Future Accelerators – part I

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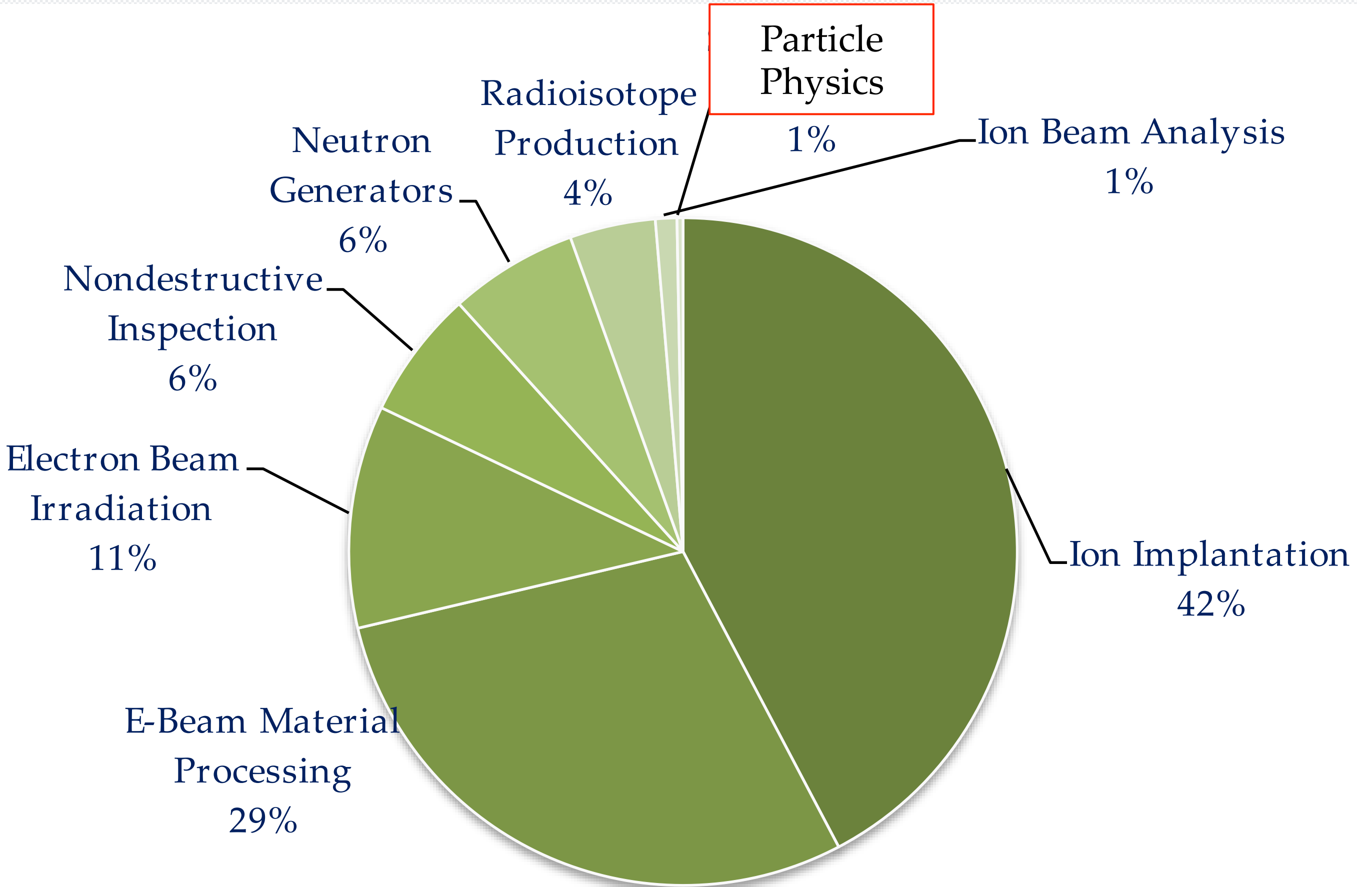
XIV ICFA School – Habana - December 2017

Source: Courtesy Oak Ridge National Laboratory

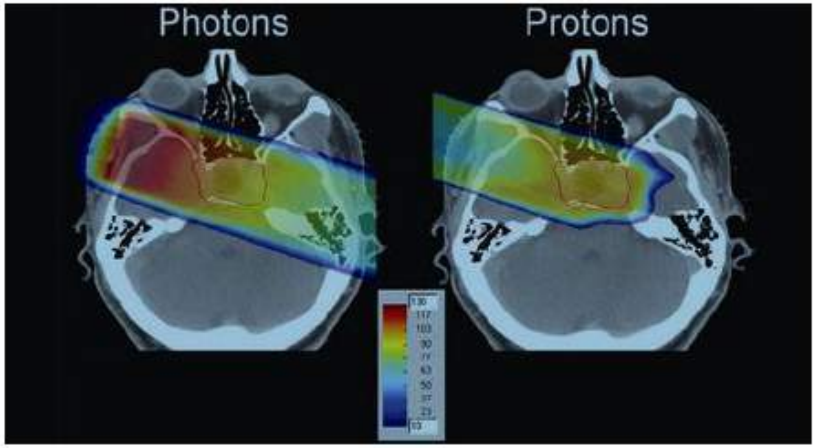
Breakdown of the cumulative number of industrial accelerators according to the application categories



Source: Adapted from Hamm, R.W. and Hamm, M.E., 2012

- More than **24,000 particle accelerators** over the past 60 years for use in the industrial processes. More than **11,000 particle accelerators** exclusively for medical therapy with electrons, ions, neutrons, or X-rays.

Examples

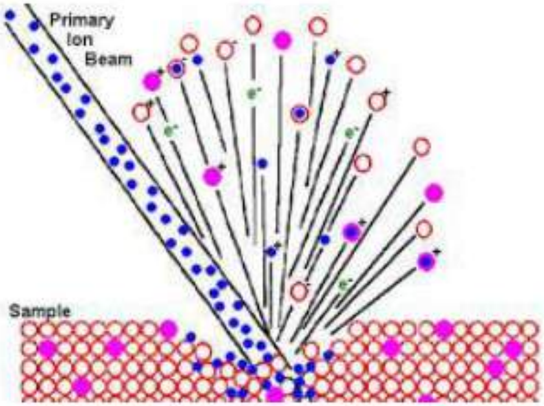


Protons

HadronTherapy

Electrons

Clean welding



Ions

Implantation

One example of such an application is the development of superabsorbent polymers, made by material scientists using accelerator generated X-rays, that are used to make more absorbent nappies to keep babies dry.

Perhaps surprisingly, accelerators could have a role in improving the quality of chocolate. Researchers at the European Synchrotron Radiation Facility (ESRF) have studied the structure of chocolate using radiation generated by a particle accelerator, passing their findings onto chocolate manufactures to help them improve their product.

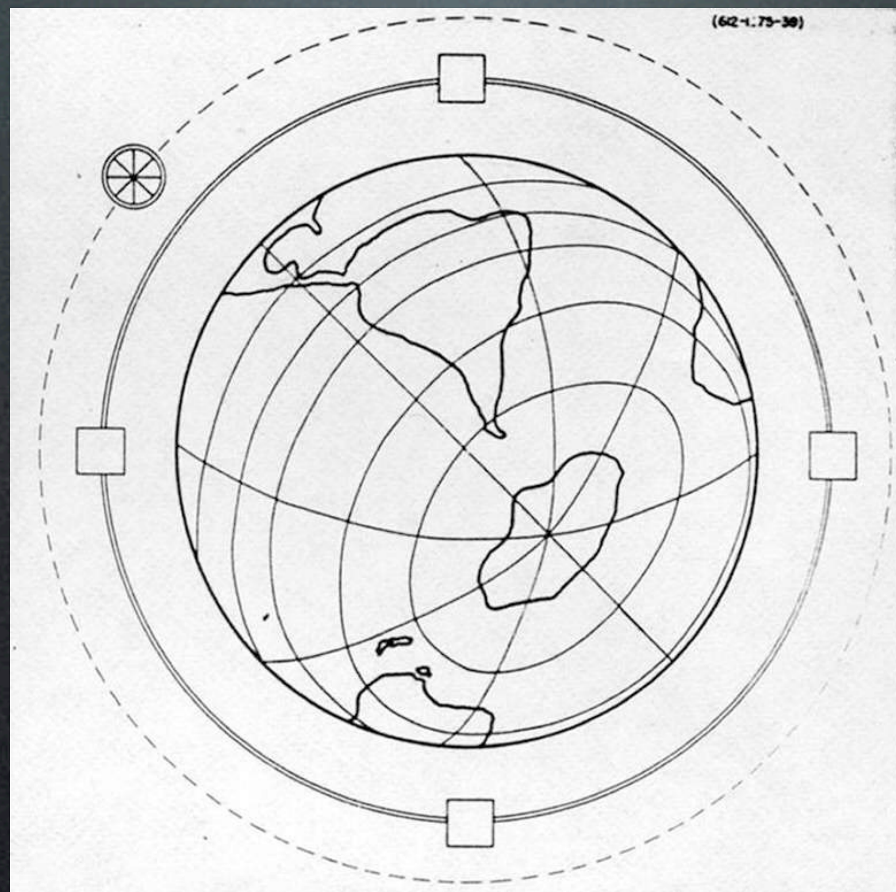
Fermi's Globatron: ~5000 TeV proton beam

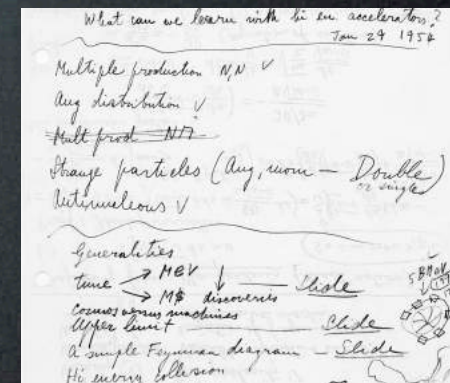
1954 the ultimate synchrotron

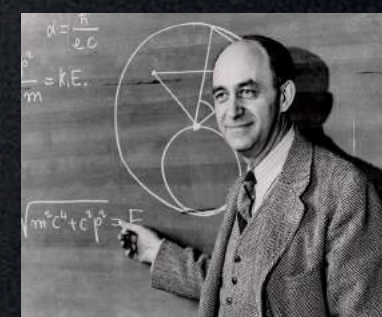
3 TeV c.m.

