# NIF Discovery Science: Enhanced Proton Acceleration Efficiency Through Electron Confinement using the NIF ARC

NIF JLF User Group Meeting 2025

D. Mariscal
on behalf of Dr. Natsumi Iwata & Team

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LLNL-PRES-872399

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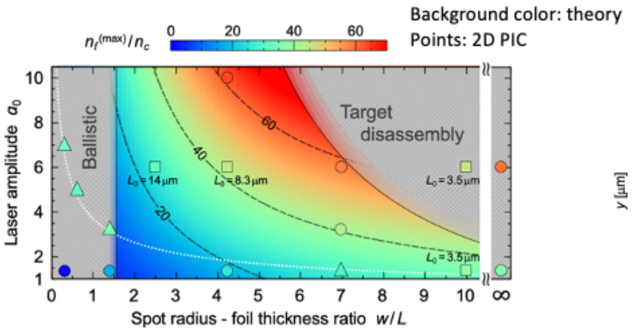
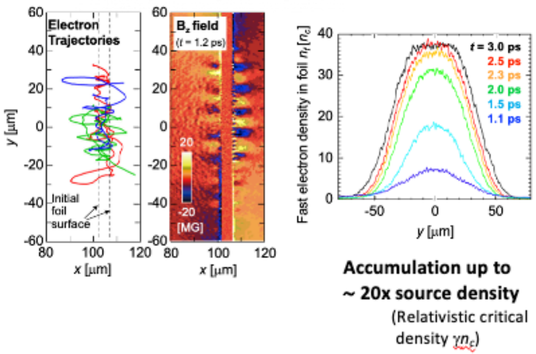
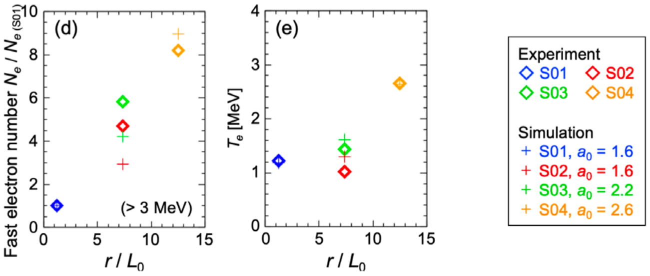
# Electron confinement enhances ion acceleration resulting in higher proton energies and conversion efficiencies*



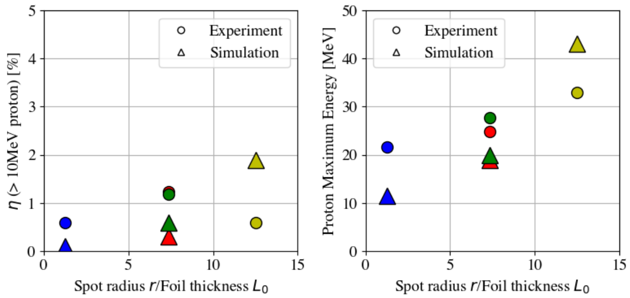

*N. Iwata, et al., PRR 3, 023193 (2021)*




## Electron Enhancements*




## Proton Enhancements*




- A predicted mesoscale (kinetic & statistical) phenomenon was investigated on the NIF's ARC platform
- Lateral electron confinement can occur when the focal spot (10's μm), energy (100's J), and pulse lengths (multi-ps) are large
- Higher electron densities lead to stronger sheath fields → more efficient ion acceleration
- NIF DS experiments show results consistent with theory and simulation



*N. Iwata, et al. (in preparation)

# Thank you to the teams that made this work possible


## ILE – Osaka University

- PI: N. Iwata, Y. Sentoku — Theory & Modeling
- A. Morace, S. Fujioka — Experiments

## LLNL (Physics Team)

- D. A. Mariscal, D. Rusby, R. Simpson, T. Ma — Experiments
- G. Cochran, A.J. Kemp, S. C. Wilks — Theory & Modeling

## LLNL (ARC Team)

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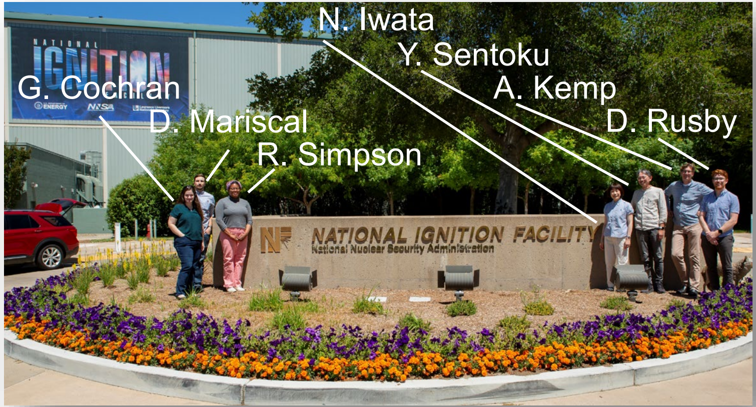
PI: Natsumi Iwata

SINCE 1972
50 YEARS
Institute of Laser Engineering
Osaka University



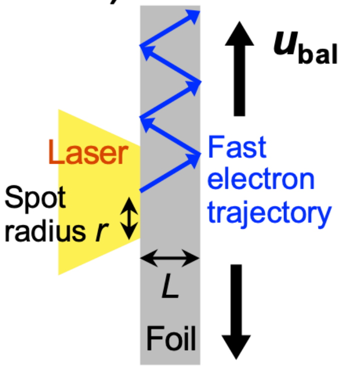

Special thanks to NIF operations, target fabrication, ARC IPT and NIF Discovery Science for enabling these experiments!

# kJ-class lasers like ARC enable access to the mesoscale regime

Typical short-pulse interactions

**Small spot**

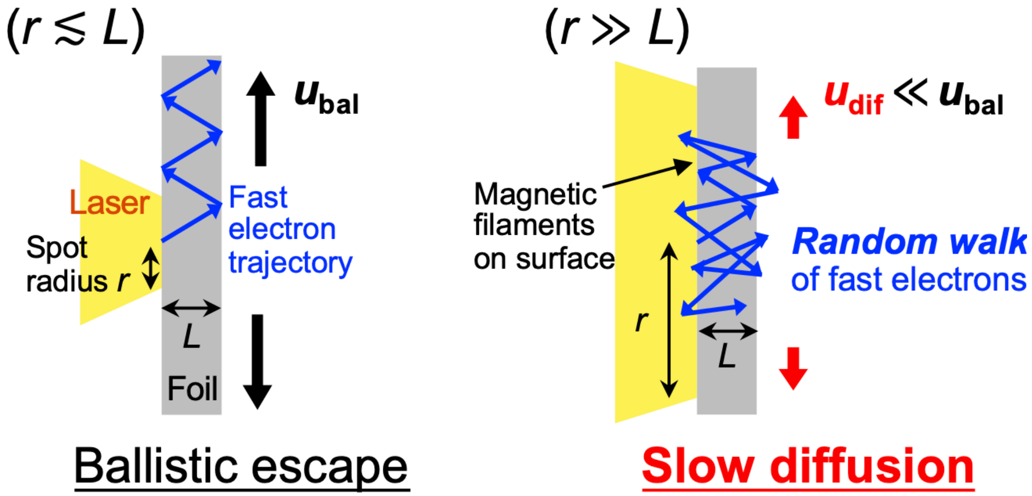
$(r \lesssim L)$




Ballistic escape

# kJ-class lasers like ARC enable access to the mesoscale regime

| Typical short-pulse interactions | Mesoscale (kJ-class) interactions |
|---|---|
| **Small spot** | **Large spot** |



