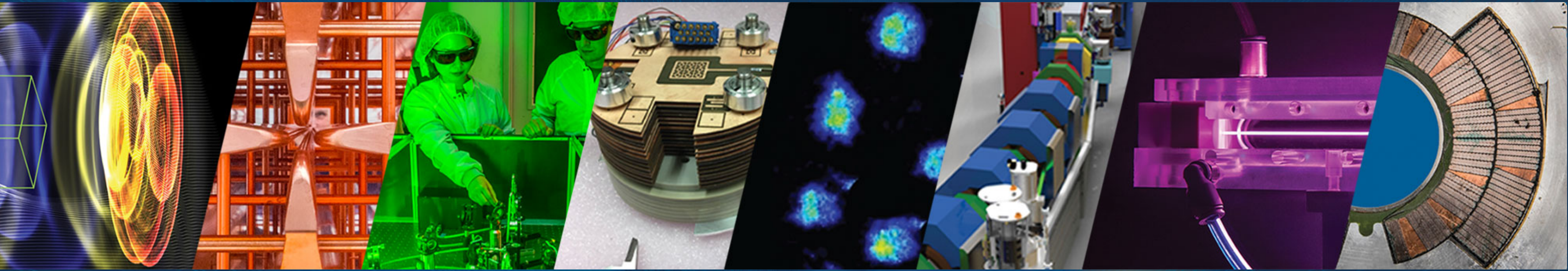
Progress in Plasma Accelerator R&D at the BELLA Center: From Early Applications to Collider-Relevant Studies

Sarah Schröder

Project Scientist

Lawrence Berkeley National Laboratory (LBNL)

European Advanced Accelerator Conference, Elba, Italy — September 22-26 2025



BERKELEY LAB

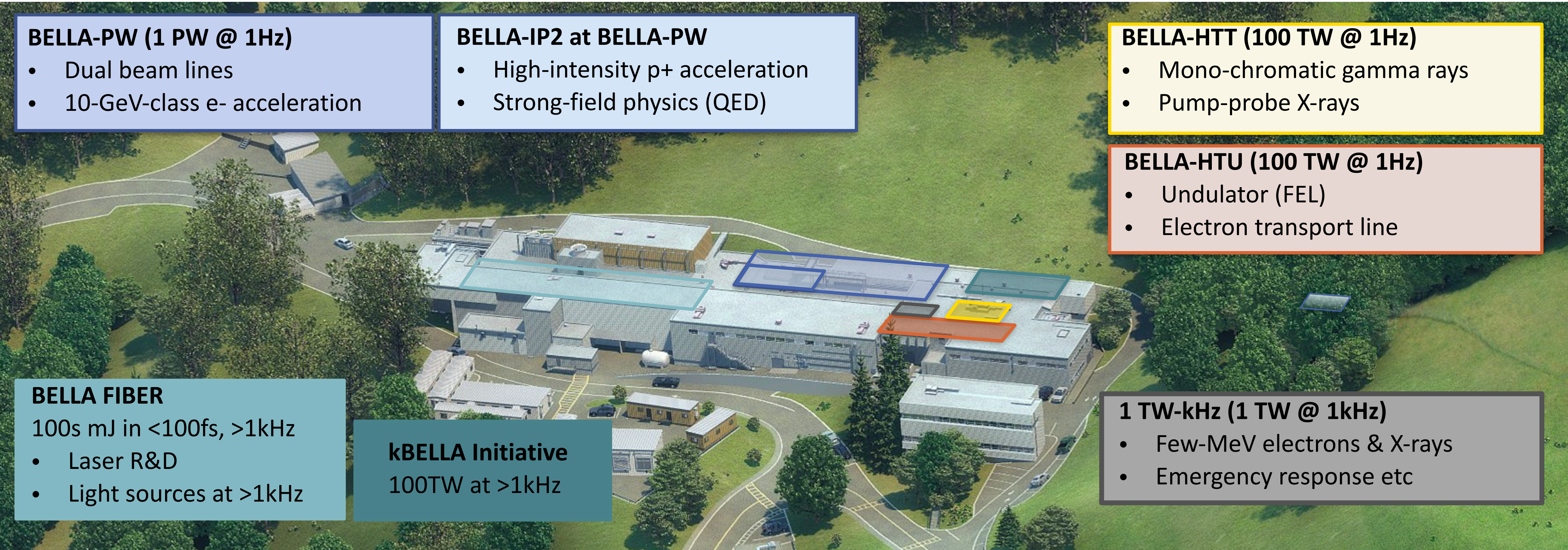
ACCELERATOR TECHNOLOGY & APPLIED PHYSICS DIVISION ATAP

U.S. DEPARTMENT OF ENERGY | Office of Science

BELLA — A Hub For Exploring The Wealth Of Laser Plasma Accelerators

BErkeley **L**ab **L**aser **A**ccelerator

5 laser-plasma accelerators, and a next-generation coherently-combined fiber laser program addressing laser, accelerator and light source R&D and applications



BELLA-PW (1 PW @ 1Hz)
- Dual beam lines
- 10-GeV-class e- acceleration

BELLA-IP2 at BELLA-PW
- High-intensity p+ acceleration
- Strong-field physics (QED)

BELLA-HTT (100 TW @ 1Hz)
- Mono-chromatic gamma rays
- Pump-probe X-rays

BELLA-HTU (100 TW @ 1Hz)
- Undulator (FEL)
- Electron transport line

BELLA FIBER
100s mJ in <100fs, >1kHz
- Laser R&D
- Light sources at >1kHz

kBELLA Initiative
100TW at >1kHz

1 TW-kHz (1 TW @ 1kHz)
- Few-MeV electrons & X-rays
- Emergency response etc

The BELLA Team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Carlo Benedetti


Stepan Bulanov


Mingshu Chen


Hao Ding


Eric Esarey


Anthony Gonsalves


Robert Jacob


Chetanya Jain


Mackinley Kath


Stanimir Kisyov


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Joe Riley


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Kyle Jensen

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Lawrence Livermore National Laboratory

radiasoft

DESY.

Colorado State University

RadiaBeam

LaserNetUS

beamNetUS
accelerating beam-based research

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Laser-plasma accelerator R&D

- > High-quality beam generation
- > Novel injection techniques
- > Plasma sources / lenses
- > Stability & reliability
- > kHz laser system
- > Staging

Theory and Simulations

- 10 TeV collider design study <
- Novel injection techniques <
- Plasma dynamics modelling <
- Experimental modeling <
- AI/ML integration <
- Digital twin <

Applications

- > Free-electron laser
- > Radiation hardness testing
- > Muon beam generation
- > FLASH radiation
- > Radiography
- > Nuclear state excitation

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Laser-plasma accelerator R&D

A. Picksley et al. 133 PRL (2025)
K. Jensen et al. (accepted in PRAB)
F. Kohrell et al. (submitted to PRAB)
R. Li et al. Rev. Sci. Instrum. 96 (2025)
F. Kohrell et al. NIMA 1073 (2025)
C. Berger et al. NIMA 1078 (2025)
A. Amodio et al. High Power Laser Science and Engineering 13 (2025)
N. Czapla et al. Scientific Reports 15 (2025)
H. Pan et al. Opt. Engin. 63 (9) (2025)
J. E. Shrock et al. PRL 133 (2024)

Theory and Simulations

D. Terzani et al. (accepted in PRAB)
N. M. Cook et al. NIMA 1079 (2025)
F. Massimo et al. PPCF 67 (2025)
D. Terzani et al. PRAB 26 (2024)
S. Bulanov, Nature Photonics 18 (2024)
S. Bulanov et al. JINST 19 (2024)
T. Barklow et al. JINST 18 (2024)
M. Garten et al. PRR 6 (2024)
S. Diederichs et al. PRL 133 (2024)

Applications

S. Barber et al. PRL 135 (5) (2025)
R. E. Jacob et al. PRL 134 (2025)
J. de Chant et al. PRAB 28 (3) (2025)
S. Hakimi et al. PoP 31 (2024)
G. Fauvel et al. Review of Scientific Instruments 96 (2025)
J. L. Inman et al. Scientific Reports 14 (1), 6119 (2024)

Lawrence Livermore National Laboratory
radiasoft
DESY.
University of Maryland 1856
Colorado State University
Northrop Grumman
TAU
RadiaBeam
U.S. Department of Energy Office of Science

Laser-plasma accelerator R&D

A. Picksley et al. 133 PRL (2025)

Matched Guiding and Controlled Injection in Dark-Current-Free, 10-GeV-Class, Channel-Guided Laser-Plasma Accelerators

Plenary talk of A. Picksley
Monday, Sept. 22, 9:15

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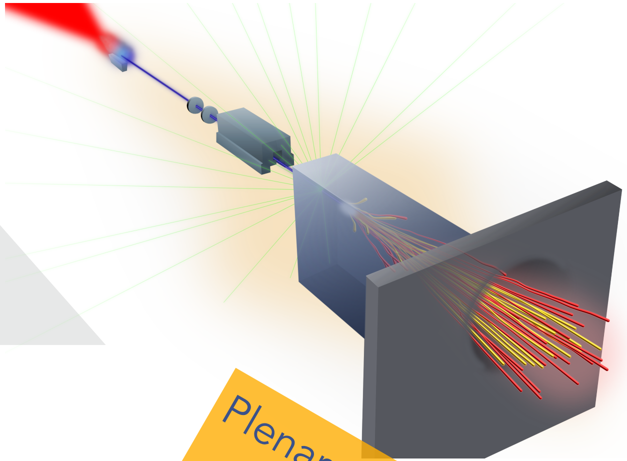

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Tuesday, Sept. 23, 12:00

Applications

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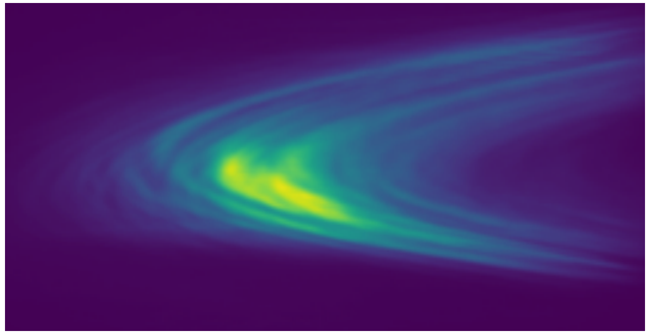
Greater than 1000-fold Gain in a Free-Electron Laser Driven by a Laser-Plasma Accelerator with High Reliability



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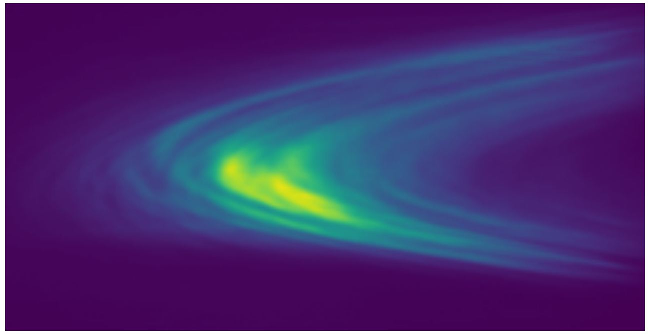

