FLASH2020+

Progress Review Meeting

FLASH2020+ Seeding Progress

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With contributions from FLASH2020+ Team

Hamburg, Feb 28th, 2025

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

DESY.

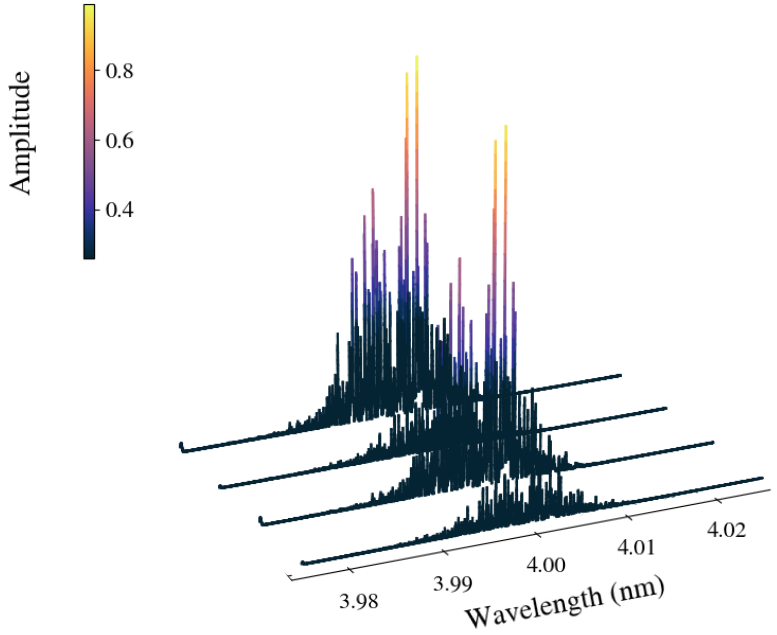
FLASH2020+ Seeding Progress:

- Why Seeding
- Introduction to Seeding
- Simulation Studies
  - Realistic Electron Beam Parameters
  - Impact of Chirp on FEL Performance
- FEL Gain Curve and Competition Between Effects
- Optimization and 2D Maps
- Multi-dimensional Optimization for Operation of FLASH2020+
- Outlook

To seed or not to seed, That is the question

SASE vs Seeded spectrum

SASE (Normalized to Max SASE)



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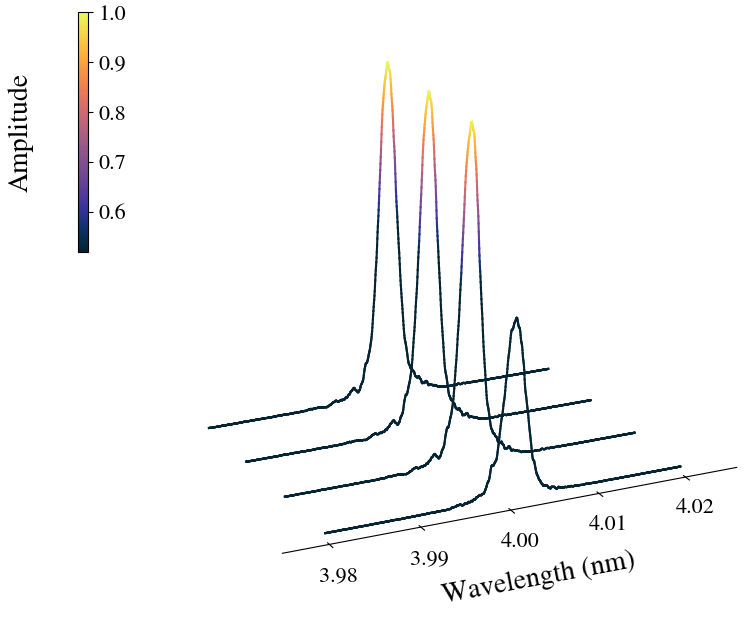

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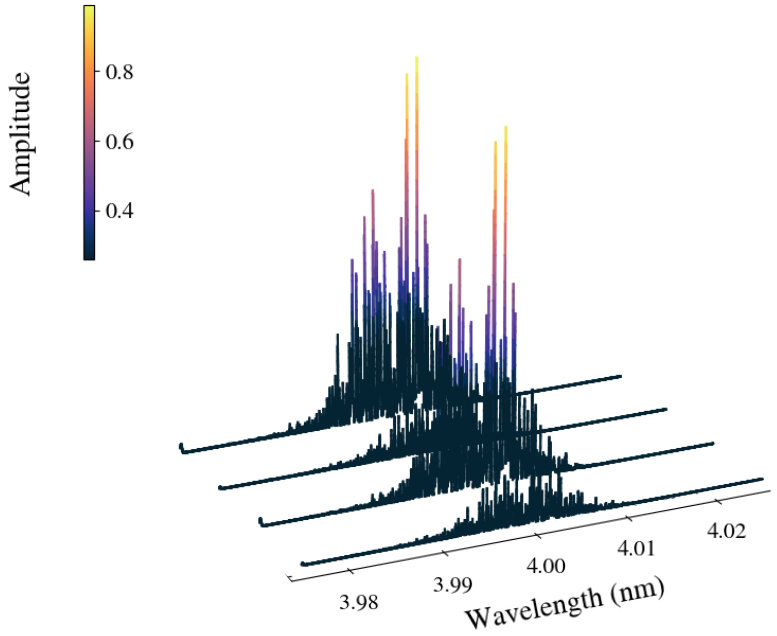
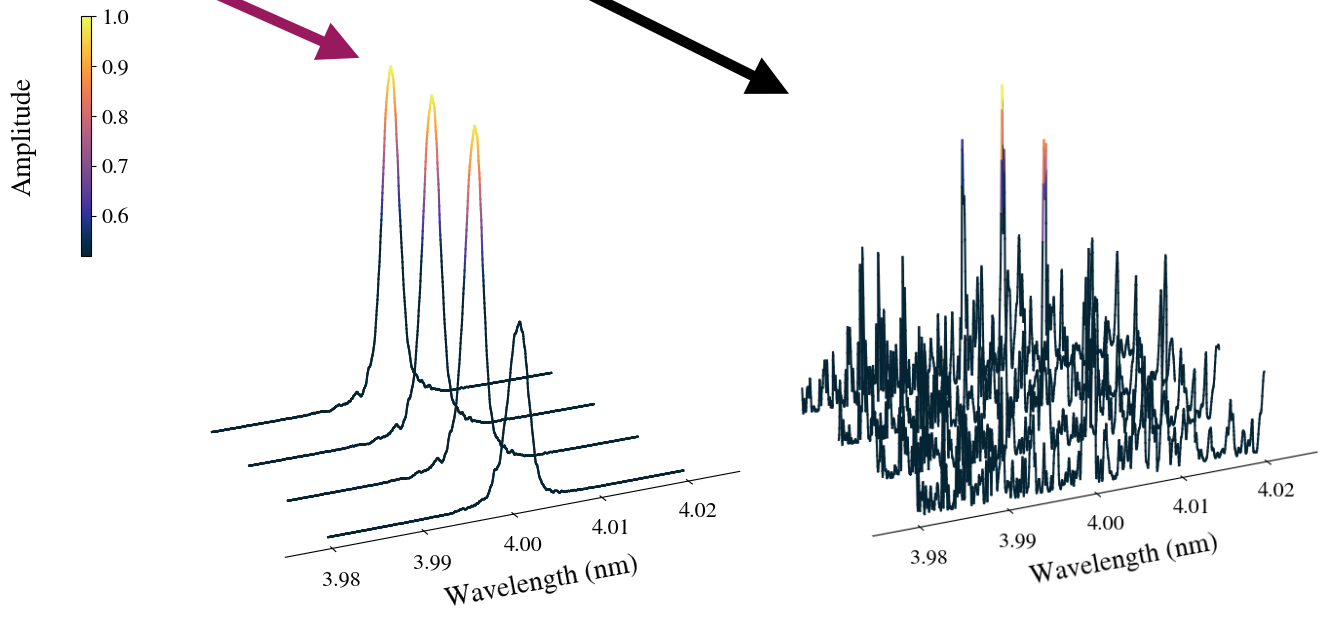


“Seeded” & “Seeded but dominated by background SASE” (Normalized to Max Seeded)



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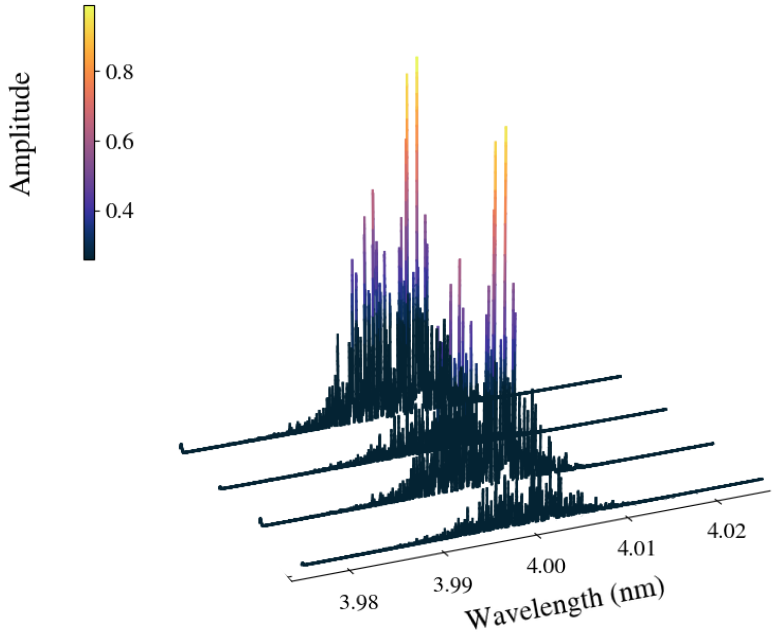

