FACET-II
Facility for Advanced Accelerator Experimental Tests

Plasma Accelerator Based FELs – Status of SLAC Task Force Efforts

FACET-II Science Workshop October 17-20, 2017

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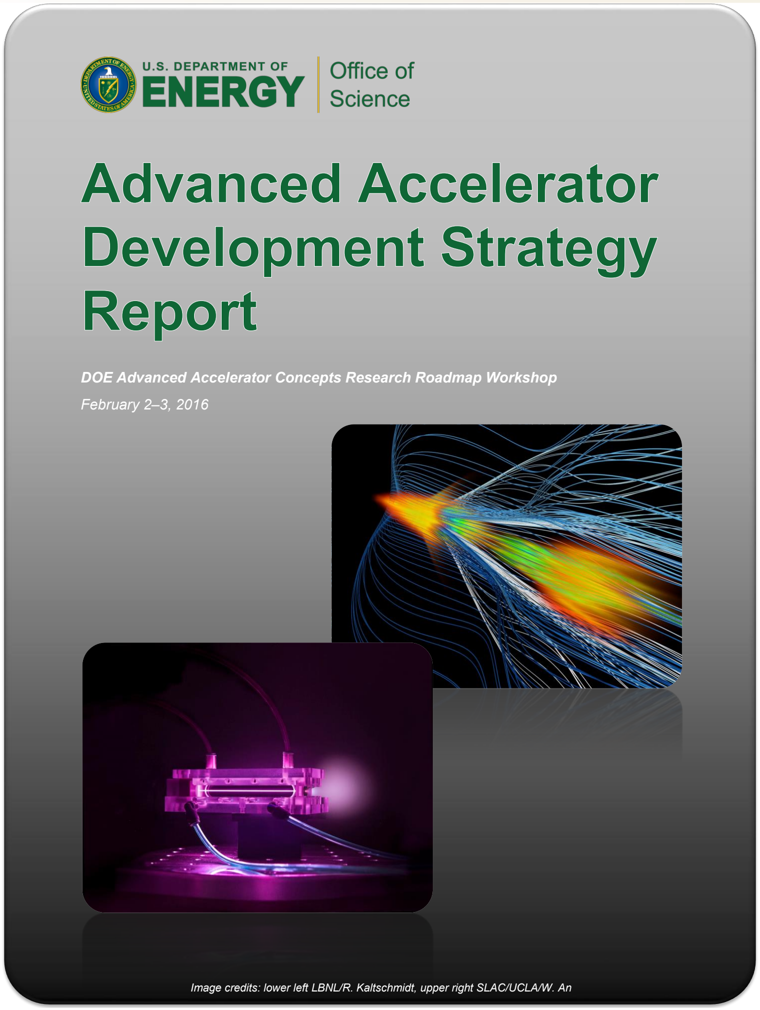
U.S. DEPARTMENT OF ENERGY
Office of Science

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

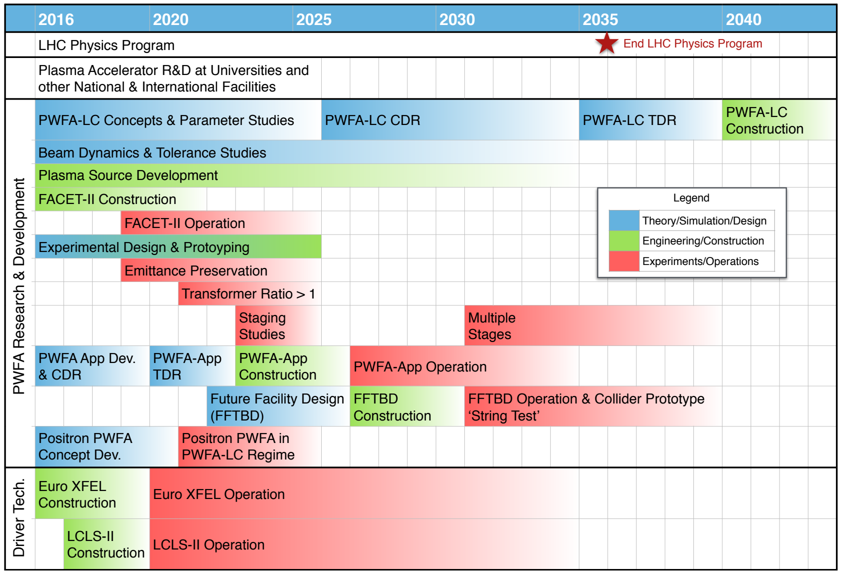
DOE Advanced Accelerator Concepts Research Roadmap Workshop

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

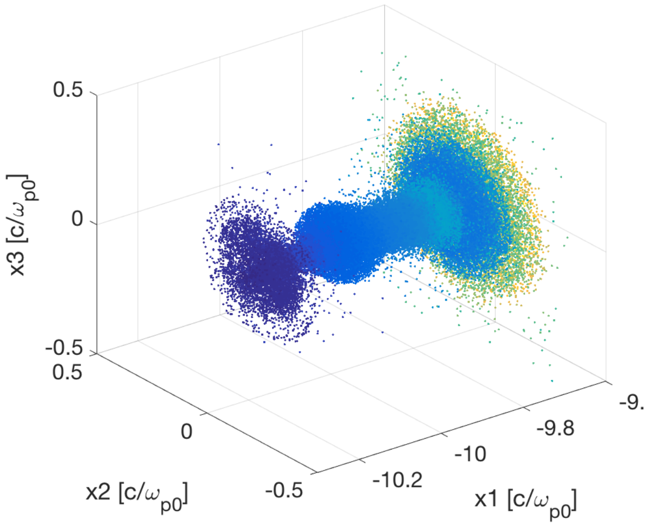
Task Force Members

- 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

Considering PWFA Technology for FEL Applications

FACET-II Driver

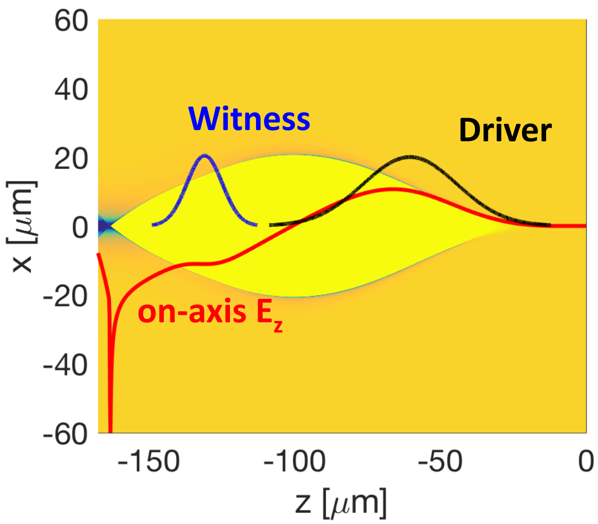
- High peak current driver (≳20kA)
- High brightness beam generated within the plasma (brightness of the driver is not critical)
- Goal: brightness transformer