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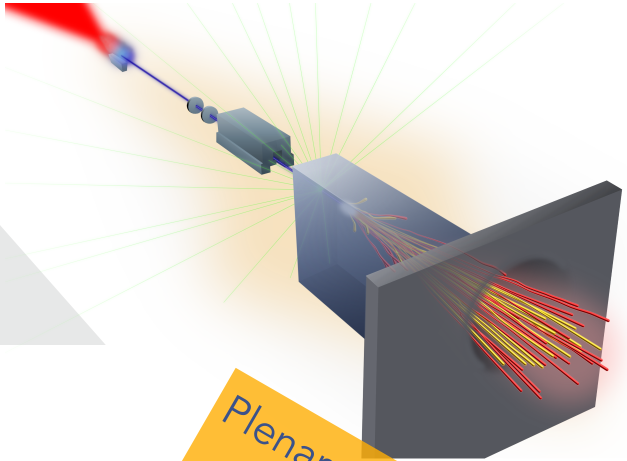

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Laser Guiding — The Essence Of Prolonged Acceleration Lengths

Matched Guiding and Controlled Injection in Dark-Current-Free, 10-GeV-Class, Channel-Guided Laser-Plasma Accelerators

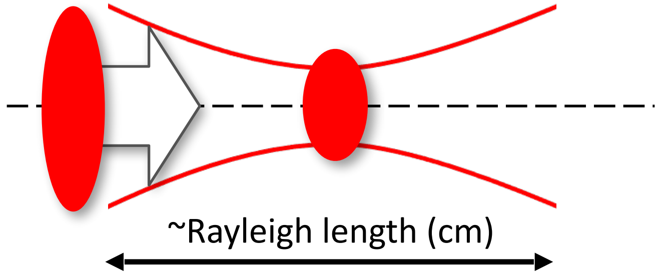
A. Picksley et al. 133 PRL (2025)

Beam energy = G * **L**

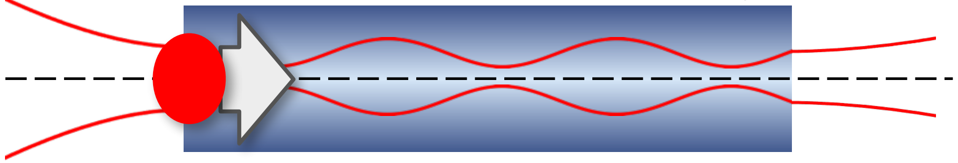
G: Gradient

L: Acceleration length

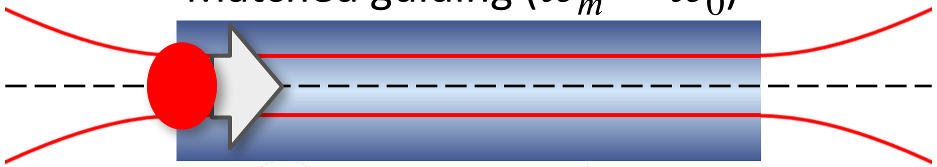
Laser diffraction in vacuum:



Mismatched guiding ($w_m > w_0$)



Matched guiding ($w_m = w_0$)



Free-Standing, Length-Adjustable Gas Jet For Effective Laser Guiding

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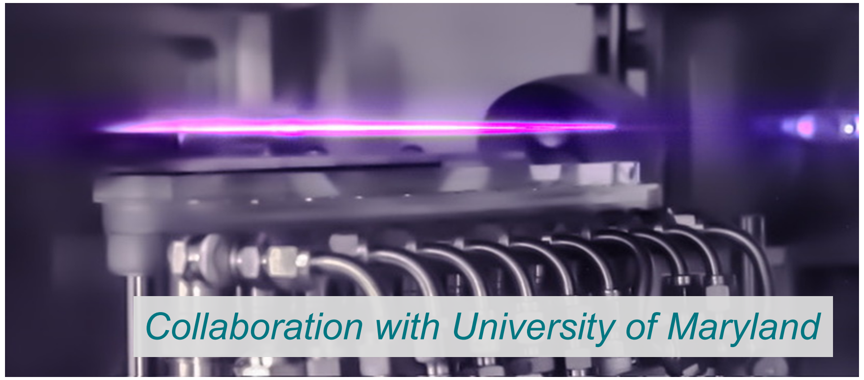
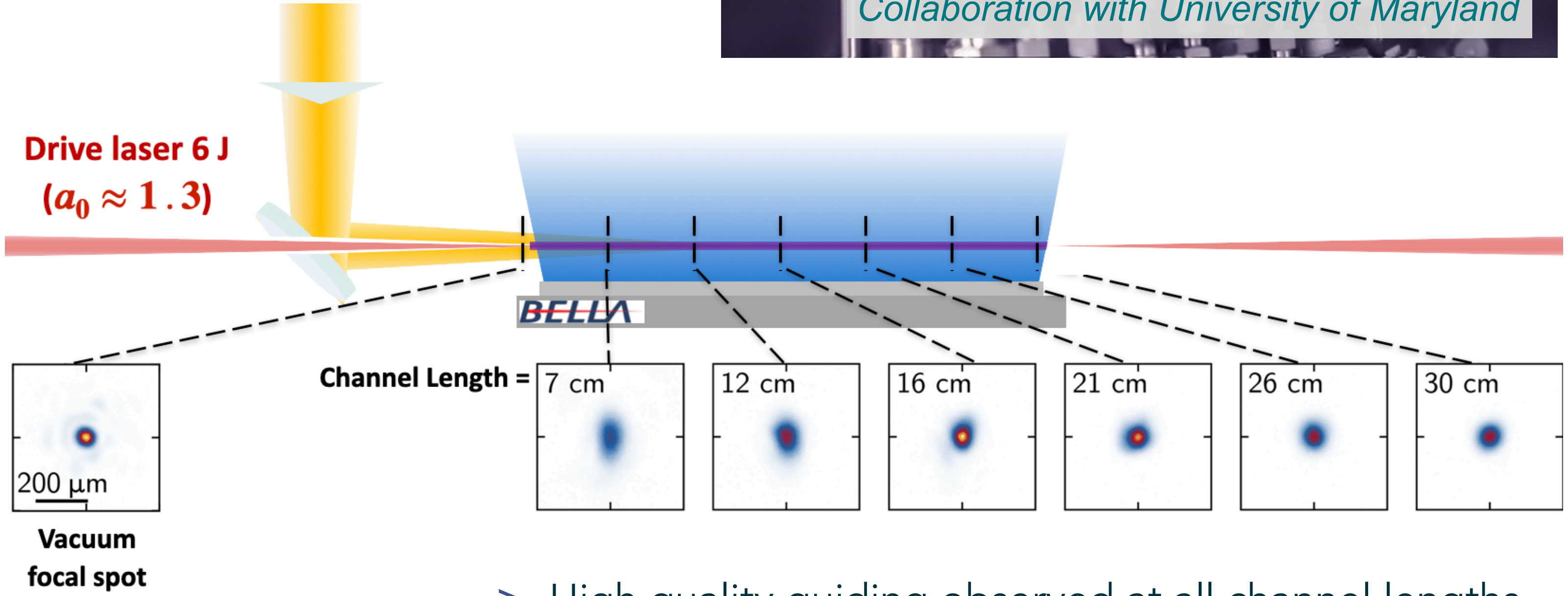
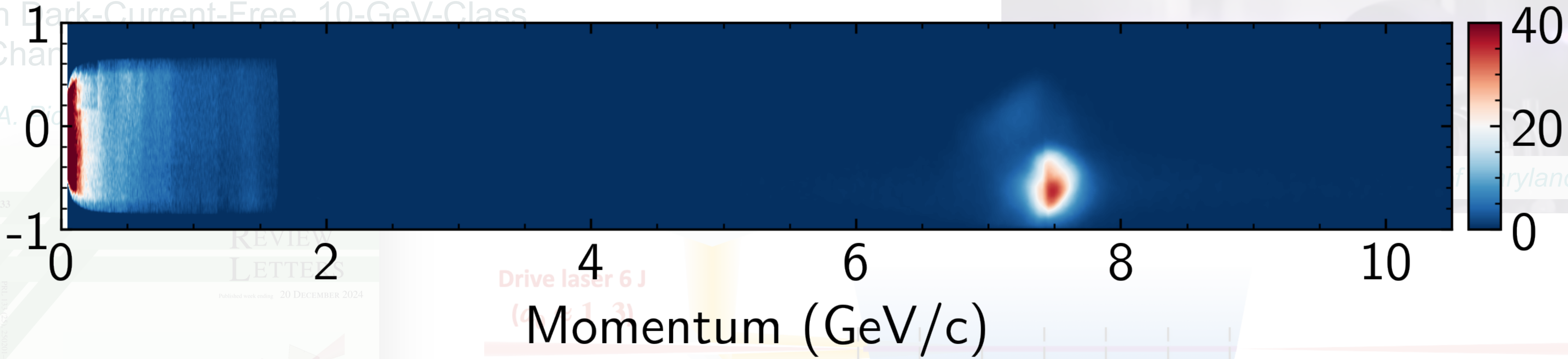




> High quality guiding observed at all channel lengths

> Enabled examination of laser-plasma interaction along the plasma channel

Free-Standing, Length-Adjustable Gas Jet For Effective Laser Guiding



- 10 GeV-level electron bunches
- %-level energy spread
- Low dark current

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Laser-plasma accelerator R&D

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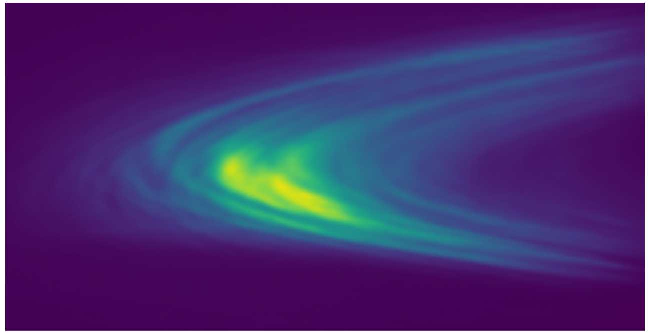

