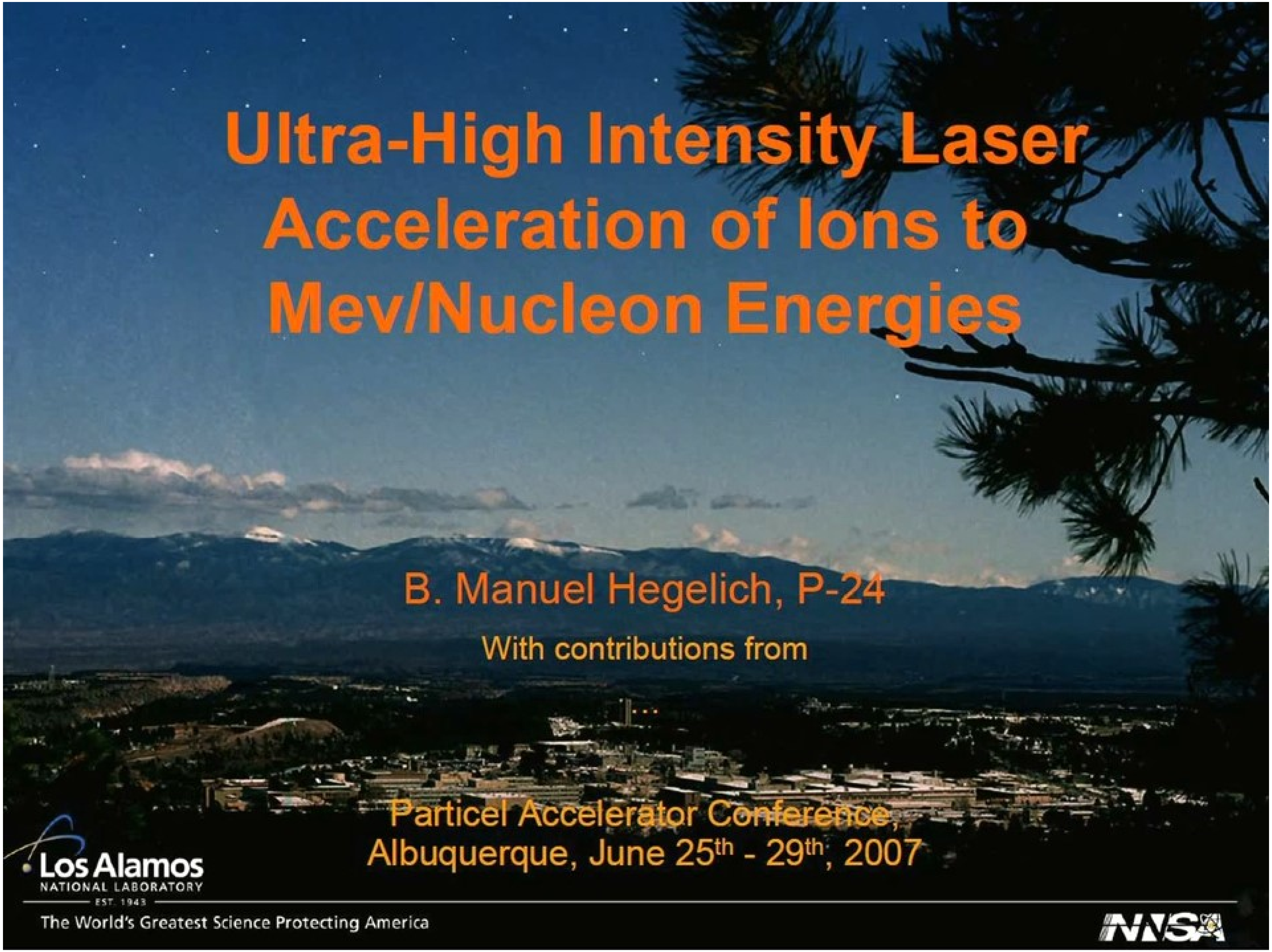

Ultra-High Intensity Laser Acceleration of Ions to Mev/Nucleon Energies
B. Manuel Hegelich, P-24
With contributions from
...
Particel Accelerator Conference, Albuquerque, June 25th - 29th, 2007
Los Alamos
NATIONAL LABORATORY
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The World's Greatest Science Protecting America
NNSA

Colleagues and Collaborators

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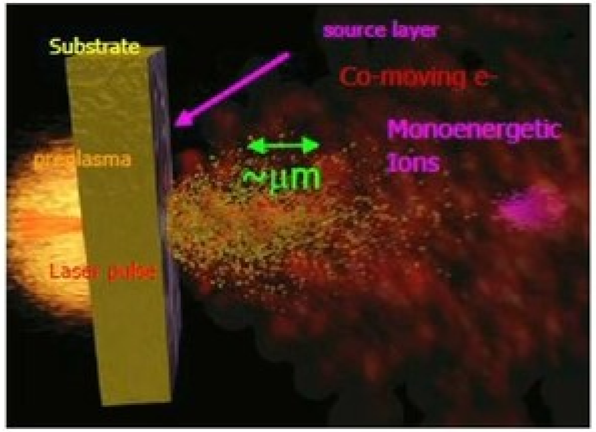
Outline

- **What?**
  - Ultrahigh Intensity Lasers (>10^{19} W/cm^2) can accelerate ions to MeV/nucleon energies.
  - Laser-accelerated ions have unique parameters.
- **How?**
  - Ultrahigh Intensity Lasers
  - The Target Normal Sheath Acceleration (TNSA) Mechanism: Laser-plasma accelerators sustain ~1,000,000x higher fields than conventional accelerators.
  - Controlling the spatial properties of the ion beam.
  - Controlling the spectral properties of the ion beam.
- **Where to?**
  - Towards GeV ion energies: a new acceleration mechanism: the Break-Out Afterburner (BOA)

Particle Acceleration

Conventional particle accelerator (LANSCE ~km)

Laser-Particle Accelerator (Trident Laser Facility ~10m)



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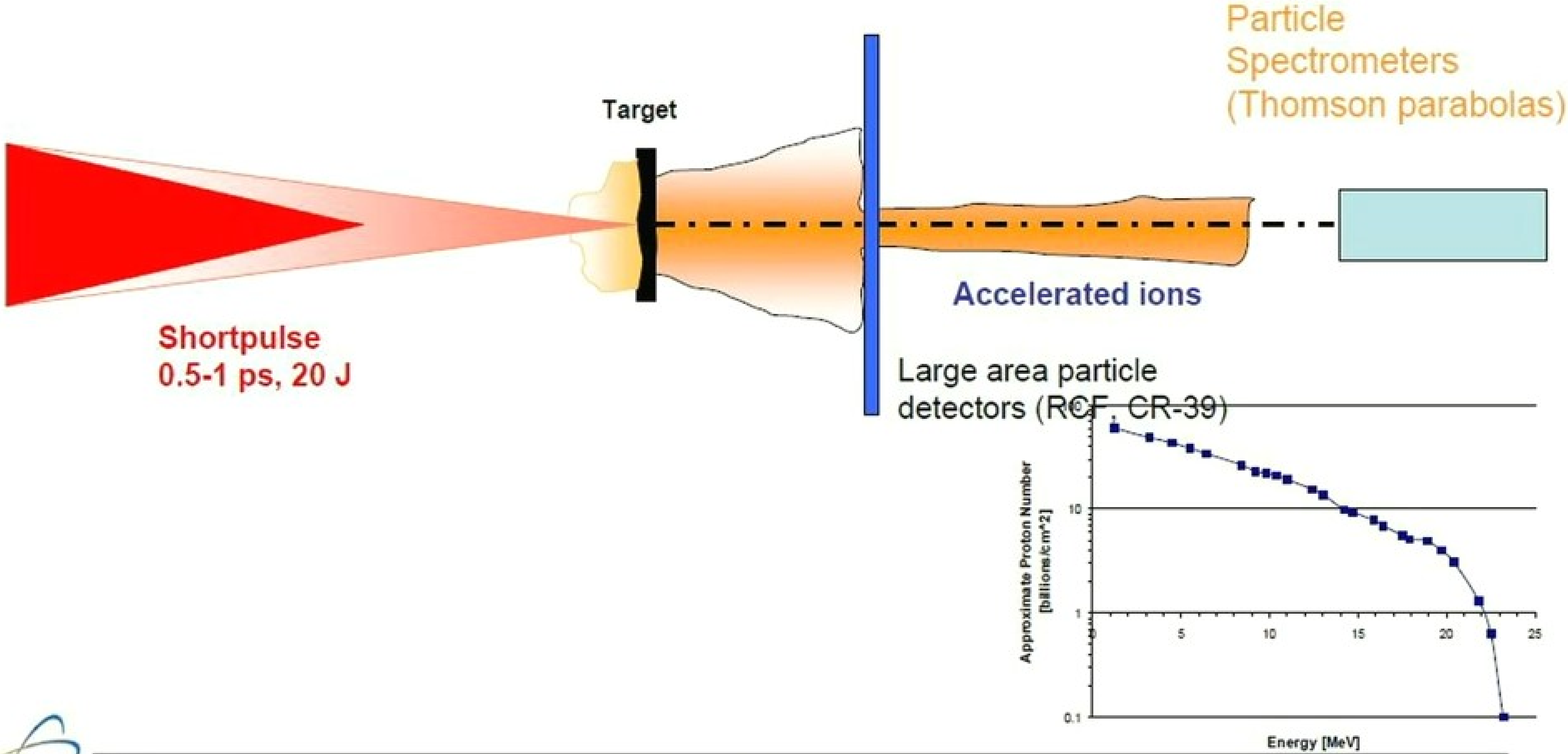
Ultrahigh Intensity Lasers accelerate ions to MeV/nucleon energies:



Laser-accelerated ion beams have unique characteristics compared to conventional accelerators:

Benefits:

- Large accelerating fields
  TV/m vs. MV/m
- Short acceleration distance
  ~10μm vs. ~100m
- Short pulse duration [1]
  <ps vs. >ns
- Small longitudinal emittance [1]
  10^{-6} eVs vs. 1 eVs (CERN SPS)
- High beam currents[1]
  kA – MA vs. μA-mA
  up to 10^{13} particles per bunch
- High Peak Power
  TW vs. kW
- Small transverse emittance [2]
  <0.001πmm-mrad vs. 1 πmm-mrad (CERN SPS)
- Tight focusing
  ~10μm vs. mm

Challenges:

- Broad Spectrum
  1-0.1 vs. 10^{-4} (GSI Unilac)
- Stability
  ~10% vs. ~0.1%
- Repetition rate
  0.001 Hz vs. MHz
- Low average power
  mW vs. ~50W (GSI Unilac)

[1] Hegelich et al., Nature **439** (2006) p441
[2] Cowan *et al.*, PRL **92** (2004) 204801

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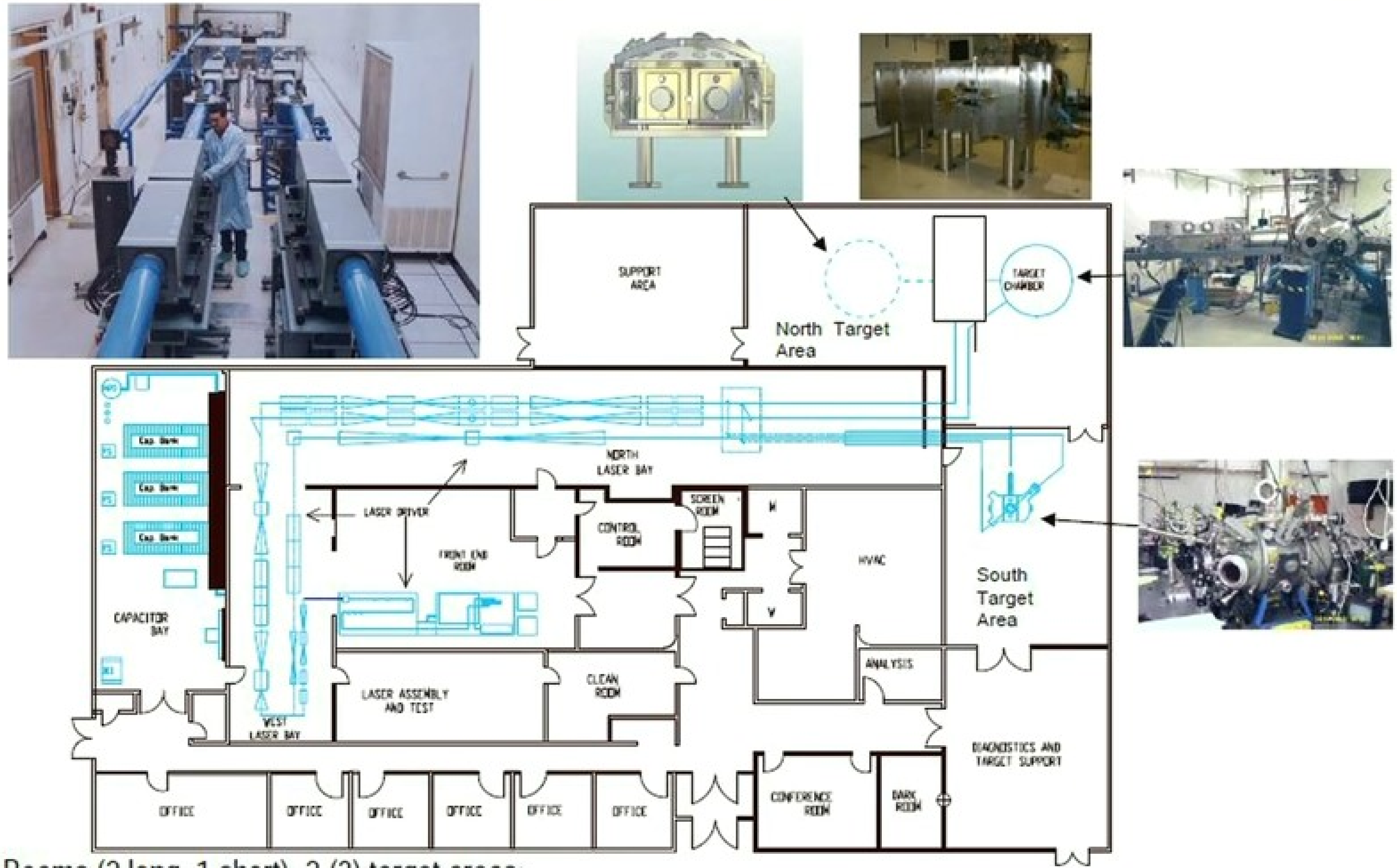
The Trident Laser Laboratory is a flexible facility with multiple target chambers & beamlines



