Effects of target material on fast electron transport and resistive collimation (from Titan to OMEGA EP)

Mingsheng Wei
Inertial Fusion Technology
General Atomics, San Diego

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Outline

- Titan laser at the Jupiter Laser Facility for fast ignition and relativistic HED science study and training graduate students (also PhD thesis research), postdocs and young researchers

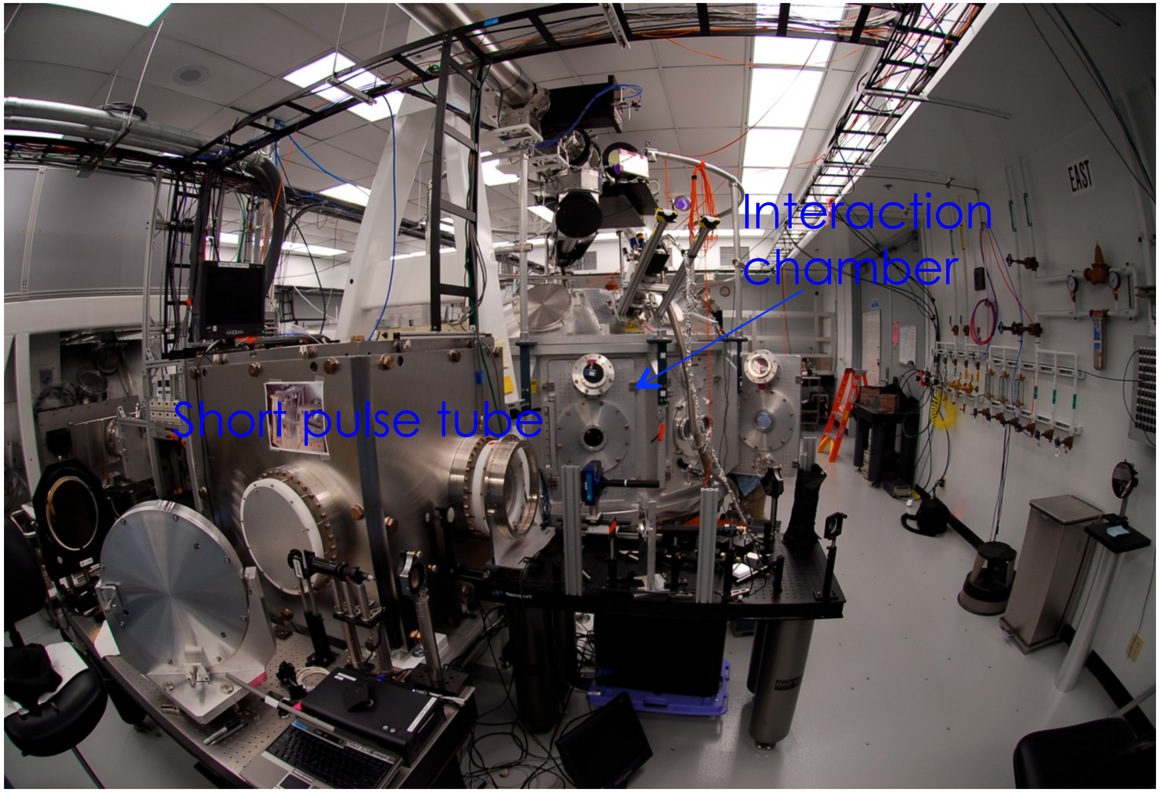
- Motivation of the experiments
- Details of the Titan experiments, results and physics understanding
- Scaled-up experiments and results using the OMEGA EP
- Summary

- Suggestions on the Titan laser operation & capability improvements

The Titan laser at JLF for Fast ignition and relativistic HED physics study

https://jlf.llnl.gov

Titan chamber area



Most well-characterized intermediate laser facility

Titan Short pulse (West) beam:

λ =1.054 μm
150 J in 0.7 ps
I_{peak}~10^{20} W/cm^2
Pedestal energy of 10-20 mJ in 2.5 ns

λ =0.527 μm, 50 J in 0.7 ps

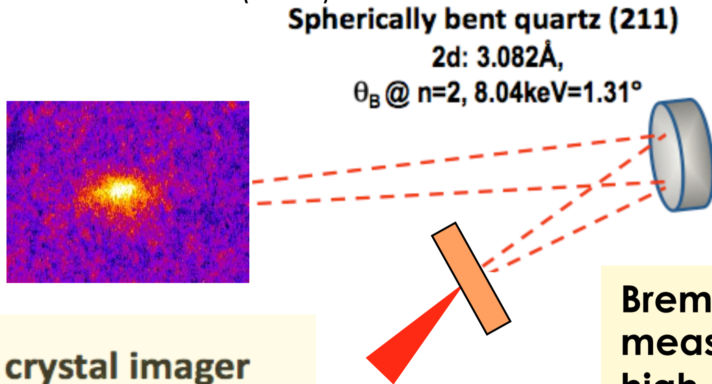
Collinear injection of additional prepulse to create a preplasma

Titan long pulse (East) beam:

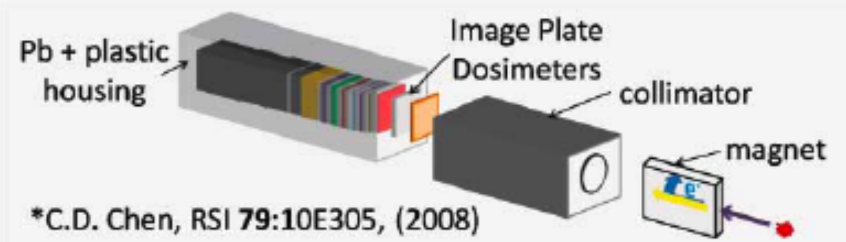
λ = 0.527 μm
380 J in a few ns
Can be injected at various angles relative to the short pulse beam

A suite of diagnostics tested and/or developed on Titan to characterize fast electron source and transport

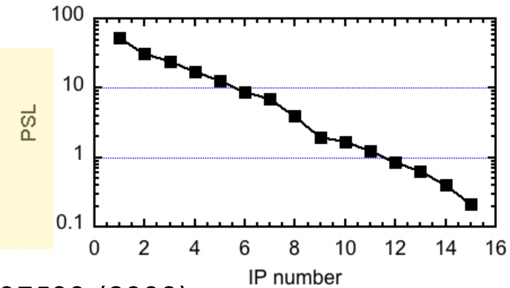
J.A. Koch et al., RSI 74, 2130 (2003)



K-α crystal imager shows the hot e⁻ spatial distribution

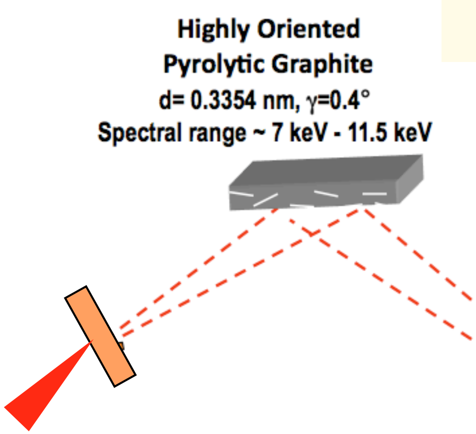


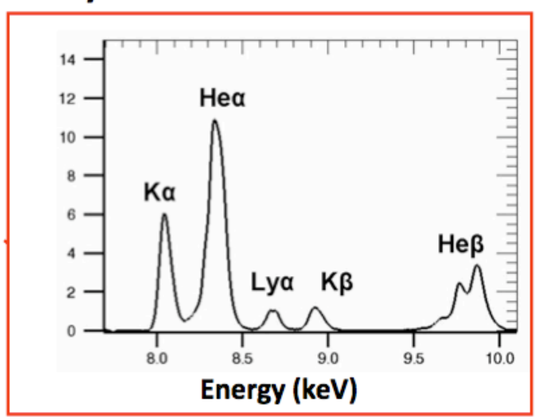
Bremsstrahlung spectrometer measures fast electron induced high energy X-rays (up to 700 keV) inside the target



A. Pak et al., RSI 75, 3747 (2004)
K. Akli et al., J. Instrum. 5, P07008 (2010)

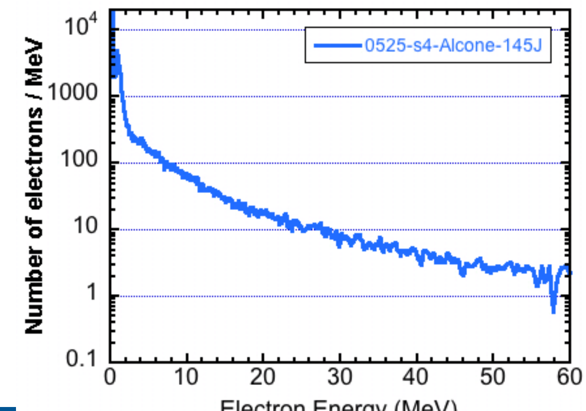
HOPG crystal spectrometer gives spectral information and absolute K-α yield





H. Chen et al., RSI 79, 10E533 (2008)

Electron spectrometer measures escaped fast electron number and energy spectrum (calibrated)



Titan provides hands-on training for graduate students, postdocs and PhD thesis research

