PEEP
Proton Energizer of Electrons in Plasma

Introduction
to our initial Workshop

CERN

September 30, October 1, 2024

Allen Caldwell
Max Planck Institute for Physics

Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

MAX-PLANCK-GESELLSCHAFT

What's Driving Us

Provide accelerator concept for future HEP projects:

- Higgs Factory as next HEP machine (ILC, CLIC, FCC-ee, CEPC, HALHF, C^3 ,…, PEEP?)
- eP/eA Collider as QCD Frontier machine (**EIC**, LHeC, VHEeP, …, PEEP2?)
- Energy frontier collider (Muon Collider, FCC-hh, CEPC-hh, …, PEEP3?)

EIC is happening. Mature concepts exist for the Higgs Factory. But

New approach can be an attractive option also for the Higgs Factory and high energy eP/eA colliders if it provides a path to future frontier machines. That's our line of attack …

Selling point: **proton-driven PWFA scales well as energy increases**

This workshop: discuss some of the issues if this approach is to be competitive

Laser Wakefield Acceleration

Acceleration is ***DEPLETION-LIMITED***

i.e., the lasers do not have enough energy to accelerate a bunch of particles to very high energies

e.g.,

$$10^{10}\ \text{electrons} \cdot 10^{12}\ \text{eV} \cdot 1.6 \cdot 10^{-19}\ \text{J/eV} = kJ$$

This is orders of magnitude larger than laser energy today[1].

If use several lasers – need to have relative timing in the 10's of fs range

[1] with useful repetition rate; i.e., not the NIF laser

Beam driven PWA

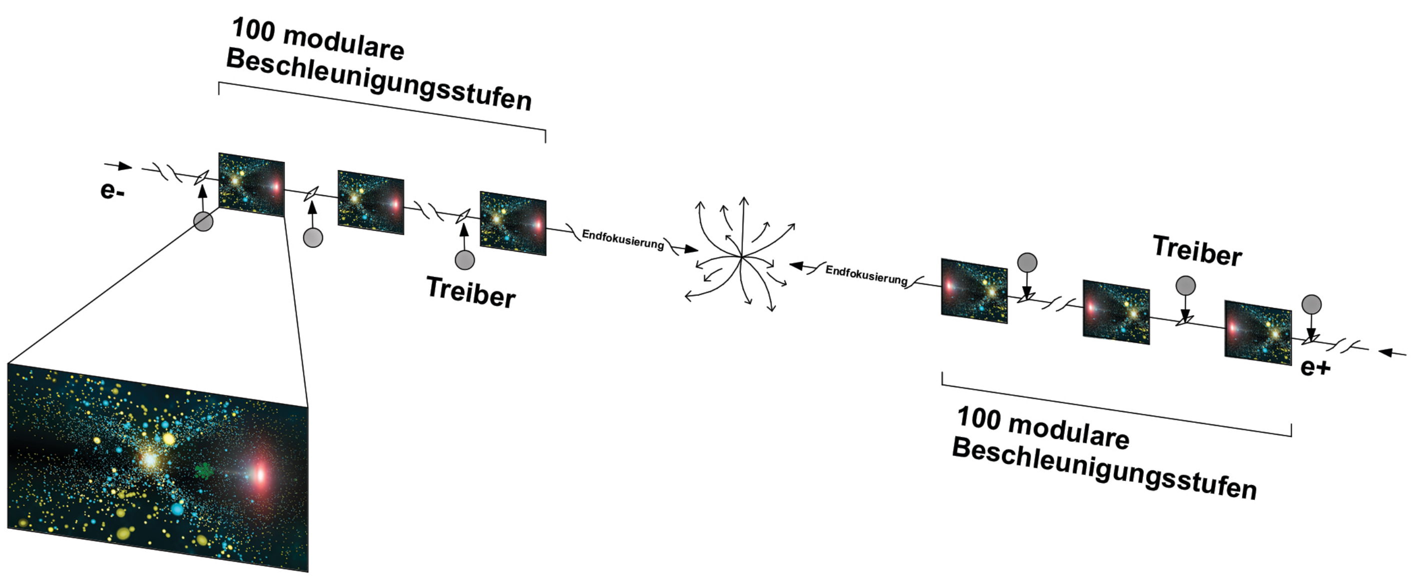
driving force: Space charge of drive beam displaces plasma electrons.

But there is a transformer limit theorem for symmetric drive beams:

$$R = \frac{\Delta T^{\text{witness}}}{\Delta T^{\text{drive}}} \leq 2 \quad \text{T is the kinetic energy}$$

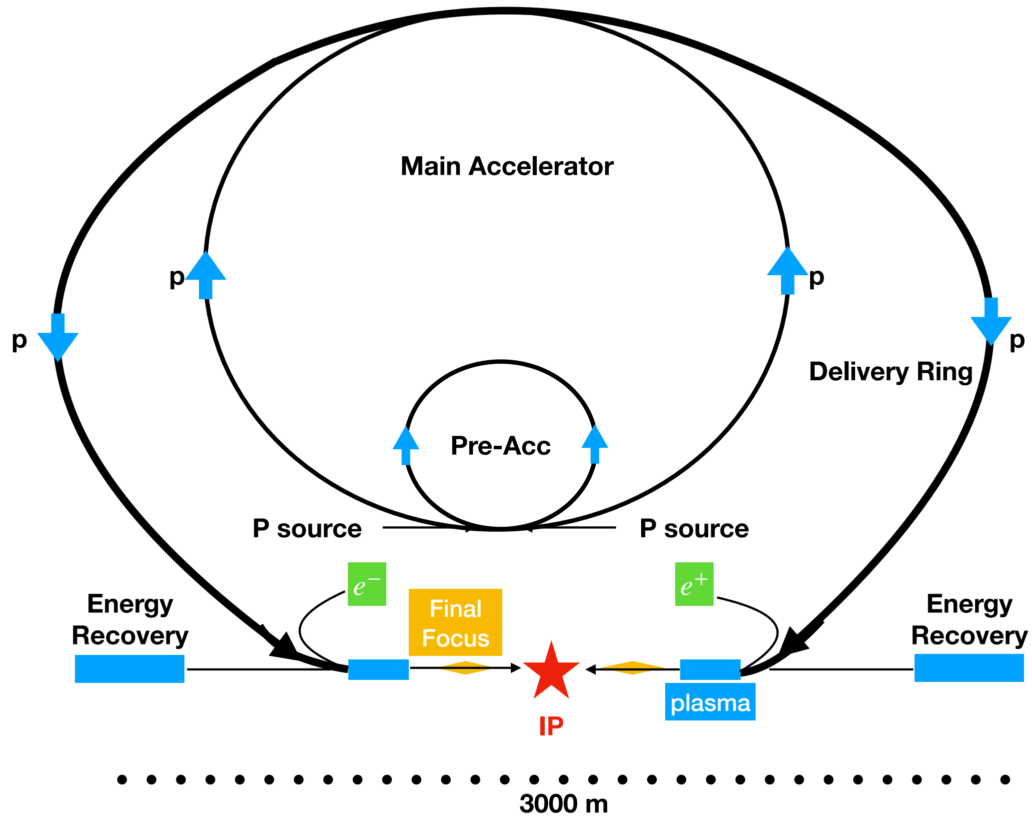
Can be somewhat overcome with drive beam shaping

Result: many stages required to produce a 1TeV electron beam from known electron beams (E.g., SLAC had 45 GeV) or laser drivers.



Proton Drivers

So why not use protons?
High energy proton beams available today



Basic idea:

- Accelerate protons in conventional circular accelerator
- Transfer energy to electrons in a plasma section
- WRT RF acceleration, much more compact - footprint, ecological impact reduced
- can approach $E_e \approx E_p$

Basic Aspects

Compact driver required !

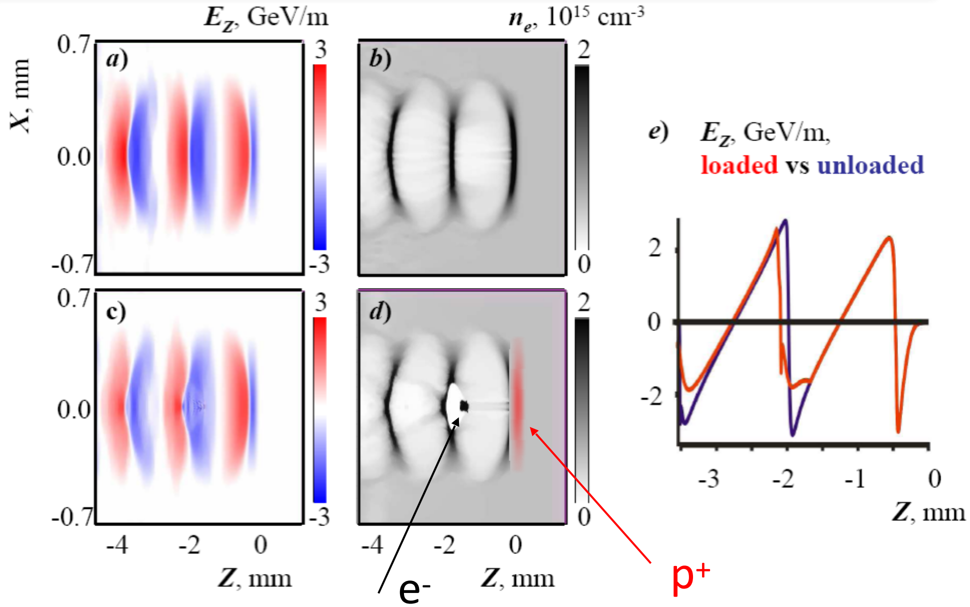
Today's proton beams have

$$\sigma_z \approx 10 - 30 \text{ cm}$$

$$E_{z,\max} \approx 2 \text{ GeV/m} \cdot \left(\frac{N_b}{10^{10}}\right) \cdot \left(\frac{100 \ \mu\text{m}}{\sigma_z}\right)^2$$

Initial study: assume existing bunches can be compressed:

Caldwell, Lotov, Pukhov, Simon, Nature Physics 5, 363 - 367 (2009)