Ultra-low emittance. 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

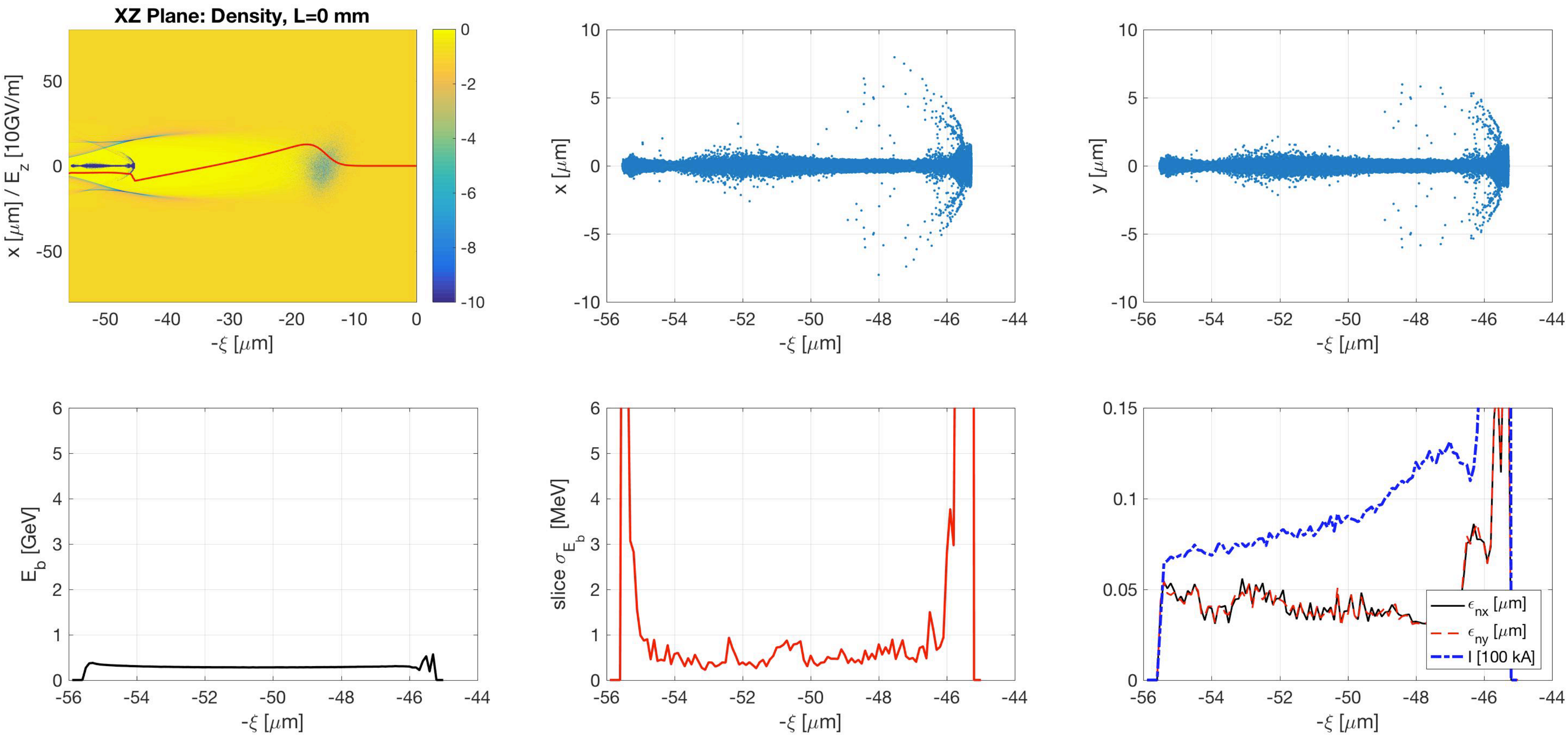


High average power. Easier stability

For details – see presentation by X. Xu

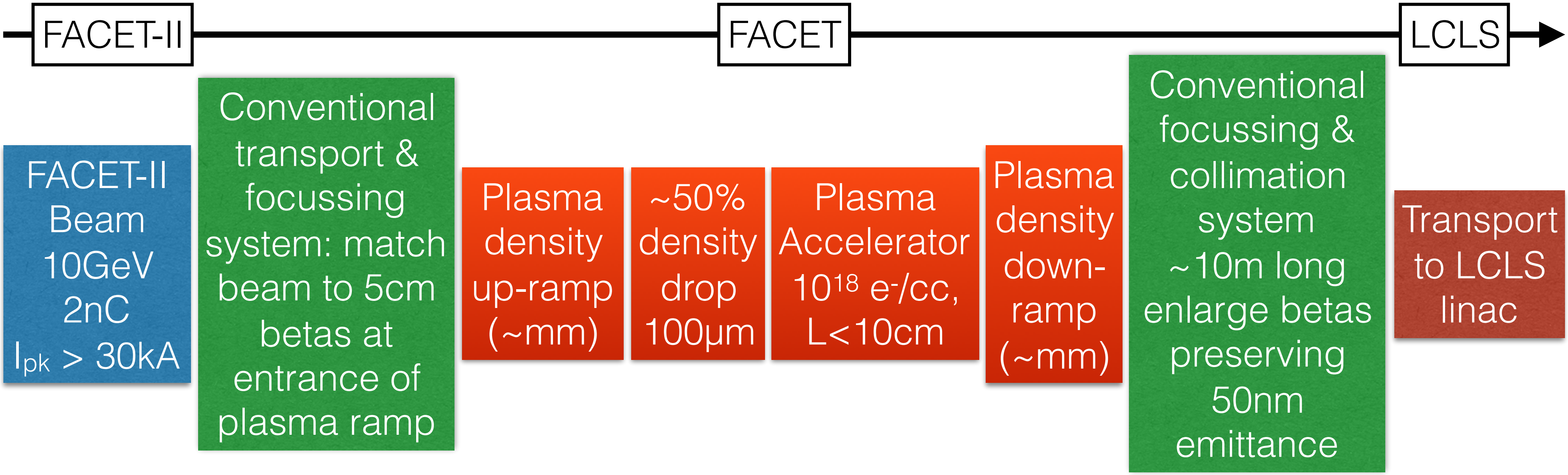
Example Density Downramp Injection Simulation

- 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. Build a second beam line to inject this new beam into the LCLS linac to diagnose, prepare and inject into existing undulators.



FACET-II

FACET

LCLS

FACET-II Beam
10GeV
2nC
$I_{pk} > 30kA$

Conventional transport & focussing system: match beam to 5cm betas at entrance of plasma ramp

Plasma density up-ramp (~mm)

~50% density drop 100μm

Plasma Accelerator
10^{18} e^-/cc,
L<10cm

Plasma density down-ramp (~mm)

Conventional focussing & collimation system ~10m long enlarge betas preserving 50nm emittance

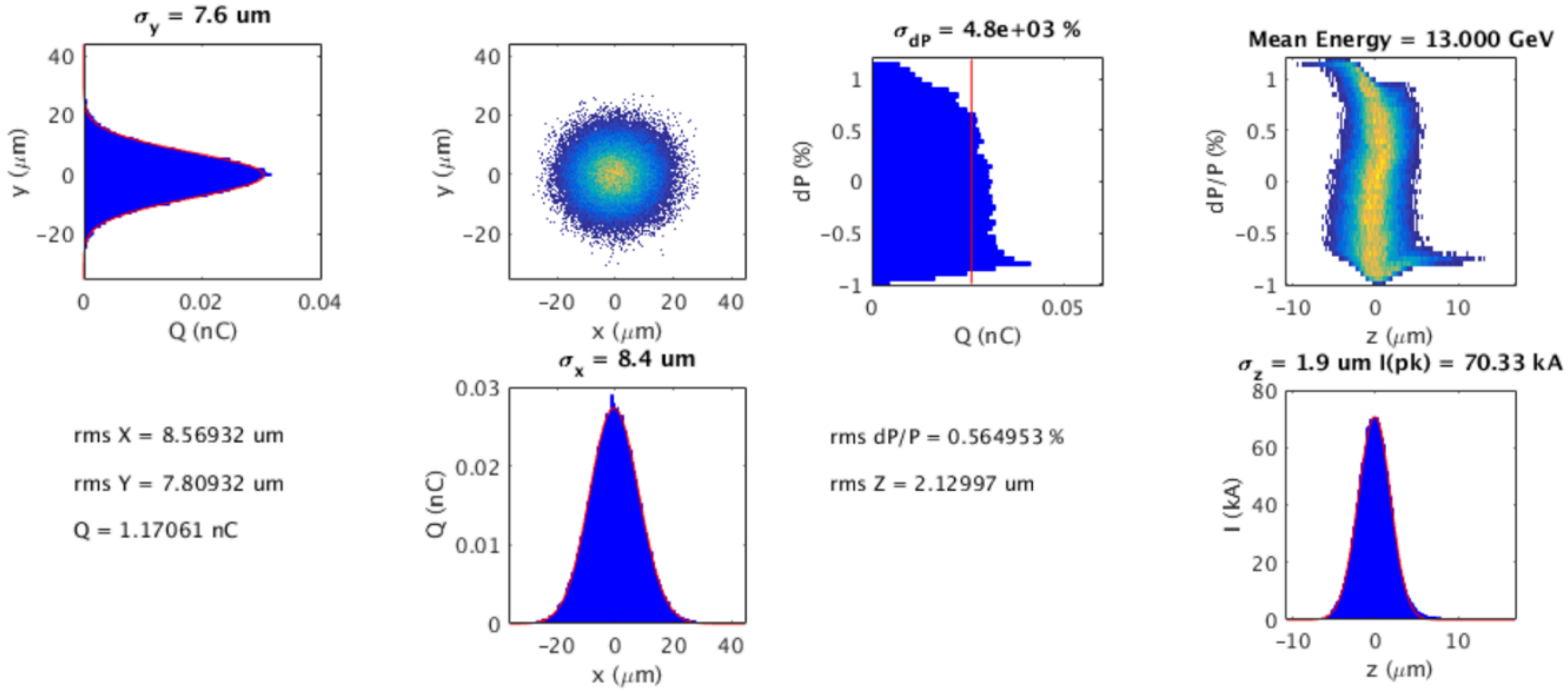
Transport to LCLS linac

Challenge: Addresses issues of plasma injector development, emittance preservation and plasma source development of the roadmap. Leverages existing infrastructure and would have an existing user community. Extreme parameters across the board: Peak current, emittance, high-density cm-length plasmas with 100's μm precision tailored density profile.

