



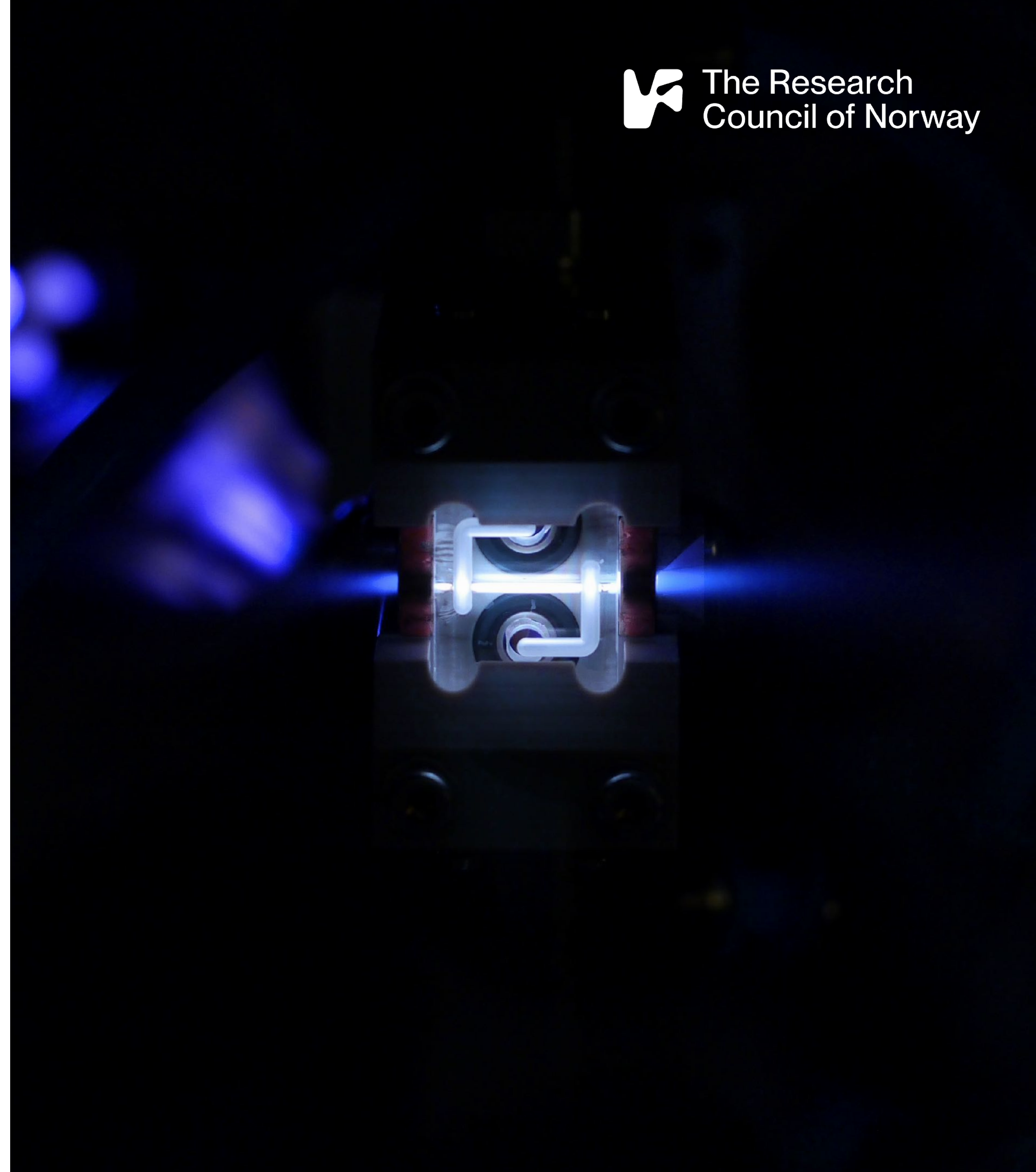
HALHF Monthly: Status on integrated simulations

Report from EAAC and moving forward

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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](#))



ABEL: The Adaptable Beginning-to-End Linac simulation framework

J. B. B. Chen, E. Adli, P. Drobnik, O. G. Finnerud, E. Horlyk, D. Kalvik, C. A. Lindström, K. Sjobak

**UNIVERSITY
OF OSLO**

Start-to-end simulation of entire beamlines

- ✓ **Modular** simulation framework
- ✓ Customise **speed vs. fidelity**
- ✓ **Multi-dimensional** parallel parameter scan
- ✓ Multi-dimensional Bayesian parameter optimisation
- ✓ Global full programme cost modelling + optimisation

A plasma-based linac or collider consists of many different beamline elements requiring specialised, often incompatible codes, limiting direct transfer of simulation outputs.

- ABEL enables **self-consistent simulation of entire beamlines** by linking a suite of specialised codes using openPMD.
- Supports specialised codes such as HiPACE++, Wake-T, ELEGANT, GUINEA-PIG, CLICopti and ImpactX.
- Object-oriented, written in Python.
- Beamline elements as Python classes with varying speed and fidelity.

Simulation and diagnostics hierarchy

- > Simulations are performed as shots.
- > Stochastic shot-to-shot effects (e.g. jitter).
- > Single shot/multi-shot/scan/optimisation.

Use case: HALF plasma linac with simplified model for transverse instability, ion motion and radiation reaction. Also self-correction in the interstages.

```

graph TD
    subgraph "Source (driver)"
        S1[Basic (HiPACE++)] --> M1[Measured 6D phase space]
        M1 --> A1[Athena]
    end
    subgraph "Source"
        S2[Basic (HiPACE++)] --> M2[Measured 6D phase space]
        M2 --> A2[Athena]
    end
    A1 --> RF[RF linac]
    subgraph RF_linac [RF linac]
        R1[Basic (energy gain)]
        R2[CLICopti]
    end
    A2 --> Stage
    subgraph Stage
        S3[Basic (energy gain)]
        S4[3D wakefields, T, stability++]
        S5[HiPACE++ (PIC)]
    end
    RF_linac --> Interstage
    Stage --> Interstage
    subgraph Interstage
        I1[Basic (debye field)]
        I2[ImpactX]
        I3[ELEGANT]
    end
    Interstage --> BCS
    subgraph BCS [BCS]
        B1[Basic (transverse)]
        B2[Transfer matrices]
        B3[Picard]
    end
    BCS --> IP
    subgraph IP [IP]
        I4[Basic (longitudinal)]
        I5[GUINEA-PIG]
        I6[ImpactX]
    end
    IP --> AnotherLinac[Another linac]
    AnotherLinac --> L[Luminosity]
    
    %% Legend
    direction LR
    L1[Increasing fidelity/complexity]
    L2[Main beam]
    L3[Drive beam]
    L4[Module Available module]
    L5[Module not yet available]
    
```