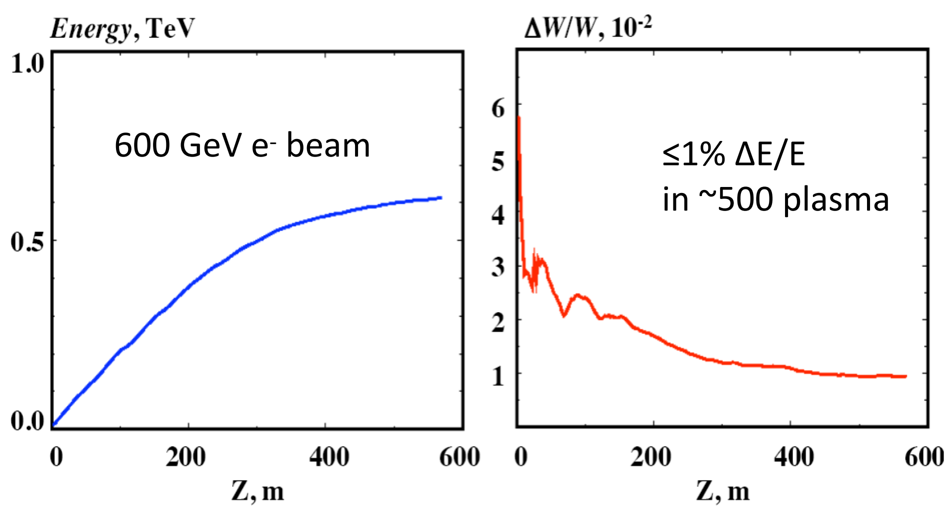


Drive beam: p^+

E=1 TeV, $N_p=10^{11}$

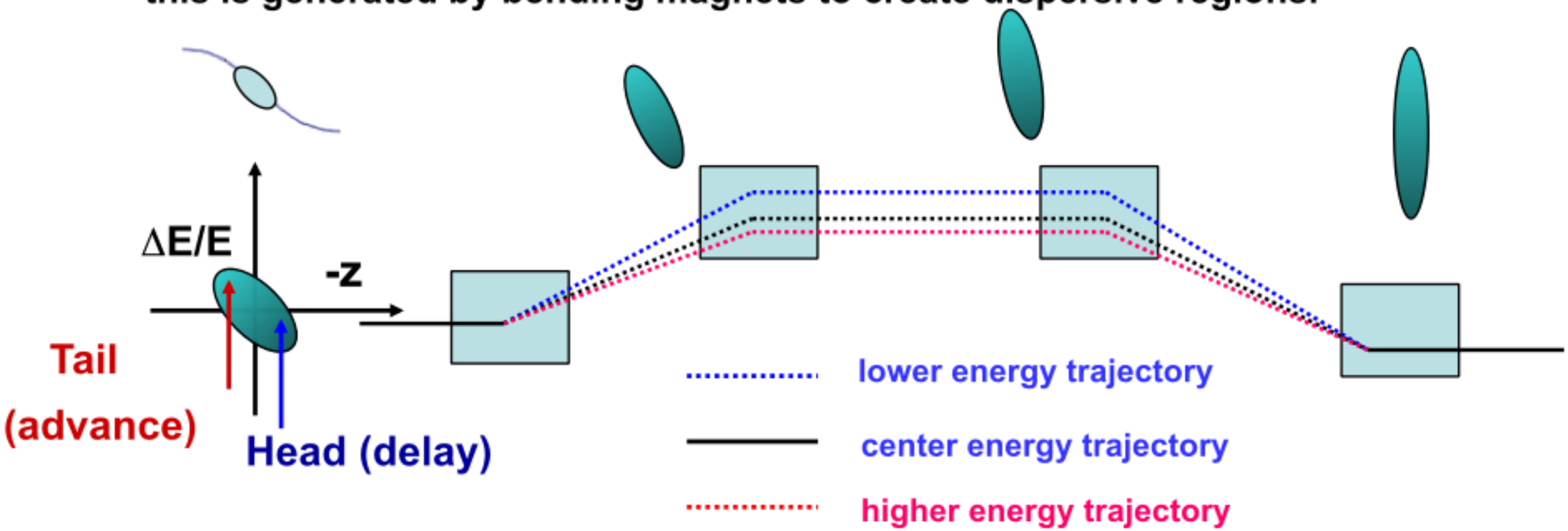
σ_z=100 µm, σ_r=0.43 mm

σ_θ=0.03 mrad, ΔE/E=10%



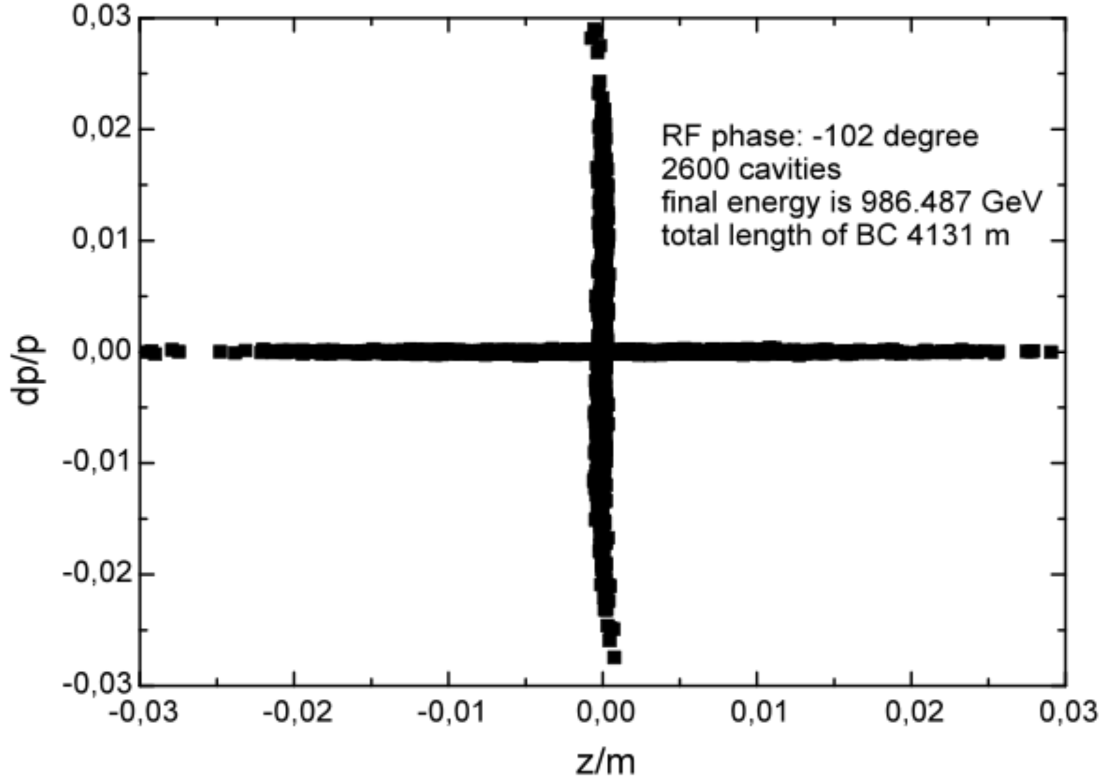
Magnetic bunch compression (BC)

- **Beam compression can be achieved:**
  - **(1) by introducing an energy-position correlation along the bunch with an RF section at zero-crossing of voltage**
  - **(2) and passing beam through a region where path length is energy dependent: this is generated by bending magnets to create dispersive regions.**



- **To compress a bunch longitudinally, trajectory in dispersive region must be shorter for tail of the bunch than it is for the head.**

Phase space of beam

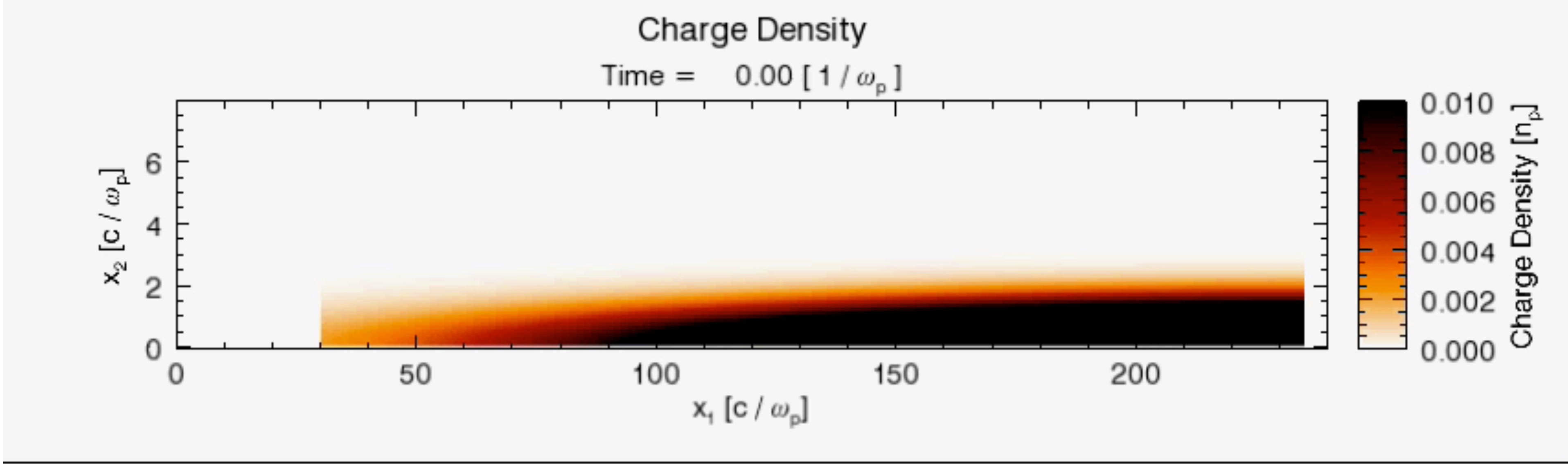


See A. Caldwell, G. Xia et al., Preliminary study of proton driven plasma wakefield acceleration, Proceedings of PAC09, May 3-8, 2009, Vancouver, Canada

Modulated Proton Beam

AWAKE Solution ! microbunches are generated by the interaction between the bunch and the plasma. The microbunches are naturally spaced at the plasma wavelength, and act constructively to generate a strong plasma wake. Investigated both numerically and analytically.

