Measurements of Radiation Doses Induced by High Intensity Laser between 10^{16} and 10^{21} W/cm^2 onto Solid Targets in LCLS MEC Instrument

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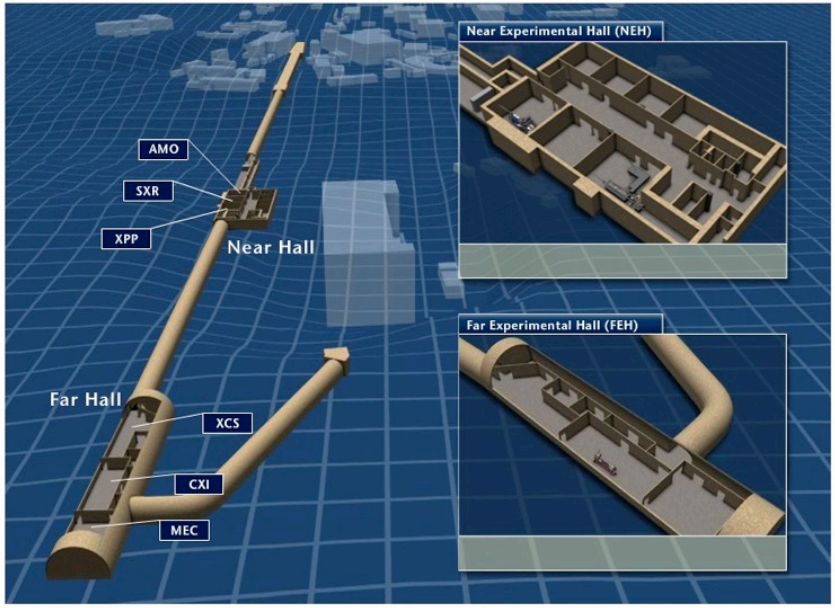
SLAC NATIONAL ACCELERATOR LABORATORY

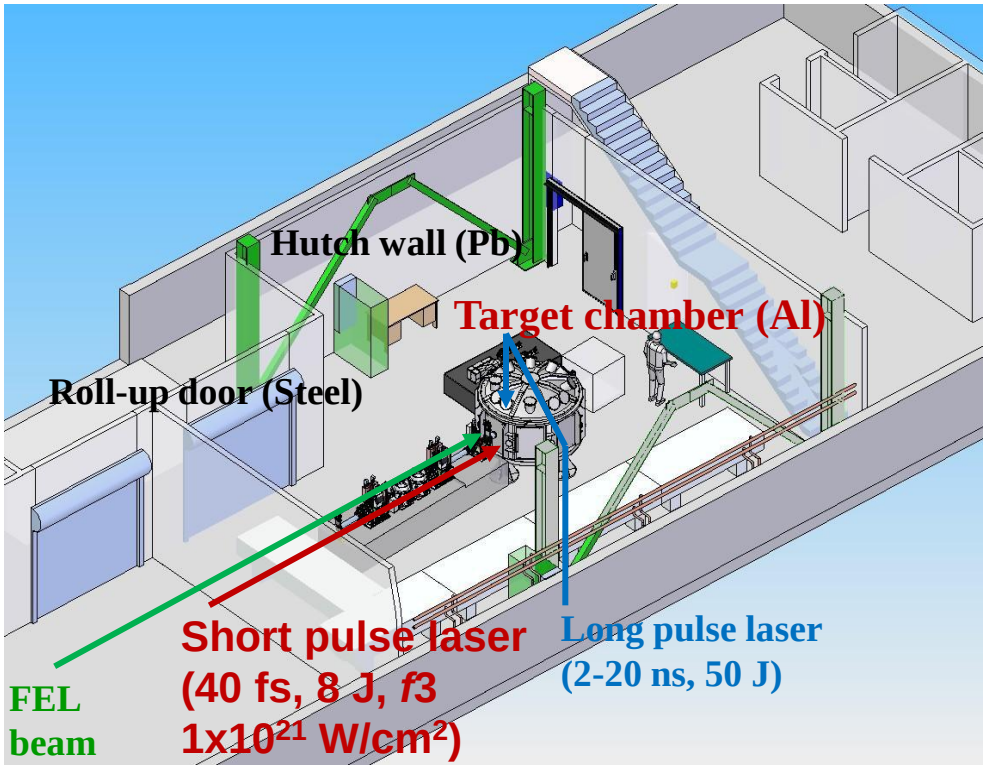
Outline

- SLAC MEC FEL and Laser Facility
- Electron and Photon Source Terms and SLAC-RP Photon Dose Yield Model
- Measurements (2011-2014)
  - Set-up of active and passive detectors
  - Characterization of Laser-optic-target parameters
  - Measured dose results
  - Comparison with RP model
  - Preliminary electron spectrometry and FLUKA and PIC code results
- Summary

LCLS Facility and MEC FEL Instrument

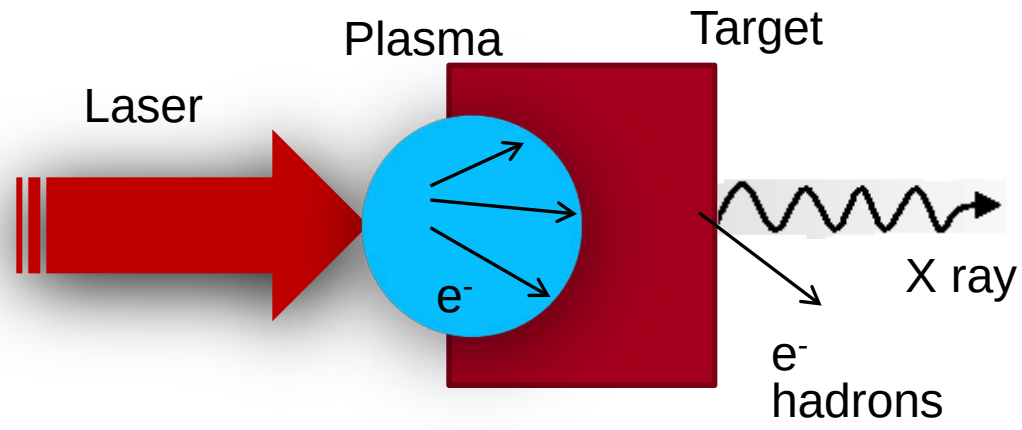
Matter in Extreme Conditions (MEC) instrument combines the unique LCLS FEL beam with **high power optical laser beam** to study the transient behavior of matter in extreme conditions.





MEC serves key scientific areas including Warm Dense Matter physics, High Pressure studies, shock physics, and High Energy Density physics.

Ionizing Radiation from High Intensity Laser on Target



H.A. Baldis, et al., "Handbook of Plasma Physics,(1991).

$$I(r) = \frac{2P}{\pi w^2} e^{-2r^2/w^2}$$

1 J, 40 fs, 10 μm 1/e² radius, I = 1.6x10¹⁹ W/cm²

Distributions are characterized by the hot electron temperature T_h

For $I \leq 10^{18}\ W/cm^2$, Maxwellian electron distribution:

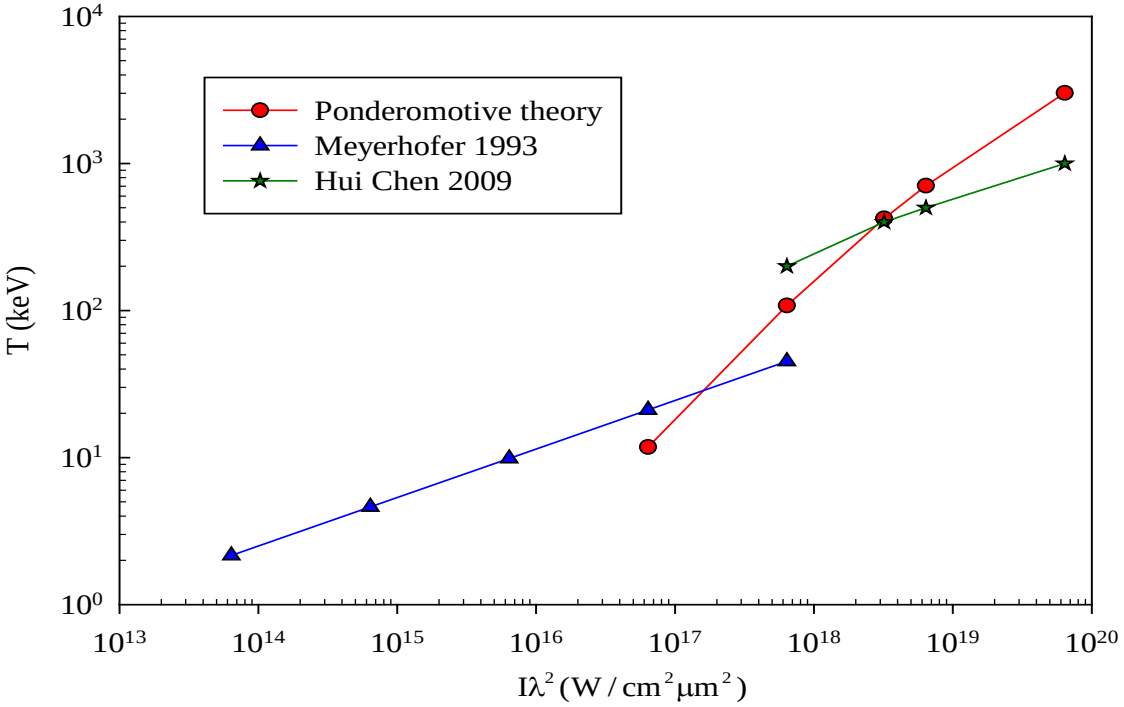
$$f(E) \sim E^{1/2} \cdot T^{-3/2} \exp\left(-\frac{E}{T_h}\right)$$