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

Projections at the entrance to the plasma are shown:



rms X = 8.56932 um

rms Y = 7.80932 um

Q = 1.17061 nC

rms dP/P = 0.564953 %

rms Z = 2.12997 um

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

Courtesy of Glen White

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

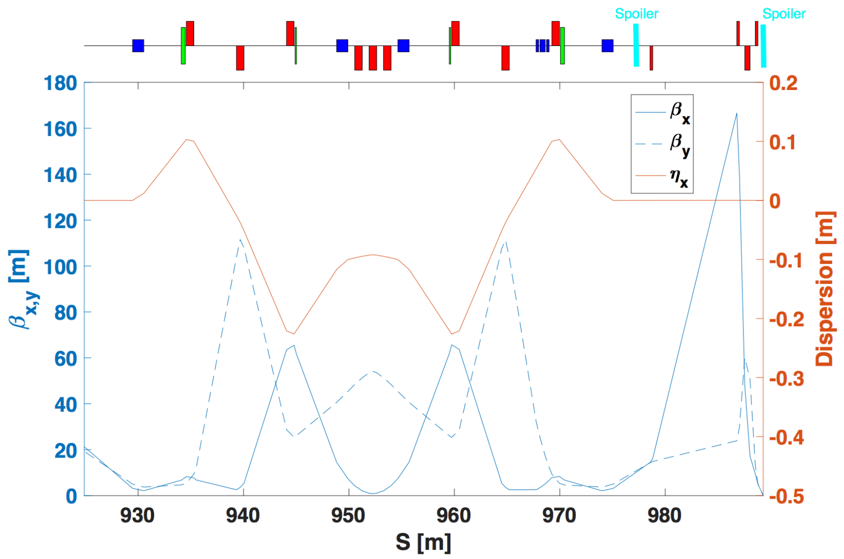
Deliver drive beam to plasma:

- 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

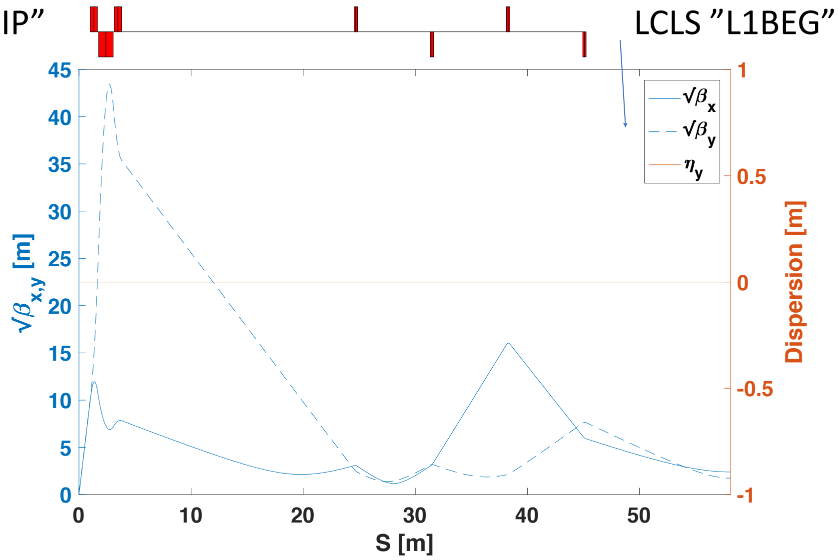
- E = 2.5 GeV
- $\beta^*_{x,y}$ = 1 cm
- Q = 20 pC
- I_{pk} = 10 kA
- 0.8 fs (rms)
- $\varepsilon_{x,y}$ = 0.05 μm-rad

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



FACET-II “MIP”

LCLS ”L1BEG”

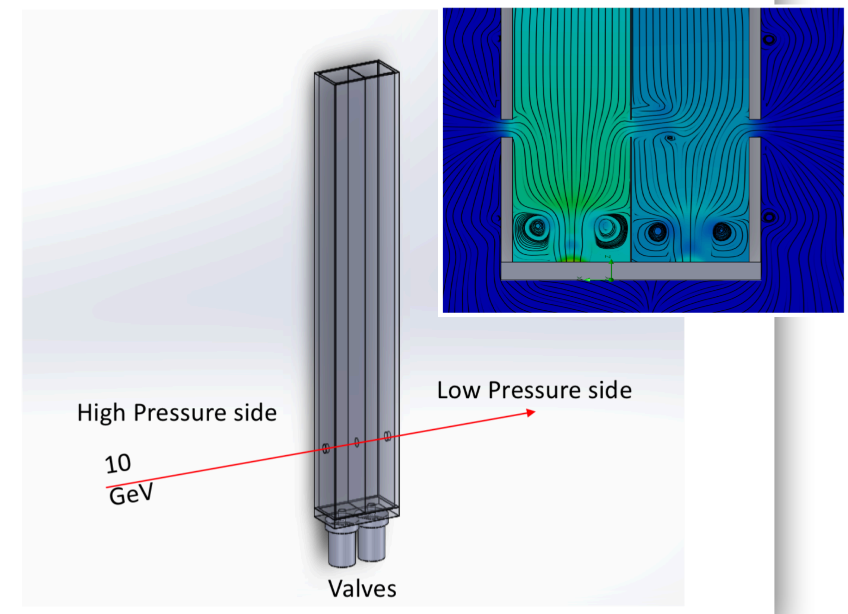


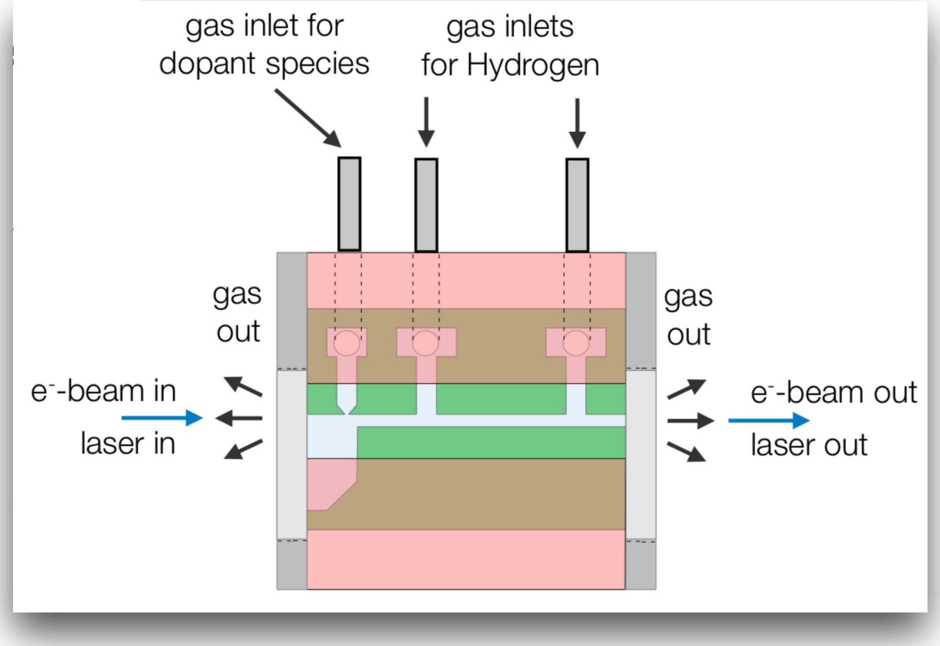
Courtesy of Glen White

Plasma Sources are Active Area of R&D

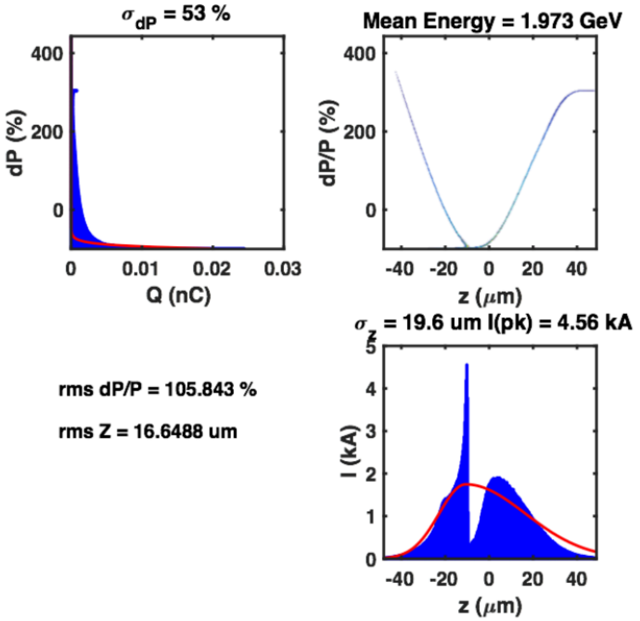
- The plasma serves many functions: injector, accelerator, focusing system…
- Injected beam brightness proportional to the plasma density
- Density downramp injection requires control of plasma density profile over length scales from 100's of microns to 10's of centimeters
- Specialized gas targets – *see e.g. talks by Ken Marsh, Jens Osterhoff*

