Hydrodynamic optical-field-ionized channel optimizations for beam brightness in a practical laser wakefield accelerator model

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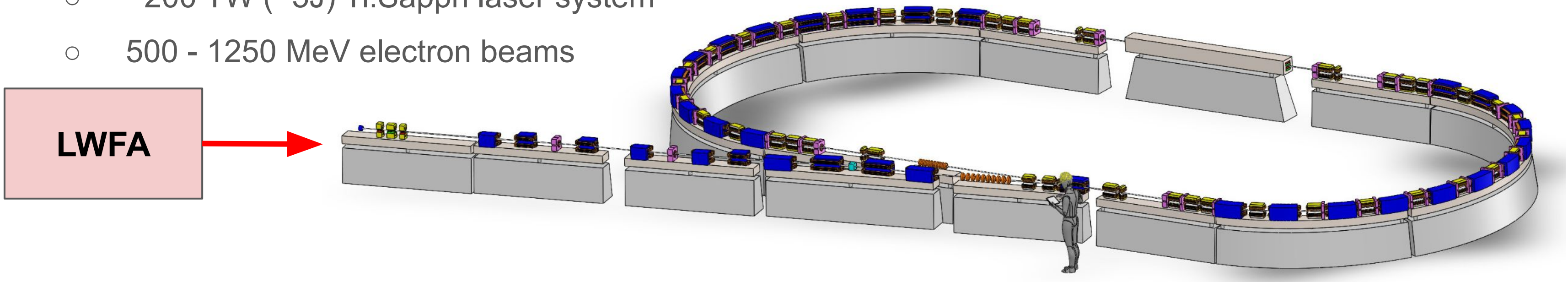
Motivation - we believe in embedded undulators in rings

- Inversion Semiconductor has been exploring LWFA HOFI channels as a source for a compact storage ring to drive undulator radiation for semiconductor applications
  - **Metrology** (low energy, smaller footprint, pictured below) and **lithography** (high energy and footprint)
- Targeting regime of modest parameters in the LWFA space:
  - ~200 TW (~5J) Ti:Sapph laser system
  - 500 - 1250 MeV electron beams



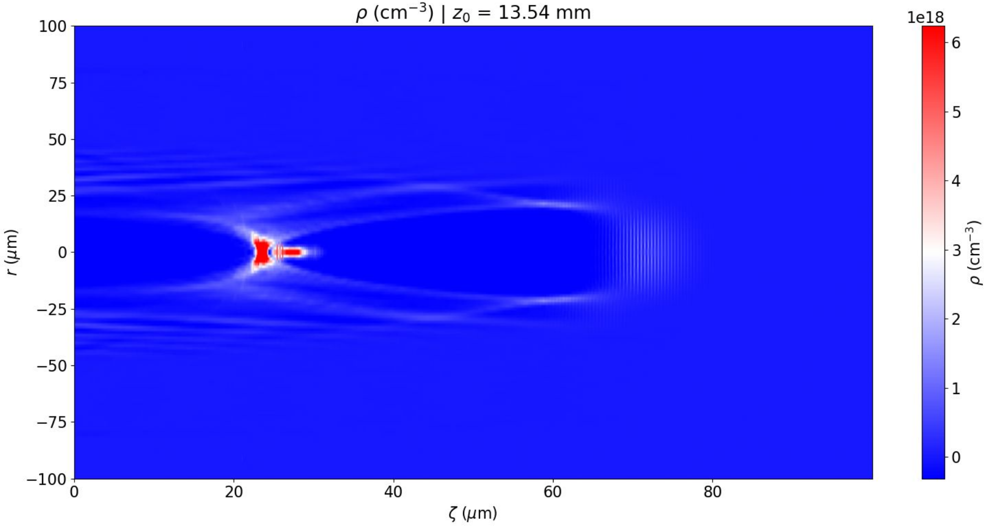
- Much of our inspiration for this injector comes from PIP4 and related work out of DESY:

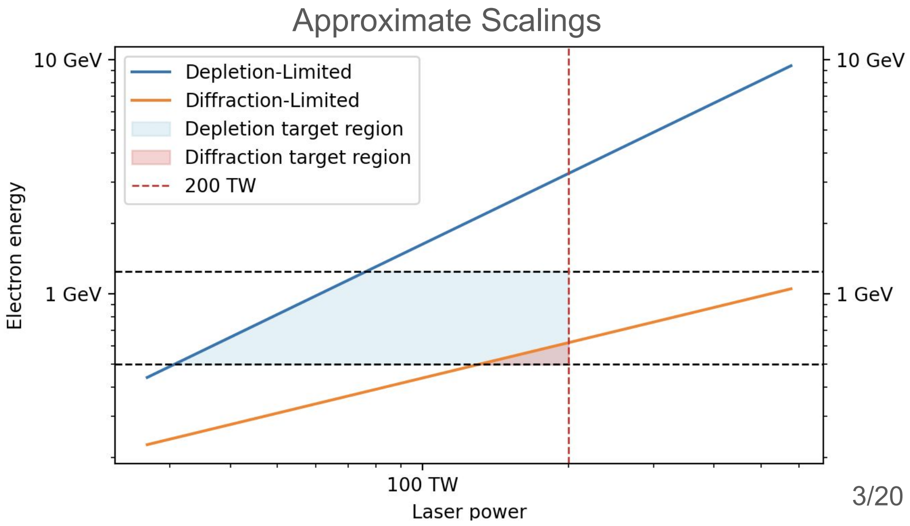
A. Martinez de la Ossa, et al., *Plasma Injector PETRA IV CDR*, Deutsches Elektronen-Synchrotron DESY (2025), DOI 10.3204/PUBDB-2024-06078.

Waveguides are an attractive option for this target regime

- In addition to reaching higher ebeam energy, HOFI waveguides have a number of pros/cons compared to diffraction-limited schemes:
  - \+ Better laser-to-ebeam efficiency, less divergence upon exit
  - \- More gas load on system, added complexity to laser system

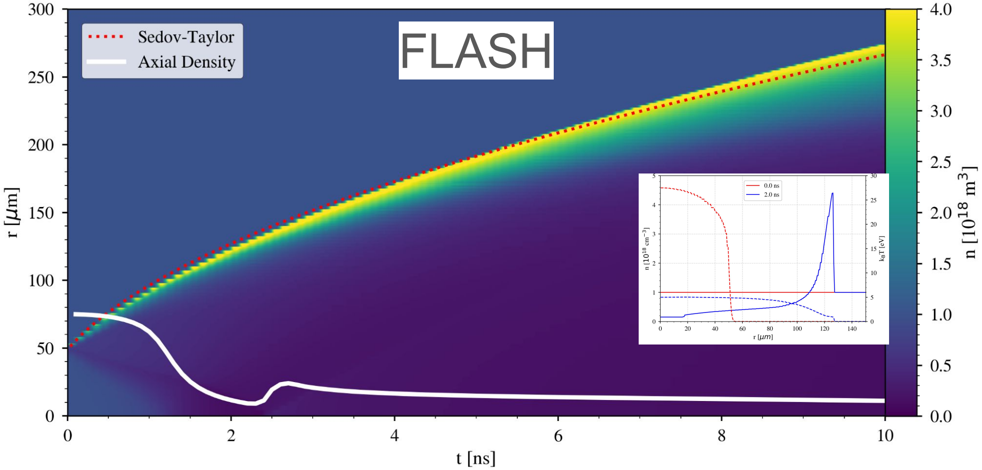
Miao *et al*. Phys. Rev. X **12**, 031038 (2022)
https://doi.org/10.1103/PhysRevX.12.031038
\+ And many more!