170 G$

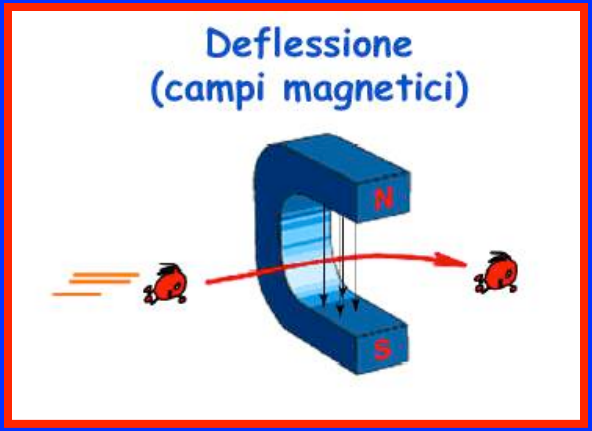
1994

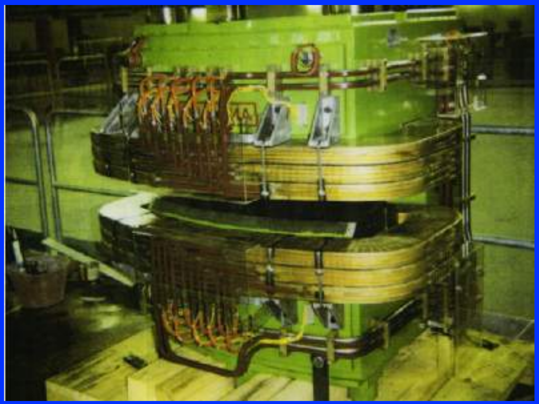


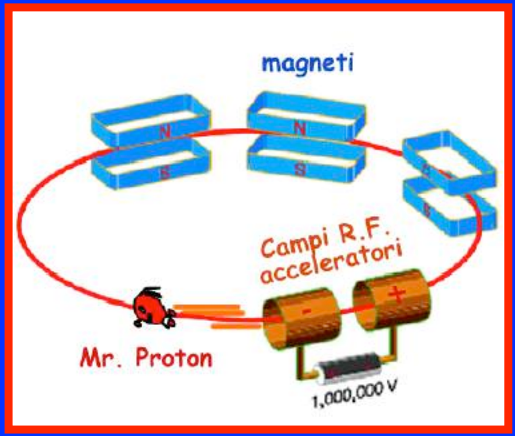




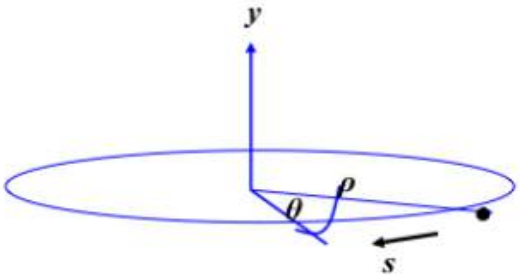
Dipole Magnets (Bending)







The ideal circular orbit



circular coordinate system

condition for circular orbit:

Lorentz force $F_L = e\,v\,B$

centrifugal force $F_{centr} = \frac{\gamma m_0 v^2}{\rho}$

$$\frac{\gamma m_0 v^2}{\rho} = e\,v\,B$$

$$\frac{p}{e} = B\rho$$

$B\rho =$ *"beam rigidity"*

Synchrotron radiation power

Power emitted is proportional to:

$$P_\gamma = \frac{cC_\gamma}{2\pi} \cdot \frac{E^4}{\rho^2}$$

$$C_\gamma = \frac{4\pi}{3}\frac{r_e}{(m_e c^2)^3} = 8.858 \cdot 10^{-5}\left[\frac{\mathrm{m}}{\mathrm{GeV}^3}\right]$$

Fermi's Globatron: ~5000 TeV Proton beam

1954 the ultimate synchrotron

B_{max} 2 Tesla

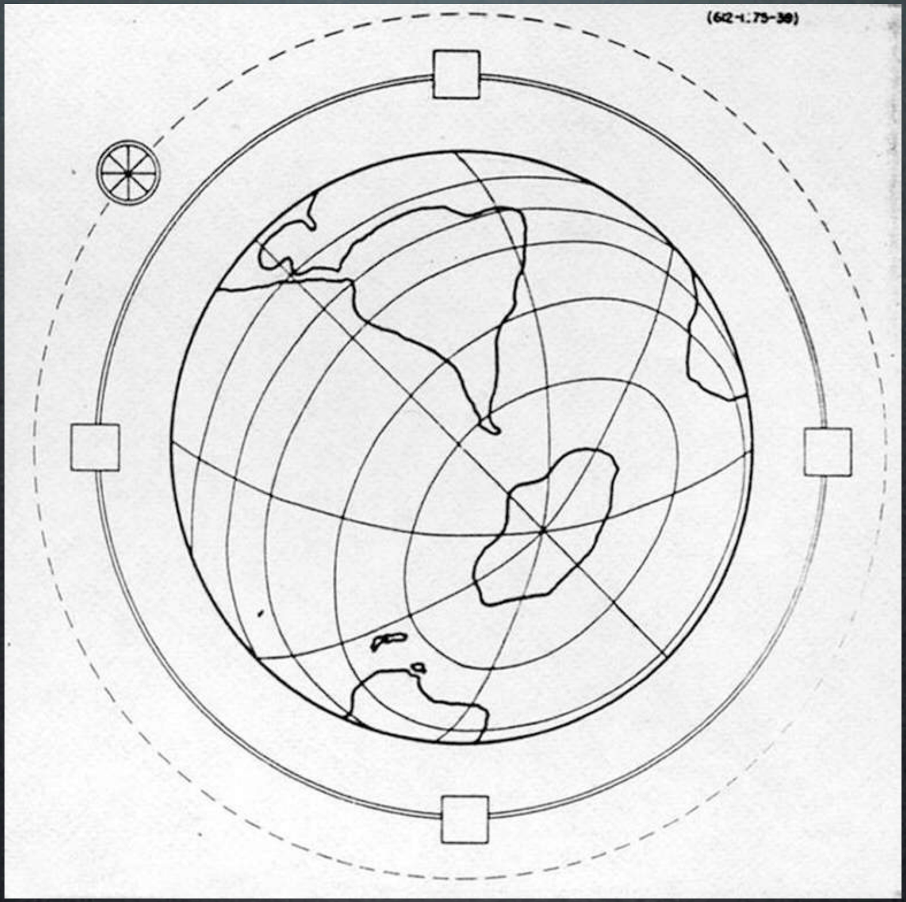
ρ 8000 km

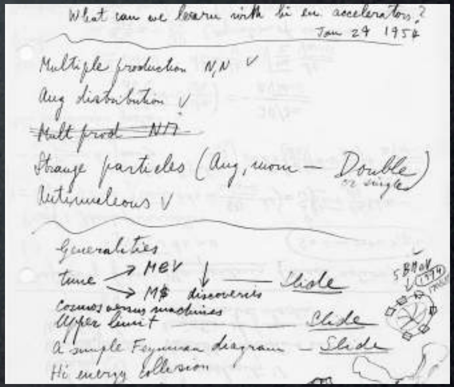
fixed target

3 TeV cm

170 G$

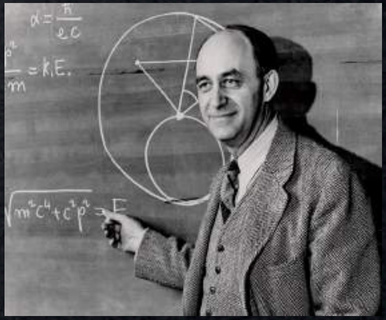
1994




What can we learn with hi en. accelerators?
Jan 24 1954

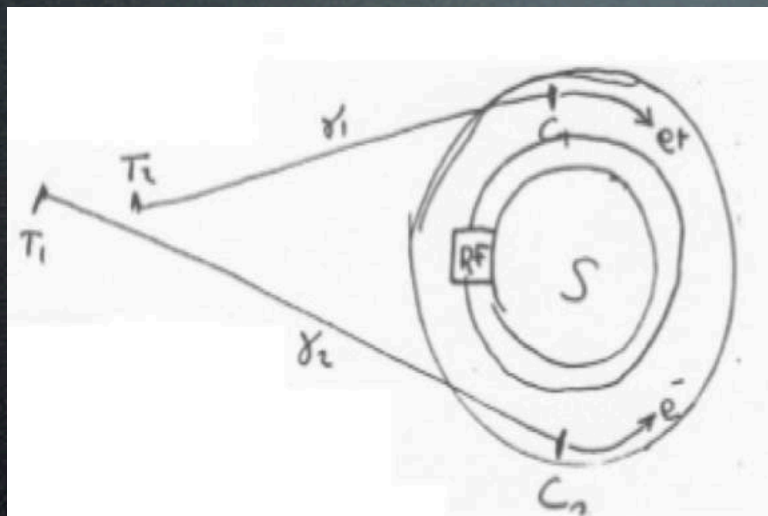
Multiple production N,N ✓
Ang distribution ✓
~~Mult prod NΠ~~
Strange particles (Ang, mom — Double or single)
Intranucleons ✓

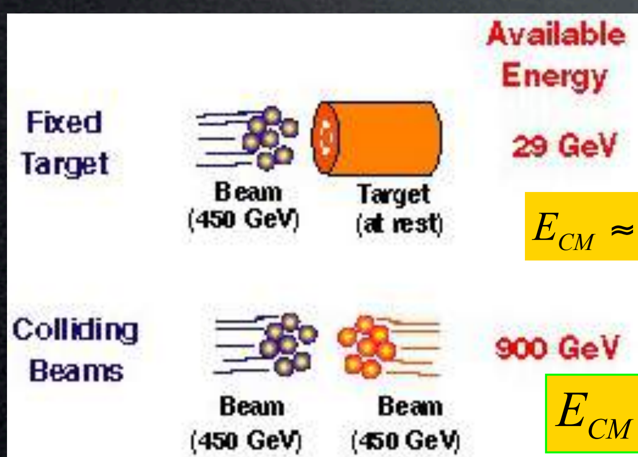
Generalities
time → MeV ↓ —— Slide
→ M$ discoveries
Cosmos versus machines
Upper limit —— Slide
A simple Feynman diagram — Slide
Hi energy collision



Touschek's Anello Di Accumulazione (ADA)

