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Demonstration of Efficient Electron-Radiation Coupling in a 7th Harmonic IFEL Interaction Experiment

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High- order Harmonic FELs For UV and X-ray Production

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Coherent X-Ray Production in a single-pass FELs with a fixed e-beam energy

SLAC LCLS (USA), DESY European XFEL (Germany), and SCSS (Japan)

14 GeV e-beam

Undulator

L~100 m; λ_u=3.3 cm; K=3.7

0.1 nm X-ray Self-Amplified Spontaneous Emission

$$\lambda_{Xray} = \frac{\lambda_u}{2\gamma^2 n}\left(1+\frac{K^2}{2}\right)$$

n=1 fundamental frequency

When K>1

n=3,5,7…high-order FEL resonances

High-Order FEL Interactions are considered both for SASE and seeded cascade FELs

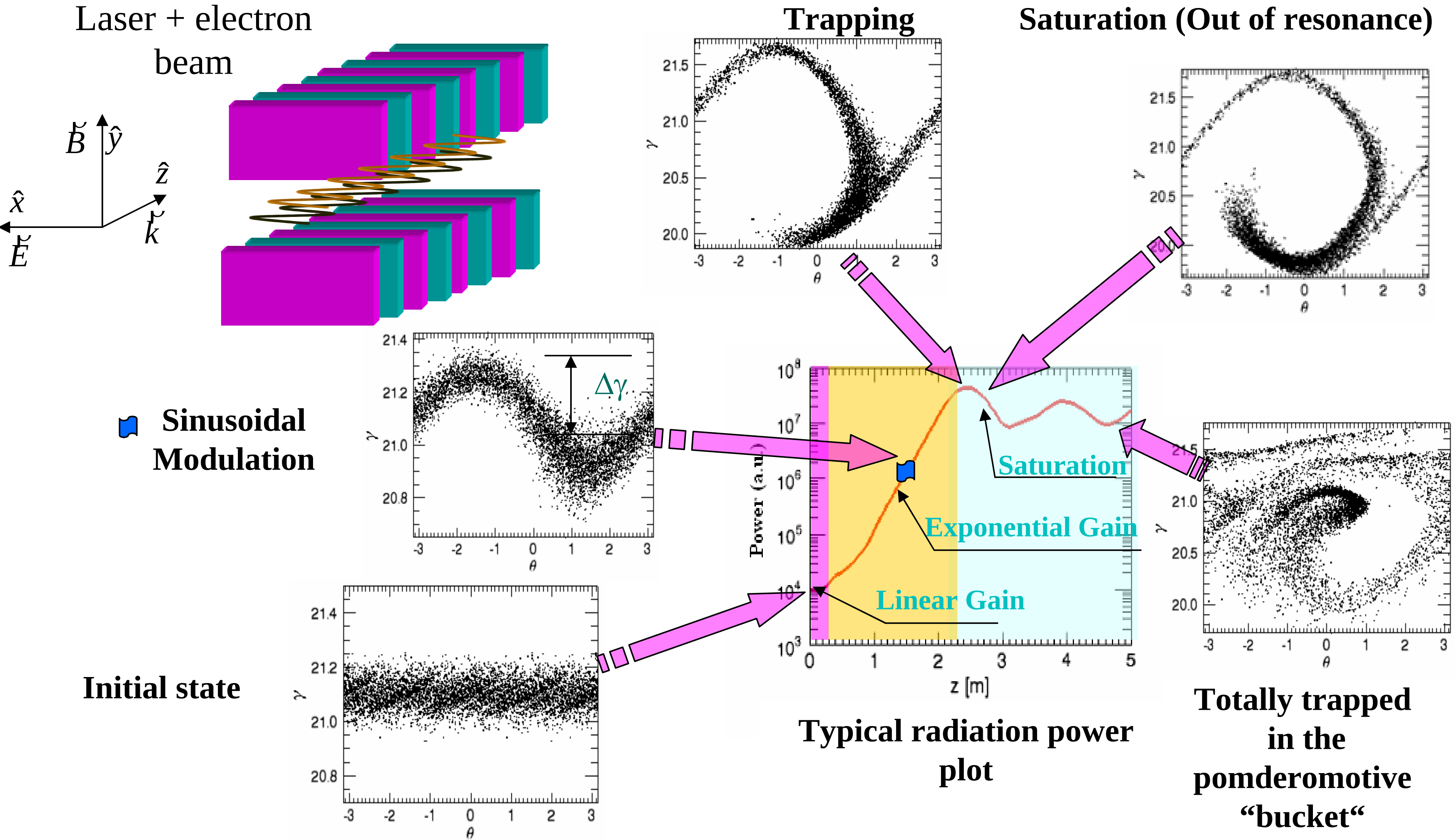
+) nλ choice for the seed

++) γ can be $\sqrt{n}$ smaller

+++) λu can be larger and K

PRL, 96,084801 (2006), New Journal of Physics, 8, 294, (2006).