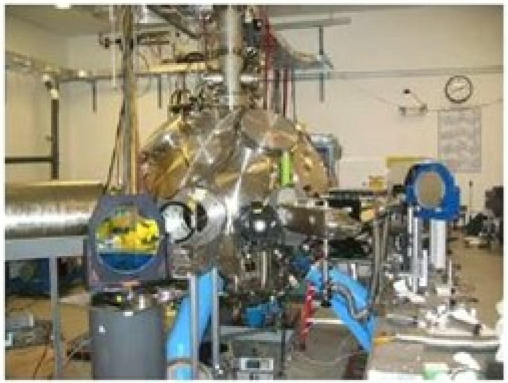
- 3 Beams (2 long, 1 short), 2 (3) target areas:
- Longpulse:
- 2 longpulse arms with 200J (green) each, 100ps – 6ms

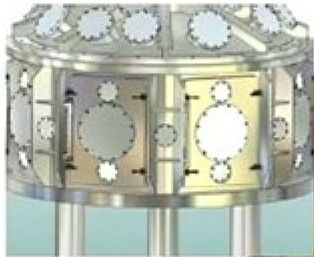
The LANL Trident Shortpulse Laser Facility: a 30TW Glass laser system (is being upgraded to 250 TW)

Shortpulse

- Energy: 20J (150J) on target
- Pulse duration: 750 (500) fs
- Focus: <14 μm diameter
- Intensity: $>2\times10^{19}$ (2×10^{20}) W/cm^2
- Prepulse: $<10^{-7}$ @ 1ns
  $<10^{-10}$ @ 5ps
- Repetition rate: 1 shot / 45 min.

DOE Milestone of >100TW in target chamber passed





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The Trident Shortpulse Laser is being upgraded:

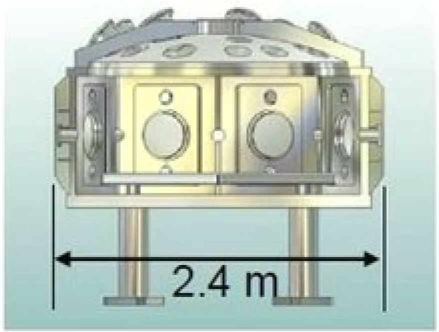
Enhancement:

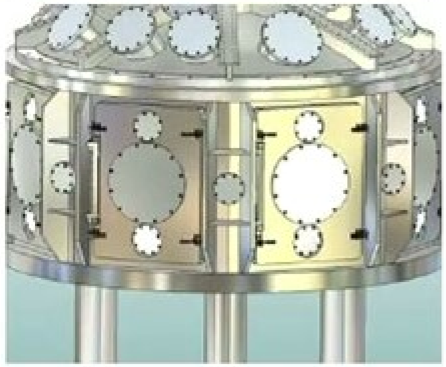
- Energy: 150J on target
- Pulse duration: 500 fs
- Focus: <14 μm diameter
- Intensity: >2x10^{20} W/cm^2

Plus:

- 3rd target chamber
- Shortpulse probe beams
- New high-contrast frontend (prepulse <10^{-10} @ 5ps

DOE Milestone of >100TW in target chamber fullfilled 2 weeks ago





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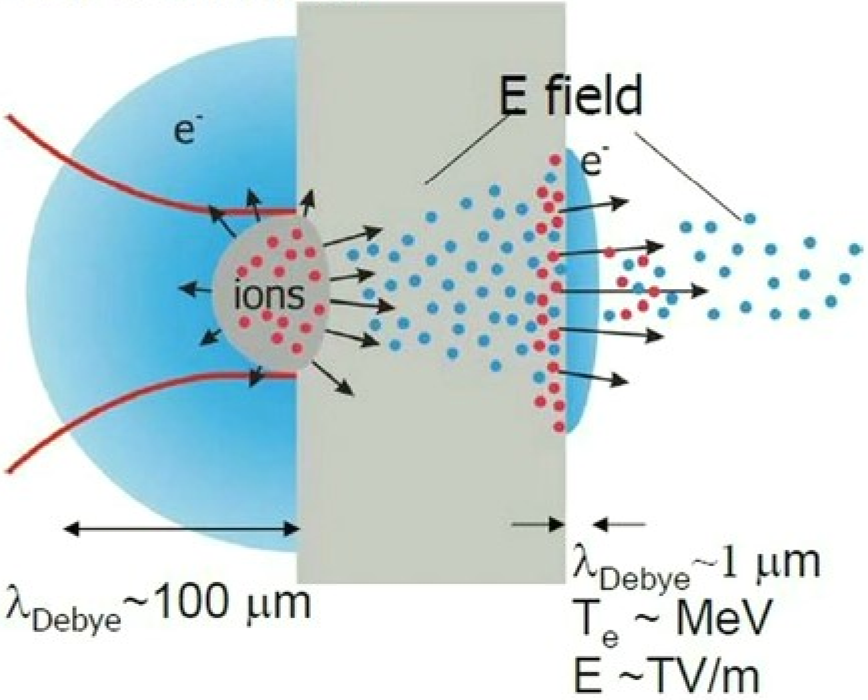
The Target Normal Sheath Acceleration (TNSA): *Rear Surface* ion acceleration mechanism

The TNSA mechanism:
laser electron acceleration → charge separation → quasi static electric field → ion acceleration

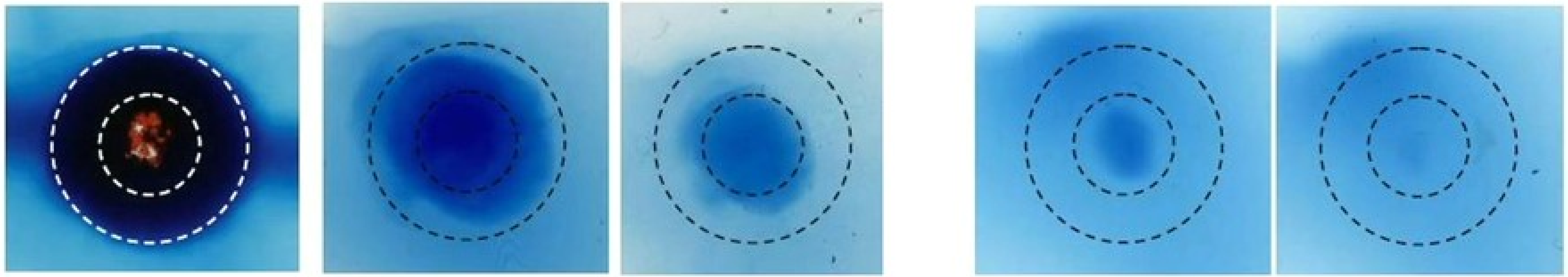


TNSA characteristics:

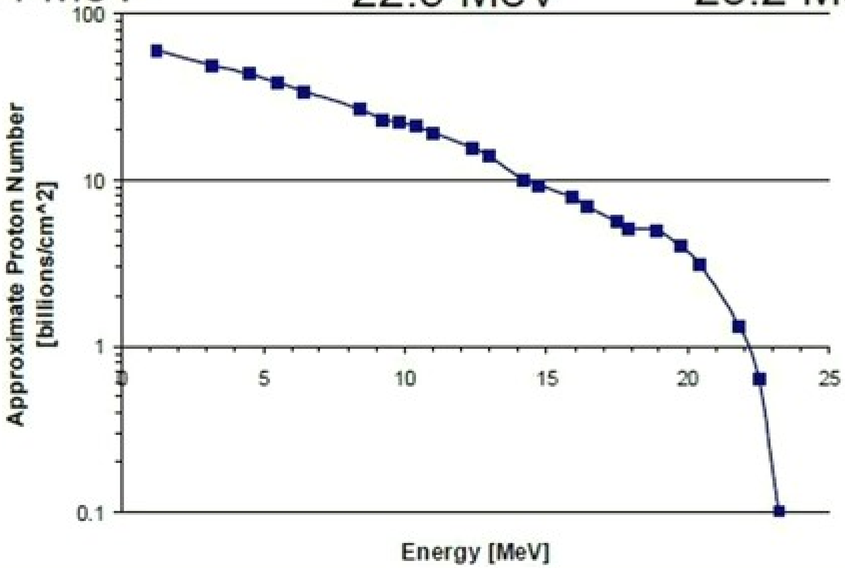
- Highest Charge-to-Mass ratio is dominantly accelerated and screens the accelerating fields:
  - ⇒ Protons from H_2O + hydrocarbons get most of the energy
  - chemical impurities
  - Target cleaning required for Z > 1 (e.g. heating, ablation, ...)
- High beam currents (kA – MA)
- Excellent emittance
- multiple charge states
- Beam is charge neutralized
- Maxwellian spectra, 100% energy spread
  - Many applications profit from, or even require a mono-energetic energy distribution

Flat Metal Foil Targets yield ~25 MeV protons for typical Trident conditions: I=1-2x10^{19} W/cm^2, E=20 J, $\Delta\tau$ =700 fs

