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

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

Introduction

A Higgs factory is a high priority for particle physics.

Plasma wakefield acceleration offers the advantage of high acceleration gradients

Proton-driven plasma wakefield acceleration would allow high energy gain in a single stage

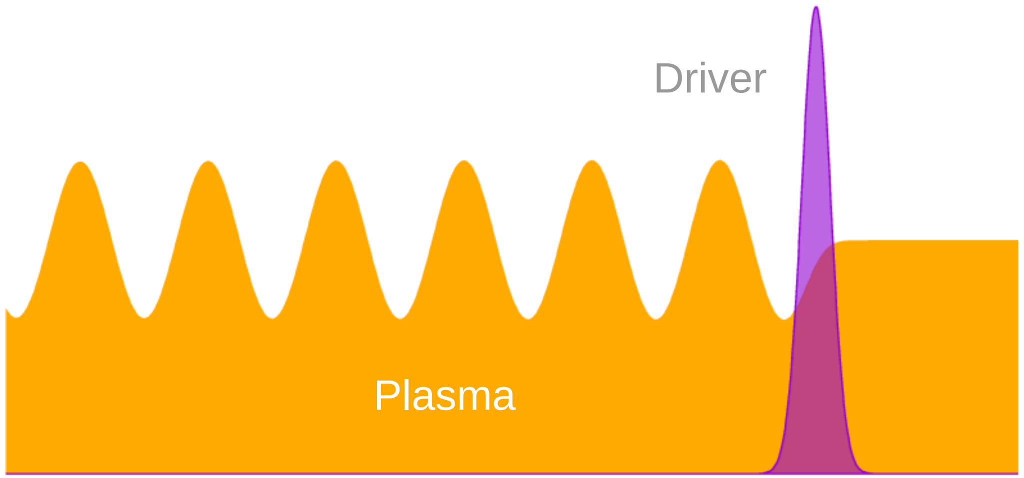
- potentially higher average gradients
- positron acceleration

Motivation: plasma wakefields

Damage threshold not a concern for plasma

– already “broken”

– gradients > 1GeV/m



Wakeboarding

Plasma wakefield acceleration

Energy gain limited by choice of driver

- laser pulse
- electron bunch
- proton bunch

Not enough energy in laser/electron driver to reach high witness energy. Solutions include

- structured driver (stability)
- staging (alignment, average gradient)

Proton-driven PWFA

Proton beams have plenty of energy

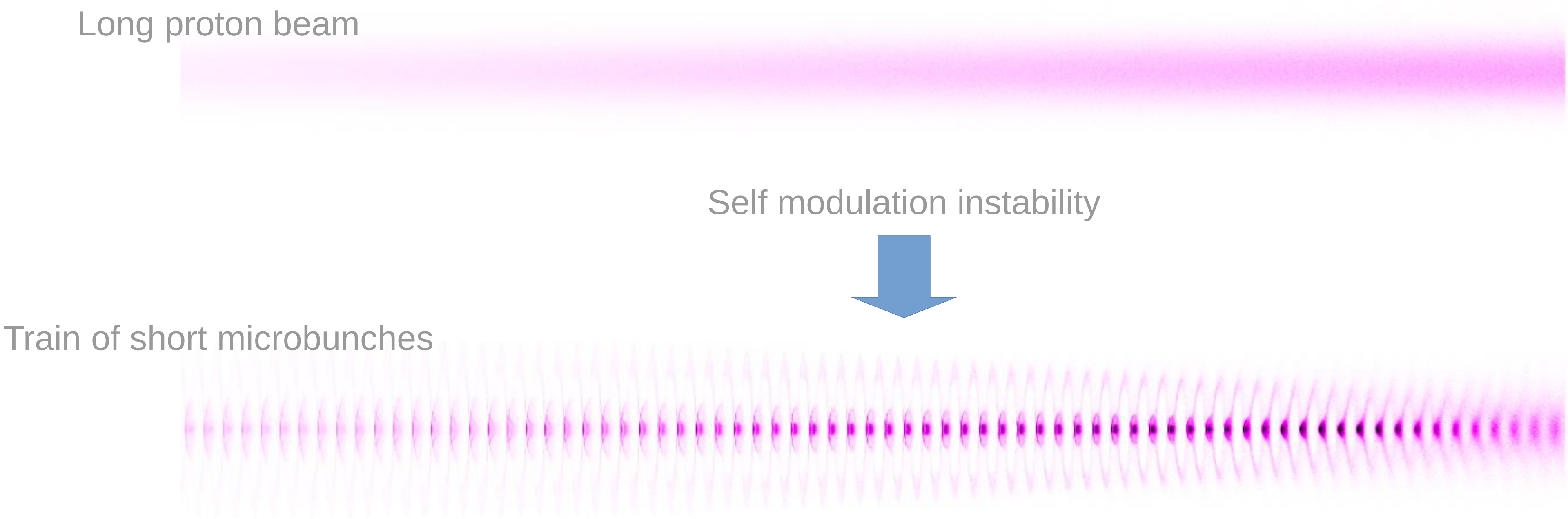
BUT available beams “too long” to efficiently drive a wake

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)

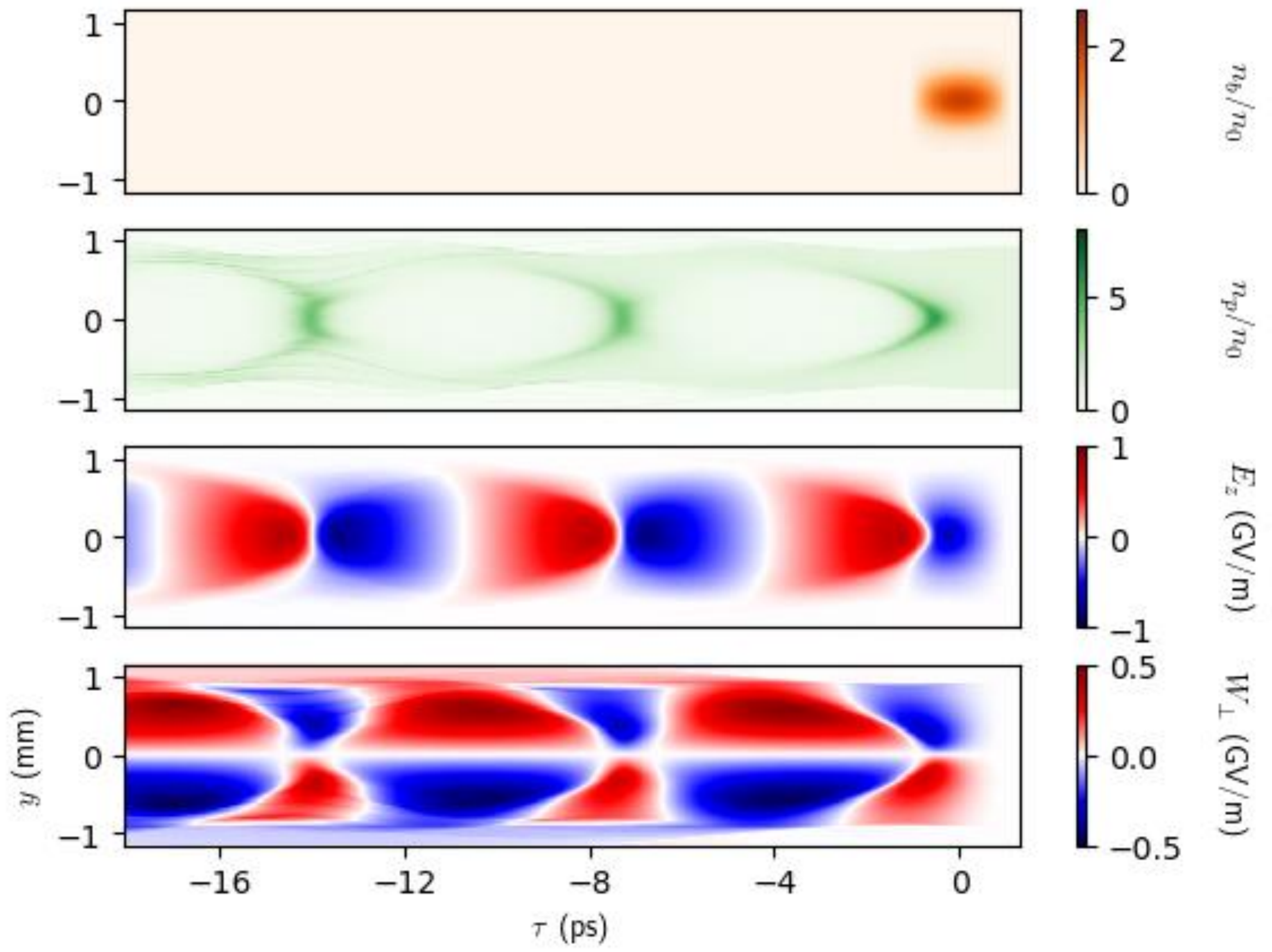
Developments in fast-ramping magnets would allow rapid-cycling (~5 Hz) synchrotrons.

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

Configuration

Assume a suitably short proton driver can be generated

Moderately nonlinear wakefield allows acceleration of both electrons and positrons



Configuration

Higgs–Z threshold is 216.4 GeV

Add some margin → collision energy of 250 GeV

- 125 GeV e^- colliding with 125 GeV e^+
- HAHLF considers 500 GeV e^- colliding with 31.3 GeV e^+

