# 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

# Colleagues and Collaborators

**K. A. Flippo, J. C. Fernández, D. C. Gautier, S. Letzring, F. Lopez, R. Johnson, T. Shimada**

*P-24, LANL*

**B. Albright, M. J. Schmitt, L. Yin**

*X-1-PTA, LANL*

**R. Perea, R. Schulze**

*MST-6/7, LANL*

**Jörg Schreiber, Andreas Henig**

*Department für Physik, Ludwig-Maximilians-Universität München*

*and Max-Planck-Institut für Quantenoptik, München, GERMANY*

**Marius Schollmeier, Knut Harres, Frank Nürnberger, Markus Roth**

*Darmstadt University of Technology, Institute of Nuclear Physics*

*GSI, Darmstadt, GERMANY*

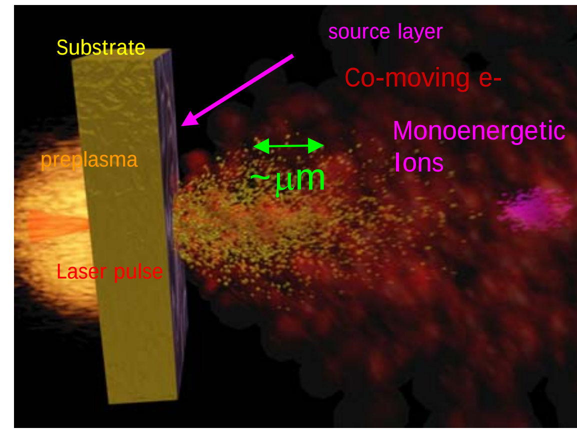
# Outline

- **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)

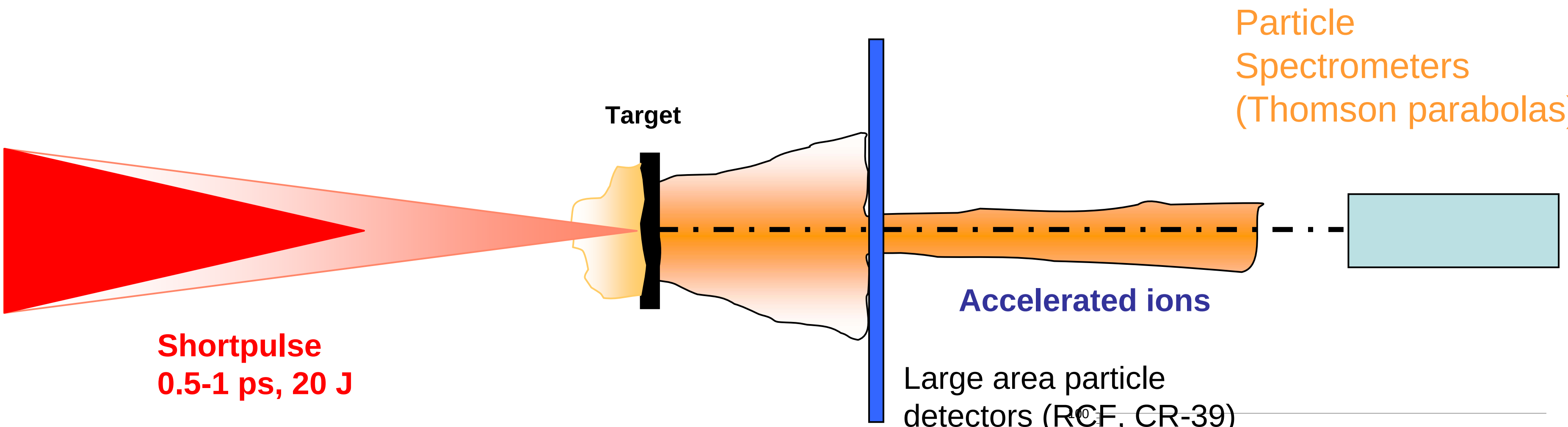
# Particle Acceleration

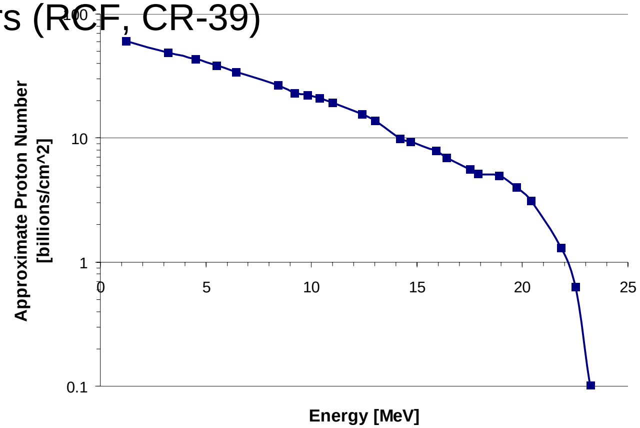
## Conventional particle accelerator (LANSCE ~km)

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




# Ultrahigh Intensity Lasers accelerate ions to MeV/nucleon energies:




B. M. Hegelich,
hegelich@lanl.gov

# 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)

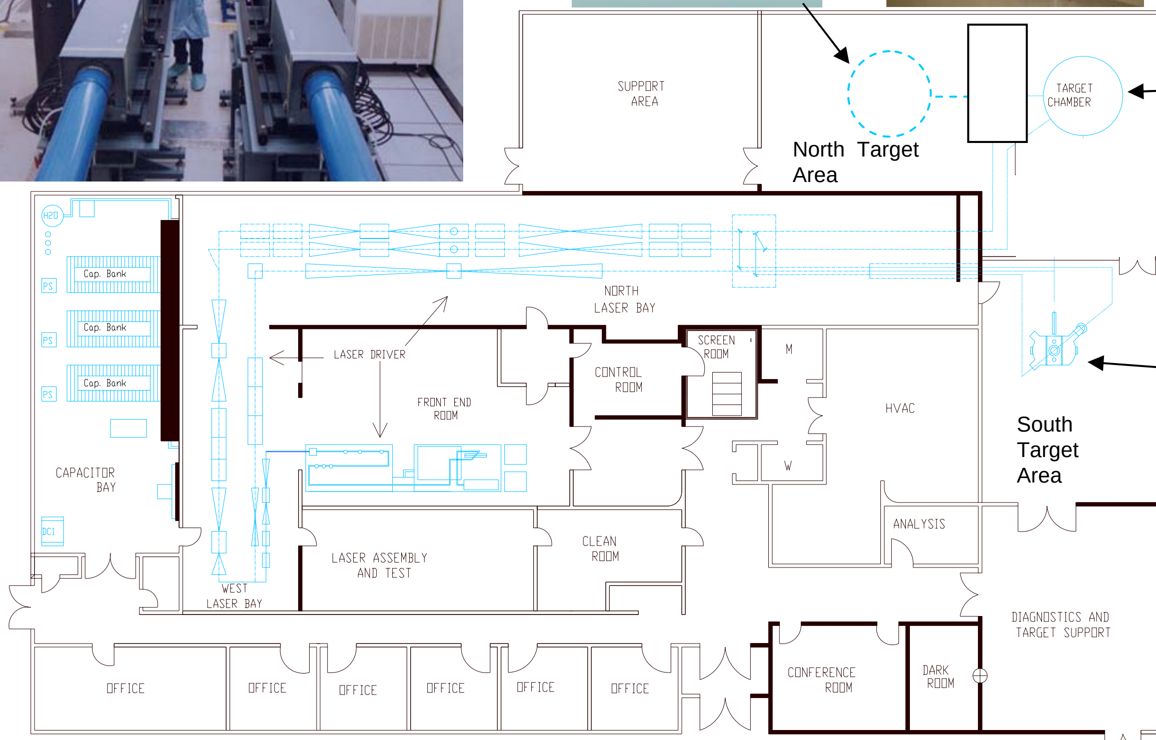
---

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

# 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)

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



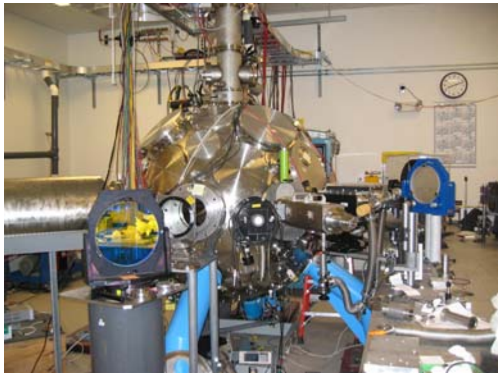

- 3 Beams (2 long, 1 short), 2 (3) target areas:
- Longpulse:
- 2 longpulse arms with 200J (green) each, 100ps – 6ms

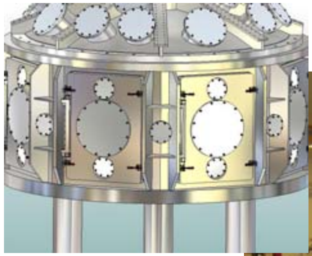
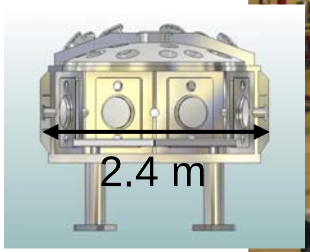
# The LANL Trident Shortpulse Laser Facility: a 30TW Glass laser system (is being upgraded to 250 TW)

Shortpulse

- Energy: 20J (150J) on target
- Pulse duration: 750 (500) fs
- Focus: <14 μm diameter
- Intensity: >2x10$^{19}$ (2x10$^{20}$) W/cm$^2$
- Prepulse: <10$^{-7}$ @ 1ns
  <10$^{-10}$ @ 5ps
- Repetition rate: 1 shot / 45 min.

**DOE Milestone of >100TW in target chamber passed**


B. M. Hegelich,
hegelich@lanl.gov

# The Trident Shortpulse Laser is being upgraded:

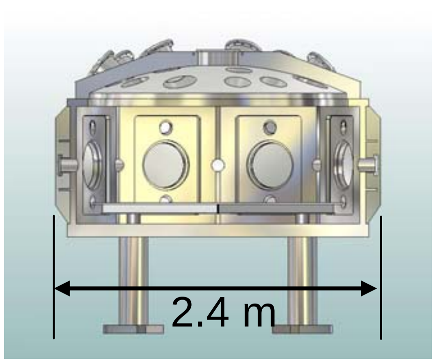
Enhancement:

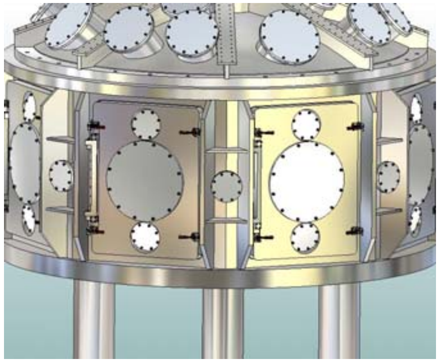
- Energy: 150J on target
- Pulse duration: 500 fs
- Focus: <14 $\mu$m diameter
- Intensity: >$2\times10^{20}$ W/cm$^2$