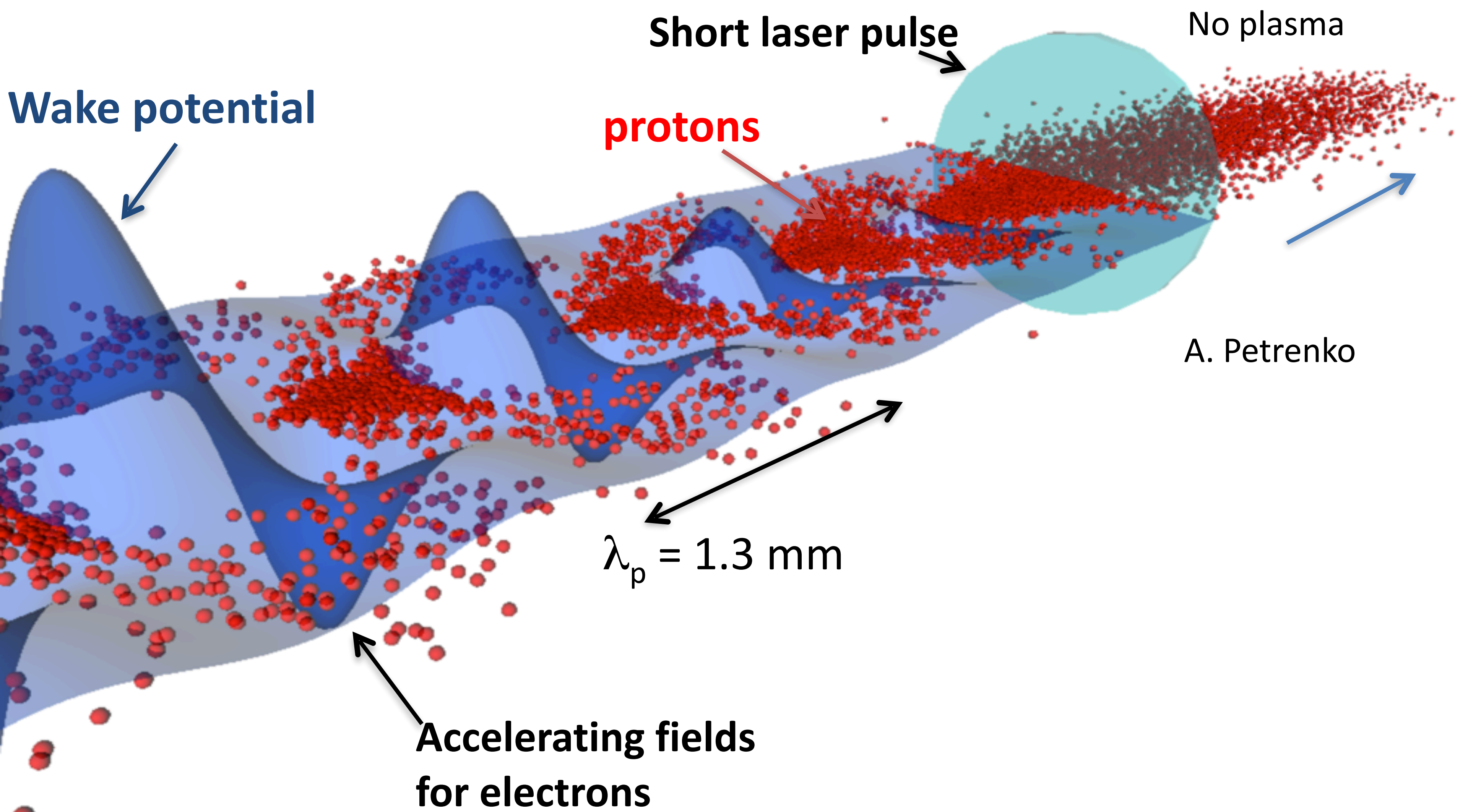
N. Kumar, A. Pukhov, and K. V. Lotov, Phys. Rev. Lett. **104**, 255003 (2010)



Propagation of a ‘cut’ proton bunch in a plasma. From Wei Lu, Tsinghua University

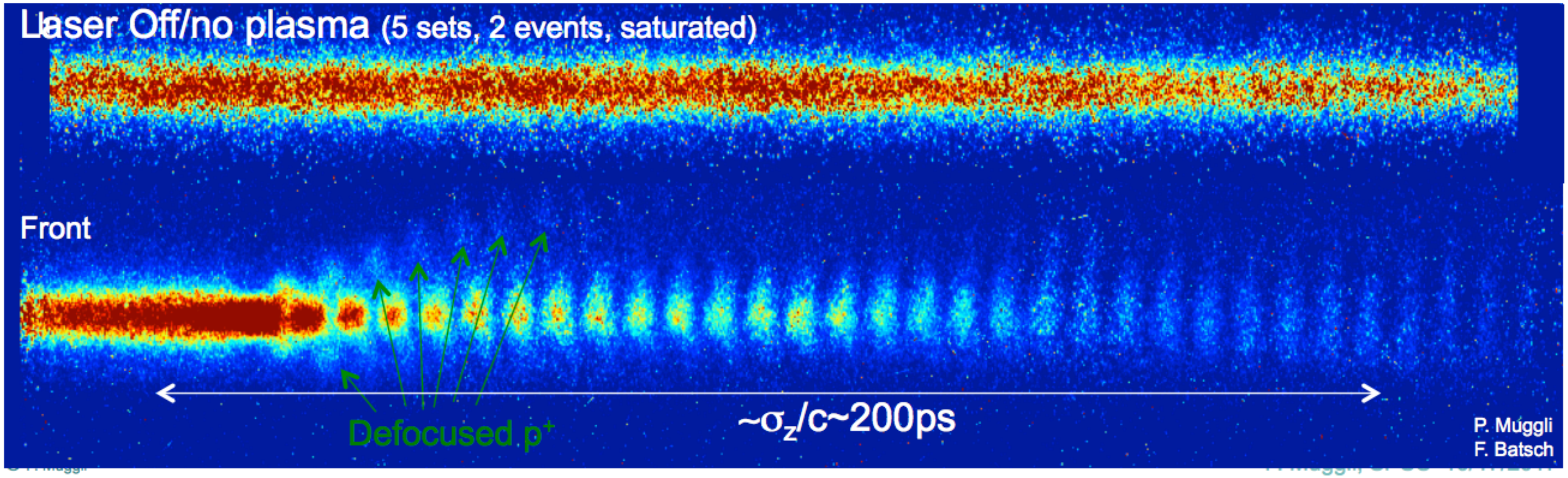
Seeded self-modulation

The self-modulation can be seeded by a sharp start of the beam (or beam-plasma interaction).



