A perspective on laser-driven ion acceleration: new mechanisms and their dependence

presented by:

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contributions by colleagues from
LANL & Collaborating Institutions

(Acknowledgements throughout the talk)

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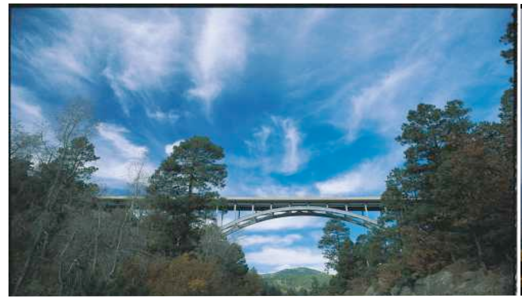

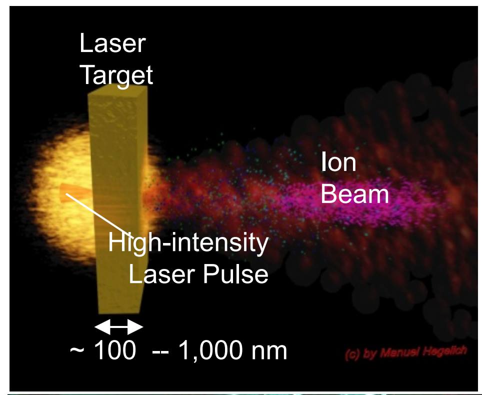

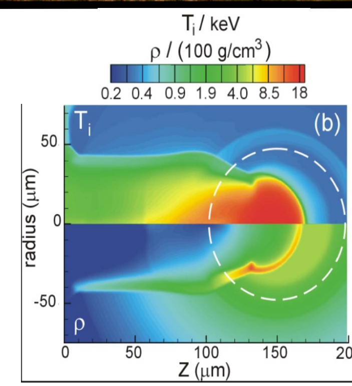

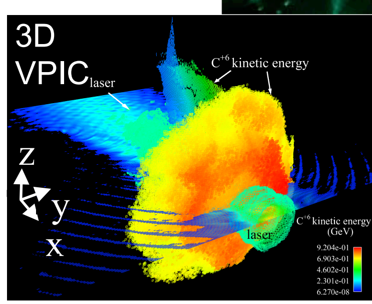

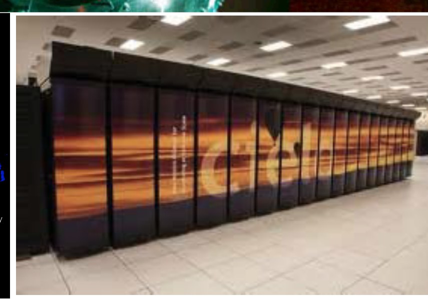

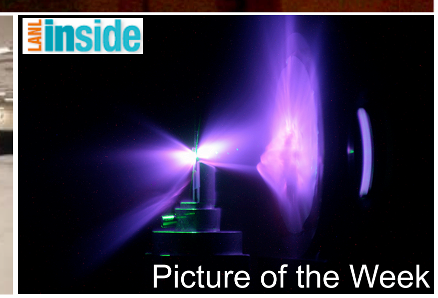

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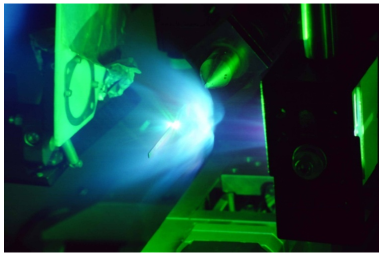
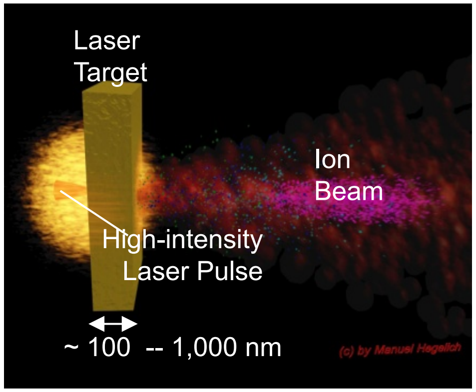
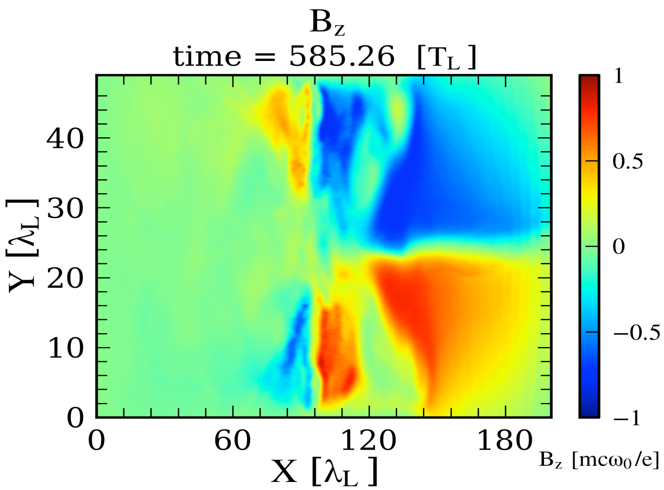
- Trident operations: LANL ICF and Weapons Science Campaigns
- Project: LANL LDRD program

