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AWAKE PEB Meeting, CERN

Warp Simulation Results for AWAKE Studies

- Plasma density ramp simulation
- SSM simulation for CPU estimation
- Beam-loading studies

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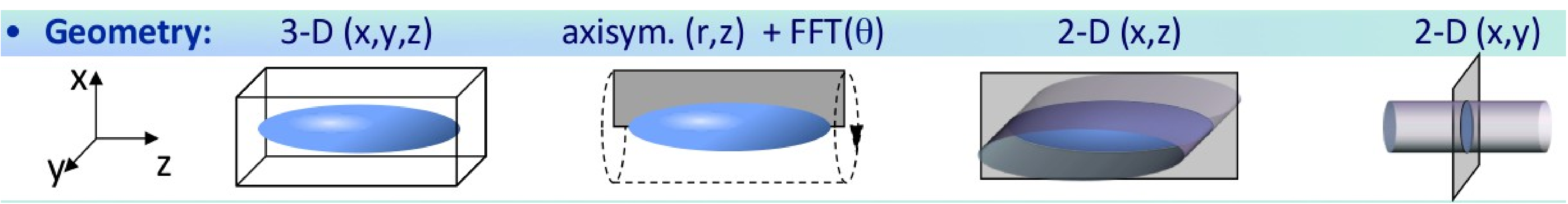
In This Talk ...

- **Warp @ CERN**
  - CERN cluster services
  - Benchmarking test
- **Simulation Projects by Warp**
  - Electron acceleration in the wakefield of a multimicrobunch proton driver
  - SSM simulation for Warp CPU estimation
  - Beam-loading studies
- **Conclusion**

About WARP

- A fully relativistic electromagnetic PIC code,
- Fully parallel,
- Good for simulation of plasma-based accelerators,
- Mainly developed at LBNL and LLNL,
- Open source [http://warp.lbl.gov/],
- Includes many physical models.



CERN Clusters for Warp

HTCondor Batch Service

- CERN main cluster with 190k CPU cores,
- Warp parallel version installed,
- Not good for MPI code,
- Maximum 8 cores to run the code.

HPC Cluster

- Small cluster granted to special groups including AWAKE
- Dedicated for users of MPI applications,
- About ~2800 CPUs are available,
- Warp parallel version installed,
- Warp jobs are run on HPC.

Benchmarking Test

Contents lists available at ScienceDirect

Nuclear Inst. and Methods in Physics Research, A

journal homepage: www.elsevier.com/locate/nima

AWAKE-related benchmarking tests for simulation codes

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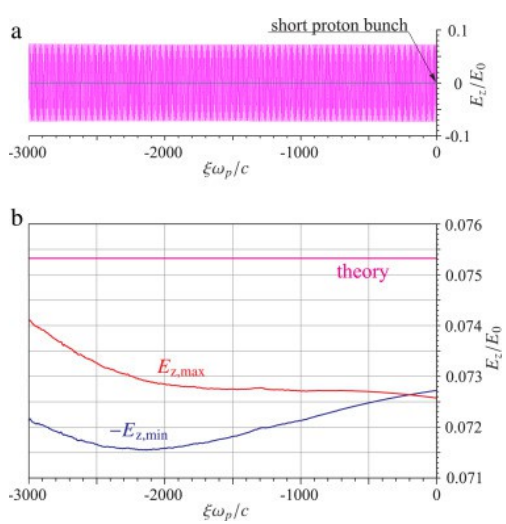
ABSTRACT

Two tests are described that were developed for benchmarking and comparison of numerical codes in the context of the AWAKE experiment.



2. Test 1: Long term behavior of a small-amplitude plasma wave

Here we follow the long term evolution of a small amplitude plasma wave generated by a short proton bunch. This test shows quality of plasma and field solvers and also helps to determine the required run resolution and number of plasma macro-particles. A small perturbation that seeds beam self-modulation in AWAKE must maintain a constant amplitude over hundreds of wave periods. The wave period must be simulated correctly to a fraction of percent, as the wave phase at the witness location would be wrong otherwise [34]. Consequently, we focus at conservation of the wave amplitude and at the wave period.

