# The UCLA program
# Advanced beam and light source physics

P. Musumeci

*Annapolis, ADRD meeting, Aug 2011*

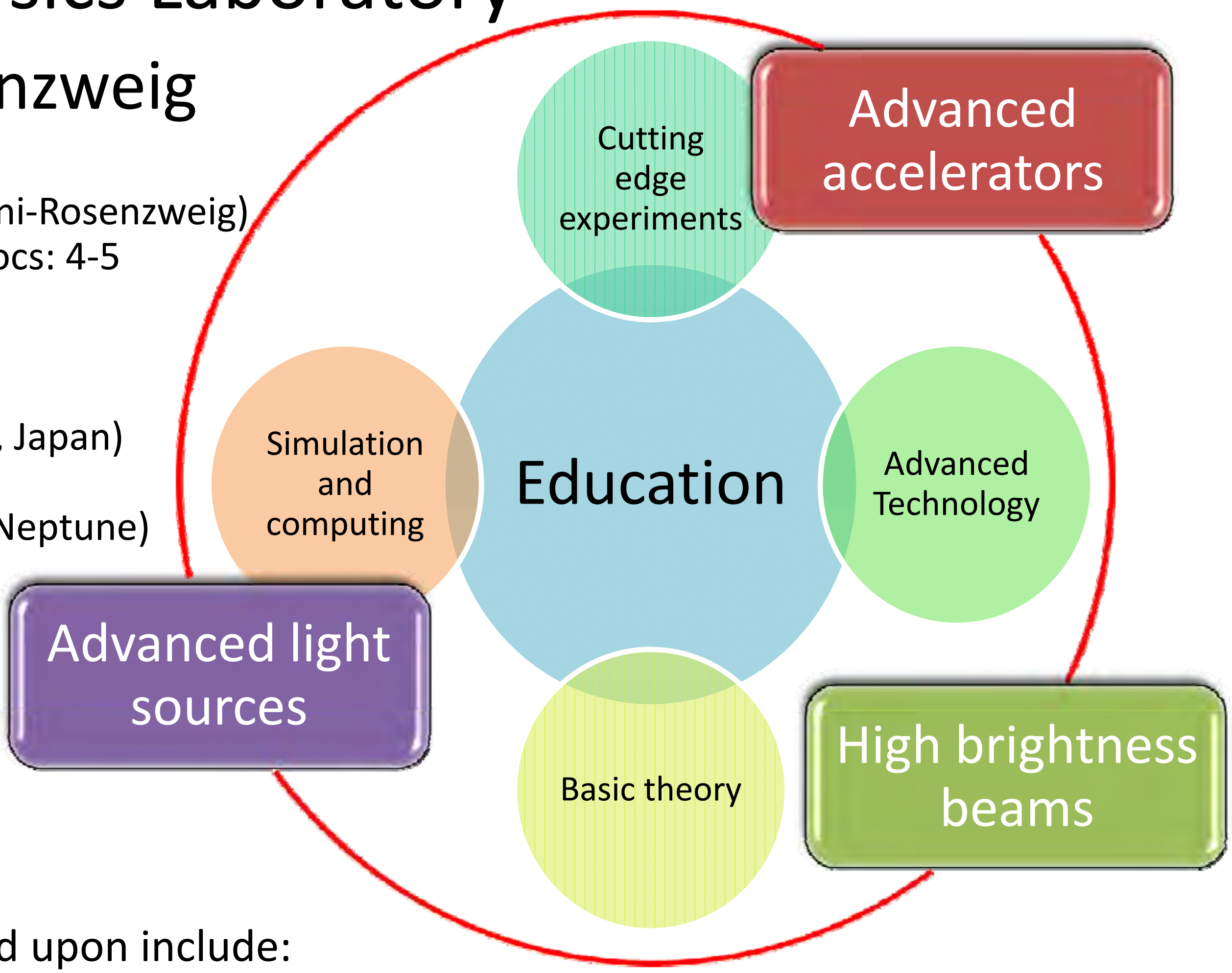
# Particle Beam Physics Laboratory

## Director: Prof. Rosenzweig

Population

Faculty: 3 (Musumeci-Pellegrini-Rosenzweig)
Profession researchers/postdocs: 4-5
Technical staff: 3-4
Graduate students: 10
Undergraduates: 10-12
Visitors (Italy, Germany, Israel, Japan)

Two on campus facilities (Pegasus, Neptune)
Many off campus collaborations.

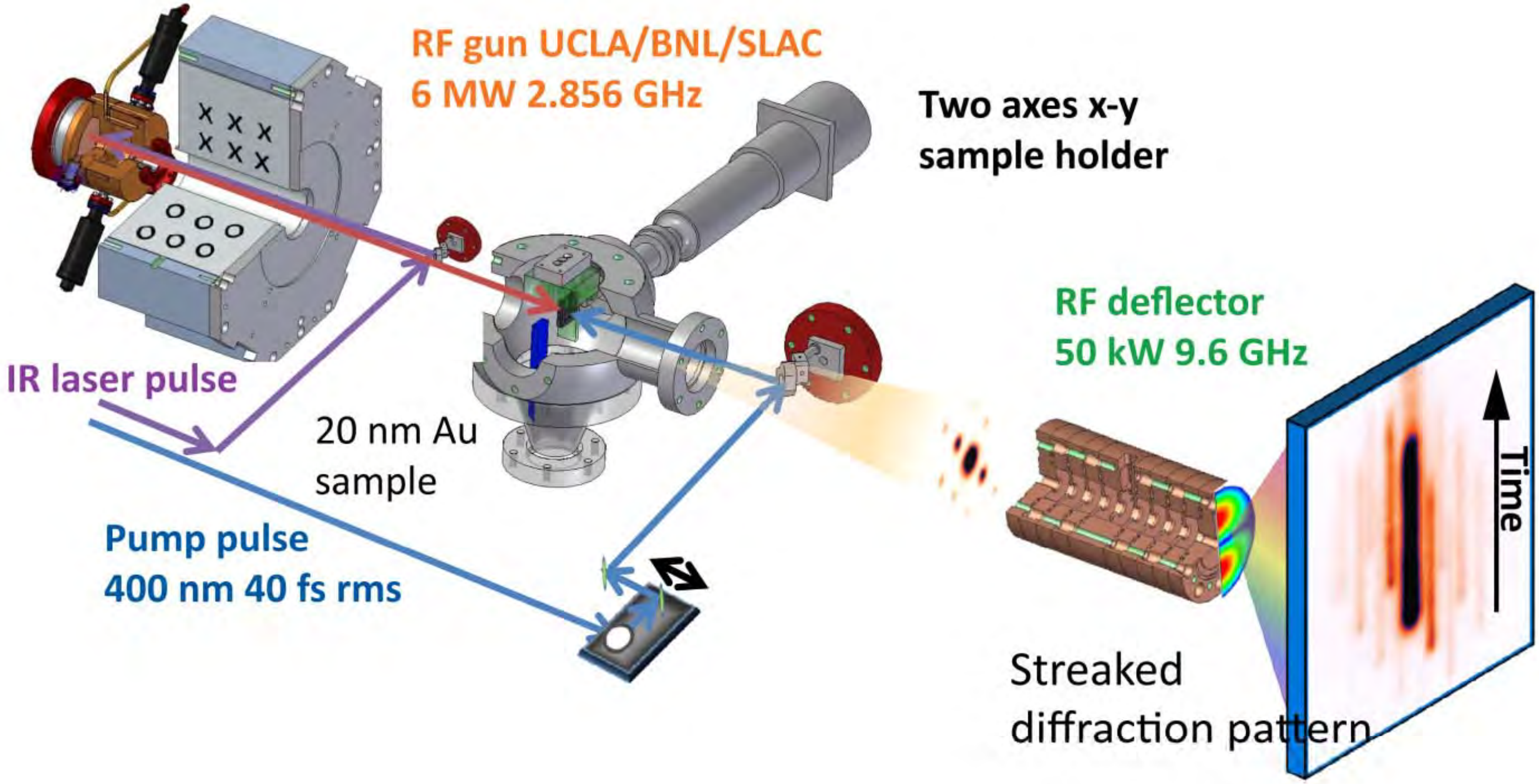



- Scientific disciplines touched upon include:
  - Beam-plasma interaction; beam material interaction
  - Collective beam effects, nonlinear beam dynamics
  - Beam-radiation interaction; instabilities
  - Device physics: high power microwaves, lasers, THz
  - Ultra-fast measurements