***S. Chawla*, R. Mishra, A. Sorokovikova, L.C. Jarrott, *B. Westover*, J. Peebles, H. Sawada, C. McGuffey**, F.N. Beg
University of California, San Diego

R.B. Stephens, J. Jaquez
General Atomics

C.D. Chen, H. Chen, H.S. McLean, P.K. Patel
Lawrence Livermore National Laboratory

Y. Sentoku
University of Nevada, Reno

A. Link, V. Ovchinnikov, K.U. Akli
The Ohio State University

H. Friesen, R. Fedosejevs
University of Alberta, Canada

A. Morace, D. Batani
University of Milano Bicocca, Italy

J. Pasley
University of York, UK

P. Koester, L. Gizzi
Intense Laser Irradiation Laboratory, INO-CNR, Pisa, Italy

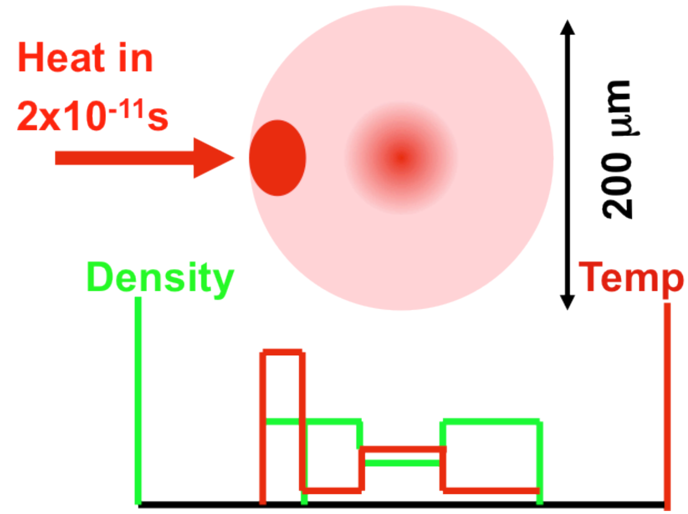
W. Theobald, C. Stoeckl
LLE, University of Rochester

Names in **bold** are graduate students and postdocs

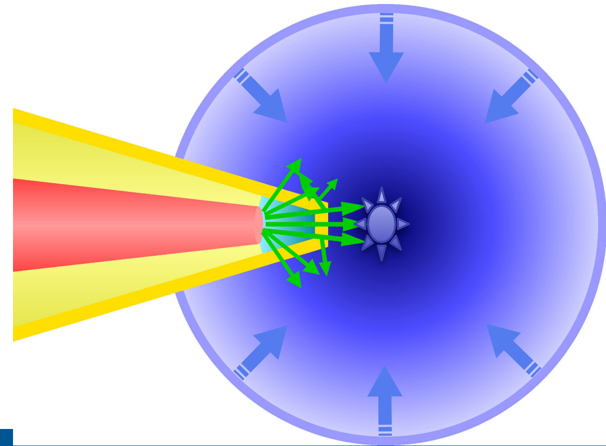
Fast ignition (FI)

- Ignition and compression separated
  - Relax implosion symmetry and driver energy requirement
  - Potentially high gain
- Isochorically compressed fuel, $\rho L \sim 1.2\ g/cm^2$
  - 1-3 MeV fast electrons
- Ignition spot size $L \sim 40\ \mu m$
  - Minimize stand-off distance to the core
  - Collimated electron beam
- Ignition pulse ~ 10 -20 ps
- Deposited energy 20 kJ
  - High intensity beam $6\times10^{19}\ W/cm^2$

M. Tabak et al. Physics of Plasmas 1, 1626 (1994)



Reentrant cone guided FI



- **Fast Ignition physics is extremely challenging and involves relativistic laser plasma interaction with High Energy Density Plasmas**
- **Understanding cone tip interaction physics is very important for cone-guided FI**

Simulations have suggested strong material dependence

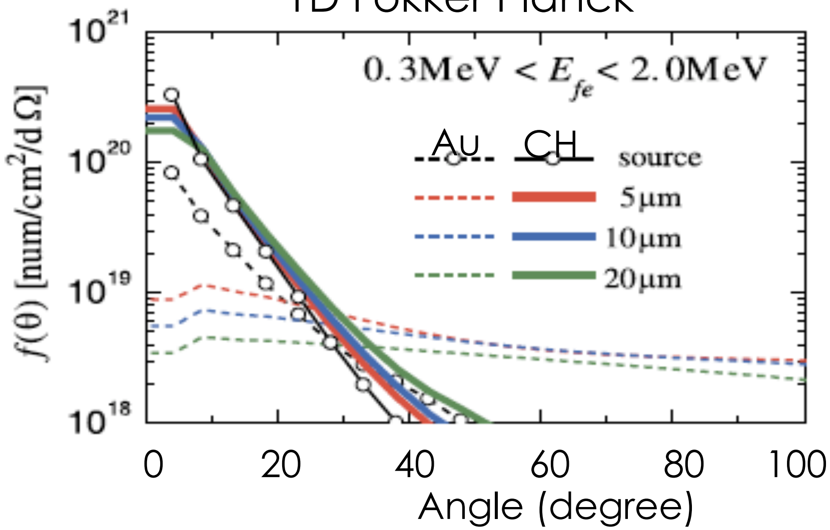
- **High-Z cone tip prevents x-ray preheat and provide protection more effectively**

- **Forward-going electron transport can be strongly affected by cone-tip material**
  - Large collisional loss and scattering in high-Z tip reduces forward energy transport*
  - Strong resistive fields in high-Z targets potentially collimating electrons#

Cone tip material and thickness need to be examined for optimizing fast electron transport and energy coupling for FI

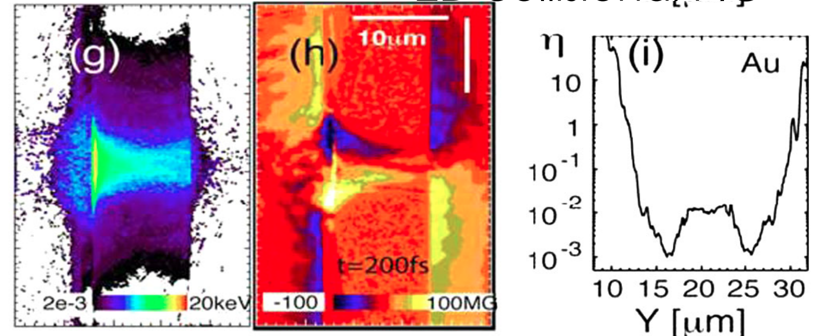
*Johzaki et al., PPCF **51**, 014002 (2009)

1D Fokker Planck



#Y. Sentoku et al., PRL 107, 135005 (2011); A.R. Bell, R.J. Kingham, PRL 91, 035003 (2003)

