Ion Coupling in Dense Matter using Nuclear Reactions for Applications to Ion Fast Ignition and HED Science

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NIF and JLF User Groups Meeting 2025
Livermore, California
Feb 12, 2025

LLNL-PROP-869533

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract DE-AC52-07NA27344. Lawrence Livermore National Security, LLC. This work was supported by LLNL LDRD 24-SI-003

Lawrence Livermore National Laboratory

Our collaboration brings together simulation and experimental experts in high energy density science

Lawrence Livermore National Lab
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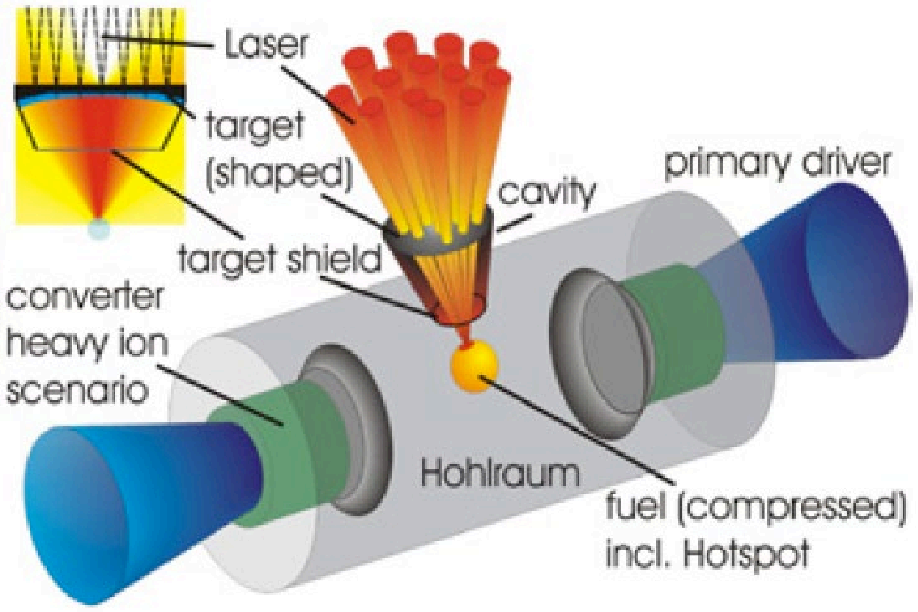
Tom Hodge

This campaign aims to directly measure the coupling and transport of ions into a dense ^{3}He fuel assembly

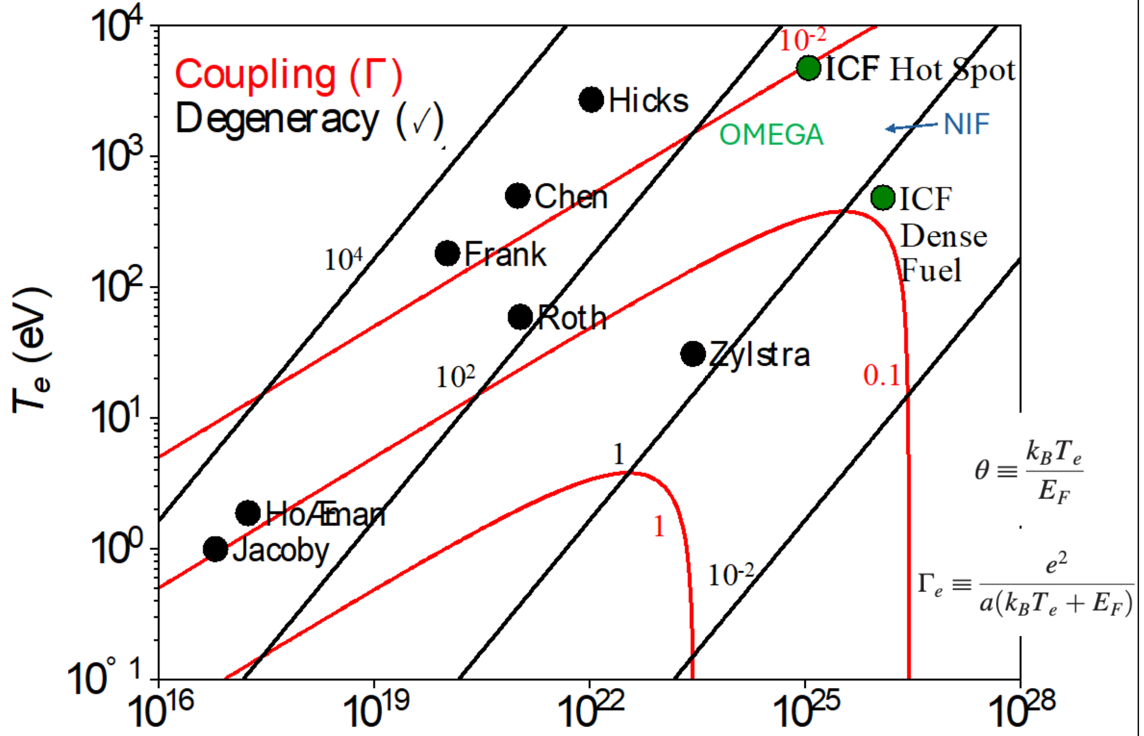
Ion Fast Ignition for Inertial Fusion Energy (IFE)*



[1] Roth et al., PRL 86, 436 (2001)
[2] Fernandez et al., Nucl. Fusion 49 065004 (2009)

*Supported by LLNL IFE LDRD

Ion Stopping Power Experiments



Adapted from :
Zylstra et al. PRL 114, 215002 (2015)

Data from these proposed experiments would be an important result for **ion coupling studies for fast ignition** but also the **transport physics of fast ions in hot dense matter** more generally, neither of which have been studied directly in the literature

We seek to use NIF and ARC in joint operations to study ion coupling in a dense convergent geometry

Proposal Objectives

- **Assemble dense (fuel: $\rho R \geq 50\ mg/cm^2$, $\rho \sim 12\ g/cc$)** cone-in-shell implosion
- Fully characterize fuel conditions **($\rho R, T_e$)** using the NIF nuclear and x-ray diagnostics
- Measure coupling of MeV deuteron ions to compressed ^{3}He gas by **measuring yield of D^{3}He protons using NIF charged particle suite**
- Probe **different density/temperature regimes** with ion source by varying the NIF-to-ARC delay

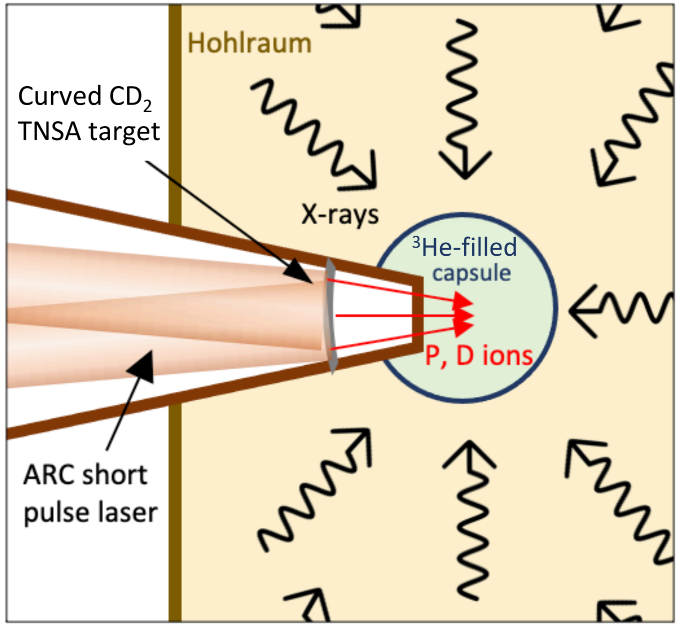
Why the NIF ?

