Kinetic Simulations of Ultra-Fast Laser-Induced Fusion in Overdense Targets

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Abstract

- Interaction of femto-second laser pulses with over-dense plasmas has led to the generation of MeV energy ions (e.g. [1])
- Triggering nuclear fusion might be a possible application of these accelerated ions
- Incorporating of a kinetic fusion model into VORPAL [2] allows to investigate these ideas
- Investigation of different mechanisms, including shock accelerated ions and ablated material

- [1] Hegelich, B., et al., PRL 89, 085002, 2002.
- [2] Nieter, C, Cary, J.R., J. Comp. Phys, 196(2), 448, 2004.

Purpose of Study:

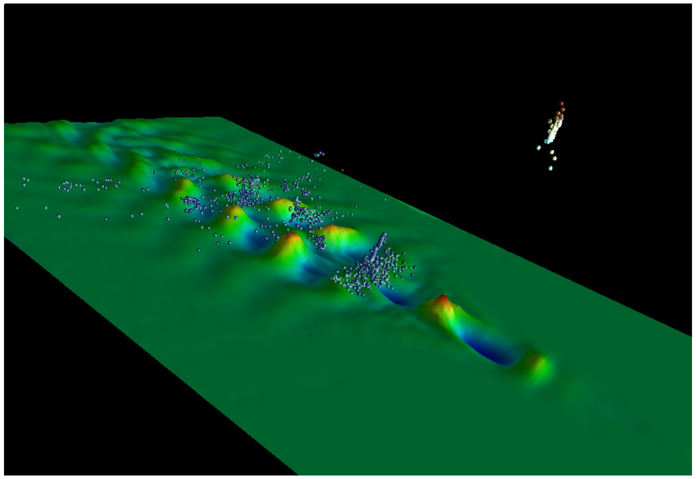
Can we use the fast ions generated in laser-overdense interactions, e.g. for neutron generation? Or as ignition beam?

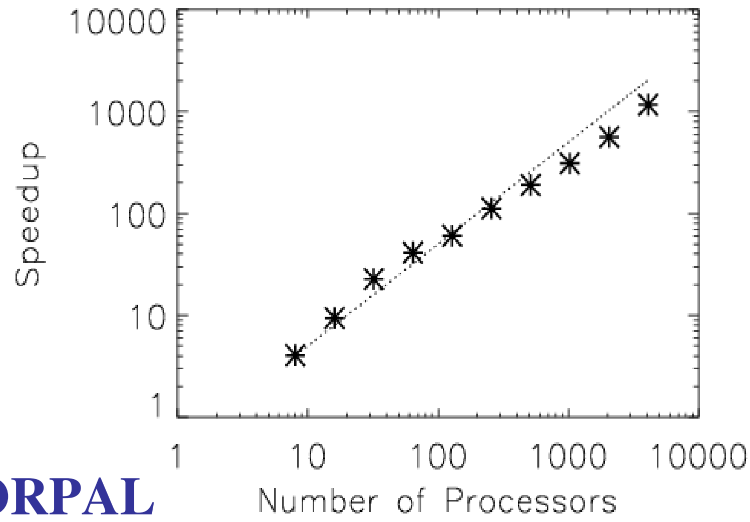
- Energies reached with laser-overdense interaction on the order of 10's of keV to MeV
- Can thin D-T targets undergo enhanced fusion? What is the neutron flux?
- Can ablated material of shaped targets be used as ignitor? Is the ablated material focused?