Double Gas Cell with Density Step

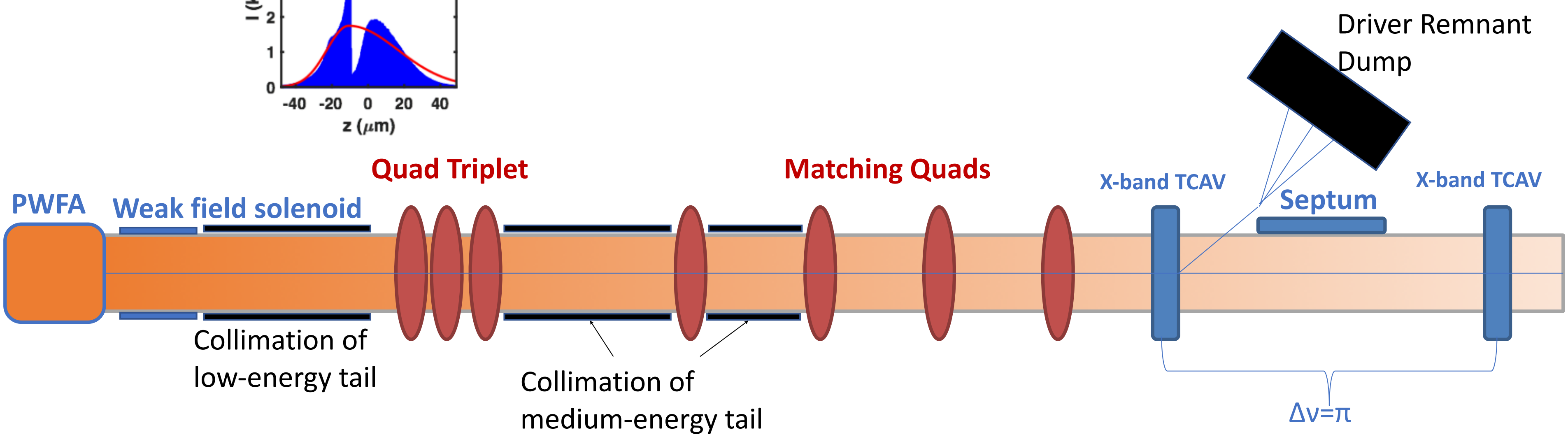




Plasma Extraction & Collimation/Dump Layout



- 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



Driver Remnant Dump

Quad Triplet

Matching Quads

X-band TCAV

X-band TCAV

PWFA

Weak field solenoid

Septum

Collimation of low-energy tail

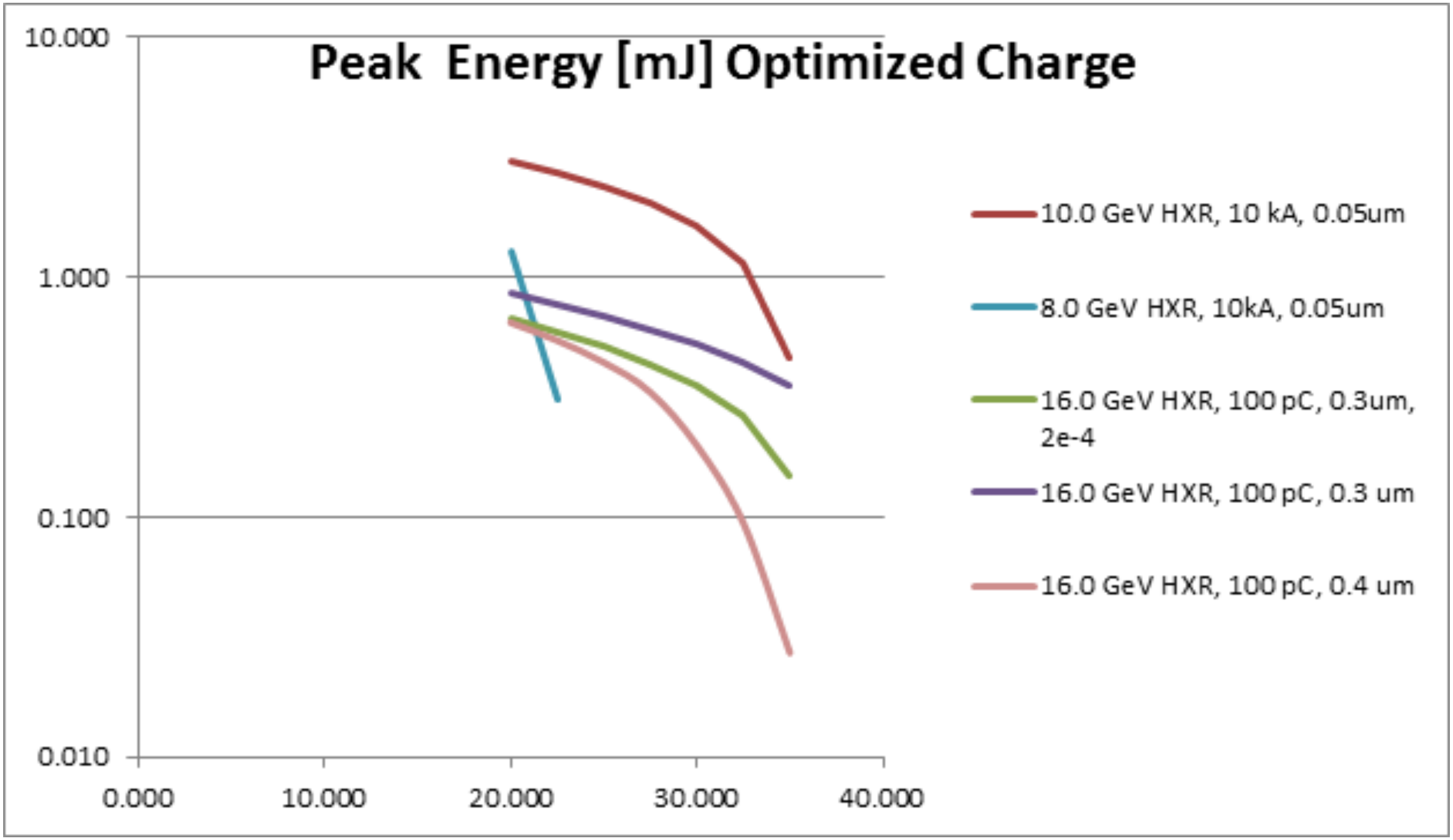
Collimation of medium-energy tail

Δν=π

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

Courtesy of Glen White & Joe Frisch

Ultra-High Brightness Beams – May Extend Capabilities for Hard X-Rays



Courtesy of Tor Raubenheimer

Extending Energy Reach to Very Hard X-Rays Opens New Possibilities

- Crystallography results in the periodically averaged crystal structure, but to study such aperiodic structures it is necessary to go beyond crystallography.
- Alternative approach is to use high energy, short wavelength, x-rays and to measure diffuse scattering over a wide range of momentum transfer.
- The advent of >hard x-ray 25 keV pulses in the LCLS-II upgrade will allow, for the first time, such experiments to be carried out using the unique structure of a free electron laser beam
- Coupling the fast time-structure of the source with ultra-fast pulsed lasers will allow time-resolved measurements of local and nanostructure on the femto and pico second time-scales. Such time-resolved experiments have been carried out at existing XFEL sources, but in materials they usually study the collective response of the system in the form of changes in Bragg peak intensity, for example.
- The PDF approach may be used to study small-molecule systems, metallic and semiconducting nanoclusters, all the way to defective and even perfectly crystalline materials. In the latter case, the method is sensitive to aperiodic responses of the system such as to correlated atom dynamics