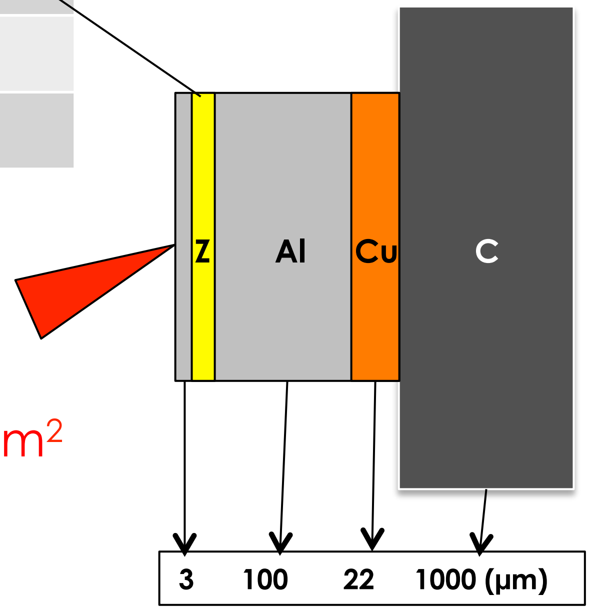
2D collisional PIC



Titan experiment to study effect of target material on fast electron transport

Z-layer	D (μm)
Au	8
Mo	14
Al	33

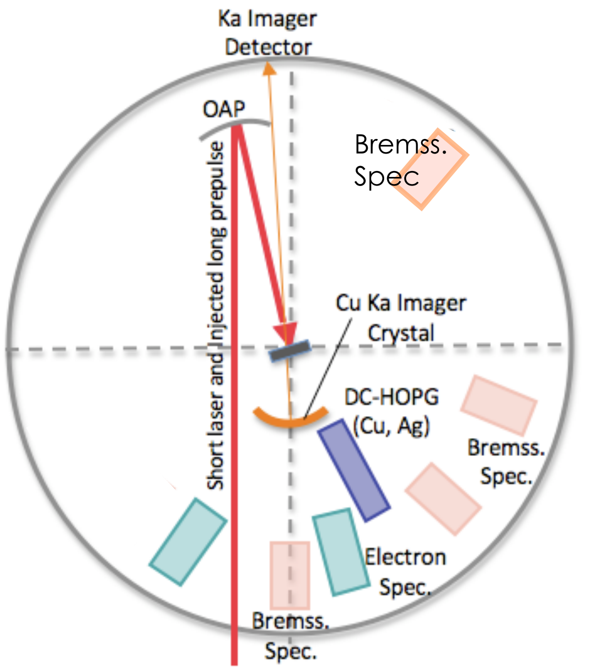
Multilayered solid foil target

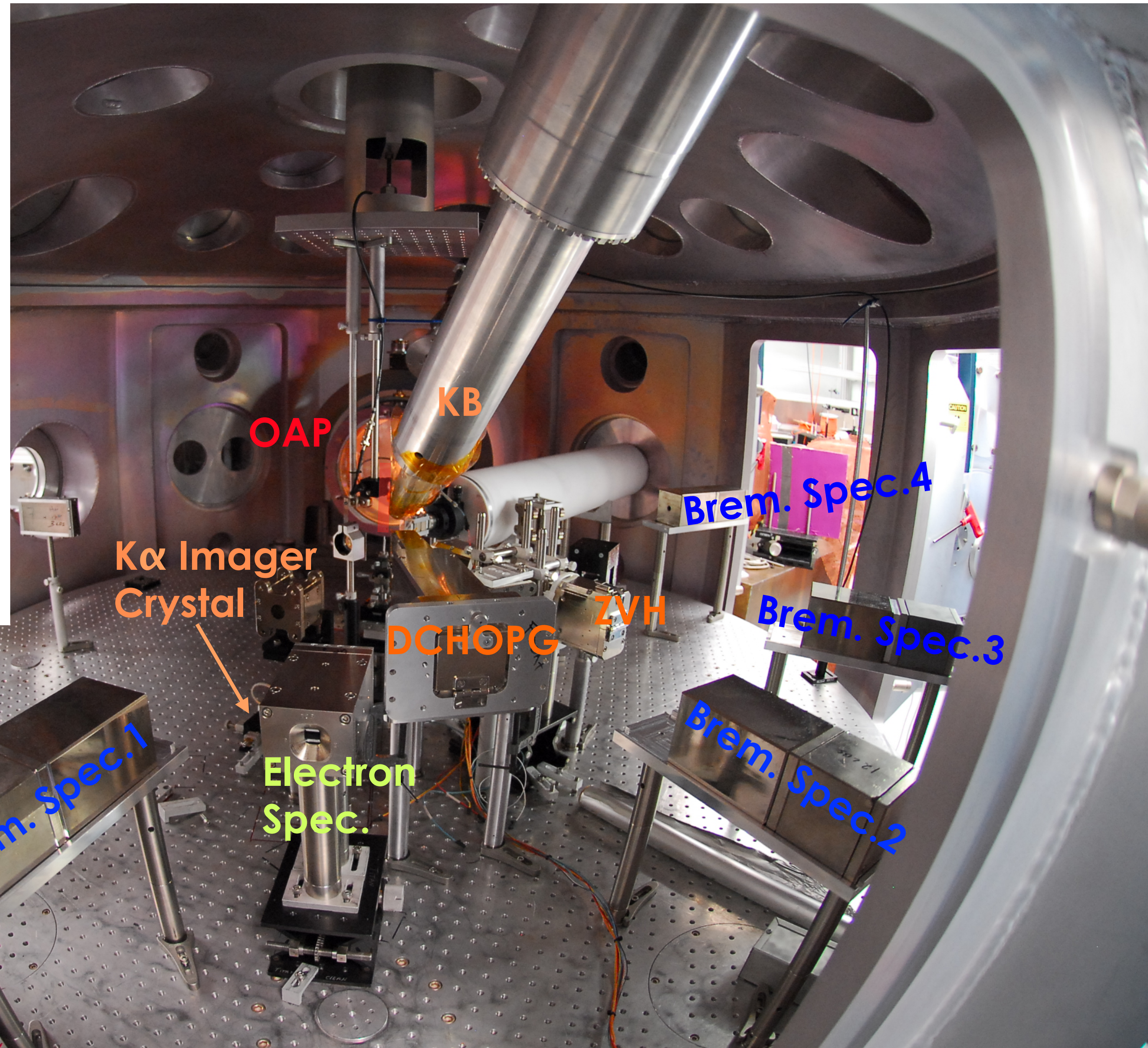


0.7 ps, 150 J, 10 μm spot, I_{peak}~10^{20} W/cm^2
~17 mJ prepulse

- **Common front Al layer ensures identical electron source from relativistic LPI**
- **Z-layer to evaluate target material effect on fast electron transport**
- **Thick and large conductive carbon back layer minimize electron refluxing**

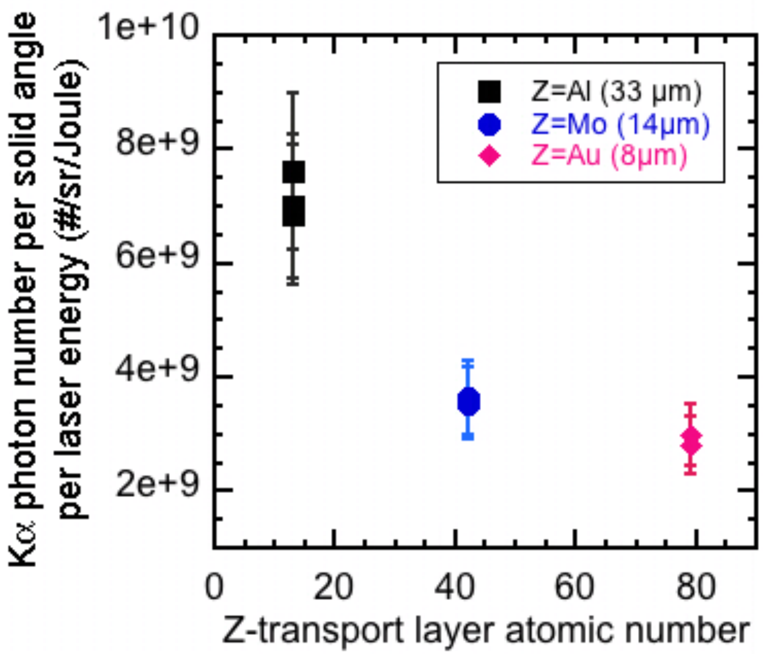
Experimental set up and diagnostics



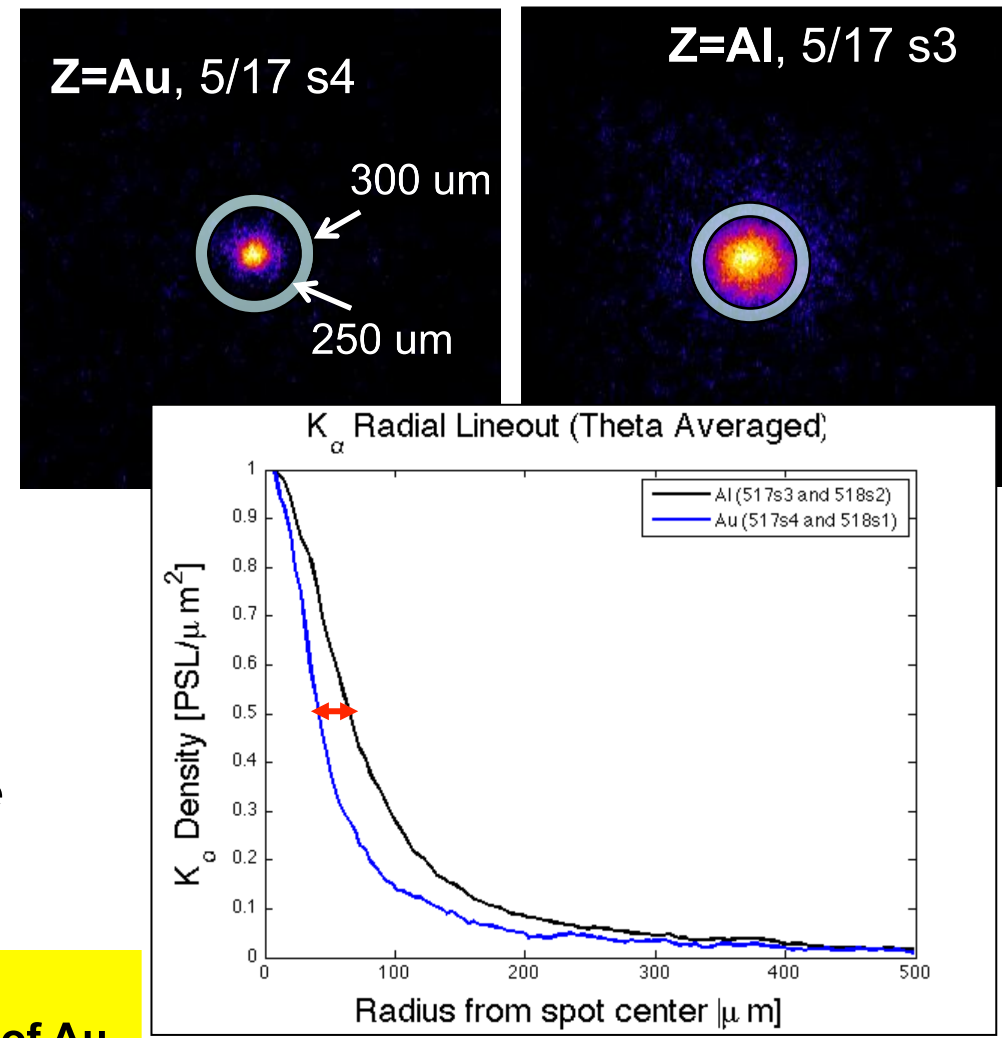


Kα data showed overall reduction in yield and spot size through high- and mid- Z transport materials