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**

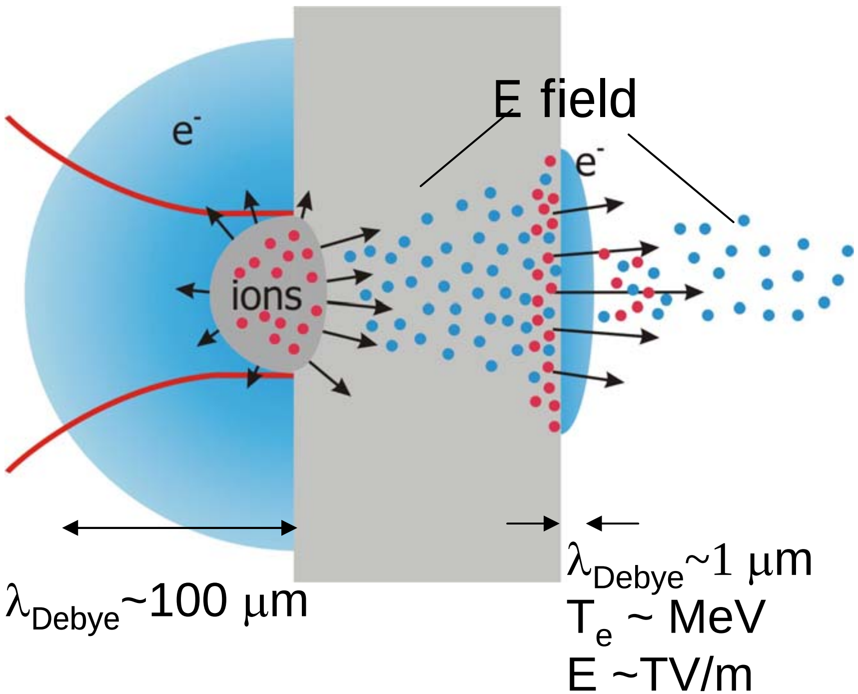



# Outline

- **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)

# 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:

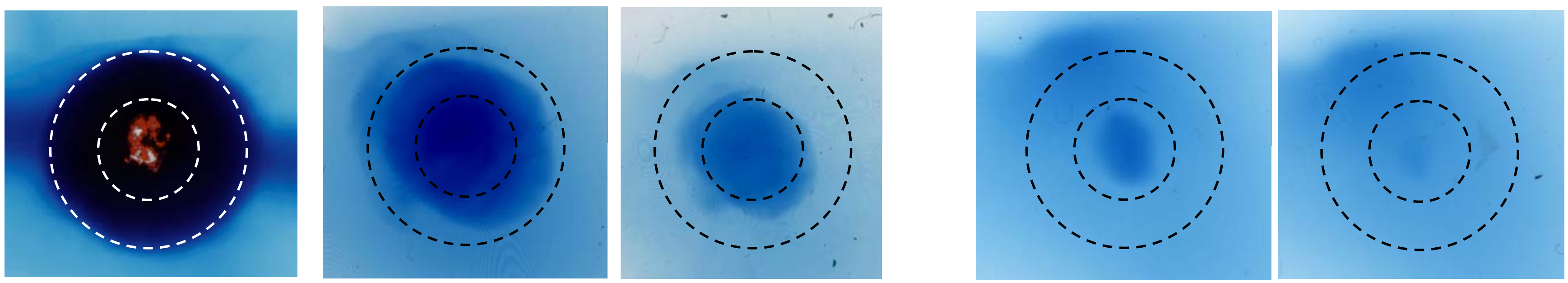
- Highest Charge-to-Mass ratio is dominantly accelerated and screens the accelerating fields:
  - ⇒ Protons from $H_2O$ + hydrocarbons get most of the energy
  - – chemical impurities
  - – Target cleaning required for Z > 1 (e.g. heating, ablation, ...)
- High beam currents (kA – MA)
- Excellent emittance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



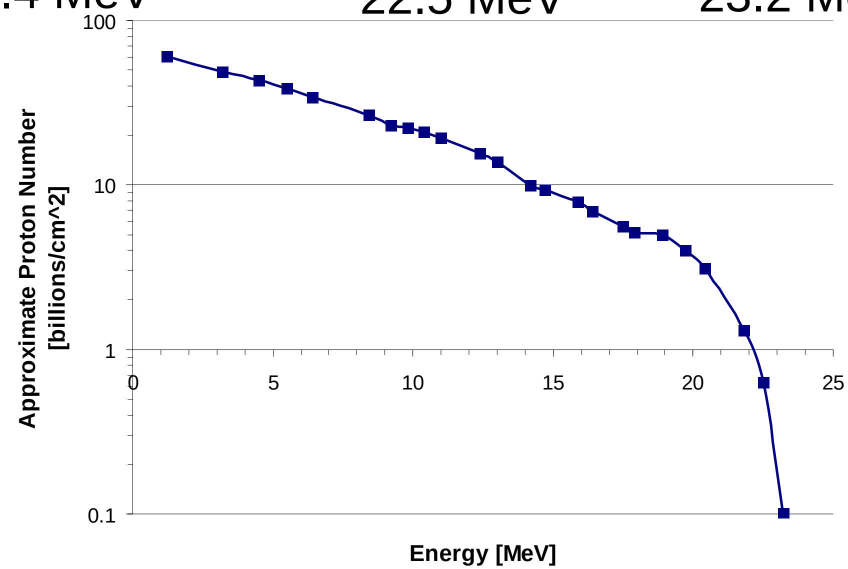
B. M. Hegelich,
hegelich@lanl.gov

# Flat Metal Foil Targets yield ~25 MeV protons for typical Trident conditions: $I=1\text{-}2\times10^{19}$ W/cm$^2$, E=20 J, $\Delta\tau$ =700 fs

HD RCF MD RCF

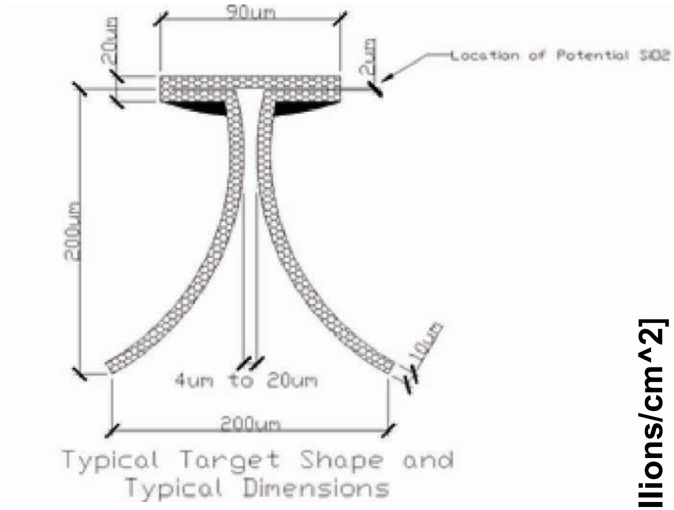


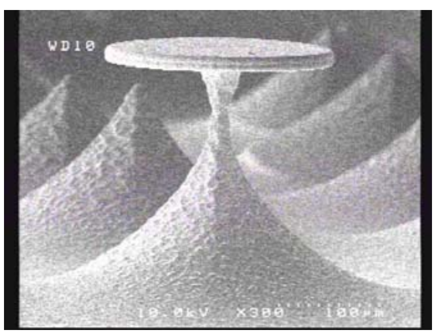
Bragg Peak Energy=
1.2 MeV 13.5 MeV 16.4 MeV 22.5 MeV 23.2 MeV



