High Brightness X-to-γ-Ray Production Using Betatron Radiation

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Collaboration

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Institutions: UCLA Dept. of Physics and Astronomy, SLAC, Univ. Strathclyde/Univ. Hamburg, RadiaBeam Tech/RadiaSoft, Ecole Polytechnique

Betatron oscillations in the PWFA blowout regime

- Very high gradient *ion focusing* in PWFA accompanies EM acceleration
- Due to blowout rarefaction of e^-s
- Gradient proportional to density

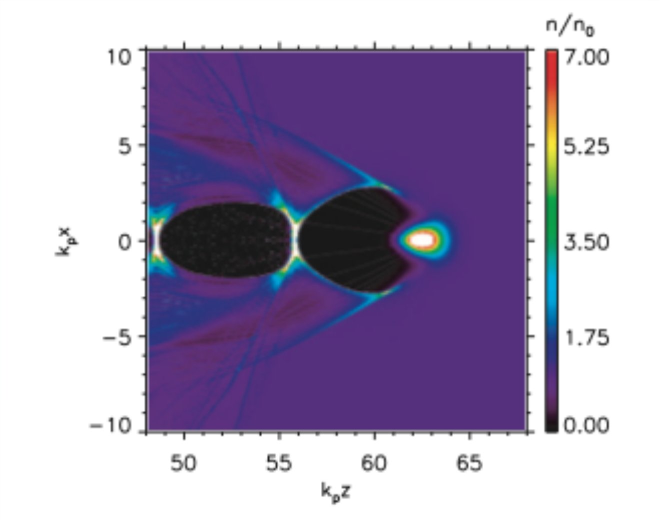
$$qE_r = -2\pi e^2 n_0 r$$

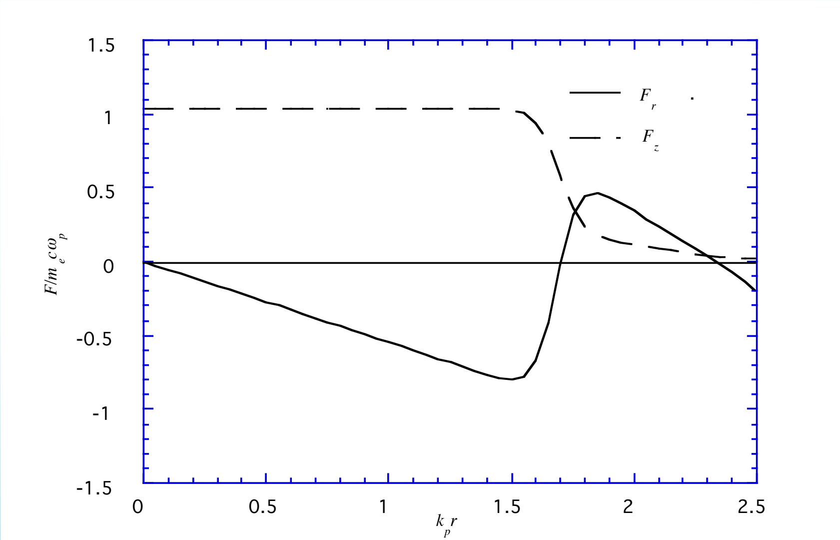
- Sinusoidal oscillations, short

$$\lambda_\beta = \lambda_p \sqrt{2\gamma}$$

For 10^{17}/cc plasma, 1 GeV e-beam

$$\lambda_\beta = 4\ \mathrm{mm}$$





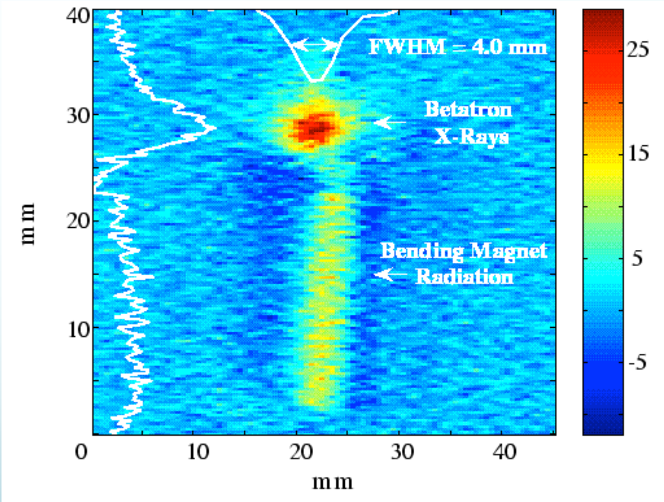
Betratron radiation

- Undulator-like radiation emitted in ion channel
- Effective *K* parameter proportional to can be very large; with offset $x_{\max}=k_p^{-1,}$ we have

$$\left\| F_{r,\max} \right\| \cong k_p m_e c^2$$

- This is *wavebreaking* amplitude field
- Example: for 10^{17}/cc plasma

$$F_{r,\max} \cong 100 \text{ GV/m, equivalent to 3000 T}$$



FFTB besed betatron radiation

The role of amplitude

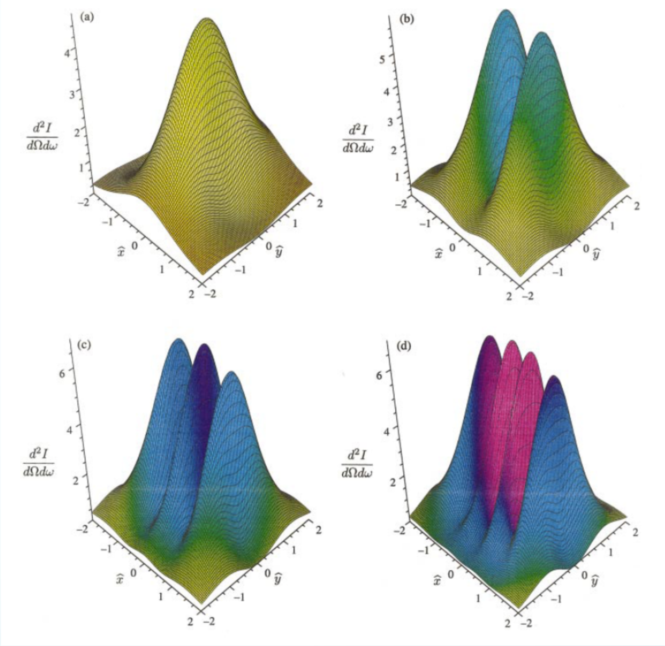
- For very high field, at cm wavelength, *K*>>1
- Radiation flux *increases* as K^2
- Wavelength is redshifted

$$\lambda_r \cong \frac{\lambda_\beta}{2\gamma^2}\left[1+\frac{K^2}{2}\right]$$

  - Limits utility of *ion channel laser*

  D. Whittum, A. Sessle, and J. Dawson *Phys. Rev. Lett.* **64**, p. 2511, 1990

- Many harmonics at high *K*
- For high quality beam, amplitude is naturally small



First 4 harmonics in large K case (Esarey et al.)

Coherent oscillations

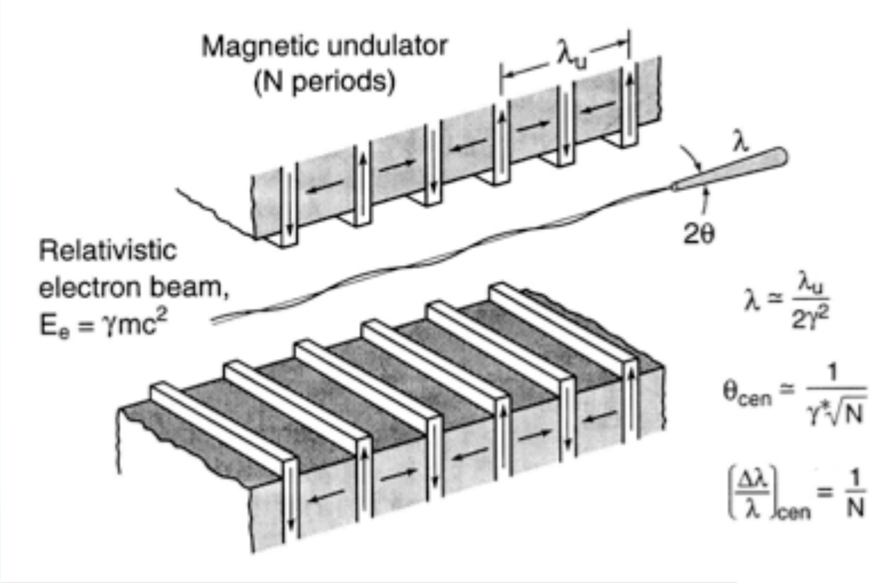
- Want to exploit possible enormous *K* undulators
- Possible solution: place entire beam into oscillation within ion channel
  - Radiation dynamics examined by Ersfeld, et al.

