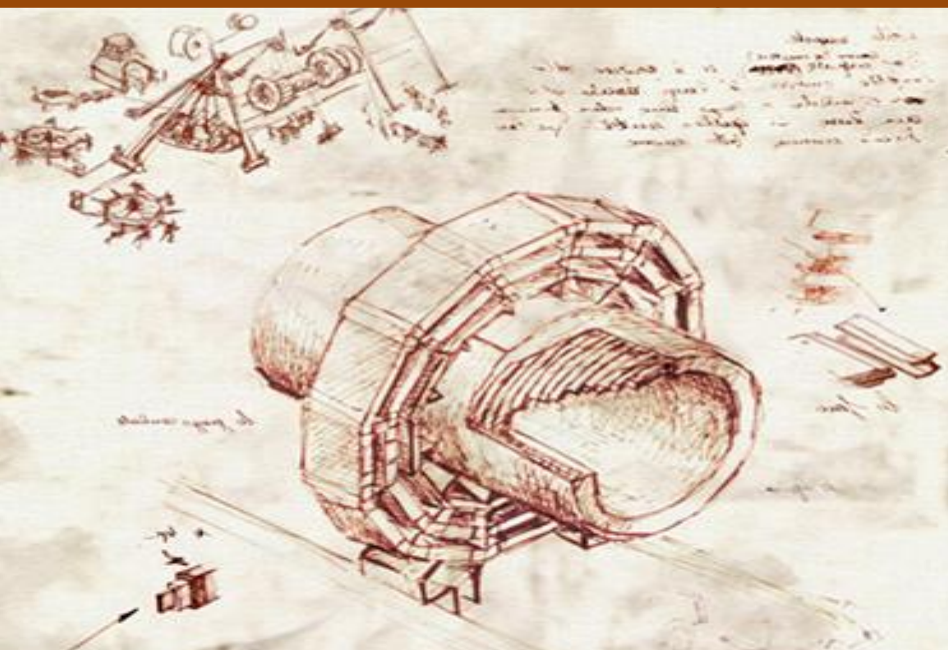
John Adams Institute for Accelerator Science

Imperial College London

Royal Holloway University of London

University of Oxford

Unifying physics of accelerators, lasers and plasma



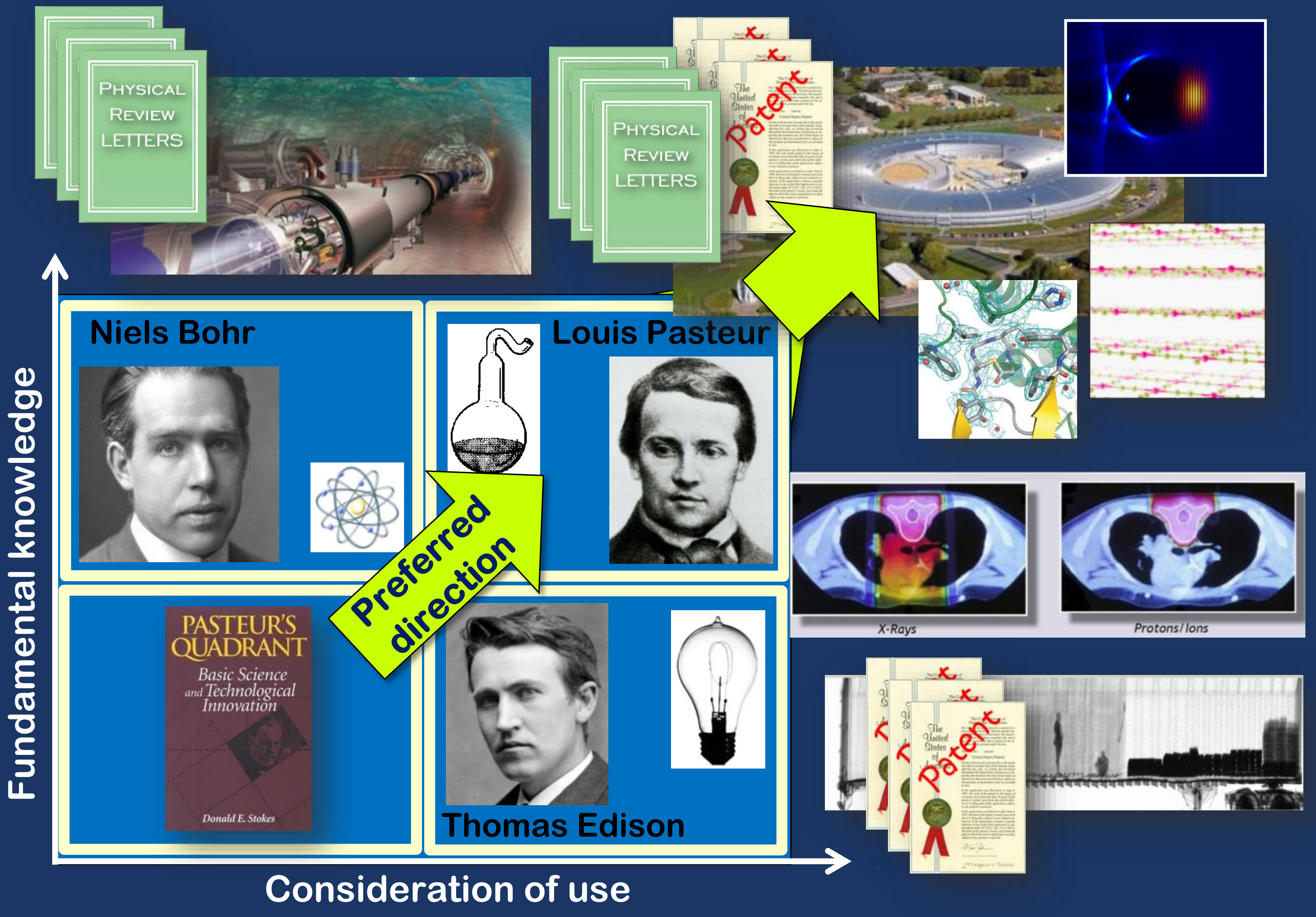
LHC sketches by Sergio Cittolin (CERN) – used with permission

Prof. Andrei A. Seryi
John Adams Institute

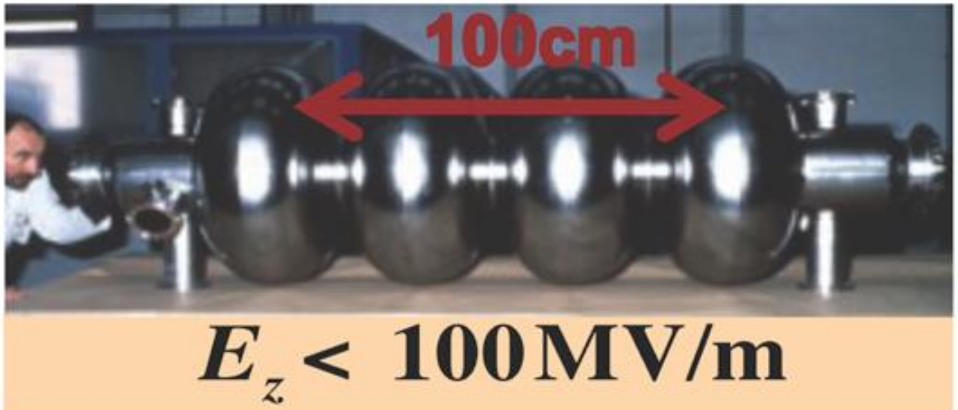
Lecture 6: Plasma acceleration

USPAS16

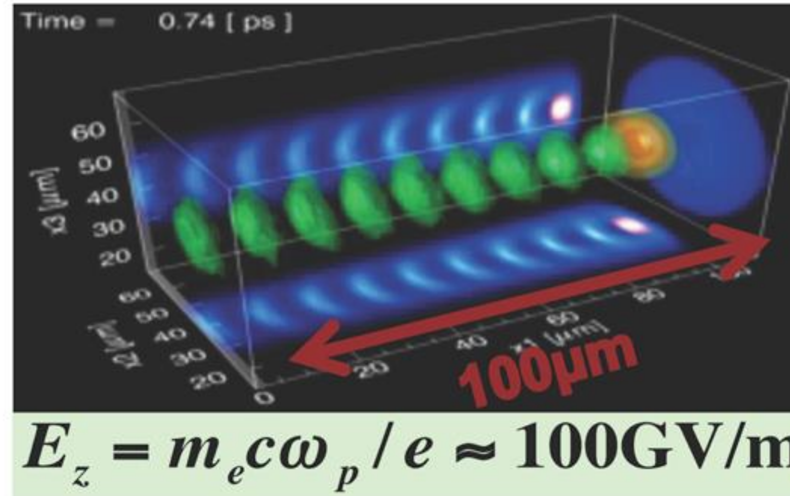
June 2016


Physical Review Letters
Physical Review Letters
Patent
Niels Bohr
Louis Pasteur
Preferred direction
PASTEUR'S QUADRANT
Basic Science and Technological Innovation
Donald E. Stokes
Thomas Edison
Fundamental knowledge
Consideration of use
X-Rays
Protons/Ions
Patent

Lasers and particle acceleration



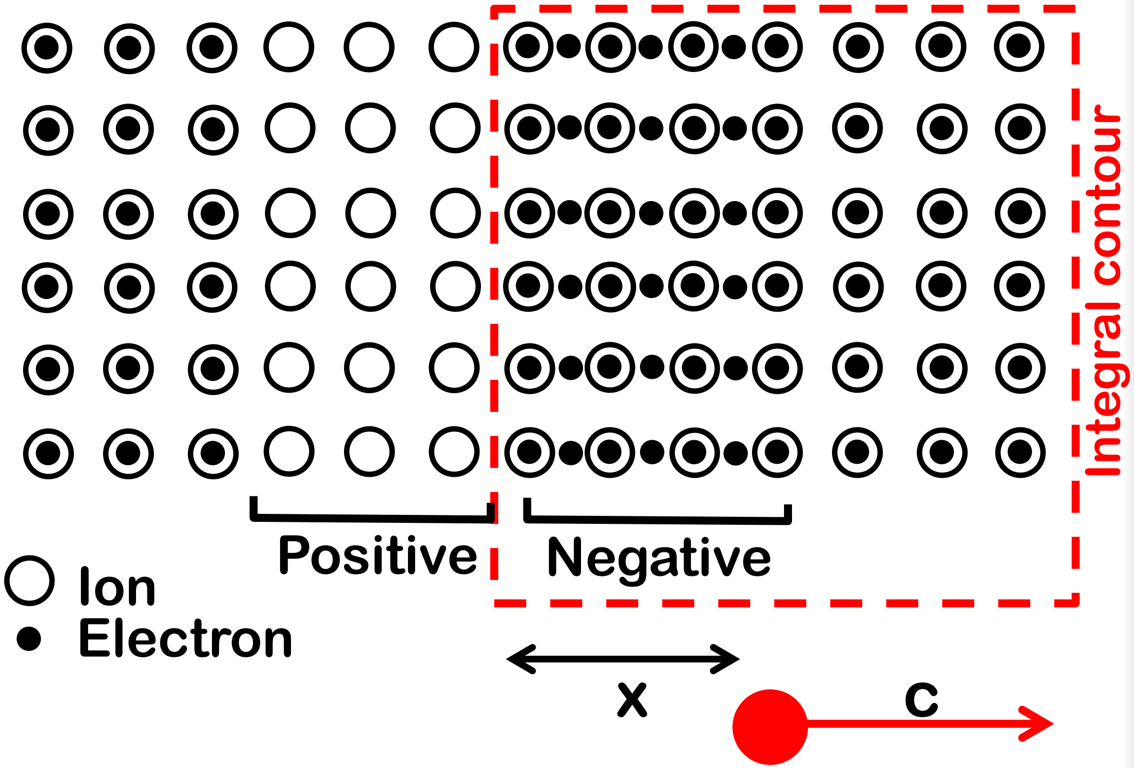
Accelerating structure, metal (normal-conductive or super-conductive)



"Accelerating structure" produced on-the-fly in plasma by laser pulse

- **Let's discuss laser plasma acceleration in detail**

Maximum field in plasma



Recall how we derived ω_p

$$\oint\!\!\oint_{\partial\Omega} \mathbf{E}\cdot d\mathbf{S} = \frac{1}{\varepsilon_0}\iiint_\Omega \rho dV \qquad E = \frac{nex}{\varepsilon_0}$$

$$F = m\frac{d^2x}{dt^2} = -eE = -\frac{ne^2x}{\varepsilon_0}$$

Oscillation frequency: $\omega_p^2 = \frac{ne^2}{\varepsilon_0 m}$

use: $r_e = \frac{1}{4\pi\varepsilon_0}\frac{e^2}{m_e c^2}$

to rewrite as: $\omega_p^2 = 4\pi n c^2 r_e$

Assume wave is excited by object moving with c

If total charge separation achieved in plasma, max field estimated taking $x \sim \lambda_p \sim \frac{c}{\omega_p}$

Thus $E_{max} \sim \frac{nec}{\varepsilon_0\omega_p} = \frac{mc\omega_p}{e}$ or $eE_{max} \cong mc^2\frac{\omega_p}{c}$

Use $f_p \sim 9000\, n^{1/2}$ (n in cm^{-3}) → $eE_{max} \approx 1\frac{eV}{cm}\cdot n^{1/2}\left(cm^{-3}\right)$

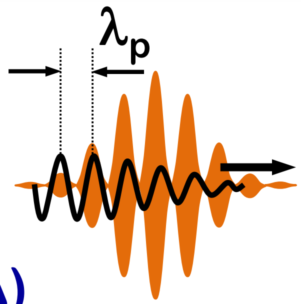
1 GeV/cm for plasma 10^{18} cm^{-3}

How to excite plasma

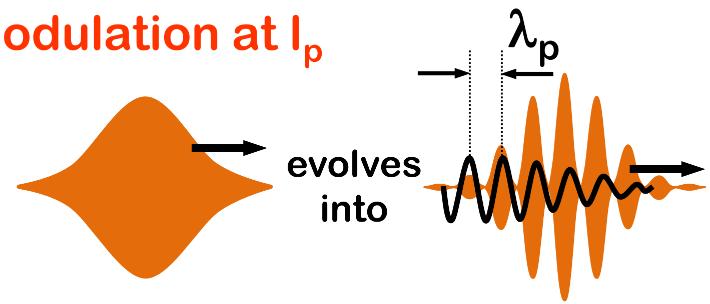
- We see that GeV/cm require plasma with $n=10^{18}$ cm^{-3}

$$\lambda_p = \frac{c}{f_p} \quad \rightarrow \quad \lambda_p \approx 0.1mm\sqrt{\frac{10^{17}\,cm^{-3}}{n}}$$

- Thus, short sub-ps pulses needed for plasma excitation
- In absence of short laser pulses other methods suggested:



- Plasma Beat Wave Accelerator (PBWA)
  - Two laser pulses of closer frequencies beat at w_p
- Self-Modulated Laser Wakefield Accelerator (SMLWFA)
  - Instability in a long laser pulse cause modulation at l_p

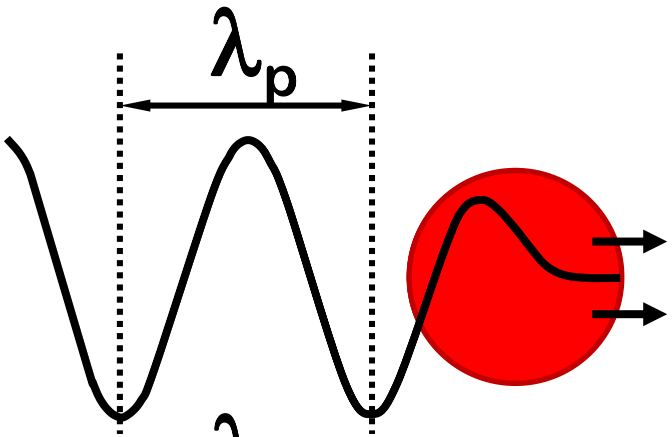


J.M. Dawson, Phys. Rev. Lett. 43, 267 (1979)

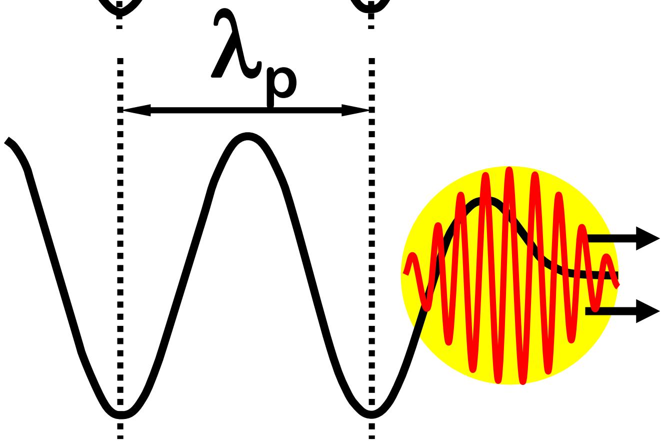
How to excite plasma

- **Availability of short sub-ps pulses of laser or beams stimulated rapid progress of plasma acceleration**

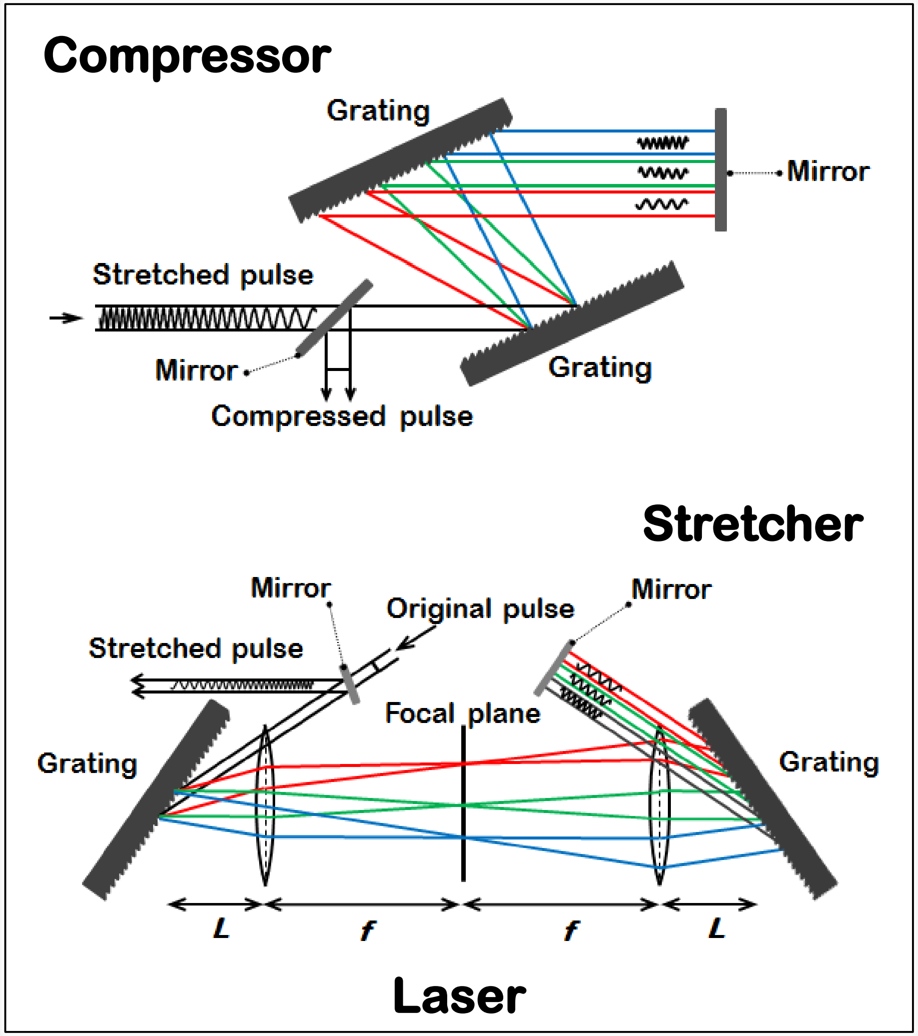
- **Plasma Wakefield Accelerator (PWFA)**
  - A short high energy particle bunch