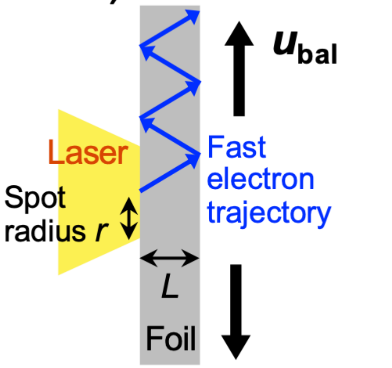

## Key features for accessing mesoscale regime

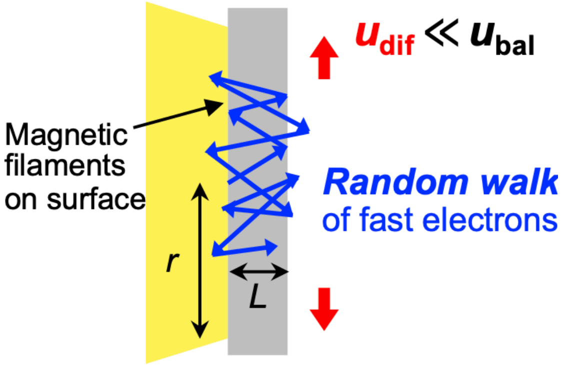
- Relativistic intensity
- 100's J - kJ energies
- >ps pulse lengths
- Large (>~50 μm) focal spots

These features enable highly efficient TNSA ion acceleration and plasma heating

# Electron escape from the focal spot can be described as slow diffusion in this regime

| Typical short-pulse interactions | Mesoscale (kJ-class) interactions |
| --- | --- |
| **Small spot** | **Large spot** |
| $(r \lesssim L)$ | $(r \gg L)$ |




<u>Ballistic escape</u>

<u>**Slow diffusion**</u>

**Diffusion model** $0 = D\dfrac{\partial^2 n_f}{\partial y^2} + S$

$n_f$: fast e- density
$D$: diffusion coef.
$S$: source

⇒ Accumulation time scale ~ ps

⇒ Achievable density **determined by the spot size/foil thickness ratio.**

$$n_f^{(\max)} = \gamma n_c \Theta_n \frac{w^2/L^2}{1+\chi w^2/L^2}\left(1 + 2\frac{u_{\rm dif}}{u_{\rm bal}}\right)$$

(Source density)

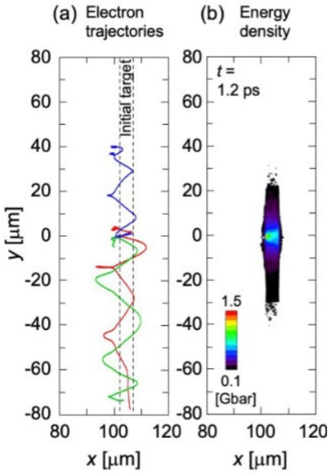
($\chi \simeq 2C_s/v$ represents the plasma expansion effect, $\Theta_n \equiv 1/(\tan\bar{\theta}\sin\bar{\theta}) \simeq 0.76$)

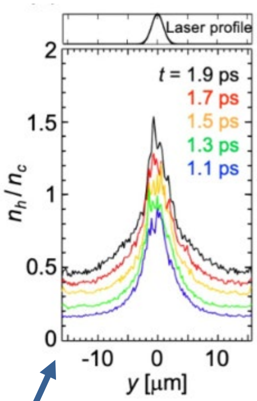
This is a statistical phenomenon that appears naturally in large-scale laser-plasma interactions



*[Iwata, Kemp, Wilks, et al., PRR 3, 023193 (2021)]

# PIC modeling has shown how magnetic filaments can result in electron accumulation

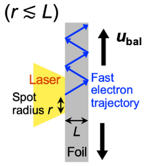


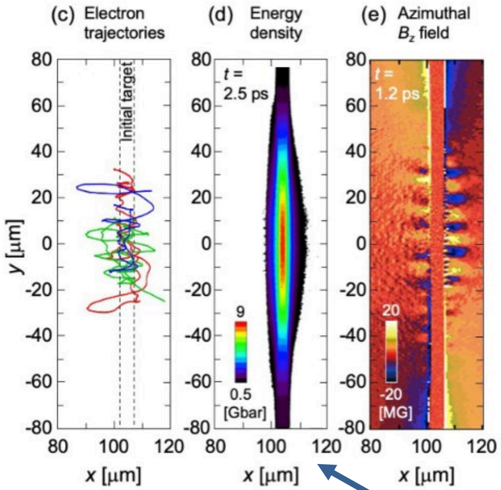

Electrons quickly escape interaction region

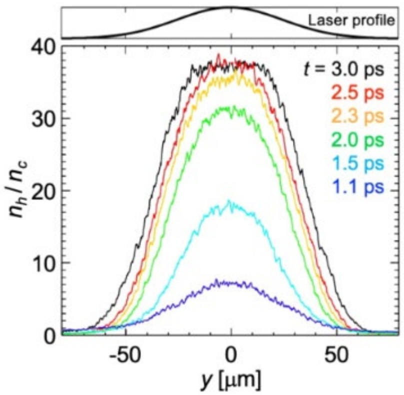
Typical short-pulse interactions

**Small spot**




Ballistic escape

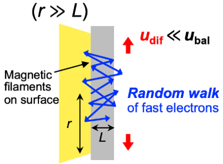



Electrons remain in / near the interaction region

Mesoscale (kJ-class) interactions

**Large spot**



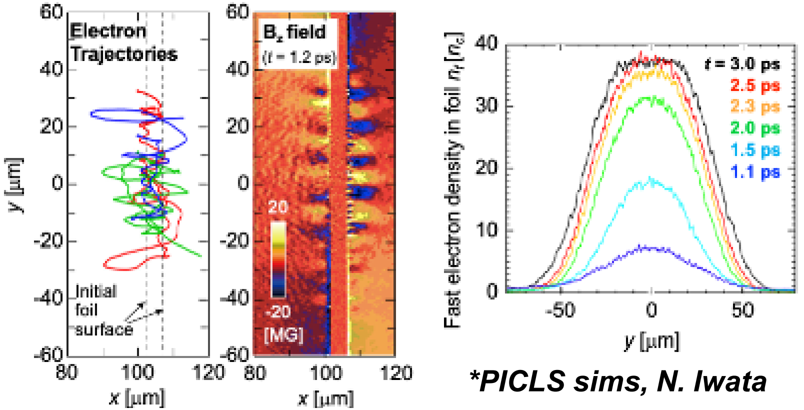

Slow diffusion



*Figs. From: Iwata, Kemp, Wilks, et al., PRR 3, 023193 (2021)

