Laser Acceleration of Quasi-Monoenergetic MeV-GeV Ion Beams

presented by:
Juan C. Fernández, Group Leader
Group P-24 Plasma Physics, Los Alamos National Laboratory

presented to:
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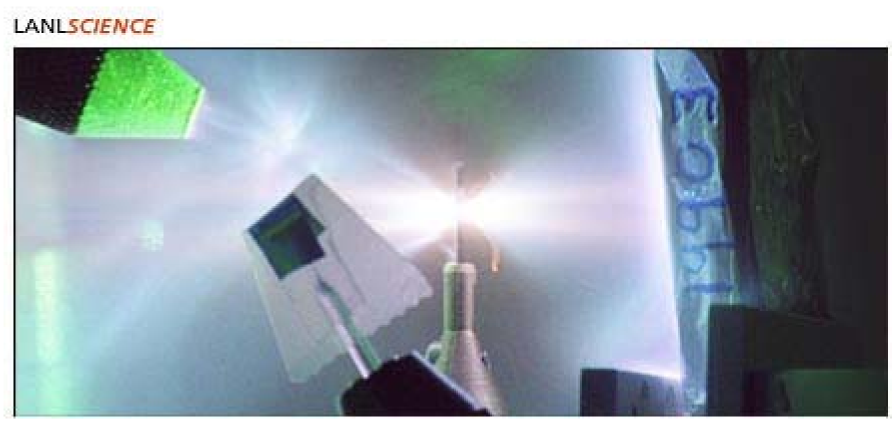


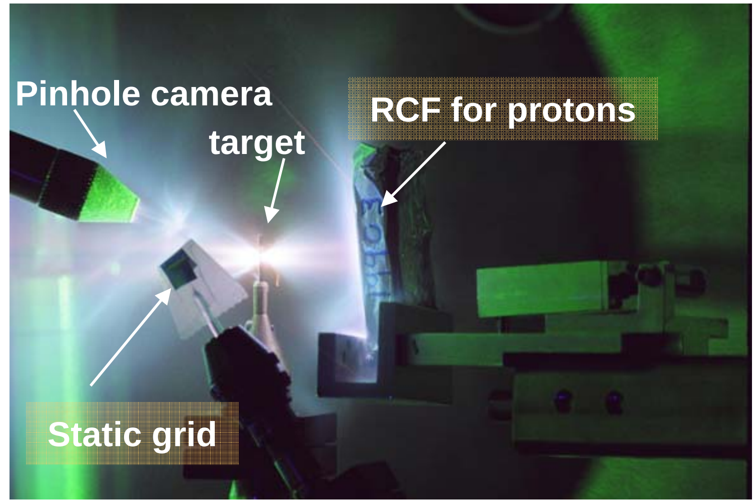
The latest C-ion acceleration project joins a multi-disciplinary team of LANL and LMU researchers.

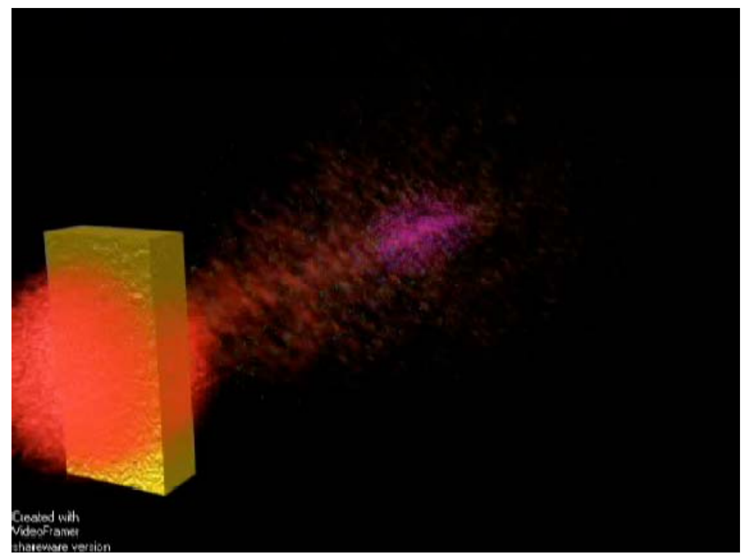
Participants	Organization	Contribution/Expertise
Juan C. Fernández	LANL P-24	Principal Investigator, experiments
Björn Manuel Hegelich	LANL P-24	Co PI, experiments on short-pulse lasers
Kirk A. Flippo	LANL P-24 P-24	Experiments on short-pulse lasers
Rahul Shah	LANL P-24 P-24	Exps. on short-pulse lasers, laser science
Randall P. Johnson	LANL P-24	Laser science, Trident
Tsutomu Shimada	LANL P-24 P-24	Laser science, Trident
Sam Letzring	LANL P-24 P-24	Experimental Operations
Cort Gautier	LANL P-24 P-24	Trident experiments, surface physics
Brian J. Albright	LANL P-24 X-1	Relativistic laser-matter theory and Sim.
Lin Yin	LANL P-24 X-1	Relativistic laser-matter theory and Sim.
Mark J. Schmitt	LANL P-24 X-1	Laser-plasma design with Rad-Hydro codes
Roland K. Schulze	LANL P-24 MST6	Surface physics & material science
Richard Sheffield	LANL LANSCE	Accelerator physics
Andreas Henig	LMU	Experiments on short-pulse lasers
Daniel Kiefer	LMU	Experiments on short-pulse lasers
Daniel Jung	LMU	Experiments on short-pulse lasers, targets

- Significant collaborations with other institutions, including students, Post Docs, professors and research staff from:
  - LLNL; SNL, LULI (Ecole Polytechnique, Palaiseau, Paris, France); GSI (Darmstadt, Germany); Technical University of Darmstadt (TUD); Ludwig Maximilians University (LMU, Munich, Germany); Univ. of Nevada, Reno (UNR); Nanolabz, Reno, NV; Queens Univ. Belfast (QUB), UK.

Outline:

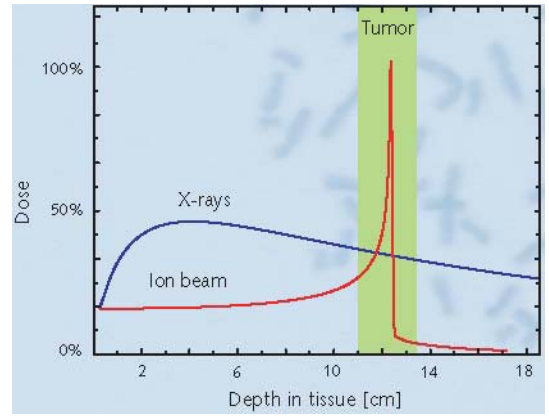
- Why laser-driven accelerators?
- Background & history
- Mechanisms for laser-driven ion acceleration
  - Target Normal Sheath Acceleration (TNSA)
  - Breakout Afterburner (BOA)
  - Radiation Pressure Acceleration (RPA)
- Future
- Summary

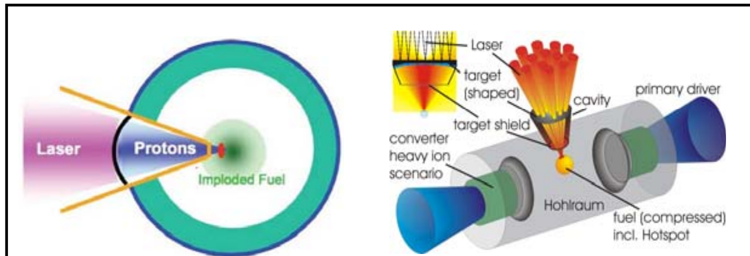




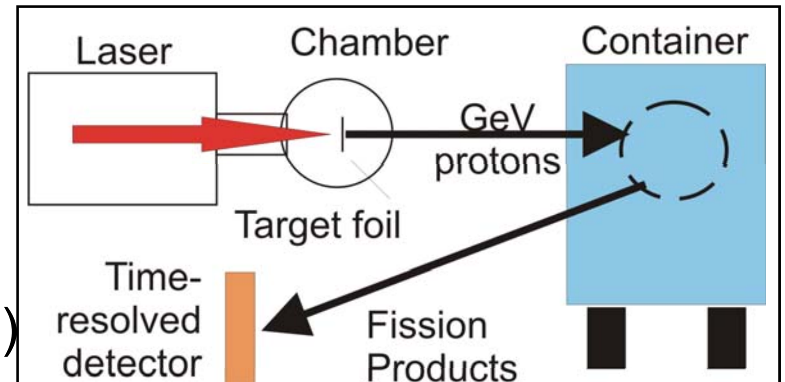
Why laser-driven ion beams?

- Characteristics
  - Smaller size (limited by laser)
  - Generated in ~ ps bunches
  - Born with high-current (~ A – MA)
    - o Neutralized beam
- Ideal applications
  - Transient phenomena (1 shot)
  - Require high energy density
  - Sensitive to capital cost
  - → Beam made *O*(cm) from target
- Examples
  - Human cancer therapy
  - Isochoric heating of matter
  - Fast ignition ICF
  - Nuclear interrogation
- Challenges
  - Energy spectrum control
  - Laser Techn. (pulse shape, rep rate)
  - Target technology





Fusion Fast Ignition



Summary of laser-driven ion acceleration:

Laser couples to target electrons → Relativistic e^- population out of equilibrium → Relativistic e^- population couples to ions → Directed ion beam

Laser couples to target electrons

- Ponderomotive force $-q^2\nabla E^2/4m\omega^2$
- Heating (with linear polarization)
- Radiation pressure (circular polarization)

Relativistic e^- population out of equilibrium

- $I\lambda^2 > 1.33 \times 10^{18}$ Wcm^{-2} μm^2, KE > rest mass
- High energy Effic. ~ 30 – 50%
- Directed motion, e.g., relativistic plasma mirror
- Expansion
- Electron transport, B-field, E-fields (internal & surface)

Relativistic e^- population couples to ions

- Charge separation,
- Kinetic instability,
- Waves, e.g., Alfvénic solitons

Directed ion beam

- MeV – GeV
- High Energy Effic. (~ 10%)
- Broad or narrow energy spread
- Born in ~ ps
- Focusable

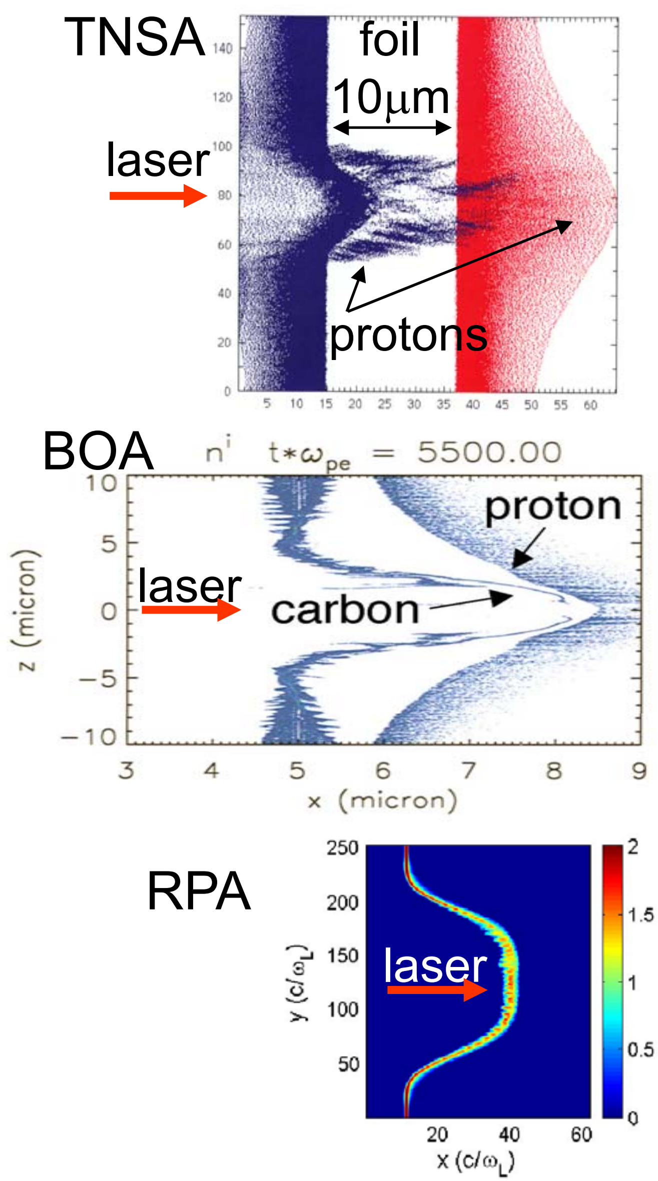
↓

- High power density

- Very large multi-scale computational problem

Ion acceleration mechanisms:

Ion acceleration mechanism	Acronym	Ion Accel. process
Target-Normal Sheath Acceleration	TNSA	Charge separation
Break out afterburner	BOA	Kinetic Instability (Buneman): relative *e-i* drift
Radiation Pressure Acceleration Aka Plasma Piston	RPA	Charge separation

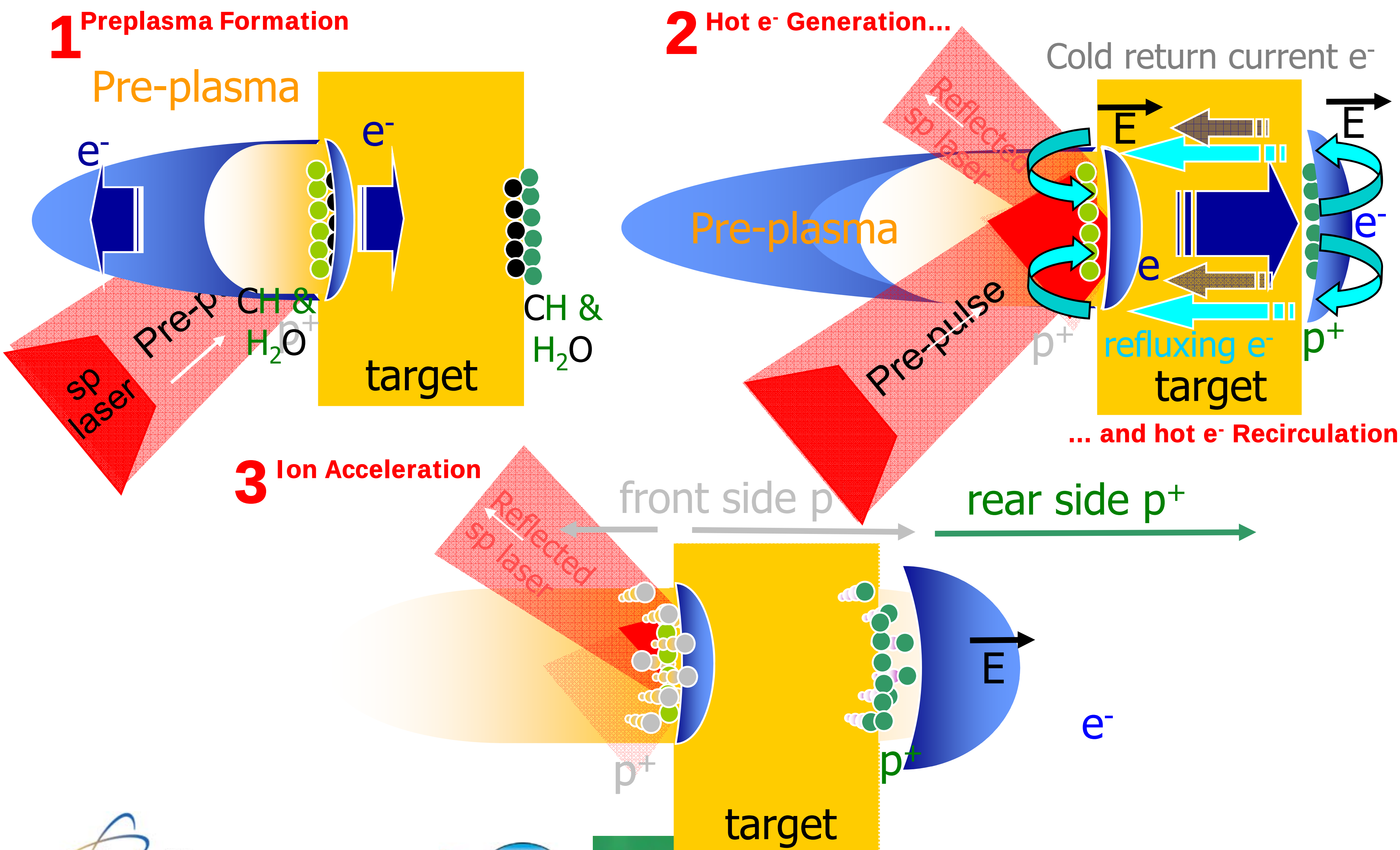


Quick historical overview of > MeV ion acceleration

Year	Key milestone	Reference
1992	Ponderomotive scaling of laser-driven hot electrons explained in PIC simulations	S. C. Wilks, *et al.*, Phys. Rev. Lett. **69**, 1383 (1992)
1999	~ 10^{13} protons, Maxwellian, ~ 60 MeV cutoff, @ NOVA PW laser - LLNL	R. Snavely *et al.*, PRL **85**, 2945 (2000)
2000	TNSA mechanism explained	S. Hatchett *et al.*, Phys. Plas. **7**, 2076 (2000)
2001-2002	Record low transverse emittance for proton beam, @ Trident (LANL) & LULI	T. E. Cowan *et al.*, Phys. Rev. Lett. **92**, 204801 (2004)
2001-2002	TNSA confirmed: protons come from target back side, @ Trident (LANL) & LULI	J. Fuchs *et al.*, Phys. Rev. Lett. **94**, 045004 (2005)
2002	TNSA heavy ion beams, @ LULI	B. M. Hegelich *et al.*, PRL **89**, 085002 (2002)
2003	Proton beam focused ballistically, @ LLNL Janusp laser	P. K. Patel *et al.*, Phys. Rev. Lett. **92**, 125004 (2003)
2005	Quasi-monoenergetic C beam, @ Trident	B. M. Hegelich *et al.*, Nature **439**, 441 (2006)
2005	BOA (~ GeV, quasi-monoenergetic) discovered in PIC simulations, @ LANL	L. Yin *et al.*, Laser Part. Beams **24,** 291 (2006) ; Phys. Plasmas **14,** 056706 (2007)
2007	RPA accessible at 10^{21} W/cm^2 with circular polarization	A.P.L. Robinson, *et al.*, New J. Phys. **10**, 013021 (2008)
2008	1st BOA & RPA experiments @ Trident	