B. Ersfeld, et al, Proc. of SPIE Vol. 8075, 80750Q (2011 SPIE)

  - "SASE ICL" proposed and analyzed; beam excitation not proposed
- How to excite large amplitude?
  - External injection (FACET II, Case (c))
  - Far off-axis injection, e.g. with Trojan Horse (problems with birth/acceleration/focusing interaction
  - **Resonant excitation with undulator**

Resonant excitation of betatron oscillations with undulator

- Superimpose undulator field and PWFA interaction



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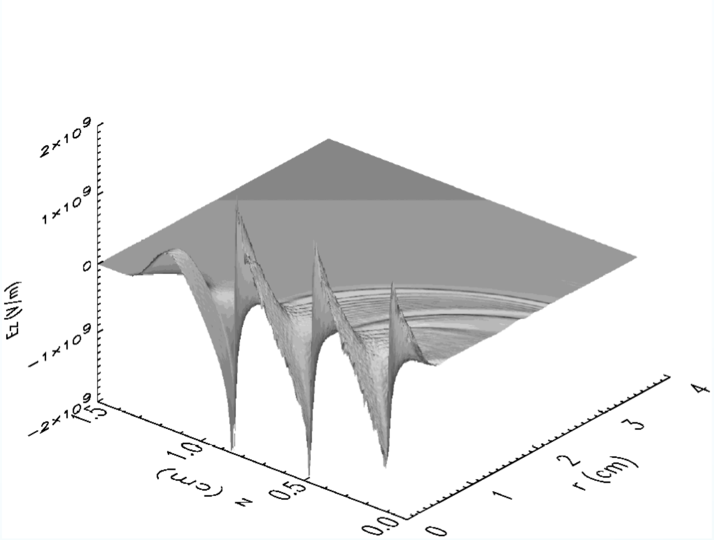


=?

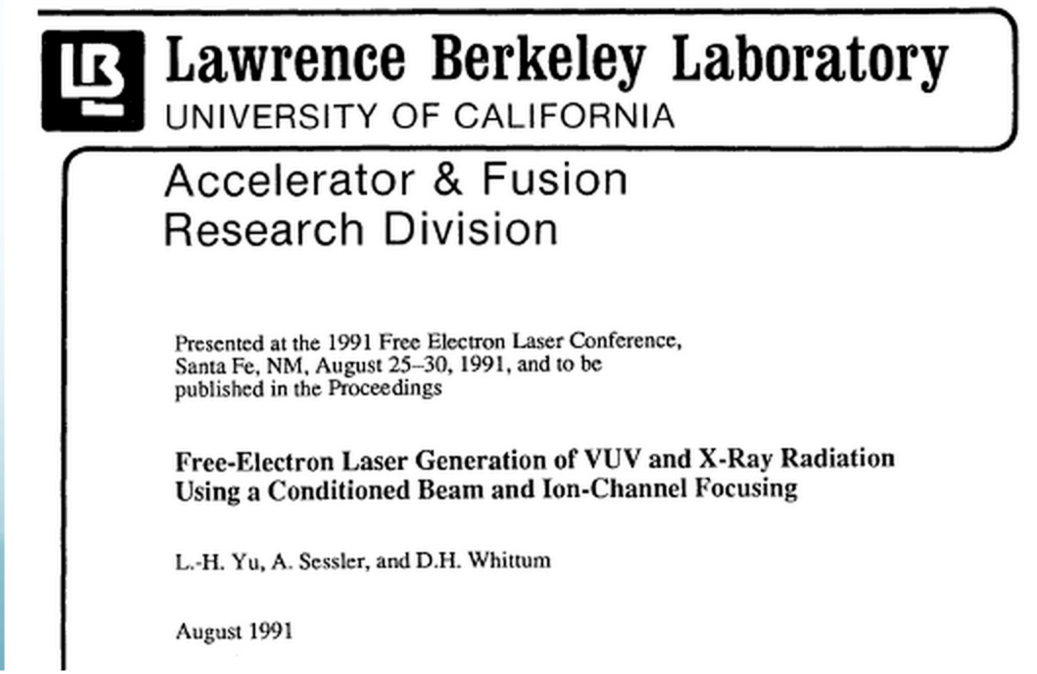
- Simple resonance condition:

$$\lambda_\beta = \lambda_u$$

- **Does magnetic field affect plasma response? Conversely, is there a diamagnetic effect from plasma?**

Not the first time ion focusing has been used in FEL context

- Ion focused regime used to increase beam density in high power microwave FEL
- Context for *beam conditioning* proposal
- *Assumed* that B field and plasma response do not disturb each other, examined lasing dynamics



Lawrence Berkeley Laboratory
UNIVERSITY OF CALIFORNIA

Accelerator & Fusion
Research Division

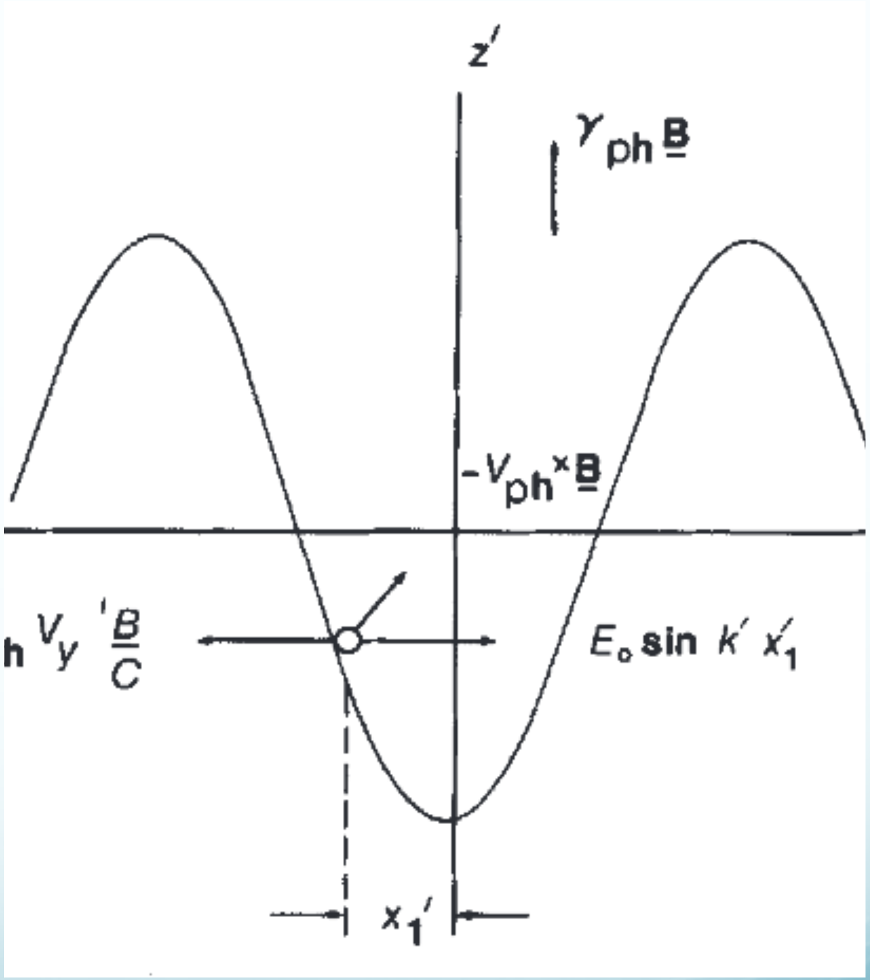
Presented at the 1991 Free Electron Laser Conference,
Santa Fe, NM, August 25–30, 1991, and to be
published in the Proceedings

Free-Electron Laser Generation of VUV and X-Ray Radiation
Using a Conditioned Beam and Ion-Channel Focusing

L.-H. Yu, A. Sessler, and D.H. Whittum

August 1991

Also relevant in advanced accelerators: surfatron idea



B-field pushes particle across phase front
Longitudinal dynamics "locked"

How does betatron undulator resonance work?

- Undamped simple harmonic oscillator (ion focusing) driven (undulator) on resonance. Similar to cavity drive with RF...

- Mathematics:

$$x'' + k_\beta^2 x = \frac{k_u K}{\gamma}\exp\left(ik_u z\right),\ K = \frac{eB_u}{k_u m_e c}$$

With resonant cond'n $k_\beta = k_u$

$$x = -i\frac{K}{\gamma}z\exp\left(ik_u z\right)$$

Response

$$x_u = -i\frac{K}{k_u\gamma}$$

Define natural amplitude of undulator

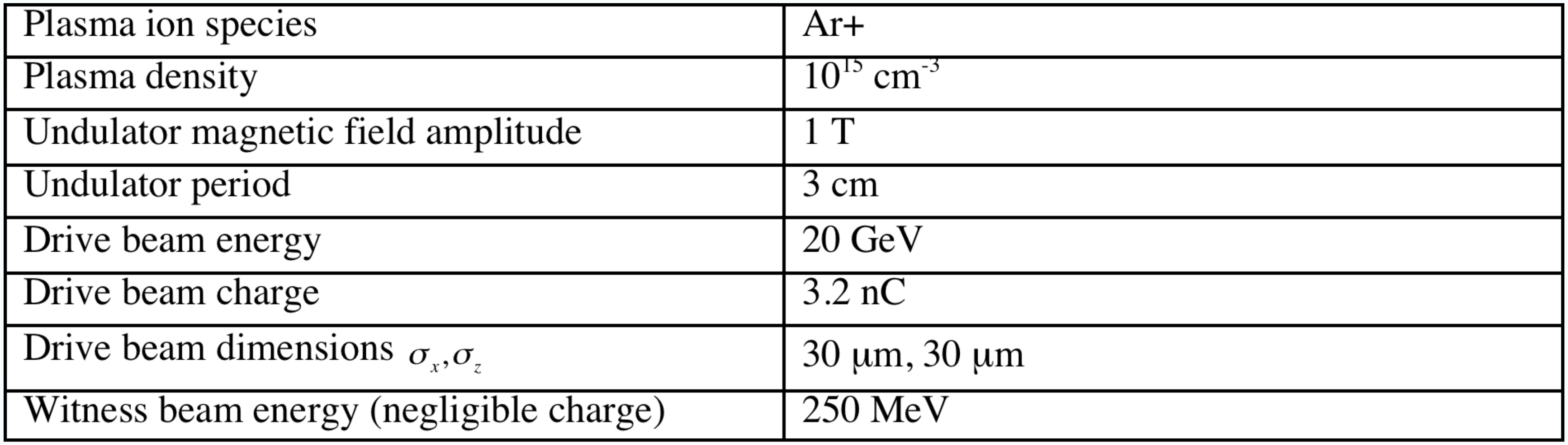
$$x = -ix_u\left(k_u z\right)\exp\left(ik_u z\right)$$

- Motion gains one undulator amplitude per radian of undulator!

