LA-UR-13-28644

Approved for public release; distribution is unlimited.

Title: Applications of laser-driven ion beams

Author(s): Fernandez, Juan C.

Intended for: Archive

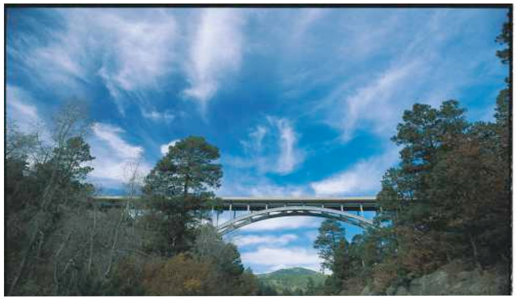
Issued: 2013-11-08

Applications of laser-driven ion beams

presented by:

Juan C. Fernández

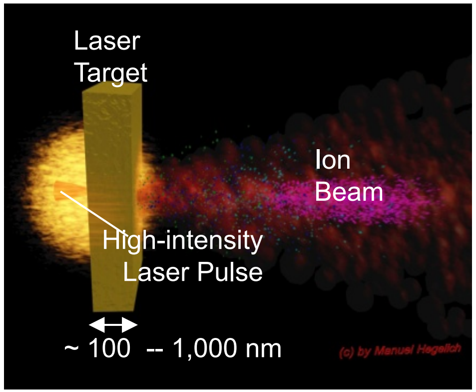
Los Alamos National Laboratory

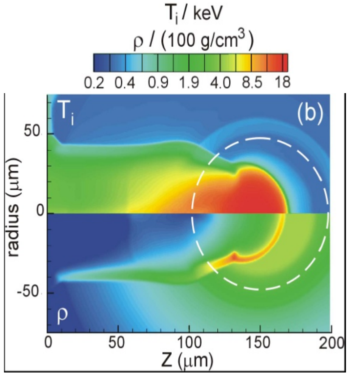


contributions from:

LANL & Collaborating Institutions

(Acknowledgements throughout the talk)





presented to:

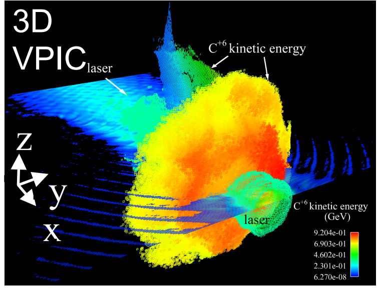
LANL ICF Update

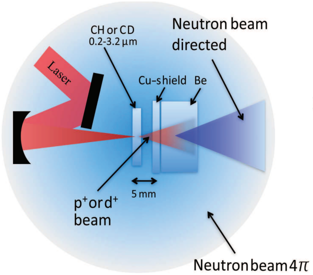
October 21, 2013

(2013 ICHED

Saint Malo, France

June 23-28, 2013)





Acknowledgements:

- LANL
  - **B. J. Albright**, P. Bradley, **A. Favalli**, D. C. Gautier, K. Falk, J. C. Fernández, N. Guler, B. M. Hegelich*, **C. Huang**, D. Jung[1], S. Letzring, S. Palaniyappan, R. Shah, E. Vold, L. Yin, C. Wilde & H. Wu[2] and others
- Univ. Politécnica de Madrid
  - J. Javier Honrubia
- Ludwig Maximilian Univ.
  - D. Habs, D. Kiefer, V. Liechtenstein, J. Schrieber
- Technical Univ. Darmstadt.
  - **M. Roth**

Funding:

- Trident operations: LANL ICF and Weapons Science Campaigns
- Project: LANL LDRD program, HEDLP Joint DOE-NNSA program

* Now at Physics Dept., Univ. Texas, Austin

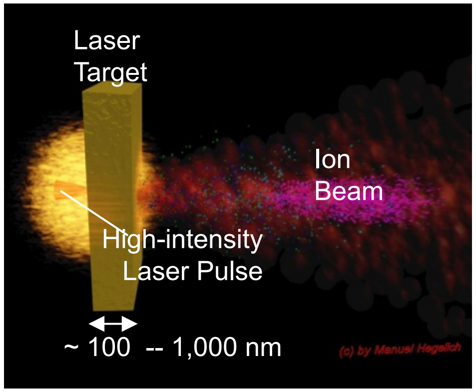
[1] Now at Queen's Univ., Belfast

[2] Now at Zhejiang University, Hangzhou, China

Outline

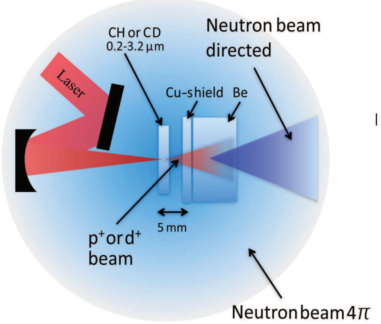
- Physics of ion acceleration
  - Mechanisms

Ion Accel.



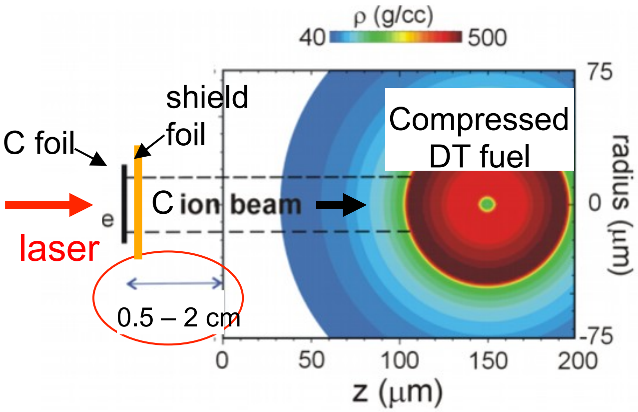
- Applications
  - Neutron generation
  - Mix across sharp interfaces with heterogeneous species
  - Ion-fast ignition
- Summary

Neutrons



Mix

Ion FI



Taxonomy of ion acceleration mechanisms:

Laser-driven ion acceleration mechanisms		**Laser-plasma regime**	
		Opaque	**Relativistically Transparent**
Laser target morphology	**Thick (micro) foils, solid density**	TNSA	
	Thin (nano) foils, solid density	RPA-LS, LICPA	BOA, ISWA
	Near critical-density, long plasmas	RPA-HB, CESA, MVA	

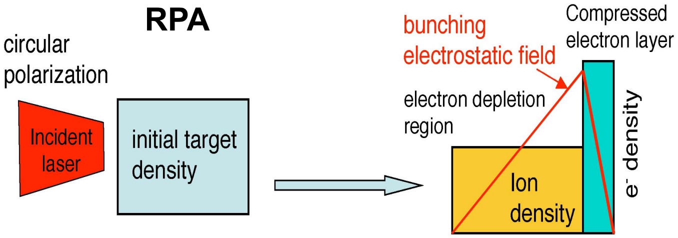
Glossary of laser-driven ion acceleration mechanisms	
BOA	Break-Out Afterburner
ISWA	Ion Solitary Wave Acceleration
RPA-LS	Radiation Pressure Acceleration, Light-Sail Regime
RPA-HB	Radiation Pressure Acceleration, Hole-Boring Regime
CESA	Collisionless Electrostatic Shock Acceleration
MVA	Magnetic Vortex Acceleration
LICPA	Laser Induced Cavity Pressure Acceleration
TNSA	Target Normal Sheath Acceleration

From Juan C. Fernandez, et al., review article to be published in Nuclear Fusion, 2013, *Fast ignition with laser-driven proton and ion beams*

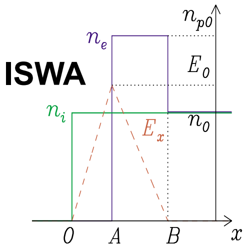
Many *distinct* ion acceleration mechanisms

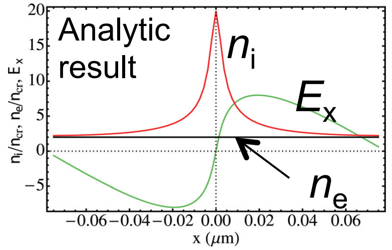
Thin foils, initially **solid-density** plasmas:

- Radiation Pressure Acceleration, light-sail regime (RPA-LS)*
    - Requires **opaque** plasma, clean charge separation (Circ. Pol. to minimize e- heating)

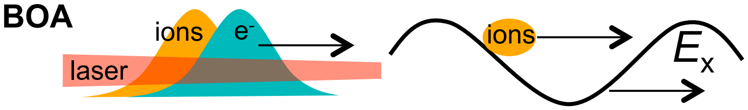


- Ion Solitary Wave Acceleration (ISWA)[1]
    - Charge Sep. → Soliton → **RIT** → ISWA



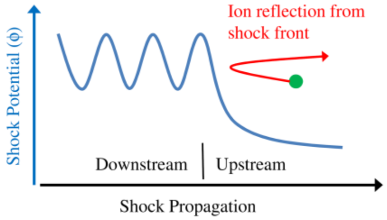


- Breakout afterburner (**BOA**)[2]
    - **RIT**→ Electron-ion drift → wave → BOA

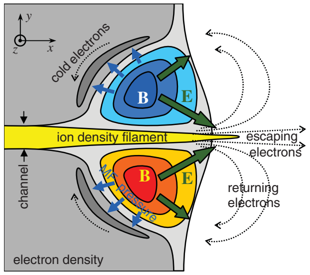


Thick (10's μm), **near n_{cr}** density, opaque plasmas:

- RP – Hole Boring Regime (RPA-HB)[3]
- Collisionless Electrostatic Shock Acceleration (CESA)[4]

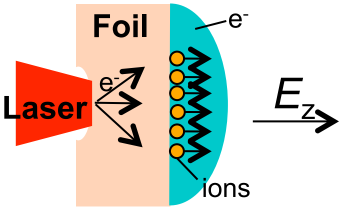


- Magnetic Vortex[6] (channel→e- current →B_θ bubble → e- expulsion → electrostatic E_z)



Thick, solid-density opaque foils:

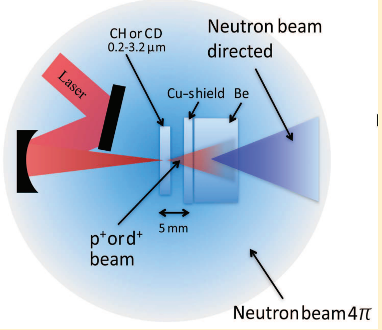
- Target normal sheath acceleration (TNSA)[5]



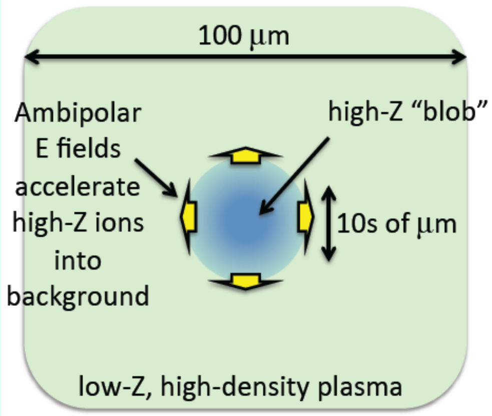
* A Macchi *et al* 2010 New J. Phys. **12** 045013; [1]D Jung *et al* 2011 PRL **107** 115002; [2]L. Yin *et al* 2007 PoP **14** 056006; B Albright *et al* 2007 **14** 094502; [3]T Schlegel T *et al* 2009 PoP **16** 083103; [4]J Denavit 1992 PRL **69**, 3052; [5] S Hatchett *et al* 2000 PoP **7** 2076; [6]S V Bulanov *et al* 1996 PRL **76** 3562

