# The BNL Accelerator Test Facility

- **Proposal-driven, advisory committee reviewed** **USER'S FACILITY** for **long-term** R&D in Accelerator and Beam Physics.
- High-brightness e beams synched to high-power lasers.
- Serving National Labs, universities and industry.
- Contributes to Graduate Education in Beam Physics.
- In-house R&D on photoinjectors, lasers, diagnostics, computer control and more.
- Support from DOE, (HEP and BES), BNL Directorate and our users.
- Great demand for our services for the past dozen years.
- ATF web site: http://www.bnl.gov/atf/

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Brookhaven National Laboratory Accelerator Test Facility ATF

# What is the purpose of the ATF?

- The long-term approach to accelerators: to explore revolutionary new methods of acceleration, generation of radiation and associated subjects.
- Provide everybody a place to carry out such R&D without having to invest in basics, excellent equipment, trained staff, full hand-holding support of users.
- The value of this approach has been recognized, leading to proposals for similar facilities:
  - ORION An Advanced Accelerator Research Facility at SLAC.
  - NICADD, Northern Illinois Center for Accelerator and Detector Development.

# Our Core Capabilities

- High Brightness laser cathode e-gun

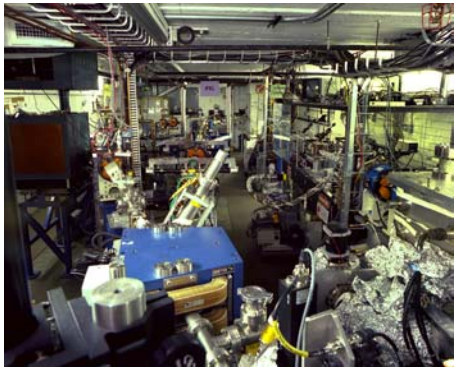
(0.05 to 1 nC, 0.5 to 1 mm mrad , 1-10 ps)

- 71 MeV linac (120 MeV upgrade planned)
- 5 GW 150 ps CO2 laser (soon 3 terawatt, 10 ps)
- Fully instrumented experiment hall, 3 beam lines
- State-of-the-art diagnostics, computer control
- Continuous improvement R&D in all of the above.

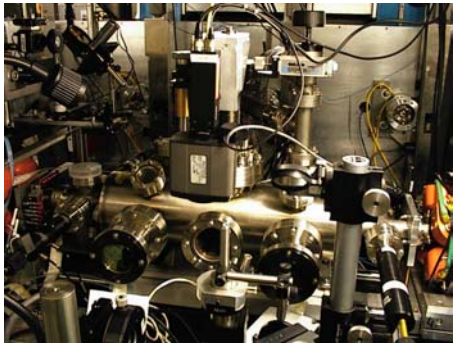
* Typically 1100 hours beam time delivered annually

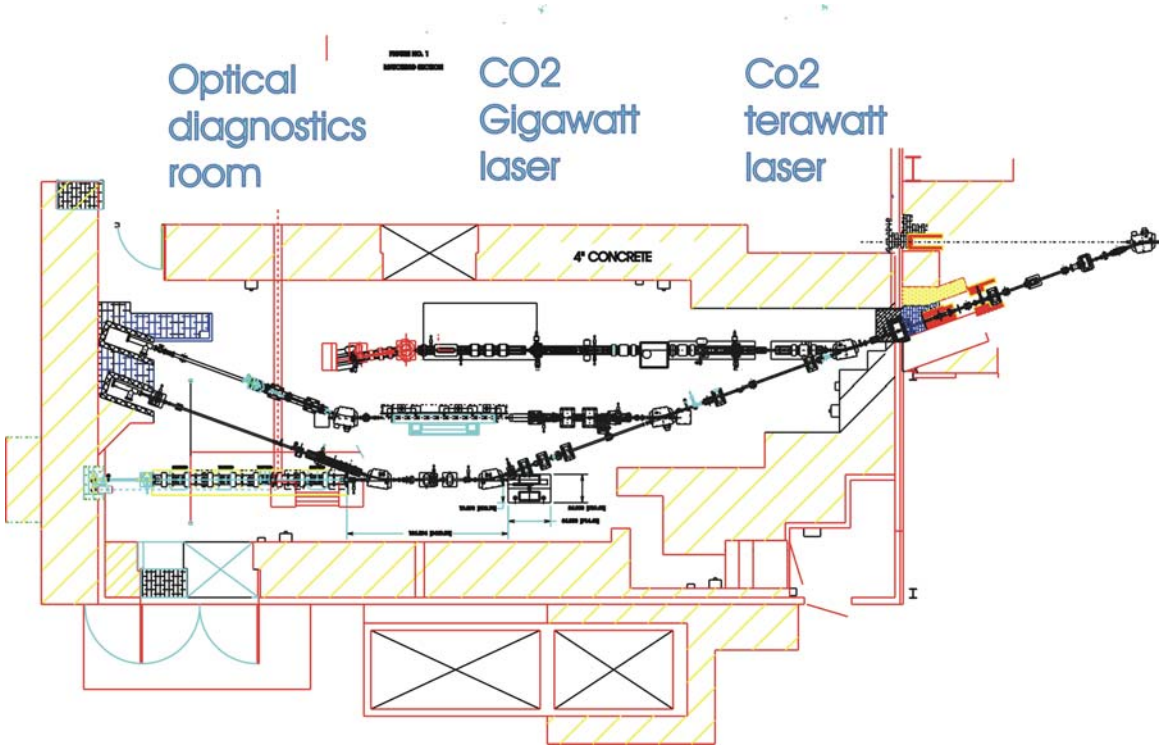
# ATF Experiment Hall

Experiment hall



Compton ps source






3 beam lines, one beam line directly past linac. Spacious control area, set-up area, optical diagnostics area, offices and more.

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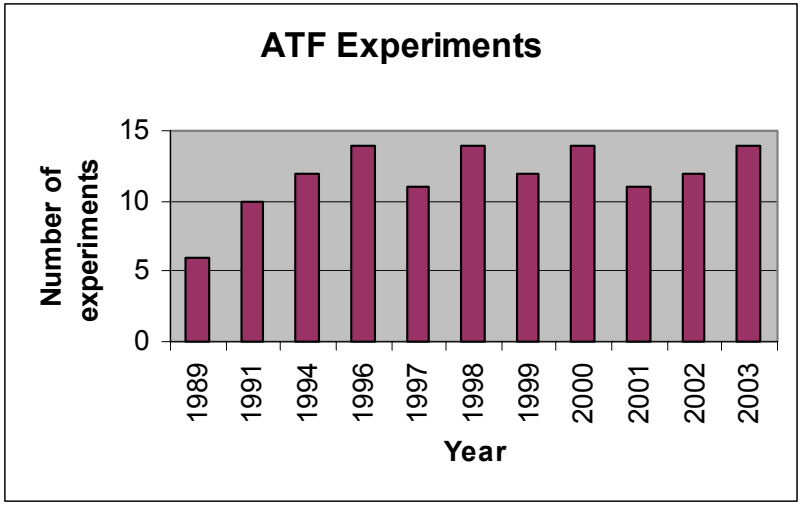
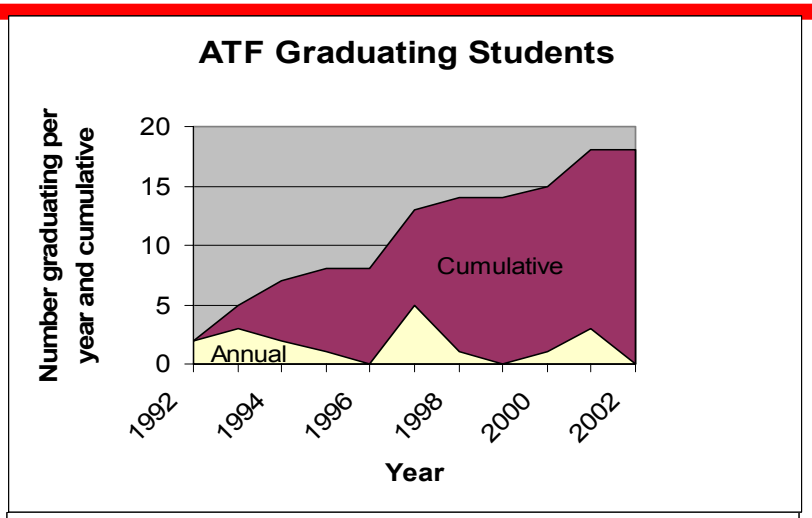
# 14 currently active experiments: 12 experiments completed

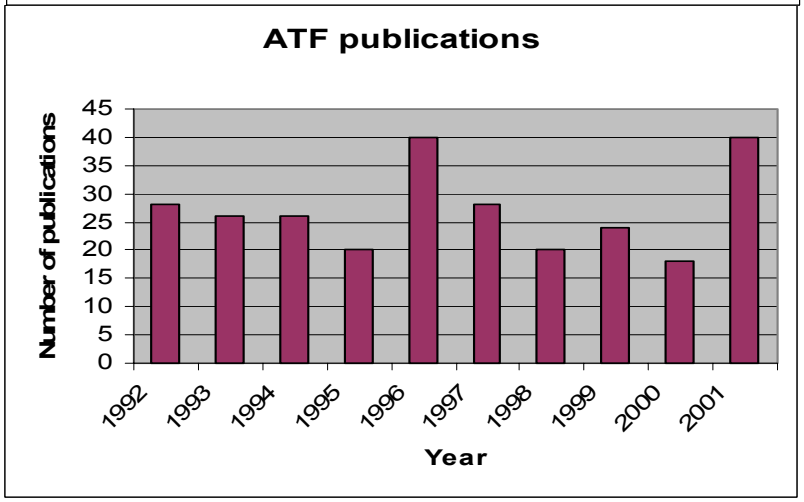
- Nonlinear-Compton Scattering
- Smith-Purcell Radiation
- Photocathode R&D
- Beam Position Monitors for Linear Colliders
- Stimulated Dielectric Wakefield Accelerator
- Staged Electron Laser Accelerator (STELLA)
- Compton Scattering of ps Electron and CO2 Beams
- Ultra-fast Optical Detection of Charged particles
- Laser Driven Cyclotron Autoresonance Accelerator (LACARA)
- A SASE-Free Electron Laser Experiment, (VISA)
- Electron Beam Compression Based Physics at the ATF
- Structure-based Laser Driven Acceleration in a Vacuum
- Optical Diffraction-Transition Radiation Interferometry Diagnostics
- Particle Acceleration by Stimulated Emission of Radiation

Steady state

# Some ATF Statistics




Run time: ~ 1100 hour / year
Graduate students: 8
Graduated students: 18
Current experiments: 14
Staff members: 8
Phys Rev X: 2 to 3 / year

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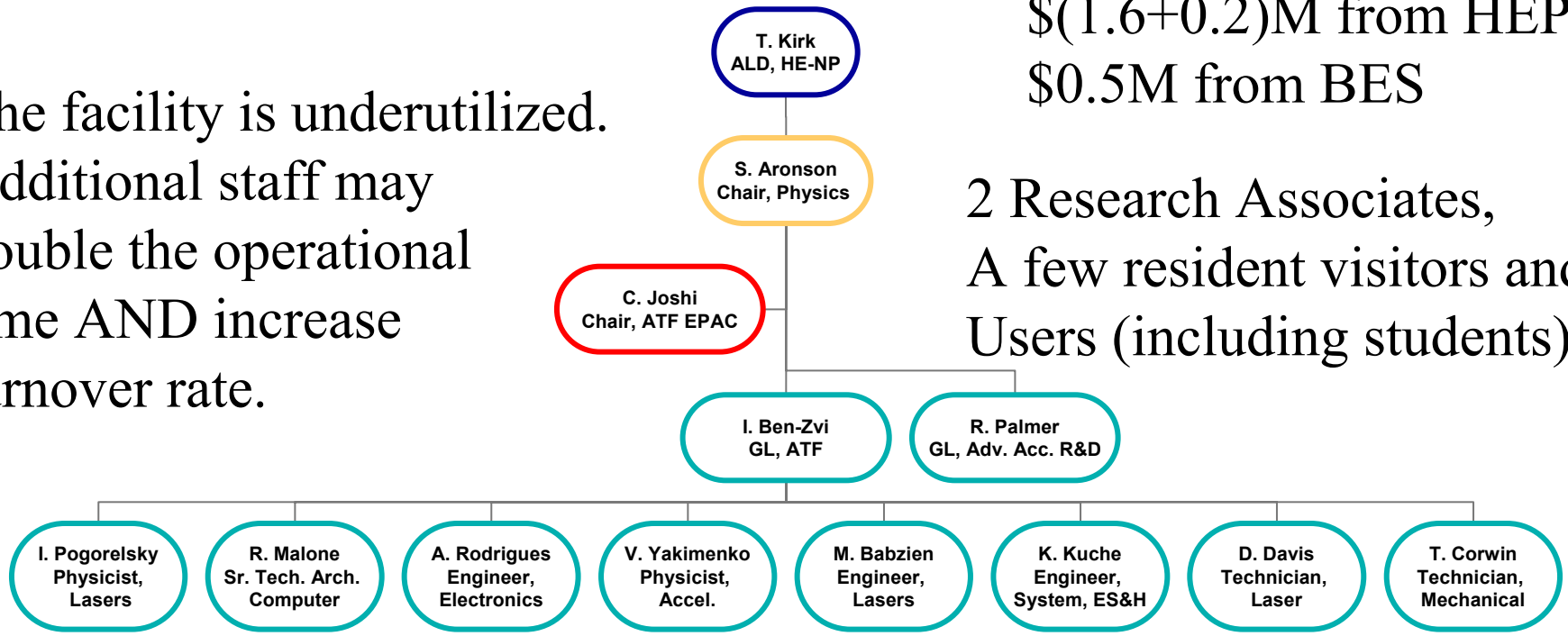
# ATF is at the Physics Department.

ATF Organizational Chart
(GL=Group Leader)




The facility is underutilized. Additional staff may double the operational time AND increase turnover rate.

Budget:

$(1.6+0.2)M from HEP

$0.5M from BES

2 Research Associates,
A few resident visitors and
Users (including students)

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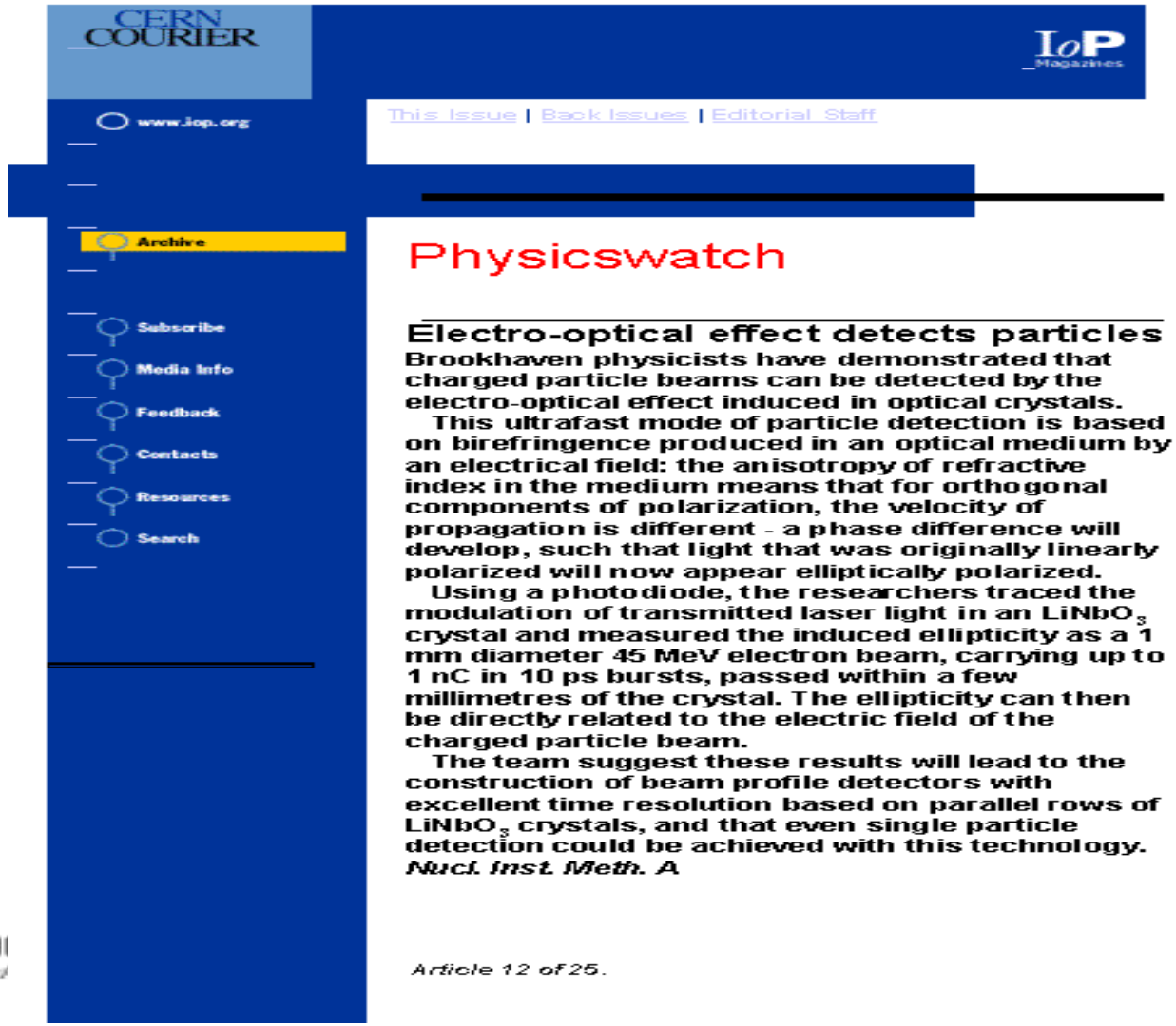
# ATF Experiments in the News



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## Physicswatch

### Electro-optical effect detects particles

Brookhaven physicists have demonstrated that charged particle beams can be detected by the electro-optical effect induced in optical crystals.

