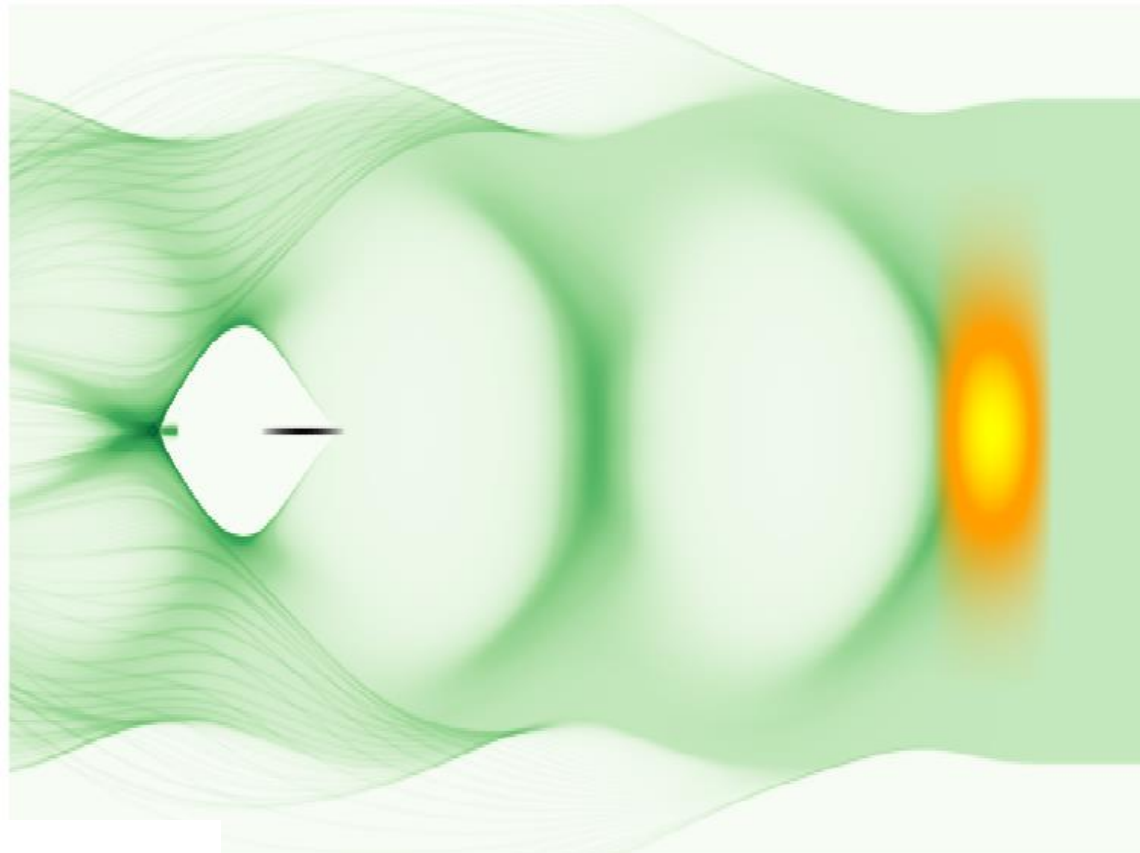


Challenges in Proton Beam-Driven Plasma Acceleration for 10 TeV colliders”



Curtesy
John Farmer



F. Willeke for the ALIVE Collaboration
ALEGRO 2025 Workshop
SLAC March 4-6

Outline

- Quick historical survey PDWFA
- Synopsis of AWAKE experimental result
- Higgs factory based on Proton Driven Plasma Wake field Acceleration
 - Parameters
 - Plasma wakefield acceleration
 - Beam-Beam Effect
 - **Fast Acceleration of Proton Beam**
 - Proton Bunch Compression
 - PDWFA based Higgs Factory Facility Layout
- 10 TeV CoM e^+e^- Collider: Continuous Proton Beams of 6 TeV

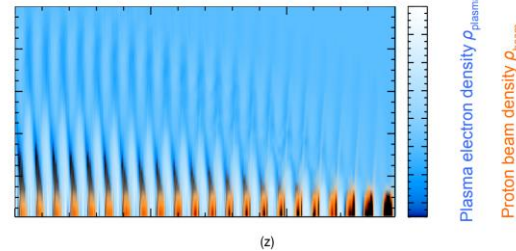
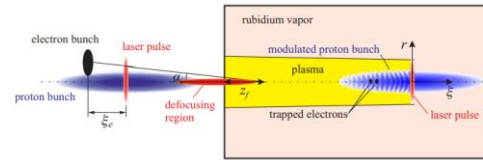
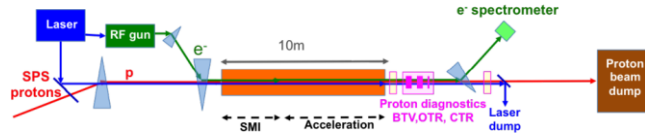


Courtesy: Flavio Cury

Plasma Wake field Acceleration

- Laser driven plasma for electron acceleration discussed since the late 1970-ties (Tajima, T. and Dawson, J. M.)
- Technique well established during 1990-ties and is continued to be improved since then
- Beam driven accelerating plasmas discussed since 1985 and experimental evidence culminating in experiments at SLAC in the first decade of 2000s by acceleration of electrons to 10's of GeV
- Proton driven plasma wake field acceleration discussed since first decade of 2000th
- Experimental verification of electron acceleration in proton beam excited plasma wake field in the AWAKE experiment at CERN
- Ideas developed on a PPWFA based $e^+ - e^-$ collider operated at HIGGS energy since 2023

AWAKE Proof of Principle Experiment



Self modulated Proton distribution (green)

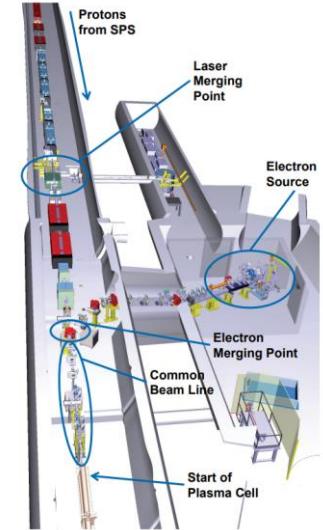


Table 1: AWAKE proton, laser beam and plasma parameters

| Parameter | Baseline |
|--|-----------------------------------|
| Proton beam | |
| Beam momentum | 400 GeV/c |
| Protons/bunch | 3×10^{11} |
| Bunch extraction frequency | 0.03 Hz (ultimate: 0.14 Hz) |
| Bunch length (σ) | 0.4 ns |
| Bunch size at plasma entrance ($\sigma_{x,y}$) | 200 μm |
| Normal. emittance (RMS) | 3.5 mm mrad |
| Relative energy spread ($\Delta p/p$) | 0.035% |
| Beta function ($\beta_{x,y}^*$) | 4.9 m |
| Dispersion ($D_{x,y}^*$) | 0 |
| Laser beam to plasma | |
| Laser type | Fibre titanium: sapphire |
| Pulse wavelength (L_0) | 780 nm |
| Pulse length | 100 - 120 fs |
| Laser power | 4.5 TW |
| Focused laser size ($\sigma_{x,y}$) | 1 mm |
| Energy stability (RMS) | $\pm 1.5\%$ |
| Repetition rate | 10 Hz |
| Plasma source | |
| Plasma type | Laser ionized rubidium vapor |
| Plasma density | $7 \times 10^{14} \text{cm}^{-3}$ |
| Length | 10 m |
| Plasma radius | ≥ 1 mm |
| Skin depth | 0.2 mm |
| Wavebreaking field $E_0 = mc\omega_{ep}/e$ | 2.54 GV/m |