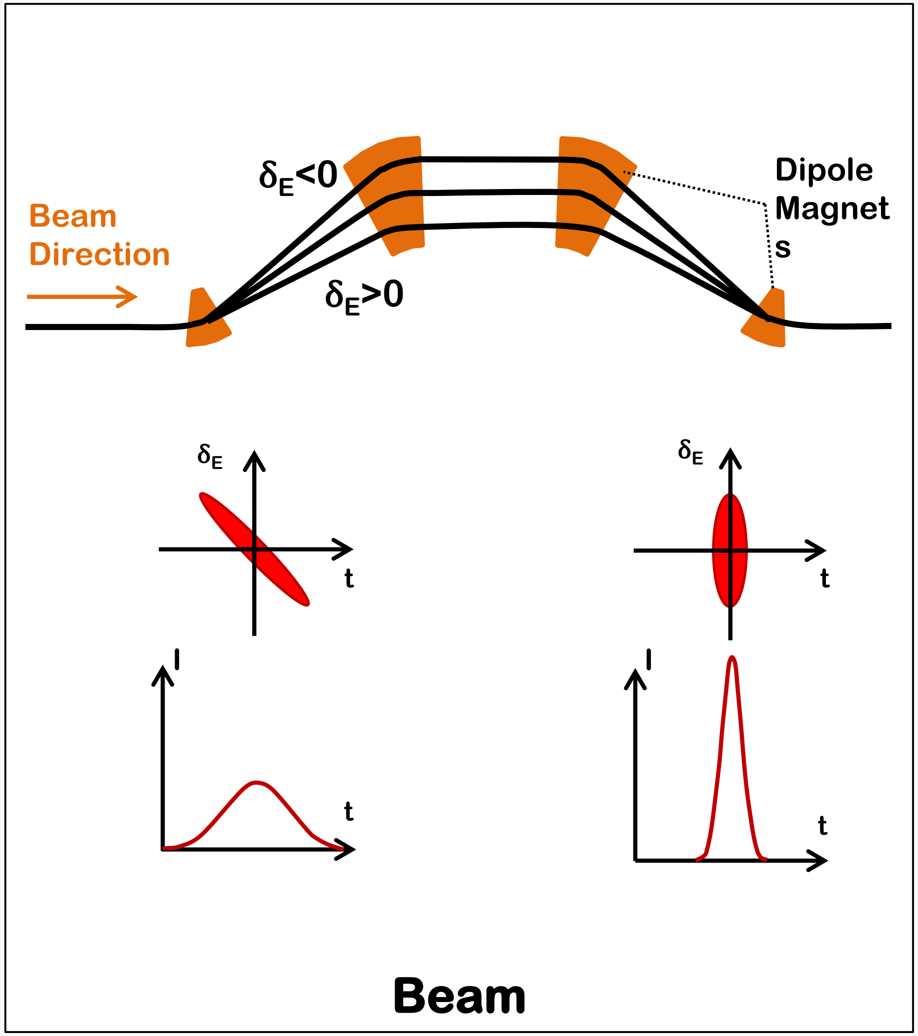


- **Laser Wakefield Accelerator (LWFA)**
  - A short laser pulse of <u>high intensity</u>



Beam and laser bunch/pulse compression

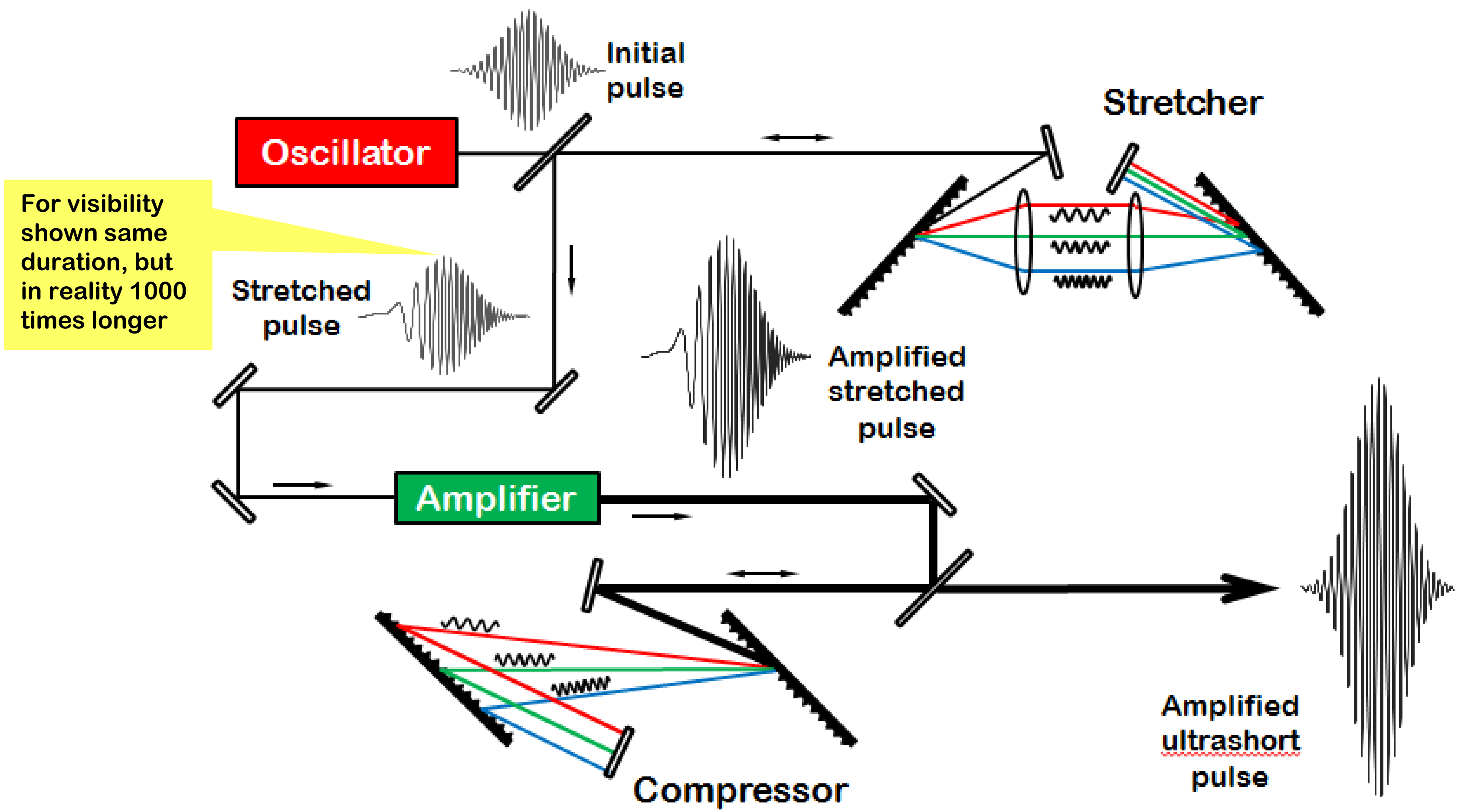




Both in laser and beam use z-Energy correlation to compress/stretch the pulse – one more general principle of AS-TRIZ

Telescope is needed inside stretcher to create "negative distance"

CPA – Chirped Pulse Amplification



- CPA: pulse stretching and compressing using time-energy correlation
  - Amplification of chirped pulses was used in radars – the trend from microwave to optical can be taken as one of generic principles for TRIZ

Laser pulse of high intensity

Laser intensity (in vacuum)

$$I = \frac{1}{2}\varepsilon_0 E_{max}^2 c \quad \textbf{(SI)}$$

$$I = \frac{1}{8\pi} E_{max}^2 c \quad \textbf{(Gaussian)}$$

Fields in practical units:

$$E_{max}\left[\left(\frac{V}{cm}\right)\right] \cong 2.75\times10^{9}\left(\frac{I}{10^{16}\,W/cm^2}\right)^{1/2}$$

$$B_{max}[\text{Gauss}] \cong 9.2\times10^{6}\left(\frac{I}{10^{16}\,W/cm^2}\right)^{1/2}$$

(useful to remember that 300 V/cm is ~ same as 1 Gauss)

Compare with field in a hydrogen atom. Bohr radius and field:

$$a_B = \frac{\hbar^2}{me^2} = 5.3\times10^{-9}\,\text{cm}$$

$$E_a = \frac{e}{a_B^2} \quad = \frac{e}{4\pi\varepsilon_0 a_B^2} \quad \approx 5.1\times10^{11}\,\frac{V}{m}$$

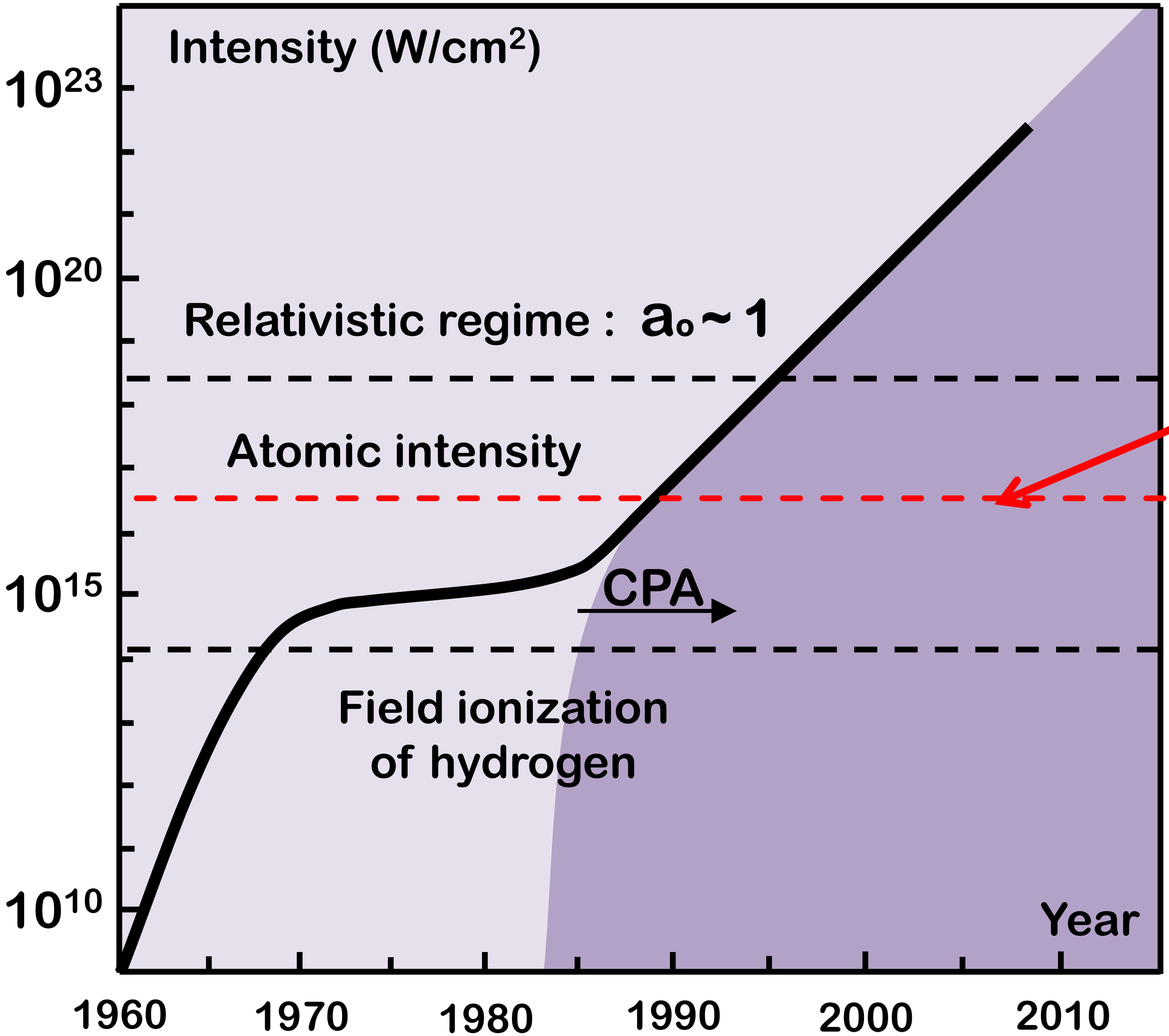
(Gaussian) **(SI)**

(Recall $\varepsilon_0 \approx 8.8\cdot10^{-12}\,\frac{A^2\cdot s^4}{kg\cdot m^3}$ **)**

Atomic intensity $$I_a = \frac{\varepsilon_0 c E_a^2}{2} \cong 3.51\times10^{16}\,\frac{W}{cm^2}$$

A laser with intensity higher than that will ionize gas immediately

Laser intensity

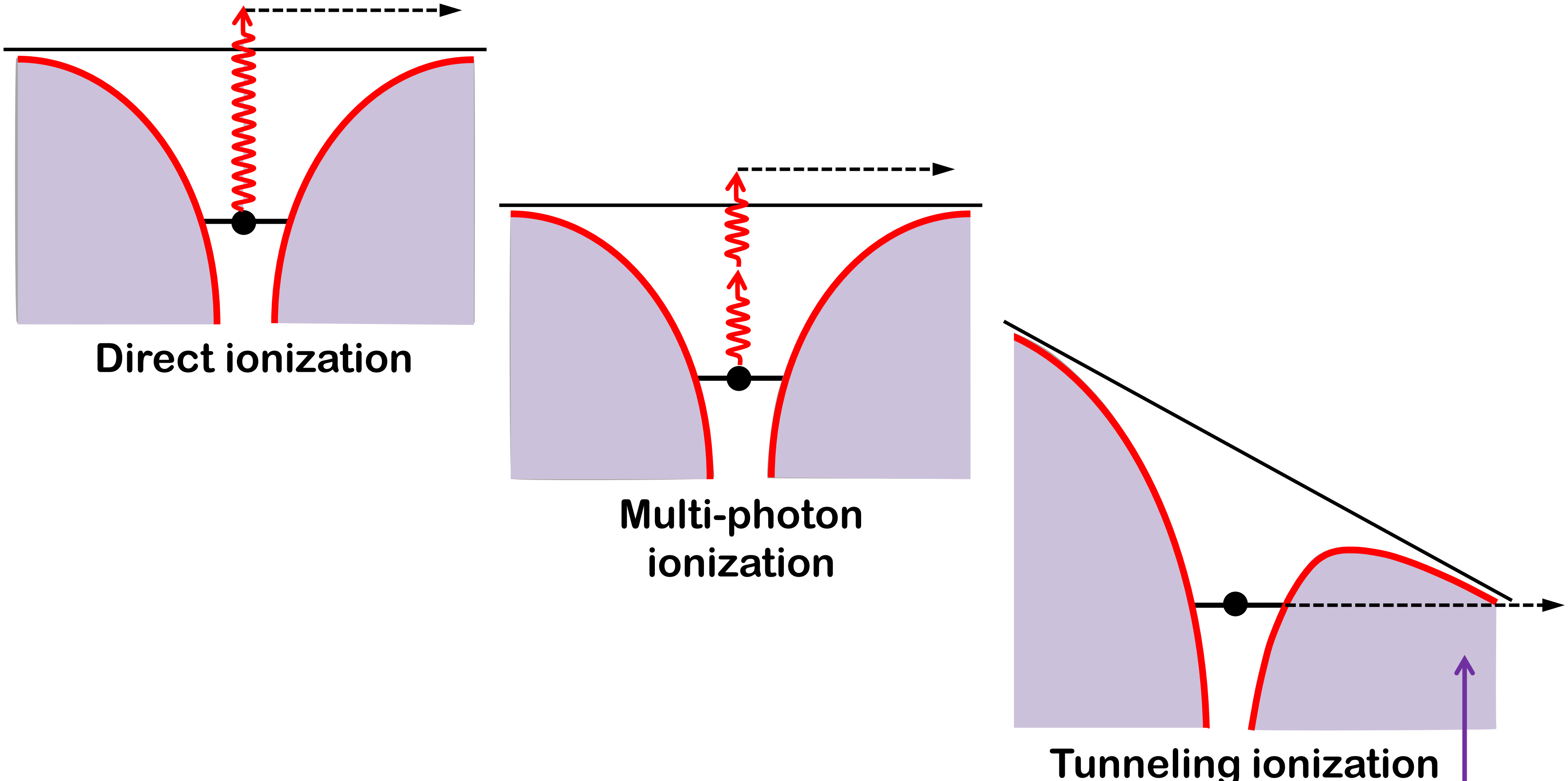


Progress in peak intensity since laser invention in 1960

$$I_a = \frac{\varepsilon_0 c E_a^2}{2} \cong 3.51\times 10^{16} \frac{W}{cm^2}$$

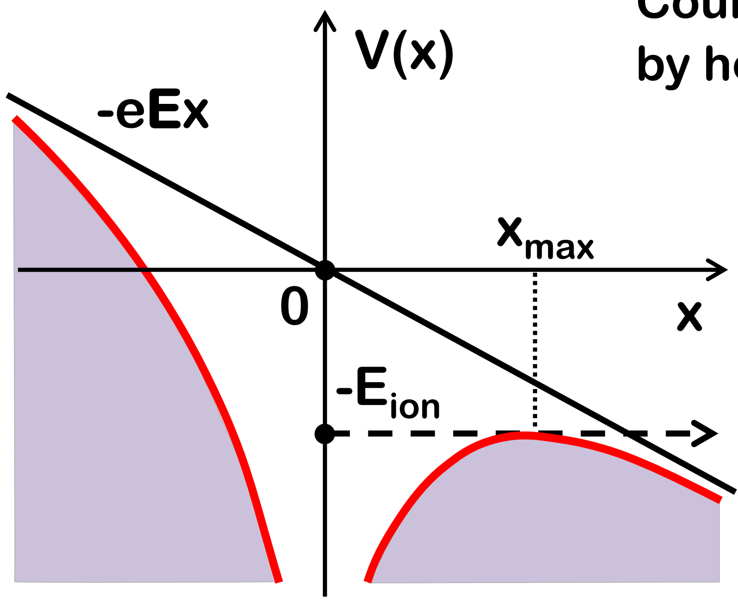
- In fact, Ionization can occur well below this threshold due to:
  - multi-photon effects;
  - tunneling ionization

Types of ionization



With even more laser intensity – barrier suppression ionization (BSI)

Laser intensity for barrier suppression ionization



Coulomb potential of hydrogen atom distorted by homogeneous field ε:

$$V(x) = -\frac{e^2}{x} - e\varepsilon x$$

Find position of the maximum:

$$x_{max} = (e/\varepsilon)^{1/2}$$

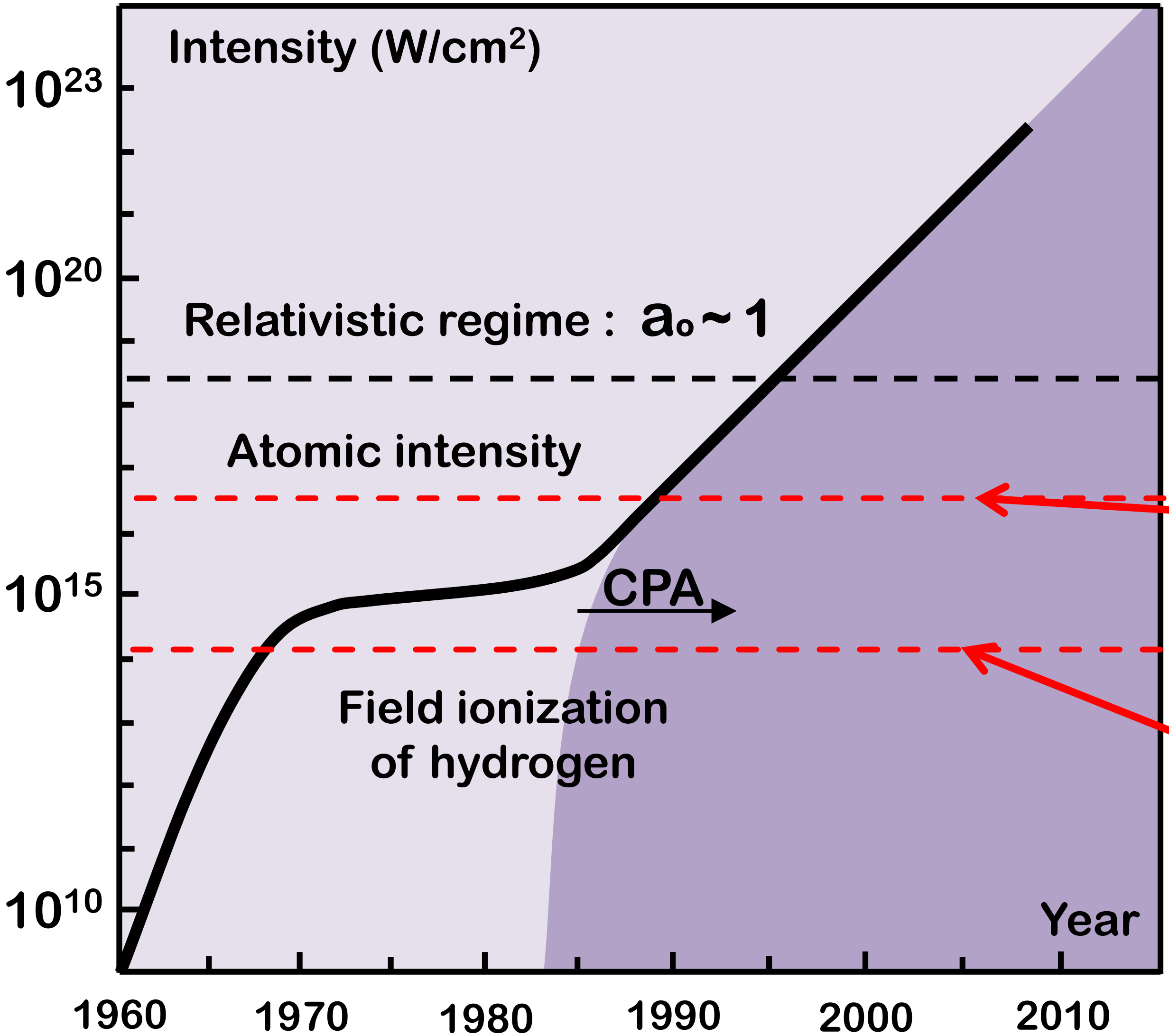
Equate potential value at max to hydrogen ionization potential

$$V(x_{max}) = 2(e^3\varepsilon)^{1/2} \quad = \quad E_{ion} = \frac{e^2}{2a_B} \approx 13.6\text{eV}$$

