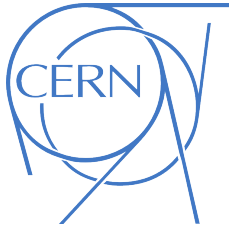


Multi-bunch acceleration: a high-lumi upgrade for AWAKE

J. P. Farmer and G. Zevi Della Porta

AWAKE Collaboration Meeting — October 4-6, 2023
https://indico.cern.ch/event/1329098

Problems and solutions

- Beam loading introduces a trade-off between:
  - (i) energy gain, (ii) energy spread, (iii) accelerated charge
  - To increase charge, we must chose between a smaller energy gain or a larger energy spread. As a result, our Run 2c parameters use O(100) pC electron bunches
- The SPS/AWAKE bunches include more drive micro-bunches than necessary
  - Wakefields stop growing (i.e. saturate) well before the end of the proton bunch
  - Most of the proton bunch energy is not used
- Physics applications of AWAKE demand higher luminosity
  - European Strategy Accelerator R&D Roadmap: *"Aspects that should be further considered are: Further study and optimisation of the AWAKE scheme, in particular to increase the luminosity."*

- Idea (proposed in slides from Eduardo Granados): use our long proton bunch to accelerate additional electron bunches

Caveat: wakefield saturation and multi-bunch driver/witness are NOT new ideas

PHYSICS OF PLASMAS **20**, 083119 (2013)

Excitation of two-dimensional plasma wakefields by trains of equidistant particle bunches

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PHYSICS OF PLASMAS **22**, 103110 (2015)

Physics of beam self-modulation in plasma wakefield accelerators

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The self-modulation instability is a key effect that makes possible the usage of nowadays proton beams as drivers for plasma wakefield acceleration. Development of the instability in uniform plasmas and in plasmas with a small density up-step is numerically studied with the focus at nonlinear stages of beam evolution. The step parameters providing the strongest established wakefield are found, and the mechanism of stable bunch train formation is identified. © *2015 AIP Publishing LLC*.
[http://dx.doi.org/10.1063/1.4933129]

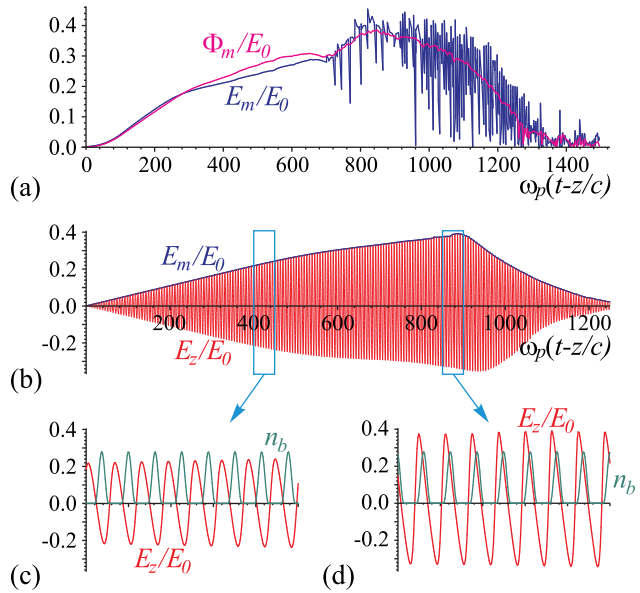

FIG. 2. Temporal growth of the wakefield (envelopes Φ_m and E_m of the wakefield potential Φ and electric field E_z) for the self-modulated AWAKE beam at $z = 4$ m (a) and for the test train of rigid bunches of the same peak density (b)–(d); zoomed fragments (c) and (d) also show the beam density n_b in arbitrary units.

PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS, VOLUME **7**, 111301 (2004)

