Fast electron generation and transport for fast ignition at 527nm

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Experiments at the Titan laser facility LLNL

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University of California San Diego

A Link, GE Kemp, KU Akli, RR Freeman, LD Van Woerkom

Ohio State University

D Hey, Y Ping, C Chen, MH Key, HS McLean, P Patel, T Doeppner

Lawrence Livermore National Laboratory

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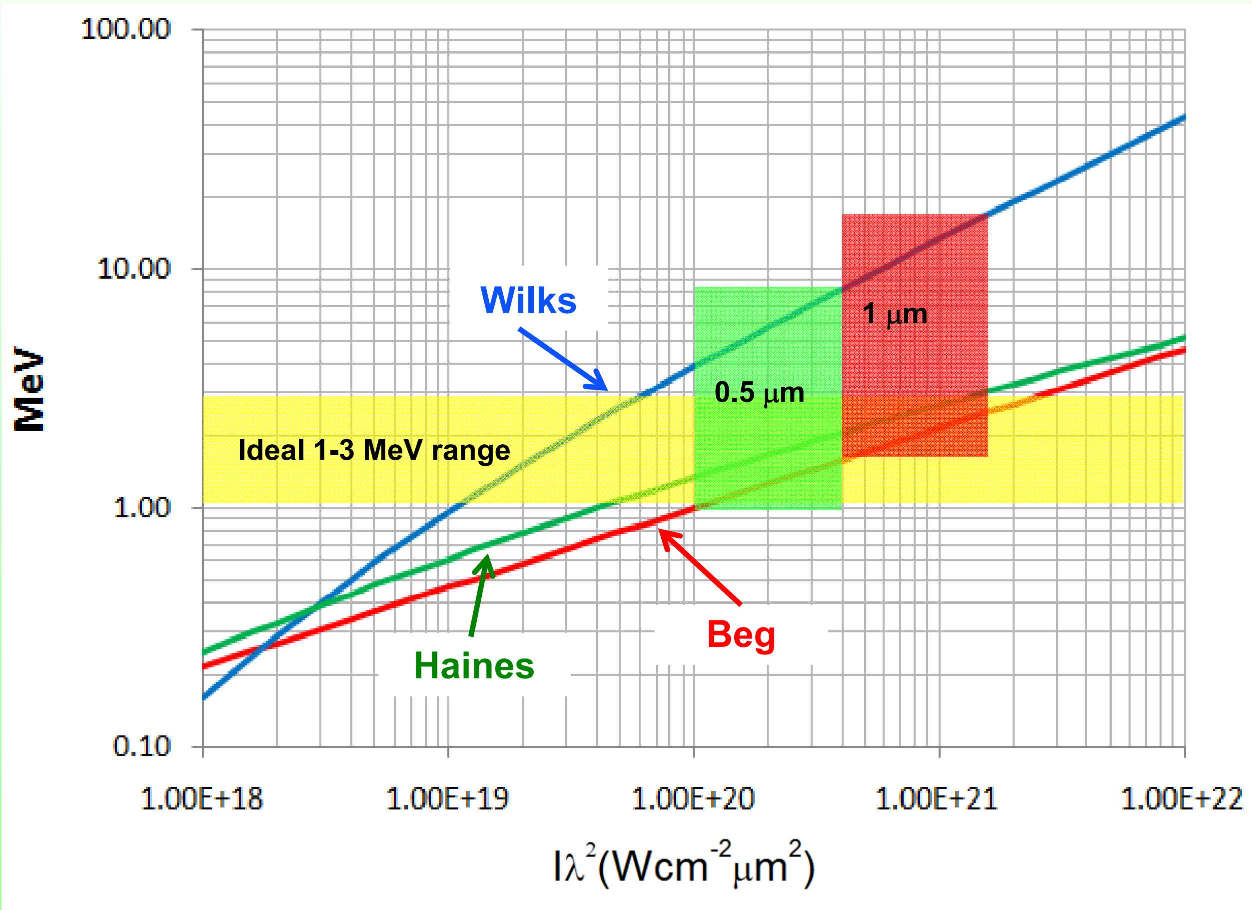
General Atomics

I Bush, J Pasley

University of York

Electron Energy Scaling

Required electron energies ~ 1-3 MeV



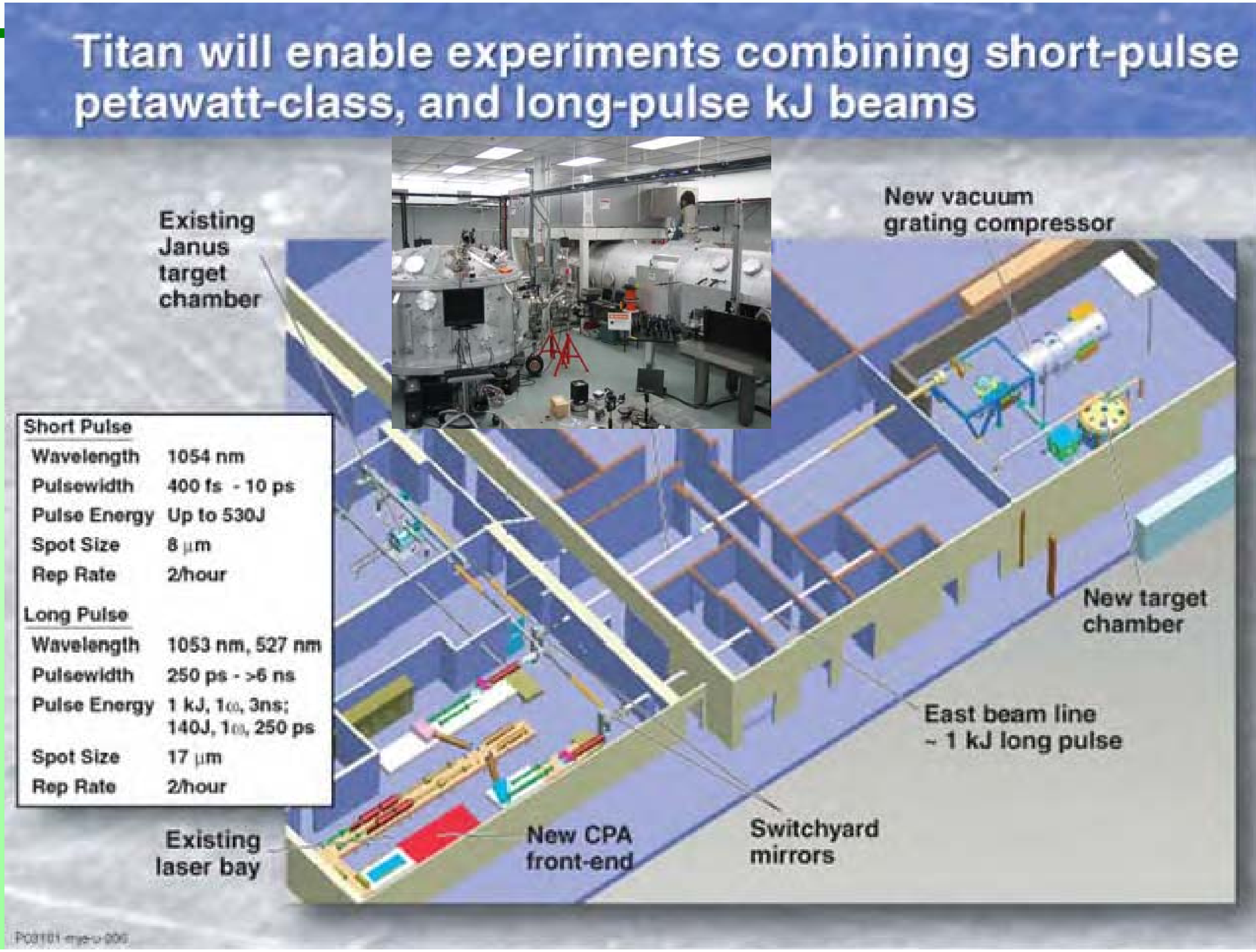
Scaling Laws:

Wilks (Ponderomotive)
PRL 69, 1383 (1992)

Beg (Exp Bremsstrahlung)
Phys.Plasmas 4,447 (1997)

Haines (Energy/Momentum)
PRL 102, 045008 (2009)

Titan Laser Facility



Short Pulse	
Wavelength	1054 nm
Pulsewidth	400 fs - 10 ps
Pulse Energy	Up to 530J
Spot Size	8 μm
Rep Rate	2/hour
Long Pulse	
Wavelength	1053 nm, 527 nm
Pulsewidth	250 ps - >6 ns
Pulse Energy	1 kJ, 1ω, 3ns; 140J, 1ω, 250 ps
Spot Size	17 μm
Rep Rate	2/hour

Titan 2ω Experiment Objectives

Determine scaling at 2ω for hot electron generation

Measure

- T_{hot}
- Electron generation efficiency
- Divergence
- Specular Beam reflection and chirp

Geometries

- Flat Foils with Cu tracer layer
- Buried Cones with Cu tracer layer
- Cone wire

Diagnostics

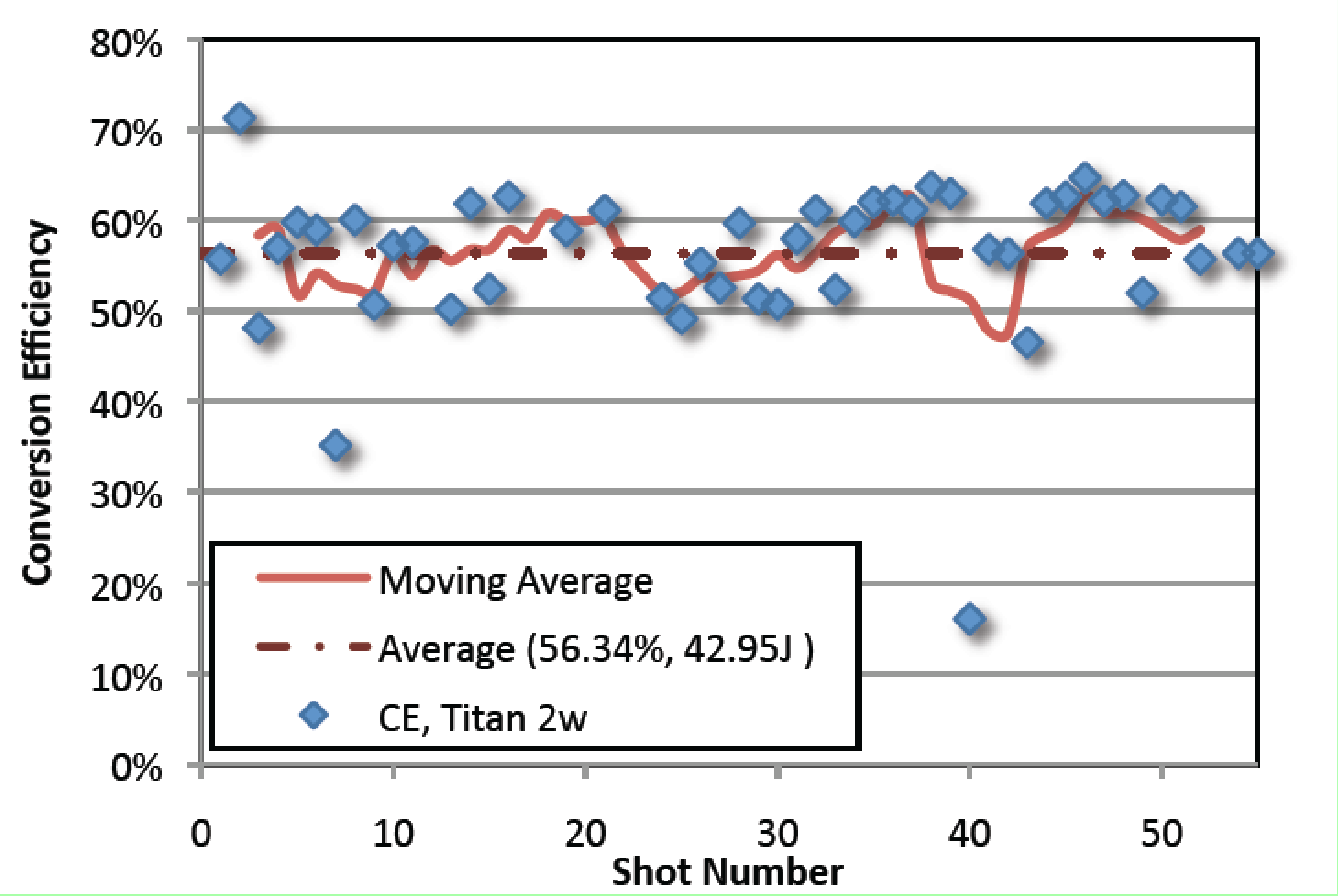
- HOPG CU K_{α} x-ray spectrometers
- Electron spectrometers
- X-ray Bremsstrahlung versus angle
- Cu K_{α} imaging crystals
- KB x-ray microscope
- Specular Reflection and FROG

