Center for Energy Research

UC San Diego

"Characterization of laser-produced plasmas in the 1-6 nm region using cryogenic Xe targets"

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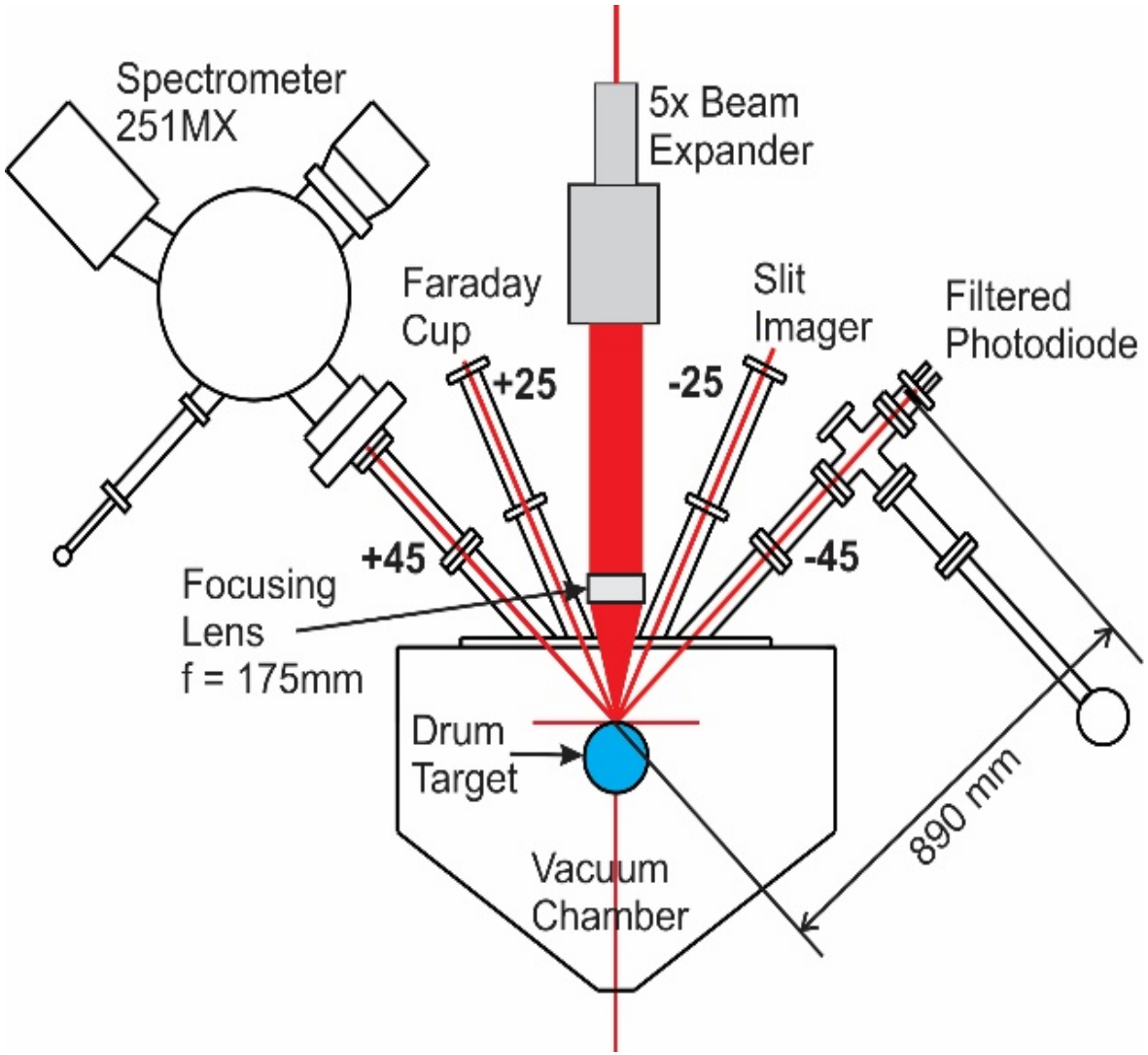
Experimental Set-up

Ekspla 355SL – 1064nm, 130-600ps up to ~300mJ on target (up to ~$5x10^{14}$ W/cm^2)

Quanta-Ray Pro – 1064nm, 6.5ns, up to ~2 J on target (up to ~$1x10^{14}$ W/cm^2)

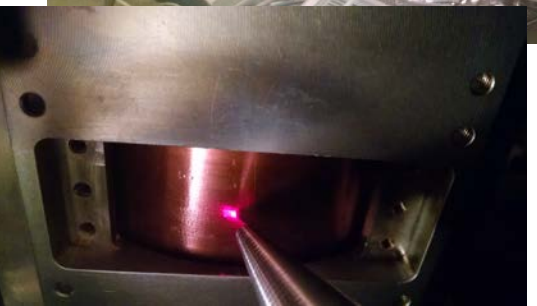


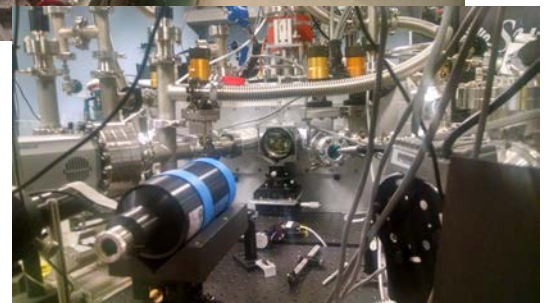
Two target systems for cryogenic Xe

LN2-cooled rotating drum

- Operates at 90 K with Xe flow 50-150 sccm
- Drum rotates at 100 rpm, and scans vertically
- 500μm thick mechanically-smoothed Xe ice layer

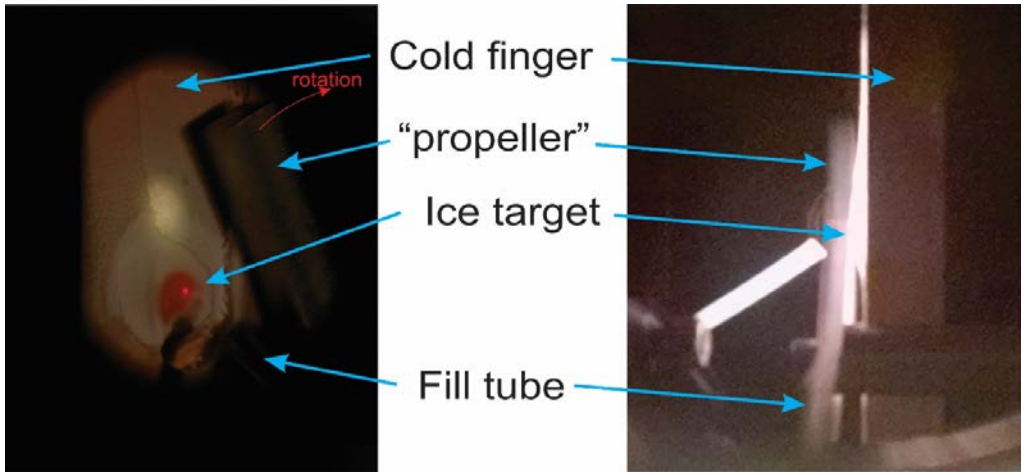
Fukugaki *et al, Rev. Sci. Instrum.*, **77**, 063114 (2006)