APPROACH: Numerical Tool

VORPAL – Plasma Modeling Framework

- Original target applications:
  Laser Wakefield Acceleration
- PIC, Fluid, Hybrid
- Multi-Dimensional (N=1,2,3)
- Fully parallel
  - Scaling for > 4000 PEs
  - Flexible domain decomp
  - Dynamic load balancing
  - C++
- Output format: HDF5
- Postprocessing/Viz:
  - IDL, OpenDX, GnuPlot

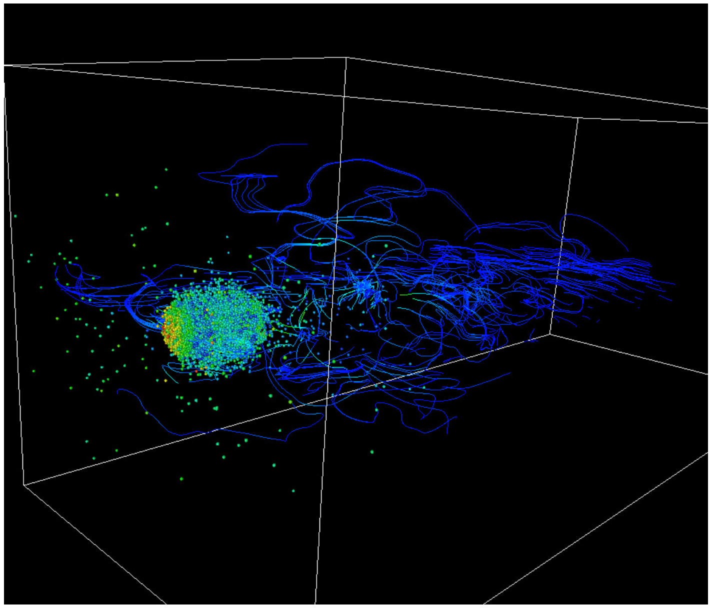


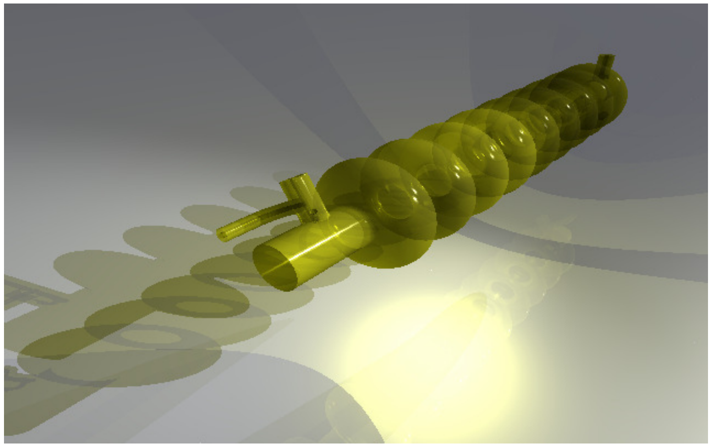


http://www.txcorp.com/products/VORPAL

Some VORPAL Features

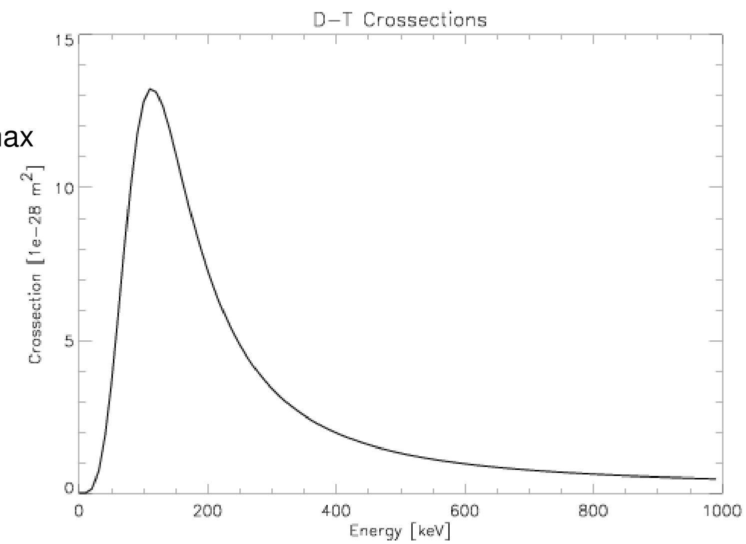
- **Full EM PIC model**
  - Moving window
  - Cut-cell boundaries
- **Variety of particle sources, emitters**
  - Space Charge limited, beam emitter
- **Parallel ES solver**
  - Variety of solvers, preconditioners
- **Collision model**
  - Direct Simulation Monte Carlo (DSMC)
  - Reactions
- **Ionization**
  - Field and impact ionization
- **Direct Coulomb interaction**
  - Hermite integrator





