Laser Plasma Acceleration Experiments with a 100-TW Class Laser and Lessons Learned

Csaba Tóth

A.J. Gonsalves, K. Nakamura, M. Bakeman, N. Matlis, G. Plateau, J. Osterhoff, S. Shiraishi, C. Lin, T. Sokollik, J. van Tilborg, C.G.R. Geddes, C.B. Schroeder, E. Esarey, and W.P. Leemans

LOASIS Program

Lawrence Berkeley National Laboratory

ICUIL 2010 – Watkins Glen, NY

September 26 – October 1, 2010

http://loasis.lbl.gov/

Outline

- Laser Plasma Accelerators (LPA) – LOASIS
- LOASIS CPA Lasers
  - — TRex design, parameters, and operation experience
  - — Upgrades/improvements:
    - XPW for contrast enhancement
    - beam pointing stabilization
- LPA experiments
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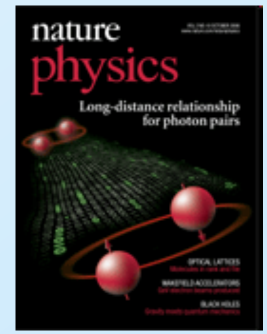
  - — stability and tuning by timing and pressure control
  - — e-beam diagnostics (ICT, phosphor, OTR, BPM)
  - — e-beam steering by quads for undulator seeding

LOASIS Program @ LBNL

LOASIS = **L**asers, **O**ptical **A**ccelerator **S**ystems **I**ntegrated **S**tudies

Program Head: Wim Leemans

LOASIS Team: 5 Staff Scientists, 3 Carrier Track Scientists, 1 Laser Engineer, 5 Post Docs, 5 PhD Students, 4 Undergrad Students, 7 Engineering & Admin. Support



Compact electron accelerators (cm, not kilometers)

- 50 MeV over ~10 m @ Advanced Light Source Linac
- **1 GeV over 3.3 cm @ LOASIS**
- 50 GeV over ~3000 m @ SLAC

All-optical accelerator drives a “Hyperspectral” light source

- in which THz radiation, x-rays, and laser beams are all inherently synchronized

Laser Plasma Accelerators: Laser Driven Plasma Waves

Tajima & Dawson, *Phys. Rev. Lett. (1979);* Esarey, Schroeder, Leemans, *Rev. Mod. Phys. (2009)*

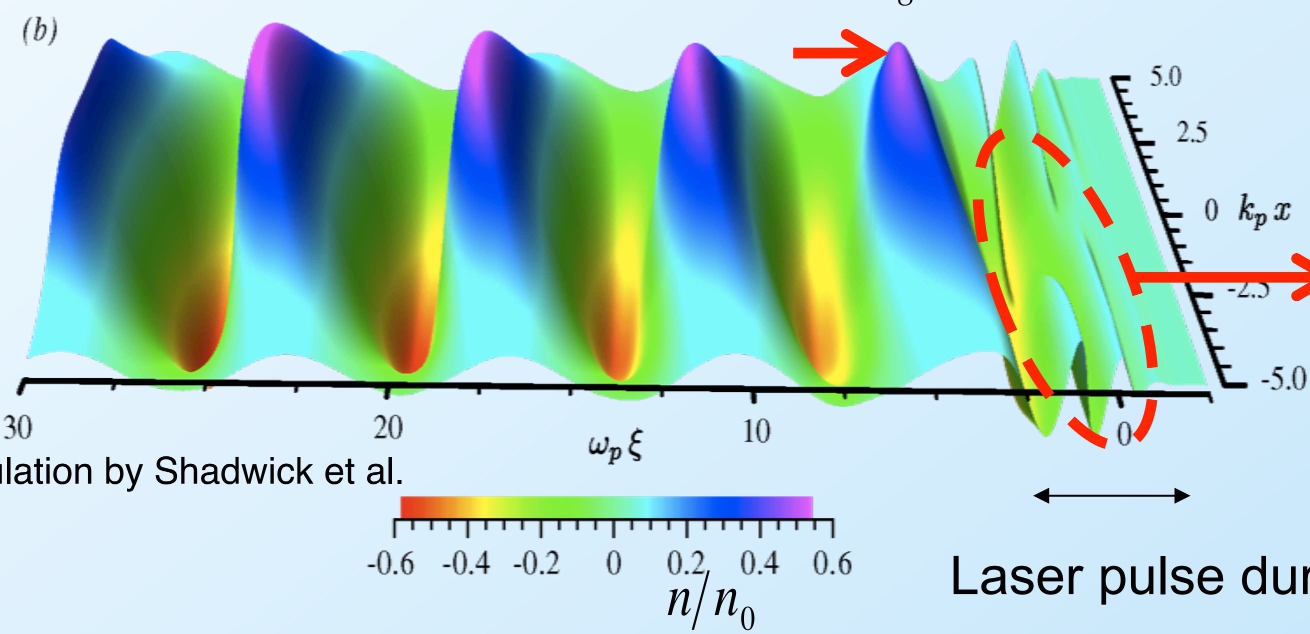
$$\left(\frac{\partial^2}{\partial t^2}+\omega_p^2\right)\frac{n}{n_0} = c^2\nabla^2\frac{1}{4}\left(\frac{eE_{Laser}}{mc^2\omega}\right)^2$$

Plasma wave: electron density perturbation

Laser ponderomotive force (radiation pressure)

E-fields: 10 – 100 GV/m

$v_{wave} \approx v_g \approx c$



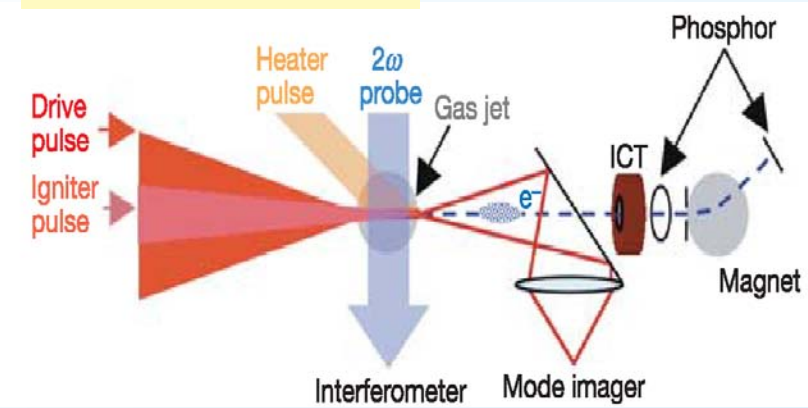
simulation by Shadwick et al.

Ti:Sapphire laser: $I\sim10^{18}$ W/cm^2

Laser pulse duration ~ λ_p/c ~ tens fs

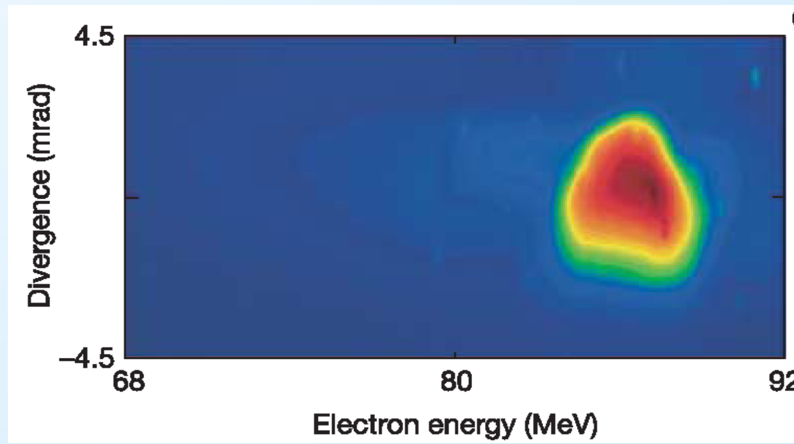
Channel Guided
Laser Plasma Accelerators

2004 Result



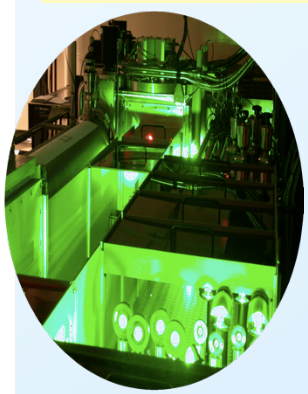
C.G.R. Geddes et al, *Nature, 431, p538 (2004)*

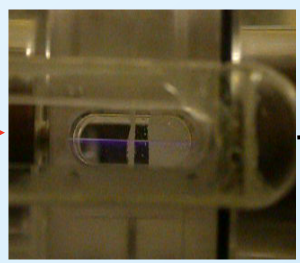
10 TW laser => 100 MeV e-beam



RAL, LOA, LOASIS

2006 Result

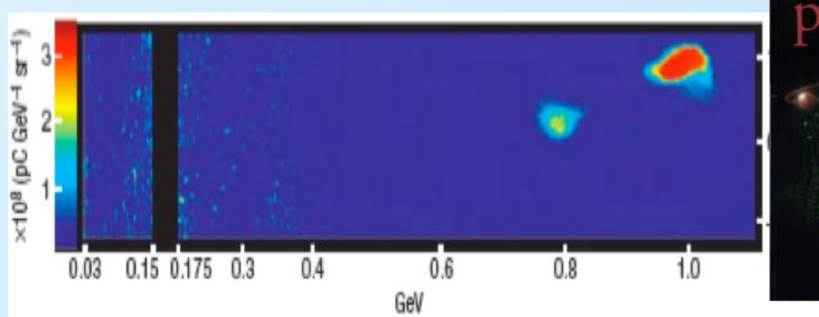


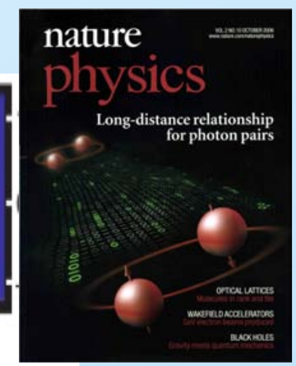


1 GeV

e⁻

40 TW laser => 1 GeV e-beam





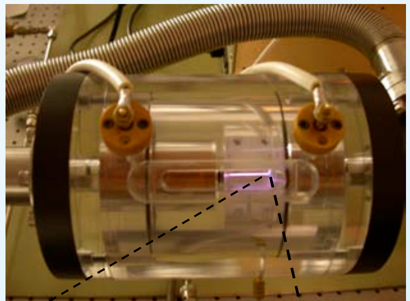
W.P. Leemans et. al, *Nature Physics* 2, p696 (2006)

Experimental Demonstration: 1 GeV Beam via Laser Plasma Accelerator

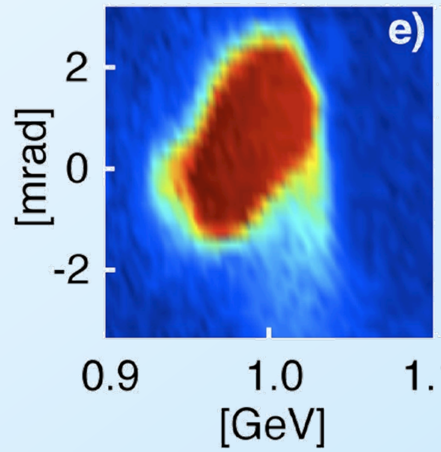
H-discharge capillary technology:
plasma channel production (1-4x10^{18} cm^{-3})

60 TW,
38 fs,
2.3 J,
10 Hz
22 micron spot
10^{18} W/cm^2

LBNL
Ti:Al_2O_3
laser



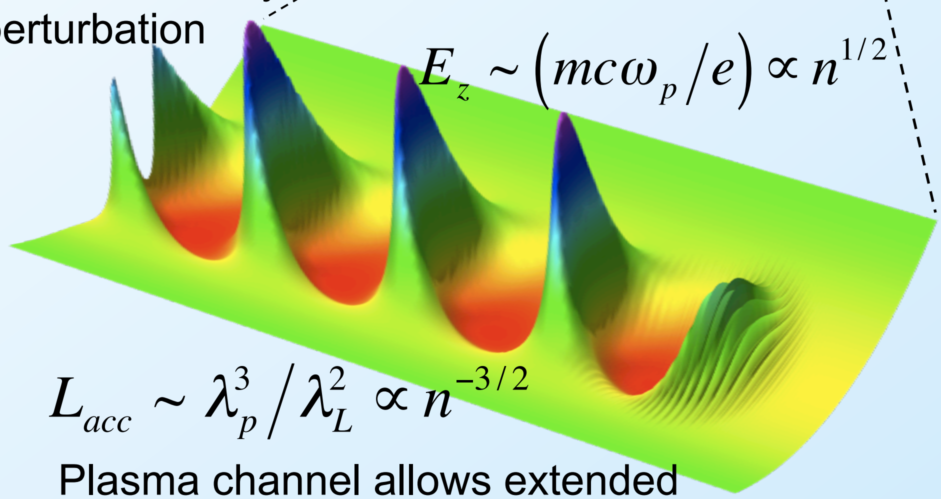
electron
beam



3 cm

Beam energy =1.0 GeV
Charge= Q~30 pC
1.6 mrad rms divergence
2.5% rms energy spread