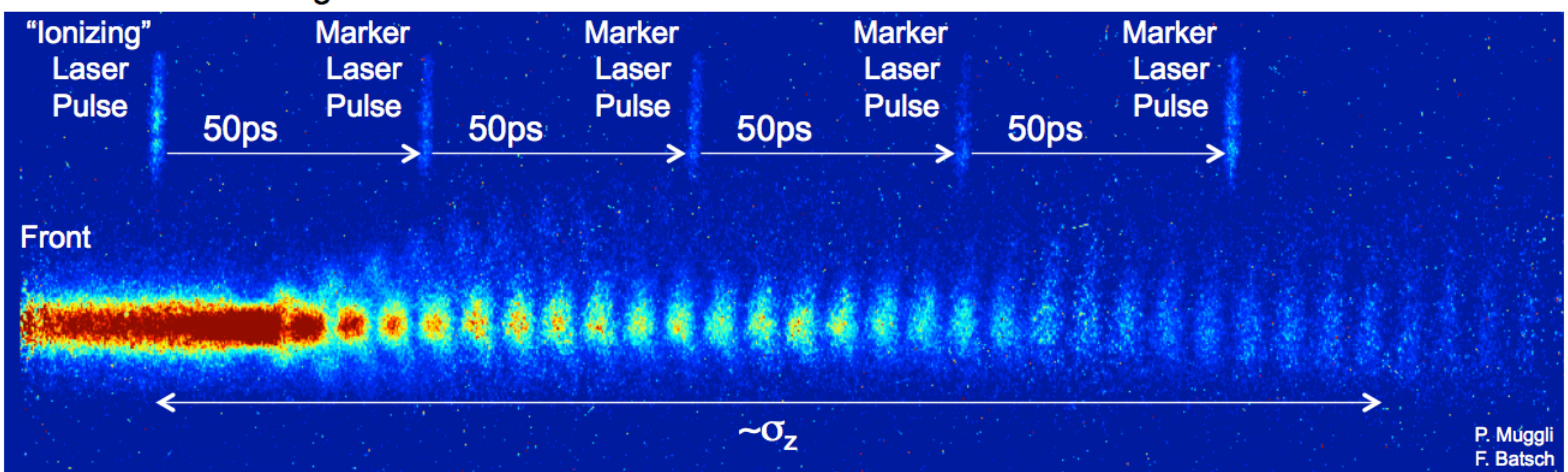
Observation of SSM

Streak camera Images



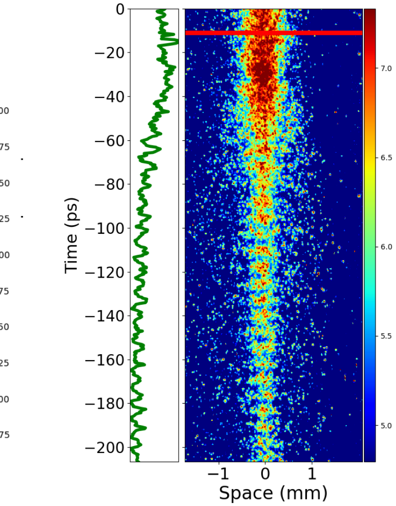
Streak camera Images

10 events each

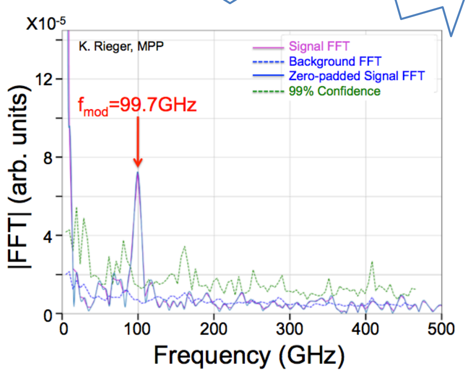


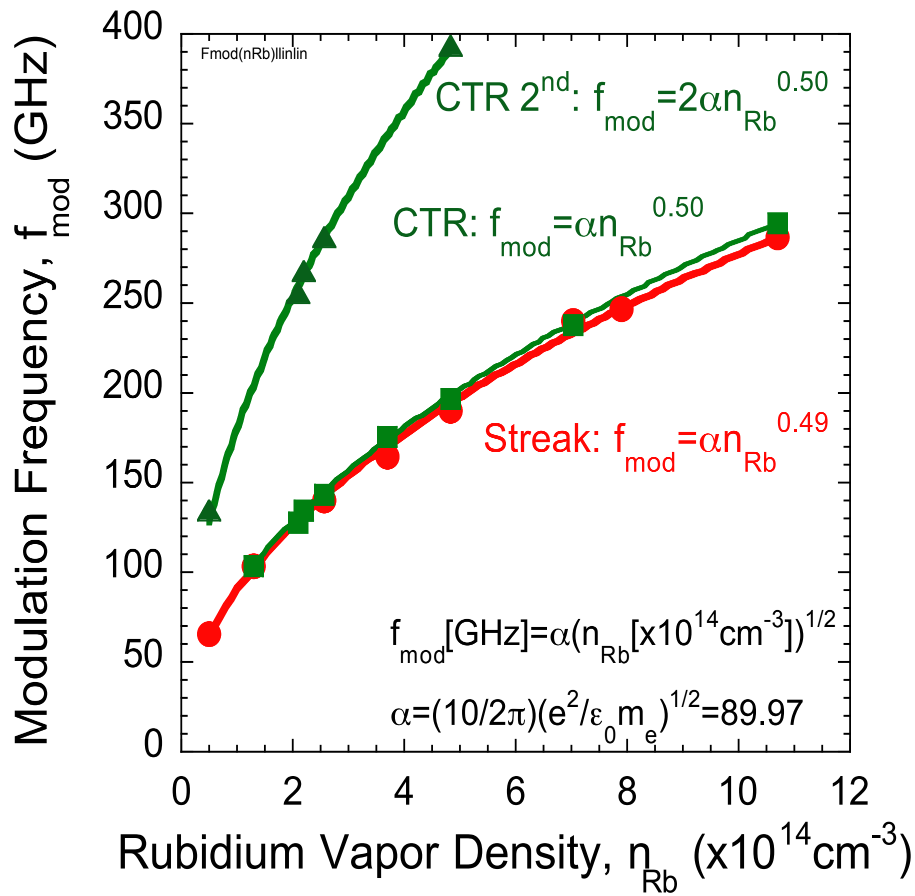
AWAKE

Modulation at the expected frequency



FFT





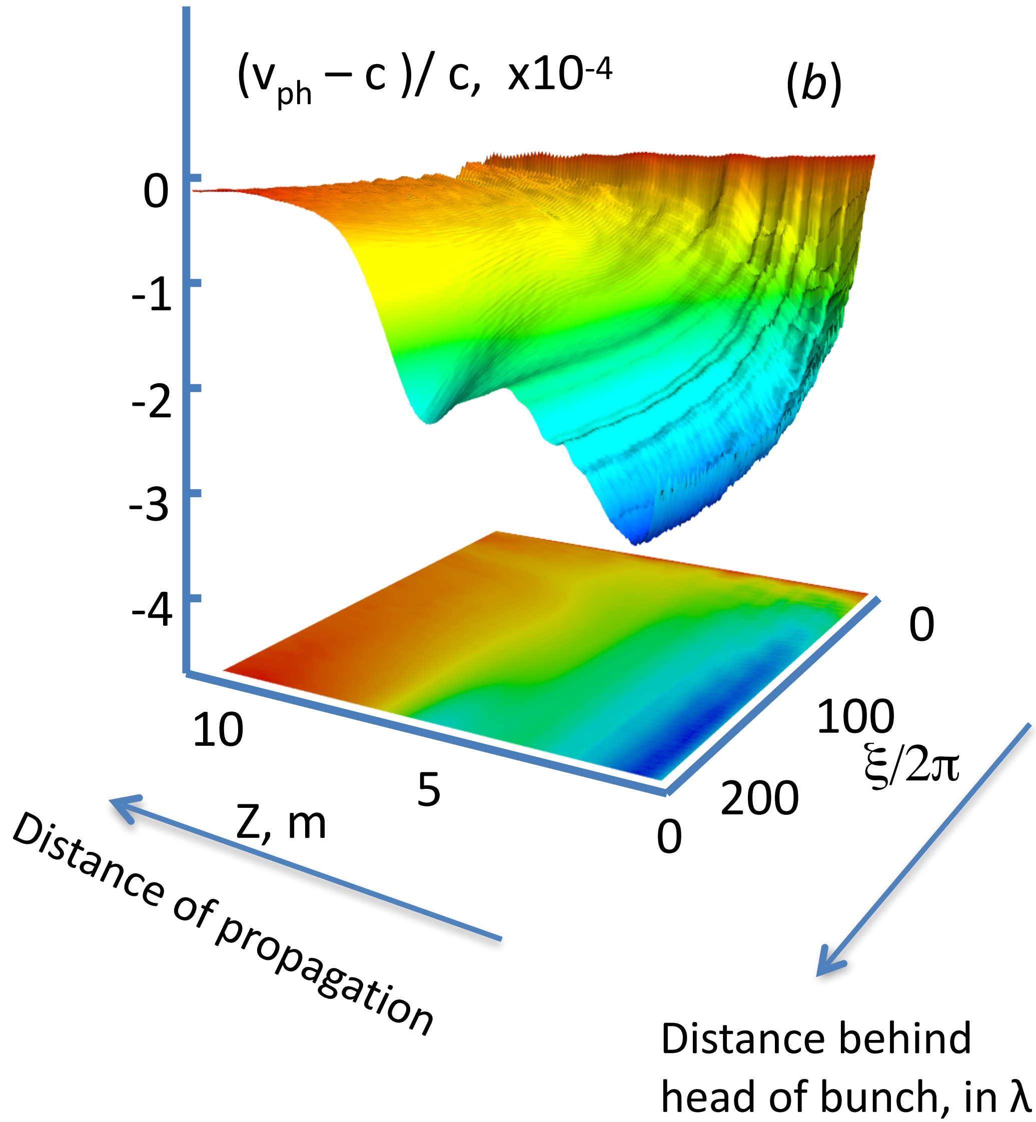
→ works exactly as predicted!

E. Adli et al.,(AWAKE Collaboration), PRL **122**, 054802 (2019)

Electron Injection

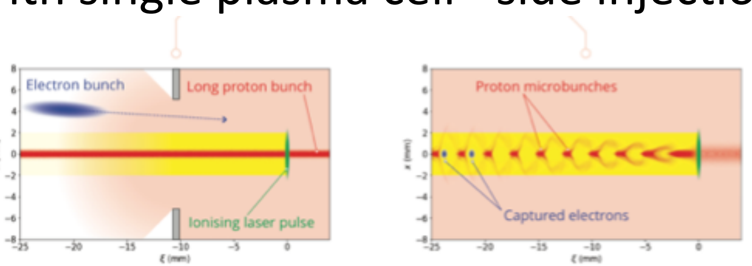
To optimize trapping & acceleration of electrons in the wake of the protons, should match the wake phase velocity to the electron velocity.

For best e-beam parameters, inject electrons after the phase velocity has stabilized.



Pukhov et al., Phys. Rev. Lett. **107**, 145003 (2011)

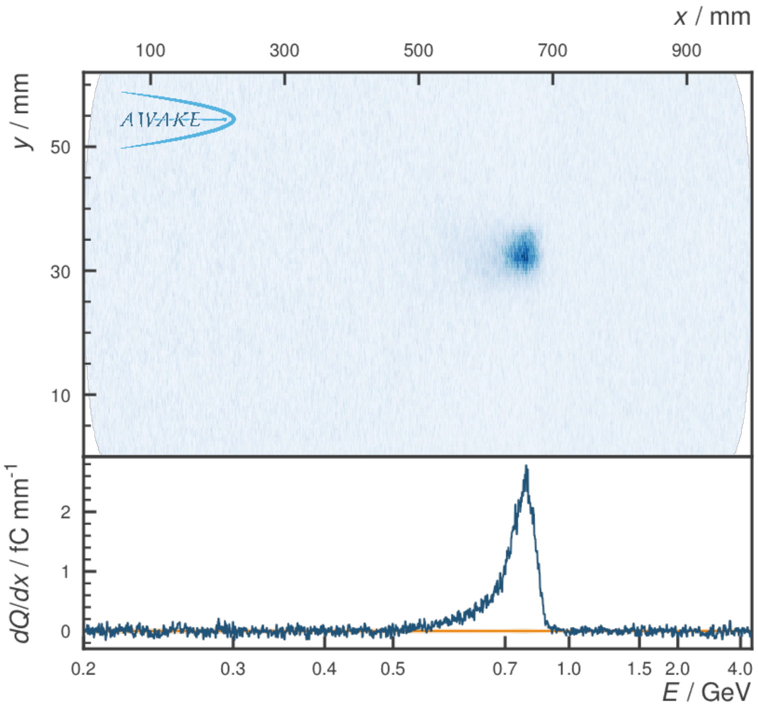
With single plasma cell - side injection

