Status of the Simulation Activity

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Laser-plasma Simulations

Laser-plasma Simulations Simulation is an indispensable tool in designing experiments and understanding the experimental results. PIC simulation requires expertise in formulating simulation parameters and post-processing the results, along with huge computational resources. Over last few years, we have gained some expertise in this field. We have been carrying out 2D and 3D particle-in-cell (PIC) simulations relevant to the experimental parameters at RRCAT for laser -plasma based electron acceleration from gas-jet plasma. In addition, simulations on high energy proton acceleration from foil targets are also carried out. We use hydrodynamic code medusa and radiation hydrodynamic code MULTI to study the time and space evolution of plasma density, material density and electron-ion temperature for long as well as short pulse domains.

The simulation group is actively involved in the simulation studies related to:

- **Electron acceleration in SMLWFA & Bubble and other novel regimes**
- **Proton / ion acceleration in RPA & TNSA and other novel regimes**
- **Hydrodynamics of plasma in nanosecond, picosecond and femtosecond regime, and hot electron transport.**

The codes used for these simulations are:

PIC Codes:

- **VORPAL-3D** (Tech-X Corp., 256 core) installed on Kshitij-3 (256 cores)
- **VLPL-3D** (Prof. Pukhov, unlimited node) installed on Kshitij-4 (480 core)
- **EPOCH-3D** (unlimited node) installed on Kshitij-4 (480 core)
- **FISCOF-1, 2D** (Prof. Sakagami) installed on LPL workstation
- **PIConGPU-3D** (Institute for Radiation Physics at HZDR , Germany), installed on LPL-GPU cluster with 4 Nvidia Quadro 4200 GPU with ~5200 cores.

Hydrodynamic / Fluid Codes:

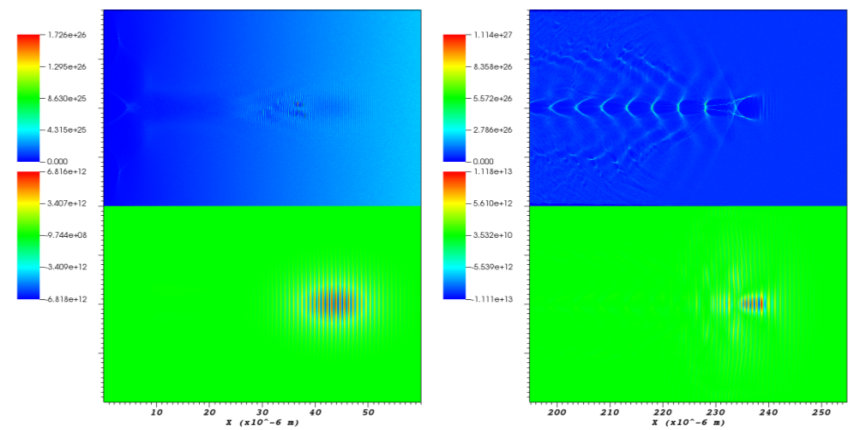
- **Multi –1,2,3D, Multifs**: installed on LPL workstation
- **BOPS** : installed on LPL workstation
- **MEDUSA 103** : installed on LPL workstation

Electron LWFA simulation using 3D particle-in-cell codes (VLPL and EPOCH)

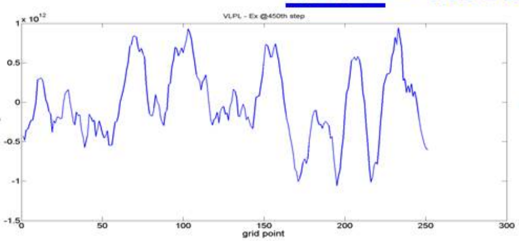
Simulation Parameters:

- ✓ Pre-formed helium plasma of density $6\times10^{19}\,cm^{-3}$ with initial linear ramp of 100 μm followed by uniform density plasma
- ✓ Gaussian laser pulse of a_0 ~ 1.65 (P_L~3 TW, ϕ_L~ 9μm, I_L~ $4.7\times10^{18}\,Wcm^{-2}$), and laser pulse length 45 fs

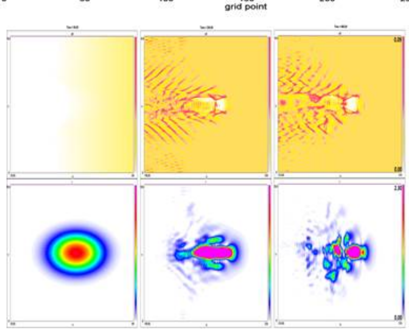
EPOCH - Results



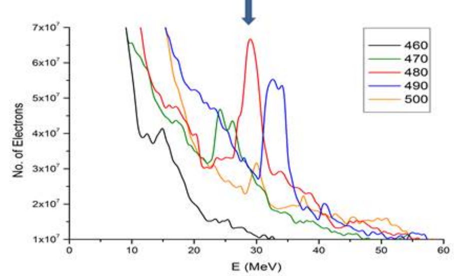
VLPL – Results



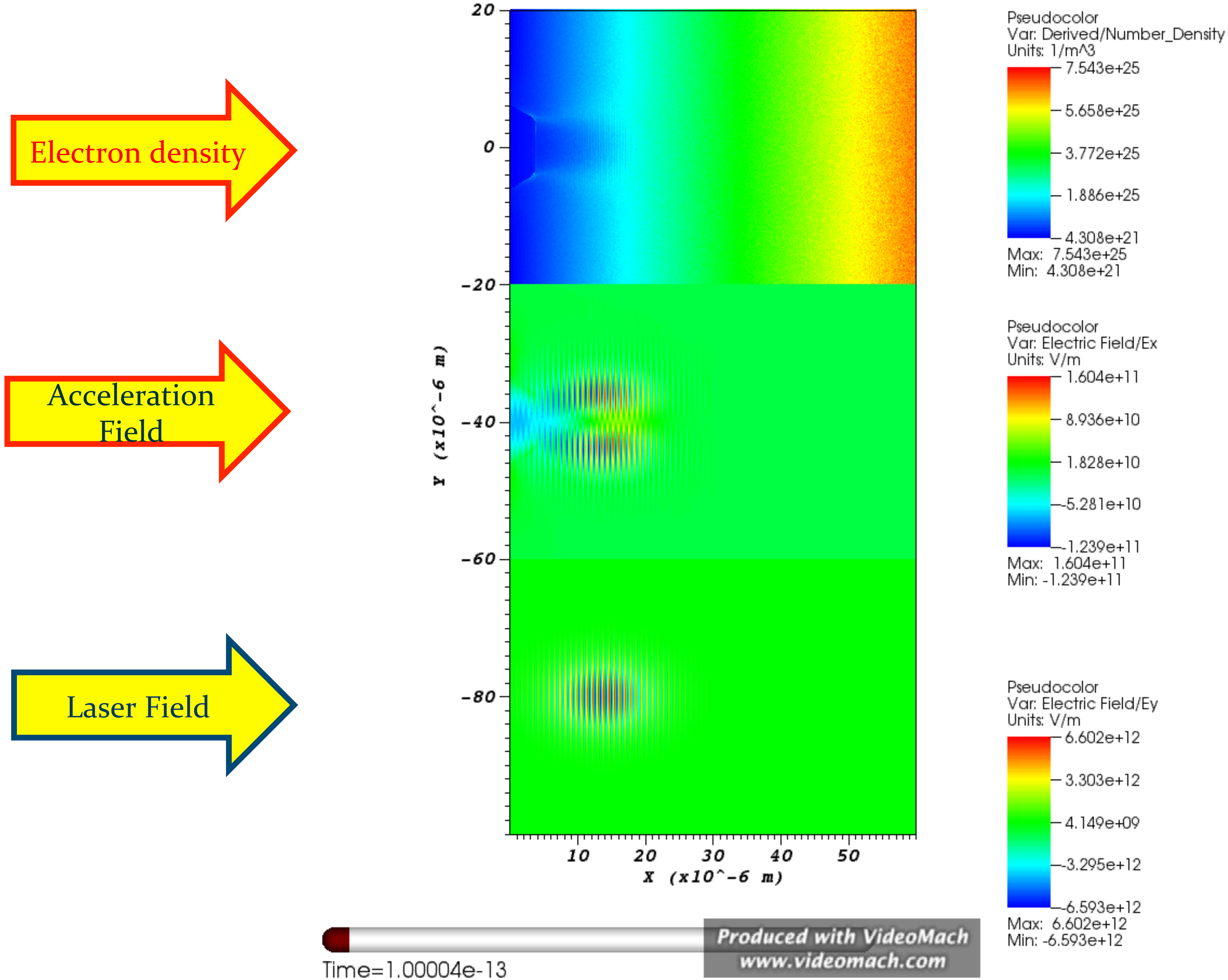
Longitudinal electric field at 460 time-step



Electron energy spectrum at time-steps 460 – 500.

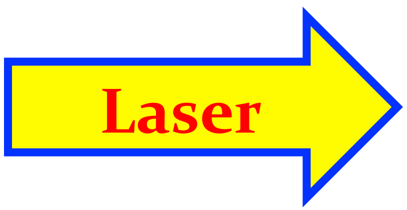


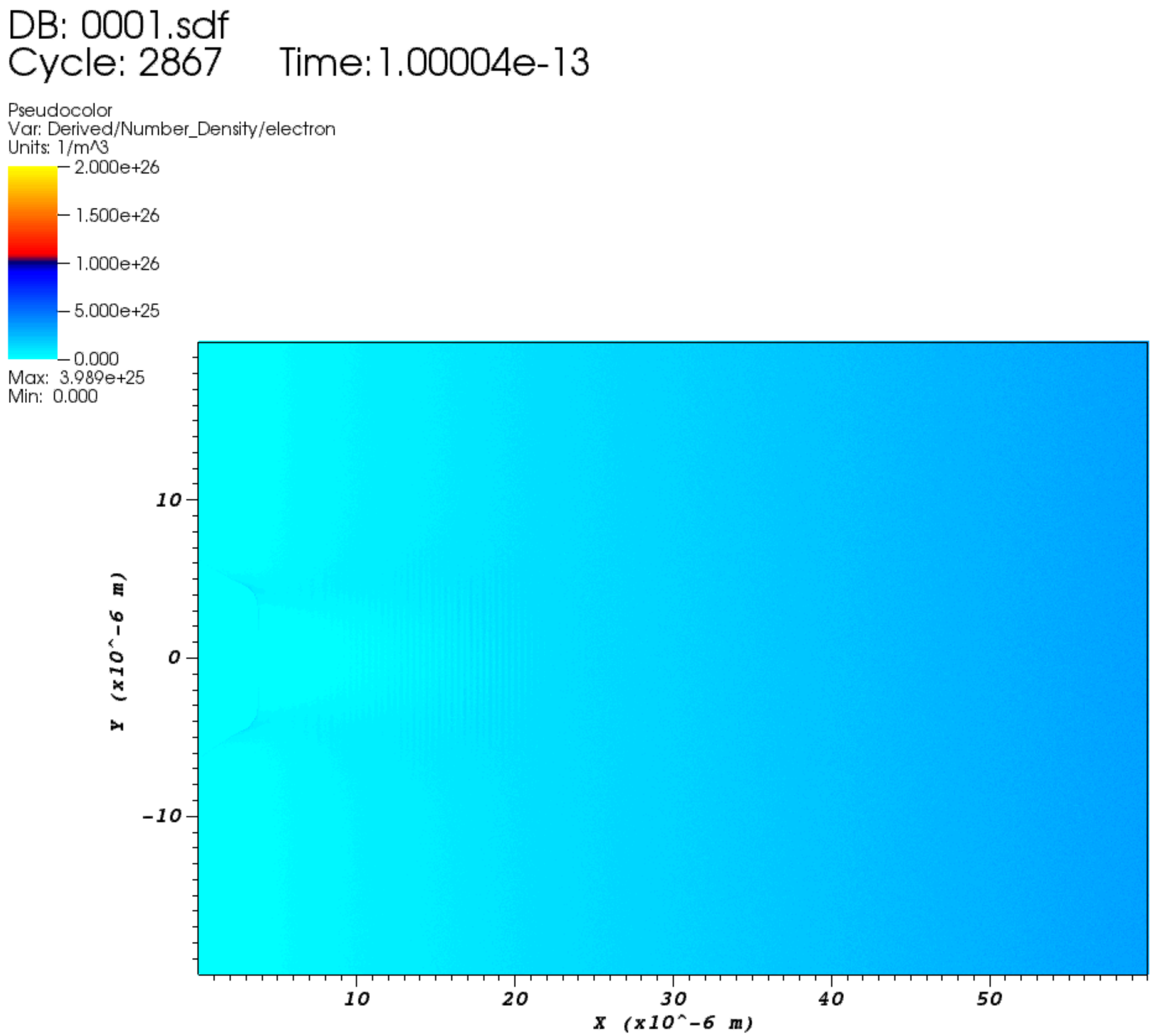
- ➢ Simulation shows strong self-modulation of the long laser pulse leading to formation of a stable cavity (bubble) and propagation upto~40μm.
- ➢ The field inside the cavity is ~1 TV/m, which yields a quasi-mono-energetic electron bunch of 32 ±3 MeV.



