High order harmonics from relativistic electron spikes: Scalings and laser requirements

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(Some slides with unpublished data are removed)

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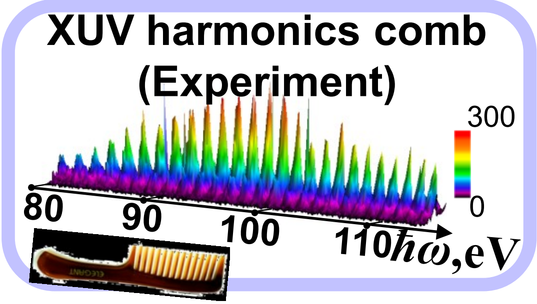
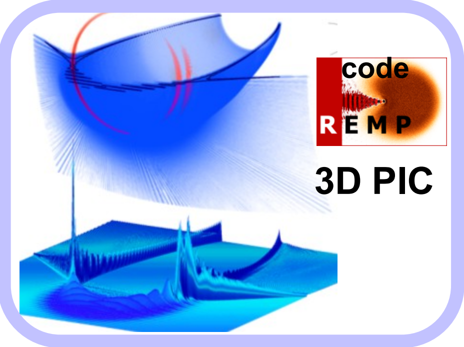
Outline

- High-Order Harmonics from Relativistic Electron Spikes
- Possible applications
- Why interesting at multi-PW? **Power**^{2} dependence
- Why good spot? Dependence on Strehl ratio
- Why high stability?
- Requirements:
  - wavefront quality
  - angular dispersion
  - compressor alignment accuracy

High-Order Harmonics from Relativistic Electron Spikes



- Experimental discovery of new HHG regime

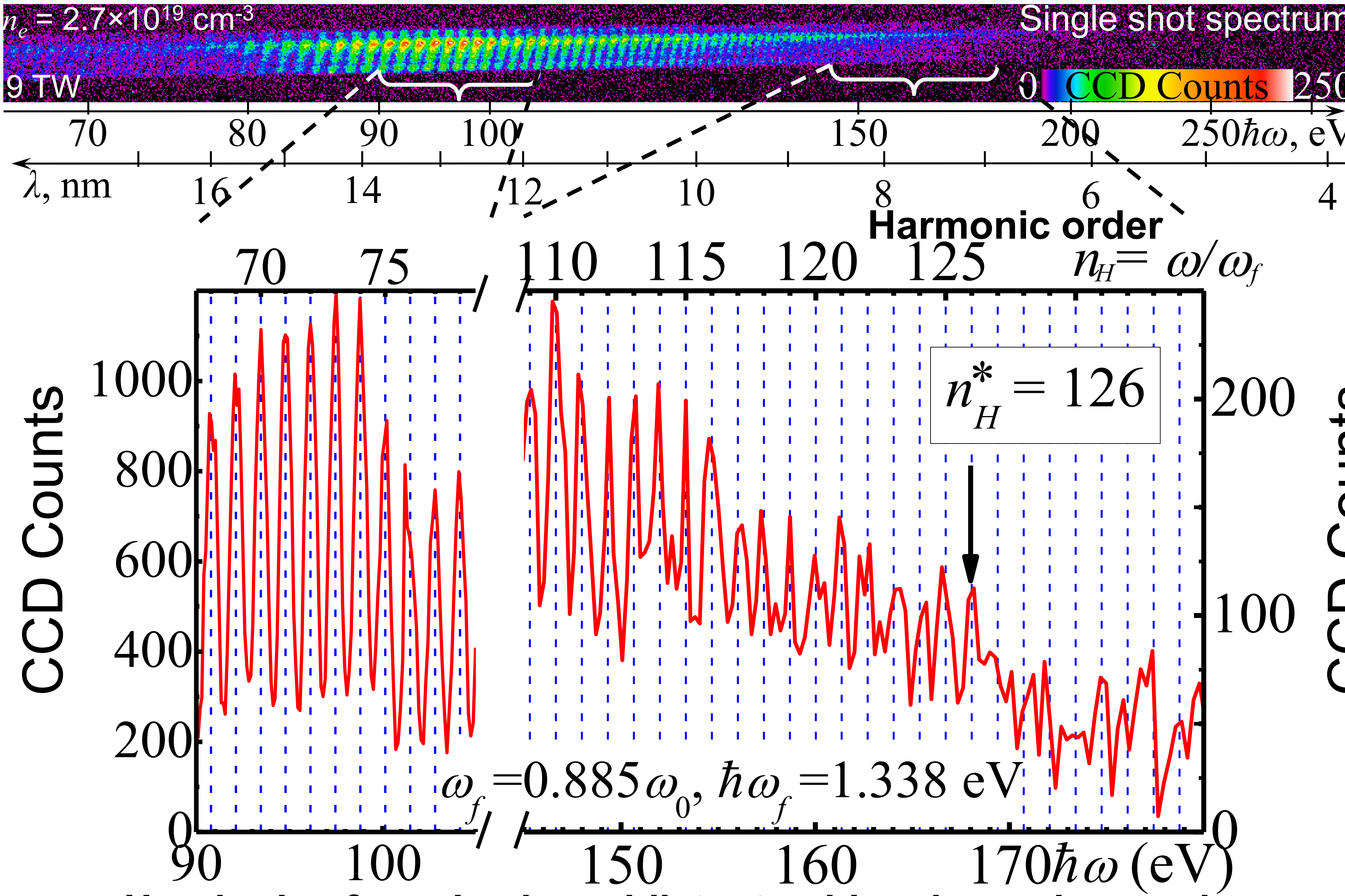


- New model of HHG by relativistic singularities

- Theory predictions confirmed experimentally:
  - Point-like double emission source,
  - Wide angular distribution

