Ion Motion, Hosing Suppression, and Beam Quality Preservation in Plasma-Based Accelerators

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Townhall Meeting #2 on High Gradient Acceleration Plasma/Laser,
May 21, 2021

Work supported by Office of Science, US DOE, Contract No. DE-AC02-05CH11231

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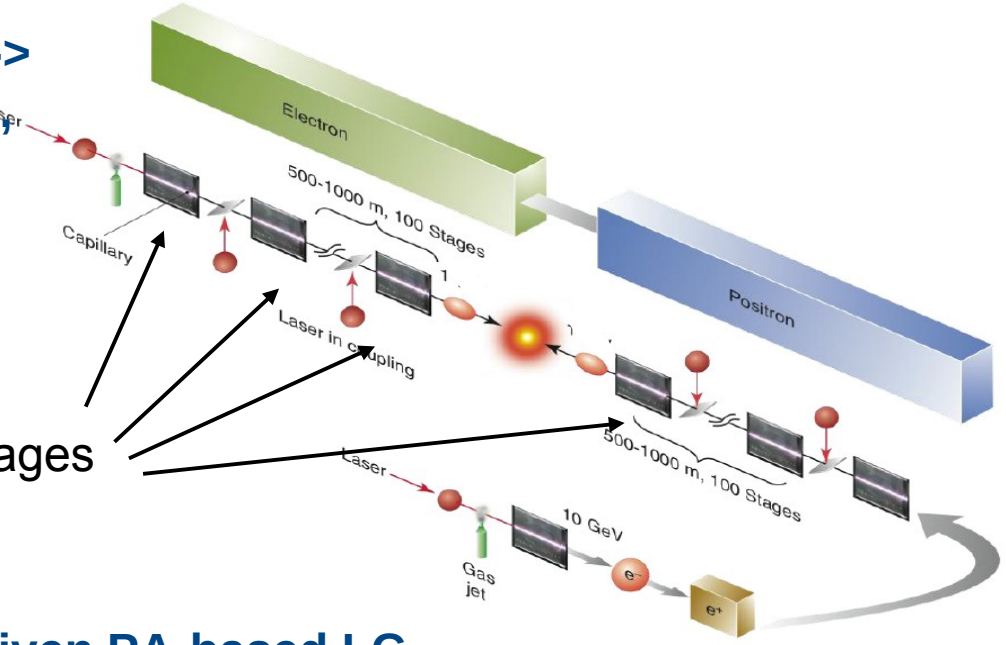
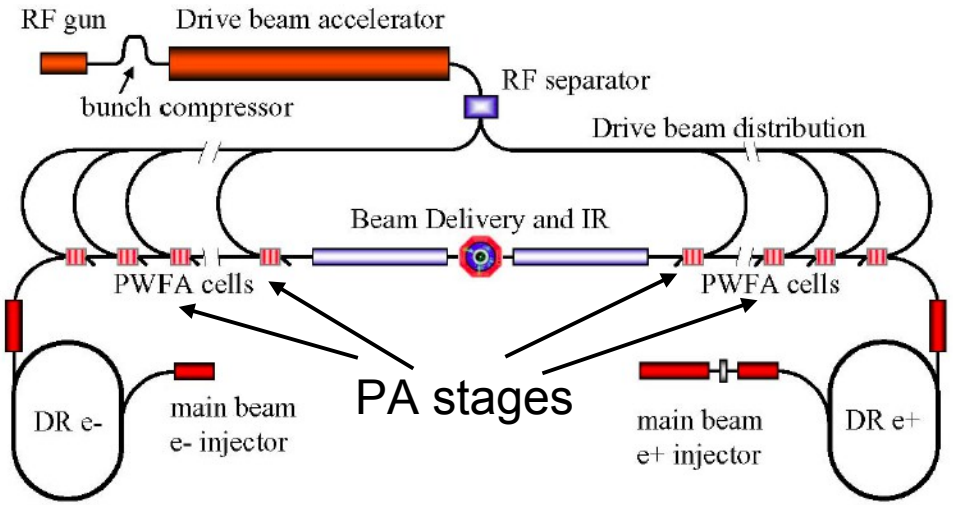
Concept for next-generation TeV-class PA-based linear collider: requires bunches with high charge and small emittance

Laser-driven PA-based LC ----------->
[all optical, driver=10s J laser, 10 kHz, 50x10GeV PA stages @ $n_0=10^{17}$ cm^{-3}]

Leemans, Esarey, Physics Today (2009)
Schroeder *et al.*, PRSTAB (2010)



PA stages



PA stages

<------- Beam-driven PA-based LC
[driver=25 GeV e-bunch, 19x25 GeV PA stages @ $n_0=10^{17}$ cm^{-3}]

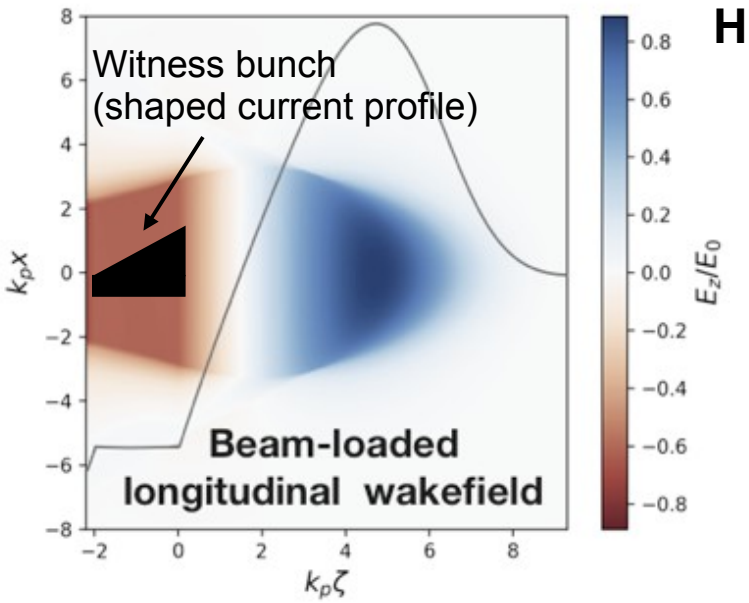
Seryi *et al.*, PAC 2009
Delahaye *et al.*, IPAC 2014

