Free electron lasers driven by plasma accelerators:

status and near-term perspectives

EAAC Workshop 2023 – Elba, Italy

Sep. 18, 2023

Michael Litos – University of Colorado Boulder

Contents

1) X-FEL

The X-ray free electron laser

Image: DESY/Lucid Berlin

1.1) The X-FEL

- Ingredients: undulation force + radiation
- Results in longitudinal microbunching with periodicity of slippage length
- Microbunching produces coherent radiation → Rad. power ~N^2 instead of ~N
- Only method able to produce the brightest X-ray pulses on Earth by orders of magnitude
- Advantages over synchrotron light sources:
    - Monochromatic photons/narrow bandwidth
    - Ultra-high brightness/brilliance
    - Ultra-fast pulse duration

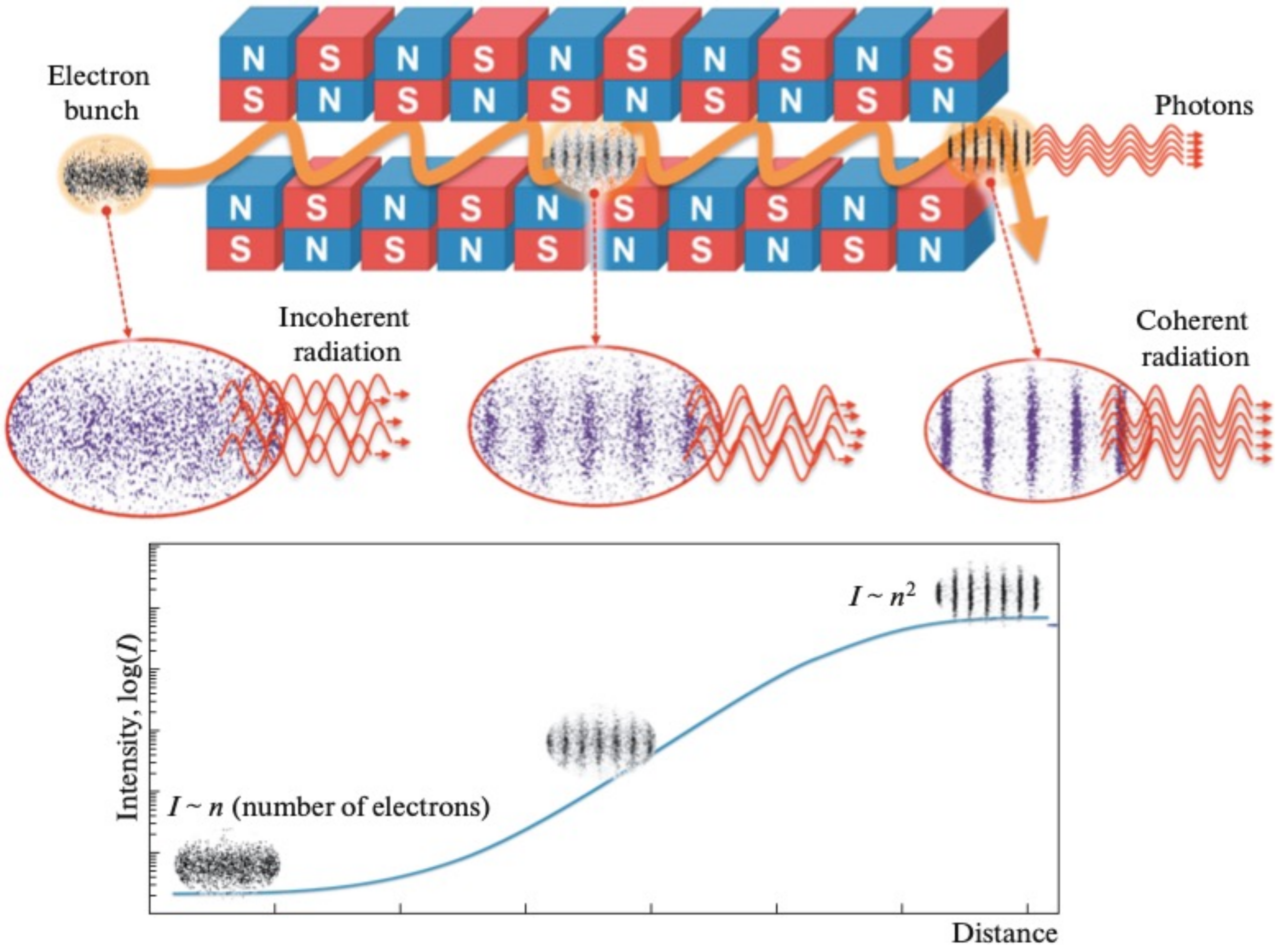

Image: M. V. Kovalchuka and A. E. Blagov, Cryst. Reports 2022

1.2) X-FEL Physical Parameters and Constraints

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- Fundamental radiation wavelength: $\lambda_r = \lambda_u(1+K^2)/(2\gamma^2)$
- Wiggler parameter: $K = eB_u\lambda_u/(2\pi mc^2)$
- Radiation bandwidth: $\sigma_{\lambda_r}/\lambda_r = 3\rho\sqrt{2L_G/z}$
- Gain length: $L_G = \lambda_u/(4\pi\sqrt{3}\rho)$ where $P_r(z) = P_r(0)e^{z/L_G}$
- Saturation length: $L_{\mathrm{sat}} \sim 10 - 20\, L_G$
- Saturation power: $P_{\mathrm{sat}} \approx \rho P_e$
- Cooperation length: $L_c = \lambda_r/(4\pi\rho)$

Pierce parameter rules all:

$$\rho = \left[\frac{1}{16}\frac{I_{pk}}{I_A}\frac{K^2[JJ]^2}{\gamma^3\sigma_r^2 k_u^2}\right]^{1/3}$$

- **Constraints on emittance and energy spread:** $\epsilon_n \lesssim (\gamma\lambda_r)/(4\pi)$ **and** $\sigma_\gamma/\gamma \lesssim \rho$

1.3) Science Enabled by X-FELs

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- AMO Science
- Matter in Extreme Conditions
- Materials Science
- Ultrafast X-Ray Physics and Optics
- Biology:
  - Proteins
  - Structural Enzymology
  - Structure-Based Drug Design
- Chemistry:
  - Mapping Chemical Bonds
  - Solvent Dynamics
  - Coupled Molecular Dynamics
  - Probing Catalytic Reactions

X-FELs allow movies of atomic and molecular processes

Image: LCLS/SLAC

1.4) X-FEL Facilities

- Currently nine operating X-FEL facilities in the world, all at national laboratories: EuXFEL, FELBE, FERMI, FLASH, LCLS, PAL-XFEL, SACLA, SwissFEL, SXFEL
- A few more coming in near future
- ***Still not enough to meet demand!***
- Wavelength range: ~0.05-100 nm
- e-beam energy: ~1-20 GeV
- e-beam charge: ~1-10's pC
- **Pierce parameter: ~10^{-3} ← This is generally the biggest challenge for PBA X-FEL**

Image: LCLS/SLAC

2) PBA X-FEL

The Plasma-Based Accelerator X-FEL

Image: University of Strathclyde

2.1) PBA X-FEL Concept

Goal: Replace kilometer-scale accelerator with centimeter-scale PBA

<u>Stages of PBA FEL Experiment:</u>

1. Injection
2. Acceleration
3. Collimation
4. Undulation
5. Dispersion

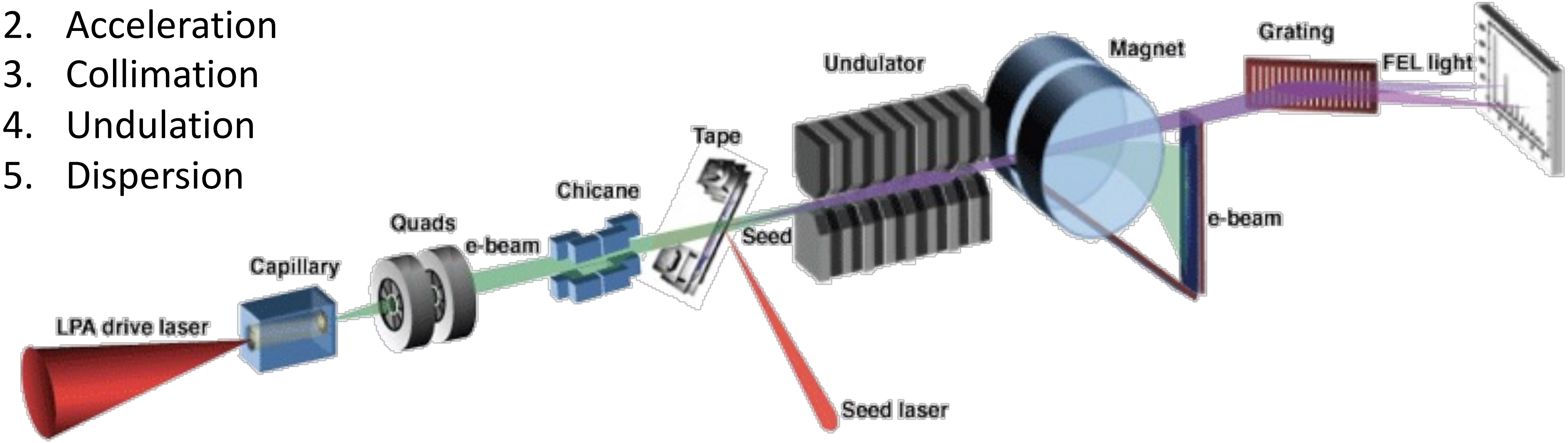

Image: BELLA, LBNL

2.2) PBA FEL Experimental Progress

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Significant progress in past two years! Reminiscent of LWFA "Dream Beams" in 2004...

<u>Three major recent experimental results in PBA FELs:</u>

1. SPARC_Lab: SASE and seeded at 826 nm
2. COXINEL: Seeded at 275 nm
3. SIOM: SASE at 27 nm

Lab	Radiation			e-Beam				Undulator		
	λ_r (nm)	N_{ph} ($\times 10^{20}$)	τ_{ph} (fs)	Q (pC)	E (MeV)	σ_E (%)	ε_n (μm)	λ_u (cm)	N_u	K_u
SPARC	826	1.1 (46)	<30 (?)	20	94	0.33	2.7	2.7	462	1.4
COXINEL	275	(?)	<900 (?)	~100	188	6.3	~0.1 (?)	2.0	97	2.5
SIOM	27	0.92	~10 (?)	30	486	0.5	~0.6 (?)	0.25	75	1.41

On track for application-dedicated PBA facility ~50 years after Tajima & Dawson? Maybe!