TNSA

Brief Overview of Laser-Ion Acceleration
Target Normal Sheath Acceleration (TNSA)



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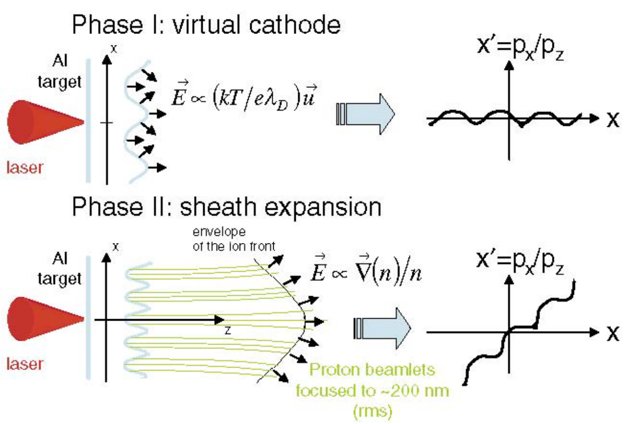
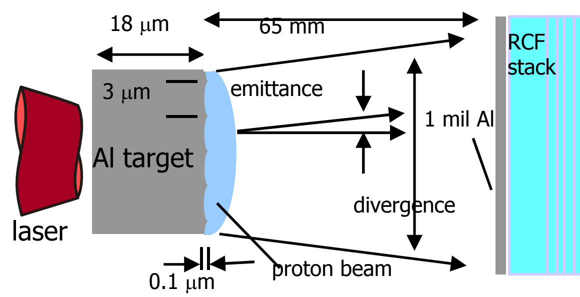
Laser-driven TNSA proton beams have extremely low transverse emittance.

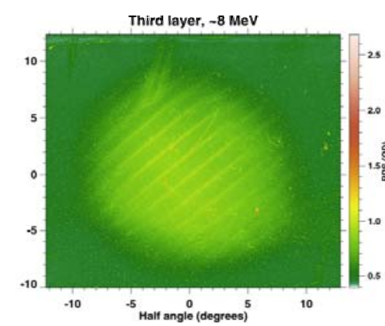
- Hot e^- → MV/μm electrostatic fields at the target rear surface (virtual cathode).

- Measured transverse emittance of TNSA proton beams at Trident (LANL) and LULI (Ecole Politechnique).





Trident experimental setup



RCF image of Trident proton beam

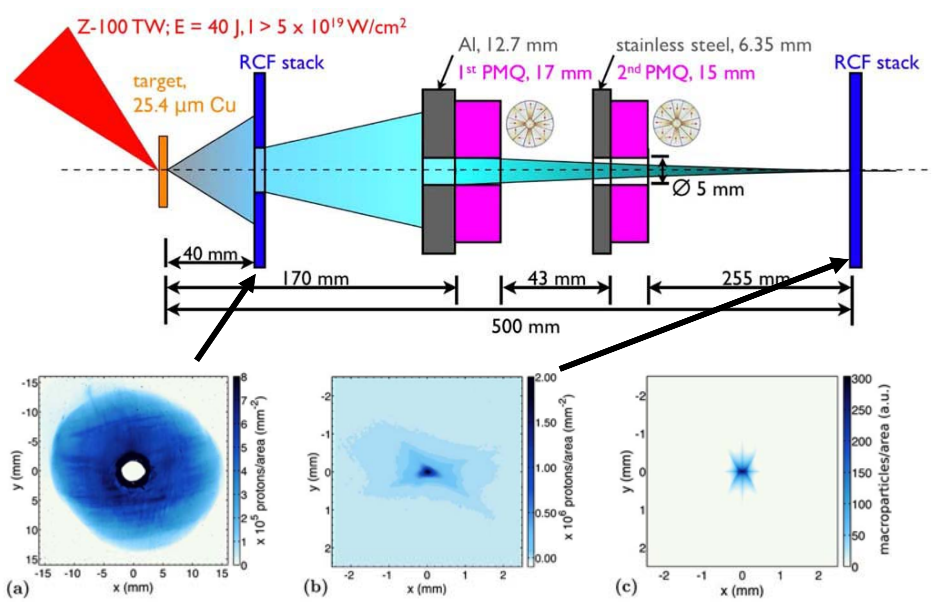
- For 8 MeV component of the Trident beam, the upper bound on the transverse normalized beam emittance is **0.004 mm mrad**, ~ 100× better than typical LINACs.

TNSA

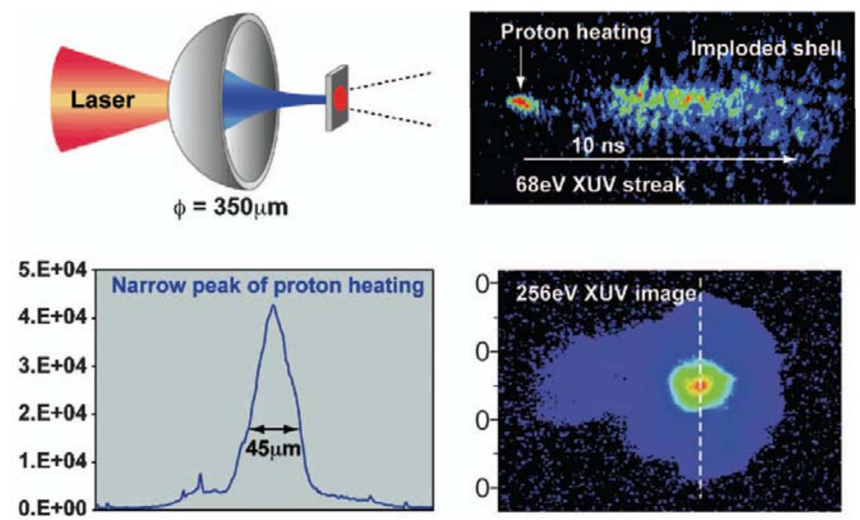
Laser-produced ion beams have been focused.

- Neutralized beam: not bound by usual current and space-charge limits
- May be focused with quadrupole lenses and ballistically

Quadrupole lens focusing



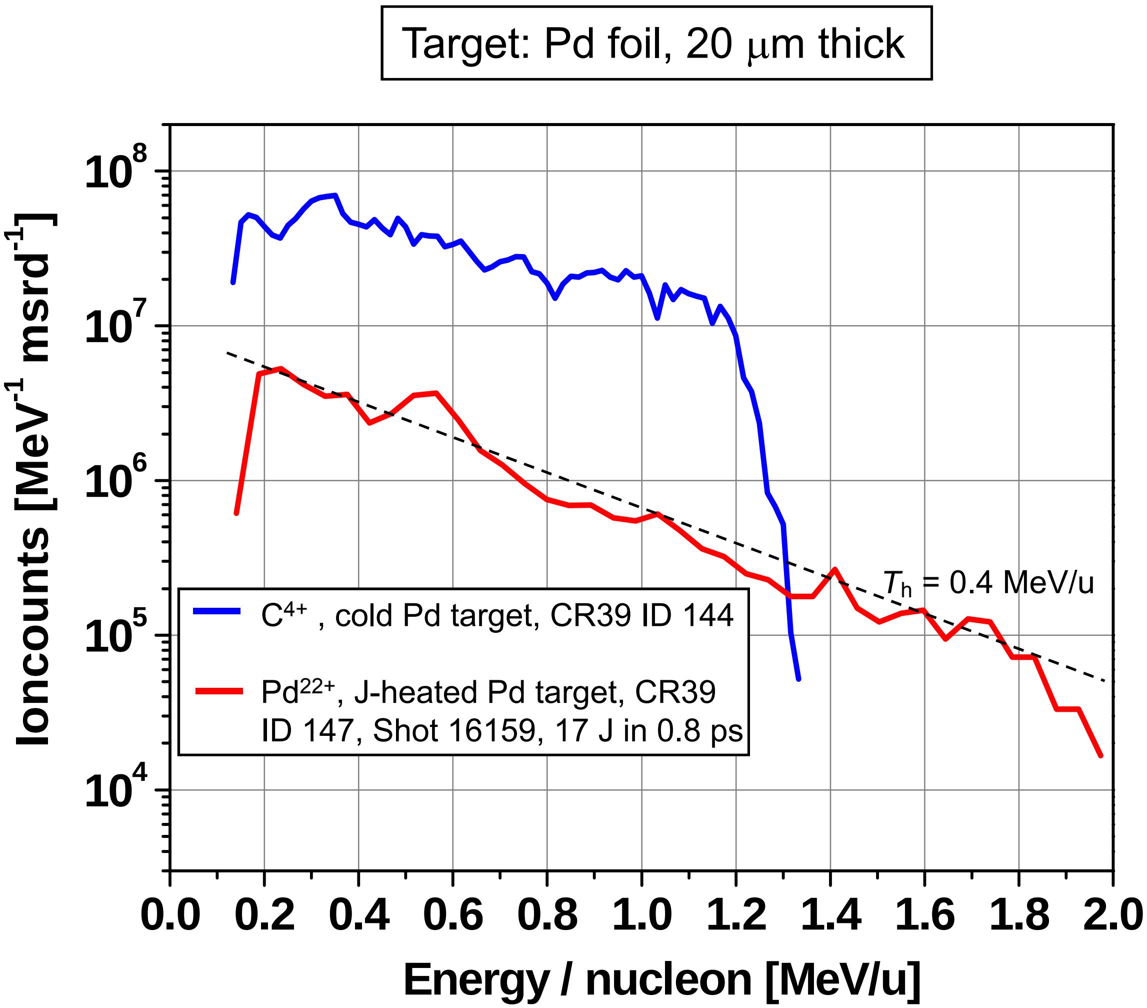
Ballistic (shaped target)



M. Schollmeier, et al., Phys. Rev. Lett. **101**, 055004 (2008)

P. K. Patel et al., Phys. Rev. Lett. **92**, 125004 (2003)
M. H. Key et al., Fusion Science & Technology **49** (2006) 440
M. H. Key, Phys. Plasmas **14** (2007) 055502

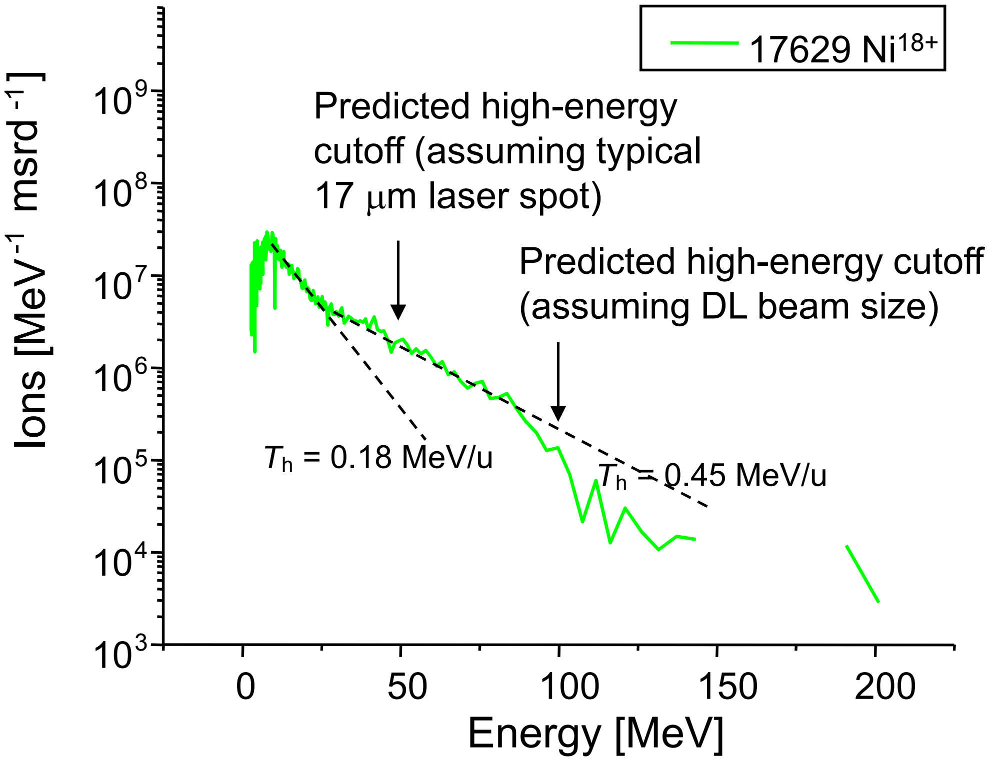
Joule heating of Pd foils (evaporate surface impurities) yields on beam with a significant yield of highly ionized heavy ions.



- Trident 30 TW data
- Pd^{22+} ions (assuming 10º beam): $1.75 \times 10^9 \geq 1$ MeV/u → 0.23% of laser energy; 2.4×10^{10} total → 1.1% of laser energy
- Pd^{4+} ions (not shown): 1.1% of laser energy
- High-energy cutoff consistent with theory

TNSA

CW laser heating of Ni foils has resulted in ~ 1% laser conversion efficiency into a Ni^{18+} ion beam.



- Target: Ni, 15 μm thick.
- $Ni^{18+} \rightarrow$ 0.8 % of laser energy on old 30 TW Trident.
- High-energy cutoff (reduced model by Albright *et al.**, $E_{I,max} \sim 2 T_h Z_I$) is higher than than expected.
- Self focusing probably increased intensity.

