Collider design issues based on proton-driven plasma wakefield acceleration

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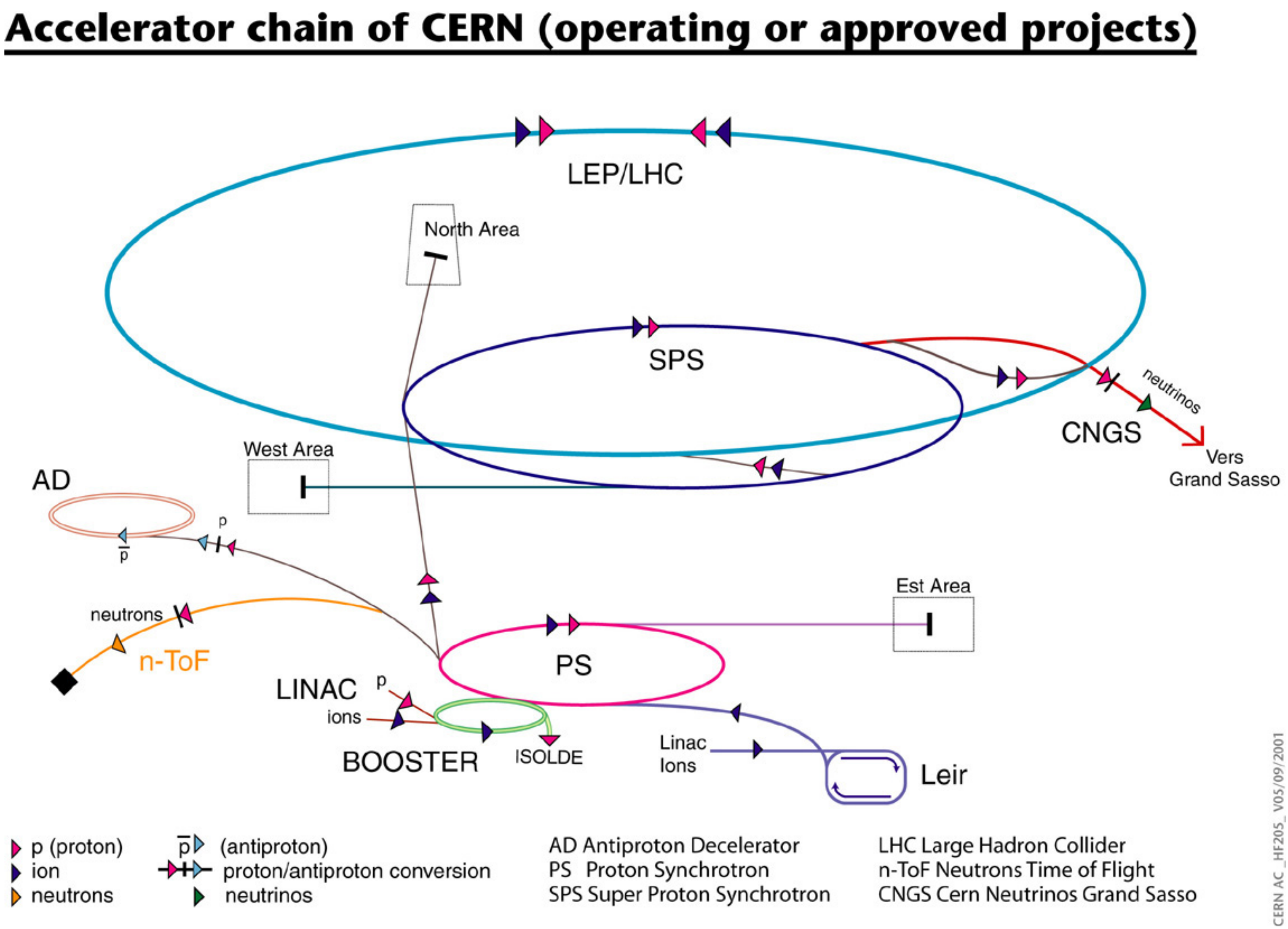
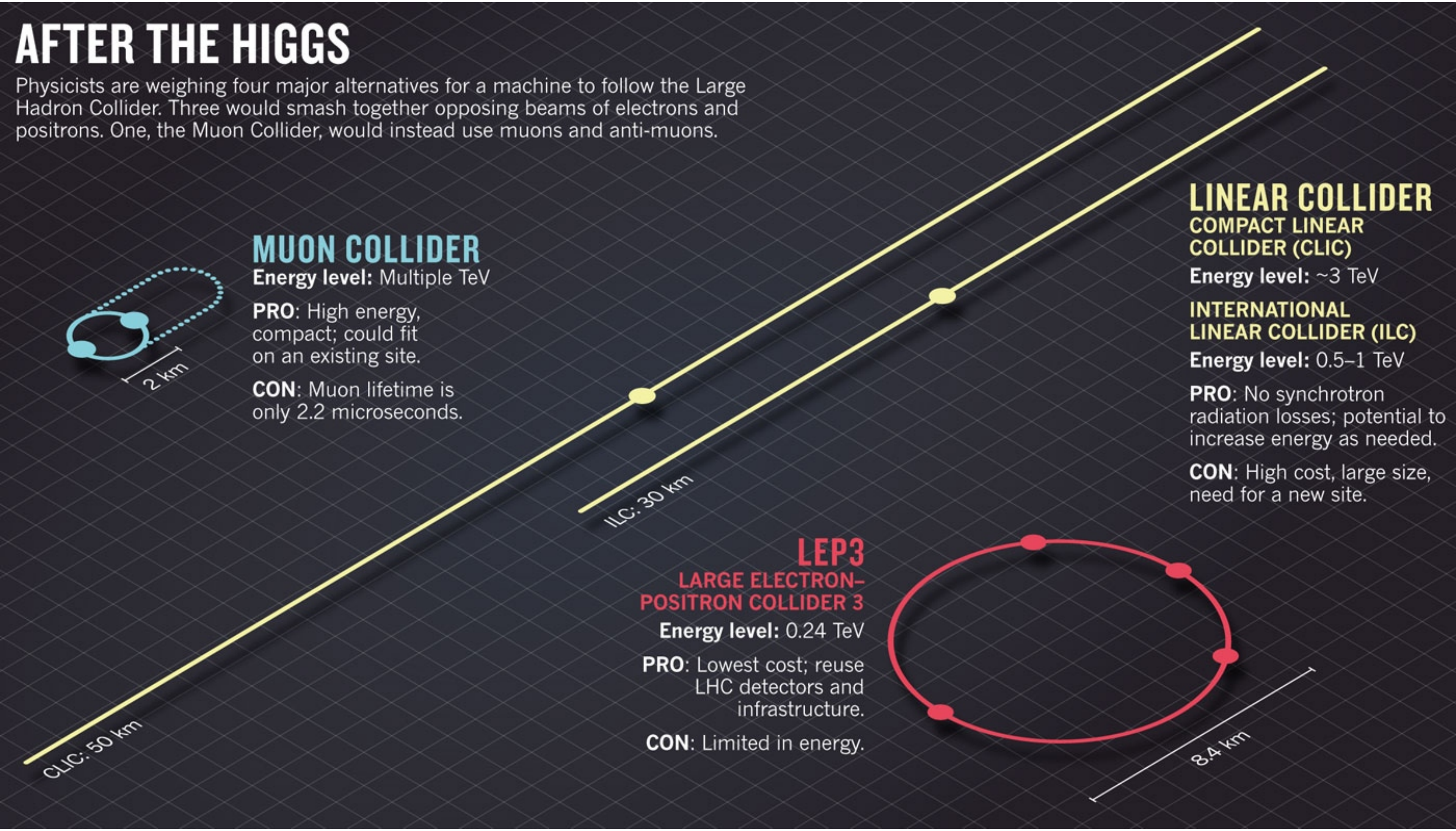
LHC Complex