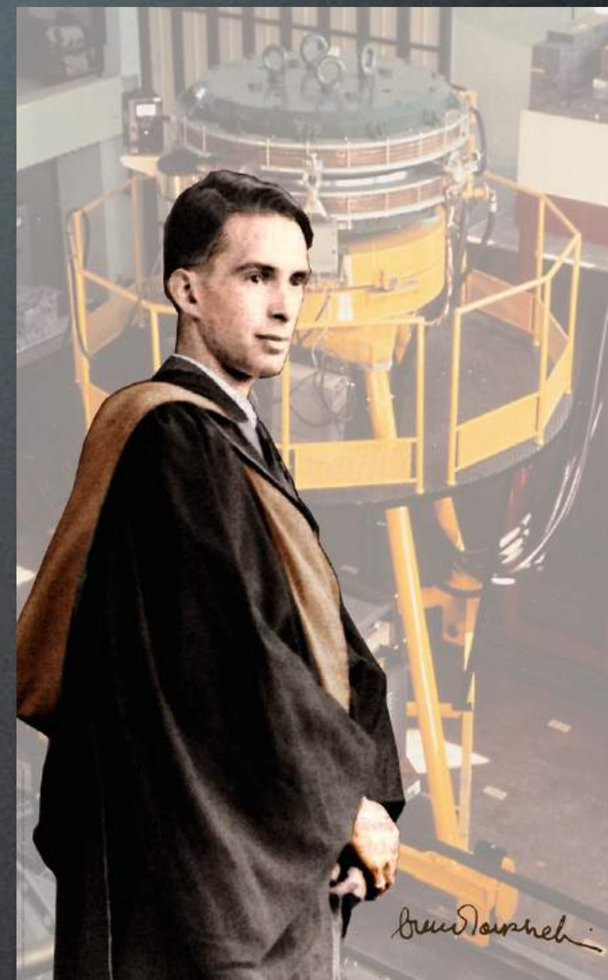
1961 the first e+e- Collider

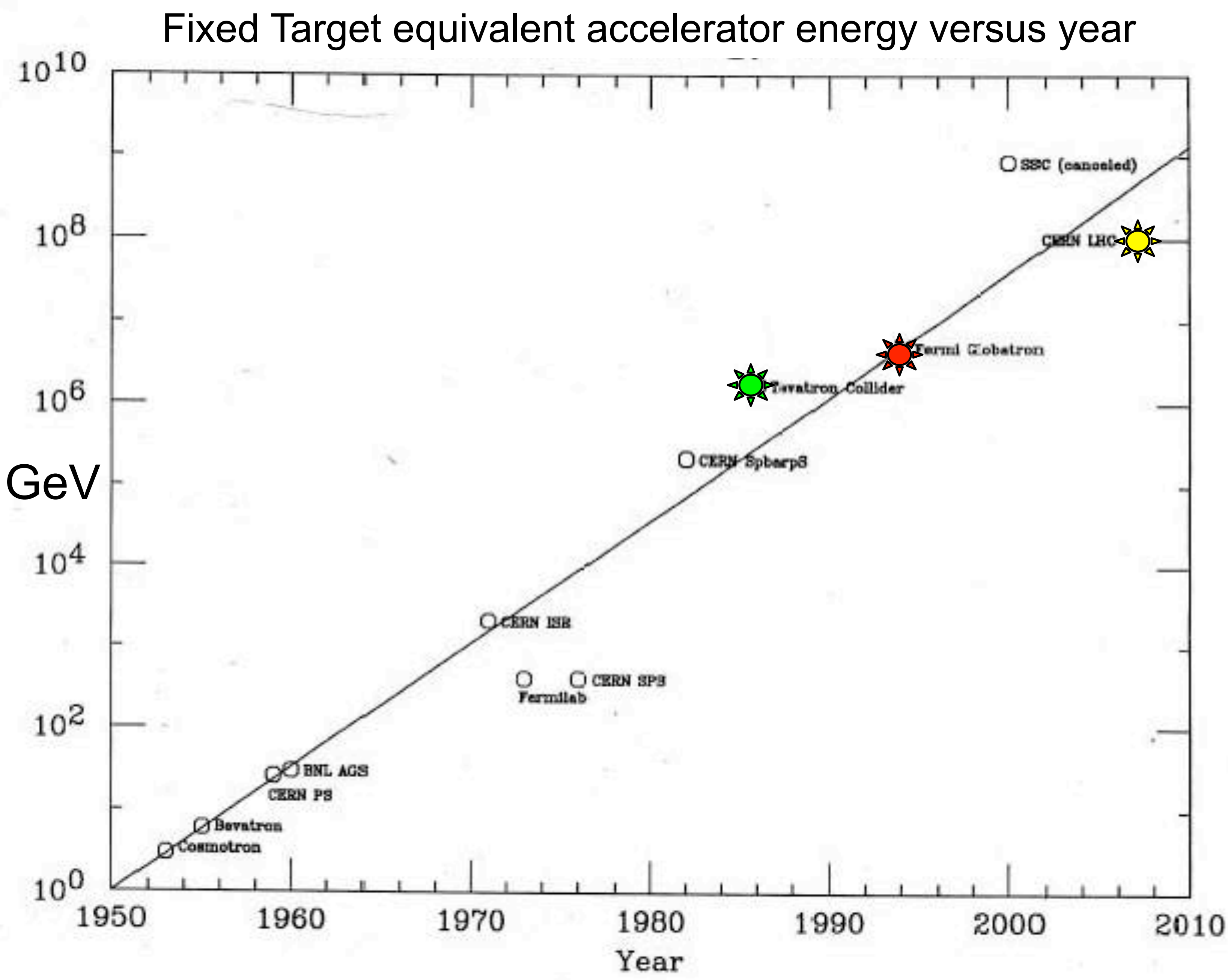




$$E_{CM} \approx \sqrt{2E_1 m_2}$$

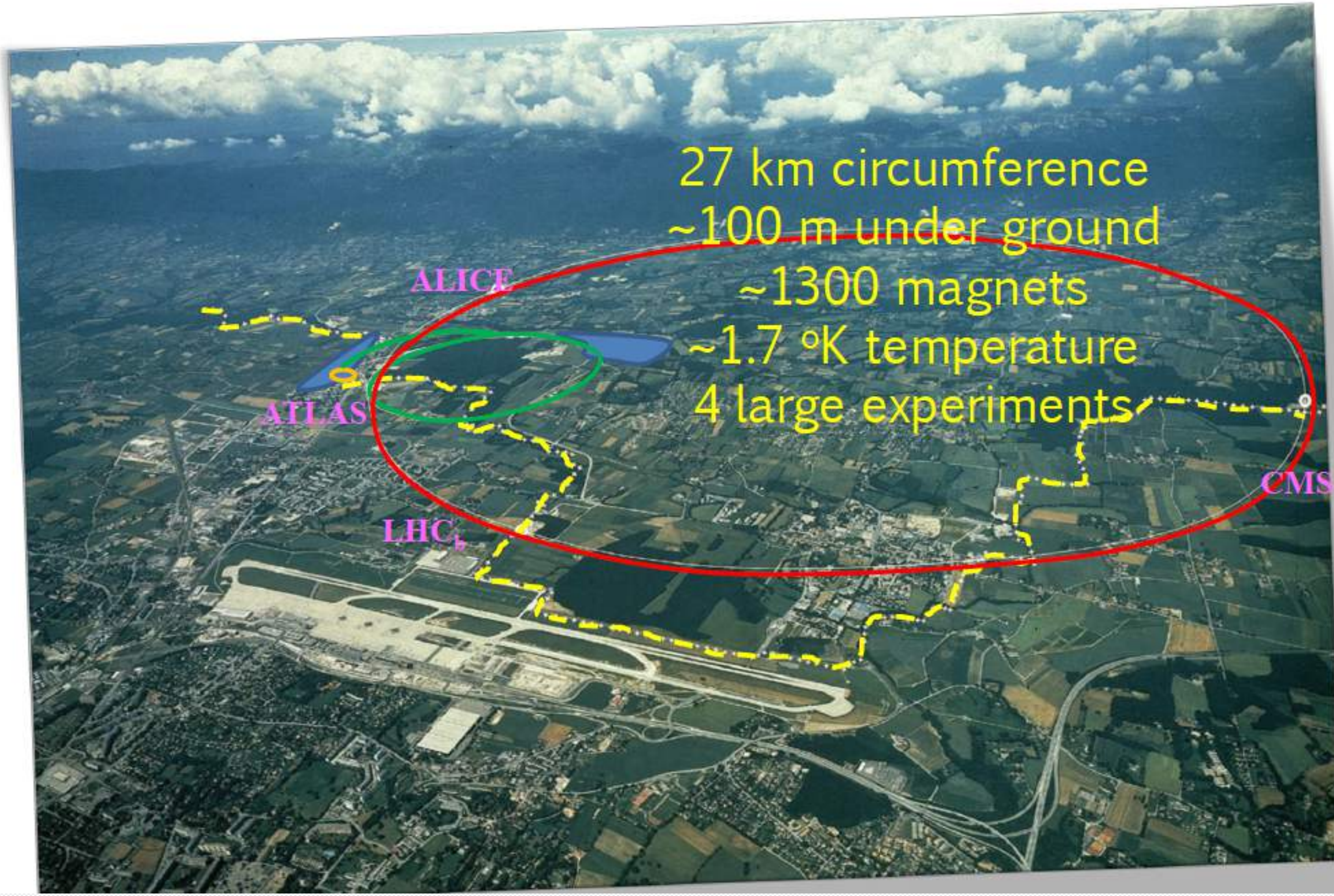
$$E_{CM} \approx 2E$$





Fixed Target equivalent accelerator energy versus year
GeV
Year
SSC (canceled)
CERN LHC
Fermi Globatron
Tevatron Collider
CERN SpbarpS
CERN ISR
Fermilab
CERN SPS
BNL AGS
CERN PS
Bevatron
Cosmotron

LHC – a few data



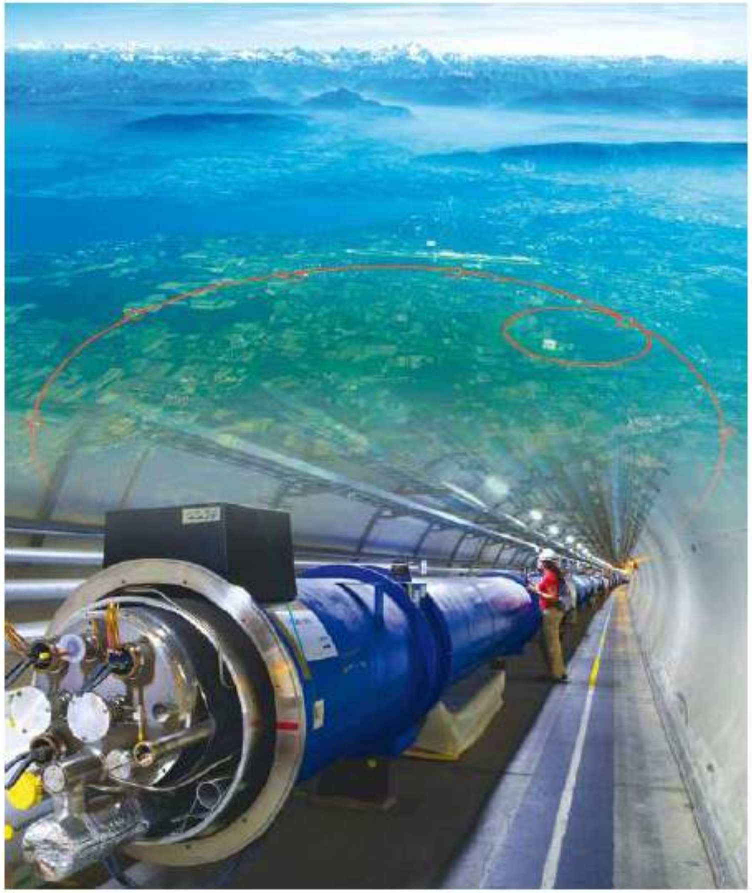
LHC (Large Hadron Collider) – a brief history

F. Bordry / CERN

14 TeV proton-proton accelerator-collider built in the LEP tunnel

Lead-Lead (Lead-proton) collisions

1983	: First studies for the LHC project
1988	: First magnet model (feasibility)
1994	: Approval of the LHC by the CERN Council
1996-1999	: Series production industrialisation
1998	: Declaration of Public Utility & Start of civil engineering
1998-2000	: Placement of the main production contracts
2004	: Start of the LHC installation
2005-2007	: Magnets Installation in the tunnel
2006-2008	: Hardware commissioning
2008-2009	: Beam commissioning and repair
2009-2035	: Physics exploitation



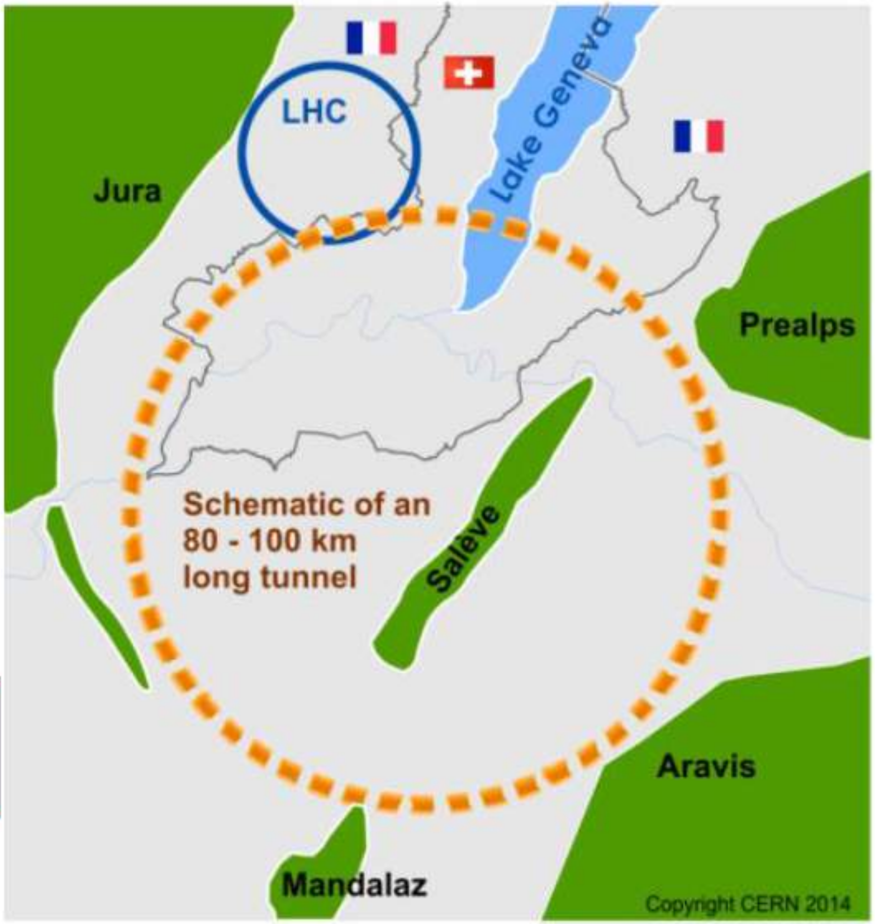
~ 30 years between the first studies and the start for the Physics

Today FCC (Future Circular Collider) study

International collaboration to study:

- ***pp*-collider (*FCC-hh*)**
- **e^+e^- collider (*FCC-ee*)**
  as potential intermediate step
- ***p-e* (*FCC-he*)**
  as an option