Pirozhkov *et al PRL* **108**, 135004 (2012)
Pirozhkov *et al NJP* **16**, 093003 (2014)

Bright resolved harmonics in the XUV



Hundreds of resolved, equidistant, odd and even harmonics

PIC Simulation

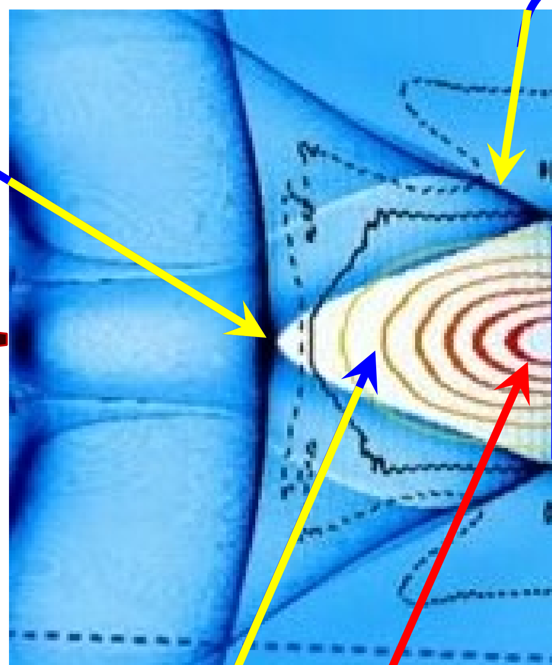
dx = λ/256, dy = λ/64, 6×10^8 particles, box $122\lambda\times100\lambda$

$\tau = 20\lambda/c$, spot = 25λ, $a_0 = 5$, $n_e = 4\times10^{-3} n_{cr}$

Lorentz force
Ponderomotive force
⇒
Wake wave
Cavity
Bow wave

Wake wave

Laser beam direction



Density lineout

Very high electron density
"Spike"

Cavity

Laser

PIC REMP code:
Esirkepov *Comput. Phys. Comm.* **135**, 144 (2001).

2D PIC in moving window (with laser pulse)
Blue colors: electron density

Cavity: Pukhov and Meyer-ter Vehn, *APB* **74**, 355 (2002)
Bow wave: Esirkepov *et al PRL* **101**, 265001 (2008)