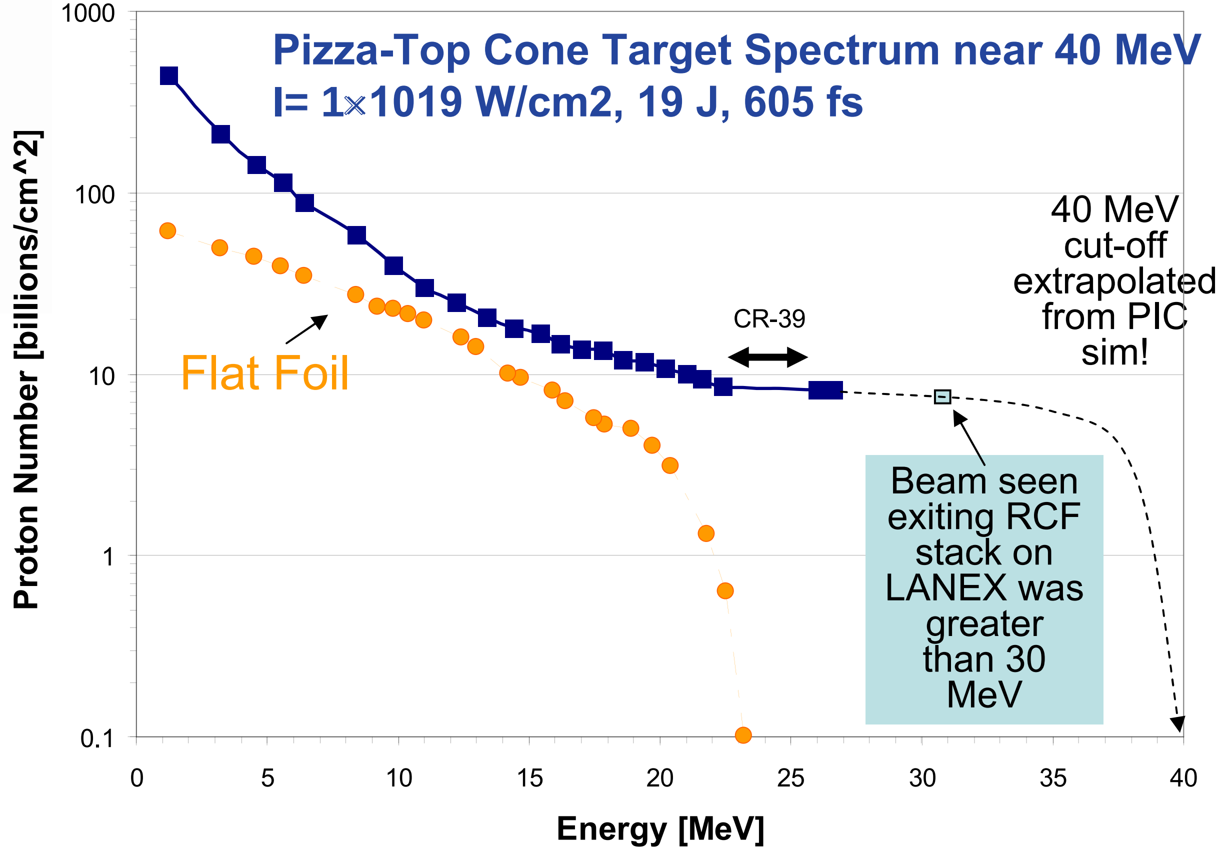

**published scaling laws predict ~10 MeV**

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




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

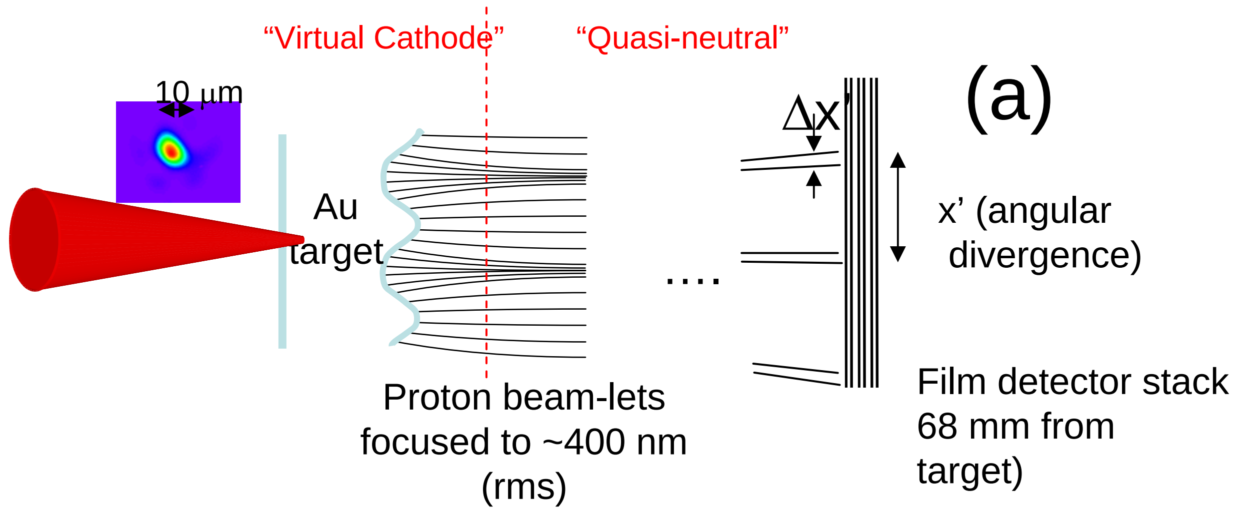


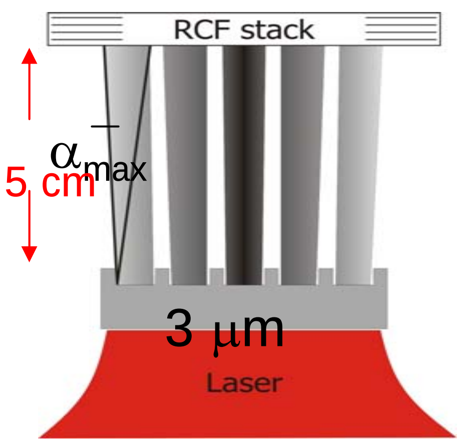

B. M. Hegelich,
hegelich@lanl.gov

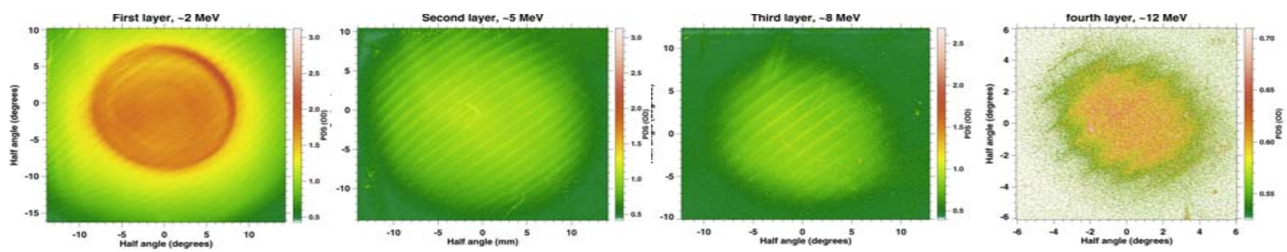
# Outline

- **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)

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



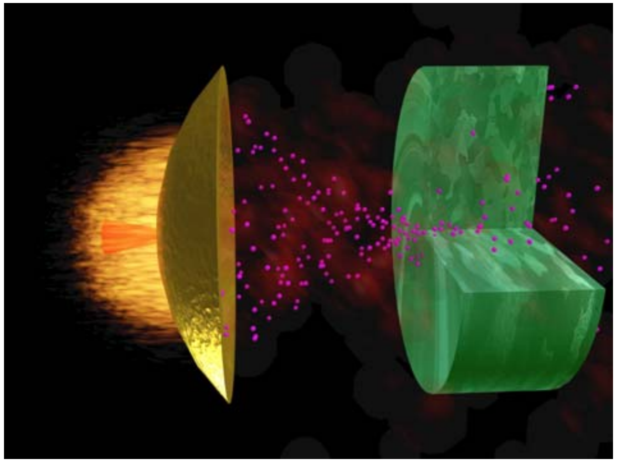

Record low-emittance:

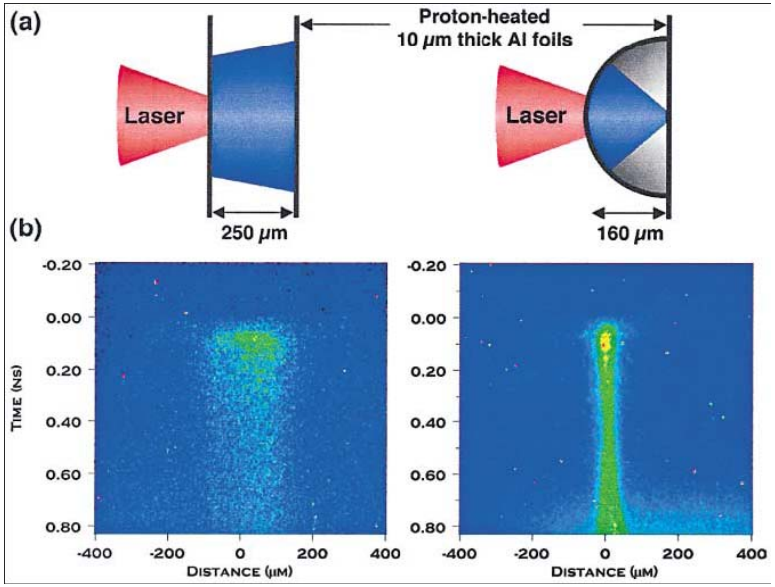
$\varepsilon_{N,rms} = \beta\gamma\ \sigma_x\ \sigma_{x'} < 0.002\ \pi$ mm-mrad

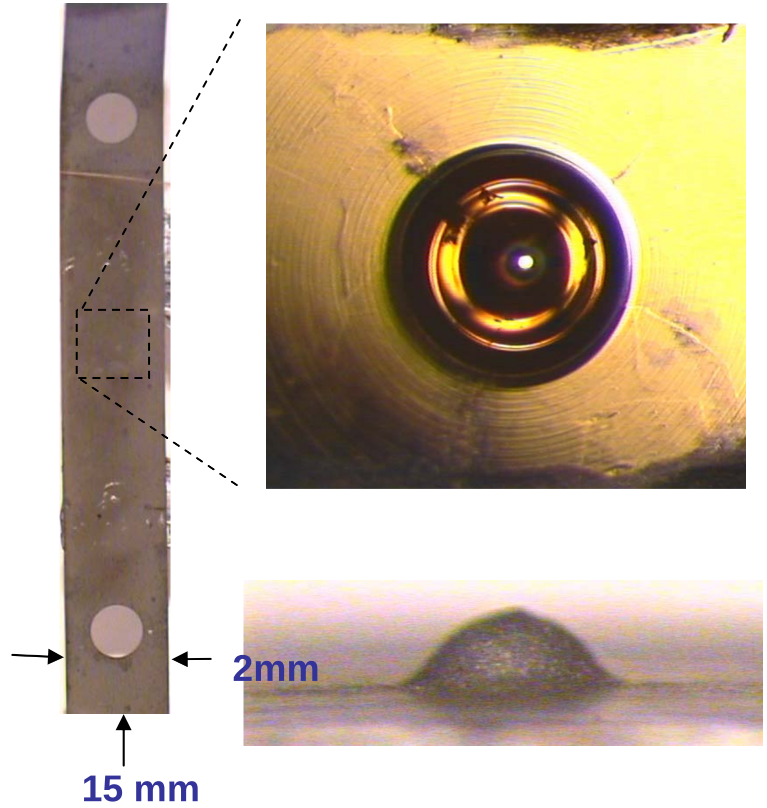
(typ RF linac: ~0.5 $\pi$ mm-mrad)

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

# Ballistic Ion Beam focusing using shaped targets

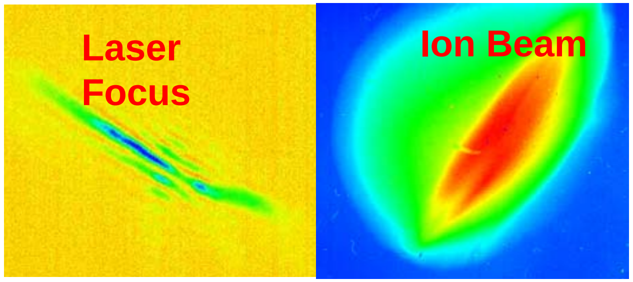




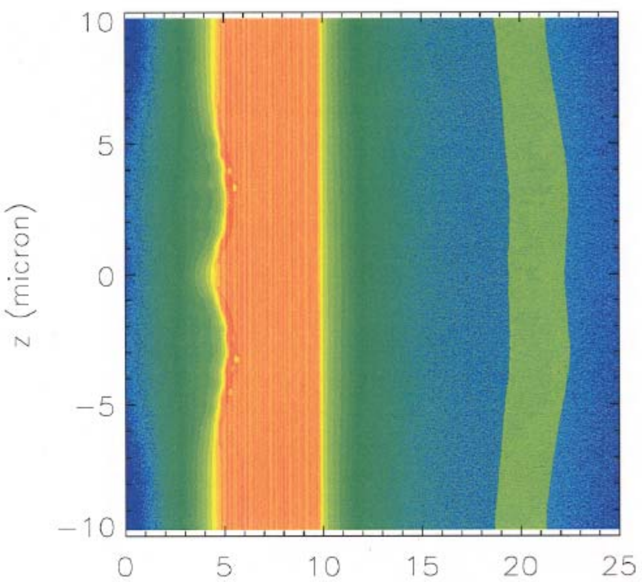




LLNL, Patel et al., PRL 91 (2003)

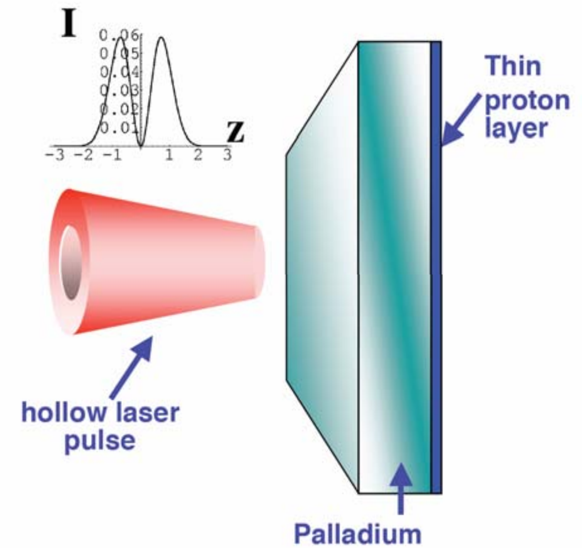
# Experimental observation of laser imprinting into ion beam suggests ion beam focusing using shaped laser beams:

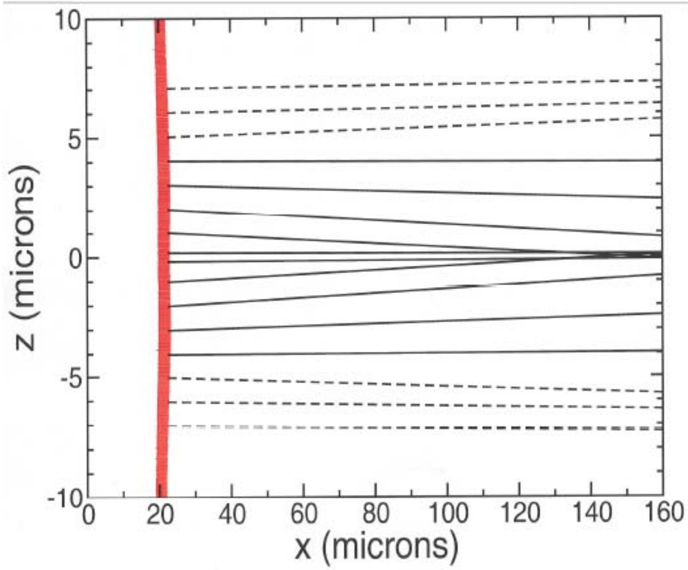



**Ion Beam shape**




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



# 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)

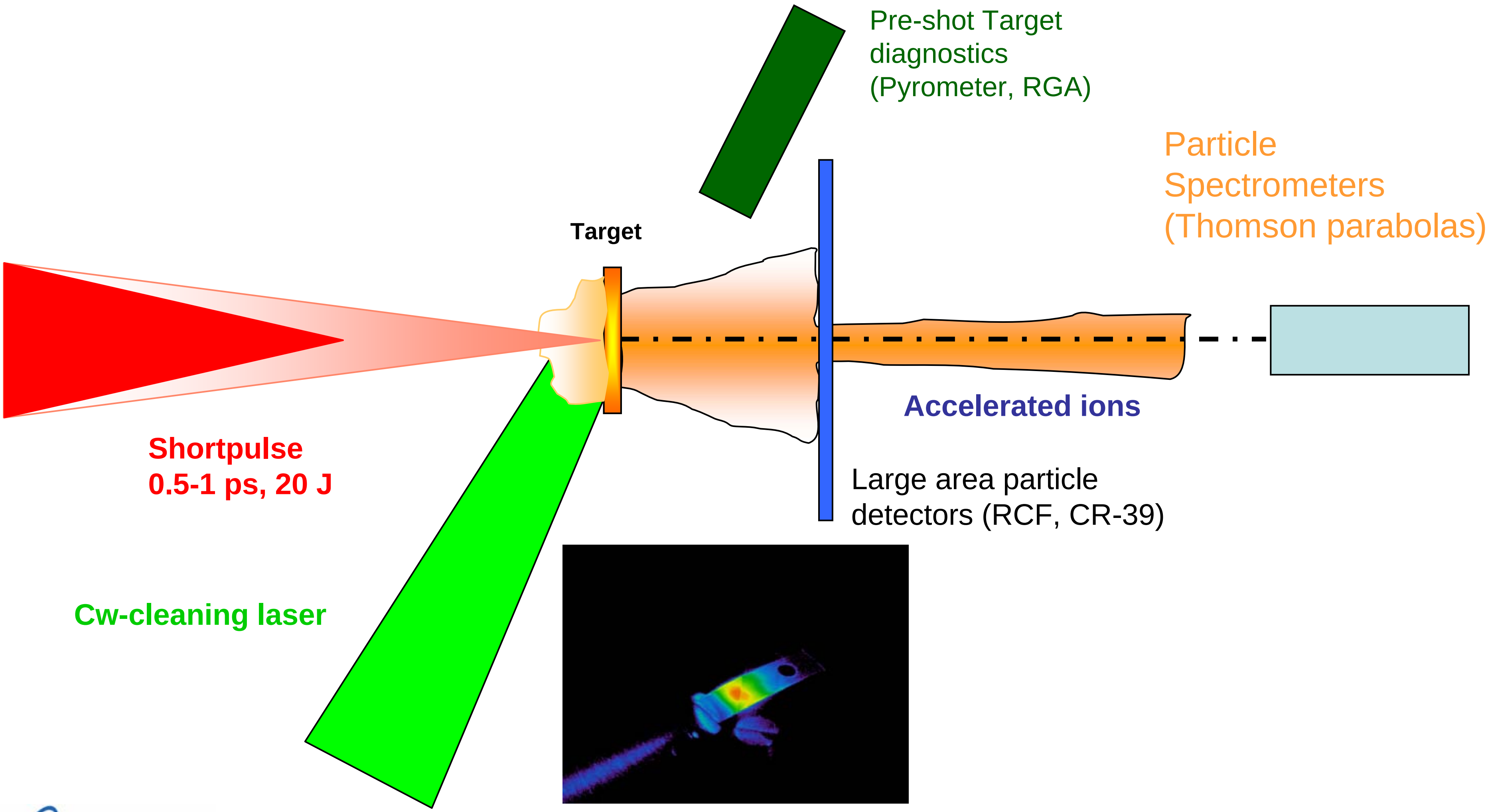
# Control of the ion species on the target surface is important to achieve heavy ion acceleration

Possible contaminants include water vapor, hydrocarbons & metal oxides

- E.g. Pd foil (no oxide, but excellent H getter):
  - 3.8 x $10^{16}$ O atoms/$cm^2$ (from 7.6 MeV He++ ions)
  - 2.4 x $10^{16}$ C atoms/$cm^2$ (5.6 MeV ions): ~ 30 Å @ 2 g/cc
  - 4.5 x $10^{16}$ 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


B. M. Hegelich, hegelich@lanl.gov

# Experimental setup and diagnostics



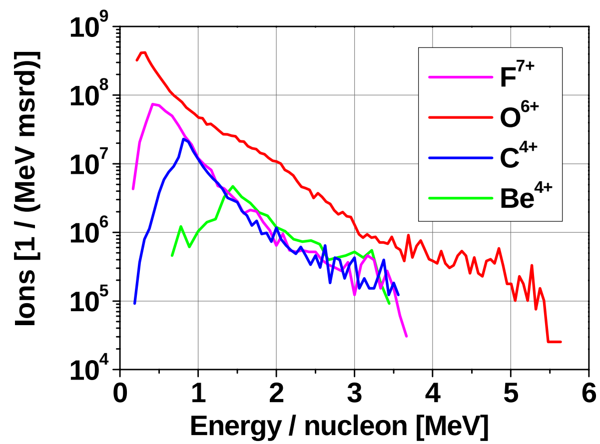
# Laser ion acceleration has been demonstrated from protons (Z=1) up to palladium (Z=46).

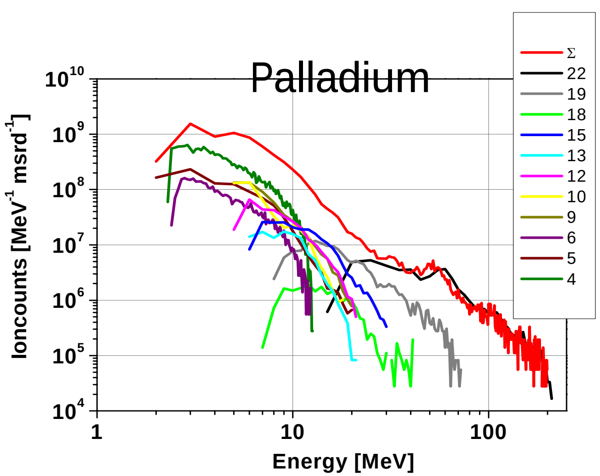
Light ions (Z ≤ 10) with E ≤ 5 MeV/u.
Hegelich et al. PRL 89 (2002).

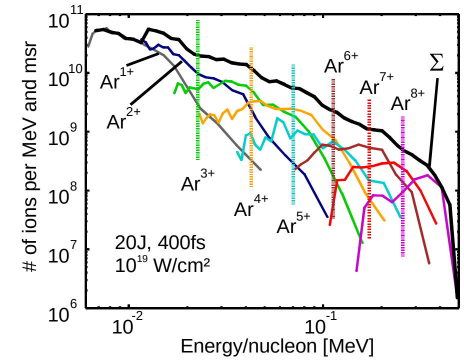
Mid-Z ions (10 ≤ Z ≤ 46) with E ≥ 2 MeV/u.
Hegelich, M. *et al.*, Phys. Plasmas, **12**, 056314 (2005).

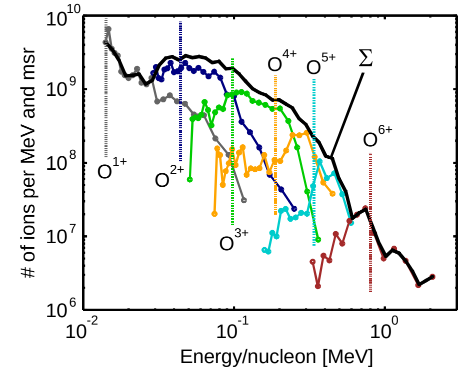
Trident Enhancement will enable heavy ions (Au, Pt, U)

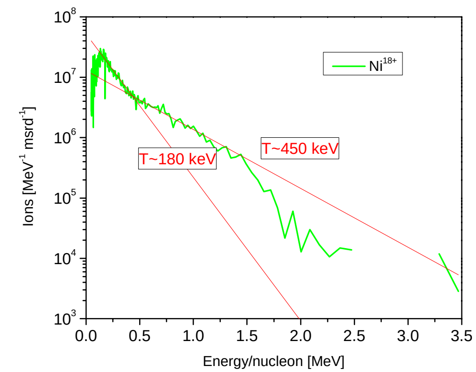
The conversion efficiency for laser energy into heavier of any charge state is on the order of a few % for Trident class lasers, as is the CE for protons.



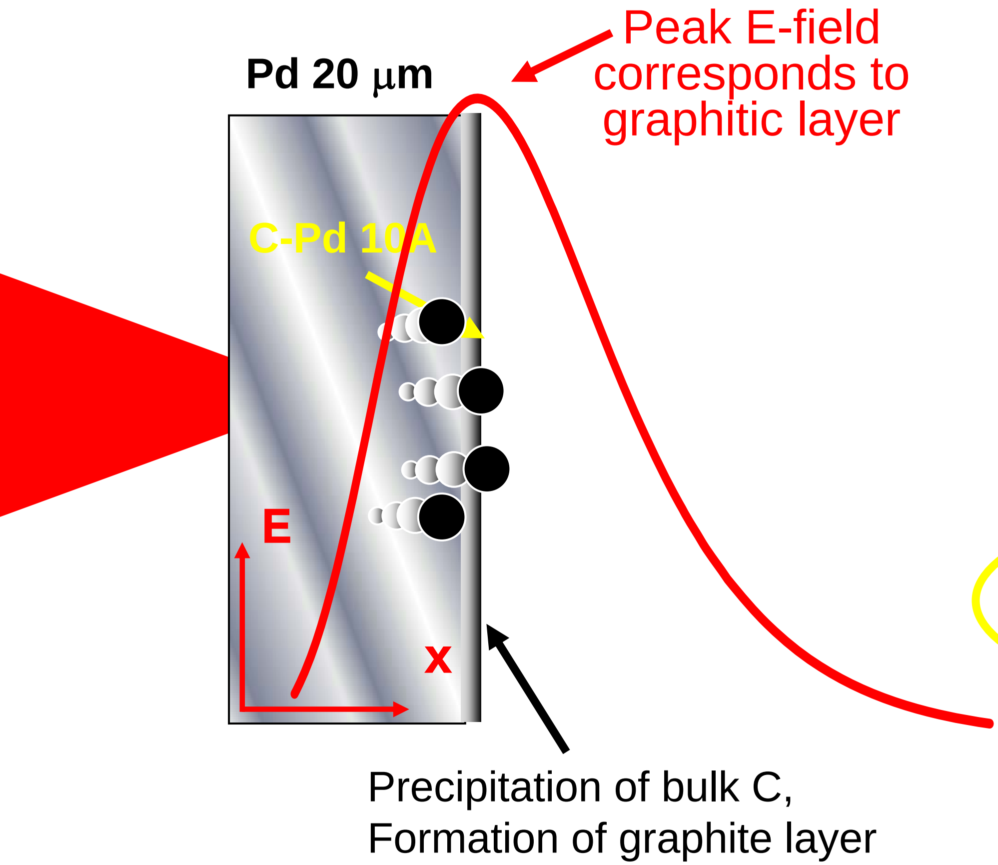



# Palladium can act as a catalysts for a phase transition of the adhered carbon contaminants, merging into a highly ordered, thin layer