Kα yield



Kα images

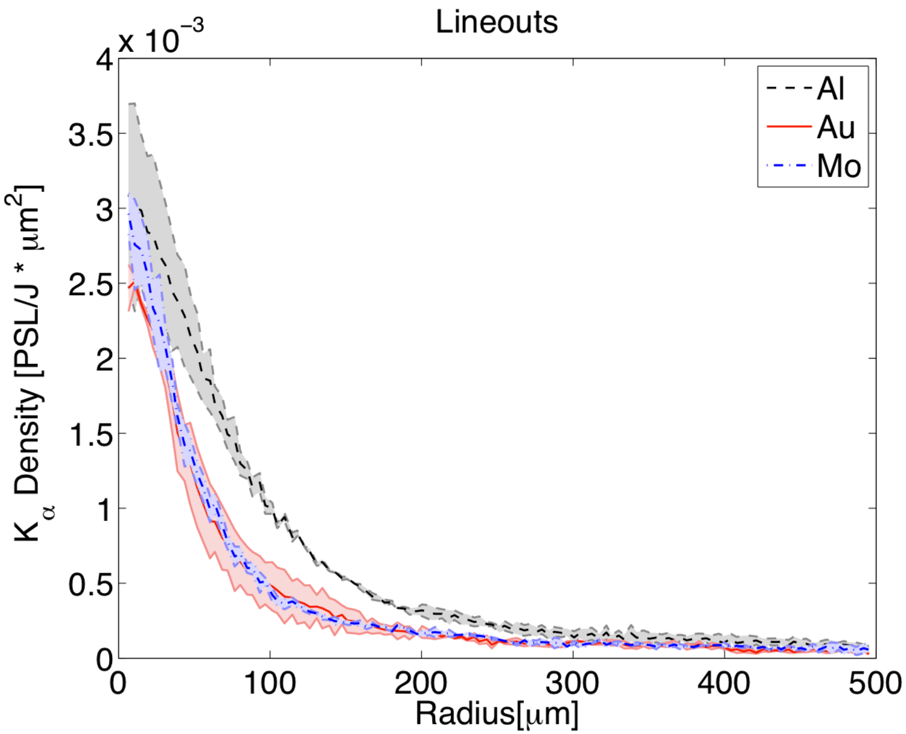


- Au or Mo transport layer reduce
  - overall Kα yield
  - Kα spot size

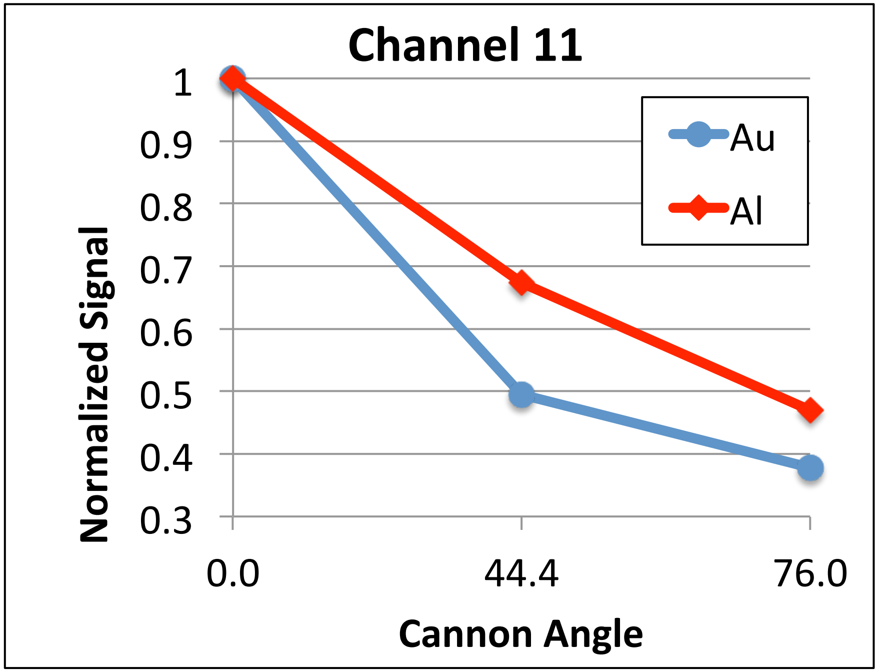
Kα spot size (FWHM) in
Al transport target is ~1.6x that of Au

Collimated electrons in high- and mid- Z transport targets

Radial profile of Kα emission



Bremsstrahlung angular profile



- Within the central 50 µm spot, all targets show similar Kα intensity
- Signal reduction occur mostly in the wings (> 50 µm) in Au and Mo cases
- Bremsstrahlung data also suggested a narrower electron beam in Z=Au target

2D Collisional PIC modeling with PICLS code* to examine the underlying transport physics

*Y. Sentoku and A. Kemp, J. Comp. Phys. **227**, 6846 (2008)
Y. Sentoku, 9th Fusion Science Center meeting, 2010

Laser pulse

I_{peak}=9×10^{19} W/cm^2, p-pol, λ =1 μm
τ = 730 fs (gaussian), spot dia.=10 μm

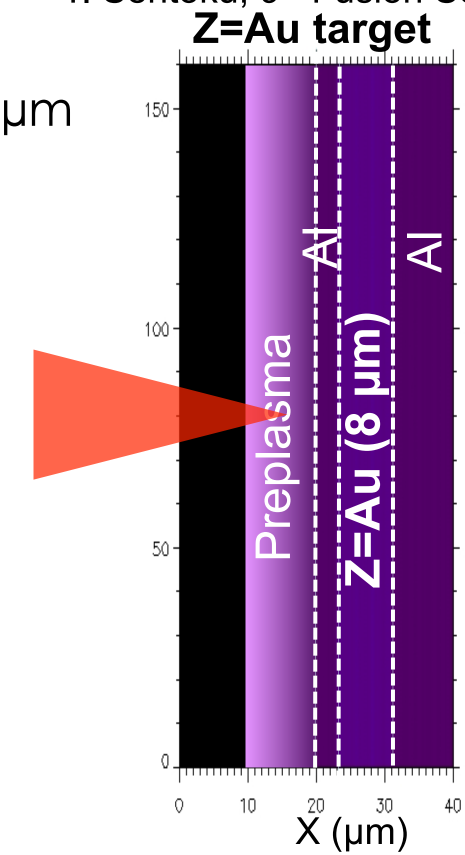
Targets

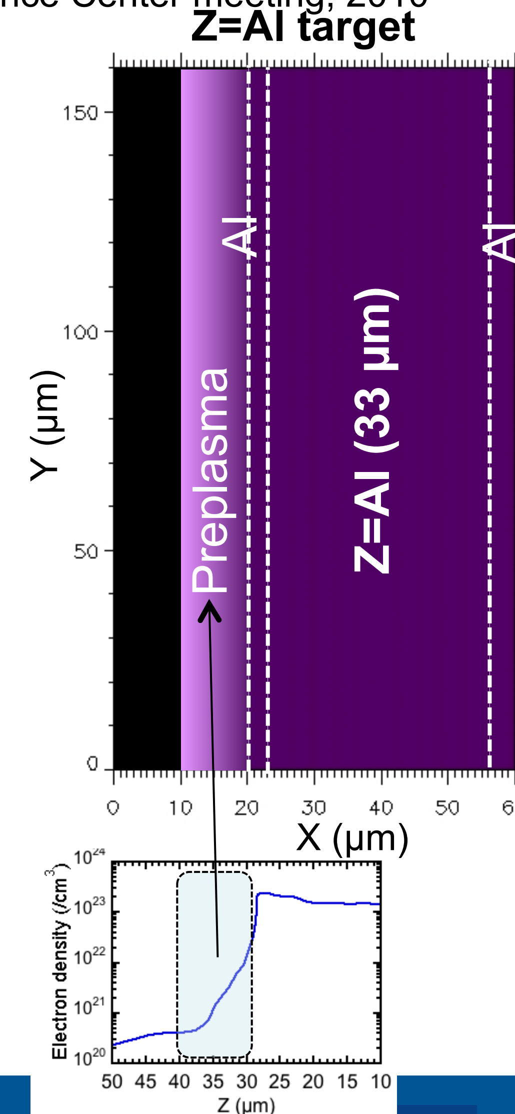
Z=Au transport target: Al/Au/Al
=10 (preplasma)+3/ +8 / +9 μm