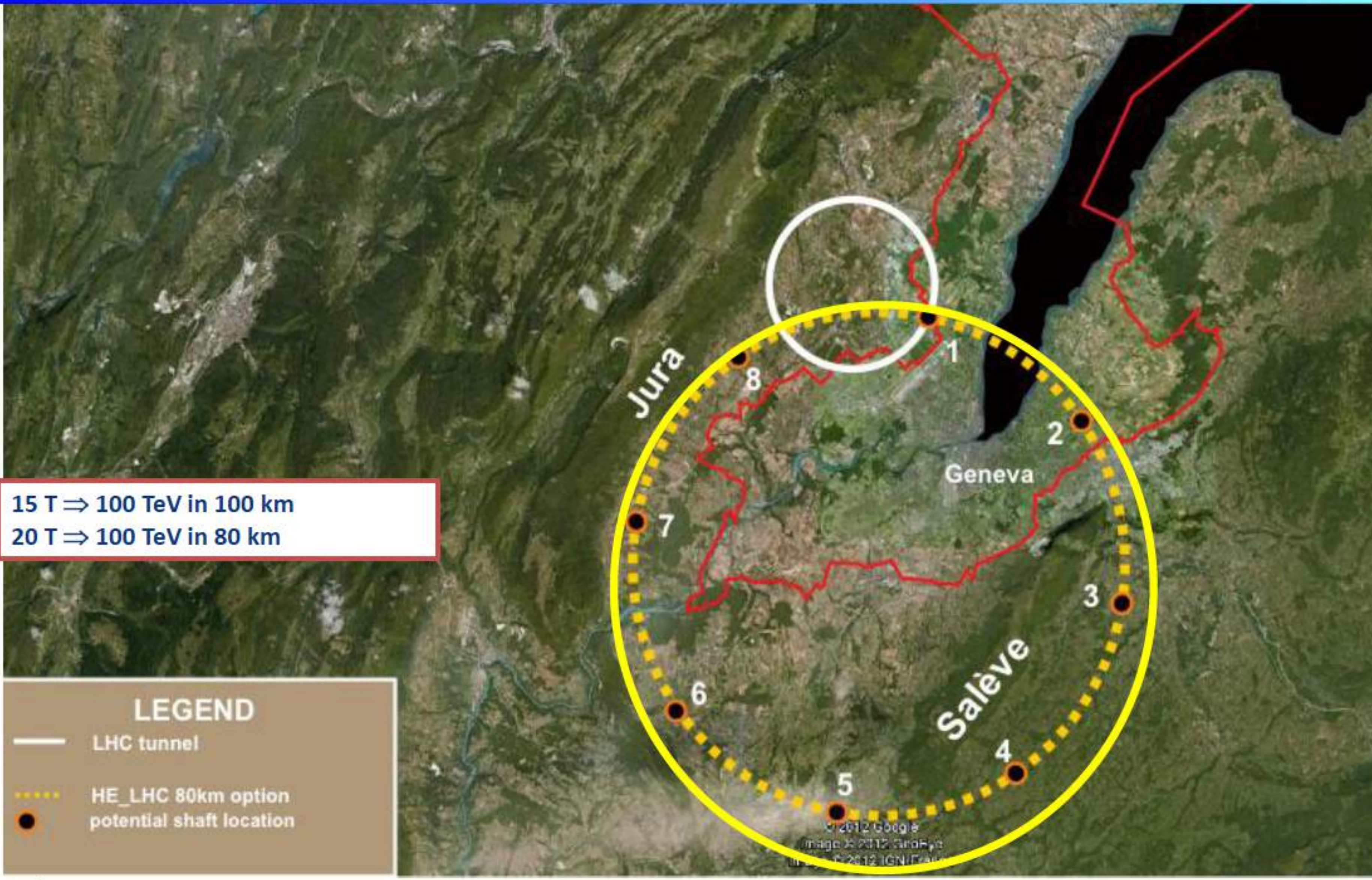
~16 T ⇒ 100 TeV *pp* in 100 km
~20 T ⇒ 100 TeV *pp* in 80 km



FCC: 80-100 km infrastructure in Geneva area

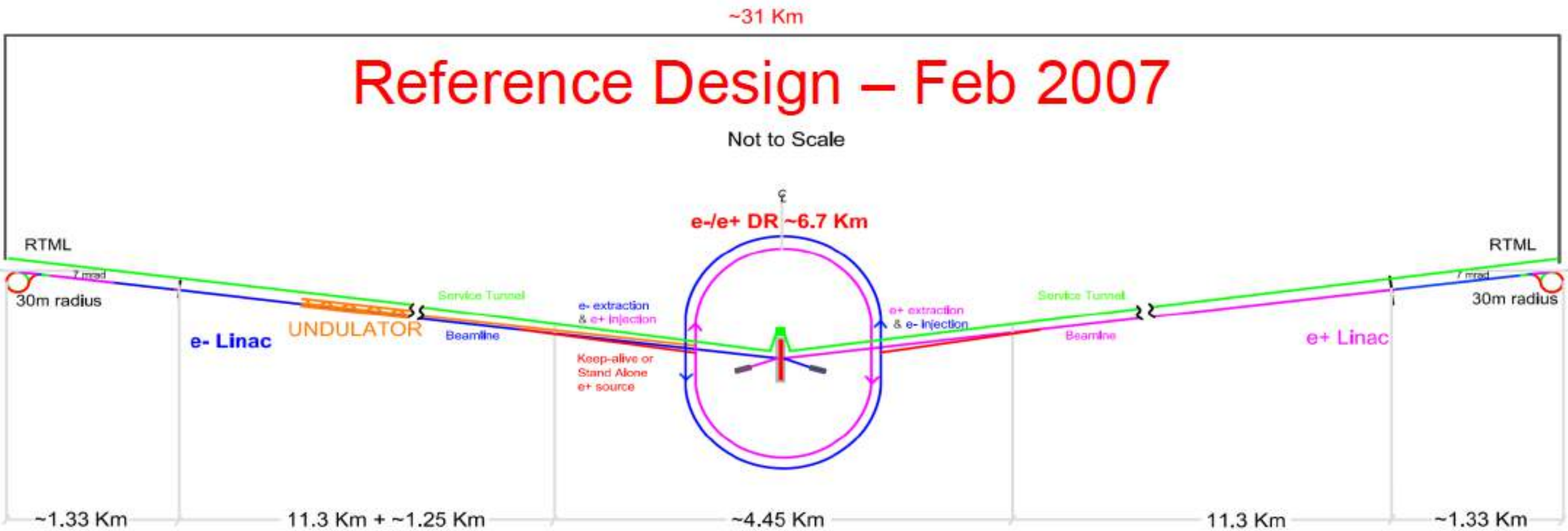
Potential footprint of FCC

15 T ⇒ 100 TeV in 100 km
20 T ⇒ 100 TeV in 80 km



ILC (International Linear Collider) $e^+ e^-$

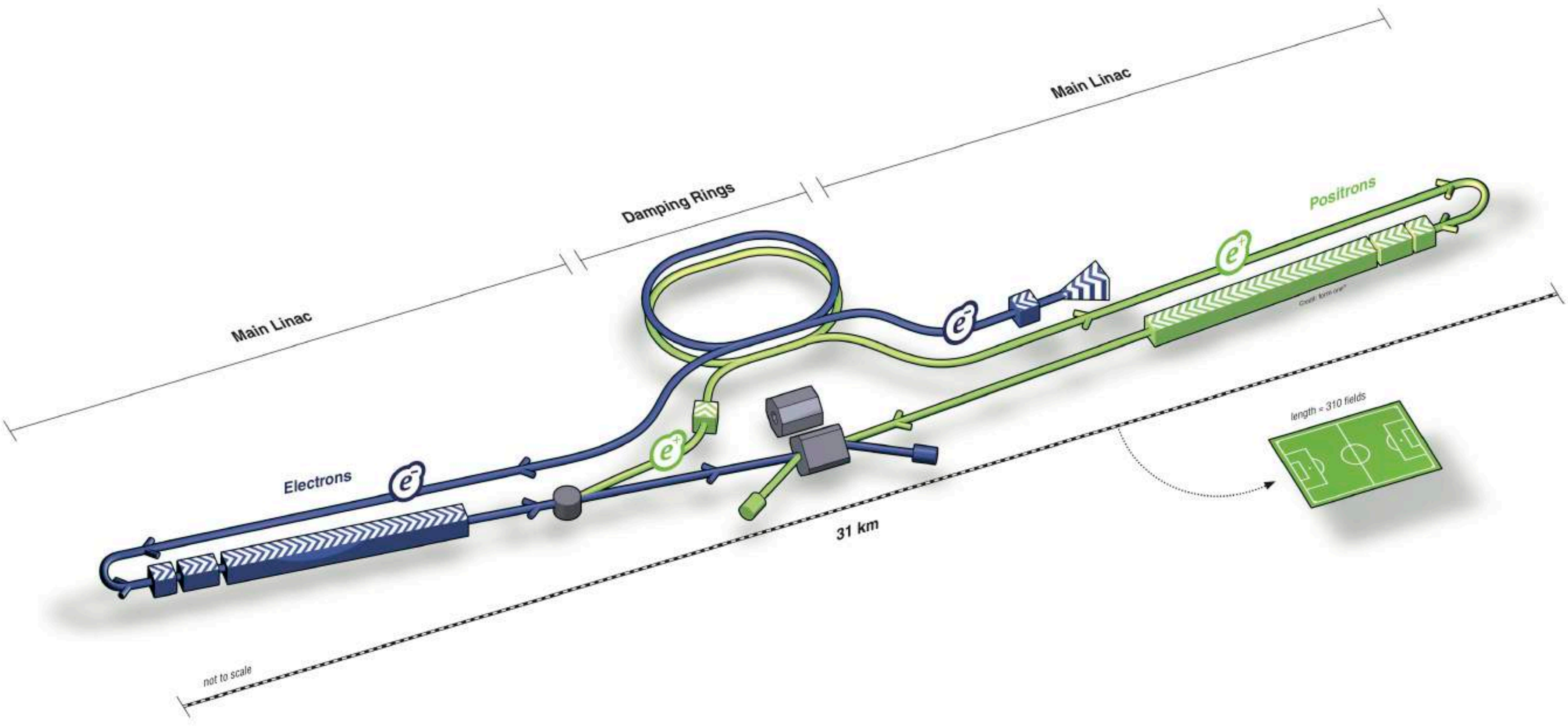
- 11km SC linacs operating at 31.5 MV/m for 500 GeV
- Centralized injector
- Single IR with 14 mrad crossing angle
- Dual tunnel configuration for safety and availability



