Laser-to-proton conversion efficiency studies for proton fast ignition

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A. Kemp

Acknowledgements

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D.Higginson, D.Mariscal, W.Riedel, R.Shepherd, R.Simpson, M.Tabak, S. Wilks, A.Zylstra

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Our study focuses on the central element of a proton fast-ignition approach to IFE

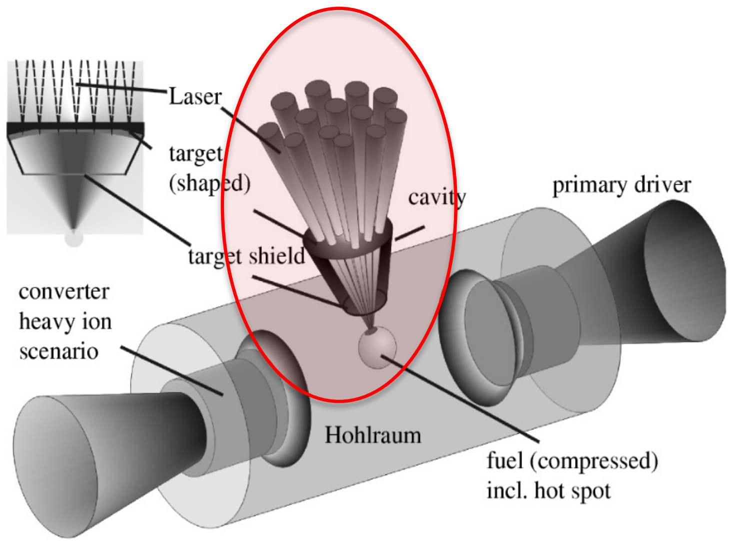

FIG. 1. Indirectly driven fast ignition using a laser accelerated proton beam (not to scale). The rear surface of the laser target is shaped to focus the ion beam into the spark volume.

[M. Roth, Phys.Rev.Lett. (2001)]

Ignition on the NIF has re-kindled interest in cost-efficient high-gain inertial fusion for inertial fusion energy (IFE)

Big-picture:

- low-entropy implosion w/ nanosecond laser-drive
  cold dense fuel; lower cost / risk than conventional hotspot
- followed by multi-picosecond intense laser pulse
- TNSA protons stop v. collisions / heat / ignite compressed core

Key question: At what cost (conversion efficiency) can we generate a proton beam with an intense laser that will ignite the compressed core?

Constraints:

- TNSA (target normal sheath acceleration) proton acceleration*
- collisional stopping in dense plasma

*Wilks et al., Phys.Plasmas 8 (2001)

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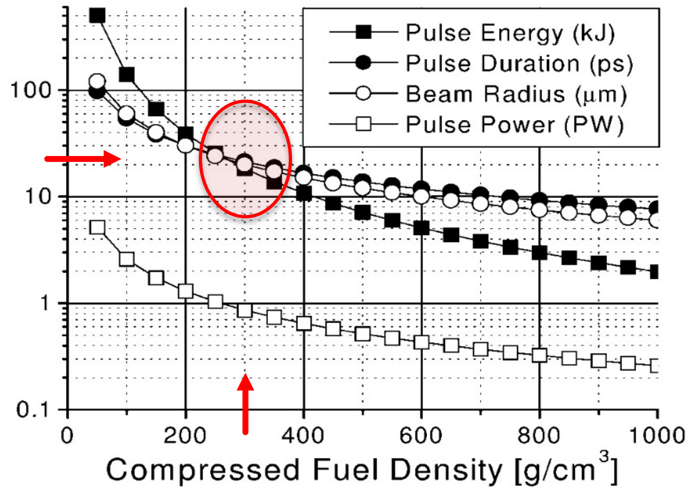


FIG. 2. Optimum parameter range for fast ignition based on 2D simulations by Atzeni.

Operational space

- At peak compression, DT fuel density=**300g/cc**
- Atzeni's model [Phys. Plasmas **6** (1999)] gives beam parameters: **20kJ deposited in 20ps in beam radius 20um**
- fuel density gives proton energy range ~**10-20MeV** / particle

(beam propagation and stopping are not part of this work)

[M. Roth, Phys.Rev.Lett. (2001)]

This talk: what's the coupling efficiency from a multi-ps laser pulse to 10MeV TNSA protons?

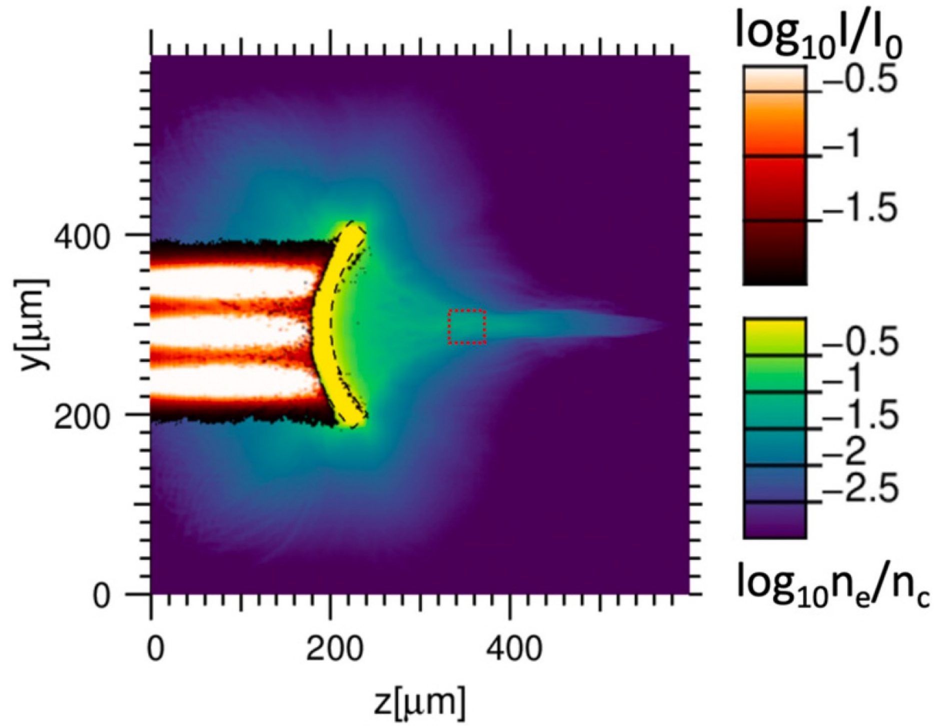
Within our operational space we have several knobs on laser and targets to optimize coupling

“design parameters”

Laser pulse
- Duration
- Spot size
- Intensity
- (Wavelength)

Target
- Thickness
- Shape
- Material (D vs D+p)
- (numerical convergence)

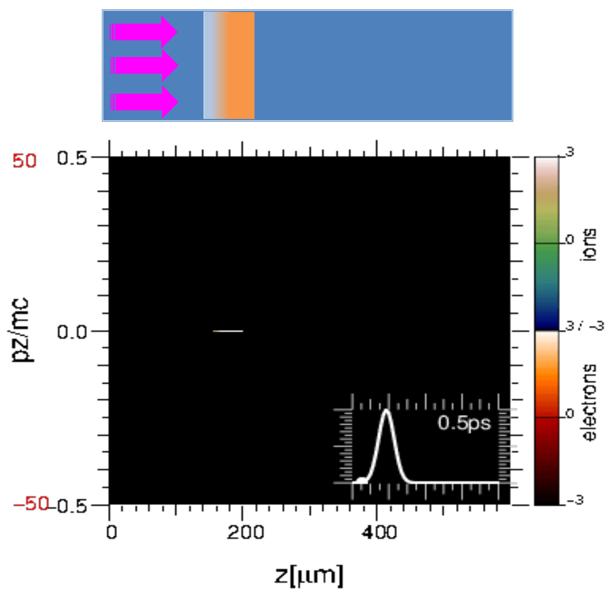
10kJ laser pulse on TNSA target, @6.5ps

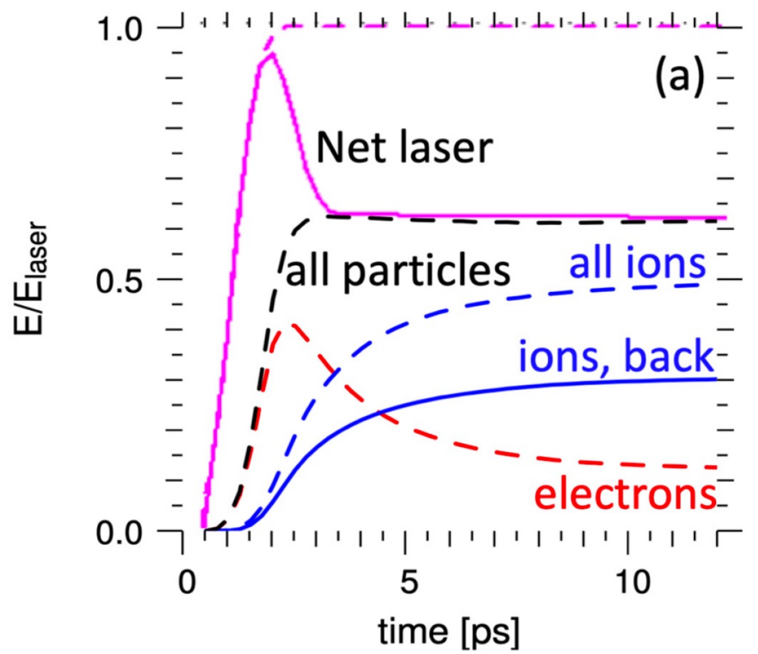


We have defined a quasi-1D reference case to investigate basic scalings

Quasi-1D surrogate case

- 10um wide periodic box, 16cpw, 40ppc, L=3um scale + 20um @ ne=ni=30ncrit
- Laser 5×10^{19} W/cm^2, 1ps fwhm plane wave, p-polarized