* B. A. Albright, et al., Phys. Rev. Lett. **97,** 115002 (2006)

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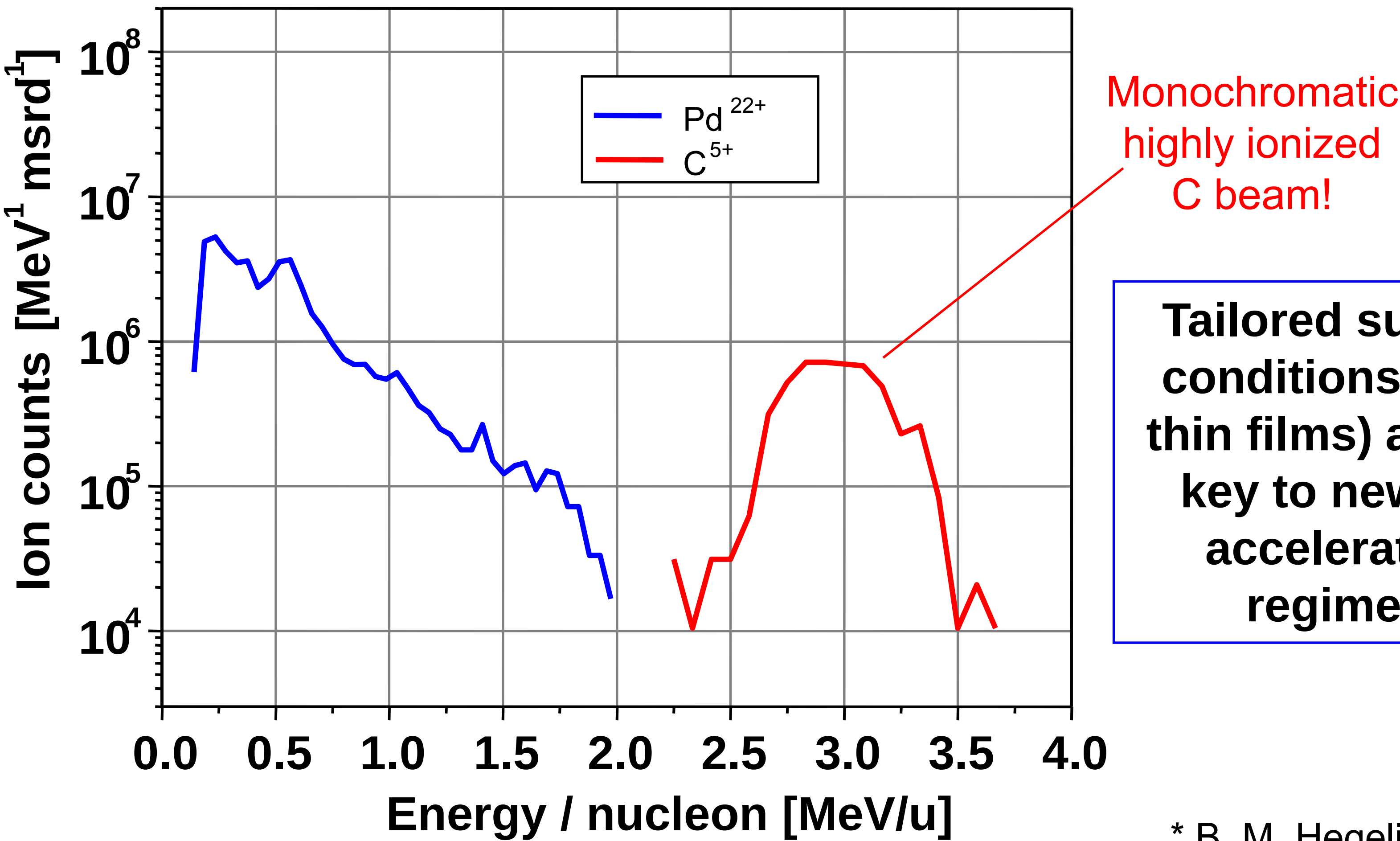
TNSA

We inadvertently exploited a surface catalytic reaction to create a nearly mono-energetic beam.*

Target: Pd 20 μm, J-heated; Trident shot #16159



Tailored surface conditions (*e.g.*, thin films) are the key to new ion acceleration regimes.

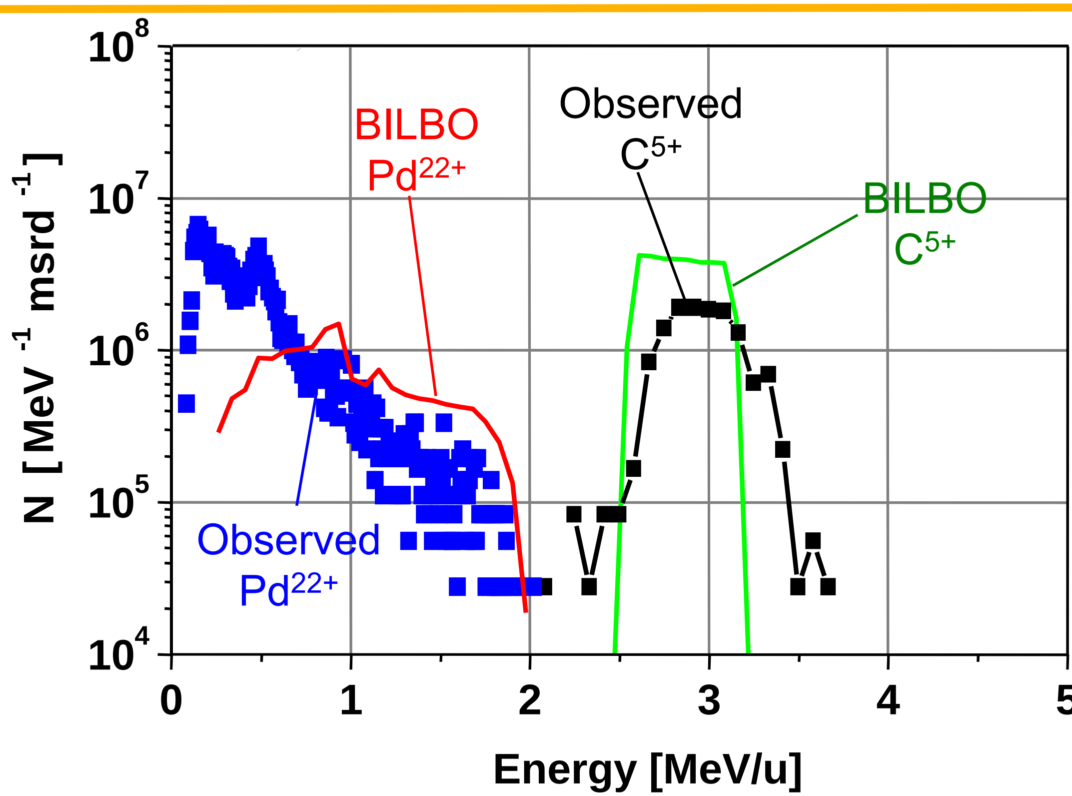
* B. M. Hegelich et al., Nature **439**, 441 (2006)

TNSA

Heating certain metals (e.g. Pd) to 800 - 1000º C catalyzes a reaction leaving a few C monolayers on the surface.

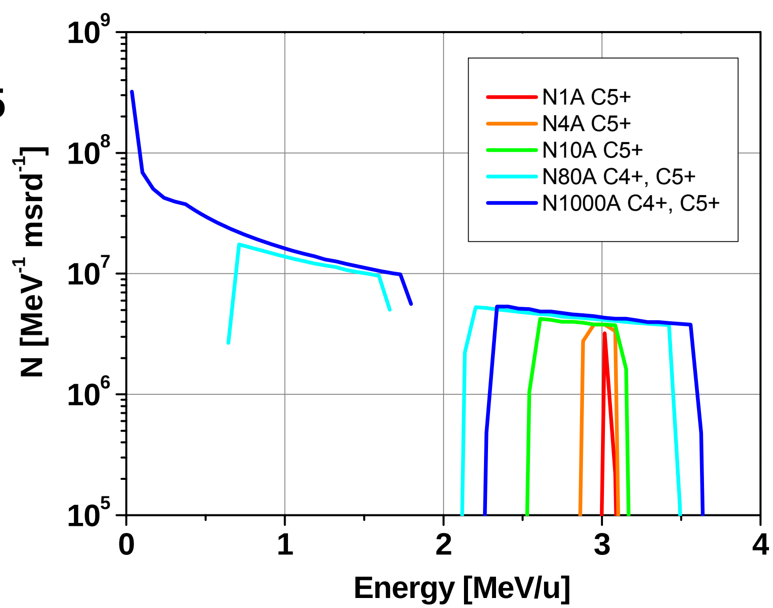
- The chamber atmosphere (~ 10^{-6} torr) provides a source of hydrocarbons.
- Heating the target to 400 - 600º C liberates all the H.
- Heating the target to 600 - 800º C leaves a carbon layer.
- Heating the target to 800 - 1000º C results in a C monolayer
- Heating the target above 1000º C liberates all surface contaminants.

Our understanding of TNSA has allowed the development of reduced models for ion-acceleration dynamics.*



1D hybrid code BILBO (Backside Ion Lagrangian Blow Off):

- Analytic solution to Vlasov-Maxwell system
- Threshold ionization model
- Hot electron cooling model

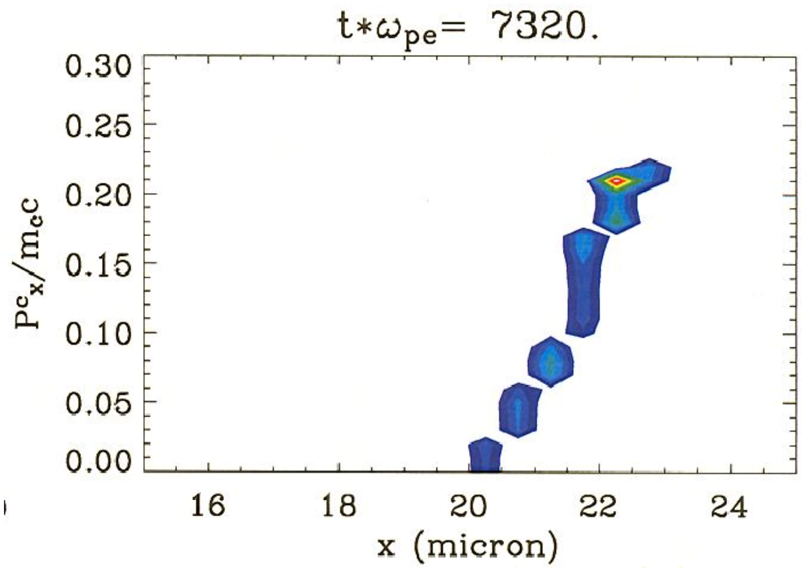


- B. J. Albright et al., Phys. Rev. Lett. **97**, 115002 (2006);
  B. M. Hegelich et al., Nature **439**, 441 (2006)

BOA

Discovery of the laser-breakout afterburner* (BOA): a path to high efficiency & high energy ion beams

- Requirements:
  - $I \sim 10^{20}$ W/cm^2 with ultra-high laser contrast
  - Ultra-thin targets (*e.g.,* ~ 30 nm C)
- 1D, 2D, 3D Simulations using VPIC code
  - Start with solid density C, including cases with H contaminants
- Mechanism:
  - Enhanced TNSA
  - Laser penetration across target
  - Electron heating & drift relative to ions
  - Electron energy → ion energy via kinetic Buneman instability.



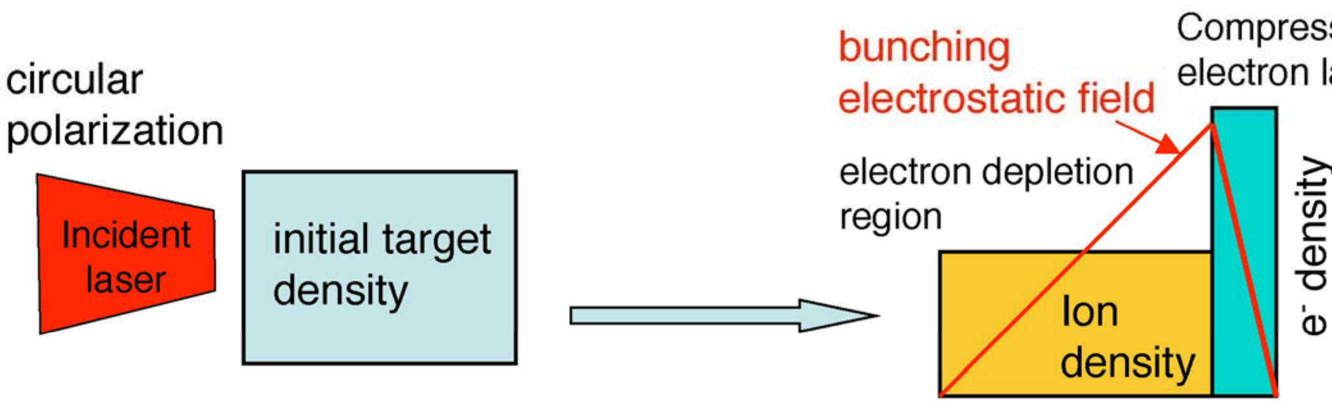
- Initial simulations ($I \sim 10^{21}$ W/cm^2 , 30 nm targets):
  - 35% (in 1D, 15% (in 2D) of all ions accelerated to 0.3 GeV ± 7%, 4% conversion efficiency.
  - C-ion acceleration is immune to surface or volumetric proton contamination!

The key to realizing this concept is having a high (~ 10^{10}) laser-pulse contrast to prevent the pre-pulse shock from destroying the target.

* L. Yin *et al.,* Phys. Plasmas **14,** 056706 (2007)

Radiation Pressure Acceleration (RPA) is another path to ~ GeV laser-driven ion beams.*

The key to realizing RPA is to push on the target electrons, rather than heating them

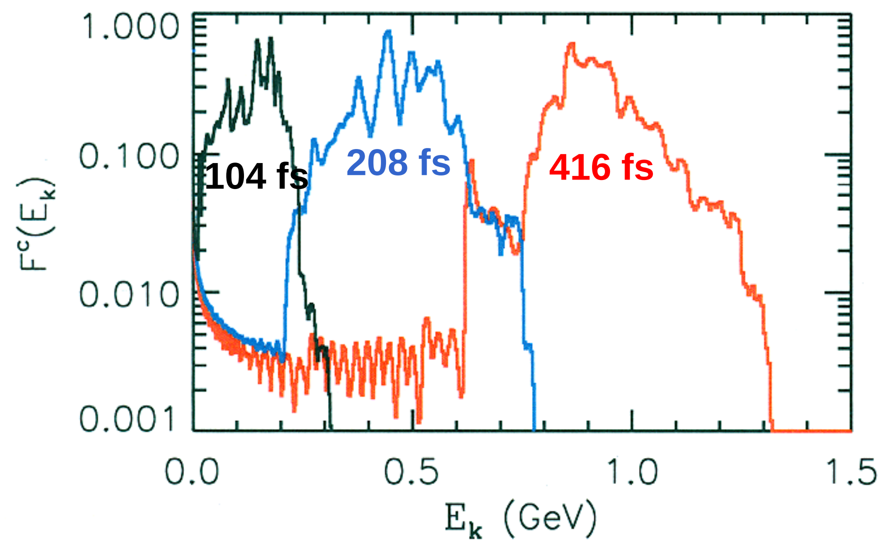


- Uses *circularly* polarized light
- Electrons pushed by light pressure, minimal heating
- Charge-separation electric field bunches ions
- Mono-energetic ions are accelerated to high energies
- Requirements:
  - $I \sim 10^{20}$ -- 10^{21} W/cm^2 with ultra-high laser contrast
  - Ultra-thin targets (*e.g.*, ~ 30 nm C)
  - Circularly polarized light

* A. P. L. Robinson *et al.*, New Journal of Physics **10,** 013021 (2008)

VPIC has been used to study RPA acceleration of C, showing acceleration to ~ GeV.

