From Megagauss Jets to Gamma-Ray Bursts:
New Frontiers in HED Laboratory Astrophysics

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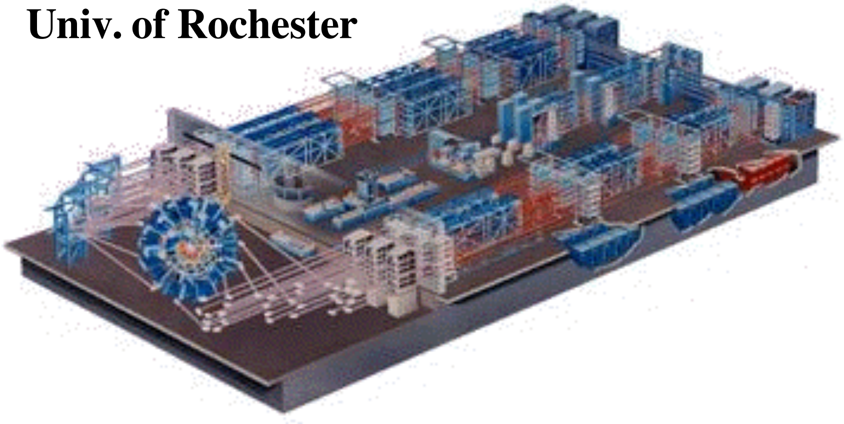
γ

Work supported by DOE

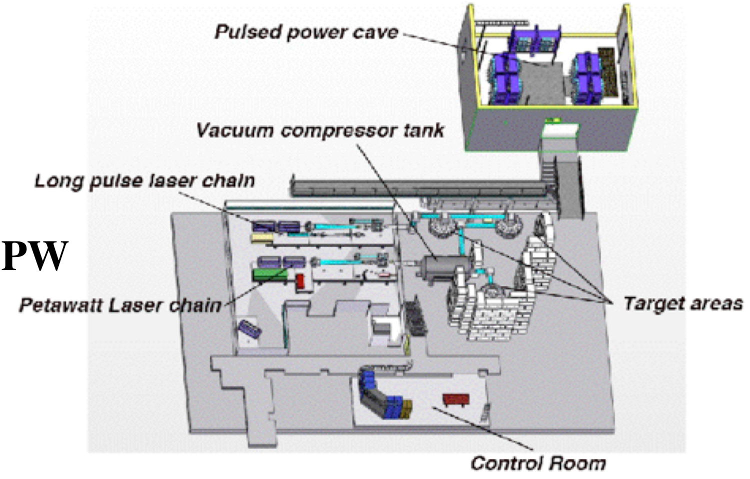
HEDP facilities are proliferating in the US, Europe and Asia

ELI

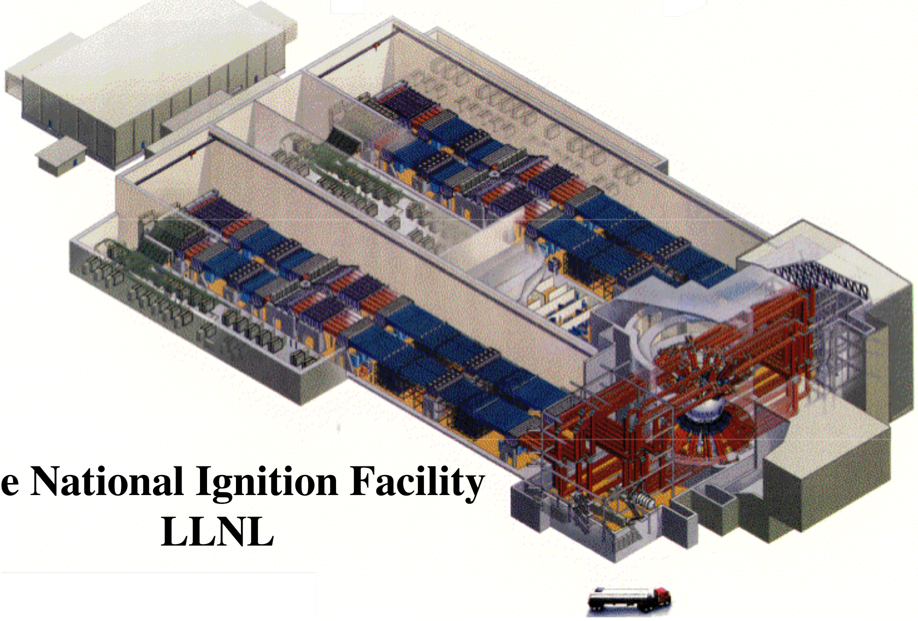
Omega laser facility, Univ. of Rochester



TPW



The National Ignition Facility LLNL



Two Frontiers of High Energy Density Physics (HEDP)
(energy density > 10^5 J/cm^3, pressure > 1 Mbar)

1. Energy Frontier (NNSA): compress matter to extreme conditions similar to those at the center of stars, using ~ ns "long-pulse" multi-beam (kJ-MJ) lasers (NIF, LMJ) or pulse power machines (Z)

2. Intensity Frontier (OFES): create high-energy beams of e-, e+, ions, γ, using ~ fs "short-pulse" PW lasers (TPW, ELI) focused to the diffraction limit to achieve relativistic intensity > 10^{19} W/cm^2.

Two HEDP experiments led by our group:
Project A falls under the Energy Frontier,
Project B falls under the Intensity Frontier.

A. Use multi-beam kJ lasers to create strongly magnetized jets and collide them to form magnetized shocks

B. Use PW laser to create dense e+e- pair plasmas and ultra-intense gamma-ray beams

Both experiments are motivated by astrophysics, but have many other applications.

Project A uses the Omega Laser at LLE, Rochester, NY

Goals: To study the formation, structure and evolution of strongly magnetized shocks formed by the head-on collision of two megagauss plasma jets created by hollow rings of laser beams.

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Froula[3], A. Birkel[4], C. Li[4], R. Petrasso[4], W. Fu[1], L. Han[1], D. Lamb[5], M. Wei[3] , ,
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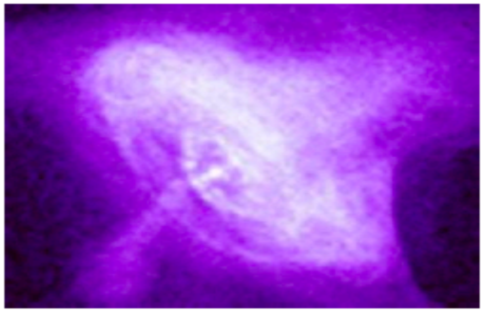
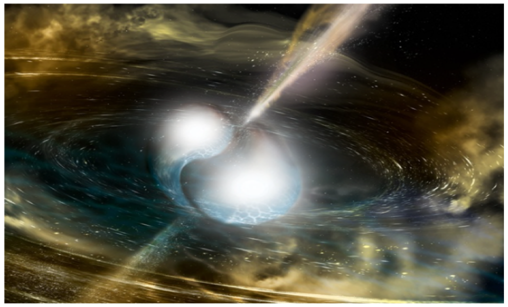
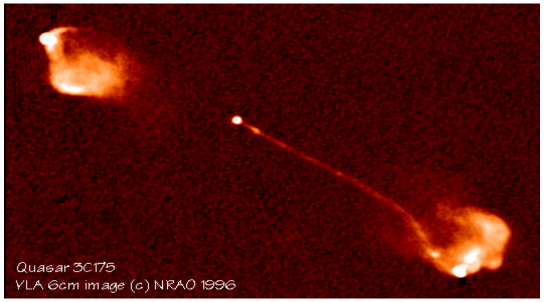
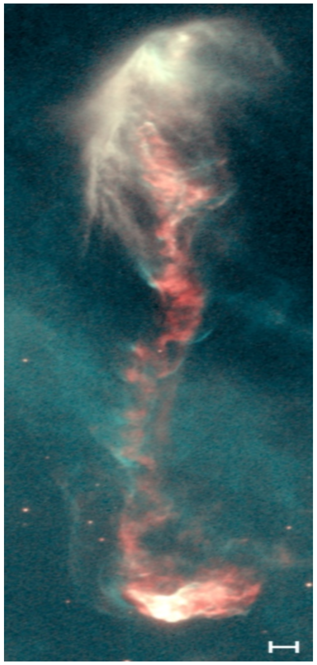
Supported by DOE NNSA NLUF

Observations suggest many astrophysical jets may be strongly magnetized

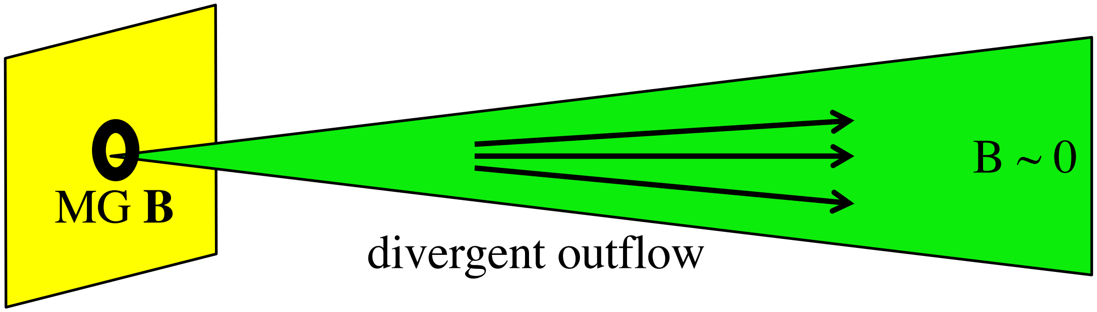








However, in laser created outflows, B field decays rapidly



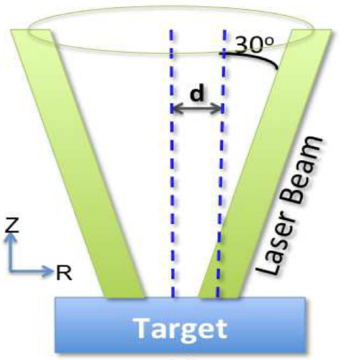
MG **B**

B ~ 0

divergent outflow

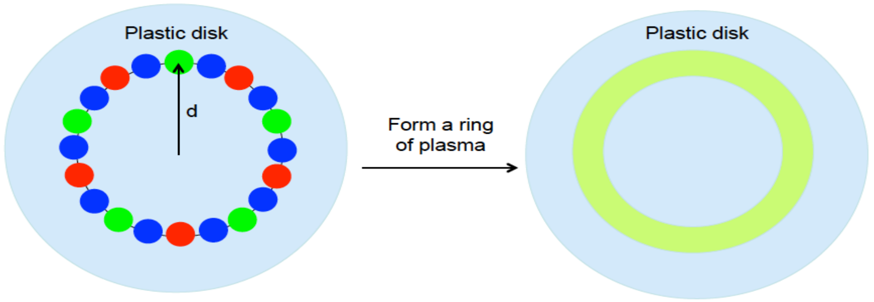
Motivation : How to create collimated strong-B outflow far from laser target ?

2015-16 Experiments used 20 OMEGA Laser Beams to form a Hollow Ring



(a)

Side view



🔴 P1 axis, Ring 1, 5 beams
🟢 P1 axis, Ring 2, 5 beams
🔵 P1 axis, Ring 3, 10 beams

The ring radius d will be changed from 0 to 800 um to see which condition generates the strongest jet

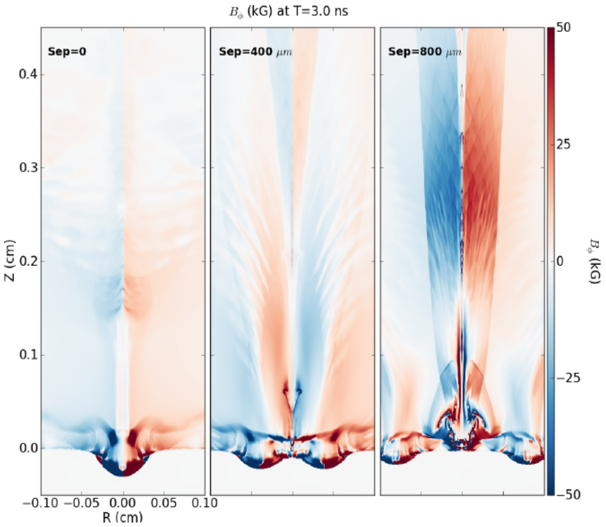
- The idea is to <u>create a narrowly collimated magnetized jet using a hollow ring of many laser beams</u>

- By varying the hollow ring radius, we can achieve a large dynamic range for the jet parameters, thus creating a highly versatile laboratory platform for laser-based astrophysics.

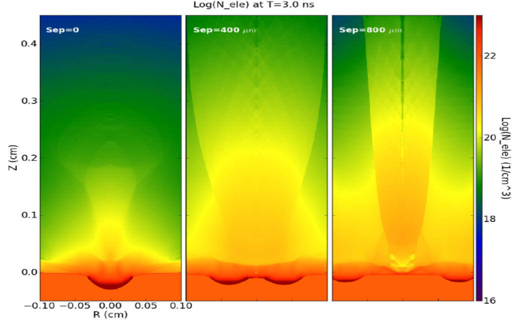
- **Fu, W., et al., High Energy Density Physics, 9, 336 (2013)**
- **Fu, W., et al., High Energy Density Physics, 17, 42 (2015)**

2D FLASH Predictions for d = 0, 400, 800 microns

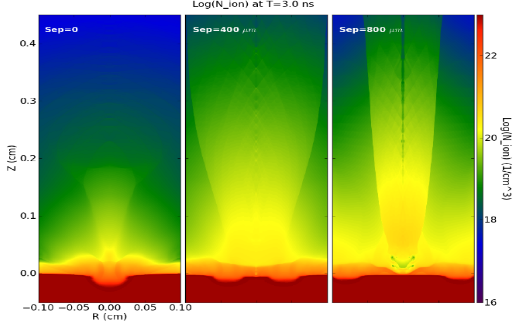
Toroidal B field at t=3.0 ns



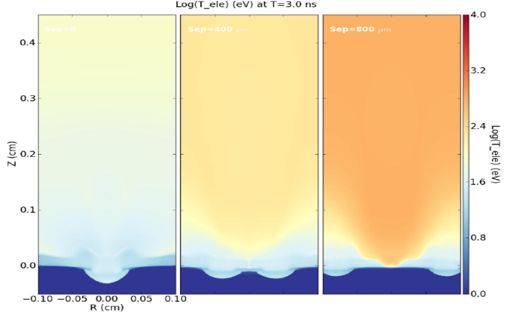
Electron number density at t=3.0 ns



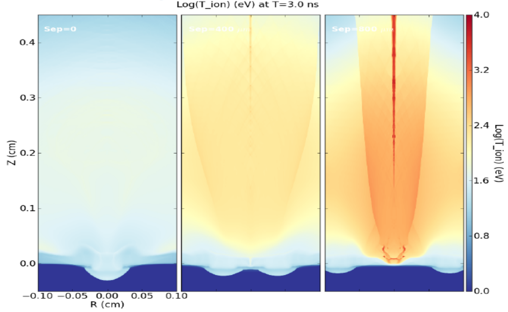
Ion number density at t=3.0 ns



Electron temperature at t=3.0 ns



Ion temperature at t=3.0 ns

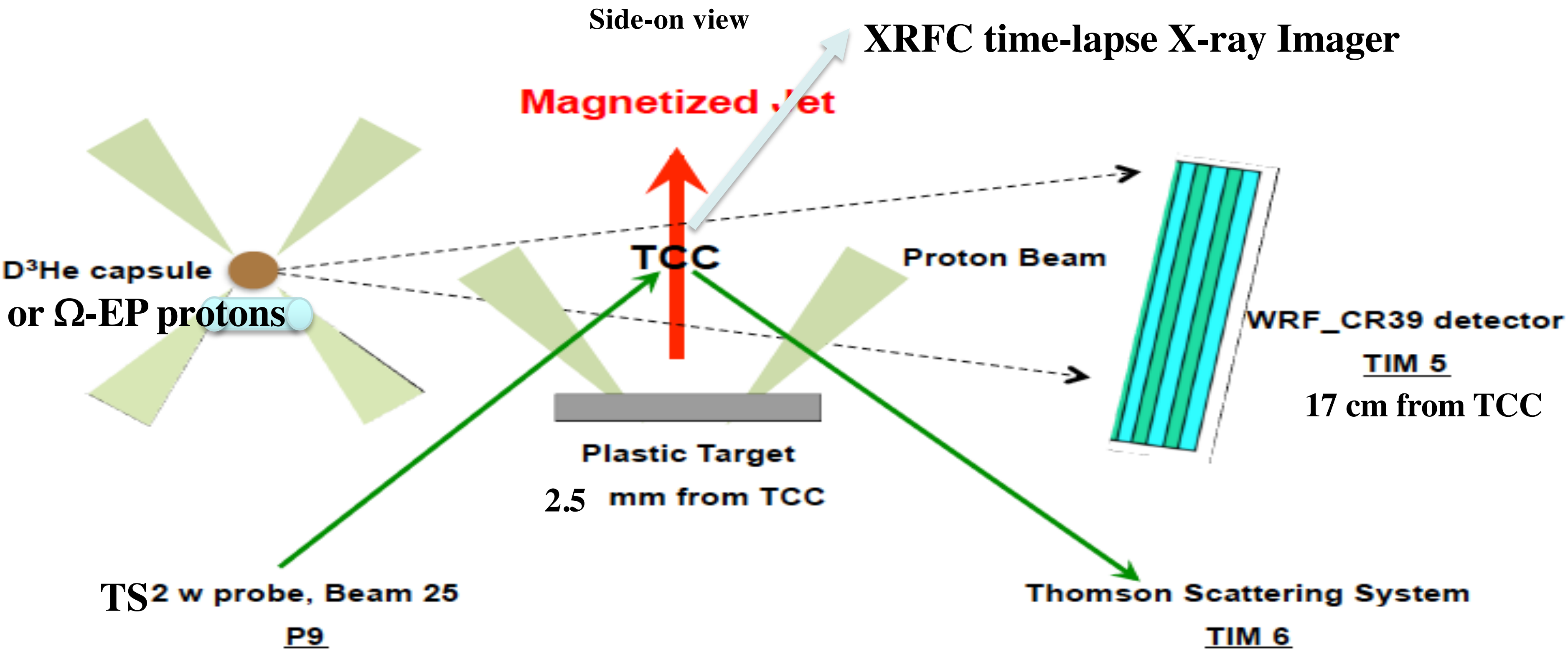


However, 2D FLASH predicts only ~10^4G toroidal magnetic fields created by the Biermann battery.

