A Review of Superintense Laser-Driven Ion Acceleration (part one)

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Outline of Part One

A review of developments on ion acceleration since the year 2000, mostly in the framework of Target Normal Sheath Acceleration (TNSA) and mostly following proton imaging experiments ("proton acceleration probed by laser accelerated protons"):

- TNSA: discovery and concept
- Basic modeling and issues
- Proton imaging of sheath physics

$\Rightarrow$ detecting electrostatic fields (2005)

$\Rightarrow$ ultrafast charging and EM dynamics (2009)

$\Rightarrow$ detecting magnetic fields (2012)

Outline of Part Two

A short selection of recent experimental and simulation work mostly oriented to “advanced” schemes of ion acceleration:

- enhanced TNSA in foam-covered and grating targets Target Normal Sheath Acceleration (TNSA):

$\Rightarrow$ surface wave coupling in the relativistic regime

- ”Light Sail” radiation pressure acceleration (LS-RPA)

$\Rightarrow$ observation of “fast” scaling in multispecies target

$\Rightarrow$ exploring “unlimited” RPA in 3D simulation

- Collisionless Shock Acceleration (CSA):

$\Rightarrow$ conditions for monoenergetic acceleration

Main coworkers for this talk

M. Borghesi[1], K. Quinn[1], L. Romagnani[1,*], G. Sarri,[1],
F. Ceccherini[2], F. Pegoraro[2], T. V.Liseykina[3]

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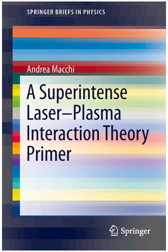
Recent reviews on ion acceleration

A. Macchi, M. Borghesi, M. Passoni,
Superintense Laser-Plasma Ion Acceleration,
Rev. Mod. Phys. (2013), in press (April issue), arXiv:1302.1775

H. Daido, M. Nishiuchi, A. S. Pirozhkov,
Review of laser-driven ion sources and their applications,
Rep. Prog. Phys. **75**, 056401 (2012).

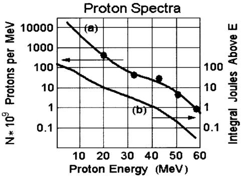
A. Macchi,
A Superintense Laser-Plasma Interaction Theory Primer (Springer, 2013)
Chap.5 (“Ion Acceleration”)
(for absolute beginners)



Discovery of multi-MeV protons from solid targets

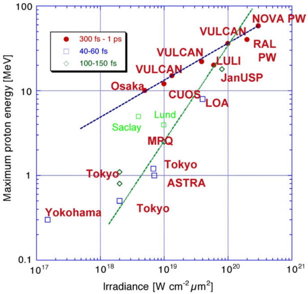
Up to 58 MeV protons observed at LLNL Petawatt by Snavely et al, PRL **85**, 2945 (2000)

See also: Clark et al, PRL **84**, 670 (2000); Maksimchuk et al, PRL **84**, 4108 (2000)



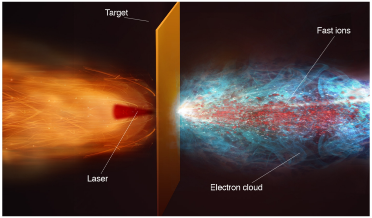
Protons have been observed and characterized in a large number of laboratories and for different laser pulse regimes

Figure from Borghesi et al, Plasma Phys. Contr. Fus. **50**, 124040 (2008)

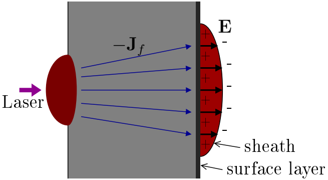


Target Normal Sheath Acceleration (TNSA)

Physics: sheath field generation by "fast" relativistic electrons at the rear surface of a solid target

