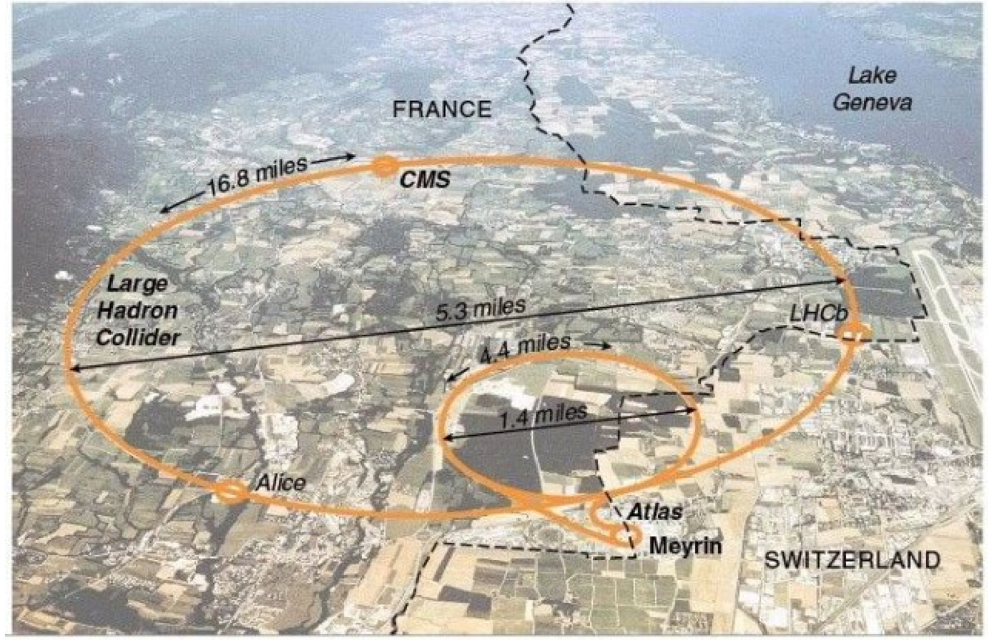
Preliminary Investigation of a Higgs Factory based on Proton-Driven Plasma Wakefield Acceleration

September 2024

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

Motivation



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

Size determined by radiation reaction.

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

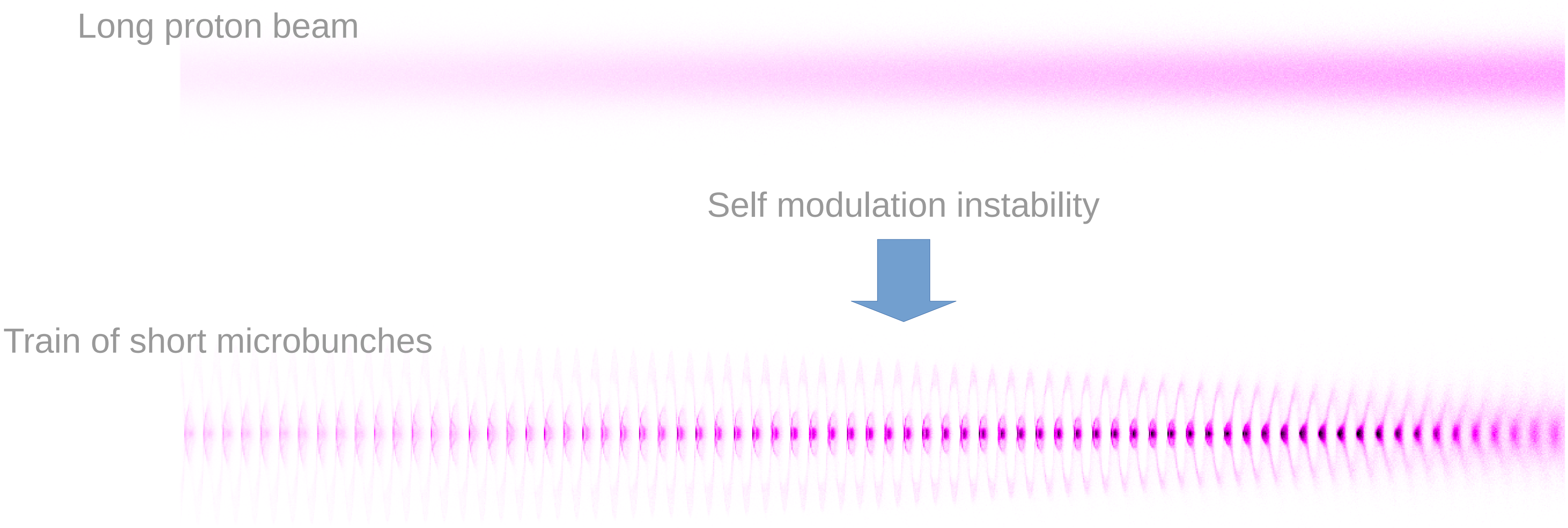
- requires short proton driver

Short driver efficiently excites wakefield

Long driver suppresses its own wake

Proton-driven PWFA

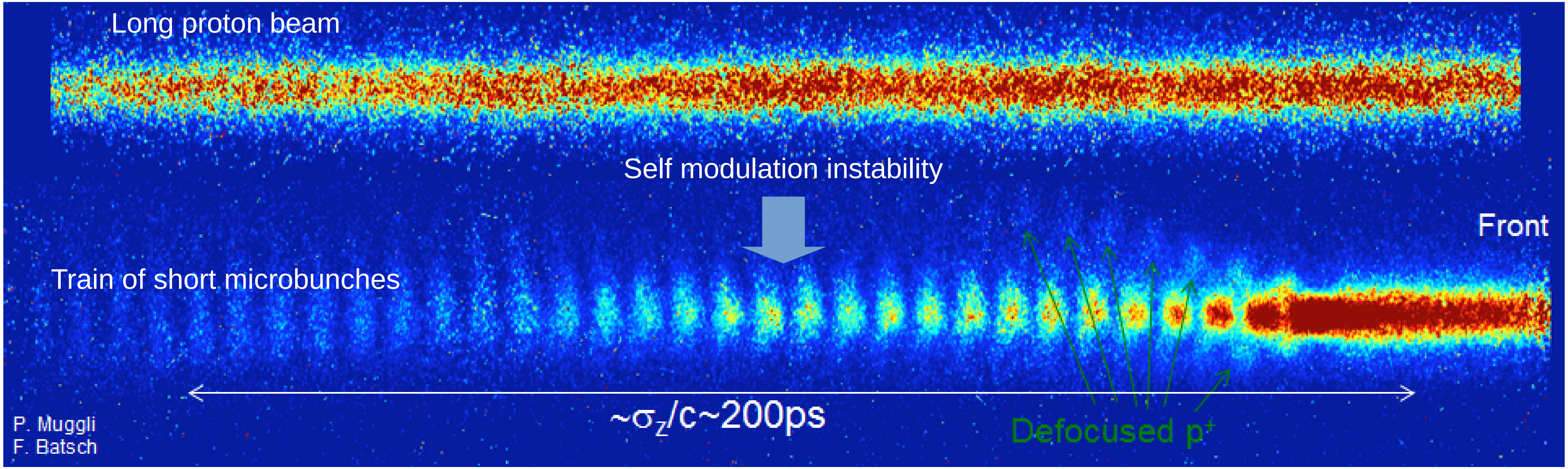
Focussing/defocussing fields in plasma



Resulting train of microbunches can drive large wakefields

Proton-driven PWFA

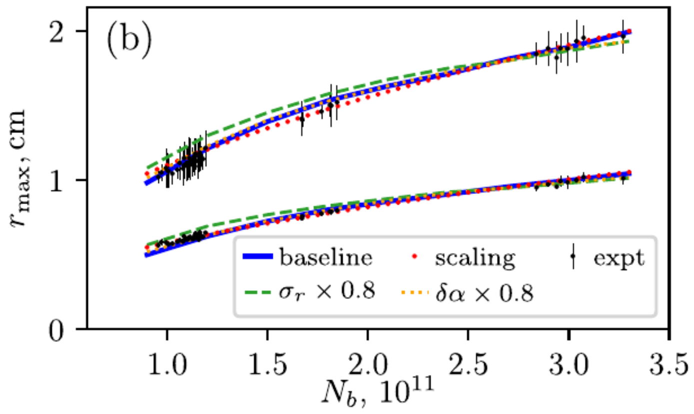
Not just an idea, this is exactly the basis of AWAKE



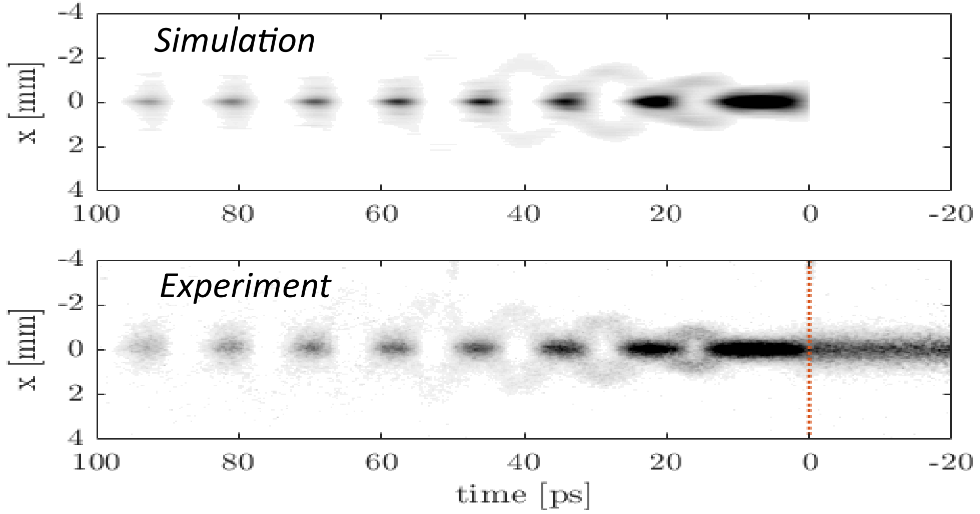
AWAKE Collaboration, Nature (2018)
F. Batsch *et al.* (AWAKE Collaboration), Phys. Rev. Lett. (2021)

Proton-driven PWFA

Beam radius after SMI at Imaging Station 2



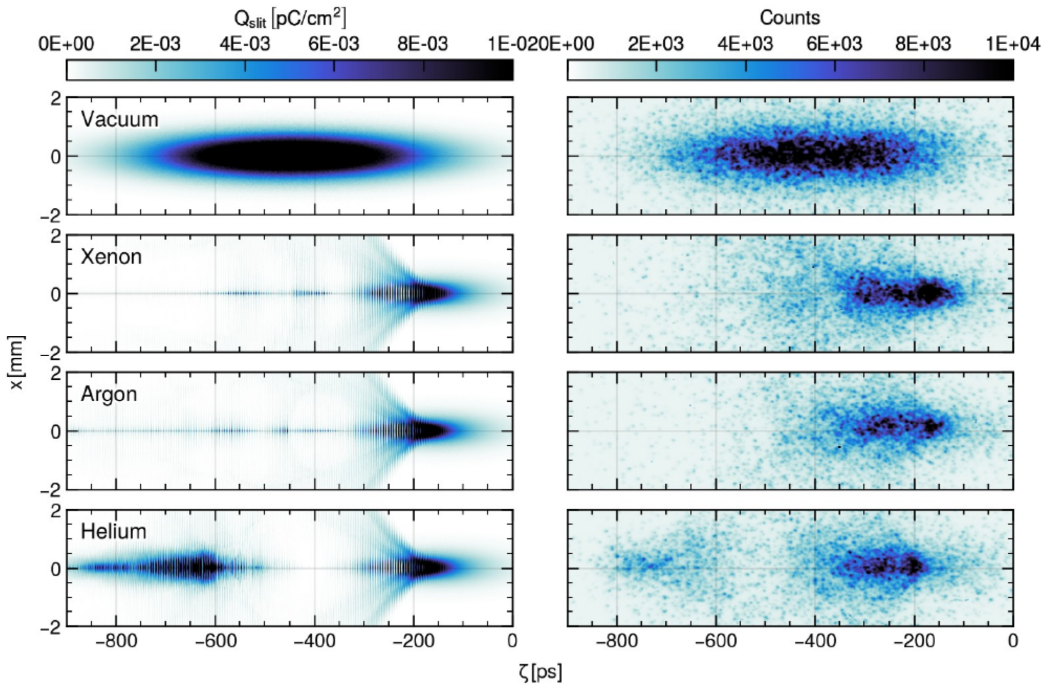
A. Gorn, PPCF (2020)



Microbunch structure at streak camera

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

Impact of ion motion on SMI imaged at streak camera



AWAKE preliminary

M. Turner *et al.* (AWAKE Collaboration), *in preparation*

Short proton drivers revisited

It’s worth revisiting short proton drivers.

