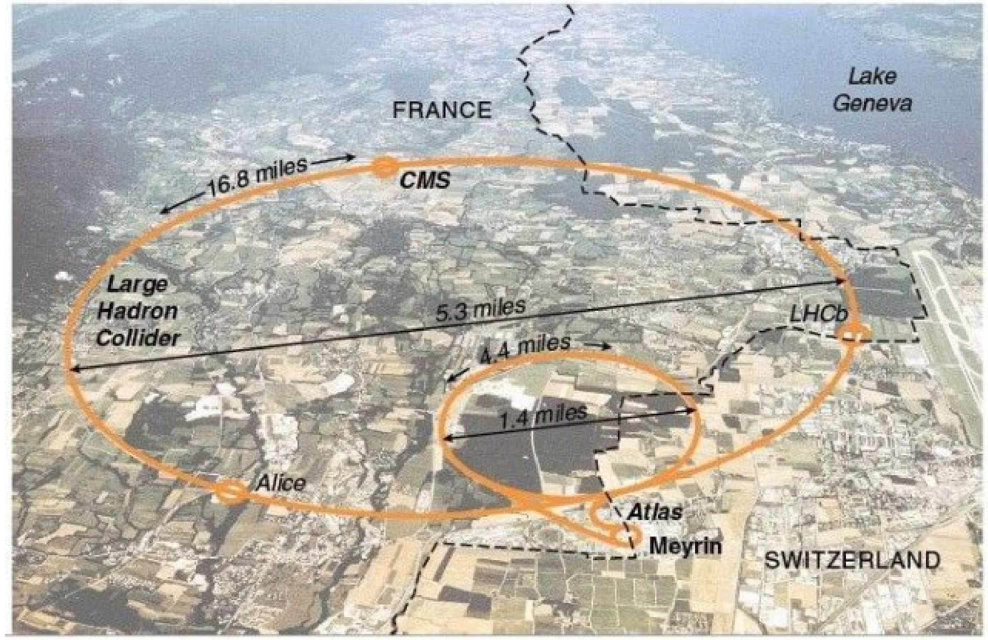
Preliminary Investigation of a Higgs Factory based on Proton-Driven Plasma Wakefield Acceleration

July 2024

J. Farmer, A. Caldwell, and A. Pukhov

Motivation

Current state-of-the-art for accelerators is the LHC



- Why large?
- Why hadrons?

Alternatively, use a linac. Size determined by acceleration gradient.

Proton-driven PWFA

Use proton driver for plasma wakefield acceleration

- High accelerating gradients
- Plenty of driver energy, no need for staging.
- Protons drive quasi-nonlinear wake
  suitable (in principle) for positron acceleration

Short driver efficiently excites wakefield

Proton-driven PWFA

Use proton driver for plasma wakefield acceleration

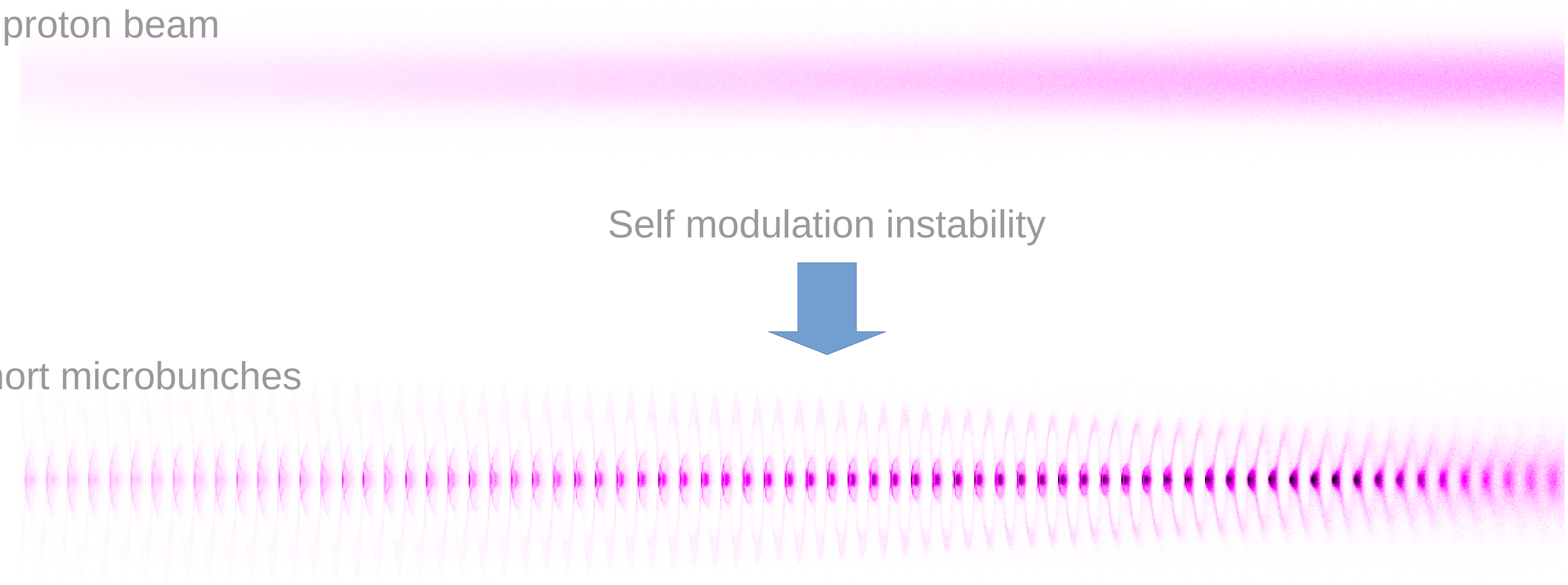
- requires short proton driver

Short driver efficiently excites wakefield

Long driver suppresses its own wake

Proton-driven PWFA

Focussing/defocussing fields in plasma



Resulting train of microbunches can drive large wakefields

Proton-driven PWFA

Focussing/defocussing fields in plasma

Resulting train of microbunches can drive large wakefields

Short proton drivers revisited

It's worth revisiting short proton drivers.

Pros:

Higher gradients

Higher efficiency

Cons:

Such drivers (L~150 µm) don't exist

Short proton drivers revisited

nature physics

ARTICLES

PUBLISHED ONLINE: 12 APRIL 2009; CORRECTED ONLINE: 24 APRIL 2009 | DOI: 10.1038/NPHYS1248

Proton-driven plasma-wakefield acceleration

Allen Caldwell[1]*, Konstantin Lotov[2,3], Alexander Pukhov[4] and Frank Simon[1,5]

Caldwell et al. (2009)

A short proton wakefield driver is not a new idea (2009).
Predates AWAKE! So why now?

Short proton drivers revisited

IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 32, NO. 6, SEPTEMBER 2022 4100404

Record High Ramping Rates in HTS Based Superconducting Accelerator Magnet

H. Piekarz, *Senior Member, IEEE*, S. Hays, B. Claypool, M. Kufer, and V. Shiltsev, *Fellow, IEEE*

Piekarz et al. (2022)

Developments in fast-ramping magnets would allow rapid-cycling (~5 Hz) synchrotrons.

Would allow for competitive luminosities for a proton-driven Higgs factory *if* bunch length can be achieved.