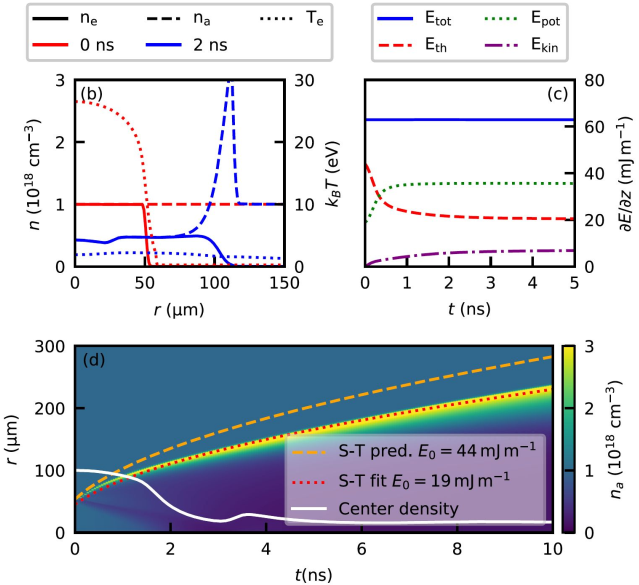


Generating HOFI channel profiles with FLASH

- FLASH provides baseline hydrodynamic evolution with relevant physics
  - Compressible flow on structured mesh; Three-temperature representation with local thermal equilibrium assumed
  - Flexible spatiotemporal source terms (density, and temperature)
  - Multi-species fluid for adjustable compositions, dopants, buffer gases
  - Flexible choice of equation of state – typically use ideal gas
- Benchmarked against published work and experiment

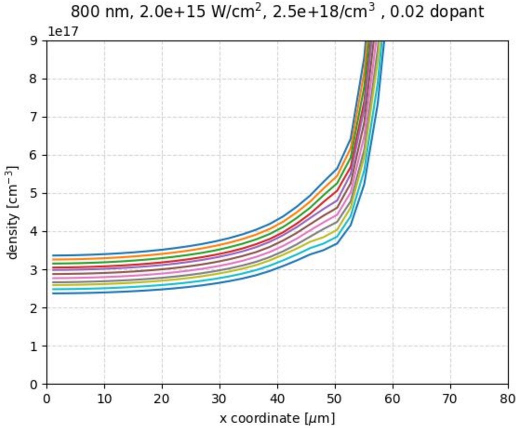


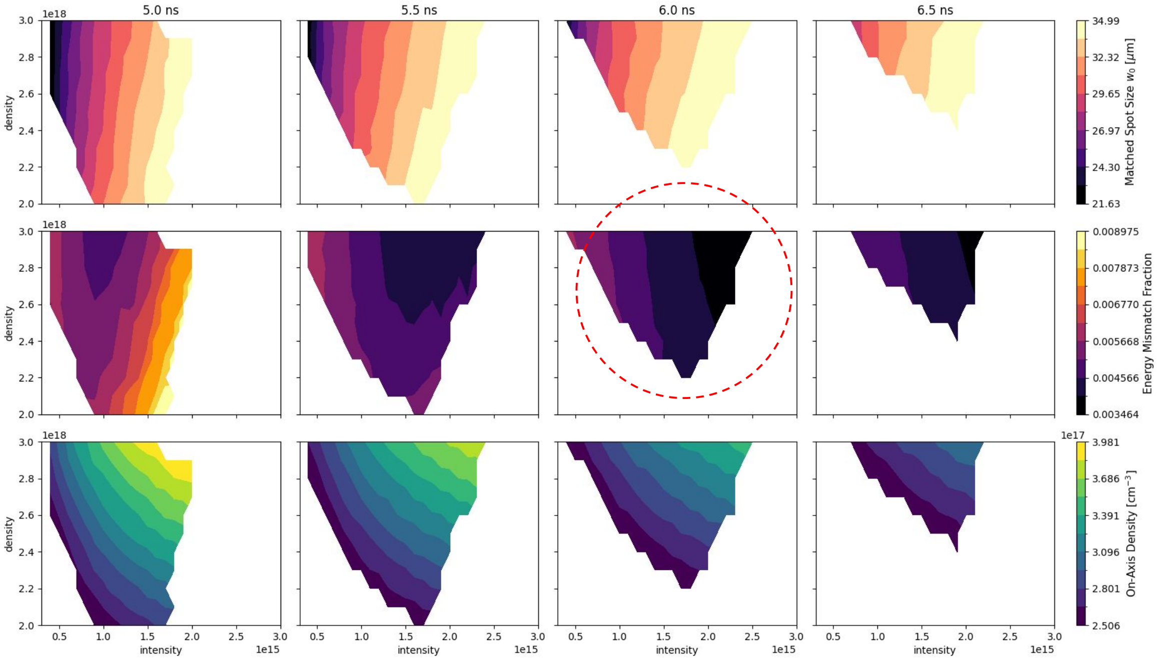
Mewes *et al*. Phys. Rev. Research **5**, 033112 (2023) 10.1103/PhysRevResearch.5.033112



Parametric scans enable identification of working point

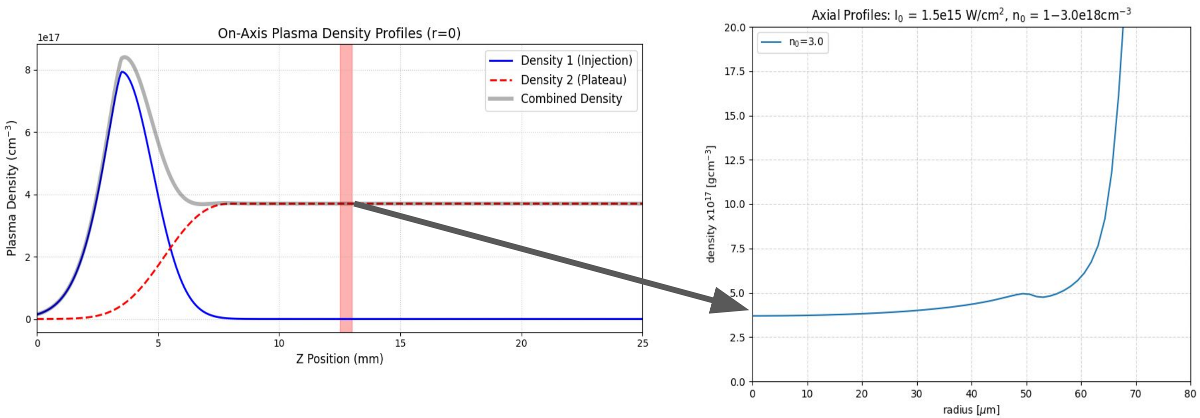
- Vary CFB intensity, spot size, gas density, and dopant fraction
- Dispatch large scans (10K+) across parametric regimes of interest
    - Built a searchable, sortable library of channels
    - Aiming for ~3e17 cm-3 with <~30um spot size