The proton beam density is

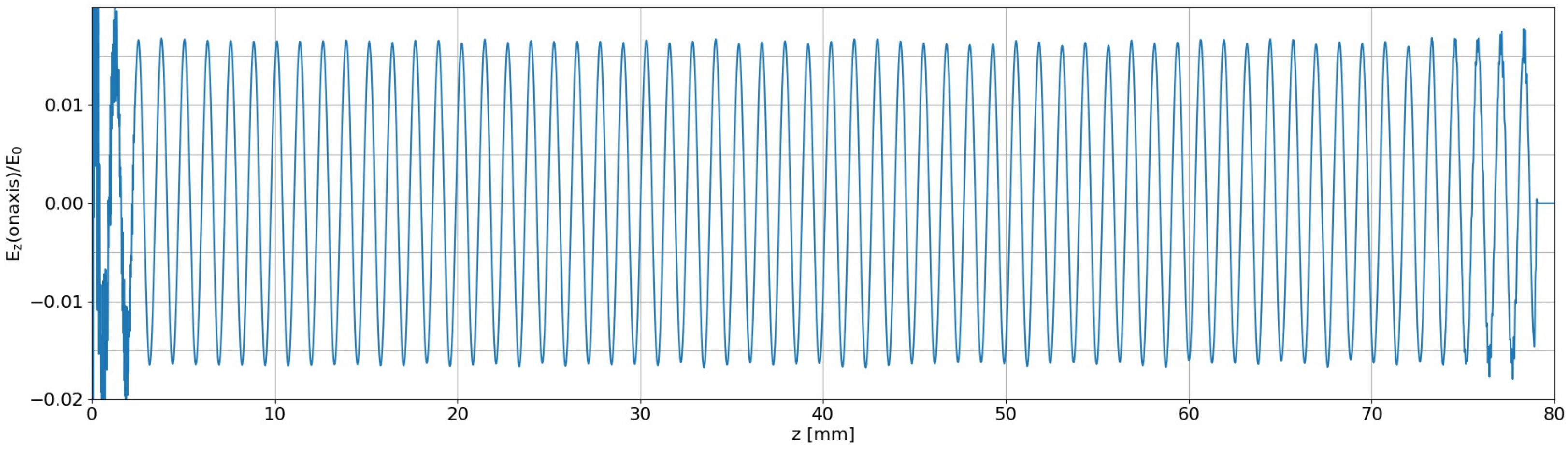
$$n_b = \begin{cases} 0.5\, n_{b0}\, e^{-r^2/2\sigma_r^2} \left[1 + \cos\left(\sqrt{\frac{\pi}{2}} \frac{\xi}{\sigma_z} \right) \right], & |\xi| < \sigma_z \sqrt{2\pi}, \\ 0, & \text{otherwise}, \end{cases} \quad (1)$$

where we use cylindrical coordinates (r, ϕ, z) and the co-moving coordinate $\xi = z - ct$; the z-axis is the direction of beam propagation. The beam parameters are

$$\sigma_r = c/\omega_p, \quad \sigma_z = c/\omega_p, \quad n_{b0} = 0.1n. \quad (2)$$

Warp Benchmarking

- Geometry: 2D cylindrical,
- Grid Size: dx=0.005 mm, dz=0.008 mm
- np = 7.e14 /cm3
- Immobile ions
- n_driver = 0.1np
- Cosine profile for driver
- sig_z=sig_r=c/w_p



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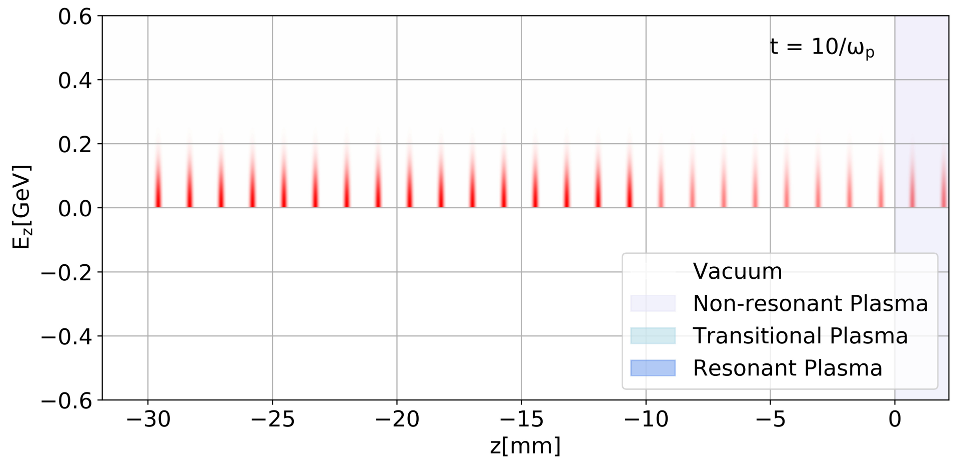
Main Idea

- We use the idea of beam loading in the following paper
  - V.K.B.Olsen, et al PRAB **21** 011301 (2018)
- Then to study
  - A multi-microbunch driver closer to the AWAKE
  - the effect of plasma density ramp,
  - Electron beam acceleration.