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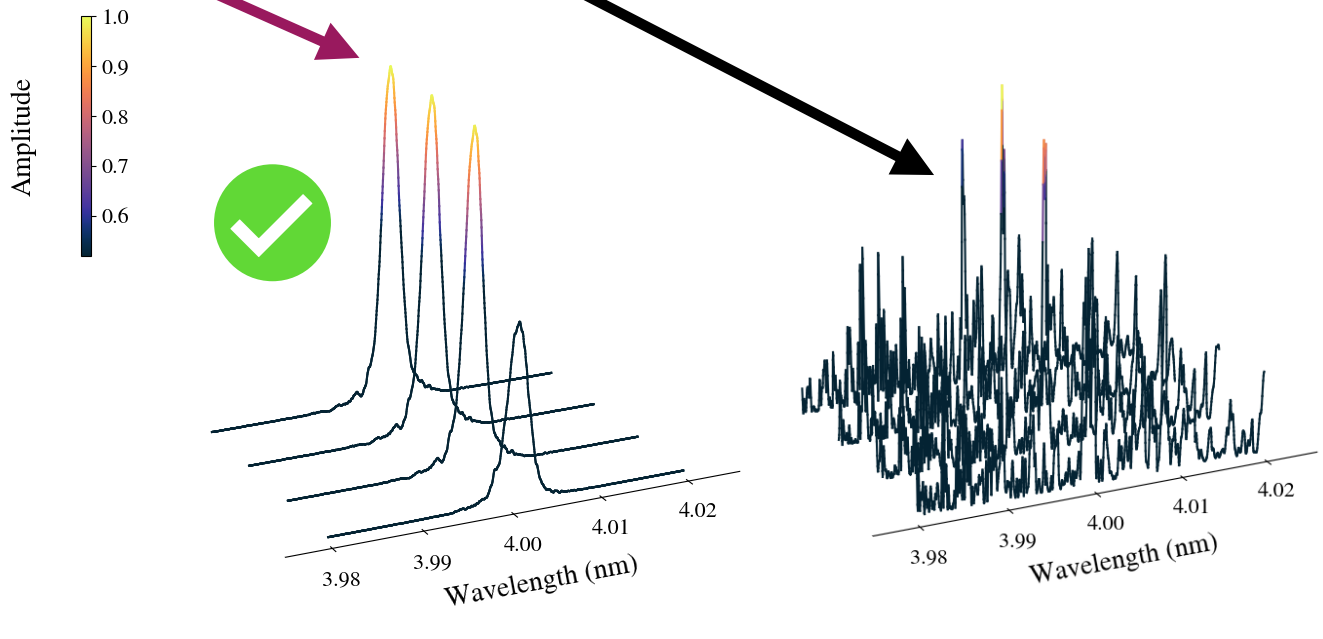

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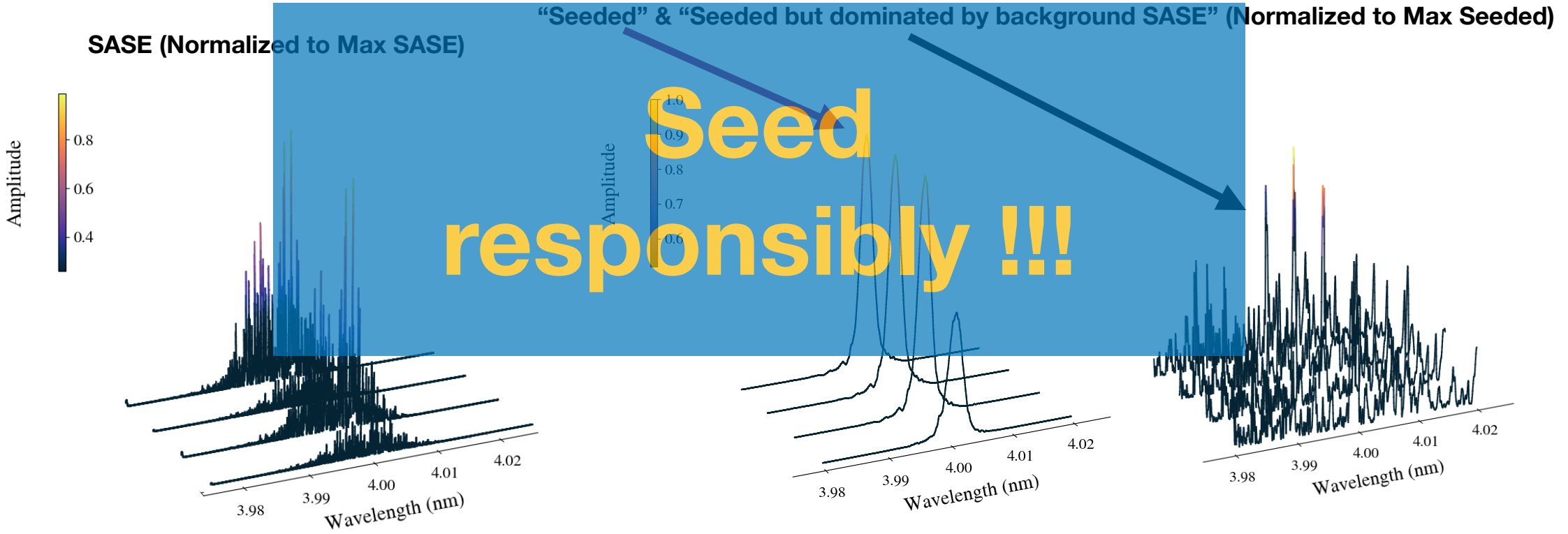
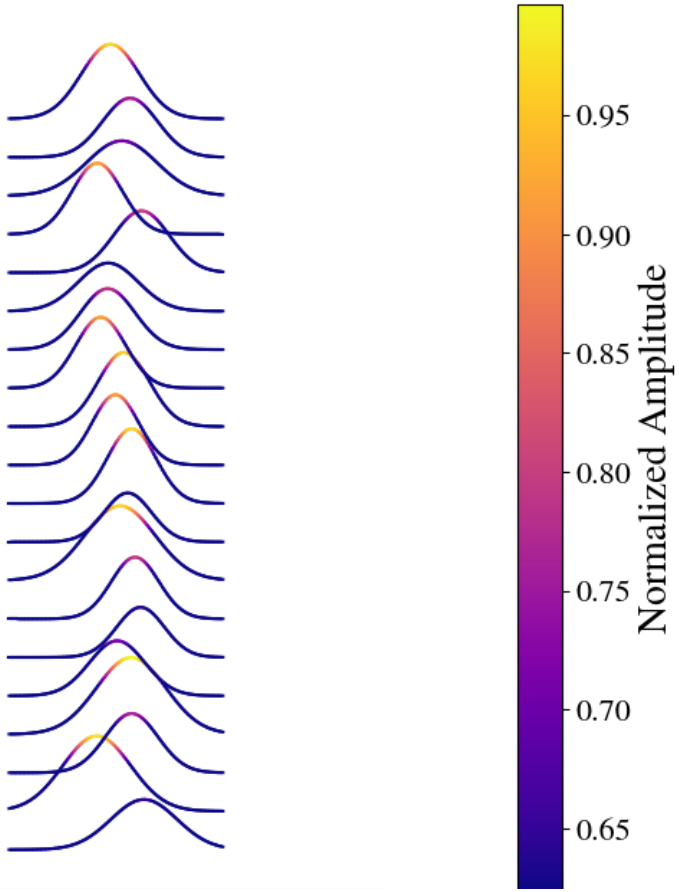
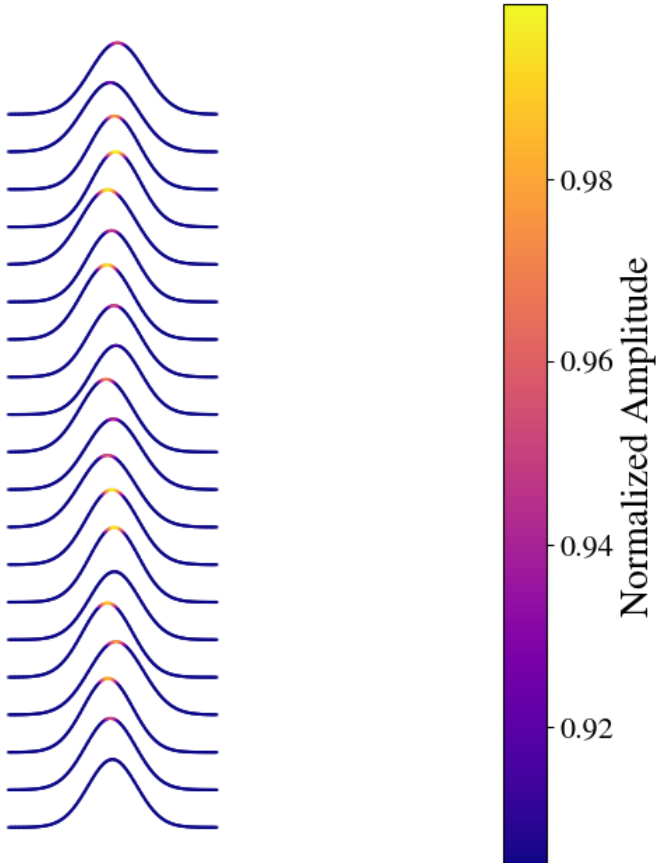