# Outline

- Moving towards applications
  - Femtosecond relativistic electron diffraction
  - Inverse Compton Scattering
  - Coherent Cherenkov Radiation / wakefields
- FEL physics
  - Orbital Angular Momentum modes
  - Short period undulators
  - FROG/single spike
- High brightness beams
  - Multiphoton photoemission
  - Bunch train production
  - Non linear longitudinal space charge oscillations
  - Longitudinal space charge instability and coherent optical radiation.
- Diagnostics
  - Longitudinal phase space measurements
  - Electro-optics sampling
  - Attoscope
- Cathode research
- Pegasus Laboratory planned upgrades

# RF streak camera based ultrafast relativistic electron diffraction

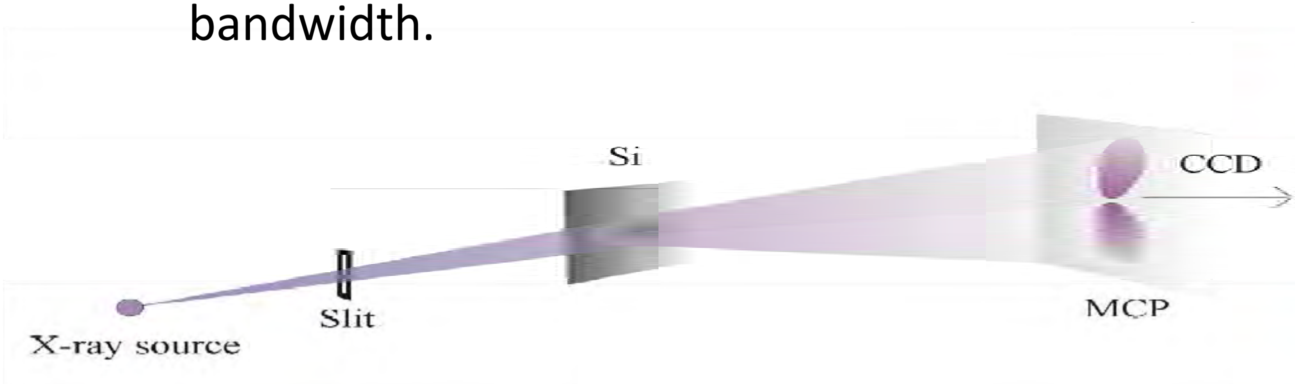


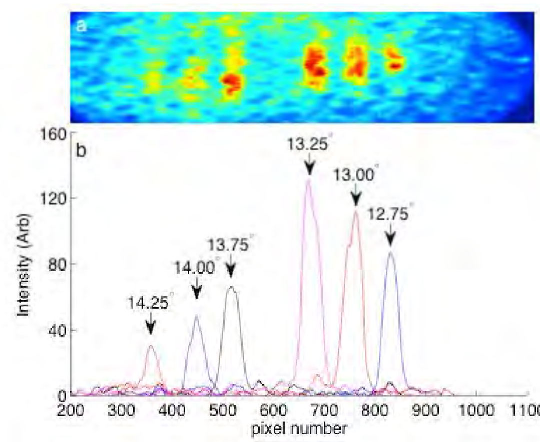

- Single shot ultrafast structural dynamics (for example determination of electron-phonon coupling constant).
- RF streak camera based UED can potentially offer sub-10 fs resolution.

# Inverse Compton Scattering at ATF-BNL

- ICS at BNL
  - high brightness electron beam
  - powerful $CO_2$ laser
- Produces copious photons
  - Tunable: 5-15 keV
- Recent work using Si single crystal diffraction:
  - 8.7 keV photons with 4.3% "near axis" bandwidth
  - Single shot diffraction with ps X-ray pulse
  - Rotating crystal and taking many shots allows direct measurement of the ICS bandwidth.

| Parameter | Value |
|---|---|
| Electron Beam | |
| Energy (MeV) | 70.0 |
| Charge (pC) | 200 |
| Energy spread FWHM | 0.3% |
| Bunch length FWHM (ps) | 4.0 |
| $\epsilon_{n,(x,y)}$ (mm mrad) | 1.0 |
| Spot size FWHM ($\mu$m) | 35 |
| $CO_2$ Laser | |
| Energy (J) | 2.0 |
| Wavelength ($\mu$m) | 10.6 |
| Pulse length FWHM (ps) | 6.0 |
| Waist size FWHM ($\mu$m) | 140 |
| Bandwidth FWHM | 0.7% |
| X-ray Pulse | |
| Photon energy at max. intensity (keV) | 8.7 |
| On-axis bandwidth | 4.3% |
| Photon count ($10^7$) | 6 |



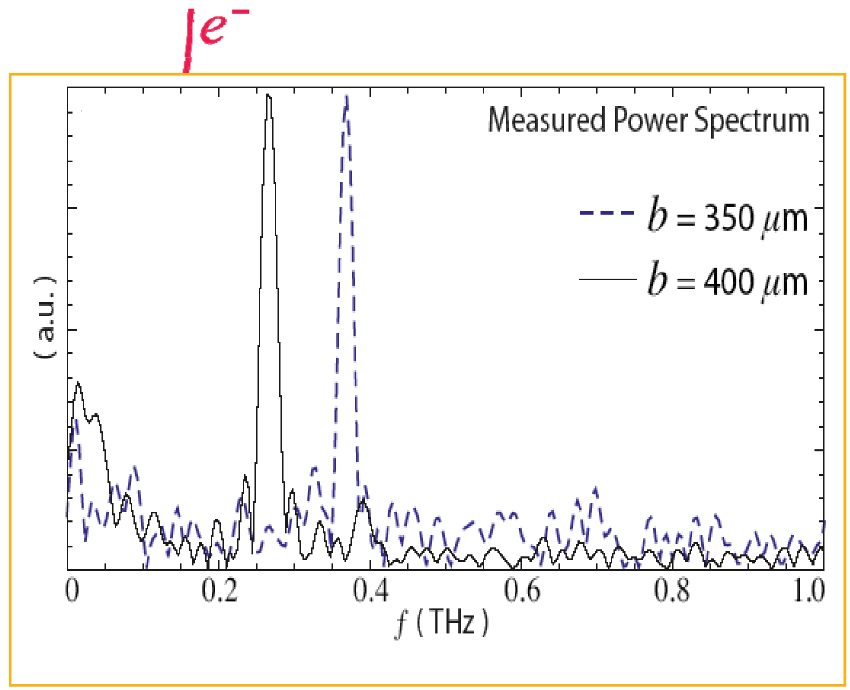
# Observation of coherent THz Cerenkov Radiation (CCR) at UCLA, BNL

**UCLA Neptune: chicane-compressed (200 mm *Q*=0.3 nC beam**

- PMQ triplet gives $s_r$~100 mm ($a$=250 mm)
- Relatively low energy (10.5 MeV)

**Single mode operation demonstrated**

- Autocorrelation of THz wave train
- Two tubes, different *b,* THz frequencies




Neptune CCR frequency spectra

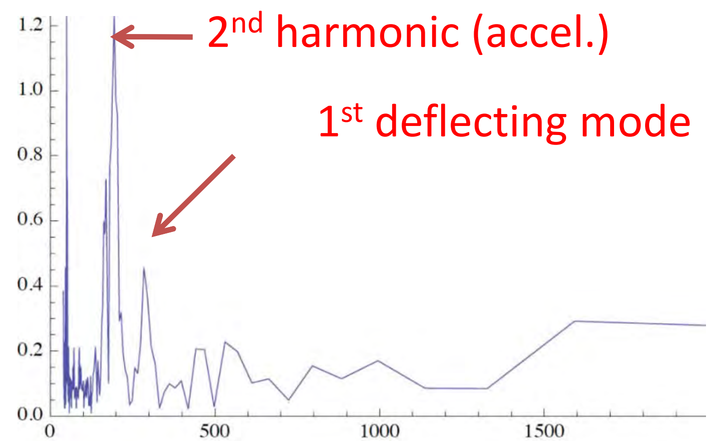
## BNL ATF: multi-bunch resonant wakes

**Single bunch wakes give fundamental**

$\lambda$ ~ 490 μm, per prediction

**Resonant wake excitation, CCR spectrum measured**

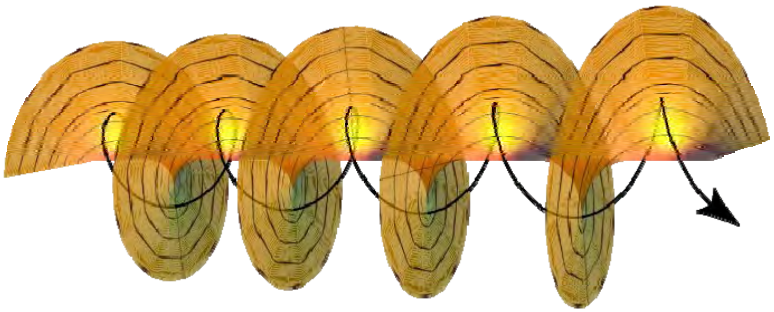
- Excited with 190 μm spacing (2nd harmonic)
- Misalignments yield $\lambda$~300 μm, 1st deflecting mode (important for transverse BBU in wakefield acceleration scenario)