Electron density
Acceleration Field
Laser Field
20
0
-20
-40
-60
-80
Y (x10^-6 m)
10
20
30
40
50
X (x10^-6 m)
Pseudocolor
Var: Derived/Number_Density
Units: 1/m^3
7.543e+25
5.658e+25
3.772e+25
1.886e+25
4.308e+21
Max: 7.543e+25
Min: 4.308e+21
Pseudocolor
Var: Electric Field/Ex
Units: V/m
1.604e+11
8.936e+10
1.828e+10
-5.281e+10
-1.239e+11
Max: 1.604e+11
Min: -1.239e+11
Pseudocolor
Var: Electric Field/Ey
Units: V/m
6.602e+12
3.303e+12
4.149e+09
-3.295e+12
-6.593e+12
Max: 6.602e+12
Min: -6.593e+12
Time=1.00004e-13
Produced with VideoMach
www.videomach.com

Laser Wakefield Formation and Electron Trapping
(for TSLL Experimental Parameters)





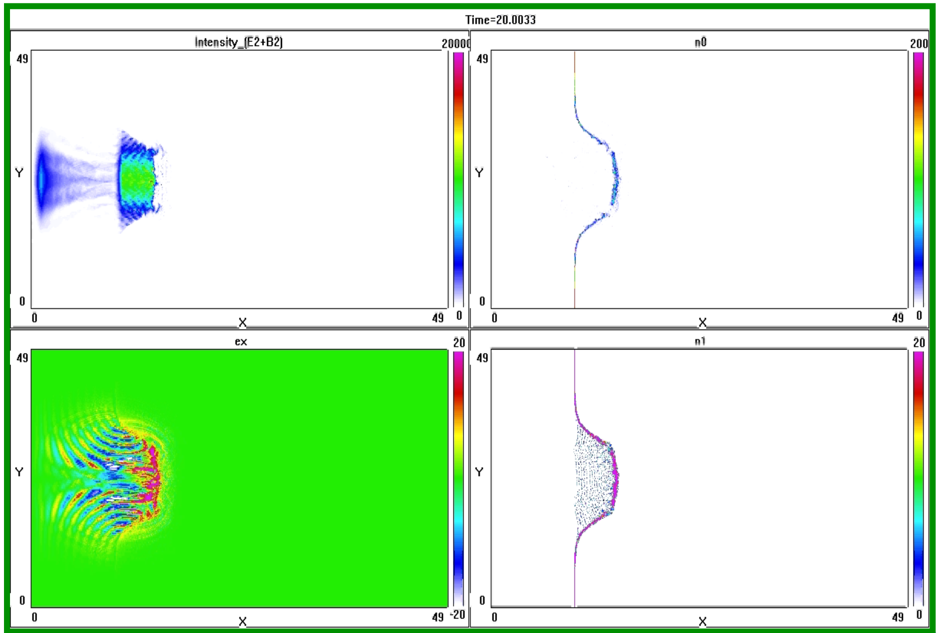
Electron Density Evolution

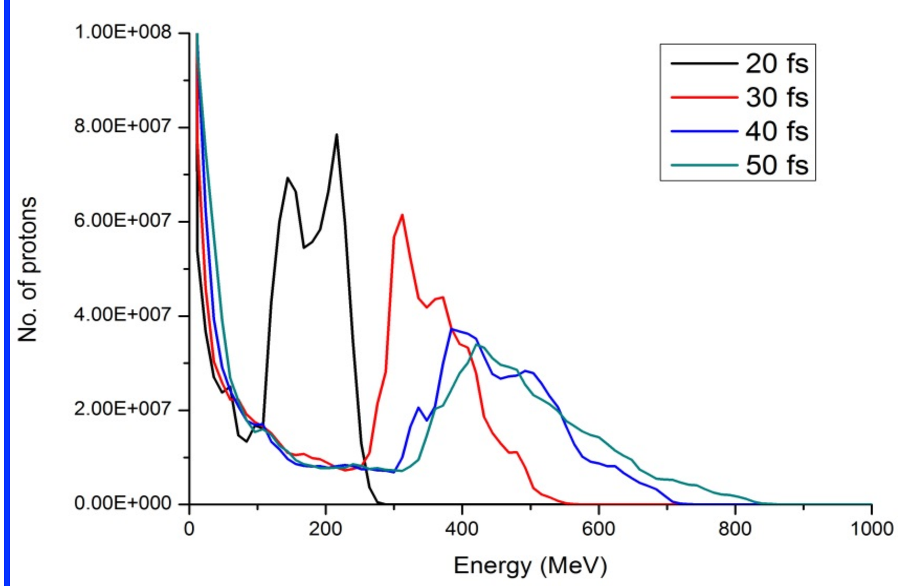
Proton acceleration for CH foil, using 3D VLPL code

- **Proton acceleration in radiation pressure acceleration (RPA) regime**

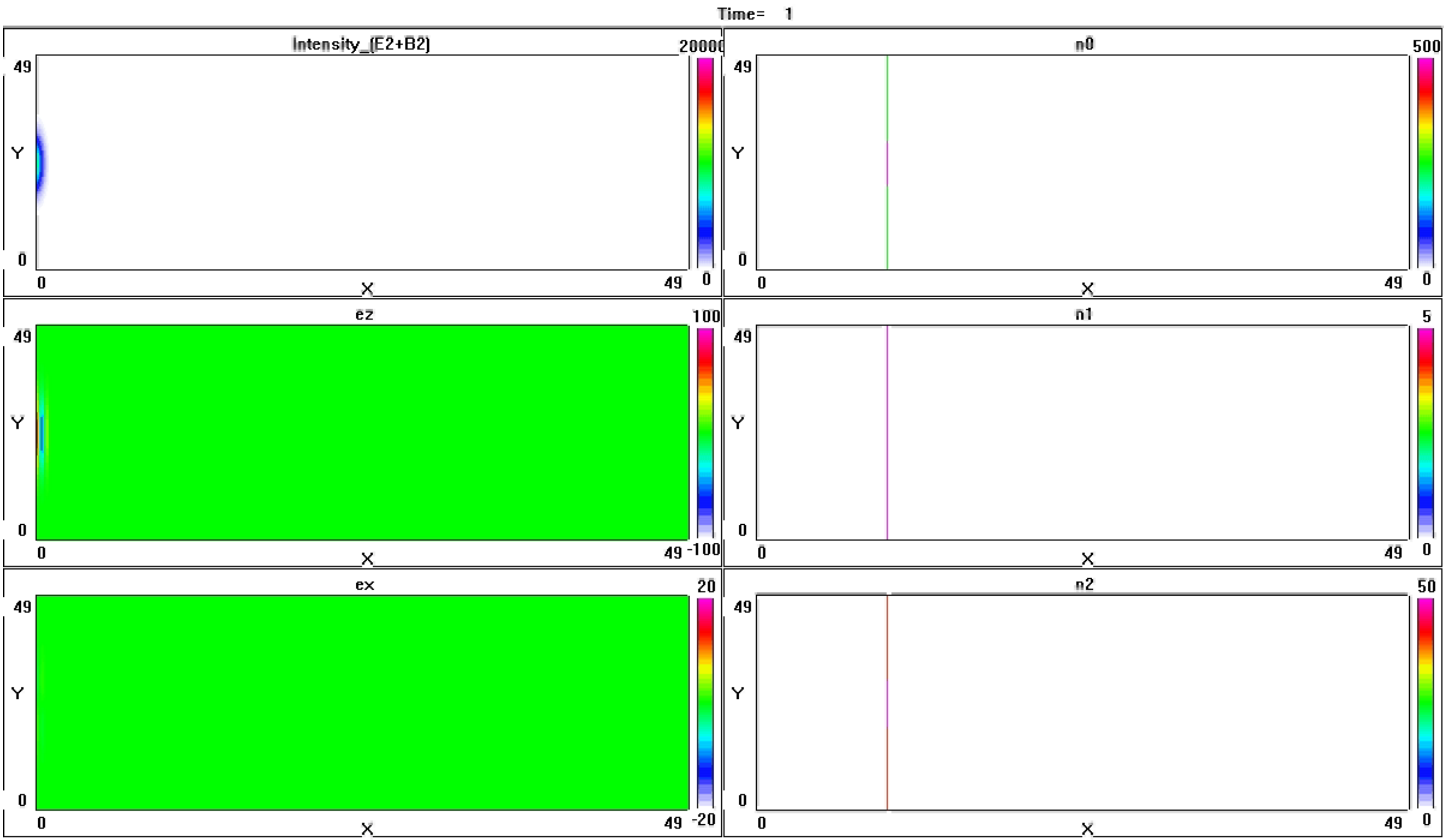
Simulation Parameters:

- ✓ CH foil of 5 micron thickness (320n_c density, where n_c is critical density of plasma)
- ✓ Laser intensity : 10^{23} W/cm^2 (a_0 = 100)
- ✓ Pulse duration : 25 fs