Seeding after FLASH2020+ Upgrade

Spectrum Desired from Train of High Repetition Seeded Pulses





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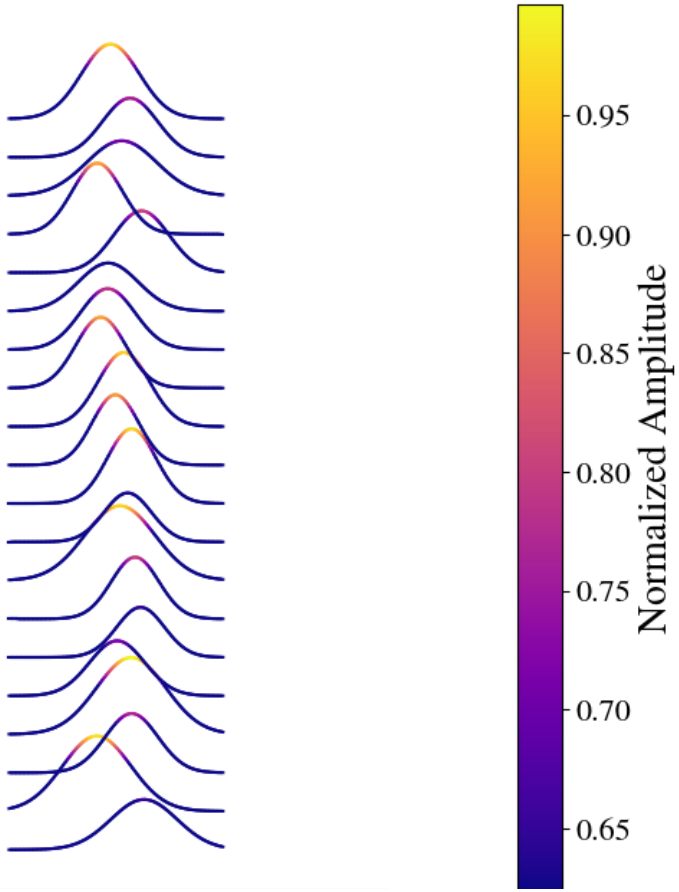
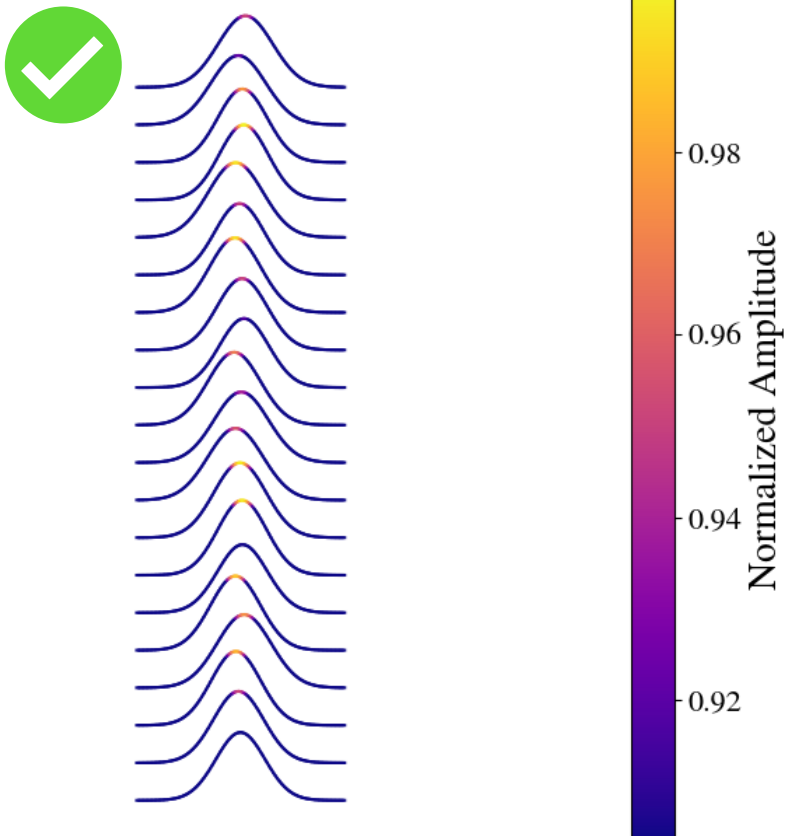
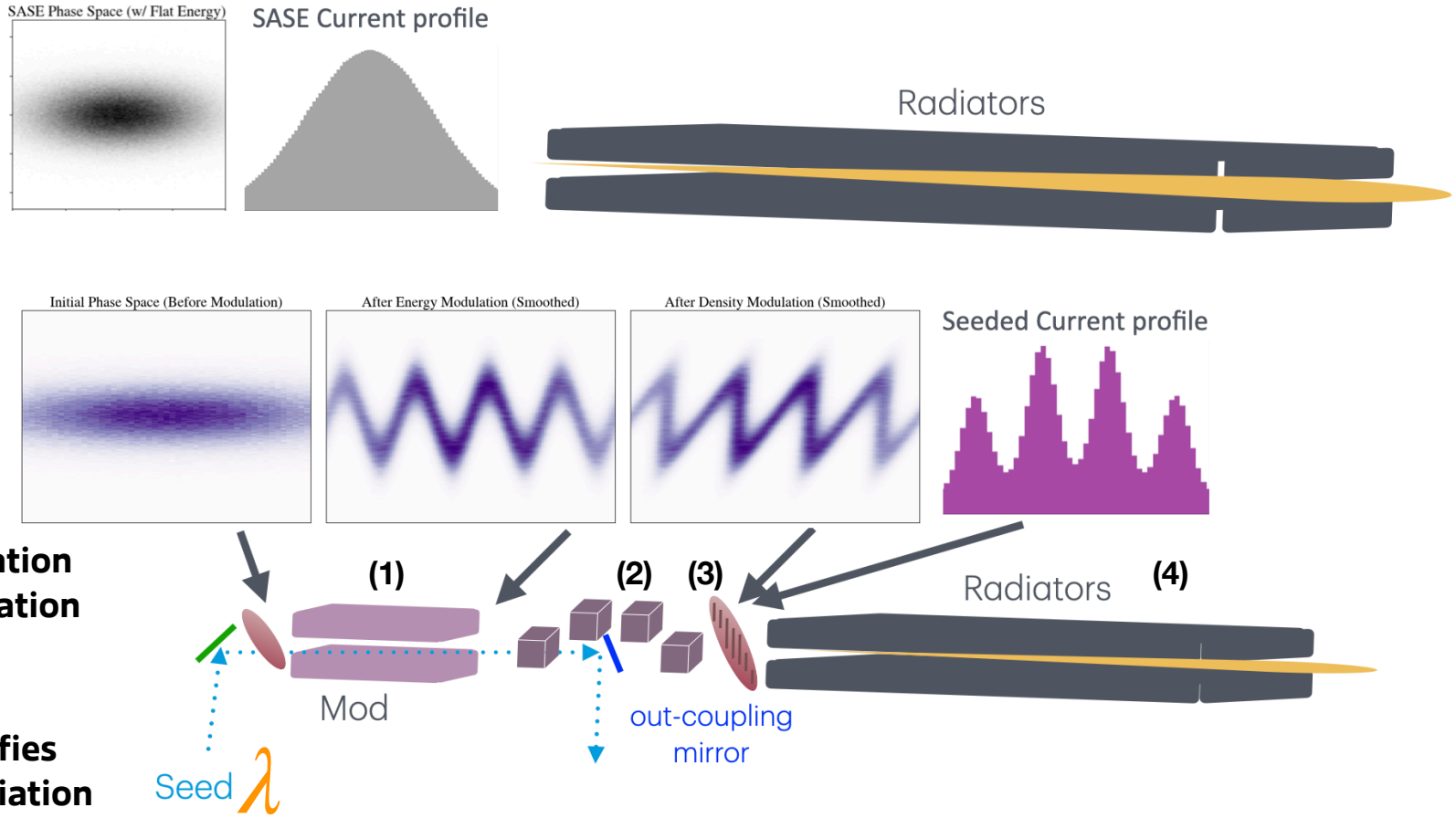