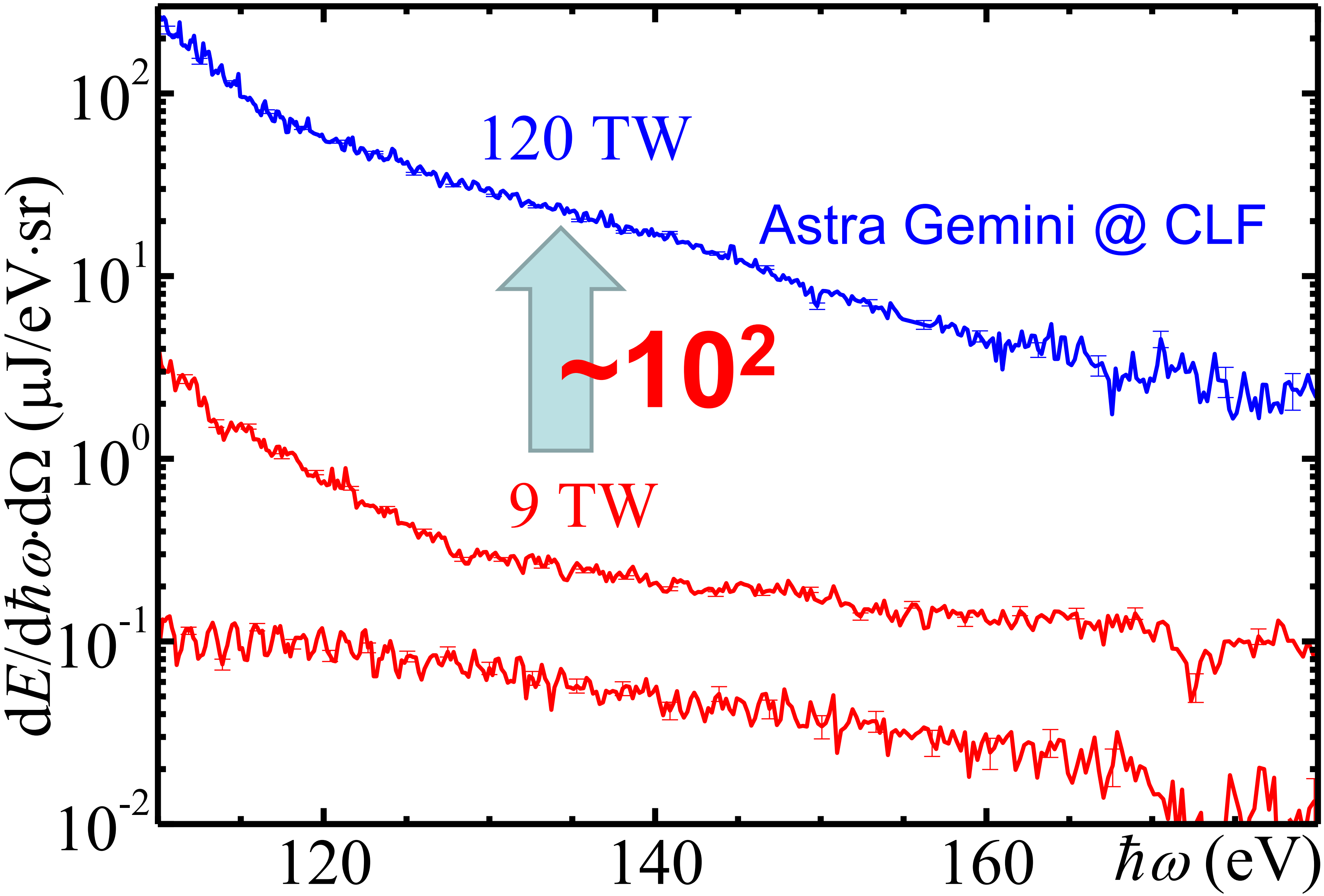
Possible Applications

- Laser-plasma interaction diagnostics
  - Bow wave generation
  - Self-focusing
- Coherent x-ray source
  - e.g. 50 nJ @60-100 eV, up to 0.5 keV @10 TW

X-ray yield ~ laser pulse Power^2

- Tested up to 0.1 PW

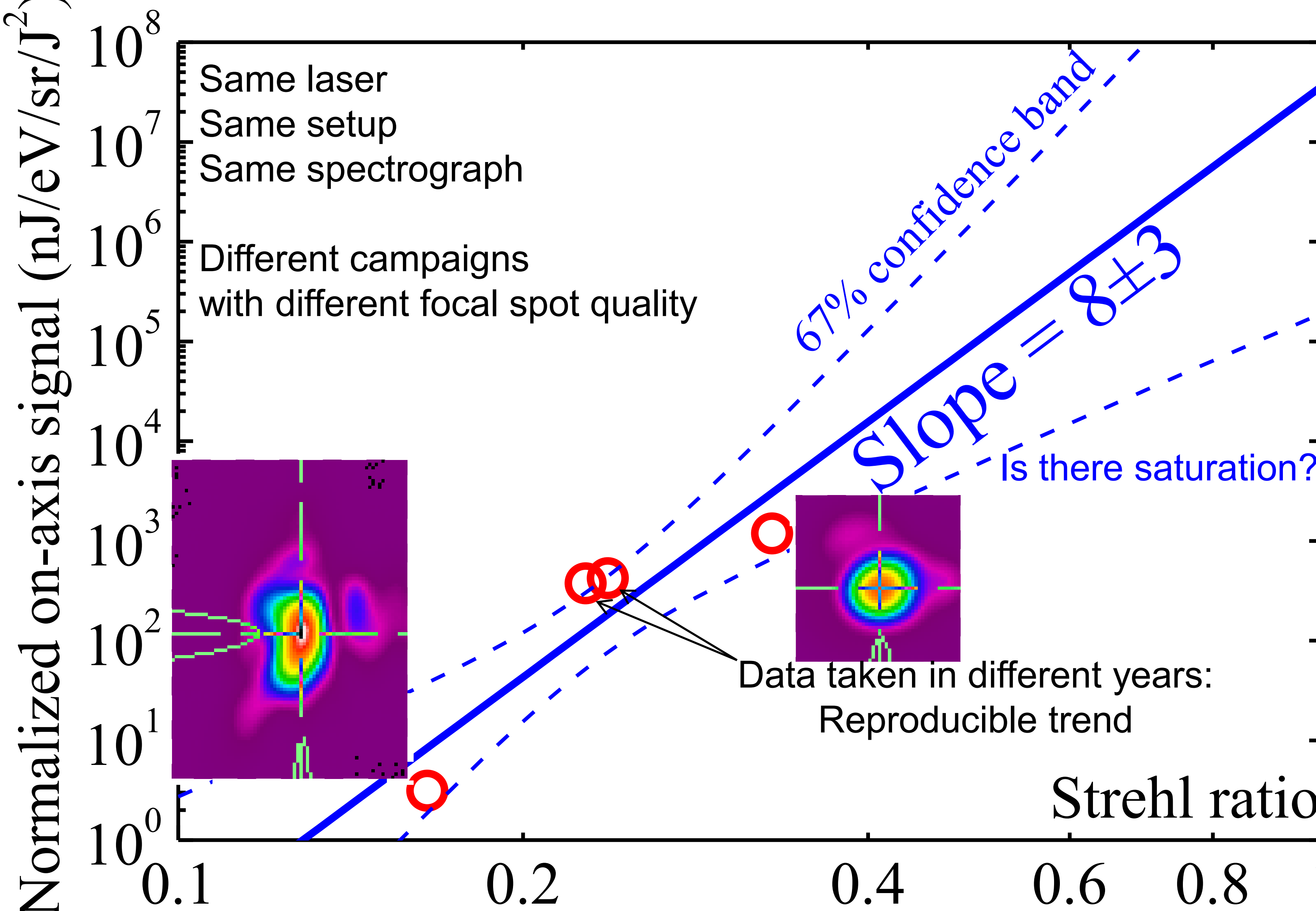
Scalability: Laser Pulse Energy/Power



Spot Quality (Strehl Ratio)

- More important than laser power

Dependence on focal spot quality



Tremendous opportunity for improvement

Spot Quality

Assuming a power law dependence:

- Higher Strehl is better^8

- More important than laser energy:

1 J, Strehl = 0.25	**0.5 J, Strehl = 0.5**	
1	(Strehl^5):	7±2
	(Strehl^8):	60±20
	(Strehl^{11}):	450±120

Assumption:
HHG ~ Strehl$^{8\pm3}$

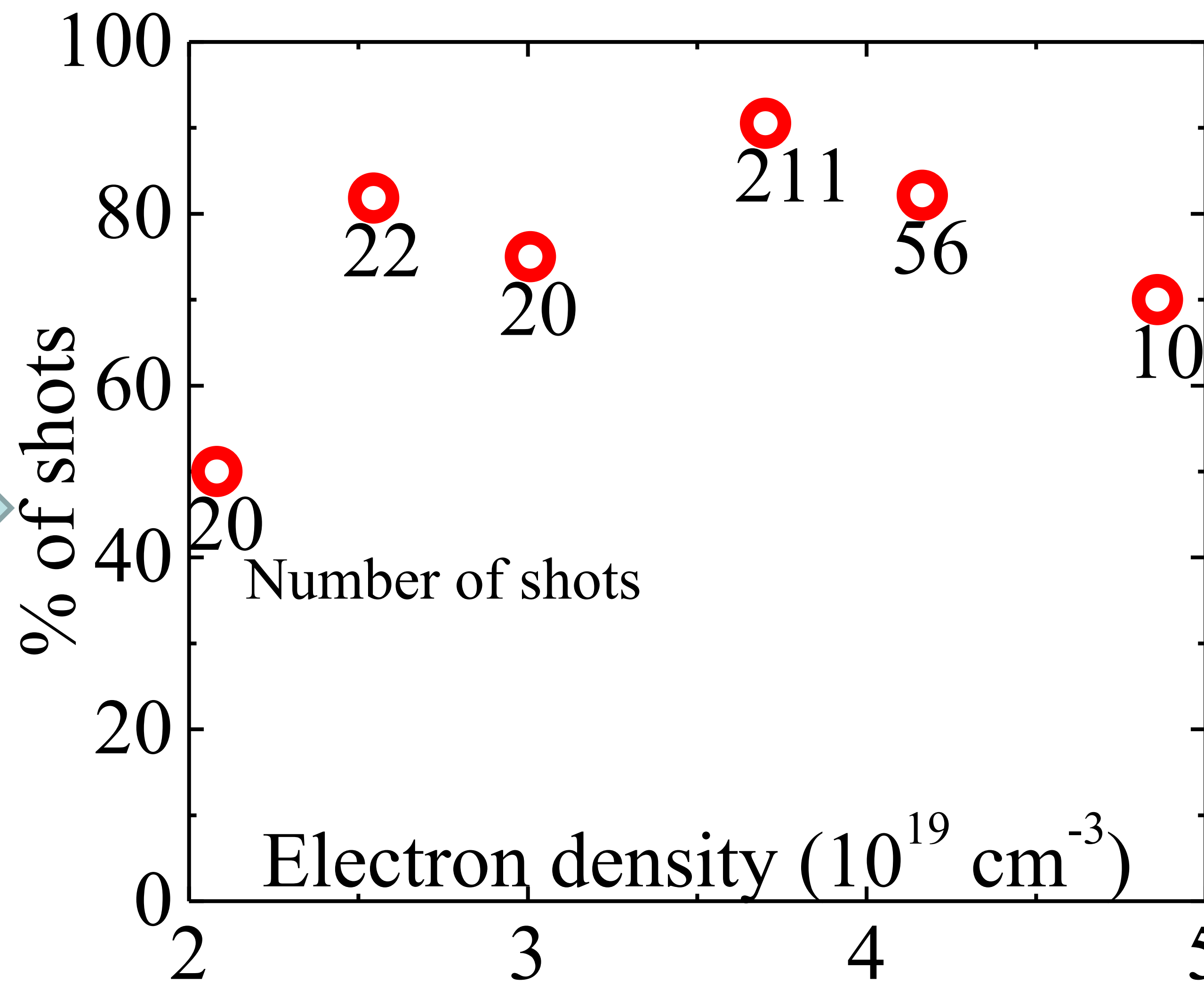
Better not to have energy outside! **50% Energy is better if Strehl is 2×**

Stability

How often?

13±5° Off-axis signal appearance probability. A good day.

497	Shots/day
18	Alignment shots
140	Reduced power shots
339	Shots for statistics
287	HHG shots
92	HHG @ reduced power



Laser Parameters Summary

Spot parameters	
FWHM x, μm	10.3±0.7 (6.8%)
FWHM y, μm	10.9±0.2 (2.1%)
FW1/e2 x, μm	21.8±3.6 (16.3%)
FW1/e2 y, μm	20.4±2.8 (13.5%)
Eff. radius, μm	7.97±0.44 (5.6%)
Energy above 1/2, %	33.8±7.1 (21.0%)
Energy above $1/e^2$, %	71.0±8.0 (11.2%)
δEnergy, %	7.04%
δFluence, %	7.48%
Pointing stability x, μm	1.8
Pointing stability y, μm	2.2
Strehl ratio	**0.26±0.03 (12%)**

Pulse parameters	
Pulse energy, J	**0.69±0.02(3%)**
FWHM, fs	44±3 (8%)
Eff width, fs	81±10 (13%)
Peak power, TW	**8.6±1.2 (14%)**