The critical field for hydrogen is therefore $\varepsilon_c = \frac{e}{16a_B^2} = \frac{E_a}{16}$

Which corresponds to intensity $I_c = \frac{I_a}{256} \approx 1.4 \cdot 10^{14}\,\text{W}/\text{cm}^2$

Laser intensity



Progress in peak intensity since laser invention in 1960

$$I_a = \frac{\varepsilon_0 c E_a^2}{2} \cong 3.51 \times 10^{16} \frac{W}{cm^2}$$

$$I_c = \frac{I_a}{256} \approx 1.4 \cdot 10^{14} W/cm^2$$

Normalized vector potential

The laser field can be written in terms of the vector potential of the laser field A as

$$\mathbf{E} = -\frac{\partial \mathbf{A}}{c\partial t}, \quad \mathbf{B} = \nabla \times \mathbf{A}$$

For linearly polarized field

$$\mathbf{A} = A_0 \cos(kz - \omega t)\mathbf{e}_\perp$$

We see that $E_0 = \frac{A_0 \omega}{c}$

Compare momentum gained by e- in one cycle of laser field $e\,E\,\Delta t \cong \frac{eE}{\omega}$ with $m_e c$

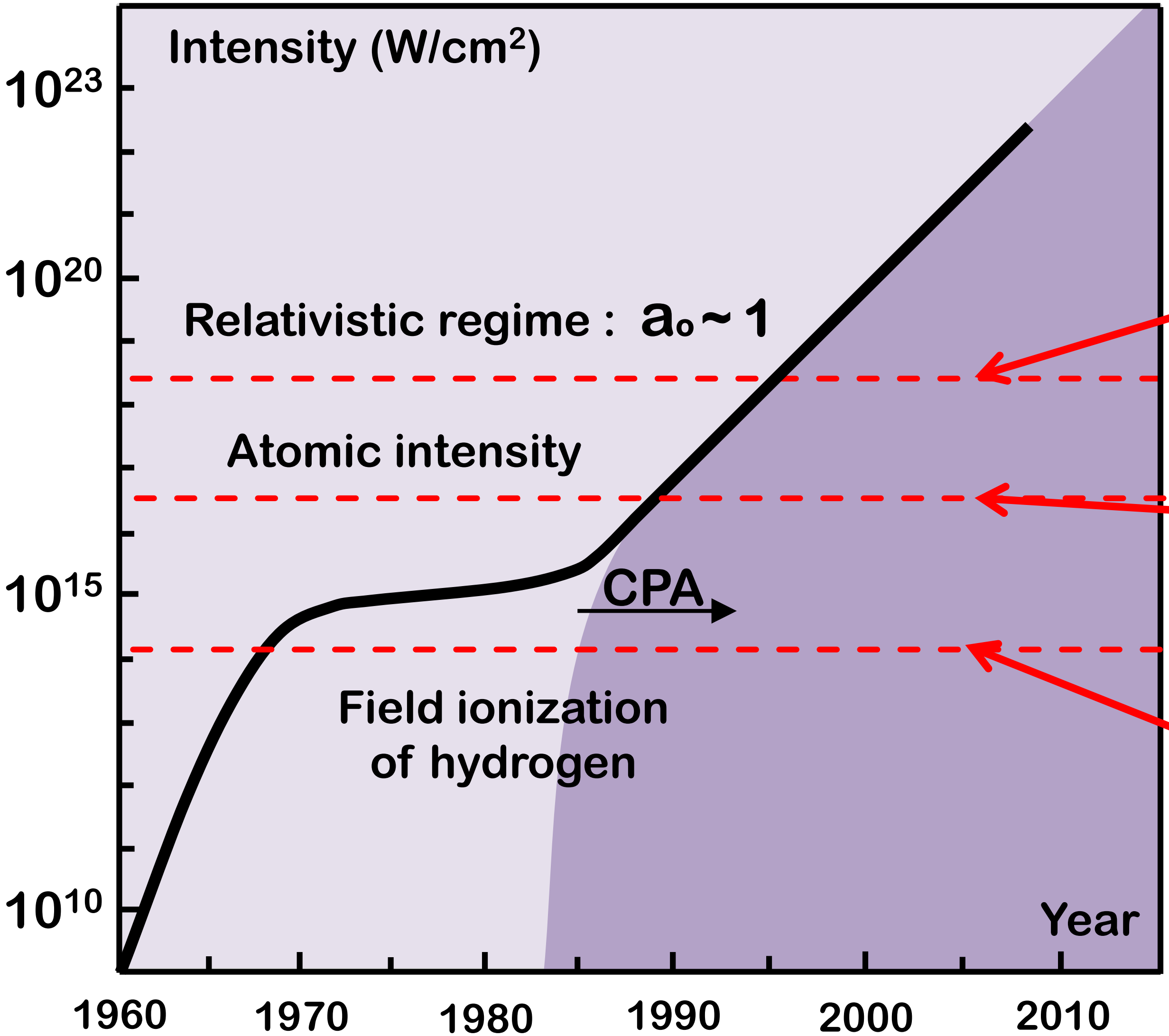
We see that it is useful to define the normalized vector potential as $\mathbf{a} = \frac{e\mathbf{A}}{m_e c^2}$ with amplitude $a_0 = \frac{eE_0}{m_e \omega c}$

The amplitude a_0 will indicate if the electron motion in laser field relativistic

a_0 >> 1 – relativistic, a_0 << 1 – non relativistic

In practical units $a_0 \approx \left(\frac{I[W/cm^2]}{1.37 \cdot 10^{18}} \right)^{\frac{1}{2}} \cdot \lambda[\mu m]$ where $\lambda = \frac{2\pi c}{\omega}$

Laser intensity



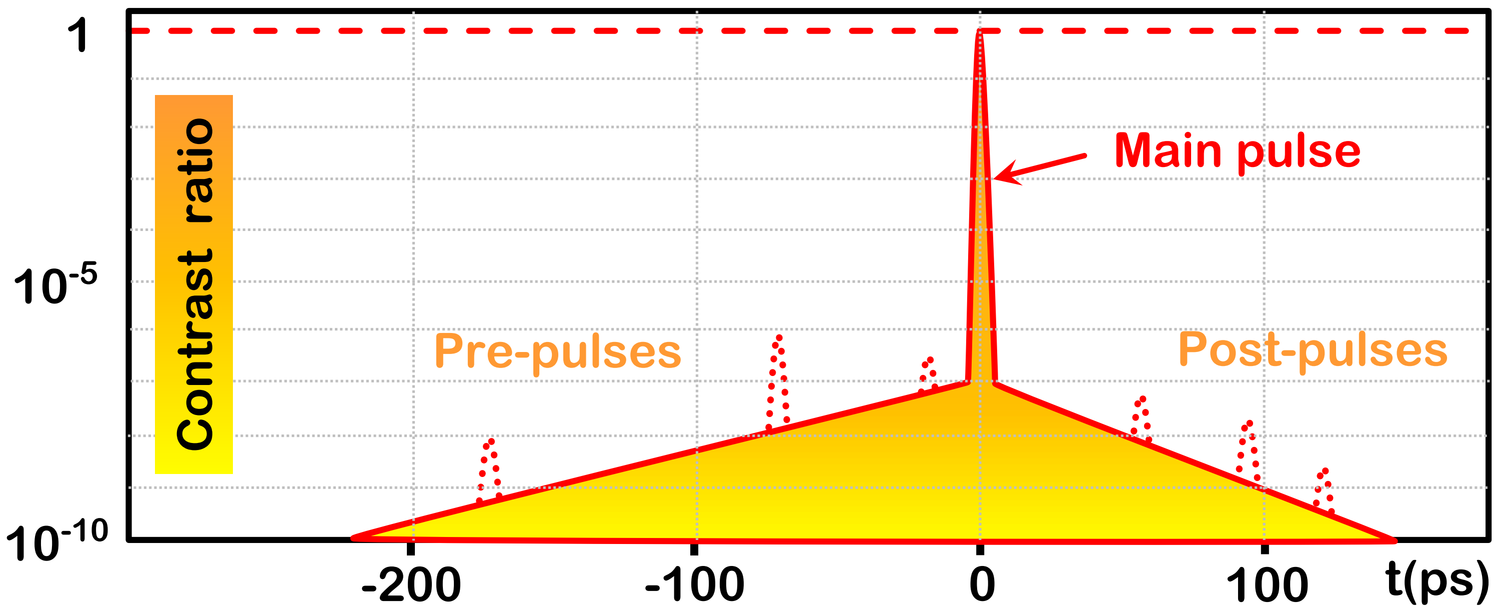
Progress in peak intensity since laser invention in 1960

a_0 ~1 for red laser

$$I_a = \frac{\varepsilon_0 c E_a^2}{2} \cong 3.51\times10^{16}\,\frac{W}{cm^2}$$

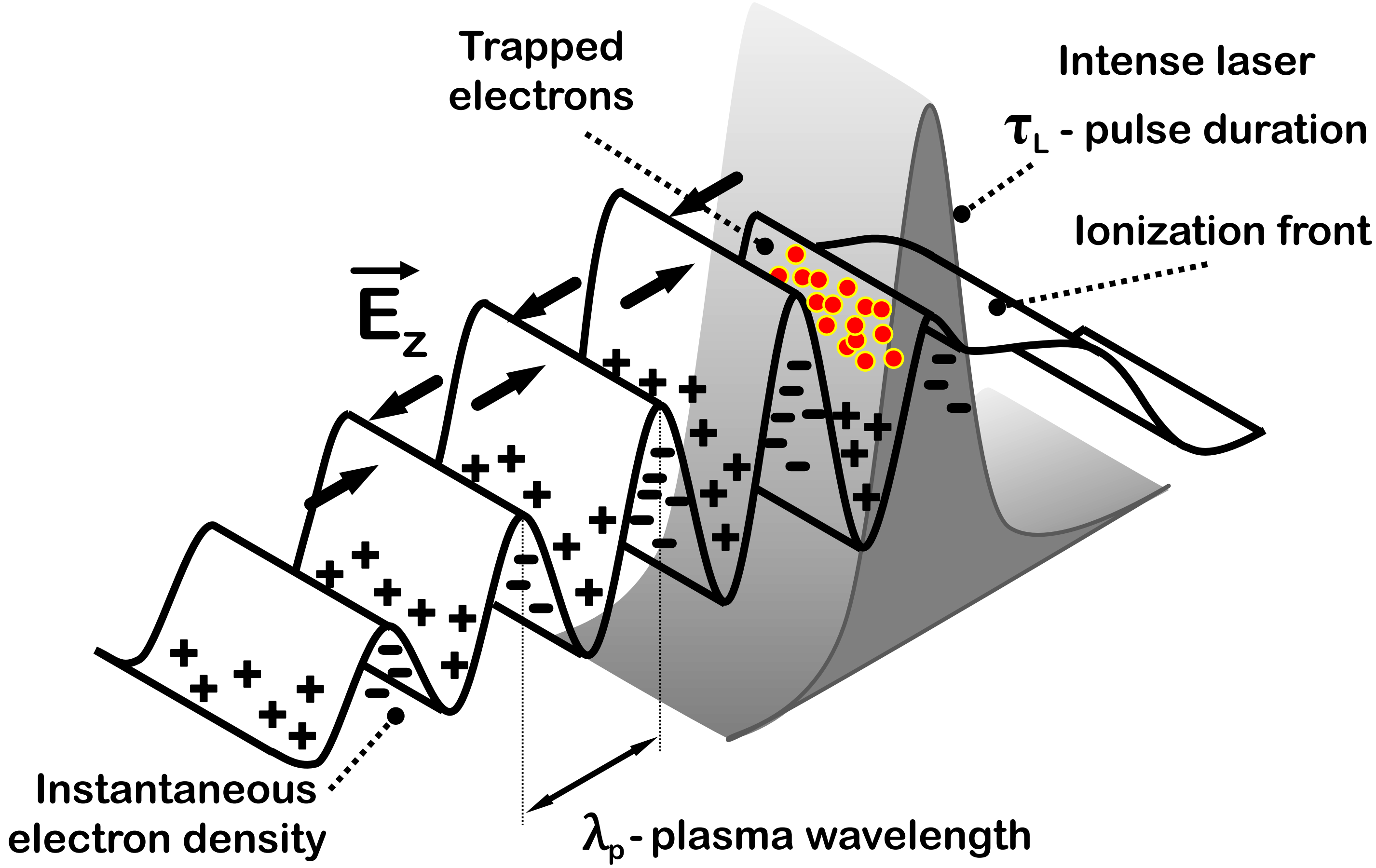
$$I_c = \frac{I_a}{256} \approx 1.4\cdot10^{14}\,W/cm^2$$

CPA-compressed pulse



- Qualitative temporal profile of CPA-compressed laser pulse
  - Pre- and post-pulses typically cased by nonlinear properties of the elements of CPA system and non-ideal properties of the initial laser pulse

Laser acceleration - conceptually



- **Note in particular**
  - Ionization front starting at the front tail of laser
  - Laser pulse length similar of shorter than plasma wavelength
  - Electrons trapped in the first bubble

Formation of bubble – ponderomotive force

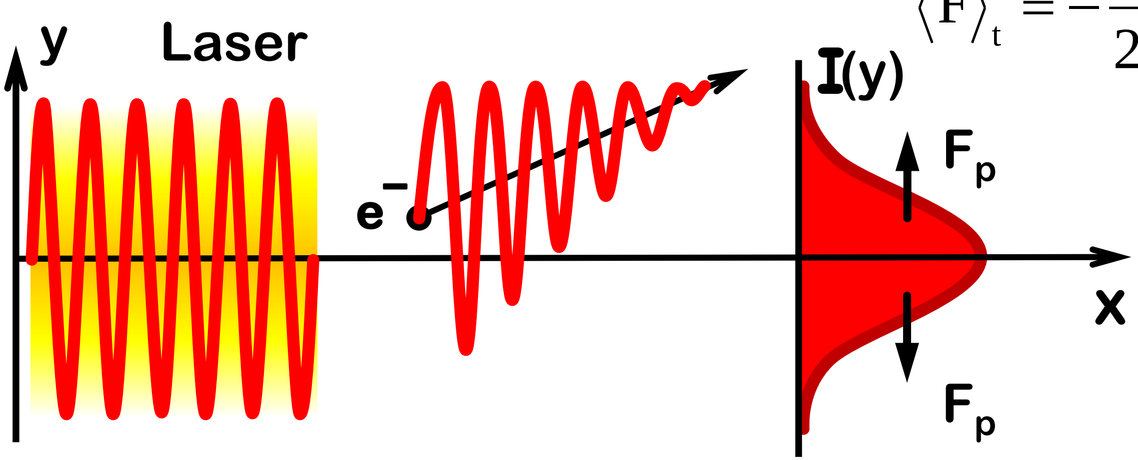
First, assume laser field homogeneous: $E = E_0 \cos(\omega t)$

Motion of electron: $\ddot{y} = \frac{F}{m} = \frac{eE}{m} \quad \Rightarrow \quad y = -\frac{eE_0}{m\omega^2}\cos(\omega t)$

Now, assume E has gradient in y: $E = E_0(y)\cos(\omega t) \approx E_0 \cos(\omega t) + y\frac{\partial E_0}{\partial y}\cos(\omega t)$

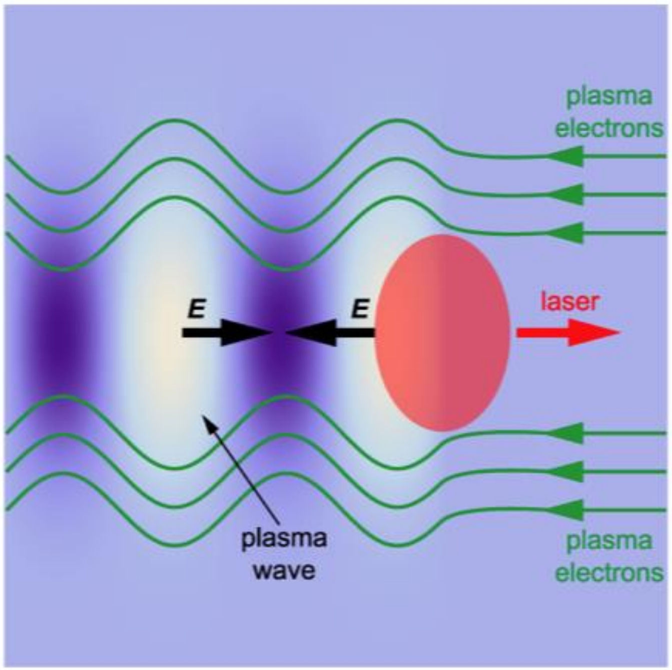
Find time average of force acting on e-: $\langle F \rangle_t = \left\langle -\frac{eE_0}{m\omega^2}\cos(\omega t)\cdot\frac{\partial E_0}{\partial y}\cos(\omega t)\right\rangle_t$

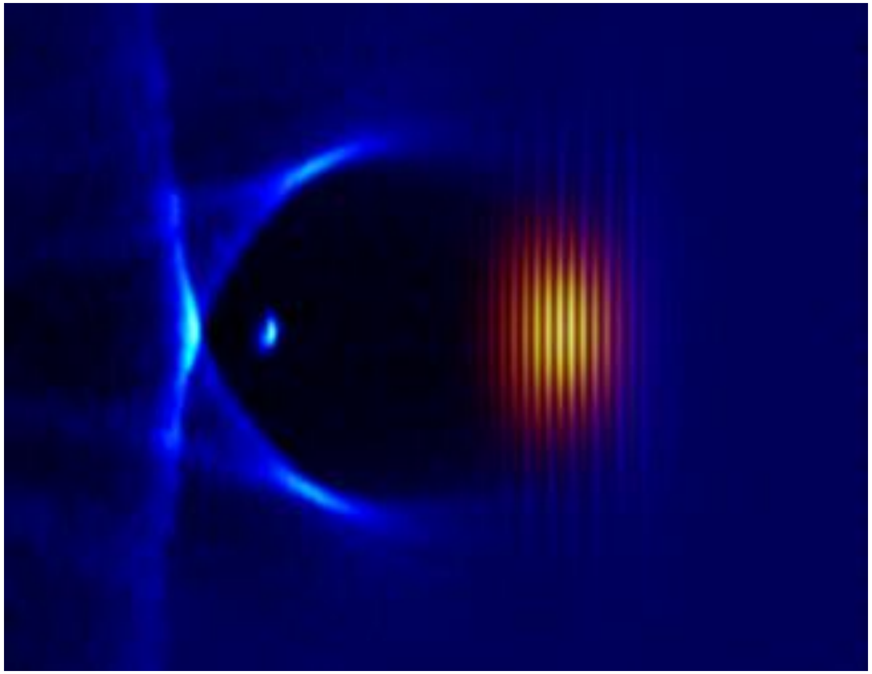
$$\langle F \rangle_t = -\frac{e^2}{2m\omega^2}E_0\frac{\partial E_0}{\partial y} = -\frac{e^2}{4m\omega^2}\frac{\partial E_0^2}{\partial y}$$



