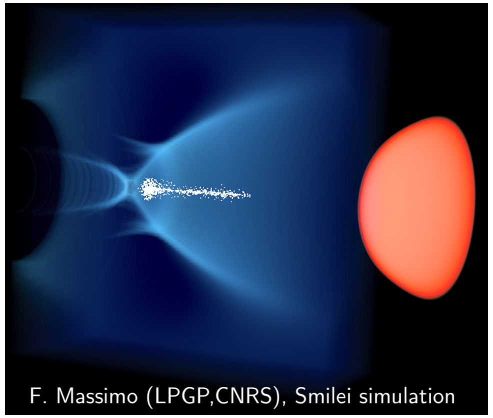
Developing Expectations with Plasma Simulations

February 2024

John Farmer, MPP

State-of-the-art Simulations

Laser-driven wakefield acceleration (EARLI)



- wakefield structure ~1 plasma wavelength
- propagate ~1000 plasma wavelengths

State-of-the-art Simulations

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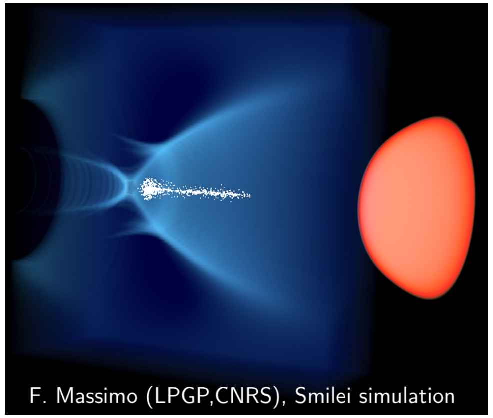
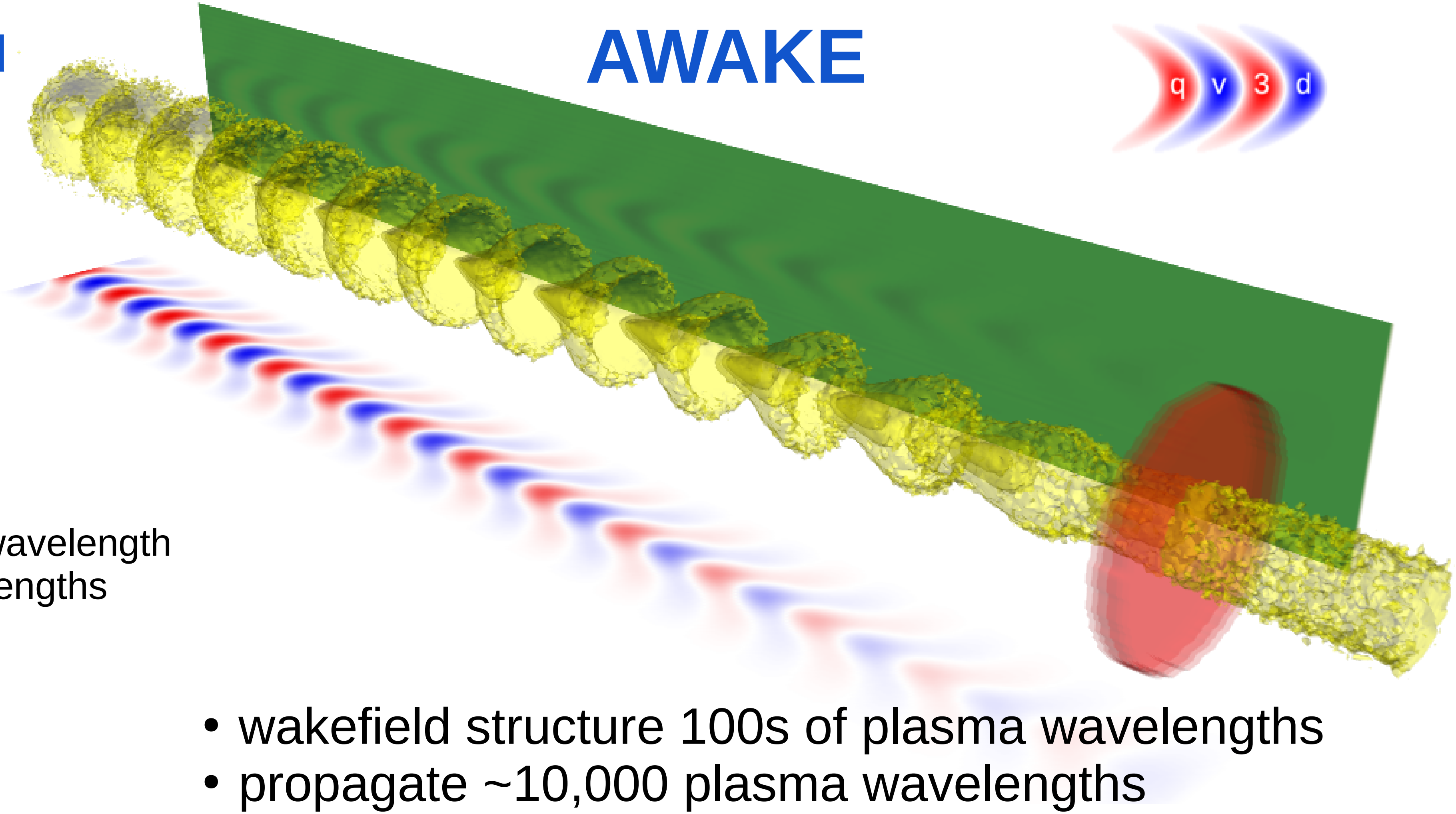


- wakefield structure ~1 plasma wavelength
- propagate ~1000 plasma wavelengths

AWAKE



- wakefield structure 100s of plasma wavelengths
- propagate ~10,000 plasma wavelengths
- ~5Mch with conventional codes

Moschuering *et al.* (2019)

State-of-the-art Simulations

IST Lisbon

Full EM-PIC
in 2D and 3D

VLPL

HHU Düsseldorf

Full EM-PIC in 3D
Quasistatic PIC in 3D

LCODE

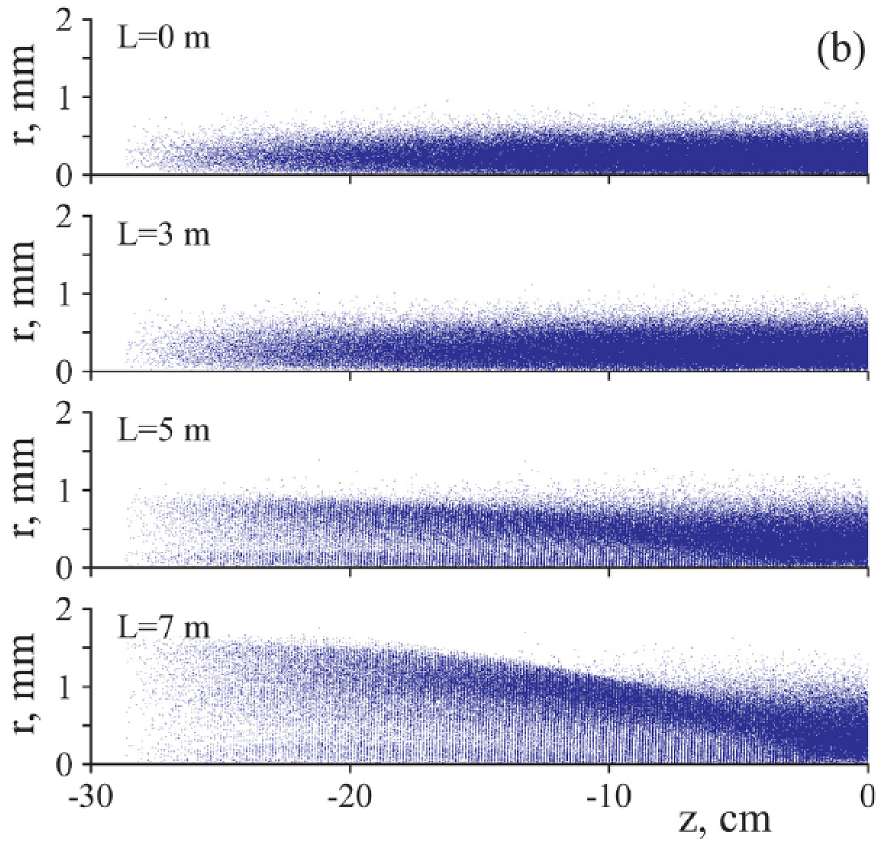
BINP Novosibirsk

Quasistatic PIC in 2D

Broad collaboration of institutes and simulation tools

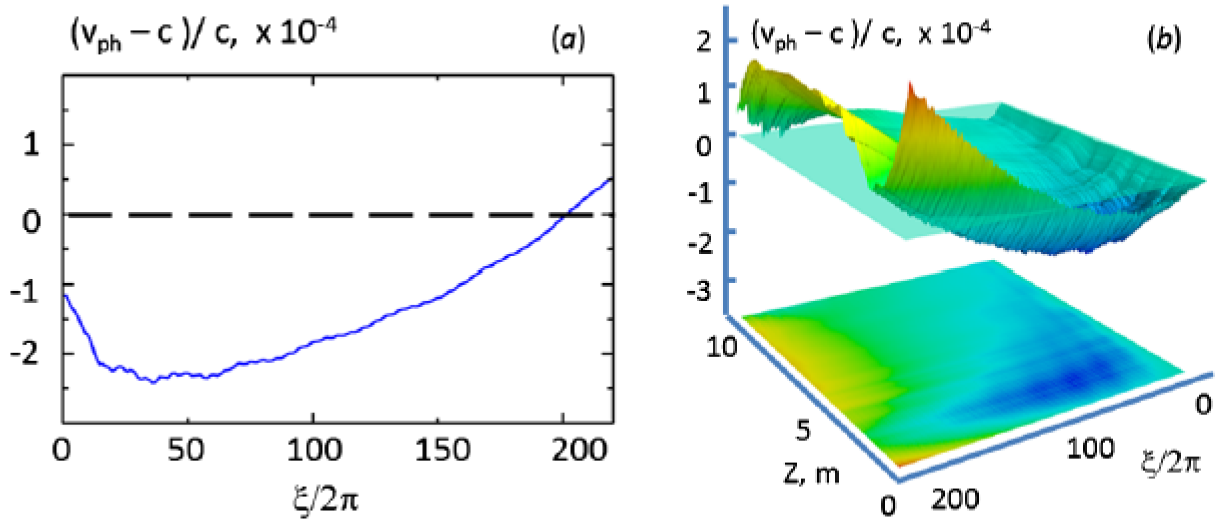
Prediction

Self modulation for acceleration
Caldwell and Lotov, PoP (2011)



Demonstrated 2017

Controlling SMI with density gradients
Pukhov *et al.*, PRL (2011)