We need to demonstrate

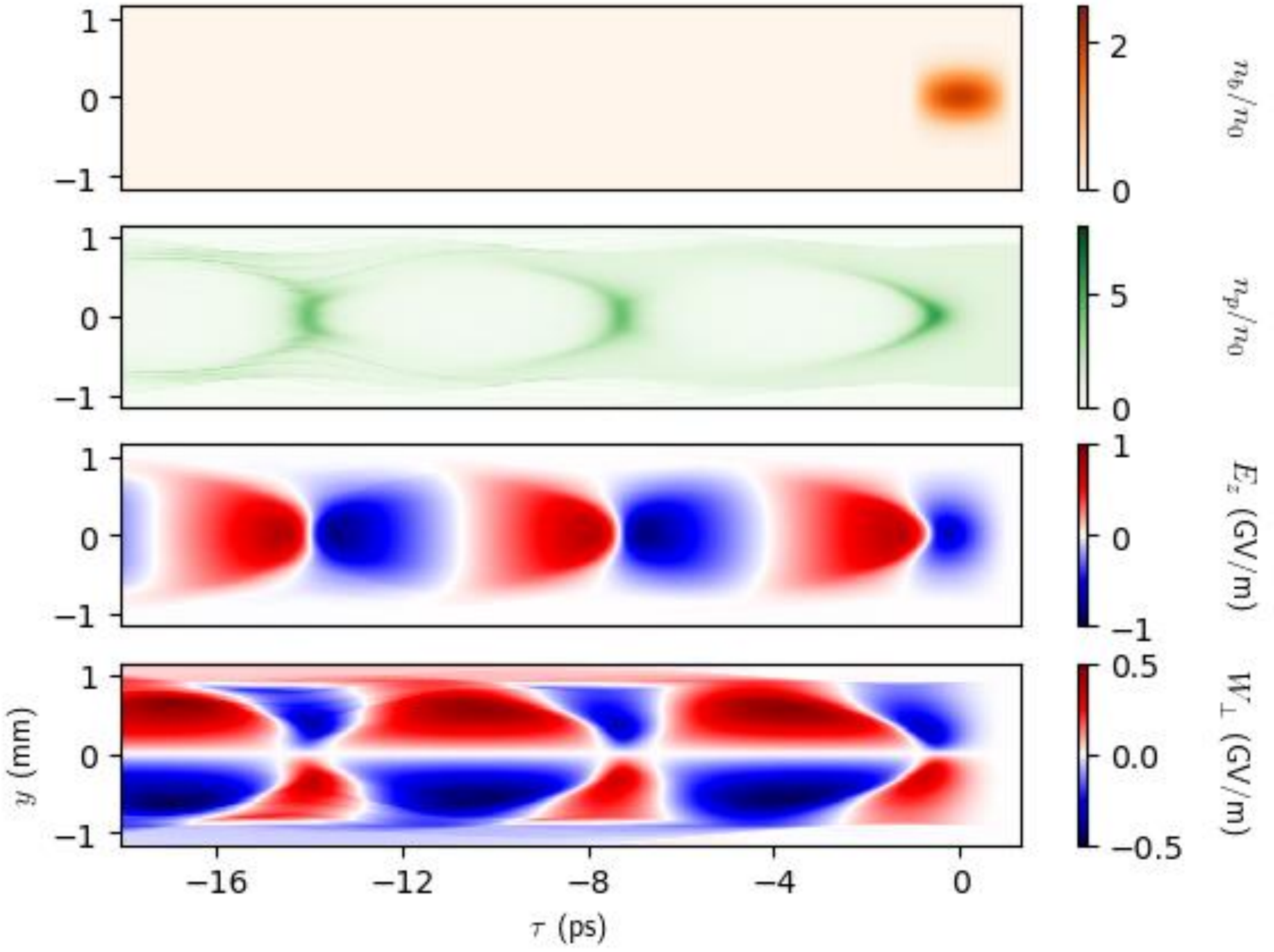
- efficiency
- stability

Picking the driver

Assume a suitably short proton driver can be generated

Need to pick driver parameters

- High efficiency
- Moderately nonlinear wake for positron acceleration

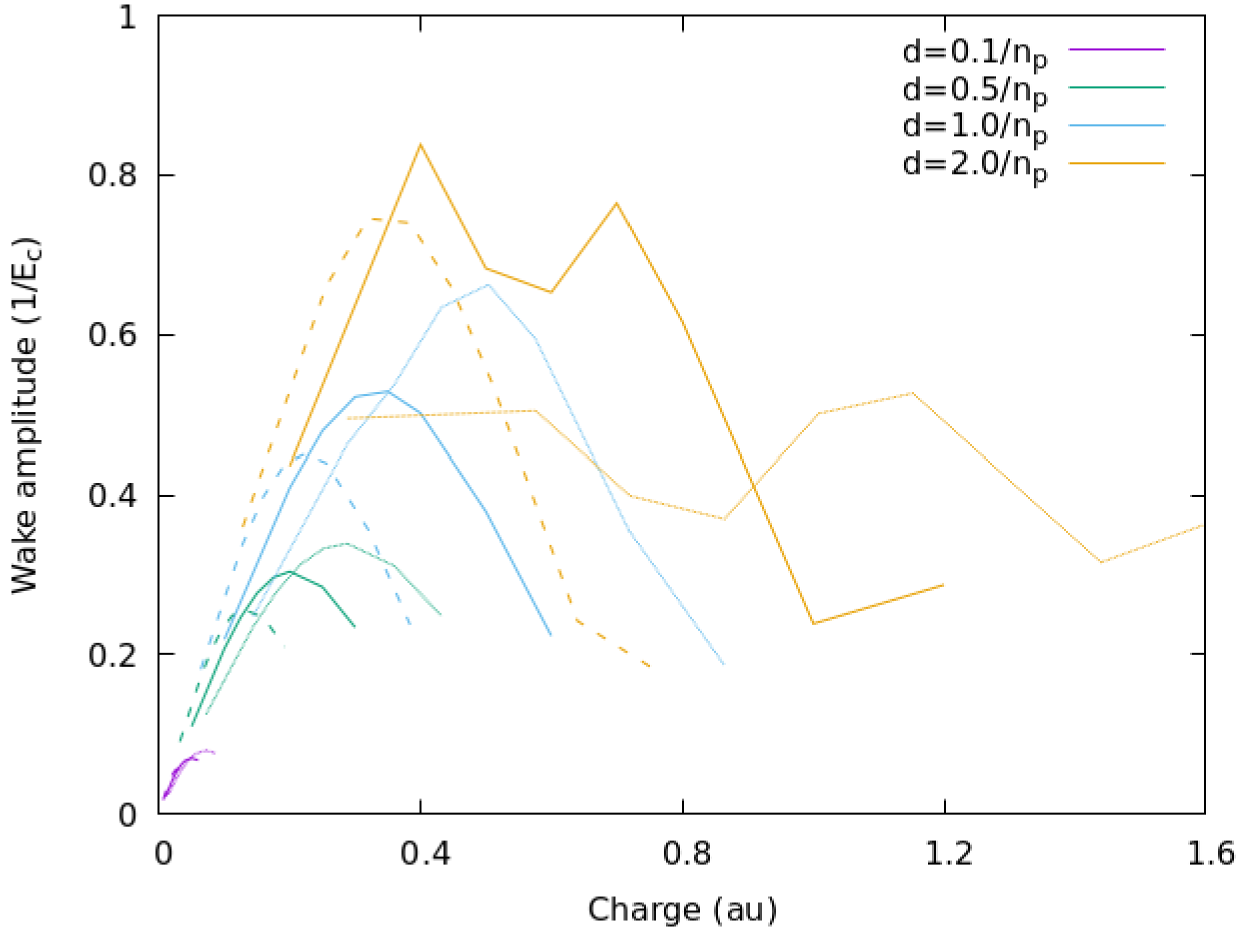


Picking the driver: efficiency

Scans with different driver length, density and radius

Optimal driver length ~driver charge density

Too-high current leads to highly-nonlinear wake



Dashed line: $k_p r = 0.8$
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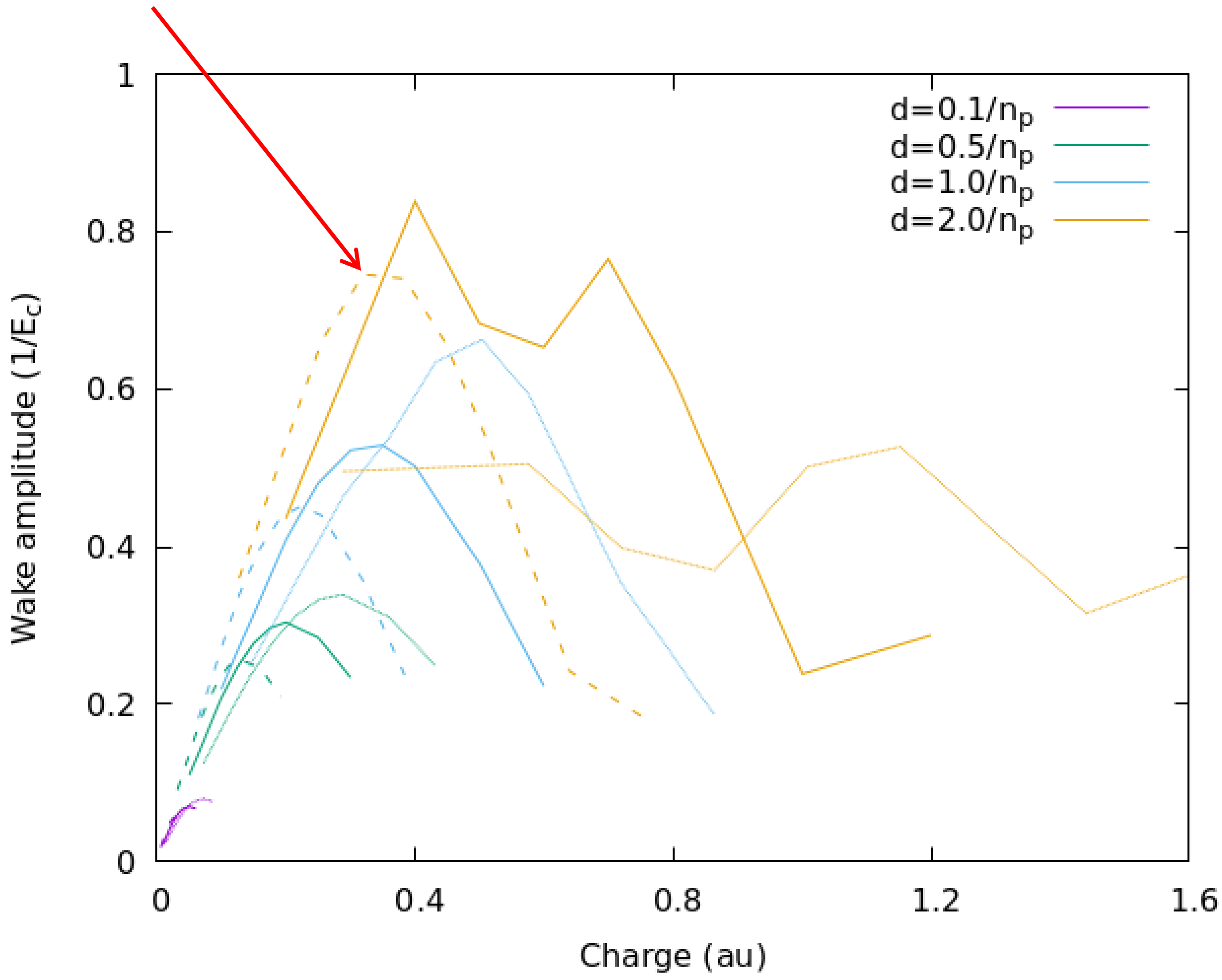

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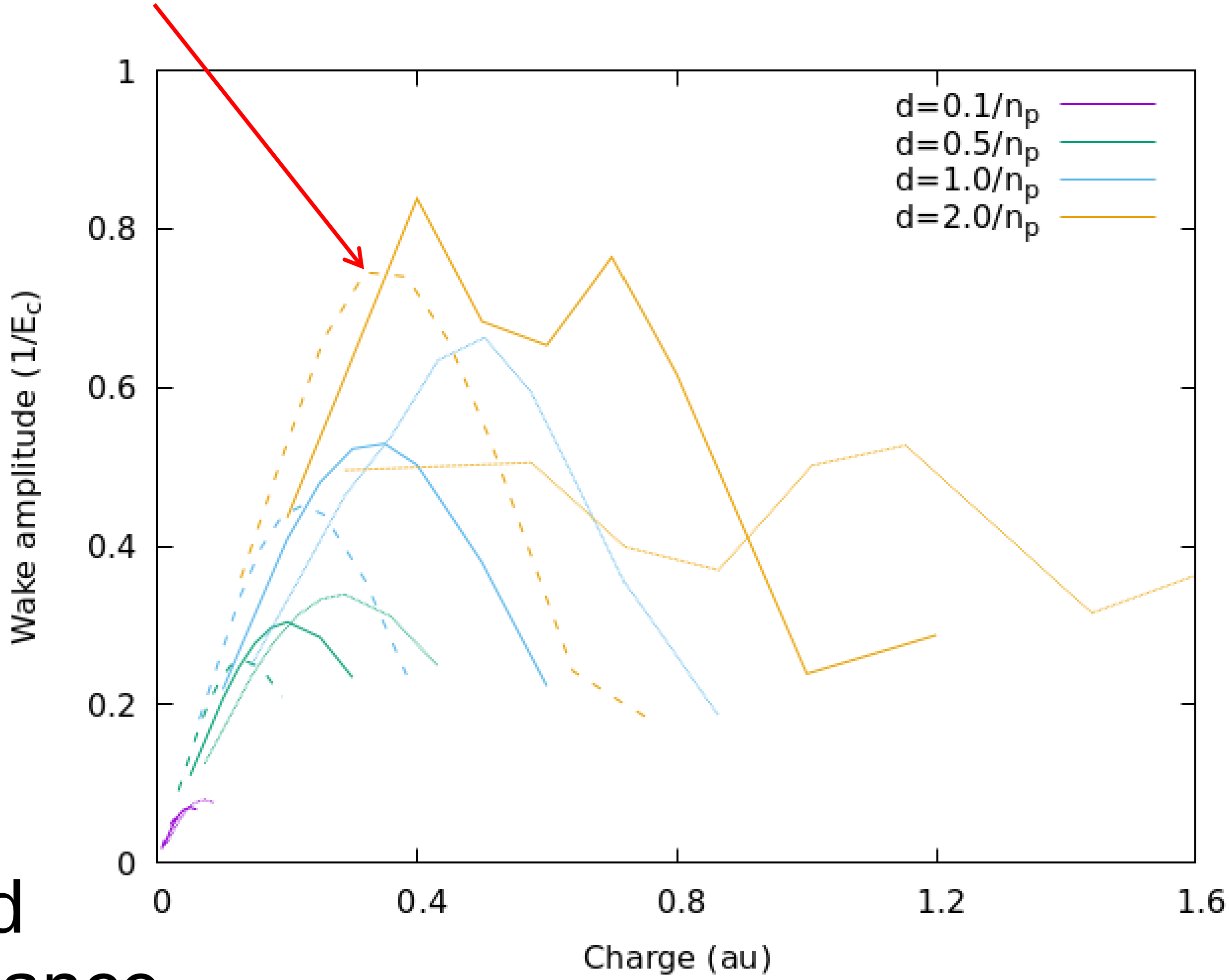
Picking the driver: efficiency

Everything scales with plasma frequency

$1x10^{11}$ protons gives

- plasma density $3x10^{14}$ cm^{-3}
- driver length 150 µm
- Initial wakefields ~ 0.8GV/m