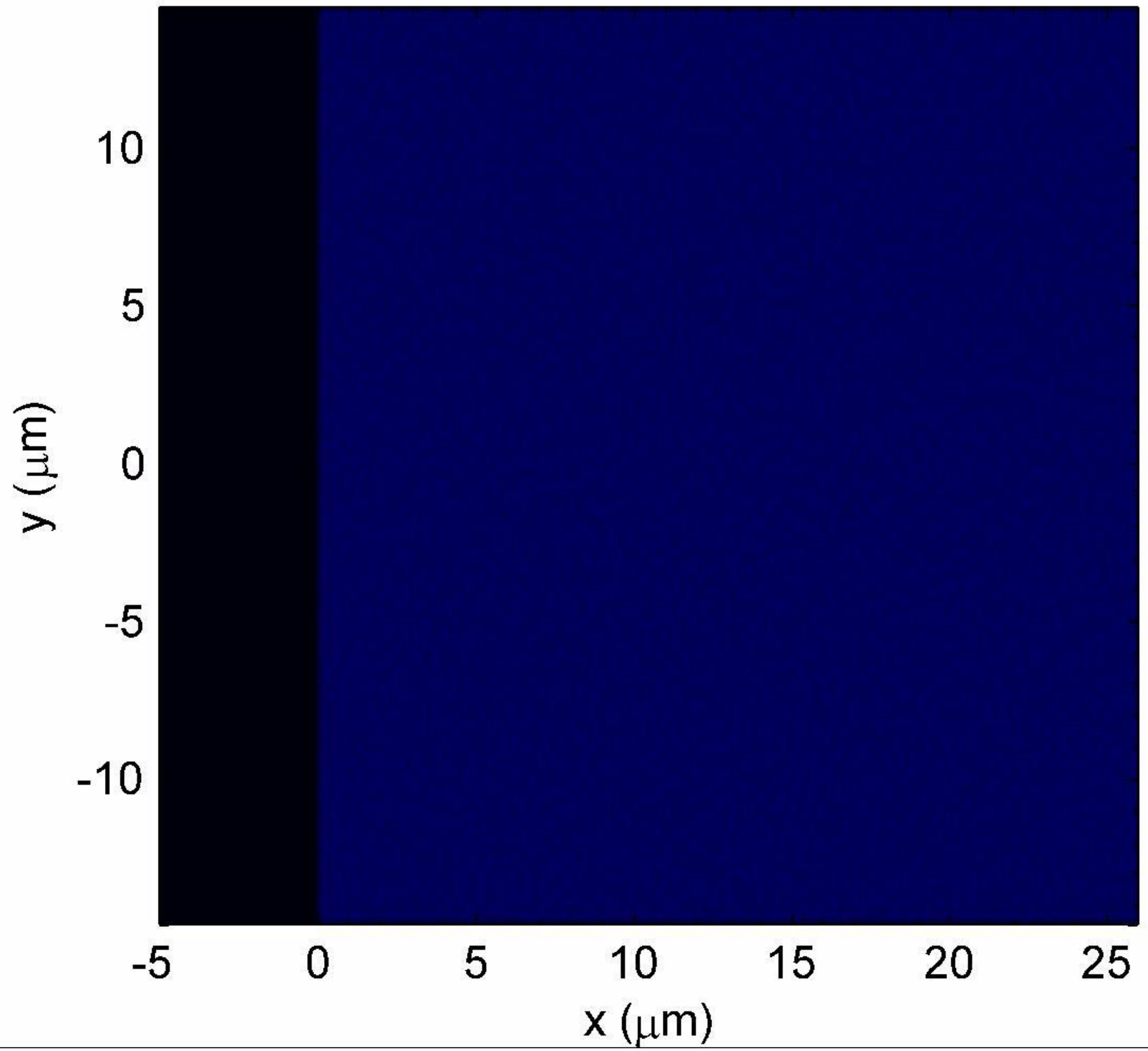
Ponderomotive force pushes electrons out from the high intensity region

Laser-Driven Plasma Acceleration





- Ponderomotive force of short (50fs), intense (10^{18} W cm^{-2}) laser pulse expels plasma electrons while heavier ions stay at rest
- Electrons attracted back to ions, forming a bubble (blow-out regime) and setting up plasma wave which trails laser pulse
- Electric fields within plasma wave of order 100 GV/m formed



Simulation courtesy Prof Simon Hooker

How e- gets into the bubble – wave breaking

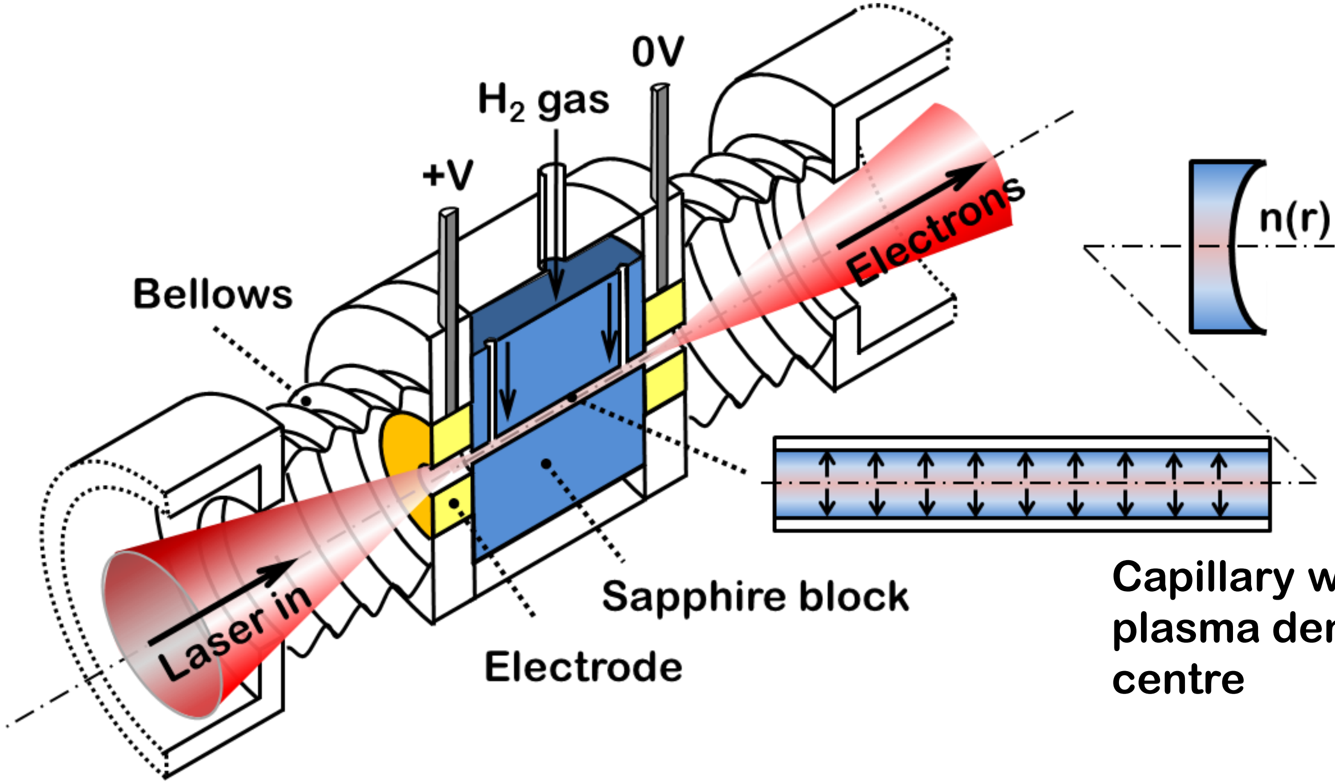
- **Wave breaking**
  - Self-injection of background plasma electrons to the wake when some particles outrun the wake

- **Other methods**
  - External injection (difficult for so short bunches)
  - Methods which involve two laser pulses and mix of two gases with different ionization potential

Importance of laser guidance

- As laser propagates through the gas/plasma, several competing effects are important
  - Dephasing
  - Depletion
  - Longitudinal compression by plasma waves
  - Self focusing
    - Including relativistic effect – electrons of plasma at centre become relativistic and have higher mass
  - Diffraction
    - Small laser beam (~30μm) will diffract very fast
    - Includes ionization caused diffraction (centre where intensity is higher ionized first)
- A possible solution – create a channel with plasma density profile n(r) to guide laser
  - A particular solution – capillary discharge channel developed in Oxford

Importance of laser guidance

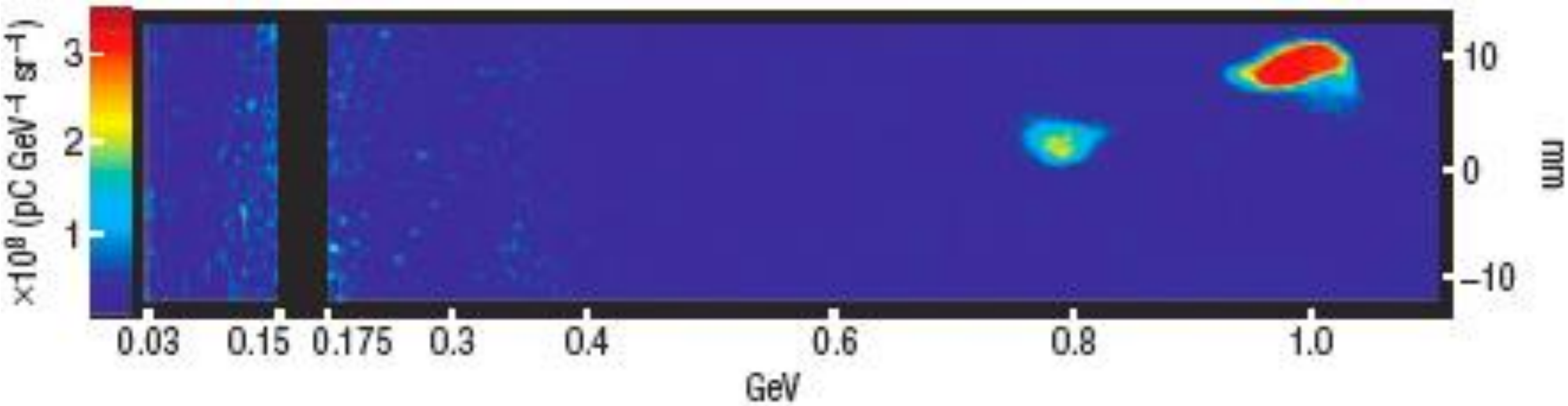


Capillary channel designed by Prof Simon Hooker

- **Capillary channel allowed exceeding 1GeV laser plasma acceleration for the first time**

First ever 1 GeV from laser plasma accelerator

- 1 GeV acceleration & monoenergetic beam
  - Use of guiding capillary was essential

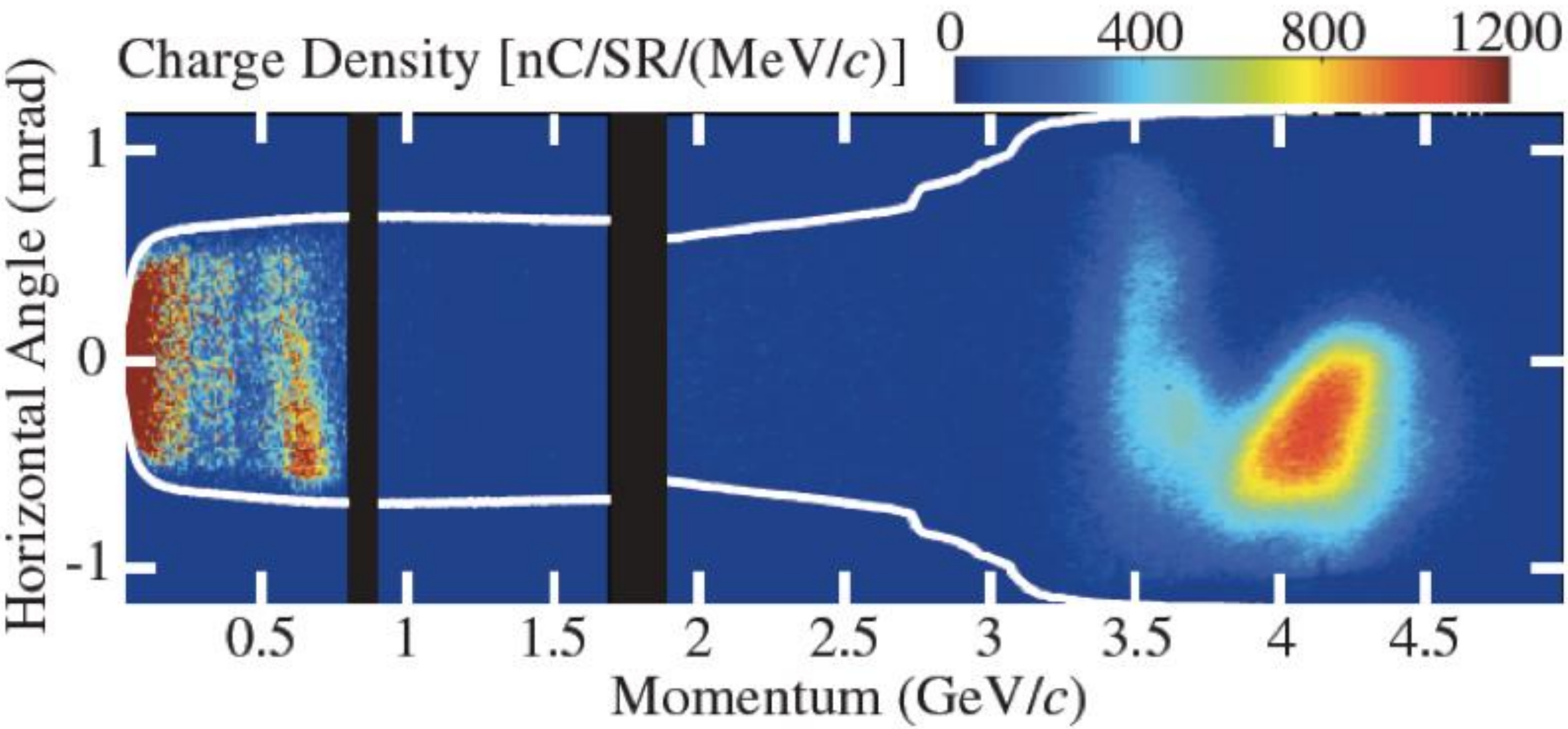


1GeV acceleration in just 3cm of plasma

W. Leemans, B. Nagler, A. Gonsalves, C. Toth, K. Nakamura, C. Geddes, E. Esarey, C. B.Schroeder, & S. Hooker, ***Nature Physics*** 2006

Plasma density 2.7x10^{18} cm^{-3}, 40 TW laser with 1018 W/cm^2

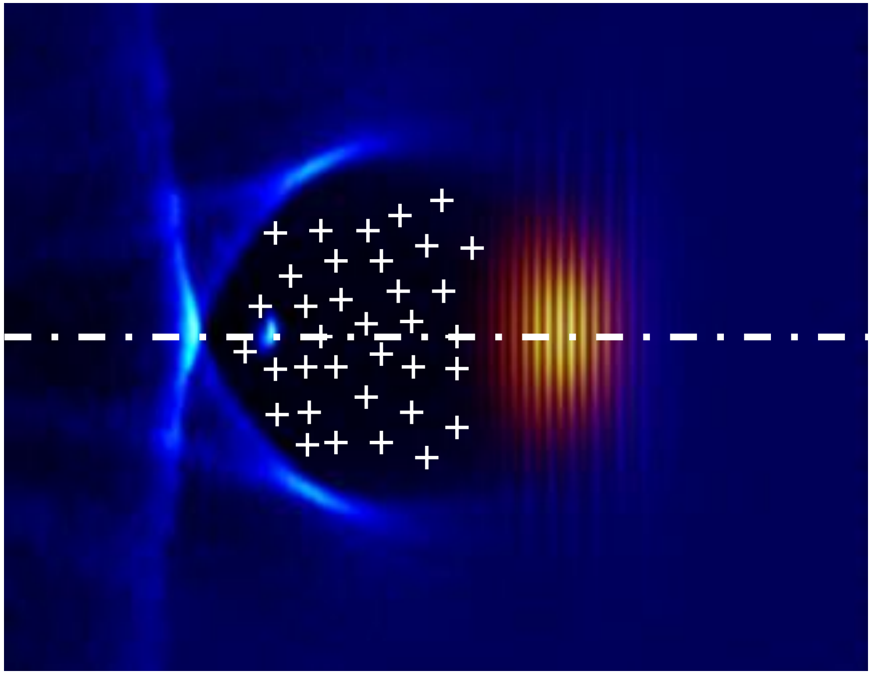
Recent energy record



4.2 GeV, 2014

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

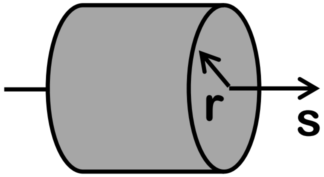
Transverse fields in the bubble



The ions are heavy and are inside of the bubble. They produce focusing force.

$$\oint \mathbf{E} \cdot d\mathbf{S} = 4\pi \int \rho dV$$ (Gaussian)

Assume cylindrical symmetry



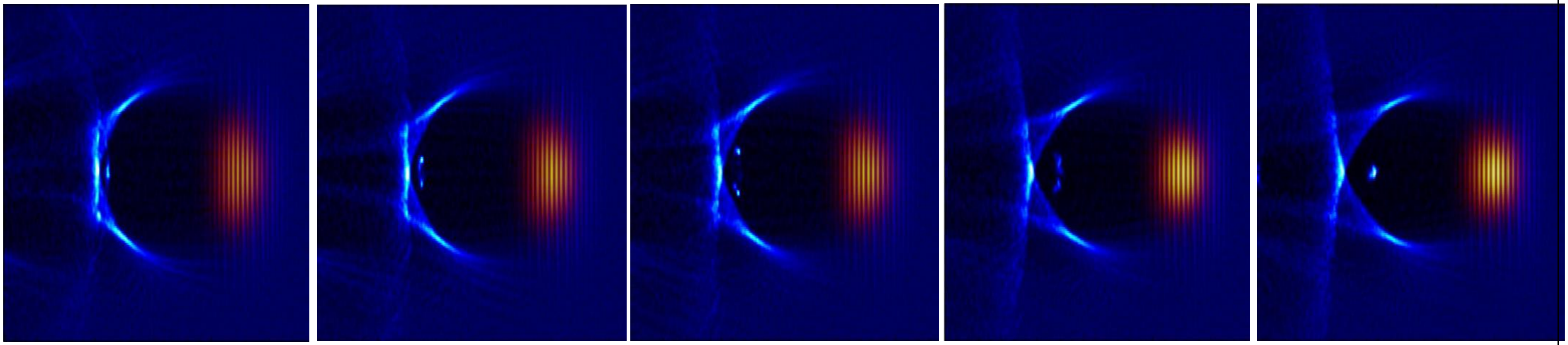
Focusing force $eE = 2\pi n e^2 r$

Assume electron is relativistic with γ

It will oscillate in this field as $$\frac{d^2 r}{ds^2} = \frac{2\pi n e^2 r}{\gamma m c^2} = \frac{\omega_p^2}{2\gamma c^2} r$$

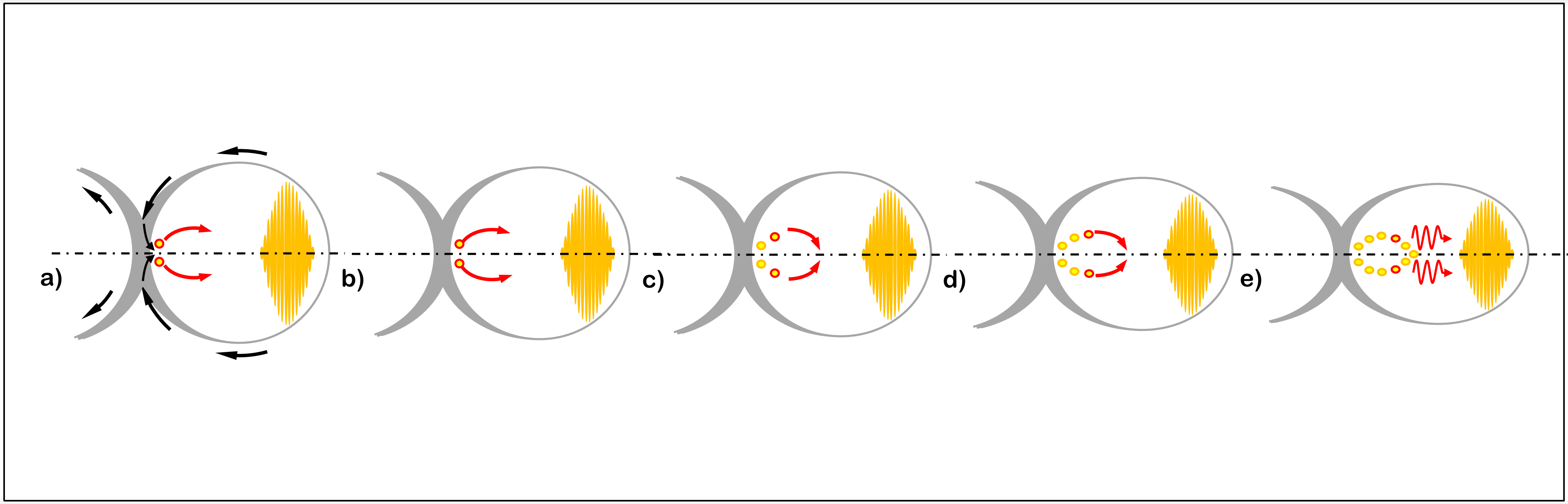
The period of oscillation is therefore $\lambda = \sqrt{2\gamma}\ \lambda_p$

