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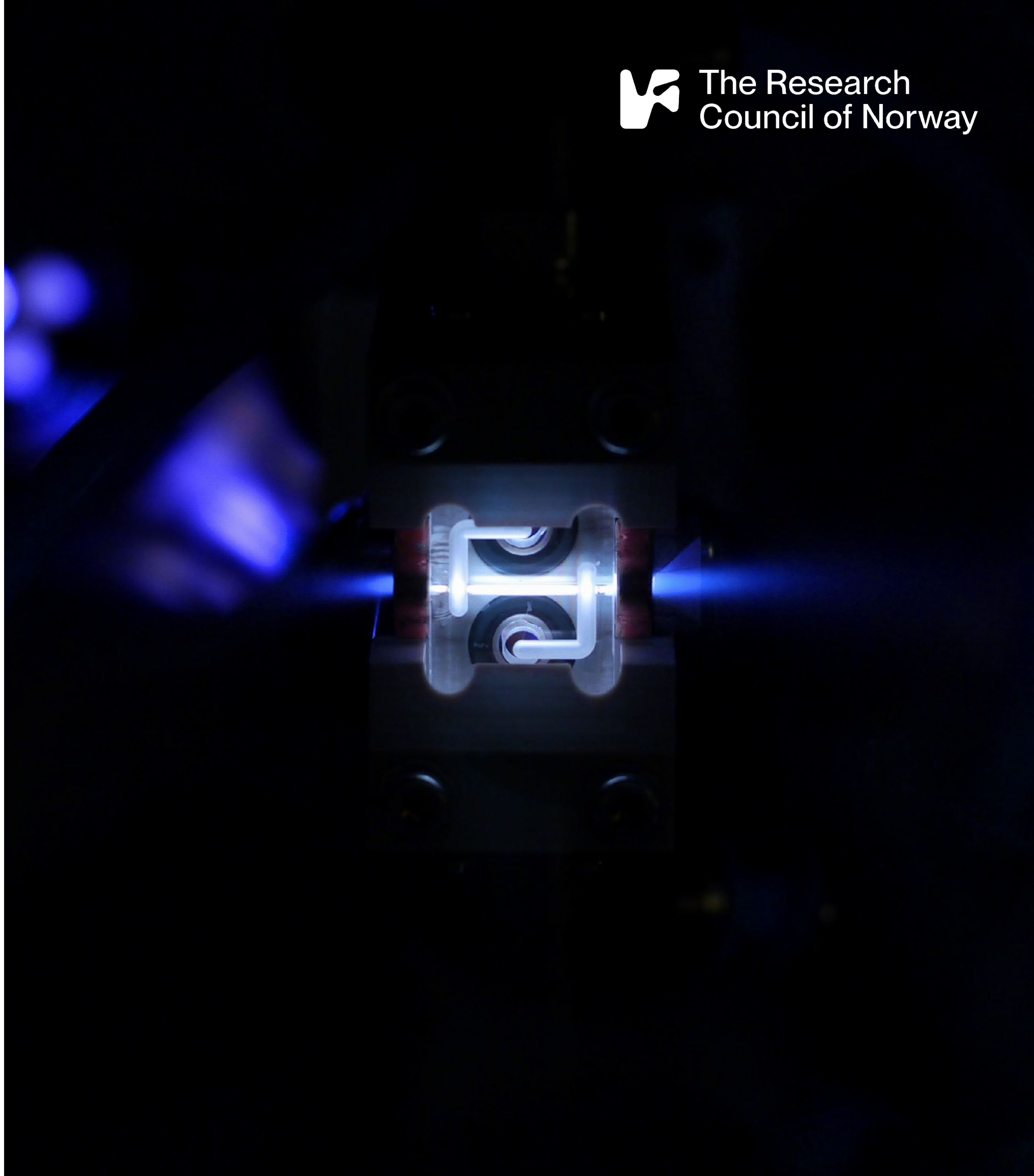

HALHF Monthly: Status on integrated simulations

Report from EAAC and moving forward

Ben Chen

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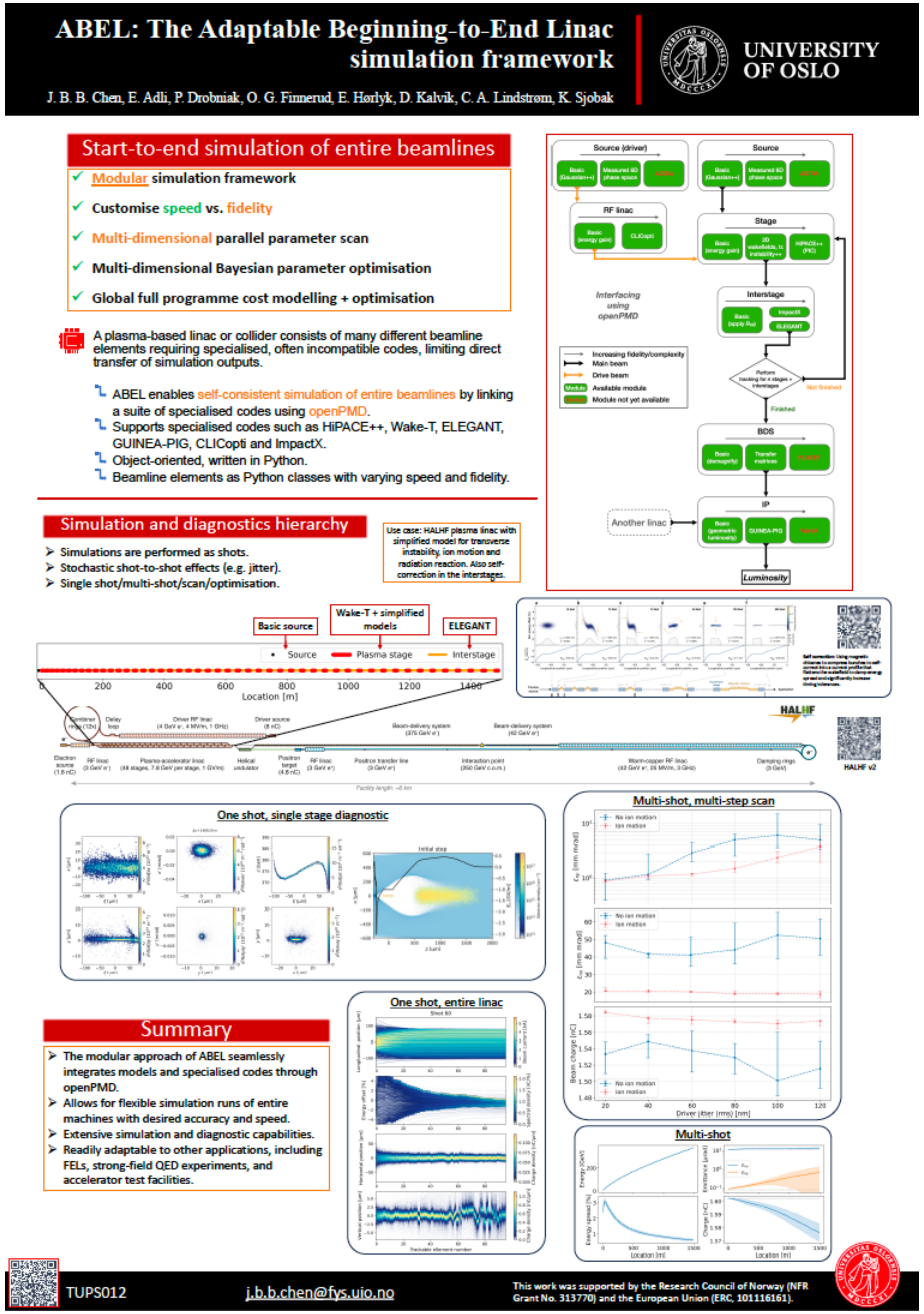
2 October 2025