For $I > 10^{18}\ W/cm^2$, Relativistic Maxwellian electron distribution:

$$f(E) \sim E^{2} \cdot T^{-3} \exp\left(-\frac{E}{T_h}\right)$$

SLAC RP Note 10-11

Hot Electron Temperature T_h



MEC λ = 0.8 μm

I (W/cm²)	T_h (MeV)
$1x10^{18}$	0.11
$1x10^{19}$	0.70
$1x10^{20}$	3.02

- For $I\lambda^2 < 1.6 \times 10^{17}\ W \cdot \mu m^2/cm^2$, Meyerhofer 1993

$$T_h[keV] = 6 \times 10^{-5}\ (I\lambda^2)^{1/3}$$

- For $I\lambda^2 \geq 1.6 \times 10^{17}\ W \cdot \mu m^2/cm^2$, ponderomotive scaling:

$$T_h[keV] = 511\ \left(-1 + \sqrt{1 + I\lambda^2/1.37 \times 10^{18}}\right)$$

SLAC RP Note 10-11

Bremsstrahlung Dose Yield and Spectrum

X-ray Dose Yield (Sv/J) at 1 m and 0-degree:

Hayashi2006 dose yield model:

- $H_x\left[\frac{Sv}{J}\right] \approx 1.8 \times \left(3.32 \times \frac{P_{ef.}}{R^2}\right) \times T_h \quad for\ T_h \geq 3\ MeV$
- $H_x\left[\frac{Sv}{J}\right] \approx 1.8 \times \left(1.10 \times \frac{P_{ef.}}{R^2}\right) \times T_h^2 \quad for\ T_h < 3\ MeV$

P_{ef} - laser energy to hot electron energy conversion efficiency
(30% for I ≤ 1x10^{19} W/cm^2 and 50% for I > 1x10^{19} W/cm^2)

T_h - hot electron temperature in MeV

R - distance from target to dose point in cm

X-ray Maxwellian Spectrum for Shielding Design:

$$N_p(E_p) = C\frac{1}{E_p}\exp(-\frac{E_p}{T})$$

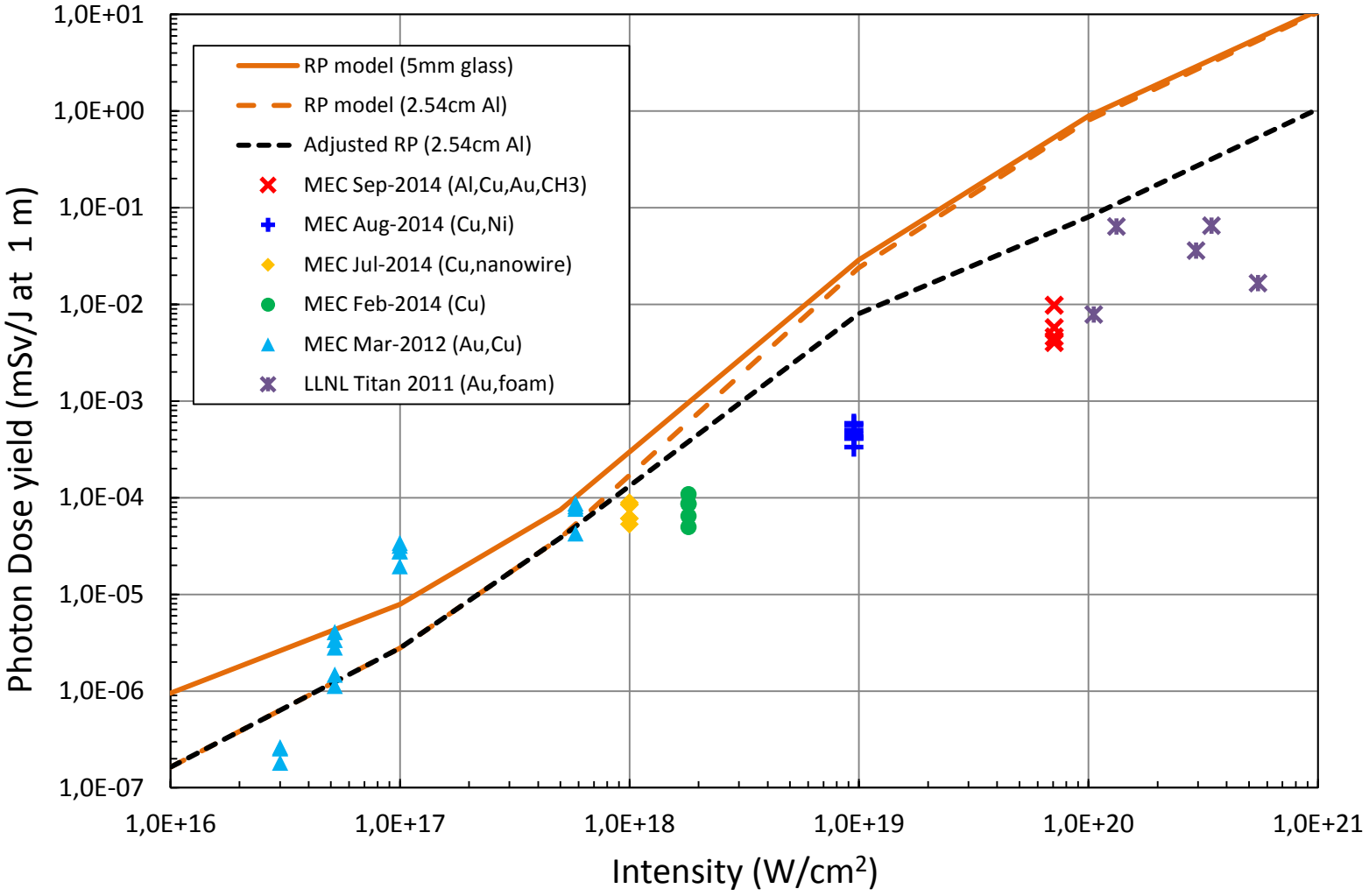
E_p - photon energy in keV

T - electron temperature in keV

C - normalization constant

SLAC RP Note 10-11

“Original” and “Adjusted” RP Photon Dose Yield Models and Maximal Doses Measured



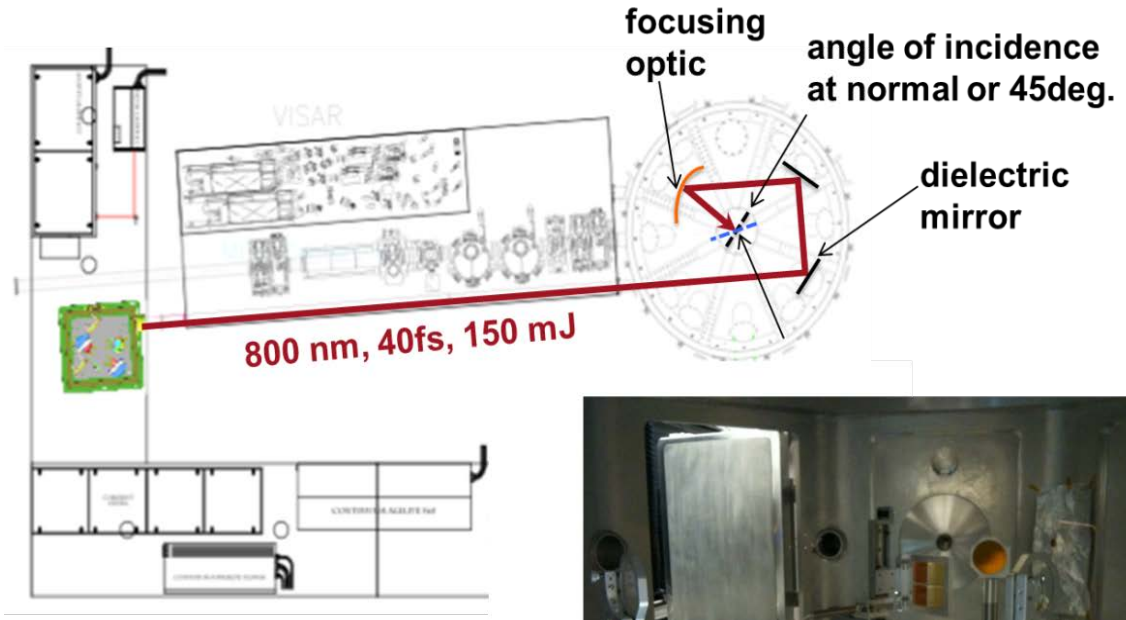
Measurements at LLNL Titan and SLAC MEC

2011 at Titan (*RP-11-11)* :

- $1x10^{20}$ to $6x10^{20}$ W/cm^2
- **50 - 400 J**
- **Single shots**
- CH foam with Au foil backing

