Plasma Acceleration

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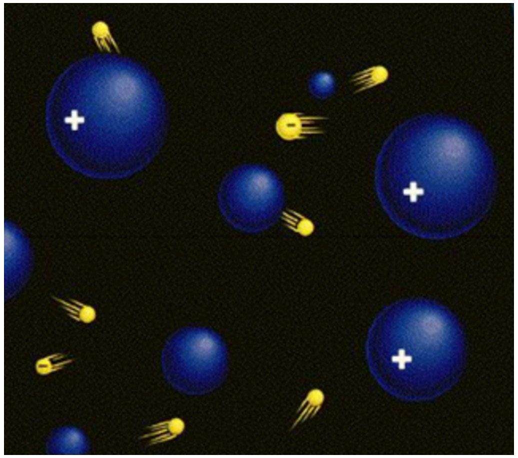
1. How it works, who does it & challenges
2. Ongoing efforts & results
3. (High Energy) Particle physics perspectives

Note: I will only report on projects aiming for HEP applications (limited time and knowledge)

ECFA Meeting, November 15, 2018

Introduction

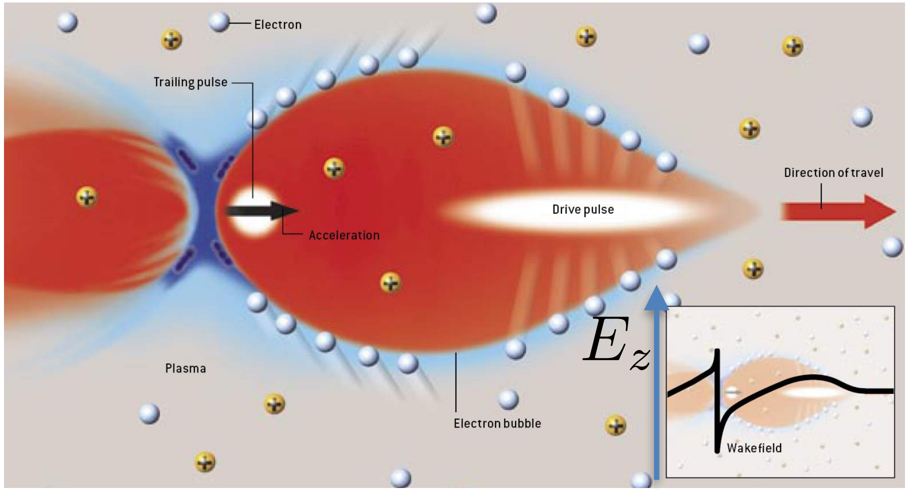


E. Adli, Oslo

A plasma: collection of free positive and negative charges (ions and electrons). Material is already broken down. A plasma can therefore **sustain very high fields.**

An intense **particle beam**, or intense **laser beam**, can be used to drive the plasma electrons into oscillation.

$$\omega_p^2 = \frac{4\pi n_p e^2}{m}$$



C. Joshi, UCLA

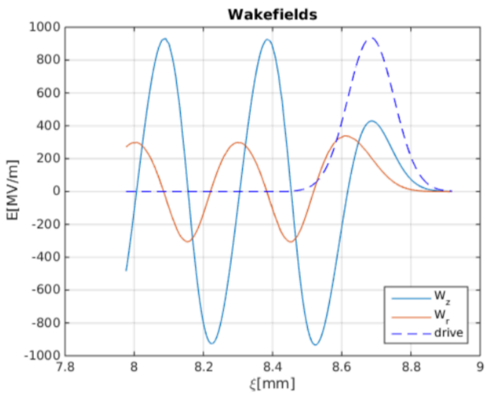
For a relativistic driver: $\lambda_p = \frac{2\pi}{k_p} = 1mm\sqrt{\frac{1 \cdot 10^{15}\ \mathrm{cm}^{-3}}{n_p}}$

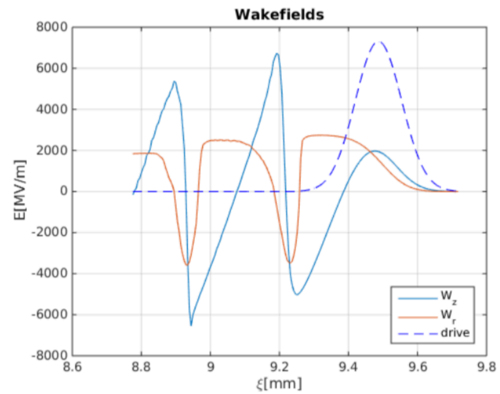
Ideas of **~100 GV/m** electric fields in plasma, using 10^{18} W/cm^2 lasers: 1979 **T.Tajima and J.M.Dawson** (UCLA), Laser Electron Accelerator, Phys. Rev. Lett. 43, 267–270 (1979).
Using partice beams as drivers: **P. Chen et al**. Phys. Rev. Lett. 54, 693–696 (1985)

Introduction

Regimes:

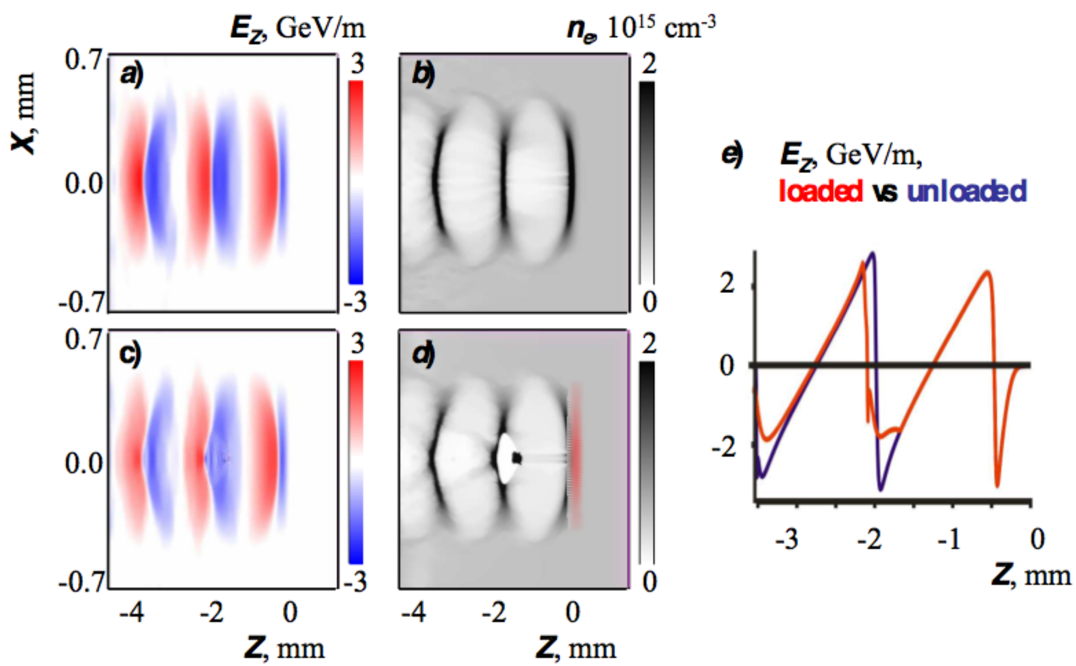
$$\text{linear} : n_b \ll n_p \qquad \text{nonlinear} : n_b \geq n_p$$



