Betatron radiation diagnostic systems for a plasma wakefield-based linear collider

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Abstract

Characterizing the beam-plasma interaction in the plasma wakefield accelerator, an essential ingredient for a potential linear collider or free-electron laser represents a significant challenge for experimental measurements. The typical dimensions involved in such diagnostic systems are below one micron, with attendant femtosecond time-resolution. Further, the plasma environment and the beam intensity generally prevent insertable, destructive diagnostics. The most robust window into this interaction is betatron radiation, which reveals beam properties such as size, emittance, matching, and development of instabilities. In this talk, we review the powerful new double-differential spectrometer under development at UCLA that is to be installed at FACET-II. We discuss the unique optics of this Compton-based spectrometer, which permits single shot measurements of incoming betatron gamma spectra ranging from 0.2 to 30 MeV. We describe significant progress in implementing machine learning techniques for reconstructing the beam-plasma interaction physics.

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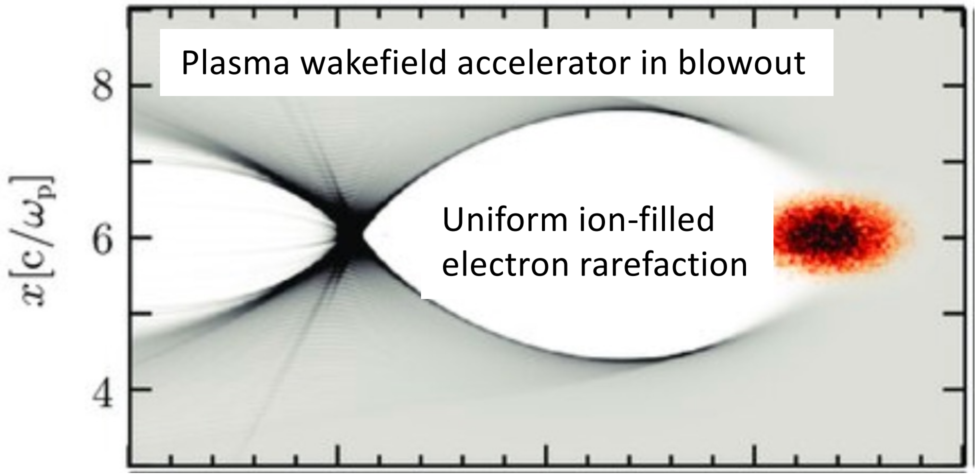
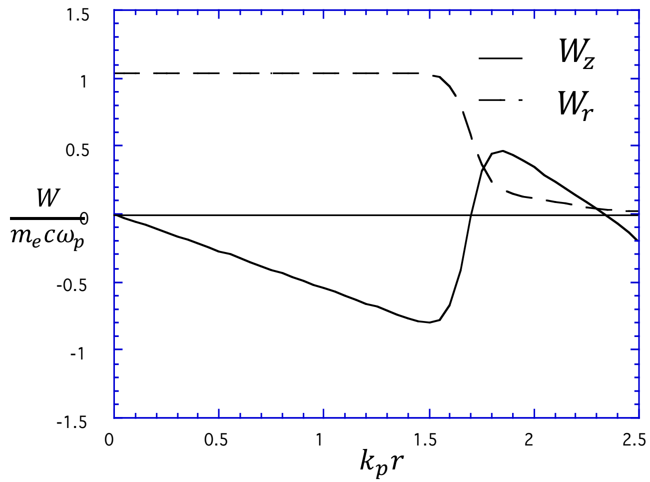
PWFA in the blowout regime

- **Paradigm since early 1990's: PWFA underdense "blowout" regime**
- Beam ejects plasma electrons from beam region, forming uniform ion-filled bubble