One shot, single stage diagnostic

Multi-shot, multi-step scan

One shot, entire linac

Summary

- > The modular approach of ABEL seamlessly integrates models and specialised codes through openPMD.
- > Allows for flexible simulation runs of entire machines with desired accuracy and speed.
- > Extensive simulation and diagnostic capabilities.
- > Readily adaptable to other applications, including FELs, strong-field QED experiments, and accelerator test facilities.

Multi-shot

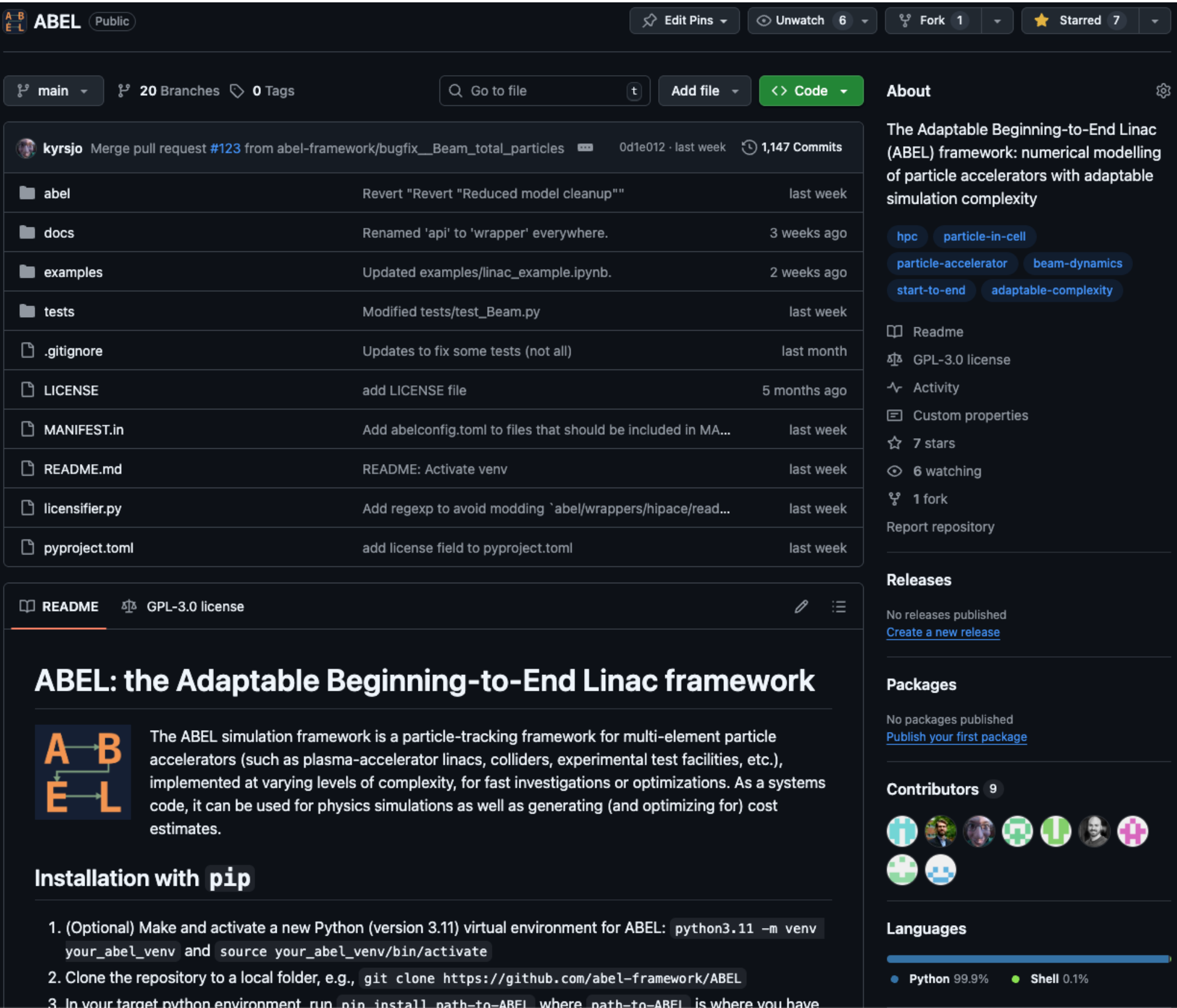
TUPS012

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Status of ABEL


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 - > Poster and demo from laptop
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 - > Erik also included results on transverse instability studies using ABEL (talk + [proceeding](#))
- > 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!