BNL ATF wavelength spectrum

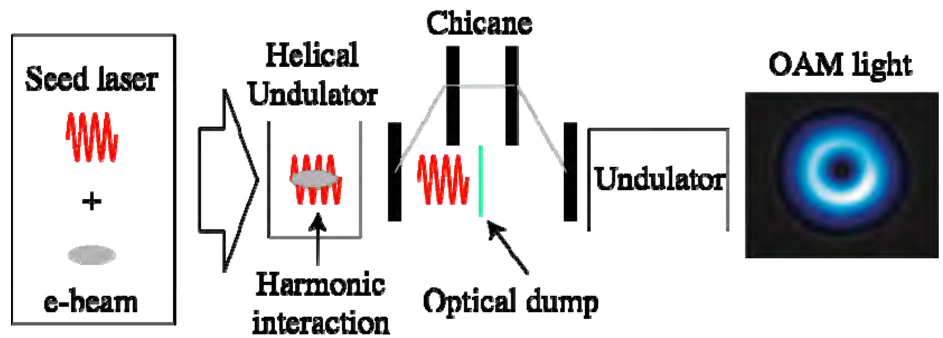
# Generation of Light with Orbital Angular Momentum in FELs

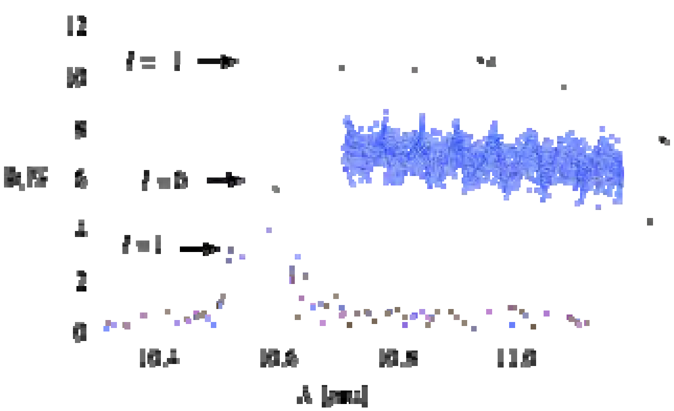
Light can carry OAM due to a helical phase. A portion of the linear momentum spirals about the axis, allowing experimental access to numerous higher-order processes (torque, quadrupolar transitions, OAM dichroism, quantum encoding/encryption, sub-diffraction limit microscopy, spectroscopy, and more)

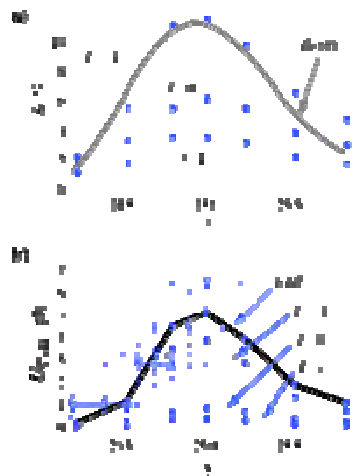


Recent work (Hemsing, et al. PRL 102, 174801 (2009)) has shown that OAM light can be generated in FELs by in situ manipulation of the electron beam micro-distribution through a harmonic IFEL interaction in a helical undulator.

A newly proposed High-Gain, High Mode Generation scheme (Hemsing, et al. PRL 106, 164803 (2011)) for high-energies produces coherent, high-brightness OAM light at the same wavelengths accessible to modern high-gain FELs => hard x-ray OAM light is possible for, eg. K-edge spectroscopy



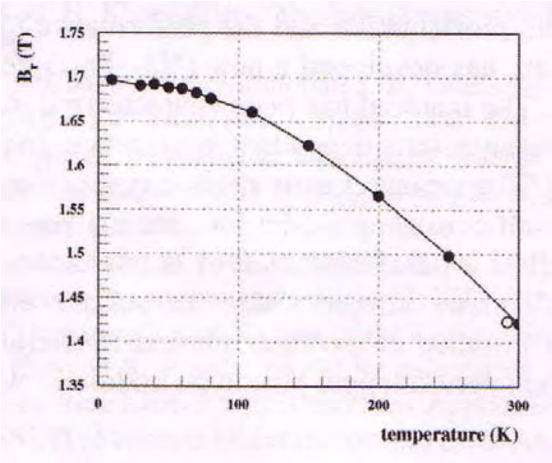



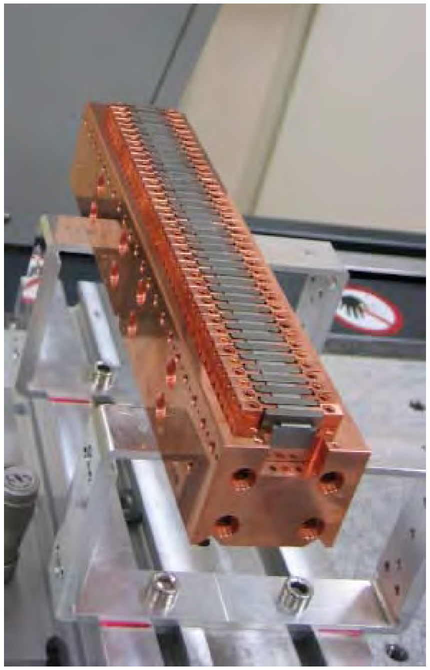


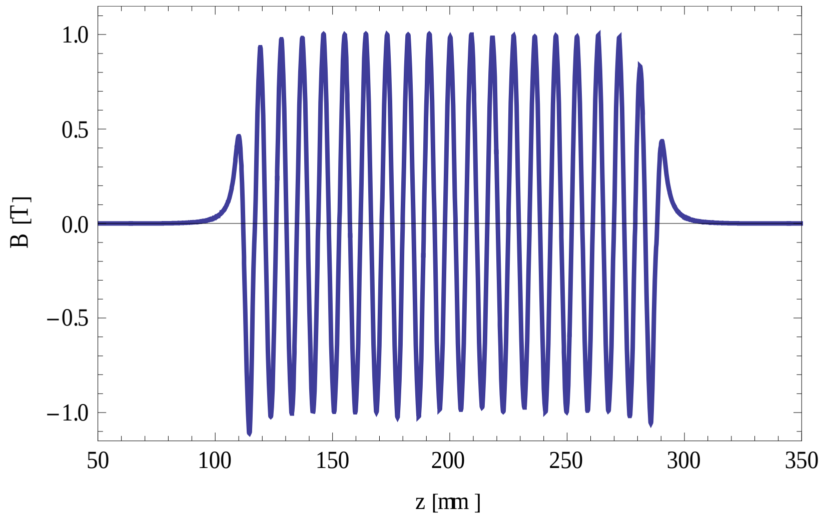
This concept was examined experimentally for the first time in 2011 at the UCLA Neptune Lab. Results successfully demonstrated the proof-of-principle: first harmonic helical IFEL interaction, and first observation of helical microbunching required for OAM emission (Hemsing, et al. Submitted to PRL (2011))