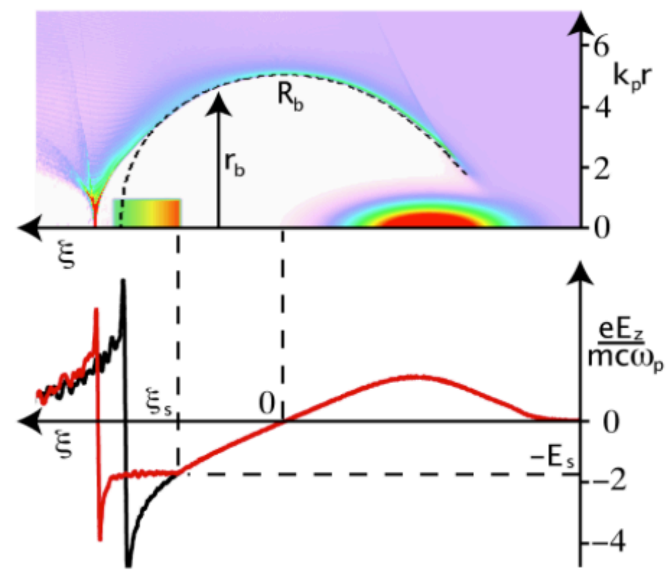


Y. Israeli, MPP

Strong field variation leads to energy spread. 'beam loading' to flatten fields



A. Caldwell, K. Lotov, A. Pukhov, F. Simon, Nature Physics 5, 363 (2009).

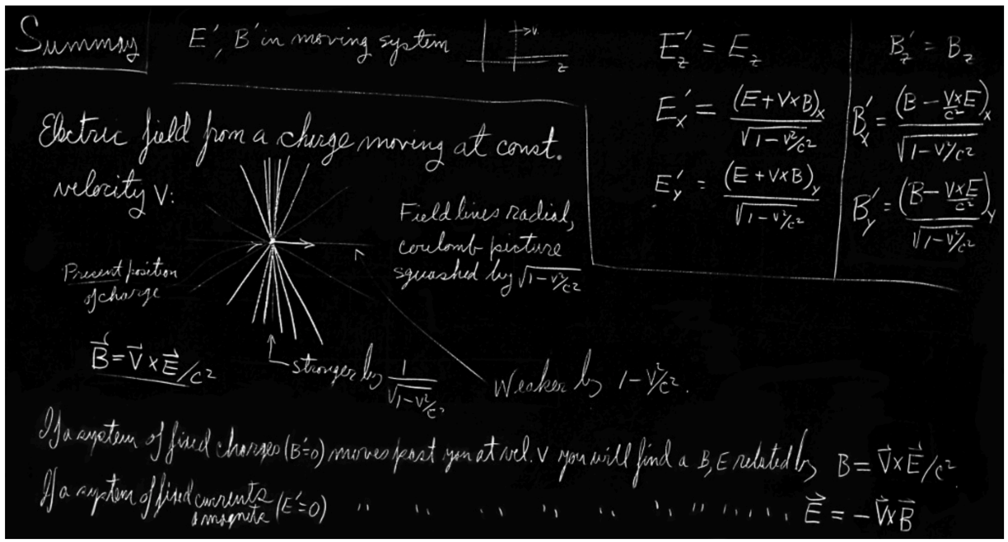


M. Tzoufras et al., Phys. Rev. Lett., **101**, 145002 (2008)

Introduction

Driver must be relativistic & short compared to plasma wavelength:

Feynman Lectures, CalTech



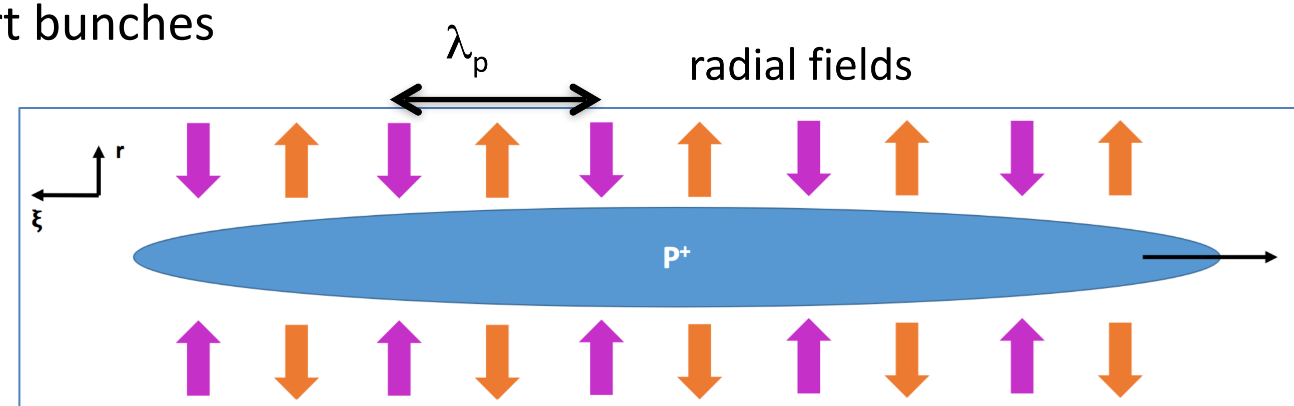
$$E_{z,\max} \approx 2\ \mathrm{GeV/m} \cdot \left(\frac{N_b}{10^{10}}\right) \cdot \left(\frac{100\ \mu\mathrm{m}}{\sigma_z}\right)^2$$

Natural for lasers. Relatively easy for electron bunches. Proton bunches ?

Introduction

Answer: Plasma creates short bunches

The radial fields of the wake modulate the beam density, creating microbunches spaced at the plasma wavelength.

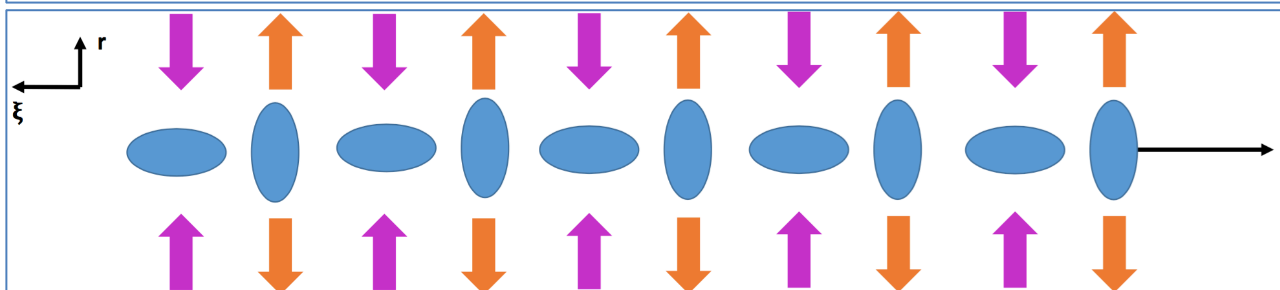


$$W_\perp(r,\xi) = -4\pi\rho_0 \int_0^\xi r_b(\xi')I_1\{k_p r(\xi')\}K_1\{k_p r_b(\xi')\}f(\xi')$$
$$k_p \sin k_p(\xi-\xi')d\xi',$$

Transverse force along the bunch

Focusing oscillates along bunch

The microbunches leads to resonant build-up of strong wake fields (of order GV/m).



Transverse beam size

$$\frac{\partial^2 r_b}{\partial\tau^2} - \frac{\mathcal{M}^2}{r_b^3} = -\frac{\omega_b^2}{\gamma_0}\int_0^\xi r_b(\xi')I_1\{k_p r_b(\xi')\}K_1\{k_p r_b(\xi')\}$$
$$f(\xi')\,k_p \sin k_p(\xi-\xi')d\xi',$$

Radial beam evolution

Transverse force felt by bunch

Graphics: TBD

Kumar et al., Phys. Rev. Lett. **104**, 255003 (2010)

Introduction

How strong can the fields be?

Scale set by the wave breaking field $E_{\mathrm{WB}} = \frac{mc\omega_p}{e}$

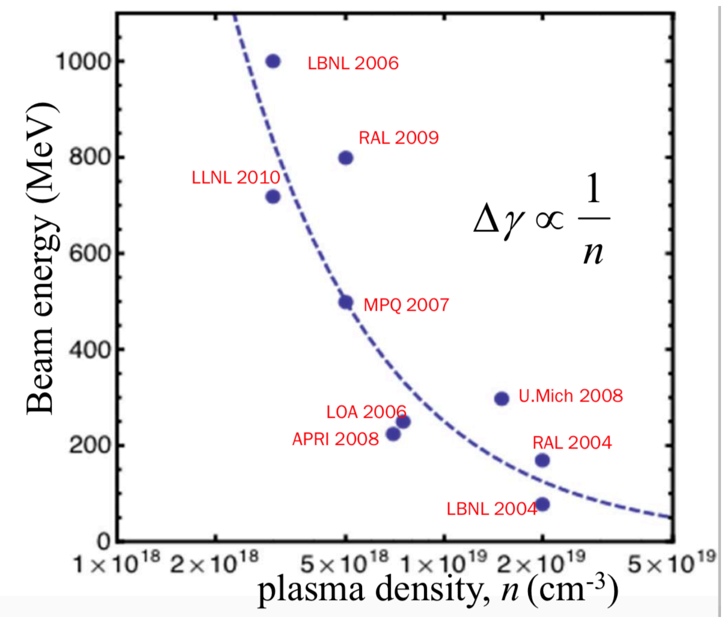
Recall: $\omega_p^2 = \frac{4\pi n_p e^2}{m}$ $\quad$ e.g. $n_p = 10^{16}\ \mathrm{cm}^{-3} \implies E_{\mathrm{WB}} = 10\ \mathrm{GeV}/m$

Want to maximize density for strongest gradients, but other issues:

laser energy depletion $\propto n_p^{-3/2}$

dephasing

$v = c/n$ index of refraction



Schroeder et al., Phys. Rev. ST. **13** 101301 (2010)

Energy gain/stage $\propto n_p^{-1}$

Target for BELLA is 10 GeV/stage

Introduction

Energy Budget:

Witness:

10^{10} particles @ 1 TeV ≈ few kJ

Drivers:

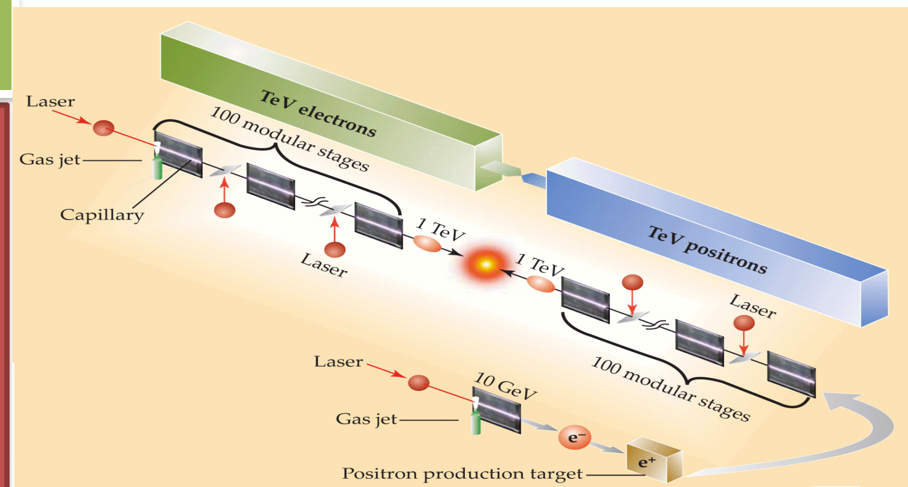
PW lasers today, ~40 J/Pulse

FACET (e beam, SLAC), 30J/bunch

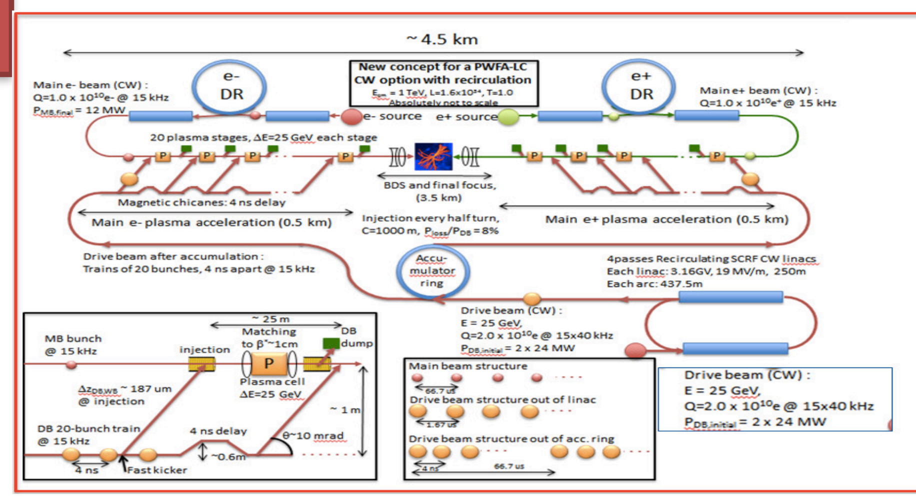
SPS@CERN 20kJ/bunch

LHC@CERN 300 kJ/bunch

Staging Concepts



Leemans & Esarey, Phys. Today ***62 #3*** *(2009)*



E. Adli et al. arXiv:1308.1145,2013

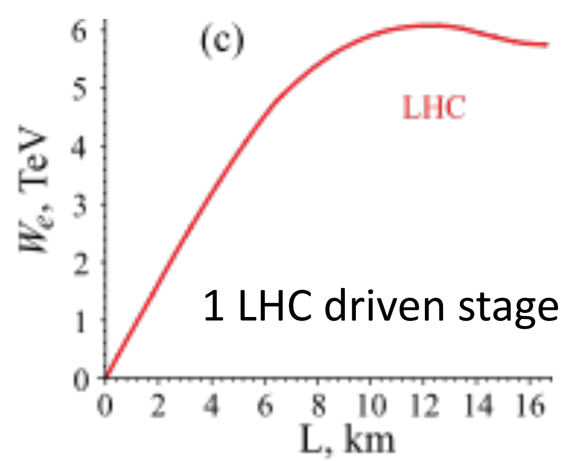
Dephasing

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

SPS: ~100m,

LHC: ~few km

FCC: ~ ∞



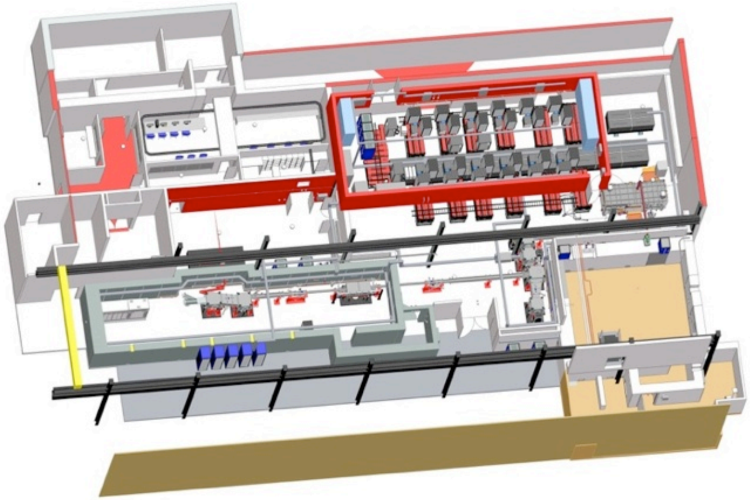
1 LHC driven stage

A. Caldwell and K. V. Lotov, Phys. Plasmas **18,** 103101 (2011)

Plasma-based R&D started in the US

Many Laser WakeField Acceleration (**LWFA**) efforts ongoing

Here BELLA (Berkeley)



PARAMETER	VALUE	NOTES
Wavelength	815 ± 10 nm	Typical Ti:sapphire wavelength
Spectral bandwidth	> 40 nm FWHM	Supports final compression to < 40 fs
Energy	> 40 J	On target
Pulse duration	< 40 fs FWHM	Controllable between 30-500 fs for wide temporal parameter studies
Repetition rate	1 Hz	Allows to scan multiple parameter space
Peak power	> 1.2 PW	@ 1 Hz, with shot on demand, too
Contrast at 1 ns and at 5 ps	> 10^9 , > 10^6	Critical for solid target experiments
Pointing stability	< 1.5 μrad rms	Interactions in capillary are sensitive to pointing
Strehl ratio in focus	~0.9	w/deformable mirror, f = 13.5 m
Pulse duration fluctuation	< 5% rms	Determines peak intensity fluctuation
Pulse energy fluctuation	< 1% rms	Determines peak intensity fluctuation
Peak fluence fluctuation	< 6% rms	@ max fluence of 0.69 MJ/cm^2
Peak power fluctuation	< 5% rms	@ max power of 1.2 PW
Peak intensity fluctuation	< 8% rms	@ max intensity of 1.5x10^{19} W/cm^2

Few beam-driven WakeField Acceleration (**PWFA**) efforts (need beam)

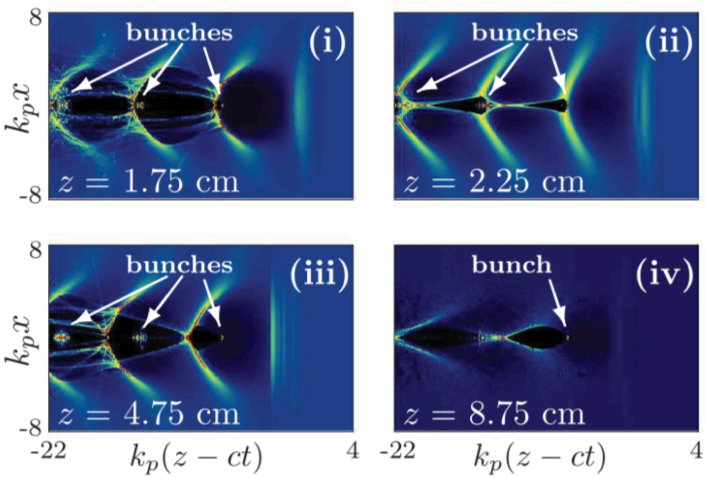
10 GeV e^- & e^+ beams, 2nC/1nC @ 30/5Hz, ~μm emittance, Ipk > 10kA

16 large projects
in Europe for Advanced Accelerator R&D

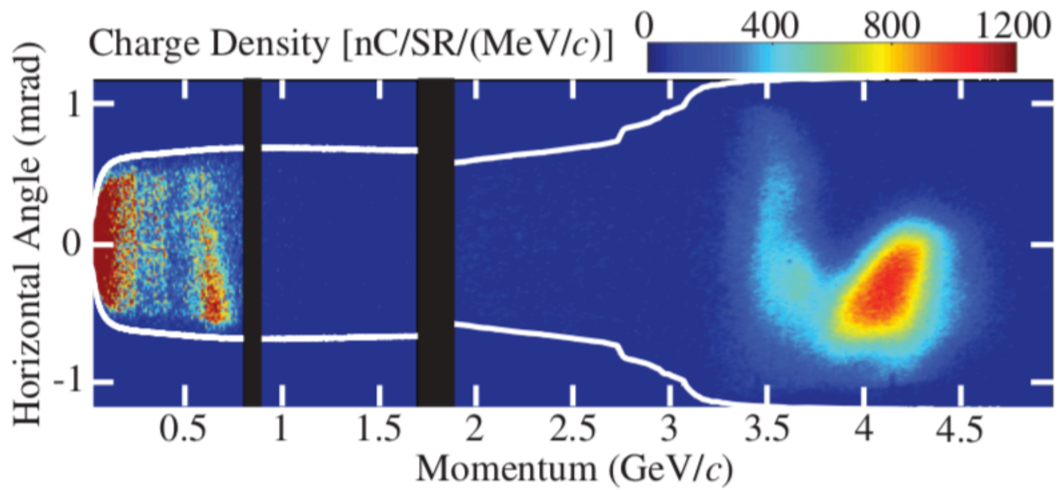
Activities of advanced accelerators in Asia