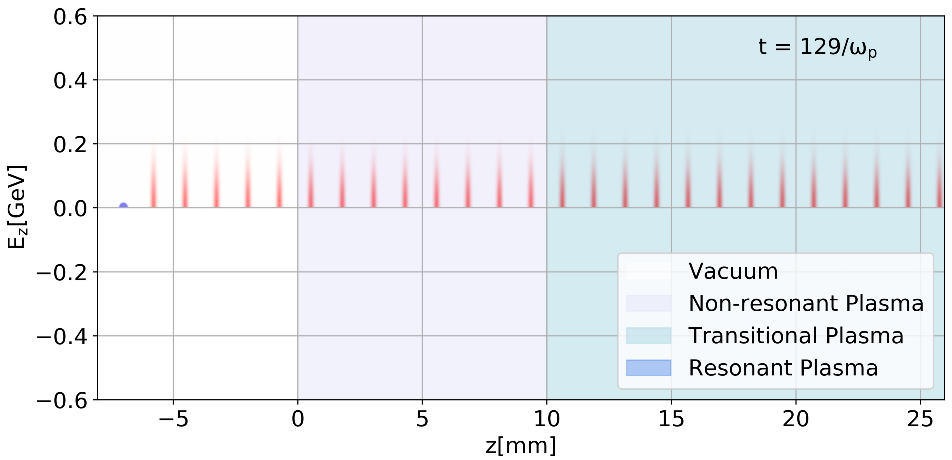
Multi-microbunch Porton Driver

- Consider 26 microbunches of protons of Gaussian profile
- Energy of 400 GeV
- Peak density: 3.087e13 /cm3
- sigr = sigz = 0.4*c/w_p = 0.08 mm
- Distance between microbunches = lambda_p = 1.26 mm



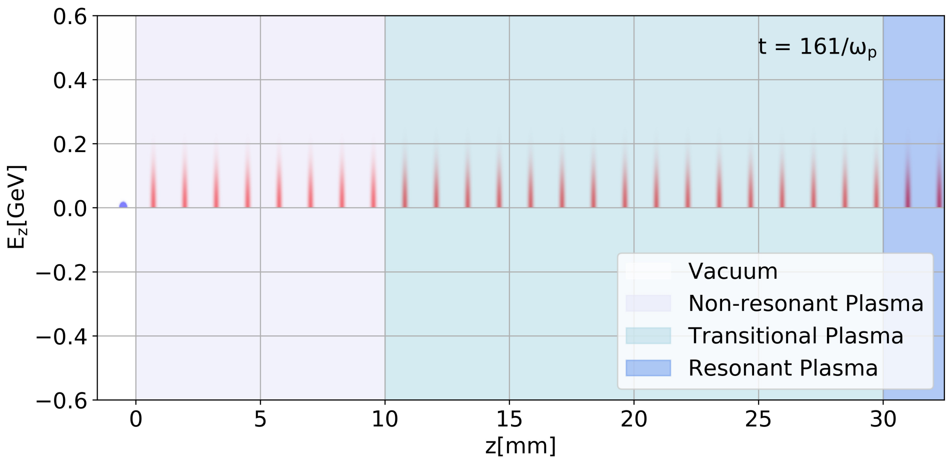
Electron Injection

- The electron beam is injected close to the plasma.
- 1.21 mm distance to the last proton micorbunch
- A Gaussian density with 100 pC charge,
- Energy of 217 MeV
- Sigz = 60 um
- Sigr = 5.25 um
- Energy spread = 0.005
- Normalized emittance = 2. mm-mrad