# Tuning the laser spot radius to target thickness ratio is predicted to result in increasing ion acceleration efficiency

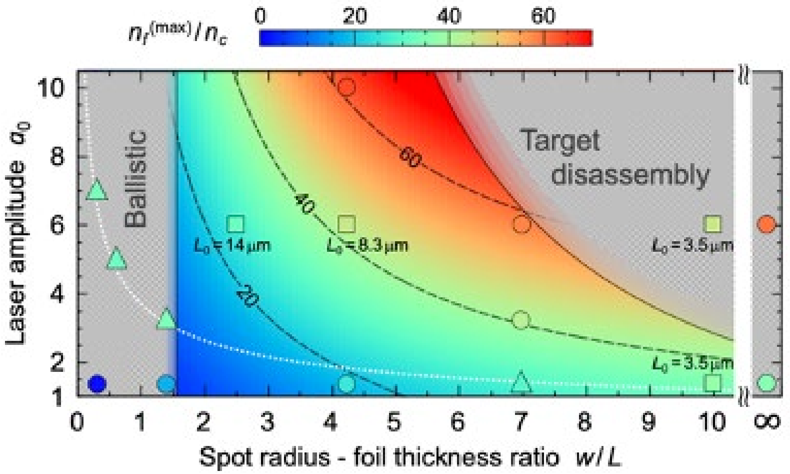
## PIC Simulations of e⁻ accumulation




***PICLS sims, N. Iwata**

Large spot + magnetic filaments minimize electron escape from interaction region

## Theoretical Parameter Space (e⁻ accumulation)




*points = PIC simulations

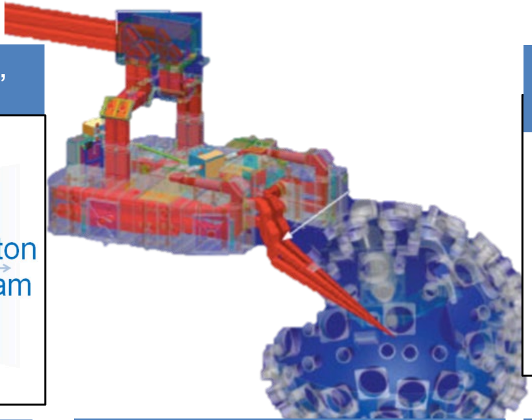
*N. Iwata, et al., PRR 3, 023193 (2021)*

**The proposed experiments aimed to utilize observations of the proton and electrons as signatures of enhanced electron confinement with large focal spots and thinner targets**

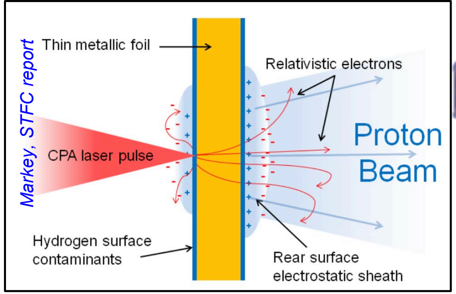


*PICLS code: Y. Sentoku, A.J. Kemp, J. Comp. Phys. (2008)

# Developing ARC's laser-driven ion beam capabilities enables a range of different studies and applications

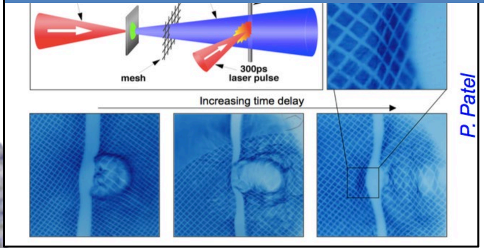


## Directed beams of MeV protons, deuterons, & neutrons



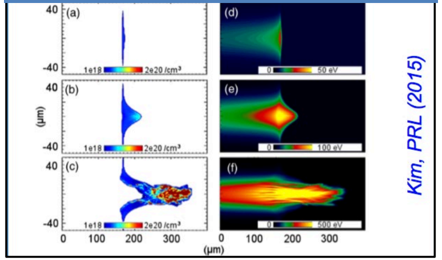

*Markey, STFC report*

## Proton radiography/deflectometry



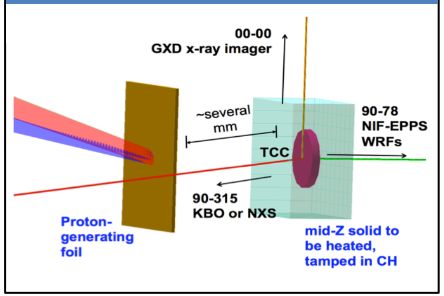

*P. Patel*

## Stopping power investigations

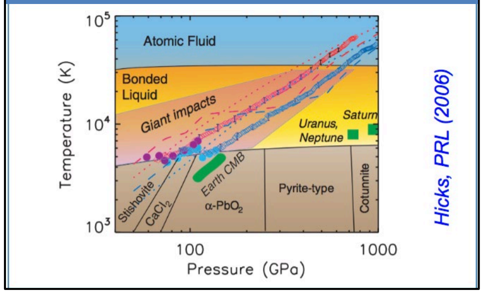



*Kim, PRL (2015)*

## Isochoric heating/WDM

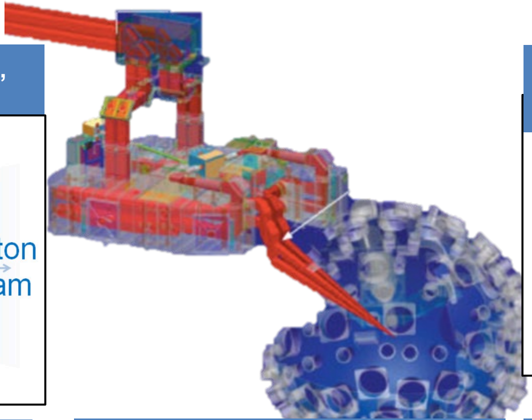



## Planetary interior studies

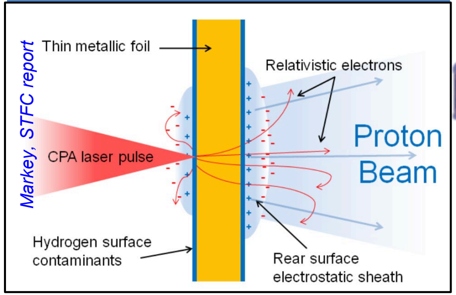



*Hicks, PRL (2006)*

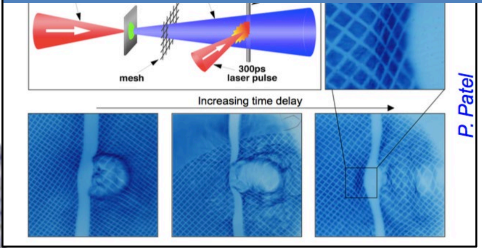
# Developing ARC's laser-driven ion beam capabilities enables a range of different studies and applications