This ultrafast mode of particle detection is based on birefringence produced in an optical medium by an electrical field: the anisotropy of refractive index in the medium means that for orthogonal components of polarization, the velocity of propagation is different - a phase difference will develop, such that light that was originally linearly polarized will now appear elliptically polarized.

Using a photodiode, the researchers traced the modulation of transmitted laser light in an $LiNbO_3$ crystal and measured the induced ellipticity as a 1 mm diameter 45 MeV electron beam, carrying up to 1 nC in 10 ps bursts, passed within a few millimetres of the crystal. The ellipticity can then be directly related to the electric field of the charged particle beam.

The team suggest these results will lead to the construction of beam profile detectors with excellent time resolution based on parallel rows of $LiNbO_3$ crystals, and that even single particle detection could be achieved with this technology.

*Nucl. Inst. Meth. A*

*Article 12 of 25.*

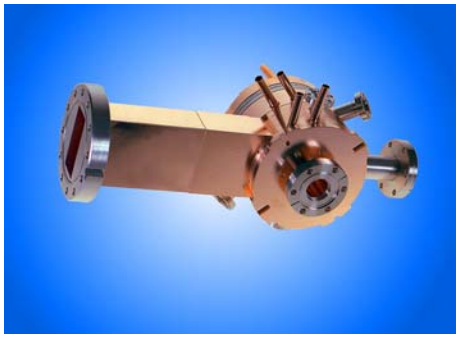
# ATF Systems in the News

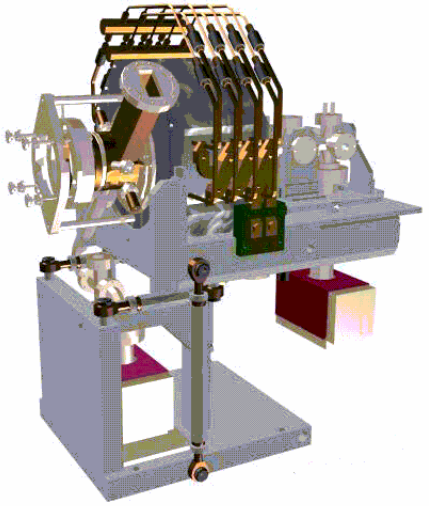
**Brookhaven's Accelerator Test Facility uses Mathcad to increase productivity and improve collaboration.**

# Photoinjector R&D

The ATF runs a complete R&D program in photocathode RF gun injection system:

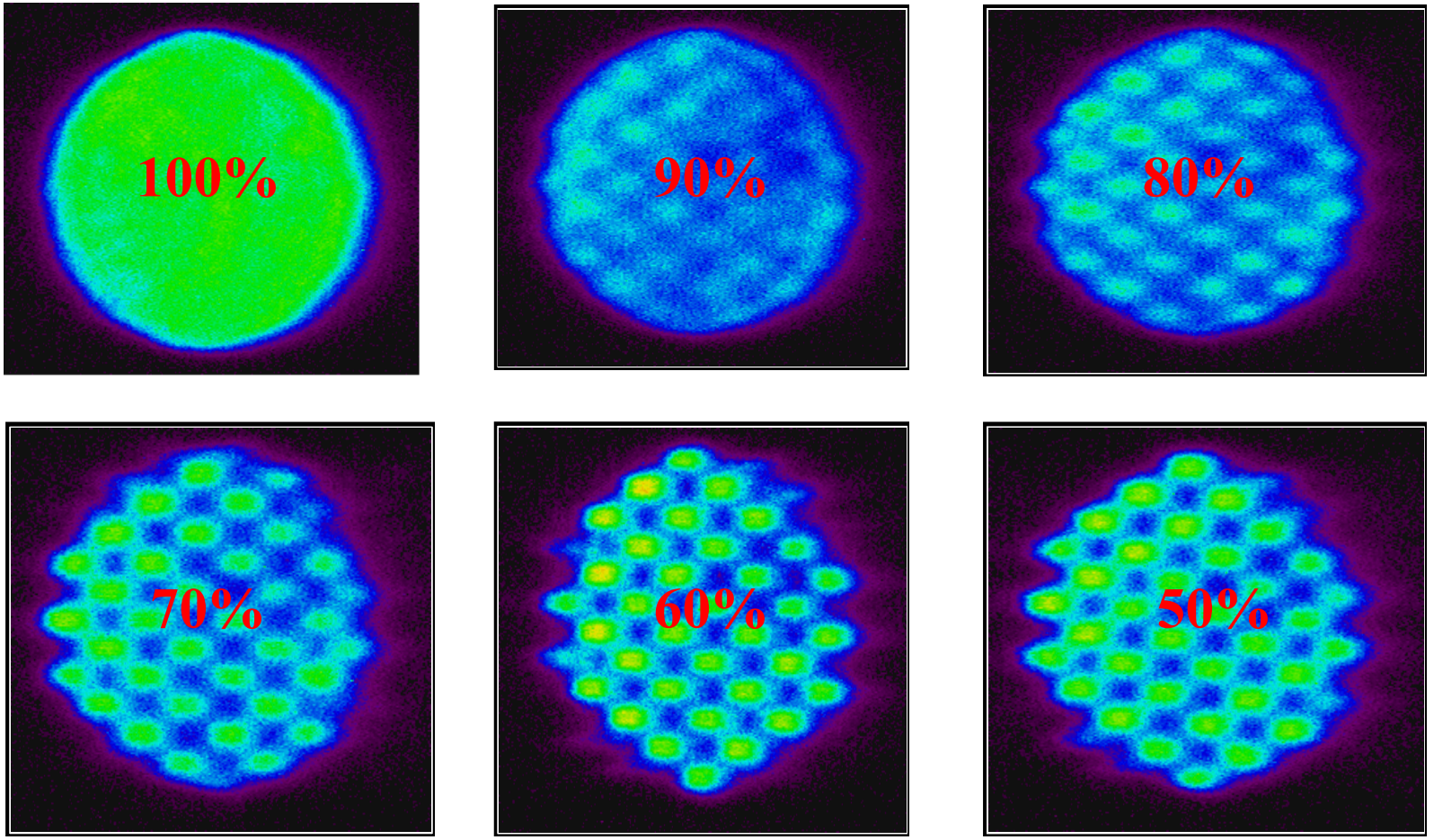
- High-duty RF gun (50 Hz) design and built by ATF is in operation at SDL, ANL and Japan. Closest to the LCLS 120 Hz design. ⇒
- A photocathode RF injection system including emittance compensation magnet, RF gun and beam diagnostics system. ⇒
- Drive laser system R&D on shaping, stability and reliability.
- Demonstrated technique of high QE Mg cathode with lifetime on the order of month.
- Superconducting photoinjector ⇒





# Emittance as a function of charge uniformity

F. Zhou, et al., PR ST-AB, **5** 094203, (2002).

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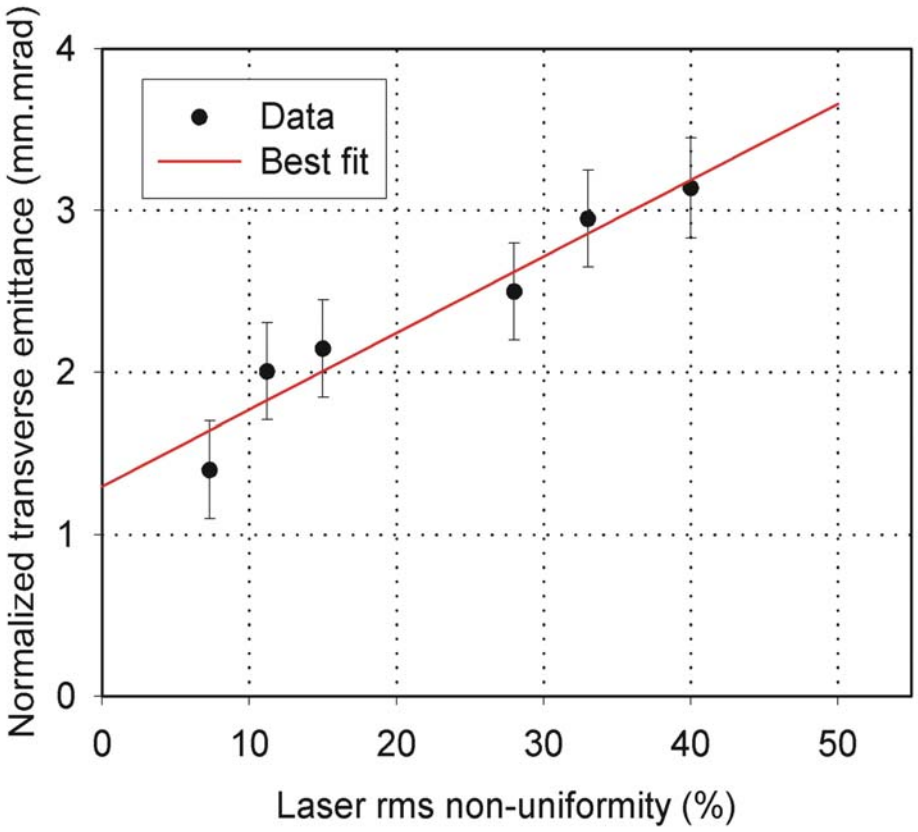
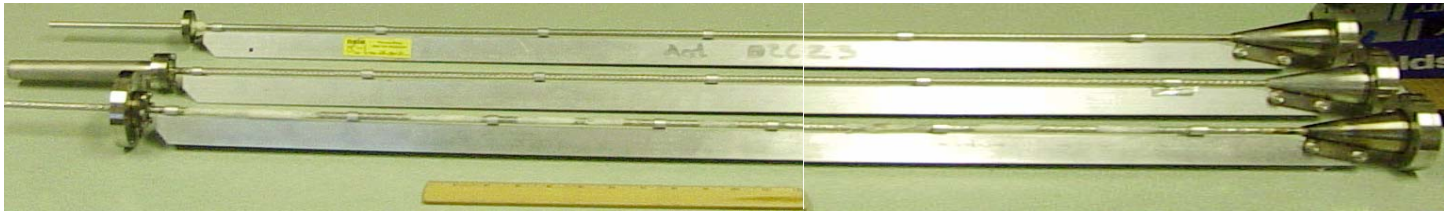
# Results of Experiment



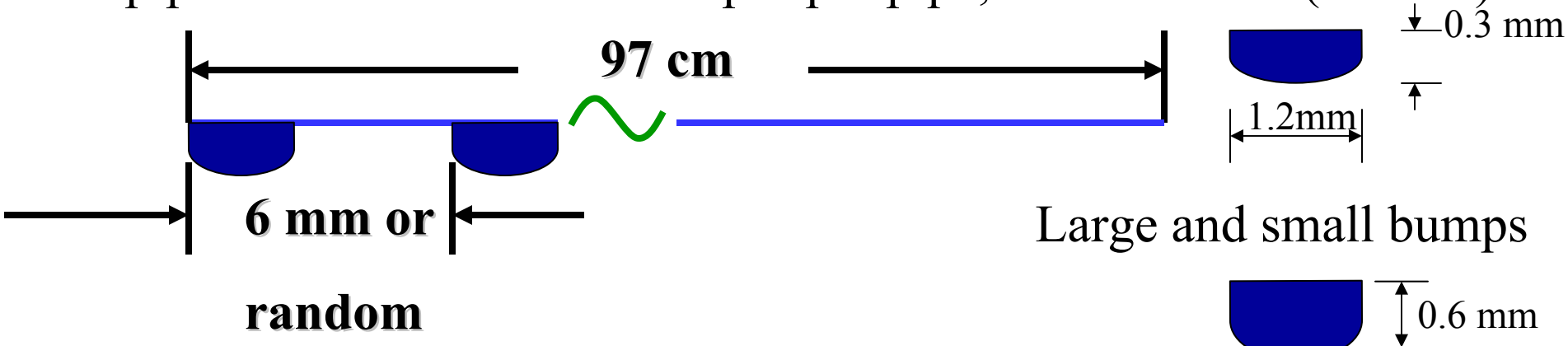
# Surface roughness wake field

F. Zhou, et al., PRL , 89 No. 17, 174801-1, (2002)

**Important subject for linear collider dynamics.**

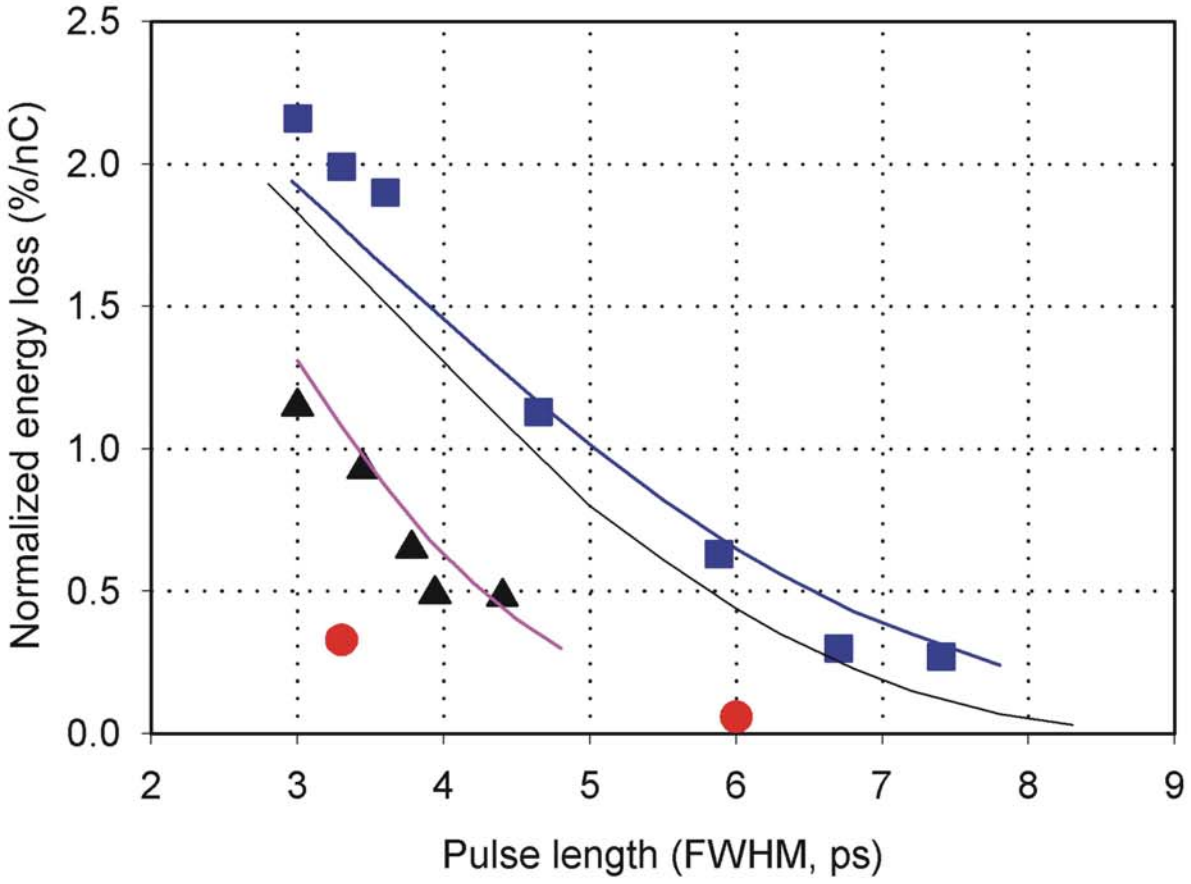


3 pipes with about 3000 “bumps” per pipe, one reference (smooth)