Configuration

(Symmetric) Higgs factory:
125 GeV e^- colliding with 125 GeV e^+

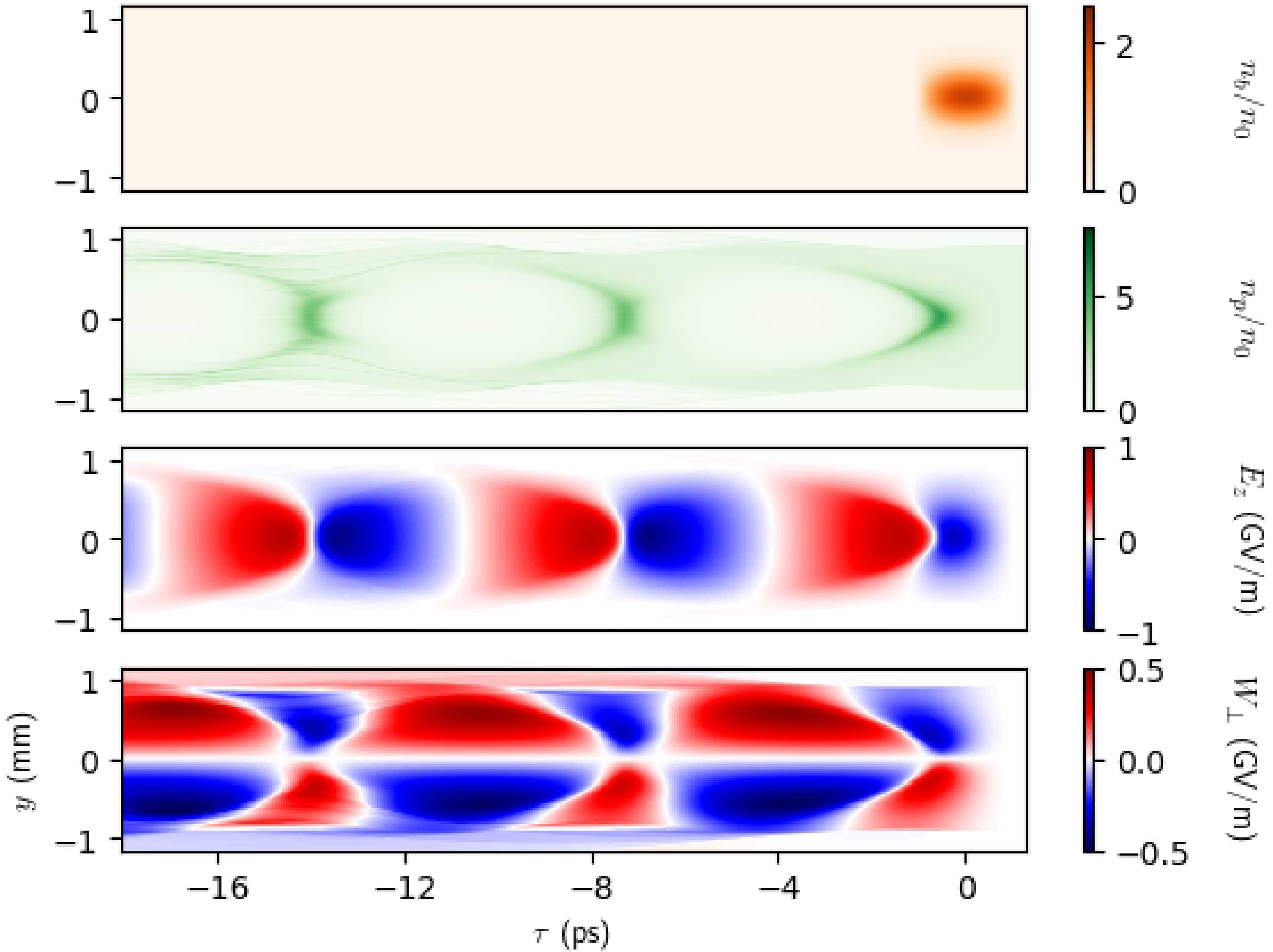
We need to demonstrate

- efficiency
- stability

Configuration

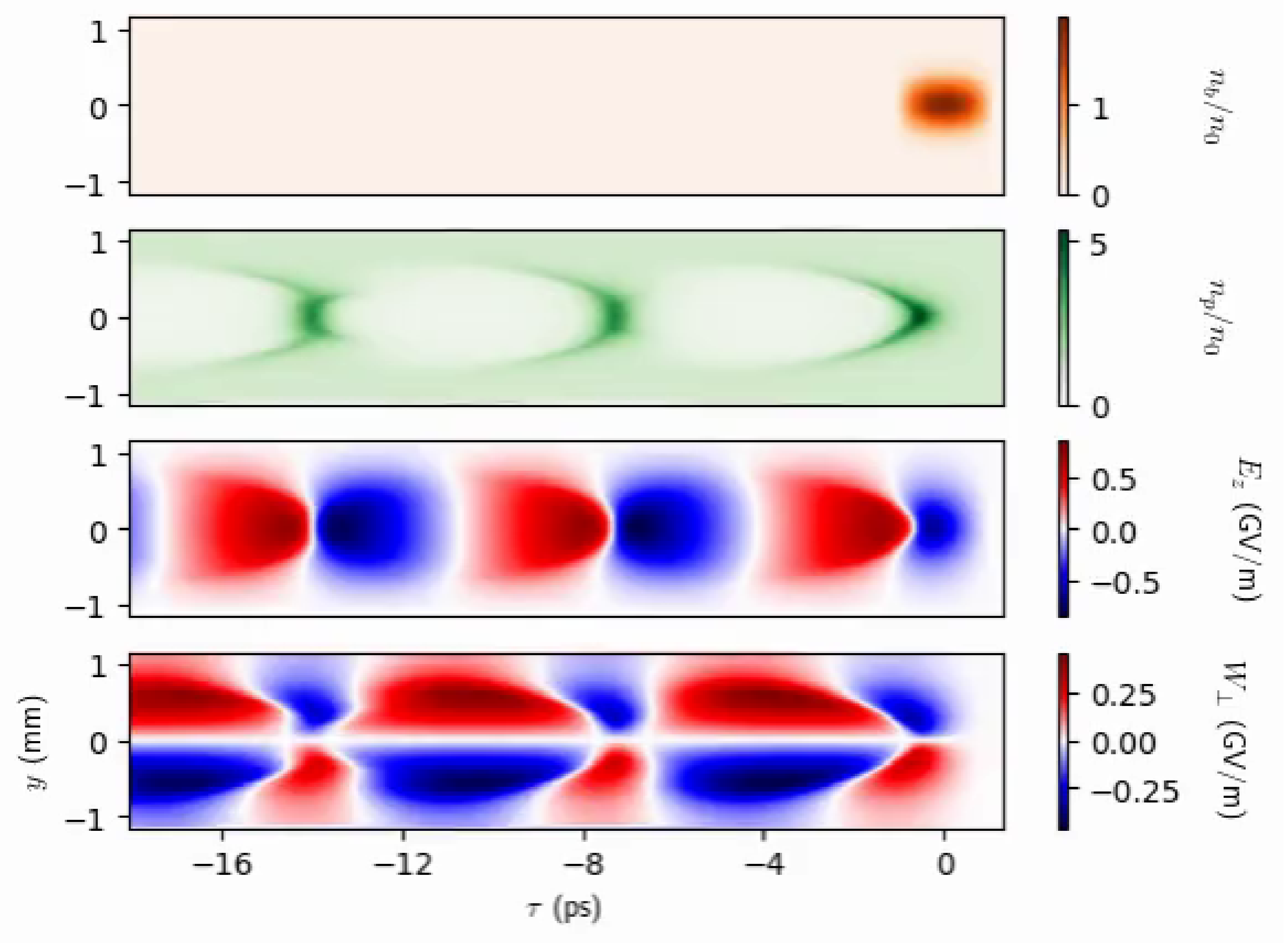
Initial proton driver chosen to generate suitable wakefields

Moderately nonlinear wakefield allows acceleration of both electrons and positrons



Picking the driver: stability

Initial proton driver chosen to generate suitable wakefields

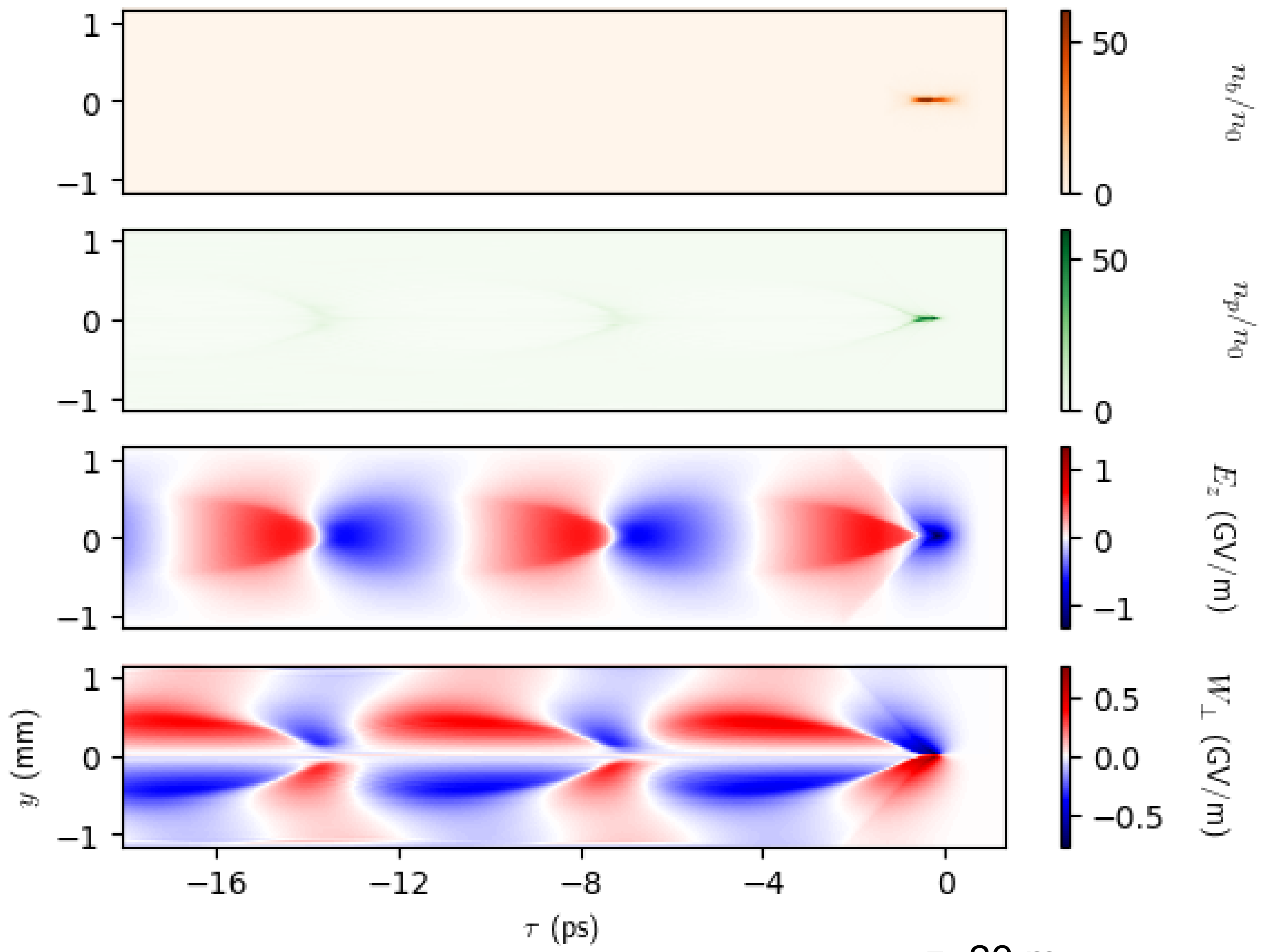


Picking the driver: stability

Initial proton driver chosen to generate suitable wakefields

Driver rapidly pinches

Highly nonlinear wakefield not suitable for positron acceleration



z=30 m

Picking the driver: stability

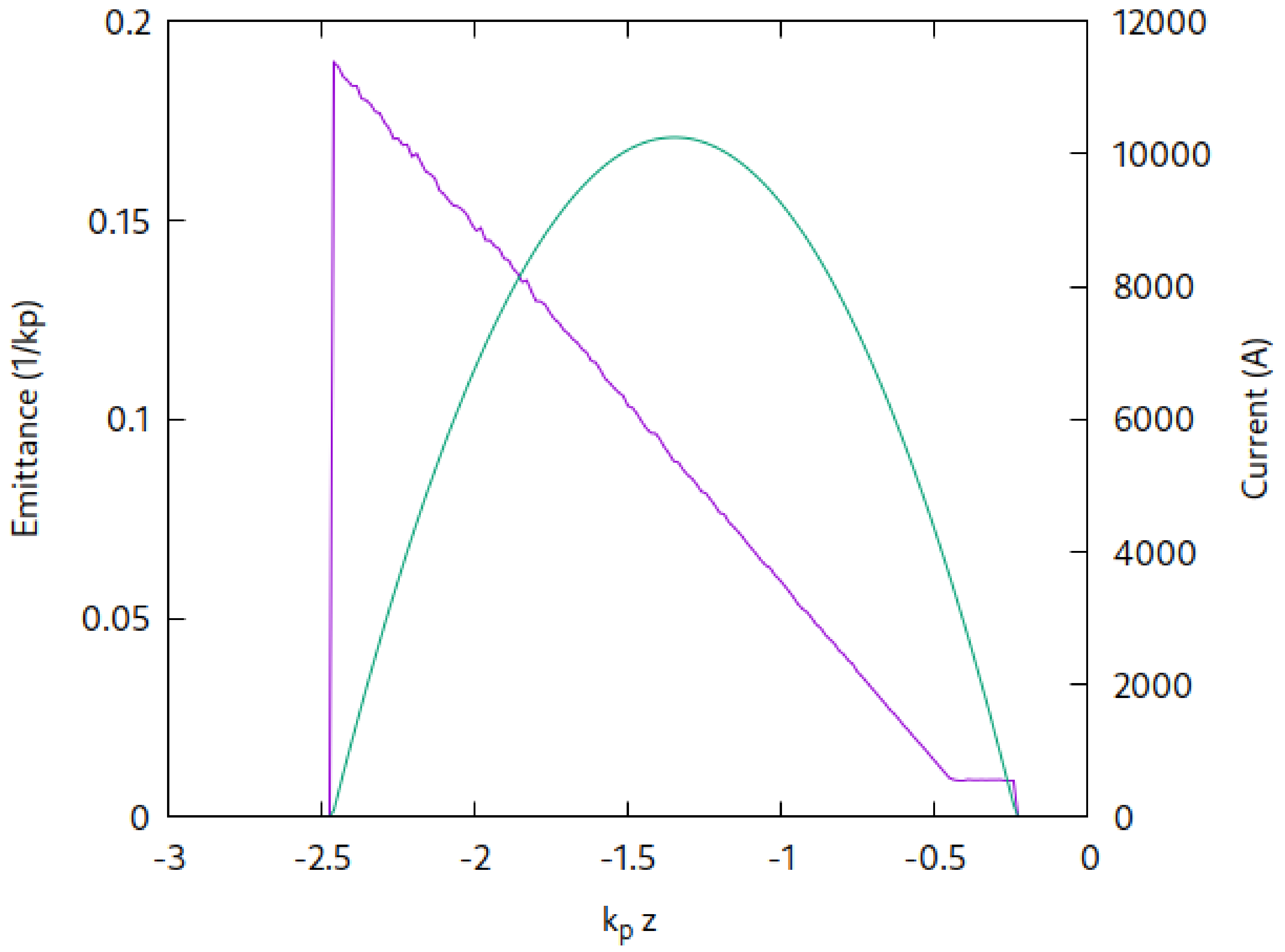
Good initial wakefields not sufficient:

- driver needs to evolve slowly
- counteract strong focussing wakefields

Picking the driver: stability

σ_z = 150 μm
σ_r = 240 μm
$n_b = 1 \times 10^{11}$
E = 400 GeV
ϵ_N = *tailored*

- 3 μm at head
- initially constant
- rises linearly to 75 μm

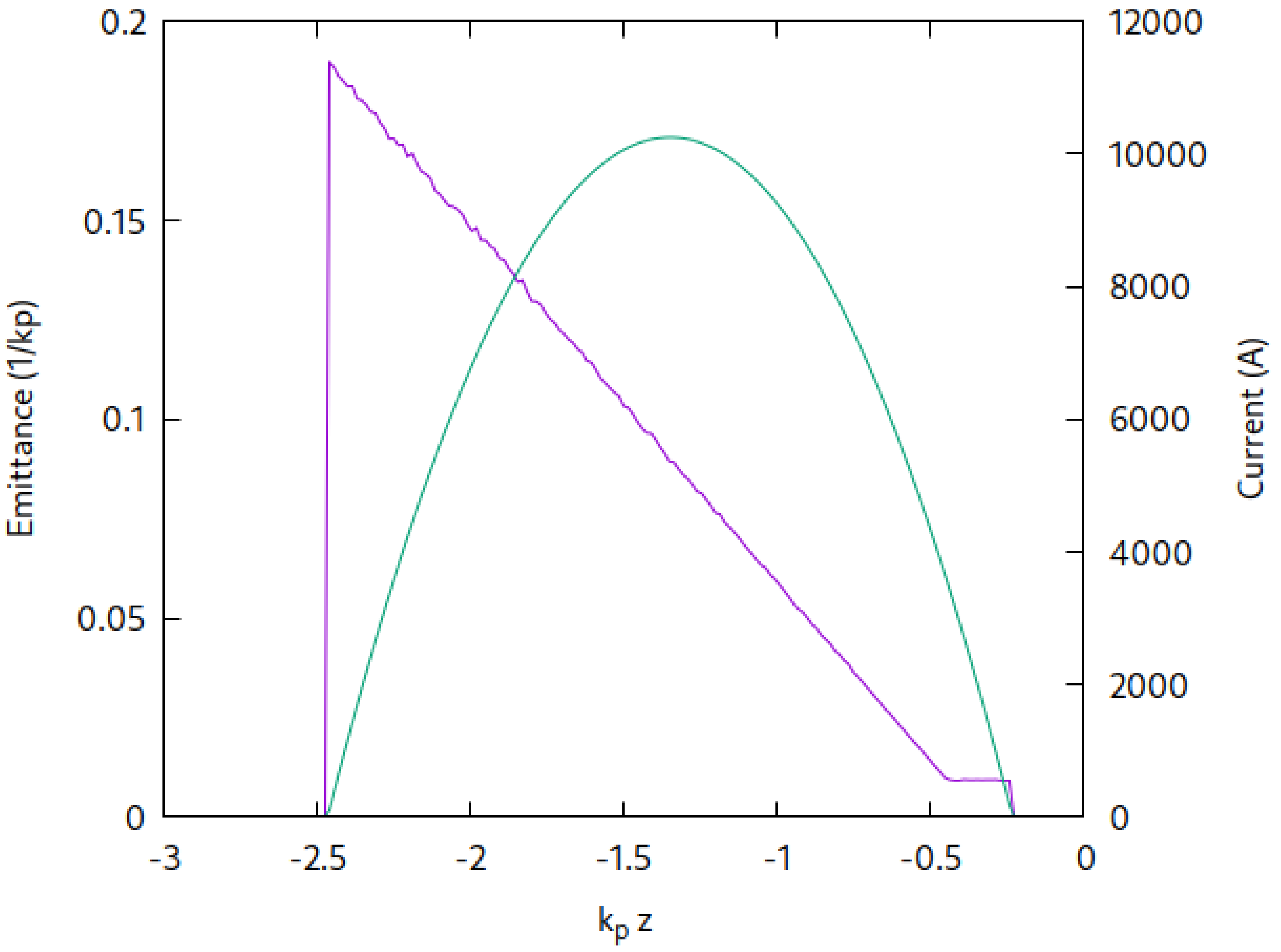


Picking the driver: stability

How can we generate a tailored emittance profile?

Most likely:
with difficulty

BUT emittance is initially constant before growing monotonically



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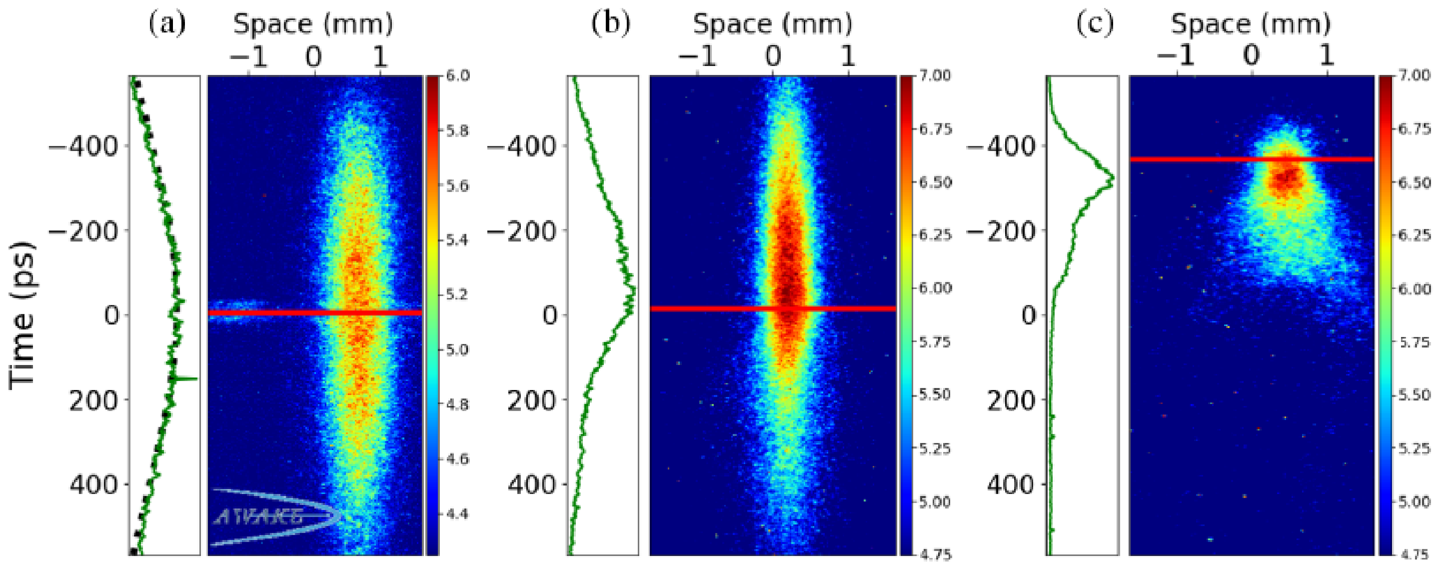
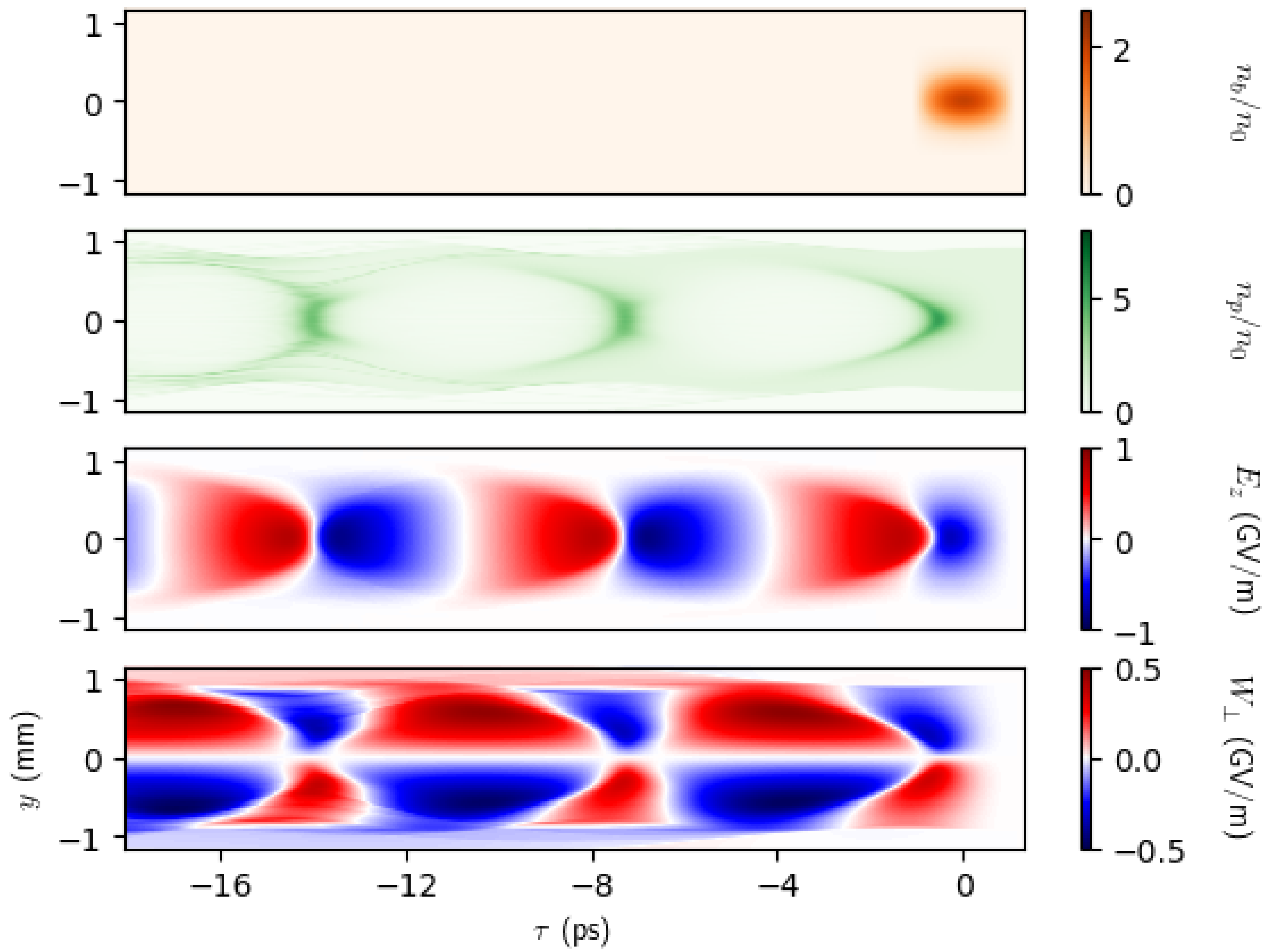


[AWAKE Collaboration, PRL (2019)]

Harness plasma instabilities?