Outline

- Our perspective from our missions
- Observed quasi-monoenergetic beams
  - Al11+ & C6+
  - How was it accomplished experimentally
- Simulations to clarify mechanism
  - Critical to do correct simulations
  - Late-time dynamics & self-organization (after laser exits)
- Relevance to ion fast ignition (FI)
  - FI requirements
  - Laser requirements
  - Focusing requirements
- BELLA-I considerations
- Summary







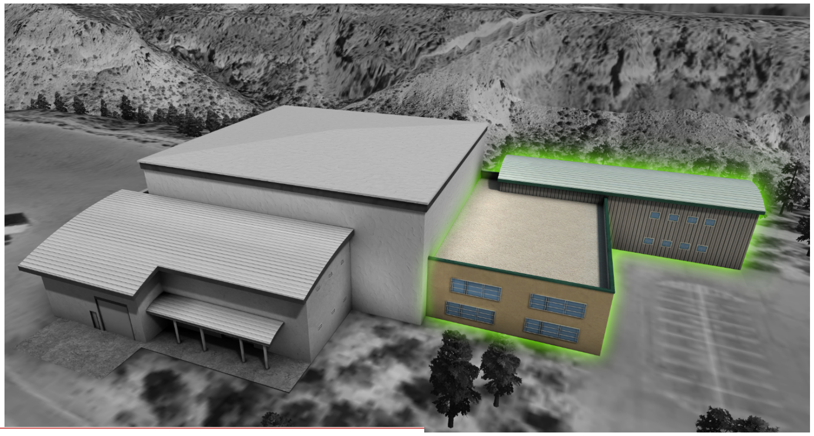
Our perspective is guided by applications of ion-beams in near and longer terms

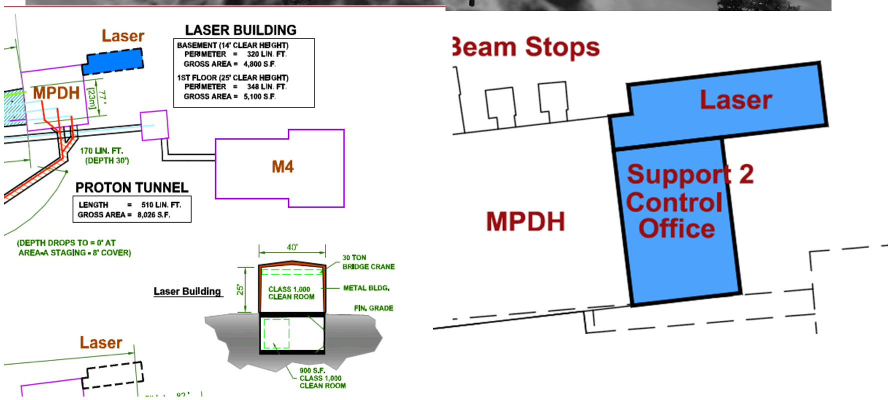
Our applications require large ion flux & benefit from peaked energy spectra

- Isochoric heating
  - Large solid & liquid samples for off-Hugoniot dynamic material experiments (LANL MaRIE signature facility, future)
  - Homogeneous warm-dense matter (*e.g.*, mix in plasma interfaces, today*)
  - Ion-driven Fast Ignition
- Neutron generation
  - Moveable system to detect fissile material (Global Security)
  - Thermometry of dynamic material samples (NRS, MaRIE)
  - Weapons physics

* W. Bang, *et al*., Sci. Reports **5**, 14318 (2015)

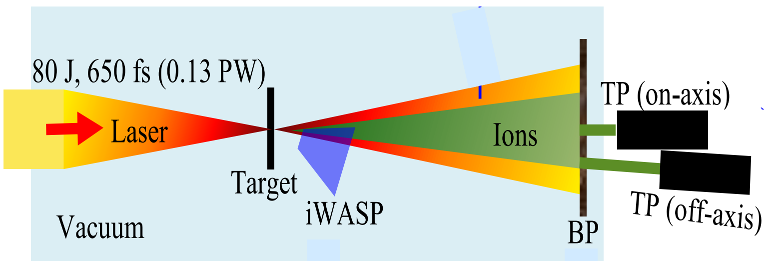
MaRIE: Materials Science Mission
42 keV XFEL & P Rad probes,
multiple dynamic loading sources
~ $2B cost, CD0 (mission need) imminent