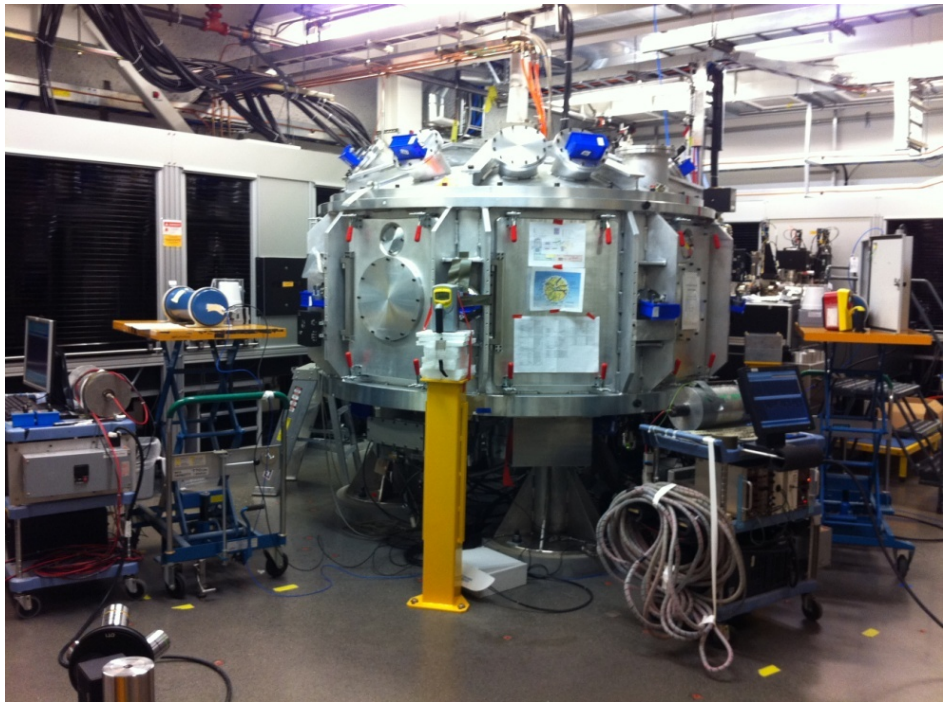
2012 at MEC (*SLAC-PUB-15889*):

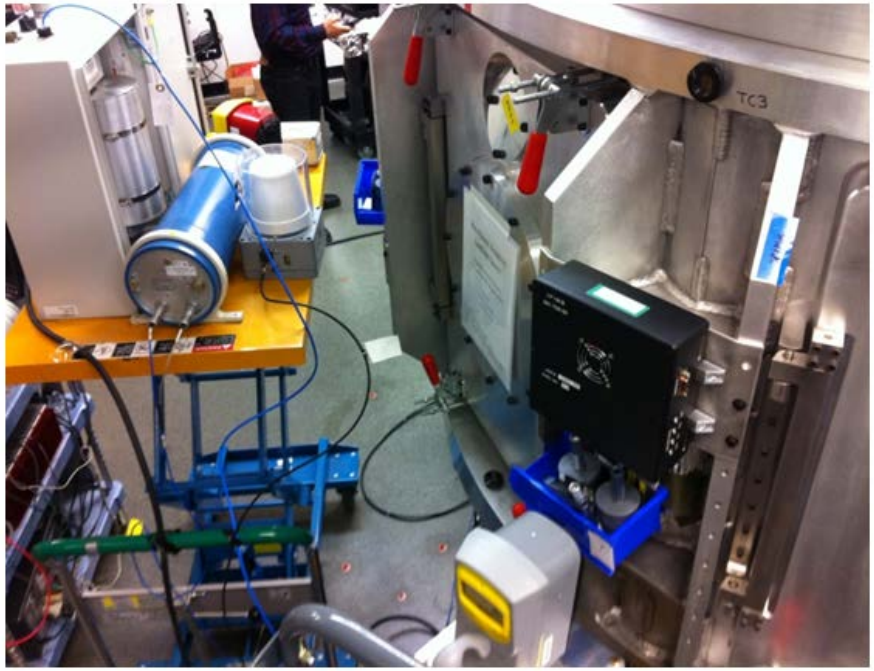
- $3x10^{16}$ to $6x10^{17}$ W/cm^2
- **30 – 138 mJ per pulse**
- **10 Hz**
- 10 & 100 μm Au, 1 mm Cu



Inside Target Chamber

Measurements around MEC Target Chamber

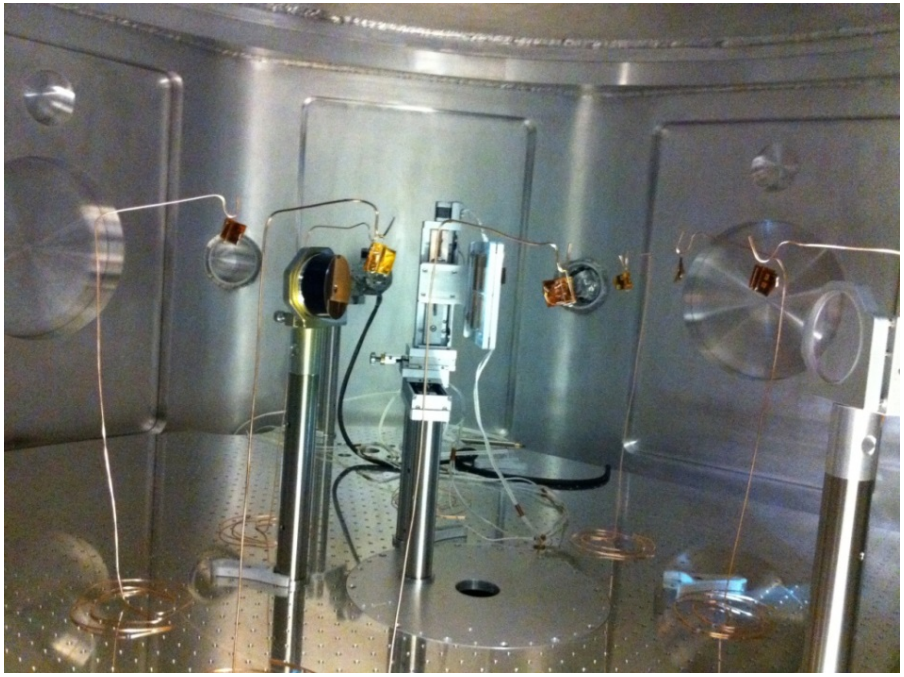




- Ion Chamber photon detectors: Victoreen 450/451, PTW, HPI
- SLAC-made moderated BF_3 neutron detectors
- Passive dosimeters (RADOS, PIC, TLD and OSLD) inside blue boxes

Target and Dosimeters inside MEC Target Chamber

Gold foil target in center



Al_2O_3

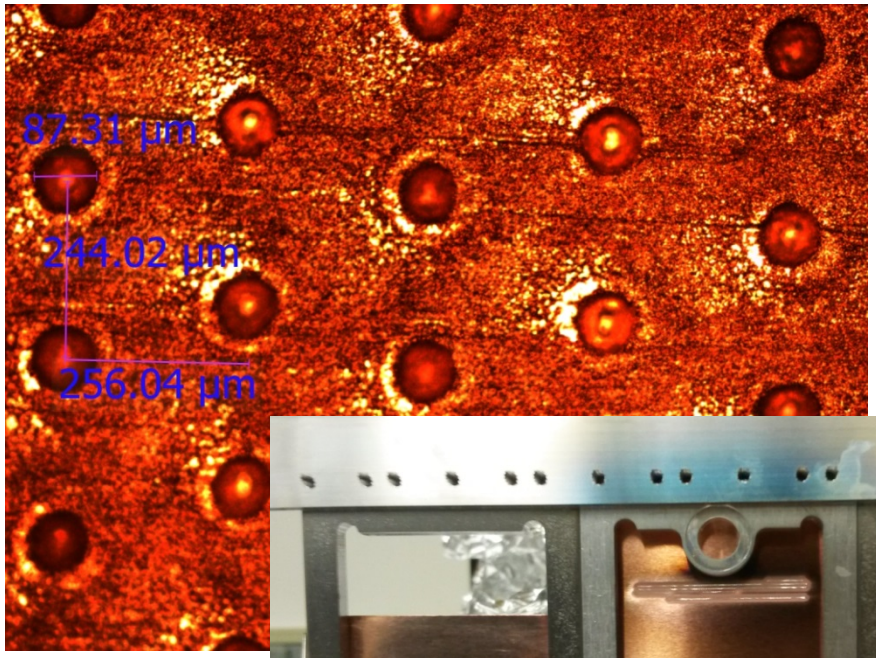
from Landauer

Landauer nanoDot OSLD ~30 cm from target

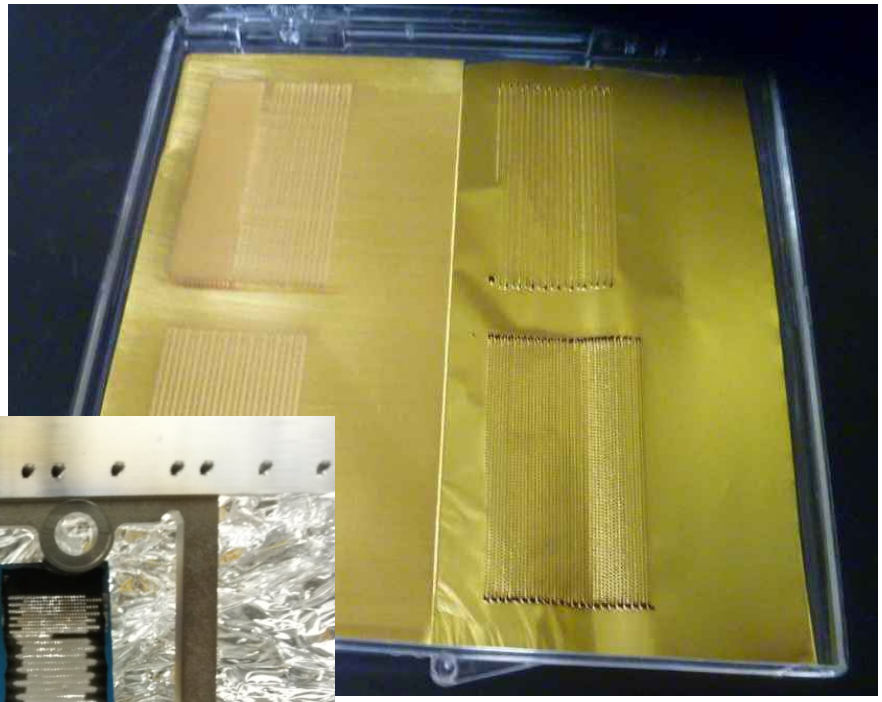
MEC Laser Shot Rastering by Moving Solid Target