- The NIF is the **only facility in the world that can achieve high-density ignition-relevant** implosions to study ion coupling in this unexplored regime
- The NIF-ARC is the world's most energetic short-pulse laser allowing for a **copious laser-driven ions** to be generated
- The charged particle, x-ray and nuclear diagnostic suite at the NIF enables **characterization of the plasma temperature, density and ion coupling**

Successful implementation of this platform on the NIF and ARC would be the first demonstration of ion coupling in a fast ignition geometry on an ignition-relevant platform

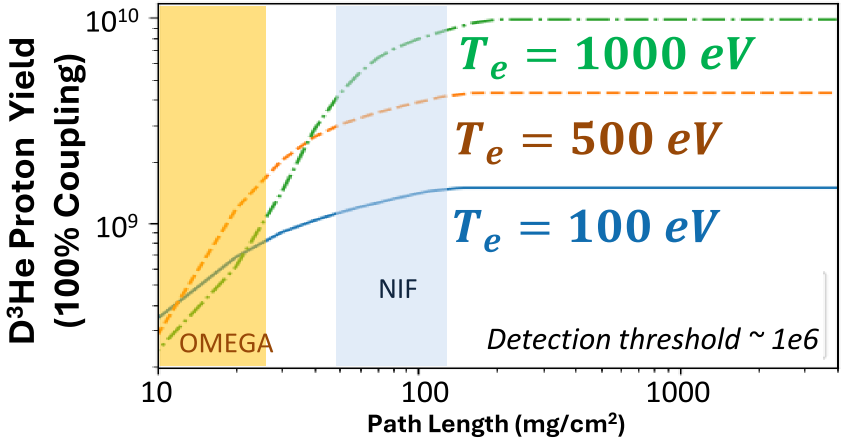
We propose to use a novel method based on nuclear reactions to study fast ion coupling into a dense plasma

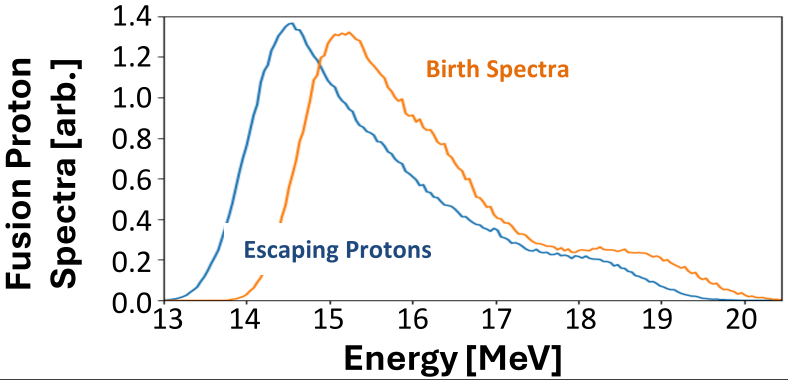
Experimental Approach



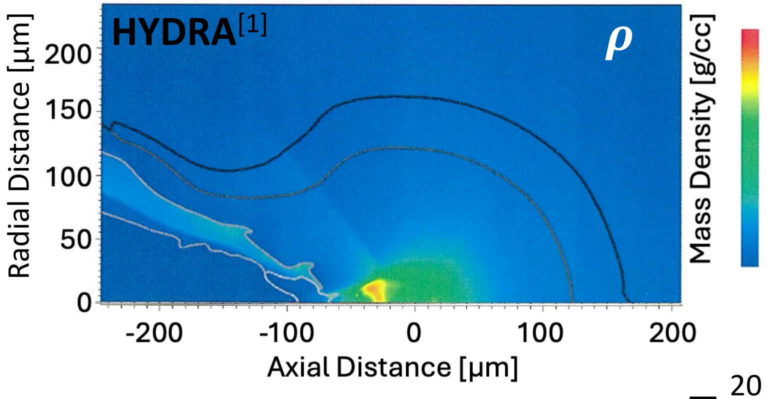
1. Diagnose implosion (ρR, T_e)
2. Measure coupling ($D^3He \rightarrow p+$)

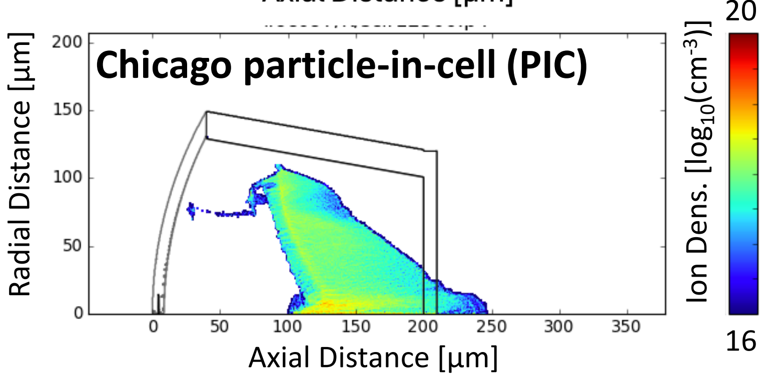
Observable Metrics





Modeling Support





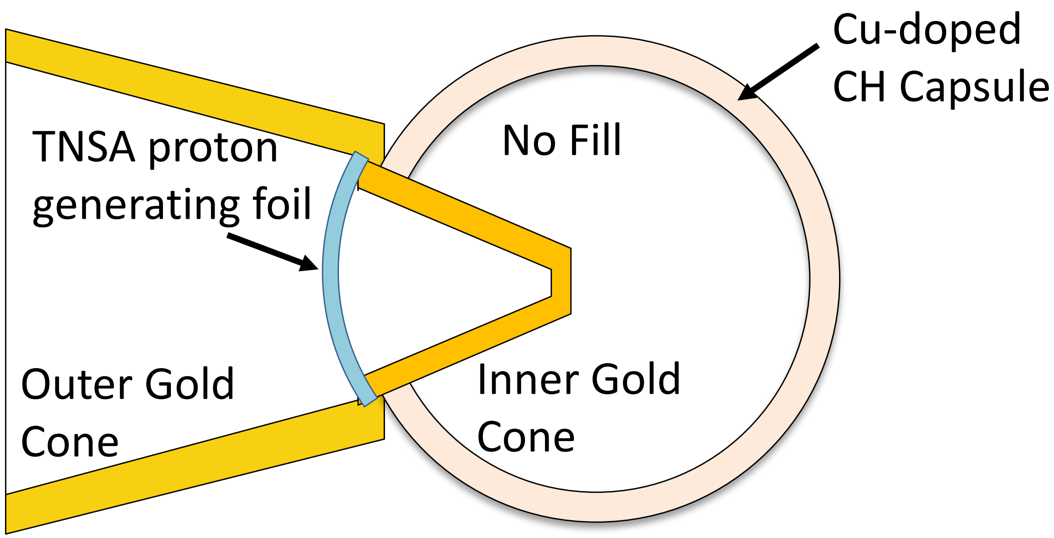
[1] Shay et al., Phys. Plasmas 19, 092706 (2012)

In this scheme, TNSA generated deuterons and ^{3}He fuel are initially separate; thus, the only way to create D^3He reactions is by coupling ions to the gas. With measurements of implosion T_e and ρ, this will constrain models of ion-to-fuel coupling

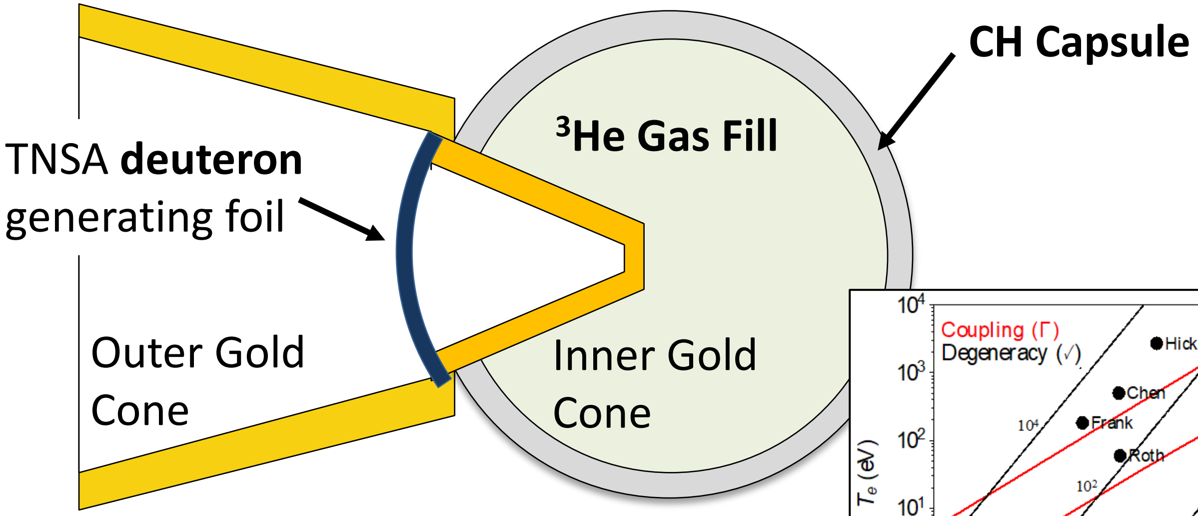
This proposal benefits from previous and upcoming experiments on the OMEGA/EP facility studying ion coupling with two different approaches

Ω/EP Joint Shots (May 2024 and May 2025)
PI: Mathieu Bailly Grandvaux (NLUF)
****First fully integrated IFI experiment ****

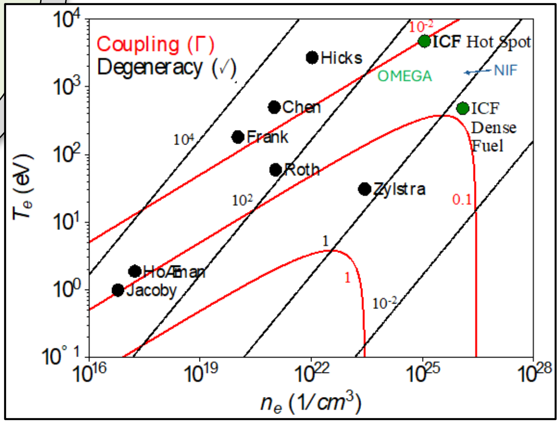
Ω & Ω/EP Joint Shots (January 2025 and May 2025)
PI: Raspberry Simpson (LBS)