Status of ABEL

- June: IPAC 2025, Taipei
  - Poster and demo from laptop
  - Proceeding: https://meow.elettra.eu/81/doi_per_institute/tups012/index.html
  - Erik also included results on transverse instability studies using ABEL (talk + poster + [proceeding](#))



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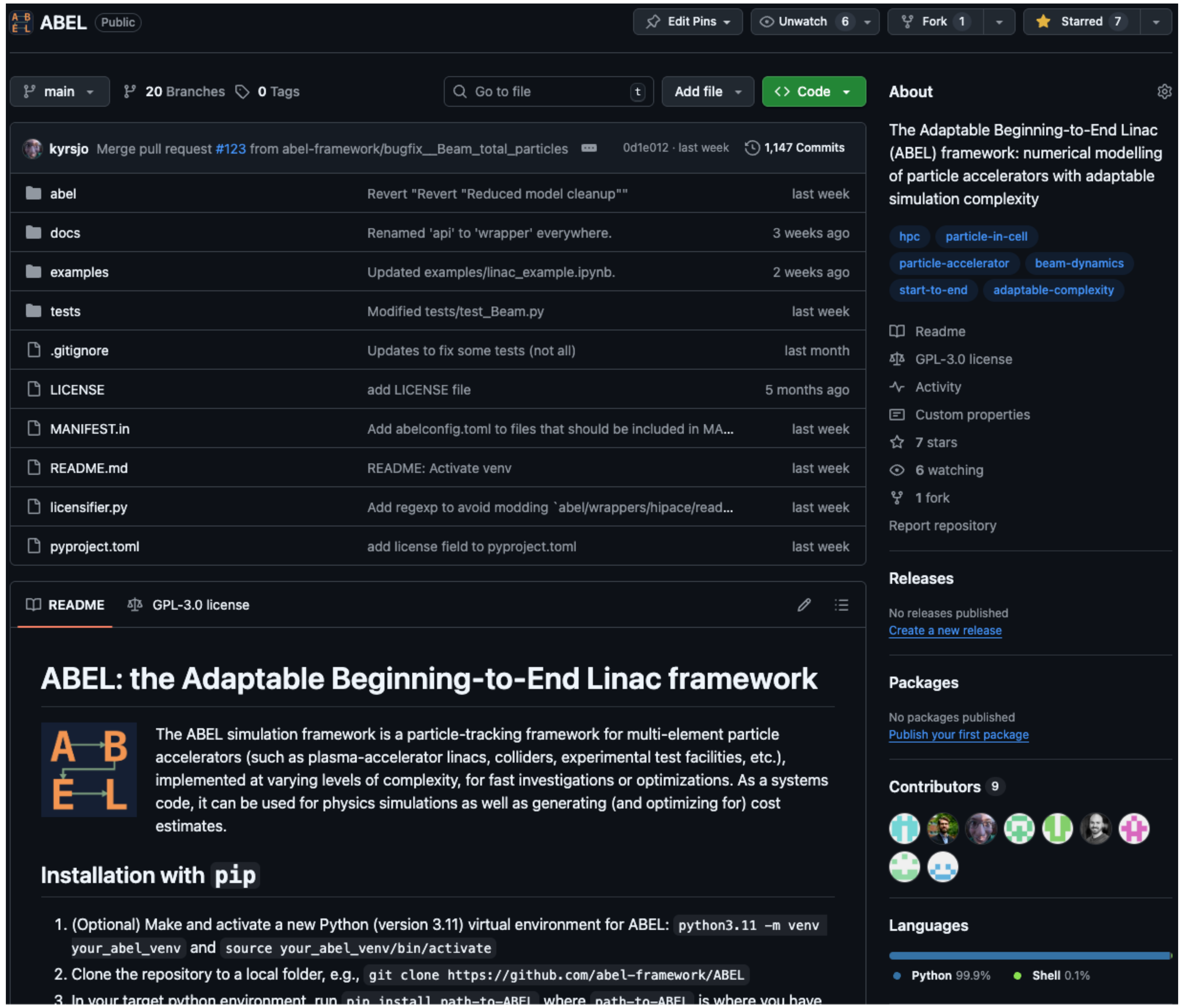
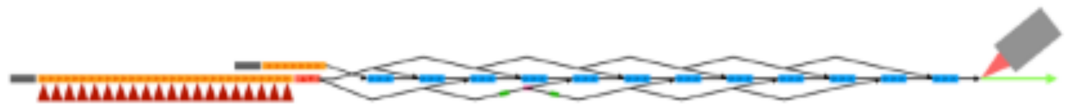
- September: EAAC 2025, Elba
  - Contributed talk: https://agenda.infn.it/event/46259/contributions/270096/
  - Mini-tutorial showcasing simple use cases.
  - Open for public as of September 25!
  - https://github.com/abel-framework/ABEL
  - Very much still in a beta phase!