Electron density perturbation



$$E_z \sim \left(mc\omega_p/e\right) \propto n^{1/2}$$

$$L_{acc} \sim \lambda_p^3/\lambda_L^2 \propto n^{-3/2}$$

Plasma channel allows extended laser-plasma interaction length

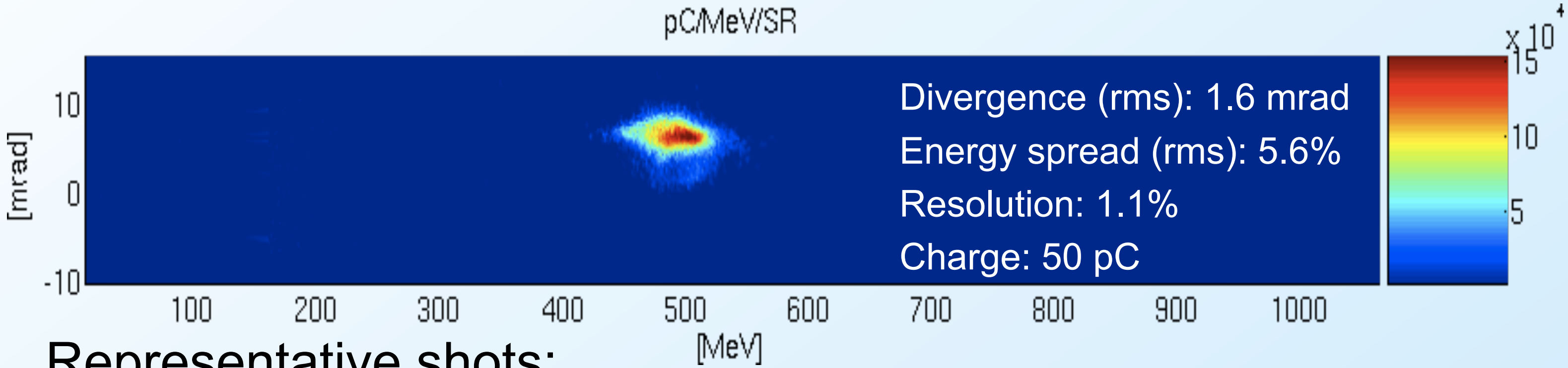
Leemans *et al.*, Nature Phys. (2006)
Nakamura *et al.*, Phys. Plasmas (2007)

$$\Delta W[\mathrm{GeV}] \sim eE \cdot L_{acc} \sim I[\mathrm{W/cm^2}]/n[\mathrm{cm^{-3}}] \propto n^{-1}$$

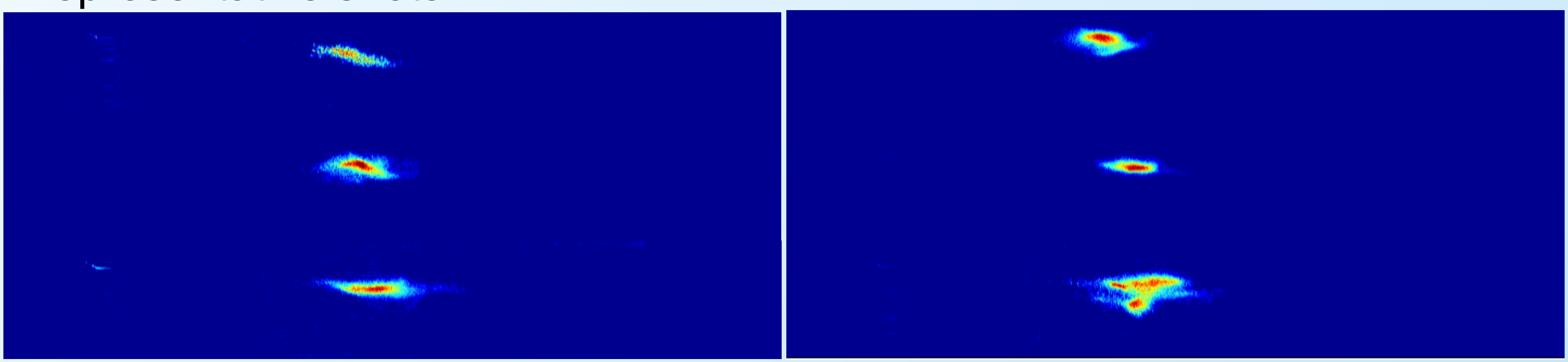
Experimental Regime for 0.5 GeV Beams

- Laser: $a_0 > 0.6$ (12 TW, 1 J, 80 fs)
- Capillary: 225 μm diameter and 33 mm length

Nakamura et al. Phys. Plasmas (2007)



Representative shots:



Charge = 32 ± 14 pC, Energy = 456 ± 45 MeV, dE/E = 6 ± 3%

In recent years stable electron beams with central energy of 200 MeV – 1 GeV independently demonstrated in many laboratories: MPQ, RAL, JAEA, LLNL, LOA … .

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LOASIS Lasers and Target Areas

Godzilla &

Chihuahua

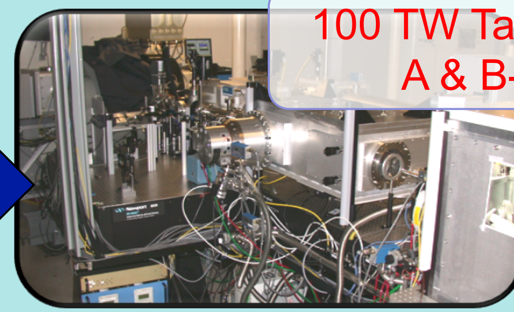
~ 10-15 TW

10 TW Target Area – B-cave

TREX

~ 50-60 TW

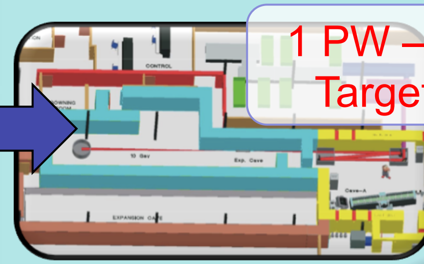
100 TW Target Area – A & B-caves



BELLA

> 1 PW

1 PW – Future Target Area



LOASIS @ LBNL
CPA Laser Beam Parameters

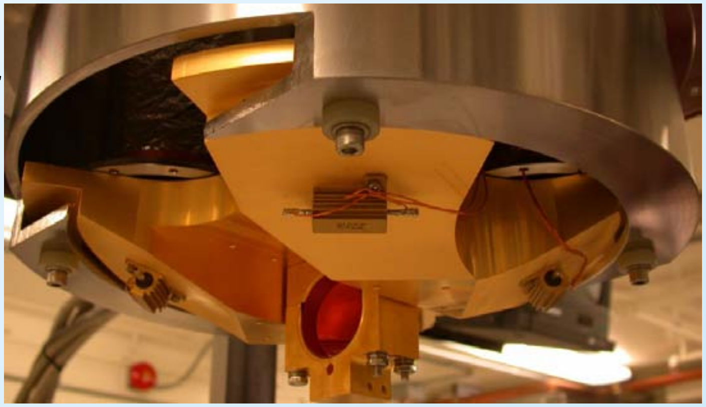
Amplifier	Purpose	Energy/ pulse	Pulse duration	Peak power	Average power
Main Power Amplifier	Wake-field Driver	550 mJ	46 fs	12 TW	5.5 W
Secondary Amp. Comp#1	Collider Beam	250 mJ	50 fs	5 TW	2.5 W
Secondary Amp. Comp#2	Plasma Ignitor	200 mJ	50 fs	4 TW	2.0 W
Secondary Amp. 4th pass - 5%	Plasma Heater	50 mJ	220 ps	0.23 GW	0.5 W
Cryo. Amp.	Wake-field Driver in Capillary Target	2.3 J	35 fs	65 TW	23 W

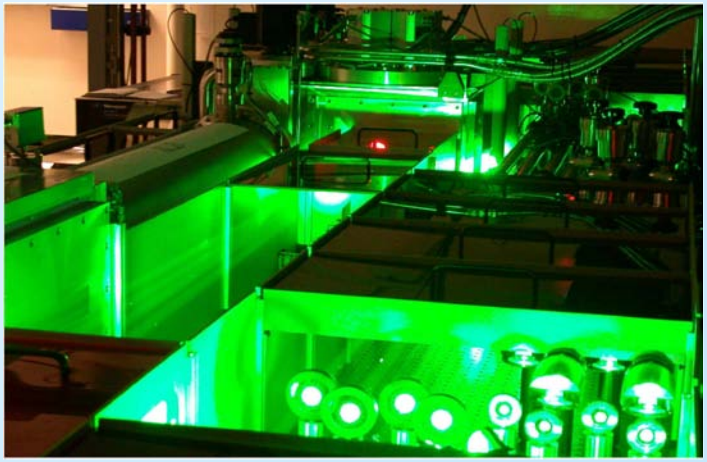
BELLA design parameters

- energy on target : > 40 J
- pulse duration: < 40 fs
- repetition rate: 1 Hz
- peak power: > 1 PW
- average power: > 40 W

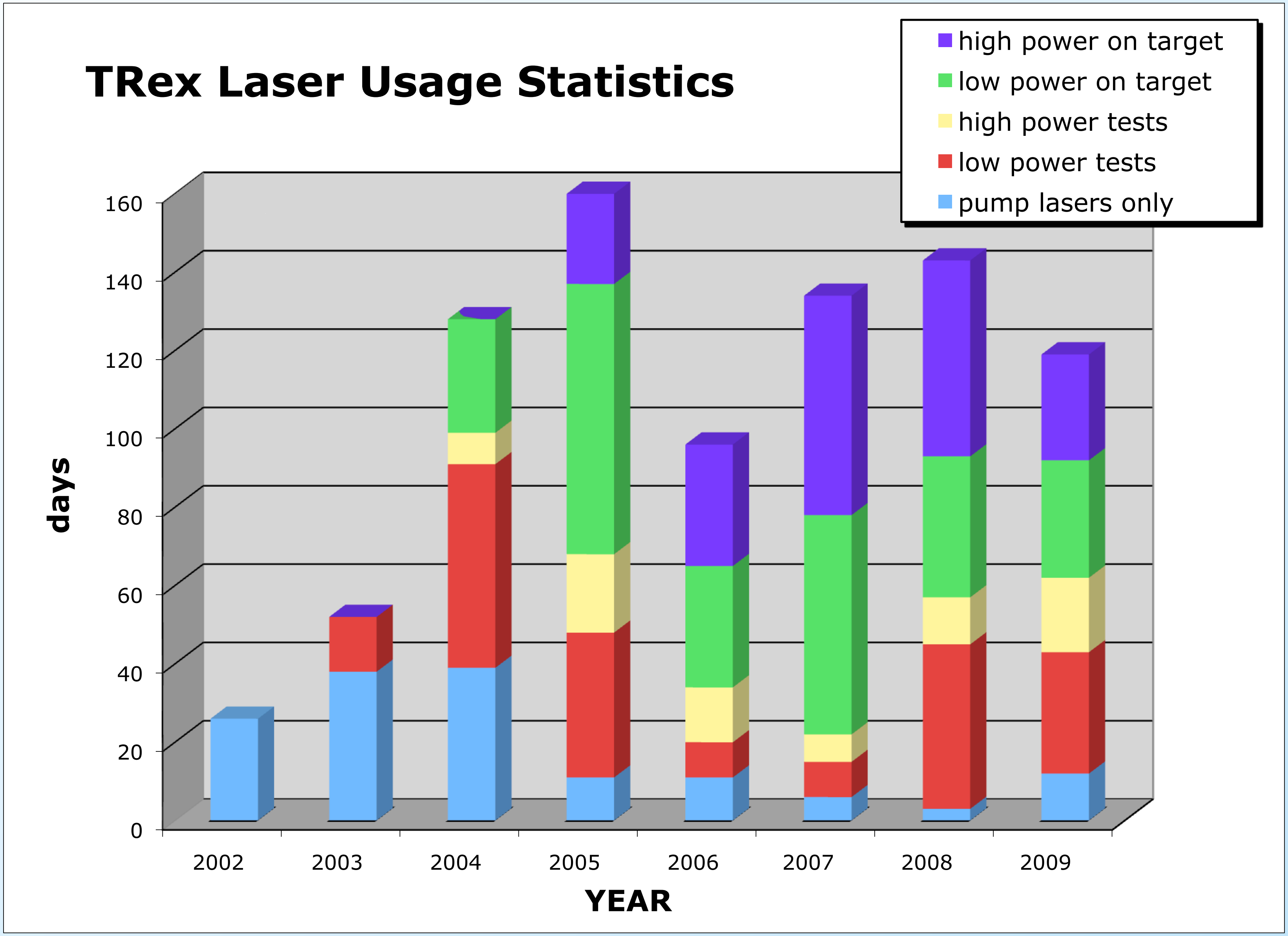
LOASIS CPA Expertise Summary

- Chihuahua and Godzilla fs Ti:sapphire CPA lasers were designed and built by LOASIS staff
  - In operation since 1997
- TREX designed and built by LOASIS staff
  - >900 days in operation since 2004
  - Driver for 1 GeV e-beam
- Knowledge gained is basis for specifying
  - 1 PW, 1 Hz BELLA laser
  - Conventional facilities
- In-house expertise allows critical evaluation of vendors' design and close monitoring of manufacturing, based on mutually agreed acceptance criteria