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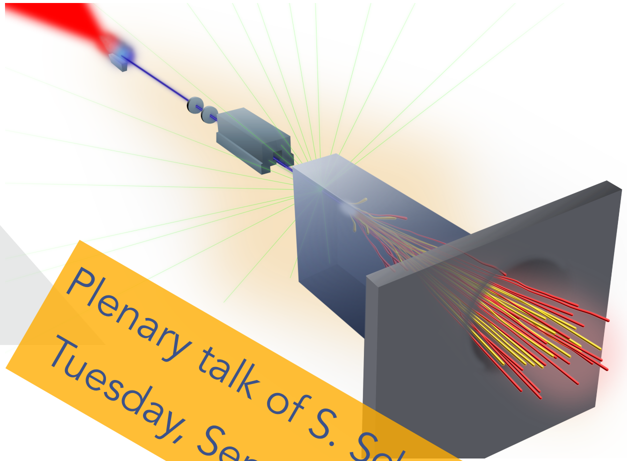

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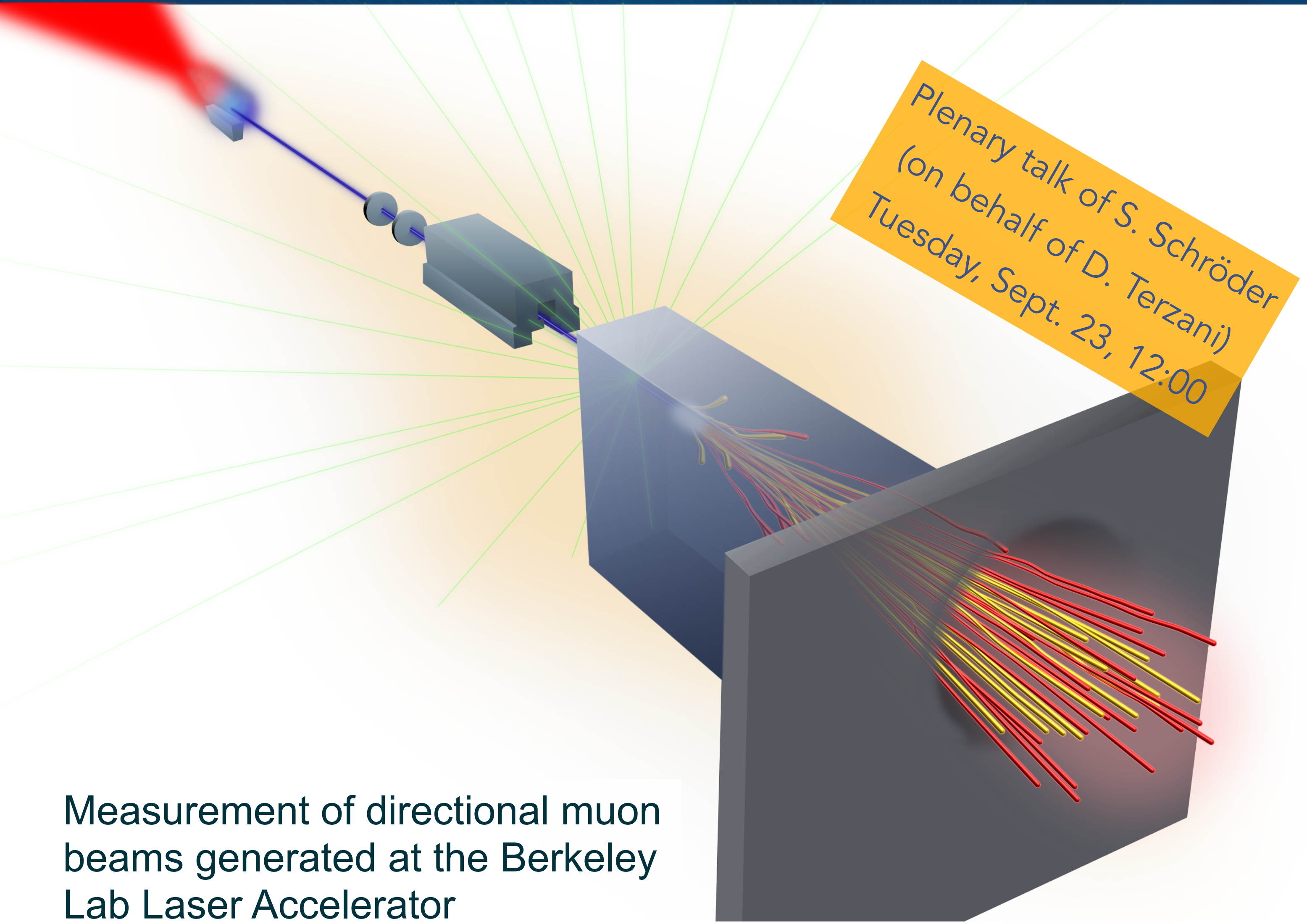
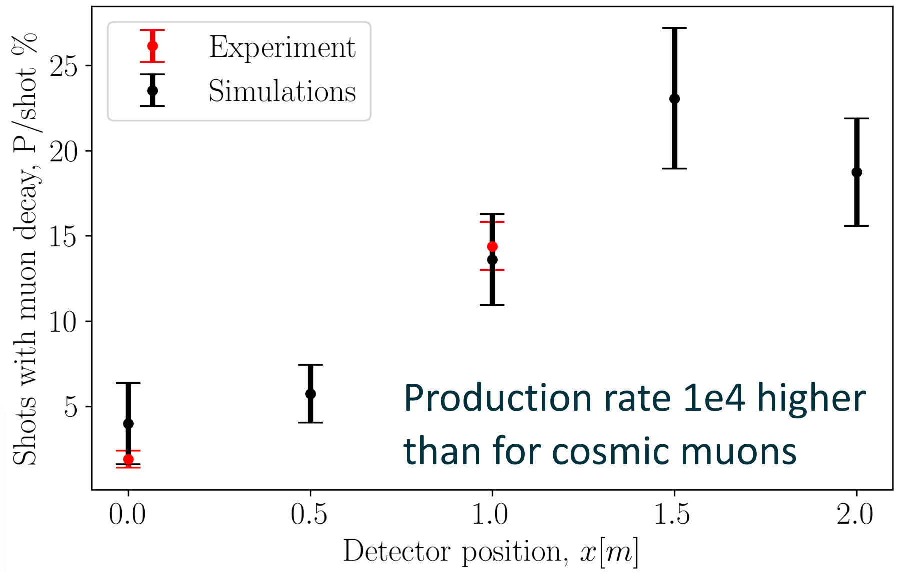
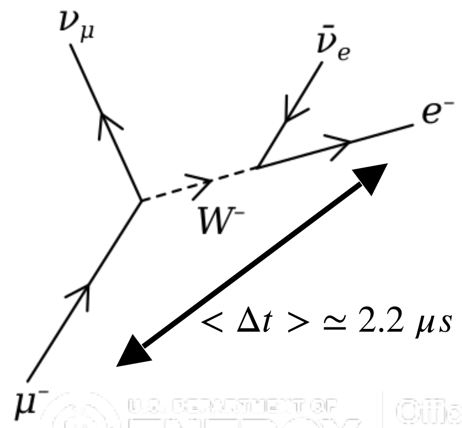
Unlocking New Applications — High-Flux, Directional Muon Production







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133
PHYSICAL REVIEW LETTERS
20 DECEMBER 2024
American Physical Society
APS

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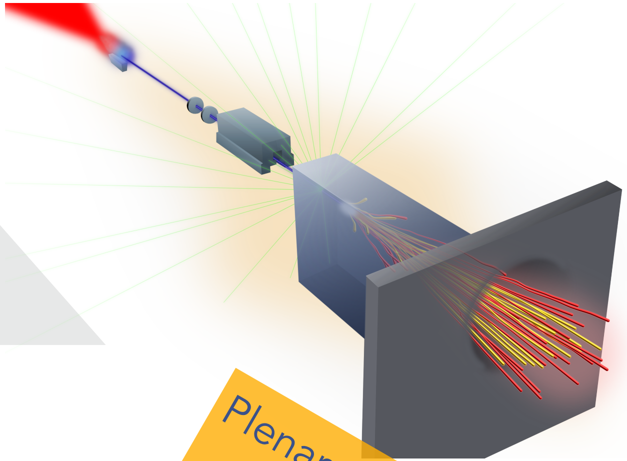

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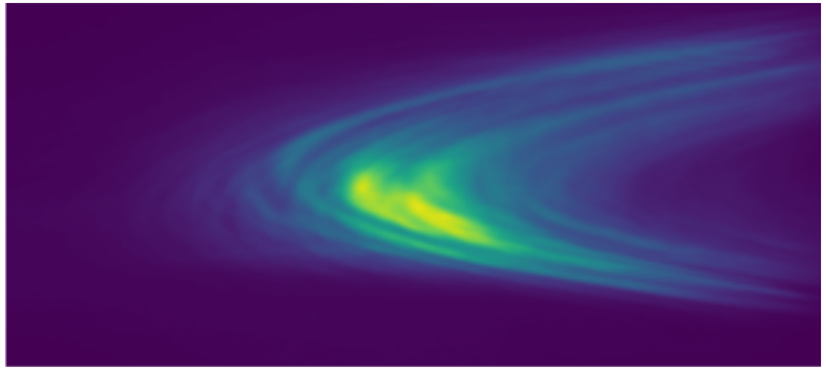
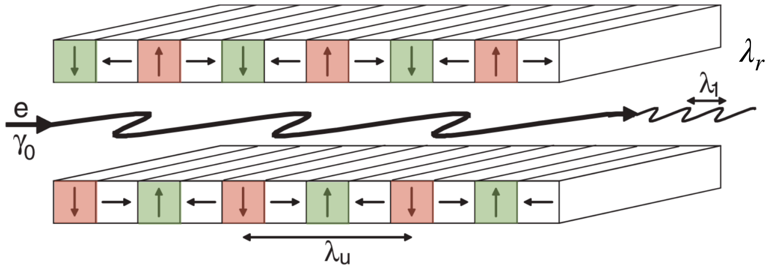


Free-Electron Lasers — Concept And Application

- > Femtosecond-pulsed, coherent X-ray light source.
- > Electron bunch propagating through alternating magnetic field.
  - > Transverse wiggeling electron bunch motion couples to the horizontal component of the radiation field.
  - > High phase space density of an electron bunch establishes FEL gain through Self-Amplified Spontaneous Emission of radiation (SASE).