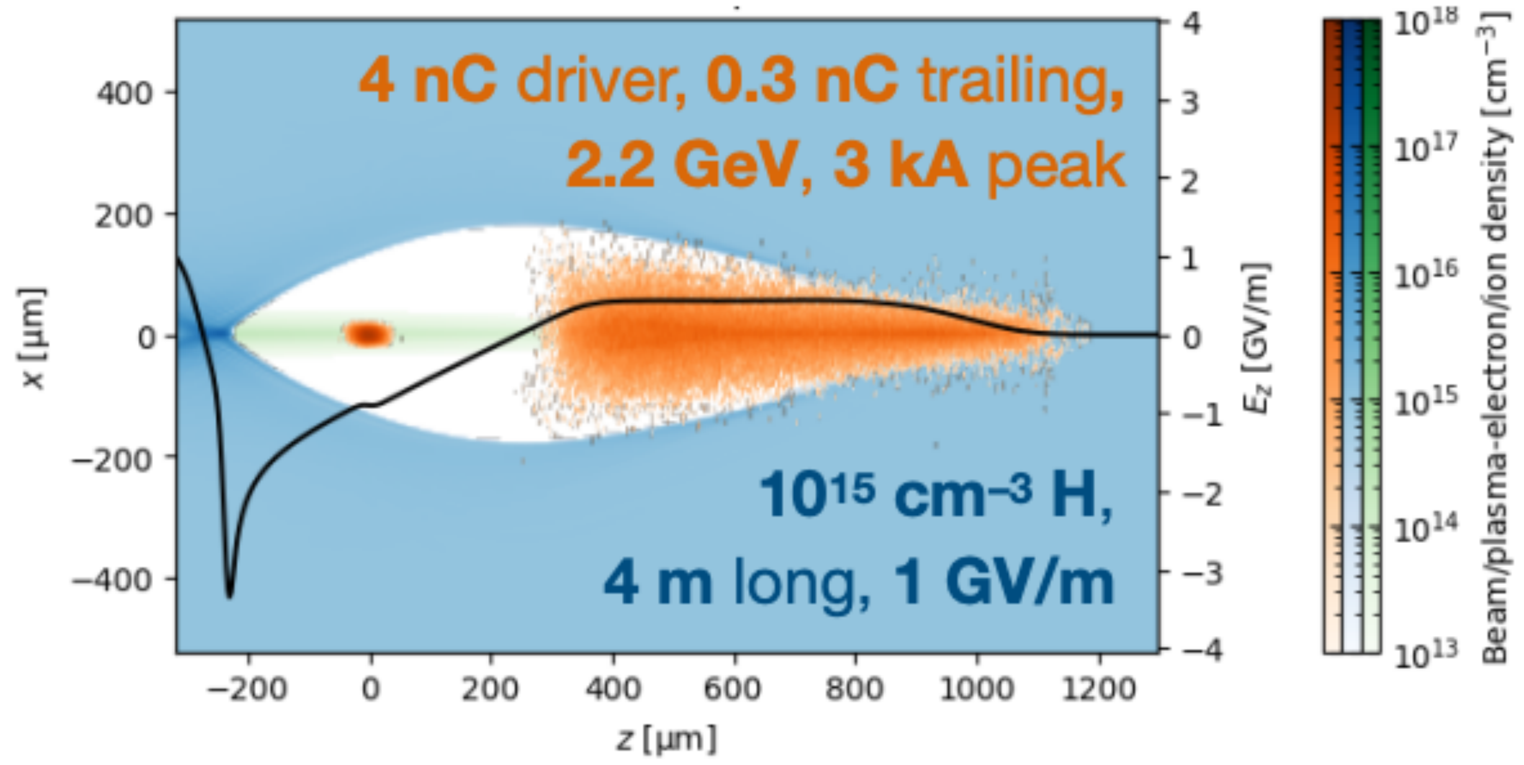
Integrated simulations on ABEL

Start-to-end simulations of the SPARTA demo

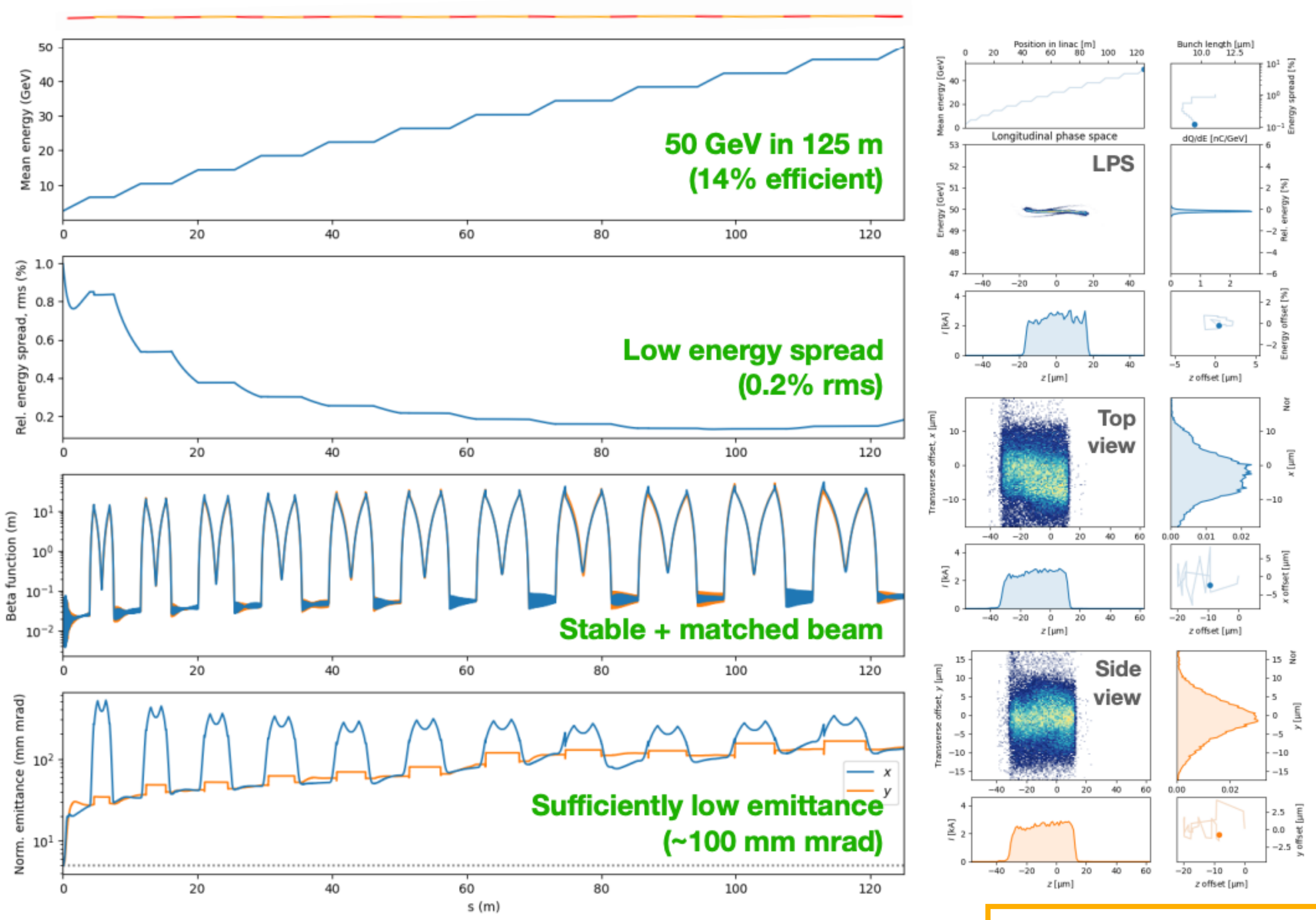


A preliminary working point

> HiPACE++ and ImpactX in ABEL
  > "Full" physics, 3D, high resolution
  > ~300 GPU hours per shot