Z=Al transport target: Al/Al/Al
=10 (preplasma)+3/ +33 / +4 μm

Simulations size

Target-1: 40 μm×160 μm
Target-2: 60 μm ×160 μm
Run time ~ 730 fs

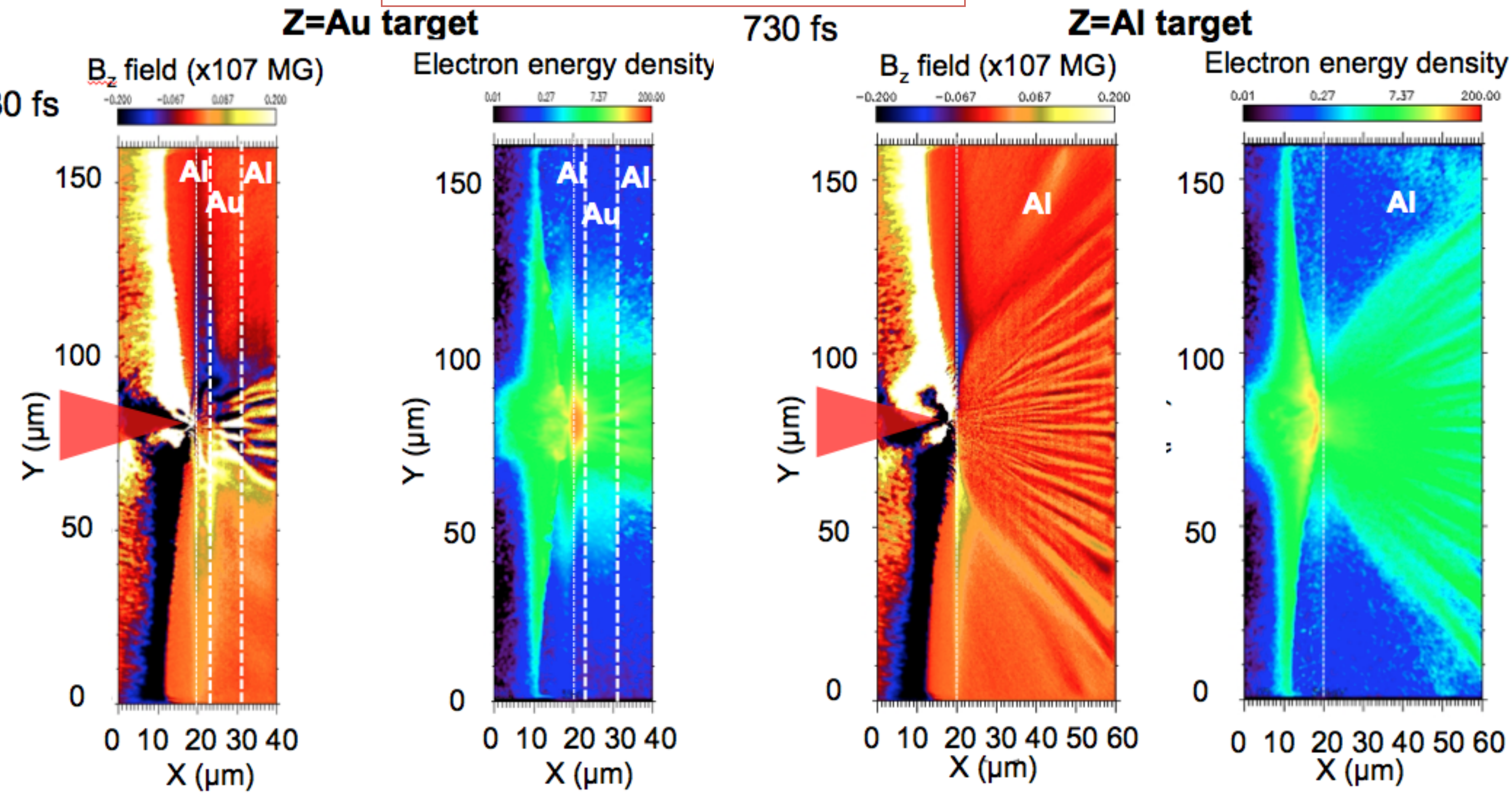




- **Radiation hydro modeled preplasma density profile with experimentally measured prepulse is included**
- **Relativistic binary collisions, impact ionization and radiation cooling are included in PICLS simulations**

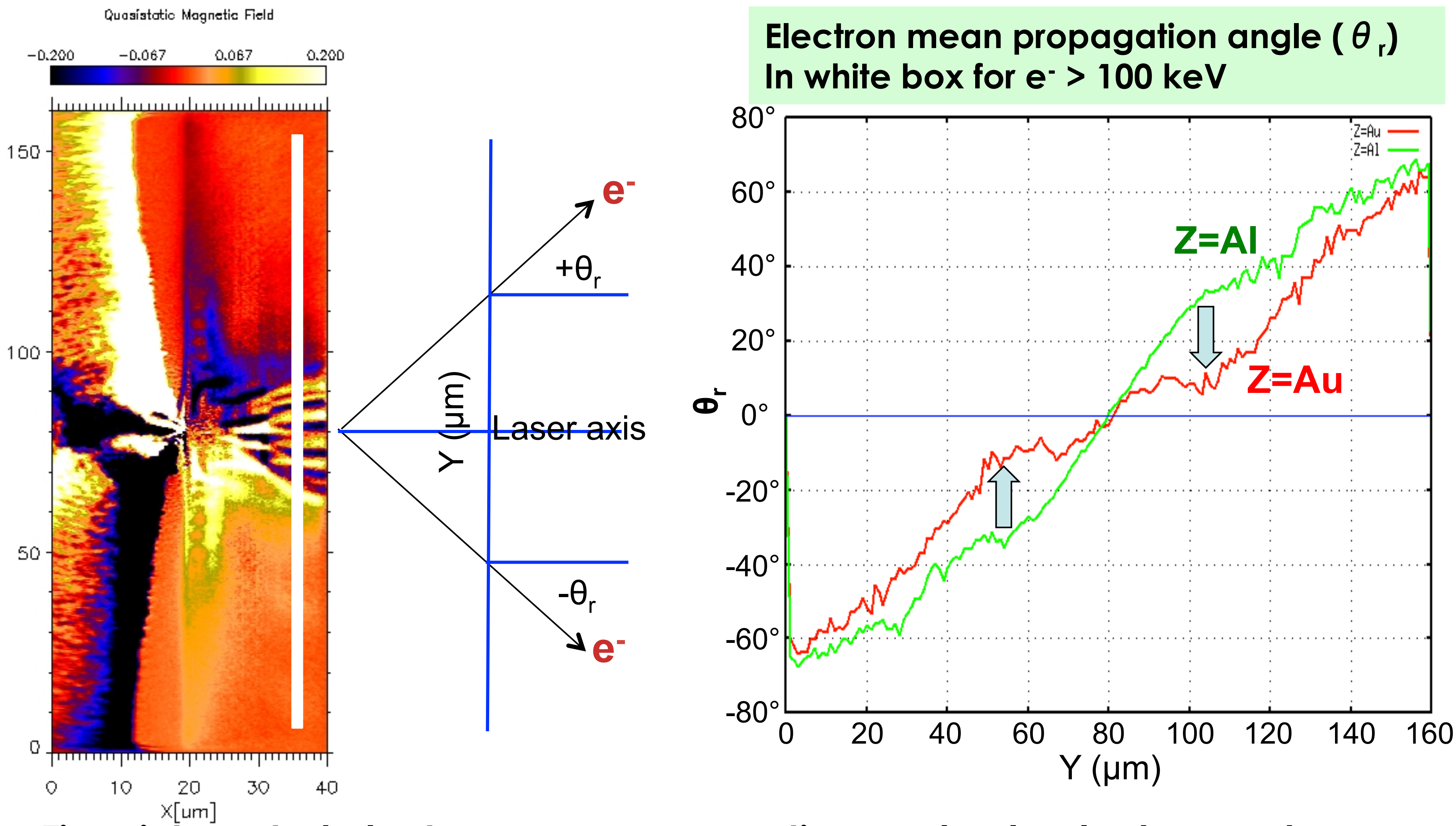
Strong resistive B-fields and magnetic channels in Au transport target

$$dB/dt|_z \sim \eta(dJ_x/dy) + J_x(d\eta/dy)$$



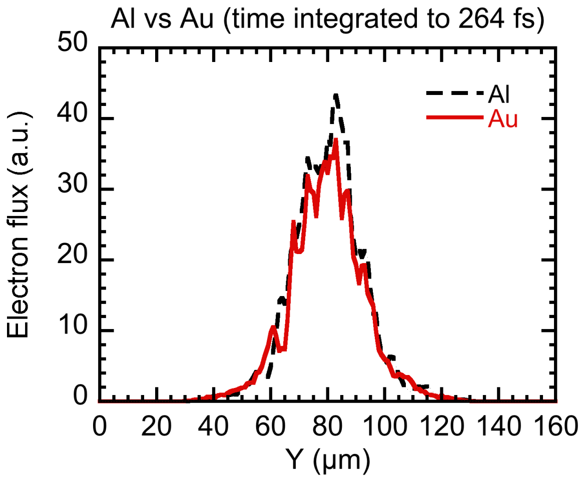
- **Electrons transport is partially collimated and guided by strong resistive fields in AU transport target – in big contrast with diverged beam propagation in Al**