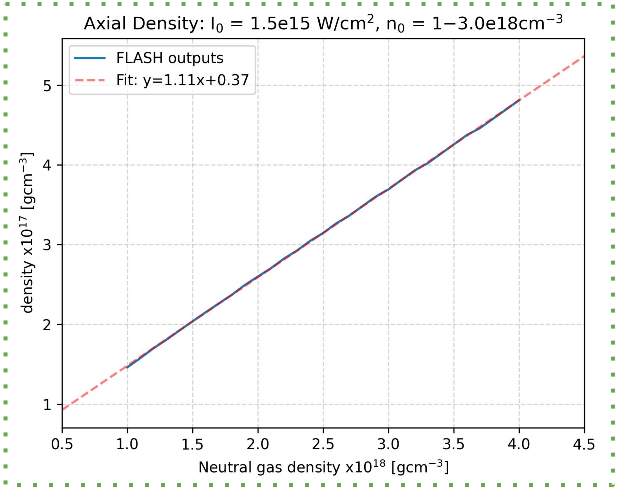




Integration of HOFI channel profiles with FBPIC

- FBPIC simulations request a longitudinal plasma profile and dopant mixture
- HOFI channel (radial) profiles are extracted from library of FLASH simulations
  - Along each z cell, a matching channel profile is obtained and stitched together to generate the overall background plasma profile
  - If *Optimas* searches axial density ranges outside of available range, linear extrapolation is used (*well supported by sims)*

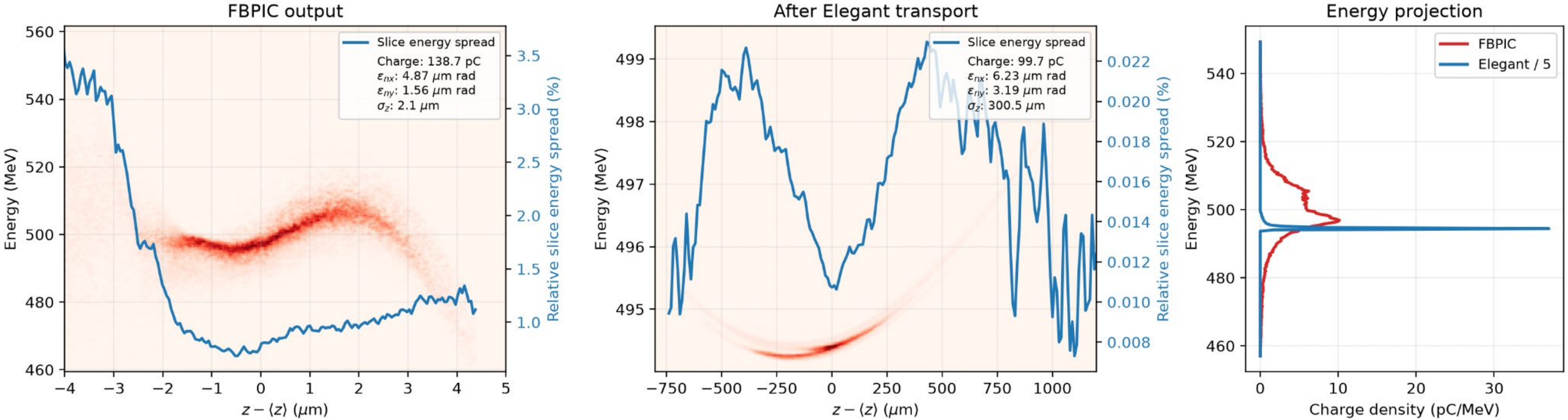




Ring injection needs high bunch length and low E spread

- Ring injection requires lower energy spread (~0.1%) and larger bunch lengths (~1mm) than what is typical of 100 pC LWFA systems.
- In a scheme used by DESY, an RF dechirper can reduce the energy spread of LWFA beams by more than an order of magnitude.
    - (Below) Our preliminary attempts at a dechirper lattice:

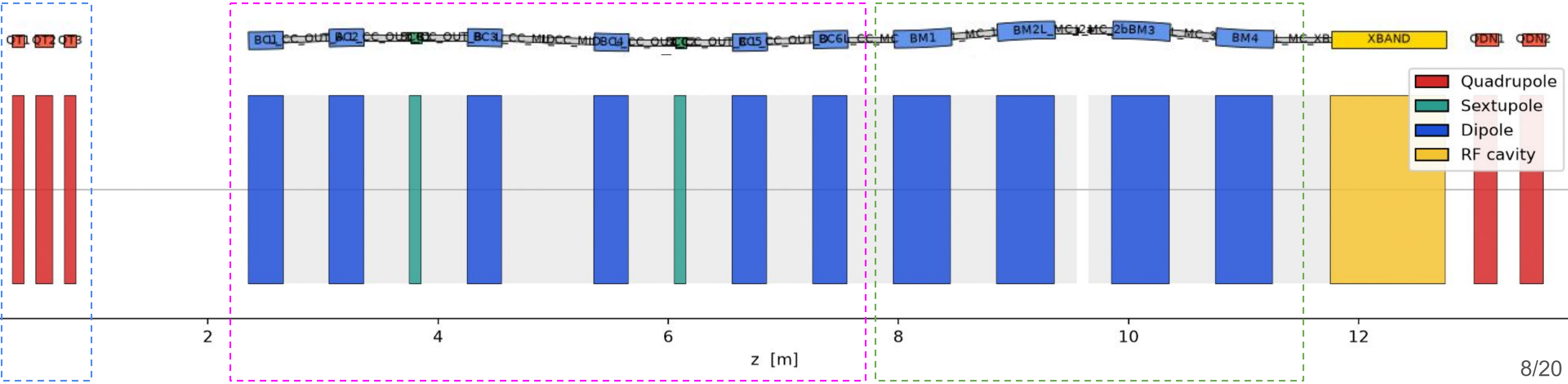
P. Winkler *et al*. Nature **640**, 907–910 (2025)
https://doi.org/10.1038/s41586-025-08772-y