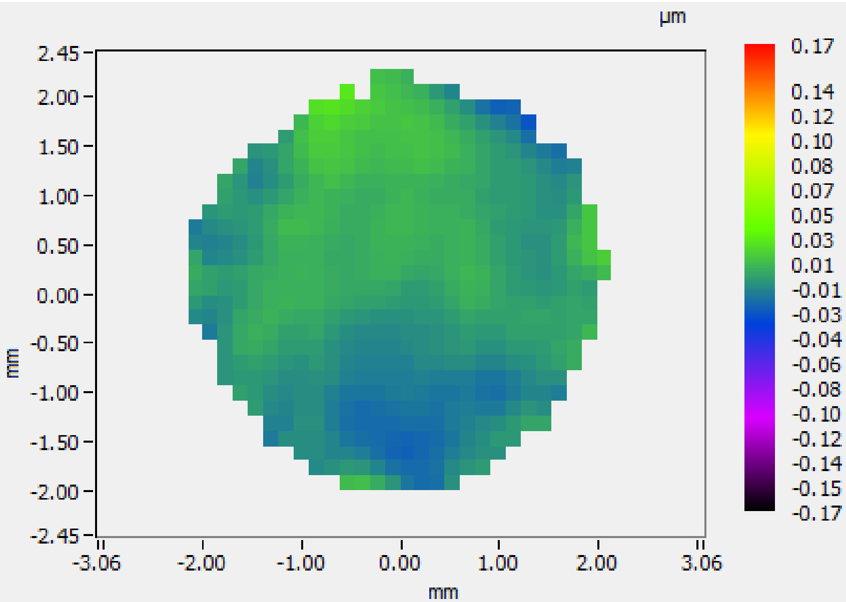
Not stable enough!

@Focus	
Peak irradiance, W/cm²	**$(4.3\pm0.7)\times10^{18}$ (16%)**
a_0	**1.46±0.12 (8%)**