APS-DPP 2024 GM10.00003
(Mathieu Bailly Grandvaux)



fuel: $\rho R \approx 15\ mg/cm^2, \rho \approx 4\ g/cc$



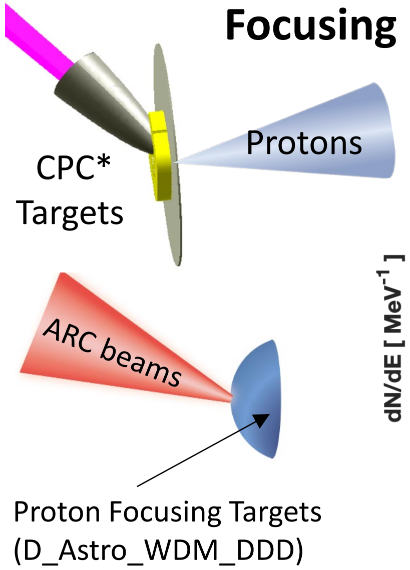
These prior Ω /EP experiments have allowed for crucial data for **benchmarking our existing HYDRA and PIC simulation** platforms enabling us to scale to the different density-temperature regime of the NIF with confidence

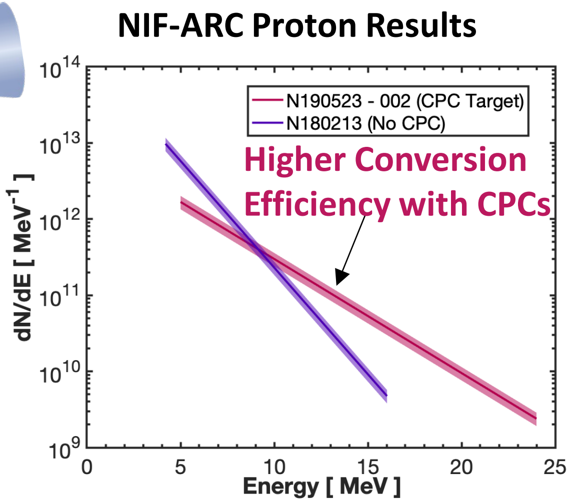
Core elements of this proposal benefit from prior work on the NIF and ARC facilities

Core Requirements of this Proposal

Ion Generation

ARC Ion Acceleration & Focusing Platform

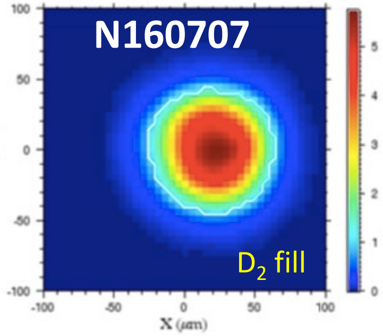




D. Mariscal et al. PoP 26 043110 (2019)
R. Simpson et al. PPCF, 63 124006 (2021)

Symmetrical High ρR Implosions

2-Shock Symcaps

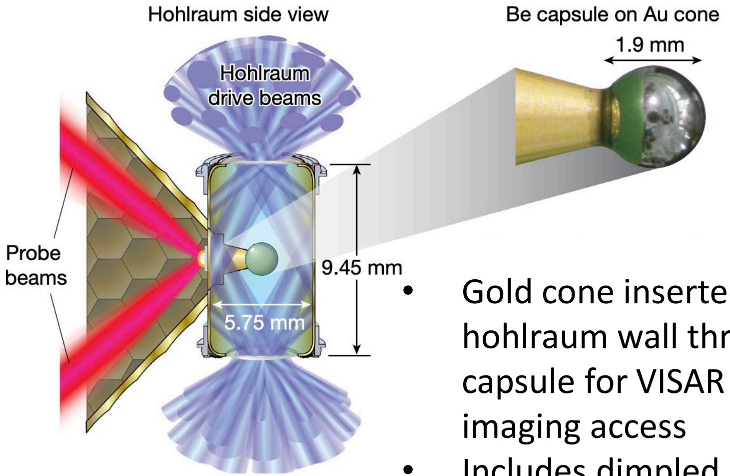


- ρR = 50-80 mg/cm^2, $\rho \sim 12$ g/cc
- Highly Symmetric (P2/P0 ~-1%)
- Cryogenically cooled, but not layered
- 2-shock laser pulse shape with relatively low total laser energy (1 MJ)

S. MacLaren et al. PoP 25 056311 (2018)

Cone-in-Shell Targets

"Keyhole Targets"



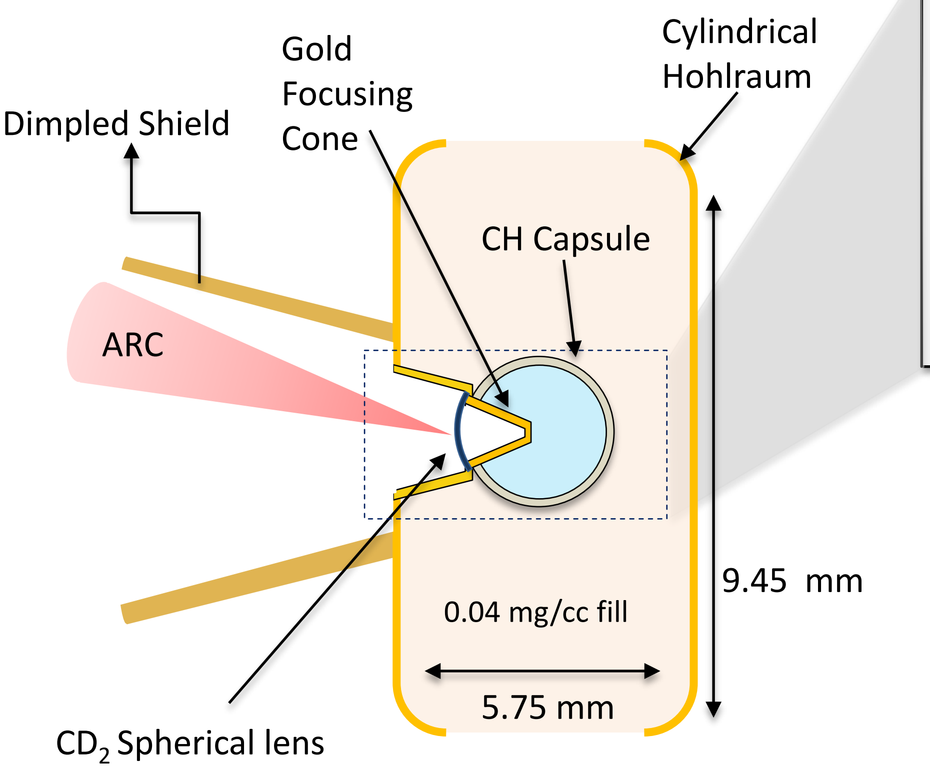
- Gold cone inserted in hohlraum wall through capsule for VISAR imaging access
- Includes dimpled shield for unconverted light
- Fielded on cyroTARPOS

T. Döppner et al. Nature 618 (2023)

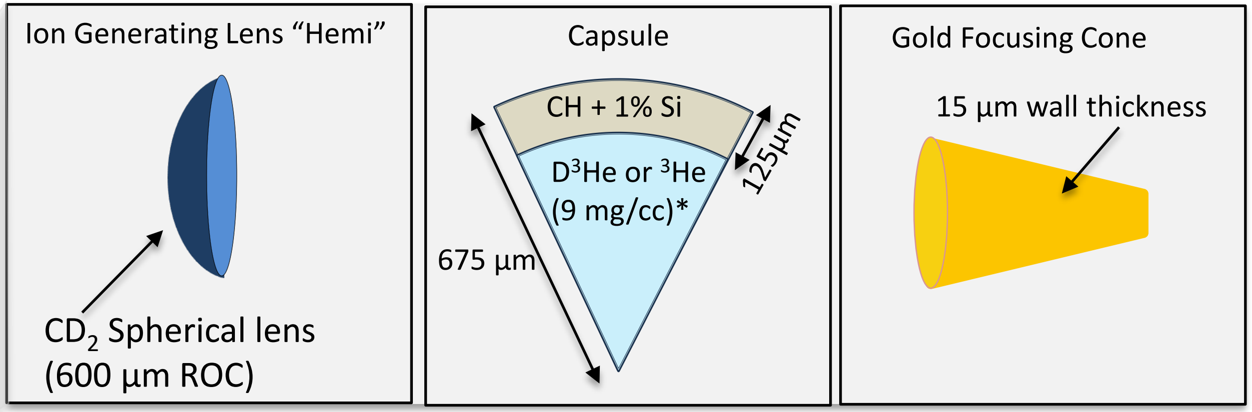
*Compound Parabolic Concentrator

Our proposed target design borrows elements from the "Keyhole", 2-shock and ARC protons platforms with some modification