- Requirements:
  - I ~ 10^{21} W/cm^2 with ultra-high laser contrast
  - Ultra-thin targets (*e.g.*, ~ 30 nm C)
  - Circular polarization
- 1D simulations using solid density C and 208 fs pulse (blue curve)
  - 60% of ions accelerated to 450 MeV ± 10%, 13% conversion eff.
  - 1D scaling with pulse length
  - C-beam energy increases with pulse length

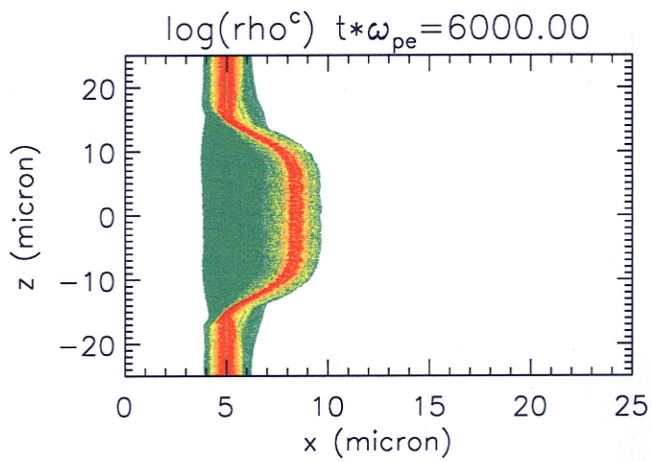


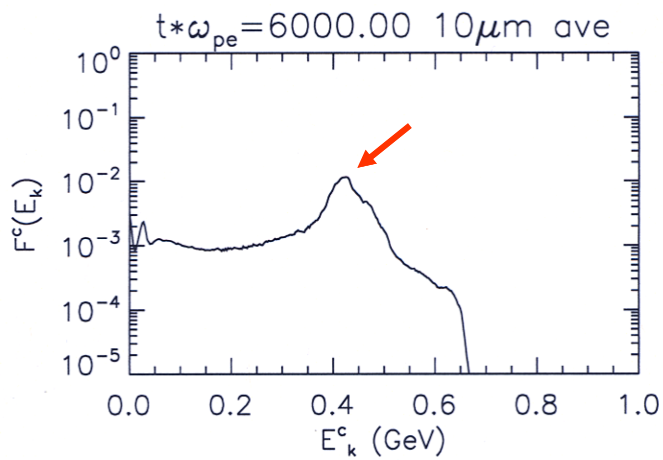
- Concern: effects of higher-dimensions
- 3D VPIC simulations show:
  - high sensitivity to curvature, which may negate benefits of circular polarization
  - ~ GeV energies
- Further optimization of RPA and BOA is needed.

RPA deserves further consideration for ~ GeV ion acceleration.

VPIC demonstrates that RPA acceleration of C in 2D requires proper tailoring of the laser pulse.

- 2D Simulation conditions (idealized case):
  - $I \sim 10^{21}$ W/cm^2
  - Supergaussian in space ~$\exp\{-[r^2/(2w^2)]^3\}$ where w = 10 micron
  - Supergaussian in time with 9 fs
  - Circular polarization
- Results at 104 fs:





There are two key technological requirements to access ion acceleration mechanisms at the GeV level:

- **Ultra-thin targets (10-100 nm)**
  - Have settled on diamond-like C (DLC) as a technologically convenient species
  - As part of our collaboration with Ludwig Maximilians University (Munich), they have provided DLC targets in thicknesses of 3, 5, 10, 30, 50 & 60 nm.

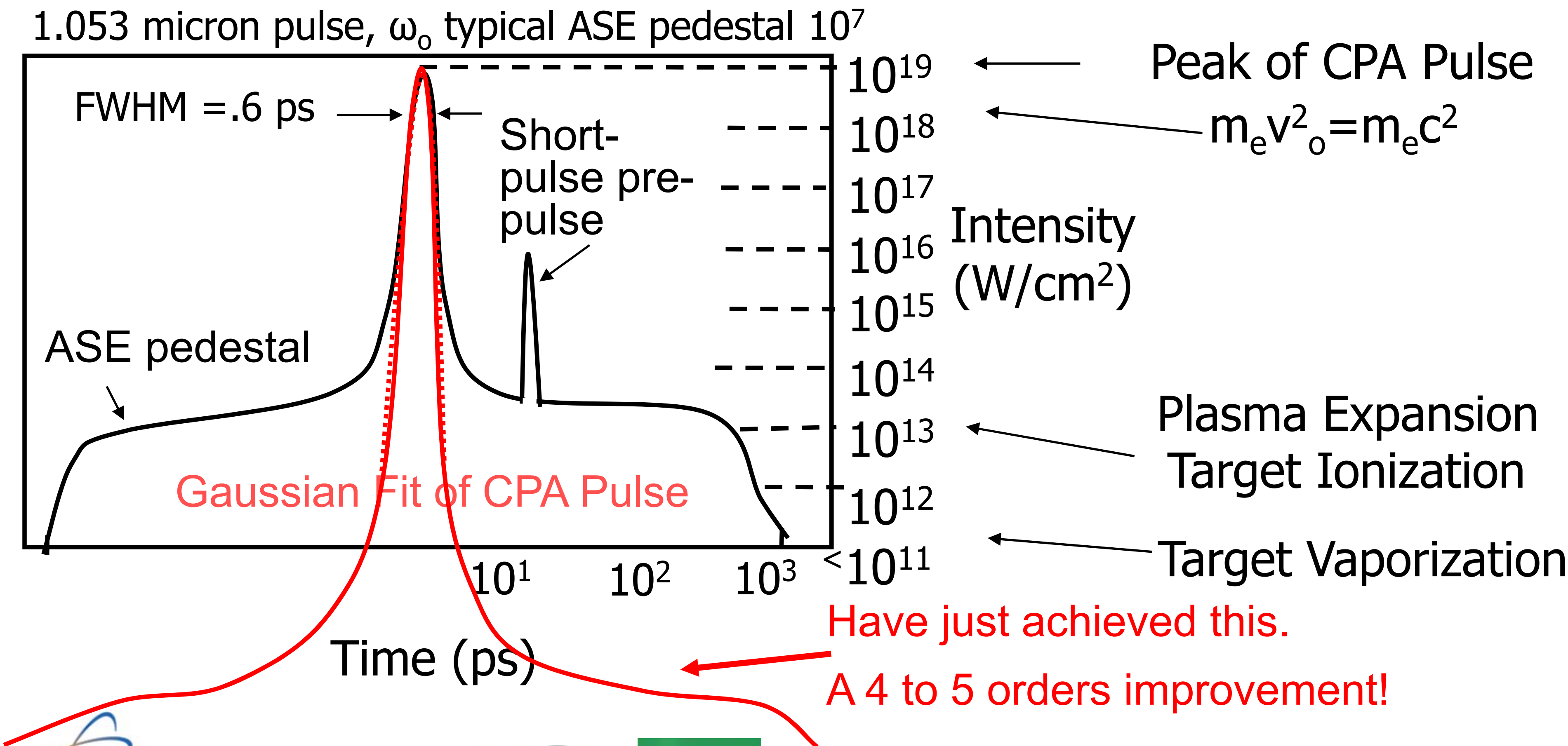
- **Laser pulses with ultrahigh contrast (~ 10^{10}) and no prepulse**
  - Have discovered that post-pulses can turn into prepulses.
  - Have determined that the laser contrast ratio on Trident (without cleaning or plasma mirrors is very good (> 10^7).
  - After looking at the emerging technology for pulse cleaning, invented a new scheme ("SPOPA") to reach our goal.*
  - These targets have been fielded successfully on Trident with new high-contrast front end.

* R. Shah, et al., Optics Letters (2008) submitted

Contrast:
The dirty truth about short-pulse lasers

Contrast comes in several varieties:

- Amplified Spontaneous Emission (ASE) Contrast: a laser pulse is only as good as its regen.
- Pre-pulse contrast, reflections can lead to pre-pulses from saturation effects of post-pulses
- Extinction ratio, a laser pulse is only as good as its Pockel's Cells to extinguish pulse train

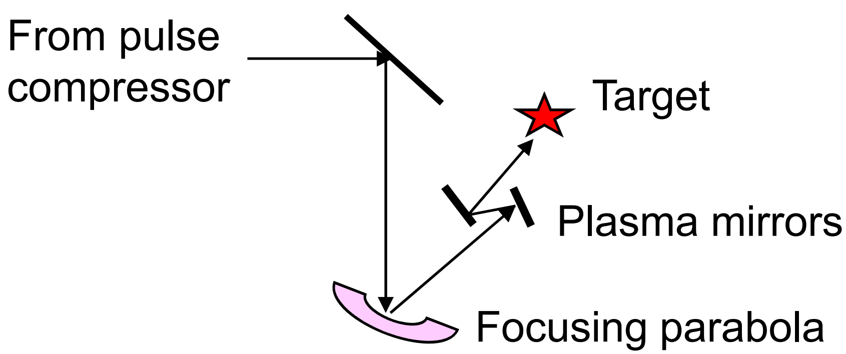


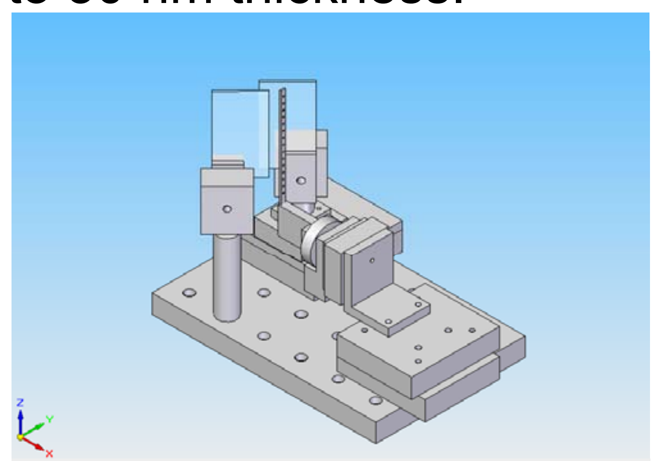
Have just achieved this.

A 4 to 5 orders improvement!

We used high-contrast laser pulses produced with plasma mirrors to validate our understanding of pre-pulse effects.

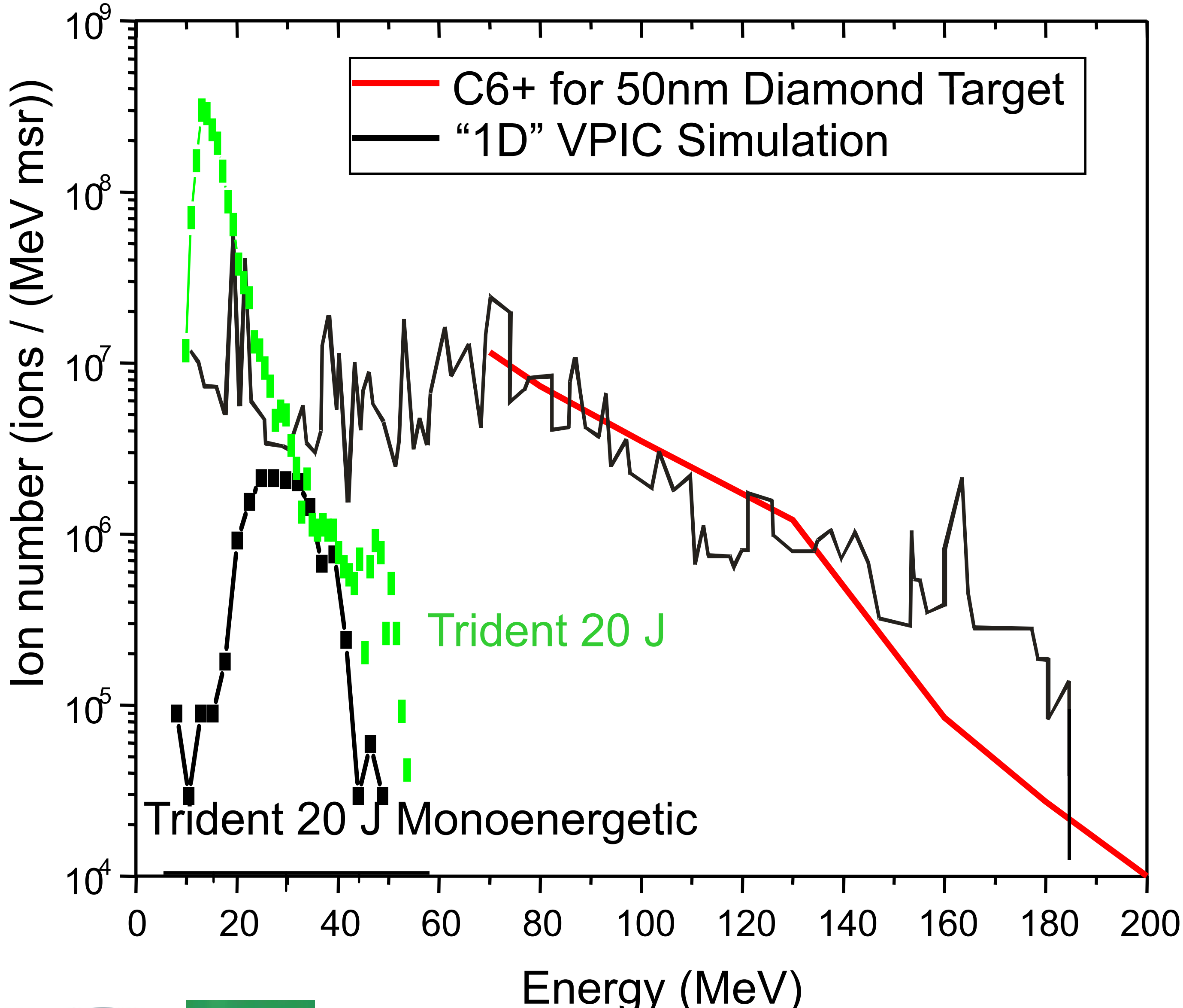
- **Done while awaiting for high-contrast front end on Trident.**
- **We shot ultra-thin DLC targets (10-50 nm)**
  - Provided by LMU
  - Hosted 2 LMU grad students and 1 QUB grad student for the run.
- **Laser pulse contrast was enhanced by using two consecutive plasma mirrors in the focusing chain.**
  - Improve contrast by ~ 10^4 (based on published results)
  - Demonstrated good performance down to 30 nm thickness.





High laser-pulse contrast on thin targets improves Carbon acceleration.

- 200 MeV Carbon with 40 J at high contrast using plasma mirrors.
- Compared to 50 MeV C^{5+} with 20 J at low contrast.
- Would expect 75 MeV from TNSA scaling [Fuchs, Nature Phys. 2007].
- Probably accessed Enhanced TNSA



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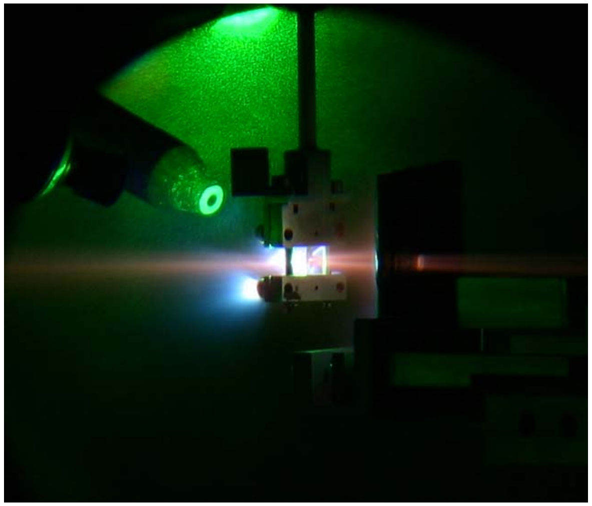
Summary:

- We have made much progress in the development of > 10 MeV/nucleon ion beams
- We have a path towards a transformational capability: laser-driven ~ GeV ion beams.
- The necessary laser and target technology has just become available, and experiments have begun.
  - 300 MeV C on Trident