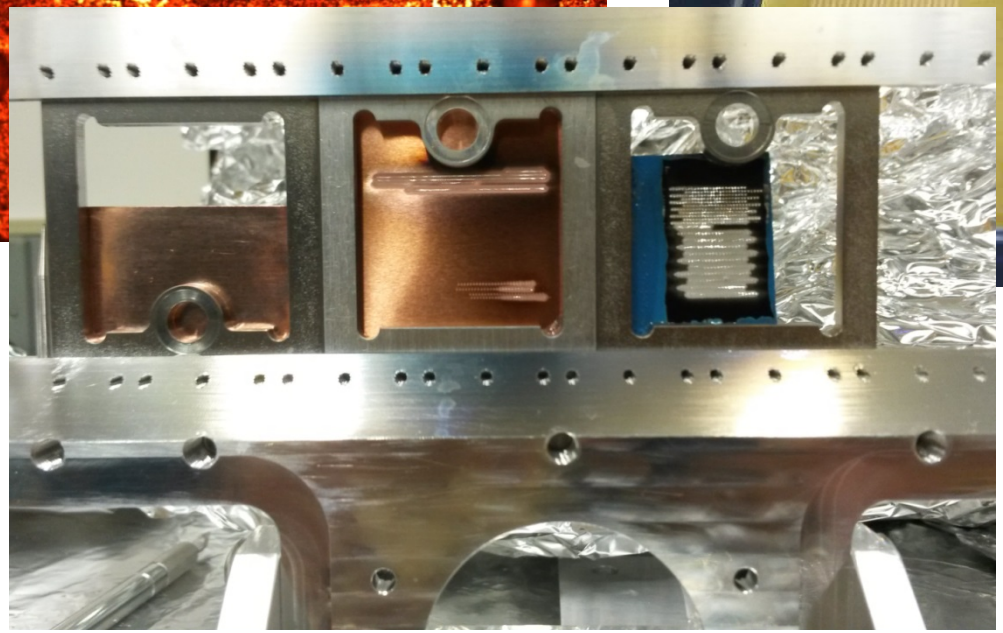
SLAC

Gold foils after shots



100 µm & 10 µm Au foils





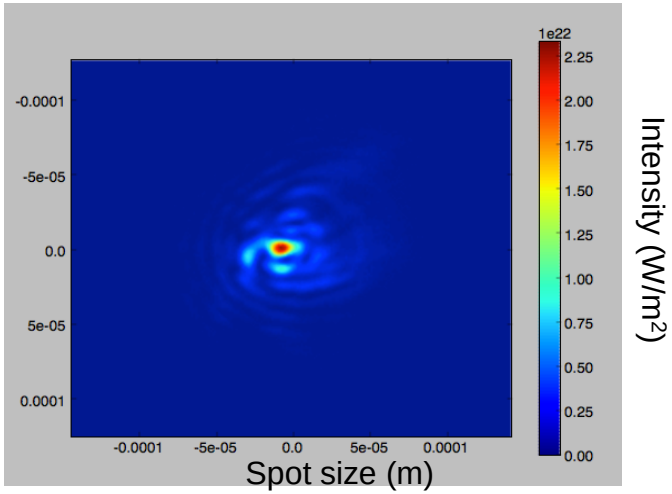
100 µm Cu plates

15 µm Ni nanowire

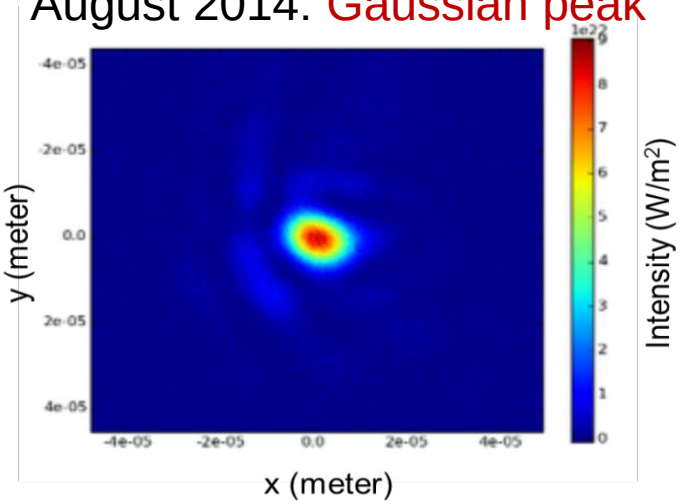
MEC Laser-Optic-Target Characterization (1 J, 25 TW)

	Feb. 2014	July 2014	August 2014	Sept. 2014
Intensity (W/cm^2)	2 x 10^{18}	1 x 10^{18}	1 x 10^{19}	7 x 10^{19}
Main peak energy on target (J)	0.2	0.7	0.7	0.3
Pulse length (fs)	70	50	50	50
1/e^2 radius HxV (μm)	13 x 8	37 x 19	11 x 9	3 x 2
Target	100 μm Cu	5 & 100 μm Cu 15 μm Ni nanowire	100 μm Cu 15 μm Ni nanowire	10 & 15 μm Al 5 μm Au and Cu 2.5 & 5 μm CH_3

Feb. 2014: Bimodal peaks

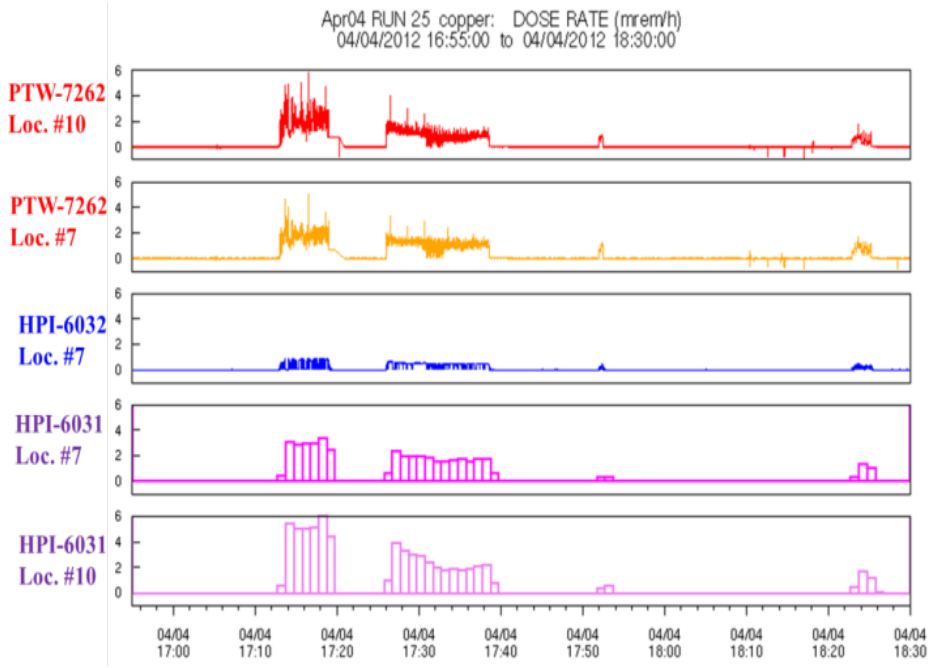


August 2014: Gaussian peak

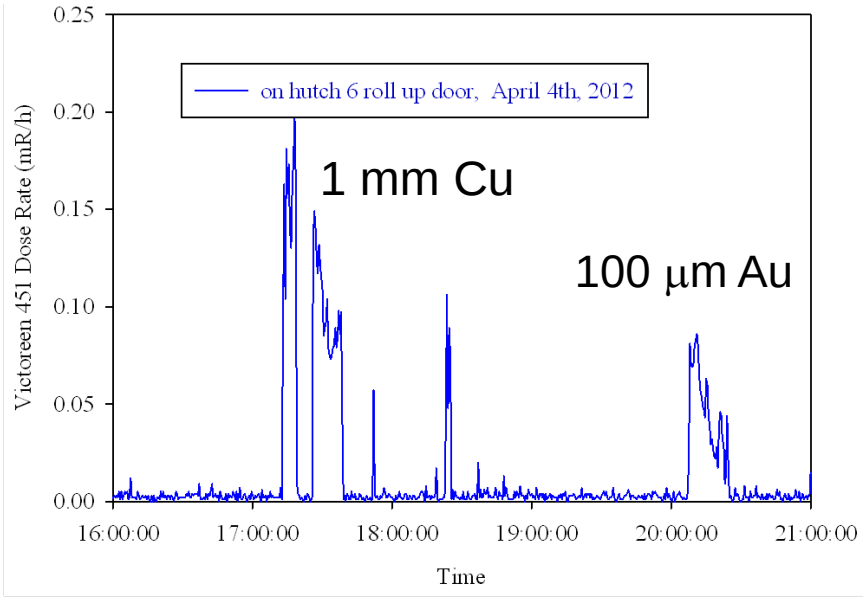


SLAC PUB-15973
RP 14-23
RP 15-04

Photon Dose Rate Measurements



$6x10^{17}$ W/cm^2, 30 mJ
10 Hz



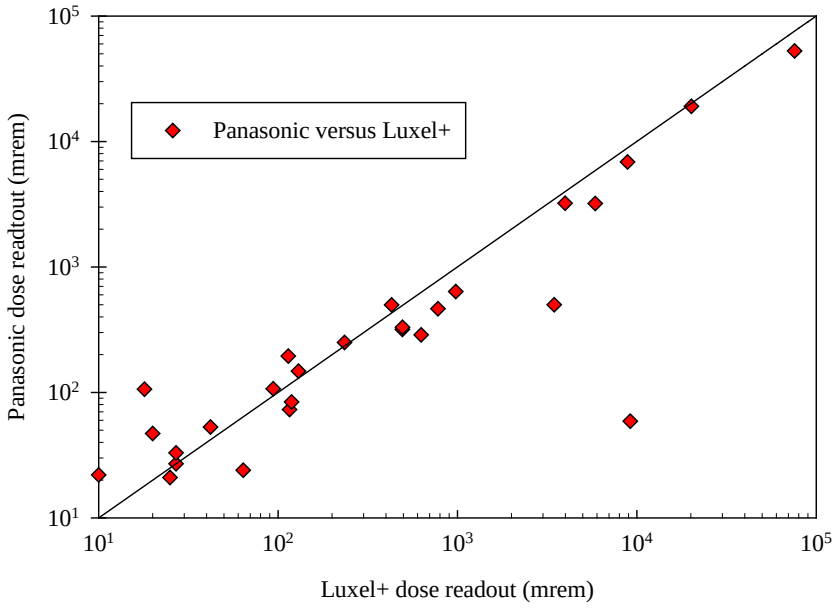
Passive and Active Detector Performance at LLNL