N. Majernik and J.B. Rosenzweig, to appear in *NIM*

Exploratory simulation studies

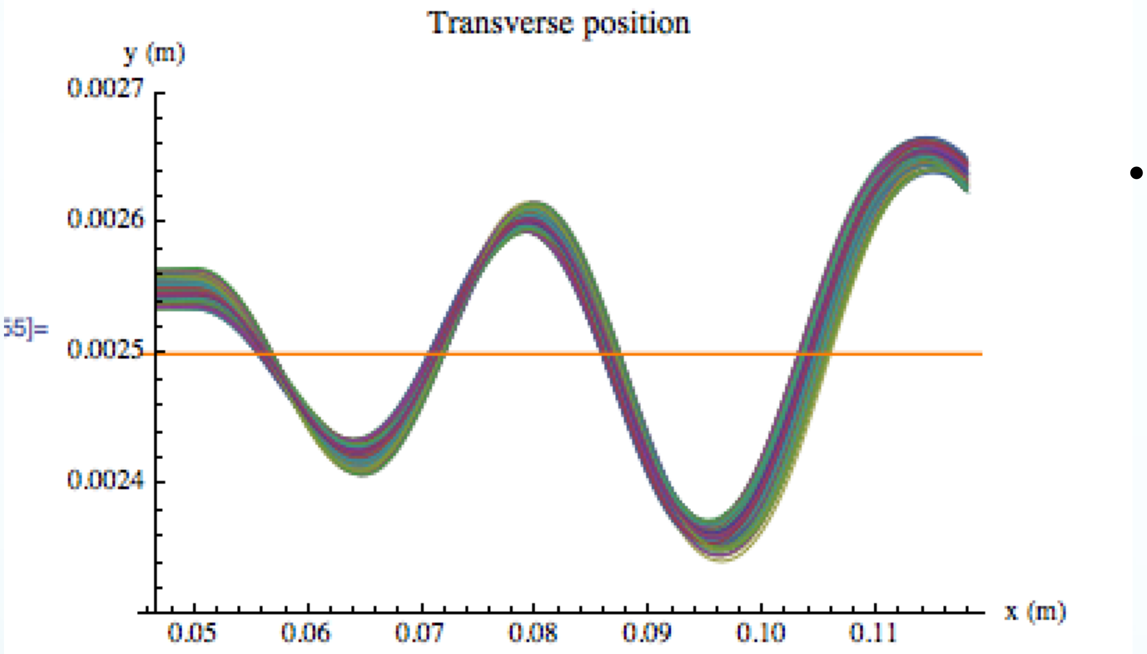
- VORPAL 3D simulations



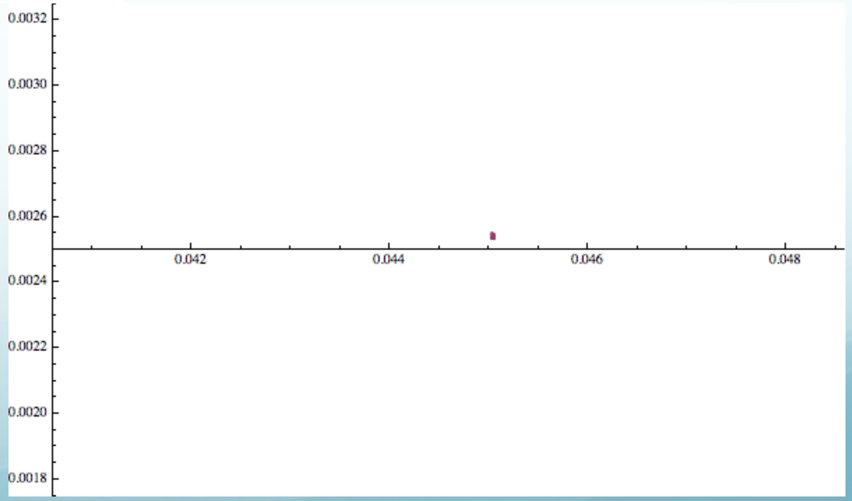
Plasma ion species	Ar+
Plasma density	10^{15} cm^{-3}
Undulator magnetic field amplitude	1 T
Undulator period	3 cm
Drive beam energy	20 GeV
Drive beam charge	3.2 nC
Drive beam dimensions σ_x, σ_z	30 µm, 30 µm
Witness beam energy (negligible charge)	250 MeV

- Examine plasma response in undulator field, simultaneously with beam response to resonant drive
- Note: **drive beam cannot have same energy as witness**, or ion channel center moves in the same way as witness in undulator: no effective resonant drive
  - Trojan Horse injection is perfect