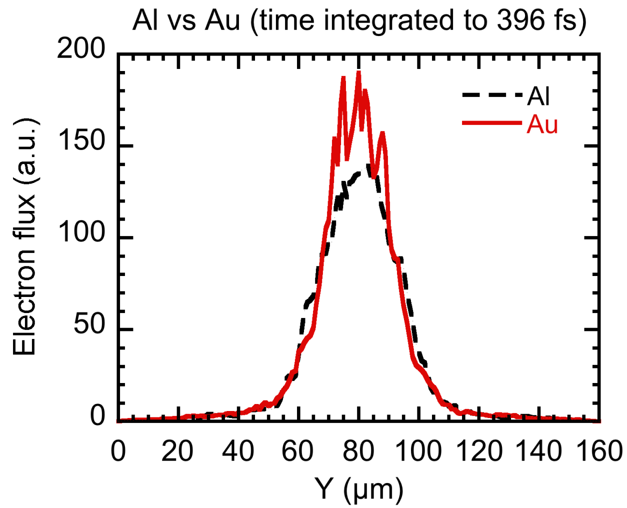
Electron divergence is suppressed by strong B-fields in Z=Au transport targets

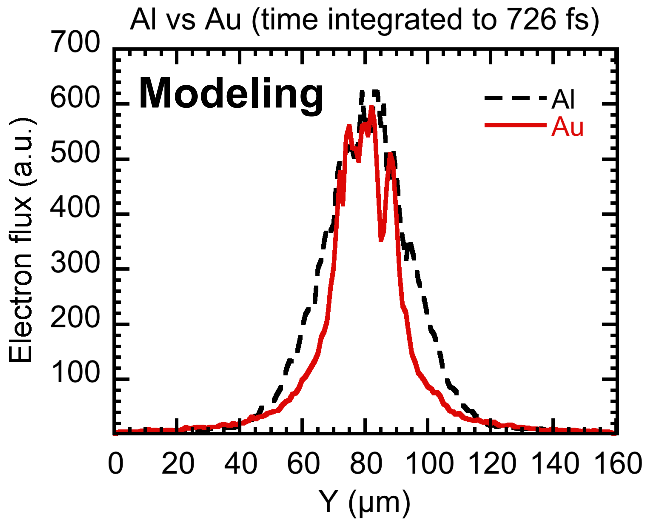


- Time integrated electron mean propagation angle clearly shows e-beam angular spread being suppressed by strongly magnetic fields in Z=Au

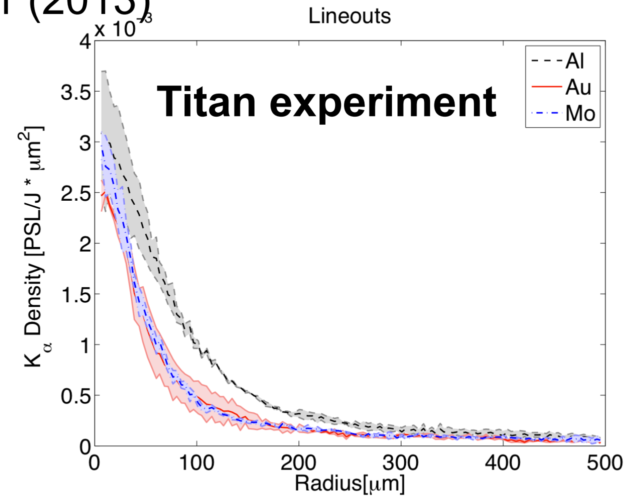
Simulations show guiding of fast electrons in the magnetic channels







S. Chawla, M.S. Wei, R. Mishra et al., *Phys. Rev. Lett* 110, 025001 (2013)

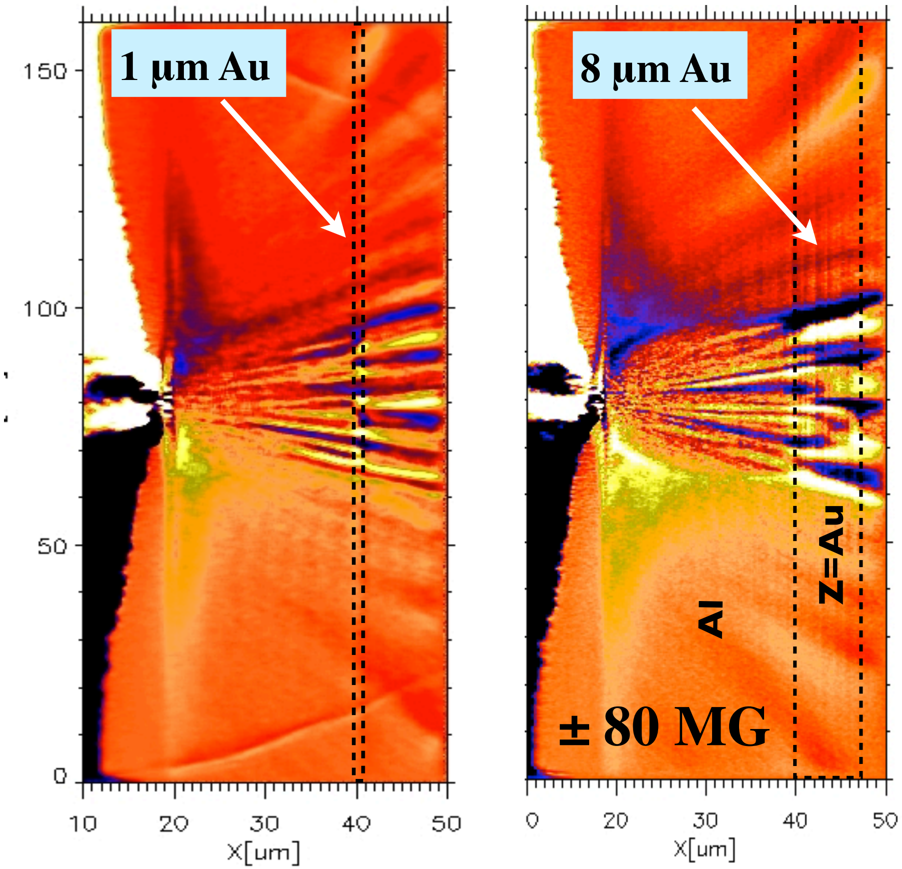


- **Modeling reproduces different electron spatial profiles observed in the experiment**
- **Simulations shows detail dynamics of field effect on fast electron transport**
  - **More stopping in Au at early time**
  - **Guiding of electrons in the magnetic channels and suppressing angular spread by B-fields**
  - **Fast electrons trapping and deflection by strong B-fields**

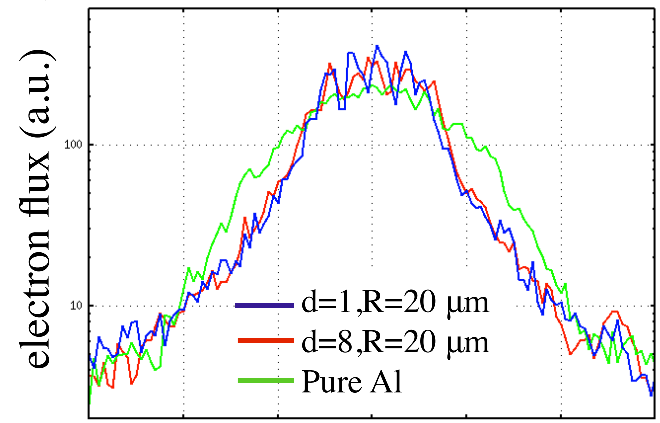
Resistive field and fast electron beam collimation have been predicted to be insensitive to high-Z layer thickness