Selected applications enabled by laser-driven ion beams

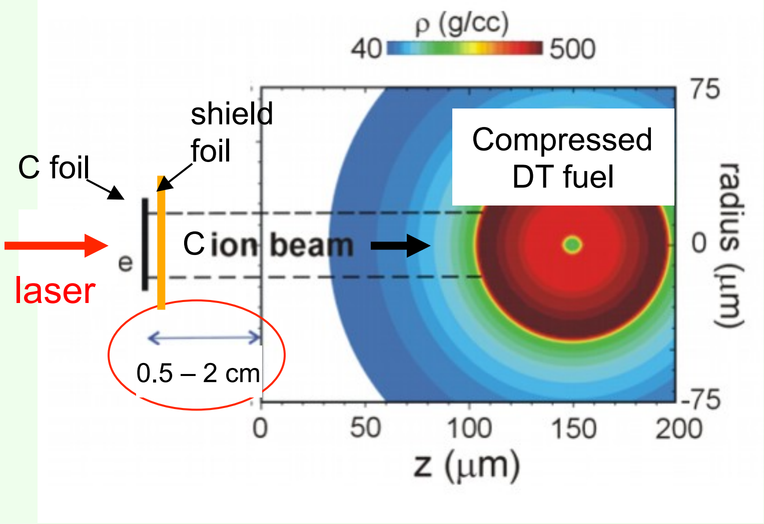
1. Laser-driven neutron beams (Roth)
   - HED-target probe
   - Active interrogation
   - Materials science

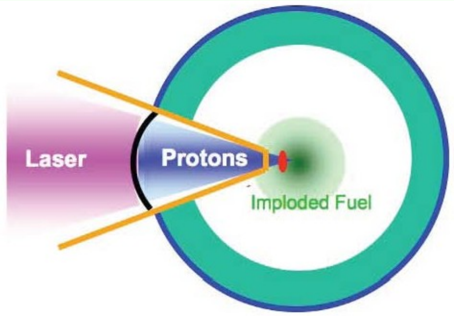


2. Evolution of high-Z or solid particulates in low-Z plasmas (Albright)
   - Mix



3. Ion-driven FI (Fdez.)
   - Laser-driven proton or ion beam ignitor of compressed DT fuel

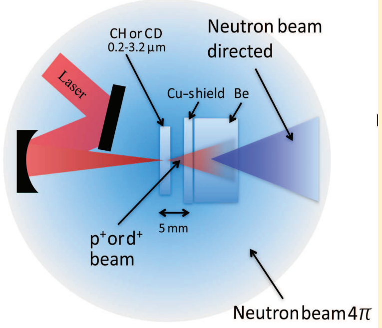




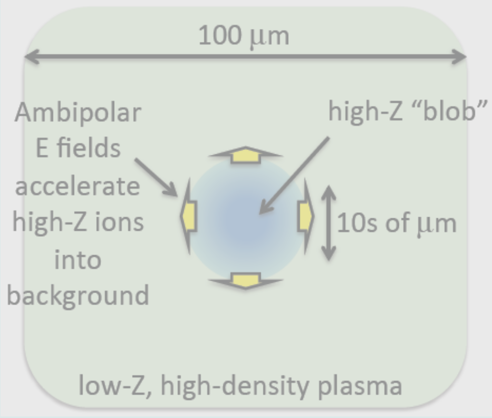
neutrons

Selected applications enabled by laser-driven ion beams

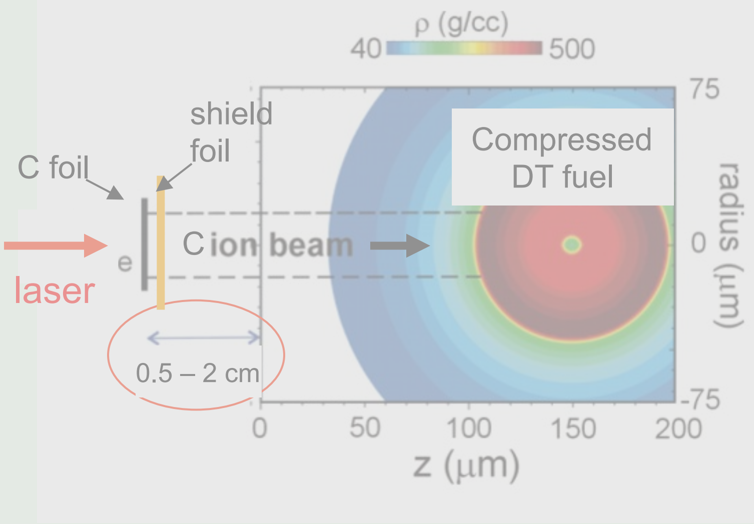
1. Laser-driven neutron beams
   - HED-target probe
   - Active interrogation
   - Materials science

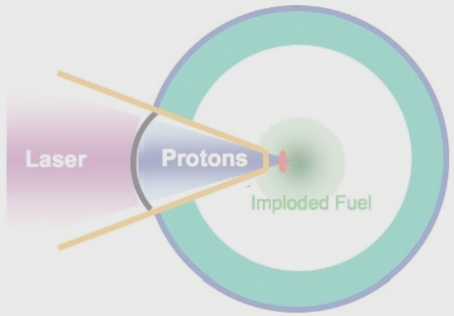


2. Evolution of high-Z or solid particulates in low-Z plasmas
   - Mix



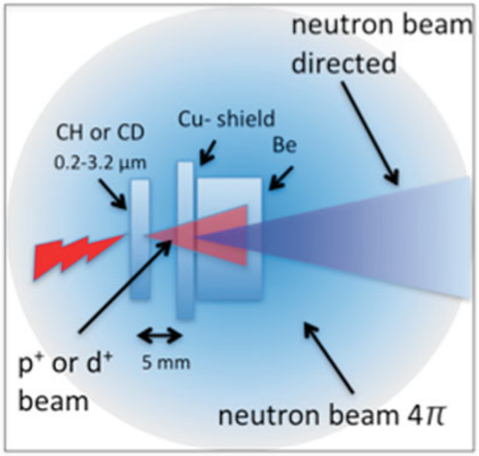
3. Ion-driven FI
   - Laser-driven proton or ion beam ignitor of compressed DT fuel



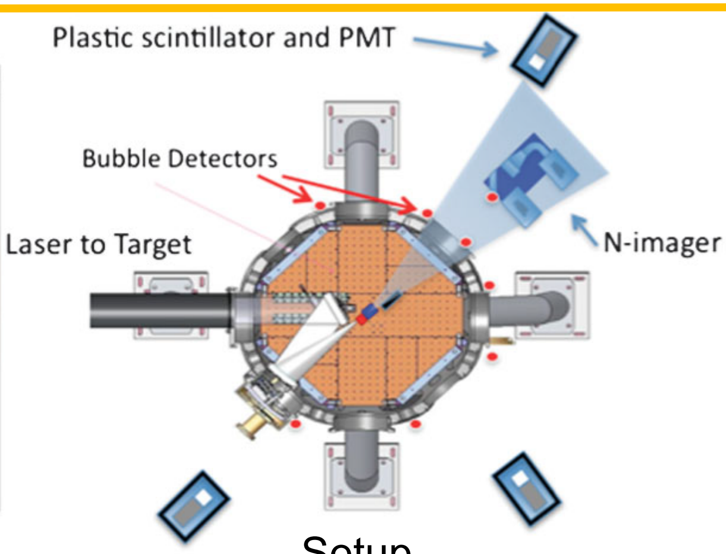


Record neutron production with Trident laser-produced deuterium beam using BOA*

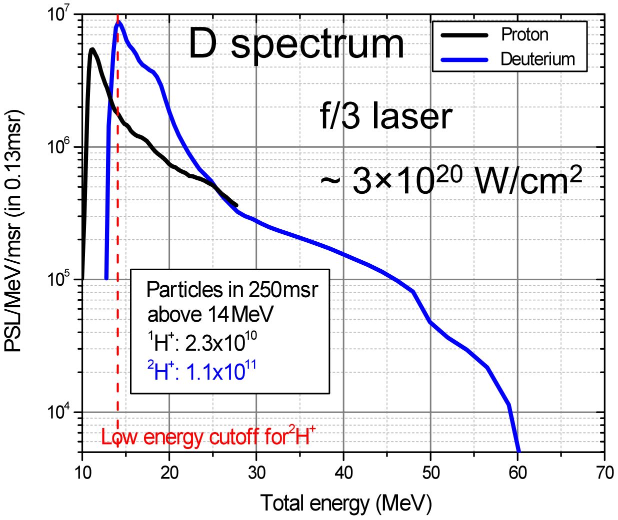
neutrons



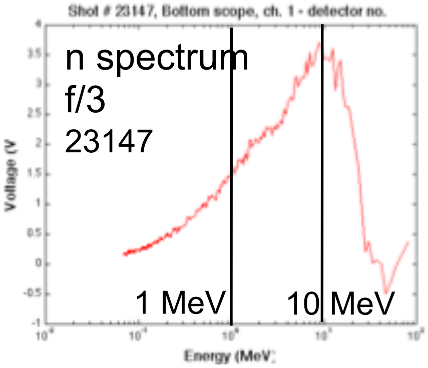
Concept

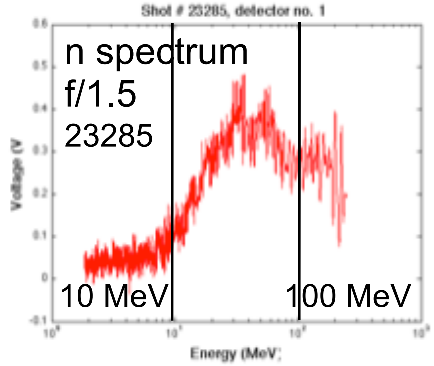


Setup



- Driven by D beam (BOA mechanism)
- Neutron source ~ ns, forward-directed (~ 0.25 - 1 Srad)
- f/3 laser: record laser-produced yield (~ 10^9 neutrons) & forward fluence (~ 5×10^9 n/strad = 50 neutrons/ μm^2 @ 1 cm), 5-15 MeV neutron energies (~ 10 MeV peak)*
- f/1.5 (~ 1.2×10^{21} W/cm^2): × 10 higher yield and forward fluence, peak energy to ~ 70 MeV, cutoff to ~ 150 MeV*





*M. Roth et al., PRL **110**, 044802 (2013); D. Jung *et al.*, accepted to PoP (2013), highlighted by APS, Nature and Physics World

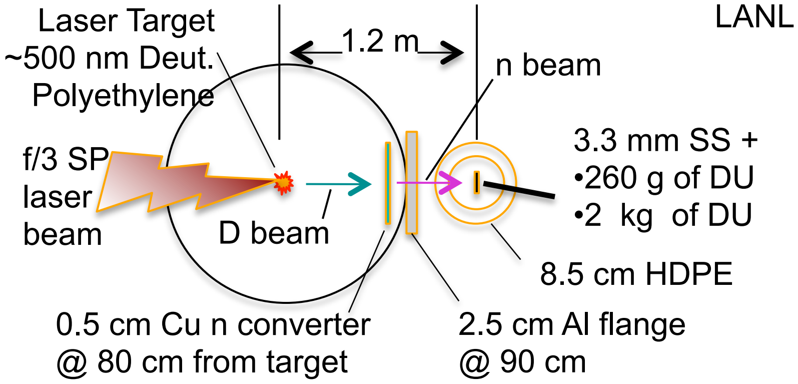
neutrons

Laser-based neutron source shown on Trident has demonstrated utility for active interrogation*