2ω Titan Run Parameters

50 J
700 fs
0.527 μm
5×10^{19} W cm^{-2}
Prepulse < 10μJ or 3mJ injected

Planar Foil Targets
Buried Cone targets
Cone foil Targets
Cone Wire Targets

Conversion Efficiency

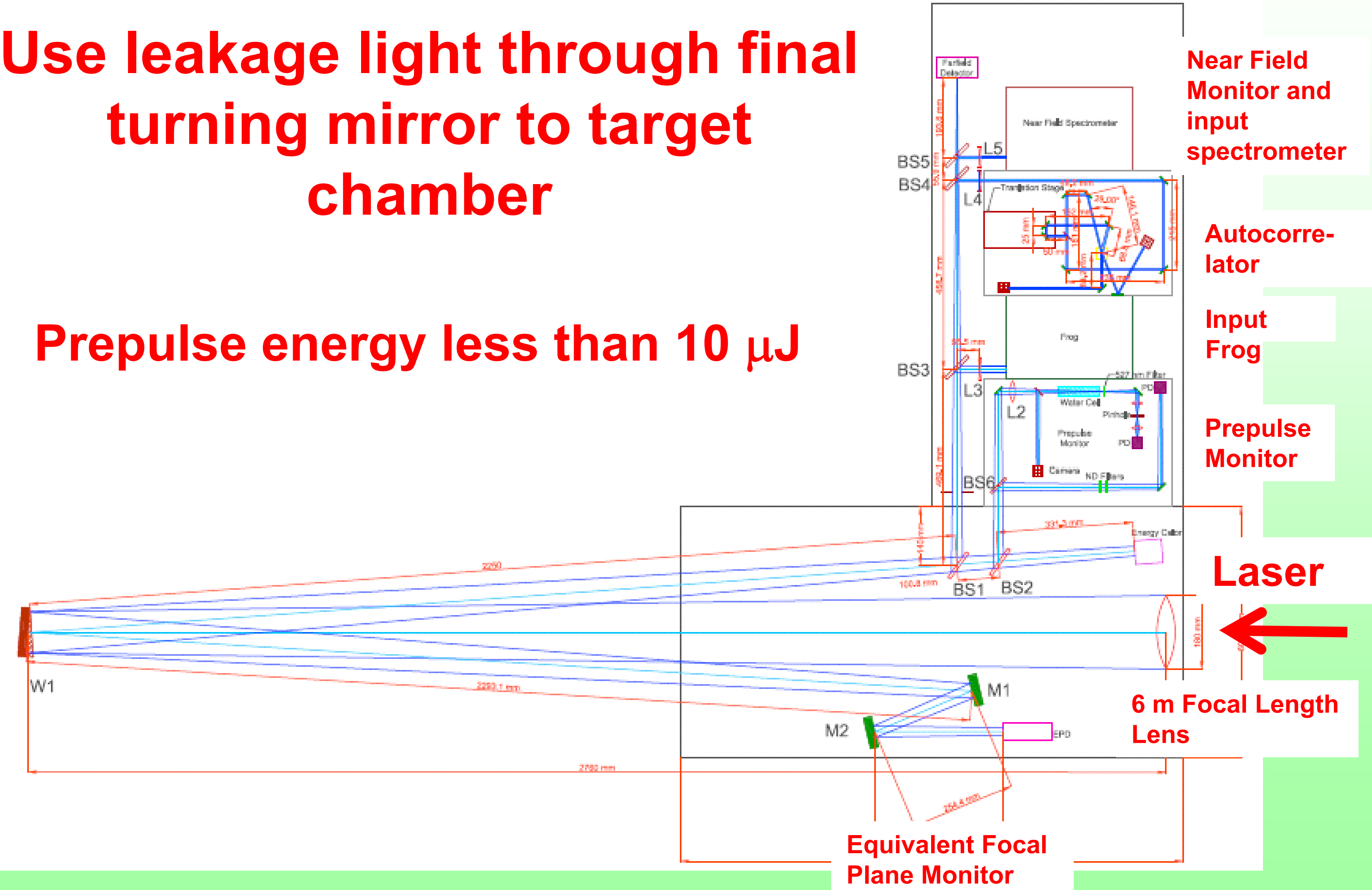


Peak Conversion efficiencies of over 60% obtained - 2mm KDP crystal

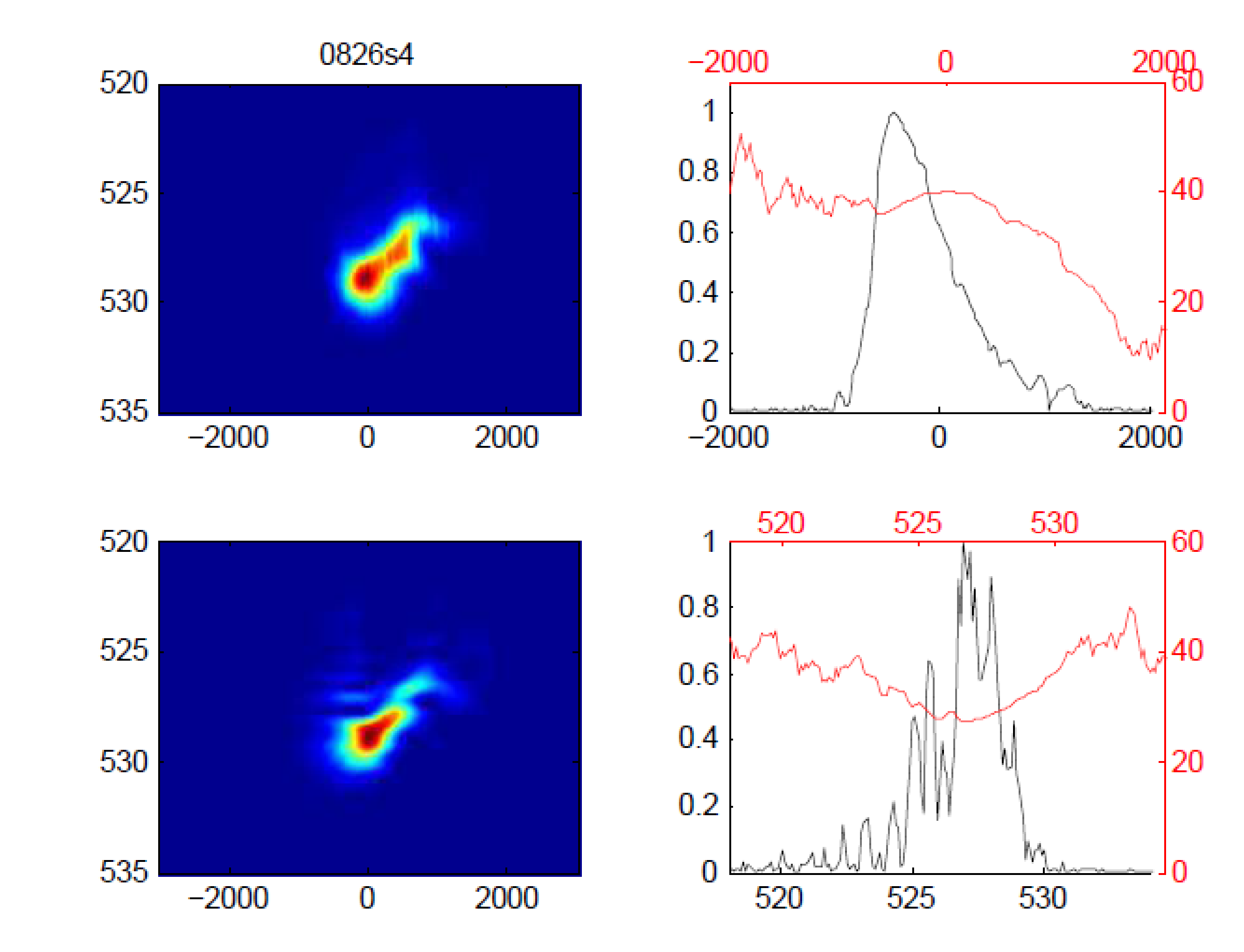
Laser Diagnostic Layout - 2ω

Use leakage light through final turning mirror to target chamber

Prepulse energy less than 10 μJ



Input FROG Signals



Duration and Phase

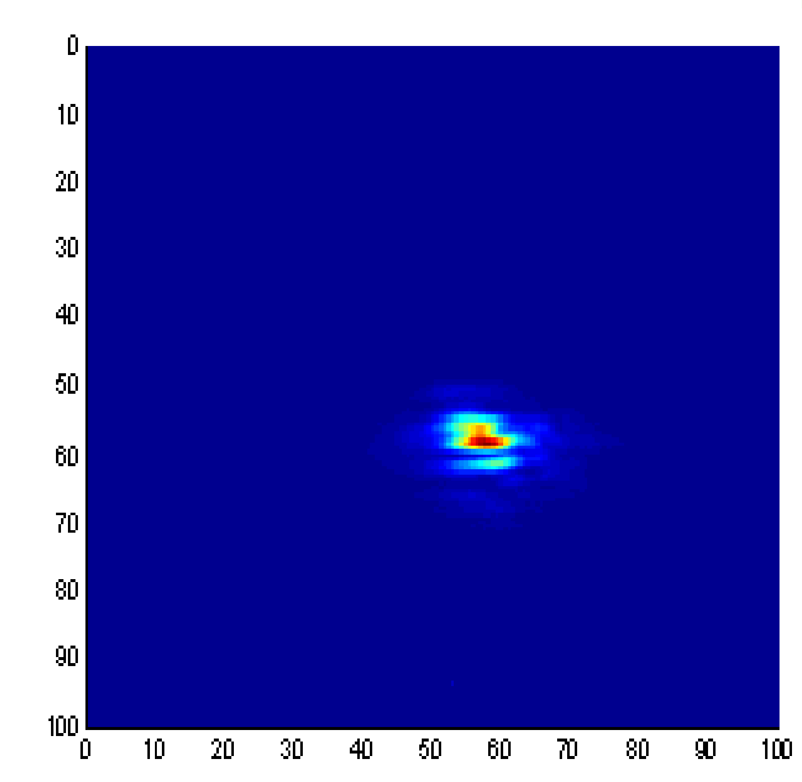
710 fs FWHM

Spectrum and Phase

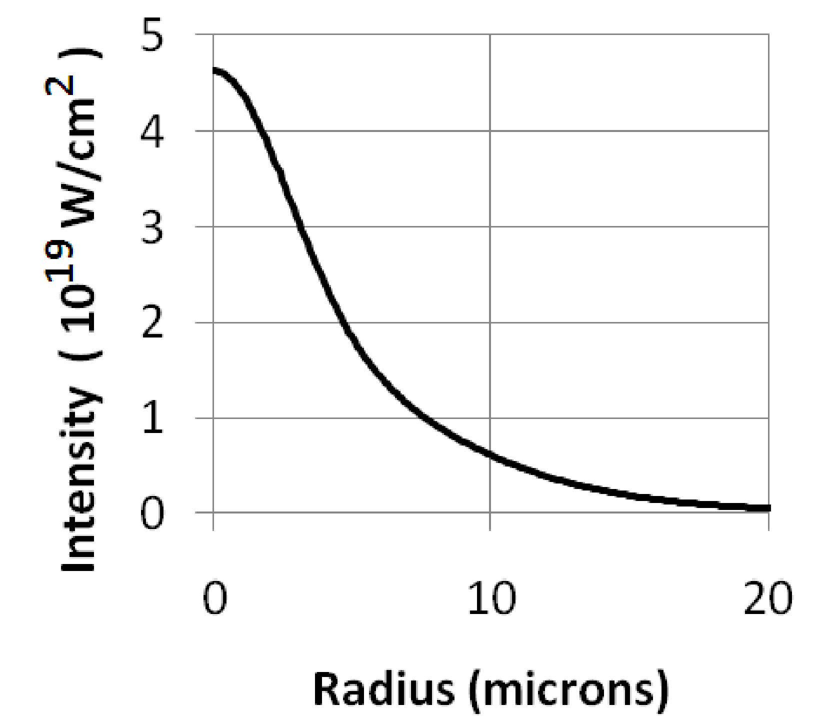
710 fs pulse duration with slight chirp

Typical Low Energy Focal Spot on Target

Low Intensity Focal Spot at TCC



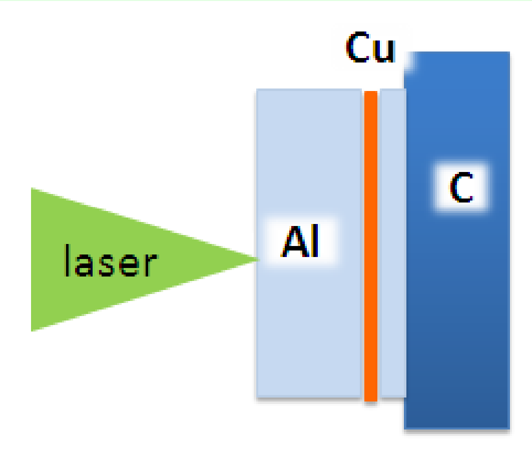
Estimated Radially Symmetric Target Intensity Distribution for 50J 700 fs