# Short period undulators

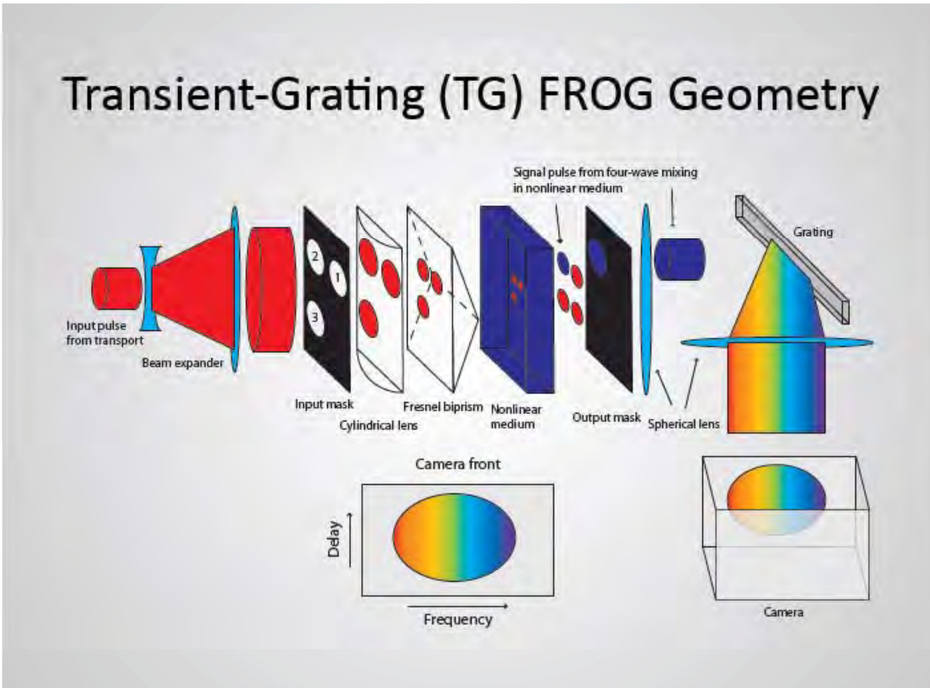
- Cryogenic undulator for increased B-field and coercivity
- 9mm period, 20 periods, 2.5mm gap
- In RE magnets Br and Hc have a negative temp. dependence
  - o Nd has a spin axis reorientation at ~140K
  - o Praseodymium Magnets.
- Cryogenically cooled to <80K
- K=1 @ T < 60K
- “Massive” copper structure used as thermal equipotential
- First measurements in agreement with simulation.



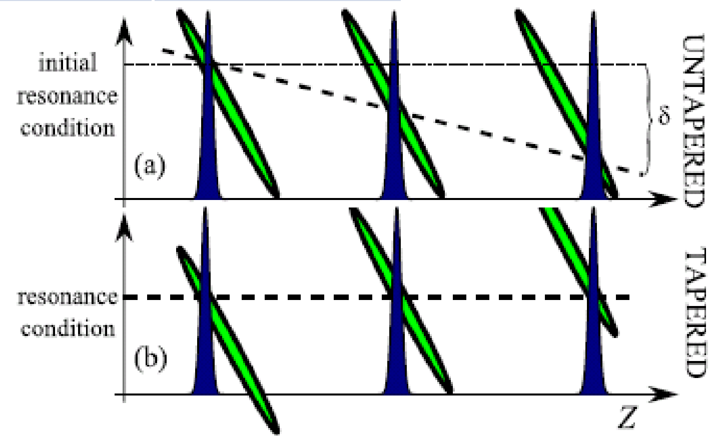





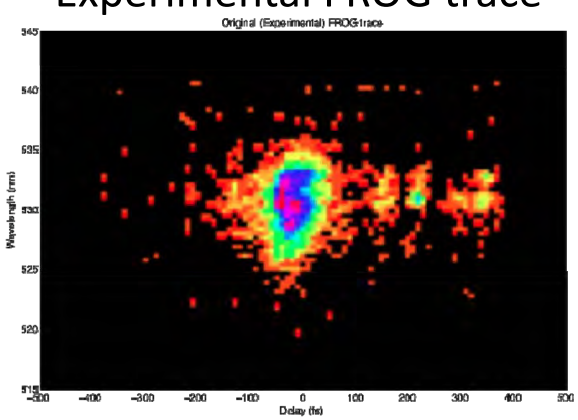
# Single spike FEL/ FROG diagnostics @ SPARC

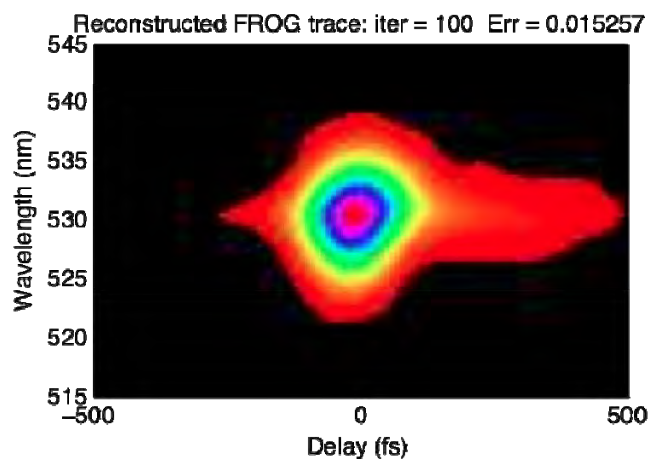



| | |
|---|---|
| Q | 250 pC |
| I | 264 A |
| E | 113 MeV |
| Chirp | -2.5 kV/um |
| emittance | 2.2 mm-mrad |