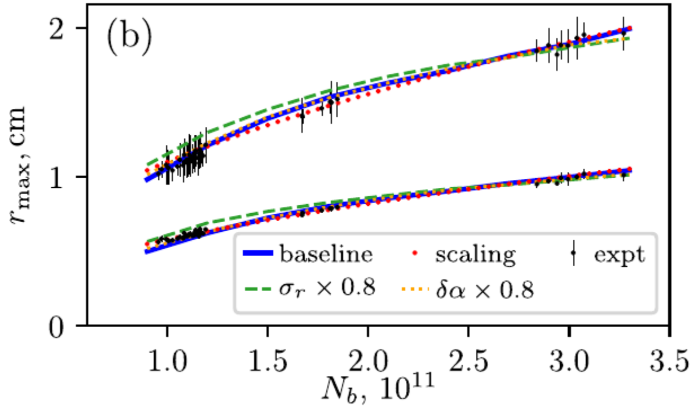


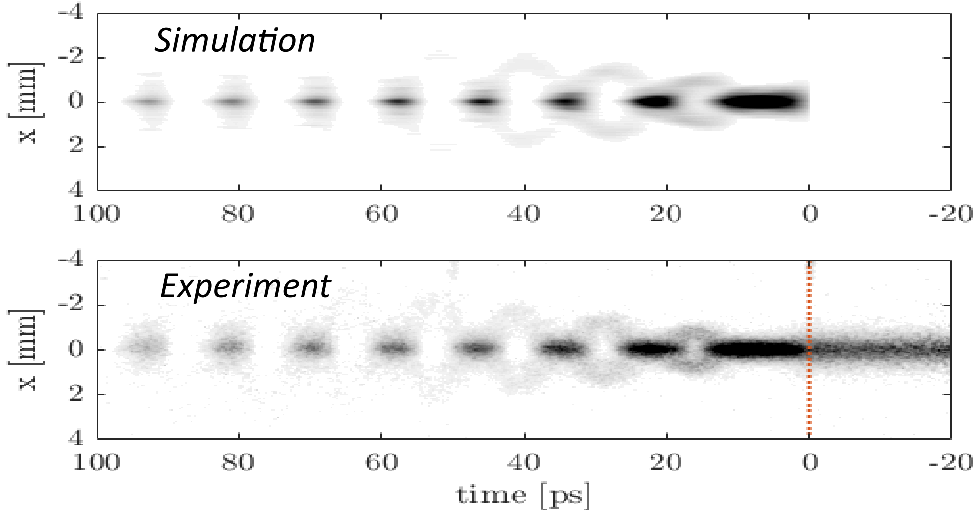
Demonstrated in 2018

Agreement

Beam radius after SMI at Imaging Station 2

A. Gorn, PPCF (2020)

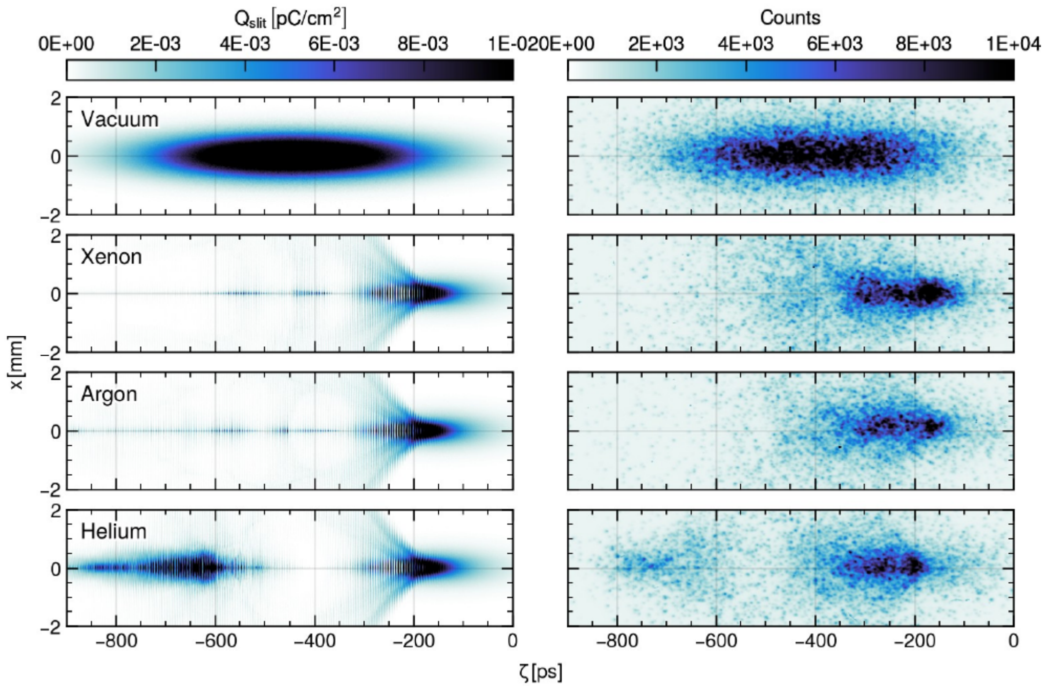




Microbunch structure at streak camera

A.-M. Bachmann, PhD thesis (2021)

Impact of ion motion on SMI imaged at streak camera

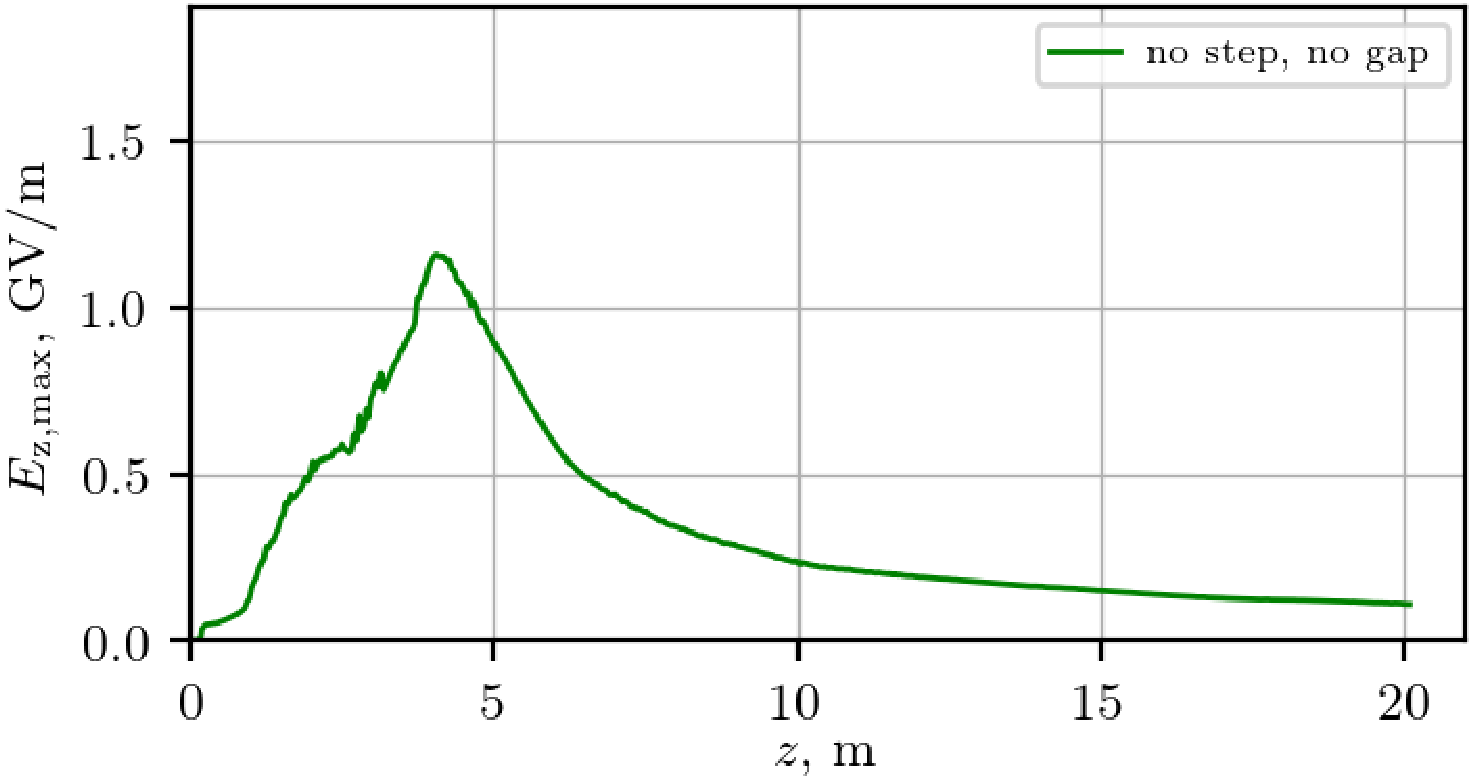


E. Walter, *in preparation*

M. Turner, *in preparation*

Controlling Self-modulation

Wakefields initially grow, before decaying.

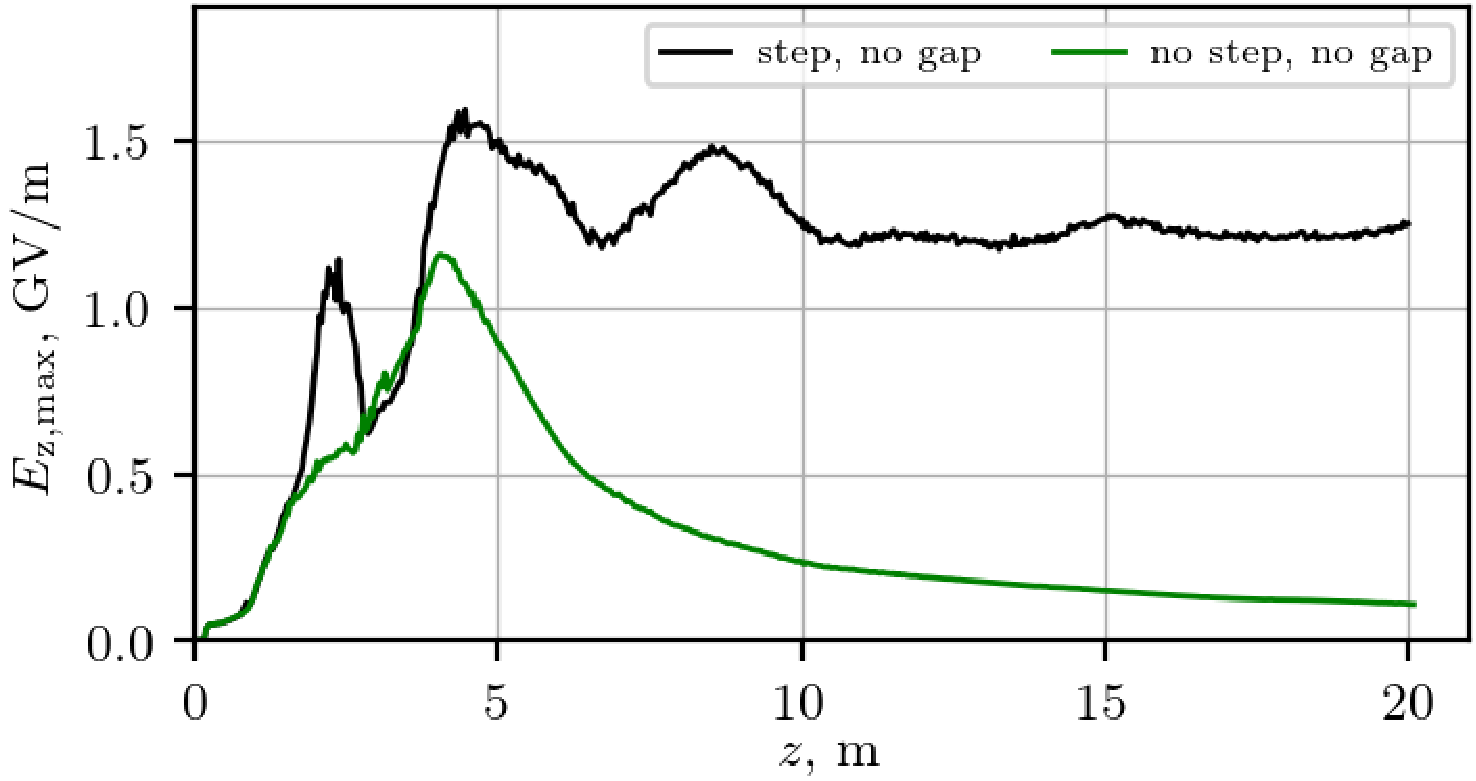


AWAKE Collaboration, Symmetry (2022)

Controlling Self-modulation

Wakefields initially grow, before decaying.

Plasma density step allows self-modulation to be controlled

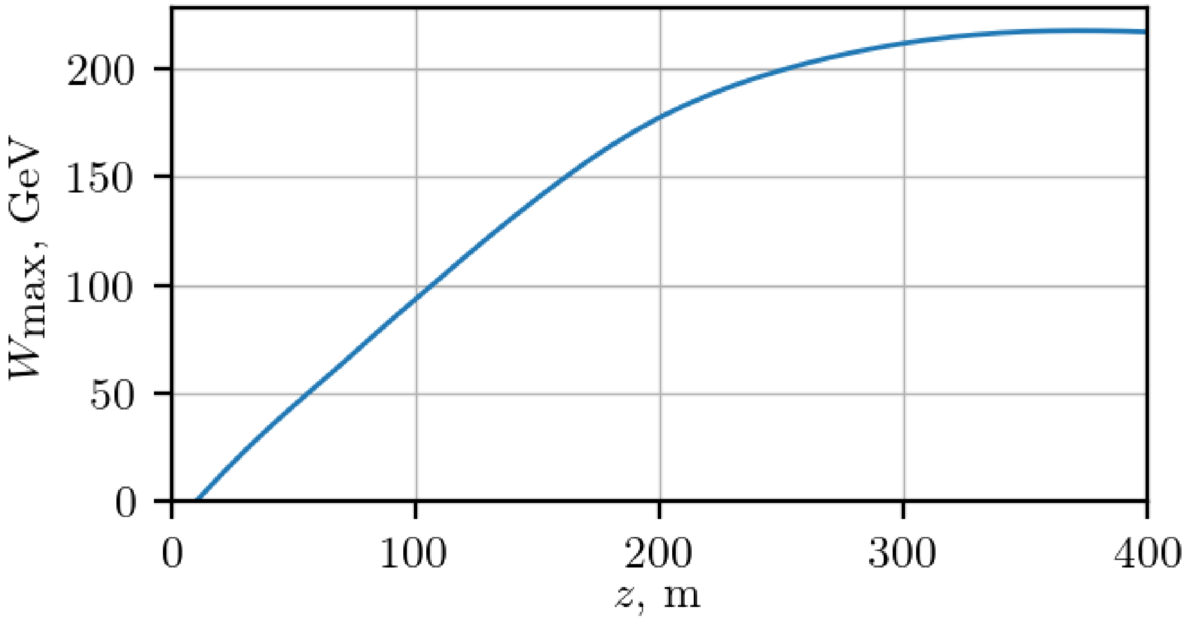


AWAKE Collaboration, Symmetry (2022)

Controlling Self-modulation

Density step allows high wakefield amplitude over hundreds of metres.