$$\frac{\partial \boldsymbol{B}}{\partial t} = \nabla \times (u \times \boldsymbol{B}) - c\nabla \times (\eta \boldsymbol{j}) + \underbrace{c\frac{\nabla P_e \times \nabla n_e}{e n_e^2}}_{\text{Biermann Battery term}}$$

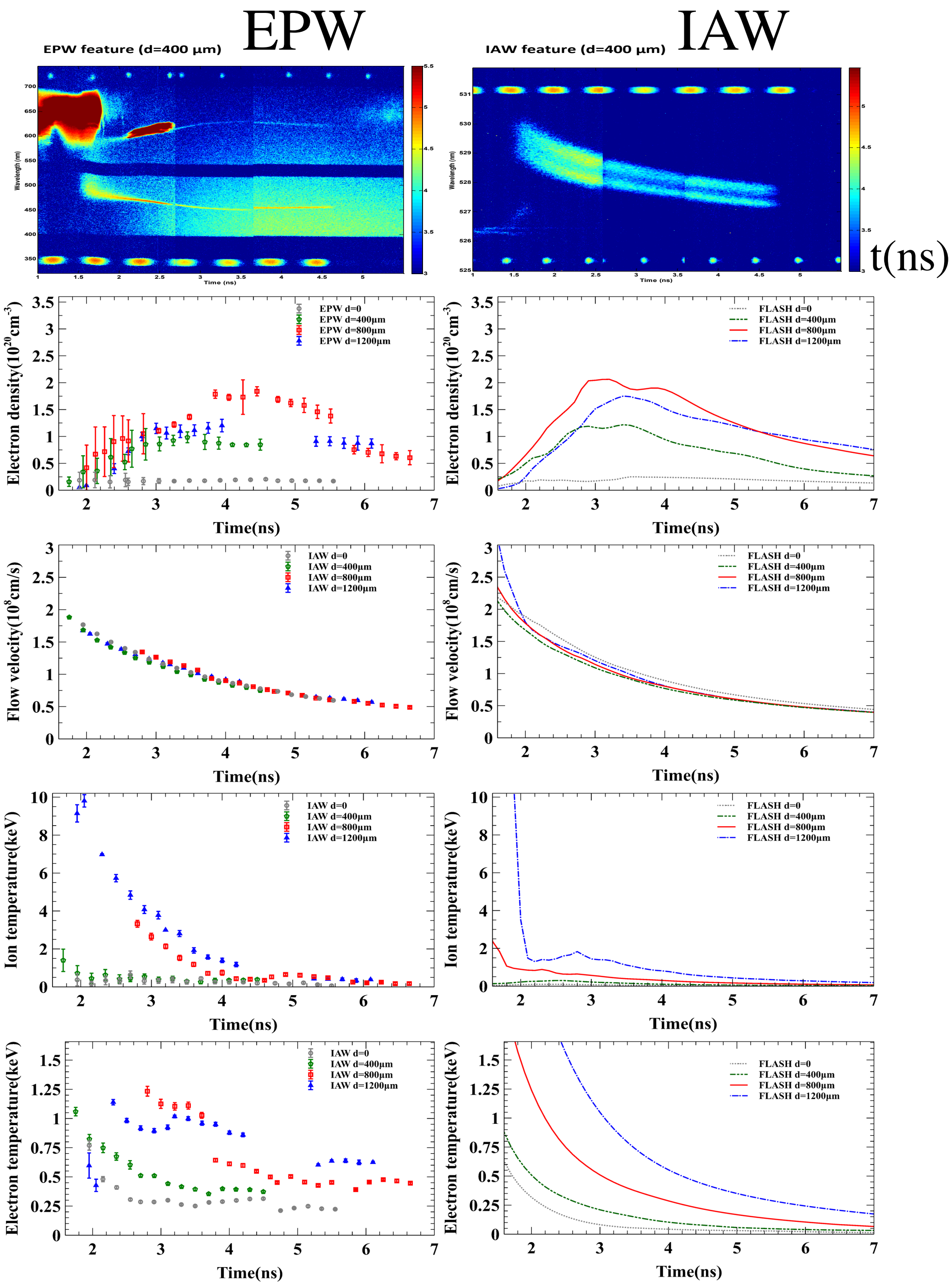
2015-16 Experiments used 20 OMEGA Laser Beams to form a Hollow Ring

Diagnostics Setup for the 20 OMEGA Beam Experiments



3 primary diagnostics: Thomson Scattering (TS) at TCC, Proton-radiography (Prad), X-Ray Framing Camera (XRFC)

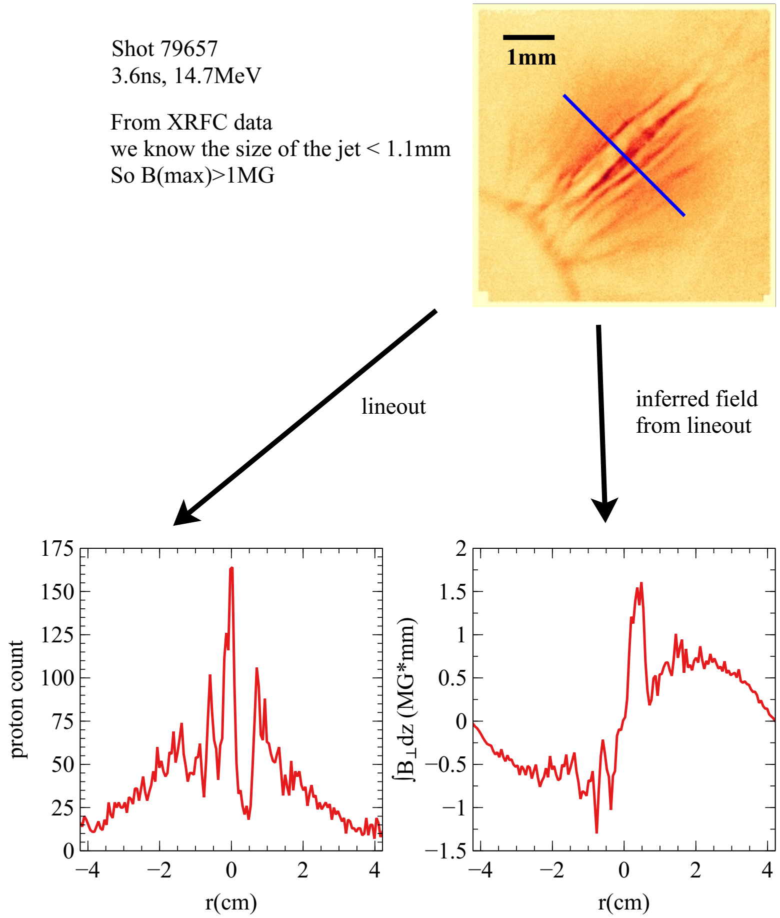
TS data at TCC generally agree with 3-D FLASH predictions



P-rad images consistent with B_z-dominated laminar fields increasingly concentrated near axis as d increases.

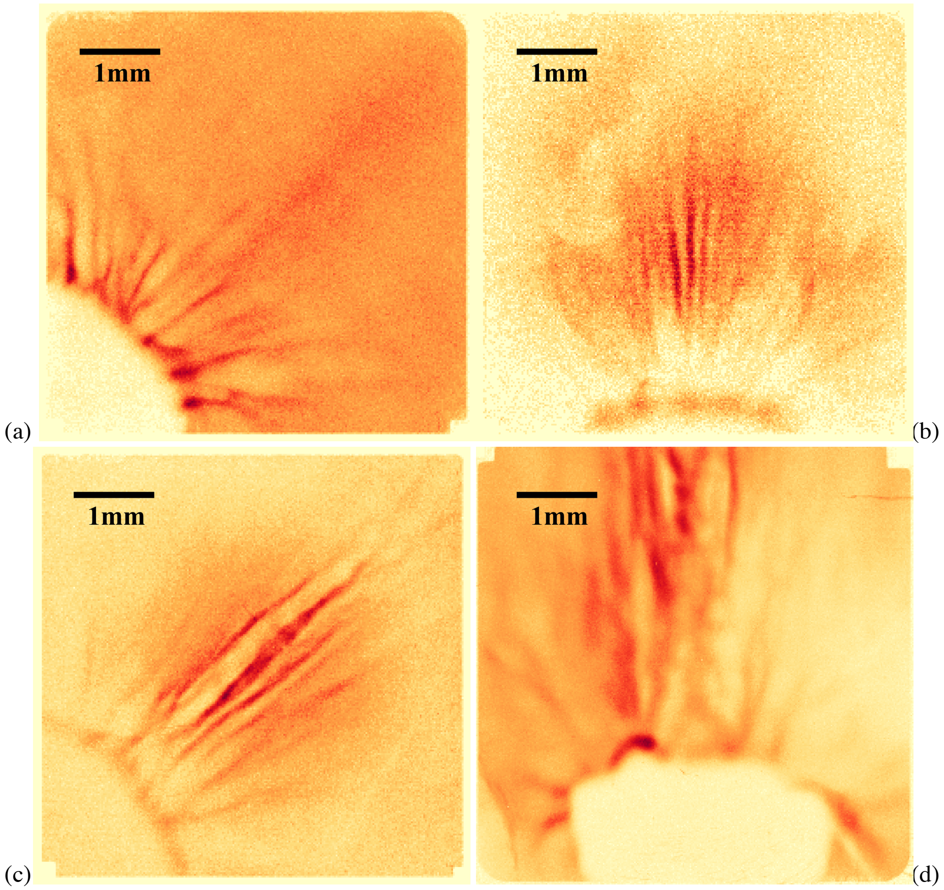
Shot 79657
3.6ns, 14.7MeV

From XRFC data
we know the size of the jet < 1.1mm
So B(max)>1MG



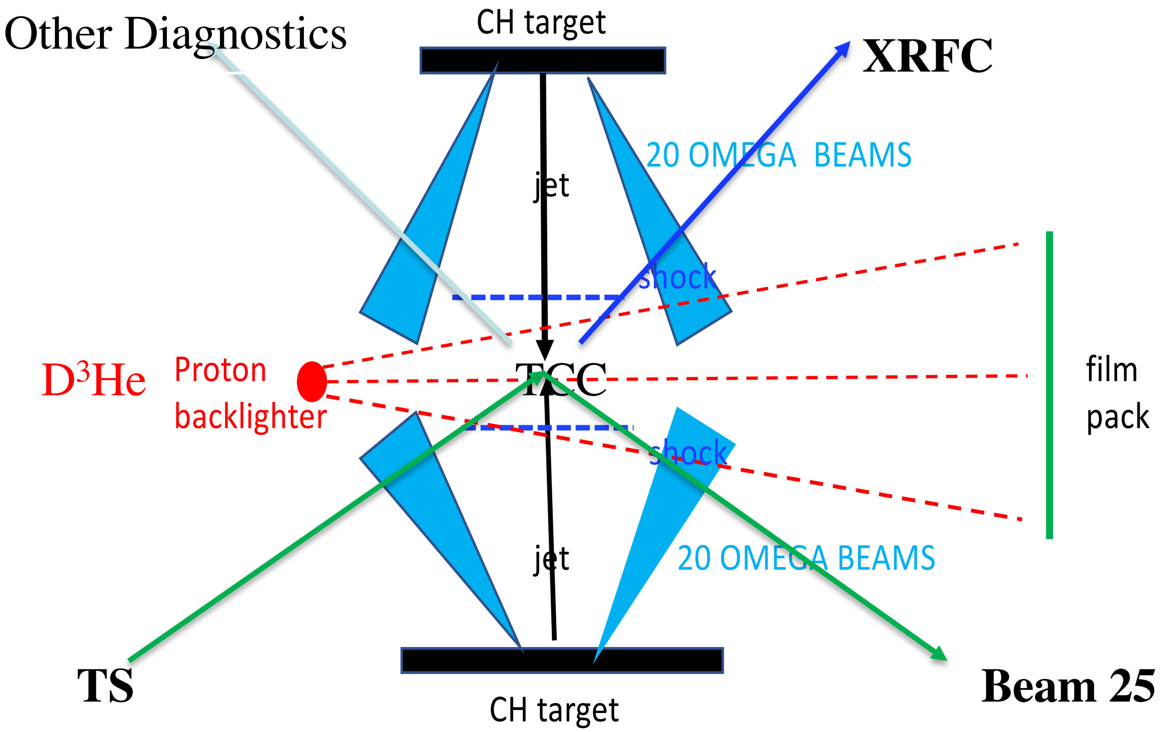
Max. B_z exceeds 1 MG

P-Rad Images at t ~ 3 – 4 ns



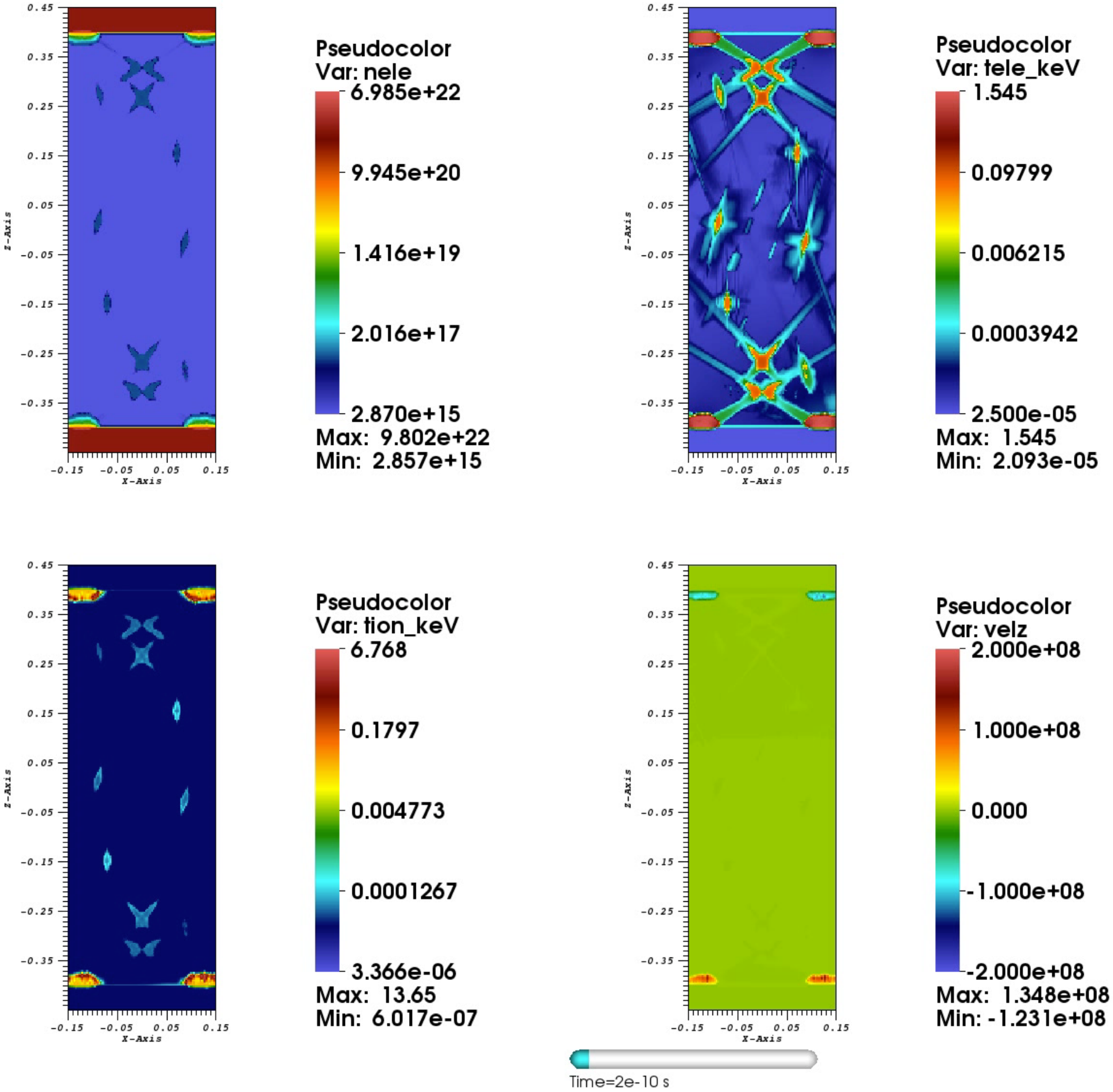
d = (a) 0, (b) 400, (c) 800, (d) 1200 μm

