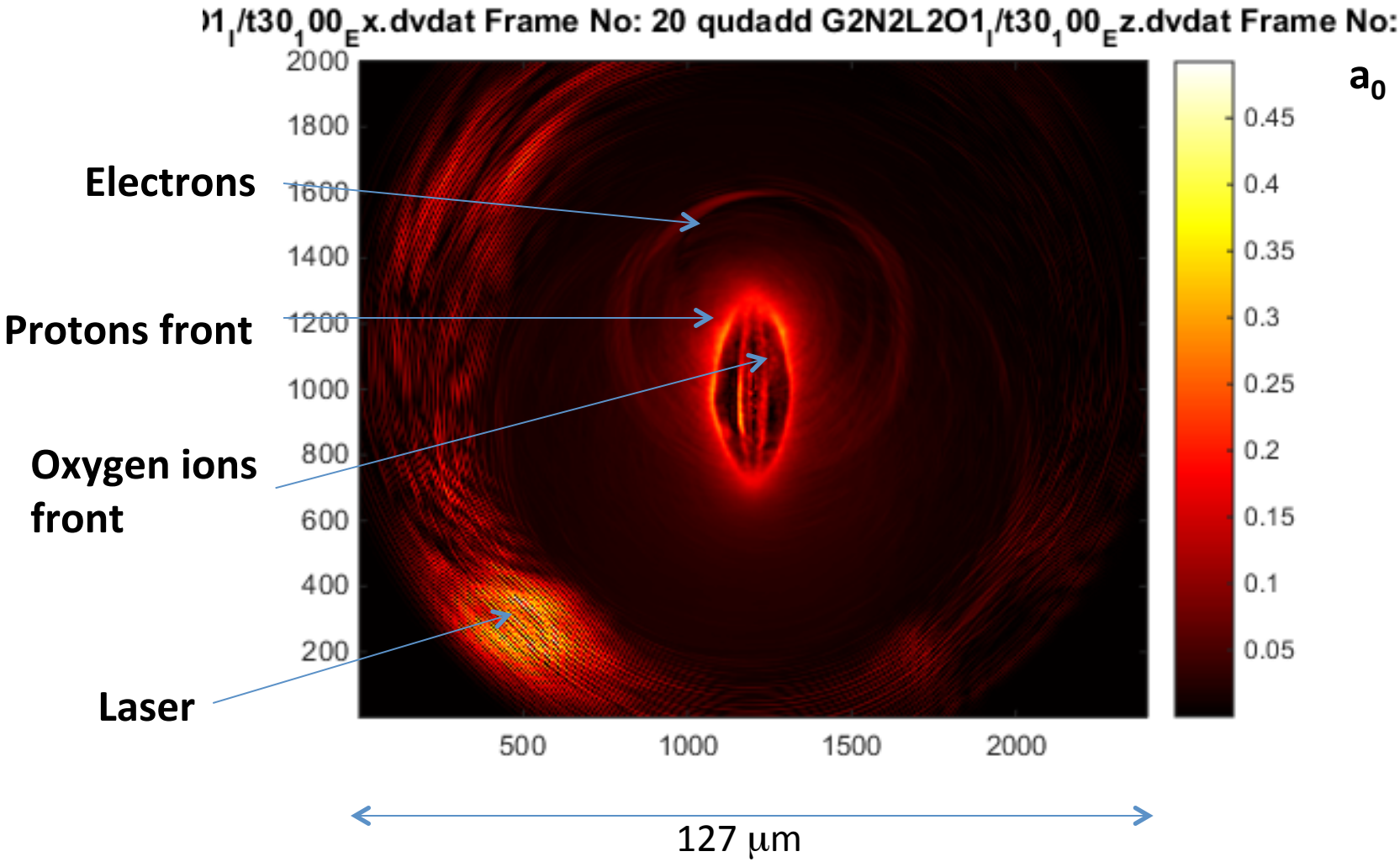
390 fs



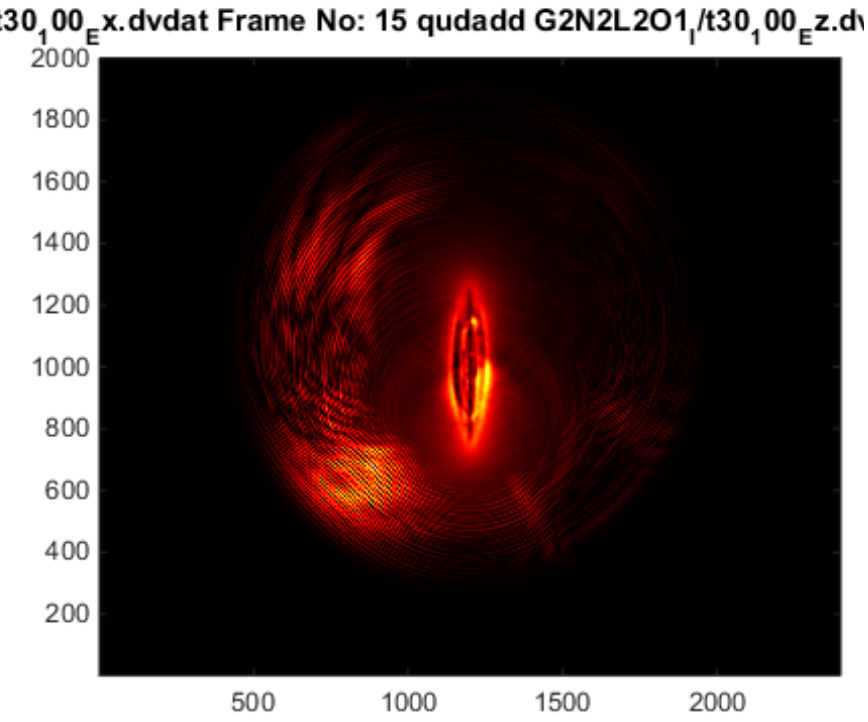
The electric field in units of a_0

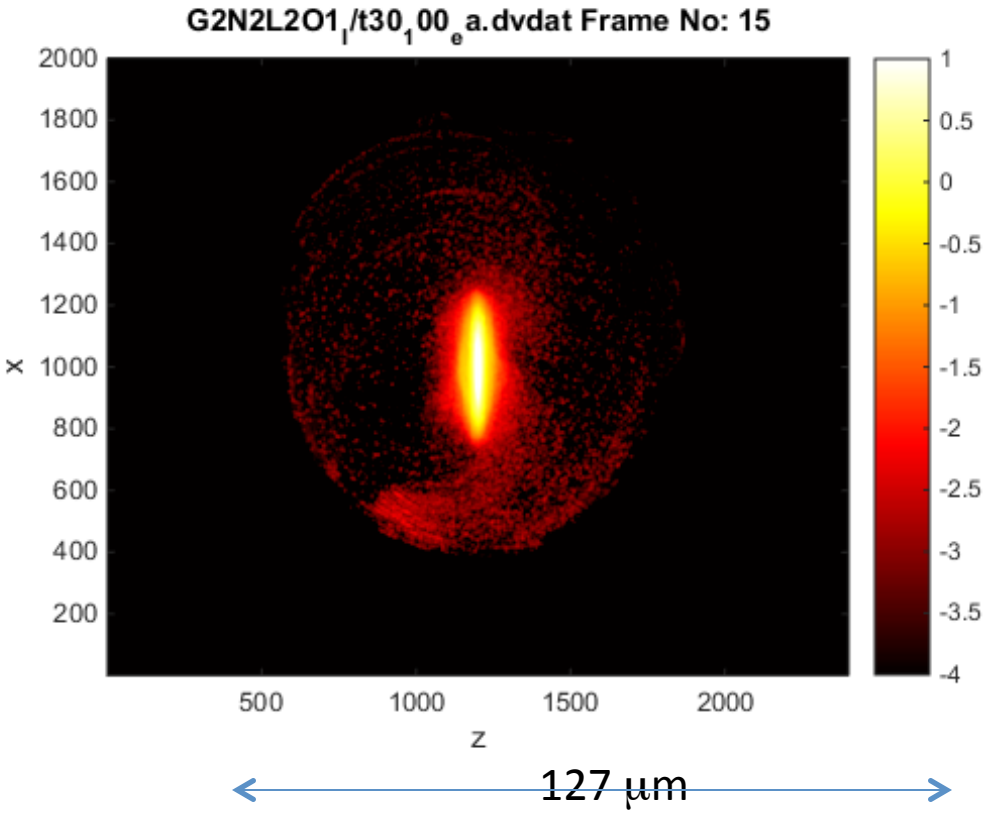
(x $1.37 \cdot 10^{11}$ V/cm) $I_L = 2.5 \cdot 10^{19}$ W/cm^2

$$a_0 = \frac{eE}{mc\omega}$$



The electric field at times shorter than 2-3 times the laser pulse duration is dominated by the electrons cloud