Kinetic fusion model implemented in VORPAL

- Recently added to VORPAL: kinetic model for particle-particle processes
  - Originally for impact ionization
  - Fusion model uses different crosssection
- Reaction processes based on DSMC-PIC algorithm
  - Push particles without collisions
  - In each grid cell, perform collisions
    - Determine maximum collision rate σ_{max}
    - Number of collisions $N = n\, v\, \sigma_{max}\, \Delta t$
      - Select N pairs of particles
      - Determine relative cross section
      - Create new particles
  - Iterate



Laser-plasma interaction leads to shock-accelerated ions

- **Laser-Overdense interaction leads to different acceleration mechanisms**

- **Sheath Normal acceleration at backside of foil**
  - Transverse electric field of laser accelerates electrons parallel to surface
  - Magnetic field of laser pulse leads to **jxB** drift into the target
  - Overshoot of electrons at the back side of target leads to the formation of a strong electric field accelerating the ions

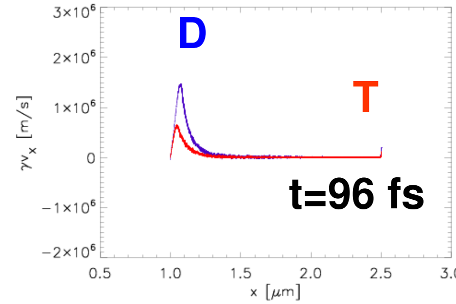
- **Shock acceleration inside the foil**
  - Laser accelerates ions to supersonic speeds
  - Formation of a shock wave traveling inside the foil
  - Ions accelerated at shock front

- Relative drift of D-T for Sheath normal accel. too small for fusion
- Drift velocity of shock accelerated ions large enough to undergo fusion

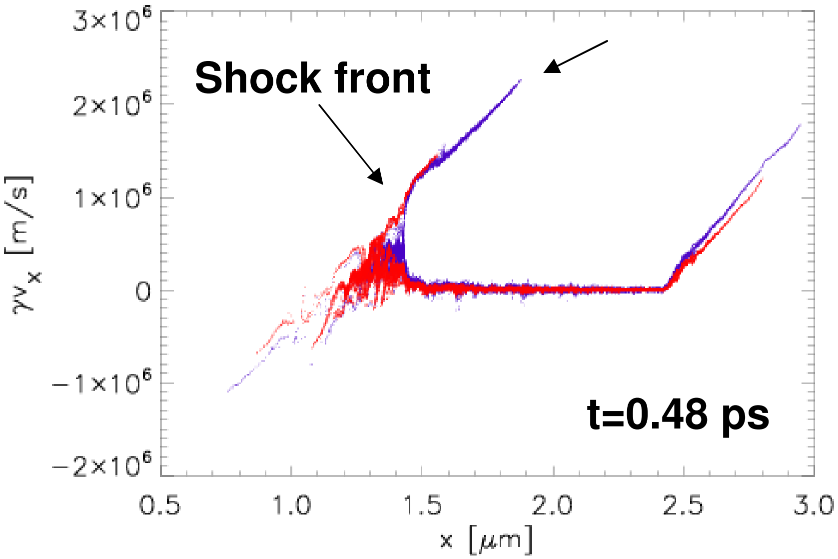
Laser-plasma interaction leads to shock-acclerated ions

