An Introduction to Plasma Accelerators

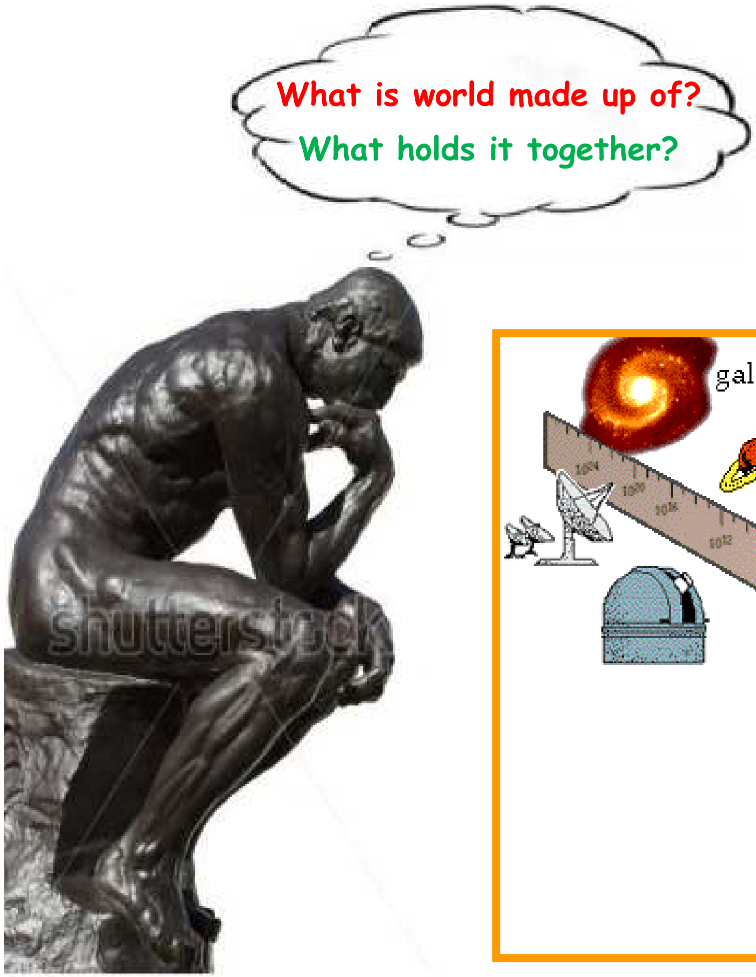
Humboldt University Research Seminar

- Role of accelerators
- Working of plasma accelerators
- Self-modulation
- PITZ Self-modulation experiment
- Application

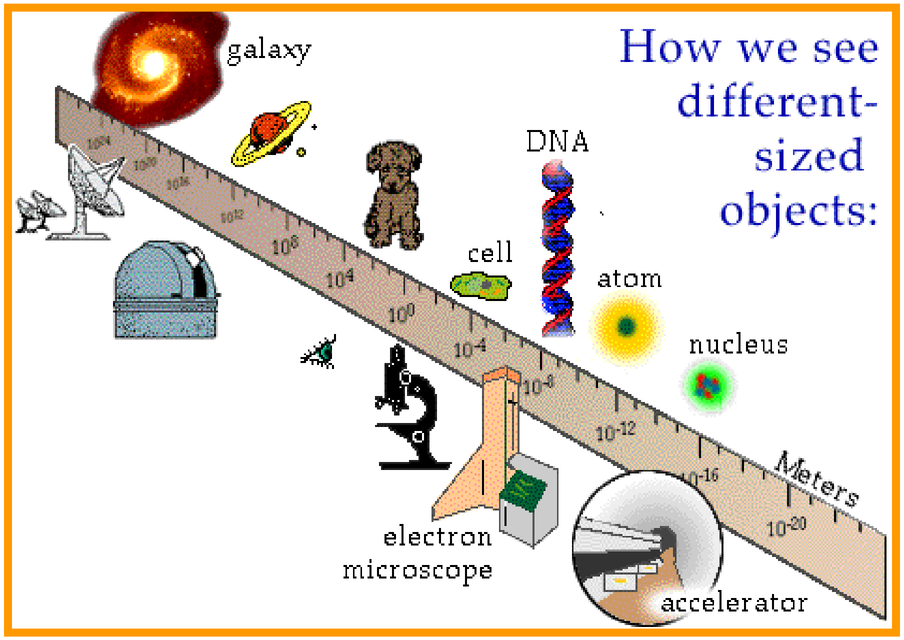
Gaurav Pathak
Universität Hamburg / PITZ,DESY
May 16, 2014

Role of High Energy Particle Accelerators

Man has always been wondering about the world around him …



Built various devices to find answers



Wavelength of the probe should be smaller than the size of the object to be probed

⇩

De’Broglie Wavelength

$$\lambda = \hbar / \sqrt{2mE}$$

⇩

To probe matter on smaller scale requires particles with higher energy

Particle Accelerator Development

1919 Rutherford gets the first nuclear reactions using natural alpha rays (radio activity) of some MeV).« He realize already that he will need many MeV to study the atomic nucleus.

1924 Ising proposes the acceleration using a variable electric field between drift tubes (the father of the LINAC).

1928 Wideroe uses Ising principle with an RF generator, 1MHz, 25 kV and accelerate potassium ions up to 50 keV.

1928 Cockcroft & Walton start designing an 800 kV generator encouraged by Rutherford.

1932 Generator reaches 700 kV and Cockcroft & Walton split lithium atom with only 400 keV protons. « received the Nobel Prize in 1951.

1956 Veksler proposed the concept of using electron beam driven plasma waves to accelerate charge Particles.

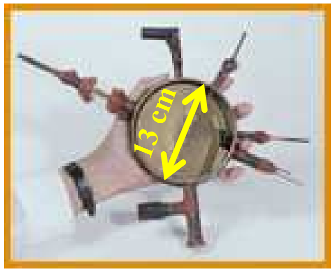
1960 T. Mainman invented the laser.

1979 Tajima and Dawson proposed to use **laser beam** to excite plasma wave for electron acceleration. The Mechanism called LWFA (Laser wakefield acceleration).

1985 Chen et. al. proposed the basic mechanism of the PWFA (Plasma wakefield acceleration) in the linear regime using **electron beam**.

2009 A. Caldwell et. al proposed to use proton driven PWFA to accelerate the particles.

80 keV Cyclotron at LBNL (1930)



7 TeV Synchrotron at CERN

A breif history and review of accelerators – P.J.Brayant, CERN, Geneva
E. Esarey, P. Sprangle, “Overview of plasma-based accelerator concepts”, IEEE transaction on plasma science, Vol. 24, No. 2, April 1996

Conventional and Wake-field Accelerators

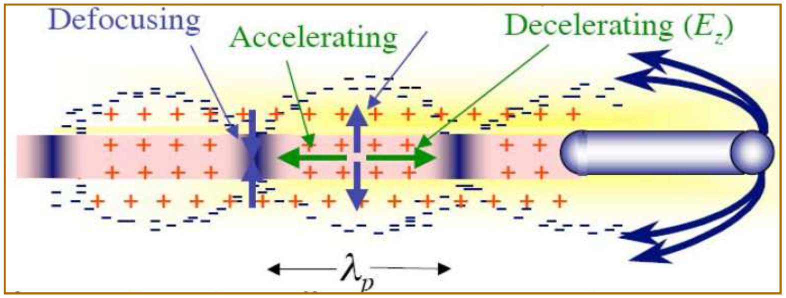
- **Conventional accelerator** based on RF cavities
  - Limited acceleration gradient : E ~50 MV/m (due to material break down)
  - Several kilometer size accelerator for TeV energy
  - Require huge money and human resources

Large Hadron Collider at CERN

- **Wake-field acceleration** based on plasma waves
  - Plasma supports high electric field : E ~ 100 GV/m (no breakdown limit)
  - Compact size accelerator of few meters size
  - Much lower cost

Small laboratories can also afford it !!!

Wake-field acceleration



E ~ GV/m (density dependent)

Quasi-monoenergetic laser-plasma acceleration of electrons to 2 GeV, X. Wang et. al., Nature Communications 4, Article number: 1988 doi:10.1038/ncomms2988

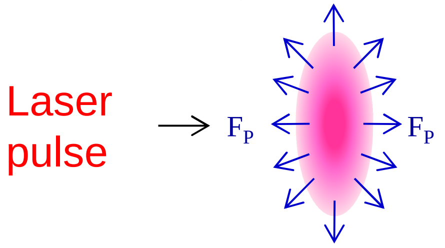
Wakefield Acceleration

Ponderomotive Force

$$\vec{F}_p = -e\,[(\vec{r}_1.\vec{\nabla})\vec{E}_{r_1=0} + (\vec{v}_1/c)\times\vec{B}] \sim -\nabla I_L$$

$$E_z \sim \sqrt{n_e}\ (\mathrm{cm}^{-3})$$

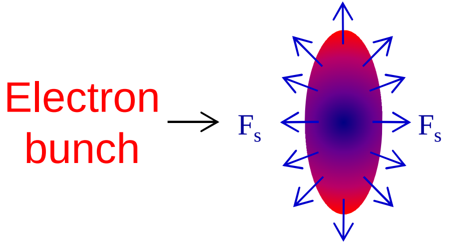
Electrons will be pushed from high to low intensity region of laser pulse.



