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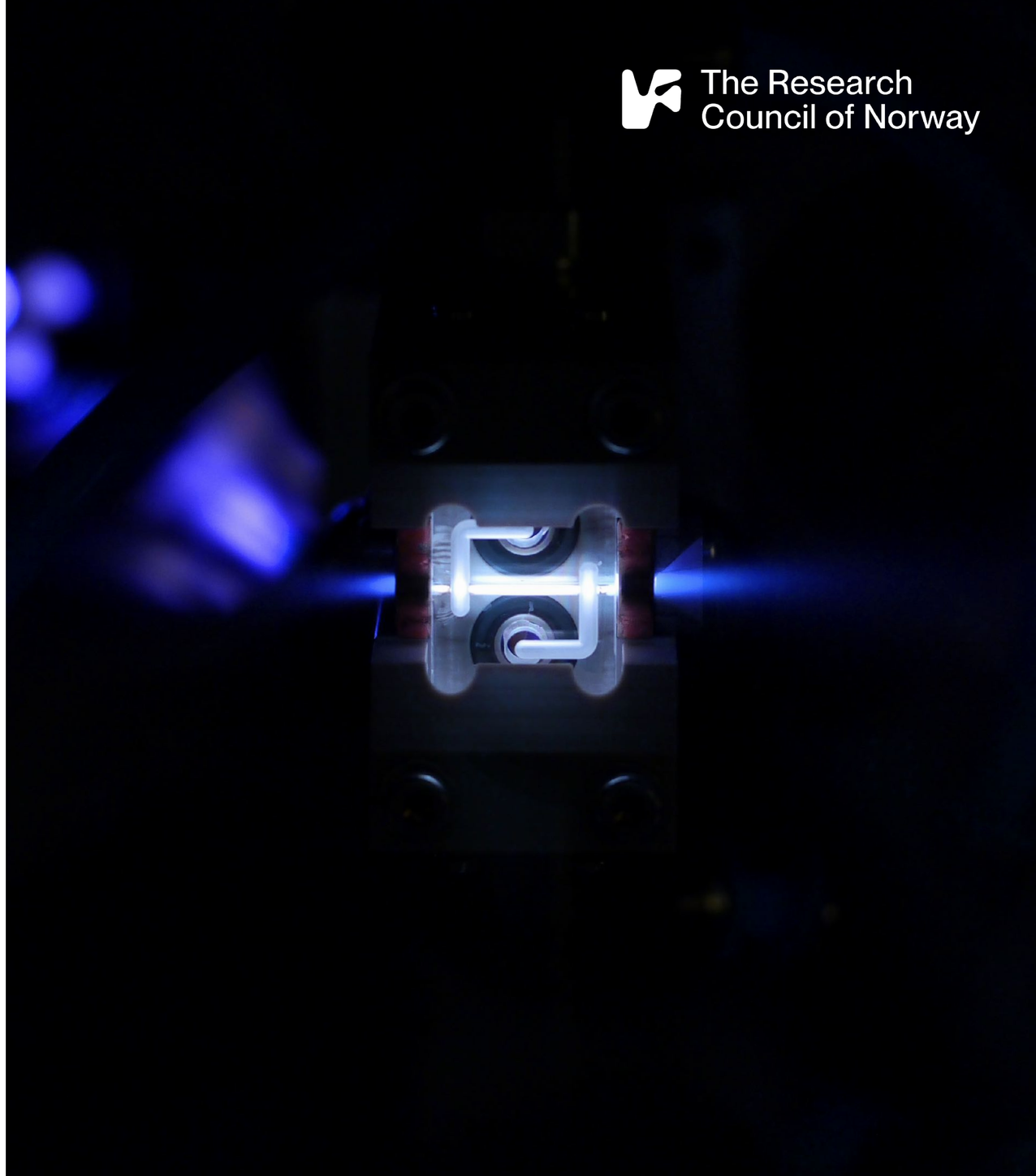

