FACET-II Facility for Advanced Accelerator Experimental Tests

Opportunities and Challenges of Using High Brightness Beams from PWFA Injectors

2019 FACET-II Science Workshop

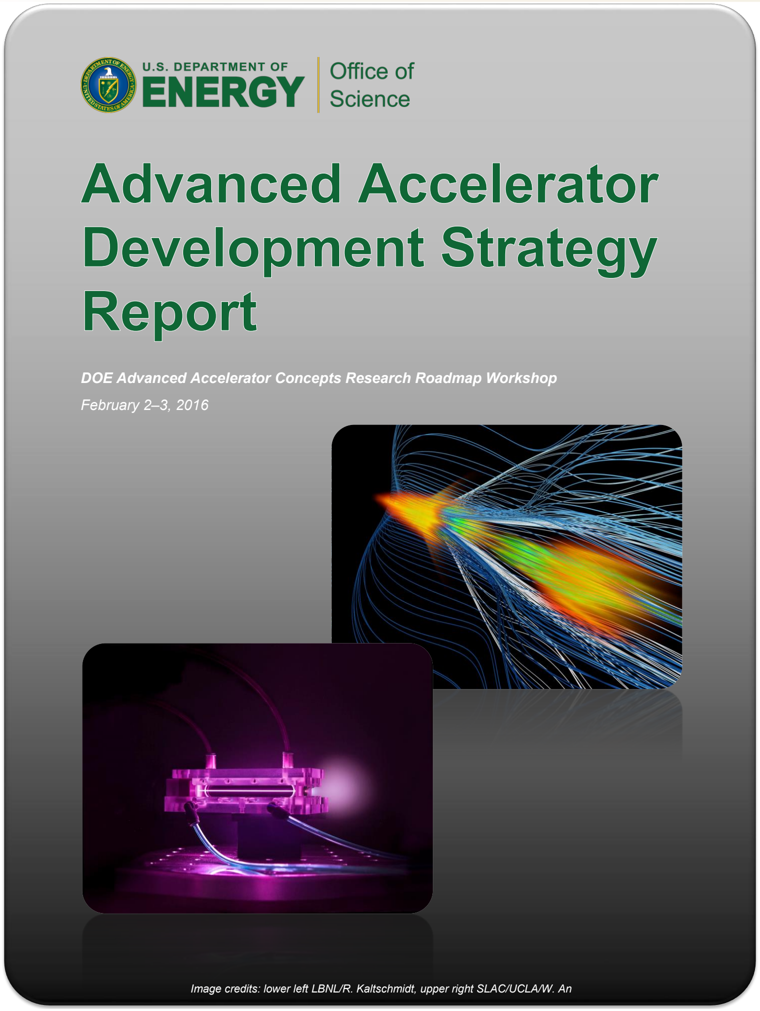
Mark J. Hogan

November 1, 2019

U.S. DEPARTMENT OF ENERGY
Office of Science

SLAC NATIONAL ACCELERATOR LABORATORY

A Roadmap for Future Colliders Based on Advanced Accelerators Contains Key Elements for Experiments and Motivates FACET-II



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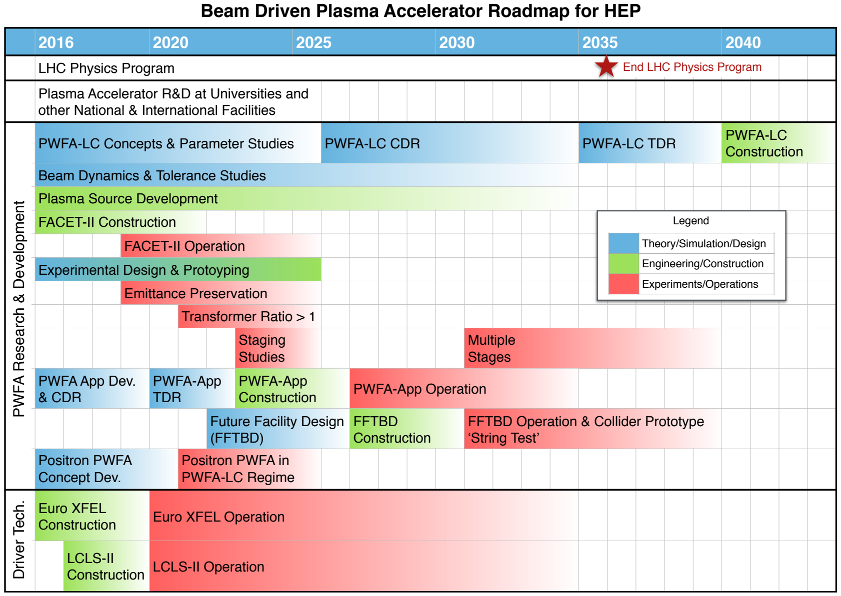
Advanced Accelerator Development Strategy Report

DOE Advanced Accelerator Concepts Research Roadmap Workshop

February 2–3, 2016

Image credits: lower left LBNL/R. Kaltschmidt, upper right SLAC/UCLA/W. An

http://science.energy.gov/~/media/hep/pdf/accelerator-rd-stewardship/Advanced_Accelerator_Development_Strategy_Report.pdf



Beam Driven Plasma Accelerator Roadmap for HEP

2016 | 2020 | 2025 | 2030 | 2035 | 2040

LHC Physics Program ★ End LHC Physics Program

Plasma Accelerator R&D at Universities and other National & International Facilities

PWFA Research & Development:

PWFA-LC Concepts & Parameter Studies | PWFA-LC CDR | PWFA-LC TDR | PWFA-LC Construction

Beam Dynamics & Tolerance Studies

Plasma Source Development

FACET-II Construction

FACET-II Operation

Experimental Design & Protoyping

Emittance Preservation

Transformer Ratio > 1

Staging Studies | Multiple Stages

PWFA App Dev. & CDR | PWFA-App TDR | PWFA-App Construction | PWFA-App Operation

Future Facility Design (FFTBD) | FFTBD Construction | FFTBD Operation & Collider Prototype 'String Test'

Positron PWFA Concept Dev. | Positron PWFA in PWFA-LC Regime

Driver Tech.:

Euro XFEL Construction | Euro XFEL Operation

LCLS-II Construction | LCLS-II Operation

Legend

🟦 Theory/Simulation/Design

🟩 Engineering/Construction

🟥 Experiments/Operations

Key Elements for PWFA over next decade:

- **Beam quality** – build on 9 GeV high-efficiency FACET results with focus on emittance
- **Positrons** – use FACET-II positron beam identify optimum regime for positron PWFA
- **Injection** – ultra-high brightness sources, **staging studies** with external injectors
- **Develop PWFA demonstration facility**

Task Force Members

Following the roadmap exercise, SLAC task force looked at some candidate ‘off-ramp’ applications

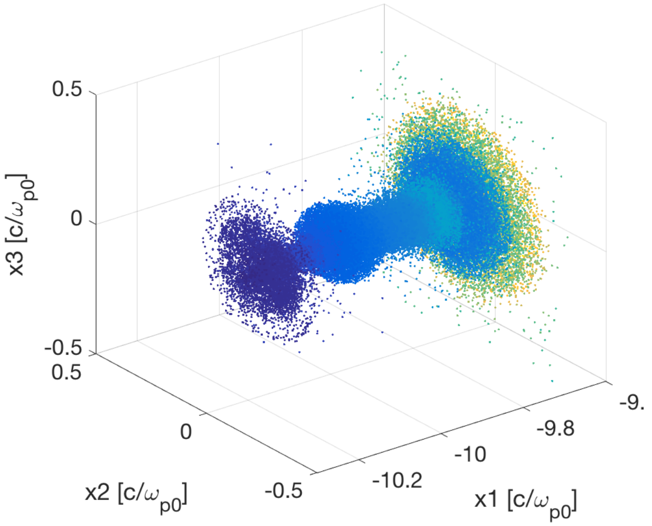
- Panos Baxevanis
- Claudio Emma
- Joel England
- Joe Frisch
- Mark Hogan
- Zhirong Huang
- Lia Merminga
- Brendan O’Shea
- Claudio Pellegrini
- Tor Raubenheimer
- John Seeman
- Gennady Stupakov
- Andrew Sutherland
- Glen White
- Vitaly Yakimenko
- Xinlu Xu

FACET-II has prompted renewed interest and recent updates led by Claudio (FEL), Xinlu (Injector) and Ago (All things attosecond)

Considering PWFA Technology for FEL Applications

FACET-II Driver

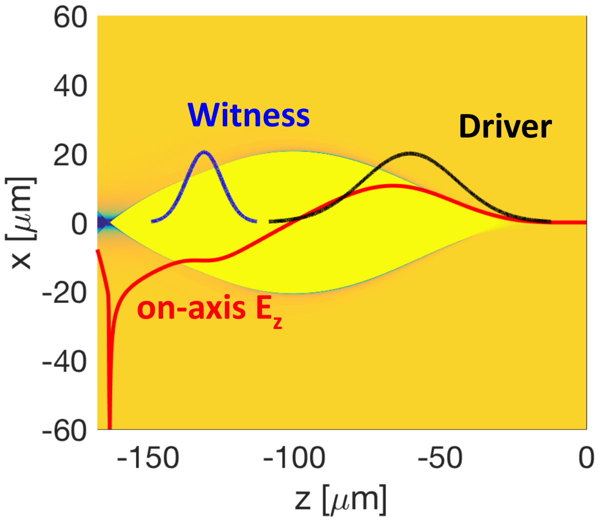
- High peak current driver (≳20kA)
- High brightness beam generated within the plasma (brightness of the driver is not critical)
- Goal: brightness transformer



Ultra-low emittance. Attosecond Pulses.