2.3a) IR PBA FEL: SPARC_LAB


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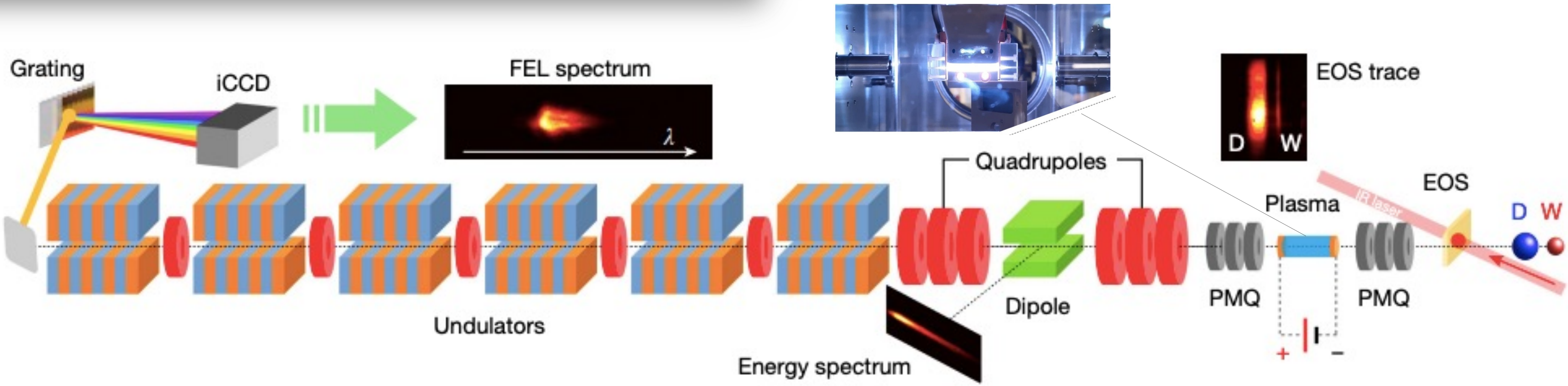
Article | Published: 25 May 2022

Free-electron lasing with compact beam-driven plasma wakefield accelerator

R. Pompili, D. Alesini, ... M. Ferrario + Show authors

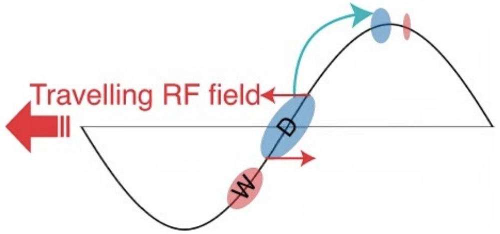
Nature **605**, 659–662 (2022) | Cite this article

- SPARC_LAB (INFN), Nature 2022, PRL 2022
- Part of EuPRAXIA
- SASE lasing at 826 nm
- Two-bunch RF source
- Beam-driven PWFA:
  - Quasi-nonlinear regime
  - +6 MeV / 3 cm: 200 MeV/m
- First experiment SASE, then seeded
- **Key technique: RF chirp / PWFA dechirp**

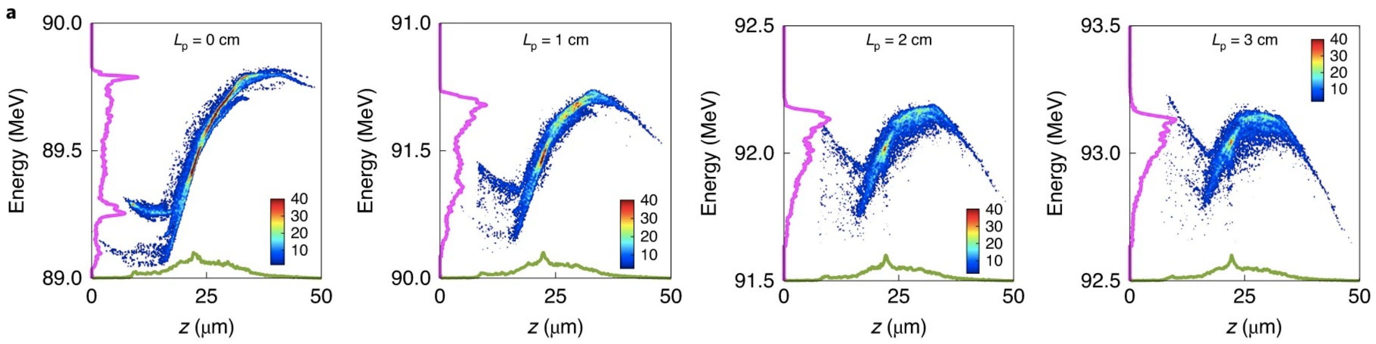


2.3b) Chirp/Dechirp

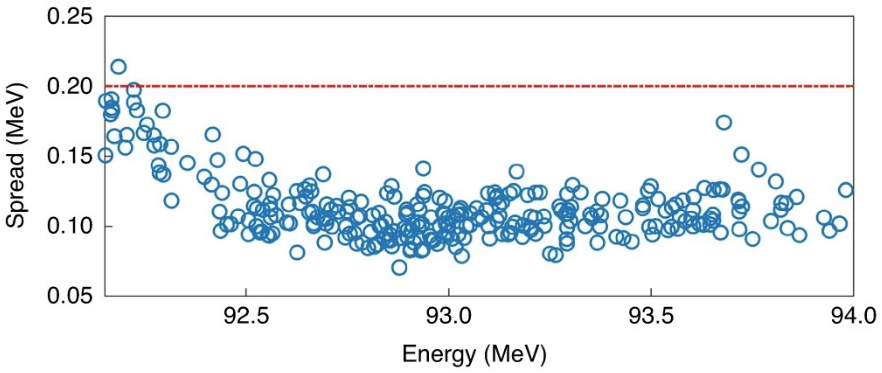
1. Positive chirp in RF accelerator



2. Underload PWFA to accelerate and dechirp simultaneously



3. Accelerate by 6 MeV; reduced E-spread from 0.19 MeV to 0.12 MeV (40% reduction)



2.3c) SASE IR PBA FEL Results

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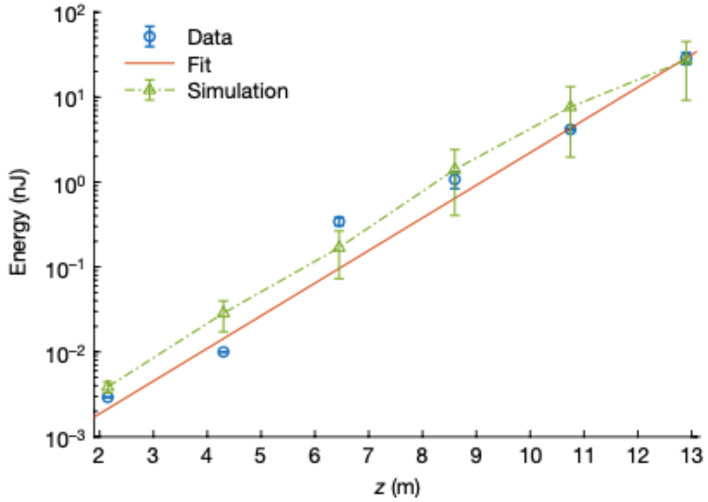
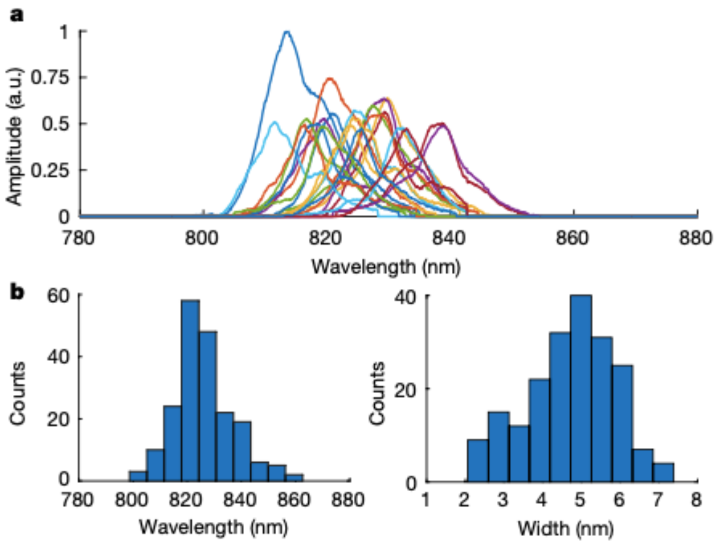
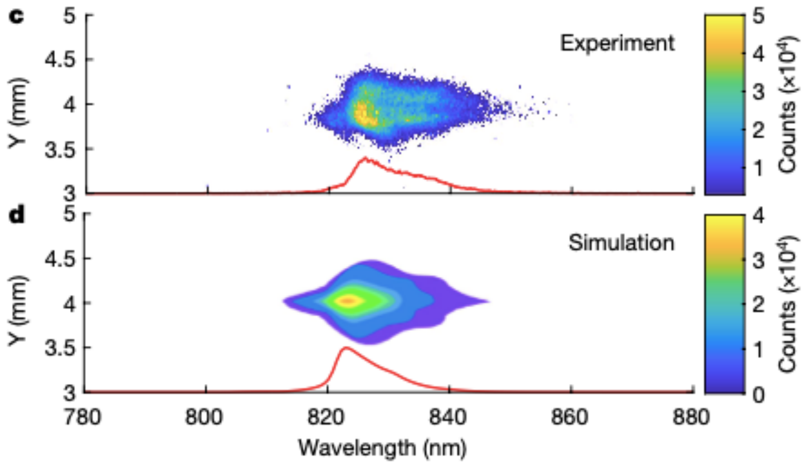
- Low energy spread and emittance permitted SASE at long wavelength
- Wavelength: 826 nm, bandwidth: 4.7 nm
- Ver clear measurement of exponential gain with L_G = 1.1 m
- Good agreement with simulations
- **Comment: Beautiful physics experiment; unclear if scalable to short wavelength**

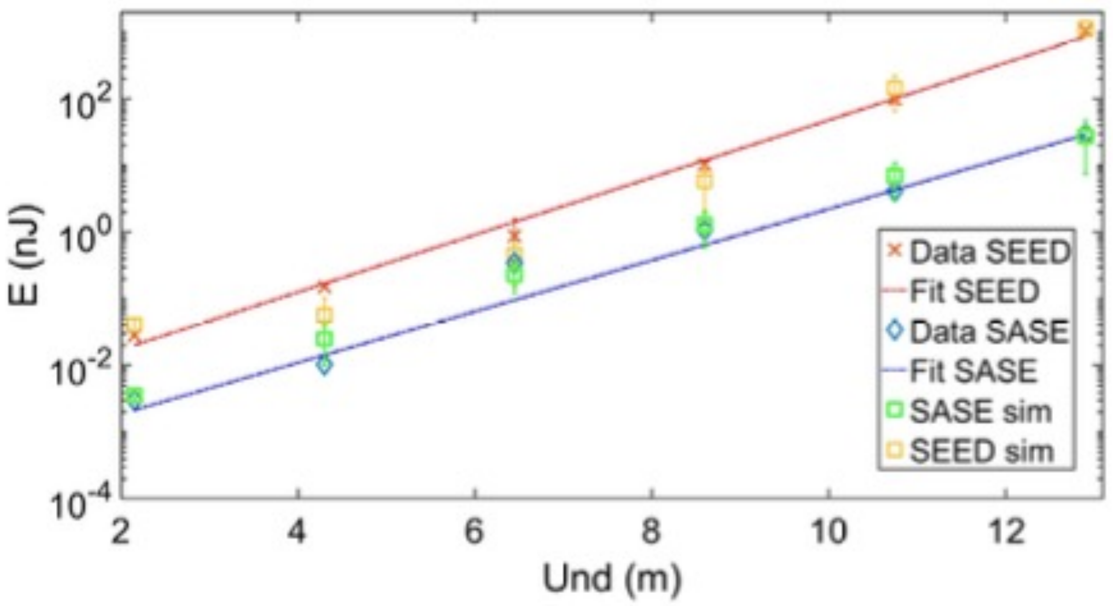


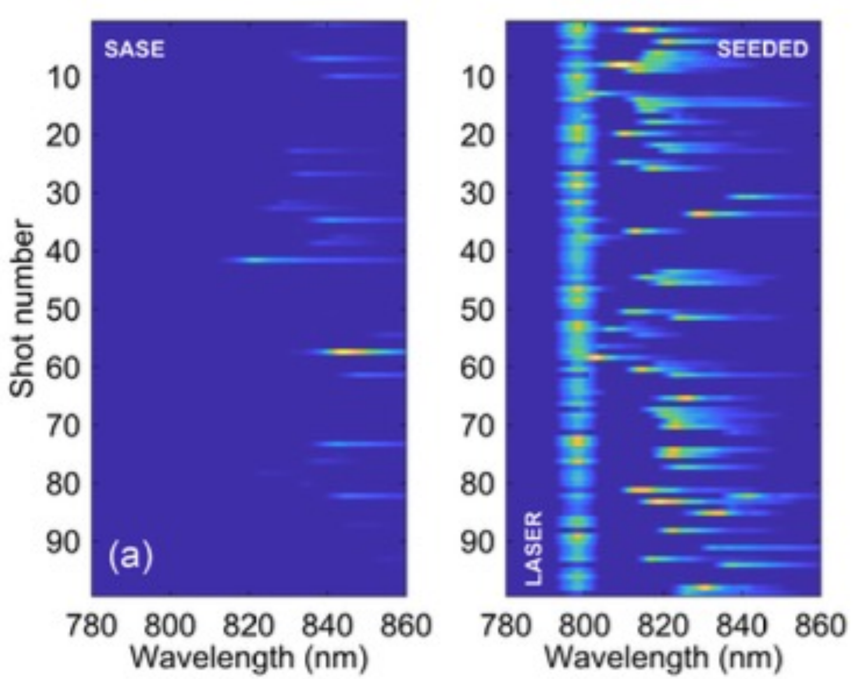




2.3d) Seeded IR PBA FEL Results

- Same setup as SASE, but seeded with Ti:sapphire pulse (20 mJ, 109 fs)
- Radiation energy enhanced by factor of 37 (1.1 μJ vs. 30 nJ)
- Lasing stability enhanced by factor of 3.3 (89% of shots vs. 27%)
- **Comment: Beautiful physics experiment; strong seed was required (20,000 x E_{rad})**