Progress on driver guiding and betatron phase advance matching

HALHF Monthly Meeting

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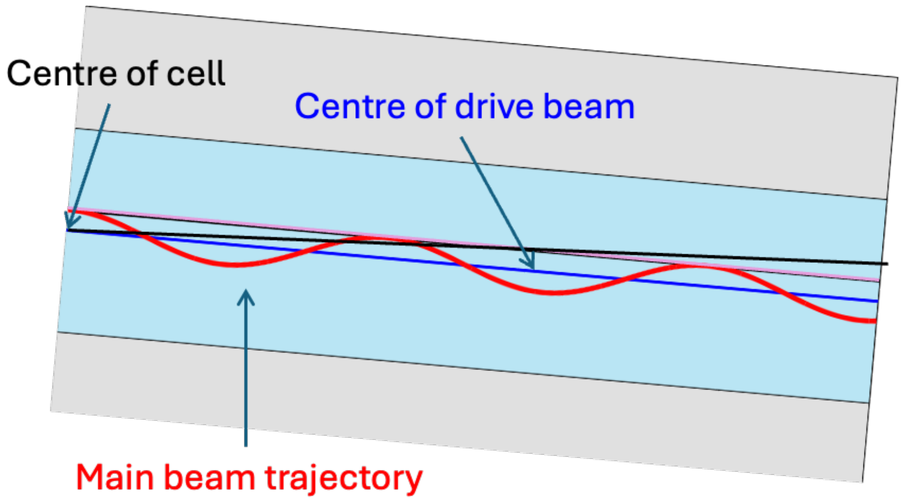
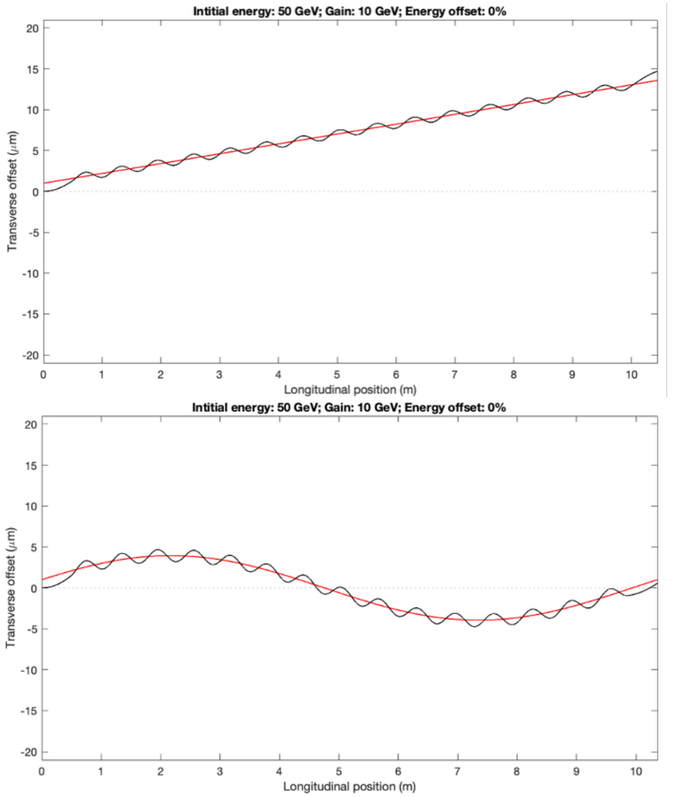
10 December 2025

Why driver guiding?



- Propagation axis in plasma channel defined by driver propagation
  - Driver with initial angular offset will trace out a tilted trajectory.
  - Main beam oscillates around this trajectory.
  - Main beam may exit the stage at a large transverse offset.
- Use driver guiding to correct the trajectory
  - Apply an external azimuthal magnetic field $\mathbf{B}_{\text{ext}} = gy\hat{\mathbf{x}} - gx\hat{\mathbf{y}}$ to give $n_{1/2}$ half oscillation in driver offset.
  - $$g = \frac{p_0}{q}\left(\frac{n_{1/2}\pi}{L}\right)^2$$
  - $n_{1/2} = 1$ seems to work best (smaller gradient)