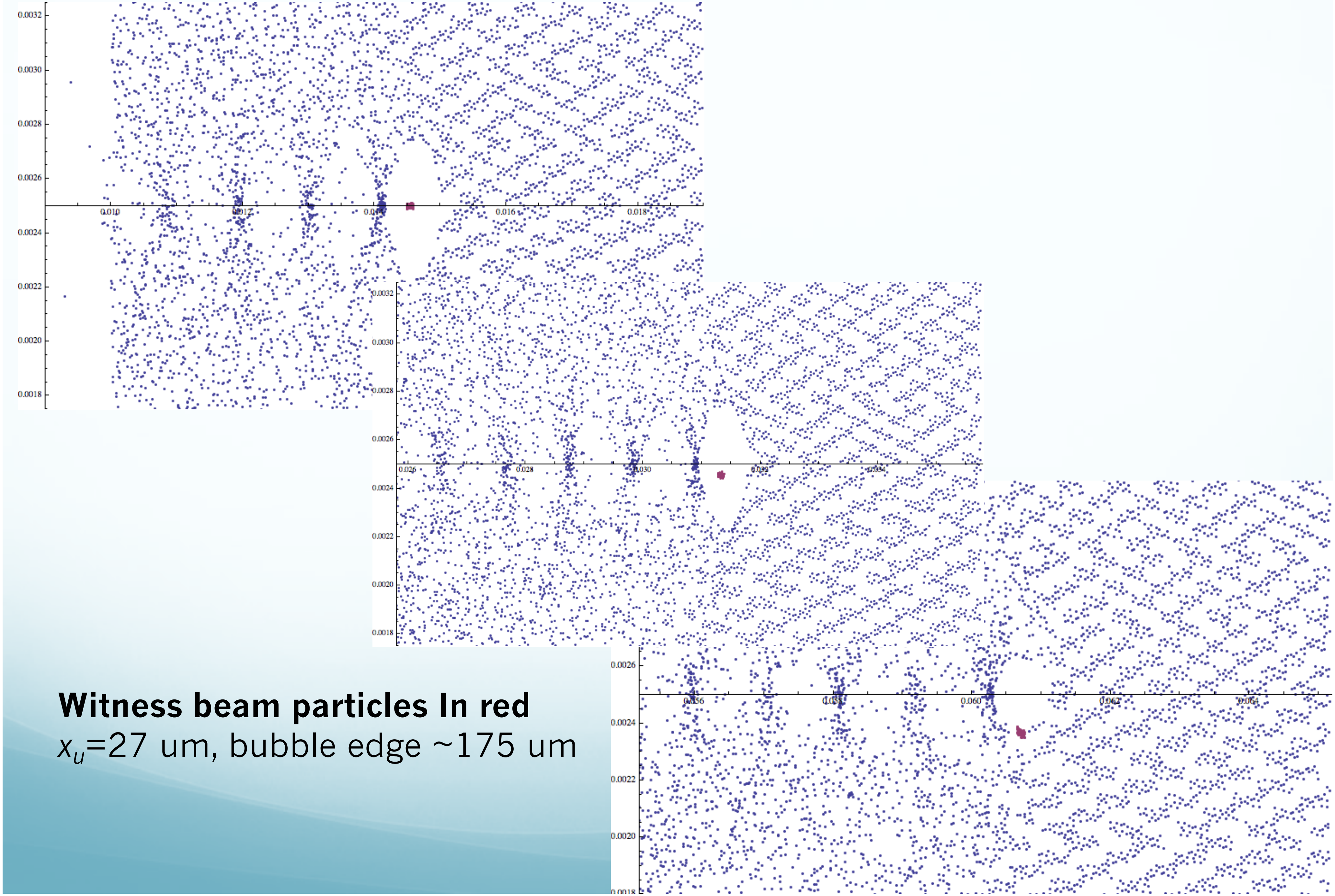
Resonant betatron excitation



- Short undulator resonantly excites betatron amplitude

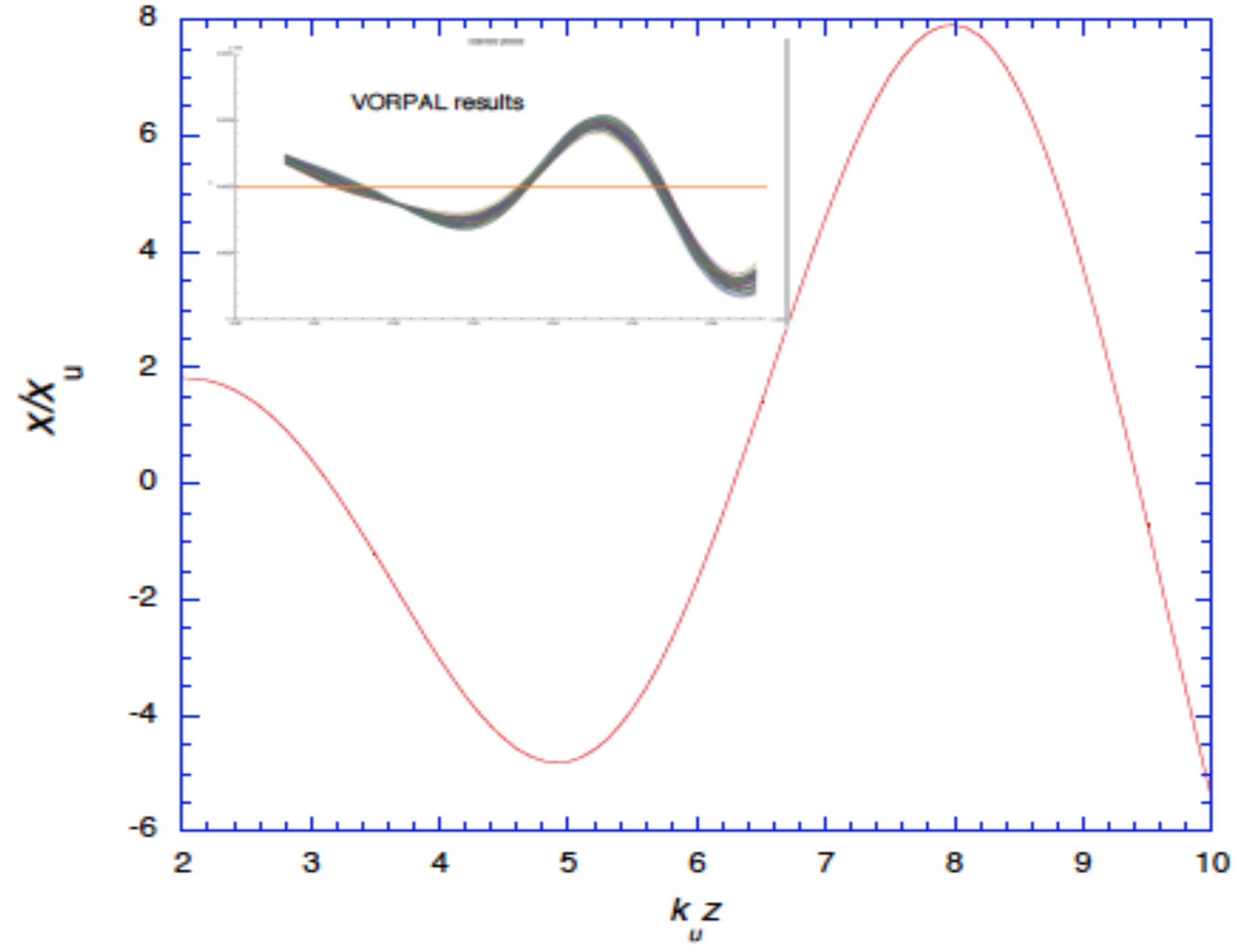


Resonant behavior observed



Witness beam particles In red
x_u=27 um, bubble edge ~175 um

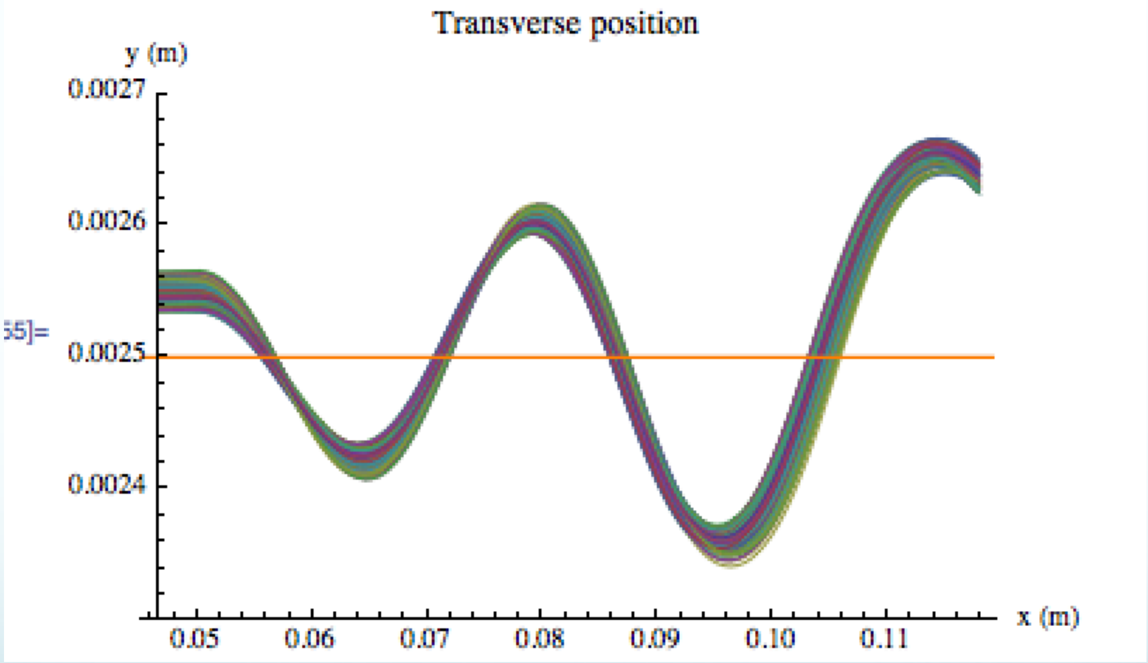
Comparison with model



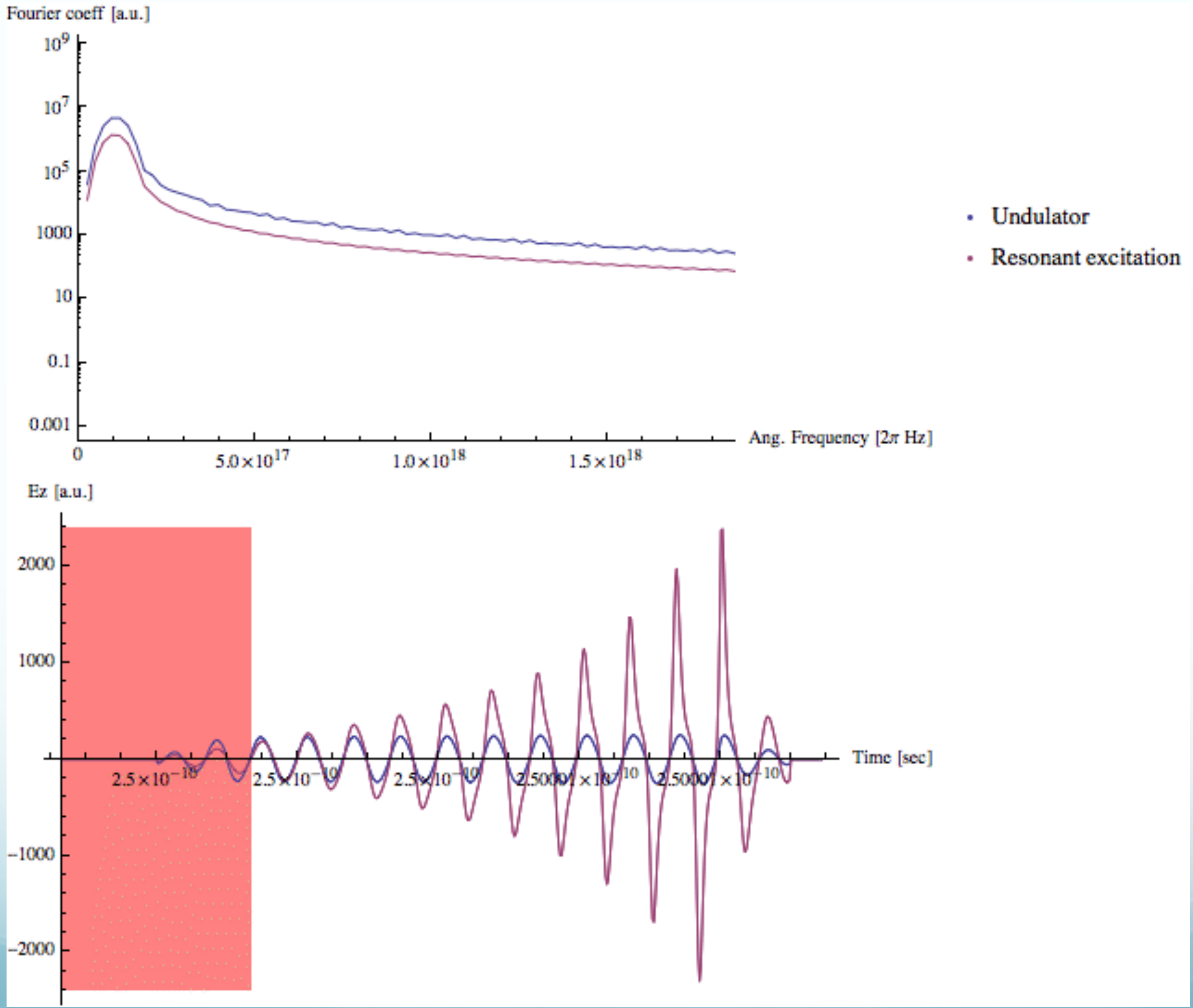
Scheme effective: plasma wake and undulator do not strongly affect each other. Field scales too different -- B is weak perturbation, with small induced diamagnetic effects.