2.4a) EUV PBA FEL: COXINEL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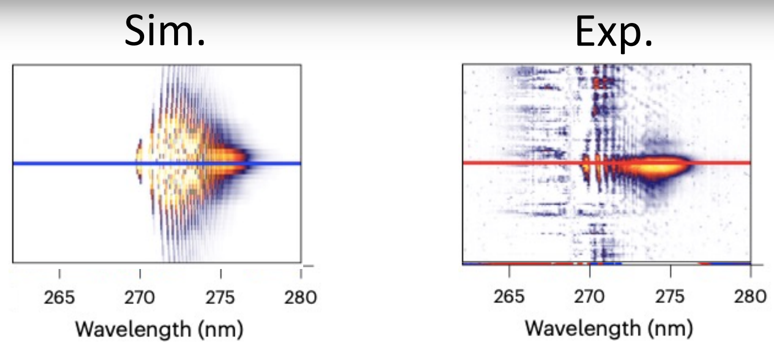
Article | Open Access | Published: 05 December 2022

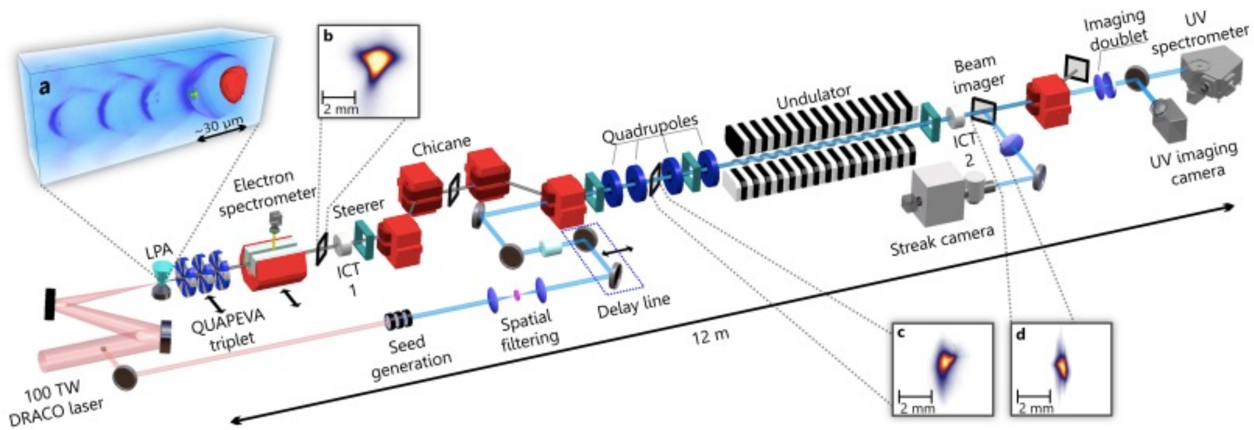
Seeded free-electron laser driven by a compact laser plasma accelerator

Marie Labat, Jurjen Couperus Cabadağ, Amin Ghaith, Arie Irman, Anthony Berlioux, Philippe Berteaud, Frédéric Blache, Stefan Bock, François Bouvet, Fabien Briquez, Yen-Yu Chang, Sébastien Corde, Alexander Debus, Carlos De Oliveira, Jean-Pierre Duval, Yannick Dietrich, Moussa El Ajjouri, Christoph Eisenmann, Julien Gautier, René Gebhardt, Simon Grams, Uwe Helbig, Christian Herbeaux, Nicolas Hubert, ... Marie-Emmanuelle Couprie + Show authors

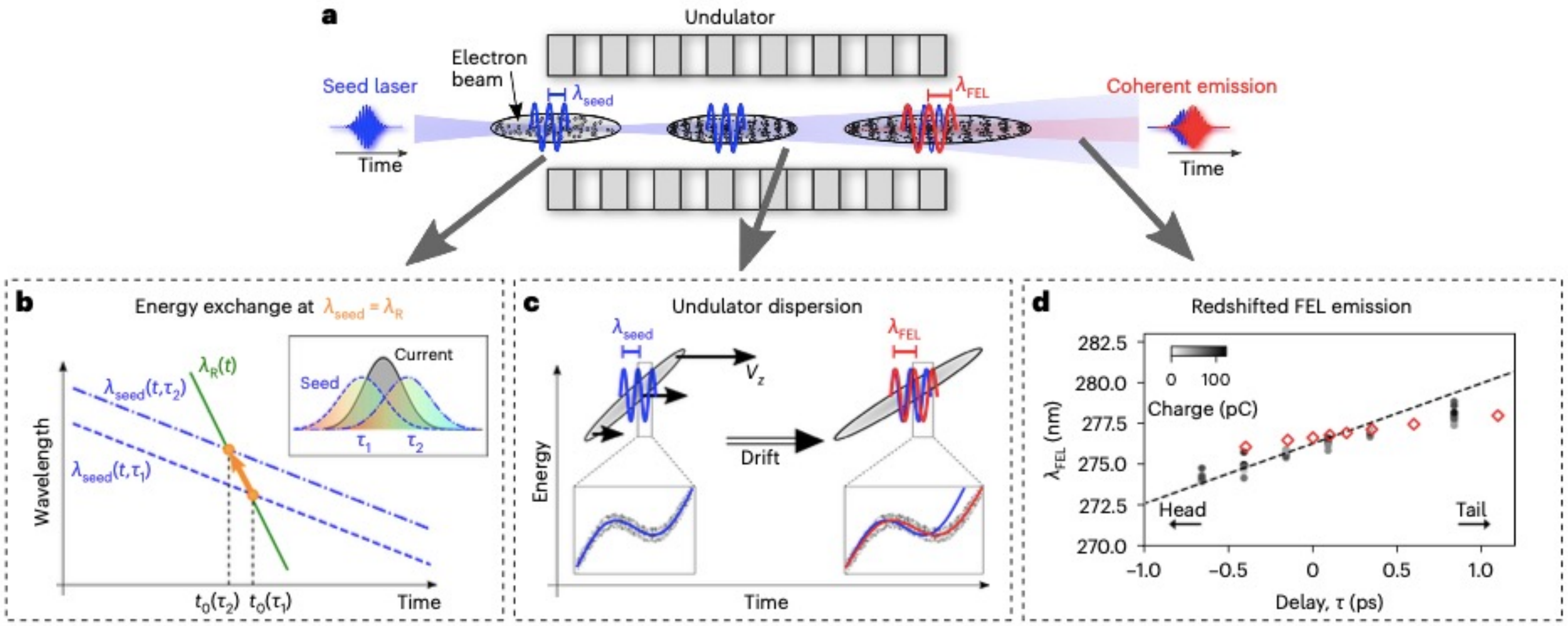
Nature Photonics **17**, 150–156 (2023) | Cite this article

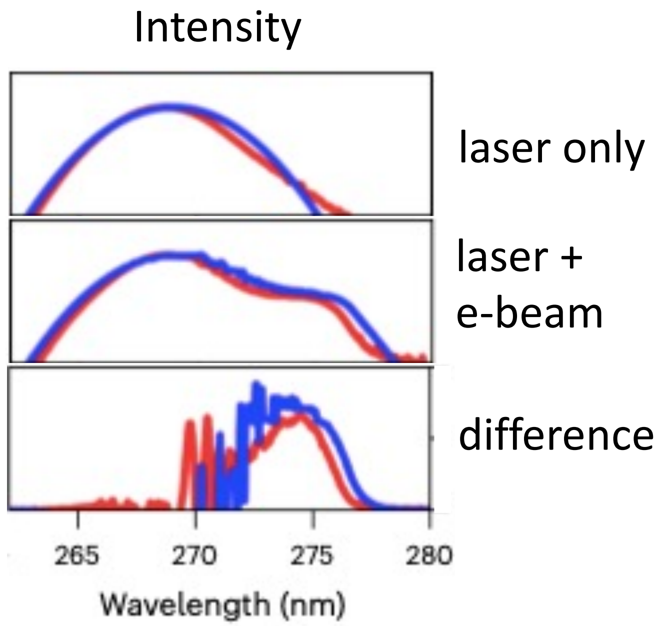
- COXINEL (HZDR), Nature Photonics 2022
- Seeded lasing at 275 nm
- LWFA:
  - Self-truncated ionization injection: stable, high charge, high energy, σ_E ~10%
  - 190 MeV / 1.1 mm : 170 GeV/m
- Frequency-converted Ti:sahhpire seed pulse
- Demonstrated tunable control over lasing wavelength λ_{FEL}
- **Key technique: beam decompression**





2.4b) Beam Decompression





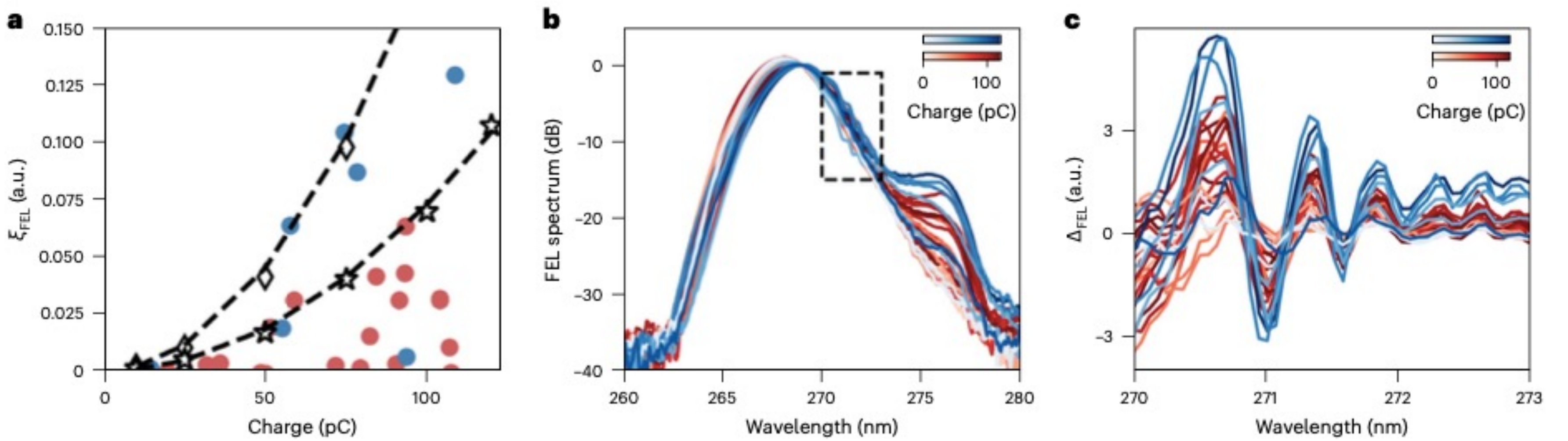
a. Chirped e-beam (~900 fs) overlapped with chirped laser pulse (~1 ps; 3.9 nm bandwidth)
b. FEL resonance occurs only at specific, tunable overlap position
c. Undulator-induced dispersion of e-beam red-shifts FEL coherent emission
d. Scan of relative delay b/w laser and e-beam shows good agreement with model:
   No lasing without overlap; linear dependence of lasing wavelength