Betatron radiation



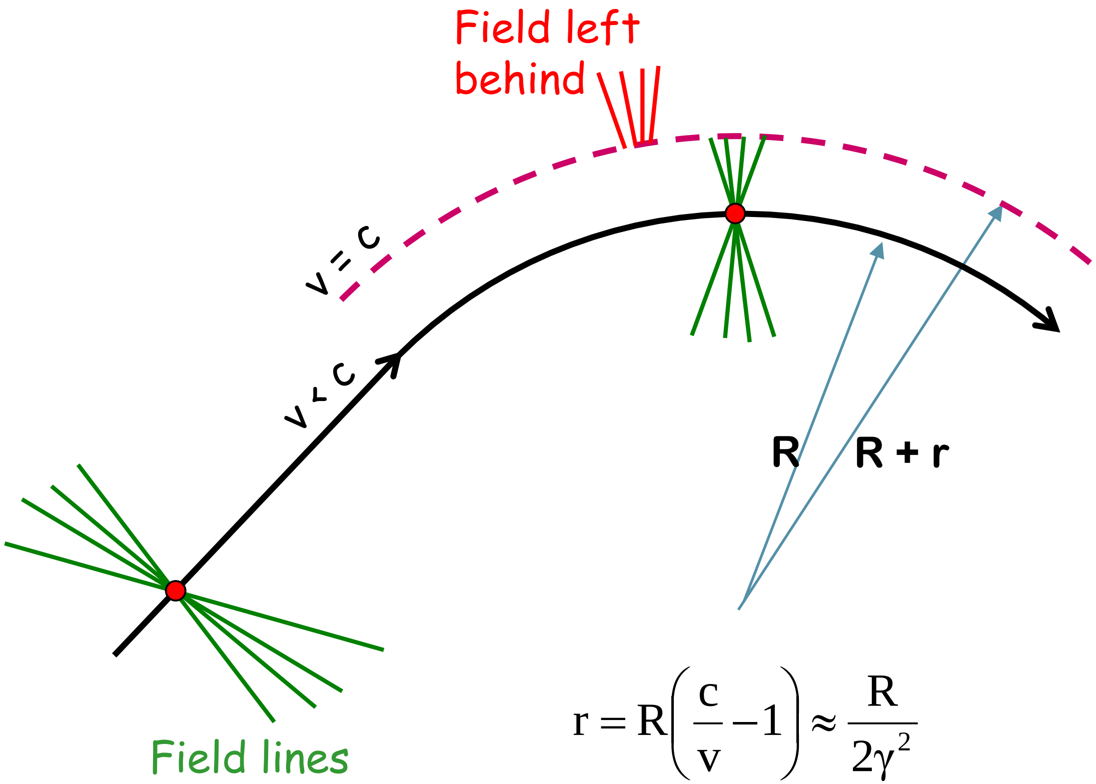
- Strong radial electric field within plasma wave cause transverse oscillation of electron bunch
- Generates bright betatron radiation in 1- 100 keV range
- Let’s estimate parameters of this radiation

Betatron radiation



- Strong radial electric field within plasma wave cause transverse oscillation of electron bunch
- Generates bright betatron radiation in 1- 100 keV range
- Let's estimate parameters of this radiation

Synchrotron radiation
on-the-back-of-the envelope – power loss (recall)



$$r = R\left(\frac{c}{v} - 1\right) \approx \frac{R}{2\gamma^2}$$

Energy in the field left behind (radiated !):

$$W \approx \int E^2\, dV$$

The field $E \approx \frac{e}{r^2}$ **the volume** $V \approx r^2\, dS$

Energy loss per unit length:

$$\frac{dW}{dS} \approx E^2 r^2 \approx \left(\frac{e}{r^2}\right)^2 r^2$$

Substitute $r \approx \frac{R}{2\gamma^2}$ **and get an estimate:**

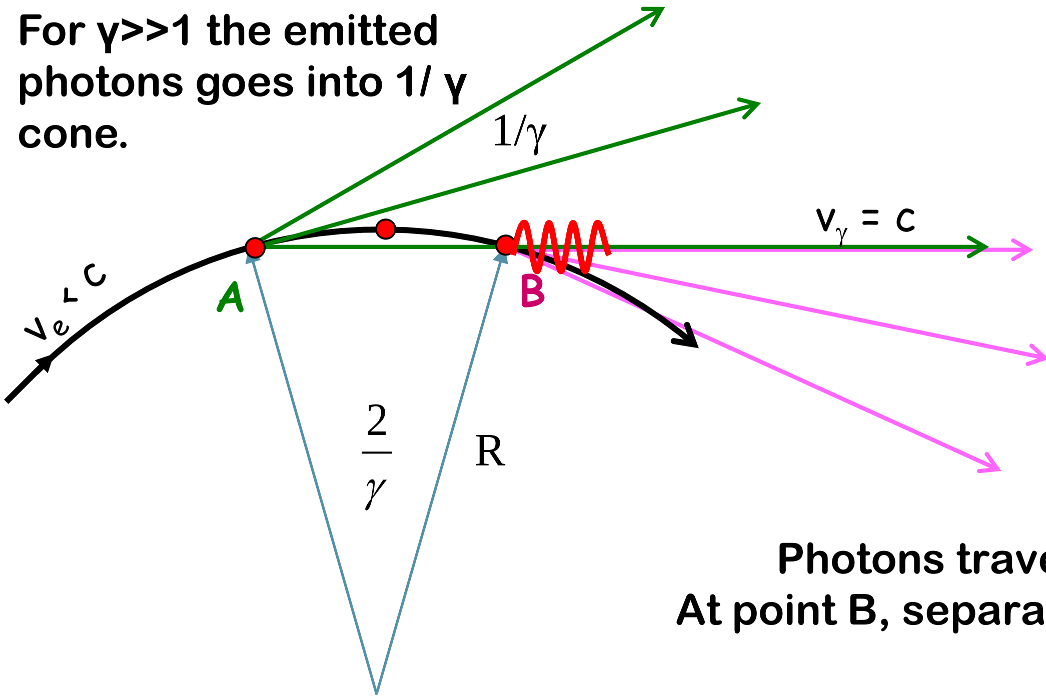
$$\frac{dW}{dS} \approx \frac{e^2\gamma^4}{R^2}$$

Compare with exact formula: $\frac{dW}{dS} = \frac{2}{3}\frac{e^2\gamma^4}{R^2}$

Gaussian units on this page!

Synchrotron radiation
on-the-back-of-the envelope – photon energy (recall)

For γ>>1 the emitted photons goes into 1/ γ cone.



During what time Δt the observer will see the photons?

Photons emitted during travel along the 2R/γ arc will be observed.

Photons travel with speed c, while particles with v. At point B, separation between photons and particles is

$$dS \approx \frac{2R}{\gamma}\left(1-\frac{v}{c}\right)$$

Therefore, observer will see photons during

$$\Delta t \approx \frac{dS}{c} \approx \frac{2R}{c\gamma}(1-\beta) \approx \frac{R}{c\gamma^3}$$

Estimation of characteristic frequency

$$\omega_c \approx \frac{1}{\Delta t} \approx \frac{c\gamma^3}{R}$$

Compare with exact formula:

$$\omega_c = \frac{3}{2}\frac{c\gamma^3}{R}$$

Synchrotron radiation
on-the-back-of-the envelope – number of photons (recall)

We estimated the rate of energy loss: $\frac{dW}{dS} \approx \frac{e^2 \gamma^4}{R^2}$ And the characteristic frequency: $\omega_c \approx \frac{c\gamma^3}{R}$

&

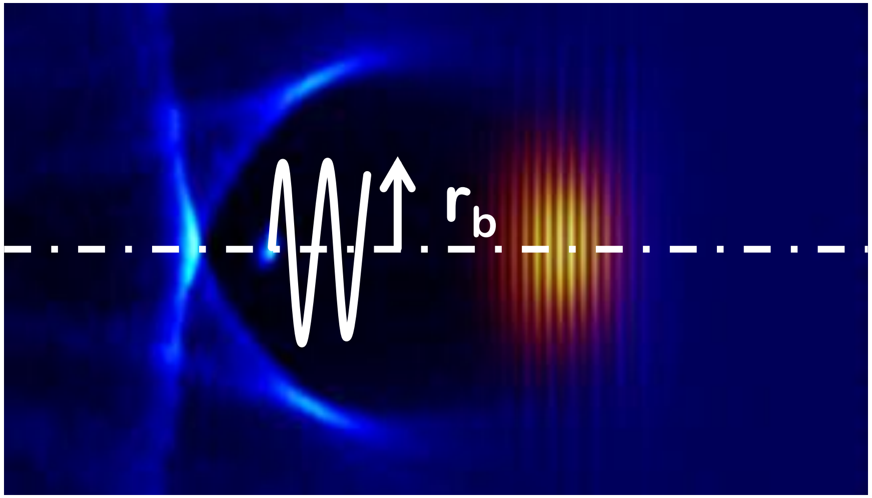
The photon energy $\varepsilon_c = \hbar\omega_c \approx \frac{\gamma^3 \hbar c}{R} = \frac{\gamma^3}{R}\lambda_e mc^2$ where $r_e = \frac{e^2}{mc^2}$ $\alpha = \frac{e^2}{\hbar c}$ $\lambda_e = \frac{r_e}{\alpha}$

=>

Number of photons emitted per unit length $\frac{dN}{dS} \approx \frac{1}{\varepsilon_c}\frac{dW}{dS} \approx \frac{\alpha\gamma}{R}$ (per angle θ: $N \approx \alpha\gamma\theta$)

Gaussian units on this page!

Estimations of betatron radiation



We found that relativistic electron with γ will oscillate in the field of ions as

$$\frac{d^2r}{ds^2} = \frac{2\pi n e^2 r}{\gamma m c^2} = \frac{\omega_p^2}{2\gamma c^2} r$$

Period of oscillation is $\lambda = \sqrt{2\gamma}\ \lambda_p$

If amplitude of oscillation is r_b then the radius of curvature of the trajectory is $R = \frac{\lambda^2}{4\pi^2 r_b}$

Substitute and get the radius of curvature as $R = \frac{\gamma \lambda_p^2}{2\pi^2 r_b}$

Substitute into $\omega_c = \frac{3}{2}\frac{c\gamma^3}{R}$ and get estimation of radiation wavelength

$$\lambda_c = \frac{\lambda_p^2}{3\pi\gamma^2 r_b}$$

Use $\frac{dN}{dS} \approx \frac{\alpha\gamma}{R}$ to estimate N_γ photons emitted per λ

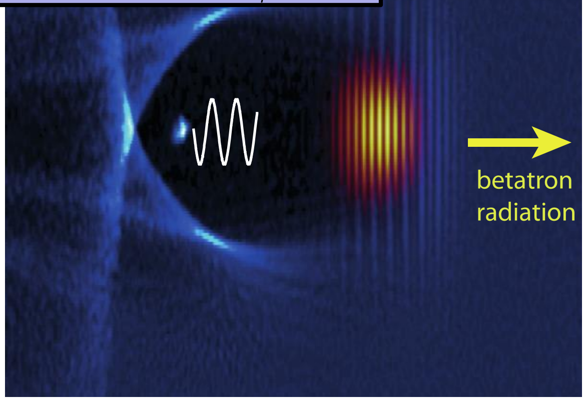
$$N_\gamma \approx \sqrt{2\gamma}\ \ 2\pi^2 \alpha \frac{r_b}{\lambda_p}$$

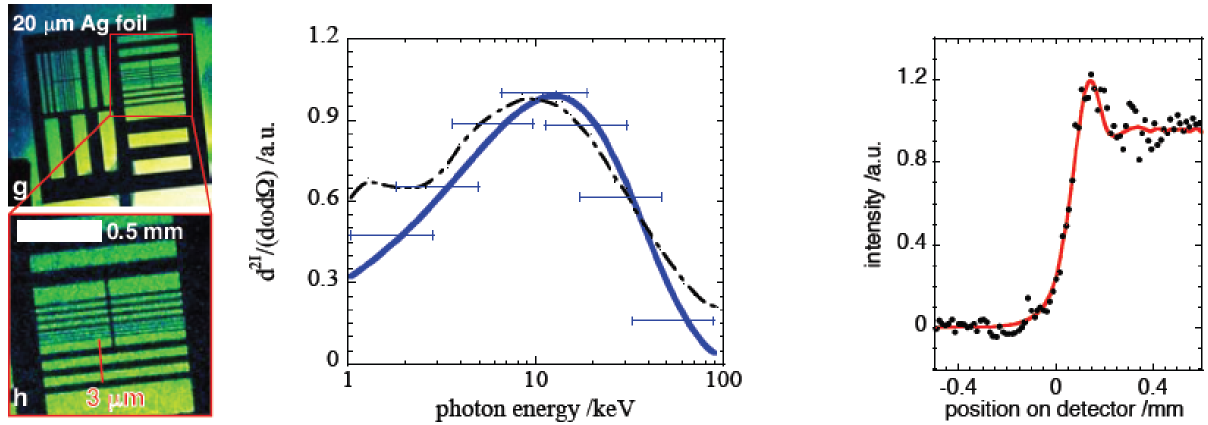
Assume 1GeV (γ=2E3), λ_p=0.03mm, r_b=0.001mm => λ_c=0.25 A or ~50 keV and N_γ per λ is ~0.3

Many hard photons!

Betatron radiation sources

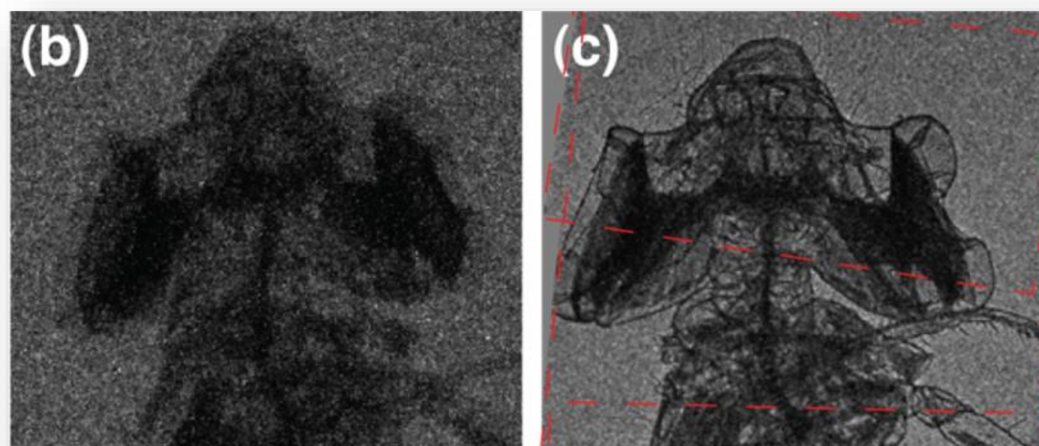
$$\lambda_c = \frac{1}{3\pi}\frac{\lambda_p^2}{r_\beta}\frac{1}{\gamma^2}$$





Imperial College /Michigan groups: Kneip Nature Phys 2010

- **Strong radial electric field within plasma wave cause transverse oscillation of electron bunch**
- **Generates very bright betatron radiation in 1- 100 keV range**

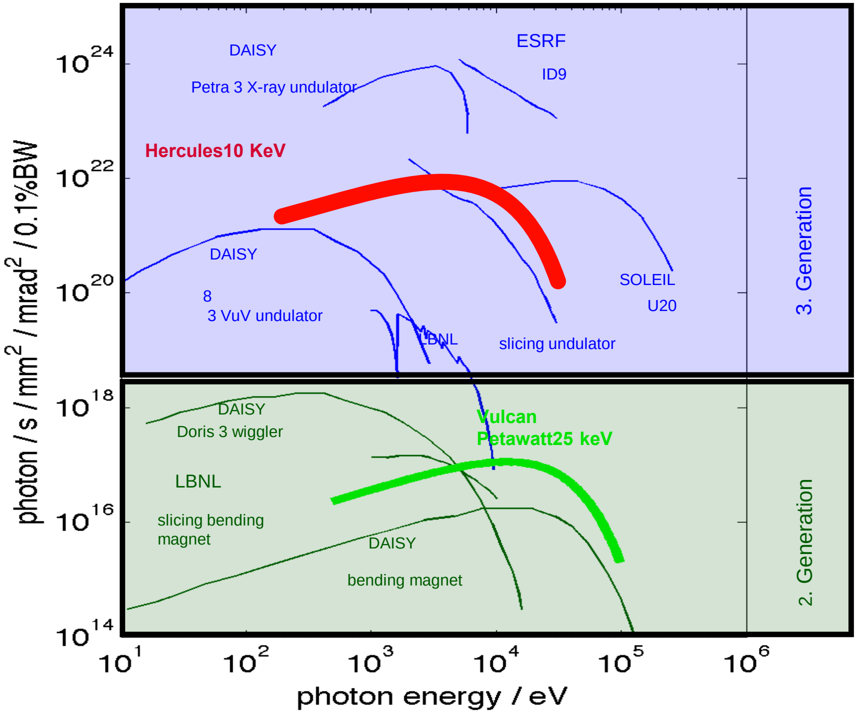


S. Kneip et al., Appl. Phys. Lett. **99, 093701 (2011)**

LP acceleration for medicine

Towards light sources

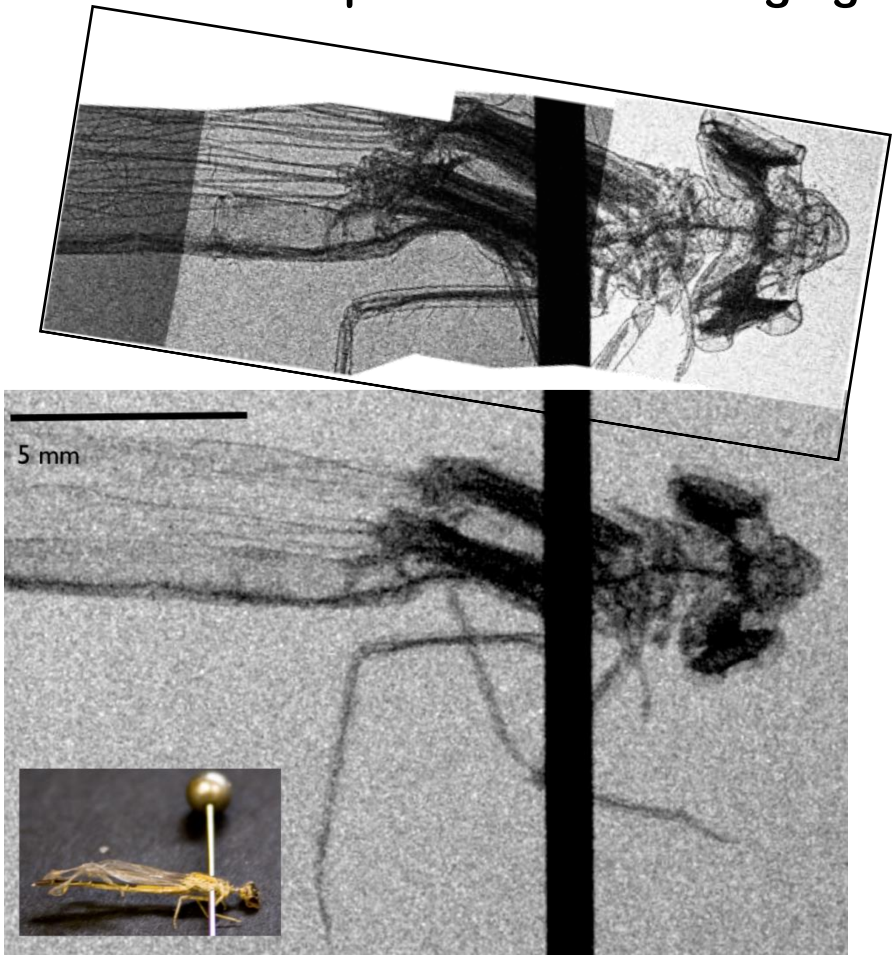
Betatron x-ray source shown to have comparable brightness to 3rd generation light source



other light sources from A. Rousse et al, EPJD, 2008

S. Kneip et al., Nature Physics 2010

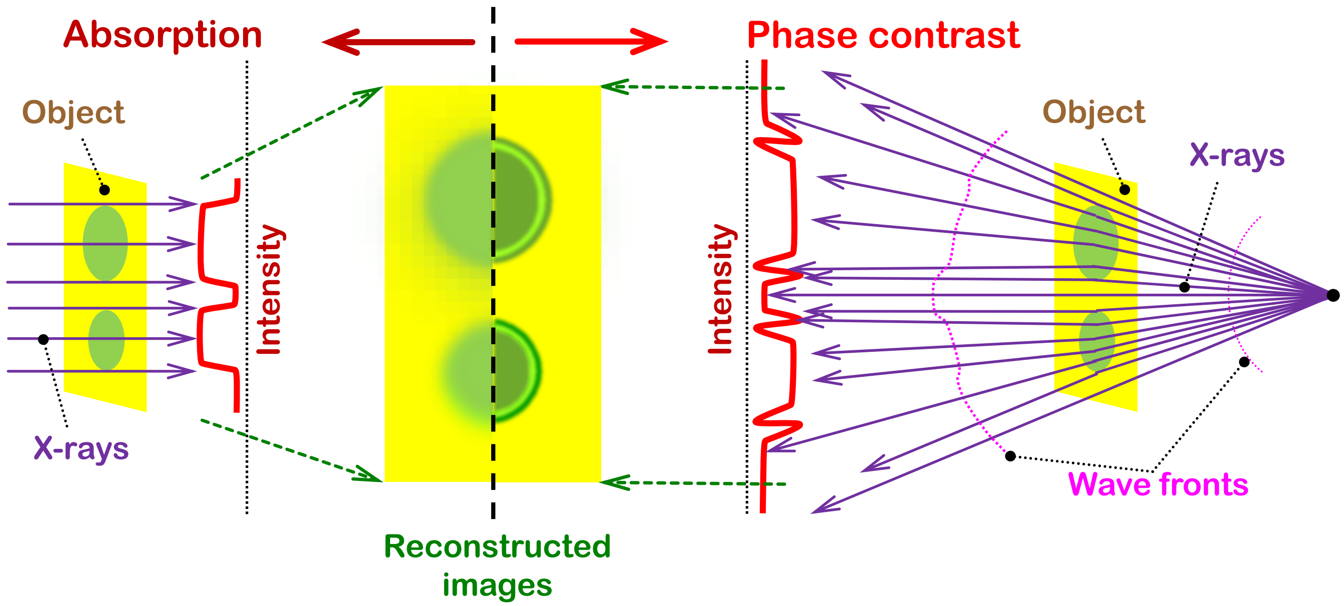
Small source size ideal for phase contrast imaging