Possibility of a multibunch plasma afterburner for linear colliders

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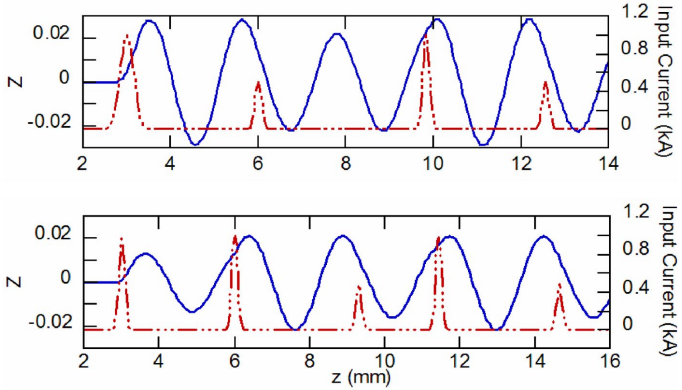
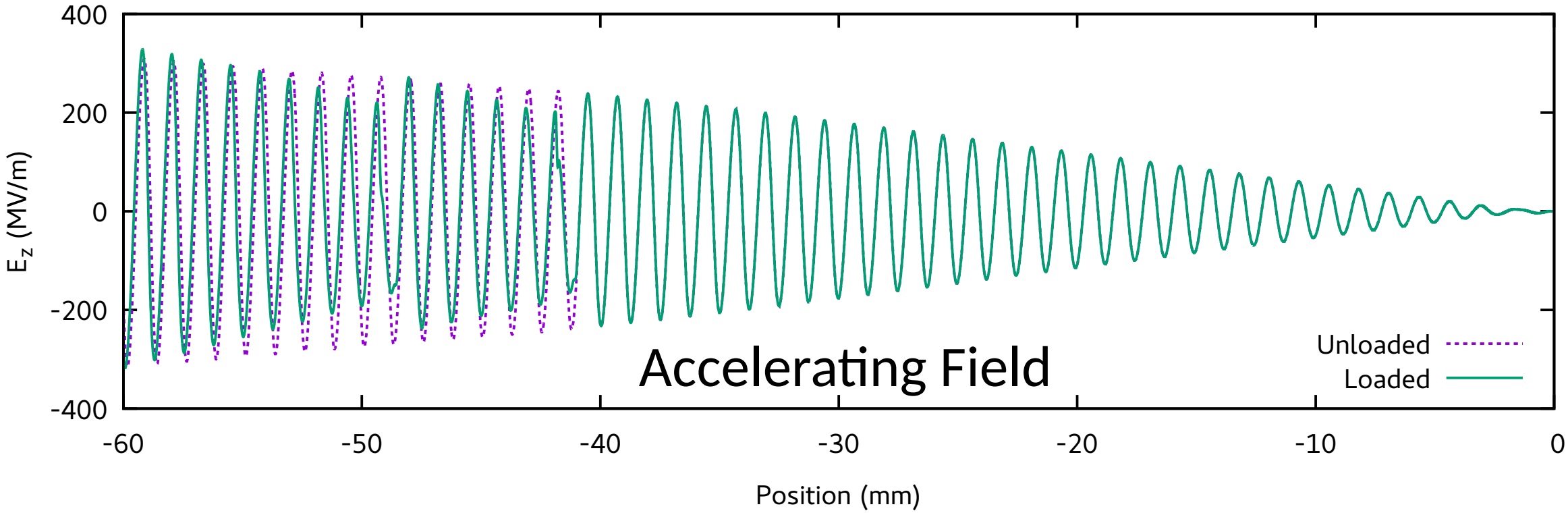


FIG. 6. (Color) Axial bunch current (dashed line) and transverse plasma wakefields for reduced bunch charge in alternate (load) bunches: (a) focusing forces for single initial drive bunch and (b) focusing forces for two initial drive bunches