Pros:

Higher gradients

Higher efficiency

Cons:

Such drivers (L~150 µm) don’t currently 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

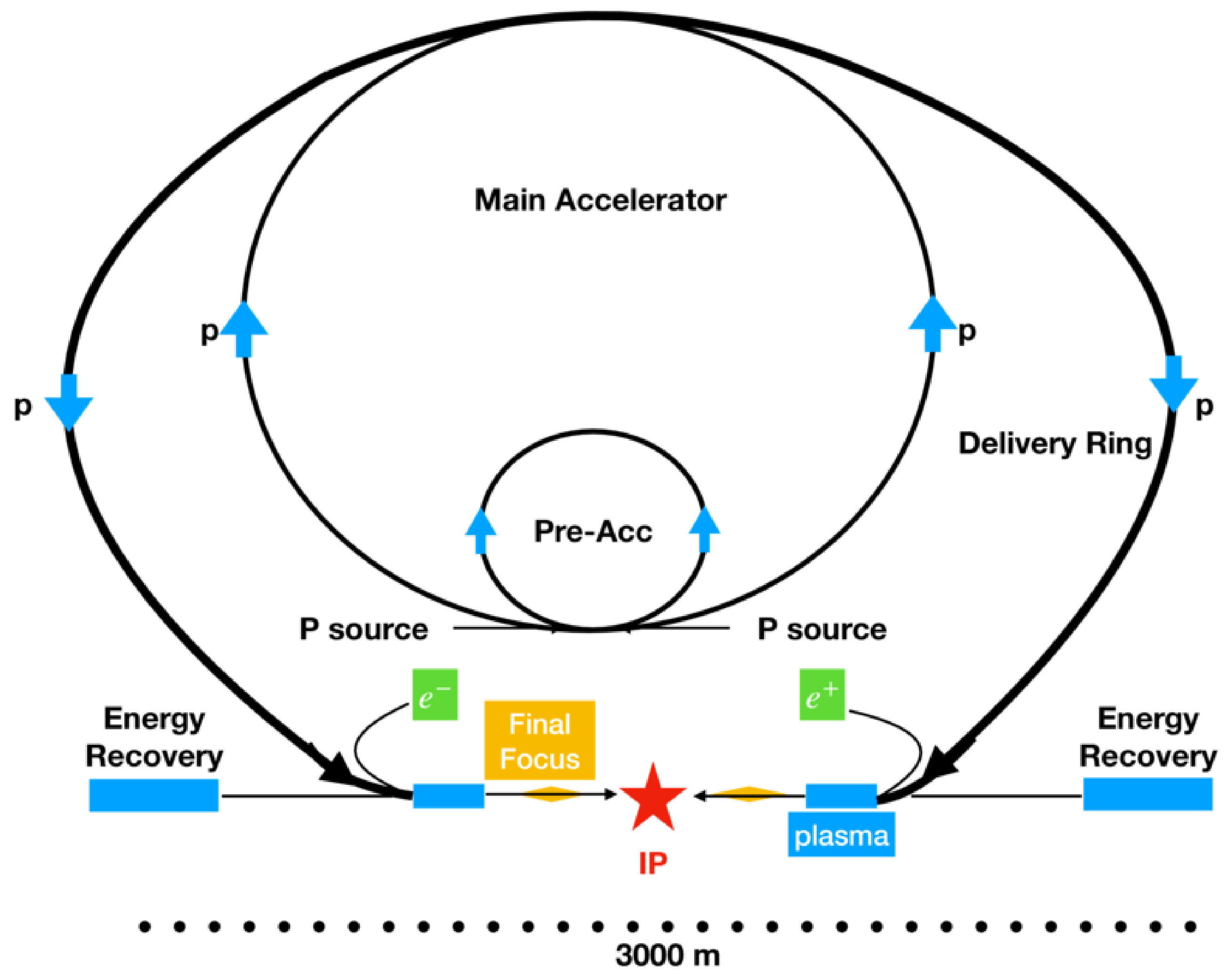
H. Piekarz, *Senior Member, IEEE*, S. Hays, B. Claypool, M. Kufer, and V. Shiltsev, *Fellow, IEEE*

[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.

A proton-driven Higgs factory



A proton-driven Higgs factory

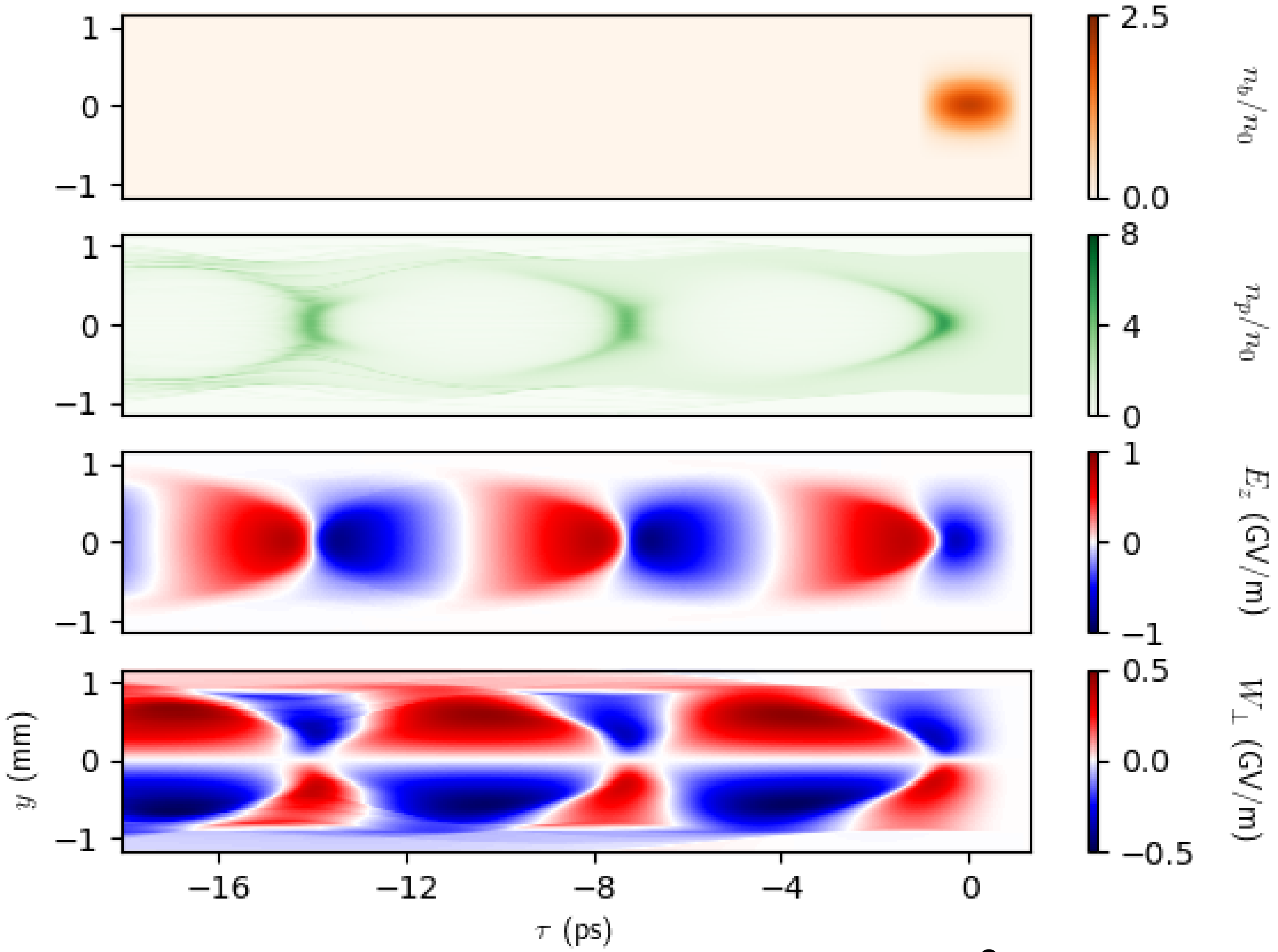
Use plasma wakefields as a transformer:
high energy protons → high energy electrons/positrons

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

Configuration

Initial proton driver chosen to generate suitable wakefields

Moderately nonlinear wakefield allows acceleration of both electrons and positrons



s=0 m

A word on lengths

Everything in plasma scales with a characteristic length, the plasma skin depth

$$\frac{1}{k_p} = \sqrt{\frac{c^2 \varepsilon_0 m}{n e^2}}$$

We pick $1/k_p = 300$ µm, $n_e = 3\text{x}10^{14}$ cm^{-3}

$L_p = 150$ µm

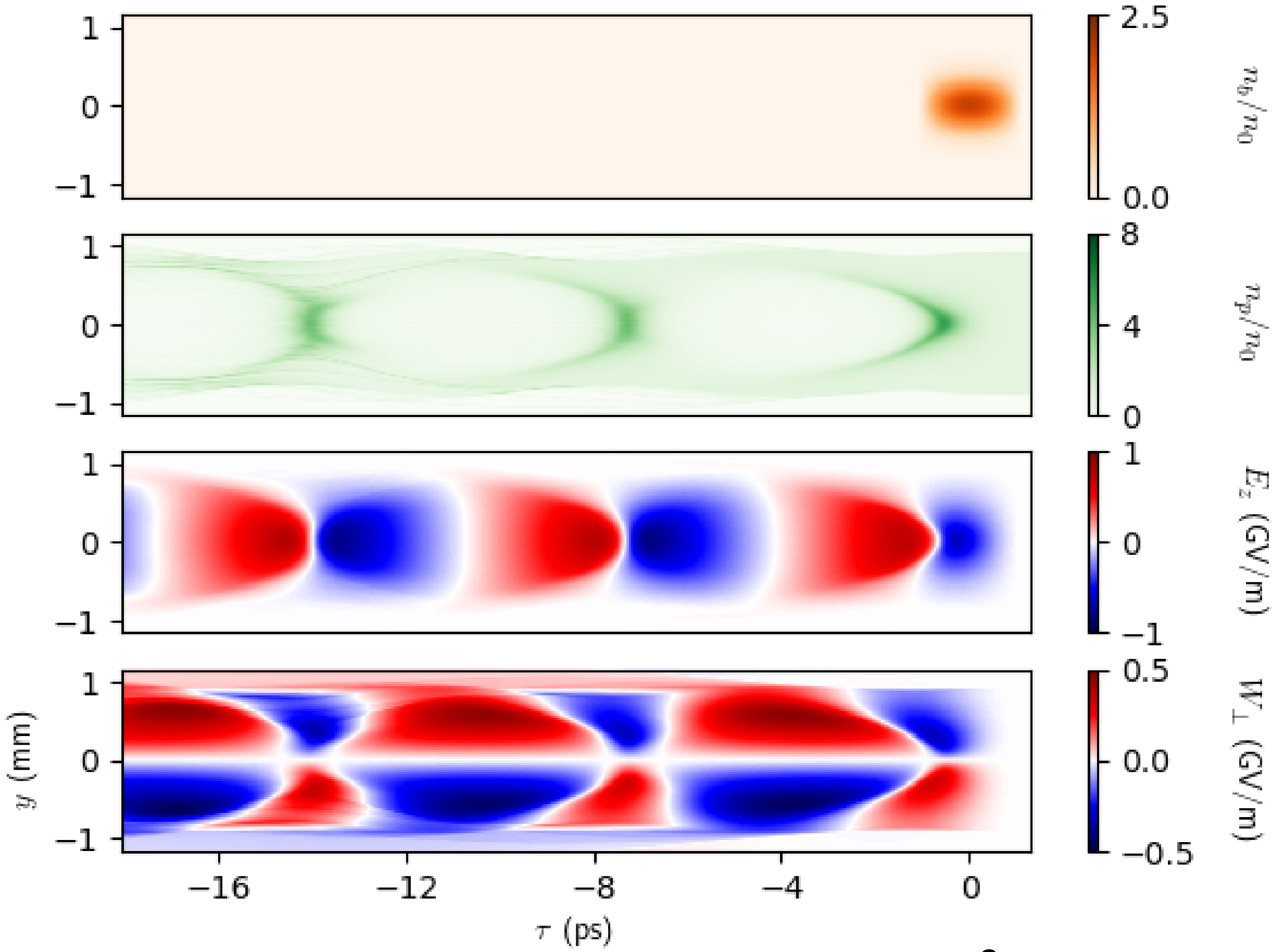
$N_p = 1\text{x}10^{11}$

$L_{acc} \sim 200$ m

Configuration

Initial proton driver chosen to generate suitable wakefields

Moderately nonlinear wakefield allows acceleration of both electrons and positrons