2011 at Titan (*RP-11-11*):

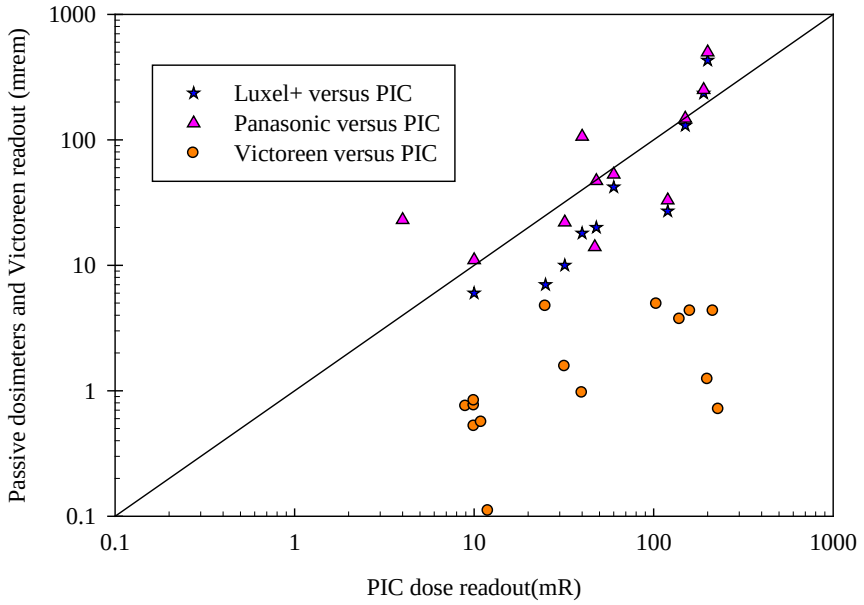
- $1x10^{20}$ to $6x10^{20}$ W/cm^2
- 50 - 400 J
- Single shots
- CH foam with Au foil backing

Active detectors, e.g., Victoreen 450 meters, affected by EMP (from laser and/or plasma)!

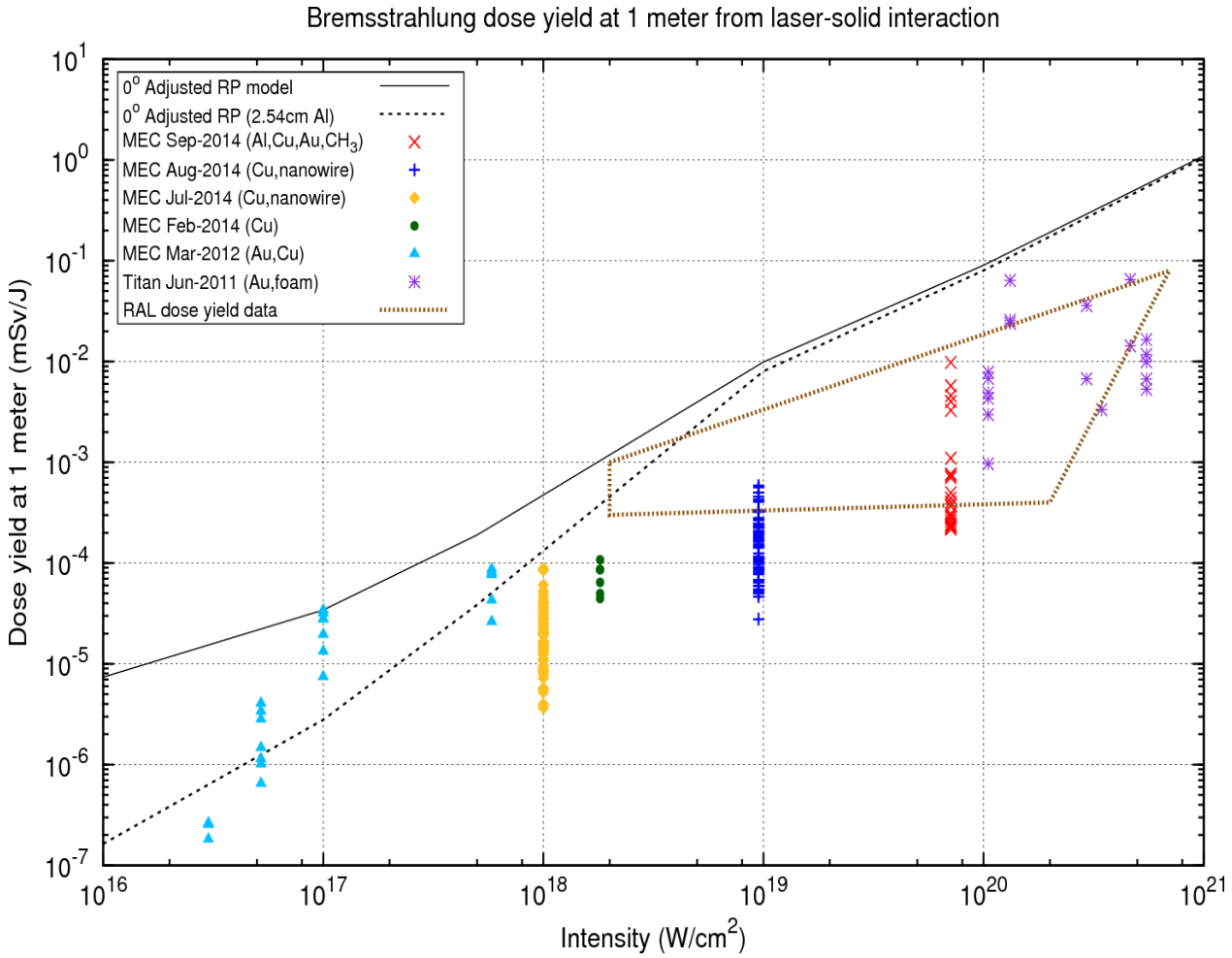
TLD agreed with OSLD



PIC agreed with TLD/OSLD

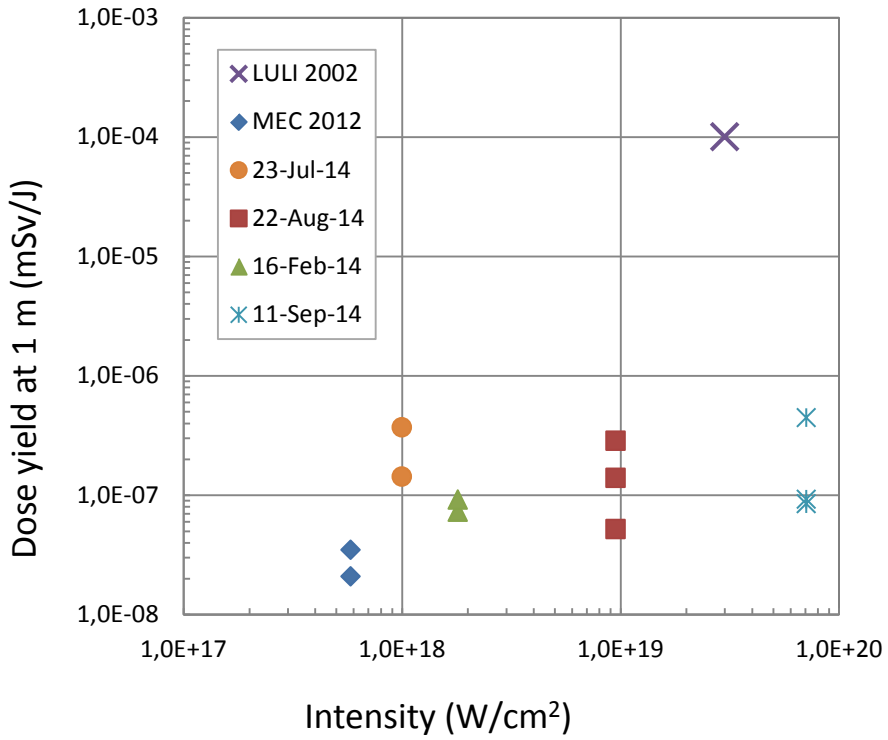


Complete Measurement Data for 10^{16}-10^{21} W/cm^2 with Adjusted RP Dose Yield Model



- Original RP model was adjusted based on measurements (account partly for electron angular distribution)
- Measurement is still 1/10 of adjusted RP model at 10^{19} W/cm^2 and 1/3 at 10^{20} W/cm^2 (due to electron spectrum model)
- Adjusted RP model used for shielding design