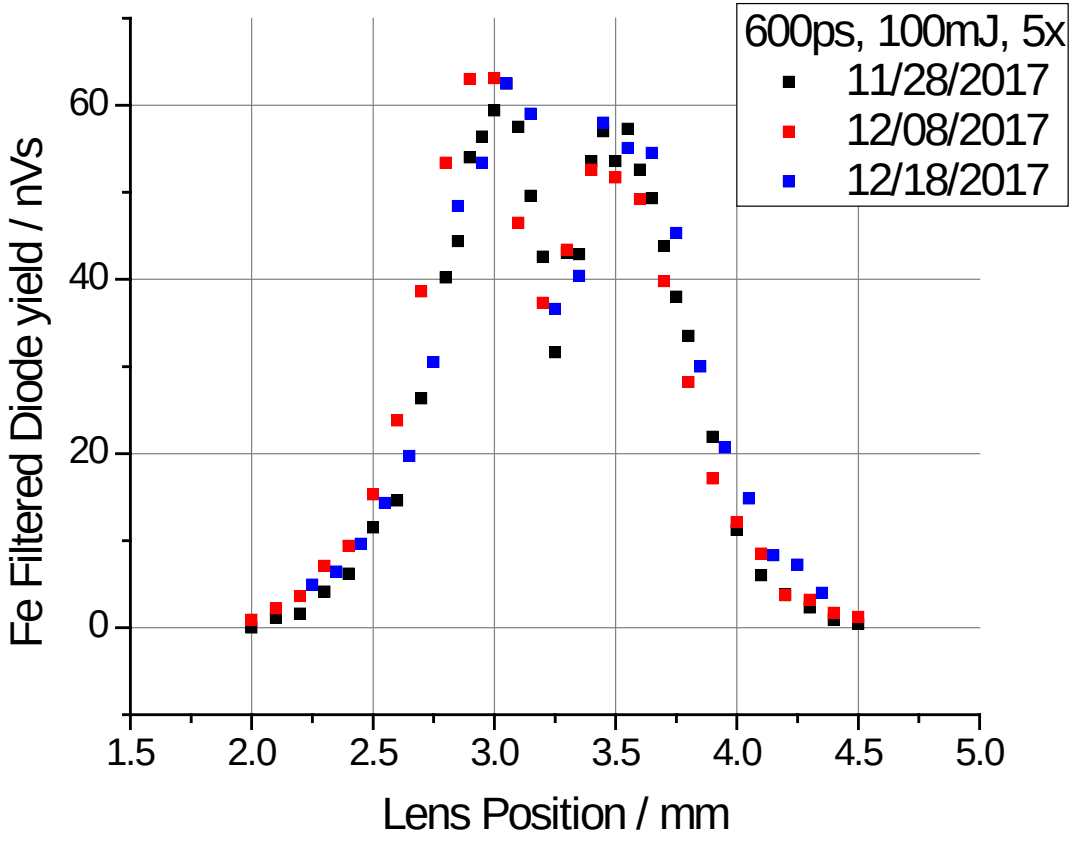
LHe-cooled cold finger + propeller

- Typically cools to 50 K for expts (11 K possible)
- Ice forms in cavity, several mm thick
- Propeller blade rotates continuously and defines ice surface position
- Xe flow on to repair ice surface between shots (90 secs), and off for shots to specified vacuum level (< $5x10^5$ torr)

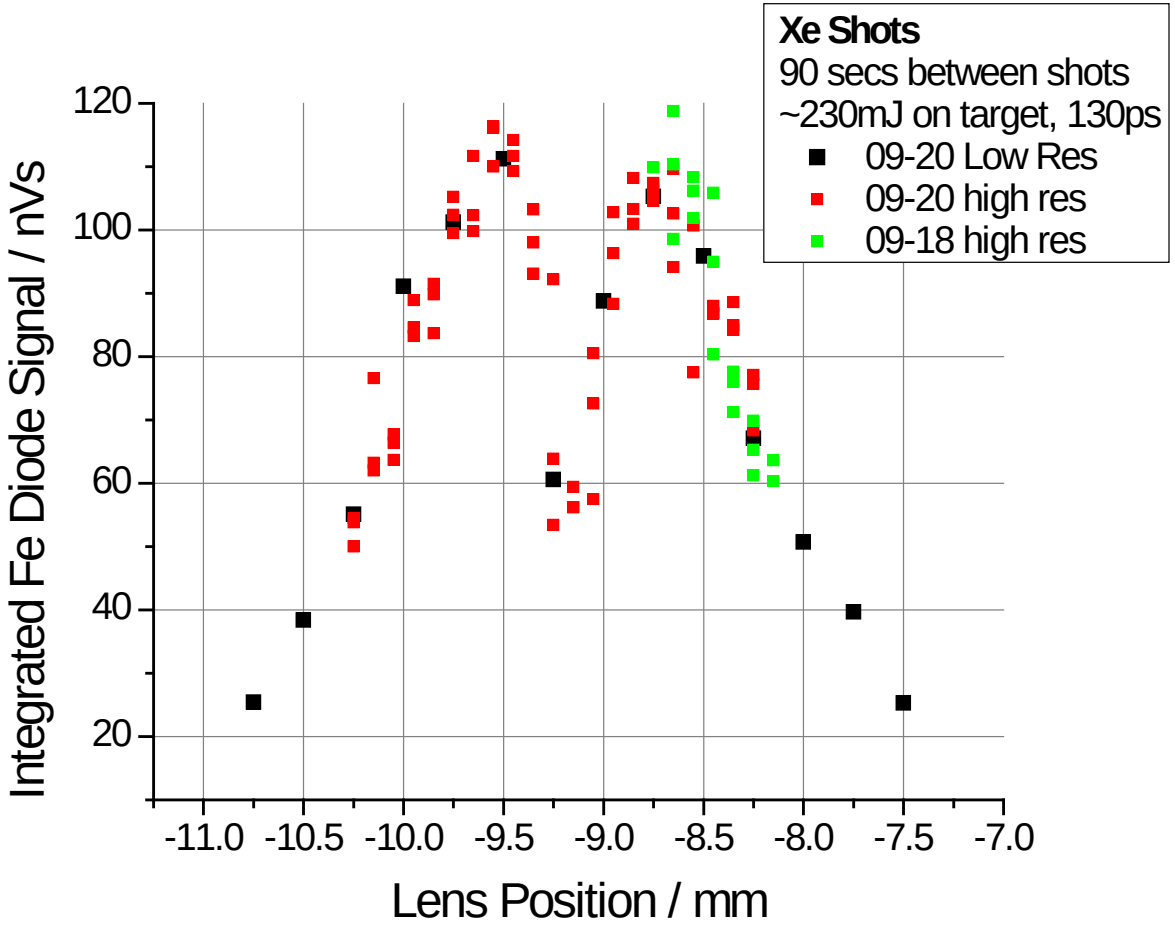


Amano *et al, Rev. Sci. Instrum.*, **85**, 063104 (2014)