Coupling: ions>1MeV =**25%** (10-20MeV) = **6%**

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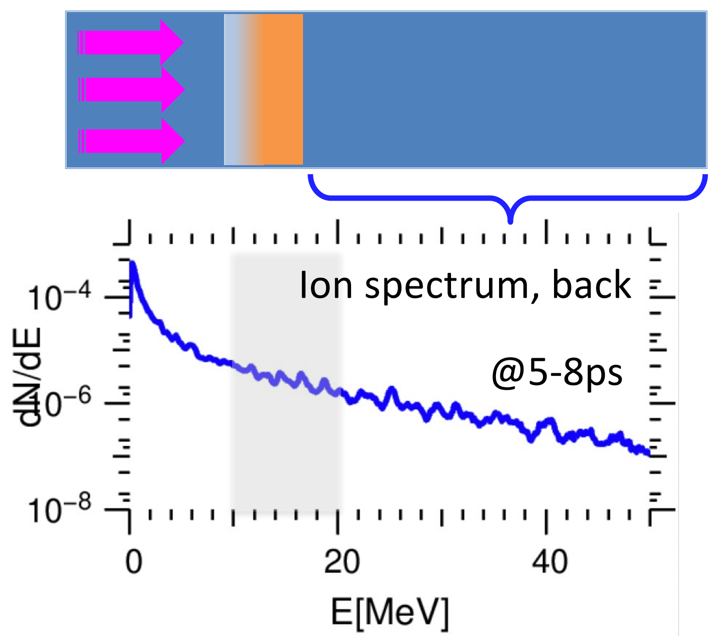

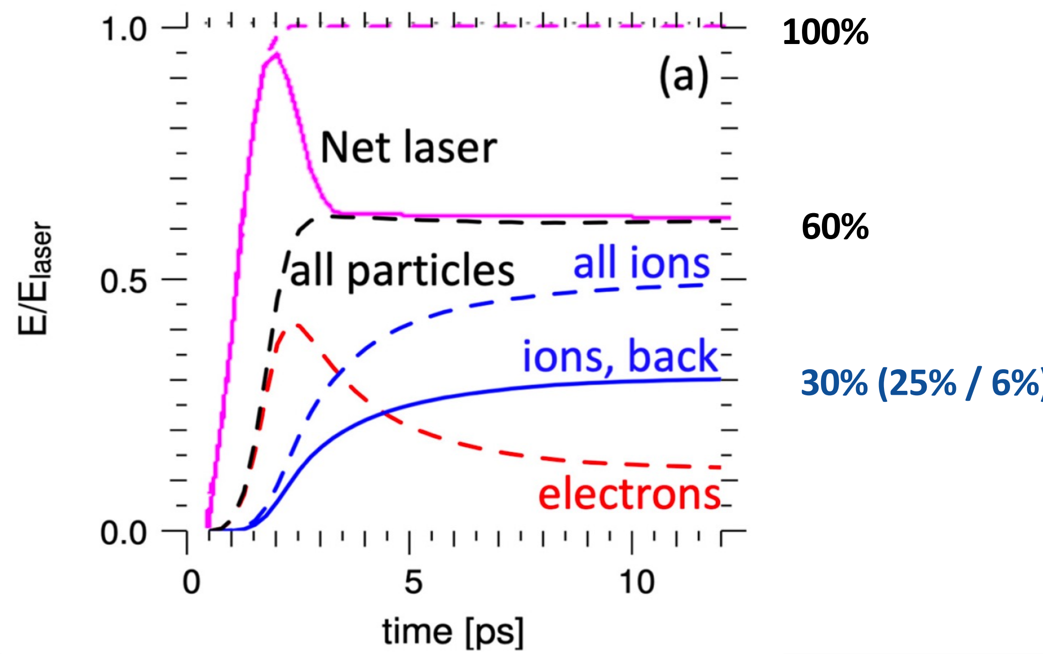

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Lower and upper ion energy cutoff have a strong impact on the coupling efficiency

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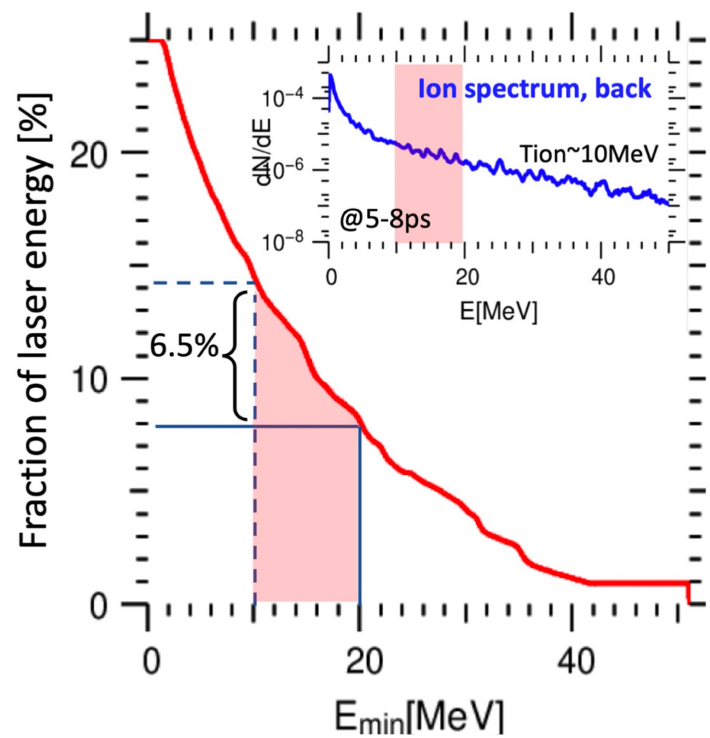
Coupling fraction depends on energy cutoffs Emin and Emax

- Plot ion energy above Emin, divided by laser energy
- Baseline case 10-20MeV gives ~6% coupling
- Maximum coupling >1MeV is 25%

Ion spectral conversion fraction



Coupling efficiency is a weak function of target thickness and laser pulse duration