Target Configuration

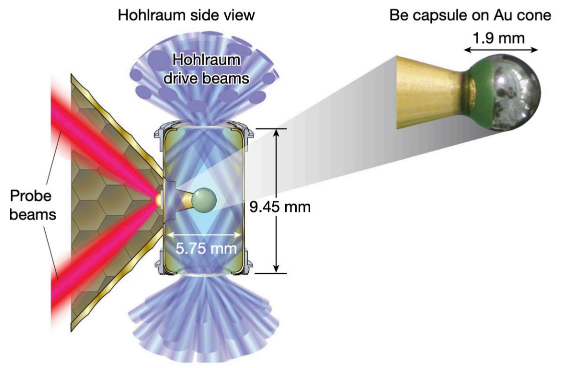


Cone-in-Shell Sub-Assembly



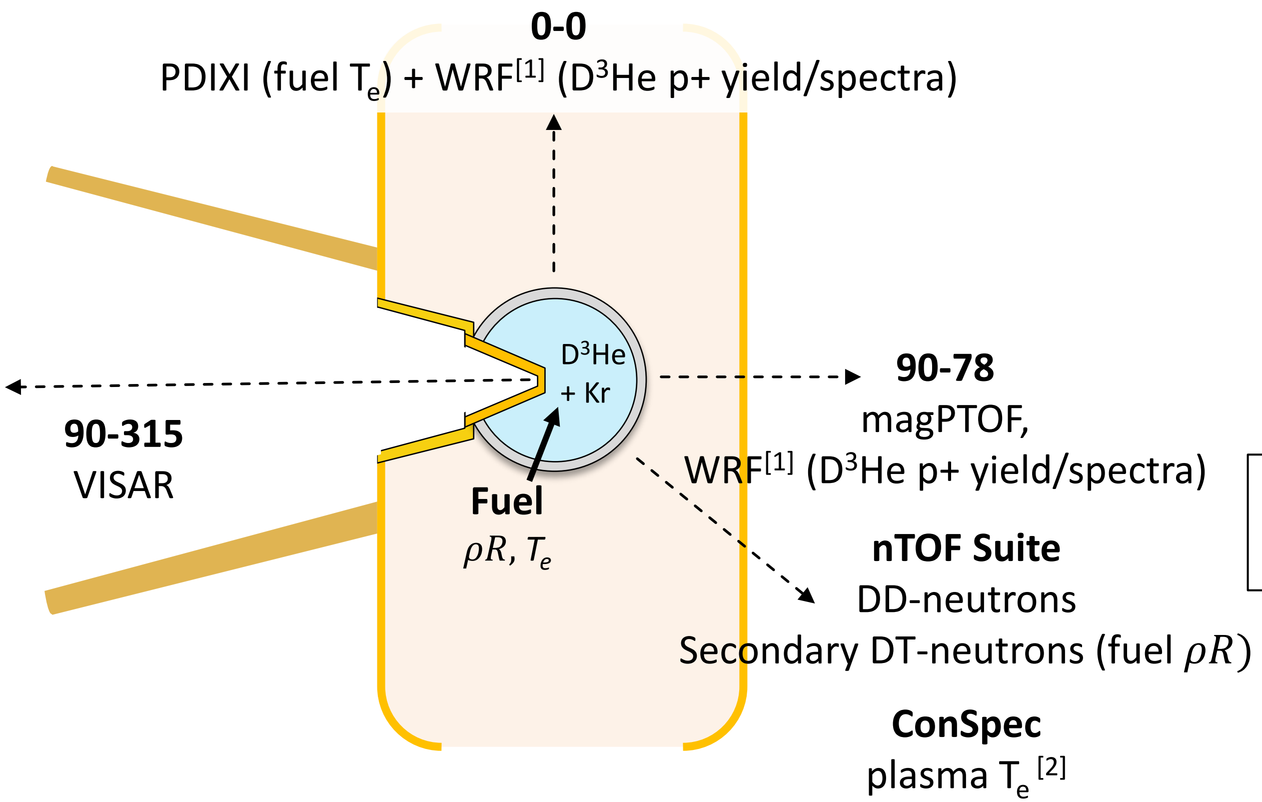
D^3He fill (Shot 1) and ^3He (Shot 2-3)

Prior "Keyhole Targets"



This proposal relies on previously utilized and qualified laser and diagnostic configurations with no modification

Diagnostic Requirements (NIF only)



Laser Requirements

2-shock pulse shape based on N160707

NIF Beam Requirements	
Drive Laser Energy	1 MJ (192 beams)
Peak Power	350 TW

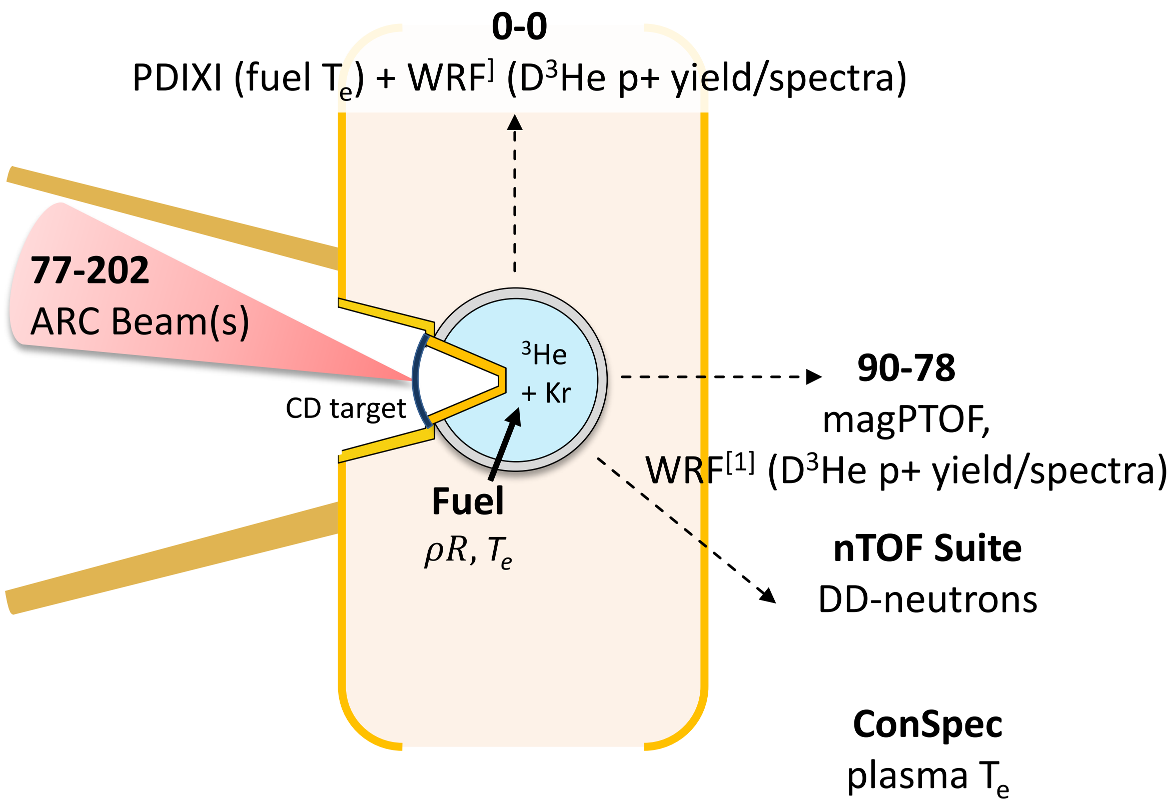
Primary : Implosion ρR , ρ, and T_e.
Cone-tip shock breakout time.

[1] Zylstra et al., RSI 83, 10D901 (2012)
[2] Hill et al PPCF 64, 105025 (2022)

The NIF's nuclear, x-ray and charged particle diagnostic suite allows for key measurement of the fuel conditions and ion coupling. No diagnostic or laser modifications or new diagnostics are needed for these proposed experiments

This proposal relies on previously utilized and qualified laser and diagnostic configurations with no modification

Diagnostic Requirements (NIF+ARC)



Laser Requirements

2-shock pulse shape based on N160707

NIF Beam Requirements	
Drive Laser Energy	1 MJ (192 beams)
Peak Power	350 TW

Primary: D^{3}He proton yield to infer ion coupling

2nd: Implosion ρ & ρR.
T_e to infer ion heating.