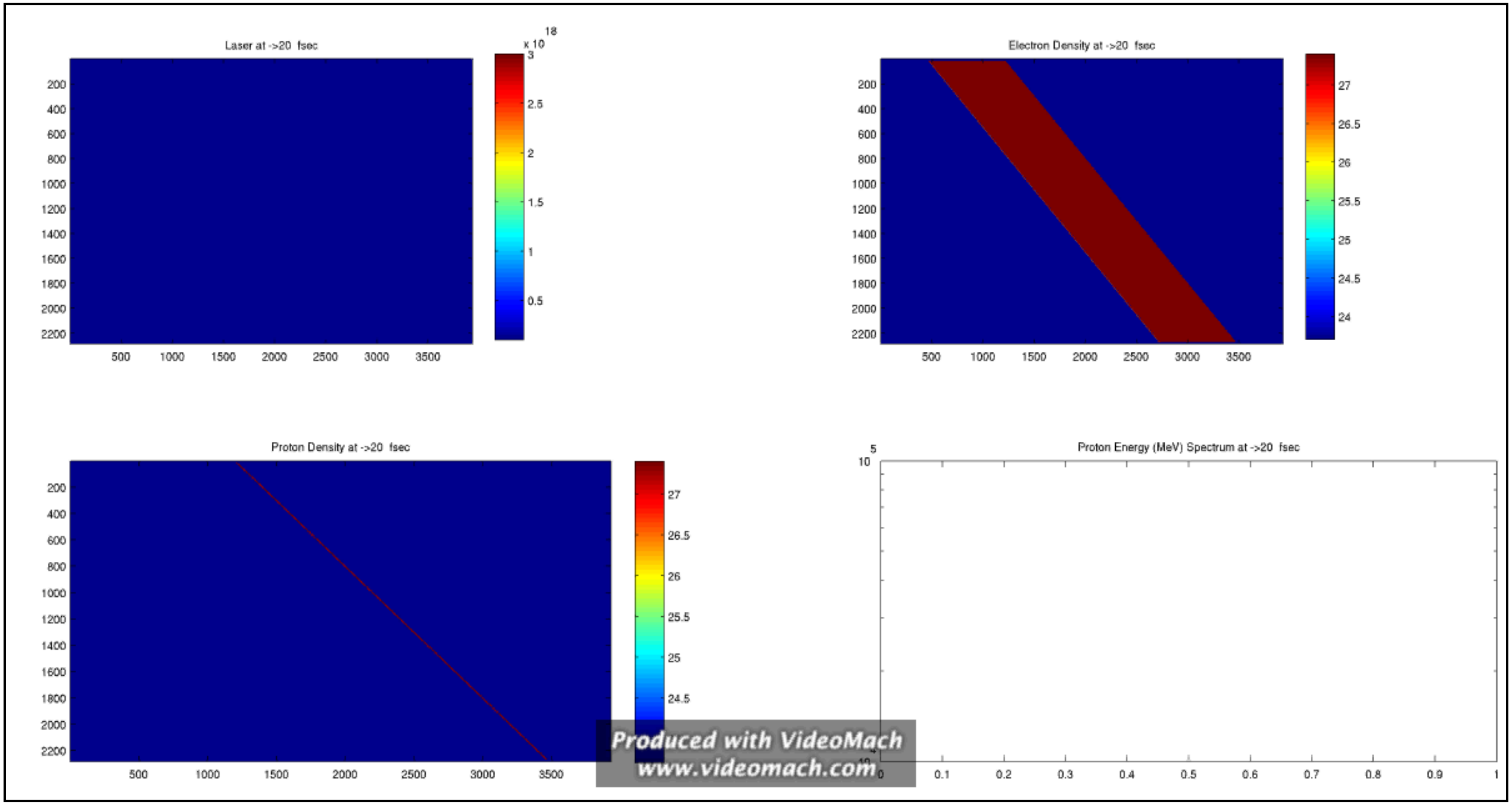
➢ **Quasi-mono-energetic protons at 200 MeV** with a maximum energy of protons extended up to 800 MeV was observed in the simulation.



Evolution of proton(n1) and Carbon density(n2) along with electron (n0) density for a super Gaussian laser pulse in RPA regime

Proton Acceleration via Target Normal Sheath Acceleration (TNSA)

- H^+ acceleration from 6.5μm thin Aluminium Foil using 10 TW Ti:Sapphire Laser System.
- Simulations using 2D & 3D PIC code EPOCH
- Snapshot of laser intensity, electron density, proton density and proton energy spectrum evolution



H^- and Proton acceleration from PMMA targets (EPOCH)

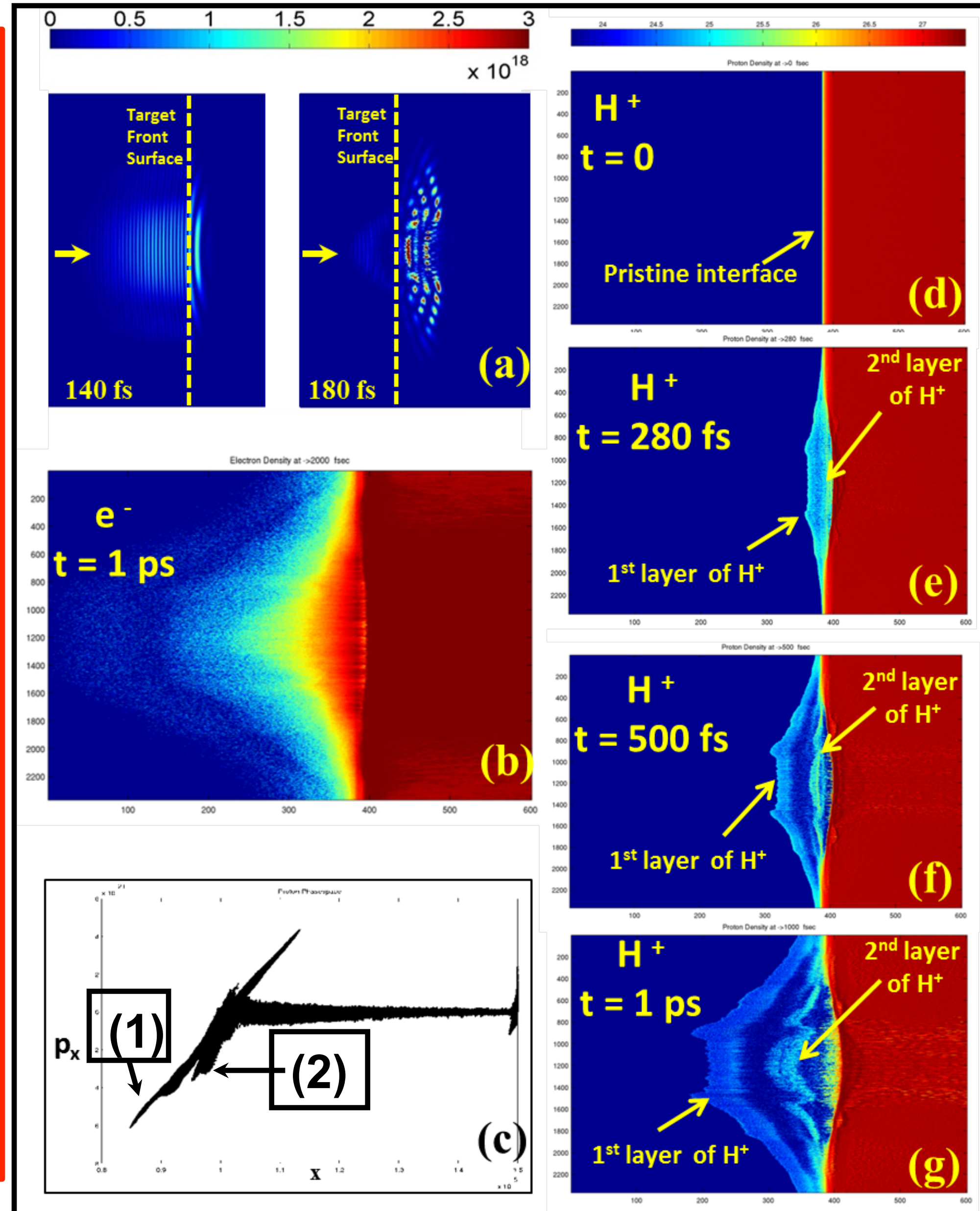
- ***First simulation*** of relativistic laser pulse propagation in transparent dielectric medium.
- High repetition rate, low debris, ***sub-surface*** H^- acceleration.

Simulation Parameters:

- ✓ Laser intensity : 3×10^{18} W/cm^2
- ✓ Pulse duration : 45 fs
- ✓ Focal Spot Size : 10 μm
- ✓ PMMA (C_5H_8O-$_2$-) target
- ✓ Pre-plasma density (0.01 n_c to .9 n_c over . 25μm) evaluated using MULTI-1D code. Where n_c is critical density of plasma) .
- ✓ Bulk target density kept around 0.9 n_{cr}- 0.99n_{cr}

Result:

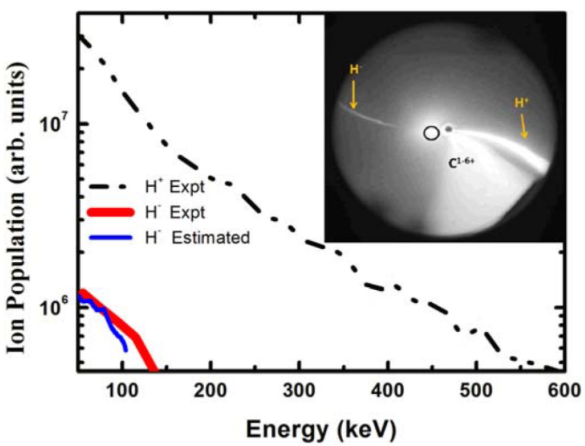
❑ Charge capturing of sub-surface H^+ ***"on the go"*** yields H^-

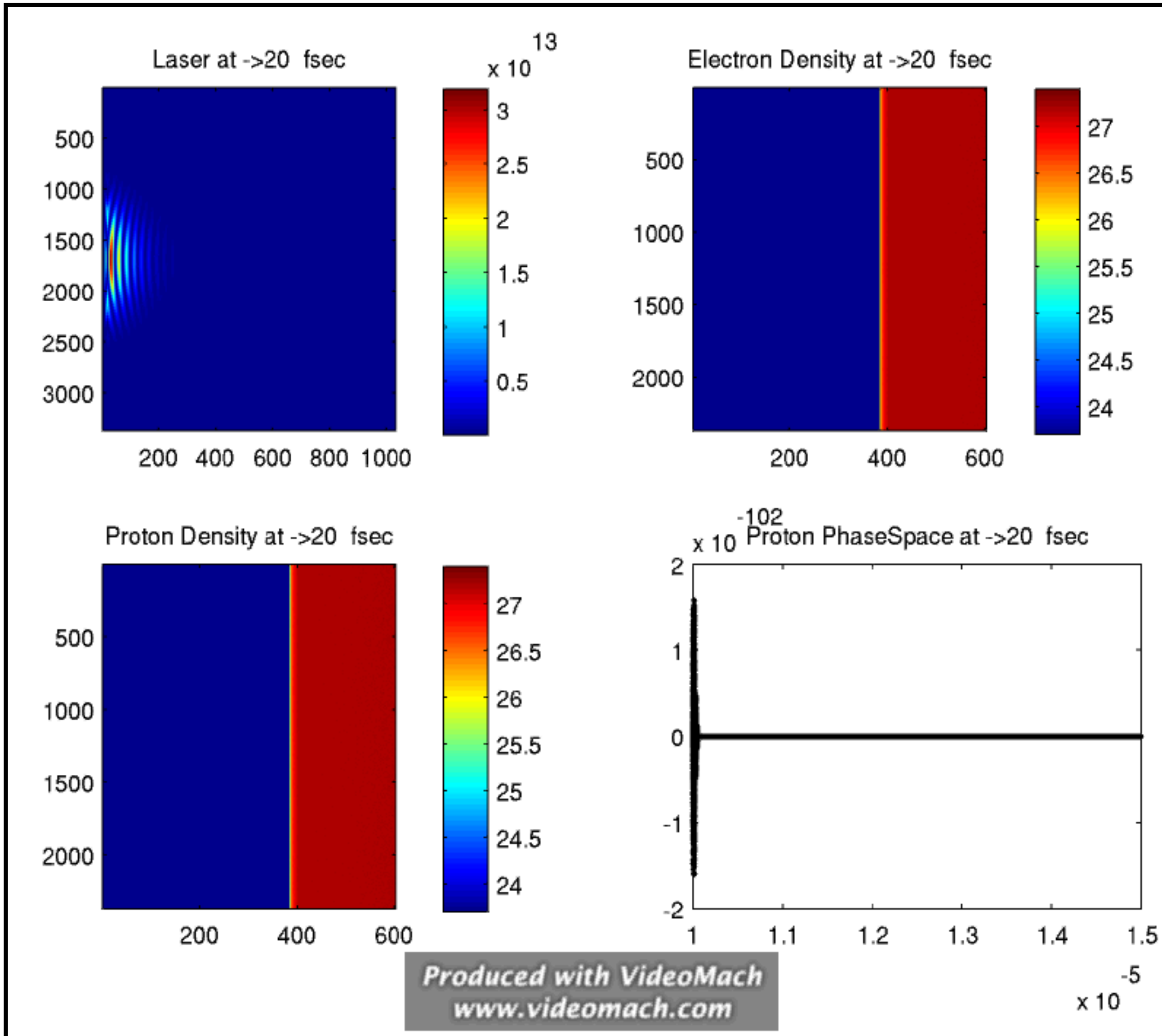


PHYSICAL REVIEW E **92**, 051103 (2015)