- Fission signatures for nuclear materials:
  - + Delayed and prompt fission neutrons,
  - + Delayed and prompt fission γ's
- Detectors
  - + Bubble & He-3 detectors (insensitive to γ's)
  - + TOF (γ flash & neutrons)
- Converters: Be (mm's from target), Cu (far)

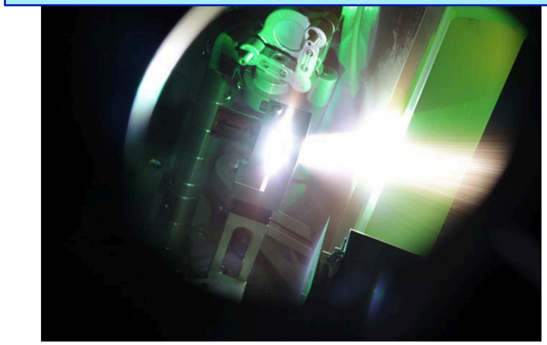
Active interrogation experiment on Trident

PI: A. Favalli*
LANL



- Application **results** so far:
  - + **Detected DU** with delayed fission neutrons with Be converter (more efficient but farther from sample)
  - + **Detected DU** with delayed fission neutrons with Cu converter (less efficient but closer to DU sample)
  - + **Irradiated Ge samples** ~ 500 n/μm^2 (radiation damage)

Using laser-driven neutrons to stop nuclear smugglers
LANL press release 6/4/2013

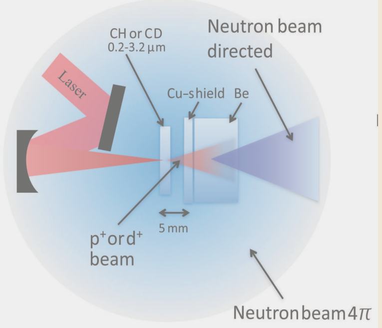


* LANL LDRD Director's Reserve, A. Favalli, PI, Early Career Research

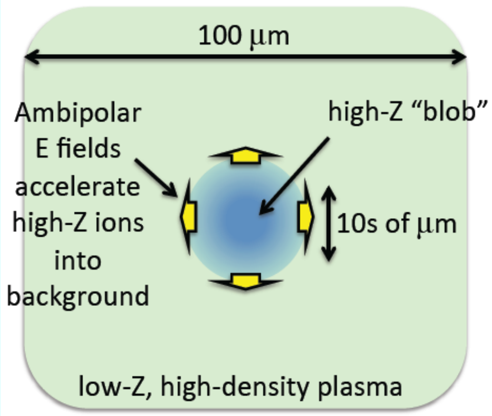
mix

Selected applications enabled by laser-driven ion beams

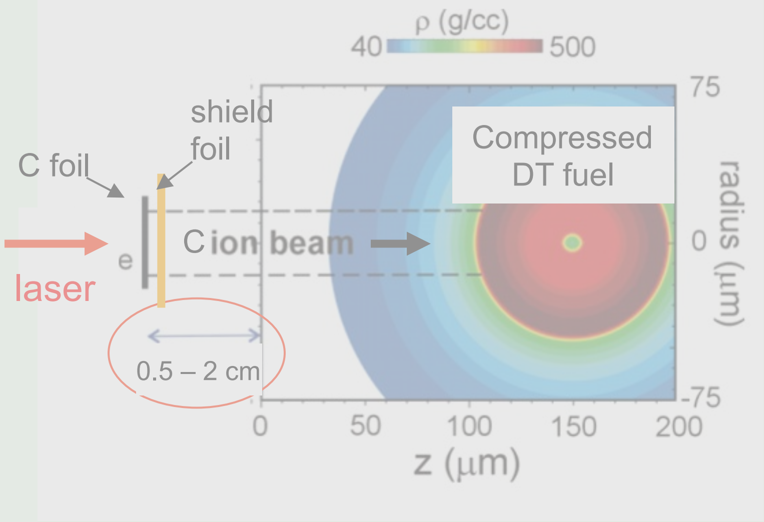
1. Laser-driven neutron beams
   - HED-target probe
   - Active interrogation
   - Materials science

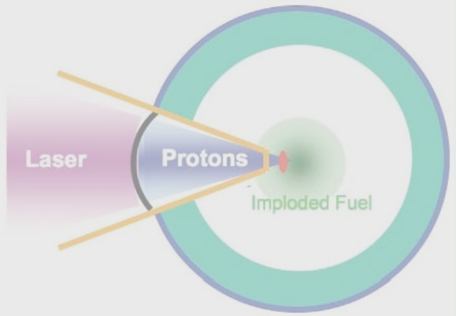


2. Evolution of high-Z or solid particulates in low-Z plasmas
   - Mix



3. Ion-driven FI
   - Laser-driven proton or ion beam ignitor of compressed DT fuel

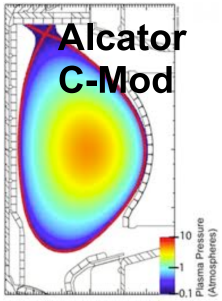




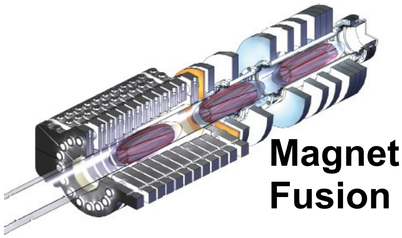
mix

Important to understand breakup & mixing of particulates & high-Z "blobs" in dense low-Z plasmas

- Ubiquitous problem, whether initial state is solid particulates or plasma "blobs"
  - E.g., comet tails, semiconductor manufacturing plasmas, tokamak edge plasmas, ICF & MICF implosions, …

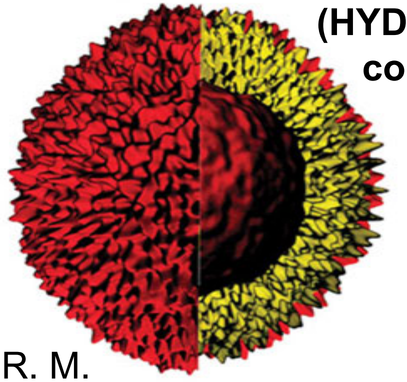


- May be key to understanding "mix" in dense plasmas
  - E.g., certain laser-fusion capsule ablators, Magnetized Target Fusion implosions
  - Atomic versus particulate **mix affects TN-burn**
  - 300-fold increase in temperature increases ion classical viscosity $\Theta^{5/2}$ by factor of ~ 10^6
  - True viscosity is uncertain, may invalidate our physical picture of compressible hydro mix (BHR*)
  - **Electrostatically-enhanced mix** may dominate



Magnetized Target Fusion (MTF)

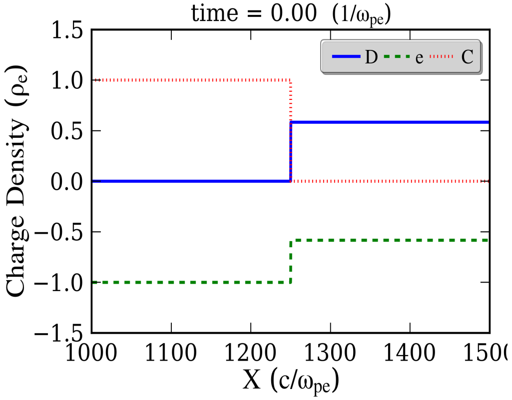
3D ICF capsule (HYDRA code)

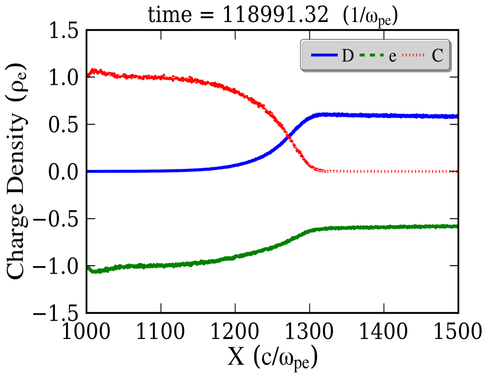


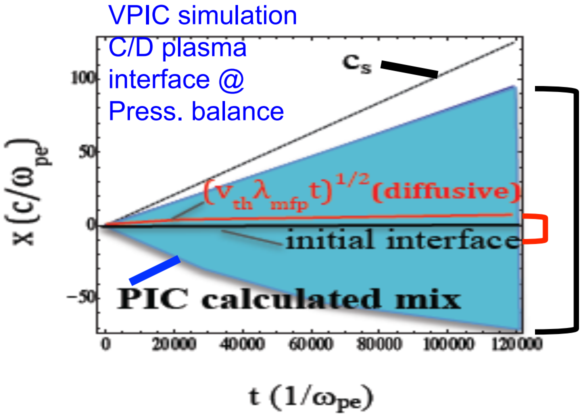
*(Besnard-Harlow-Rauenzahn), D. C. Besnard, F. H. Harlow, and R. M. Rauenzahn, Los Alamos National Laboratory Report No. LA-10911-MS, 1987; A. Banerjee et al., Phys. Rev. E **82**, 046309 (2010)

Mixing across sharp interfaces with heterogenous species likely dominated by plasma effects

- PIC simulations show multi-species plasma mixing at ~ sonic (ion-sound) speeds, >> diffusive speeds
  - ***Electrostatically-enhanced mix*** (EEM) requires experimental test
- VPIC simulation of representative case: isobaric, C-D interface





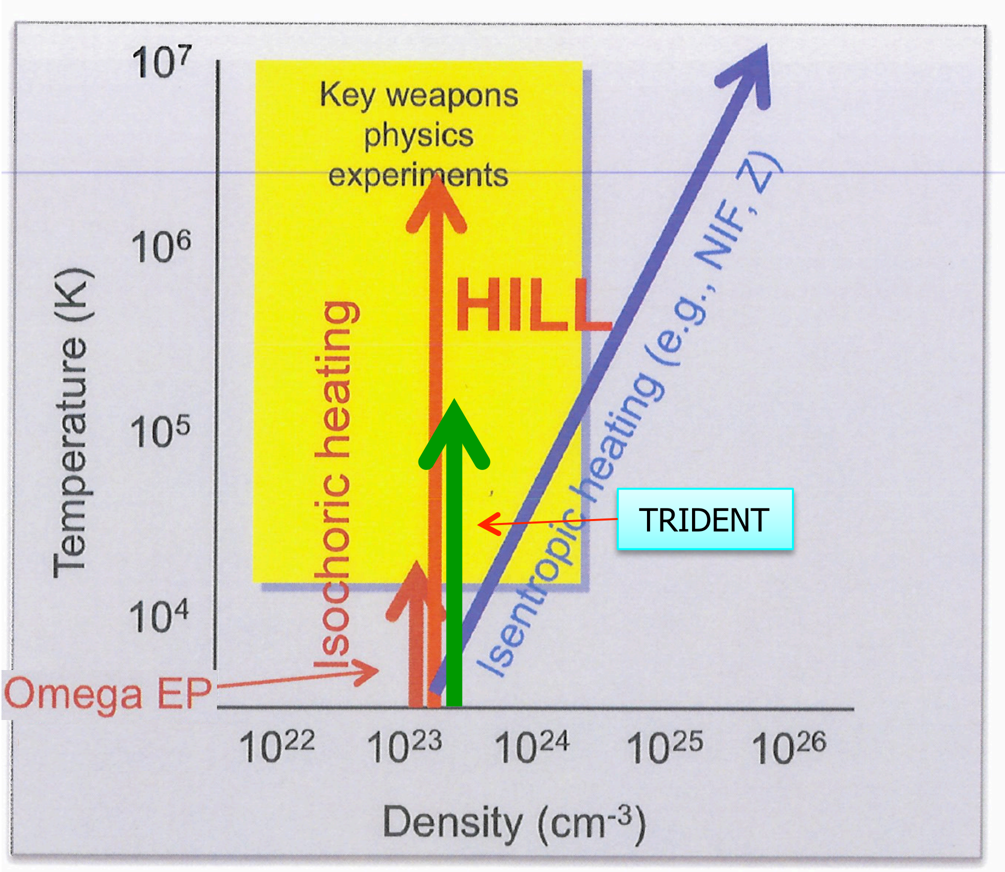


- May dominate "mix" in dense plasmas that affects TN burn
  - Plasma effects can be implemented in mix models like BHR*
- Designed an experiment on Trident to test EEM (new LDRD-DR)
  - Use BOA beams to ***isochorically heat*** a sharp interface

*(Besnard-Harlow-Rauenzahn), D. C. Besnard, F. H. Harlow, and R. M. Rauenzahn, LANL Report No. LA-10911-MS, 1987; A. Banerjee et al., Phys. Rev. E **82**, 046309 (2010)

Why hasn't this been experimentally tested before?