Colliding Jets Experiment Set-up & Diagnostics on Oct 13, 2020 and August 11, 2021



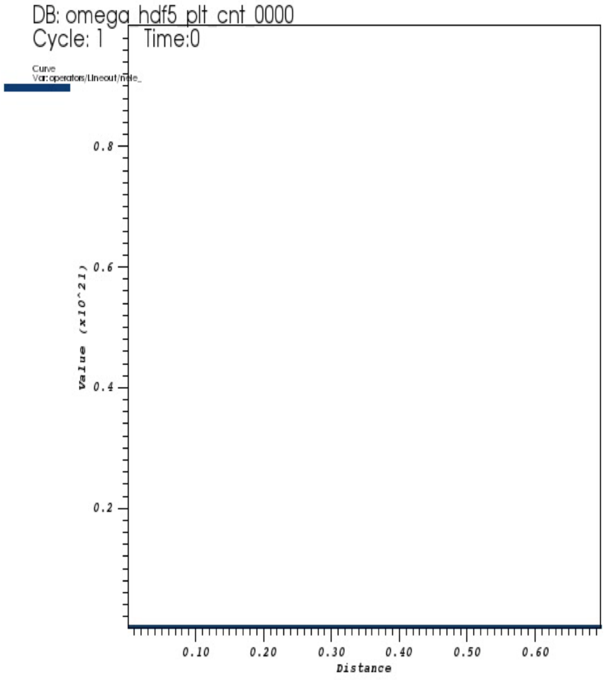
D=800μm, separation = 6.4 mm

3D FLASH Simulations of d=800μm colliding jets

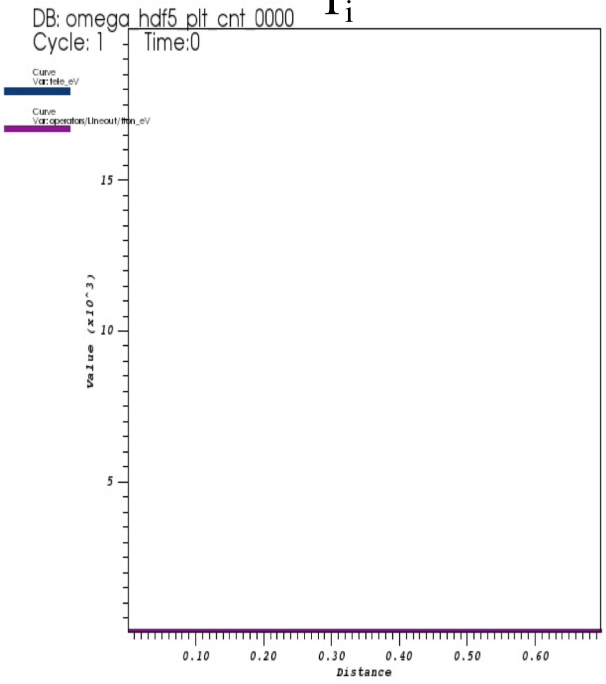


Time evolution of colliding jet parameters along jet axis

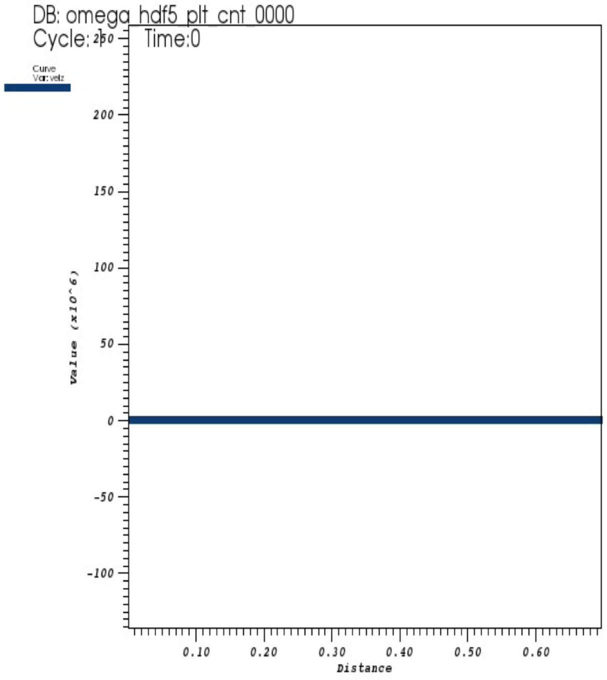
density



T_e , T_i

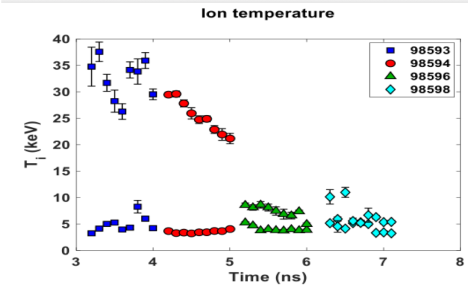


v_z

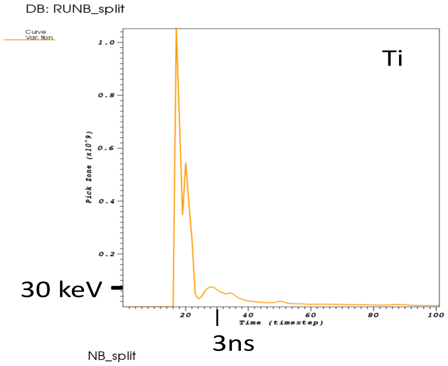


3D FLASH predictions consistent with TS data @ TCC

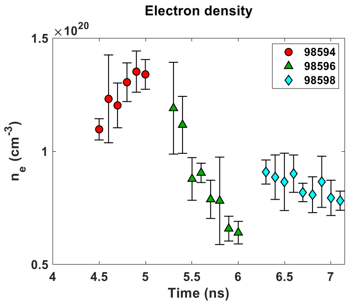
TS data

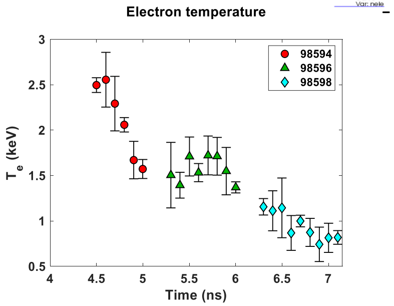


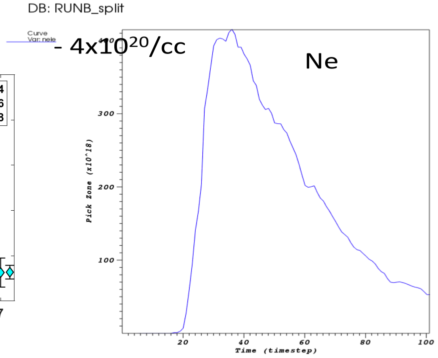
3D FLASH

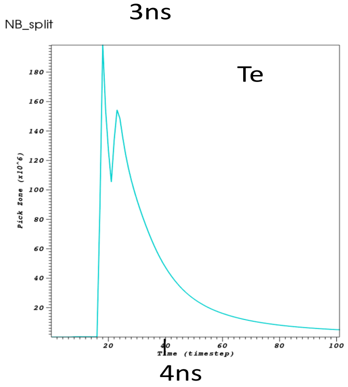


EPW results

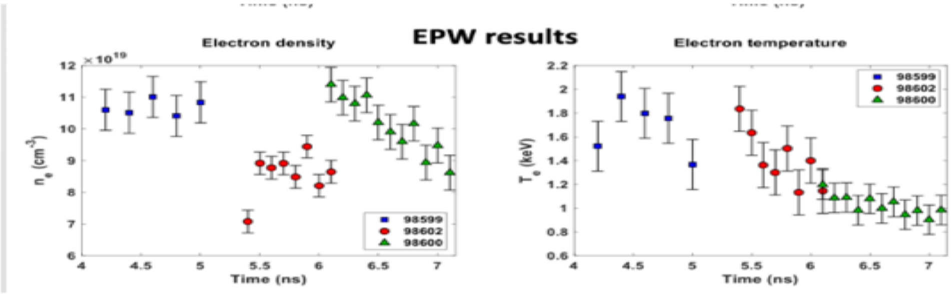


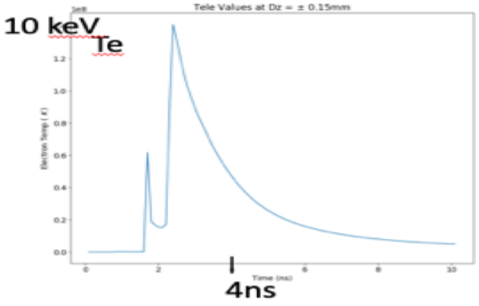


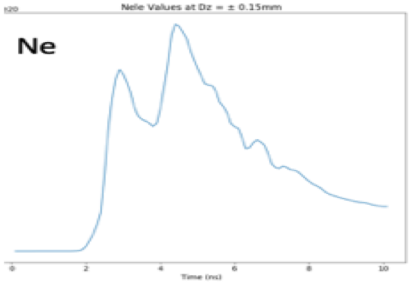


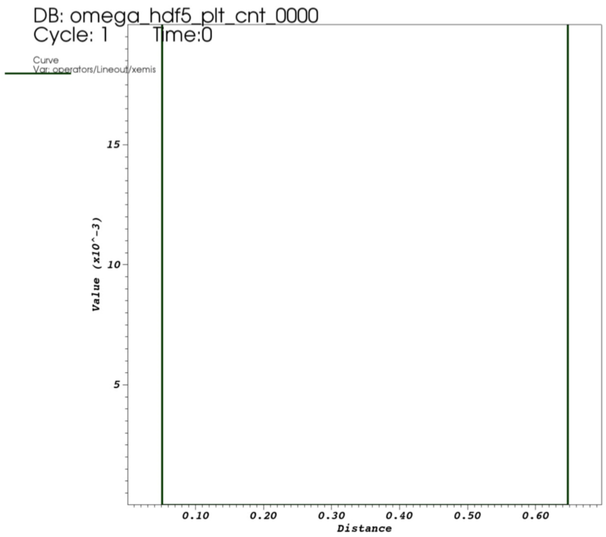


At 0.15mm from TCC, TS gave lower Te than 3D FLASH prediction

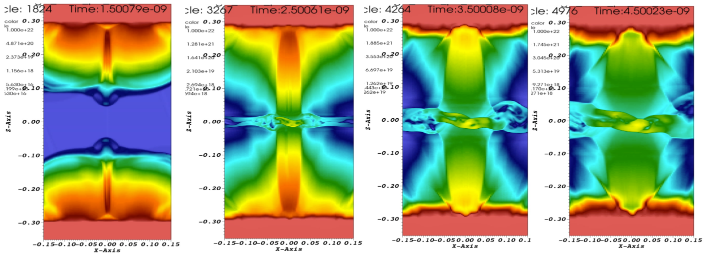






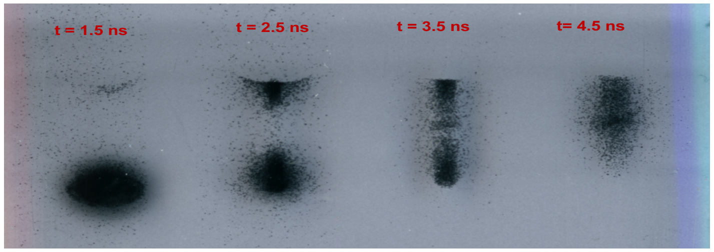


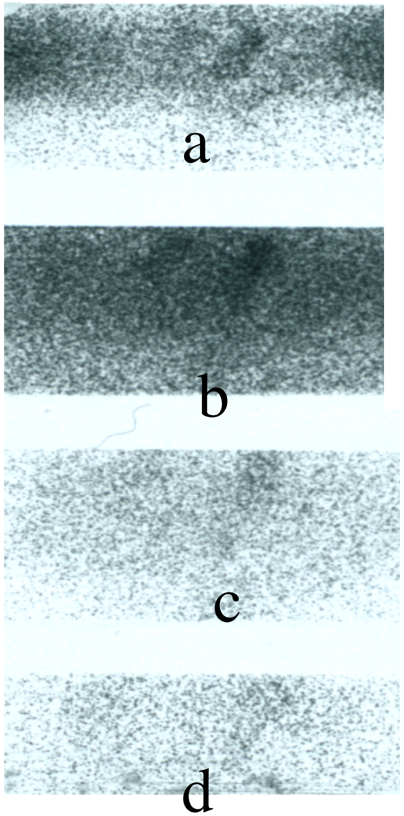
3D FLASH

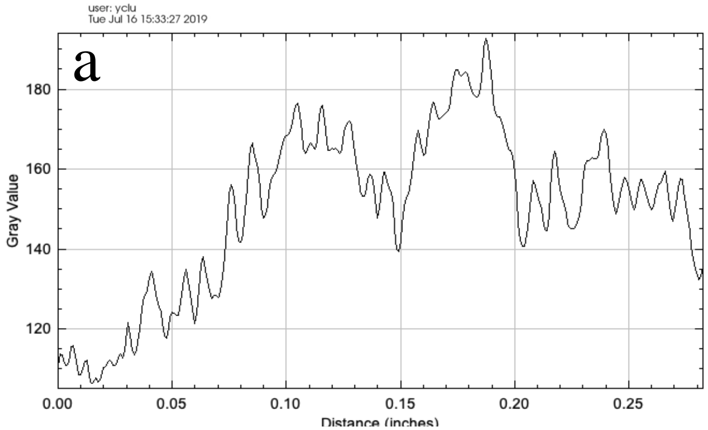


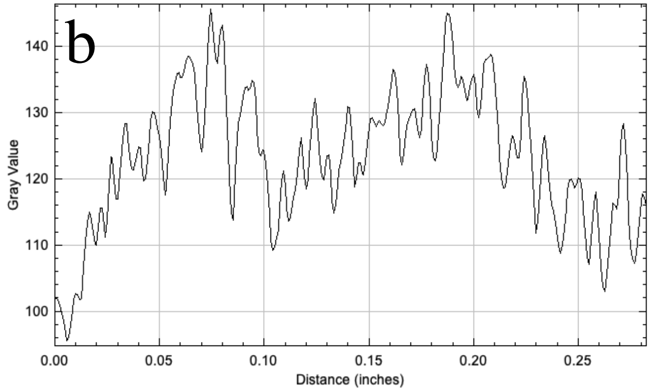
XRFC images morphology compare favorably with 3D FLASH predictions