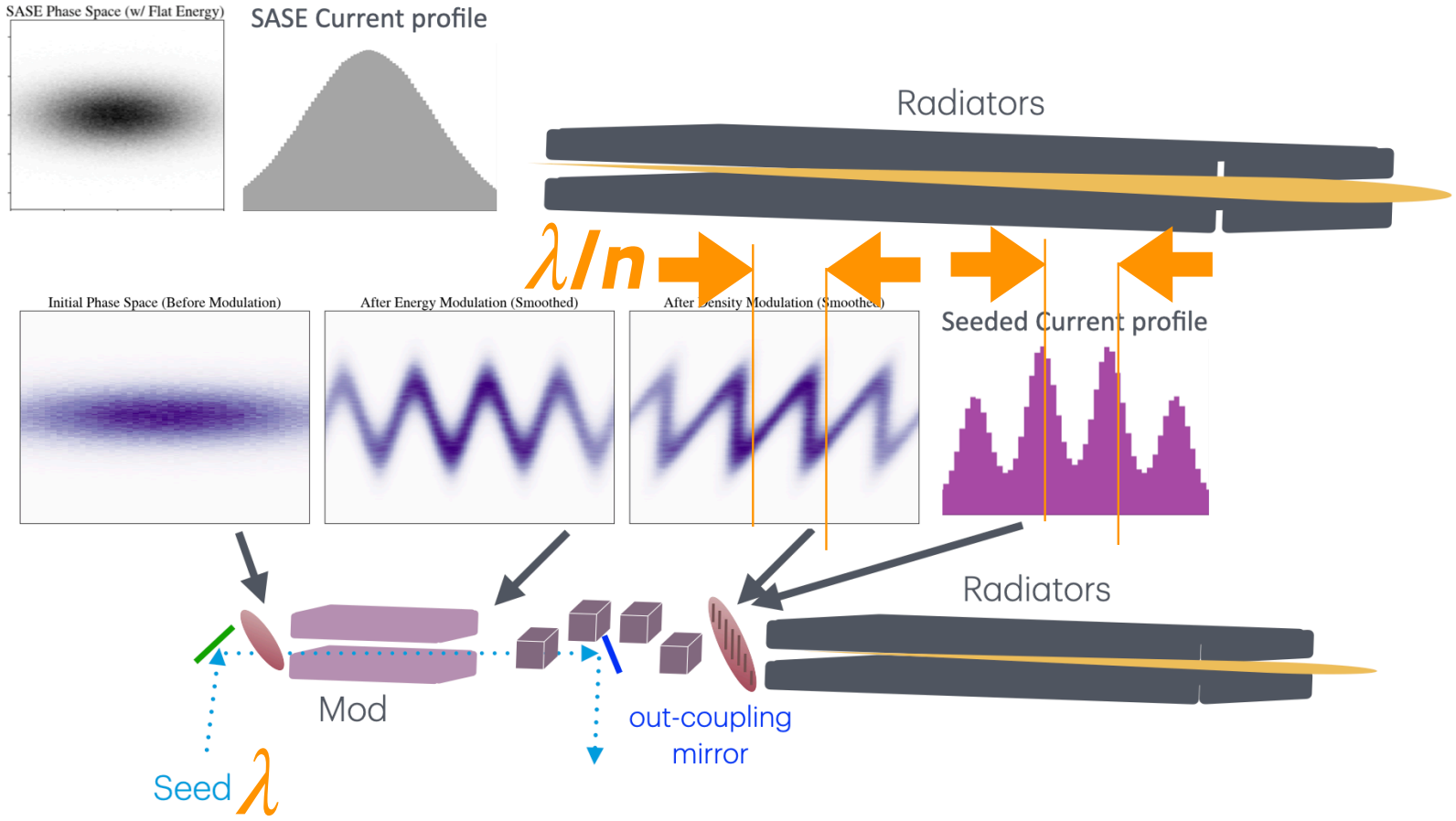


The Basic concept behind Seeding
High Gain Harmonic Generation

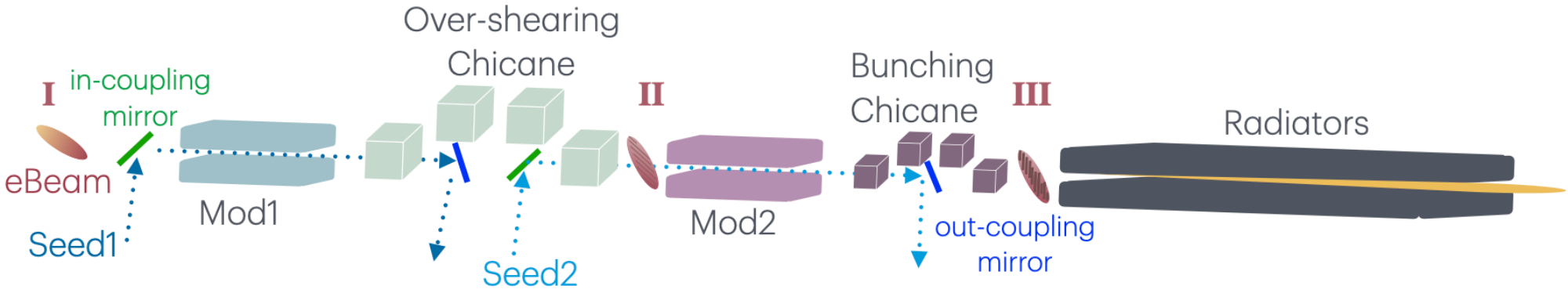


1) Energy modulation
2) Density Modulation
3) microbunching occurs λ/n
4) Radiator amplifies the harmonic radiation

The Basic concept behind Seeding
High Gain Harmonic Generation (n in range of 12)



EEHG: Echo-Enabled Harmonic Generation.
2 stages: here n can be much higher than for HGHG



Over-shearing Chicane is Orders of magnitude stronger than chicane in HGHG.

Similar to the chicane in HGHG

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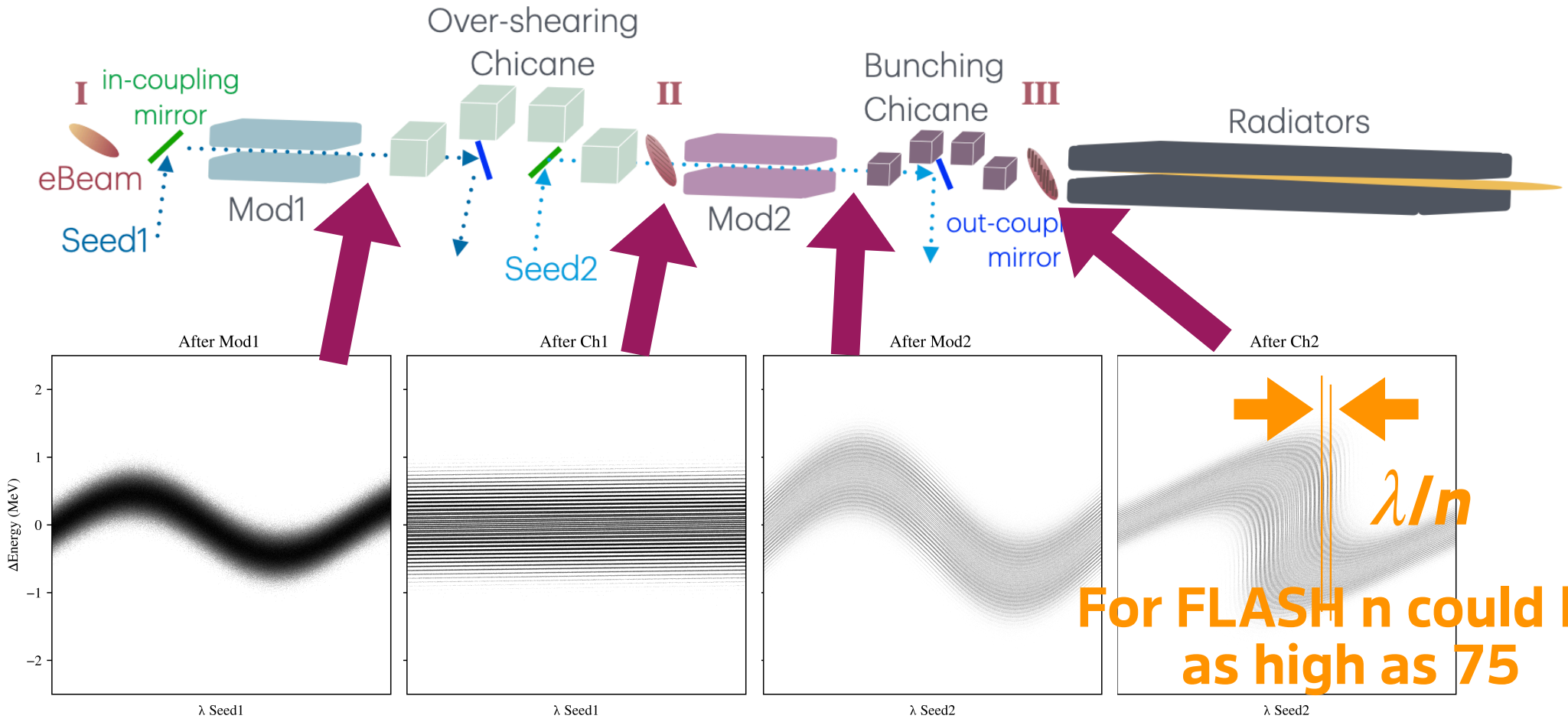
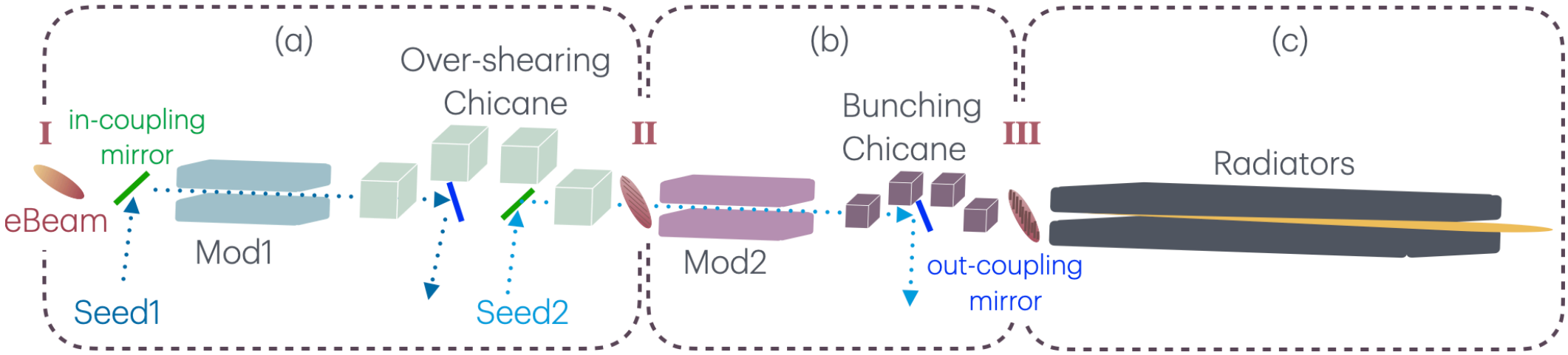