Jianfei Hua, AAC 2018

LWFA State-of-the-Art



PIC simulation of electron acceleration: 16J BELLA laser focused at the entrance of a 9 cm channel. Plasma density $n_p = 7 \cdot 10^{17} \mathrm{cm}^{-3}$



W. P. Leemans et al., PRL **113,** 245002 (2014)

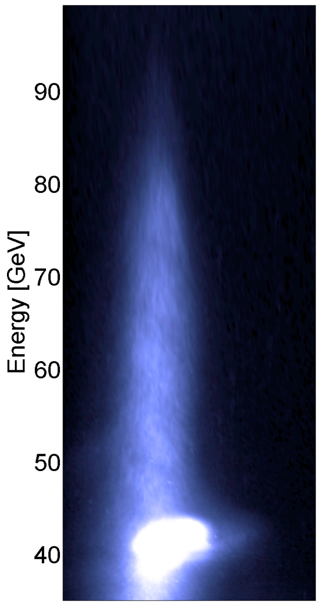
	Exp.	Sim.
Energy	4.25 GeV	4.5 GeV
ΔE/E	5%	3.2%
Charge	~20 pC	23 pC
Divergence	0.3 mrad	0.6 mrad

First results on external electron bunch injection, two-stage acceleration (S. Steinke et al., Nature **530**, 190 (2016))

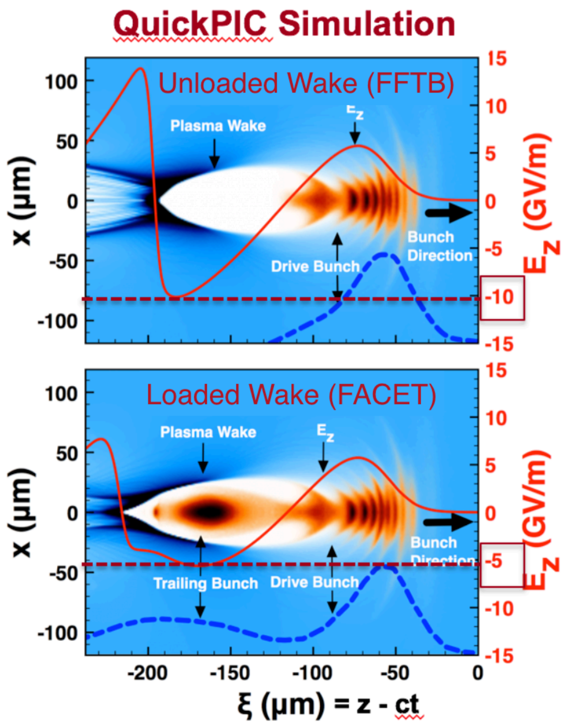
See also X. Wang et al., Nat. Comm. 2013, H.T.Kim et al., Sc. Reports 2017, C. Clayton et al., PRL 2010,

PWFA State-of-the-Art

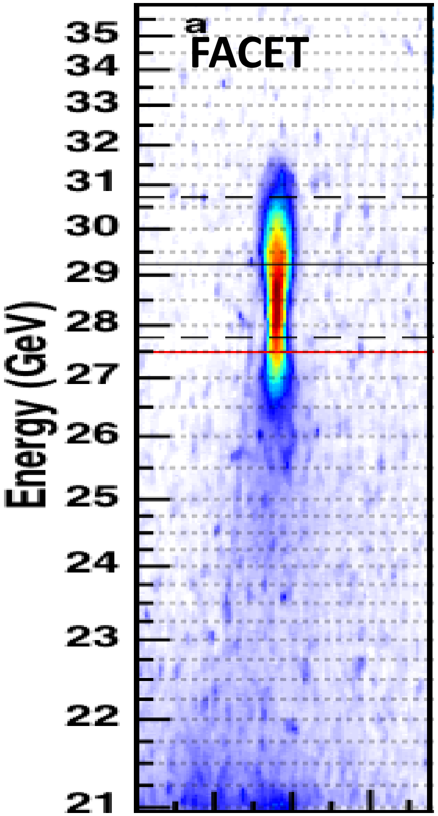
43 GeV energy gain
FFTB



SLAC



9 GeV energy gain,
efficiency 20%

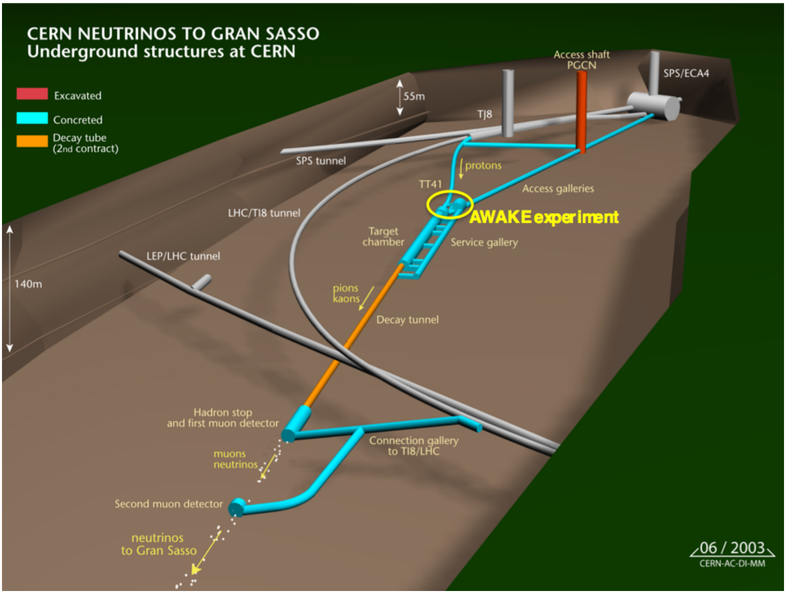


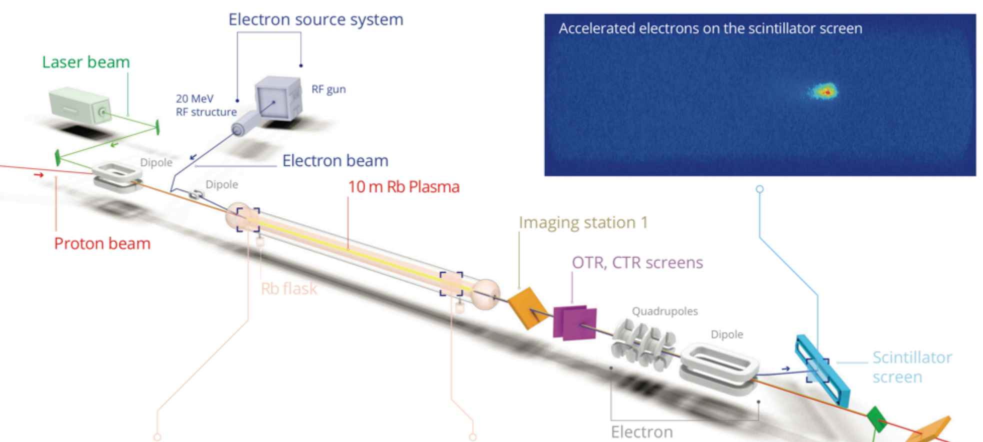
Blumenfeld et al., Nature **445**, 741 (2007), Muggli et al., New Jour. of Phys **12** , 045022 (2010) , Litos et al., Nature **515,** 92 (2014)

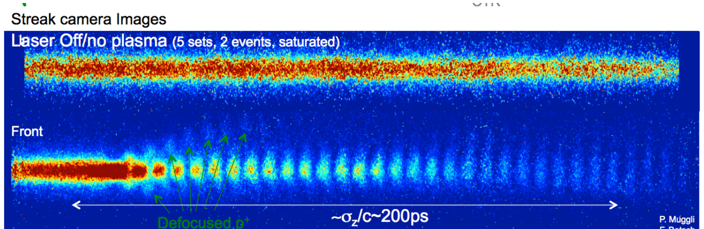
Narrow energy spread acceleration with high-efficiency has been demonstrated. Next decade will focus on simultaneously preserving beam emittance and addressing acceleration of positrons. (Courtesy: M. Hogan, SLAC)