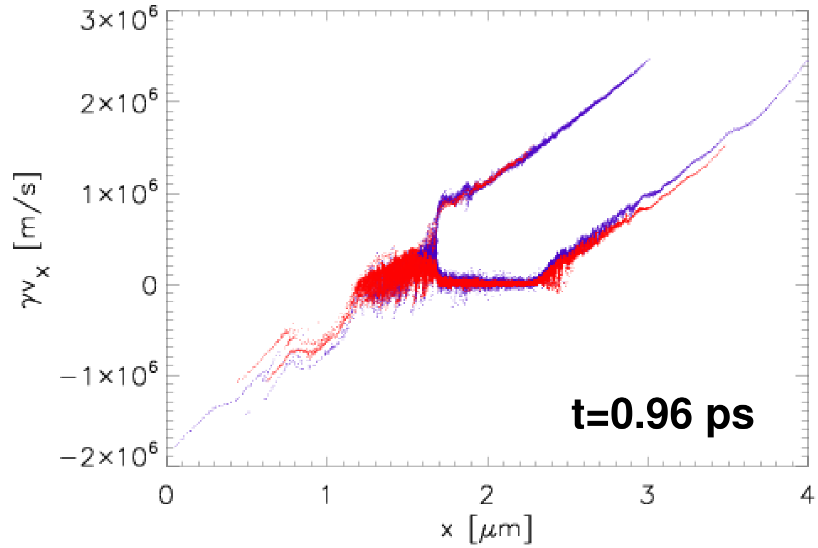
- 60 fs pulse, 0.8µm
- 3 µm spot size
- I = $1.8 \cdot 10^{17}$ W/cm^2
- D-T plasma, n/n_c = 1.6 (e.g. Foam or Jet)

