Net Acceleration of an Optically Microbunched Electron Beam

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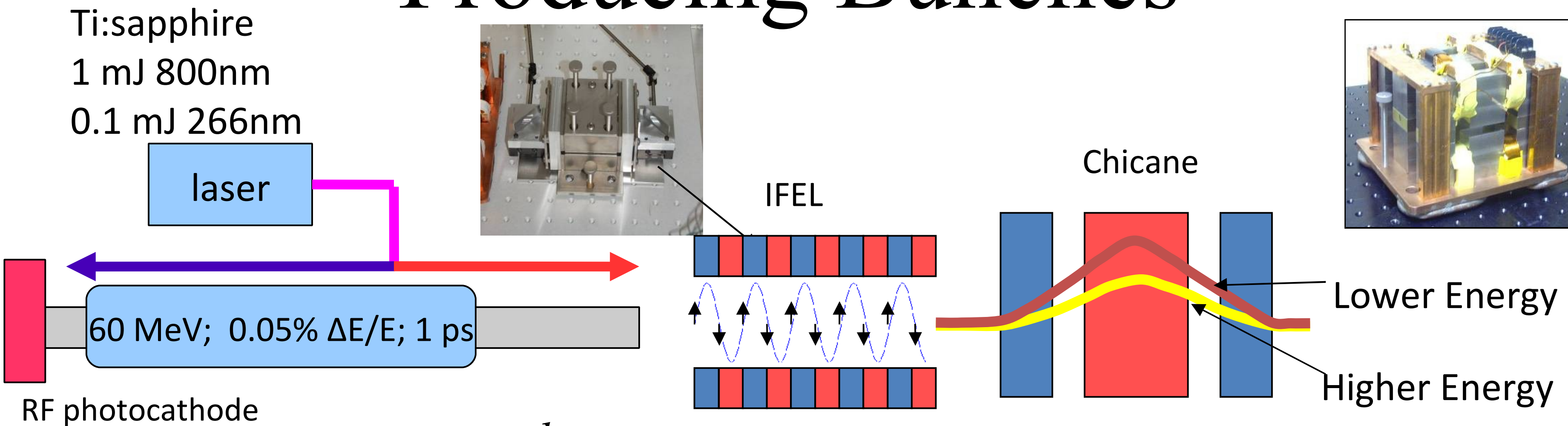
Talk Outline

- Producing Microbunches:
  - Characterization with Coherent Optical Transition Radiation
- Net Acceleration of an Optically Microbunched Beam
  - Simulation & Results

Producing Bunches



$$mc^2 \frac{d\gamma}{dt} = q\vec{v} \cdot \vec{E}_{laser}$$

Undulator

- Laser & e-beam copropagate in sinusoidal static B field
- Electrons accelerated transversely by laser field
- Undulator resets the electron trajectory to match slip w.r.t. laser phase
- From Lorentz force eqs.
  - Resonance eq. $\lambda_l = \frac{\lambda_w}{2\gamma^2}\left(1 + \frac{K_w^2}{2}\right)$

And energy Modulation $\Delta\gamma = \frac{\pi N K_r K_w}{\gamma} \frac{\lambda_w}{\lambda_l} \cos(k_l z_0)$

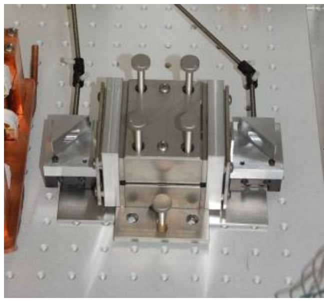
Chicane

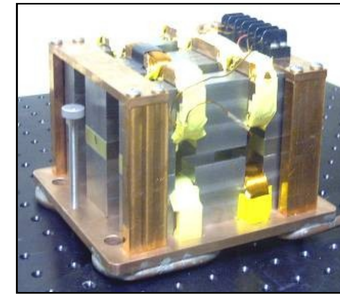
- Bend angle in magnet inversely proportion to energy
- Lower energy particles take longer path
- (again from Lorentz eqs):

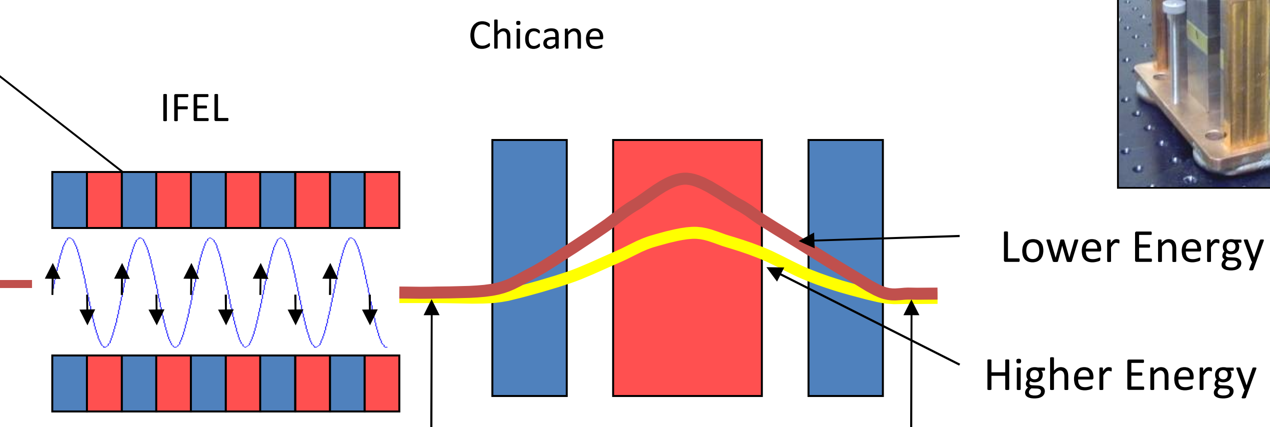
$$R_{56} = \frac{L}{\gamma^2} + \left(\frac{q}{\gamma\, mc}\right)^2 \int_{-\infty}^{\infty} \left[\int_{-\infty}^{z} B(z')dz'\right]^2 dz$$

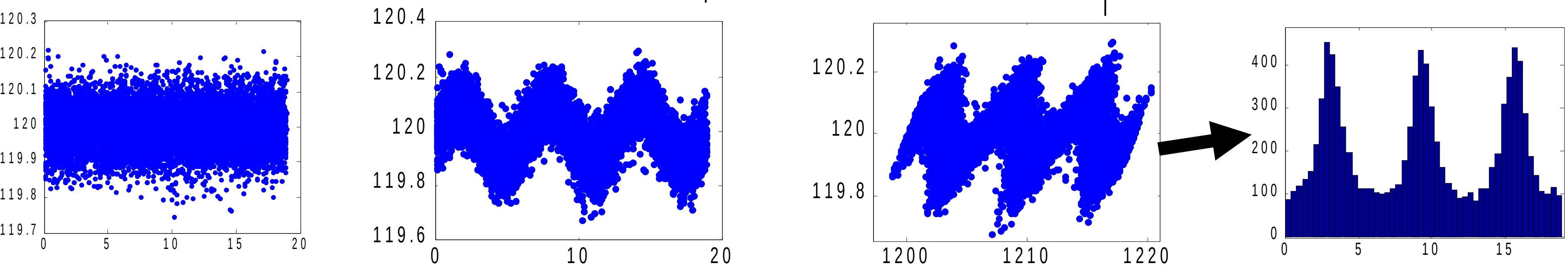
velocity bunching ~5% of total

Producing Bunches 2









σ_γ

$\gamma_i \rightarrow \gamma_i + \eta \sin k_l z$

$z_i \rightarrow z_i + R_{56} \gamma_i$

bunch'o math

$$\rho(z) = \rho_0 \left[1 + 2\sum_{n=1}^{\infty} J_n \left(n k_l R_{56} \frac{\eta}{\gamma_0} \right) \exp\left[-\frac{1}{2} \left(n k_l R_{56} \frac{\sigma_\gamma}{\gamma_0} \right)^2 \right] \cos(n k_l z) \right]$$