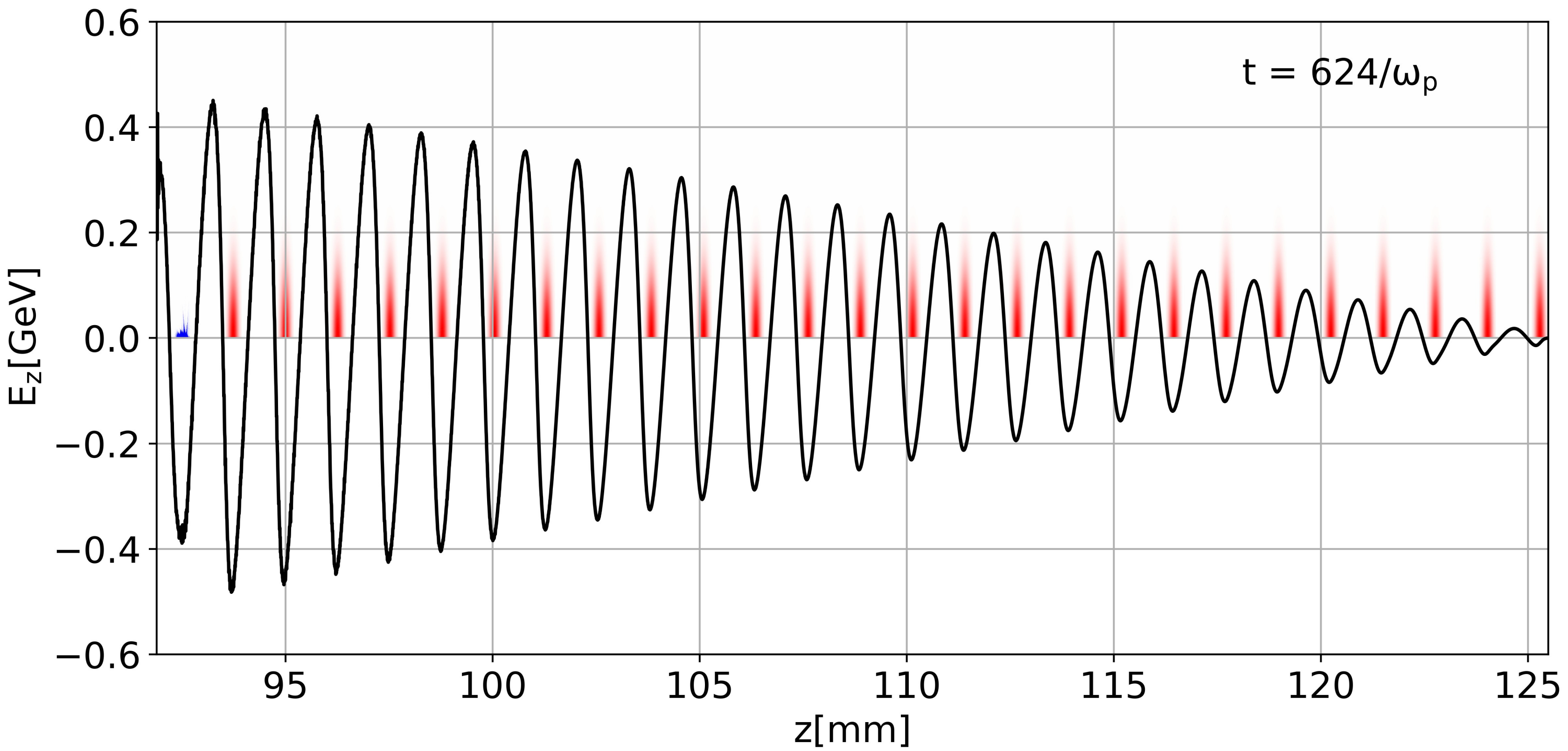


Plasma density profile

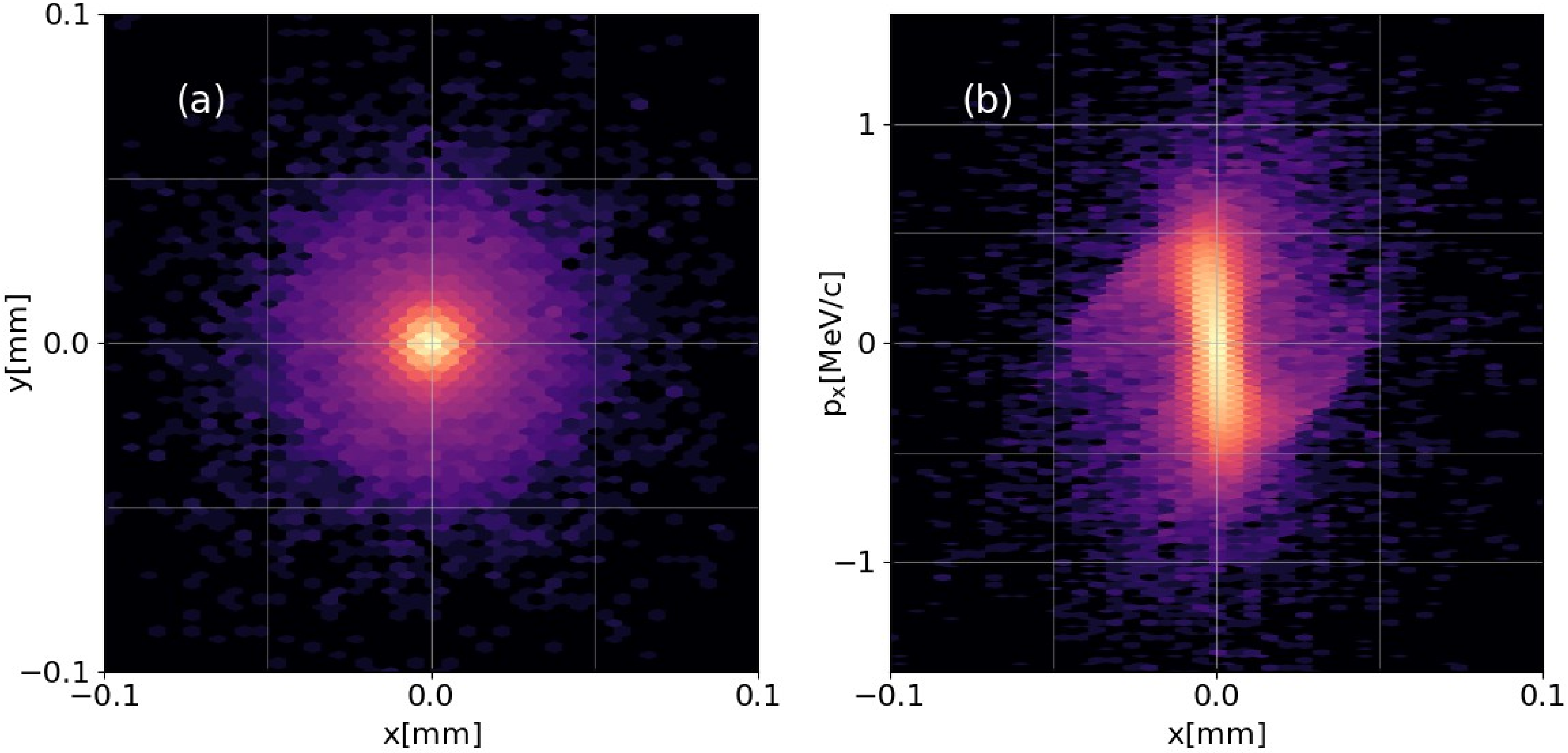
- Three regions of plasma density:
- Resonant plasma n0=7e14 /cm3
- Non-resonant plasma: 1cm long, n1=1.3n0
- Transitional plasma: cosine like profile with 2.cm long
- The rest is resonant plasma with n=n0