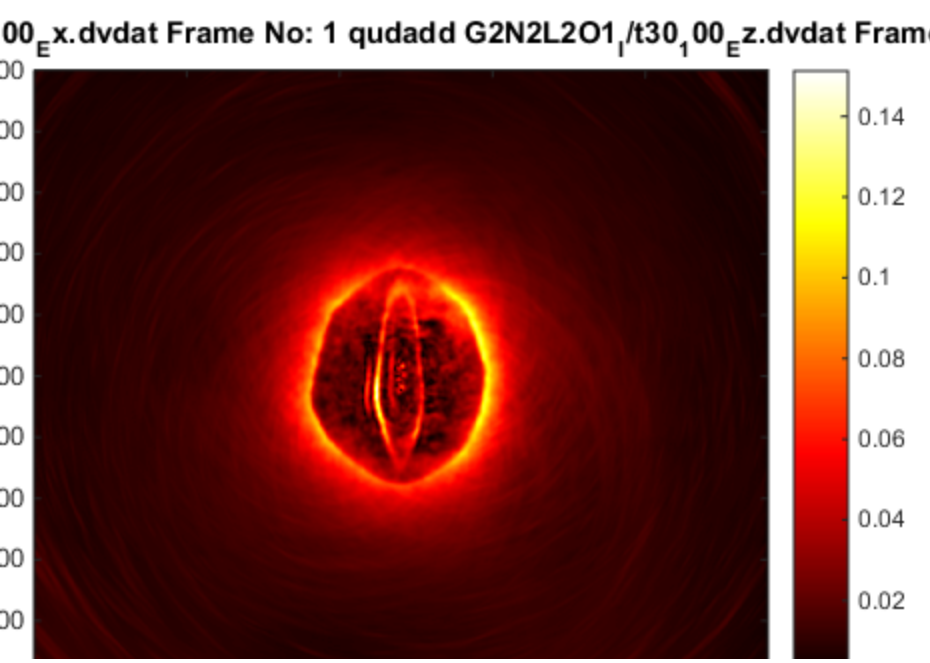


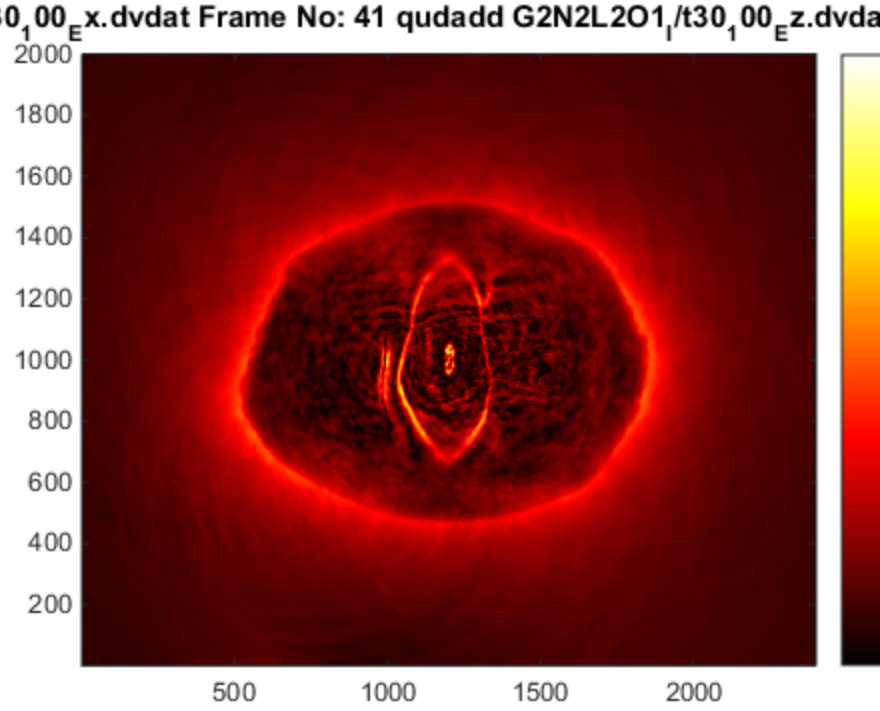


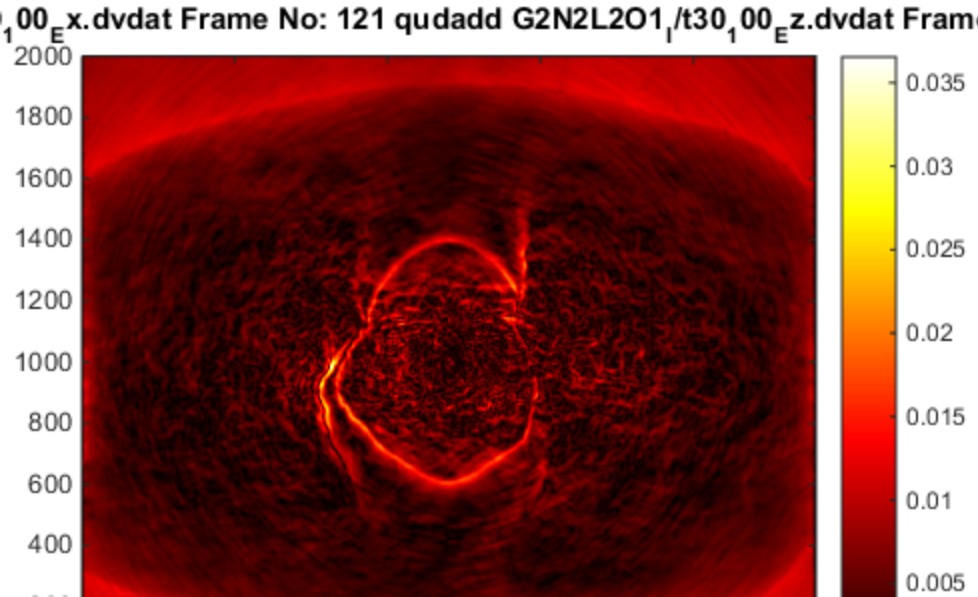
Electric field in a_0

Electrons spatial distribution