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



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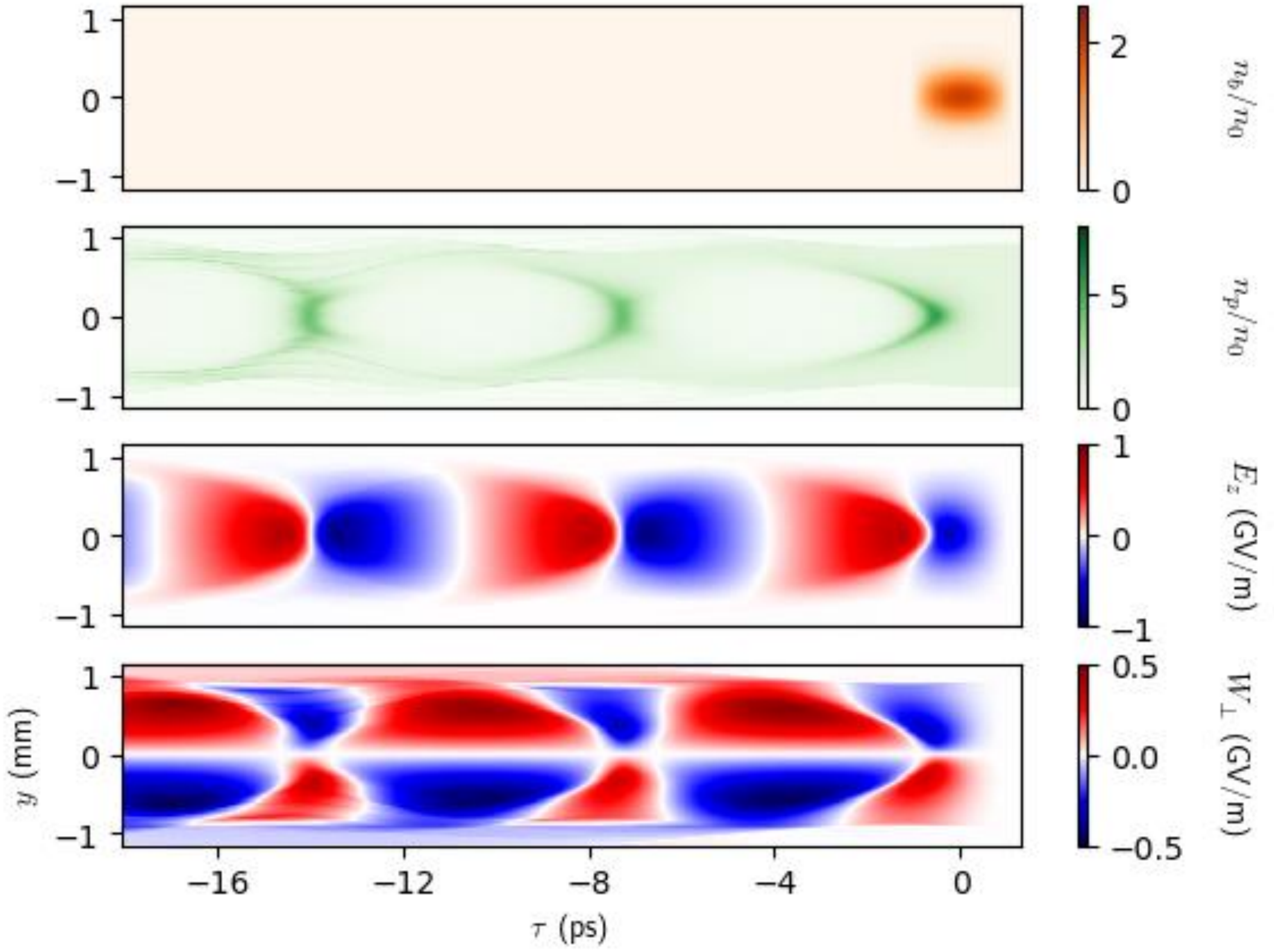
Picking the driver: stability

Initial proton driver chosen to generate suitable wakefields



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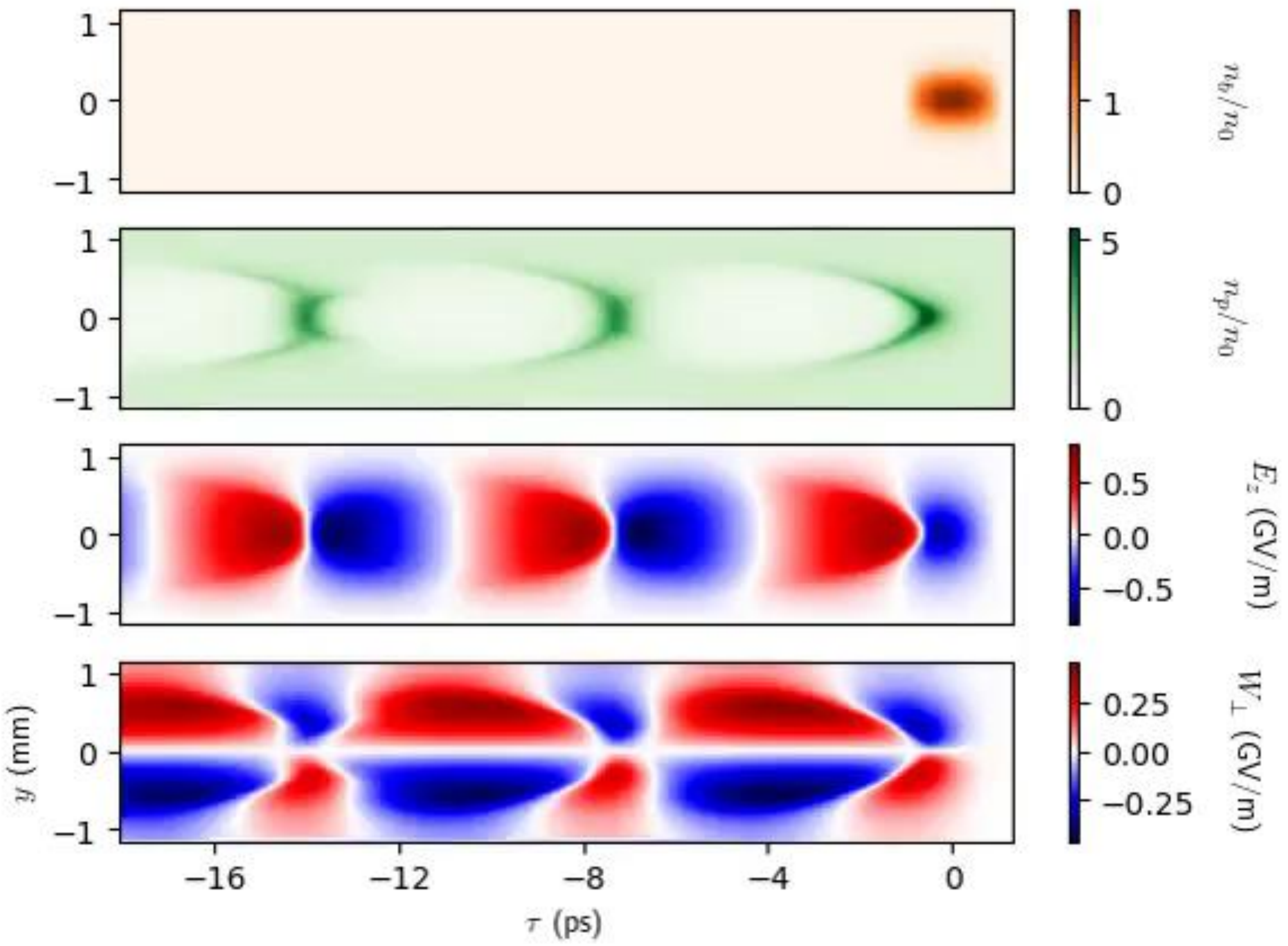
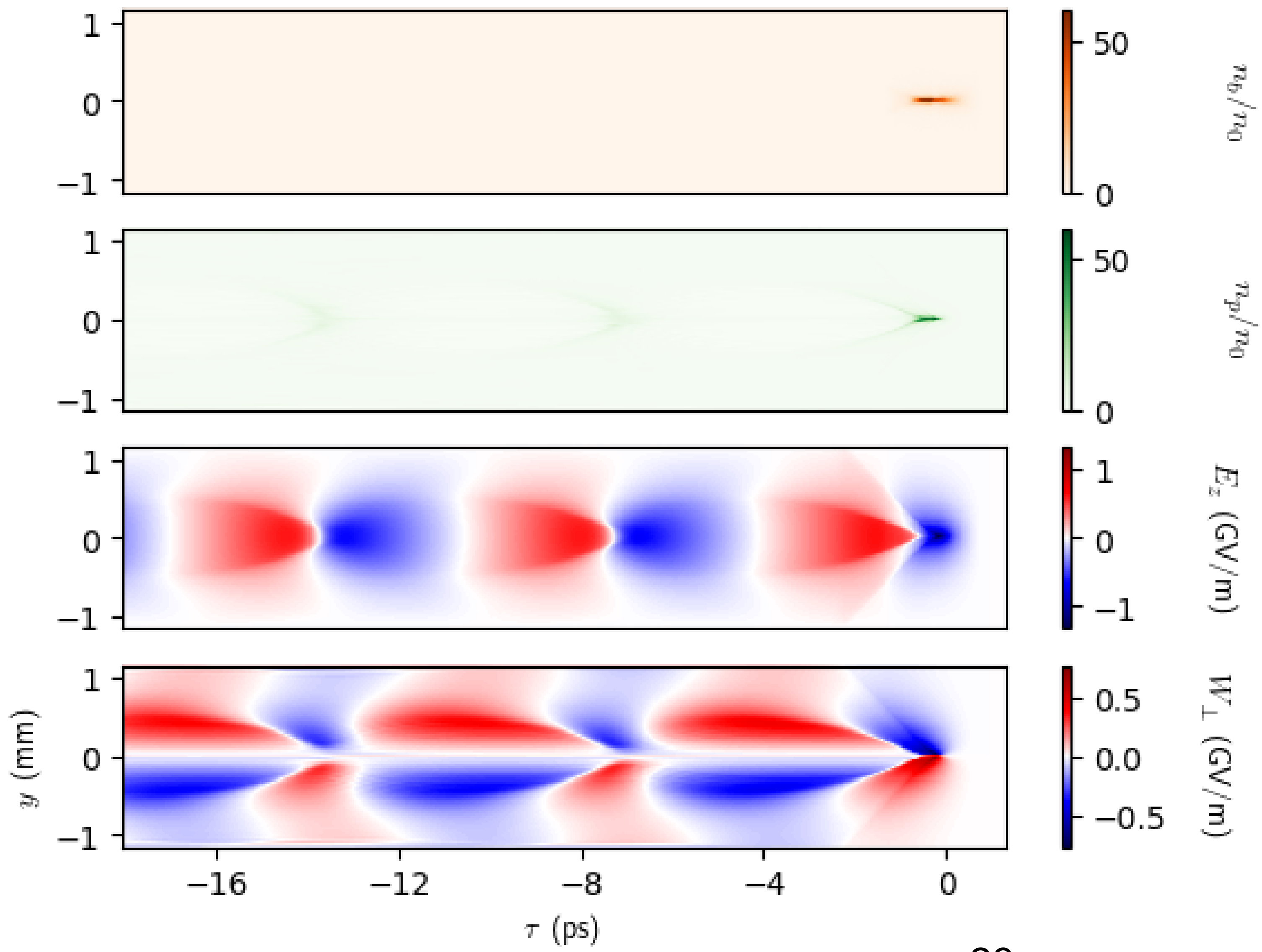