Schematic Layout of the 500 GeV Machine

Documented in Reference Design Report

ILC – International Linear Collider



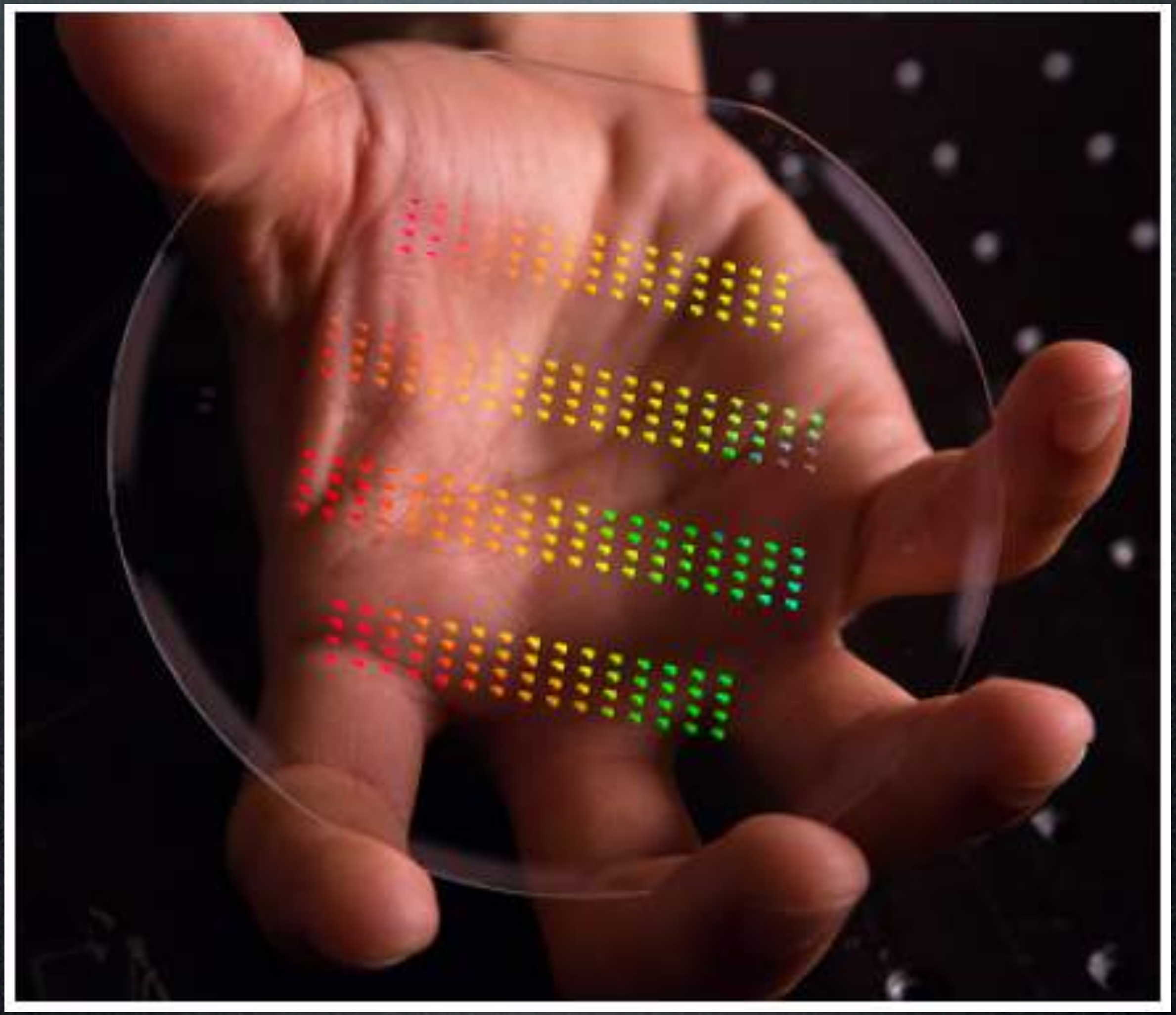
Hawking: the Solartron

Towards the Planck scale

Without further novel technology, we will eventually need an accelerator as large as Hawking expected.

“The Universe in a Nutshell”, by Stephen William Hawking, Bantam, 2001

Accelerator on a Chip?



SLAC Now and Tomorrow?

LORENTZ FORCE: ACCELERATION AND FOCUSING

Particles are accelerated through electric fields and are bended and focused through magnetic fields. The basic equation that describe the acceleration/bending/focusing processes is the **Lorentz Force**.

$\vec{p} = momentum$

$m = mass$

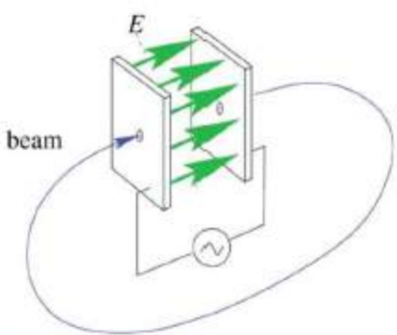
$\vec{v} = velocity$

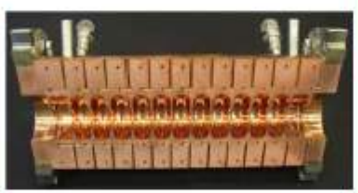
$q = charge$

$$\frac{d\vec{p}}{dt} = q\left(\vec{E} + \vec{v} \times \vec{B}\right)$$

ACCELERATION

To accelerate, we need a force in the direction of motion

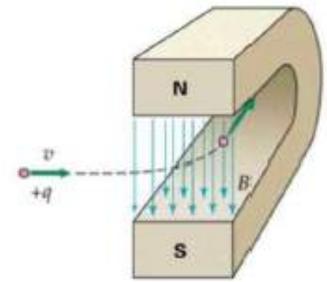


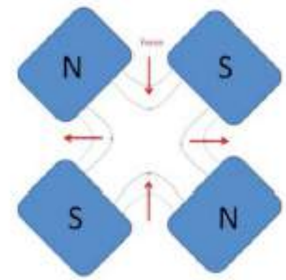


Longitudinal Dynamics

BENDING AND FOCUSING

2^{nd} term always perpendicular to motion => no acceleration





Transverse Dynamics

HIGH GRADIENT AAC ROAD MAP

① Miniaturization of the accelerating structures (~resonant)

② Wake Field Acceleration (~transient) (LWFA, PWFA, DWFA)

- Power sources
- Accelerating structures
- High quality beams

Modern accelerators require high quality beams:

==> High Luminosity & High Brightness

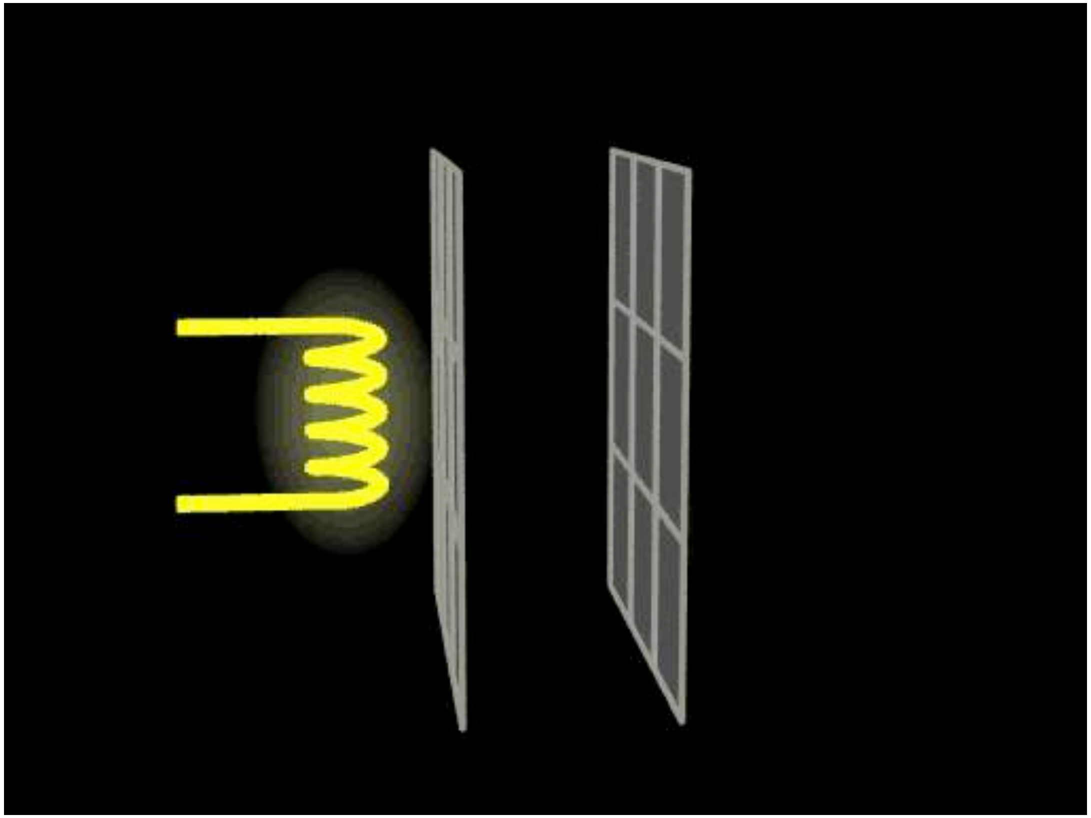
==> High Energy & Low Energy Spread

$$\uparrow \quad L = \frac{N_{e+} N_{e-} f_r}{4\pi \sigma_x \sigma_y}$$

- –N of particles per pulse => 10^9
- –High rep. rate f_r => bunch trains
- –Small spot size => low emittance

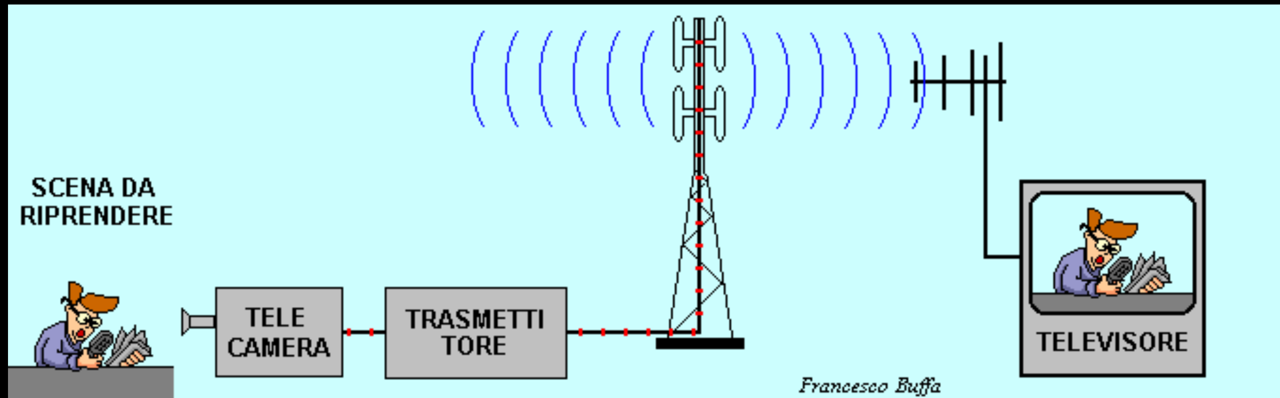
$$\uparrow \quad B_n \approx \frac{2I}{\varepsilon_n^2}$$

- –Short pulse (ps to fs)
- –Little spread in transverse momentum and angle => low emittance

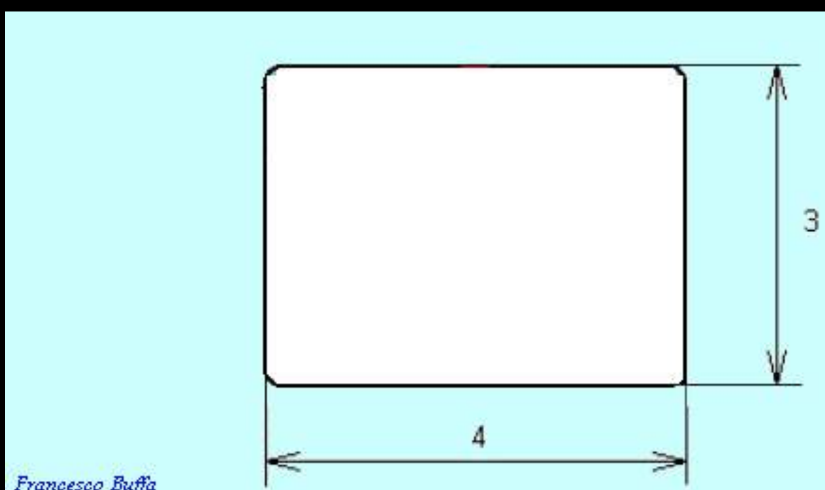


$T = q\Delta V$


Rai


SCENA DA
RIPRENDERE
TELE
CAMERA
TRASMETTI
TORE
TELEVISORE
Francesco Buffa

E = 10 keV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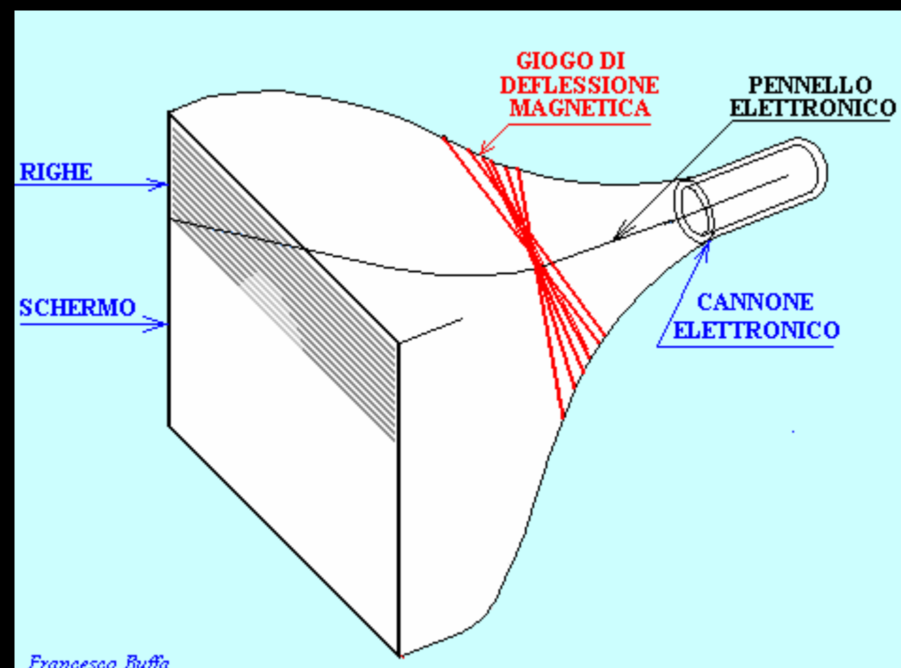
Francesco Buffa