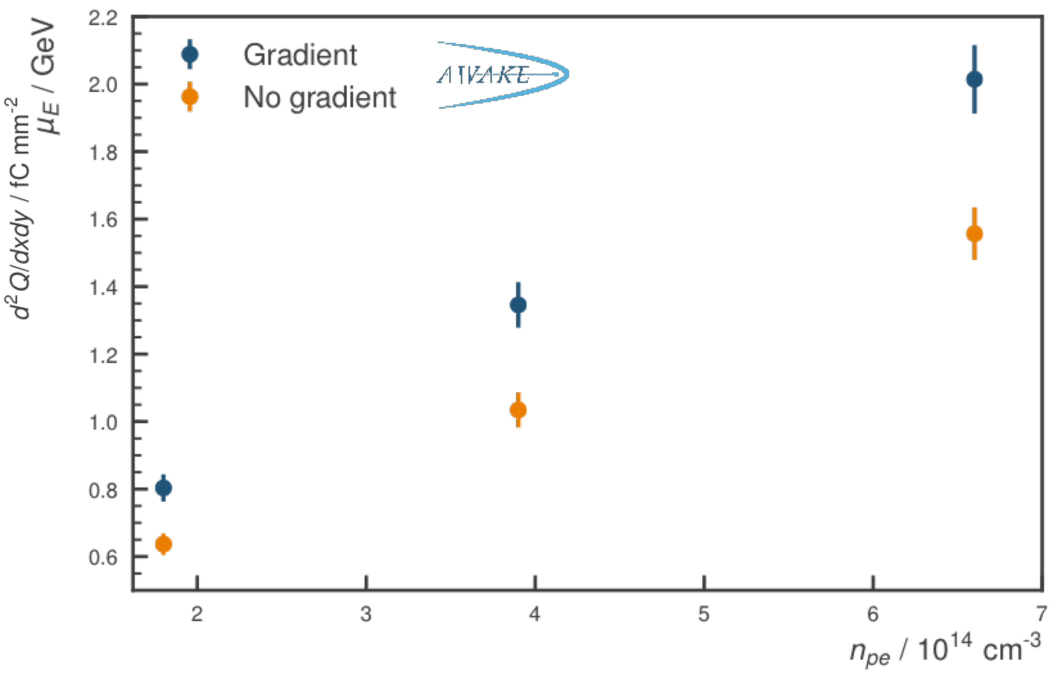


AWAKE

Electron Acceleration Results

E. Adli et al., AWAKE Collaboration, Nature **561,** 363 (2018)

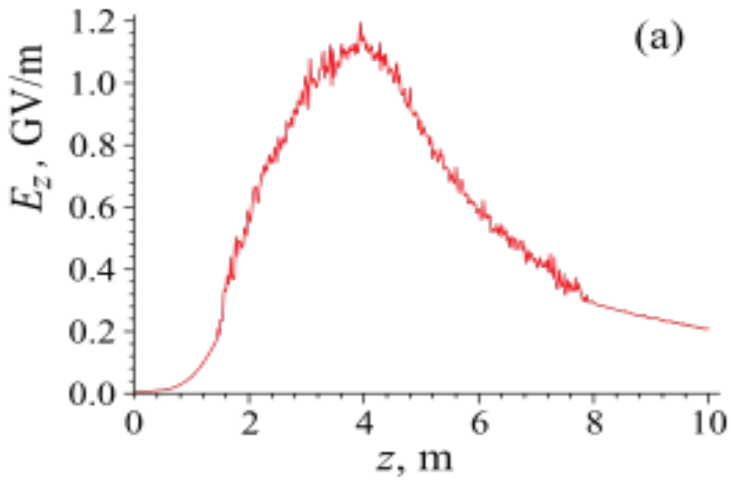


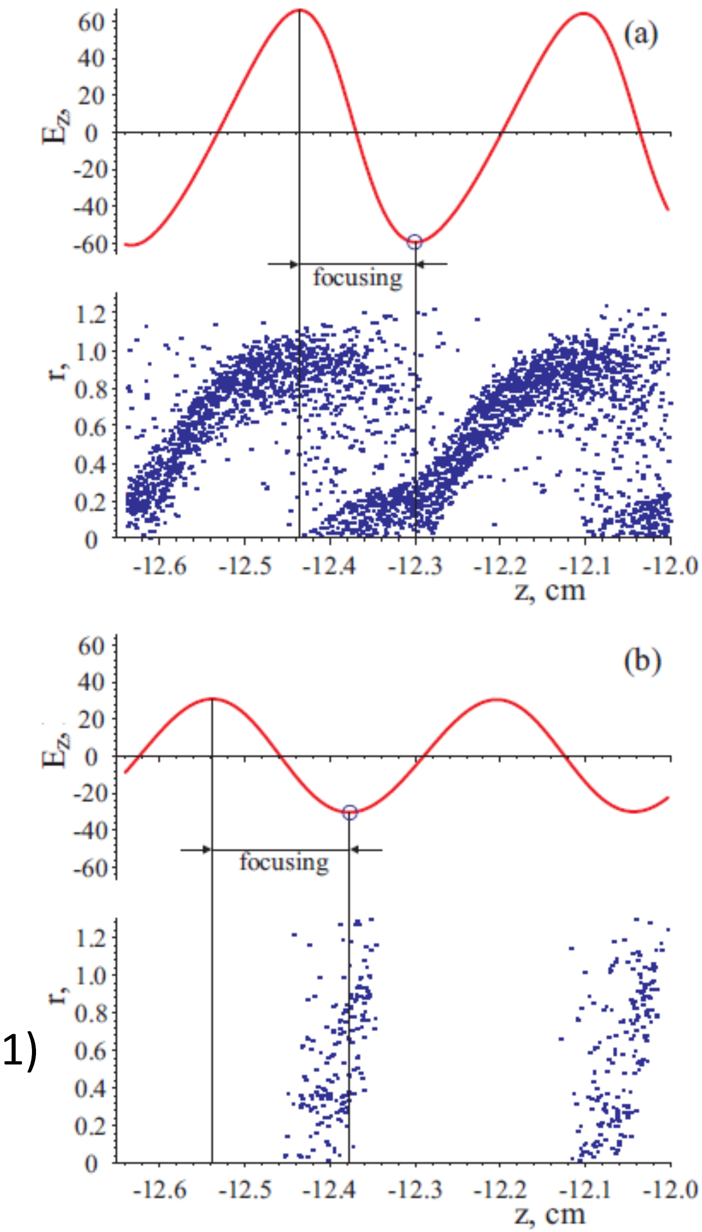


Electron acceleration in a proton-driven plasma wakefield works !

With todays existing proton bunches via seeded self-modulation!

Freezing the Modulation





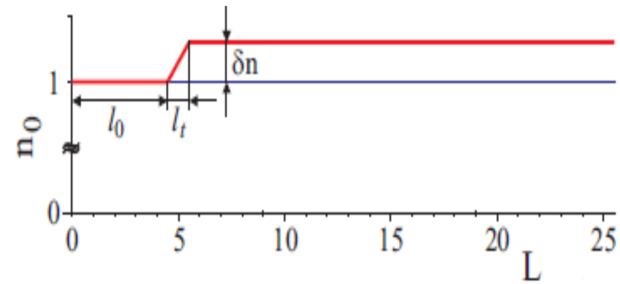
... wakefield amplitude quickly drops after the beam gets modulated.

Reason: defocusing regions keep on moving along the beam and destroys the bunches.

A. Caldwell, K. V. Lotov, Phys. Plasmas **18**, 13101 (2011)

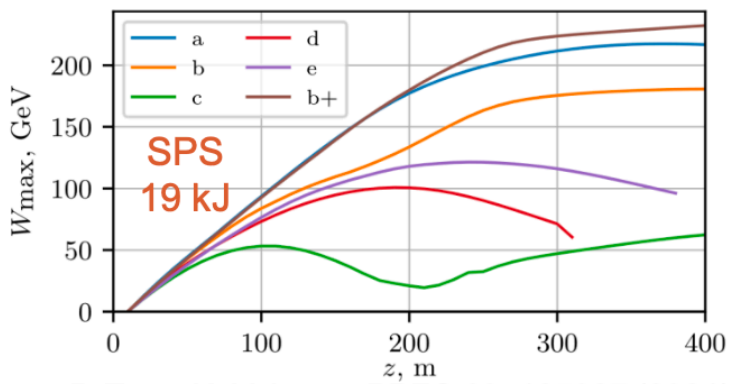
Freezing the Modulation

Remedy: control of the wave phase by the plasma density profile



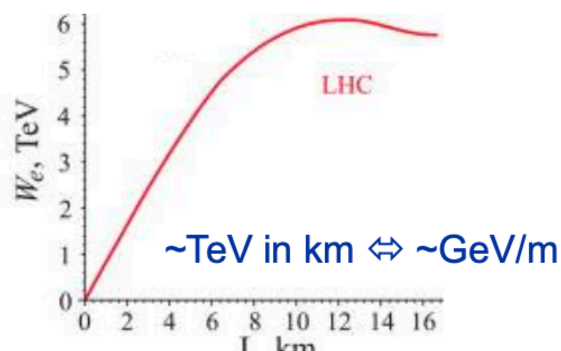
2D numerical simulation results

SPS Driver (19 kJ):
~ 200 GeV in ~200 m
~ 10^9 e^-



P. Tuev, K. V. Lotov, PPFC 63, 125027 (2021)

LHC Driver (112 kJ):
~ 5 TeV in ~7 km
~ 10^9 e^-

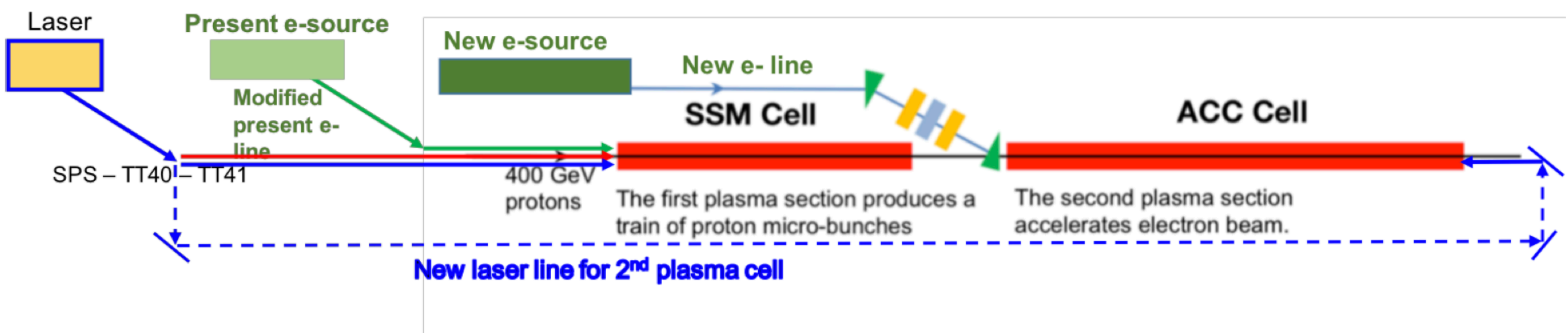


A. Caldwell, K. V. Lotov, Phys. Plasmas 18, 13101 (2011)

Run 2 (2021-)

Goals:
stable acceleration of bunch of electrons with high gradients over long distances
'good' electron bunch emittance at plasma exit
Be prepared to start particle physics experiment after Run 2

Baseline design



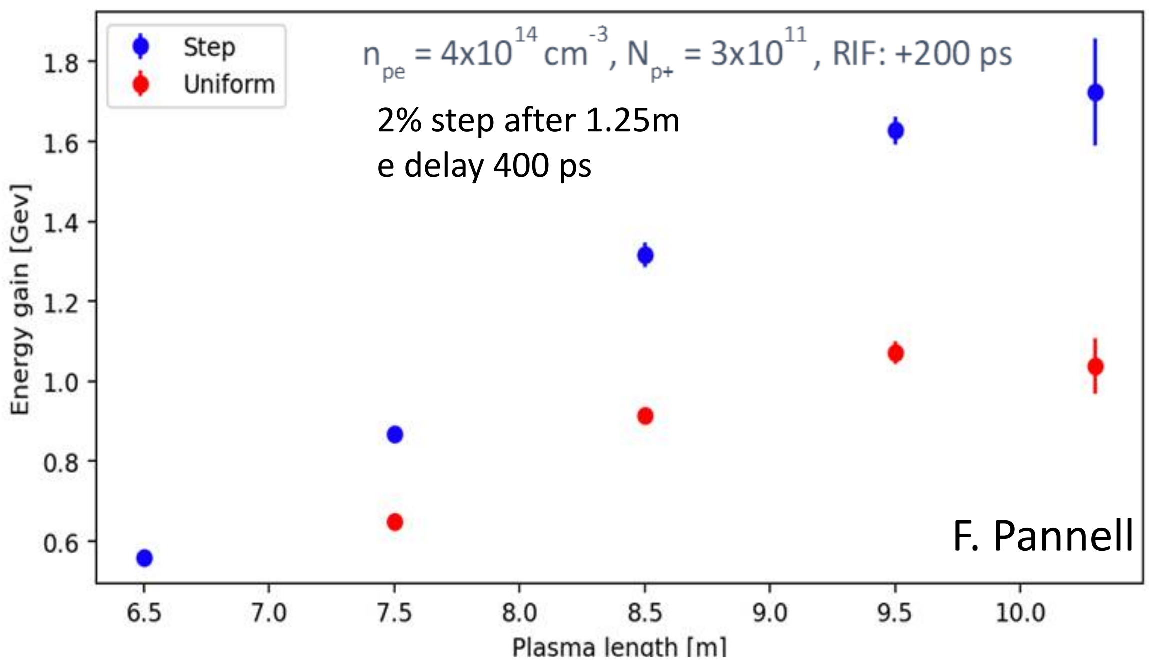
Four phases:

a) seeding the SSM with an electron bunch (2021-2022)
b) plasma cell with density step to freeze the modulation structure (2023-2024)
c) inject electrons & accelerate without emittance blowup (2028-)
d) implement scalable plasma cell technologies (2028-)