Acceleration: dephasing

Initial proton driver chosen to generate suitable wakefields

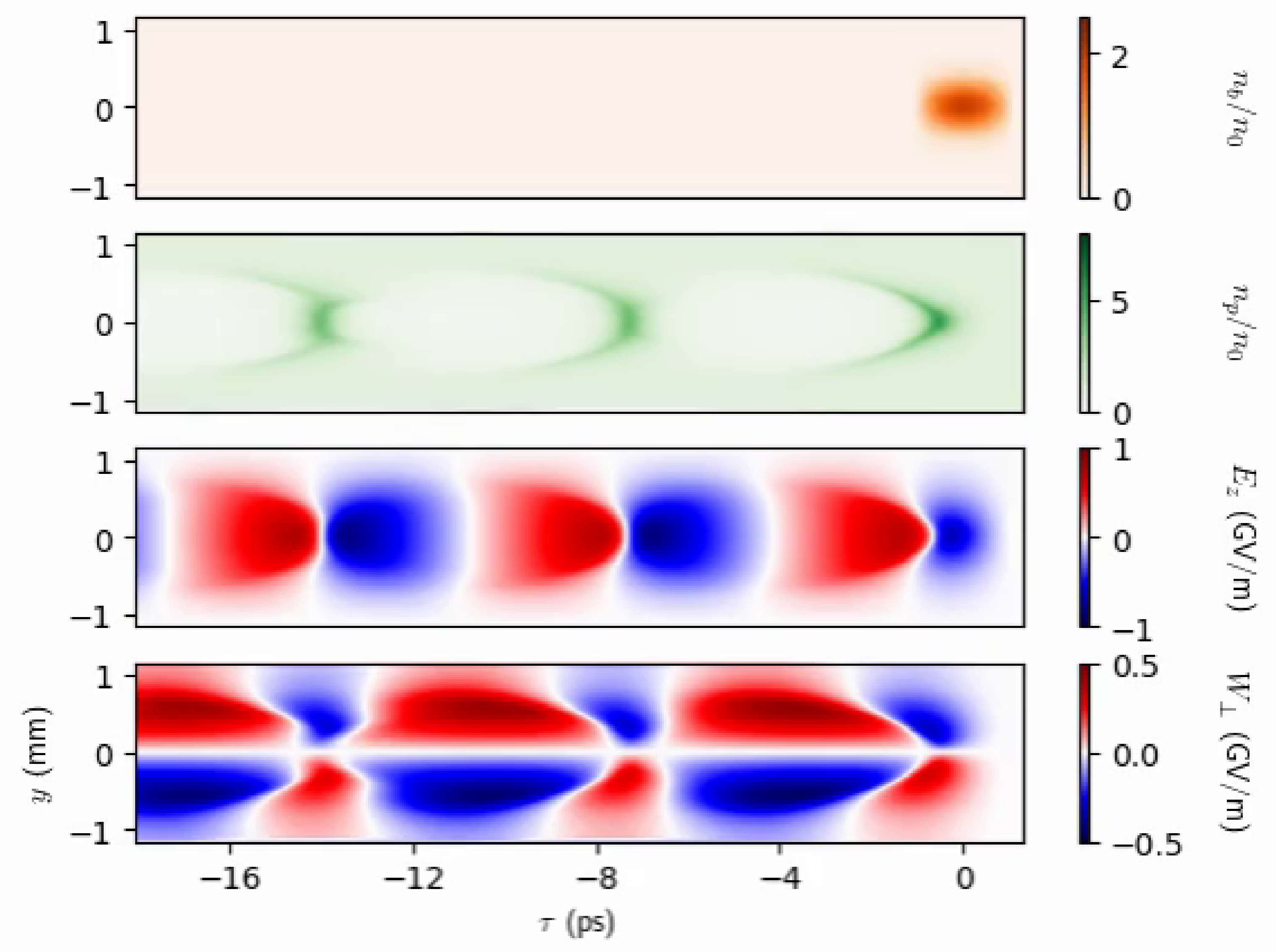


Acceleration: dephasing

Initial proton driver chosen to generate suitable wakefields

Tailored emittance profile stops the bunch from pinching

BUT:
protons “fall back” in the light frame



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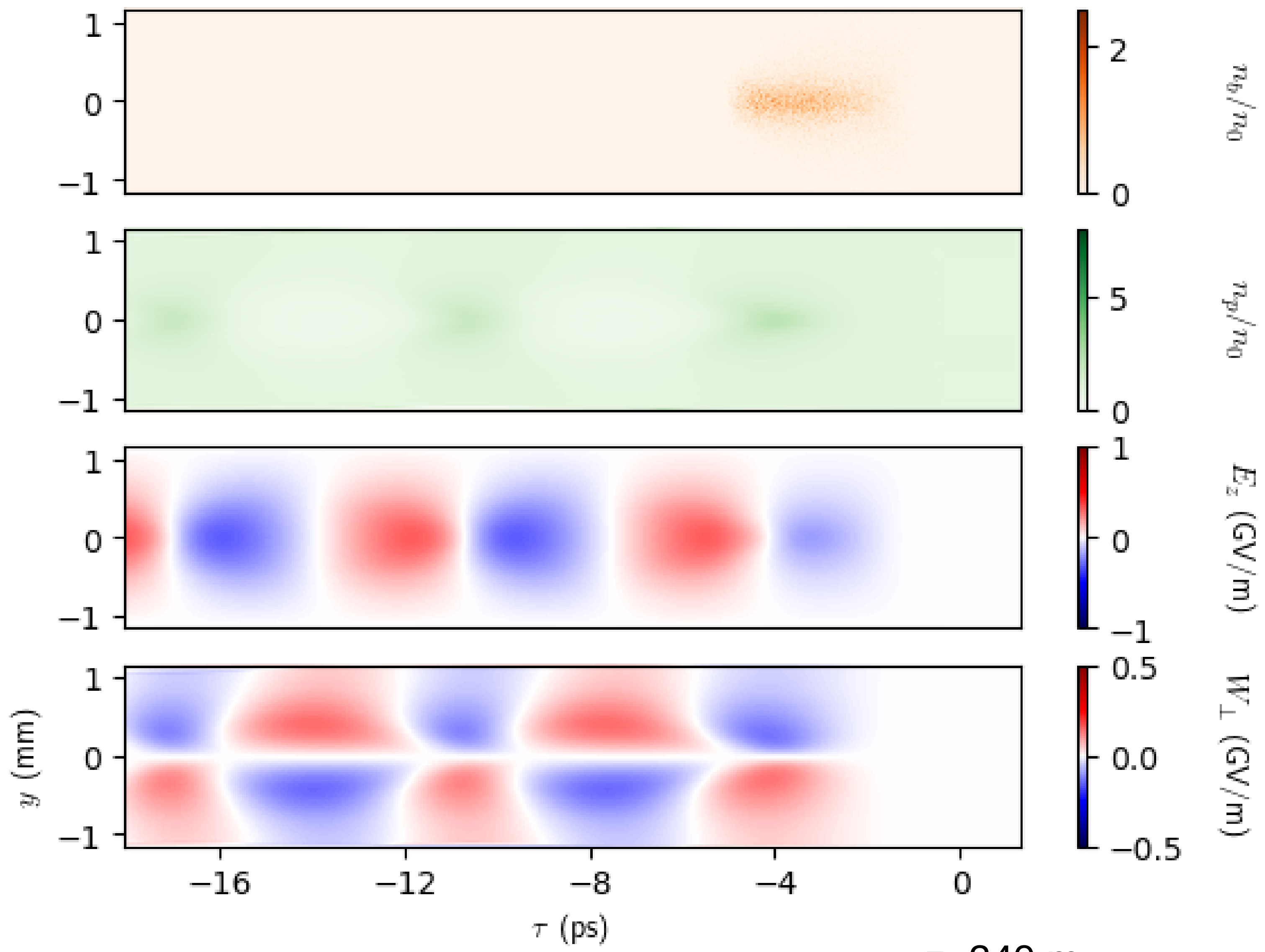


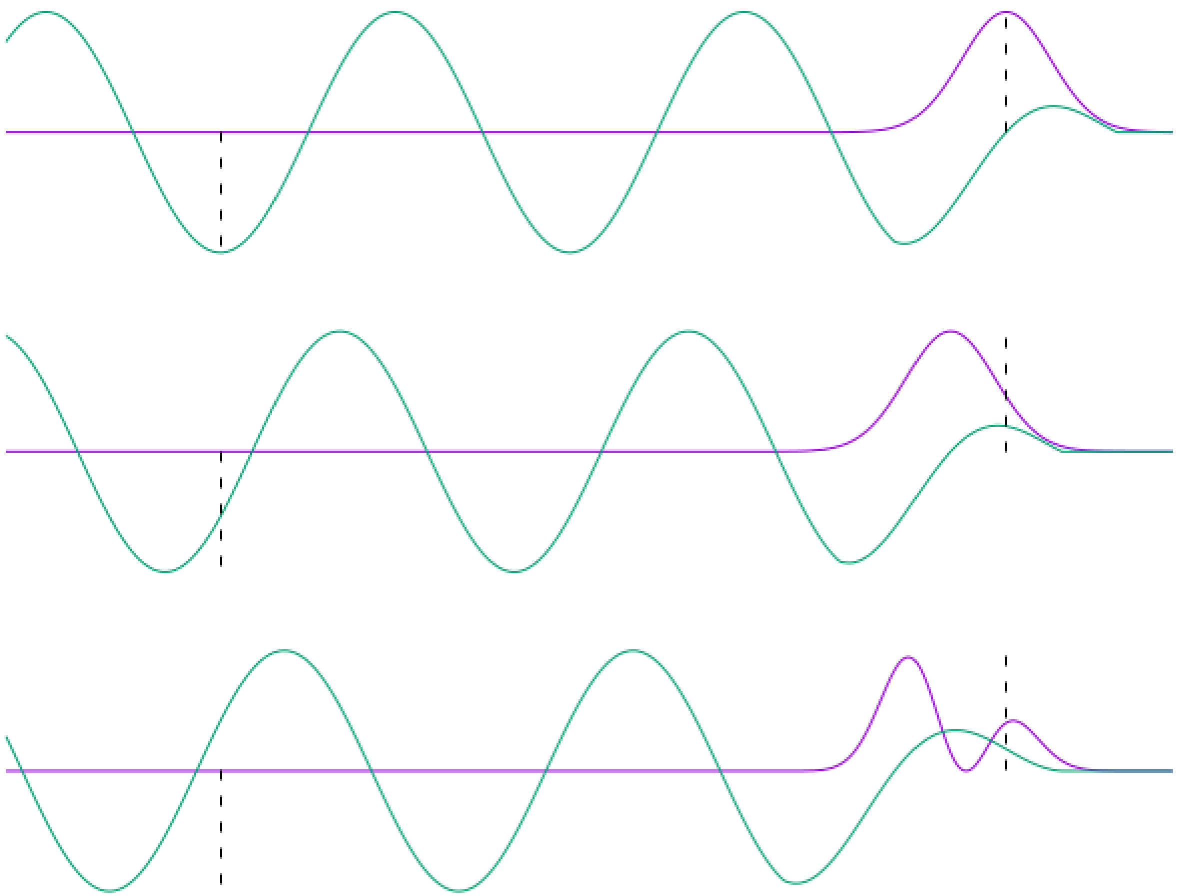
z=240 m

Acceleration: dephasing

Protons are fast,
but not that fast.

Driver evolution
will also modify
wakefield phase.

Witness will “catch up”
with the driver.



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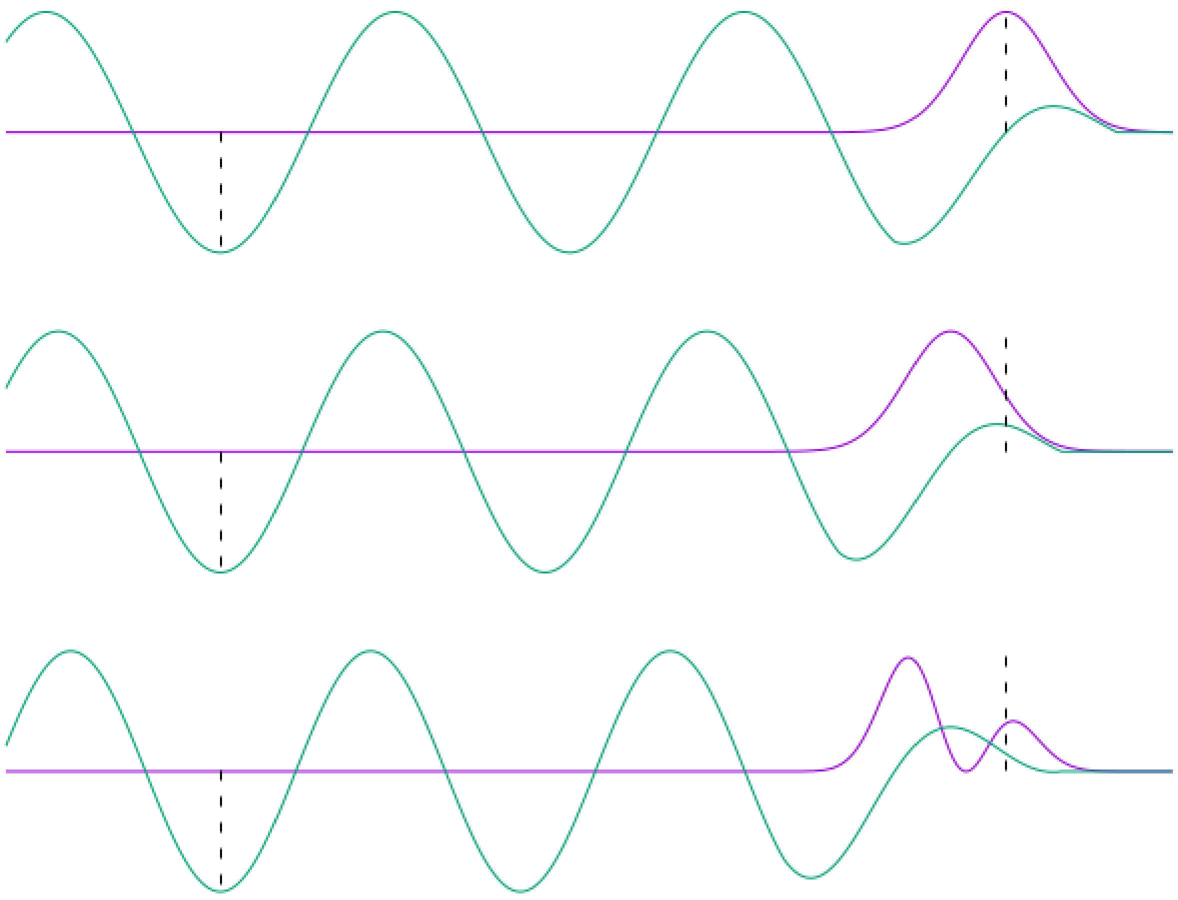
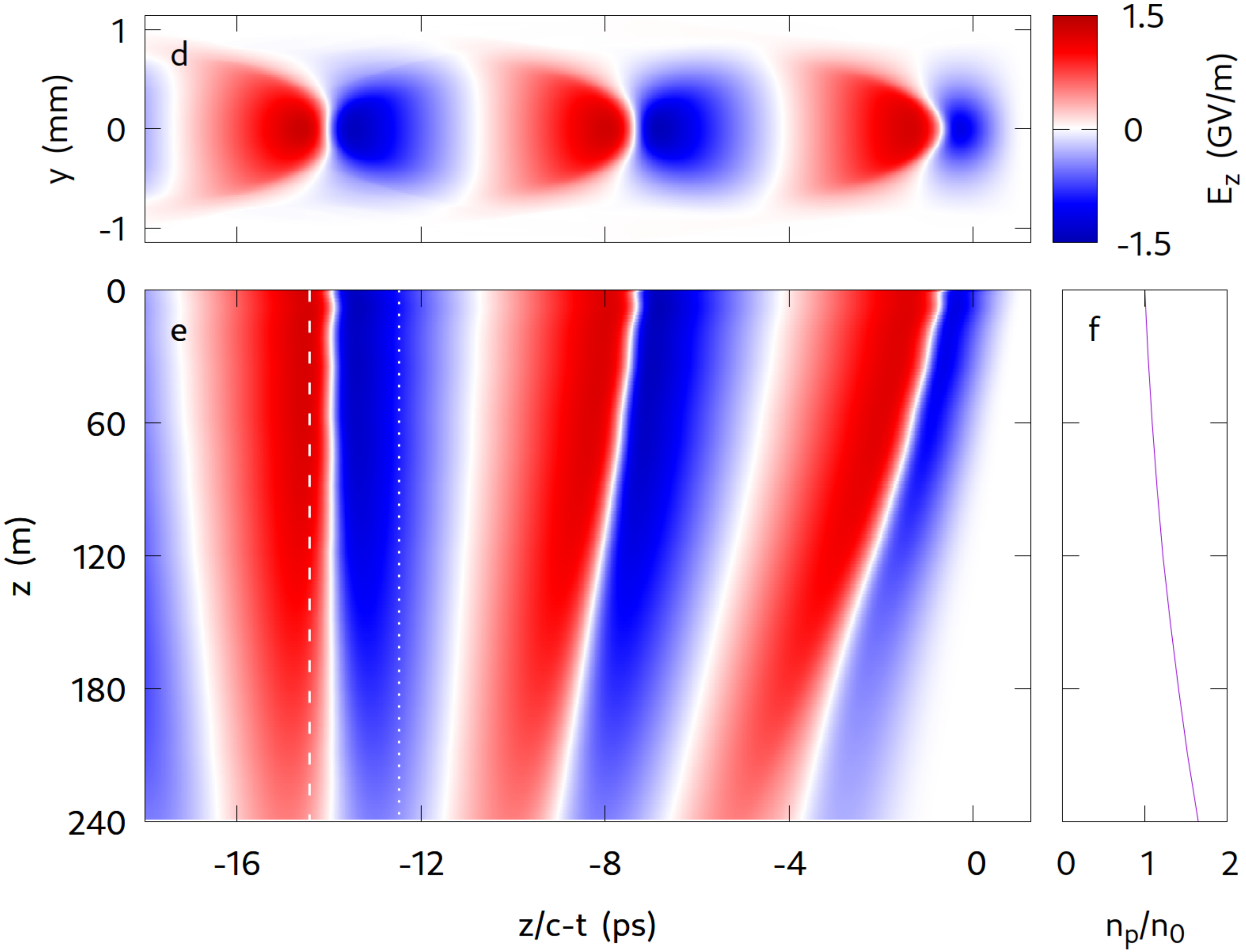