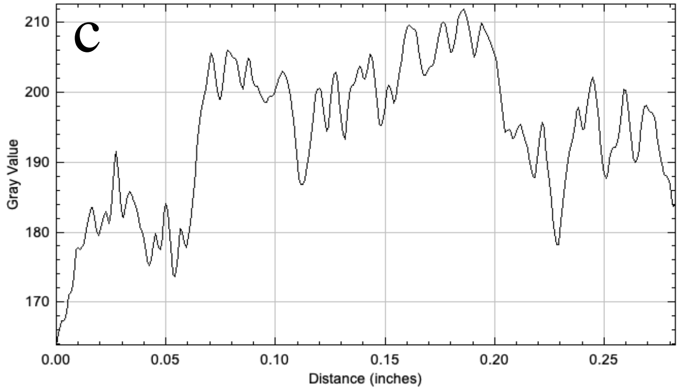
XRFC

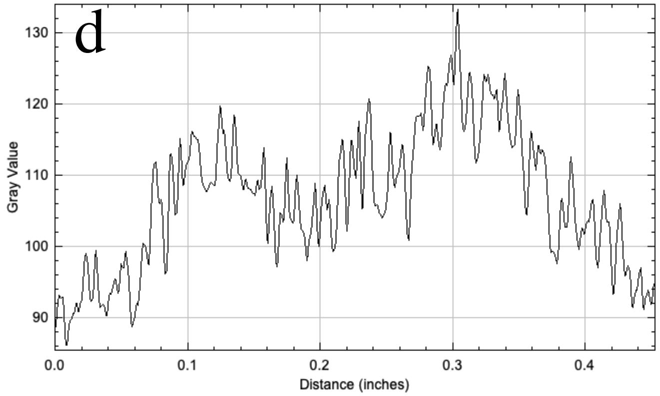




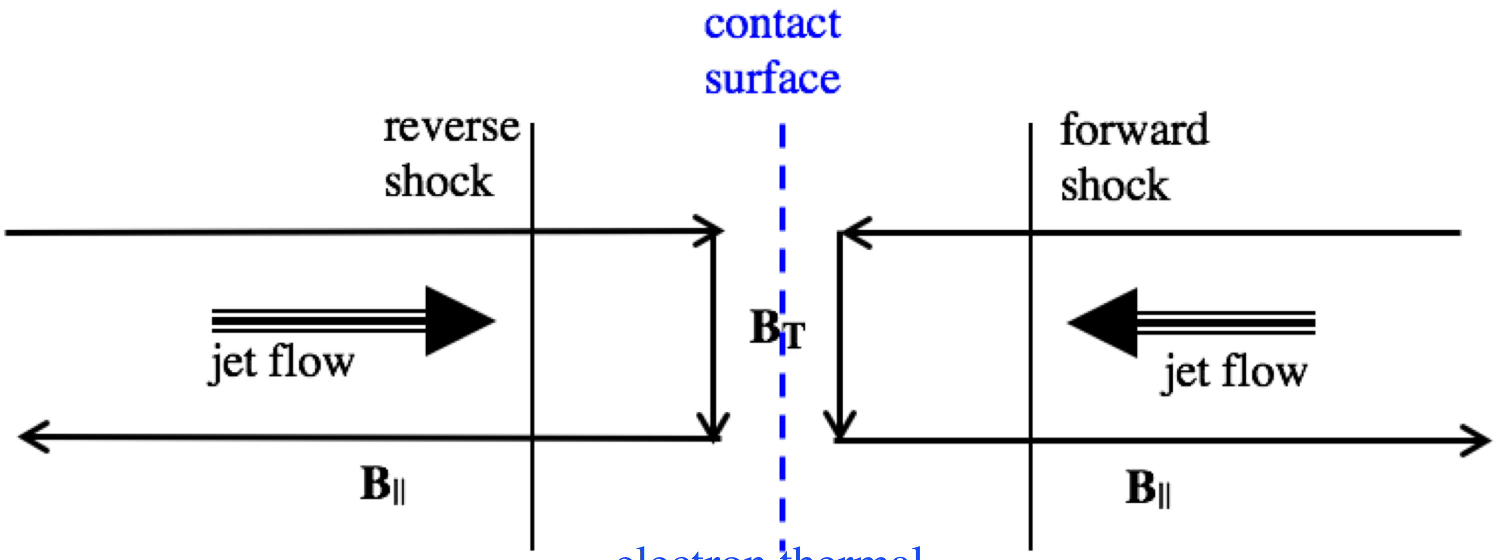








Colliding jets should create strongly magnetized shocks with transverse B-fields near the contact surface and parallel B-fields upstream

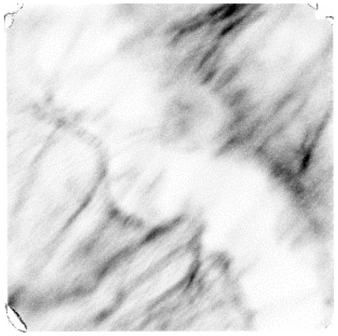


electron thermal conduction should be inhibited near contact surface

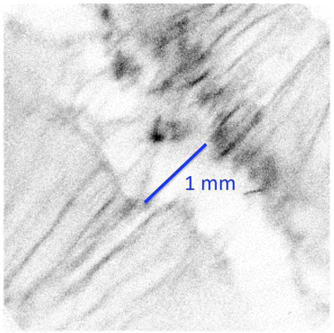
98593 t=2.3 – 2.5 ns

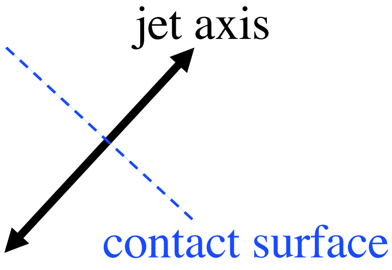
Prad data

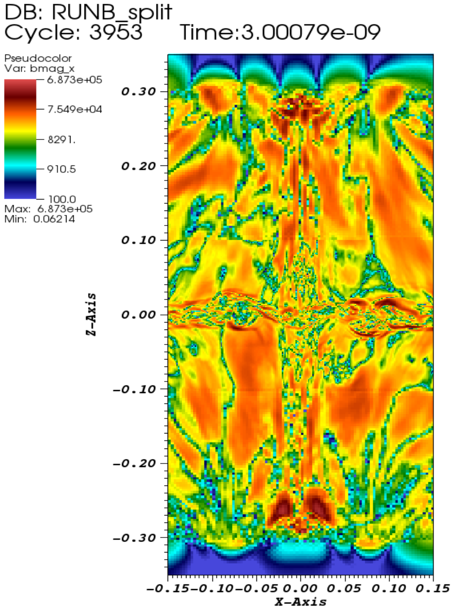
Bert (3 MeV)



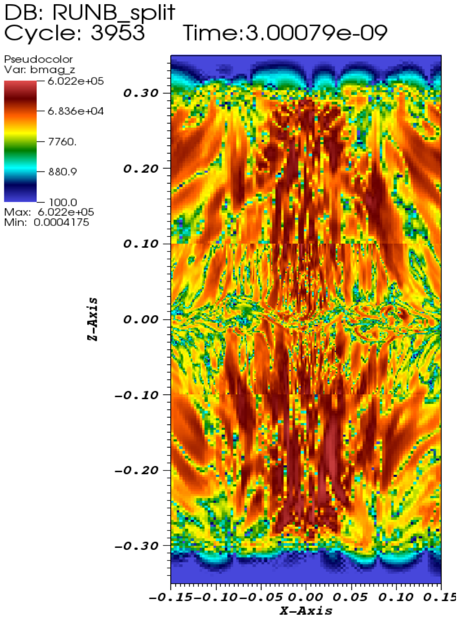
Ernie (15 MeV)



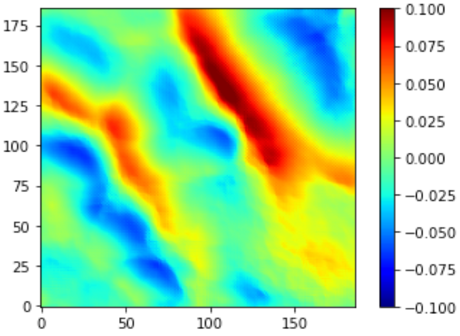




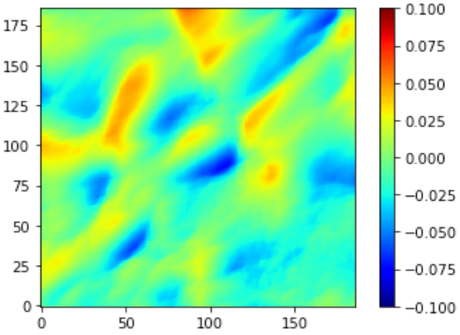
B_|_



$B_{||}$



B_|_



$B_{||}$

Next experiments planned for Project A

- Add Fe & Sn dopants to CH targets to increase radiative cooling, to study radiative magnetized shocks.

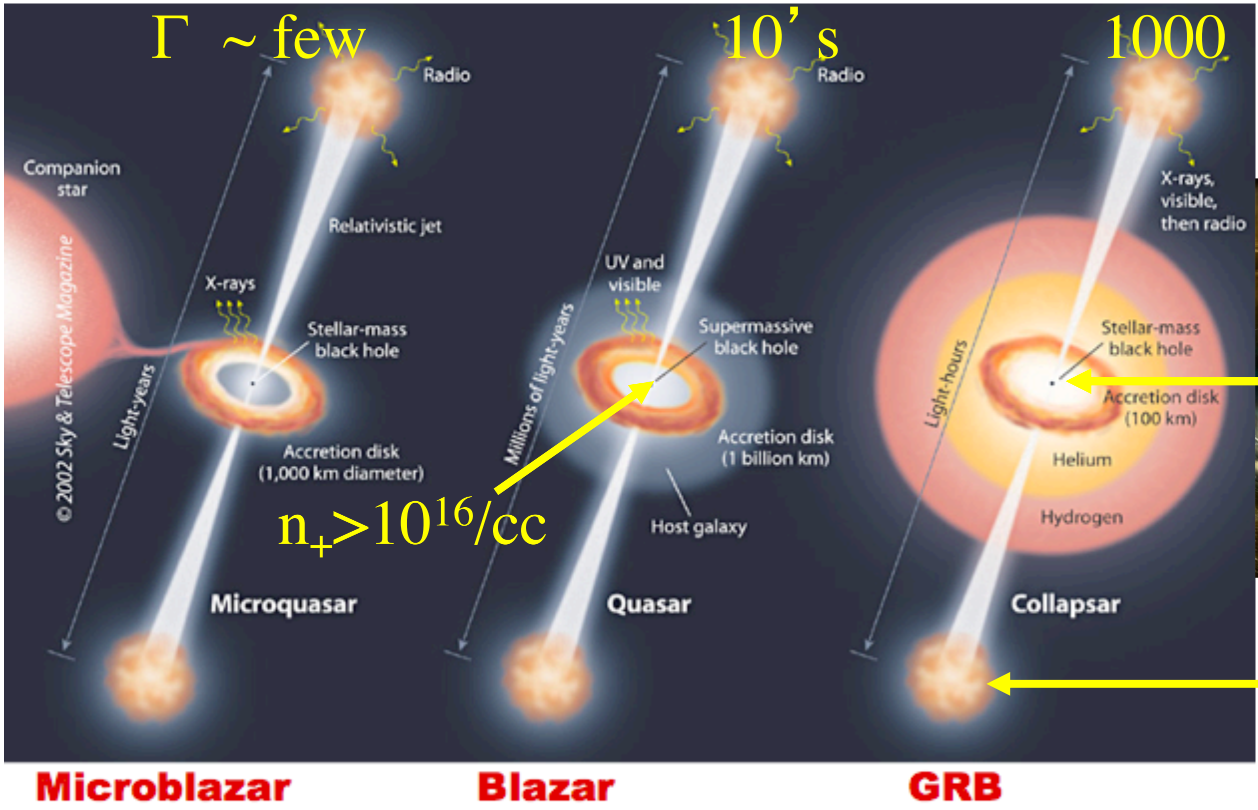
- Study nonthermal particle acceleration by the magnetized shocks

- Study fusion reactions of D, T, Li in strong magnetic fields.

- Propose much larger scale experiments on NIF , using 64 NIF beams for each hollow ring.

Project B uses the TPW laser in Austin, TX

Goals: create & study the physics of pair plasmas and GRBs



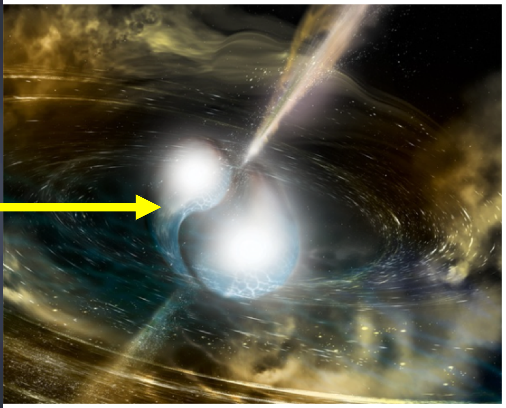
Γ ~ few

10's

1000

$n_+ > 10^{16}$/cc

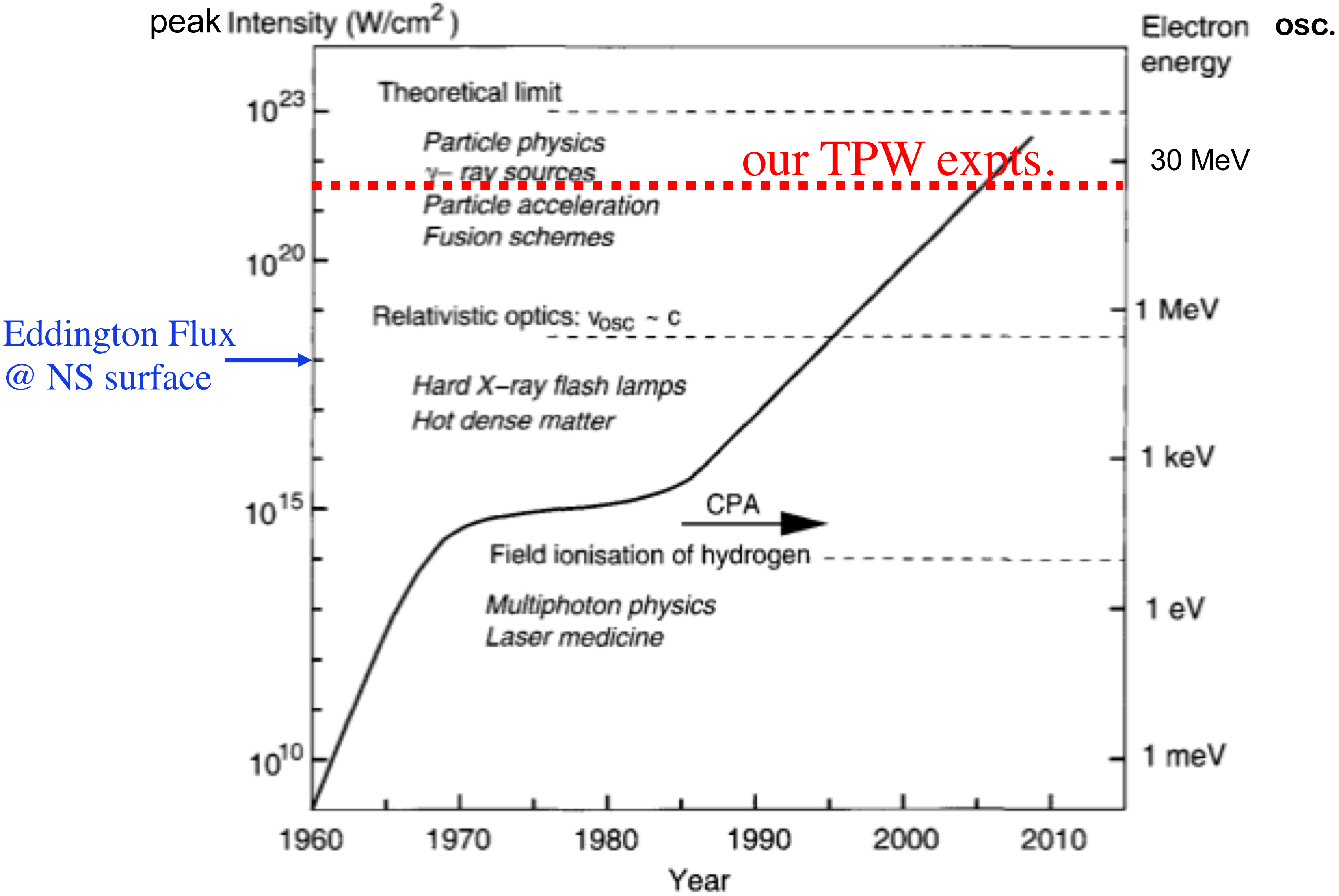
GW 170817



$n_+ > 10^{13\text{-}14}$/cc

$\varepsilon_\gamma > 10^{11\text{-}12}$ erg/cc

relativistic outflows in astrophysics emit intense gamma-rays and are likely dominated by e+e- pairs