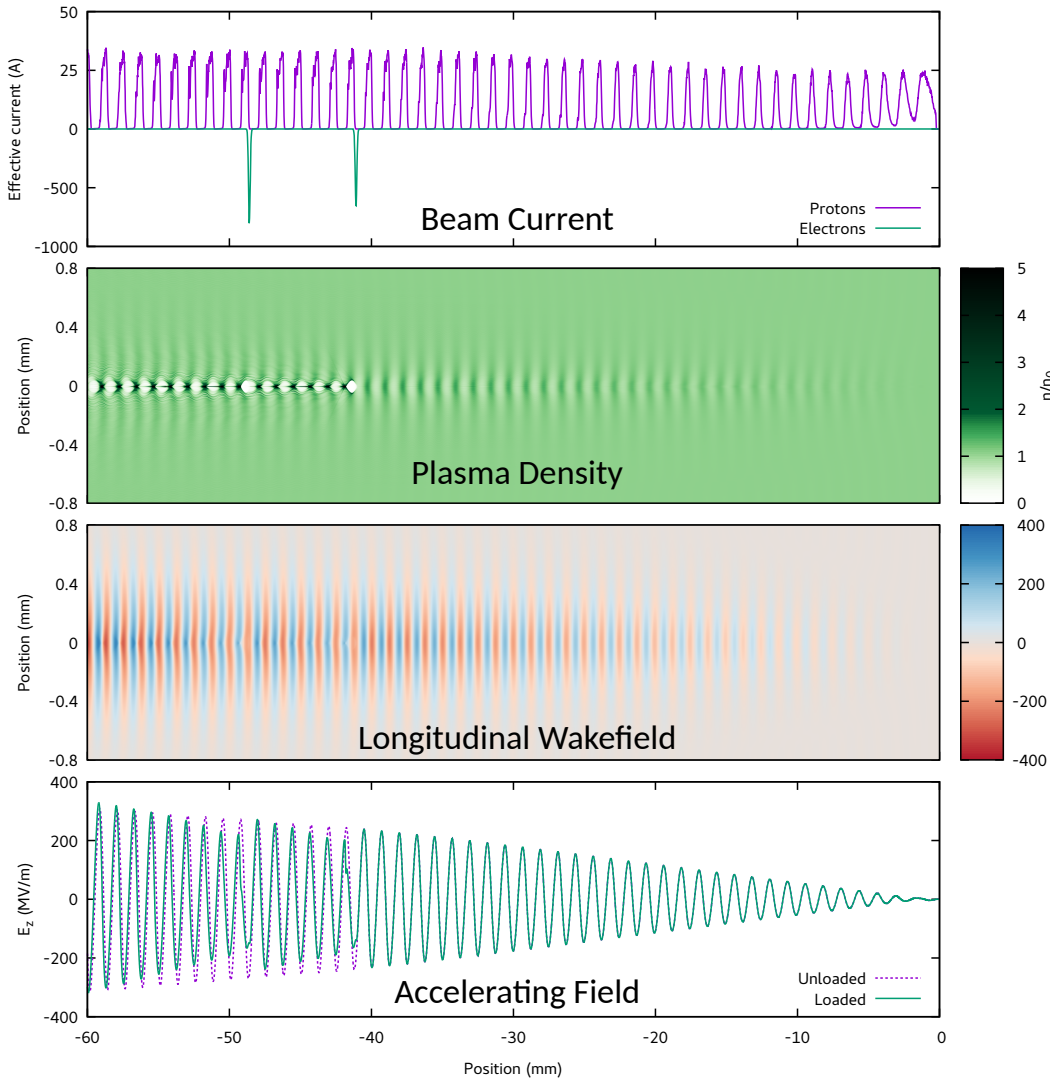
First step: load 2 electron bunches

- Ideal bunch (Run 2c params): 100 pC
- Wakefields are reduced after loading, but they recover quickly thanks to p^+ micro-bunches
  - Even before wakefield saturation, growth is much larger after beam loading
- We can inject a 2nd (identical) e^- bunch, with charge tuned to obtain the same final energy
- LCODE: 2 meters, Run 2c bunches (150 MeV, 200 fs, etc), injected after 10 m self-modulation