Preliminary Results Run 2b

Plungers installed every meter

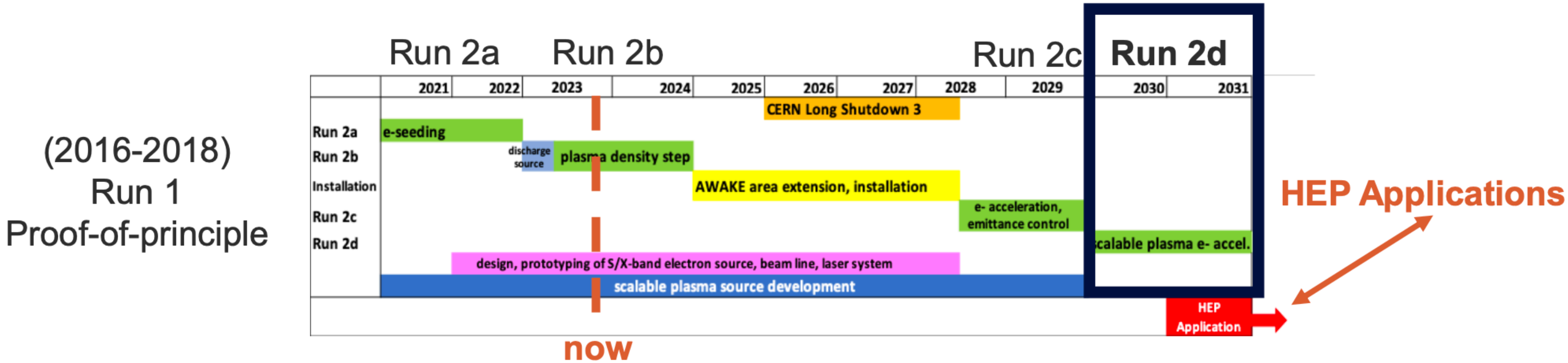
- better alignment
- can vary plasma length and directly measure gradient



Large parameter space - scan in next runs.

And increase the plasma density

Clear Time Line Towards an Accelerator



➢ **Milestones for AWAKE Run 2: → transition from proof-of-principle to applications**

M. Turner, SPSC Nov 2023

- **Physics with a high energy electron beam**
  - search for dark photons in beam dump experiments
  - Fixed target experiments in new energy regime

Energy & Flux important - luminosity determined by target properties. Much more relaxed parameters for plasma accelerator

- **Physics with an electron-proton or electron-ion collider**
  - Low luminosity version of LHeC
  - Very high energy electron-proton, electron-ion collider

New energy regime means new physics sensitivity even at low luminosities !

Beyond AWAKE

AWAKE approach will provide mid-term particle physics opportunities

Longer-term:

- for collider applications, need scheme to reach interesting luminosity
- only fraction of protons in bunch contribute to generating useful wakefield - limiting energy efficiency
- long proton bunches susceptible to hosing instability. May limit full use of proton bunch
- acceleration of electrons using many micro bunches requires very uniform plasma

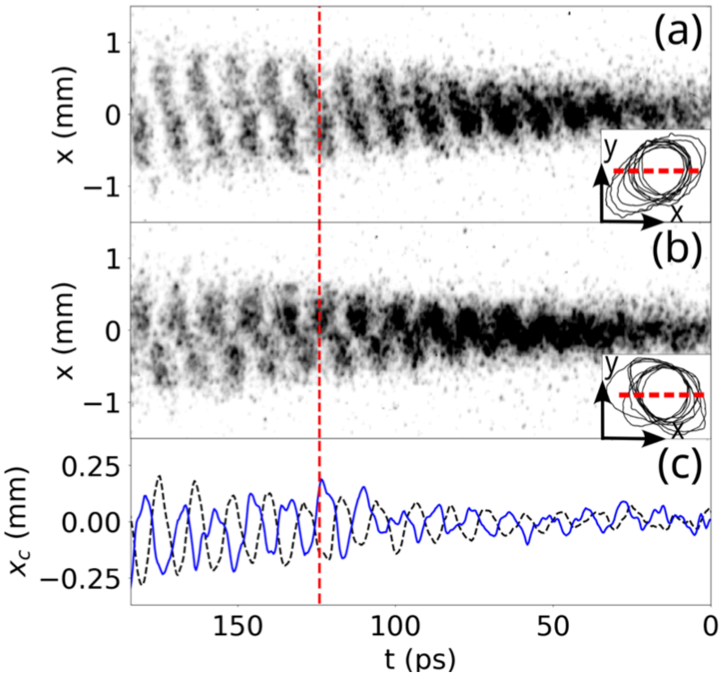
Investigate:

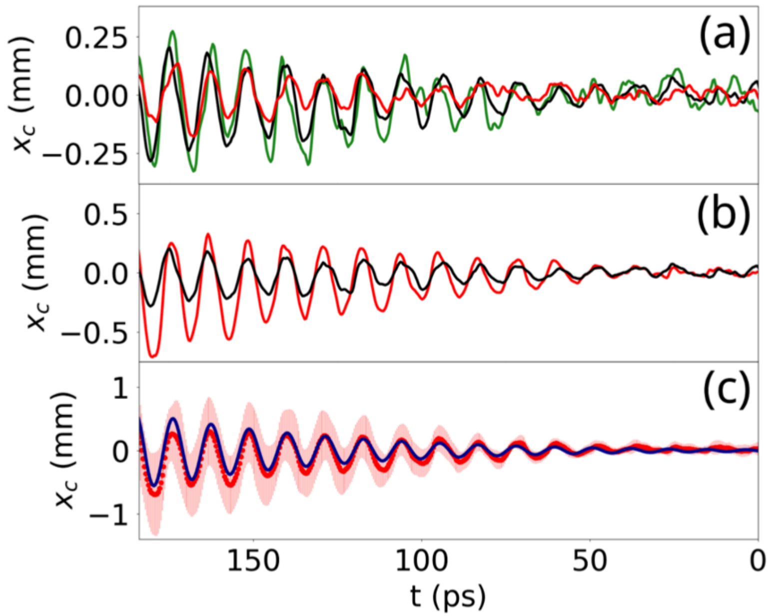
- high repetition rate proton accelerator → luminosity

- short proton bunches → eases plasma requirements, more efficient use of protons

Hosing - experimental study

Using electron bunch seeding



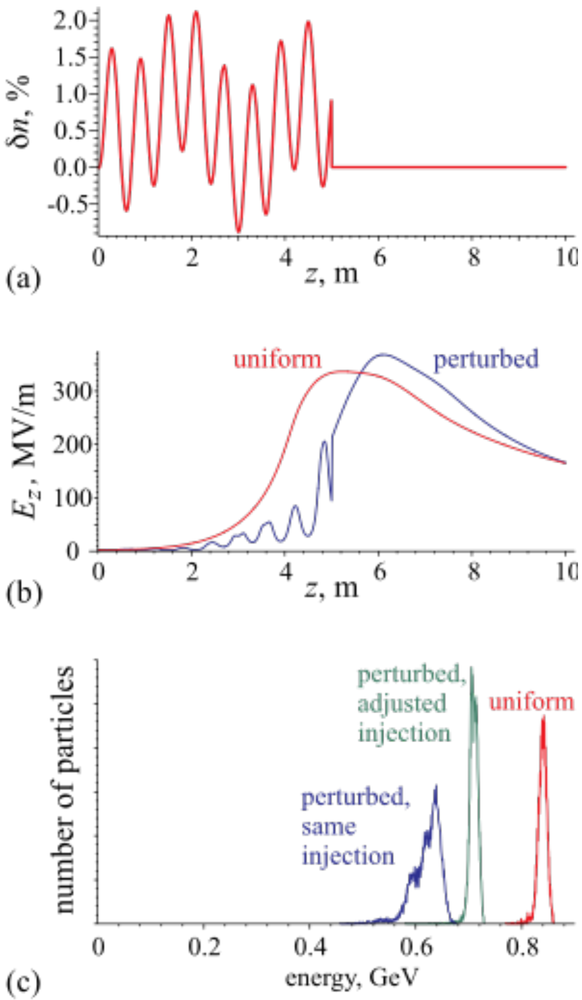


Hosing of a Long Relativistic Particle Bunch in Plasma

T. Nechaeva et al., AWAKE Collaboration
Phys. Rev. Lett. 132, 075001 (2024)

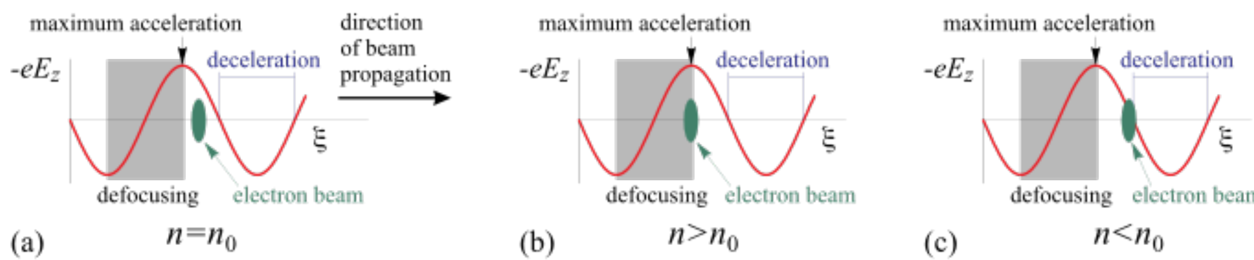
Triggering the hosing instability can be avoided with aligned seeding.

Plasma Uniformity



Nonuniformities can be tolerated in the modulation stage

But are dangerous for electron trapping and acceleration.



$$\delta n_{\max} \approx \frac{0.25}{N_{\text{periods}}}$$

But smooth gradients can be tolerated …

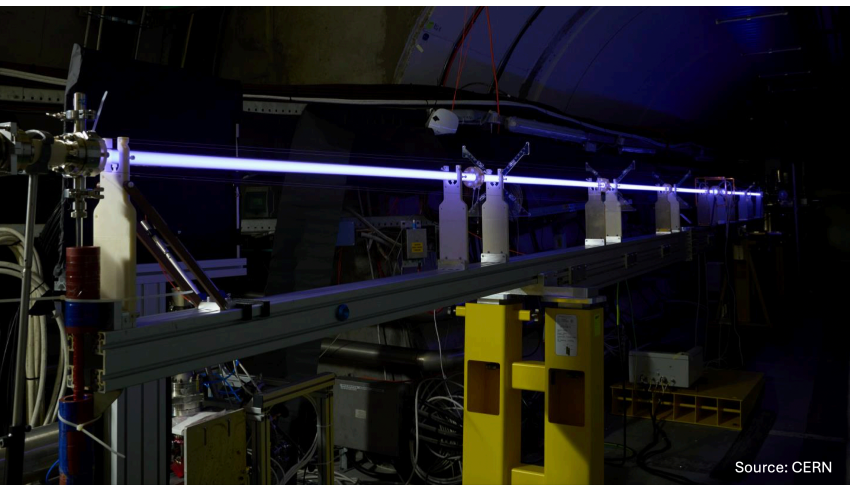
Lotov, Pukhov, Caldwell, Phys. of Plasmas, **20**, 013102 (2013)