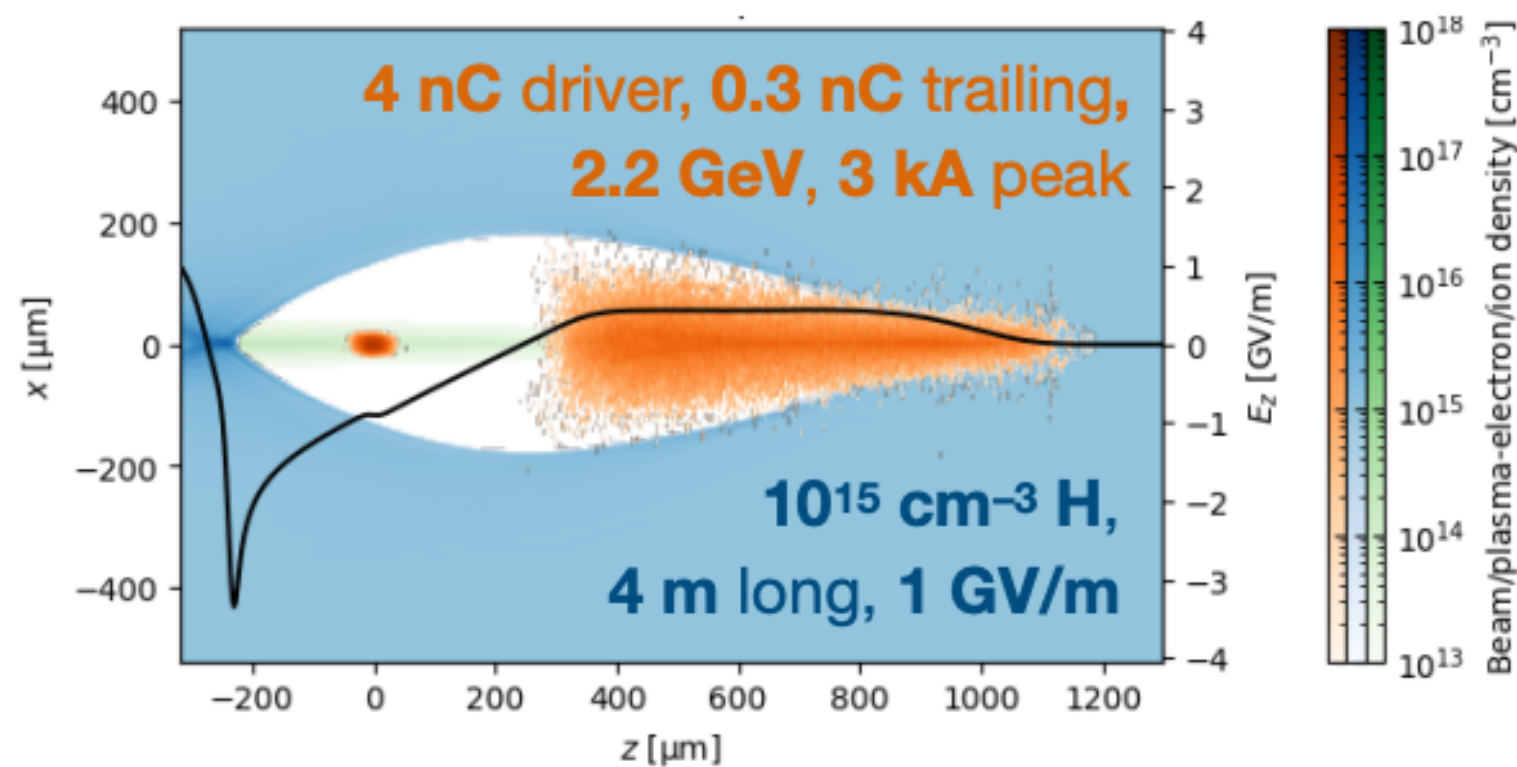


Integrated simulations on ABEL

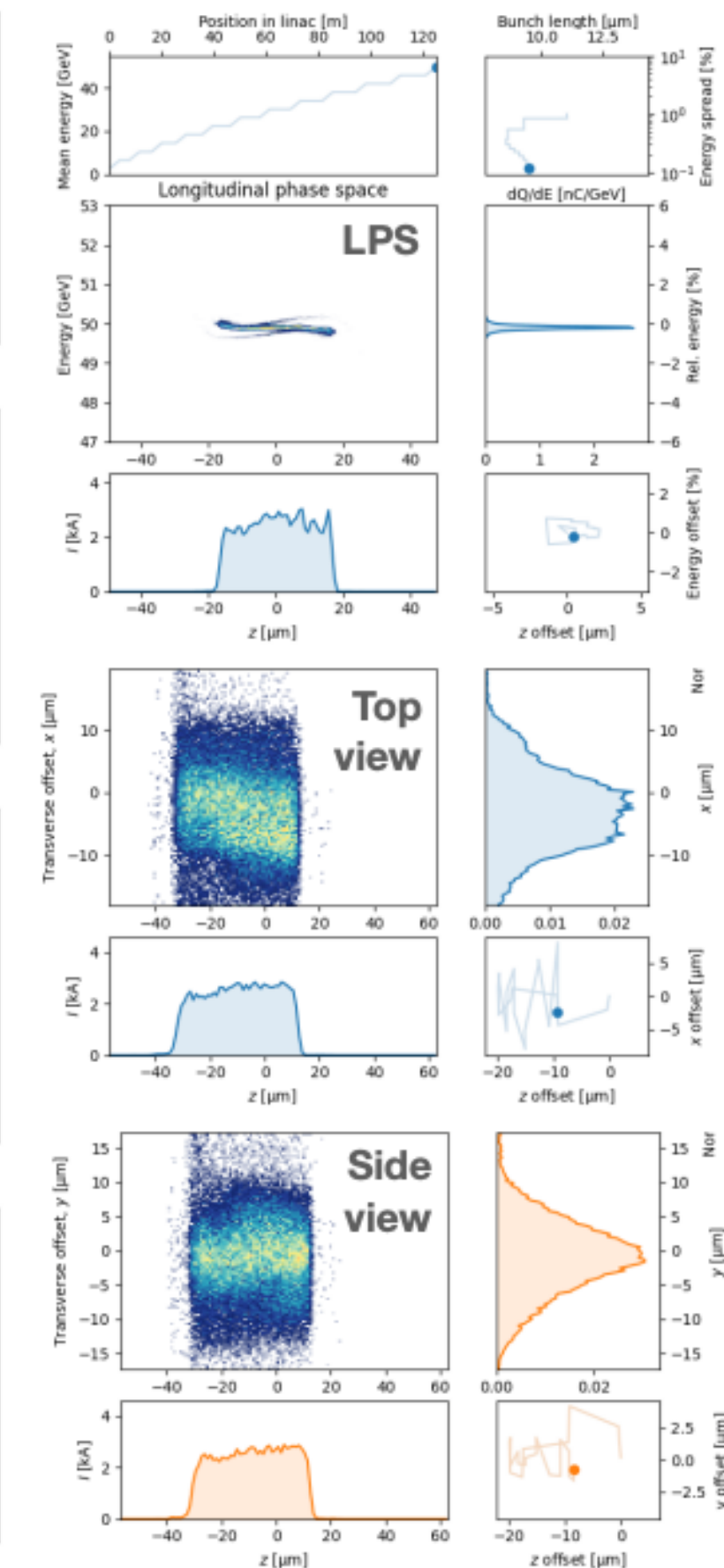