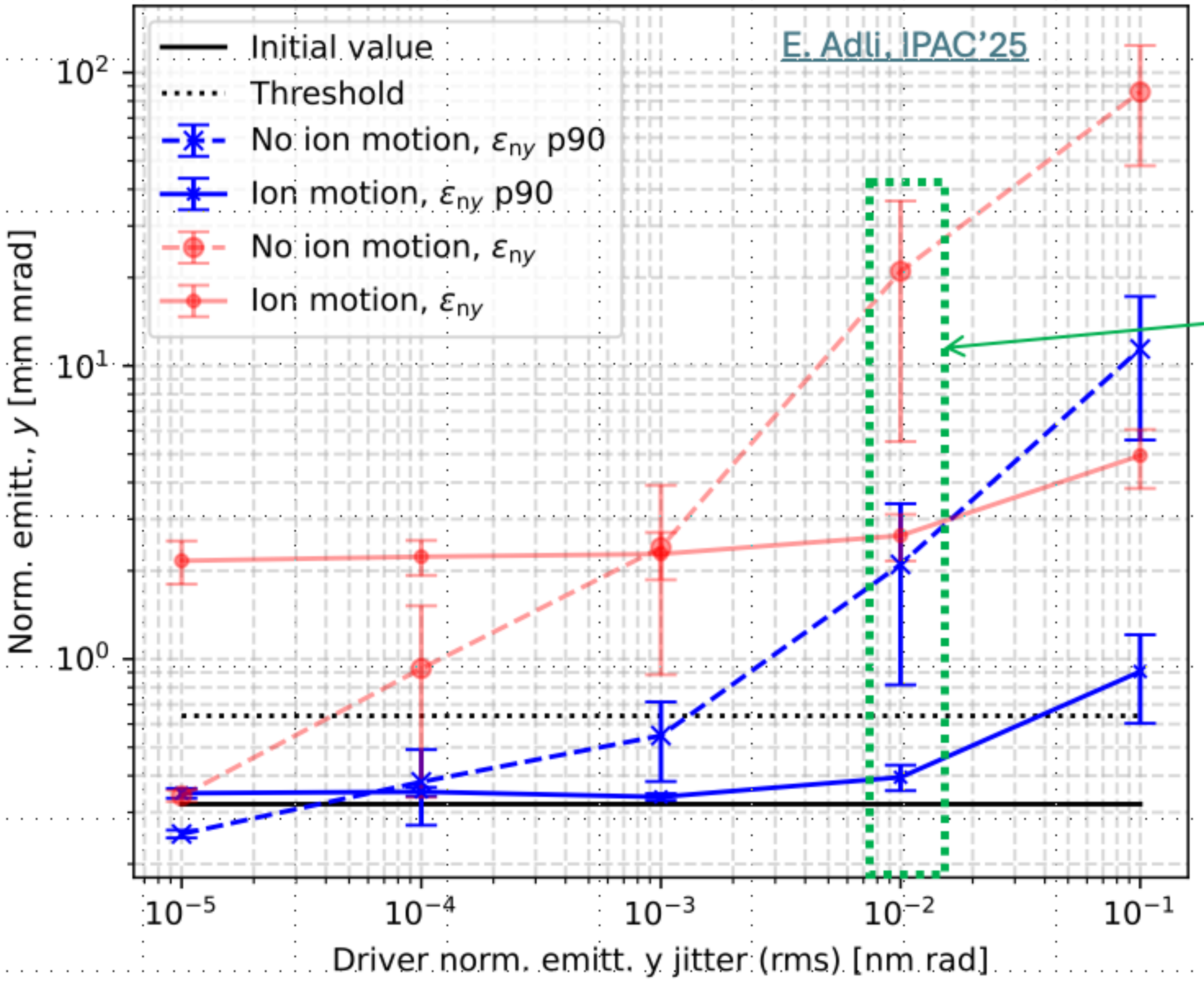
> **Realistic jitters** (sampled in 3 shots)
— Driver synchronization: 10 fs rms
— Driver jitter emit.: 0.04 mm mrad
— Plasma lenses: 1 µm rms (offsets)
(Gaussian, sampled at every stage)



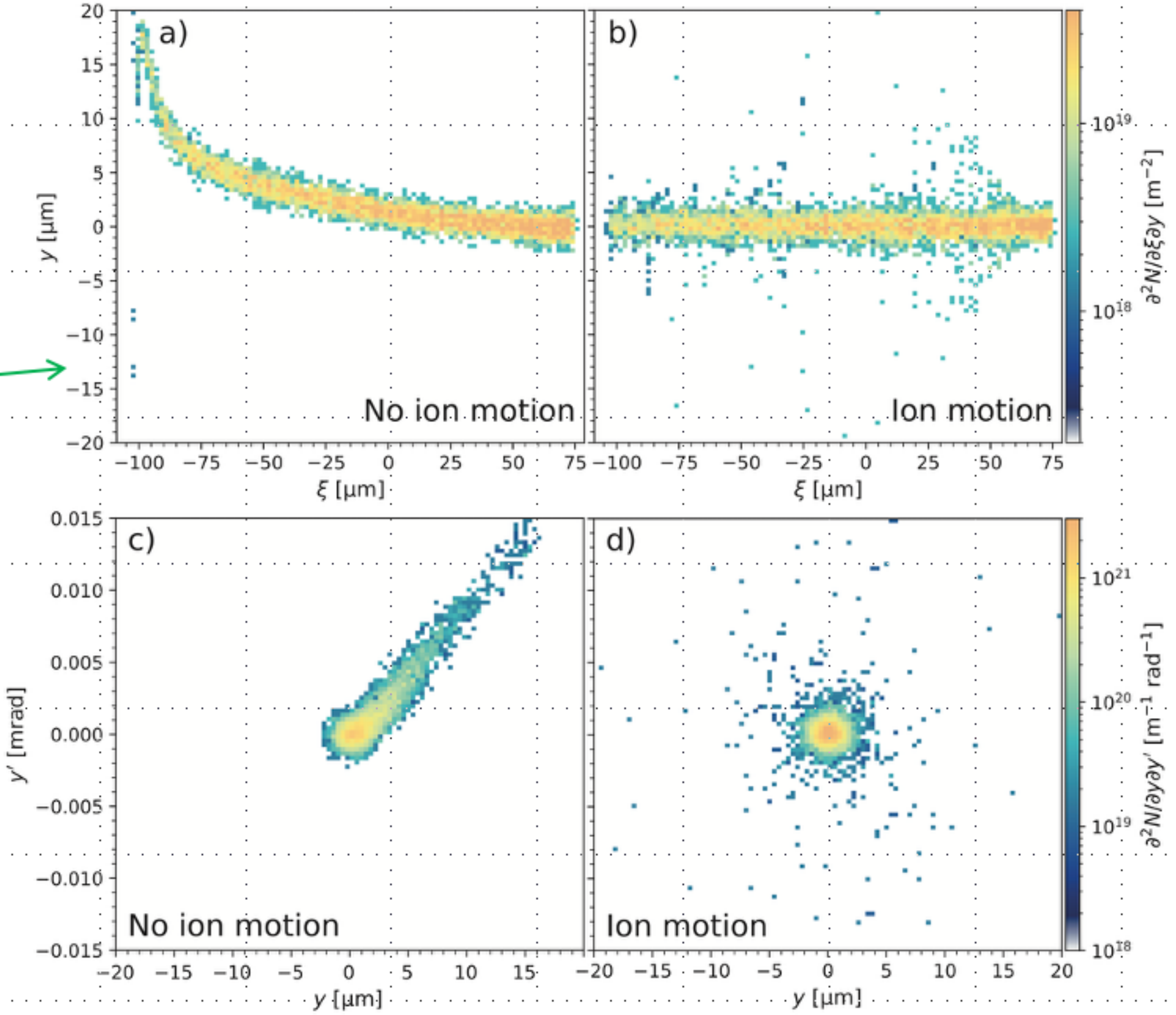
From Carl's contributed talk at EAAC.