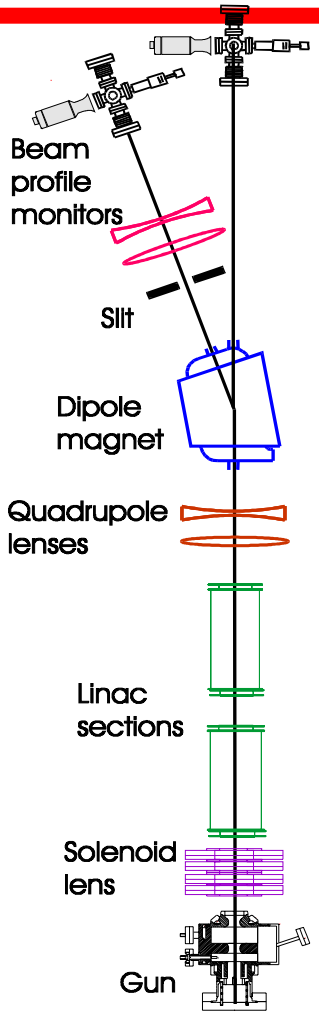
# One of the Measurements (Energy loss vs. bunch-length)

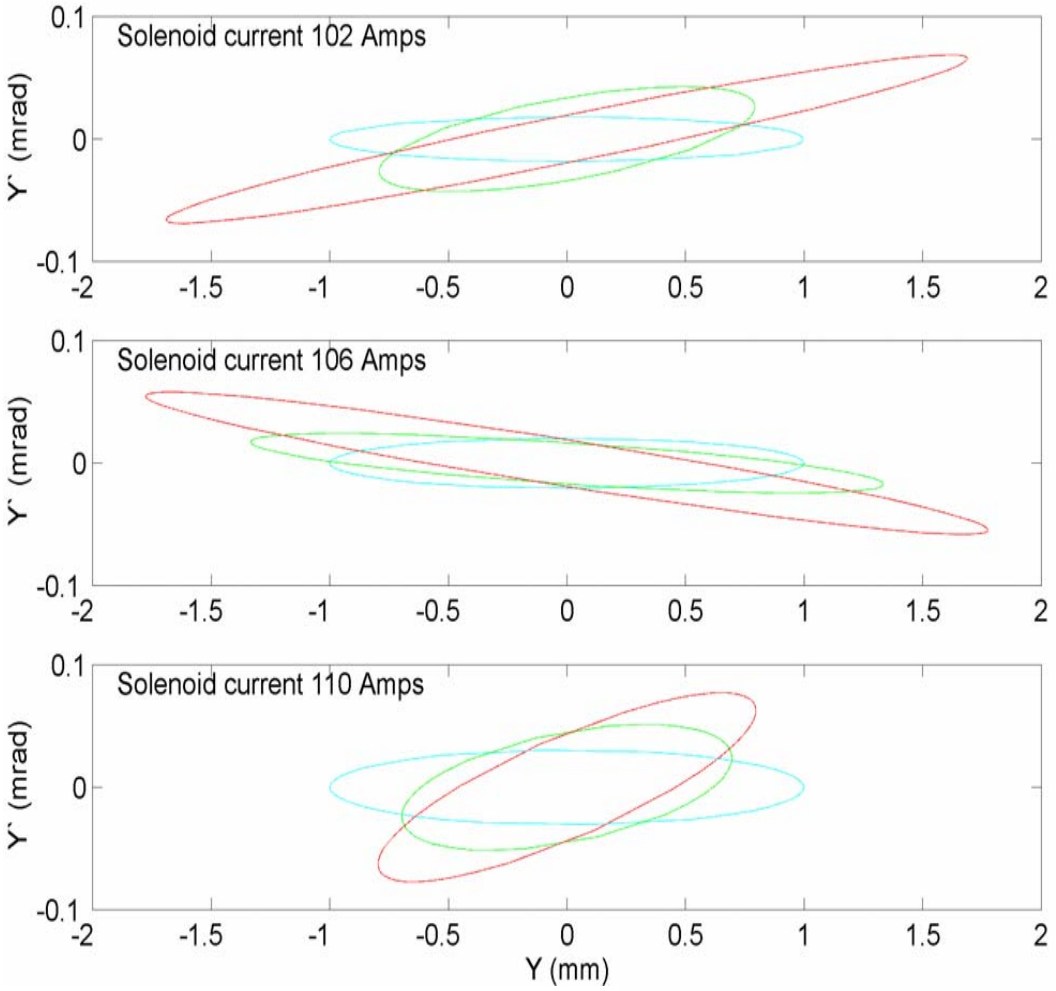
- Large bumps, ordered
- Small bumps, ordered
- Large bumps, random



# Picosecond 'Slice' emittance

## X. Qiu, et al., PRL **76**, 3723 (1996)

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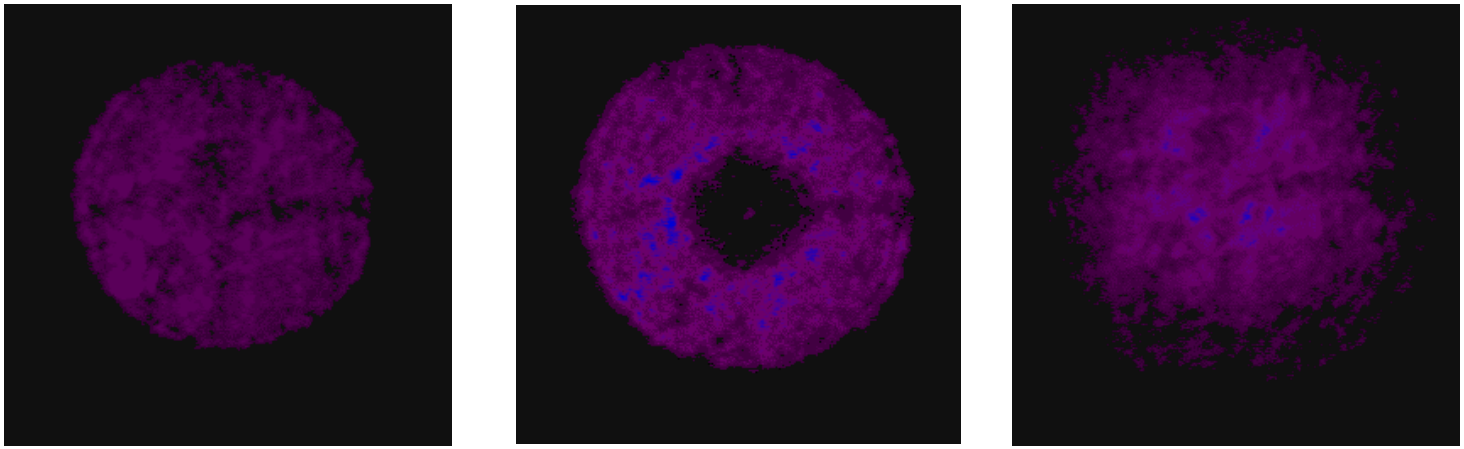
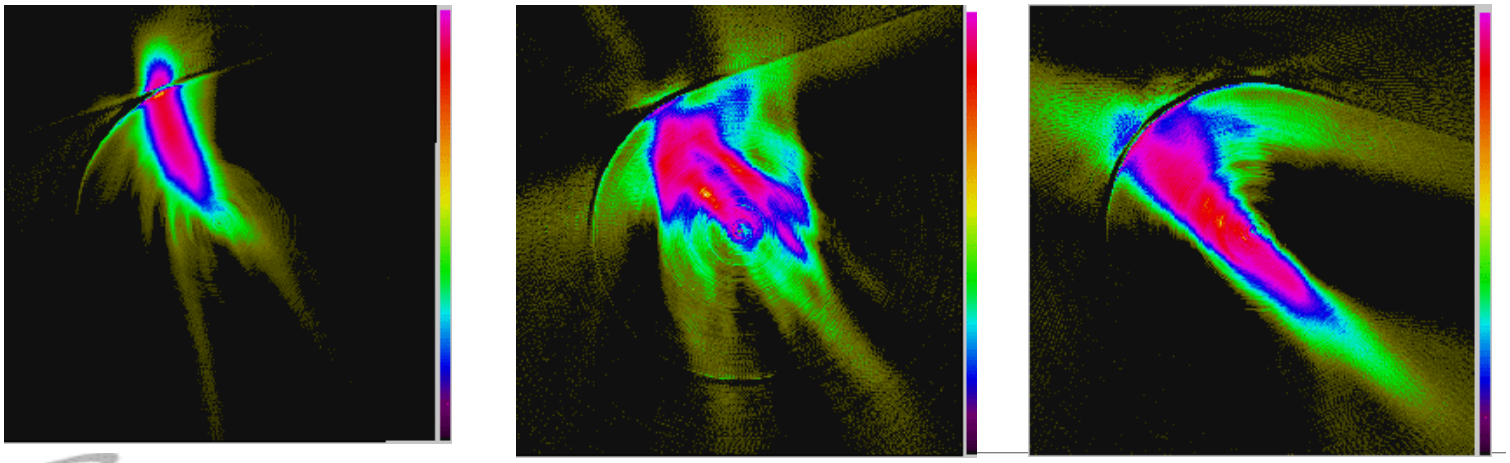
# Tomographic Studies of the phase space of an electron beam

Laser Profiles On Cathode:

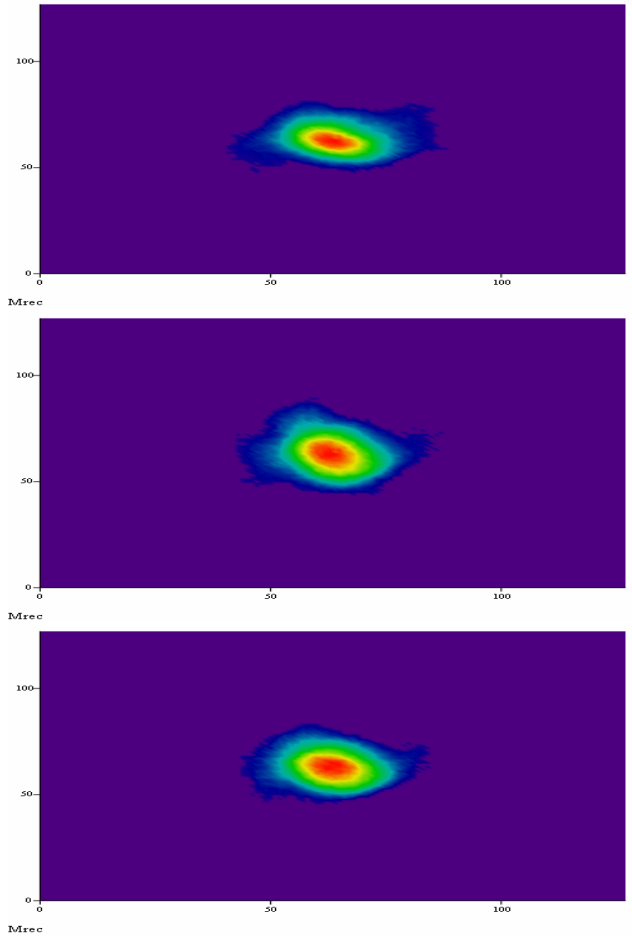


Phase-Space Density Map:



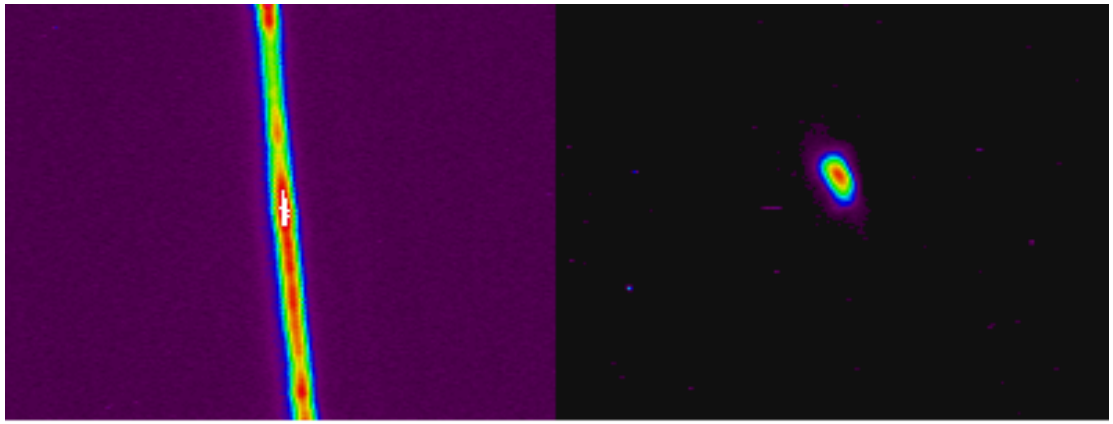
# Slice Emittance + Tomography!

- Measure electron density in phase space of a photoinjector.
- Slice emittance – a peek into the heart of emittance compensation.
- Phase-space tomography – what emittance really means.
- On right: Measured Transverse phase space of three different 1.5 ps slices of a 5 ps bunch.



# Small emittance and beams

- We measured an emittance of 0.8 microns at a charge of 0.5 nC (record)
- Made small beams (below, right) 10 microns rms spot size (see 30 micron diameter wire on left)



# Optical Stochastic Cooling (LDRD) in collaboration with LBNL

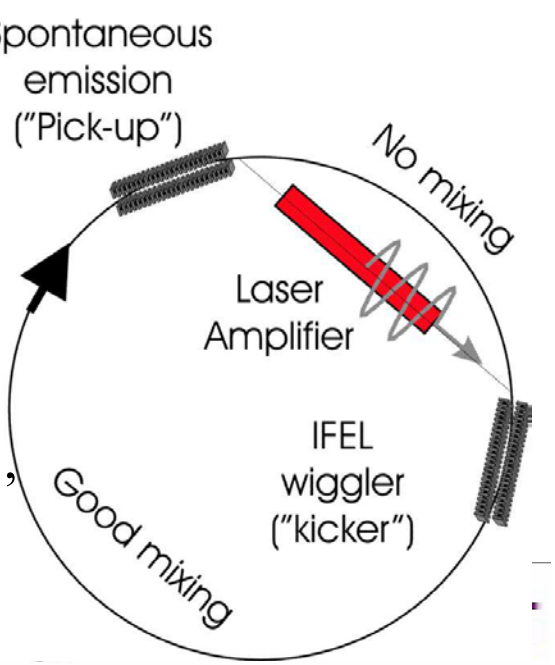
**Repeat $n_d$ times for 1/e reduction of emittance**

- 'Read' particle by spontaneous emission wiggler.
- Amplify signal with laser
- Apply correction 'kick' to the particle in IFEL wiggler
- 'Mix' particles (to de-phase spurious part.)