2.4c) Seeded EUV PBA FEL Results

- FEL wavelength was controllable with relative delay due to electron-beam and seed chirps

$$\lambda_{\mathrm{FEL}} = \left(\lambda_0 + \frac{t_0 - \tau}{D_\lambda}\right) \times \left(1 - \frac{1 + K_{\mathrm{u0}}^2/2}{\gamma(t_0)^2 R_{56}} L_{\mathrm{eff}}\right)$$

- For best shots, gain increased quadratically with charge
- FEL radiation redshifted with respect to seed due to undulator dispersion
- Phase-locking between the seed and FEL pulses: evidence of temporal coherence
- **Comment: Creative approach and impressive analysis; Efficiency may be a challenge**



2.5a) Soft X-ray PBA FEL: SIOM


nature

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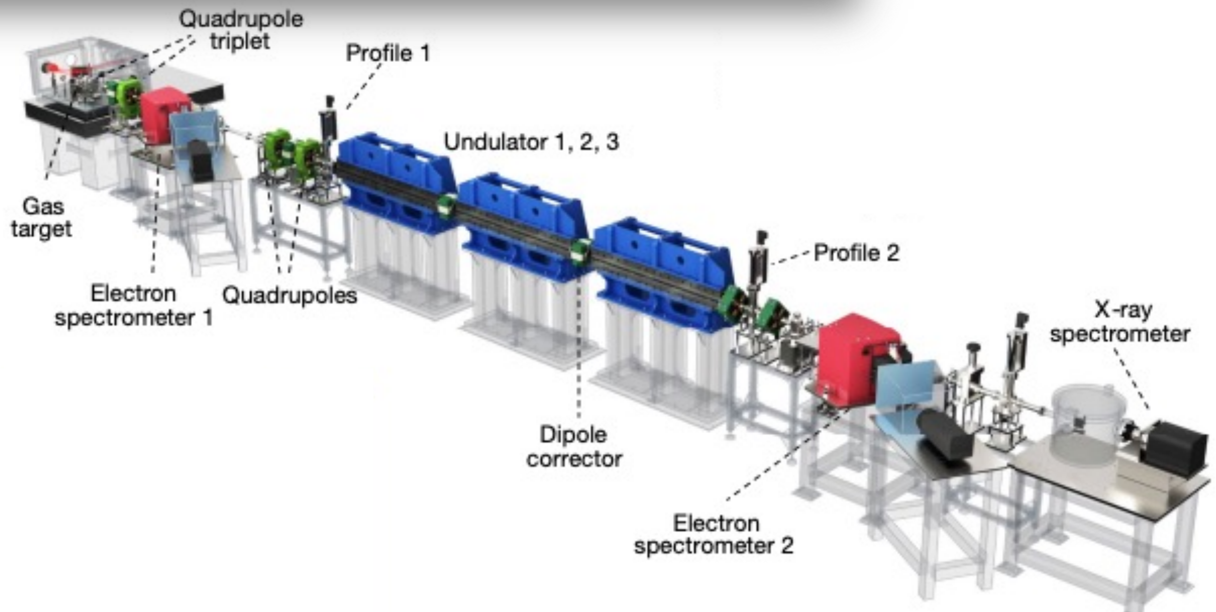
Article | Published: 21 July 2021

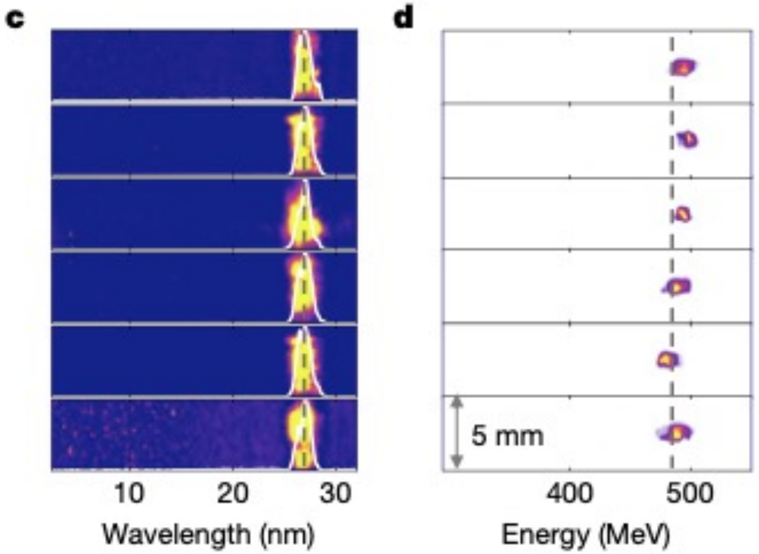
Free-electron lasing at 27 nanometres based on a laser wakefield accelerator

Wentao Wang, Ke Feng, Lintong Ke, Changhai Yu, Yi Xu, Rong Qi, Yu Chen, Zhiyong Qin, Zhijun Zhang, Ming Fang, Jiaqi Liu, Kangnan Jiang, Hao Wang, Cheng Wang, Xiaojun Yang, Fenxiang Wu, Yuxin Leng, Jiansheng Liu, Ruxin Li & Zhizhan Xu

Nature **595**, 516–520 (2021) | Cite this article

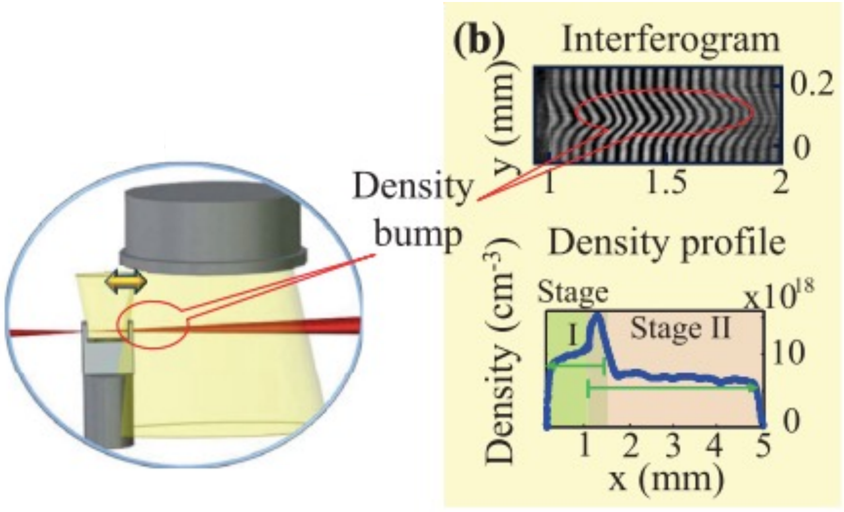
- SIOM, Nature 2021
- SASE lasing at 27 nm
- LWFA:
  - two gas jets at different densities
  - 490 MeV / 5 mm: 98 GeV/m
- Most straight forward PBA-FEL experiment
- Most successful PBA-FEL experiment
- Enabled by high-brightness e-beam
- **Key technique: cascaded LWFA scheme**

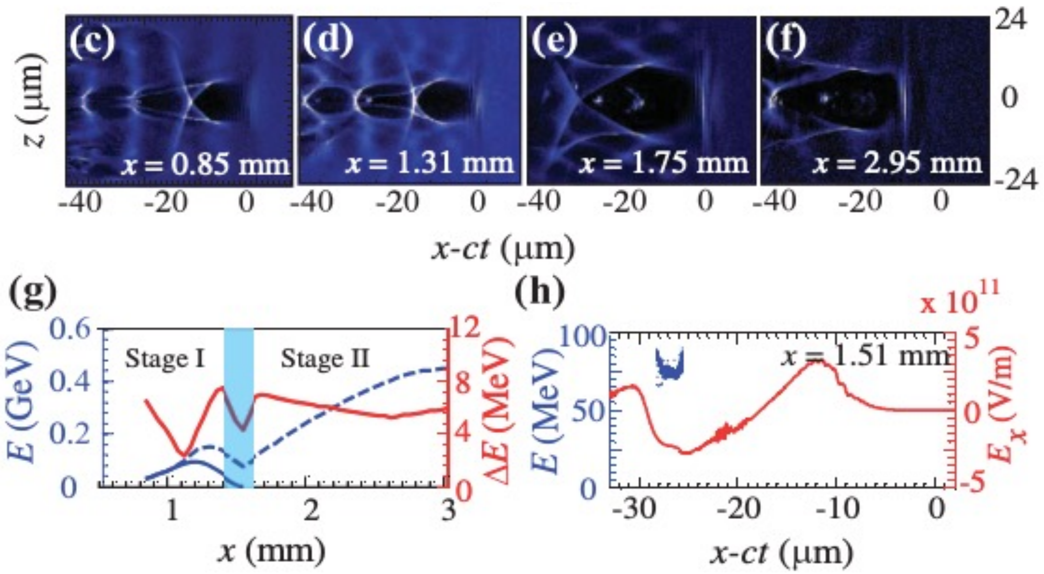


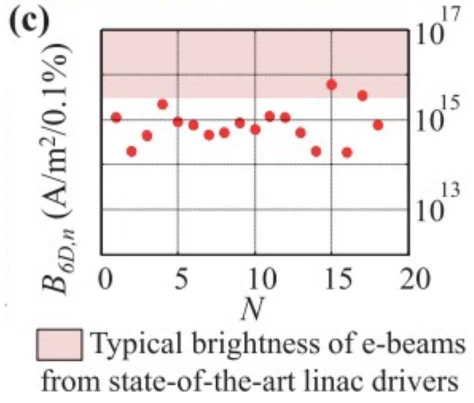


2.5b) Cascaded LWFA

- Two gas jets near each other produce density bump followed by low density region
- Electrons self-injected into wakefield
- Modulating the wake phase velocity leads to...
  - Electrons from second bucket seeded into first
  - Alternate chirping and de-chirping of e-beam
- Net result is a minimized energy spread and unprecedented brightness from LWFA

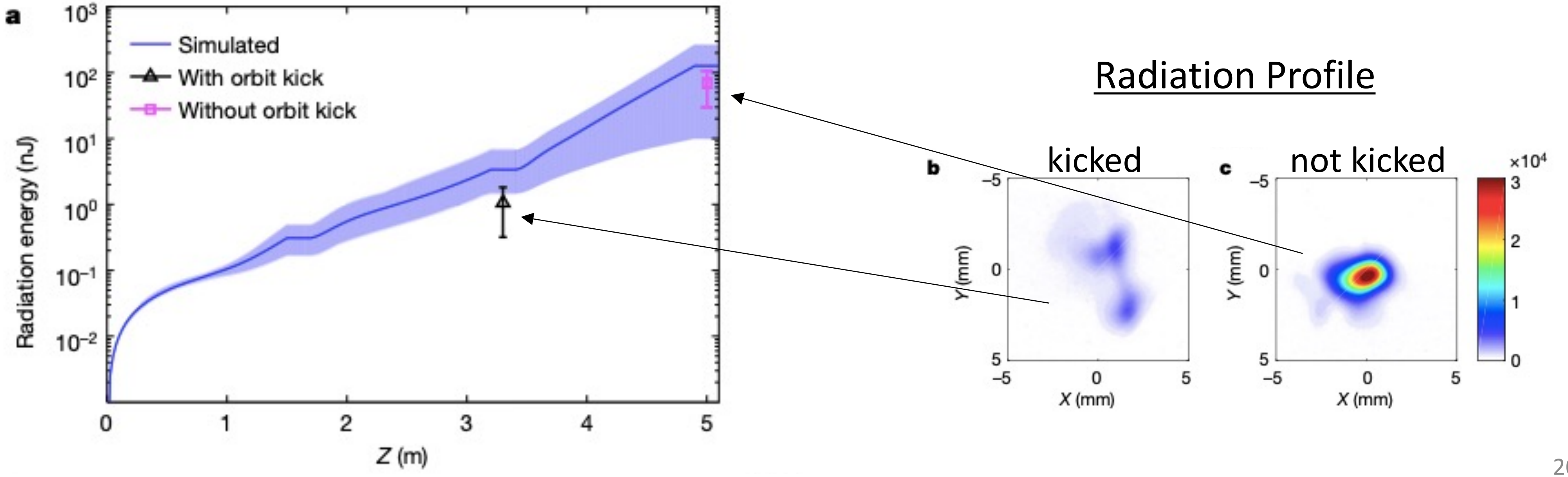






2.5c) SASE Soft X-Ray PBA FEL Results

- No surprise: brightest e-beam led to brightest & most energetic photons
- Cascaded LWFA technique deceptively simple; surprising how "easily" it worked
- Wavelength: 27 nm, bandwidth: 1.9 nm
- Decent measurement of exponential gain with L_G = 23 cm
  - Kicked beam part way through undulator to prematurely terminate lasing
- Good agreement with simulations
- **Comment: Incredible results; Can hard X-rays be reached?**