$5x10^{19}$W/cm^2, 1ps

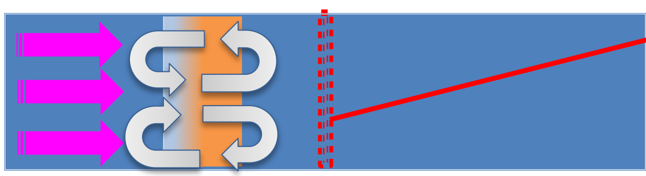
`Quasi-1D surrogate case`

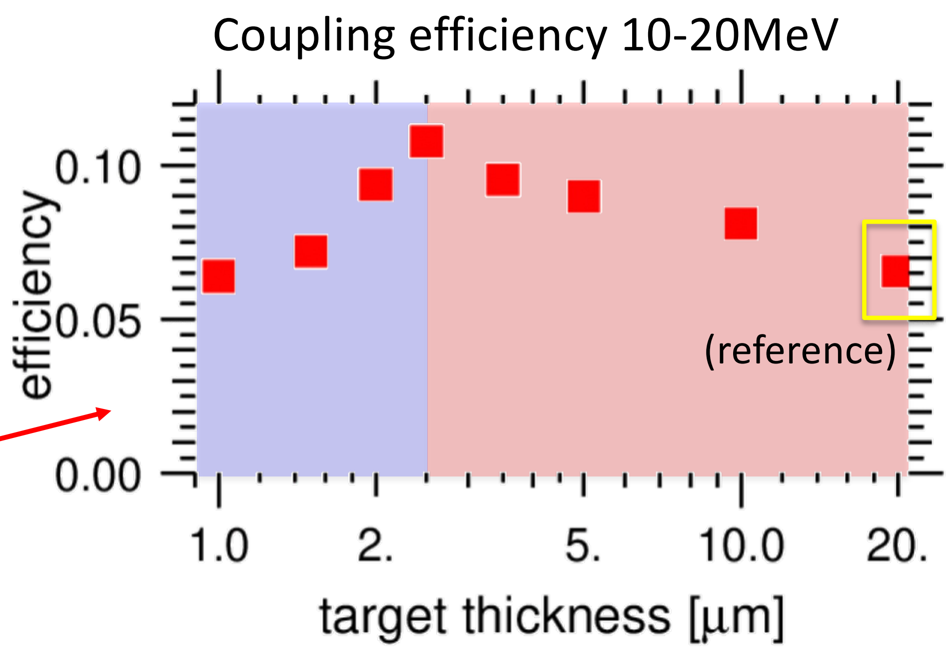
- `10um wide periodic box, 16cpw, 40ppc, L=3um scale + Xum @ ne=ni=30ncrit`
- `Laser` $5x10^{19}$ `W/cm`^{2}`, 1ps fwhm plane-wave, p-polarized`

Optimum coupling wrt thickness determined by

- Disassembly time -- laser pulse duration
- Enhancement of 'effective density of hots'

Recirculation of electrons in target enhances pressure





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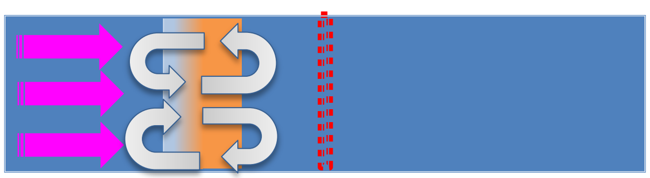
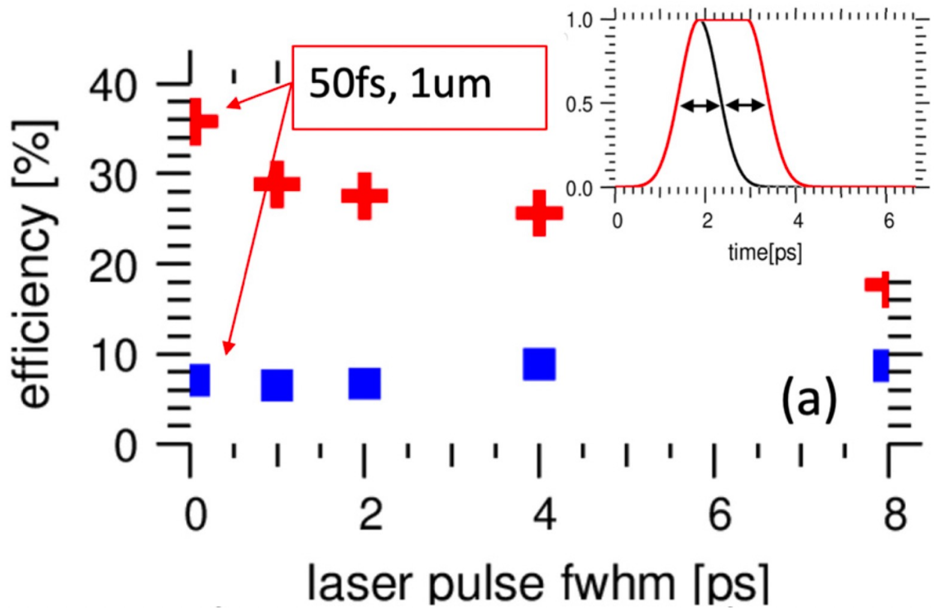
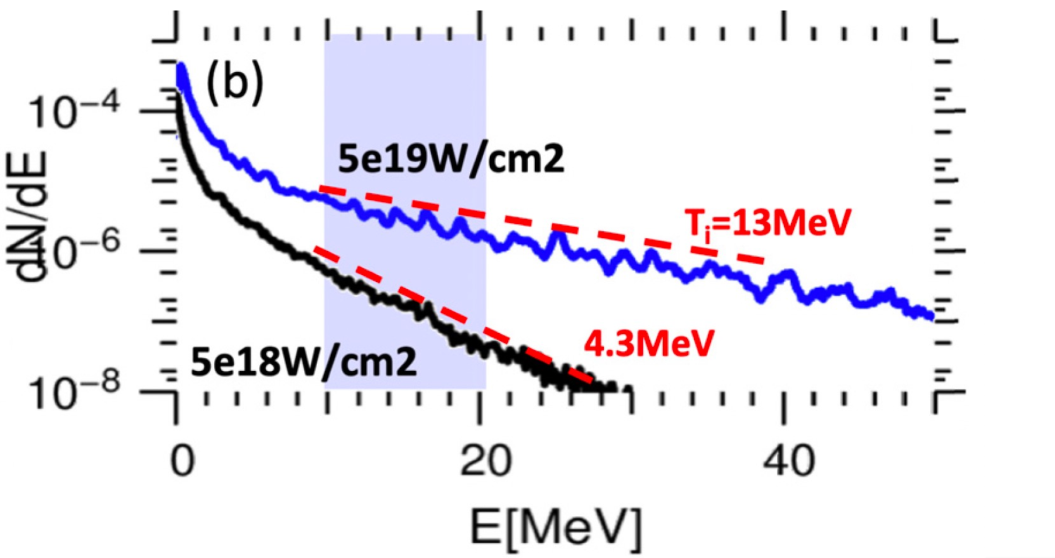




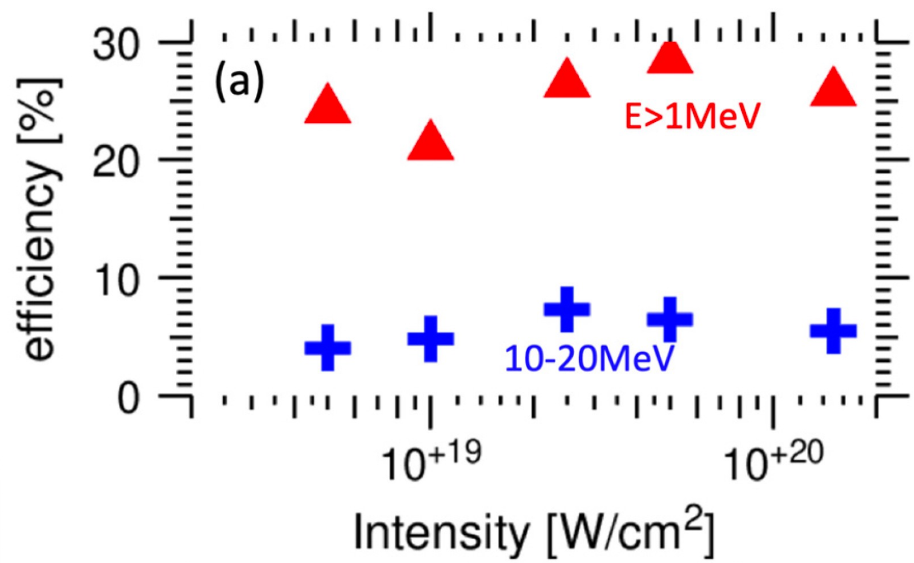
Coupling efficiency into MeV protons is a weak function of laser intensity

Quasi-1D surrogate case

- 10um wide periodic box, 16cpw, 40ppc, L=3um scale + 20um @ ne=ni=30ncrit
- Laser 1ps fwhm plane wave, p-polarized



Coupling efficiencies



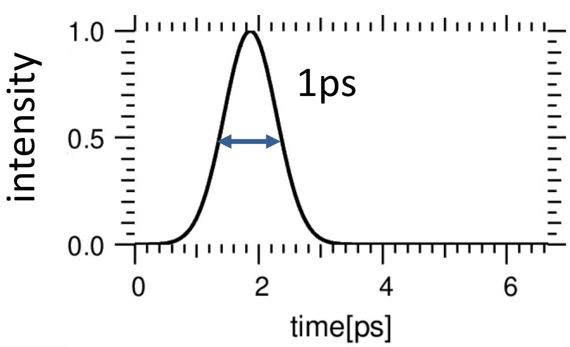
Coupling efficiency into MeV protons is a weak function of target density: TNSA and target explosion can be separated