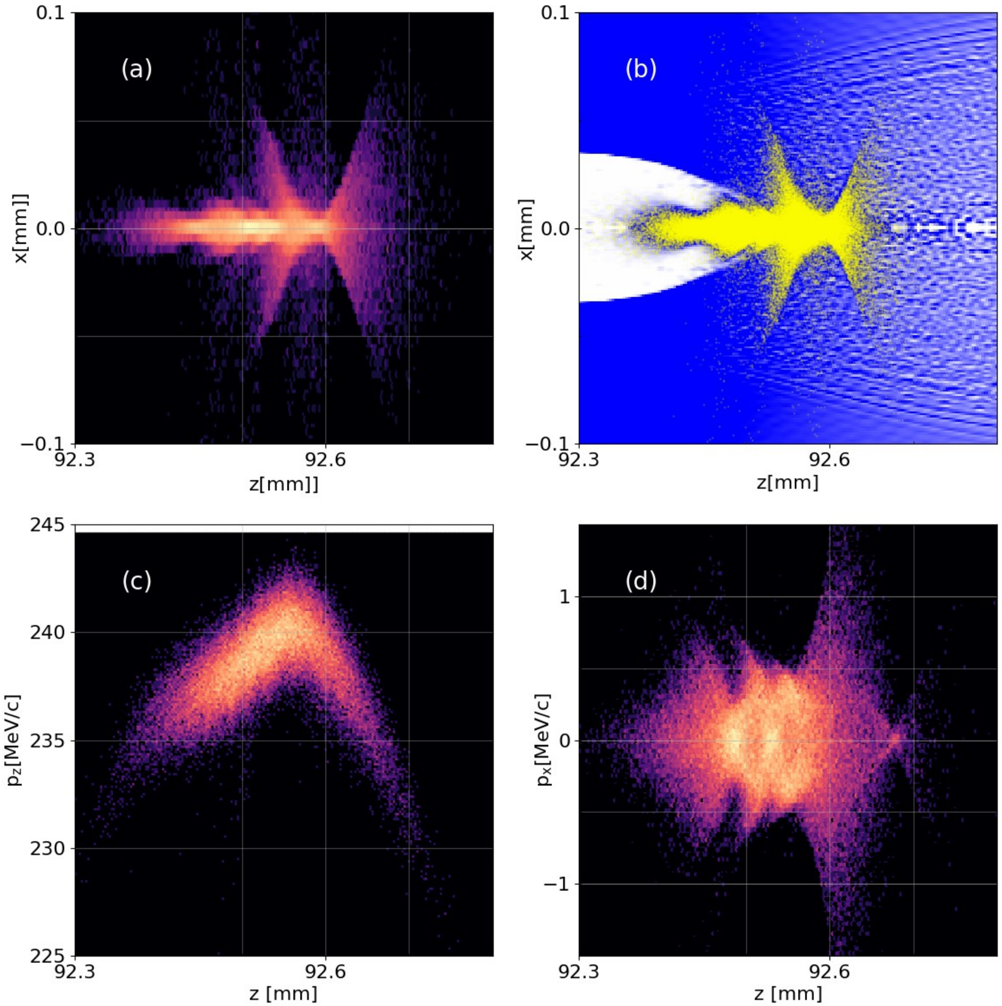
Resonant Wakefield [t=624/w_p]



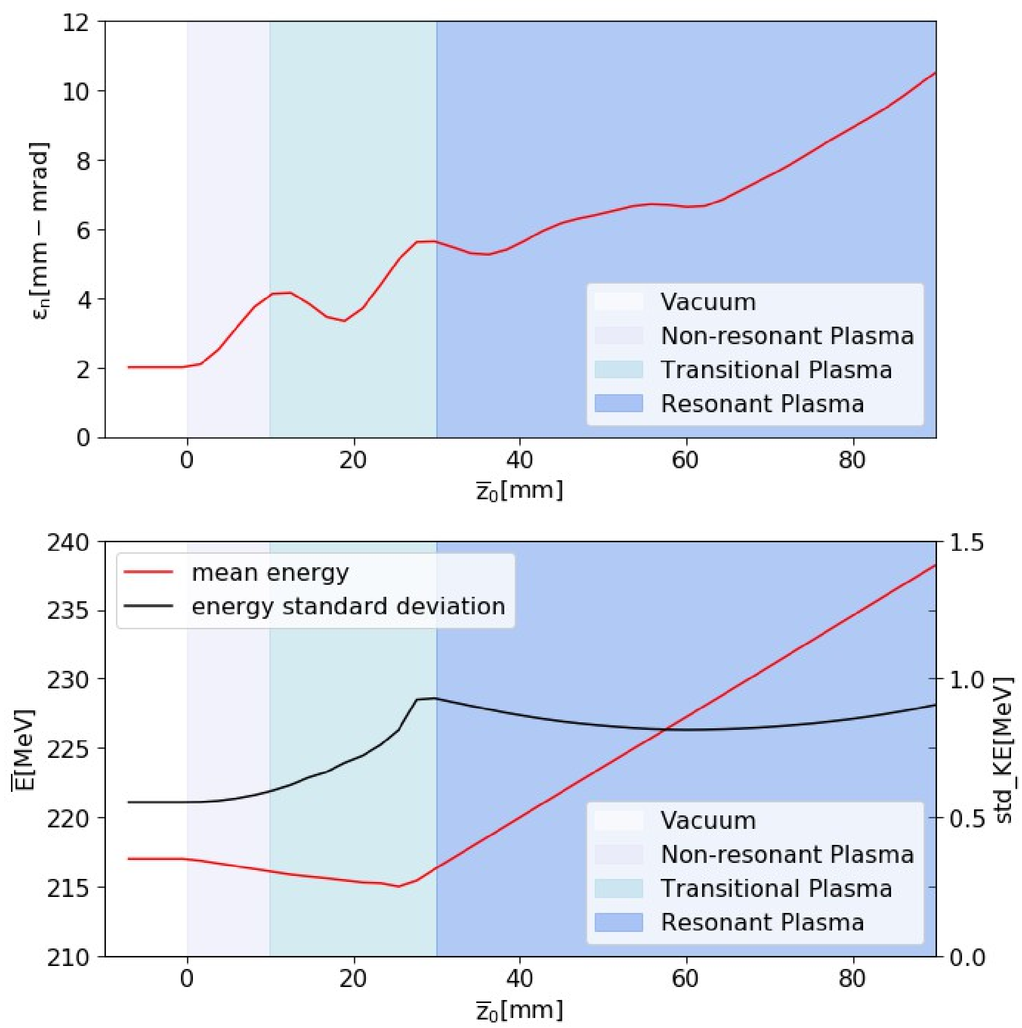
Transverse Phase-space [t=624/w_p]