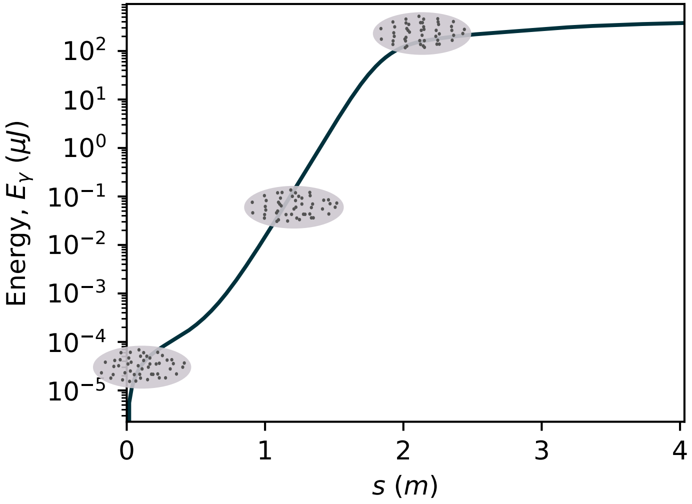
Electron propagating in an undulator



$$\lambda_r \approx \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2}\right)$$

Z. Huang, K.-J. Kim PRSTAB 10, 034801 (2007)

Radiation enhancement



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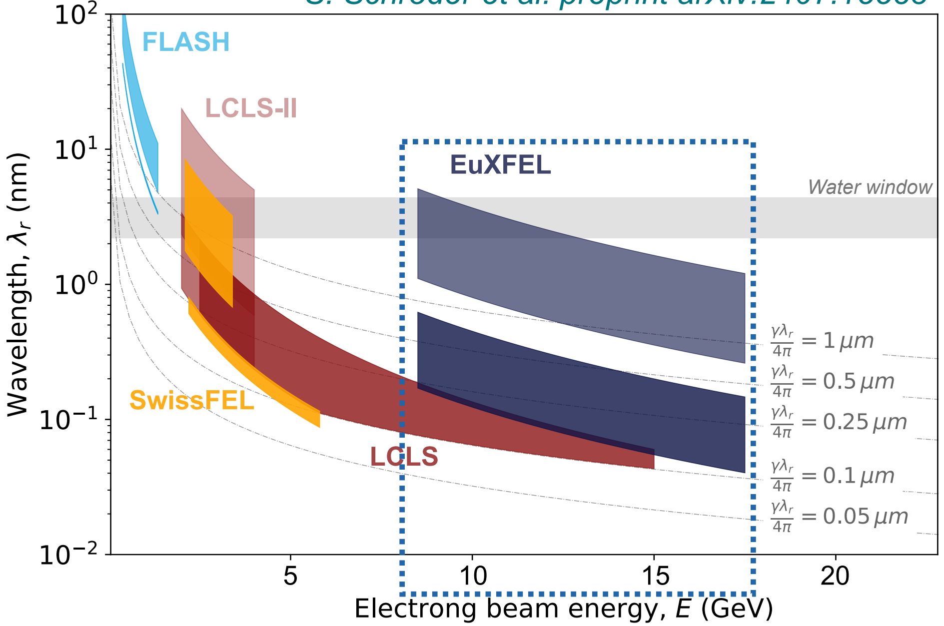
  - High phase space density of an electron bunch establishes FEL gain through Self-Amplified Spontaneous Emission of radiation (SASE).
- Radiation wavelength $\lambda_r \propto 1/\gamma^2$
  - Scale of operational FELs: O(100m)-O(km)

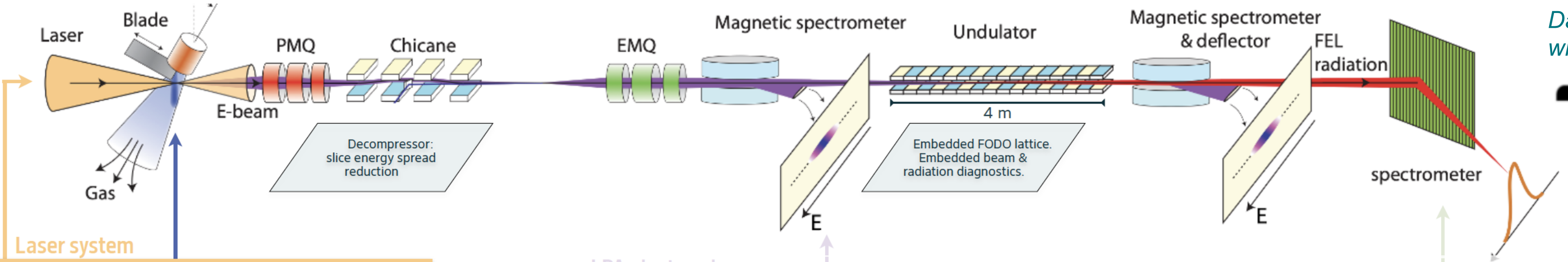
S. Schröder et al. preprint arXiv:2407.15583



A compact FEL design will enhance accessibility for research and enable potential industrial use.

W. Wang et al. Nature 595, 516–520 (2021)
M Labat et al. Nature Photonics 17, 150–156 (2023)

BELLA HTU — Building A Reliable LWFA-Based FEL Prototype

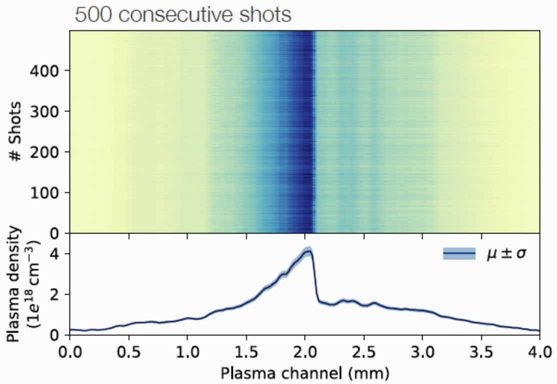


Data taken in partnership with TAU Systems Inc.

Laser system

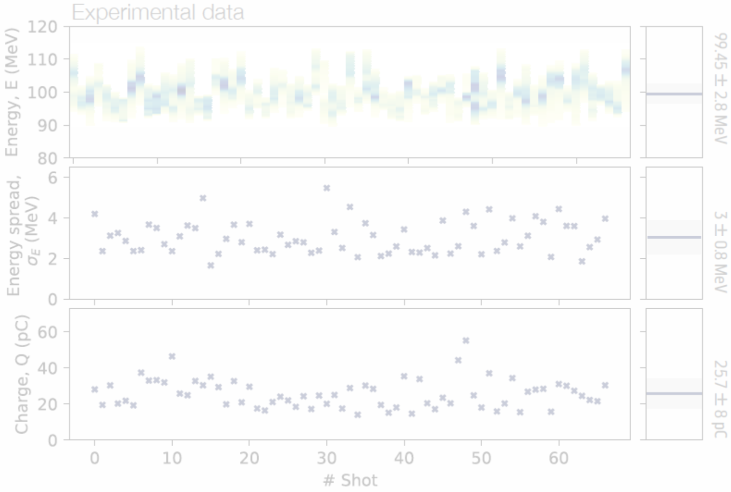
- 100TW, 5Hz, 0.8 μm
- At full capacity: 2.5 J, w_0: 38 μm, σ_t: 37 fs.
- Active stabilisation systems.

Plasma source



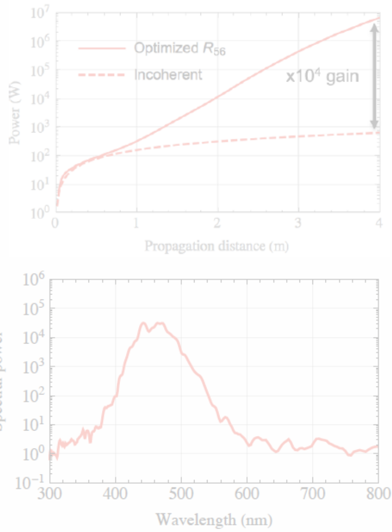
- Supersonic jet with adjustable blade system.
- On-axis density measurement via phase modulation of a transverse probe.

LPA electron beam



- 30 pC @ 100 MeV beams are routinely achieved.
- 3% mean energy jitter.
- 20% charge jitter.

Undulator radiation



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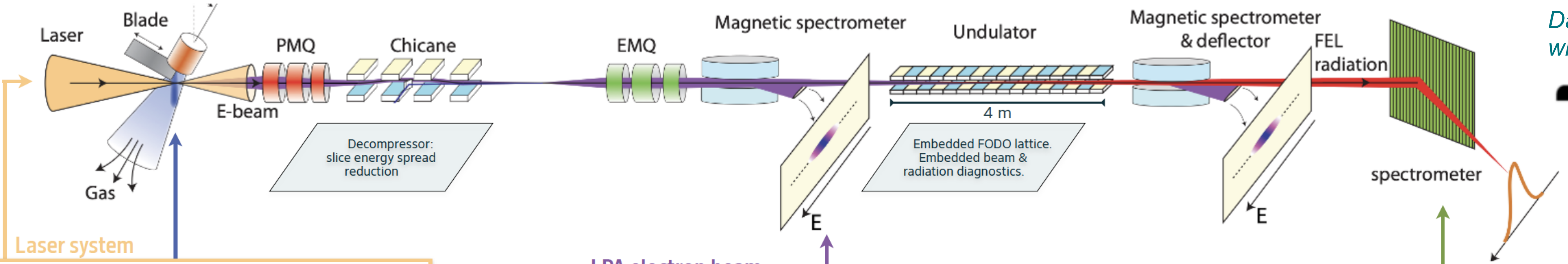

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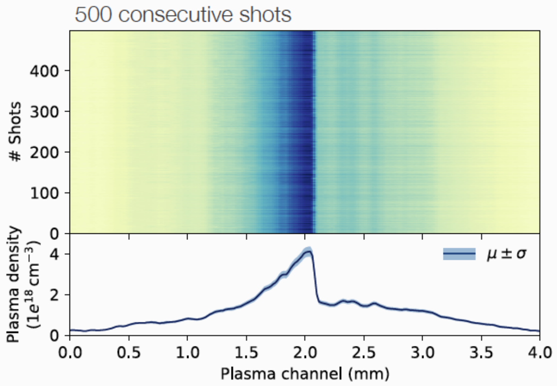

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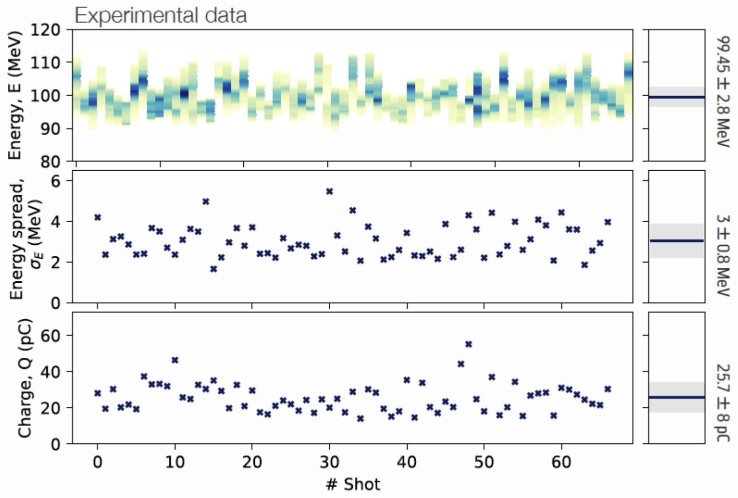