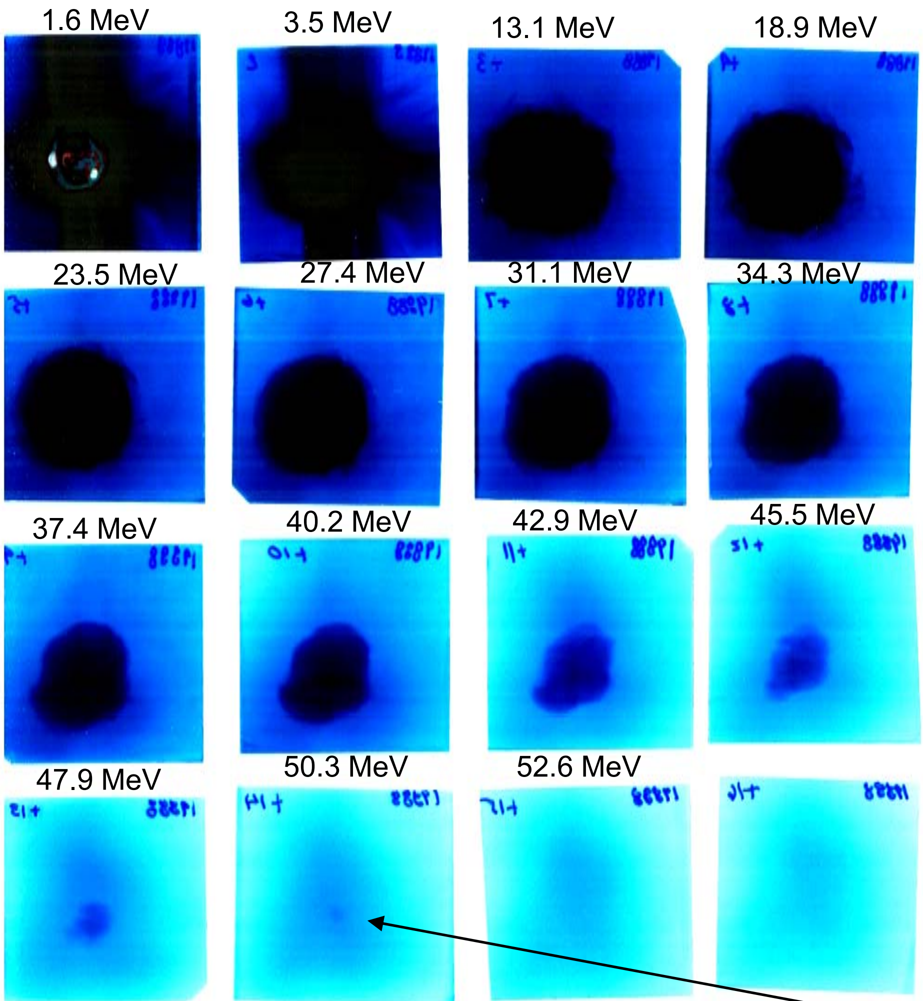


Selected references for some identified ion acceleration mechanisms

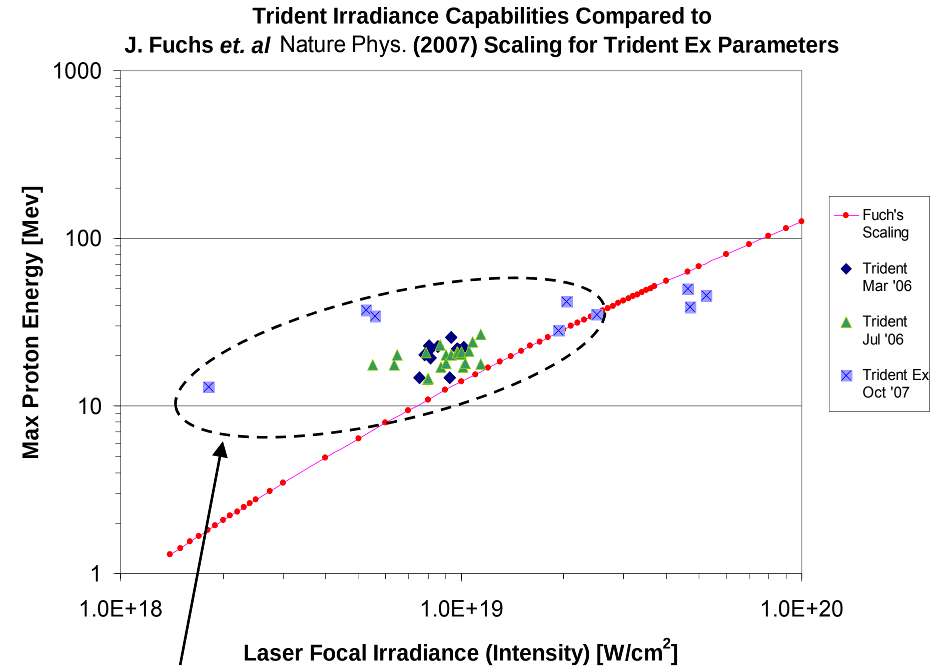
- Target Normal Sheath Acceleration (TNSA)
  - Theory & Modeling: S. P. Hatchett, et al., Phys. Plasmas 7, 2076 (2000); S. Wilks, et al., Phys. Plasmas **8**, 542 (2001);
  - Experiments: R. A. Snavely, et al., Phys. Rev. Lett. Plasmas **85**, 1945 (2000); T. E. Cowan, et al., Phys. Rev. Lett. **92**, 204801 (2004); J. Fuchs, et al., Phys. Rev. Lett. **94**, 045004 (2005); B. M. Hegelich, et al., Nature **439,** 441 (2006)
- Radiation Pressure Acceleration (RPA), aka Plasma Piston
  - Theory: A.P.L. Robinson, et al., New J. Phys. **10**, 013021 (2008); T. Esirkepov, et al., Phys. Rev. Lett. **92**, 175003 (2004); T. Esirkepov, et al., Phys. Rev. Lett. **96**, 105001 (2006); G. Marx, et al., Nature **211,** 22 (1966)
- Laser Break-Out After Burner (BOA)
  - Theory: L. Yin, et al., Laser Part. Beams **24,** 291 (2006) ; L. Yin, et al., Phys. Plasmas **14,** 056706 (2007); B. J. Albright, et al., Phys. Plasmas **14** (2007)
- Alfvénic solitons
  - Theory: B. Rau and T. Tajima, Phys. Plasmas **10**, 3575 (1998)

TNSA

Max proton energies on Trident with thin targets match or exceed published, contrast-limited scaling laws.



15 μm Moly target @ 4.6x10^{19} W/cm^2
85 J



Enhanced Trident exceeds scaling laws by an order of magnitude at low irradiance. At high irradiance, it approaches scaling laws, i.e., contrast limited.

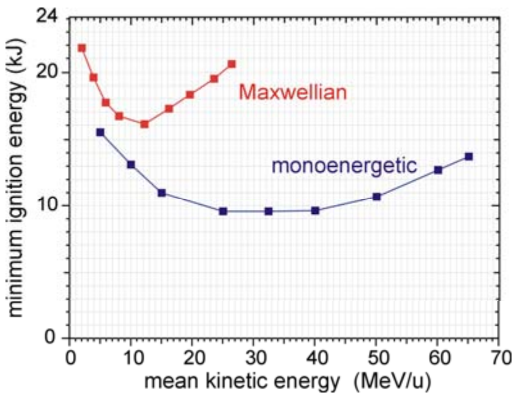
Petawatt Performance at 120 TW
Trident: 50 MeV at 5x10^{19} W/cm^2
NOVA Petawatt: 58 MeV at 3x10^{20}
RAL PW: 53 MeV at 6 x10^{20}

K. Flippo, C. Gautier, and J. Workman (P-24)

Background

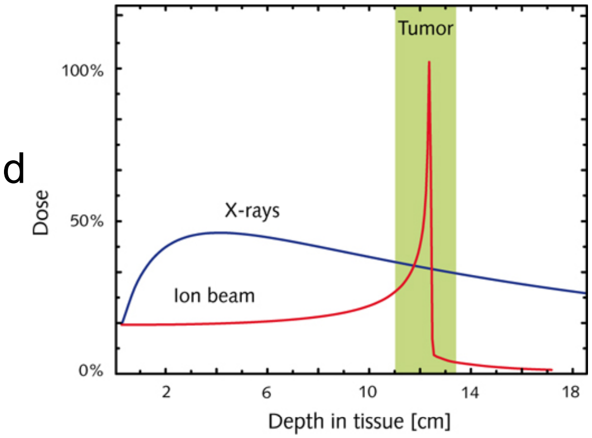
Advanced, compact laser-driven ion accelerators may enable new scientific research and practical applications.

- Fusion energy
  - **Proton-driven fast ignition** [M. Roth, et al. Phys. Rev. Lett. **86,** 436 (2001); M. H. Key et al., Fusion Science & Technology **49,** 440 (2006) 440; M. H. Key, Phys. Plasmas **14,** 055502 (2007)]
  - **Light-ion FI** [J. C. Fernández et al., J. Physics : Conf. Series 112, 022051 (2008); B. J. Albright et al., ibid 112, 022029 (2008); J.J. Honrubia et al., Hirschegg 2008 Workshop & 35th EPS Plasma Conference, 2008; , paper P-5.125; V. Yu. Bychenkov, Plasma Phys. Reports **27,** 1017 (2001)])



Minimum beam ignition energy for a C beam ($\delta E/E$ ~ 10%) to ignite DT fuel core compressed to ρ= 500 g/cc with a size FWHM = 82 μm.

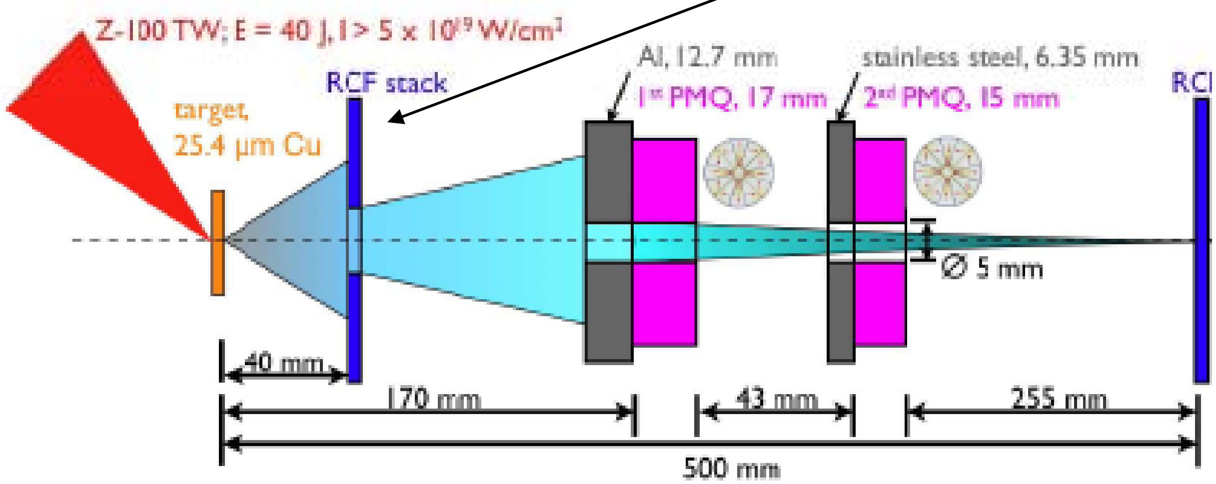
- Detection of fissile materials
  - Compact **proton accelerators** for active interrogation (DNDO, DTRA)
- Nuclear physics
  - **Particle production** (e.g., pions [V. Yu. Bychenkov, JETP **74,** 586 (2001)])
  - **Colliders,** e.g., of short-lived particles (e.g., pions) using high-luminosity, compact laser-driven proton and heavy ion beams
- Probe warm dense matter
- Cancer tumor therapy using laser-driven affordable, compact ion accelerators
  - Exploiting **Bragg peak** of low-Z (e.g.) beams

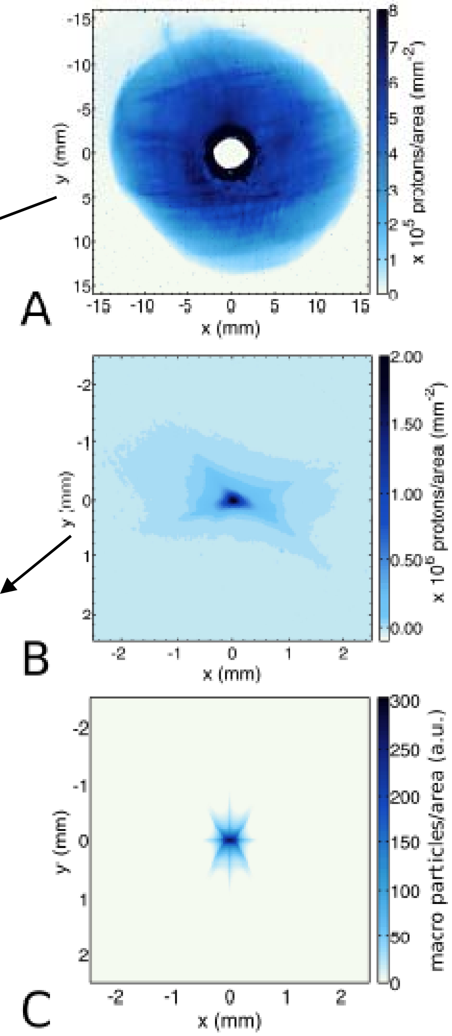


TNSA

Miniature Magnetic Lenses Can Be Used to Focus Laser Produced Ion Beams.*

- Quasi-neutral beam is easily stripped of co-moving electrons by strong permanent (NdFeB) magnets
- 8×10^5 protons were focused to a spot 1000 times smaller!
- Line-outs show a Lorentzian focal spot $f=\sigma/(x^2 \times \sigma^2)$, where 2σ= 286 μm Horz. (173 μm Vert.)





14 MeV proton beam at 40mm from target

14 MeV proton beam at mag. lens focus

Calculated 14 MeV beam at magnet focus

With Matthias Geissel, Jens Schwarz, Patrick Rambo, Sandia National Laboratories and Jörg Schütrumpf, TUD Darmstadt - M. Schollmeier, et al., Phys. Rev. Lett. **101**, 055004 (2008)

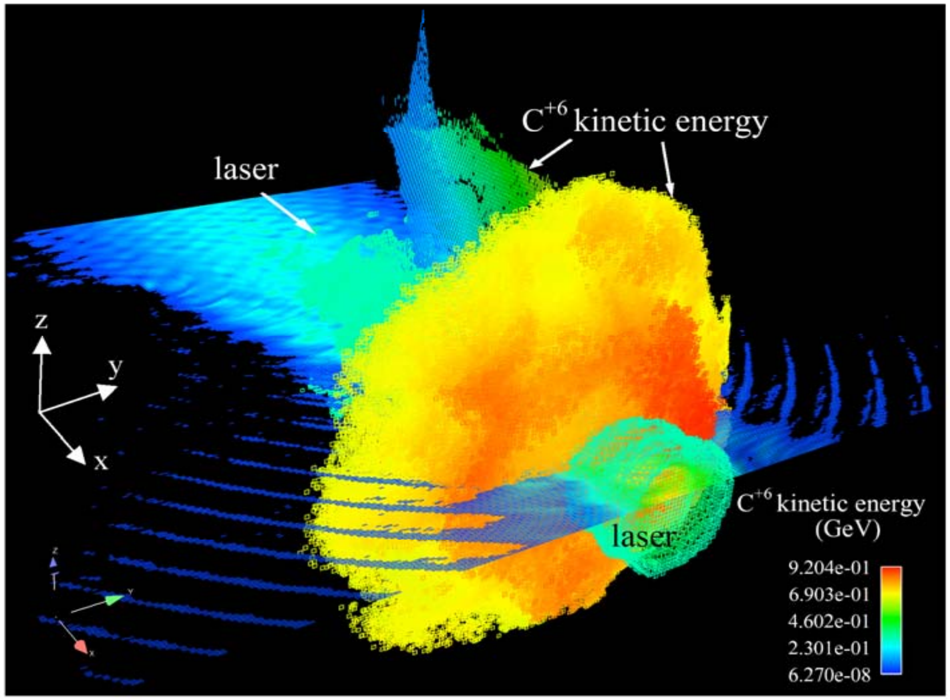
Results

3D simulation of RPS Carbon acceleration

Circular polarization, 30nm C and $I_0=10^{21}$ W/cm^2 & 312 fs pulse

Our largest simulation to date on ion acceleration (run on Roadrunner base system):

- Physical domain 25x25x20 μm w. solid target density
  14×10^9 cells, 21×10^9 particles, 4096 processors
- Contrasting with sim. size at the time of the proposal:
  0.5×10^9 cells, 2.2×10^9 particles, 510 processors
- 3D visualization using EnSight server-of-servers mode enables viewing, analysis of very large (multiple-TB) data sets.