Quantifying Microbunching with Coherent Optical Transition Radiation

COTR from Microbunches

For radiation pattern not a function of particle position

$$\frac{dI_{tot}}{d\Omega d\omega} = N\left[1 + N|f(\Omega,\omega)|^2\right]\frac{dI_0}{d\Omega d\omega}$$

where $f(\Omega,\omega) = \frac{1}{\rho_0}\int d\vec{x}dt\,\rho(\vec{x},t)\,e^{i(k\cdot\vec{x}-\omega t)}$

$$\rho(\vec{x},t) = \frac{1}{\pi\sigma_r^2}\exp\left[-\frac{r^2}{\sigma_r^2}\right]\rho(z)$$

Frank-Ginsburg

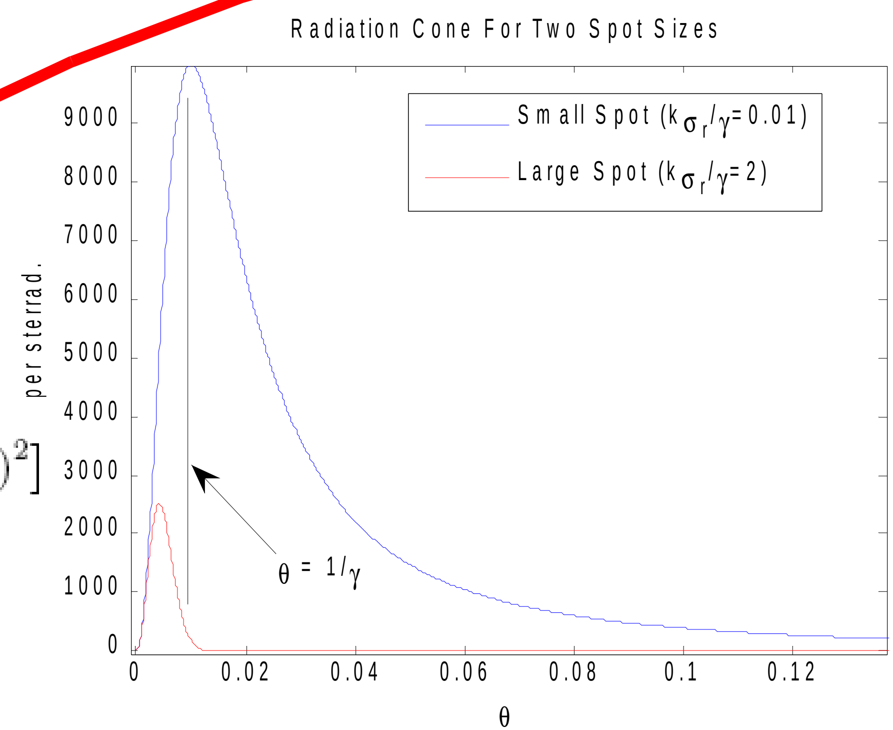
$$\frac{dI_{TR}}{d\vec{k}d\omega} \cong \frac{e^2}{16\pi^3\varepsilon_0 c}\frac{\theta^2}{\left(\frac{1}{\gamma^2}+\theta^2\right)^2}$$

note: no frequency dependence (ideal conductor)

I_{tot} frequency dependence due to bunching only!

$$\frac{dI_{COTR,n}}{d\theta} \cong \frac{N^2e^2b_n^2}{16\pi\sqrt{2\pi}\varepsilon_0\sigma_z}\frac{\theta^3}{\left(1/\gamma^2+\theta^2\right)^2}\exp\left[-(k\sigma_r\theta)^2\right]$$

$$b_n = J_n\left(nk_LR_{56}\frac{\eta}{\gamma_0}\right)\exp\left[-\frac{1}{2}\left(nk_LR_{56}\frac{\sigma_\gamma}{\gamma_0}\right)^2\right]$$



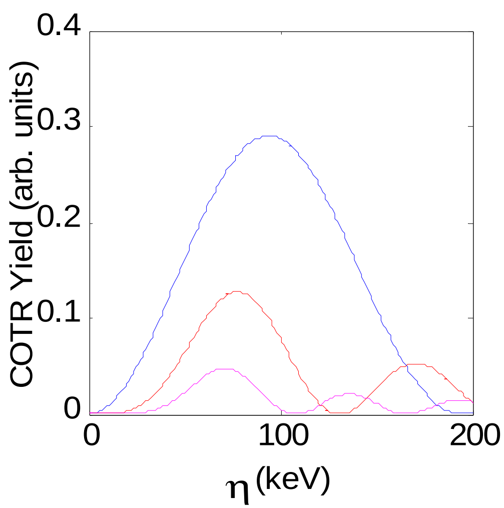
θ

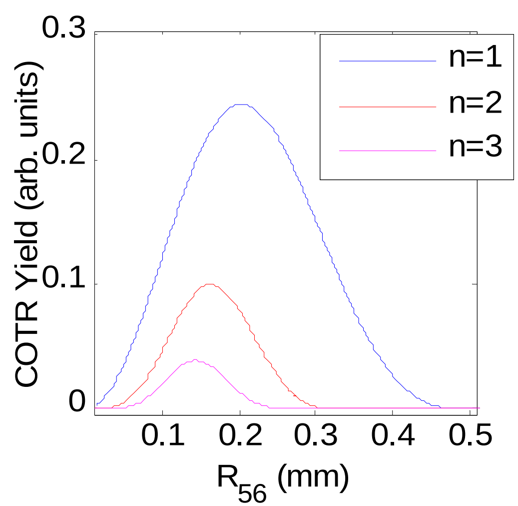
Plan for the microbunching experiment:

$$I_{tot,n} \propto b_n^{\;2}$$

$$b_n = J_n\left(nk_L R_{56}\frac{\eta}{\gamma_0}\right)\exp\left[-\frac{1}{2}\left(nk_L R_{56}\frac{\sigma_\gamma}{\gamma_0}\right)^2\right]$$

- COTR prop. to bunch factors
- difficult to compare absolute yields
- study functional dependence on η & R_{56}