Picking the driver: stability

Initial proton driver chosen to generate suitable wakefields

Driver rapidly pinches



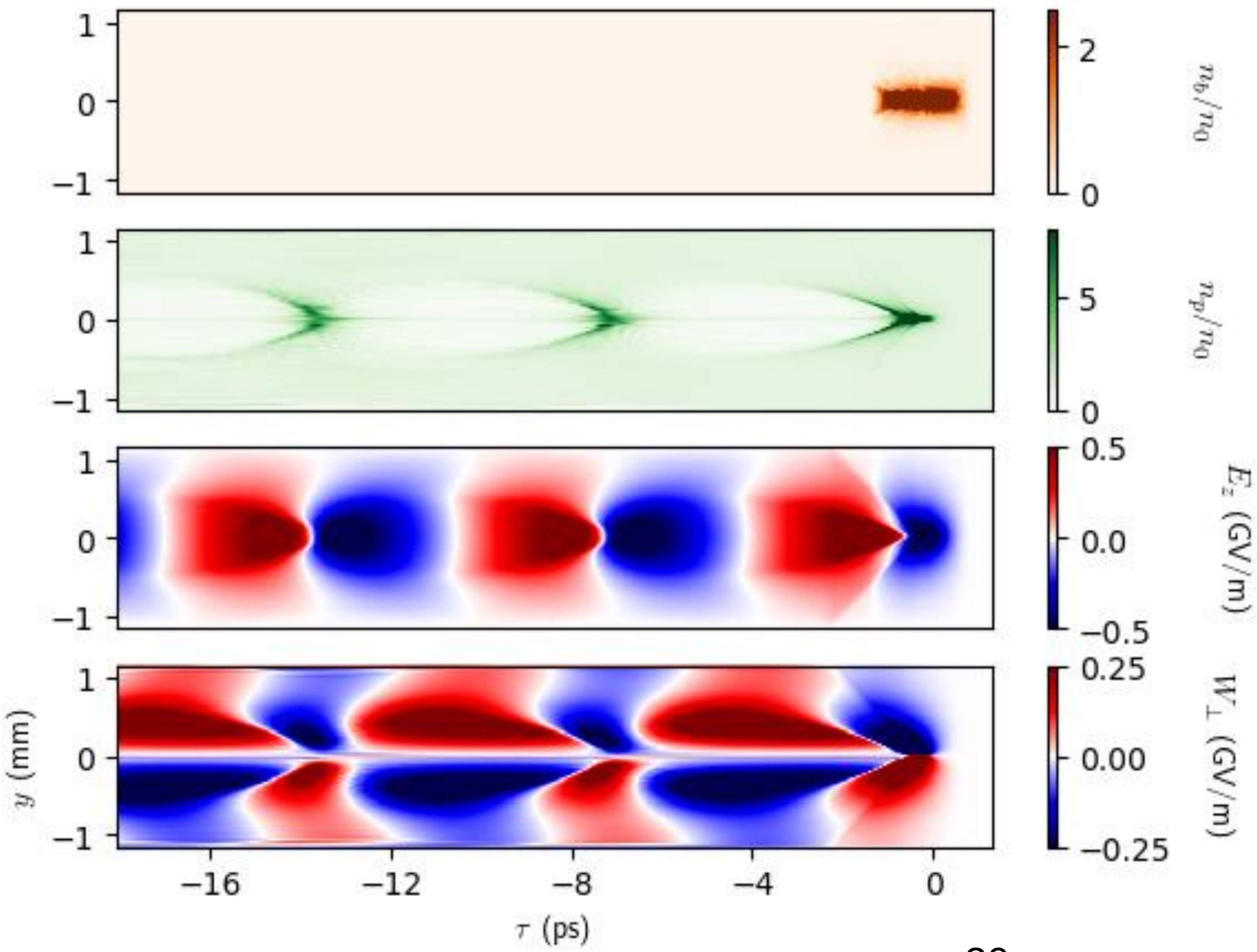
z=30 m

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

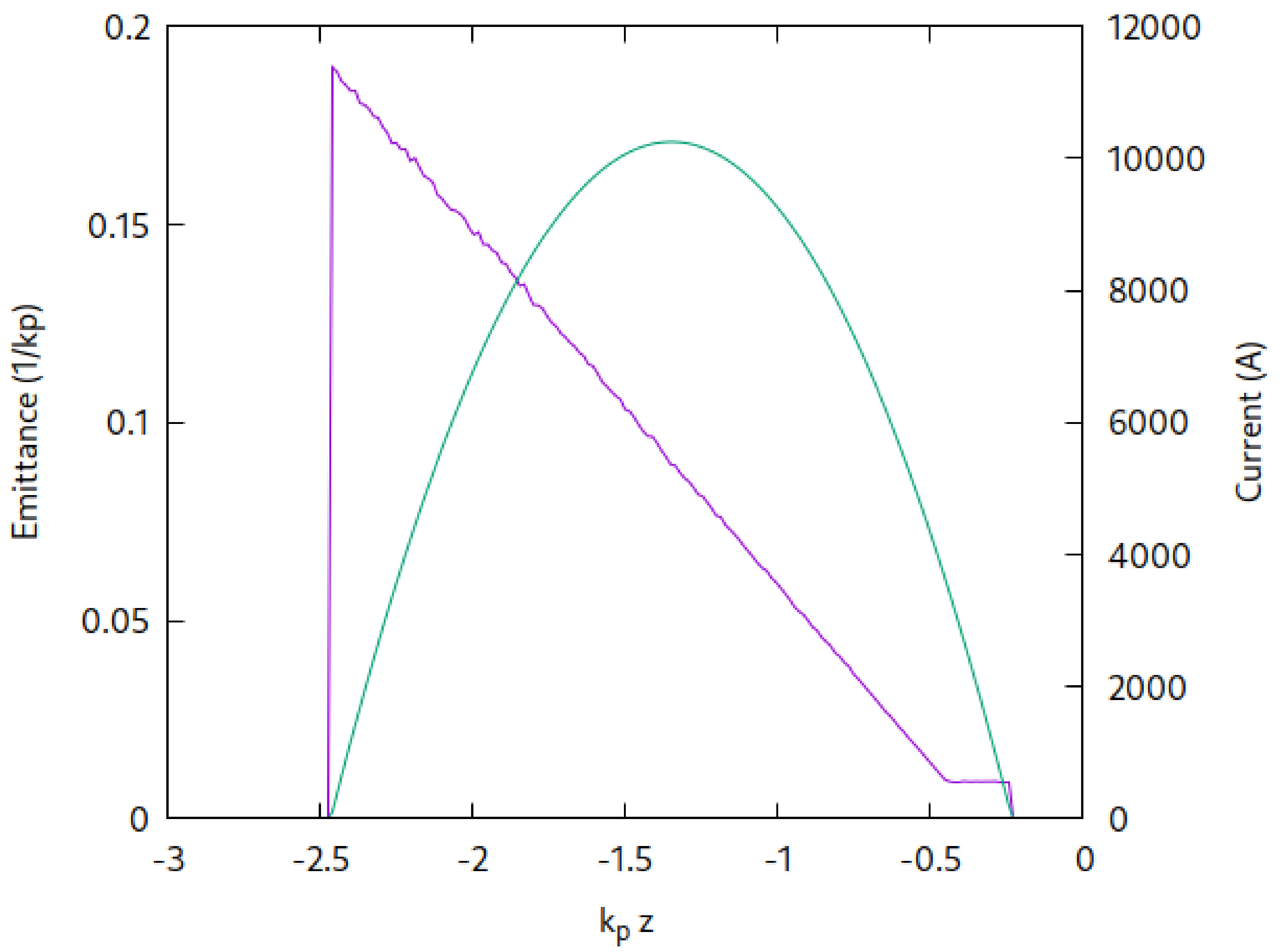
Good initial wakefields not sufficient:

- driver needs to evolve slowly
- counteract strong focussing wakefields

Picking the driver: stability

$\sigma_z = 150\ \mu m$
$\sigma_r = 240\ \mu m$
$n_b = 1x10^{11}$
$E = 400$ GeV
ϵ_N = *tailored*

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

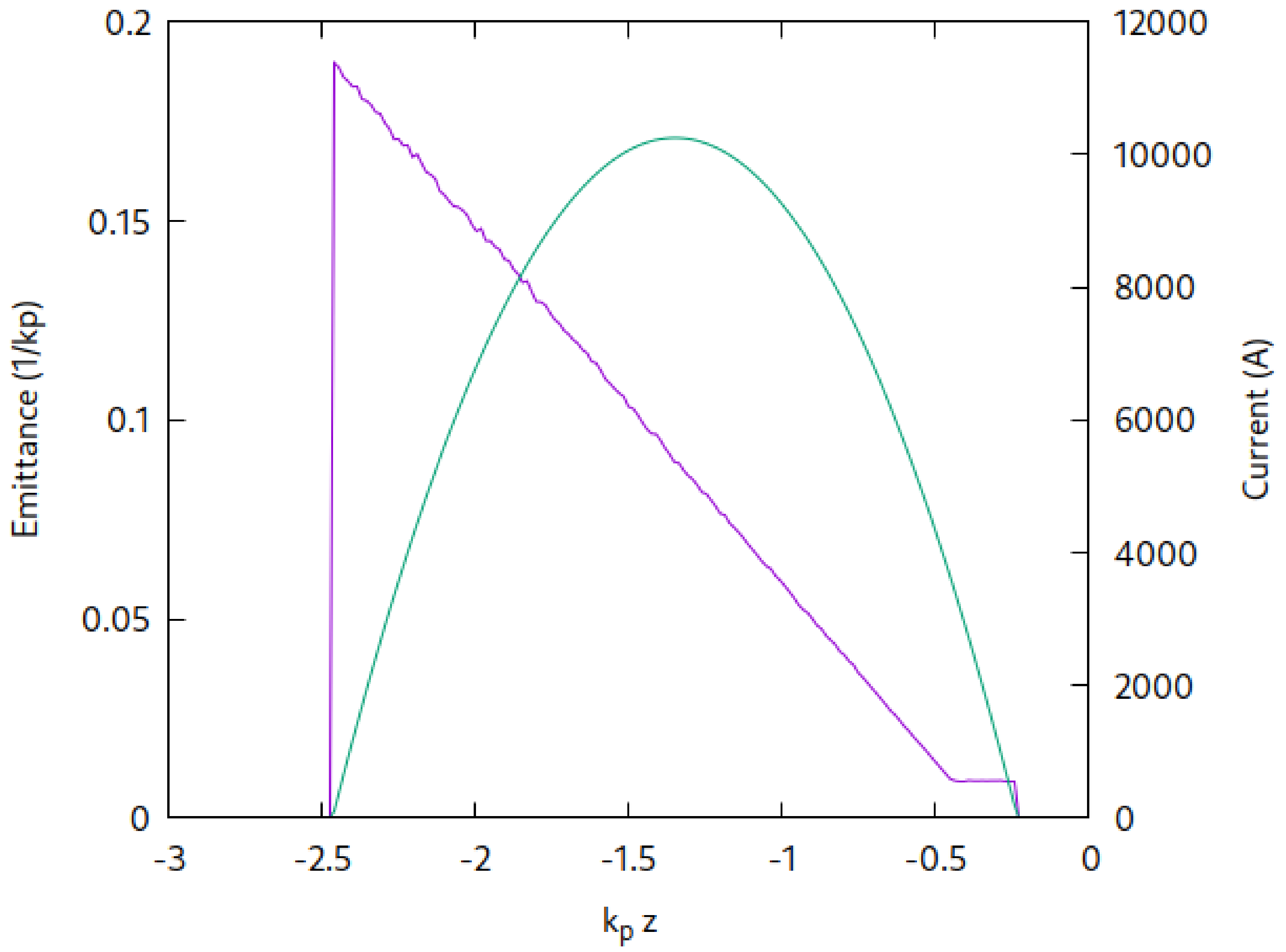


Picking the driver: stability

How can we generate
a tailored emittance profile?