Seeded FEL/IFEL interactions



Harmonic coupling in an IFEL undulator

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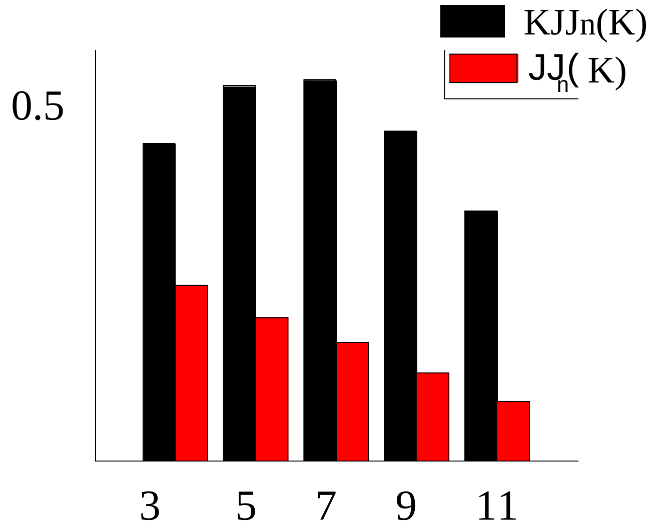
If K≥1, transverse motion is relativistic and spectrum of the undulator radiation gains odd harmonics n=3,5,7 …

$$\lambda_{seed} = \frac{\lambda_u}{2\gamma^2 n}\left(1 + \frac{K^2}{2}\right)$$

Lorentz Force IFEL equations

$$\frac{\partial \gamma}{\partial z} = \frac{k a_0 K}{2\gamma} \sum_n JJ_n \sin(\psi + k_u z(n-1))$$

$$\frac{\partial \psi}{\partial z} = k_u - k \frac{1 + K^2/2 + \gamma^2\theta^2}{2\gamma^2}$$

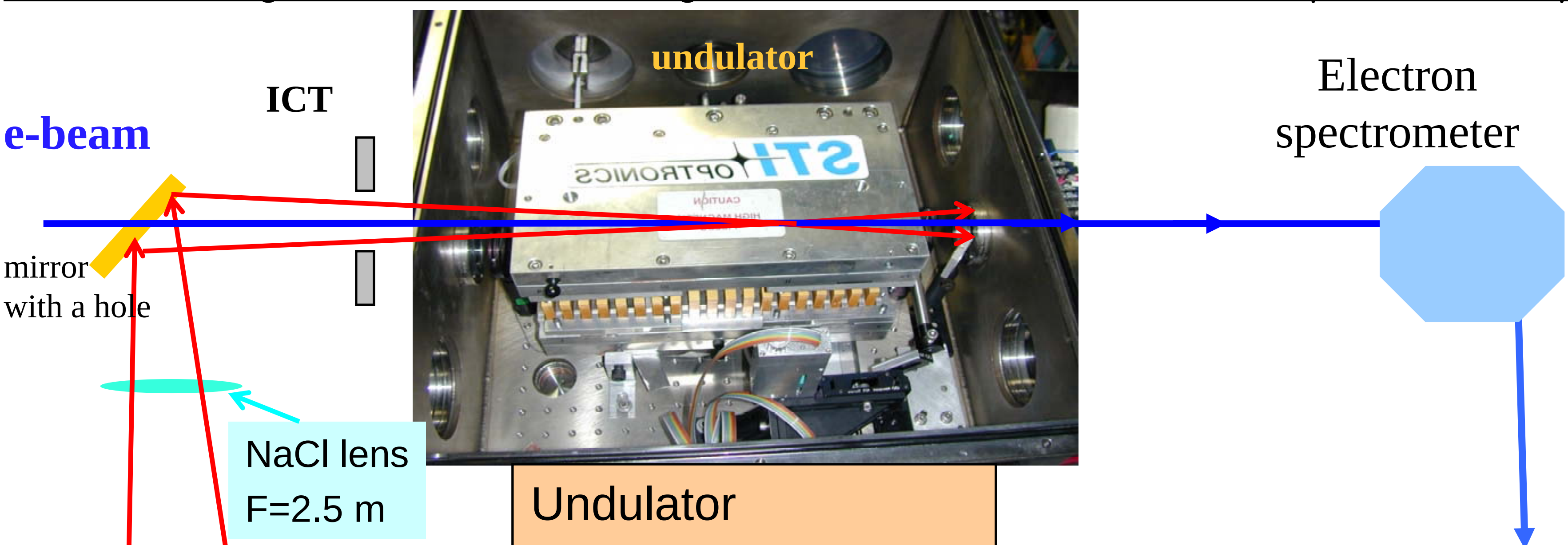


$$\lambda_u = 3.3 cm; K = 1.8$$

UCLA P. Musumeci et al, Phys. Rev. Lett, 94 016501 (2005)
SLAC C.M.S Sears et al, Phys. Rev. Lett, 95, 194801 (2005)