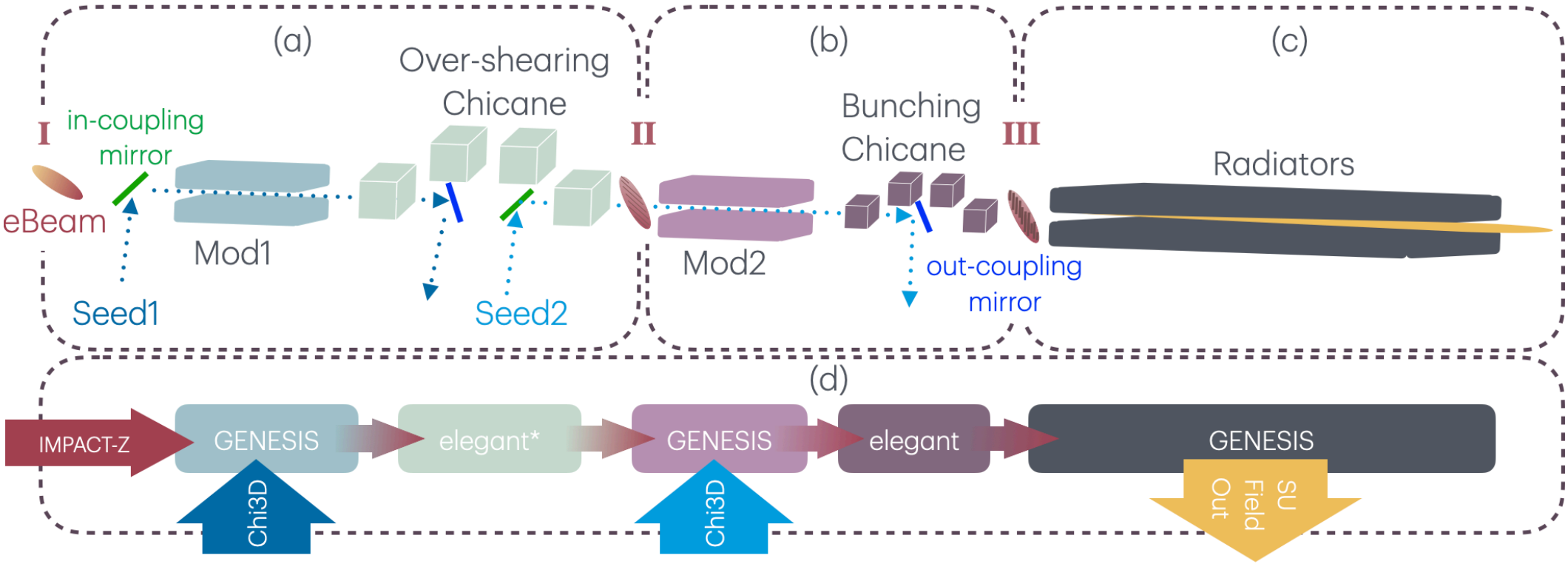
For FLASH n could be as high as 75

Echo-Enable Harmonic Generation
Modeling the seeded setup with simulation tools in three stages (a-c)

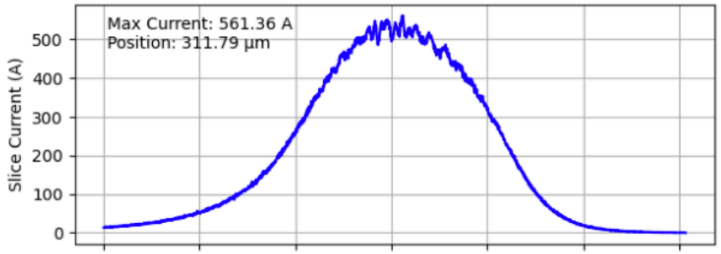


I: Initial Current profile (From accelerator)
II: Current profile with fine structure from (strong chicane)
III: Seeded pre-bunched beam

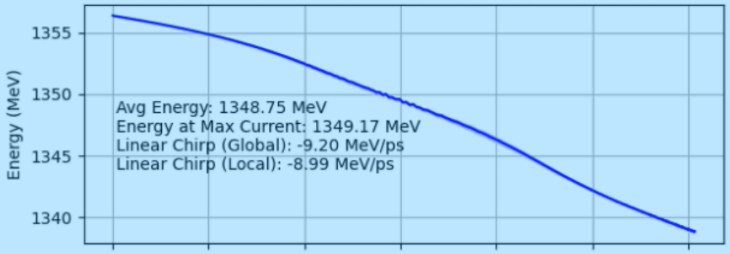
Optimization of EEHG or HGHG setup
In-house developed interfacing tools for efficent workflow (d)



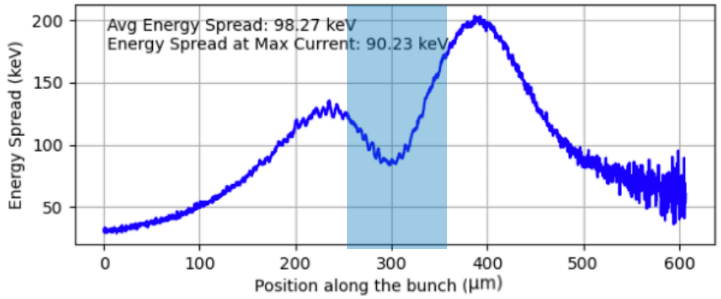
Start to End Simulation (Full Beam ~1680 slices)
Beam I properties at the end of LINAC



Initial Current profile



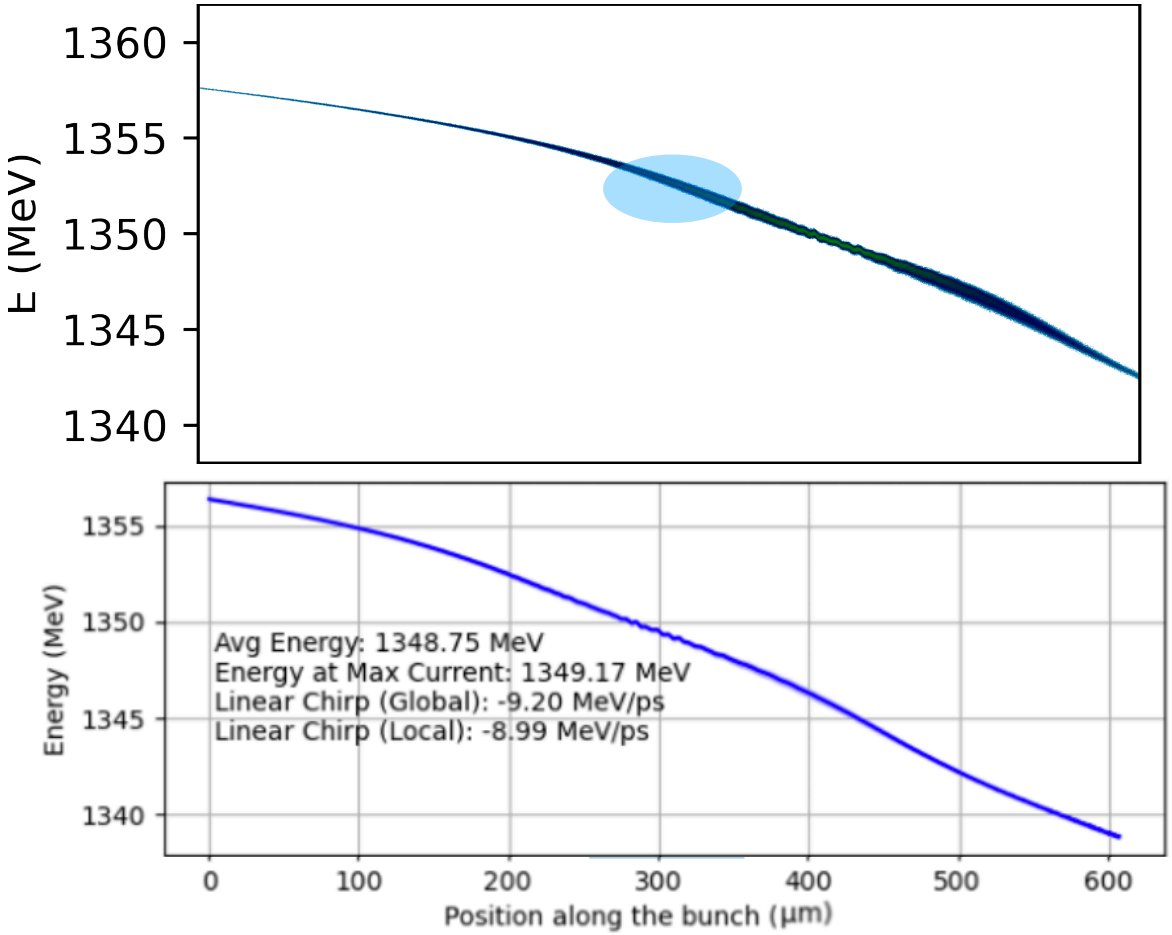
Chirp 9-20 MeV/ps (without dechirper)



Expected variation of energy spread along the Bunch profile we use the 150 keV as worst case scenario

Note: bunch is centered around 300 micron

Start to End Simulation
FEL performance depends on the Longitudinal phase space of the beam