- Compact machine (1 TeV): ≤1 km for PA-based LC VS ~30 km for RF-based (ILC)
- Requirements on witness bunch:

  → N_b~ 10^{10} part./bunch (~ nC), ε_n < 100 nm, high wake → witness bunch efficiency (~40%)

*Ellis and Wilson, Nature (2001); Hinchliffe and Battaglia, Phys. Today (2004)

Witness bunch parameters of interesest for a plasma-based collider induce hosing and ion motion resulting in emittance degradation or bunch loss

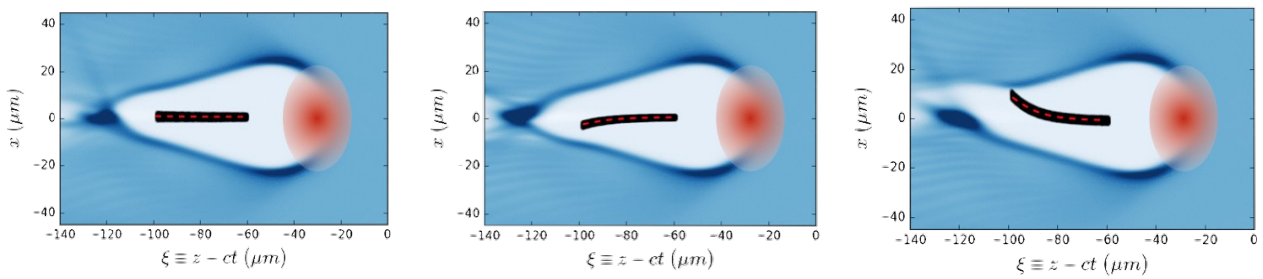


High charge + high-efficiency:

→ large longitudinal wake driven by beam (i.e., high beamloading)

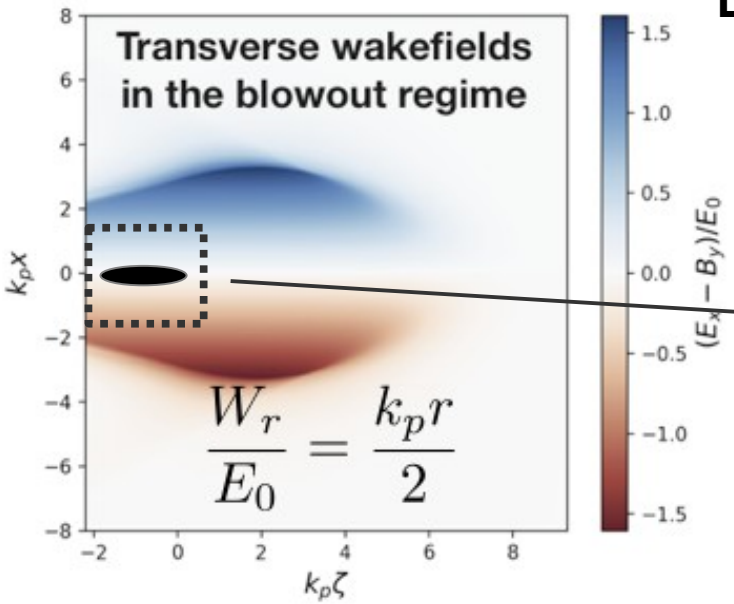
→ high beamloading implies strong coupling between beam and wake

→ resonance between beam centroid motion and wake centroid → **hosing**



Whittum et al., PRA (1992)
Schroeder et al., PRL (1999)
Huang et al., PRL (2007)
Lehe et al., PRL (2017)
Mehrling et al., POP (2018)

Lebedev et al., PRAB (2017)

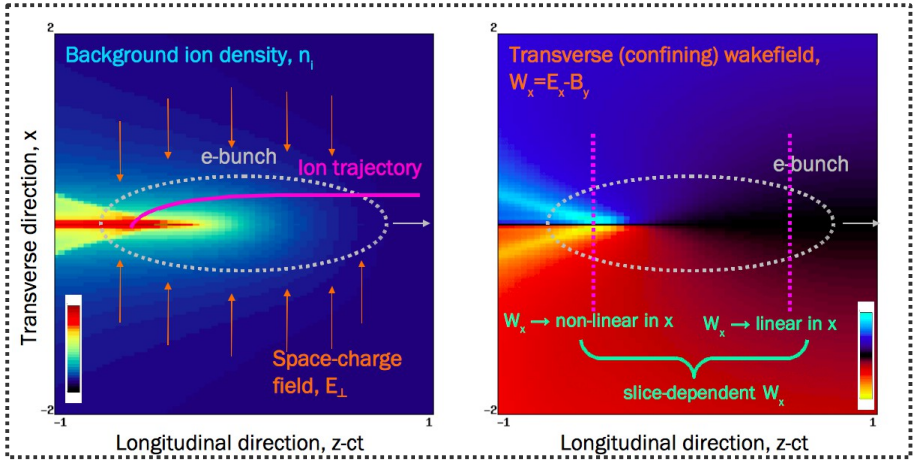


Low emittance + high charge + high energy:

→ small matched beam size and high beam density

→ large beam space charge fields → **background ion motion**

$$\sigma_x^2 = \frac{\epsilon_n}{\gamma k_\beta} = \sqrt{\frac{2}{\gamma}}\frac{\epsilon_n}{k_p}$$



Condition for ion motion:

$$\Gamma = Z_i \frac{m}{M_i}\frac{n_{b,0}}{n_0}(k_p L_b)^2 \sim 1$$

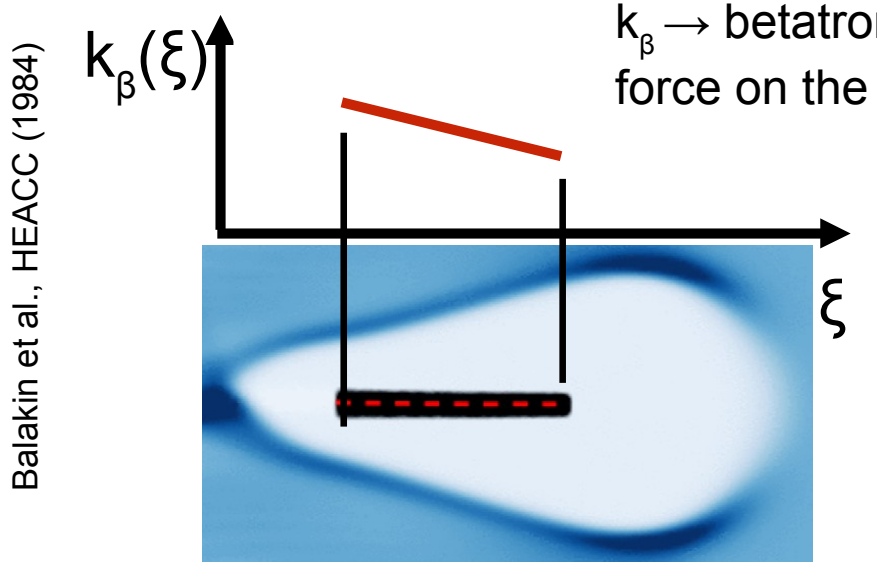
Rosenzweig et al., PRL (2005)
An et al., PRL (2017)
Benedetti et al., PRAB (2017)

Emittance growth / bunch loss!

Chirp of betatron frequency suppresses hosing

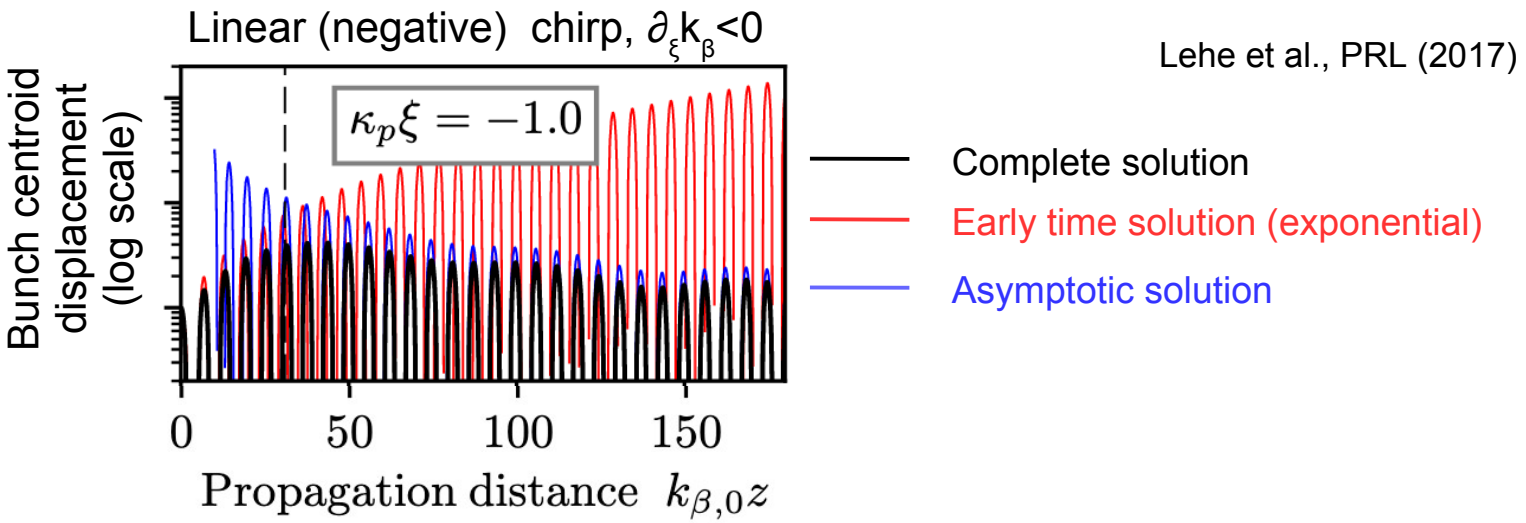
- Hosing equation with slice-by-slice varying focusing force: $\partial_z^2 x_c(\xi, z) + k_\beta^2(\xi)\, x_c(\xi, z) =$

$$k_c^2 \int_\xi^0 \frac{n_b(\xi')}{n_p} x_c(\xi', z) \sin[\kappa_p(\xi' - \xi)]\, \kappa_p d\xi'$$



Balakin et al., HEACC (1984)

$k_\beta \rightarrow$ betatron frequency = focusing force on the bunch



Lehe et al., PRL (2017)