2.6a) Ongoing / Future Work

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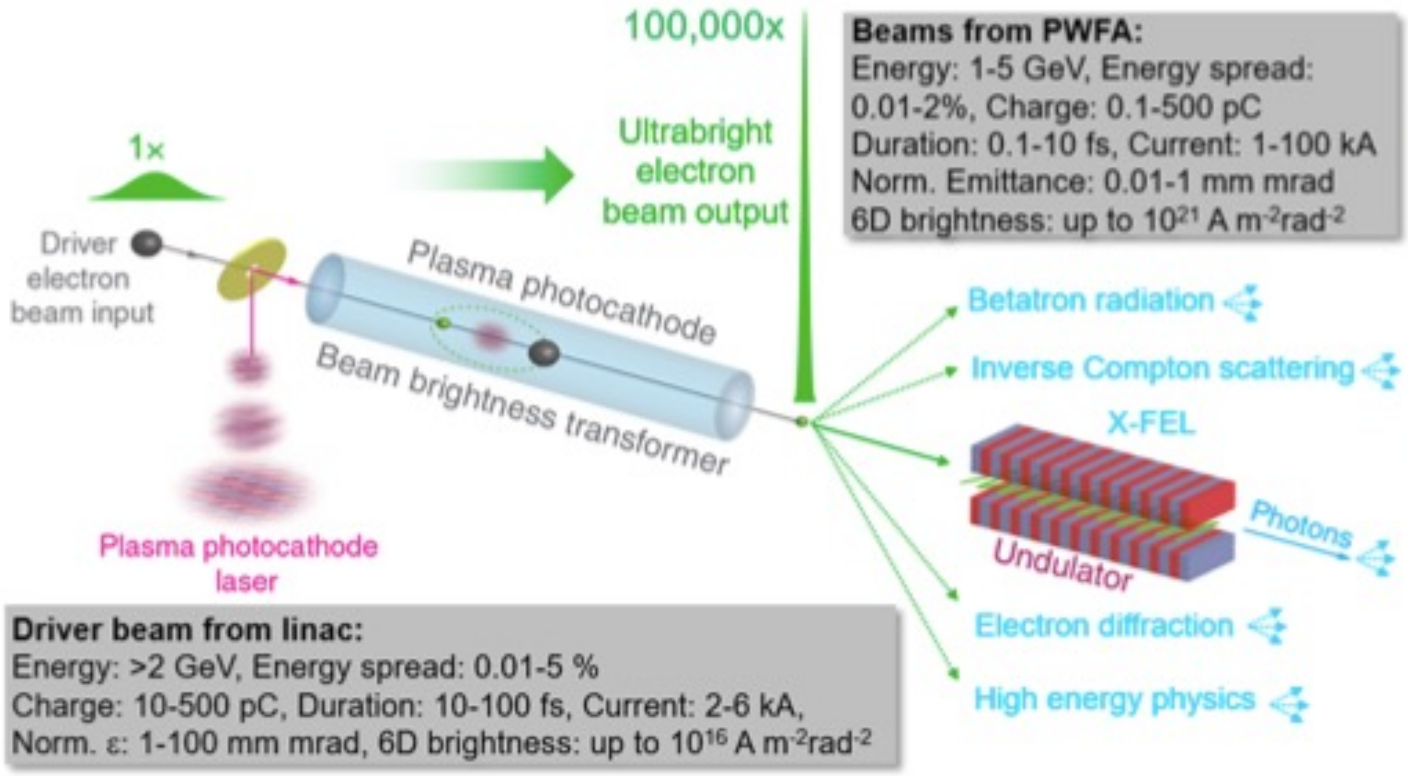
- **Major challenges:**
  - Continuing to improve e-beam 6D brightness (esp. energy spread)
  - Stability: wavelength, bandwidth, flux
  - Efficiency: photons per electron
  - Repetition Rate: kHz possible? 100 Hz? 10 Hz?

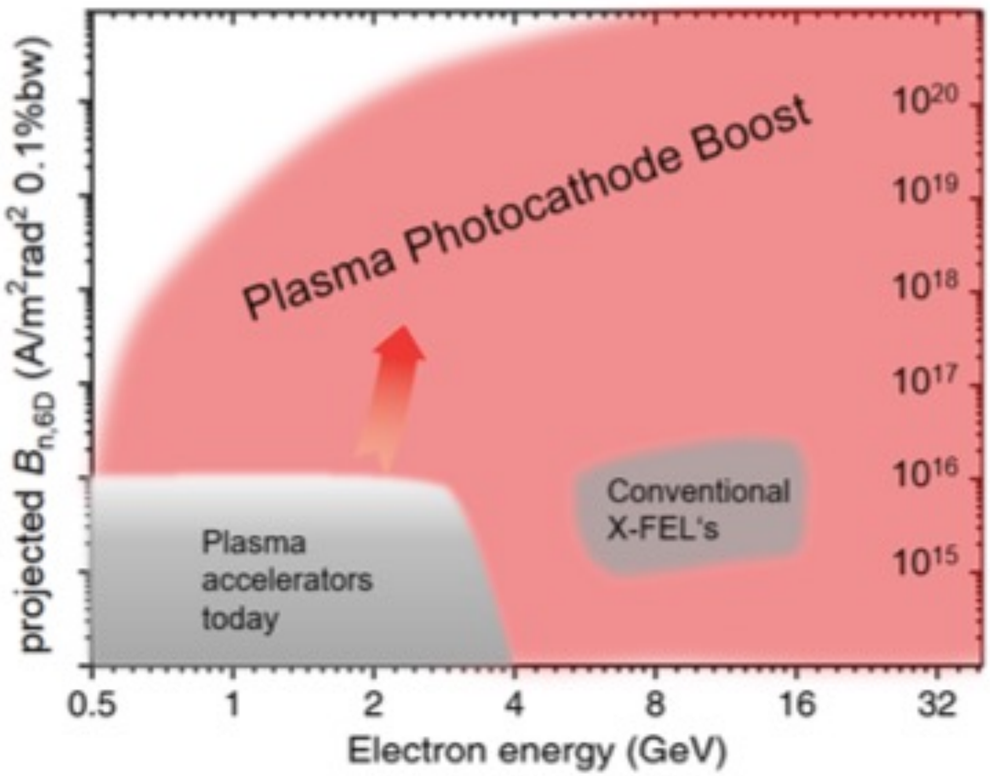
- **Areas of focus:**
  - Injection techniques/improved control
  - Energy spread mitigation
  - Emittance-preserving transport
  - Accommodating undulator design
  - Improved/new seeding techniques

Valuable Reference:
C. Emma, et al. "Free electron lasers driven by plasma accelerators: Status and near-term prospects", High Power Laser Science and Engineering, 9, E57 (2021)

2.6b) Plasma Photocathode Injection – TH Group

- **Trojan Horse plasma photocathode injection to produce ultra-high brightness beam**
- High brightness makes everything easier/better!

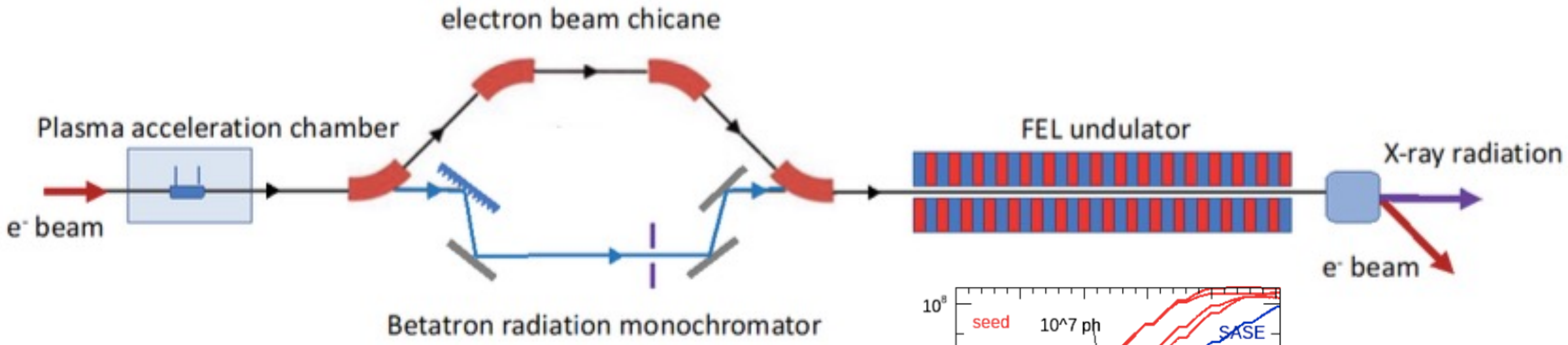


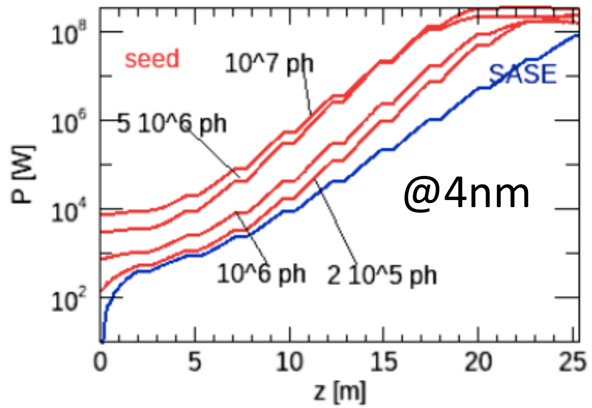


(See B. Hidding's talk)