Both system show excellent repeatability of yield over the lens focusing range

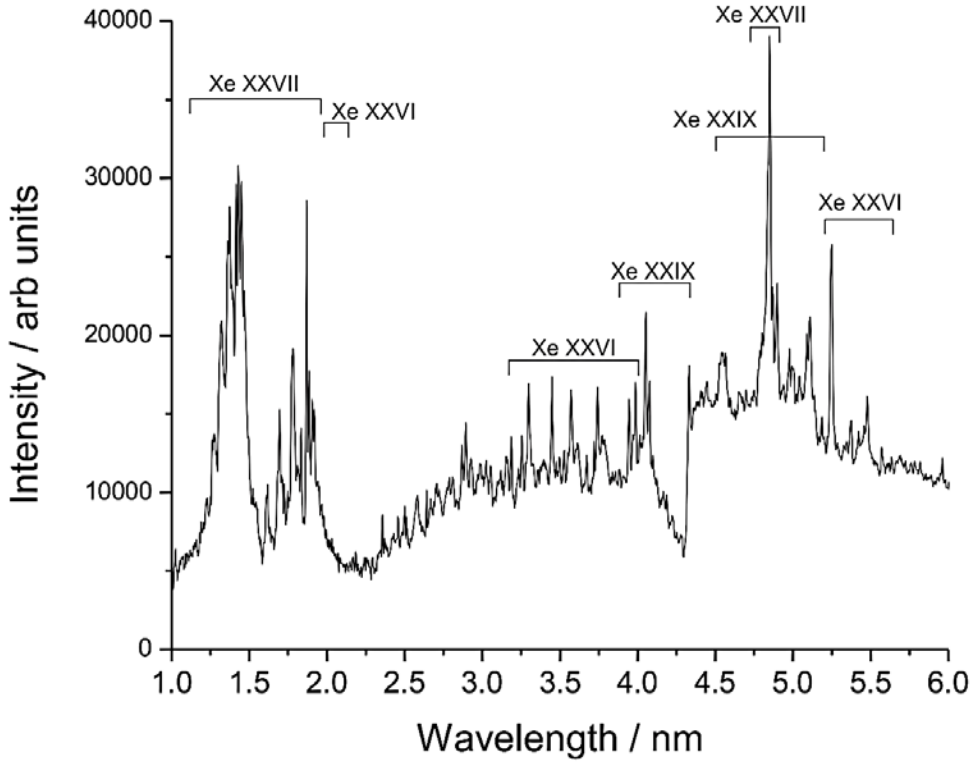


Drum Target



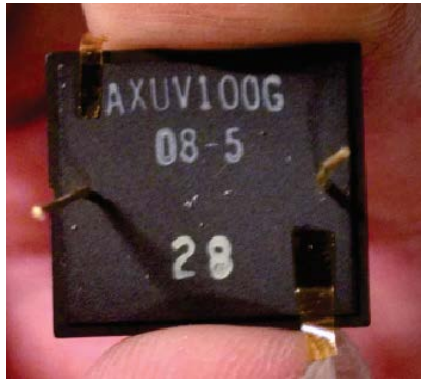
Propeller Target

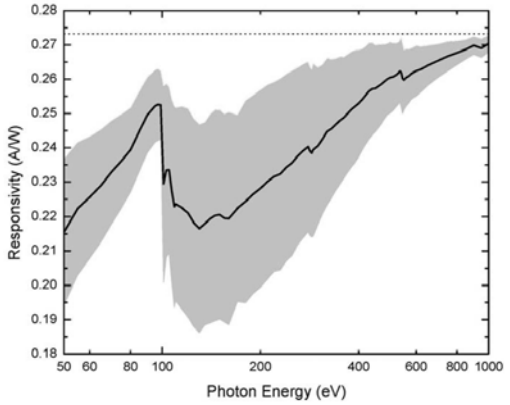
Cross calibration of spectra with diode traces