> External driver guiding
> Moderate ion motion
> plasma-lens interstage

HALHF results



At the end of the HALHF linac:



Preliminary results for HALHF (simplified interstage, driver guiding assumed): With no ion motion, the BBU is large. With ion motion, the BBU is efficiently mitigated **up 10^{-2} nm rad drive-beam jitter-emittance** – "state of the art" FLASH@DESY - **position jitter of ~30 nm**. A halo of large amplitude particles has formed, driving up the rms emittance, while the 90%-percentile emittance is better preserved.

E. Adli, Tolerances, EAAC2025

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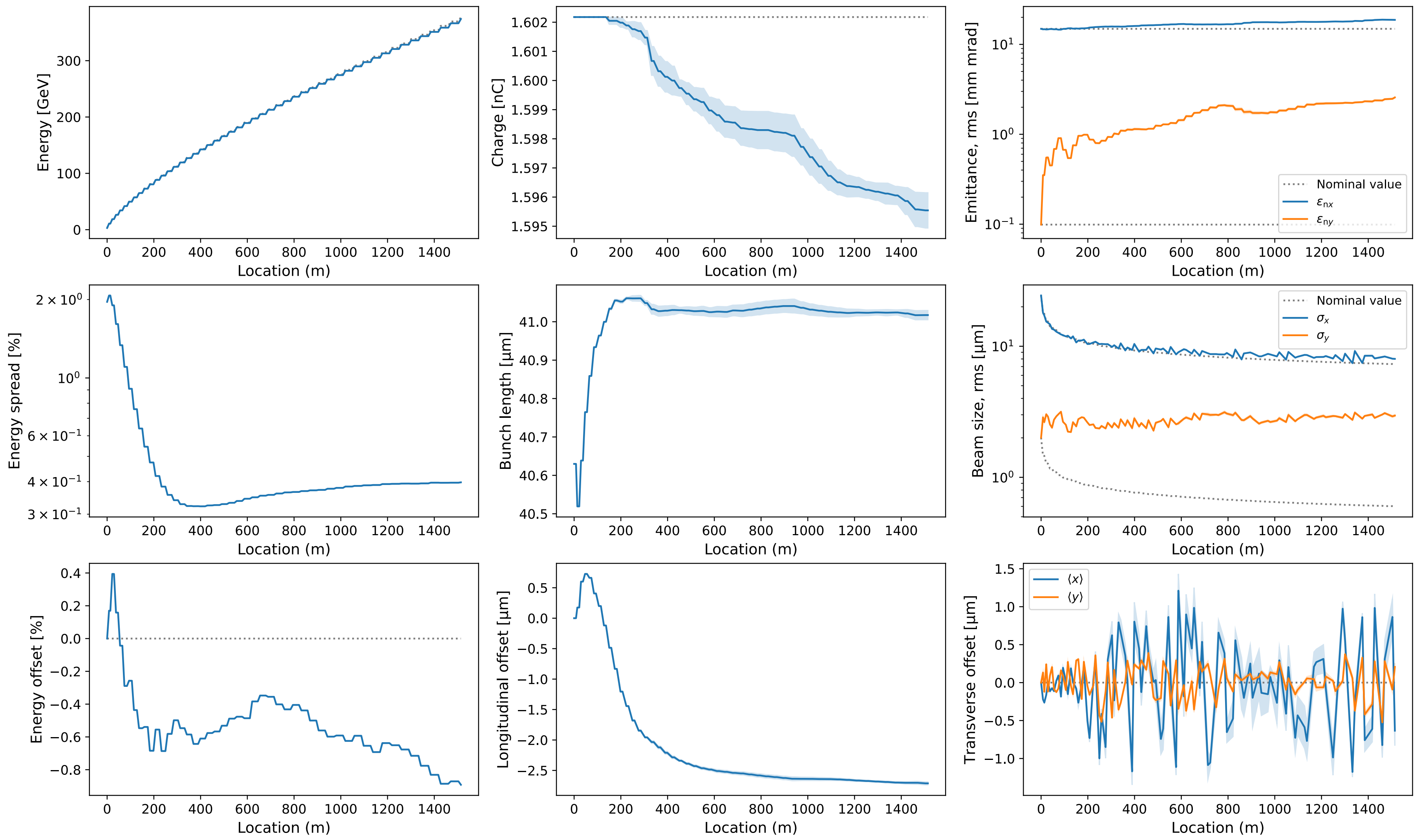
From Erik's contributed talk at EAAC.