Change plasma density to keep phase constant

Acceleration: dephasing

Change plasma density to keep phase constant



Acceleration

We now have all the building blocks for Higgs factory

- Large accelerating wakefields
- Regions suitable for electron and positron acceleration
- Stable accelerating phase

Just (!) need to simulate acceleration

Acceleration

Plasma provides large accelerating fields,
but also large focussing fields

- extremely small witness radius at high energy
  - ~0.3 μm for electrons at 125 GeV with 0.1 μm emittance
  - ~0.1 nm for positrons at 125 GeV with 0.1 μm emittance

Many headaches

- secondary ionization
- ion motion
- nonphysical effects in simulations

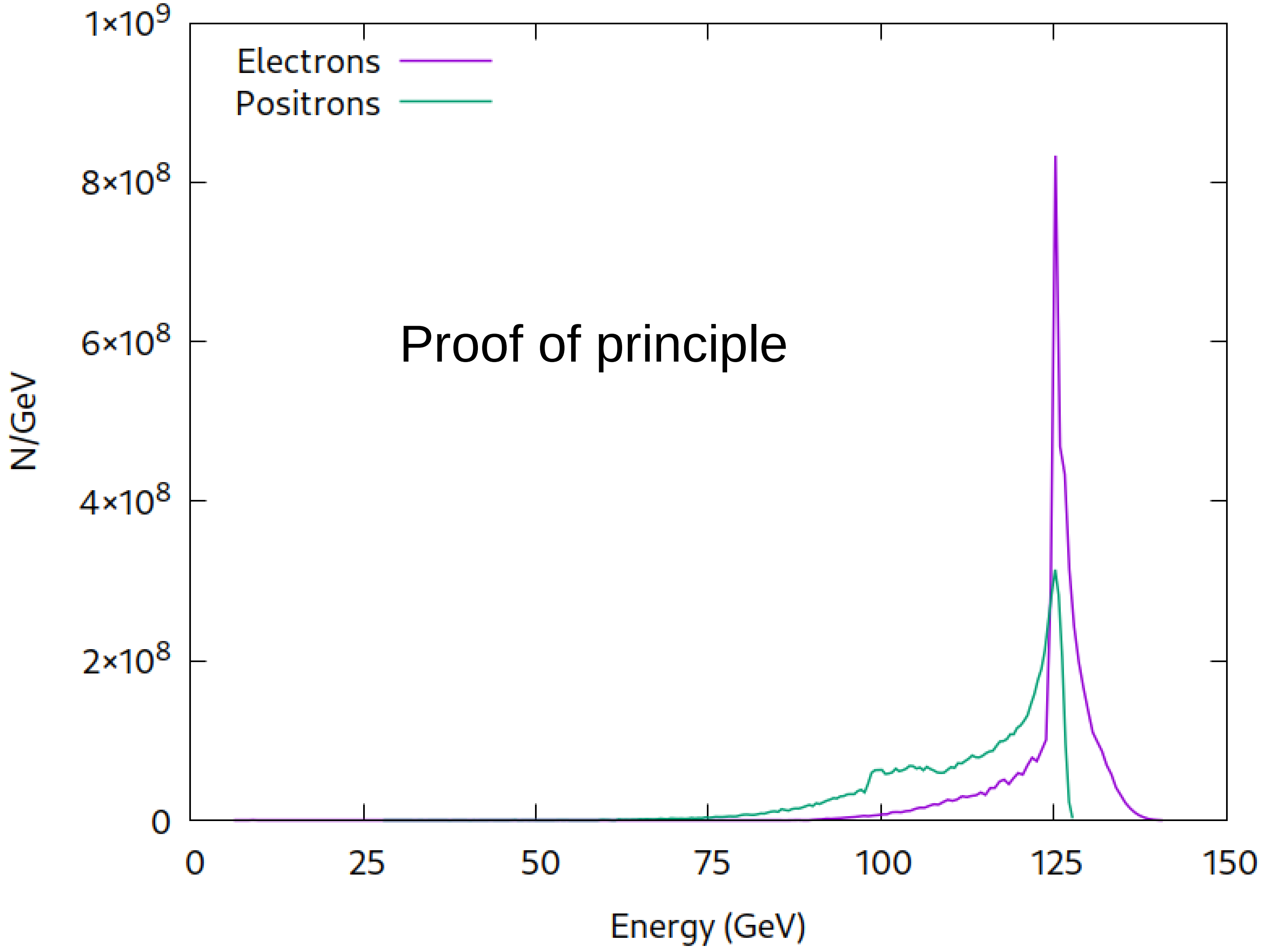
Acceleration

10^{11} protons at 400 GeV

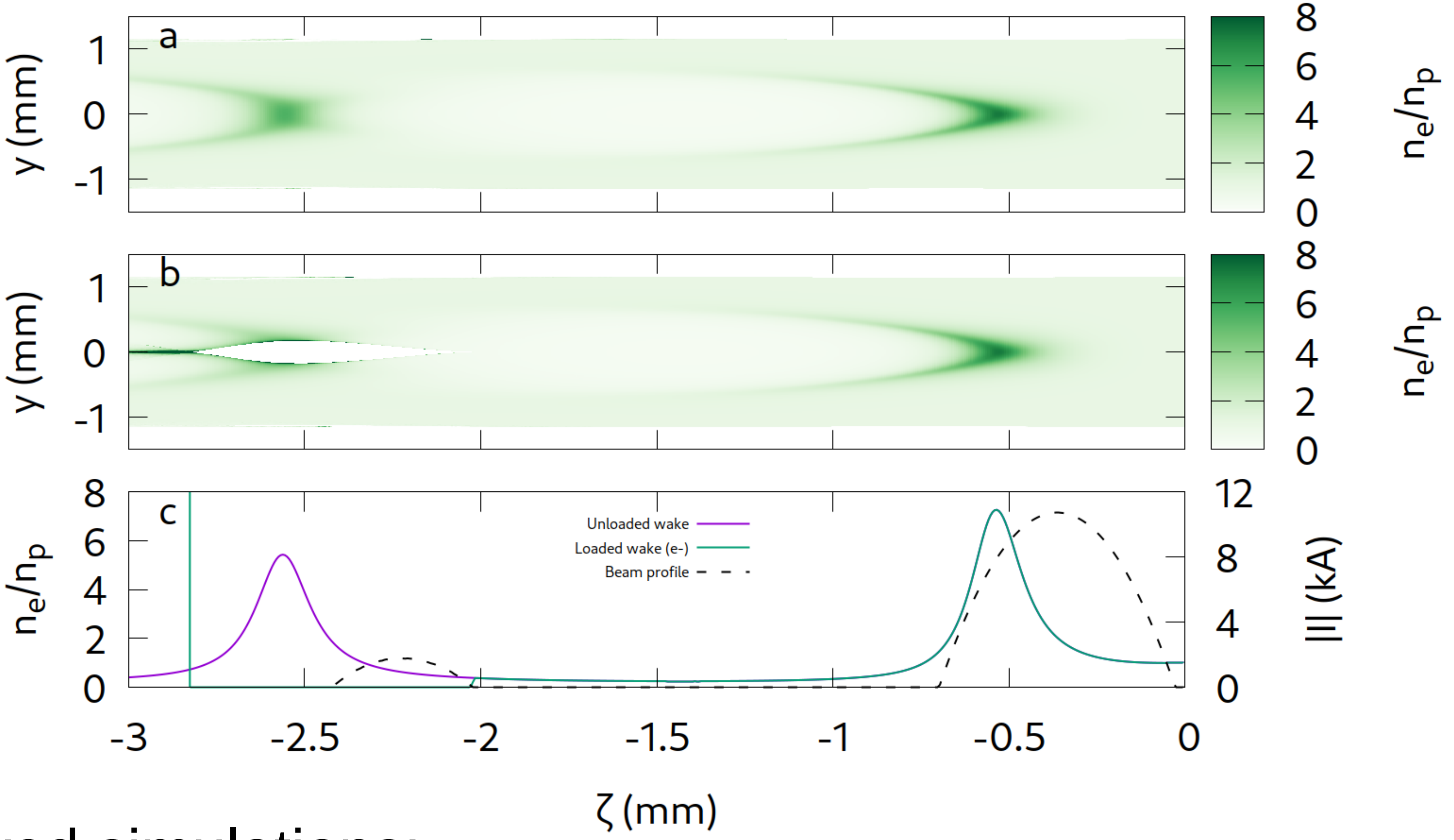
10^{10} electrons/positrons injected at 1 GeV

Full 3D simulations

- no ionization
- no ion motion
- energy spread is nonphysical!