LCLS-II Driver

- Modest current driver (≅2kA)
- Two bunches (drive and witness) generated at photoinjector
- Goal: double energy and preserve brightness

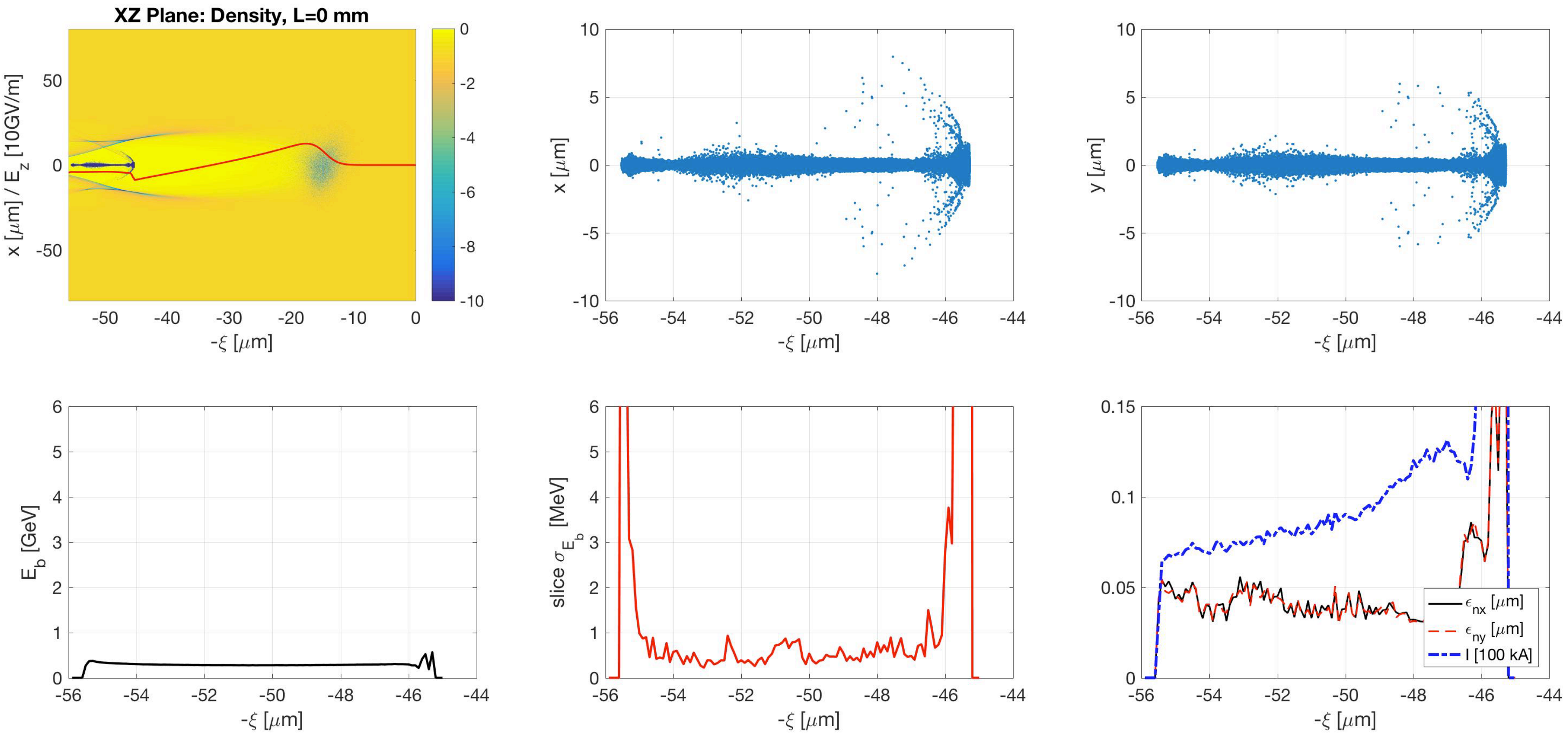


High average power. Easier stability

For details – see presentation later today by X. Xu

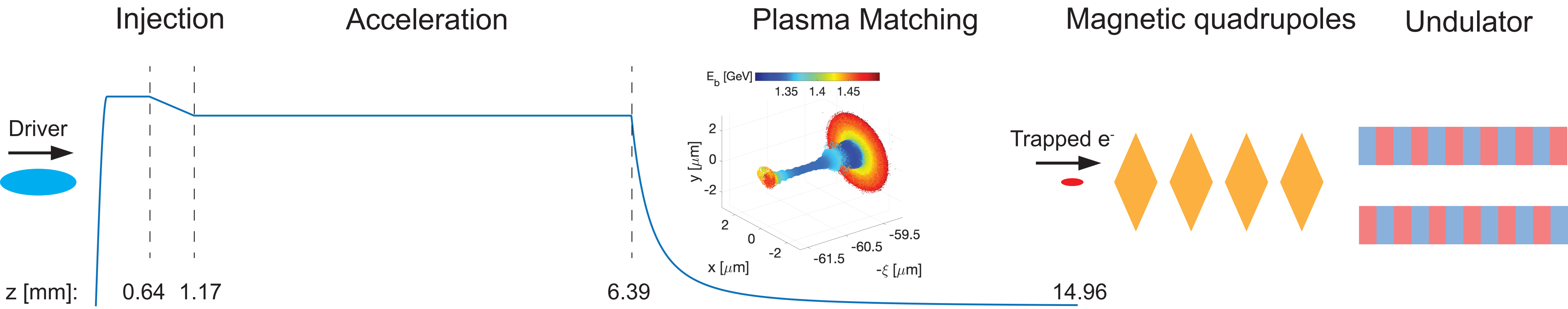
Example Density Downramp Injection Simulation

- Target beam parameters: E ~ 10GeV, I_{pk} ~ 10kA, ε_n ~ 50nm
- Concentrated on DDR, but benefits & complexities of other injection techniques techniques (ionization, TH, CP…) also need to be evaluated



Plasma Injector for FEL – a Group Idea and Effort

Proposal & Opportunity: Use FACET-II linac to drive a high-brightness plasma injector in FACET experimental area. Consider a second beam line to inject this new beam into the LCLS linac to diagnose, prepare and inject into existing undulators.

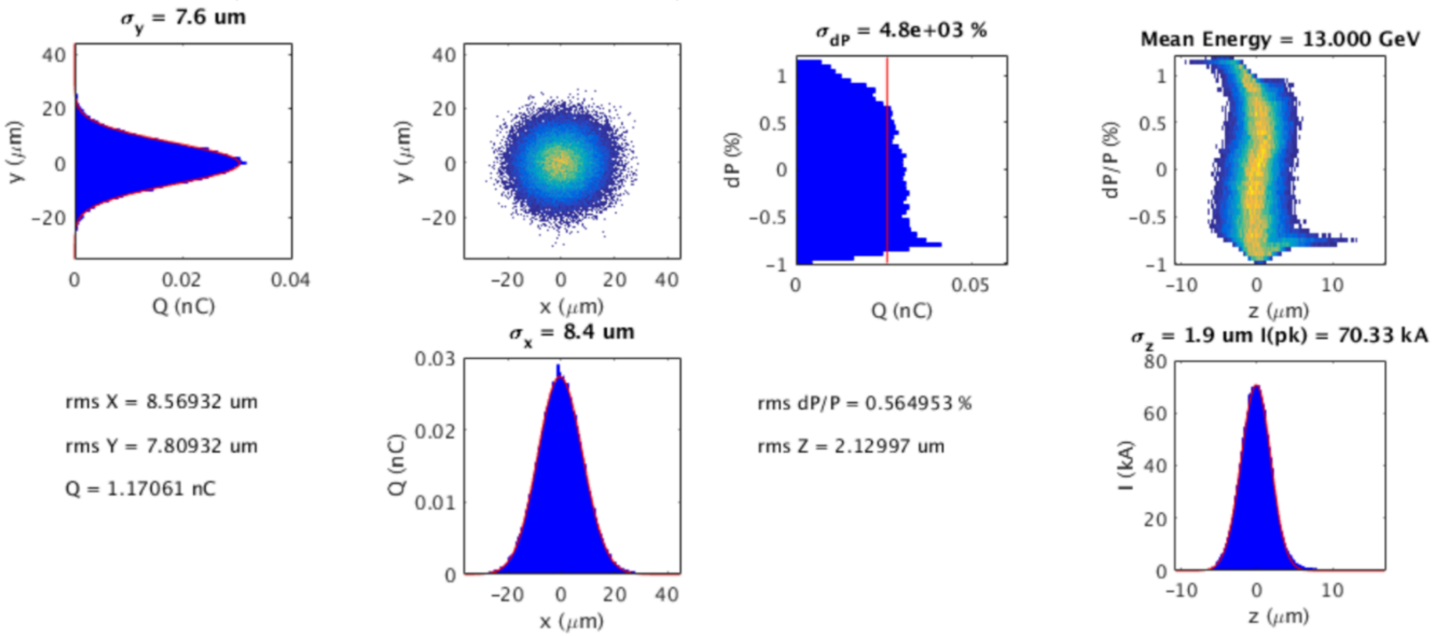


Challenge: Extreme parameters across the board: Peak current, emittance, high-density cm-length plasmas with 100's μm precision tailored density profile, tolerances, drive beam preparation and extraction….and preserving brightness of high current beam in 1km of linac!

Start to End Particle Tracking for FACET-II

- Track 20M macro particles from the cathode to the IP
- IMPACT-T for cathode to the entrance of L1 at 135 MeV
- Entrance of L1 to the IP tracked using the 6D tracking code Lucretia, including wakefields, ISR, CSR and longitudinal space charge effects

Spoiler foils used to smooth beam profile and minimize incoming noise/ correlations on drive beam



rms X = 8.56932 um

rms Y = 7.80932 um

Q = 1.17061 nC

rms dP/P = 0.564953 %

rms Z = 2.12997 um

Requires < 10% transverse asymmetry in drive beam
Correlations and noise can trigger hosing – numerical, real?

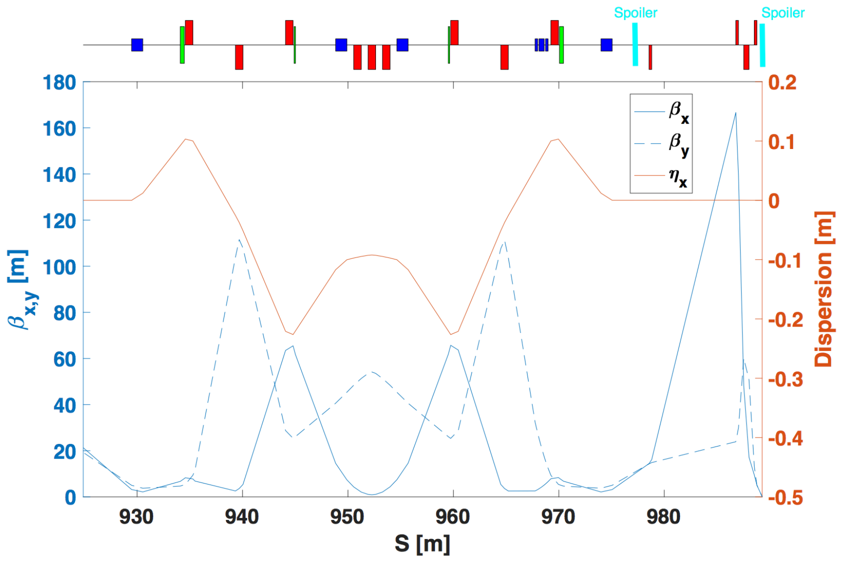
FACET-II accelerator compression and focusing systems need to be optimized to minimize beam asymmetries and correlations

Courtesy of Glen White

Plasma Cell Optics – Match Drive Beam In & Injected Beam Out

Deliver drive beam to plasma:

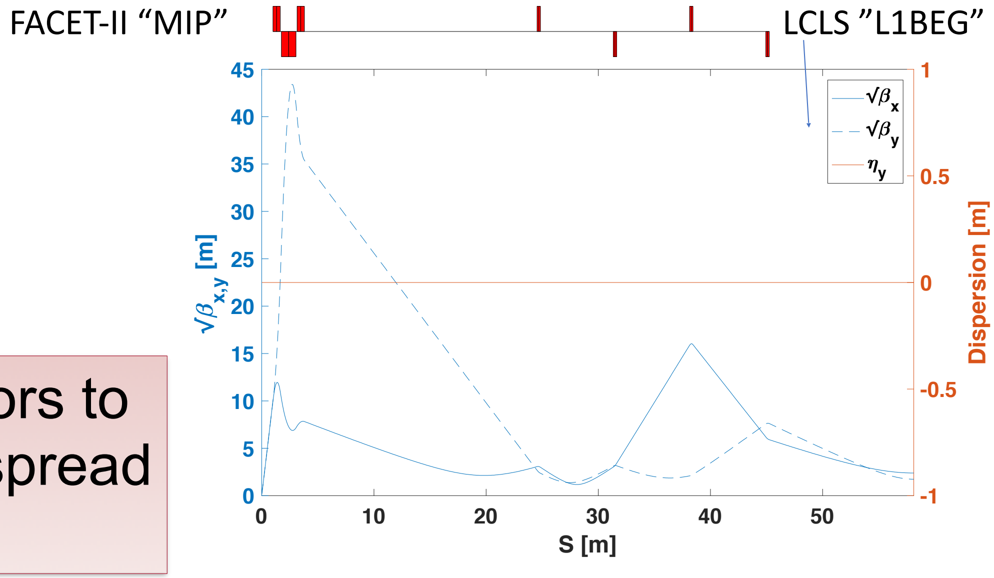
- Redesigned BC20 & FFS
- Aberrations @ IP minimized
- Q = 2 nC, $\beta^*_{x,y}$ = 5 cm, $\sigma^*_{x,y}$ = 8 μm, I_{pk} = 70 kA
- Emittance increased 6->15 μm-rad using spoilers to symmetrize beam



Match output from plasma cell to LCLS

- E = 2.5 GeV
- $\beta^*_{x,y}$ = 1 cm
- Q = 20 pC
- I_{pk} = 10 kA
- 0.8 fs (rms)
- $\varepsilon_{x,y}$ = 0.05 μm-rad

Extraction is a reverse final focus system and wants percent level energy spread, not the large chirps common in many PWFA injection beams

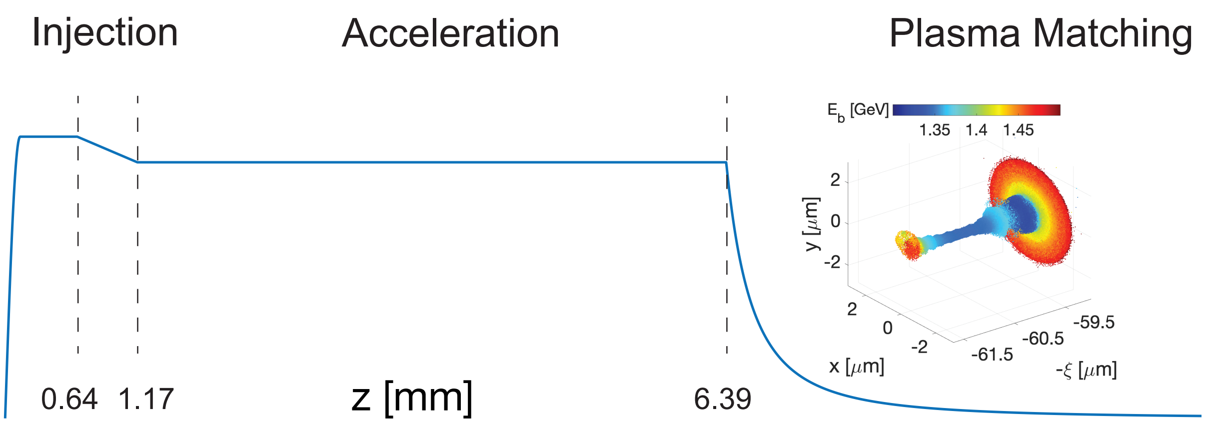


Exit energy and chirp are important factors to limit degradation of emittance & energy spread – loading, de-chirpers…

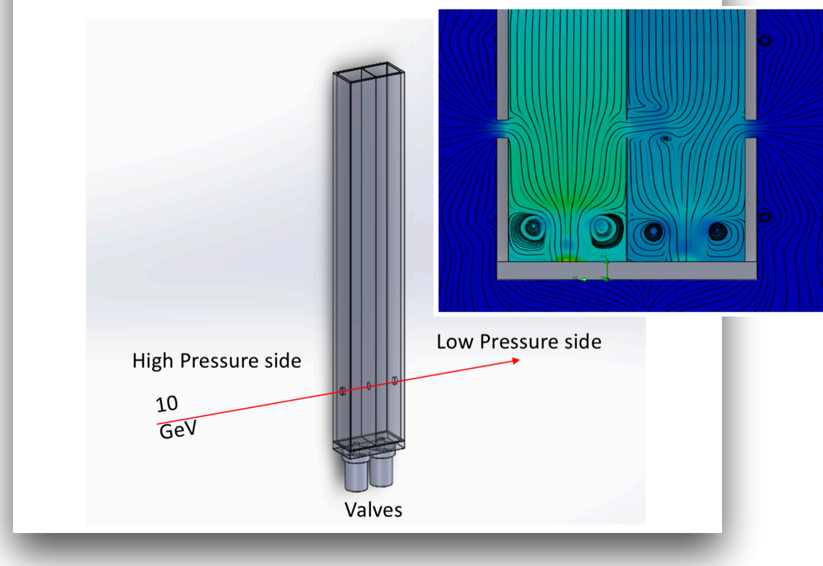
Courtesy of Glen White

Plasma Sources are Active Area of R&D

- The plasma serves many functions: injector, accelerator, focusing system…
- Injected beam brightness proportional to the plasma density
- Density downramp injection requires control of plasma density profile over length scales from 100’s of microns to 10’s of centimeters
- Specialized gas targets will need to be developed

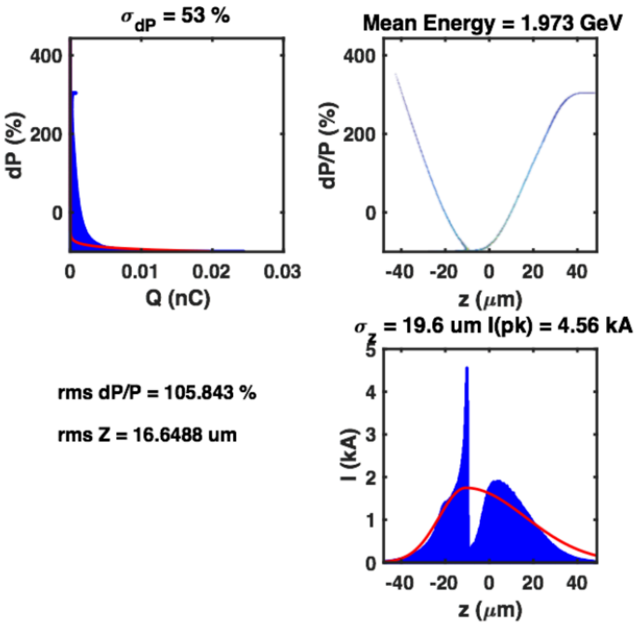


Double Gas Cell with Density Step



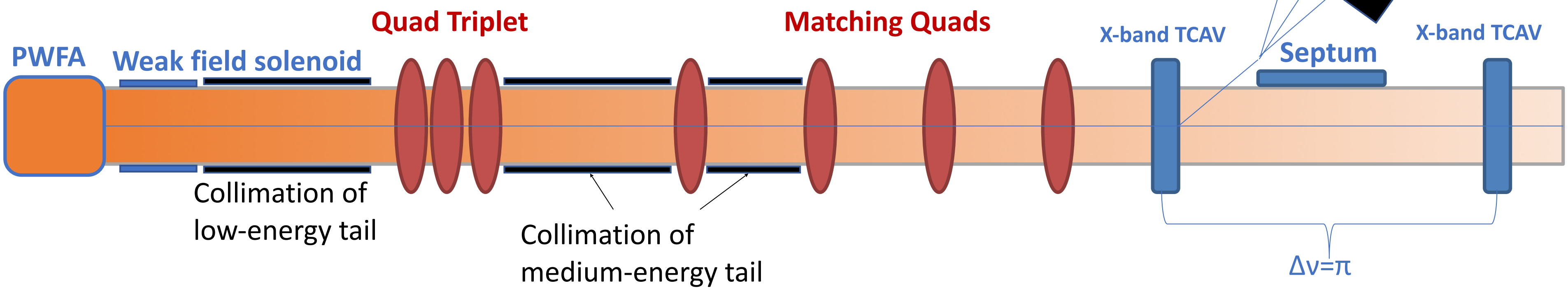
Suitable plasma sources need to be developed and demonstrated – may use mechanical or optical techniques for generating optimal profile

Plasma Extraction & Collimation/Dump Layout



- Low energy tail of driver bunch is collimated after initial magnet elements
- Remnant of driver separated by TCAV and septum bend
- Beam quality of witness beam preserved

High-brightness beams don't like to be bent. Extraction seems feasible but devil will be in the details.