Transport prepares LWFA beam for RF Dechirper

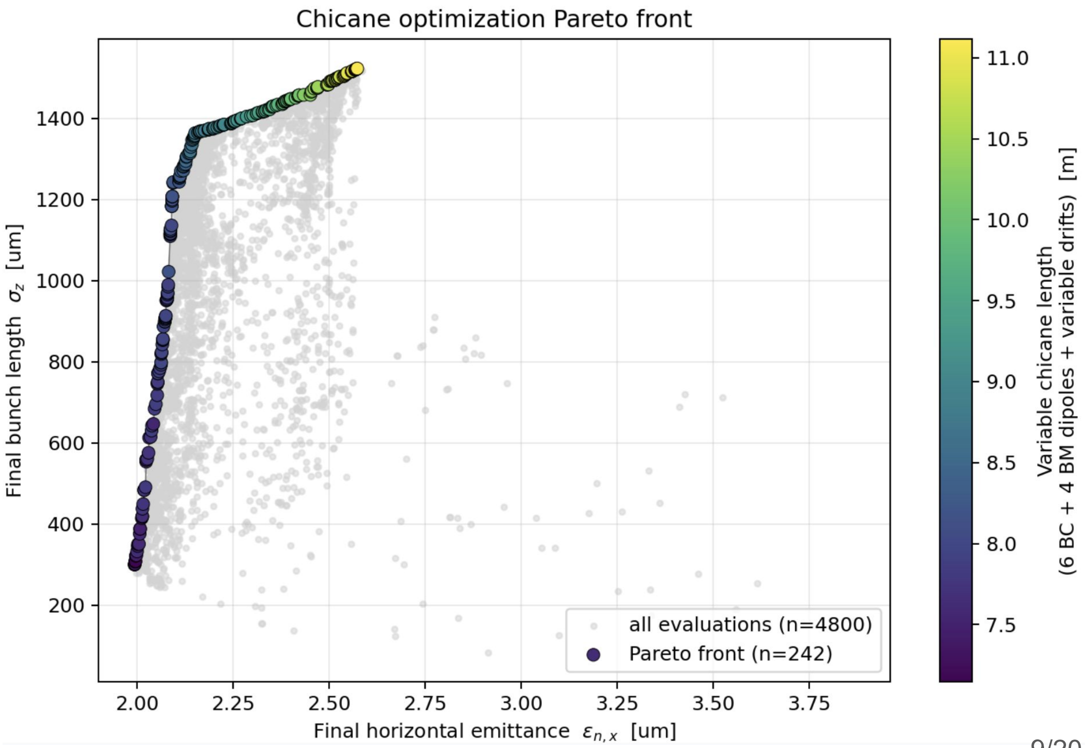
- Focusing triplet controls divergence, followed by a chromatic, S-type chicane to minimize the large horizontal emittance growth after the LWFA.
- C-type chicane stretches the ebeam prior to the RF cavity

S.A. Antipov *et al*. Phys. Rev. Accel. Beams. **24**, 111301 (2021) https://doi.org/10.1103/PhysRevAccelBeams.24.111301



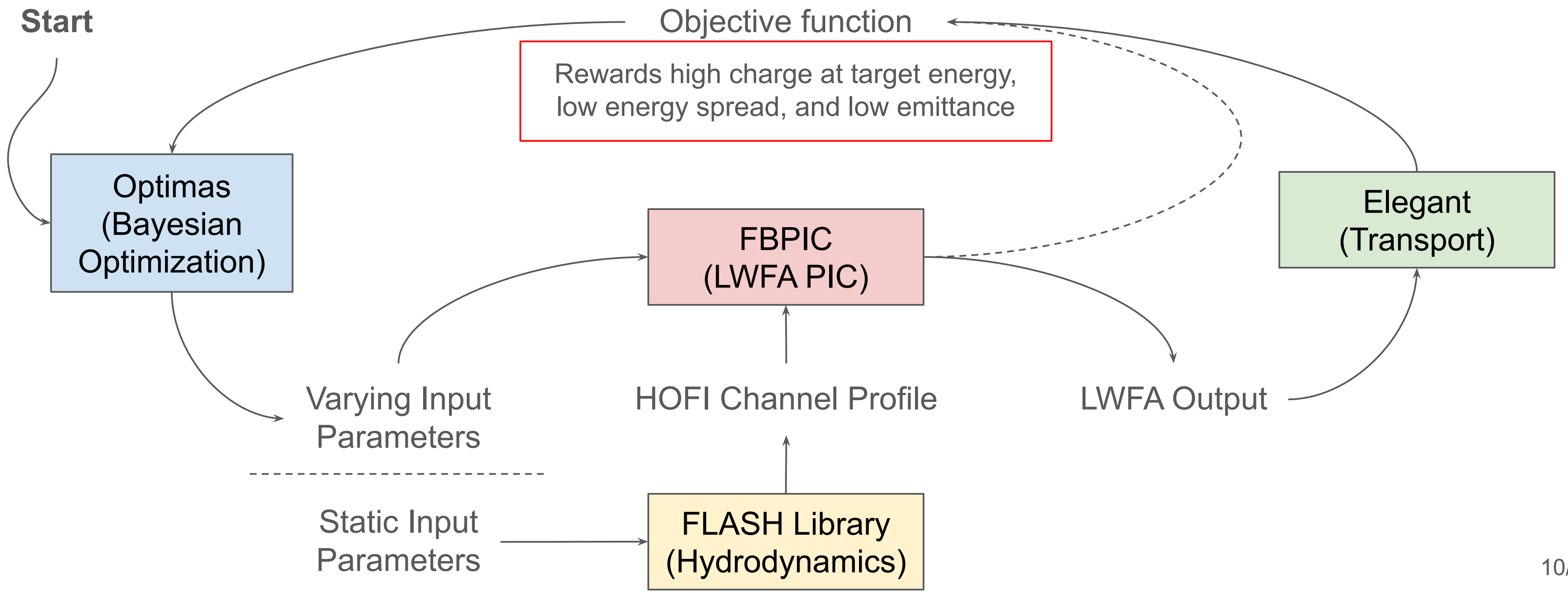
Lattice elements can be tuned to different final outcomes

- For a given beam, the lattice can be optimized a number of ways:
  - Minimize emittance growth
  - Maximize stretching
  - Minimize total footprint
- The “knee” of this front signifies where the chromatic chicane begins making a tradeoff between lengthening R56 and worsening CSR



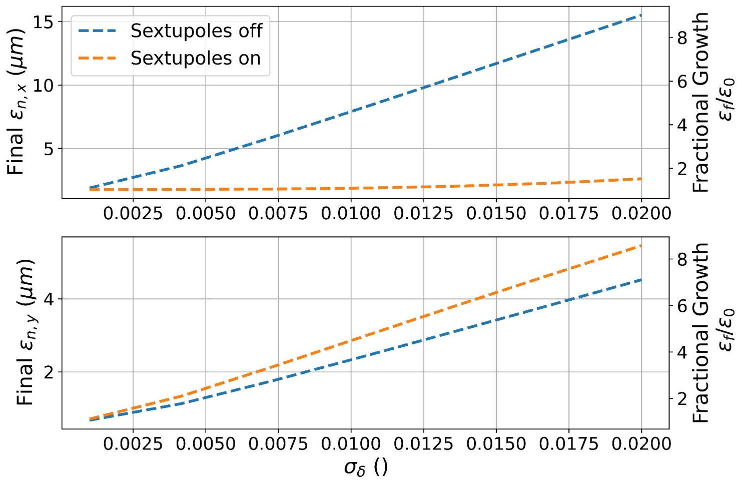
Computational approach

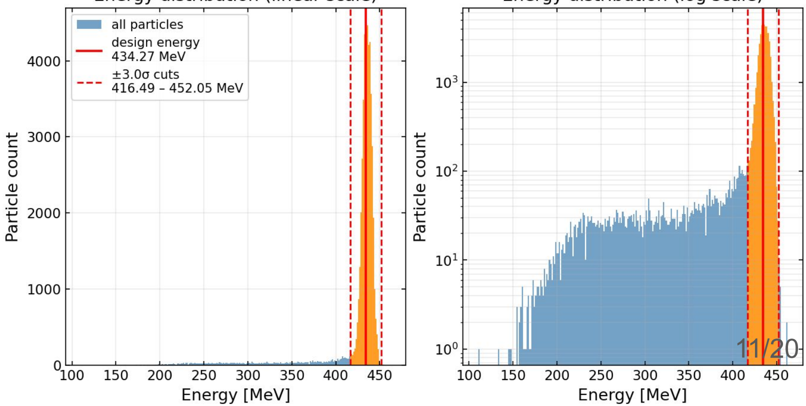
We deploy a suite of simulation codes wrapped inside Bayesian optimization:



Lattice Optimization in Elegant

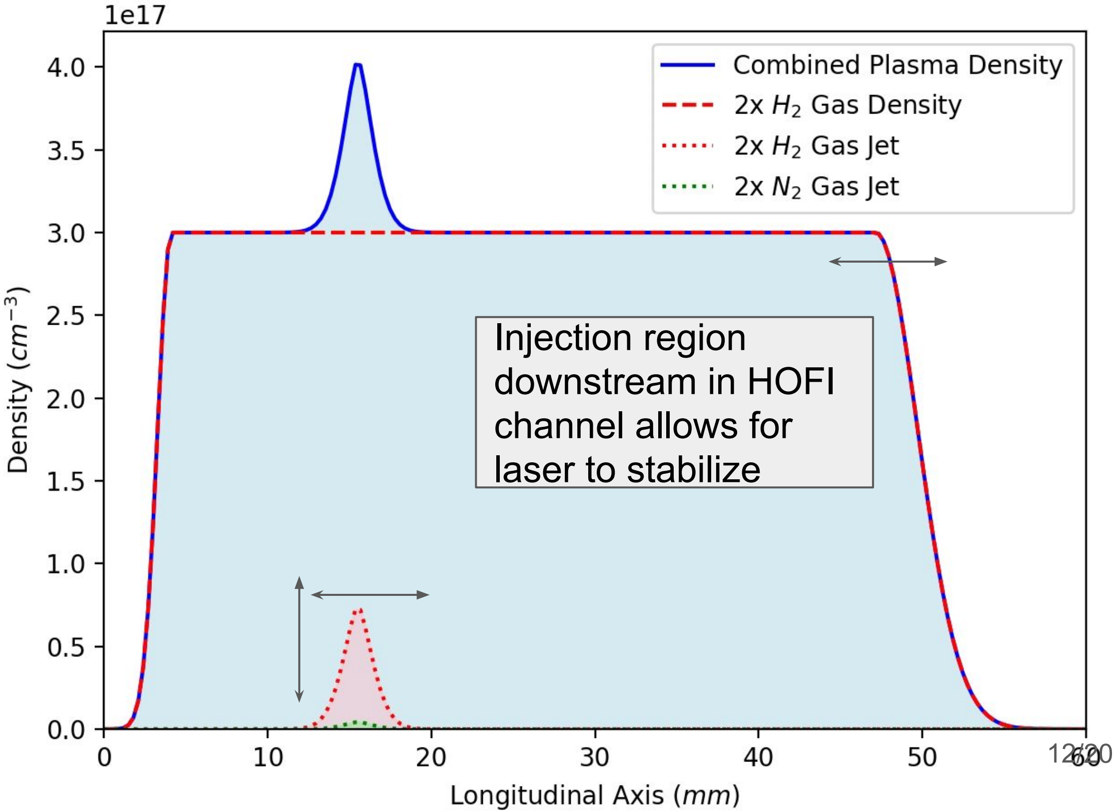
- Once per configuration:
  - Optimize capture triplet to maintain beam size through transport line
  - Tune two sextupoles in chromatic correction chicane to minimize horizontal emittance growth (top-right)
- Every trial:
  - Measure core of the initial distribution (bottom-right) to construct longitudinal covariance matrix
  - Set the total voltage for the X-band cavity
  - Perform moment propagation based on calculated chicane R56 to find the chirp we need to cancel at the end of the transport





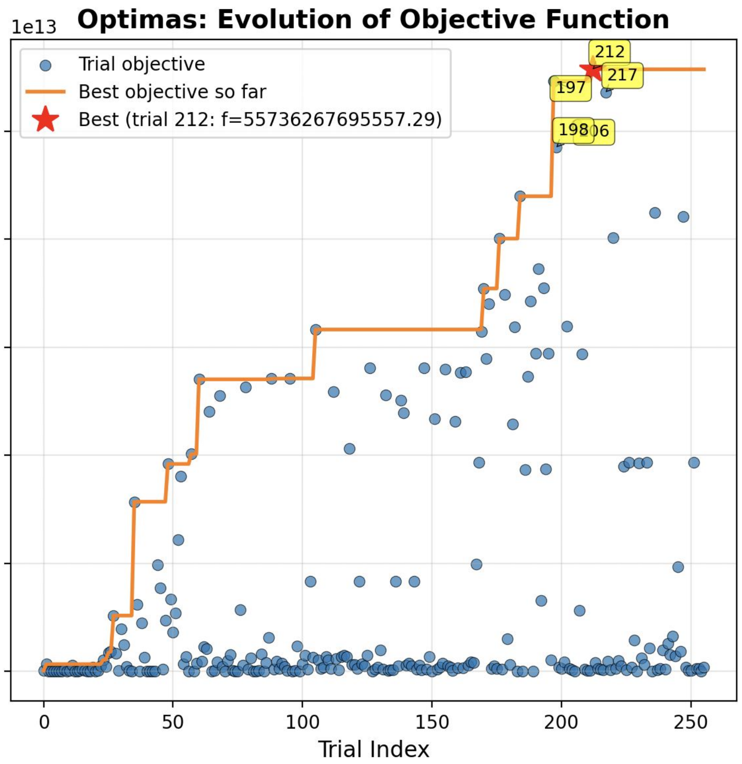
Laser parameters and longitudinal plasma profile is varied