ARC Beam Requirements	
Drive Laser Energy	600 J per beamlet
Pulse Duration	10 ps
# Beamlets	2 to 4

The NIF's nuclear, x-ray and charged particle diagnostic suite allows for key measurement of the fuel conditions and ion coupling. No diagnostic or laser modifications or new diagnostics are needed for these proposed experiments

We were awarded two shot days to explore our proposal goals: 1 shot NIF-only, 1 shot NIF+ARC joint operations

Proposal Objectives

- **Assemble dense (fuel: $\rho R \geq 50\ mg/cm^2$, $\rho \sim 12\ g/cc$)** cone-in-shell implosion
- Fully characterize fuel conditions $(\rho R, T_e)$ using the NIF nuclear and x-ray diagnostics
- Measure coupling of MeV deuteron ions to compressed ^3He gas by **measuring yield of D^3He protons using NIF charged particle suite**
- Probe **different density/temperature regimes** with ion source by varying the NIF-to-ARC delay

Shot 1

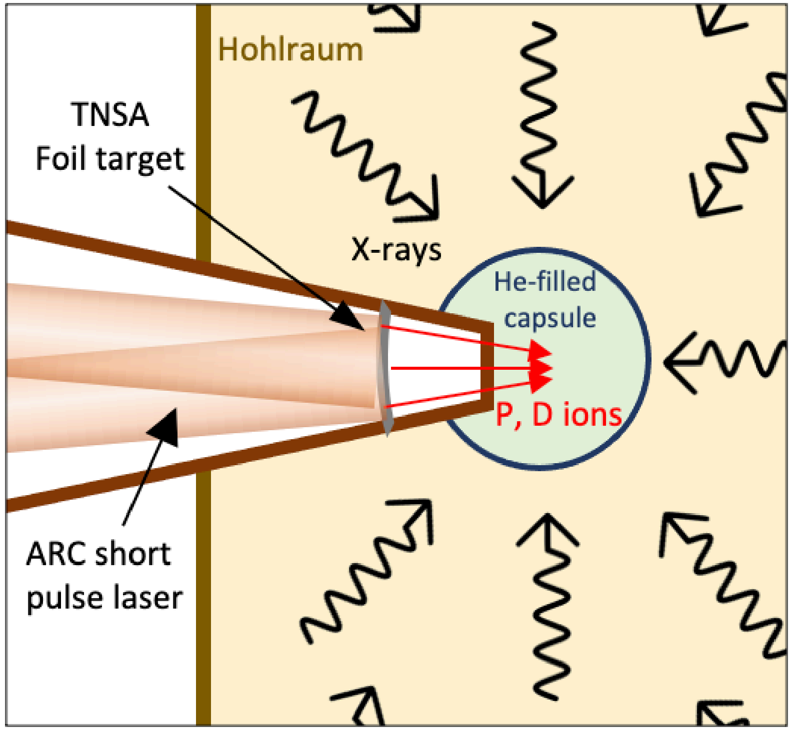
NIF-only
Demonstrate assembly of cone-in-shell (D^3He fill) implosion with areal density above 50 mg/cm^2

Shot 2

NIF+ARC Joint
Proceed with NIF-ARC joint operations to measure ion coupling

These shots will tentatively be scheduled in FY26 and FY27

These experiments would provide the first measurement of ion coupling in an IFI experiment at ignition-relevant densities



Data from this experiment would provide:

- Demonstration of dense ($\rho R \sim 50\ mg/cm^2, \rho \sim 12\ g/cc$) cone-in-shell implosions with characterized fuel conditions ($\rho R, T_e$) of dense cone-in-shell implosions.
- First measurement of coupling of MeV ions into pre-compressed fuel assembly in an ignition-relevant platform; and in different density/temperature regimes.
- High-impact impact publications and high visibility for scientific progress in inertial fusion energy.
- A necessary steppingstone to an ignition-scale-implosion experiment.

Data from these proposed experiments would be an important result for ion coupling studies for fast ignition but also the transport physics of fast ions in hot dense matter more generally, neither of which have been studied directly in the literature

Lawrence Livermore
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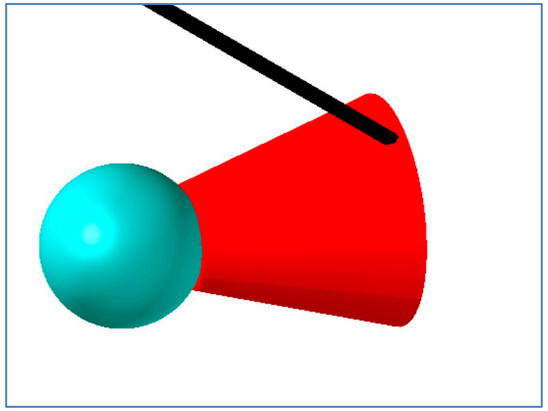
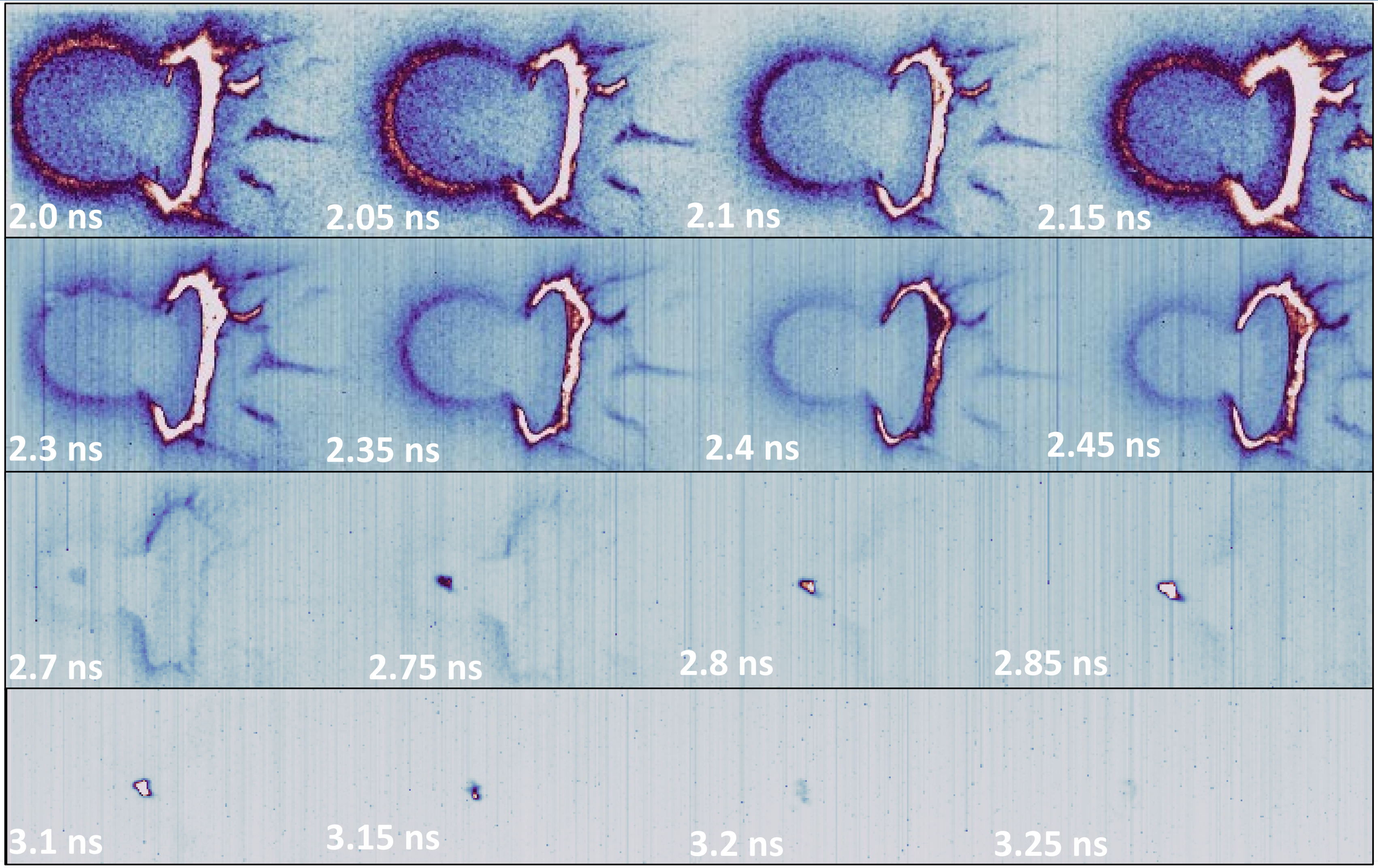
We collected great X-ray framing camera (XRFC) of the implosion dynamics on most shots