- PA stage operating in the quasilinear regime
  → head-to-tail variation in focusing force provides betatron chirp that suppresses hosing

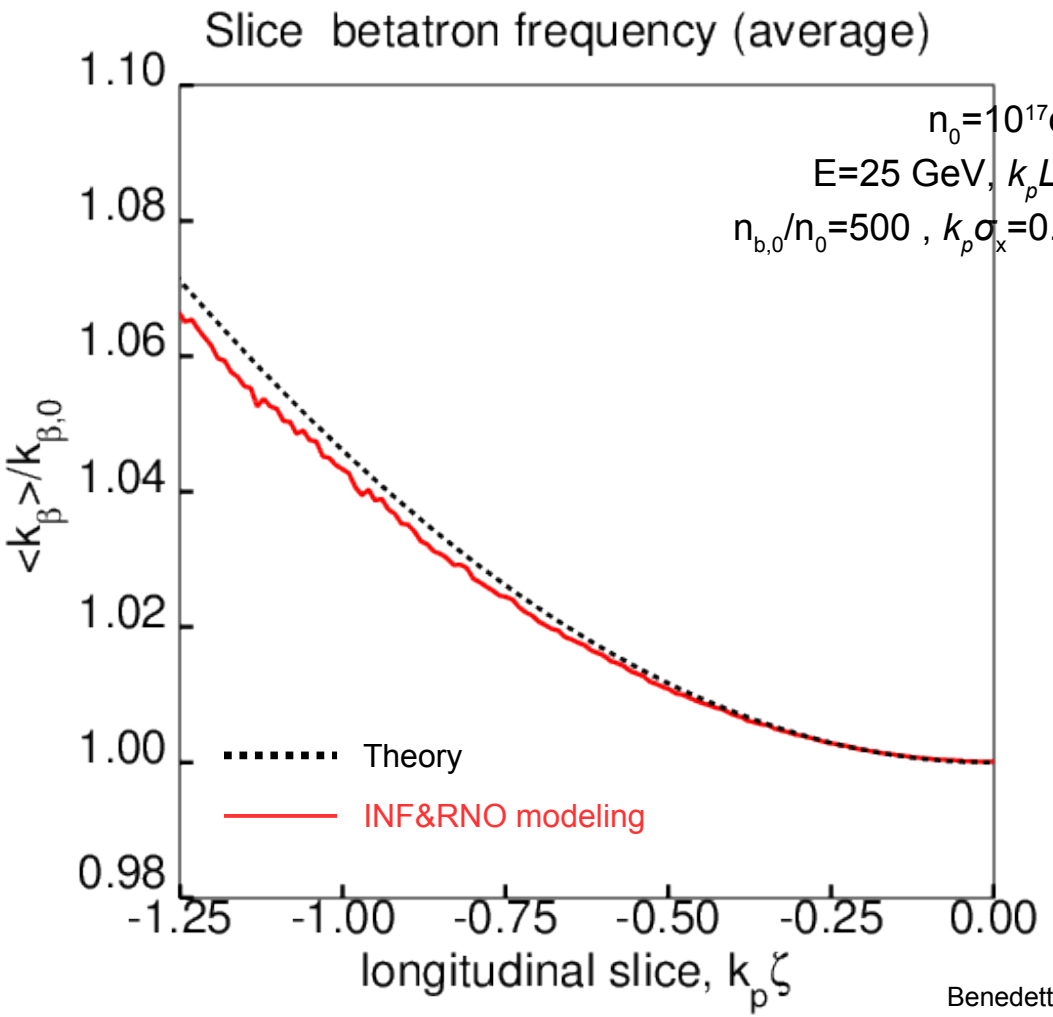
- PA stage operating in the nonlinear/blowout regime (= linear trans. wakefield)
  → head-to-tail variation achieved by energy chirp (similar to BNS dampin
  → **head-to-tail variation provided by ion motion!**

~10s% energy spread required for strongly beamloaded regimes → not desirable for colliders