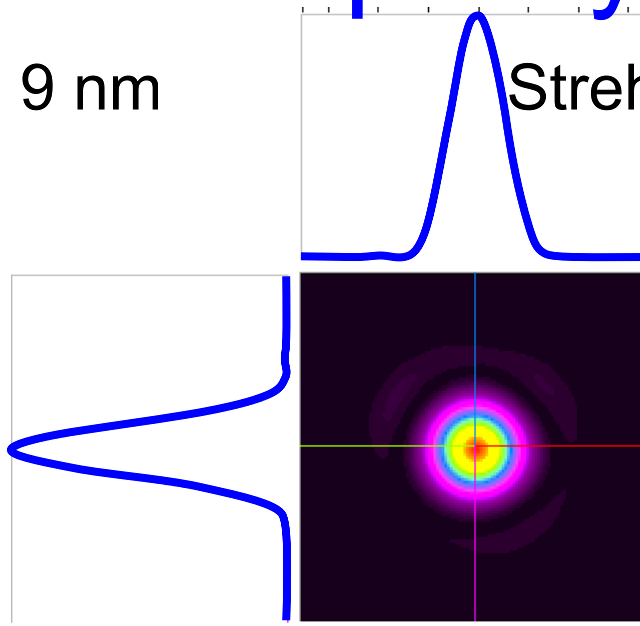
Requirements

- Wavefront rms
- Angular chirp
- Compressor alignment accuracy

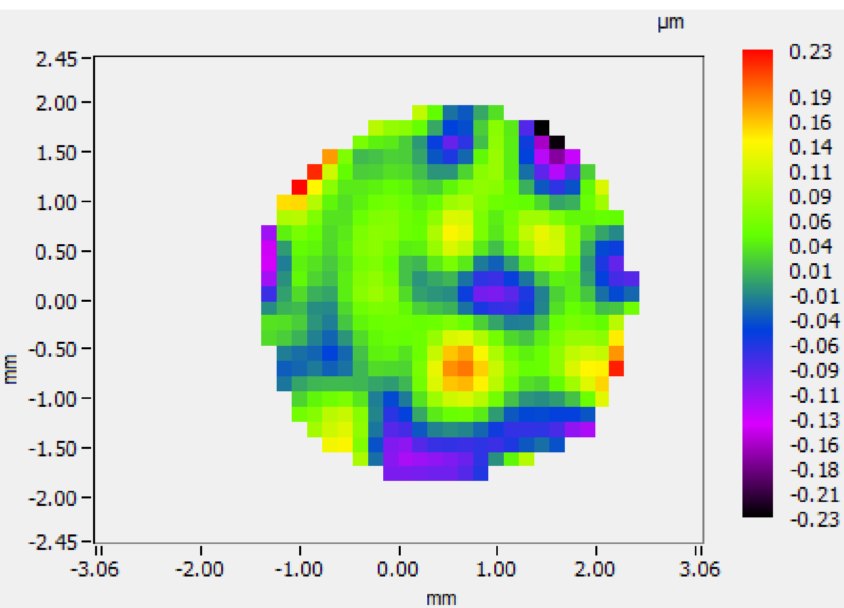
Strehl vs. wavefront quality



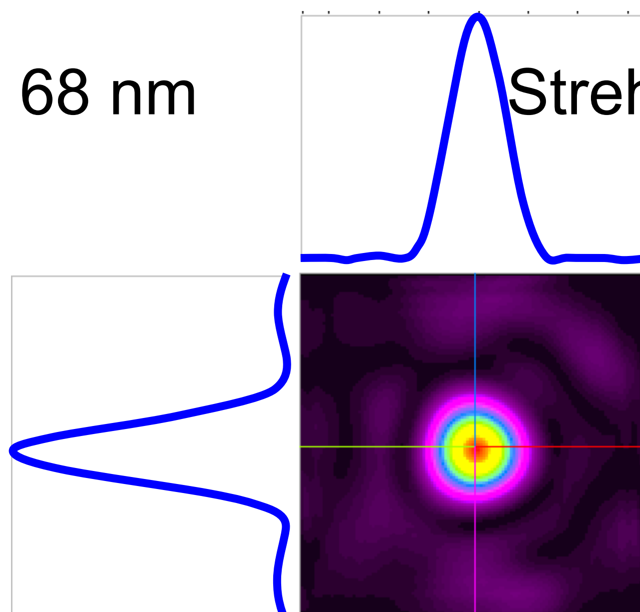
rms = 9 nm



Strehl = 0.99

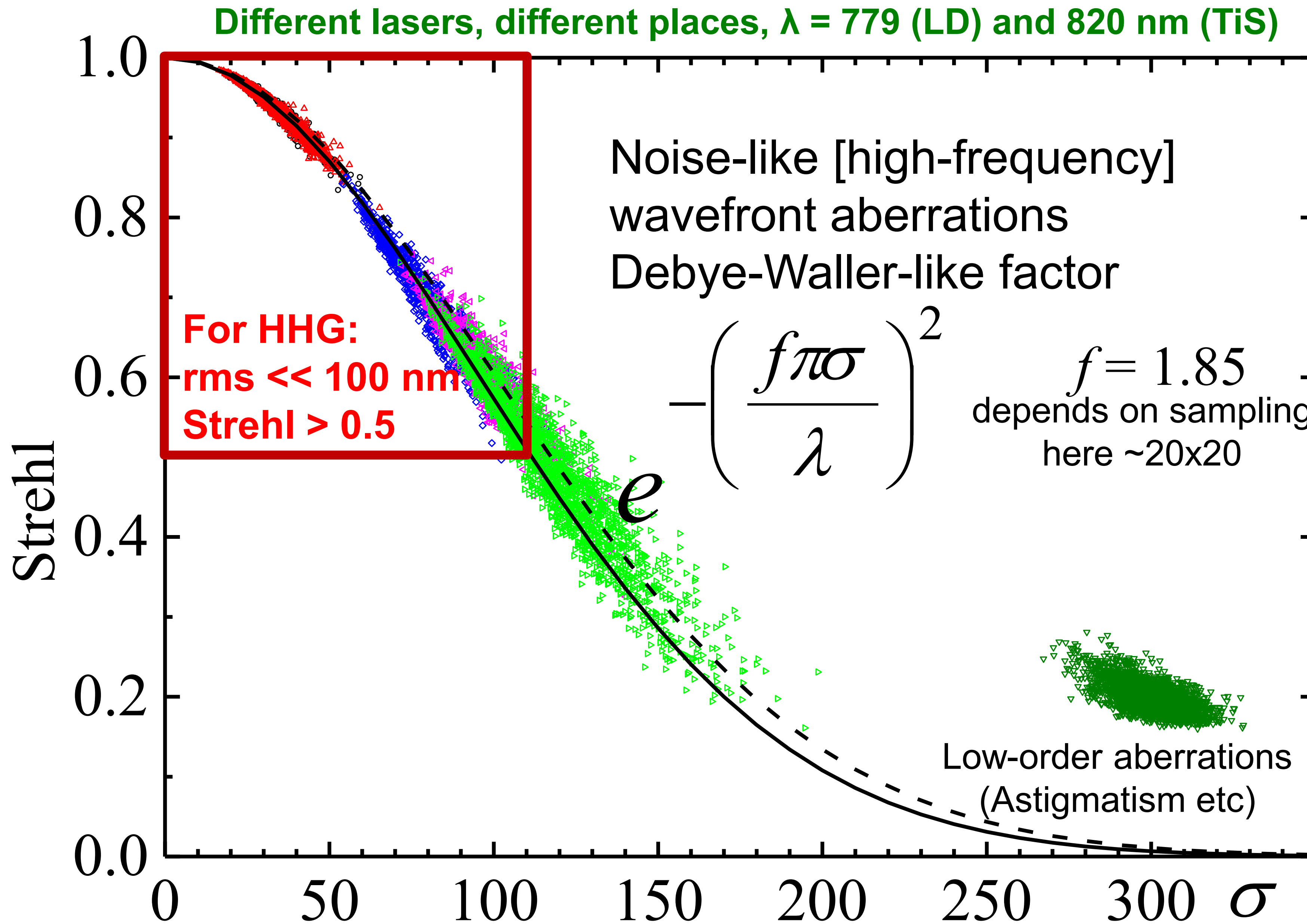


rms = 68 nm

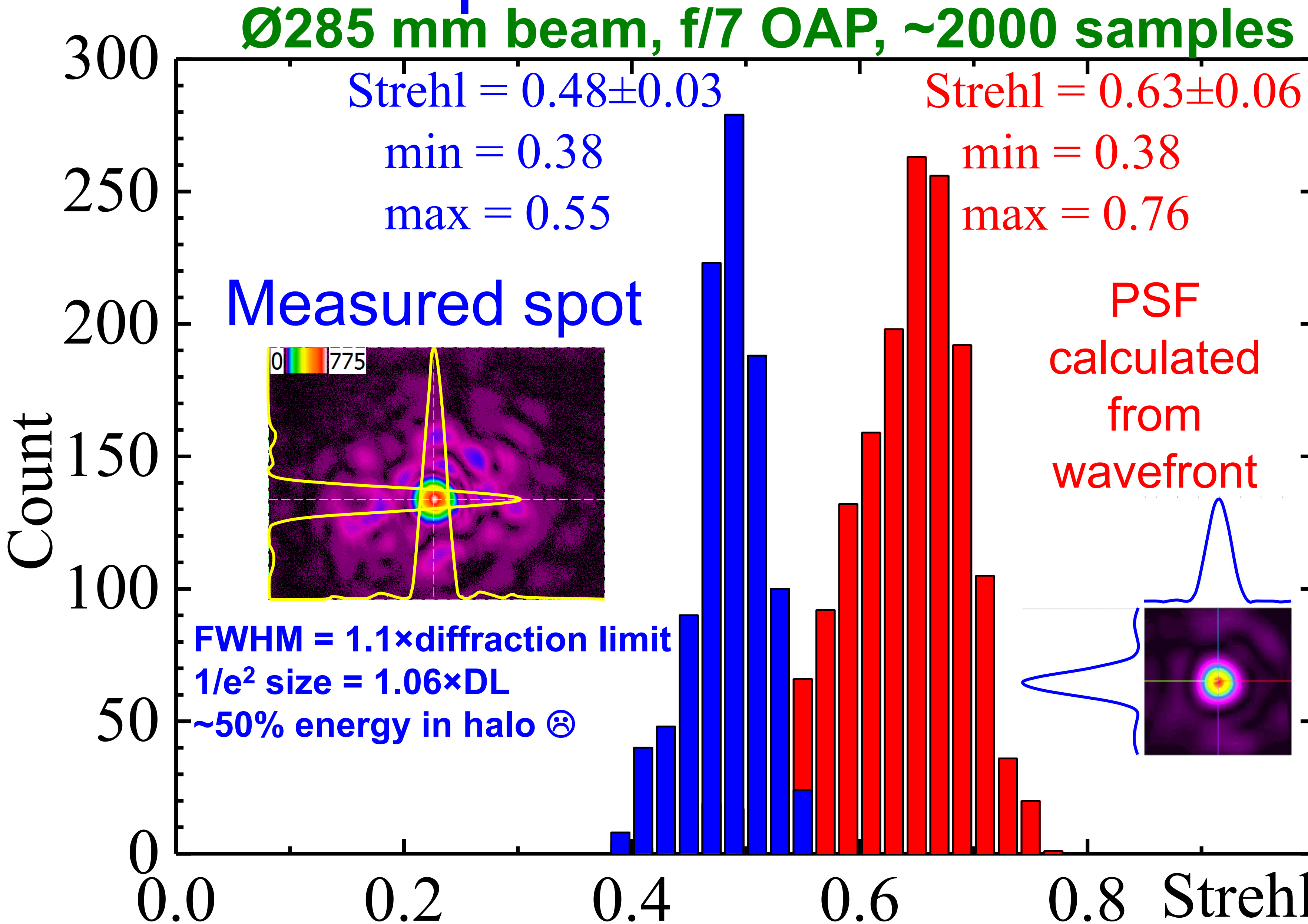