Courtesy of Jerry Hastings

List of ongoing & further studies

- Drive beam optimization to remove residual correlations
- Jitter analysis & optimization to minimize orbit errors into undulator
- 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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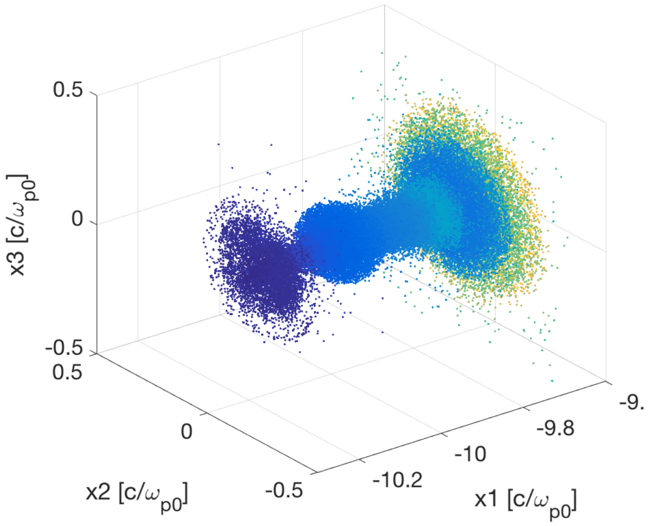
- High brightness beam generated within the plasma (brightness of the driver is not critical)
- Goal: brightness transformer



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

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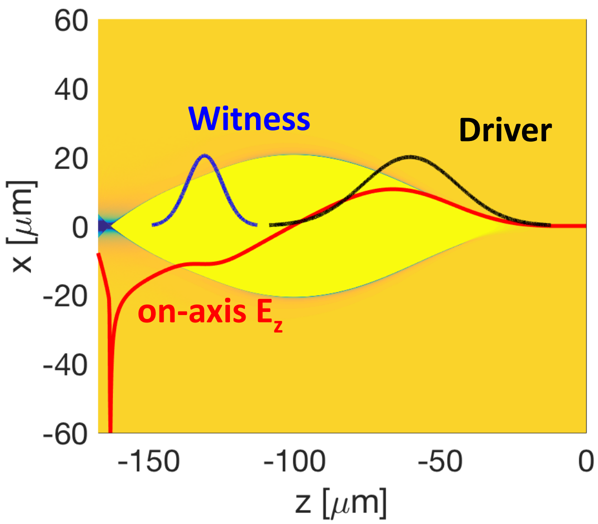
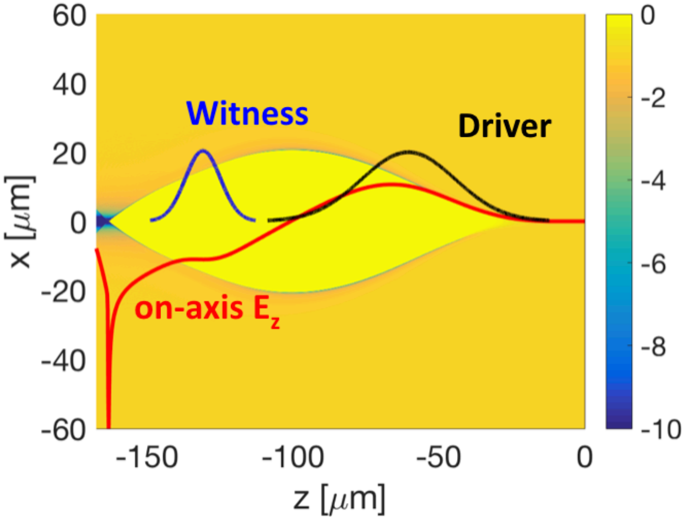


High average power. Easier stability

LCLS-II HE Afterburner Parameters

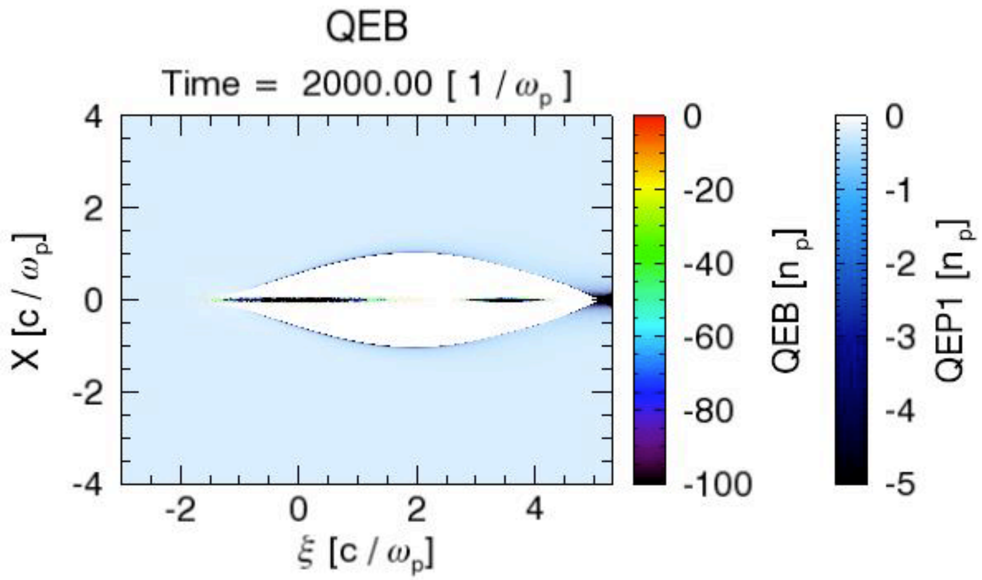
- With proper choice of plasma density can double the energy of a witness beam, preserve emittance at 0.4μm level and load the wake for narrow energy spread
- For Gaussian beams ~70% of energy doubled beam has desirable slice dE/E for good FEL performance
- Fairly insensitive to variations in witness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

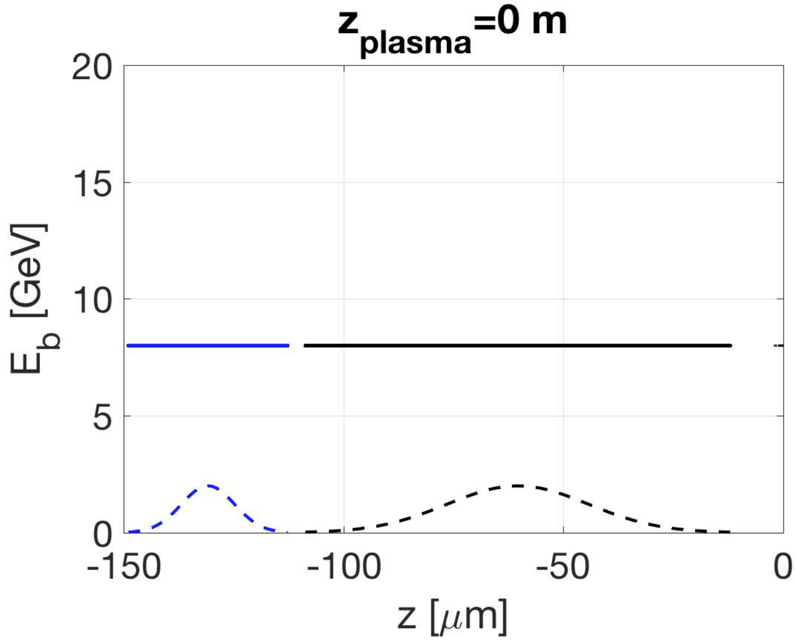
	I [kA]	σ_z [μm]	ε_n [μm]	σ_r [μm]	Q [pC]	E_b [GeV]	σ_{Eb} [keV]
Driver	2	16	1.2	0.52	269	8	80
	I [kA]	σ_z [μm]	ε_n [μm]	σ_r [μm]	Q [pC]	E_b [GeV]	σ_{Eb} [keV]
Witness	2	6	0.4	0.3	103	8	80
	n_p [cm^{-3}]	k_p^{-1} [μm]					
Plasma	7e16	20					