Table 2: AWAKE electron beam parameters

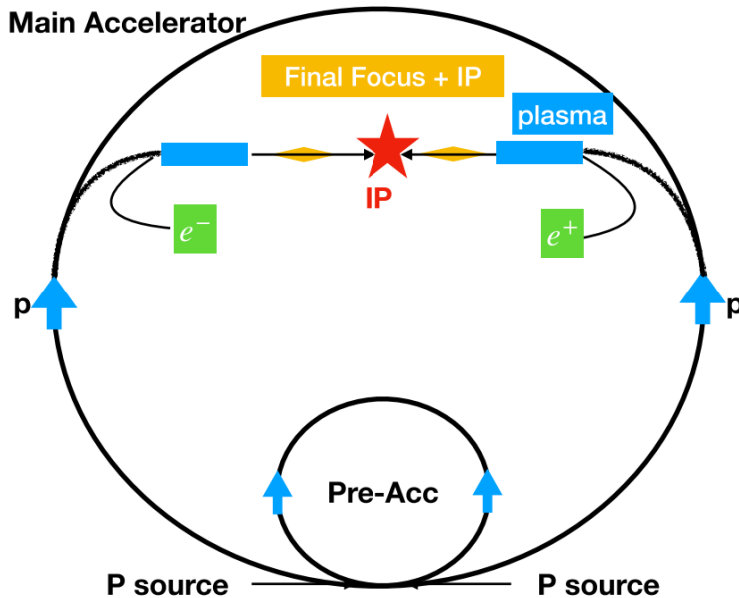
| Parameter | Baseline | Possible Range |
|---------------------------------|-------------------|----------------|
| Beam energy | 16 MeV | 10-20 MeV |
| Energy spread | 0.5 % | 0.5 % |
| Bunch length (σ) | 4 ps | 0.3-10 ps |
| Beam size at focus (σ) | 250 μm | 0.25-1 mm |
| Normalized emittance (RMS) | 2 mm mrad | 0.5-5 mm mrad |
| Charge per bunch | 0.2 nC | 0.1-1 nC |

Proton Bunch $N_p = 3 \cdot 10^{11}$, 400 GeV/c $\sigma_s = 12$ cm
 Self-modulated
 Electron Injection Energy 18 MeV
 Electron final Energy **2 GeV**
 Accelerated in a 10 m long plasma
 $\rightarrow \sim 0.2$ GeV/m

AWAKE Upgrade in Preparation

Fast Acceleration of Protons to High Energy

- Success of the AWAKE experiment at CERN encouraged a studying feasibility of a 250 GeV CM e^+e^- collider with competitive luminosity based on PDPWFA



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

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arXiv:2401.14765v1

| Proton Accelerator Parameters | |
|--|--|
| Proton Energy | 500 GeV |
| Proton Bunch Frequency | 7.5 kHz |
| Protons per bunch | $1 \cdot 10^{11}$ |
| Proton RMS Bunchlength | 1 mm |
| Proton Transverse RMS Beam Size | 250 μm |
| Normalized transverse emittance | $3 \pi \text{ radm} \cdot 10^{-6}$ |
| Proton Beam Power (2 trains) | 120 MW |
| Plasma Parameters | |
| Plasma Cell length ² | 240 m |
| Initial Plasma Density | $3.2 \cdot 10^{14} \text{ cm}^{-3}$ |
| Final Plasma Density | $5.2 \cdot 10^{14} \text{ cm}^{-3}$ |
| Plasma Relaxation Time | $\approx 1 \mu\text{s}$ |
| Plasma Medium | Rubidium Vapor |
| Lepton Beam Parameters | |
| Injection Energy | 1 GeV |
| Final Energy | 125 GeV |
| Particles per Bunch | $2 \cdot 10^{10}$ |
| Normal. Transv. Emittance | $100 \pi \text{ nm rad}$ |
| Horizontal β -function β_x^* at IP | 13 mm |
| Vertical β -function β_y^* at IP | 0.41 mm |
| Horizontal Beam Size at Collision Point | 73 nm |
| Vertical Beam Size at Collision Point | 0.409 nm |
| Luminosity Parameters | |
| Center of Mass Energy [GeV] | 250 GeV |
| Luminosity Enhancement Factor \mathcal{H} | 2 |
| Vertical Disruption | 73.6 |
| Luminosity | $6.5 \cdot 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ |
| Facility Power | $\approx 500 \text{ MW}$ |

Pros and Cons

- **What makes such scheme attractive?**
 - Compact facility, small footprint,
 - possibility to use existing infrastructure (minimizing conventional facility cost)
 - Opens the door to very high energy e^+e^- collisions, eg 10 TeV cm
- **What are the disadvantages?**
 - Large Power Consumption >5 times larger than linear collider
 - need to provide intense, high energy, extremely short proton bunches at high rate
 - Requires to develop novel technical components

Challenges of Proton driven Plasma Wakefield Acceleration

- **Energy efficiency:**

Proton-Acceleration-Efficiency times Plasma Acceleration efficiency
< 50% X < 3% = < 1.5 % → **needs substantial improvement**
Large power density: 100 MW distributed over 6.9 km @ 14kW/m

- **Plasma Uniformity and Stability over ~250 m → Modular Discharge Plasma source**
currently addressed in experiments and simulation studies, 10 kHz rep rate ok

- **Stability of the proton drive bunch**

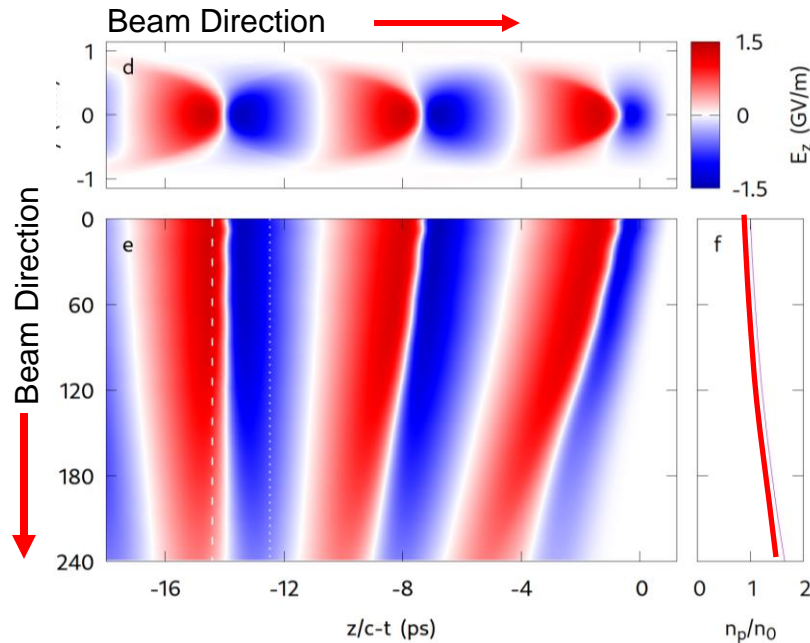
- **Positron Acceleration**

- **“Circular” lepton Beams**

PDPWFA require $\varepsilon_x = \varepsilon_y$: strong pinching, no disadvantage

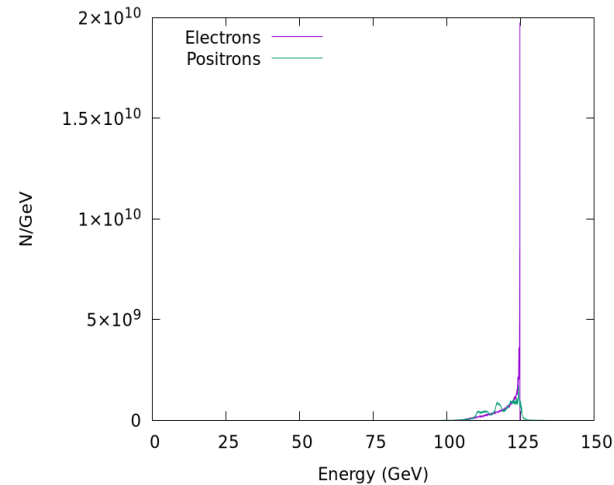
- **Production of high energy, proton bunches at high, steady rate**

Proton-driven wakefield acceleration



Dephasing avoided using density gradient.