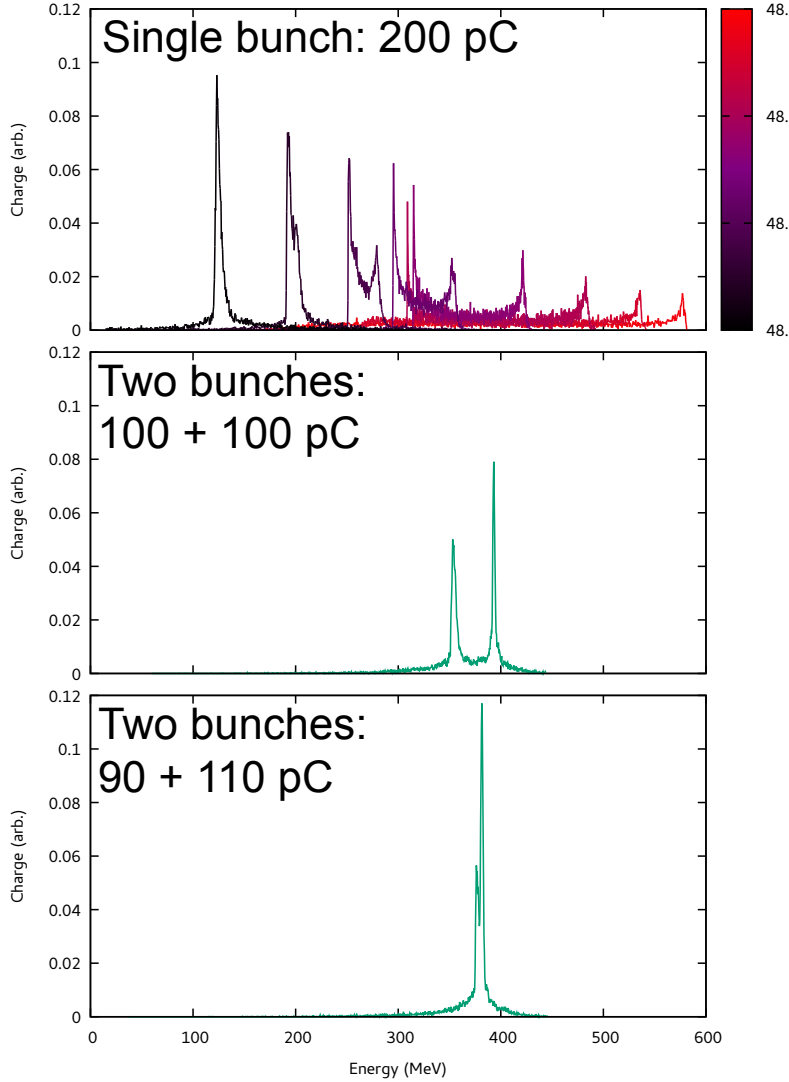


LESSON 1: Wakefield regeneration is faster than growth (only a few periods). Scheme is viable

First step: load 2 electron bunches



- Inject an ideal bunch (Run 2c params): 100 pC
- Wait sufficient periods, then inject an identical e^- bunch
- Tune charge of second bunch to obtain the same energy
- LCODE: 2 meters, Run 2c bunches (150 MeV, 200 fs, etc), injected after 10 m self-modulation