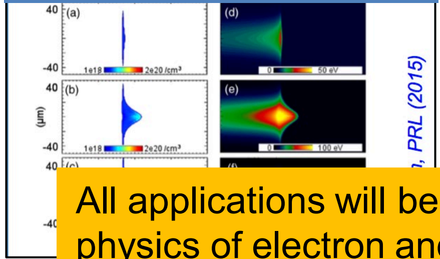
**Directed beams of MeV protons, deuterons, & neutrons**




**Proton radiography/deflectometry**




**Stopping power investigations**

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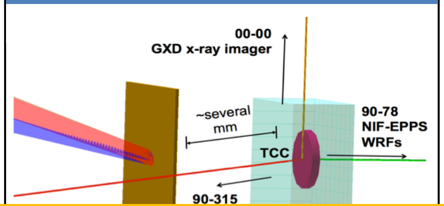
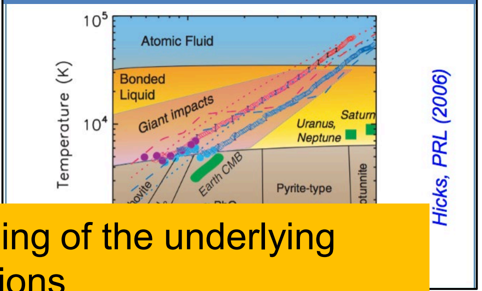


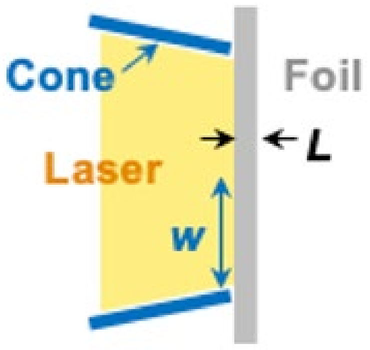

**Planetary interior studies**




All applications will benefit from a better understanding of the underlying physics of electron and ion dynamics at ARC conditions

# Using CPC's* ensures a consistent interaction region for multi-beam ARC operation

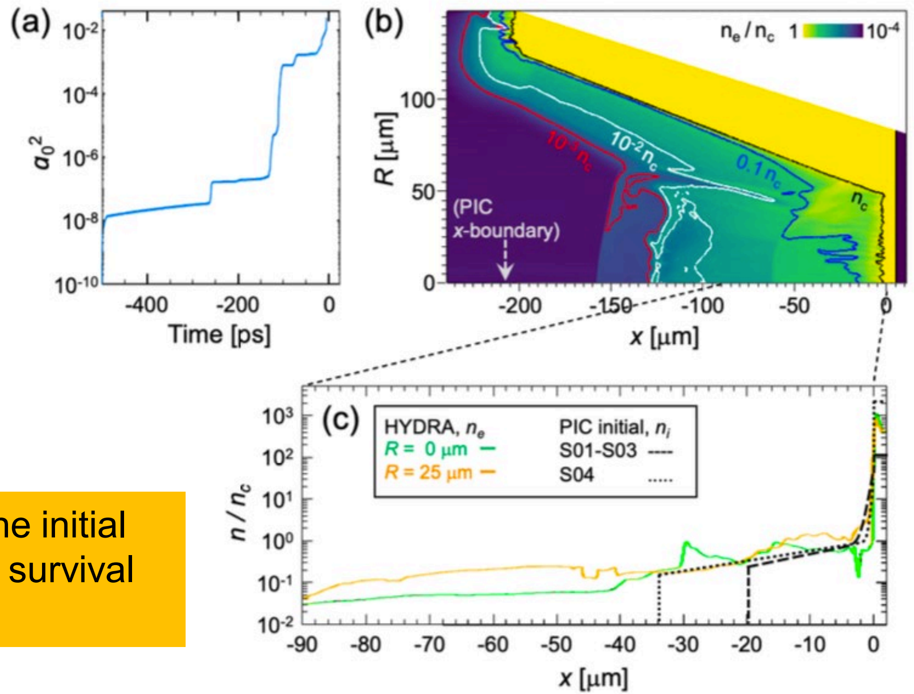
## Cone Use




Cone

Approx. ARC pre-pulse profile

Initial Conditions from rad-hydro




G. Cochran, HYDRA

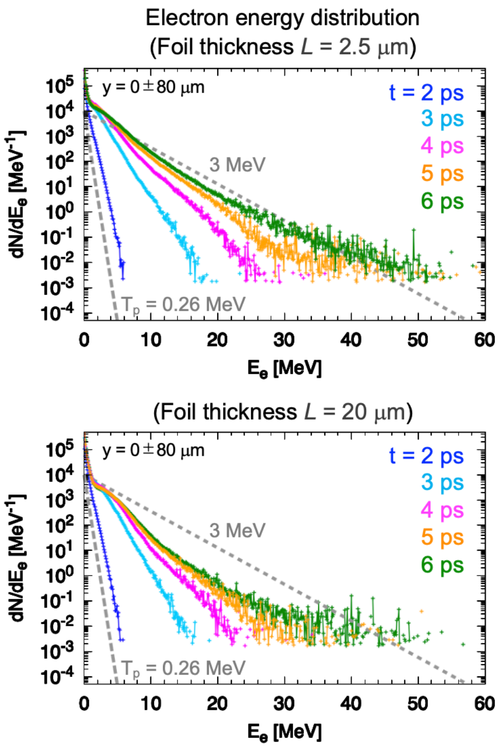
*N. Iwata, et al. (in preparation)

Using rad-hydro simulations, we can predict the initial conditions for PIC simulations and assess the survival of thin foils in the presence of pre-pulses

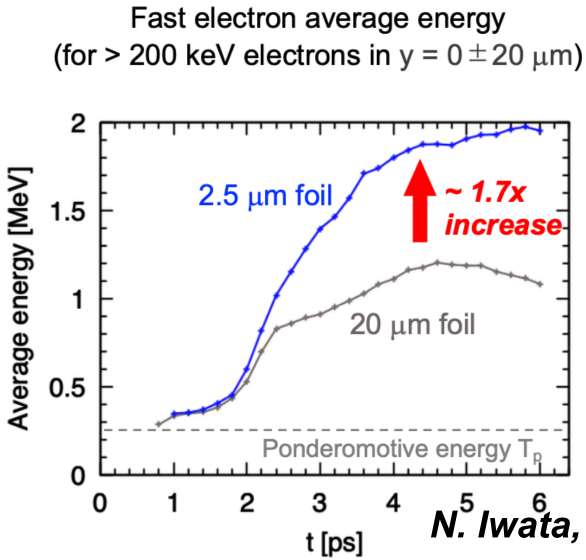


*A. MacPhee, et al., Optica (2020)