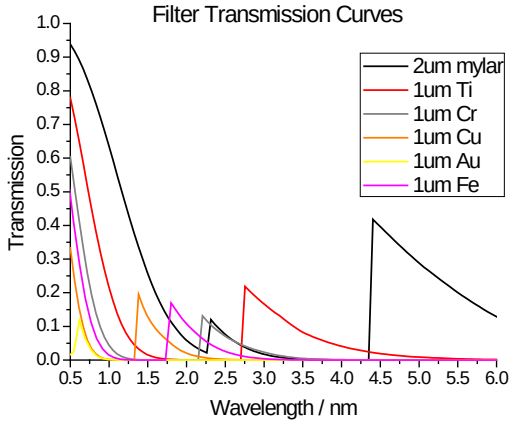


Grating Efficiency
CCD Efficiency
Filter transmission

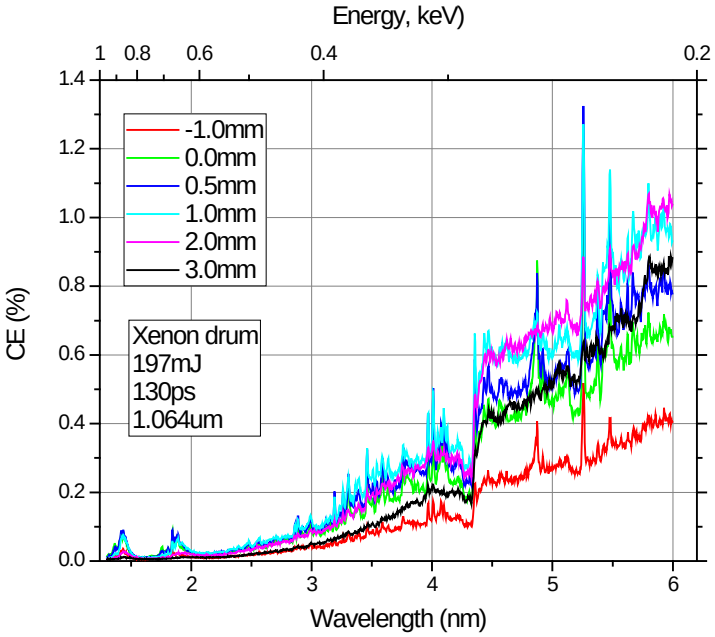
Absolute Conversion Efficiency

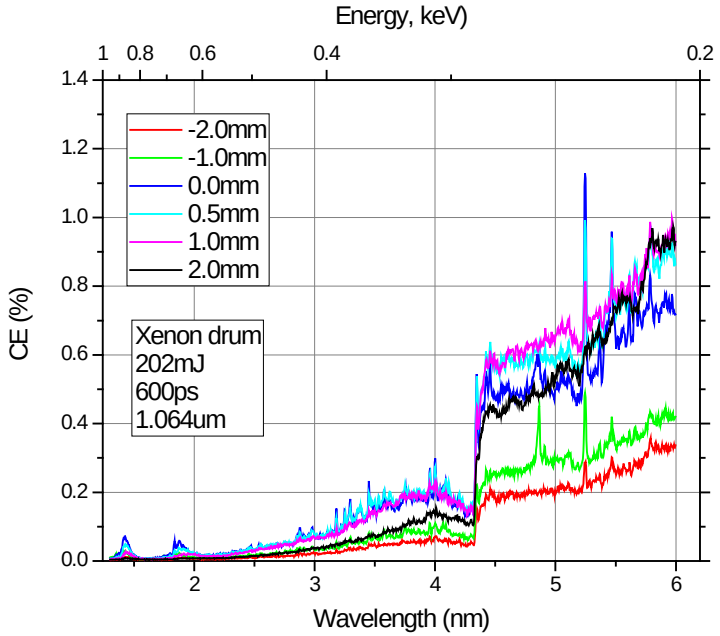


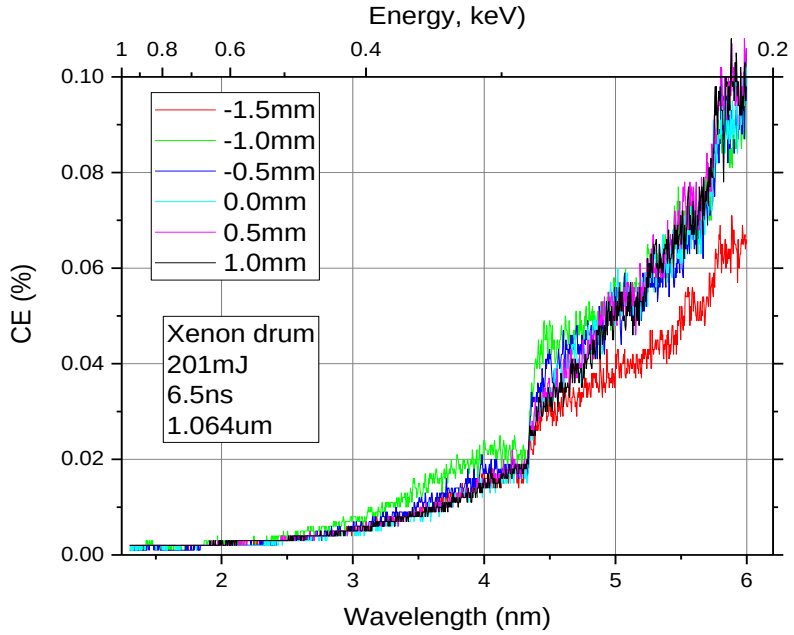




Variation of Conversion Efficiency with Laser Pulse Length

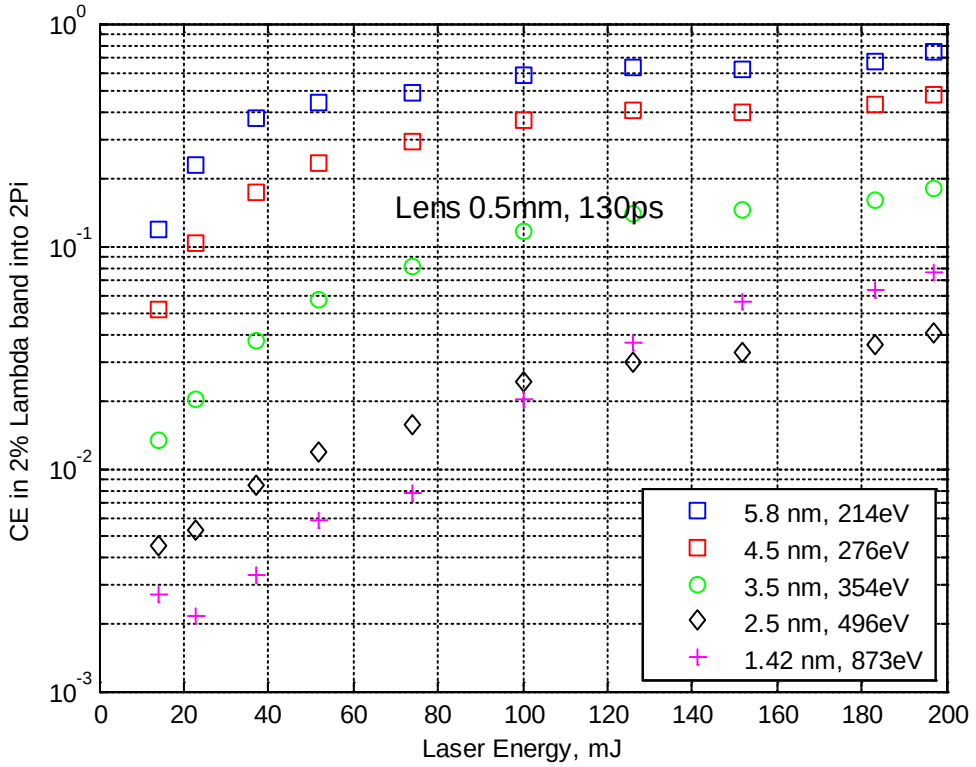


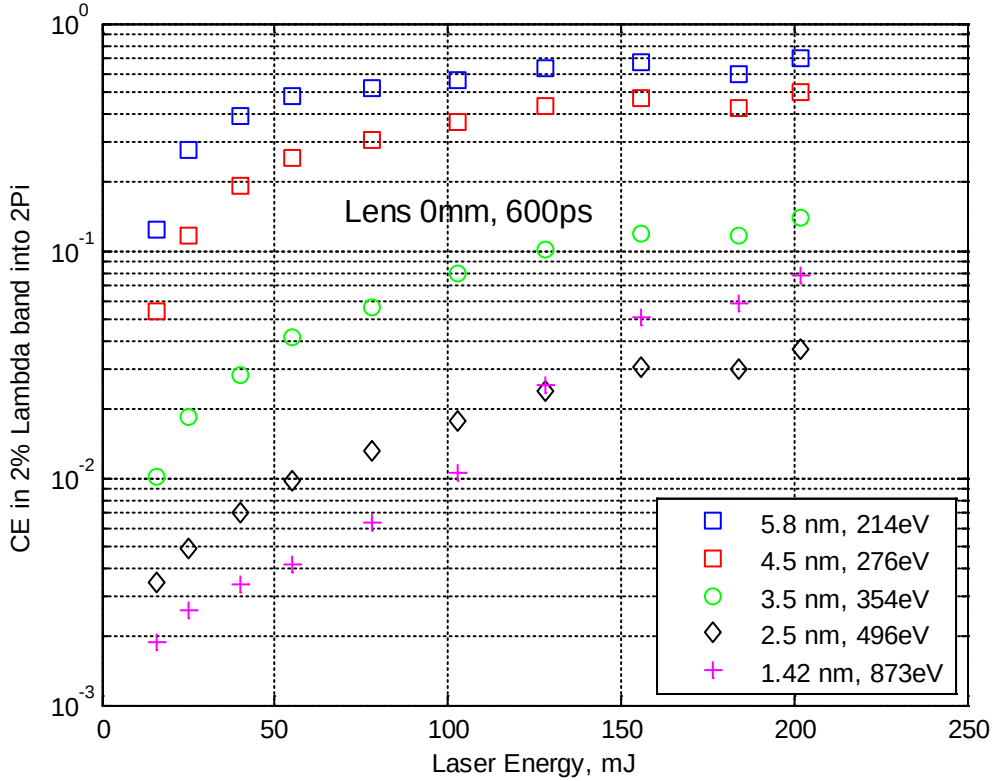




- Maximum observed CE is about same for 130ps and 600ps pulses. Variation of CE with energy and beam spot is similar for both pulse durations.
- For 6.5ns pulse length, short wavelength (<3nm) lines, essentially eliminated
- Absolute CE at 6nm (~200eV) is about 1%
- For short wavelengths (1.4nm, 870eV) the best observed CE~0.08%

Energy Requirements for peak conversion efficiencies

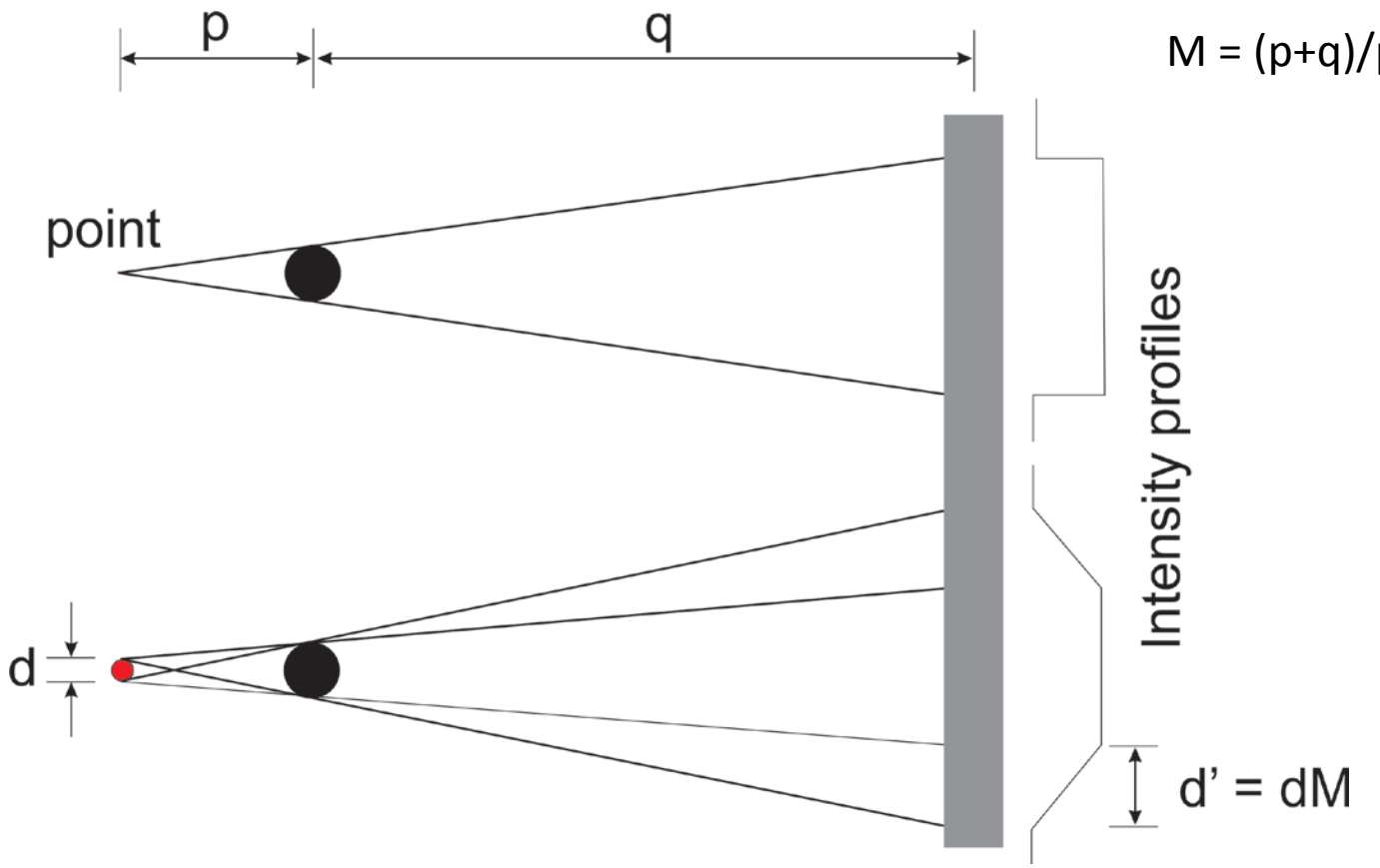




- Observed CE scales with incident laser energy – again similar trends for 130ps & 600ps
- Energy of >100mJ on target is required for achieving peak CE at shorter wavelength
- Energy of >200mJ on target is required for achieving peak CE at shorter wavelength