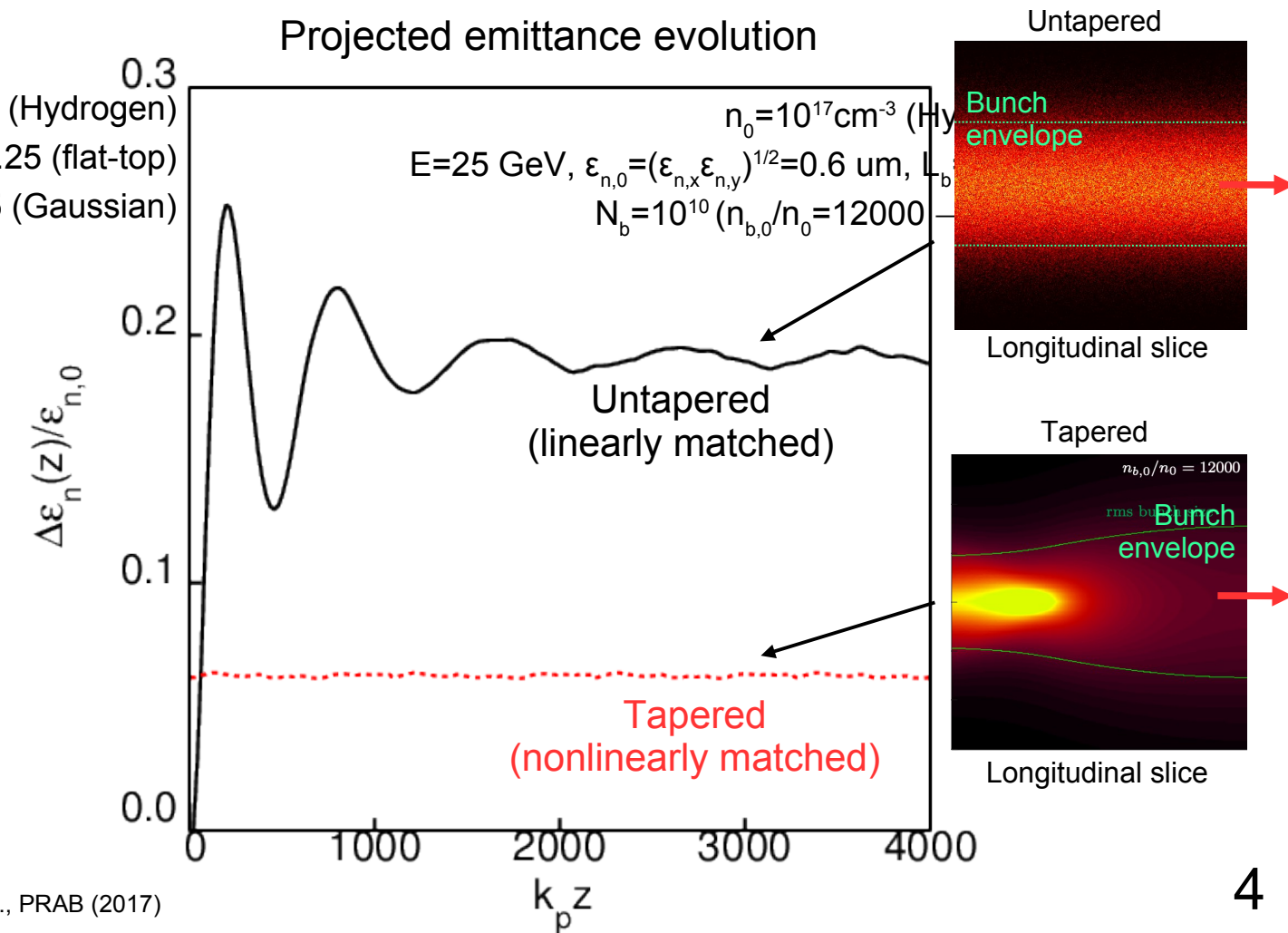
Ion motion induces betatron frequency chirp. Associated emittance degradation suppressed by slice-by-slice bunch matching.

- Betatron frequency chirp:

$$\frac{k_\beta^2(\zeta)}{k_\beta^2(\zeta=0)} = 1 + \log(2)\frac{Z_i}{2}\frac{m}{M_i}\frac{n_{b,0}}{n_0}(k_p\zeta)^2$$

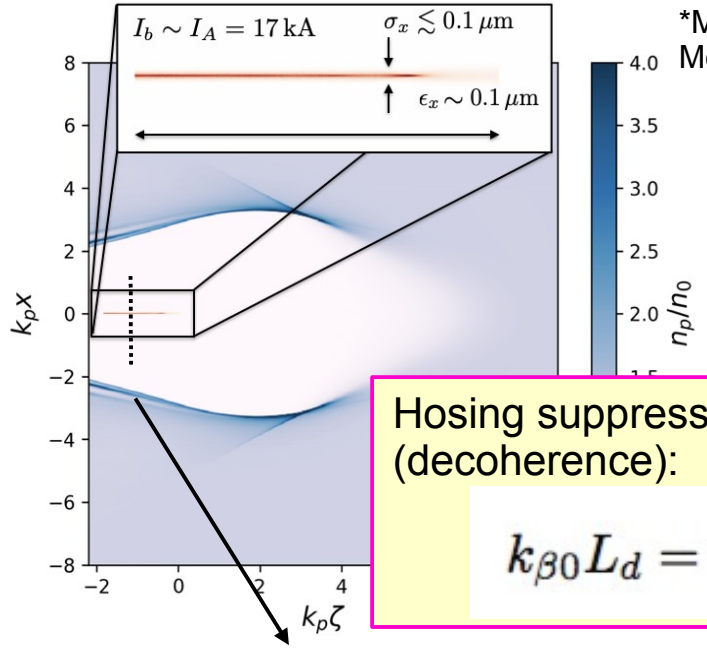


- Matching the bunch in the presence of ion motion requires longitudinally tailoring the bunch transverse phase-space distribution (w/ fixed slice emittance, arbitrary current profile)



Benedetti et al., PRAB (2017)

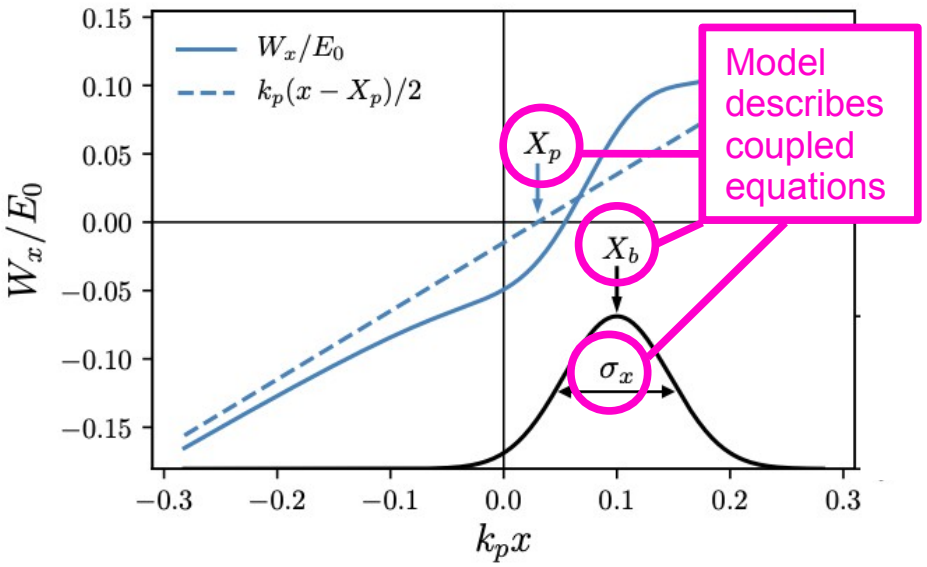
Ion motion suppresses hosing.
Emittance is preserved if tapered beams are used.