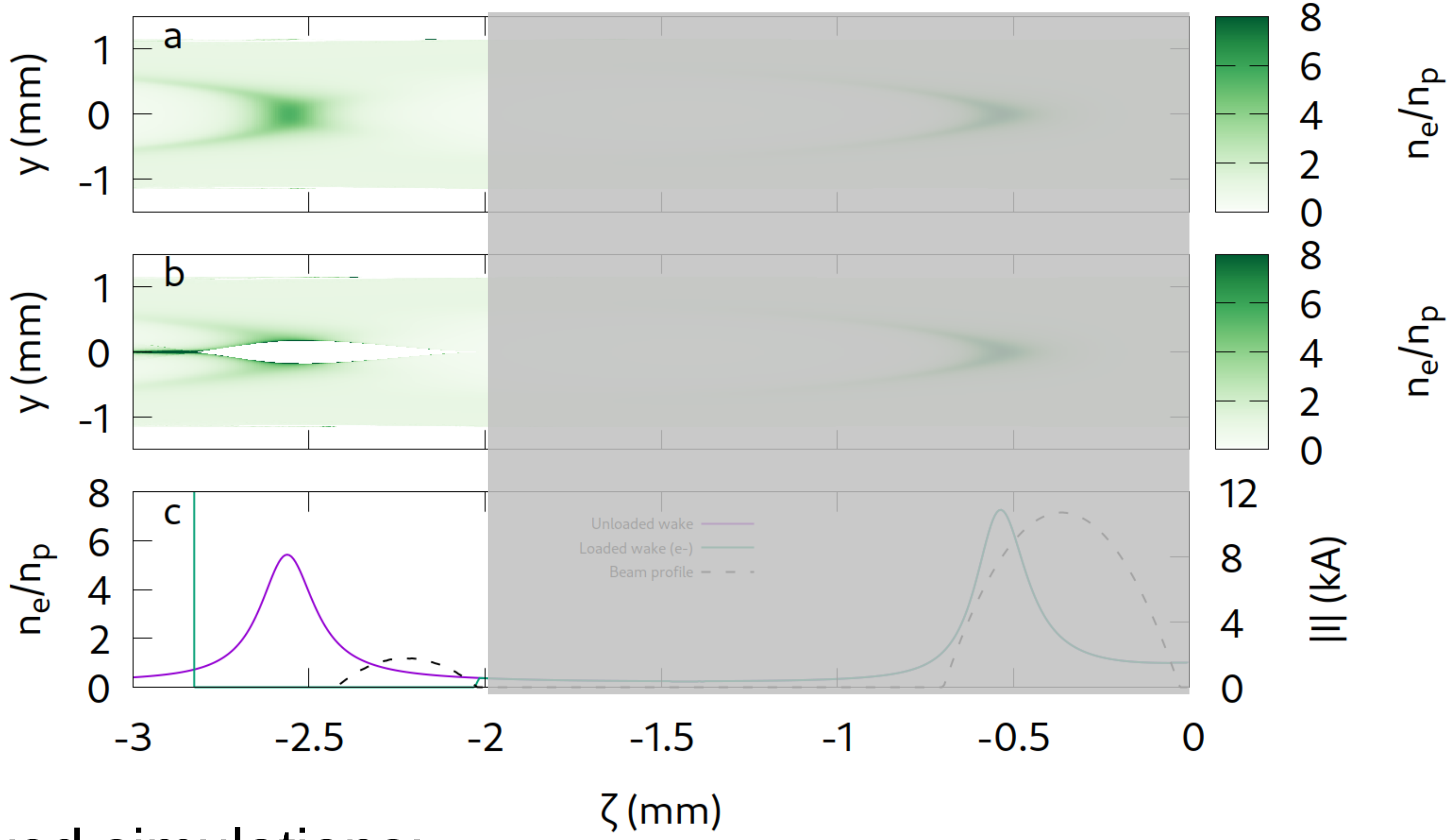


Acceleration



First resolved simulations:
2D geometry (LCODE), frozen driver, electron witness.

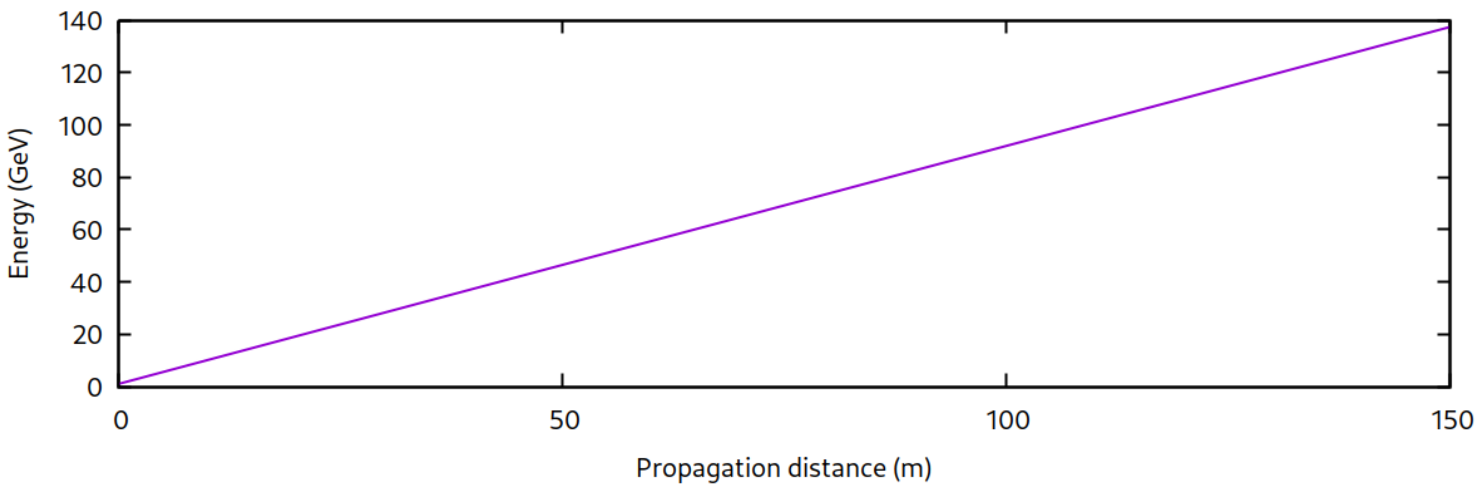
Acceleration



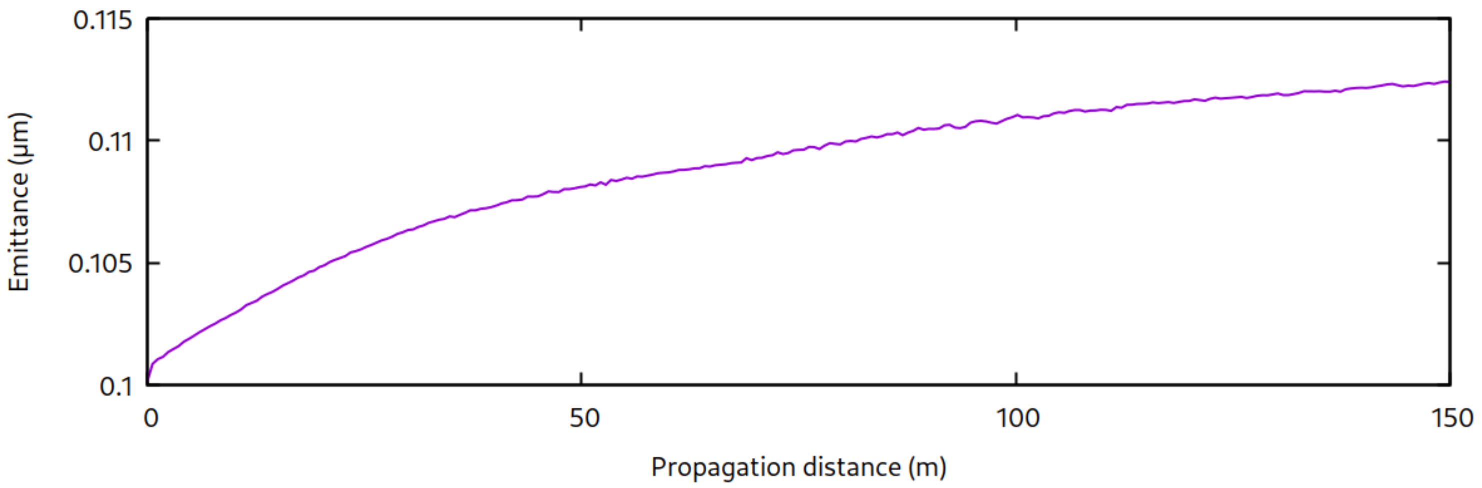
First resolved simulations:
2D geometry (LCODE), frozen driver, electron witness.

Acceleration

Energy gain
(trivial for frozen driver)

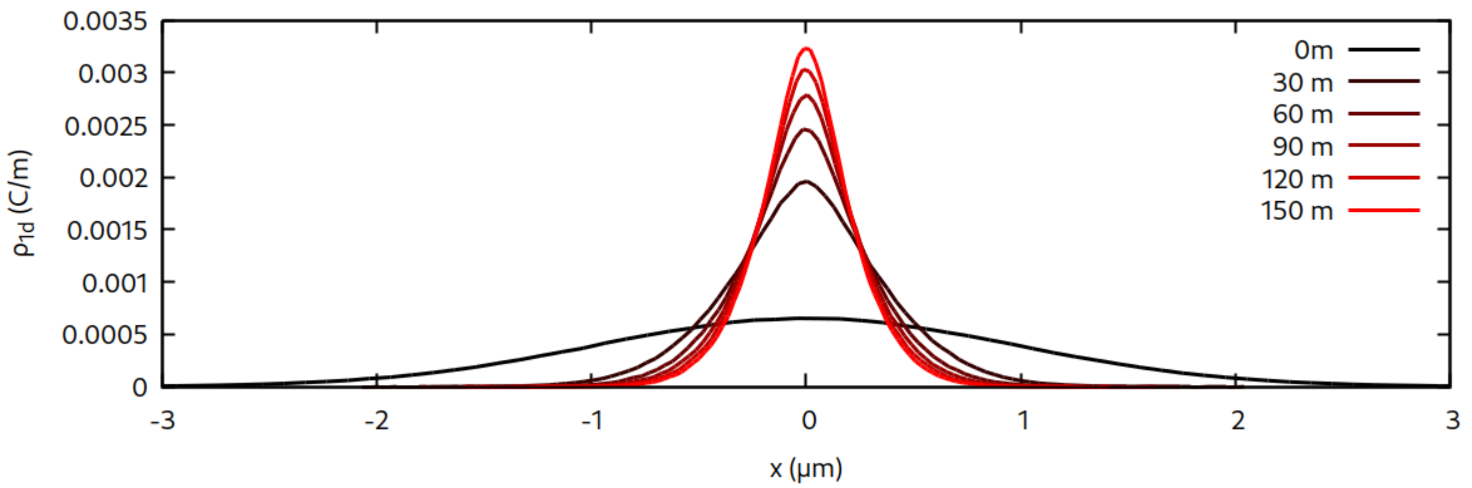


Emittance growth
due to ion motion
(lithium)