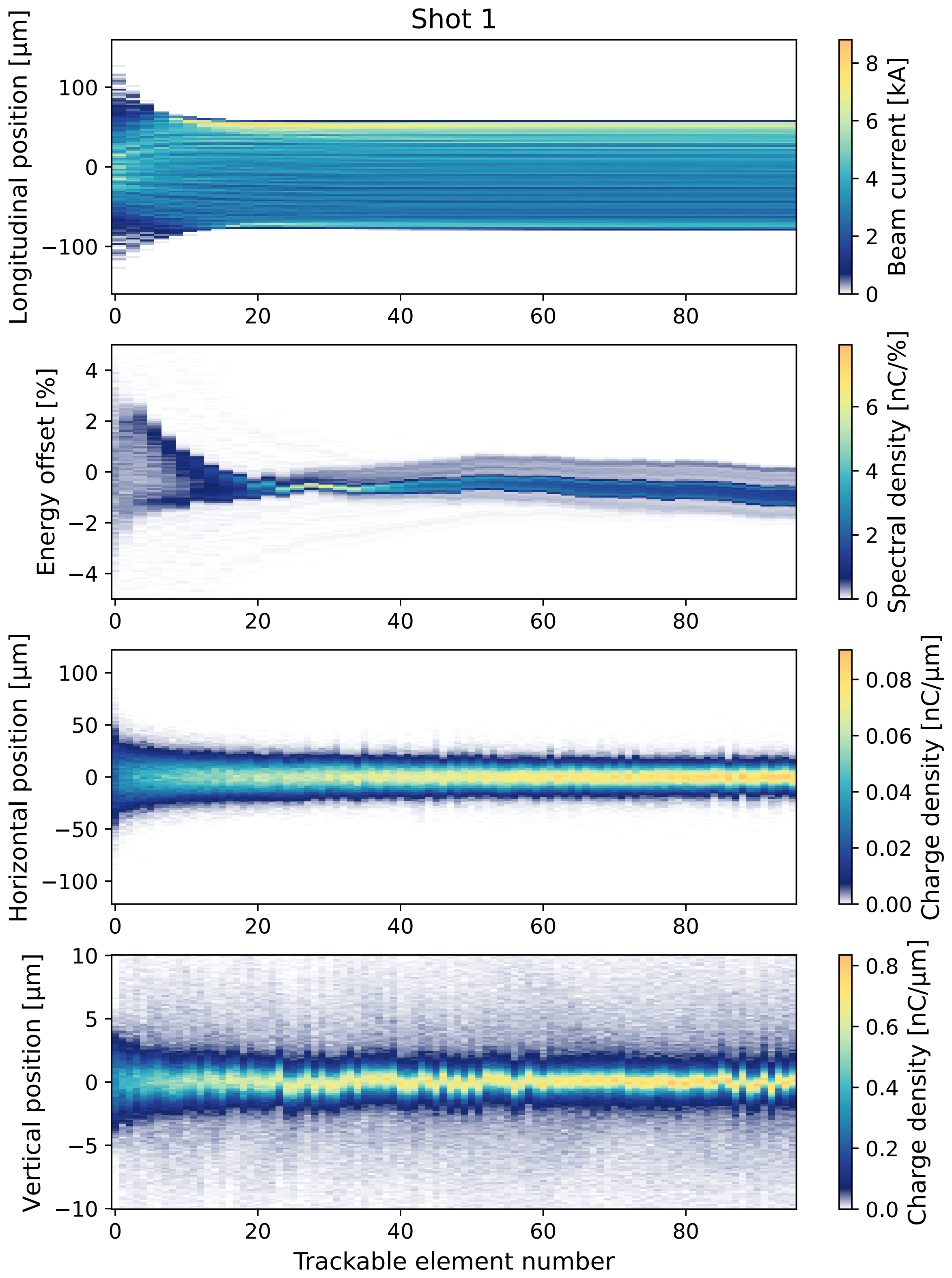
Example: HALHF plasma linac using reduced models

```
############# Define drive beam source #############
driver = SourceTrapezoid()
driver.current_head = 0.1e3                                      # [A]
driver.bunch_length = 1050e-6                                    # [m]
driver.z_offset = 1615e-6                                        # [m]
driver.num_particles = 30000
driver.charge = 5.0e10 * -SI.e                                   # [C]
driver.energy = 4.0e9                                            # [eV]
driver.gaussian_blur = 50e-6                                     # [m]
driver.rel_energy_spread = 0.01
driver.emit_nx, driver.emit_ny = 50e-6, 100e-6                   # [m rad]
driver.beta_x, driver.beta_y = 0.5, 0.5                          # [m]
driver.jitter.x = 100e-9                                         # [m], std
driver.jitter.y = 100e-9                                         # [m], std
driver.symmetrize = True

############# Define main beam source #############
main = SourceBasic()
main.bunch_length = 40.0e-06                                     # [m], rms
main.num_particles = 10000
main.charge = -e * 1.0e10                                        # [C]
main.energy = 3e9                                                # [eV]
main.rel_energy_spread = 0.02                                    # Relative rms energy spread
main.emit_nx, main.emit_ny = 15e-6, 0.1e-6                       # [m rad]
main.beta_x = beta_matched(plasma_density, main.energy) * 10.0   # [m]
main.beta_y = main.beta_x                                        # [m]
main.z_offset = 0.00e-6                                          # [m]
main.symmetrize_6d = True

############# Define the stages #############
stage = StageReducedModels()
stage.time_step_mod = 0.04                                       # In units of betatron wavelengths/c.
stage.nom_energy_gain = 7.8e9                                    # [eV]
stage.length_flattop = 7.8                                       # [m]
stage.plasma_density = 6.0e+20                                   # [m^-3]
stage.driver_source = driver
stage.ramp_beta_mag = 10.0
stage.enable_tr_instability = True
stage.enable_radiation_reaction = True
stage.enable_ion_motion = True
stage.ion_charge_num = 1.0                                       # [e]
stage.ion_mass = 6.646477e-27                                    # [kg], He mass
stage.upramp = PlasmaRamp()
stage.downramp = PlasmaRamp()

############# Define interstages #############
interstage = InterstageElegant()
interstage.beta0 = lambda energy: stage.matched_beta_function(energy)
interstage.length_dipole = lambda energy: 1.0 * np.sqrt(energy/10e9)   # [m(eV)], energy-dependent length
interstage.field_dipole = lambda energy: np.min([0.52, 40e9/energy])   # [T]

############# Define linac #############
linac = PlasmaLinac(source=main, stage=stage, interstage=interstage, num_stages=48)
```

*The standard interstage lattice has been changed since this simulation, such that this setup no longer produces the same results.

> **Linac level diagnostics**:





More on transverse instability and tolerances, see E. Adli's talk tomorrow 17:20, Sala Biodola

Outlook

Tentative plans for the coming 6 months

- A laundry list of things to be done for ABEL
  - Proper documentation.
  - Expand tests (currently at 67% coverage).
  - Easier setup for other clusters.
  - Structural changes for the RFAccelerator class.
- Talk at LCWS next month
- Paper for ABEL: Computer Physics Communications?
- Paper for HALHF transverse tolerance studies
  - More robust benchmarking for the reduced models against PIC.
  - Bayesian optimisation?
- Full PIC simulation for all 48 stages?