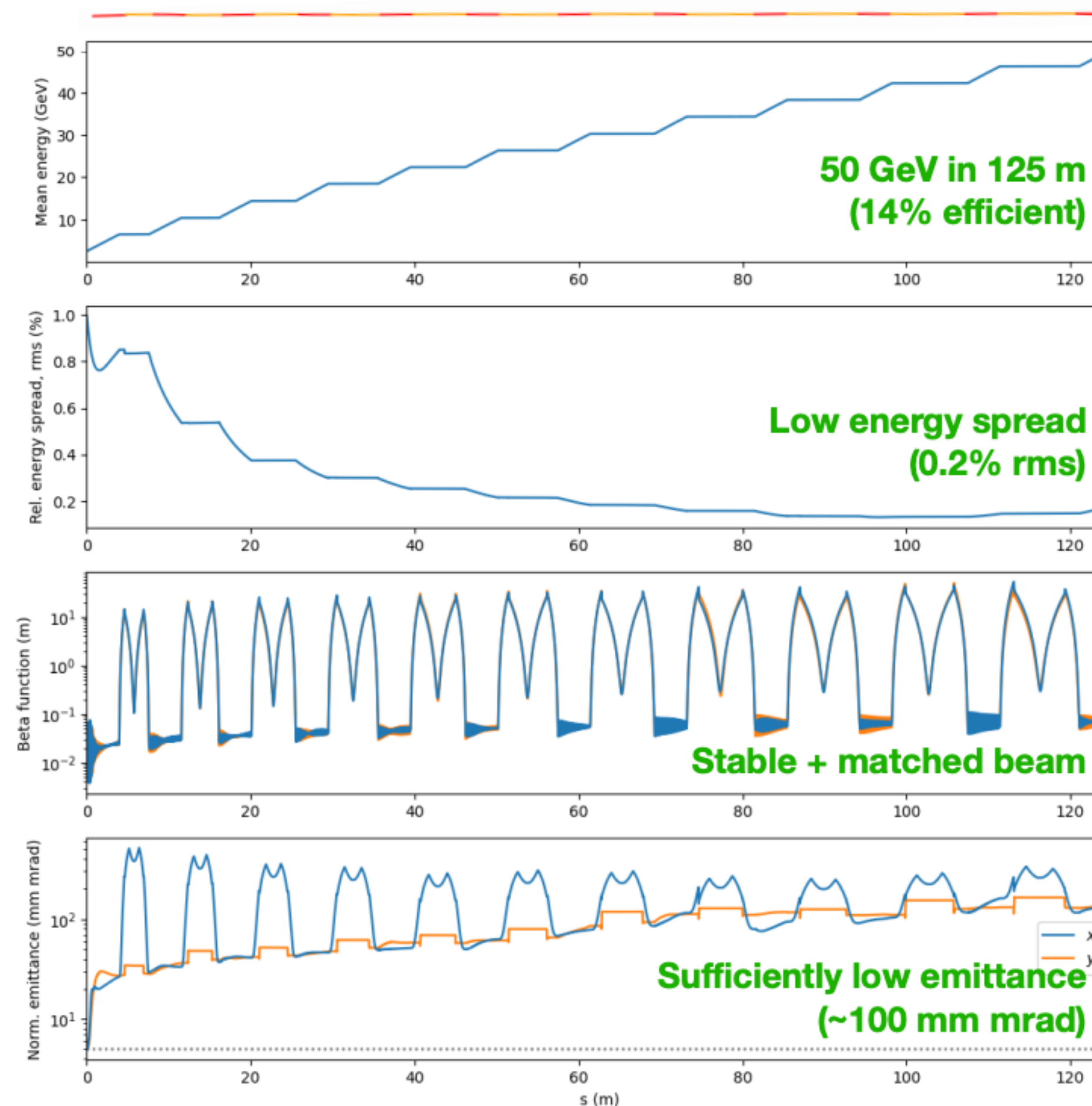
Start-to-end simulations of the SPARTA demo

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)