7th order IFEL experiment at the UCLA Neptune Laboratory

<u>Microbunching in the undulator using 7th order IFEL interactions10.6 μm x 7=74.2 μm</u>



Undulator

L=33 cm; λ_u=3.3 cm

K=1.8

CO_2 Laser

1 Hz PRF

P= 40 MW

4mJ, 100 ps

Electron beam

E=12.4 MeV

ε=6 mm x mrad

C~500 pC

<u>Gaussian Laser beam</u>

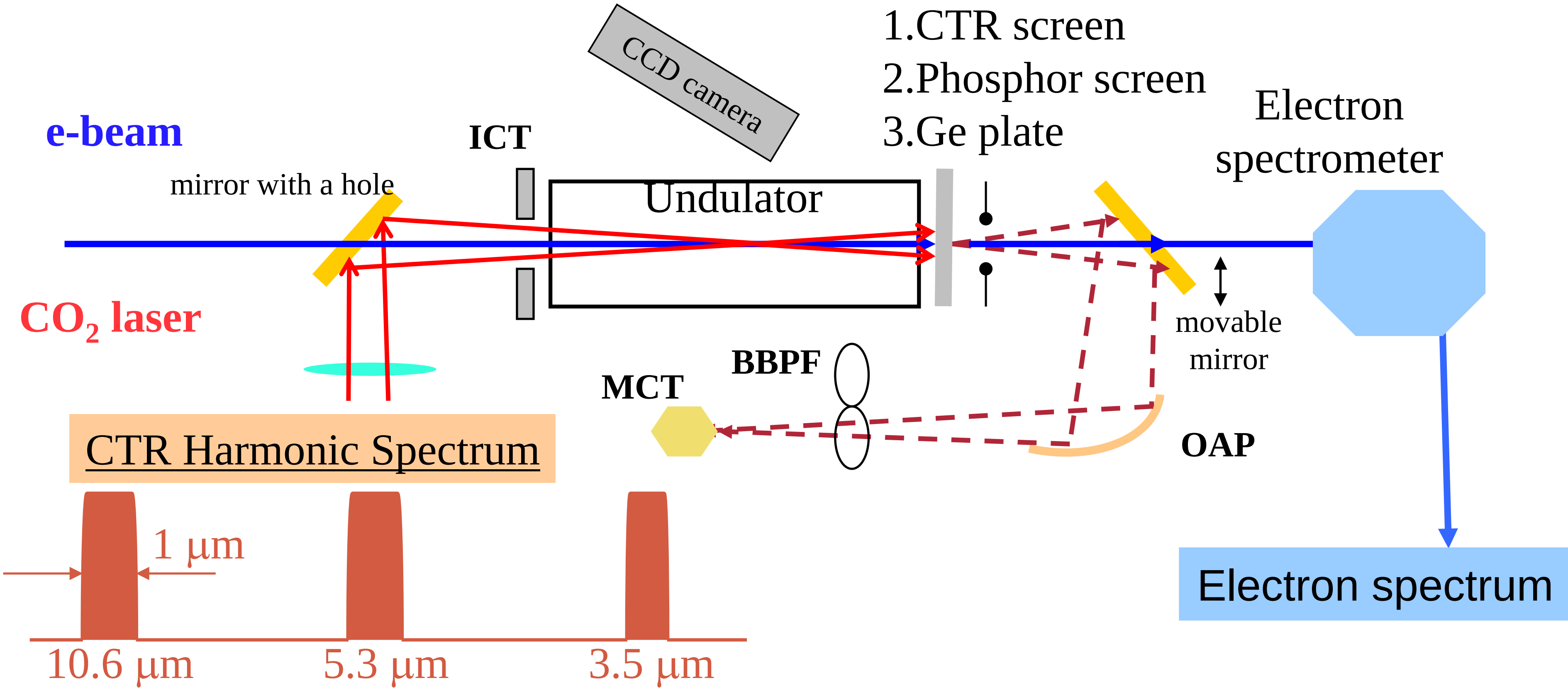
F/100 focusing provides w_0=700 μm

Z_R=14.5 cm; $L_{undulator}$~ $2Z_R$

With 20 MW of power I~1 GW/cm^2

CTR Diagnostic for Bunched Beam

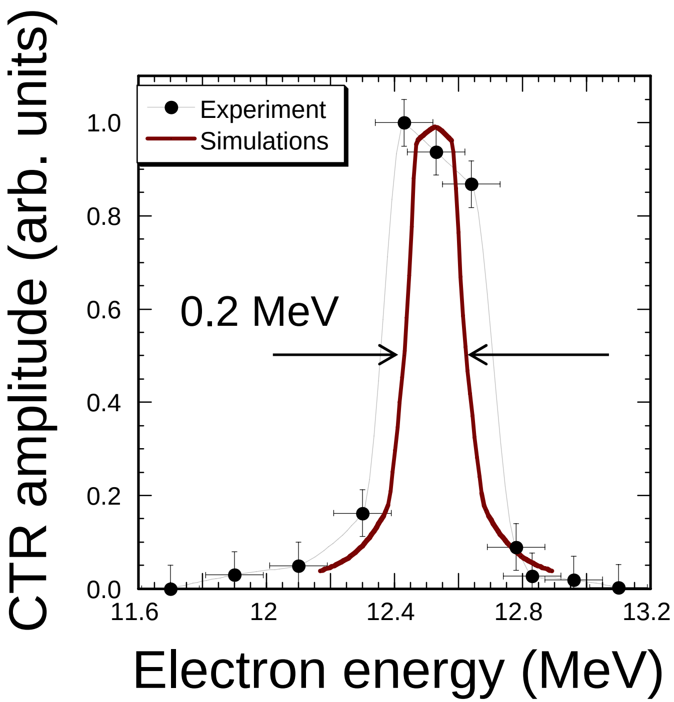
Microbunching on fundamental λ$_{mb}$~10.6 μm, 2nd-λ$_{mb}$~5.3 μm and 3rd-λ$_{mb}$~3.5 μm harmonics