Strehl = 0.77

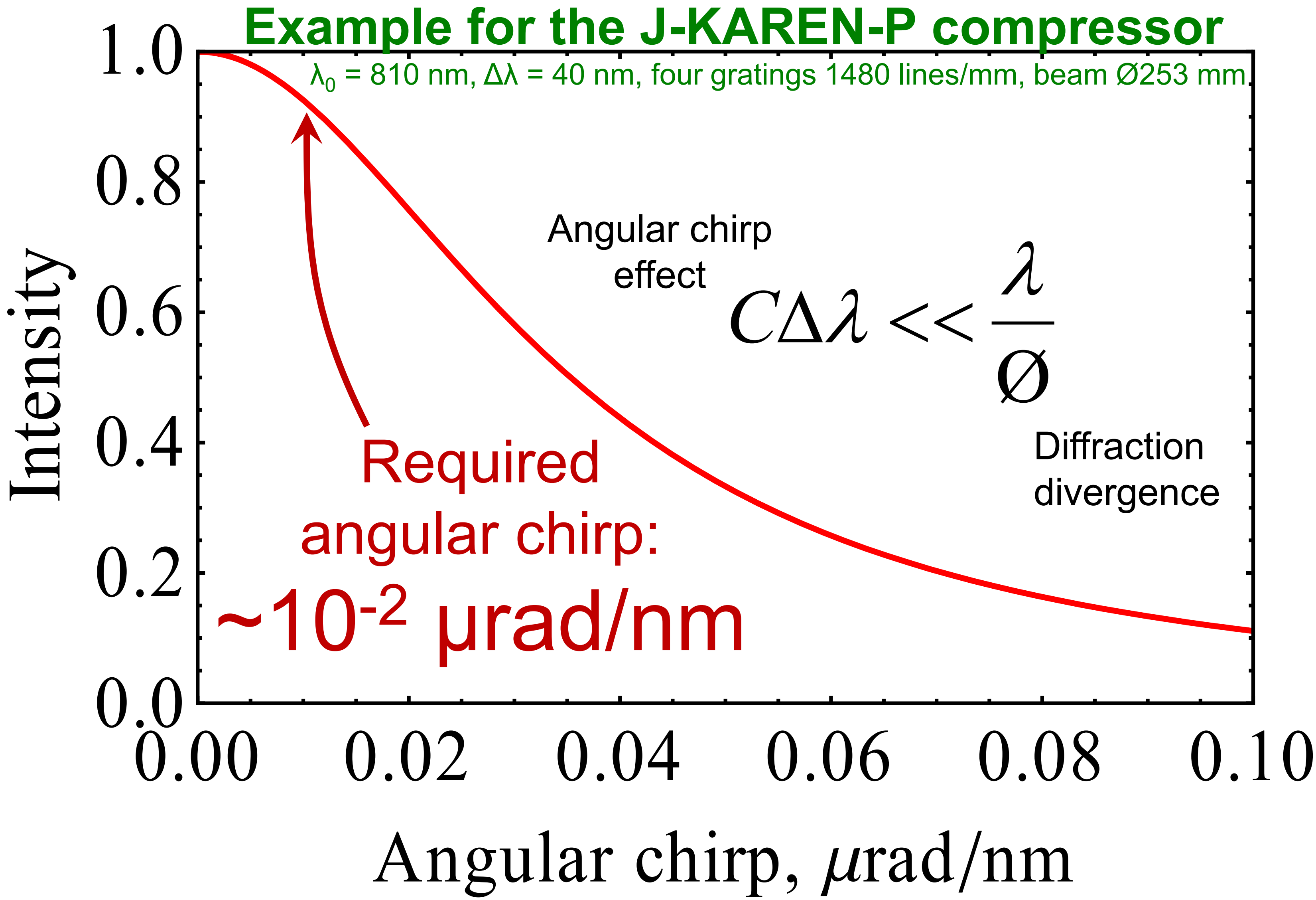
Strehl vs. rms wavefront error



Measured spot vs. calculated PSF

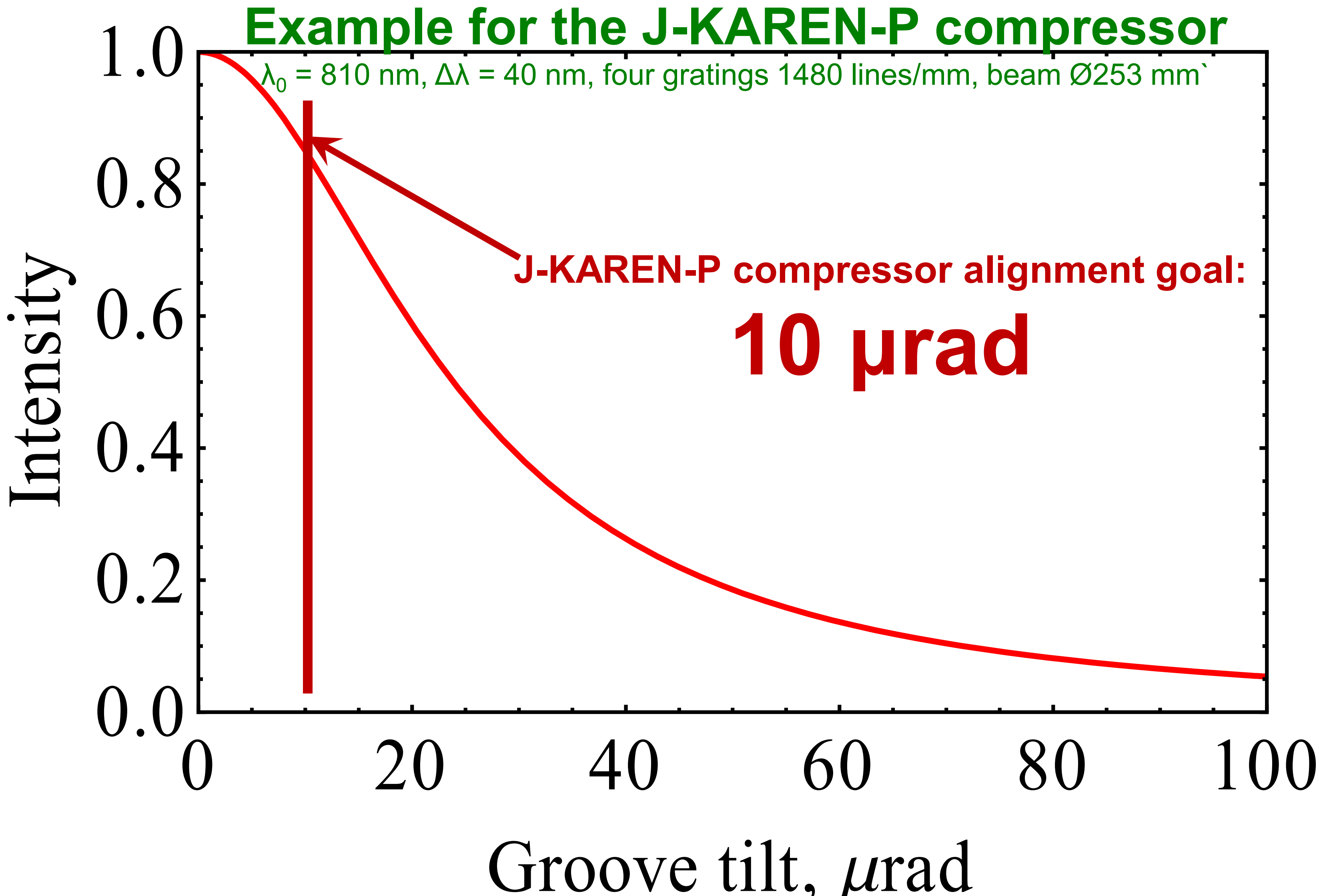


Angular Chirp Effect



Estimate based on: Pretzler *et al*. *Appl. Phys. B* **70**, 1 (2000)

Compressor Alignment Accuracy



Estimate based on: Pretzler *et al*. *Appl. Phys. B* **70**, 1 (2000)

“Laser is The Key” (Kiminori Kondo)

- HHG efficiency ~ $Power^2$ (tested up to ~ 0.1 PW)
- Focal spot quality: need Strehl > 0.5
- Wavefront: rms << 100 nm
- Angular chirp: < a few 0.01 μrad/nm
- Compressor alignment: ~ 10 μrad accuracy
- Diffraction-limited PW pulses
- Stability!!!

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