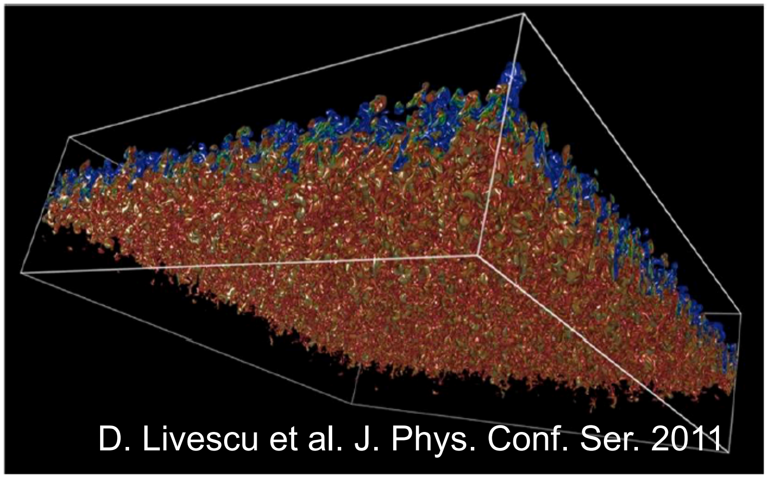
- Exploring the physics requires *macroscopic* (~0.1mm) quantities of matter under *quasi-uniform* conditions
- Heating must be *isochoric*, or faster than hydro disassembly (~ns) to avoid large gradients
  - Poorly matched to drivers like NIF and Z that operate over ~ns
- Other short-pulse lasers lack the required performance
- **Intense ion beams from Trident *can* do this**



Our motivation is to understand mix in the plasma phase

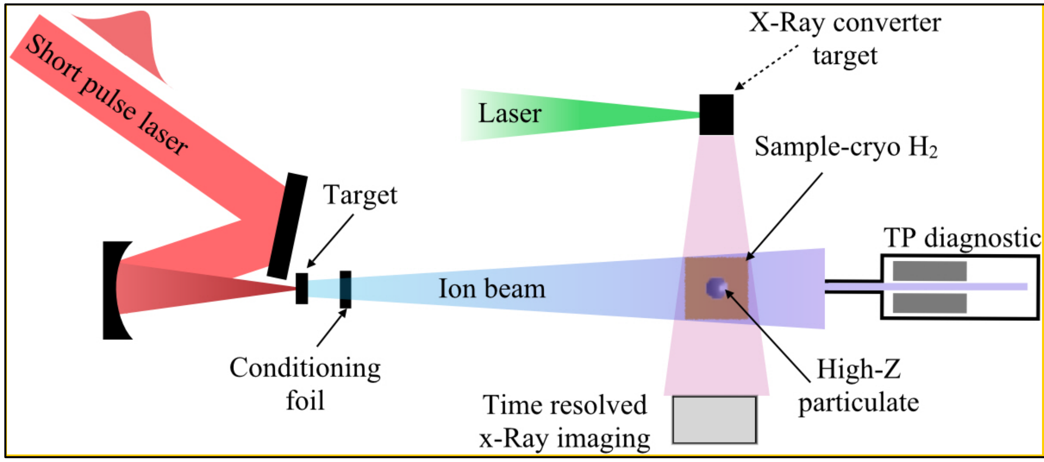
- Understanding mix is vital to being able to predict the onset and progression of thermonuclear burn
- The Laboratory has invested heavily in development of a Common Mix Framework based on extensions of the BHR model, intended to model mix in a range of conditions, from fluids to plasmas
- Additionally, plasma transport terms are going into Rage, as well as DNS codes used to inform the Common Mix Framework
- Verifying the existence of EEM would promote emphasis on improving present phenomenological, unvalidated (in the plasma regime) effort

■ ***No controlled mix experiments exist yet in the plasma phase*, where theory and simulations predict large electric fields at material interfaces that may greatly enhance atomic mixing**



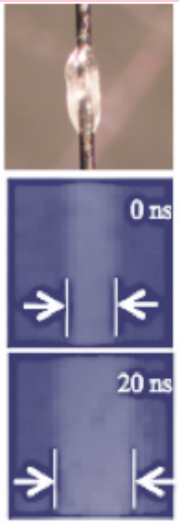
D. Livescu et al. J. Phys. Conf. Ser. 2011

Experiments on particulate evolution in dense plasmas on the Trident short-pulse laser have been designed.

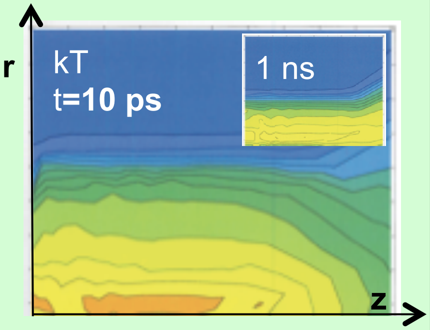


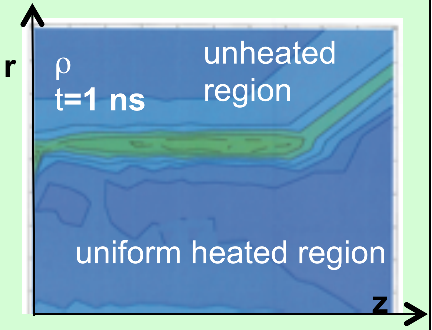
- Frozen H_2 using technique pioneered by TU Darmstadt or CH foam
- High-Z particulate, wire, foil, ~ 10 μm

Preliminary data



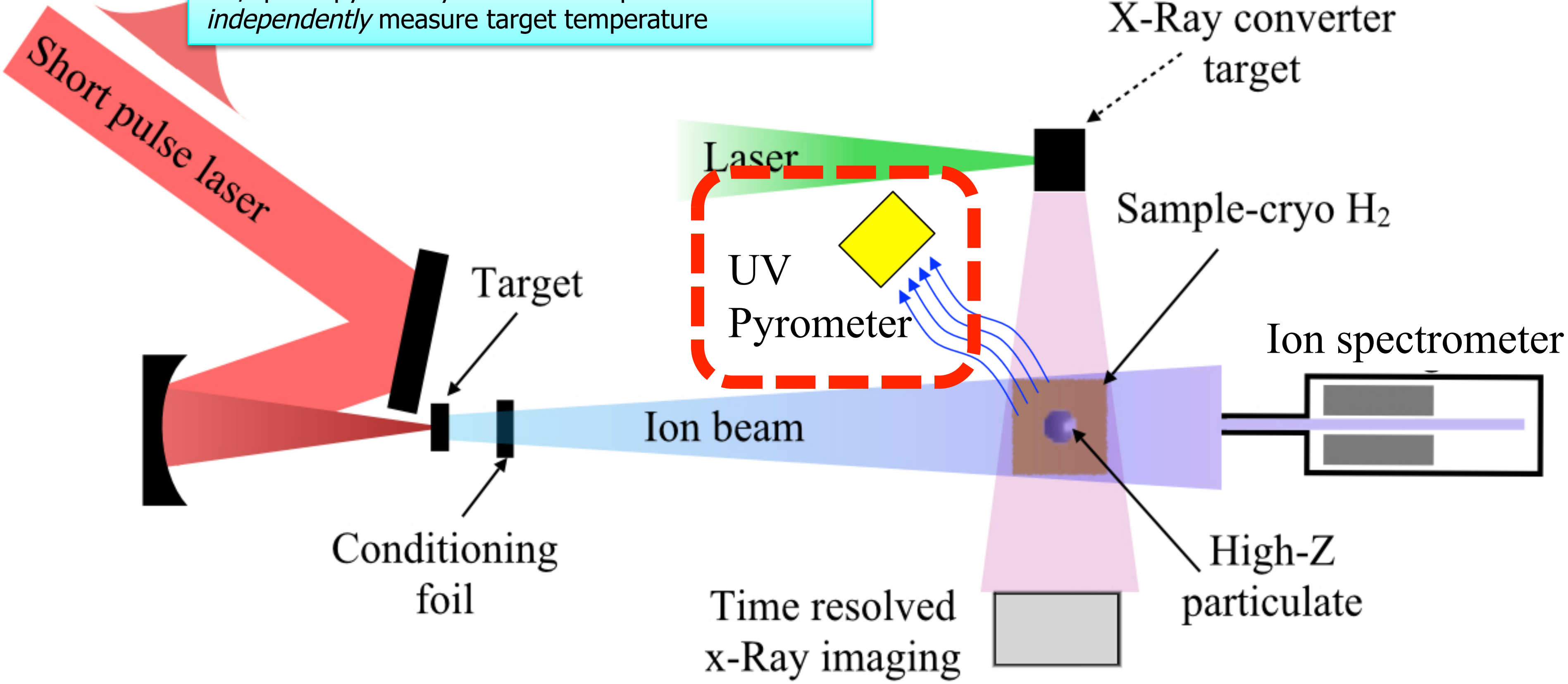
- Low-Z “background” dense plasma
  - Solid density, T_e ~ 1 -- 20 eV
  - Size ~ (100 μm)^3
  - Frozen H_2, CH_2, …
  - Heated by a Trident proton or C beam (ultra-thin CH_2 foils, BOA mechanism) NOT ranging in the sample (known energy deposition)
  - Quasi-homogeneous (simulation)