PMMA Target :

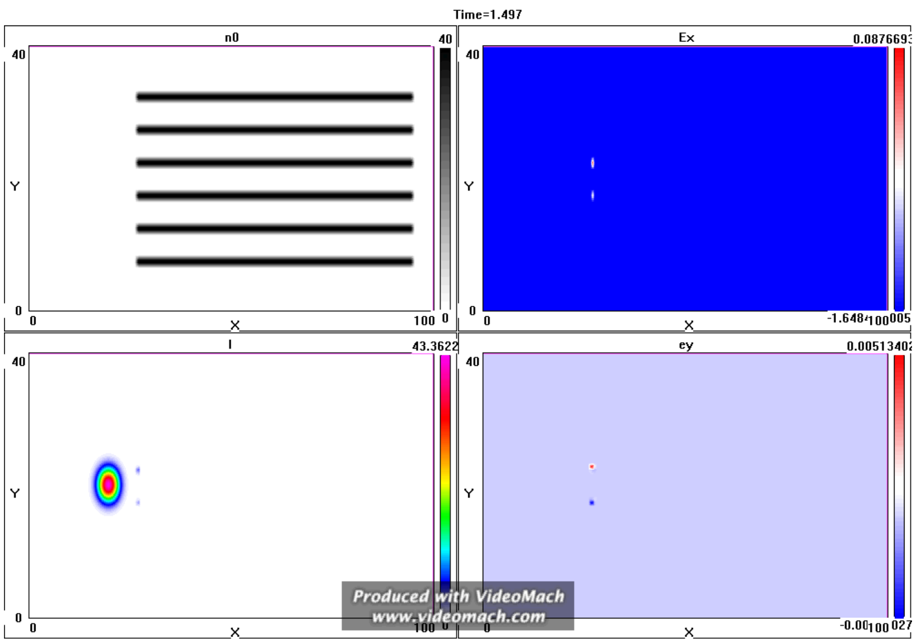
Evolution of laser pulse, electron density, Proton density, and proton energy spectrum for laser (I_L~$3x10^{18}$ W/cm^2, 45 sec) focussed on PMMA target with focal position 500 μm inside the target from the front surface



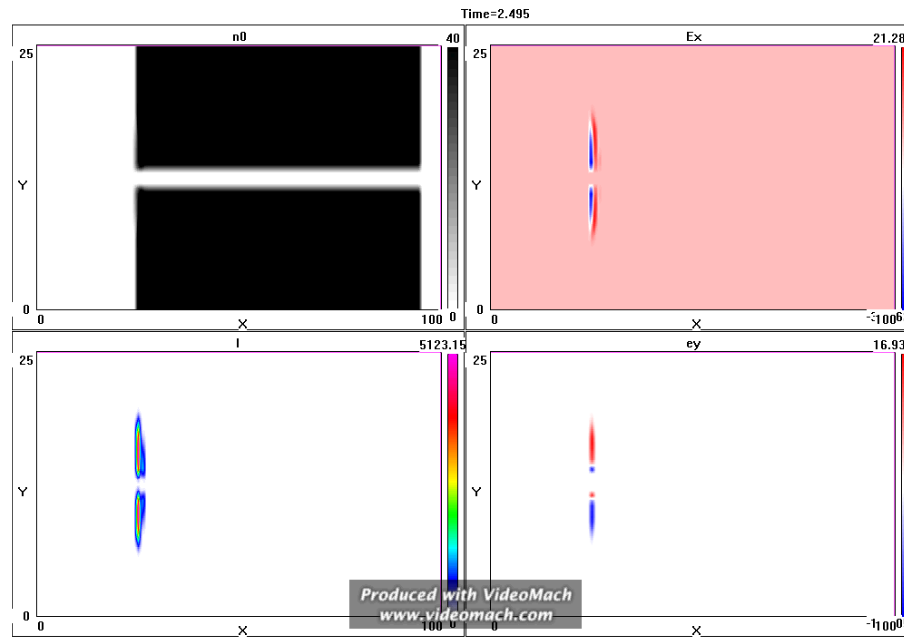


Exotic Targets:

- 3D – PIC simulation of Carbon Nanotubes, Nano-holes and nano-spheres using VLPL
- 2D & 3D PIC simulation (using EPOCH) of structured target like 10nm diameter Gold nanoparticles embedded in 30 nm thick Carbon layer deposited on a Silicon sheet.

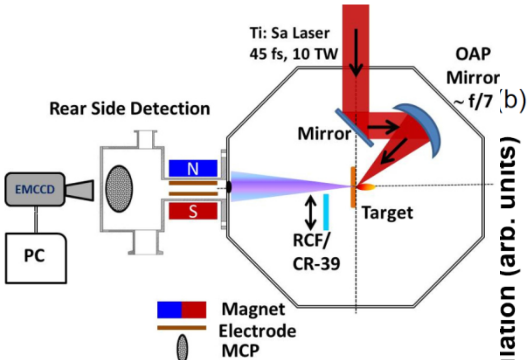


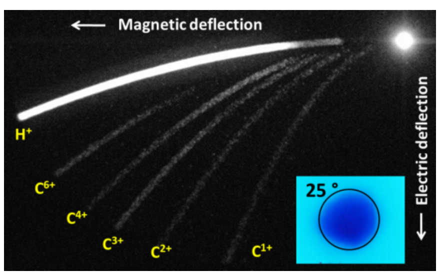
Density and field evolution of nanotube 9 equi-spaced tubes in 3D (central plane shown here)

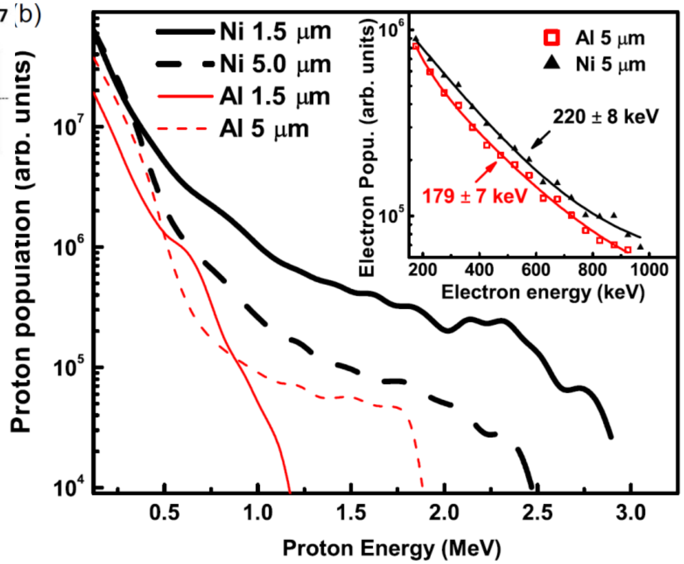


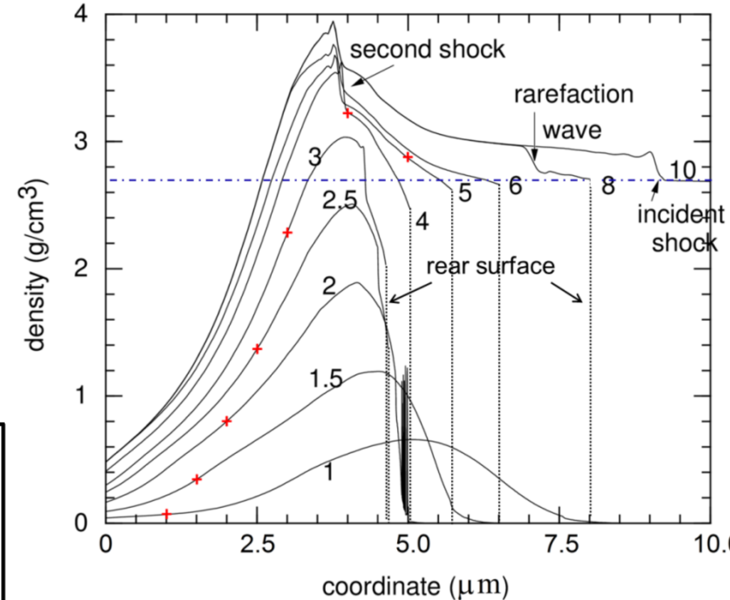
Density and field evolution of single nano-hole in 3D (central plane shown here)

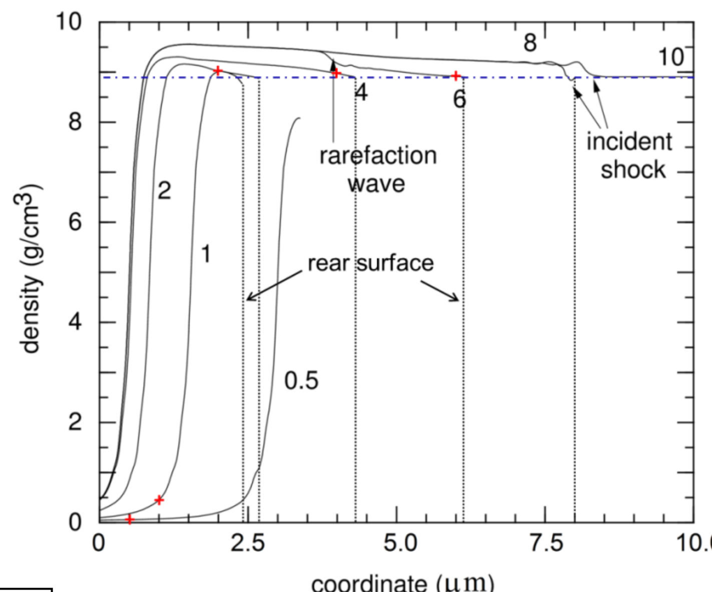
Results of MULTI-1D Hydro-code: Shock deformation of rear surface in Al thin foils leading to poor TNSA below 6 μm. {Role of target material in proton acceleration from thin foils irradiated by ultrashort laser.}