GIOGO DI
DEFLESSIONE
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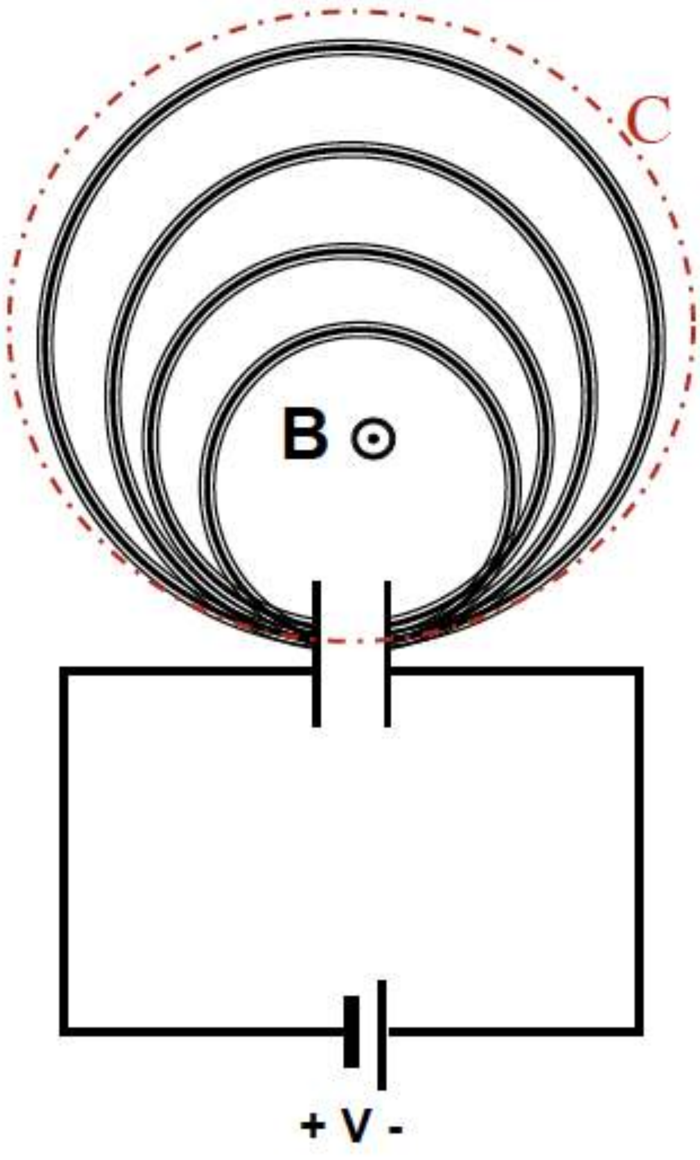
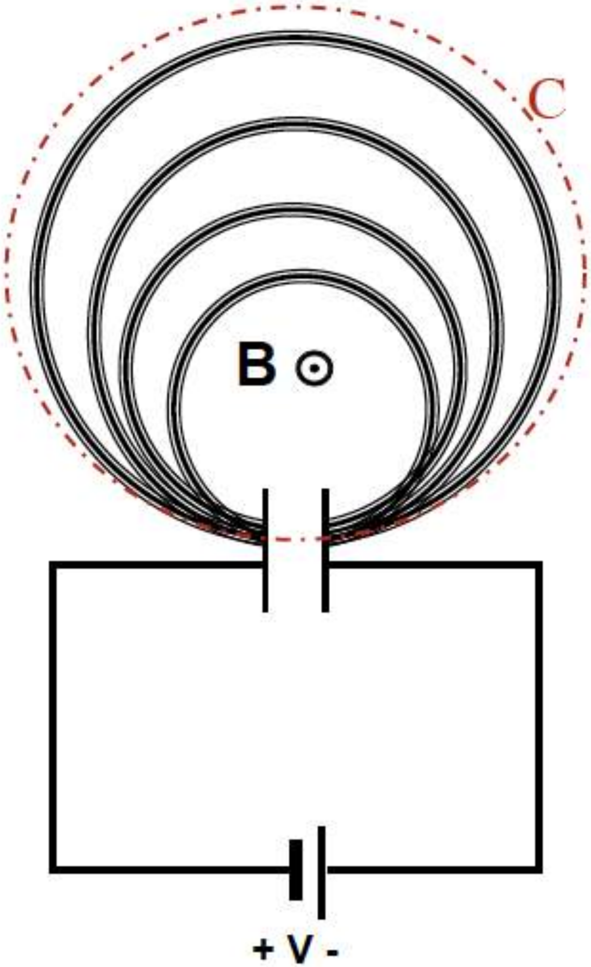
PENNELLO
ELETTRONICO
RIGHE
SCHERMO
CANNONE
ELETTRONICO
Francesco Buffa

Possible DC accelerator?



Maxwell forbids this!



$$\nabla \times \mathbf{E} = -\frac{d\mathbf{B}}{dt}$$

or in integral form

$$\oint_C \mathbf{E} \cdot d\mathbf{s} = -\frac{\partial}{\partial t}\int_S \mathbf{B} \cdot \mathbf{n}\, da$$

∴ **There is no acceleration without time-varying magnetic flux**

$\Delta V_T = 0$

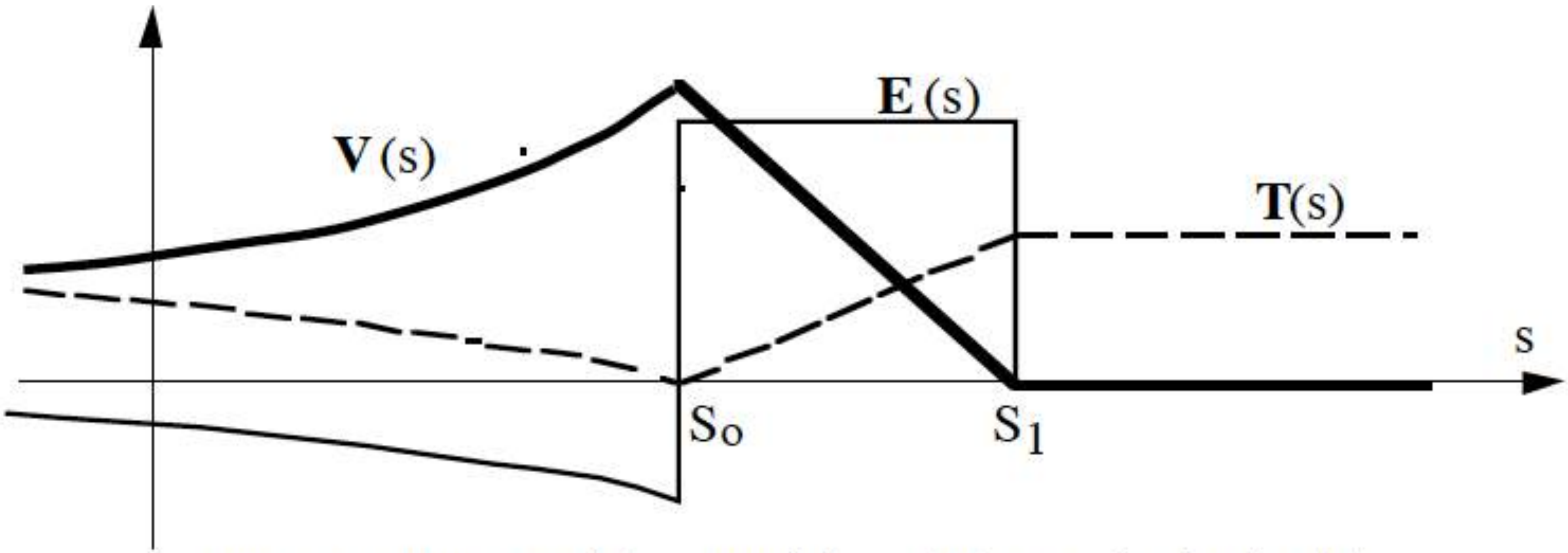
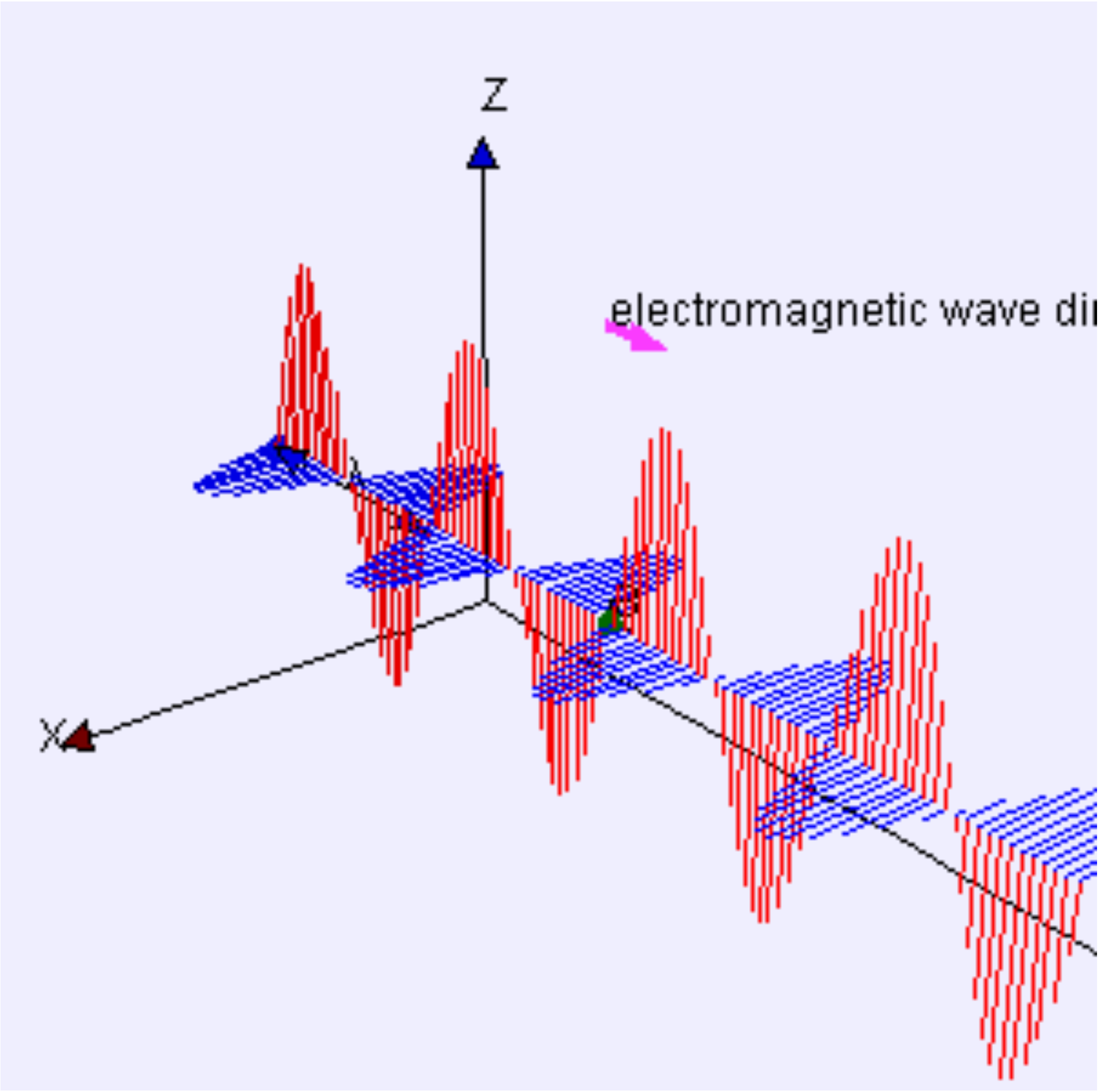