Fields inside plasma electron rarefaction region. $E_{max} > E_{WB}$

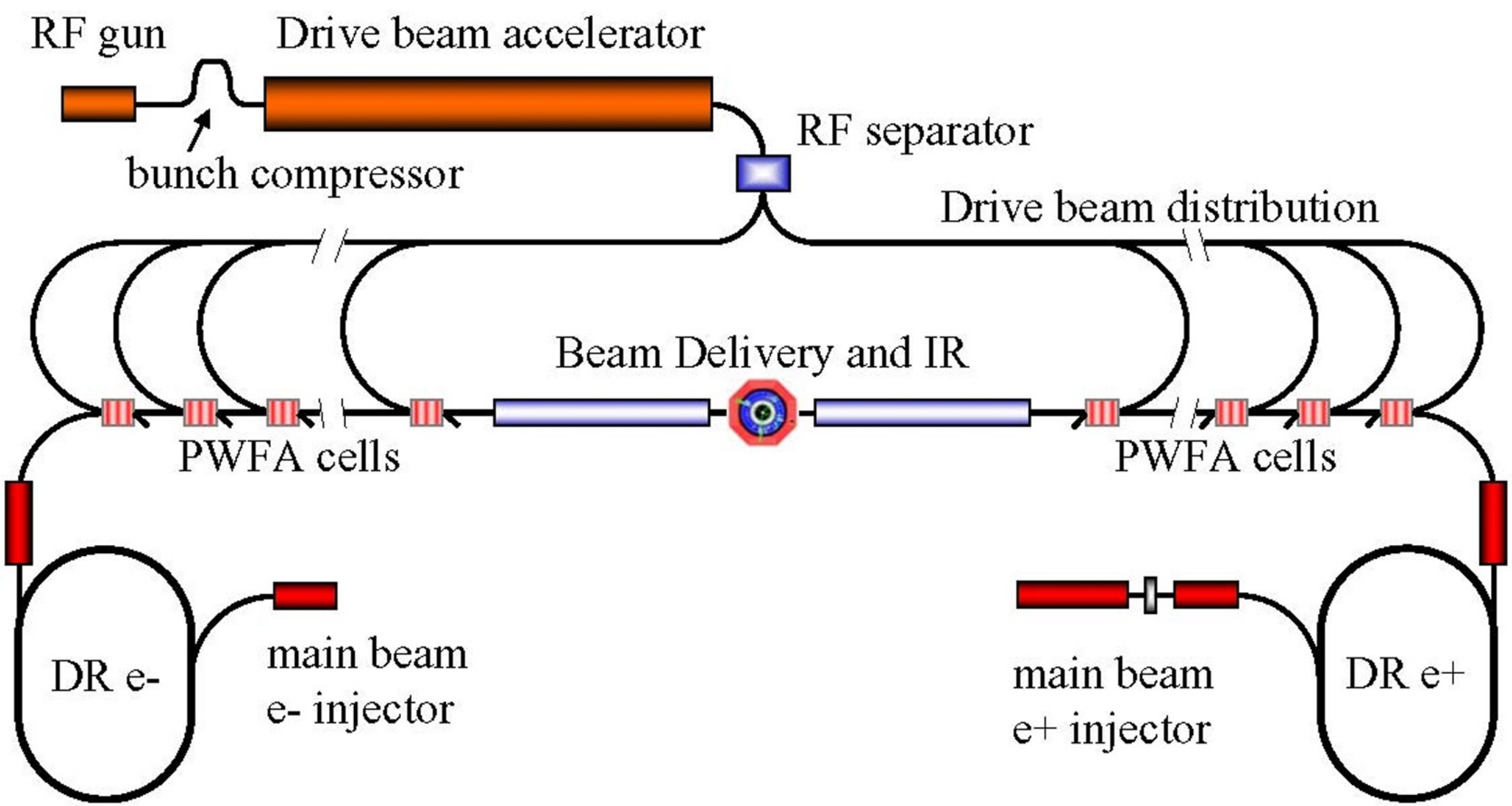


PWFA in blowout ideal for acceleration and ion *focusing*

Nearly all lInear collider PWFA development in blowout regime

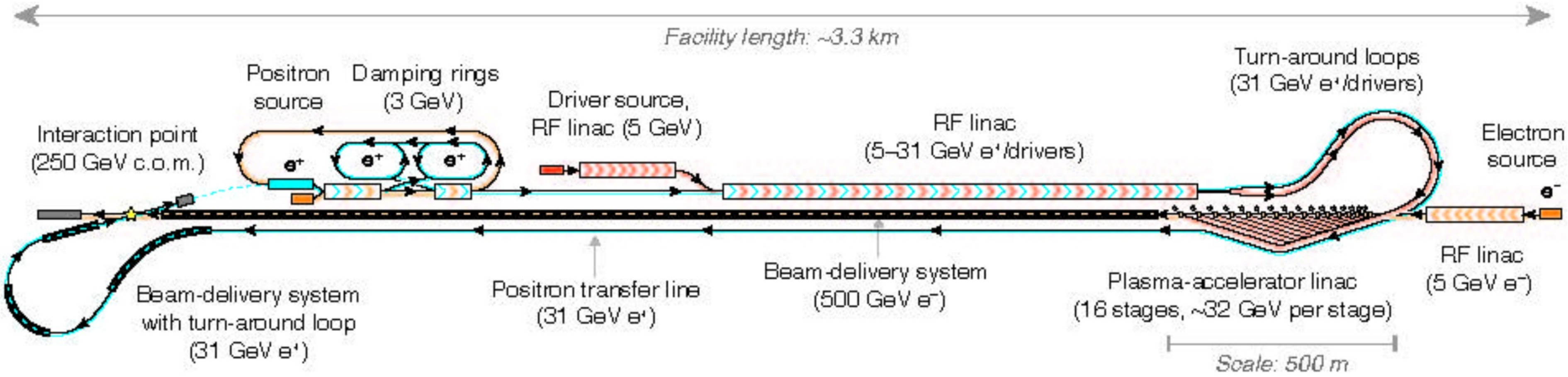
J. B. Rosenzweig, *et al.*, *Phys. Rev. A -- Rapid Comm* . **44**, R6189 (1991).