Slit imager – point projection method

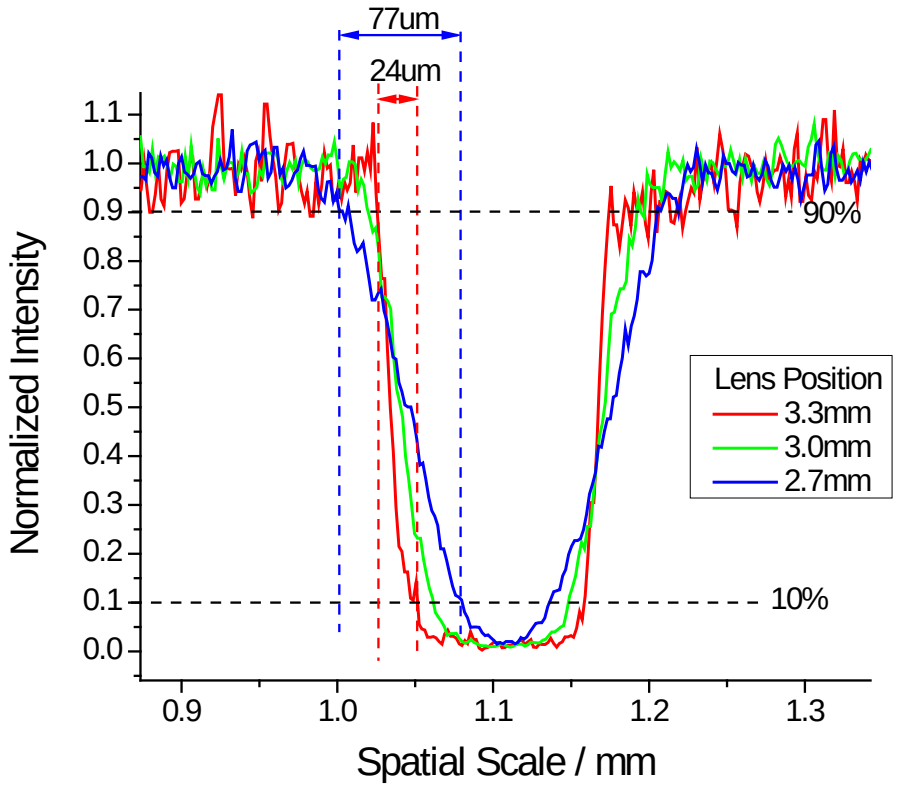
- Laser spot size is not necessarily the emission spot size, so measuring laser spot in may not be ideal, especially at higher intensities.
- Measuring the emission spot directly is more useful for metrology etc.
- Point projection backlighting can be use to directly measure the spot size, b measure the edge spread of an edge imaged at high magnification

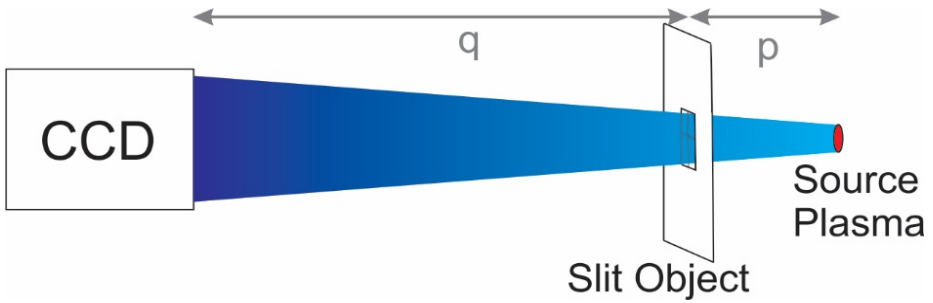


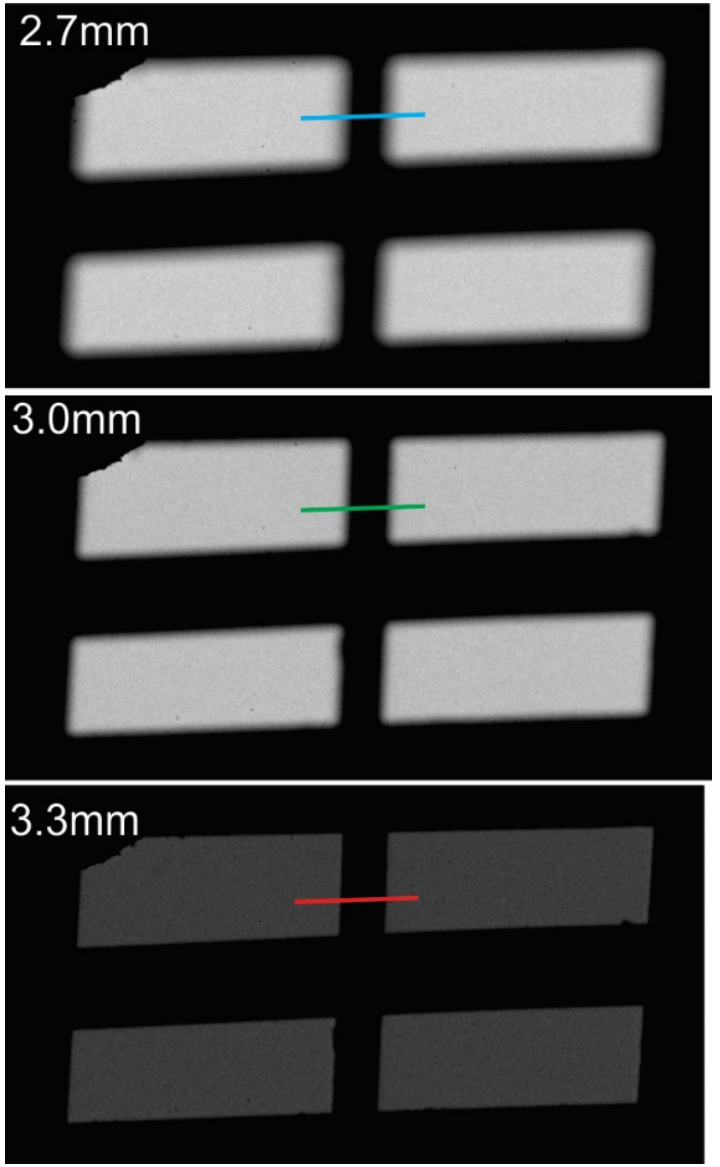
Pikuz *et al, Proc. SPIE 5196*, 25 (2004)

Slit imager – data analysis

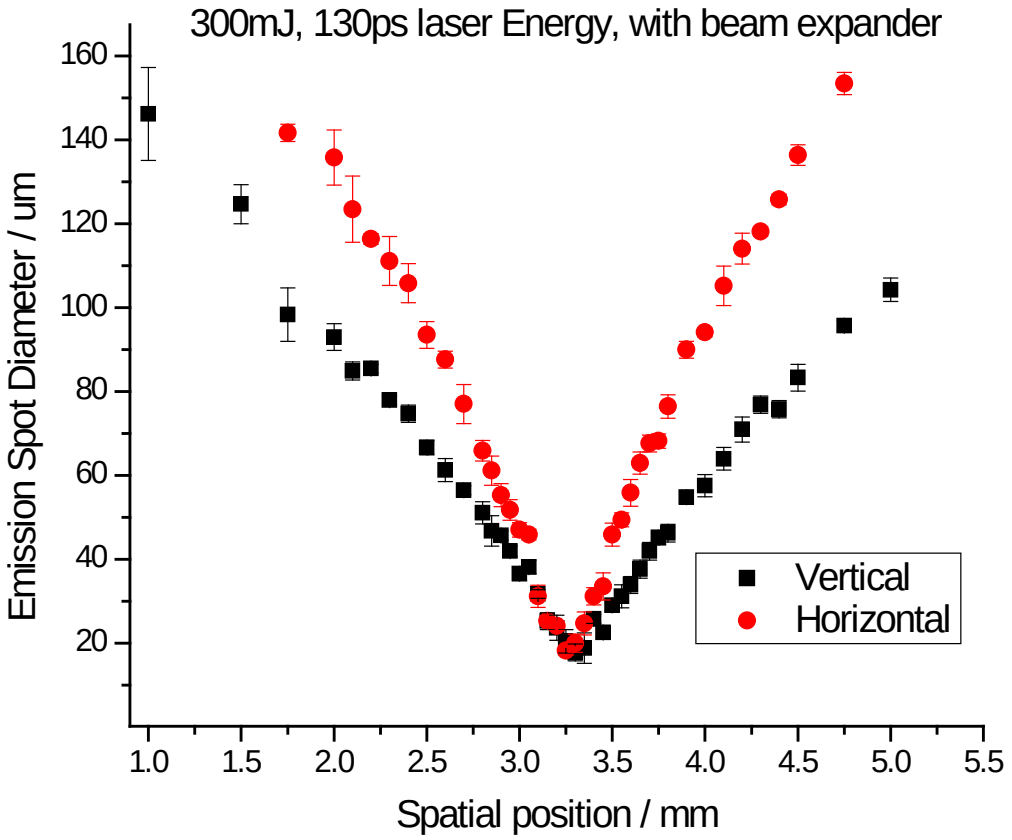
- Imaging target uses a ‘grid’ of wires to give multiple edge measurements
- Magnification = 6.2
- Errors dominated by determination of the magnification, and resolution across images (not better than 5%)