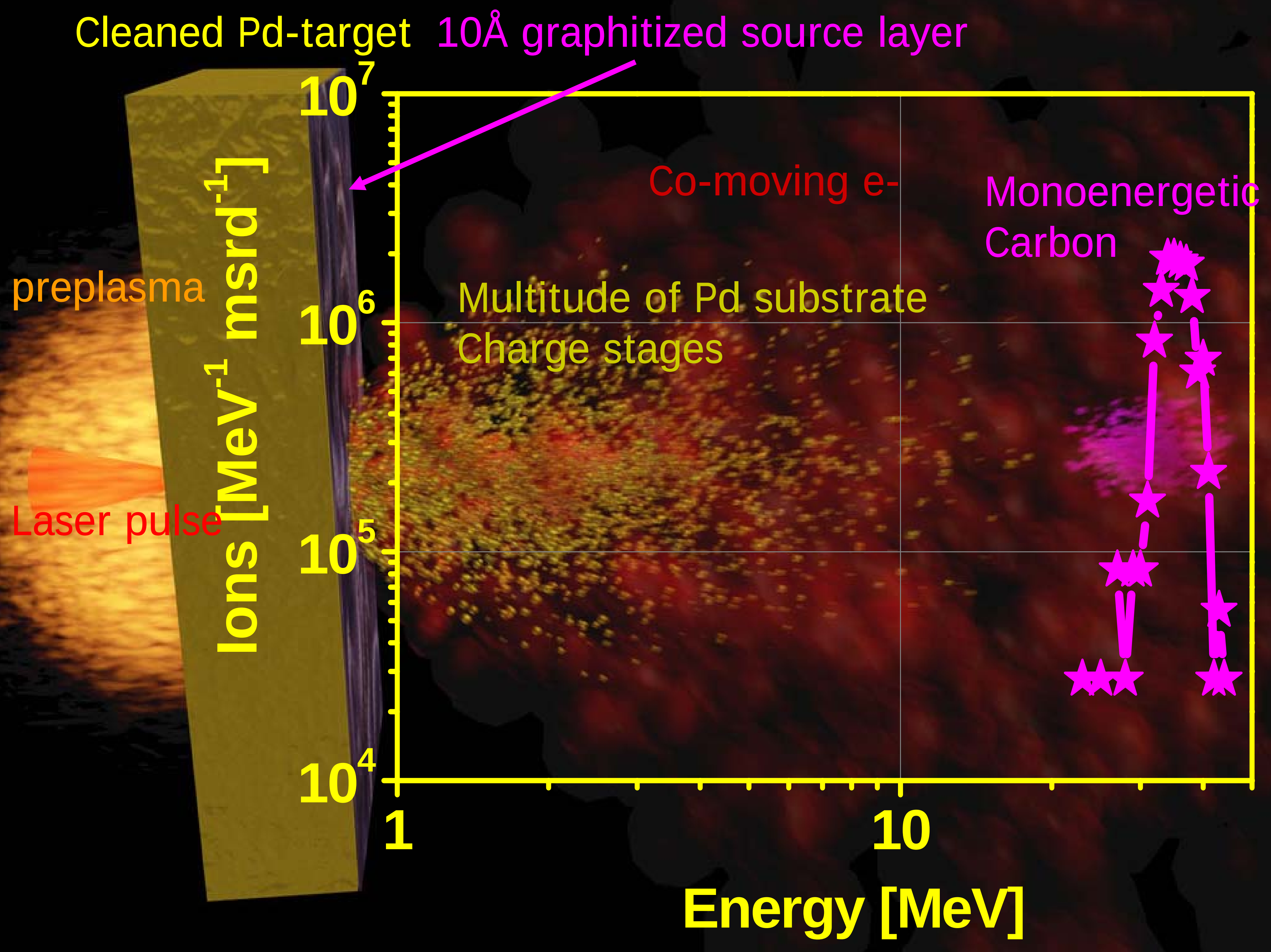



Heating of Pd:
T < 300 °C:
$C_xH_y$ and H species on surface

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

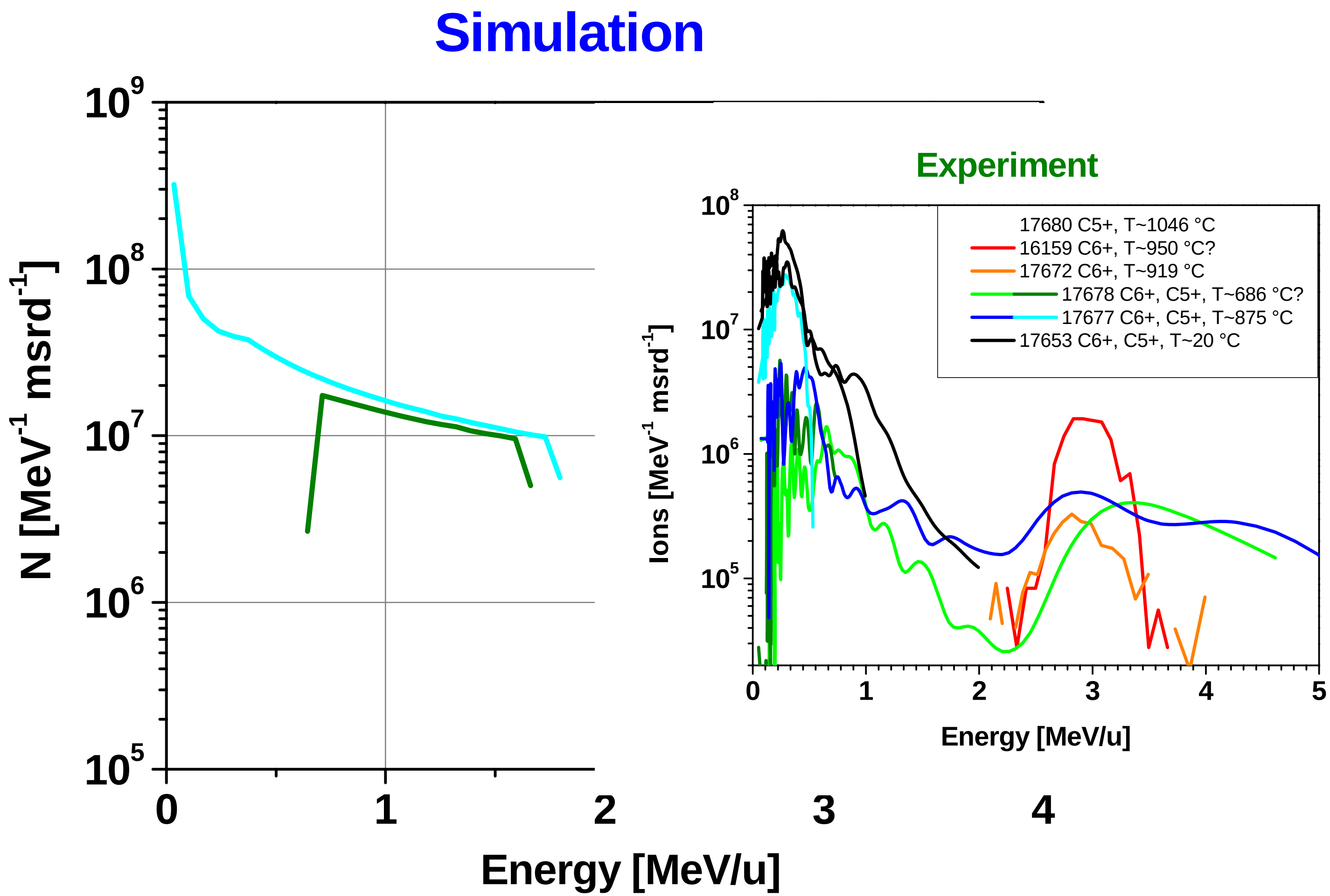
T > 750 °C:
Graphitization of surface

T > 950 °C:
Clean Pd surface



Cleaned Pd-target
10Å graphitized source layer
Co-moving e-
Monoenergetic
Carbon
preplasma
Multitude of Pd substrate
Charge stages
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.



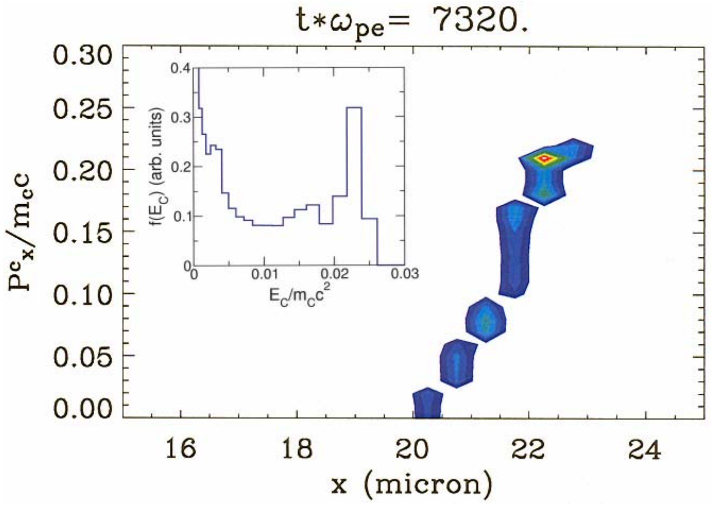


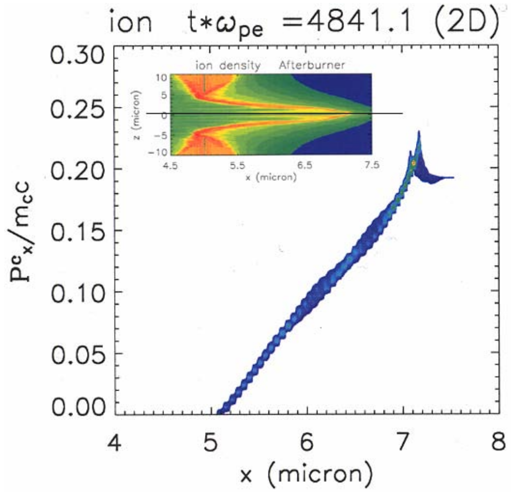

B. M. Hegelich,
hegelich@lanl.gov

# 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).

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



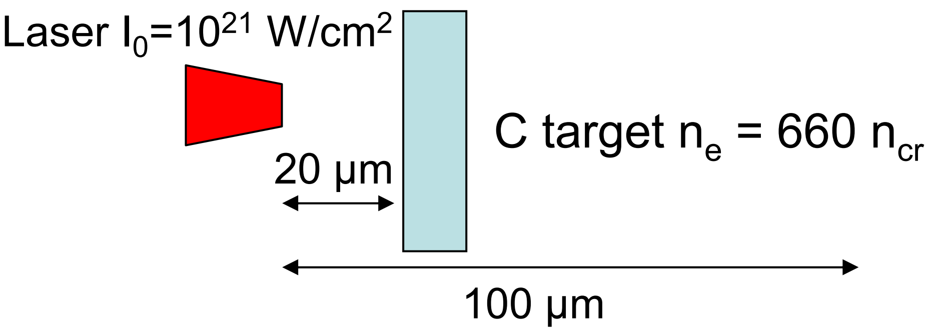



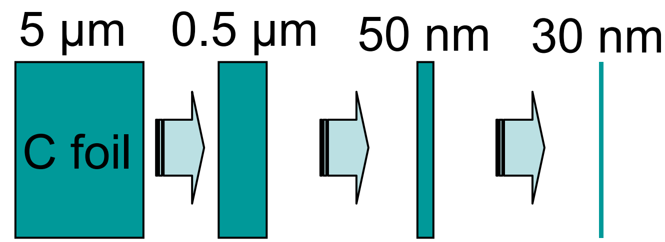

LANL simulations showing the new Break-Out Afterburner (BOA) mechanism. BOA has the potential to boost the ion energy and the acceleration efficiency by more than 2 orders of magnitude (GeV, >10%), enabling cheap, ultracompact accelerators which can be used e.g. for tumor therapy or compact plasma/field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