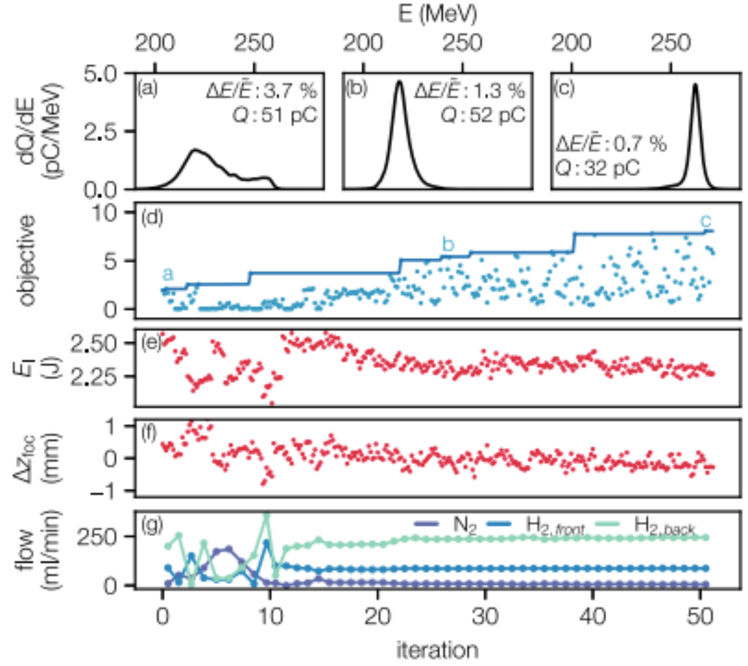
2.6c) Betatron-Seeded FEL – SPARC_Lab

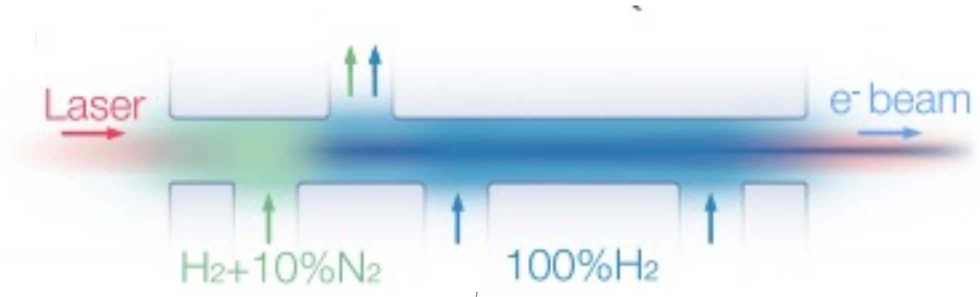
- **FEL seeded by PWFA betatron radiation at SPARC_Lab, INFN, EuPRAXIA**
- Chicane + monochromater to select portion of betator radiation
- Seed at short wavelength natural byproduct of PFWA
- Aiming for 4 nm seed & FEL radiation

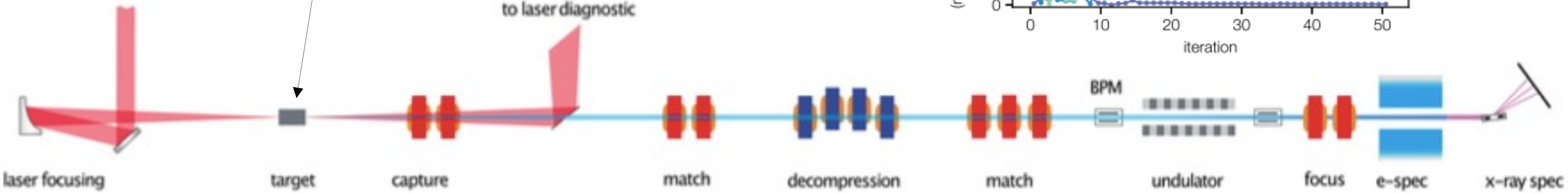




- **LWFA FEL with emphasis on stability at LUX, DESY**
- Straight forward design using decompression scheme
- Hydrogen-filled continuous-flow capillary for reproducible conditions on every shot
- Bayesian optimization of LWFA







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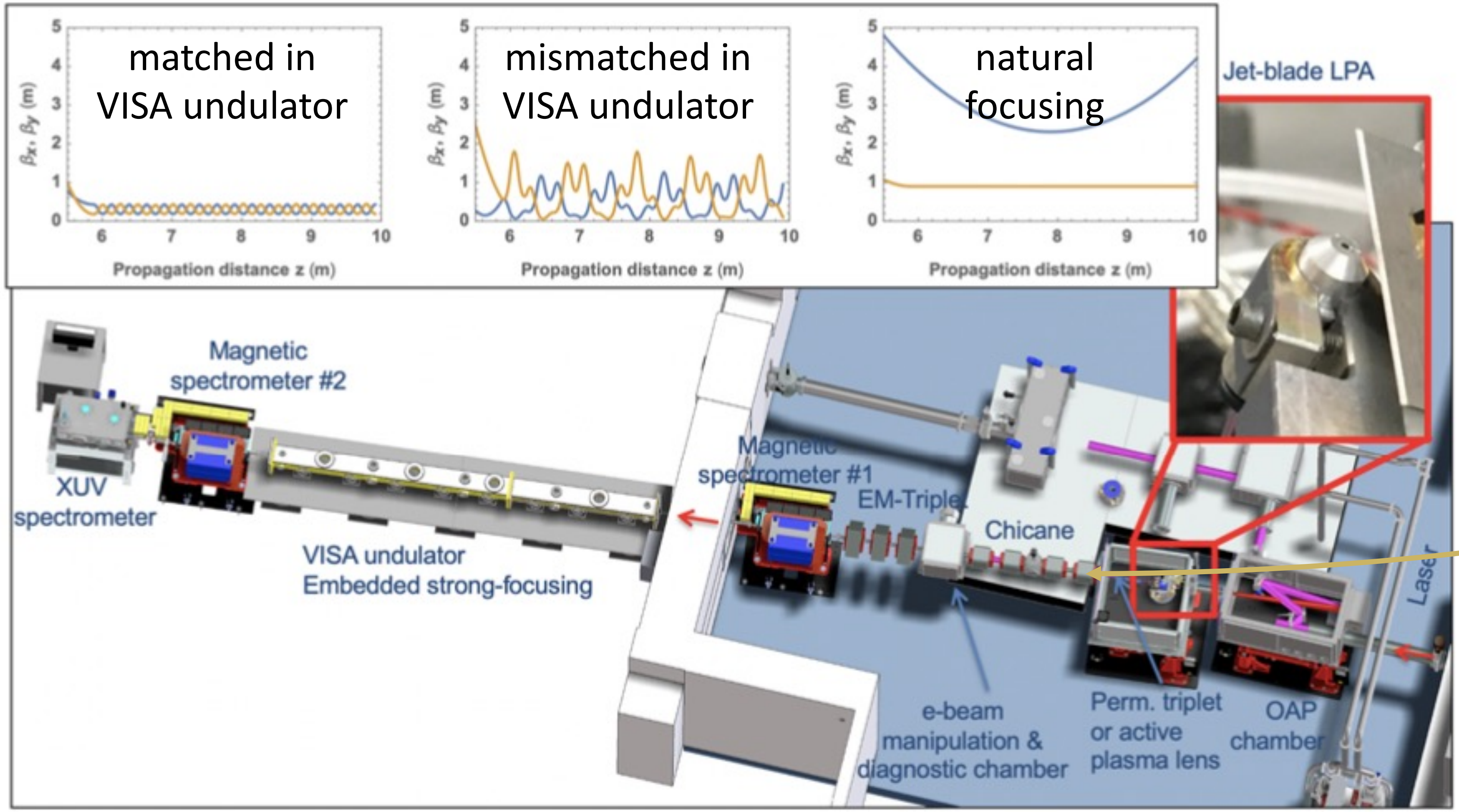
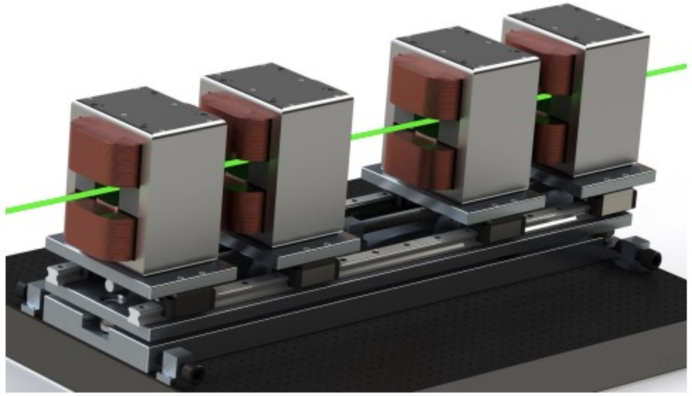
- **LWFA FEL at BELLA, LBNL**
- Low aspect ratio chicane for decompression
- Visible-Infrared SASE Amplifier (VISA) undulator with integrated strong focusing





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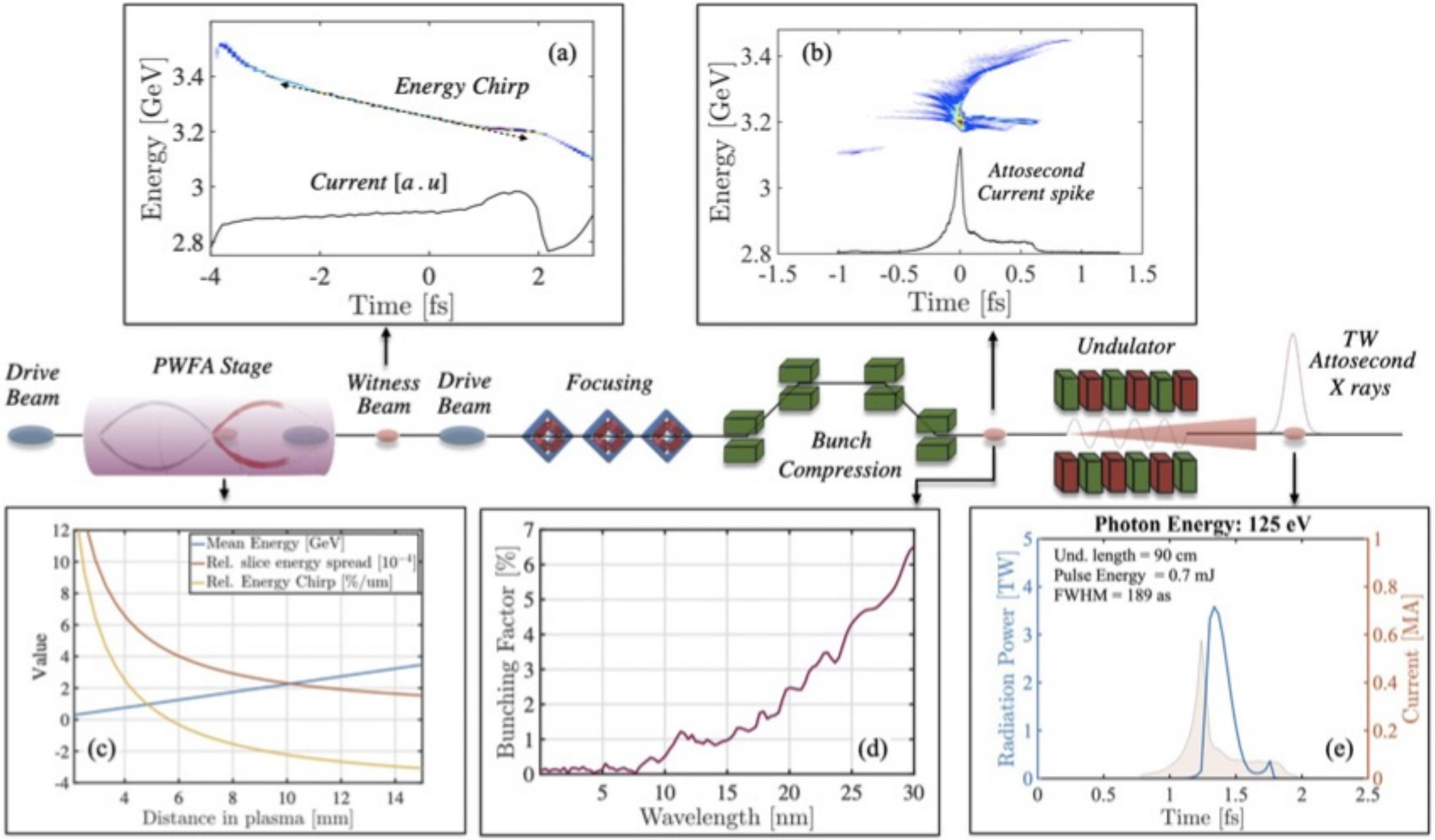
- **PWFA-Driven Attosecond X-Ray Source (PAX) at FACET-II, SLAC**
- Chirped femtosecond PWFA beam compressed to attosecond duration
- Acts like single microbunch in undulator