- Non power-limited $n_d \approx 2eN_s \quad N_s = \frac{\lambda}{3\Gamma}\frac{N_i}{\sigma_l}$
- Power-limited

$$\frac{1}{n_{x,\varepsilon}^2} = \frac{16}{\mathrm{e}}\frac{P}{I\frac{\Delta E}{q}}\frac{\delta E}{\Delta E}N_u \Gamma f_{x,\varepsilon},$$

$$\delta E = 4.12 q^2 k \frac{K^2}{2+K^2}\left[J_0\left(\frac{1}{2}\frac{K^2}{2+K^2}\right) - J_1\left(\frac{1}{2}\frac{K^2}{2+K^2}\right)\right]^2,$$

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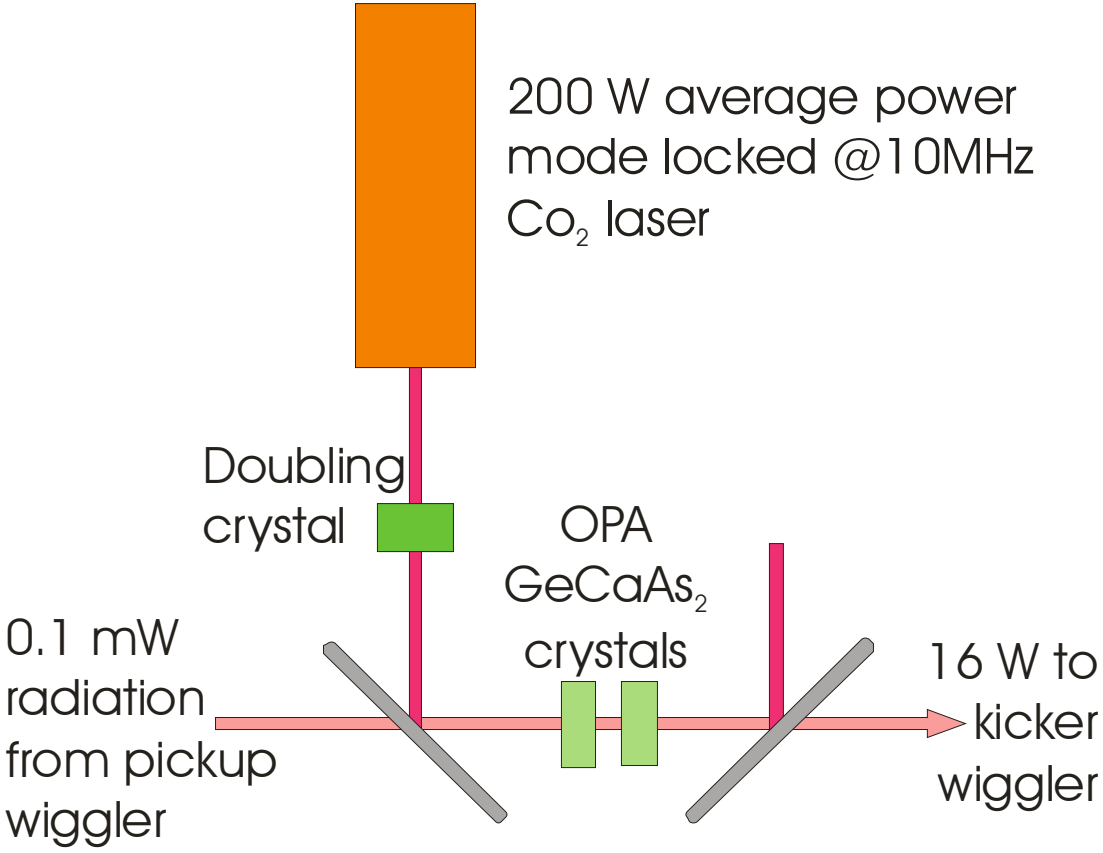
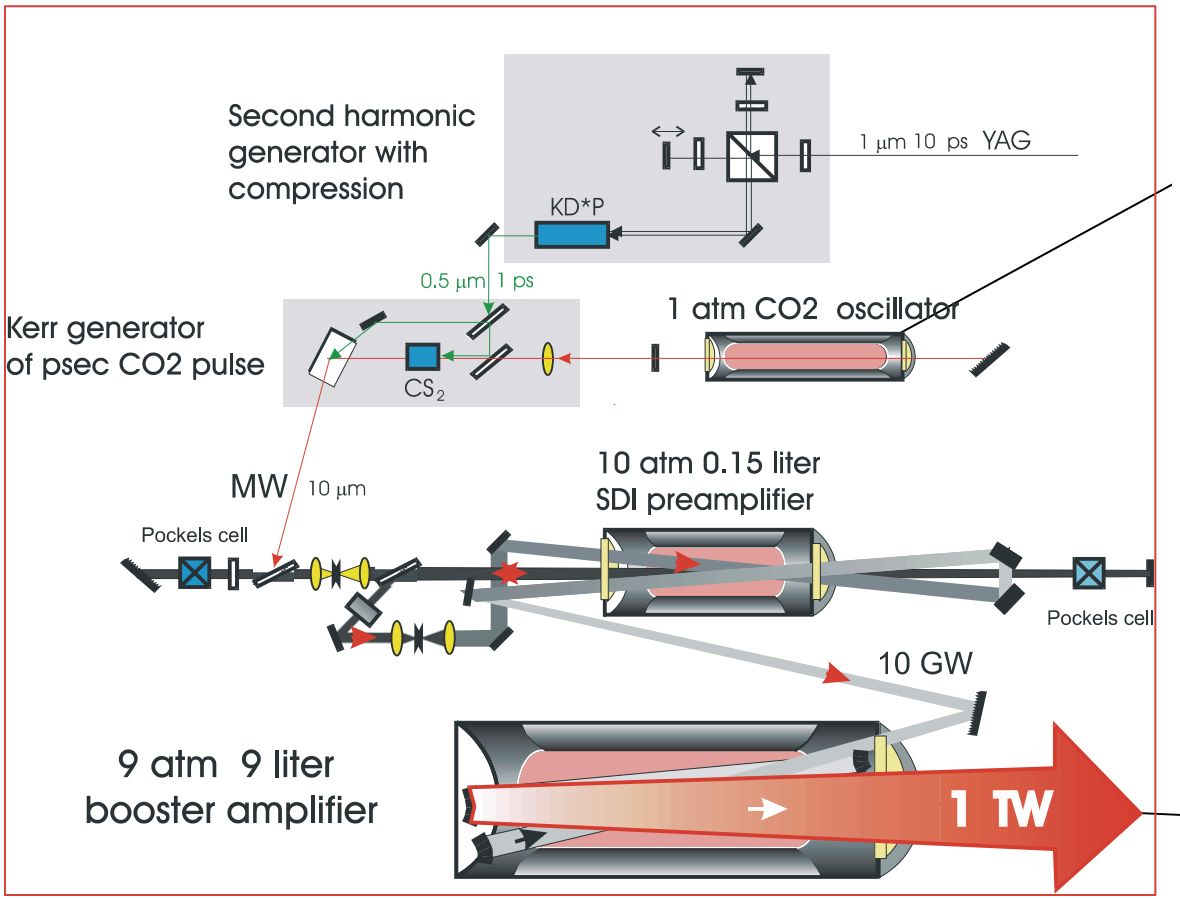
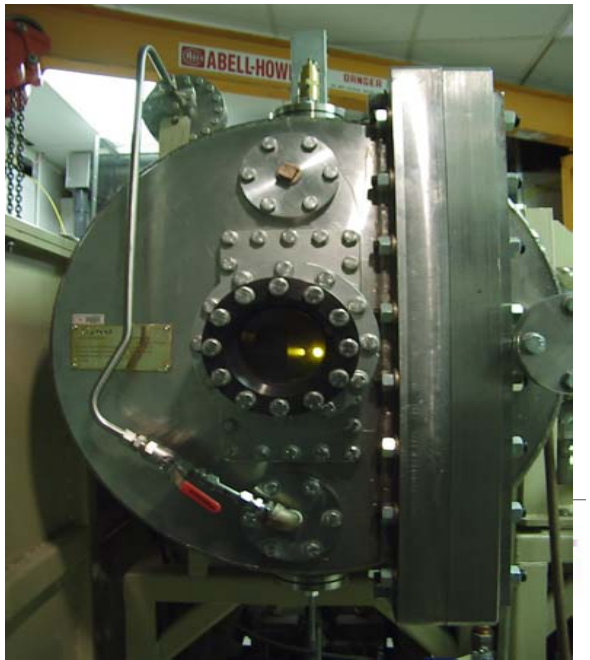
# OPA for the OSC Amplifier (LDRD)



# ATF $CO_2$ Laser System



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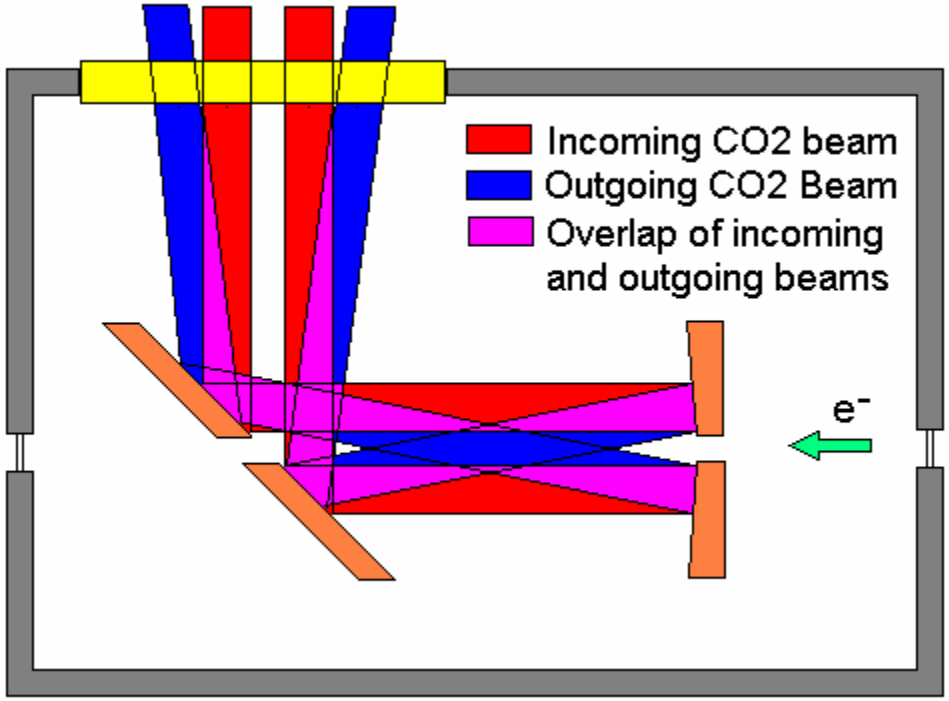
# ICA experiment AE06

## W.D. Kimura, et al., PRL **74**, 546 (1995)

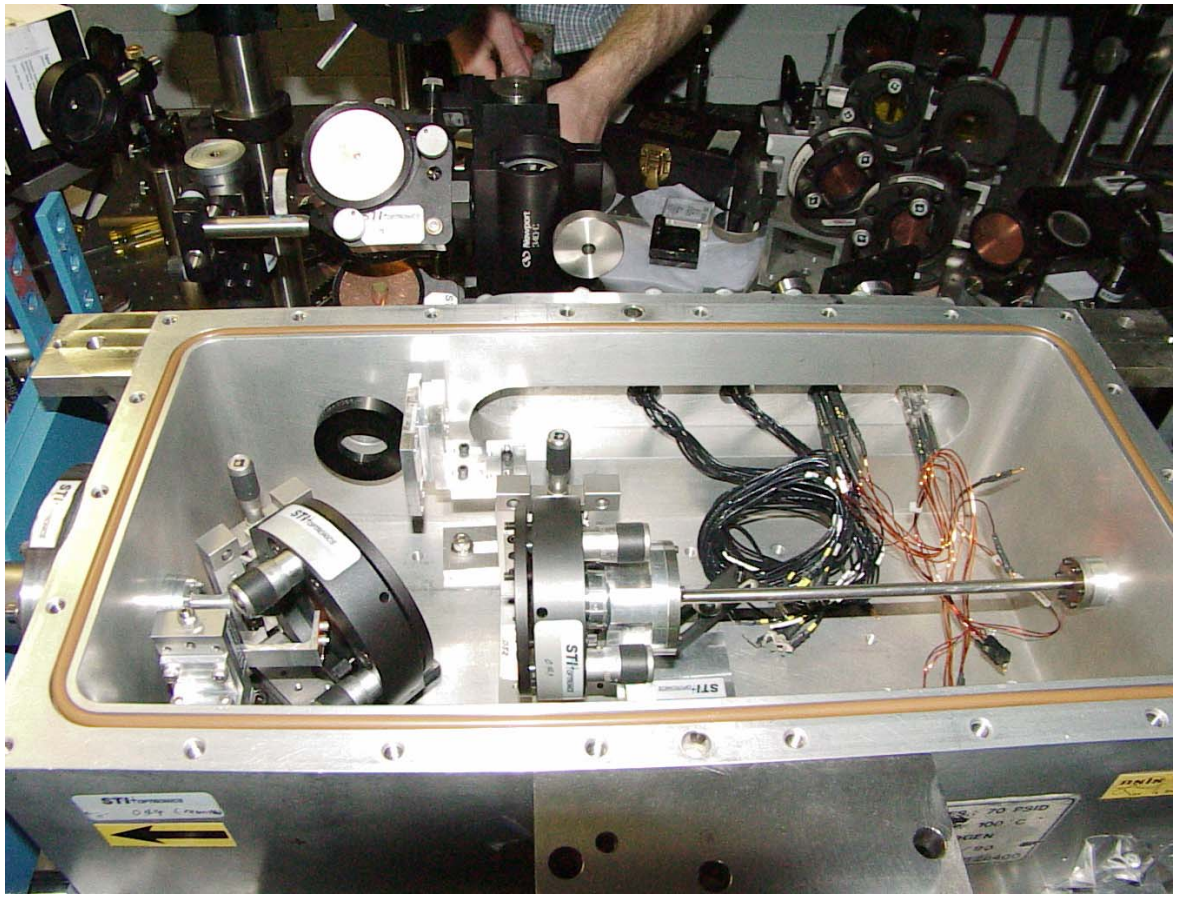



$$\Delta\varphi = \left(\frac{1}{\beta\, n} - \cos\theta\right) kl$$

ICA parameter set (as of 1995):

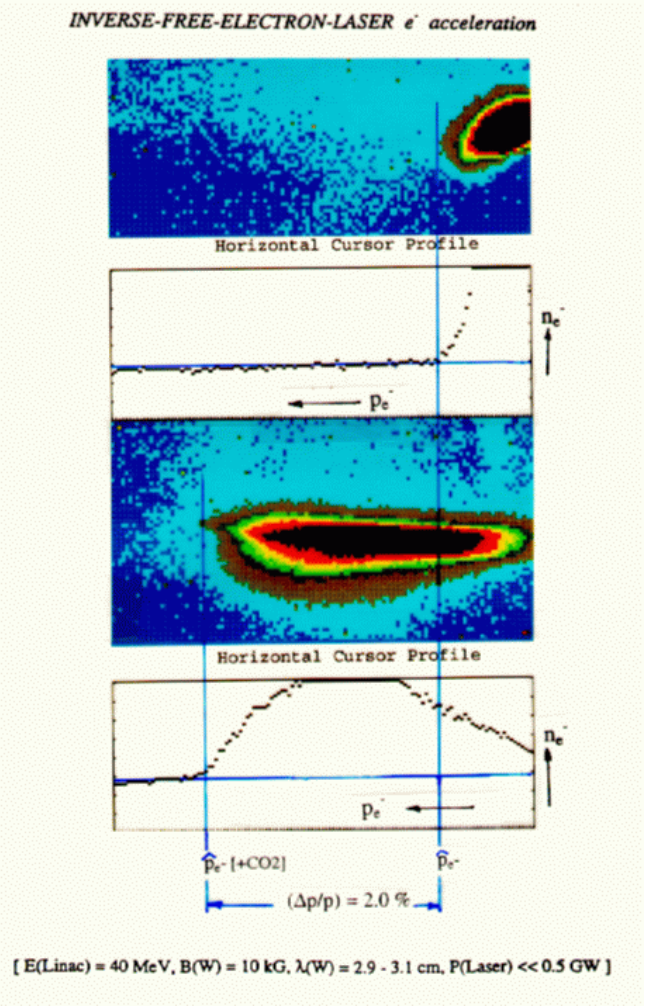
- Laser Pulse length 220 ps
- Peak power at IR 0.6 GW
- (Limited by input window)
- Cherenkov angle 20 mrad
- Hydrogen pressure 2 atm.
- Measured acceler. 3.5 MeV