Longitudinal Phase-space [t=624/w_p]



Emittance and Mean Energy



Animation of electron bunch evolution

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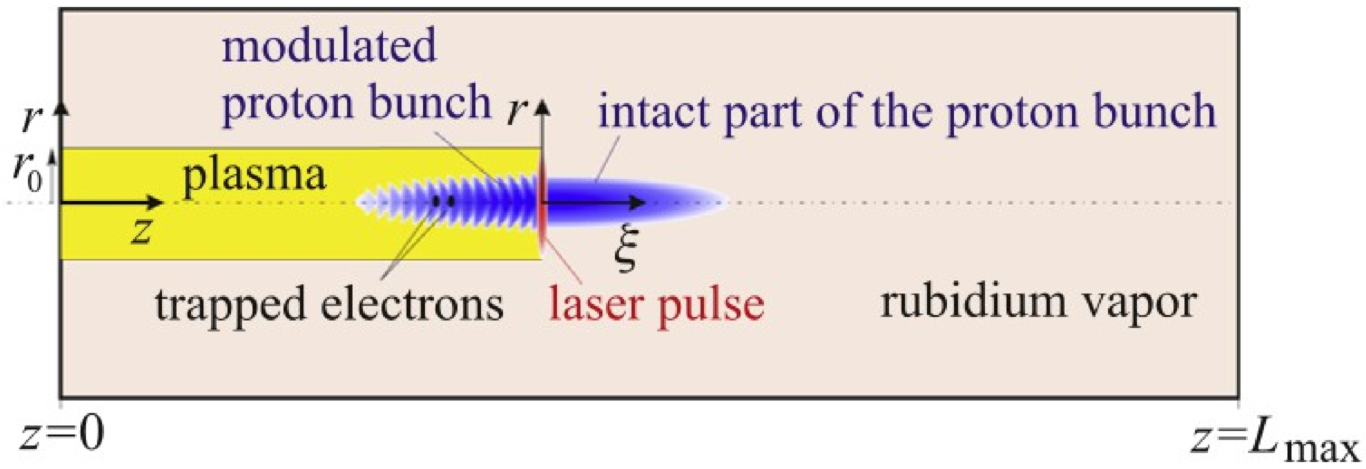
Main Idea

- Find the CPUs needed for a 3D Warp simulation,
- 3D SSM of a proton driver will be investigated.
  - Proton beam length 12 cm!
  - Simulation window ~ 3.2mm * 3.2mm * 8cm
  - Hundred thousands of time steps



Warp SSM Simulation: small window

- 2 cm proton driver cut in half,
- Window dimension: 2.4 mm * 2.4 mm * 1.2 cm
- Simulation over 6 m (500k time steps)
- 320 CPU cores
- Run time ~ 2days: 5hours
- 17k cpu-hours

Computer Needs for a Larger Window

A rough estimate

➔ Simulation window dimension

2.4mm * 2.4mm * 1.2cm ~ times 7 =======> 2.4mm * 2.4mm * 8.4cm

➔ CPU needs

320 CPU (10 Nodes) ~ times 7 =======> 2240 CPU (70 Nodes)

➔ Run time

~ 2days:5hours

➔ Run time in CPU hour

~ 1.7e4 CPU hour ~ times 7 =======> 1.19e5 CPU hour

➔ Diagnostics, resolution and the number of macro-particles can increase the CPU needs and run time.