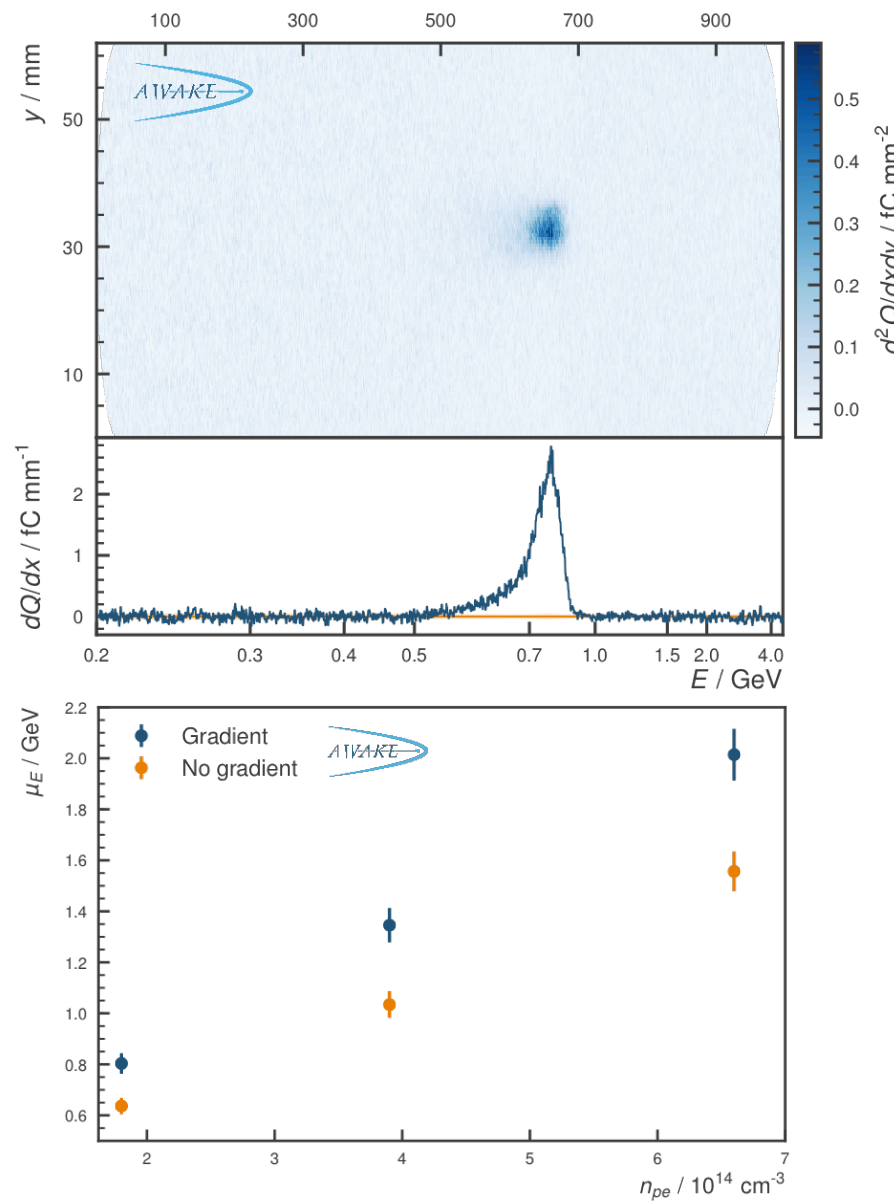
AWAKE

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









Seeded self-modulation robust !

Beyond Energy Gain

Emittance: to achieve required luminosity (see later), need high enough phase-space density of accelerated particles.

Currently - energy spread $\Delta E/E \sim \text{few } \%$ (LWFA and PWFA)

transverse emittance $(\Delta\theta \cdot \Delta r) \sim 100 \text{ mrad} - \text{mm}$ (PWFA, C. Joshi, AAC)

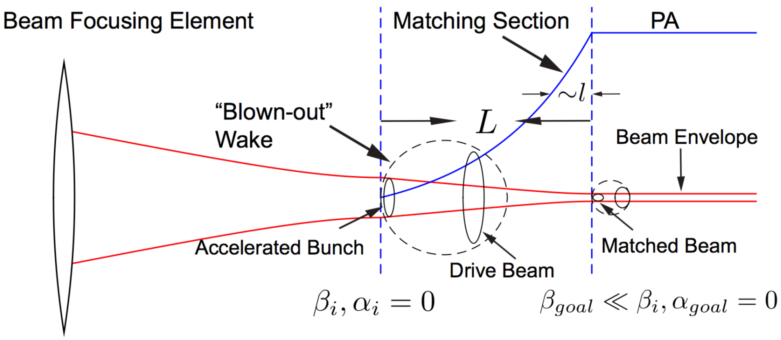
Understanding and mitigating the sources of emittance growth a focus of the community (LWFA, PWFA)

- inject electron bunch with low emittance
  - external or internal ?
- maintain emittance during acceleration
  - impact of hosing ?
  - impact of ion motion ?
  - impact of transverse tolerances ?
- if stages - maintain emittance while transitioning
  - impact of energy spread
  - alignment
  - matching

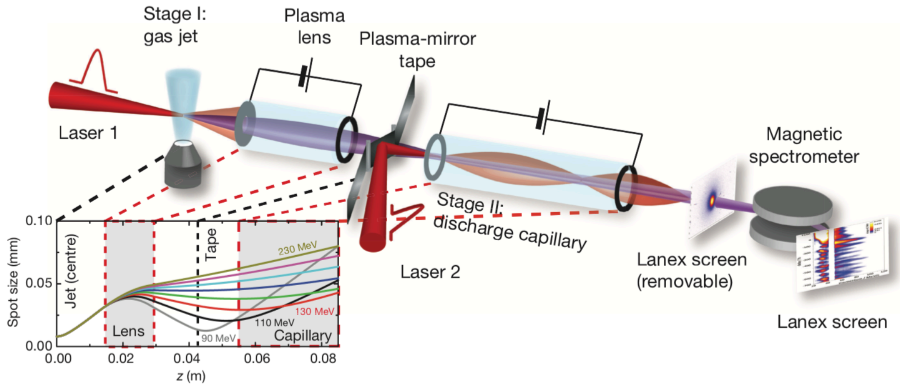
Beyond Energy Gain

Efficiency: The driver wall-plug efficiency needs to be high, as well as the efficiency of energy transfer in the plasma.

Electron injection/Staging (e, laser driven): Progress & new ideas

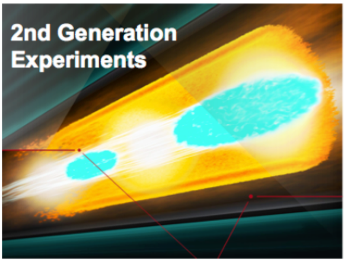


W. Lu et al., Phys. Rev. Lett. 96, 165002 (2006); W. Lu et al., Phys. Rev. ST Accel. Beams 10, 061301 (2007).



S. Steinke, Nature 530, 190 (2016)

Positron acceleration: Difficult - focusing forces different for positrons



Positron propagation, wake excitation, acceleration in a 30 cm hollow plasma channel

S. Gessner et al., Nature Com 2016

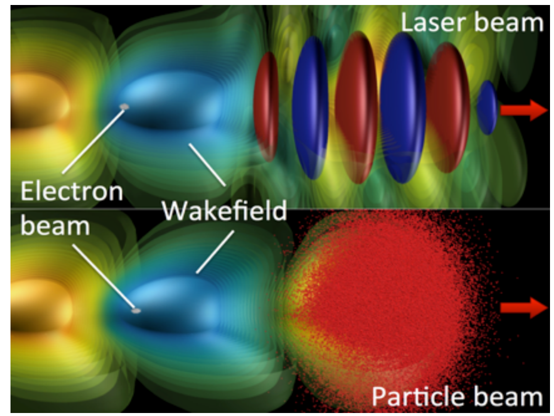
Good prospects
Creative physicists at work !

Beyond Energy Gain

Simulations: complicated feedback between driver/plasma/witness
Need multi-scale simulations: very time intensive.

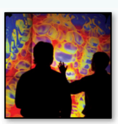
Simulations can currently take days for 1 stage (sometimes in RZ).

Need for ×10s-1000s stages ×10s ensemble ×100s 3D!
(J.-L. Vay, LBNL, Head of WARP-X project)



Capable Exascale System Applications Will Deliver Broad Coverage of 6 Strategic Pillars

National security
- Stockpile stewardship



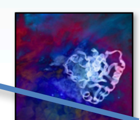
Energy security
- Turbine wind plant efficiency
- Design and commercialization of SMRs
- Nuclear fission and fusion reactor materials design
- Subsurface use for carbon capture, petro extraction, waste disposal
- High-efficiency, low-emission combustion engine and gas turbine design
- Carbon capture and sequestration scaleup
- Biofuel catalyst design

Economic security
- Additive manufacturing of qualifiable metal parts
- Urban planning
- Reliable and efficient planning of the power grid
- Seismic hazard risk assessment

Scientific discovery
- Cosmological probe of the standard model of particle physics
- Validate fundamental laws of nature
- Plasma wakefield accelerator design
- Light source-enabled analysis of protein and molecular structure and design
- Find, predict, and control materials and properties
- Predict and control stable ITER operational performance
- Demystify origin of chemical elements

Earth system
- Accurate regional impact assessments in Earth system models
- Stress-resistant crop analysis and catalytic conversion of biomass-derived alcohols
- Metagenomics for analysis of biogeochemical cycles, climate change, environmental remediation

Health care
- Accelerate and translate cancer research



10 Exascale Computing Project

Recognized as key application

More powerful computing +
New algorithms on the way !