S. Kneip et al., Applied Physics Letters 2011

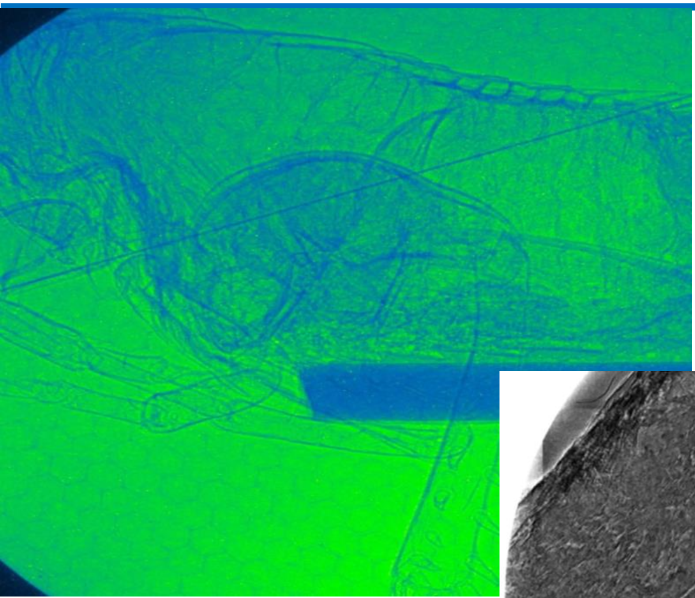
Z.Najmudin, et al

Phase contrast imaging



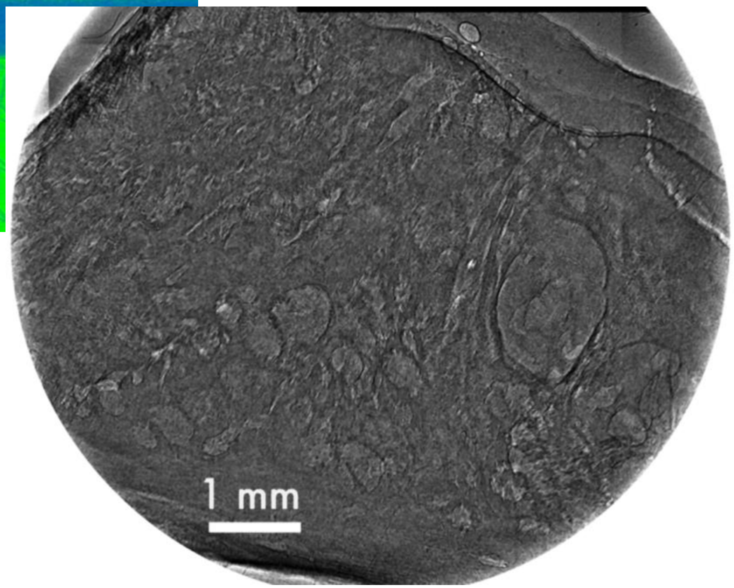
- **Absorption (left) and phase contrast (right) X-ray imaging**
  - and comparison of reconstructed image (middle)

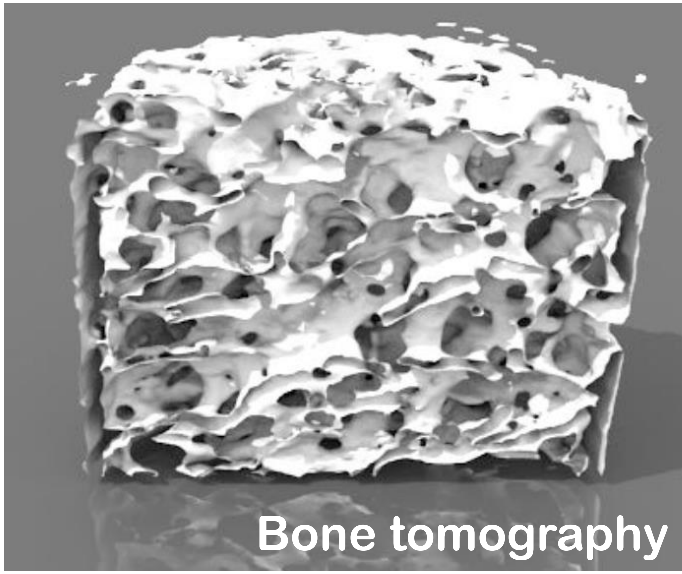
LP acceleration for medicine



Imaging with Gemini laser-plasma acceleration and betatron radiation

Small size of emitting area => use of phase contrast technique => many applications in medical imaging





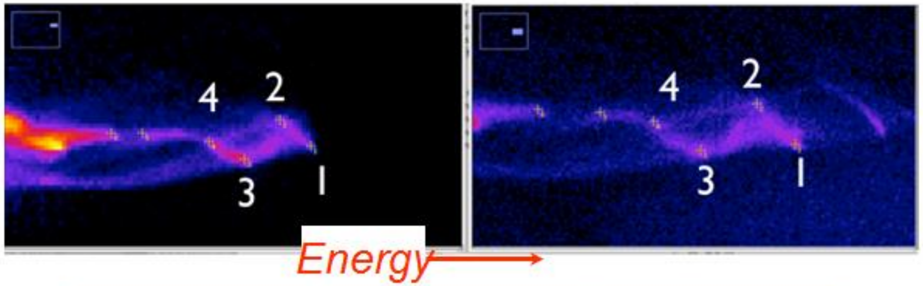
Laser-Plasma X-ray Src & FEL

Lopes N. et al. “X-ray phase contrast imaging of biological specimens with femtosecond pulses of betatron radiation from a compact laser plasma wakefield accelerator.” In Preparation (2016).

Cole J. et al., Sci. Reports (2015) “X-ray phase contrast imaging of biological specimens with femtosecond pulses of betatron radiation from a compact laser plasma wakefield accelerator.”.

Z.Najmudin, et al

Challenge of stability pulse-to-pulse

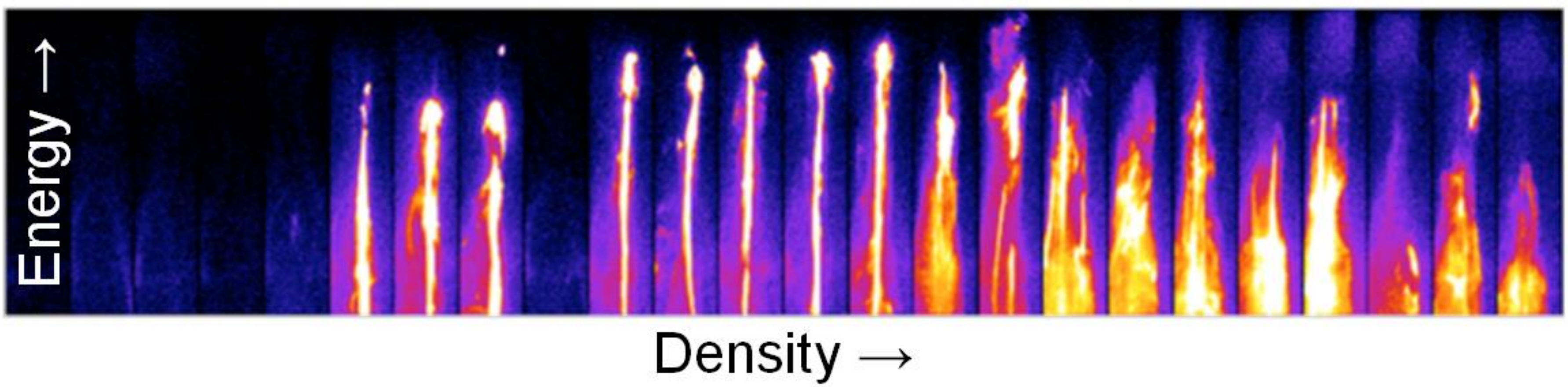


Point	Energy [MeV]	Pointing Angle [rad]
1	1336	-0.003
2	1275	-0.002
3	1156	-0.002
4	1086	-0.001

Gemini 10J, 50 fs, 20 µm (FWHM)

Energies observed > 1.3 GeV
Typical charge > 100 pC @ > 0.5 GeV

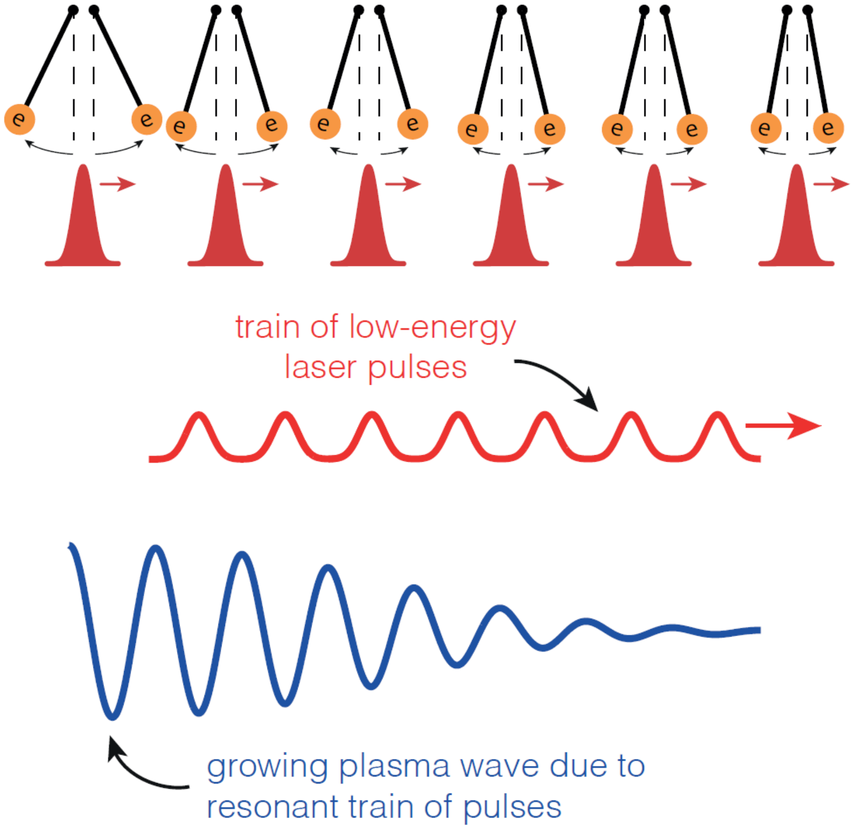
Density Scan of electron beam behaviour, 1.5 cm plasma

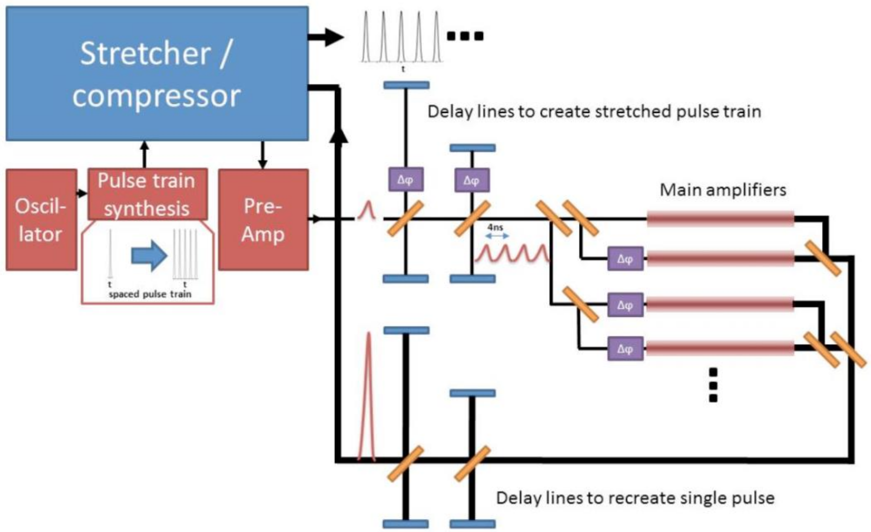


Bloom, M. et al. Hard X-rays Produced by Betatron Motion of Self Injected Electrons in a Laser Wake Field Accelerator. In preparation (2014).

Challenge of efficiency & repetition rate

- Use a train of pulses separated by plasma period to resonantly excite wakefield – MP-LWFA
- Energy stored efficiently in plasma wave
- Can tune pulse separation to avoid saturation (unlike beat-wave scheme)

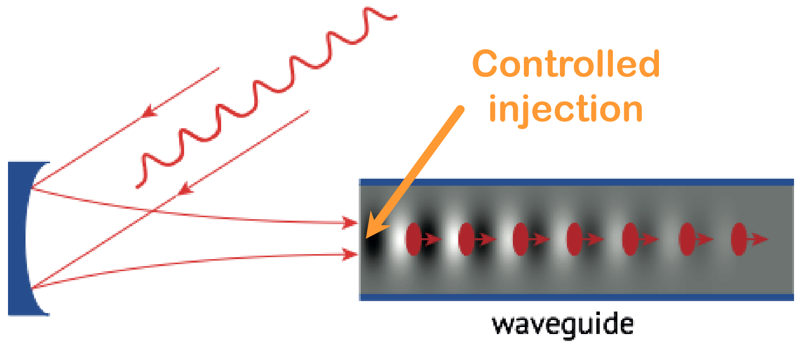


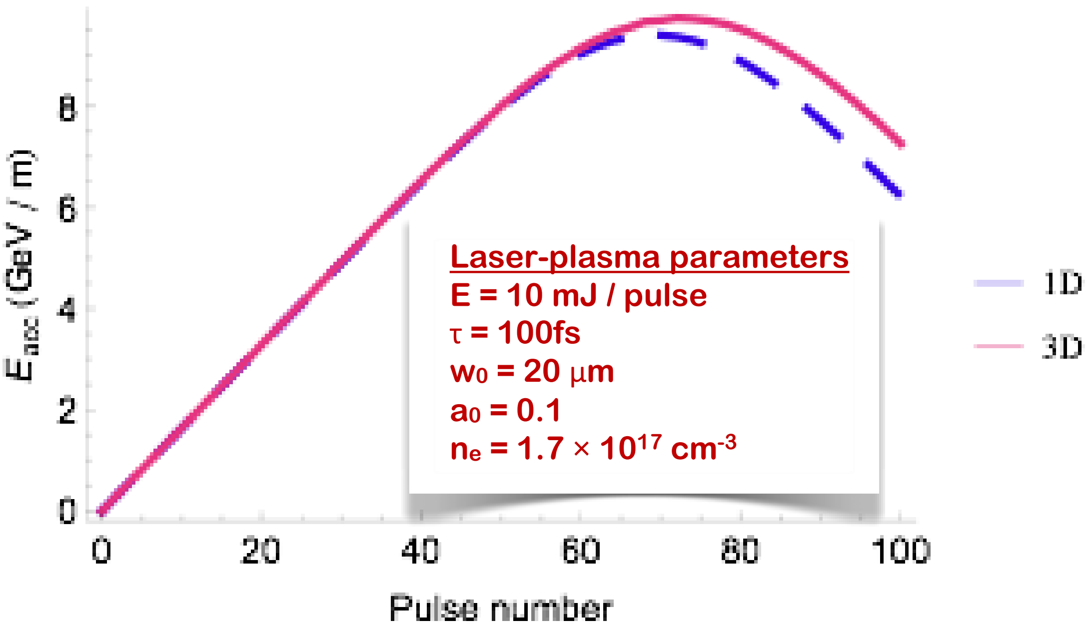


- Fibre lasers: ~kW <u>average</u> power at wall-plug efficiencies > 20%
- Fibre lasers can generate trains of short pulses

S.Hooker, R.Bartolini, S.Mangles, A.Tünnermann, L.Corner, J.Limpert, A.Seryi, R.Walczak. Jan 30, 2014, J.Phys. B47 (2014) 234003

MP-LWFA: outline concept





Simulations by Naren Ratan

- **1D and 3D fluid simulations show:**
  - **Single pulse E_{acc} = 0.160 GV/m**
  - **Gradient increases linearly up to ~ 60 pulses**
  - **Max E_{acc} = 9.6 GV/m (~70 pulses)**
  - **ΔW = 2.5 GeV in L_d = 265 mm**
  - **E_{acc} rolls over due to loss of resonance (relativistic mass increase)…**
  - **… but this can be overcome by re-tuning pulse train**

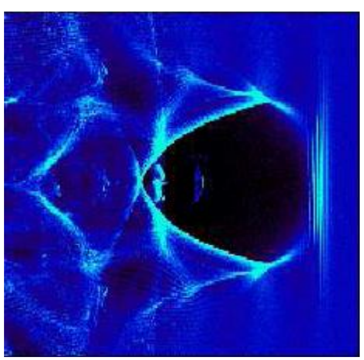
JAI team, in collaboration with Jena (Germany)