Initial acceleration of ions



Shock accel. ions

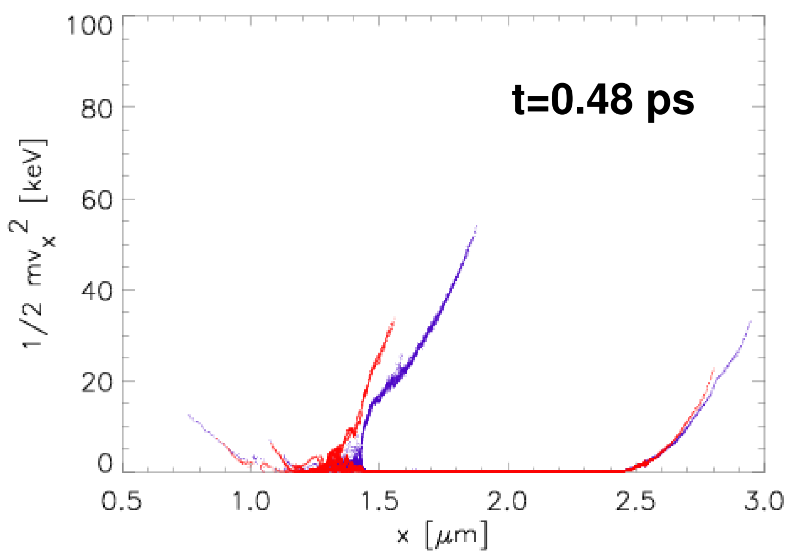


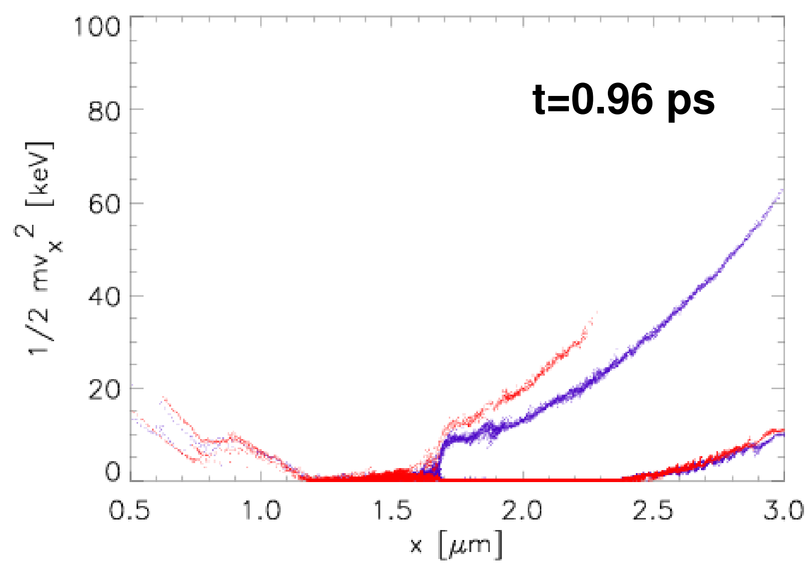


Shock-accelerated ions are fast enough to undergo fusion