10^{11} protons at 400 GeV accelerate
 10^{10} e⁺/e⁻ to 125 GeV.



Farmer *et al.*, NJP (2024)

Fixed relative phase
driver-witness



Tailored Plasma
density profile
along accelerator

Parabolic driver and witness, plenty of room for optimization:

- shape driver – reduce longitudinal dispersion, higher efficiency from driver to plasma.
- shape witness – control beam loading, higher efficiency from plasma to witness.

Result so far:

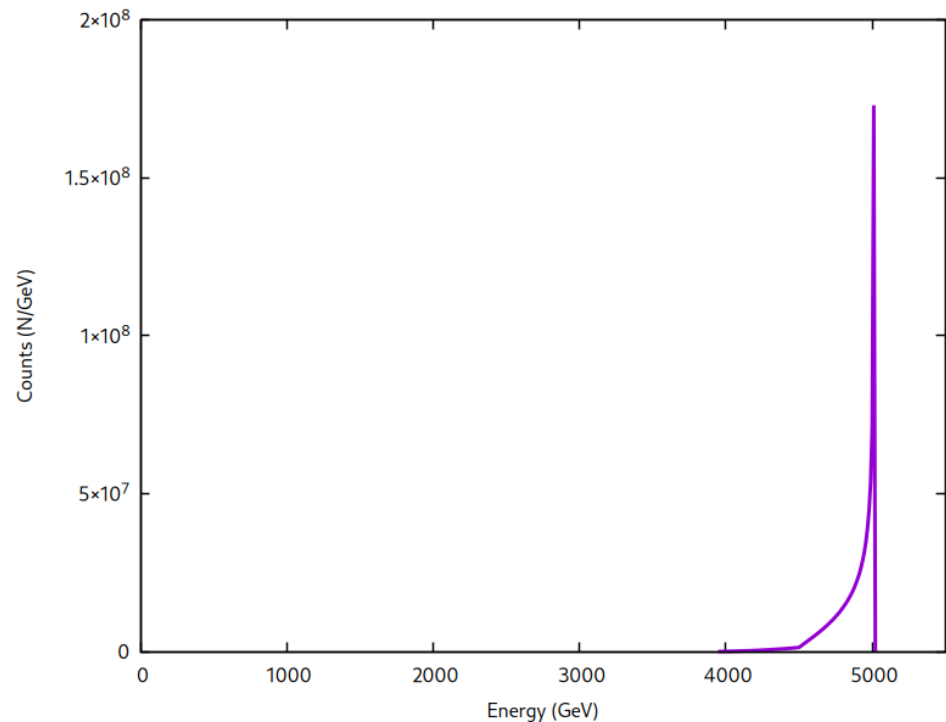
10^{11} proton drive bunch with 150 mm RMS bunch length in 200 m plasma yields
Electron acceleration from 1 GeV to 125 GeV

Upgrade path towards 10 TEV Collider

6.8 TeV driver (LHC energy)
allows acceleration of a
witness bunch to 5 TeV.

Usual paths for optimization

- shape driver
- shape witness
- external focusing



Flat vs. Round beam Simulations in Guinea-Pig

- Round beams pinch strongly during the interaction, greatly increasing total luminosity, but broadening the energy spread.
- Plasmas naturally produce round beams, but may be flattened via beam optics or further manipulation in plasma.
- A completely round beam sees a drop of ~10% Luminosity in the top 10% of energy compared to the CLIC-like beam.
- Flattening a round beam to the CLIC beta-star values gives the same luminosity at high energy as an unaltered round beam!

We choose parameters such that

$$(\sigma_x \sigma_y)^{1/2} = 20.8 \text{ nm}$$

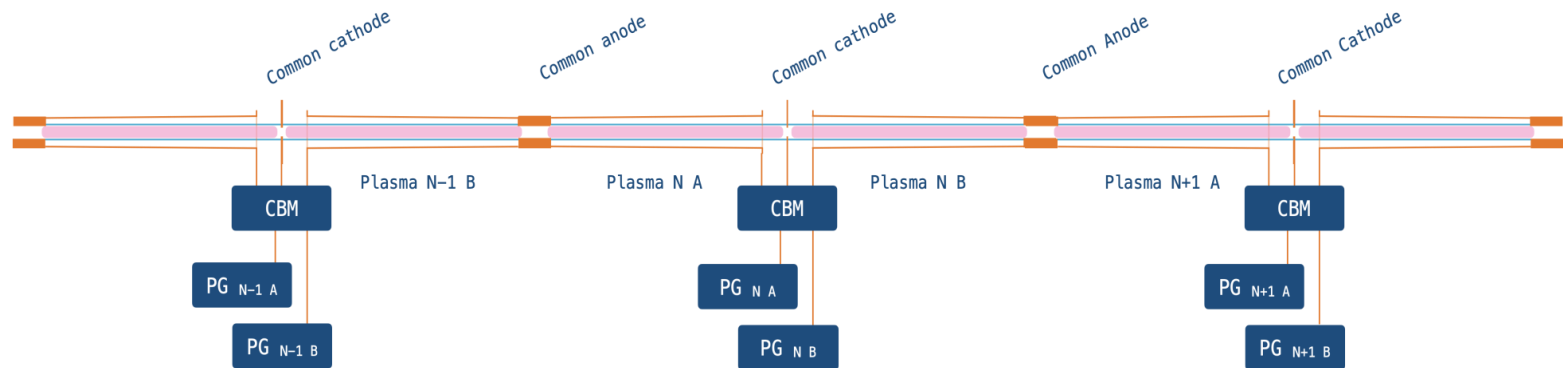
$$(\epsilon_x \epsilon_y)^{1/2} = 169 \text{ nm rad}$$

and vary the proportions of these quantities

| | σ_x / σ_y | ϵ_x / ϵ_y |
|-------------------|-----------------------|---------------------------|
| CLIC-like | 49.7 | 31.7 |
| flat-focus | 8.8 | 1 |
| round | 1 | 1 |

| | Total Luminosity | Luminosity in the top 10% |
|-------------------|-------------------------|----------------------------------|
| CLIC-like | 6.30×10^{33} | 5.81×10^{33} |
| flat-focus | 1.22×10^{34} | 5.32×10^{33} |
| round | 3.58×10^{34} | 5.32×10^{33} |

Discharge plasma Source



Nobel Gas Plasma

∅ 25mm

L= 10...20-30? Scalable 100 m?