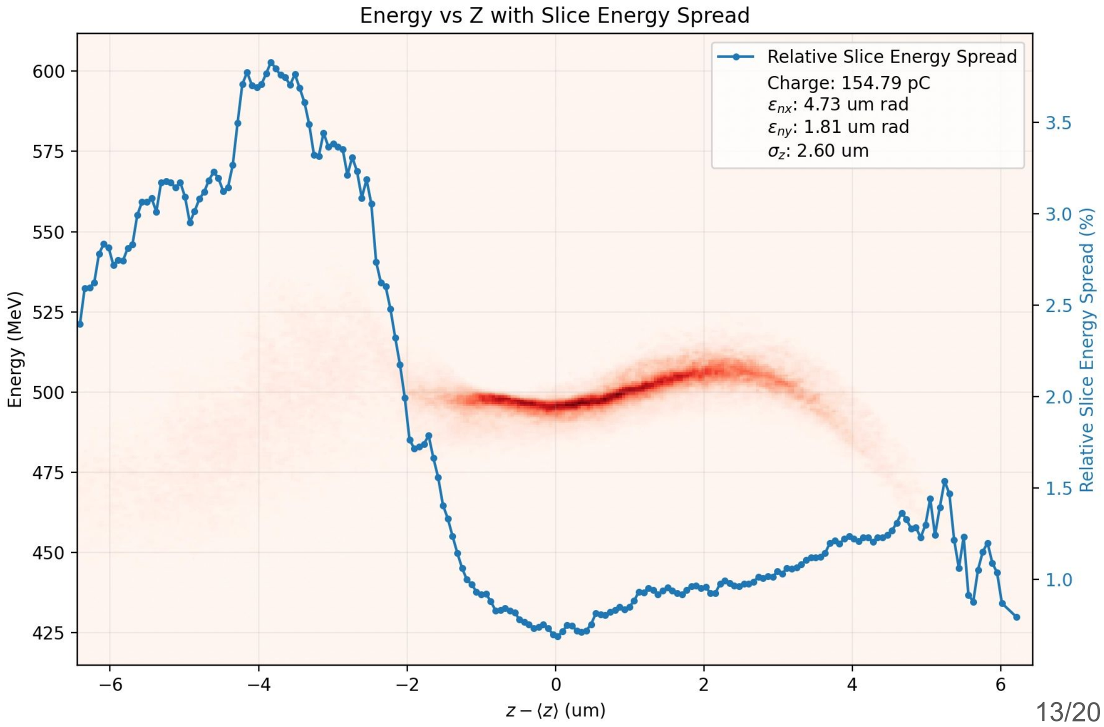
- Laser Parameters:
  - Laser energy
  - Focus size
  - Focus position
- Injection Jet Parameters:
  - Longitudinal position
  - Longitudinal width
  - Amount of H2
  - Doped level of N2
- Gas Parameters:
  - Full length of bulk flattop



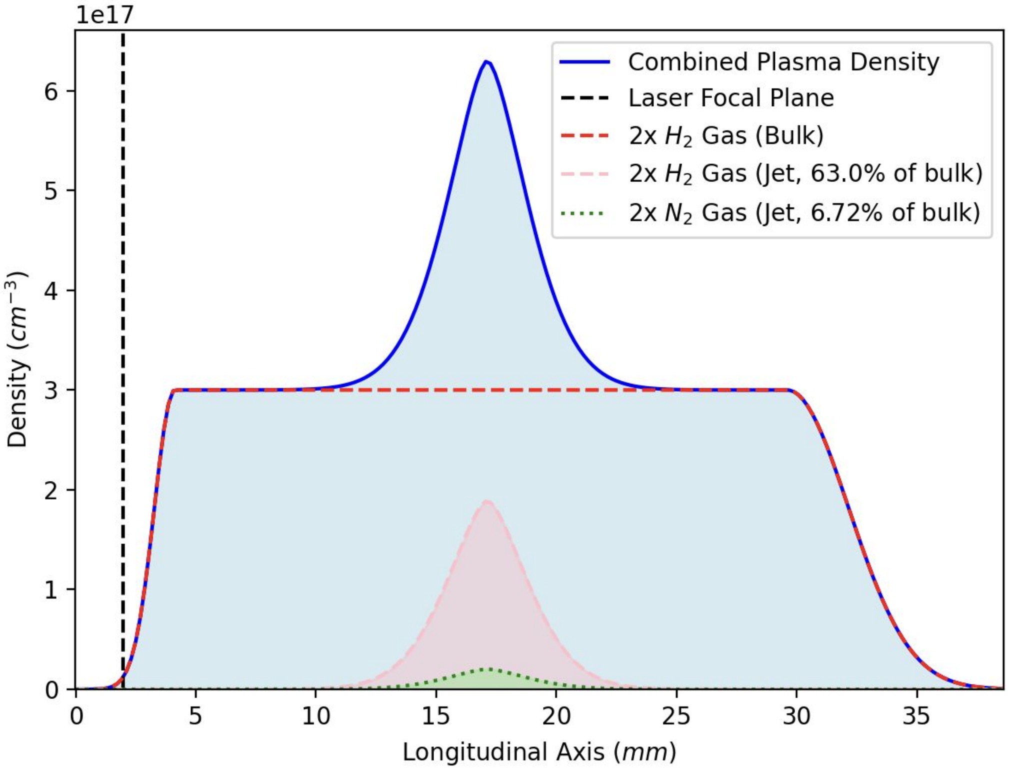
Optimization with LWFA-Only successful after >200 sims

Each sim is run on 2x B200 with 40 cells per lambda in z, Lorentz boost of 5





Plasma profile is optimized for injection and beam loading



Fixed Laser Parameters:

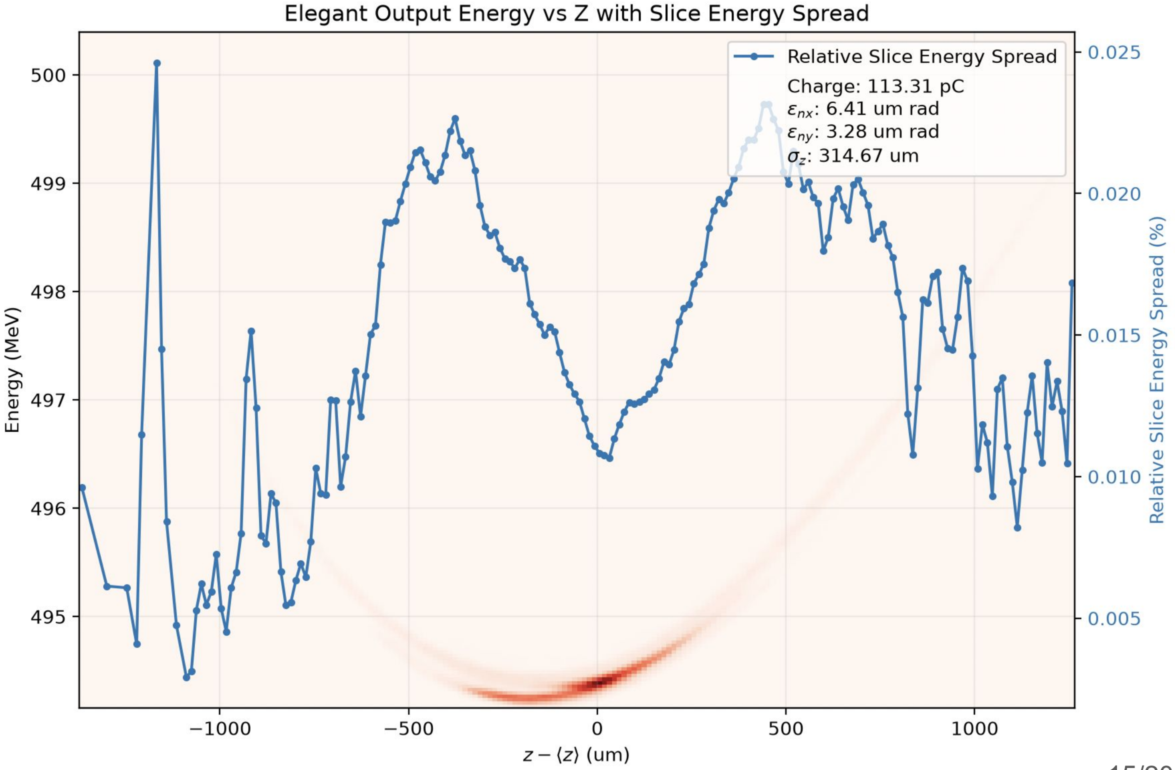
- Wavelength = 800 nm
- Pulse Width = 30 fs
- Shape: Gaussian

Optimized Laser Parameters

- Energy: 3.84 J
- Vacuum Spot Size: 26.2 um
- Focal Plane: 1.96 mm

Dechirper lattice lengthens and reduces energy spread

- We transfer this FBPIC output into the Elegant transport lattice optimization
- 113 pC bunch lengthed to 315 um rms, <0.025% slice energy spread, and 6.4 x 3.3 um-rad emittance
- How does this compare to when we optimize using the output of the transport lattice directly?