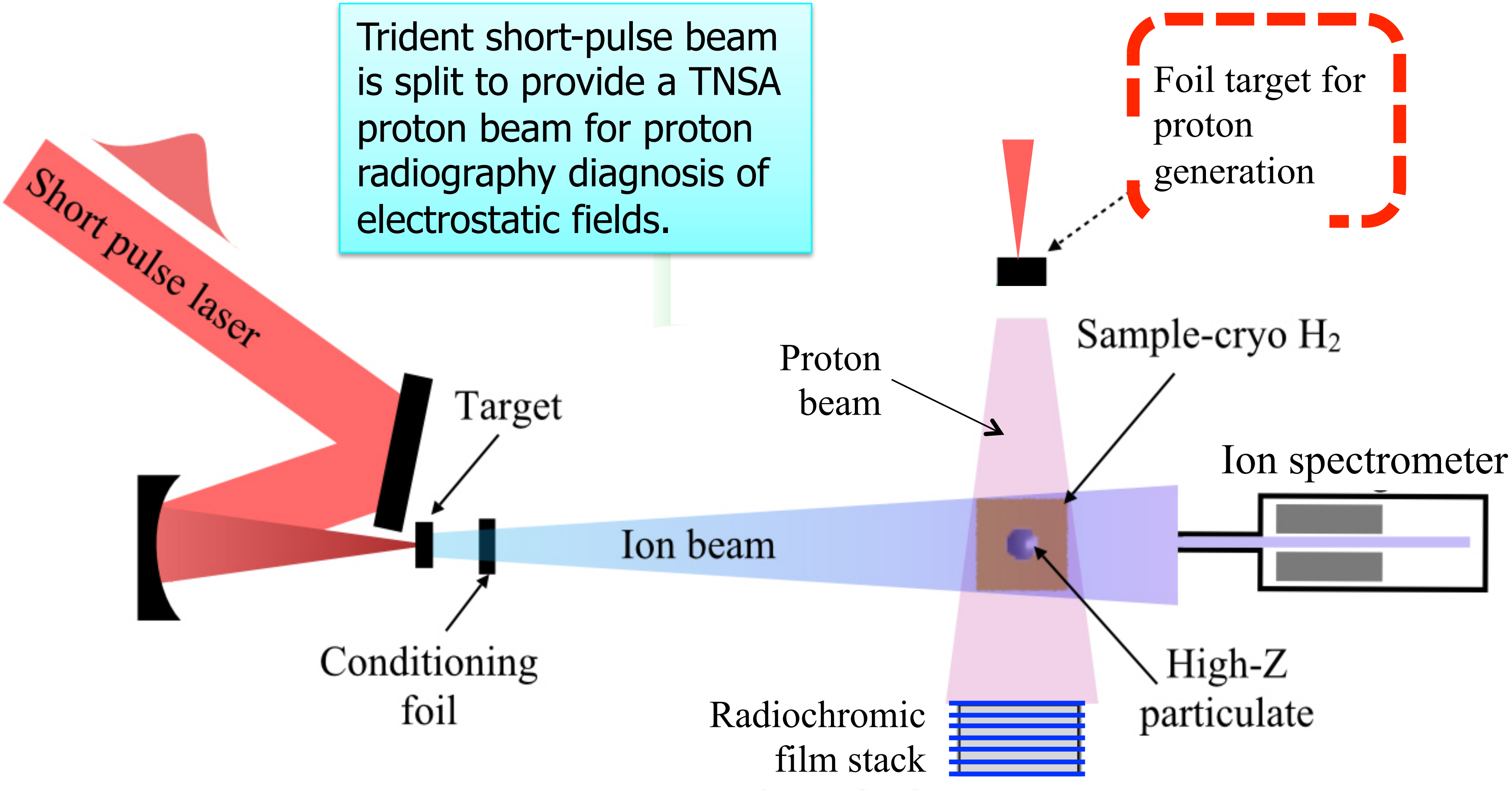
Experimental setup update I – UV pyrometry

UV/optical pyrometry will be developed to *independently* measure target temperature



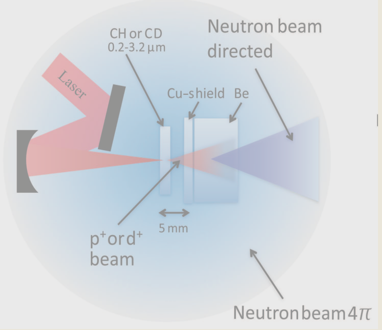
Experimental setup update II – proton radiography to be used to diagnose EEM

Trident short-pulse beam is split to provide a TNSA proton beam for proton radiography diagnosis of electrostatic fields.

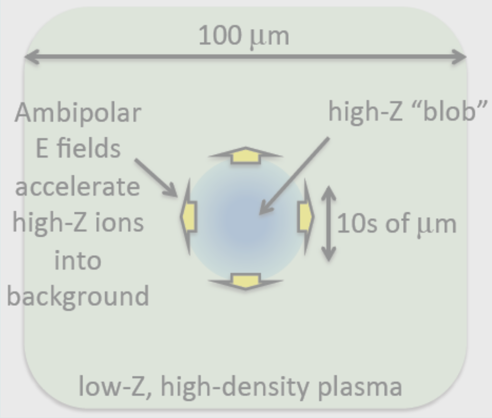


Selected applications enabled by laser-driven ion beams

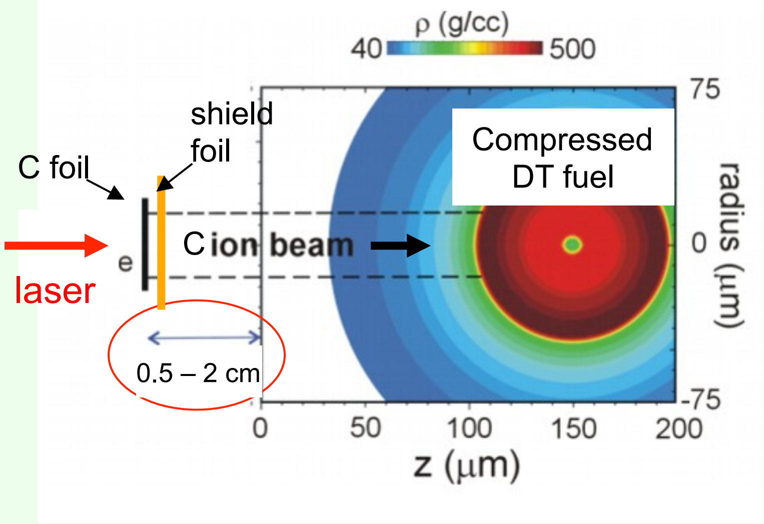
1. Laser-driven neutron beams
   - HED-target probe
   - Active interrogation
   - Materials science

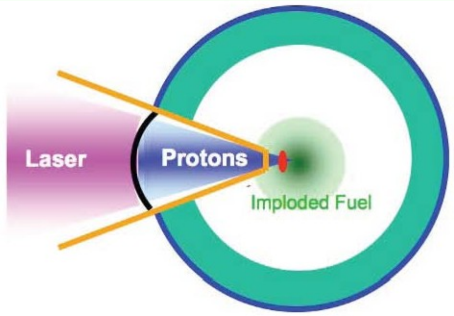


2. Evolution of high-Z or solid particulates in low-Z plasmas
   - Coulomb explosion
   - Mix



3. Ion-driven FI
   - Laser-driven proton or ion beam ignitor of compressed DT fuel

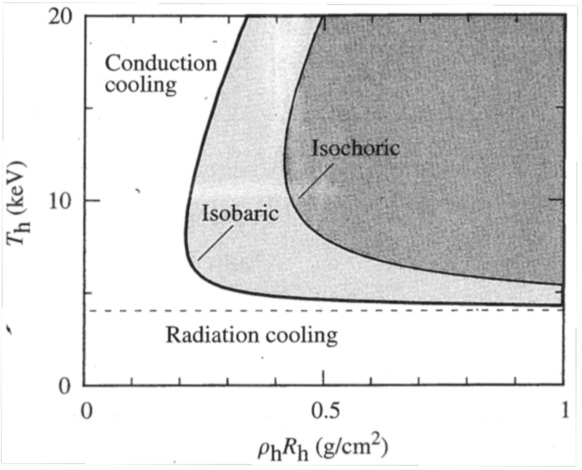


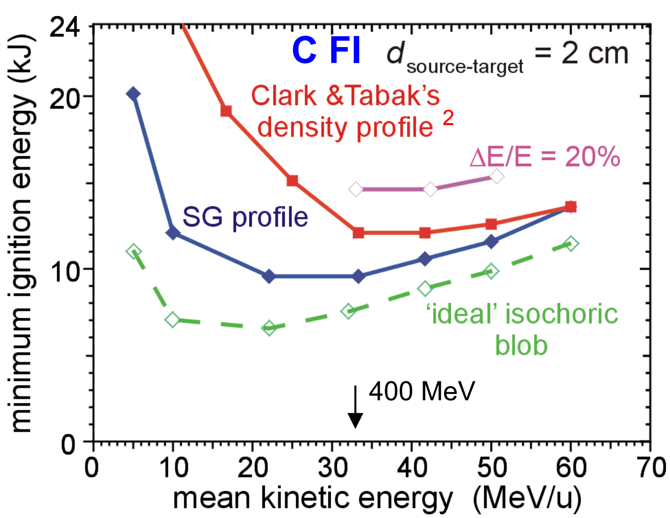


Ion FI

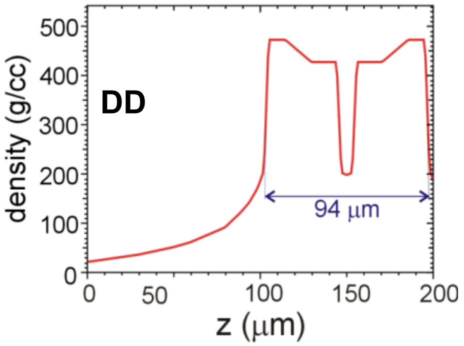
FI of DT fuel assembled with long-pulse laser places specific requirements on ion-beam.*

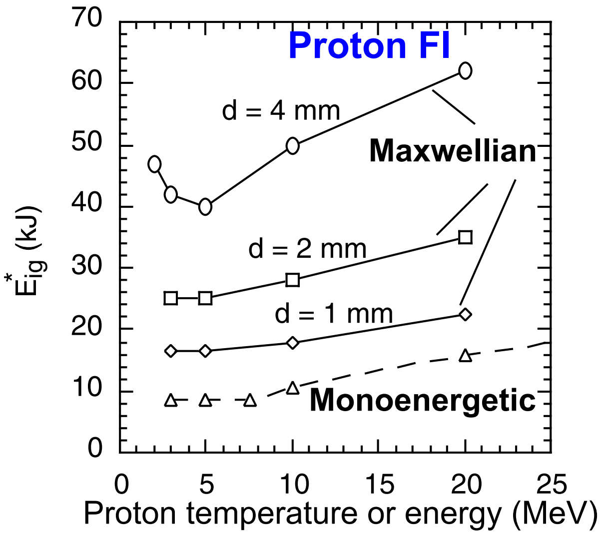
- Ignition HS conditions set by heating & cooling rates[1]
- Total ion energy required independent of ion species
- Fuel ρr ~ particle range → laser I_L
  - e^- : ~ 1 MeV → $I \sim 5\times10^{19}$ W/cm^2
  - **Protons: ~ 10 MeV → $I_L \sim 10^{20}$ W/cm^2**
  - **C: ~ 450 MeV → $I_L \sim 10^{21}$ W/cm^2**





DT fuel assembly²





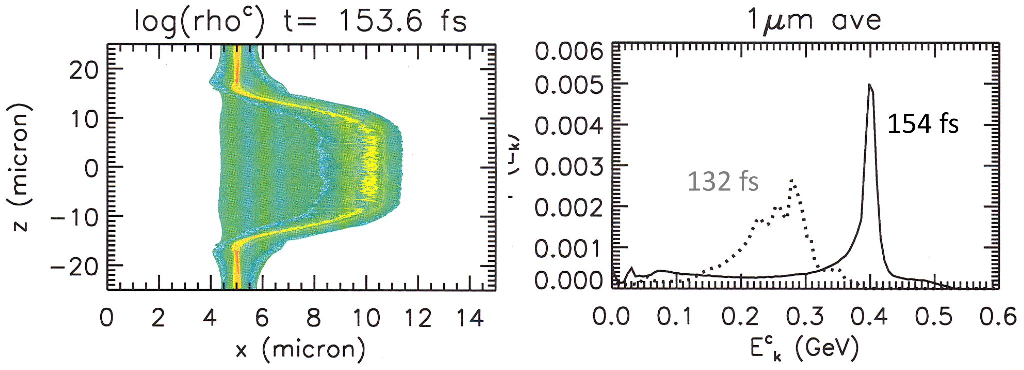
* E.g., S. Atzeni, *et al*., Nuclear *Fusion* ***42***, *L1 (2002); J.C. Fernández, et al., NF* ***49***, *065004 (2009)*