$n = 1 \dots 10 \cdot 10^{14} \text{ e/cm}^3$

Double plasma, cathode in center

Ignition $2\mu\text{s}$ by inductive discharge

Pre-Heating by capacitive discharge

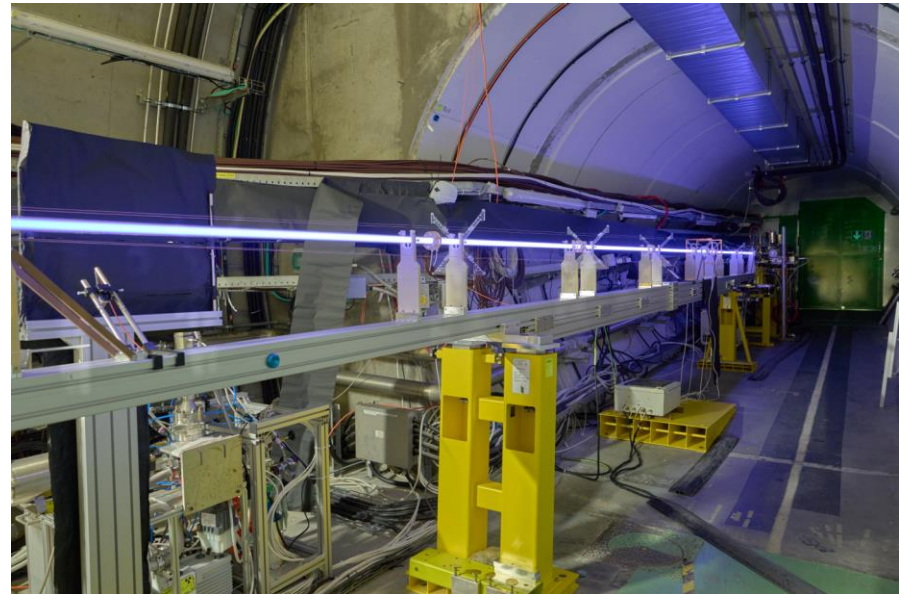


Photo: CERN Document Server

Fast Proton Acceleration

GOAL: Proton (and e+,e-) bunch frequency limited by Beam Power **100 MW**

- **Linear accelerator 500 GeV:**
 - no, would be cheaper to built Linear Collider
- **Recirculating LINAC GeV:**
 - Either too expensive or too many circulations
- **Rapid Cycling Synchrotron:**
 - hard to get high bunch repetition rate pre-accelerator chain will limit bunch rate even more
- **Non-scaling FFAG:**
 - relatively few turns N , voltage requirement too large $eU = E / N$, too expensive
- **Scaling FFAG:**
 - Very complex beyond state-of-the-art superconducting magnets

Rapid Cycling Synchrotron (RCS) Cascade

- **H⁻ source**, 50 mA, need 7 μ s long pulse for $4.4 \cdot 10^{12}$
- **1 GeV Proton linac**, $f_{\text{rep}} = 47.6$ kHz 0.03% duty factor
- **BOOSTER**: 287 m 1.7-7 GeV, charge exchange injection, 6 turns, $t_{\text{fill}} = 7$ μ s, *Space charge limited* bunching and 52 MHz RF capturing 5 ms, 44 bunches, $f_{\text{cycle}} = 62$ Hz, $f_{\text{rep}} = 47.6$ Hz
- **MEB**: 987 m 7-50 GeV, inj: long stacking 3 trains, $t_{\text{fill}} = 63$ ms, $f_{\text{cycle}} = 50$ Hz, $f_{\text{rep}} = 12$ Hz
- **Main Accelerator**: 6900 m, 50-500 GeV, 8 train-inj, $t_{\text{fill}} = 664$ ms, $f_{\text{cycle}} = 50$ Hz, $f_{\text{rep}} = 1.15$ Hz
- **Stretcher ring**: 6900 m 500 GeV with 1008 bunches with $N_p = 10^{11}$,

Proton Beam Power: ~9.4 MW

Extraction Rate = 1.2 kHz, 640 Hz per proton chain → Luminosity $0.52 \cdot 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$

Conclusion:

- Ambitious, but feasible scheme
- The luminosity falls short of desired values by at least factor of 2
- All magnets normal conducting $B < 2$ T to maximize cycle rate

Bunch Compression

To maximize the plasma acceleration fields, high intensity (10^{11}) proton bunches with a rms half bunch length of 1 mm are deemed necessary

Ambitious Parameters before compression:

$$N_p = 10^{11}$$

$$E_p = 500 \text{ GeV}$$

$$\text{RMS } \sigma_s = 12 \text{ mm}$$

$$\text{RMS } \Delta E/E = \varepsilon = 0.001$$

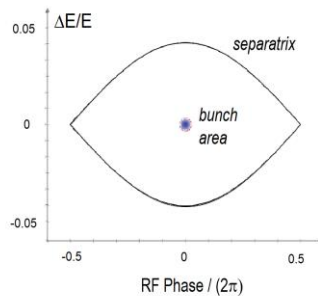
$$J_s = 0.032 \text{ eVs } U_{rf} = 330 \text{ MV}$$

$$\text{Momentum Compaction } \alpha_{mc} = 5 \cdot 10^{-5}$$



RMS half bunch length $\sigma_s = 1 \text{ mm}$
RMS relative energy spread $\varepsilon = 0.01$

Initial phase space



Bunch Compression by Bunch rotation enabled by RF amplitude modulation with $2 f_s$

- confirmed in routine operation (HERA injection)
- concern whether this works for strong bunches 10^{11} due to collective effects
- requires a full energy compressor ring.

Needs more study

Bunch Rotation

Linearization

For bunch rotation need to linearize RF by introducing 2nd and 3rd harmonics

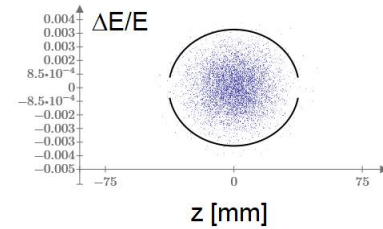
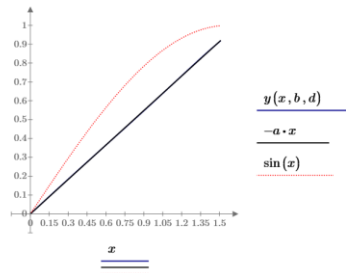


$$U_{\text{rf}} = 446 \text{ MeV}$$

$$f_{\text{rf}} = 200 \text{ MHz}$$

$$U_{2\text{nd}} / U_{\text{rf}} = -0.264$$

$$U_{3\text{rd}} / U_{\text{rf}} = 0.048$$



Matched linearized phase space



Modulation:

$$U_{\text{mod}} / U_{\text{RF}} = 1$$

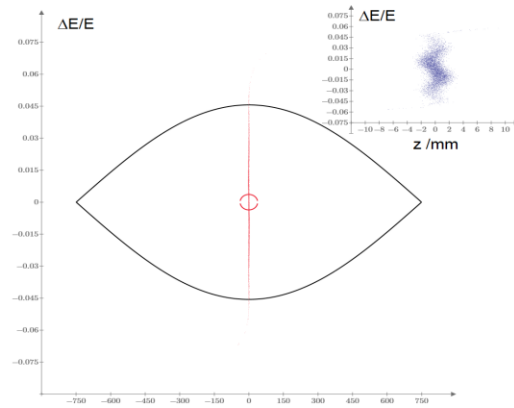
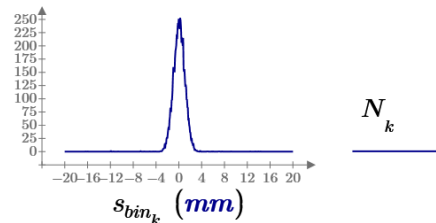
$$f_{\text{mod}} = 1.89 f_s$$

number of turns: $n_{\text{turn}} = 608$

“submillimeter” σ_{rms}

99.4% of simulated

Particles insite +/- 20mm



rotated bunch in phase space

This result needs to be

Confirmed in presence of collective effects!