PWFA linear collider schematic layout



- 25 GeV drive beam (~50 for future linear collider
- Other models such as HALHF under discussion
- Very high brightness beams undergoing strong focusing

PWFA linear collider schematic layout



HALHF layout

- 25 GeV drive beam (~50 for future linear collider
- Other models such as HALHF under discussion
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The challenge of measuring beam properties in applications - linear collider

- Very strong ion focusing
  - $r'' + k_\beta^2 r = 0$, with $k_\beta^2 = \frac{e^2 n_0}{2\beta^2 \gamma m_e \varepsilon_0} \simeq \frac{k_p^2}{2\gamma}$
  - Beta function $\beta_{\mathrm{eq}} = \sqrt{2\gamma} k_p^{-1}$; at 25 GeV, this is ~1 cm. Short
  - With emittance of 1E-6 m-rad, this implies $\sigma_{\mathrm{eq}} \simeq 0.3\ \mu\mathrm{m}$
- Challenges in measurements
  - Suboptical size
  - Hostile plasma environment
  - Beam intensity
  - Measure accelerating beam *with* drive beam present
- *Need non-destructive methods*
  - Ion focusing is key; based on (usually) simple harmonic oscillations
  - **Betatron radiation gives plethora of information**

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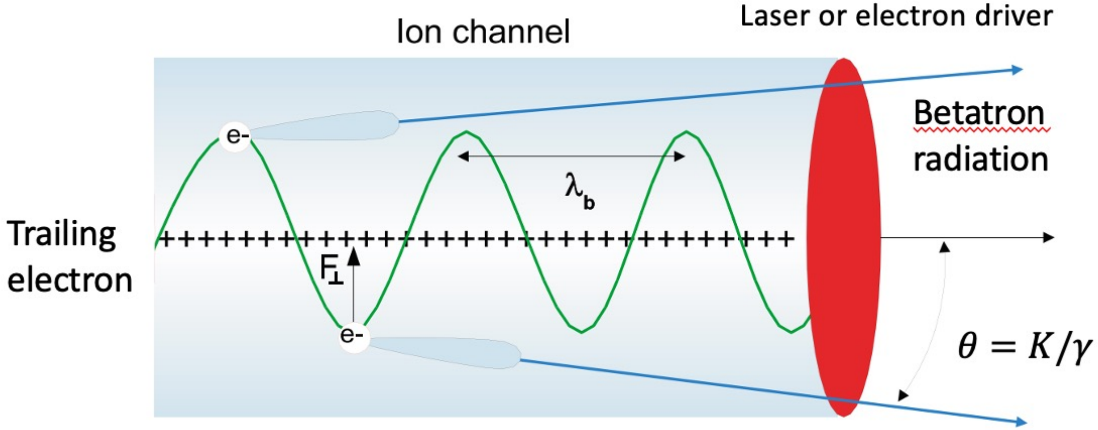
Betatron radiation mechanism

- Simple harmonic oscillations similar to undulator motion; period λ_{p}



Small K_u resonance $\lambda_r = \frac{\lambda_\beta}{\beta_z \cos\theta} - \lambda_\beta \simeq \frac{\lambda_\beta}{2\gamma^2}\left[1 + \frac{1}{2}K_u^2 + (\gamma\theta)^2\right]$

- Energy not conserved in motion (ignorable at high γ)
- Amplitude (K_u) and polarization set by initial conditions (i.e. $x = x_0$)

$$K_u = \frac{1}{\sqrt{2}}\gamma k_\beta x_0$$

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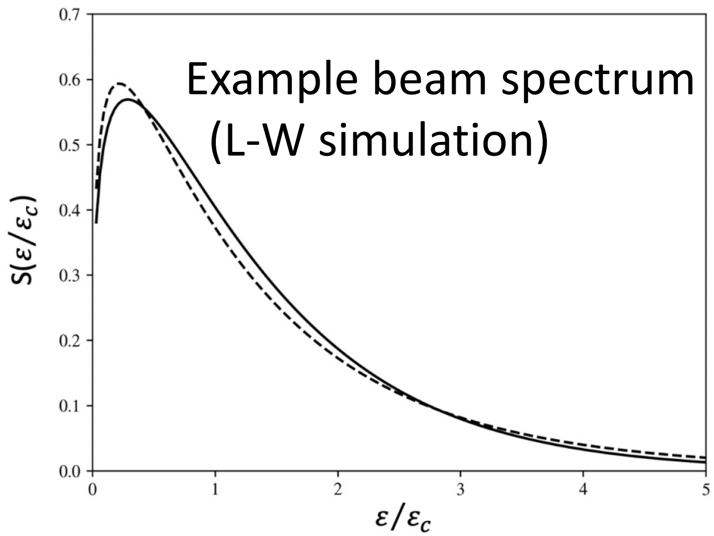
Betatron radiation spectra

- With small beam sizes ($K_u \leq 1$), one may have undulator spectra – fundamental and harmonics
  - Spread in amplitudes can measure emittance! $\Delta\lambda_{r,rms} \simeq \frac{\pi\varepsilon_n}{\gamma}$
- Large K_u gives wiggler (synchrotron-like) radiation spectrum



Critical energy

$$\varepsilon_c = \frac{3}{2}\hbar c K_u k_\beta$$

- This is the most commonly encountered situation
- The critical the critical energy increases only as $\gamma^{\frac{1}{4}}$.
  - Spectrum is similar for all energies in PWFA collider