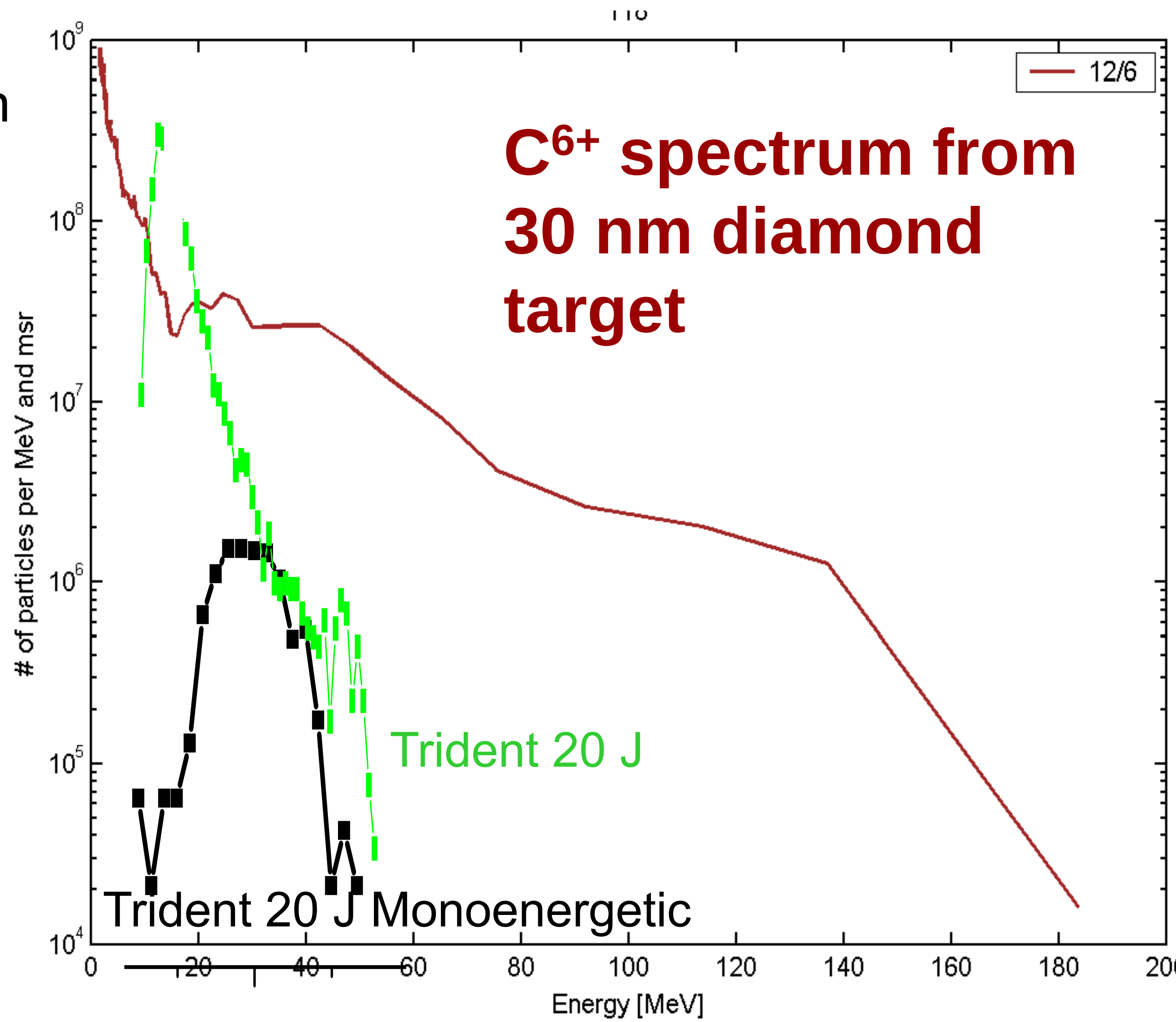


- VPIC has been modified to run efficiently on Roadrunner (Opteron hosted hybrid supercomputer with 12960 IBM Power Xcell 8i chips)
- We anticipate an additional factor of ~10 in speed over Opteron, enabling routine trillion-particle PIC simulations
- We have obtained a significant allotment of time (13 million hours, >1/3 of time when whole system is available) on the full 3 Pflop/s (single precision) Roadrunner system

Results

High laser-pulse contrast on thin targets improves Carbon acceleration.

- 180 MeV Carbon with 40 J at high contrast using plasma mirrors.
- Compared to 50 MeV C^{5+} with 20 J at low contrast.
- Expected 75 MeV from high contrast scaling.

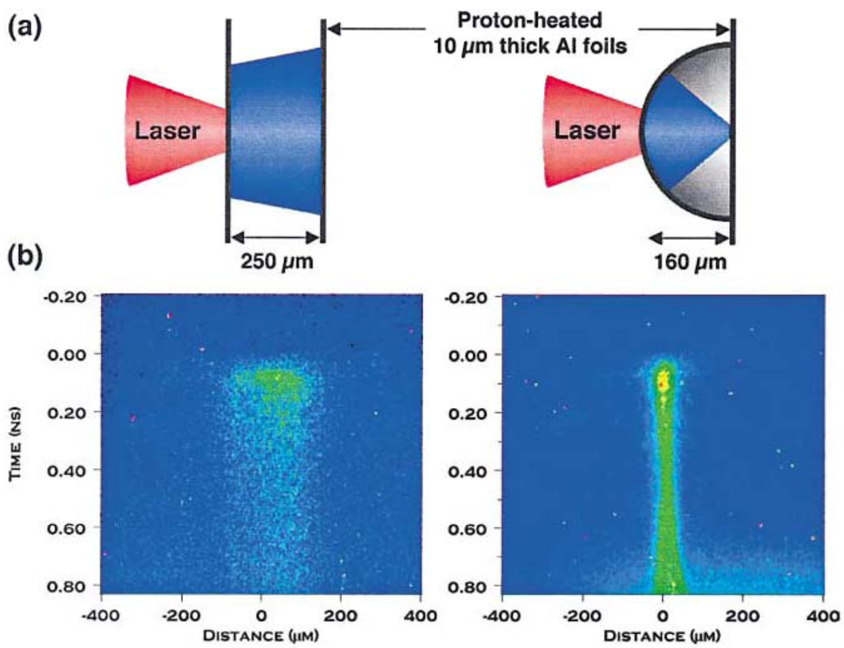


TNSA

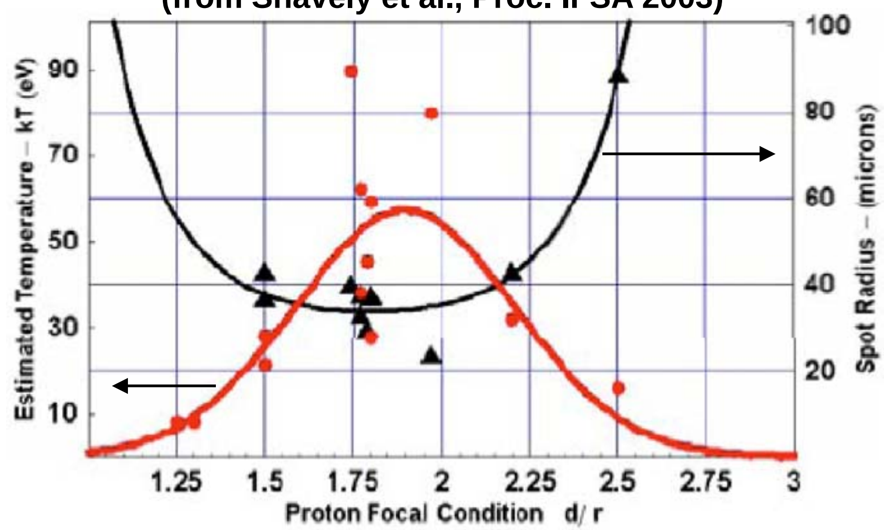
The ion-beam focusing is influenced by target-surface geometry and by the radial profile of the electric sheath.

- Ballistic proton focusing has been demonstrated with hemi-shell targets.*
- Focus is beyond center of curvature due to divergence induced by sheath radial profile.

Measurement at JANUSP, LLNL



Data from 250 J, 1 ps pulses at Gekko (from Snavely et al., Proc. IFSA 2003)



* Patel *et al.*, Phys. Rev. Lett. **91** (2003) 125004

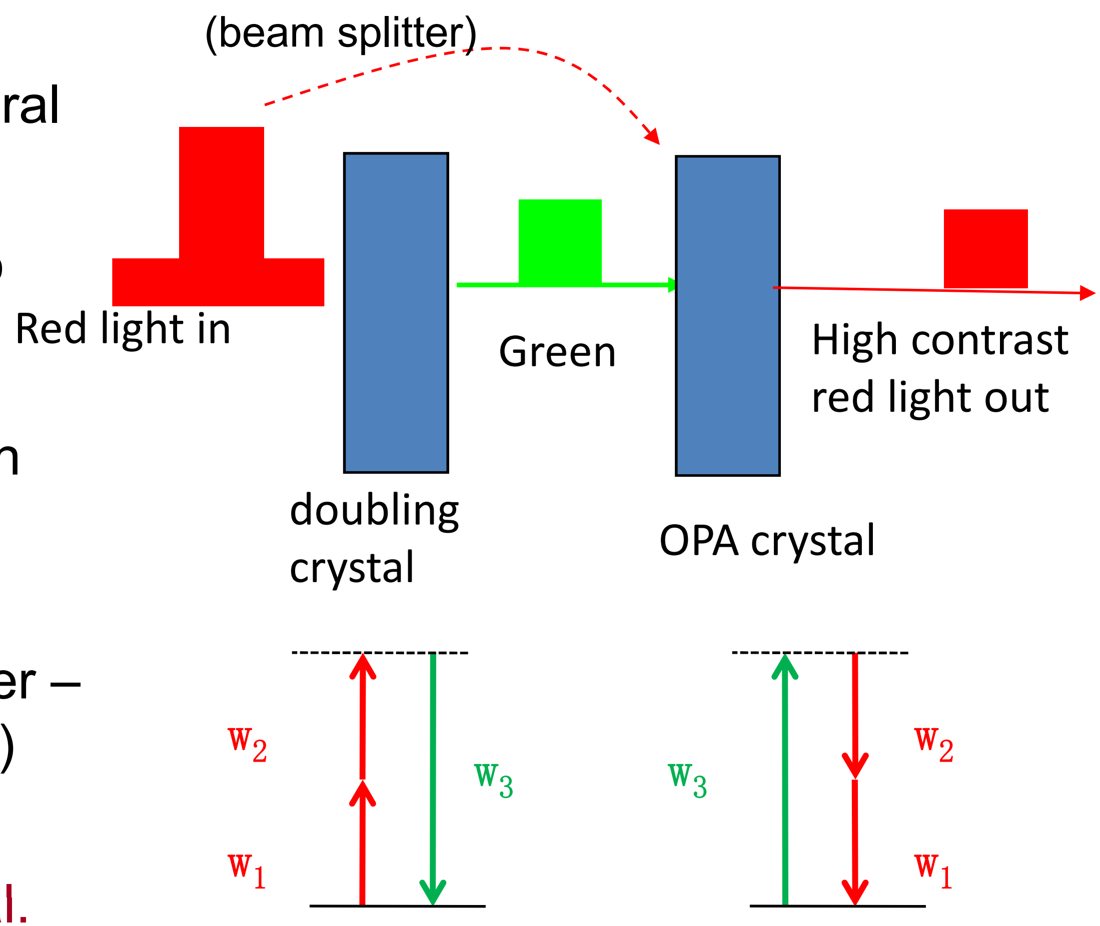
LANL approach to contrast cleaning is to double red to green and then reverse the process.

- Motivated to find scalable approach operating at low intensities which avoid B integral and vacuum chamber

- Green to red requires seed to dictate how energy divides, and is otherwise known as optical parametric amplification (OPA)

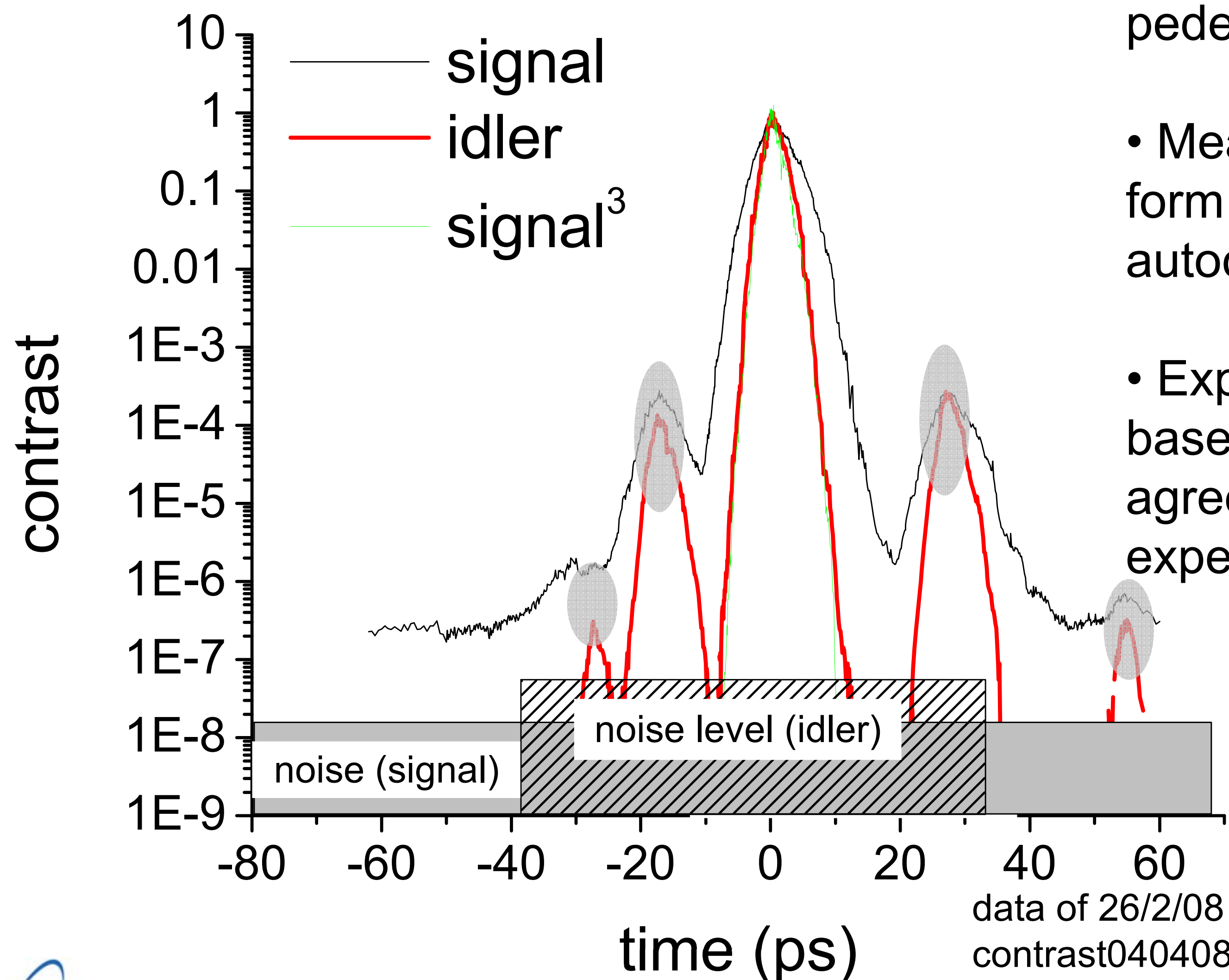
- Short pulse pump windows generation of high contrast idler – SHORT PULSE OPA (SPOPA)

- Original split signal pulse is amplified, but still has pedestal. Idler grows from noise, has ~ no pedestal.



Predict net ~ 10% optimized efficiency for a cleaned pulse.

Contrast measurement shows cubic cleaning, as expected from theory.