HD RCF | MD RCF

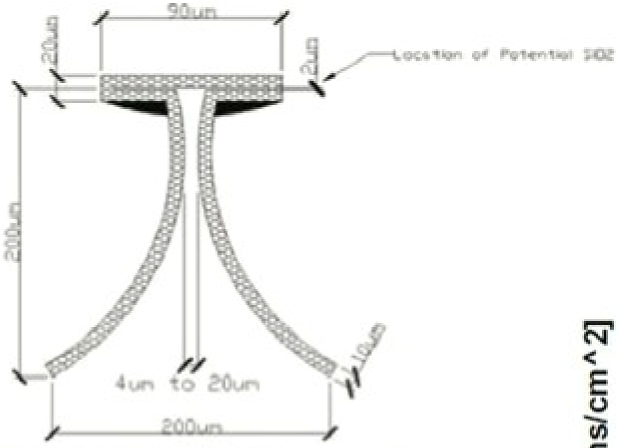


Bragg Peak Energy=
1.2 MeV | 13.5 MeV | 16.4 MeV | 22.5 MeV | 23.2 MeV

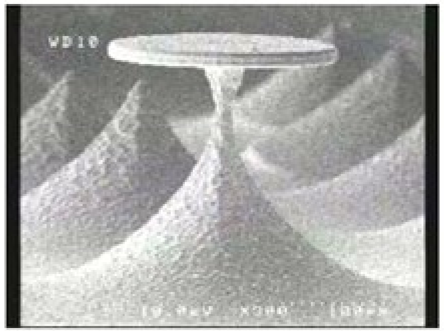


published scaling laws predict ~10 MeV

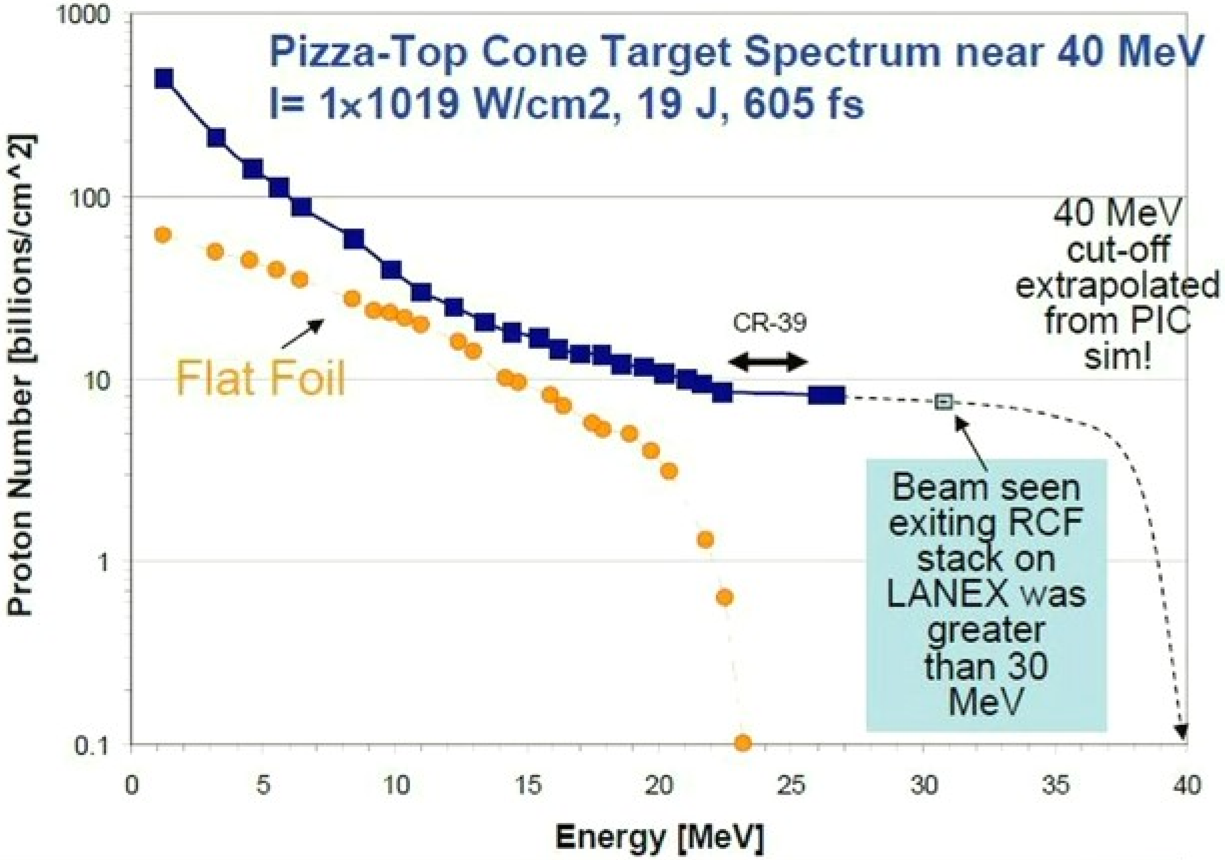
Advanced "Pizza-Cone" targets for ion acceleration deliver increased proton energies and conversion efficiencies.



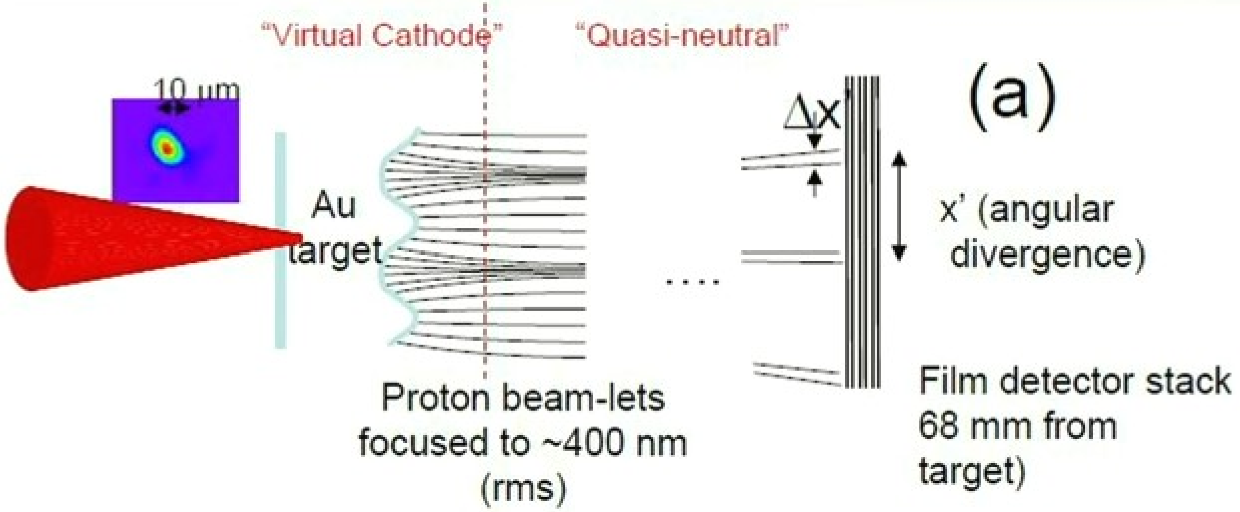
Typical Target Shape and Typical Dimensions

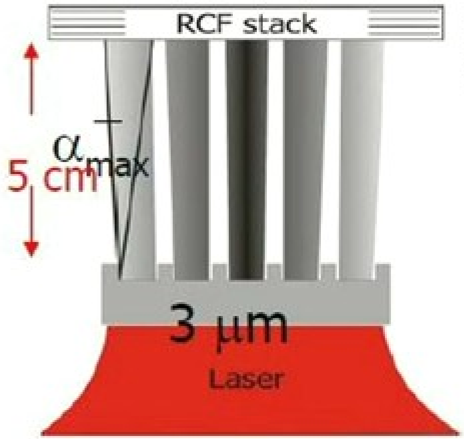


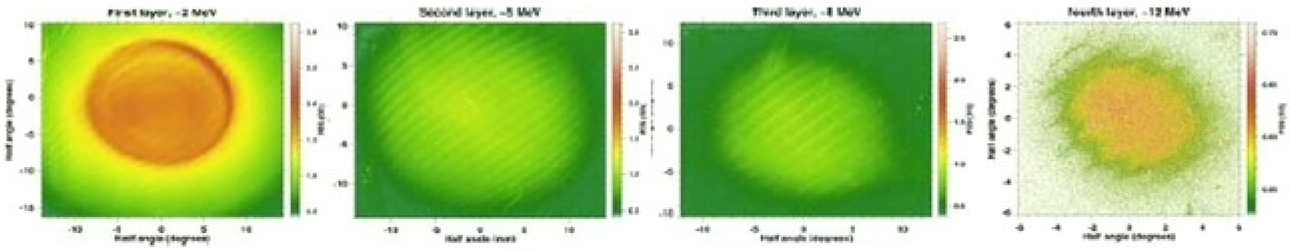
More than 5 times the number of protons/MeV in the high energy tail!



Ultra-low transverse emittance is observed: $\varepsilon_N < 0.002\ \pi$ mm-mrad







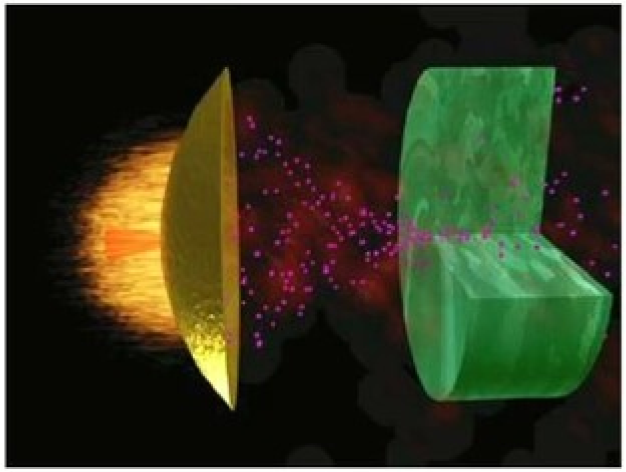
Record low-emittance:

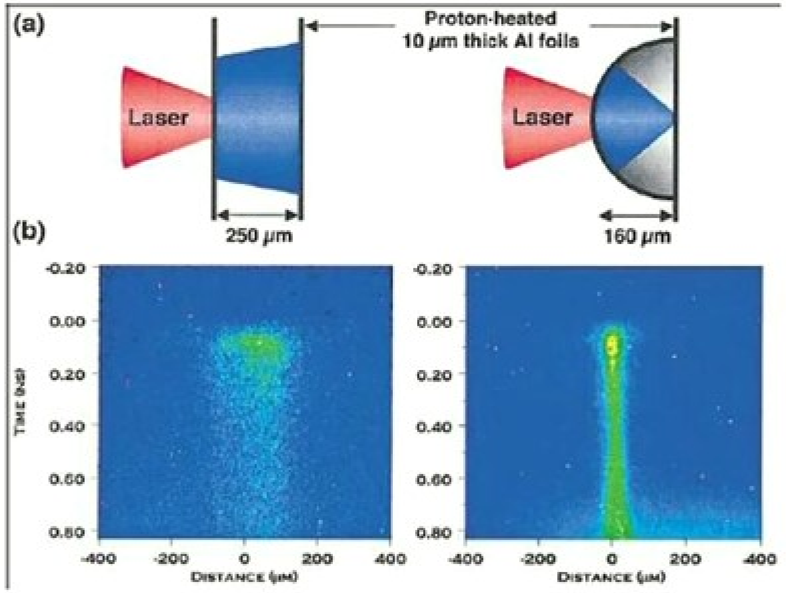
$\varepsilon_{N,rms} = \beta\gamma\ \sigma_x\ \sigma_{x'} < 0.002\ \pi$ mm-mrad

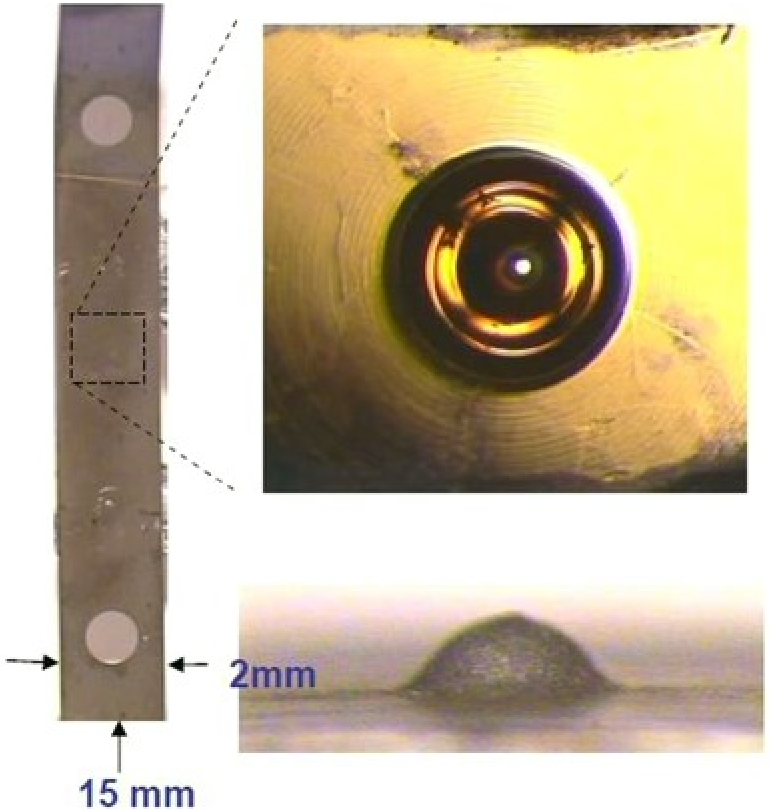
(typ RF linac: ~0.5 π mm-mrad)

* Cowan *et al.*, PRL **92**, 204801 (2004).

Ballistic Ion Beam focusing using shaped targets







LLNL, Patel et al., PRL 91 (2003)

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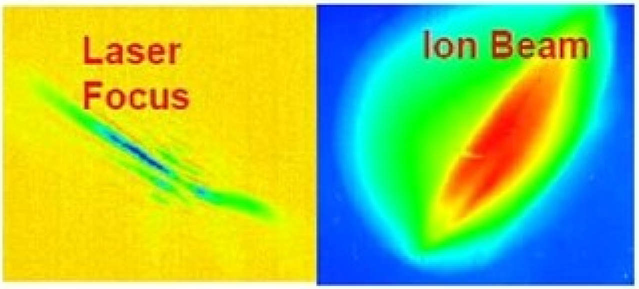
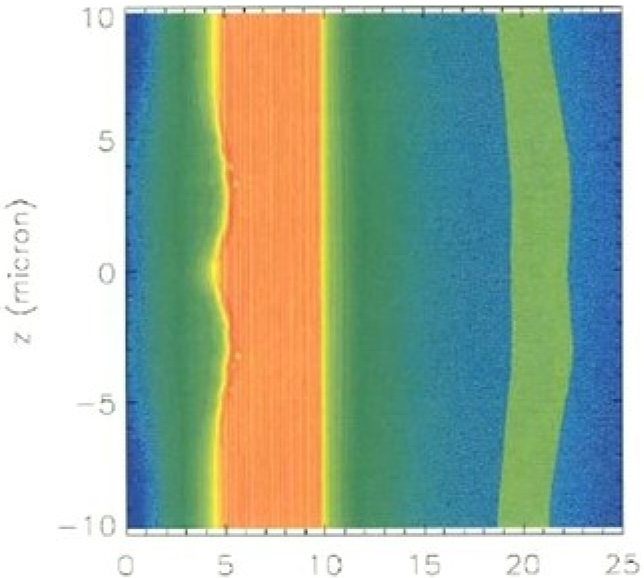
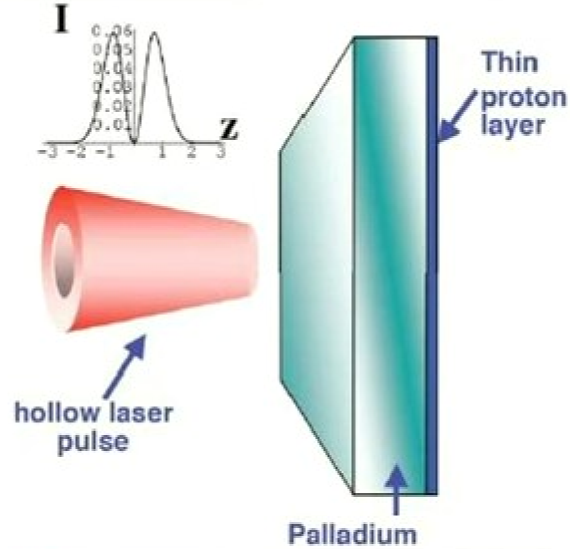
Experimental observation of laser imprinting into ion beam suggests ion beam focusing using shaped laser beams:

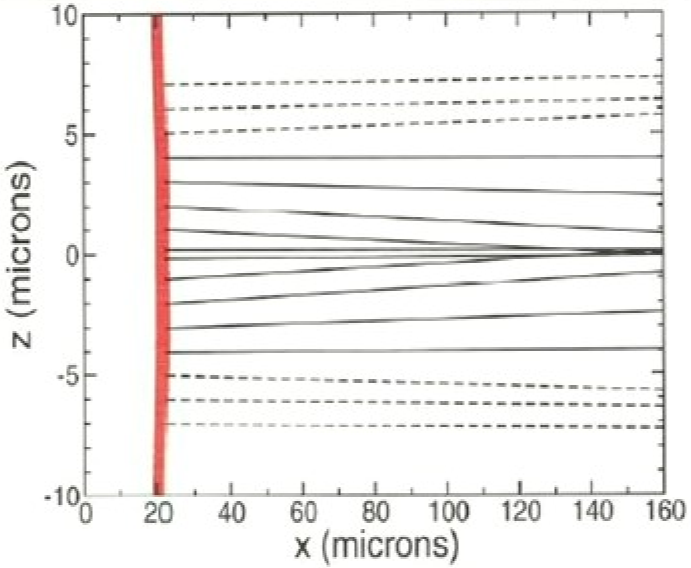


Ion Beam shape



2D-PIC simulations (L. Yin, LANL, VPIC)



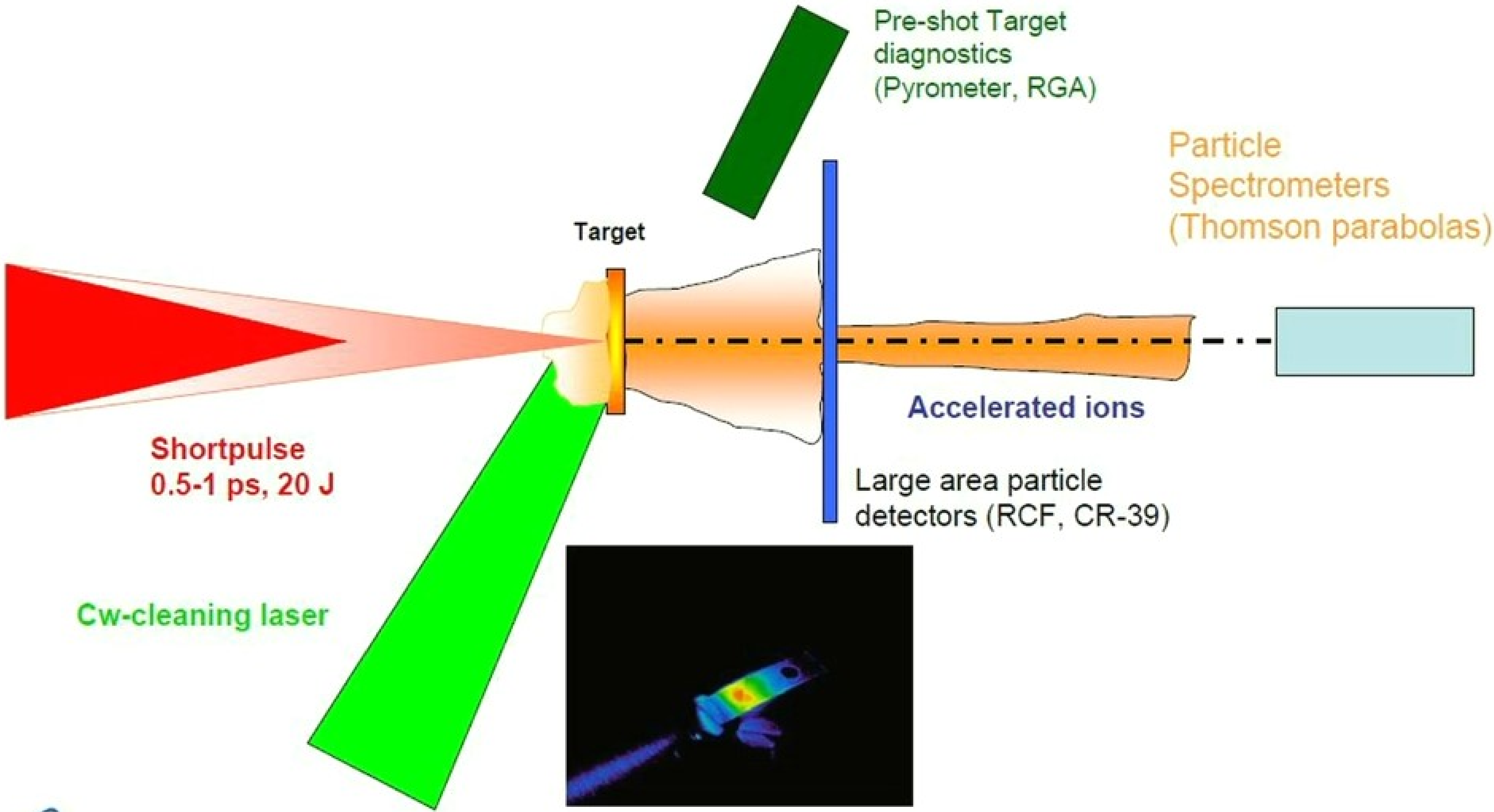


Control of the ion species on the target surface is important to achieve heavy ion acceleration

Possible contaminants include water vapor, hydrocarbons & metal oxides

- E.g. Pd foil (no oxide, but excellent H getter):
  - 3.8×10^{16} O atoms/cm^2 (from 7.6 MeV He++ ions)
  - 2.4×10^{16} C atoms/cm^2 (5.6 MeV ions): ~ 30 Å @ 2 g/cc
  - 4.5×10^{16} H atoms/cm^2 (0.6 MeV ions)
- Hydrogen bearing surface contaminants can be dislodged by simply heating the target ~1000 degrees C
  - Ohmic heating (DC current) or Joule heating (CW laser)
- Oxides and Carbides require other methods due to there high binding energies.
  - Laser Ablation
  - Ion gun
  - Target material
- Target can be layered with desired species
  - Manufactured
  - In Situ

Experimental setup and diagnostics



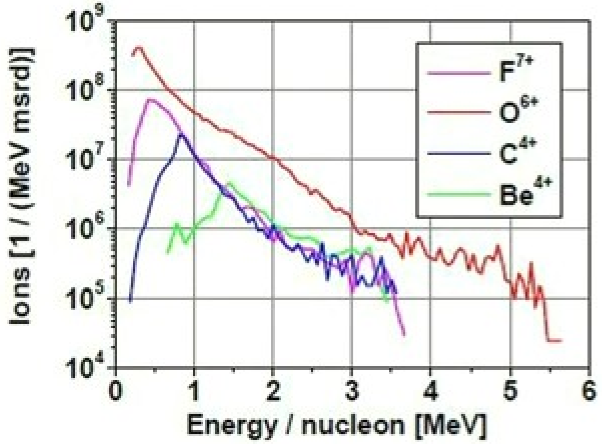
Laser ion acceleration has been demonstrated from protons (Z=1) up to palladium (Z=46).

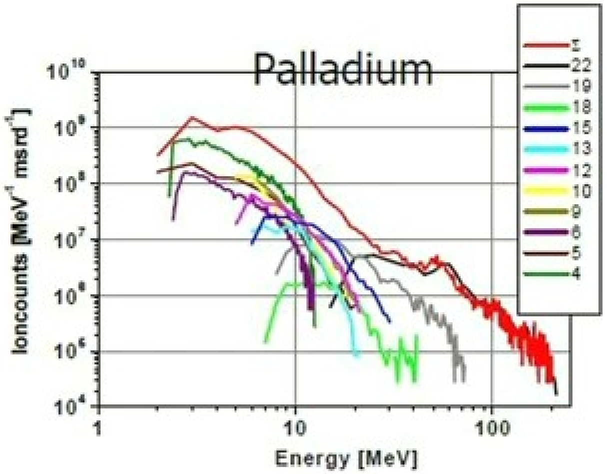
Light ions (Z ≤ 10) with E ≤ 5 MeV/u.
Hegelich et al. PRL 89 (2002).

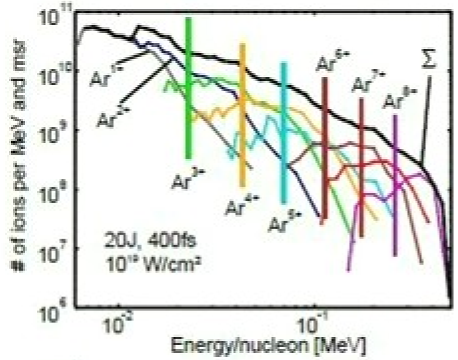
Mid-Z ions (10 ≤ Z ≤ 46) with E ≥ 2 MeV/u.
Hegelich, M. *et al.*, Phys. Plasmas, **12**, 056314 (2005).

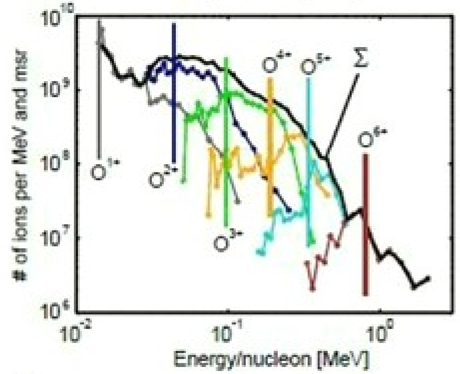
Trident Enhancement will enable heavy ions (Au, Pt, U)

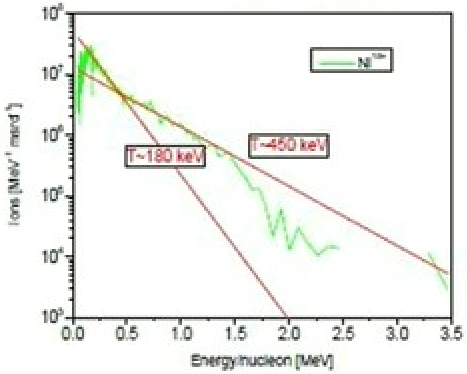
The conversion efficiency for laser energy into heavier of any charge state is on the order of a few % for Trident class lasers, as is the CE for protons.



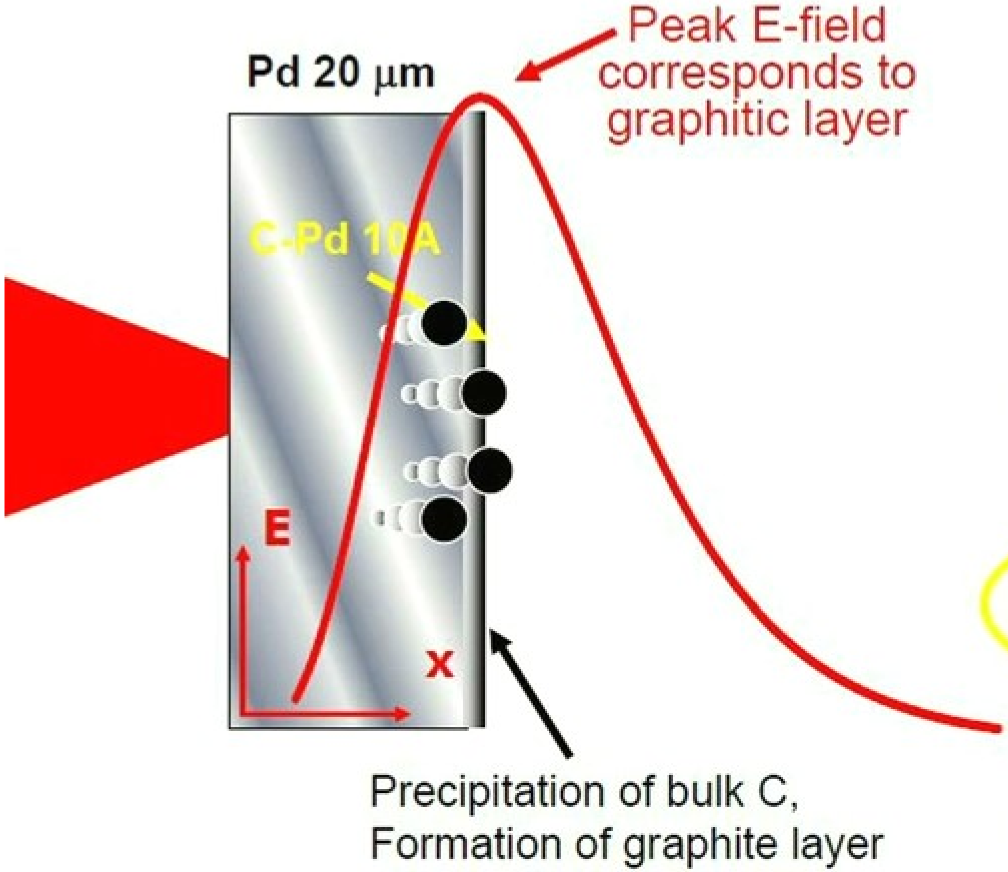








Palladium can act as a catalysts for a phase transition of the adhered carbon contaminants, merging into a highly ordered, thin layer