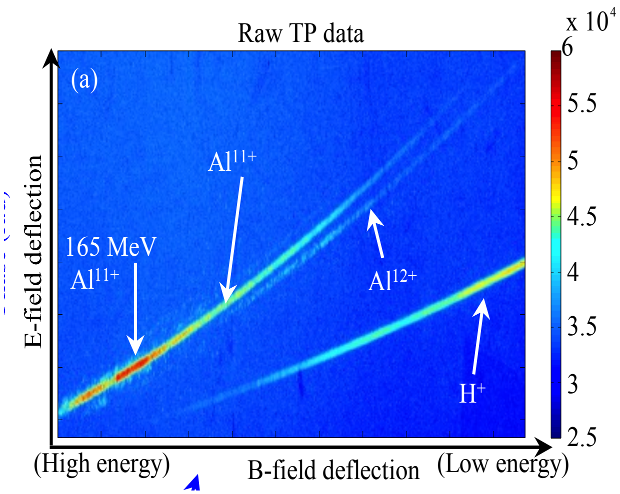
Even for basic research supported by LDRD – must deliver experimentally

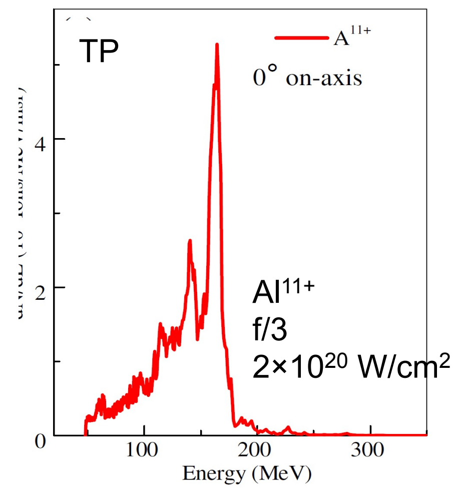
Trident experiments demonstrate peaked laser-driven ion spectra in relativistic transparency regime*

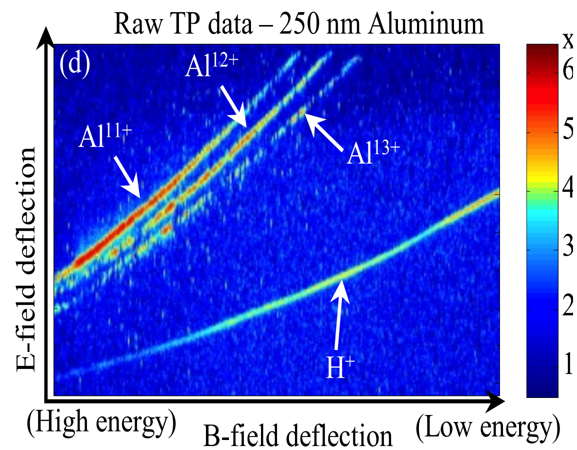


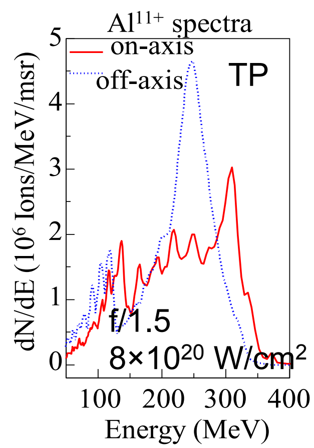
- Targets: **Al 110 nm** (f/3) & **250 nm** (f/1.5)
- Linearly polarized, 1054 nm, 650 fs FWHM Gaussian laser pulse
- ~ 5% efficiency