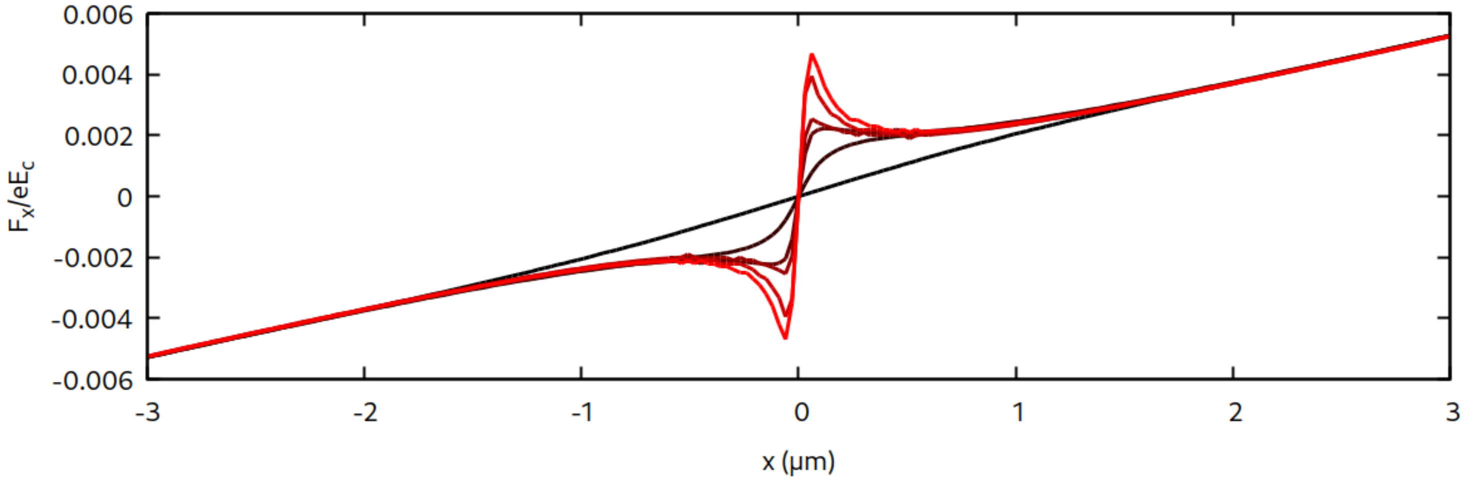


Acceleration

Adiabatic focussing of witness during acceleration
1µm → 0.23 µm



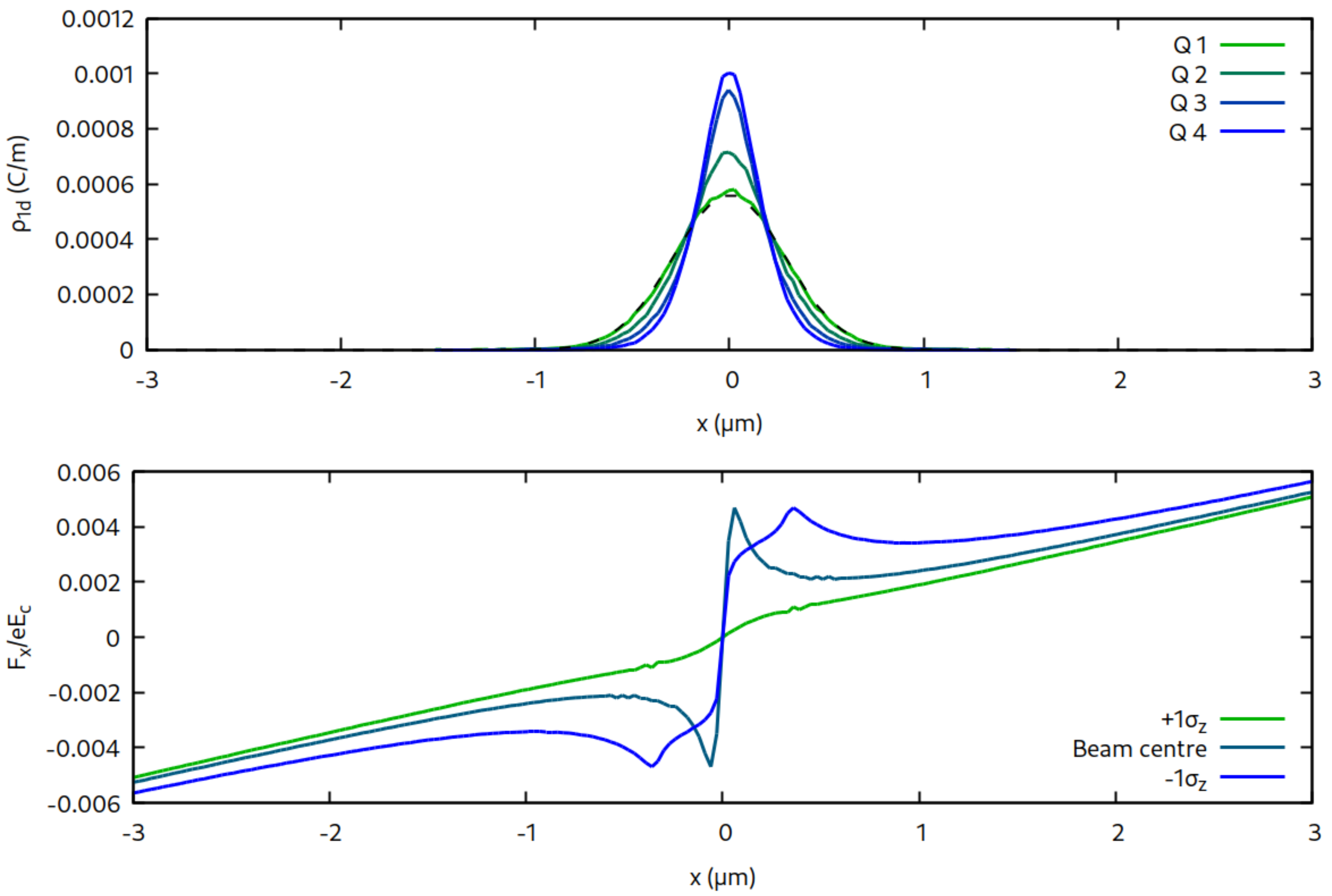
Focussing field becomes increasingly nonlinear



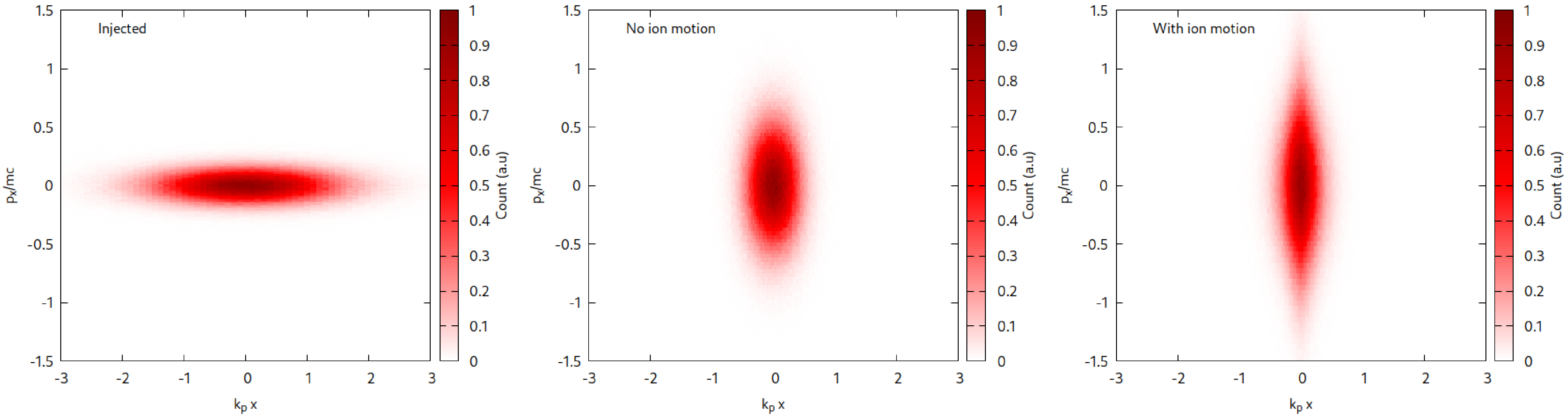
Acceleration

Different longitudinal slices of the witness have different profiles

Head-to-tail variation of focussing fields.



Acceleration



Suggests adiabatic focussing allows witness to self-match to nonlinear focussing fields

Luminosity

Combine everything:

- Assume proton beams at 5 Hz, with 1000 bunches per beam
- Assume witness beams with 20% driver charge, 100 nm emittance*, ILC optics, and negligible energy spread

*Flat beams should be investigated

and this scheme is competitive:

1.7×10^{34} cm^{-2}s^{-1}

Proton Accelerator Parameter	Symbol	Unit	Value
Proton energy	E_p	GeV	400
Refill Time	τ	s	0.2
Bunch population	N_p	10^{10}	10
Number of bunches	n		1000
Longitudinal RMS	σ_z	µm	150
Transverse RMS	$\sigma_{x,y}$	µm	240
Normalized transverse emittance	$\epsilon_{T,p}$	µm	$3 - 75$ µm
Power Usage	P	MW	150
Plasma Parameters	**Symbol**	**Unit**	**Value**
e^- cell Length	L_{e^-}	m	240
e^+ cell Length	L_{e^+}	m	240
density - upstream	n_p	10^{14} cm^{-3}	3.2
density - downstream	n_p	10^{14} cm^{-3}	5.2
$e^\pm$ Bunch Parameters	**Symbol**	**Unit**	**Value**
Injection Energy	$E_{e,in}$	GeV	1
Final Energy	E_e	GeV	125
Bunch population	$N_{e^\pm}$	10^{10}	2
Normalized transverse emittance	$\epsilon_{T,e}$	nm	100
Hor. beta fn.	β_x^*	mm	13
Ver. beta fn.	β_y^*	mm	0.41
Hor. IP size.	σ_x^*	nm	73
Ver. IP size.	σ_y^*	nm	13
e^-e^+ Collider Parameter	**Symbol**	**Unit**	**Value**
Center-of-Mass Energy	E_{cm}	GeV	250
Average Collision Rate	f	kHz	5
Luminosity	$\mathcal{L}$	cm^{-2}s^{-1}	1.7×10^{34}

Luminosity

Combine everything:

- Assume proton beams at 5 Hz, with 1000 bunches per beam
- Assume witness beams with 20% driver charg…
  100 nm …
  a…

*Flat…

and thi… …petitive:

1.7x1… $cm^{-2}s^{-1}$

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Now on arXiv

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Refill Time	τ	s	0.2
Bunch population	N_p	10^{10}	10
Number of bunches			1000
Longitudinal …		µm	150
		…m	240
		…m	3 – 75 µm
		…V	150
			Value
			240
			240
			3.2
			5.2
			Value
			1
	E_e	GeV	125
	$N_{e\pm}$	10^{10}	2
…transverse emittance	$\epsilon_{T,e}$	nm	100
Hor. beta fn.	β_x^*	mm	13
Ver. beta fn.	β_y^*	mm	0.41
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Upgrade path

Witness energy gain limited by dispersion of driver.

Witness energy gain scales as

$$\gamma_W \sim \gamma_D^{3/2}$$

$t\bar{t}$ collider with 525 GeV driver.

HALHF-like 500 GeV electron witness with 1 TeV driver.

Conclusions and outlook

Proof-of-principle simulations for stability and energy gain
(evolving driver, 3D simulations)

Proof-of-principle simulations for emittance control
(electron witness, frozen driver, 2D simulations)

Key challenges:

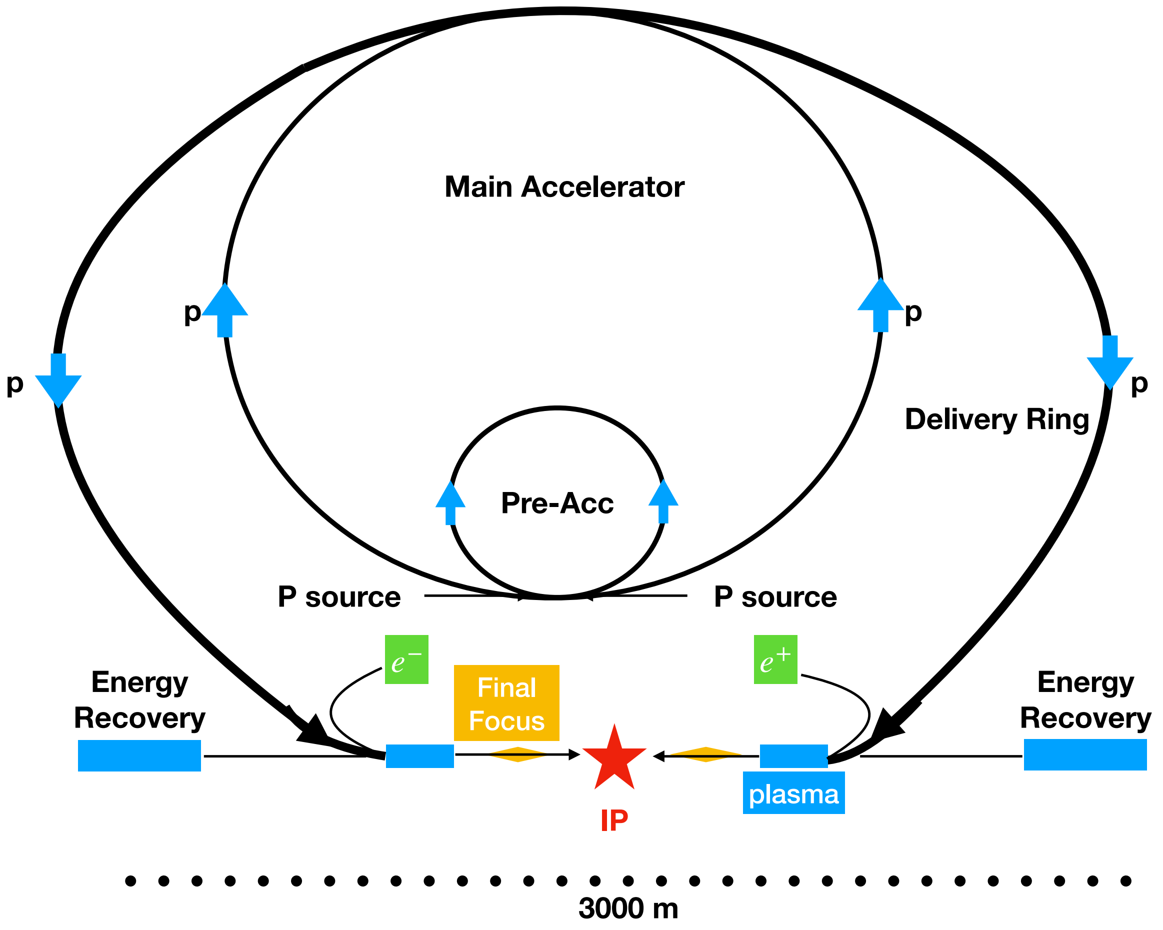
- short proton bunches with high rep rate
- PWFA acceleration of positron bunches
- long plasma stages with 100% ionization at high rep rate