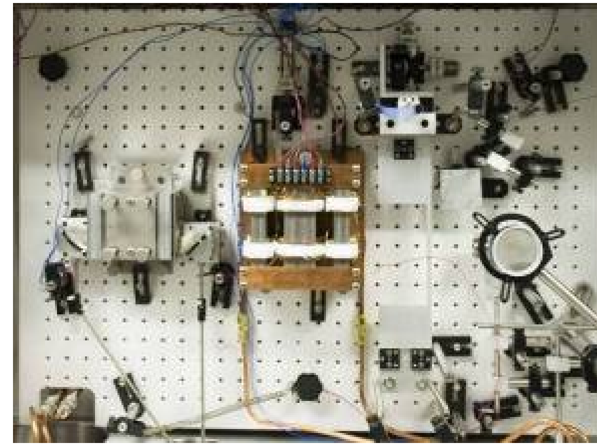




Actual experimental data restricted to smaller range of η & R_{56}

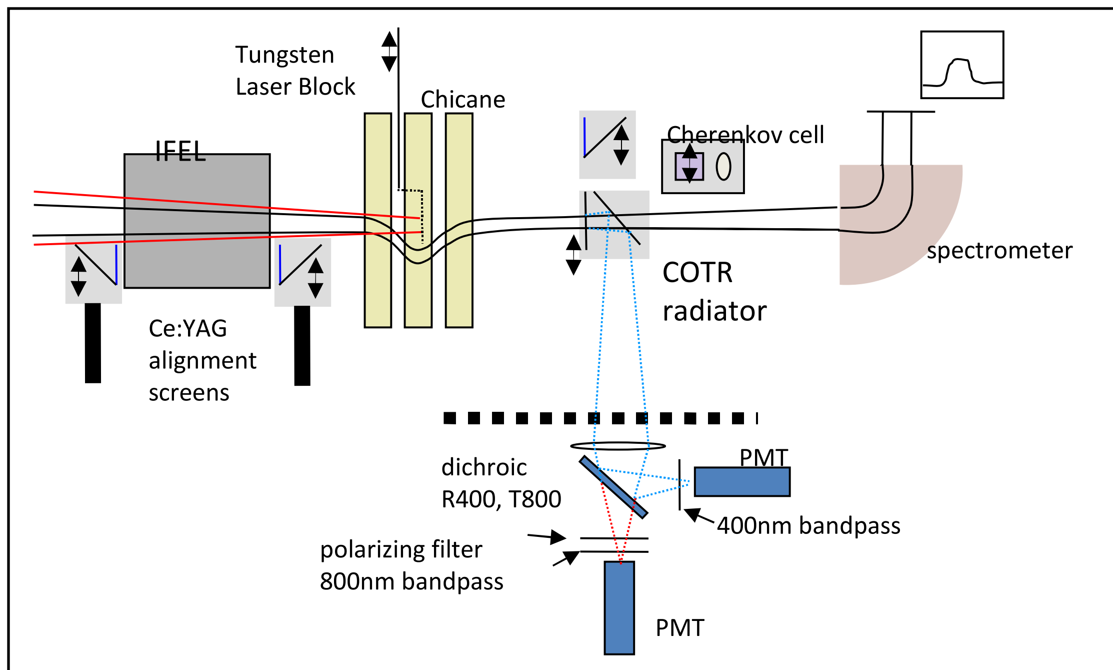
Experiment Setup

- Beam run off-crest with chicane collimator closed to obtain stable ($\delta_{E0} \approx$ 6 keV), low energy spread beam
- Timing obtained to ~25ps with streak camera and Cherenkov light
- Overlap beams on alignment screens
- Run!



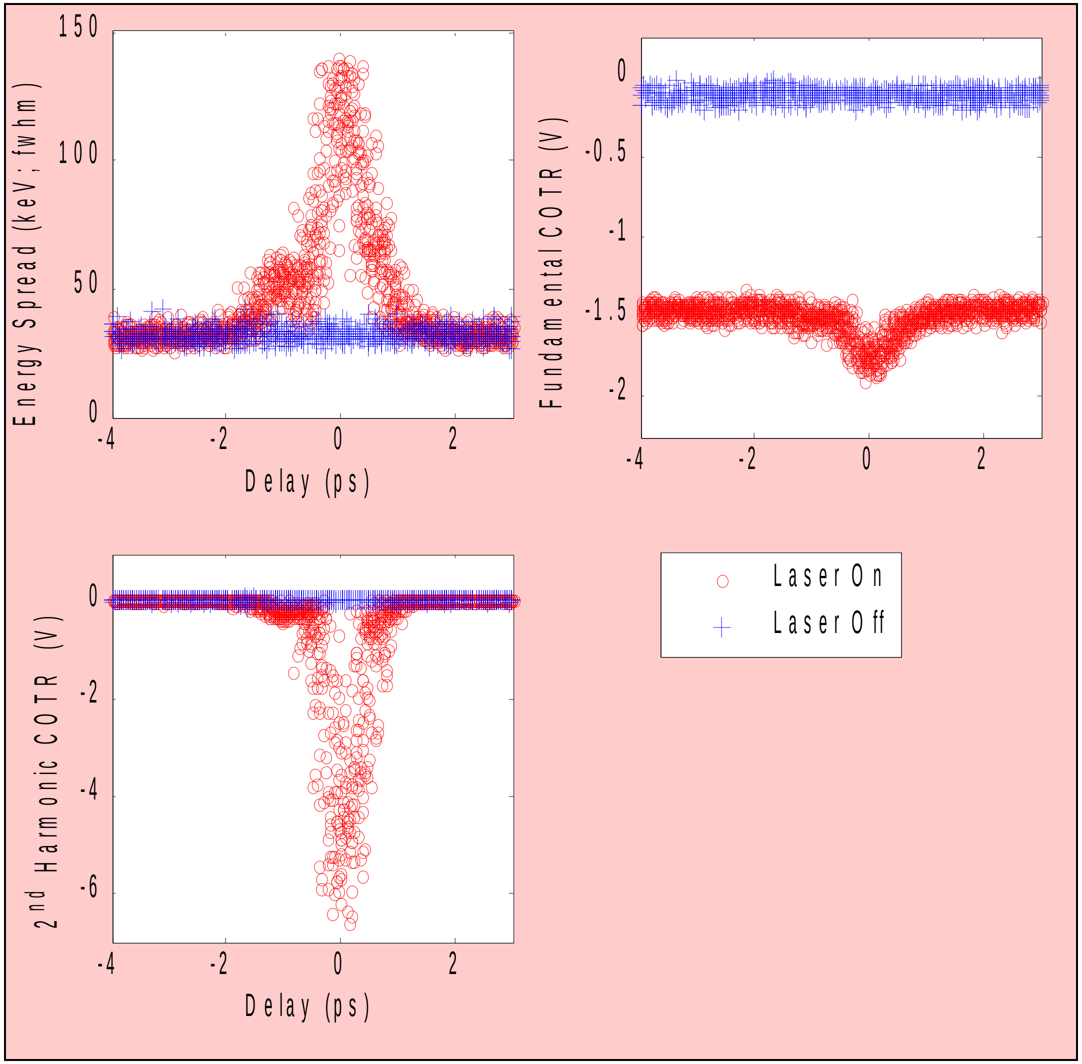
Parameter	Value
Energy	60 MeV
Energy Spread	30 keV (typ)
Electron Pulse Length	0.8 ps
Electron Spot Size	100 μm
Bunch Charge	1 pC
Laser Wavelength	785 nm
Laser Energy	0.6 mJ/pls
Laser Pulse Length	0.5ps
Laser Spot Size	200 μm
Undulator Period	1.8cm
Number of Periods	3
Undulator Strength (a_w)	0.46
Chicane R_{56}	0.04-0.16 mm

all width values fwhm

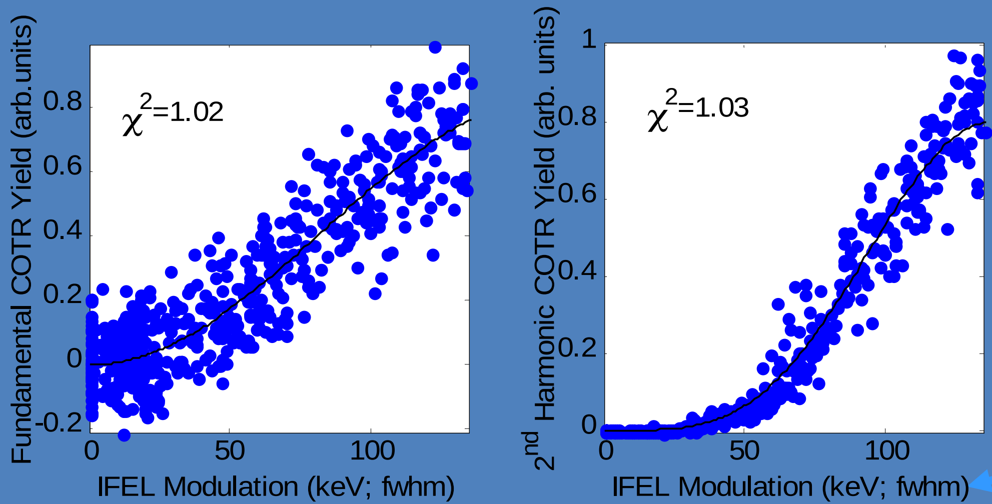


A Typical Data Run

- 500-2000 events, 75% laser on, 10 ps scan window
- Time scanned with fast actuator mounted retro-reflector in laser path to form cross-correlation
- Fundamental COTR signal shows large offset between ‘off’ & on events due to bleed through
- COTR PMTs boxcar integrated, sent to DAQ