Line of Sight from TIM2 – XRFC

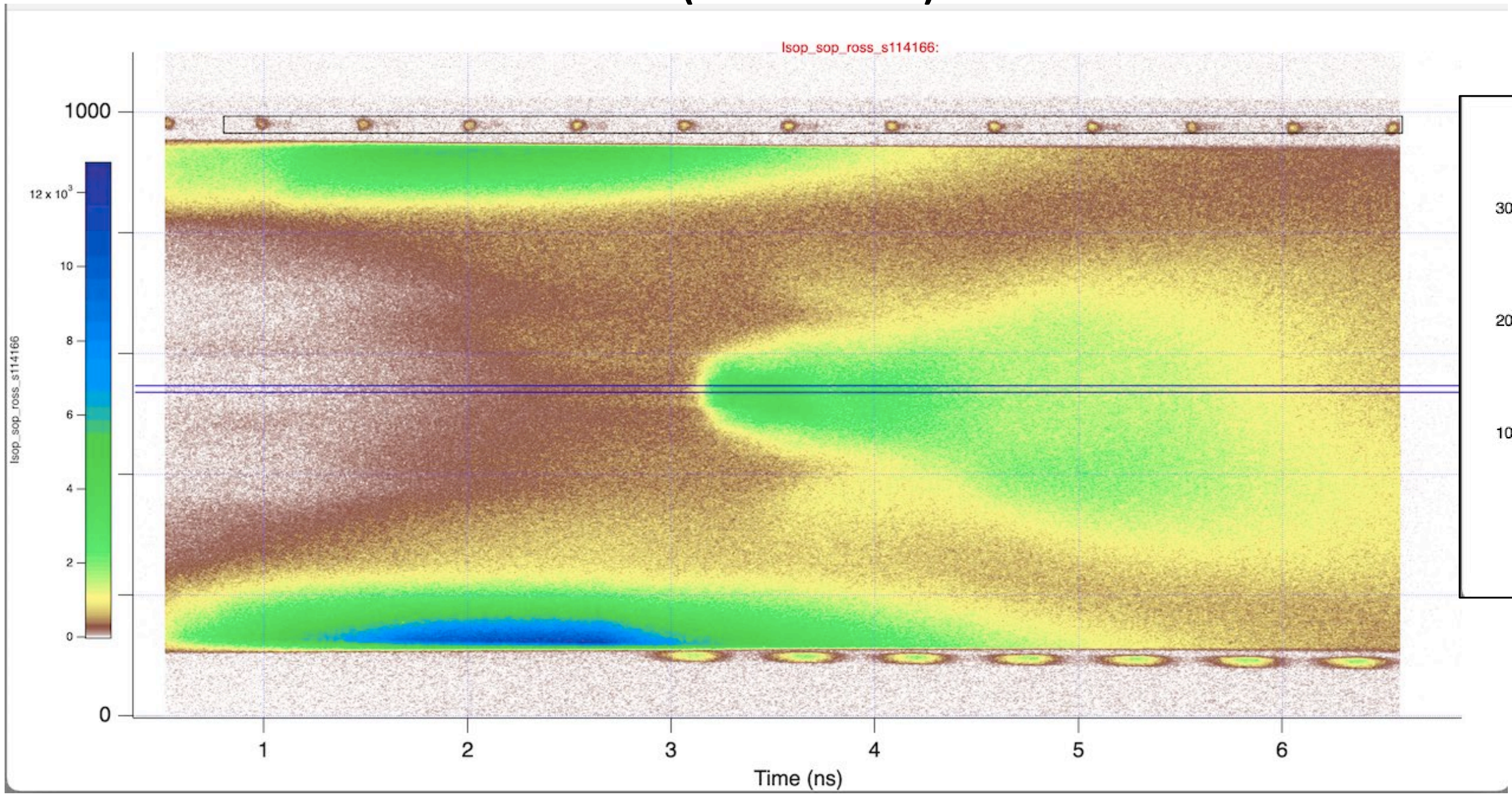




Different color scales for the four framing camera strips

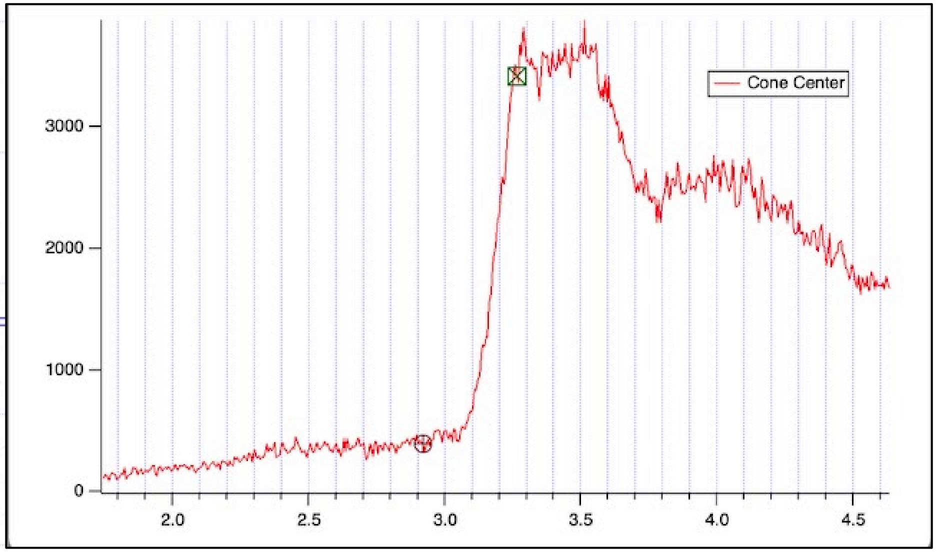
We were able to use SOP and unexpectedly also VISAR as a shock breakout diagnostic for the cone tip on most shots

SOP (Shot 114166)