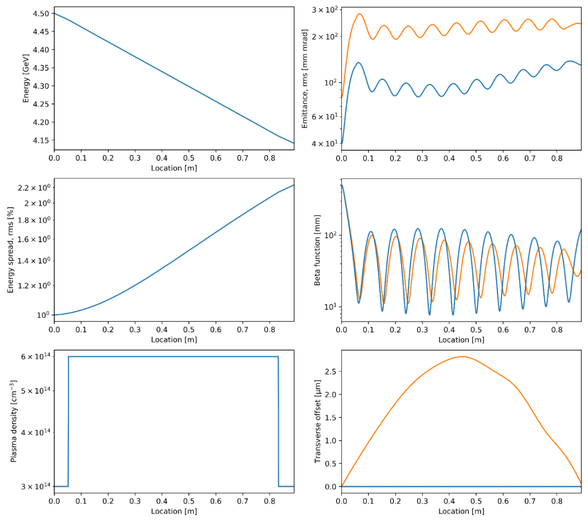


C. A. Lindstrøm

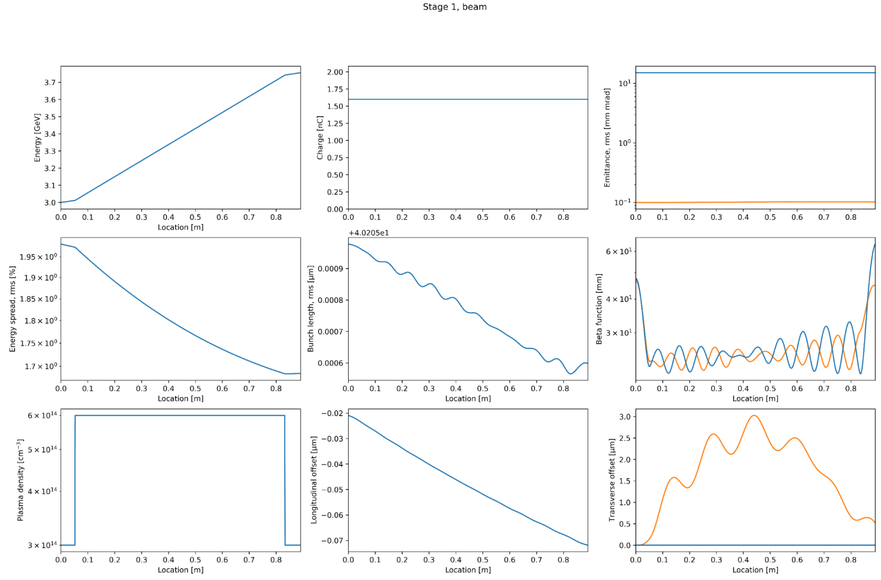
HiPACE++ simulations

Preliminary results!

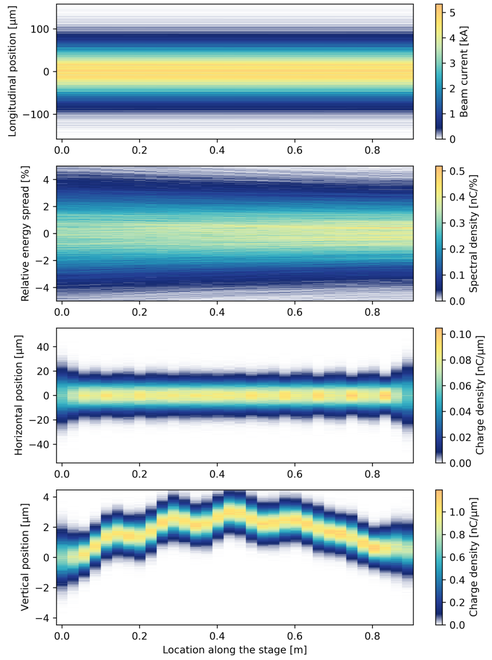
- Scan of initial driver angular offset in y [0.1, 1, 5, 10, 100] µrad
  - HALHF v2 parameters, single shortened stage
  - Uniform ramps, no ion motion
  - 10 µ rad example