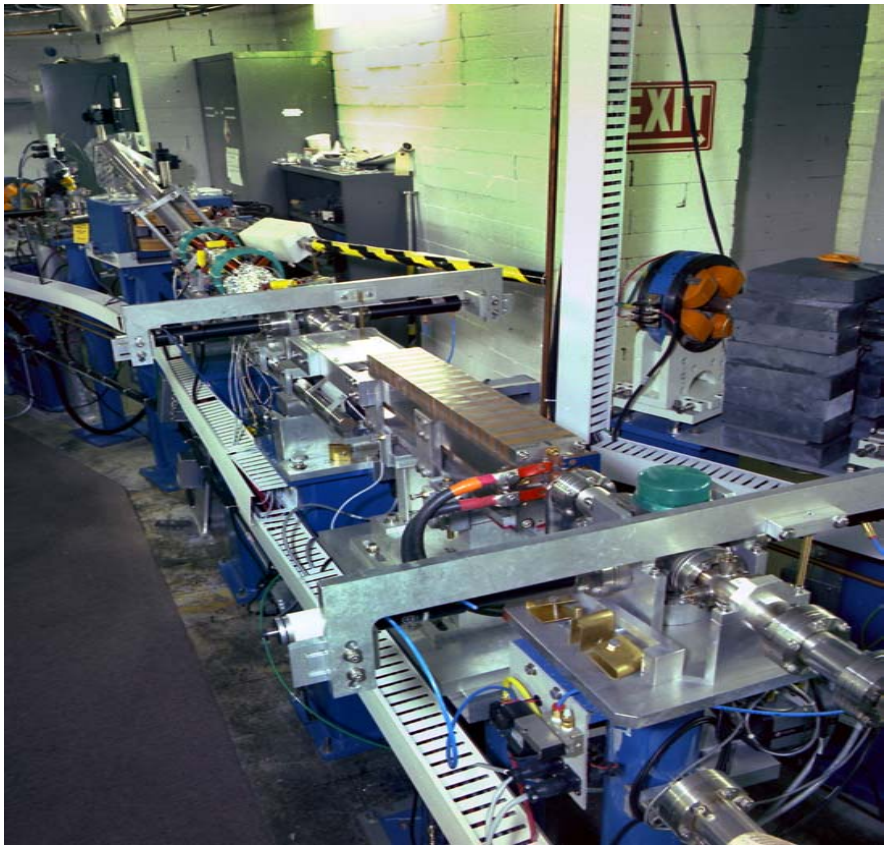
# ICA cell



# Inverse FEL AE02 Laser Acceleration

## A. van Steenbergen, et al., PRL **77**, 2690 (1996)

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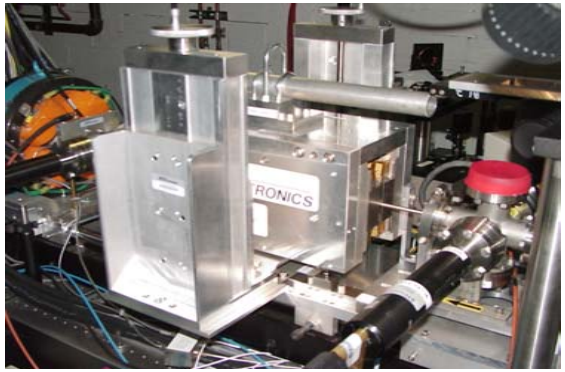
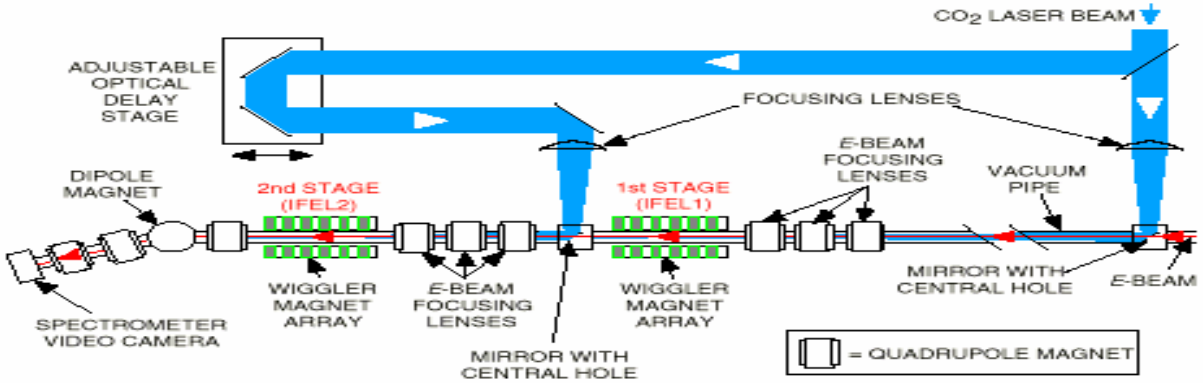
# Staged Electron Laser Accelerator (STELLA)

## W. D. Kimura, et. al., PRL **86** no. 18, 4041 (2001)

- Demonstrated staged laser acceleration
- Demonstrated 3 fs FWHM bunching



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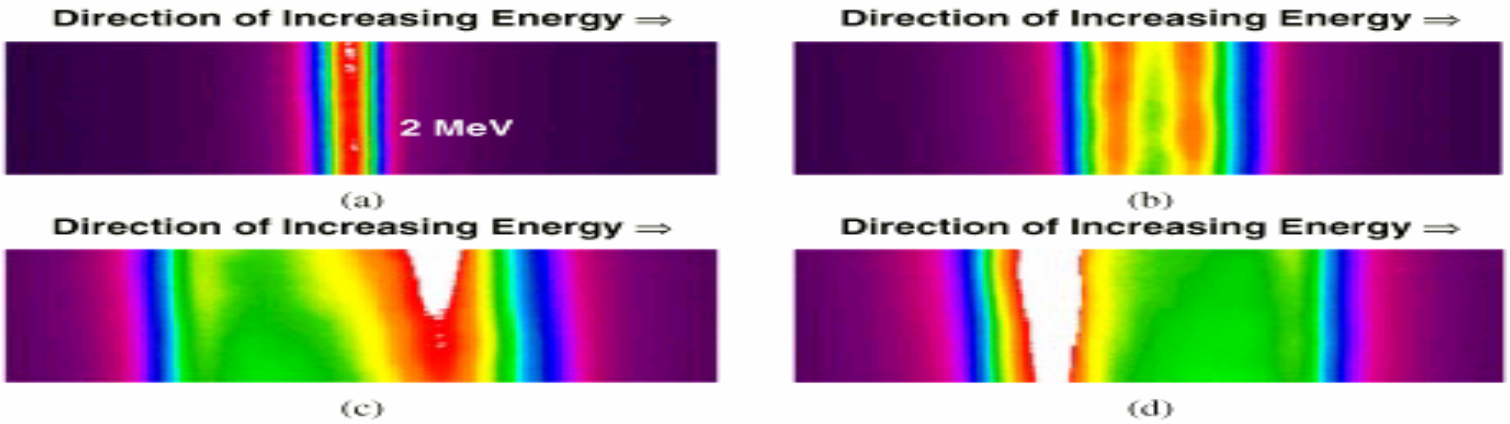
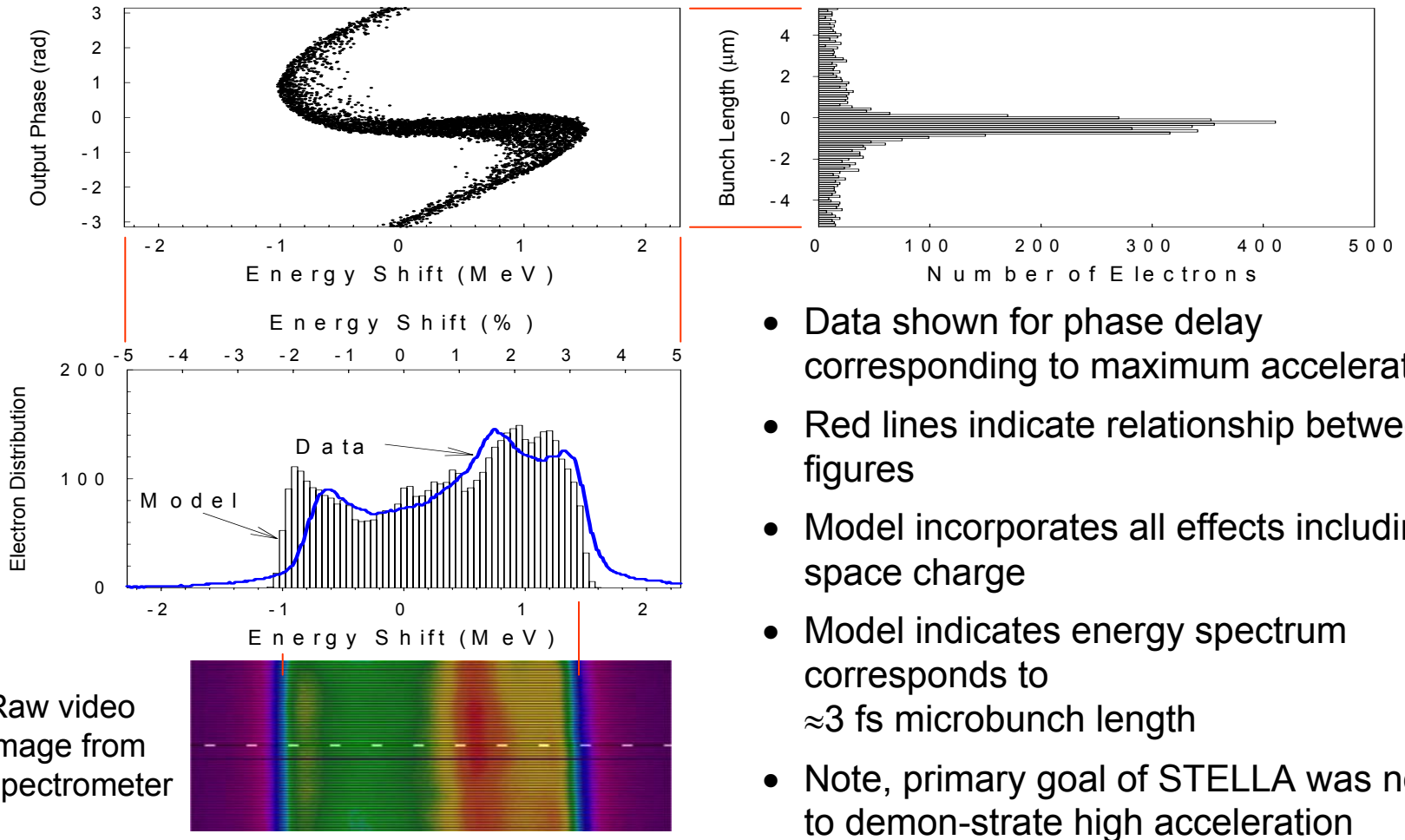
# Results from STELLA Experiment

- Stable, reproducible phase control on an optical scale




Raw video images from electron energy spectrometer for the conditions given in Table 1. (a) Laser off to both IFELs. Signal strength increases from violet, blue, green, yellow, to red. White is saturation. (b) Sinusoidal energy modulation from first IFEL only. (c) Lasers on to both IFELs. Phase delay set for maximum acceleration. (d) Same conditions as (c) with phase delay set 180° from (c).

# STELLA Results Agree Well With Model



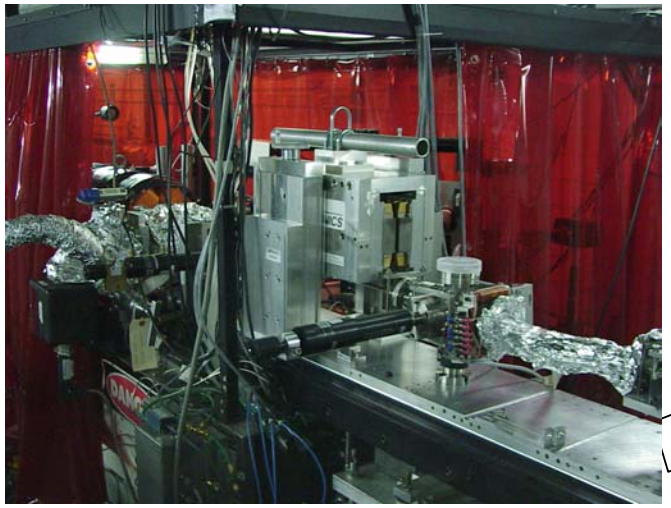

Raw video image from spectrometer

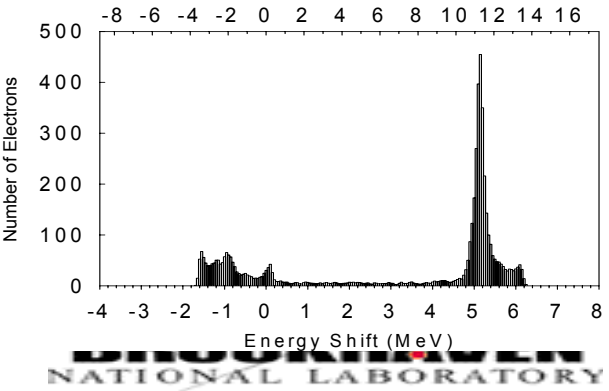


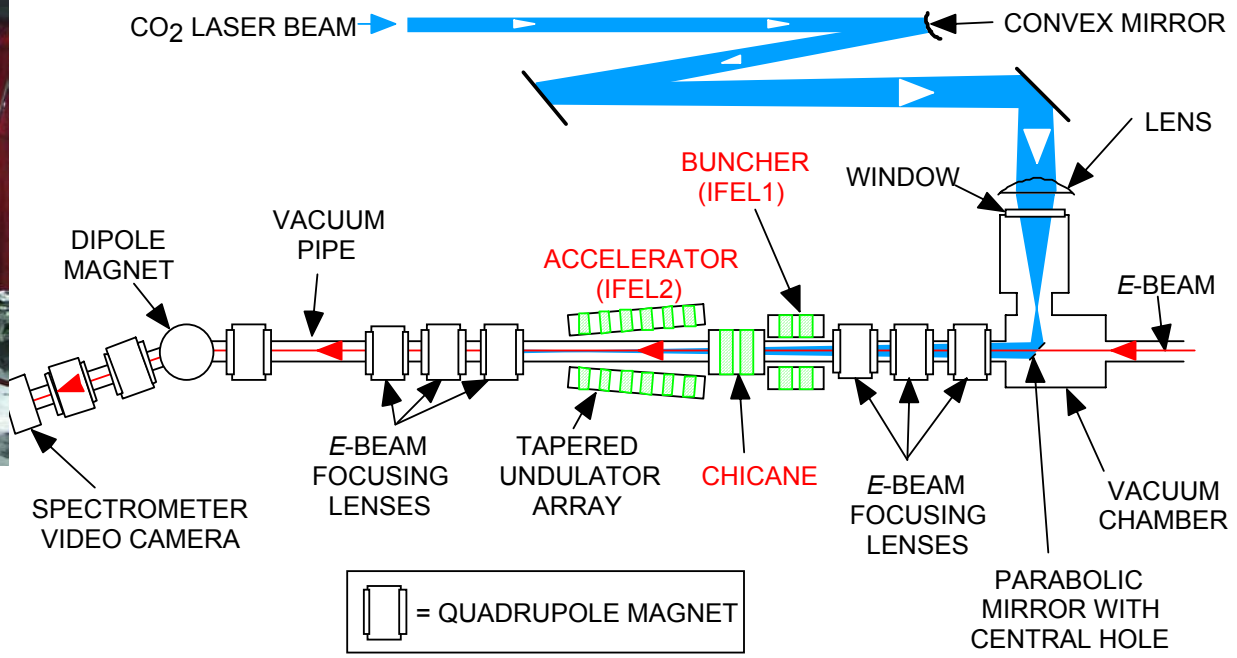
- Data shown for phase delay corresponding to maximum acceleration
- Red lines indicate relationship between figures
- Model incorporates all effects including space charge
- Model indicates energy spectrum corresponds to ≈3 fs microbunch length
- Note, primary goal of STELLA was not to demon-strate high acceleration