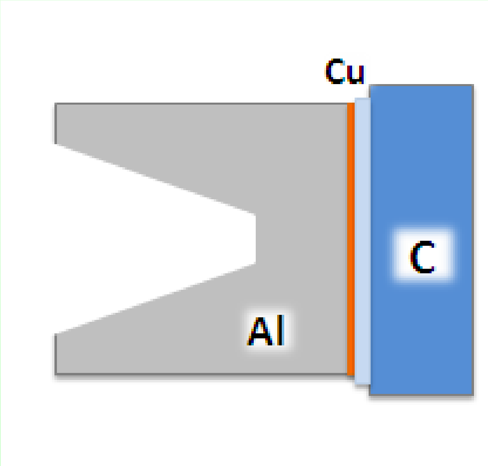
Equivalent FWHM Spot Diameter = 8 μm

Targets used

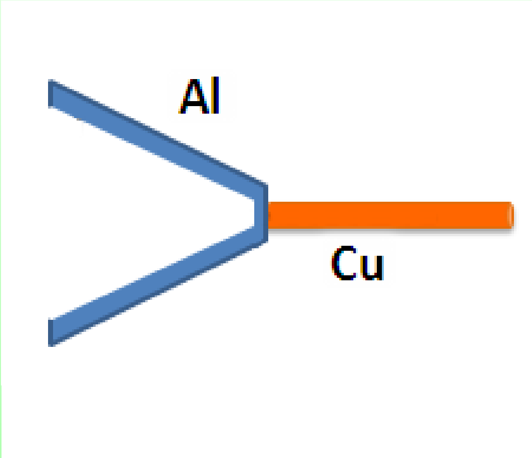
Planar with buried Cu tracer layer



Solid Al cone with buried Cu tracer layer

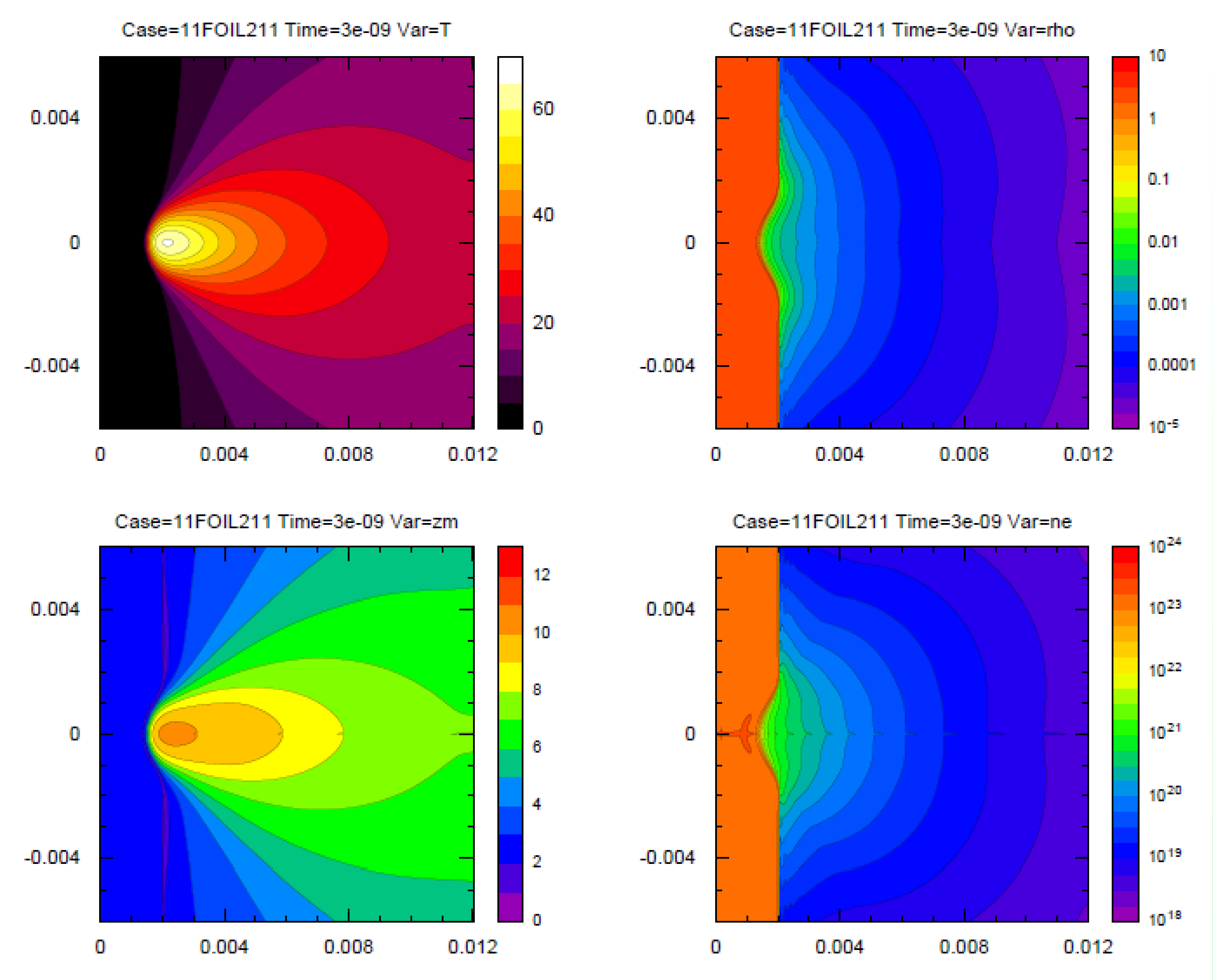


Thin Al cone Cu wire

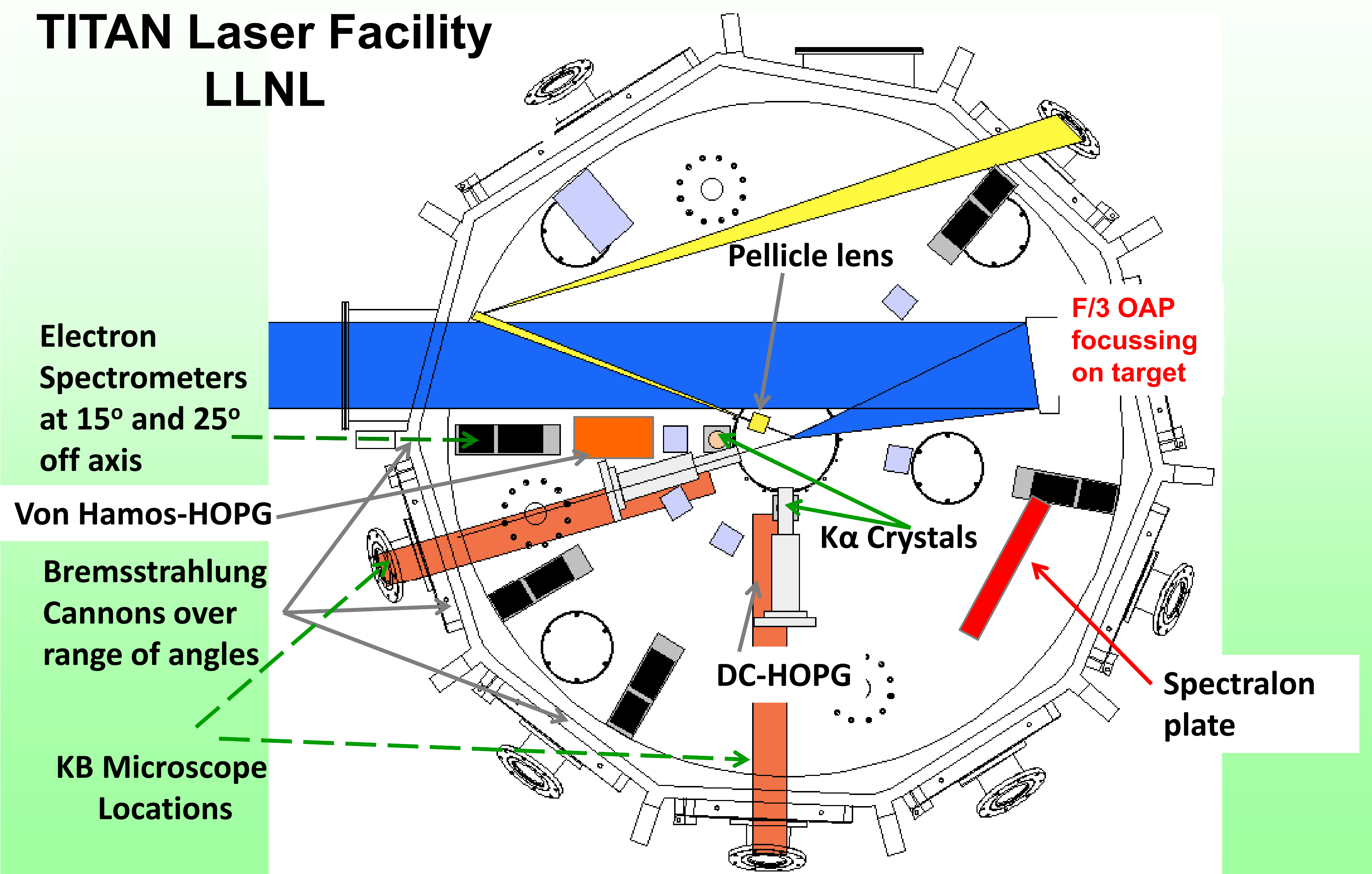


Shots taken with no prepulse (<10 μJ) or with injected 3mJ 3ns 2ω prepulse

2D MULTI Calculations of 3mJ Prepulse Plasma - Rafael Ramis

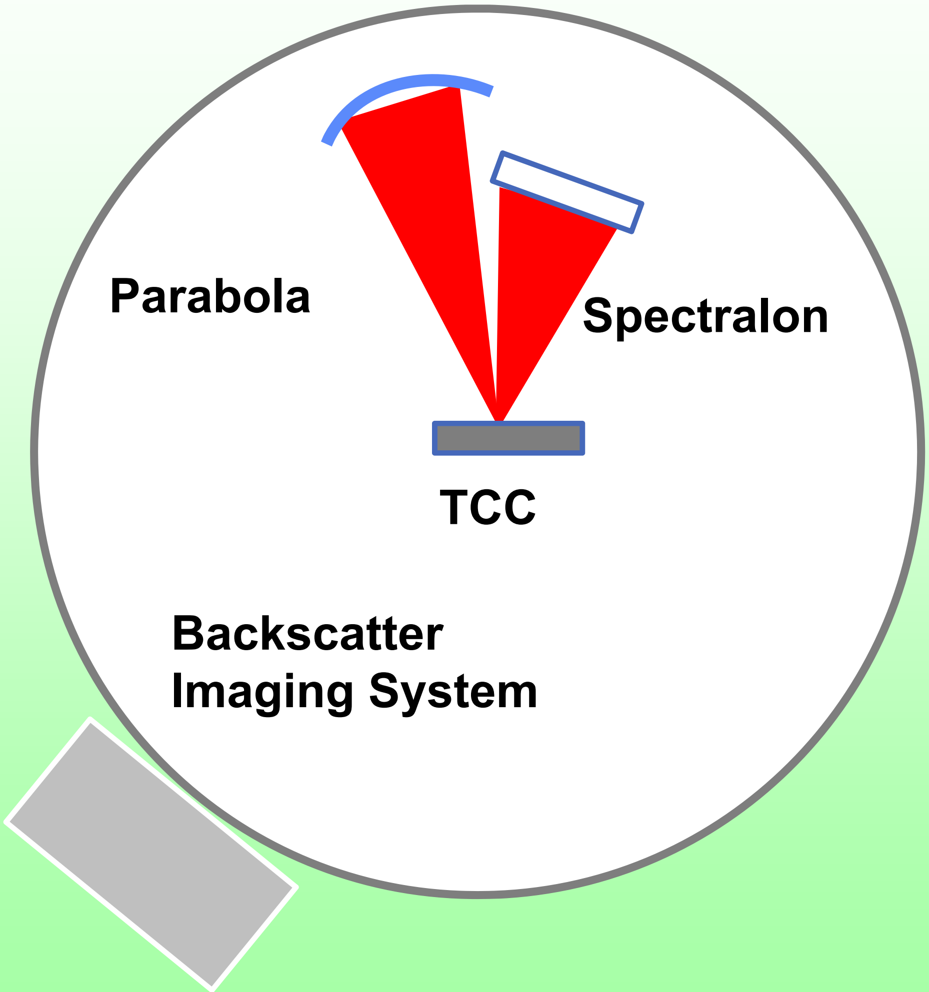


Experimental Diagnostic Layout



Spectralon Reflectivity Mesurement Setup

THE OHIO STATE UNIVERSITY DEPARTMENT OF PHYSICS

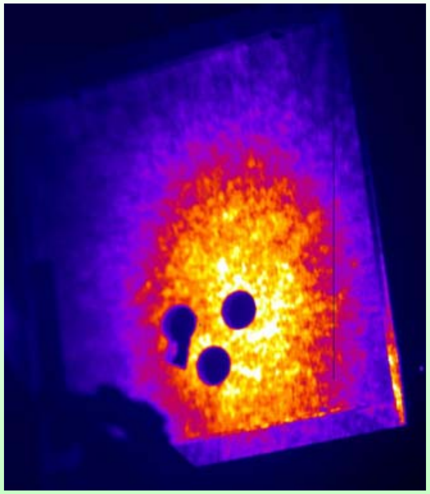


Imaging System
- On Door H
- Looking through Port H1

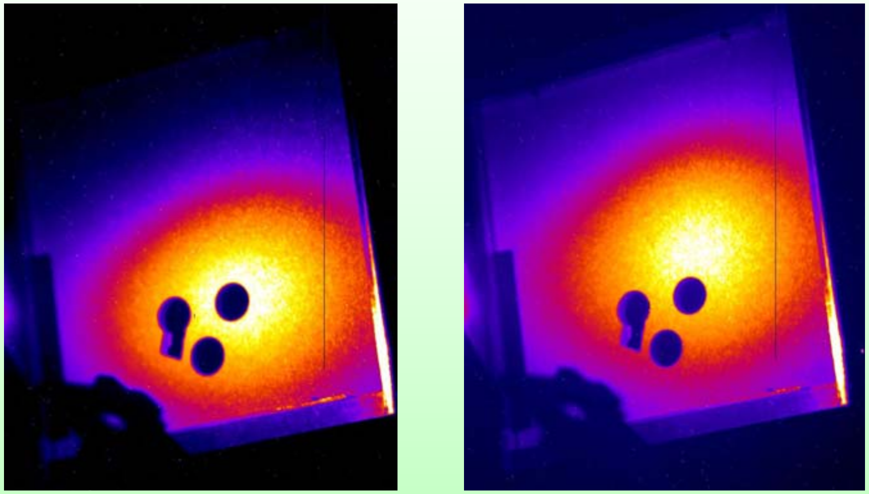
Spectralon
- 10” x 10” spectralon
- In front of Door E
- Holes aligned to allow FROG through port E2
- F/1.5 beam collection

Specular Reflectivity Images
Titan 2w run

No prepulse



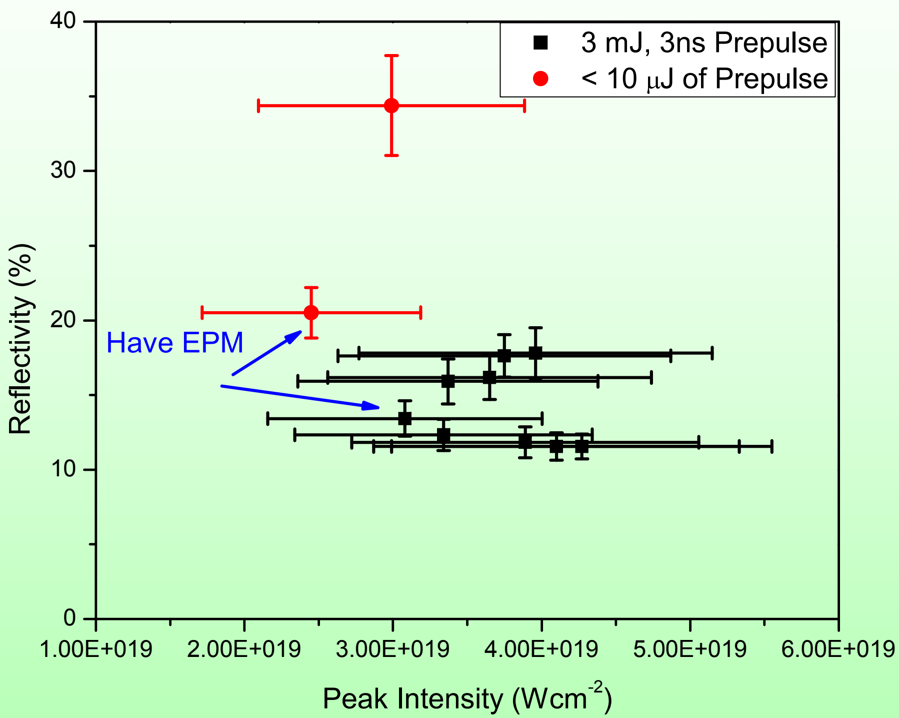
3mJ prepulse



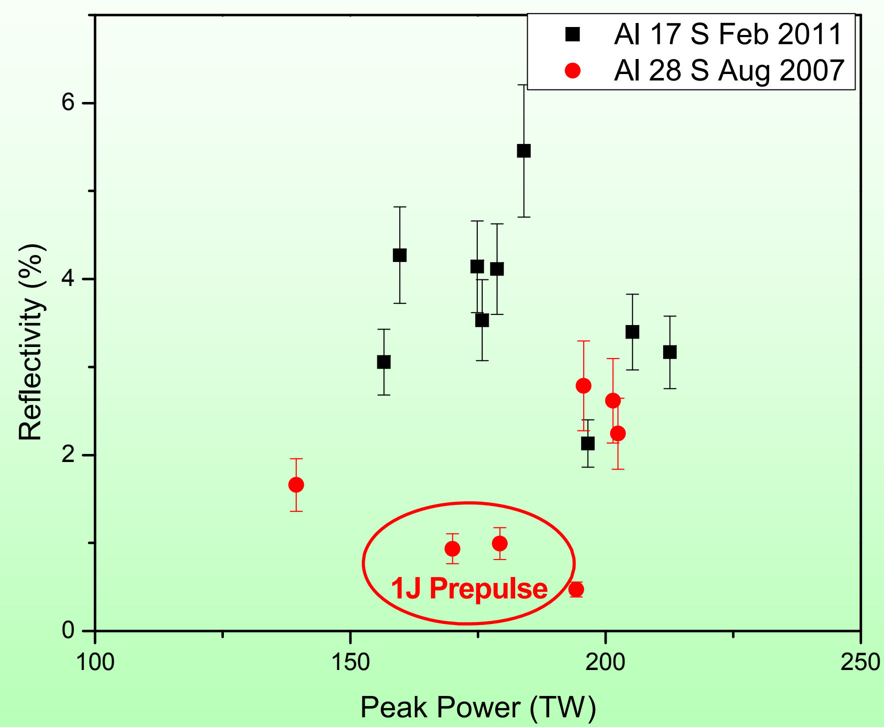
- **Speckle pattern seen from no prepulse shots – speckle from surface roughness**
- **Smooth pattern seen for shots with prepulse – smoothing from preplasma**