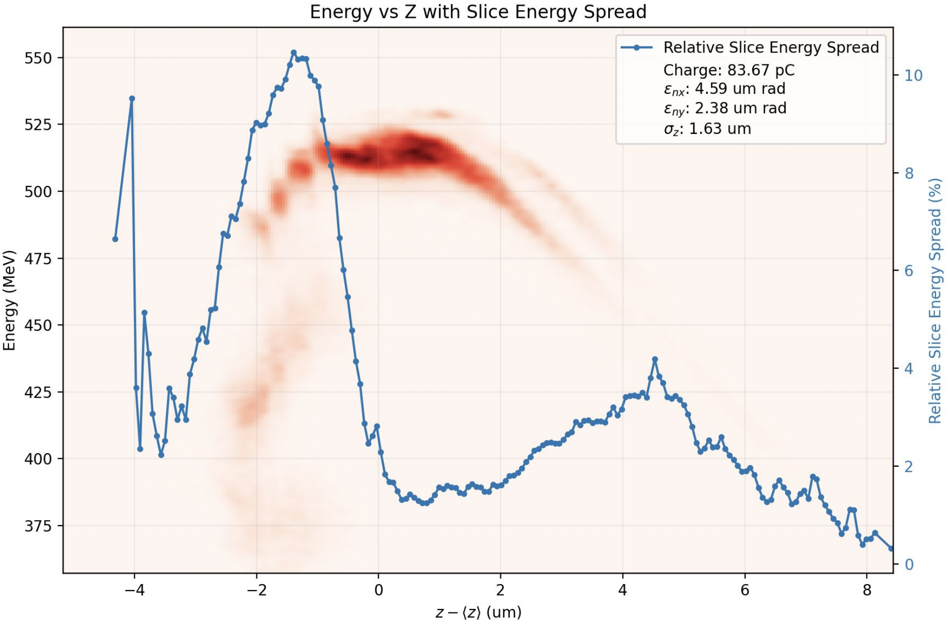
Optimizing at transport exit prefers wider injection regions

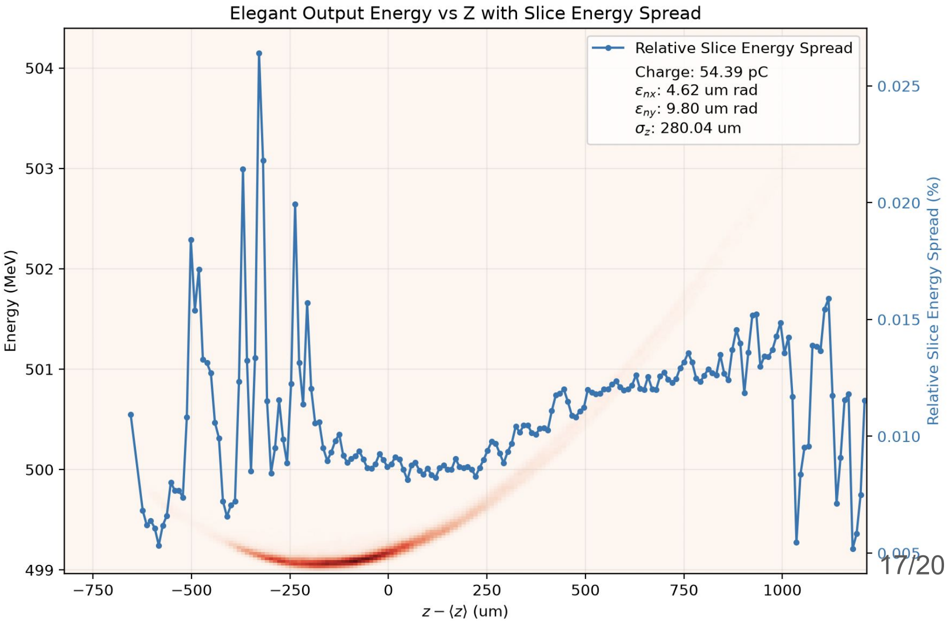
Target Energy	Objective Function Evaluation Location	Laser Energy	Laser Focal Plane	Laser Spot Size	Gas Jet Position	Gas Jet Width (Full width half max)
500 MeV	Plasma Exit	3.84 J	1.92 mm	26.2 um	17.1 mm	3.8 mm
500 MeV	Transport Exit	4.85 J	-1.33 mm	42.0 um	12.0 mm	8.0 mm
1250 MeV	Transport Exit	4.38 J	2.58 mm	33.8 um	19.0 mm	8.0 mm

Target Energy	Objective Function Evaluation Location	Total Flattop Plasma Length	Final ebeam Charge	Final ebeam slice energy spread	Final ebeam transverse emittance
500 MeV	Plasma Exit	25.5 mm	113.31 pC	< 0.025%	6.4 x 3.3 um-rad
500 MeV	Transport Exit	14.0 mm	54.4 pC	< 0.025%	4.6 x 9.8 um-rad
1250 MeV	Transport Exit	36.9 mm	84.2 pC	< 0.008%	6.7 x 2.3 um-rad

Optimizing using Elegant output gives similar end results

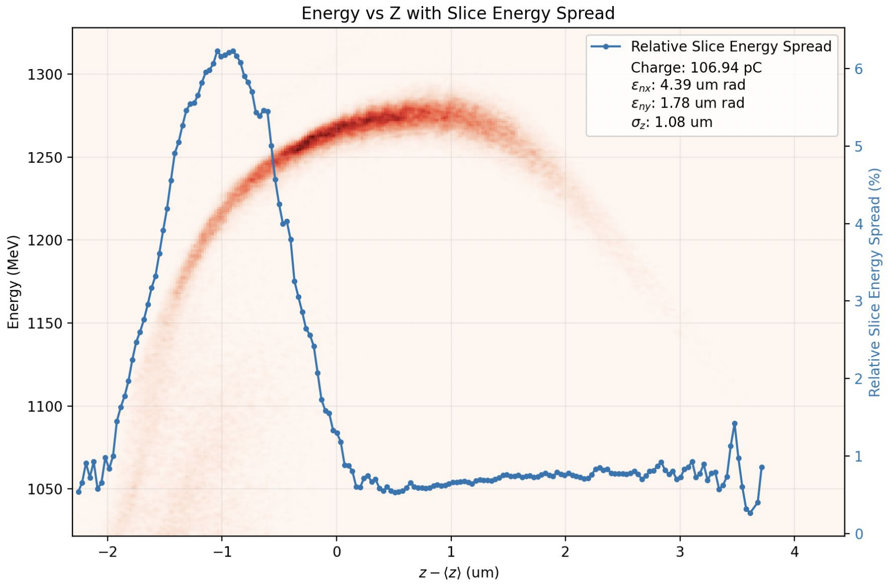
- More work is needed to adjust the objective function and add more lattice manipulations during each trial (adjust capture triplet, chromatic chicane, etc)
- Transport lattice is forgiving and can clean up fairly poor quality LWFA ebeams