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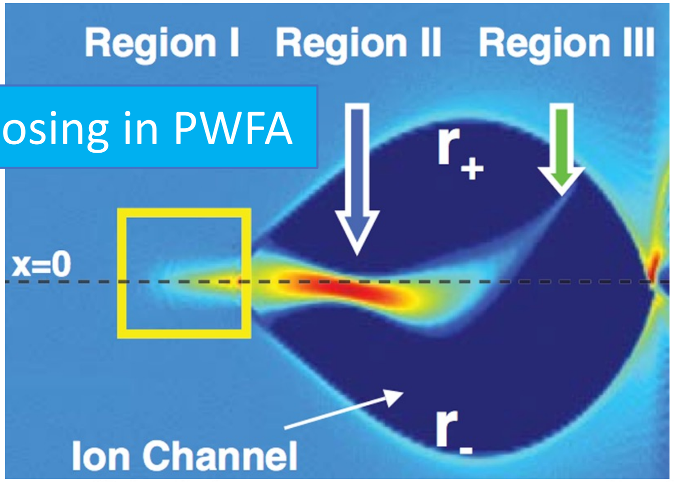
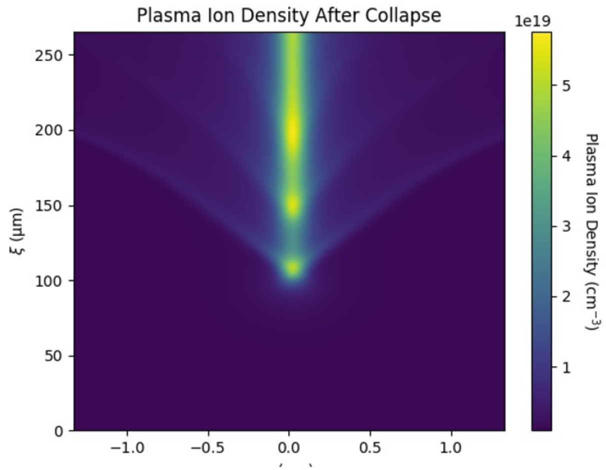
Non-ideal behavior can be revealed in DDS

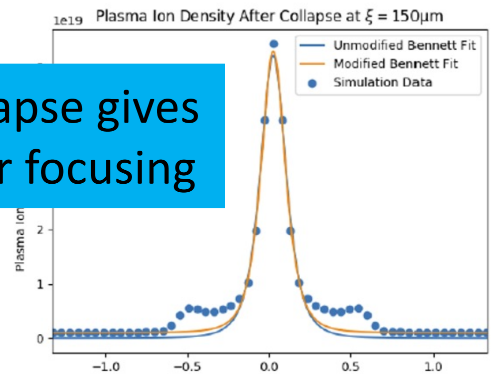
- Hosing/banana beam induces **directional** and enhanced radiation
- Ion collapse dramatically changes and enhances beam radiation
- Positron propagation inherently nonlinear