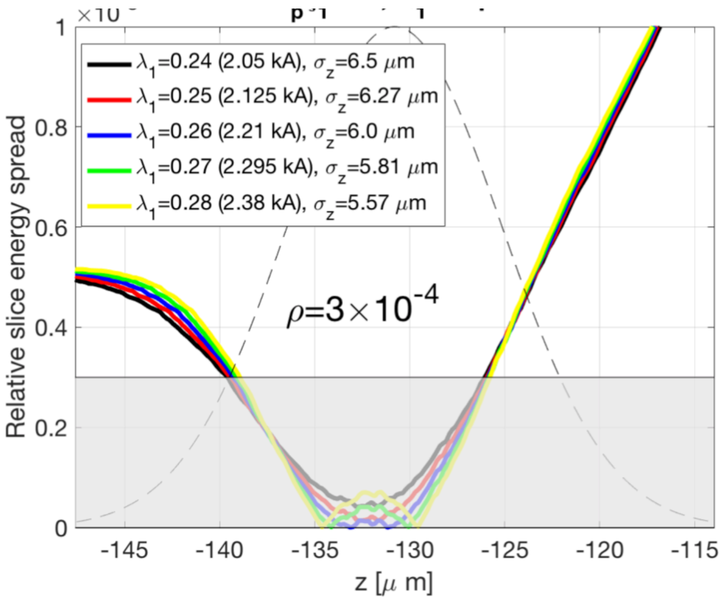


Courtesy of Xinlu Xu

Use QuickPIC to Model Expected Performance

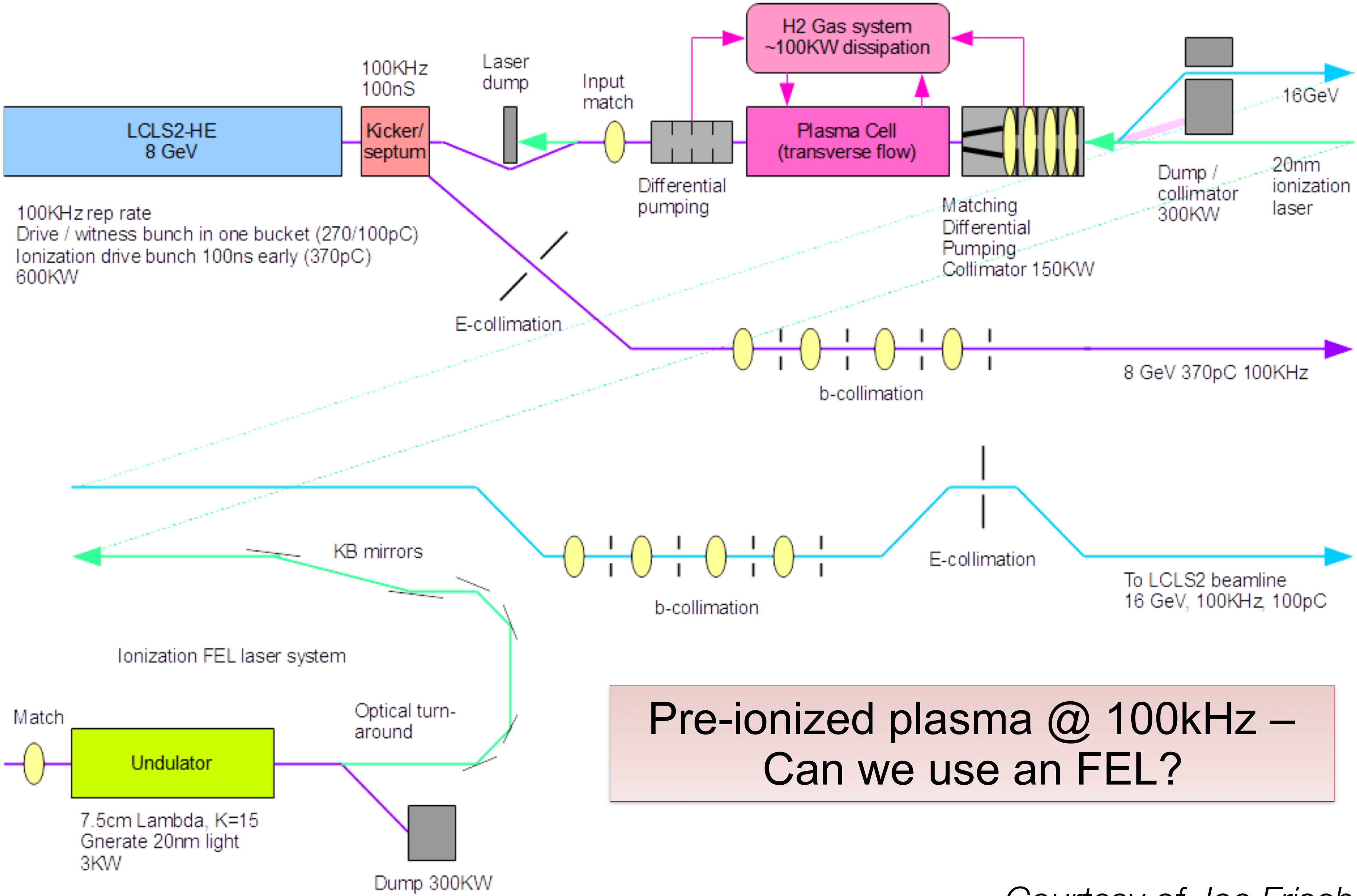






Lower charge with preserved emittance will impact peak FEL performance. Produces higher energy beams for shorter wavelengths and high average power.

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

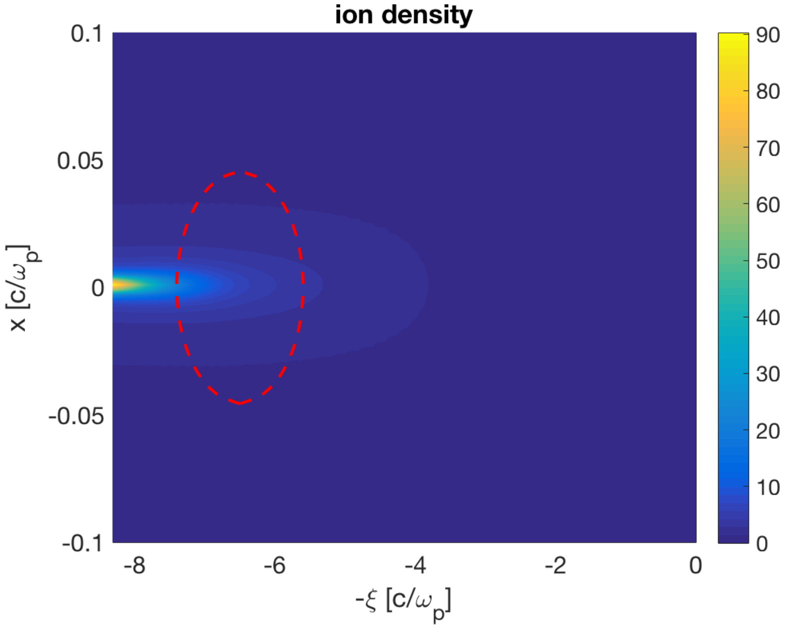
Ion Motion May Affect the Energy Spread – Important for FEL Applications

	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					

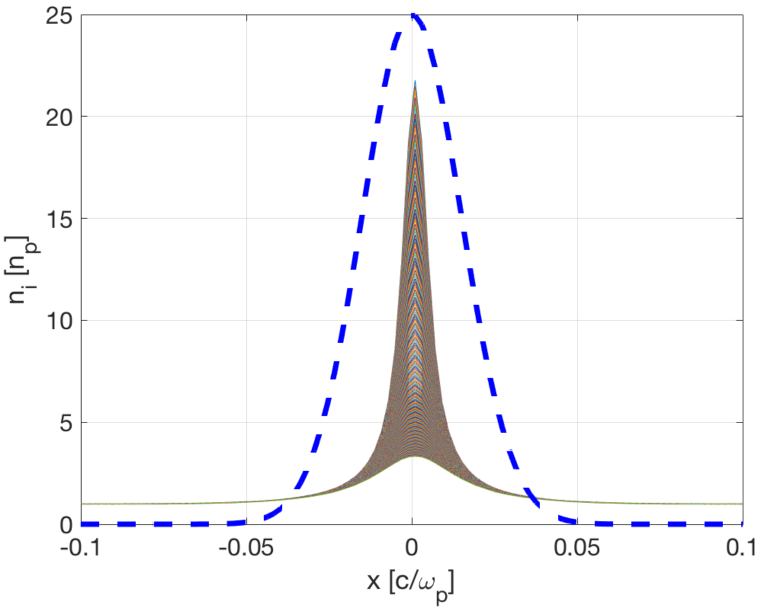
Peak beam density will cause slight ion motion

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

QuickPIC one-step simulation



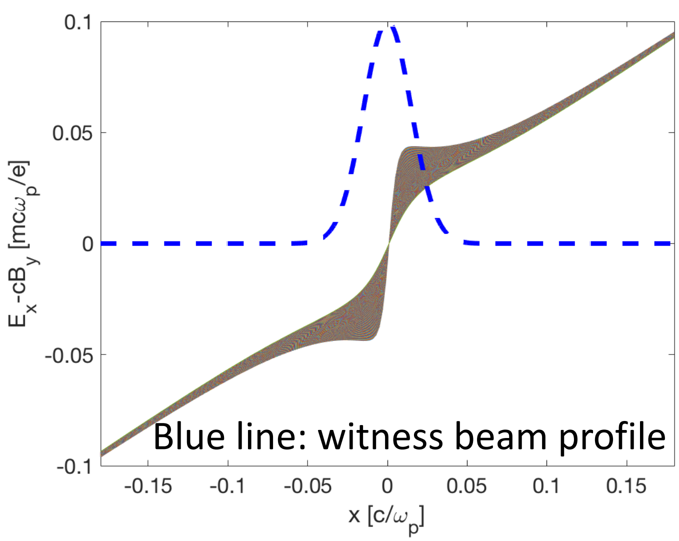
Red line: 3-sigma boundary of the witness beam