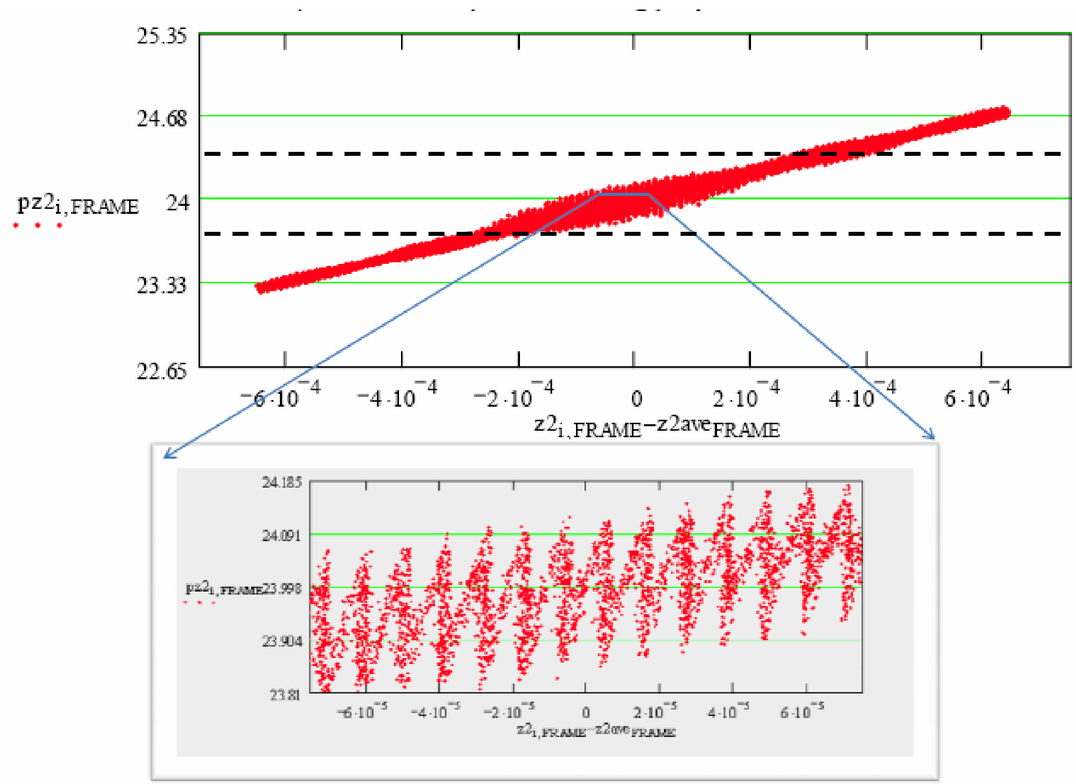


A set of BBP filters provides an adequate determination of harmonic content.
Background is down to ~0.5 pJ, the S/N ratio is 200-2.

Resonant Condition for 7th order IFEL

A correlated rms energy spread is 0.7% measured with and without the undulator

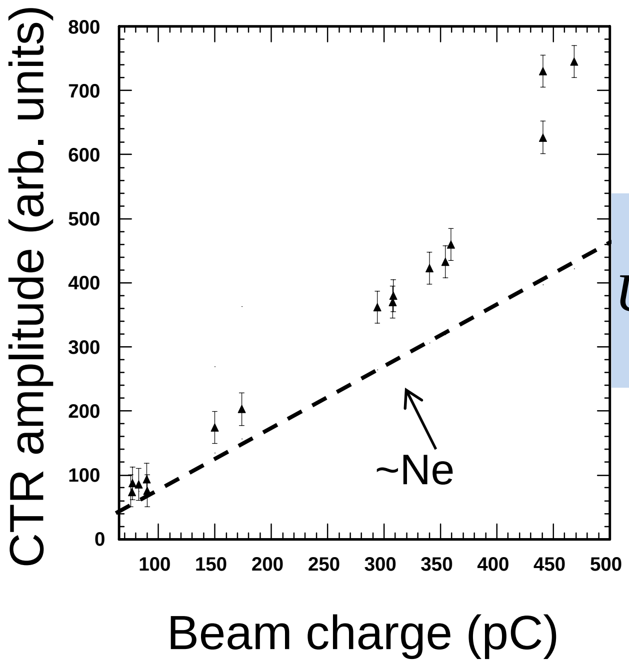




A slice of the beam over which the IFEL interactions take place is 100μm (~300 fs), results in effective energy spread of 0.02% and provides microbunching of almost the whole beam or part of the beam at a detuned energy.