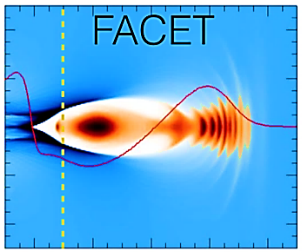
PWFA Research Priorities at FACET-II
Stage 1 Funded. Stage 2 & 3 will Fully Exploit the Potential of FACET-II

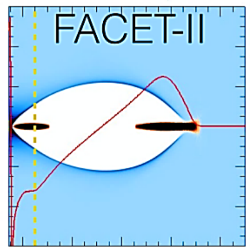
SLAC

Emittance Preservation with Efficient Acceleration
FY19-21

- High-gradient high-efficiency (instantaneous) acceleration has been demonstrated @ FACET
- Full pump-depletion and Emittance preservation at μm level planned as first experiment

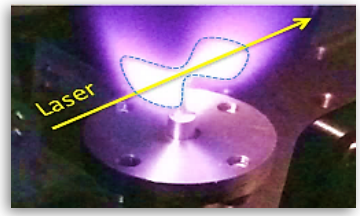
Stage 1

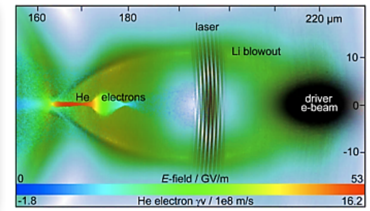




High Brightness Beam Generation & Characterization
FY20-22

- 10's nm emittance preservation is necessary for collider apps
- Ultra-high brightness plasma injectors may lead to first apps



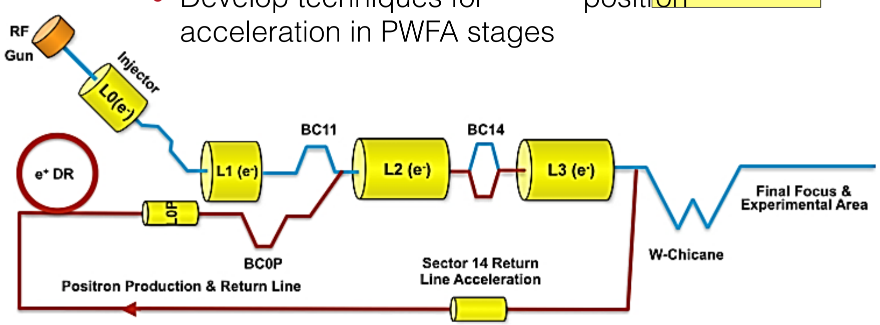


Stage 1

Positron Acceleration
FY21-24

- Only high-current positron capability in the world for PWFA research will be enabled by Phase II
  - Develop techniques for positron acceleration in PWFA stages

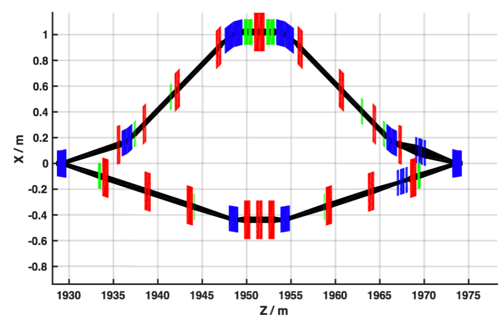
Stage 2

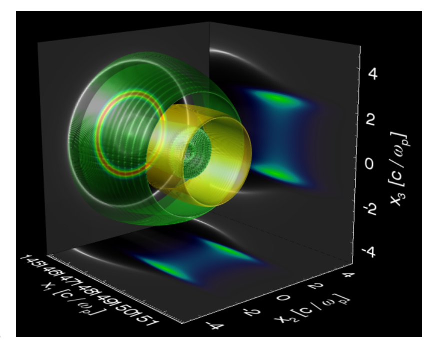


Simultaneous Deliver of Electrons & Positrons
FY22-25

- Positron Acceleration on Electron Beam Driven Wakefields

Stage 3





Gradual introduction of capabilities works well with level of demand for FACET-II

BELLA-I - a facility for high energy density physics and discovery plasma science at Berkeley Lab

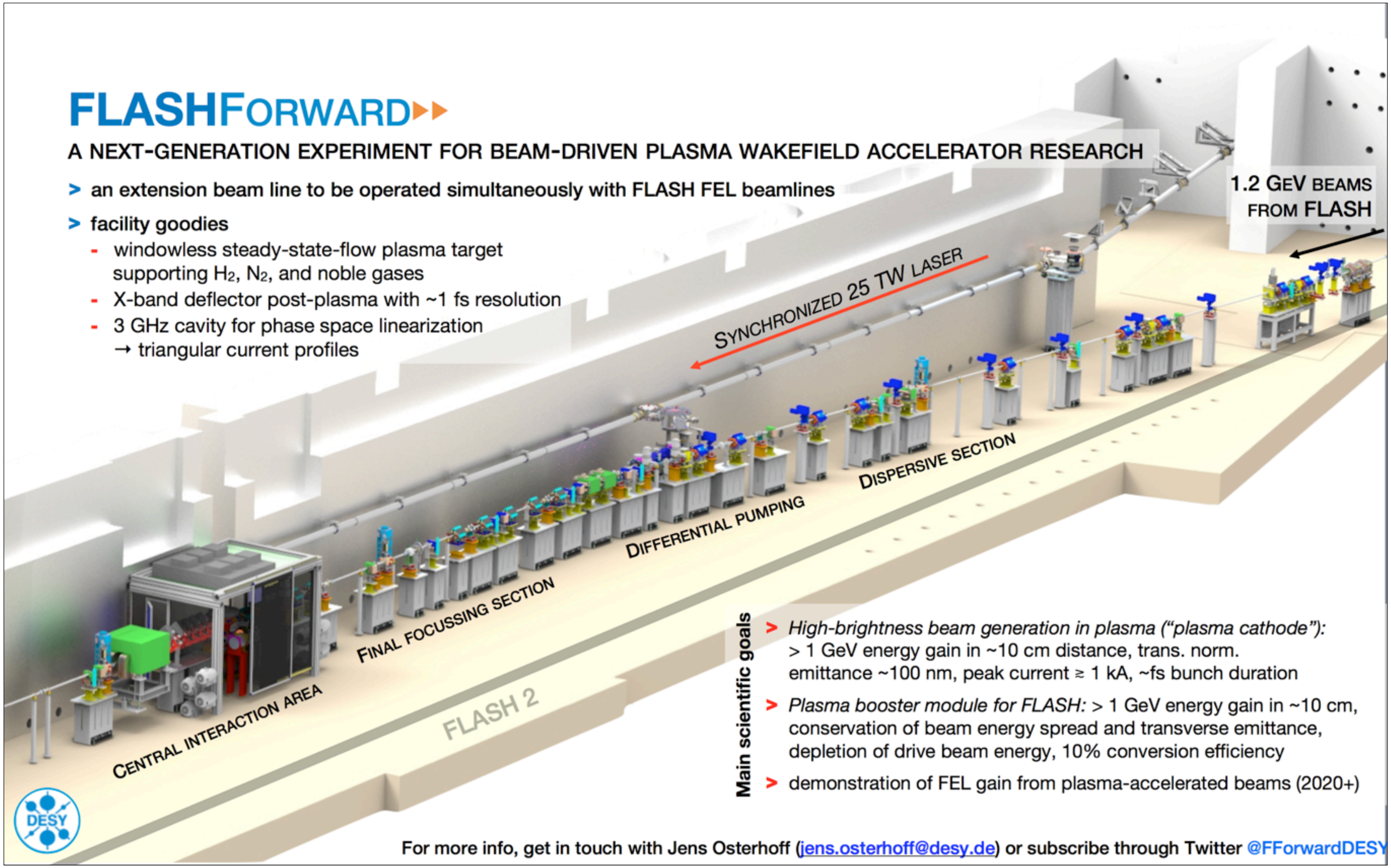
BELLA-i	1	2	3
peak intensity (W/cm^2)	2 x 10^{19}	3 x 10^{21}	3 x 10^{21}
pulse length	30 fs	30 fs	30 fs
peak pulse energy	40 J	40 J	40 J
laser spot size	55 µm	[illegible]	5 µm
peak repetition rate	1 Hz*	1 Hz*	1 Hz
contrast (ns)	10^{-10}	10^{-14}	$>10^{-14}$
diagnostics (details to be determined)	• optical spectrometers • ion and electron spectrometers • …	• optical pump- probe • betatron x-rays • MeV protons • …	• same as 2 • beamline for experiments with laser accelerated ions • …
1st access (estimates)	2017-2018	2018-2019	2019-2020

From C. Toth, AAC, August 2018

1. Experiments with the existing, long focal length BELLA beamline in the existing cave
2. Experiments in the existing BELLA cave with a new dual-beam line
   * shielding in the BELLA cave limits the repetition rate for experiments with generation of intense pulses of >20 MeV protons
3. Experiments in a new cave with a beam line for laser accelerated ions
   * improved shielding in a three-times larger experimental area for continuous operation at 1 Hz

DESY – Beam-Driven Plasma Acceleration: FLASHForward

(J. Osterhoff et al)



European Plasma Accelerator Project (H2020 DS)

40 institutes from Europe, Asia and United States

EuPRAXIA

16 EU laboratories are beneficiaries. **24 associated partners** from EU, Europe, Asia and US contribute in-kind. Deliverable: **CDR for Oct 2019**.