The electric field evolution at later times (in a_o)





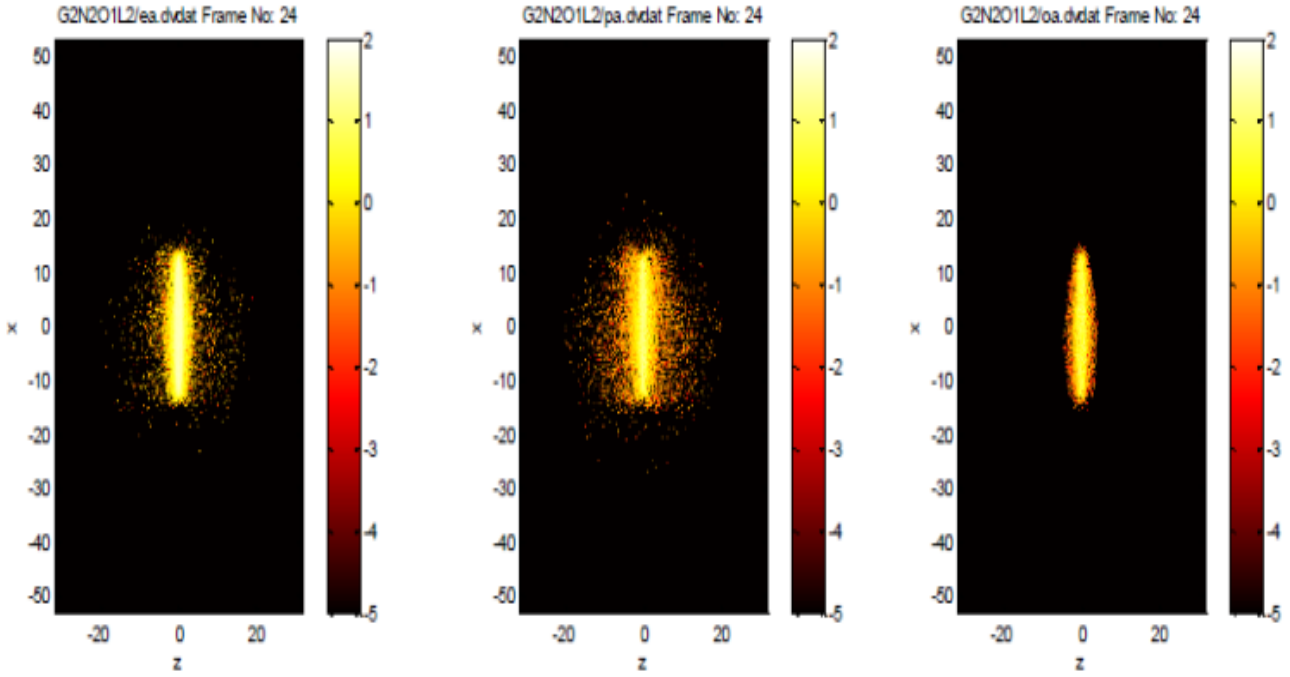


The outer shell moves with the protons front.

The inner shell moves with the oxygen ions front.