# STELLA II, AE20

- Improved version of a highly successful experiment
- Target: monoenergetic laser acceleration



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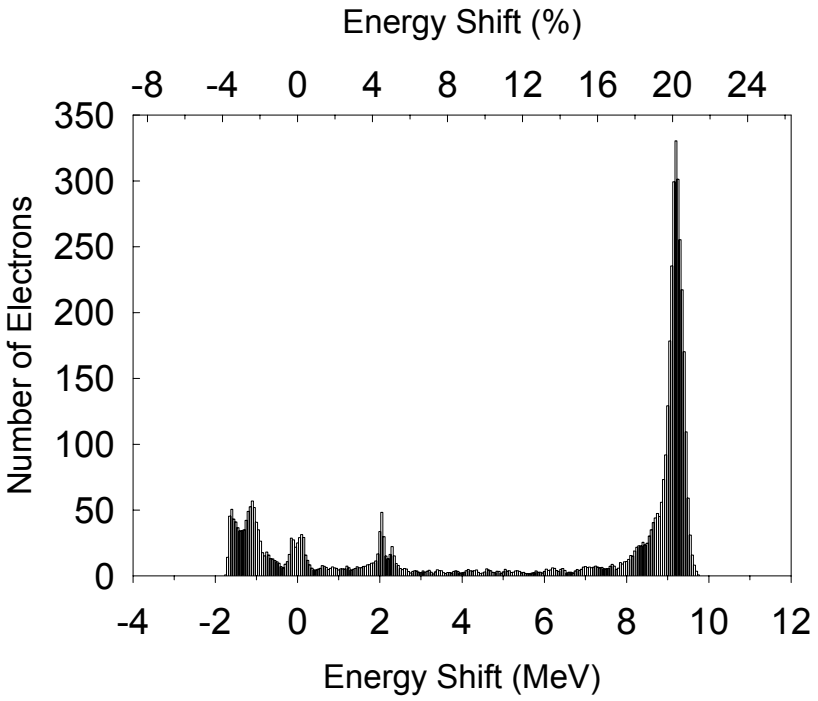
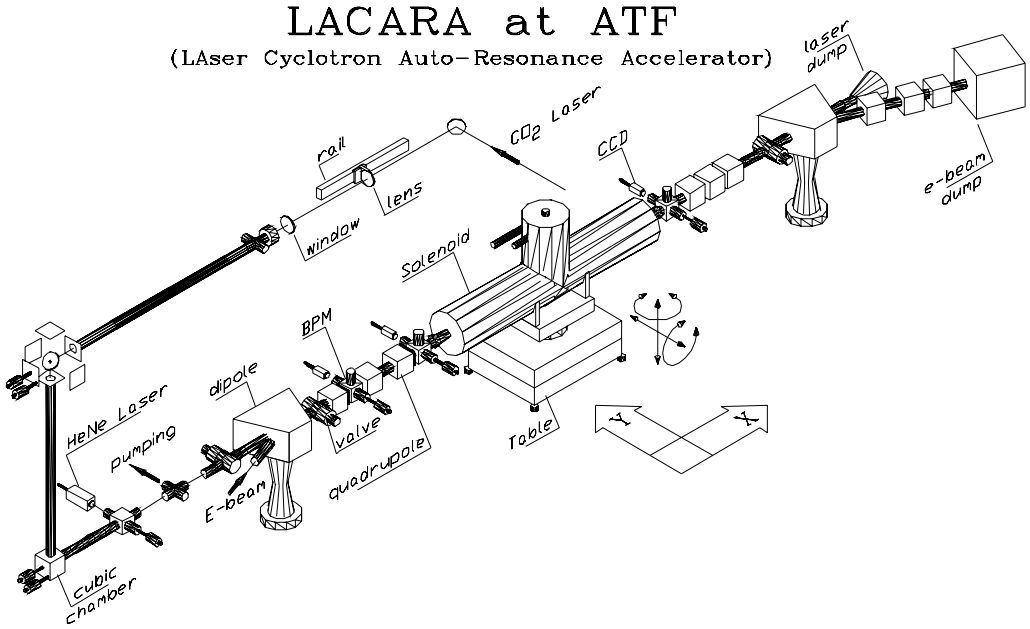
# Model Predictions for STELLA-II

- Assume using upgraded ATF $CO_2$ laser and high-resolution spectrometer
  - 19% gap taper, 1 TW/cm$^2$ at center of undulator
  - Chicane phase selected for minimum energy spread of microbunch



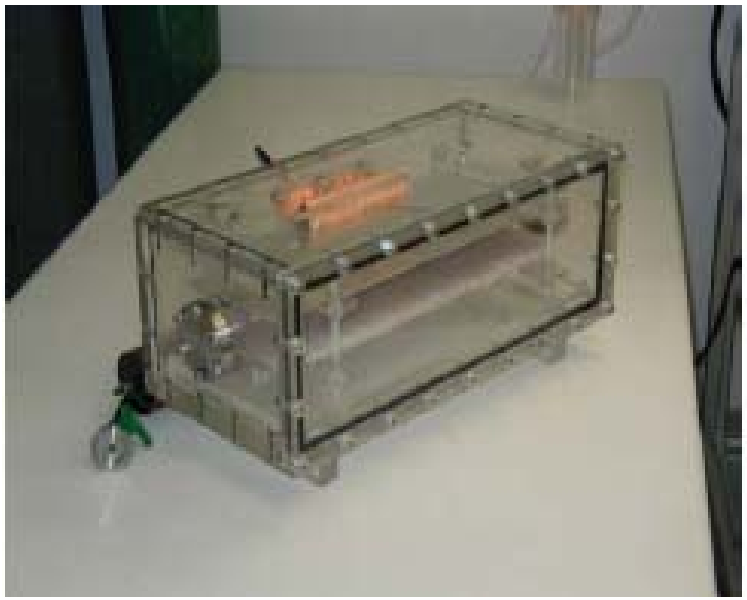
# Laser Cyclotron Resonance Accelerator, (LACARA), AE25

- Experiment in advanced construction stage
- Will use 2 meter long solenoid, $CO_2$ laser
- Expect 50 MeV acceleration



# Particle Acceleration by Stimulated Emission of Radiation (PASER) AE30

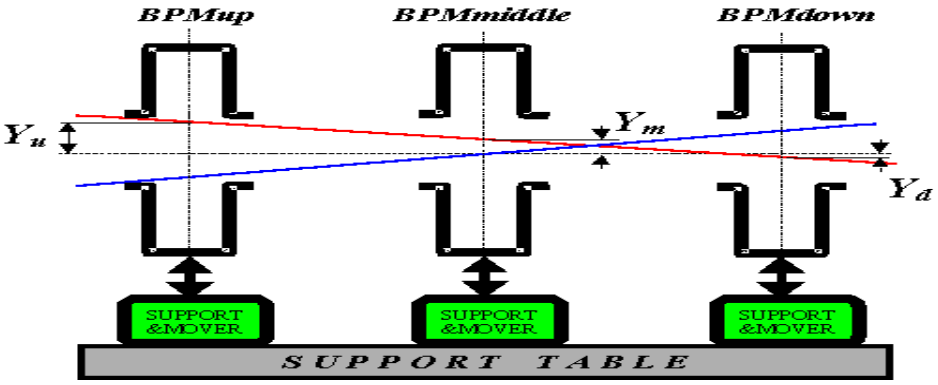
- In the ATF's PASER experiment, a modulated electron beam will be injected into an active medium whose resonance matches the modulation frequency and examine the energy distribution of the emerging electrons.
- The beam modulator will be the IFEL.

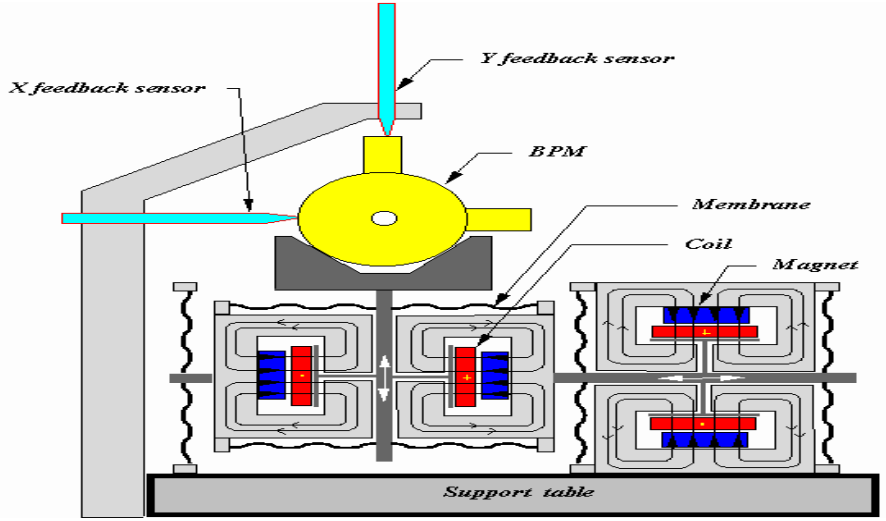


PASER Cell

# Nanometer scale, non-intercepting Beam Position Monitors for Linear Colliders, AE16

- 3 cavities for complete redundancy
- Precision movers, 0.3 μm resolution
- Sophisticated detection electronics

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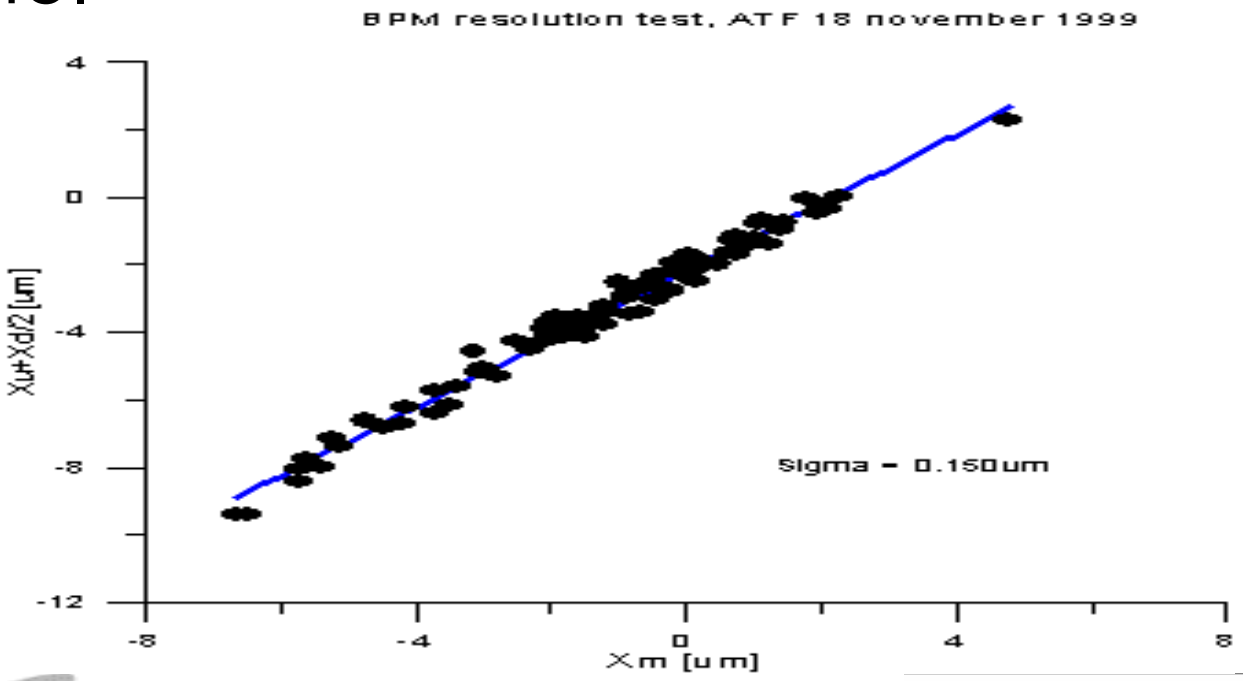
# Experimental results

- Potential resolution < 0.1 μm
- Measured resolution 0.16 μm for single pulses of 0.5 nC.

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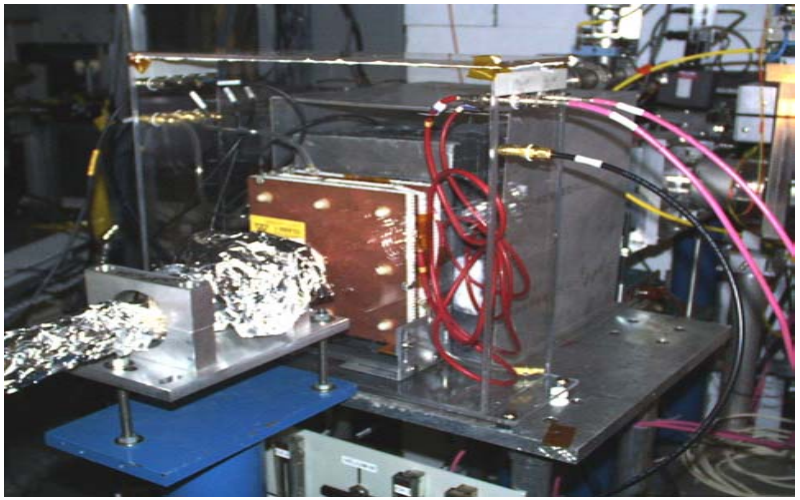
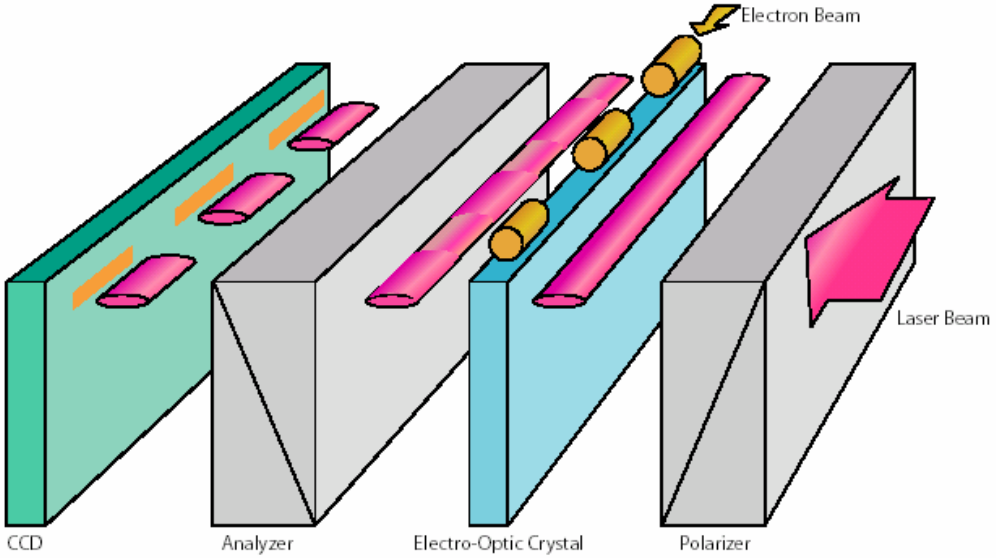
# Fermilab's MINOS Beam Monitoring Detectors, AE28

- The goal of the experiment was to learn how ionization in gases saturates at high charged particle intensities.
- Experiment completed successfully



# Ultra-fast Optical Detection of Relativistic particles, AE23

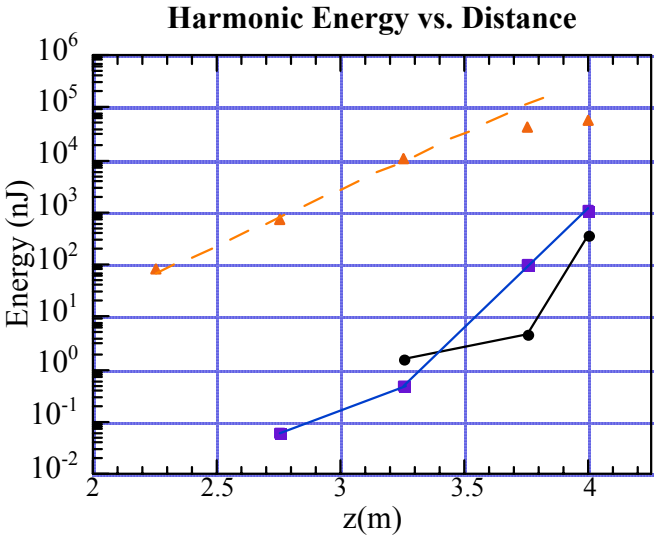



- The ``EO flash photo technique"
- The beam's temporal charge distribution is transformed into a spatial distribution.
- Very Promising New Detector with many Applications

# VISA: Proof-of-Principle for the LCLS

A. Tremaine, et. al., PRL **88** no. 20, 4081, 2002.
A. Tremaine, et al., Phys. Rev. E **66**, 036503 (2002)

- Unique strong-focusing wiggler.
- Unique electron diagnostics (Slice, tomography).
- Advanced photon diagnostics.
- Benchmark SASE theory.
- Test of photoinjector performance.