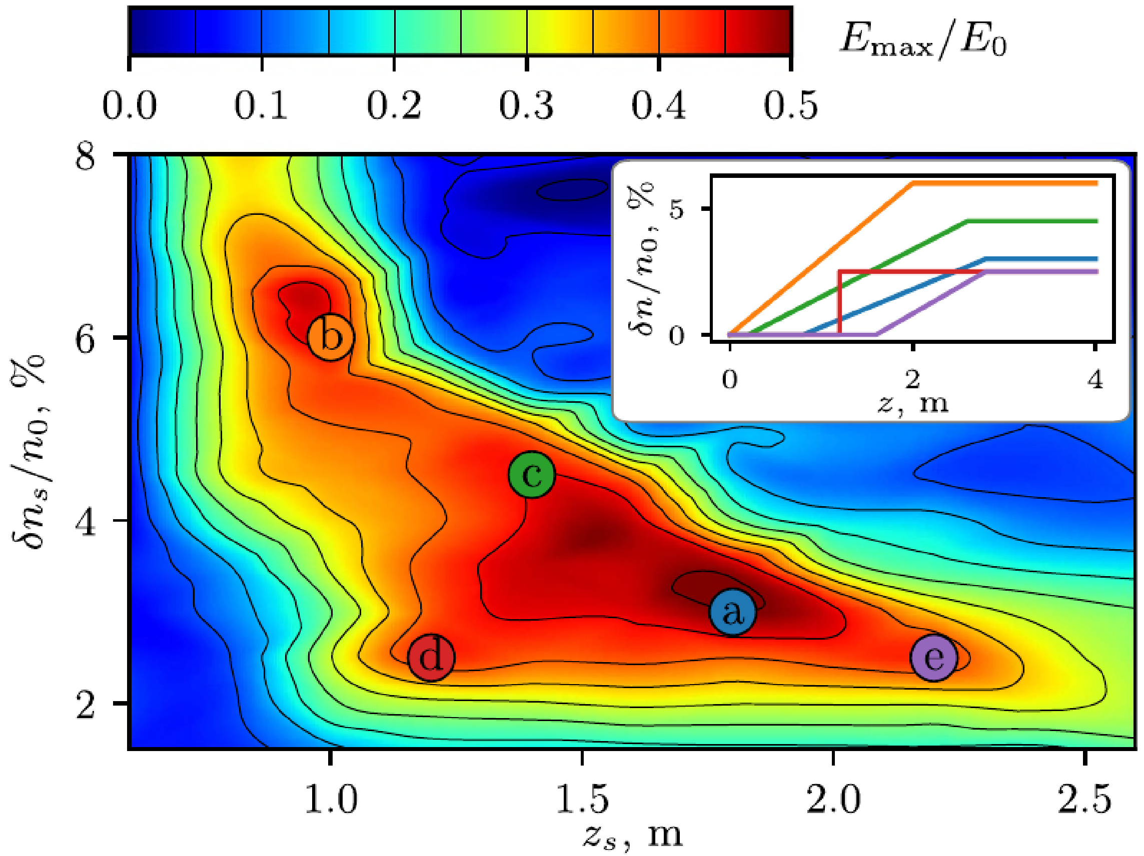
Energy gain of ~150 GeV in 200 m (after beamloading)



Lotov and Tuev, PPCF (2021)

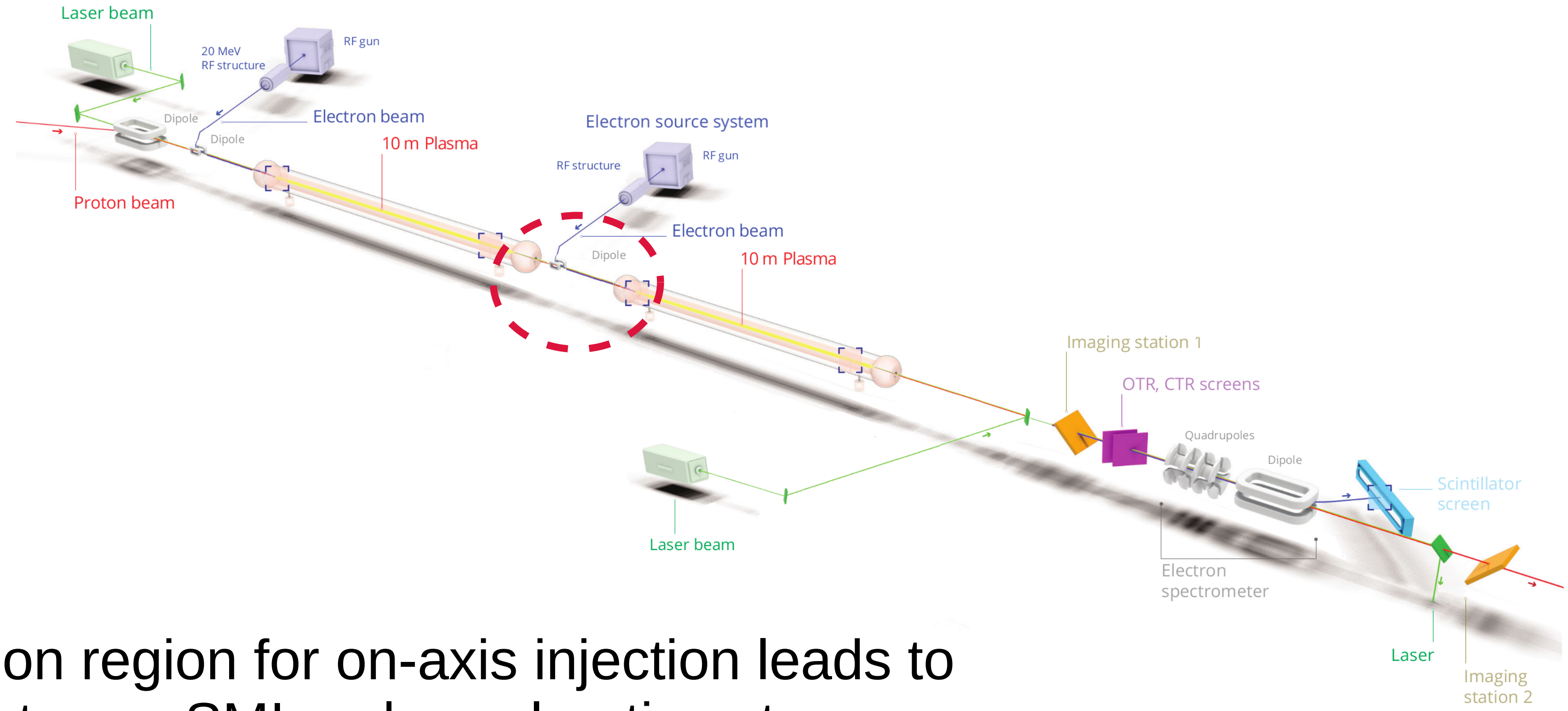
Controlling Self-modulation

Wakefields after 20 metres show broad tolerances for step position and height.



Lotov and Tuev, PPCF (2021)

Controlling Self-modulation



Integration region for on-axis injection leads to a gap between SMI and acceleration stages.

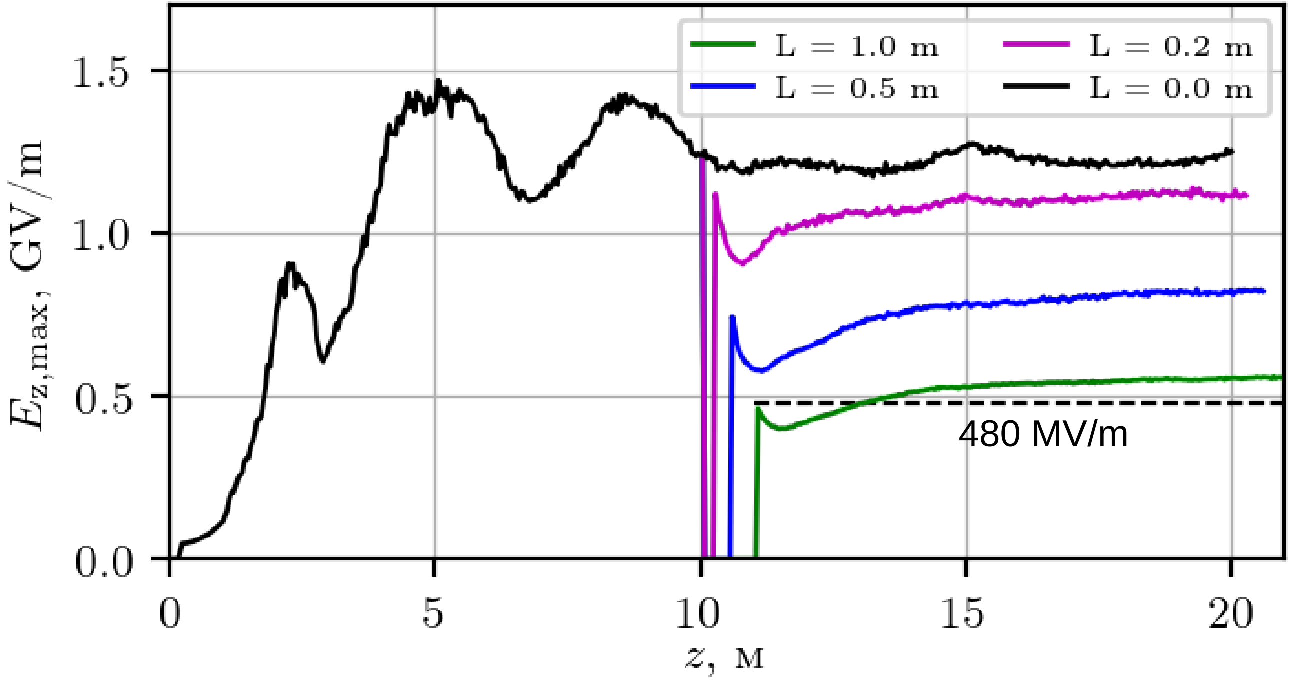
Modulated proton beam evolves in this gap.

Injection Studies

Gap reduces wakefields,
but amplitude remains stable.

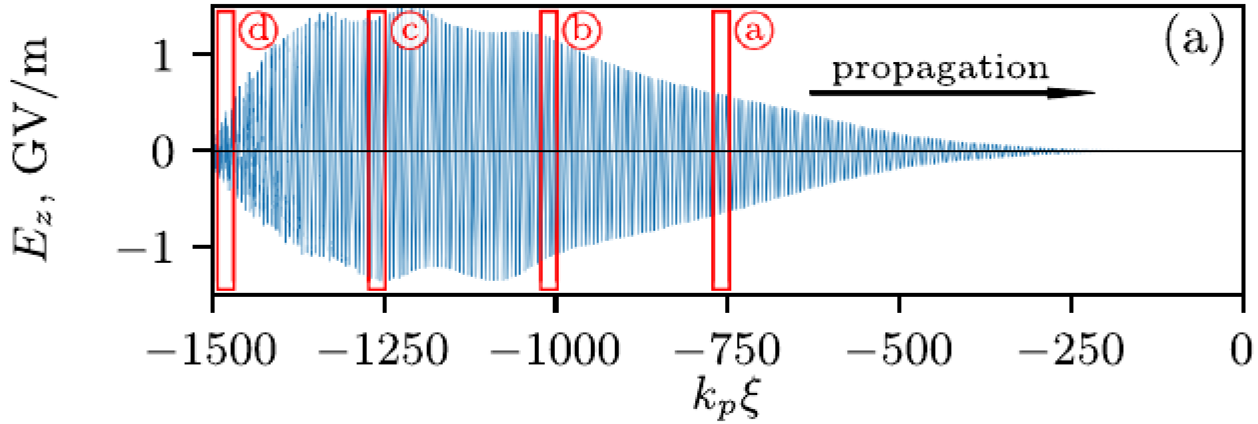
Accelerating gradient
depends on gap length.