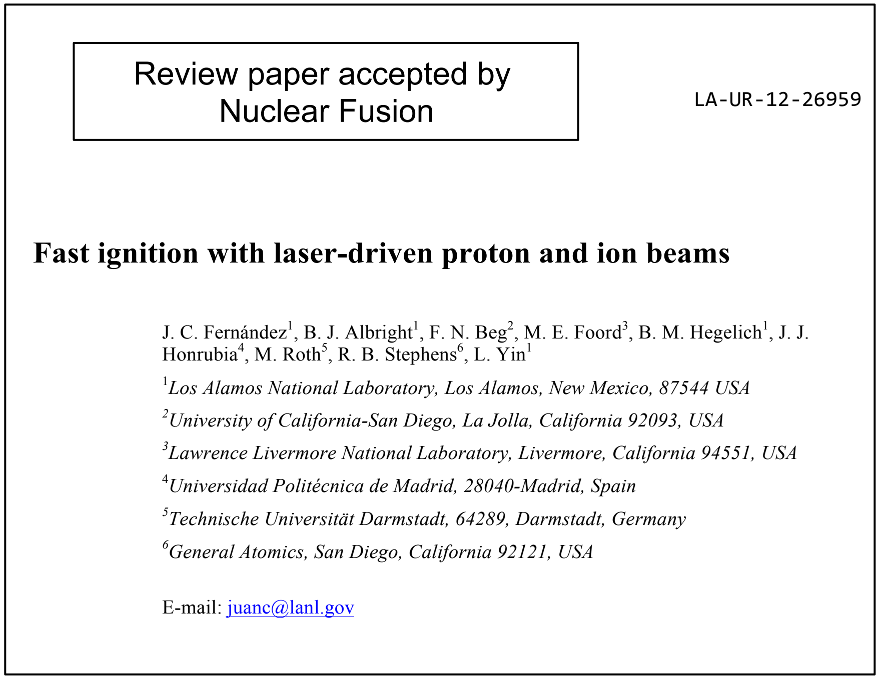
[1] *S Atzeni S and J Meyer-Ter-Vehn 2004* The physics of inertial fusion (Oxford: Oxford Univ. Press)

[2] D. Clark & M. Tabak, Nucl. Fus. **24,** 1147 (2007)

RPA → BOA ion FI design

VPIC simulation supporting FI design





Review paper accepted by
Nuclear Fusion

LA-UR-12-26959

Fast ignition with laser-driven proton and ion beams

J. C. Fernández[1], B. J. Albright[1], F. N. Beg[2], M. E. Foord[3], B. M. Hegelich[1], J. J. Honrubia[4], M. Roth[5], R. B. Stephens[6], L. Yin[1]

[1]*Los Alamos National Laboratory, Los Alamos, New Mexico, 87544 USA*

[2]*University of California-San Diego, La Jolla, California 92093, USA*

[3]*Lawrence Livermore National Laboratory, Livermore, California 94551, USA*

[4]*Universidad Politécnica de Madrid, 28040-Madrid, Spain*

[5]*Technische Universität Darmstadt, 64289, Darmstadt, Germany*

[6]*General Atomics, San Diego, California 92121, USA*

E-mail: juanc@lanl.gov

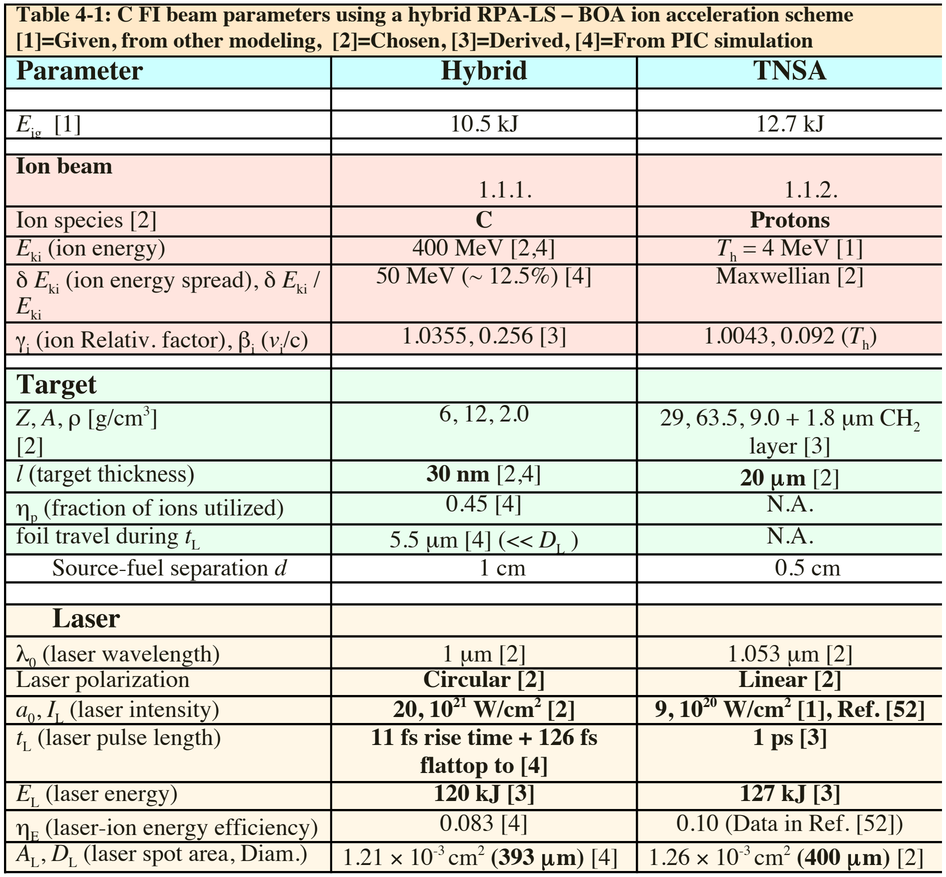
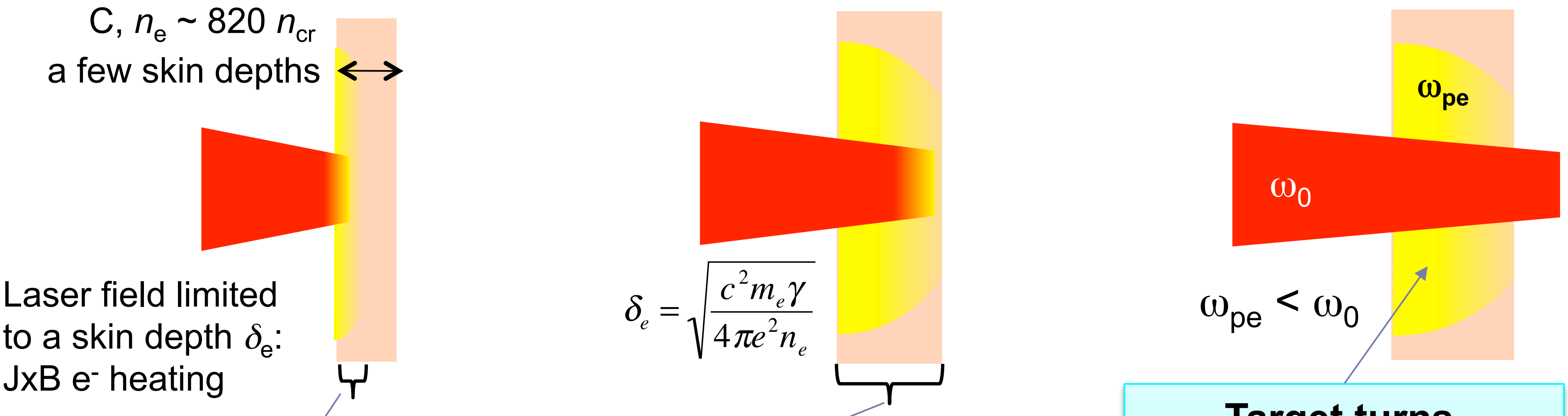


Table 4-1: C FI beam parameters using a hybrid RPA-LS – BOA ion acceleration scheme
[1]=Given, from other modeling, [2]=Chosen, [3]=Derived, [4]=From PIC simulation

Parameter	**Hybrid**	**TNSA**
E_{ig} [1]	10.5 kJ	12.7 kJ
Ion beam	1.1.1.	1.1.2.
Ion species [2]	**C**	**Protons**
E_{ki} (ion energy)	400 MeV [2,4]	$T_h = 4$ MeV [1]
δE_{ki} (ion energy spread), $\delta E_{ki} / E_{ki}$	50 MeV (~ 12.5%) [4]	Maxwellian [2]
γ_i (ion Relativ. factor), β_i (v_i/c)	1.0355, 0.256 [3]	1.0043, 0.092 (T_h)
Target		
Z, A, ρ [g/cm^3] [2]	6, 12, 2.0	29, 63.5, 9.0 + 1.8 μm CH_2 layer [3]
l (target thickness)	**30 nm** [2,4]	**20 μm** [2]
η_p (fraction of ions utilized)	0.45 [4]	N.A.
foil travel during t_L	5.5 μm [4] (<< D_L)	N.A.
Source-fuel separation d	1 cm	0.5 cm
Laser		
λ_0 (laser wavelength)	1 μm [2]	1.053 μm [2]
Laser polarization	**Circular [2]**	**Linear [2]**
a_0, I_L (laser intensity)	**20, 10^{21} W/cm^2 [2]**	**9, 10^{20} W/cm^2 [1], Ref. [52]**
t_L (laser pulse length)	**11 fs rise time + 126 fs flattop to [4]**	**1 ps [3]**
E_L (laser energy)	**120 kJ [3]**	**127 kJ [3]**
η_E (laser-ion energy efficiency)	0.083 [4]	0.10 (Data in Ref. [52])
A_L, D_L (laser spot area, Diam.)	1.21 × 10^{-3} cm^2 **(393 μm)** [4]	1.26 × 10^{-3} cm^2 **(400 μm)** [2]

Ion Accel.