Saturation of amplitude

- Can be due to off-resonant conditions
- In this case we reach the edge of the bubble: resonator detuned.

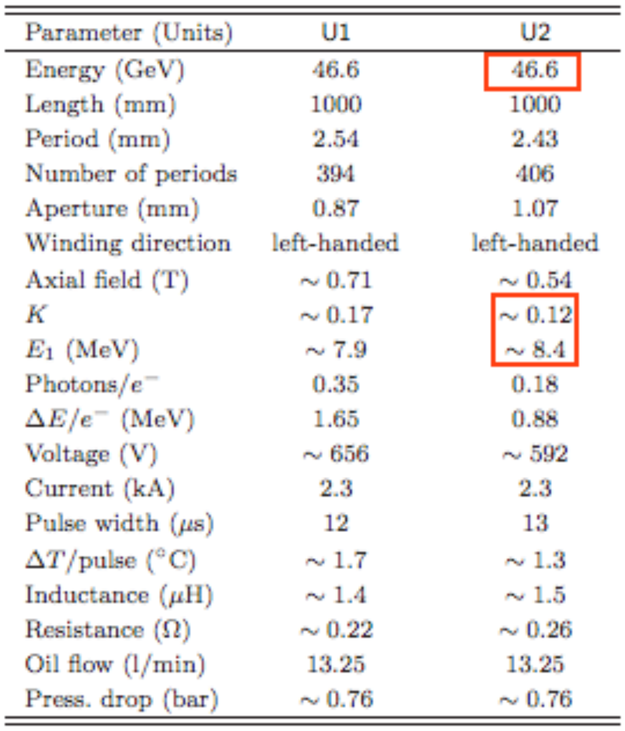


Radiation output enhanced

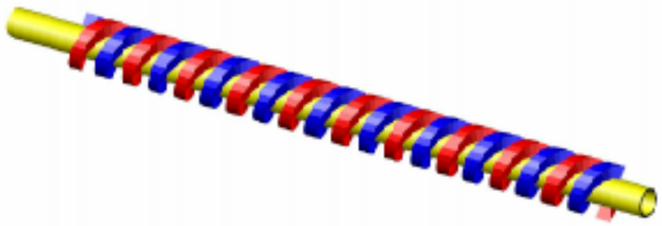


Polarized Positrons

- E166 at FFTB ~47 GeV beam
- Production of 80% polarized positrons
- "Polarized positrons can be produced via the pair-production process initiated by circularly polarized photons … higher intensity beams … than decays from radioactive nuclei"
- **"The value of K in the present experiment was small, about 0.17, because of practical limitations to the current in the (pulsed) undulator."**

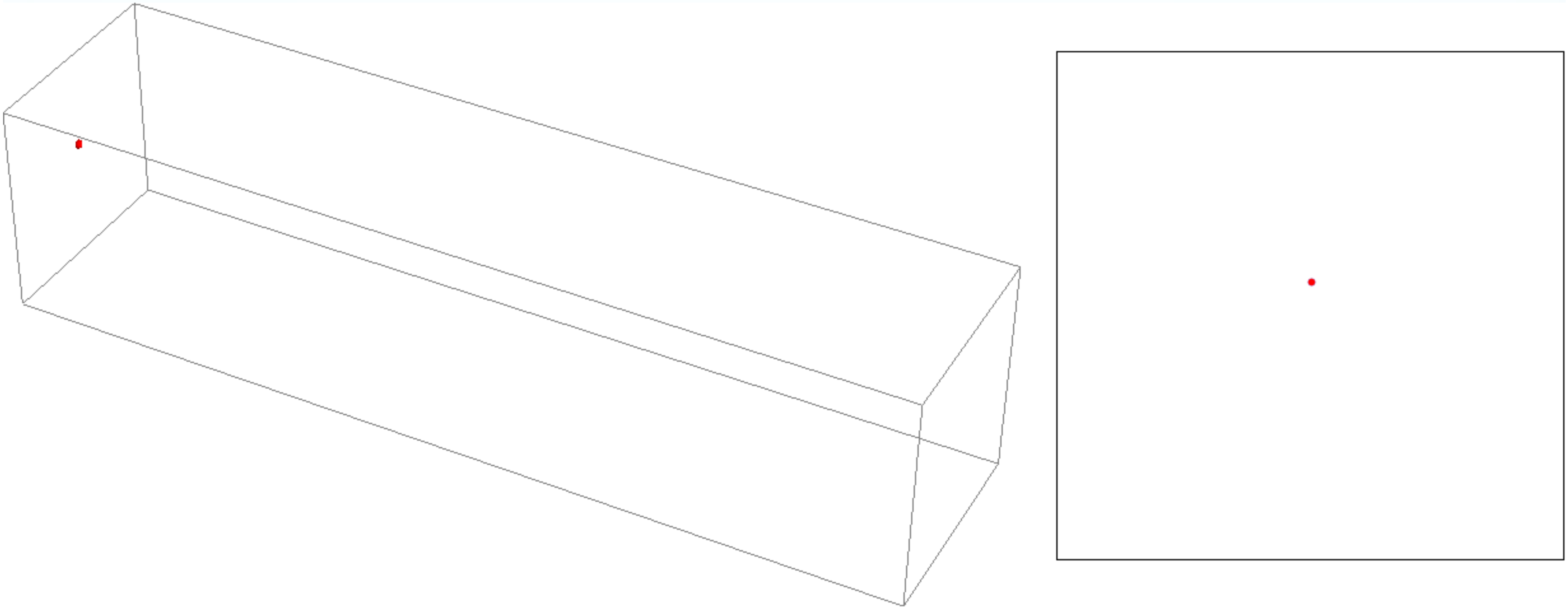


Parameter (Units)	U1	U2
Energy (GeV)	46.6	46.6
Length (mm)	1000	1000
Period (mm)	2.54	2.43
Number of periods	394	406
Aperture (mm)	0.87	1.07
Winding direction	left-handed	left-handed
Axial field (T)	~ 0.71	~ 0.54
K	~ 0.17	~ 0.12
E_1 (MeV)	~ 7.9	~ 8.4
Photons/e^-	0.35	0.18
$\Delta E/e^-$ (MeV)	1.65	0.88
Voltage (V)	~ 656	~ 592
Current (kA)	2.3	2.3
Pulse width (μs)	12	13
ΔT/pulse ($^\circ$C)	~ 1.7	~ 1.3
Inductance (μH)	~ 1.4	~ 1.5
Resistance (Ω)	~ 0.22	~ 0.26
Oil flow (l/min)	13.25	13.25
Press. drop (bar)	~ 0.76	~ 0.76