Accelerator chain of CERN (operating or approved projects)
LEP/LHC
North Area
SPS
neutrinos
CNGS
Vers
Grand Sasso
West Area
AD
p
p
neutrons
n-ToF
LINAC
p
ions
BOOSTER
ISOLDE
PS
Est Area
Linac
Ions
Leir
p (proton)
ion
neutrons
p (antiproton)
proton/antiproton conversion
neutrinos
AD Antiproton Decelerator
PS Proton Synchrotron
SPS Super Proton Synchrotron
LHC Large Hadron Collider
n-ToF Neutrons Time of Flight
CNGS Cern Neutrinos Grand Sasso
CERN AC _HF205_ V05/09/2001

HEP machines beyond LHC



Collider design

- Plasma accelerator technique finds its application to e^+e^- colliders in the TeV energy range
- Two competing proposals: electron beam-based from SLAC/UCLA/USC and laser-based from LBNL
- Figure of merit
  - Luminosity

$$L = \frac{fN^2}{4\pi\sigma_x\sigma_y} = \frac{P_{beam}}{4\pi E_b}\frac{N}{\sigma_x\sigma_y}$$

$N/\sigma_x\sigma_y$ is limited by the disruption and beamstrahlung

Wall-plug effciency P_{beam}/P_{total} is one of biggest concern.

  - CoM energy

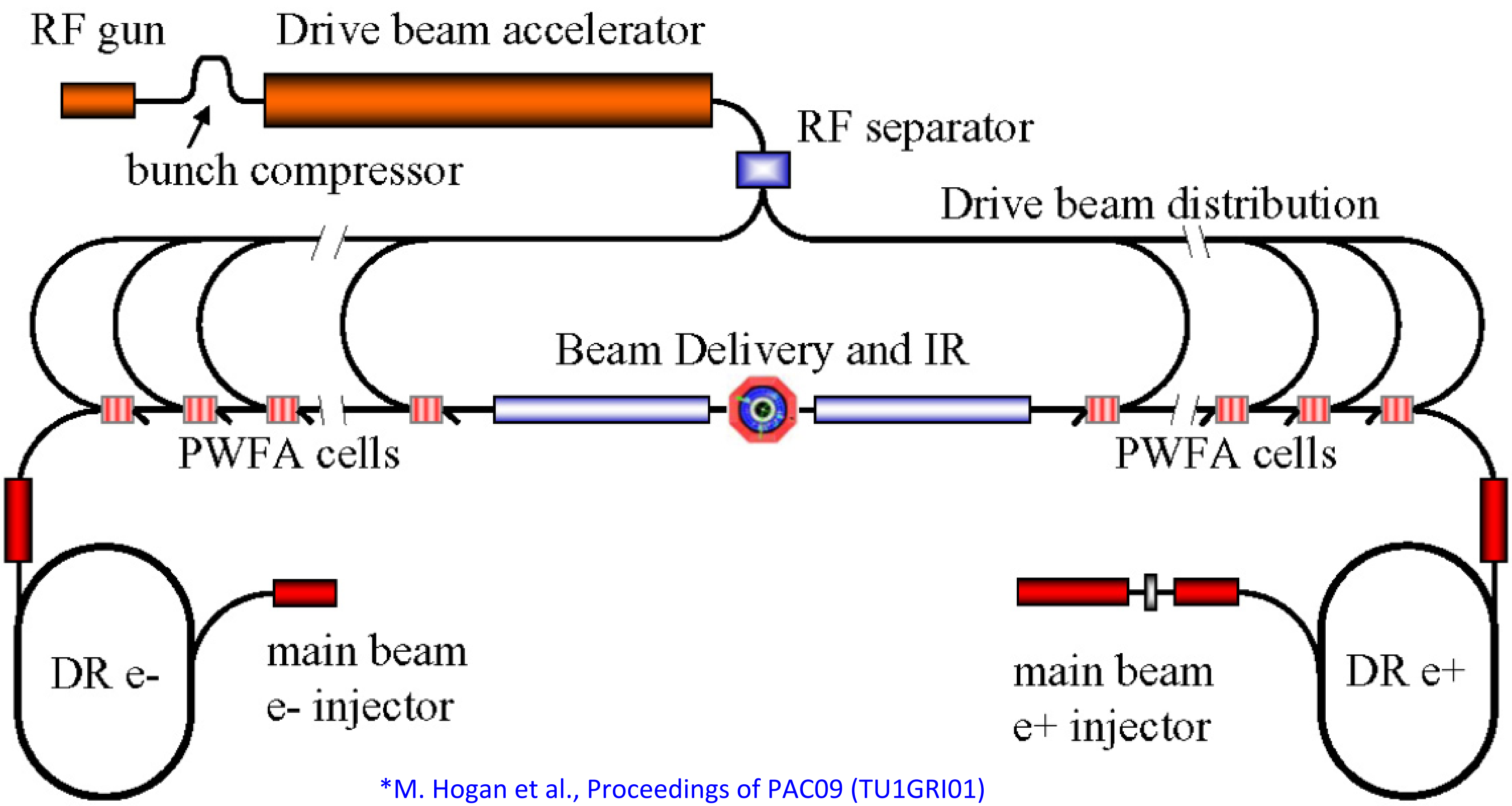
Head-on collision: $E_{com}=2E_b$ (for $e^+ e^-$ collider)