Ion acceleration in a new regime: relativistic induced transparency (RIT)



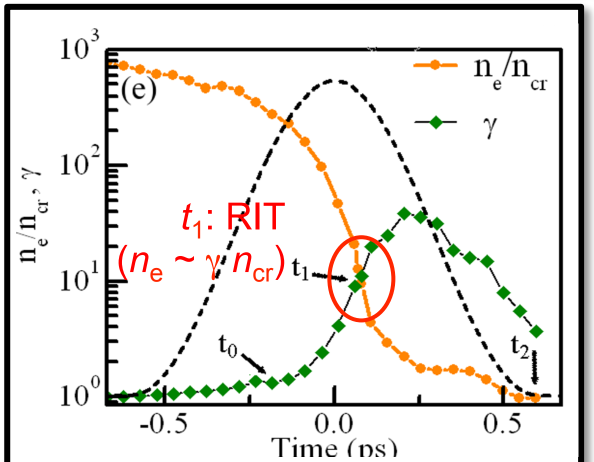
Laser field limited to a skin depth δ_e: JxB e^- heating

$$\delta_e = \sqrt{\frac{c^2 m_e \gamma}{4\pi e^2 n_e}}$$

Initially, heating is confined to the front of the target

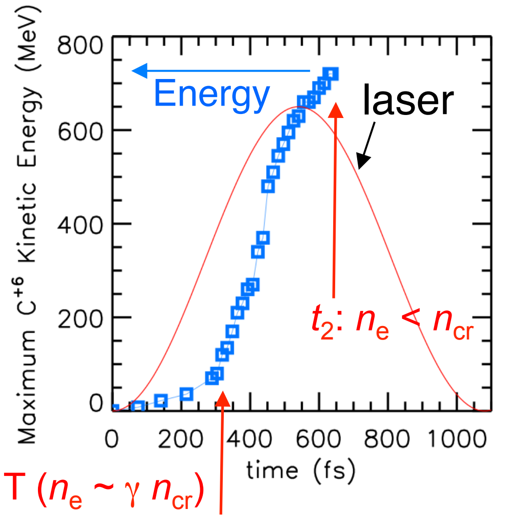
Target expands and δ_e widens – volumetric heating of entire target

Target turns relativistically transparent – BOA ion acceleration



VPIC simulation,
Trident, 100nm Diamond

Dominant ion energy gain in PIC simulations during RIT

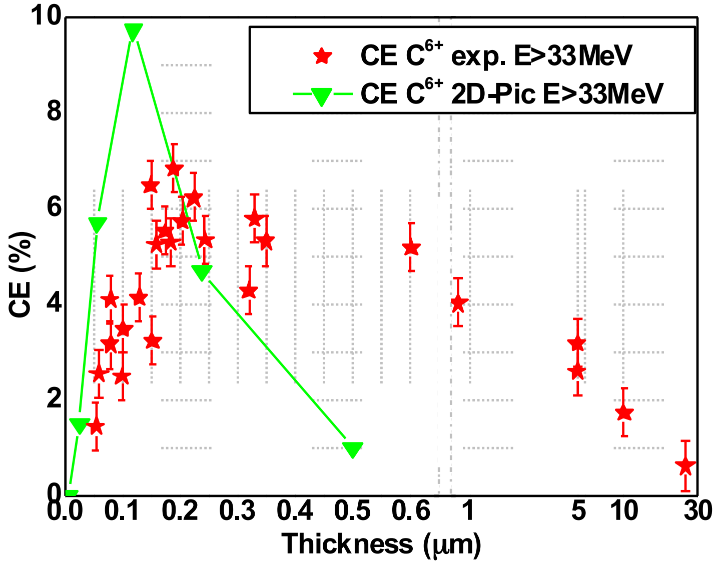


Ion Accel.

BOA dependence on thickness: really an optimization of relativistic transparency with with laser pulse length.

- **Trident experiments**
- **Targets: Diamond uncleaned**

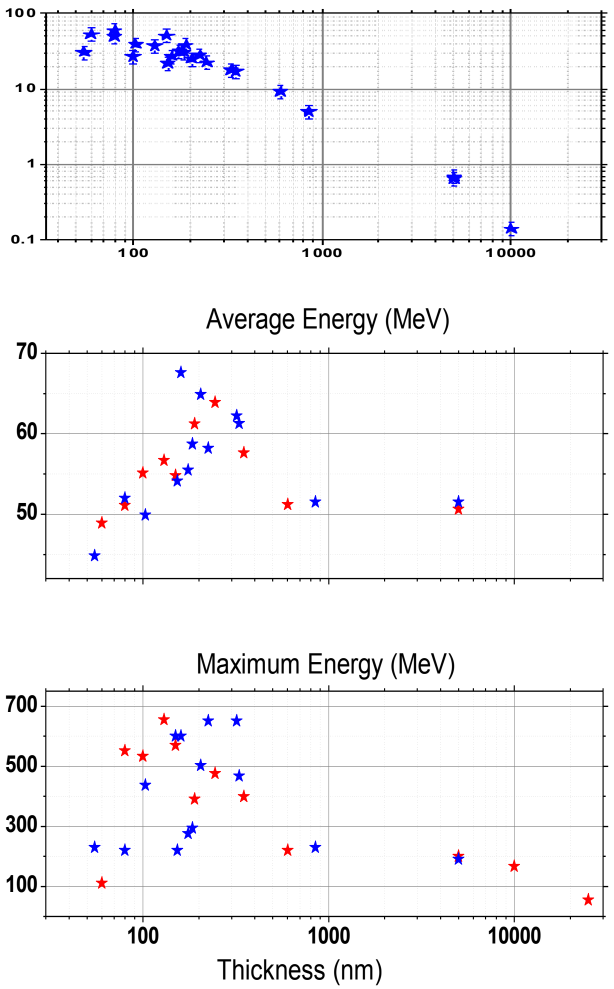
Conversion Efficiency



BOA → **TNSA**

D. Jung, *et al.*, 2013
NJP **15** 023007

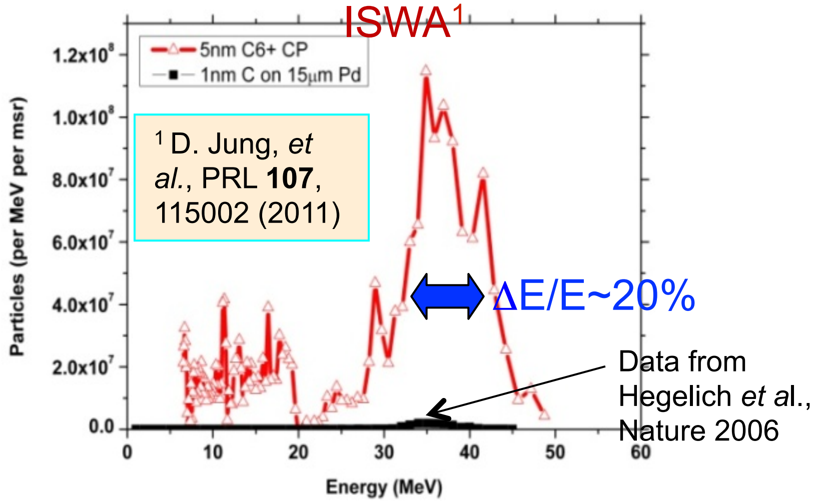
Percentage of particles in focal volume



BOA → **TNSA**

Ion-beam spectral control is improving on Trident, even with non-optimal Gaussian laser pulse shape.

C^{6+} spectrum, TP, 5 nm DLC target, f/3, ISWA[1]



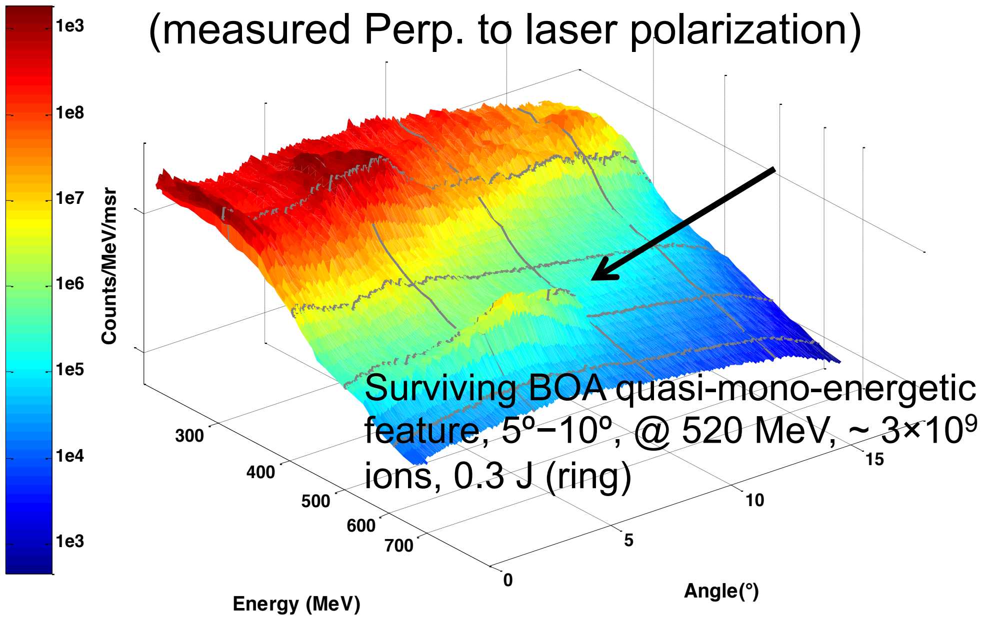
[1] D. Jung, *et al.*, PRL **107**, 115002 (2011)

ΔE/E~20%

Data from Hegelich *et al.*, Nature 2006

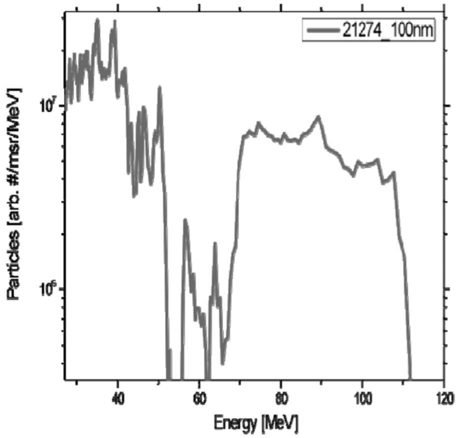
C^{6+} spectrum, DLC 100 nm uncleaned target, f/3, BOA

(measured Perp. to laser polarization)

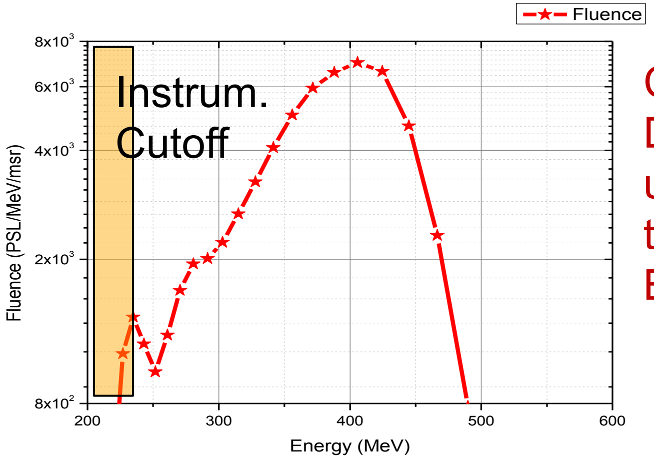


Surviving BOA quasi-mono-energetic feature, 5°−10°, @ 520 MeV, ~ 3×10^9 ions, 0.3 J (ring)

C^{6+} spectrum, TP, 100 nm DLC target, f/8, BOA



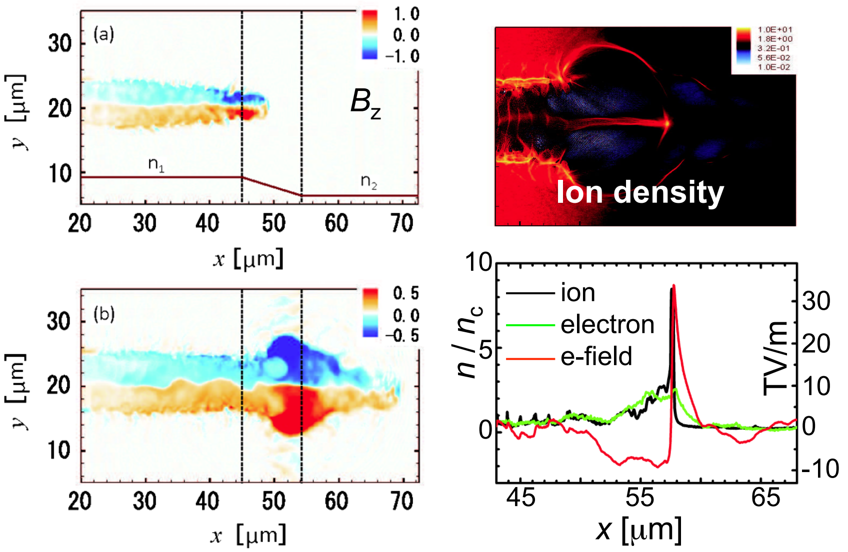
B.M. Hegelich, *et al.*, Nucl. Fusion **51**, 083011 (2011);