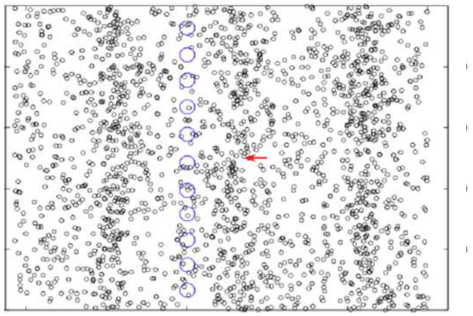
Space charge Force

$$E_z \propto N_b/\sigma_z^2$$

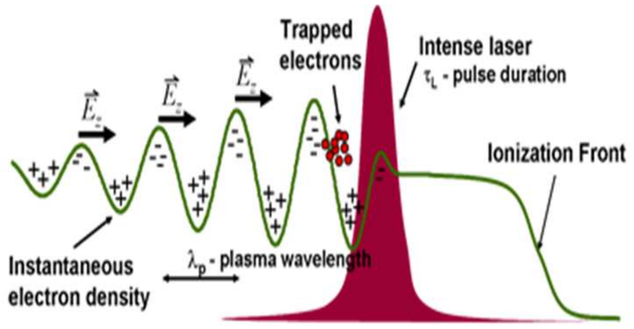
Electrons will be pushed by space charge force of charged particle beam.



Plasma Wave

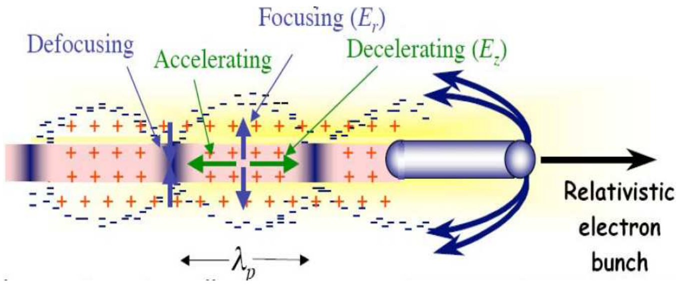


Laser Wake-Field Acceleration



$$c\tau_{laser} \approx \lambda_p / 2$$

Plasma Wake-Field Acceleration



$$\lambda_p = \sqrt{2}\pi\sigma_z$$

LWFA - $E_z \sim 100$ GV/m for $n_e = 10^{18}\ \mathrm{cm}^{-3}$

PWFA - $E_z \sim 3$ GV/m for $n_e = 10^{15}\ \mathrm{cm}^{-3}$

E. Esarey, P. Sprangle, “Overview of plasma-based accelerator concepts”, IEEE transaction on plasma science, Vol. 24, No. 2, April 1996

1-D Theory for PWFA

$\frac{\partial n}{\partial t} + \nabla.(n\vec{v}) = 0$ - Equation of continuity

$\frac{\partial \vec{v}}{\partial t} + (\vec{v}.\nabla)\vec{v} = \frac{e}{m}(\vec{E} + \vec{v} \times \vec{B})$ -Equation of motion

Let $n_0 = plasma\ density$

$n_b = beam\ density$

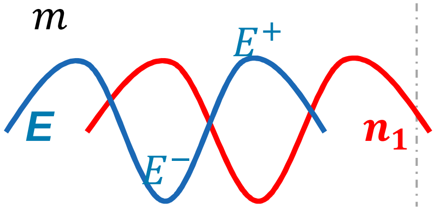
$n_1 = perturbation\ due\ to\ beam\ propagation$

$and\ n_1 \ll n_0$

Keeping only linear terms and combining both equation yields the **equation of density perturbation**

$$\boxed{\frac{\partial^2 n_1}{\partial t^2} + \omega_p^2 n_1 = -\omega_p^2 n_b \quad -(1)}$$

where $\omega_p^2 = \frac{4\pi n_0 e^2}{m}$



Consider a 1-D case for beam

$$n_b = \sigma\delta(z - v_b t) \qquad -(2)$$

where $\sigma = uniform\ surface\ number\ density$

$\delta = Dirac\ delta\ function$

Substituting (2) in (1) and solving yields the density perturbation induced by the injected beam

$$\boldsymbol{n_1 = \begin{cases} k_p\sigma \sin(k_p z - \omega_p t) & k_p z - \omega_p t < 0 \\ 0 & k_p z - \omega_p t > 0 \end{cases}}$$

Substituting this into Maxwell's first equation

$\nabla.\vec{E} = 4\pi e(n_1 + n_b)$ gives

$$E = \begin{cases} 4\pi e\sigma\ cosk_p y & k_p z - \omega_p t < 0 \\ 2\pi e\sigma & k_p z - \omega_p t = 0 \\ 0 & k_p z - \omega_p t > 0 \end{cases}$$

Which shows that E field is 90^o out of phase with density perturbation

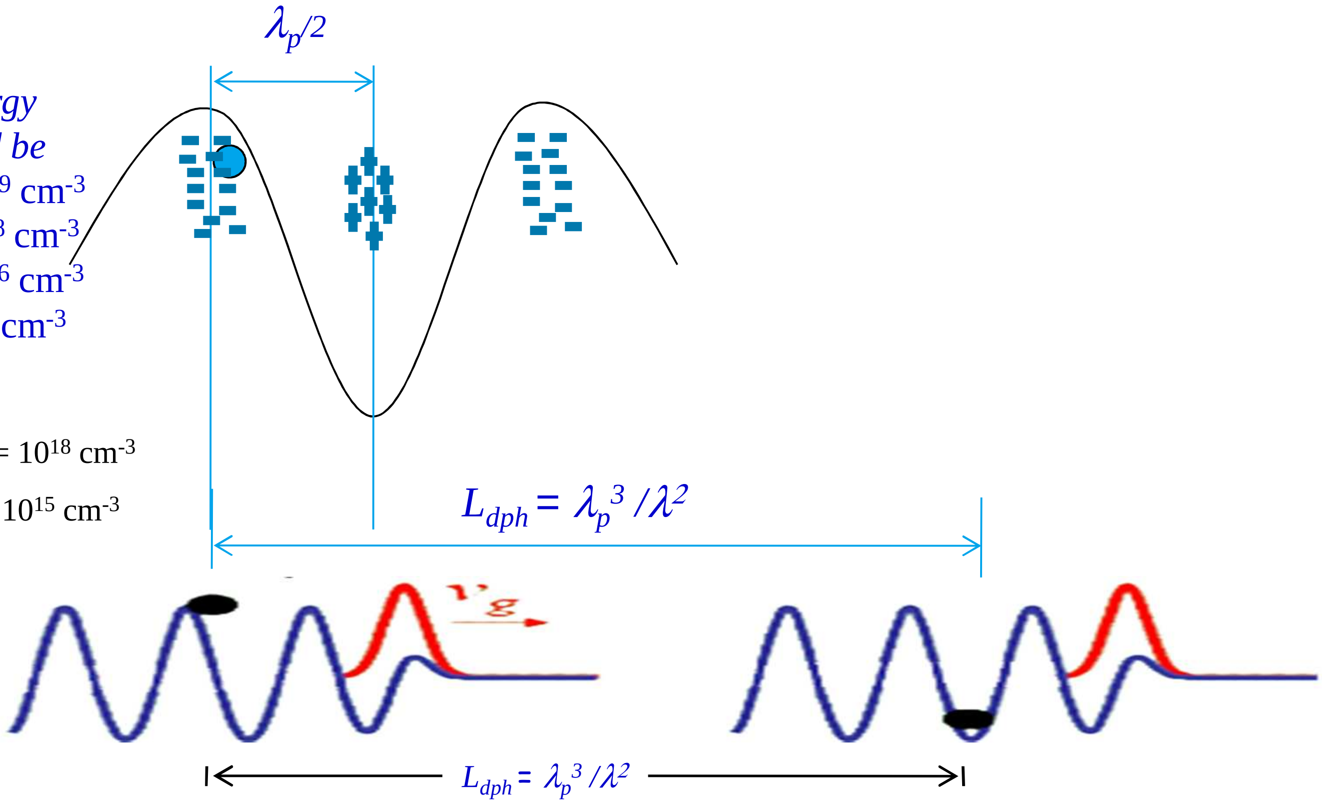
E. Esarey, P. Sprangle, "Overview of plasma-based accelerator concepts", IEEE transaction on plasma science, Vol. 24, No. 2, April 1996

LWFA vs PWFA

Dephasing: The length in the laboratory frame in which the accelerating electrons slips by 90º in phase with respect to the plasma wave.

For gaining 1GeV energy dephasing length would be

L_{dph} ~ 1 mm - for $n_e \sim 10^{19}\ \mathrm{cm}^{-3}$
L_{dph} ~ 1 cm - for $n_e \sim 10^{18}\ \mathrm{cm}^{-3}$
L_{dph} ~ 10cm - for $n_e \sim 10^{16}\ \mathrm{cm}^{-3}$
L_{dph} ~ 1m - for $n_e \sim 10^{14}\ \mathrm{cm}^{-3}$