- **Al ion beam at ~ 150 MeV (f/3) is being used for isochoric heating****





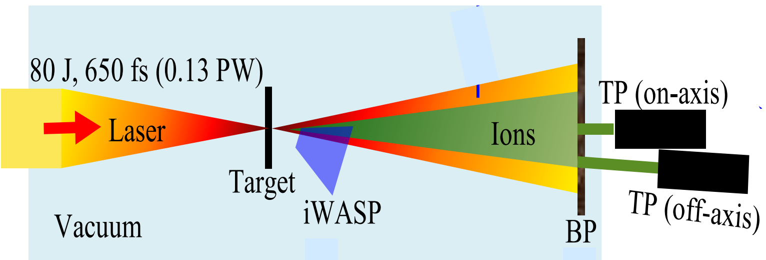


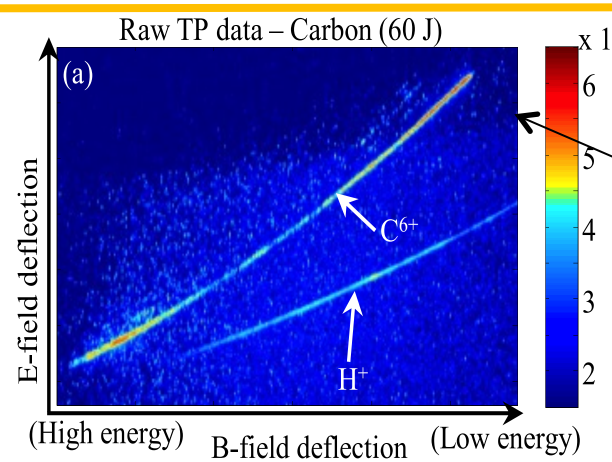


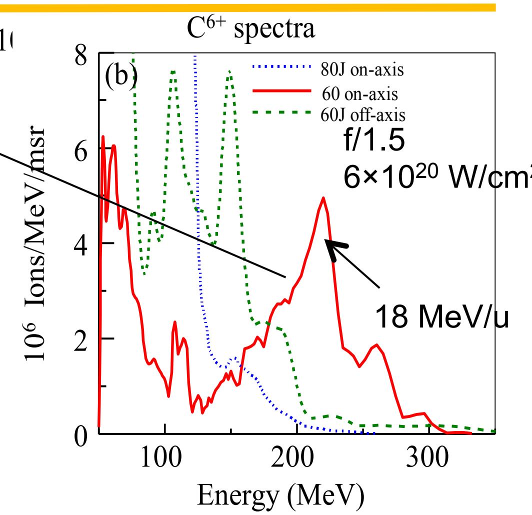
* S. Palaniyappan, C. Huang, *et al.*, Nature Comm. 6, 10170 (2015)
** W. Bang, *et al.*, Sci. Reports **5**, 14318 (2015)

Experiment

Laser-driven ion beams with narrow spectra have been obtained with diamond & multilayer (Al/C) targets*







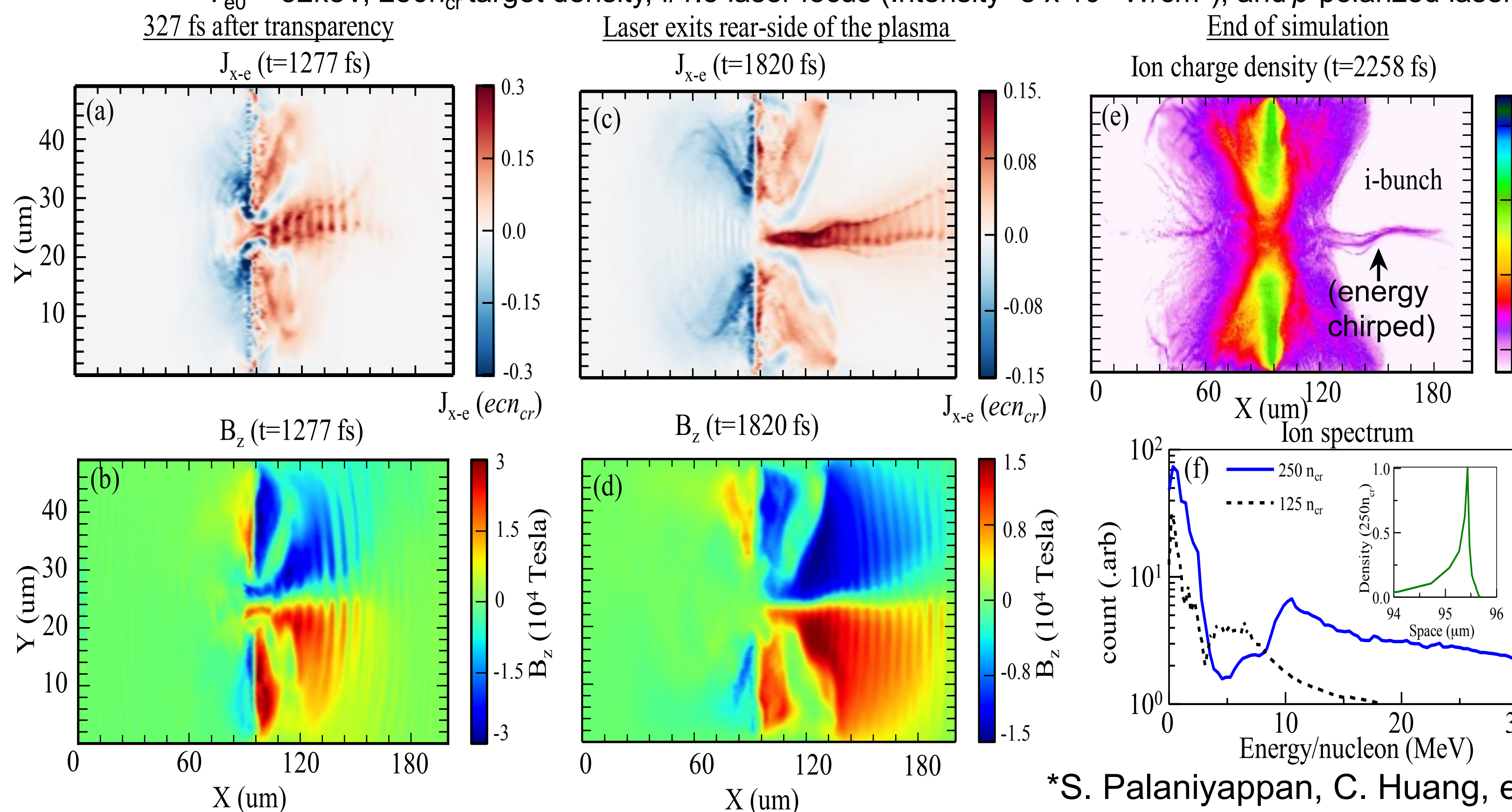
- Targets: **diamond 250 nm** thick (@f/1.5)
- Linearly polarized, 1054 nm, 650 fs FWHM Gaussian laser pulse
- ~ 5% efficiency
- Ion beam portion with narrow spectrum has a relatively narrow divergence
- Operational keys to obtain such spectra with diamond:
  - + back off on the laser energy and intensity – control premature prepulse-induced target disassembly*
  - + choose target thickness so that relativistic transparency ensues during the peak of the (Gaussian) laser pulse
- **C result is very relevant to Fast Ignition**