Plasma Uniformity

Challenge: produce long plasmas (hundreds of meters/kilometers) with very uniform density

Candidates:

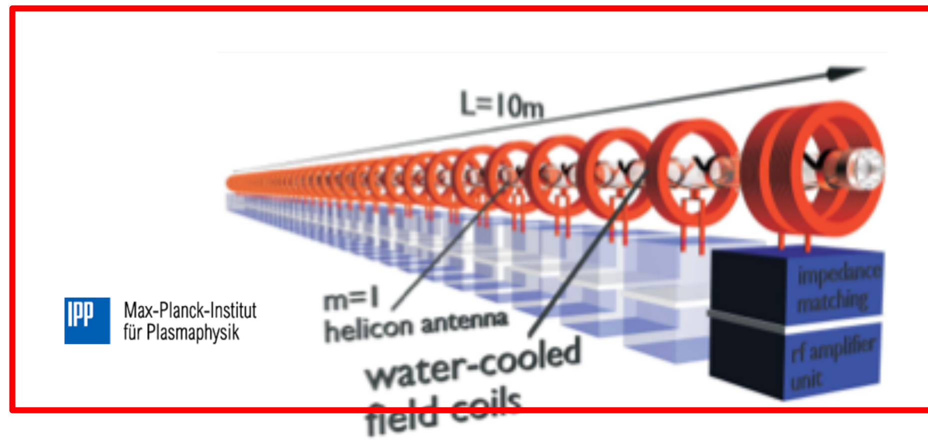
Discharge



IST - Lisbon, CERN and Imperial College

Helicon

Max Planck IPP, U. Wisconsin, EPFL, CERN

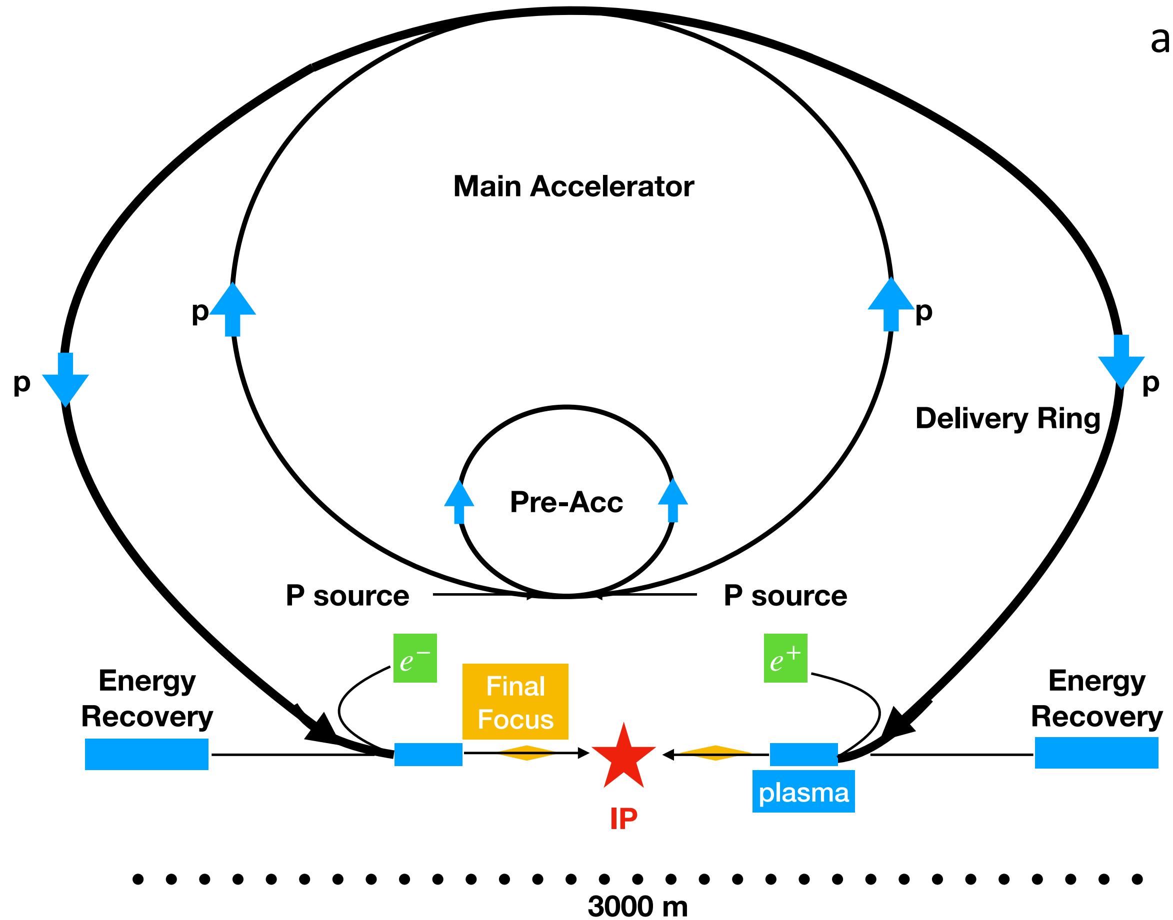


Both technologies allow to reach the wanted plasma densities. Uniformity still to be confirmed.

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

J. Farmer,[1,*] A. Caldwell,[1,†] and A. Pukhov[2,‡]
[1] Max-Planck-Institut für Physik, München, Germany
[2] Heinrich-Heine-Universität Düsseldorf, Düsseldorf, Germany

arXiv:2401.14765



take Higgs Factory as concrete example and ‘generate buzz’

Proton Driver

Based on:

- Fast cycling proton synchrotron concept discussed at FNAL for muon/neutrino production
- Assuming short proton bunches could be somehow achieved

FERMILAB-TM-2402-APC
February 15, 2008

Fast-Cycling Superconducting Synchrotrons and Possible Path to the Future of US Experimental High-Energy Particle Physics

Henryk Piekarz

Fermi National Accelerator Laboratory, Batavia, Illinois 60510, USA

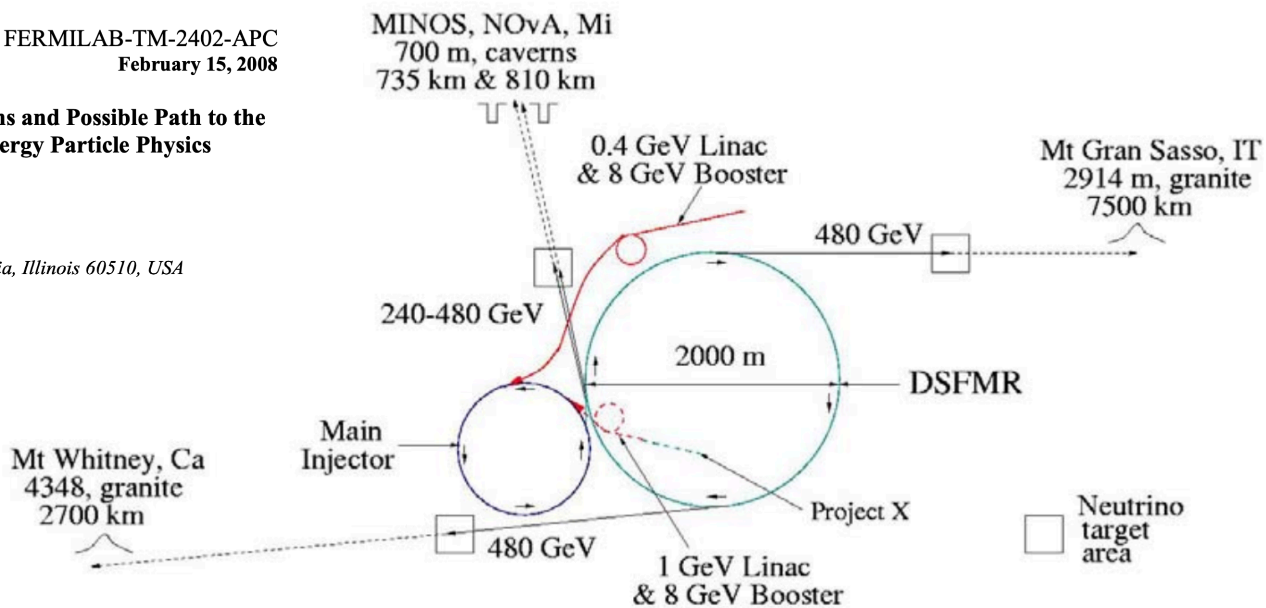


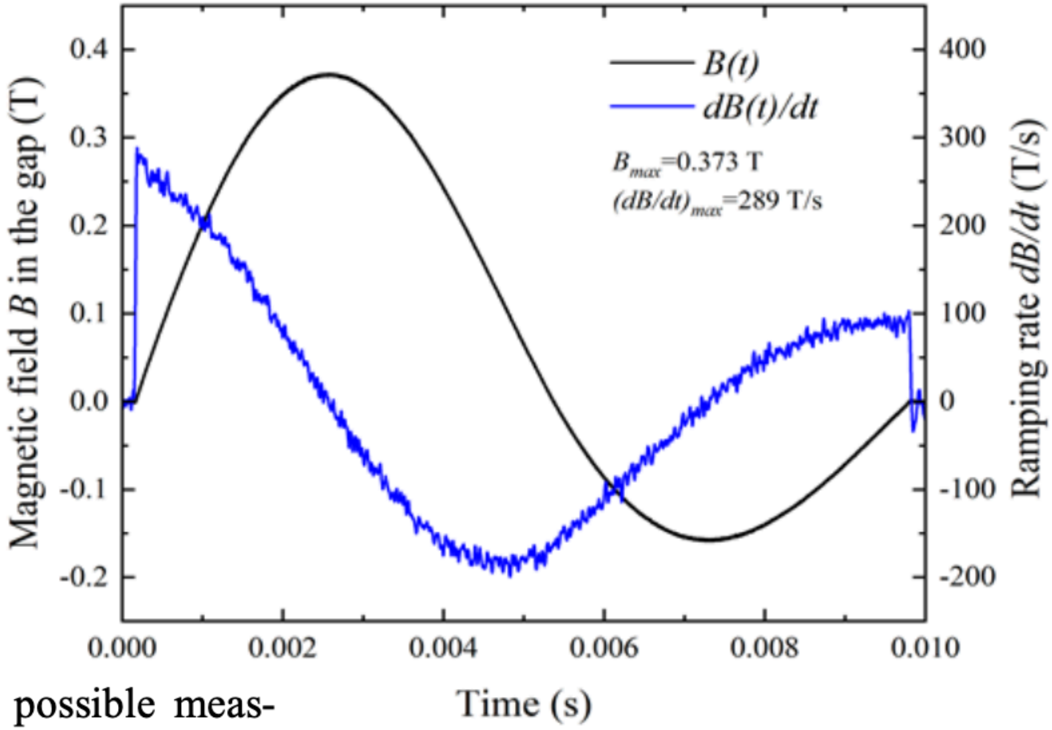
Fig.4. Proposed arrangement of DSFMR at the Fermilab accelerator complex