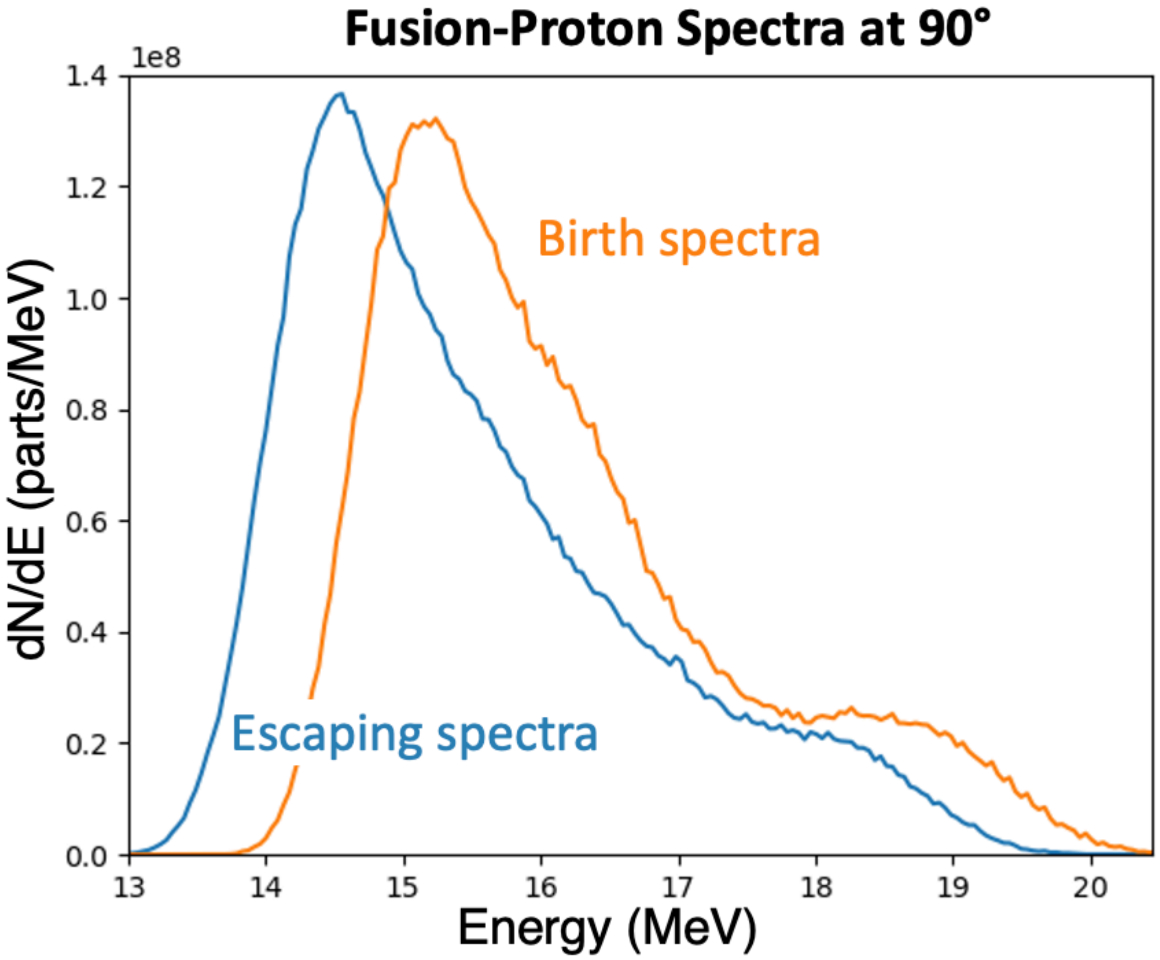
Analysis by M. Millot

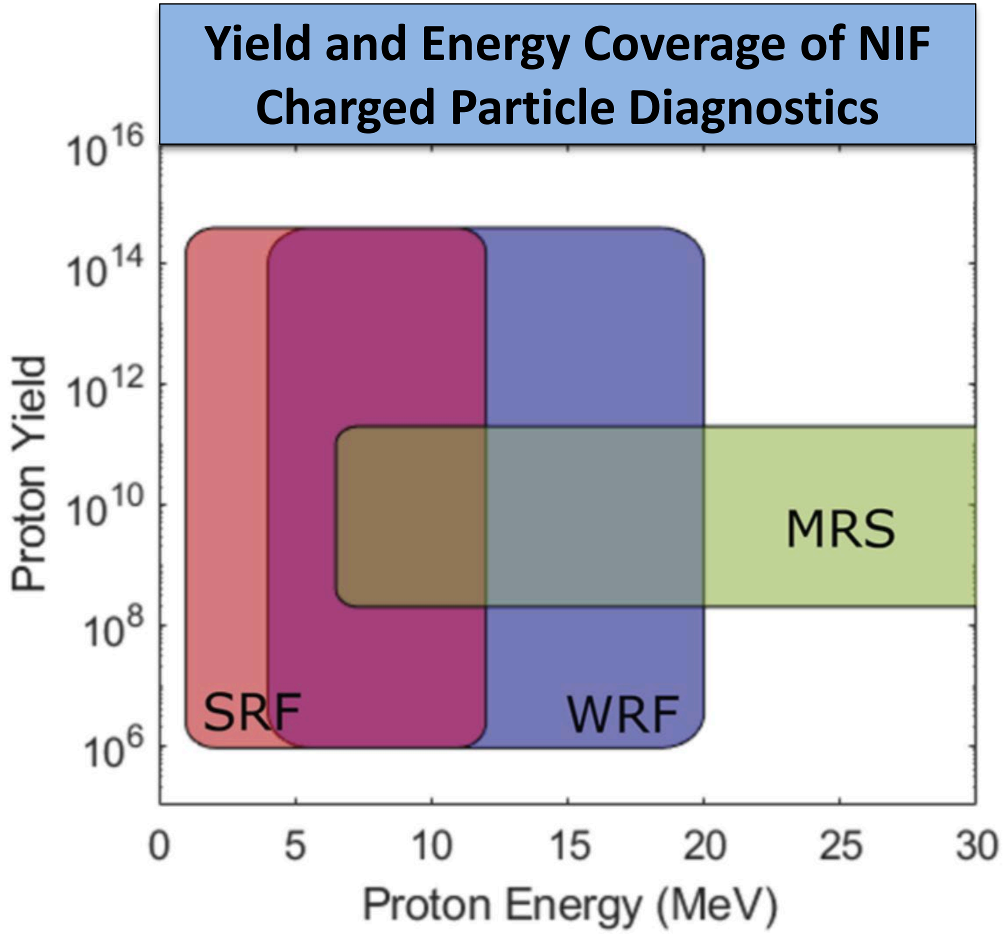
Analysis by M. Millot



Time (ns)

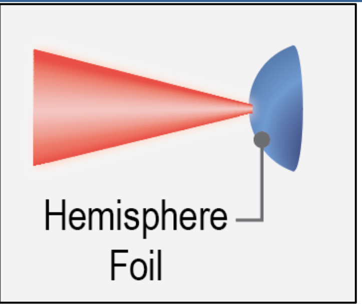
The expected fusion proton spectra and yield is easily measured by the NIF Wedge Range Filters (WRF)



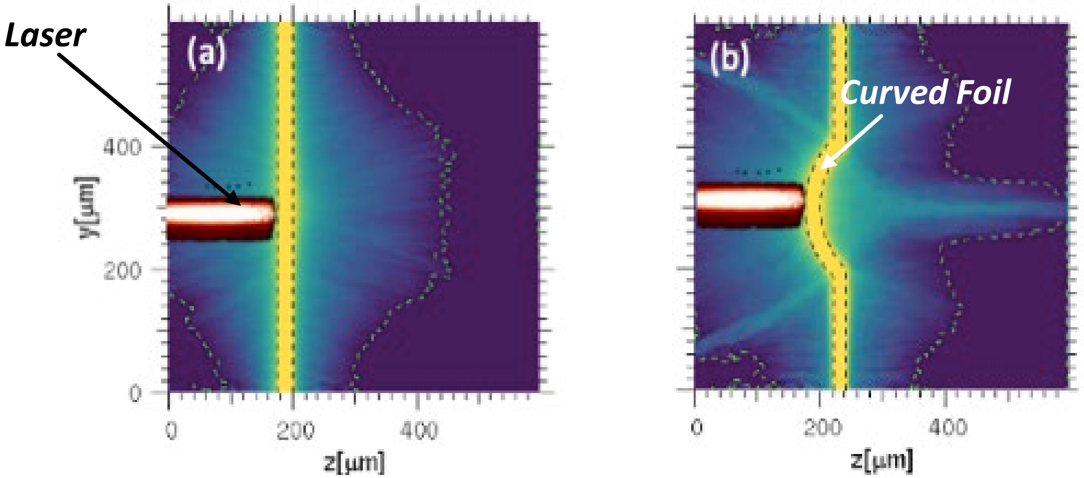


Reproduced from M. Gatu Johnson PoP (2023)

Curved ion generating targets have been shown in experiment and simulation to provide focusing for laser-driven ion sources



2D PIC simulation of TNSA laser ion acceleration off a (a) flat foil and (b) curved foil

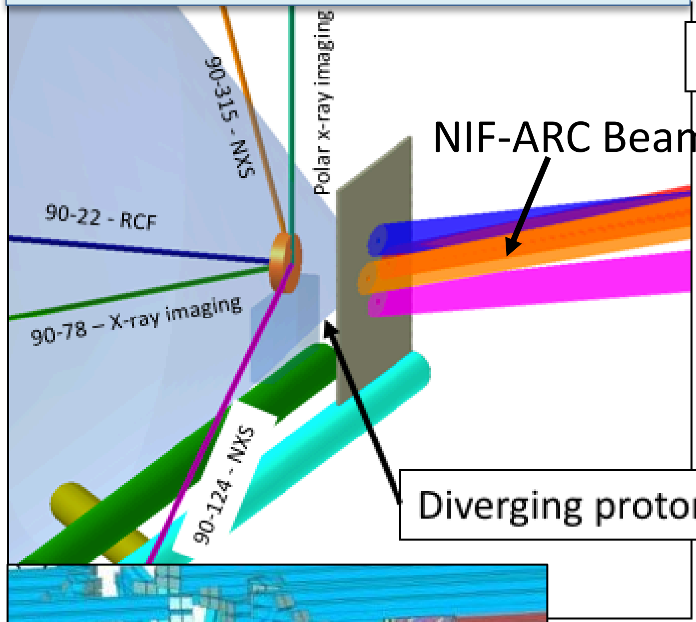


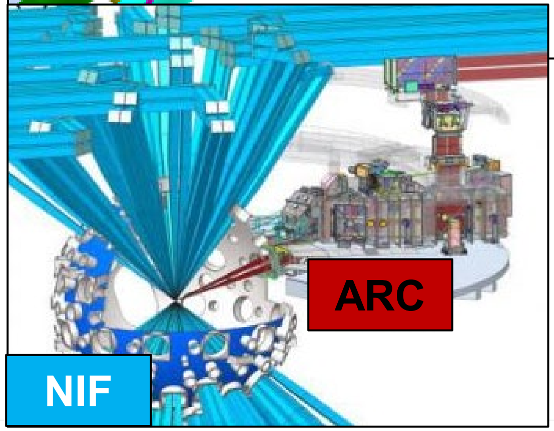
A. Kemp *Phys of Plasmas* 31 042709 (2024)

T. Bartal et al., Nature Physics 8, 139 (2012).
McGuffey et al., Sci. Reports 10, 9415 (2020)
Bhutwala et al., Phys. Rev. E 105, 055206 (2022)

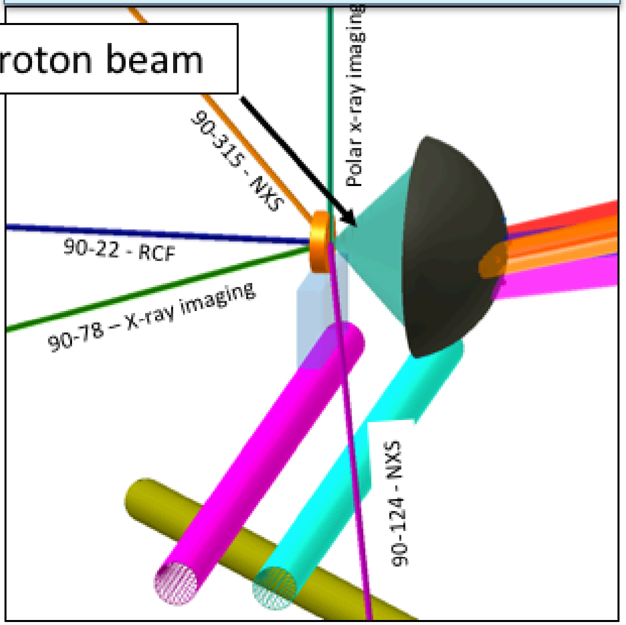
We have explored using hemispherical targets on the NIF-ARC to focus laser-driven ions for applications to isochoric heating