Preliminary Reflectivity Data 1ω vs 2ω

Intensities either Good EPM or Extrapolated from Good EPM



2ω Data



1ω Data

2ω Reflectivty

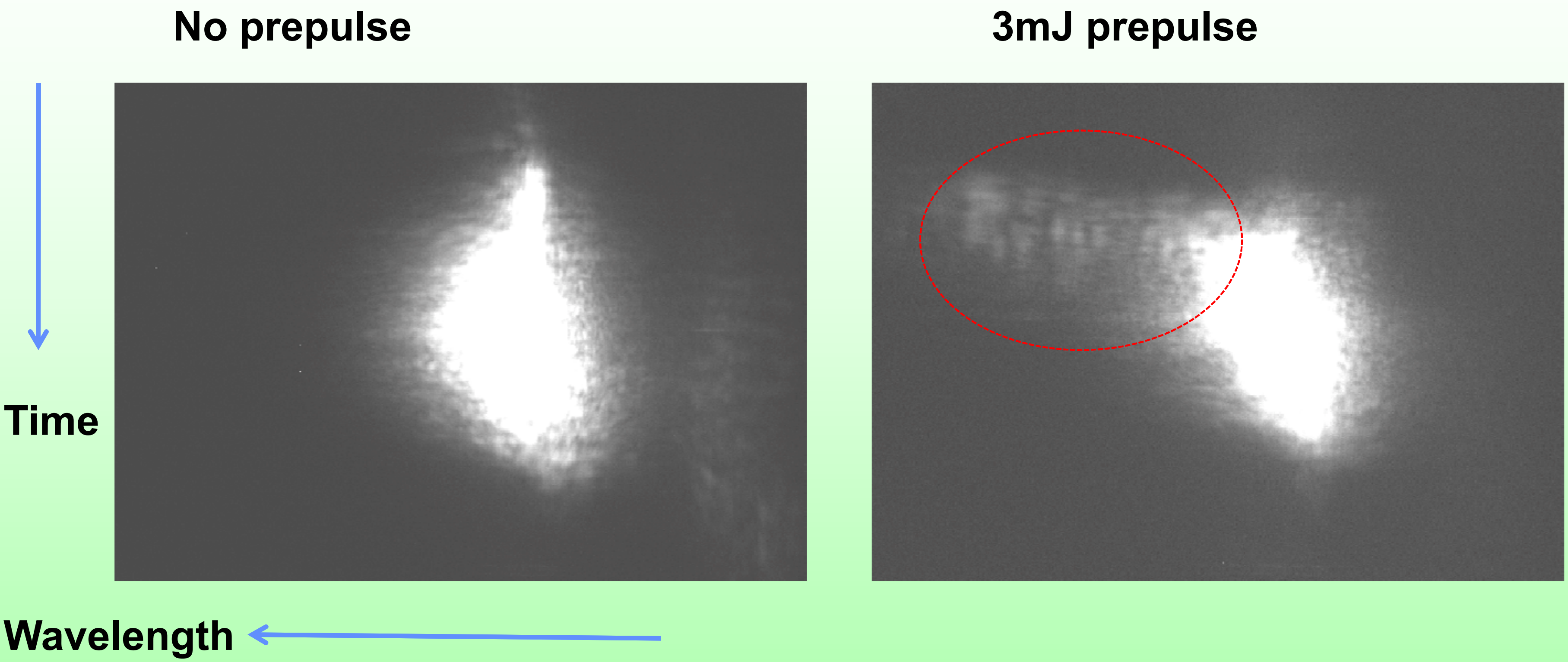
R_{npp} ~ 27%

R_{wpp} ~ 14%

1ω with intrinsic pp

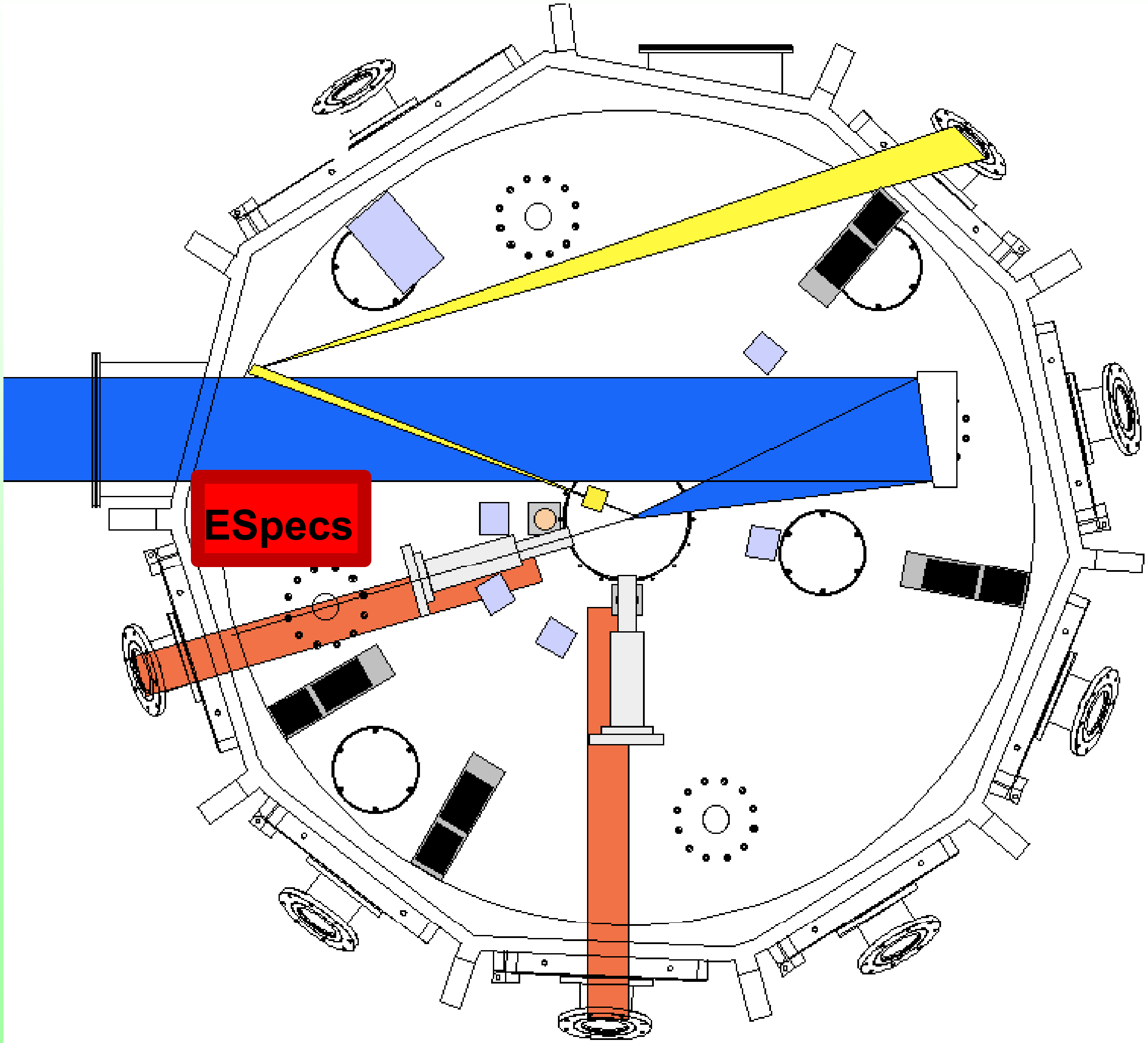
$R_{1\omega}$ ~ 4%

Specular FROG data shows prepulse effect



- Large red shift at the beginning: due to pushing in of preplasma
- Very reproducible

Magnetic Electron Spectrometer Measurements of Escaping Electron Distribution Functions

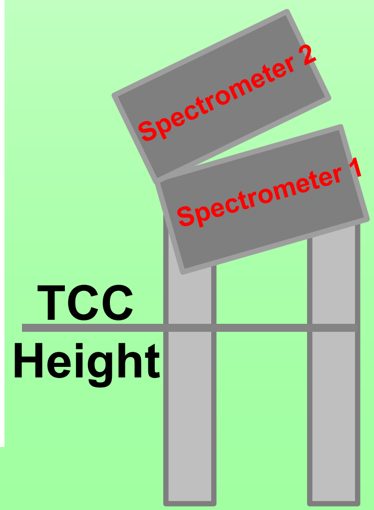


Especs
Located Above Cannon 1

Horizontal Angles
- 0 wrt Target Normal
- 16° wrt to Laser Axis

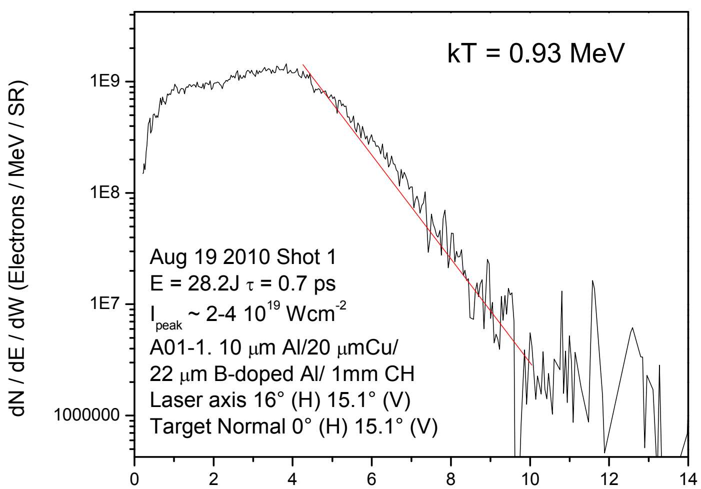
Vertical Angles
- 15° out of the plane
- 25° out of the plane
- plane, looking down to TCC

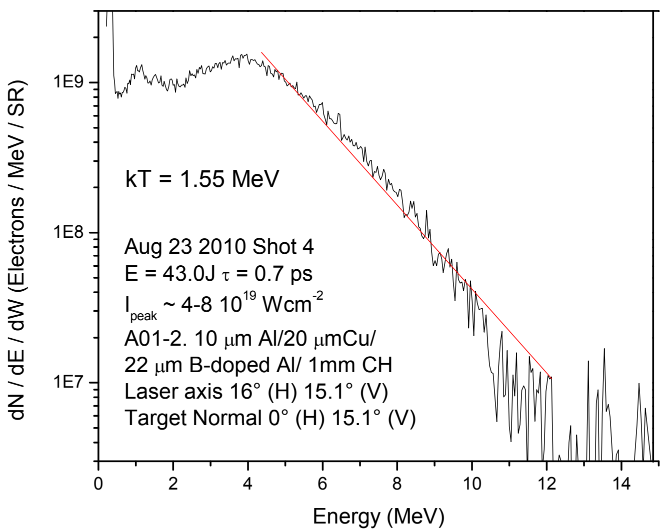
Distance
- center of slit 80 cm from stalk at TCC