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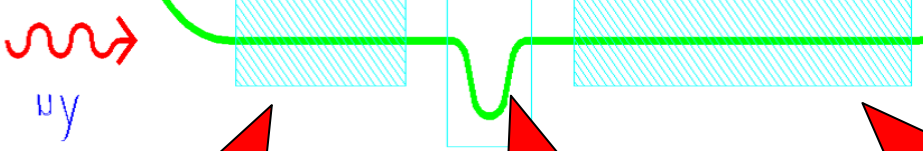
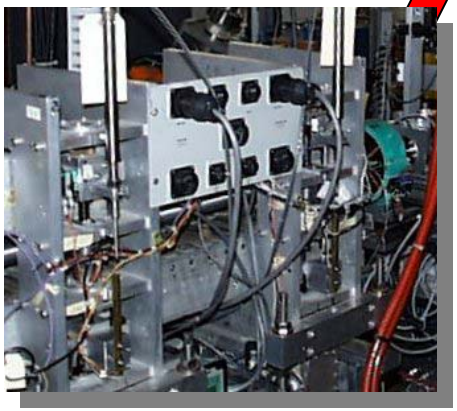
# First High-Gain Harmonic-Generation FEL

A. Doyuran, et al., PRL **86** no. 26, 5902, 2001.
L.-H. Yu, Science, **289** (2000) 932

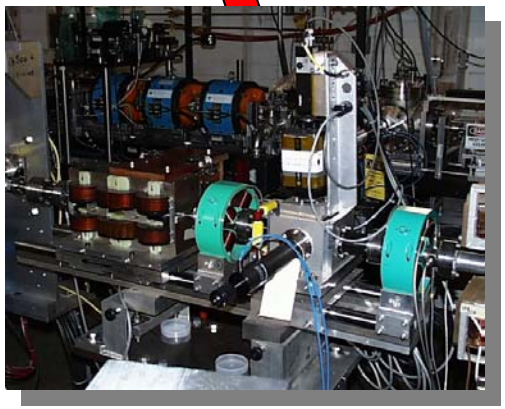
Seed Laser
$\lambda$=10.6$\mu$m
$P_{pk}$=0.7 MW



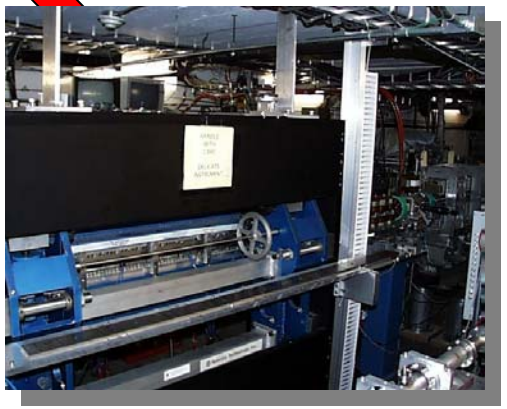

HGHG FEL
$\lambda$=5.3 $\mu$m
$P_{pk}$=35 MW



Modulator Section



Dispersion Section



Radiator Section

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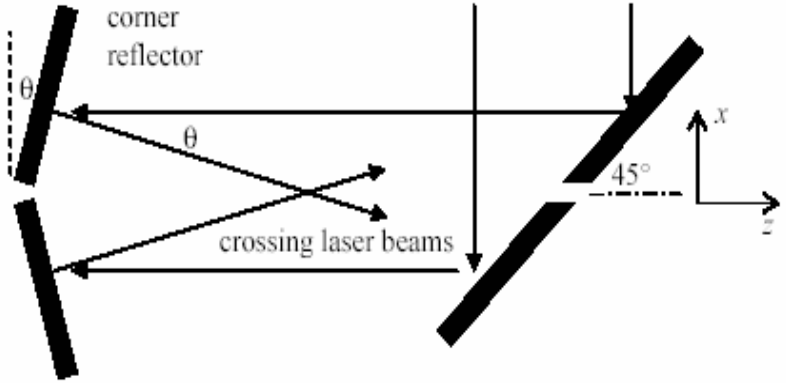
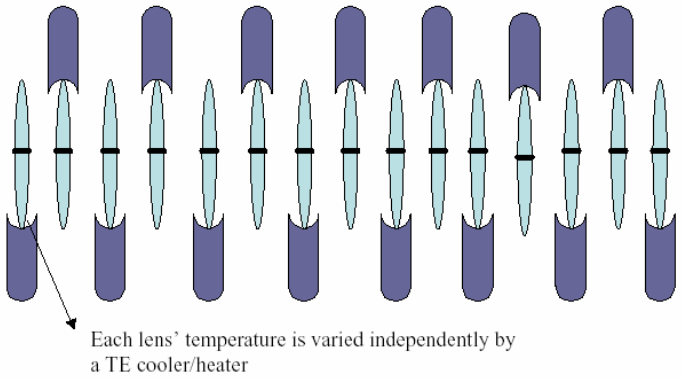
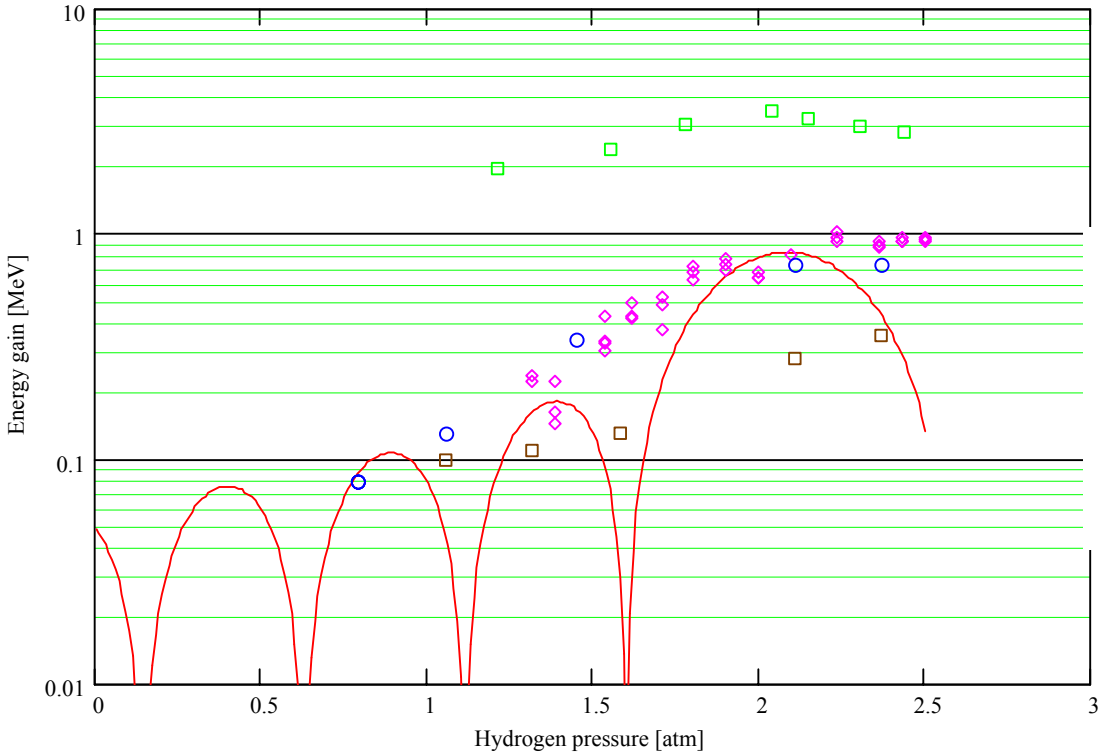
# Structure-Based Laser Driven Acceleration in Vacuum, AE27

- Single Stage
- Multi-Stage
- CVD diamond optics



# ICA experiment as VA test




**Calculation for single electron**
**1995 experiment data for long IR**
**Low spectrometer resolution data**
**High spectrometer resolution data**
**Smaller divergence angle**

We were unable to register acceleration in vacuum in the last run. We did observed acceleration in the “detuned ICA regime”. Attempt will be repeated after $CO_2$ is upgraded.

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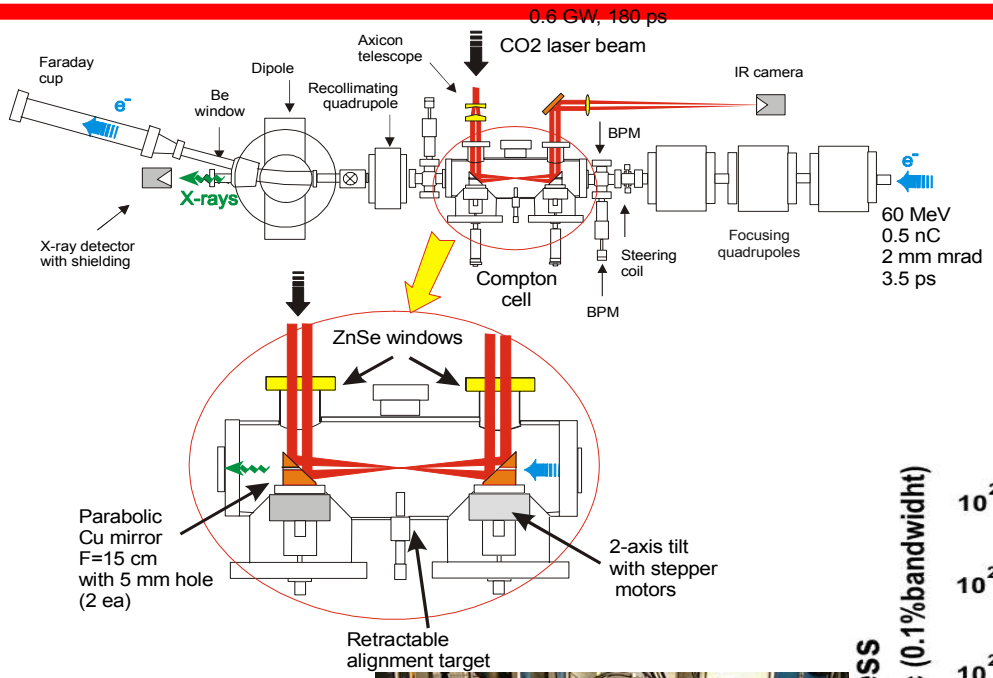
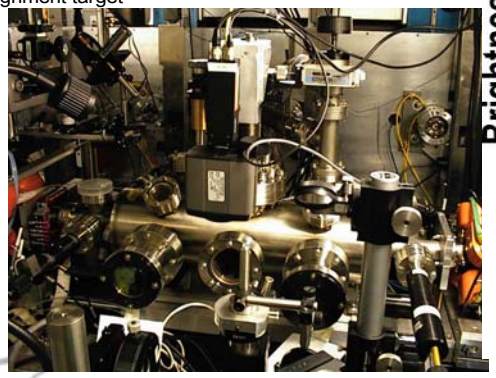
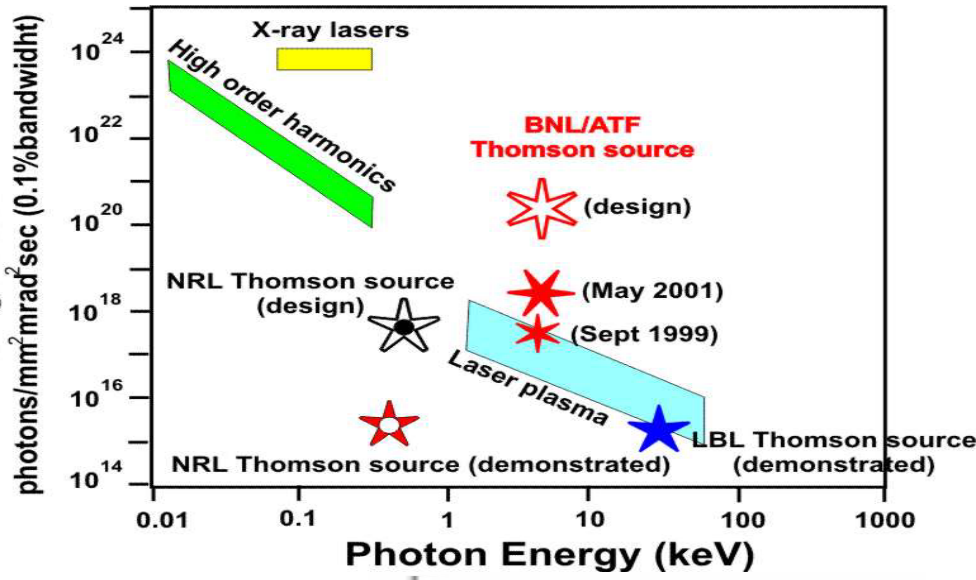
# Compton Scattering AE22

## I.V. Pogorelsky, et al., PR ST-AB, **3**, 090702, (2000)



**Source of high peak flux picosecond x-rays, R&D towards a source of Polarized positrons for Linear colliders.**

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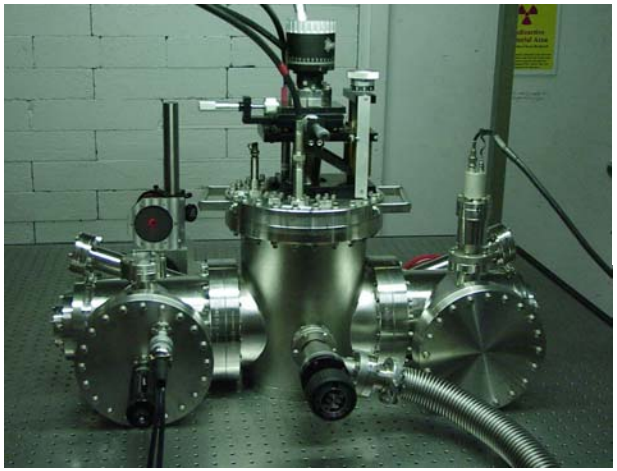
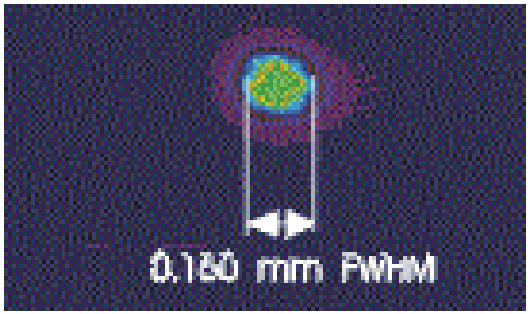
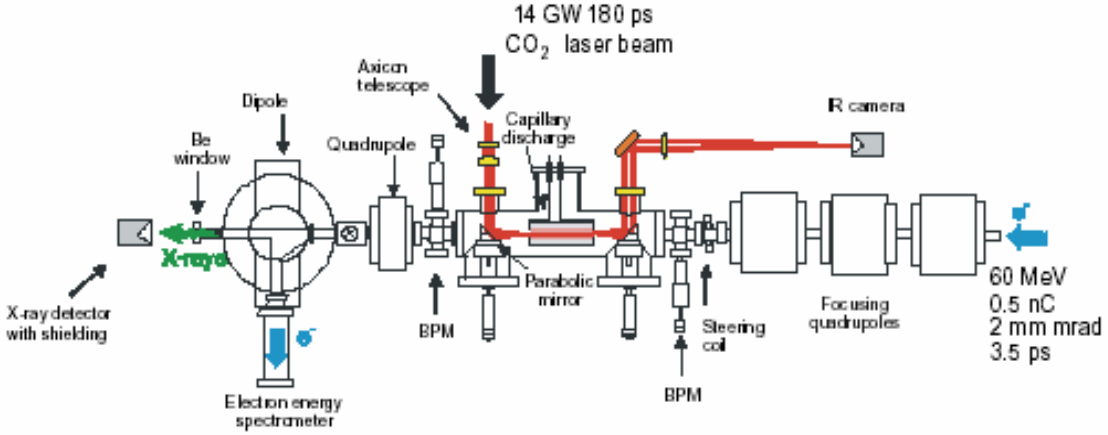
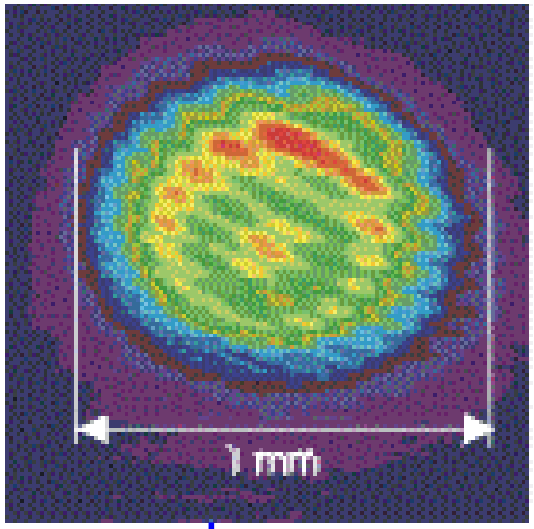
# Capillary Plasma Channeling of $CO_2$ laser