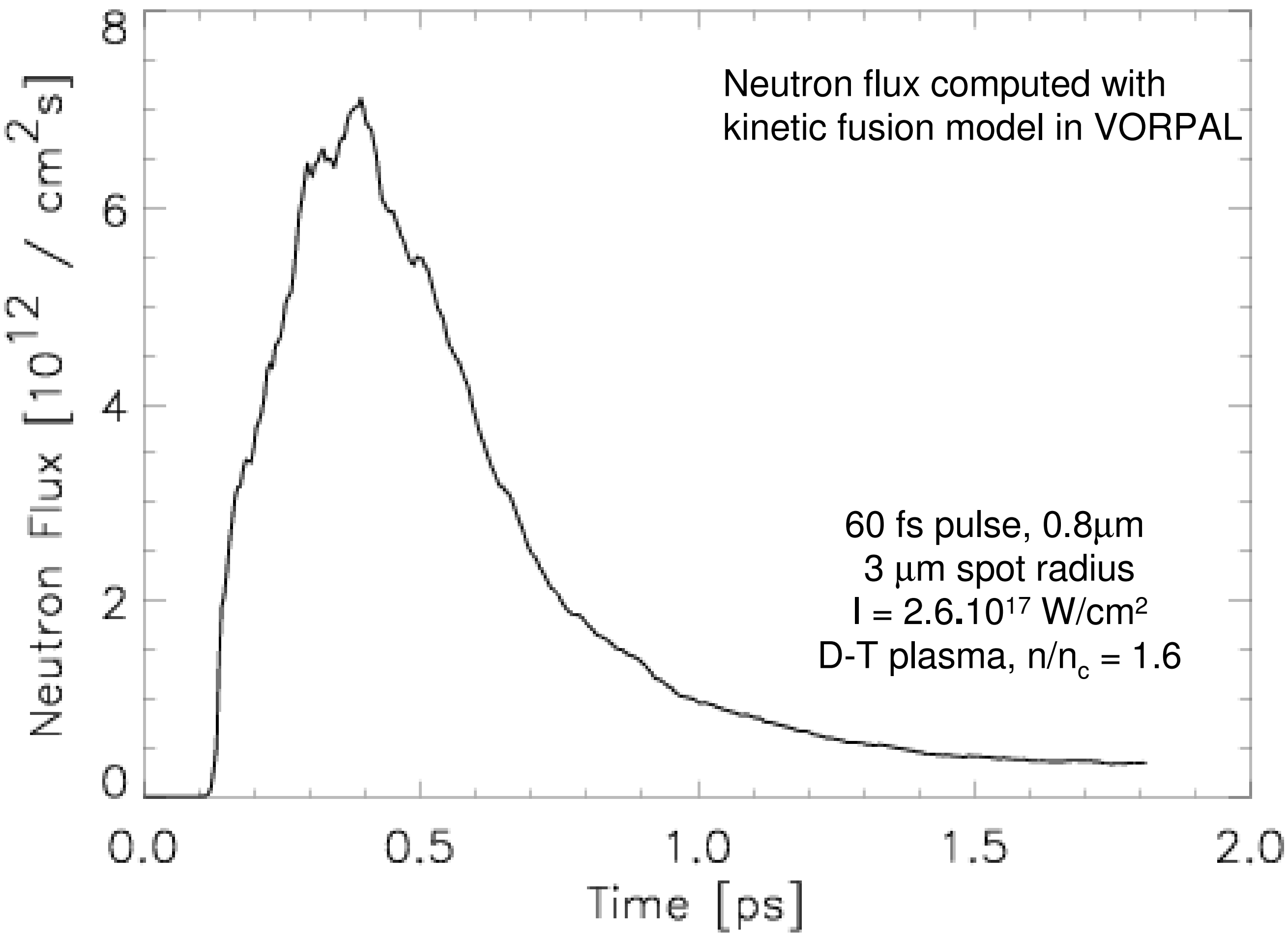
- Peak of D-T fusion cross-section at ~ 120 keV
- Energies reached with shock-accelerated ions
- Shock accelerated ions streaming through background undergo fusion