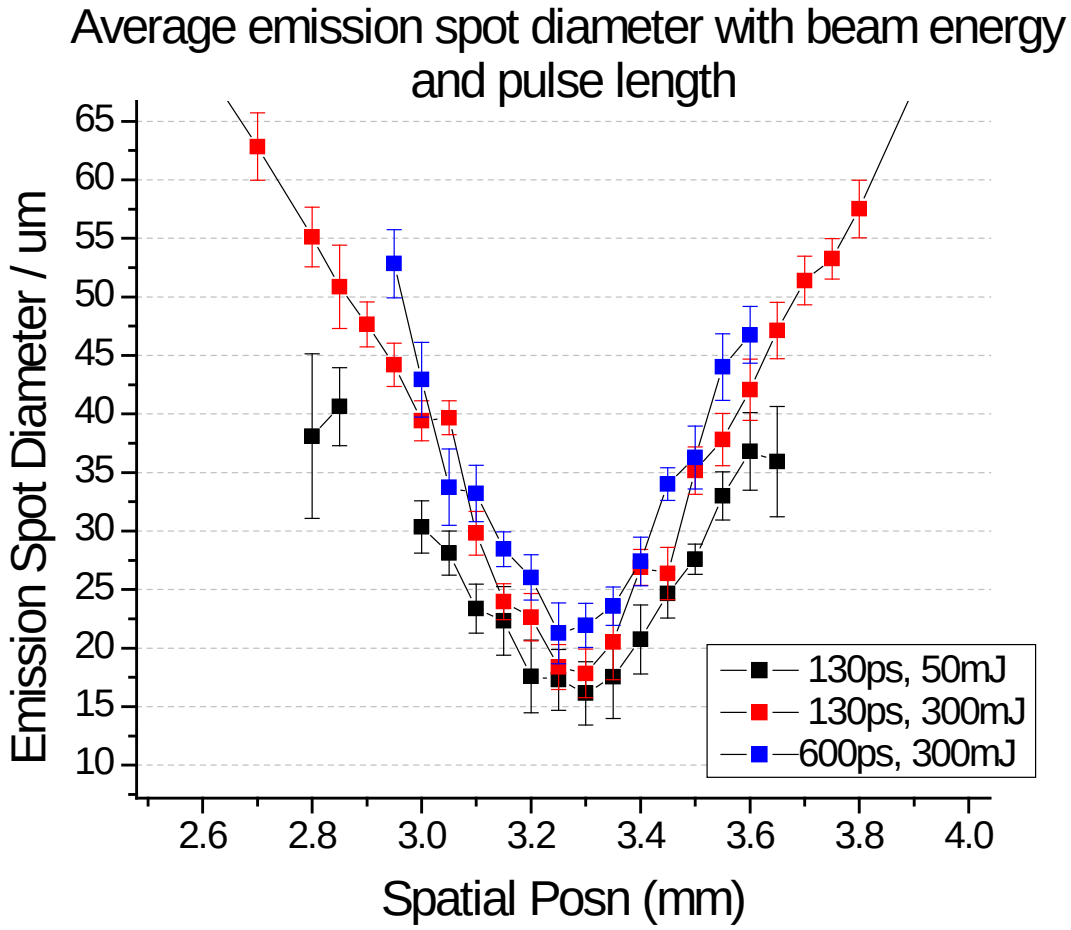






Slit imager results





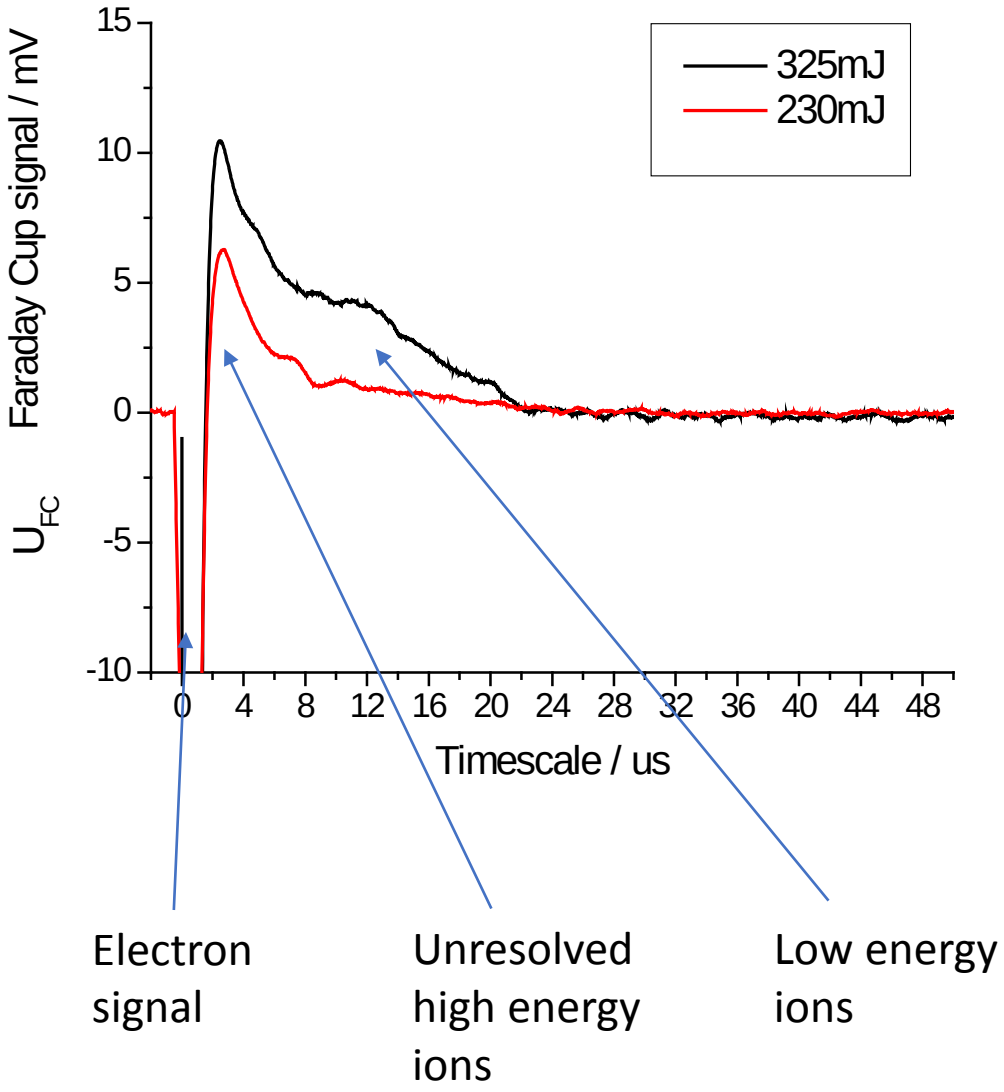
- Known beam asymmetry measured by slit images
- No clear trend with laser energy or pulse length

Ion Spectra Measurements

- FC Set at 470 mm from the target.
- A voltage of 100 V was applied to the retarding grid and -30 V to the suppression grid
- Low energy ions only (i.e. long TOF) due to FC placement (E_{ion} < few keV)

$$\frac{dN}{dE} = -\frac{m_{ion}^{\frac{1}{2}} x}{(2E)^{\frac{3}{2}} R_{osc} Ze} U_{FC}\left(\sqrt{m_{ion}\, x^2/2\, E}\right)$$