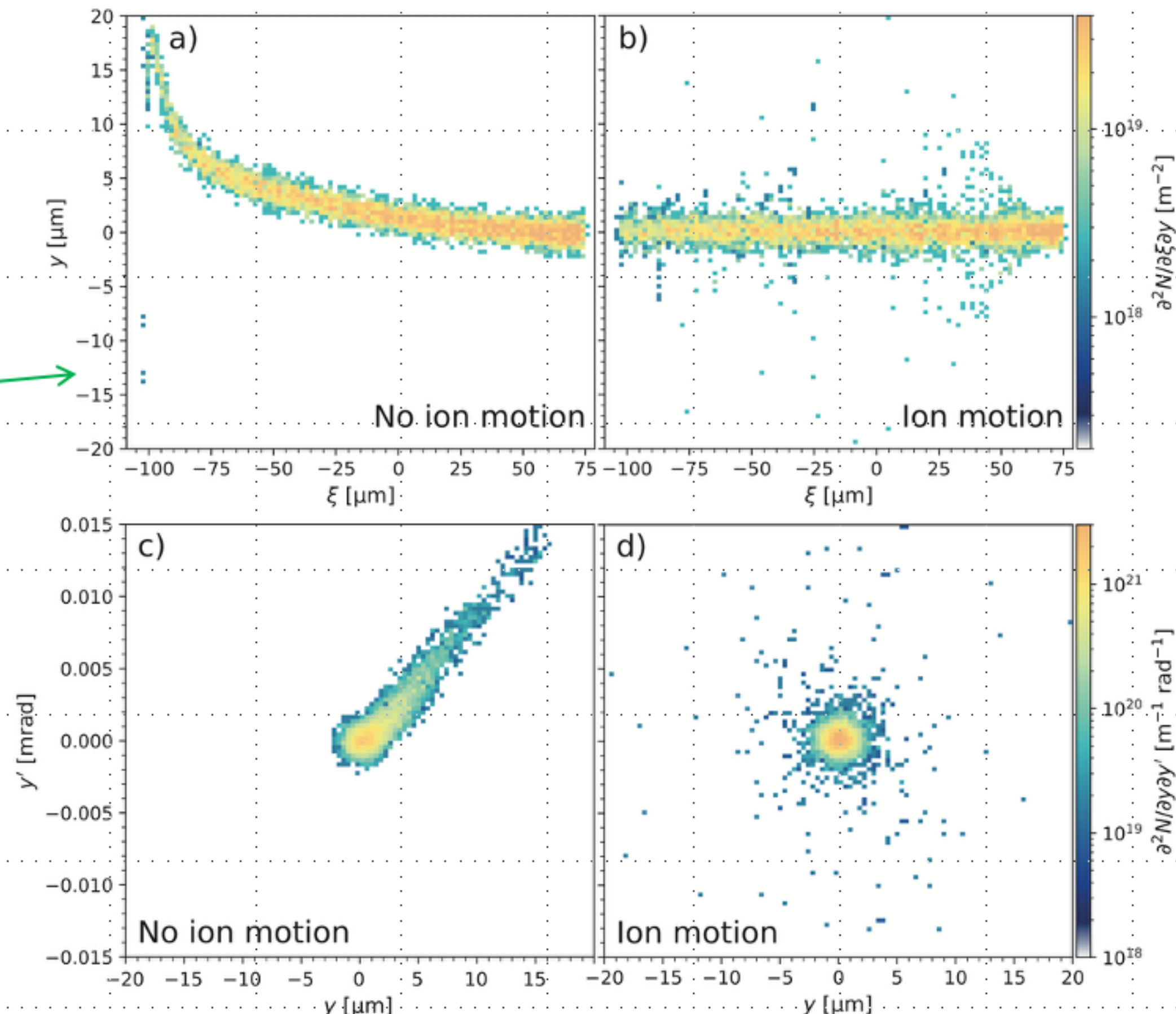
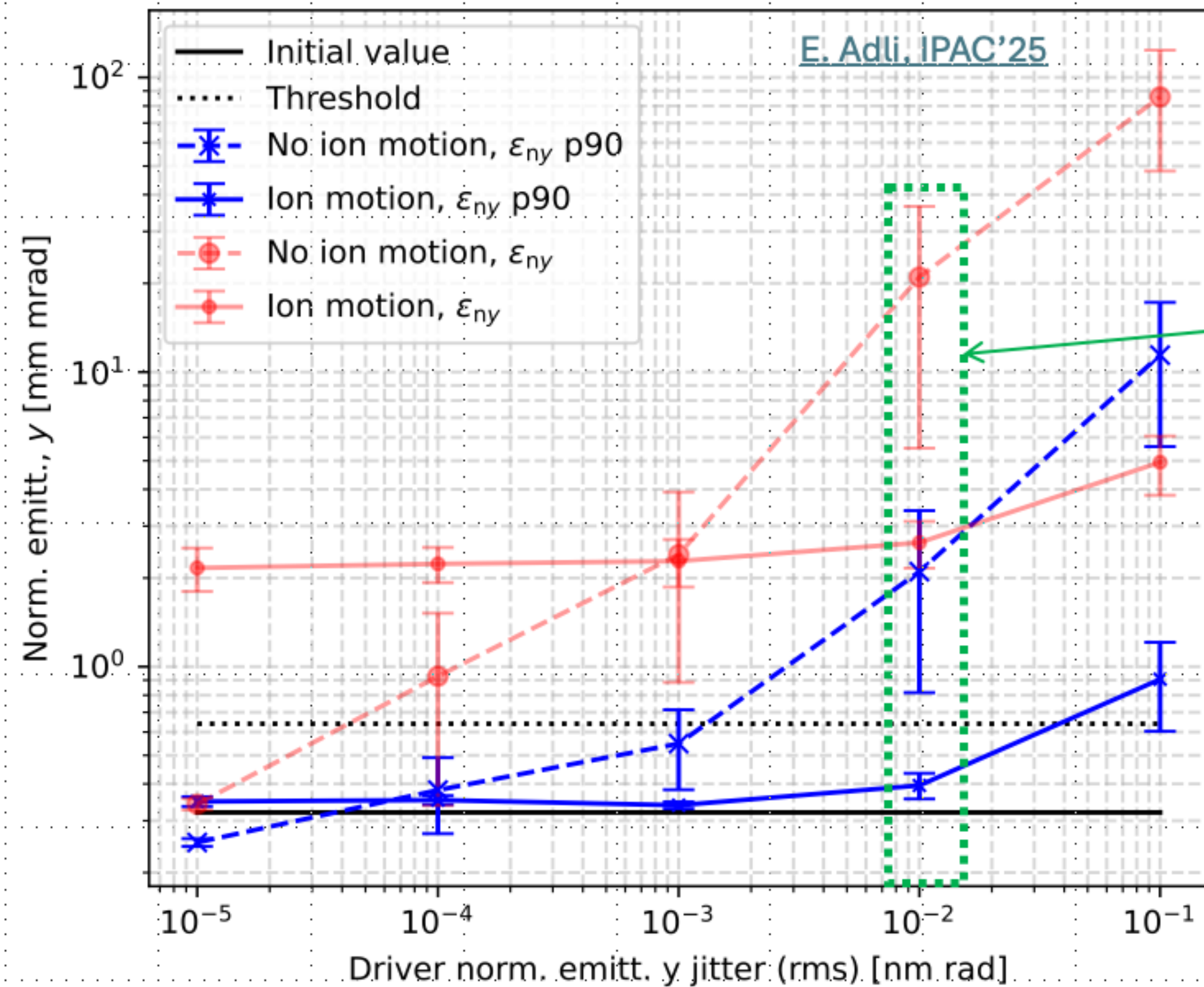


From Carl's [contributed talk](#) at EAAC.