Times: 430 fs, 784 fs, 1492 fs after start of interaction

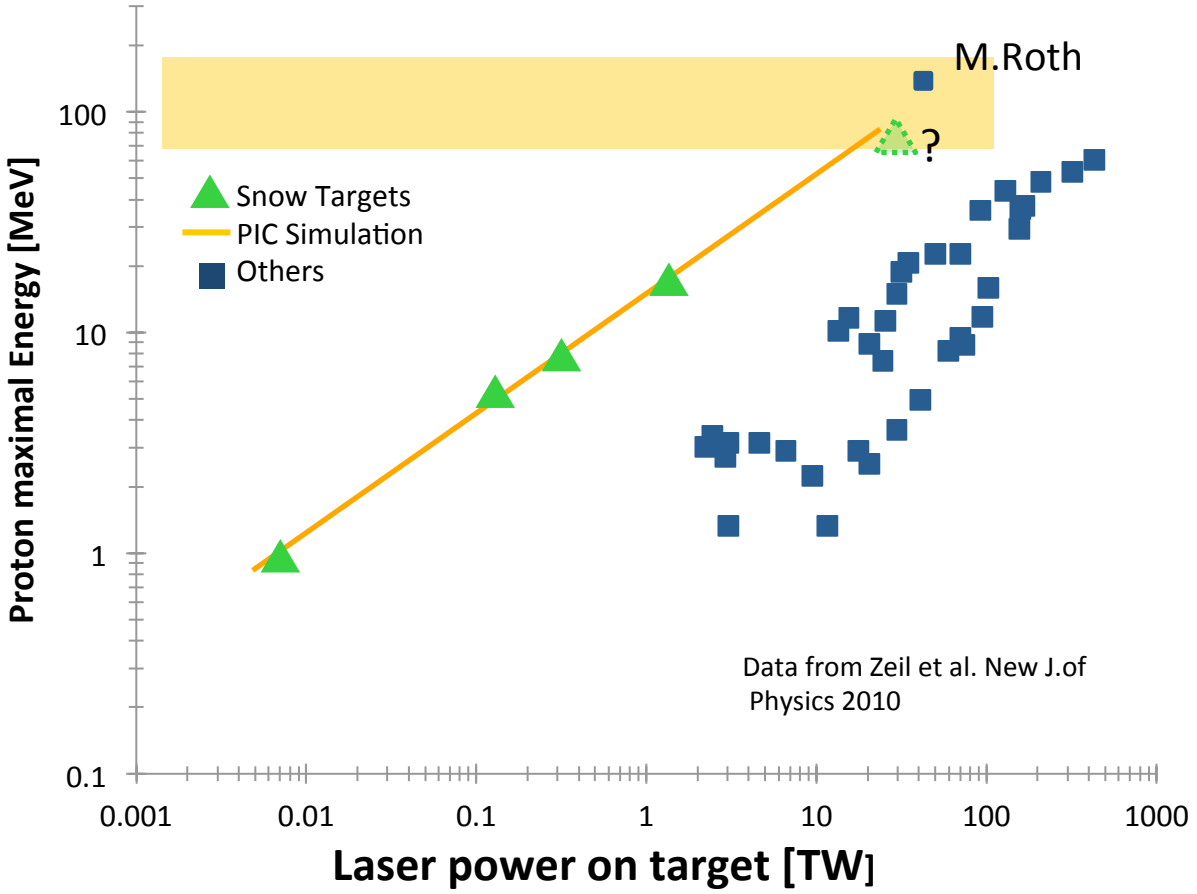
Constant solid density



Electrons **Protons** **Oxygen**

I_L = $2.5 \cdot 10^{19}$ W/cm^2, propagating at 45^o relatively to the whisker major axis.
Time = 672 fs after the laser pulse hit the whiskers.

Proton energy vs. Laser power




Thank you

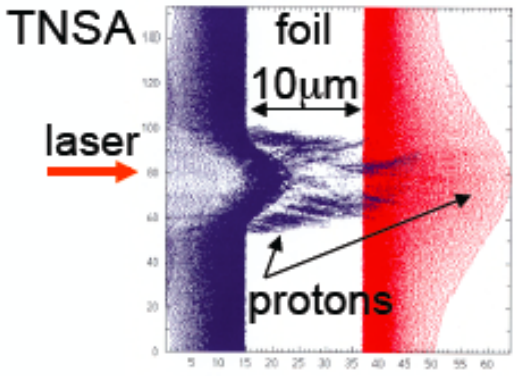
Output of 1D model - accelerated protons energy

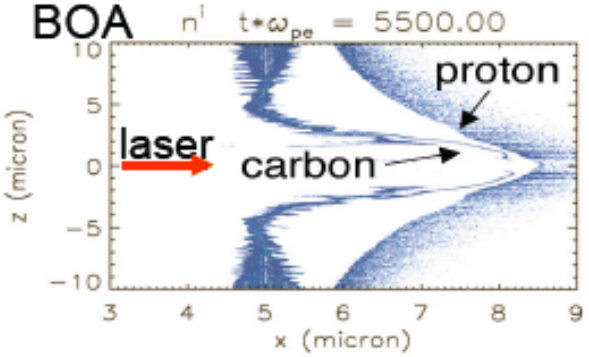
- Field enhancement: $a_{0eff} \sim 3a_0$
- Hot electrons: $k_B T_h = m_e c^2 [\sqrt{1 + \frac{I\lambda^2}{1.37 \cdot 10^{18}}} - 1]$
- Short length scale: $L \sim 0.05\lambda$
- Accelerating field: $E_{acc} \approx \frac{kT_{hot}}{eL}$
- Ion energy: accelerated along one wavelength

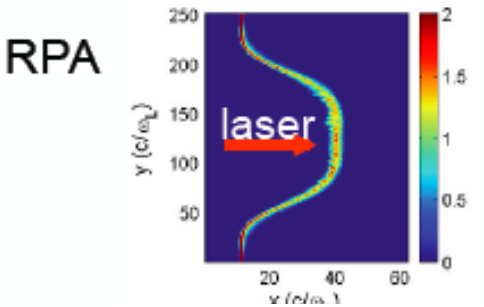
$$E_{proton} \cong E_{acc} \times \lambda = 20kT_{hot} = 6MeV$$

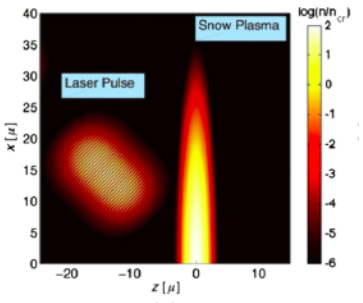
At $k_B T_h \sim 300$ keV

Ion acceleration mechanism	Acronym	Ion Accel. process
Target-Normal Sheath Acceleration S. Hatchett *et al.*, Phys. Plas. **7**, 2076 (2000)	TNSA	Charge separation GeV protons? X
Break out afterburner L. Yin *et al.*, Laser Part. Beams **24,** 291 (2006) ; Phys. Plasmas **14,** 056706 (2007)	BOA	Kinetic Process (Buneman): relative *e-i* drift GeV protons? ✓ Linear Polar.
Radiation Pressure Acceleration, Aka Plasma Piston E.g., A.P.L. Robinson, *et al.*, New J. Phys. **10**, 013021 (2008)	RPA	Charge separation GeV protons? ✓ Circular Polar.
Field Enhancement by Microwires Zigler et al PRL 2013	**FEM**	**Charge separation 150 MeV protons by 200 TW**