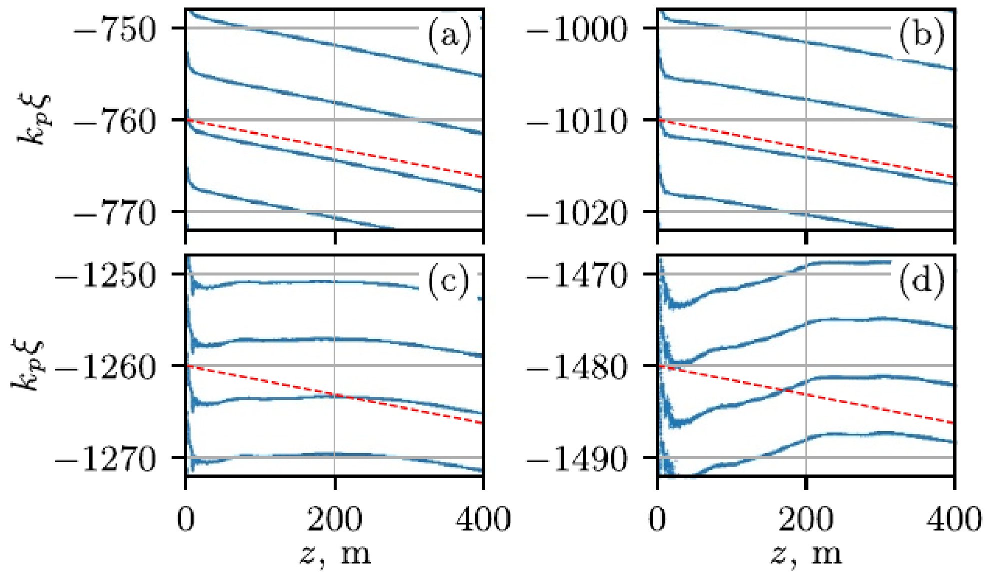
Assume 1 m gap (480 MV/m)
as “worst case” scenario.



V. Yarygova (2023)

Injection Studies





SMI growth allows wakefields with luminal phase.

Lotov and Tuev, 2021

Assume wakefield phase velocity equals proton velocity as “worst case” scenario

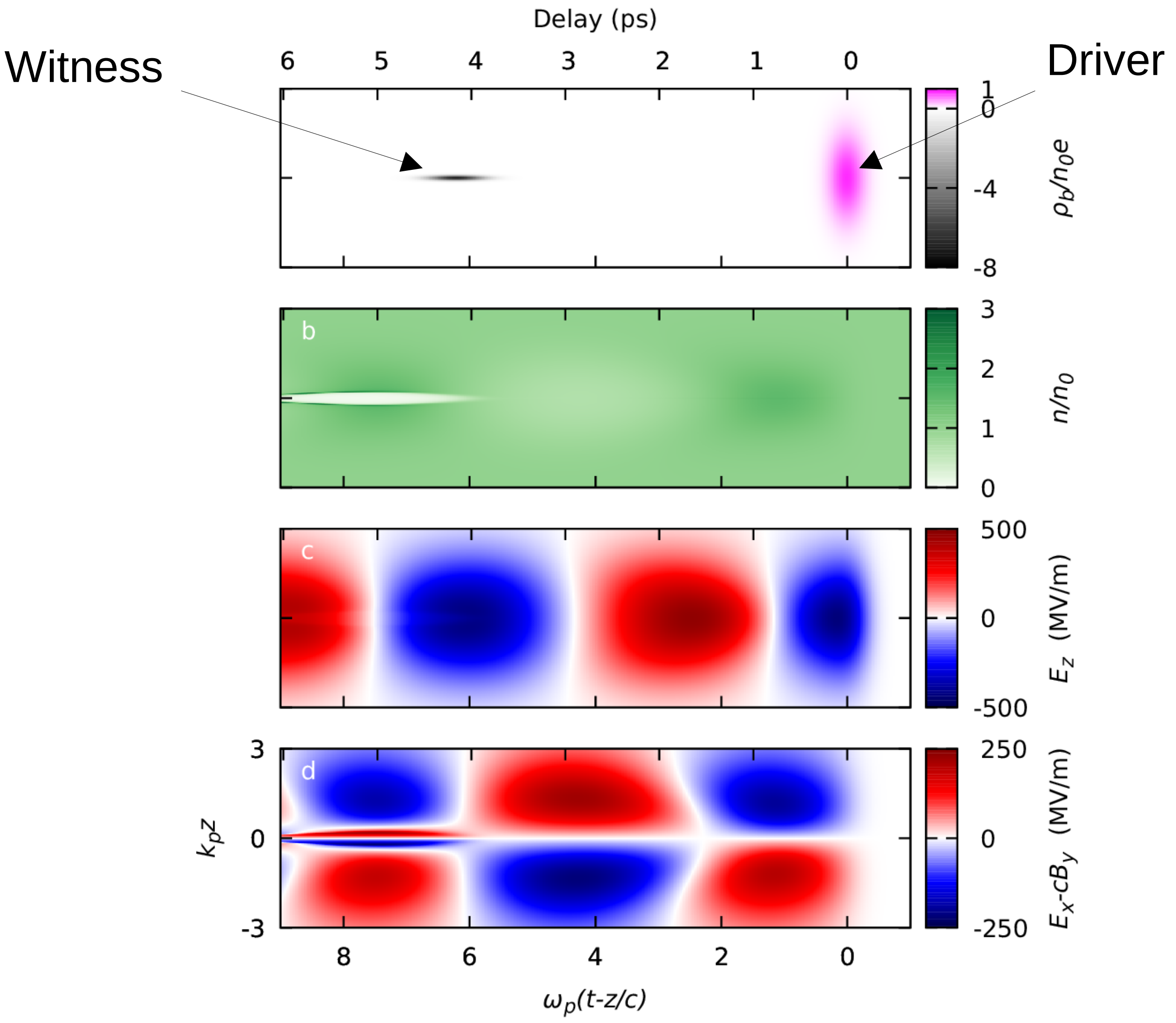
Blue – wakefield phase
Red – driver velocity

Injection Studies

These assumptions allow physics studies using "toy models".

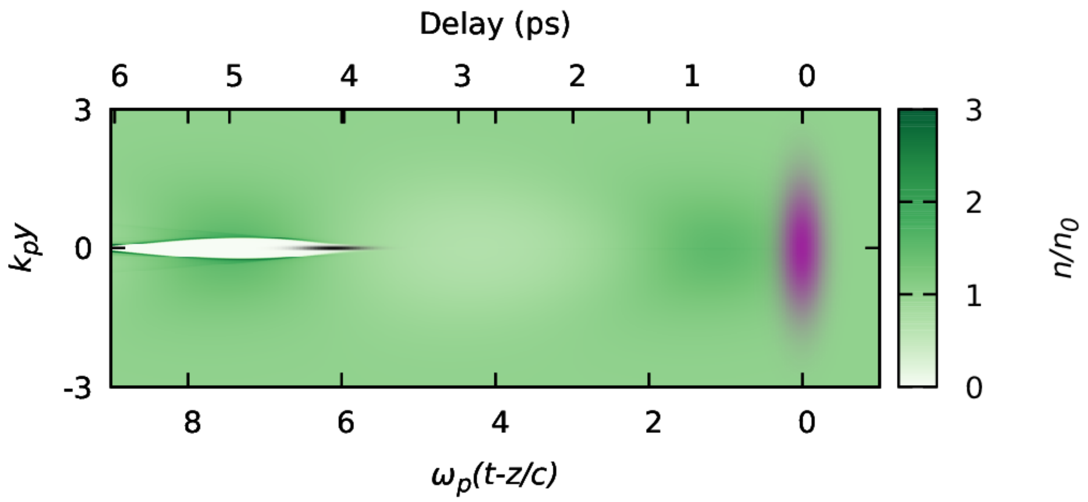
Short driver generates a quasilinear wake (E_z=480 MV/m, γ_ϕ=426).

Allows rapid investigation of parameter space.



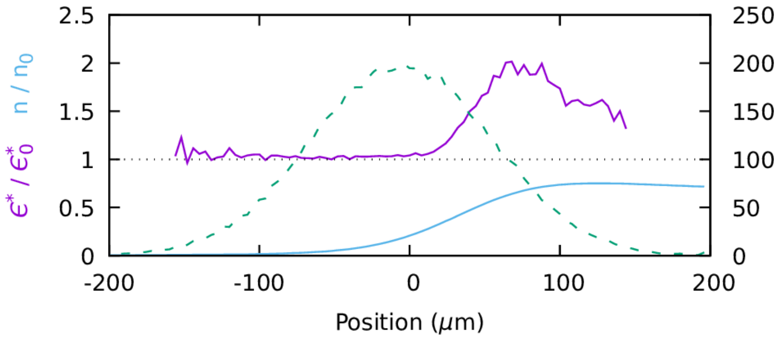
V. Olsen *et al.*, PRAB (2018)
J. Farmer *et al.*, *in preparation*

Injection Studies



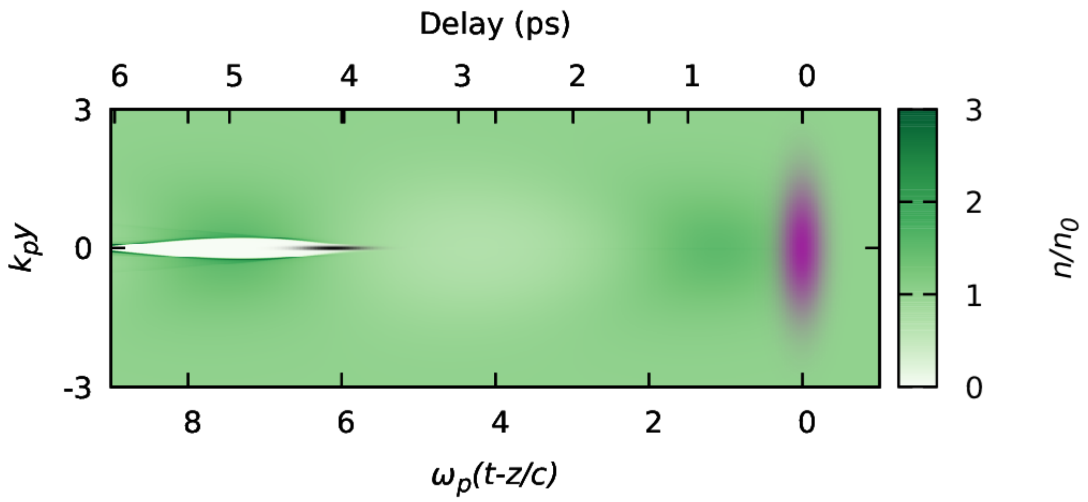
Conventional wisdom:
need a blowout to conserve emittance.

Low-emittance witness drives its own!