Most likely:
with difficulty

BUT emittance is initially constant before growing monotonically



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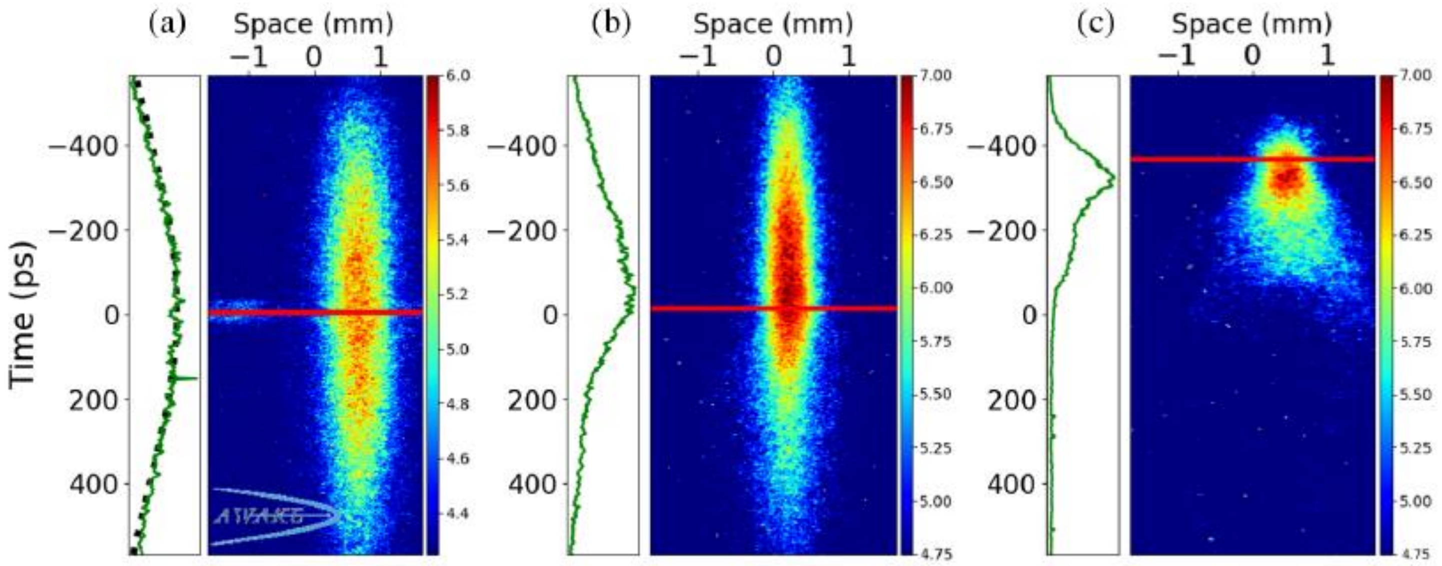
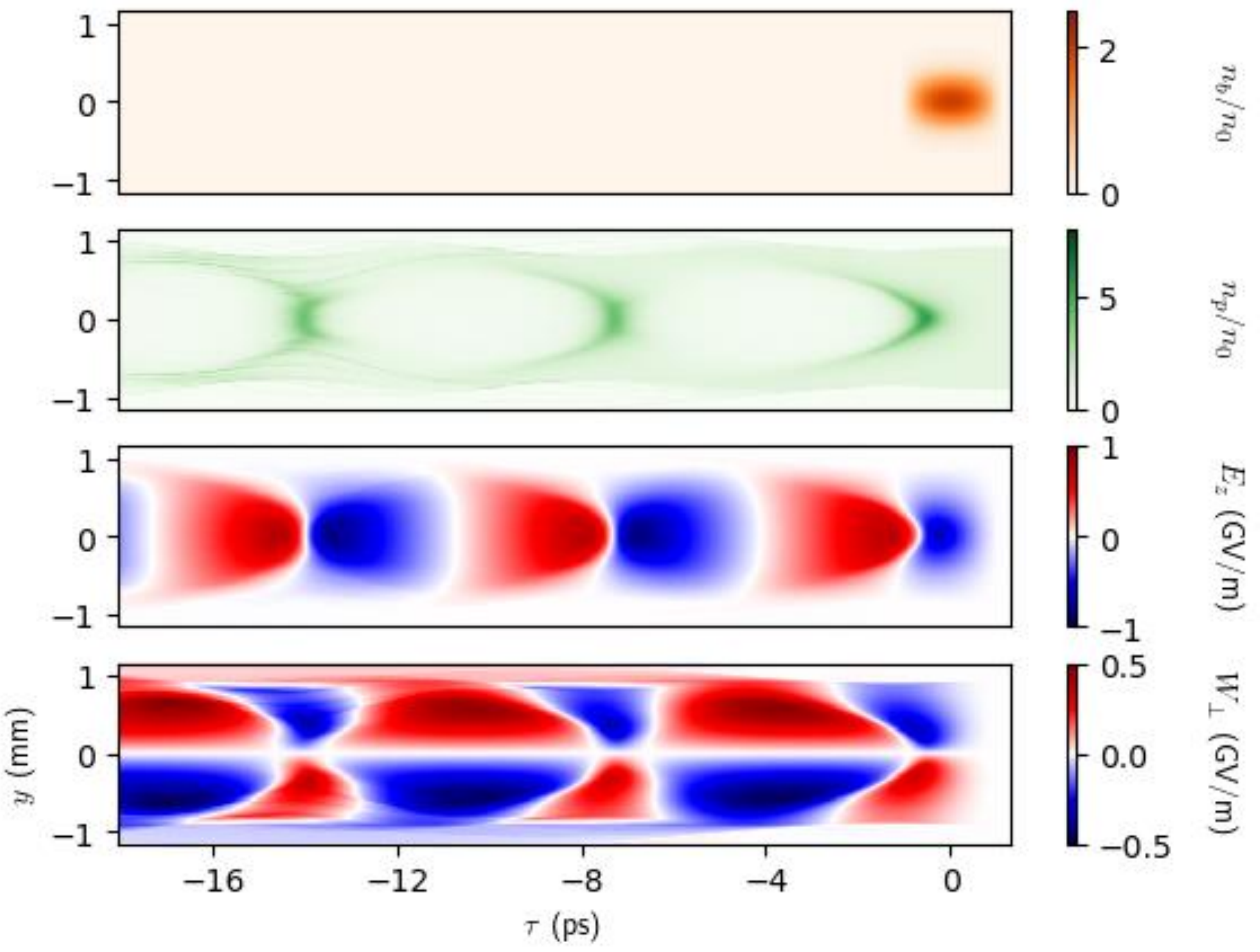


AWAKE Collaboration, PRL (2019)

Harness plasma instabilities?

Acceleration: dephasing

Initial proton driver chosen to generate suitable wakefields

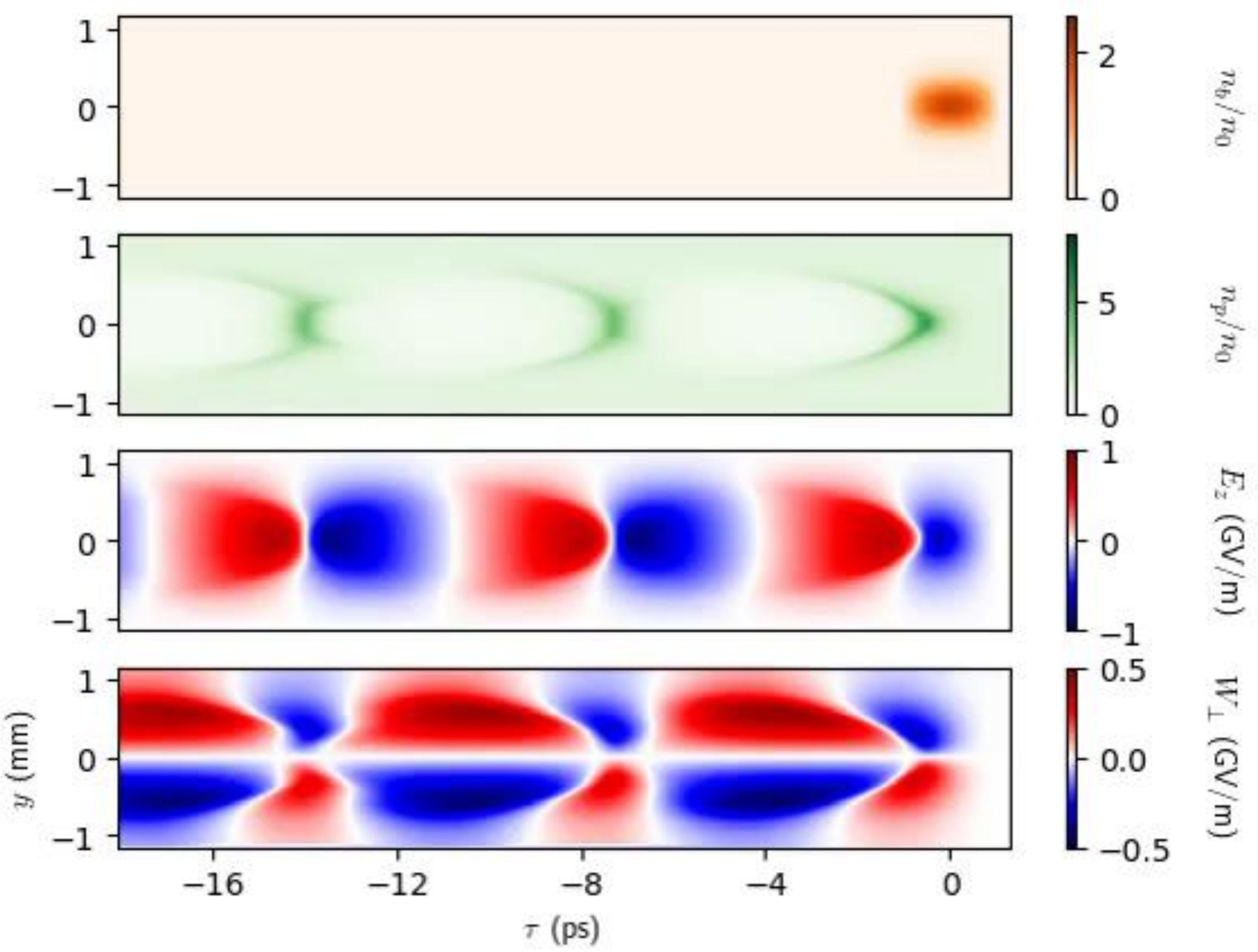


Acceleration: dephasing

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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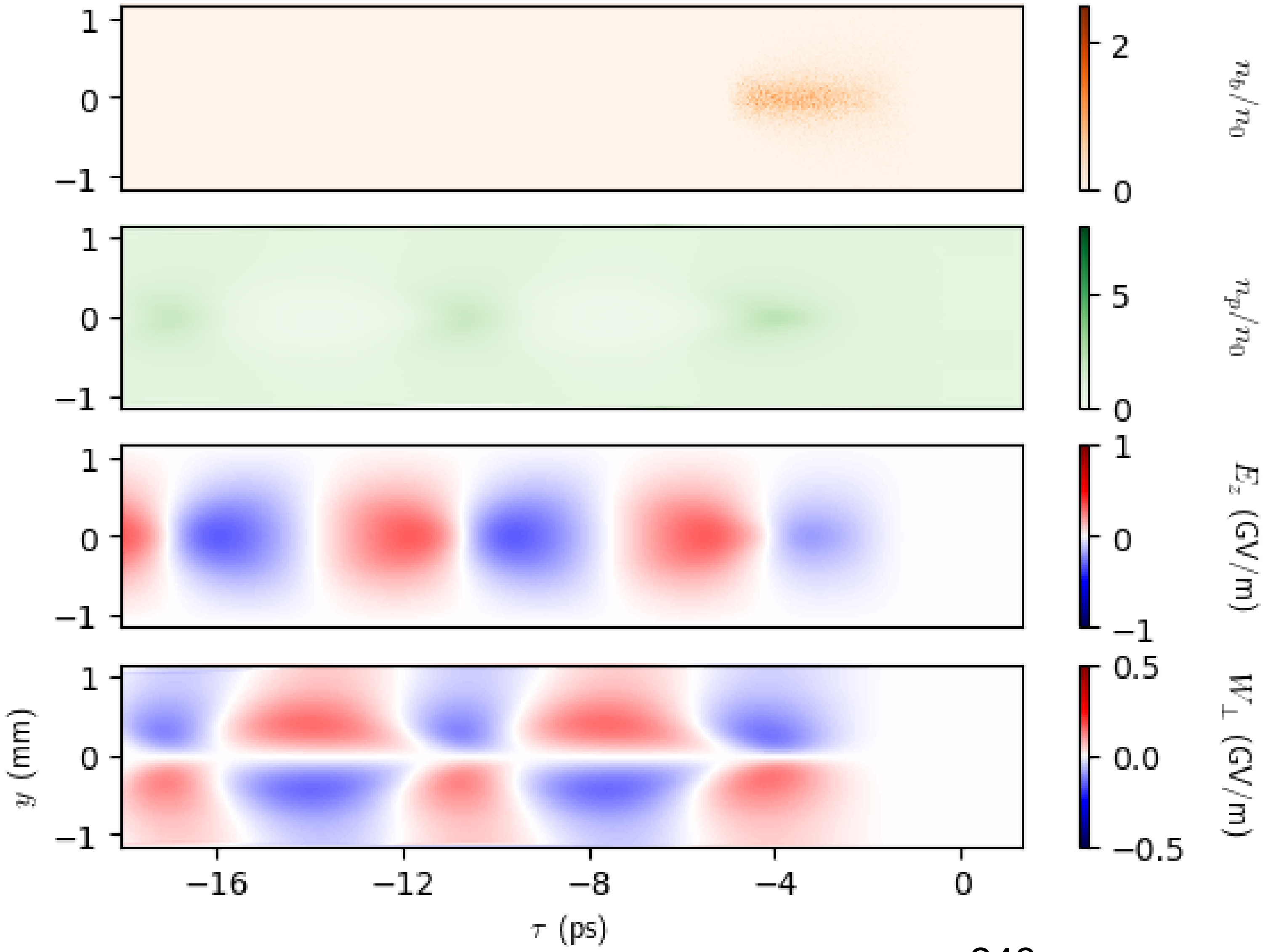
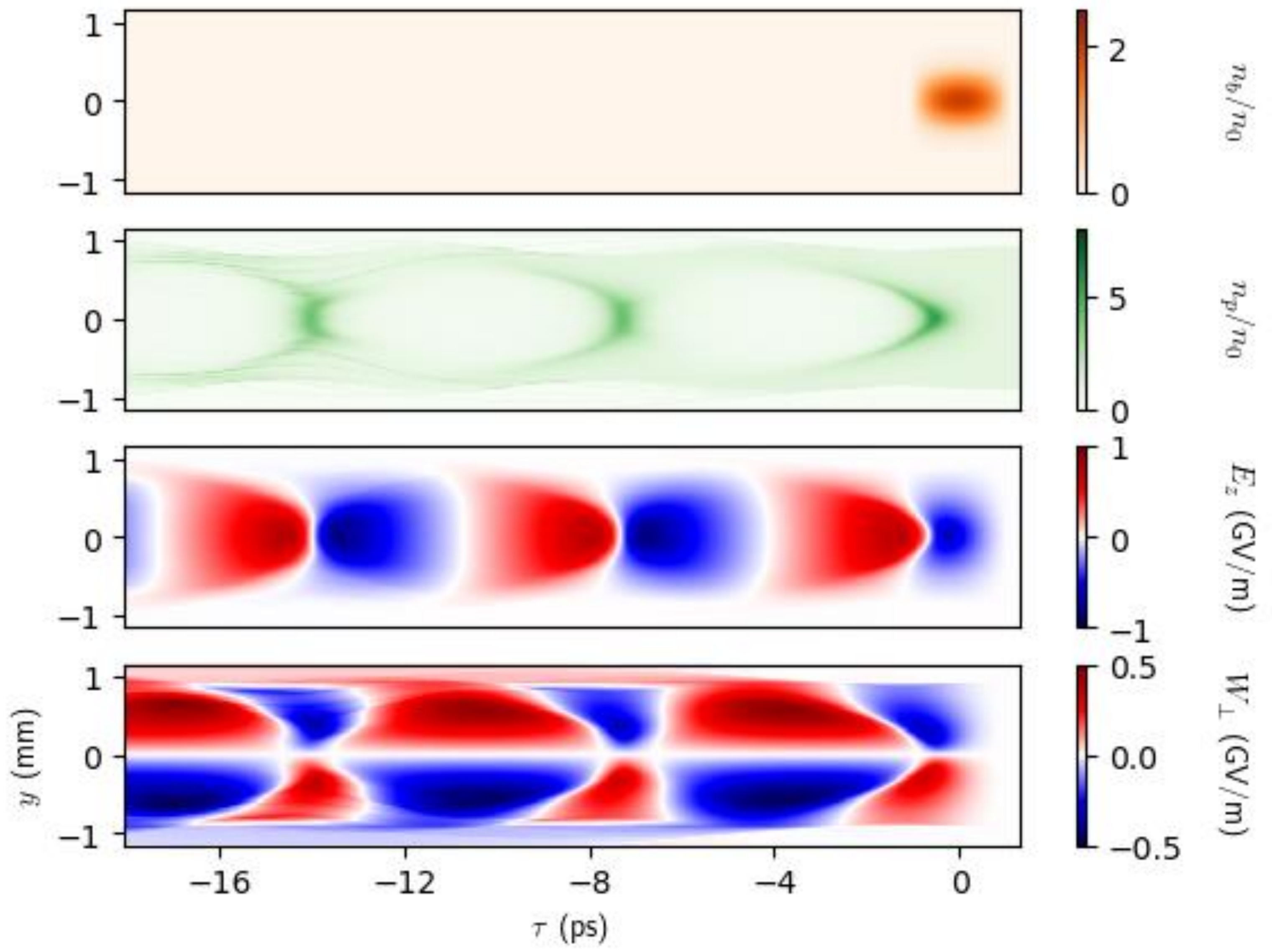