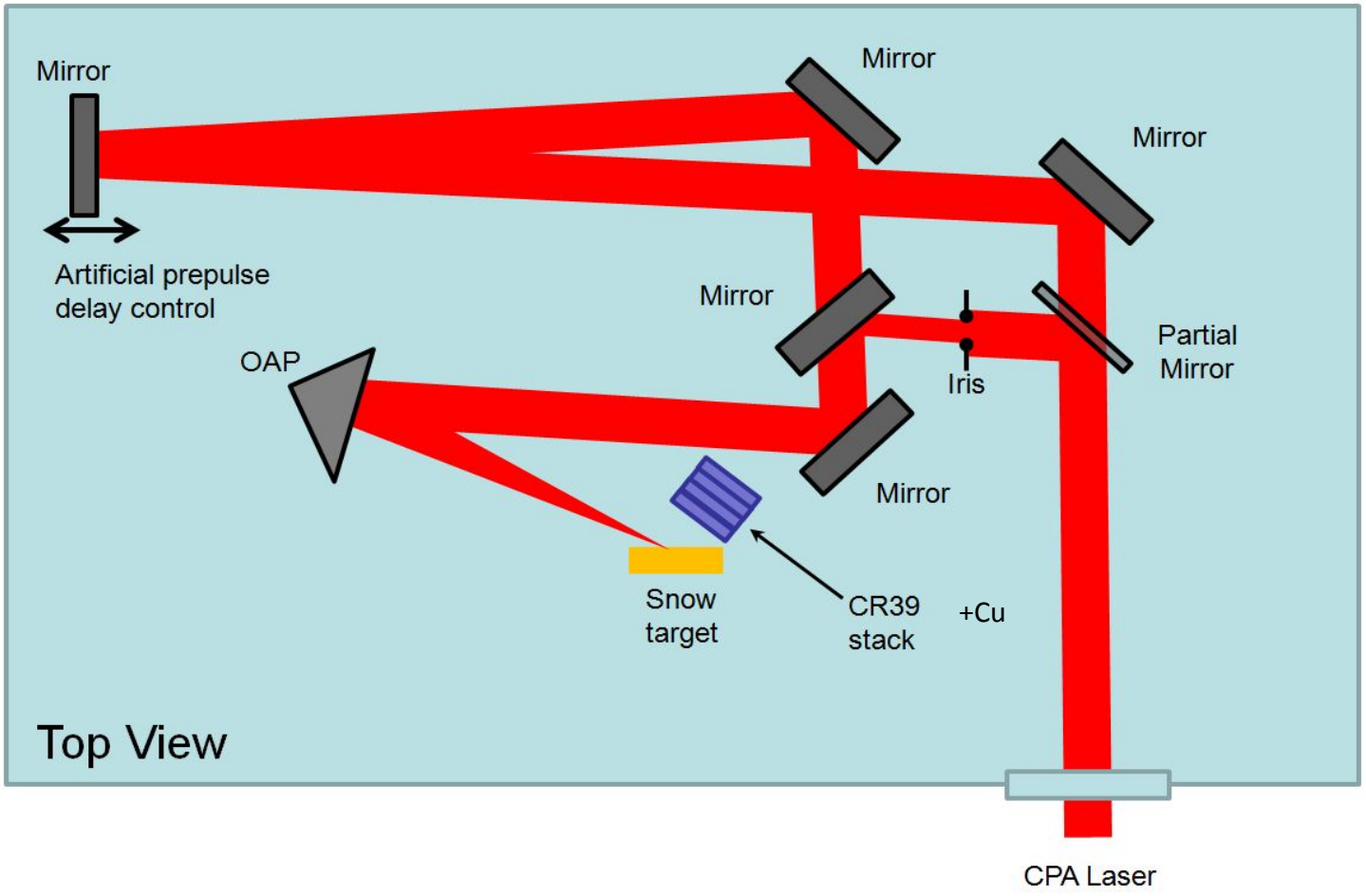






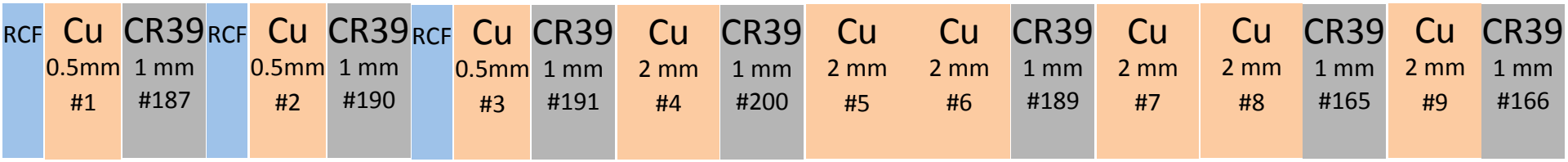


Experiments of proton acceleration with snow targets



Shot 7354 Texas PW (42TW on Target)

- AR plasma mirrors slides
- Stack (protons arrive from the left):



- Geiger counter - Cu#1 signal

Cu Activation (TU)

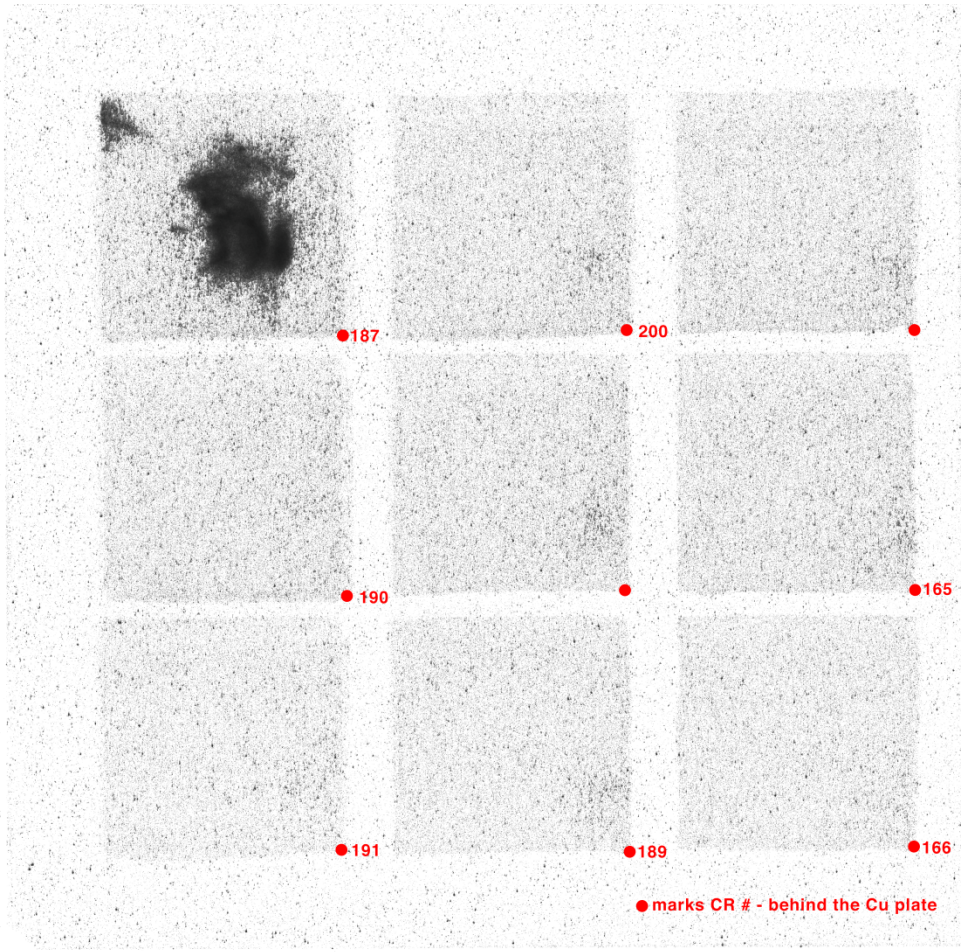


Image plate scan (with grey level adjusted)