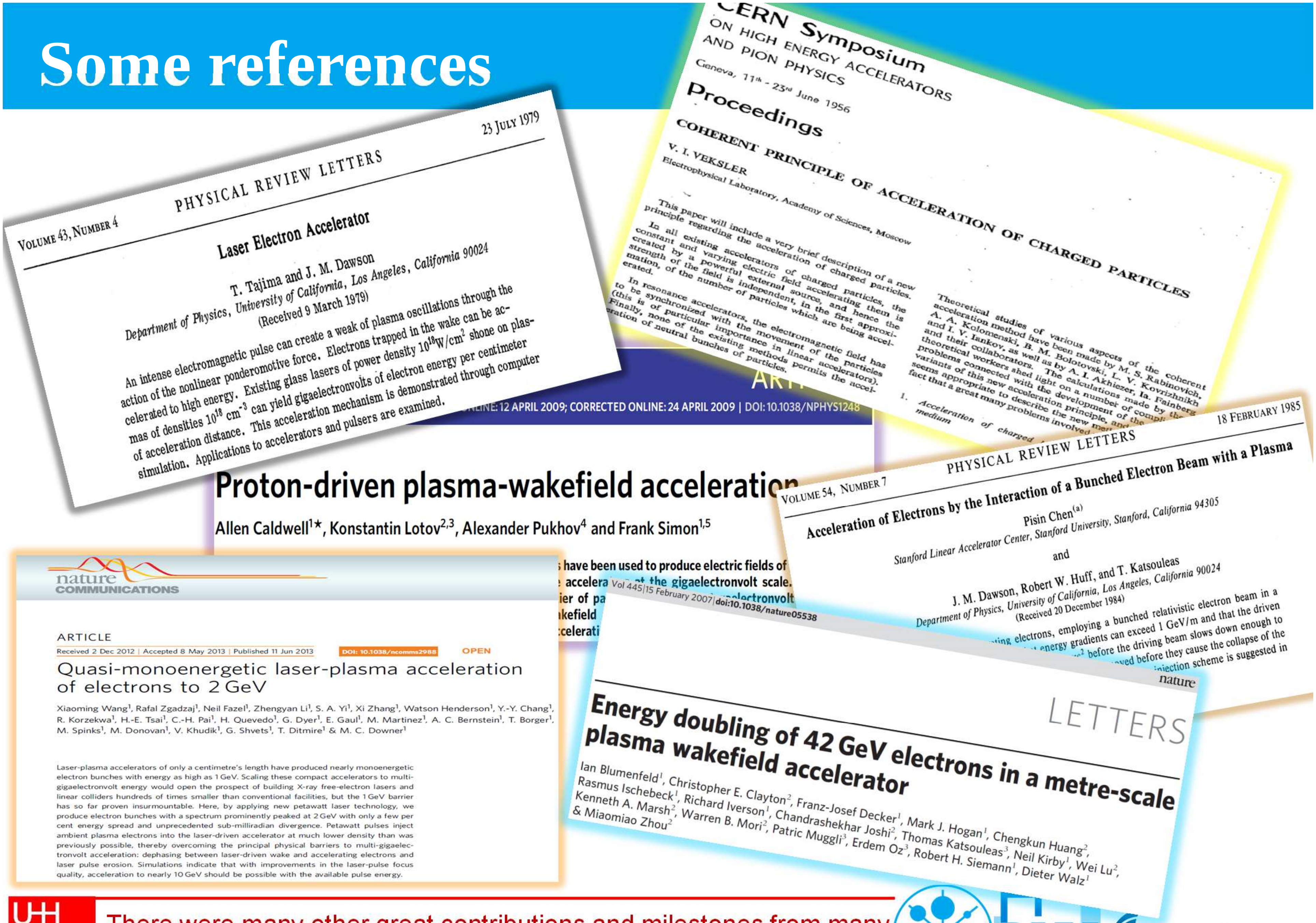
LWFA - $E_z \sim 100$ GV/m for $n_e = 10^{18}\ \mathrm{cm}^{-3}$

PWFA - $E_z \sim 3$ GV/m for $n_e = 10^{15}\ \mathrm{cm}^{-3}$

Although in PWFA the gradient is not as high as already achieved in LWFA, the 1-GeV/m gradient is much larger than that achieved in any accelerating metallic structure.

E. Esarey, C. B. Schroeder, and W. P. Leemans, “Physics of laser-driven plasma-based electron accelerators” Reviews of Modern physics, vol. 81, Jul-Sep. 2009.

Some references



VOLUME 43, NUMBER 4 PHYSICAL REVIEW LETTERS 23 JULY 1979

Laser Electron Accelerator

T. Tajima and J. M. Dawson
Department of Physics, University of California, Los Angeles, California 90024
(Received 9 March 1979)

An intense electromagnetic pulse can create a weak of plasma oscillations through the action of the nonlinear ponderomotive force. Electrons trapped in the wake can be accelerated to high energy. Existing glass lasers of power density 10^{18}W/cm^2 shone on plasmas of densities 10^{18} cm^{-3} can yield gigaelectronvolts of electron energy per centimeter of acceleration distance. This acceleration mechanism is demonstrated through computer simulation. Applications to accelerators and pulsers are examined.

CERN Symposium
ON HIGH ENERGY ACCELERATORS
AND PION PHYSICS
Geneva, 11th - 23rd June 1956

Proceedings

COHERENT PRINCIPLE OF ACCELERATION OF CHARGED PARTICLES

V. I. VEKSLER
Electrophysical Laboratory, Academy of Sciences, Moscow

This paper will include a very brief description of a new principle regarding the acceleration of charged particles.

In all existing accelerators of charged particles, the constant and varying electric field accelerating them is created by a powerful external source, and hence the strength of the field is independent, in the first approximation, of the number of particles which are being accelerated.

In resonance accelerators, the electromagnetic field has to be synchronized with the movement of the particles (this is of particular importance in linear accelerators). Finally, none of the existing methods permits the acceleration of neutral bunches of particles.

Theoretical studies of various aspects of the coherent acceleration method have been made by M. S. Rabinovich, A. A. Kolomenski, B. M. Bolotovski, L. V. Kovrizhnikh and I. V. Iankov, as well as by A. I. Akhiezer, Ia. Fainberg and their collaborators. The calculations made by the theoretical workers shed light on a number of compl… problems connected with the development of the … variants of this new acceleration principle, and … seems appropriate to describe the new met… fact that a great many problems involved…

1. *Acceleration of charged … medium*

…LINE: 12 APRIL 2009; CORRECTED ONLINE: 24 APRIL 2009 | DOI:10.1038/NPHYS1248

Proton-driven plasma-wakefield acceleration

Allen Caldwell[1]*, Konstantin Lotov[2,3], Alexander Pukhov[4] and Frank Simon[1,5]

…s have been used to produce electric fields of
… accelera… at the gigaelectronvolt scale.
…ier of pa… …electronvolt
…kefield
…celerati…

VOLUME 54, NUMBER 7 PHYSICAL REVIEW LETTERS 18 FEBRUARY 1985

Acceleration of Electrons by the Interaction of a Bunched Electron Beam with a Plasma

Pisin Chen[(a)]
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305

and

J. M. Dawson, Robert W. Huff, and T. Katsouleas
Department of Physics, University of California, Los Angeles, California 90024
(Received 20 December 1984)

…ting electrons, employing a bunched relativistic electron beam in a … energy gradients can exceed 1 GeV/m and that the driven …^{2} before the driving beam slows down enough to …ved before they cause the collapse of the …injection scheme is suggested in

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nature COMMUNICATIONS

ARTICLE

Received 2 Dec 2012 | Accepted 8 May 2013 | Published 11 Jun 2013 DOI: 10.1038/ncomms2988 OPEN

Quasi-monoenergetic laser-plasma acceleration of electrons to 2 GeV

Xiaoming Wang[1], Rafal Zgadzaj[1], Neil Fazel[1], Zhengyan Li[1], S. A. Yi[1], Xi Zhang[1], Watson Henderson[1], Y.-Y. Chang[1], R. Korzekwa[1], H.-E. Tsai[1], C.-H. Pai[1], H. Quevedo[1], G. Dyer[1], E. Gaul[1], M. Martinez[1], A. C. Bernstein[1], T. Borger[1], M. Spinks[1], M. Donovan[1], V. Khudik[1], G. Shvets[1], T. Ditmire[1] & M. C. Downer[1]

Laser-plasma accelerators of only a centimetre's length have produced nearly monoenergetic electron bunches with energy as high as 1 GeV. Scaling these compact accelerators to multi-gigaelectronvolt energy would open the prospect of building X-ray free-electron lasers and linear colliders hundreds of times smaller than conventional facilities, but the 1 GeV barrier has so far proven insurmountable. Here, by applying new petawatt laser technology, we produce electron bunches with a spectrum prominently peaked at 2 GeV with only a few per cent energy spread and unprecedented sub-milliradian divergence. Petawatt pulses inject ambient plasma electrons into the laser-driven accelerator at much lower density than was previously possible, thereby overcoming the principal physical barriers to multi-gigaelectronvolt acceleration: dephasing between laser-driven wake and accelerating electrons and laser pulse erosion. Simulations indicate that with improvements in the laser-pulse focus quality, acceleration to nearly 10 GeV should be possible with the available pulse energy.

Vol 445|15 February 2007|**doi:10.1038/nature05538**

nature

LETTERS

Energy doubling of 42 GeV electrons in a metre-scale plasma wakefield accelerator

Ian Blumenfeld[1], Christopher E. Clayton[2], Franz-Josef Decker[1], Mark J. Hogan[1], Chengkun Huang[2], Rasmus Ischebeck[1], Richard Iverson[1], Chandrashekhar Joshi[2], Thomas Katsouleas[3], Neil Kirby[1], Wei Lu[2], Kenneth A. Marsh[2], Warren B. Mori[2], Patric Muggli[3], Erdem Oz[3], Robert H. Siemann[1], Dieter Walz[1] & Miaomiao Zhou[2]

There were many other great contributions and milestones from many people.

Motivation

A Proton driven plasma wakefield acceleration was proposed by A.Caldwell et. al. in 2009 →

- A proton driver "suck" the plasma electrons leading to the electron density enhancement on-axis
- This sets the plasma electrons into oscillation.
- The oscillation of plasma electron set up an oscillating electric field given by

$$E_z = 240(MV\ m^{-1})\left(\frac{N_b}{4\times10^{10}}\right)\left(\frac{0.6}{\sigma_z(mm)}\right)^2$$

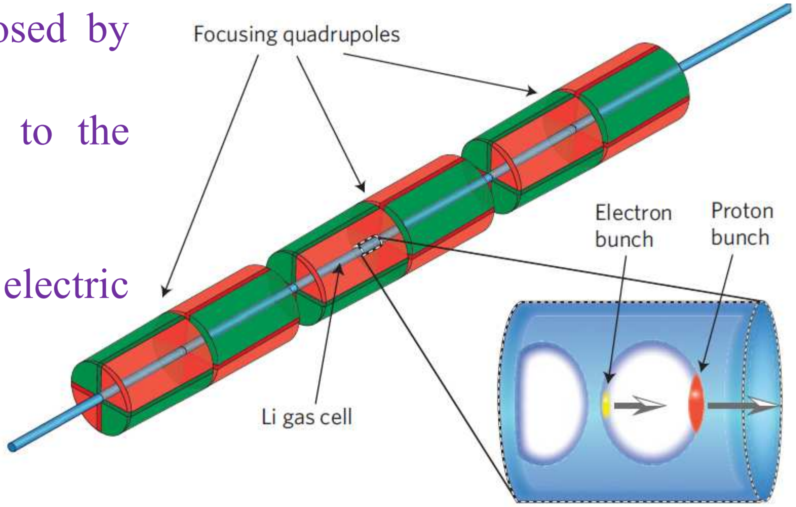


Figure 1 | A schematic description of a section of the plasma-wakefield-accelerating structure. A thin tube containing Li gas is surrounded by quadrupole magnets with alternating polarity. The magnification shows the plasma bubble created by the proton bunch (red). The electron bunch (yellow) undergoing acceleration is located at the back of the bubble. Note that the dimensions are not to scale.