*Mehrling et al., PRL (2018)
Mehrling et al., POP (2018)

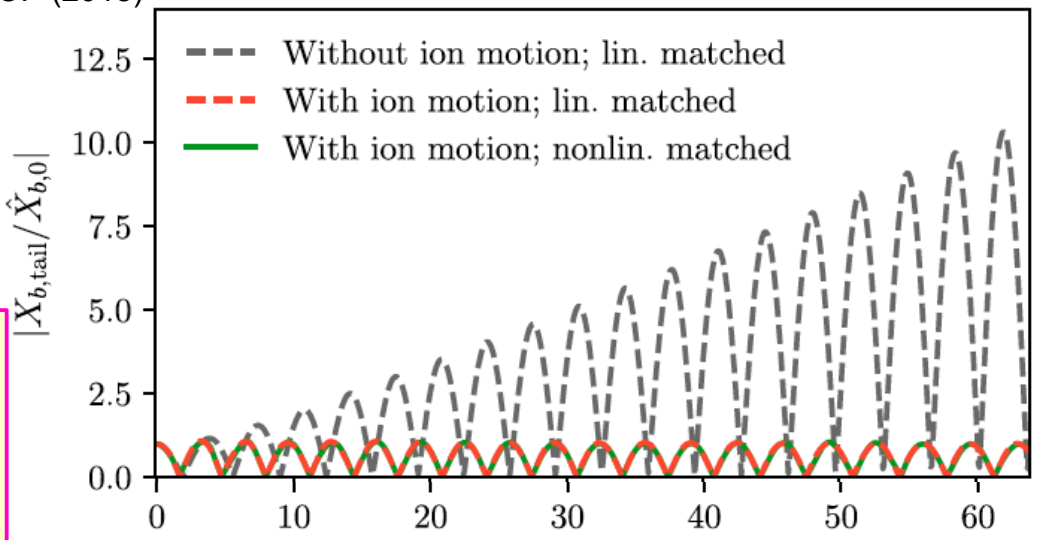
Hosing suppression length (decoherence):

$$k_{\beta 0} L_d = \frac{8\pi}{\Gamma}$$

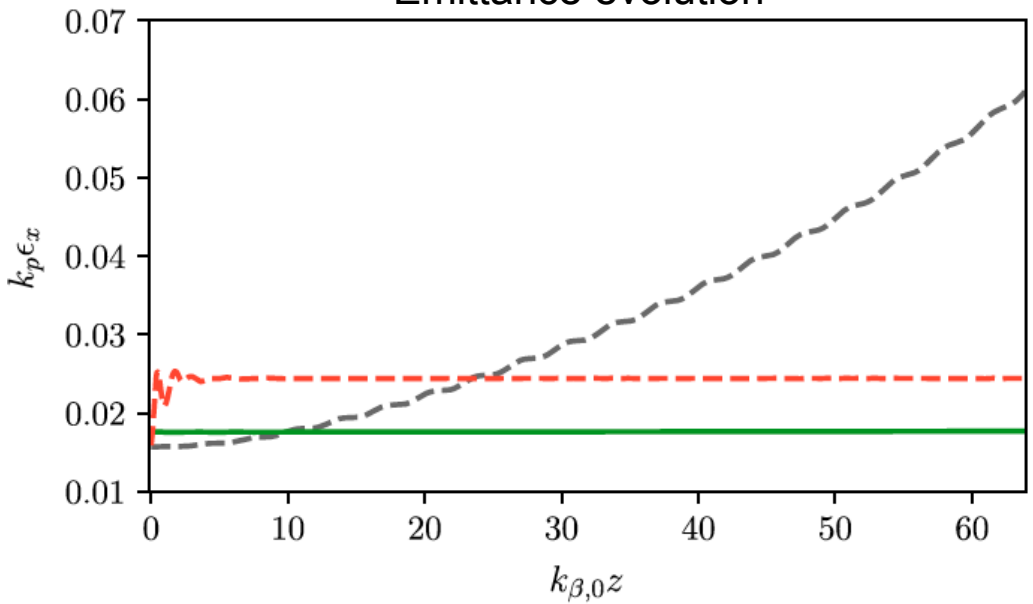


Model describes coupled equations

Centroid evolution



Emittance evolution



$n_0=10^{17}\mathrm{cm}^{-3}$ (Hydrogen)
E_b=25 GeV, $\varepsilon_{n,0}$=0.26 um,
σ_b=0.17 um, L_b=33 um,
$N_b=1.5\cdot 10^{10}$ [trapezoidal]
($n_{b,0}/n_0$=31000 → Γ=68),

Very rapid (<1 betatron period) decoherence

* NO ion motion → hosing, large emittance growth (beam breakup)