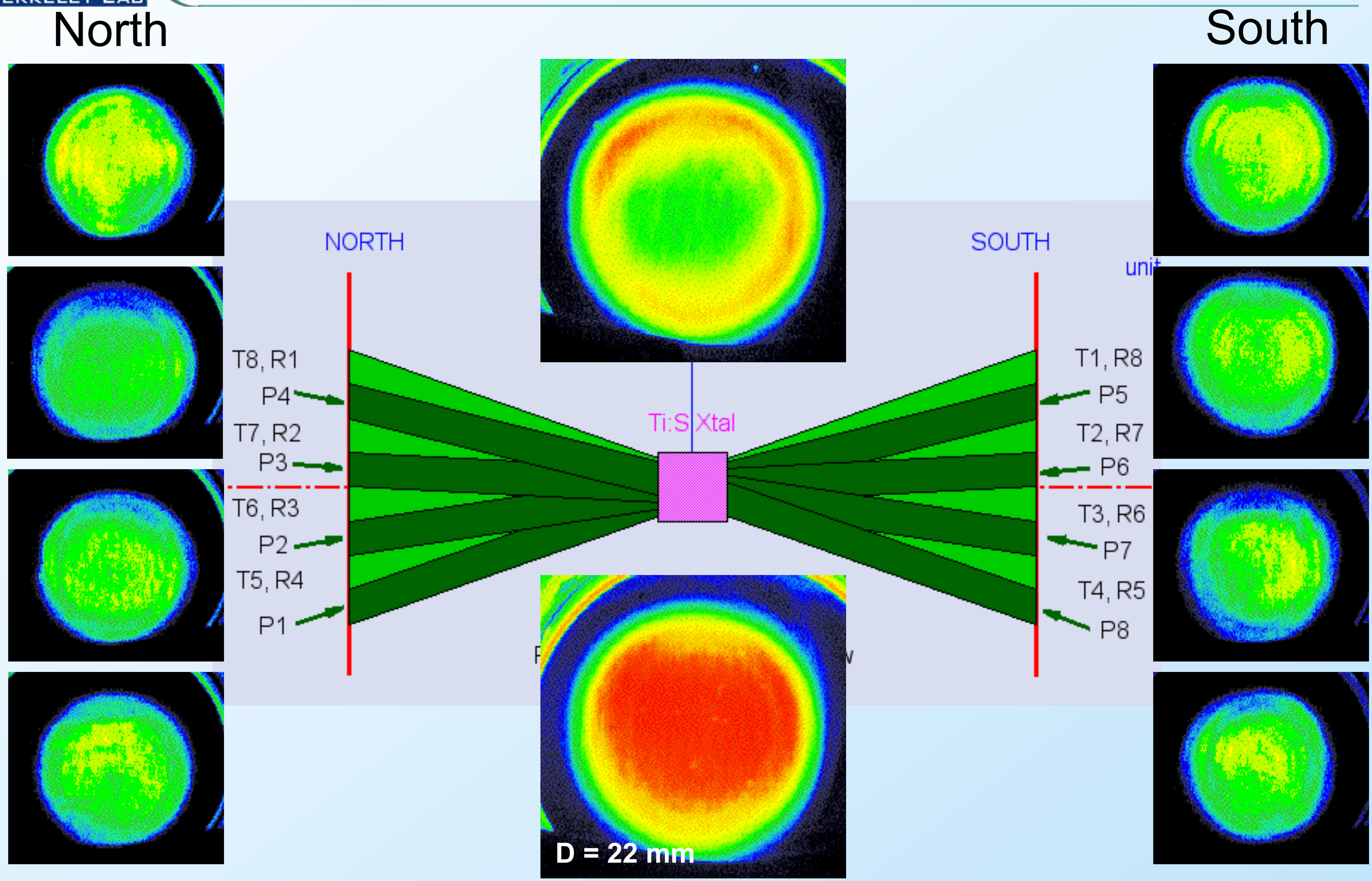




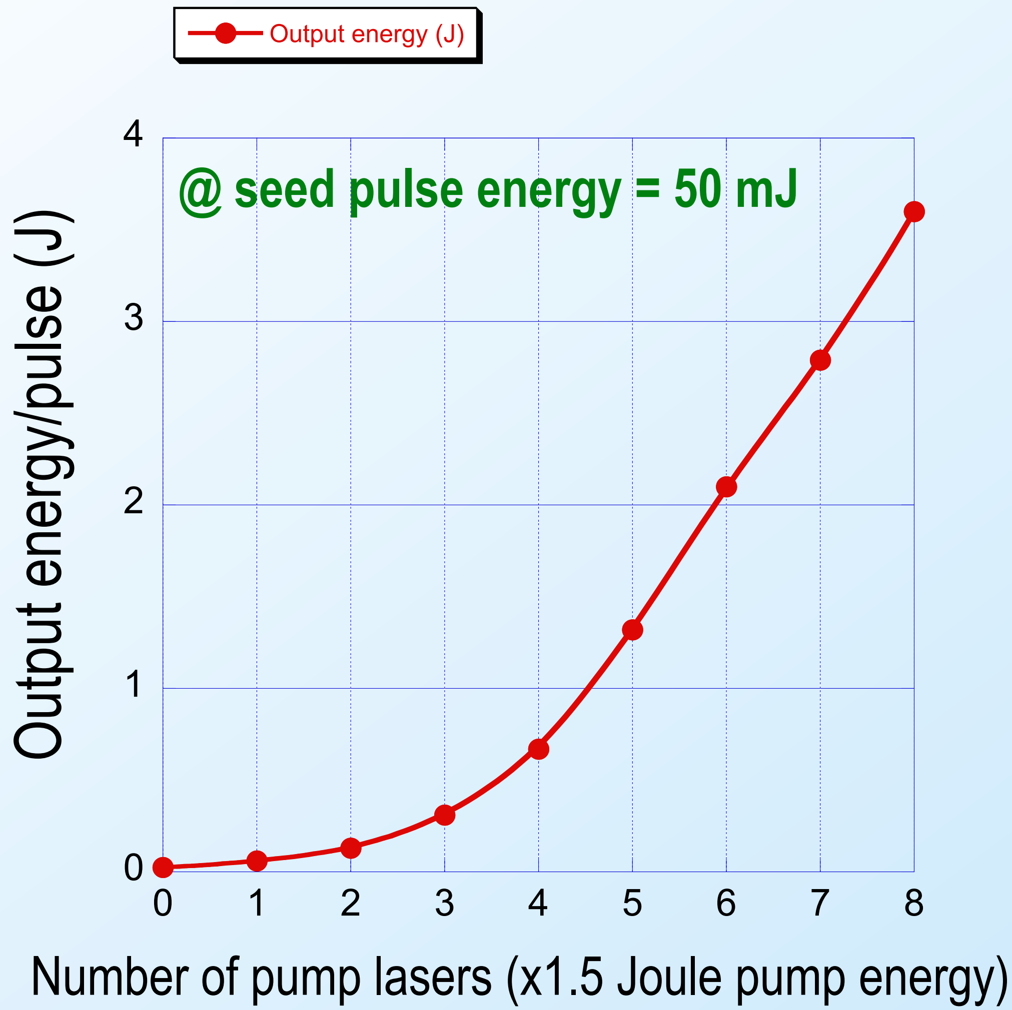
LOASIS TRex CPA Usage Shifts from "Commissioning" to "High-Power-on-Target"



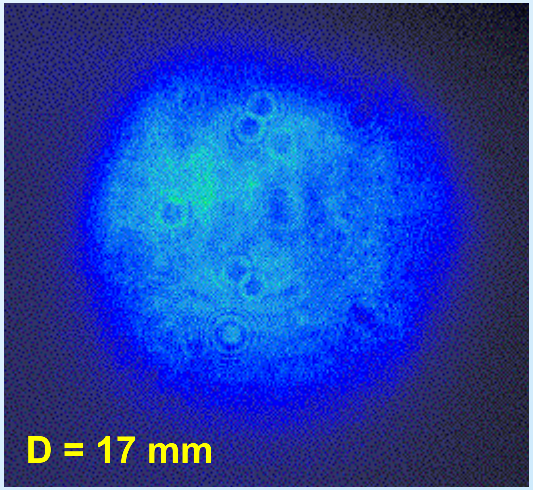
Relay Imaged Pump Beam Profiles & Depletion in Cryo-Cooled Amplifier

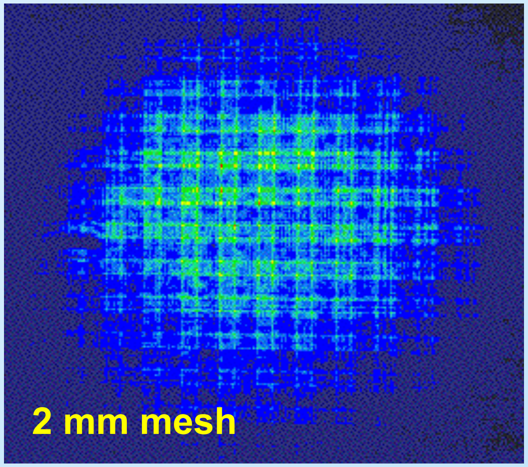


Gain and Output @ 800 nm



T-Rex @ 2.9 J





Compressor and Focusing Setup

- **Compressed energy, E:**
  1.6 J (2.3 J, max)

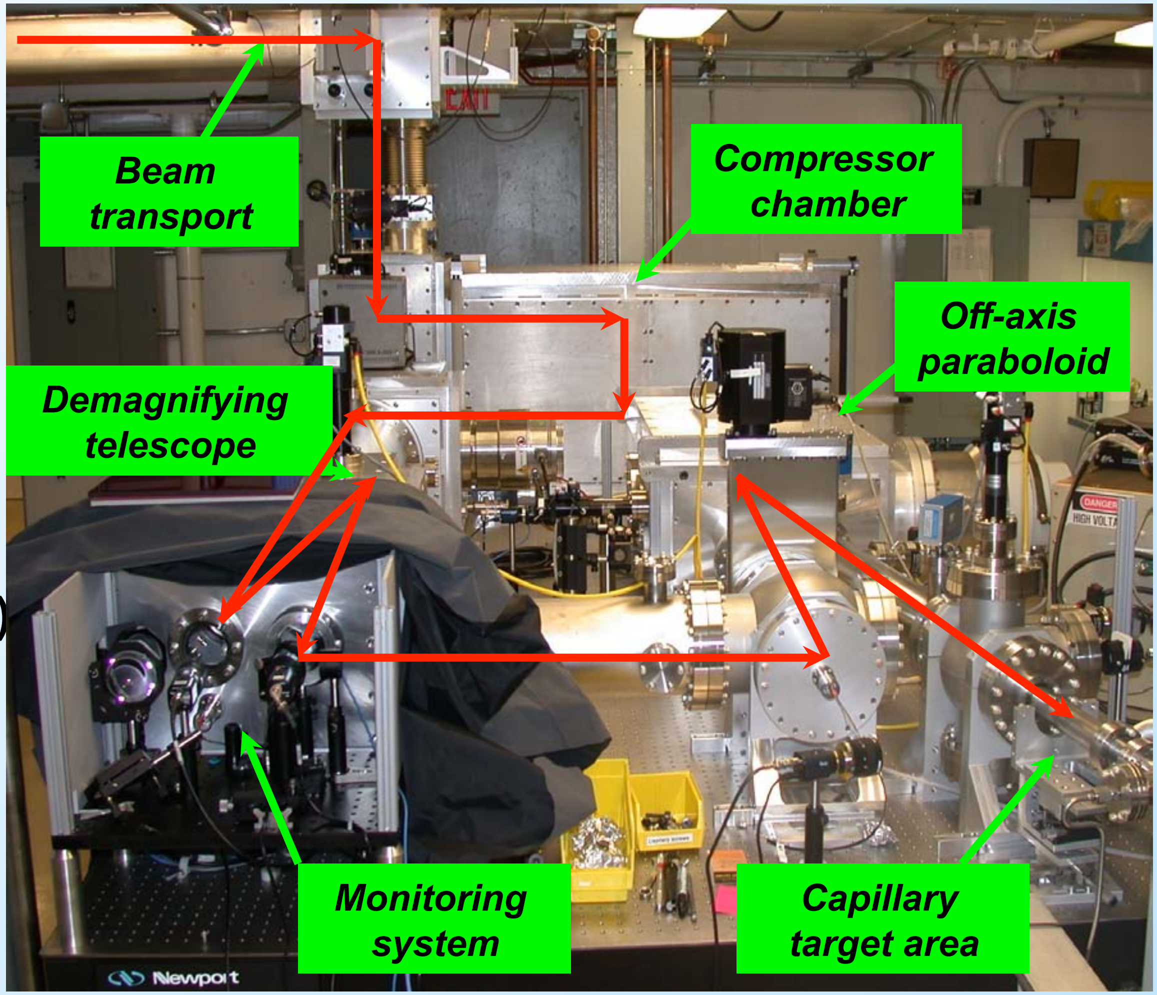
- **Compressed pulse duration,**
  40 fs (35 fs, min)

- **Power, P:**
  40 TW (65 TW, max)

- **Focal spot size, σ:**
  26 μm x 33 μm (22 μm, min)