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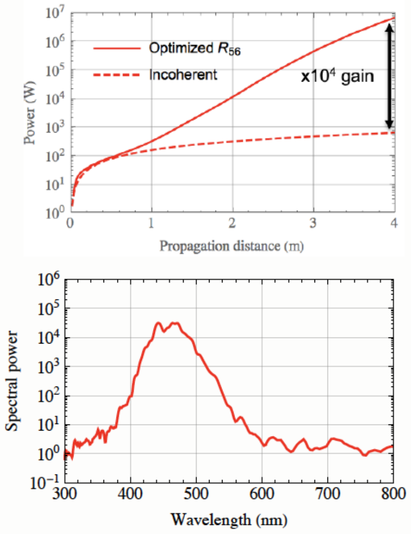
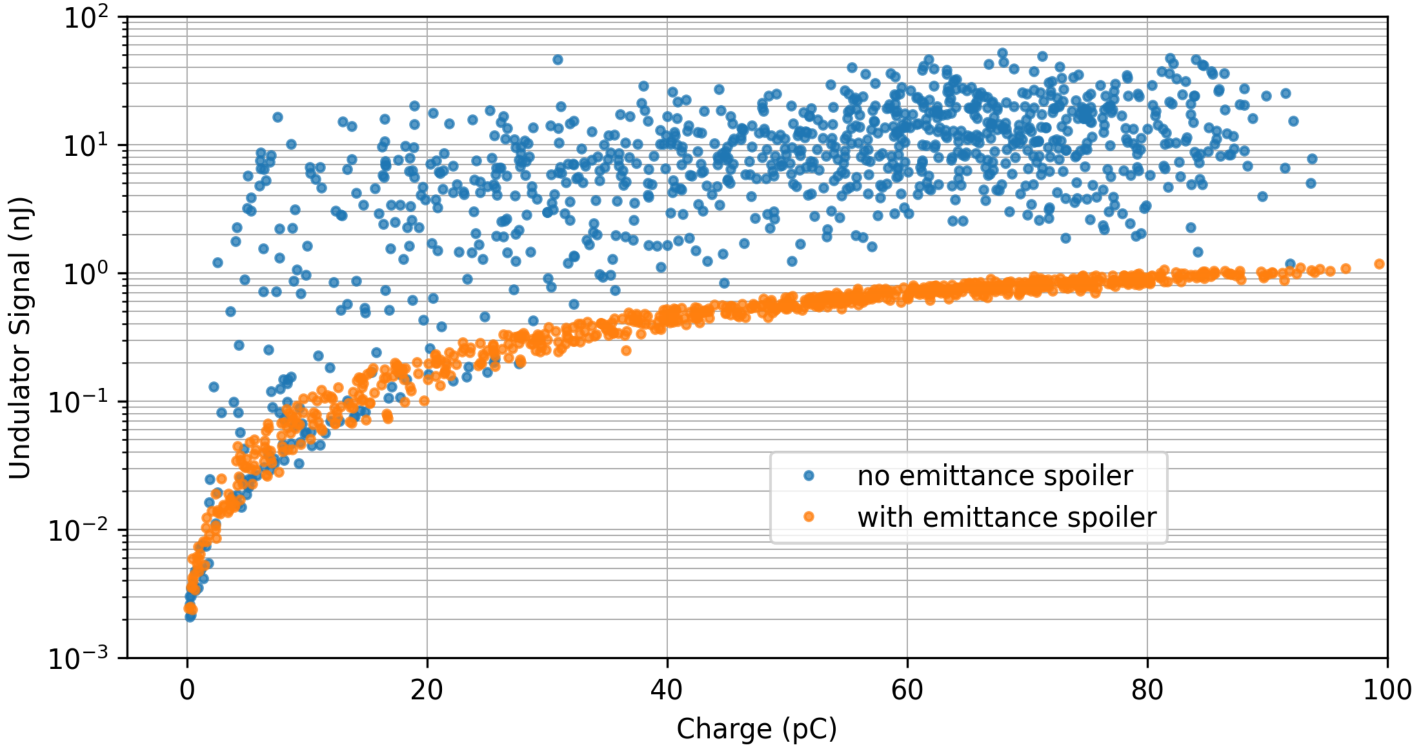
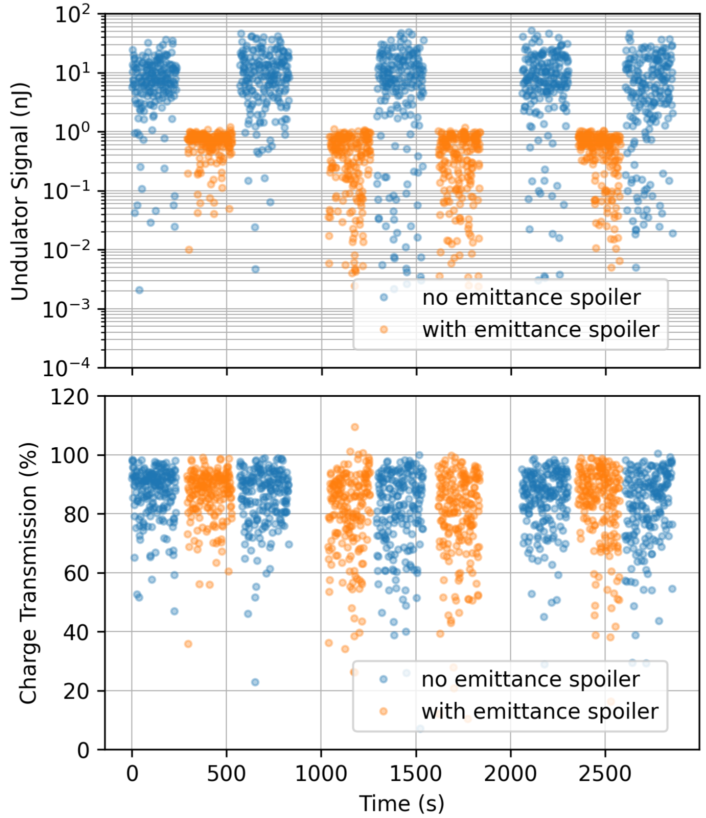


Reliable Incoherent FEL Gain Driven By A Laser-Plasma Accelerator



- Gain over incoherent undulator radiation on >90% of shots
- Ratio FEL to incoherent: ~200-300x (max), 50-100x (average)

Undulator radiation signal measured over 1 hour



- Stable operation of FEL over hours
- Charge transmission unaffected by emittance spoiler

S. Barber et al. PRL 135 (5) (2025)

Critical system developments along the way:

F. Isono et al, High Power Laser Sci. Eng. 9, e25 (2021)
C. Berger et al, PRAB **26** 032801 (2023)
K. Jensen et al. (accepted in PRAB)
F. Kohrell et al. (submitted to PRAB)

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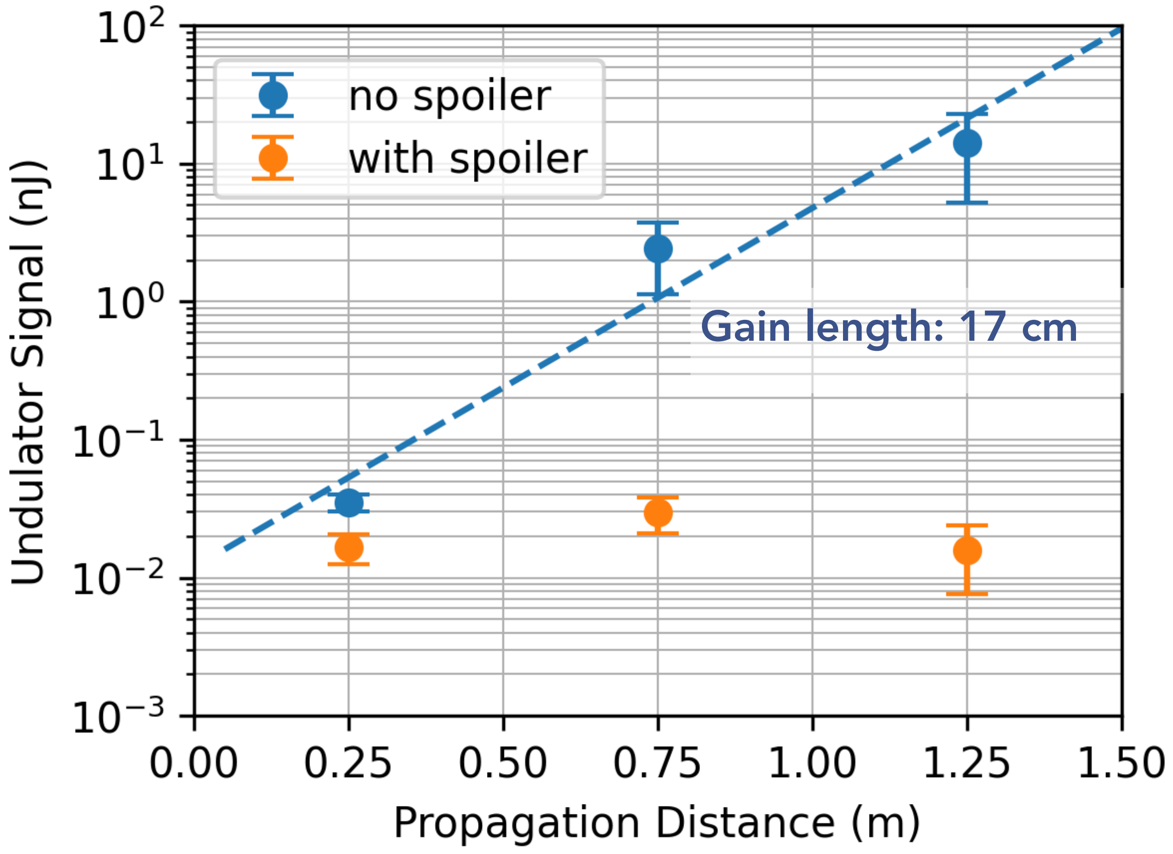
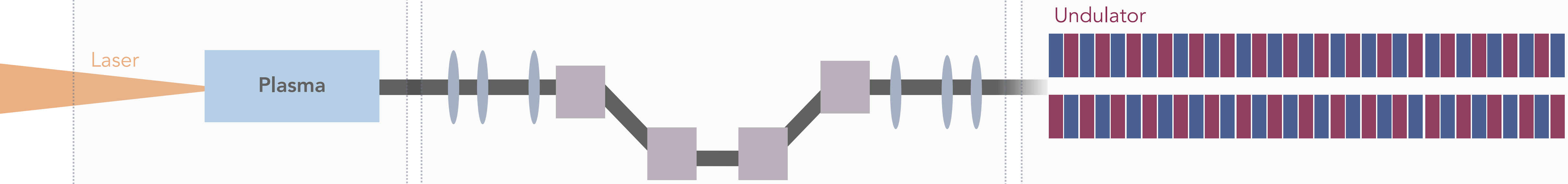


> Why does the FEL process breaks up after ~1m?