Hosing in PWFA



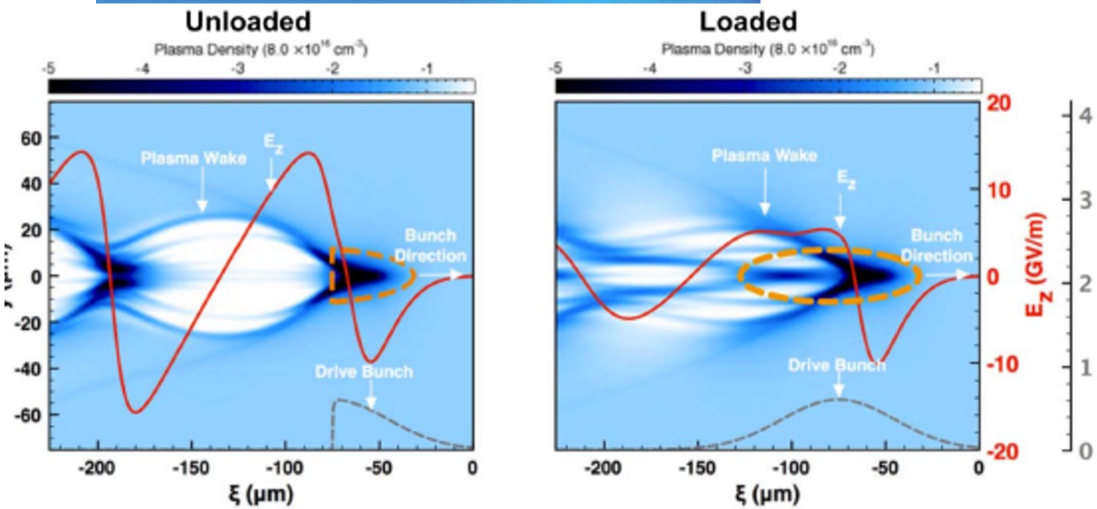


Ion collapse gives stronger focusing



E

Ic



e+ beam distributions in PWFA

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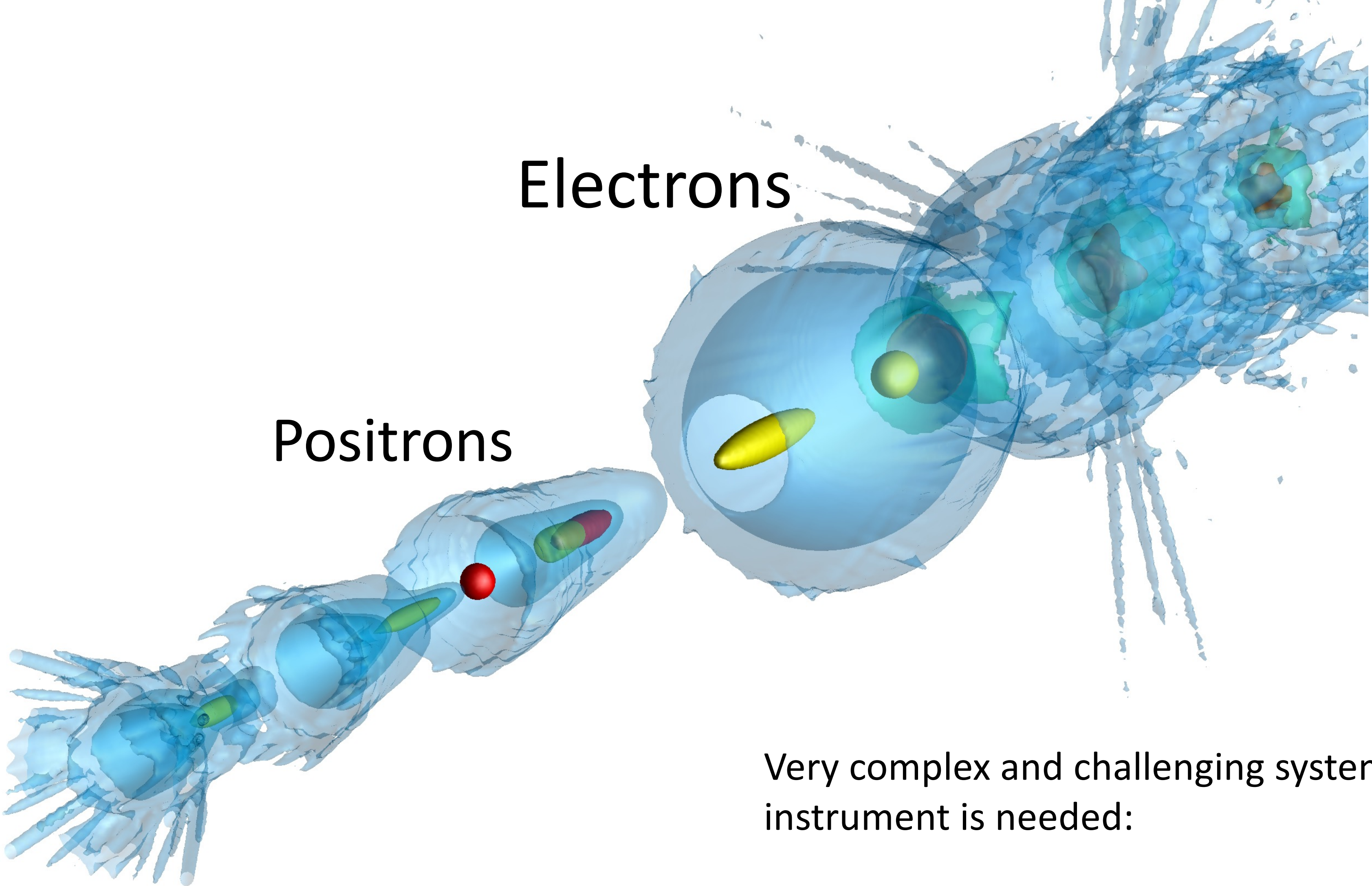
Measuring beam characteristics with betatron radiation