~ Fin ~

~ Backups ~

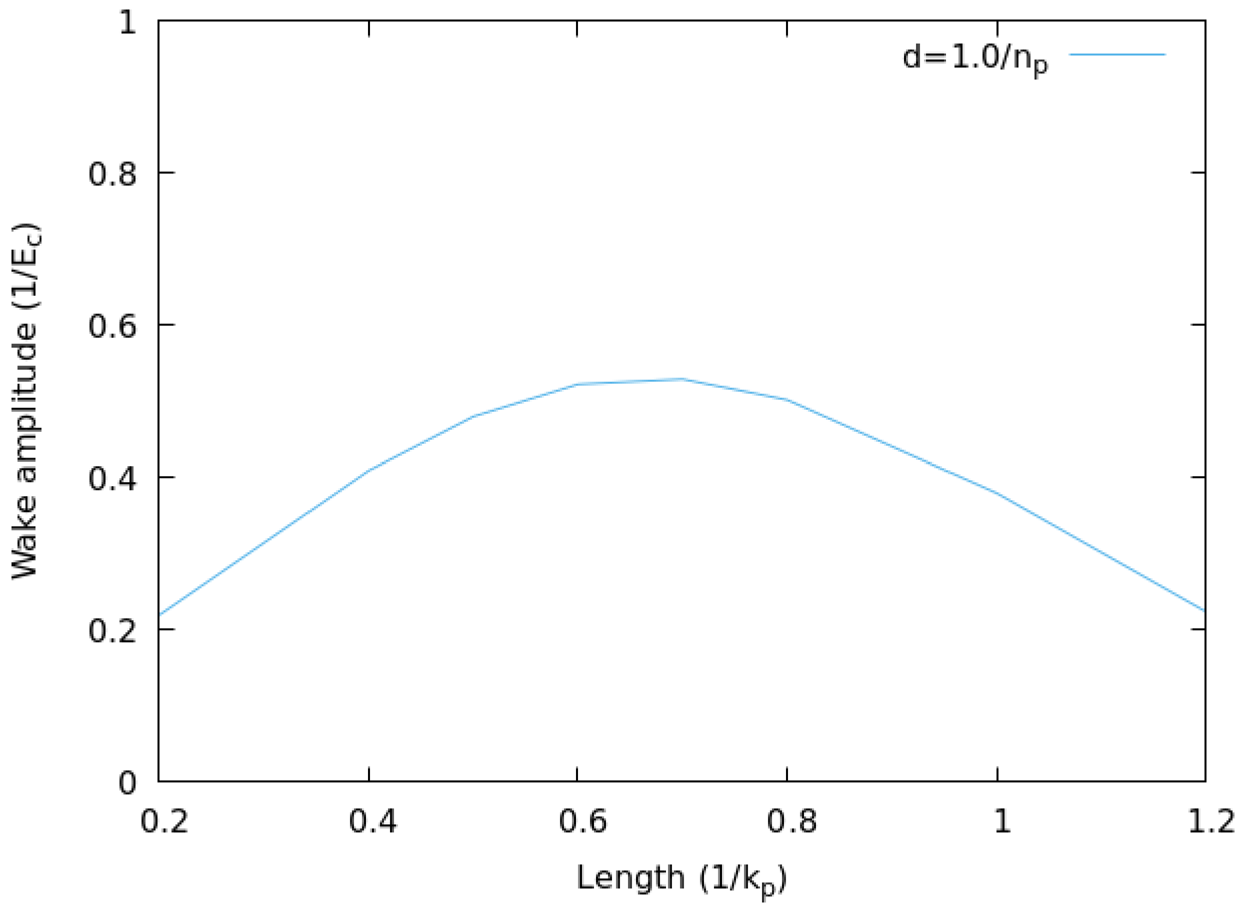
Footprint

Fits on the Fermilab site
(P5 review)



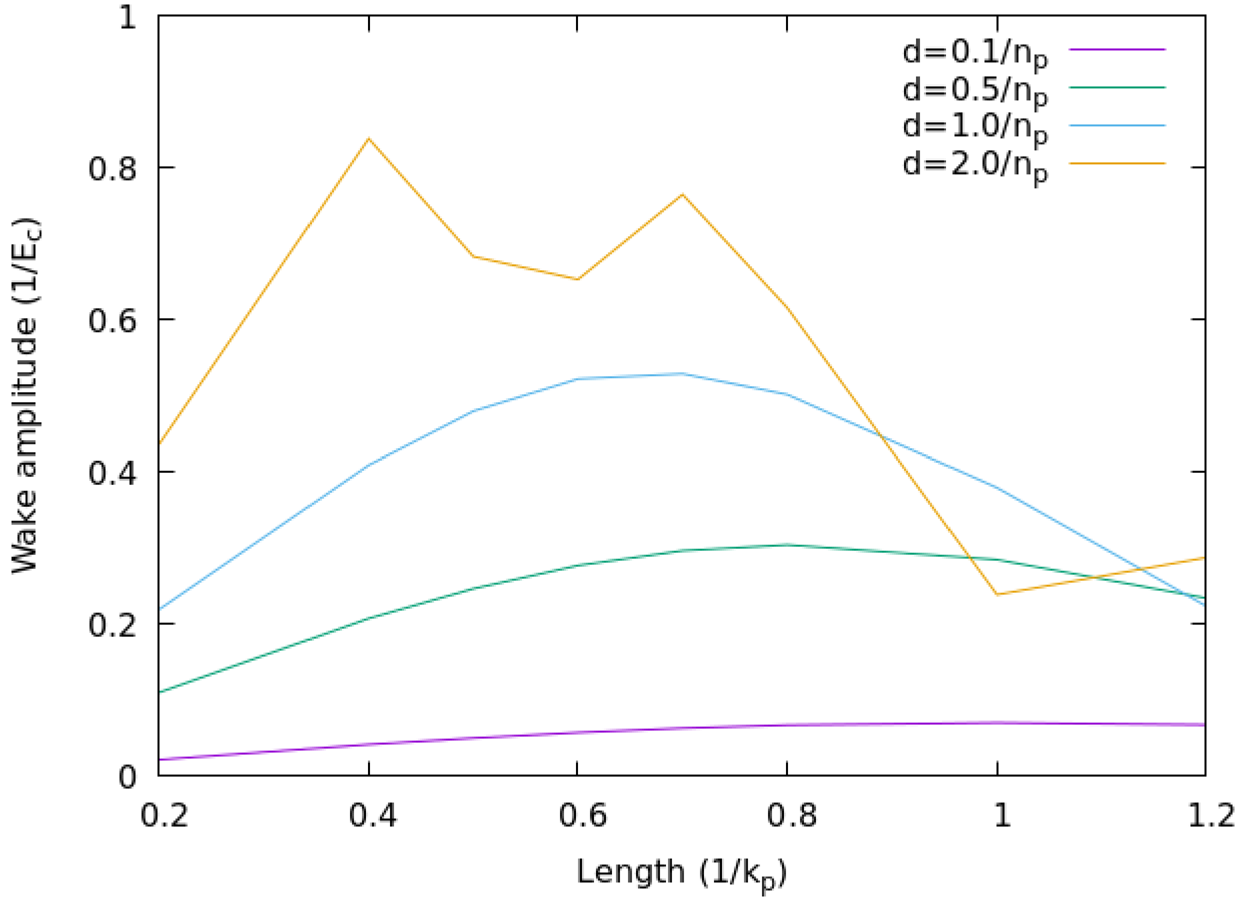
Picking the driver: efficiency

Optimal length
for proton driver



Picking the driver: efficiency

Optimal length
for proton driver
depends on charge density.



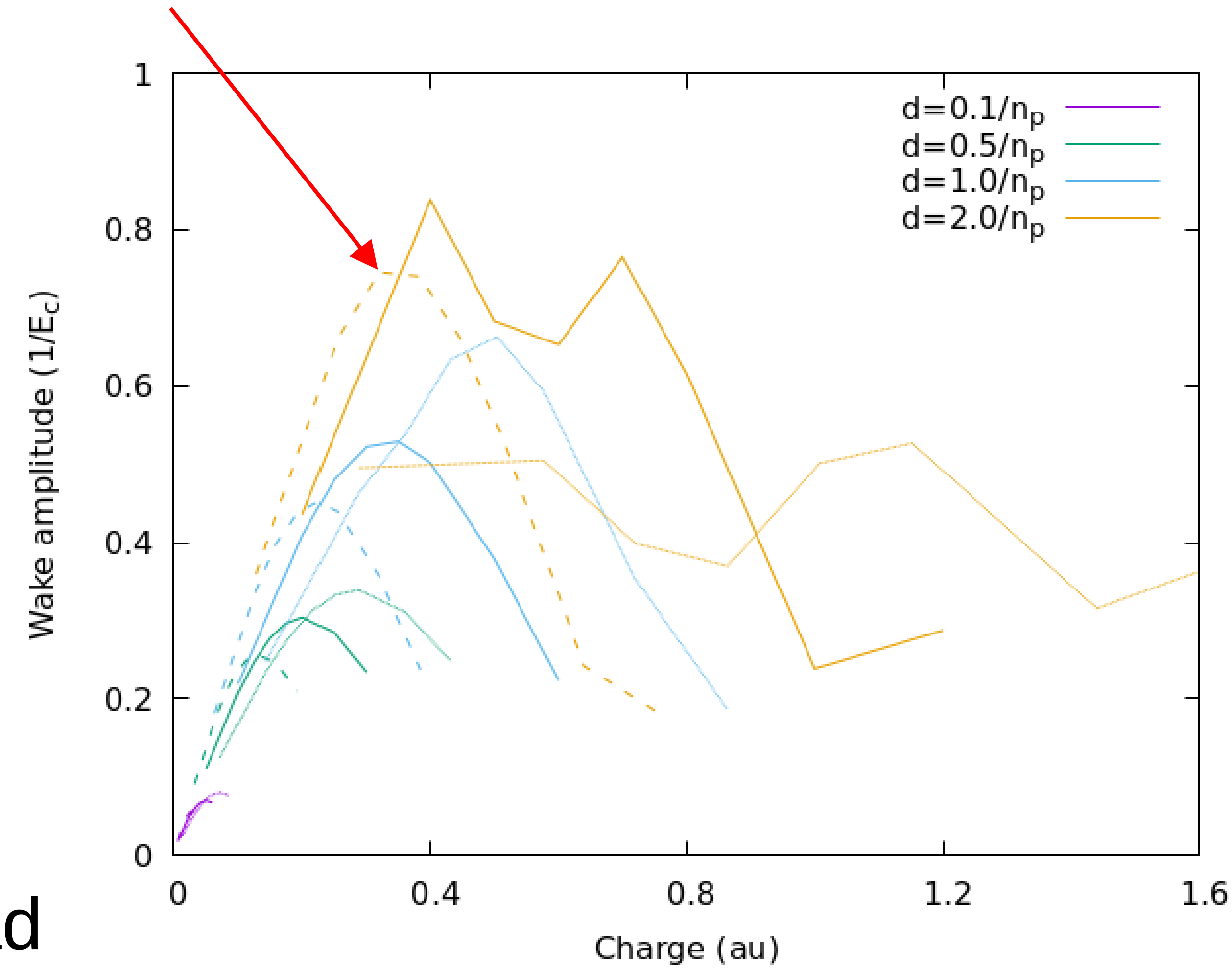
Picking the driver: efficiency

Everything scales with plasma frequency

1×10^{11} protons gives

- plasma density 3×10^{14} cm^{-3}
- driver length 150 µm
- Initial wakefields ~ 0.8GV/m

Pick 10% driver energy spread for “realistic” longitudinal emittance



Dashed line: $k_p r = 0.8$
Solid line: $k_p r = 1.0$
Dotted line: $k_p r = 1.2$

Cooling

Witness with 10% driver charge
absorbs ~20% of wakefield energy

Witness with 20% driver charge
absorbs ~40% of wakefield energy

Assume acceleration over 240m,
gives required cooling as 12.5 kW/m

Cooling

Moderately nonlinear wakefields retain their structure after loading.

Could use a second witness bunch to “mop up” excess wakefield