Head-on collision: $E_{com} = 2\sqrt{E_e E_p}$ (for $e^- p^+$ collider)

Collider design

- The TDR of the ILC and the CDR of CLIC have been finished, from which a conventional accelerator can bring an e^+e^- collider up to 3 TeV with luminosity of 10^{34} $cm^{-2}s^{-1}$.
- To compete with ILC or CLIC designs, a plasma-based concept needs to achieve a luminosity of ~10^{34} $cm^{-2}s^{-1}$ at ~ TeV com energy.
- A plasma-based collider is being offered to the HEP community as a cost-saving proposal (or as an after-burner).
- The proponents argue that plasma-based colliders could cost less because they could be made shorter (in overall length) and with fewer components;

PWFA-based collider



*M. Hogan et al., Proceedings of PAC09 (TU1GRI01)

*A. Seryi et al., Proceedings of PAC09 (WE6PFP081)

LWFA-based collider

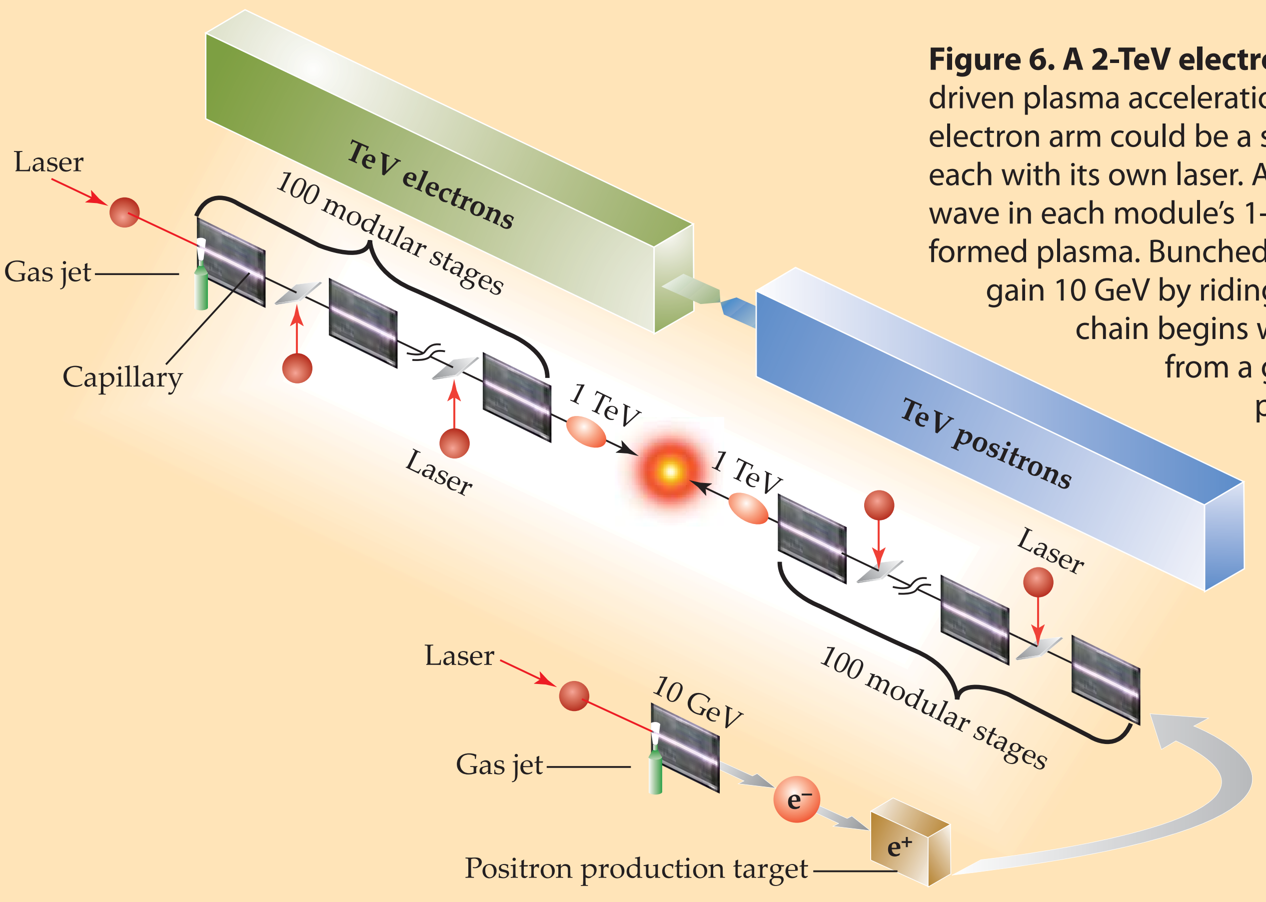
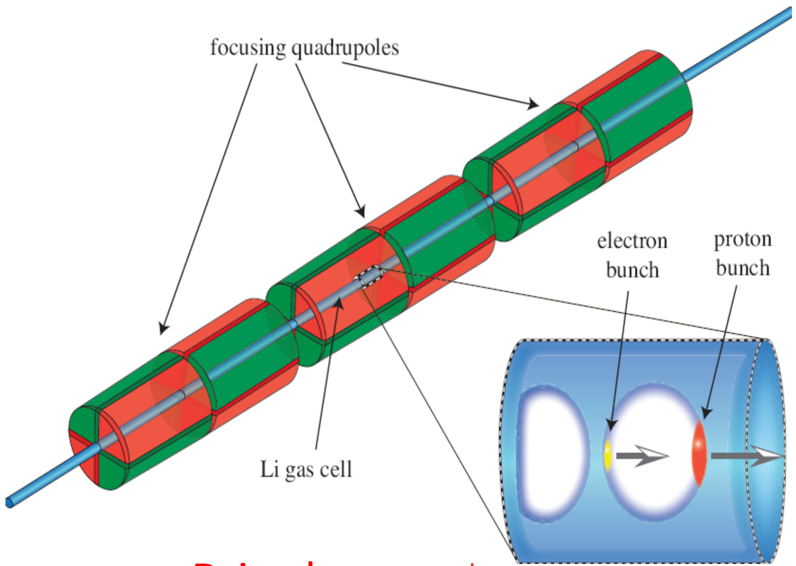
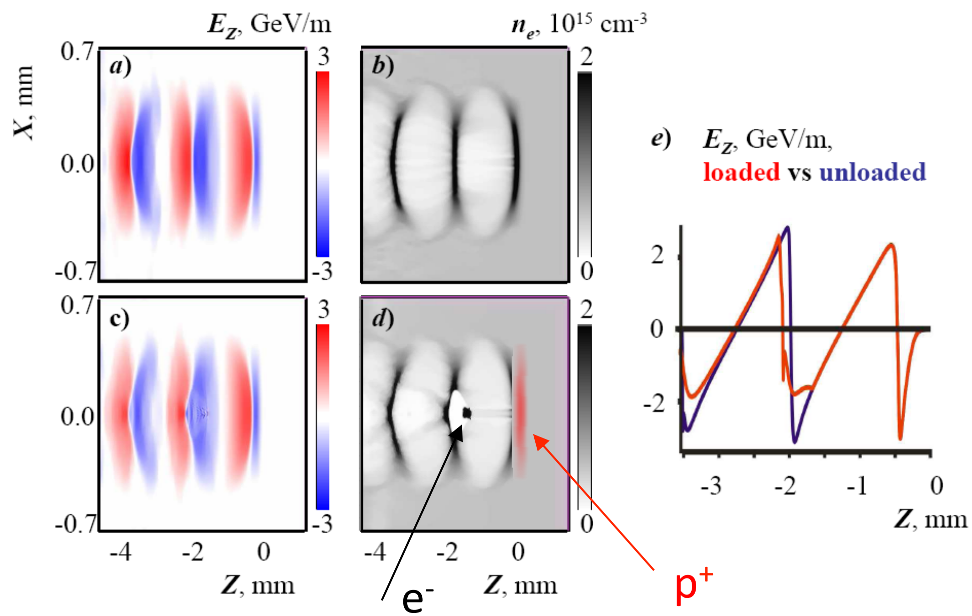