3) ICL

The Ion Channel Laser

3.1) ICL Concept

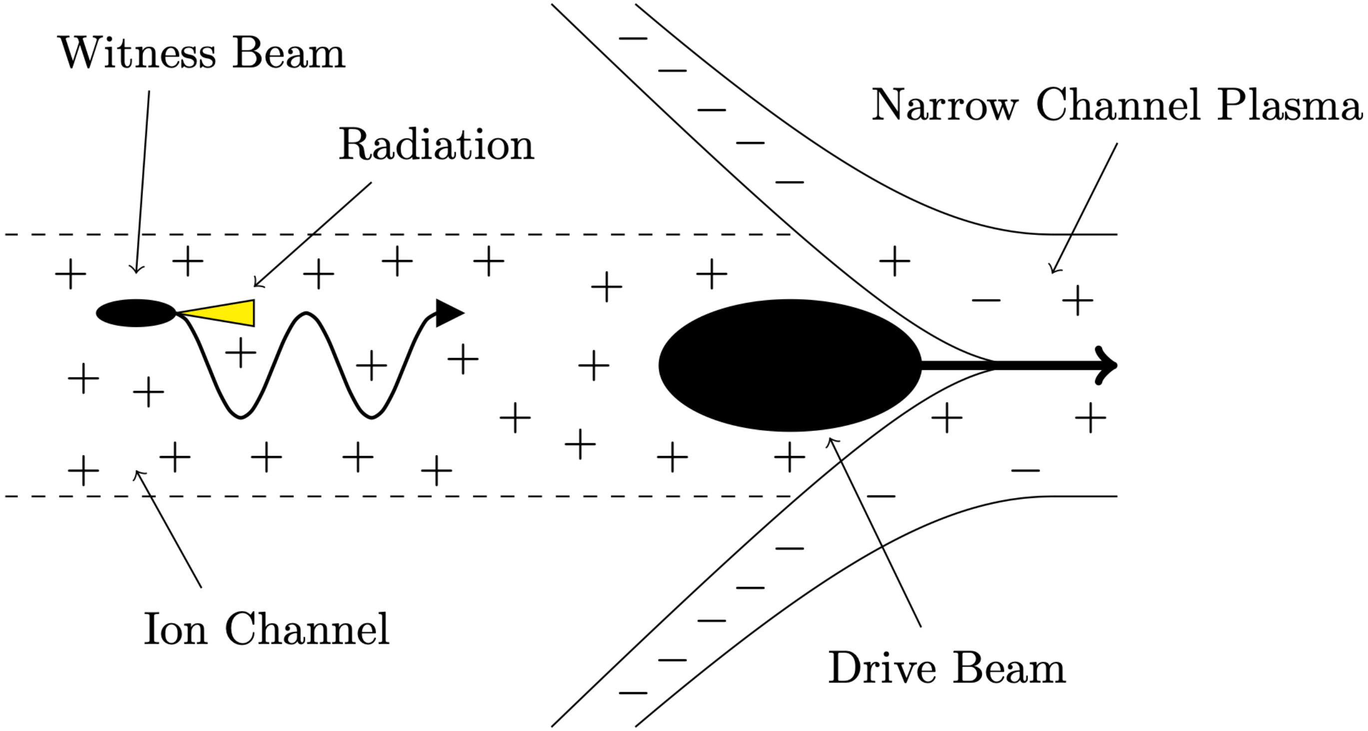
- Replaces magnetic undulator with strong focusing ion channel

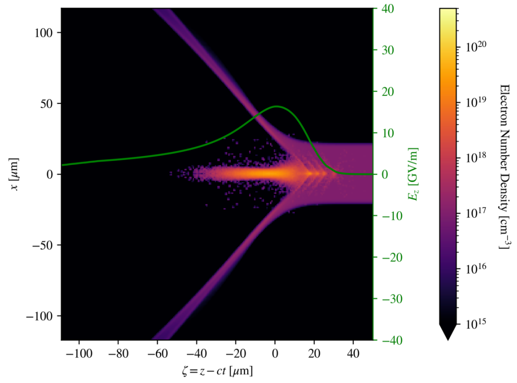
- Linear focusing force produces periodic betatron oscillations

$$F_r = -\frac{e n_0}{2\epsilon_0} r$$

$$r(z) = r_m \cos(k_\beta z + \phi)$$

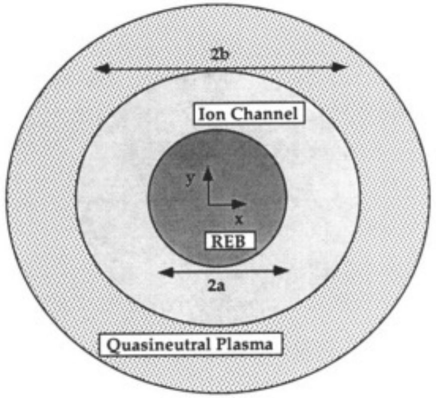
- Key to experimental realization: Narrow plasma channel + strong drive beam to create "wakeless" ion channel





QuickPIC simulation of ion channel formation

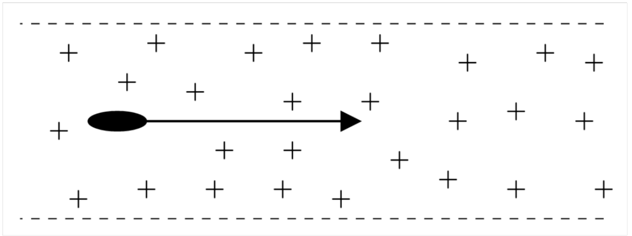
- First appearance: *Whittum, Sessler, and Dawson, "Ion Channel Laser", Phys. Rev. Lett. 1990*



- Most literature until 2014 (including above) consider only on-axis beam configuration

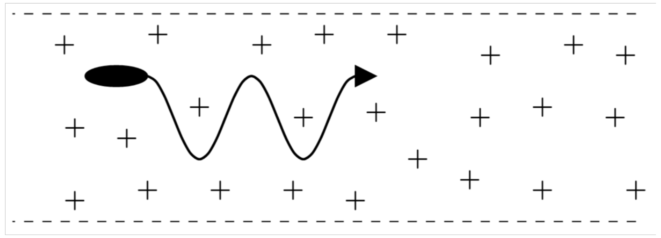
- Only 2 peer-reviewed papers consider off-axis beam:
  - *Ersfeld, et al., New J. Phys. 2014*
  - *Davoine, et al., J. Plasma Phys. 2018*

On-Axis ICL



- On axis requires unrealistically small emittance

Off-Axis ICL



- Off axis, however, is feasible, if challenging

- Need more theory development (working on it!)

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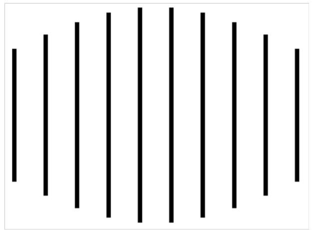
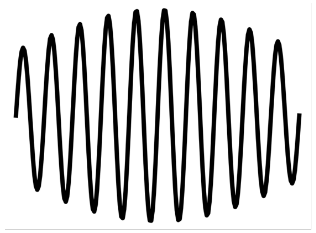
- Instead of microbunching, ICL "microsnakes" e-beam

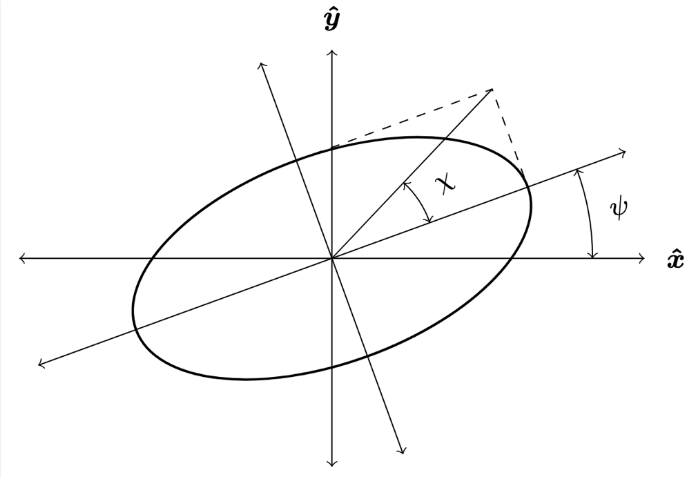


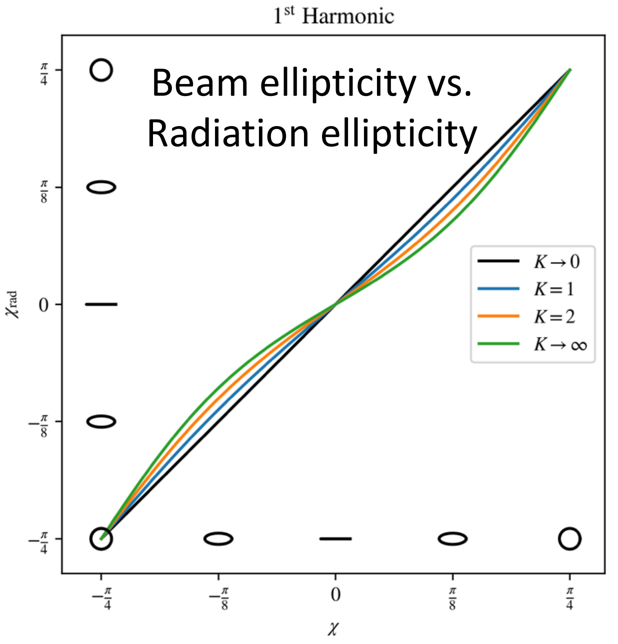
Microbunching



Microsnaking

- ICL can produce linear, circular, or elliptically polarized light with same "undulator"; simply depends on orbit of e-beam





3.4) ICL vs. FEL

- **Biggest difference between ICL & FEL:**
  - Strong focusing in ICL leads to smaller beam size...
  - Leads to much larger Pierce parameter:

$$\rho_{\mathrm{ICL}} \gtrsim 10 \times \rho_{\mathrm{FEL}}$$

$$\lambda_r = \lambda_\beta \frac{1 + \frac{K^2}{2}}{2\gamma^2}$$

$$\rho_{\mathrm{1D}} = \left(\frac{I_{\mathrm{pk}}}{I_A} \frac{[\mathrm{JJ}]^2 \mathcal{I}^2}{8\gamma} \right)^{\frac{1}{3}}$$

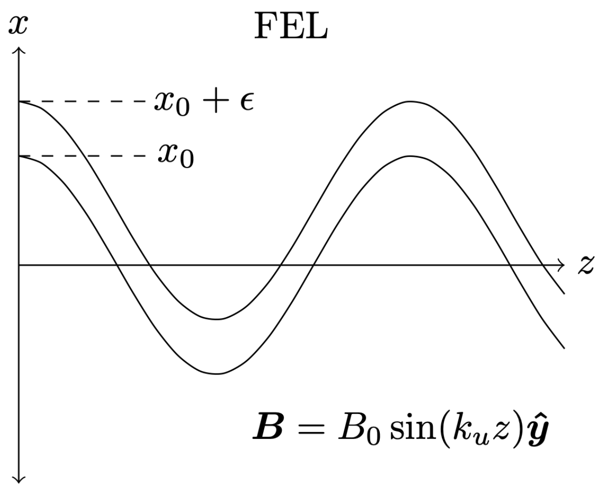
$$L_G^{\mathrm{1D}} = \frac{\lambda_\beta \mathcal{I}}{4\pi\sqrt{3}\rho_{\mathrm{1D}}}$$