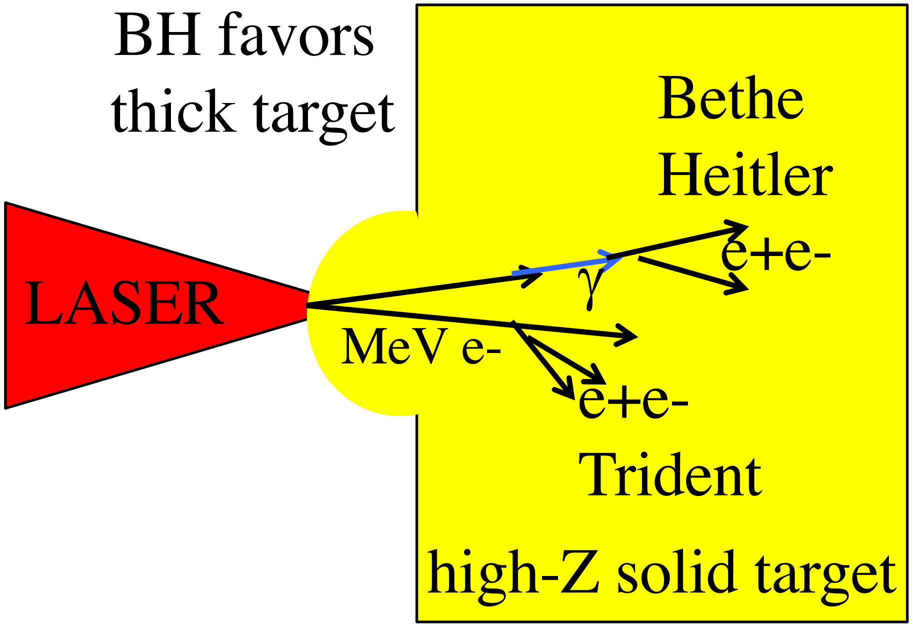
our TPW expts.

Eddington Flux
@ NS surface

Fig. 1.1 Progress in peak intensity since the invention of the laser in 1960.

Ultra-intense laser irradiating thick high-Z solid targets is the most efficient tool to create dense gamma-rays & pairs

(Cowen 1999, Chen 2009, 2010, Gahn 2000, Sarri 2015)



BH favors thick target

LASER

MeV e-

γ

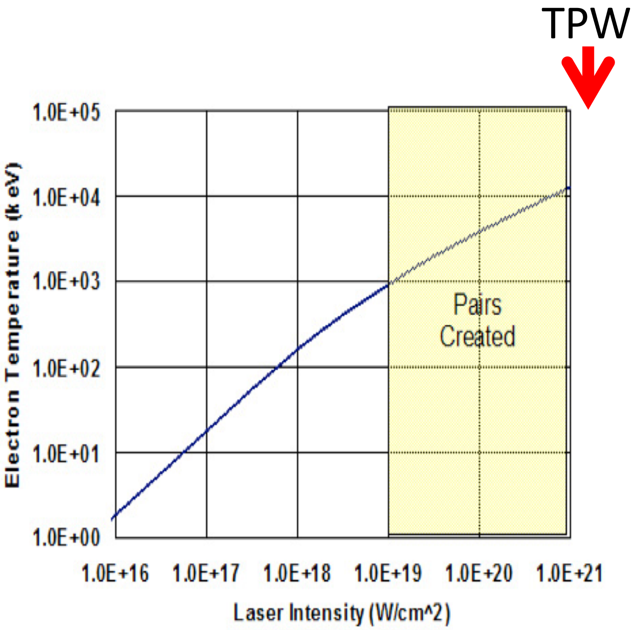
Bethe Heitler

e+e-

e+e-

Trident

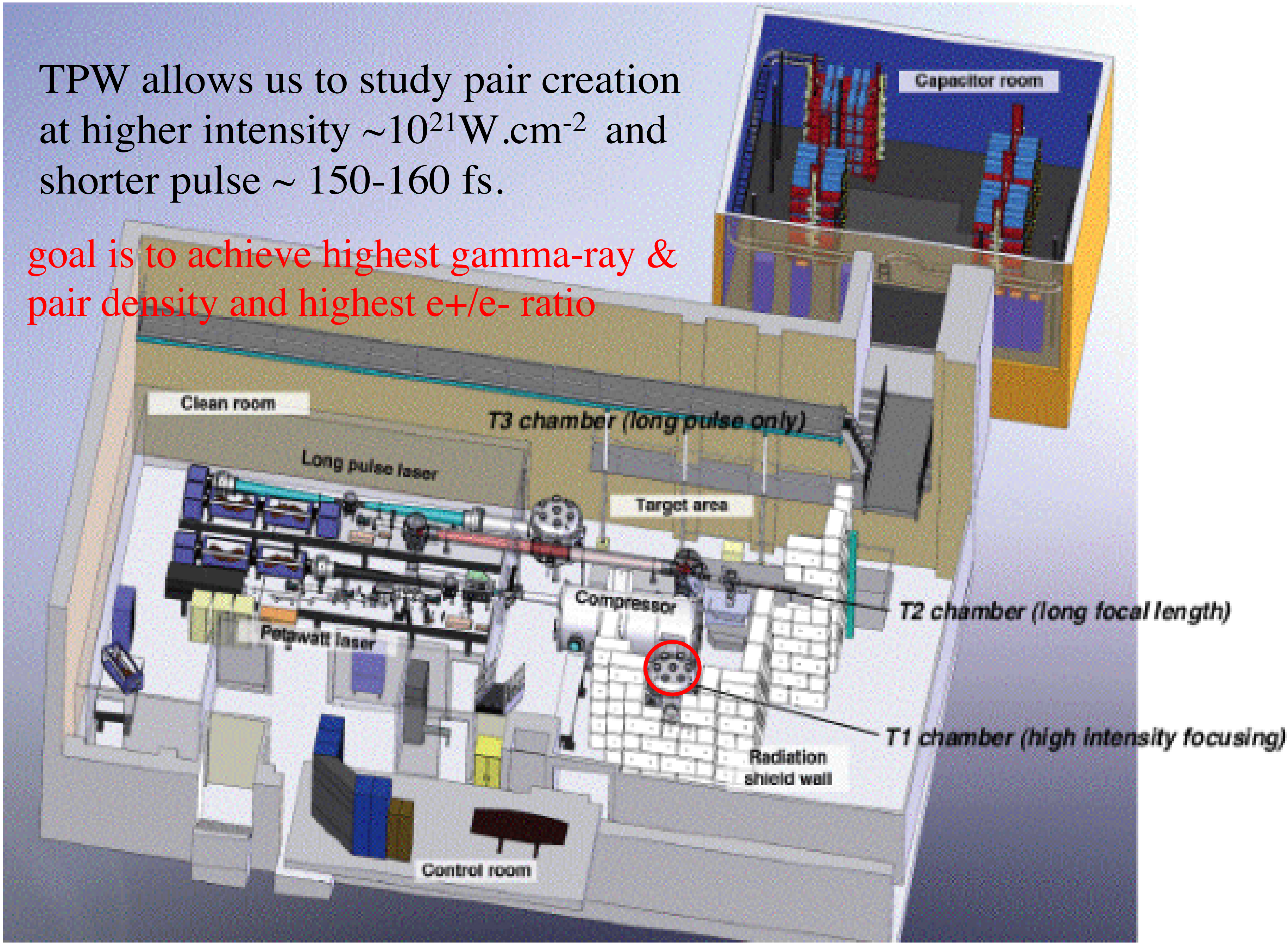
high-Z solid target



higher laser intensity => hotter electrons => more & higher energy gammas => more pairs + easier escape

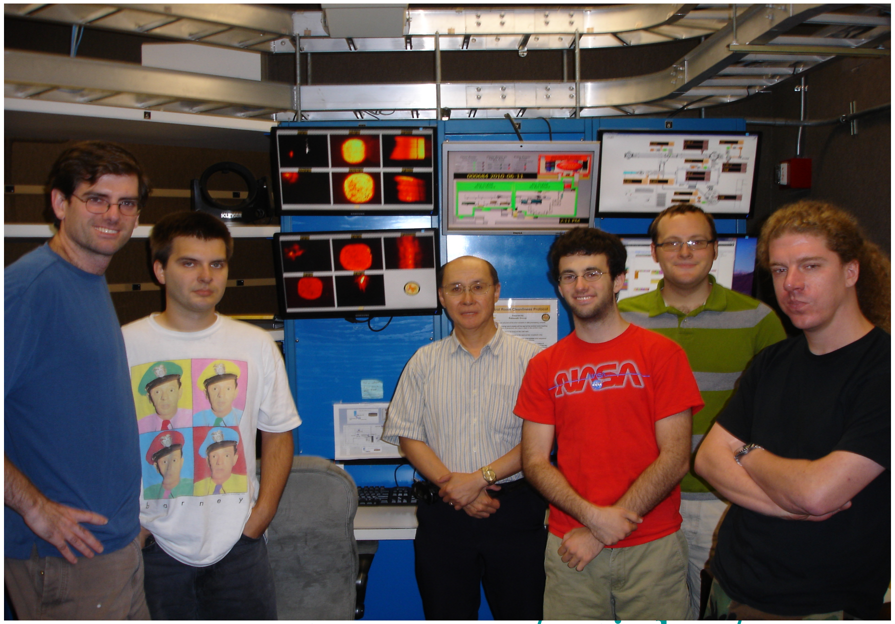
TPW allows us to study pair creation at higher intensity ~10^{21}W.cm^{-2} and shorter pulse ~ 150-160 fs.

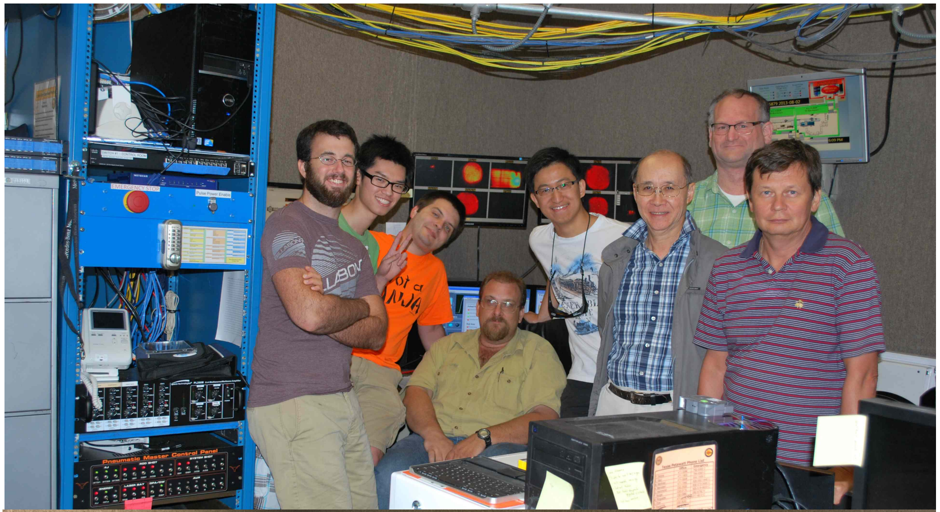
goal is to achieve highest gamma-ray & pair density and highest e+/e- ratio

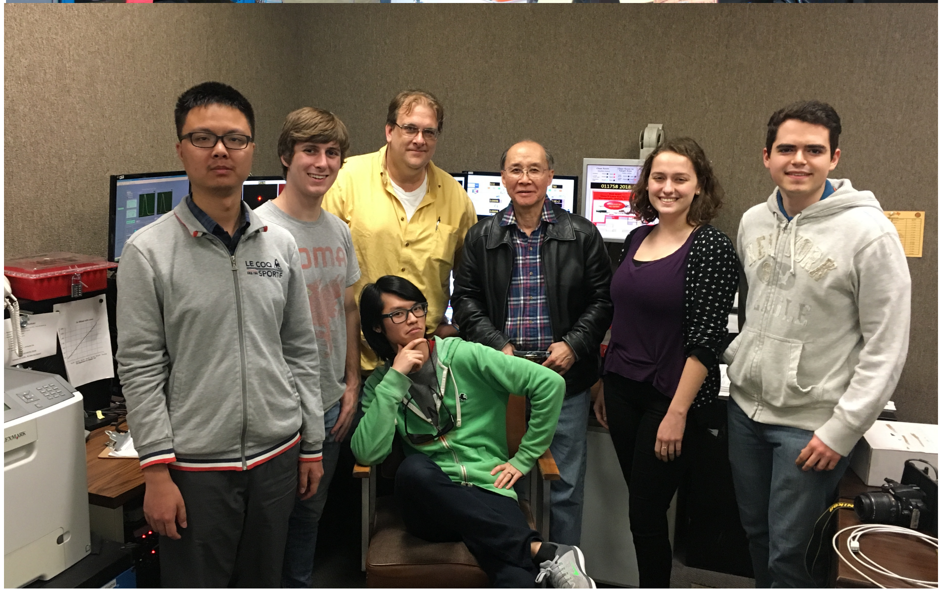


Collaborators

Rice: Zheng, Burns, Lo, Henderson, Chaguine, Taylor, Clarke, Cen, Zhou, Hua, Yao, Lu, Marchenka, Fasanelli, Zhang, Wang, Fu; UT : Dyer, Hasson, Dashko, Glen, Riley, Serratto, Tiwari, Quevedo, Donovan, Ditmire; MD Anderson : Wong, Zhang





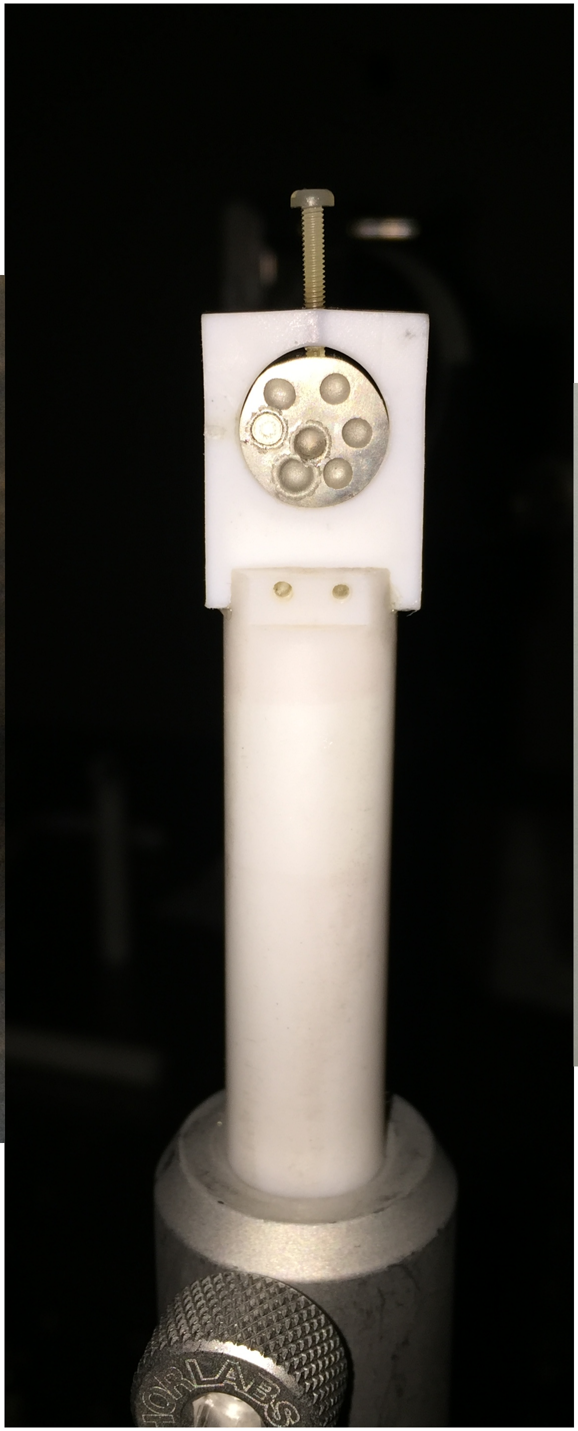


(see www.nature.com/articles/srep13968 for earlier results)