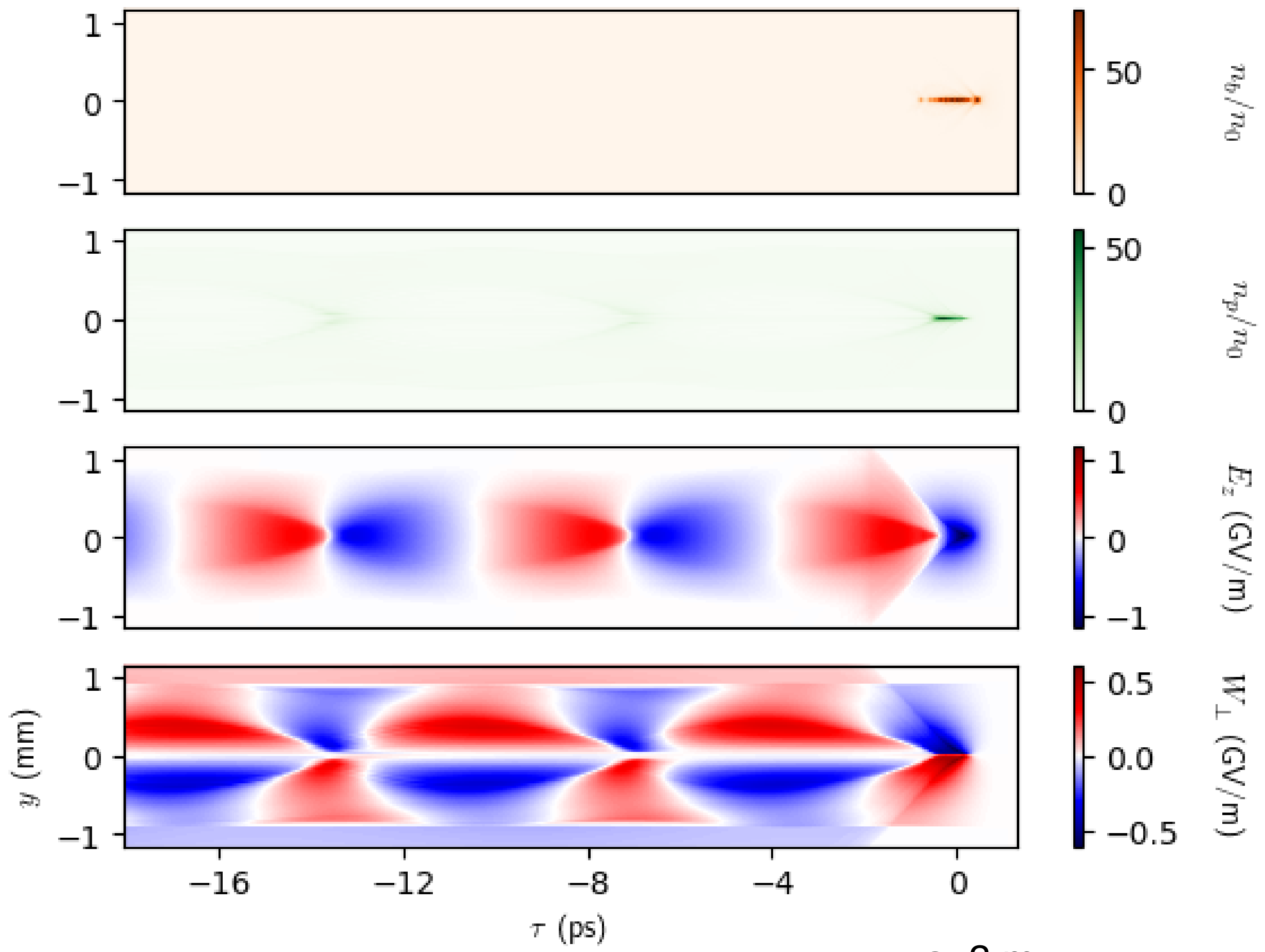


s=0 m

Picking the driver: stability

Initial proton driver chosen to generate suitable wakefields

Driver rapidly pinches



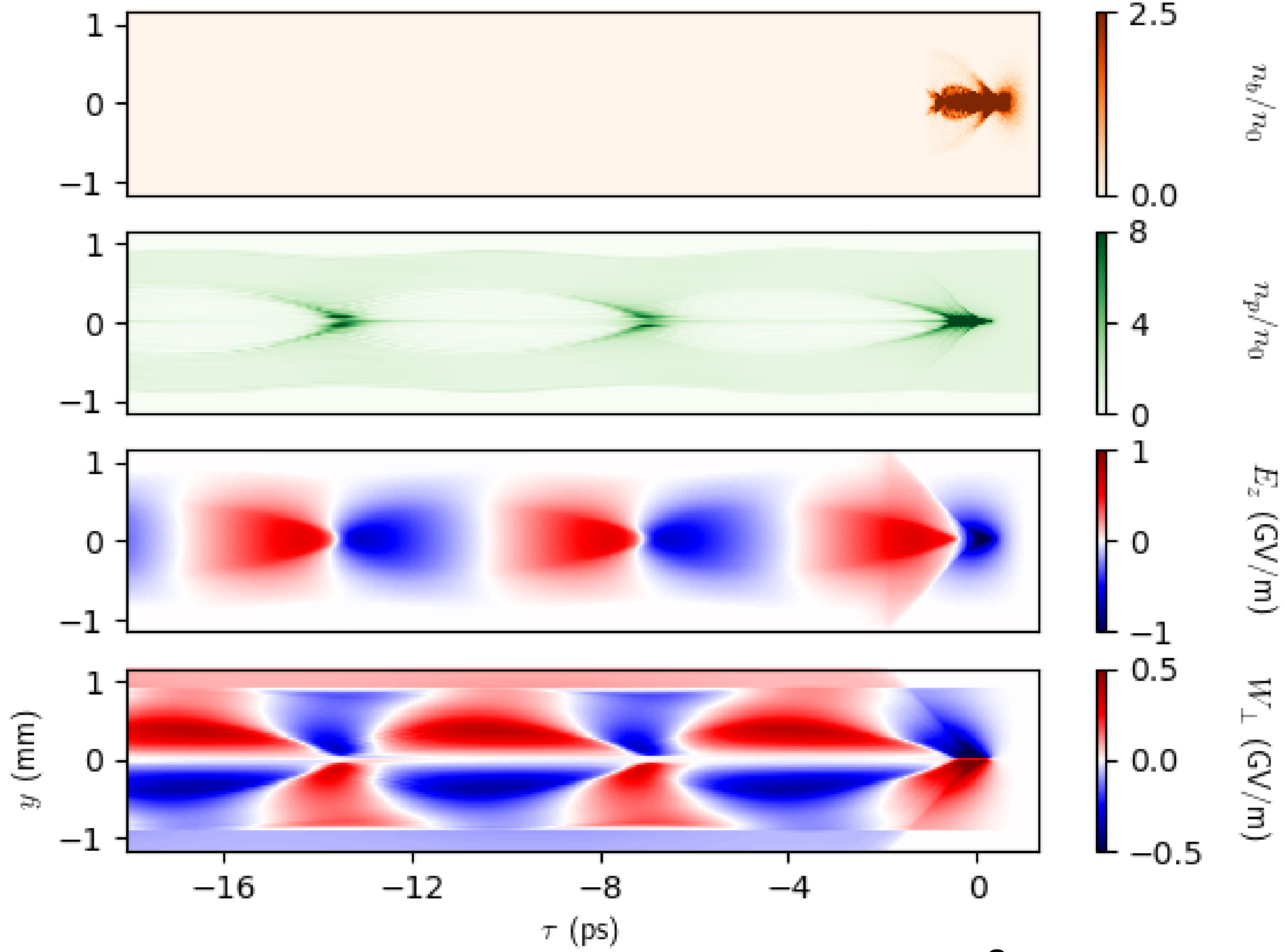
s=2 m

Picking the driver: stability

Initial proton driver chosen to generate suitable wakefields

Driver rapidly pinches

Highly nonlinear wakefields pose several potential problems



s=2 m

Picking the driver: stability

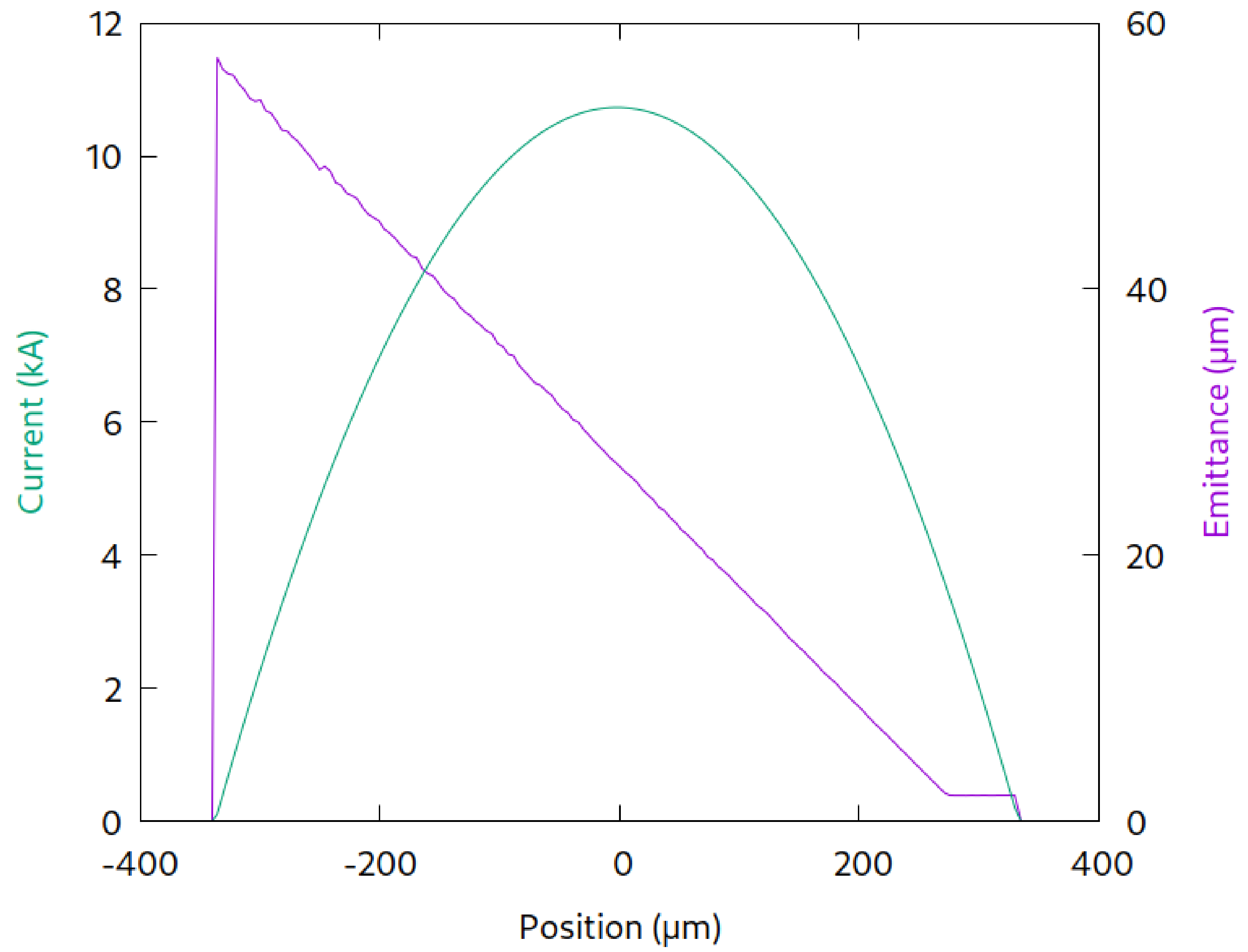
Good initial wakefields not sufficient:

- driver needs to evolve slowly
- counteract strong focussing wakefields

Picking the driver: stability

σ_z = 150 μm
σ_r = 240 μm
$n_b = 1\times10^{11}$
E = 400 GeV
ϵ_N = *tailored*

- 2 μm at head
- initially constant
- rises linearly to 58 μm

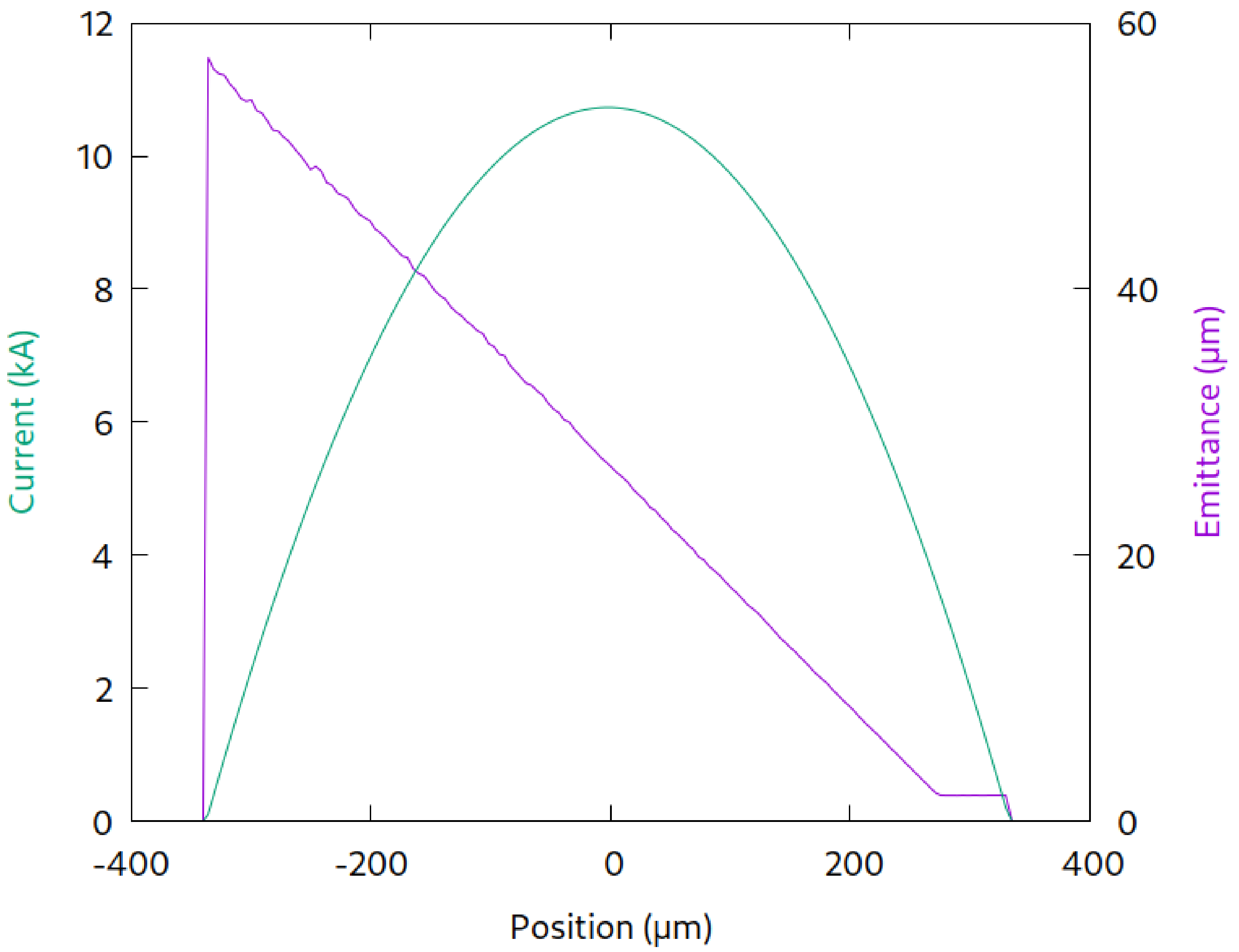


Picking the driver: stability

How can we generate a tailored emittance profile?

Most likely:
with difficulty

BUT emittance is initially constant before growing monotonically



Picking the driver: stability

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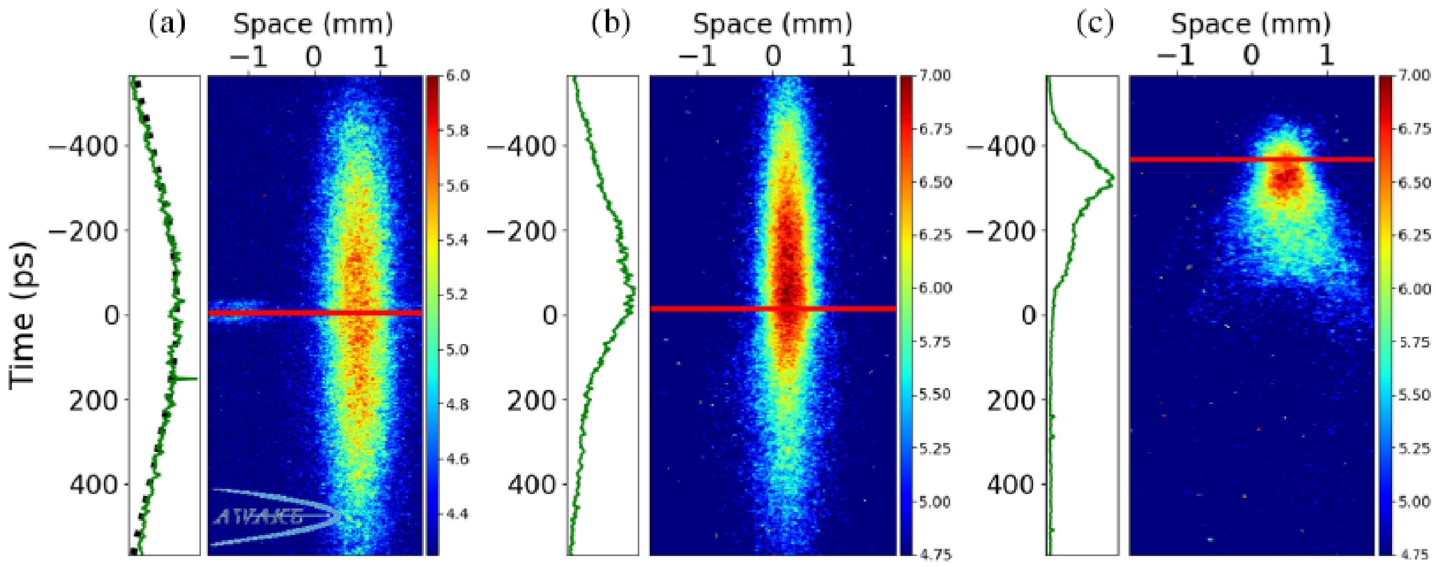


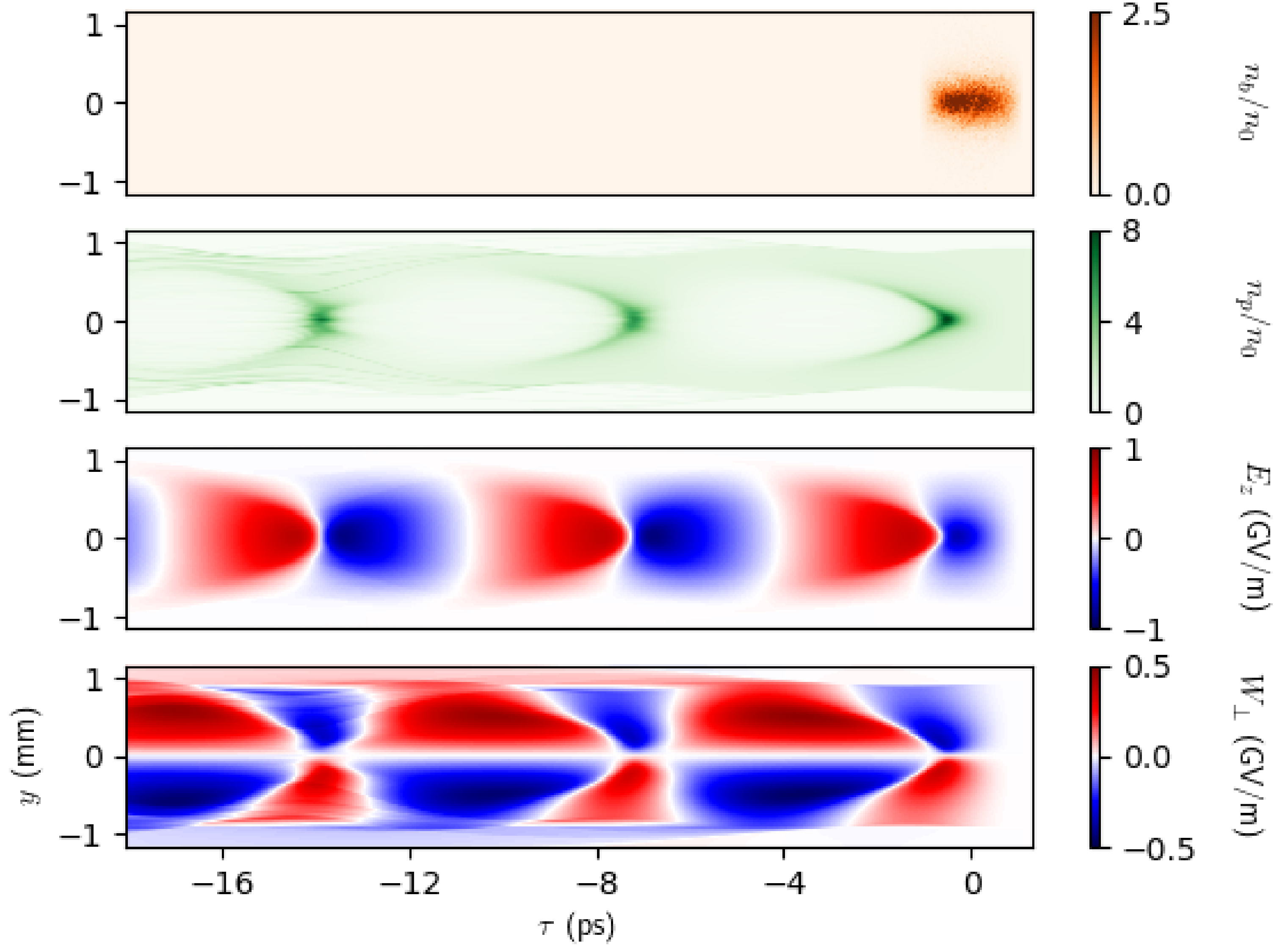
AWAKE Collaboration, PRL (2019)

Harness plasma instabilities?