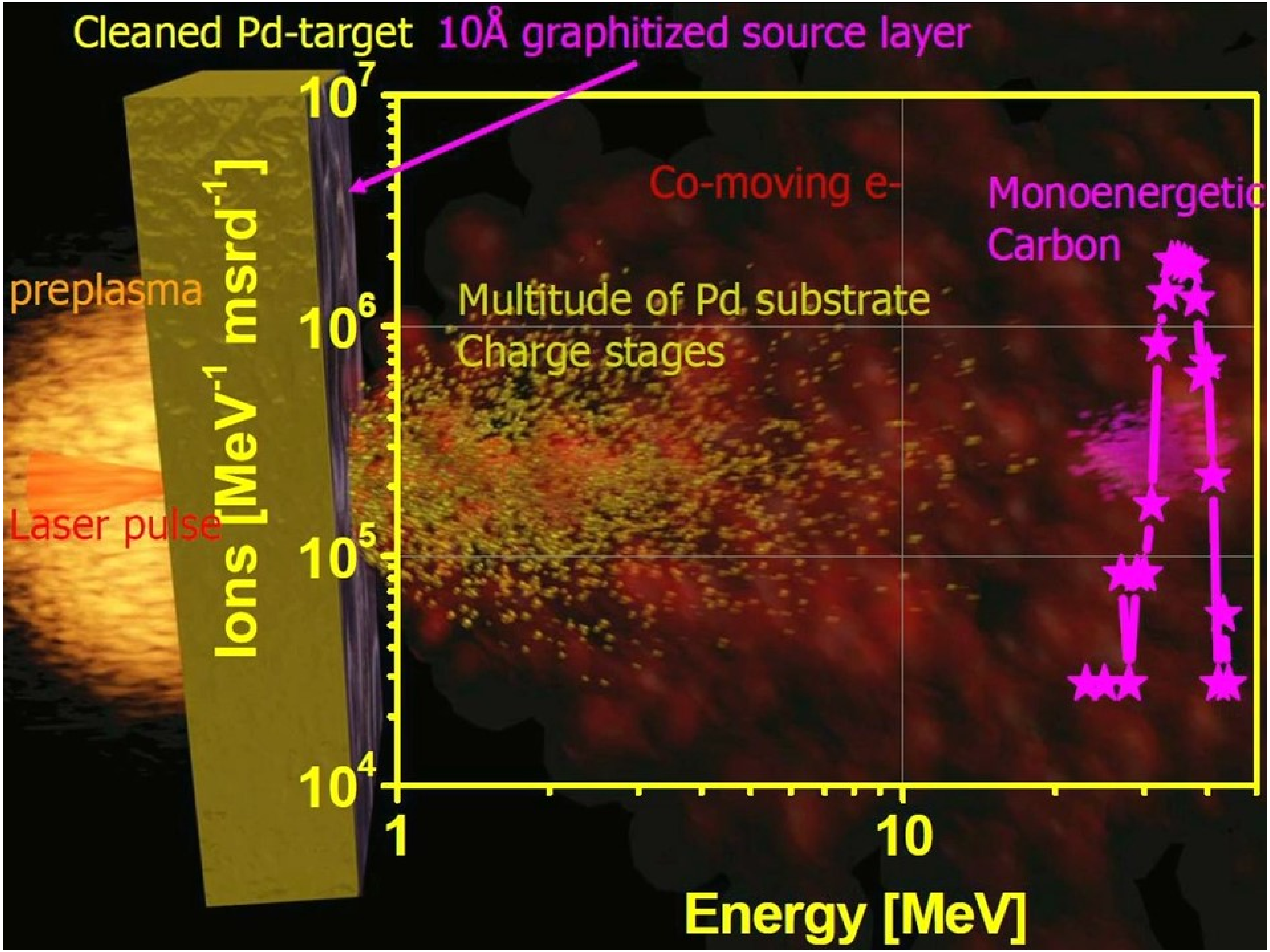


Heating of Pd:
T < 300 °C:
C_xH_y and H species on surface

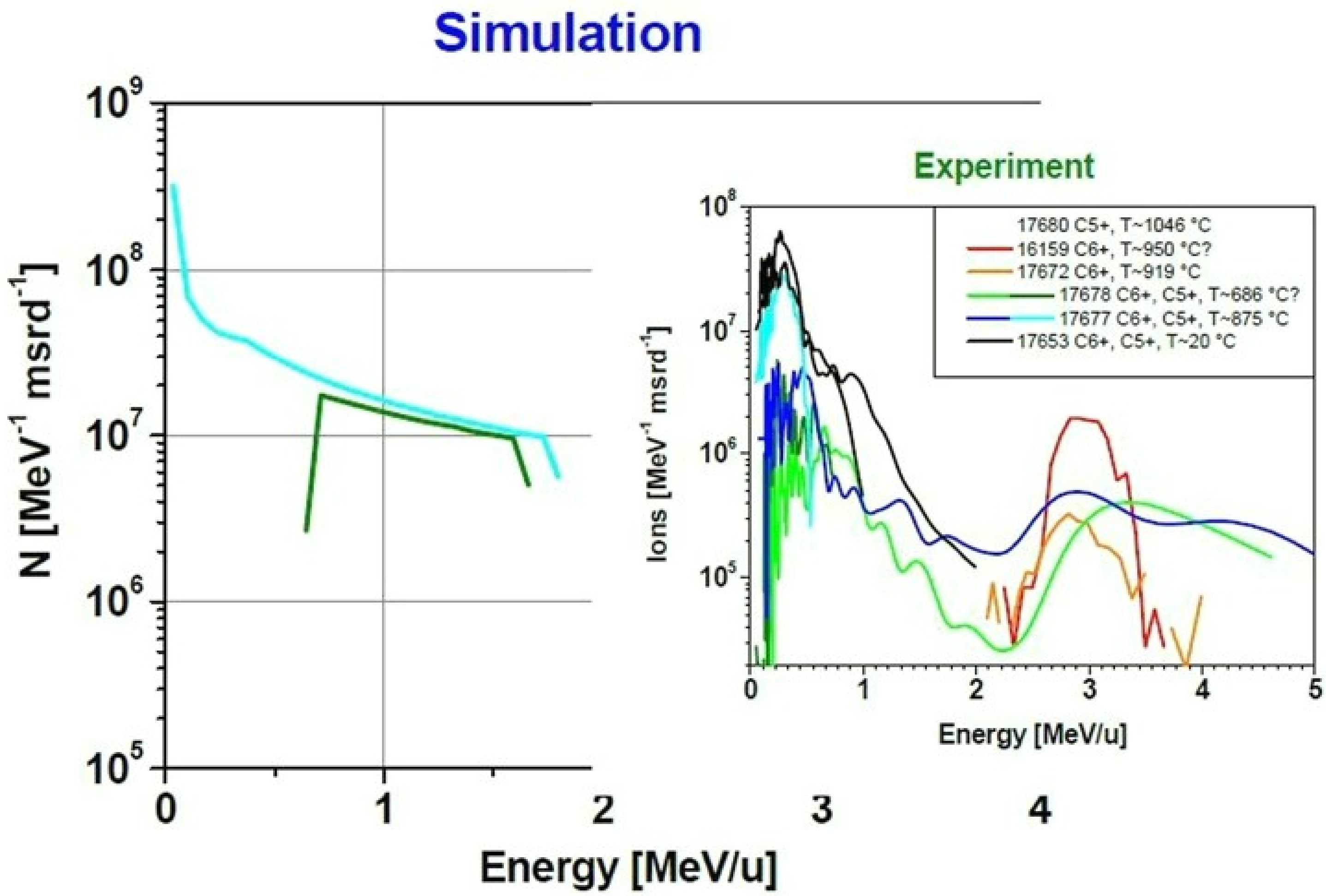
T > 300 °C:
Start dehydrogenation, leaves various C(ads)

T > 750 °C:
Graphitization of surface

T > 950 °C:
Clean Pd surface


Cleaned Pd-target
10Å graphitized source layer
Co-moving e-
Monoenergetic
Carbon
Multitude of Pd substrate
Charge stages
preplasma
Laser pulse
Ions [MeV-1 msrd-1]
10^7
10^6
10^5
10^4
1
10
Energy [MeV]

The ion energy spectrum can be controlled by controlling the source layer thickness.



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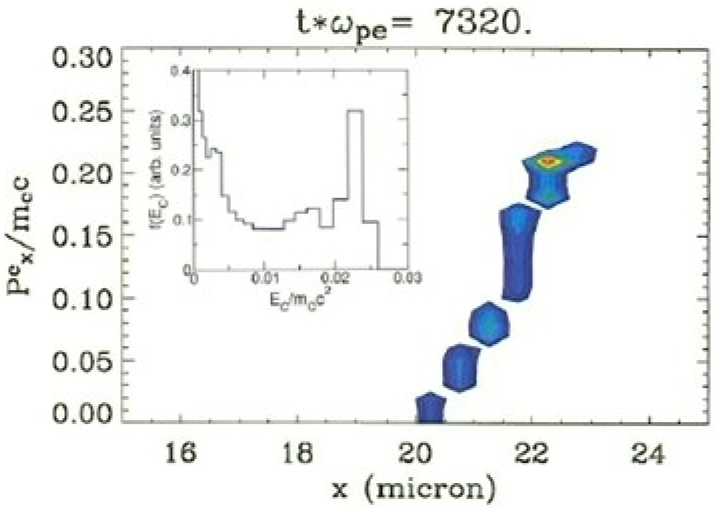
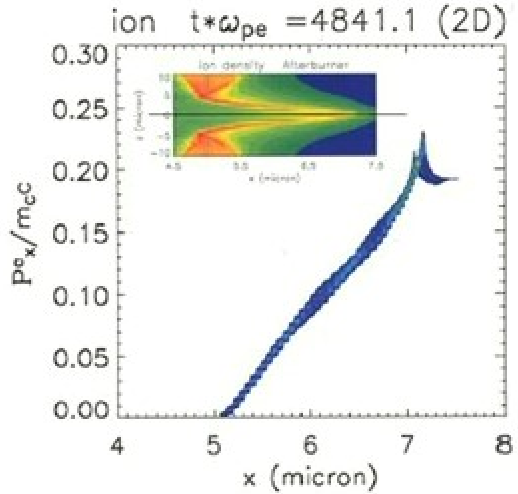
Discovery of the new Break-Out Afterburner (BOA) mechanism in massively parallel computer simulations.

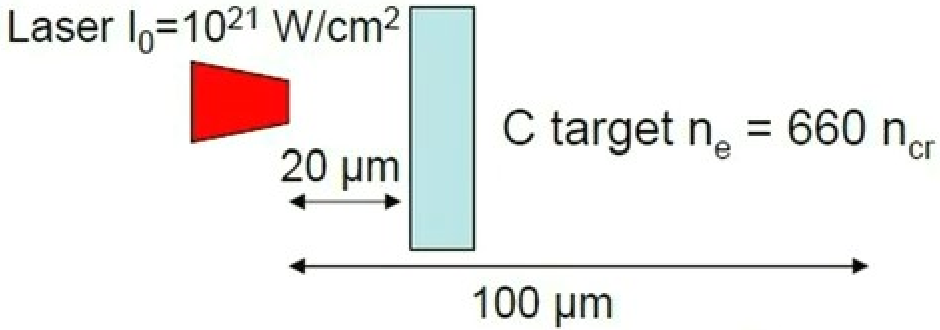


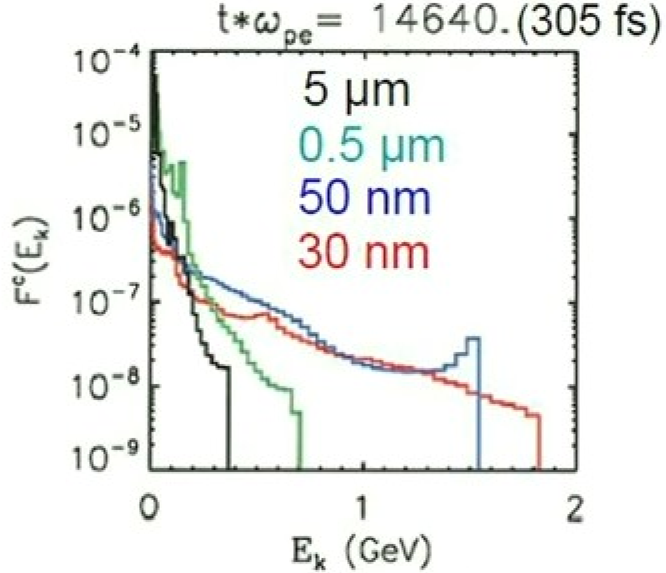


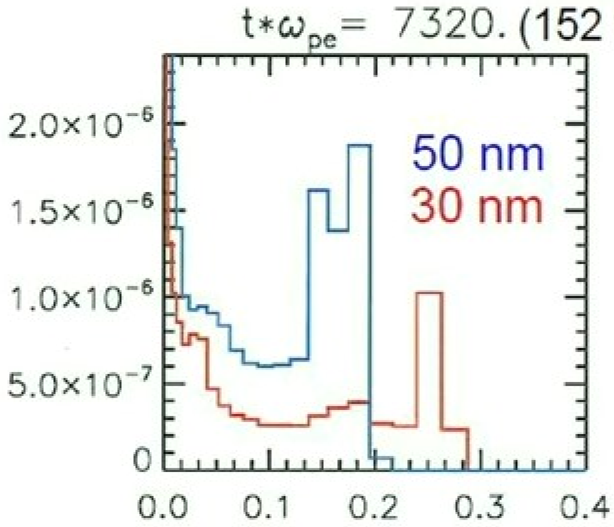
LANL simulations showing the new Break-Out Afterburner (BOA) mechanism. BOA has the potential to boost the ion energy and the acceleration efficiency by more than 2 orders of magnitude (GeV, >10%), enabling cheap, ultracompact accelerators which can be used e.g. for tumor therapy or compact plasma/field probes for large, dynamic plasma volumes.