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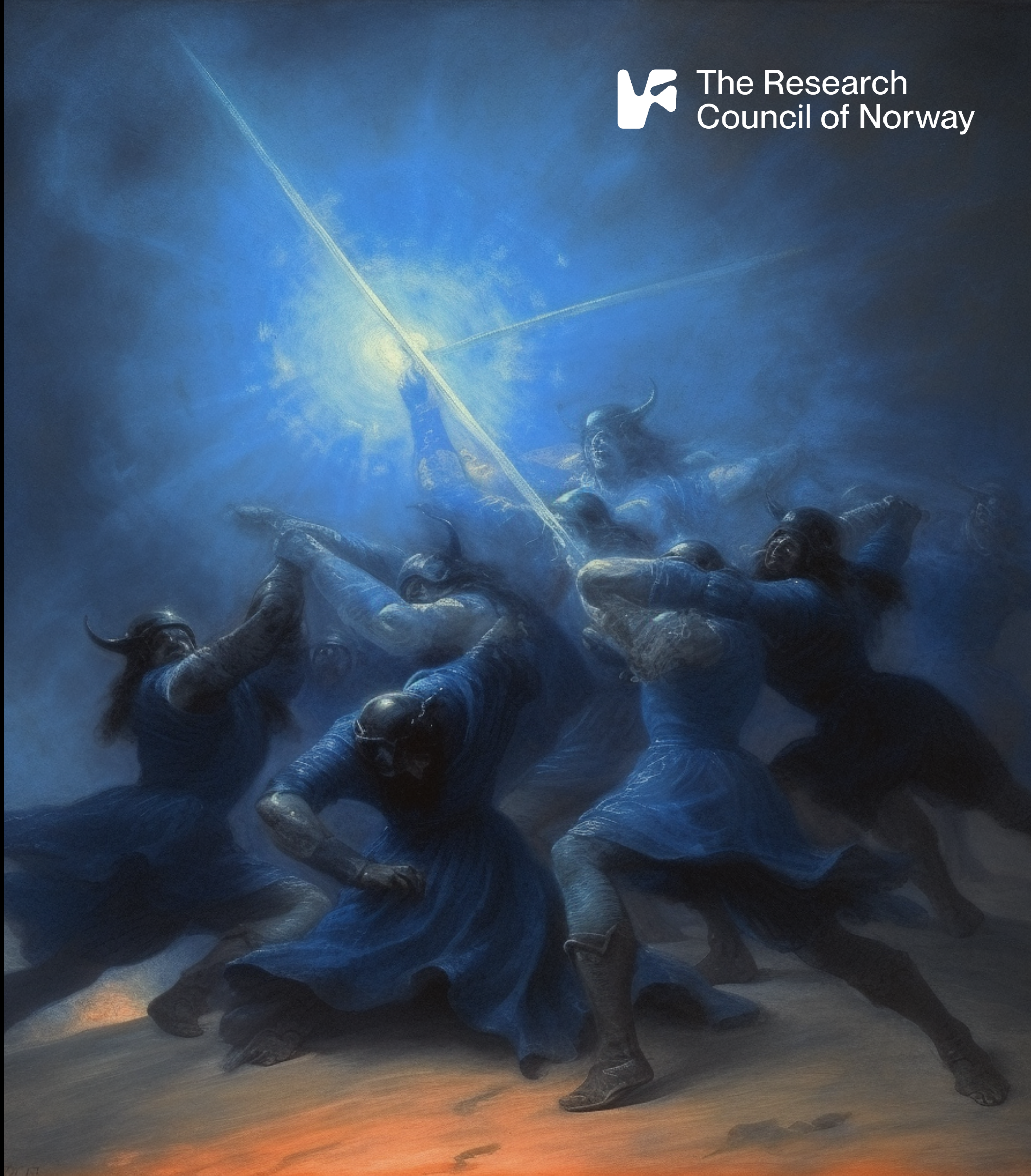
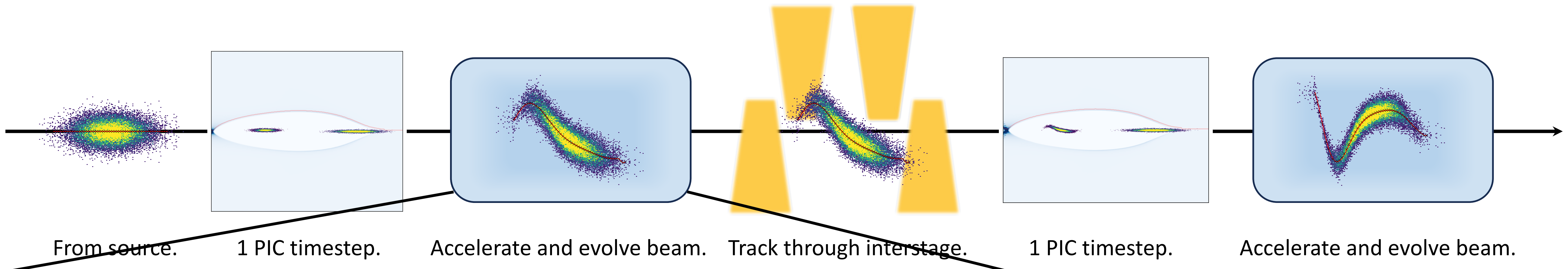


Simplified transverse wake instability model

> Wakefield formalism has been used in CLIC to study the limitations on charge and efficiency.

> Ansatz: for small offsets/perturbations, transverse instability in PWFA should behave similarly to BBU in conventional accelerators.



Outline for start-to-end simulation processes using simplified transverse instability model. Wake-T is used instead of PIC here.

> Transverse intra-beam wakefield (G. Stupakov):

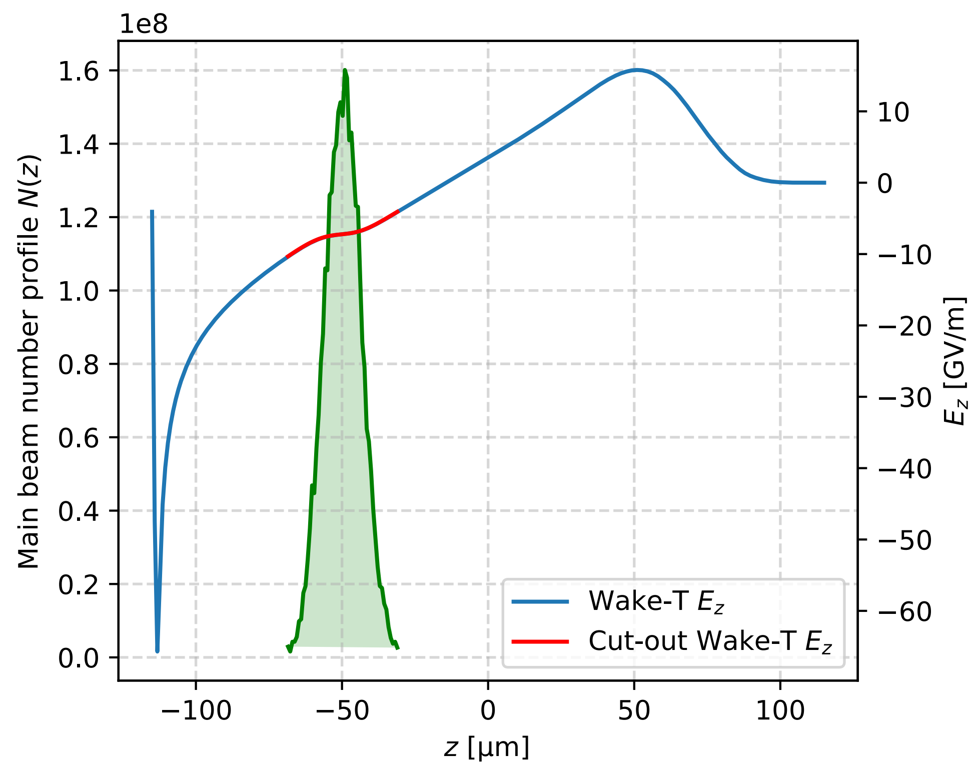
$$\mathscr{W}_x(\xi, s) = -\frac{2e}{\pi\varepsilon_0}\int_{\xi_{\mathrm{H}}}^{\xi} \frac{\xi' - \xi}{(r_{\mathrm{b}}(\xi') + \alpha k_{\mathrm{p}}^{-1})^4}\Theta(\xi' - \xi)\lambda(\xi', s)x(\xi', s)\,\mathrm{d}\xi'$$