Drive beam



Main beam



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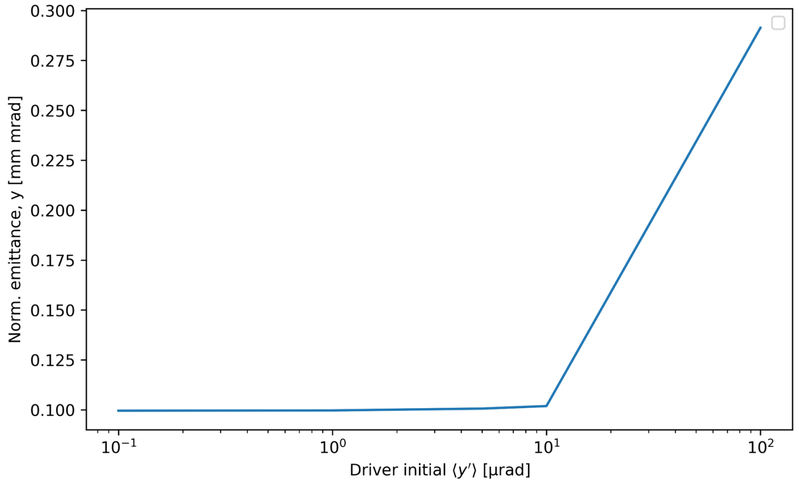
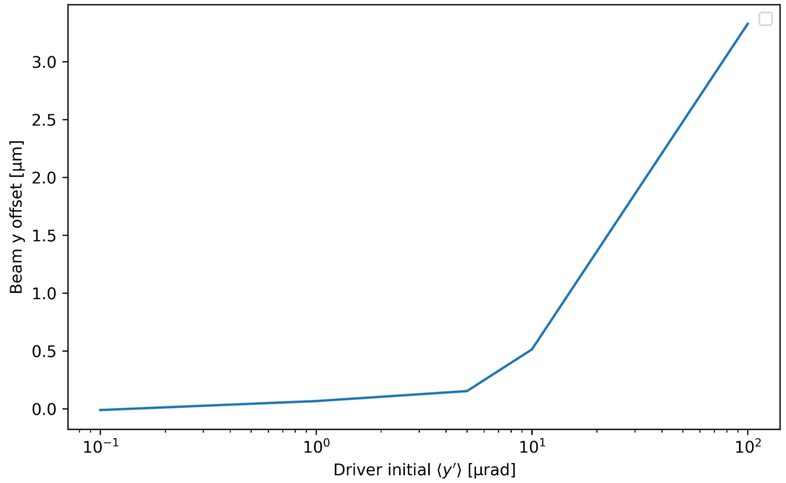
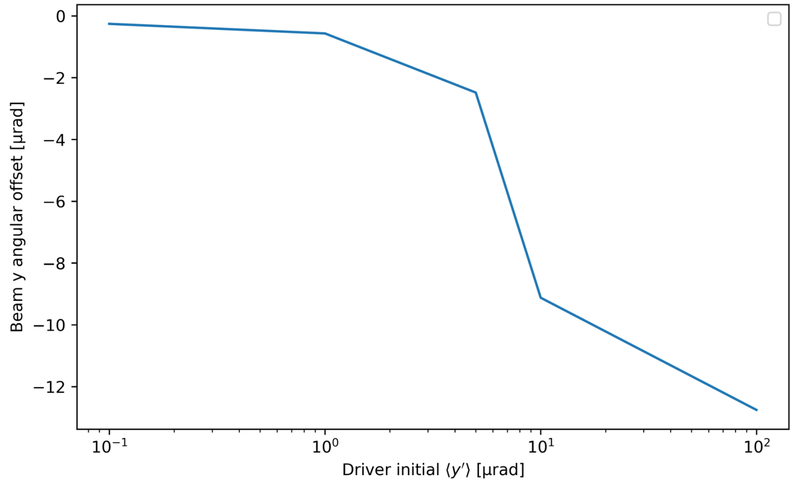