- **Intensity in focus, I:**
  3 x 10^{18} W/cm^2

12” diam. grating pair: 1480 l/mm

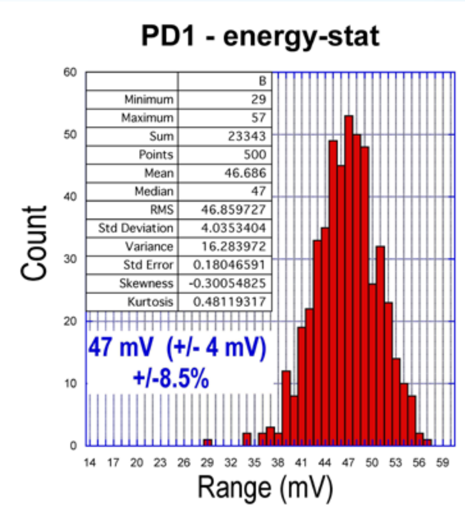


Off-axis paraboloid, OAP f=2 m

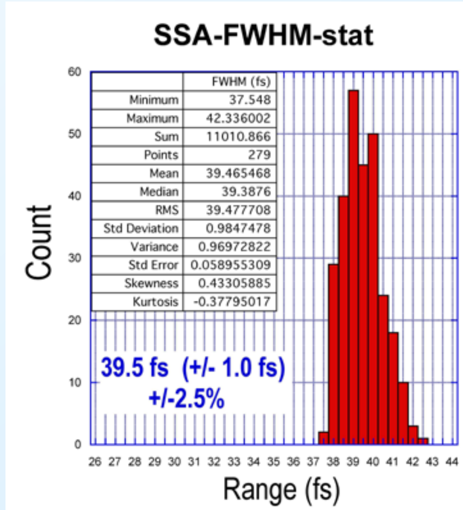
TREX Amplifier – Example Statistics

- Beam parameters are extensively studied

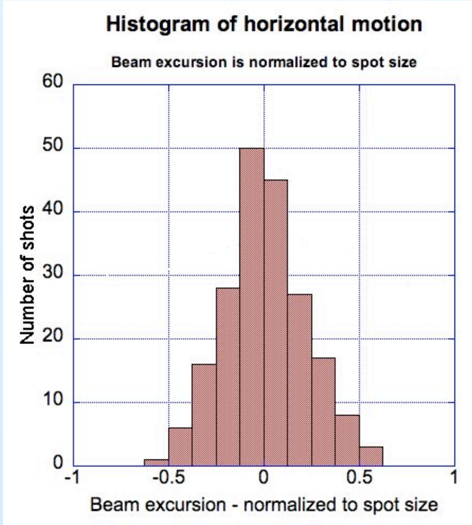
Amplitude



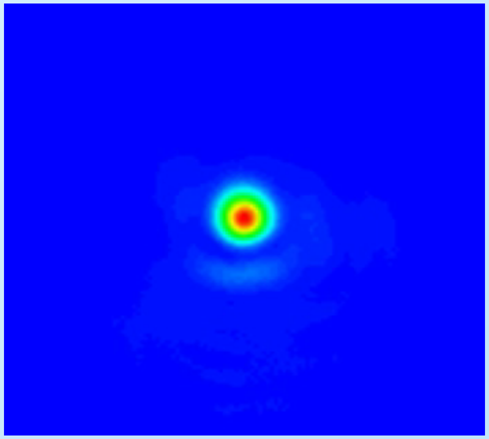
Pulse duration



Pointing stability



- Focal spot centroid, quality, $M^2 < 1.3$
- Focal spot diameter (25 micron)
- Spectrum, chirp, wavefront
- No deformable mirror on system
- R.M.S. pointing stability: 2.5 micro-rad



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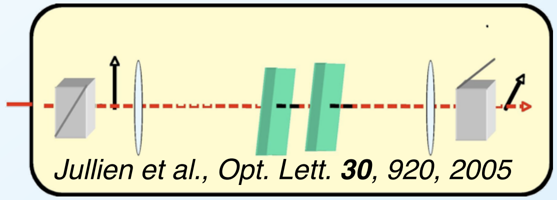
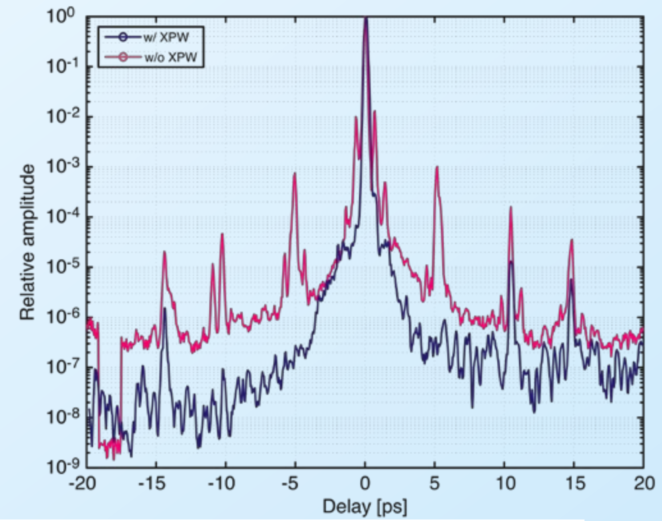
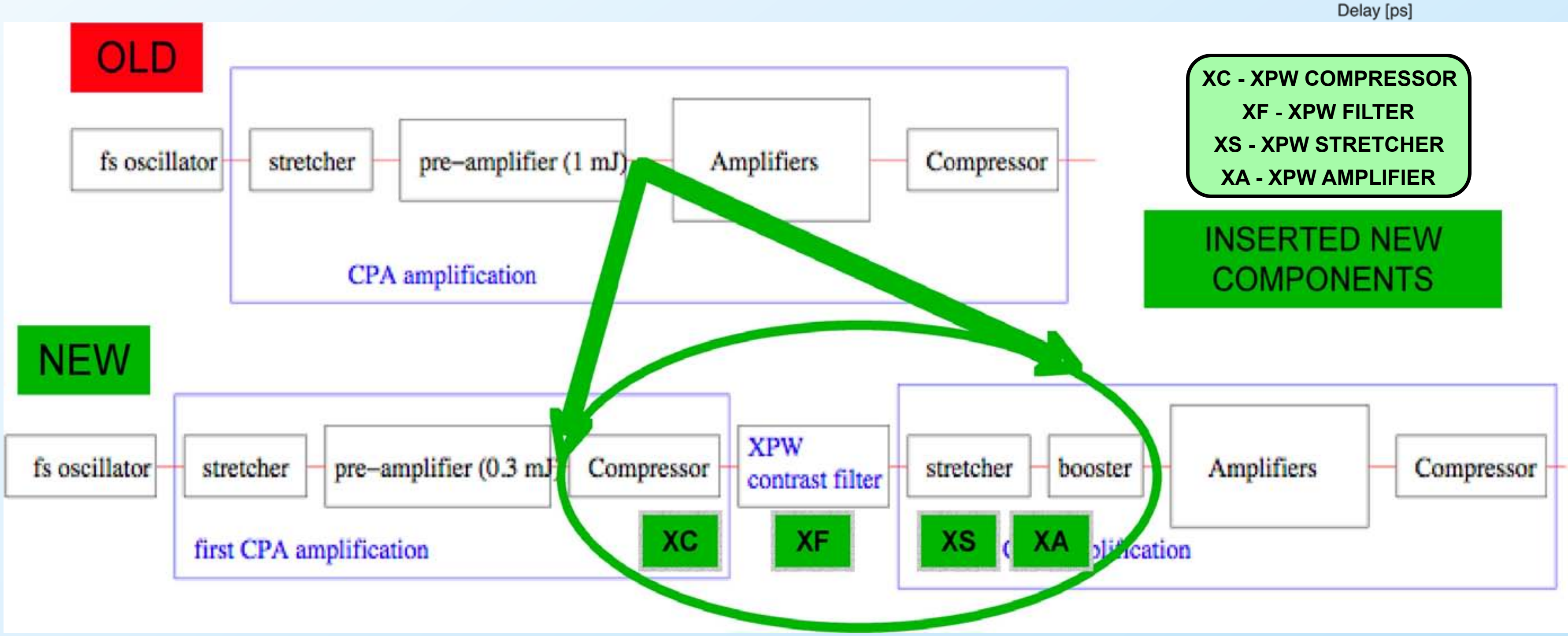
Cross-Polarized Wave Contrast Improvement Implementation at LOASIS

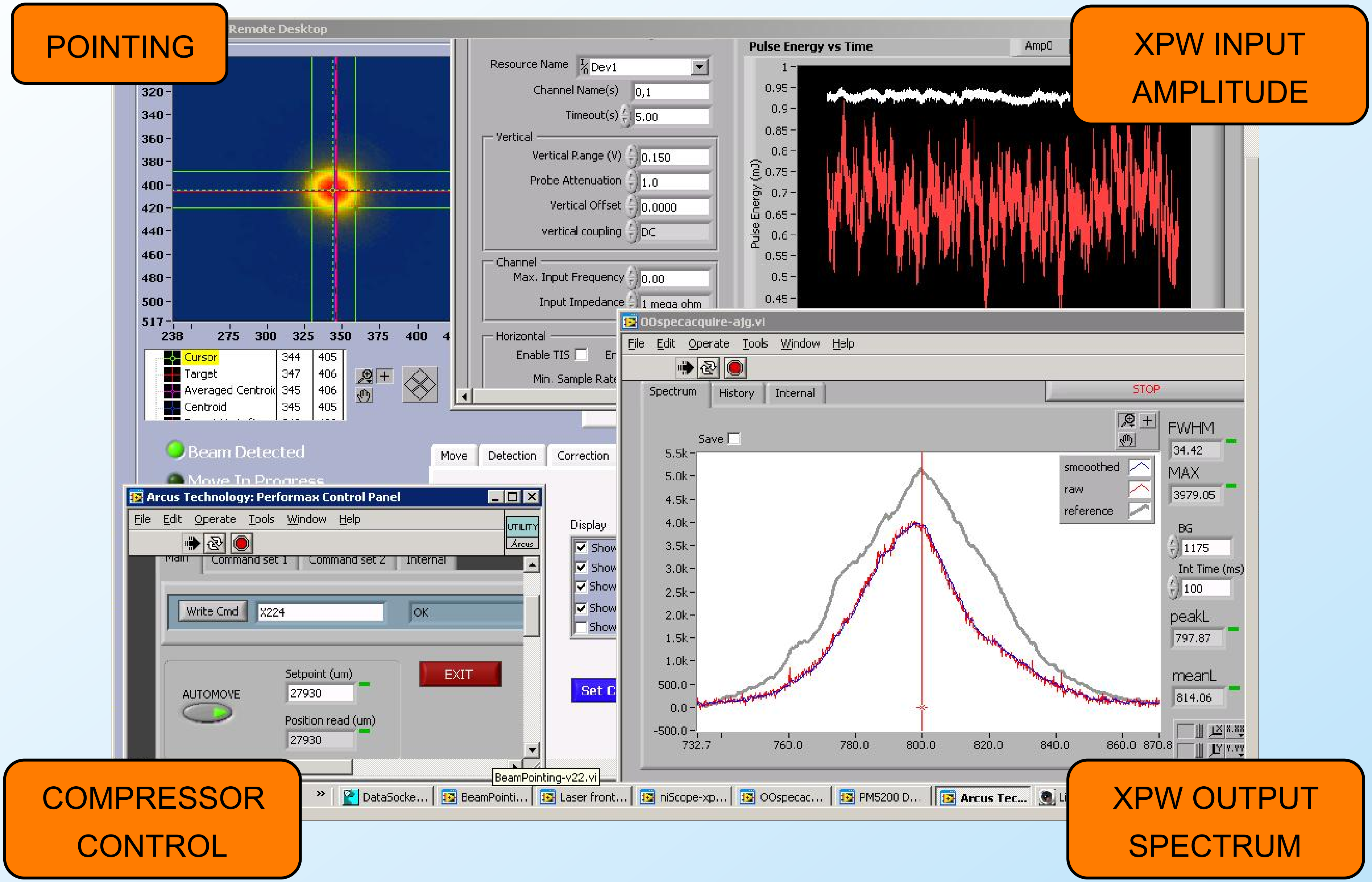
- Designed by O. Albert *(LOA, France)*
- Non-linear birefringence in BaF_2
- Operates in air, not vacuum
- Contrast improvement is limited by the polarizer/analyzer-pair extinction ratio (~5×10^5)
- Spectrum, spectral phase, and spatial mode unchanged, or improved
- 3rd order cross-correlator measurements show the 3-4 orders of magnitude improvements



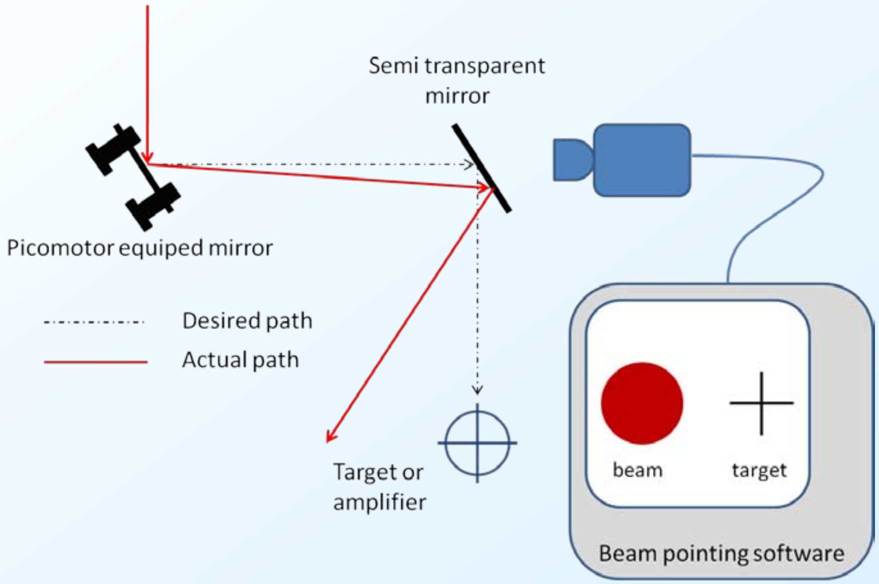




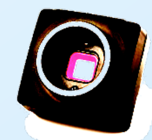
Diagnostics Suite for Online Front-End Monitoring