*S. Palaniyappan, C. Huang, et al., Nature Comm. **6**, 10170 (2015)

Spectral peaks form after the laser is gone*

- Key times for VPIC simulation*:
  - Laser enters box @ 0 fs, leaves at 2100fs, end of simulation at 2258 fs
  - Laser reaches target: 360fs, RIT: 950 fs, peak laser intensity: 1015 fs
  - Laser exits rear side of plasma: 1820 fs (ion spectrum still exponential)
- $n_{e0} = 250n_c$. 2x lower -> premature RIT, lower e- current, 3x lower B_z
- Ion spectral peaks arise after laser is gone

T_{e0} = 32keV, 250n_{cr} target density, f/1.5 laser focus (Intensity- 8 x 10^{20}W/cm^2), and *p*-polarized laser

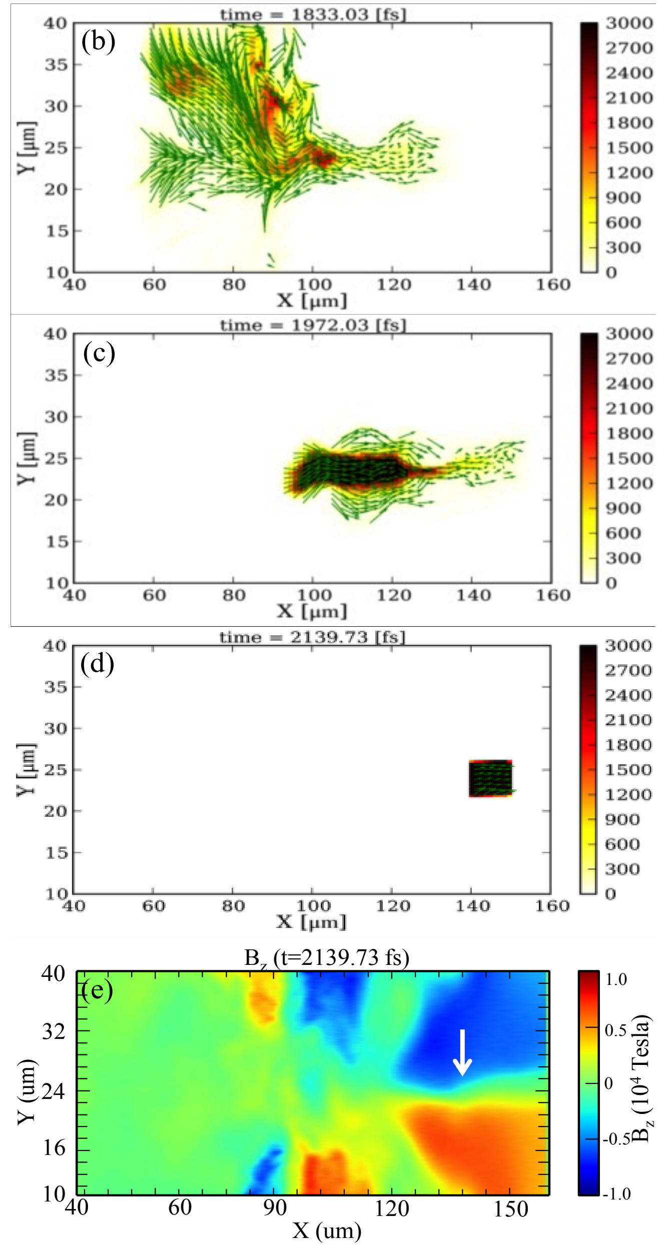


*S. Palaniyappan, C. Huang, et al., Nature Comm. **6**, 10170 (2015)

Modeling

Electron injection into plasma channel

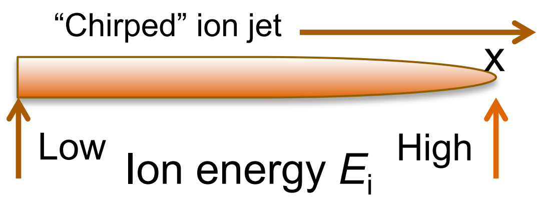
- Tracked electrons associated with ions in the 10.6 MeV/u ion peak @ 2140 fs
- Electrons from front accelerated to ~ 1—3 MeV and move through channel (ergo, not MVA)
- Electrons within B_z are strongly magnetized, ions are not -> electrons may bottle up
- Electrons do not have a clear shot thru channel and localize @ mouth of funnel and @ kink (white arrow)
- Charge imbalances set up and persist due to electron localization
- Charge imbalances create electrostatic fields that peak the ion-energy distribution
- Kink in B-field travels to the right, but ions outrun it