Witness slice emittance
after 10m acceleration

Injection Studies



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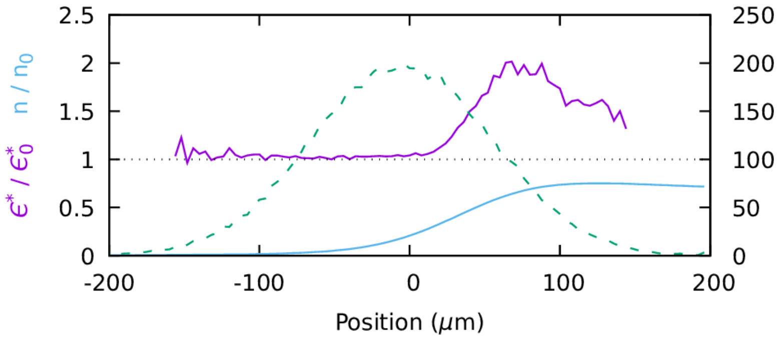
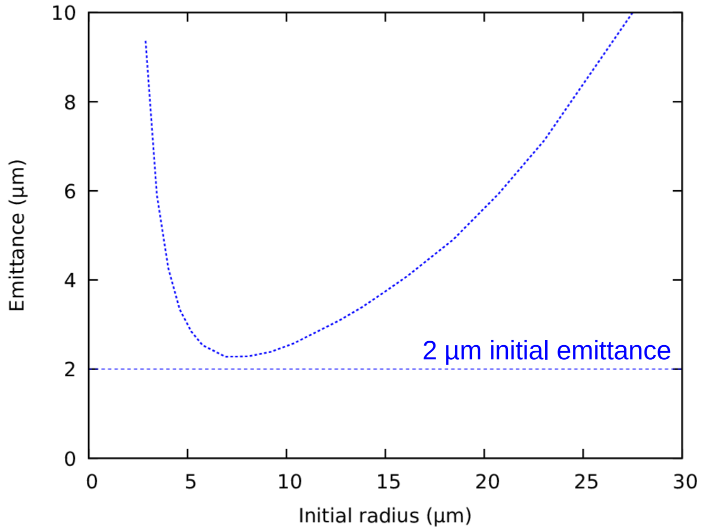


Witness slice emittance after 10m acceleration

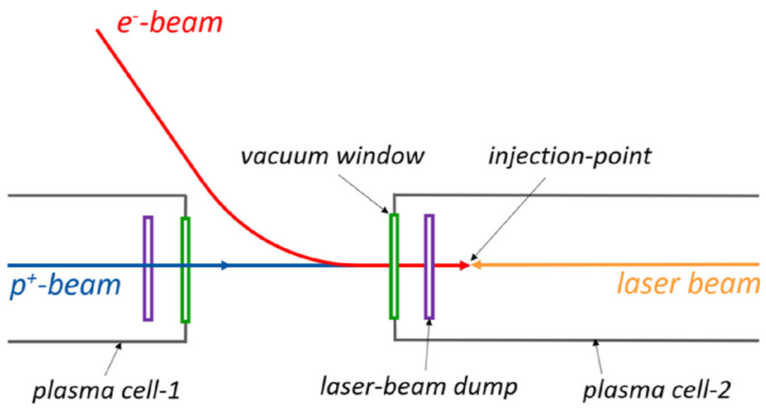
Projected emittance after 10m acceleration has only weak dependence on initial radius (5-15μm)

- broad tolerances



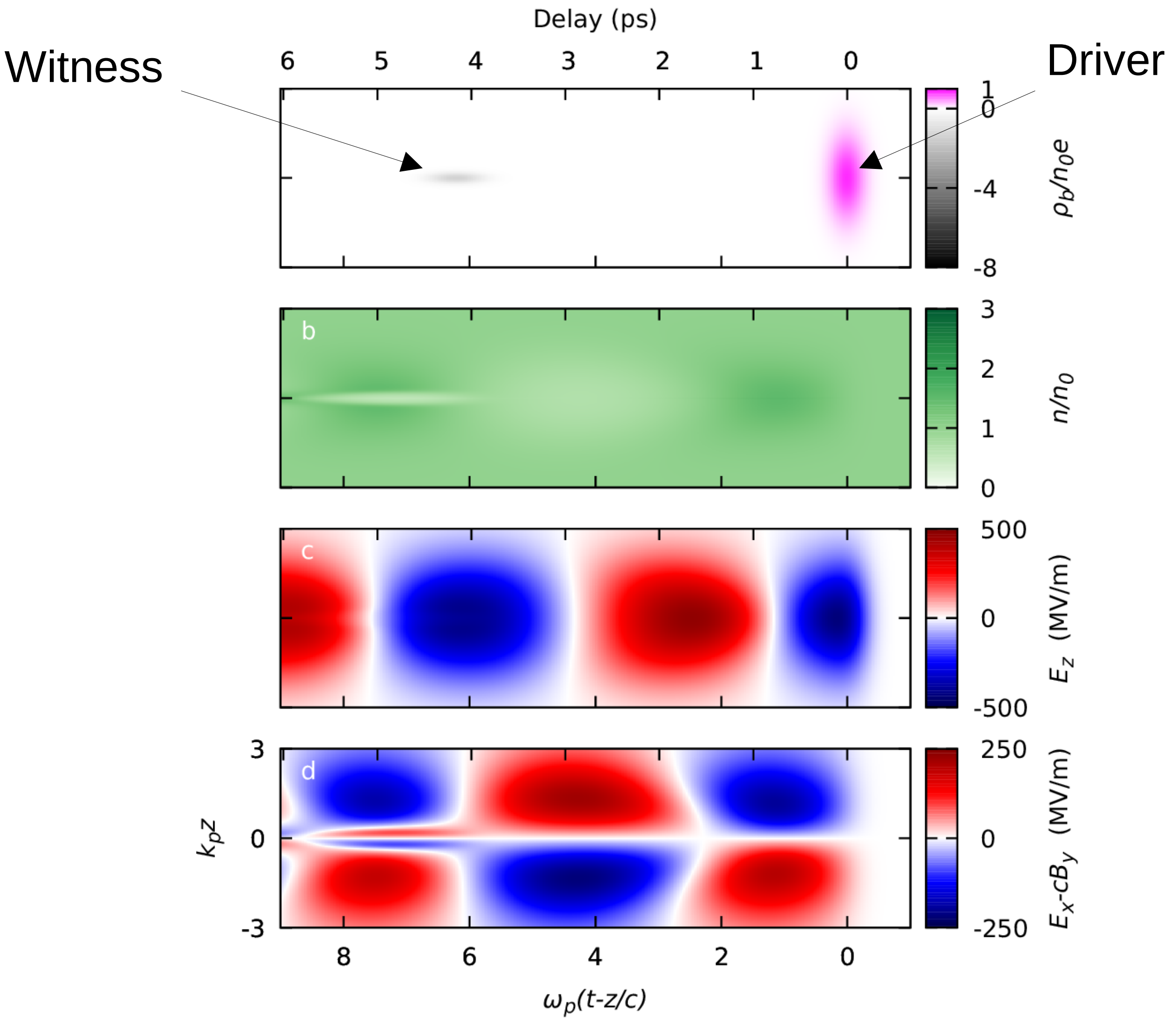
Witness projected emittance after 10m acceleration

Injection Studies



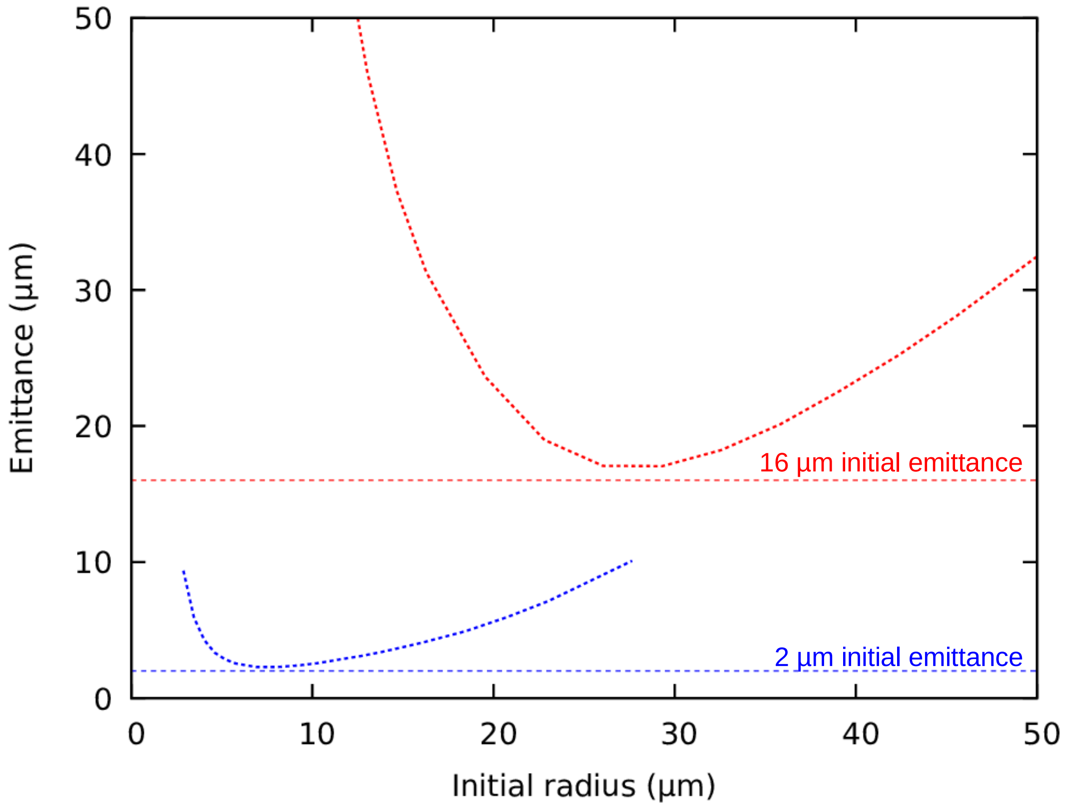
Technical constraints mean that it may be necessary to inject through the laser beam dump.

This will lower the charge density of the beam in the plasma, preventing the formation of a complete blowout.



J. Farmer *et al.*, *in preparation*

Injection Studies



Projected normalized emittance after 10m acceleration for different initial radii

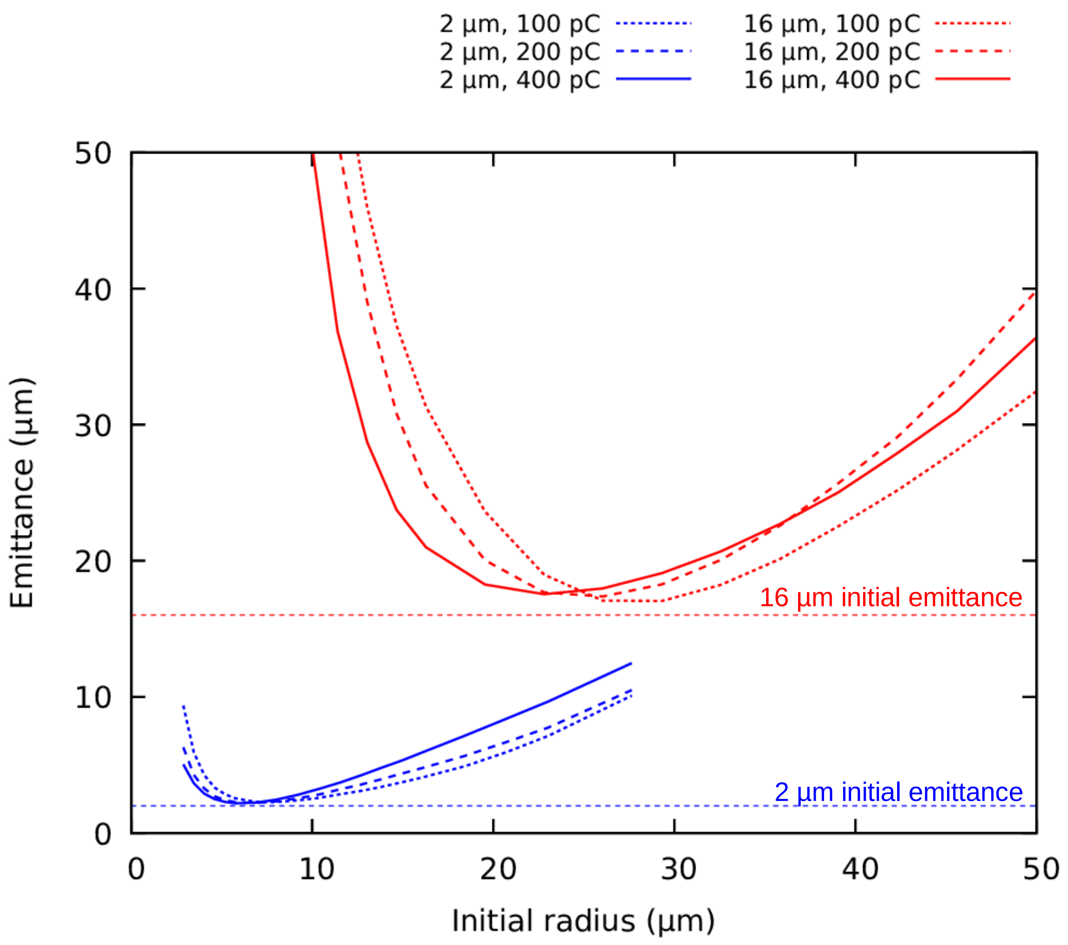
Emittance control *is* still possible with higher-emittance beams

- "quasi-matching" to nonlinear wakefield
- same broad tolerances

Similar schemes exist for positron beams

c.f. C. S. Hue *et al.* (2021)