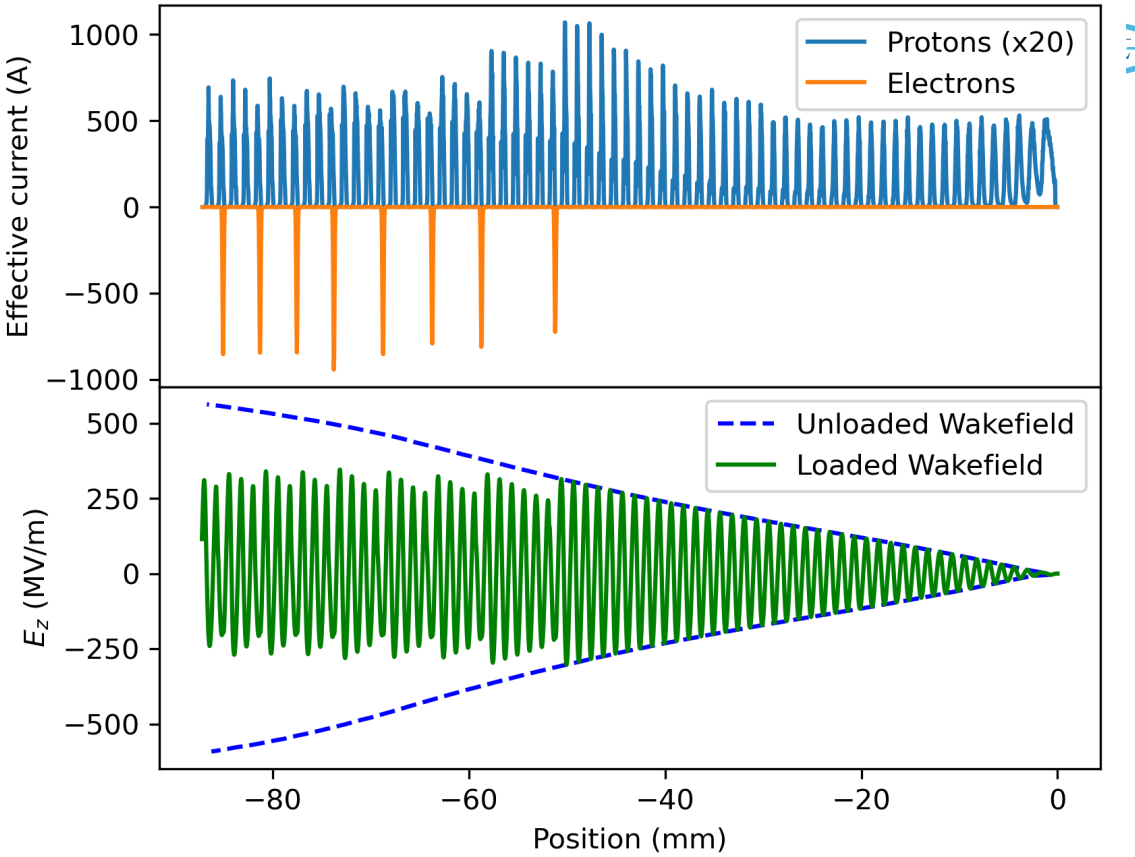


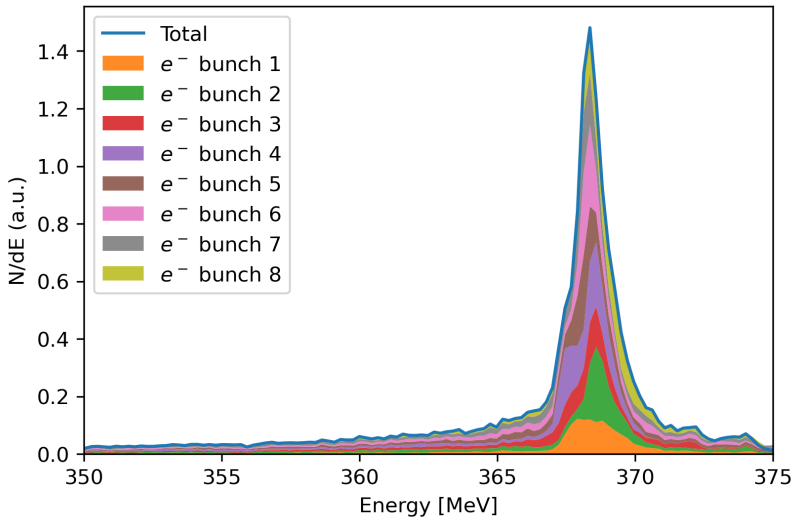
LESSON 2: By tuning phase and charge, we can achieve mono-energetic final beams

Towards high luminosity

- To inject more than 2 bunches, reduce simulation to 1 m and setup LCODE simulations to 'continue' in ζ
  - Each new bunch is added without re-simulating the ones ahead
  - For each bunch, tune 2 parameters: phase and bunch charge
  - Final configuration is checked with a single simulation
- Final result:
  - 8 bunches injected (0.9 nC)
  - > 200 MeV gained in 1 m, with 60% of charge within ±0.5% of peak
- Further improvements within reach:
  - Energy spread can be further reduced through tuning
  - Only half of the proton bunch used: might be able to gain another factor of 2

LESSON 3: Regeneration continues after the second bunch, increasing accelerated charge by a factor of 10