d = 1 µm R = 20 µm

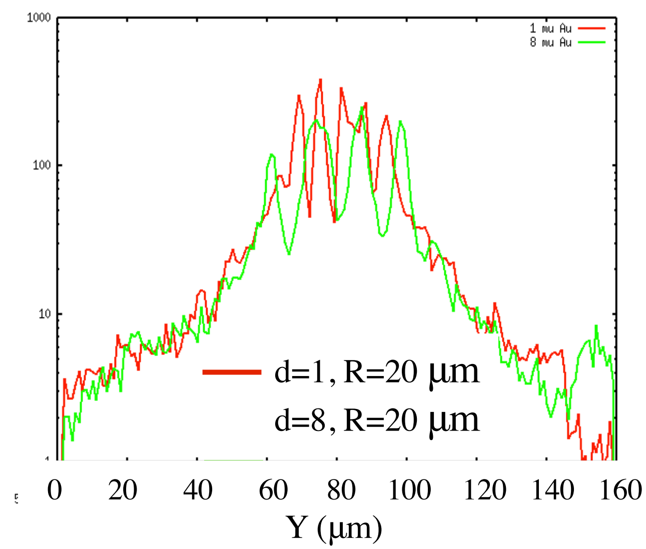
d = 8 µm R = 20 µm



time averaged e- flux before Z layer

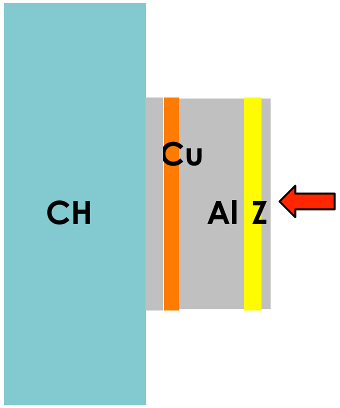


time averaged e- flux after Z layer

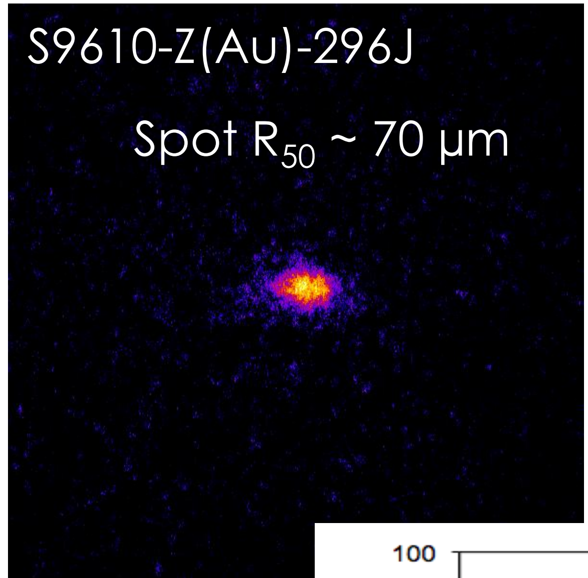


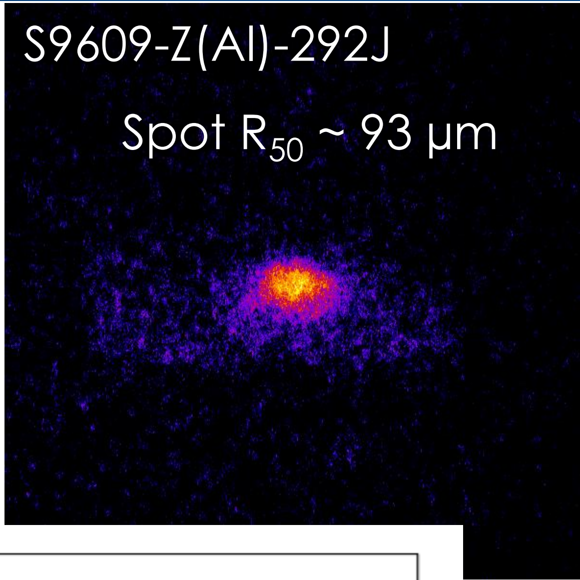
R. Mishra et al., APS DPP (2012)

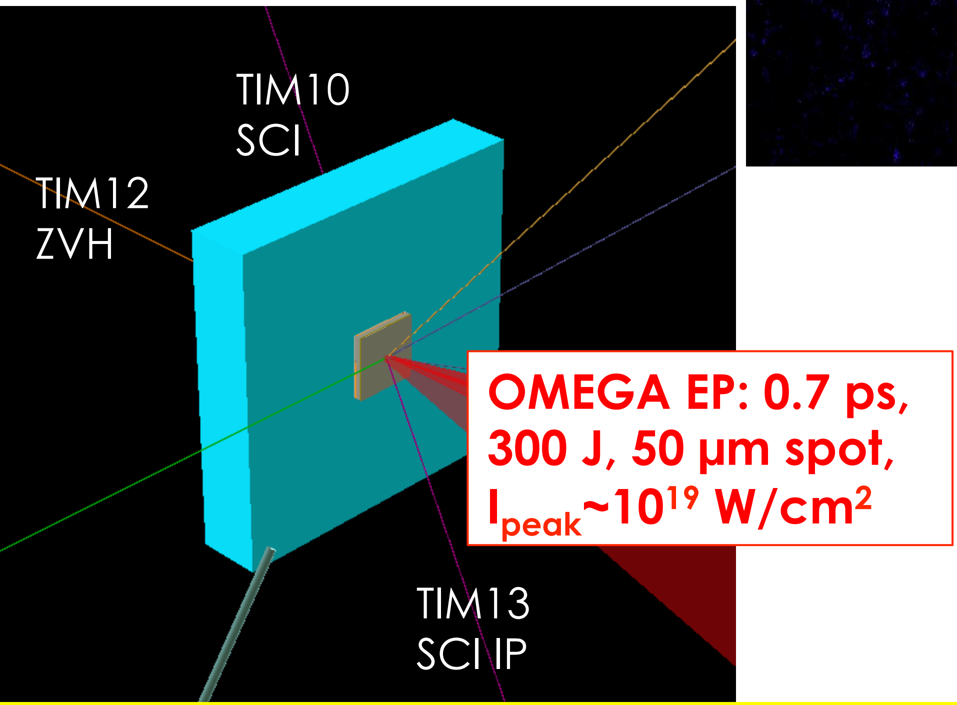
OMEGA EP experiment with sub-ps pulses at 2x high energy showed consistent results with Titan

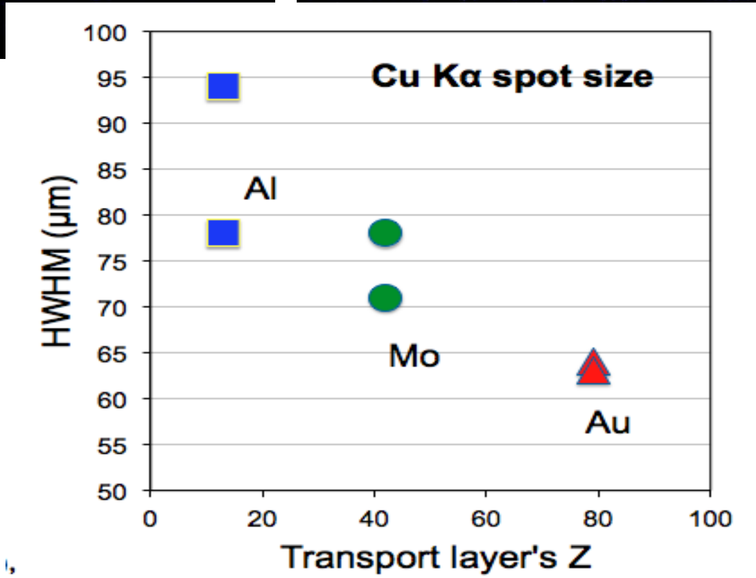


Z-layer	D (μm)
Au	10
Mo	10
Al	25







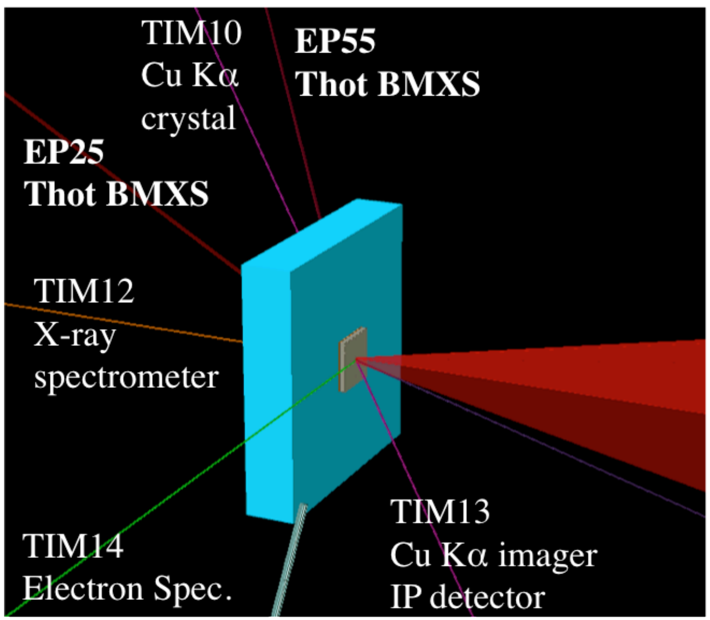


Successful demonstration on Titan led to a NLUF grant and laser beam times on OMEGA EP

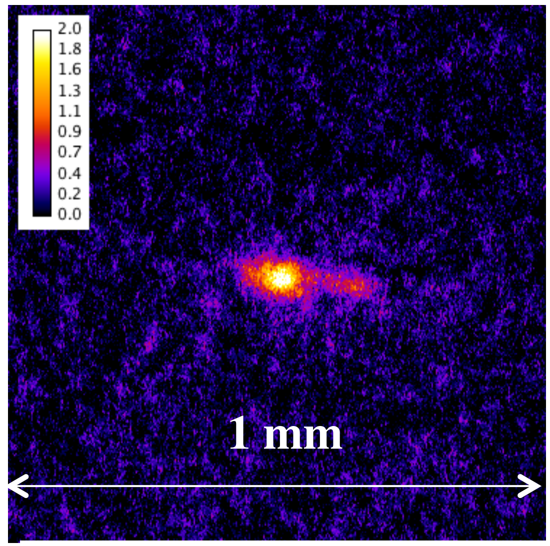
See J. Peebles' Poster, this meeting

We have extended this study to kJ, 10 ps pulses

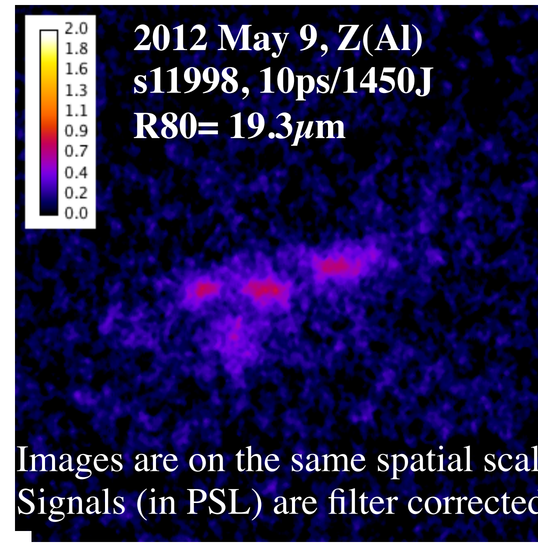
High contrast OMEGA EP
- Spot = R_{80}~ 20 μm
- Intensity ~ $2x10^{19}W/cm^2$
- 10 ps, maximum 1500J
  - Start with ~ 100 mJ prepulse
  - Improved contrast <1mJ