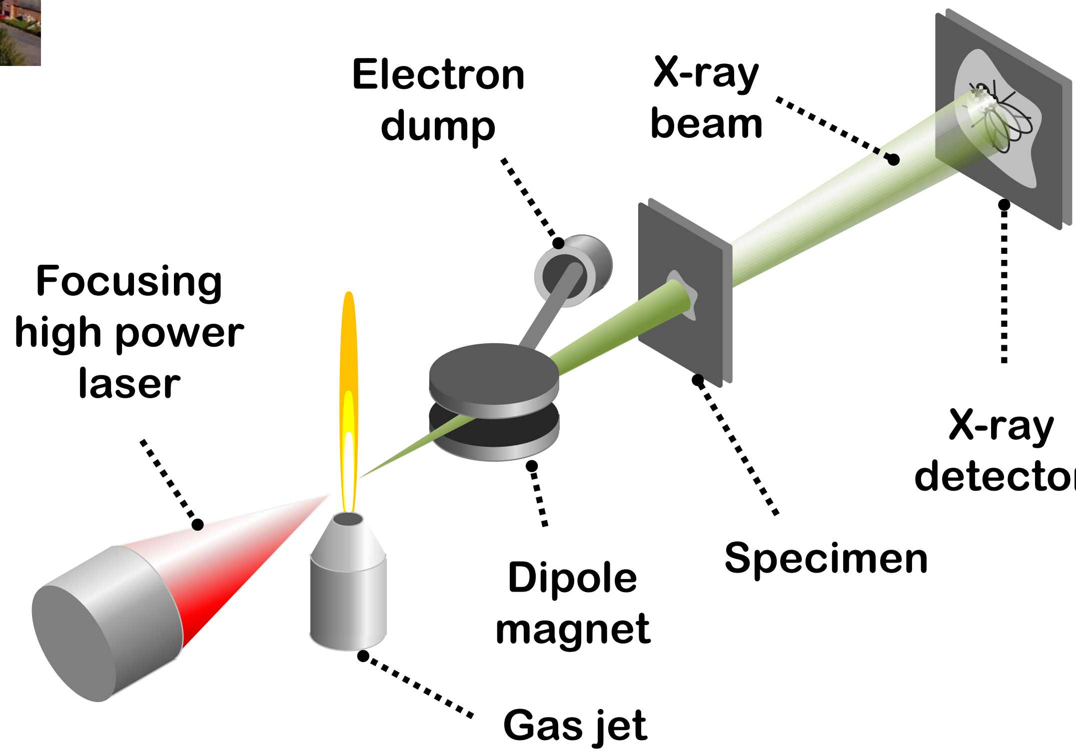
Laser Plasma accelerator

Modern synchrotrons-based light sources are big machines (several 100s meters)

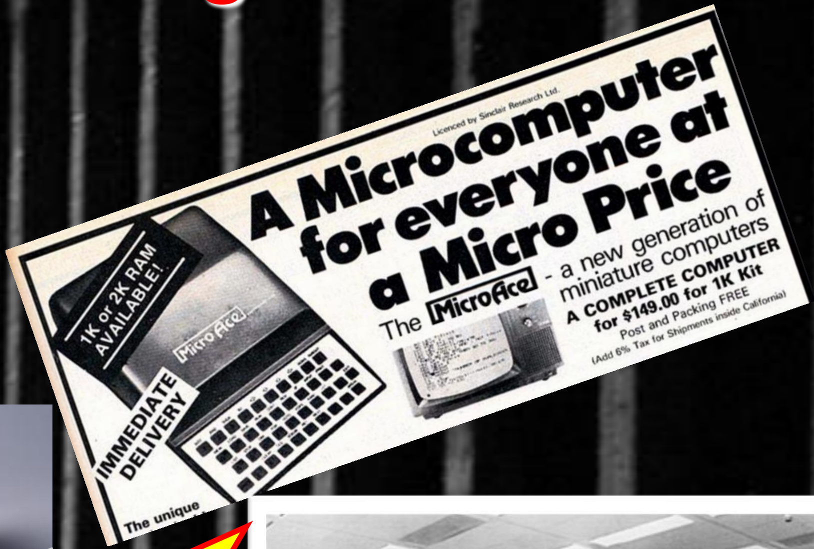
Provided that we solve the challenges of stability, efficiency and repetition rate, we can create, based on plasma acceleration, compact (~10m) light sources – betatron X-ray and eventually an FEL

Similar electron energies (3-6 GeV) as in synchrotrons, can be reached in a much more compact plasma accelerator using the "wake" created by a laser in a gas jet.



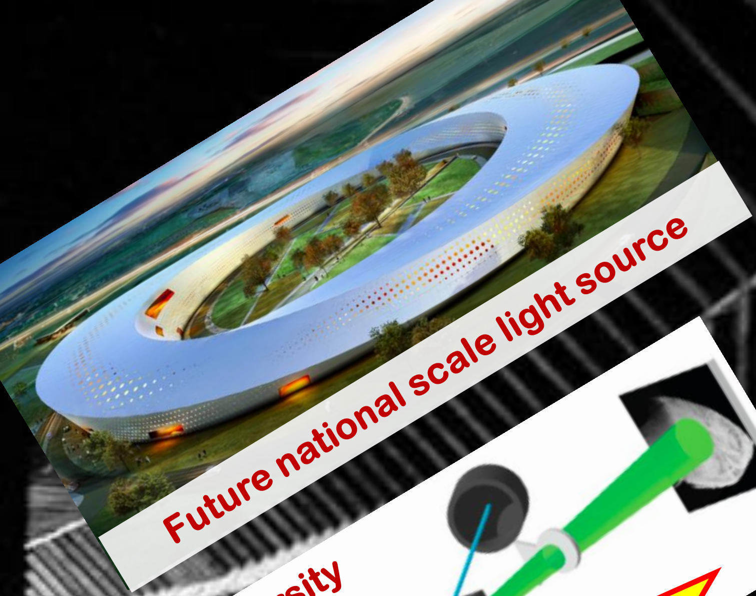


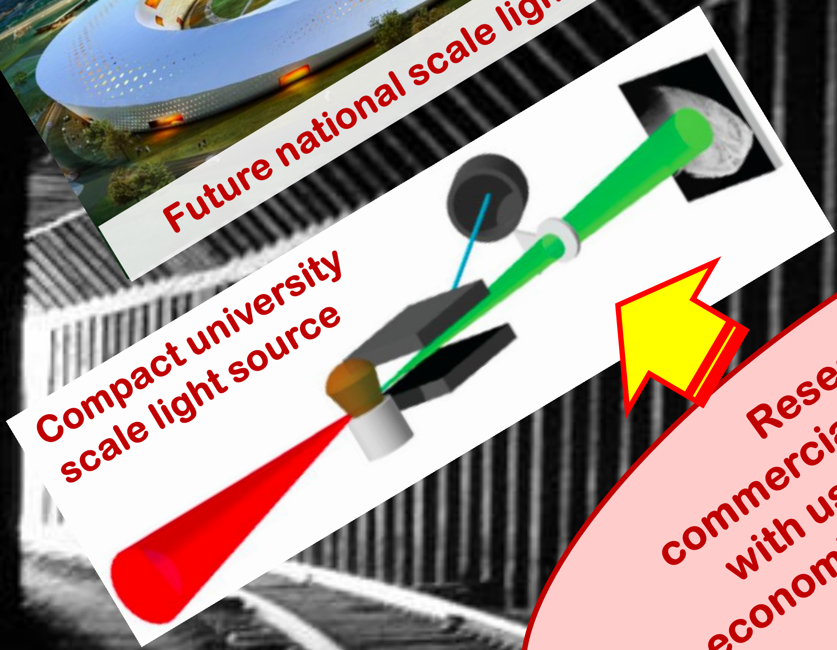
Evolution of computers and light sources



"IBM bringing out a personal computer would be like teaching an elephant to tap dance" cca. 1981

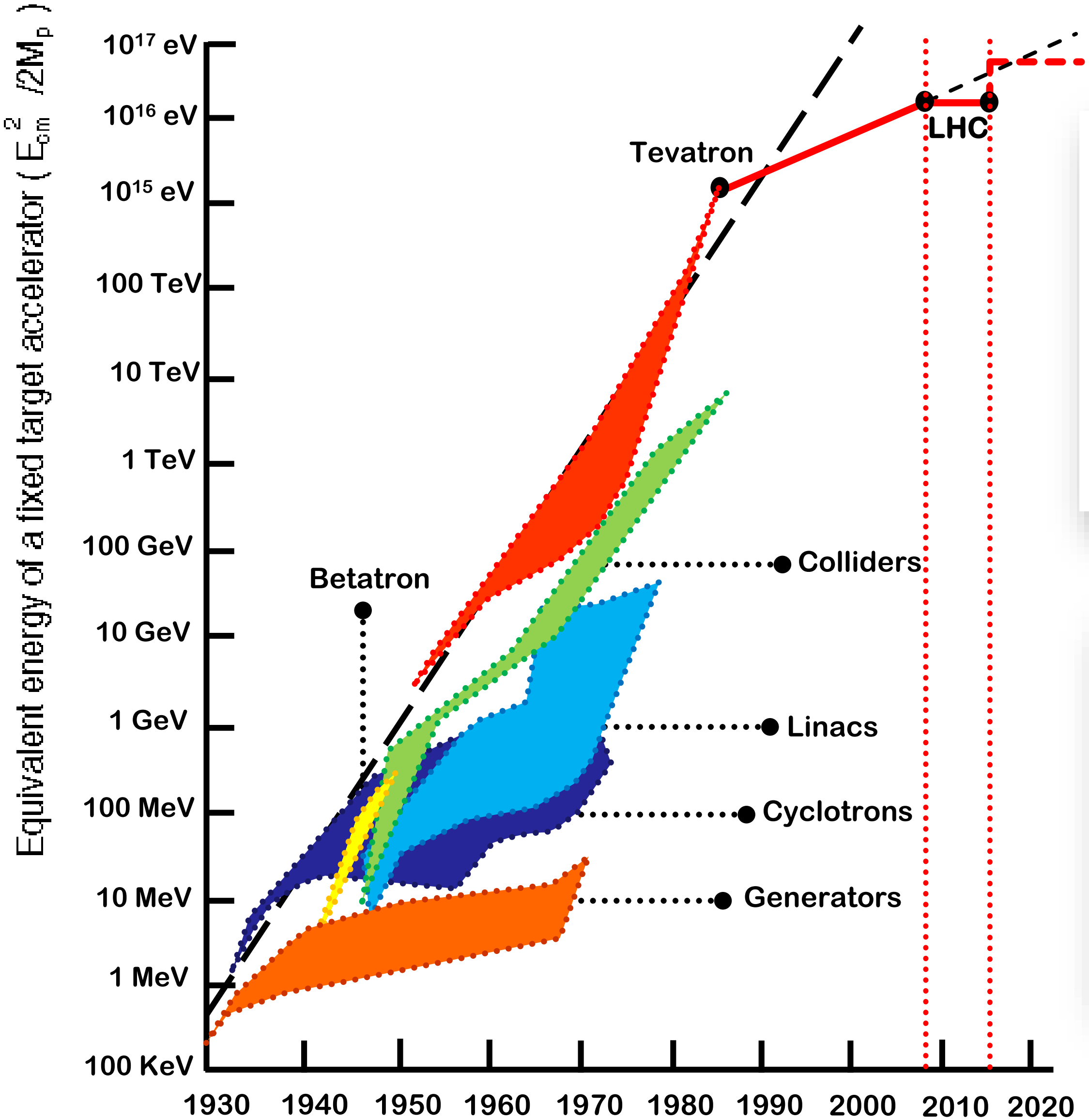
Evolution of computers and light sources



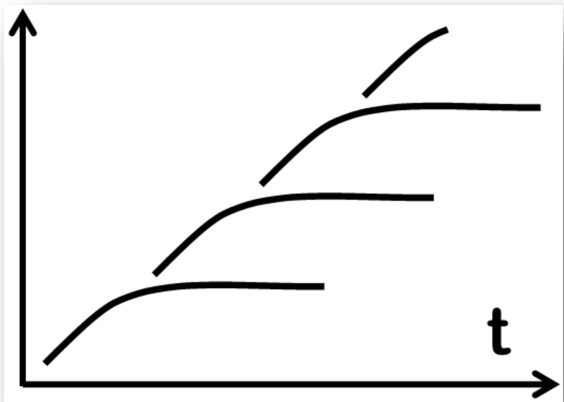


Research, commercialisation, work with users, industry, economists, to change the paradigm

Motivation



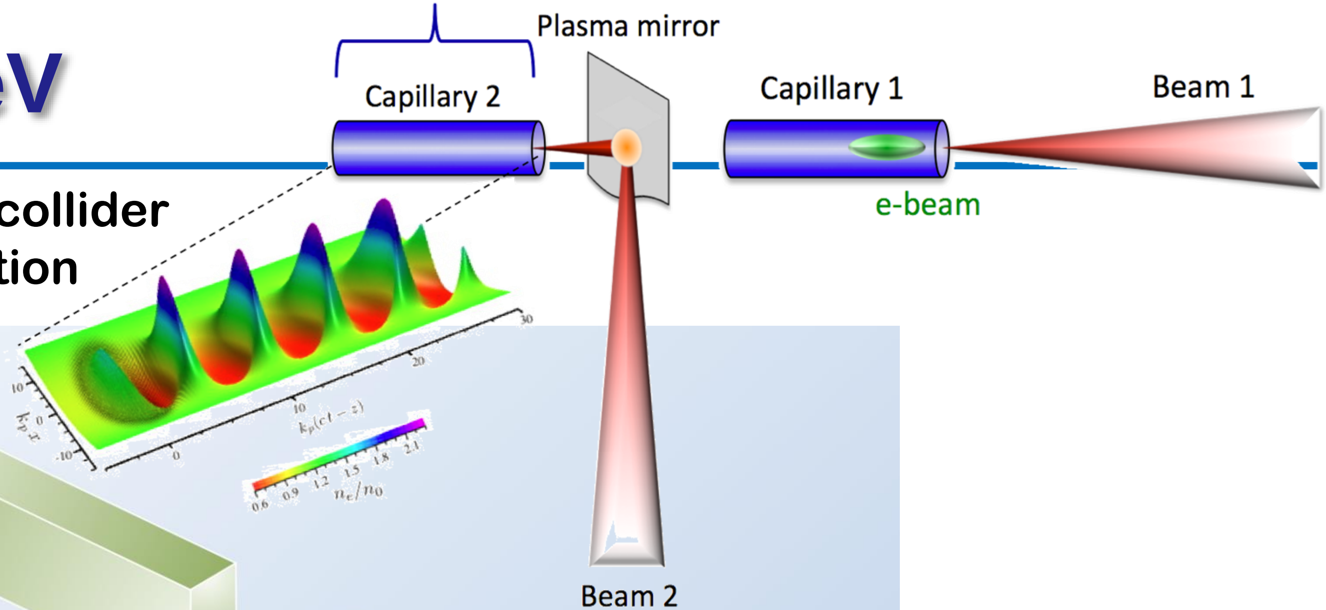
- "Livingston plot" shows great history of accelerators and great inventions
- … and shows signs of the need for the next revolution in accelerator technology

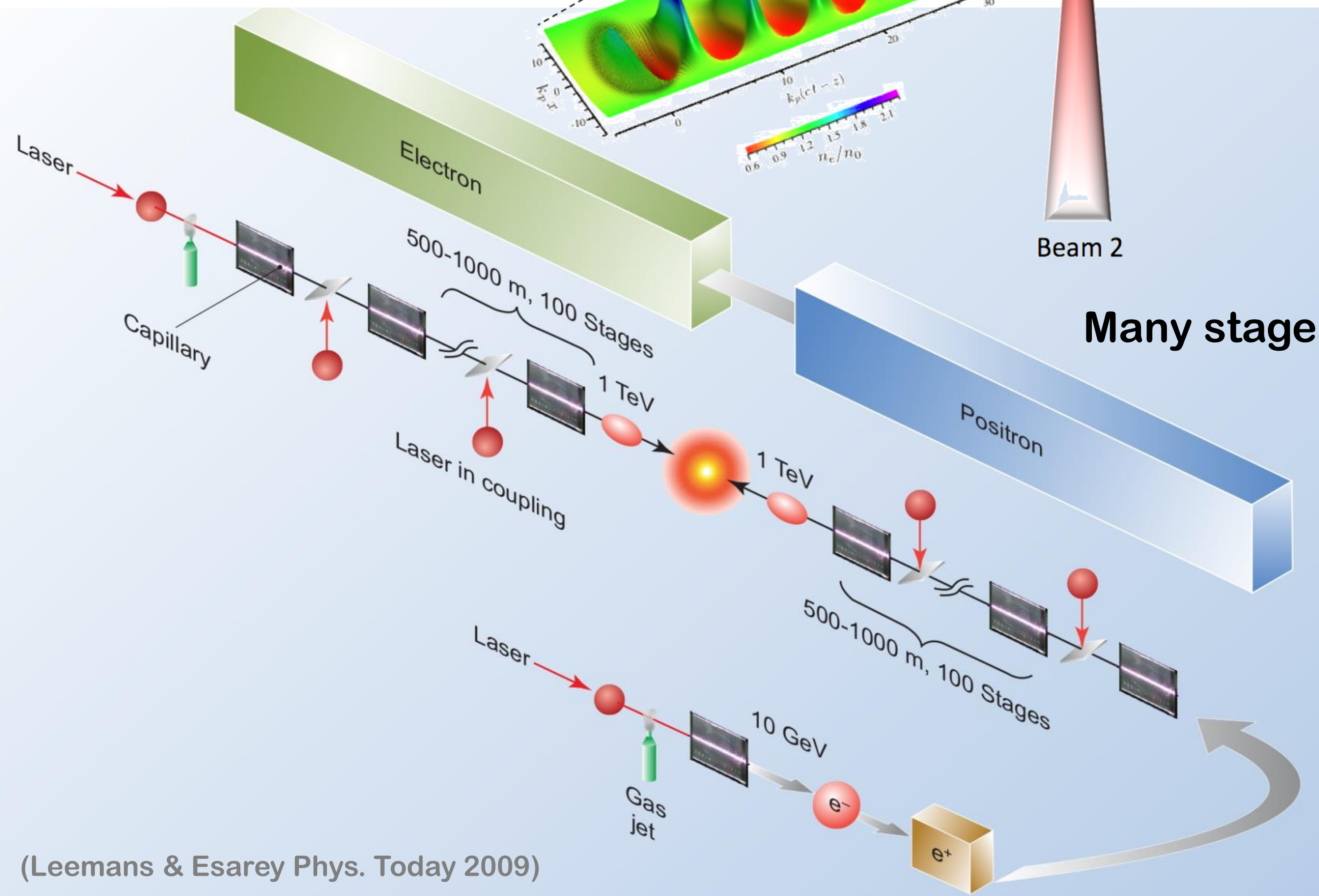


Can the next collider be based on plasma acceleration?