Figure 6. A 2-TeV electron–positron collider based on laser-driven plasma acceleration might be less than 1 km long. Its electron arm could be a string of 100 acceleration modules, each with its own laser. A 30-J laser pulse drives a plasma wave in each module's 1-m-long capillary channel of pre-formed plasma. Bunched electrons from the previous module gain 10 GeV by riding the wave through the channel. The chain begins with a bunch of electrons trapped from a gas jet just inside the first module's plasma channel. The collider's positron arm begins the same way, but the 10-GeV electrons emerging from its first module bombard a metal target to create positrons, which are then focused and injected into the arm's string of modules and accelerated just like the electrons.

W. Leemans and E. Esarey, Phys. Today 62 (3), 44 (2009).

Proton-driven plasma wakefield acceleration





Drive beam: p^+

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

$\sigma_r=0.43$ mm, $\sigma_\theta=0.03$ mrad,

$\sigma_z=100$ μm, $\Delta E/E=10$ %

Witness beam: e^-

$E_0=10$ GeV, $N_e=1.5\times10^{10}$

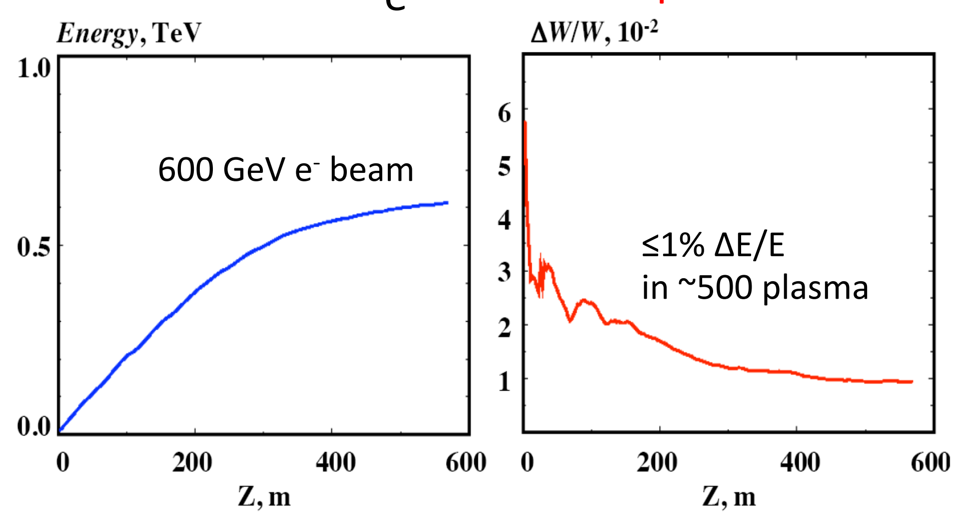
Plasma: Li^+

$n_p=6\times10^{14}$cm^{-3}

External magnetic field:

Field gradient: 1000 T/m

Magnet length: 0.7 m



A. Caldwell et al, Nature Physics 5, 363 (2009).

High energy protons as driver

- Huge energy stored in current proton machines like Tevatron, HERA, SPS and LHC, will be ideal as driver for the plasma wakefield accelerator
- Energies in today's proton synchrotrons
  - **SPS (450 GeV, 1.3e11 p/bunch) ~ 10 kJ**
  - **Tevatron/HERA (1 TeV, 1e11 p/bunch) ~ 16 kJ**
  - **LHC (1 TeV, 1.15e11 p/bunch) ~ 20 kJ**
  - **LHC (7 TeV, 1.15e11 p/bunch) ~ 140 kJ**
  - **SLAC (50 GeV, 2e10 e-/bunch) ~ 0.1 kJ**
  - **ILC (250 GeV, 2e10 e-/bunch) ~ 0.8 kJ**
- How to couple the energies of drivers to the plasmas and to the witness beams efficiently (e.g. a few percent efficiency)?
- One stage acceleration from PDPWA can bring particles to the energy frontier, therefore the collider based on this scheme eliminate the problems due to alignment and synchronization of multi-stages.

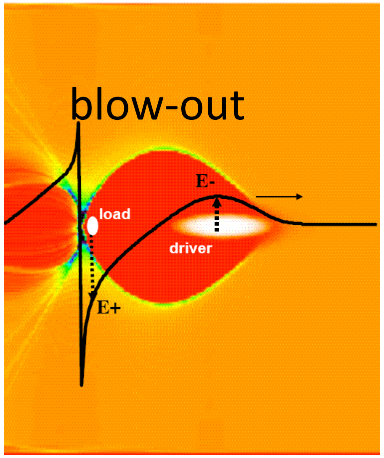
PWFA and PDPWA

Pros. of PWFA

Plasma electrons are expelled by space charge of e- beam, a nice bubble will be formed ideally for beam acceleration and focusing.

The short electron beam is relatively easy to get (bunch compression).

Wakefield phase slippage is not a problem (due to small gamma factor).



Cons. of PWFA

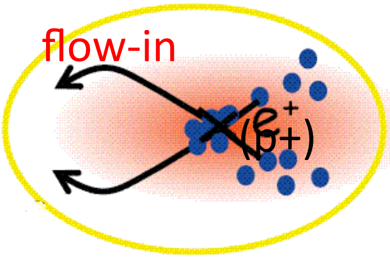
One stage energy gain is limited by transformer ratio, therefore maximum electron energy is about 50 GeV using SLAC beam.

subject to the head erosion, not a very long plasma.

Pros. of PDPWA

Very high energy proton beam are available today, the energy stored at SPS, Tevatron, HERA, LHC

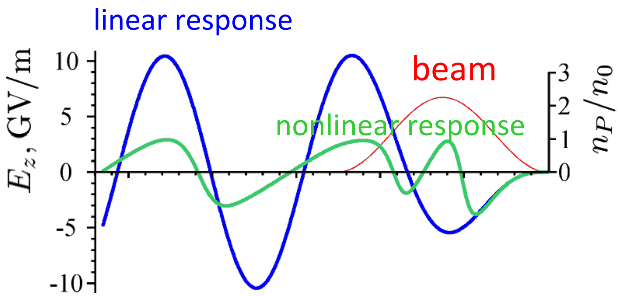
One stage acceleration make the HEP collider design easier.



Cons. of PDPWA

Flow-in regime responds a relatively low field *vs*. blow-out regime.

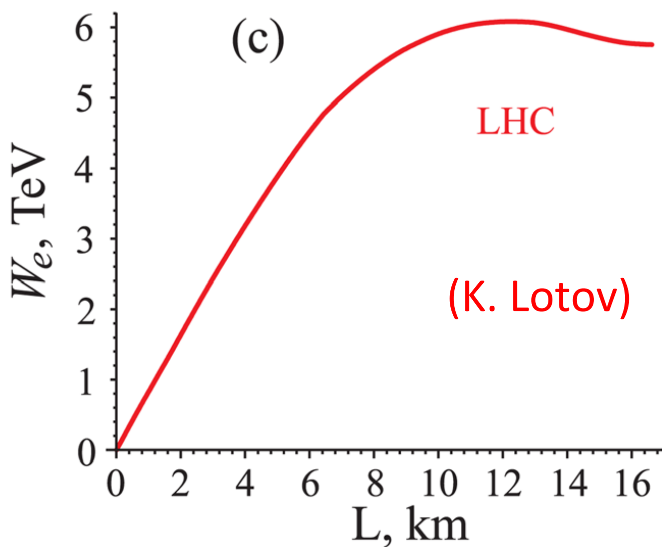
Long proton bunches (~ tens centimeters), bunch compression is Difficult. Wave phase slippage for heavy mass proton beam (small γ factor), especially for a very long plasma channel.