CTR scaling

The CTR signal on fundamental versus the charge and the spot size on the screen.

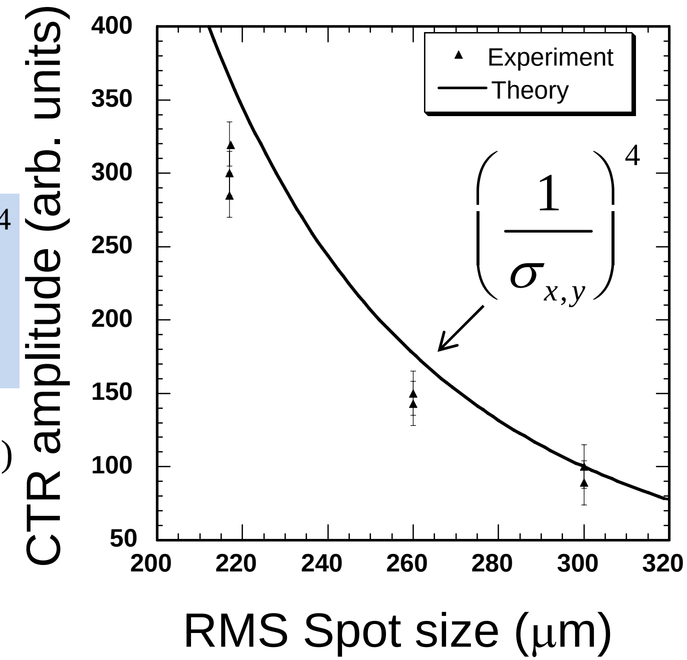


Normal incidence

Forward CTR:

$$U_h \approx \frac{N^2 e^2 b_h^2}{4\sqrt{\pi}\sigma_z}\left(\frac{\gamma}{hk_r}\right)^4\left(\frac{1}{\sigma_{x,y}}\right)^4$$

A. Tremaine, PRL 81,5816(1998)



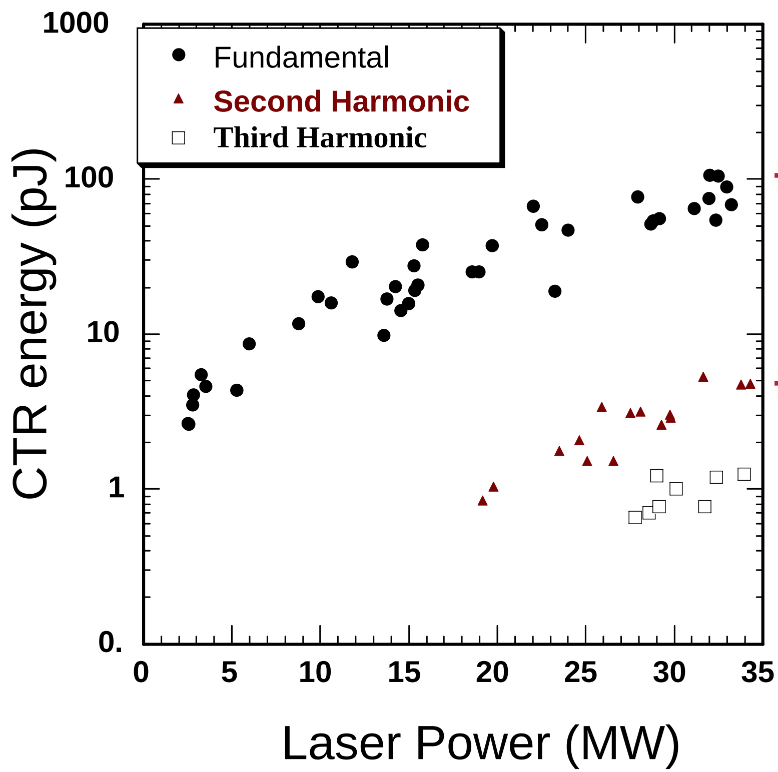
Clear nonlinear CTR signal increase versus charge was observed.

Strong $(1/\sigma_{x,y})^4$ scaling is very close to one observed in the experiment.