FFAG

- FFAG provide continuous stream of **uniformly spaced bunches** → high bunch frequency, limited by beam power $f_b = 15 \text{ kHz} \rightarrow L = 3.3 \cdot 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$

FFAG proposed in 1956: fixed field combined function alternating gradient lattice.

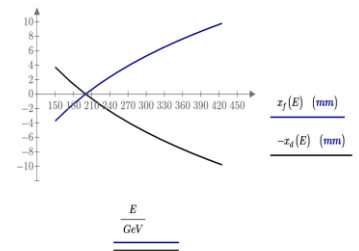
Beam moves radially to larger magnetic field matching changing beam energy

Recent realizations EMMA, CBETA (e-) **non-scaling FFAG**, few turns, tunes different on each turn, "jump" over resonances

- Proton driver needs many turns N_{turn} to limit $U_{\text{RF}} = \Delta E / N_{\text{turn}} \rightarrow$ **need scaling FFAG** constant tune and lattice functions during acceleration implying

$$G \sim (dB/dx) / B = \text{constant}$$

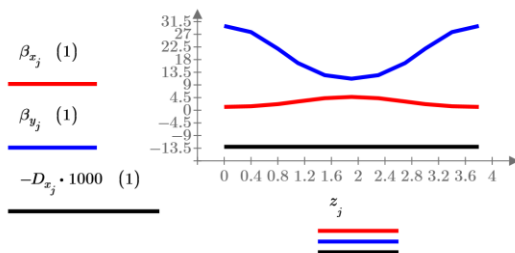
$$\rightarrow B(x) = B_0 \cdot \exp(x / x_0)$$



- x_0 controls the focusing $k = 1/(x_0 \rho)$

and orbit length during acceleration $\Delta T_{\text{rev}} = 2\pi x$

- Combined Function Alternating Gradient Lattice strong horizontal focusing



Almost isochronous lattice

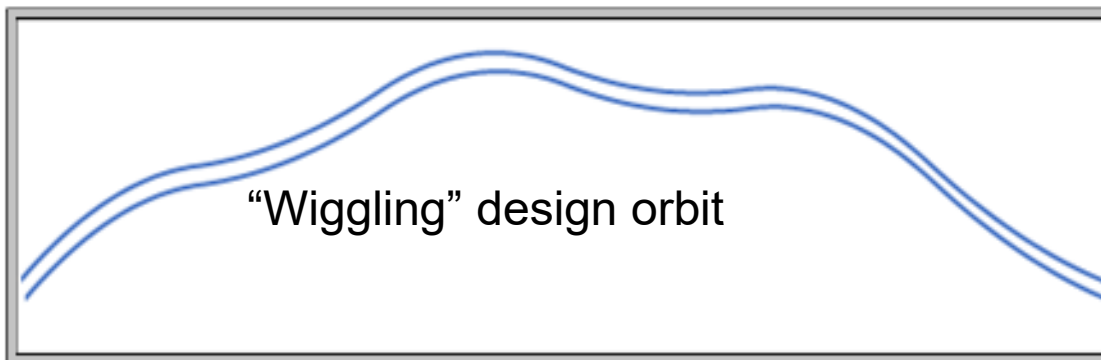
$$\alpha_{\text{mc}} = 10^{-5}$$

Scaling-FFAG Design Orbit

- Note $G_f \sim B_f$ and $G_d \sim B_d$ $G_f / |G_f| = - G_d / |G_d| \rightarrow B_f / |B_f| = - B_d / |B_d|$

This Lattice has reversed bends!

- inward bends $(BI)_f$ should be as strong as possible & outward bends $(BI)_d$ should be as weak as possible, however $k=1/(x_0\rho)$, and kl_f / kl_d are bound by optical stability condition $kl_f = -0.65 kl_d \rightarrow l_d/r = -0.65 l_f/r @ BI_d \sim -0.65 \cdot BI_f$
- $BI_d \sim -0.65 \cdot BI_f \rightarrow$ need $(1.65/0.35) \sim$ **5 X** stronger fields than in a synchrotron

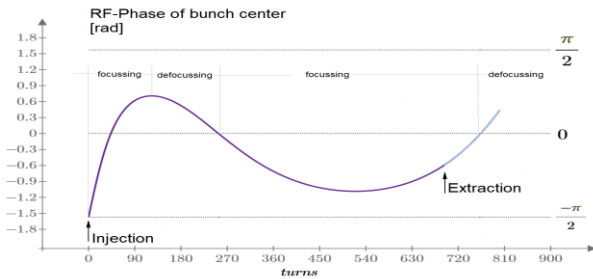


very inefficient bending!
very strong bends!
Peak Energy 500 GeV,
Circ. = 6900 m
 $B_{\text{peak}} = 10.2 \text{ T}$

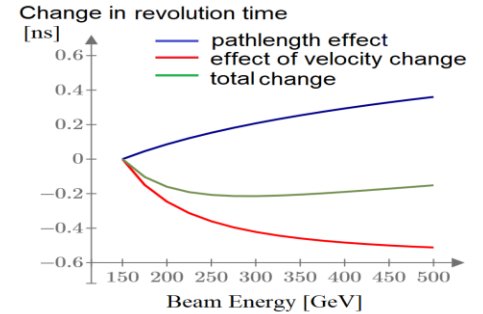
FFAG Acceleration Study

FFAG Acceleration requires a nearly constant revolution time for all energies, thus relativistic velocity change balances by

increase in orbit length $2\pi \cdot x_0 \rightarrow \Delta T_{rev} = \Delta \left[\frac{\beta(E) \cdot c}{2\pi \cdot x(E)} \right] \approx 0$

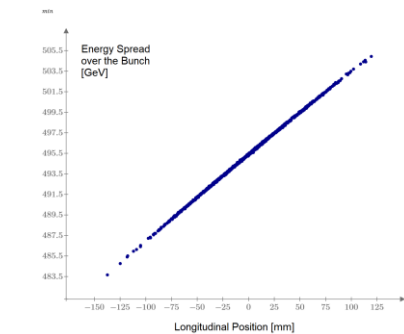
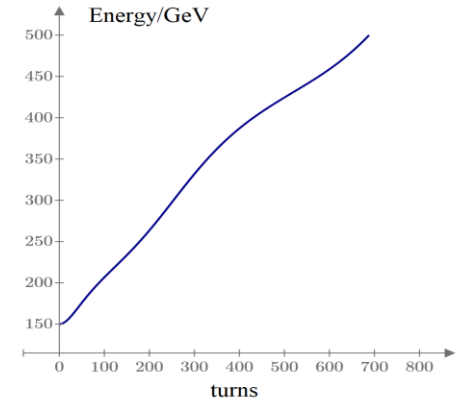


\rightarrow Almost constant acceleration rate

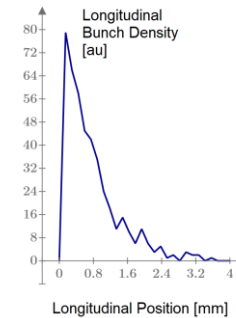
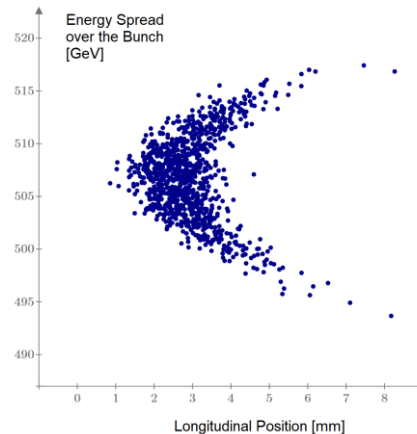