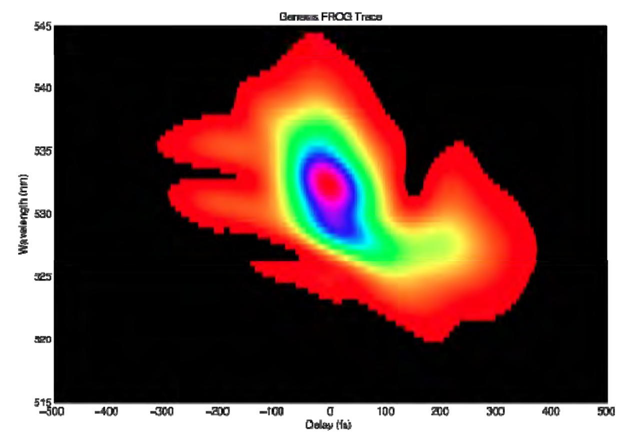



Experimental FROG trace

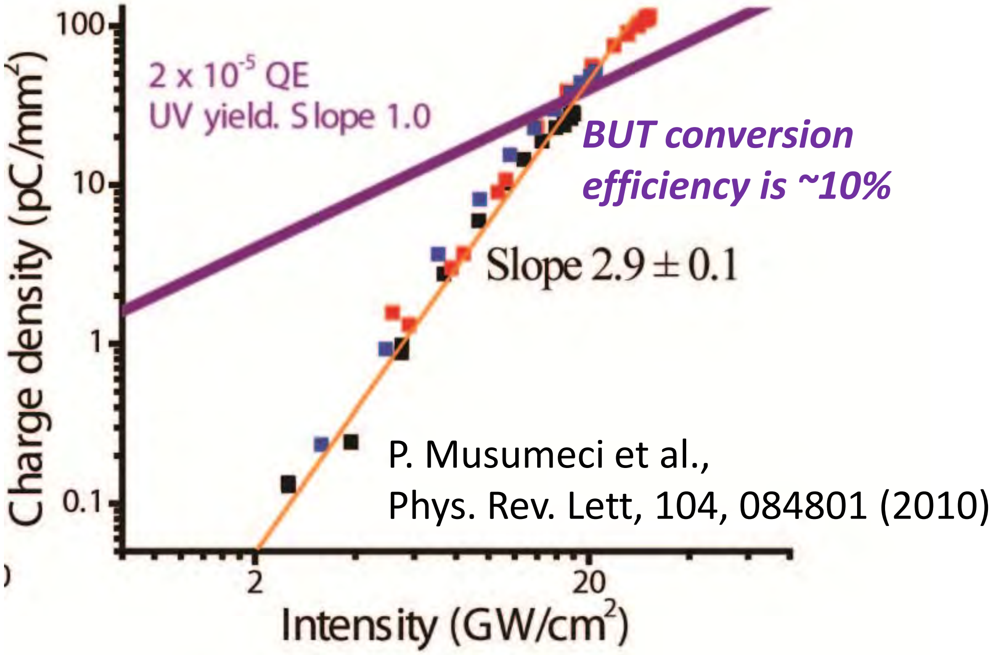


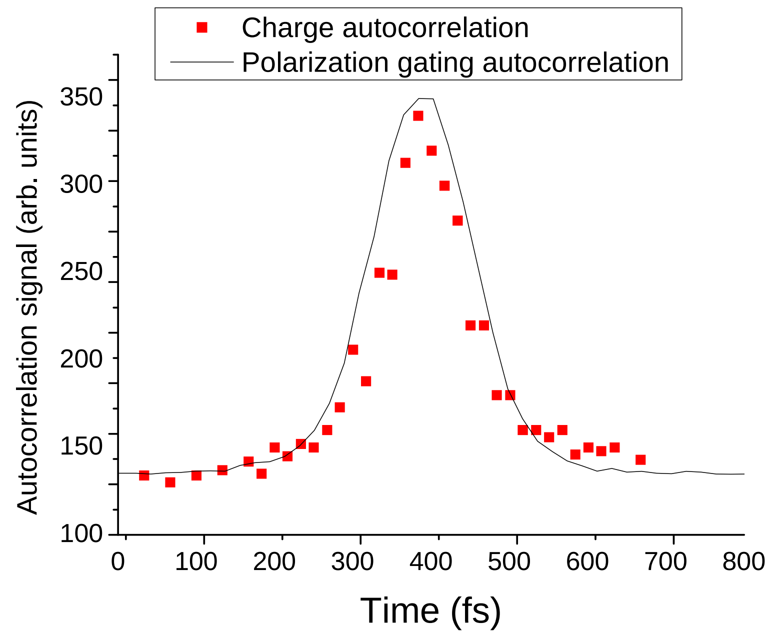




Genesis simulation



# Save laser energy. Use IR photons on the cathode




Measure yield for different spot sizes.

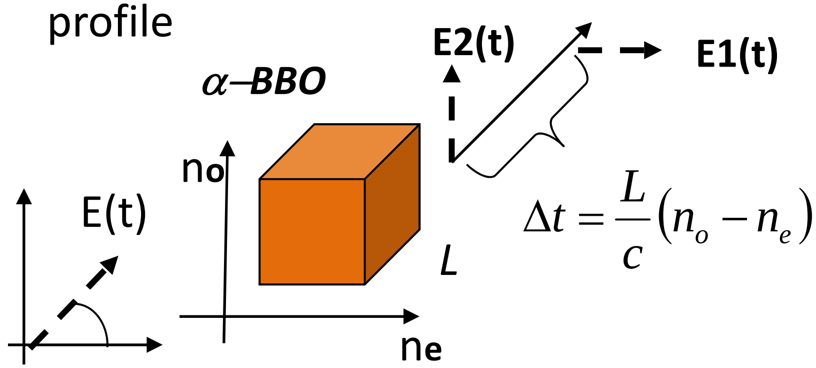
Autocorrelation of two IR pulses on the cathode shows promptness of emission.

*Question: Why hasn't this been done before?*

- Recent interest in pancake regime. Ultrashort beam at cathode => uniformly filled ellipsoidal beam.
- Very high extraction field in RF photoinjector: away from space-charge induced emission cutoff. (Early experiments using low gradient setups.)
- Damage threshold few 100 GW/cm$^2$ at sub-100 fs pulse lengths.
- AR coating on the cathode improves charge yield. (**at Pegasus 2 μJ of 800 nm -> 50 pC** )

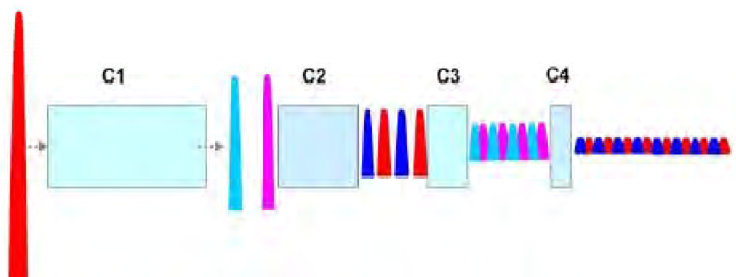
# Bunch train generation: THz and wakefield

- Use birefringent alpha-BBO crystals to manipulate longitudinal laser profile

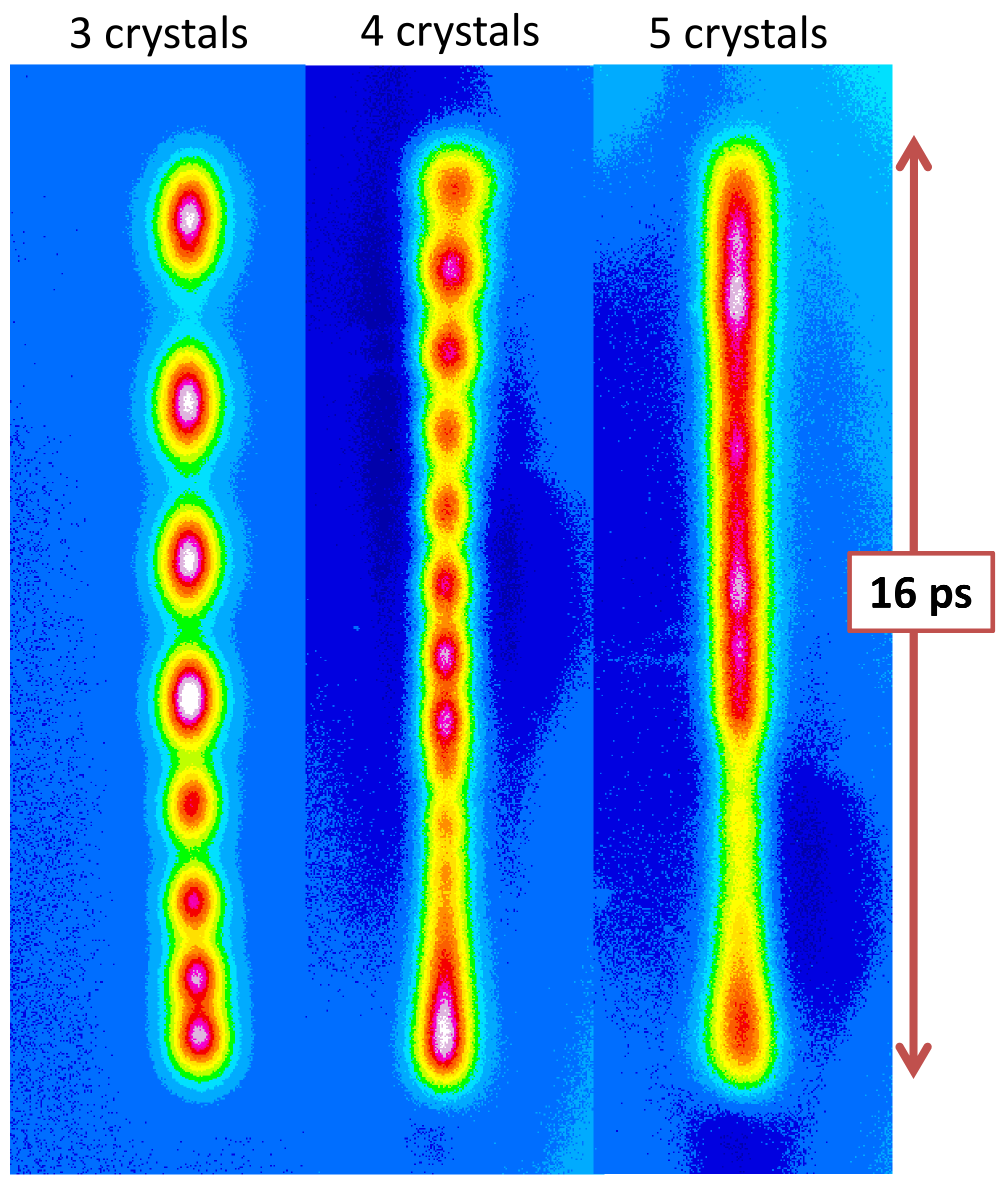



$$\Delta t = \frac{L}{c}\left(n_o - n_e\right)$$

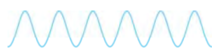
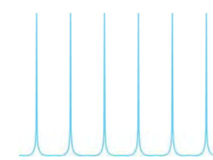
- $2^n$ pulses
- 1 mm smallest thickness -> 0.5 ps spacing
- n = 5 crystals of increasing thickness