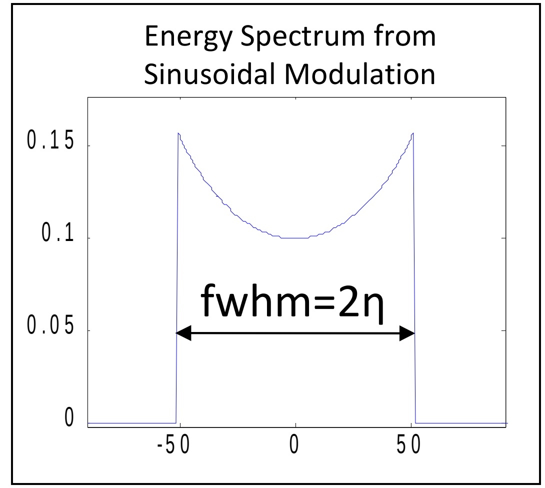


IFEL Interaction strength versus COTR output



$$I_{COTR} \propto J_n\left[nk_l R_{56}\left(\frac{\eta}{\gamma_0}\right)\right]^2 \exp\left[-\left(nk_l R_{56}\left(\frac{\sigma_\gamma}{\gamma_0}\right)\right)^2\right]$$

$$\left(\sigma_{IFEL} = \sqrt{\sigma_{TOT}^2 - \sigma_{init}^2}\right)$$



- Take a single long run and plot IFEL modulation vs. COTR signals. COTR signals inverted, rescaled, and baseline subtracted
- About fit: take vertical scale and η as free parameters. η treated as free since modulation of peak radiating electrons is not the same as modulation of entire bunch (which we measure)
  - find η optimal ~30% greater than $\sigma_{IFEL}/2$. This roughly agrees with analytic treatment taking into account form factors for laser & electron beam.

What is the microbunch duration?

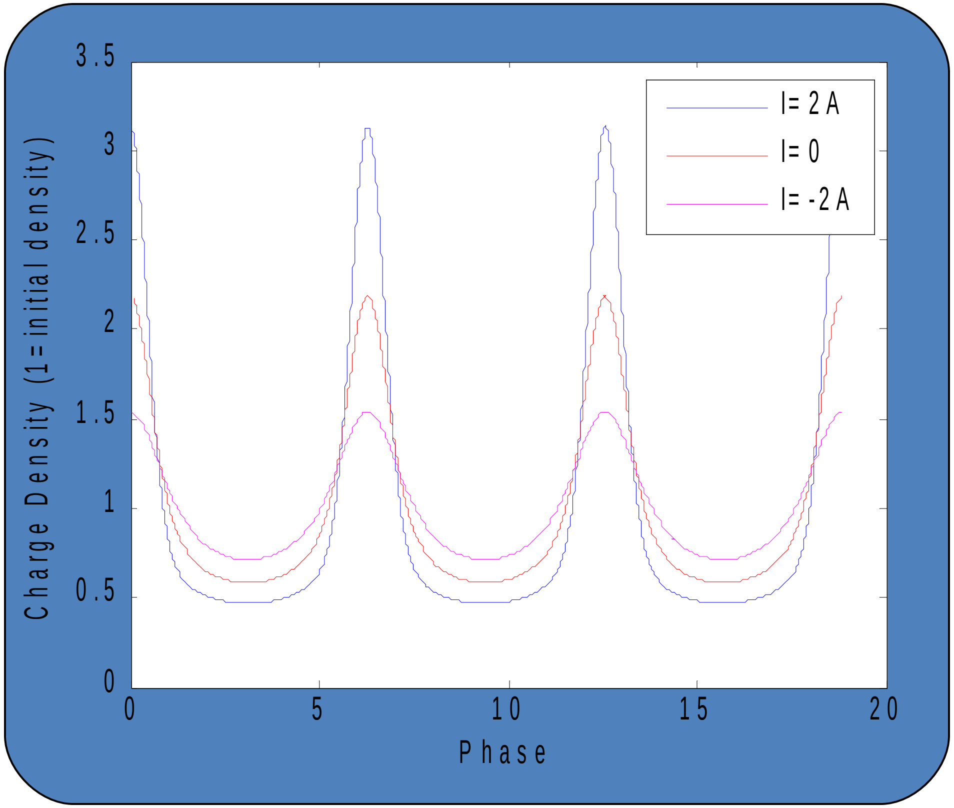
Chicane & interaction variation validate applying 1D model

1D model → 410as fwhm microbunches

Peak Current ~ 3 times unbunched current

40% of charge with fwhm of microbunch

$$b_n \equiv J_n\left[nk_l R_{56}\left(\frac{\eta}{\gamma_0}\right)\right]\exp\left[-\frac{1}{2}\left(nk_l R_{56}\left(\frac{\sigma_\gamma}{\gamma_0}\right)\right)^2\right]$$