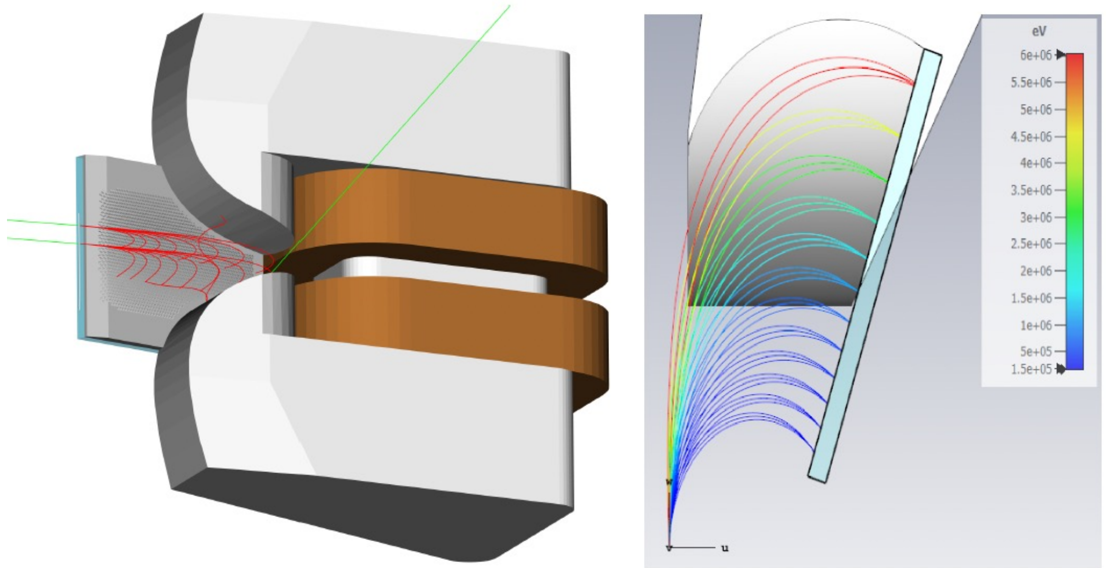


Very complex and challenging system A new instrument is needed:

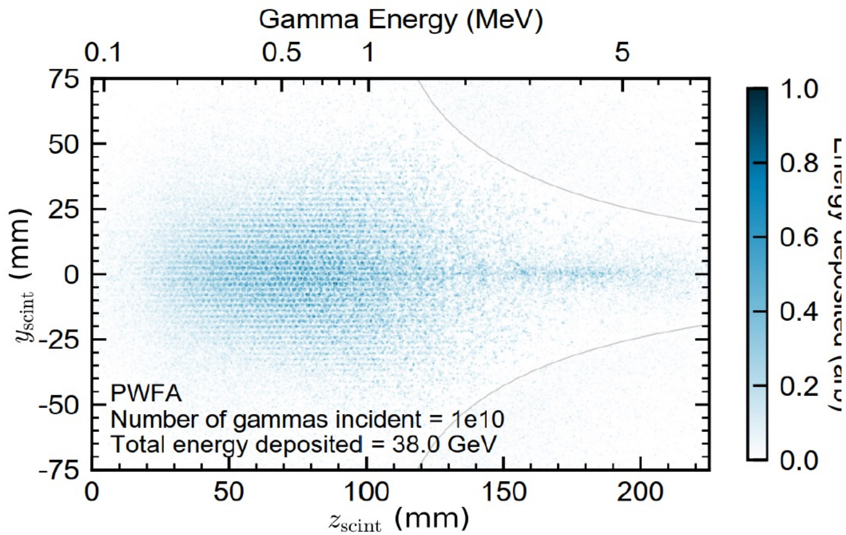
Double differential spectrometer

Novel Compton spectrometer for FACET-II: CPT

- Based on Compton scattering in converter wire
  - Kinematic replica e-
  - Gives double differential spectrum (DDS)
- Compact (50 cm)
- Broad range
  - Sextupole-like magnet
  - 200 keV– 30 MeV
  - Upper limit set by onset of pair production
- Lower limit from new approach
  - Pixelated directional tungsten collimator removes non-replica electrons
  - 500 keV -> 200 keV limit



Trajectories of Compton e- in CPT



DDS detection plane simulation

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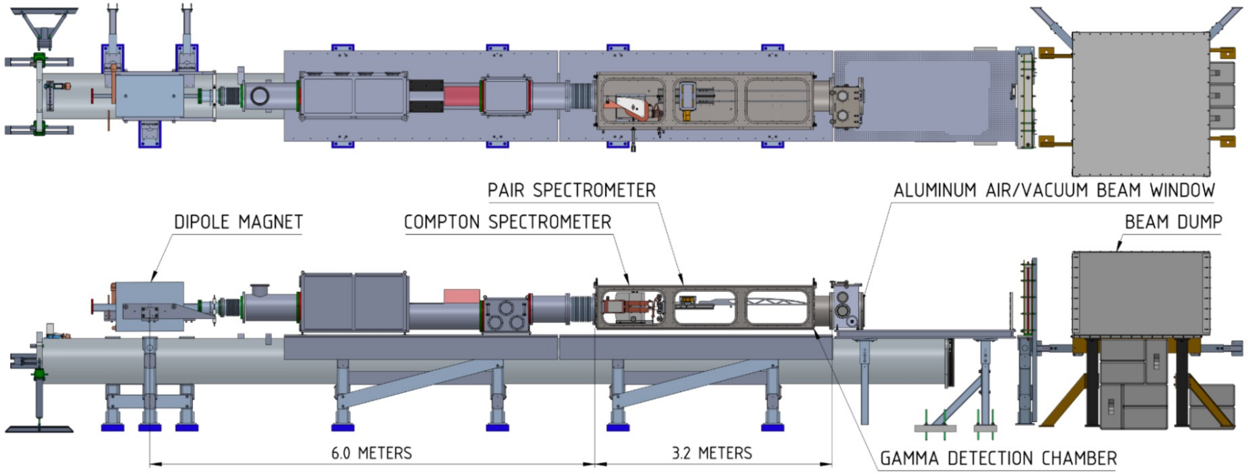
Installation at FACET-II

- Install in dump line downstream of IP



- Large vacuum box for CPT and pair spectrometer PEDRO (SFQED expt)