➡ **Establish a model of the experiment**

S. Barber et al. PRL 135 (5) (2025)

Modelling Framework



Laser-plasma accelerator

Physics objective:
Electron bunch generation
Electron bunch acceleration

Software:
WarpX & Wake-T

Beam transport

Physics objective:
Beam tracking
Collective effects: space charge / synchrotron radiation

Software:
ImpactX

FEL process

Physics objective:
FEL process
Electron bunch dynamics

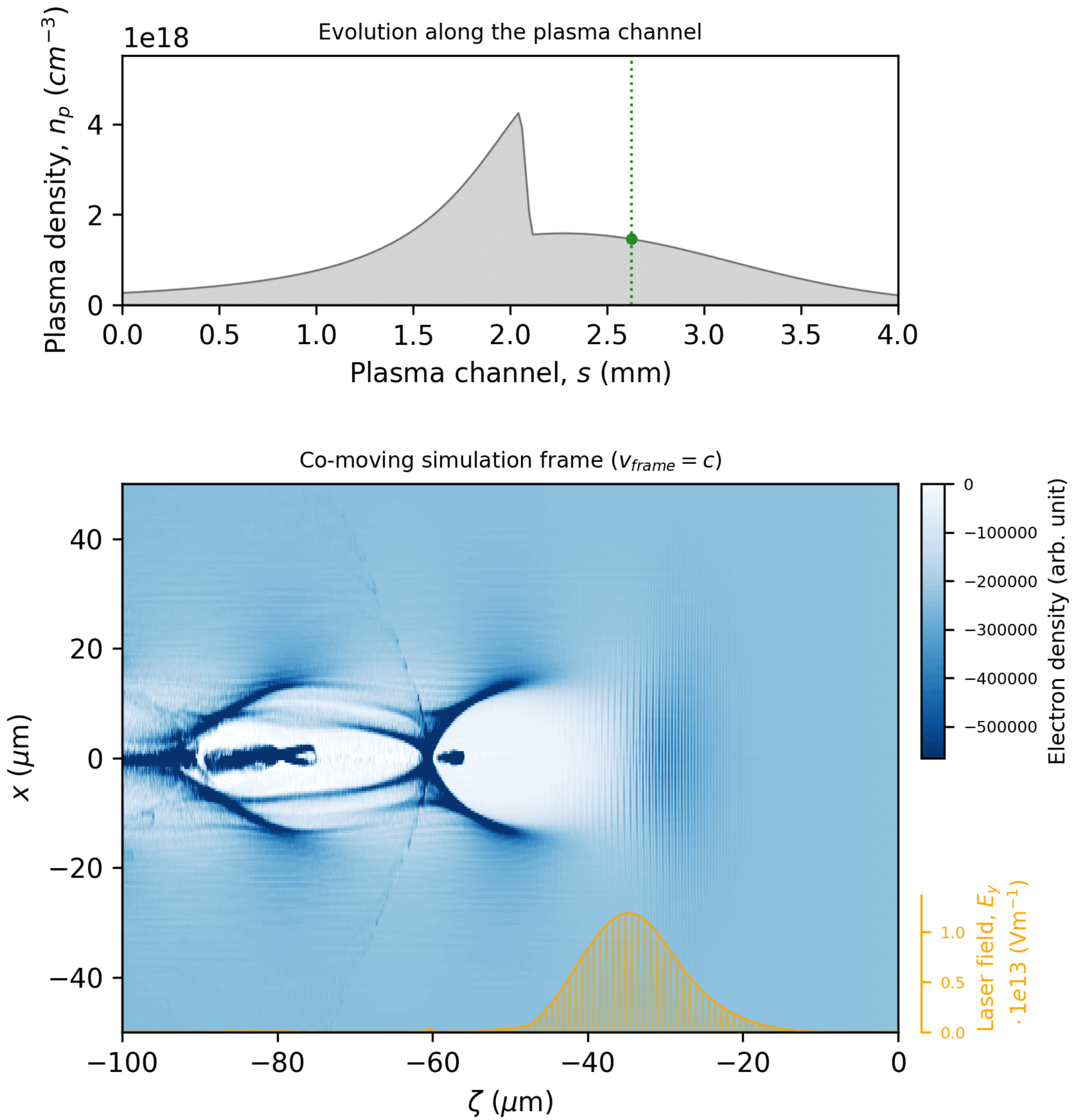
Software:
Genesis-1.3 / WarpX / (optimas)

Linking software packages necessary to model the diverse physics of LWFA-based FELs

Electron Bunches From Plasma Accelerators Offer Unique Opportunities — And Challenges

- LWFAs beam characteristics:
  - Excellent slice emittance (nm)
  - Ultrashort bunches (fs)
  - Large correlated energy spread (%)
  - Injection-technique dependent current profile

FEL operation methodology must adjust for unique beam characteristics, and the impact of instabilities rigorously examined.



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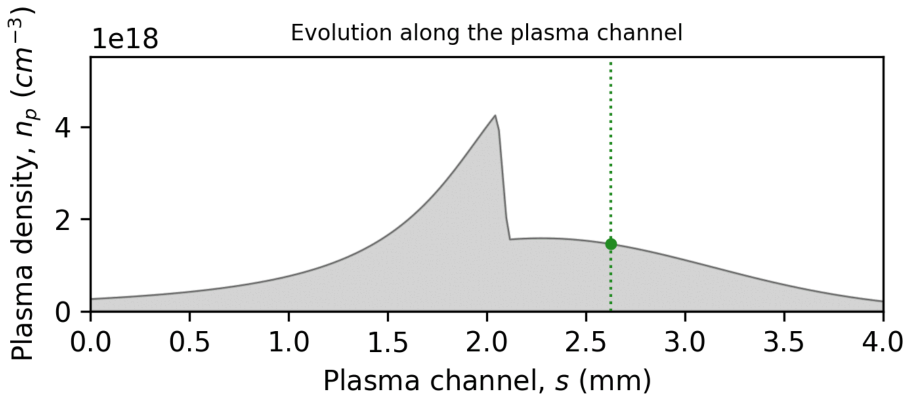
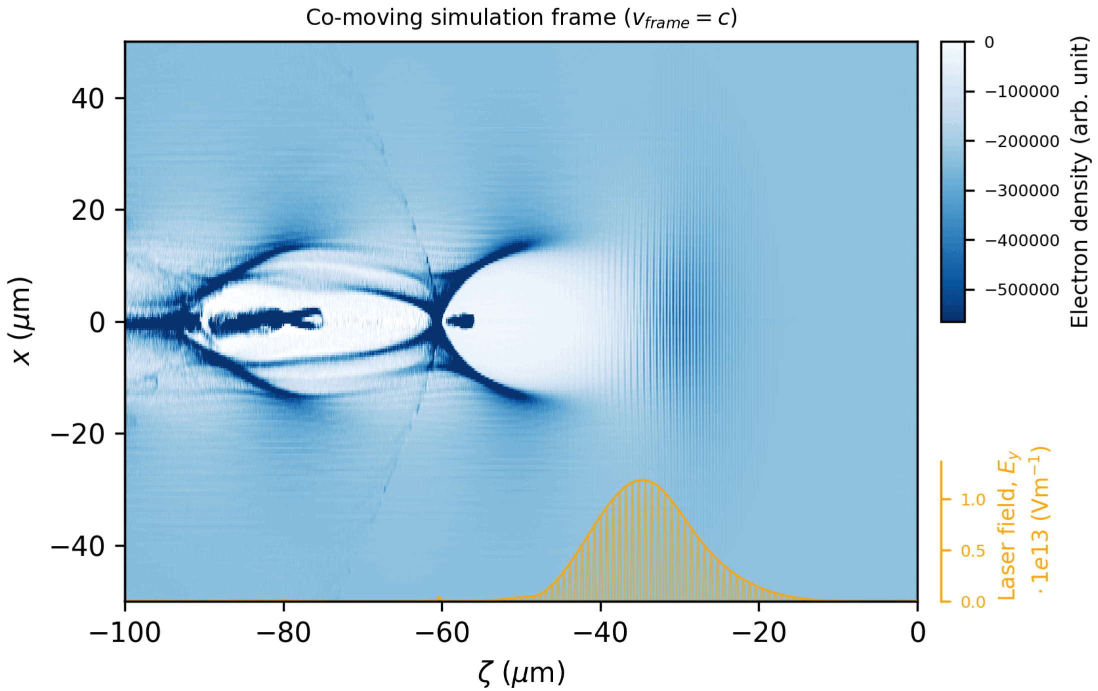




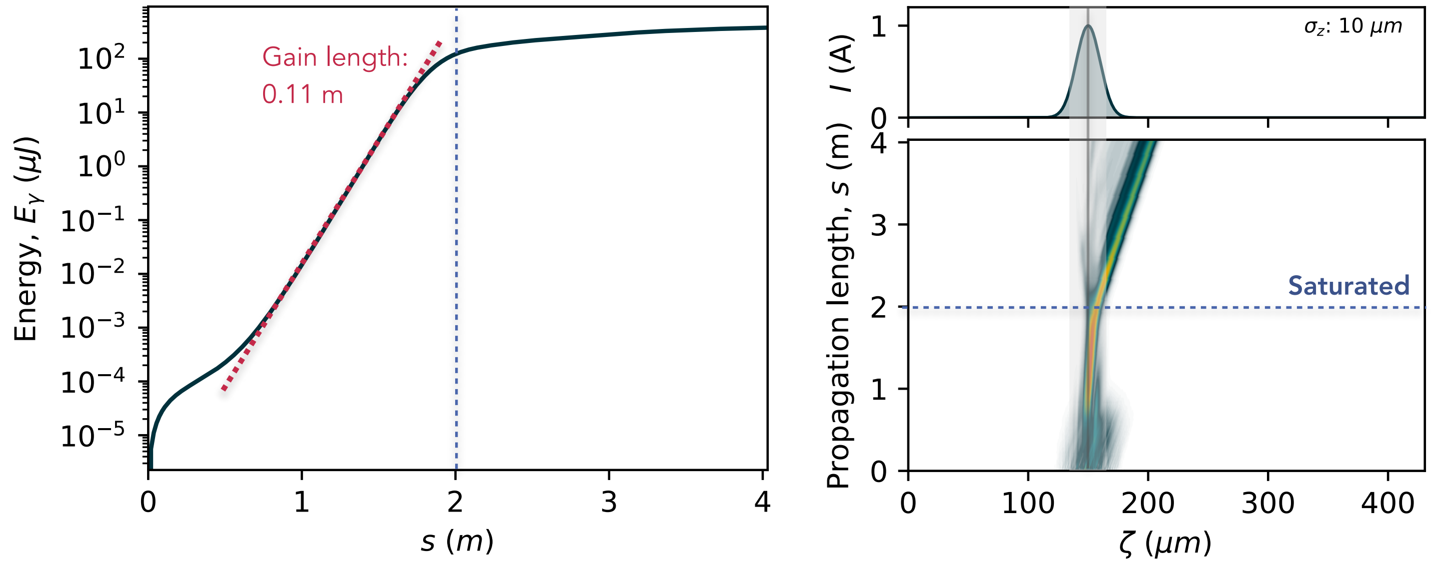
FEL Process Simulations Of The BELLA HTT Setup

> VISA undulators
  — originally designed to verify fundamentals of SASE theory.