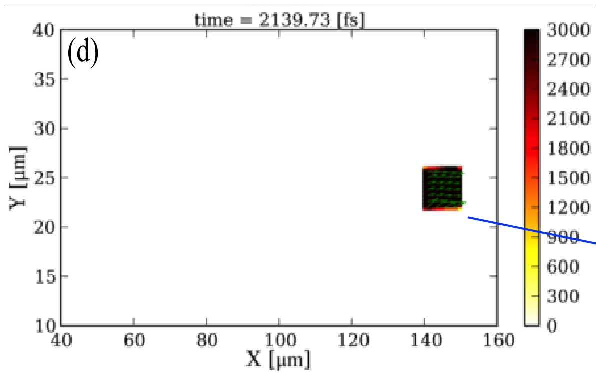


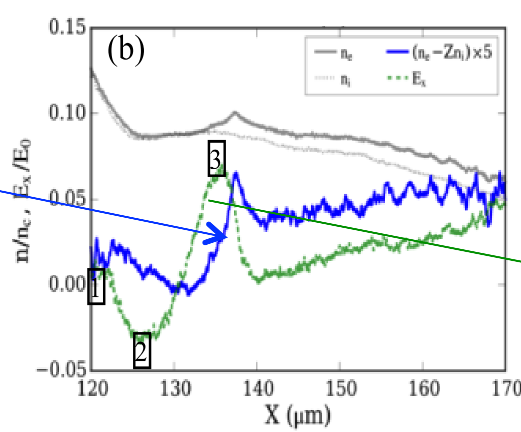
*S. Palaniyappan, C. Huang, et al., Nature Comm. **6**, 10170 (2015)

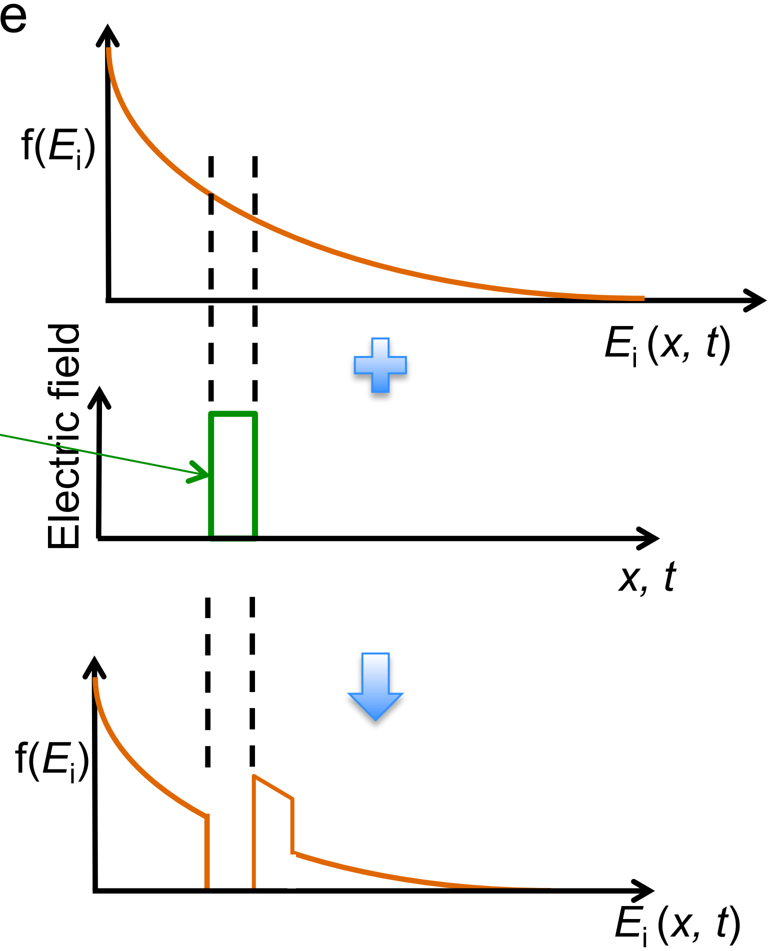
Electric field from electron accumulation causes ion-beam spectral peaking.

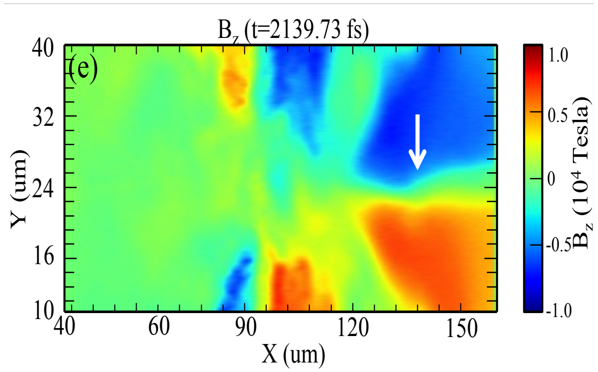
- A localized electric field of finite duration arises (opportunely for a certain ion population) from the bottled-up electrons at the channel kink
- Electric field rotates the beam in phase space making a narrow energy peak