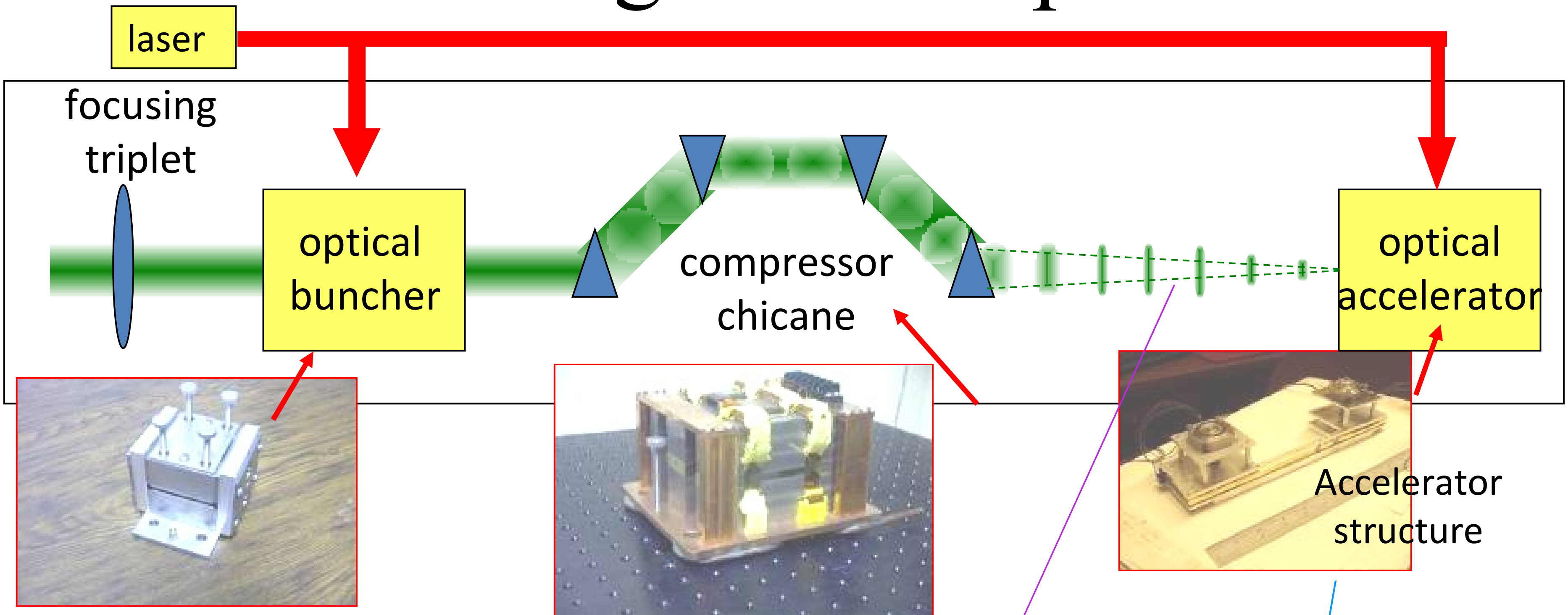


So at optimal bunching, we have b_1=0.52, b_2=0.39

Net Acceleration of Electrons with Light

- Combine microbunching hardware with ITR accelerator to obtain net acceleration
- laser power split between IFEL and ITR
- Careful beam control and electron filtering to avoid interference and obtain signal

The Staged Concept



The IFEL

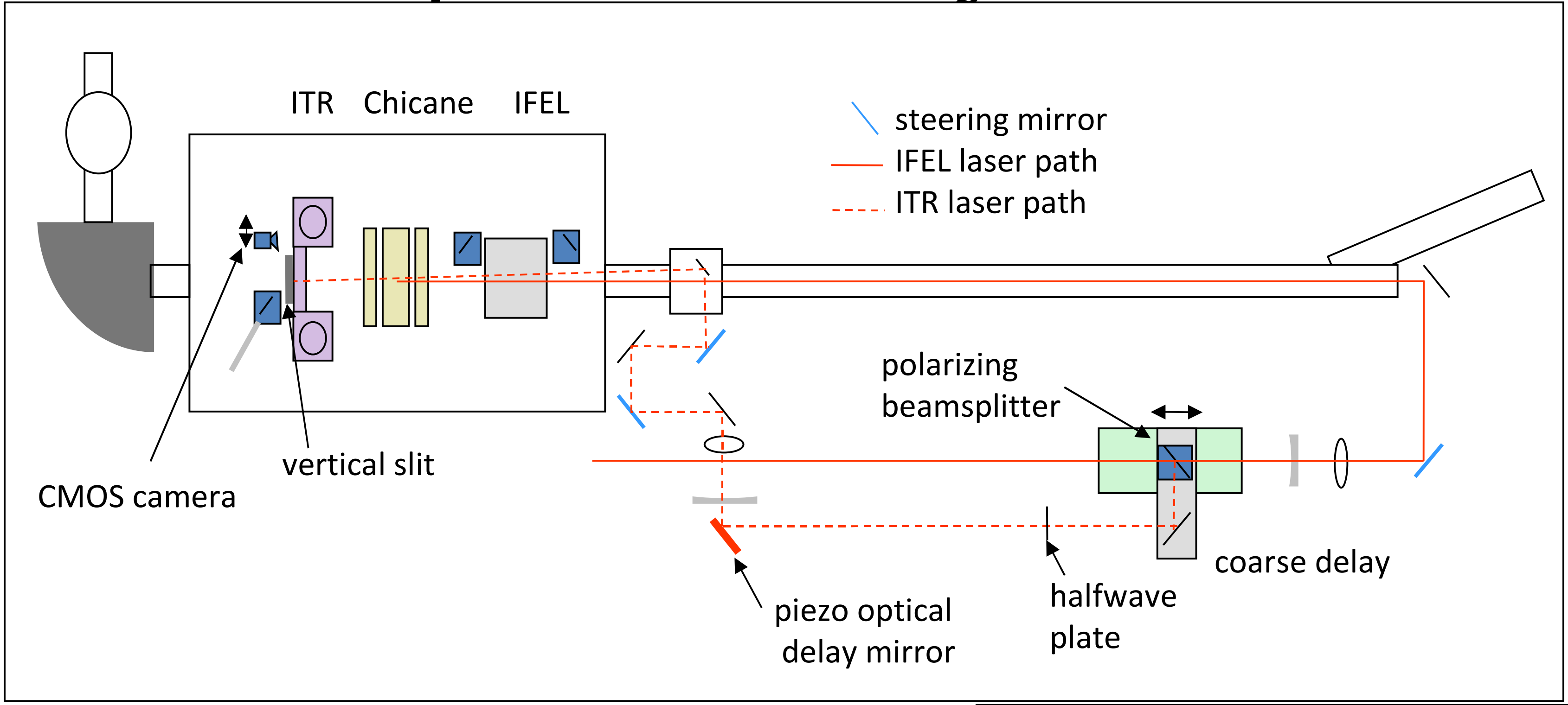
The compressor chicane

Net acceleration of entire bunch

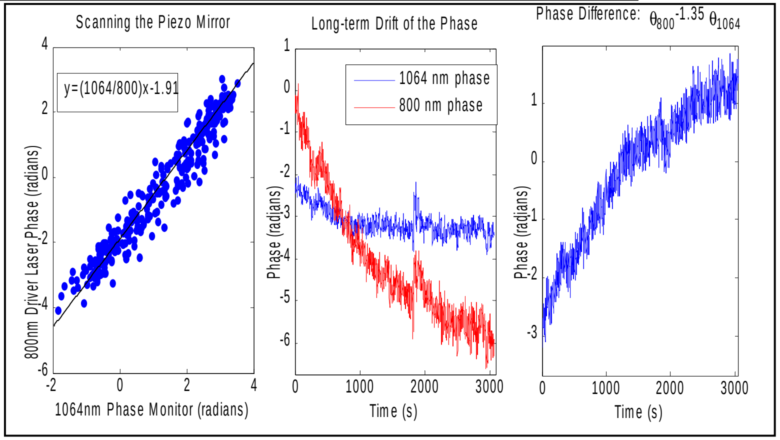
$$\Delta E = \frac{1}{\lambda_l \rho_0} \int_0^{\lambda_l} \rho_0 \left[1 + 2 \sum_{n=1}^{\infty} b_n \cos(n k_l z) \right] A \cos(k_l z + \phi)\, dz$$