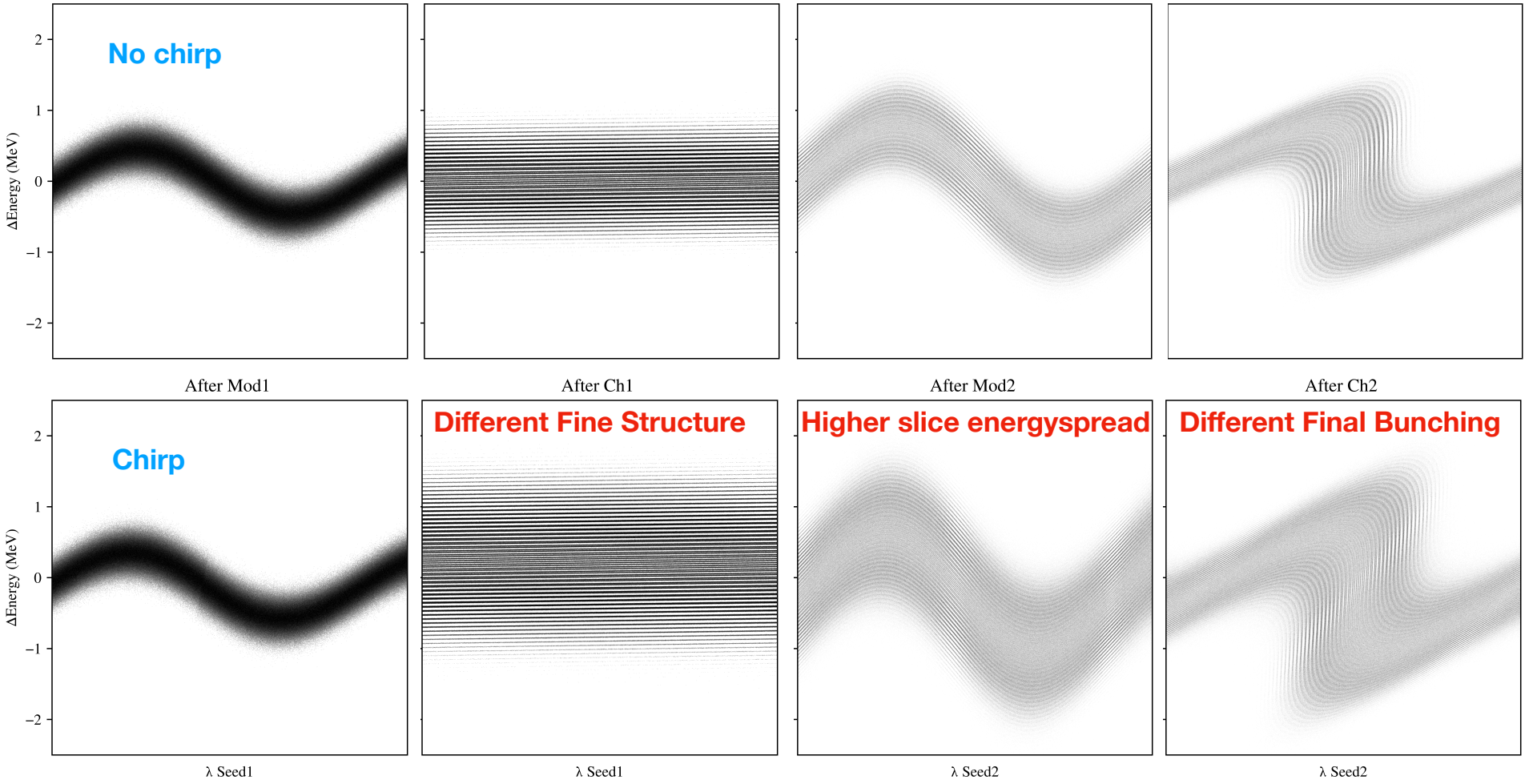


Longitudinal phase space gives the relationship between the position of an electron in the beam and its energy

The linear chirp (energy variation along bunch) is one of the most consequential properties of the beam

EEHG scheme and FLASH beam (one slice)

The negative chirp of the beam affects the it's longitudinal phase space



Effect of Beams Linear Chirp on CSR-induced Chirp
Also affects phase space and impacts wavelength and bandwidth

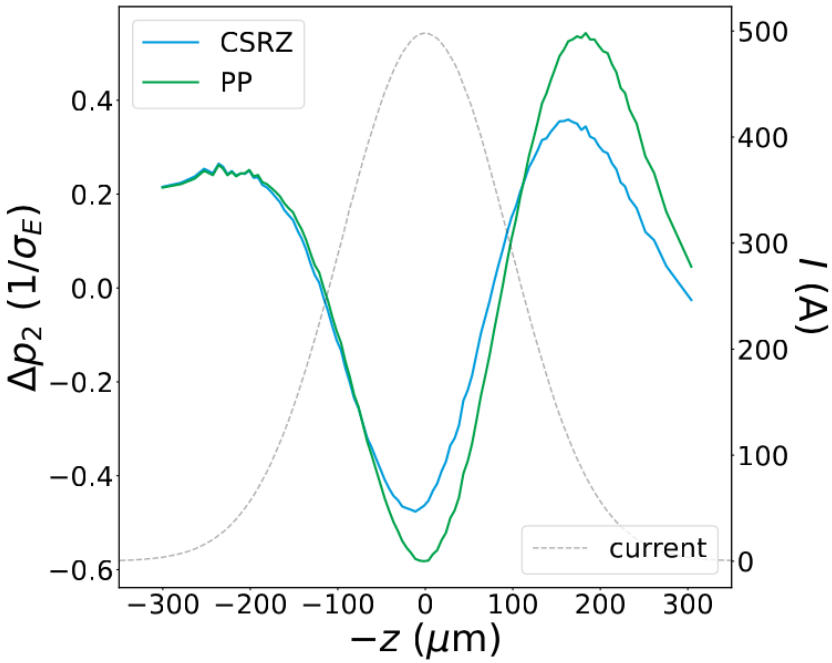
Coherent Synchrotron Radiation (CSR):

When an electron beam passes through a curved path (e.g., a chicane), it emits synchrotron radiation.

CSR can distort the **longitudinal phase space**, introducing **energy spread** and **beam degradation**, negatively impacting FEL performance.

In our case, the **nonlinear CSR-induced chirp combined with the electrons' linear chirp effects bandwidth and** the maximum bunching.

Two different models for calculating change in Energy centroid at the exit of the strong chicane due to CSR. (Bunch current profile is given in grey)



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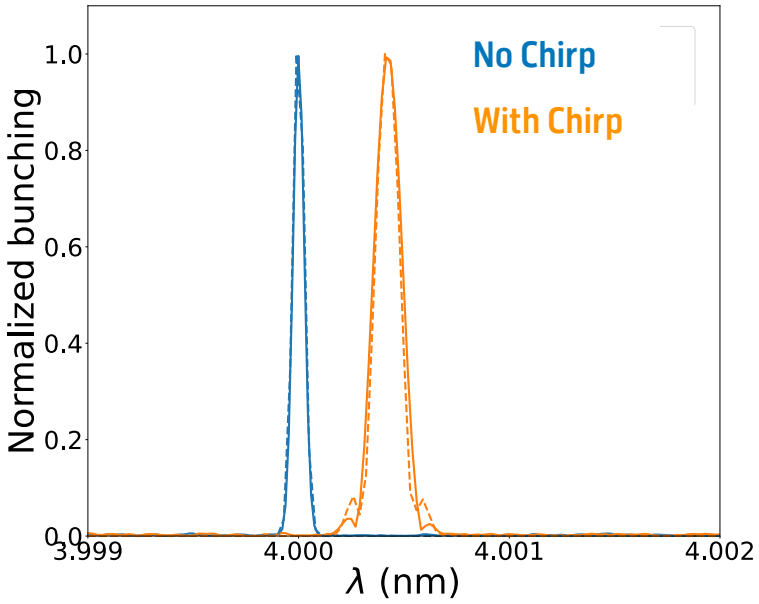
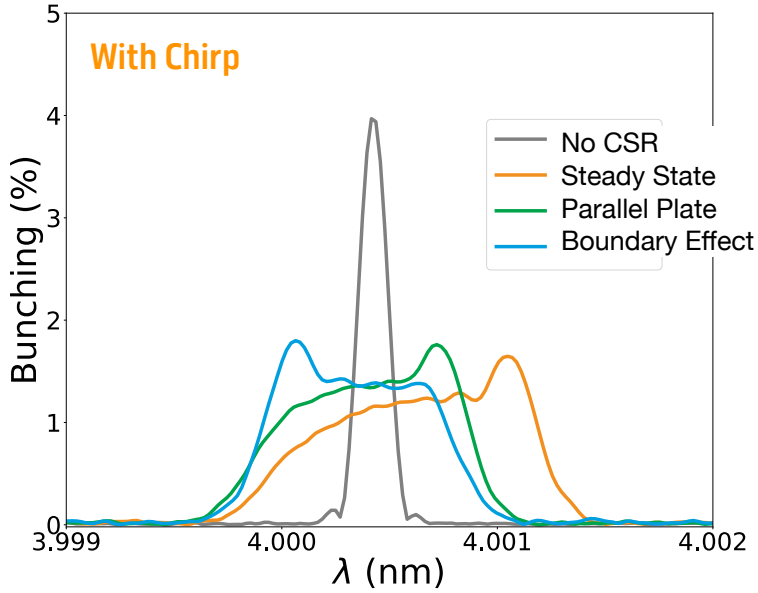
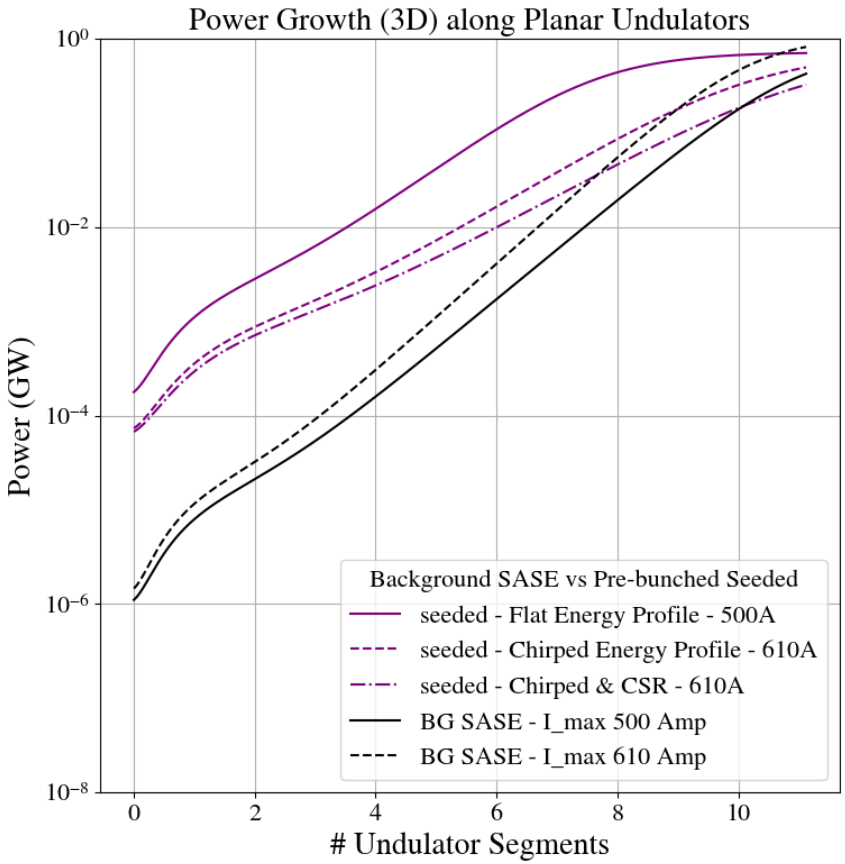