G. Alexander *et al.*, Nucl. Instrum. Meth. **A610**, 451 (2009).

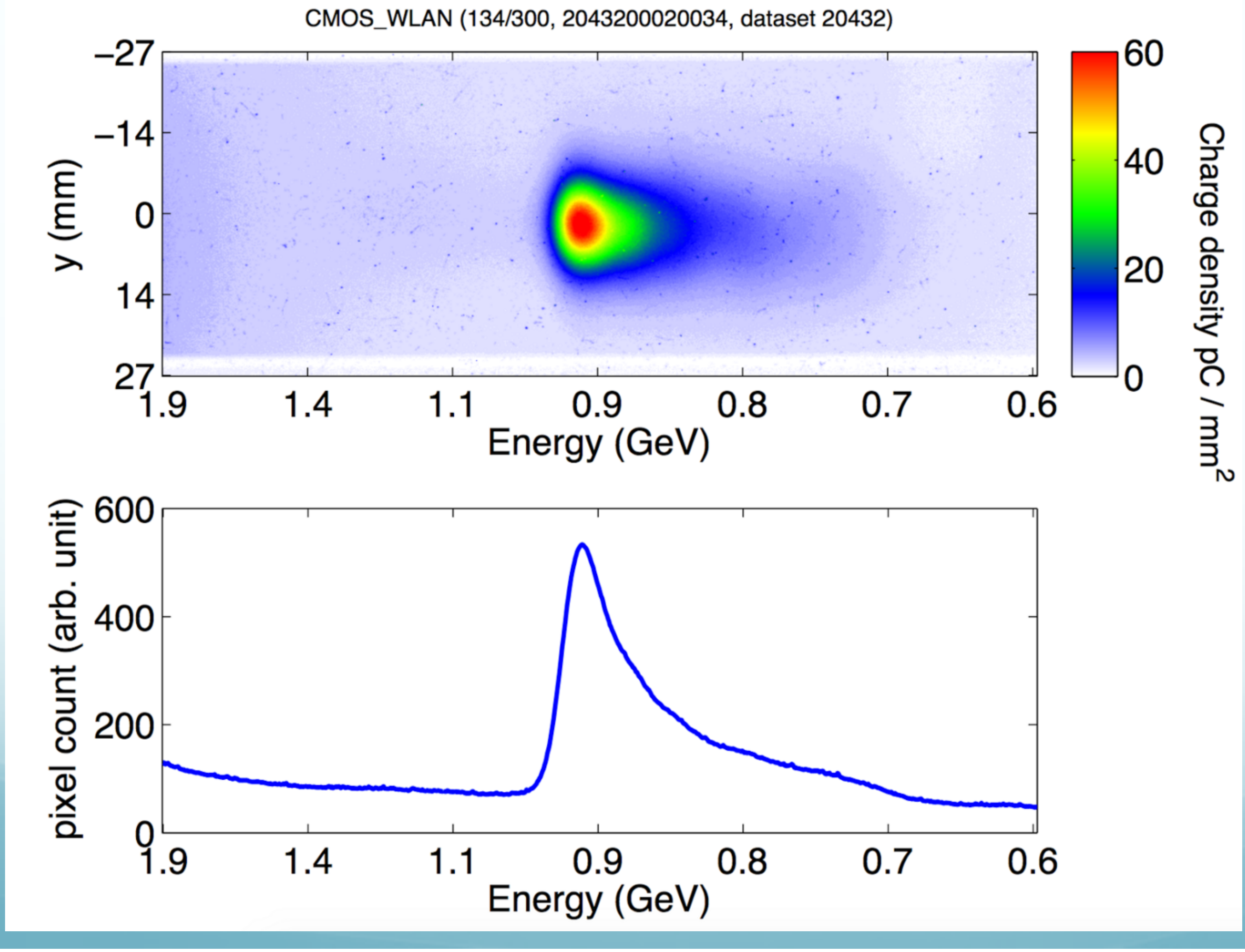
Unique opportunity for helical betatron undulator



- Pair **helical undulator with PWFA** over ~meter length scales.
- Case shown includes demonstration of detuning from resonance

FACET-II experiment E210 Beam Ideal

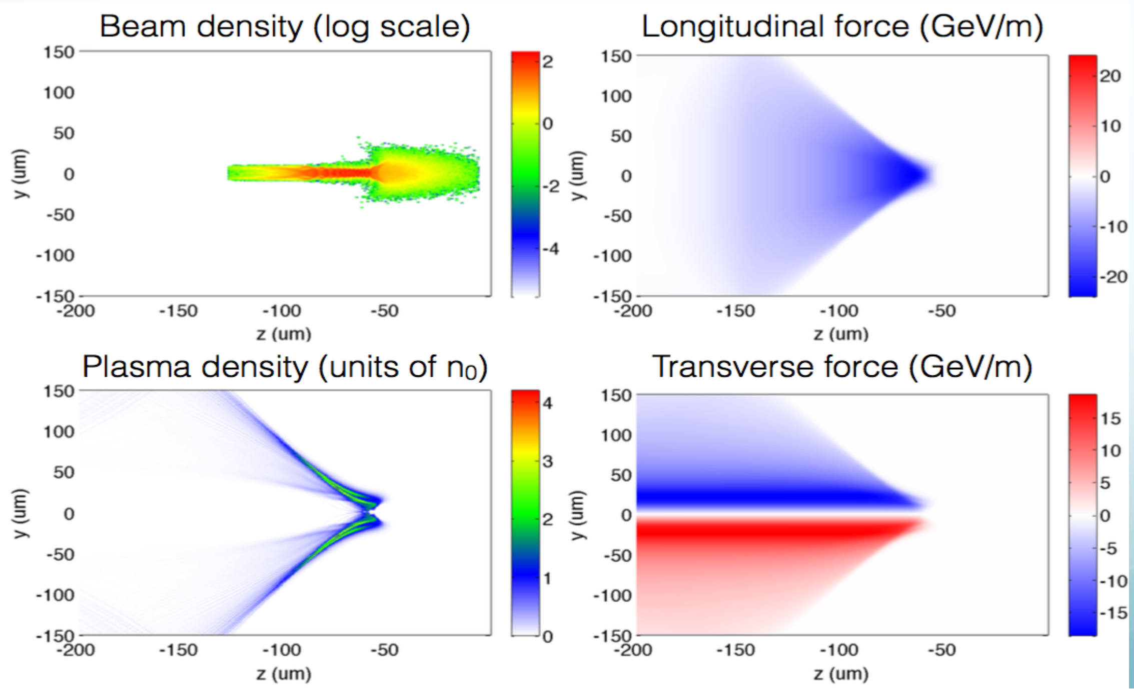
- Spectrometer image gives energy spectrum and emittance upper limit

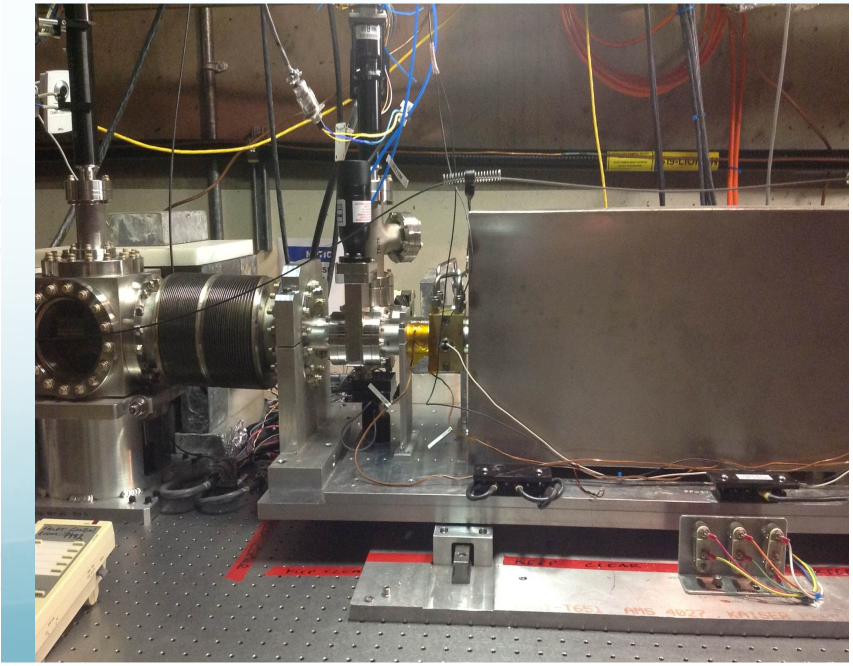


Preliminary
- 12 fs
- 30 pC
- Few mm-mrad

FACET experiment: the plasma source

- Need uniform plasma at/past undulator
- Need to **diminish or eliminate witness beam acceleration** – narrow, *wakeless* plasma $R_p < r_{\mathrm{blowout}}$
- Signatures observed in E210, other expt's



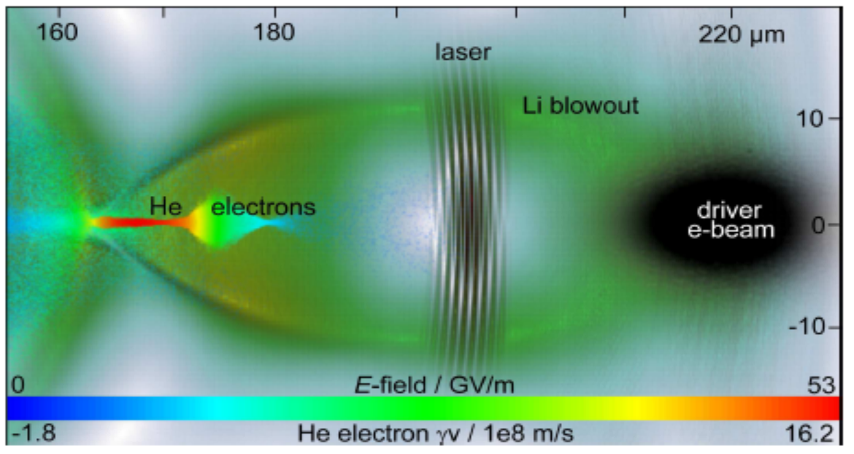


FACET II Experiment: 3 ways to inject low energy beam

- Case (a) Witness beam via entrance injection (observed/described at FFTB) from a short higher n_0 plasma region – ~4x downstream n_0 . Acceleration in high n_0 0.25-1 GeV. Short undulator follows density down ramp (FACET II design report)