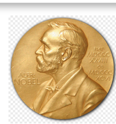
This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 653782.

IZEST/ICAN

There are very interesting developments ongoing in the Laser community that could have great impact on a future Laser Driven PWA.

IZEST/ICAN – coherent amplification network. Many fiber lasers in phase could bring needed energy, rep rate and efficiency.

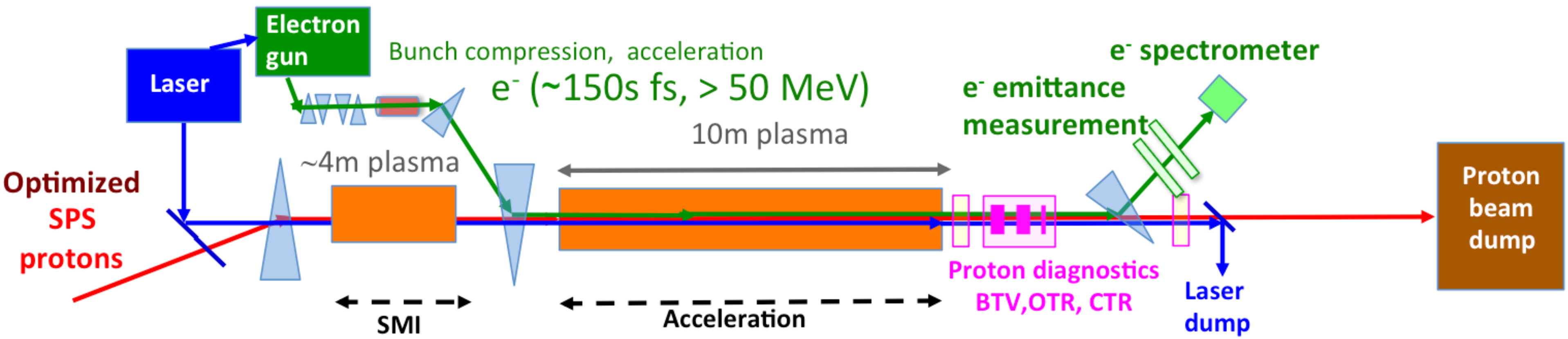
IZEST: G. Mourou, T. Tajima leaders



aim for PeV energies !

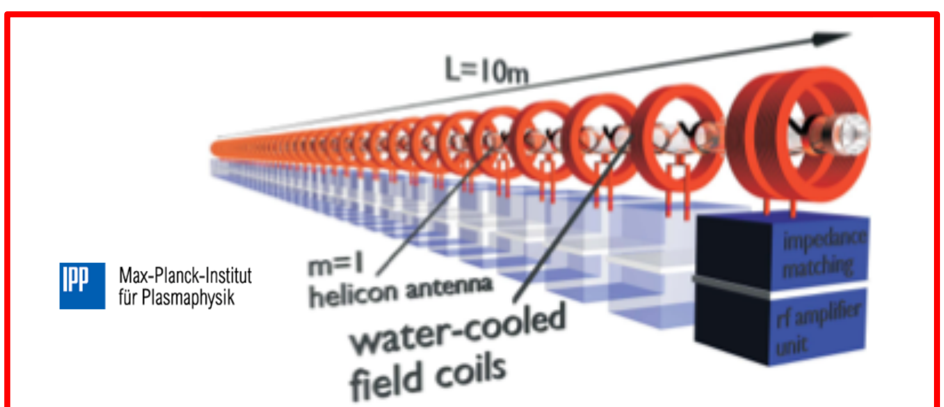
AWAKE Run II (2021-2024)

Goals:
- stable acceleration of bunch of electrons with high gradients over long distances
- ‘good’ electron bunch emittance at plasma exit



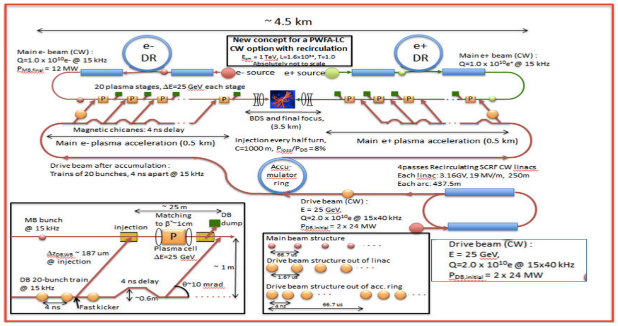
O. Grulke, IPP
O. Schmitz, Wisconsin

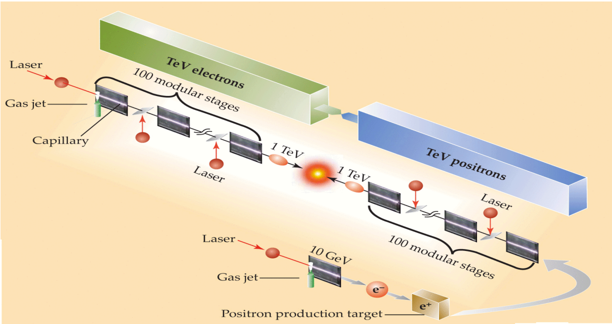
Novel plasma cell concept



Particle Physics Applications

Focus of Advanced Accelerator Community has been on high energy, high luminosity electron-positron collider - goal given by HEP community





◇ Ambitious long term goals (0.5 to 30TeV)

◇ Advanced Linear Collider (ALIC), 30 TeV CM collision energy, luminosity in the 10^{36} $cm^{-2}s^{-1}$ for studying Higgs coupling to the top quark, Higgs self-coupling and for precision measurements

ALEGRO

Advanced LinEar collider study GROup

◇ ALEGRO will submit (dec 2018) a document for the European Particle Physics Strategy Update

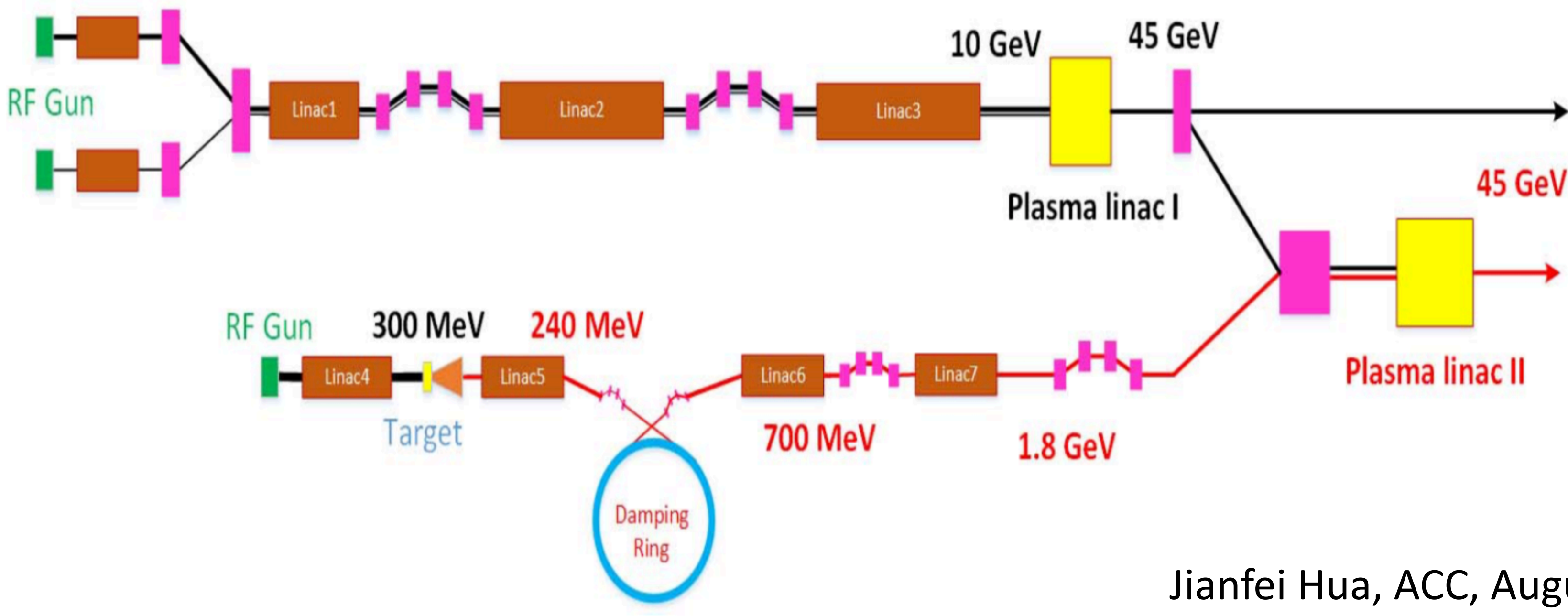
B. Cros, AAC Workshop, August 2018

Particle Physics Applications

A possible middle step for AAC towards colliders

Plasma based injector for 100km CEPC

A preliminary design of CEPC plasma based high energy injector



Jianfei Hua, ACC, August 2018

Particle Physics Applications

Should also consider other applications:

- **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

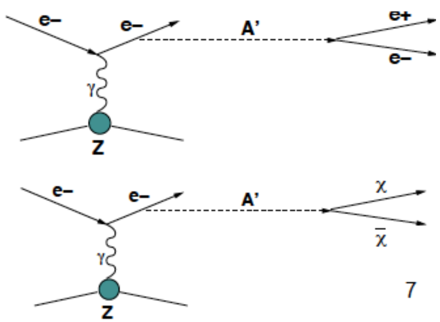
New energy regime means new physics sensitivity even at low luminosities !