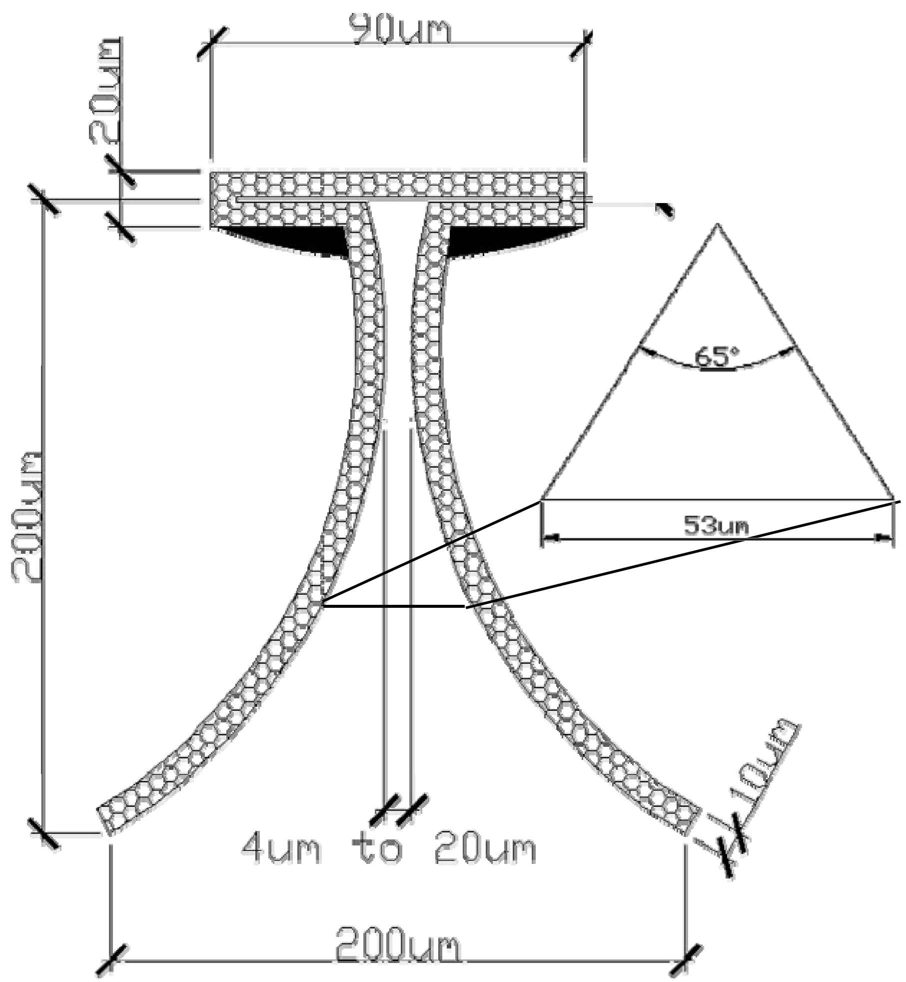


data of 26/2/08
contrast040408.opj

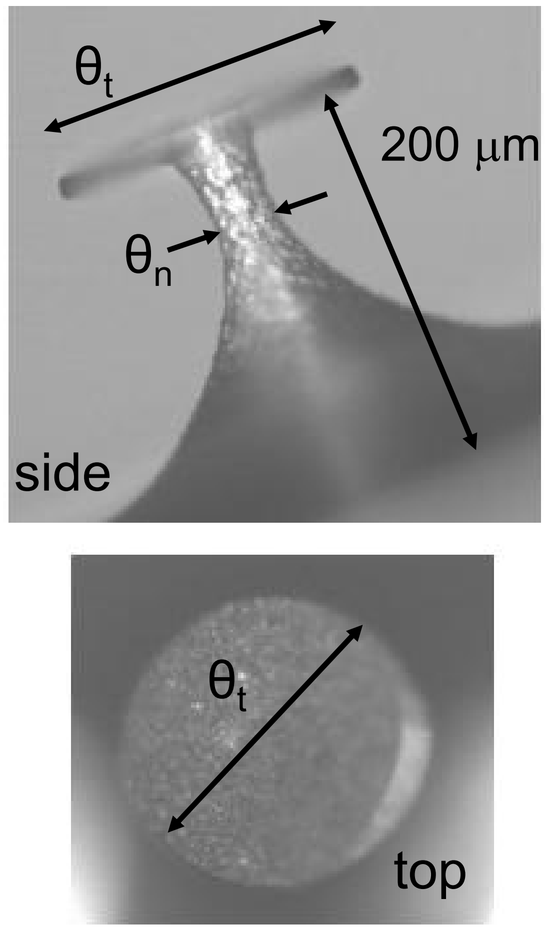
- Noise around 5 x 10^{-8} limiting observation of pedestal after cleanup
- Measurement artifacts form after cleanup, in autocorrelator
- Expect cubic relation based on low gain, agreement with experiment (green curve)

Target morphology:
Improved TNSA via novel cone targets

Typical Target Shape and Dimensions



Flared Flat-Top Cone



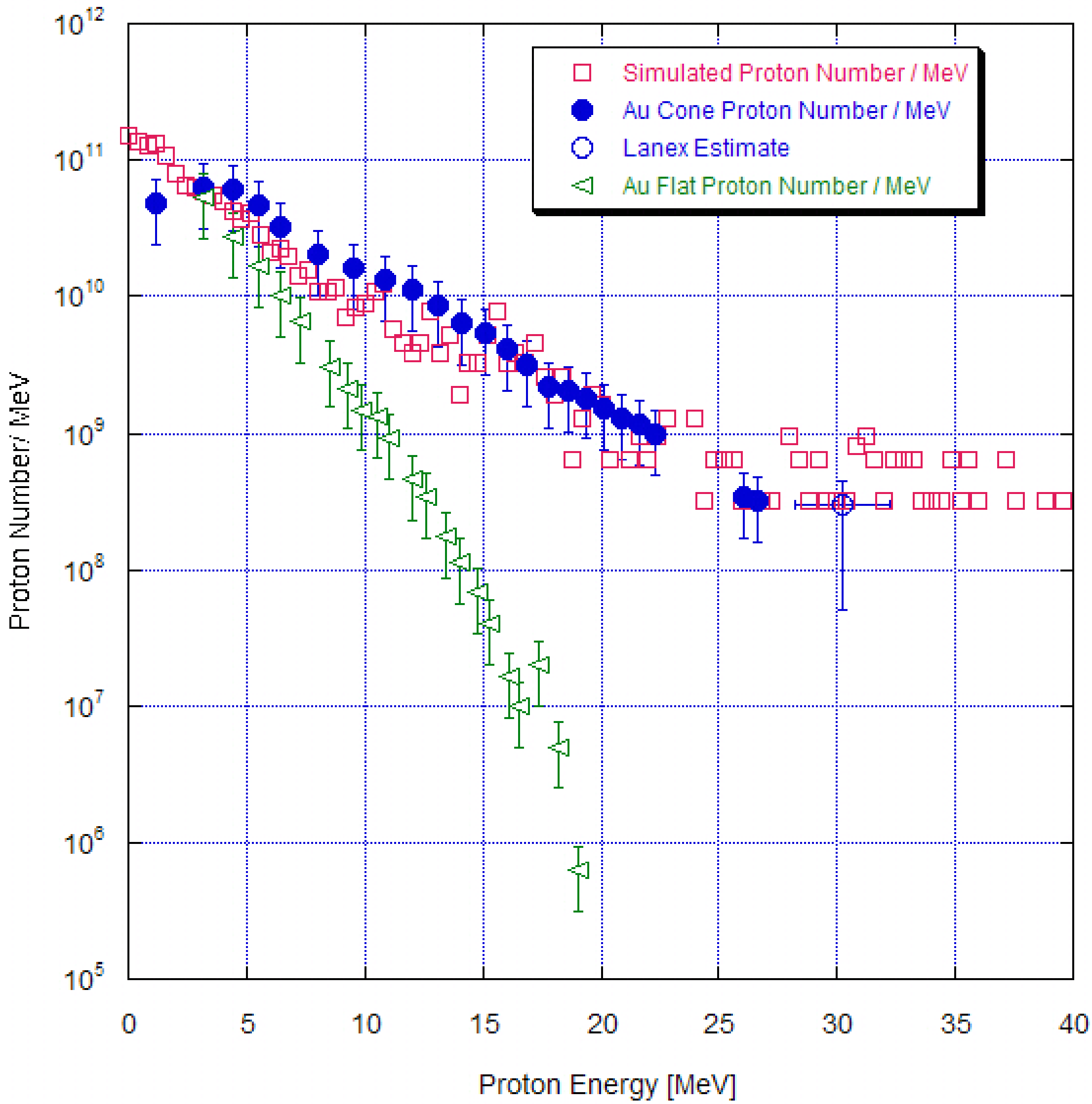
θ_n = 15 -135 μm

θ_t = 75 - 440 μm

Results

Simulated Flat-Top Cone vs. Experiments

- 2-D PICLS simulation
- Reproduces spectrum well, if assumptions are made about source size.
- And encourages us that we had more than 30 MeV, possibly up to 40 MeV!
- We know from previous simulation work that cone increase the hot electron population

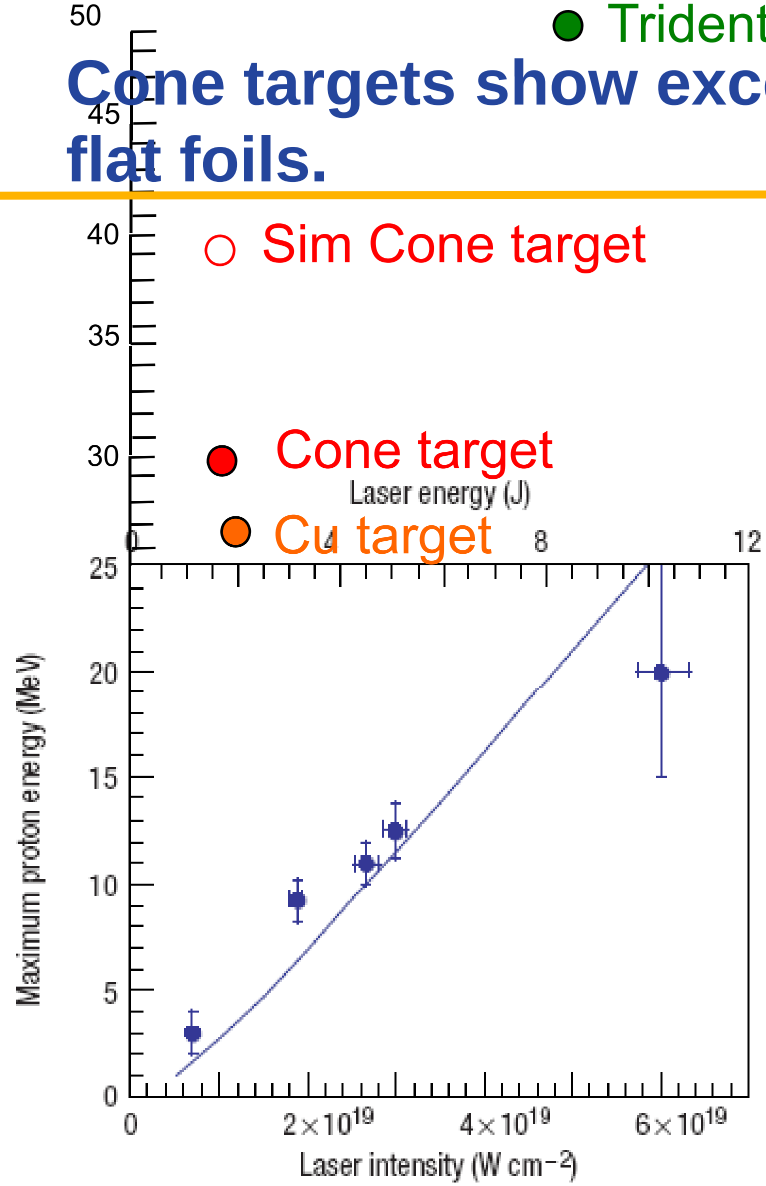


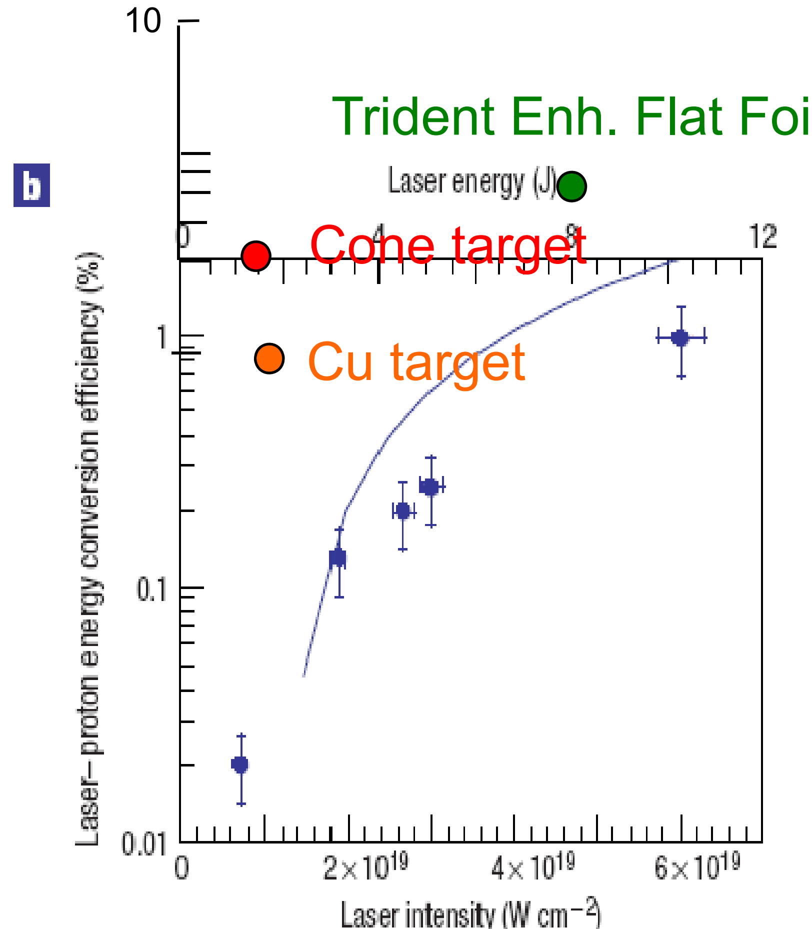
K. Flippo, *et al. Phys. Rev. Lett.* (submitted)

K. Flippo, *et al. Phys. Plasma* May 2008 [invited]

Results

Cone targets show excellent performance compared to flat foils.





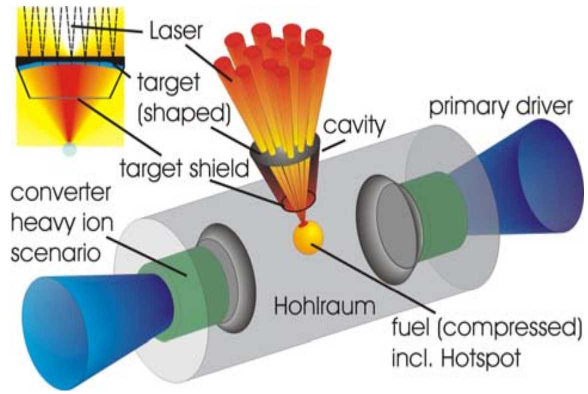
Trident: τ =600 fs, I=1×10^{19} W/cm^2

(τ_{laser}= 320 fs for protons > 4 MeV)

From J. Fuchs *et al.*, Nature Physics **1,** 199 (2005)

Los Alamos NATIONAL LABORATORY EST. 1943 Trident LMU NNSA

Quasi-monoenergetic mid-Z ions have potential advantages as a fusion ignitor beam.