> Strong-focusing FODO lattice embedding the undulators keeps the electron bunch spot size small.

A. Tremaine et al. PAC Proceeding (2001)
A. Murokh et al. NIM A 507, 1-2 (2003)

Radiation enhancement **Radiation slippage**



Undulator parameters

λ_u: 0.018 m

λ_r: 430 nm (@ 100 MeV)

L: 4 m

K: 1.28

L_G: <0.2 m

Beam parameters

E: 100 MeV

dE: 0.3%

Q: 100 pC

$\varepsilon_{x,n} = \varepsilon_{y,n} = 0.5$ μm

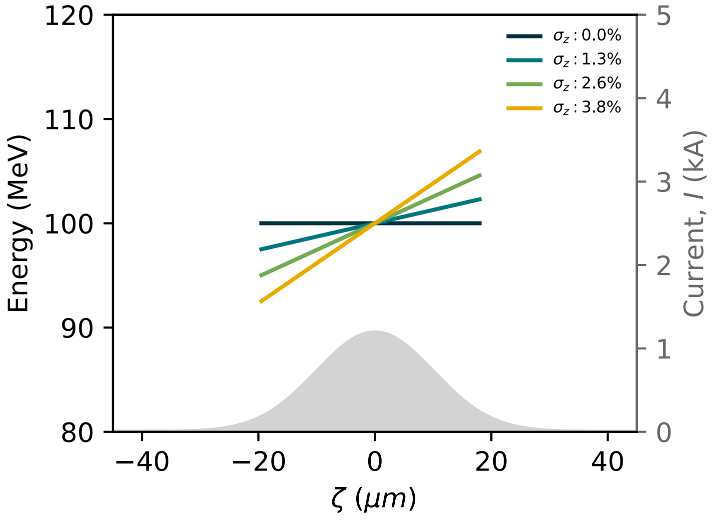
$\sigma_z = 10$ μm

Correlated Energy Spread

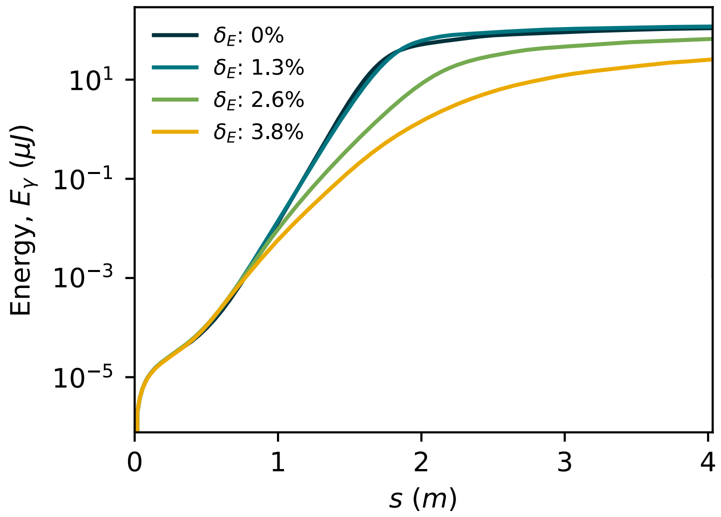
- LWFAs deliver bunches with:
  - Permille-level slice energy spread
  - Percent-level correlated energy spread
- Impact: Spectral broadening and radiation power reduction

Energy spread and chirp control via the injection mechanism and the de-compression chicane is essential for high-quality FEL operation at HTT.

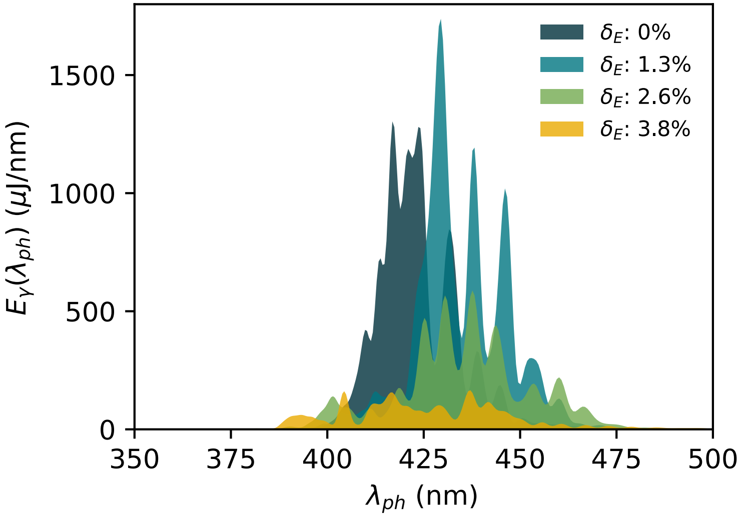
Linear energy chirp model



Radiation enhancement



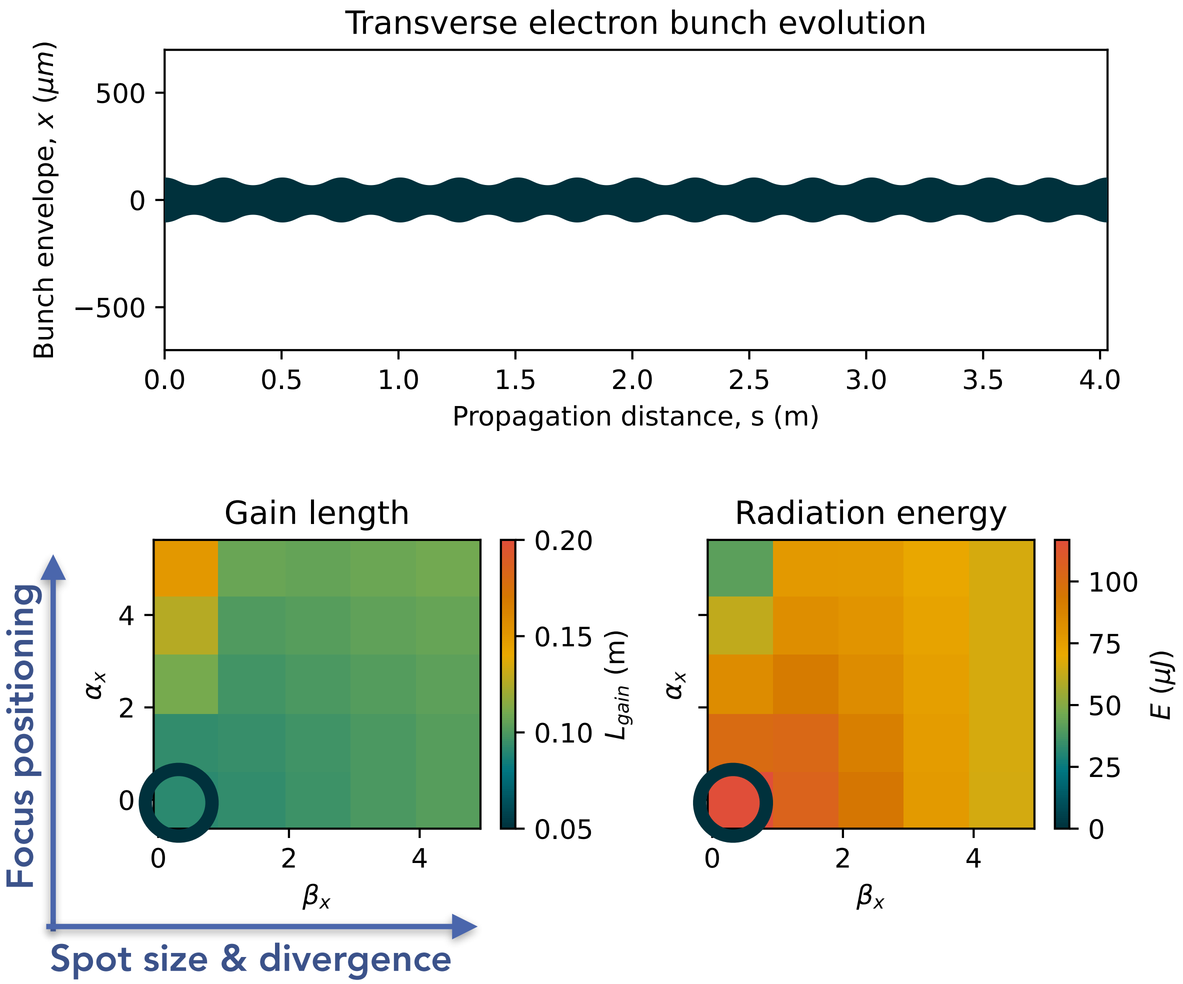
Radiation spectrum



Mismatch Sensitivity

- Strong-focusing FODO lattice embedding the undulators keeps the electron bunch spot size small.
- A mismatch of electron beam spot size or divergence changes its envelope evolution.
  - Enlarged electron spot size throughout the interaction.
  - Reduced transverse overlap of electrons and radiation.