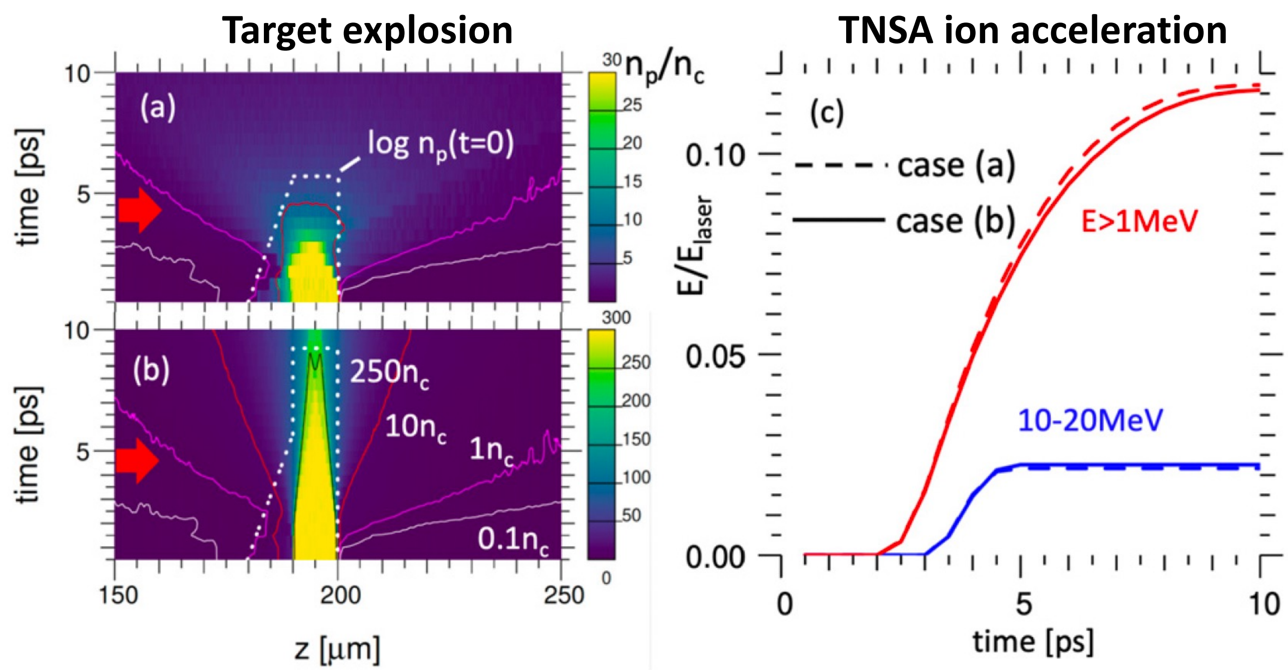
1D test case

- `100cpw, 300/3000ppc`
- `Laser 1ps fwhm plane wave, p-polarized`

a) Nmax = 30ncrit / `300ppc`
with L=3um gradient

b) Nmax = 300ncrit / `3000ppc`
with same gradient

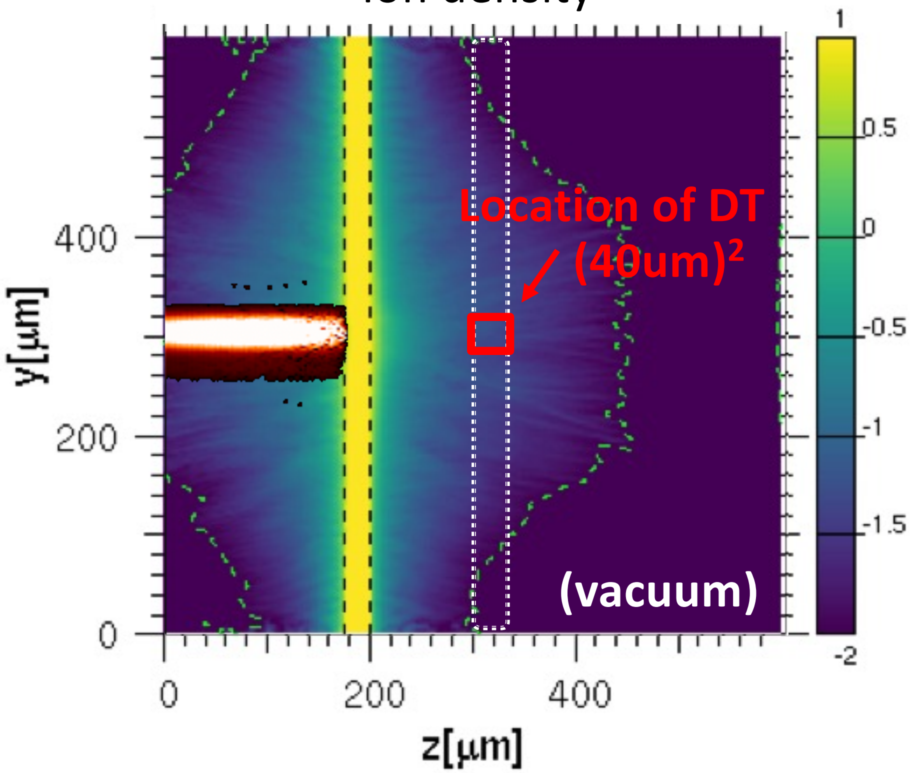




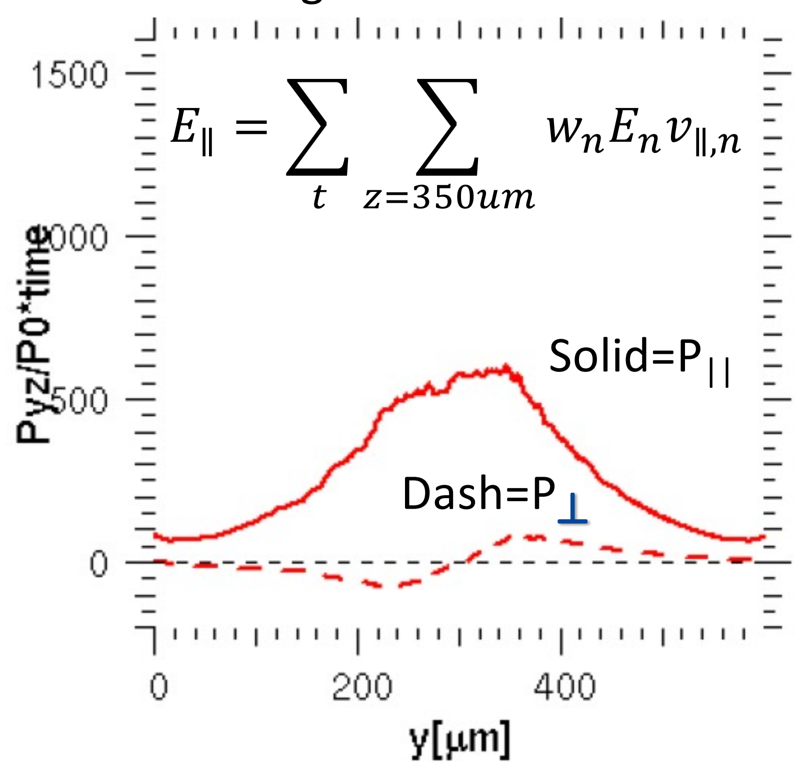
2D PIC simulations with finite laser spot - TNSA beams off flat targets diverge - coupling into compressed region ~3%

5×10^{19} W/cm^2, 1ps fwhm, 2D ARC-like profile "1kJ"