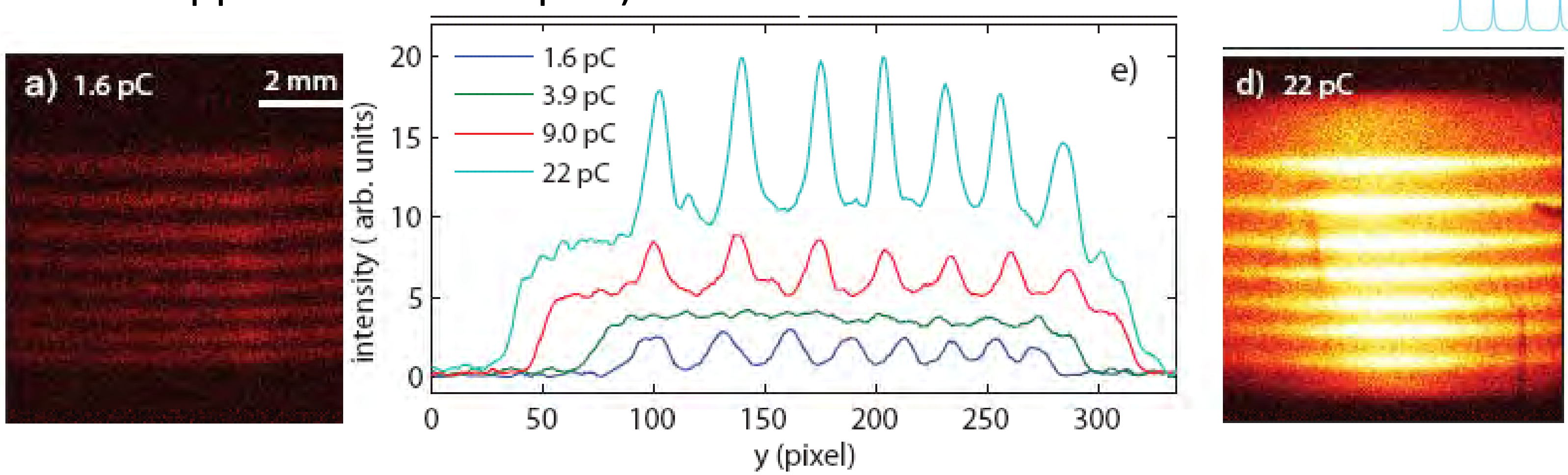



For small spacing, the space charge removes current modulation and one has a quasi flat-top beam.



# Non linear longitudinal space charge oscillations in relativistic electron beams

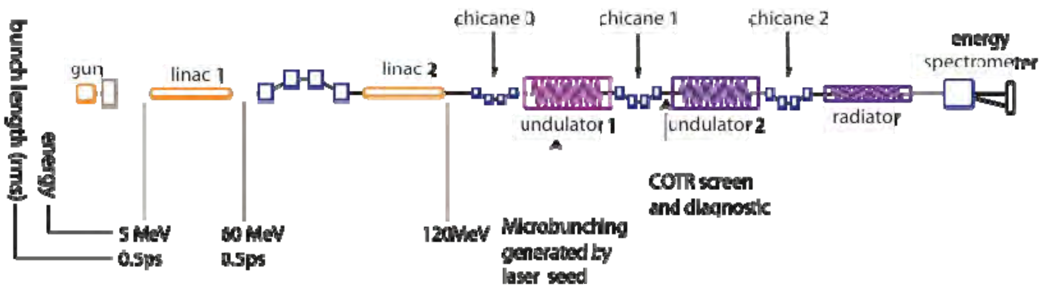
- Start with e-beam modulated at the cathode. 
- By increasing charge, modulation washes out.
- After a ¼ plasma period, beam distribution is completely flat (shot noise suppression techniques).
- After ½ plasma oscillation, linear theory predicts modulation to come back. 
- Nonlinear theory is even better… Modulation comes back with increased harmonic content and enhanced peak current !!! 




P. Musumeci, R. K. Li and A. Marinelli, Phys. Rev. Lett. 106:184801 (2011)

# Microbunching and coherent radiation Experiments at SLAC NLCTA

Plasma dynamics and amplification of optical microbunching




Measure COTR at 3 locations:

-after chicane 0 $\quad \tilde{n} = \tilde{n}_0$

-before chicane 1 $\quad \tilde{n} = \tilde{n}_0 \Gamma \cos \Omega_+ T$

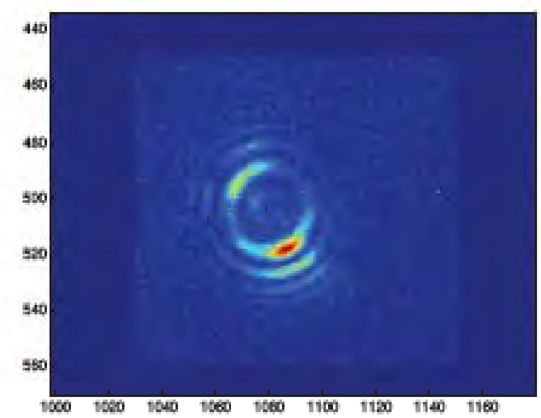
-after chicane 1 $\quad \tilde{n} = -\tilde{n}_0 \frac{\omega_p}{c} \gamma^2 R_{56} e^{-\frac{K_\phi^2}{2}} \Gamma \Omega_+ \sin \Omega_+ T$

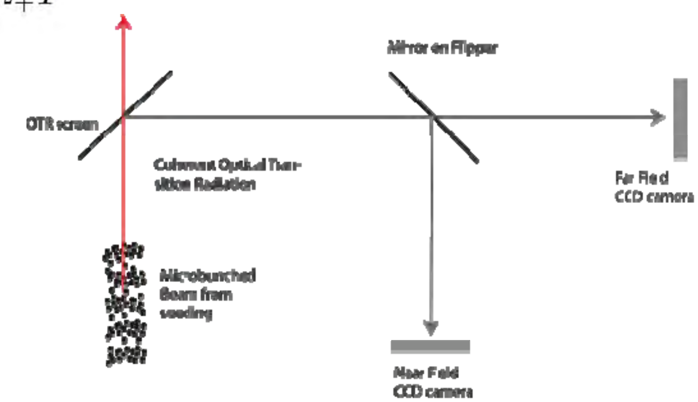
6D analysis of space-charge interactions in terms of plasma-waves. (Marinelli et al.)

$$\left(\frac{1}{D^2}\nabla_\perp^2 - 1\right) E_z = \int E_z(X') H(X, X') d^2 X'$$