High mismatch tolerance enables reliable FEL operation at BELLA HTU



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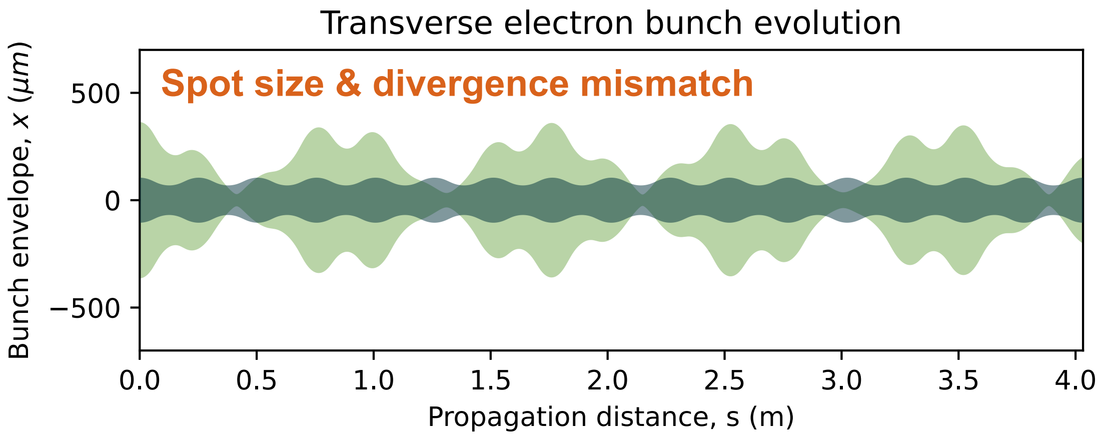

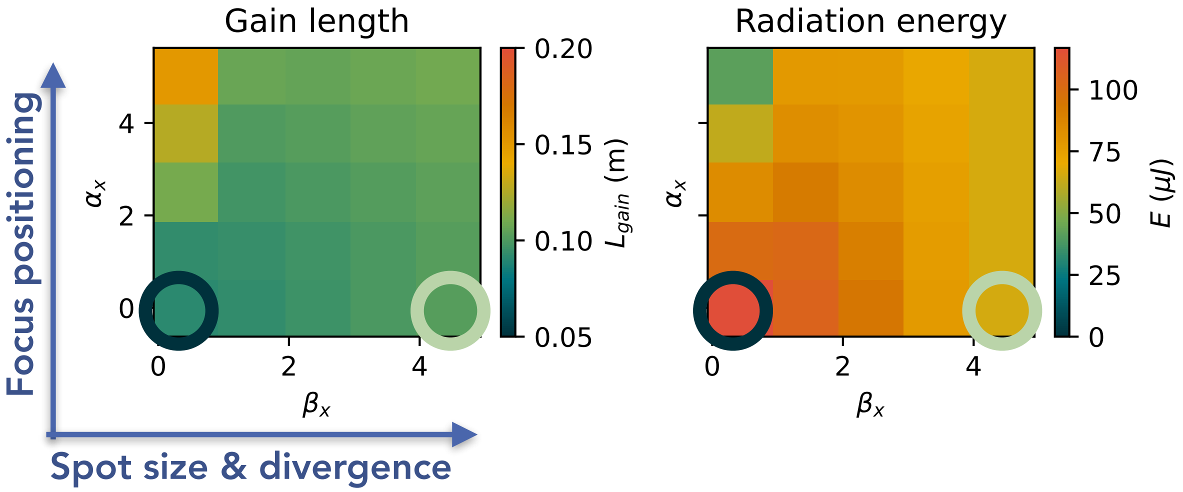

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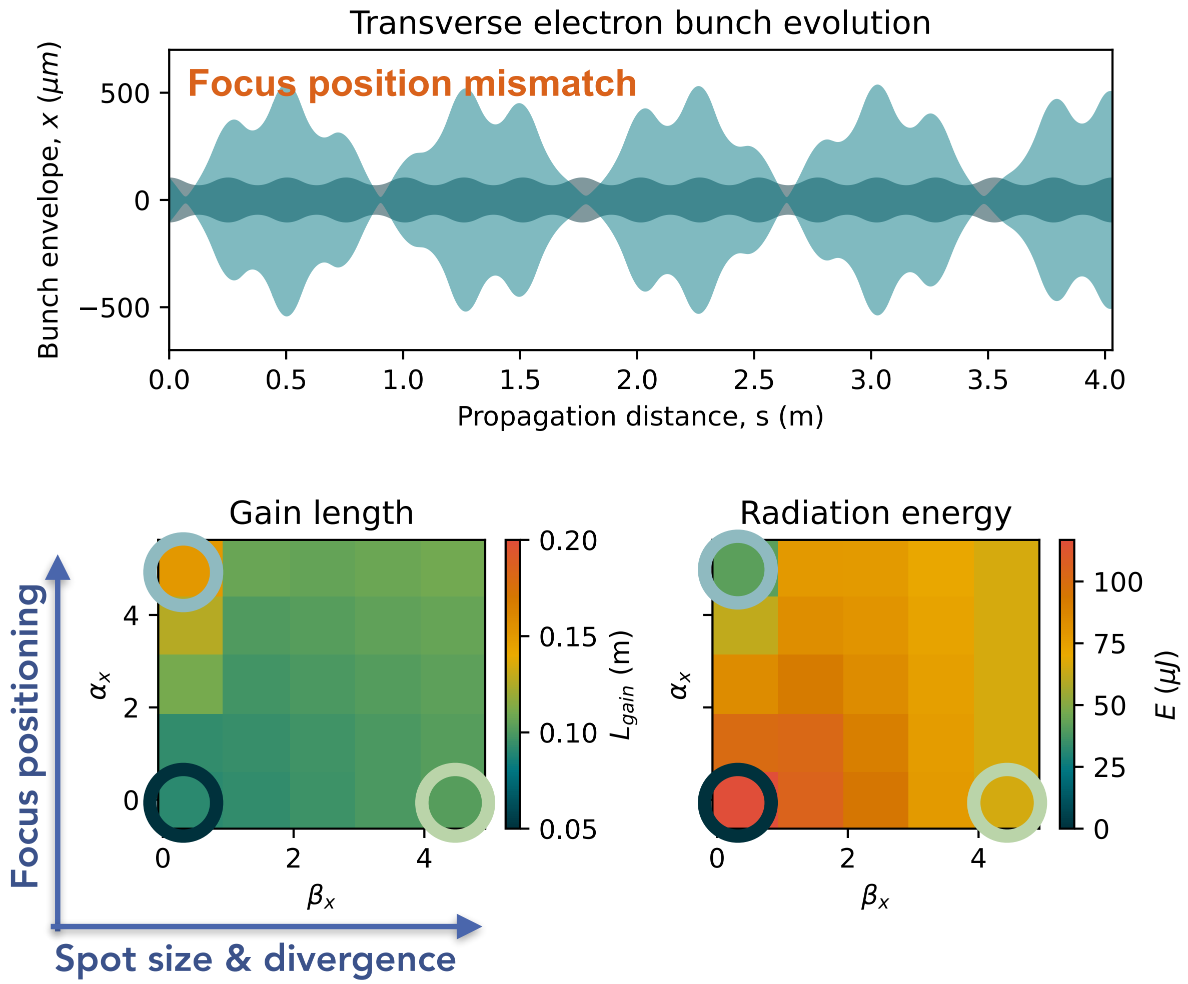
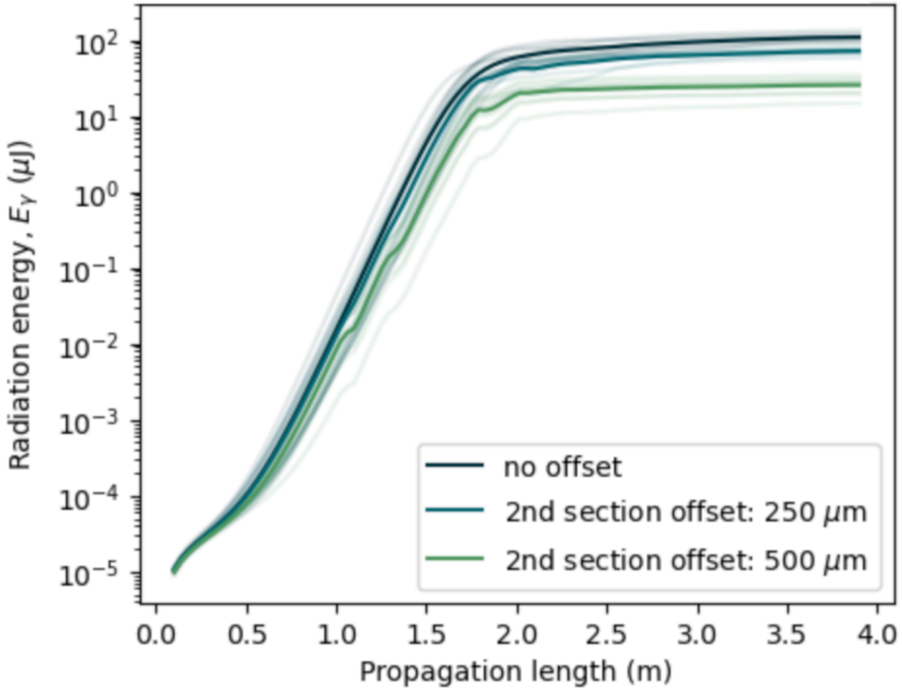
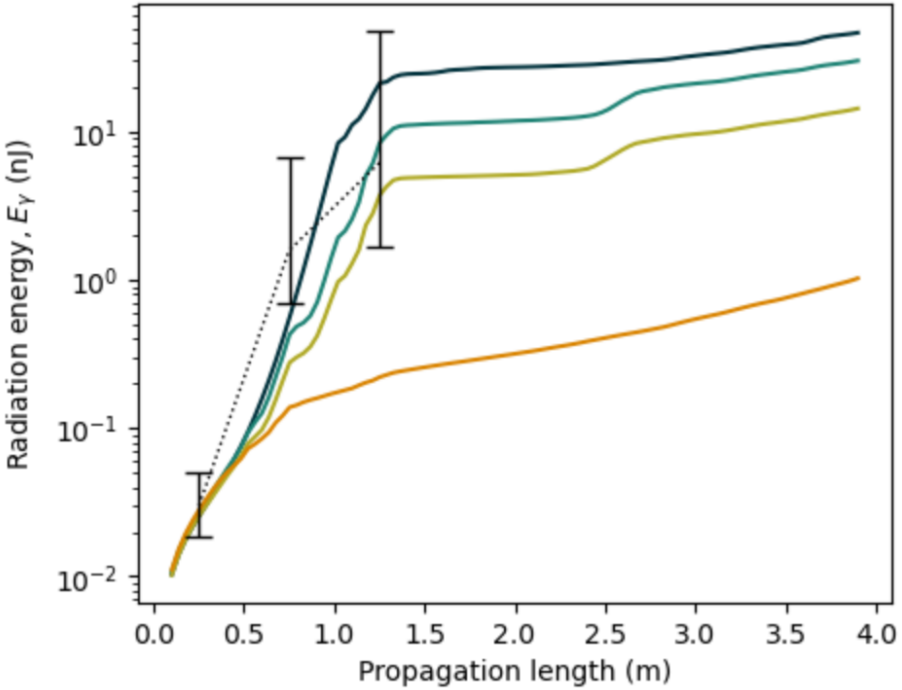


Beamline Element Alignement Impefections

Transverse misalignement of **second undulator section**



Transverse misalignment of **second undulator section** (1.5 mm) and **quadrupoles**



No quad misalignement

Last quad in first undulator section offset by 250 μm

Second to last quad in first undulator section offset by 250 μm

Last two quads in first undulator section offset by 250 μm

Experimental data

Beamline imperfection a likely cause for the FEL gain breakup after 1m.

Outlook & Conclusion

> At BELLA we develop laser plasma accelerators for applications and have demonstrated:

- dark-current free electron beams with 9.2 GeV peak energy with 500 TW (21 J) laser pulses from a 30 cm HOFI waveguide.

  A. Picksley et al., Physical Review Letters 133.25 (2024)

- muon production using these beams

  D. Terzani et al., arXiv 2411.02321 (2024), accepted in PRAB

- reliability free-electron laser with greater than 1000-fold gain driven by a laser-plasma accelerator

  S. Barber et al., Phys. Rev. Lett. 135, 055001 (2025)

Thank you!

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