# With only a change in target thickness, PIC modeling predicted a substantial increase in the average e⁻ energy




N. Iwata, PICLS

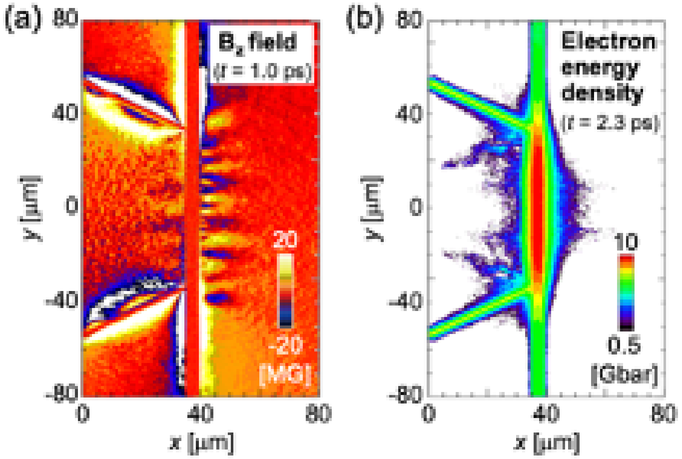



N. Iwata, PICLS

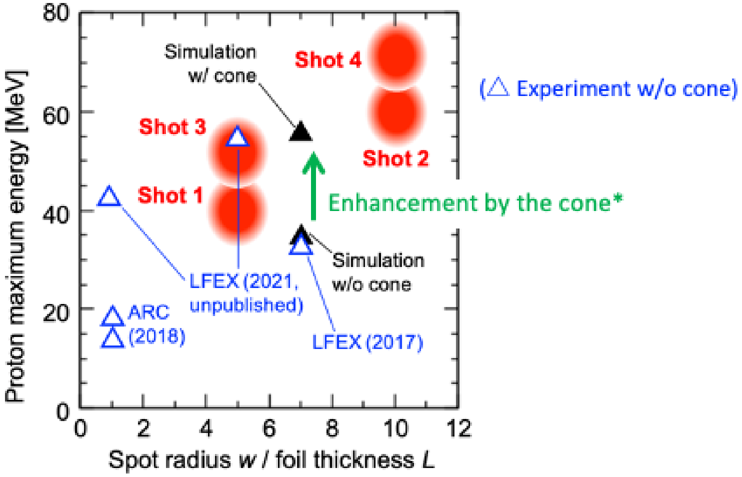
Laterally-confined fast electrons have an increased chance to be accelerated to higher energies in the thinner target

# While using a CPC offsets the original predictions from PIC simulations, the expected trends are unchanged

## 2D PIC simulations w/CPC




## Proton Maximum Energy

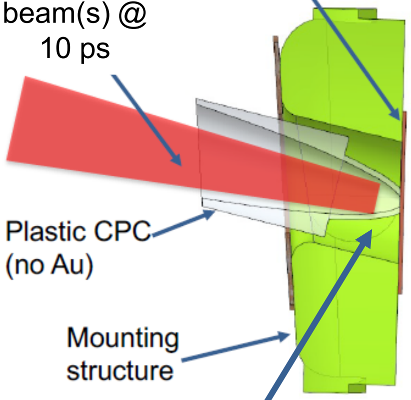



Fast e⁻ accumulation still predicted to reach up to 30X source density

With a fixed *w* (spot radius), we studied whether the electron distribution and proton maximum energy scale as predicted

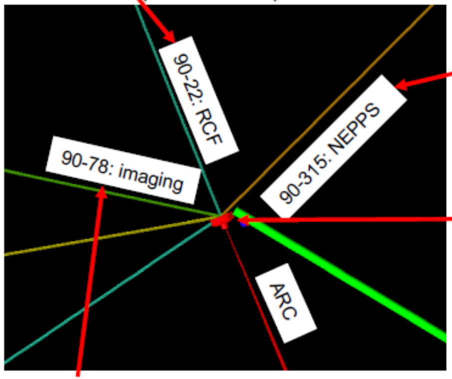
# The CPC proton target used a special design that enables easier build while reducing mass at the cone tip

## Targets: CPC's + Foils




## Diagnostics to characterize interaction

RCF: Proton energy distribution and spatial distribution (~ 5-60 MeV)




X-ray pinhole imaging
- Spatial extent of fast e- interaction (Bremsstrahlung (70-200 keV))
- Cu heating (Characteristic x-rays (~ 8 keV))

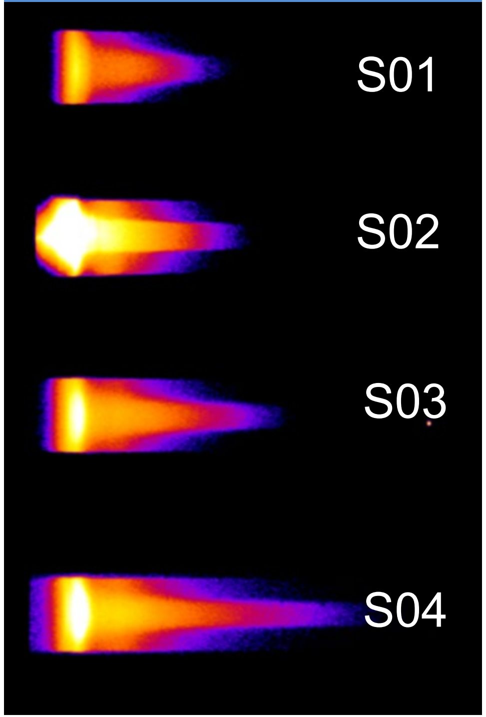
## Laser and Target Characteristics

| Shot No. | Laser energy | Pulse width | Peak amplitude | Cone tip radius $r$ | Foil thickness $L_0$ |
|---|---|---|---|---|---|
| S01 | 562 J | 10.1 ps | 1.6 | 25 μm | 20 μm |
| S02 | 590 J | 8.9 ps | 1.7 | | 3.4 μm |
| S03 | 1218 J | 8.8 ps | 2.2 | | 3.4 μm |
| S04 | 2290 J | 10.5 ps | 2.6 | | 2.0 μm |

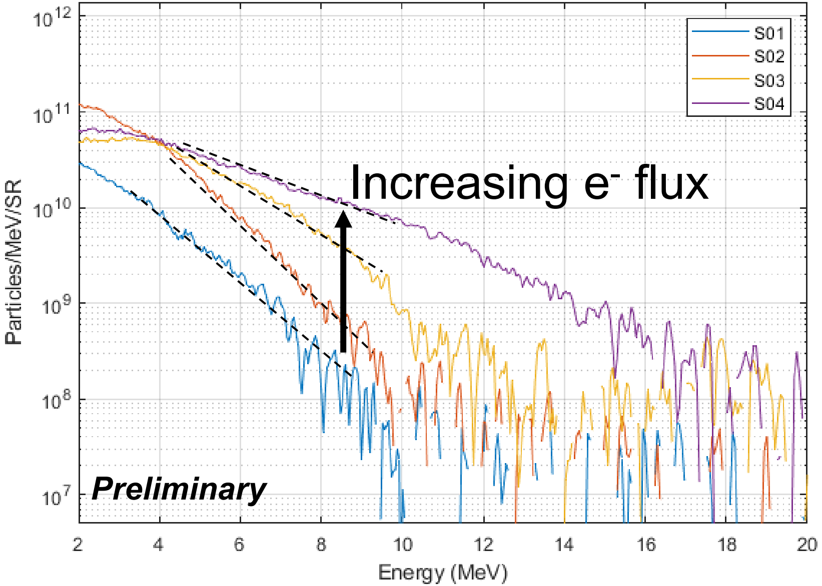
With NIF's suite of MeV particle diagnostics we were able to assess the proton and electron characteristics