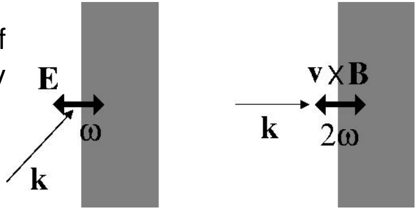


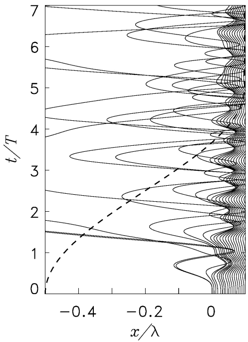
Protons originate from a surface impurity layer at the rear of the target



Fast electron generation: simple picture

Needs periodic push-pull of electrons across the density gradient



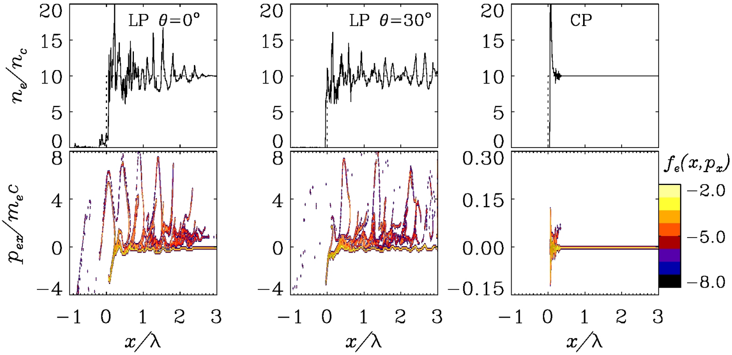


Electrons perform “half-oscillations” in vacuum and re-enter in the plasma with approximately the “quiver” energy

Oscillations driven by:

- $\mathbf{E}$ for P–polarization
- $\mathbf{v} \times \mathbf{B}$ for S–polarization or normal incidence

Fast electron generation: 1D simulations



Linear Polarization: fast electron bunches at rate ω (for $\theta = 30^\circ$, P-pol.) or 2ω (for $\theta = 0^\circ$)

Circular Polarization at $\theta = 0^\circ$: *no fast electrons* ($(\mathbf{v} \times \mathbf{B})_{2\omega} = 0$)

Fast electron generation: typical relations

$$\mathscr{E}_f = m_e c^2(\gamma - 1) \sim m_e c^2 \left(\sqrt{1 + a_0^2/2} - 1 \right)$$

$a_0 = \left(I\lambda^2 / 10^{18} \text{ W/cm}^2 \right)$ relativistic parameter

$\eta_f \simeq 10^{-2} - 10^{-1}$ (conversion efficiency) , $n_f \simeq 10^{20} - 10^{21}$ (density)

Current density $\sim 10^{12}$ A/cm^2, typically ~ 10 MA over the laser spot

Static modeling of TNSA

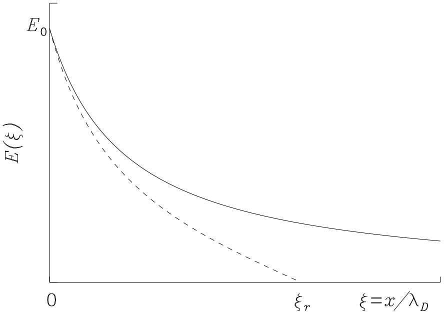
Assume fast electrons in Boltzmann equlibrium with density n_e and temperature T_e as the only parameters to evaluate sheath extension L_s and potential drop $\Delta\Phi = \mathscr{E}_{\text{max}}/Ze$:

$$L_s \simeq \lambda_D = (T_e/4\pi e^2 n_e)^{1/2} \,, \qquad \Delta\Phi \simeq T_e/e \qquad \mathscr{E}_{\text{max}} \simeq ZT_e$$