Why short proton bunches required?

To maximize E_z the plasma wavelength should have a definite relation to the length of the driving bunch:

$$\lambda_p = \sqrt{2}\pi\sigma_z$$

$$\lambda_p = 1mm\sqrt{\frac{10^{15}cm^{-3}}{n_p}}, \lambda_p(mm) = \begin{cases} 3.16 & for 10^{14}cm^{-3} \\ 1 & for\ 10^{15}cm^{-3} \\ 0.31 & for 10^{16}cm^{-3} \end{cases} \longleftarrow$$

Tradeoff between $\lambda_p, \sigma_z\ and\ E_z$

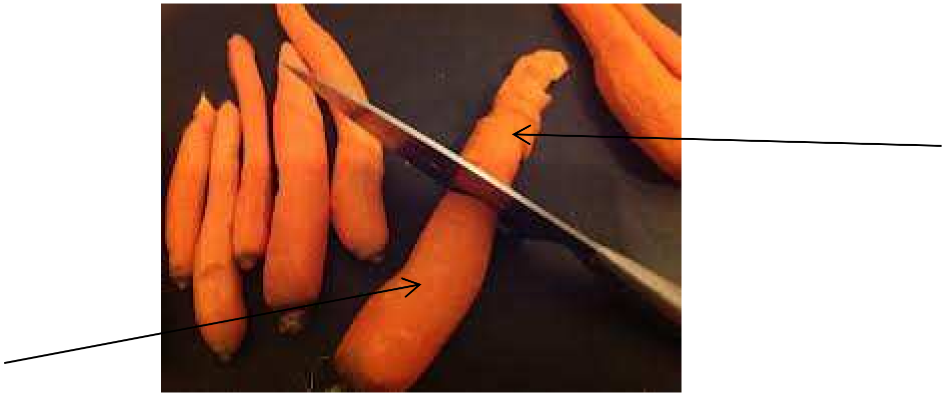
The CERN SPS bunch has length ~12cm (120mm).

How to generate short proton bunches?

A. Caldwell et. al. Proton-driven plasma-wakefield acceleration, Nature Physics 5, 363 - 367 (2009)

Self-modulation

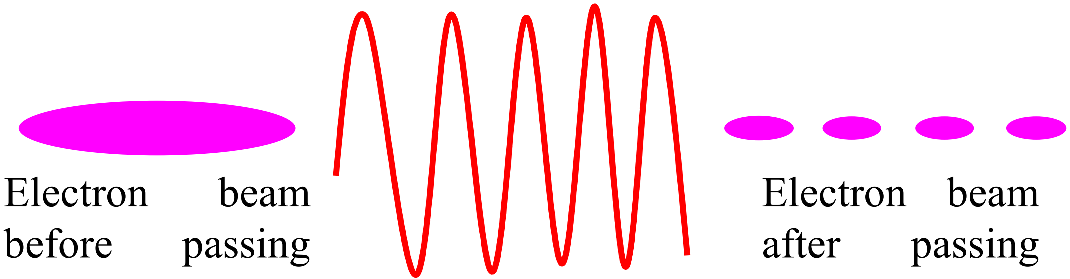
To generate a short proton bunches a technique viz. self modulation is proposed by N. Kumar and A. Pukhov in 2010.



After passing through knife

Before passing through knife

Simply speaking if a charged particle bunch travelling through plasma is long in comparison to the plasma wavelength then it can get self-modulated, splitting itself into short bunches via electric fields of plasma.



Electron beam before passing through plasma

Plasma E field

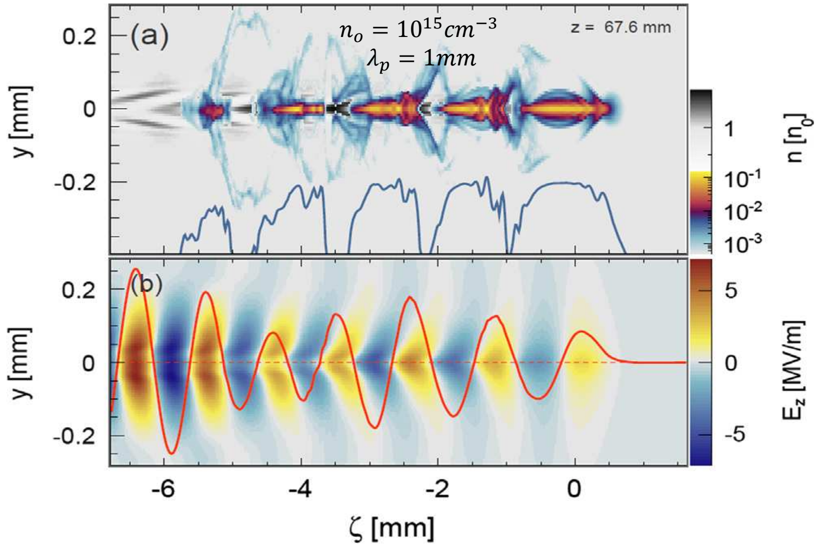
Electron beam after passing through plasma

This principle can be applied to the long electron bunch also.

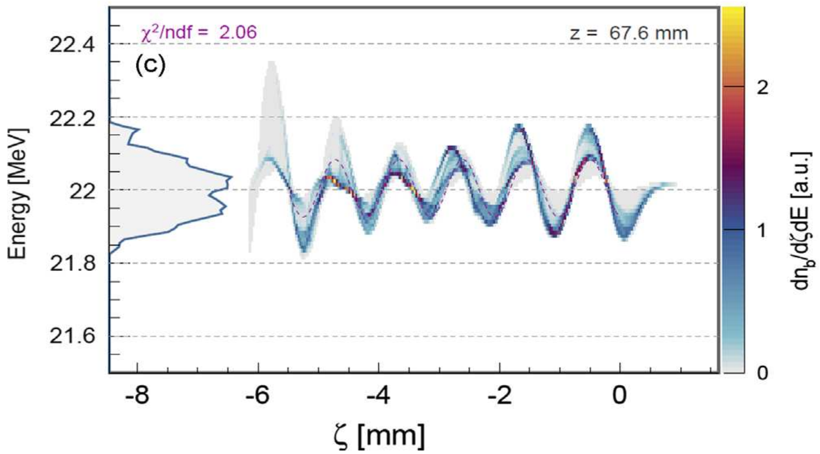
N. Kumar and A. Pukhov, "Self-modulation instability of a long proton bunch in plasmas", PRL104, 255003 (2010)

Self-Modulation Experiments at PITZ

- Favorable circumstances
  - Very high level photo injector test facility
  - Worldwide unique laser system (pulse shaper)
  - Well developed diagnostics (high resolution electron spectrometer, etc.); soon: transverse deflecting cavity + dispersive section for longitudinal phase space measurements



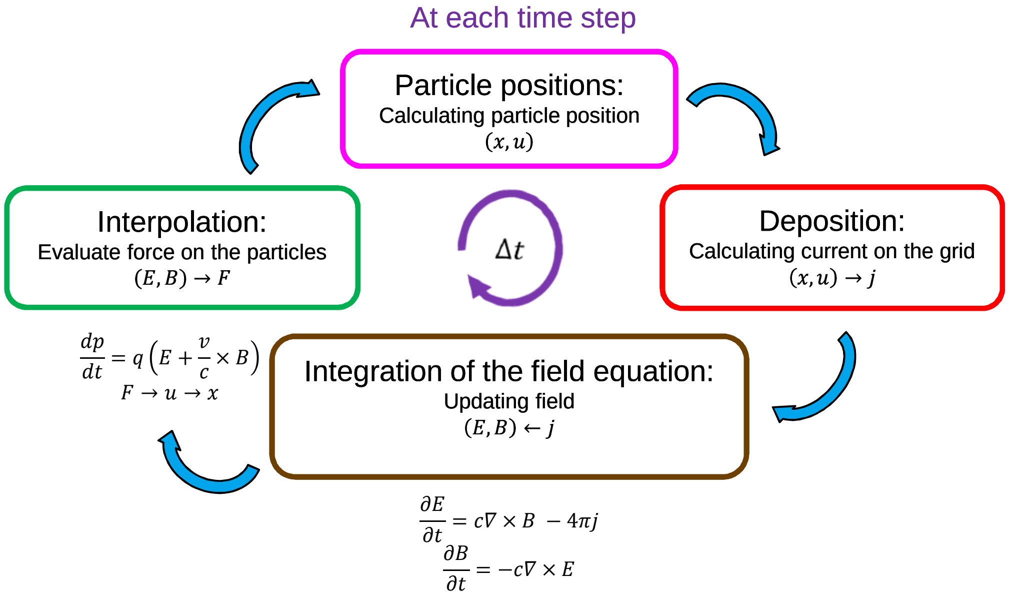
- Needed for preparation: PIC simulations
  - OSIRIS (full PIC code)
  - HiPACE (quasi-static) - Efficiency