Power loss seems manageable at 120Hz. Detailed design will depend on details of phase space of exiting beams

Courtesy of Glen White & Joe Frisch

Outline

- Since task force concluded there is renewed interest in studying high-brightness PWFA beams for FEL applications
- Current focus is on soft X-rays and attosecond pulses, aiming for shorter pulses and higher peak power than available with LCLS

- Will discuss two here:
  1. Attosecond PWFA-FEL schemes – PLEASE (with/without external laser)
  2. PWFA-FEL with an advanced gradient undulator

FACET-II Facility for Advanced Accelerator Experimental Tests

PWFA FEL Summary Slides

C. Emma
October 2019

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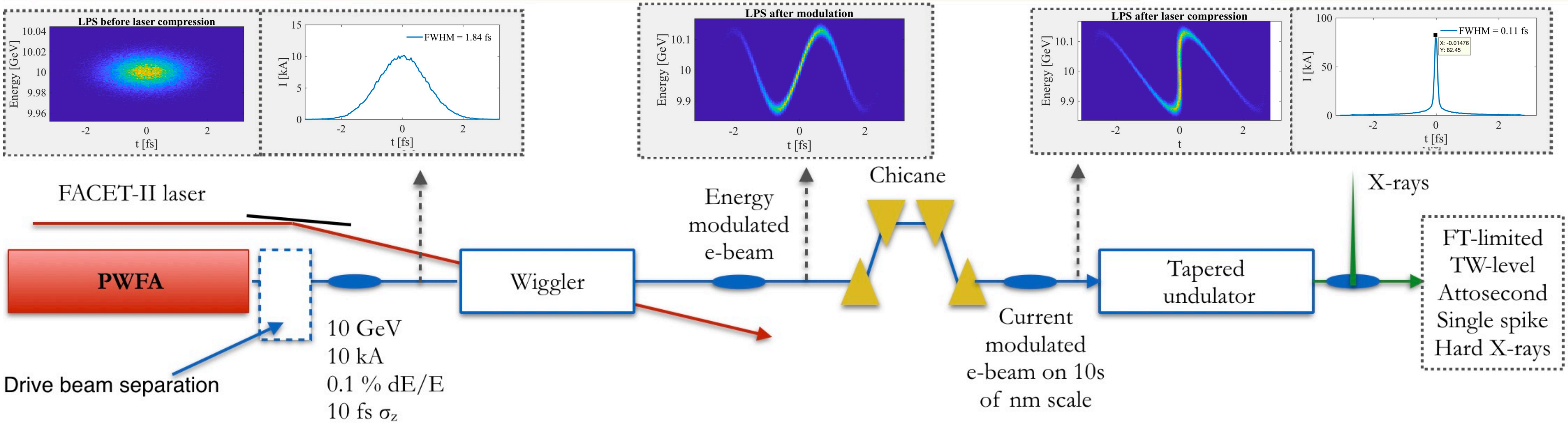
Attosecond pulses from PWFA + eSASE-FEL (PLEASE)
Plasma-driven Laser-Enhanced Amplified Spontaneous Emission

Goal:

- Generate very short (10s of as) X-ray pulses taking advantage of high brightness ultra-low emittance (nm level) beam from plasma photo injector.

Approach:

- Use laser-based compression to reduce pulse length from ~fs to ~as level with a short wiggler & chicane
- Note: initially investigated with aspirational beam parameters, heading to start to end simulations now



FACET-II laser

PWFA

Drive beam separation

10 GeV
10 kA
0.1 % dE/E
10 fs σ_z

Wiggler

Energy
modulated
e-beam

Chicane

Current
modulated
e-beam on 10s
of nm scale

Tapered
undulator

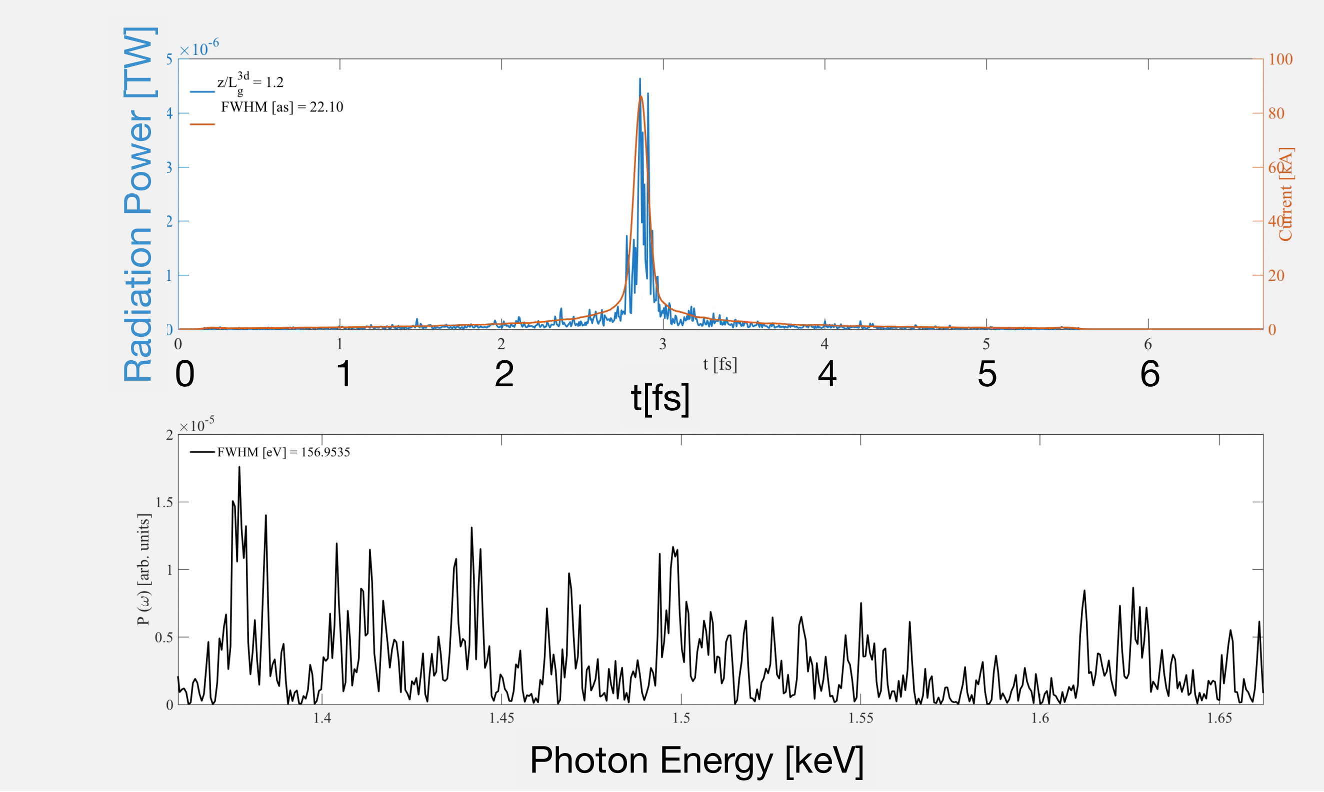
X-rays

FT-limited
TW-level
Attosecond
Single spike
Hard X-rays

GENESIS Simulation Results and Future Study

- Simulation gives 2 TW power in 5 m with FWHM 42 as and 46 eV bandwidth
- Time-bandwidth product is 1.93 eV*fs, very close to the Fourier limit (1.8 eV*fs)
- Future study needed to quantify emittance degradation in compression process and design drive beam separation

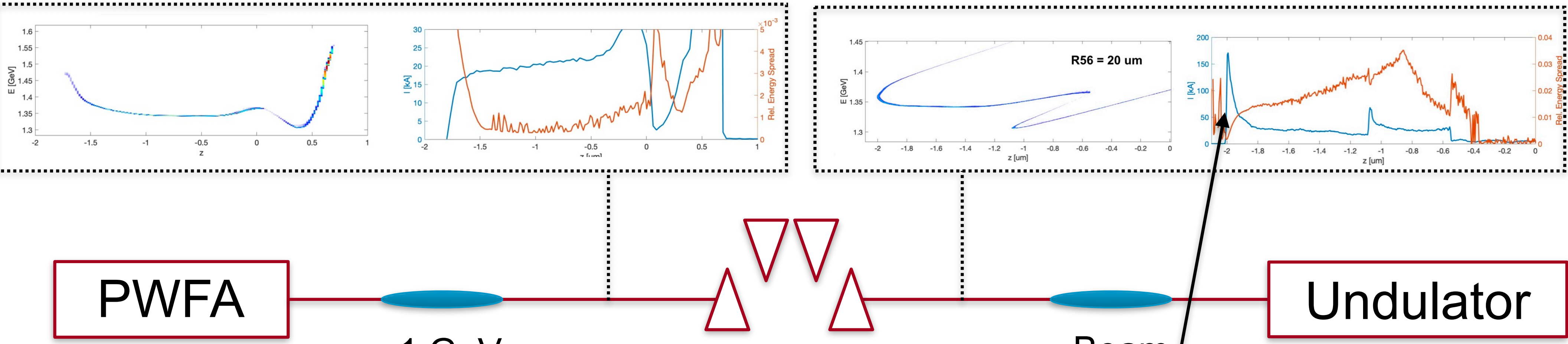
Electron Beam	**Value**
Energy	10 GeV
Peak Current	10 kA
Emitttance	50 nm
Energy Spread (pre-compression)	10^{-3}
Undulator (LCLS-II SXRU)	
Period	3.9 cm
Peak K (planar)	5.5
FEL parameters	
Photon Energy	1.5 keV
Pierce Parameter (80 kA after compression)	10^{-2}
Gain Length	25 cm



Attosecond Pulses from PWFA - no External Laser and Wiggler

Goal:

- Use quadratic chirp at the tail of the high quality PWFA accelerated beam to compress in a small chicane and generate short current spike at tail
- Lase on the tail spike in a short undulator and get TW-level short pulses



PWFA

1 GeV
10^{-3} σ_e
0.1 um
20 kA
300 pC

Small R56
Chicane

Beam
With compressed
Tail
>150kA

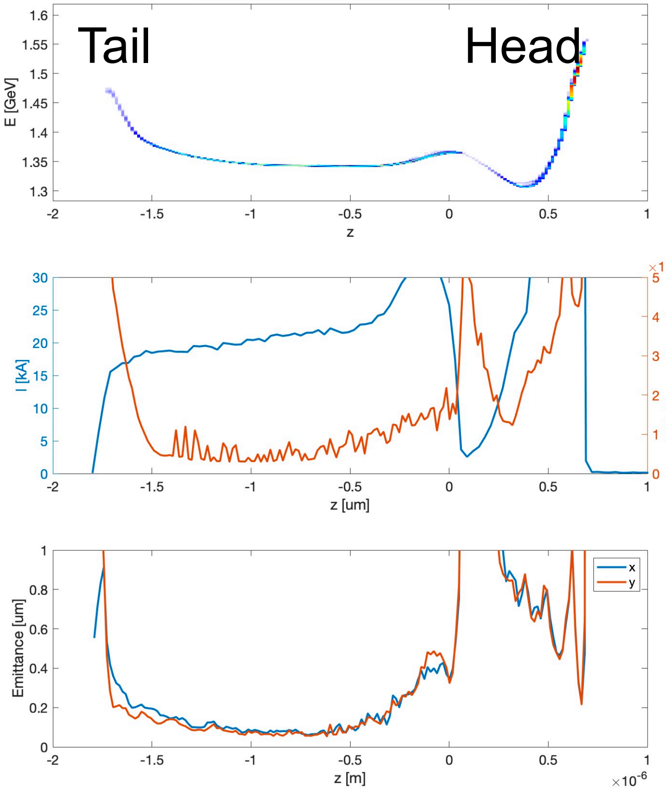
Undulator

Now using beam phase space from actual DDR simulations enroute to start-to-end. Matching and extraction etc still to come