Automated Beam Pointing Control Allows Repeatable Experiments

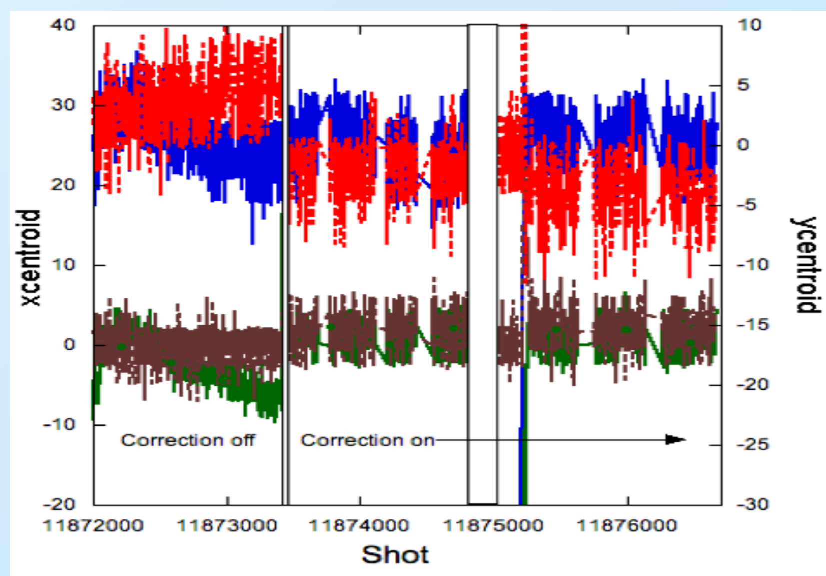


- GPIB/serial controlled picomotors
- Cameras


- Client-server system for whole lab

On target spot stabilization



- Increased safety: reduced beam viewing by operator
- Increased speed: Laser system start up with automated alignment
- Triggerable cameras for final amps/target
- Few micron on-target stability and <50 fs timing drift over hours achieved

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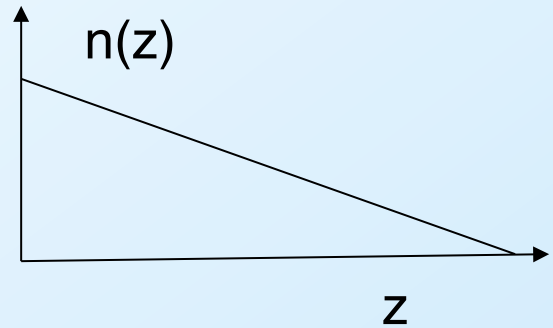
Longitudinal Plasma Density Tailoring: Triggered Trapping via Density Gradient

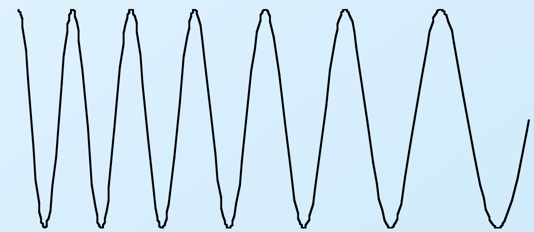
- Triggered trapping via plasma density gradient [Bulanov et al. PRE (1998)]: Plasma wave phase velocity is reduced to allow trapping of background plasma electrons.
  - Plasma wave phase:

$$\psi = k_p\left[z - v_g t\right] = k_p(z)\zeta$$

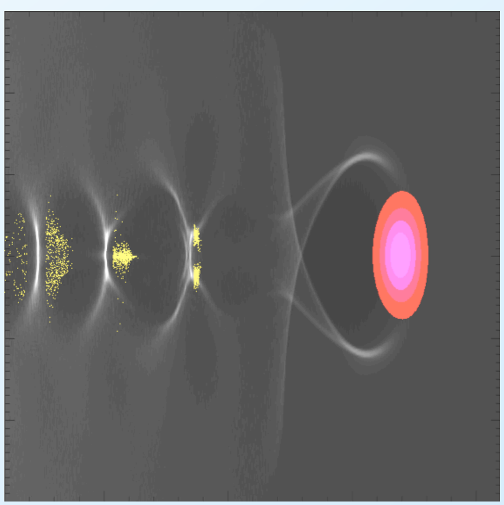
  - Plasma wave phase velocity:

$$\beta_\psi = \frac{\omega}{ck} = \frac{-\partial_t\psi}{\partial_z\psi} = \frac{\beta_g}{\left(1+\zeta\dfrac{dk_p}{k_p dz}\right)}$$

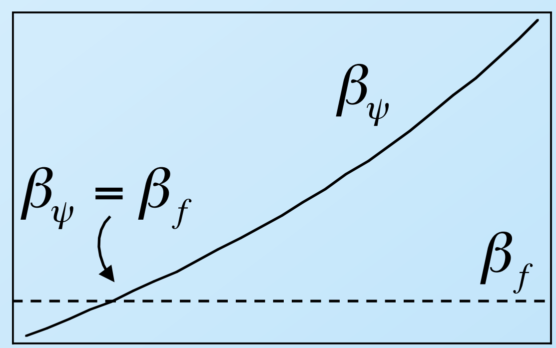




$$E \propto \exp\left[ik_p(z)\left(z - v_g t\right)\right]$$

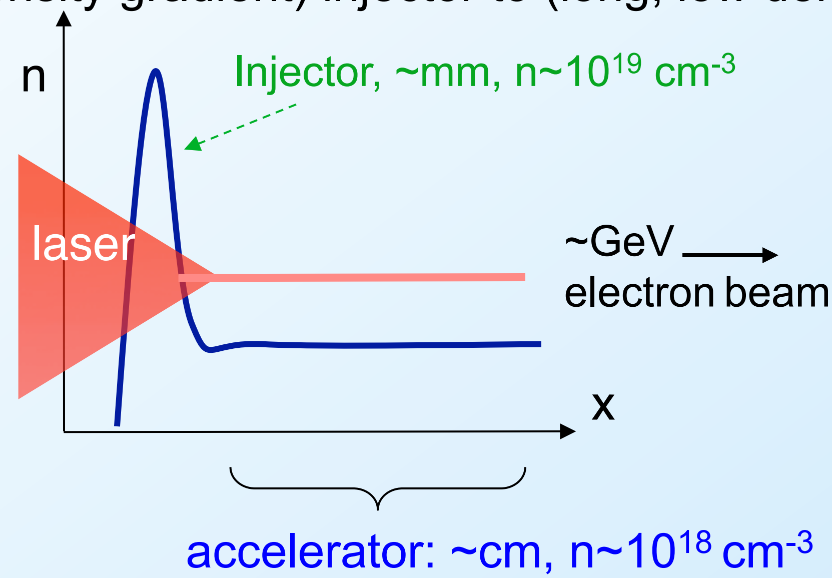


- Trapping of background plasma electrons controlled by ramp:
  - gradient
  - length

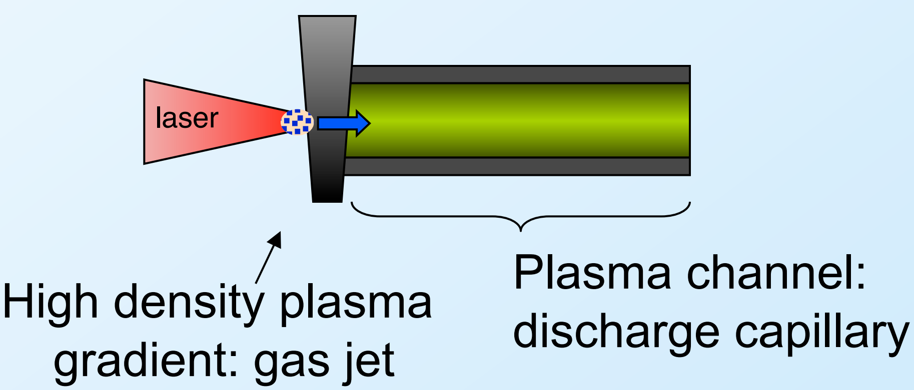


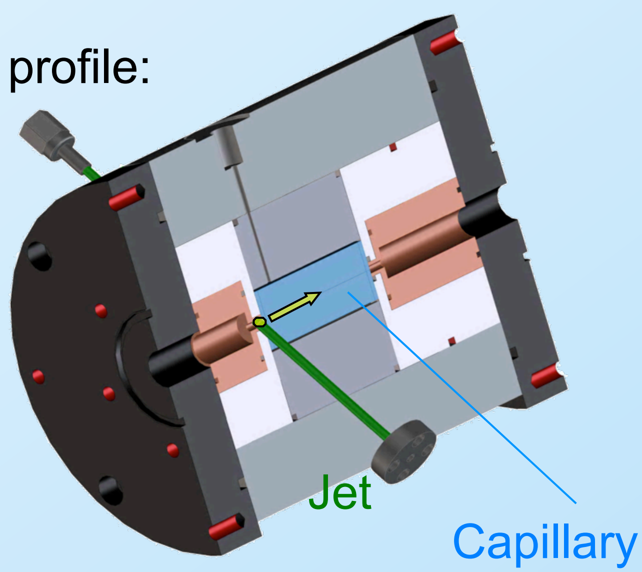
Integrated Injector and Capillary for Stability and Improved Beam Quality

- Couple (plasma density gradient) injector to (long, low density) plasma channel:



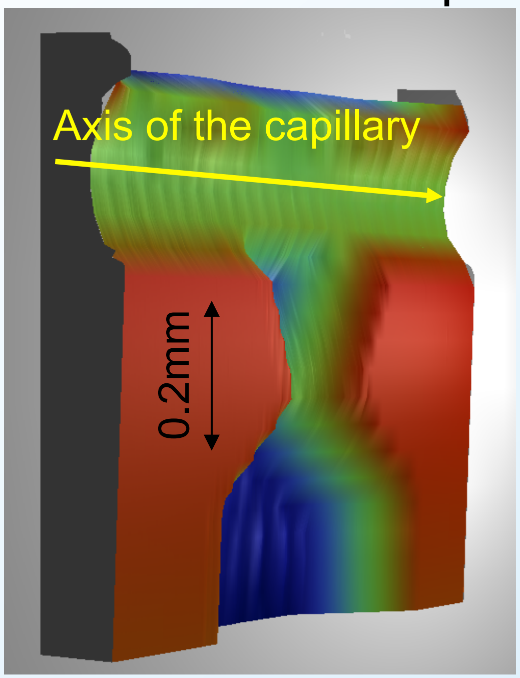
- Experimental implementation of plasma density profile:

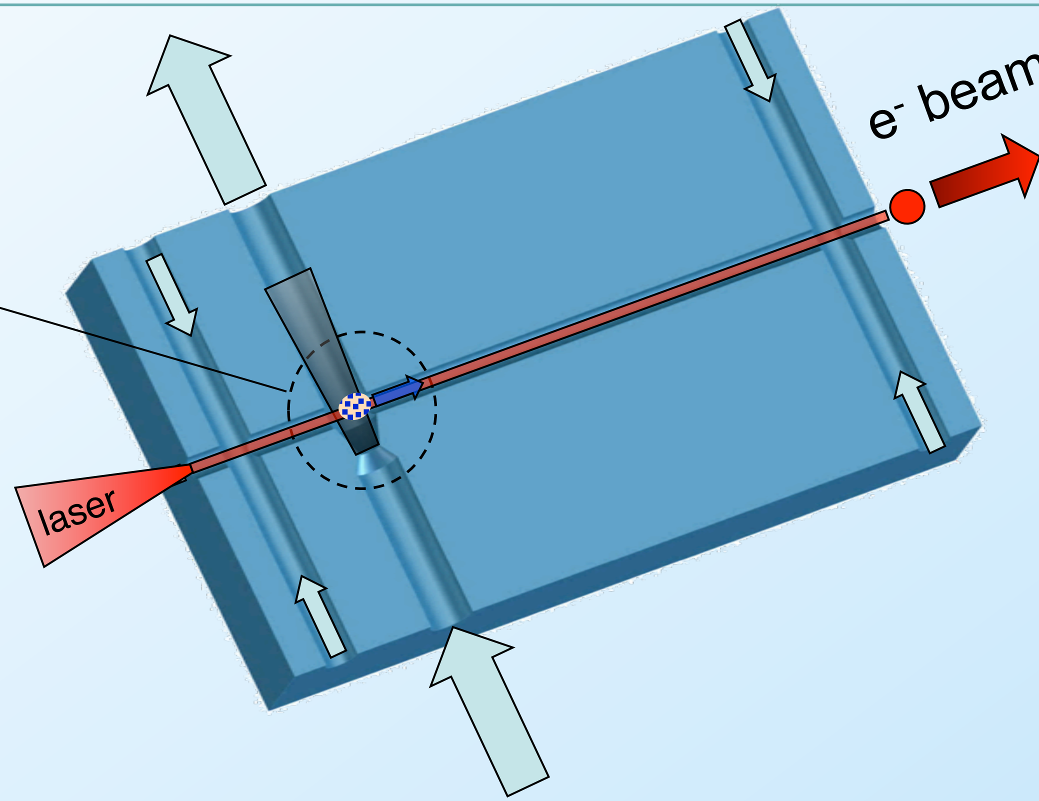


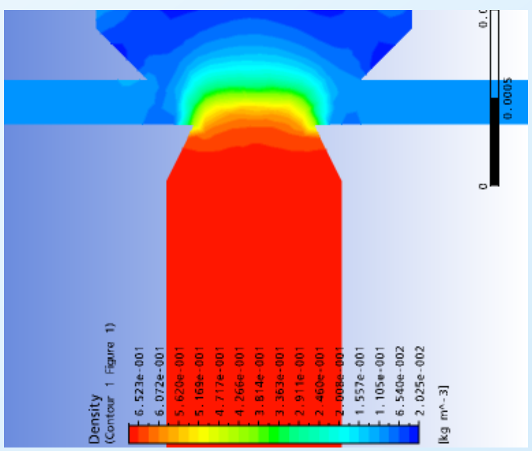


Gas Jet Nozzle Machined into Capillary Provides Local Density Perturbation

Measured surface profile

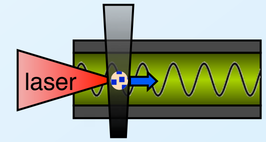






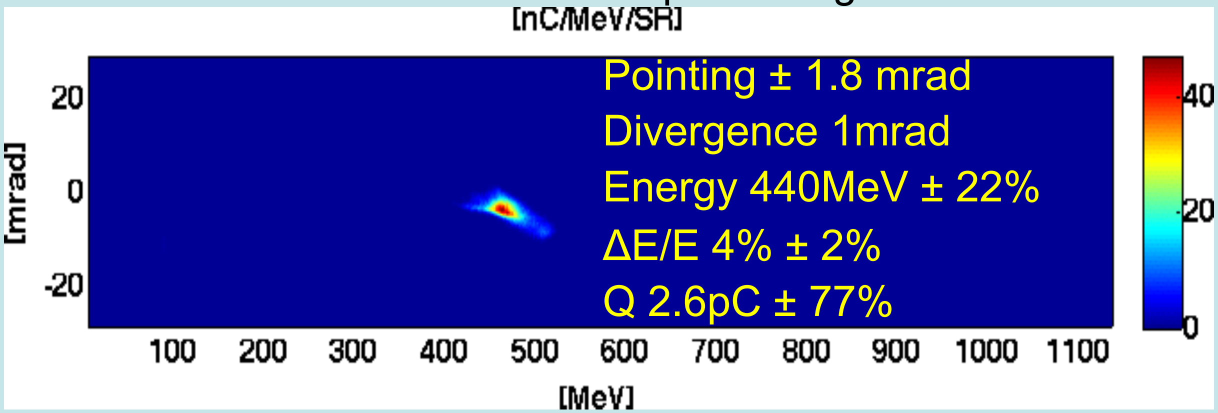
Density profile in capillary obtained from fluid simulation (benchmarked by interferometry)

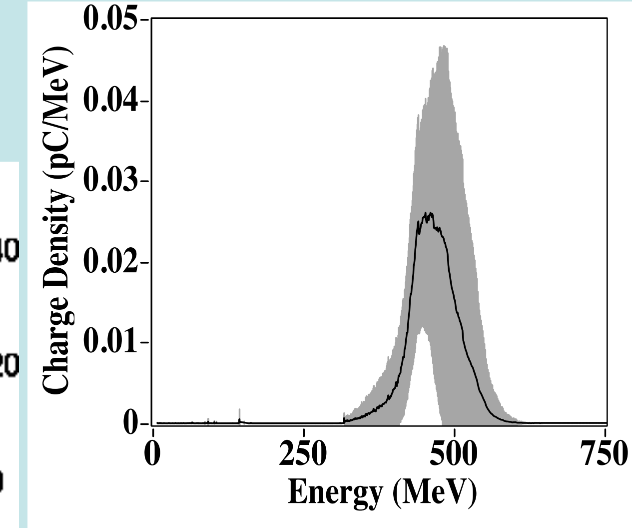
Jet with Capillary Produces Improved Beam Stability



Best stability without jet

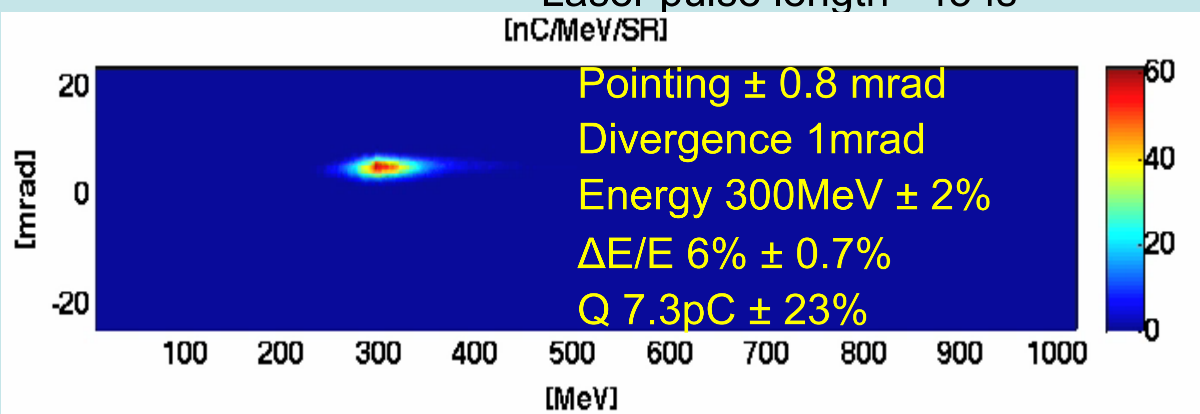
no jet in cap,
$Ne_{cap} \approx 2\text{x}10^{18}\ \text{cm}^{-3}, a_0 \approx 1$ (25TW),
Laser pulse length≈ 45 fs

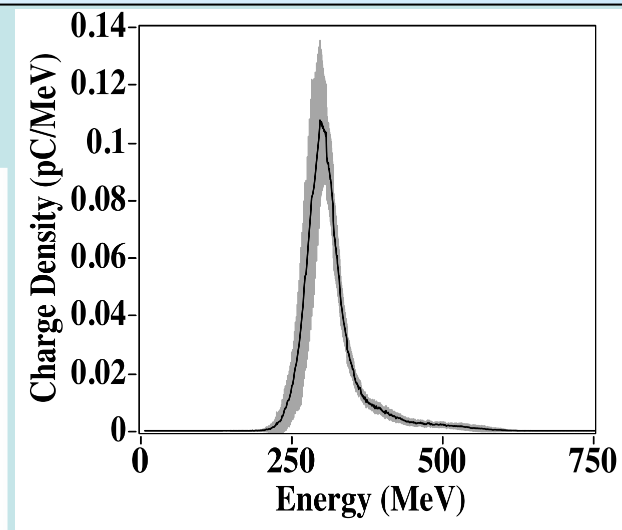




Stability with jet

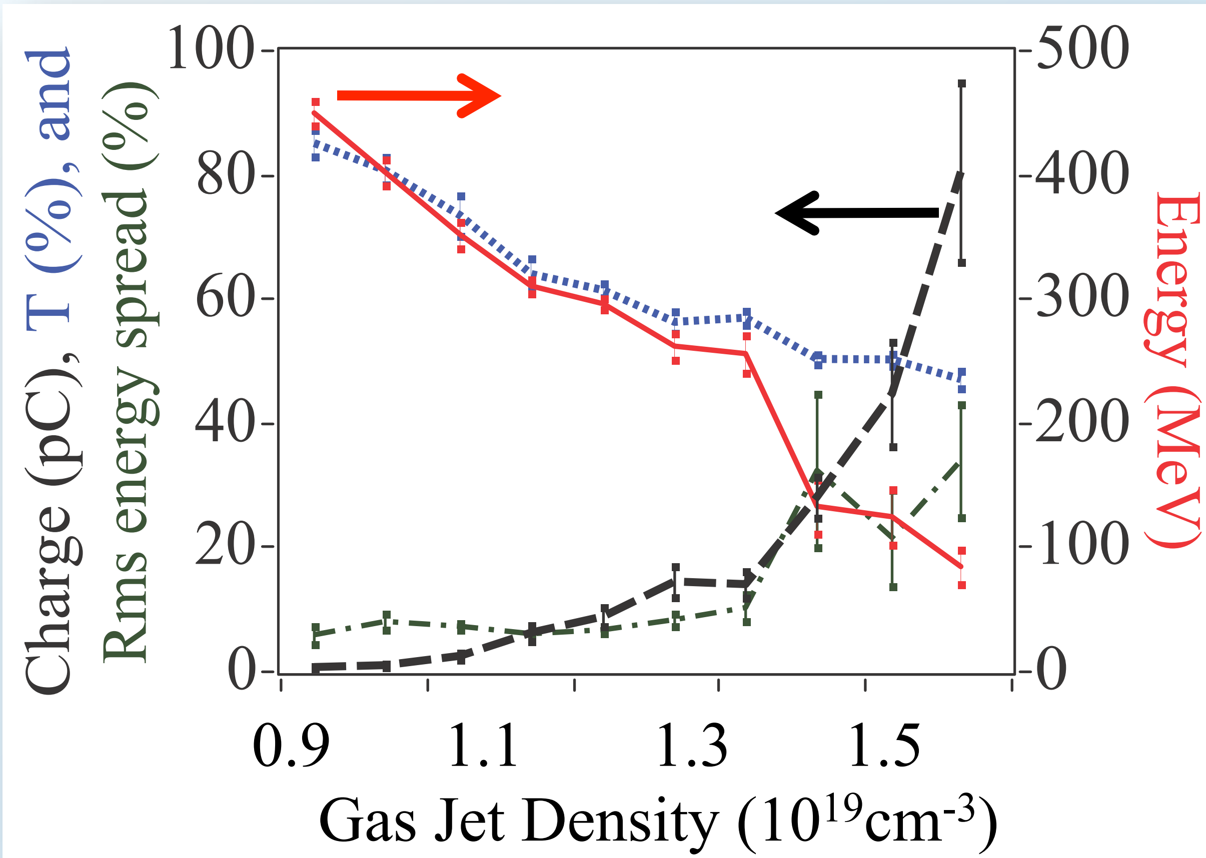
$Ne_{jet} \approx 1.4\text{x}10^{19}\text{cm}^{-3}$ FWHM 0.5mm,
$Ne_{cap} \approx 2\text{x}10^{18}\ \text{cm}^{-3}, a_0 \approx 1$ (25TW),
Laser pulse length≈ 45 fs





Energy Control by Varying Jet Density

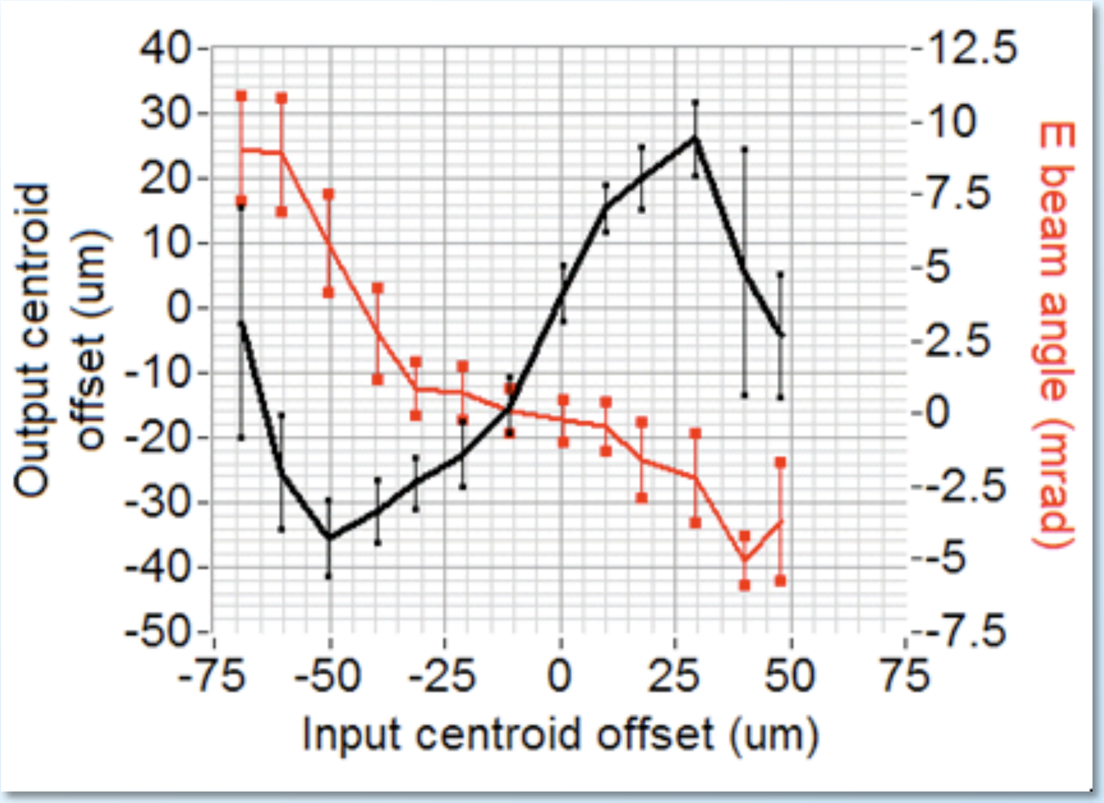
- Energy control without significant increase in energy spread