- > 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
driver.bunch_length = 1050e-6
driver.z_offset = 1615e-6
driver.num_particles = 30000
driver.charge = 5.0e10 * -SI.e
driver.energy = 4.0e9
driver.gaussian_blur = 50e-6
driver.rel_energy_spread = 0.01
driver.emit_nx, driver.emit_ny = 50e-6, 100e-6
driver.beta_x, driver.beta_y = 0.5, 0.5
driver.jitter.x = 100e-9
driver.jitter.y = 100e-9
driver.symmetrize = True

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

##### Define the stages #####
stage = StageReducedModels()
stage.time_step_mod = 0.04
stage.nom_energy_gain = 7.8e9
stage.length_flattop = 7.8
stage.plasma_density = 6.0e+20
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
stage.ion_mass = 6.646477e-27
stage.upramp = PlasmaRamp()
stage.downramp = PlasmaRamp()

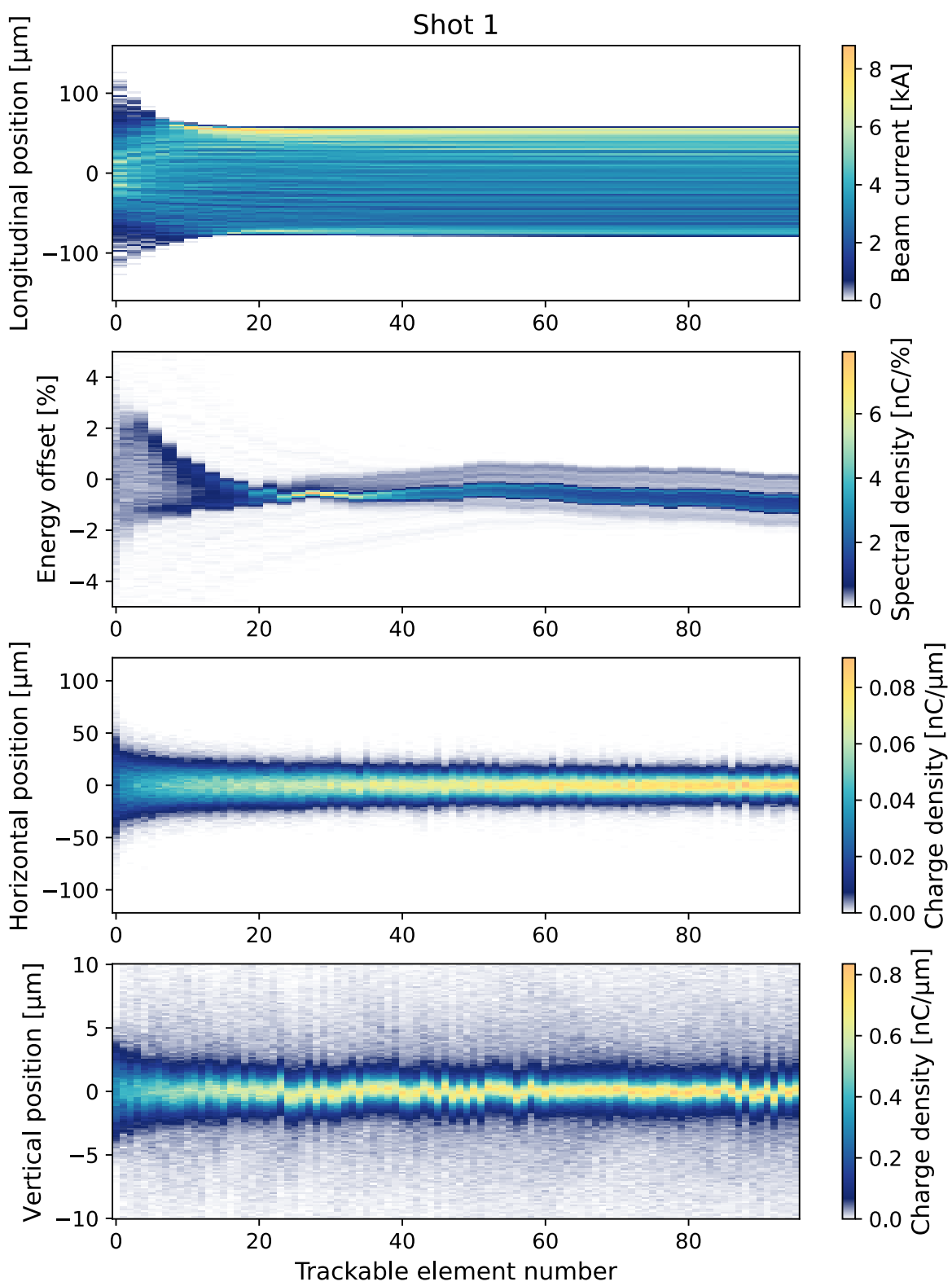
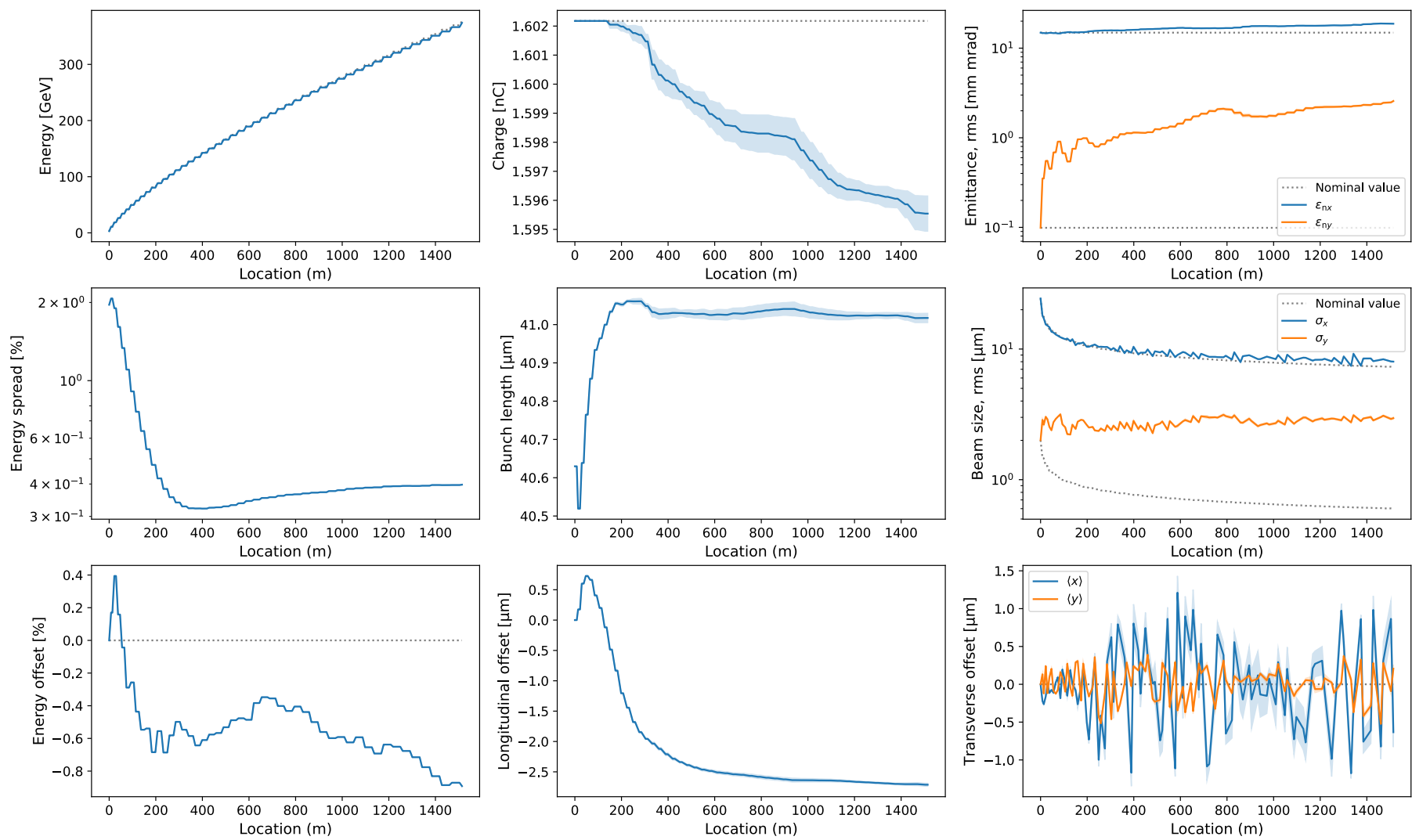
##### Define interstages #####
interstage = InterstageElegant()
interstage.beta0 = lambda energy: stage.matched_beta_function(energy)
interstage.length_dipole = lambda energy: 1.0 * np.sqrt(energy/10e9)
interstage.field_dipole = lambda energy: np.min([0.52, 40e9/energy])