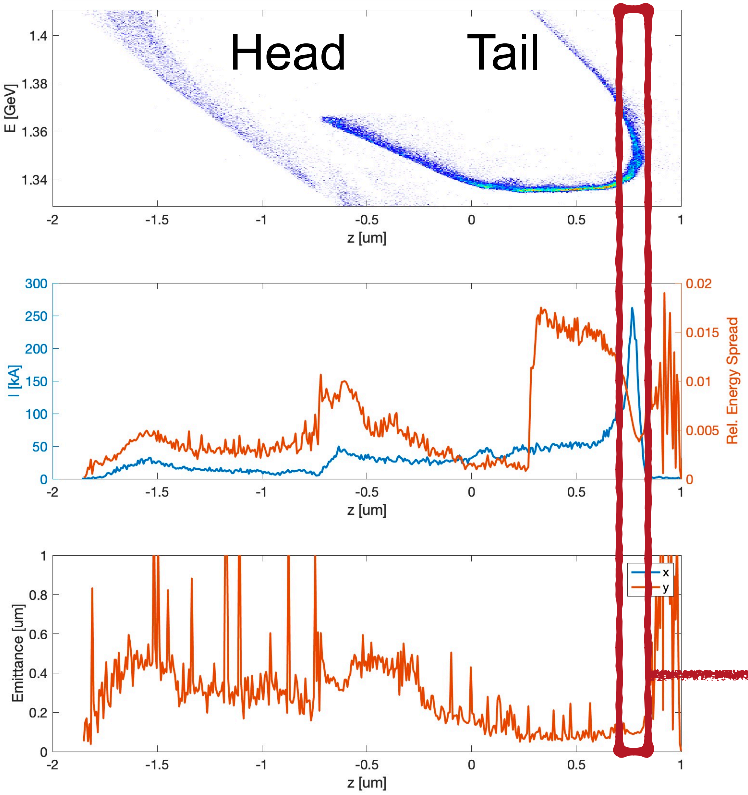
Simulating the Effect of the Small Chicane on PWFA Beam

- There doesn’t appear to be any emittance growth due to CSR
- CSR model is 1D formula from Stupakov which is employed in ELEGANT

Beam from Xinlu



After ELEGANT chicane 50 um

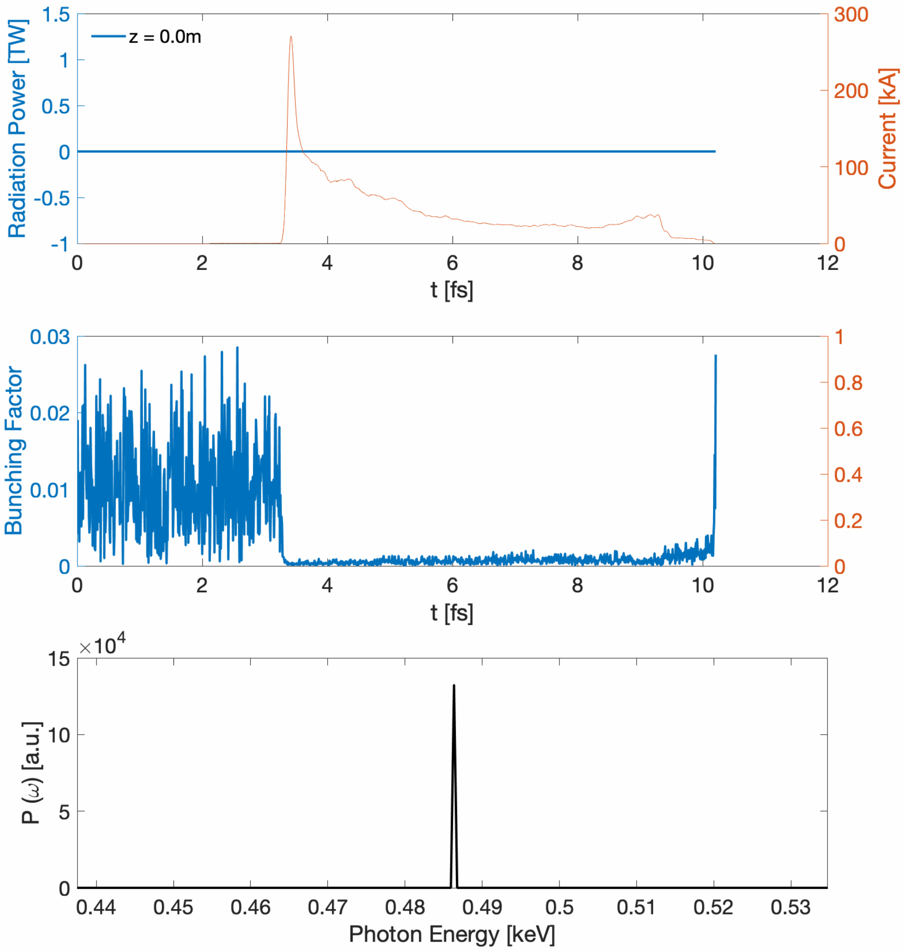


Chicane parameters	Value
Bend Length	15 cm
Drift Length	0.9 m
Bend Angle	32 mrad
Simulation parameters	
# bins for CSR wake in bend	500
# kicks in bend	100
Interval between CSR kicks in drift after bend	1 cm

250kA peak current, 0.2 mm-mrad

GENESIS Results at 500eV with Beam from ELEGANT Chicane

- 1 TW in a 2m undulator with 260 as FWHM and a nearly single spike bandwidth of 4.86 eV
- Still room to play with taper optimization



E-Beam	**Parameter**
Energy	1.3 GeV
Peak Current	250 kA (tail)
Emitttance (x,y)	0.18 um
Energy Spread	10^{-3}
Beta Function	20 m
Rms Spot size	35 um
Undulator	**(LCLS-II SXRU)** $\Delta K/K = -0.05$
Period	2 cm
Peak K (planar)	1.25
Photon Energy	500 eV

List of ongoing & further studies

- Drive beam optimization to remove residual correlations etc
- Jitter analysis & optimization to minimize or mitigate orbit errors into undulator and quantify tolerances
- Plasma source design with correct density profile & ionization method
- Refine injection for better loading or add de-chirper
- Refine extraction and collimation optics
- FEL performance optimization
- …

Considering PWFA Technology for FEL Applications

FACET-II Driver

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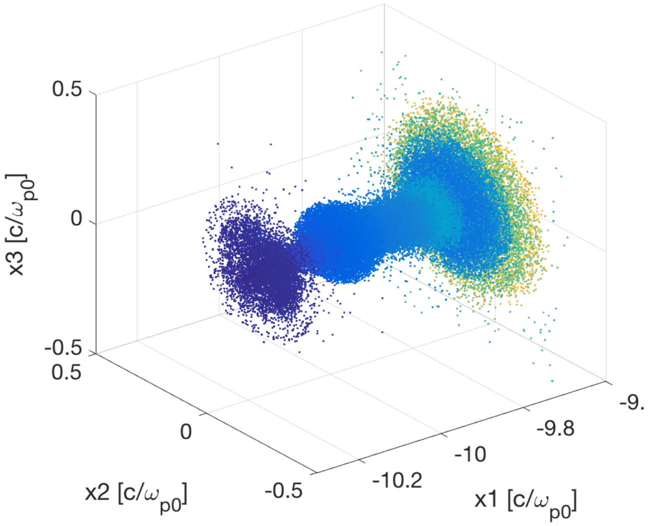
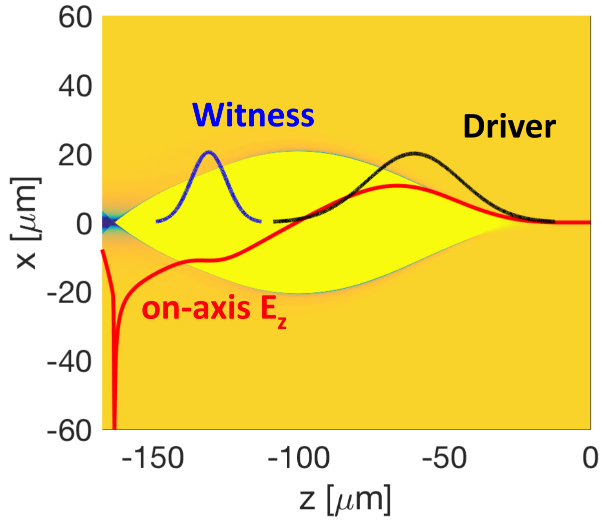
- High brightness beam generated within the plasma (brightness of the driver is not critical)
- Goal: brightness transformer



Ultra-low emittance. Hard X-rays. Peak Brightness

LCLS-II Driver

- Modest current driver (≅2kA)
- Two bunches (drive and witness) generated at photoinjector
- Goal: double energy and preserve brightness

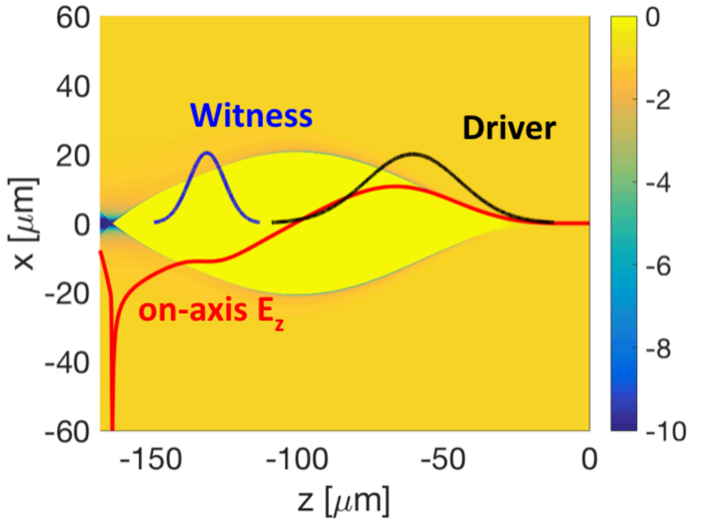


High average power. Easier stability

LCLS-II HE Afterburner Parameters

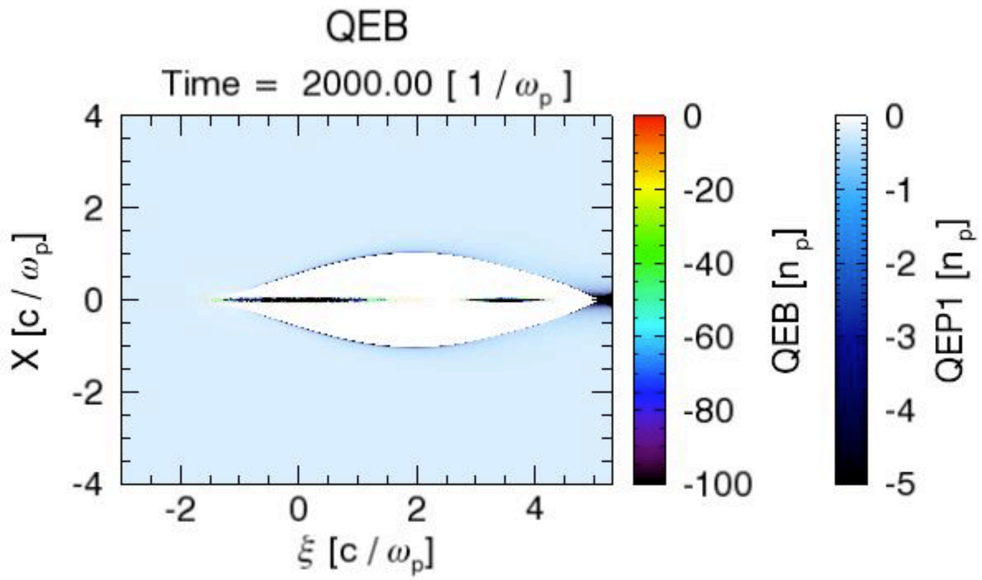
- With proper choice of plasma density can double the energy of a witness beam, preserve emittance at 0.4μm level and load the wake for narrow energy spread
- For Gaussian beams ~70% of energy doubled beam has desirable slice dE/E for good FEL performance
- Fairly insensitive to variations in witness beam bunch length, charge and separation from drive beam
- Creating this pulse structure from LCLS-II is non-trivial