$$\Delta E = A b_1 \cos\phi$$

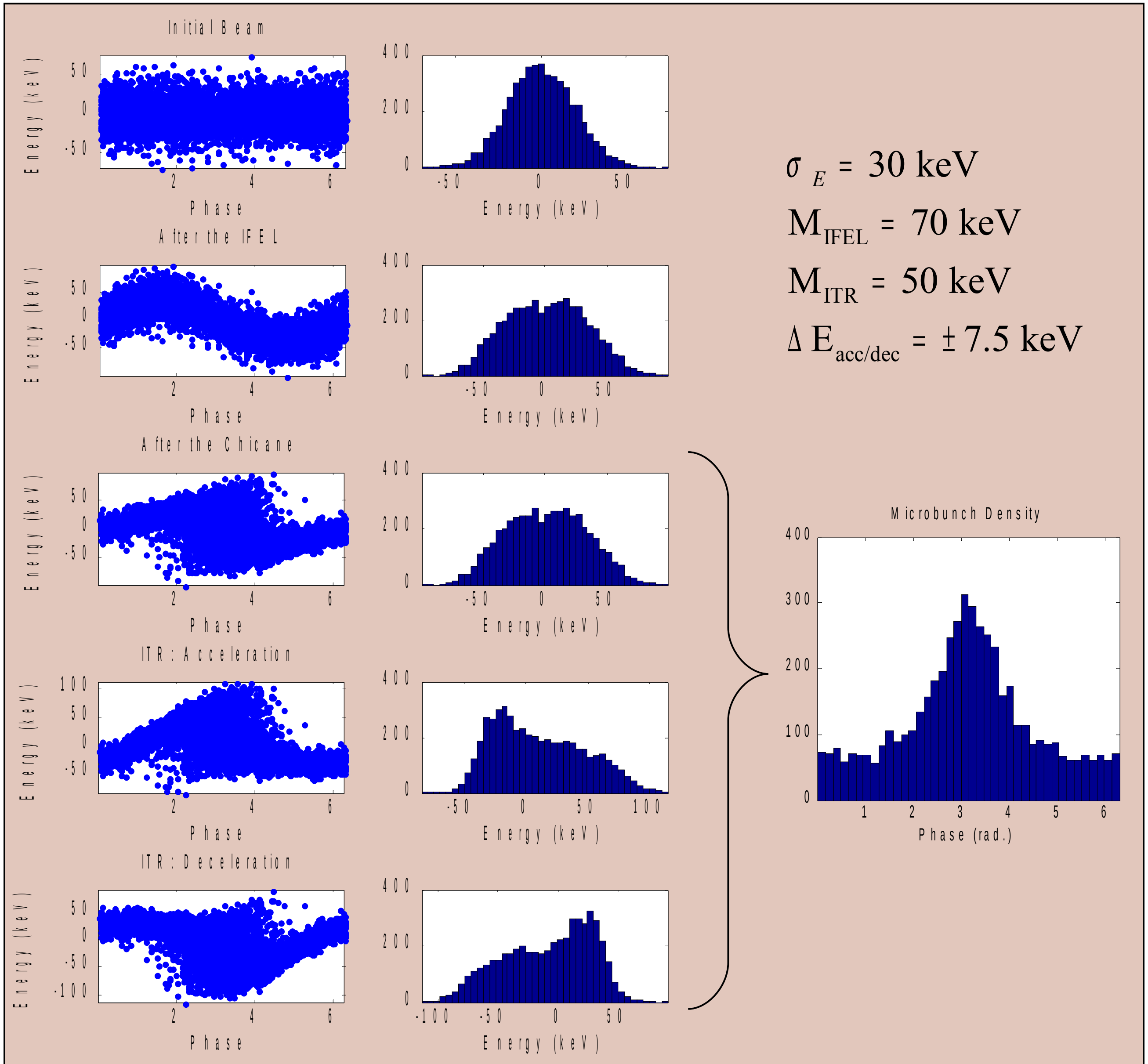
Experiment Layout



- Builds on hardware of microbunching experiment
- add: ITR & its electronics
  - 2nd set of focusing/steering optics
  - means for phase control & monitoring



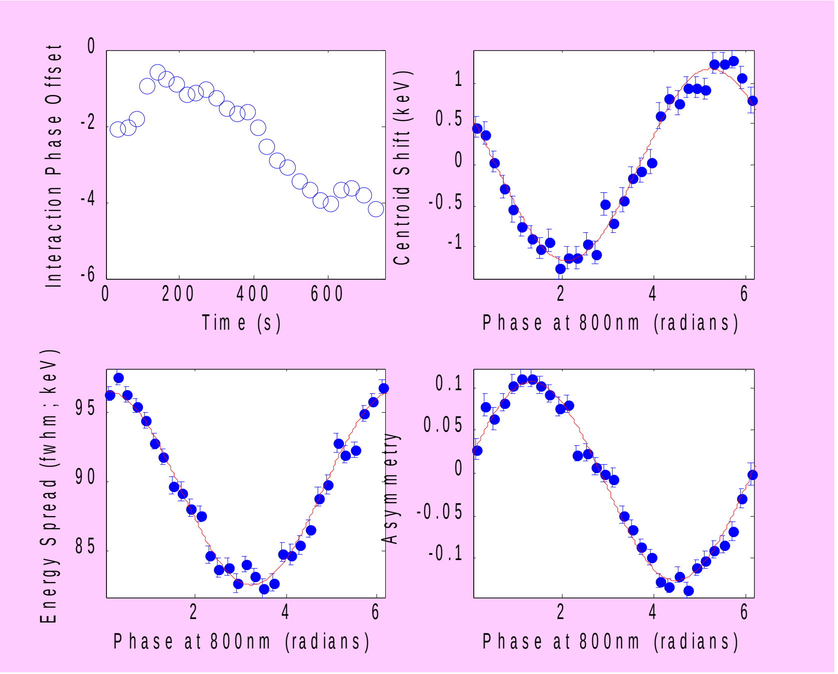
Experiment Monte Carlo

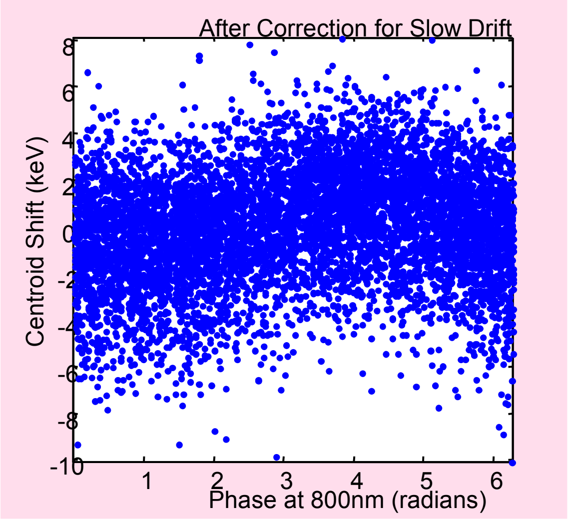


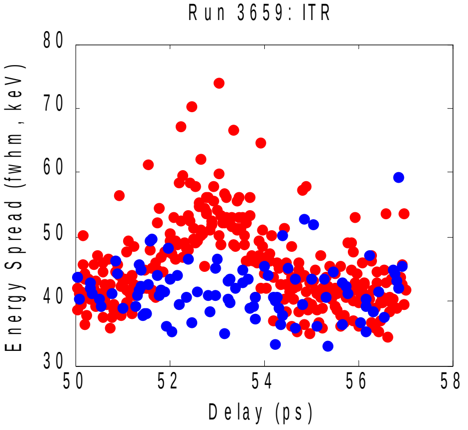
Experimental Result

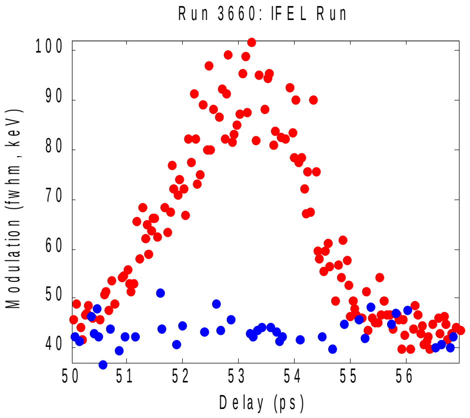
- Phase monitor versus energy spectra quantities
- Observe 1-2 keV amplitude net acceleration signal

- Expect:
  - Initial (aka Laser Off) energy spread: 48 keV fwhm → b_1= 0.35
  - ITR interaction: 35 keV fwhm
  - IFEL interaction: 84 keV fwhm
  - Expected signal:
    - 0.35*0.5*35 = 6 keV Amplitude