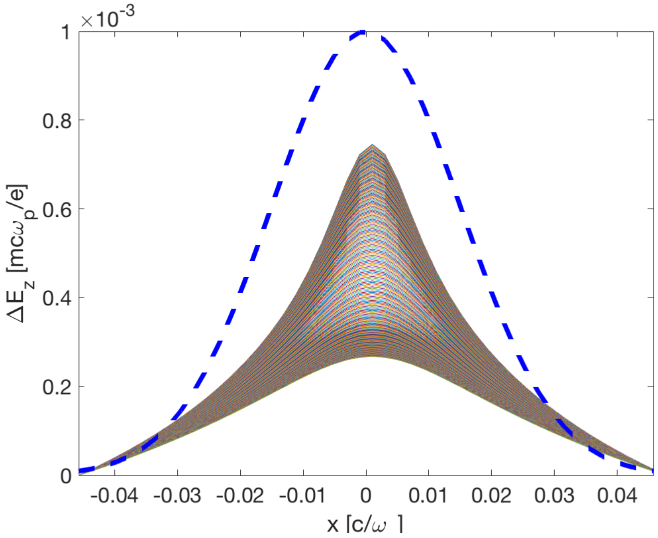


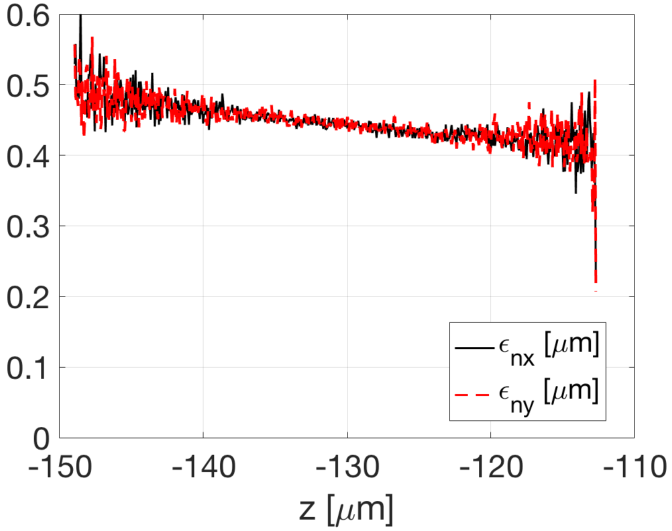
Blue line: witness beam profile

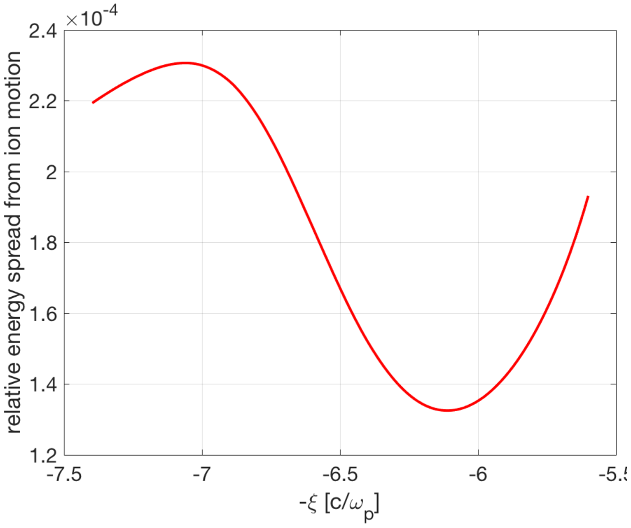
Ion Motion Causes Aberration to Focusing & Accelerating Fields

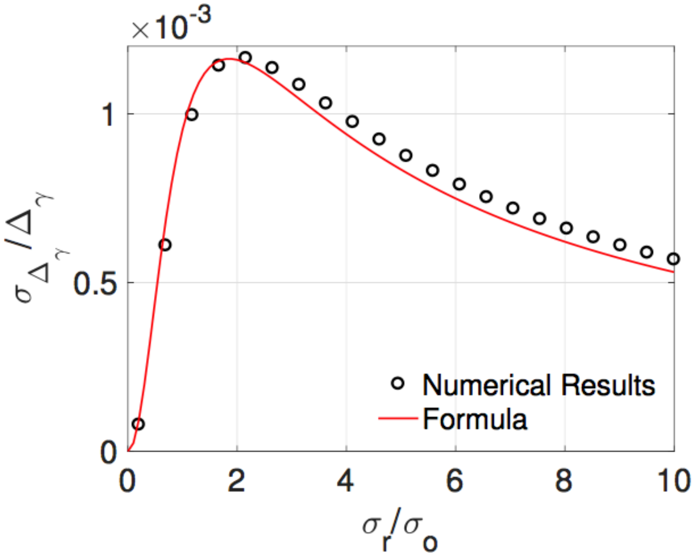
- Transverse and longitudinal fields connected through the Panofsky-Wenzel Theorem