# Clear signatures of electron confinement are present in the observed electron spectra

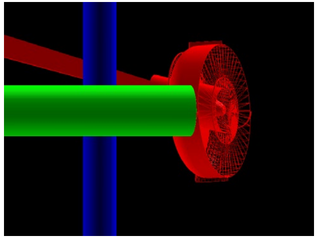
NEPPS: raw e⁻ data




NEPPS: raw e⁻ data




NEPPS POV (90-315)



Only small changes to temperature while fluence is greatly increased with thinner targets & more laser energy

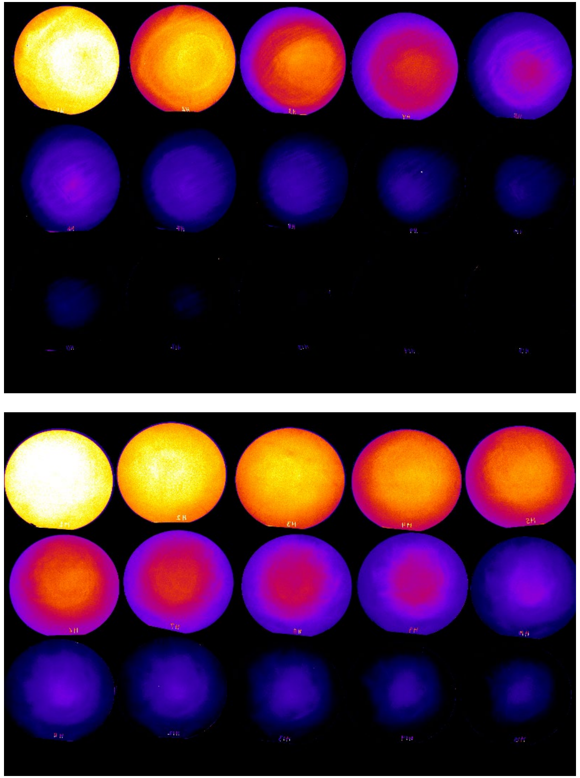


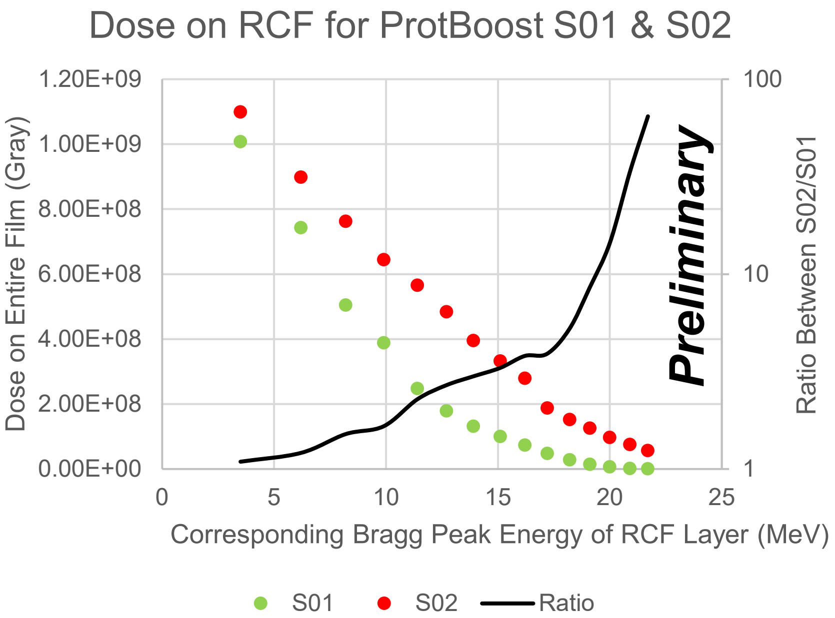
***Analysis: D. Rusby***

# The first series clearly showed increased flux and maximum proton energy with thinner target, as predicted

S01 – 20 um Copper Foil

S02 – 3.4 um Copper Foil

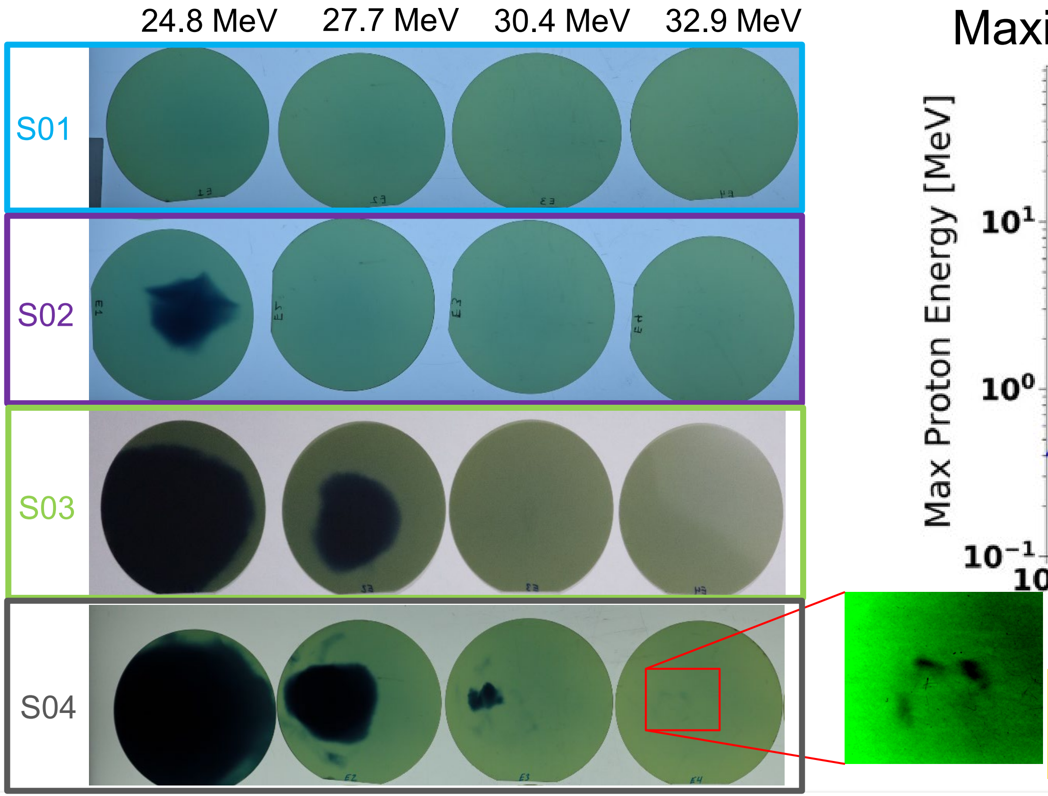




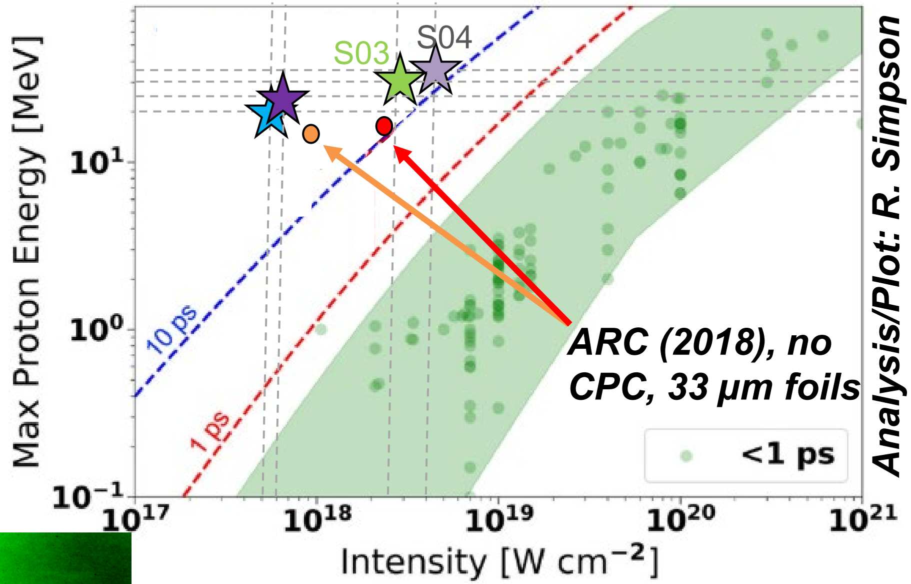

Proton fluence was substantially increased with the thinner foil (higher w/L ratio)

*Analysis: R. Simpson / D. Rusby*

# We observe highest dose and max proton energies on the S03 and S04, as expected with given laser and target parameters




Maximum proton energies comparison*