$$D = k_z \sigma_x / \gamma$$

Phase retrieval of COTR images for the reconstruction of 3D microbunching

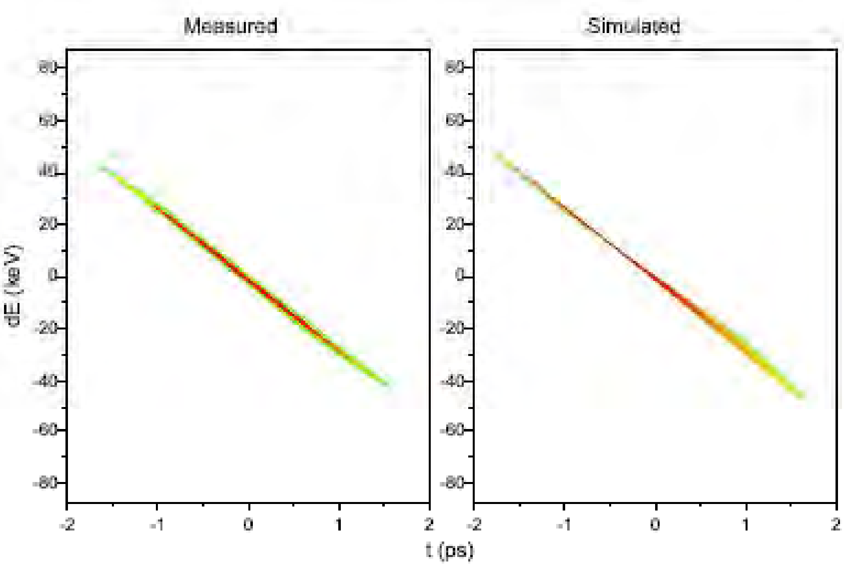


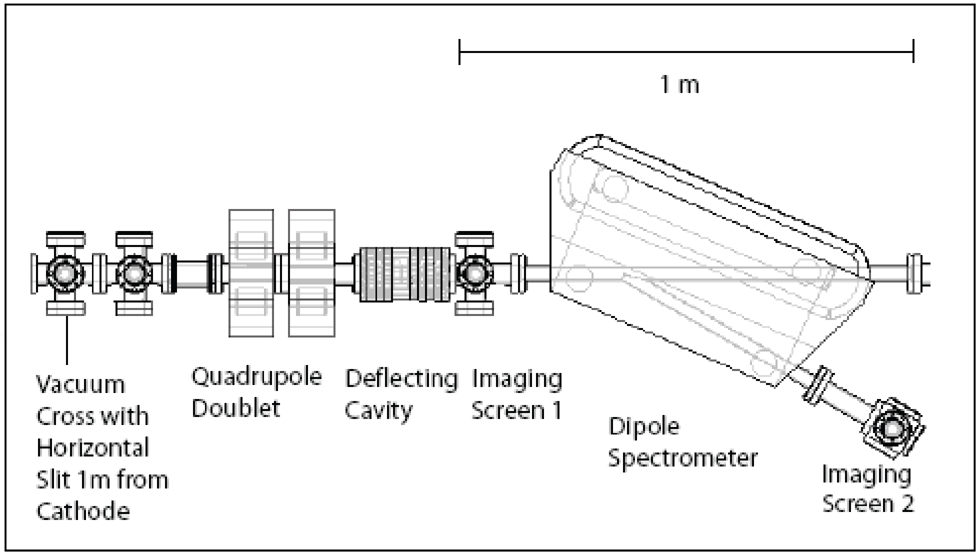


# Longitudinal phase space measurements

- Control the induced energy spread from the cavity as predicted by Panofsky-Wenzel theorem
- Record resolution in time (50 fs) and energy (1 keV).
  - Advantages of measurement on low energy beams.

LPS measurement compared with GPT simulation.




**Very linear phase space**

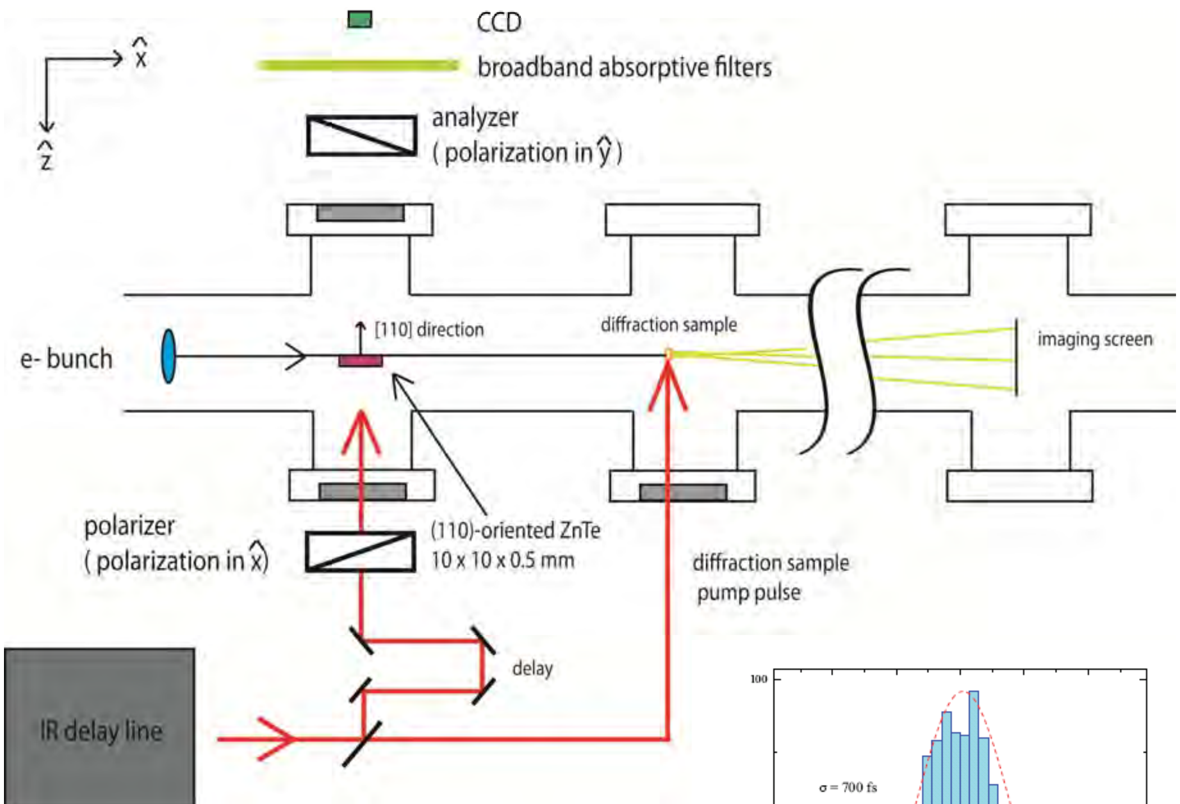
**High 6D beam brightness**

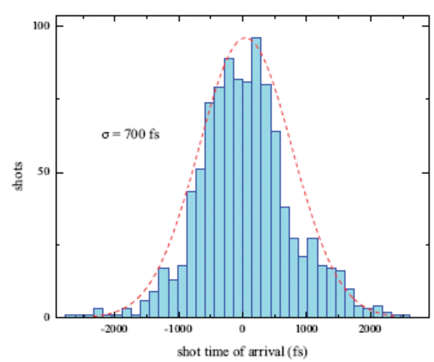
**Ultralow longitudinal emittance (<0.5 um)**

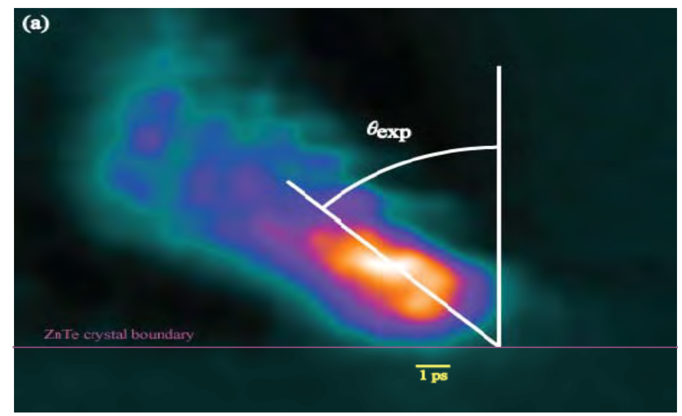
# Electro-Optic Sampling based time-stamping

For synchronization tolerances < 10s fs there is no real alternative to time-stamping.
Pioneered at SPPS@SLAC. Cavalieri et al. Clocking fs X-rays. PRL, 94, 114801 (2005)

C. M. Scoby, P. Musumeci et al., PRSTAB **13**, 022801 (2010)

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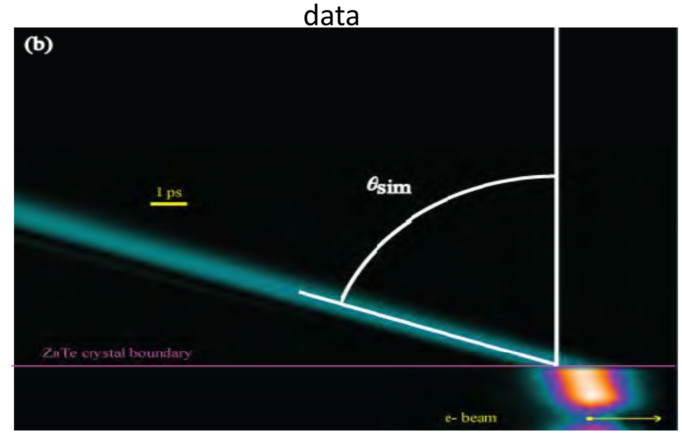
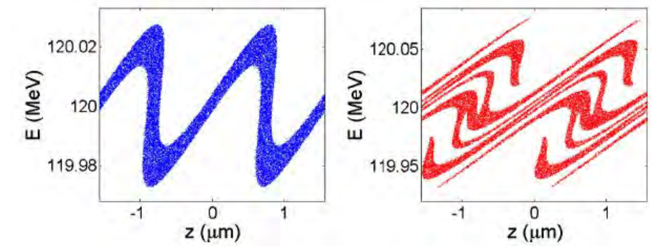