Harmonics of the Bunched Beam

Microbunching on fundamental λ_{mb}~10.6 μm, 2nd-λ_{mb}~5.3 μm and 3rd-λ_{mb}~3.5 μm harmonics.

$$\frac{U_1}{U_h} \approx \frac{N_1^2 b_1^2}{N_h^2 b_h^2}(h)^4$$



$$\frac{U_1}{U_2} \approx 17$$

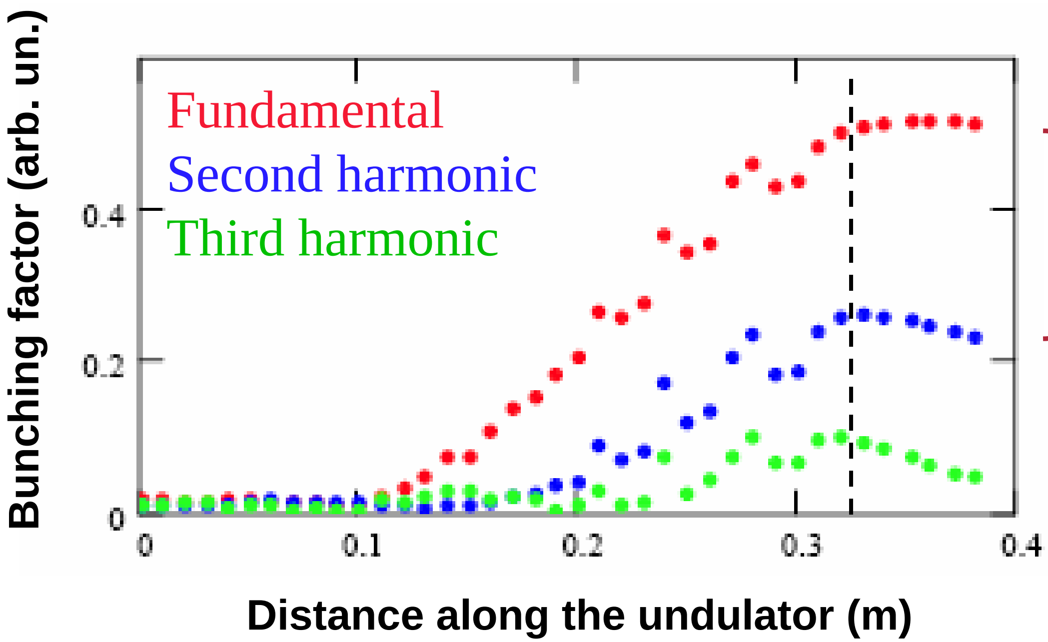
$$\frac{U_1}{U_3} \approx 70$$

Experimentally achieved coupling efficiency is comparable to that for n=1 case!

See S.Ya. Tochitsky et al., Phys. Rev. STAB 12, 050403 (2009).

3D Simulations of a Bunched Beam

TREDI simulations for laser power 35 MW, w_0=600 μm and σ_{rms}=400 μm



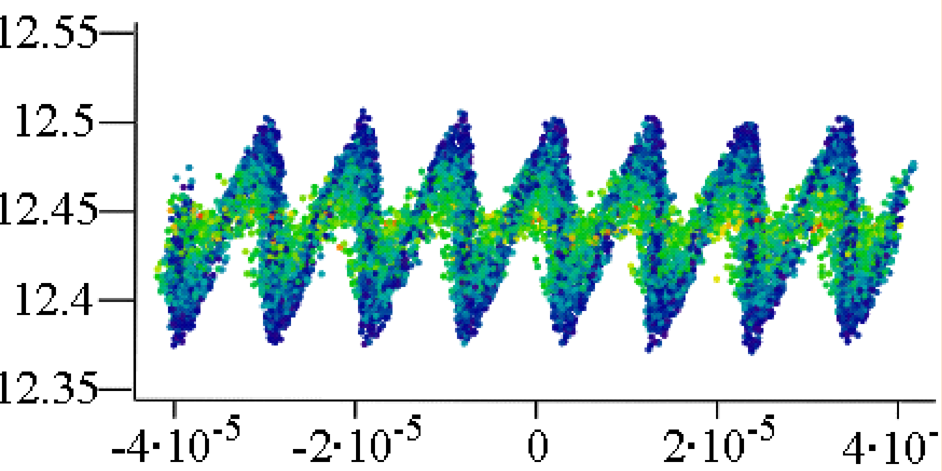
$$\frac{b_1}{b_2} \approx 2 \qquad \frac{b_1}{b_3} \approx 4$$