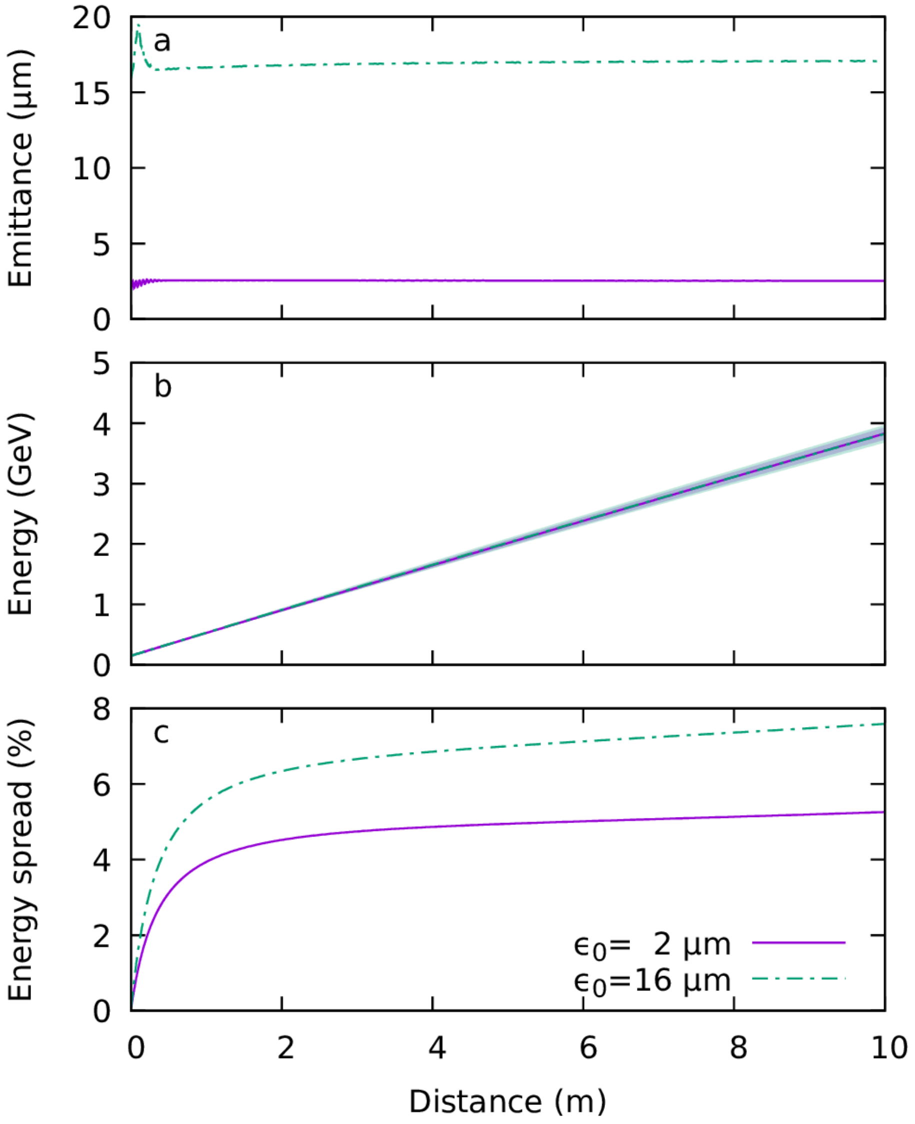
Injection Studies



Projected normalized emittance after
10m acceleration for different initial radii

Further optimisation possible through tuning electron line or varying witness charge

Injection Studies



Rapid initial evolution before reaching equilibrium.

- allows scaling to large distances/high energy.

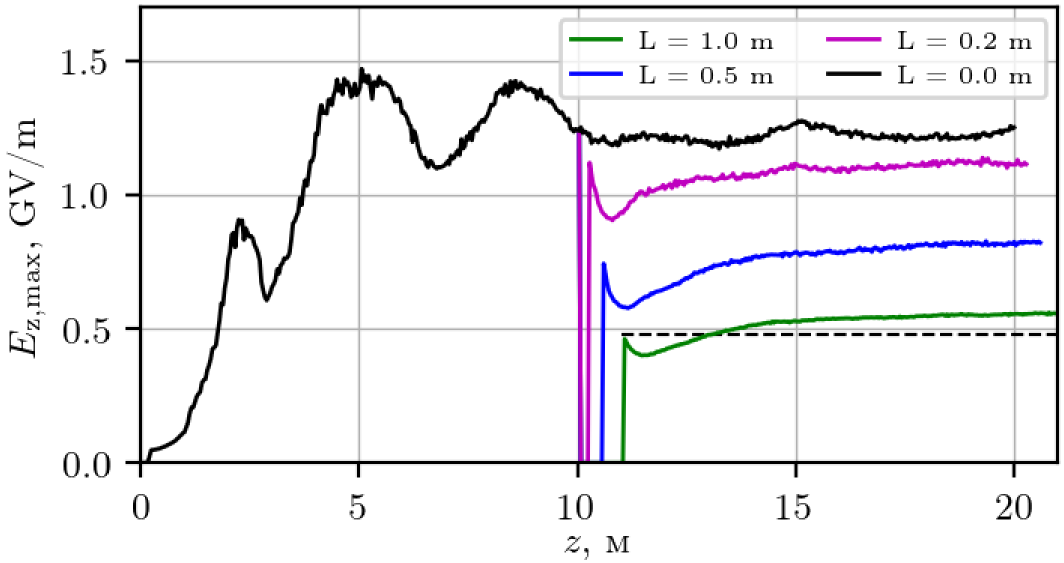
Over 10m:

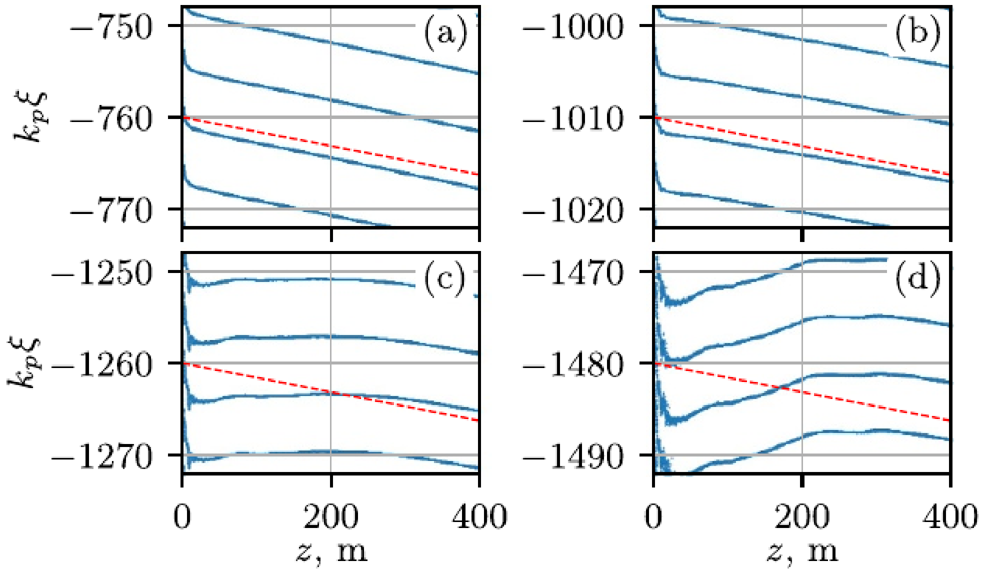
- negligible emittance growth
- 4 GeV energy gain
- 5-8% energy spread

Injection Studies

Clear paths to improve these values:

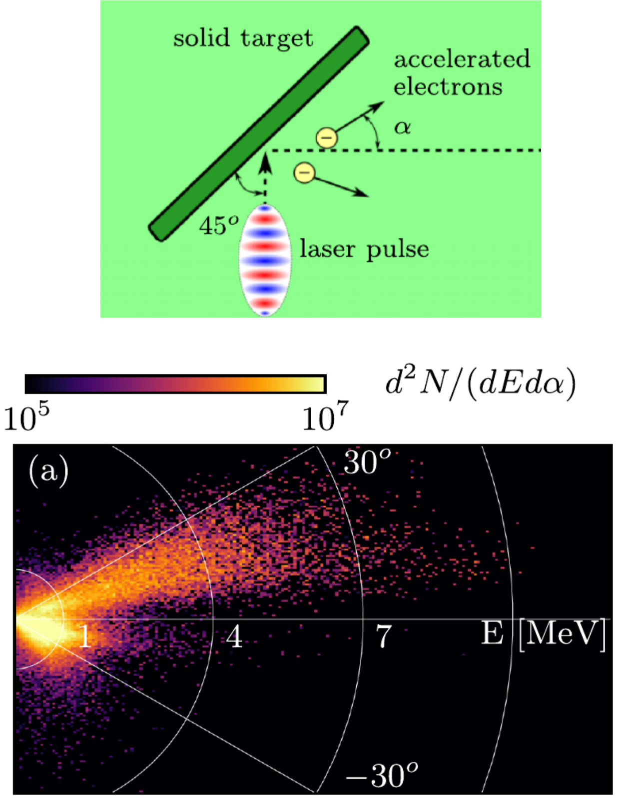
- smaller gap
- control wakefield phase



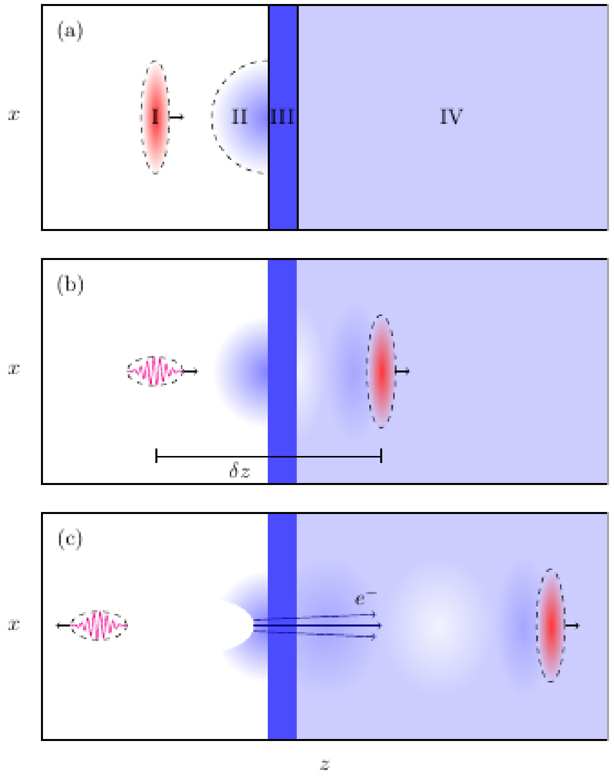


Alternative Injection Schemes

Laser-foil injector

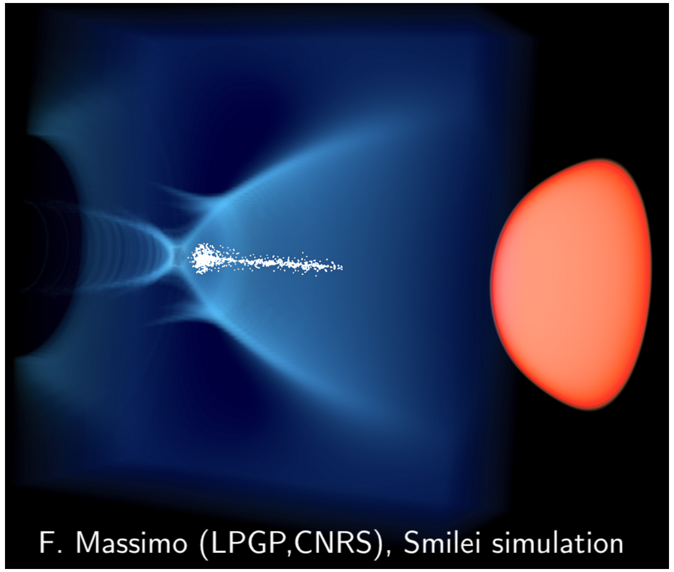


Khudiakov and Pukhov,
PRE (2021)



Wilson *et al.*
submitted.