Monoenergetic and GeV ion acceleration from the laser break-outafterburner using ultrathin targets
L. Yin, B. J. Albright, B. M. Hegelich, K. J. Bowersz, K. A. Flippo, T. J. T. Kwan, and J. C. Fernández
Phys. Plasmas, (May 2007), accepted for publication
GeV laser ion acceleration from ultrathin targets: The laser break-out afterburner
L. Yin, B. J. Albright, B. M. Hegelich, and J. C. Fernández
Laser and Particle Beams 24 (2006), 1–8

Scaling of energy spectra with target thickness gives us a clue: use ultrathin targets





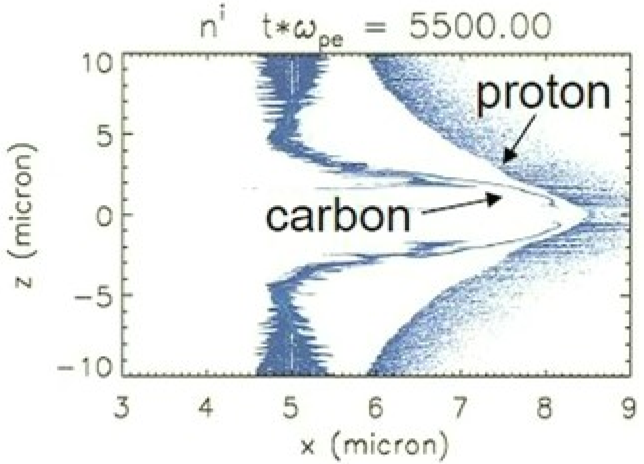


For 10s nm thickness
--> GeV C energy

mono-energetic C
200 -- 300 MeV
efficiency ~ few %

In situ self cleaning is a generic feature of the BOA

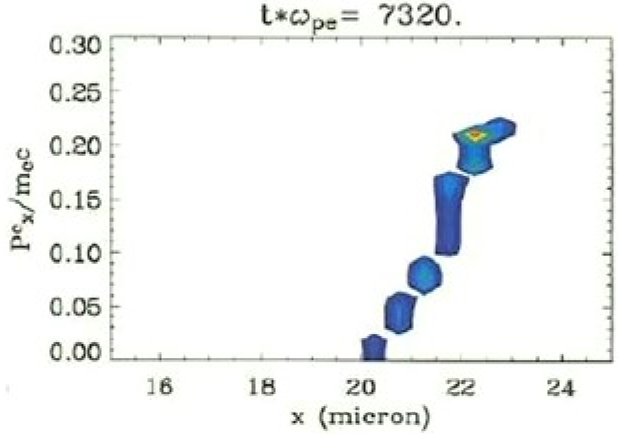
- During the early phases of the BOA, the protons accelerate ahead of the carbon layer.
- In late stages of the BOA, the **E** field increases and peaks at the bulk of the **carbon** ions, not the **protons**.
- Mono-energetic carbon feature is **more pronounced** and **persists longer** with protons present
- These results are verified in 2D VPIC simulations
- **Self-cleaning greatly simplifies the application of BOA ion beams to settings like fast ignition.**

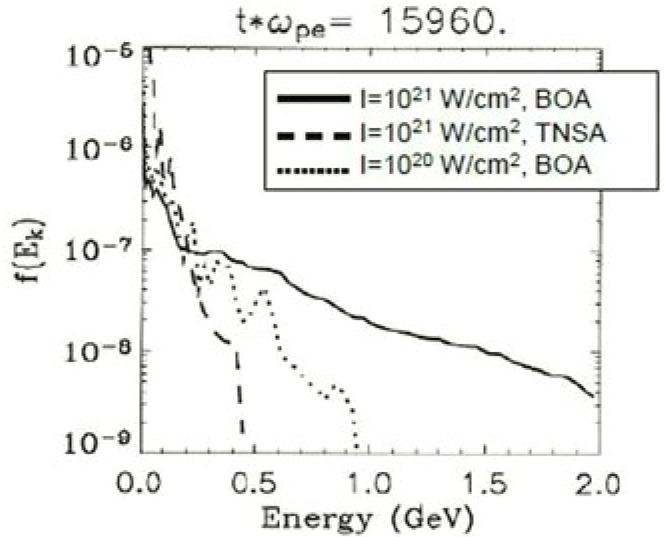


2D simulation of BOA with C target & proton layer

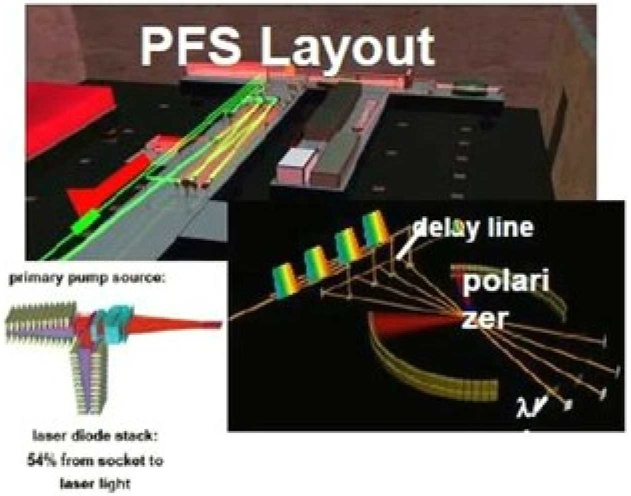
BOA mechanism shows promise of high efficiency (~5%) monoenergetic high-energy ion acceleration.

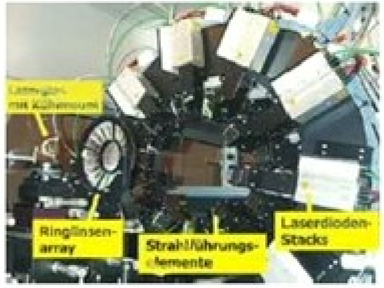
- Electrons transfer energy to ions via a kinetic Buneman instability and get reheated by the laser.
- Ion energy peaks about $0.22 M_C c^2$ » 300 MeV and comprises » 35% of the ions within the layer (FWHM 15%).
- 4% of the incident laser energy has been converted to the energy of the quasi-monoenergetic ion beam.
- If acceleration process is allowed to continue spectrum evolves into maxwellian with ion energies of greater than 2 GeV.





Advances in Laser Technology will address rep-rate / average power challenge





Multiple Projects world wide work on High-Average Power Lasers:

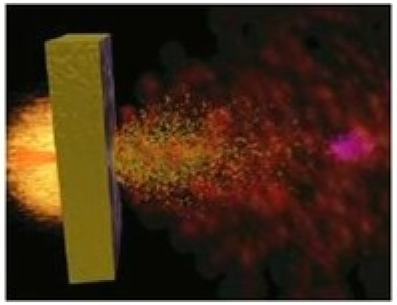
Mercury, US
HALNA, Japan
Polaris + PFS, Germany

- Replacing flashlamp pumping by diode pumping,
- improving cooling
- Overspecing the sytems
- KrF – Elektra (NRL)
- CO_2 (Oak Ridge)

•10 Hz, 100 J possible now

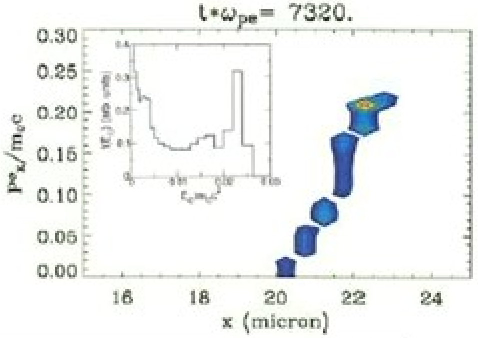
Summary

- Good progress in laser-accelerated ions:
  - Unique characteristics: pulse length, emittance, current, focus, …
  - Range of species: H, Be, C, O, F, Ni, S, Pd, Pt MeV/amu ion energies, up to 10^{13} ions per pulse2 High-Z (46), MeV/nucleon ions
  - Monoenergetic ions
  - Spectral shaping



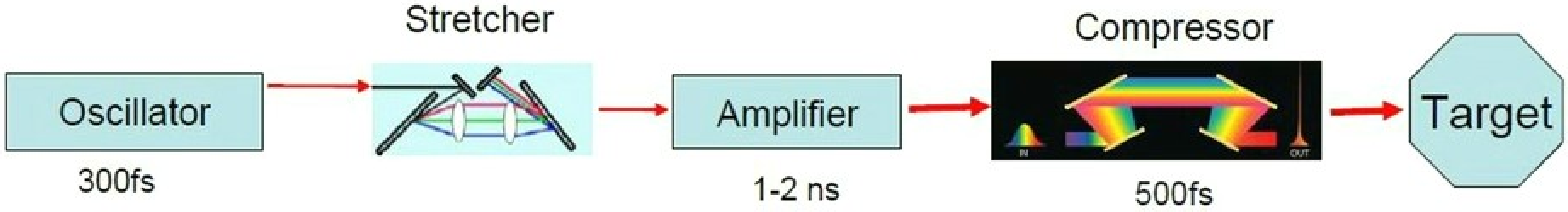
- A new ion acceleration mechanism, the laser break-out afterburner, has been discovered in VPIC simulations using ultrathin targets.
  - For petawatt-class lasers, the BOA markedly improves upon TNSA generation of monoenergetic beams (>10X the efficiency) as well as quasi-Boltzmann beams (>10X higher peak energy).
  - Higher ion energies: GeV
  - Higher efficiencies

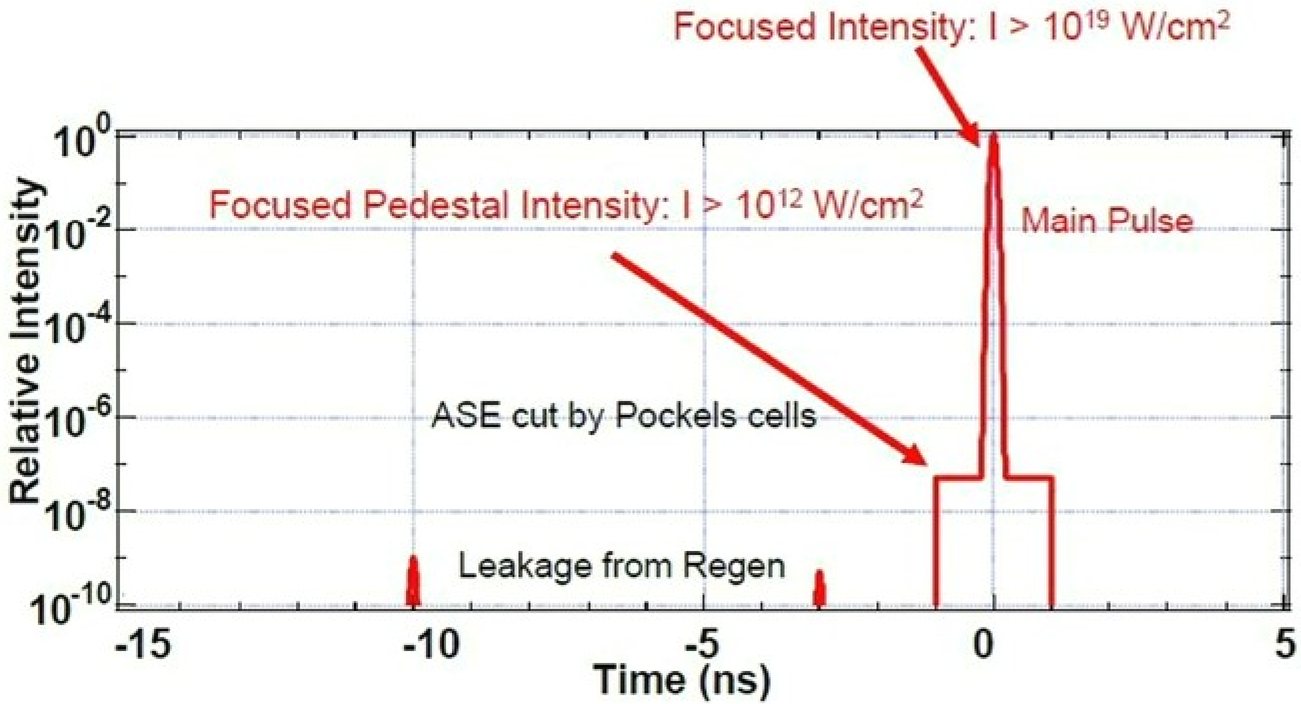
- New Laser Technology will enable higher repetition rates
  - 1 – 10 Hz possible today
  - kHz still research stage
  - Challenges for target mechanisms