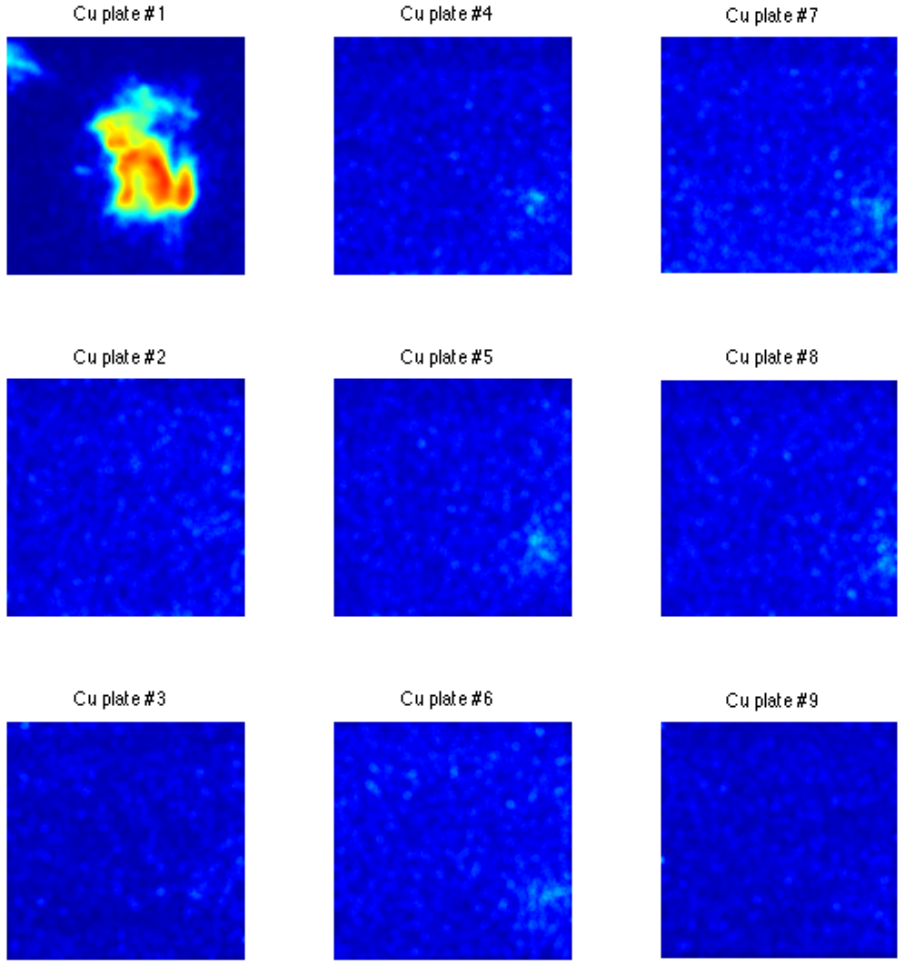
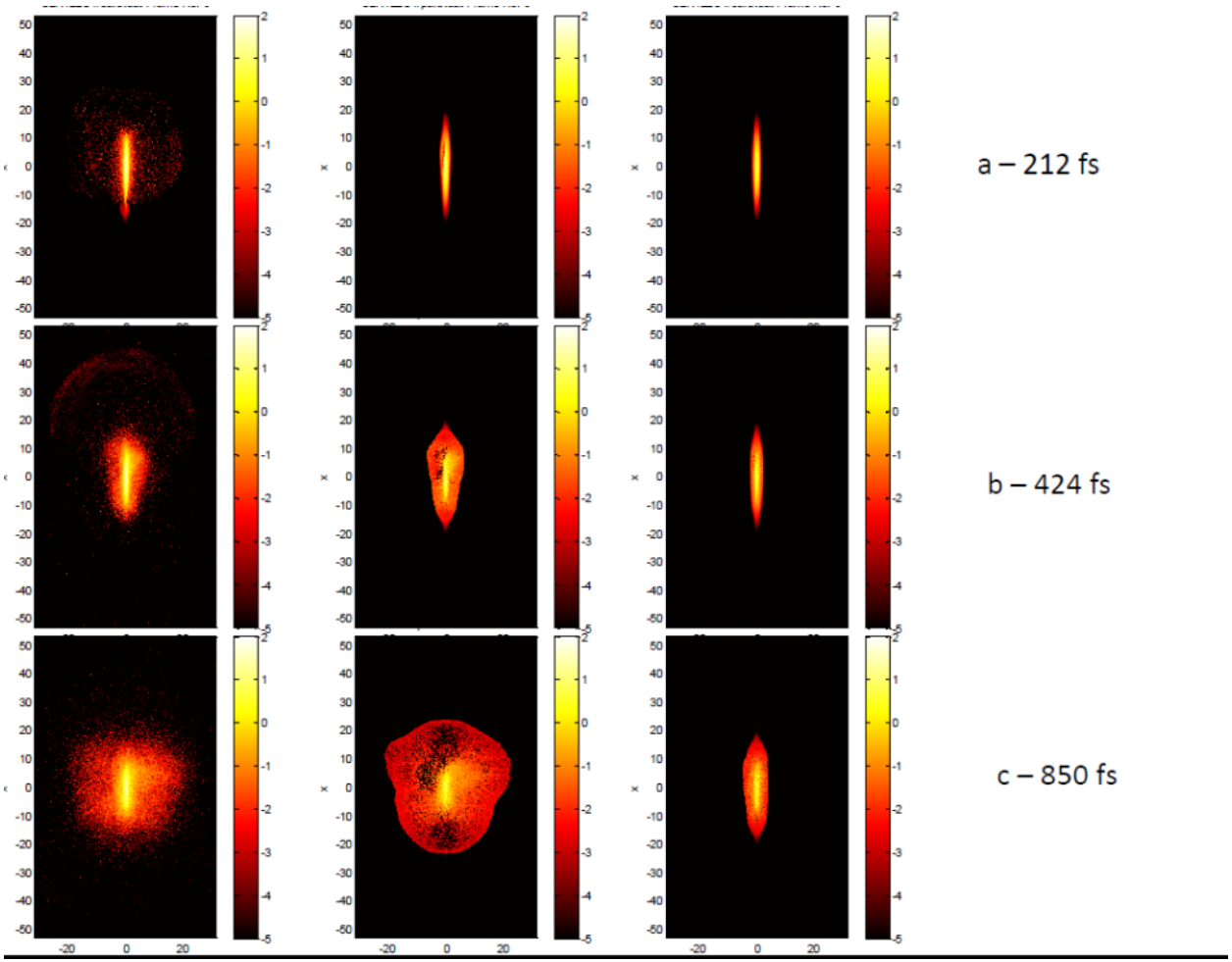
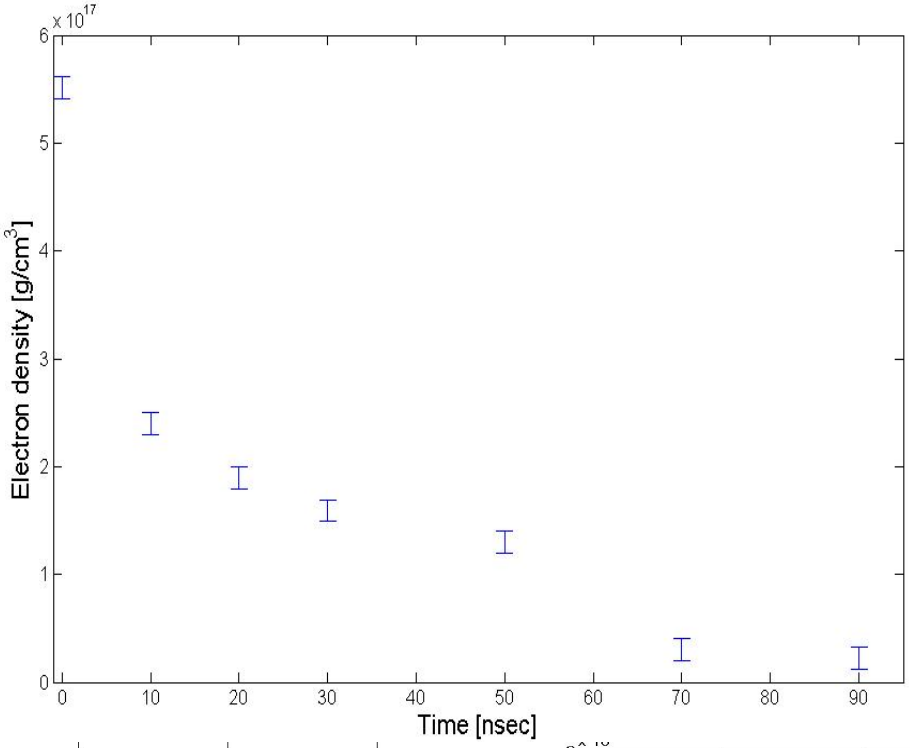