Osiris Simulations

M.Gross et. al, “Preparations for a plasma wakefield acceleration (PWA) experiment at PITZ”, NEMA, 740 (2014) 74-80

HiPACE - Algorithm of the Code



At each time step

Particle positions: Calculating particle position (x, u)

Deposition: Calculating current on the grid $(x, u) \rightarrow j$

Integration of the field equation: Updating field $(E, B) \leftarrow j$

$$\frac{\partial E}{\partial t} = c\nabla \times B - 4\pi j$$
$$\frac{\partial B}{\partial t} = -c\nabla \times E$$

Interpolation: Evaluate force on the particles $(E, B) \rightarrow F$

$$\frac{dp}{dt} = q\left(E + \frac{v}{c} \times B\right)$$
$$F \rightarrow u \rightarrow x$$

Δt

- **Quasi-static or frozen field approximation converts Maxwell's equations into electrostatic equations**

Maxwell equations in Lorentz gauge

$$\left(\frac{\partial^2}{c^2\partial t^2} - \frac{\partial^2}{z^2}\right)\hat{A} = \frac{4\pi}{c}j$$
$$\left(\frac{\partial^2}{c^2\partial t^2} - \frac{\partial^2}{z^2}\right)\varphi = 4\pi\rho$$

Transforming to co-moving frame

$$\begin{array}{l} \xi = z - ct \\ t = \tau \end{array} \longrightarrow \begin{array}{c} \dfrac{\partial}{\partial t} = \left(\dfrac{\partial}{\partial \tau} - c\dfrac{\partial}{\partial \xi}\right) \\ \dfrac{\partial}{\partial z} = \dfrac{\partial}{\partial \xi} \end{array}$$

Quasi-static approximation

$$\xrightarrow{\quad \frac{\partial}{c\partial\tau} \ll \frac{\partial}{\partial\xi} \quad}$$

Reduced Maxwell equations

$$-\nabla^2\hat{A} = \frac{4\pi}{c}j$$
$$-\nabla^2\varphi = 4\pi\rho$$

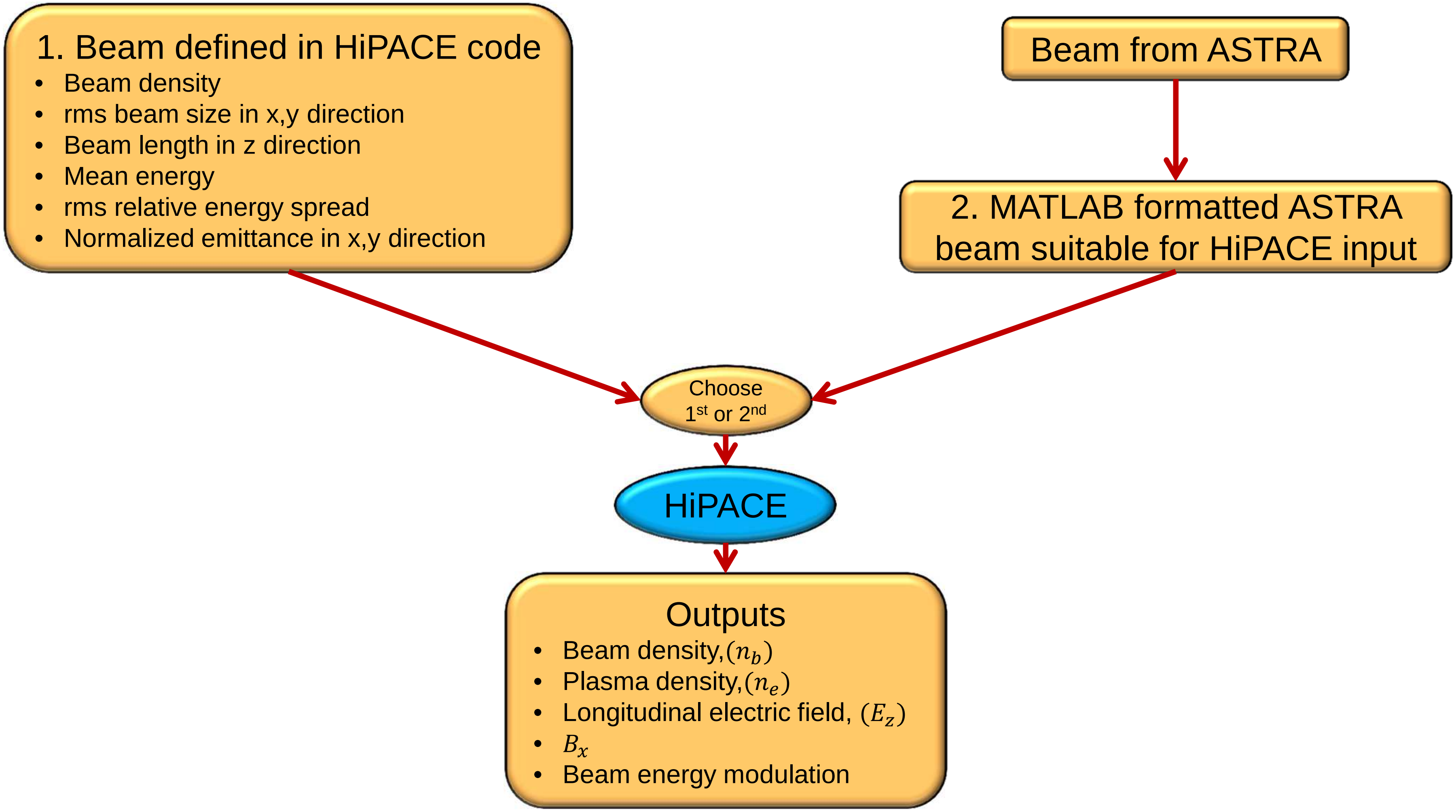
❑ Solving these reduced equation saves the time.

❑ Quasi-static codes are already tested and shows good resembles with full PIC codes.*

Courtesy C. Benedetti, T. Mehrling, A. M. de la Ossa, J. Osterhoff C. Schroeder, DESY

*C.Huang et.al. doi:10.1088/1742-6596/46/1/026

HiPACE code – Input and Output



1. Beam defined in HiPACE code
- Beam density
- rms beam size in x,y direction
- Beam length in z direction
- Mean energy
- rms relative energy spread
- Normalized emittance in x,y direction

Beam from ASTRA

2. MATLAB formatted ASTRA beam suitable for HiPACE input

Choose 1st or 2nd

HiPACE

Outputs
- Beam density, (n_b)
- Plasma density, (n_e)
- Longitudinal electric field, (E_z)
- B_x
- Beam energy modulation

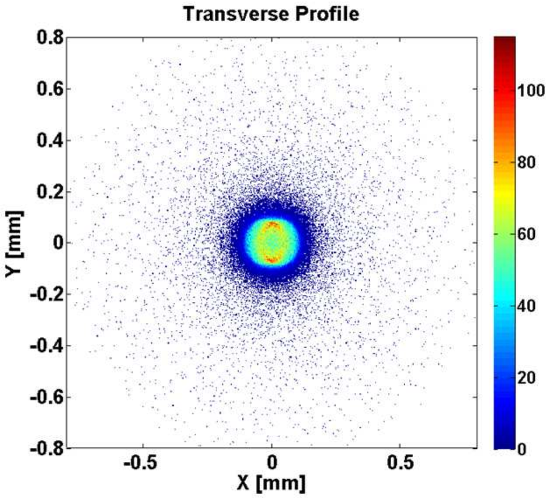
Courtesy C. Benedetti, T. Mehrling, A. M. de la Ossa, J. Osterhoff C. Schroeder, DESY

Initial Beam Parameters

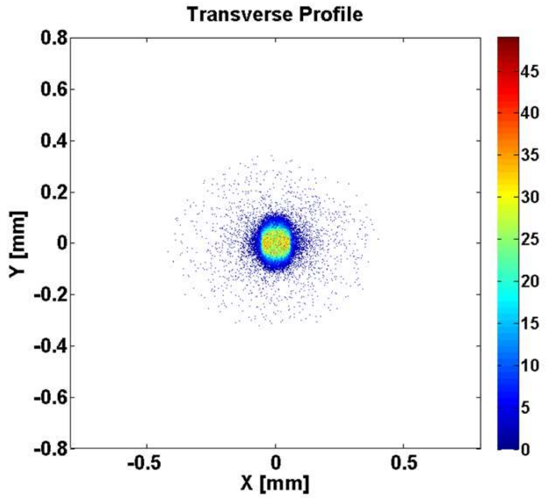
Two simulation were performed to see the effect of different beam size.