Ion density



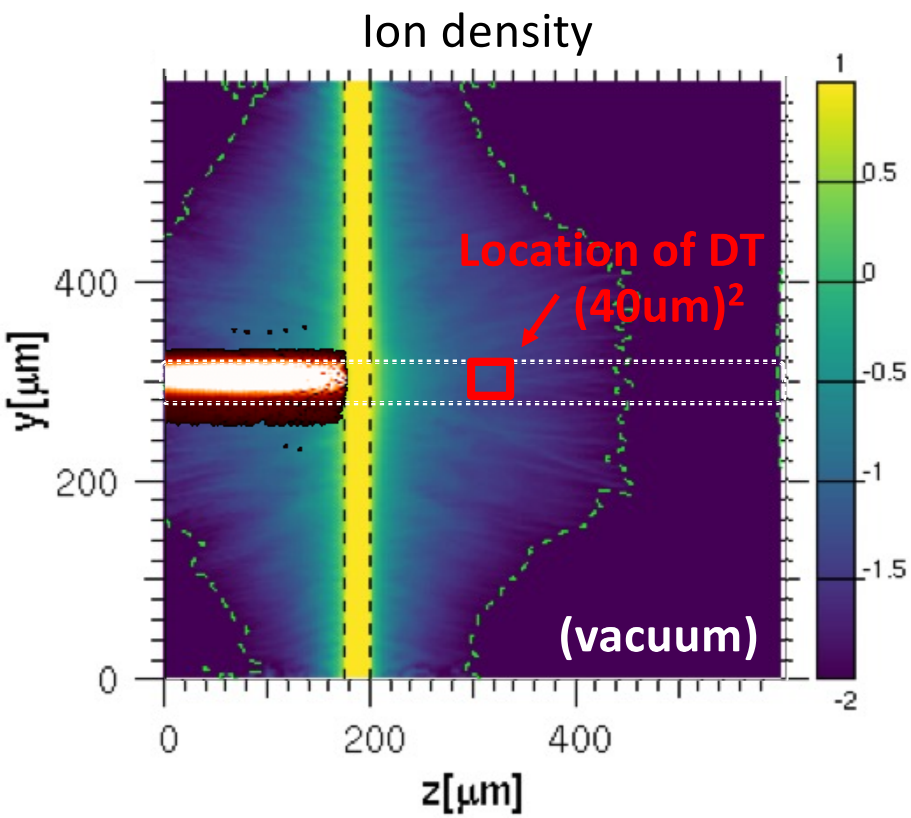
Time-integrated flux at z=350um

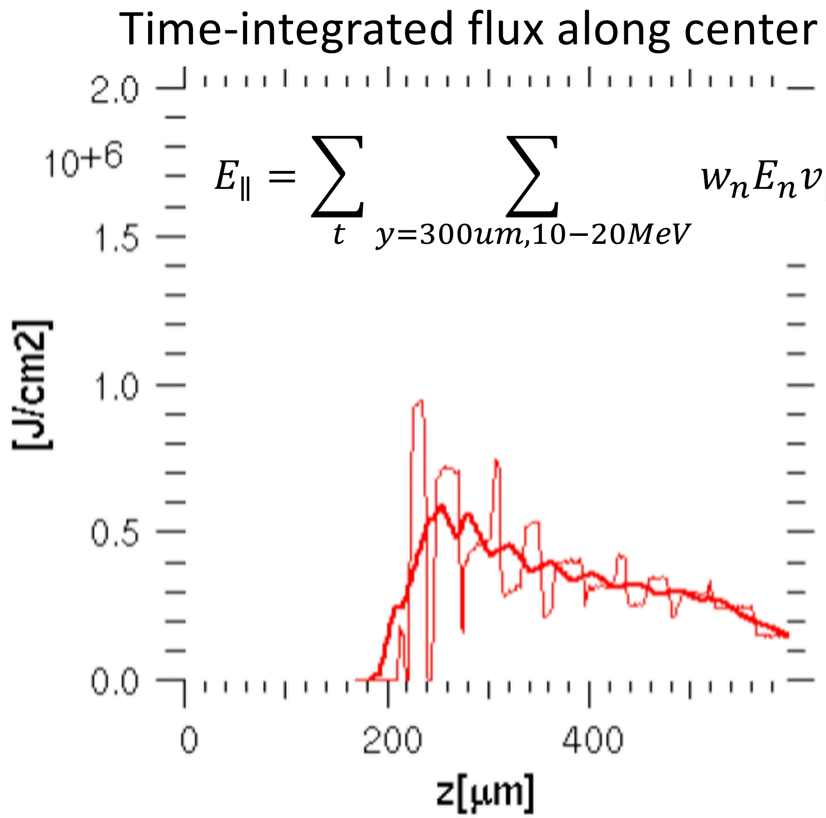


Total coupling into ions ~20%; in box: 3% into >MeV / 0.8% into 10-20MeV

2D PIC simulations with finite laser spot - TNSA beams off flat targets diverge - coupling into compressed region ~3%

$5\text{x}10^{19}$ W/cm^2, 1ps fwhm, 2D ARC-like profile “1kJ”



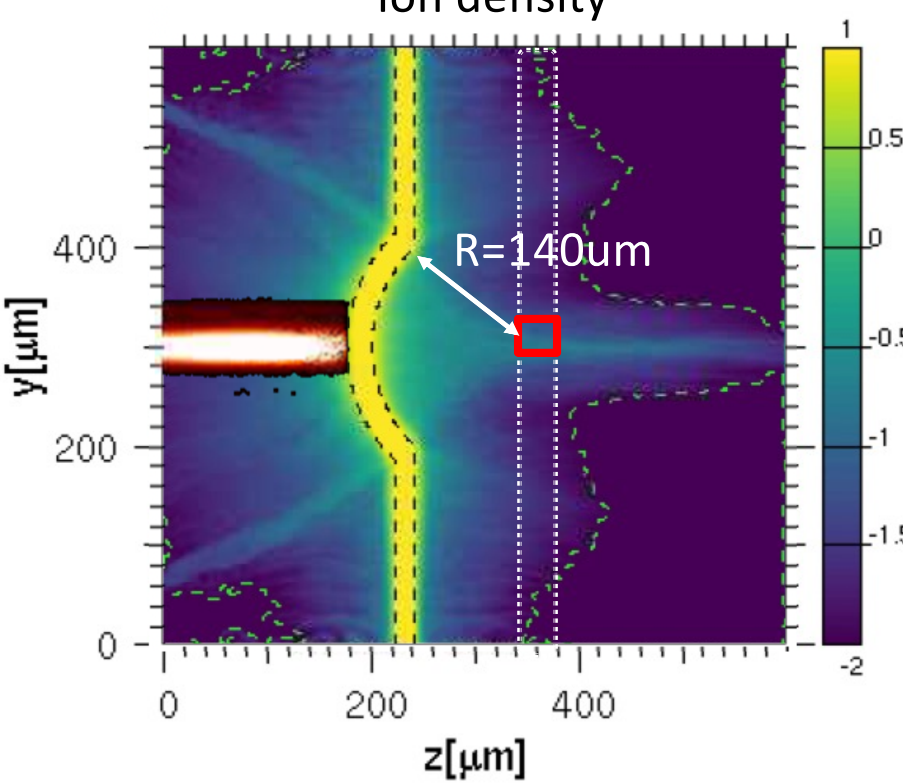


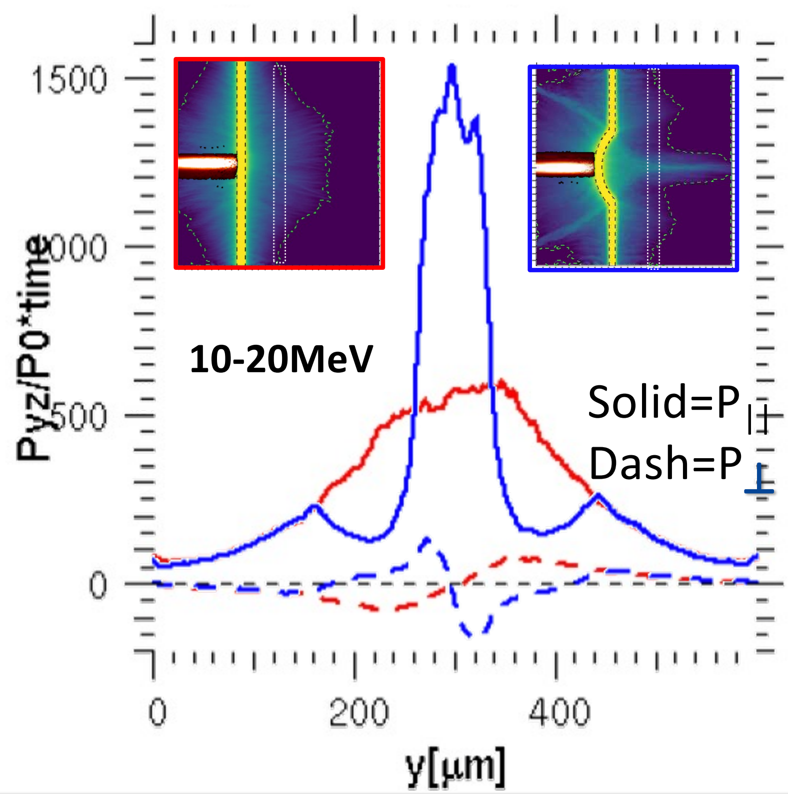
$$E_{\parallel} = \sum_{t} \sum_{y=300um,10-20MeV} w_n E_n v_{\parallel,n}$$

Total coupling into ions ~20%; in box: 3% into >MeV / 0.8% into 10-20MeV

Focusing targets can drastically enhance coupling to MeV protons – coupling into compressed region ~10%

$5x10^{19}$ W/cm^2, 1ps fwhm, 2D ARC-like profile “1kJ”