(see https://youtube/oB2WtiEfyBQ for APS TPW movie)

Sample Slugs with Multiple Craters

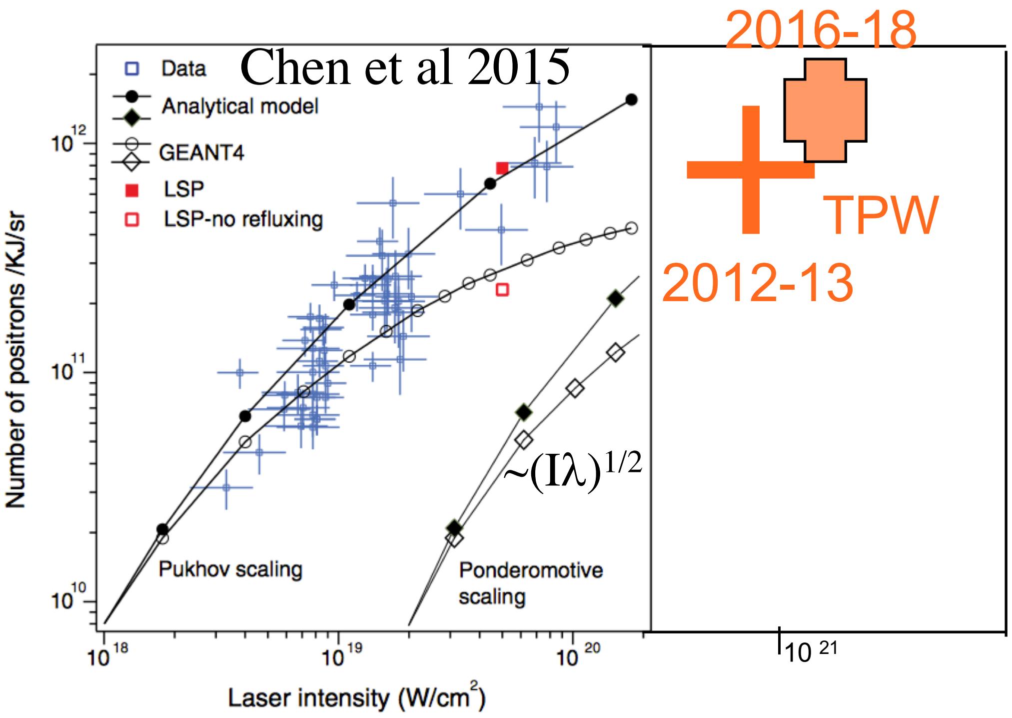
Au craters are larger than Pt craters



Major milestones achieved in recent TPW experiments

1. Maximum gamma-ray yield ~ 5% of laser energy
2. Emergent γ-ray density from target is similar to γ-ray density observed in cosmic GRBs (~10^{11}erg/cc).
3. Emergent pair density reaches ~ $10^{15}/\mathrm{cm}^3$, exceeding the pair densities postulated in GRBs. Also R ~ $5c/\omega_+$, marginally qualifying the pairs as a "plasma"
4. For cm-size large targets, we discovered e+/e- >>1 within a cone centered between Laser Forward and Target Normal directions.

Comparison of TPW e+ yield with previous laser experiments and theoretical models



We are at the threshold of achieving a true"pair plasma"

to characterize and study a "pair plasma", we need pair jet transverse size R >> "pair skin depth"

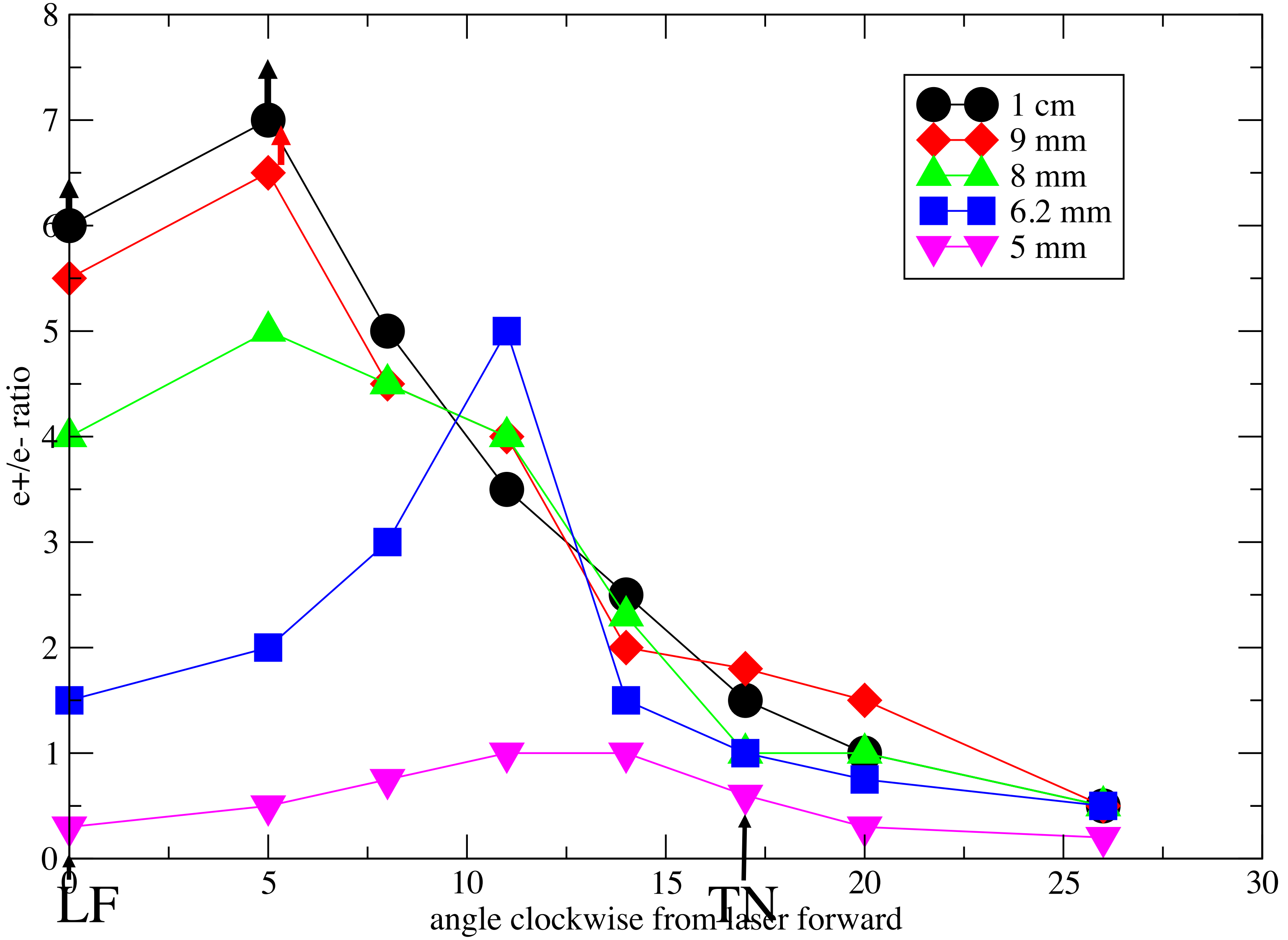
$$R\omega_+/c \sim (N_+/\Delta t)^{1/2}$$

$$R\omega_+/c\gamma^{1/2} \sim (N_+/\gamma\Delta t)^{1/2}$$

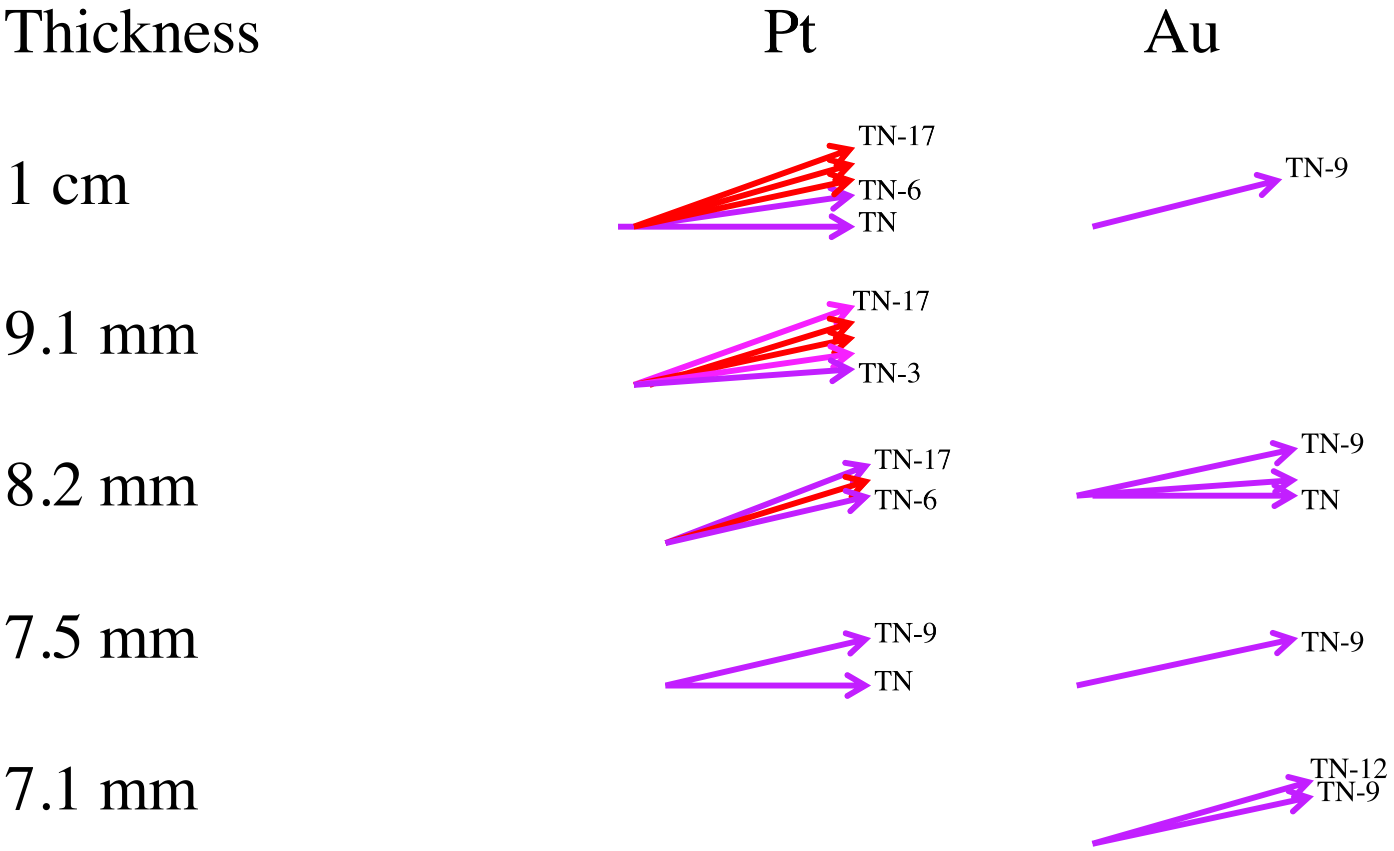
Our Max $(R\omega_+/c) \sim 5$

Our Max $(R\omega_+/c\gamma^{1/2}) \sim 2$

We found e+/e- ratio > 1 within a cone between LF and TN for target thickness ≥0.6 mm



Pt produces higher e+/e- than Au



Cone lies between Laser Forward and Target Normal.

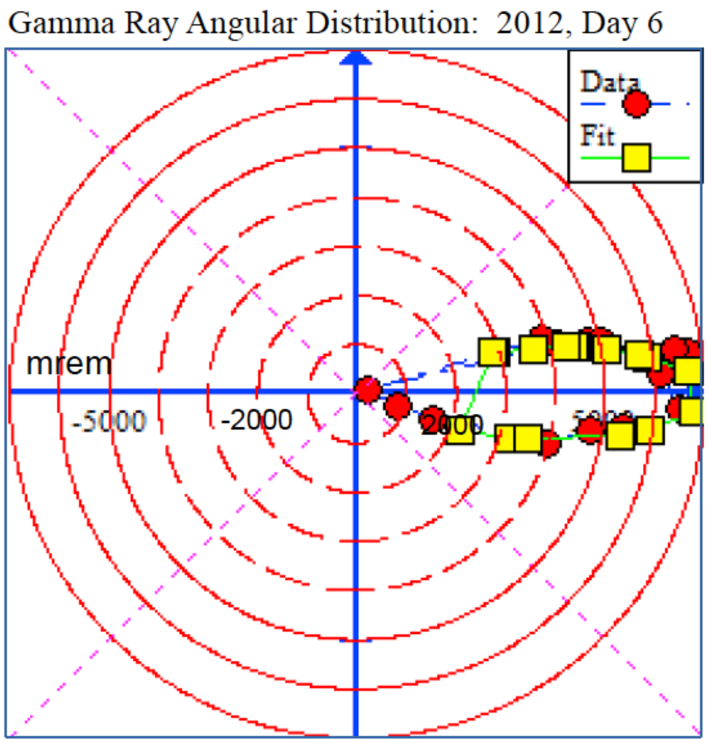
Red arrows denote e+/e- > 5. Purple denotes e+/e- >1.

electrical conductivity likely played a role in the suppression of e- emission

positron results summary

We have experimentally demonstrated a new way to create a dense ($\geq 10^{15}/cm^3$), short-pulse (<100fs), multi-MeV "pure" positron jet.

If such positrons can be trapped magnetically, we can create a long-living dense pure positron plasma.

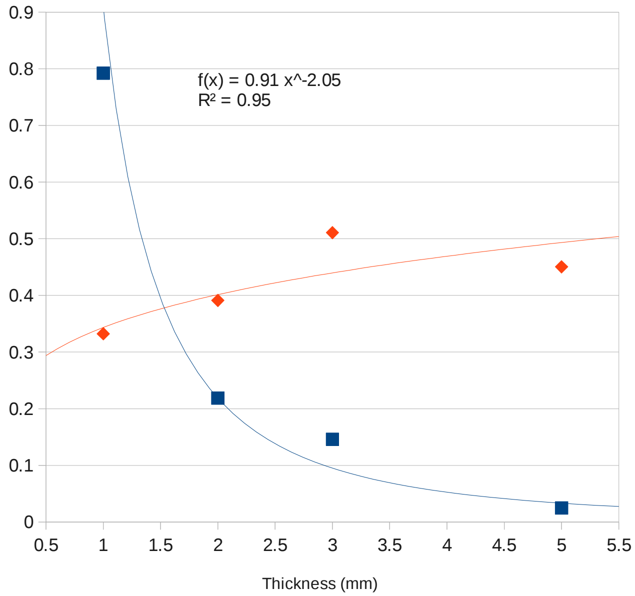


Gamma ray angular distribution on Day 6 of the 2012 TPW experiments.

Gamma-Ray Data

1. total gamma yield ~ 5% of laser energy
2. dosimeter data show 15° gamma-ray beam centered @ ~10° from Laser Forward
3. Broad Band spectra were consistent with ~few MeV bremsstrahlung.

Biggest challenge: how to measure short-pulse ultra-intense γ-ray spectrum since single-photon counting does not work?



Current Spectrometers for Short-Pulse Intense Gamma-Rays

- Filter Stack or Wedge Attenuation: limited to a few energy channels <~ 6 MeV
- Forward Compton Scattering: low S/N, limited to high flux, low background
- Nuclear activation Threshold: limited to high flux, very few energy channels

New Approach:
Use high-resolution 2D imaging of light pattern emitted by finely pixelated scintillator matrix

had been used in High Energy Physics, also recently in LWFA accelerator experiments, for gamma-rays ≥ 100 MeV, with limited success. So far only crude model input spectrum with few parameters has been obtained using iterative Monte Carlo simulations

……………..