I = 1.8·10^{17} W/cm^{2}

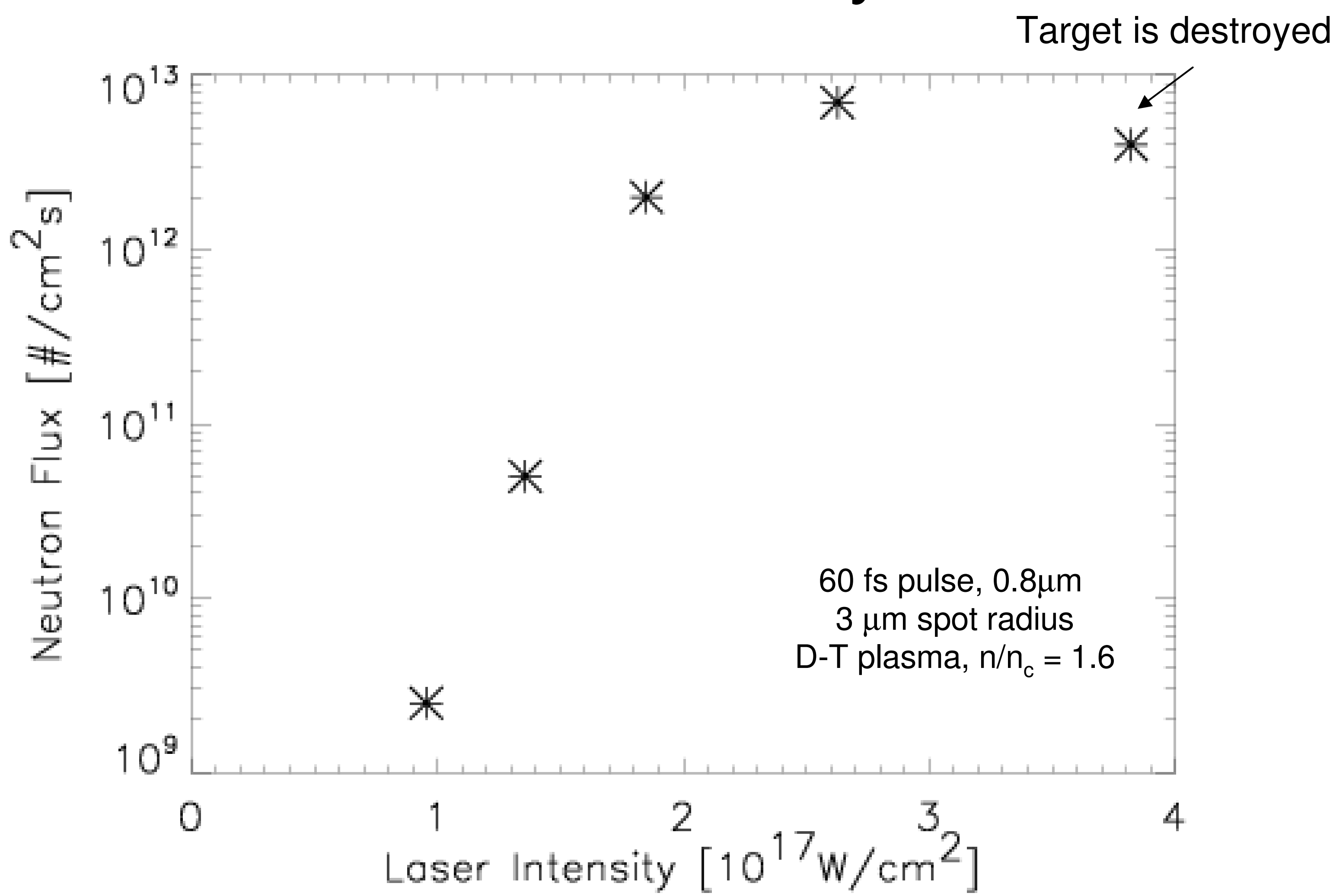




Shock-accelerated ions can be used to generate neutrons with modest laser intensities