##### 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?

Acknowledgements

Oslo accelerator group ABEL contributors:

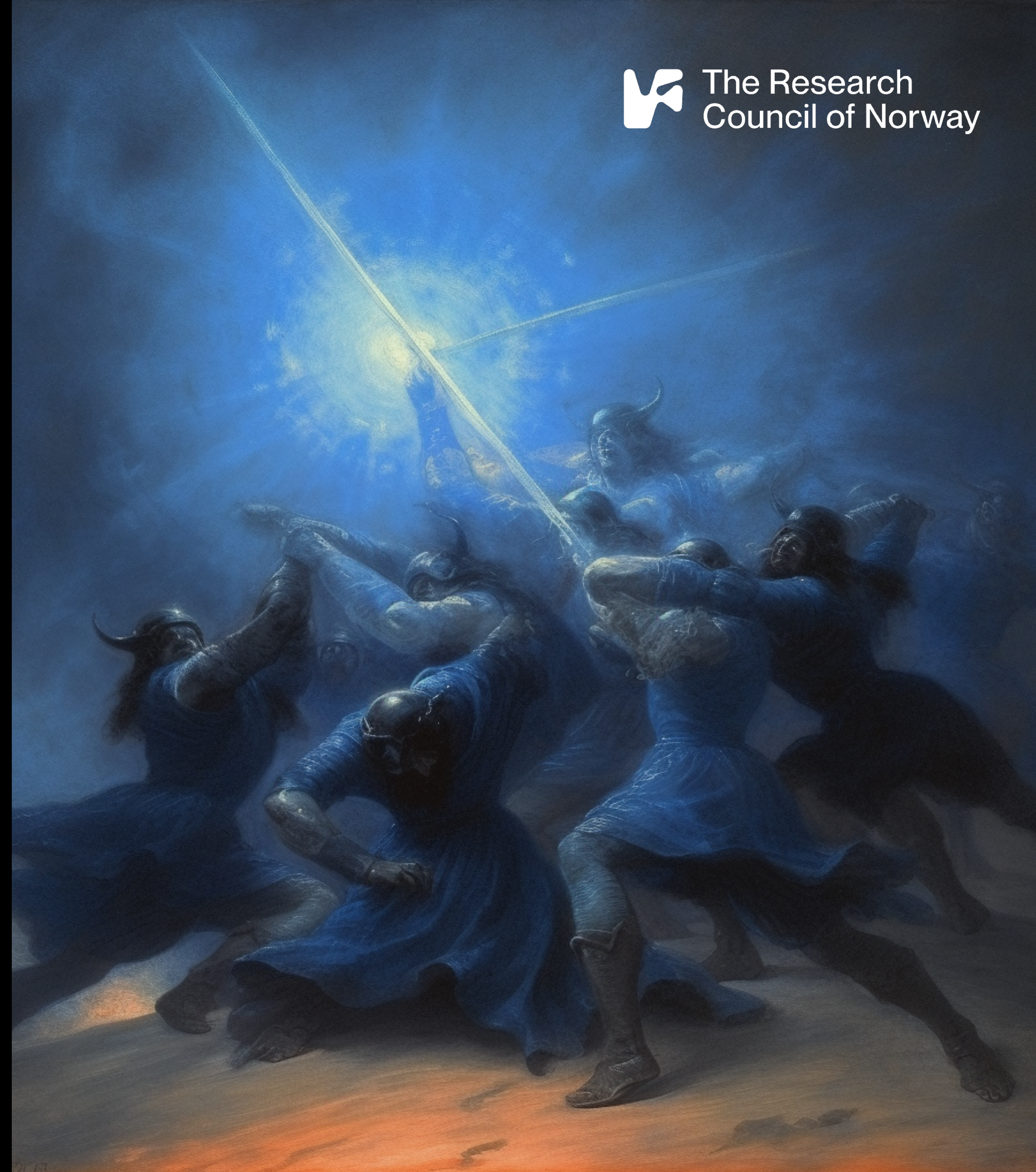
Erik Adli, Kyrre N. Sjøbæk, Carl A. Lindstrøm,
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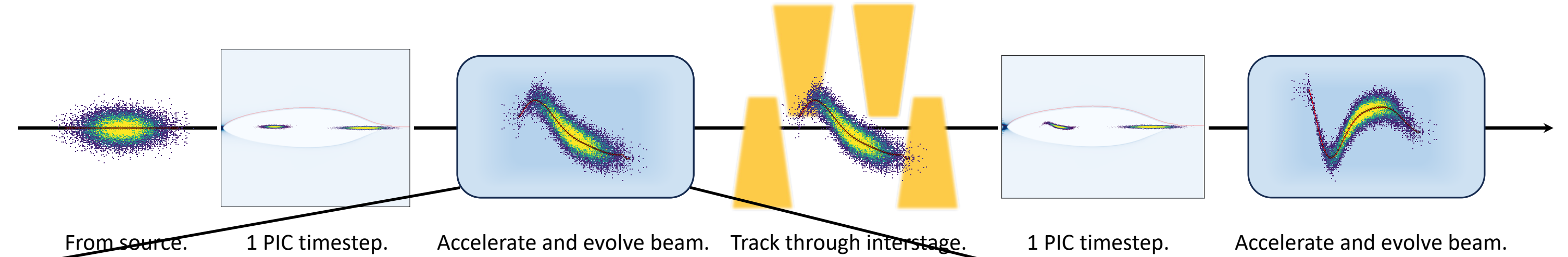
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Simplified transverse wake instability model