Aiming to TeV

Concept of 1 TeV linear collider based on laser acceleration





Many stages of acceleration are necessary

(Leemans & Esarey Phys. Today 2009)

The need for multi-stage acceleration

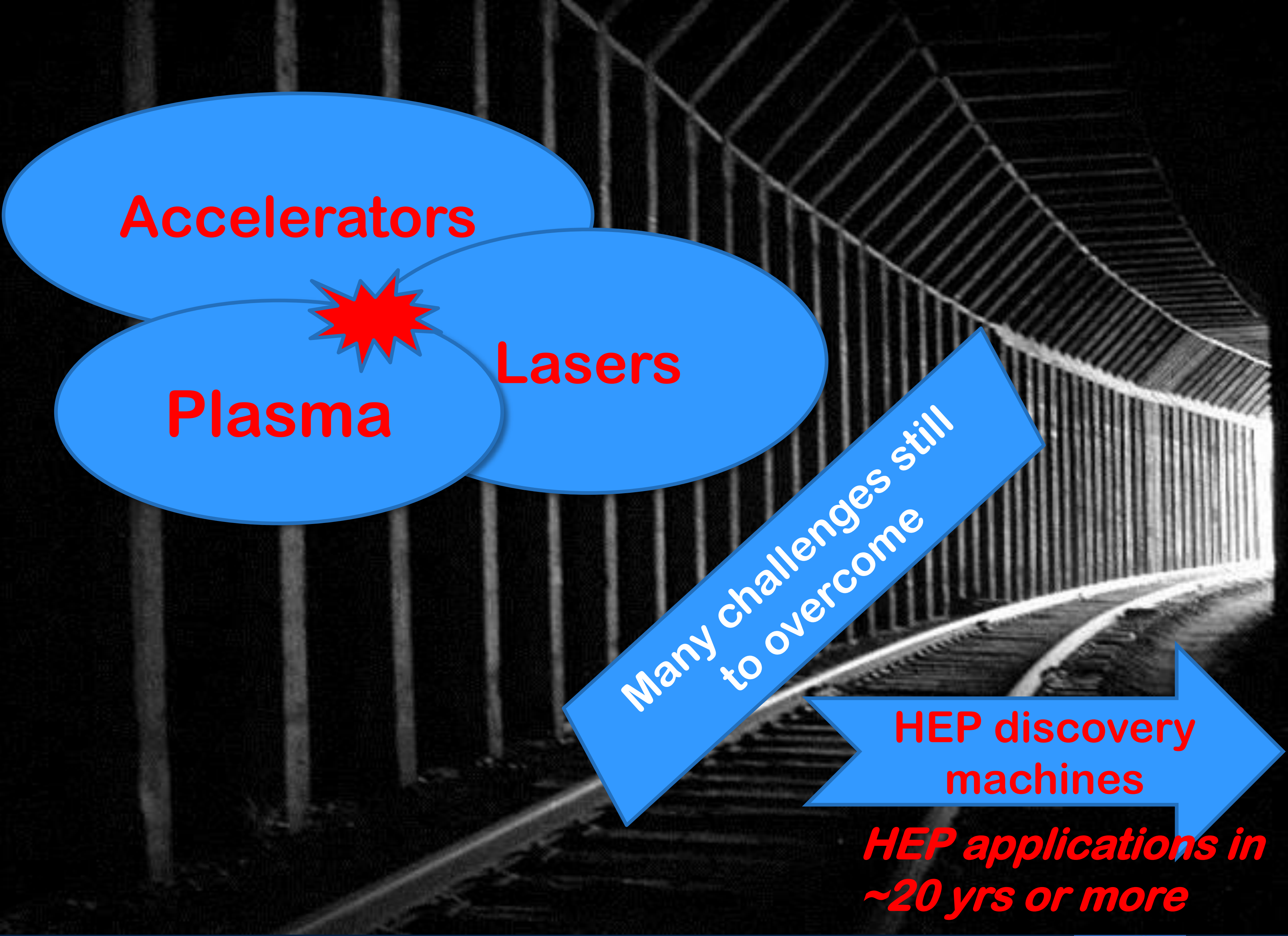
- **In beam driven acceleration, the driver has v=c and de-phasing of witness from driver is not an issue**
- **For laser acceleration, laser propagating in media (plasma) has v<c and accelerating electrons will soon de-phase from plasma wave**

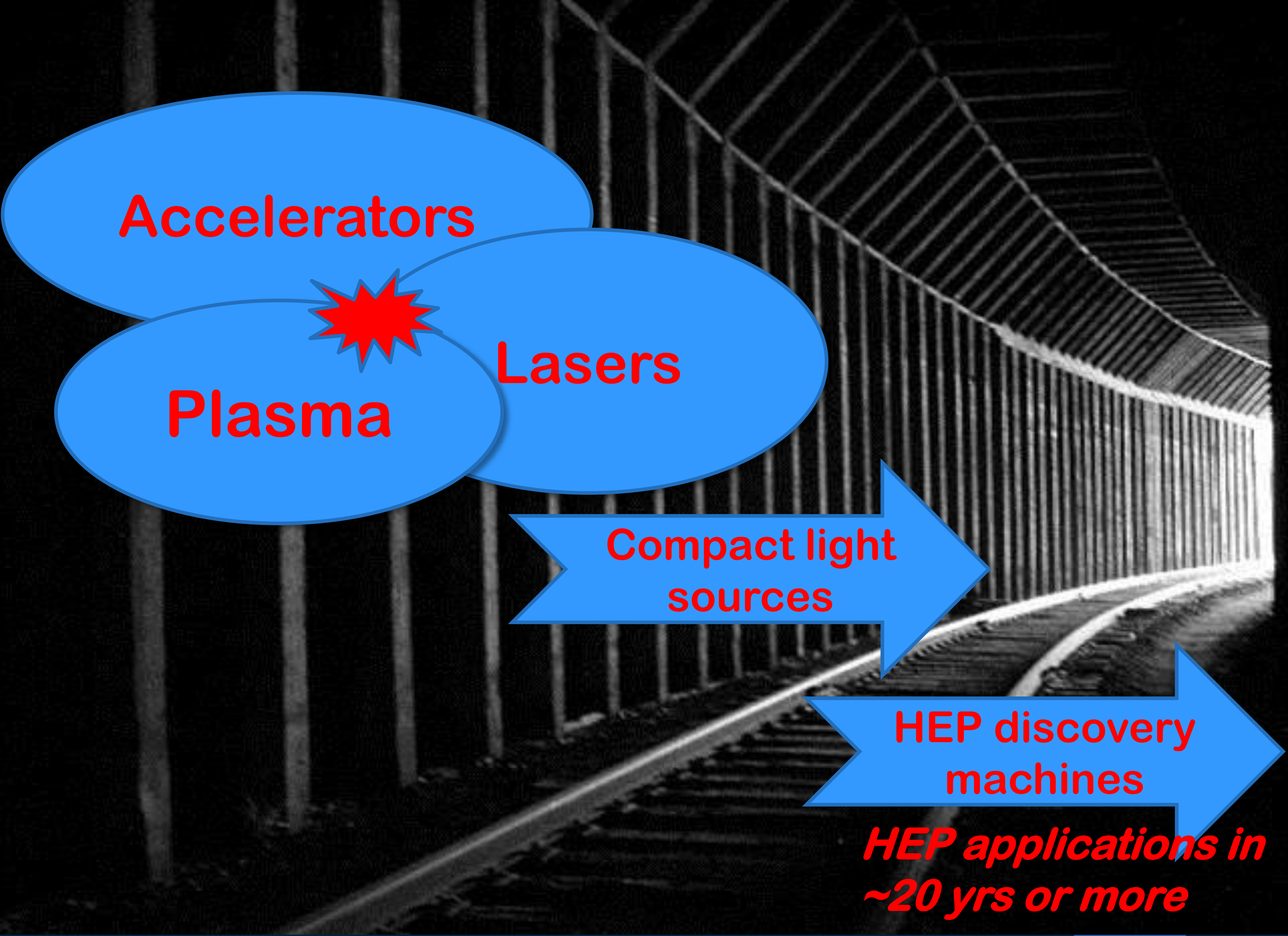
For laser drive the group velocity $v_g = \sqrt{1 - \frac{\omega_p^2}{\omega^2}}$

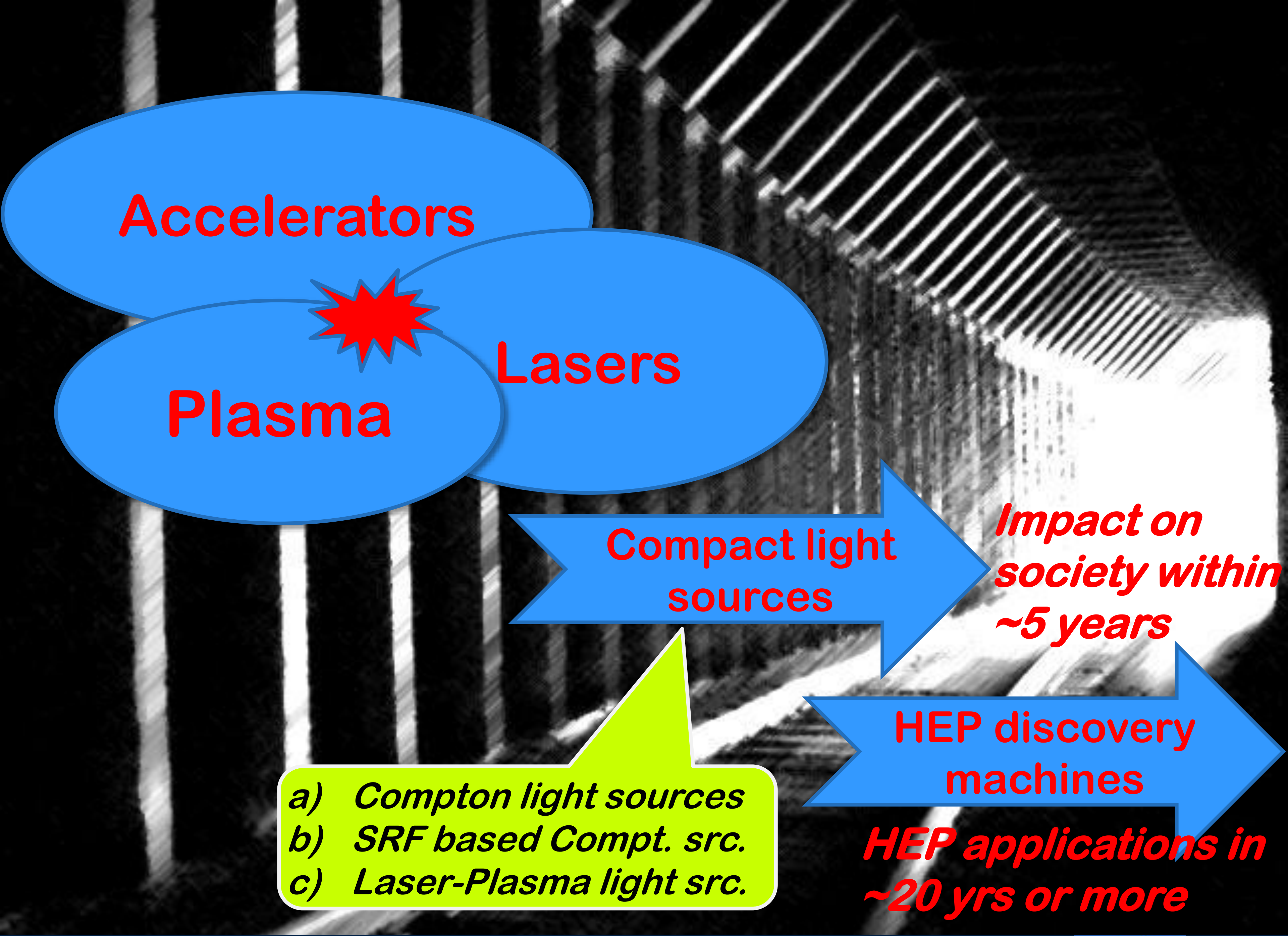
Dephasing happen when electron outrun wave by half a period

For relativistic electron the dephasing time t_d thus given by $(c - v_g)\, t_d = \frac{\lambda_p}{2}$

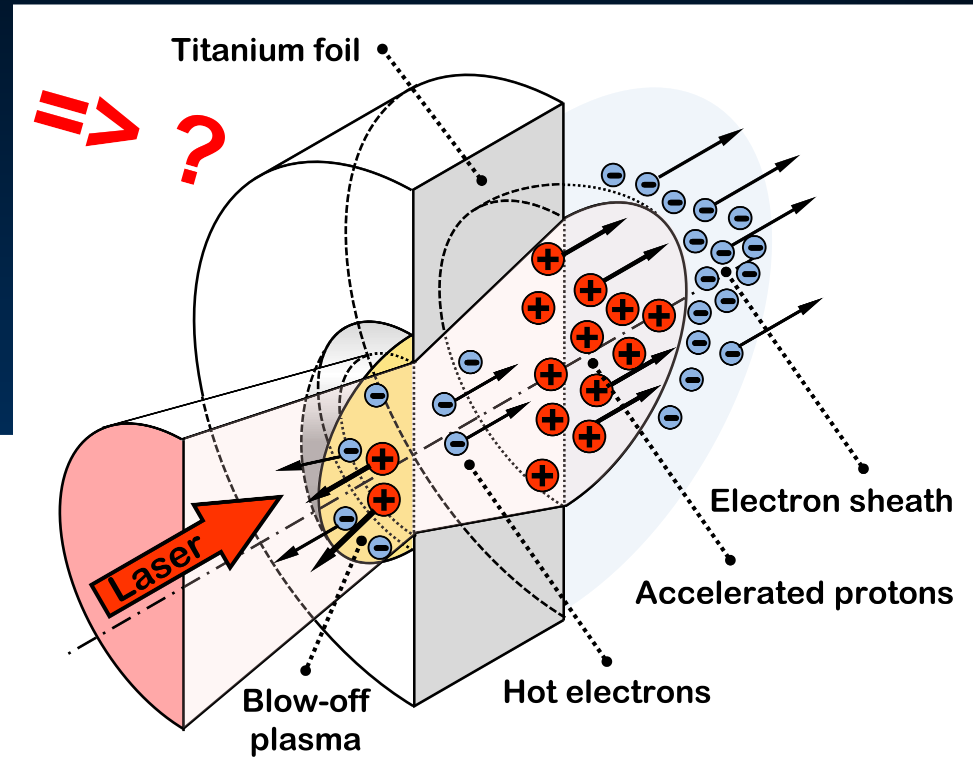
Substitute the above and get dephasing length $L_d \approx \lambda_p \frac{\omega^2}{\omega_p^2}$


Accelerators
Lasers
Plasma
Many challenges still to overcome
HEP discovery machines
HEP applications in ~20 yrs or more

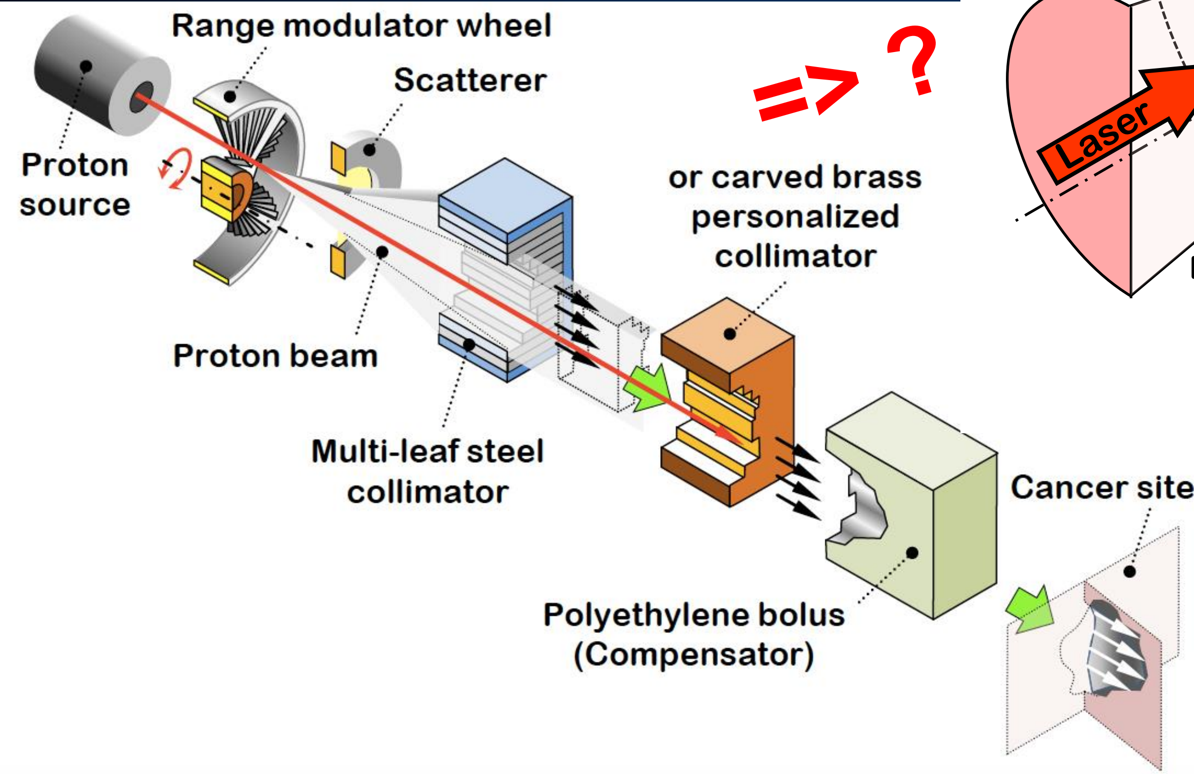

Accelerators
Lasers
Plasma
Compact light sources
HEP discovery machines
HEP applications in ~20 yrs or more


Accelerators
Lasers
Plasma
Compact light sources
Impact on society within ~5 years
a) Compton light sources
b) SRF based Compt. src.
c) Laser-Plasma light src.
HEP discovery machines
HEP applications in ~20 yrs or more

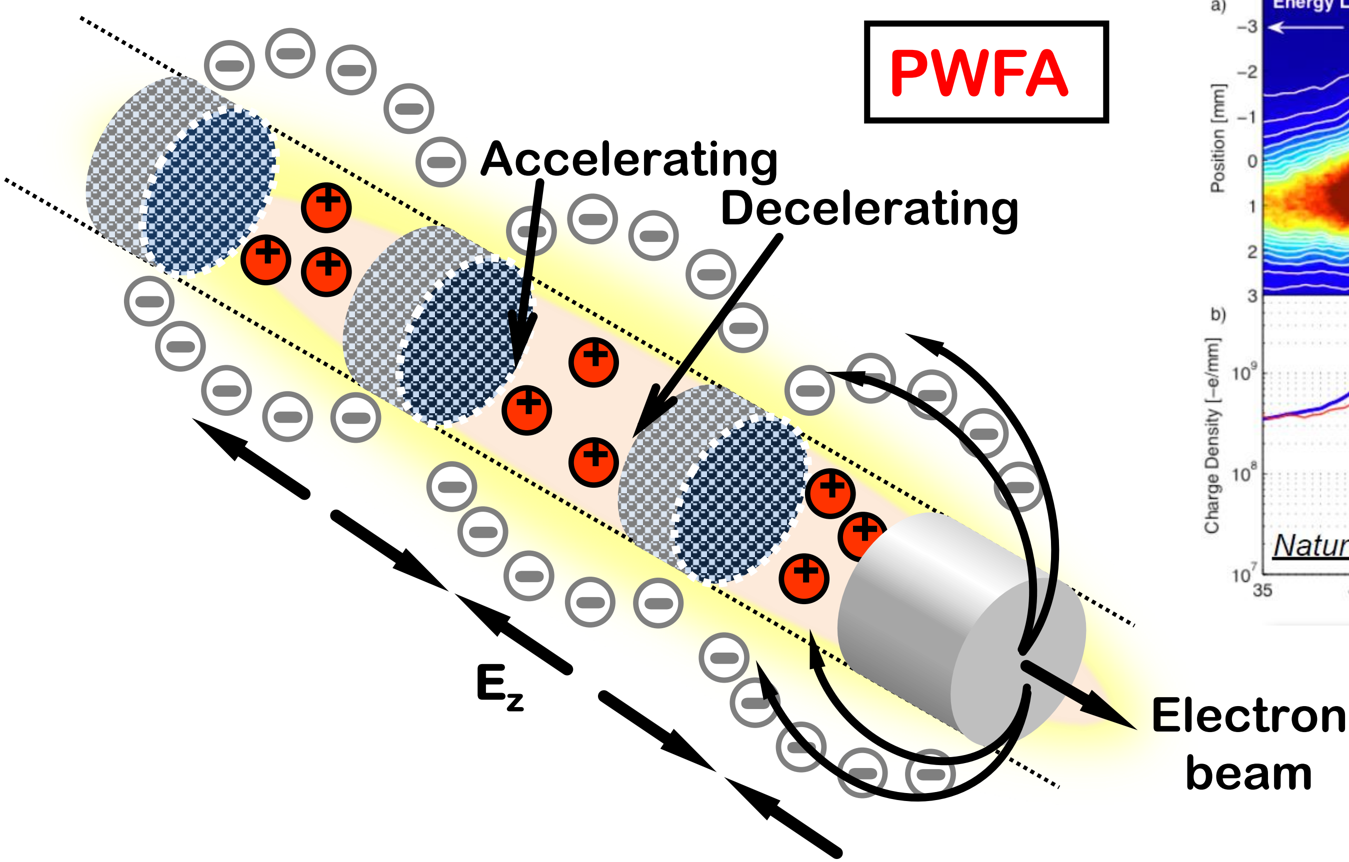
Ion acceleration

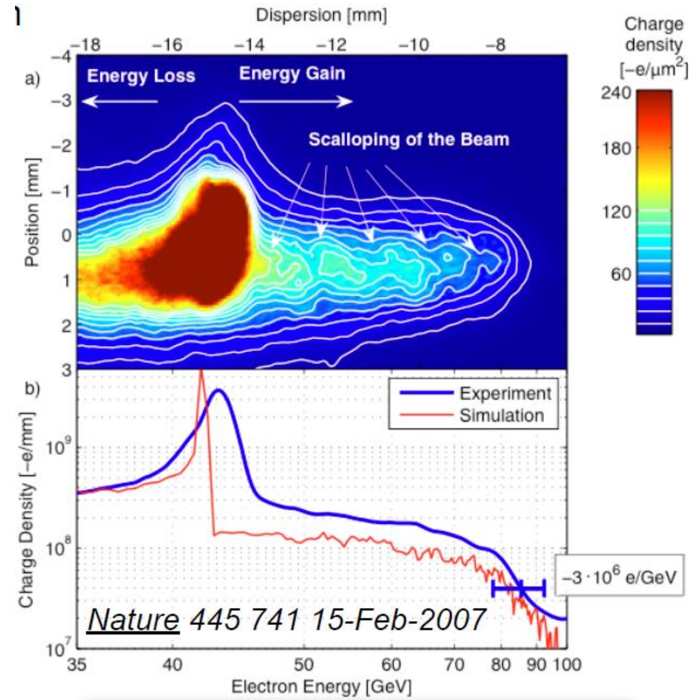


TNSA (RPA, light sail, etc.)



Strongest motivation – proton therapy





- **Beam-driven plasma acceleration**
- **Max energy achieved 80 GeV (doubling SLAC linac energy)**
- **Next gen experiments at FACET (SLAC)**