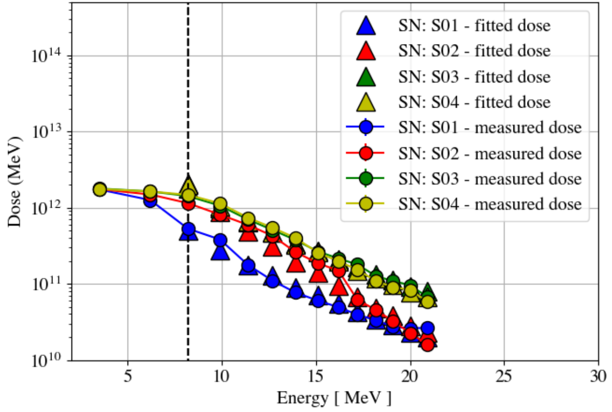

These are some of the highest proton energies observed on ARC to-date



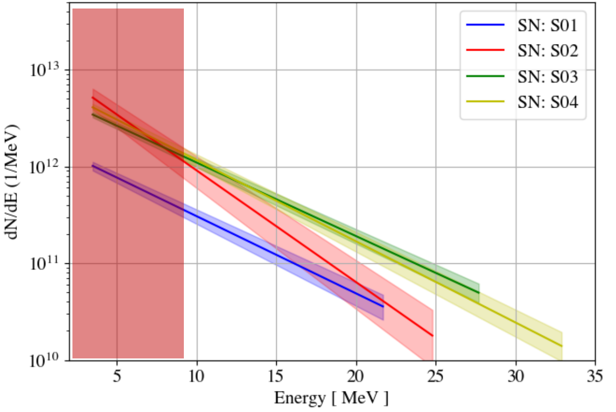
*Mariscal, et al., Phys. Plasmas 26, 043110 (2019)

# Proton spectra and maximum energy increased substantially through the first three experiments

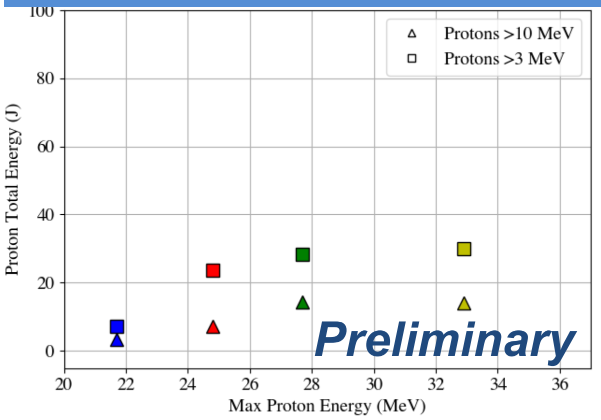
## Dose Fitting: HD-type films




## Fitted Spectra




## Inferred Total Energy (protons)

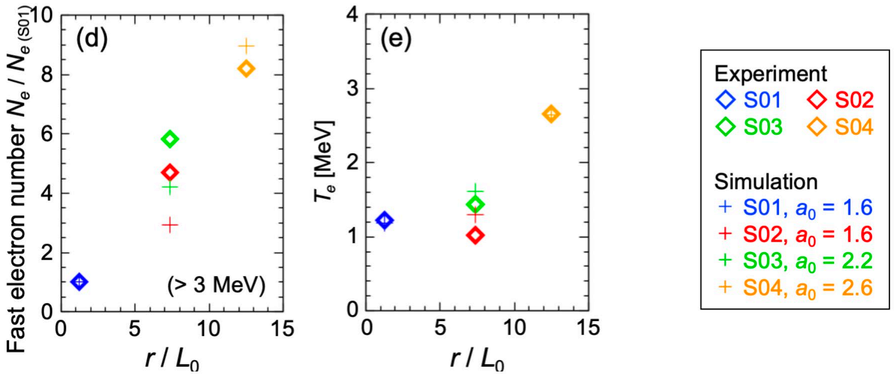



***Analysis: R. Simpson, D. Rusby***

The total proton fluence increased through the first three shots, however, it did not increase on the fourth

# Post-shot modeling is able to capture many of the trends in experimental observables

## Electron Enhancements*




***Expt. Analysis: R. Simpson, D. Rusby***

*N. Iwata, et al. (in preparation)

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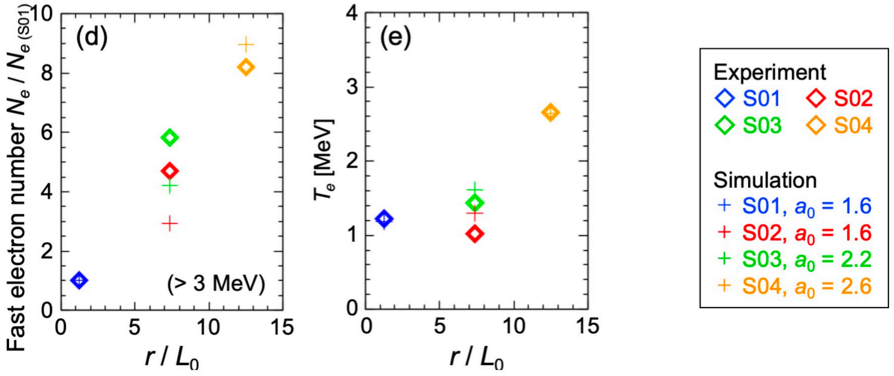