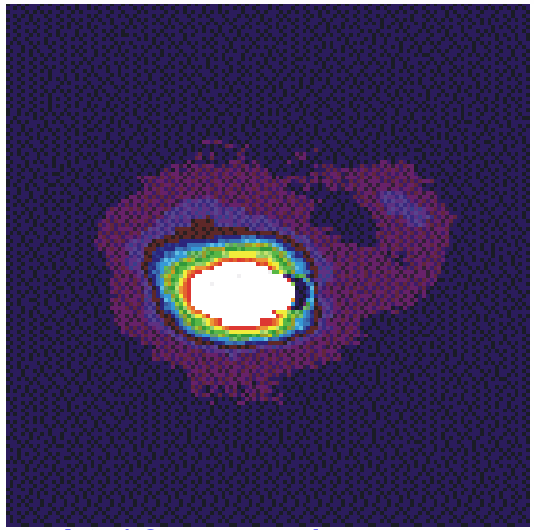



At focal point



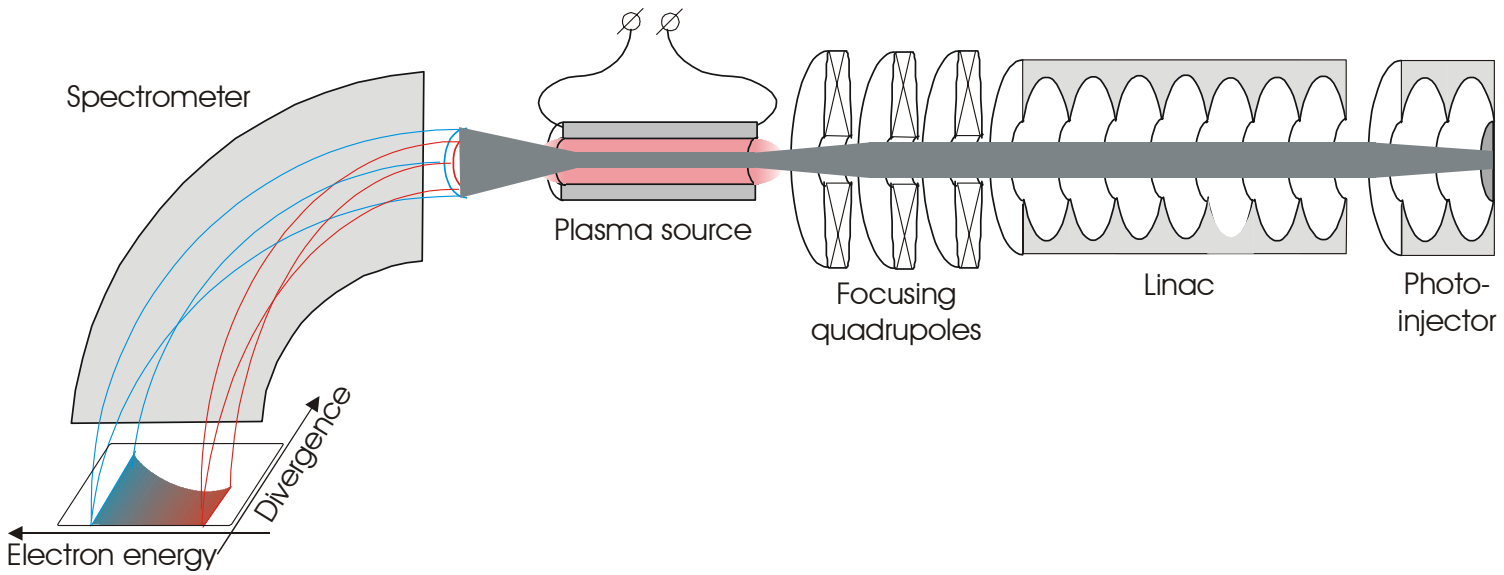




18 mm downstream



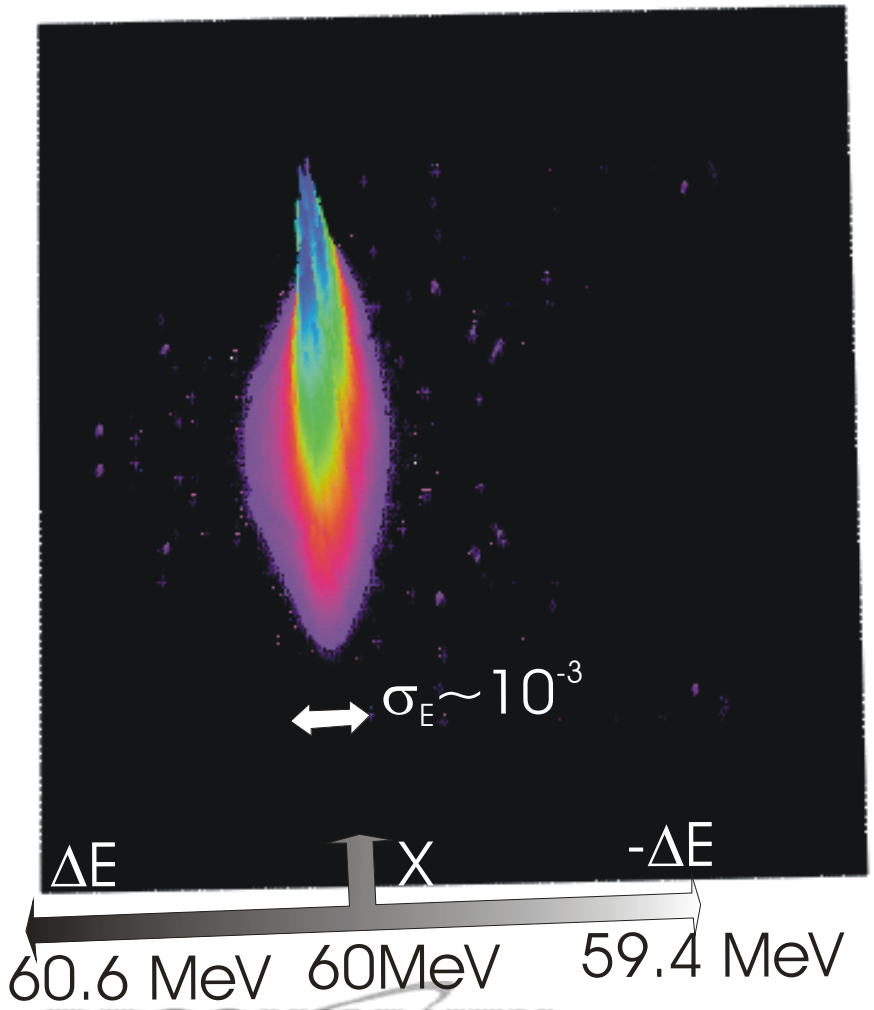
At 18 mm, plasma on

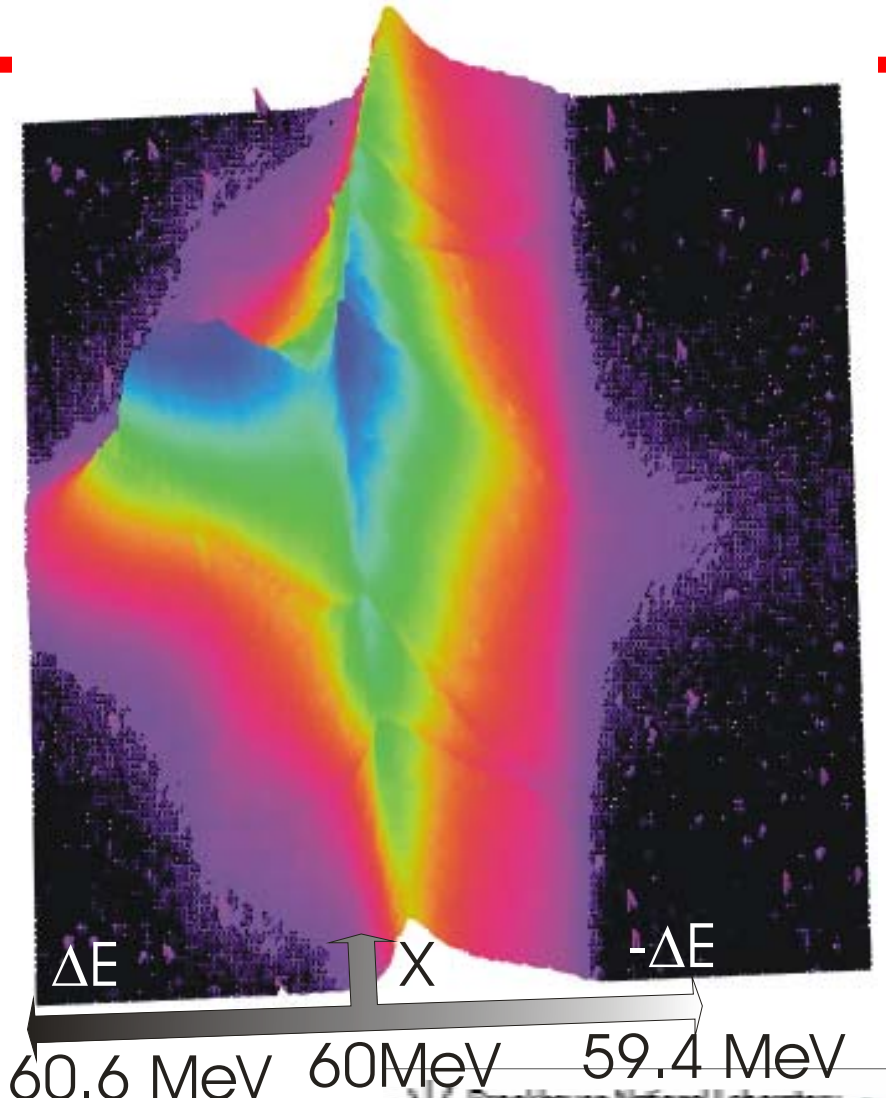
# Plasma Wakefield Schematic




**Goal of the experiment:** 45 MeV, 1 nC electron beam excites plasma waves. As a result we observe acceleration and focusing.

# Images from the spectrometer

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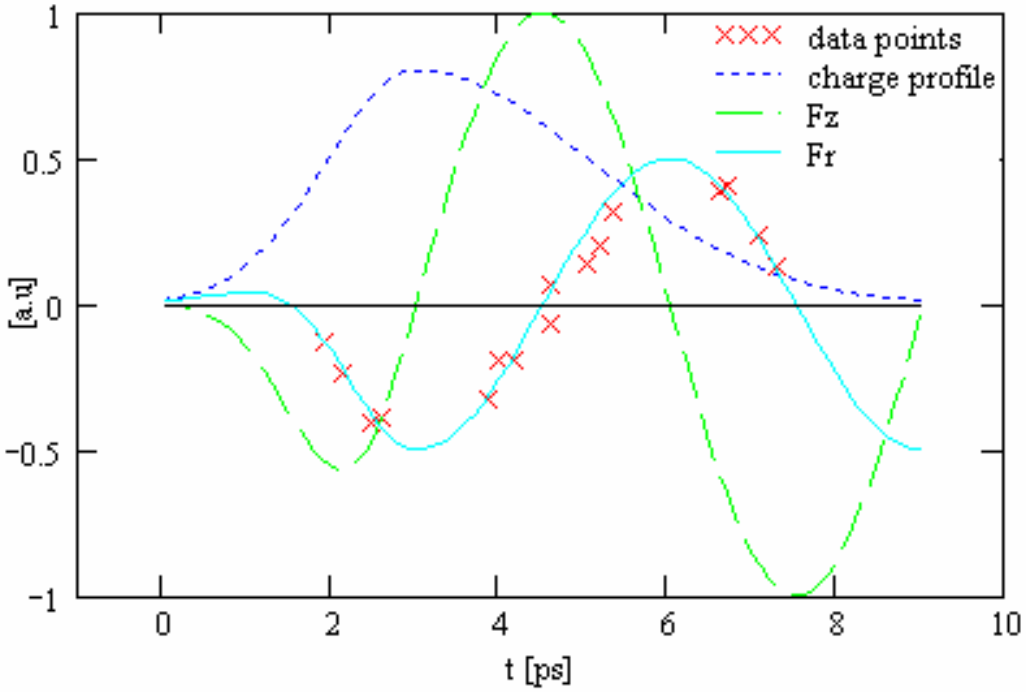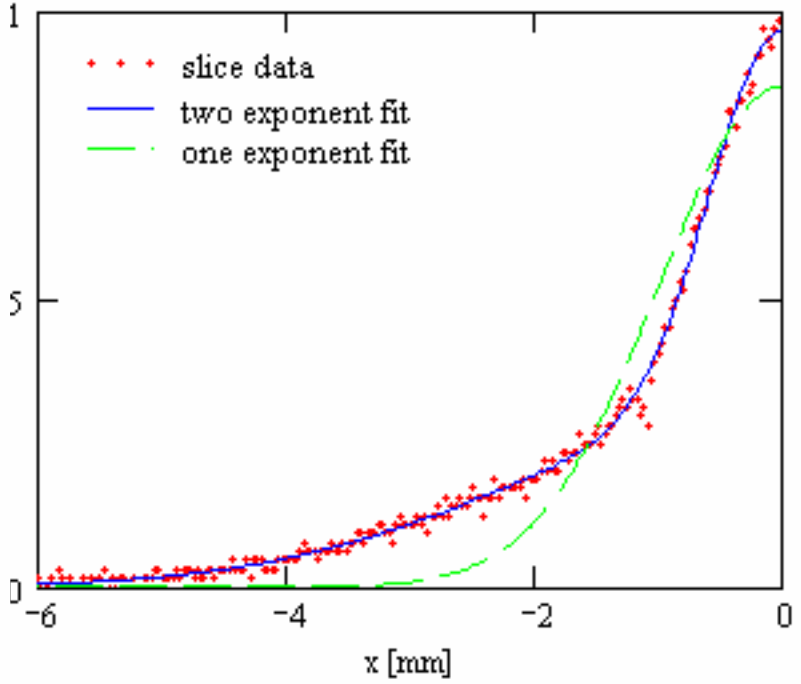
# Focusing as function of phase