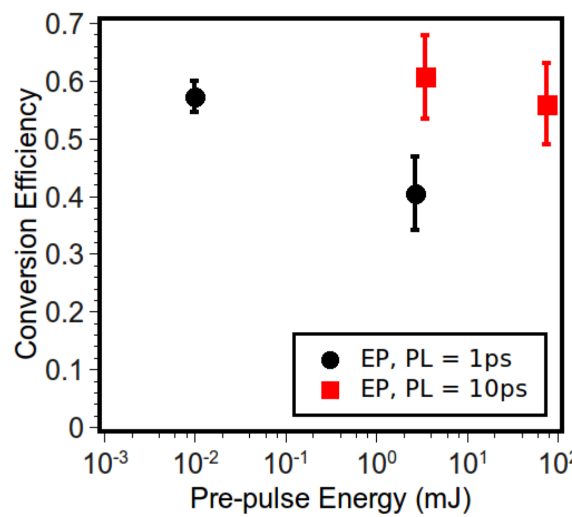


Kα spot with high contrast EP pulses



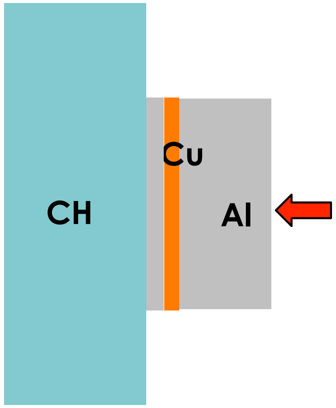
Data from a previous experiment before contrast improvement (~100 mJ)

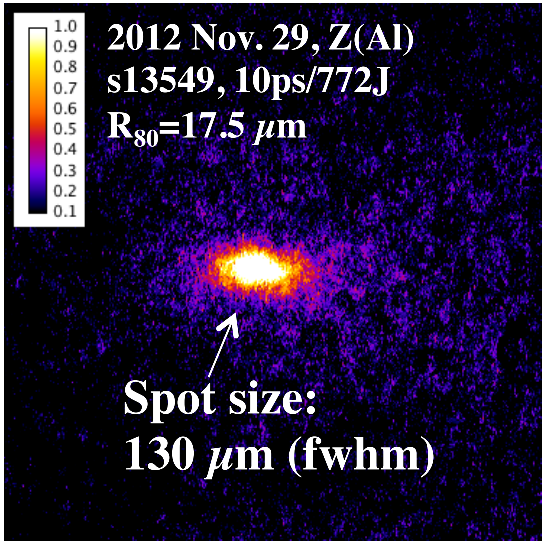


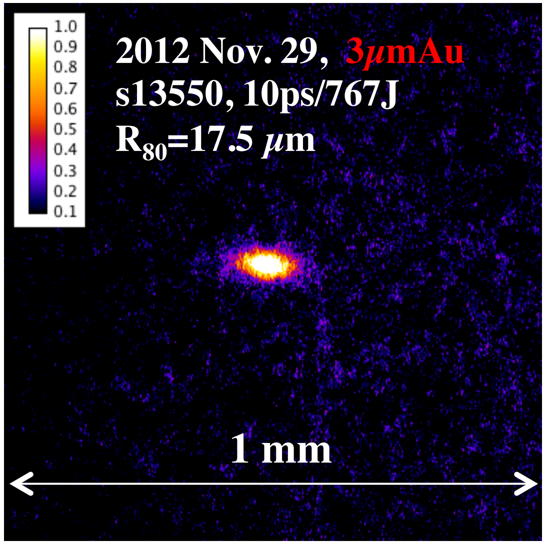


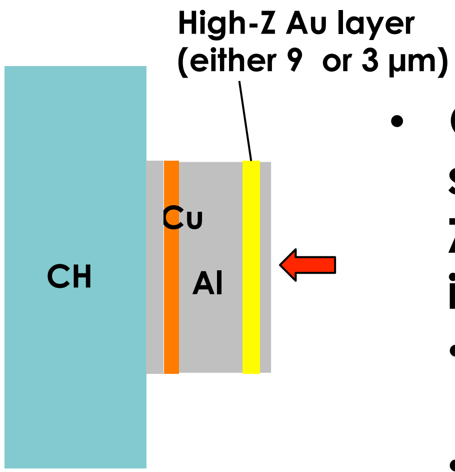
- **Improved energy coupling with the high contrast EP pulses**
- **Facilitate resistive collimation study to 10 ps pulses**

Resistive collimation confirmed using the high contrast kJ EP laser at 10 ps

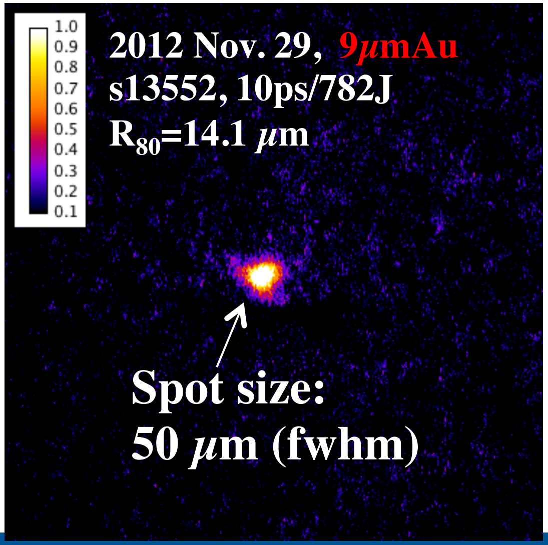








- Observed better collimated single electron beam with Z=Au transport target in 10 ps interactions
  - Consistent with sub-ps Titan results
  - Data confirms the modeling prediction - Insensitive to the Au layer thickness



Data analysis and transport modeling underway

Summary

- We have investigated fast electron transport on transport target material and successfully demonstrated collimation of fast electrons by self-generated resistive B-fields in a simple target geometry
  - First explored and demonstrated on the Titan laser
  - Further investigated on the scaled-up OMEGA EP spanning both energy and temporal parameter space

- Collisional PIC simulations reproduced experiments and revealed resistive fields generation in high-Z Au transport targets that lead to
  - Suppress of electron beam divergence by B-fields → smaller spot
  - Guiding of fast electron transport in magnetic channels → maintaining high flux in the central spot

- This simple collimation scheme can be easily incorporated in cone targets to improve energy coupling to the core in future integrated FI experiments on OMEGA (EP) and NIF (ARC)

Suggestions/wishlist to improve Titan laser operation and facility capability

Improved operation bases on the current infrastructure

- **Bring Titan back to its designed full capacity and operate with improved shot quality and productivity**
  - **Maintain the well-characterized high quality laser beam**
    - Reliability of the laser beam energy
    - Pulse duration and shape
    - Prepulse monitor on every-shot
    - In-suite laser focal spot measurement
  - **Reduce beam downtime and provide sufficient target area support**
    - **Need a dedicated fully staffed team of laser and target area operators**

Wish list for added capability

- **Improve Titan pulse contrast to achieve *high contrast* high intensity**
  - **Facilitate fast electron source and energy coupling study**
  - **Applications such as radiation pressure acceleration for protons/ions**

- **Add a second sub-ps, 100 J level high intensity pulse to Titan**
  - **Particle/x-ray probing of laser/particle plasma interaction**
  - **Explore relativistic HED science with flexible beam configurations**

List of recent publications from Titan experiments

Prof. Farhat Beg's HED group at UCSD

1. **S. Chawla**, M.S. Wei, R. Mishra et al., *Phys. Rev. Lett* **110**, 025001 (2013)
2. **T. Yabuuchi**, R. Mishra, C. McGuffey et a., *New. J. Phys*. **15**, 015020 (2013)
3. **T. Ma**, H. Sawada,, P.K. Patel et al., *Phys. Rev. Lett* **108**, 115004 (2012)
4. **H. Sawada**, D.P. Higginson, A. Link et al., *Phys. Plasmas* **19**, 103108 (2012)
5. **B.S. Paradkar**, M.S. Wei, T. Yabuuchi et al., *Phys. Rev. E* **83**, 046401 (2011)
6. **B. Westover**, C.D. Chen, P.K Patel et al., *Phys. Plasmas* **18**, 063101 (2011)
7. **B. Westover,** A .MacPhee, C. Chen et al., *Phys. Plasmas* **17**, 082703 (2010)
8. **D.P.Higginson**, J.M. McNaney, D.C. Swift et al., *Phys. Plasmas* **18**, 100703 (2011)
9. **D.P. Higginson**, J.M. McNaney, D. C. Swift et al., Phys. Plasmas **17**, 100701 (2010)