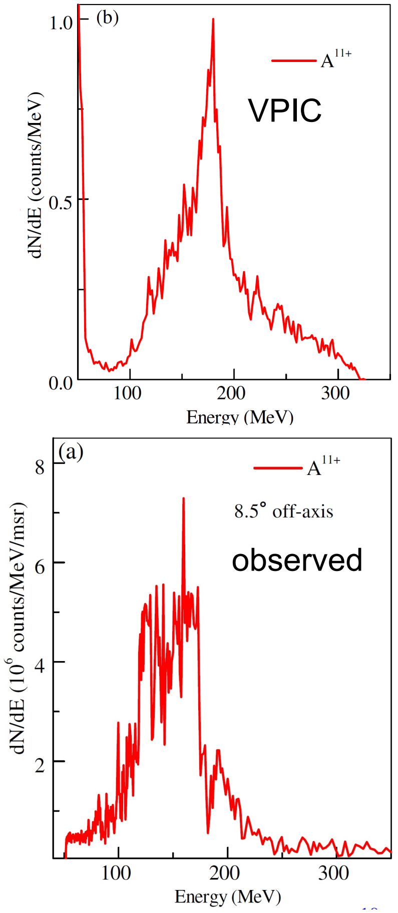
Instrum. Cutoff

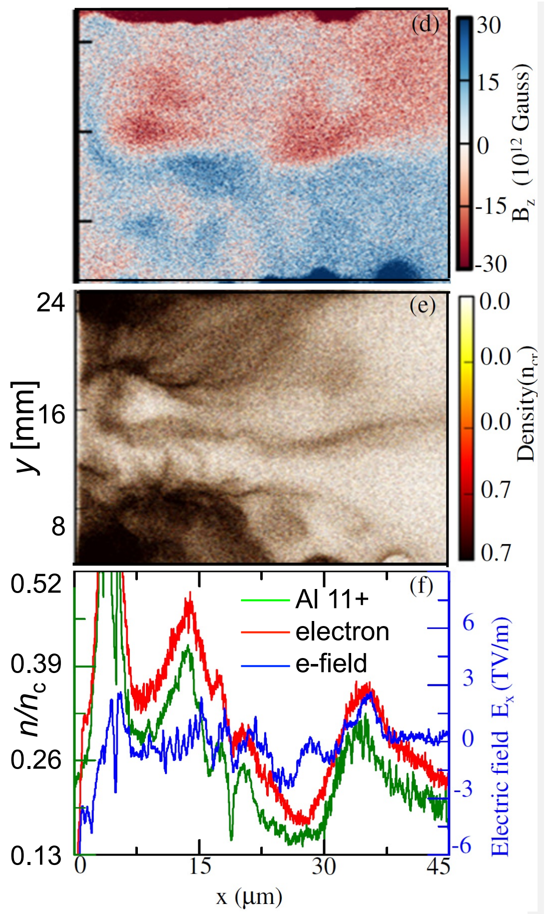
C^{6+} spectrum, DLC 30 nm uncleaned target, *f*/3, BOA, 9−16°

Magnetic Vortex Acceleration* realized on Trident[1]



- Near critical plasmas
- Magnetic vortex forms at laser-pulse trailing edge
- Vortex expands in rear towards decreasing density
- Magnetic pressure pushes electrons forward ➔ longitudinal *E* field
- *E* field accelerates ions



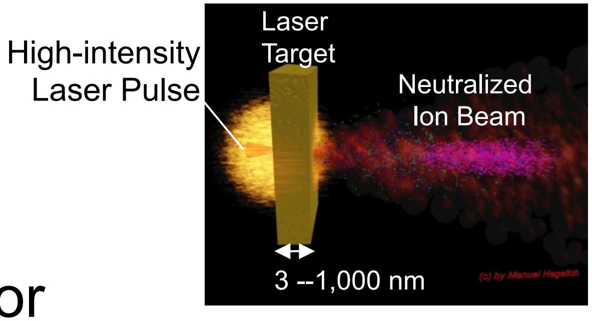


- ~ 110 nm metal foil on Trident led to MVA
- VPIC simulations show characteristic “bubble” formation & multi-charged states
- Result is an Al^{11+} beam with narrow energy spread ($\delta E_i / E_i \sim 0.3$)

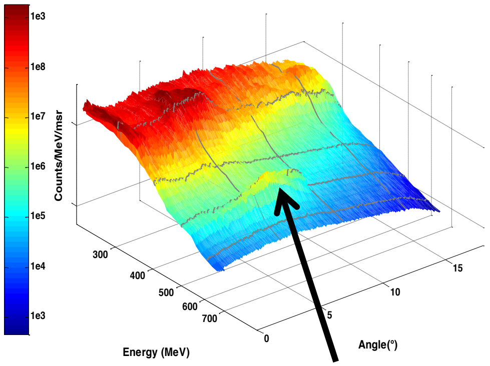
*T Nakamura *et al* 2010 PRL **105** 135002; [1]S Palaniyappan *et al* 2013 Nature, to be submitted

Summary

- Many mechanisms for ion acceleration



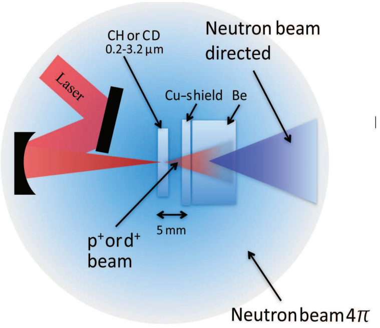
- Laser-driven ion beams on Trident used for neutron generation



5º -- 10º, 520 MeV

- Laser-driven ion beams to be used on Trident for electrostatically-enhanced mix studies

- Laser-driven ion beams an excellent candidate for FI



Future

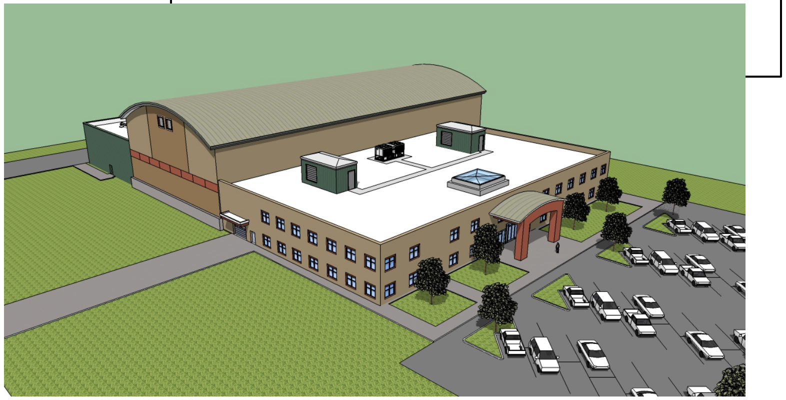
This is a critical “first experiment” for the High Intensity Laser Lab (HILL) facility proposed by LANL.

- HILL is a 2-beam kJ class 15 fs laser facility designed to probe the high-intensity frontier of HEDP.
- HILL is designed to fill a performance gap in accessing extreme states of matter that cannot be reached with existing facilities.
- At a cost of $125 – 250 M$ over 5 – 10 years, HILL will enable forefront discovery science, resolve national security questions, and attract the workforce of tomorrow.
- HILL has been proposed to the NNSA facilities roadmap process & DOE OSC FES facility-roadmap call.

High-Intensity Laser Laboratory
February 7, 2012

HILL: The High-Intensity Laser Laboratory

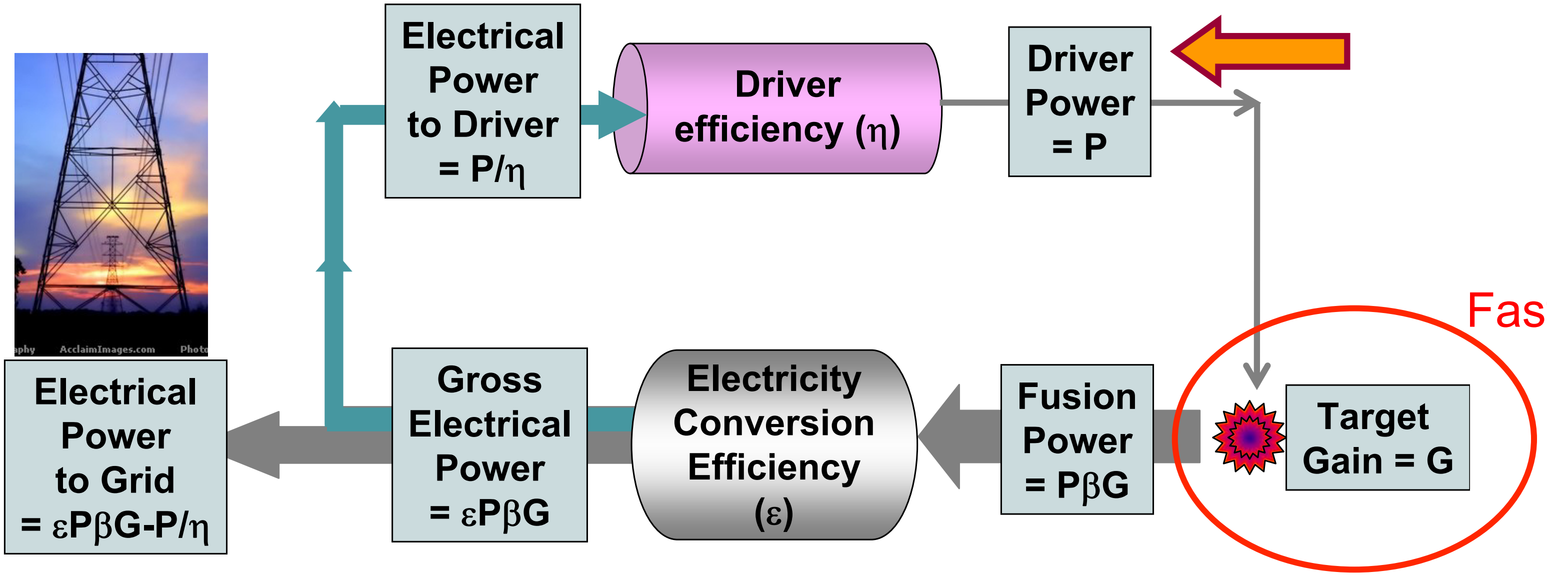
A proposal submitted by Los Alamos National Laboratory in response to the NNSA call for New Flagship Experimental ST&E Facility Concepts.



High target gain is strong lever for plant economics

Power Flow in a Fusion Reactor

ε = conversion efficiency, η = driver efficiency, G = gain, β = Burnup in blanket



Electrical Power to Driver $= P/\eta$

Driver efficiency (η)

Driver Power = P

Fast Ignition

Target Gain = G

Fusion Power $= P\beta G$

Electricity Conversion Efficiency (ε)

Gross Electrical Power $= \varepsilon P\beta G$

Electrical Power to Grid $= \varepsilon P\beta G - P/\eta$

Electrical Power to Grid $= P/\eta\ ((1/f) - 1)$

$f = 1/\varepsilon\,\eta\,\beta G$

$\equiv$ Recirculating Power Fraction

Courtesy of John Sethian, NRL