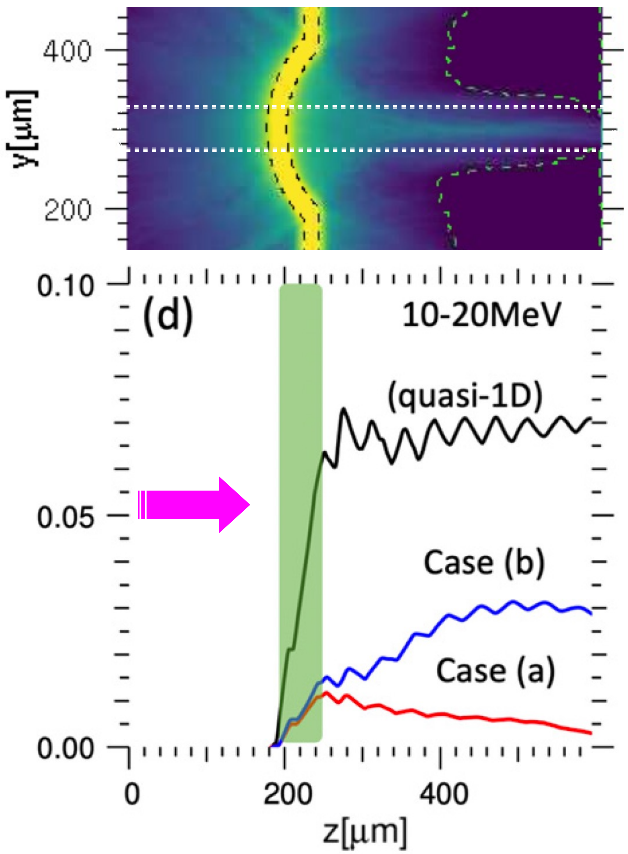




Total coupling into ions ~20%; in box: 10% into >MeV / 2.4% into 10-20MeV

Focusing geometries can give us a 3x enhancement of coupling efficiency into MeV protons

$5x10^{19}$ W/cm^2, 1ps fwhm, 2D ARC-like profile "1kJ"



target	Conversion to >MeV ions	Conversion to 10-20MeV ions
Quasi-1D	**25%**	**6%**
Curved foil	**10%**	**2.4%**
Flat foil	**3.2%**	**0.8%**
(3D curved foil)	**(15%)**	**(2.5%)***

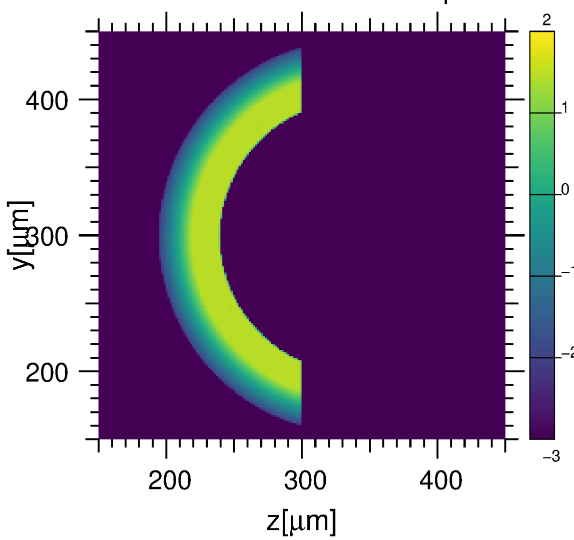
(conversion to ions along axis +/- 20um)

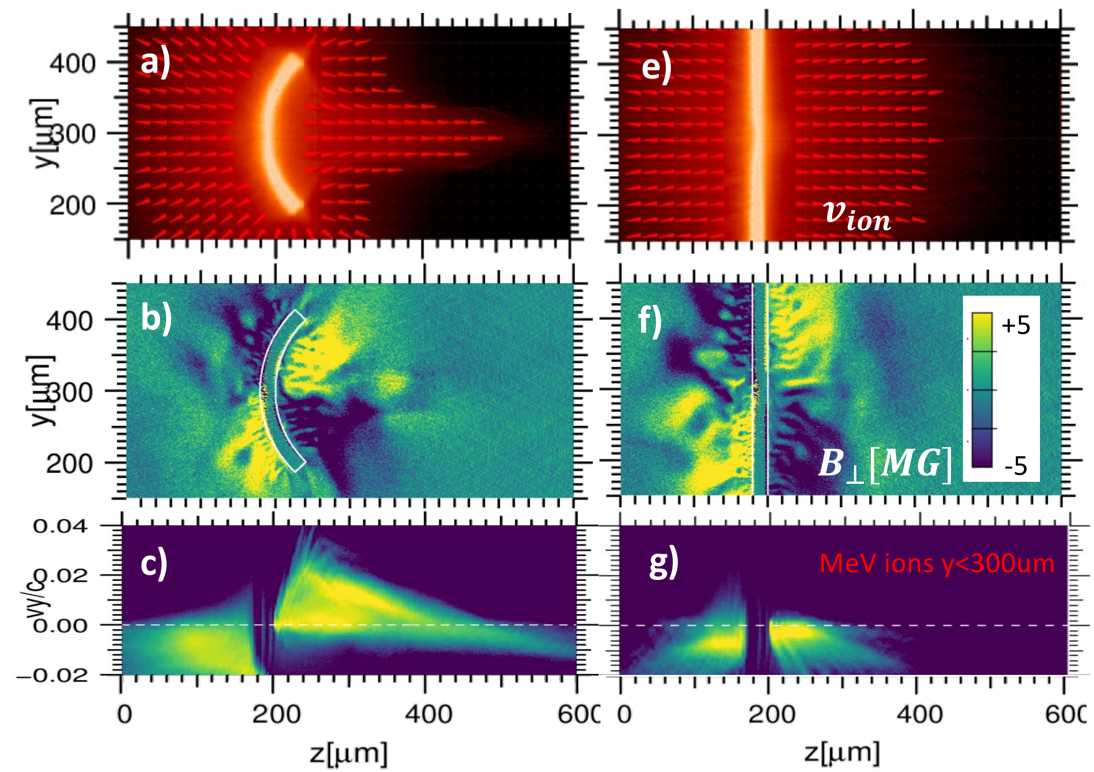
(3D based on doubling the contribution of the ion beam 'wings')

Ions are guided on non-ballistic trajectories by electromagnetic fields driven by hot electrons

`5x10^19 W/cm^2, 1ps fwhm, 2D ARC-like profile "1kJ"`

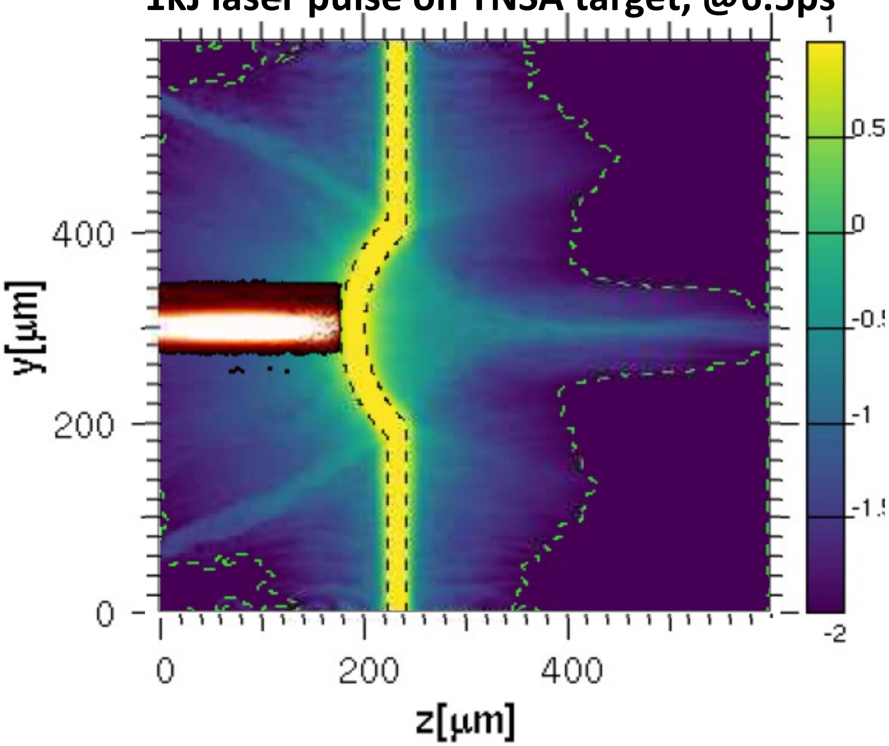
Ion trajectories are consistent with their Larmor radius in imprinted B fields