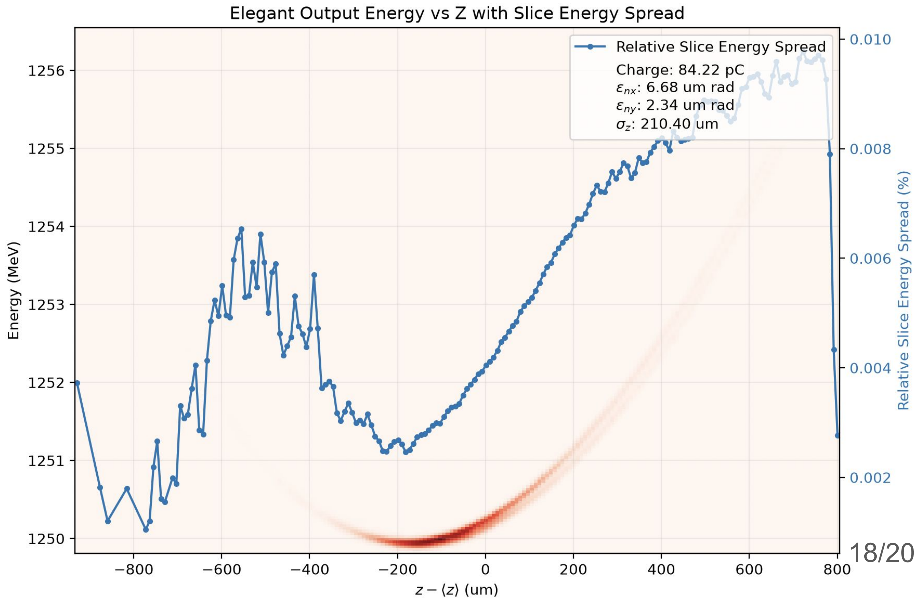




Same approach with minimal change at 1250 MeV target

- Plasma is much longer, but otherwise the elegant lattice is able to re-optimize for higher energy ebeams.
- Some post-processing of the lattice is needed to lengthen the RF element and swap the triplet for PMQs





Discussion

- We are exploring different schemes of plasma injectors into compact storage rings. DESY-style RF dechirper transports are promising because they can be very forgiving to the ebeam that is exiting the LWFA.

- Bayesian optimization of the full hydrodynamic expansion + LWFA + transport lattice has produced some useful utilities, particularly with building a library of radial hydrodynamic density profiles. Approach is robust for wide target energy range.

- Next steps is to backtrack through the FLASH model to find the initial neutral gas density profile before ionization. Can this profile be engineered?

Thank you!

We are hiring!
Feel free to reach out if you'd like to work on building LWFA+compact ring.
cedoss@inversionsemi.com

Backup: Details of HOFI Channel Model

Spatiotemporal model for plasma channel heating for arbitrary laser profiles

1. Numerically integrate laser profile through 2D gas slice
   a. Compute ionization fraction
   b. Compute momentum transfer
   c. Increment kinetic energy
   d. Thermalize electrons

$$A = A_0(-\delta \sin(k_i\xi)\hat{x} + (1-\delta^2)^{1/2}\cos(k_i\xi)\hat{y})$$

$$\delta_t\left(\frac{n}{n_g}\right) = \left[1 - \frac{n}{n_g}\right] W(t)$$

$$\mathrm{T} = \sum_{\mathrm{x,y}} K_{\mathrm{x,y}}/3e$$

$$K_{\mathrm{x,y}} = 0.5\mathrm{m}_e c^2 a^2_{\mathrm{x_i,y_i}}$$

2. Seed FLASH simulations with temperature profile
3. Run simulations for array of laser, gas conditions and extract density profiles
4. Compute relevant figures of merit
   a. Axial density, matched spot, and effective error are targets
   b. Matched spot size is computed iteratively for a given drive pulse profile
   c. Effective error is quantified as the pulse energy which is not matched to the channel mode

Backup: Quantifying the HOFI channel quality

- Modal decomposition characterizes fundamental mode(s) of channel
  - Develop and invert Laplacian operator representing the channel density
  - Iteratively apply to a trial profile to obtain lowest order eigenmodes

$$\left[\frac{n_e(r)}{n_0} - \nabla_\perp^2\right]\psi(r) = \lambda\psi(r)$$

- Overlap integral with trial beam enables identification of matched spot
  - Scan through a range of potential matched spots to find best fit

$$I_{\mathrm{overlap}}(w_0) = \int_0^{r_{\max}} g_{\mathrm{trial}}(r, w_0) \cdot g_1(r) \cdot r\,dr$$

  - Residuals from the overlap integral calculation give an estimate of the mismatch

$$\lambda_E(w_0) = \frac{\int g_{\mathrm{trial}}^2\, r\,dr}{\left(\int g_{\mathrm{trial}} \cdot g_1\, r\,dr\right)^2} - 1$$

- Typically, channels are close to parabolic - (up to a few % mismatch)
  - At early timescales, interference effects near primary axis drive the largest mismatch
  - ***Higher channel quality favors longer delay times!***

Backup: FBPIC Simulation Parameters

Simulation:

- Lorentz Boost: 5
- Number of Modes: 2
- N_order: 32
- Ionization Injection: ON
- PPC (H2) 16 = 2x2x4
- PPC (N2) 128 = 4x4x8

Grid:

- Z: 100um window, 5000 cells
- R: 240um window, 200 cells

Backup: Objective Function

We use the same objective function as is described in the PIP4 CDR:

$$f = S_\Delta / \hat{\sigma}_p / \hat{E}_\mathrm{L}$$

I. Agapov et al., *Plasma Injector PETRA IV CDR*, Deutsches Elektronen-Synchrotron DESY (2025), DOI 10.3204/PUBDB-2024-06078.

- First term is the average spectral density of the beam: charge within momentum window divided by the momentum window, where the momentum window is calculated from the median absolute deviation.

- Second term is the relativistic average deviation with respect to the target momentum: $\hat{\sigma}_p = \sqrt{(\sigma_p/\bar{p})^2 + (1 - \bar{p}/p_\mathrm{goal})^2}$

- Third term is the laser energy used relative to a base case (I.E., 0.5 for half)

Backup: Plasma Profile for 2nd and 3rd cases

Left: 500 MeV

Right: 1250 MeV