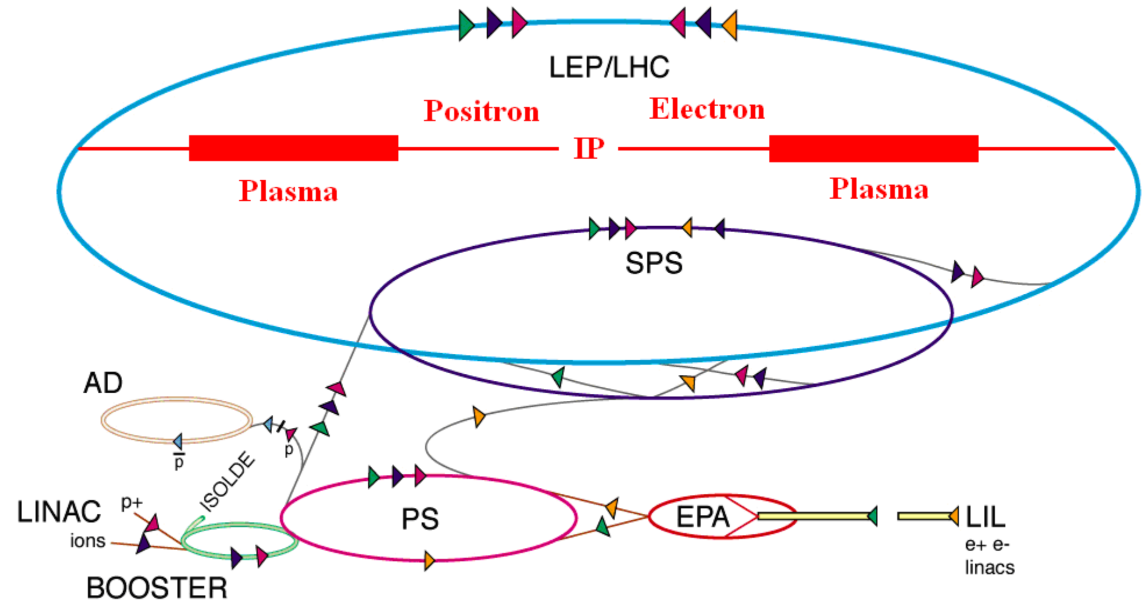


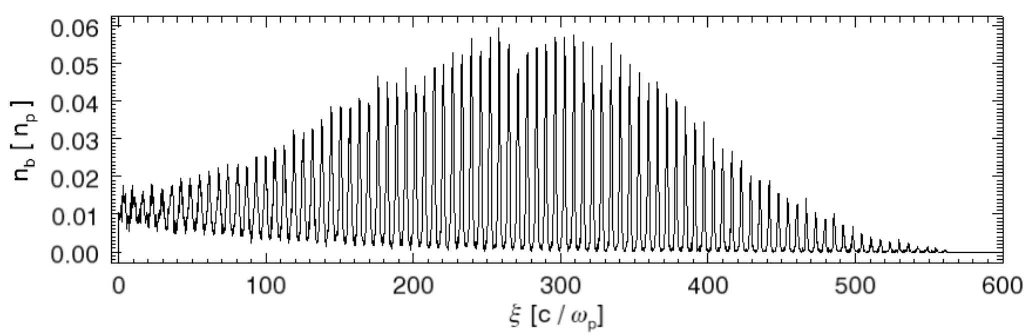
Collider design based on PDPWA

- Based on recently published European Strategy on Particle Physics, linear collider is still placed at a high priority place. And the LHeC is not in the list at all. Therefore, a collider design (e.g. electron-proton collider) based on CERN existing infrastructure looks promising!
- Either an e^-/e^+ collider or an e^-/p^+ collider could be designed based on existing CERN infrastructure;
- The key issues in collider design (e.g. efficiency, CoM energy, luminosity, dephasing, efficiency, positron acceleration, etc.).

Multi-TeV lepton collider at LHC







Luminosity

$$L = f\frac{N_1 N_2}{4\pi\sigma_x\sigma_y}$$ Gaussian shaped beams

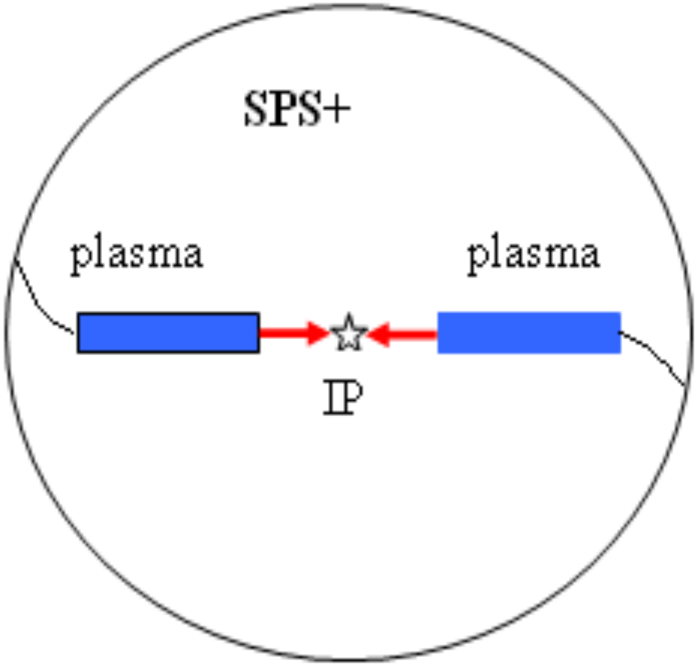
suppose $N_1 = N_2 = 10^{11}$

SPS cycle time $22s$ 288 bunches

so assume $f = 15$ Hz

$$L \approx \left(\frac{1\ \mu\mathrm{m}^2}{\sigma_x\sigma_y}\right) 10^{30}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$$

IP beam sizes: 60 nm (horizontal) and 0.7 nm (vertical)



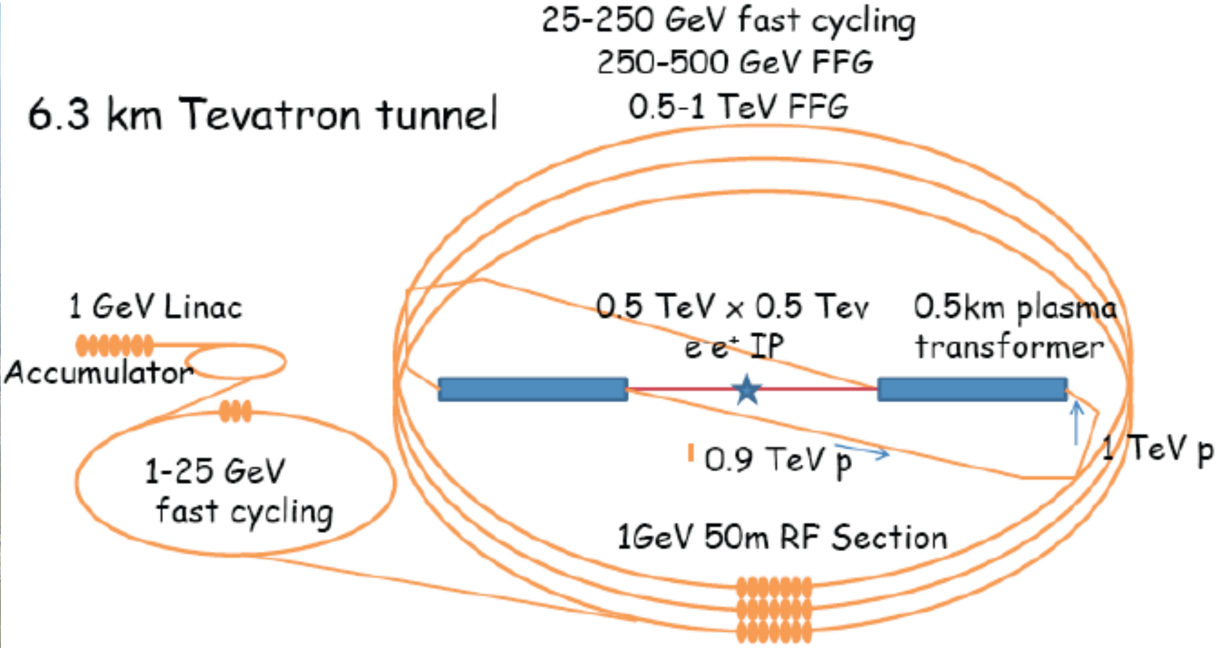
$L = 5\times10^{32}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$