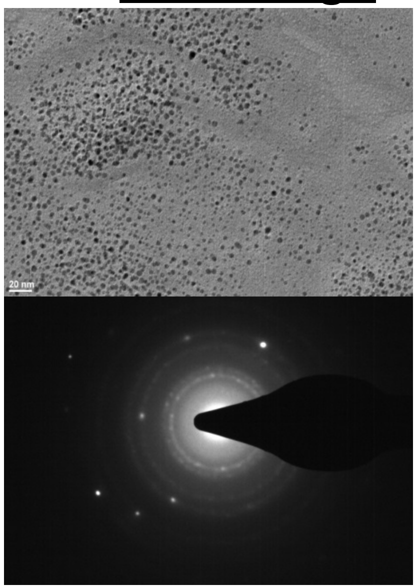


Phys. Rev. E 90, 023103 (2014)

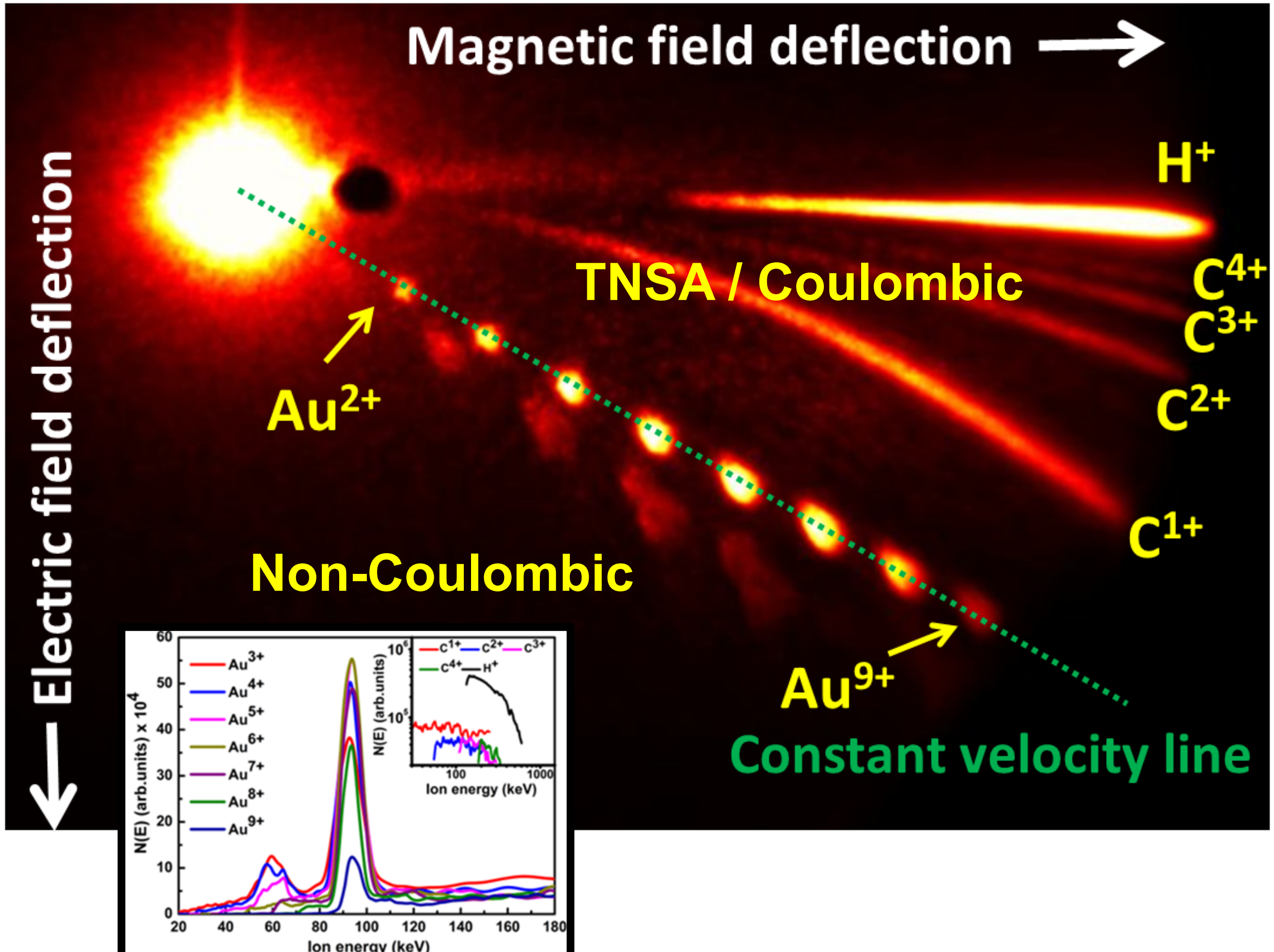
MULTI-1D Simulation Results:
Appl. Phys. Lett. 103, 054107 (2013)
Appl. Phys. A, 115, 4, 1457 (2014)
Plas. Phys. Cont. Fus. 57, 125013 (2015)

Quasi-monoenergetic Heavy Ions (recorded from the front side of target)

TEM Image

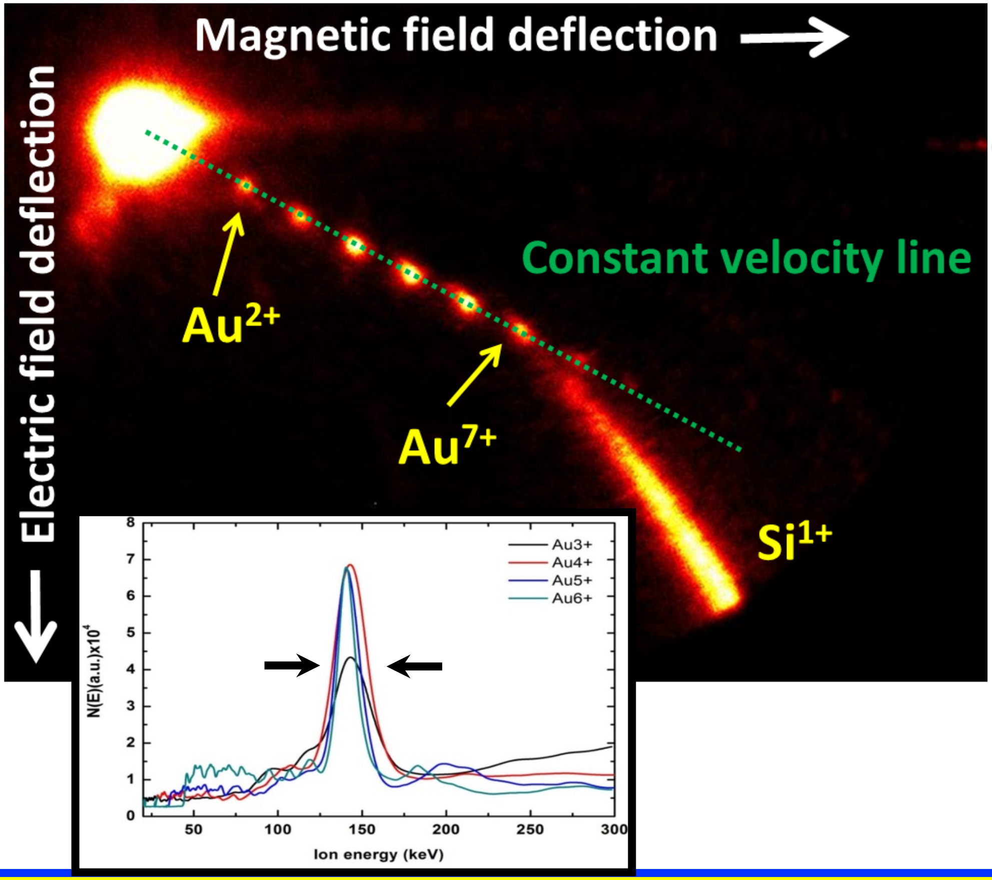


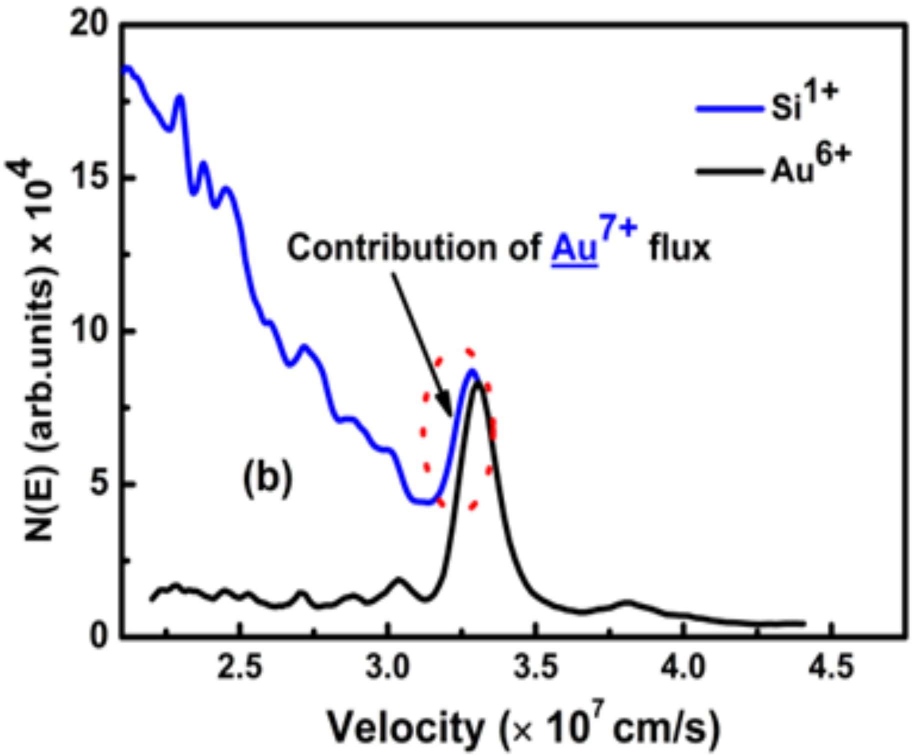
Selected Areaa
Electron Diff. Pattern



- **Target Composition:** 3 – 8 nm AuNPs embedded in 30-40 nm thick C film on Al
- Simultaneous detection of two different Acceleration Process
- TNSA / Coulombic process characterized by continuous energy spectra
- Non-Coulombic Acceleration: All the charged states of Gold have same energy

With a different substrate (Si)