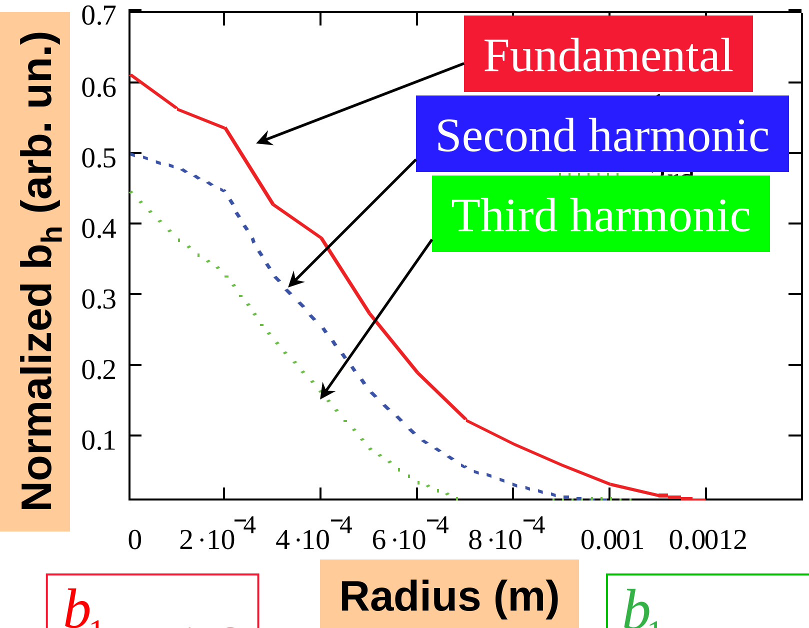
$$\frac{U_1}{U_h} \approx \frac{b_1^2}{b_h^2}(h)^4$$

The harmonic ratios extracted from simulations U1/U2=64 and U1/U3=2025 are grossly off the measured values.

Transverse effects in bunched beam

TREDI simulations for laser power 35 MW, w_0=600 μm and σ_{rms}=400 μm





$$\frac{U_1}{U_h} \approx \frac{N_1^2 b_1^2}{N_h^2 b_h^2}(h)^4$$

$$\frac{b_1}{b_2} \approx 1.2$$

$$\frac{b_1}{b_3} \approx 1.33$$

The e-beam is bunched stronger on axis and the effective beam size are smaller for higher harmonics $\sigma_{x,y}$=380 μm; 2nd $\sigma_{x,y}$=335 μm; 3rd $\sigma_{x,y}$=295 μm, then for this effective beams harmonic ratios U1/U2=14 and U1/U3=53.

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Summary

1) We report efficient coupling between the relativistic electrons and seed radiation in a 7th harmonic IFEL interaction.

2) We experimentally characterized the strength of this high-order IFEL interactions by analyzing a fundamental, the second and the third harmonics of a microbunched beam in CTR spectrum.

3) Comparison between the measurements and 3D simulations revealed that for a seeded IFEL/FELs there is a difference in transverse bunching on different harmonics which may play an important role on the CTR spectrum.

4) Inclusion of the high-order IFEL/FEL interactions ($n \geq 3$) on equal footage with the regular ones adds flexibility in designing undulator based systems.

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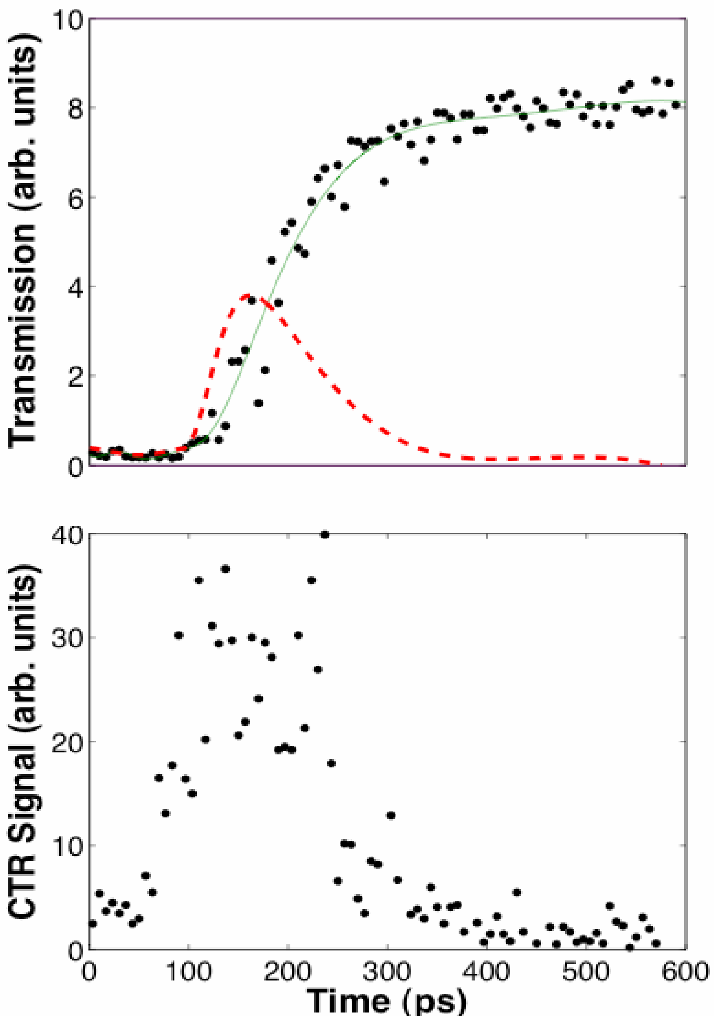
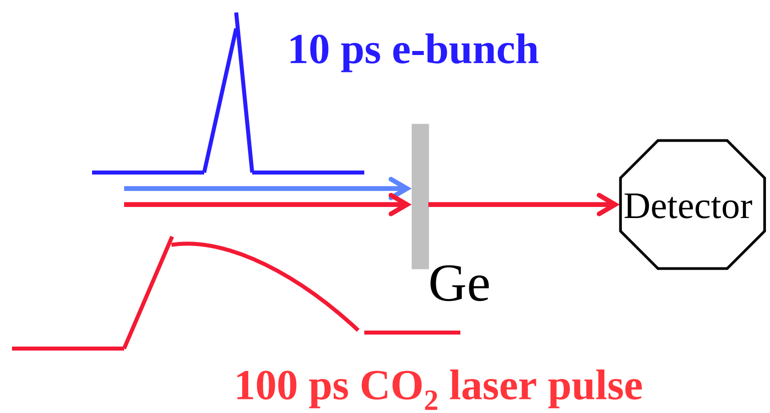
Synchronization of e-beam and 10μm pulse on a picosecond scale