Note that the luminosity of SLC and LEP was $6\times10^{30}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$ and $1\times10^{32}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$, respectively.

Luminosity

- We should keep in mind that the LHC injector ramping time is about 20 s, and the LHC ramping time is about 20 minutes, therefore if we use LHC as drive beam for plasma-based collider design, the repetition rate is too low to get a high luminosity (repetition rate: 2880/1200 ~ 2).
- To increase the repetition rate, we may consider to do recycle or do energy recovery for the spend proton beam as Yakimenko and Katsouleas suggested at LPAW09 meeting.
- Or we may seek to get a fast ramping machine.

High repetition rate collider



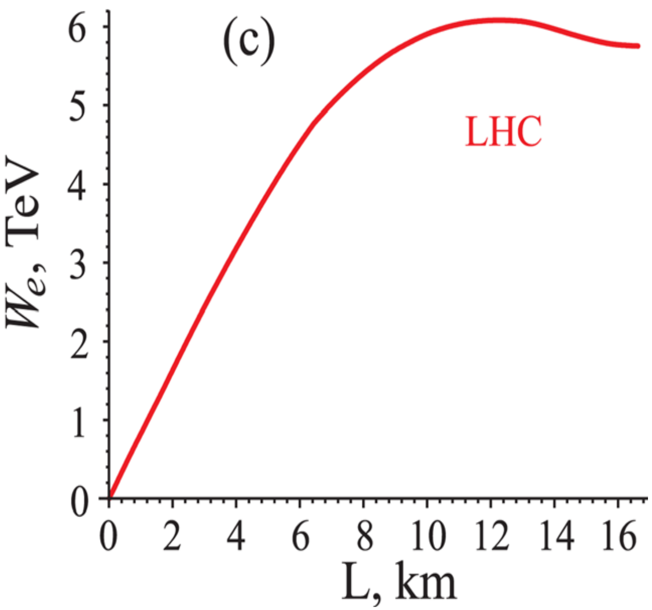
Concept for high repetition rate of proton driven plasma wakefield acceleration

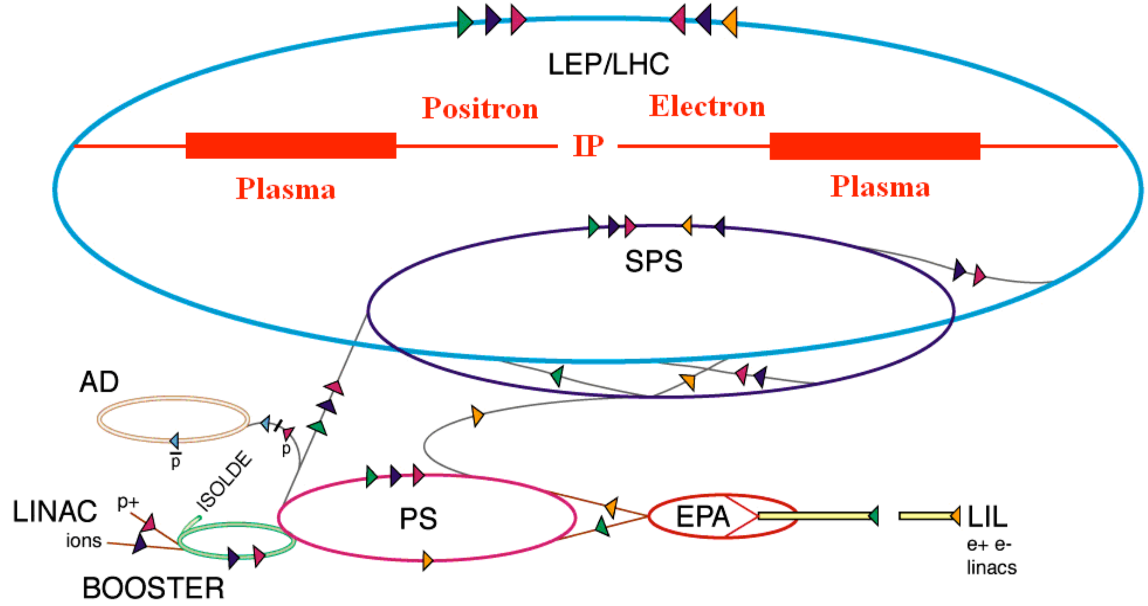
3 ring + injectors + recovery

V. Yakimenko, BNL, T. Katsouleas, Duke, LAPW09

Centre-of-mass energy

E_{com}= 2 TeV $e^+ e^-$ collider !





2 km plasma cell (take into account the LHC radius of 4.3 km and the focusing the beam before the plasma and the beam deliveries and IPs may also need some space), we may achieve the 1 TeV electron and positron beams from the LHC beams. Figure above shows a schematic layout of a 2 TeV centre-of-mass energy e^+-e^- collider located at the LHC accelerator complex (the plasma accelerators is marked in red).