Typical 2ω Electron Spectra 15°

No Prepulse





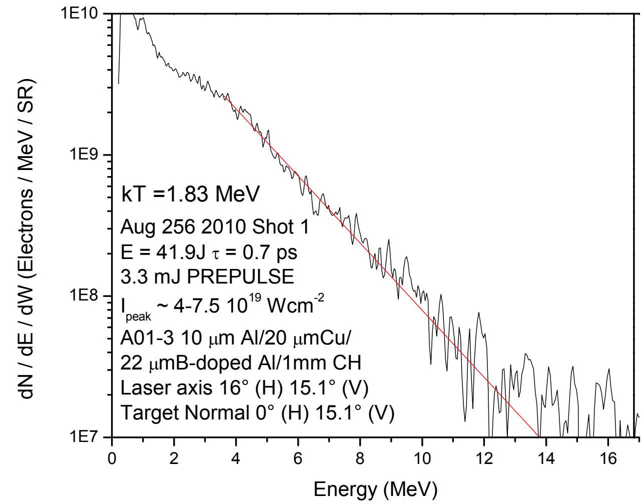
2 w

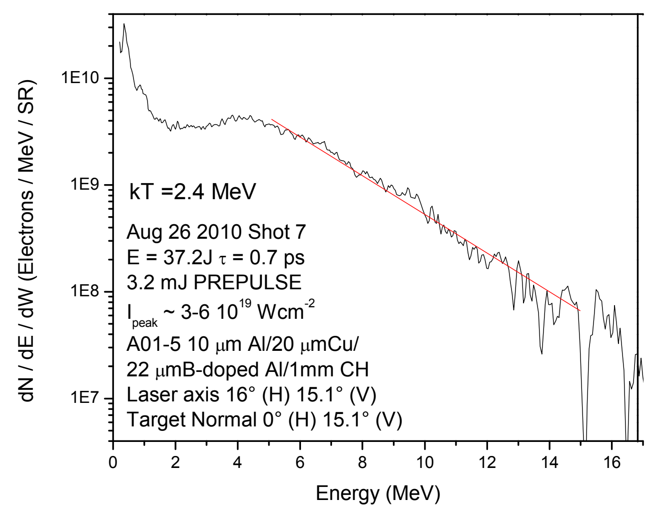
T_{hnpp} ~ 1.5 MeV

T_{hwpp} ~ 1.9 MeV

T_{hnpp} / T_{hwpp} ~ 0.8

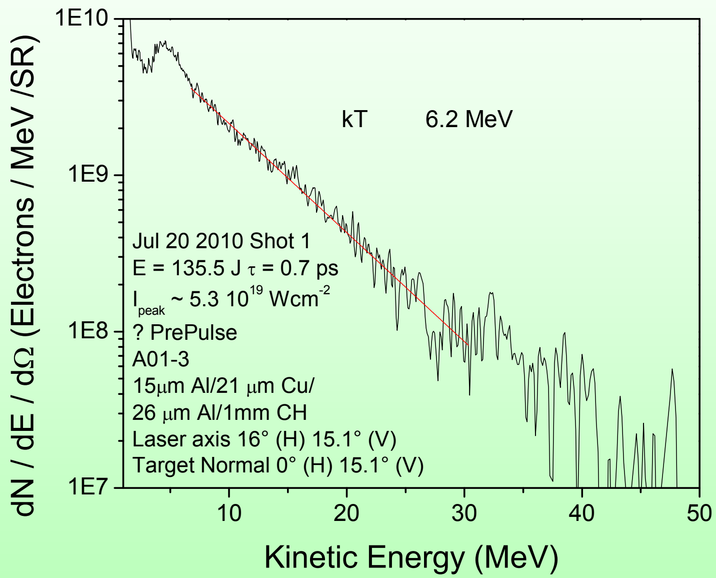
With Prepulse

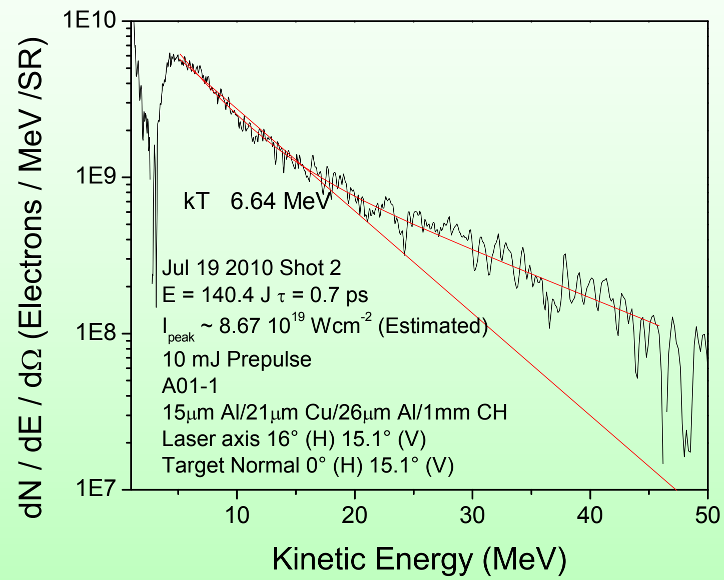




Typical 1ω Electron Spectra 15°

Measured with the same spectrometer and similar targets



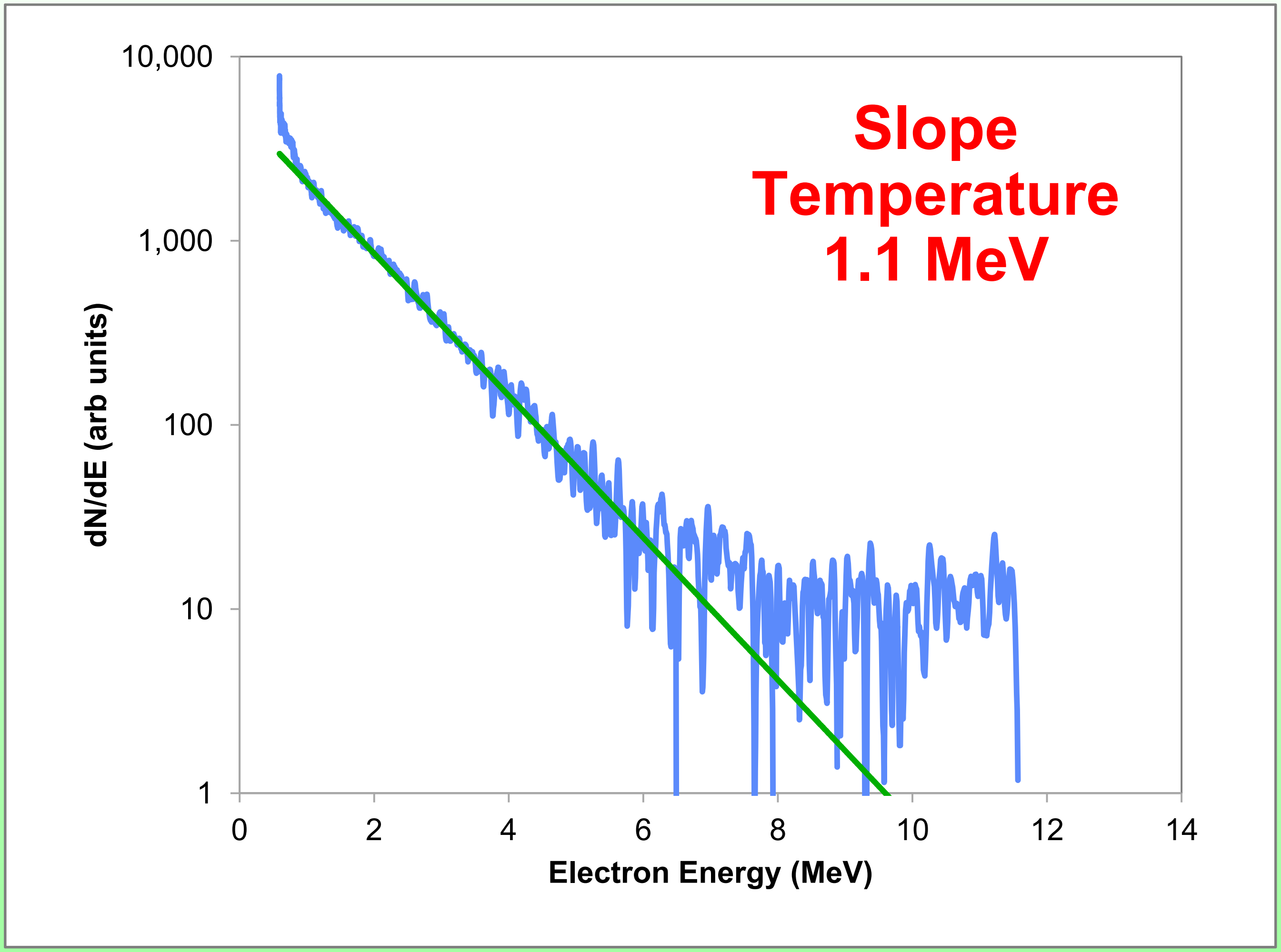


T_{hot} ~ 6 MeV

at 1 ω

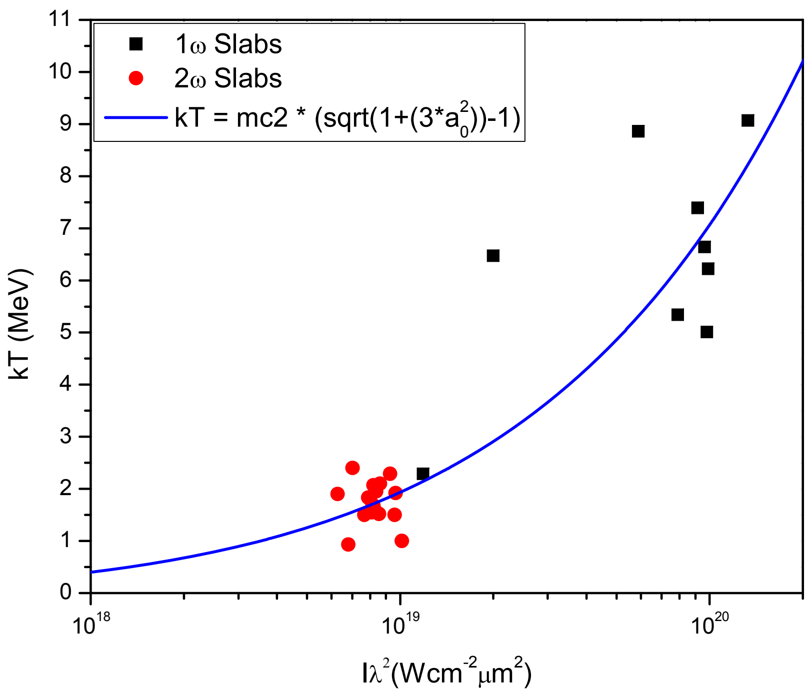
Electron Spectrometer 25° off axis

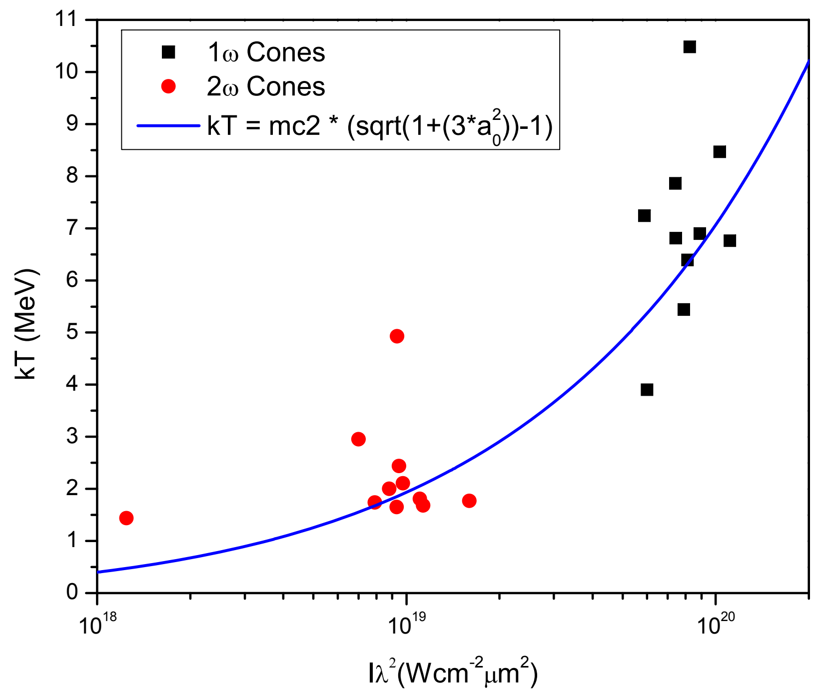
T_h at 25° ~ 0.6 x T_h at 15°



Escaping Electron Spectrometer Summary
1ω vs 2ω

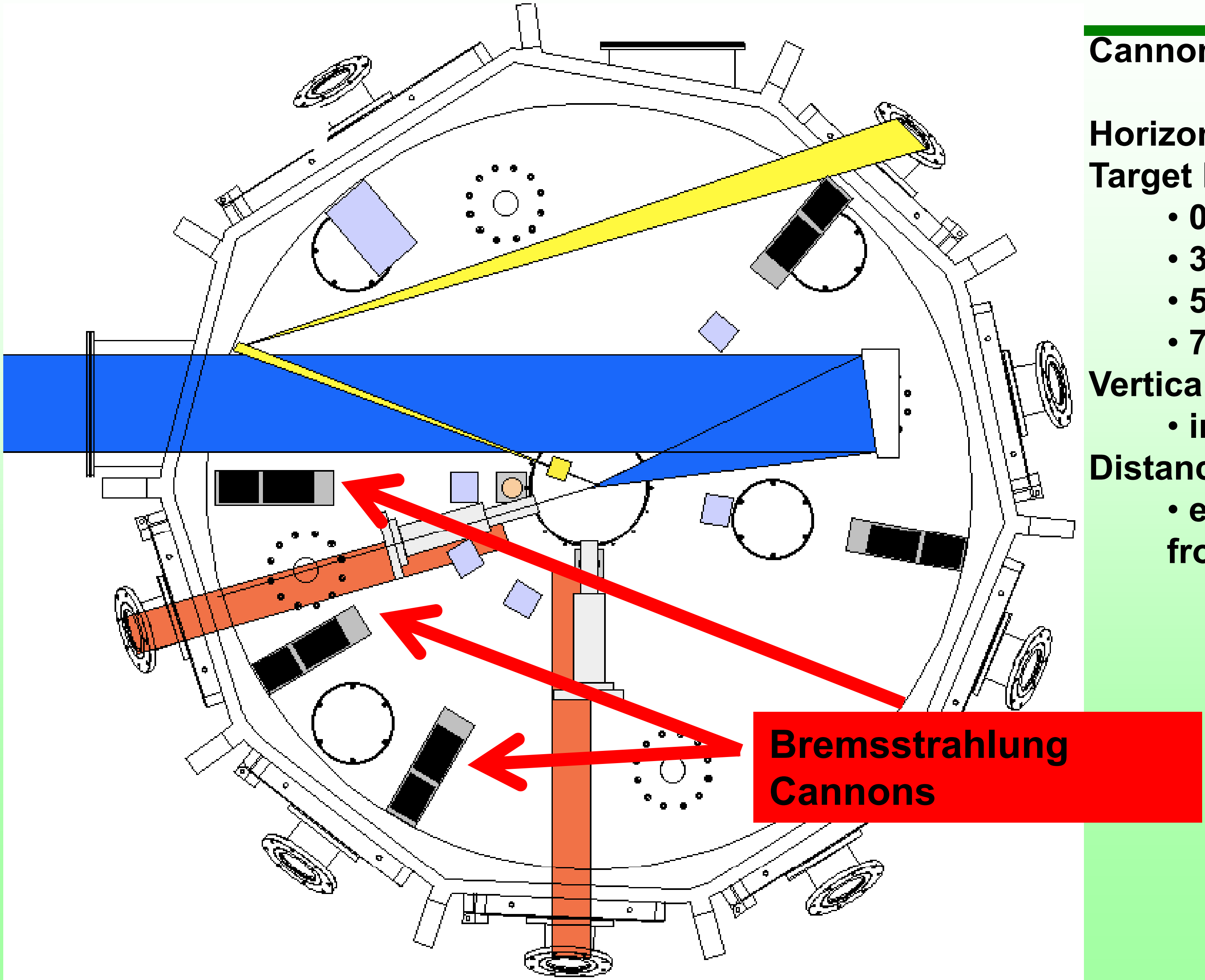
T_h fits modified Pondermotive scaling law
($T_h \sim 1.7\ T_{PM}$)





However, there is a large space charge effect from the escaping electrons themselves which inhibits low energy electrons from escaping

Hard X-ray Emission Versus Angle Measured with Bremsstrahlung Cannons



Cannons

Horizontal Angles wrt to Target Normal

- 0°
- 35°
- 55°
- 76°

Vertical Angles

- in the target plane

Distance

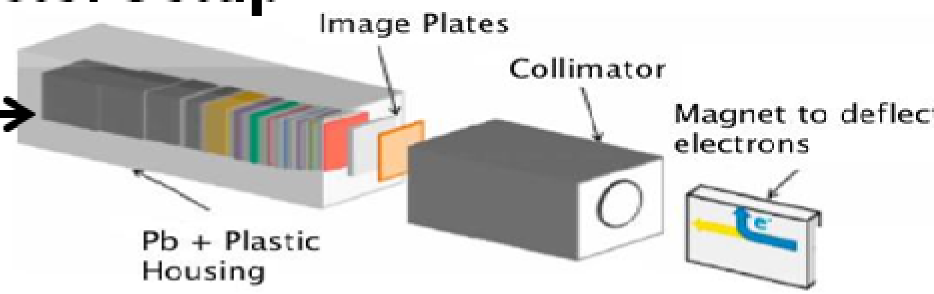
- entrance at ~80 cm from TCC

Hard X-ray Bremsstrahlung Cannon Spectrometers

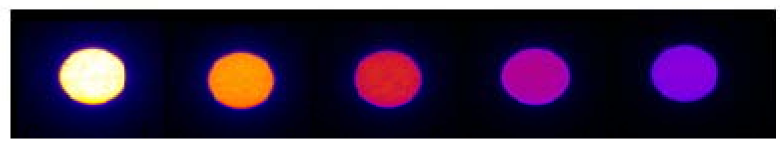
Filtered image plate stack with Pb collimator sensitive up to 500keV

X-Ray Spectrometer Setup

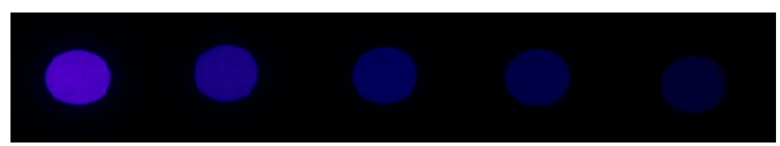
Schematic of X-Ray Spectrometer setup. Image plates and filters are alternated in stacked order



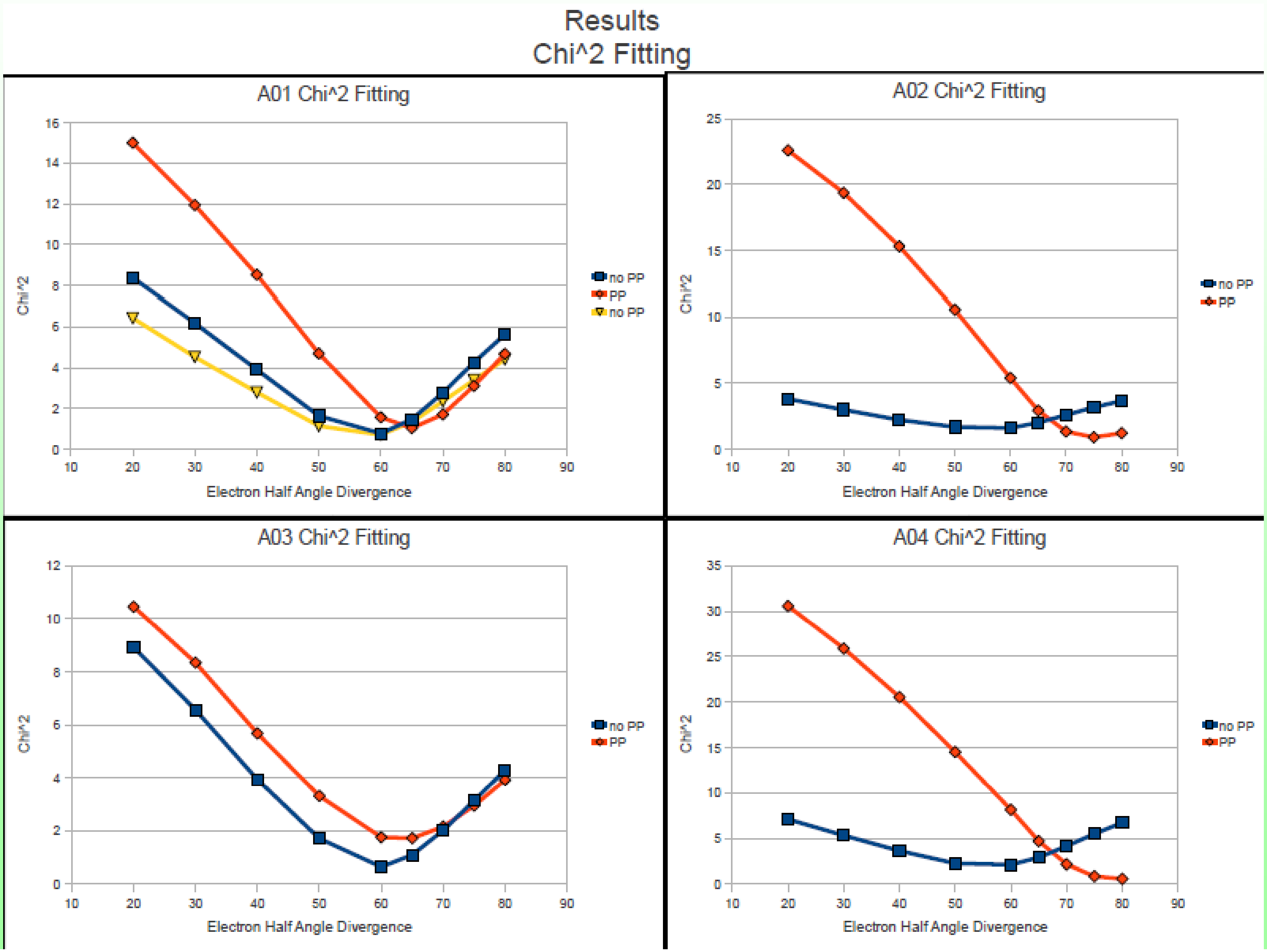
Raw X-Ray Spectrometer data for first 5 channels for 1ω light



Raw X-Ray Spectrometer data for first 5 channels for 2ω light



Bremsstralung Cannon Data Fits vs Electron source Divergence



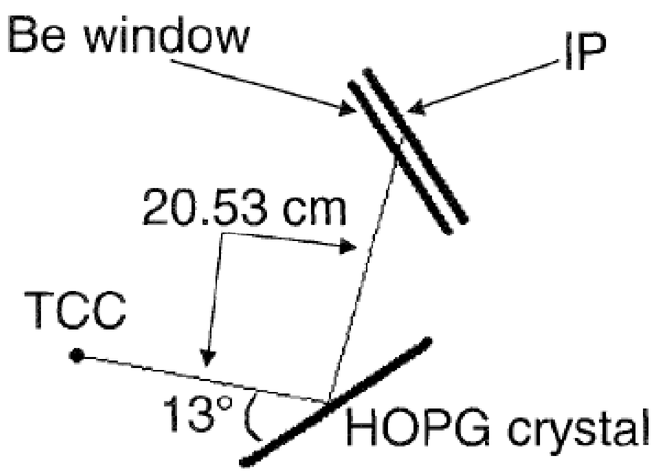
Bremsstralung Cannon Preliminary Summary