Flat Target

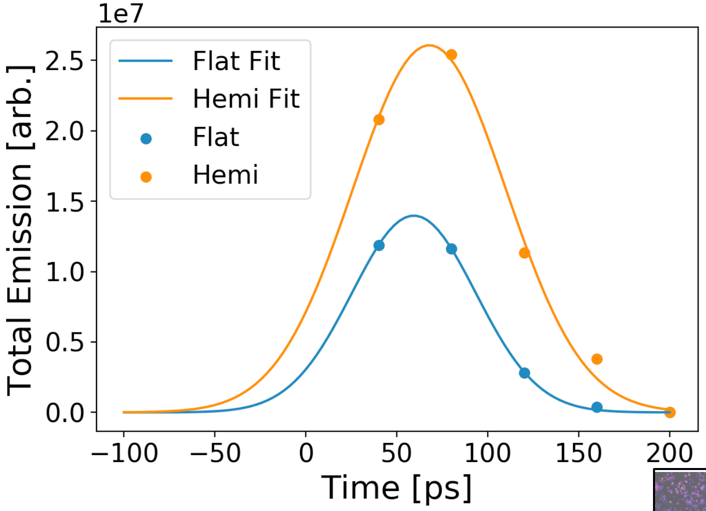


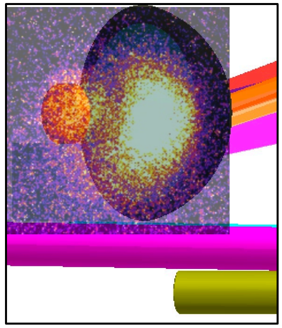


Hemispherical Target



Streaked X-ray Pinhole Images of Heated Sample

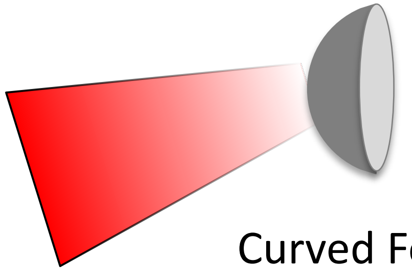




There is evidence of increased proton heating with the hemispherical target but will add a spectral temperature measurement with follow up shots next year

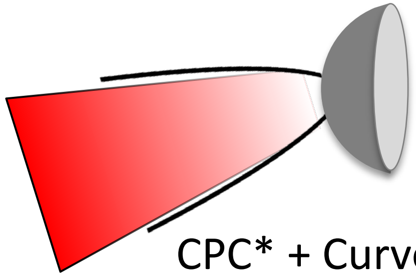
In upcoming experiments on the NIF-ARC, we will be testing four different proton focusing target types

Focusing Target #1



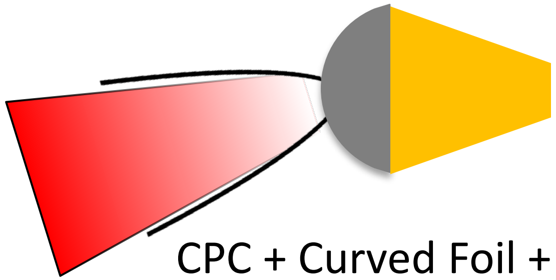
Curved Foil

Focusing Target #2



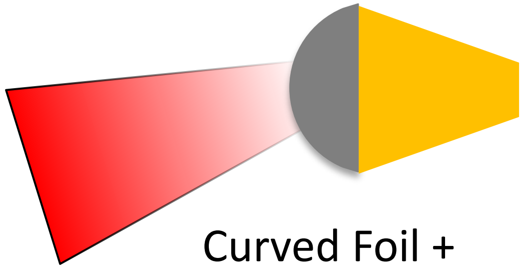
CPC* + Curved Foil

Focusing Target #3



CPC + Curved Foil + Cone Focusing Structure

Focusing Target #4

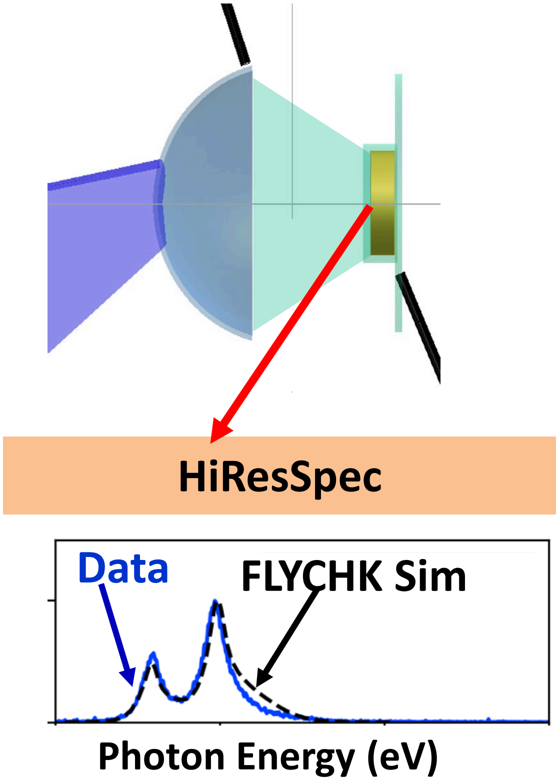


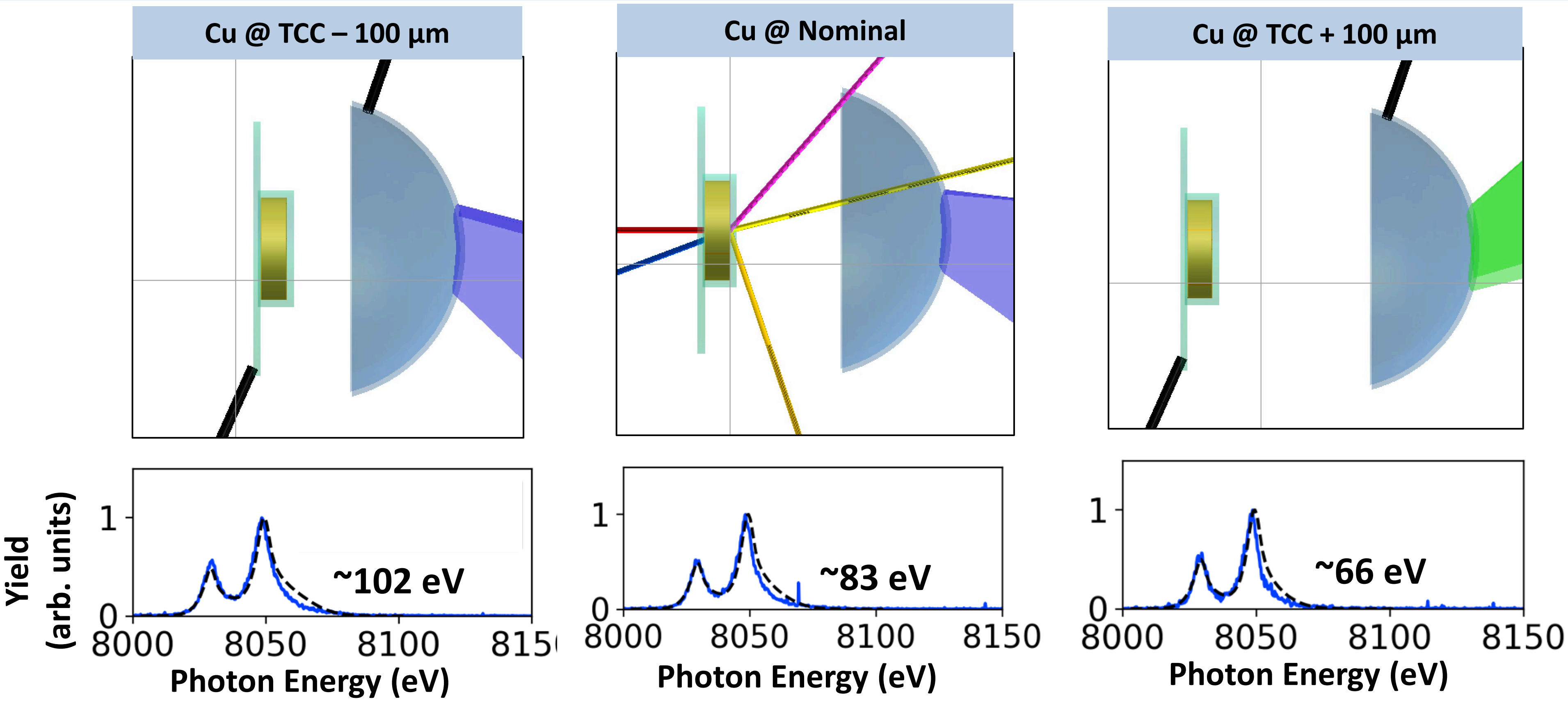
Curved Foil + Cone Focusing Structure

Using four NIF-ARC shots, we will serially test the impact of the hemisphere foil radius of curvature, CPC and focusing structure on the proton spatial profile, focusing and heating

**Compound Parabolic Concentrator*

Time integrated HiResSpec (high resolution spectrometer) data shows similar temperatures trends to the low resolution spectrometer





Longer pulse durations with the sample closer to the geometric focus of the hemisphere show hotter temperatures