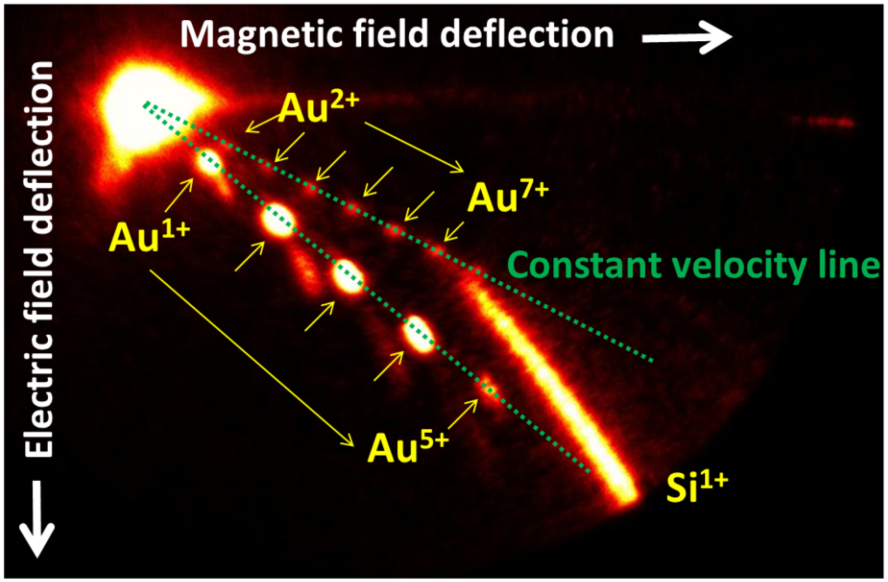


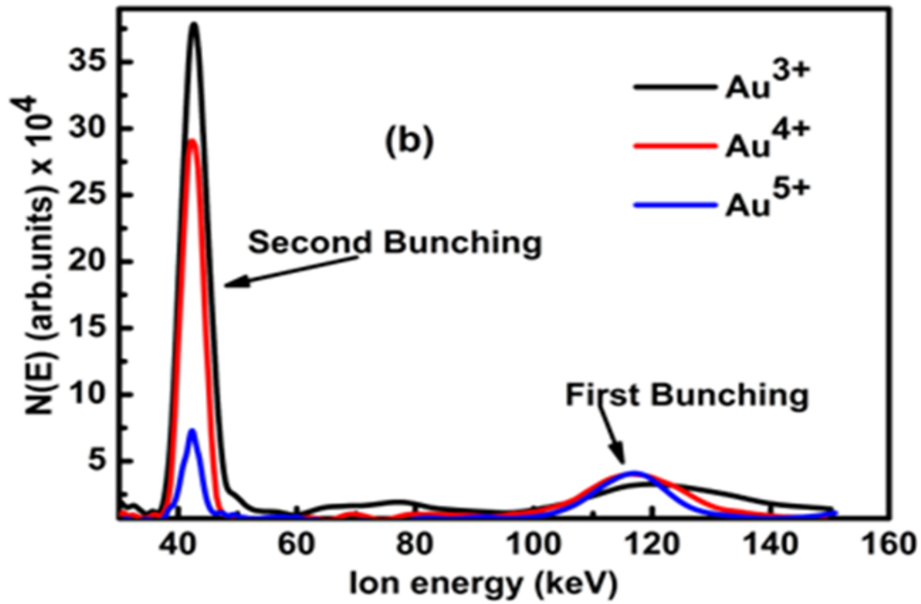
$$\left(\frac{q}{m}\right)_{Si^{1+}} = (28.086)^{-1} = 0.0356$$

$$\left(\frac{q}{m}\right)_{Au^{7+}} = \left(\frac{196.97}{7}\right)^{-1} = (28.138)^{-1} = 0.0355$$

- Substrate (Si) shows continuous trace
- Embedded Au Nano-Particles reveals mono-energetic feature
- Matches well with the expected Overlap of parabolic trajectories