Acceleration: dephasing

Initial proton driver chosen to generate suitable wakefields

Tailored profile stable for 2 m

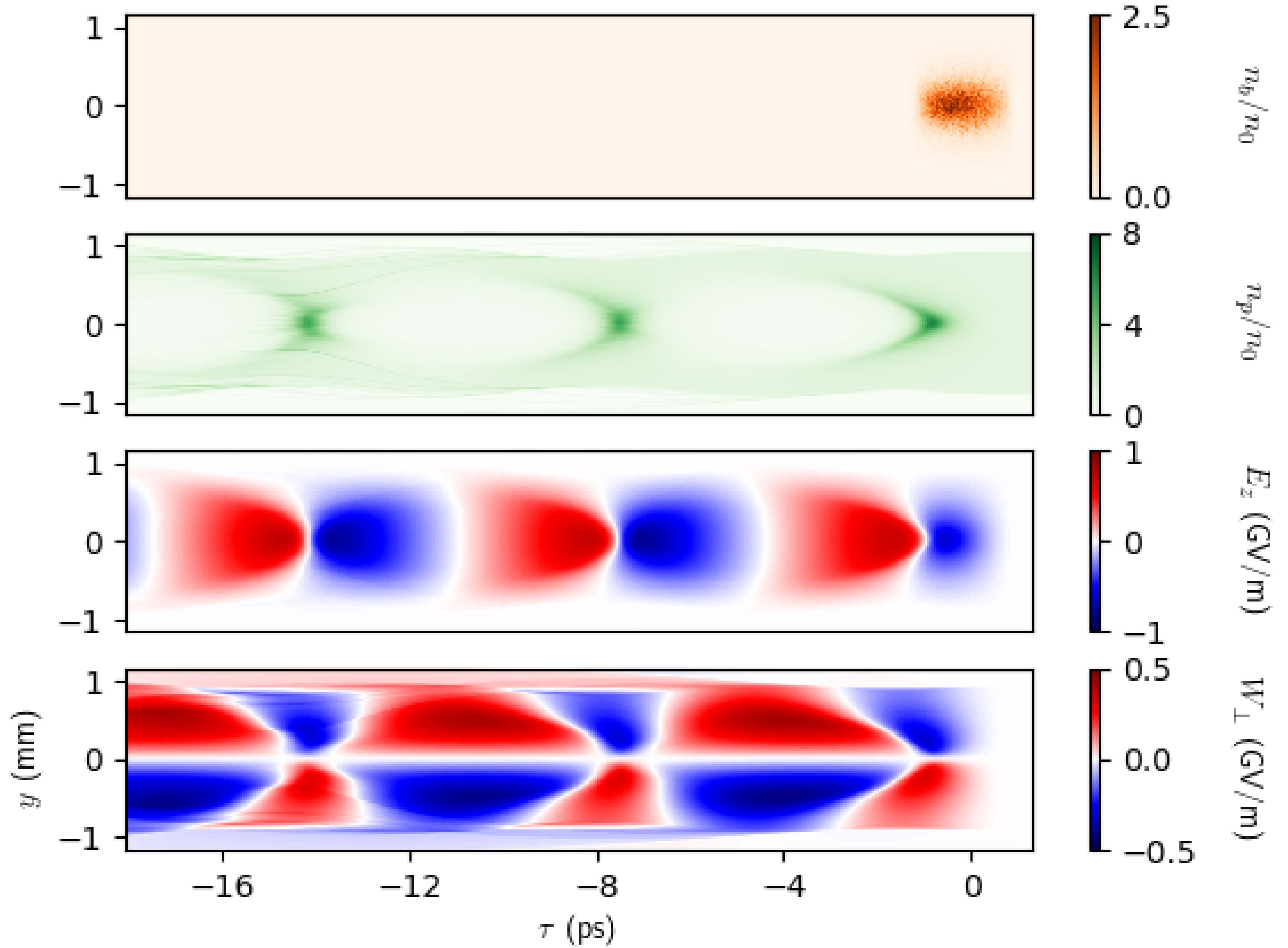


s=2 m

Acceleration: dephasing

Initial proton driver chosen to generate suitable wakefields

Tailored profile stable for 20 m



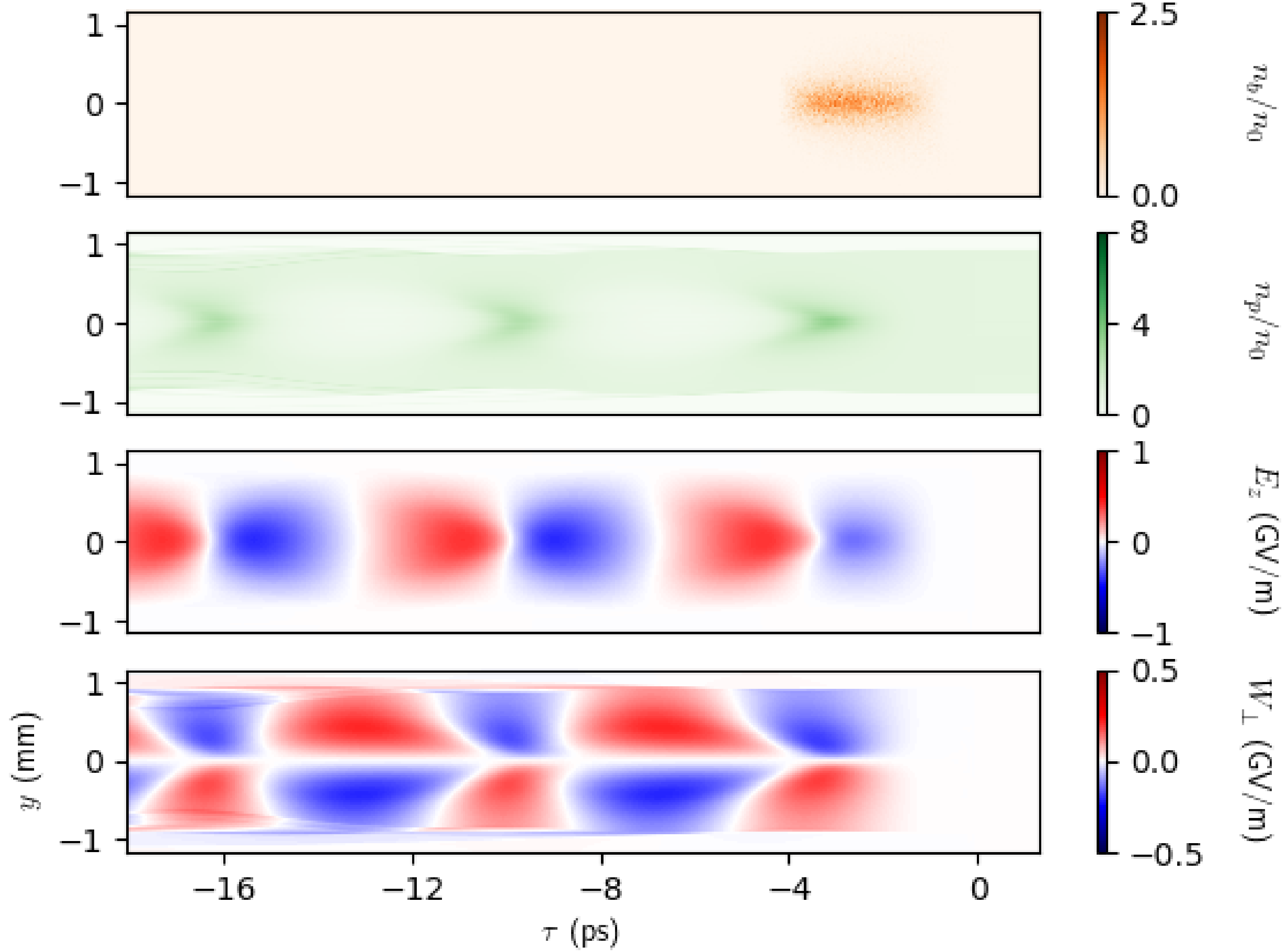
s=20 m

Acceleration: dephasing

Initial proton driver chosen to generate suitable wakefields

Tailored profile stable for 200 m

BUT:
protons "fall back" in the light frame



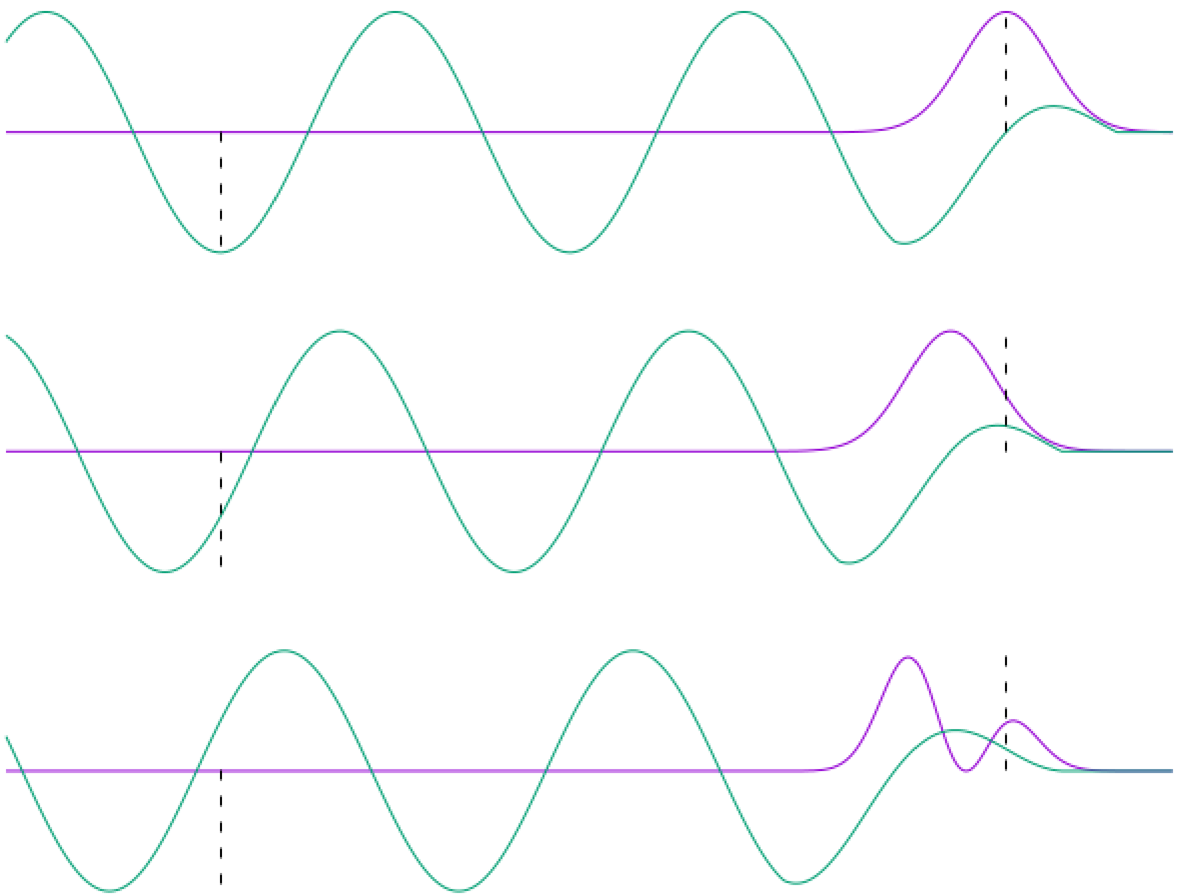
s=200 m

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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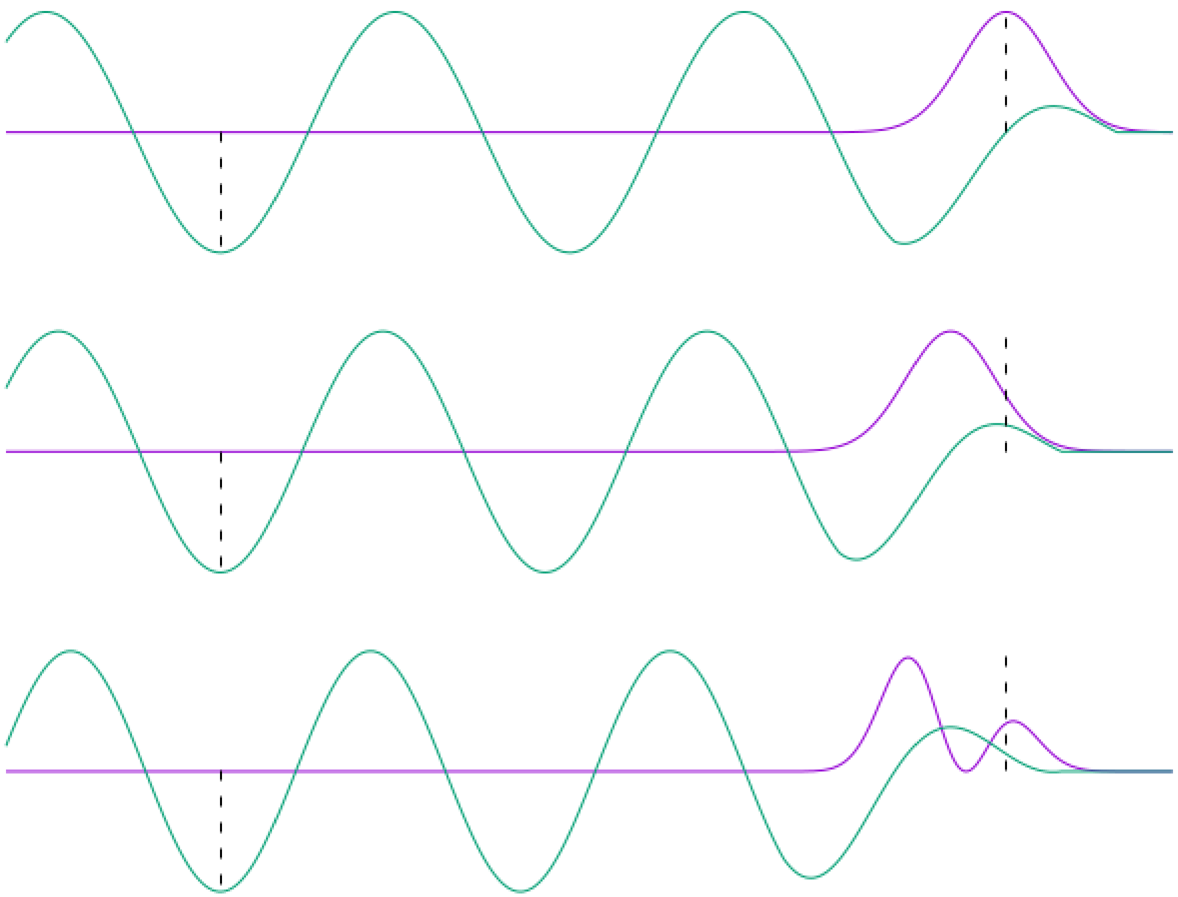
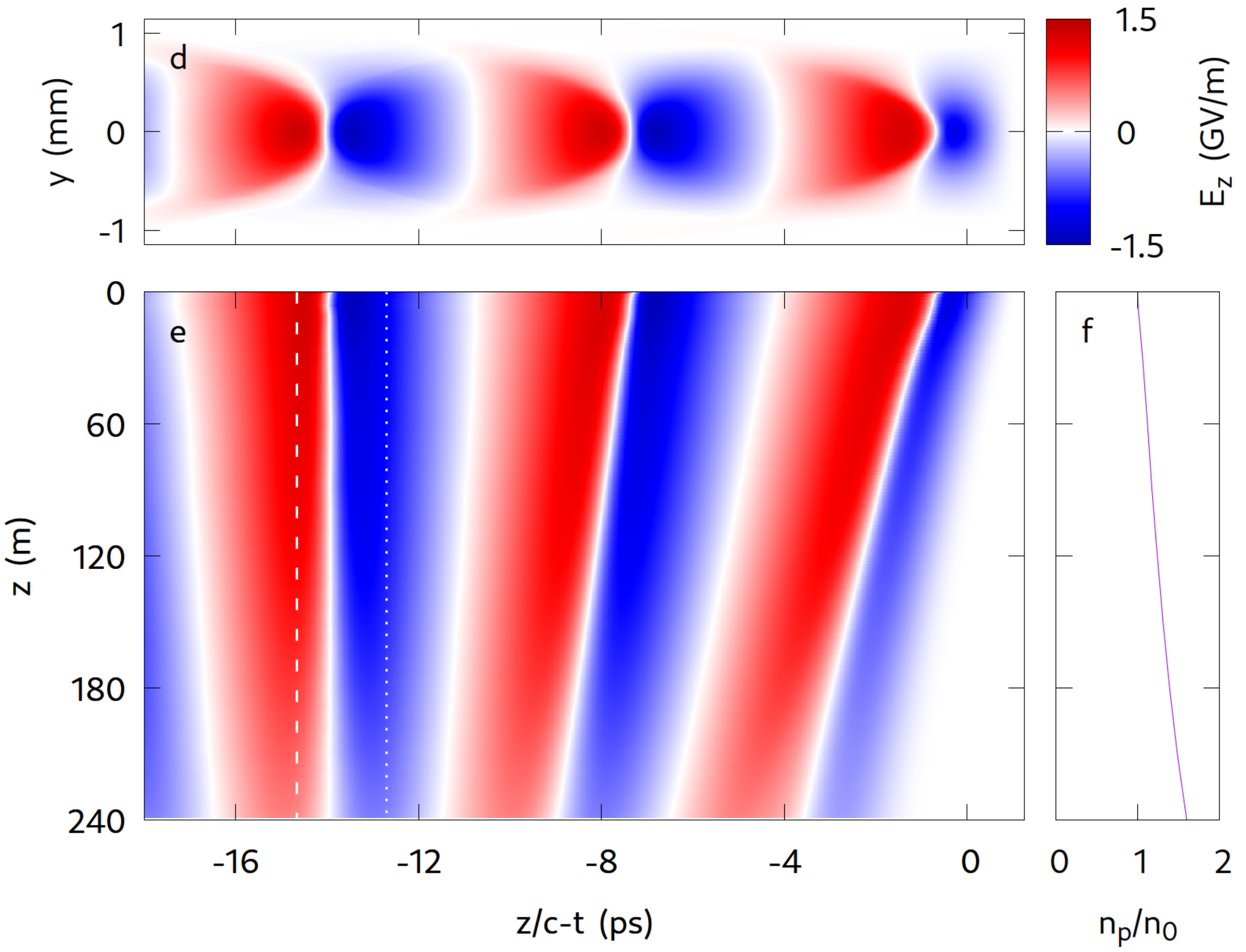