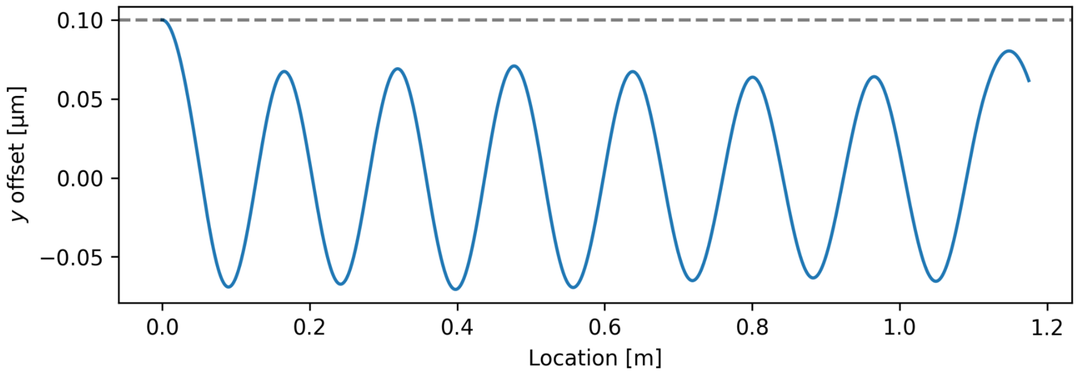
Betatron phase matching

- Adjust the length of the plasma stage such to give an integer number of main beam betatron oscillations.
  - At the end of the stage, the main beam is at the same betatron phase as it started with. I.e. same position and angular offset.
  - Can also be used to damp the buildup of transverse instability between stages?
- Can predict the length that is required and set the stage length accordingly
  - The total phase advance in the flattop plasma stage is given by

$$\mu = \int_0^L \frac{\mathrm{d}s}{\beta(s)} \approx \int_0^L \frac{\mathrm{d}s}{\beta_\mathrm{m}(s)}, \qquad \beta_\mathrm{m}(s) = \frac{\sqrt{2\gamma(s)}}{k_\mathrm{p}} = \frac{1}{k_\mathrm{p}}\sqrt{\frac{2}{mc^2}(\mathscr{E}_0 + qE_z s)}\,.$$

  - Solving the integral yields

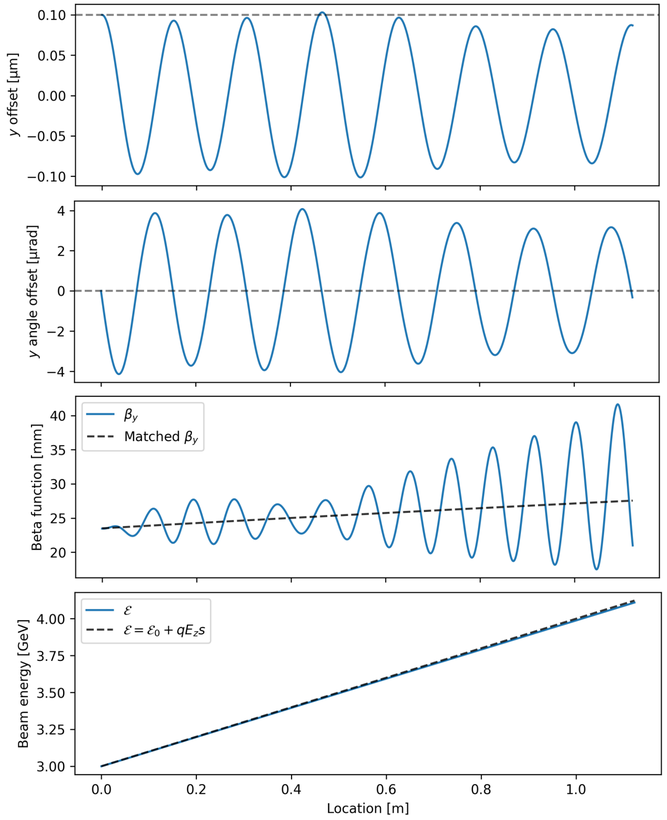
$$L = \left(\left(\frac{\eta}{2}\right)^2 qE_z + \sqrt{\mathscr{E}_0}\eta\right), \qquad \eta(\mu) = \frac{\mu}{k_\mathrm{p}}\sqrt{\frac{2}{mc^2}}\,.$$