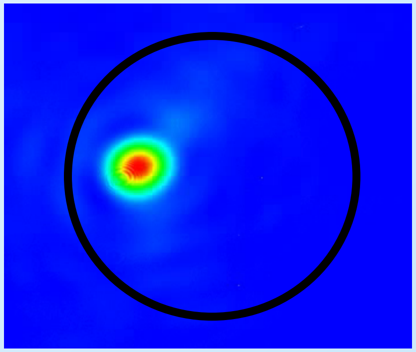


- Beam parameters not independent *yet*

Electron Beam Steered with Offset Between Axis of Laser Pulse and Plasma Channel

- Pointing control important for applications
  - Propagating electron beam between stages of a collider
  - Alignment to FEL or second laser pulse for gamma ray source





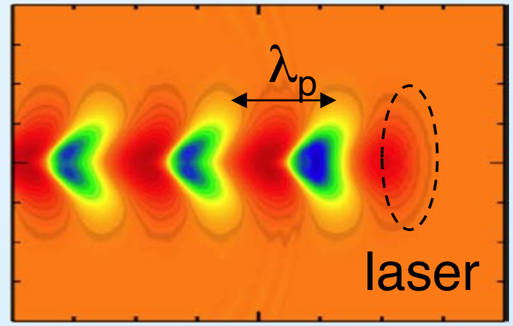
a_0=0.9; $N_e(0)$=1.2x10^{18}; τ_{FWHM}=40fs; t_d=300ns

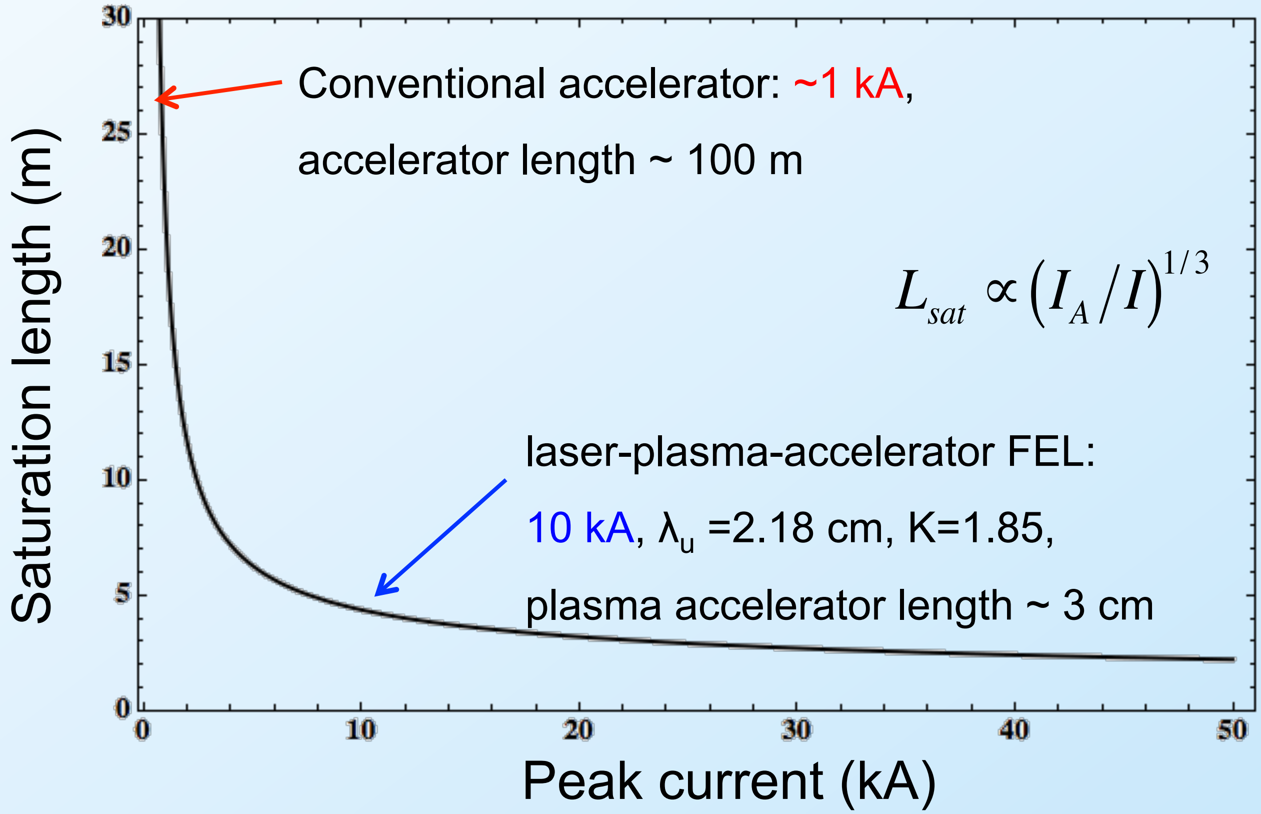
Gonsalves et al. Phys. Plasmas (2010)

LPA Application: High Beam Current Allows Compact FEL

- plasma-based accelerators are intrinsically sources of femtosecond beams:
  - Bunch duration << $\lambda_p/2$
  - Simulations confirm ~ 5 fs

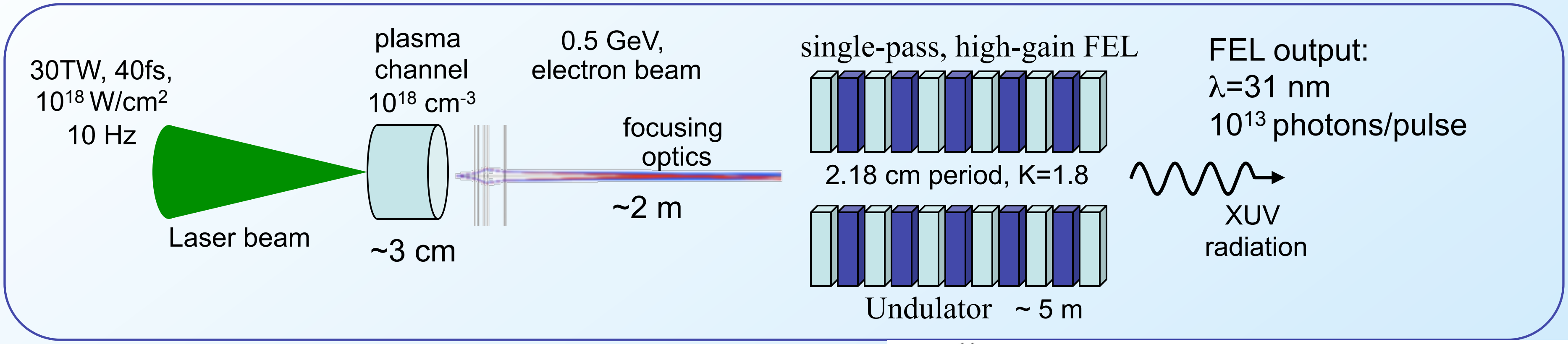
I_{peak} >10 kA



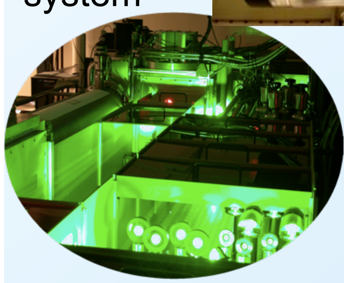


- Ultra-high peak current ⇒ reduced undulator length for saturation

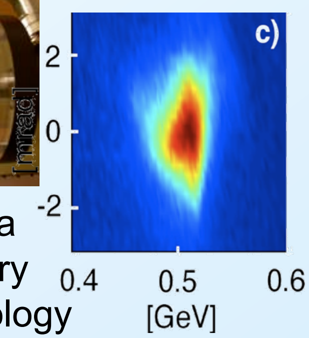
Laser Plasma Accelerator Driven XUV FEL at LBNL



Ti:Al_2O_3 laser system



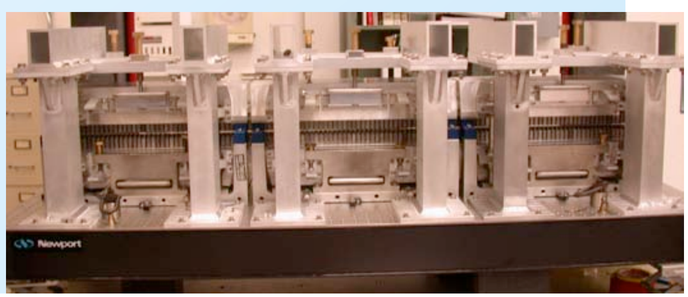
Plasma capillary technology

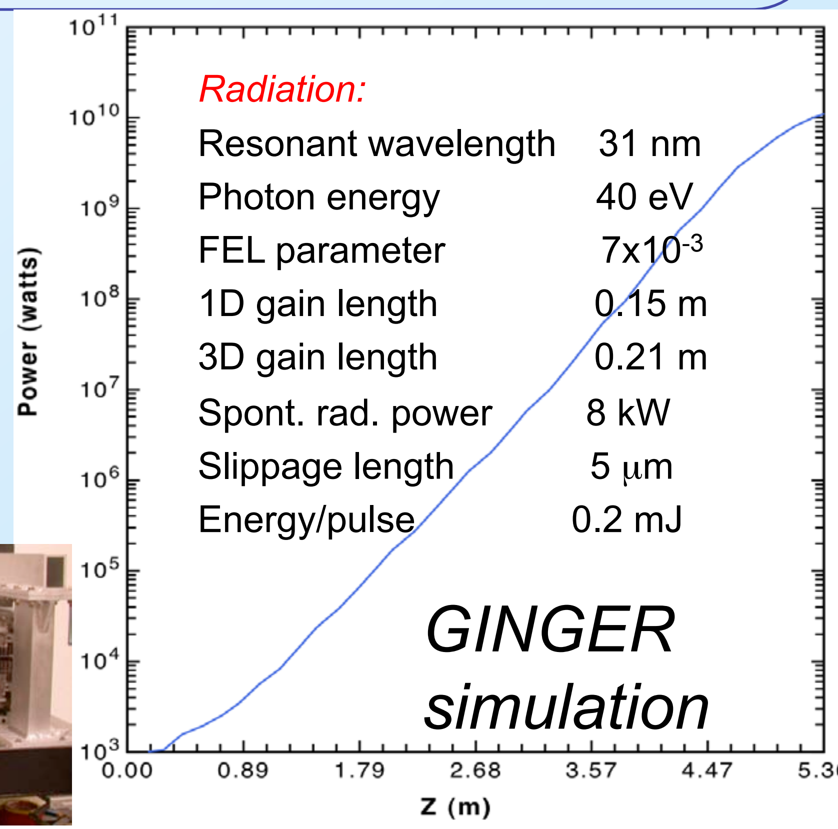


LPA electron beam

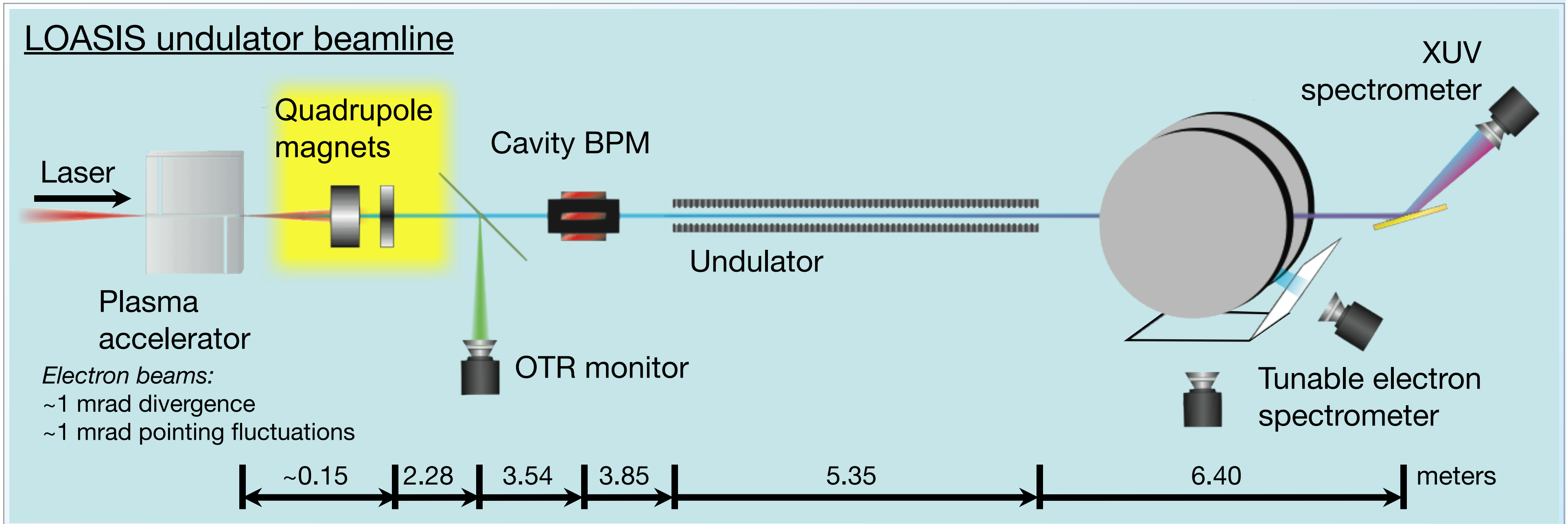
conventional undulator (THUNDER)