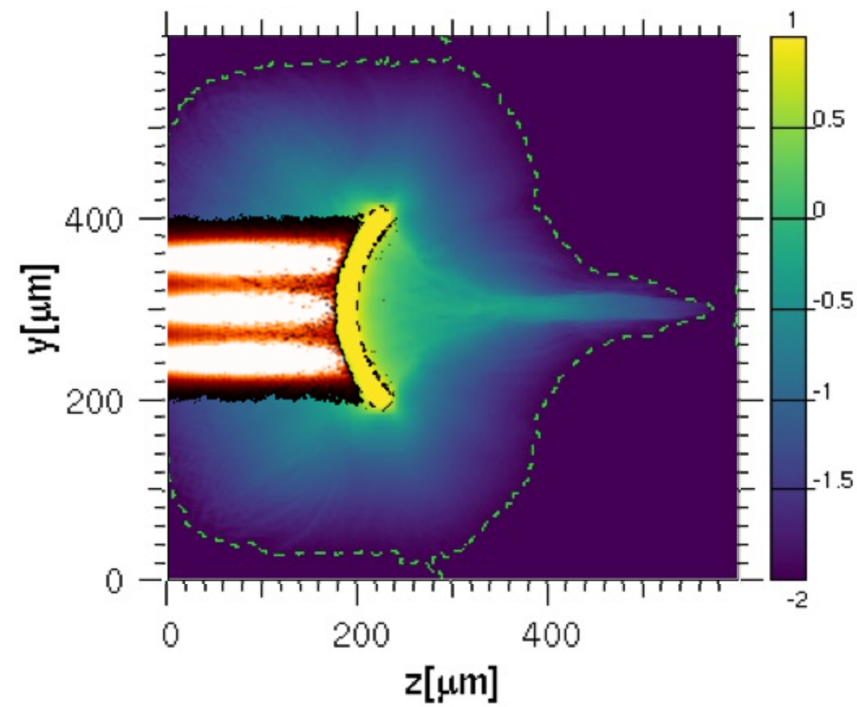


Irradiating the foil with multiple beams at the same coupling efficiency

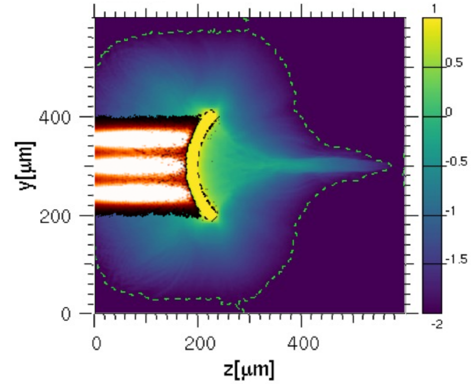
1kJ laser pulse on TNSA target, @6.5ps



“10kJ laser pulses” on TNSA target, @6.5ps



Conclusions



- Under optimal (quasi-1D) conditions we get 25% coupling and 6-10% into 10-20MeV ions
- But, for proton FI we need to couple to a 40um wide spot, Eion ~ 10-20MeV (limits vary)
- With a finite laser spot we expect <1% coupling
- With a curved foil we can improve 3x due to focusing B fields
- Coupling relatively insensitive to intensity, pulse duration, laser spot size and target thickness

- Future work – TNSA beam propagation into low-density plasma (SI LDRD, S.Maclaren)

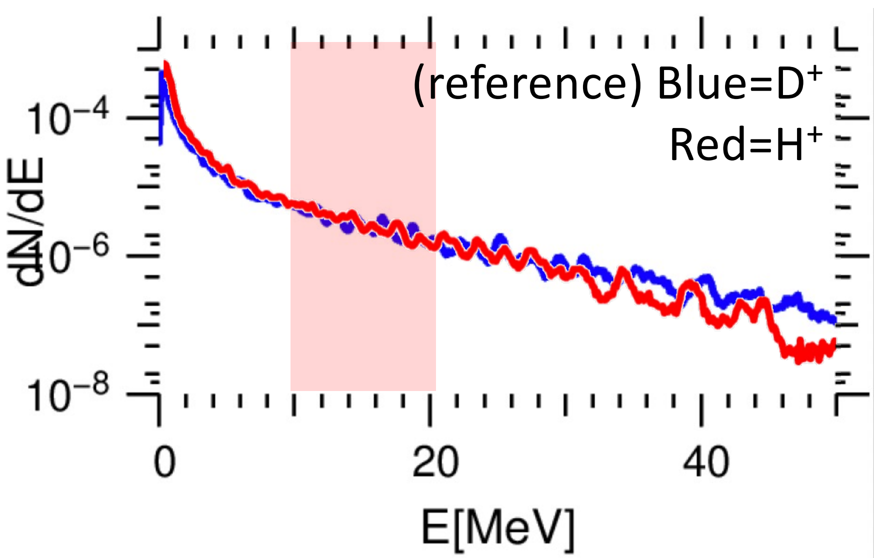
target	Conversion to >MeV ions	Conversion to 10-20MeV ions
Quasi-1D	25%	6%
Curved foil	10%	2.4%
Flat foil	3.2%	0.8%

See Kemp, Wilks, Tabak, Physics of Plasmas **31** (2024)

The effective layer depth for >10MeV ions is about 400nm, larger than usual TNSA "pump oil film" sources

A) Uniform plasma

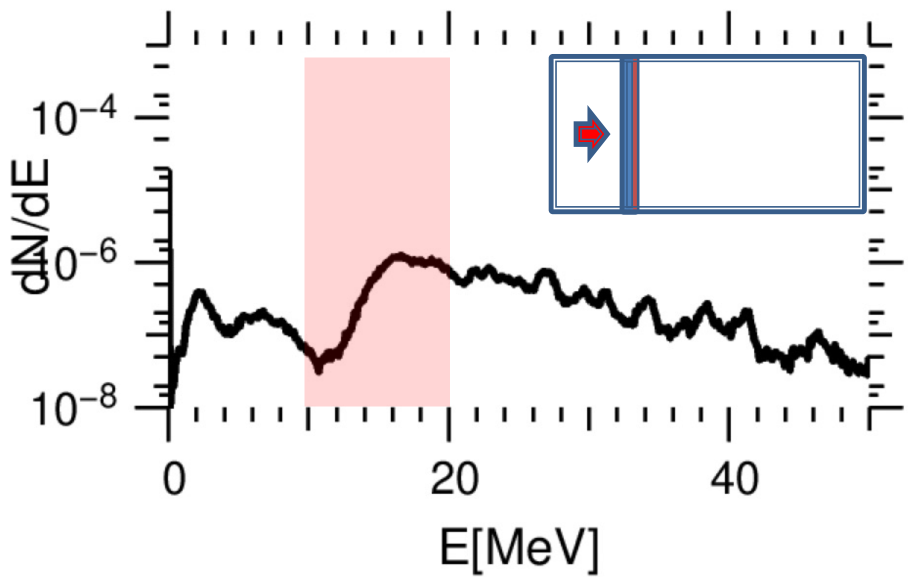
Eta=25% all energies
6% into 10-20MeV



E>10MeV: 400nm deep layer *

B) Proton layer on D

Eta=6% all energies
2% into 10-20MeV



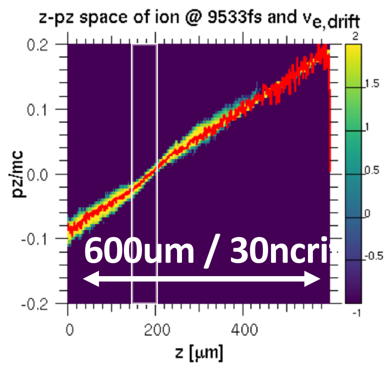
20um Deuterium + 250nm of p

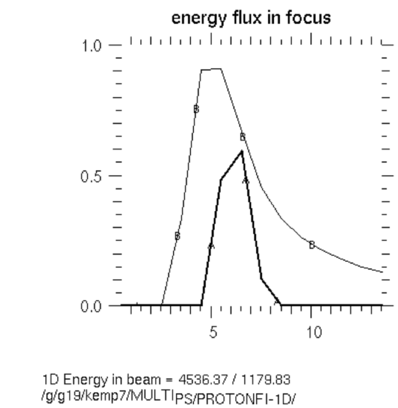
* Integrating ion spectrum & assuming our initial density 30nc

Higginson et al, PRR4 (2022)

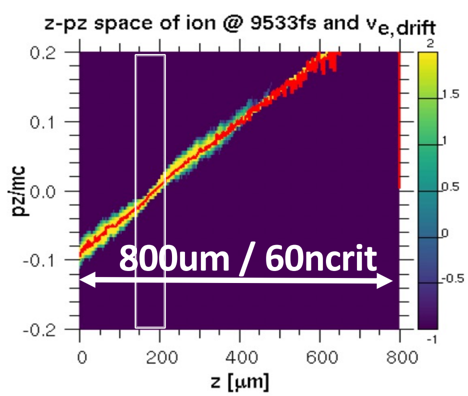
Convergence test with 200um longer box, 32 cells per micron, 60ncrit - Instead of 16 cells per micron, 30ncrit gives consistent result