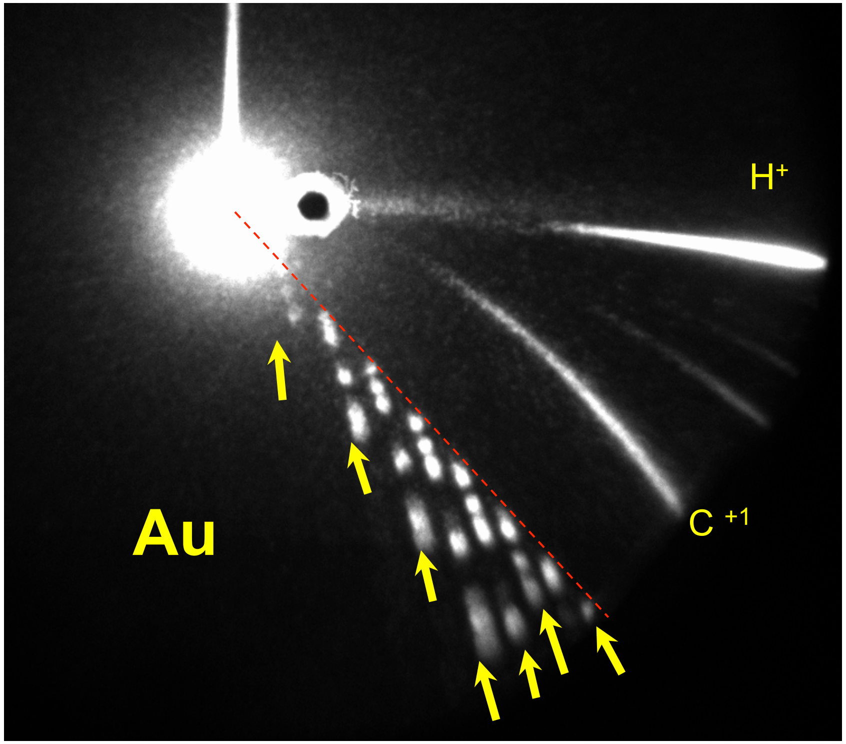
Double Bunching of Heavy Gold Ions

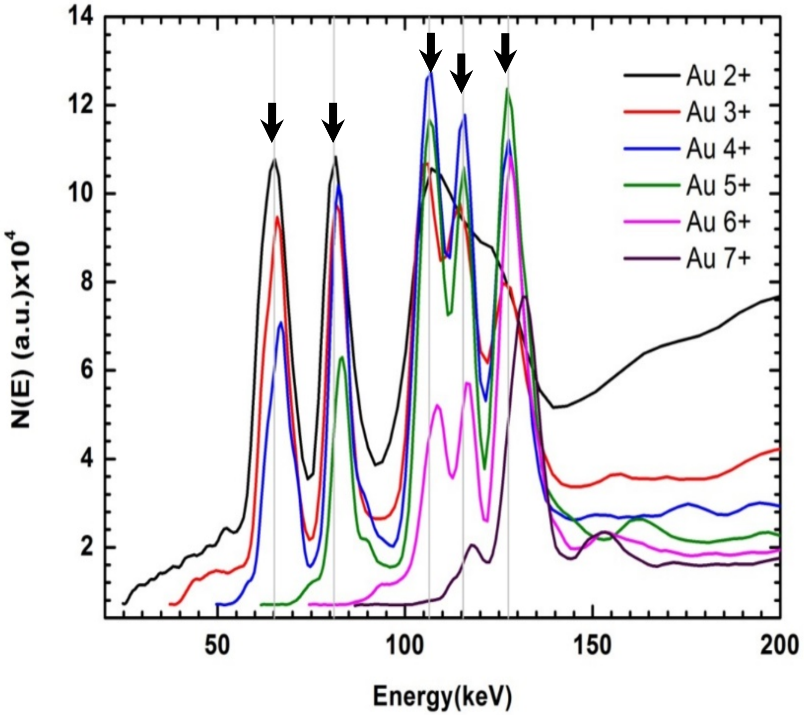




- Two distinct sets of gold ion bunches observed on many occasions

Multiple Bunching of Heavy Gold Ions

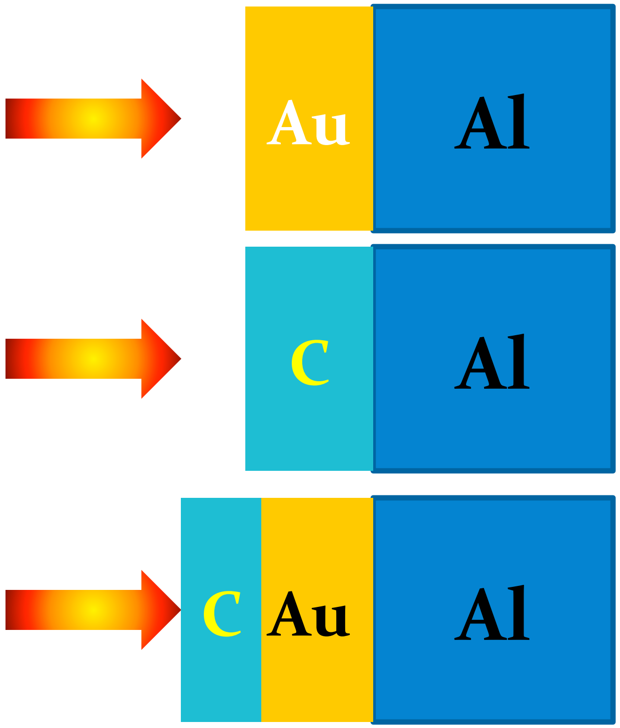




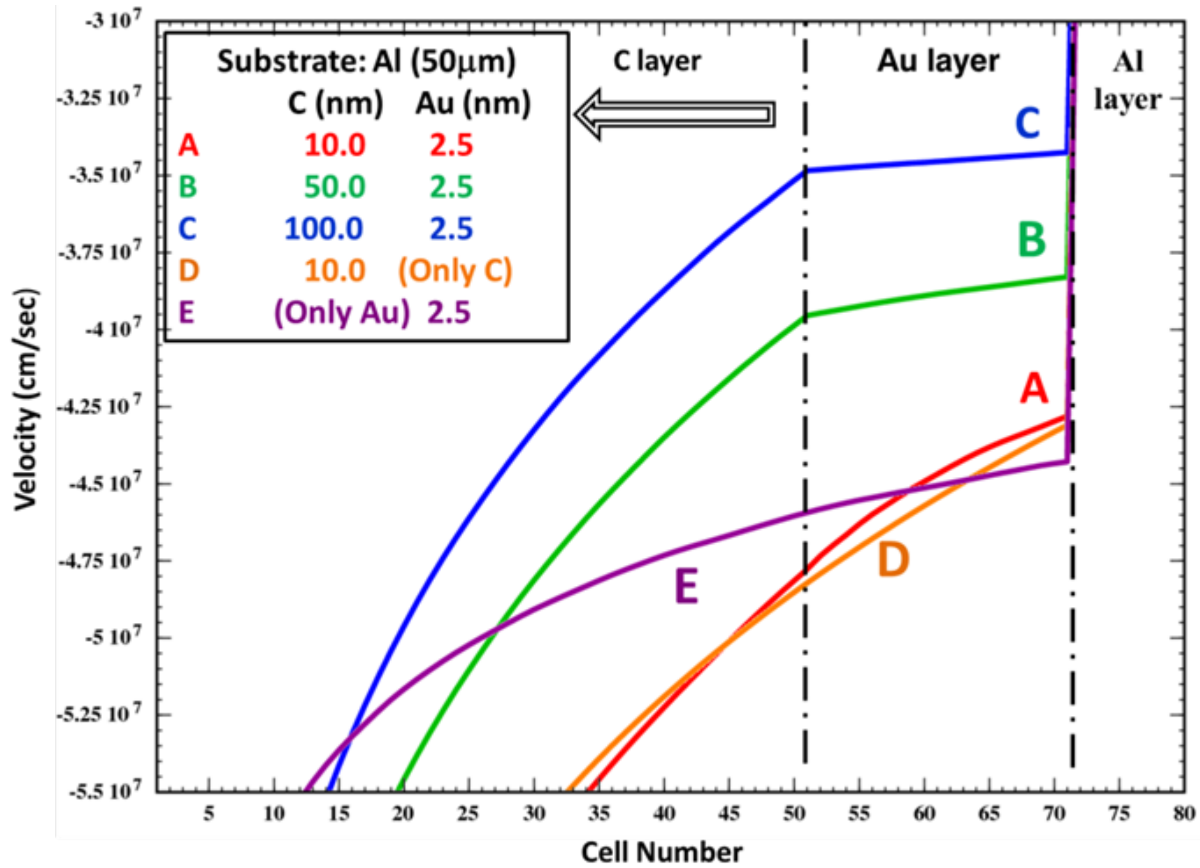
Multiple Quasi Mono-energetic

First Experimental demonstration

Results of 1D Hydrodynamic Simulation

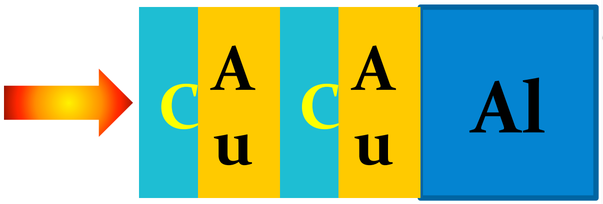


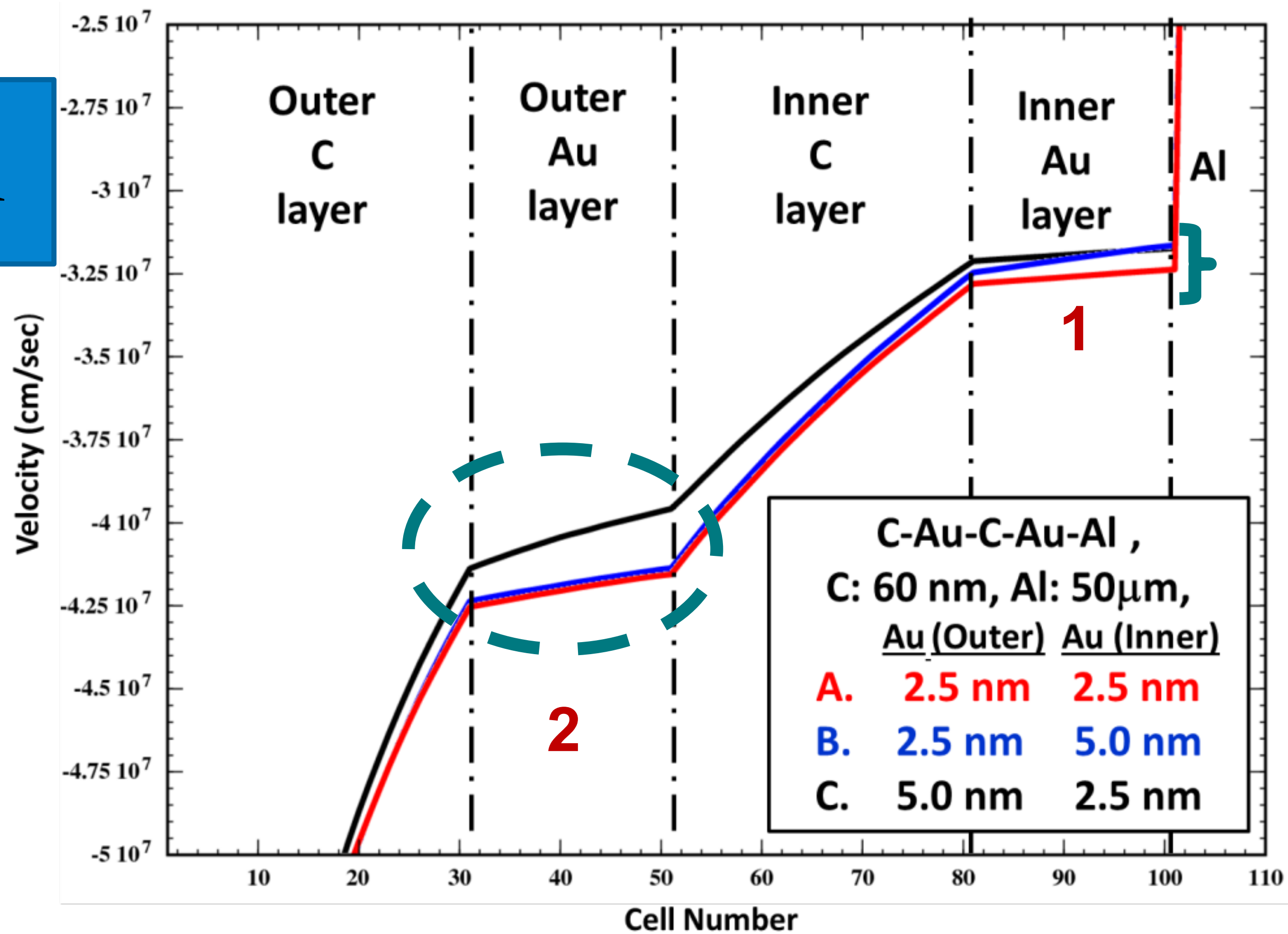
Single Layer(s) of Au and C



- ❑ Presence of only Au or C results in continuous energy distribution
- ❑ Presence of C on Au results in reduction of spread in velocity distribution of Au

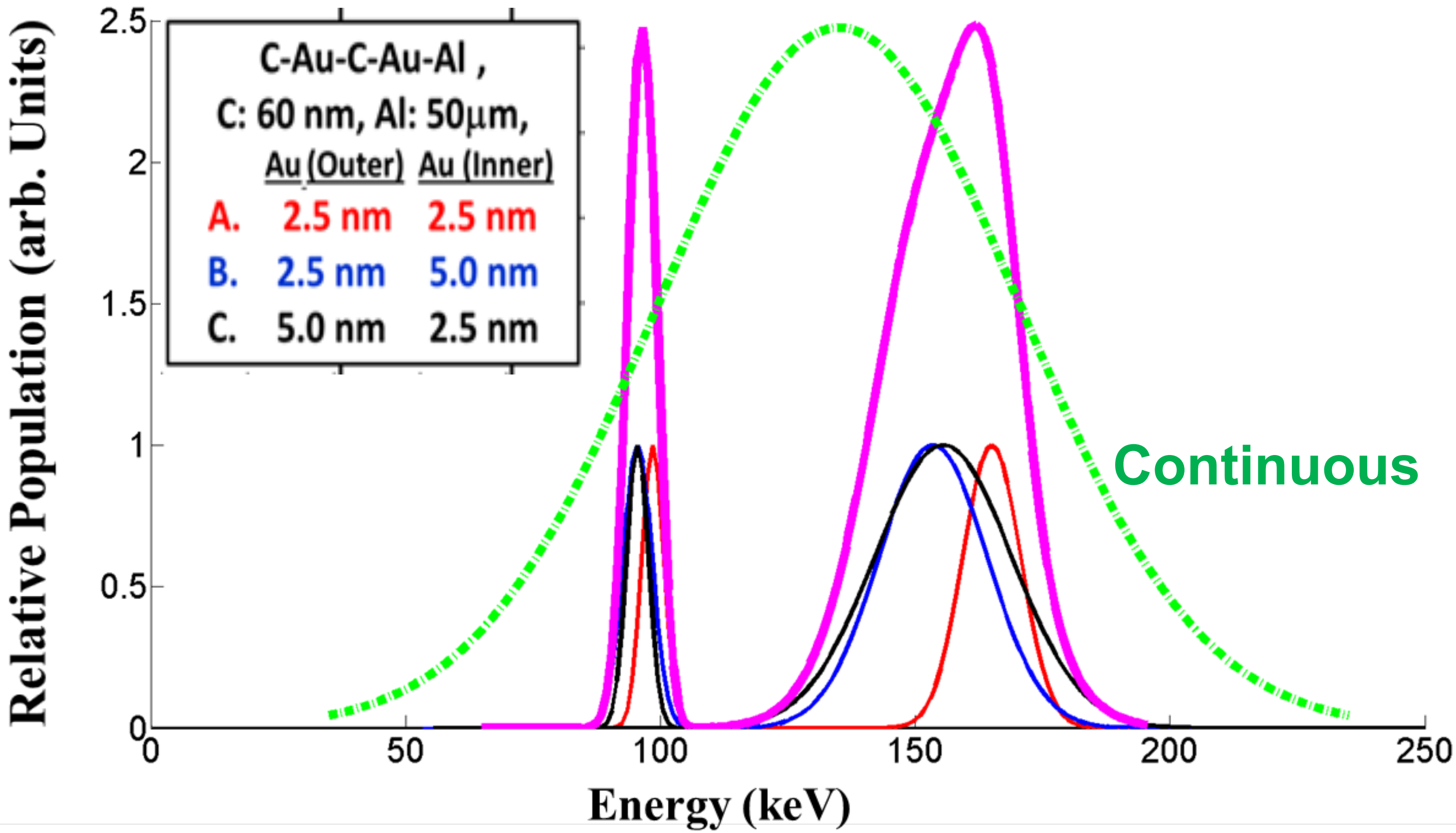
Double Layer(s) of Au and C





- ❖ Two distinct bunches of Au ions observed
- ❖ Extension of single layer effect

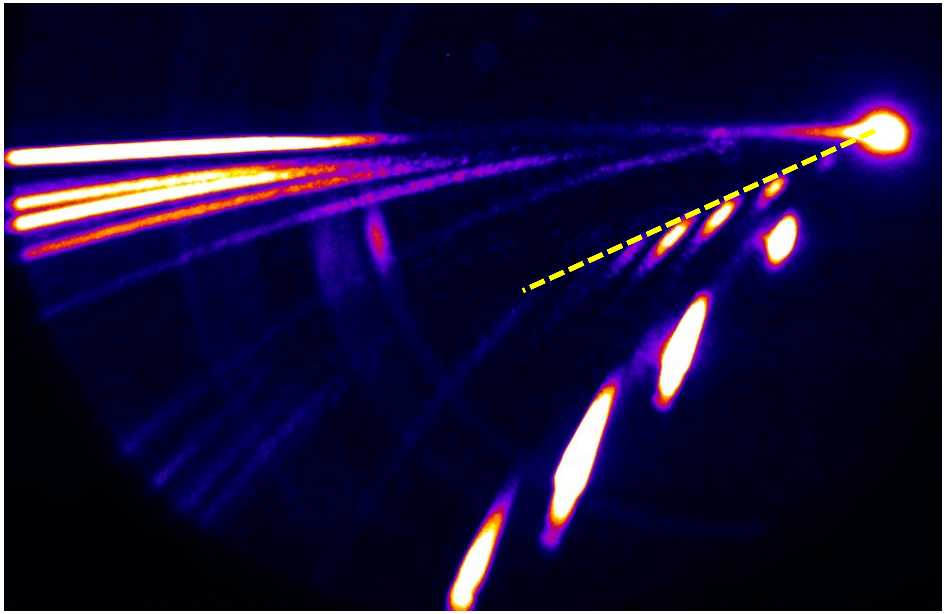
Resulting Au Ion Energy Distribution



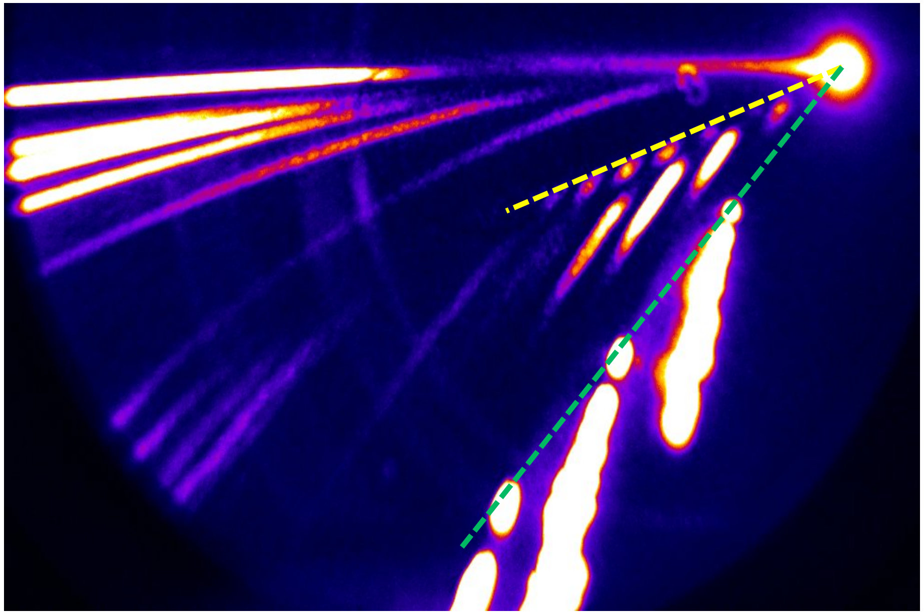
❖ Simple 1D Simulation Qualitatively reproduces the essence of the experimental observation nicely