Neutron Doses



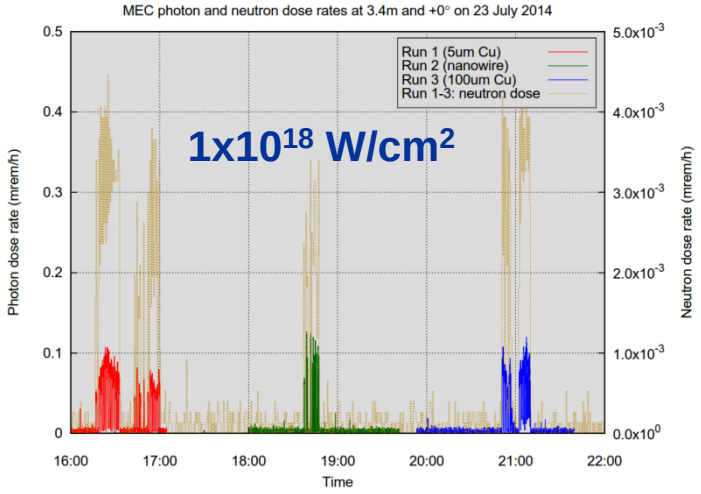


Figure 15: Victoreen 451 and BF_3 photon and neutron dose rates at 3.4m and +0° on 23 July 2014 ($I = 1.0 \times 10^{18}$ W/cm^2, 0.7 J in 50 fs at 1 Hz)

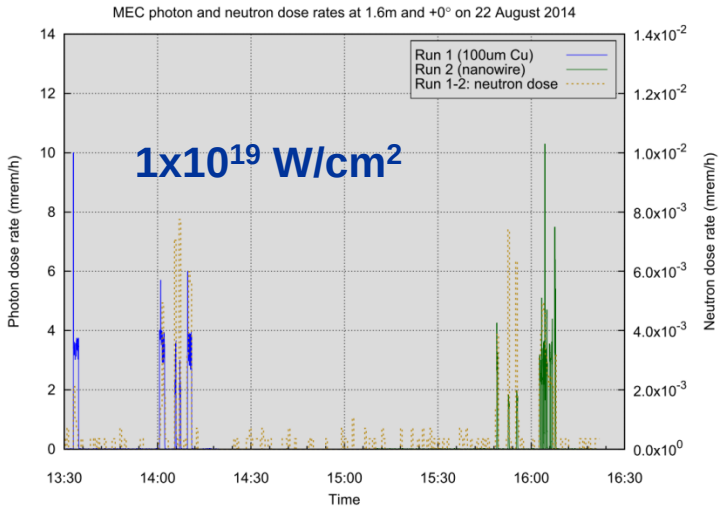
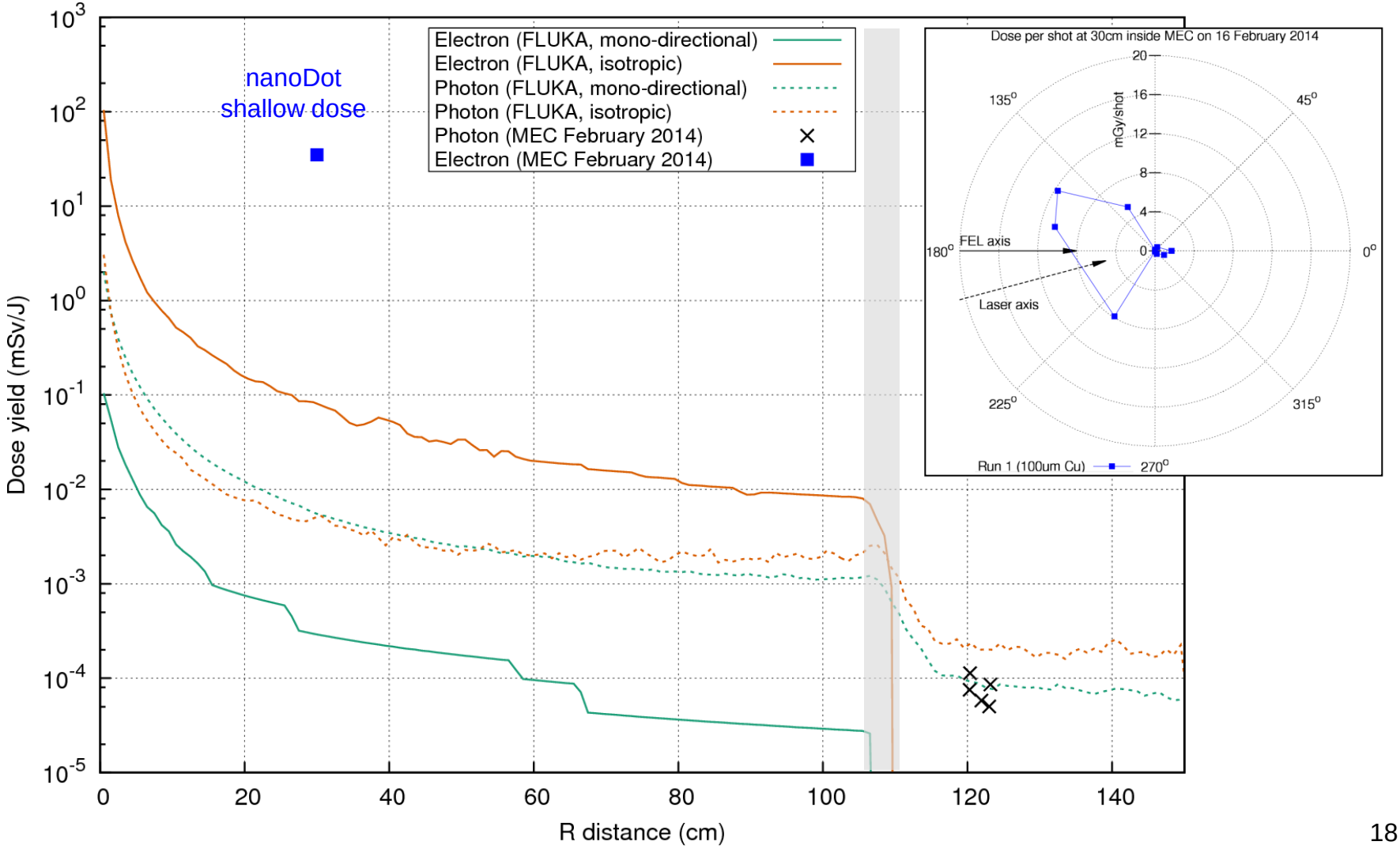


Figure 19: Victoreen 451 and BF_3 photon and neutron dose rates at 1.6m and +0° on 22 August 2014 ($I = 1.0 \times 10^{19}$ W/cm^2, 0.7 J in 50 fs at 1 Hz)

- Correlation between neutron and photon
- Nearly isotropic angular distribution

Dose Comparison between FLUKA and Measurements



Current Work

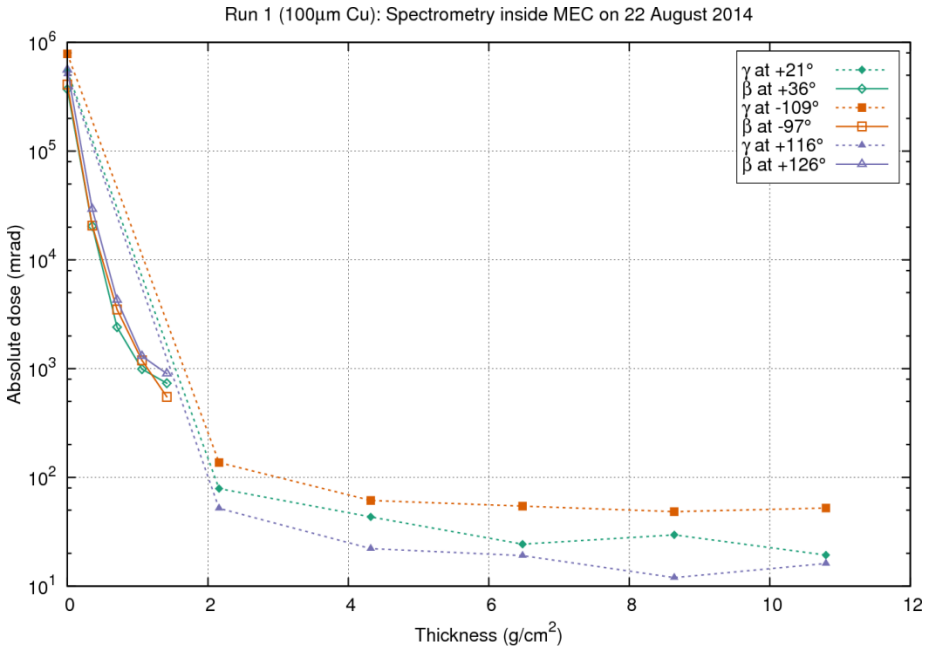
- Refine hot electron source term

	Current Model	Refined Model
Laser to hot electron conversion	30% or 50%	Lower for < 10^{19} W/cm^2
Hot electron energy distribution	Maxwellian and Rel. Maxwellian	?
Hot electron angular distribution	Mono-directional	Emitted in 4π, Not Isotropic