Beam parameters	Setup (1)	Setup (2)
Total charge, pC	100	100
X rms beam size, µm	75.0	47.0
Y rms beam size, µm	79.0	47.0
Z rms, mm	1.7	1.7
Average Momentum, MeV/c	22.0	22.0
Momentum Spread, keV/c	24.45	24.96
ϵ_x, mm mrad	0.352	0.366
ϵ_y, mm mrad	0.352	0.379
Number of particles	200,000	200,000

Plasma Density $n_o = 10^{15} cm^{-3}$



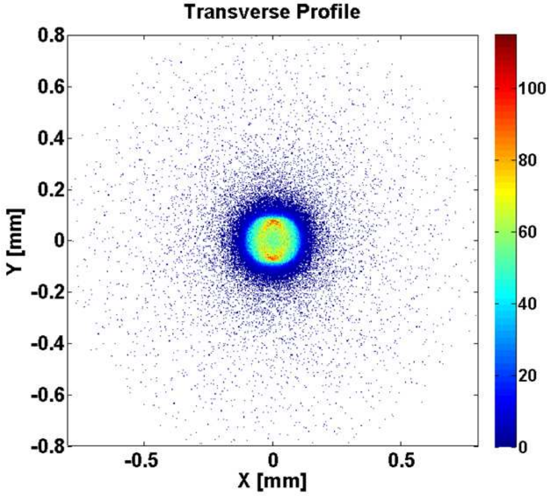
(1)

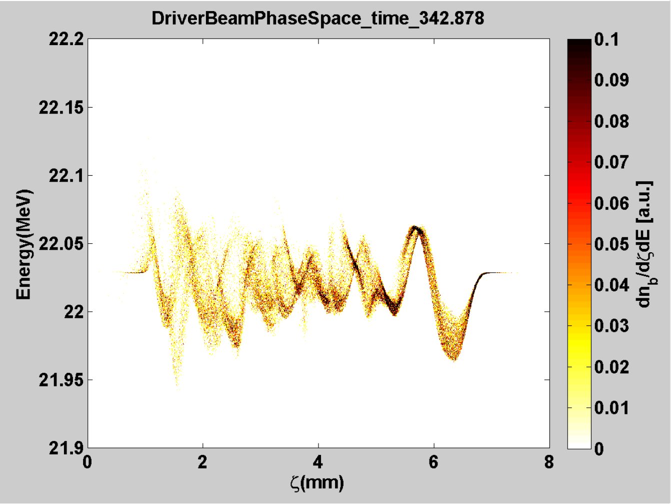


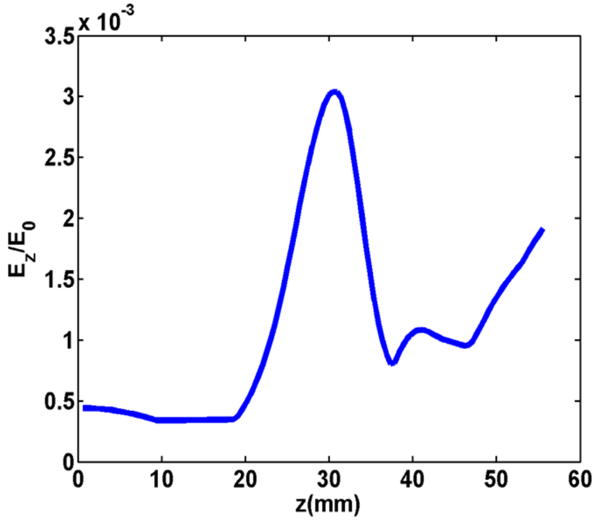
(2)

Results - Energy Modulation and Ez

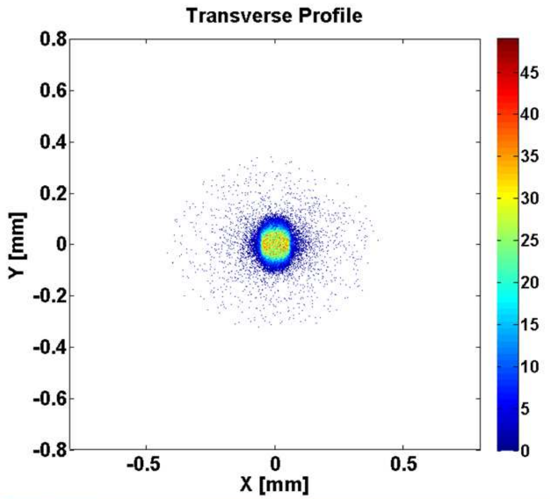
Setup 1

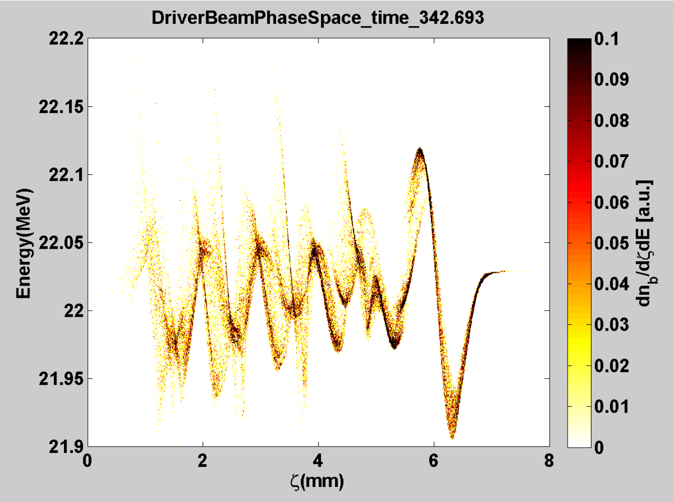


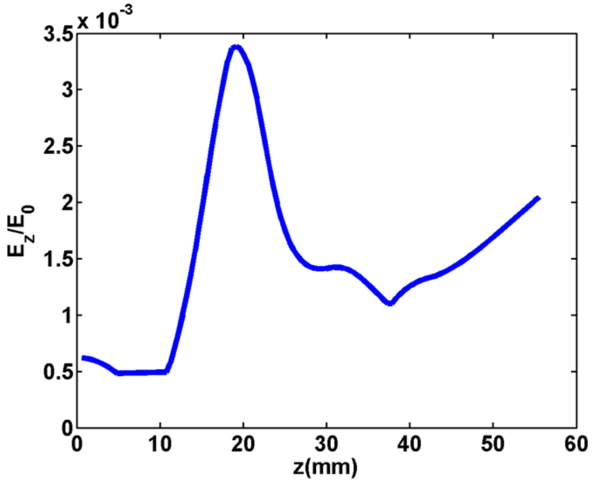




Setup 2

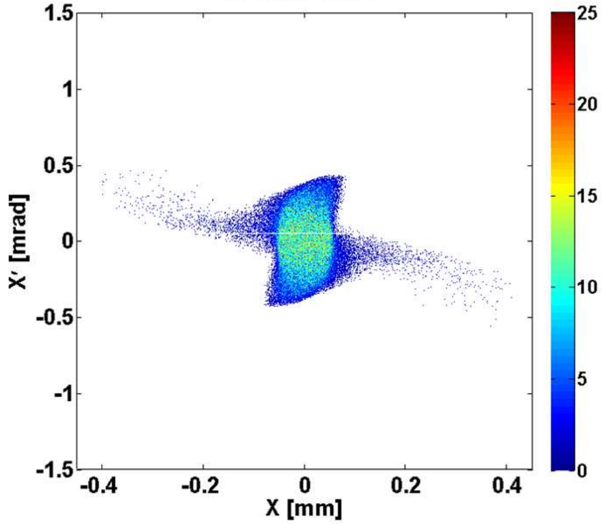


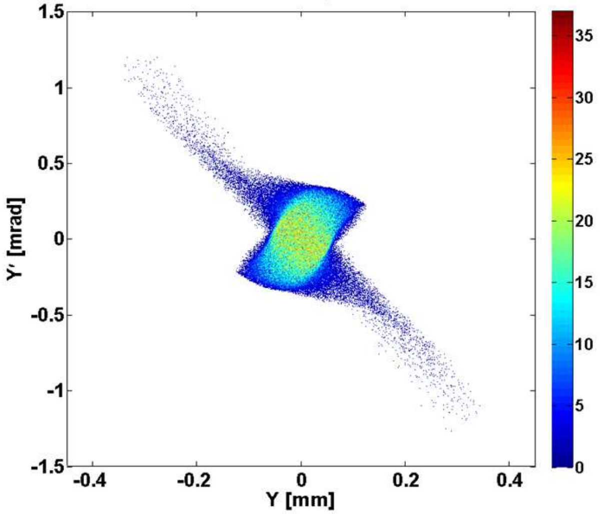


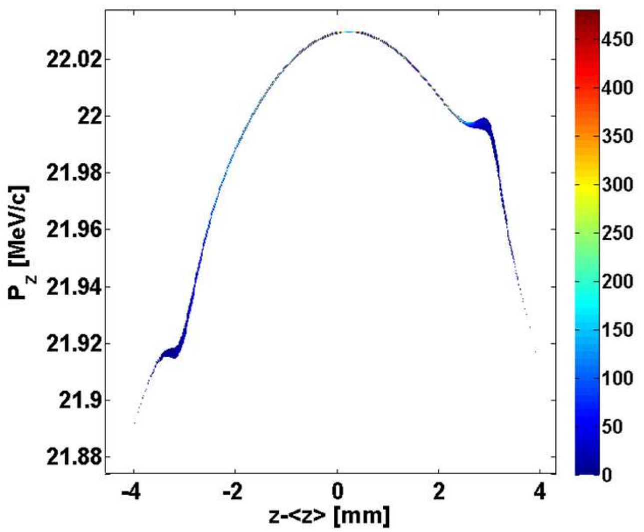


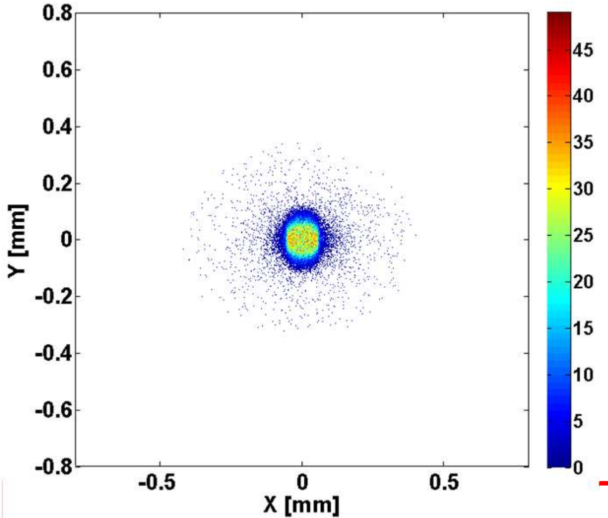
Parameters of Setup (2)