Phase slippage

- When electron gains energy from the wakefield, it can reach the relativistic energy regime very quickly.
- Gamma factor for a 1 TeV proton is smaller than that of 1 GeV electron, therefore when the proton drive beam loses its energy, its velocity may be smaller than the velocity of electron.
- For the collider design based on proton-driven plasma wakefield acceleration, the phase slippage may become significant for a very long acceleration channel.
- The relative path difference due to the velocity difference is given by

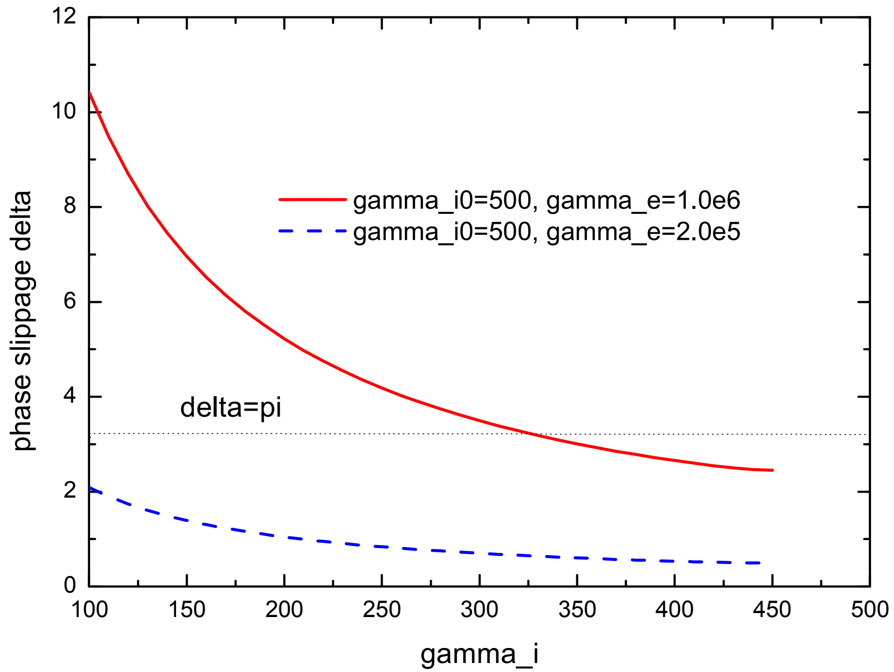
$$\Delta L = \frac{1}{c}\int_0^L | v_i(s) - v_e(s) | \, ds$$

- The phase slippage can be written as

$$\delta = k_p \frac{\Delta L}{L} \approx \frac{1}{eE_{acc} / m_e c\omega_p}\left(\gamma_e - \gamma_{e0}\right)\left[1 - \frac{\left(\gamma_i - \gamma_{i0}\right)}{\left(\sqrt{\gamma_i^2 - 1} - \sqrt{\gamma_{i0}^2 - 1}\right)}\right]$$

here $k_p = \omega_p / c$ $\qquad \omega_p = \left(n_p e^2 / \varepsilon_0 m_e\right)^{1/2}$

Phase slippage



Phase slippage for an SPS proton beam as a function of gamma_i, the final of the proton drive beam for a single stage 500 GeV and 100 GeV electron beam production, respectively

$$\delta = \frac{\pi L}{\lambda_p}\left[\frac{1}{\gamma_{1i}\gamma_{1f}} - \frac{1}{\gamma_{2i}\gamma_{2f}}\right] \approx \frac{\pi L}{\lambda_p}\left[\frac{M_P^2 c^4}{E_{driver,i}E_{driver,f}}\right]$$

For 1 TeV LHC like beam,

$$L \leq \frac{1}{2}\left[\frac{E_{driver,i}E_{driver,f}}{M_P^2 c^4}\right]\lambda_p \approx 300 \text{ m for } E_{driver,i} = 1TeV, E_{driver,f} = 0.5TeV, \lambda = 1mm$$

Few hundred meters possible but depends on plasma wavelength

Positron acceleration

- The HEP community is asking for an electron-positron collider, or gamma-gamma collider, NOT an electron-electron collider. Therefore, it is important for a plasma-based concept to work equally well for both electrons and positrons.
- In principle, positrons can be accelerated in the wakefield driven by the modulated proton bunch as well, the only difference is the accelerating phase is about 180° reverse.
- The previous simulation results from our collaborators demonstrated it;
- The full simulation for positron acceleration based on AWAKE parameters are underway.

Electron-hadron collider

- Lepton-hadron collisions have been playing an important role in exploration of deep insides of matter. For example, the quark-parton model originated from investigation of electron-nucleon scattering.
- To build a collider based on a moduated proton driven plasma wakefield acceleration, we could also think about an electron-hadron collider based at the CERN accelerator complex.
- The advantage of this design is based on the fact that the plasma-based option may be more compact and cheaper since it does not need to build a new electron accelerator.

Electron-hadron collider

- The SPS drive beam needs to be guided to the plasma cell.
- A 170 m long plasma cell is used to accelerate the electron beam energy to 100 GeV.
- The electrons are then extracted to collide with the circulating 7 TeV proton beam.
- The centre-of-mass energy in this case is about 1.67 TeV
- Initial estimate shows that the luminosity is about 10^{30} cm^{-2} s^{-1}.

G. Xia et al., IPAC12

Physics at high energies but low luminosity

European Strategy for Particle Physics

10-12 September 2012
Krakow, Poland

Particle Physics at High Energies but Low Luminosities

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1 Introduction

The main focus of the particle physics community, when considering future accelerators, has been on high luminosity colliders since s-channel cross sections scale as $1/s$, with s the square of the center-of-mass energy. This focus has led to ILC, CLIC or Muon Collider parameter sets requiring luminosities in excess of 10^{34} cm^{-2} s^{-1} for center-of-mass energies beyond 1 TeV. This requirement on the luminosity then leads to very demanding requirements on parameters such as beam sizes at the interaction point, repetition rate, etc., and huge power requirements. The former will be difficult to achieve technologically, while the latter will be very hard to justify in an age of diminishing energy resources and increasing energy costs.

Classicalization in electroweak processes; QCD and beyond Standard Model physics; Lorentz invariance and streaking the vacuum; Study of source of high energy cosmic rays; Many others…

Thanks for your attention !