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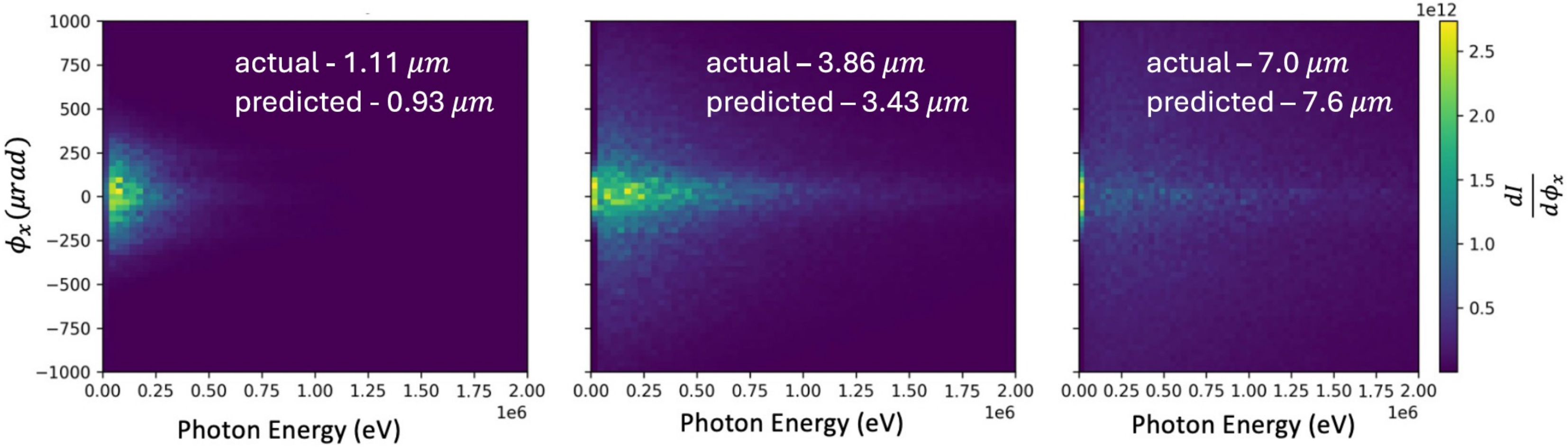
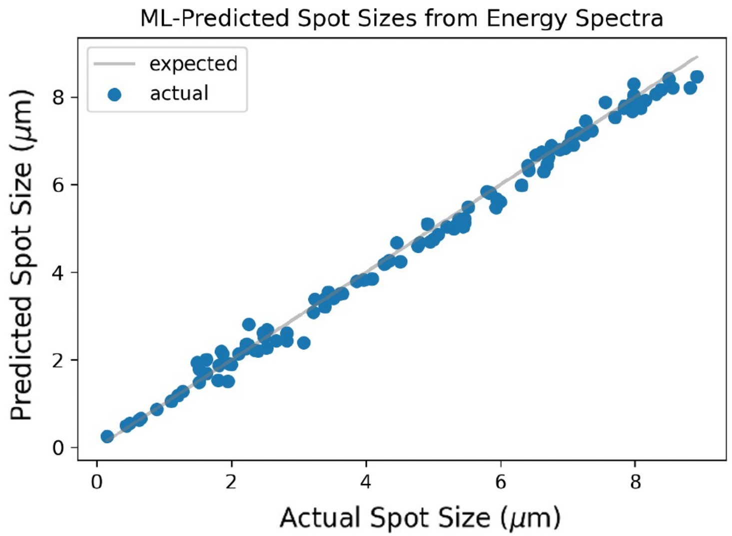
How to use data? Machine learning analysis

- DDS data fed into ML model trained on simulation data



- Results of beam size reconstruction robust even with 1D data

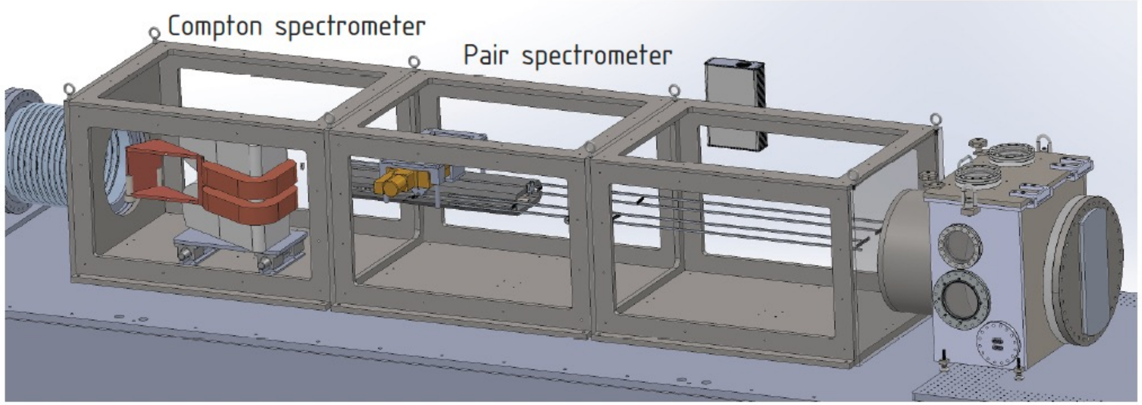
Beam emittance, energy, also extracted by ML analysis