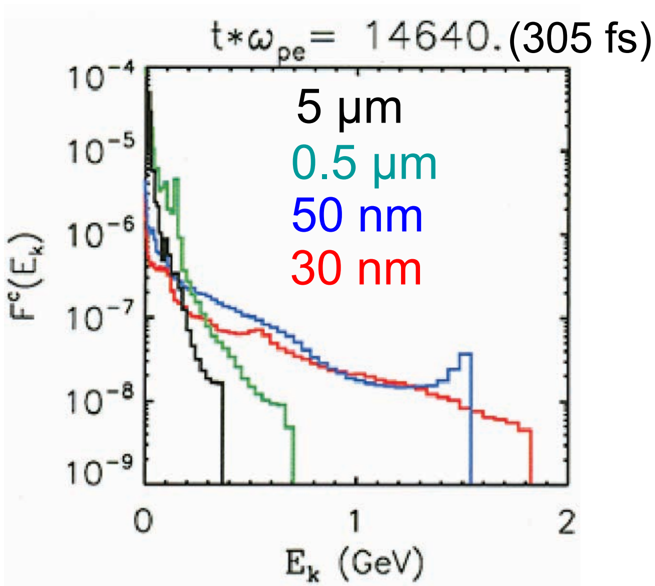

**Monoenergetic and GeV ion acceleration from the laser break-outafterburner using ultrathin targets**
L. Yin, B. J. Albright, B. M. Hegelich, K. J. Bowersz, K. A. Flippo, T. J. T. Kwan, and J. C. Fernández
**Phys. Plasmas, (May 2007), accepted for publication**

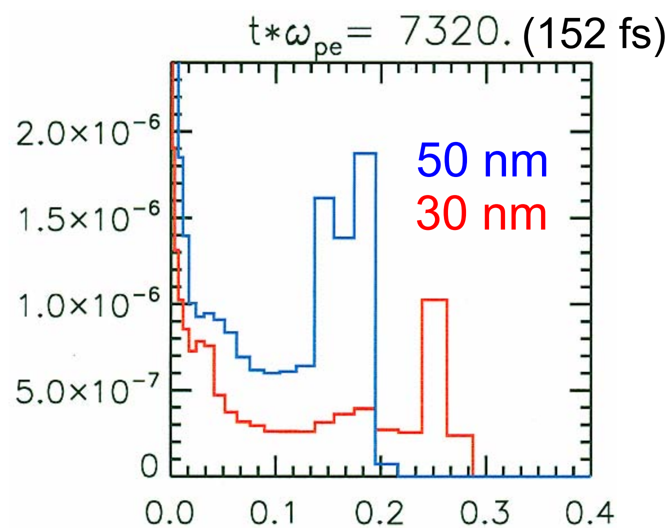
**GeV laser ion acceleration from ultrathin targets: The laser break-out afterburner**
L. Yin, B. J. Albright, B. M. Hegelich, and J. C. Fernández
**Laser and Particle Beams 24 (2006), 1–8**

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



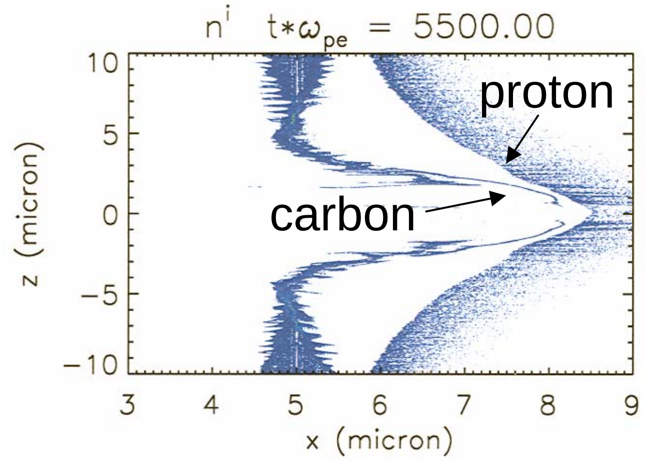




For 10s nm thickness
--> GeV C energy

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

# *In situ* self cleaning is a generic feature of the BOA

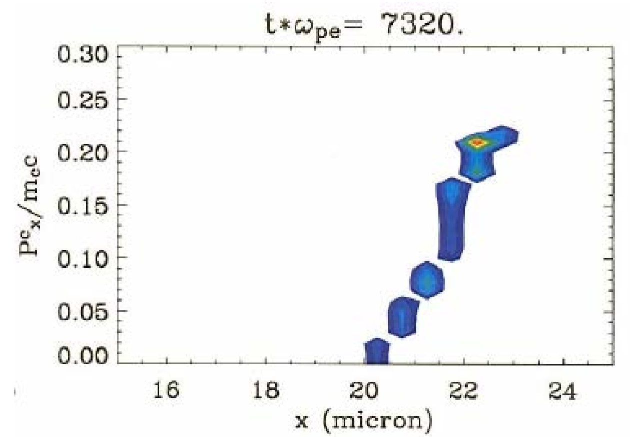
- During the early phases of the BOA, the protons accelerate ahead of the carbon layer.
- In late stages of the BOA, the E field increases and peaks at the bulk of the **carbon** ions, not the **protons**.
- Mono-energetic carbon feature is **more pronounced** and **persists longer** with protons present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

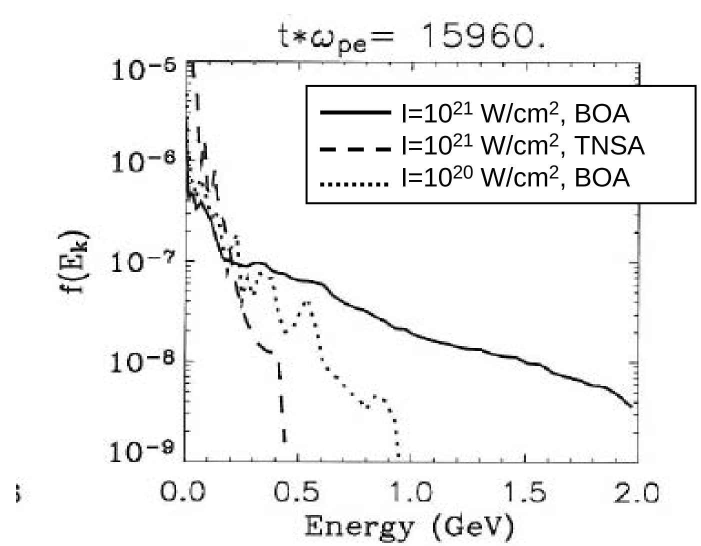



**2D simulation of BOA with C target & proton layer**

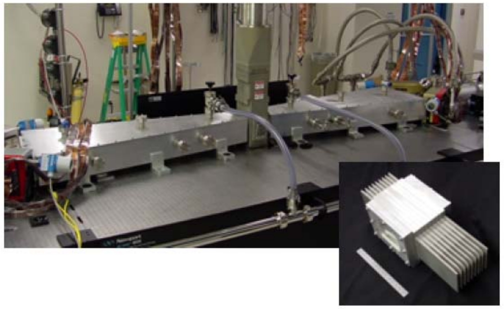
# BOA mechanism shows promise of high efficiency (~5%) monoenergetic high-energy ion acceleration.

- Electrons transfer energy to ions via a kinetic Buneman instability and get reheated by the laser.
- Ion energy peaks about $0.22M_Cc^2$ » 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.



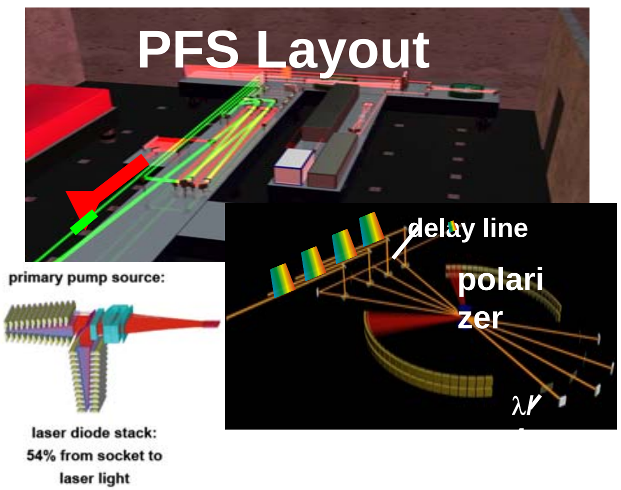



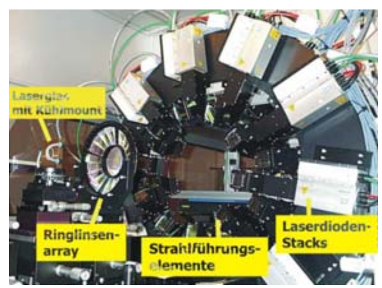
# Advances in Laser Technology will address rep-rate / average power challenge

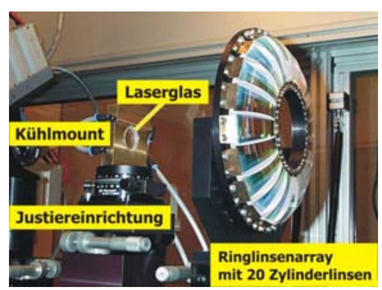


Multiple Projects world wide work on High-Average Power Lasers:

Mercury, US
HALNA, Japan
Polaris + PFS, Germany



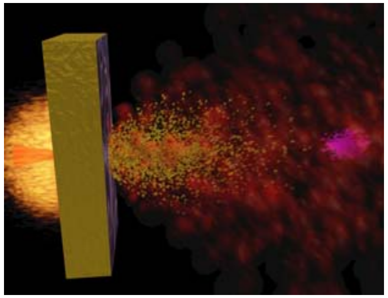




- Replacing flashlamp pumping by diode pumping,
- improving cooling
- Overspecing the sytems
- KrF – Elektra (NRL)
- $CO_2$ (Oak Ridge)