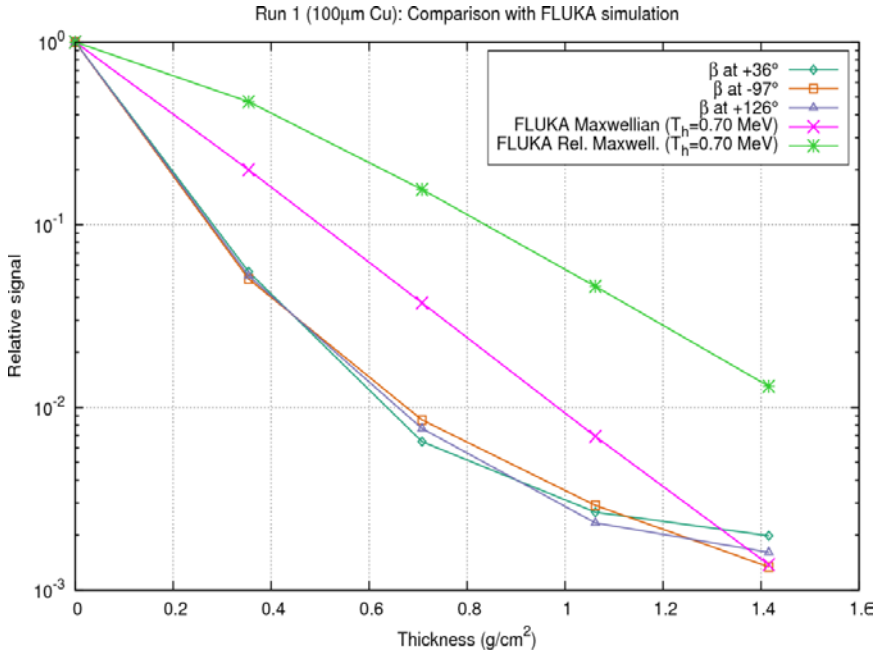
- Refine photon dose yield model
- Refine shielding attenuation

By comparing electron spectrometry results with FLUKA simulation and PIC calculations

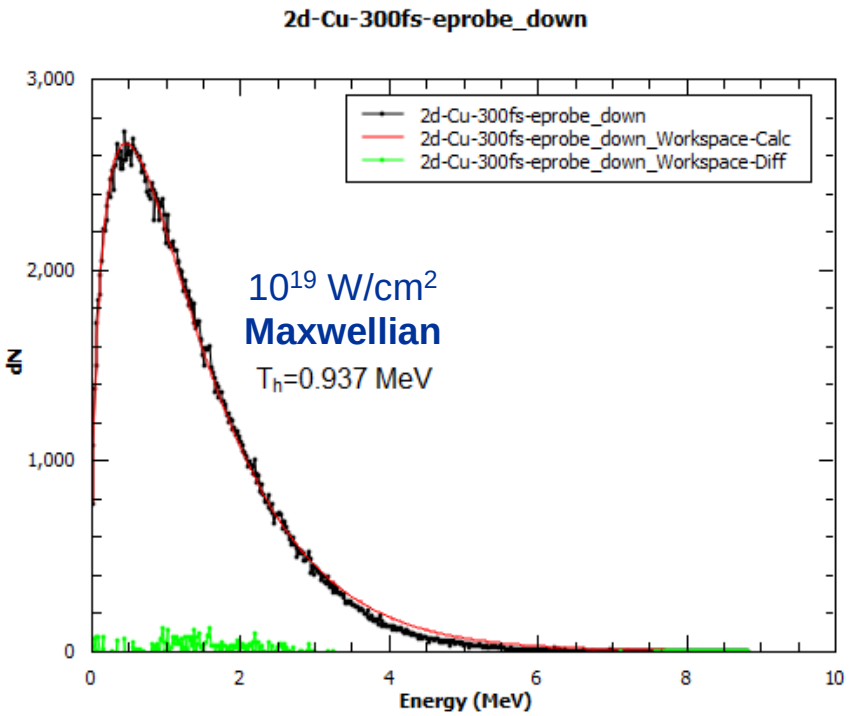
10^{19} W/cm^2, T_h = 0.70 MeV
100 μm Cu foil (0.7 J, 340 shots on target)



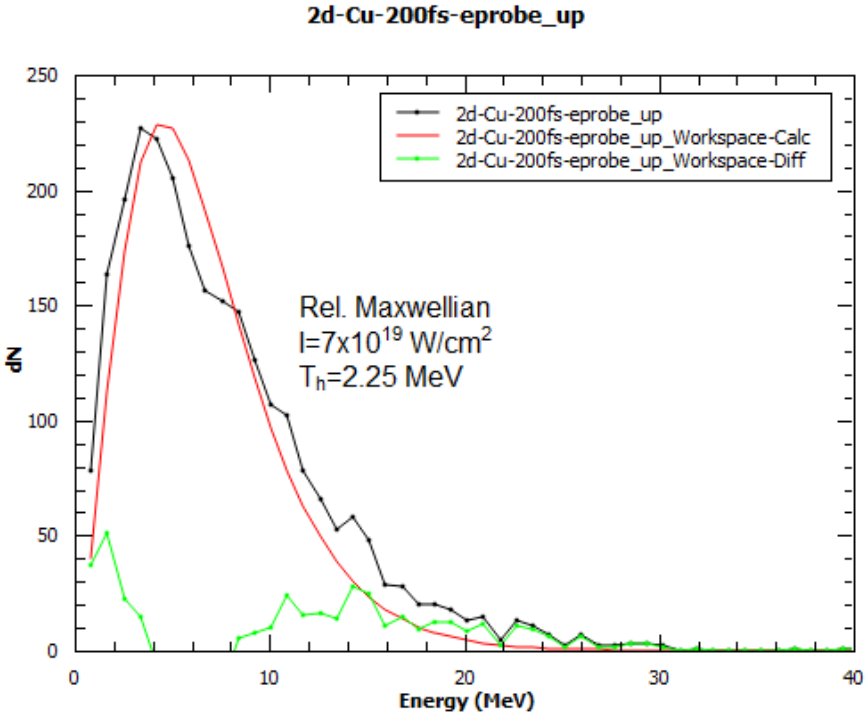
FLUKA simulation with T_h = 0.70 MeV shows Maxwellian spectrum agrees better with measured depth-dose curves



Electron Spectrum Shape and T_h from PIC Calculations



Ponderomotive formula gives
T_h = 0.70 MeV

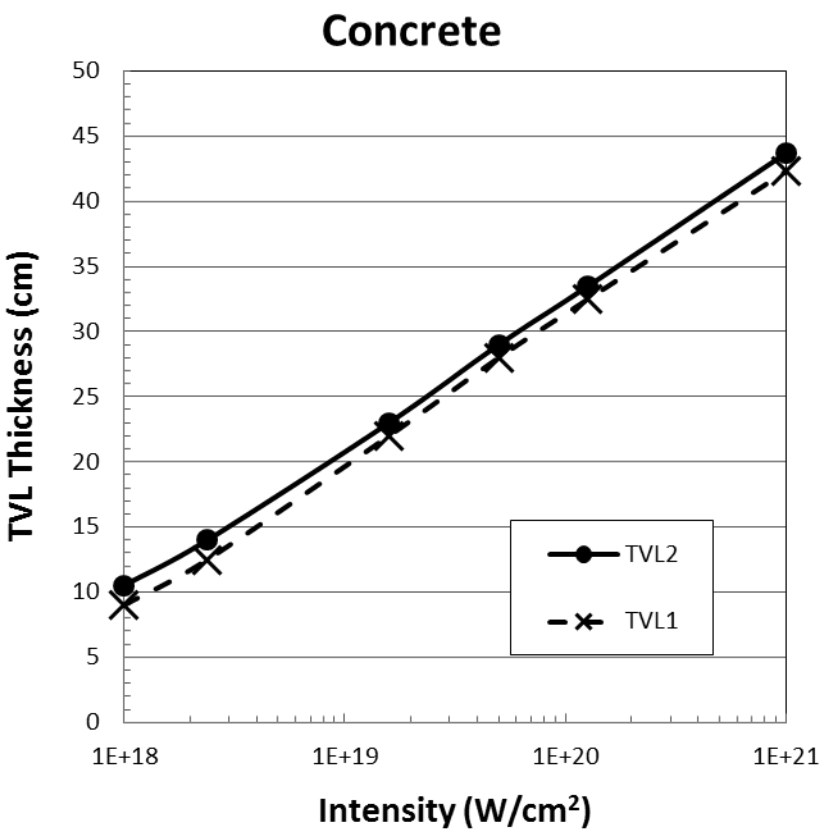


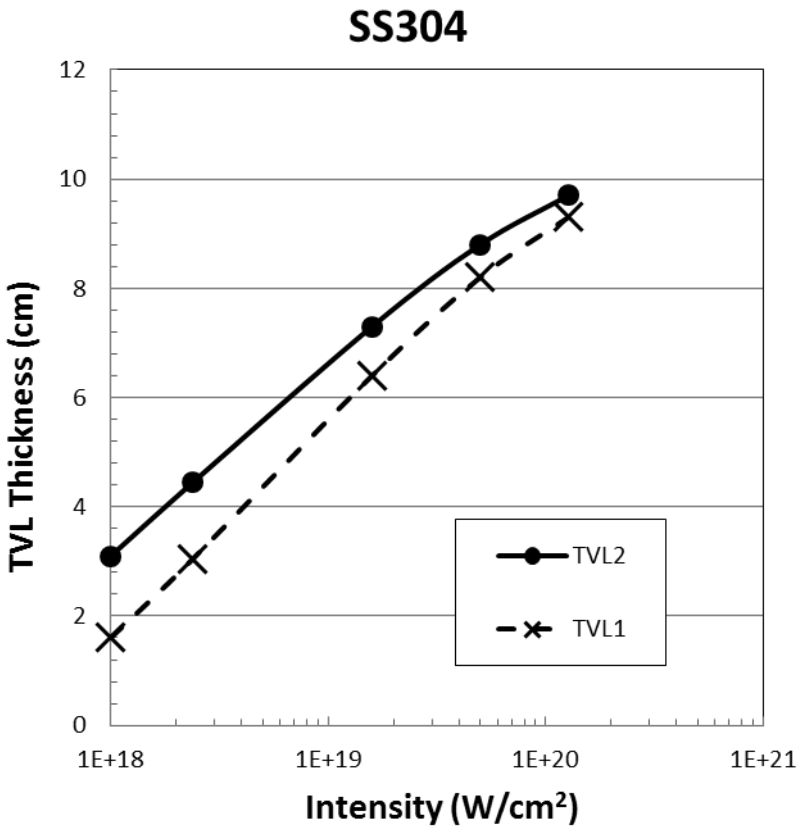
Ponderomotive formula gives
T_h = 2.4 MeV

PIC (particle-in-cell) is a multi-dimensional, fully electromagnetic, relativistic code that simulates higher energy density physics such as the generation of plasma from a high intensity laser interacting with matter.