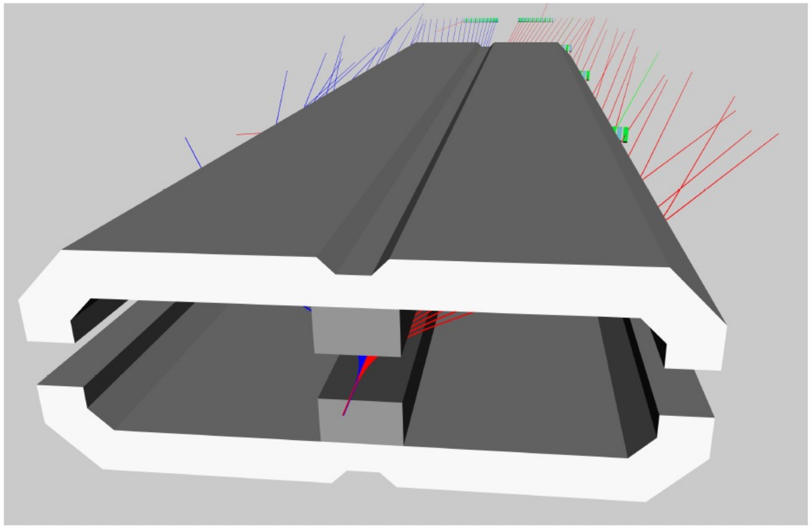
This is a dramatic improvement over previous expts.

Higher energy diagnostics: pair spectrometer

- At FACET-II UCLA is also building a pair spectrometer (PEDRO) to measure to 10 GeV γ's for SFQED. Hardware cohabitates with CPT



- PEDRO design (below can be used in LC environment at high energy



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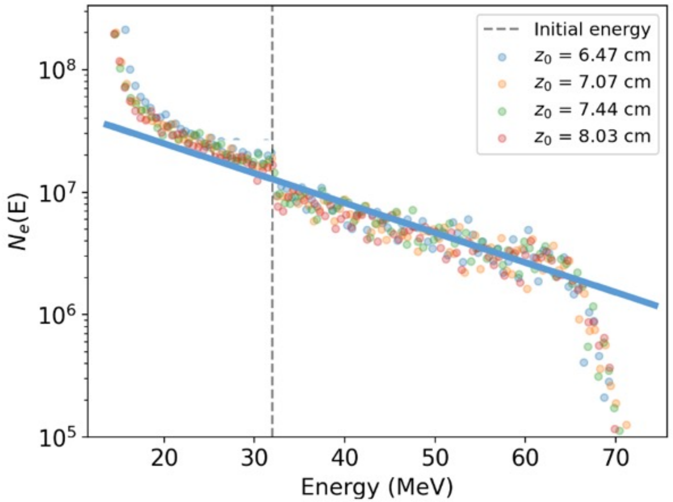
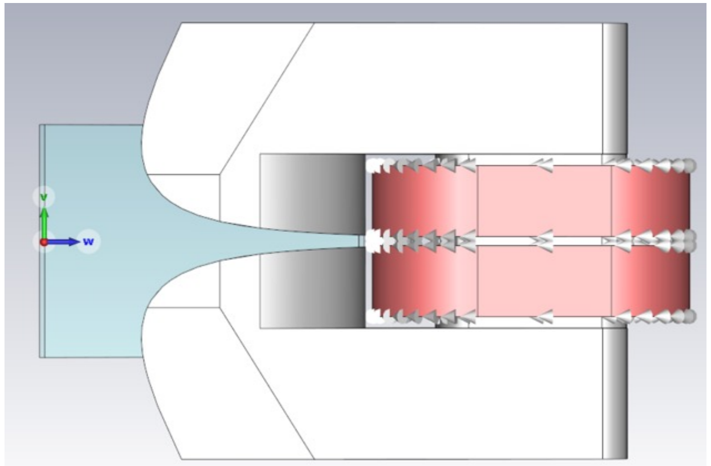
Spin-off application: drive beam spectrometer

- To obtain a broad range spectrometer in “space-radiation simulator” PWFA experiments at UCLA we are repurposing the sextupole spectrometer magnet for 3-60 MeV use



PWFA “stopped beam” spectrum



Modified CPT magnet spectrometer

- Can this usefully be extended to ~25 GeV drive beam
  - What is the effect on accelerating beam? Sextupole may permit small pert.

Conclusions

- Betatron radiation gives key information for beam properties in PWFA needed for collider performance
- Innovative new gamma-ray spectrometers under development and commissioning (soon) at FACET-II
- Machine learning analysis methods show the way for reconstructing beam properties
- A good start to build hardware and software tools for PWFA collider beam measurements based on betatron radiation
  - These tools are explained in a series of arXiv and PRAB papers by Yadav, et al. and Naranjo, et al.
- Much more work to be done