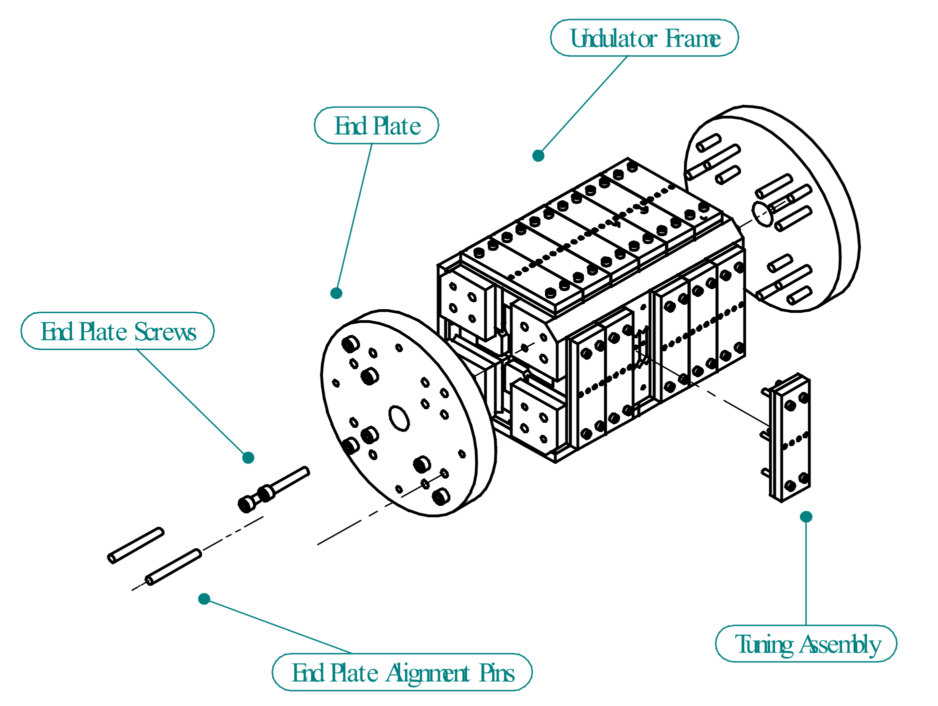
- Case (b) Same as (a), but using Trojan Horse injection. Can inject far off axis (some beam quality issues) to excite betatron oscillations w/o undulator (or use to modify amplitude). Good beam control.

- Case (c) External injection using photoinjector. Also permits off-axis injection, dedicated beam diagnosis before injection.



FACET-II experiment: undulator

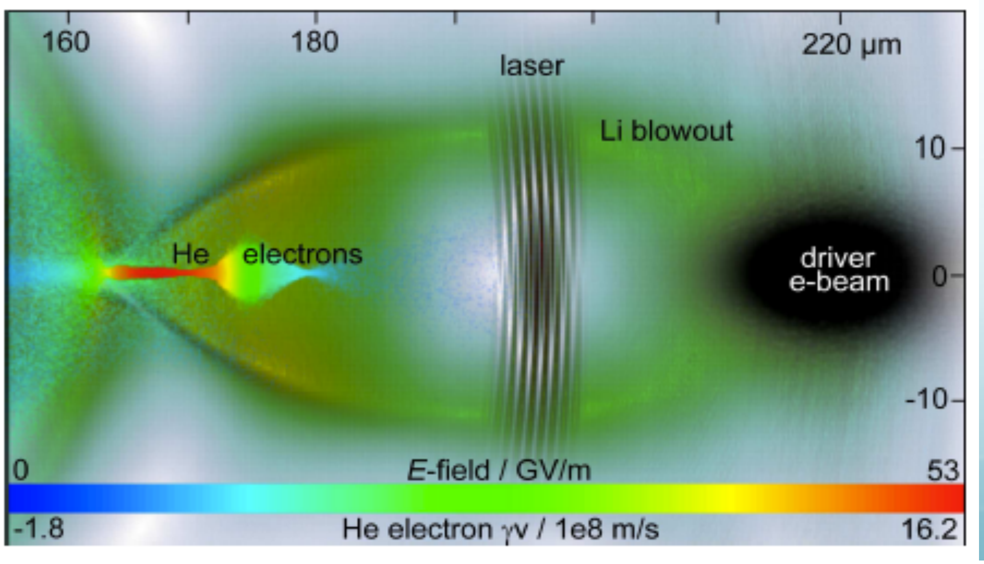
- Relatively simple, few period undulator
  - Example: B=1 T, λ=3 cm, 3-6 periods
- UCLA has built several (more challenging) recently

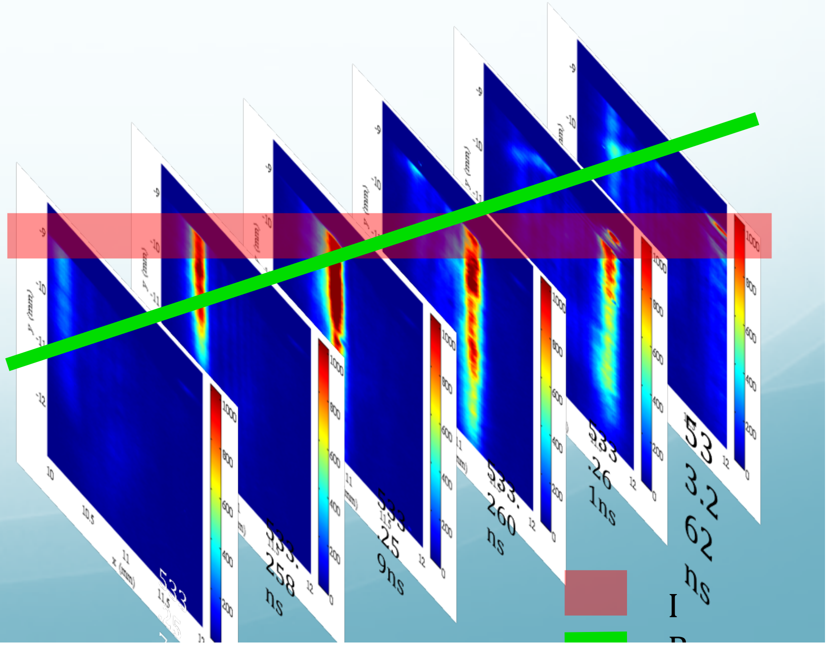


Assembly drawings for permanent magnet helical undulators at UCLA.
(E. Hemsing, M. Dunning, D. Xiang, A. Marinelli, C. Hast, T. Raubenheimer, A. Knyazik and J. B. Rosenzweig, *Nature Physics* **9,** 549 (2013))

Experimental signals

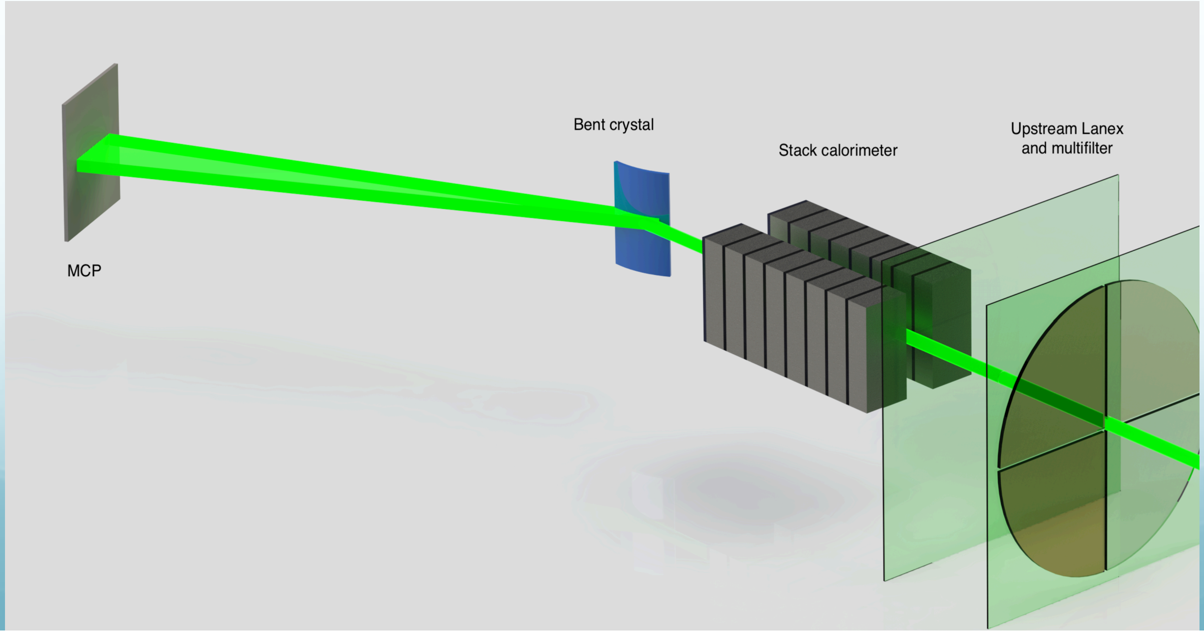
- Need to create narrow spectrum, high quality 0.25-1 GeV beam
  - Far-off-axis Trojan is interesting in own right (E210)
- Laser-electron timing remains critical (EOS). Particularly useful for Case (c)
- Betatron radiation; flux and spectrum are excellent diagnostics
  - Beam can be very short: coherence on low harmonics?
  - Example: For K=15 in simulation, λ=6 um; simulations indicate we can reach σ_z<2 um in Trojan injection