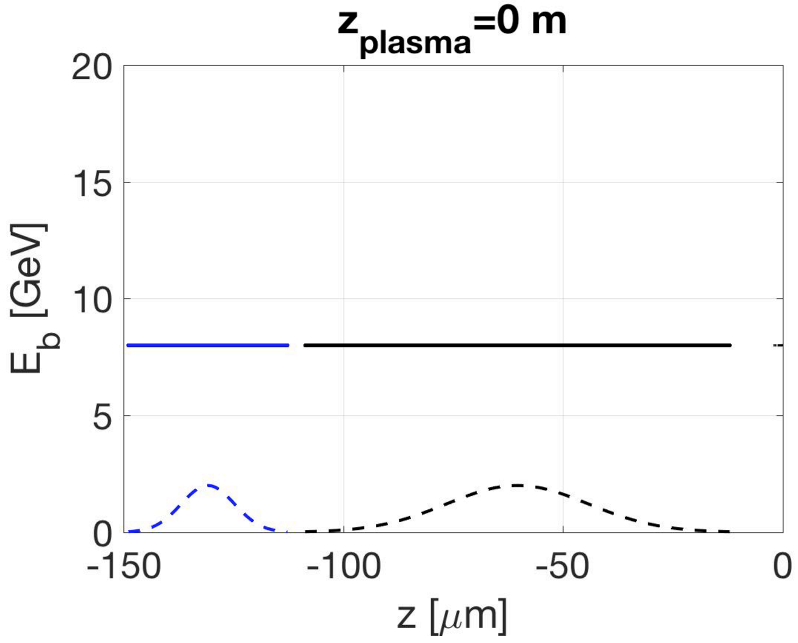
	I [kA]	σ_z [μm]	ϵ_n [μm]	σ_r [μm]	Q [pC]	E_b [GeV]	σ_{Eb} [keV]
Driver	2	16	1.2	0.52	269	8	80
	I [kA]	**σ_z [μm]**	**ϵ_n [μm]**	**σ_r [μm]**	**Q [pC]**	**E_b [GeV]**	**σ_{Eb} [keV]**
Witness	2	6	0.4	0.3	103	8	80
	n_p [cm^{-3}]	**k_p^{-1} [μm]**					
Plasma	7e16	20					

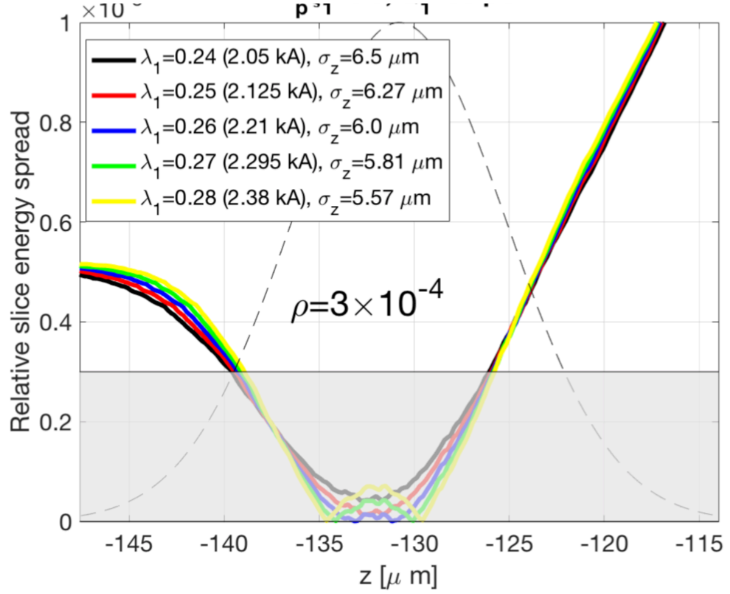


Courtesy of Xinlu Xu

Use QuickPIC to Model Expected Performance

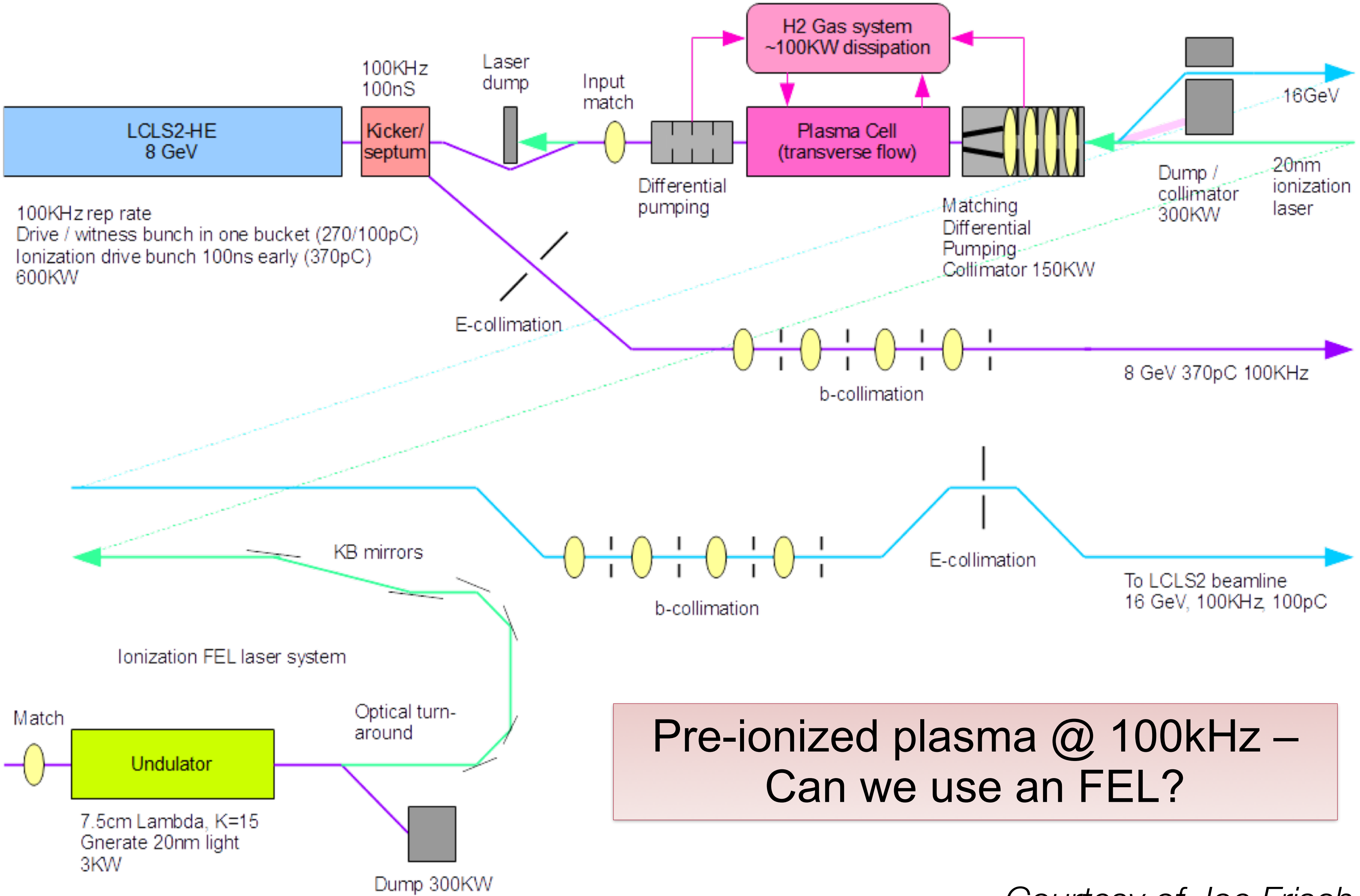






Lower charge with preserved emittance will impact peak FEL performance. Produces higher energy beams for shorter wavelengths and high average power.

Components for LCLS-II HE Energy Doubler are Similar to High Brightness Injector with Some Important Differences



Pre-ionized plasma @ 100kHz –
Can we use an FEL?

Courtesy of Joe Frisch

For details and mitigations – see presentation by X. Xu 2017 Workshop

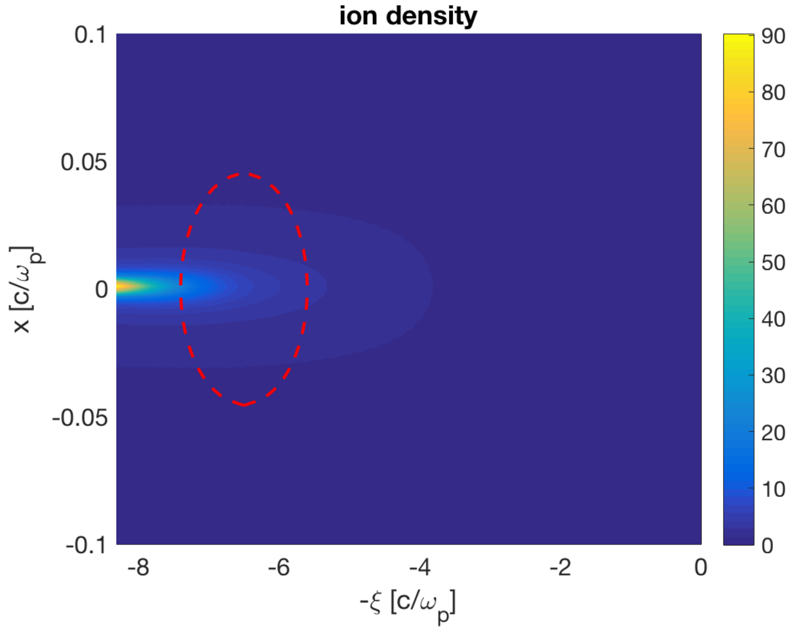
Ion Motion May Affect the Energy Spread – Important for FEL Applications