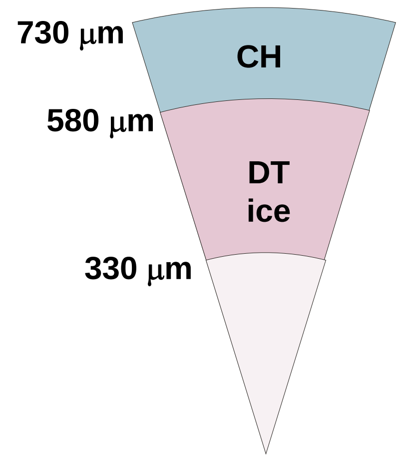


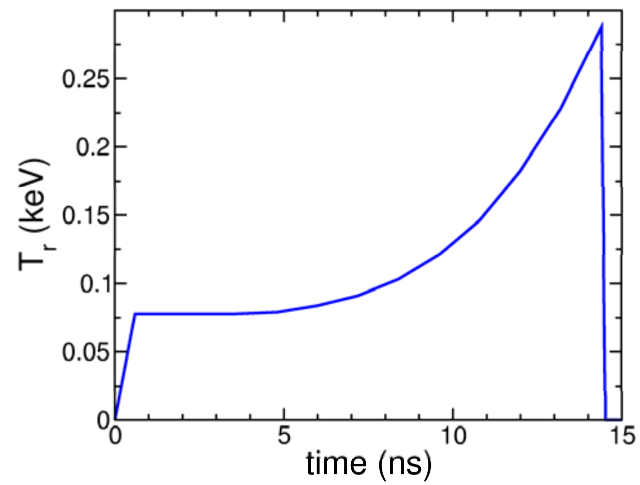
- Requirements for Inertial Fusion Energy:
  - Compressed fuel ~ 500 g/cc
  - 10 kJ ignitor beam ranging within (~ 25 μm)[3]
  - E.g., 10^{14} C ions at ~ 400 MeV
- Potential advantages over electron* or proton-based[1] FI:
  - Monoenergetic ion source far from the fuel
  - Range is better matched (efficiency)
  - Sharp deposition (efficiency)
  - More robust ion-beam transport
  - Fewer particles required (easier target Fab.)
- Potential performance:
  - Fusion **gain of 50-100**, assuming laser-beam conversion efficiency of 10%[2]

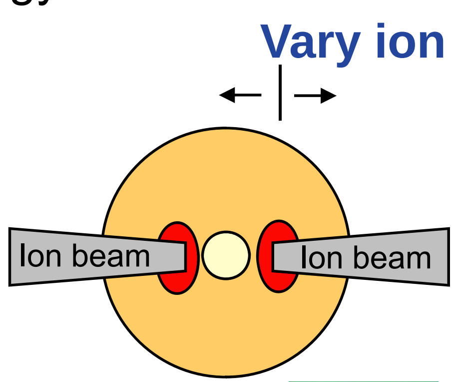
* Tabak *et al*., PoP **1**(1994) 1626
[1] Roth *et al.,* PRL **86** (2001) 436
[2] JJ. Honrubia et al., 2008 Hirschegg Wkshop

Integrated LASNEX designs in 2D for proof of principle experiments have been carried out with LASNEX hydro code.

- Simulated proof of principle experiment:
  - Capsule with cryogenic DT, plastic ablator
  - Various ignitor beam species
- Capsule implosion
  - Compression with radiation source
  - 14.2 ns pulse (foot + $P \sim t^{3.5}$ pulse)
  - Energy absorbed: 35.5 kJ
  - Fuel density: $\rho_{DT} \sim 150$ g/cc
- Two (symmetric) ignitor beams
  - Vary ion energy (C: 375 – 750 MeV ± 10%)
  - Beam energy: 7.2 kJ Ea.







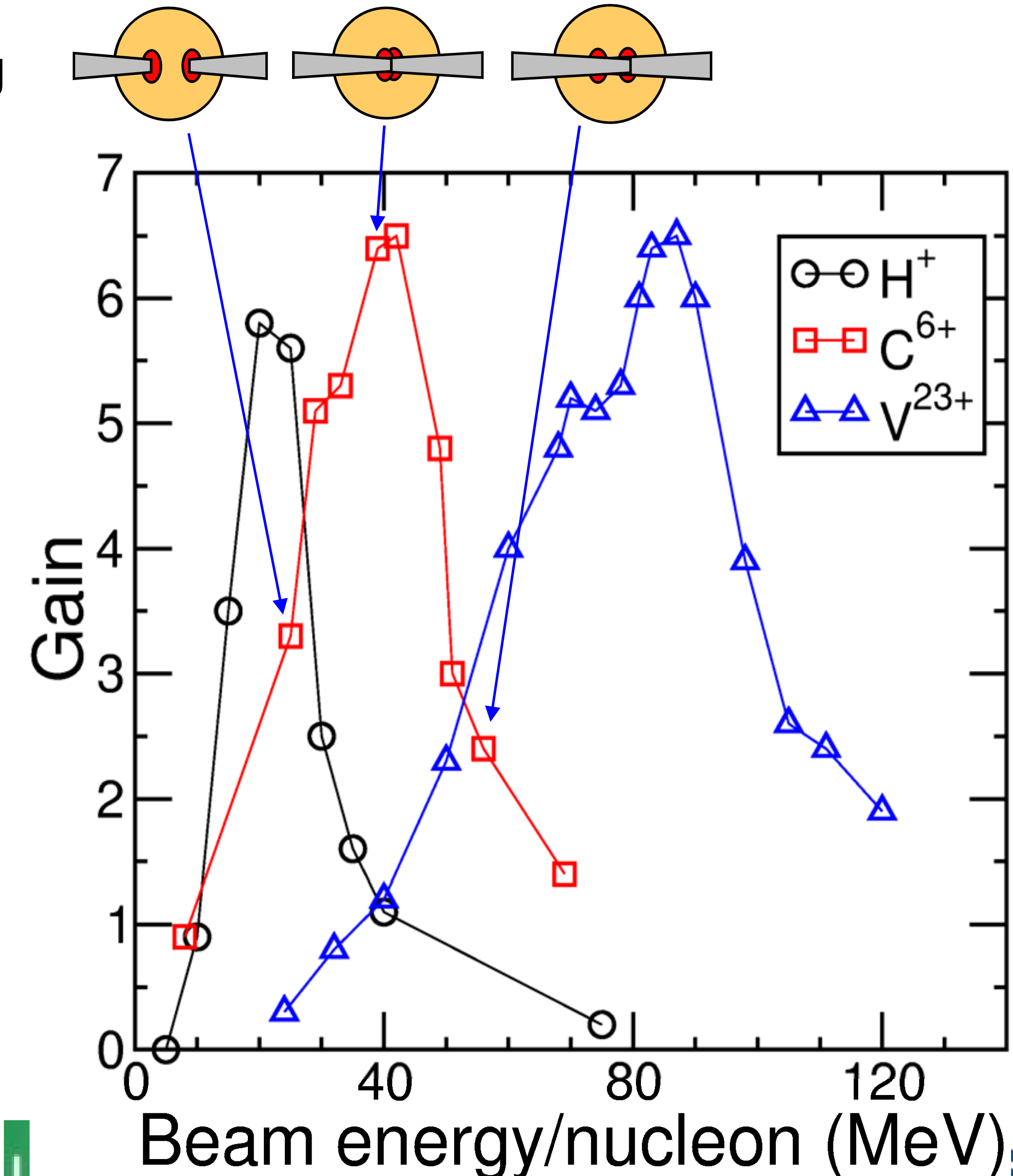
For all ignitor beam ion species studied, gain is max when counter-propagating beams overlap.

- Beams are a pair of counter-propagating 7.2 kJ ion beams injected along capsule symmetry axis
- energy spread: +/- 10%

- Beams injected so that deposition occurs at time max DT fuel density in compressed capsule

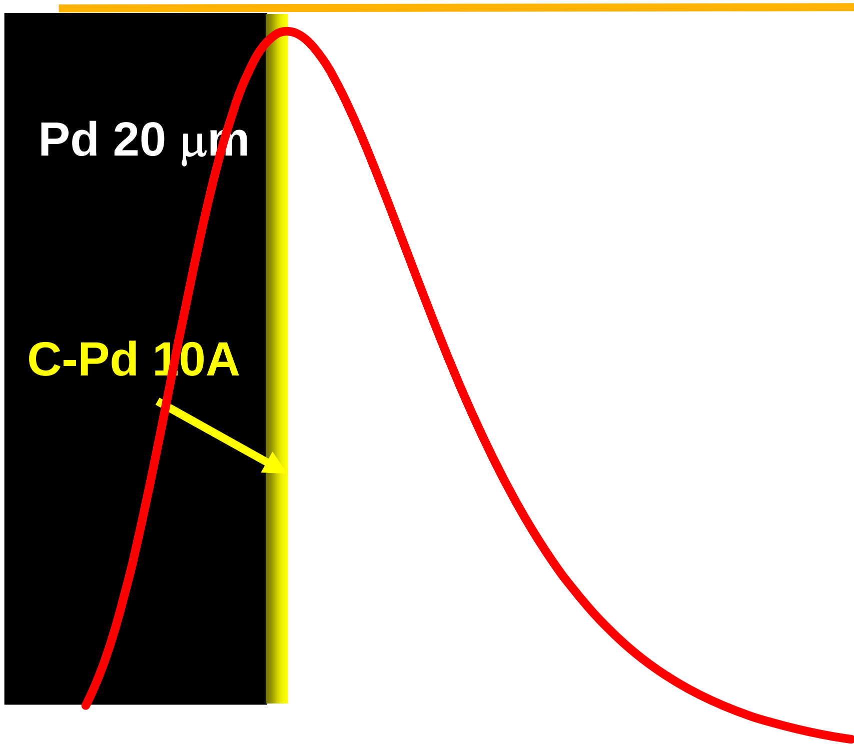
- Maximum gain found to be similar for all ignitor ion species

- Maximum gain peaks with slight beam overlap.
  - Importance of ion-stopping model.



Los Alamos NATIONAL LABORATORY EST. 1943 Trident

Properties of the observed mono-energetic carbon bunch



beam angle ~5°:

~ 8.6 x 10^8 C^{5+}

Pulse length ~ 1 ps

⇒ Current A = 0.7 kA

Longitudinal emittance:

Laser: ε_l ~ 3 x 10^{-6} eV s

CERN SPS: ε_l ~ 0.5 eV s

Transverse emittance (for H+ beams):

Laser: ε_n < 0.004 mm mrad

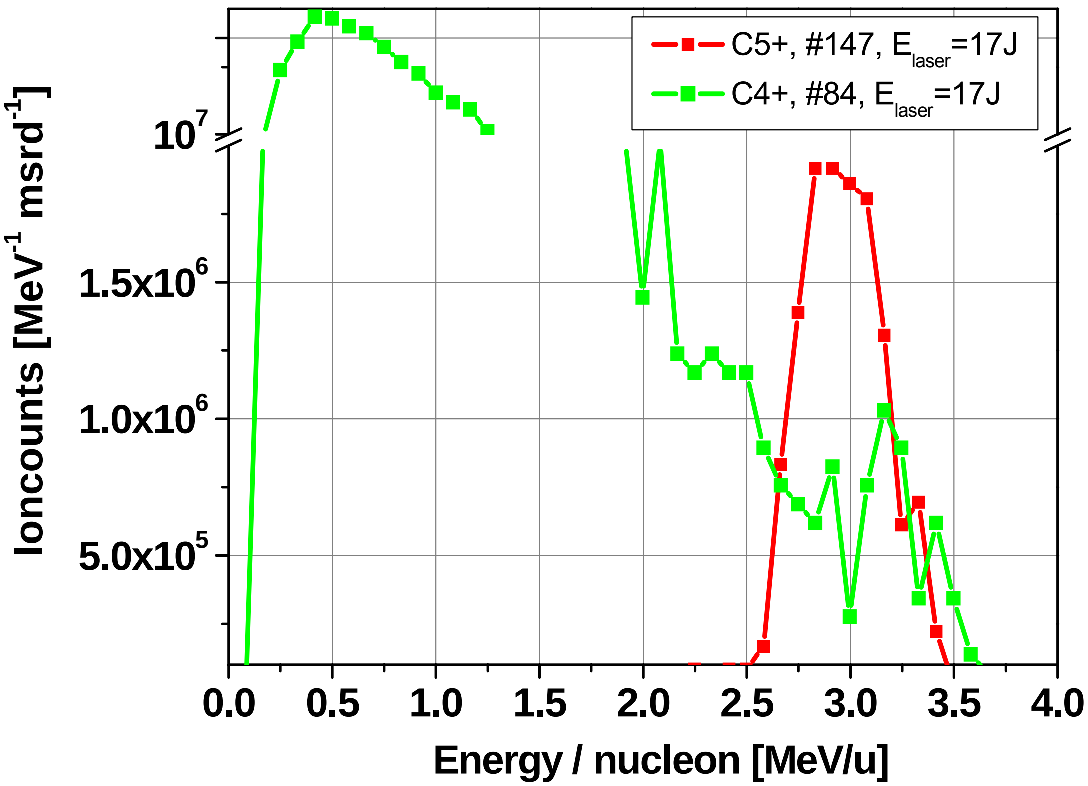
Cowan et al., PRL 92, 204801 (2004)

CERN SPS: ε_n ~ 1 mm mrad

- only 1 Carbon charge state at 0°

Results

Beam parameters; comparison with typical C-spectrum



Mono-energetic Beam:

SA	~ 65 msrd
N	~ 8.6×10^8 C^{5+}
E_{tot}	~ 5 mJ
C_{tot}	~ 0.7 nC
CE	~ 0.03 %

Maxwellian Beam (same energy range):

SA	~ 65 msrd
N	~ 4×10^8 C4+
E_{tot}	~ 2 mJ
C_{tot}	~ 0.26 nC
CE	~ 0.01 %

- Factor 2 increase in the number of high energy ions
- Factor 2.5 increase in energy content and conversion efficiency
- Factor 3 increase in beam current

Successful low- and mid-Z ion acceleration at Trident

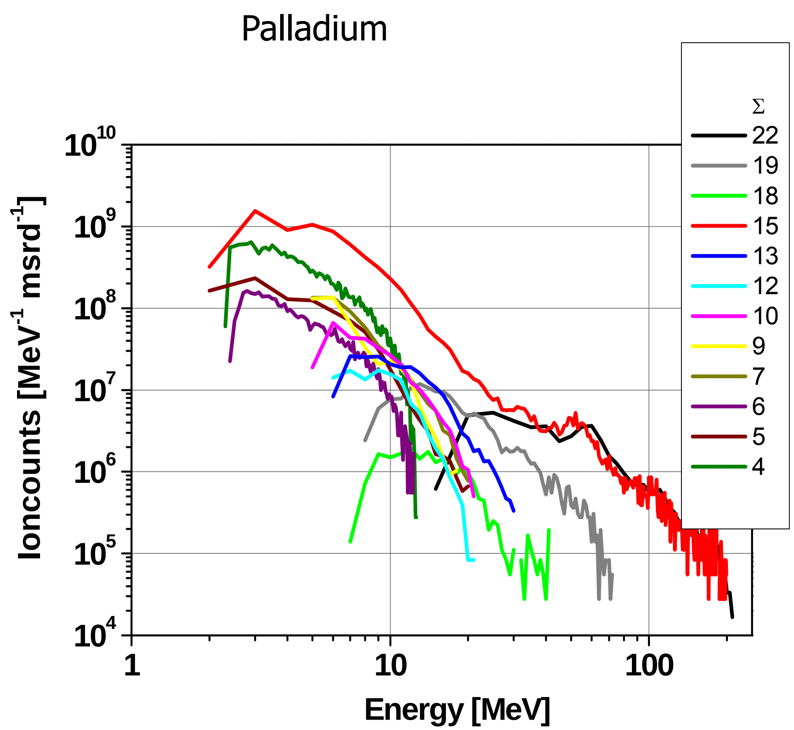
Results

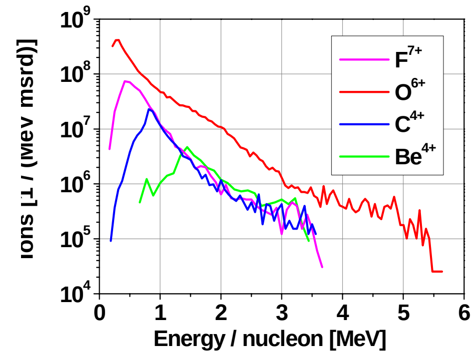
beam angle ~10°:
~1.8×10^9 Pd^{22+} with E > 1 MeV/u.

$E_{total,Pd22+}$(1MeV/u) ~ 38mJ ⇒ conversion efficiency
η_{Pd22+}(1MeV/u) ~ 0.2%.

total #Pd^{22+} ~ 2.4×10^{10},
$E_{total,\ Pd22+}$ ~ 184mJ ⇒
η_{Pd22+} ~1.1%.

The conversion efficiency for laser energy into Pd-ions of any charge state is on the order of a few %.





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Laser

- Nova
  - Nova PW