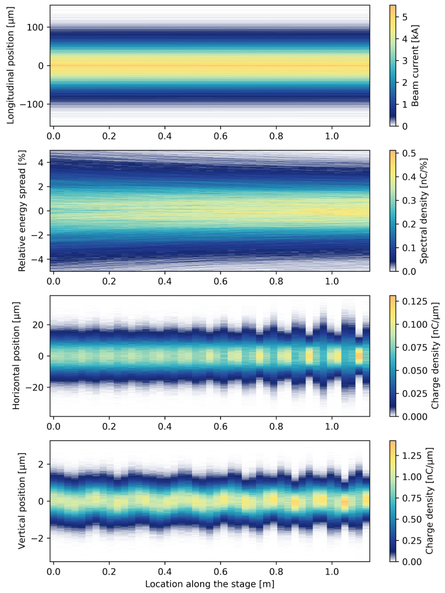


HiPACE++ simulations

HALHF v2 parameters, 100 nm main beam y offset, no ion motion

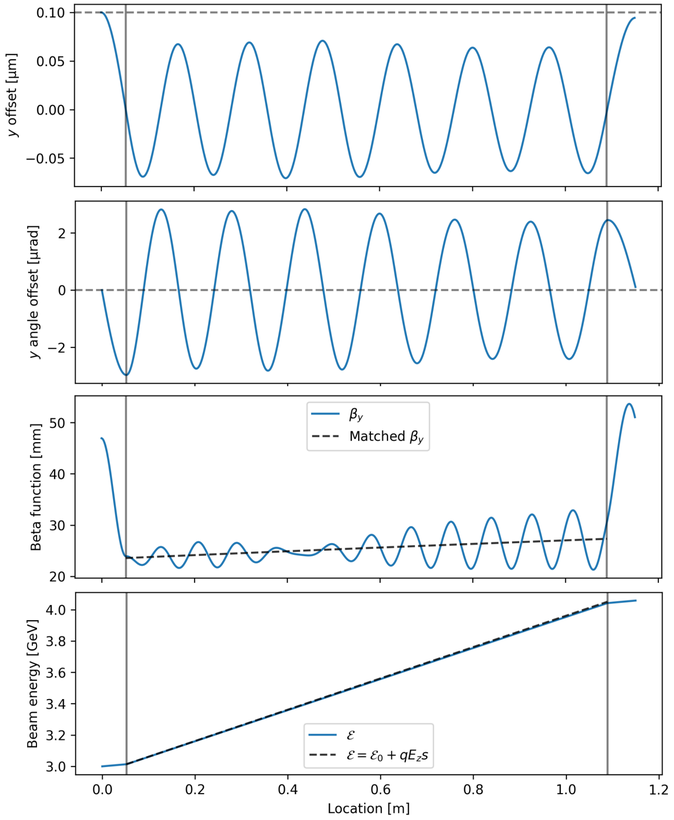
> No ramps, $n_\beta = 7$

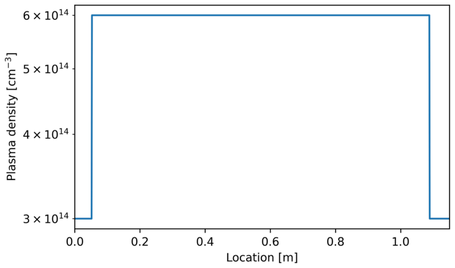




$n_\beta = \mu/(2\pi)$

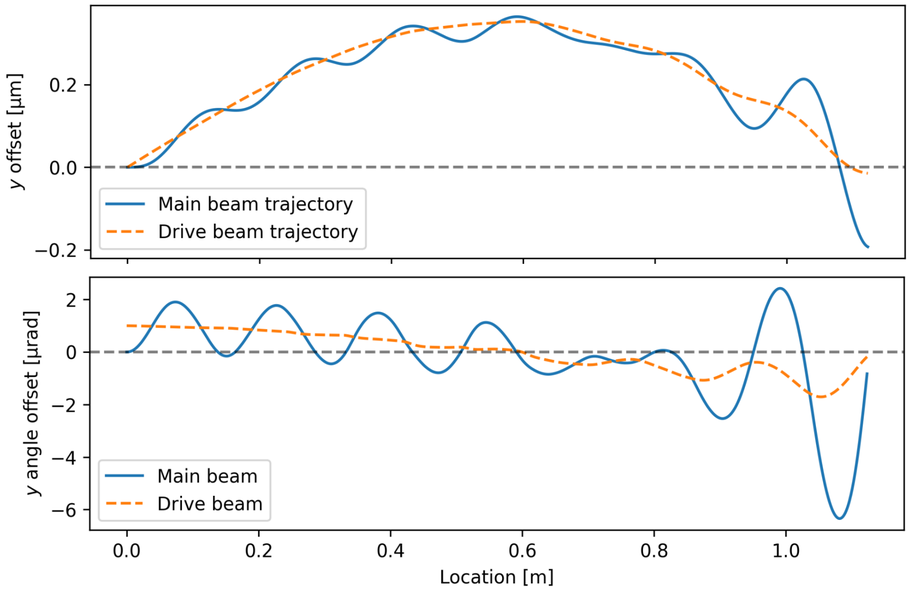
> Uniform ramps, $n_\beta = 7$

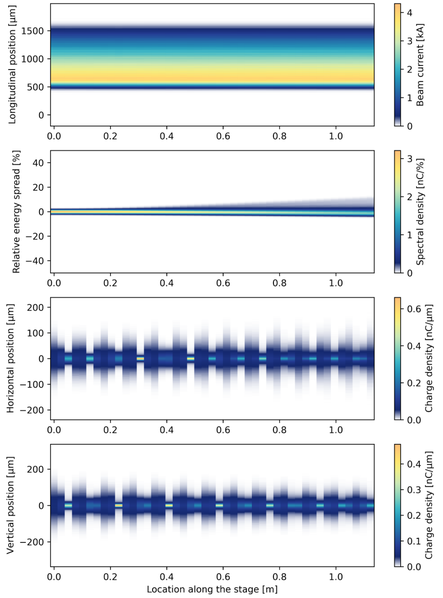




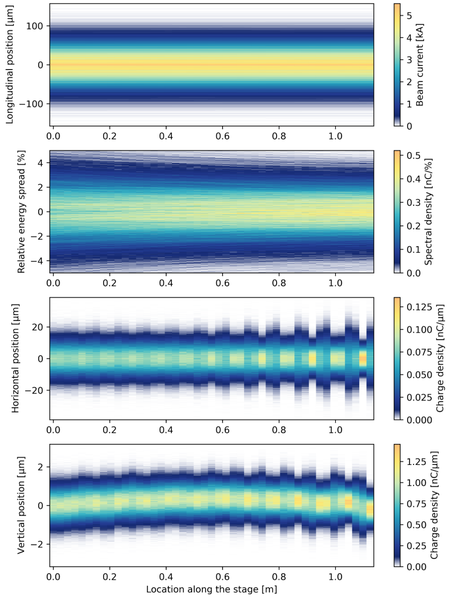
Combine driver guiding and betatron phase matching

- No ramps, no ion motion, attempt to match stage length to give $n_\beta = 7$
- Too much fluctuation in the drive beam beta function for a short stage to give a well-defined trajectory?





Drive beam



Main beam

Summary

- Driver guiding and betatron phase matching are promising for mitigating transverse instabilities.
  - Require better understanding for and conduct tolerance studies.
  - Betatron phase matching should have better tolerance at high energies due to longer betatron wavelength.
  - Timing jitter may affect the betatron phase matching, as the stage length calculations assume nominal acceleration gradient.
  - Driver energy depletion may cause issues.