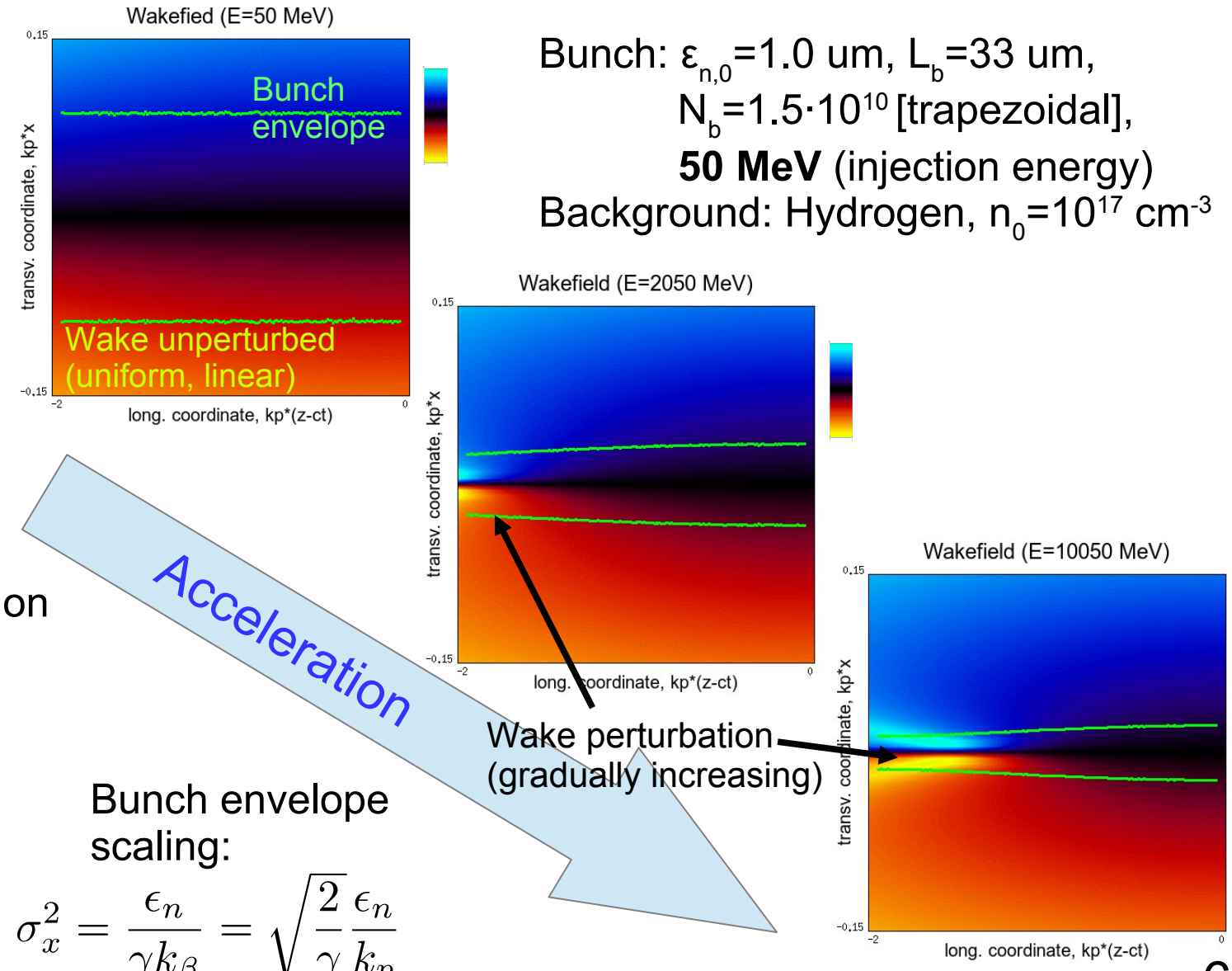
* WITH ion motion → hosing suppressed, but emittance growth (+60%) from ion motion

* WITH ion motion + NONLIN. Matched → hosing suppressed & no emittance growth

Tapered beams can be obtained with an adiabatic matching procedure during plasma acceleration of an initially low-energy beam.

- Low energy: ion motion small ($\Gamma \sim \gamma^{1/2}$) → a longitudinally uniform beam is (quasi-) matched in (quasi-)unperturbed wakefield
- Energy gain compresses beam: gradual compression of beam triggers ion motion & wakefield perturbation
- Beam distribution adiabatically adjusts, slice-by-slice, to ion-motion-perturbed wakefields maintaining the matching condition

Bunch: $\varepsilon_{n,0}$=1.0 um, L_b=33 um,
N_b=1.5·10^{10} [trapezoidal],
50 MeV (injection energy)
Background: Hydrogen, n_0=10^{17} cm^{-3}



Bunch envelope scaling:

$$\sigma_x^2 = \frac{\epsilon_n}{\gamma k_\beta} = \sqrt{\frac{2}{\gamma}}\frac{\epsilon_n}{k_p}$$

Benedetti et al., POP (2021)