Warp SSM Simulation: long window

- Identical parameters with 7 times larger window/driver.
- Run time ~ 5day:9hours
- 2240 CPU cores
- The output diagnostics increased the run time.

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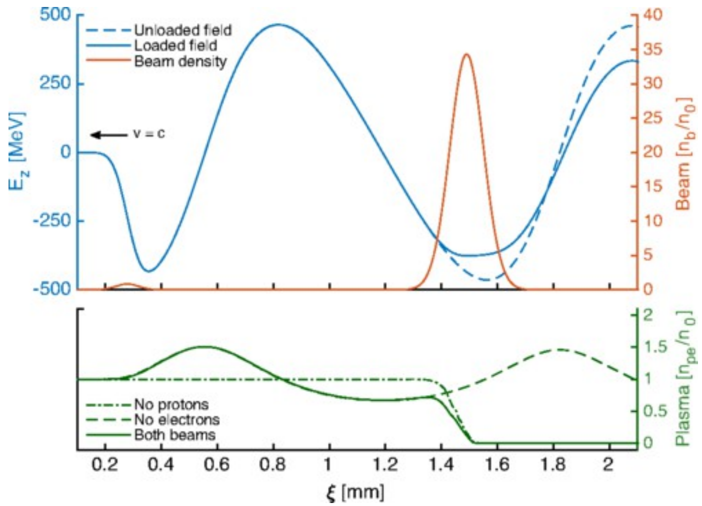
Main Idea

- The goal is to use the idea of beam loading and emittance preservation of the following paper
  - V.K.B.Olsen, et al PRAB **21** 011301 (2018)

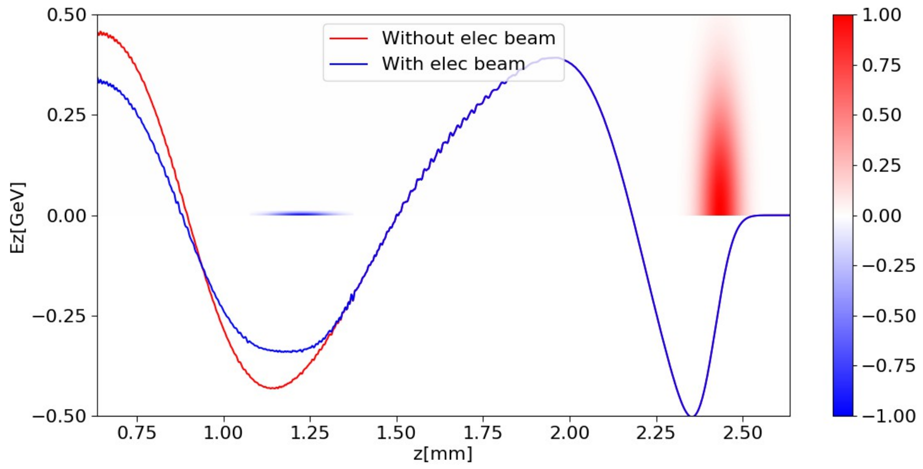
1) Reproduce the results of the paper by Warp for n_plamsa = 7e14 /cm3

2) Obtain the optimum parameters for n_plasma = 2e14 /cm3



Beam-loading effect by Warp

- Reproduce Veronica's paper plot for n=7e14 /cm3
- The effect of electron beam on the wakefield can be seen the plot.



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Conclusions

- ✓ Warp can be a useful simulation tool for the AWAKE when full PIC simulation is needed.

- ✓ Simulation of electron acceleration in the wakefield of a multi-microbunch driver interacting with a plasma density ramp

- ✓ Warp jobs usually needs many CPUs to run.

- ✓ Other codes by Warp developers at Berkley may also be useful for AWAKE
  - WarpX: an advanced development of Warp
  - FBPIC: a quasi-3d full PIC code