Team members: Kevin Qinyuan Zheng, Kelly Yao, Willie Lo, Aileen Zhang, Rice University; Gary Wong, Yuxuan Zhang, MD Anderson Cancer Center; Andriy Dashko, Hannah Hasson, Hernan Quevedo, Todd Ditmire, UT Austin

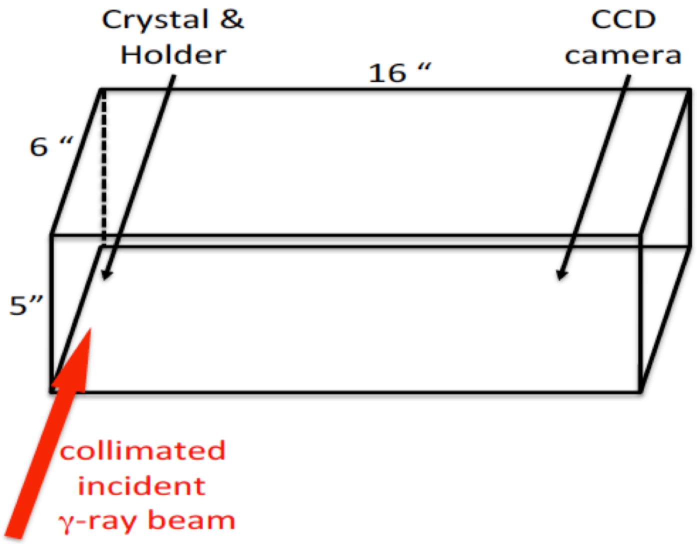
SAS (Scintillator Attenuation Spectrometer) adopts new advances in medical imaging technology

- Large 2D matrix (e.g. 36x60) of mm-sized pixels provides high resolution images with hundreds of bright pixels.
- LYSO.Ce scintillator has highest light output (50000 blue photons per MeV energy absorbed). High-Z and high density (7.8gm/cc) can attenuate 50 MeV gamma-rays in a few cm.
- 100% reflective coating for each pixel traps all light emitted in each pixel. Emergent light from each pixel faithfully represents energy deposited in each pixel with no light contamination between pixels.
- Sensitive high-speed high-contrast non-cryogenic CCD camera capable of high rep-rate imaging of LYSO light pattern even from faint gamma-ray sources
- Insensitive to EMP and high neutron flux

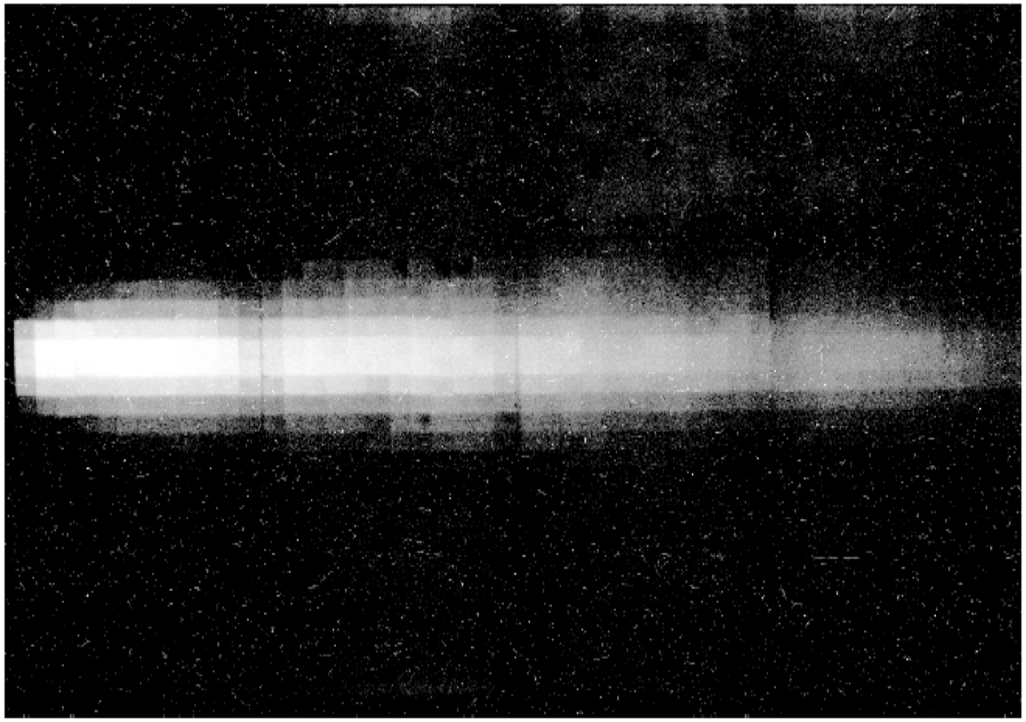
Design and Layout of SAS

LYSO matrix block, crystal holder and CCD camera are housed in a black light-tight box the size of a shoe box

collimated gamma-rays



36 x 48 matrix measures 6 cm H x 8 cm W x 1 cm D
3mm – 6mm pinhole collimates gamma-rays along central axis



Sample SAS image of LYSO scintillation light pattern of Shot 10026 from a 2016 TPW experiment. This image contains over 400 bright pixels.

Use GEANT4 to accurately simulate light patterns from LYSO matrix

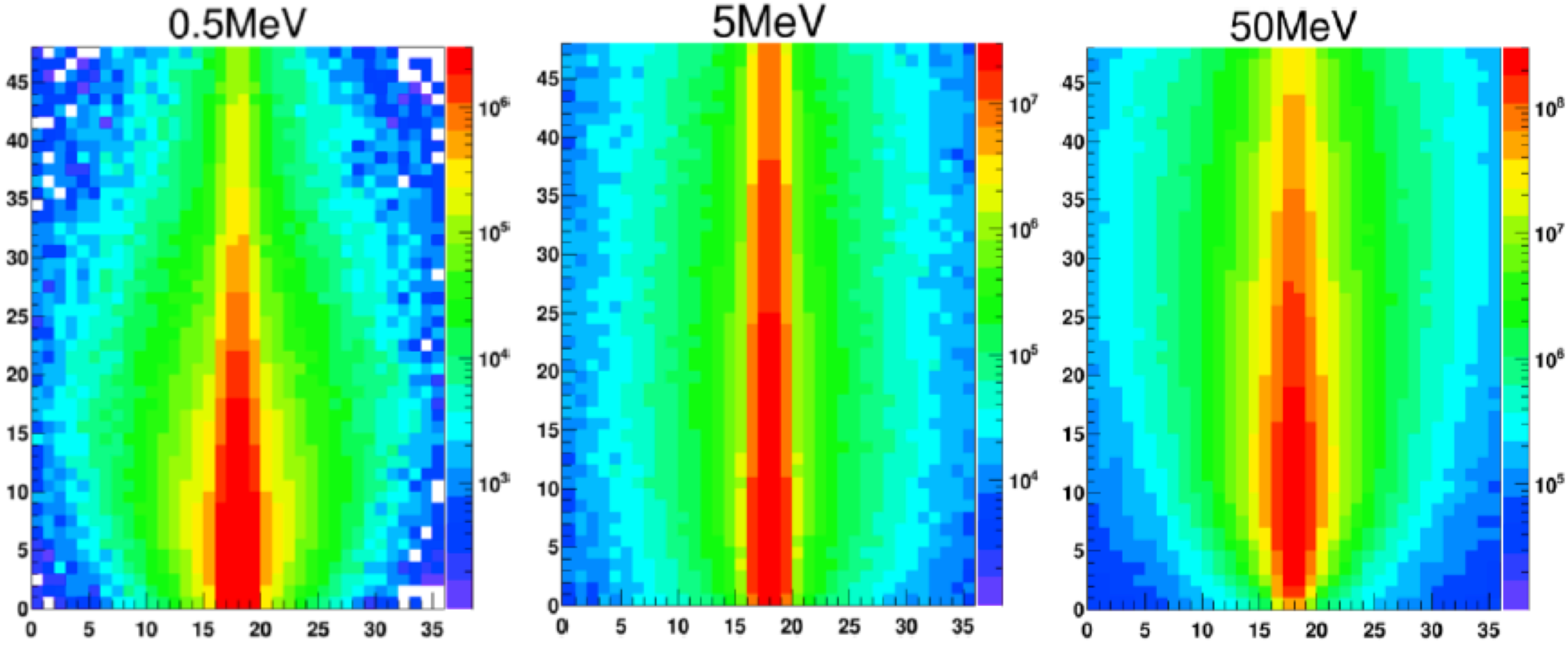
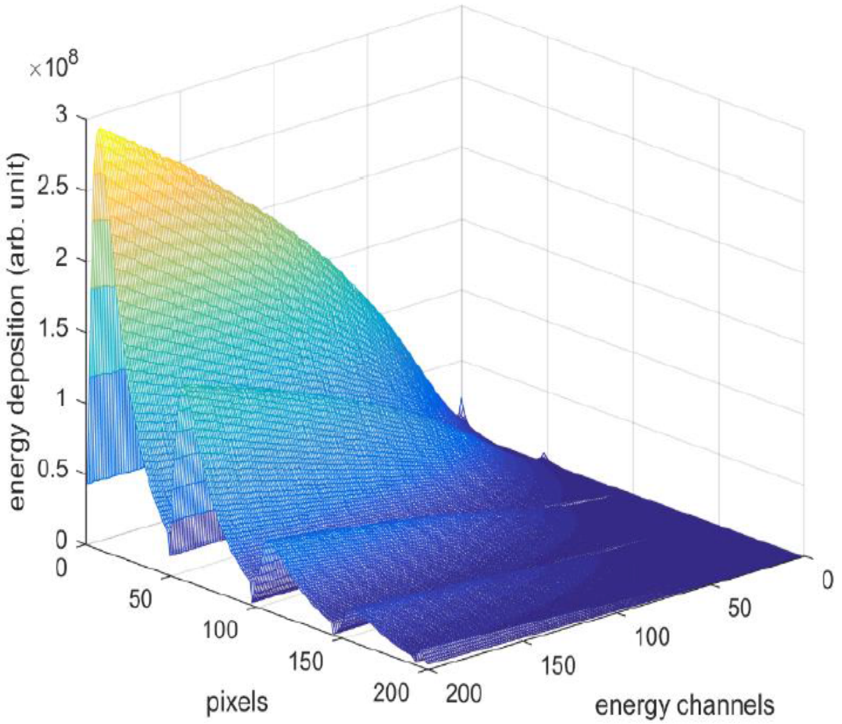
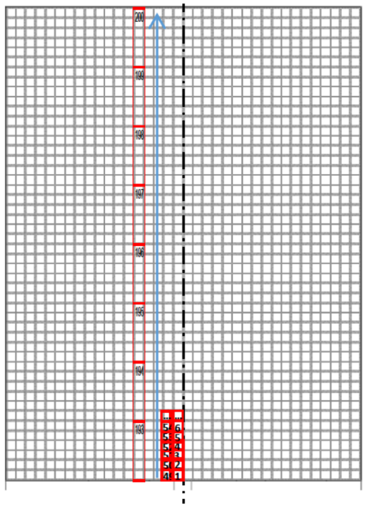


Fig 3.5 Log Scale light profiles from 0.5 to 50MeV.

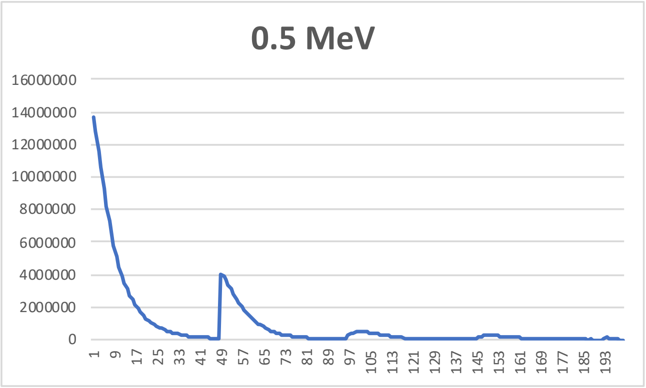
We create 200 light patterns from 200 GEANT4 simulations of monoenergetic gamma-ray energies from 0 – 50 MeV with 0.25 MeV intervals

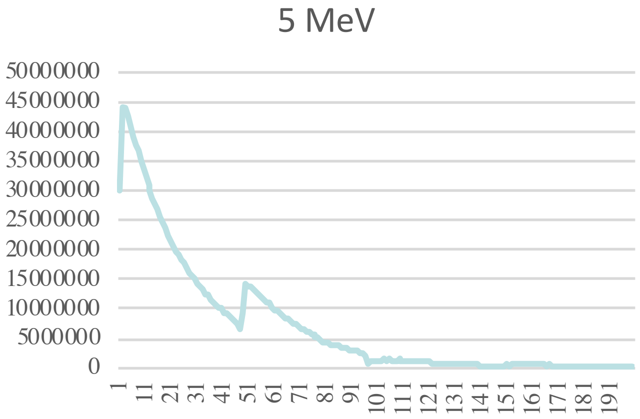
200 x 200 Detector Response Matrix shows importance of 2D imaging

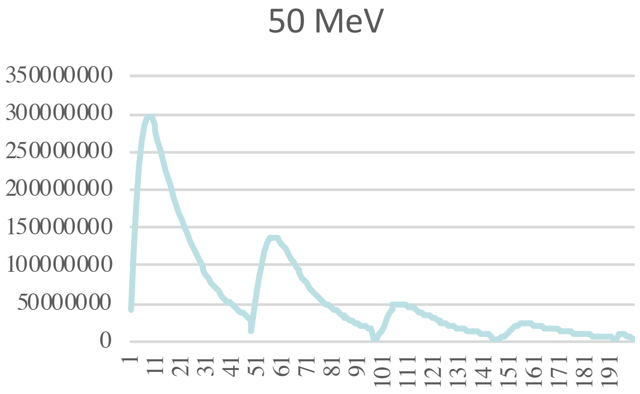




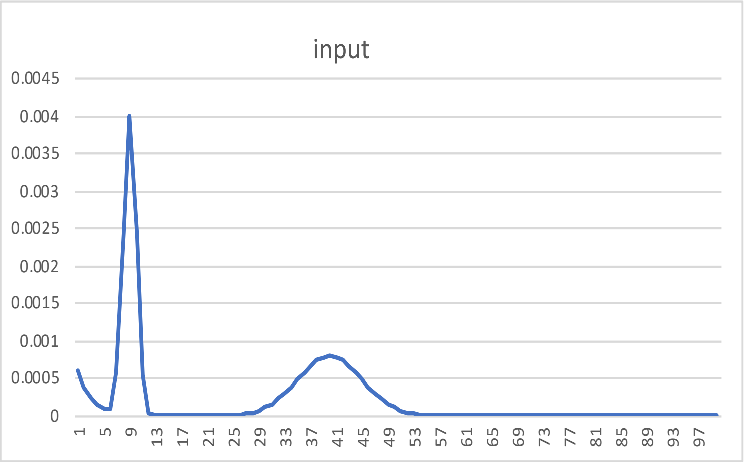
5 columns of 48 pixels combined into 200 "effective pixels"