BUT: solving Poisson's equation actually yields

$$L_s \to \infty \qquad \Delta\Phi \to \infty$$

Boltzmann's distribution needs to be "truncated" at high energy



Charging and "truncation" by electron escape

- An isolated, warm plasma in "real" 3D space becomes charged due to the escape of N_{esc} electrons with energy $> U_{\text{esc}}$ (since the binding electrostatic potential is limited)
  - Assuming a simple spherical emitter of radius R and temperature T_e containing N_0 electrons:

$$N_{\text{esc}} = N_0 \exp(-U_{\text{esc}}/T_e) \qquad U_{esc} = e^2 N_{\text{esc}}/R$$

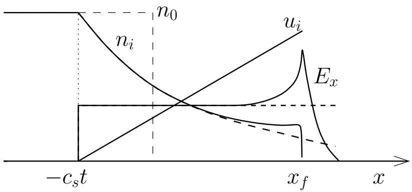
- *Open question*: is a solid target heated by an ultrashort pulse either a grounded or an isolated system? What is the role of transient effects?

Dynamic modeling of TNSA

Plasma expansion model: rarefaction wave solution "patched" at the ion front where quasi-neutrality breaks down

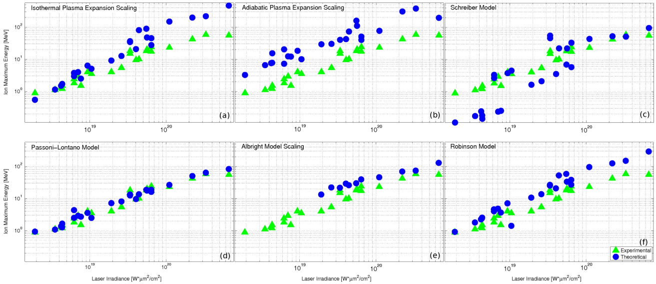
$$c_s = \left(\frac{ZT_e}{m_i}\right)^{1/2}, \quad u_f \equiv u_i(x_f) = c_s[2\ln(\omega_{pi}t)+1], \quad \mathscr{E}_{\text{max}} = \frac{m_i}{2}u_f^2 \propto ZT_e$$

Infinite energy gain is due to infinite energy reservoir: a finite model is needed (e.g thin foil expansion)
(OR extra patch: assume a finite acceleration time)



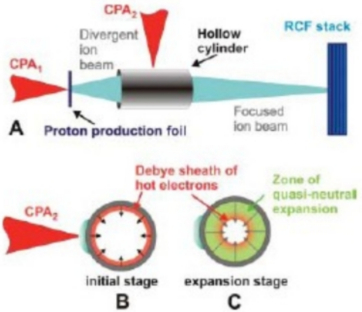
Some models fit better than others

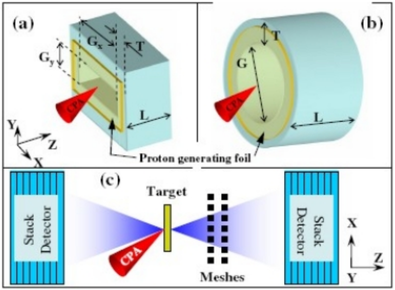
Comparison of several models with experimental energies
[Perego et al, Nucl.Inst.Meth.Phys.Res.A **653**, 89 (2011)]



Fitting parameters include laser pulse energy, power, intensity and duration; fast electron energy, density and divergence, ion surface density; target density and thickness; . . .

TNSA engineering



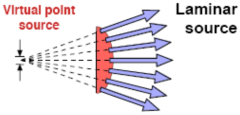


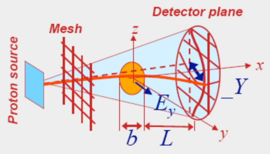
Toncian et al, Science **312**, 410 (2006)   Kar et al, PRL **100**, 105004 (2006)

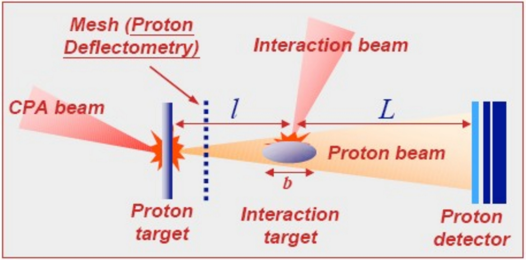
TNSA-based laser-driven “lenses” for dynamic control and focusing of protons
Question: how fast they are? Are they electrostatic?