z=240 m

Acceleration: dephasing

Initial proton driver chosen to generate suitable wakefields

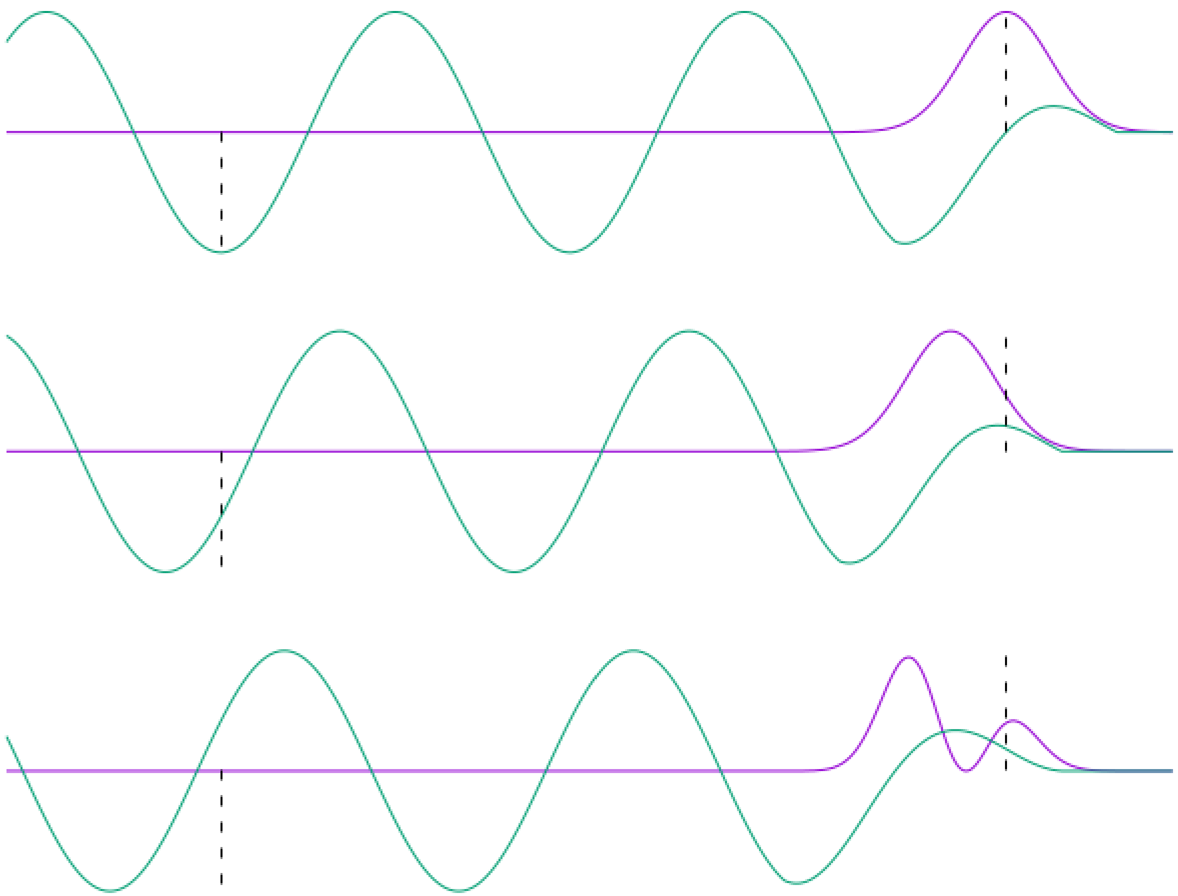


Acceleration: dephasing

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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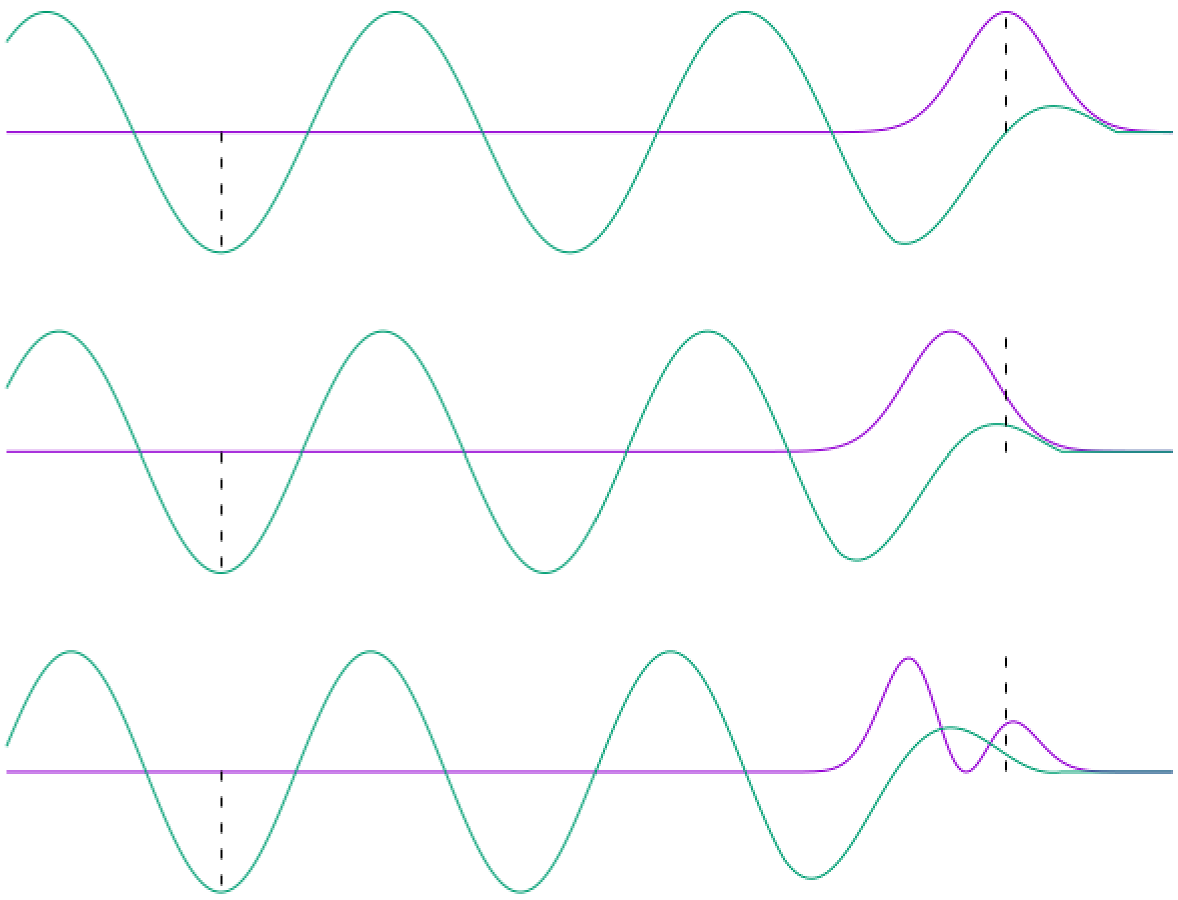

Driver evolution
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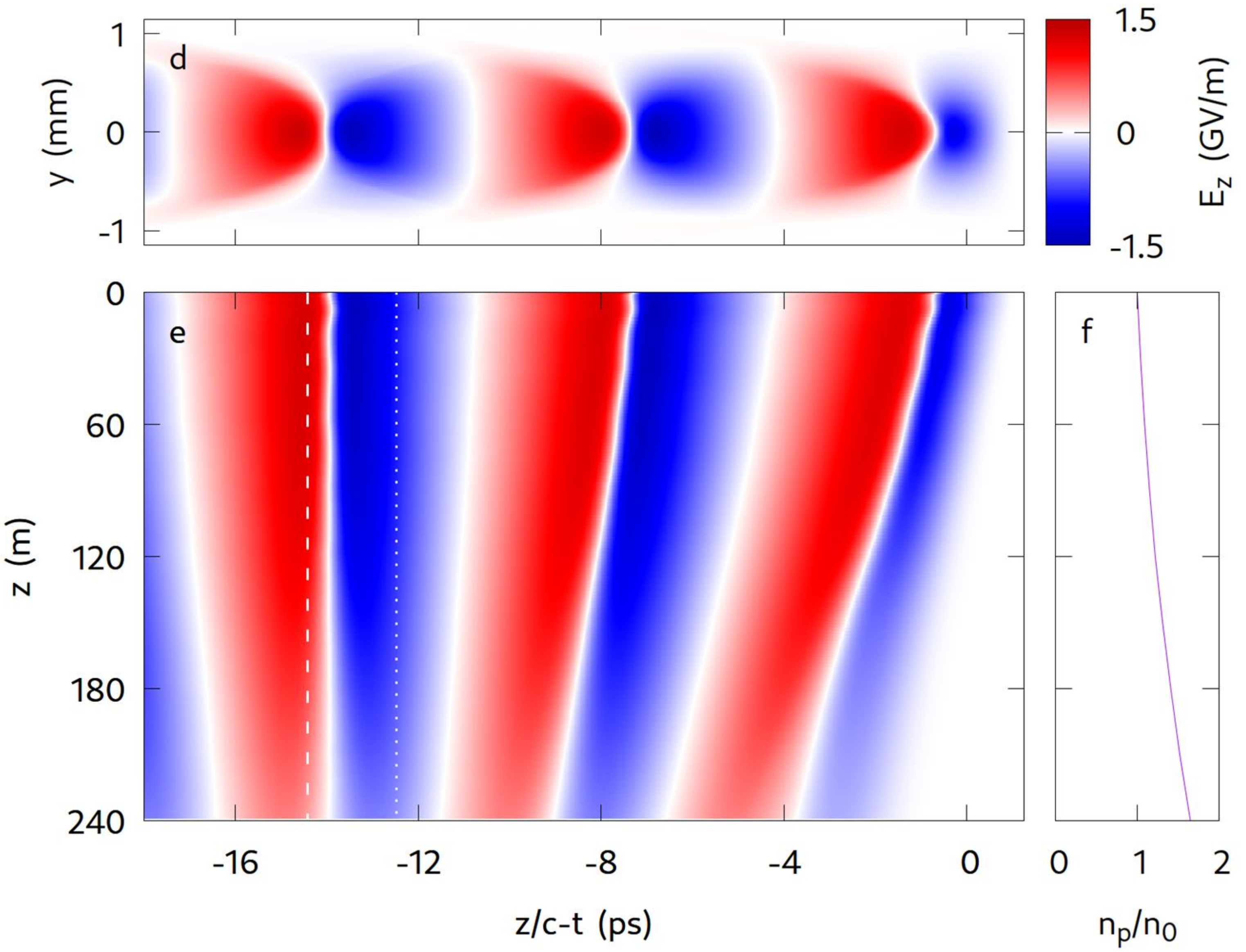
Change plasma density to keep phase constant