< BW increase by ~ 0.02 % due to Chirp in EEHG setup in every CSR model

∧ Shift by 0.013 % due to Chirp in EEHG setup

FEL Gain Curve for Seeded pre-bunched beams (modified Ming Xie)
Competition Between EEHG and SASE



Radiation \ Mode / Parameters	SASE	Seeded
Wavelength (nm)	4.0	4.0
Electron Beam	**no CSR**	**incl. CSR**
Energy (GeV)	1.35	1.35
Chirp (MeV/ps)	10	10
Energy Spread (keV)	90	354–610
Bunching Factor	≈ 0.005	0.07–0.014
Peak Current (A)	500–610	500–610
Emittance ϵ_n (mm-mrad)	0.6	0.6
Size σ_x/σ_y (μm)	45	45
Average β (m)	5–10	8–10
Undulators	**planar**	**planar**
Period (m)	0.033	0.033
a_w Parameter (variable gap)	0.831873	0.831873

FEL Gain Curve for Seeded pre-bunched beams (modified Ming Xie)
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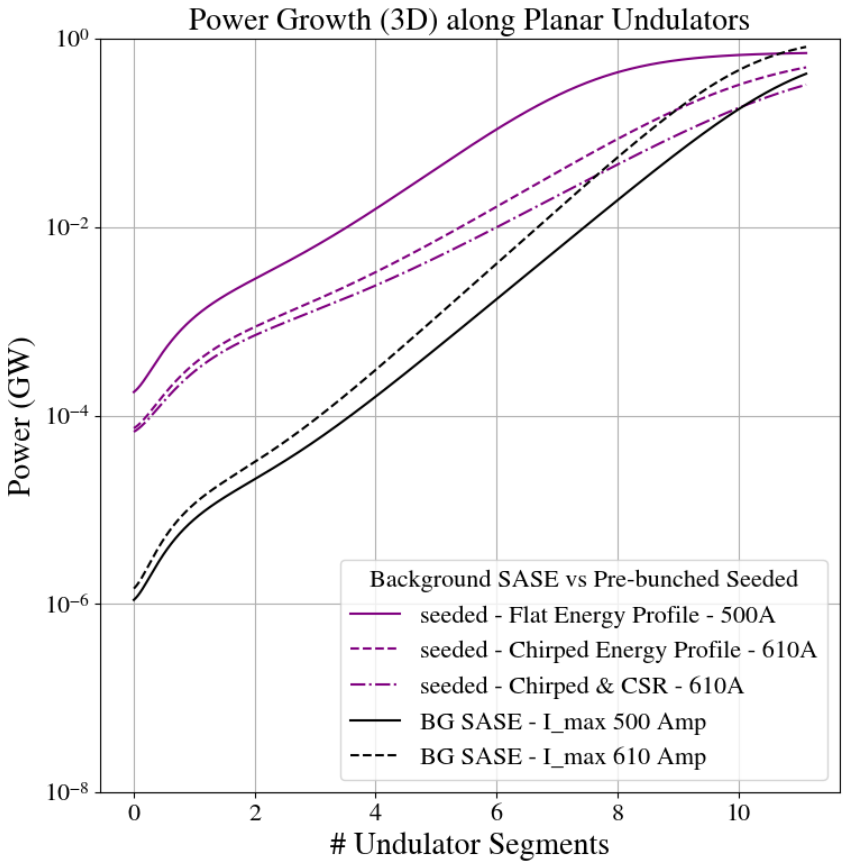


Linear chirp:

Leads to higher current due to compression

Increase in slice energy spread.

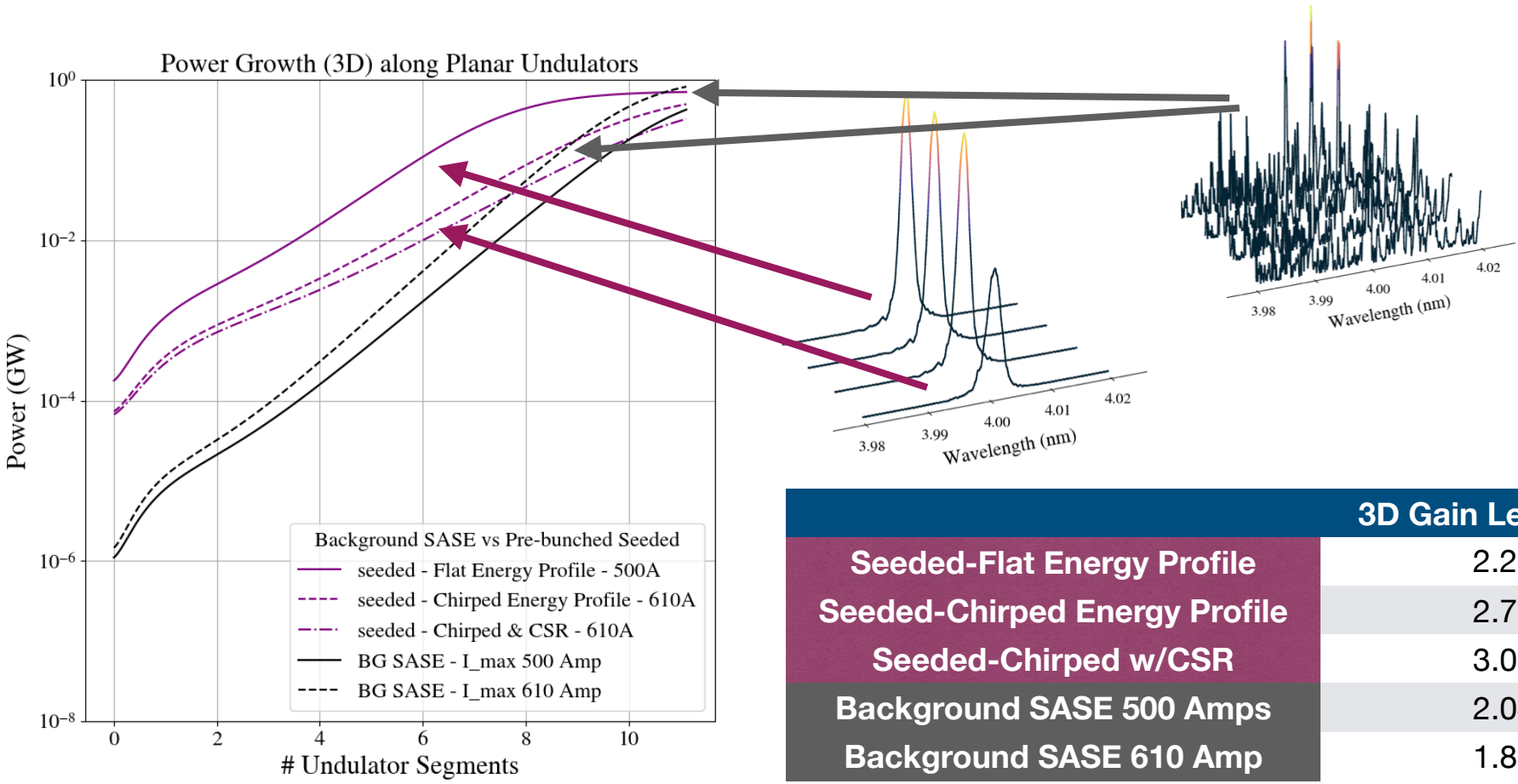
Changes the working point

Leads to an Increase in Gain Length

Typically leads to less extractable power

FEL Gain Curve for Seeded pre-bunched beam and SASE

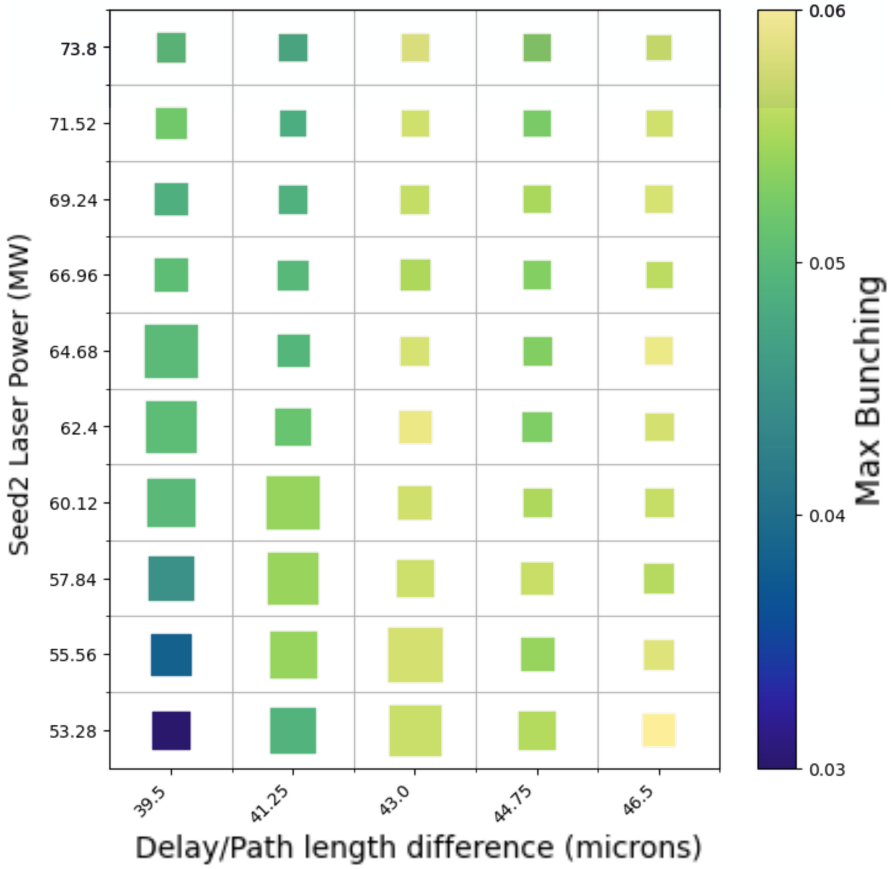
Higher current mean SASE Gain Length is shorter, and it can dominate EEHG