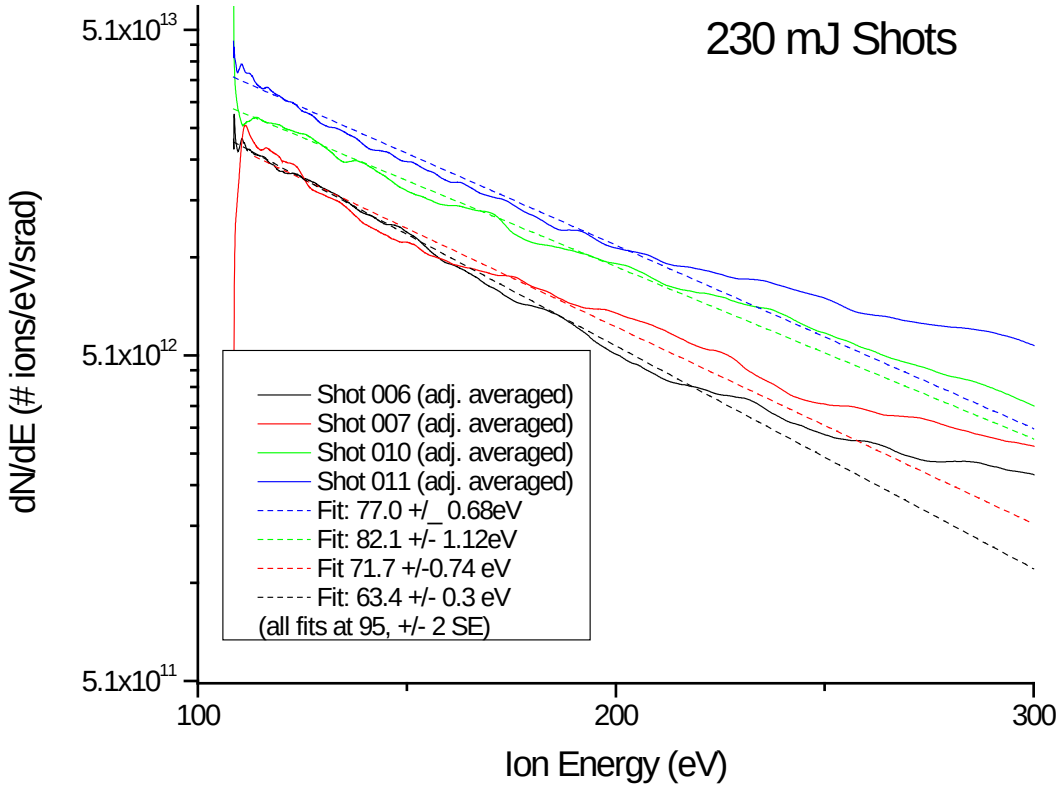
R_{osc} = 1kΩ, x = 470mm, Z assumed to be 5

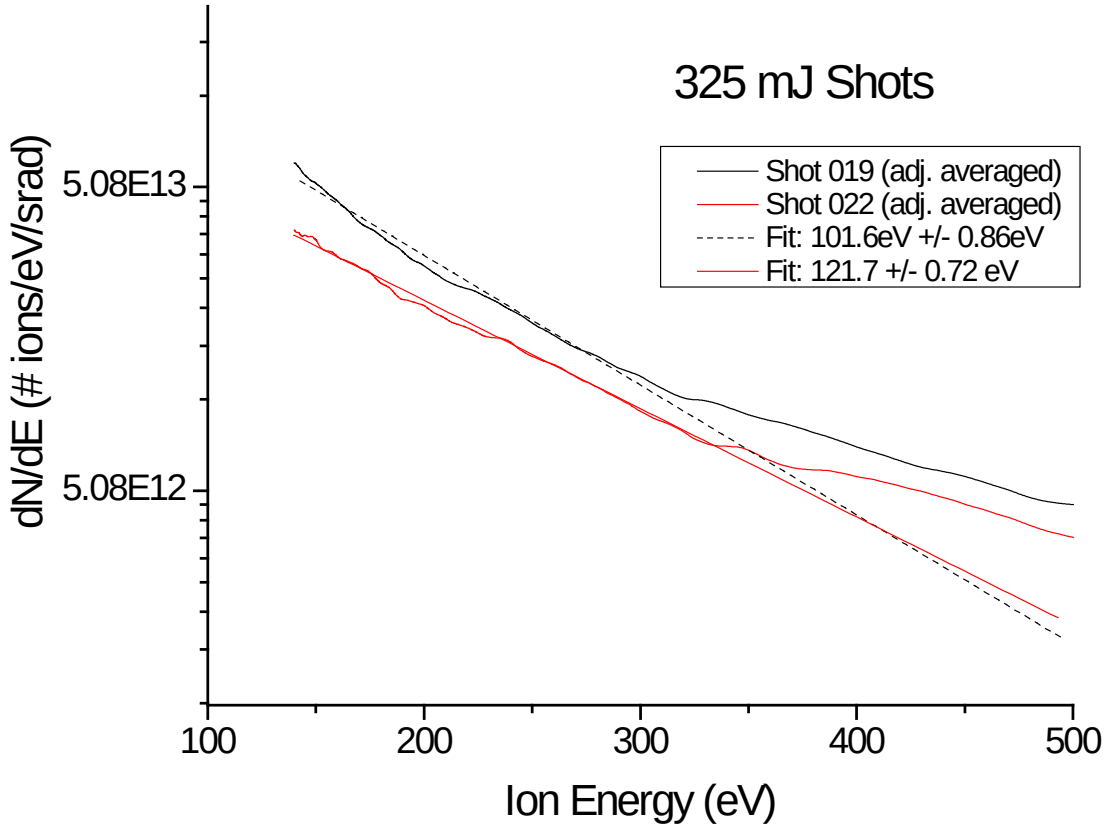


FC Data from drum target

- The low energy distribution is close to linear, for the first decade drop in ion number
- This suggest a single temperature plasma that can be fit assuming a Maxwellian distribution covering the bulk of the ion population