K. Robinson et al., IEEE QE (1987)





Beam Transport Along ~6.5 m Undulator Beamline



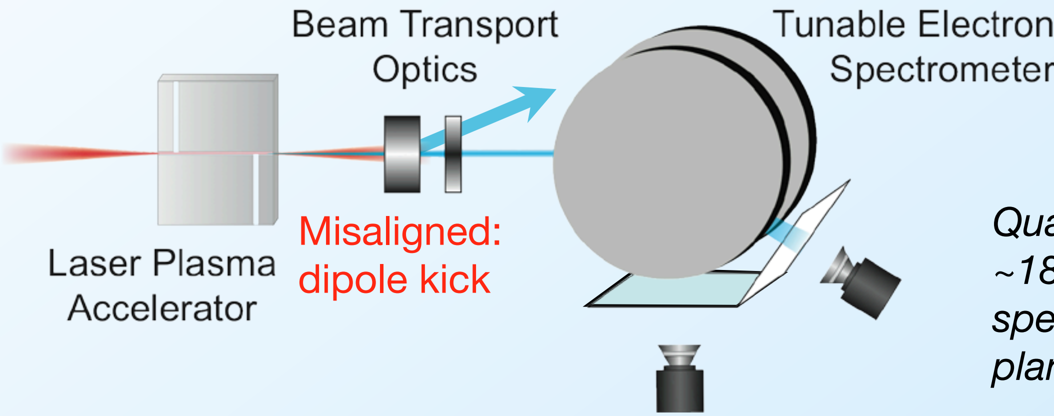
Electron beam transport by quadrupole magnets will allow for

- controlled, low-angular-jitter propagation of electron bunches through the undulator
- imaging of the electron beam waist into the undulator (with a large beta-function)
  → improves XUV beam quality
- steering of the electron beam

In addition: source imaging onto the electron spectrometer screen reduces measurement errors arising from beam divergence and pointing fluctuations

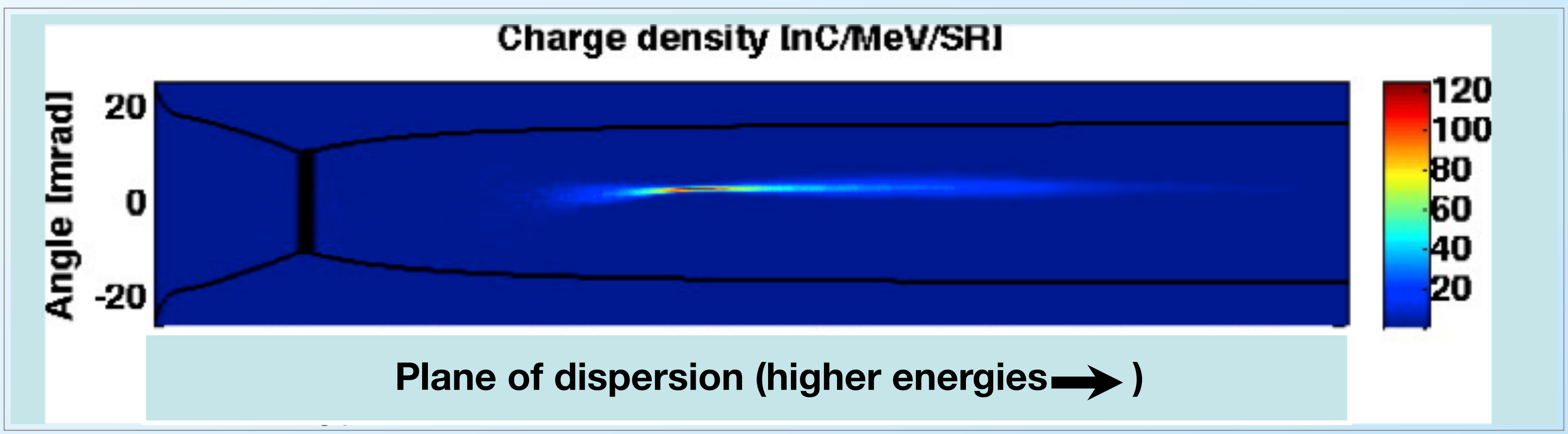
Quads Allow for Source Imaging onto Spectrometer Phosphor Screen

Experimental setup



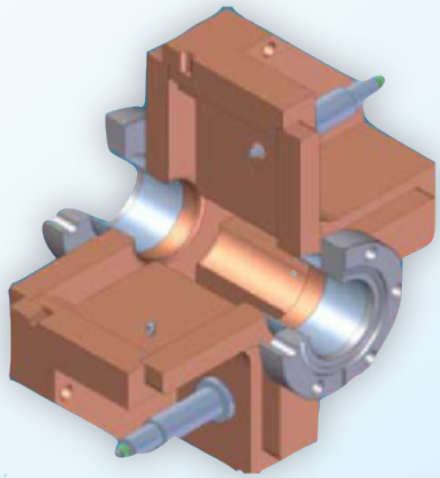
Quads positioned to image ~180 MeV electrons into spectrometer detection plane (1.3 m from source)

Detected electron spectrum on phosphor screen (with quads)

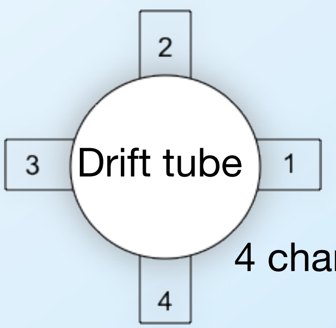


Noninvasive e-Beam Position Diagnostic: Cavity Based BPMs

Cavity BPM schematic

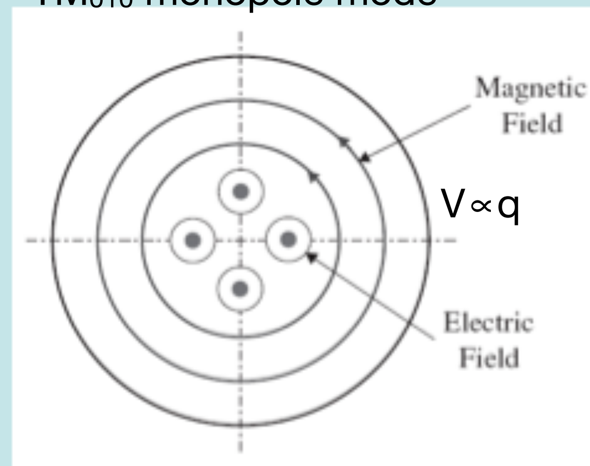


BPM on loan from SLAC

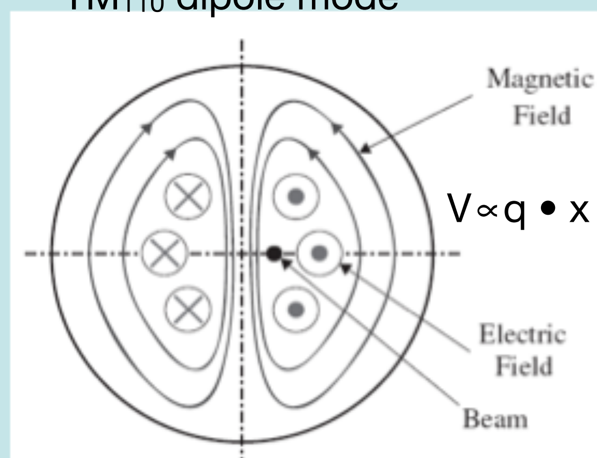


4 channels

TM010 monopole mode



TM110 dipole mode

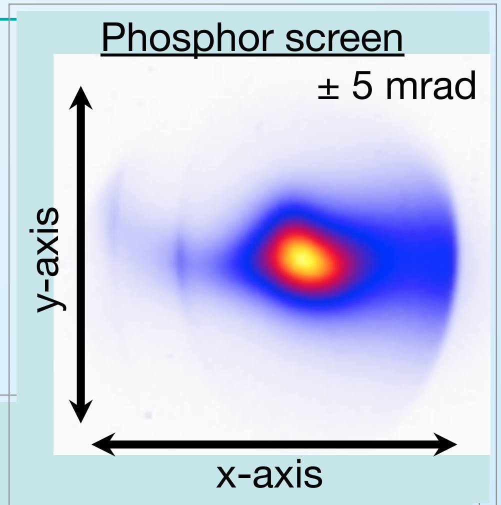


Figures from *Nucl. Instr. and Meth. A* **578**, 1 (2007)

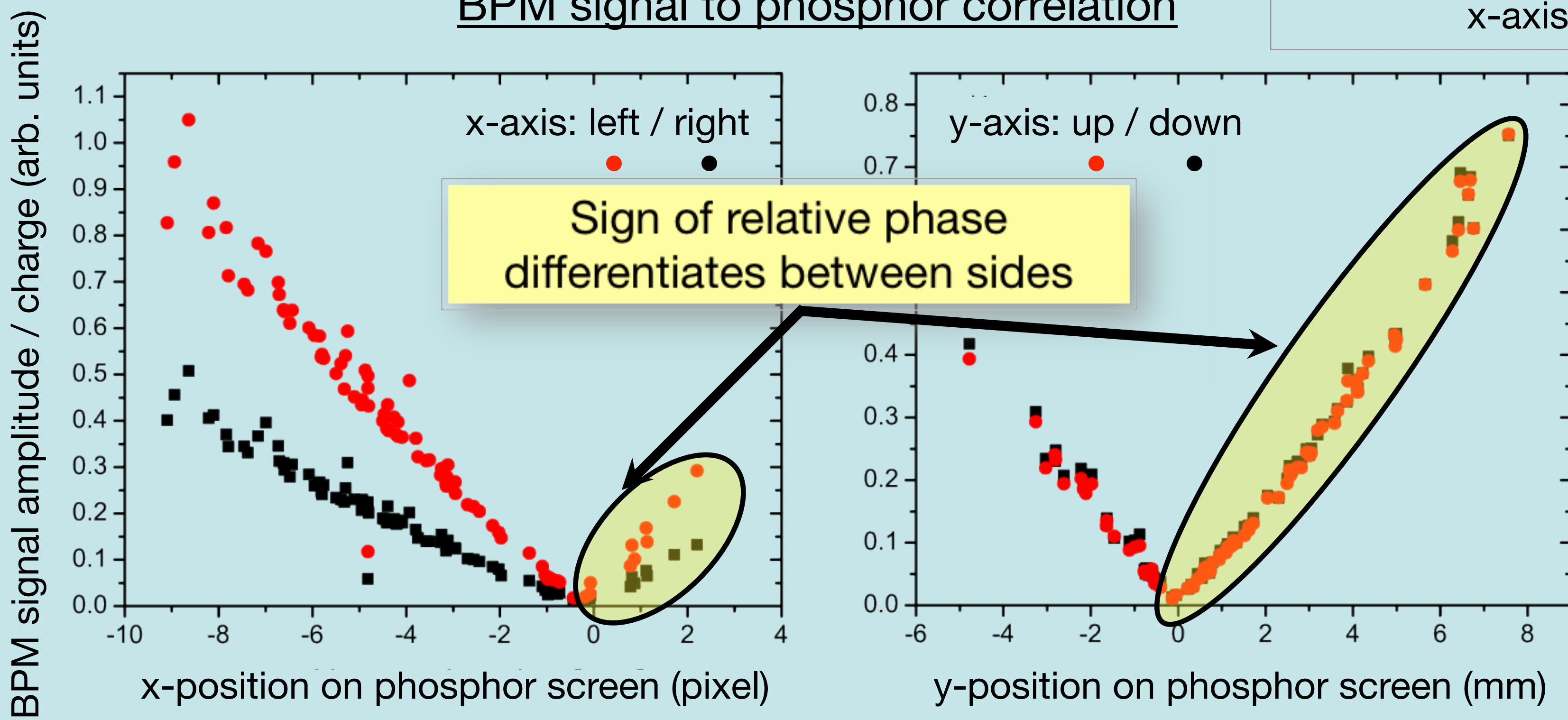
Cavity primarily supports dipole resonance

Preliminary BPM Calibration Results

- Calibrated against charge and position from a phosphor screen
- Sub-mm spatial resolution (limited by phosphor screen resolution)
- ~pC charge level sufficient to produce signal



BPM signal to phosphor correlation



Summary:
Toward LPA-based Hyperspectral Source

A well-controlled CPA laser will result in a well-controlled LPA and together enable a complex facility that deliver:

- Laser light – TW/PW source itself
- Electrons – LPA source itself
- THz radiation – via CTR
- VUV/XUV photons – via undulator
- X-rays – via betatron
- Gamma rays – via Thomson
- Protons, neutrons, etc

Femtosecond
Intense
Synchronized
Fits in few rooms
Relatively inexpensive


Thank you!