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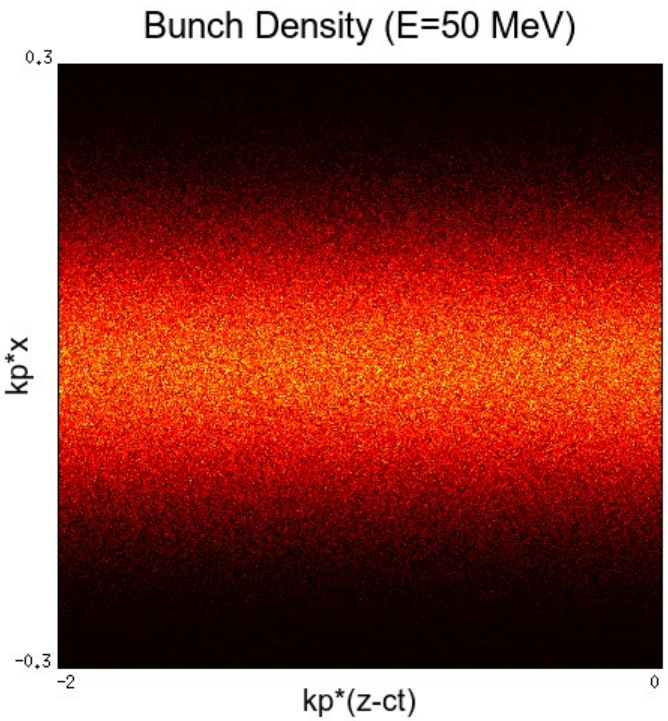
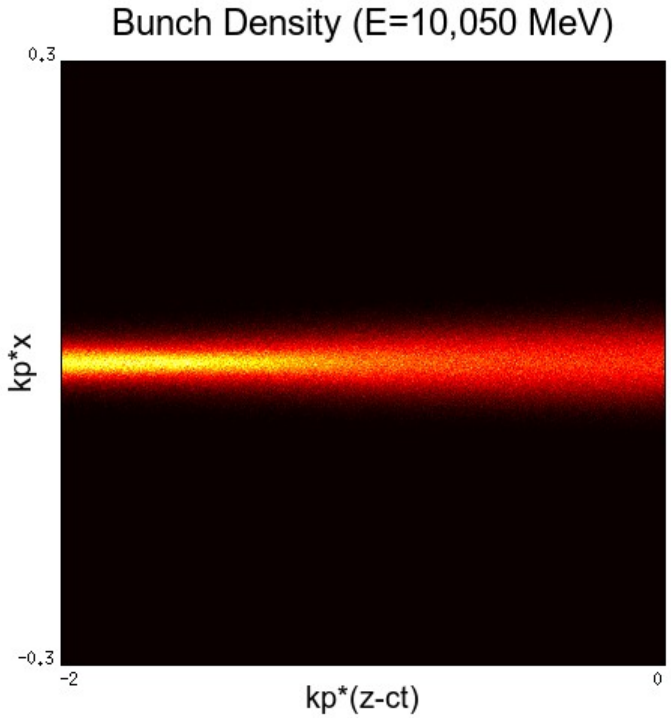
- Beam distribution adiabatically adjusts, slice-by-slice, to ion-motion-perturbed wakefields maintaining the matching condition

→ **a slice-by-slice, nonlinearly matched beam is produced**



← Initial (untapered)

Final (tapered) →



Benedetti et al., POP (2021)

Summary

- Witness bunch parameters of interest for future plasma-based colliders trigger ion motion and hosing that lead, potentially, to severe emittance degradation or beam breakup;

- Analytic model describing hosing in presence of ion motion has been derived:
  → model predicts suppression of hosing owing to detuning associated with ion motion;
  → 3D PIC simulations confirm suppression of hosing in presence of ion motion for collider-relevant witness bunch parameters in strongly beamloaded regimes;

- Beam quality preservation possible with slice-by-slice matching of witness bunch:
  → optimal tapering can be produced with adiabatic matching procedure;

Stable, high-efficiency, high-quality acceleration of e-beams in plasma-accelerators possible
→ **enables use of plasma-based acceleration for HEP applications**

Questions / Part 1
[relevant to hosing, ion motion, and beam quality preservation]

1) Where do you see HEP applications of advanced accelerators in 30 years?

- (towards) e-/e+ collider

2) What intermediate physics applications/steps do you see until a HEP linear collider?

- Investigate role of background ion motion in witness (and driver) beam evolution;
- Demonstration of bunch emittance preservation in the presence of ion motion with bunch tapering.

3) What is the synergy with related fields?

- Explore plasma-based generation of high-quality beams;
- Plasma-based beam phase-space manipulation;

4) What is the role of your work here?

- Hosing instability in strongly beamloaded PA stages can be suppressed by the chirp in the focusing force induced by background ion motion. By proper tapering bunch quality can be preserved. A plasma-based method, based on an adiabatic matching procedure, to generate the tapered equilibrium bunch distribution in the presence of ion motion has been proposed.

Questions / Part 2
[relevant to hosing, ion motion, and beam quality preservation]

1) What are the important milestones for the next 10 years to get there from today?

- Investigation of the role of ion motion in the stability of the witness (and driver) bunch;
- Exploration of plasma-based production of high-quality beams;
- Exploration of plasma-based techniques to perform beam manipulation (tapering).

2) What additional support is needed to achieve these?

- Beam-test facilities to explore these concepts.

3) What should be proposed as deliverables until 2026? Please list in order of priority.

- Investigation of the role of ion motion in the stability of the witness (and driver) bunch;
- Exploration of plasma-based production of high-quality beams;
- Exploration of plasma-base techniques to perform beam manipulation (tapering).

4) Is the R&D work for each of those deliverables already funded and, if not, what additional resources / support would be needed?

- Partially funded.

Questions / Part 3
[relevant to hosing, ion motion, and beam quality preservation]

1) What key R&D needs can be achieved in existing R&D facilities?

- Stability & bunch quality preservation R&D.

2) What is the role of the already planned future facilities in Europe and world-wide?

- Additional facilities could accelerate the progress.

3) What can be done with the existing and planned funding base?

- Hosing and ion motion could be investigated, to some extent, at FLASHForward and FACET-II.

4) Is a completely new facility needed?
N/A

5) Are additional structures needed beyond existing networks and projects, e.g. a design study for a collider or an advanced accelerator stage?

- Yes, these concepts need to be integrated into a conceptual design.