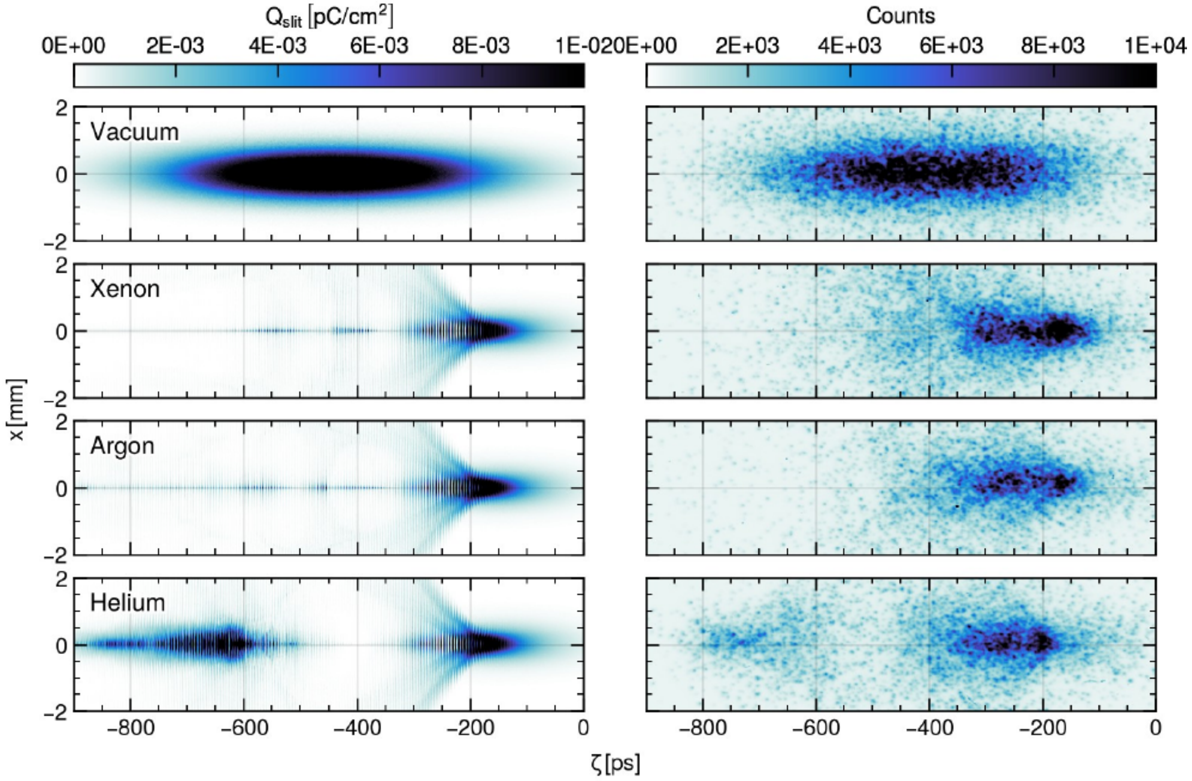
Laser-plasma injector



Minenna *et al.*
(EARLI Collaboration),
submitted.

Associated Physics

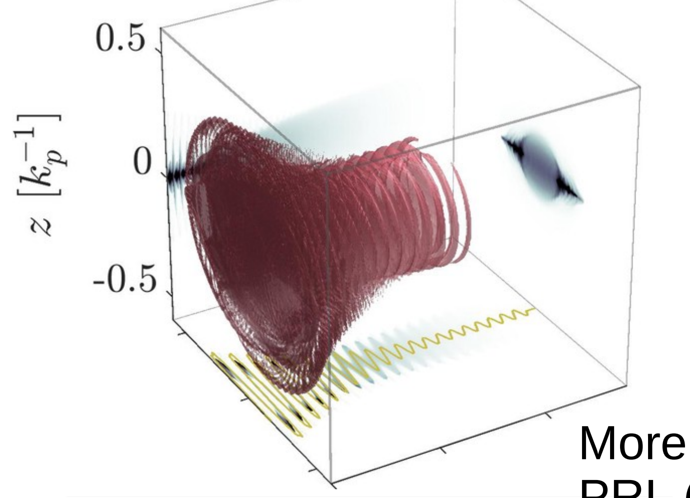
Ion motion



E. Walter *et al.*,
in preparation

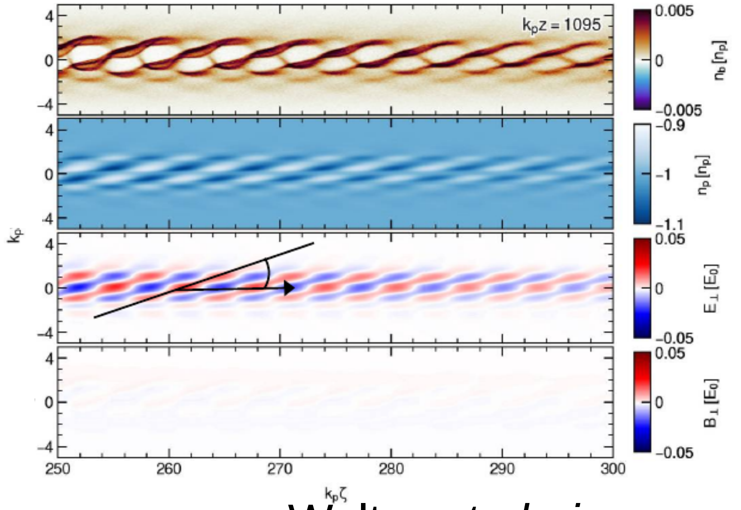
M. Turner *et al.*,
in preparation

Control of hosing



Moreira *et al.*,
PRL (2023)

Filamentation



Walter *et al.*, *in preparation*

Impact Beyond AWAKE

Development and validation of simulation tools

Excellent test bed for global push towards
High Performance Computing at the exascale

Tolerances for external injection in quasilinear wakes

- also relevant for positron acceleration

Outlook

Comprehensive simulation programme ahead of Run 2c:

- integrated simulations, simultaneously resolving witness bunch emittance and full proton beam
- further optimisation to maximise gradients after the gap
- further optimisation of witness parameters at injection

Conclusions

AWAKE simulations have proven ability to predict and reproduce experimental results.

Physics studies carried out with simulations show

- control of wakefield gradients over long distances
- control of witness emittance during acceleration
- broad tolerances in both cases

<u>Provides confidence that the Run 2c/d goals are achievable</u>

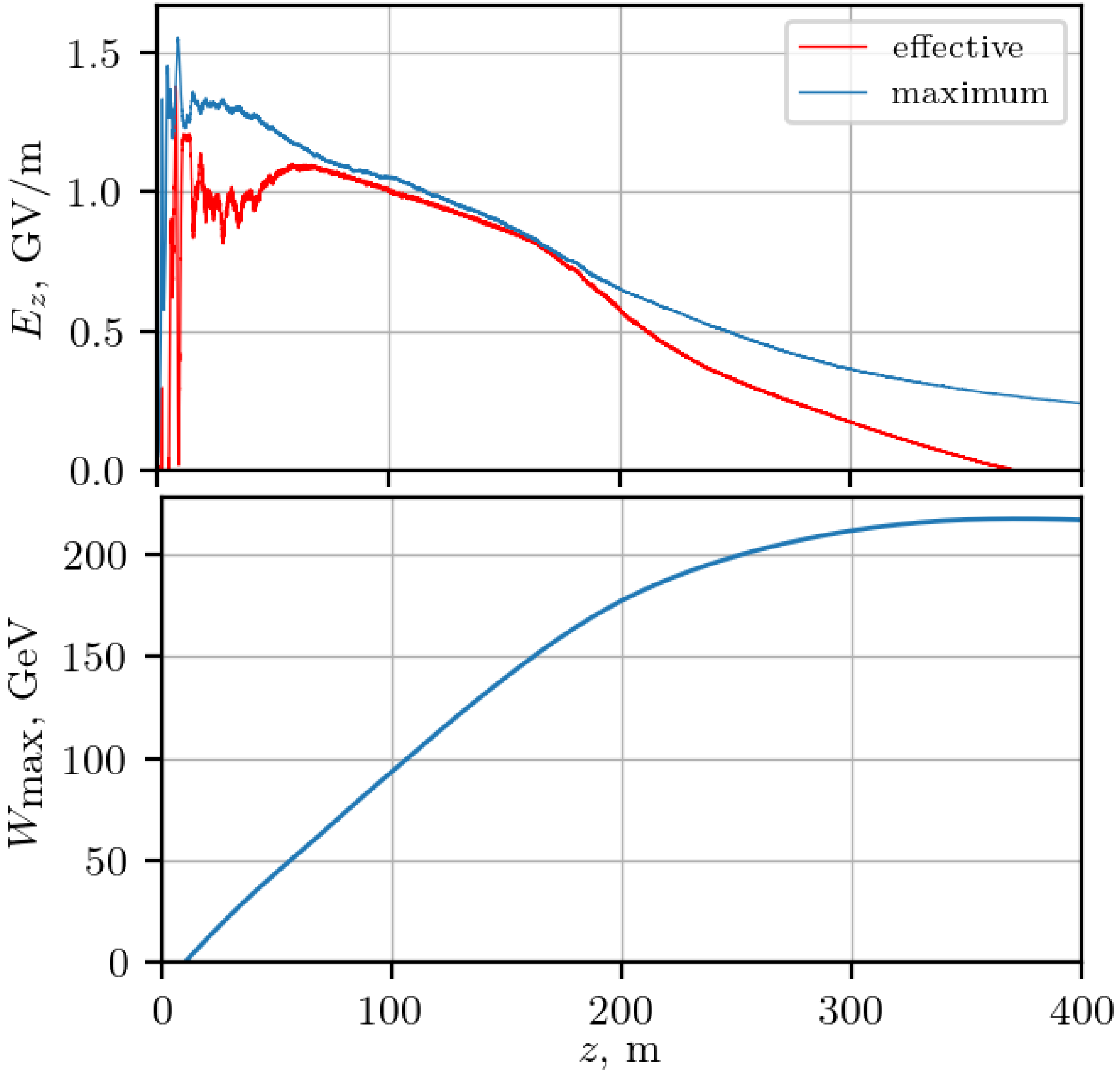
Thank you

Bonus content

Controlling Self-modulation

Density step allows high wakefield amplitude over hundreds of metres.

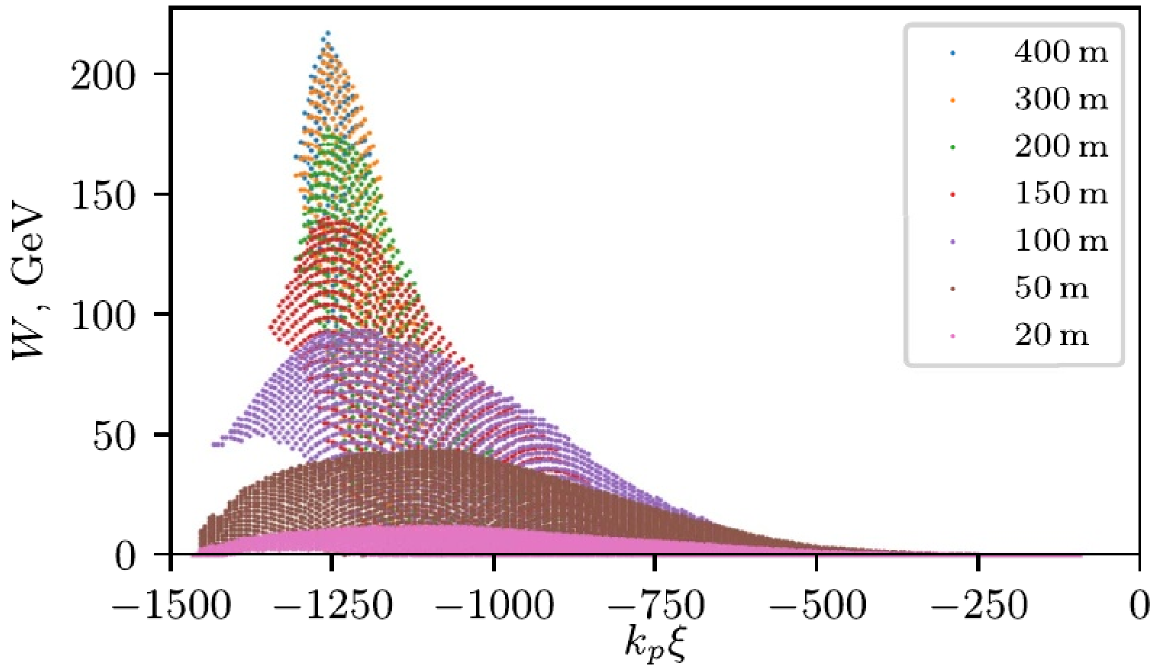
Energy gain of ~150 GeV in 200 m (after beamloading)



Controlling Self-modulation

What are the constraints for injection?