Measuring Betatron Radiation

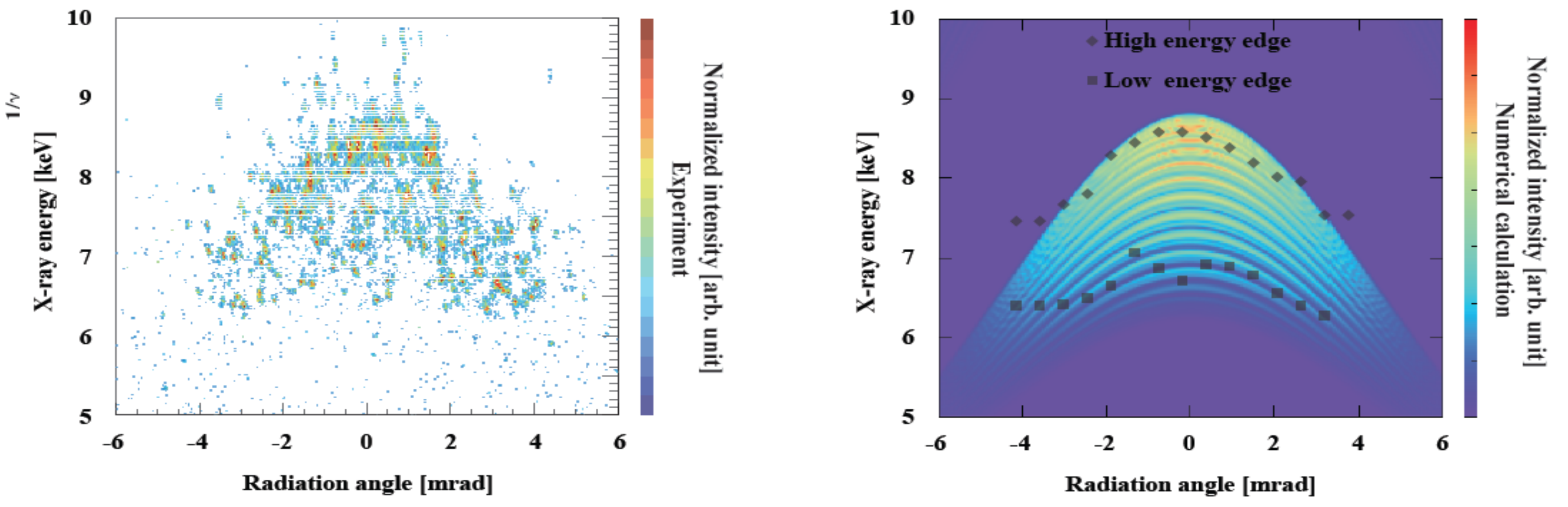
- Dedicated betatron radiation spectrometer proposed by UC-Boulder-Ecole Poly-UCLA
- Based on two proven techniques
  - 0.1-2 MeV, stack calorimeter, with spatial information
  - <100 keV, bent crystal spectrometer
- Missions: ND emittance measurement; beam dynamics in plasma, betatron-undulator resonance, etc.



$$\Delta\lambda_{rms} = 2\varepsilon_{rm}$$

Betatron radiation double differential spectrum (DDS)

- Based on ICS experimental demonstration at UCLA-ATF expt.
- Bent crystal disperses, angular information along slit (inside calorimeter stack for FACET-II case)
- Can resolve large wavelength and angular spectra



Emittance measurement

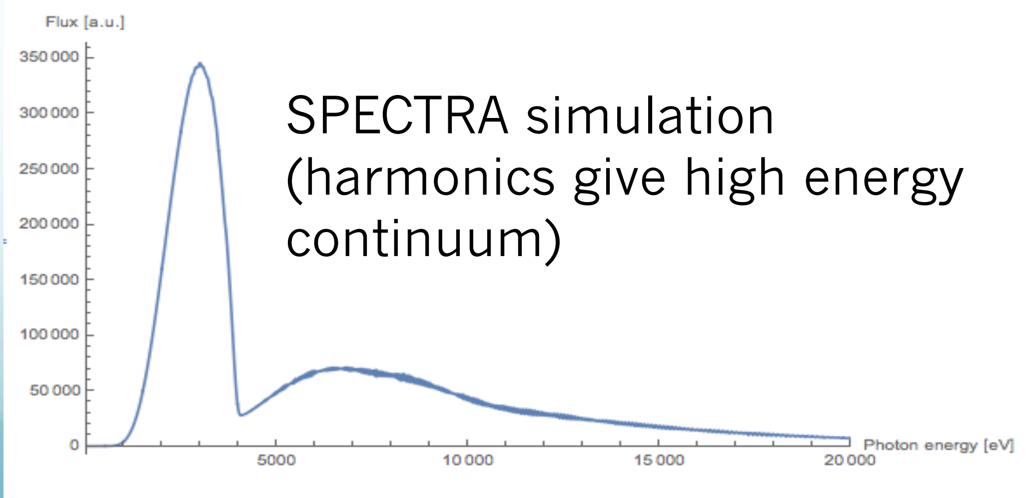
- Assuming Gaussian betatron amplitude distributions, rms line-width gives emittance through spread in *K* redshifts

$$\Delta\lambda_{rms} = 2\varepsilon_{rms,n} / \gamma$$

- Note that betatron radiation line scales strongly with energy

$$\lambda_\beta \propto \gamma^{-3/2}$$

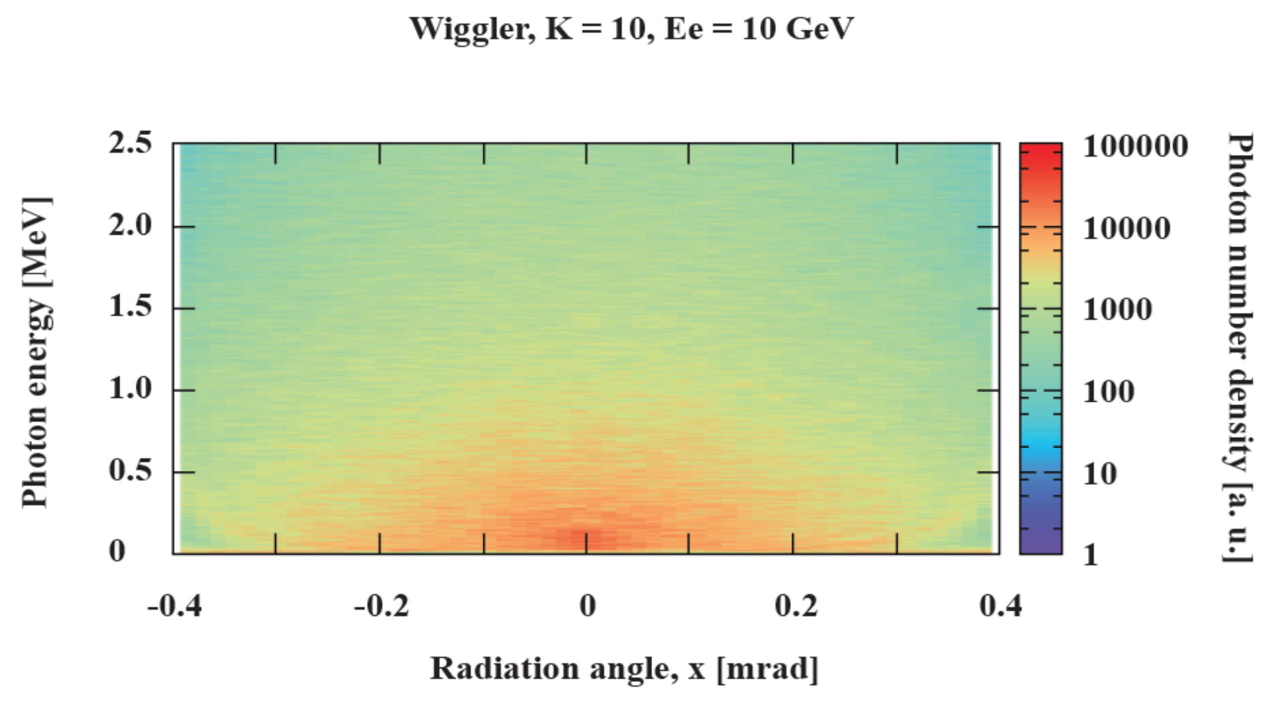
- Smaller energy permits manageable redshifts
- Example: ε_n=0.1 mm-mrad, U=2 GeV, $n_0=10^{17}$ cm^{-3}
- On-axis spectrum: $U_{\beta,0} = 12.5$ keV, and ΔU_{rms} =4.5 keV (35% BW)



SPECTRA simulation (harmonics give high energy continuum)

Measuring large amplitude spectrum

- At very large amplitude, transition to wiggler (synchrotron) radiation spectrum defined by critical energy
  - Drive beam shows this
- Detailed interpretation is more challenging
- Comment:Best for "FEL" experiment to operated <2 GeV (LCLS-like) to control *K* and its rms spread. Good emittances needed!



Lenard-Wiechert simulation of 10 GeV, *K*=15, 1E17/cc plasam case

Conclusions

- We wish to create and study coherent betatron oscillations through their radiation
  - Potential to create new class of very high field undulator (K>>1)
  - Could enhance short period low-K micro-undulators to K~1 regime (MEMS undulators at UCLA)
  - Helical undulator can be created
- Fundamental beam-plasma physics through superposition of PWFA and undulator interactions
- Wakeless plasma is key innovation
- Numerous possibilities for injection
- Synergistic with other uses of betatron radiation
- Highly leveraged off of previous UCLA and collaborator experience, including E210 and other FACET experiments