Change plasma density to keep phase constant

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

Acceleration

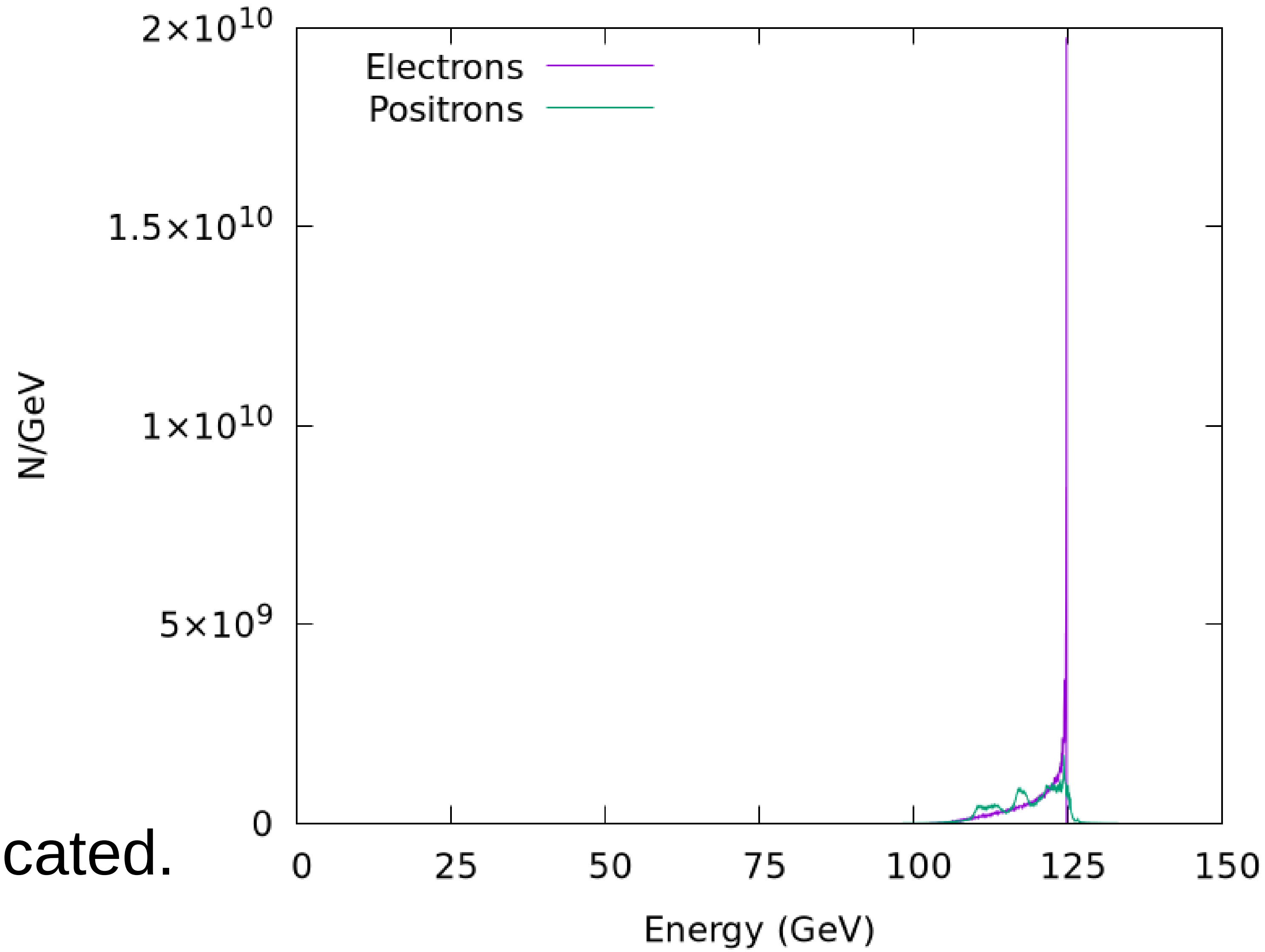
10^{11} protons at 400 GeV

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

Electron emittance and slice energy spread are conserved.

Beamloading would give a narrower peak.

Positrons are more complicated.



Acceleration: beamloading

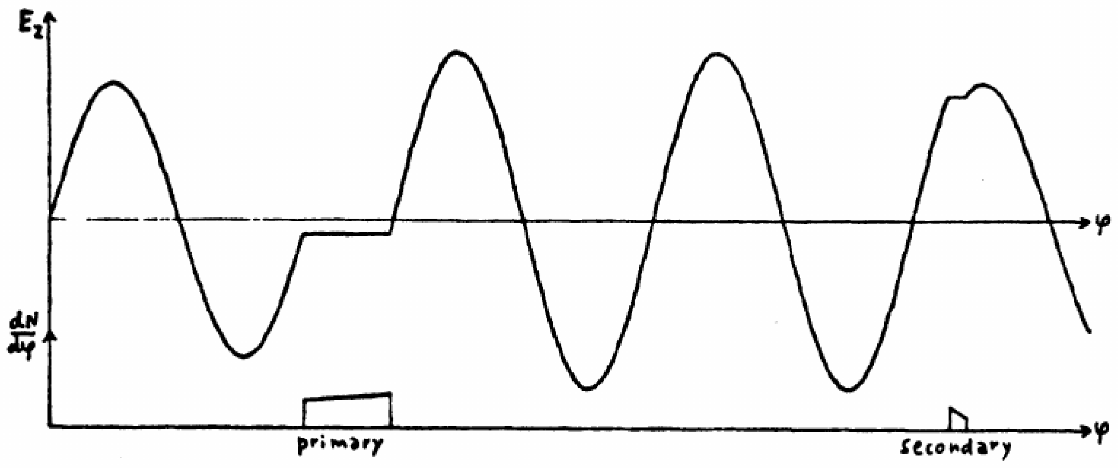


Fig. 3 - Continuous operation. Intervals between primary and secondary bunches may be changed by multiples of 2π.

Van der Meer (1985)

Witness drives its own wakefield, and is subject to the combined wakes of driver and witness

Witness evolution

Plasma provides large accelerating fields,
but also large focussing fields.

Emittance preservation relies on choosing the witness radius such that the emittance pressure compensates the focussing.

$$\sigma_r = \sqrt[4]{\frac{2}{\gamma}}\sqrt{\frac{\epsilon_N}{k_p}}$$

- extremely small witness radius at high energy:
  0.27 µm for electrons at 125 GeV with 0.1 µm emittance.

Witness evolution

The transverse fields from such a tightly focussed beam are extreme. For our ~1.5 kA peak current, E_r = 150 GV/m.

Leads to some headaches

- secondary ionization
- ion motion

Witness evolution: ionization

We can use the PPT (1966) ionization model for tunnel ionization in a static field:

$$w_{\text{stat}}(F) = \omega_0 |C_{\varkappa l}|^2 (2l+1) \frac{(l+|m|)!}{2^{|m|}(|m|)!(l-|m|)!} \times \left(\frac{2F_0}{F}\right)^{2\lambda-|m|-1} \exp\left\{-\frac{2}{3}\frac{F_0}{F}\right\},$$

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F – applied field

F_0 – critical field of ionization

Everything else: O(1) (C_{xl} from ADK (1985))

Witness evolution: ionization

Critical field varies for atom, ionization level, state:

$F_{\text{He II}} = 3.6$ TV/m

$F/F_{\text{He II}} = 0.042$

Characteristic tunnelling time 0.3 ps.

the length of our witness!

Not impossible, could use higher emittance (lowers luminosity) or lower-density plasma (lowers gradient).

Witness evolution: ionization

Critical field varies for atom, ionization level, state:

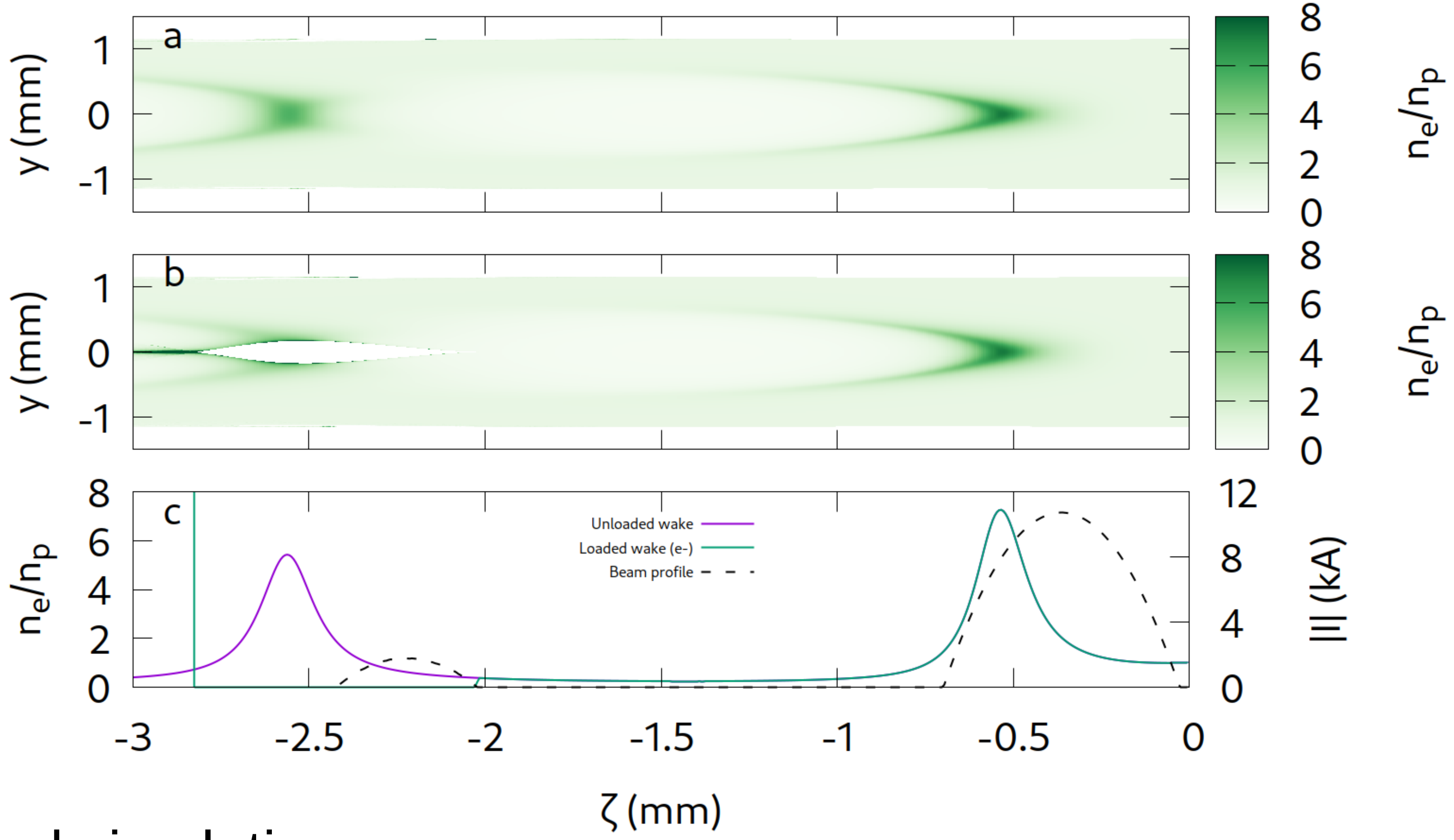
$F_{Li\ II}$ = 6.7 TV/m

$F/F_{He\ II}$ = 0.023

Characteristic tunnelling time 0.4 µs.