Proton Driver

Record High Ramping Rates in HTS Based conducting Accelerator Magnet

H. Piekarz, S. Hays, B. Claypool, M. Kufer and V. Shiltsev

IEEE Trans.Appl.Supercond. 32 (2022) 6, 1-4



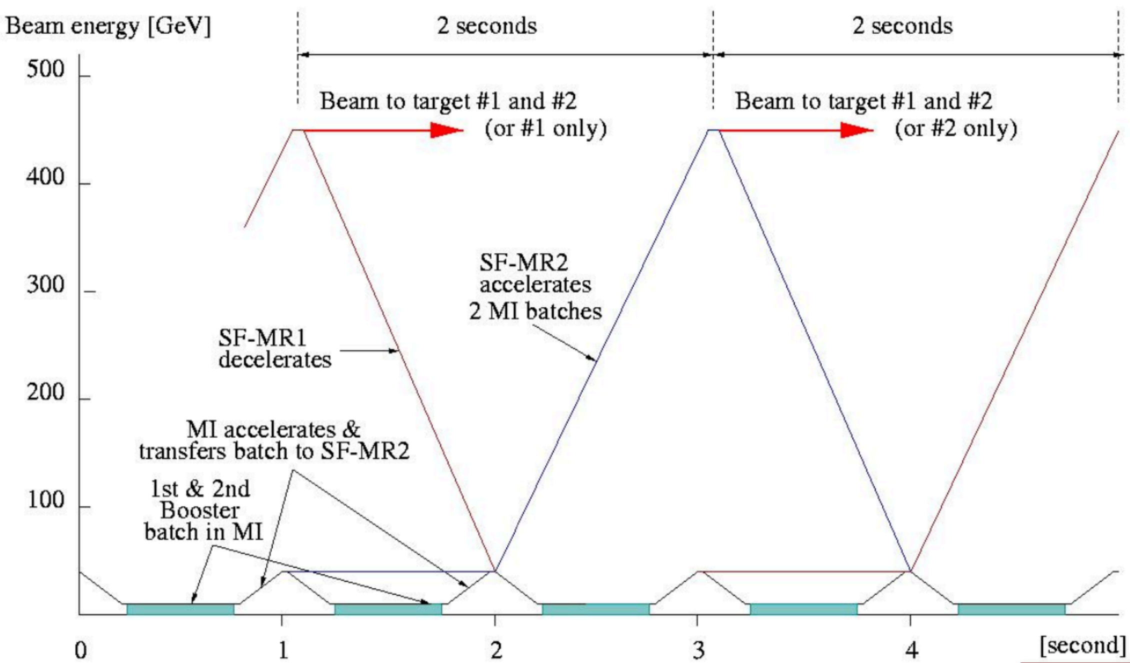
Our future work includes as accurately as possible measurements of the test magnet cable cryogenic power losses. We also will upgrade the magnet power supply to double the discharge voltage of the capacitor bank. This will allow to increase operating current to 2 kA, and the B-field in magnet gaps up to 0.8 T. With such upgrade the dB/dt ramping rates of up to 600 T/s should be achievable allowing to determine cryogenic power losses with higher precision and make projection of required cryogenic support for the future large accelerators more reliable.

Assuming HTS magnets for accelerators become reality, magnet cycling time can be (small) fraction of 1s.

We assume 0.2s cycling time.

Proton Driver

Piekarz, FERMILAB-TM-2402-APC



$\cdot\, 10^{-1}$

assuming HTS development

Fig.5. Time sequence for beam stacking, ramping and extraction onto ne
production targets with DSFMR.

We further take the number of bunches and proton/bunch from the Piekarz paper

$n = 10^3$ $\quad N_p = 10^{11}$ $\quad$ and $E_p = 400$ GeV $\quad \sigma_z = 150\ \mu$m $\quad \Delta E_p/E_p = 0.1$

Details in John's talk

Proton Driver

A completely different concept based on a FFAG design is being developed by Ferdinand Willeke which

- Provides a high rep rate
- **Produces short proton bunches**

A big part of this meeting will be dedicated to discussions after hearing from Ferdinand and the follow-up studies done at CERN. See talks by Ferdi & Jake Flowerdew

Electrons/Positrons

We did not do any work on the electron/positron source or the beam delivery to the IP

Assumed input normalized emittance $\epsilon_T = 100$ nm and $N_e = 2 \cdot 10^{10}$ el/positrons per bunch

Emittance preservation (within ~10%) during plasma acceleration shown for electrons
For positrons …. will be challenging

see talks by Alexander Pukhov, John Farmer, Severin Diederich

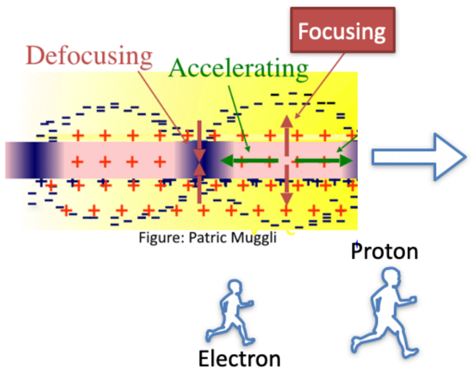
For our beam delivery and luminosity estimates, we took parameters from the ILC assuming that the round beams coming out of the plasma can be manipulated as needed to produce the flat beams. Clearly another point that needs to be investigated

see talk Vera Cilento

Plasma

We assumed that we can have a 50 kHz rate of proton bunches in the plasma
(extract one bunch from the ring every revolution)

The plasma length needed is ca 180m, plasma needs to be tapered in density to offset dephasing
$n_e = 3 - 6 \cdot 10^{14}\ \mathrm{cm}^{-3}$.

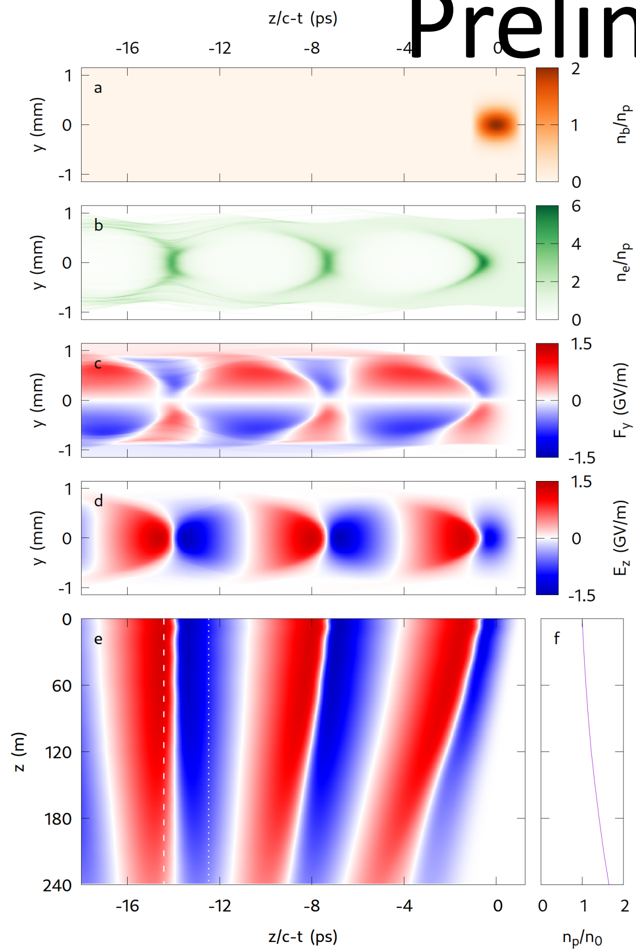


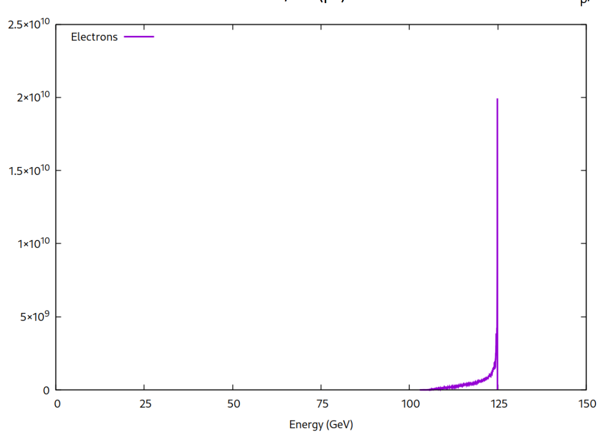
$$\delta \approx \frac{\pi L}{\lambda_p} \frac{1}{\gamma^2}$$

Considerations: secondary ionization, ion motion, scattering and emittance growth …

see talk Nelson Lopes for first ideas

Preliminary Investigation





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}

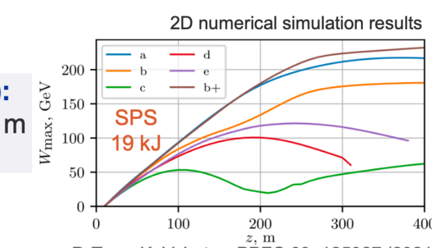
Comments

Clearly many open issues to be resolved, but

- proton accelerator tunnels exist
- protons can be accelerated in circular accelerators to 7 TeV today : driver energy not a limitation so single stage acceleration of leptons in principle possible
- scaling to higher energies should be a big advantage

SMI scheme investigated
TBD: scaling with short proton bunches

SPS Driver (19 kJ):
~ 200 GeV in ~200 m
~ 10^9 e^-



P. Tuev, K. V. Lotov, PPFC 63, 125027 (2021)

LHC Driver (112 kJ):
~ 5 TeV in ~7 km
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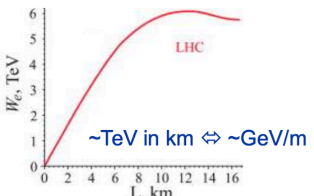

A. Caldwell, K. V. Lotov, Phys. Plasmas 18, 13101 (2011)

- ee or $\gamma\gamma$ collider can be considered
- eP, eA & QCD as exciting intermediate project

This Workshop

Present the preliminary concepts and get feedback from experts!

- high rep rate proton bunch acceleration/compression?
- emittance preservation for positrons in plasma?
- round beams in plasma and flat beams at IP?
- plasma boundary conditions can be met?
- …

We are looking forward to lots of discussion!

https://indico.cern.ch/event/1458898/timetable/#20240930

On **Tuesday, 1 October**, **major traffic disruptions** are expected on the **roads around the Meyrin site** from **10.30 a.m. to 12 noon** and from **4.30 to 6 p.m**. including the Route de Meyrin and roads between the CERN Meyrin site and Geneva airport.

These disruptions may also affect **bus 68** and **tram 18** to and from CERN.