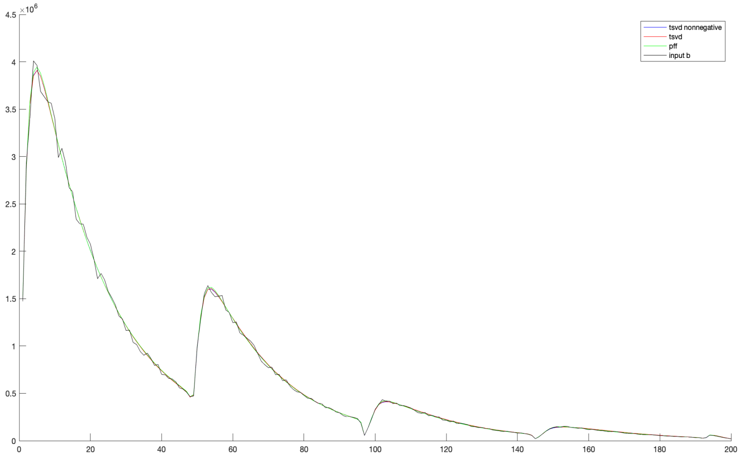


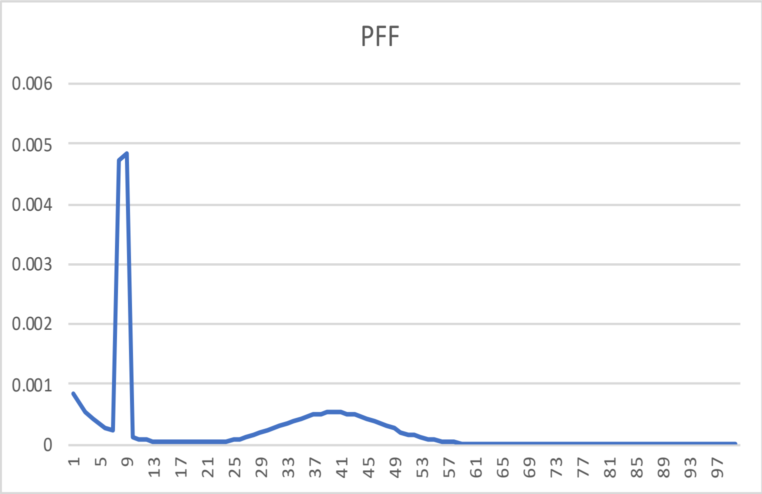


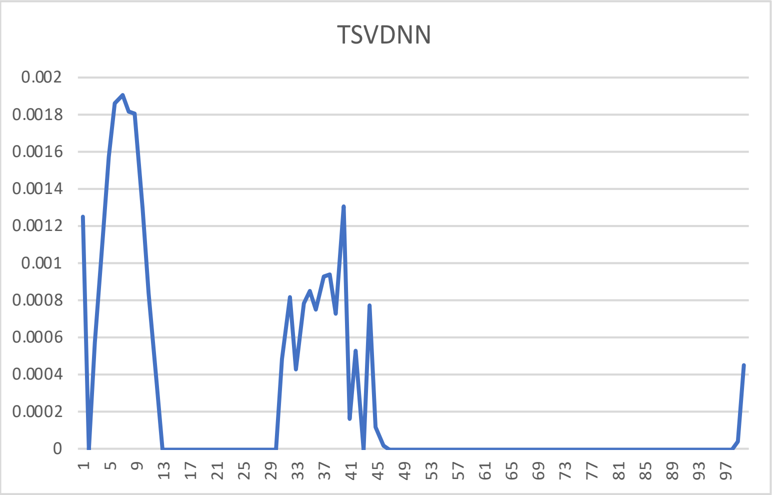


Test with 3-component incident model spectrum

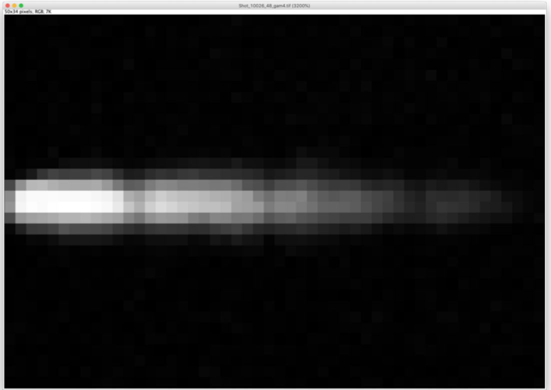

input

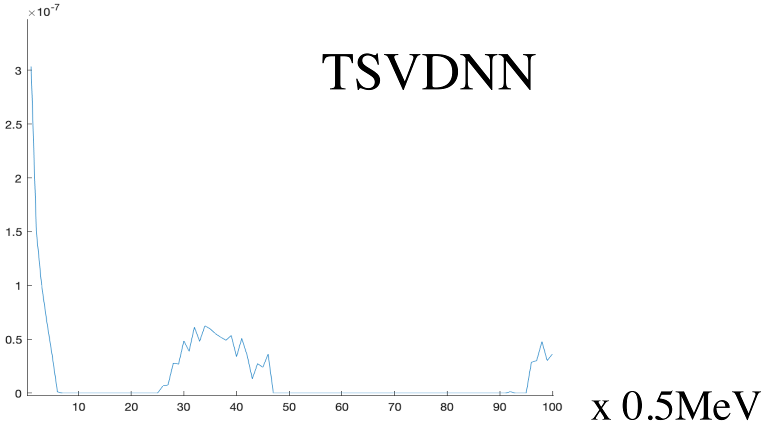


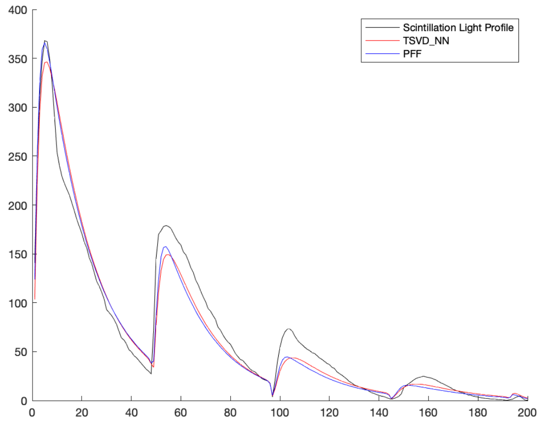

PFF

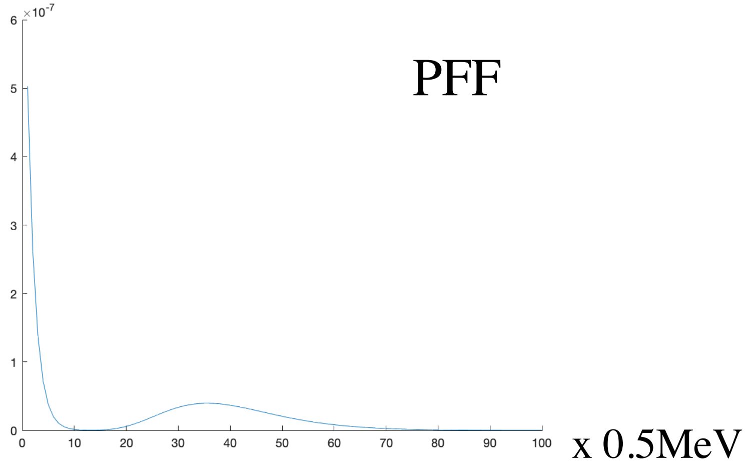

TSVDNN

Gamma-ray Spectrum Inverted from Shot 10026 SAS Image







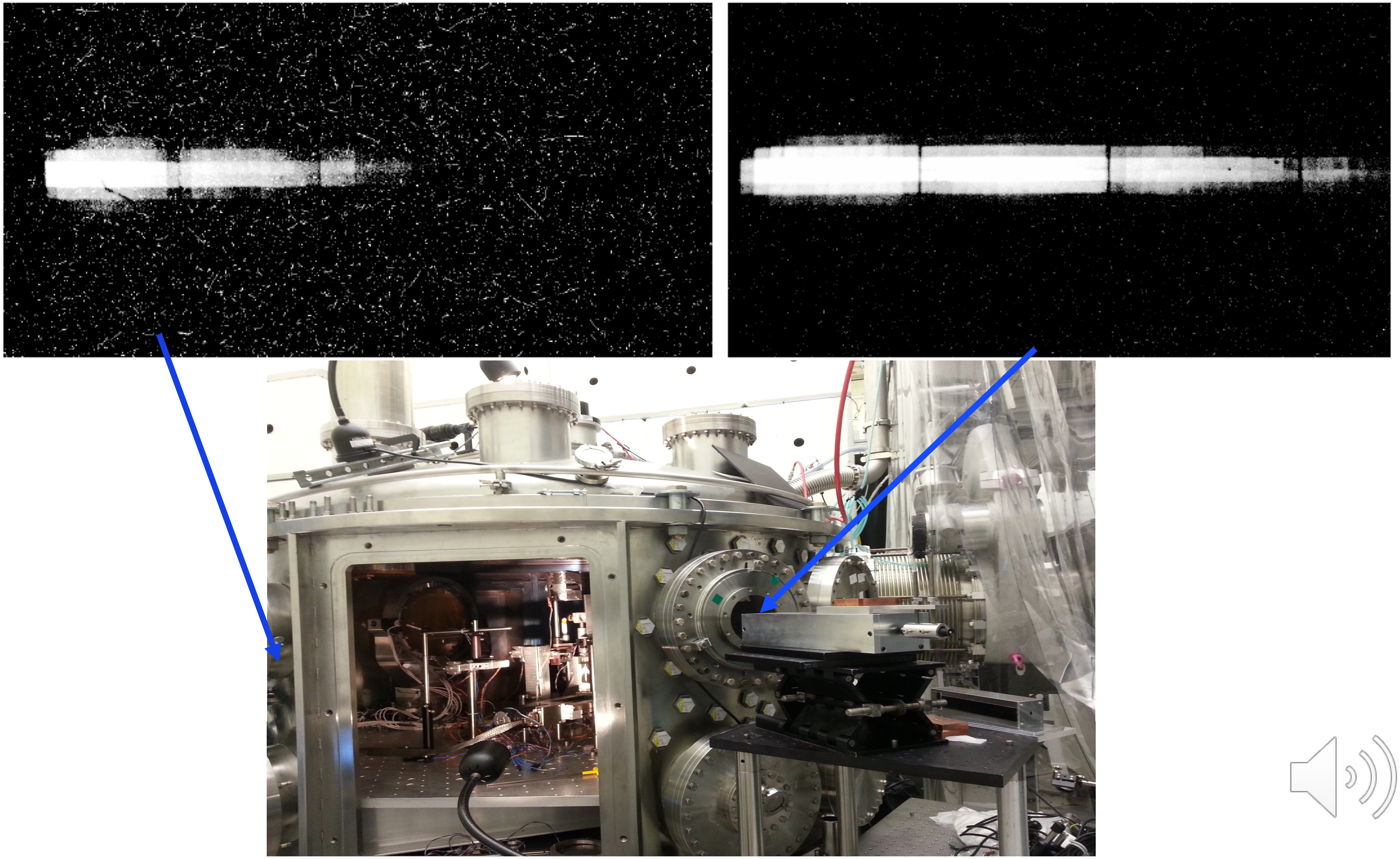


~ MeV exponential + 17-18 MeV bump

Sample 2018 TPW SAS Data

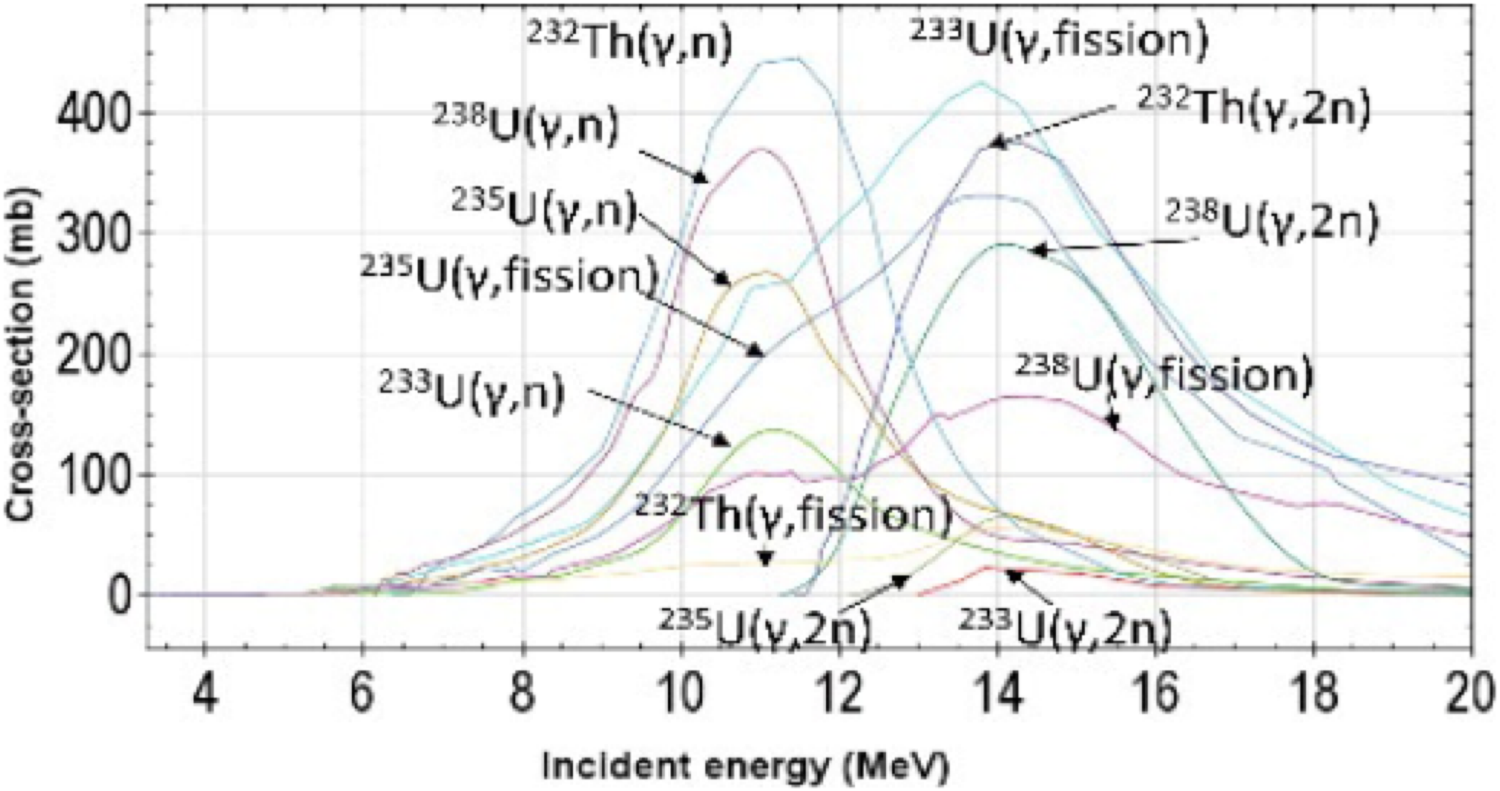
TN + 90°

TN



Next TPW experiments in 2022

- New application: exploit the 15-20 MeV gamma- ray excess to study photo-nuclear



Summary of Project B

- SAS is a new type of gamma-ray spectrometer designed for high resolution, high S/N, high rep-rate applications in short-pulse laser experiments
- Can measure gamma-rays up to 100 MeV with 0.5 MeV spectral resolution
- We have developed a robust, stable inversion algorithm to extract reliable spectrum
- SAS led to discovery of 17-18 MeV gamma-ray “bump” in TPW experiments

Table 1. Sample parameters of the d=800 mm jet at 3.5 ns and 2.5 mm from laser target compared to those of YSO jets.

d=800 mm OMEGA jet	YSO jet
Electron density $n_e \sim 1.5 \times 10^{20}$ cm^{-3}	$\sim 10^2 - 10^5$ cm $^{-3}$
Electron temperature $T_e \sim 1$ keV	$\sim 10^4$ K – few x 10^6 K
Ion temperature $T_i \sim 2.5$ keV	$\sim T_e$
Ionization $\langle Z \rangle \sim 3.5$	low – 100%
Flow velocity $v \sim 1.2\text{x}10^8$ cm/s	~ few x 10^7 cm/s
Magnetic field $B \sim 10^6$ Gauss	~ 20 – 500 mG
Plasma Beta $\beta = 8\pi P_g/B^2 \sim 10$	$\sim 10 - 10^3$
Mach number $M=v/c_s \sim 3$	~few - 10
Alfven Mach number $M_A = v/v_A \sim 8$	$\sim 10^2$
Reynolds number $R_e \sim 10^4$	$\sim 10 - 10^3$
Magnetic Reynolds number $R_{eM} \sim 10^4$	~ few x 10^2
Peclet number $P_{e\|\|} = 1.5kn_e vR/k_{T\|\|B} \sim 0.3$	unknown
$P_{e\ orth} = 1.5kn_e vR/k_{T\ orth\ B} \sim 30$	unknown
Hydro time/Rad. cooling time (CH) ~ 0.01	various
Hydro time/Rad. cooling time (2%Fe) ~ 1	
Electron skin depth $c/\omega_e \sim 0.4$ μm	
Ion skin depth $c/\omega_I \sim 24$ μm	
Debye length $v_e/\omega_e \sim 0.01$ μm	
Electron gyroradius $v_e/\omega_{Be} \sim 0.6$ μm	
Ion gyroradius $v_i/\omega_{Bi} \sim 20$ μm	
Coulomb scattering mean free path $l_{ei} \sim 20$ μm	