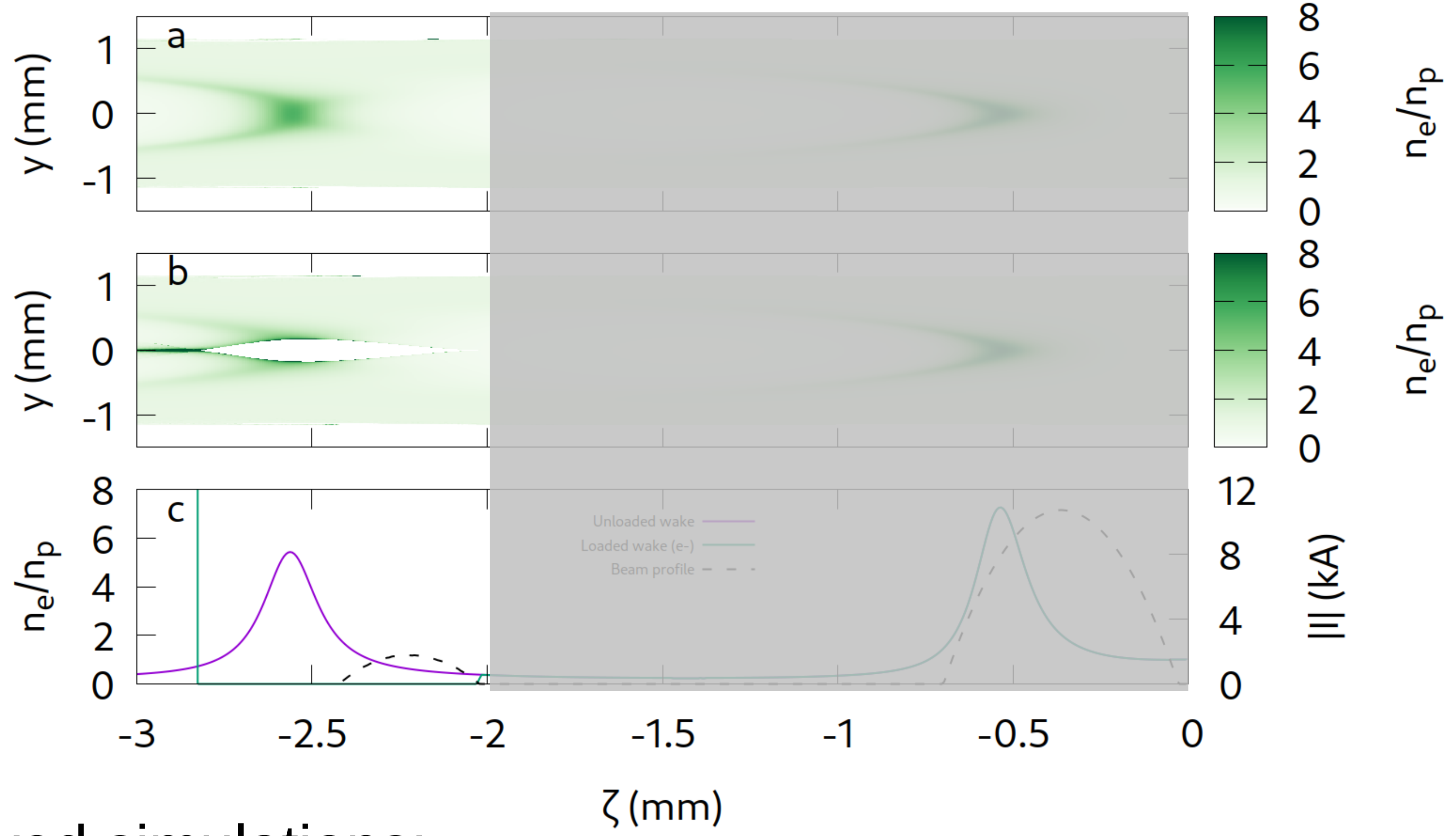
Certainly some challenges to create a lithium discharge,
but also need to consider the motion of ions in this field.

Acceleration: ion motion



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

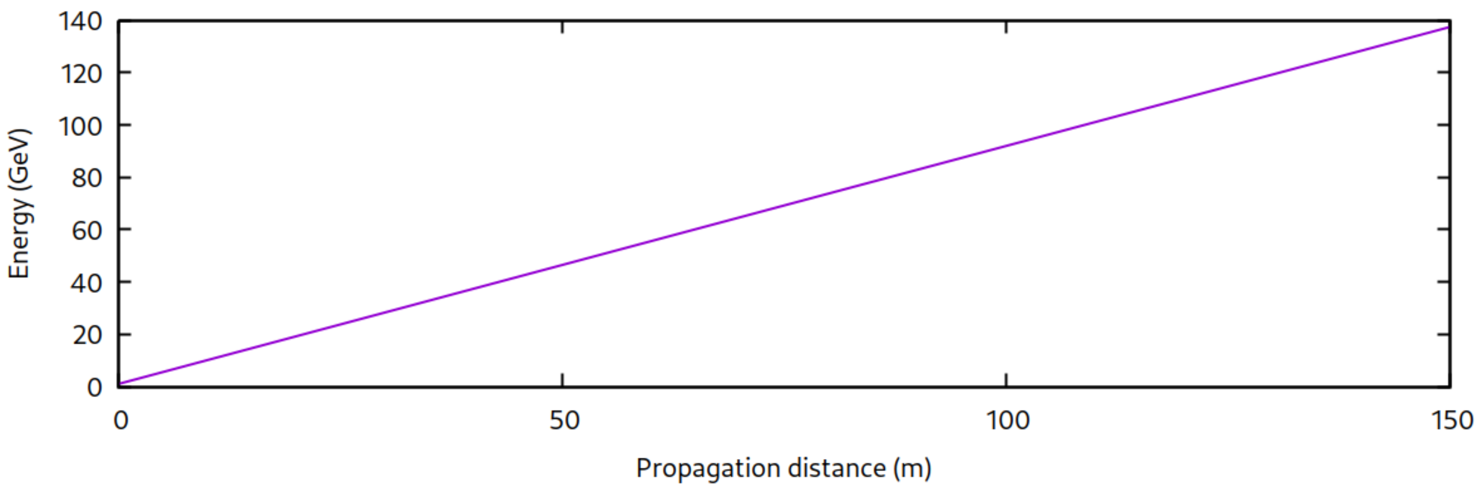
Acceleration: ion motion



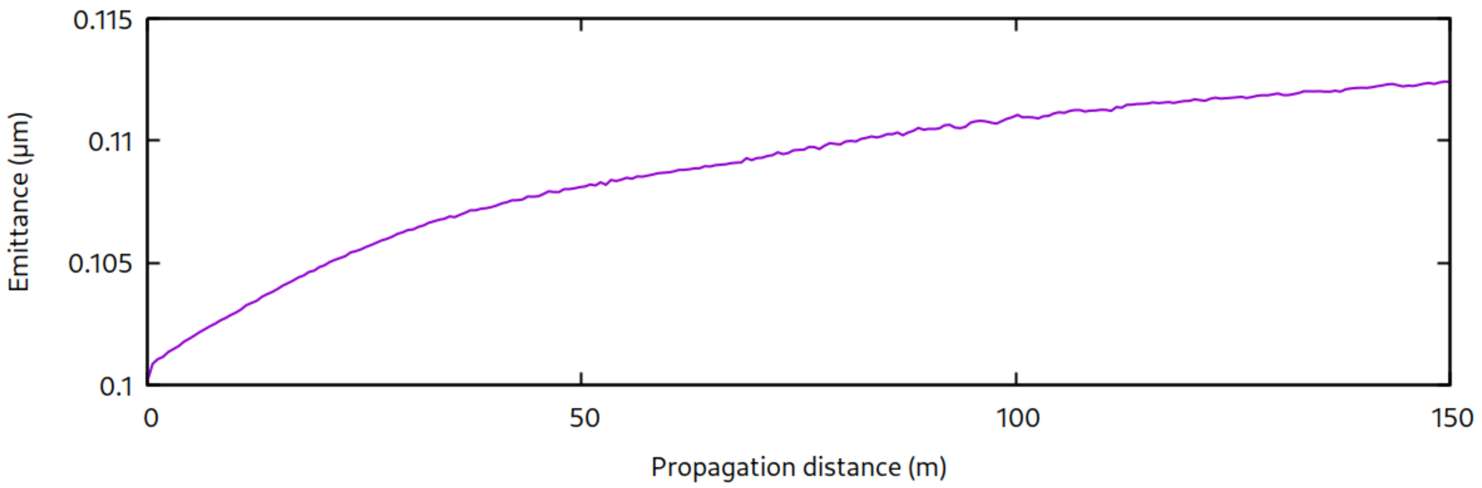
First resolved simulations:
2D geometry (LCODE), frozen driver, electron witness.

Acceleration: ion motion

Energy gain
(trivial for frozen driver)



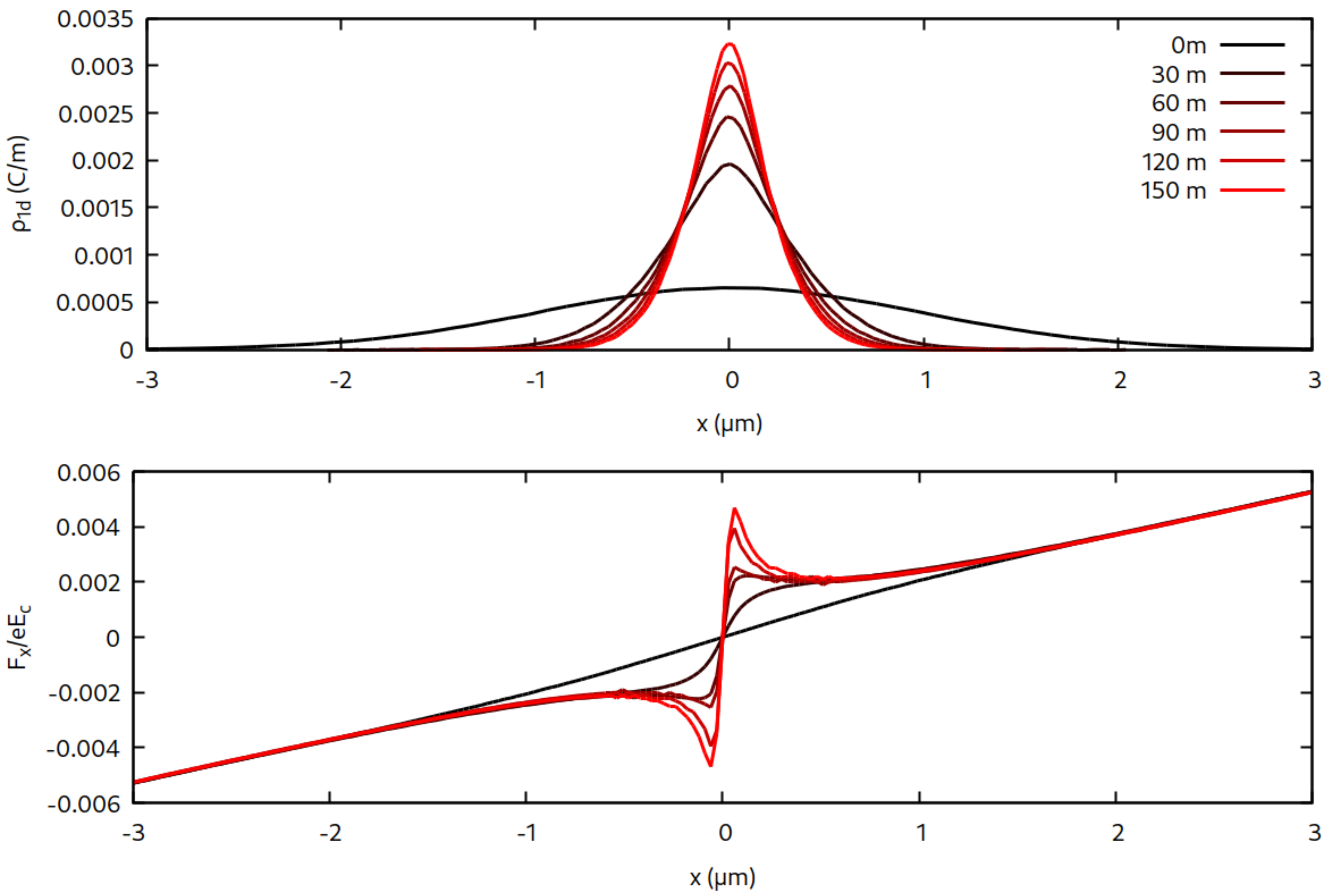
Emittance growth
due to ion motion
(lithium)