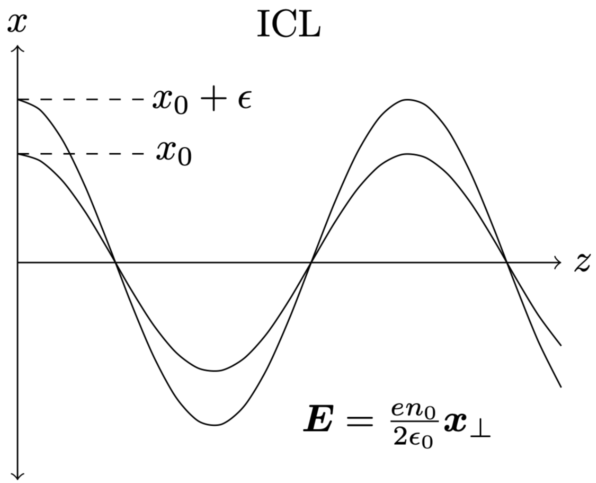
$$\text{where} \ \ \mathcal{I} \equiv \frac{4(2+K^2)}{4+K^2}, \quad 2 \leq \mathcal{I} \leq 4$$

- **Consequences for ICL:**
  - ***Much larger energy spread tolerance (~1%!)***
  - Much shorter (1D) gain length
  - Shorter cooperation length
  - Larger radiation bandwidth
  - Diffraction more significant
    (not good, but not a problem)

3.5) Most Stringent ICL Requirement

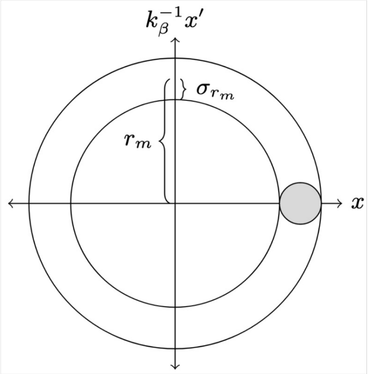
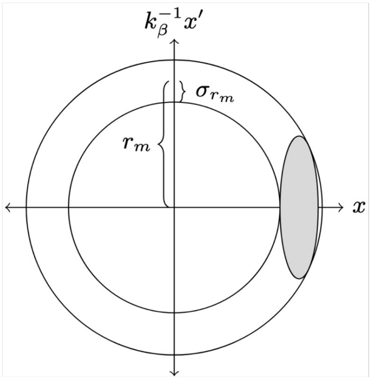
- Each particle has unique wiggler parameter K that changes constantly: $K_j = \gamma_j k_\beta(\gamma_j) r_{m,j}$
- Therefore, each particle has different, constantly changing resonant wavelength
- Leads to most stringent requirement for ICL: $\frac{\sigma_\lambda}{\lambda} < \rho \rightarrow \boxed{\frac{\sigma_{r_m}}{r_m} < \frac{1+\frac{K^2}{2}}{K^2}\rho}$





3.6) Optimizing Phase Space for ICL

- Resonant wavelength spread requirement implies particles must lie within narrow annular band in normalized transverse phase space
- Properly mismatched beam can significantly loosen emittance requirement

Type	FEL	Matched ICL	Optimally Overfocused ICL
Phase Space			
Emittance Constraint	$\frac{\epsilon_n}{\gamma\lambda} < \frac{1}{4\pi}$	$\frac{\epsilon_n}{\gamma\lambda} < \frac{1}{\pi}\frac{1+\frac{K^2}{2}}{K^2}\rho^2$	$\frac{\epsilon_n}{\gamma\lambda} < \frac{32}{27\pi}\sqrt{\frac{1+\frac{K^2}{2}}{K^2}}\rho^{\frac{3}{2}}$
λ = 1 nm, E = 10 GeV ρ = 0.05, K = 2	$\epsilon_n < 1.6\ \mu\text{m}$	$\epsilon_n < 12\ \text{nm}$	$\epsilon_n < 71\ \text{nm}$

3.7a) ICL Simulation Work

- FEL codes like GENESIS inappropriate; need full 3D PIC code
- Multiscale physics makes lab frame unfeasible; need Lorentz boosted frame
- Additional Galilean boost further reduces computational expense

Undulator: 1 m
e-Beam: 1 µm
Radiation: 1 nm
9 Orders of Magnitude

→ Lorentz boost to e-beam frame (γ=2000)

Undulator: 0.5 mm
e-Beam: 2 mm
Radiation: 4 µm
2.7 Orders of Magnitude

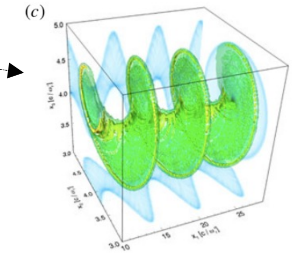
→ Galilean boost to follow plasma

Undulator: 0.5 mm
Radiation: 4 µm
2.1 Orders of Magnitude

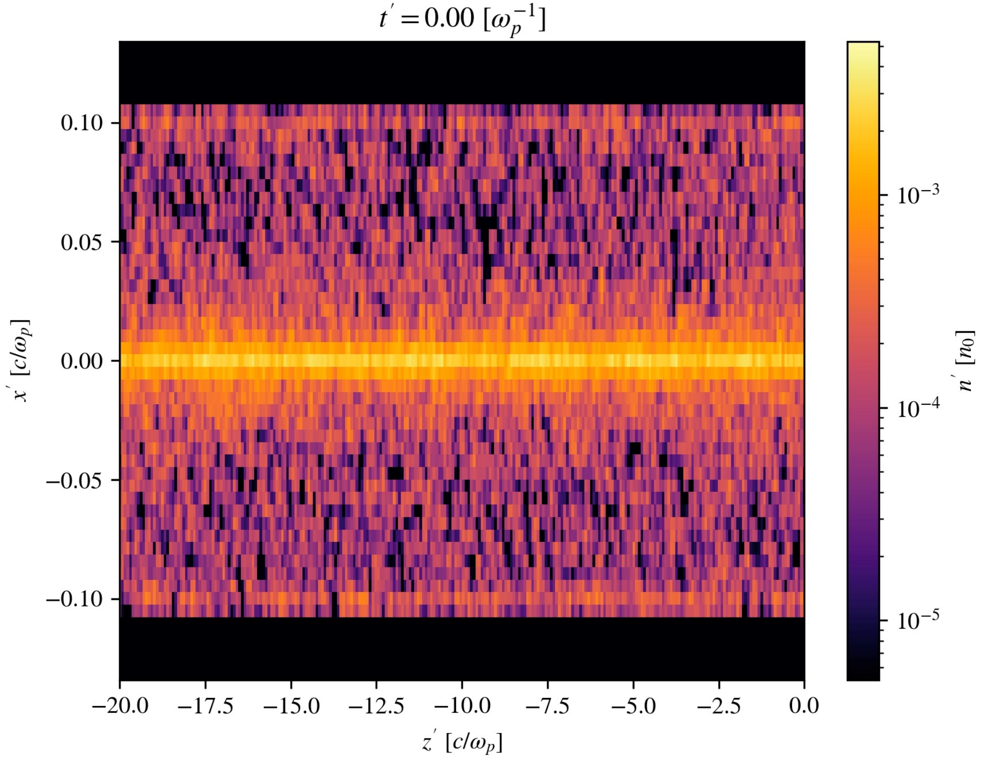
- Currently working with UCLA plasma simulation group to simulate ICL using OSIRIS
  - Step 1: understand basic physics of ICL instability
  - Step 2: explore experimentally relevant parameters

3.7b) ICL Simulation Examples

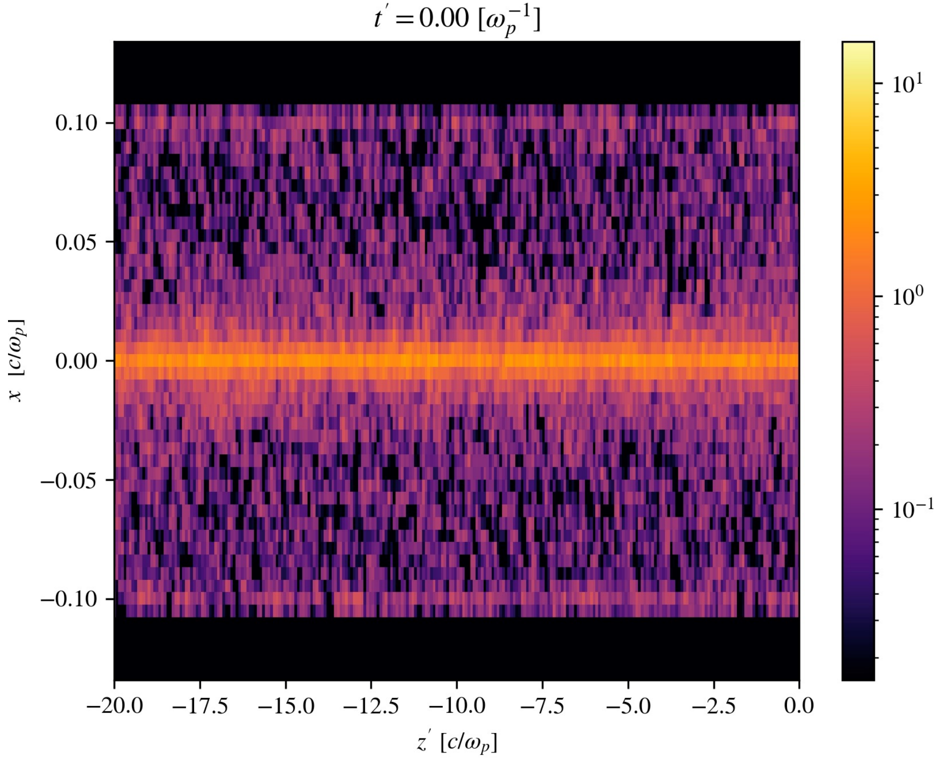
- Recent simulations of contrived beams showing evidence of high-gain lasing in ICL
- Circular polarization seed used – expect fusilli microsnaking
- Preliminary work-in-progress



1 A beam:
No microsnaking.



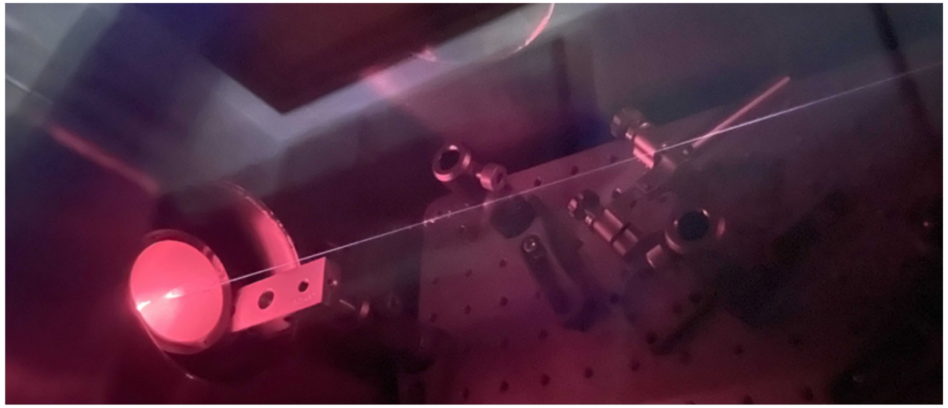
1 kA beam:
Microsnaking!



3.8) ICL Research Plans: E-306 at FACET-II

University of Colorado **Boulder**

- FACET-II well suited for first experimental demonstration of ICL, designated E-306:
  - High charge, high energy drive beam
  - High current, low(ish) emittance witness beam
  - EOS-BPM to measure offset of witness beam (designed by us!)
  - Long, tunable, laser-ionized plasma source (designed by us!)
  - Narrow plasma dovetails with E-333 positron PWFA experiment (**see Valentina Lee's poster**)
  - Advanced PWFA-like plasma source diagnostics (**see Valentina Lee's talk**)



Plasma source and diagnostic development at Univ. of Colorado

- Two phases envisioned:
  - E-306a: seeded lasing at 400 nm using FACET-II linac witness beam
  - E-306b: SASE lasing in XUV using plasma-injected beam (DDR, TH, BII, etc.)

3.9) Acknowledgement

ICL theory and simulation work by **Claire Hansel**

University of Colorado Boulder graduate student in my group

Currently stationed at SLAC

Paper coming soon!

Thank you!

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