RF phase is always accelerating

Bunch length and energy spread grow during acceleration with constant longitudinal action $J_s = 0.03$ eVs

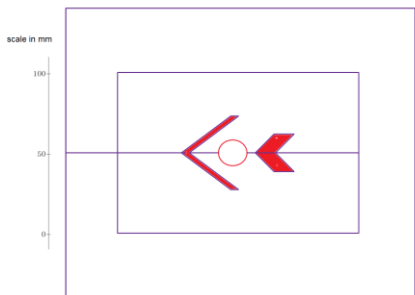


After chicane with $R_{56} = 9.1$ mm



RMS $\frac{1}{2}$ bunch length 0.7 mm

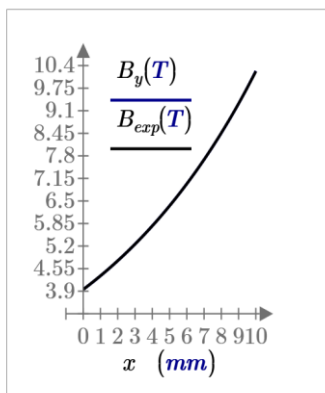
“Exponential” Magnet



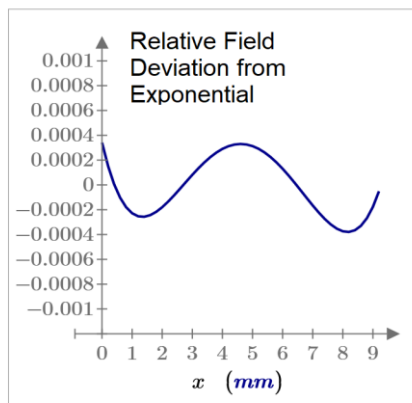
Possible Air Coil Geometry
magnet cross section approx. 20 cm x 15 cm
for 20 m FODO cell length

Need very high
current density
5 kA / mm²

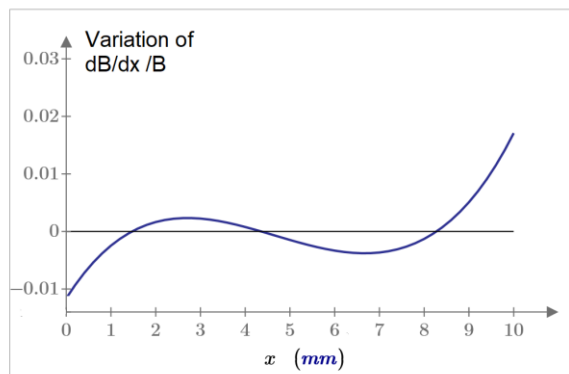
s.c. conductor with
such current density
not feasible yet



Analytic field Calculation
(no steel)



Relative field error $\sim \pm 0.1\%$



Gradient Error $\pm 2.5\%$
Needs to be reduced by factor 10
to limit tune variation

Residual
variation of
focusing still
causes
 $\Delta Q \sim 3$
Needs further
optimization

Note: Alignment tolerances will be very challenging
1 micron level @ 30 MeV or $\Delta E/E = 10^{-4}$

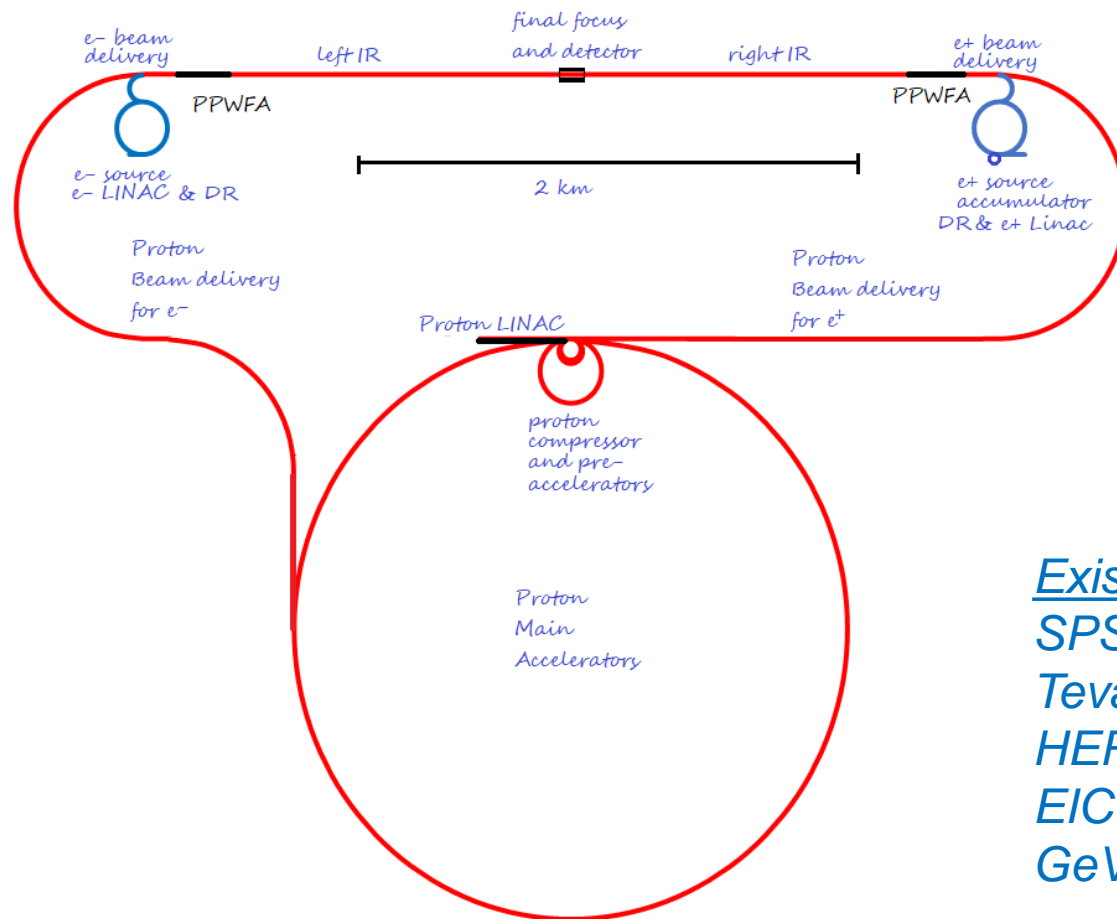
Very challenging s.c. magnet
Unclear whether this will be feasible