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

Large focussing fields mean extremely tiny witness radius at high energy

- ~1 µm for electrons
- ~100 nm for positrons

Simulations don't resolve this

- Nonphysical emittance growth
- Nonphysical energy spread growth

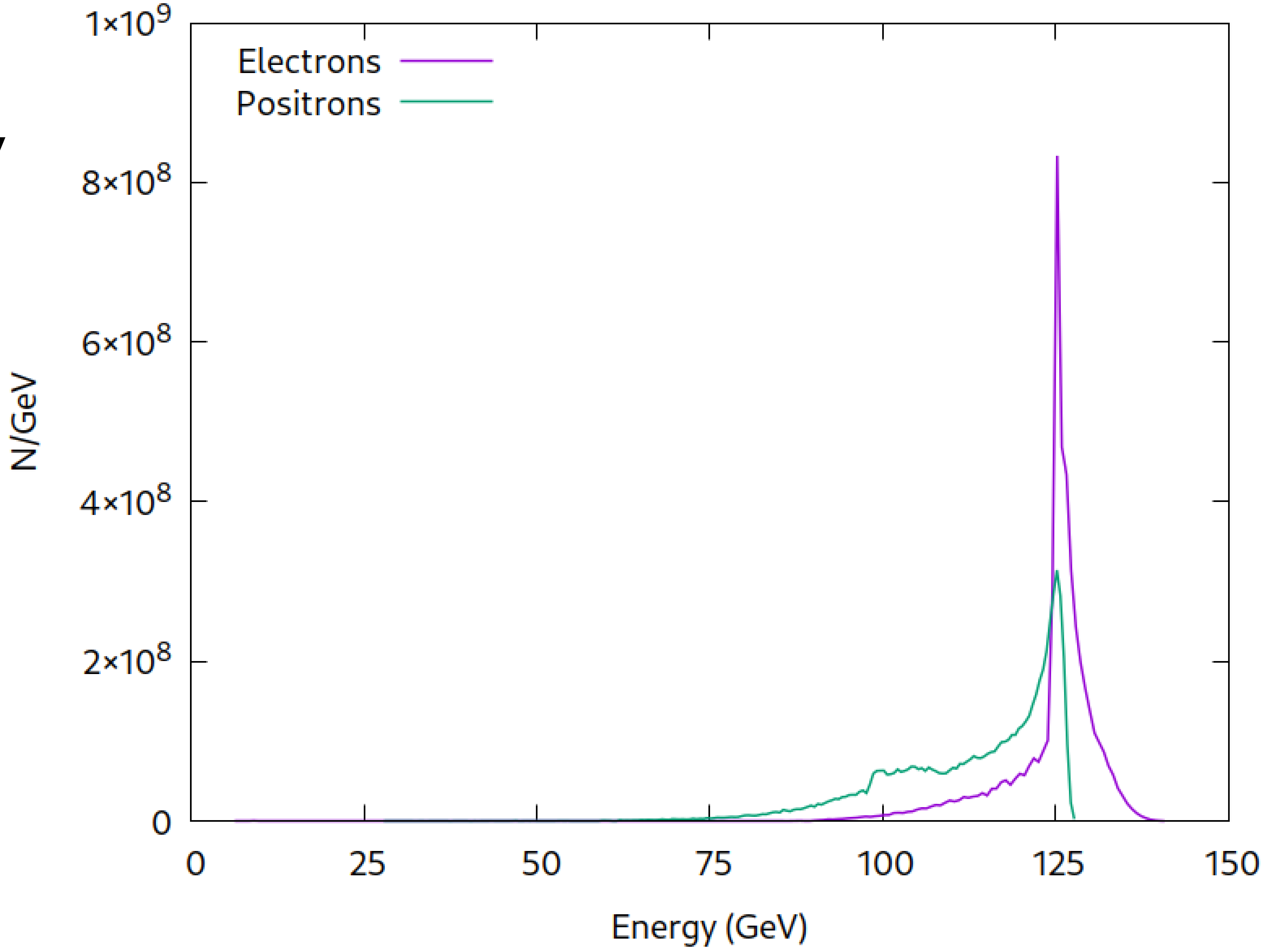
However, simulations do provide proof-of-concept for energy gain

Acceleration

Driver:
10^{11} protons at 400 GeV

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

Energy spread is nonphysical!



Acceleration

Simulations show proof-of-concept for acceleration

- 10% of driver charge accelerated to 125 GeV in ~180 m

With tailored witness current profile, 20% should be possible

S. van der Meer, CLIC Note (1985)

Requires long plasma stage:

- CERN is already investing in this technology

N. E. Torrado et al (2023)
B Buttenschön, N Fahrenkamp and O Grulke (2019)

Luminosity

Simulations don’t resolve emittance or energy spread,
so we assume that these can be controlled.

For electrons: AWAKE Run 2c

Olsen et al. (2019), Farmer et al (arXiv)

For positrons: simulation study by Hue *et al.*

C. S. Hue et al. (2021)

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

Cor...bine everything:

•As... ...ams at 5 Hz,
wi... ...m

•...
2...

and neg...

*Flat beams should be investigated

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

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Now on arXiv

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
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Bunch population	N_p	10^{10}	10
Number of bunches	n		1000
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Normalized transverse emittance	$\epsilon_{T,p}$	µm	$3 - 75$ µm
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e^- cell Length	L_{e^-}	m	240
...ll Length	L_{e^+}	m	240
[illegible]	n_p	10^{14} cm^{-3}	3.2
[illegible]	[illegible]	10^{14} cm^{-3}	5.2
[illegible]	[illegible]	**Unit**	**Value**
[illegible]	[illegible]	GeV	1
[illegible]	[illegible]	GeV	125
[illegible]	[illegible]	10^{10}	2
[illegible]	[illegible]	nm	100
[illegible]	[illegible]	mm	13
[illegible]	[illegible]	mm	0.41
[illegible]	σ_x^*	nm	73
[illegible]	σ_y^*	nm	13
e^-e^+ ...	...ymbol	**Unit**	**Value**
Center-of-Mass En...	$E_{\rm cm}$	GeV	250
Average Collision Rate	f	kHz	5
Luminosity	$\mathcal{L}$	cm^{-2}s^{-1}	1.7×10^{34}

Outlook

Key challenges:

- rapid-cycling proton synchrotron with short bunches
- demonstration of drive bunches with tailored emittance
- experimental demonstration of emittance control for PWFA acceleration of positron bunches
- acceleration of flat witness bunches
- long plasma stages at high rep rate

~ Fin ~

~ Backups ~

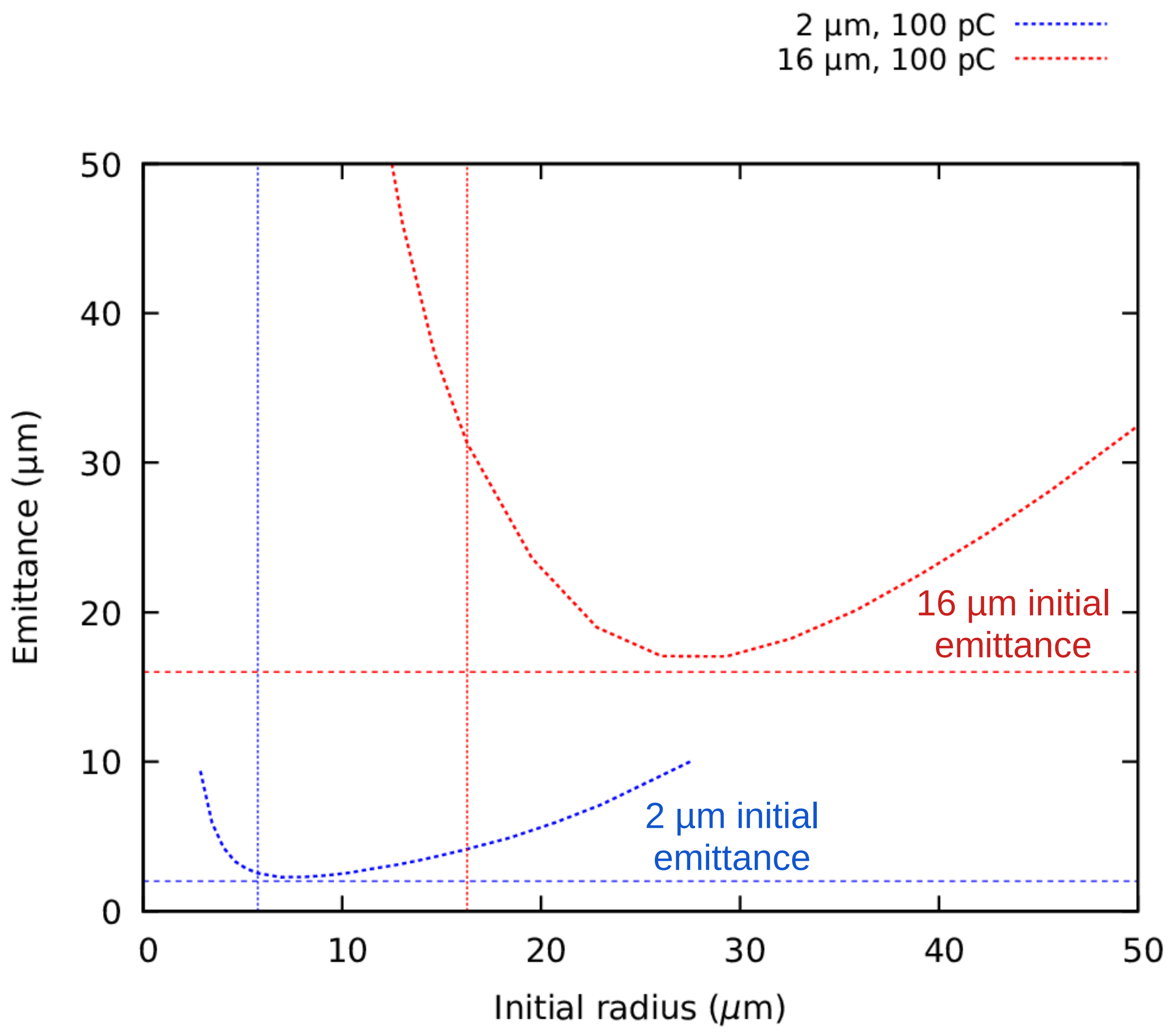
Footprint

Fits on the Fermilab site
(P5 review)

Emittance

Simulations for AWAKE Run 2c how that a blowout is *not* required to have emittance control.

Obviously a big gap between this and positron beams with sub-µm emittance!



Adapted from [Farmer et al (arXiv)]

Extension to HALHF

Acceleration limited by dispersion, not energy depletion: scales as $1/\gamma^2$.

Use a 800 GeV driver, accelerate to ~500 GeV in ~1 km.

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

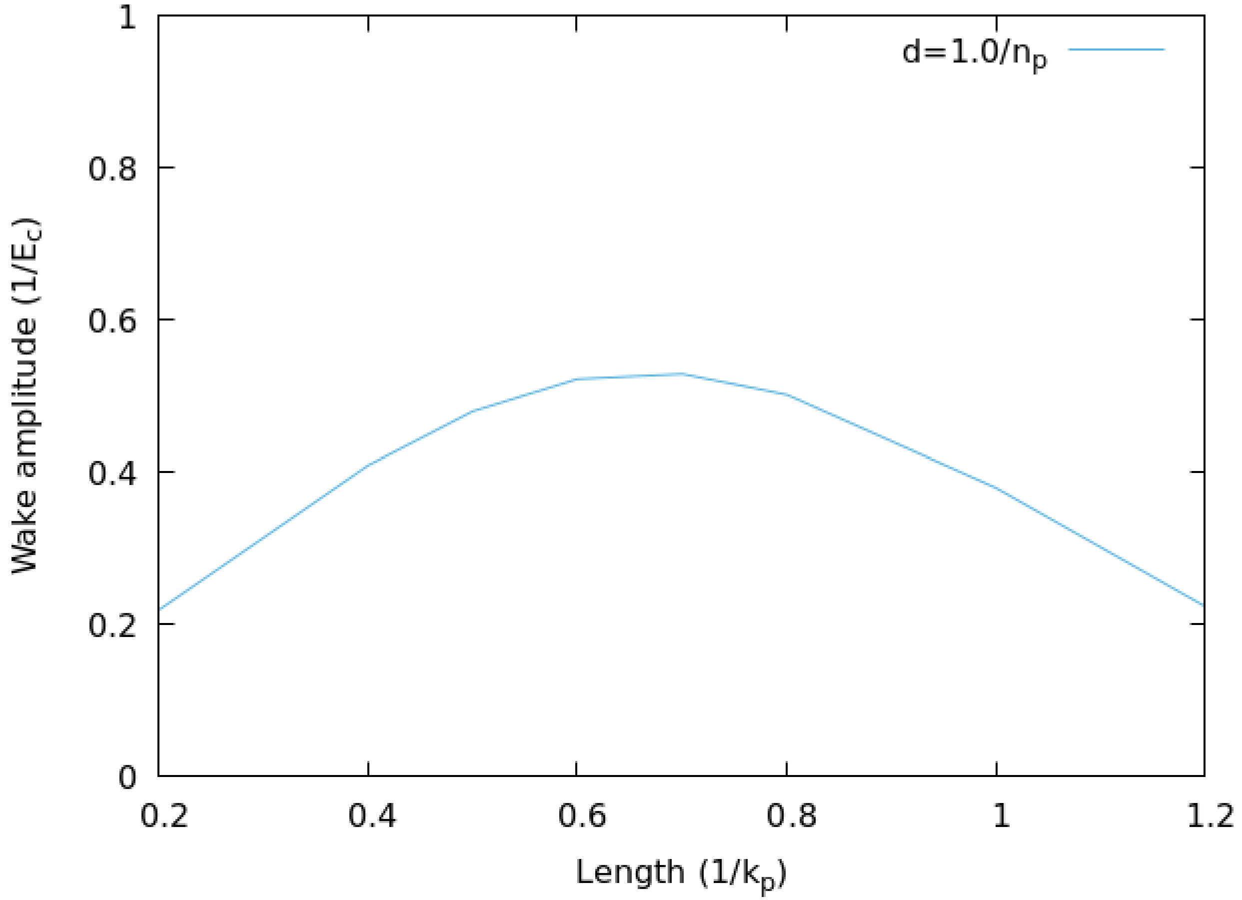
Cooling

Moderately nonlinear wakefields retain their structure after loading.