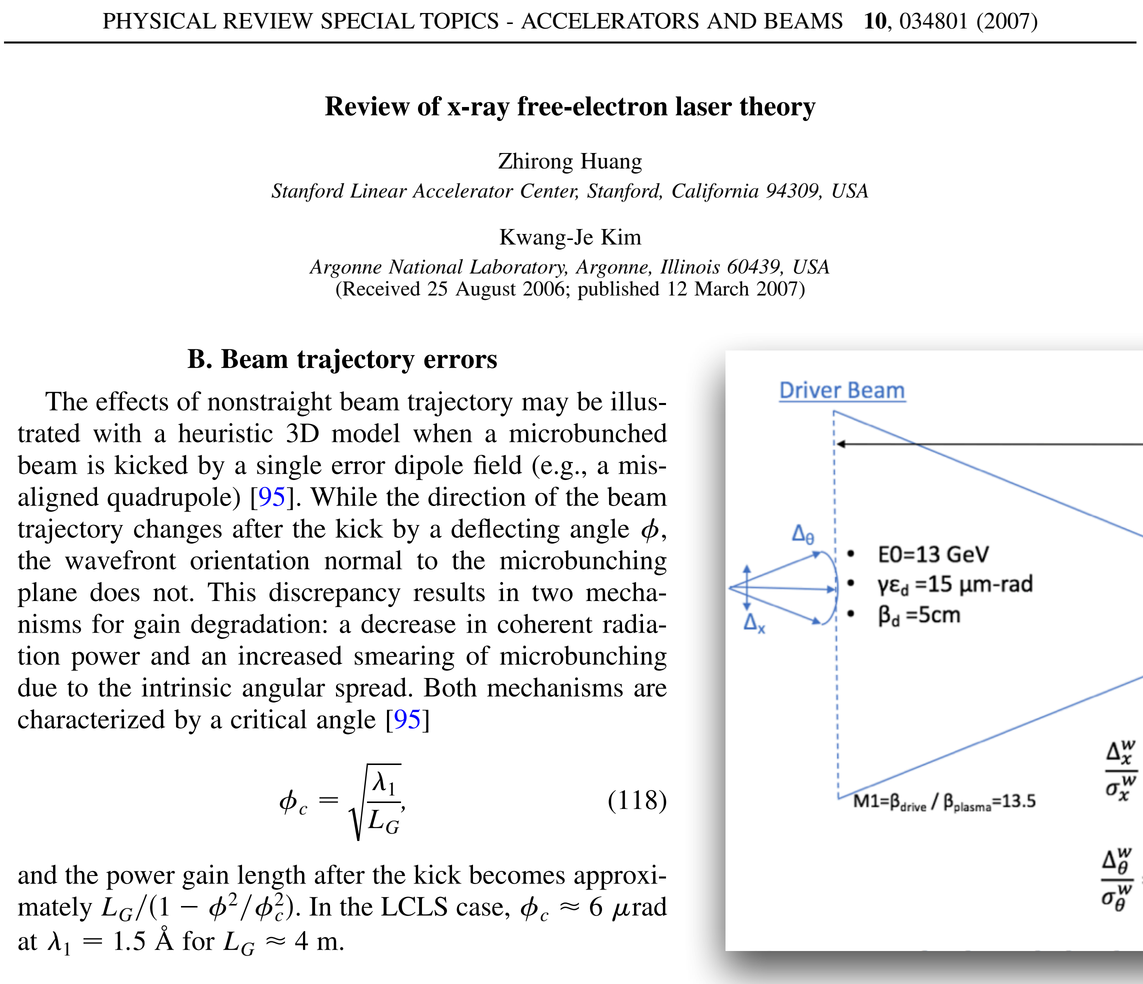








Output Jitter Can Reduce FEL Performance



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

Review of x-ray free-electron laser theory

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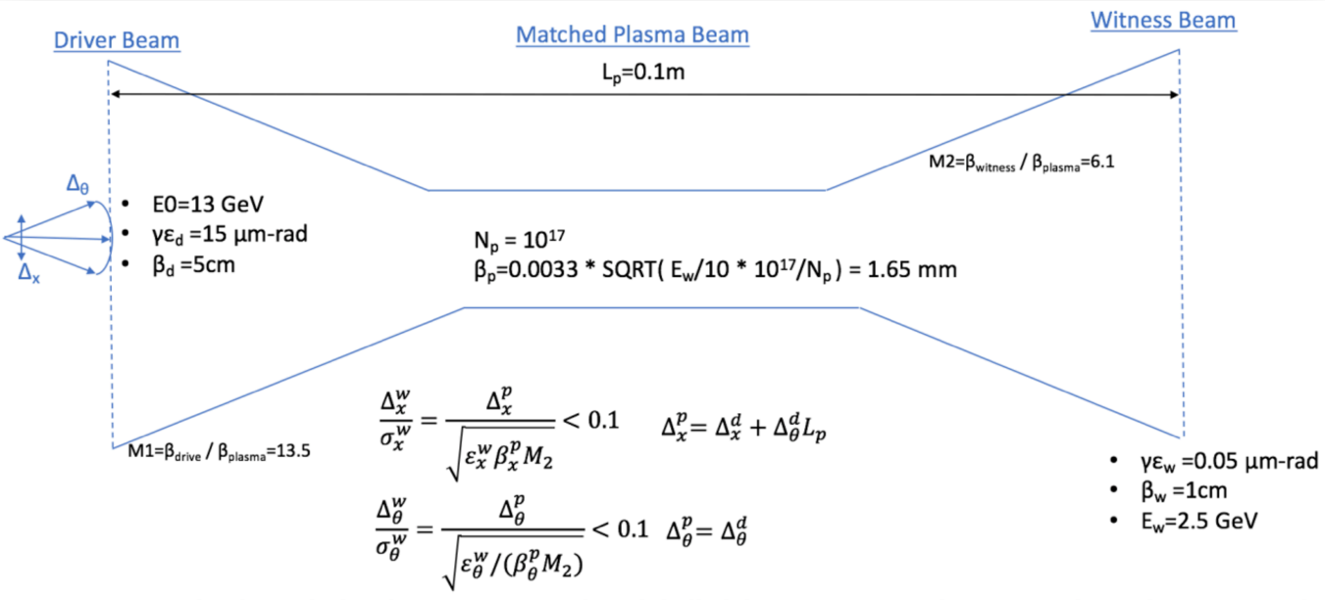
(Received 25 August 2006; published 12 March 2007)

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]

$$\phi_c = \sqrt{\frac{\lambda_1}{L_G}}, \tag{118}$$

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



Driver Beam

Matched Plasma Beam

Witness Beam

L_p=0.1m

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

$N_p = 10^{17}$
β_p=0.0033 * SQRT(E_w/10 * 10^{17}/N_p) = 1.65 mm

M1=β_{drive} / β_{plasma}=13.5

M2=$\beta_{witness}$ / β_{plasma}=6.1

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

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

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

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

Courtesy of Glen White, Tor Raubenheimer

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

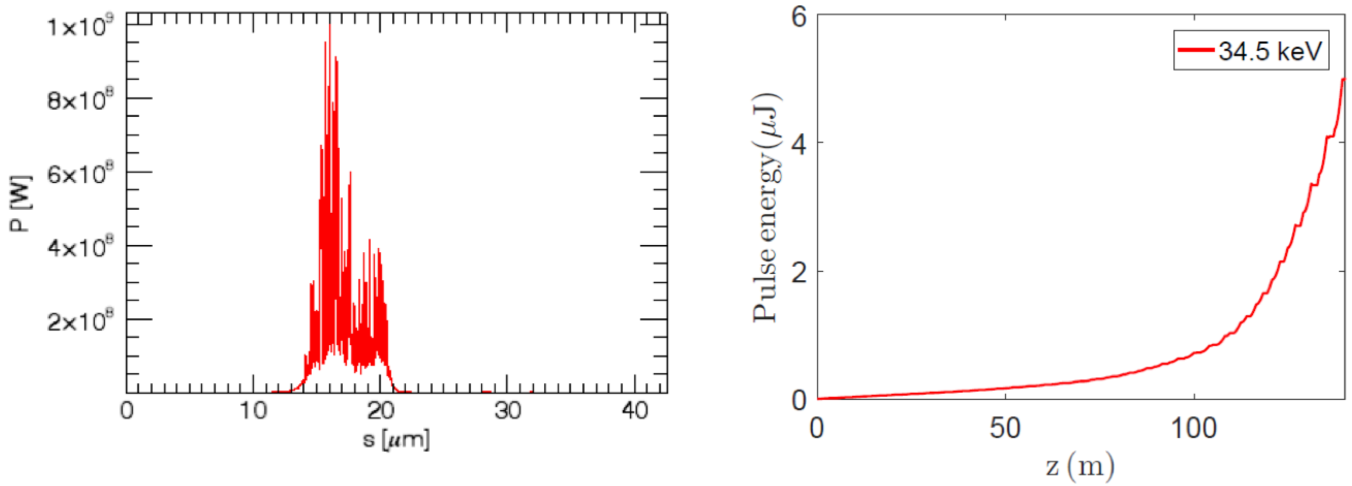


Figure 2: Radiation power along the bunch (left) and pulse energy along the undulator (right) for the 34.5 KeV case. The left plot assumes z = 140 m (the nominal end of the LCLS-II lattice).

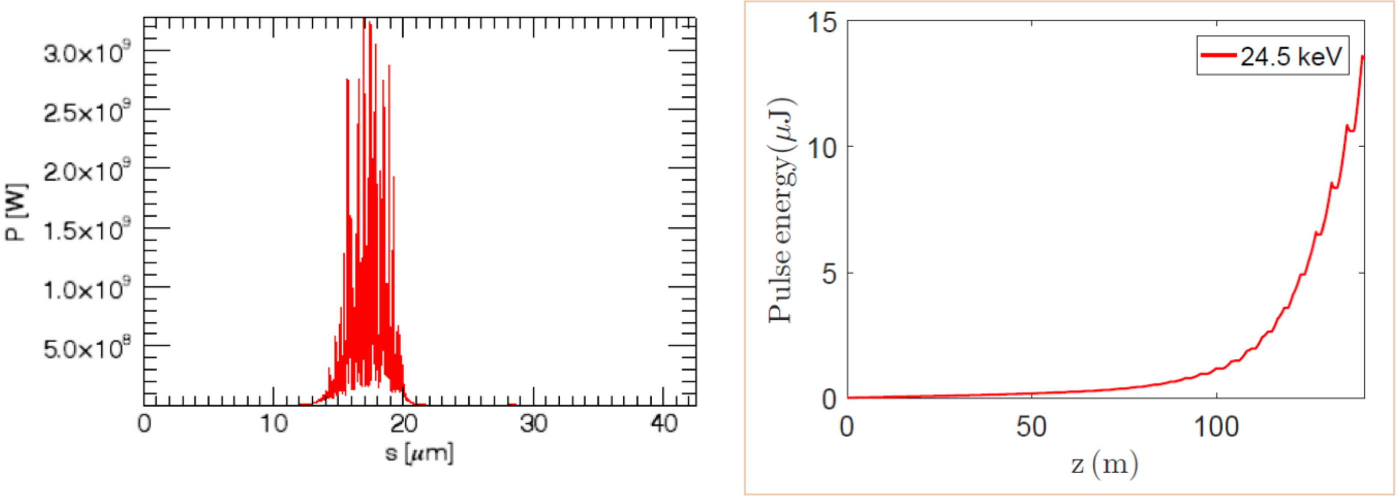


Figure 3: Radiation power along the bunch (left) and pulse energy along the undulator (right) for the 24.5 KeV case. The left plot assumes z = 140 m (as in Figure 2).

- 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^{2}mrad^2 extending the LCLS-II HE brightness curve to even harder X-rays

Courtesy of Zhirong Huang, Panos Baxevanis

Summary

- A task force has been studying potential intermediate applications of Plasma Wakefield Acceleration
- Recent focus on two candidate FEL applications: brightness transformer and energy doubler
- Have 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
- Goal is to produce a white paper early in 2018