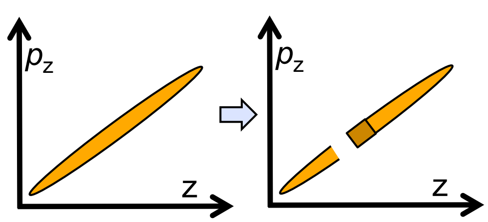






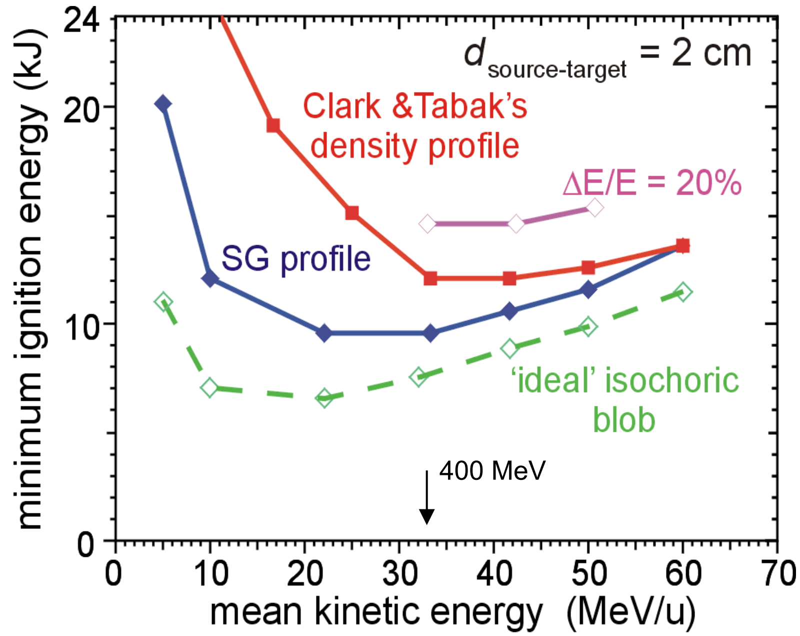






FI with light ions (such as C) of DT fuel assembled with long-pulse laser places specific requirements on ion-beam.*

- Leverage ability of NIF-like laser to assemble DT fuel[1,2]
- Requirements for FI with C ion beam[3]
  - Ion energy E_i ~ 400 MeV (to penetrate capsule corona)
  - Low ion-energy spread of ~ 10% (to deliver required power)
  - laser-ion conversion efficiency ~ 10% (to make FI driver feasible)



- C ions (220 MeV, 5% efficiency) @ Trident (~10^{21} W/cm^2) are half the values required for FI (E_i and efficiency)
- Since $E_i \sim I_L^{1/2}$, ~ 400 MeV C requires ~ 3 -- 4×10^{21} W/cm^2
- Challenges
  - scaling of efficiency
  - focusing the ions to ~ 30 μm

* E.g., J.C. Fernández, *et al.*, Nuclear Fusion 49, 065004 (2009);
[1] D. Clark & M. Tabak, Nucl. Fus. **24,** 1147 (2007);
[2] A. Mackinnon, *et al.*, PRL **108**, 0215005 (2012);
[3] J. Honrubia, *et al.*, Phys. PoP **16**, 102701 (2009)