Concluding Remarks

- An optically microbunched beam has been produced
  - Good shot-to-shot stability
  - Short duration with minimal energy spread increase
  - Available for future acceleration Direct Laser Acceleration Experiments

SLAC NATIONAL ACCELERATOR LABORATORY

E-163

Alexander von Humboldt Stiftung / Foundation

Many Thanks

The E-163 Collaboration

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Not in photo

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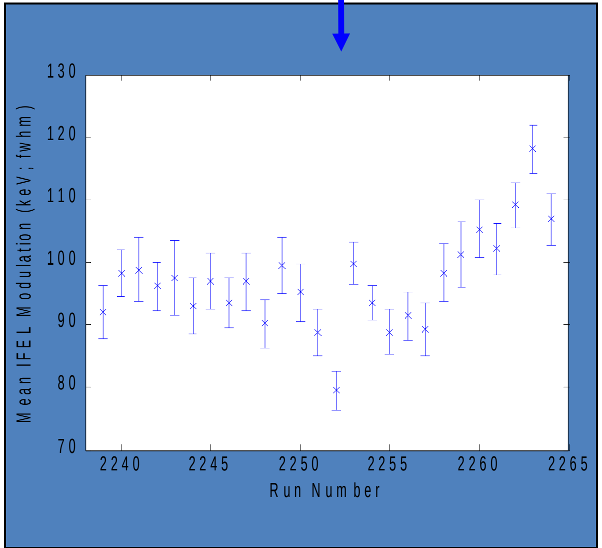
Dieter Walz
Joel England

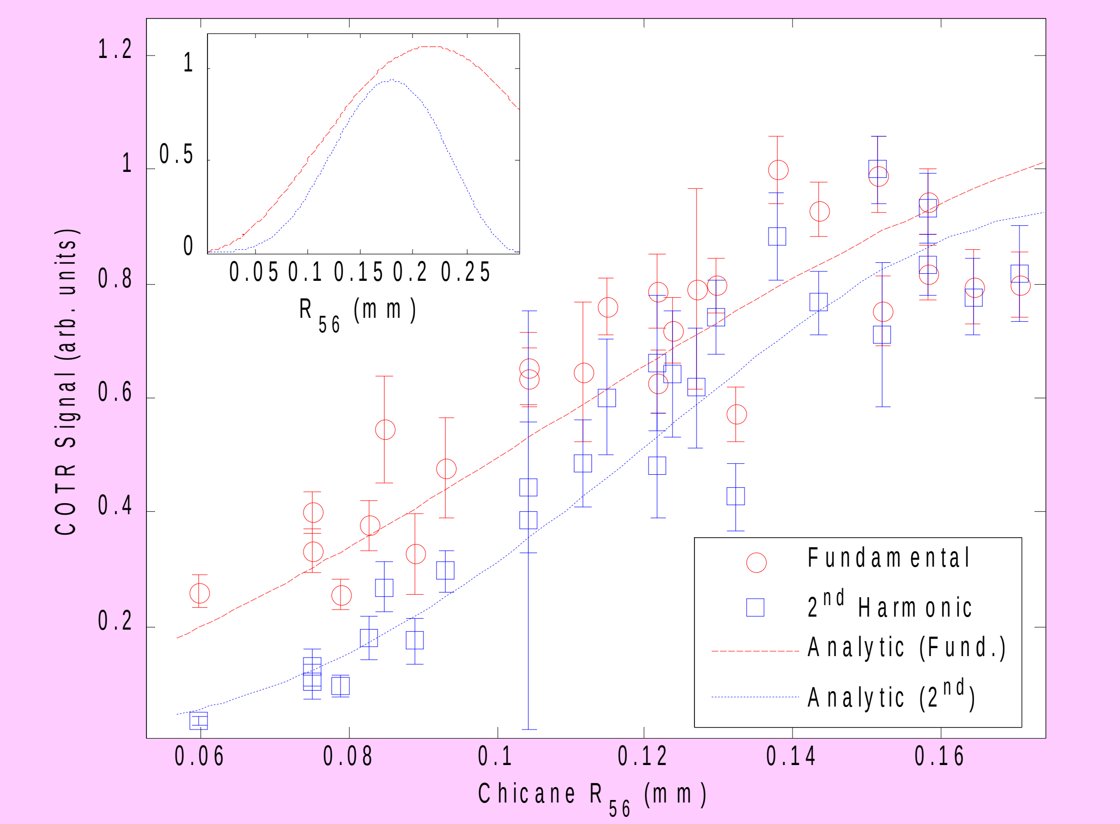
- Janice Nelson, Doug McCormick, Justin May, Tonee Smith, Keith Jobe, and Richard Swent
- Zach Wolf, Scott Anderson, & rest of magnetic measurement group
- Denise Larsen, Mike Racine, & Roger Carr

Additional slides

Varying the Chicane Strength

- Many small runs of ~400events, 1 chicane value per run
- Each point on graph is obtained by fitting a Gaussian through the cross-correlation. Error from boot-strap method
- Data taken over 1+ hours during which charge & interaction drifted