[1] Hegelich et al., Nature 439, p441 (2006).
[2] Hegelich et al., Phys. Plasmas, 12, 056314 (2005).
[3] Yin et al., Phys. Plasmas 14, 056706, (2007)

Chirped Pulse Amplification and Contrast Issues:





At >10^{19} W/cm^2 peak power:

- Pedestal at >10^{12} W/cm^2
- i.e. pre-pulse strong enough to create plasma and launch shocks
- Ion acceleration requires unperturbed rear surface
- Shock-transit time limits minimal target thickness

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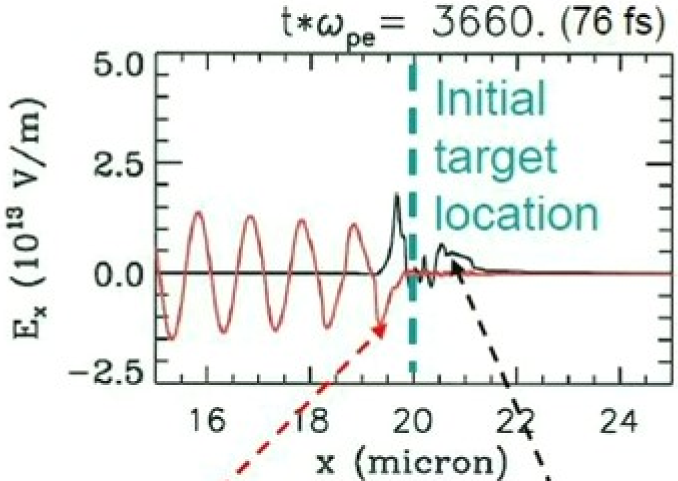
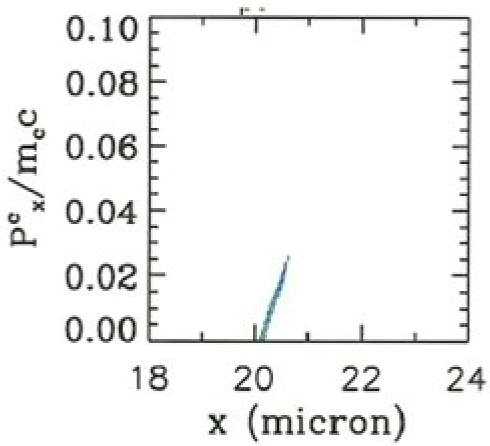
Thin targets support a new acceleration mechanism: the laser break-out afterburner (BOA)*

The BOA exhibits 3 stages:

I. Brief TNSA Phase



Modest Ion acceleration
~ 1 MeV

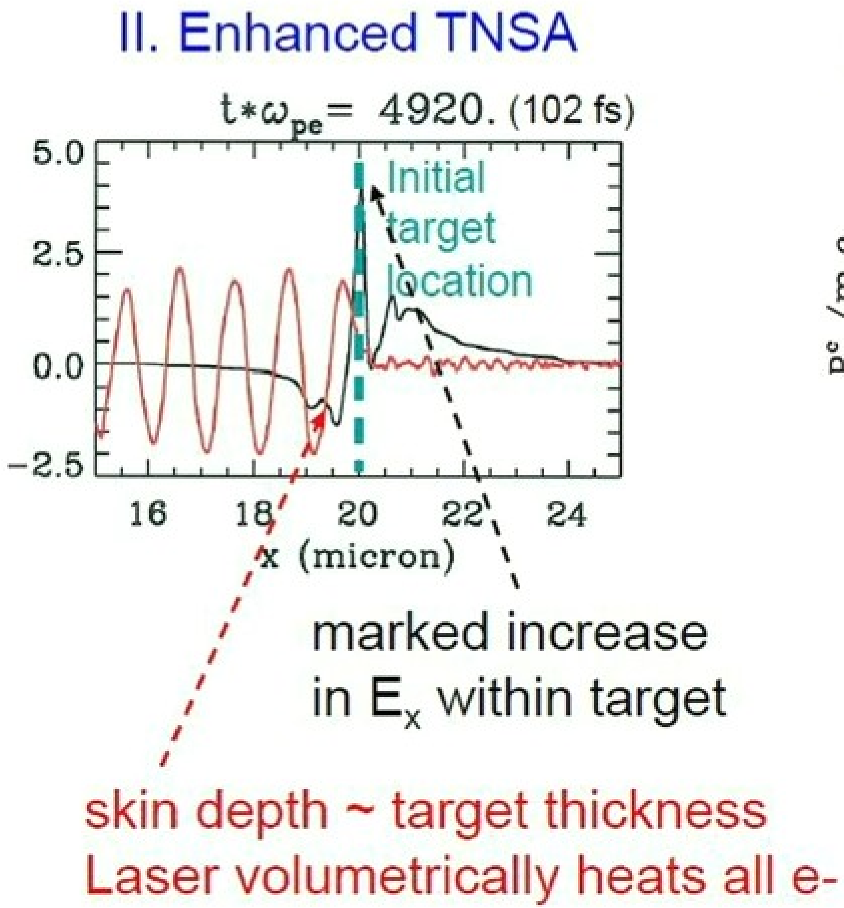


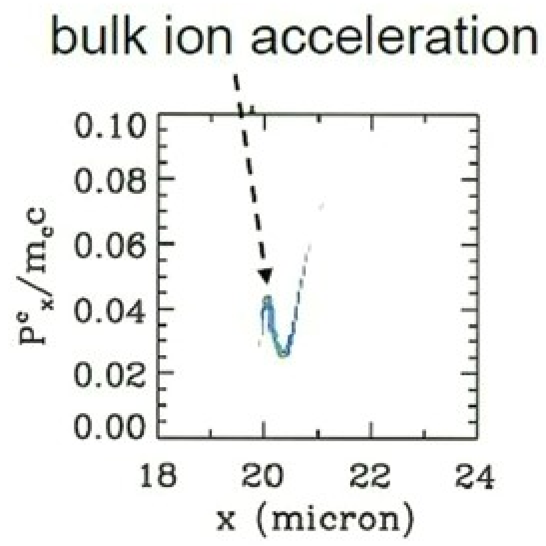
laser field limited to the front surface

sheath on the rear: heated e- that traverse the target

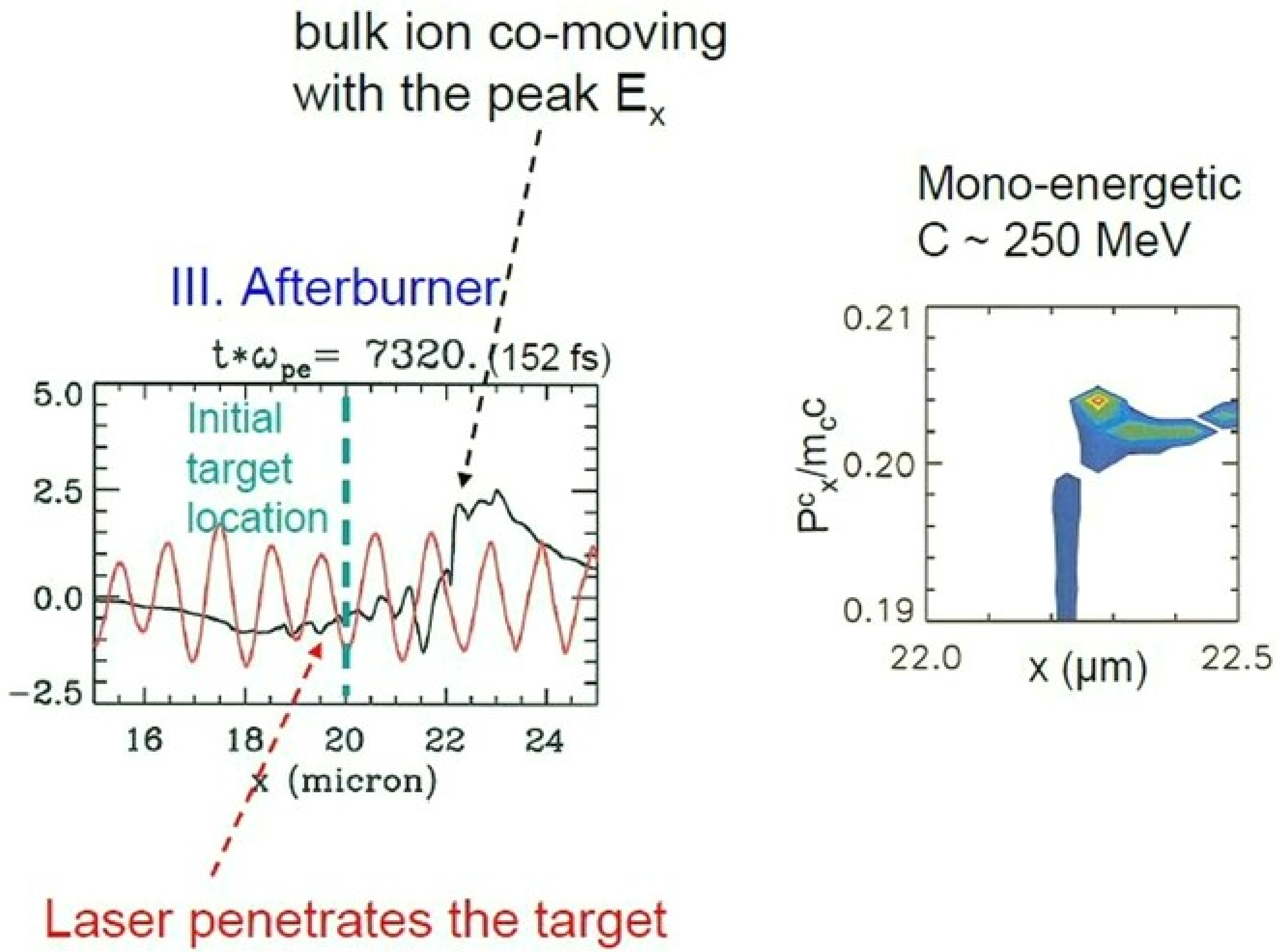
* Yin, et al., *Laser and Particle Beams* **24**, 2, 291-298 (2006)].

Second stage: Enhanced TNSA



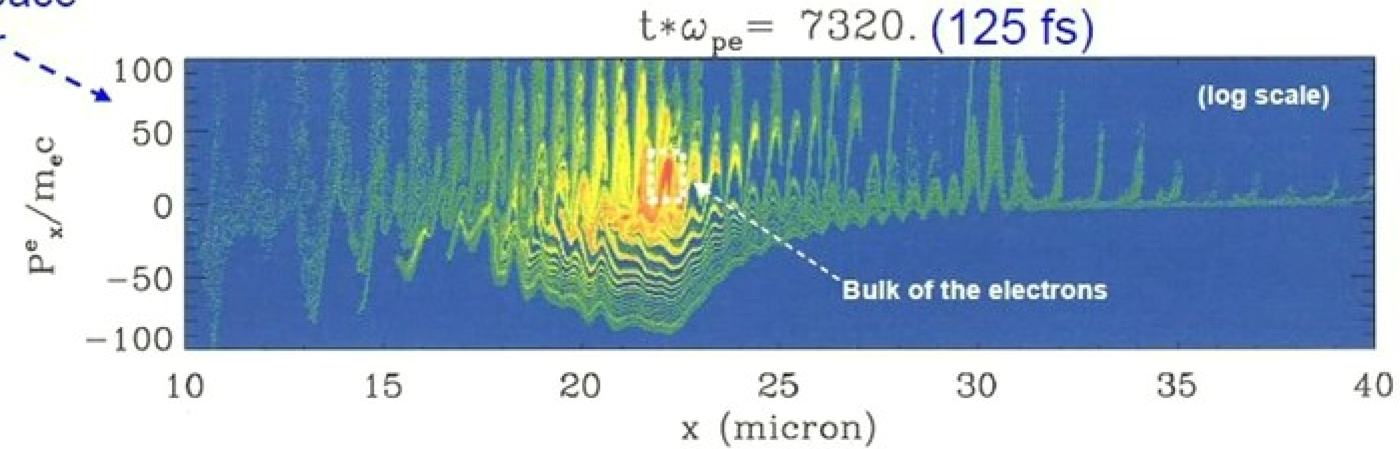


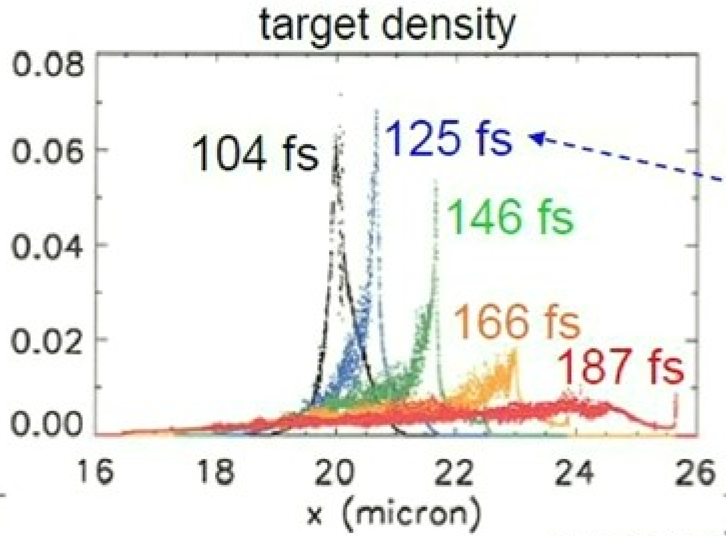
Third stage: The laser break-out afterburner (BOA)