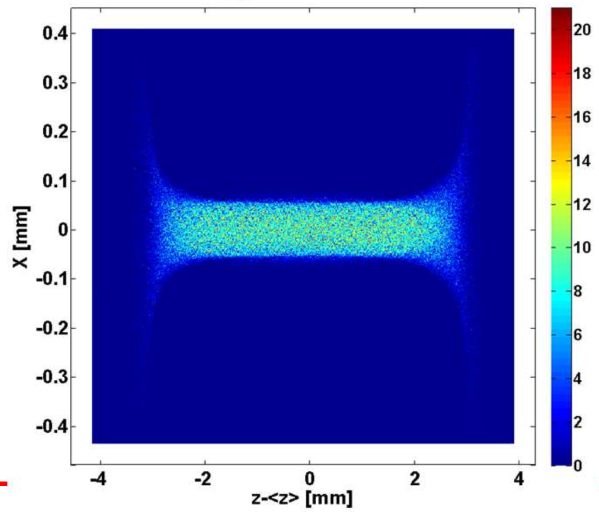
ASTRA Input

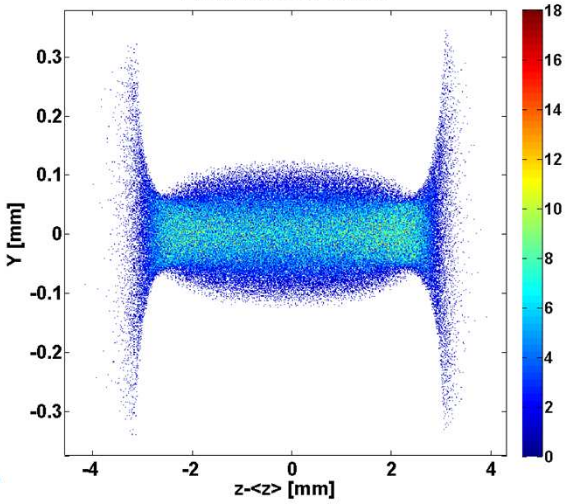

X Trace Space


Y Trace Space

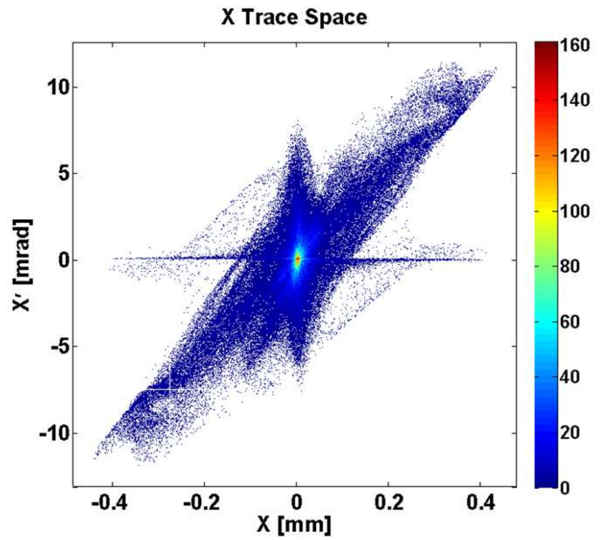

Longitudinal Phase Space


Transverse Profile


Longitudinal X-Profile


Longitudinal Y-Profile

Phase space after plasma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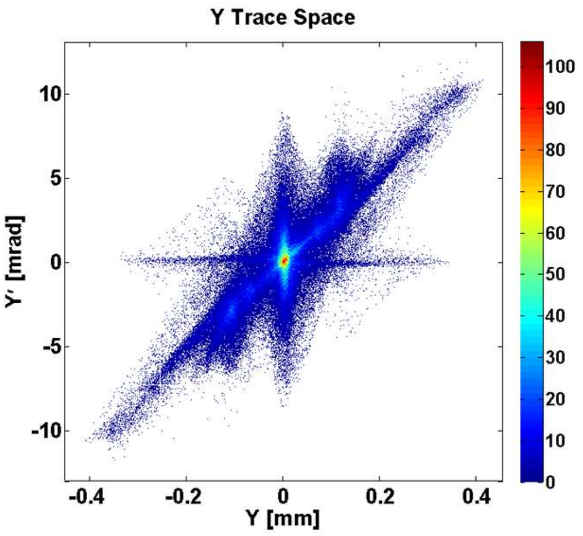
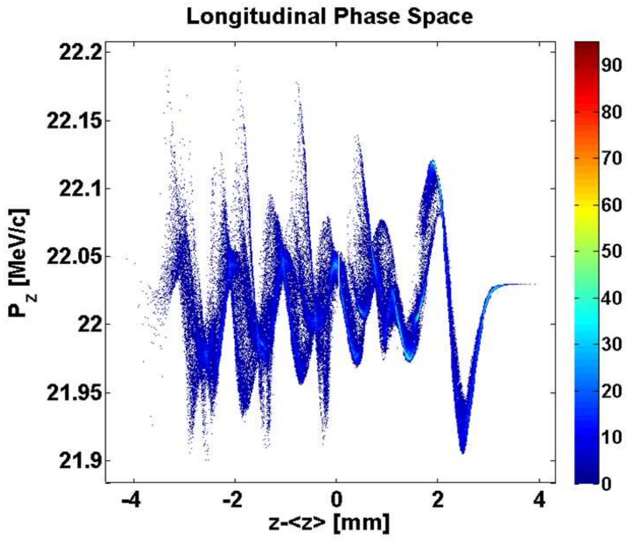
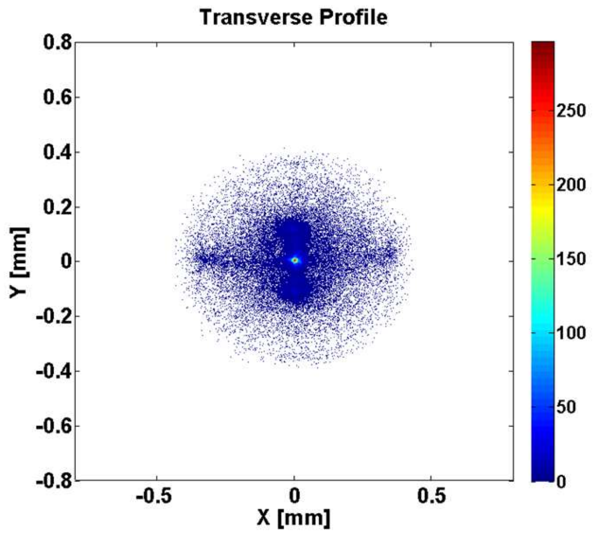
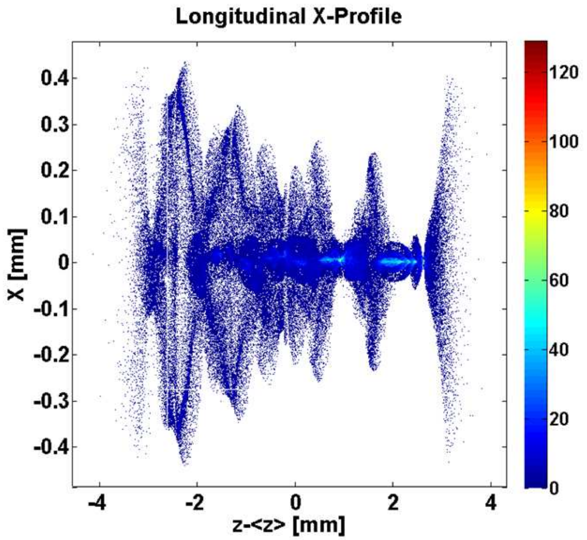
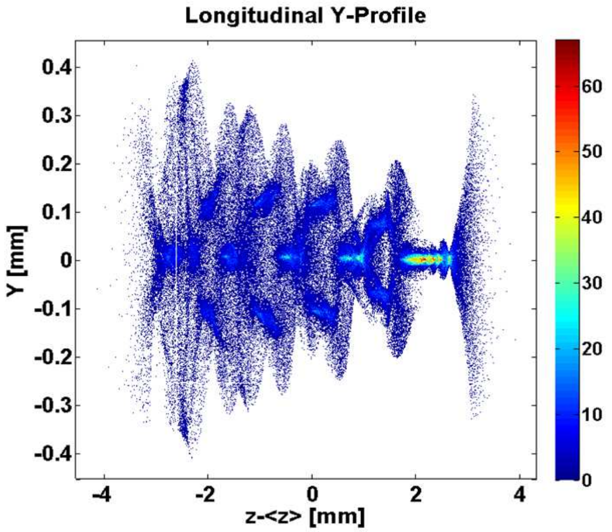