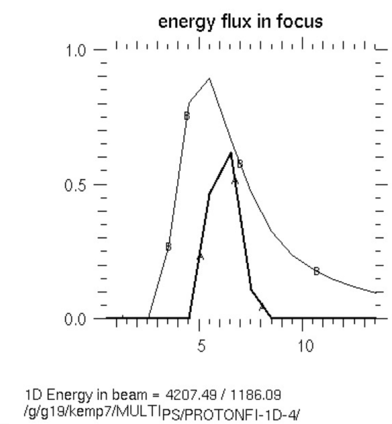
Reference case





- More space behind target
- Higher density
- 2x spatial resolution

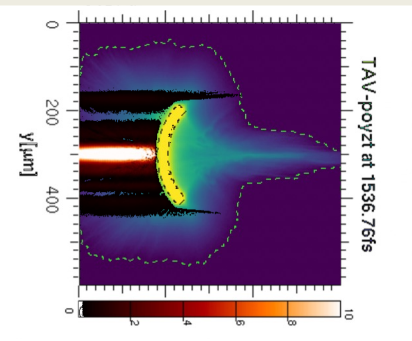


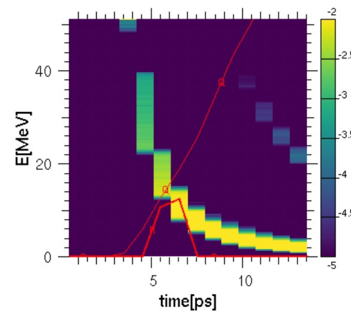


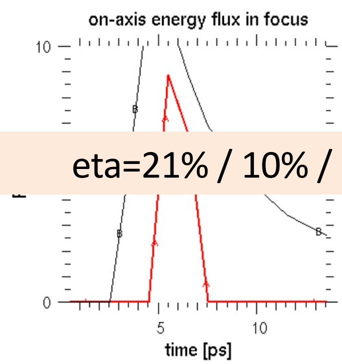
Same coupling efficiency

2D TNSA simulations show ion dose and energy flux increase proportionally with number of beams – constant coupling efficiency

1. Elaser (3D) =38x38 x 1e-8*1e-12*5e19= **720J**

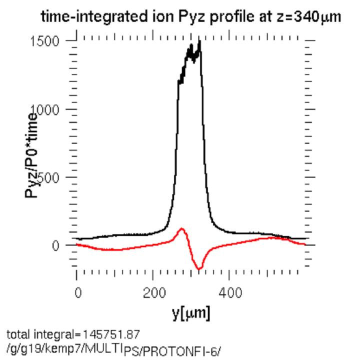




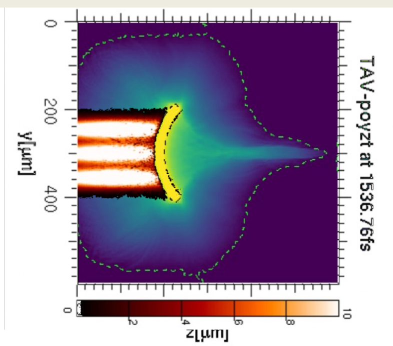


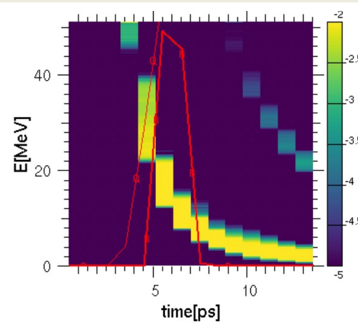
eta=21% / 10% / 2%

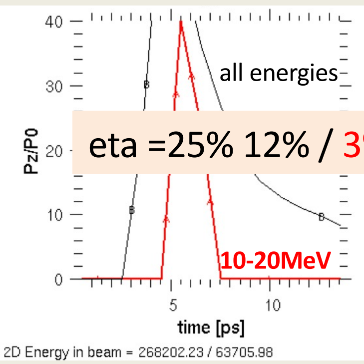
laser energy=38x1000x(5e19/2.74e18)=700,000 au



2. Elaser (3D) =9 x 38x38 x 1e-8*1e-12*5e19=9x 720= **6.5kJ**

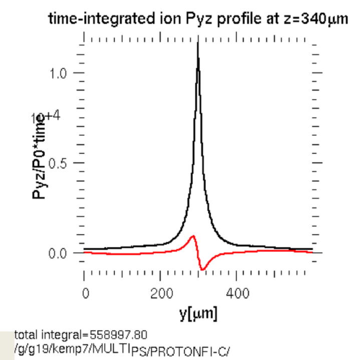






eta =25% 12% / 3%

laser energy=**3x** 38x1000x(5e19/2.74e18)=2,100,000 au



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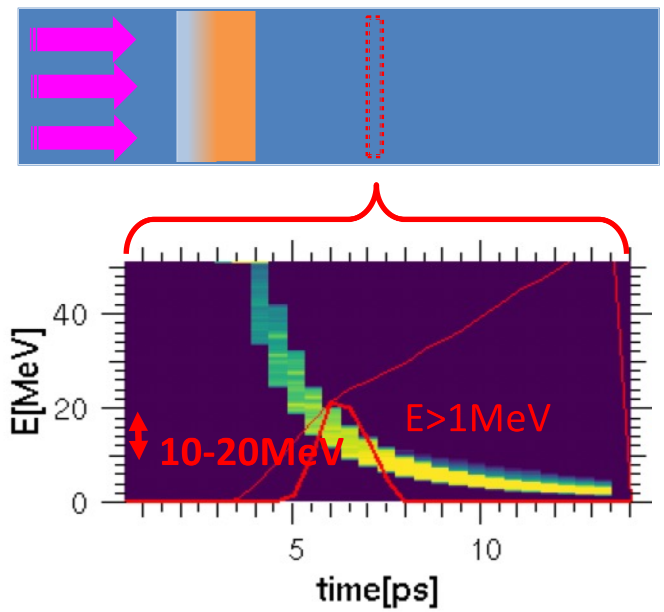

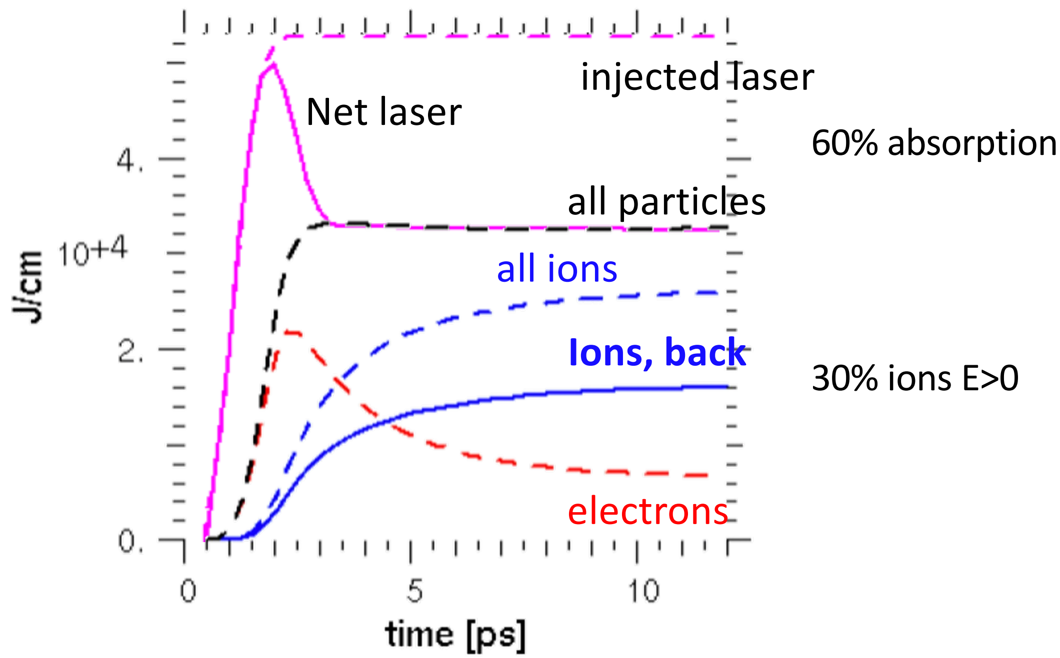

Coupling: ions>1MeV =**25%** (10-20MeV) = **6%**