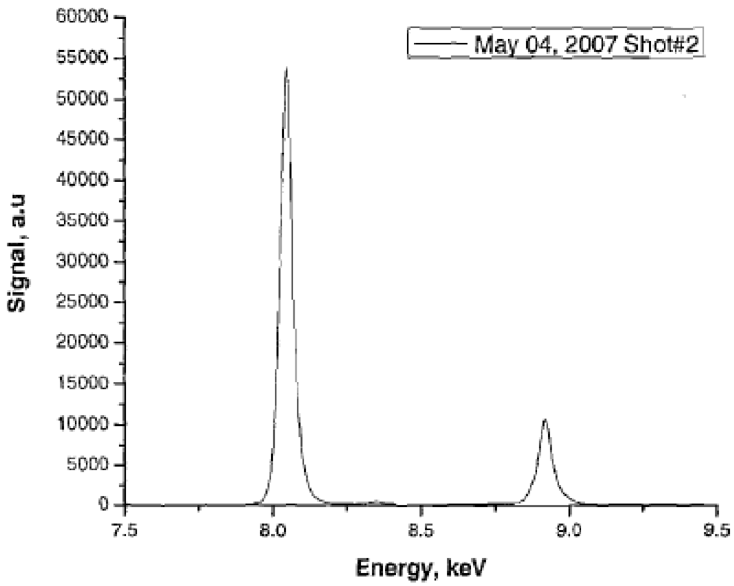
	Half Width	T_{hot}	Conversion Efficiency
Planar no pp	60°	0.37 MeV	11 %
Planar with pp	71°	0.50 MeV	17 %

Compare to 1ω data for Ag target (Westover APS 2010):
- **Electron Divergence ~ 60° (HW)**
- **Conversion Efficiency ~ 32%-38%**

Compare to 1ω data for Al target (Chen PoP 16, 082705 2009):
- **T_{hot} ~ 1.3 MeV**
- **Conversion Efficiency ~ 20-40%**

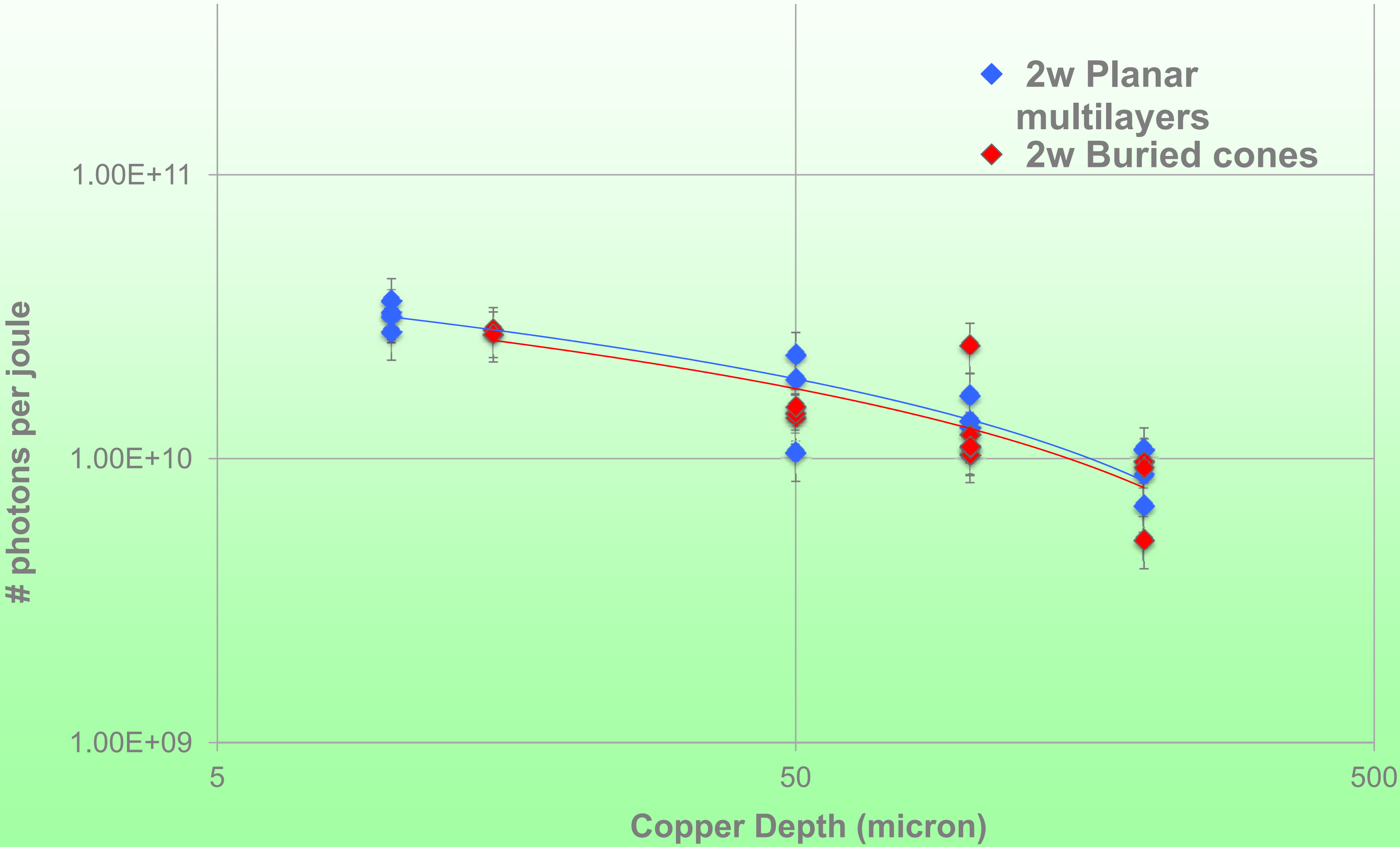
Highly Oriented Pyrolitic Graphite keV X-ray Sepctrometer



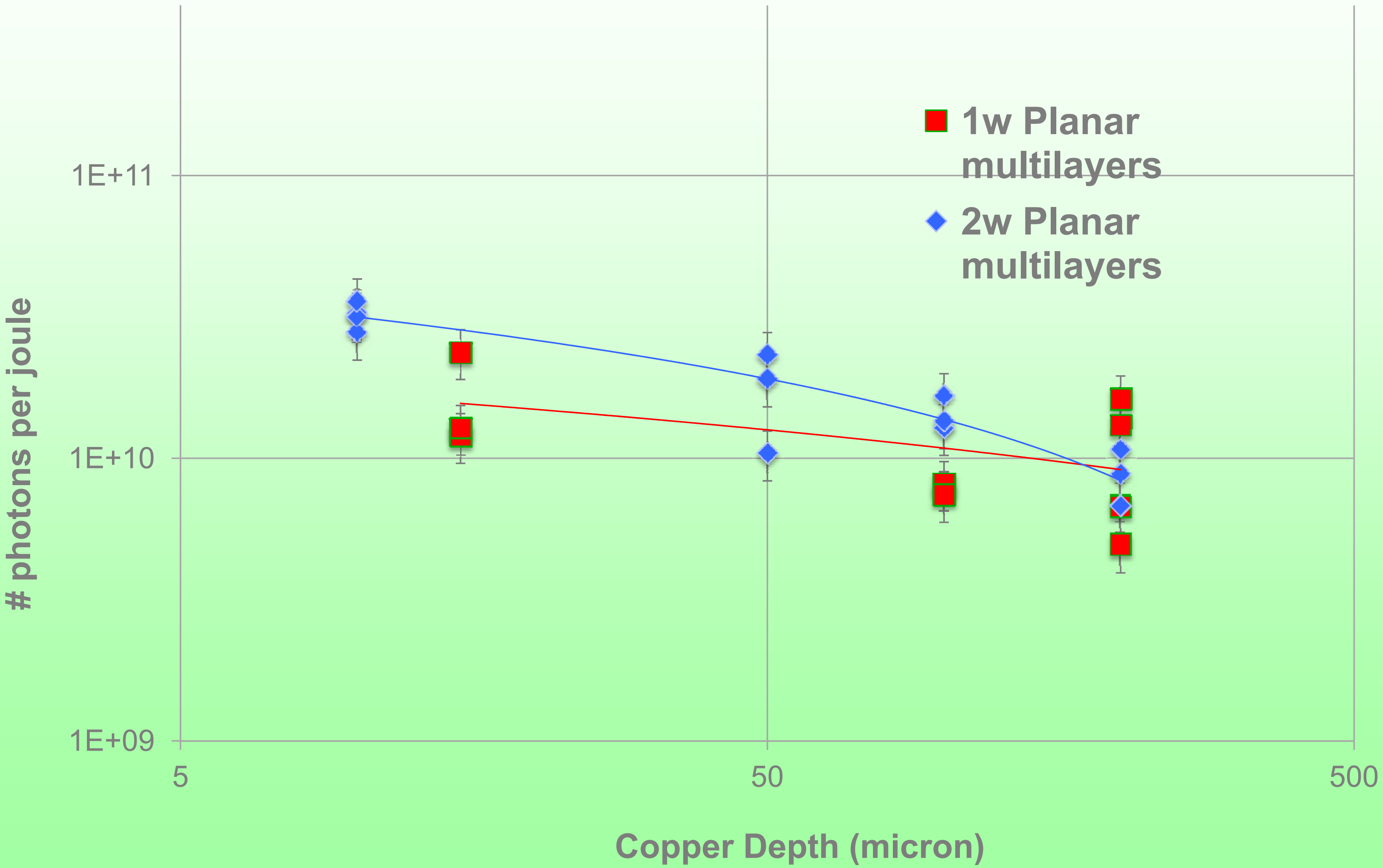


HOPG crystal: width 50 mm, height 75 mm.
IP: height 50.5 mm

Cu K_α HOPG Data: Buried Cones vs Planar (2ω)

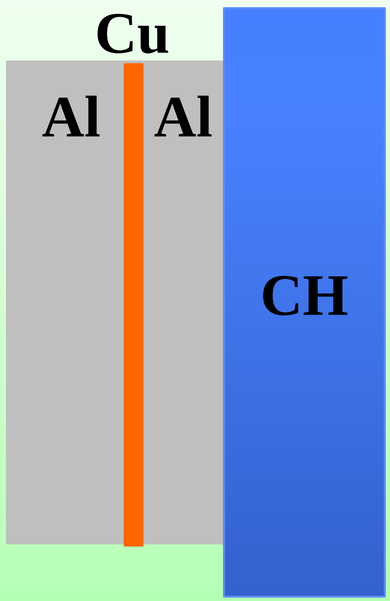


Cu K_α HOPG Data: 1ω vs 2ω - Planar



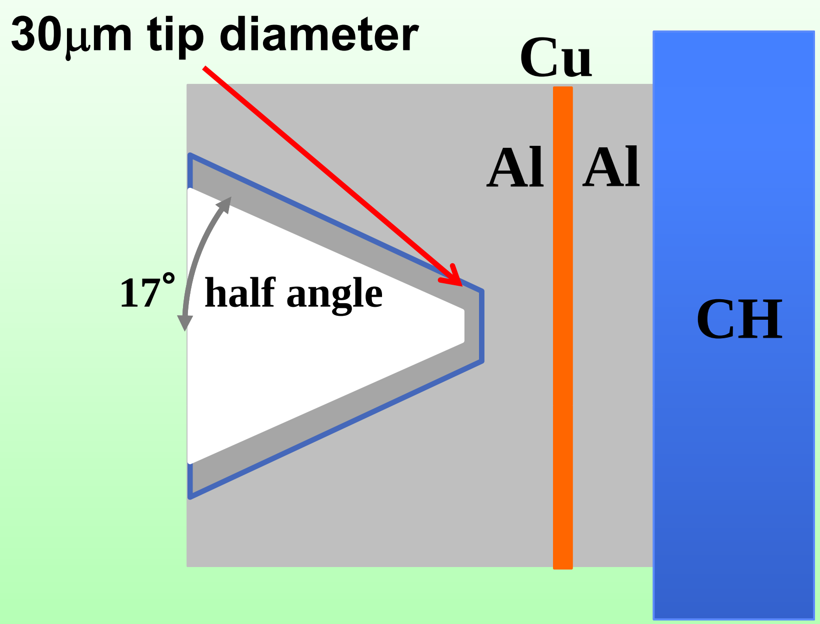
Electron Imaging Divergence Measurements