Fig.2.2. Campo e.s.(E), potenziale e.s.(V), energia cinetica(T)

Interaction with a plane wave in Vacuum



Let us consider a charge co-propagating in the z direction with a wave having a longitudinal component E_z

$$\begin{cases} v_z = \beta c \\ E(z,t) = E_z(z)\, e^{i(\omega t - kz)} \end{cases}$$

the particle experiences an accelerating voltage:

$$V_{acc} = Re \int_o^L E_z(z) e^{i(\omega t - kz + \phi_o)} dz$$

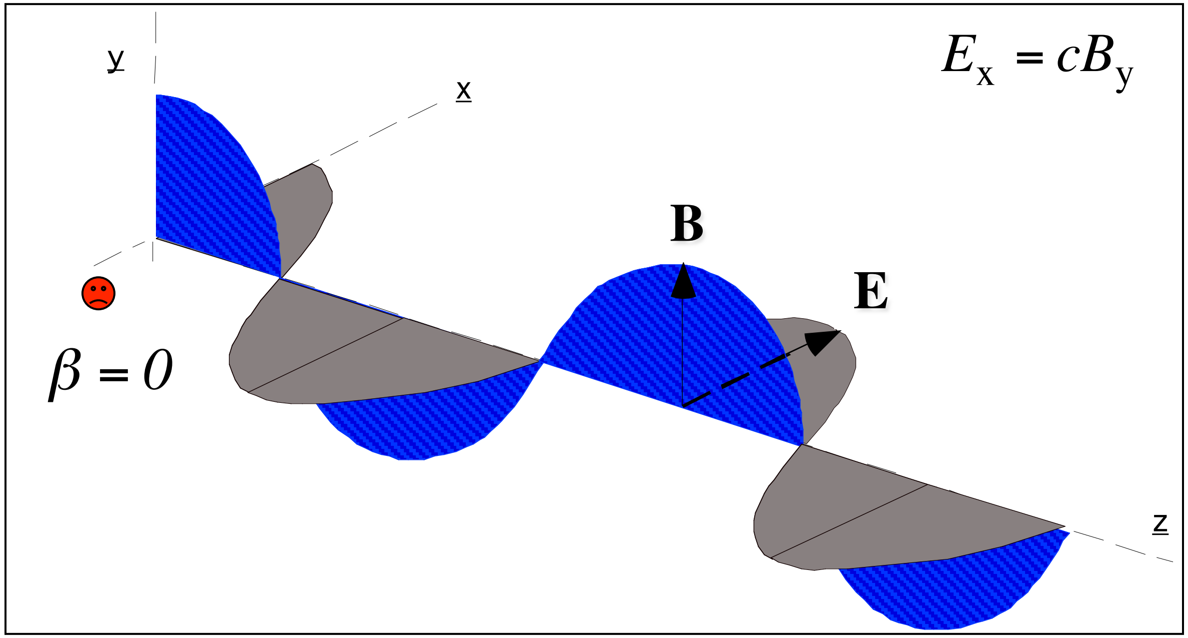
$$z = \beta c t \qquad V_{acc} = Re \int_o^L E_z(z) e^{i\left(\omega \frac{z}{\beta c} - kz + \phi_o\right)} dz$$

The energy gain depends on the spatial pattern of the field and on the phase relation (phase slippage)

The wave is syncronous when: $\frac{\omega}{k} = \beta c$

$$V_{acc} = Re \int_o^L E_z(z) e^{i\phi_o} dz$$

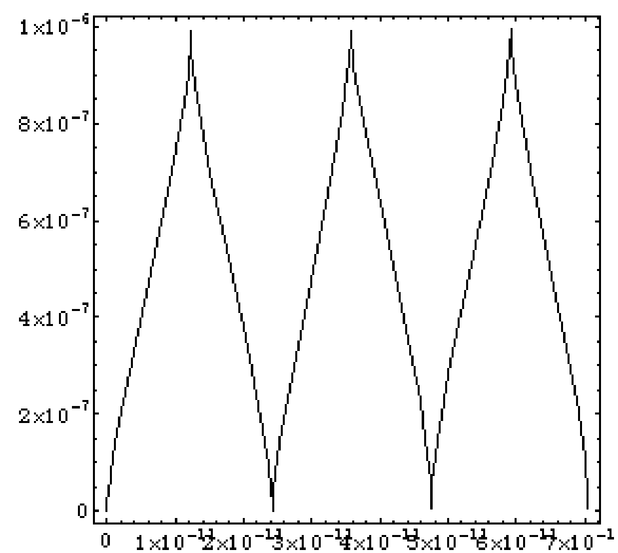
Interaction with a plane wave: particle at rest



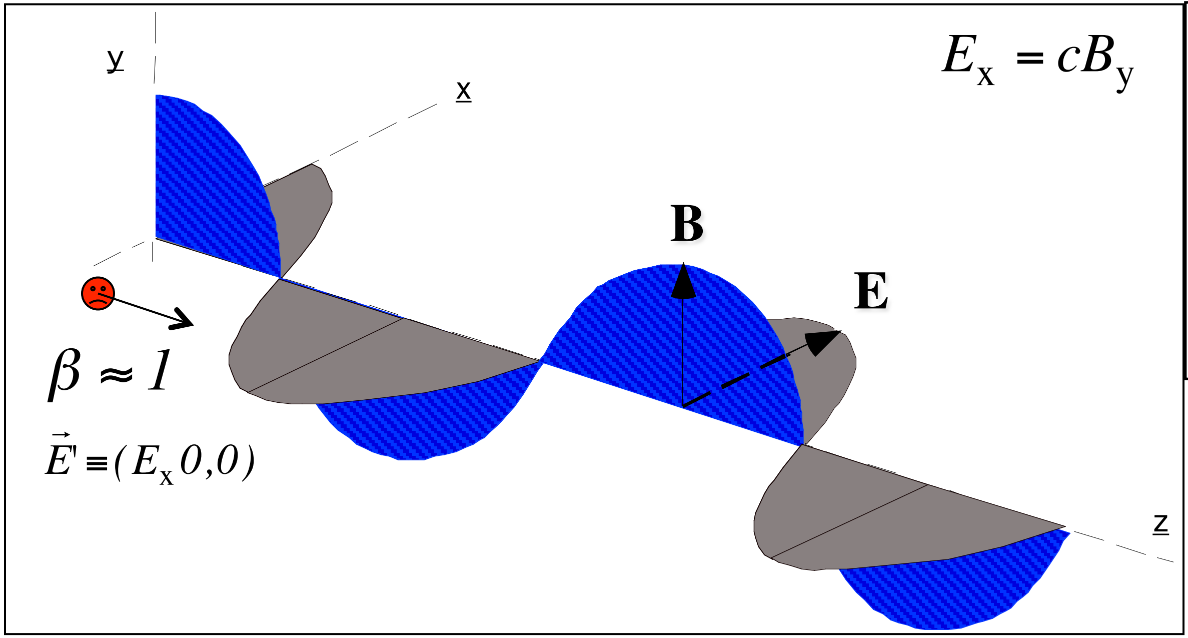
Non relativistic approx:

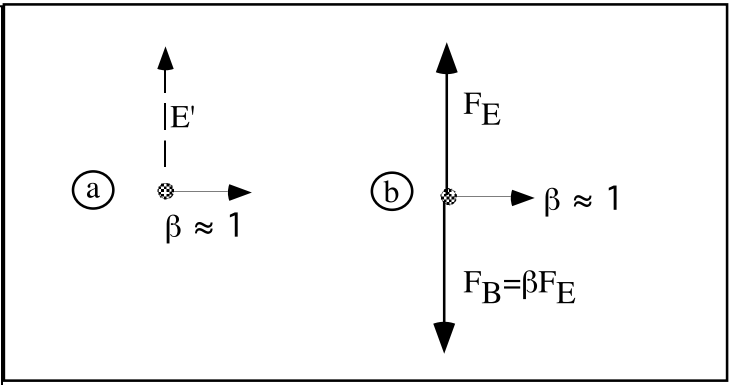
$$\ddot{x} = \frac{e}{m_o}\left(E_x - v_z B_y\right)\cos\left(\omega t - kz + \varphi_o\right)$$

$$\ddot{z} = \frac{e}{m_o} v_x B_y \cos\left(\omega t - kz + \varphi_o\right)$$



Interaction with a plane wave: particle co-propagating





$$\begin{cases} E_x = \gamma E_x' \\ B_y = \gamma \dfrac{\beta}{c} E_x' = \dfrac{\beta}{c} E_x \end{cases}$$

$$F_\perp = e\left(E_x - \beta c B_y\right) cos\left(\omega t - kz\right)$$

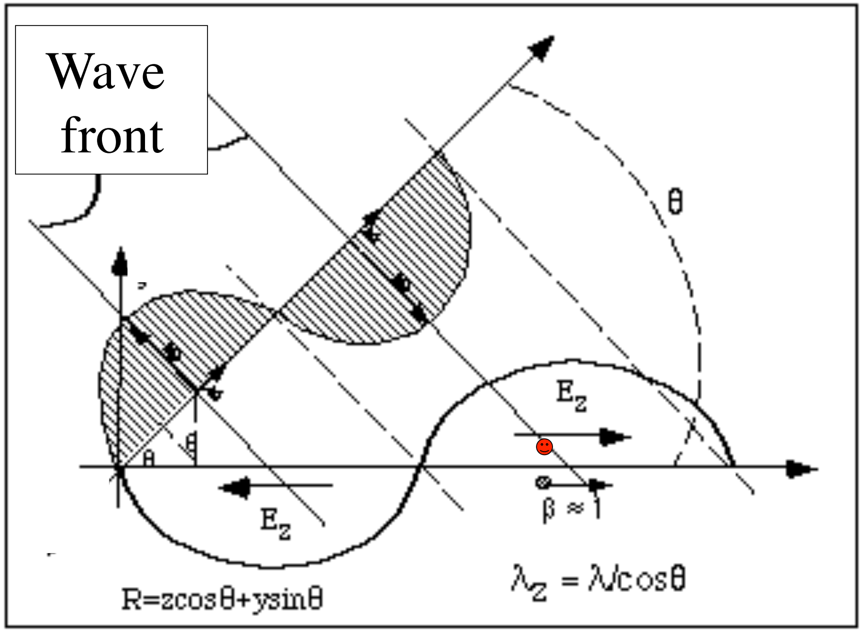
$$kz = k\beta ct = \omega\beta t$$

$$= e\left(1-\beta\right)E_x\, cos\left(\omega\left(1-\beta\right)t\right)$$

$$\beta = \sqrt{1-\frac{1}{\gamma^2}} \approx 1 - \frac{1}{2\gamma^2}$$

$$\cong \frac{eE_x}{2\gamma^2} cos\left(\frac{\omega t}{2\gamma^2}\right)$$

Interaction with a plane wave with an angle



$$E_z = -E_o \sin\theta \cdot e^{i[\omega t - k(z\cos\theta + y\sin\theta) + \varphi]}$$

Not yet suitable

$$v_{\phi z} = \frac{\omega}{k_z} = \frac{\omega}{k\cos\theta} = \frac{c}{\cos\theta} > c$$