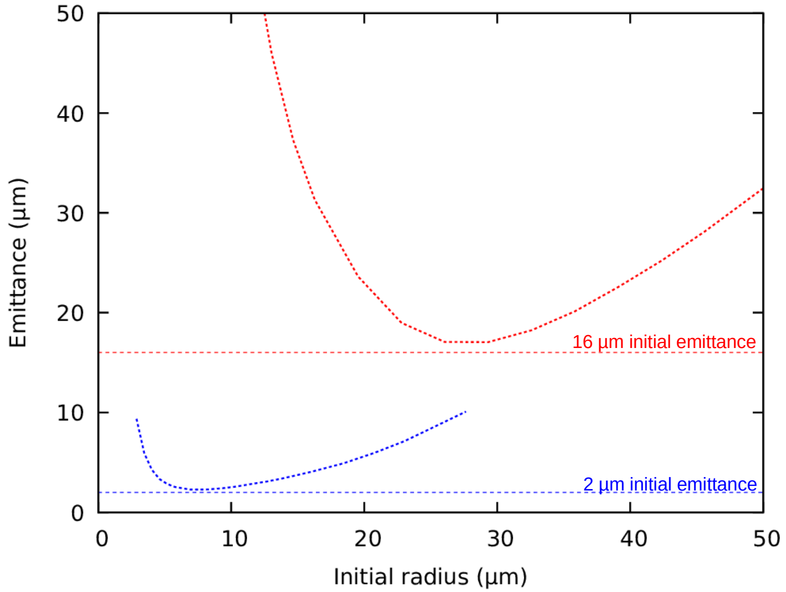
- For first 40 m acceleration, broad tolerances for witness delay



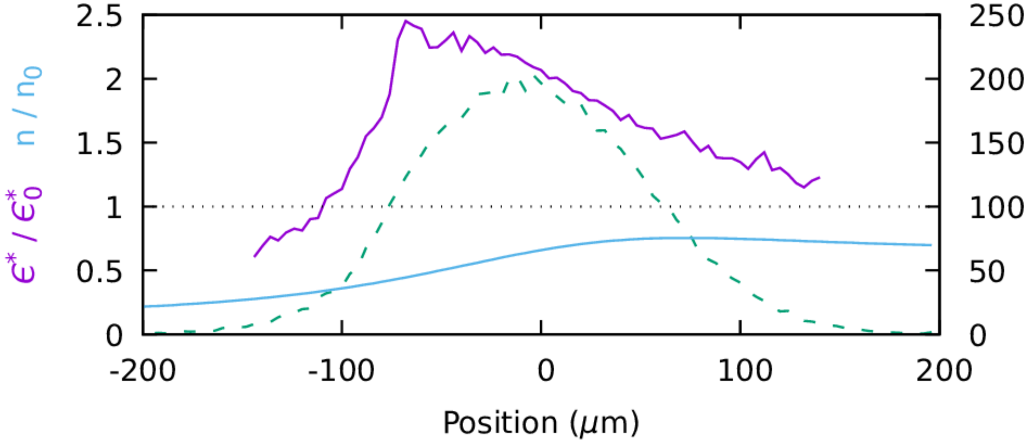
Lotov and Tuev,
Plasma Phys. Control. Fusion (2021)

Injection Studies

Emittance after 10 m acceleration for 16 µm initial emittance.

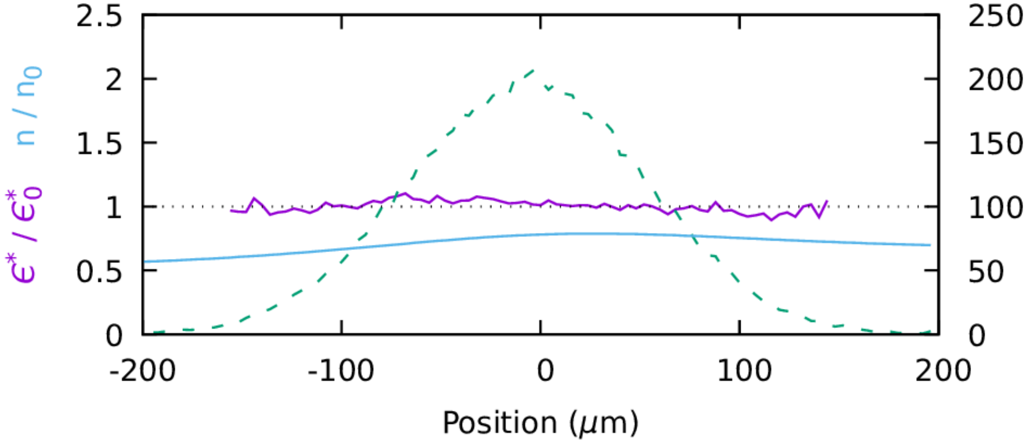


Blowout-matched radius



ϵ^*_0 = 16 µm, σ_0 = 16 µm

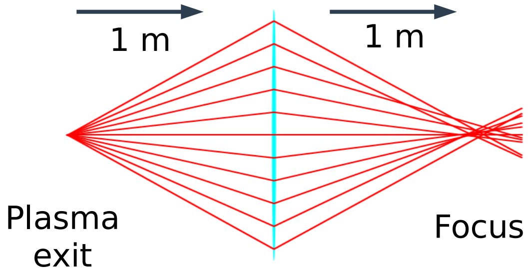
Optimal radius (self-matching)

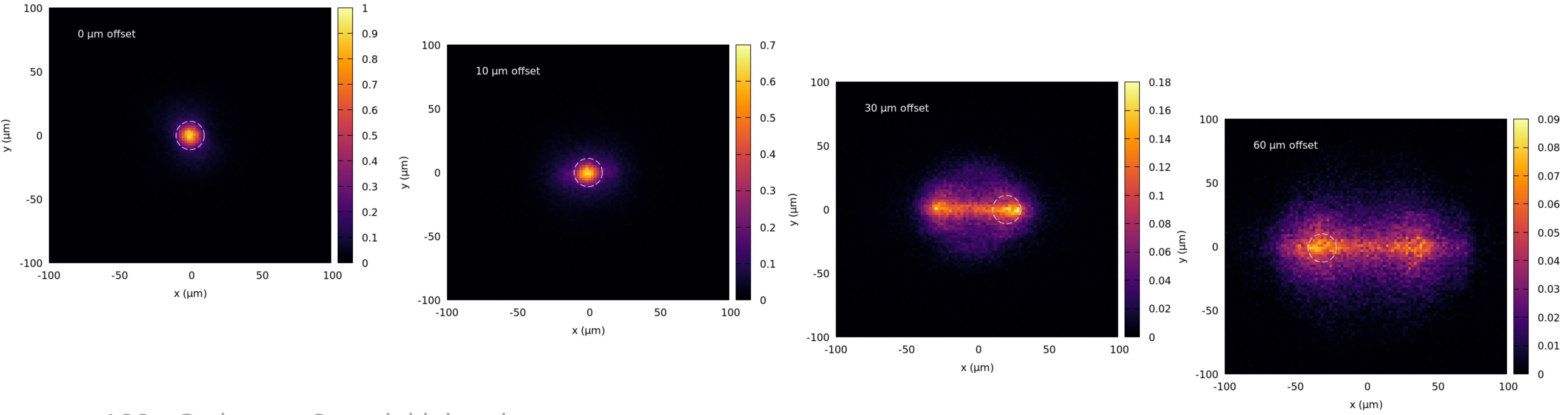


ϵ^*_0 = 16 µm, σ_0 = 26 µm

Injection Studies

Simulations for different transverse offsets show smeared-out bunch at focus.

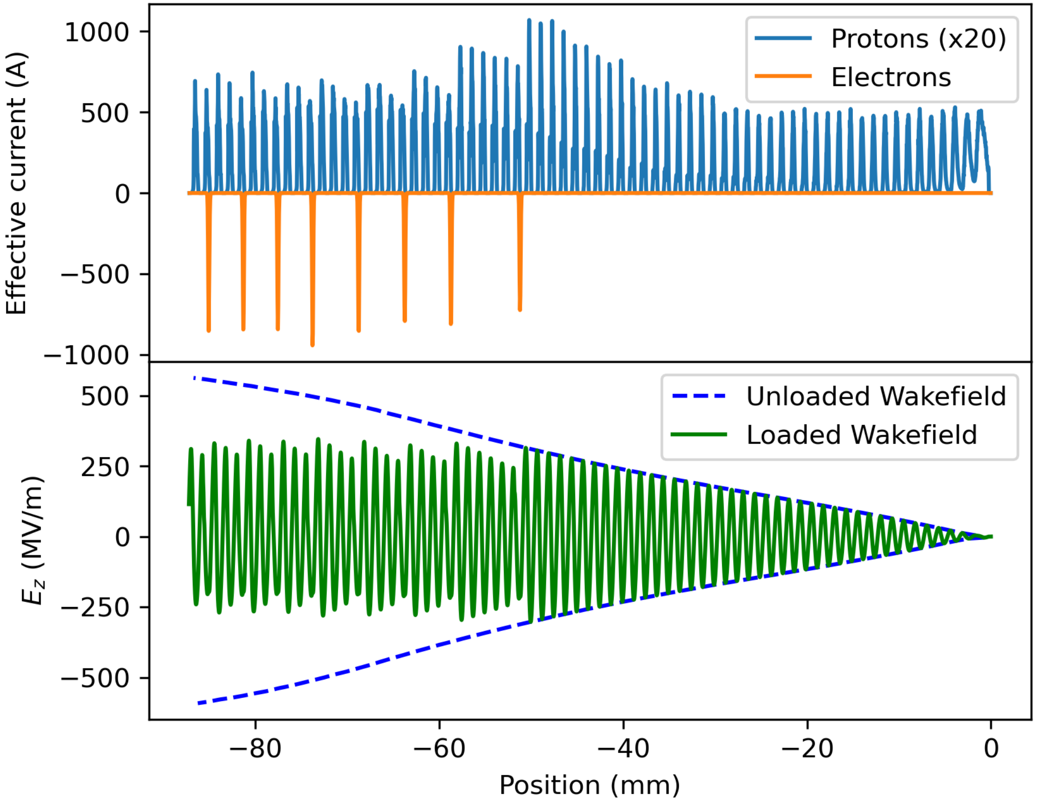




100 pC charge, 8 μm initial emittance

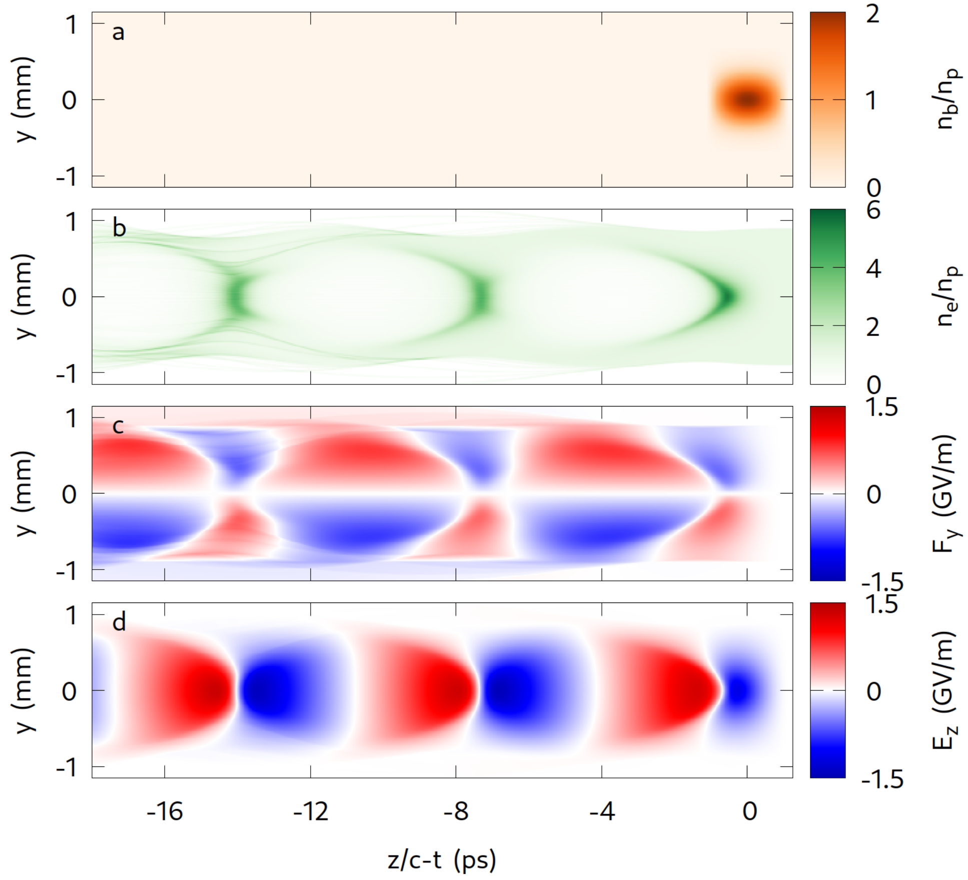
Beyond Run 2

Multi-bunch injection



Farmer and Zevi Della Porta
in preparation

Short-proton driver



Farmer, Caldwell and Pukhov,
in preparation