Y Trace Space

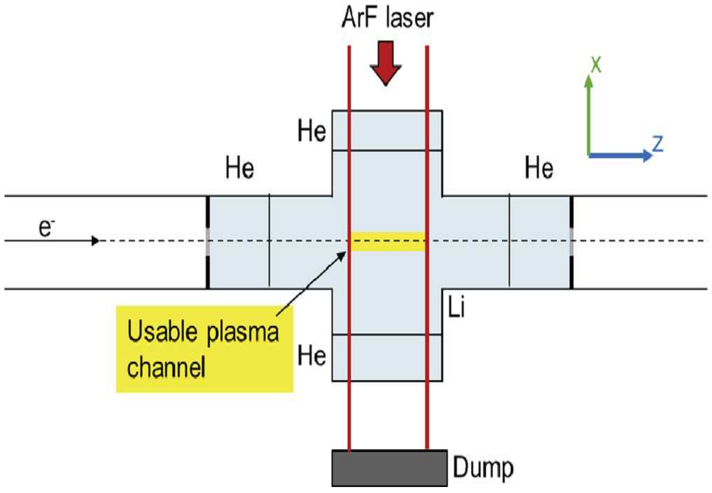

Longitudinal Phase Space


Transverse Profile

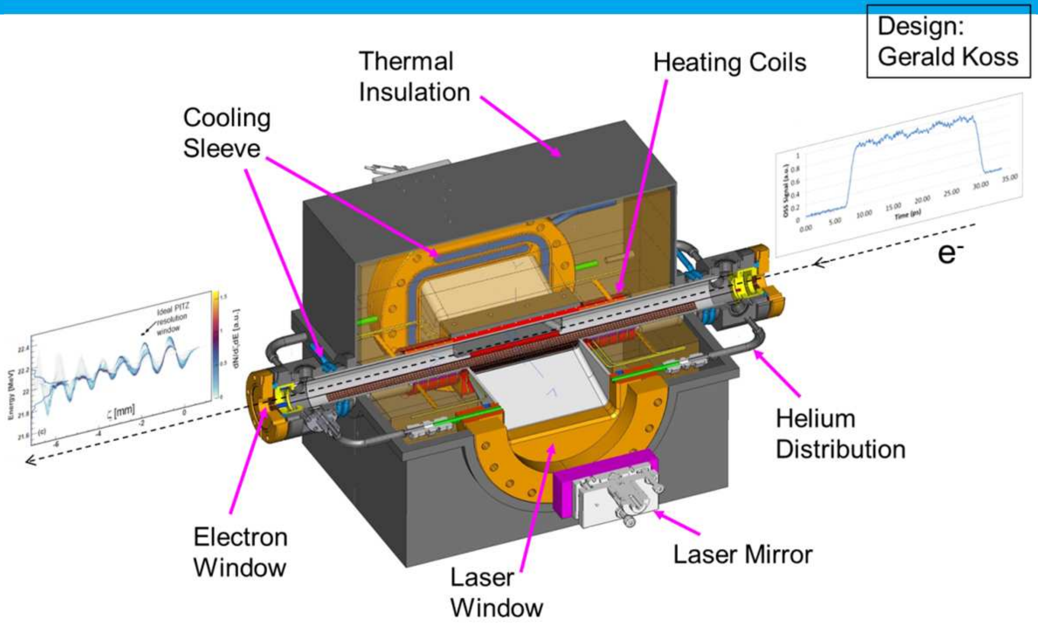

Longitudinal X-Profile


Longitudinal Y-Profile

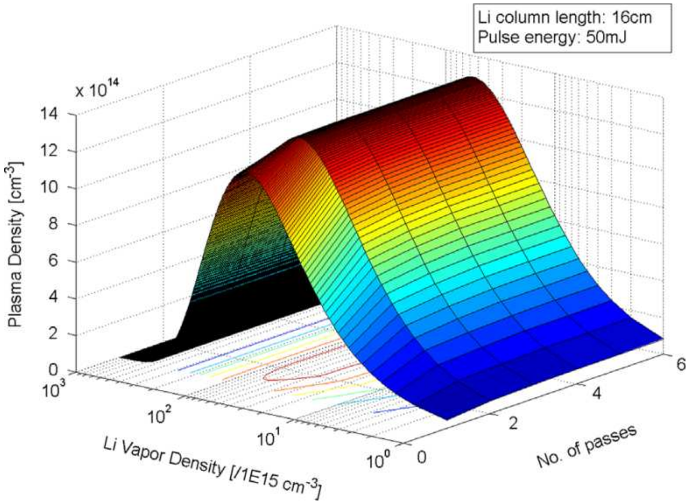
PITZ Self-modulation experiment approach



Ionization with ArF laser (top view)



Plasma Cell Design



An ionization laser pulse energy of a few $100mJ$ is needed to generate a plasma channel of 10mm diameter and 60 mm length with a plasma density of $10^{15}cm^{-3}$.

M.Gross et. al, “Preparations for a plasma wakefield acceleration (PWA) experiment at PITZ”, NEMA, 740 (2014) 74-80

Application - Intense X-rays from Undulator

$$\lambda = \frac{\lambda_u}{2h\gamma^2}\left(1 + \frac{K^2}{2} + \theta^2\gamma^2\right)$$

h-harmonic number

Undulator radiation

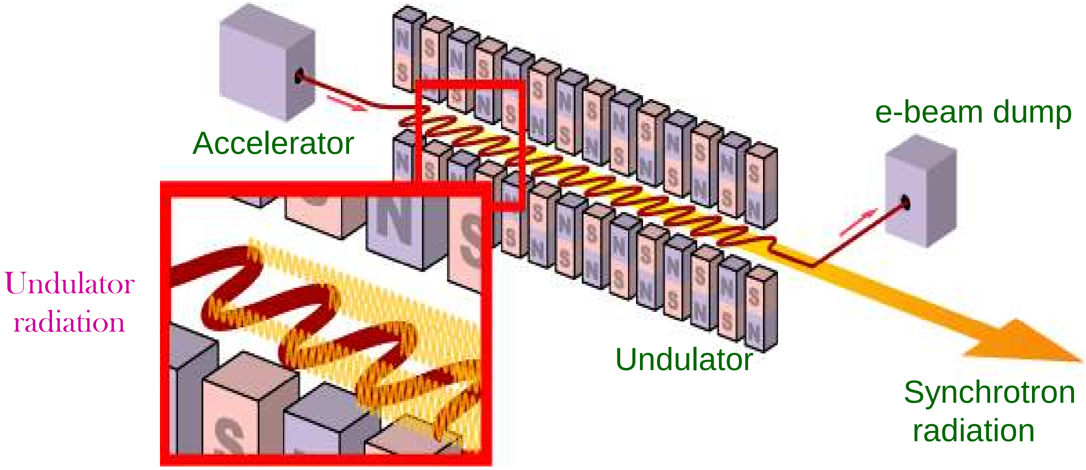
$$\theta_{cen} \cong \frac{1}{\gamma\sqrt{N}} \qquad \frac{\Delta\lambda}{\lambda} = \frac{1}{N}$$

$$K \equiv \frac{eB_0\lambda_u}{2\pi mc} = 0.9337 B_0(\mathrm{T})\lambda_u(\mathrm{cm})$$

Wavelength of radiation :

$$\lambda(\mathrm{nm}) = \frac{1.306\lambda_u(\mathrm{cm})\left(1 + \frac{K^2}{2} + \gamma^2\theta^2\right)}{E_e^2(\mathrm{GeV})}$$

- Tunability: by varying electron energy, period and amplitude of magnetic field

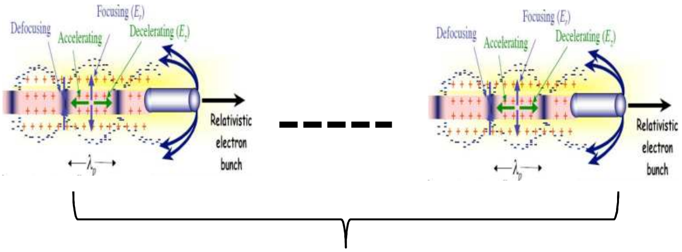


Relativistic electrons in a magnetic field follow a curved trajectory and therefore they are accelerated. The acceleration results in emission of radiation into a narrow cone (lab frame of reference).

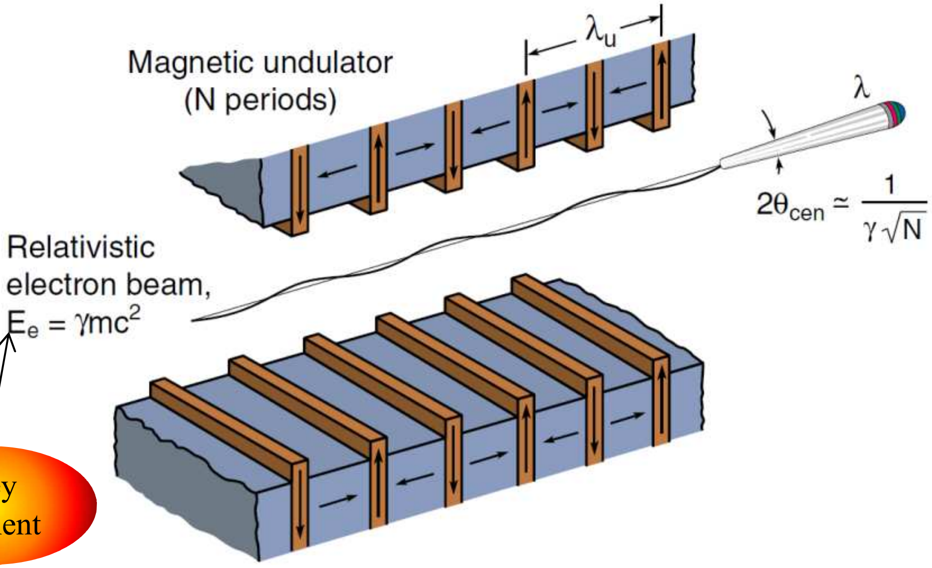
The Science and Technology of Undulators and Wigglers – J.A. Clarke, Oxford Univ. Press

Application - Intense X-rays from Undulator

- Energy of the electrons is higher (synchrotrons are operating with GeV electrons)
- Wavelength of the undulator field is larger (of the order of cm in the laboratory frame)



50GeV in 5m for $n_e \sim 10^{16}\ cm^{-3}$



Key element

V.Malka et. al., “Principle and applications of compact laser plasma accelerators”, Nature Physics 4, 447 - 453 (2008)

Summary

Features of plasma accelerated electron beams

- 🙂 High peak current (up to 100 kA)
- 🙂 Ultrashort bunch length (down to 10fs)
- 🙂 Compact & low cost
- 🙂 Excellent emittance
- 😐 High bunch charge (up to nC)
- 🙁 Energy Spread
- 🙁 Reproducibility of beam
- 🙂 The field is full of excitement !

THANK YOU

E. Esarey, C. B. Schroeder, and W. P. Leemans, "Physics of laser-driven plasma-based electron accelerators" Reviews of Modern physics, vol. 81, Jul-Sep. 2009.