	I [kA]	σ_z [µm]	ε_n [µm]	σ_r [µm]	Q [pC]	E_b [GeV]	σ_{Eb} [keV]
Driver	2	16	1.2	0.52	269	8	80
Witness	2	6	0.4	0.3	103	8	80
	n_p [cm^{-3}]	k_p^{-1} [µm]					
Plasma	7e16	20					

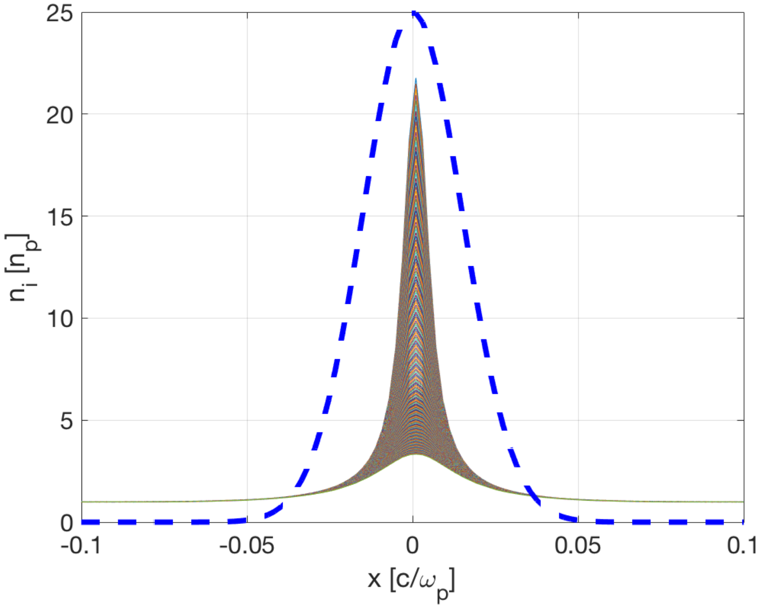
Peak beam density will cause slight ion motion

- $n_d \approx 350\ n_p$
- $n_w \approx 1000\ n_p$
- $m_i = 1836 m_e$

QuickPIC one-step simulation



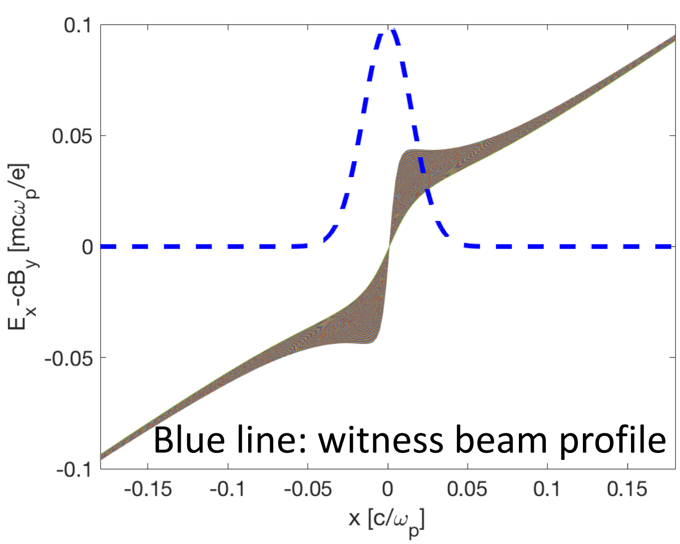
Red line: 3-sigma boundary of the witness beam



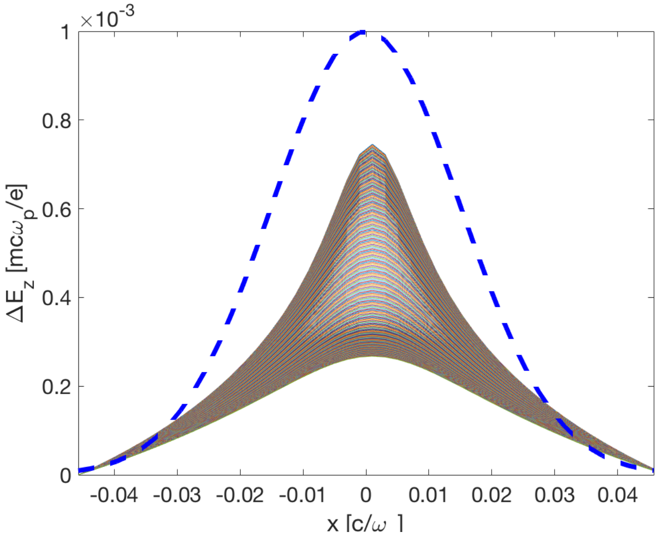
Blue line: witness beam profile

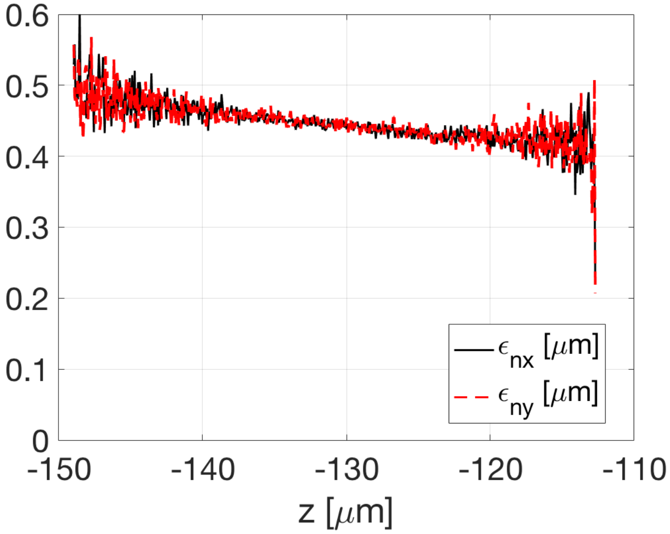
Ion Motion Causes Aberration to Focusing & Accelerating Fields

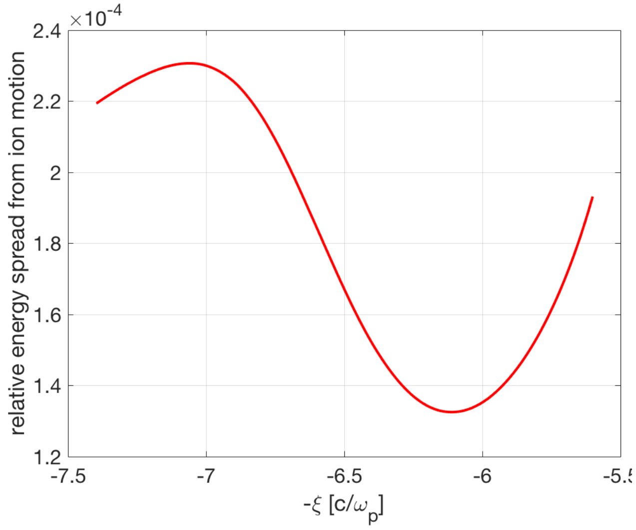
Transverse and longitudinal fields connected through the Panofsky-Wenzel Theorem

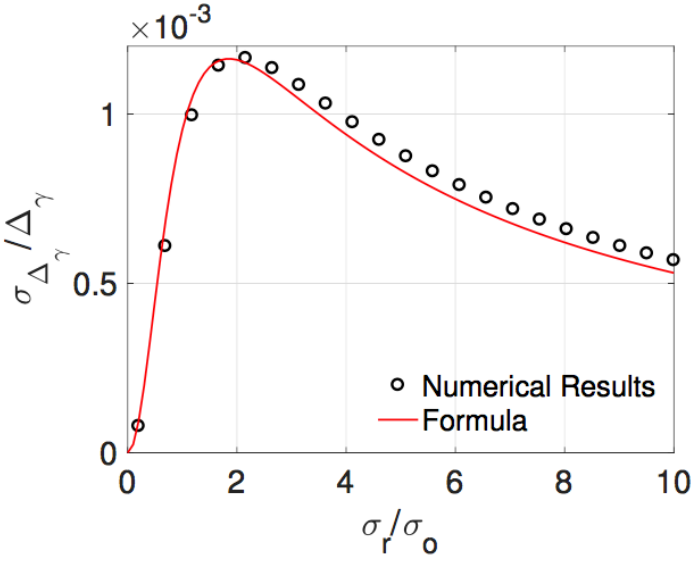


Blue line: witness beam profile

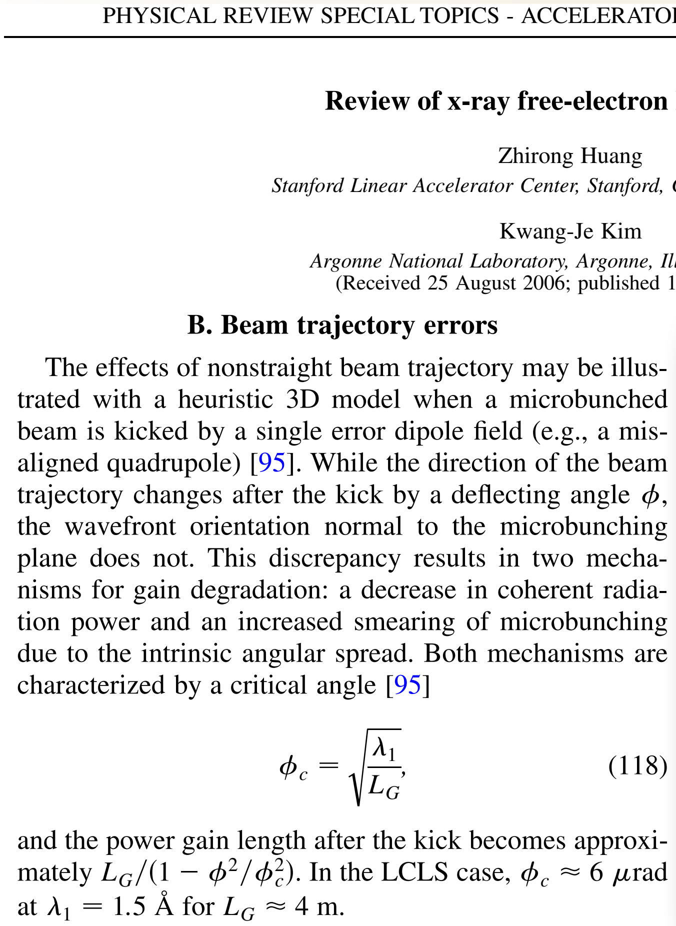








Output Jitter Can Reduce FEL Performance



PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS **10**, 034801 (2007)

Review of x-ray free-electron laser theory

Zhirong Huang
Stanford Linear Accelerator Center, Stanford, California 94309, USA

Kwang-Je Kim
Argonne National Laboratory, Argonne, Illinois 60439, USA
(Received 25 August 2006; published 12 March 2007)