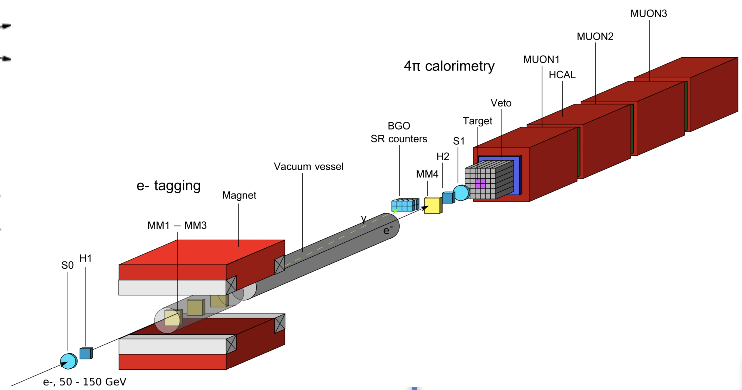
- **To be evaluated:**
  - AWAKE-like scheme with ions
  - acceleration of muons in LEMMA scheme
  - AWAKE-like scheme with FCC

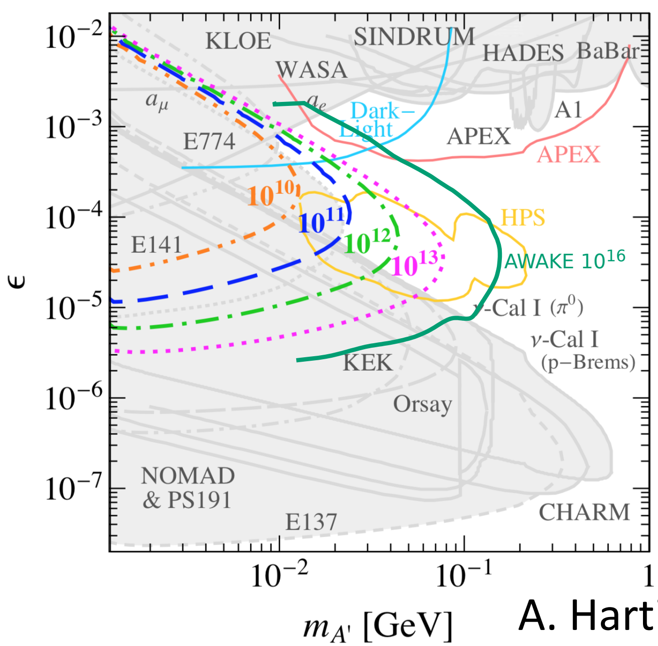
We have just started to evaluate the particle physics potential of plasma acceleration. Need creative thinking !

Dark Photon Search

NA64-like experiment with parameters that could become available with AWAKE-like acceleration of electrons using the SPS proton bunches



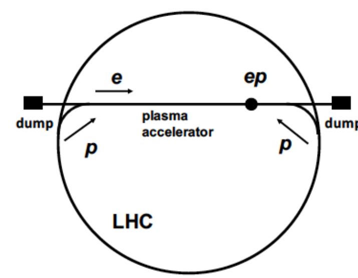


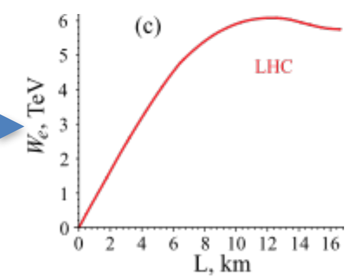


A. Hartin, UCL

Fixed Target

LHC Driver





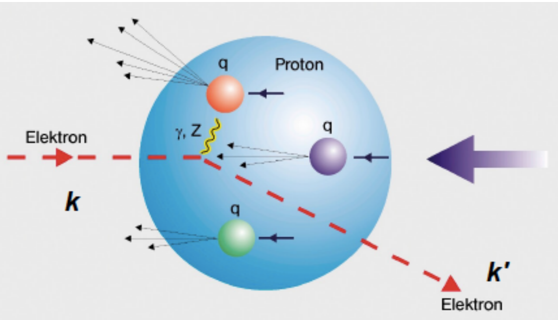
$$E_{\rm CM} = \sqrt{2M_P E_e} = 75\ {\rm GeV}$$

Compass: ~20 GeV

EIC: 100-140 GeV

Deep Inelastic Scattering

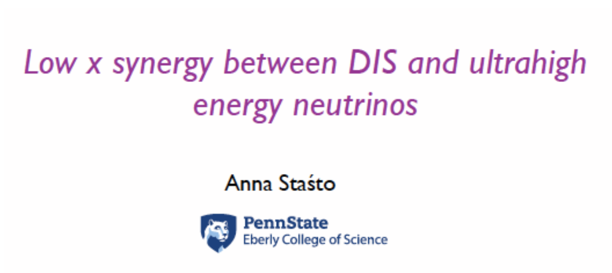
Topics: VHEeP Workshop, Munich 2017



Focus on QCD:

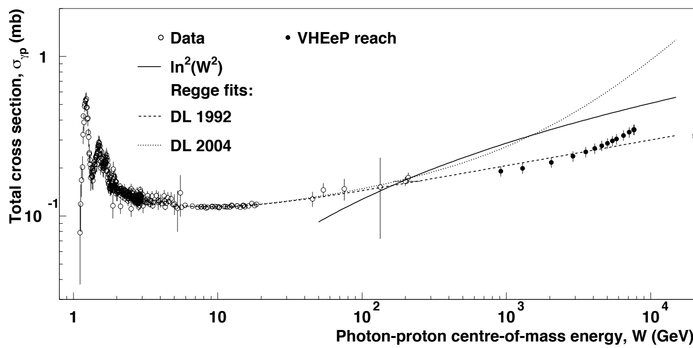
- Large cross sections – low luminosity (HERA level) enough
- Many open physics questions !
- Matching proton beam sizes means normalized emittance 10-100 mm-mrad

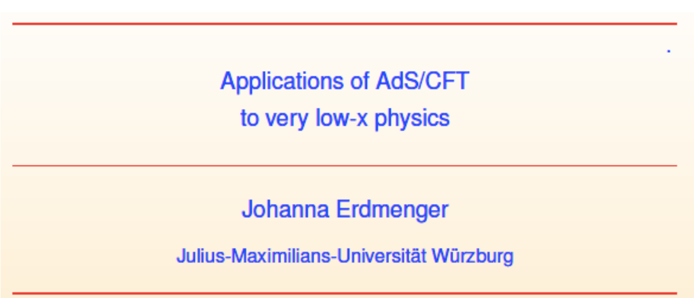
real & virtual photon cross sections


Low x synergy between DIS and ultrahigh energy neutrinos

Anna Staśto

PennState
Eberly College of Science

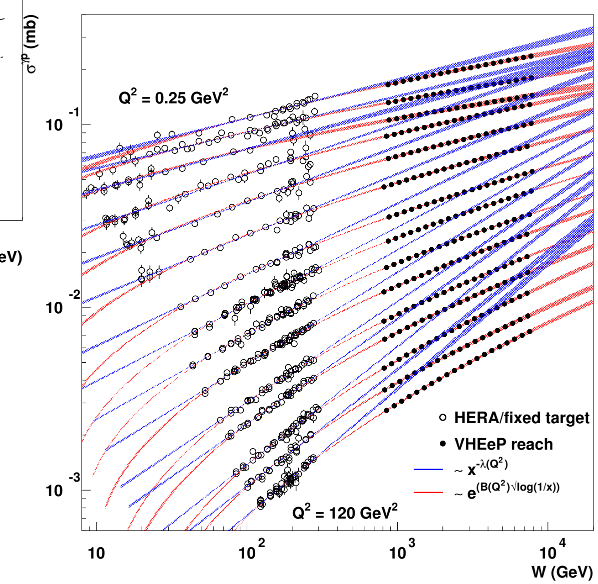



Applications of AdS/CFT
to very low-x physics

Johanna Erdmenger

Julius-Maximilians-Universität Würzburg

protons grow with energy, similarly to black holes … connections between QCD & gravity ?



Support Now !

Personal remarks:

The plasma acceleration community has been told to aim for a high energy, high luminosity electron-positron collider.

My concern: progress will be judged by how rapidly this goal is approached.

There are many exciting physics opportunities along the way that can be taken up - not only a super ILC!

The technology development is important for its own sake - the future uses are not yet all known

Strong support now can make the future come sooner !

Conclusion

Plasma acceleration interesting for HEP applications
(and many others, not discussed)

Many efforts world-wide, primarily in laser-driven PWA.

Strong gradients demonstrated. Emittance, staging, etc. tbd

Many exciting physics opportunities, also in the near/mid-term, that don’t require ultimate goals to be reached.

Strong support required for rapid developments !