•10 Hz, 100 J possible now

# Summary

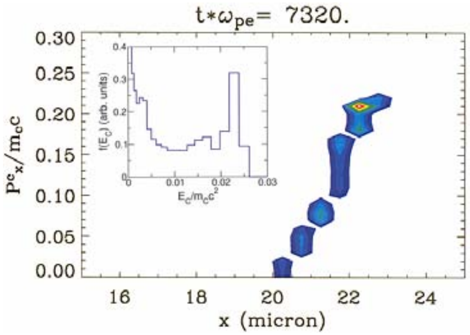
- Good progress in laser-accelerated ions:
  - Unique characteristics: pulse length, emittance, current, focus, …
  - Range of species: H, Be, C, O, F, Ni, S, Pd, Pt MeV/amu ion energies, up to $10^{13}$ ions per pulse2 High-Z (46), MeV/nucleon ions
  - Monoenergetic ions
  - Spectral shaping
- A new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




nature

LETTERS

Laser acceleration of quasi-monoenergetic MeV ion beams



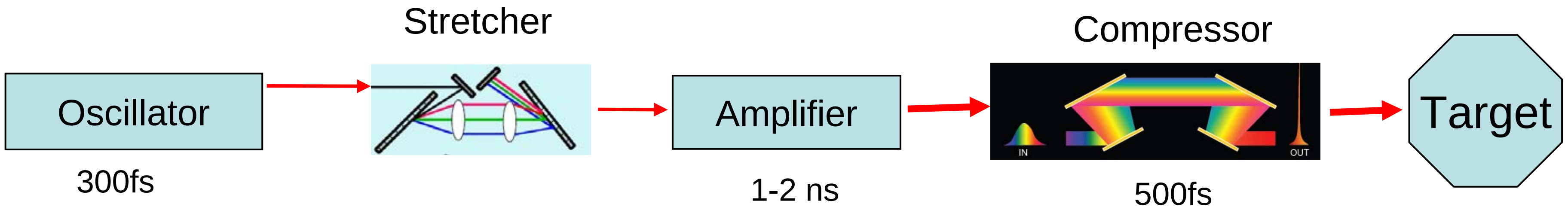

[1] Hegelich et al., Nature 439, p441 (2006).
[2] Hegelich et al., Phys. Plasmas, 12, 056314 (2005).
[3] Yin et al., Phys. Plasmas 14, 056706, (2007)

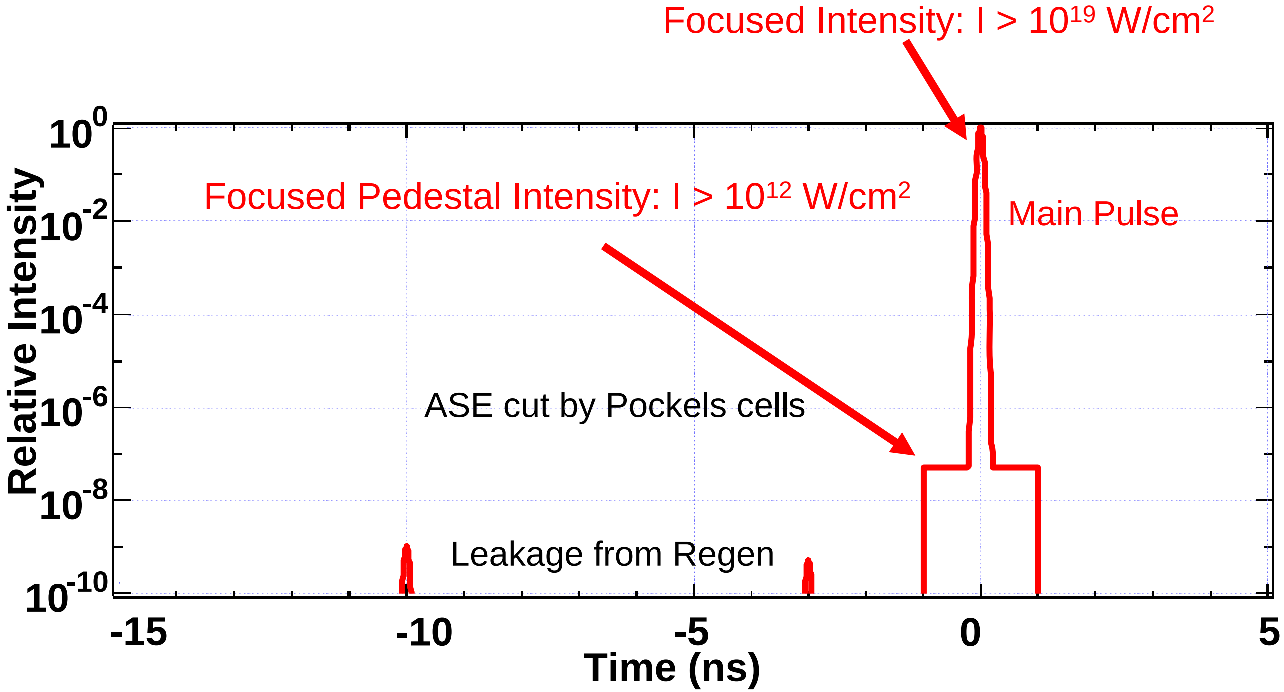
# Thank you for your attention!

# BOA backup slides


B. M. Hegelich,
hegelich@lanl.gov

# Chirped Pulse Amplification and Contrast Issues:



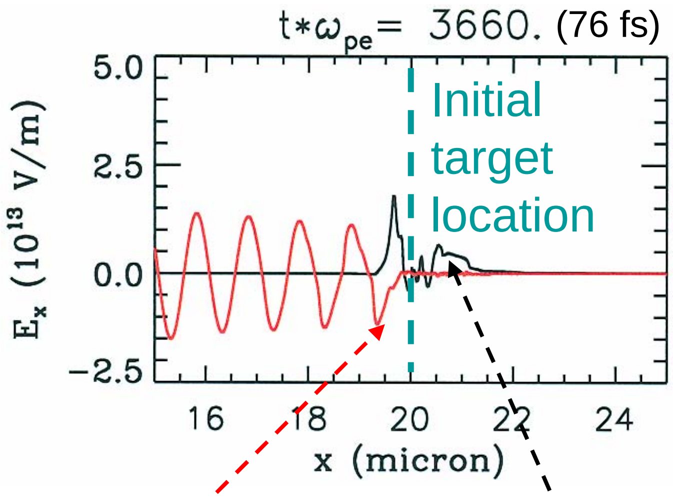

At $>10^{19}$ W/cm$^2$ peak power:

- 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

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

## The BOA exhibits 3 stages:

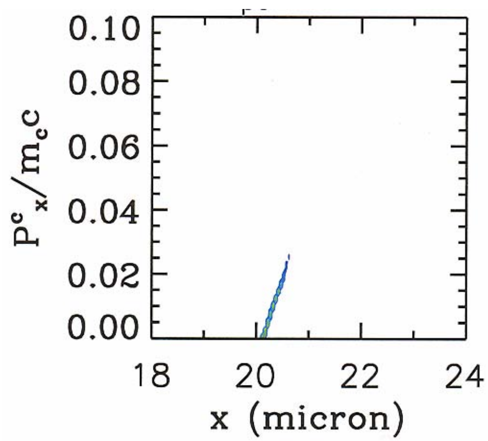
I. Brief TNSA Phase




laser field limited to the front surface

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

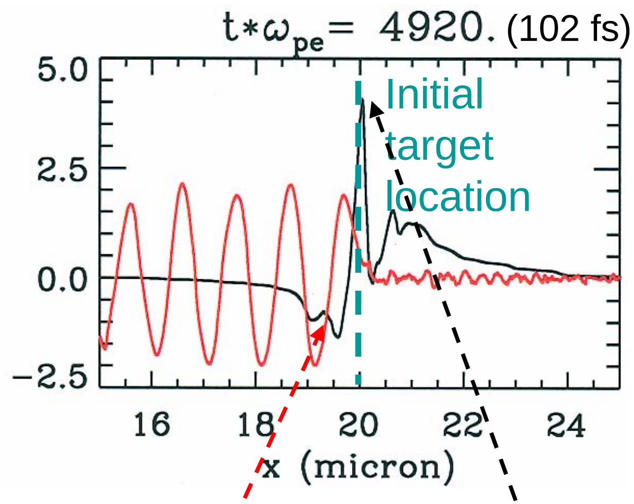
Modest Ion acceleration ~ 1 MeV



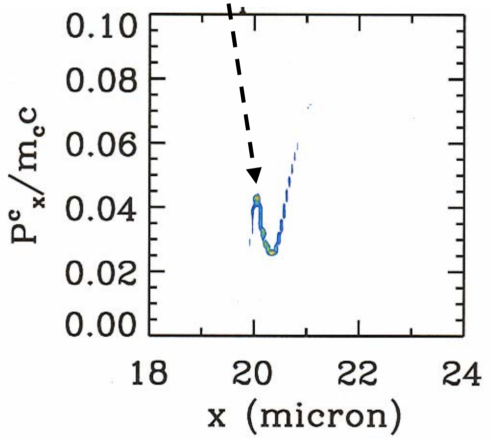

* Yin, et al., *Laser and Particle Beams* **24**, 2, 291-298 (2006)].

# Second stage: Enhanced TNSA

II. Enhanced TNSA




bulk ion acceleration



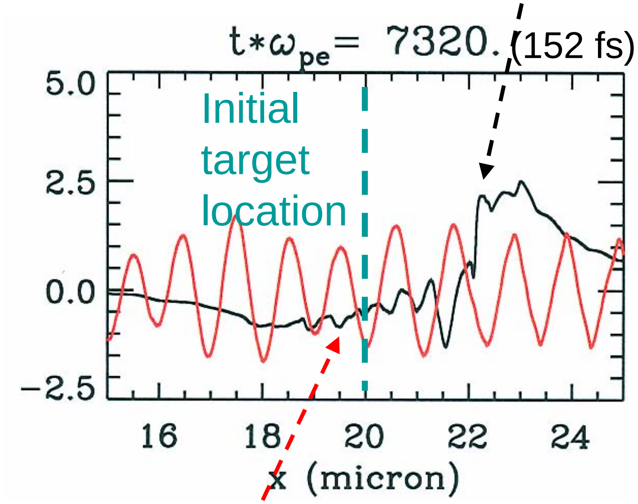

marked increase
in $E_x$ within target

skin depth ~ target thickness
Laser volumetrically heats all e-

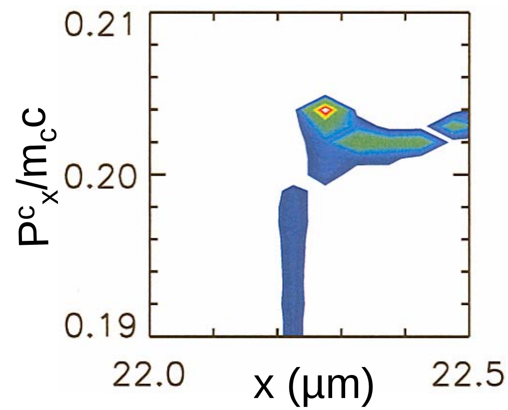
# Third stage: The laser break-out afterburner (BOA)