FFAG Injector Chain

- **50 mA (ECR) source:** 0.32 μs train with 10^{11} protons at $f_{\text{rep}} = 15 \text{ kHz}$ $\eta = 0.5\%$
- **10 GeV multi stage s.c. LINAC**
Final 0.5 GeV stage: different frequency $\Delta f = 1/2 f_{\text{rep}}$ \rightarrow linear energy spread of 1 GeV over the entire train
- Bunch trains enters **compressor ring**, large α_{comp} , compresses bunch over 200 turns to 19 cm (to be captured by a 52 MHz RF bucket)
- Bunch injected into a **cascade of accelerator rings**
- Injectors must supply proton bunches at the same rate than the main accelerator
- \rightarrow All circular accelerators must be **FFAG**
- Low energy rings, large β -swing need large aperture to maintain a nearly constant revolution time and RF phase during acceleration

| E_{ini} | E_{fin} | Circ. | T_{rev} | ΔT_{rev} | Δ_x | ρ | Ap. | B_{min} | B_{max} | $k=$ | URF | Turns |
|------------------|------------------|-------|-------------------|-------------------------|------------|--------|------|------------------|------------------|---------------------|------|-------|
| [GeV] | [GeV] | [m] | [μs] | [ns] | [cm] | [m] | [cm] | [T] | [T] | [m^{-2}] | [MV] | |
| 10 | 16 | 400 | 1.33 | 3.52 | 16.80 | 44.6 | 7.9 | 3.52 | 5.62 | 0.1335 | 10 | 600 |
| 16 | 50 | 1200 | 4.00 | 3.37 | 16.10 | 133.7 | 18.3 | 1.87 | 5.86 | 0.0465 | 50 | 680 |
| 50 | 150 | 6900 | 23.00 | 1.98 | 9.46 | 768.7 | 10.4 | 1.02 | 3.06 | 0.0138 | 50 | 2000 |
| 150 | 500 | 6900 | 23.00 | 0.22 | 1.05 | 768.7 | 1.3 | 3.06 | 10.19 | 0.1238 | 700 | 500 |

Footprint of a Possible Facility



Existing Rings this Size:
SPS
Tevatron
HERA
EIC (not quite for 500 GeV)

Proton bunch train is split into two trains upon extraction

Conclusion

- Tools are being developed for optimizing proton driven plasma wakefield operation for yielding 125 GeV lepton beams with acceptable energy profile, work in progress
- Overall efficiency is the major challenge, this should improve at higher electron energies
- Production of high intensity highly compressed proton bunches is technically challenging and expensive compared to existing machines
- Solutions to some of the technical challenges go beyond the state of the art
 - high gradient s.c. 52 MHz rf, - very special and strong superconducting magnets
- Compression of hadron to 1 mm bunch length seems possible in single particle model. Collective effects still need to be evaluated
- First simulation results on 5 TeV electrons available now

While this technique is very challenging, results so far are encouraging further study is required as well as R&D on components

Backup Slides

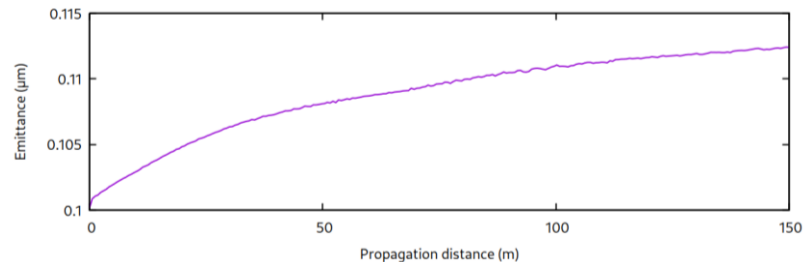
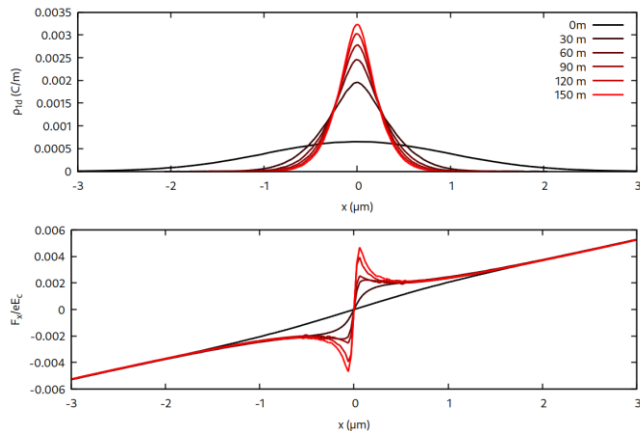
Summary and Conclusion Acceleration

- **Rapid cycling synchrotron:**
technically challenging but most likely feasible,
Luminosity limited by the 1 kHz maximum proton bunch rate,
need a stretcher ring at flat top to produce protons at a constant rate.
need a 50 GeV injector that provides a quasi continuous beam
e+-e- luminosity of $0.5 \cdot 10^{34} \text{cm}^{-2} \text{s}^{-1}$ possible with LC-like e beam parameters
 - **FFAG acceleration:** The proton bunch rate is only limited by the proton beam power.
Assuming a proton beam power of 100 MW → e+-e- luminosity of $5 \cdot 10^{34} \text{cm}^{-2} \text{s}^{-1}$
 - bending efficiency is extremely poor, feasibility depends on development of magnet technology
 - Acceleration range is limited to factor ~3,
→ need a low energy 150 GeV FFAG as part of the injector chain.
 - Continuous stream of proton bunches imply continuous stream of electrons
(implies a large DR with wigglers for e+).
- To be investigated:** Mixed scheme with FFAG for low energy and synchrotron for the last high energy stage of acceleration. This could lead to Luminosity above 10^{34}

Proton-driven wakefield acceleration

Acceleration in a single stage

- inject once at (relatively) low energy
- slow evolution of focusing fields due to ion motion allows for self-matching
- positrons remain challenging



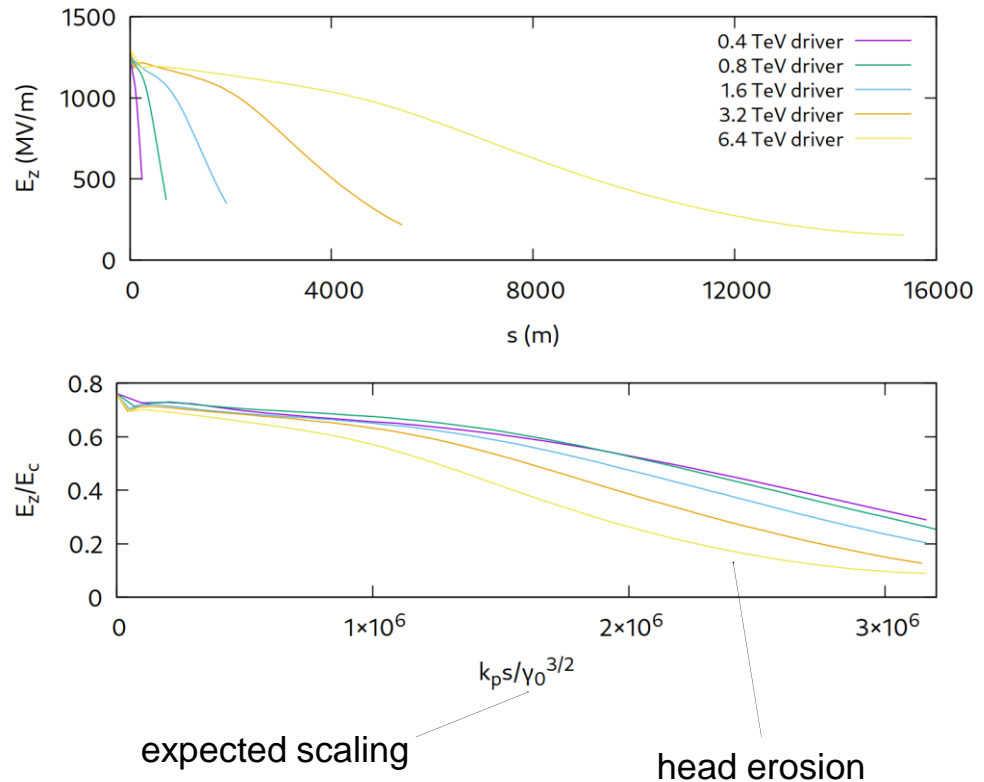
Adiabatic self-matching of electrons to nonlinear fields caused by ion motion leads to minimal emittance growth (shown here for Li).