Lessons from our work

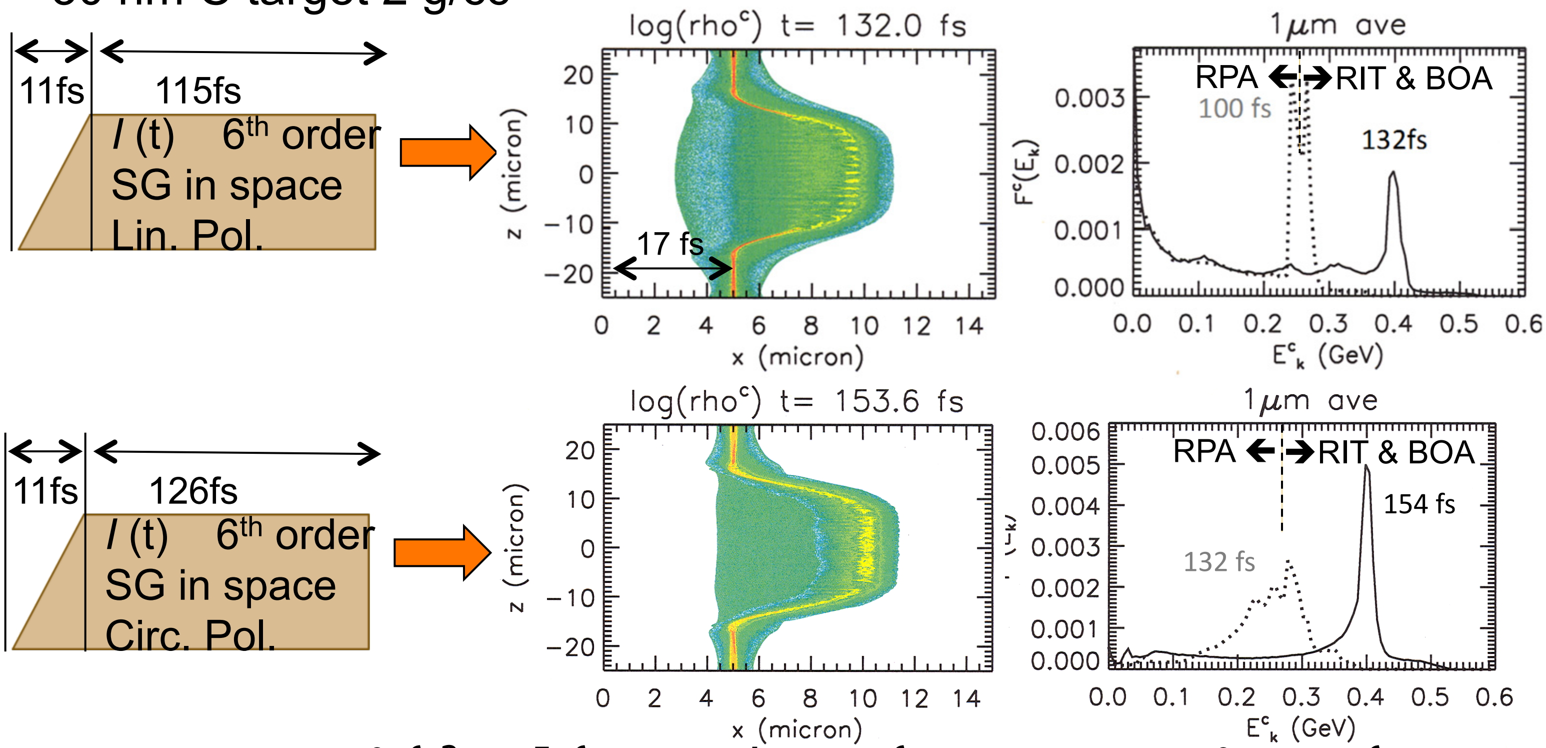
- Our best results are with initially solid-density nanofoil targets
  - Near critical-density can provide ion beams peaked in energy on Trident
- It is hard to avoid relativistic induced transparency (RIT) with nanofoils
  - Target disassembly, B-fields and RIT are sensitive to pedestal AND near-peak laser-pulse contrast (~ 10^{12} pedestal contrast [10^8 – 10^9 W/cm^2] can mess up performance of ~100 nm foils on Trident)
  - Scalings are tricky (BS?), need to measure *reflected* and/or transmitted laser pulse
  - We have not been able to demonstrate light-sail (LS) RPA on Trident
  - Therefore, LS RPA is hard; better use all possible technology tricks
- Explore other ion-acceleration mechanisms (MVA?)
- Consider late-time dynamics to rotate ion beam in phase space
  - Cooling of co-moving electrons
- Inadequate PIC simulations (too small a box, not resolving Debye length, not minding the preplasma, etc) can lead us astray
- Published "RPA" experiments may not be RPA at all – late-time dynamics?

Why BELLA-I for ion acceleration? Considerations

- For DOE: what is the unique value proposition?
  - Unique scientific mission?
  - Performance vis-à-vis Gemini, Apollon, upgraded GIST … (More energy? Higher intensity? Better contrast? High rep rate? Laser quality control?)
  - What program in the US to pay for HEDP research and for what? (e.g., issues with HEDLP Joint Program)
  - Development for MEC/LCLS-II, MaRIE @ LANL
  - Proximity to UC Berkeley
- Some mechanisms require or work best in “1D” geometry (RPA, BOA)
  - Temporal intensity variation leads to energy spread in BOA, temporal pulse shaping controls spread
  - Radial intensity gradient ➔ “plasma “bowing,” radial flows (collective effects & beam spread)
- Chance to have a 30 fs beam simultaneously “better” in key aspects
  - Spatially shaped (e.g., nearly flat radially) even at the cost of peak intensity (maybe ~ 10^{21} W/cm^2 may be realistic)
  - High contrast (pedestal & near pulse)
  - Well characterized, routinely diagnosed ➔ highly reproducible
- Evaluate known concepts and try novel ones in the ~ 30 fs pulse regime

Possible performance of a BELLA-I first experiment on ion acceleration

- 2D highly resolved simulations* with VPIC by Lin Yin
  - Debye length resolved at t=0
  - 10^{21} W/cm^2 6th order super Gaussian
  - 30 nm C target 2 g/cc



η_E = 4.4%, η_p = 20%

η_E = 8.3%, η_p = 45%

- RPA LS: $E_{ki}=Am_pc^2\xi^2/2[\xi+1]$, where $\xi = 2I_Lt_L/\rho lc^2$ and $\xi < 1$ here
- LP case: want constant ξ (i.e., t_L/l) ➔ 30 fs, **11nm C foil @ 2 g/cc**, **250 MeV C ions**

* J. C. Fernández et al., NF **54** (2014) 054006

Summary

- Our perspective from our missions
- Observed quasi-monoenergetic beams
  - Al11+ & C6+
  - How was it accomplished experimentally
- Simulations to clarify mechanism
  - Critical to do correct simulations
  - Late-time dynamics & self-organization (after laser exits)
- Relevance to ion fast ignition (FI)
  - FI requirements
  - Laser requirements
  - Focusing requirements
- BELLA-I considerations
  - Performance in a possible RPA experiment