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

Picking the driver: efficiency

Scan driver length.



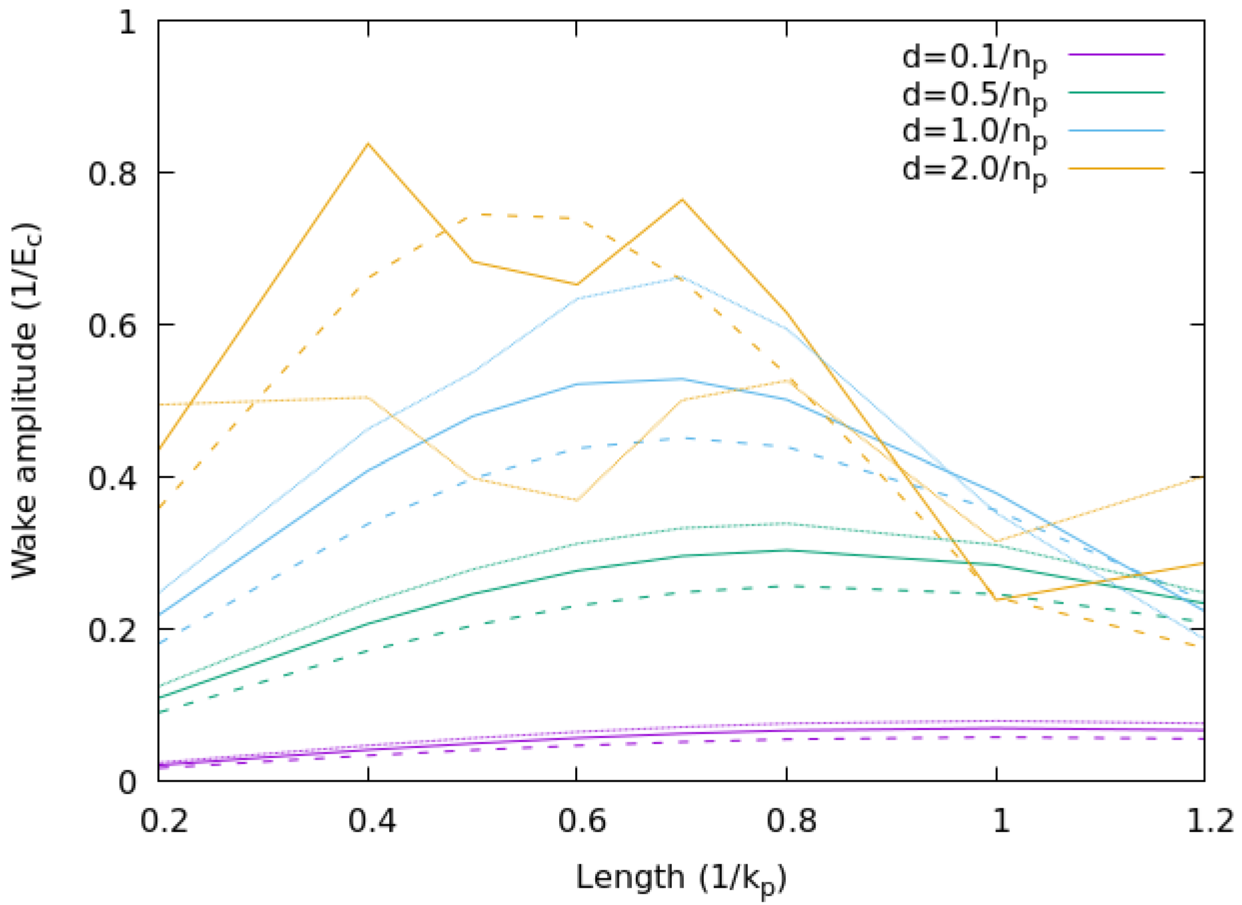
Solid line: $k_p r = 1.0$

Picking the driver: efficiency

Scan driver length.

Optimal length depends on beam charge density.

High current leads to nonlinear plasma response.



Dashed line: $k_pr = 0.8$

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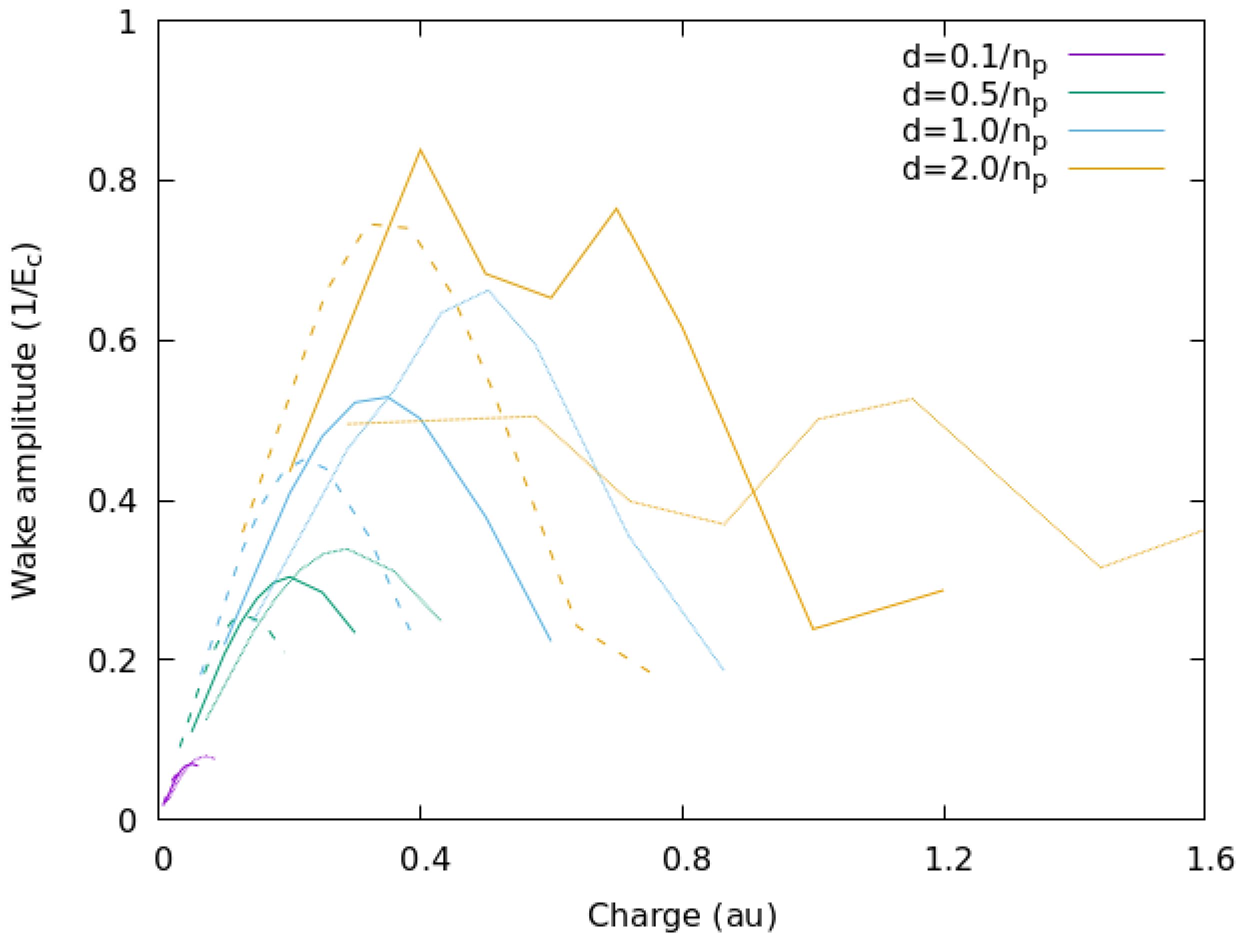
Picking the driver: efficiency

Replot wakefield as a function of beam charge.



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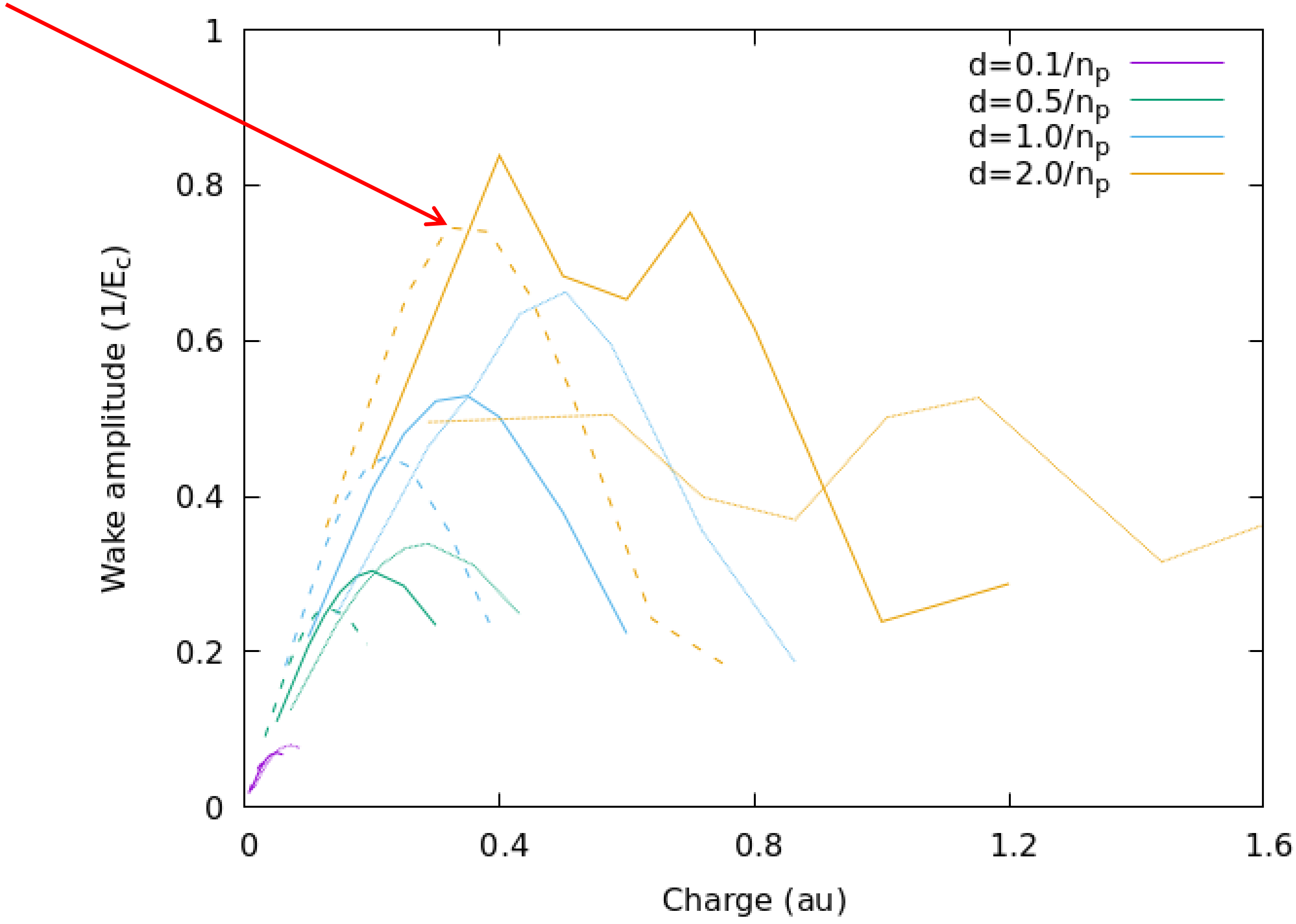
Picking the driver: efficiency

Replot wakefield as a function of beam charge.

Optimal is best gradient per unit charge.



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