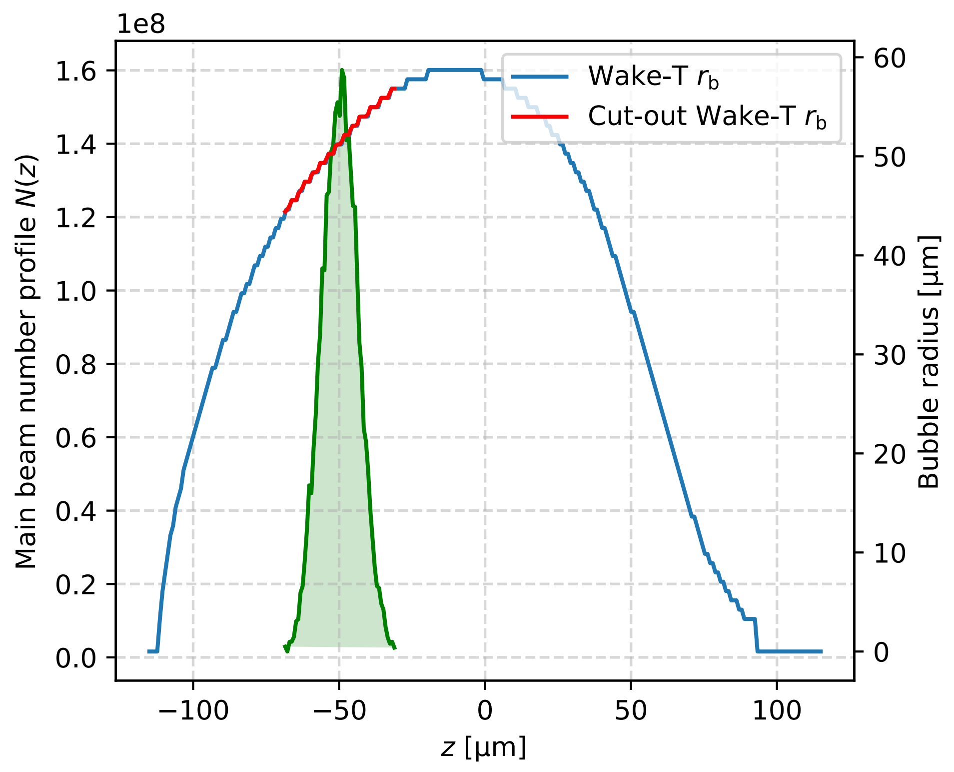
> Combine with Deng et al. equations for radiation reaction:

> $$\frac{1}{c}\frac{\mathrm{d}u_x}{\mathrm{d}t} \approx -\frac{1}{2}k_{\mathrm{p}}^2 x - \frac{e}{m_{\mathrm{e}}c^2}\mathscr{W}_x - \frac{1}{2}k_{\mathrm{p}}^2 c\tau_{\mathrm{R}}u_x\left(1 + \frac{1}{2}k_{\mathrm{p}}^2\gamma(x^2 + y^2)\right)$$

> $$\frac{1}{c}\frac{\mathrm{d}u_z}{\mathrm{d}t} \approx k_{\mathrm{p}}\frac{E_z}{E_0} - \frac{1}{4}k_{\mathrm{p}}^4 c\tau_{\mathrm{R}}\gamma^2(x^2 + y^2)$$

> $$\frac{\mathrm{d}x}{\mathrm{d}t} \approx \frac{u_x}{u_z}c$$





Need initial $E_z(\xi)$ and $r_{\mathrm{b}}(\xi)$ as inputs from e.g. a PIC code (Wake-T used here).

s: beam location.
ξ': long. coordinate of driving particle.
ξ: long. coordinate of reference particle.
ξ_{H}: long. coordinate of beam head.
α: numerical factor ~1.
k_{p}^{-1}: plasma skin depth.
$\Theta(\xi)$: Heaviside step function.
$\lambda(\xi, s)$: long. beam number density.
$x(\xi, s)$: particle transverse offset.
$\mathbf{u}(\xi, s) = \mathbf{p}/m_{\mathrm{e}}c$: normalised e^- momentum.
$\tau_{\mathrm{R}} = 2r_{\mathrm{e}}/3c$
$E_0 = m_{\mathrm{e}}c\omega_{\mathrm{p}}/e$: wavebreaking field.

Benchmarks against HiPACE++

Benchmarks of wakefields

- [Benedetti et al.](#)
- A beam with transverse E-fields $\mathbf{E}_\perp(\mathbf{r},\zeta)$ perturbs the background focusing fields $k_\mathrm{p}\mathbf{r}/2$ so that (moderate non-relativistic ion motion)
- $$\frac{\mathscr{W}_\perp(\mathbf{r},\zeta)}{E_0} = \frac{k_\mathrm{p}}{2}\mathbf{r} + Z_\mathrm{i}\frac{m_\mathrm{e}}{M_\mathrm{i}}k_\mathrm{p}^2\int_\zeta^0(\zeta-\zeta')\frac{\mathbf{E}_\perp(\mathbf{r},\zeta')}{E_0}\mathrm{d}\zeta' = \frac{k_\mathrm{p}}{2}\mathbf{r} + \delta\mathscr{W}_\perp.$$
- I.e. integrate $E_{x,y}$ from head of drive beam to tail of main beam and modify the transverse eq.o.m. with a term $\sim \delta\mathscr{W}_{x,y}$.