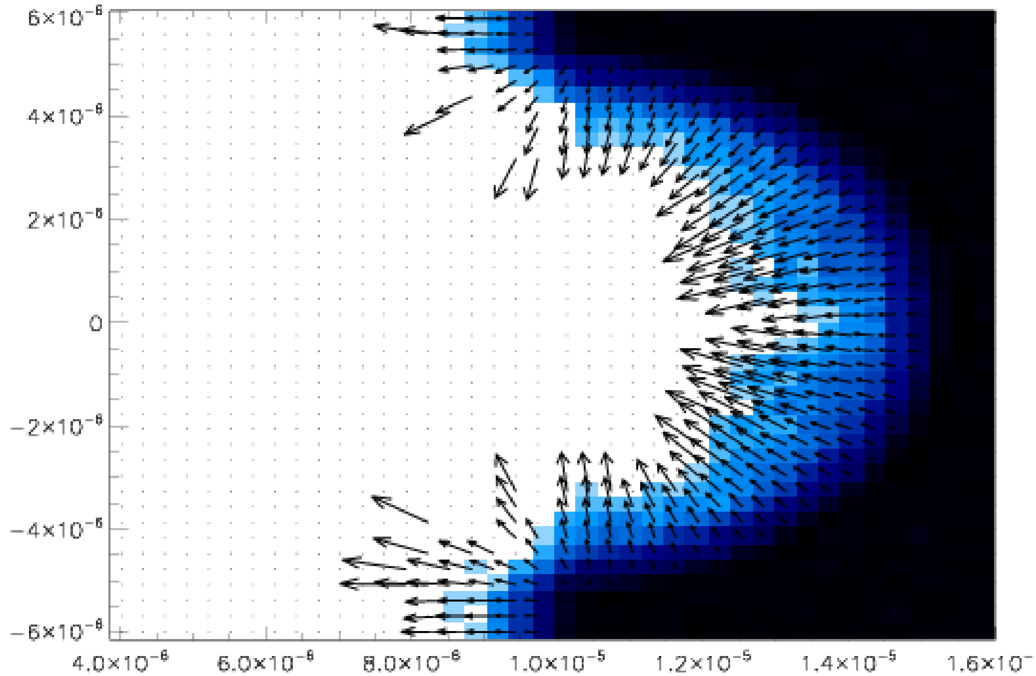


Neutron flux increases exponentially with laser intensity

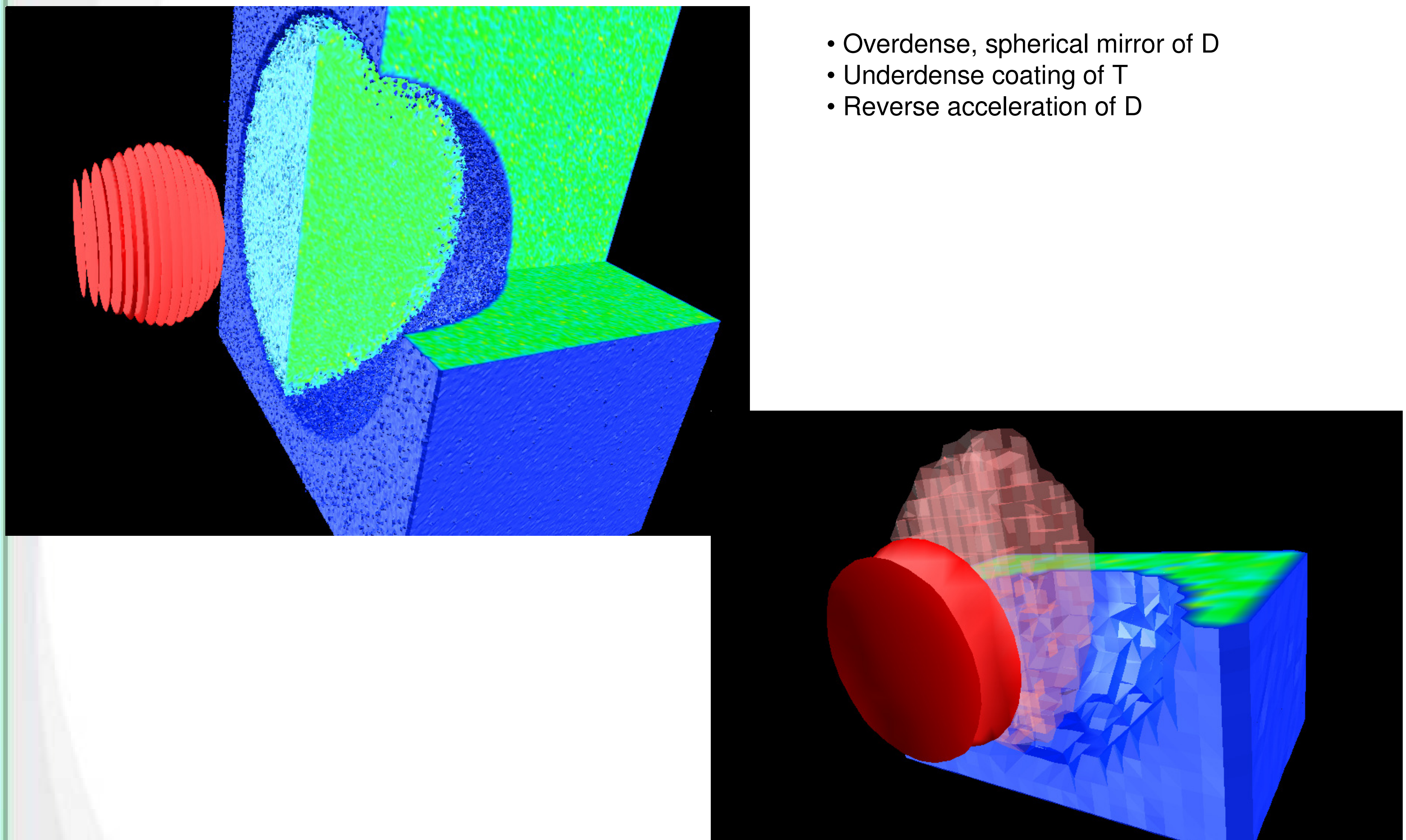


Can ablated material be focussed and used as ignitor?

- Focusing of ablated material in shaped target
- Use of focused beam as fusion ignitor?



3D simulation of spherical mirror target (in progress)



- Overdense, spherical mirror of D
- Underdense coating of T
- Reverse acceleration of D

Conclusion and Future Work

- **Kinetic reaction model in VORPAL**
  - Based on DSMC-PIC algorithm
  - Cross-sections for D-T fusion
- Interaction of modest intensity laser with overdense target leads to shock formation
- Shock-accelerated ions have sufficient energy to undergo fusion
- **Neutron flux generated by laser-overdense interaction is reasonable for applications**
- Observation of focusing of ablated material
- Could it be used for ignition?

- Continue with 2D and 3D simulations (mainly a question of computing resources)
- Need experiments with overdense D-T plasmas