<u>Cross-correlation between 10 μm laser pulse and electrons in Ge slab and Al foil</u>



E–beam induced carrier generation in Ge

$$\frac{dN}{dt} = -\alpha N + \frac{\beta J(t)}{e}, \beta is cros sec tion$$



Accuracy of synchronization is limited by

10 ps bunch length e-beam duration

Transition Radiation as a Diagnostic for Bunched Beam

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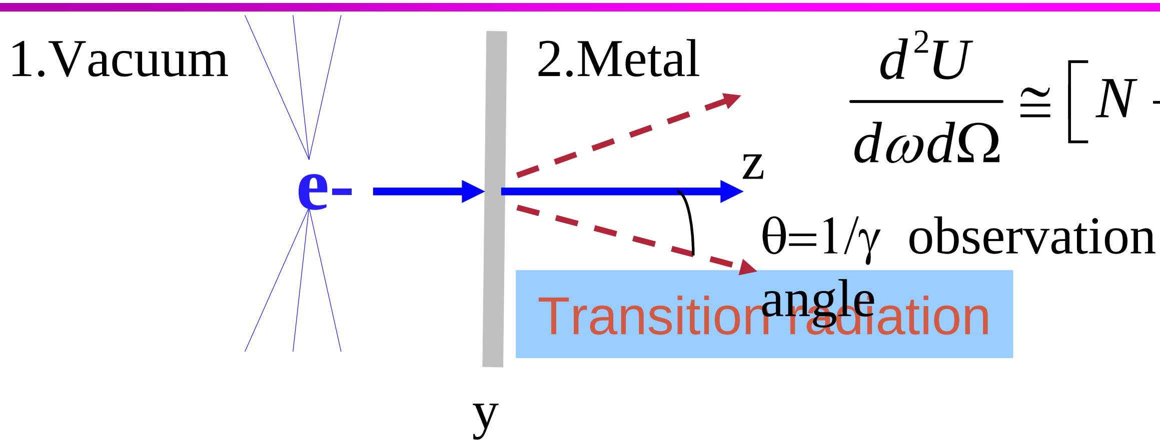
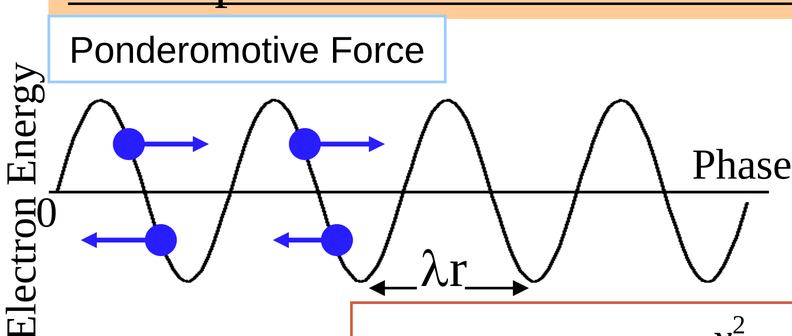


$$\frac{d^2U}{d\omega d\Omega} \cong \left[N + N^2 F_{Long}(\omega) F_{Trans}(\omega) \right] \frac{d^2U}{d\omega d\Omega}\bigg|_{1e}$$

Fourier transform of the e-beam profiles

CTR Spectrum of a Microbunched beam



E-beam charge

$$\rho(x,y,z) = \frac{eN \exp\left(-\frac{x^2}{2\sigma_x^2} - \frac{y^2}{2\sigma_y^2} - \frac{z^2}{2\sigma_z^2}\right)}{(2\pi)^{3/2}\sigma_x\sigma_y\sigma_z} \times \left[1 + \sum_{n=1}^{\infty} b_h \cos(hk_r z)\right]$$

h- Harmonics in CTR spectrum

Since the beam has has Fourier components at k_r and its harmonics, the CTR spectrum