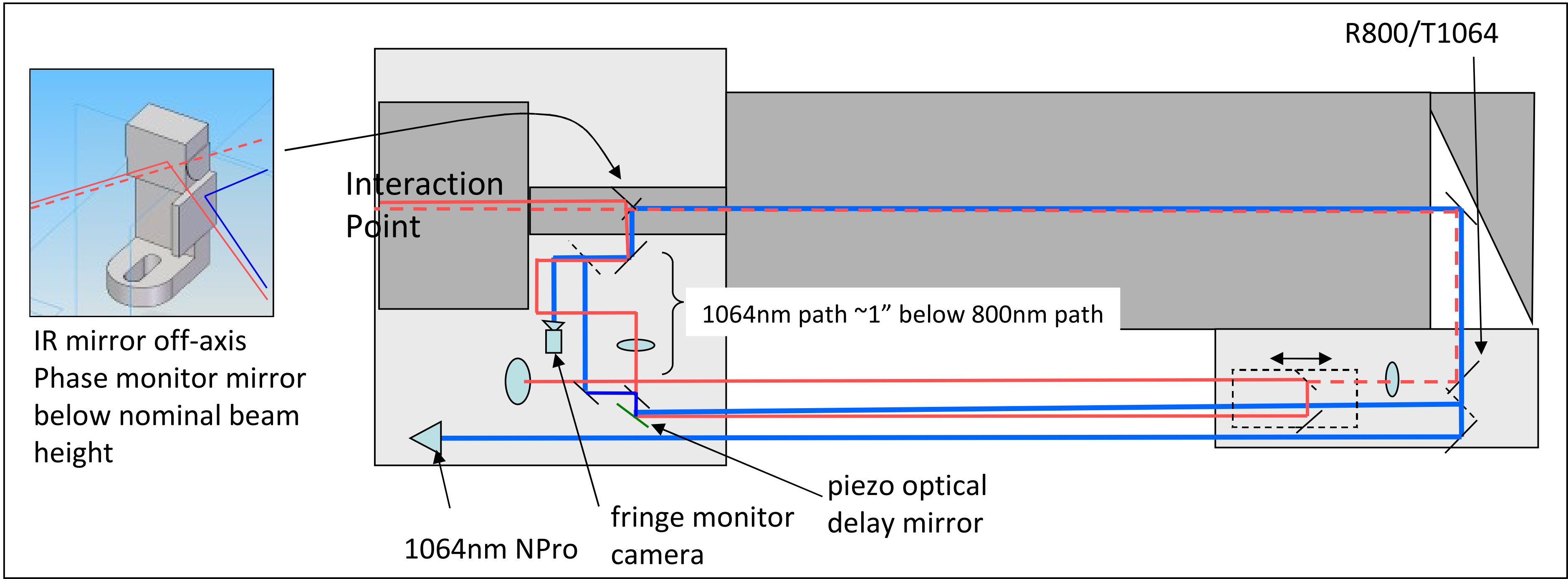




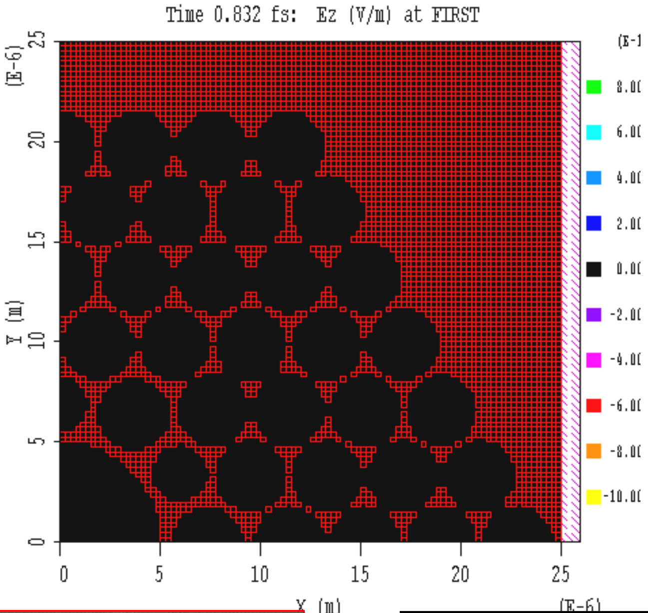
- both harmonics show saturation at lower value that analytic
  - some electrons modulated more strongly & therefore are overbunching → less COTR
- important to independently measure optimum R_{56} rather than rely solely on the analytic!

Phase Stability, monitoring & Control

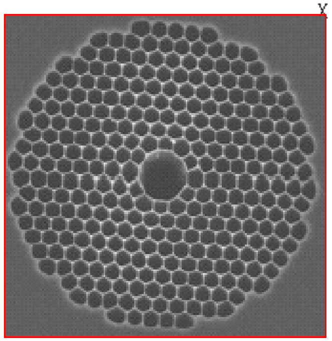
- Net acceleration experiment = large interferometer
  - e-beam communicates optical phase between IFEL & ITR
- Noise reduction: 1” optical posts, isolation for pumps & chiller, covers for optical tables



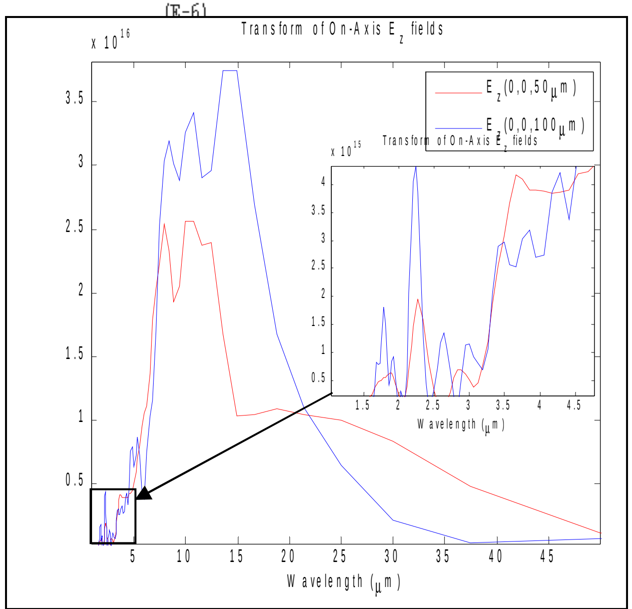
3D Case: Resonant Wakefield in a Photonic Bandgap fiber

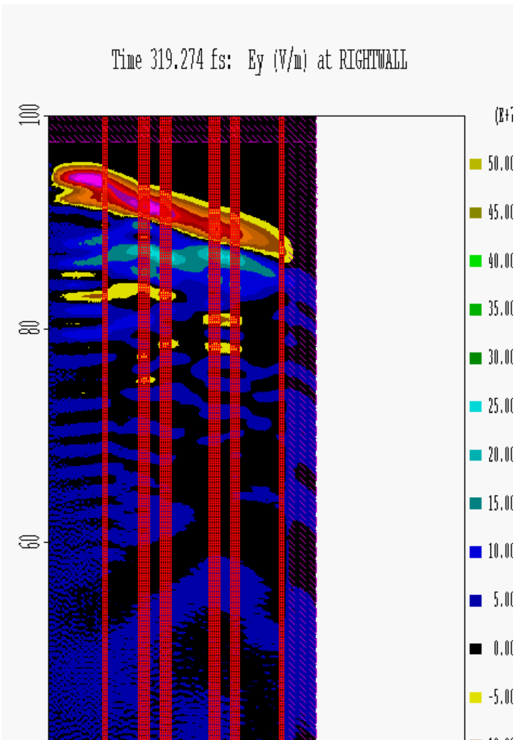


- Simulated Fiber similar to commercially available fiber
- Short pulse to see induced wakefield, real experiment would rely on incoherent excitation from long pulse
- Observe with spectrometer to infer SOL modes



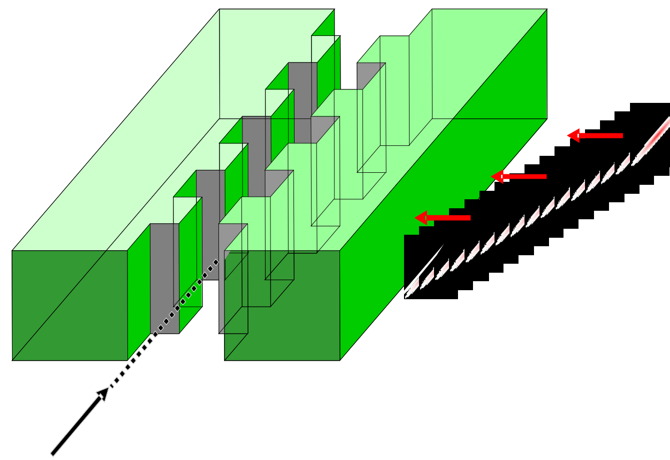
Thorlabs HC-1550-2





Planar Accelerator Structures

- Type 1
  - no propogating waveguide mode
  - laser energy propogates transverse to ebeam
- Type 2
  - more traditional waveguide
  - light coupled in by grating on inner surface of waveguide



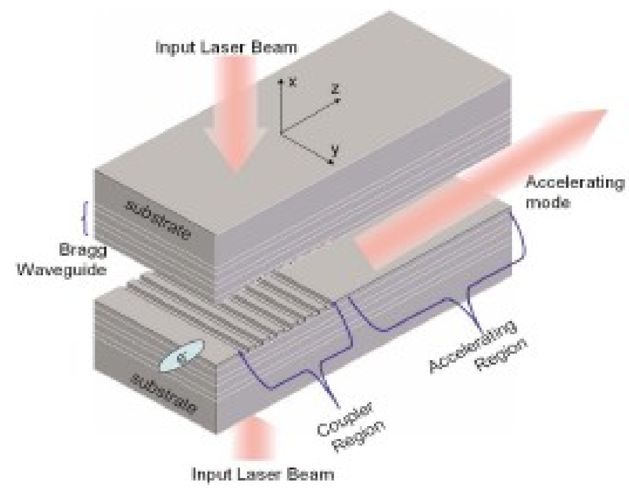


FIG. 1. (Color) Schematic diagram of a planar accelerator structure with distributed grating-assisted coupler (DGAC).