Validation of Simulation

Single Layer of C & Au on Al



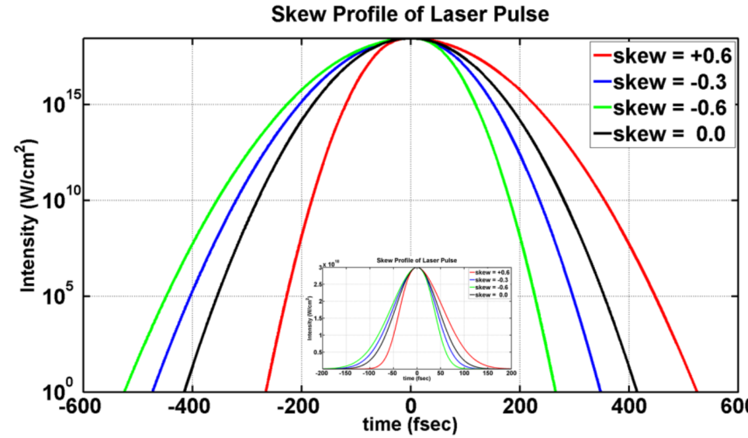
Double Layer of C & Au on Al



- Experiments on Layered targets based on the prediction of 1D Hydrodynamic Simulation yield consistent Heavy Gold Ion Bunching
- Highly Reproducible

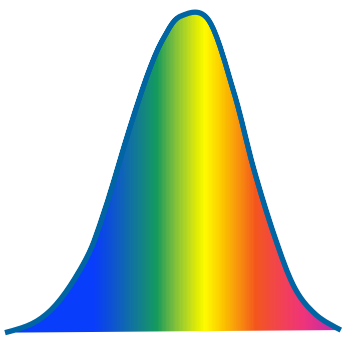
Pulse Chirp and Skew

❖ Detuning the grating pair introduces chirp as well as pulse shape asymmetry

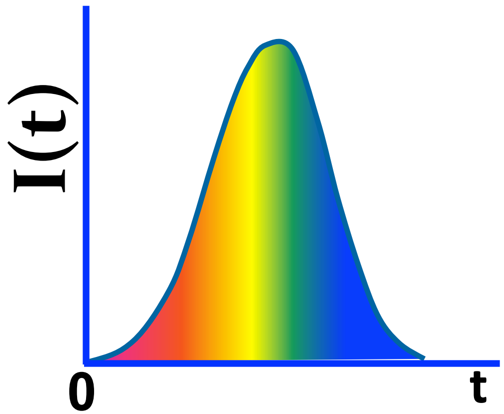


$$\omega = \omega_0 \pm \frac{\partial \omega}{\partial t}$$

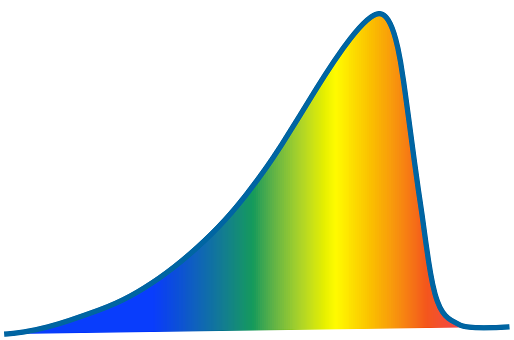
Chirp (±Δω)



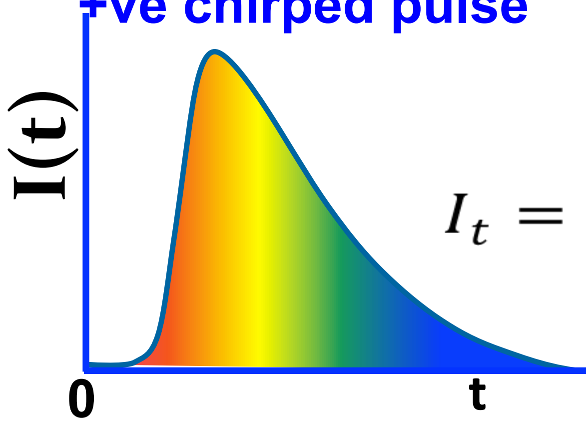
-ve chirped pulse



+ve chirped pulse



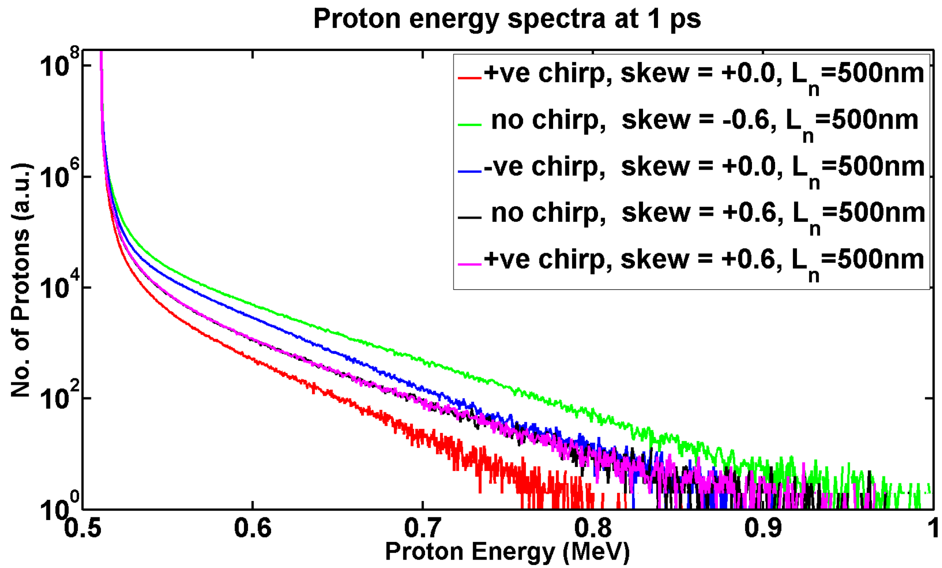
-ve chirped pulse
with –ve skew

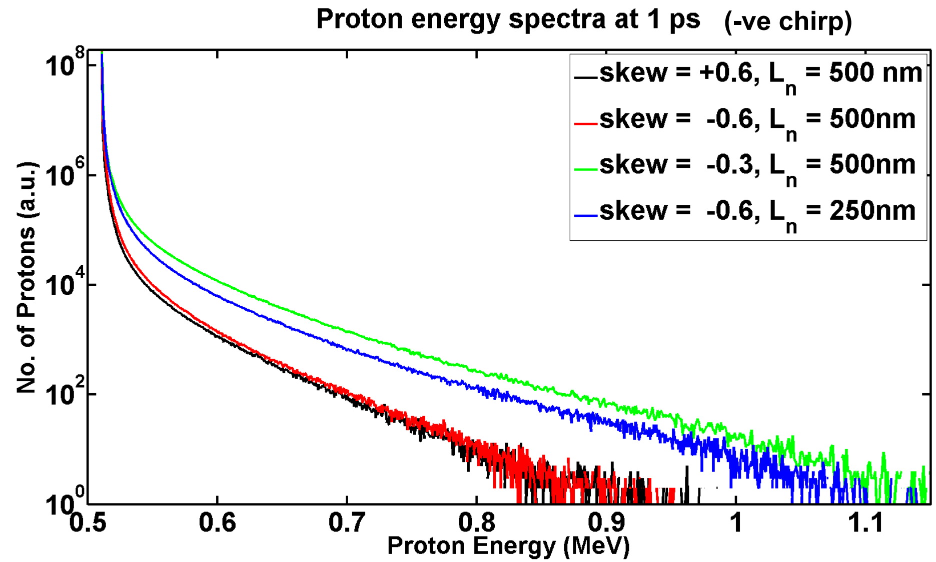


+ve chirped pulse
with +ve skew

$$I_t = I_0\ exp\left(\frac{-\frac{t^2}{2t_0^2}}{1+\frac{bt}{\sqrt{t^2+t_0^2}}}\right)$$

Skew (±b)





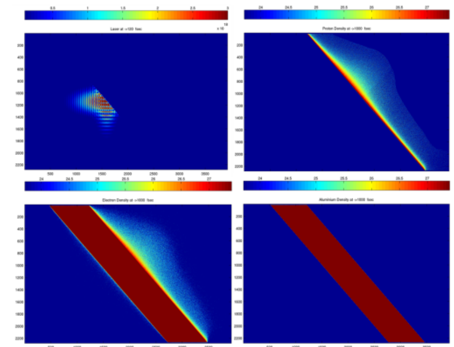
➢Linear chirp plays no significant role. Enhanced proton energy with negative skew pulses. Lesser skew leads to higher value of maximum proton energy.

➢Sharper initial density gradient leads to higher value of maximum proton energy.

➢Negatively chirped pulses in simulation give higher proton energy and population as compared to positively chirped laser pulses of same laser pulse duration. A negative chirp pulse with medium level of skew leads to better RA as compared to a pulse with larger skew.

➢L/λ <<1 points towards role of vacuum heating in enhanced proton acceleration.

➢Pulse shape asymmetry explains the observed difference in electron and proton energy spectra.



Simulation box size : 20 μm × 30 μm, Grid size : 10 nm × 10 nm, 50 particles per cell. 6.5 μm Al foil is in the centre of the box with 100 nm proton layer on both the side of the Al foil. Plasma electron density : 100 n_c, Al pre-ionized to Al^{3+} with density 33 n_c ($n_c = 1.72 \times 10^{21}$ cm^{-3} @ 800 nm). Laser pulse duration is varied, keeping the fluence constant at ~ 67 J-cm^{-2} (~3×10^{18} W-cm^{-2} for 45 fs pulse).The pulse durations are 45 fs and 250 fs, with and without chirp and skew. Laser pulse is focussed on the front edge of the plasma.

Thank you

Simulation Team:

1. *Dr. J. A. Chakera, SO-H*
2. *Dr. Ajit Upadhyay, SO-F*
3. *Mr. Deepraj Phadte, SO-D*
4. *Mr. K. Madhu Babu, TO-C*
5. *Dr. Prateek Varshney, Post-Doc. Fellow*