Shielding Tenth Value Layer (TVL)

- FLUKA calculations with Maxwellian photon spectrum
- Approaching equilibrium TVL at high intensities

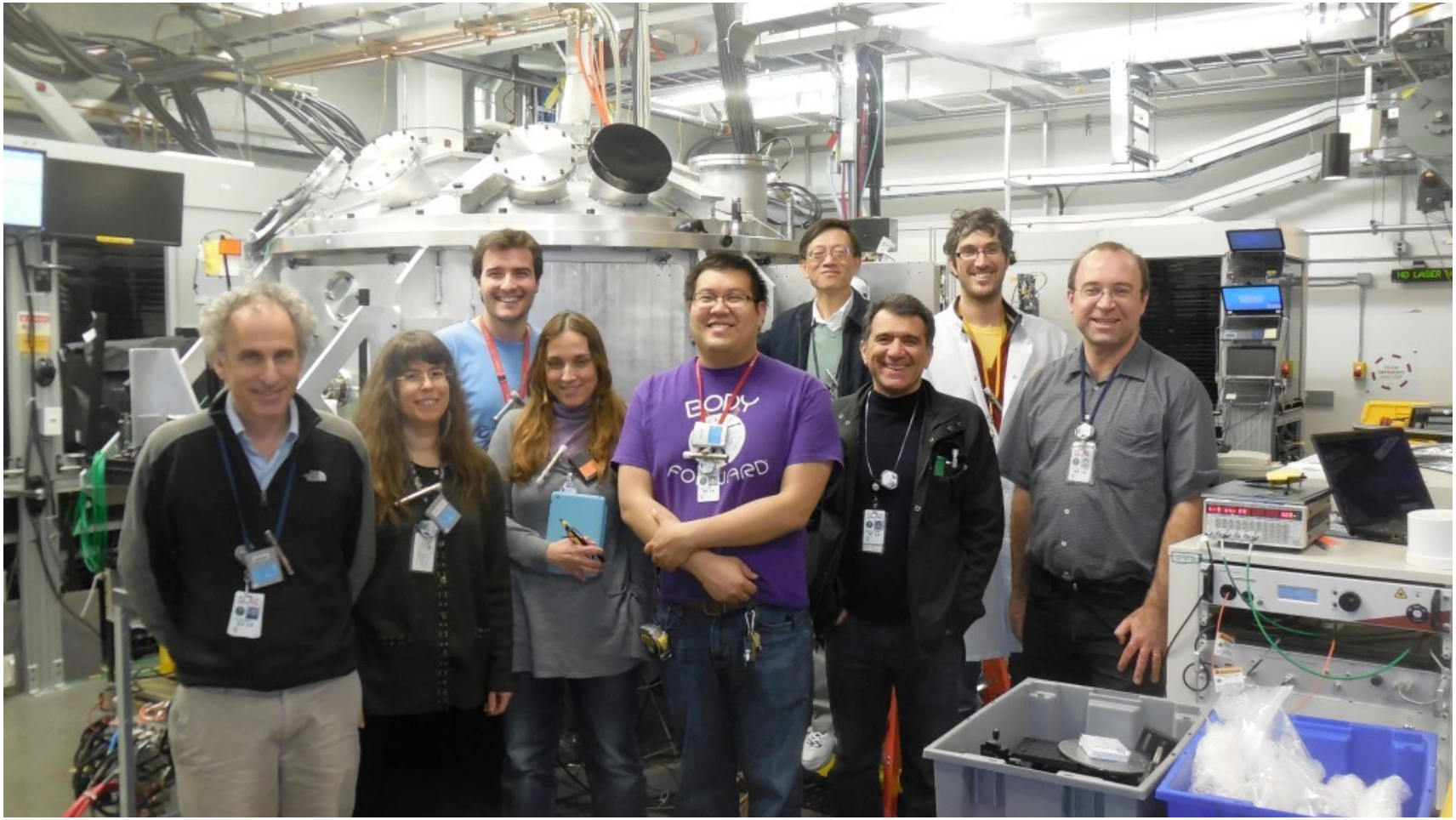




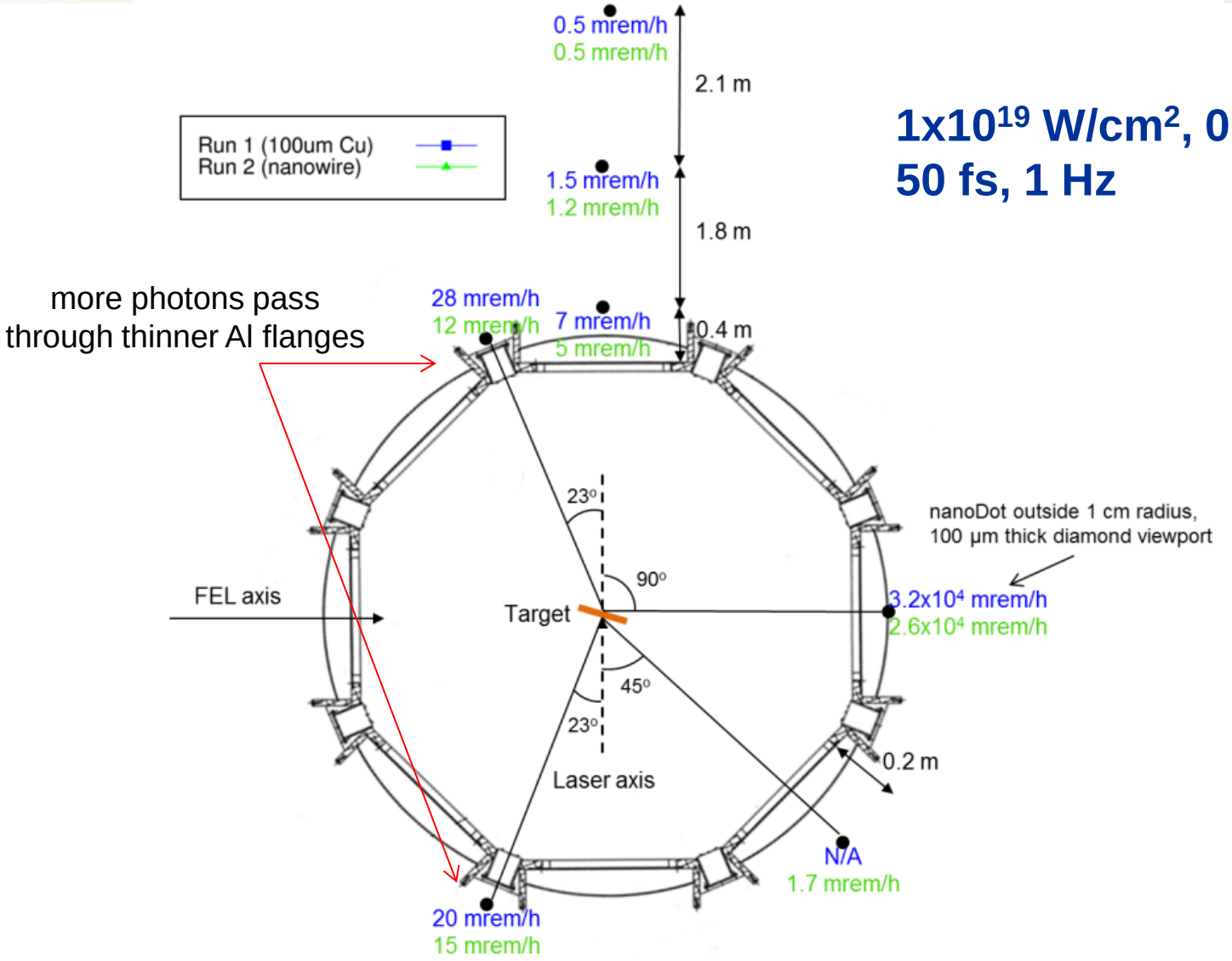
Summary

- Systematic and comprehensive **measurements** performed for laser focused onto solid targets between $3x10^{16}$ to $6x10^{20}$ W/cm^2
  - Various types of active and passive dosimeters
  - Characterization of laser and optic parameters
  - Photon doses detected starting at $3x10^{16}$ W/cm^2
  - Low **neutron** doses detected starting at $6x10^{17}$ W/cm^2
  - High doses from low-energy electrons inside chamber
- **RP photon dose model adjusted** to be reasonably conservative based on measurements (still overestimates by x10 at 10^{19} W/cm^2)
- **Hazard analysis and controls,** including shielding and interlocked system, for MEC user experiments and future PW facility
- Work on electron source terms with PIC/FLUKA and photon TVLs with FLUKA

Thank You!



Maximum Photon Dose Rates from Victoreen 451



$1x10^{19}$ W/cm^2, 0.7 J
50 fs, 1 Hz