Proton probing of laser-plasma interactions

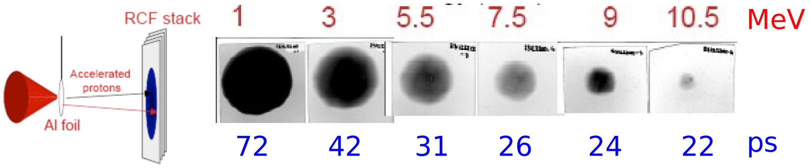
- charged beam:
  - ▶ field detection
- low emittance:
  - ▶ imaging capability
- laser driver:
  - ▶ easy synchronization
- broad spectrum:
  - ▶ time-of-flight arrangement
- short duration:
  - ▶ ultrafast resolution



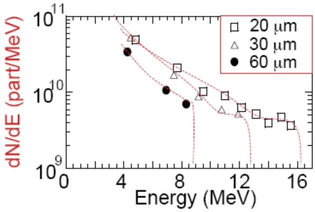




Achieving single-shot “movies”

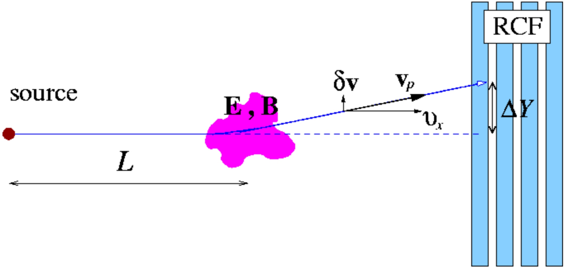


In a time-of-flight arrangement, each RCF layer produces a “snapshot” at a given proton energy $\rightarrow$ probing time (values refer to 1 mm flight distance)
Achievable resolution up to ~ 1 ps



Proton "image" formation

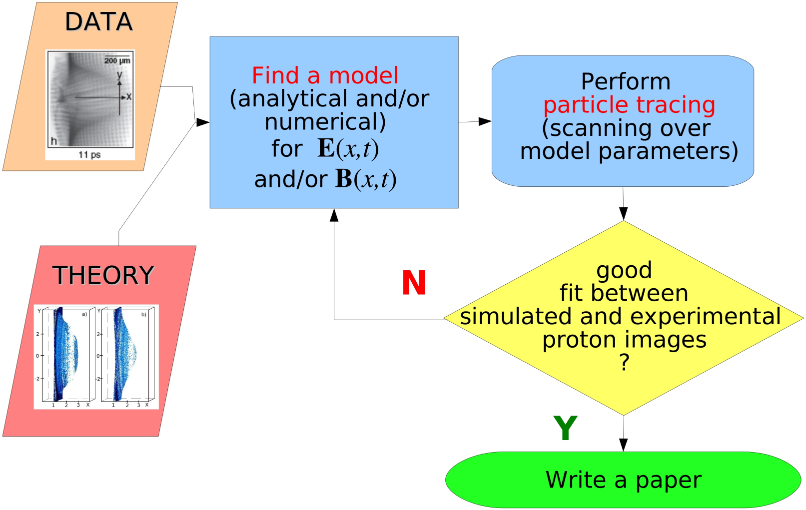
Small angle deflections by $\mathbf{E}$ and $\mathbf{B}$ distributions create a density modulation δn on the RCF detector plane producing an "image" (with magnification M)