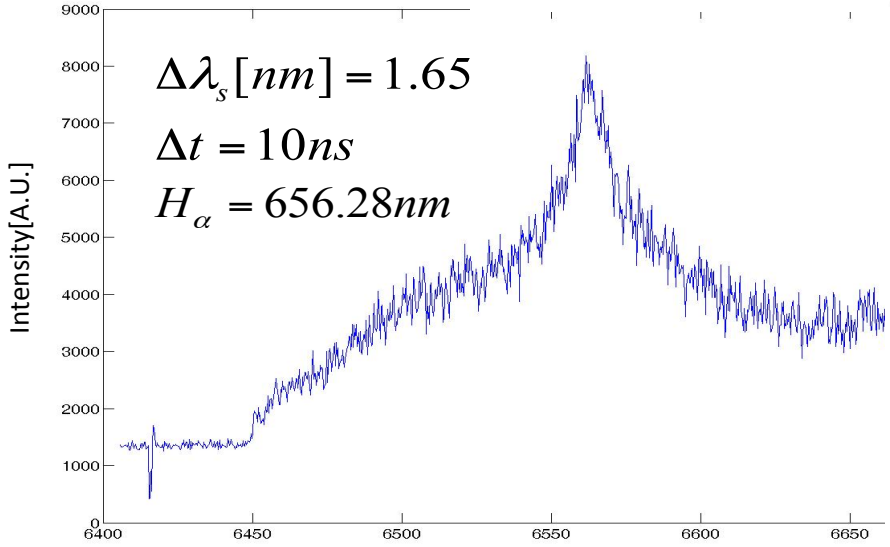
Image plate scan (with spatial 1mm average)

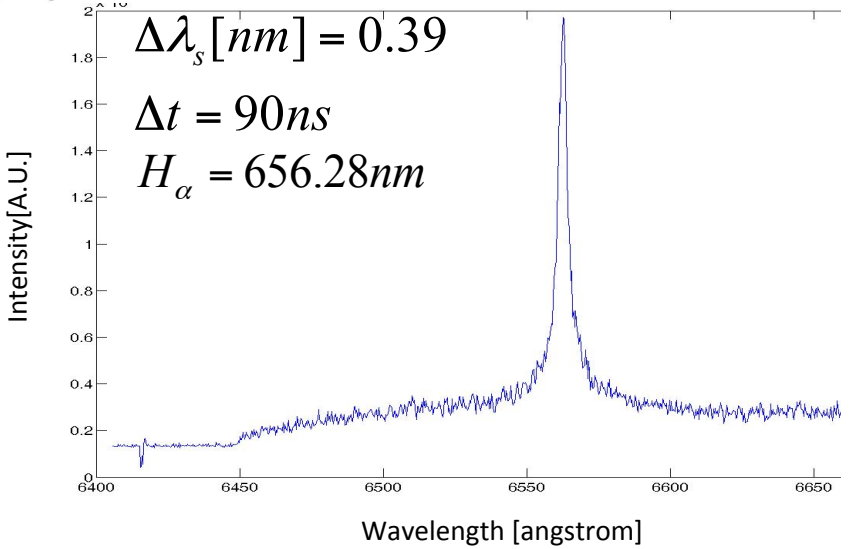
$I_L = 2.5 \cdot 10^{19}$ W/cm^2, 90^o irradiance, at 141 fs.