	3D Gain Length (m)
Seeded-Flat Energy Profile	2.29
Seeded-Chirped Energy Profile	2.78
Seeded-Chirped w/CSR	3.03
Background SASE 500 Amps	2.04
Background SASE 610 Amp	1.89

Multi-dimensional Optimization for Operation of FLASH2020+
Visualization tools for displaying 2D parameter spaces

- Visualize the results of an optimization or parameter scan
  - Cell width represents the parameter A
  - Color represents the parameter B
- Results are mapped across two parameter dimensions here (seed2 laser power and R56 (delay) of bunching Chicane)
- Bunching BW is represented with the width
- Colors represent Max Bunching



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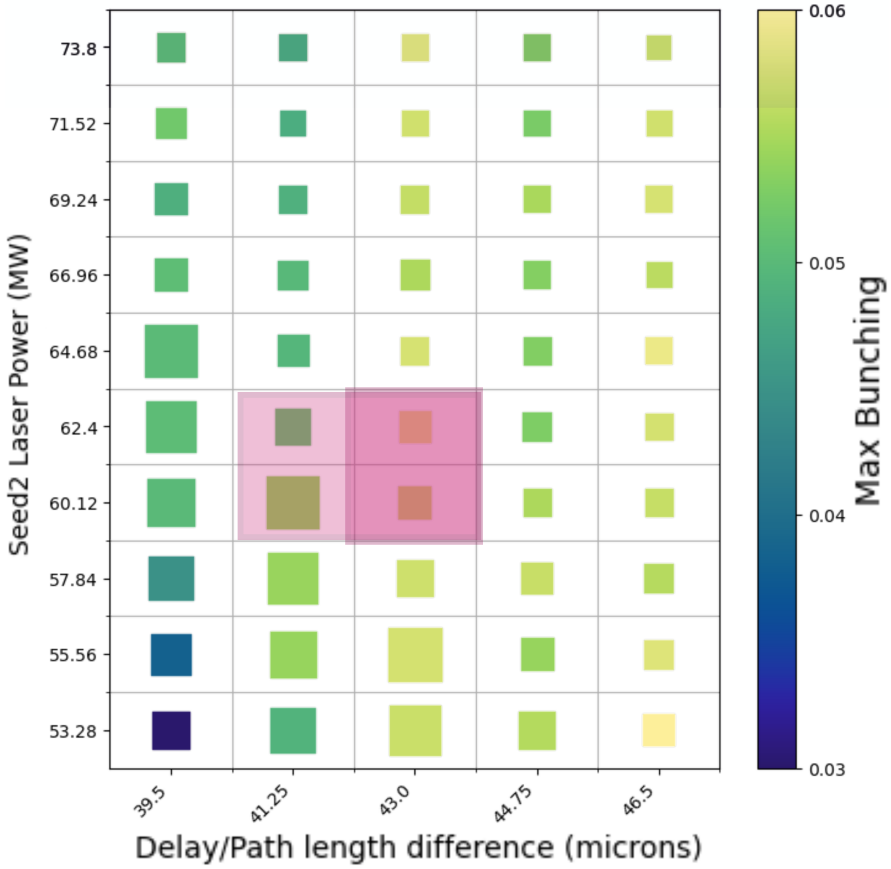
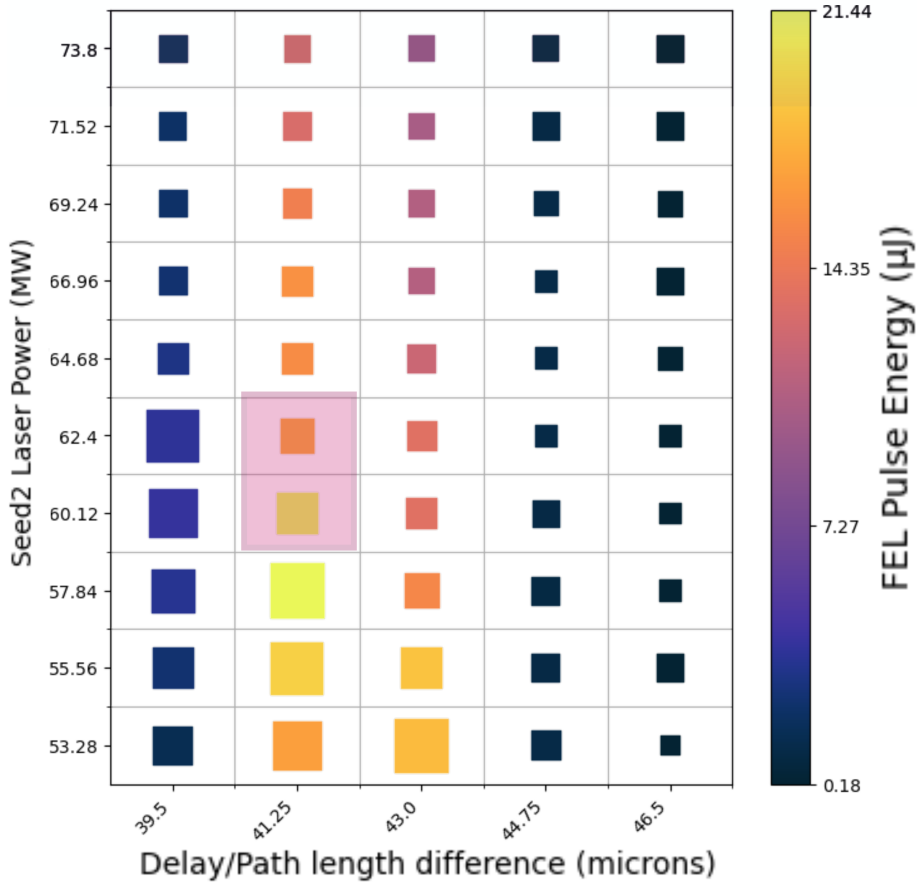


Multi-dimensional Optimization for Operation of FLASH2020+
Testing Multiobjective Optimization (2 or more)

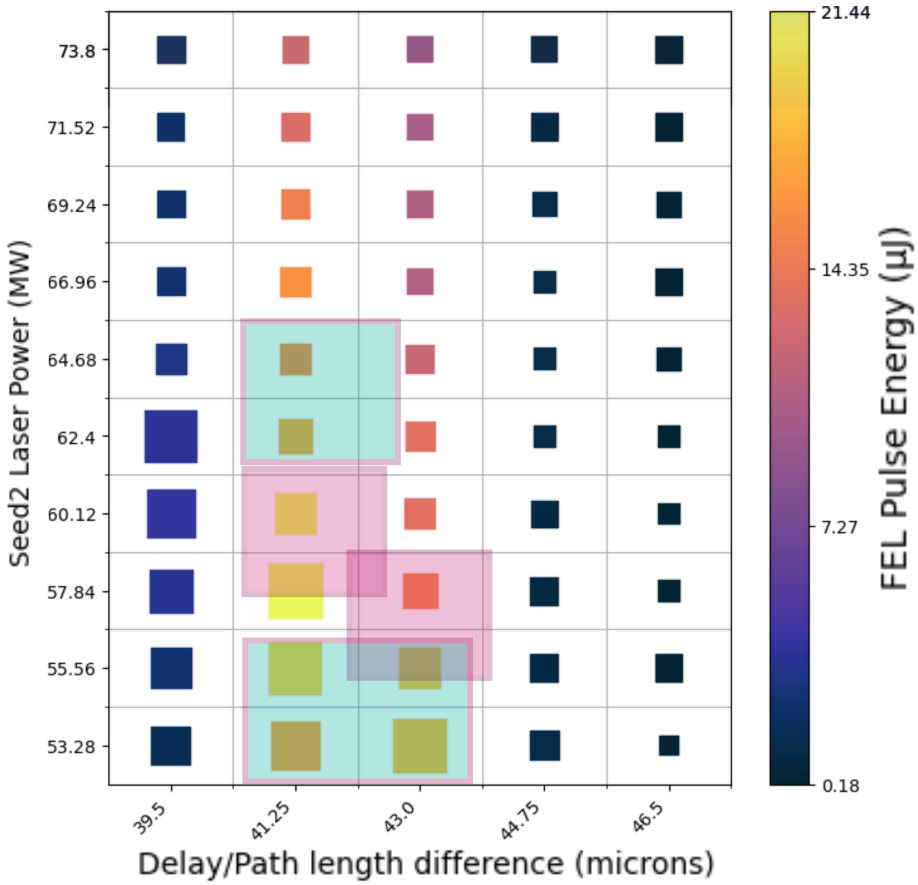
- **Max power**
- **Min Bandwidth**
- **Pulse length approaching theory value.**
- **Lower laser power**
- **Less sensitivity to change in laser parameters**
- **Less sensitivity to change in electron parameters**



Use Past 2D Scan sets for Machine Learning Bayesian Optimization (BoTorch)

- I only explored potential stable regions in the high energy or optimum pulse length areas.

- Regions with previously under-sampled area that may contain an unoptimized trade-off (with ML library)



Summary and Future Plans

- Poorly controlled seeding can lead to SASE-like spectrum.
- Distortions in the Longitudinal phase space of the electron beam impact the FEL performance.
- Linear Chirp and CSR induced Chirp reduce Max Bunching & increase Bandwidth.
- FEL Gain Curve & Competition Between SASE and EEHG because of chirp, compression, and Higher current
- Testing Multiobjective Optimization and ML libraries for future optimization