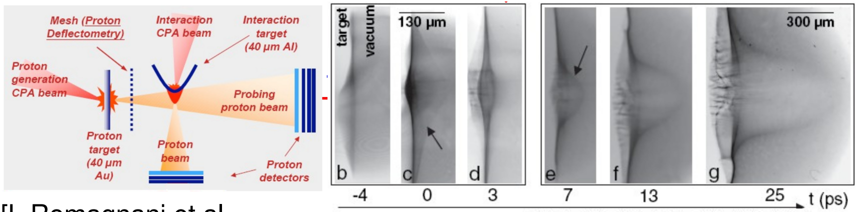
$$\Delta Y = |\delta \mathbf{v}|\Delta t \simeq \frac{eL}{2\mathscr{E}_p}\int (\mathbf{E}+\mathbf{v}_p\times\mathbf{B})_\perp dx$$

$$\frac{\delta n}{n_0} \simeq -\frac{1}{M}\nabla\cdot\Delta\mathbf{Y} \simeq \frac{-2\pi eLb}{\mathscr{E}_p M}\int_{-b/2}^{+b/2}\left(\rho - \frac{\mathbf{v}_p\cdot\mathbf{J}}{c^2}\right)dx$$

“Algorithm” for proton imaging analysis

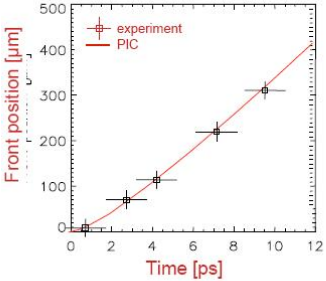


Transverse probing of TNSA fields



[L.Romagnani et al, Phys.Rev.Lett. **95** (2005) 195001]

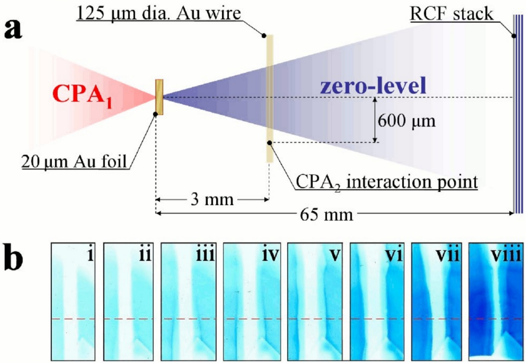
Front position $x_f(t)$ can be fitted by PIC electrostatic simulations of plasma expansion
$\rightarrow$ first "direct" test of the dynamic TNSA model



Probing ultrafast charging

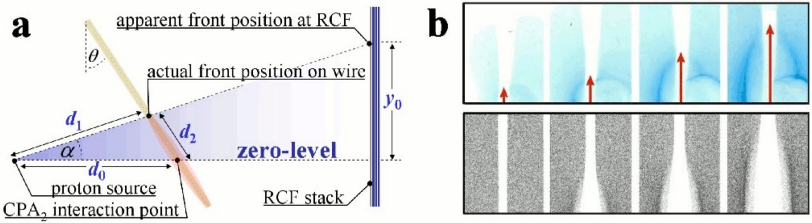
Purpose: shoot at some point of a wire to image (dis-)charging and current propagation

Problem:
the propagation of the discharging front is *not* resolved for a "*vertical*" wire (perpendicular to the probe axis)



Resolving relativistic propagation

Idea: incline the wire the exploit differences in time of flight of protons with the same energy



A field front propagates along the wire with velocity

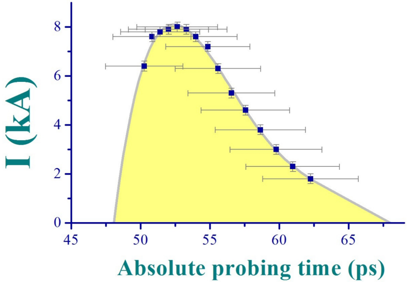
$$v_f = 0.96 \pm 0.04c$$

[K.Quinn et al, Phys.Rev.Lett **102**, 194801 (2009)]