SLAB Targets



Variable Cu fluor depths for divergence calculation

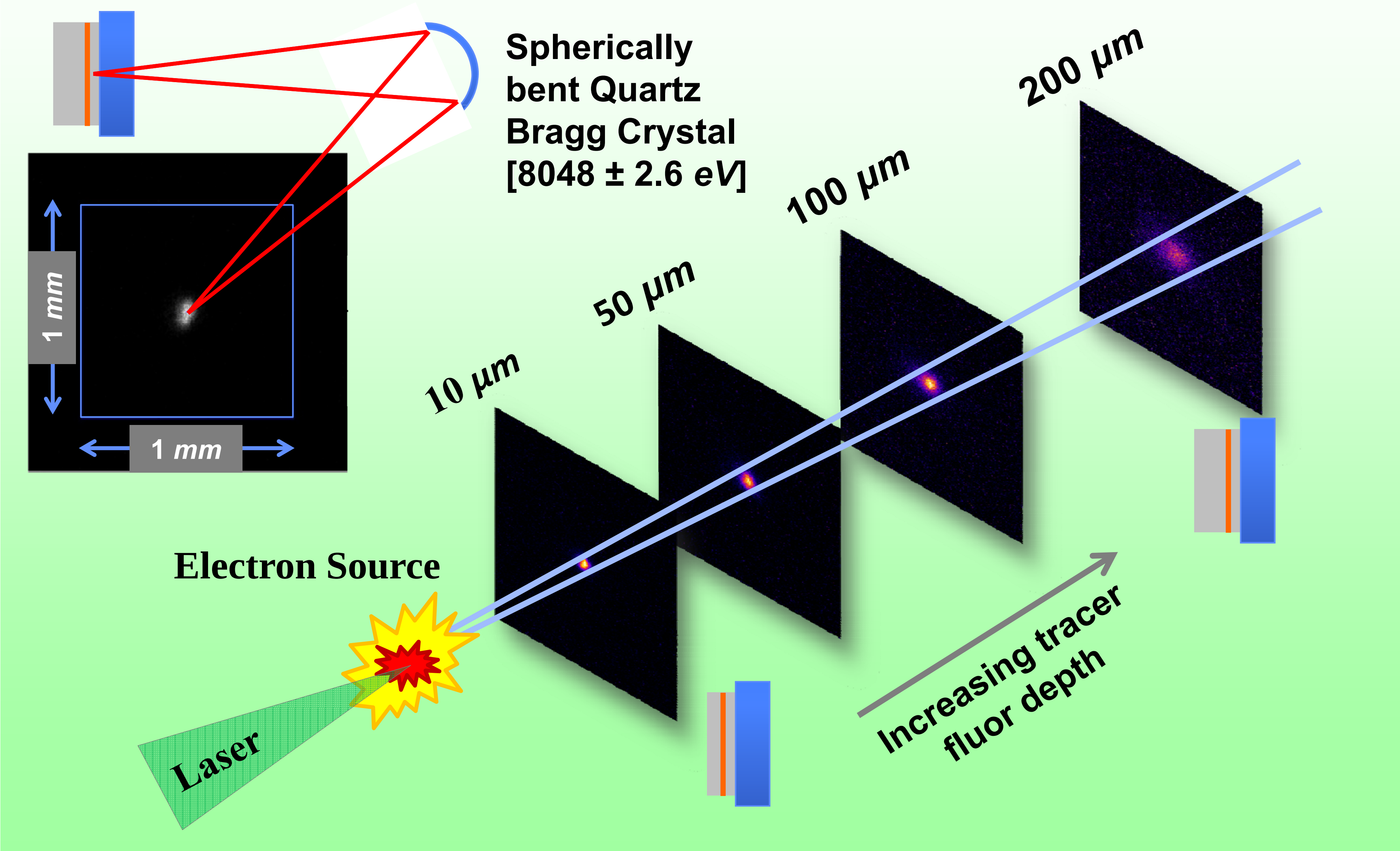
Buried Cone Targets



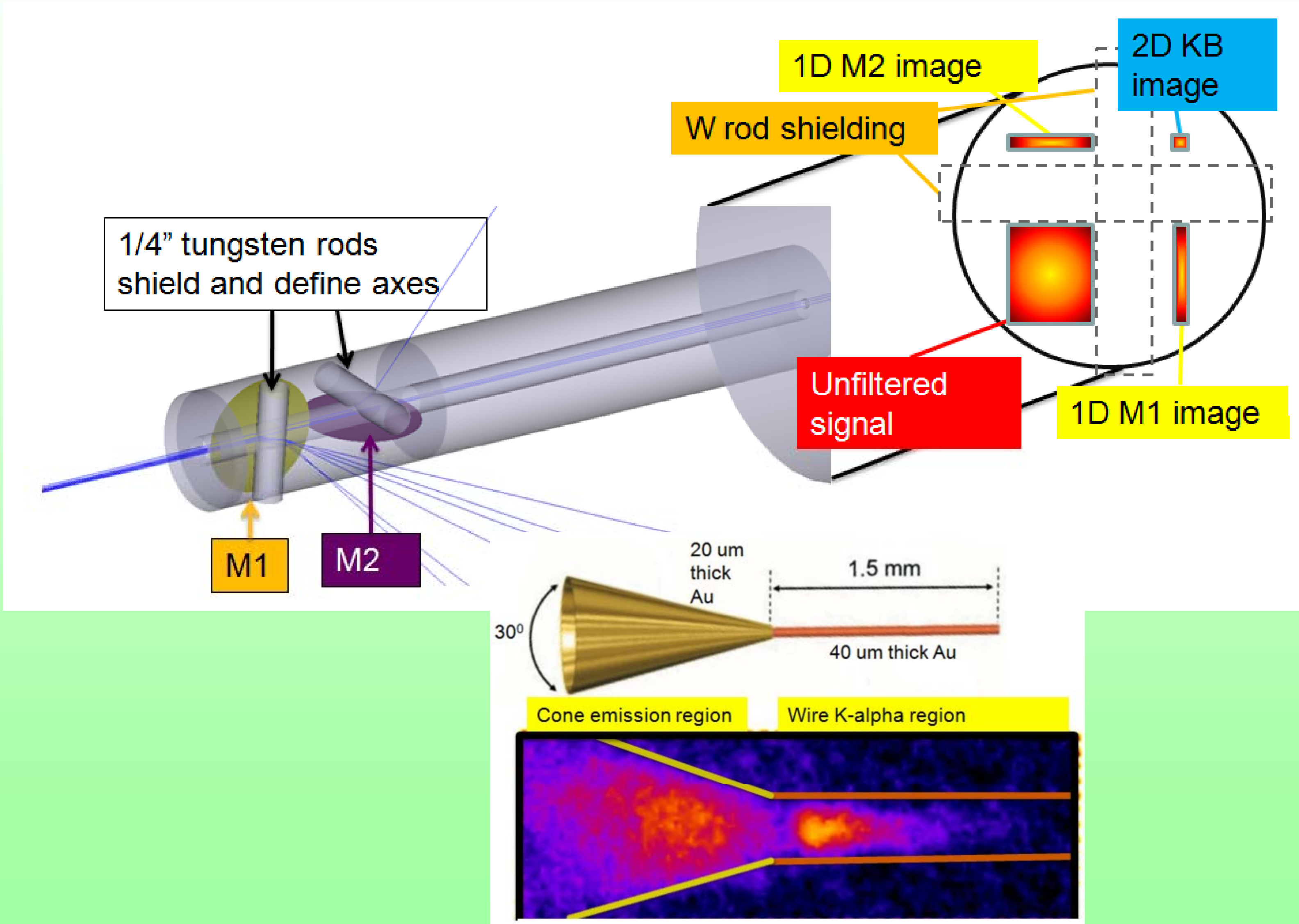
Surrogate for a cone surrounded by a conducting plasma

Thick 1mm CH layer to avoid electron refluxing

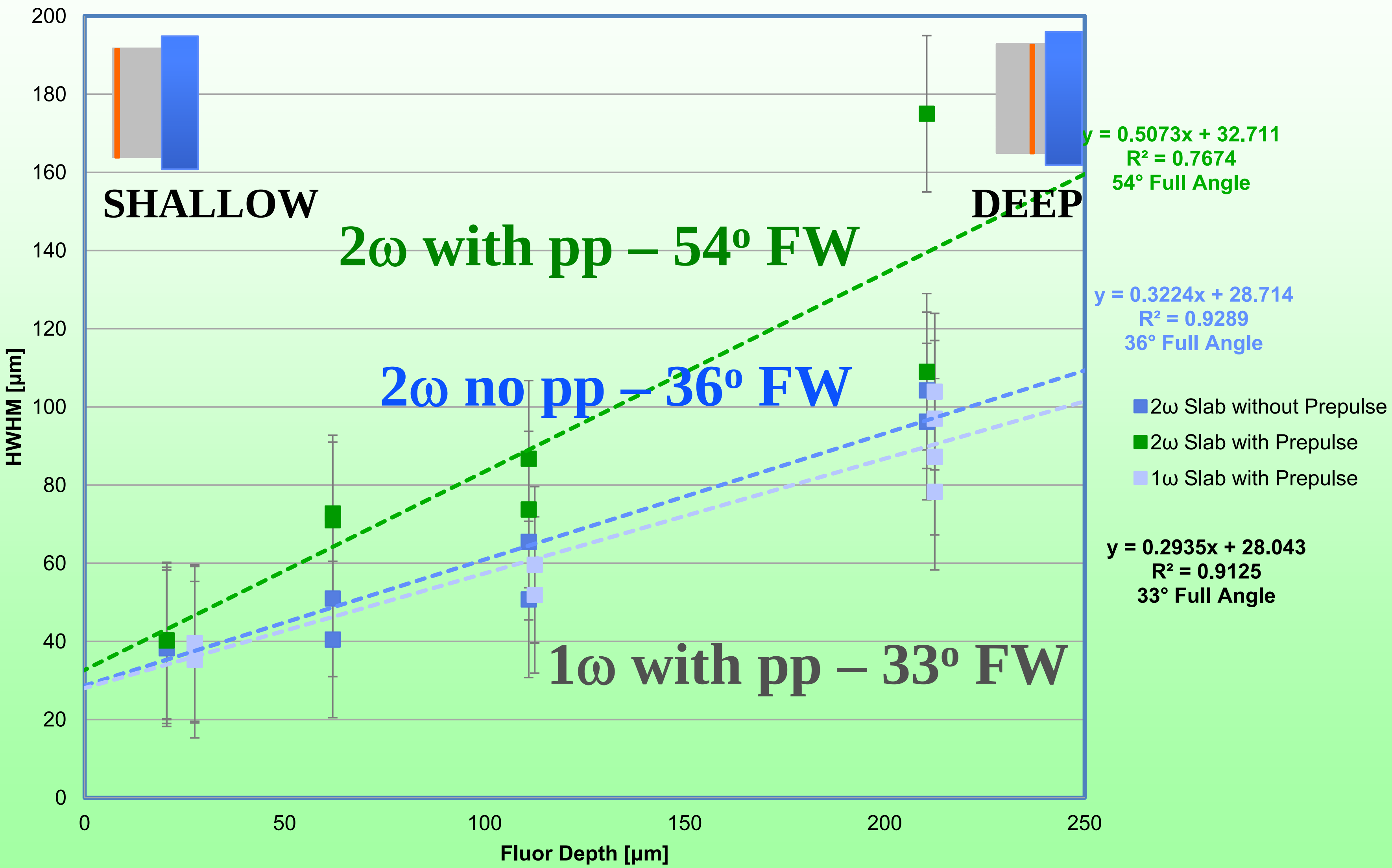
Electron Beam Divergence from Bragg Crystal Imager K_α Images



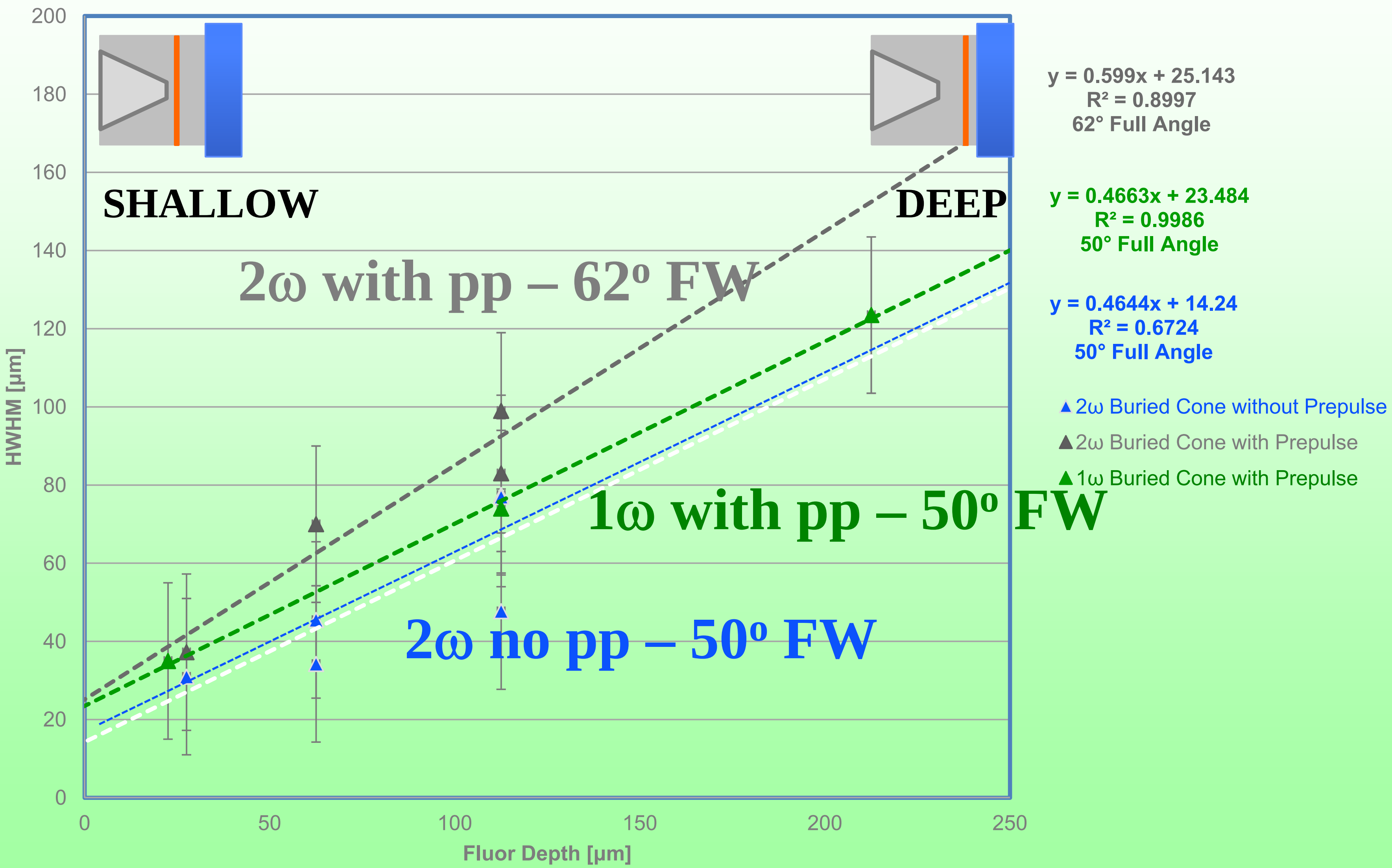
Electron Beam Divergence from Kirkpatrick-Baez 7- 9 keV X-ray Imager



Preliminary Electron Beam Divergence - Planar



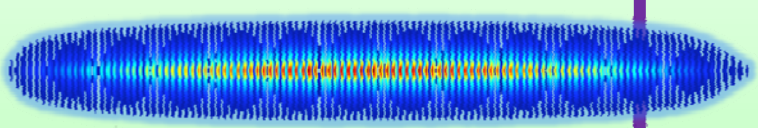
Preliminary Electron Beam Divergence – Buried Cones

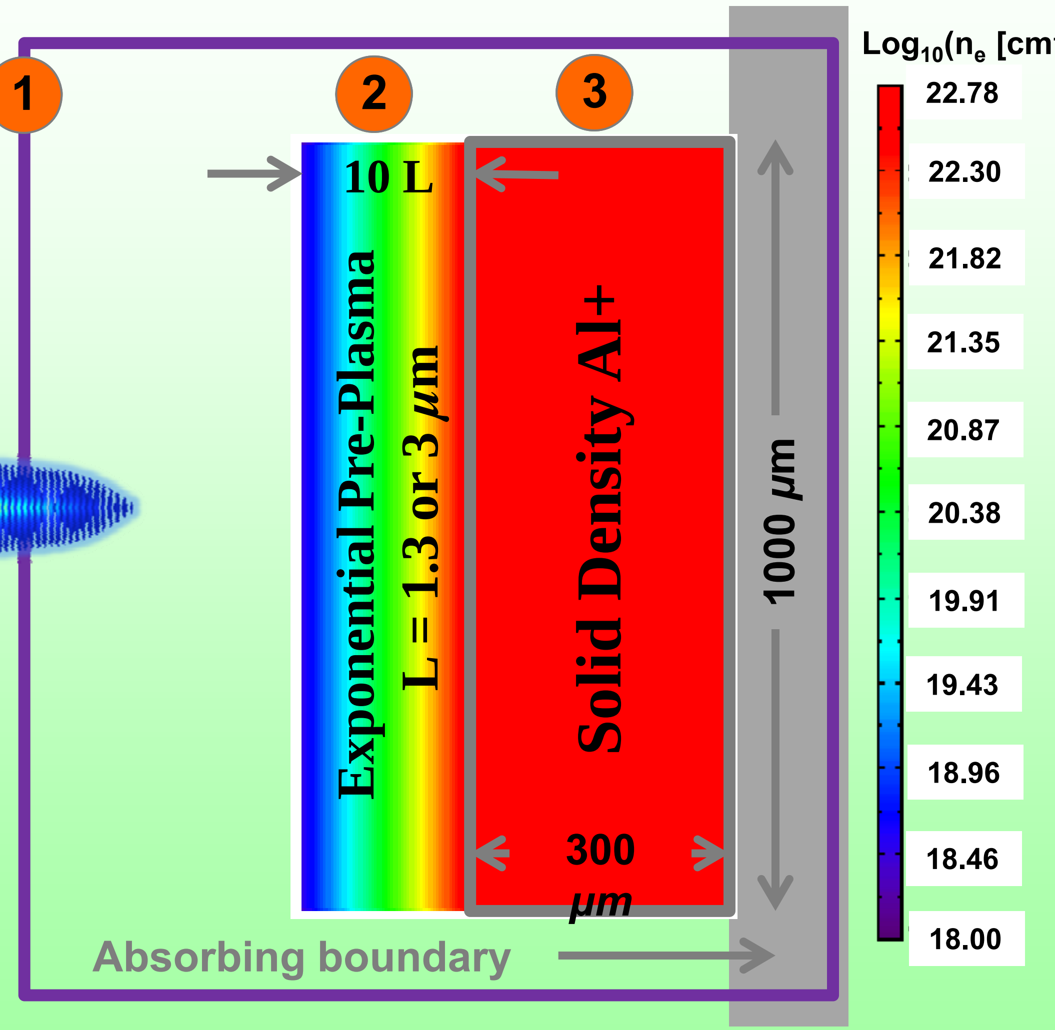


Preliminary LPI 2D3V fully collisional kinetic PIC simulations in LSP* to gain further insight about pre-plasma effects

Elijah Kemp (OSU)   APS 2011

LASER:
Polarized in the plane
λ_o = 527 *nm* (2ω)
τ_{FWHM} = 700 *fs*
x_{FWHM} = 8 *μm* focal spot
I_{peak} = 4.6 x 10^{19} *W/cm²*





SIMULATED DIAGNOSTICS:

1. Unabsorbed light fraction
2. n_e profile steepening
3. Cu K_α divergence

Pre-plasma environments chosen using the reflectivity data

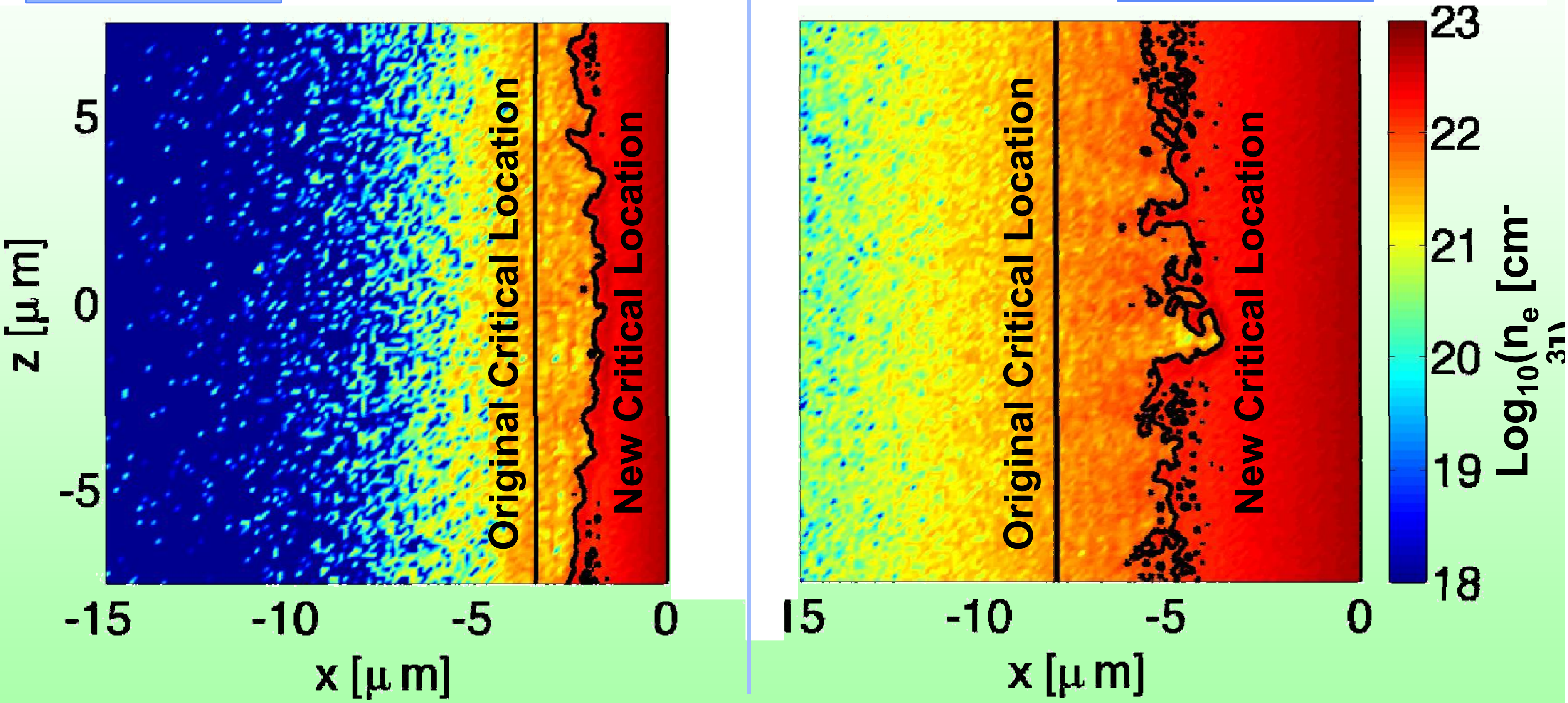
* Welch et al, Phys. Plasmas 13, 063105 (2006)

Simulated motion of critical surface consistent with rising edge red shift seen in specular pulse

L = 1.3 *μm*

Elijah Kemp (OSU) *APS 2011*

L = 3 *μm*



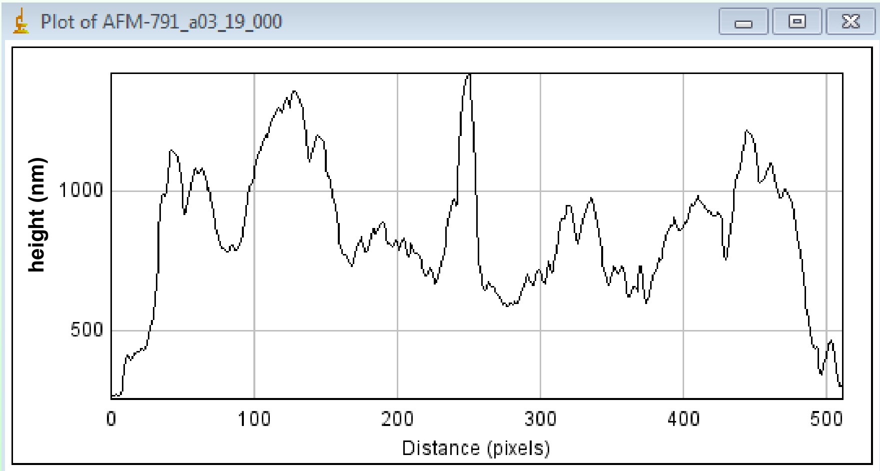
Experimental Results
No pre-pulse: $\Delta\lambda/\lambda_o < 0.5\%$
3 *mJ* pre-pulse: $\Delta\lambda/\lambda_o \cong +2.5\%$

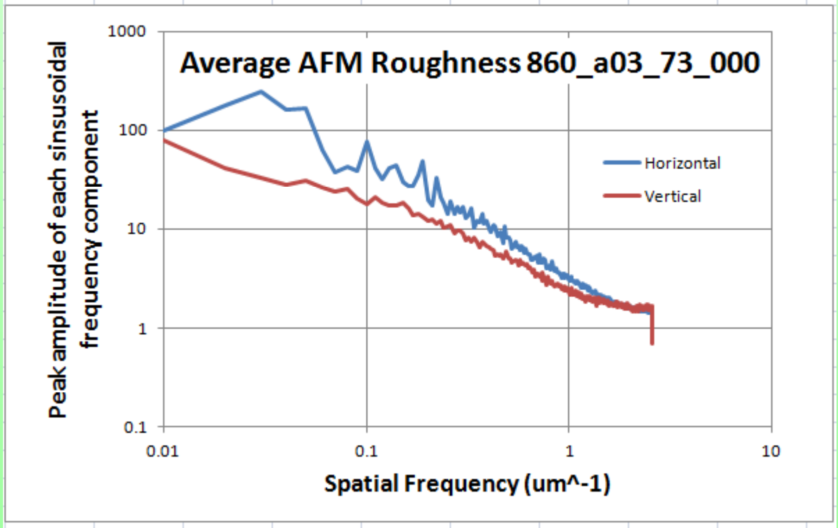
Simulation Results
L = 1.3 *μm*: $\Delta\lambda/\lambda_o \cong +1.4\%$
L = 3 *μm*: $\Delta\lambda/\lambda_o \cong +5\%$

Target Roughness May Also Play a Role in Electron Divergence

More recent targets measured with AFM

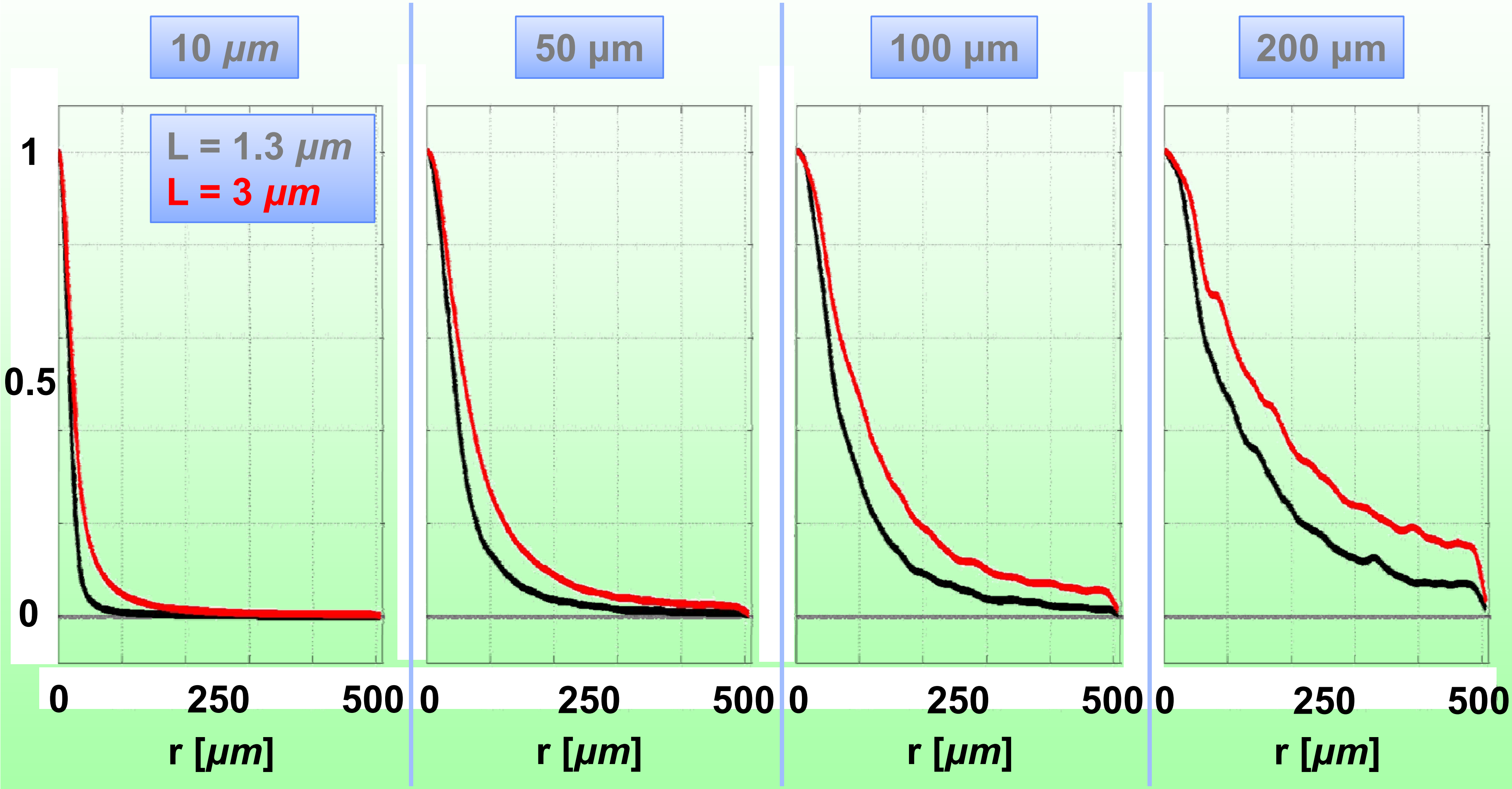
100 μm x 100 μm





Measured Roughness is on the order of 100nm to 150nm rms over 10 μm spots

Increased simulated K_α divergence (~40%) with increased pre-plasma

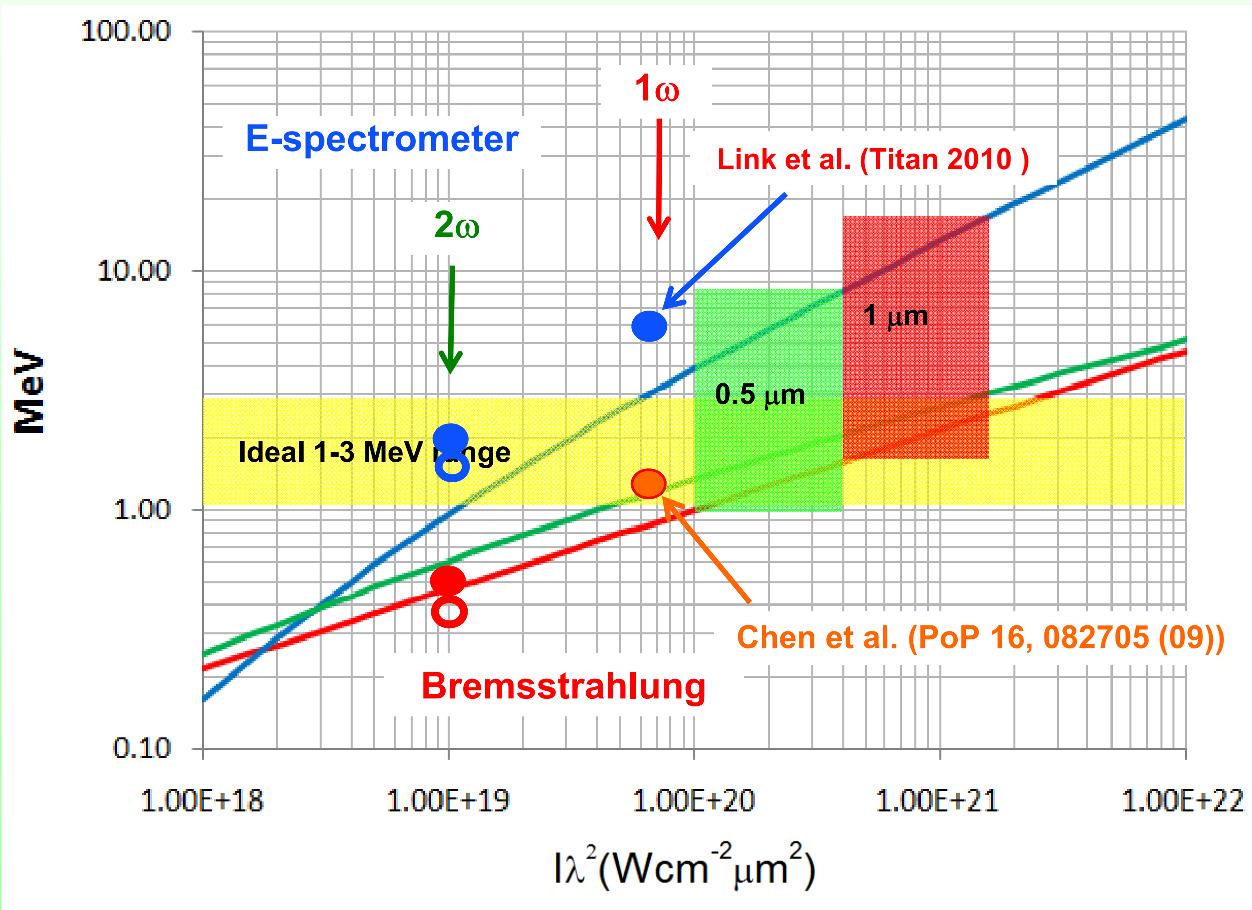


Simulation Results
L = 1.3 μm : 35°
L = 3 μm: 50°

Elijah Kemp (OSU) APS 2011

Summary - Electron Energy Scaling

Experimental Results



Scaling Laws:

Wilks (Ponderomotive)
PRL 69, 1383 (1992)

Beg (Exp Bremsstrahlung)
Phys.Plasmas 4,447 (1997)

Haines (Energy/Momentum)
PRL 102, 045008 (2009)

Summary FI Experiments

- Successful implementation of 2ω target experiments at 50J 700fs level at the TITAN facility up to 5 x 10^{19} W cm^{-2}
- 2ω Conversion efficiencies over 60% obtained, < 10 μJ pp
- Hot electron temperature scaling inside the target looks good for 2ω FI (follows Beg $(I\lambda^2)^{1/3}$ scaling)

  T_{hot} ~ 0.37 – 0.50 MeV (Bremsstrahlung)
  ~ 1.5 – 1.9 MeV (escaping hot electrons)

- Major Issue is large electron divergence angle
  - FW ~ 120° – 142° Bremsstrahlung
  - FW ~ 36° – 54° K_α imaging ⟶ slope angle edges
- Absorption and electron yield lower than 1ω as expected for lower $I\lambda^2$ - expect to increase with $I\lambda^2$
  - η_{e-} ~ 11 – 17 %
  - R ~ 27 – 14%

Thank You