Farmer *et al.*, LCWS proceedings (2024)

Upgrade path

At low (up to 1 TeV) driver energy, acceleration length is limited by longitudinal dispersion of the drive beam.

- better than linear scaling with energy ($\gamma^{3/2}$)
- for higher driver energy, erosion of the driver head plays a larger role.

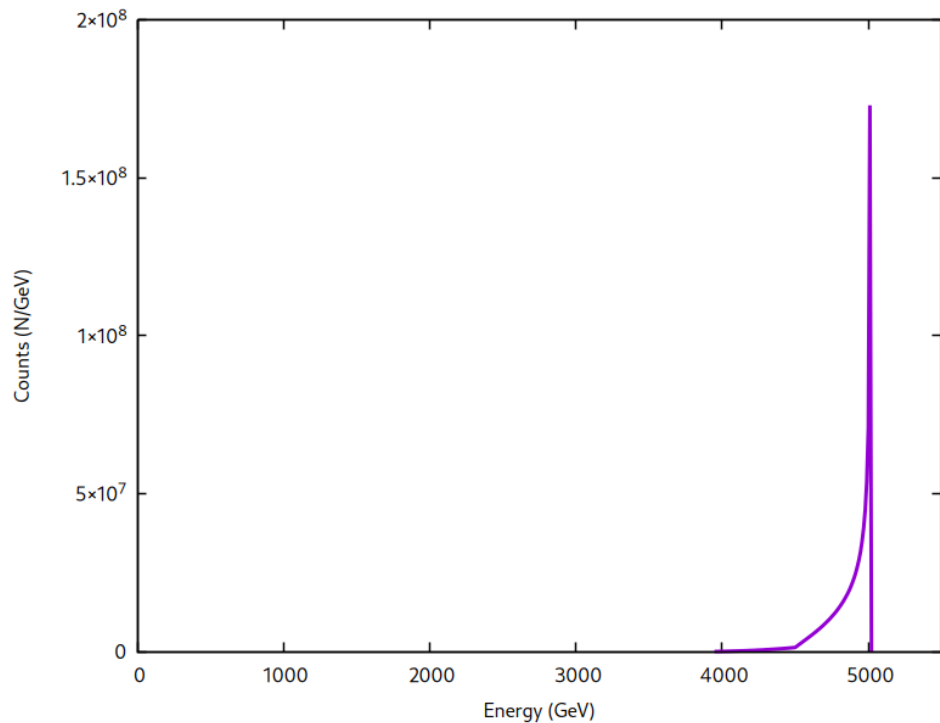


Upgrade path

6.8 TeV driver (LHC energy) allows acceleration of a witness bunch to 5 TeV.

Usual paths for optimisation

- shape driver
- shape witness
- external focussing



DPS... a length scalable discharge plasma for AWAKE

Requirements

Electron density

Range 1 - 10 × 10¹⁴ cm⁻³ ✓

Uniformity / reproducibility / control ~ 0.1%

In progress ~1% currently

Ion Mass

>= Argon ✓

Plasma length

✓ In progress

~10 m (R2C) , ~200 m (R2D) , ~5 km (>R2D)

Discharge Plasma Source (DPS)

Ignition (HV) + Heating (HC)

heating pulse ~ 500 A, ~10 μs (l=10m, d=25 mm)

Length scalability

Plasma sections w/ 5-20 m w/ common electrodes

Magnetic current balancing

CERN - AWAKE May 23 experiment



DPS technology program

> 21 k plasmas made w/ length 3.5, 6.5 and 10 m

Density 0.1- 30 × 10¹⁴ cm⁻³ (Xe) - 0.1- 3 × 10¹⁴ cm⁻³ (He)

Easy integration in accelerator complex

Science program

Proton beam self modulation - verified in all AWAKE plasma densities

Ion mass effect - ion motion increasing for Xe, Ar and He plasmas

Beam filamentation at highest densities

Plasma length scans

Wakefield plasma-light

N. C. Lopes¹, C. Amoedo^{1,2}, Z. Najmudin³, J. F. Silva¹, A. Sublet², N. Torrado¹, C. Torres³ and the AWAKE team

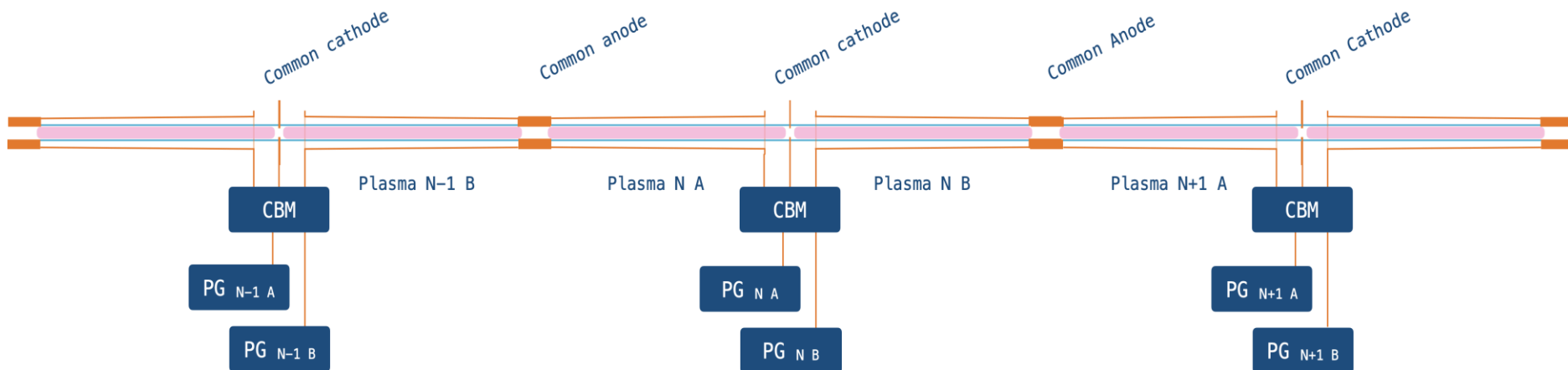
¹ Instituto Superior Técnico, Lisbon, ² CERN, ³ Imperial College



HF DPS for a length scalable collider

Length scalability

- > Sequence of 10-20 m plasmas with common cathodes and anodes...
- ... equal currents forces in each plasma by magnetic chokes
- ... partially demonstrated, full demonstration for AWAKE run 2D in 2025



Length scalability scheme

Simpler monopolar case (for low rep. rate plasmas)

HF DPS for a length scalable collider

Length scalability

- > Sequence of 10-20 m plasmas with common cathodes and anodes...
- ... equal currents forces in each plasma by magnetic chokes
- ... partially demonstrated, full demonstration for AWAKE run 2D in 2025

>= 10 kHz repetition rate

- > First plasma requires tube ignition (H Voltage) + heating (H current)
- > Following plasmas with re-heating pulse only (incomplete recombination)
- > Plasma longitudinal flow due to non negligible duty cycle...
- ... mitigated by plasma re-heating with bipolar alternating discharge

Power reduction and full ionization

- > re-heating to full ionisation costs ~ 0.4 GW / km (Argon, 10 kHz, Diameter 25 mm)
- ... alkali vapour may reduce power by ~ 10 x
- ... close to 1 ionisation fraction essential with intense beams
 - ... ~ 1 T solenoid field enhances ionisation fraction (preliminary, in progress)

Intense beams constrains

- > Electron beams reach field ionisation threshold
- ... use ions with large first-second ionisation potential gap
- > Intense beams move ions and degrade wakefields
- ... avoid light ions (e.g. lithium)
- > Best compromise likely Potassium or Rubidium