Ultrafast discharging

From the measurement of the radial field $E_s(t)$ at the wire surface the total current I flowing trough the wire is estimated:

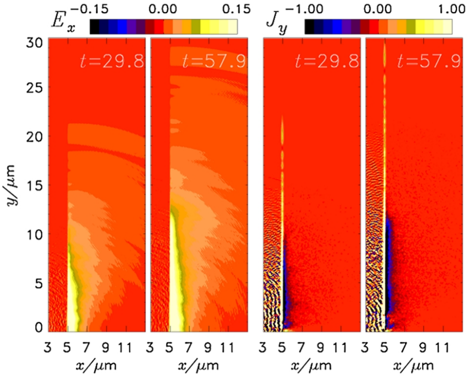
$$I(t) = \frac{\pi r_w^2}{2} \upsilon_f E_s(t)$$



The current flow implies the escape of some $\sim 10^{11}$ electrons (roughly $\sim 1\%$ of the fast electrons generated by the interaction)

"Antenna" fields observed in simulations

2D simulations of a model problem show that the front of lateral current spreading extends at $\sim 0.4c$ behind an EM front at velocity $\sim c$ that drives a return current on the rear surface

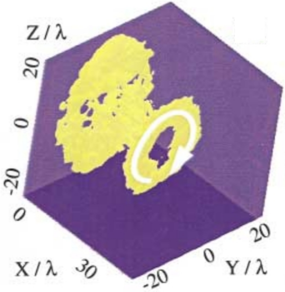


The EM fields are generated by the transient charge distribution in vacuum which behaves as a dipole antenna

PIC simulations by T. V. Liseykina and A. Macchi

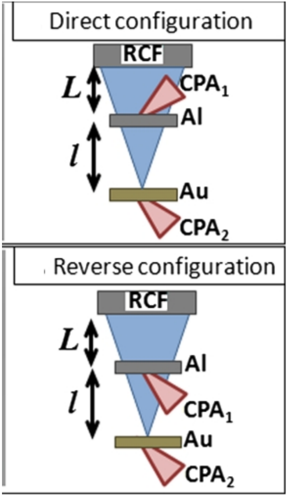
Probing magnetic fields

Purpose: detect magnetic fields "surrounding" the sheath region

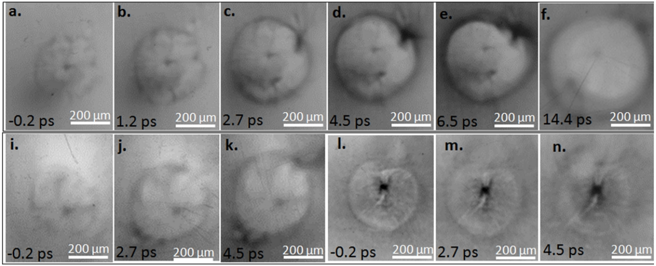


Technique: probing perpendicular to the target surface, (anti/)parallel to the symmetry axis of $\mathbf{B}$

[$\mathbf{B}$-field in 3D simulation - A.Pukhov, PRL **86**, 3562 (2001)]



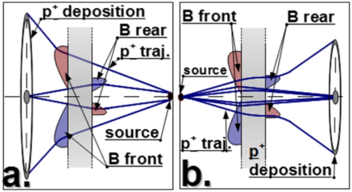
"Double-ring" pattern from magnetic field deflections



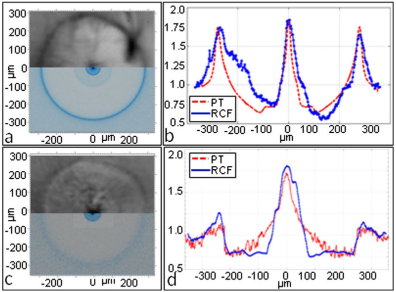
(**a-k**: *direct* config., **l-n**: *reverse* config.)