Acceleration: ion motion

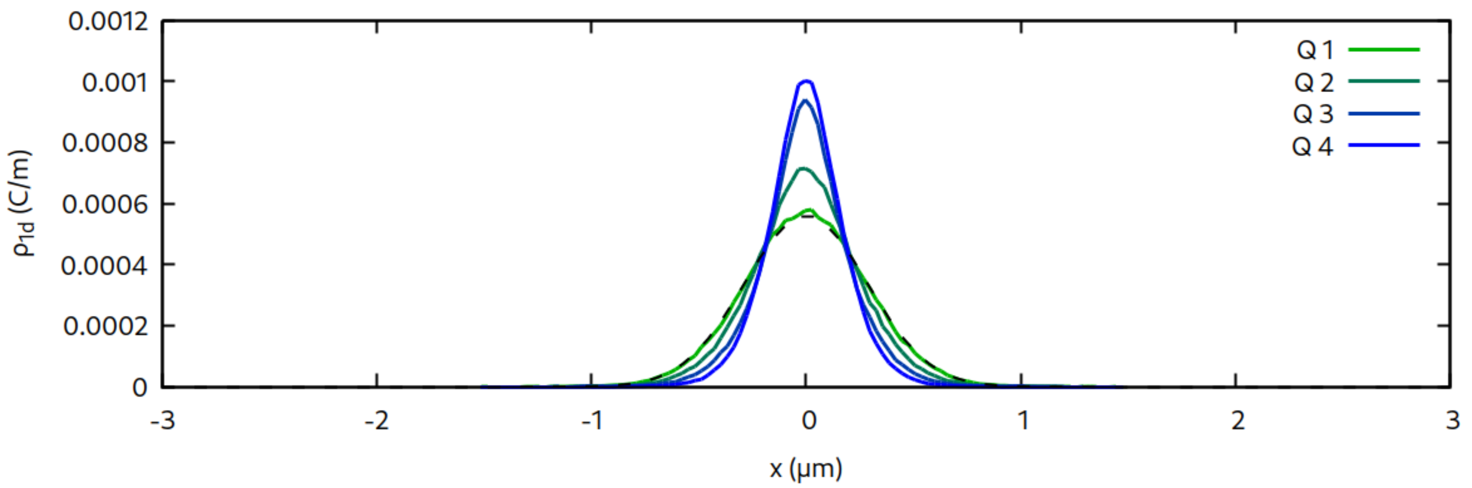
Adiabatic focussing of witness during acceleration
1µm → 0.23 µm

Focussing field becomes increasingly nonlinear

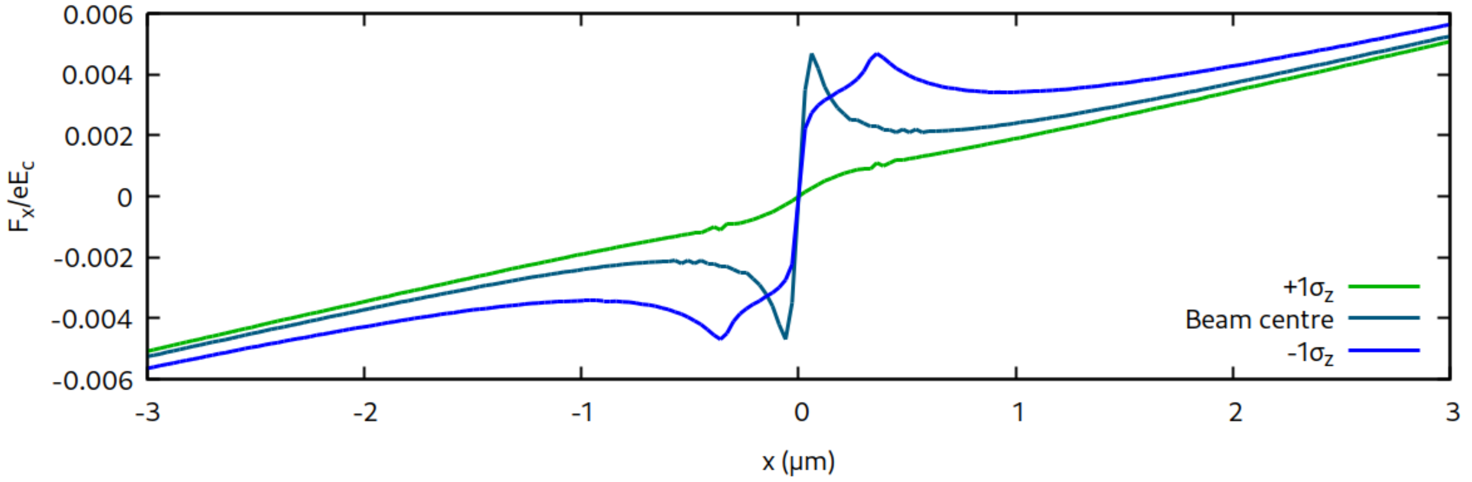


Acceleration: ion motion

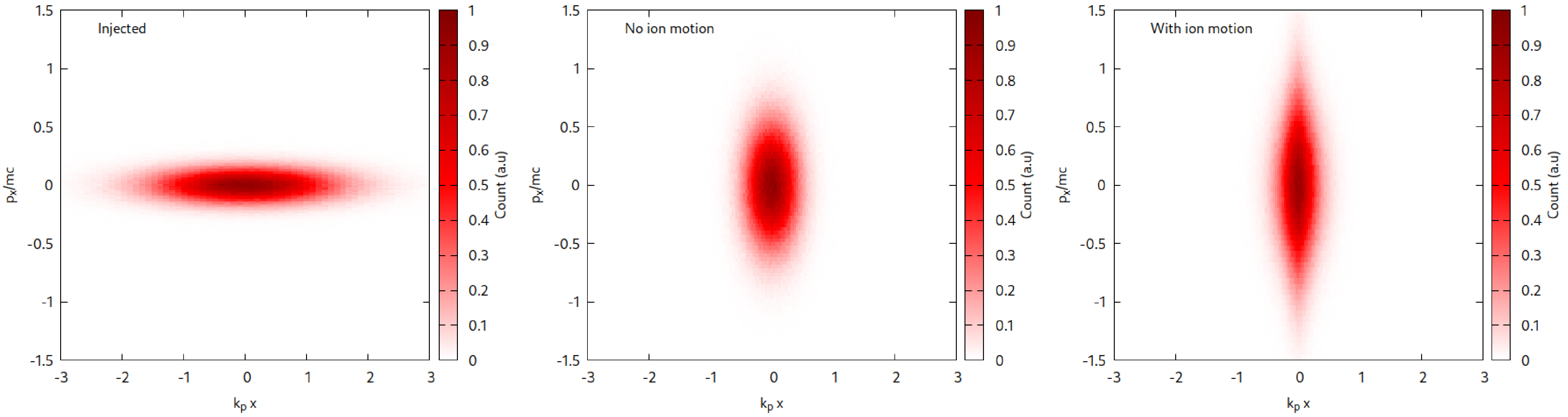
Different longitudinal slices of the witness have different profiles



Head-to-tail variation of focussing fields.



Acceleration: ion motion



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 wit… 20% driver charg… 100 nm e… a…

*Fla…

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

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Now on arXiv

and th… …etitive:

1.7x1… $cm^{-2}s^{-1}$

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			1000
Longitudinal…		μm	150
T…		…m	240
		…n	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
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}

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)

Acceleration to high energy is possible,
moderate driver-to-witness efficiency, clear path to improve this.

Conclusions and outlook

Key challenges:

- Short proton bunches with high rep rate
  - Ferdinand, Jake, today, working session today
- Energy recovery
  - Working sessions today, tomorrow
- PWFA acceleration of positron bunches
  - Alexander, Severin, tomorrow
- Suitable plasma source
  - Nelson, tomorrow
- Beam delivery
  - Vera, tomorrow

~ Fin ~

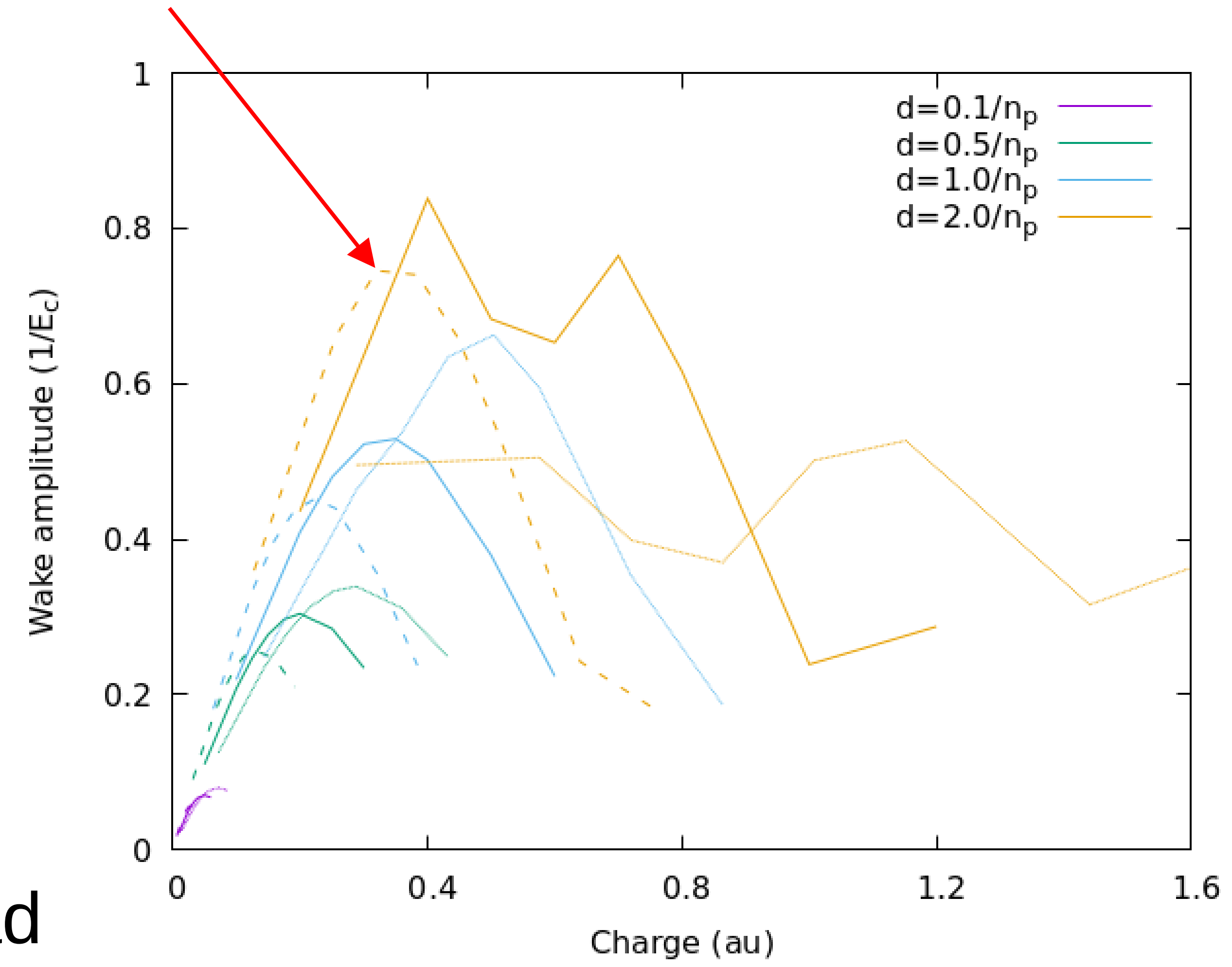
~ Backups ~

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