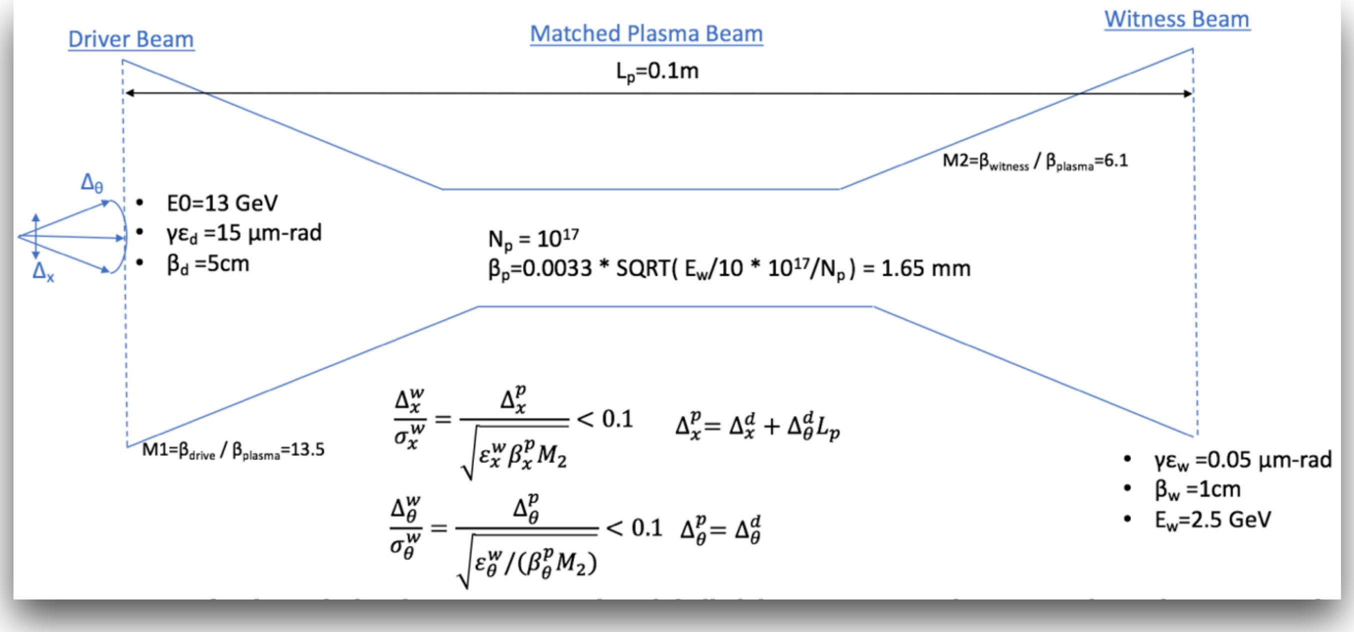
B. Beam trajectory errors

The effects of nonstraight beam trajectory may be illustrated with a heuristic 3D model when a microbunched beam is kicked by a single error dipole field (e.g., a misaligned quadrupole) [95]. While the direction of the beam trajectory changes after the kick by a deflecting angle ϕ, the wavefront orientation normal to the microbunching plane does not. This discrepancy results in two mechanisms for gain degradation: a decrease in coherent radiation power and an increased smearing of microbunching due to the intrinsic angular spread. Both mechanisms are characterized by a critical angle [95]

$$\phi_c = \sqrt{\frac{\lambda_1}{L_G}}, \qquad (118)$$

and the power gain length after the kick becomes approximately $L_G/(1 - \phi^2/\phi_c^2)$. In the LCLS case, $\phi_c \approx 6$ μrad at $\lambda_1 = 1.5$ Å for $L_G \approx 4$ m.

$$\left(\frac{\Delta_y^w}{\sigma_y^w}\right)^2 = \frac{L^2N^2\{\varepsilon_y^d/\beta_d M\}}{\varepsilon_y^w \beta_w M} \quad and \quad \left(\frac{\Delta_\theta^w}{\sigma_\theta^w}\right)^2 = 0$$



- E0=13 GeV
- $\gamma\varepsilon_d$ =15 μm-rad
- β_d =5cm

$$\frac{\Delta_x^w}{\sigma_x^w} = \frac{\Delta_x^p}{\sqrt{\varepsilon_x^w \beta_x^p M_2}} < 0.1 \qquad \Delta_x^p = \Delta_x^d + \Delta_\theta^d L_p$$

$$\frac{\Delta_\theta^w}{\sigma_\theta^w} = \frac{\Delta_\theta^p}{\sqrt{\varepsilon_\theta^w/(\beta_\theta^p M_2)}} < 0.1 \quad \Delta_\theta^p = \Delta_\theta^d$$

- $\gamma\varepsilon_w$ =0.05 μm-rad
- β_w =1cm
- E$_w$=2.5 GeV

G. R. White and T. O. Raubenheimer, Proc. IPAC’19. doi:10.18429/JACoW-IPAC2019-THPGW087
G. R. White and T. O. Raubenheimer, Proc. NAPAC’19. WEYBA3

Realizing the benefits of ultra-low emittance beams will require tight tolerances on orbit jitter into undulator

FEL Performance Using LCLS-II HXR Undulators – Typically μJ of Energy per pulse and GW Peak Power

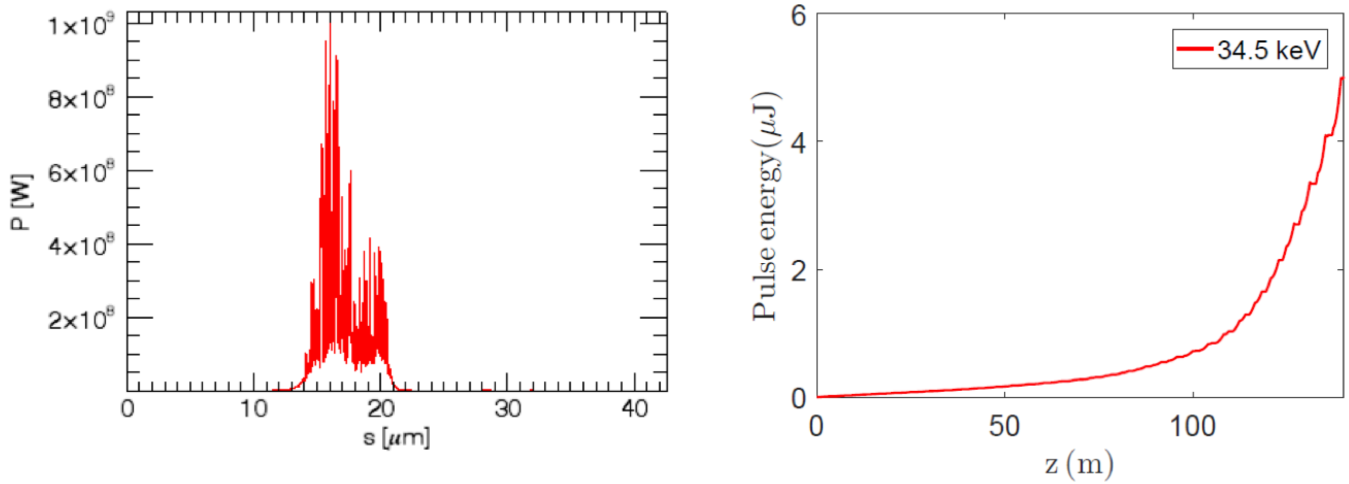


Figure 2: Radiation power along the bunch (left) and pulse energy along the undulator (right) for the 34.5 KeV case. The left plot assumes z = 140 m (the nominal end of the LCLS-II lattice).

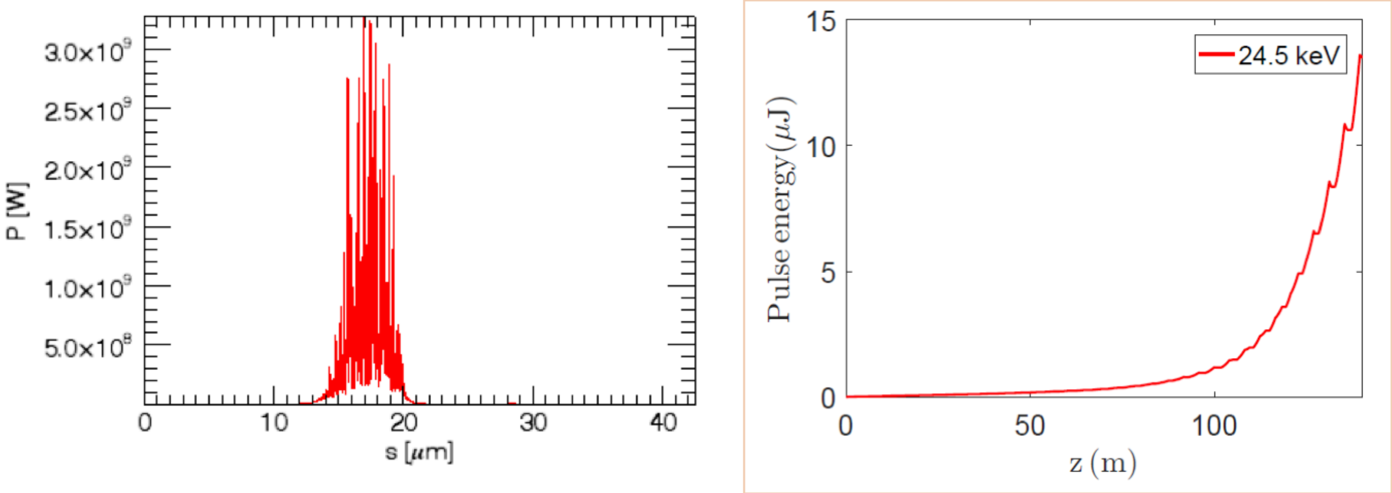


Figure 3: Radiation power along the bunch (left) and pulse energy along the undulator (right) for the 24.5 KeV case. The left plot assumes z = 140 m (as in Figure 2).

- The FEL radiation will not saturate above 34 keV in the LCLS-II HXR undulator line
- @ 1 MHz repetition rate the average brightness of the X-rays from 24 keV to 34 keV is on the order of 10^{25} photons/sec/0.1%BW/mm^2mrad^2 extending the LCLS-II HE brightness curve to even harder X-rays

Courtesy of Zhirong Huang, Panos Baxevanis

Summary

- A SLAC task force studied potential intermediate applications of Plasma Wakefield Acceleration
- Focus on two candidate FEL applications: brightness transformer and energy doubler
- Identified many issues to study for major components
- Anticipated FACET-II experimental program will play a critical role in assessing the viability of these concepts
- Demonstration facility beyond FACET-II will benefit from continued feedback between experiments, theory and simulation to achieve a robust technical design
- Recent focus on attosecond soft X-ray pulses and working towards start-to-end simulations