- > 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](#)):

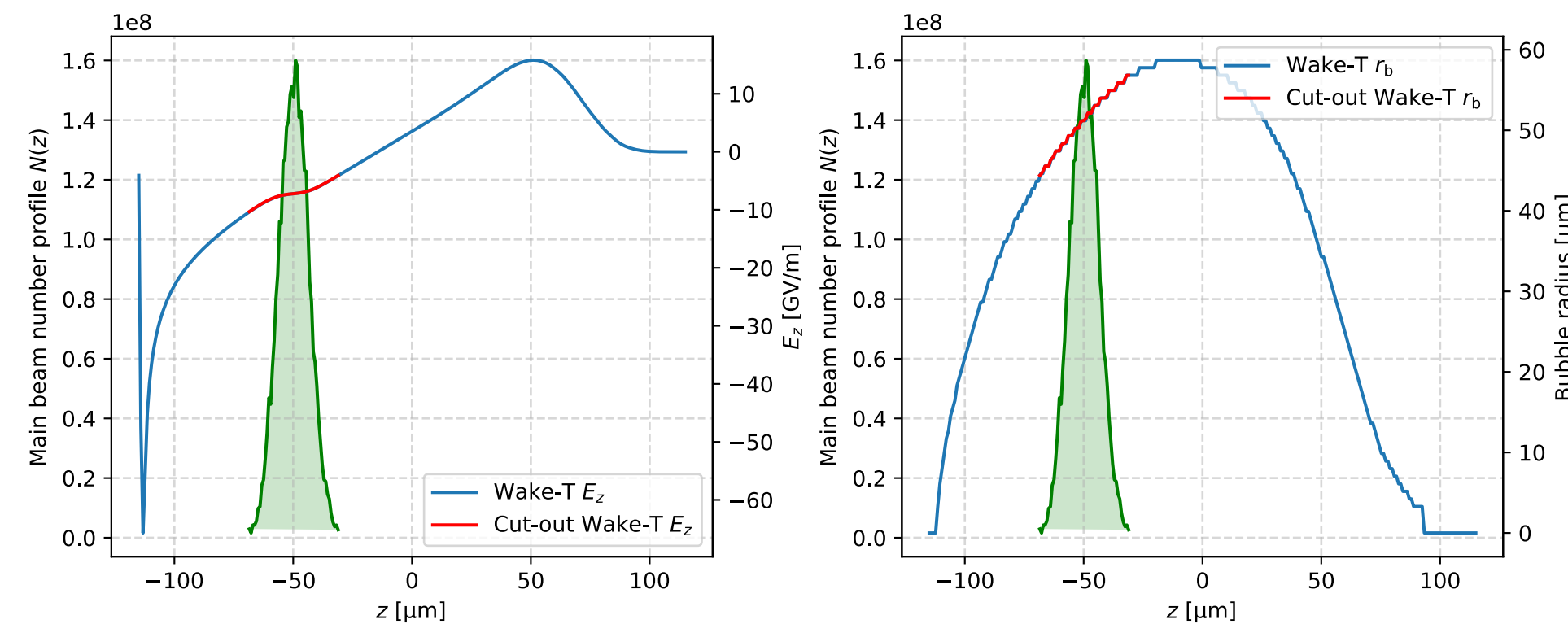
$$\mathcal{W}_x(\xi, s) = -\frac{2e}{\pi\epsilon_0} \int_{\xi_H}^{\xi} \frac{\xi' - \xi}{(r_b(\xi') + \alpha k_p^{-1})^4} \Theta(\xi' - \xi) \lambda(\xi', s) x(\xi', s) d\xi'$$

- > Combine with [Deng et al.](#) equations for radiation reaction:

$$\frac{1}{c} \frac{du_x}{dt} \approx -\frac{1}{2} k_p^2 x - \frac{e}{m_e c^2} \mathcal{W}_x - \frac{1}{2} k_p^2 c \tau_R u_x \left(1 + \frac{1}{2} k_p^2 \gamma (x^2 + y^2) \right)$$

$$\frac{1}{c} \frac{du_z}{dt} \approx k_p \frac{E_z}{E_0} - \frac{1}{4} k_p^4 c \tau_R \gamma^2 (x^2 + y^2)$$

$$\frac{dx}{dt} \approx \frac{u_x}{\gamma c}$$



Need initial $E_z(\xi)$ and $r_b(\xi)$ 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.
 $\mathbf{u}(\xi, s) = \mathbf{p}/m_e c$: normalised e^- momentum.
 $\tau_R = 2r_e/3c$
 $E_0 = m_e c \omega_p / e$: 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 $k_p \mathbf{r}/2$ so that (moderate non-relativistic ion motion)

$$\frac{\mathcal{W}_\perp(\mathbf{r}, \zeta)}{E_0} = \frac{k_p}{2} \mathbf{r} + Z_i \frac{m_e}{M_i} k_p^2 \int_{\zeta}^0 (\zeta - \zeta') \frac{\mathbf{E}_\perp(\mathbf{r}, \zeta')}{E_0} d\zeta' = \frac{k_p}{2} \mathbf{r} + \delta \mathcal{W}_\perp.$$

> 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 $\sim \delta \mathcal{W}_{x,y}$.