bulk ion co-moving
with the peak $E_x$

III. Afterburner




Mono-energetic
C ~ 250 MeV

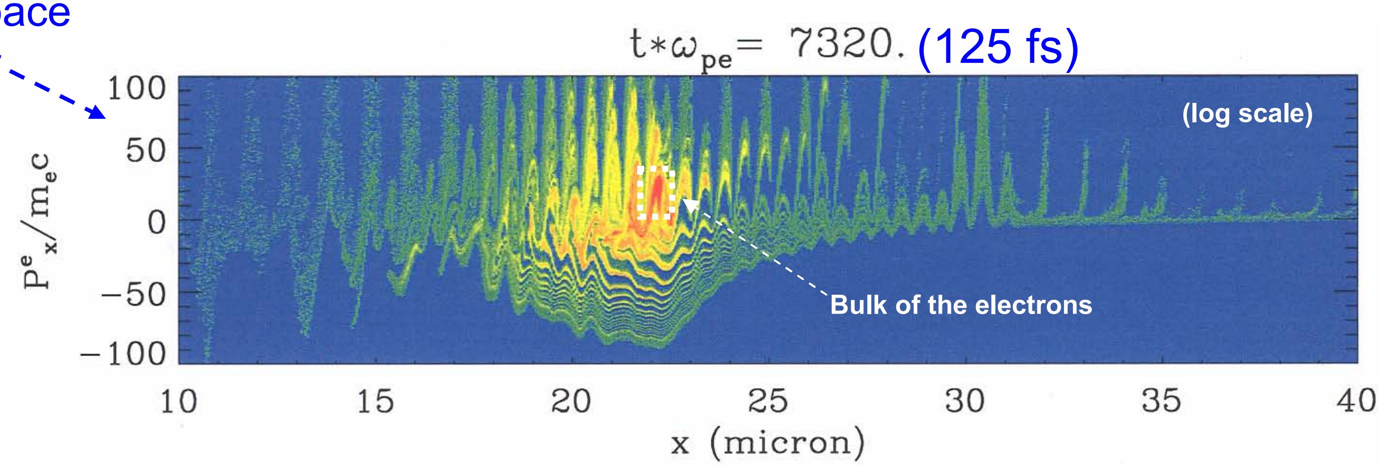


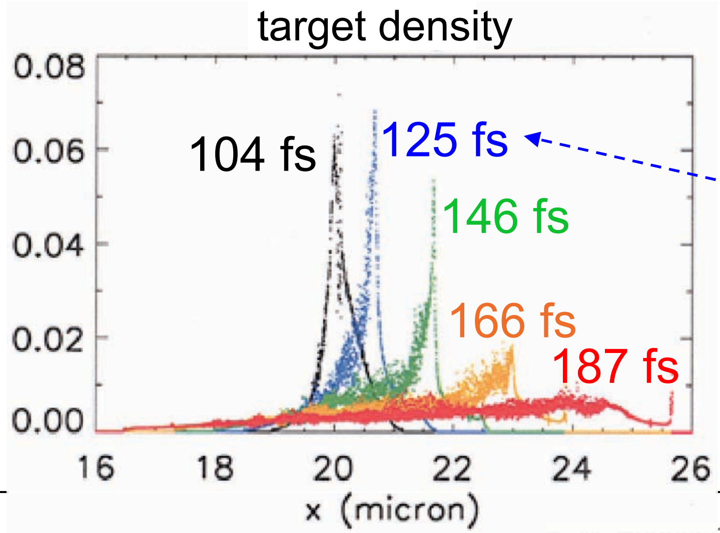

Laser penetrates the target


B. M. Hegelich,
hegelich@lanl.gov

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

Electron phase space during afterburner

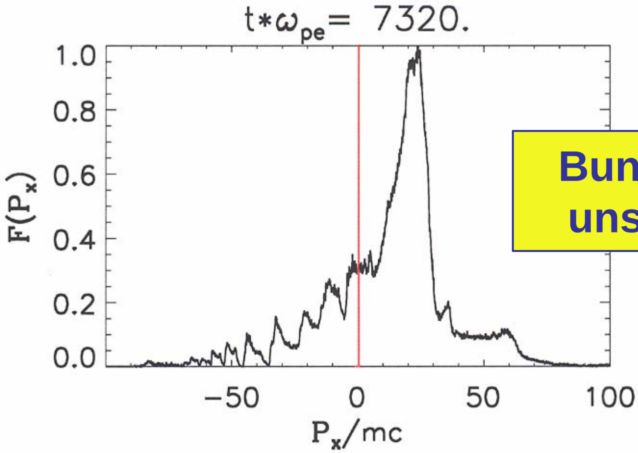


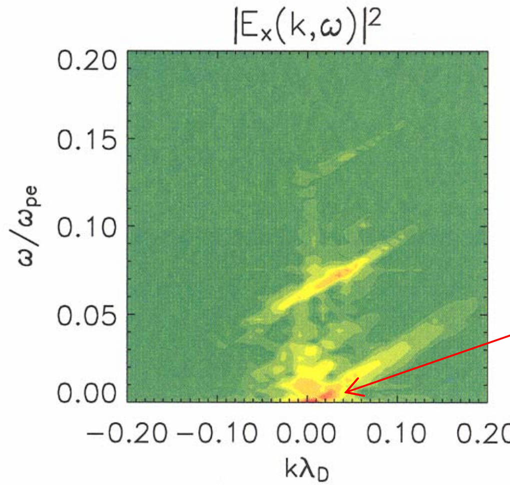

During afterburner laser penetrates target:
- target marginally overdense
- skin depth ~ target thickness at FWHM

# The BOA produces a relativistic Buneman instability

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




**Buneman unstable**



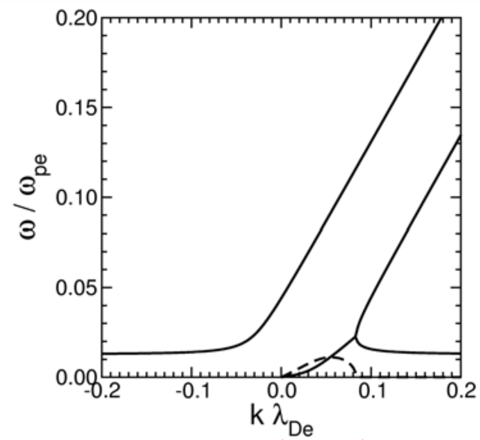

Max spectral energy at low phase speed

(resonant with ions)

Relativistic Buneman instability dispersion relation*

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

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



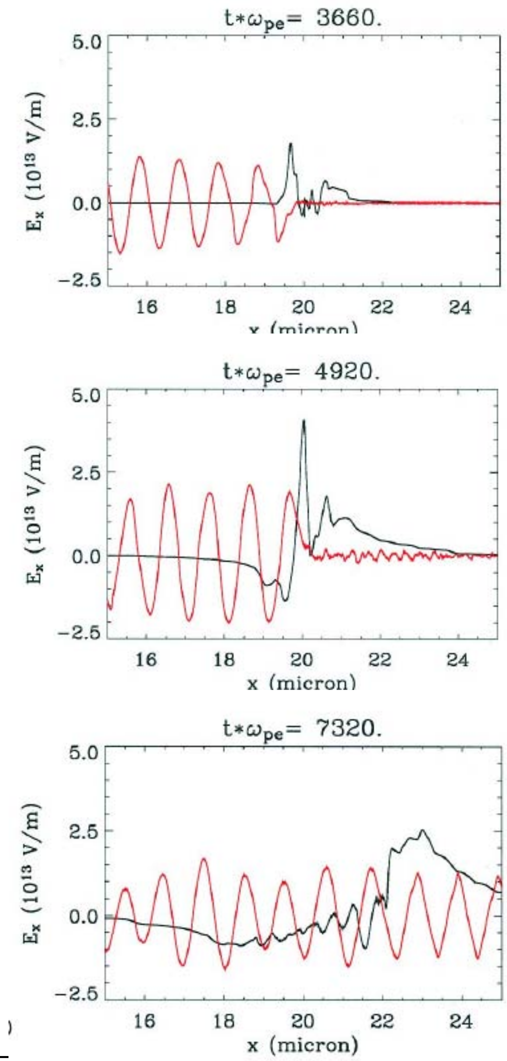

positive growth

# 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.

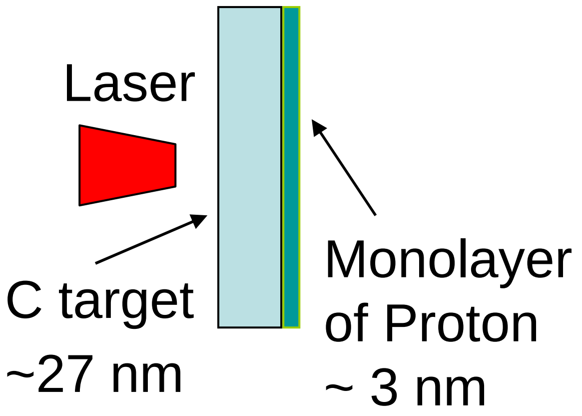


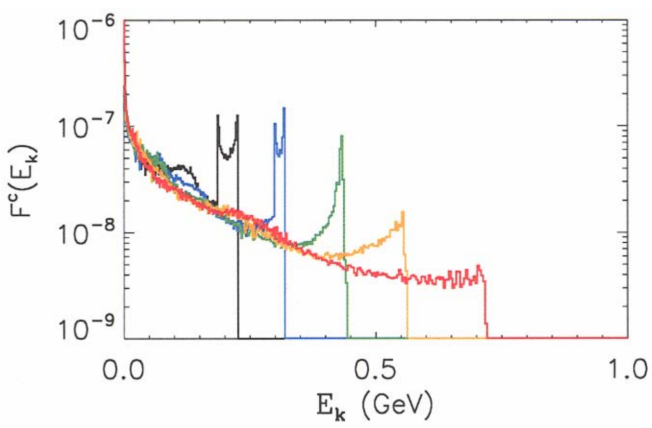
# Experimental realization of BOA: need to revisit target cleaning

- 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

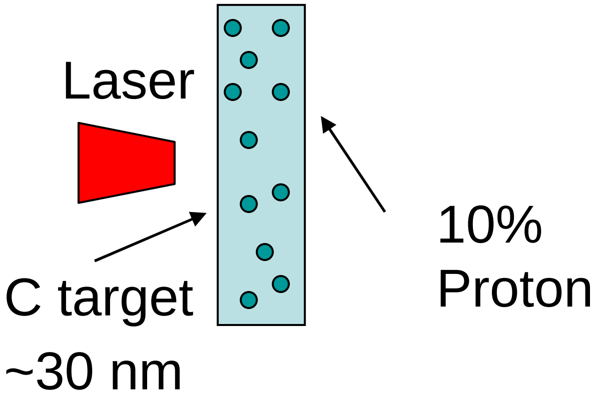


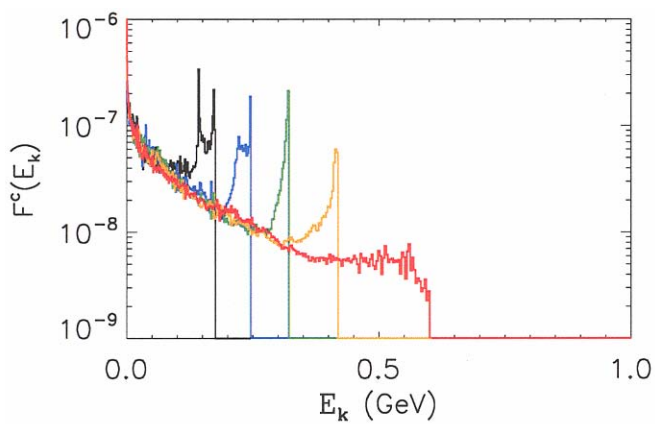




**1D VPIC simulation of BOA with C target & proton layer**

# 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**


B. M. Hegelich, hegelich@lanl.gov

# 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, $5.75 \times 10^8$ cells, $1.8 \times 10^{10}$ particles, sustained performance: ~1.4 Tflop/s.