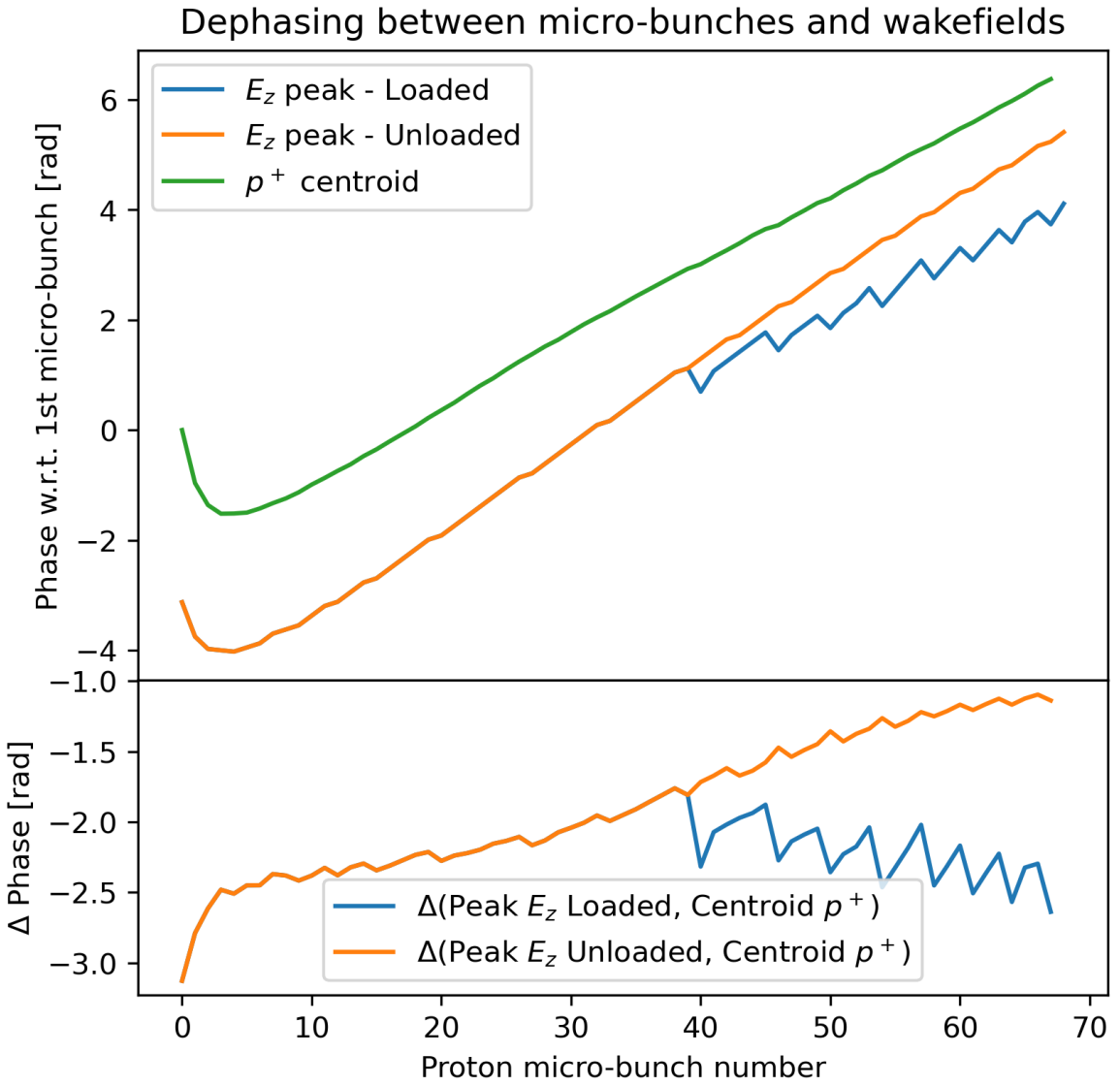




Wakefield recovery through re-tuning

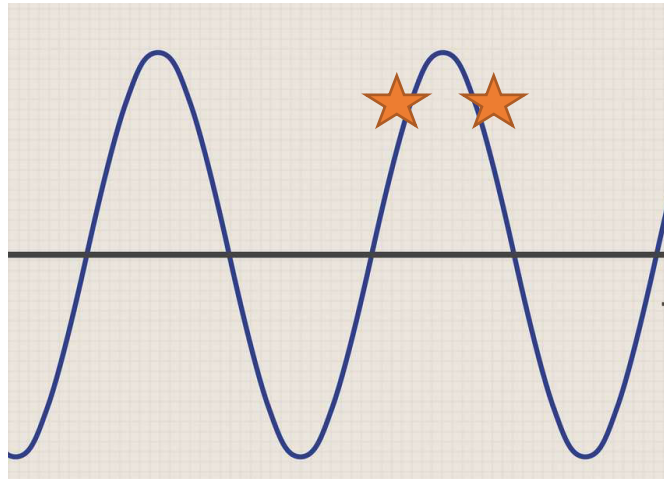
- Saturation is caused by detuning between driver micro-bunches and excited wakefields
  - Phase difference (ΔPhase) between E_z peaks and p^+ centroids is not constant
- Beam-loading "shifts" the wakefields, re-tuning them with the proton micro-bunches
  - After re-tuning, E_z growth increase dramatically
- *Surprising: phase which minimizes e- energy spread also produces re-tuning*

LESSON 4: Beam-loading re-tunes the wakefield with the micro-bunches, enhancing wakefield growth



Discussion and Implementation

- Trains of arbitrarily spaced electron bunches are challenging to produce
  - 4-6 plasma periods at 7E14/cm3: ~6 mm or ~20 ps
  - Electron gun (S-band) period is 333 ps



- Two bunches would be enough to test the concept
  - Explore wakefield recovery
  - Evaluate tolerances ($\Delta\phi$ vs ΔE) and stability

- Proposal: use the Run 2c electron line to produce 2 similar bunches
  - Split/delay of UV line, position bunches equidistant from crest
  - Use buncher / accelerator cavities for further adjustment, as done in Frascati
  - Explore this configuration during the 2025-26 commissioning on the surface