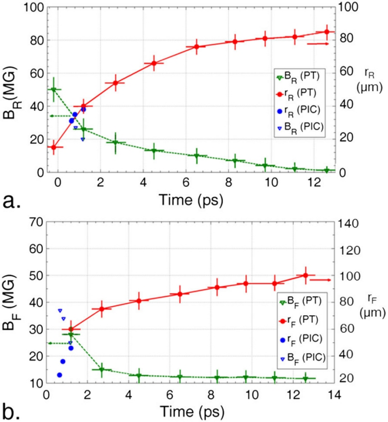
Front/rear side magnetic fields of opposite polarity cause focusing/defocusing of protons

[G.Sarri et al, PRL **109**, 205002 (2012)]



Temporal evolution of magnetic fields



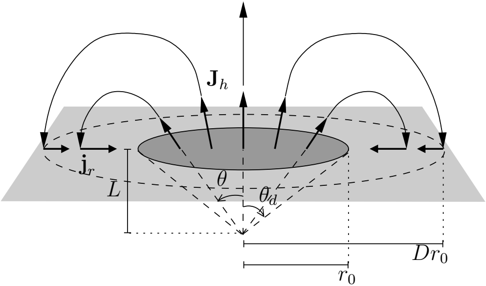


$\mathbf{B}$-field amplitude $B_{R/F}$ and radius $r_{R/F}$ inferred from particle tracing simulations

Values up to $B \sim 80$ MG and "deceleration" of $r(t)$ suggest that $\mathbf{B}$ confines the sheath radially

Toy model of the “fountain effect”

The divergent flow of fast electrons from the rear side forms loops due to the “gravity” action of $\mathbf{E}$-field: a net current circulates



Proposed scaling for $\mathbf{B}$-field
$$B_{\text{max}} \simeq \frac{8T_e}{eEr_0}\theta_d\frac{\mu_0 I_0}{2\pi r_0}$$

Experimental value of B_{max} consistent with
$T_e \simeq 0.5$ MeV, $E \simeq 10^{12}$ V/m, $r_0 = 15$ μm, $\theta_d = 25°$

A.Macchi, *Toy model of the ‘fountain effect’ for magnetic field generation in intense laser-solid interactions*, arXiv:12012.0389

Conclusions

- TNSA is an established mechanism for proton acceleration
- Modeling of TNSA still calls for improvements
- Proton imaging has provided an insight on TNSA physics:

$\Rightarrow$ test of the plasma expansion model

$\Rightarrow$ ultrafast charging and transient effects

($\rightarrow$ EM modeling may be required)

$\Rightarrow$ ~ 100 MG magnetic field generation

($\rightarrow$ magnetic confinement effects may be important)

Full references for proton probing experiments

- L.Romagnani, J.Fuchs, M.Borghesi, P.Antici, P.Audebert, F.Ceccherini, T.Cowan, T.Grismayer, S.Kar, A.Macchi, P.Mora, G.Pretzler, A.Schiavi, T.Toncian, O.Willi, Phys.Rev.Lett. **95**, 195001 (2005)
- K.Quinn, P.A.Wilson, C.A.Cecchetti, B.Ramakrishna, L.Romagnani, G.Sarri, L.Lancia, J.Fuchs, A.Pipahl, T.Toncian, O.Willi, R.J.Clarke, D.Neely, M.Notley, P.Gallegos, D.C.Carroll, M.N.Quinn, X.H.Yuan, P.McKenna, T.V.Liseykina, A.Macchi, M.Borghesi, Phys.Rev.Lett. **102**, 194801 (2009)
- G.Sarri, A.Macchi, C.A.Cecchetti, T.V.Liseykina, X.H.Yang, M.E.Dieckmann, J.Fuchs, M.Galimberti, L.A.Gizzi, R.Jung, I.Kourakis, J.Osterholz, F.Pegoraro, A.P.L.Robinson, L.Romagnani, O.Willi, M.Borghesi, Phys.Rev.Lett. **109**, 205002 (2012)