Afterburner: Increased (relativistic) skin depth allows laser to penetrate the target

Electron phase space during afterburner



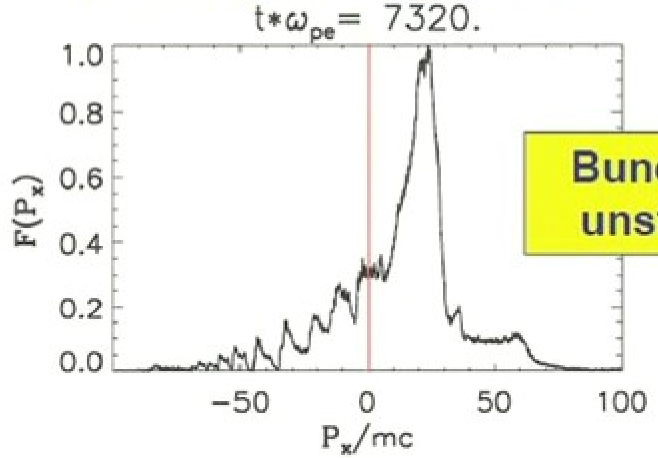


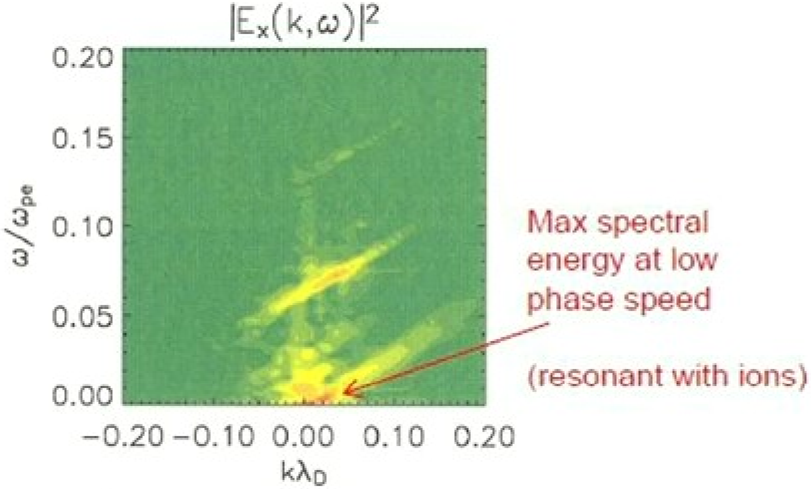
During afterburner laser penetrates target:

- target marginally overdense
- skin depth ~ target thickness at FWHM

The BOA produces a relativistic Buneman instability

Electron distribution function in x at peak of E_x field & bulk of C ions

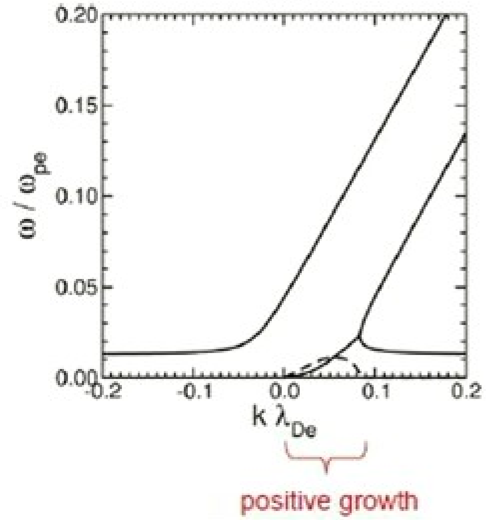




Relativistic Buneman instability dispersion relation*

- assumes cold, drifting e-, slowly drifting ions
- plasma parameters from simulation

$$1-\frac{\frac{\omega_{pe}^2}{\gamma_{e0}^3}\left(1+\frac{p_{e0y}^2}{m_e^2c^2}\right)}{\left(\omega-kv_{e0x}\right)^2}-\frac{\omega_{pi}^2}{\omega^2}=0$$

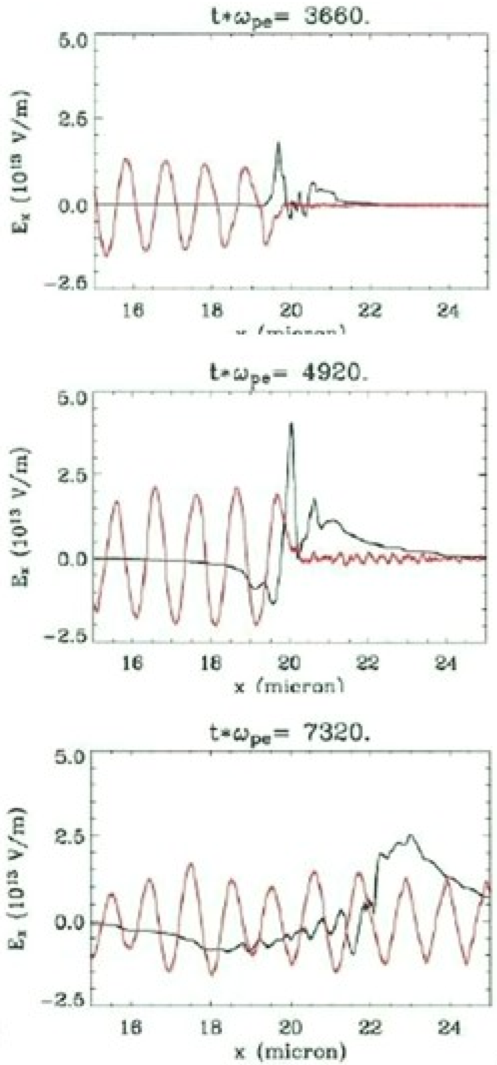


The Laser Break-Out Afterburner (BOA) ion acceleration mechanism [L. Yin et al., LPB, 24 (2006)]

- Standard TNSA: Only a small fraction of the available electrons is promoted to ‘hot’ by the laser and sets up the accelerating field: I=10^{21} W/cm^2 $\Rightarrow$ E ~ 8 TV/m.

- Enhanced TNSA: All electrons are promoted to ‘hot’: $\Rightarrow$ E ~ 15 TV/m. Skindepth increases.

- **Break-Out Afterburner (BOA):** The laser burns through the target and reheats the electrons to higher energies (afterburner): $\Rightarrow$ E ~ 30 TV/m. Electron transfer energy to ions by kinetic instability and get reheated by laser.

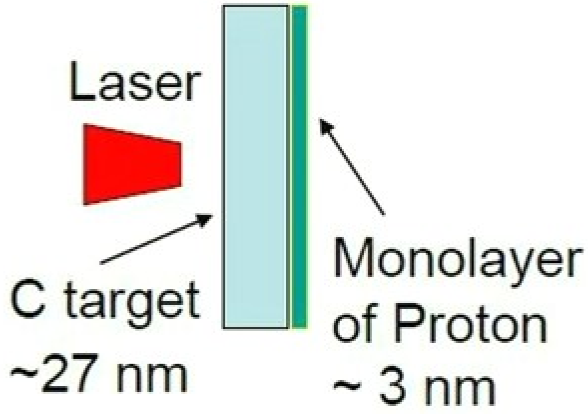


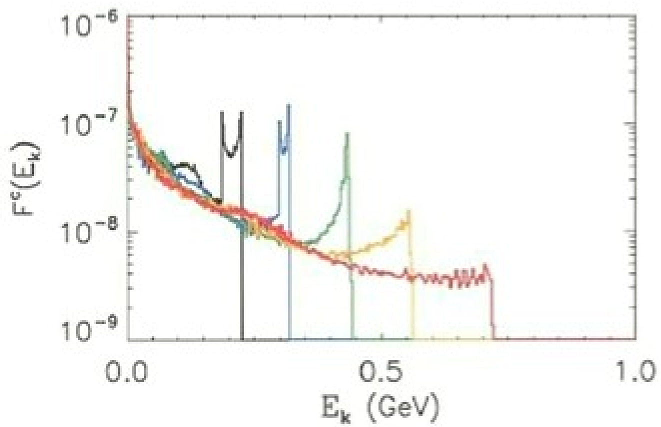
Experimental realization of BOA: need to revisit target cleaning

- With the advent of high-contrast-ratio short-pulse laser, use of 10s nm targets are possible.
- In mid- to high-Z TNSA, the targets are cleaned to remove impurities (protons: larger charge-to-mass ratio gains the most energy)
- With fragile, ultra-thin (10s of nm) targets, cleaning may be difficult or impractical.
- **How will low-Z contaminants affect the BOA process?**

BOA process still occurs with a carbon target with proton layer

- Protons are expelled during the early phases of the BOA
- In the afteburner phase, no protons are present near the target
- Beam retains monoenergetic features out to energy ~500 MeV

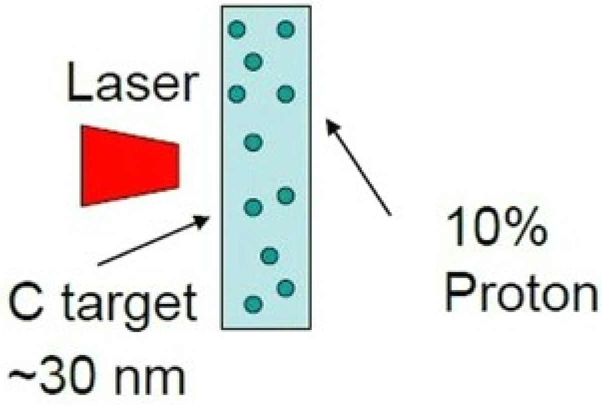


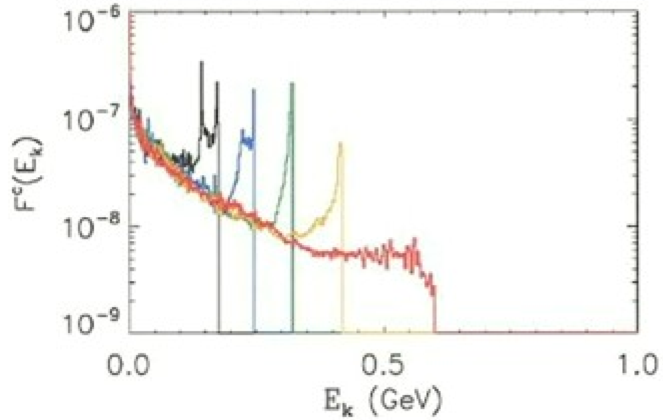


1D VPIC simulation of BOA with C target & proton layer

BOA process occurs even using a target of carbon ions embedded with protons

- Again, protons are expelled early
- Beam retains similar monoenergetic features out to energy ~500 MeV
- In both, the target <u>self-cleans</u>—no ancillary target cleaning required.





1D VPIC simulation of BOA with C target & embedded protons

Supplemental:
Summary of VPIC explicit PIC code:

- VPIC architect: Kevin Bowers.
- Currently maintained in LANL X-1-PTA by Brian Albright.
- Fully relativistic 3D charge-conserving PIC code.
- Particle push optimized for commodity architectures.
- Efficient use of hardware enables big problems; operates near theoretical limit of floating point subsystem.
- O(N) in-place sort to improve cache performance.
- Controls numerical errors (radiation damping, Marder pass for E, B divergence cleaning).
- Highly efficient FDTD Yee mesh field solve on superhexahedral domain decomposition.

Supplemental: VPIC performance numbers

- Test of single processor throughput: On ASC Lightning/Bolt, we get 9.7M particle pushes/sec/processor. This exceeds 90% of the theoretical limit of the floating point subsystem.
- Test of scaling of field solve: Measured >99.85% scaling on 512 processors on T-Division Linux cluster.
- Test of "real-world" performance on large problem: 3D LPI problem on dual-core segment of ASC Lightning/Bolt: 1008 processors, 5.75×10^8 cells, 1.8×10^{10} particles, sustained performance: ~1.4 Tflop/s.