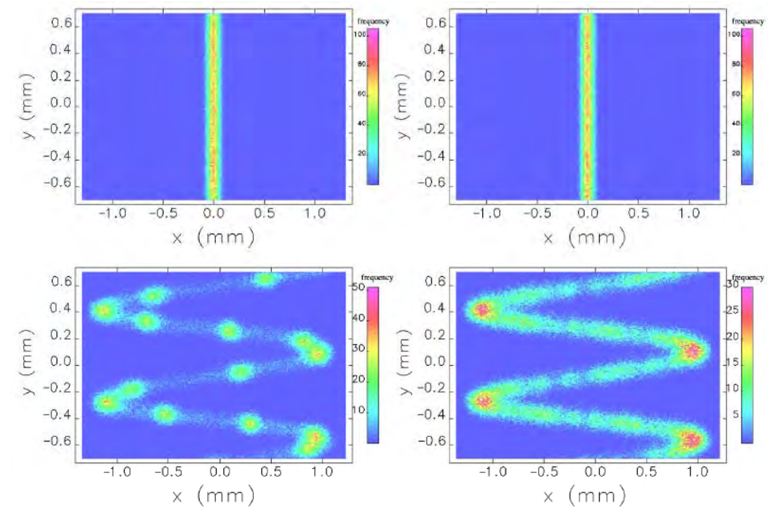

OOPIC Simulation

# Sub-fs longitudinal diagnostic for high brightness beams

- Longitudinal profile in time domain with <fs resolution
- Angular modulation after laser/undulator interaction
- Requires $TEM_{10}$ laser mode
- Modulation proportional to laser power, inversely proportional to beam energy
- Vertical sweep provided by deflector
- Sinusoid pattern observable on standard screen
- Enhanced resolution compared to deflector alone

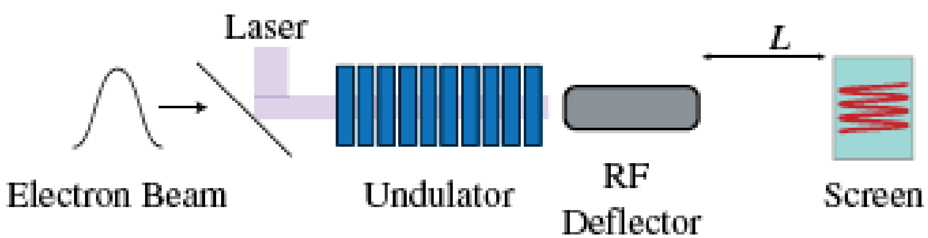
Slac Echo Enabled FEL



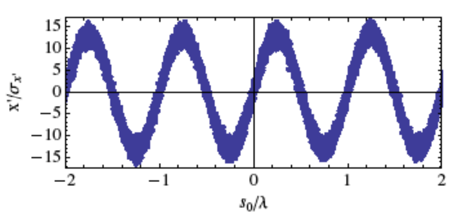



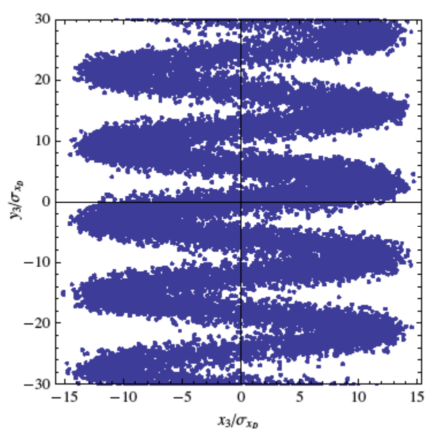

Elegant simulations

General Layout




Analytical Treatment



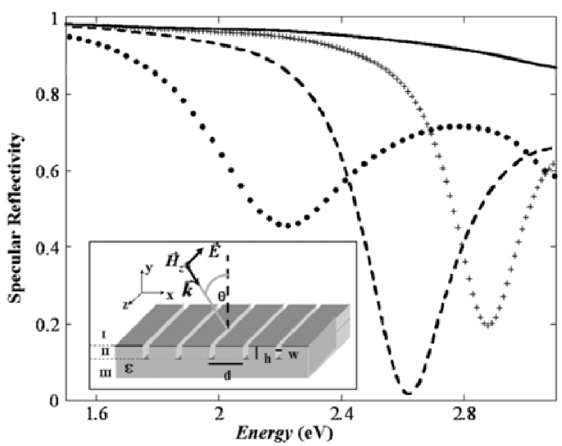




G. Andonian et al. PRSTAB,**14**, 072802, 2011

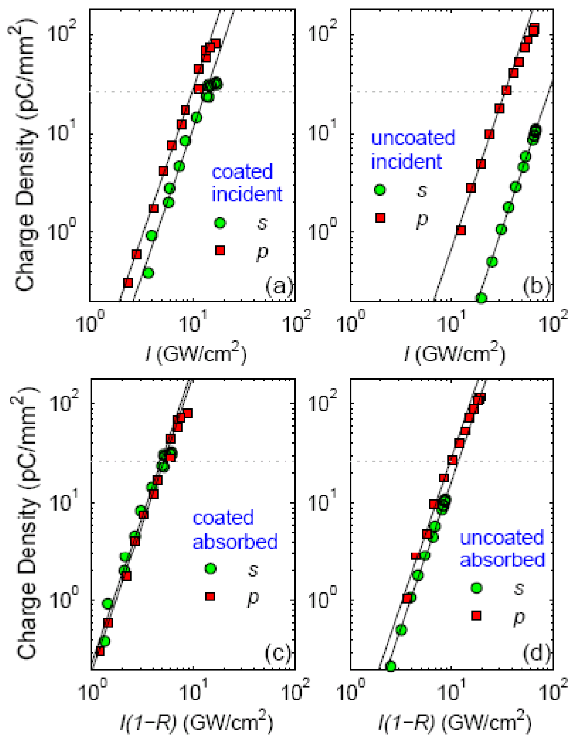
# Cathode research at Pegasus

- Plasmon-assisted photoemission

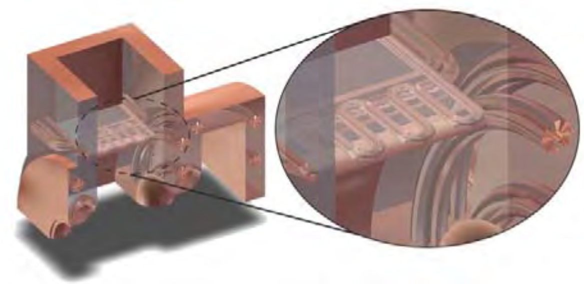
- Surface plasmon assisted intensity enhancement (x100 possible) could greatly increase multiphoton charge yield.



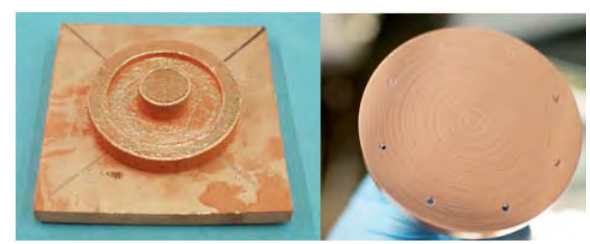

- **Vectorial/surface photoelectric effect studies**
- P-polarization and oblique incidence enable surface photoelectric effect.
- No optical field enhancement.
- Path to smaller thermal emittance?




- **SOLID FREEFORM FABRICATION (SFF)**
- SFF is an additive manufacturing process where end-use, metal, parts are directly fabricated, layer by layer, from a digital model



- SFF copper cathode cathode recently successfully tested at UCLA's Pegasus photoinjector under high RF power



# Pegasus upcoming upgrades

- Laser upgrade 2 TW 100 mJ/50 fs
  - 20 MW @ THz power
  - Pump irreversible phase transition.
  - Inverse Compton Scattering. Create LCLS photons
  - External injection. Create linear plasma wakes with 2 TW + inject RF photoinjector generated beam.
- RF hybrid gun
- Coupled-slot linac accelerating section
  - 15 MeV energy
  - RF compression