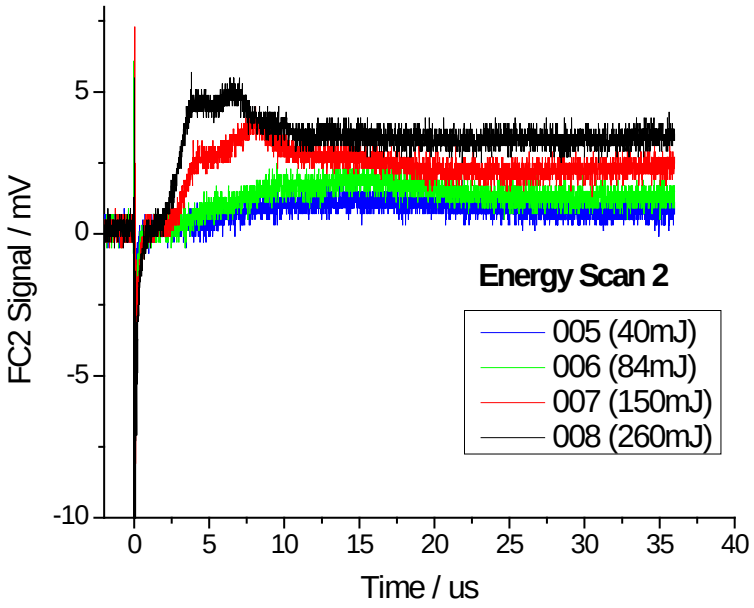
$$\frac{dN}{dE} = A_0 e^{-E/kT}$$



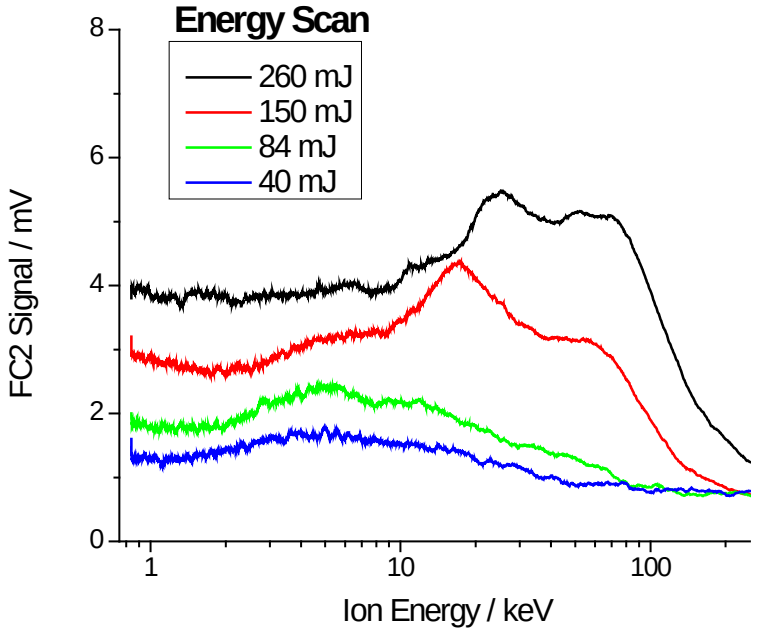


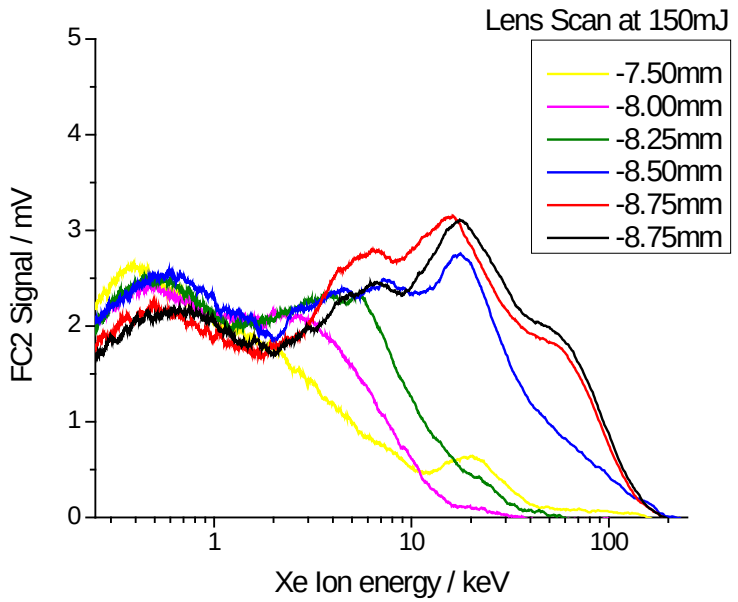
FC Data from Propeller Target

Raw Data



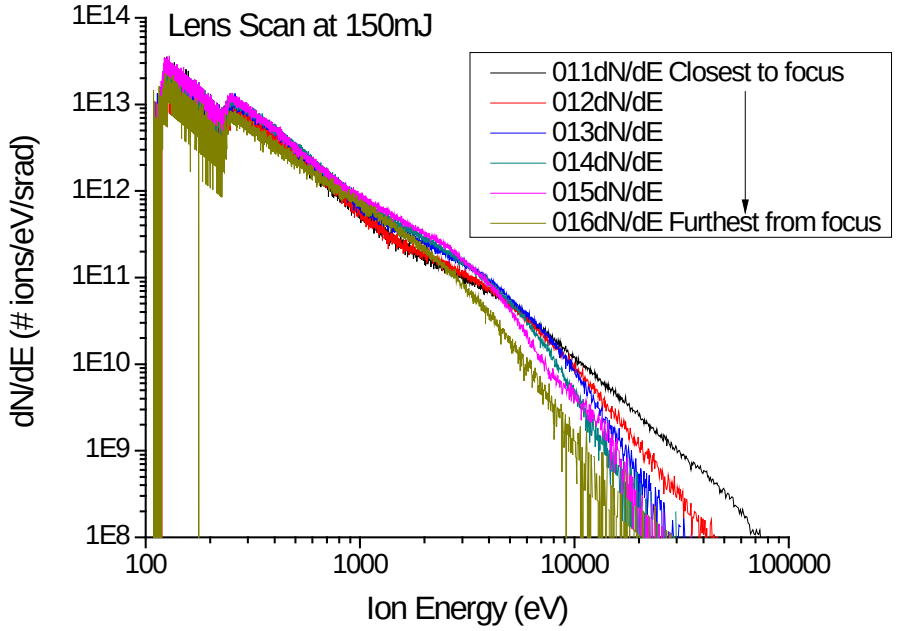
Ion Energy Plots

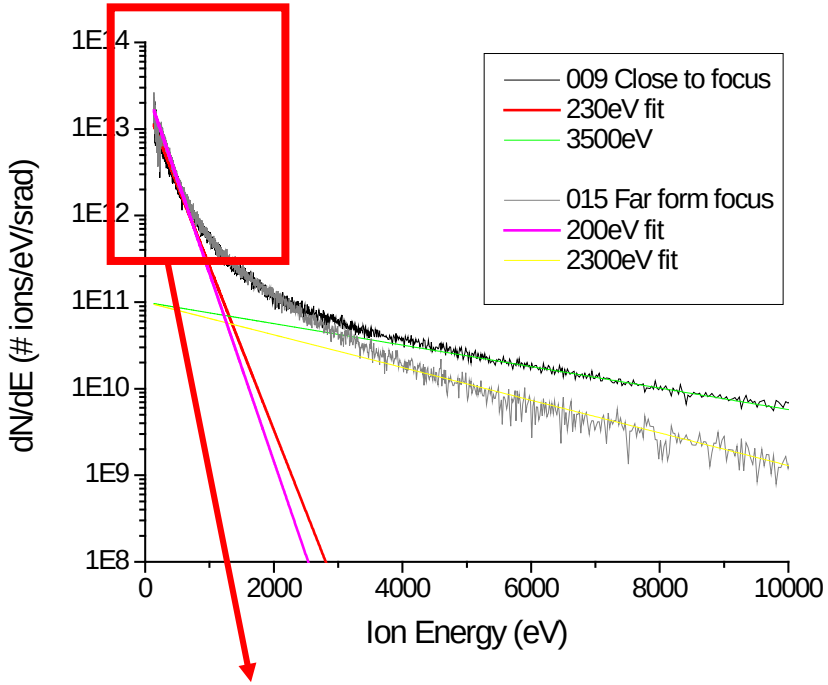


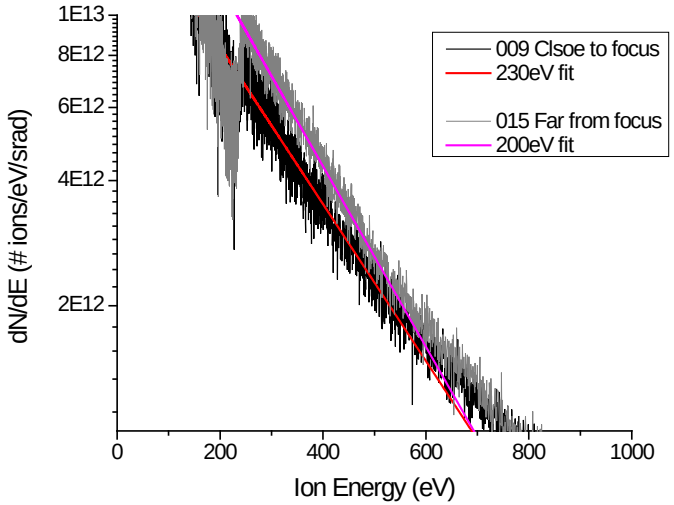


- FC moved to 112cm to capture high energy spectrum
- Clear scaling with laser energy and focal position
- Energy spectrum shifts to higher energy with increasing intensity

Propeller Target Temperature fits to ion spectrum







- Ion spectrum extends to 100keV, but populations drops rapidly with increasing energy
- Can use 2 temperature fit to characterize spectrum – probably an upper limit for bulk temperature
- Bulk of ions can again be described with a single temperature (~200eV). High Energy tail shows few keV ions
- Both values increase with laser intensity

Conclusions

- ***The CE measurements are the first for Xe in 1-6nm range***
  - No strong effect of laser pulse length (intensity) at the same configuration (130ps vs 600ps)
  - Maximum conversion efficiency requires >100mJ on target
- ***Slit imager reports accurate dimensions of the emitting plasma directly, and is simple to implement and analyze***
  - Emission spot sizes <20μm observed
- ***The fits to the low energy ion spectra looks like a useful way to infer plasma temperature***
  - The fitted temperatures scale as expected with laser energy and focal position
  - Ion spectrum extends to very high energy (>100keV) but yield dominated by low energy (<1keV)
  - High energy tail strongly dependent on laser parameters
- ***Use of fitted temperatures from FC may allow recovery of density of the emitting plasma through spectral fitting***