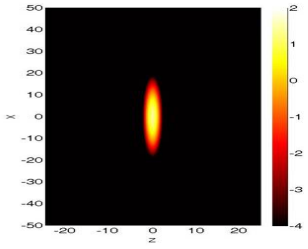
Pre-plasma density temporal profile

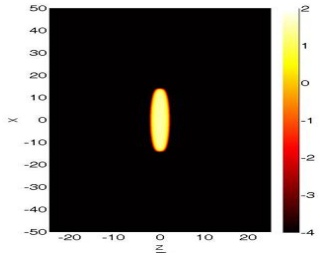


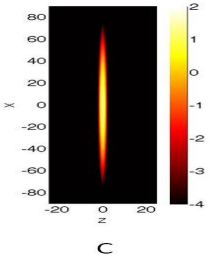


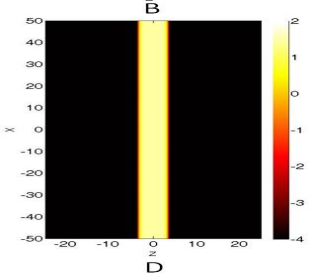


Protons energy spectrum

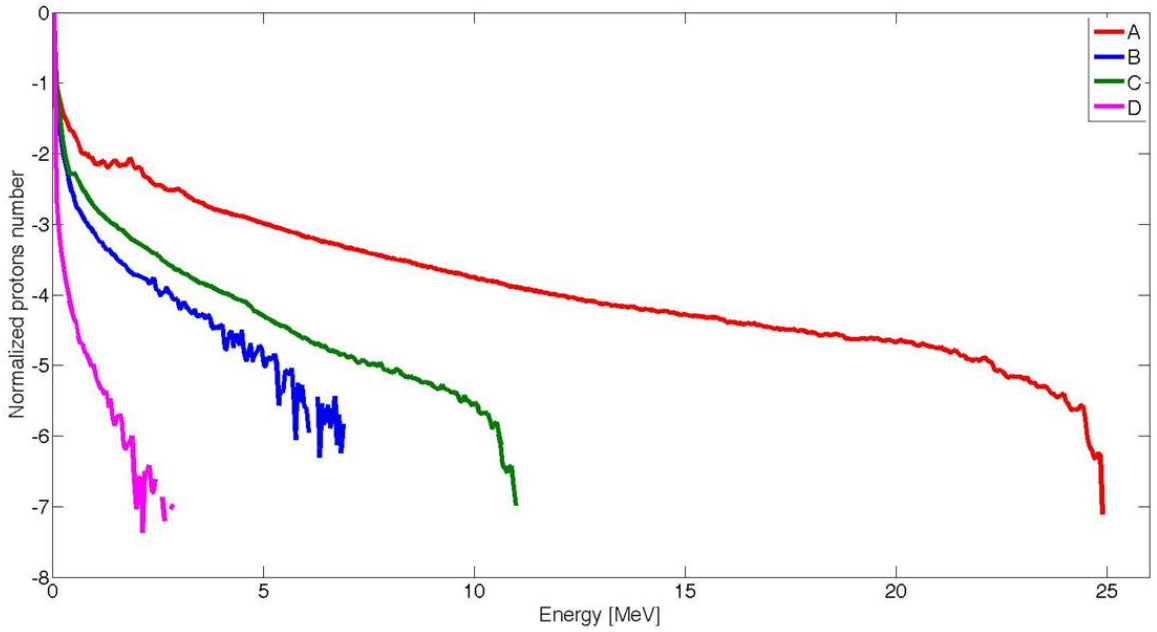








$I_L = 2.5 \cdot 10^{19}$ W/cm^2, propagating at 45^o.



Collisionless plasma description

$$
\begin{cases}
\dfrac{\partial f_j}{\partial t} = -\mathbf{v}\cdot\dfrac{\partial f_j}{\partial \mathbf{x}} - q_j\left(\mathbf{E}+\dfrac{\mathbf{v}}{c}\times\mathbf{B}\right)\cdot\dfrac{\partial f_j}{\partial \mathbf{p}} \\
\nabla\cdot\mathbf{E} = 4\pi\rho \\
\nabla\times\mathbf{E} = -\dfrac{1}{c}\dfrac{\partial \mathbf{B}}{\partial t} \\
\nabla\times\mathbf{B} = \dfrac{4\pi}{c}\mathbf{J}+\dfrac{1}{c}\dfrac{\partial \mathbf{E}}{\partial t} \\
\nabla\cdot\mathbf{B} = 0
\end{cases}
$$

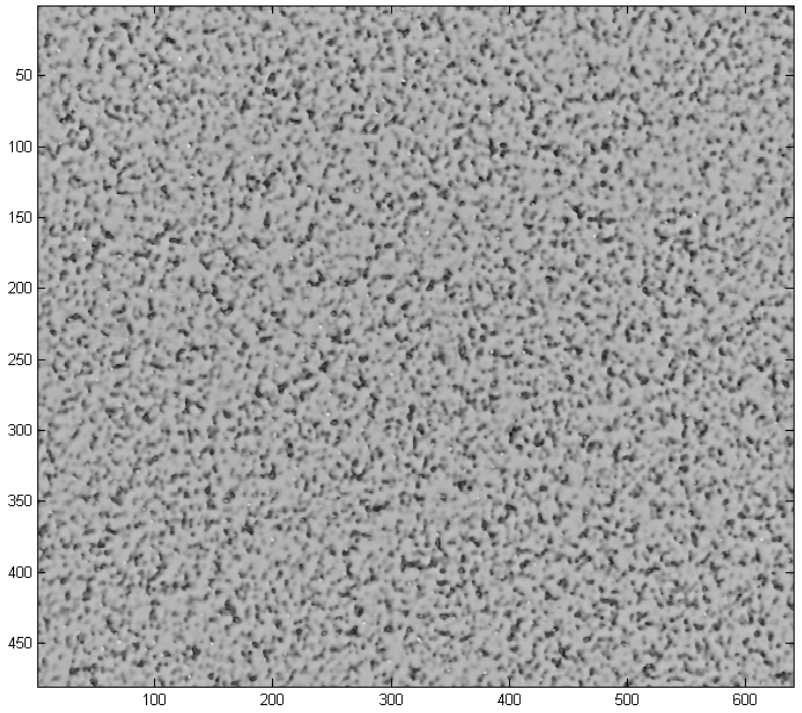
$$
\rho = \sum_j q_j \int f_j(\mathbf{x},\mathbf{p},t)\,\mathrm{d}\mathbf{p}
$$

$$
\mathbf{J} = \sum_j \frac{q_j}{m_j}\int \mathbf{p} f_j(\mathbf{x},\mathbf{v},t)\,\mathrm{d}\mathbf{p}
$$

D1 protons >1MeV

- Distribution relatively uniform.
- Counts (based on 30 images) > 2E5 protons/mm^2
- Total counts is 10^8 protons

FOV is 100um



D3 proton > 20 MeV

- Highly non-uniform (bunch)
- Counts (average 30 images) : 10^5 protons/mm^2
- Total count ~ 10^6

FOV is 100um