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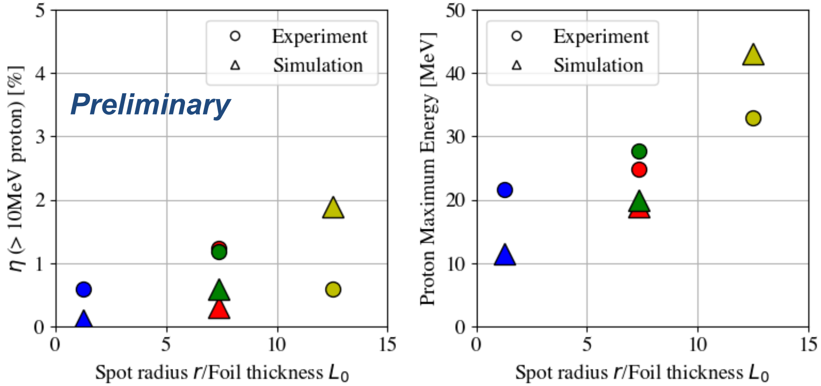


***Expt. Analysis: R. Simpson, D. Rusby***



*N. Iwata, et al. (in preparation)

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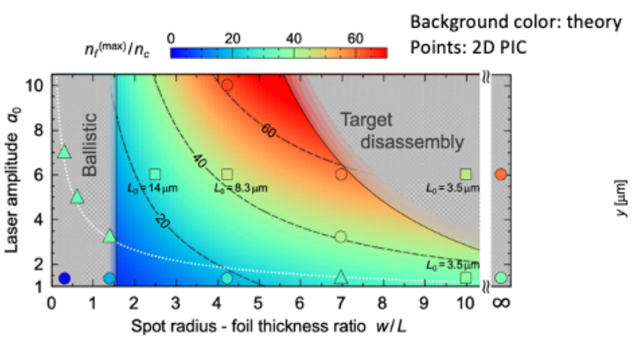
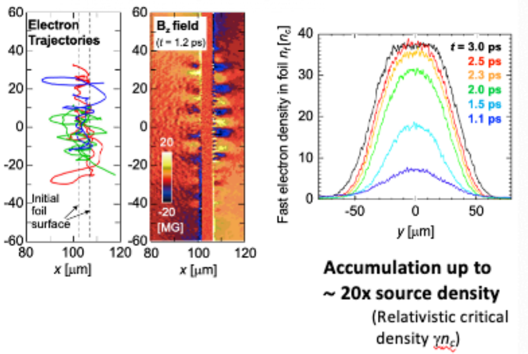



N. Iwata, et al., PRR 3, 023193 (2021)

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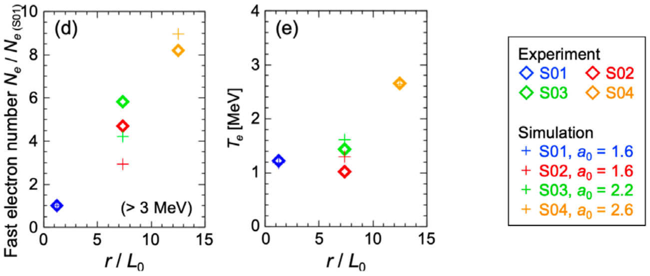
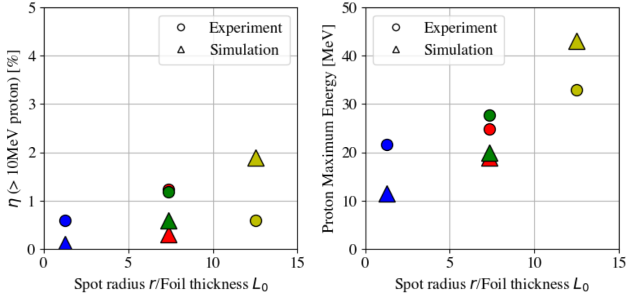



## Proton Enhancements*




- A predicted mesoscale (kinetic & statistical) phenomenon was investigated on the NIF's ARC platform
- Lateral electron confinement can occur when the focal spot (10's μm), energy (100's J), and pulse lengths (multi-ps) are large
- Higher electron densities lead to stronger sheath fields → more efficient ion acceleration
- NIF DS experiments show results consistent with theory and simulation

*N. Iwata, et al. (in preparation)

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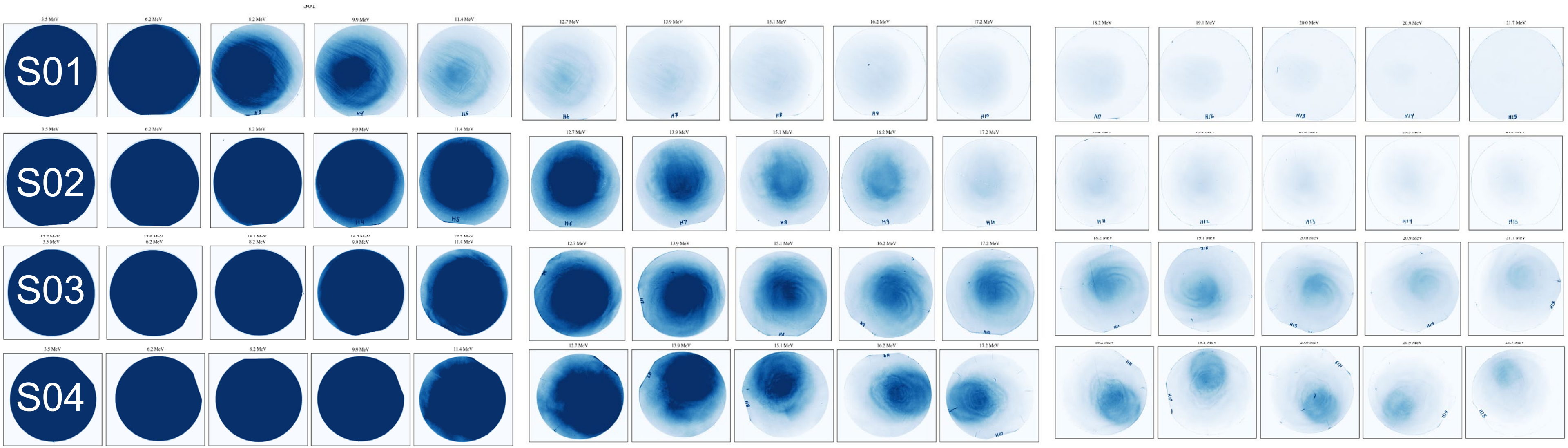
# All RCF Comparison




Courtesy: R. Simpson