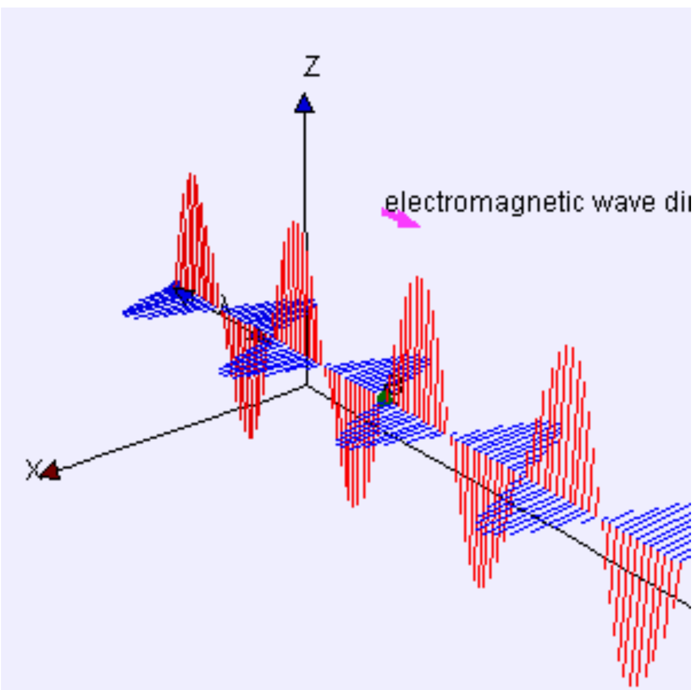
$$\frac{\Delta\phi}{\Delta t} = \omega\left(1 - \beta\cos\theta\right)$$

Lawson-Woodward Theorem

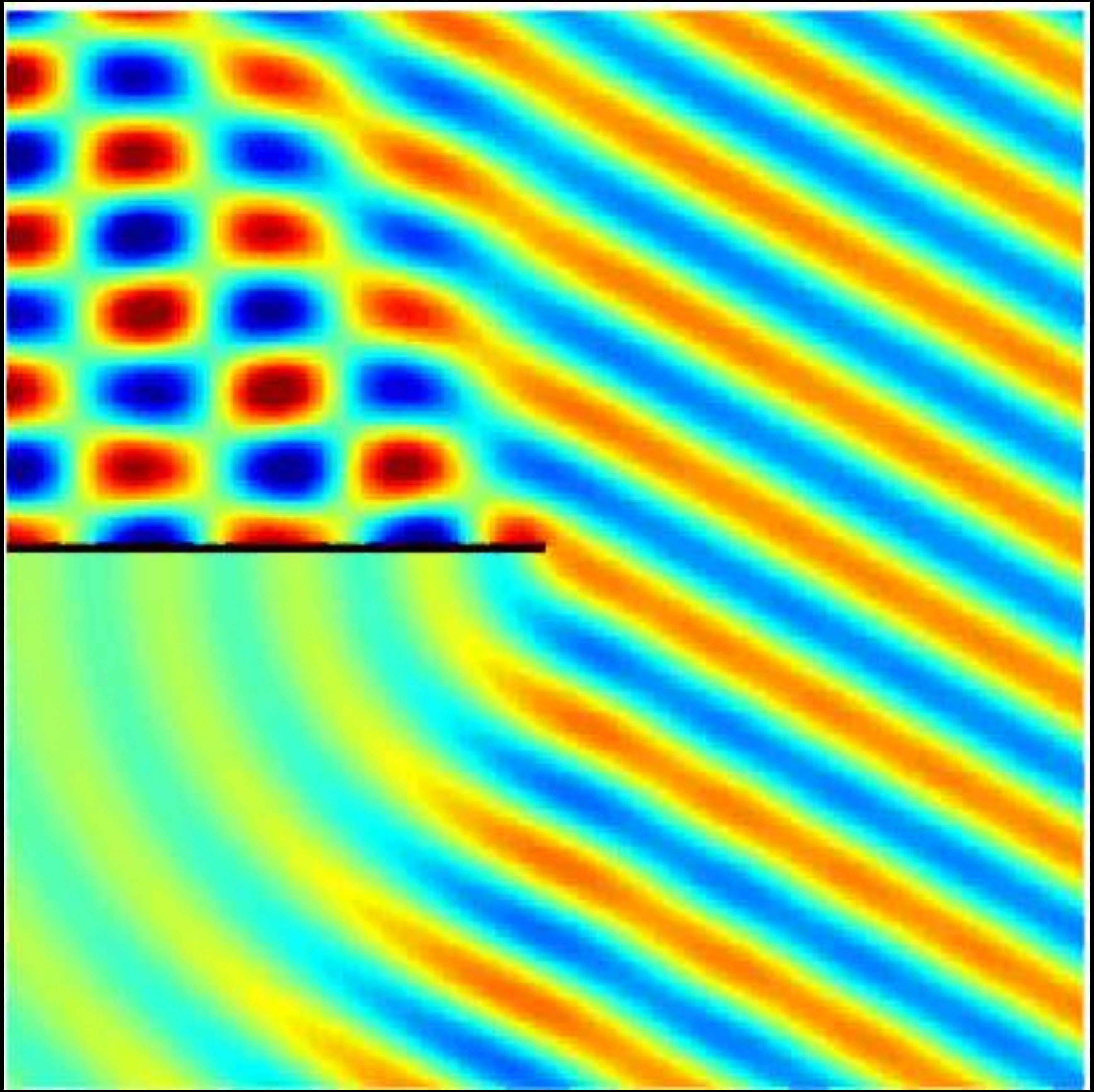
(J.D. Lawson, IEEE Trans. Nucl. Sci. NS-26, 4217, 1979)

The net energy gain of a relativistic electron interacting with an electromagnetic field **in vacuum** is zero.

The theorem assumes that
(i) the laser field is in vacuum with no walls or boundaries present,
(ii) the electron is highly relativistic (v ≈ c) along the acceleration path,
(iii) no static electric or magnetic fields are present,
(iv) the region of interaction is infinite,



$$F_{\perp} \cong \frac{eE_x}{2\gamma^2}\cos\left(\frac{\omega t}{2\gamma^2}\right)$$

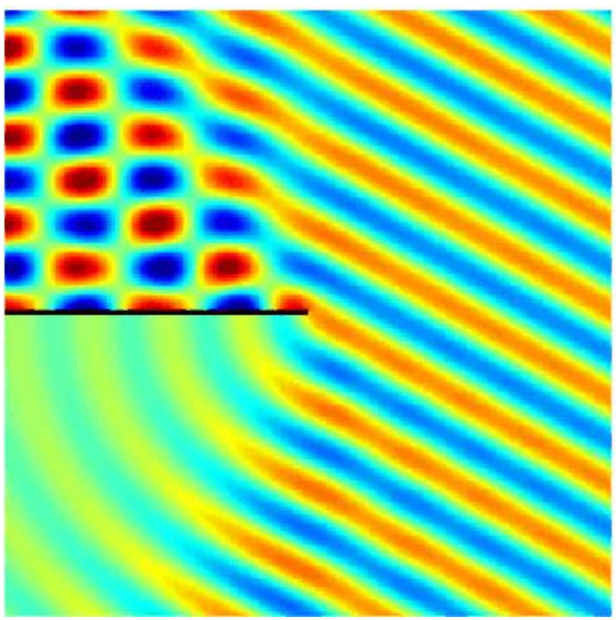


Taking into account the boundary conditions the accelerating component of the field becomes:

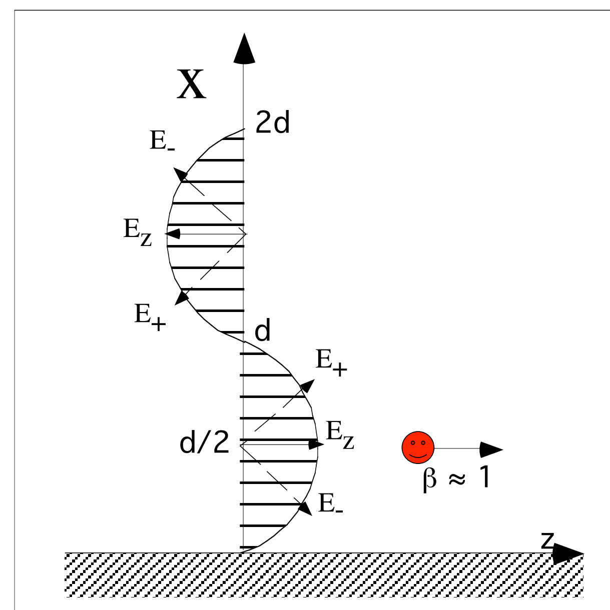
$$E_z(x,z,t) = (E_+ \sin\theta)e^{i\omega t - ik(z\cos\theta - x\sin\theta)} - (E_+ \sin\theta)e^{i\omega t - ik(z\cos\theta + x\sin\theta)}$$

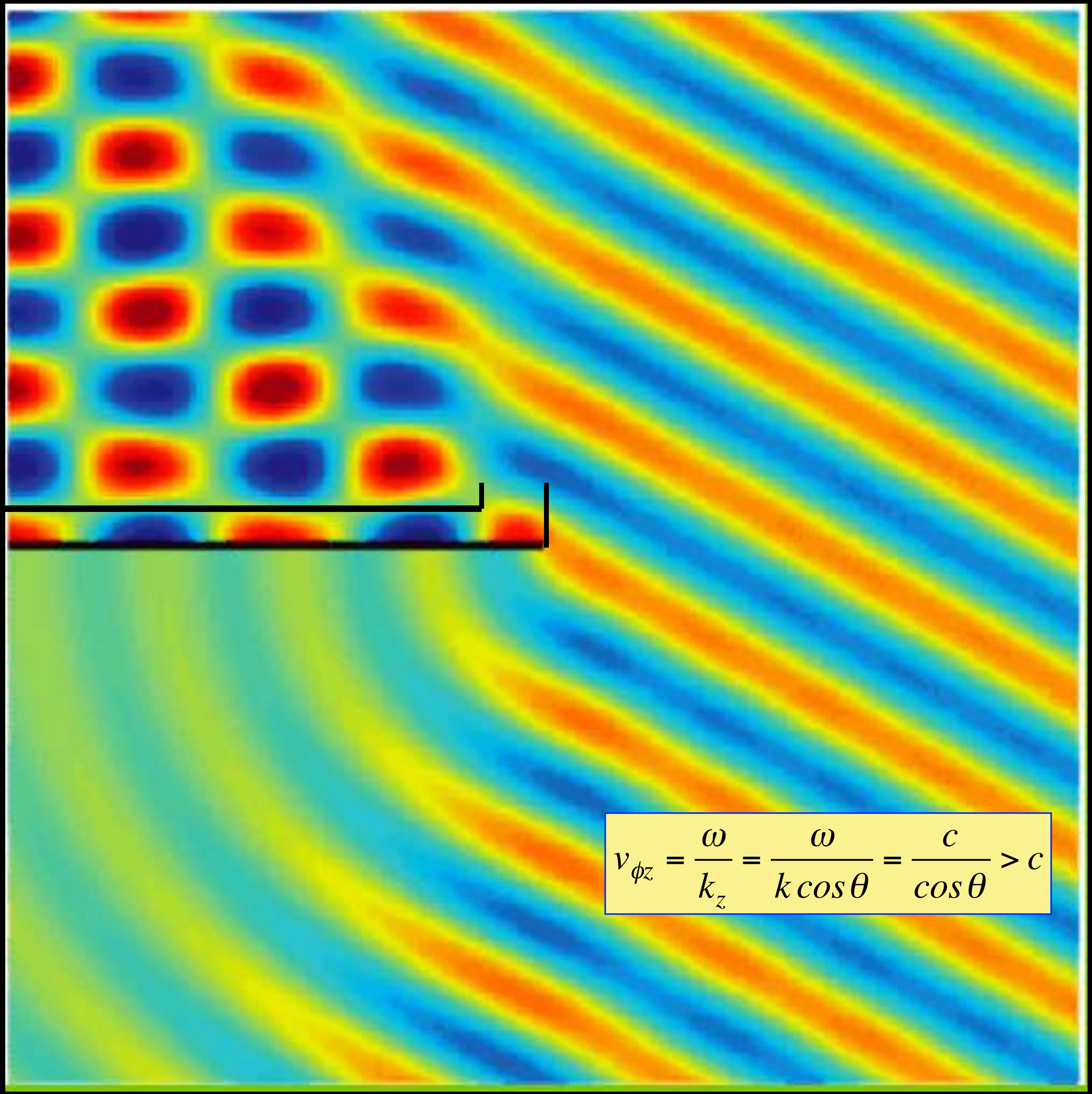
$$= 2iE_+ \sin\theta \sin(kx\sin\theta)e^{i\omega t - ikz\cos\theta}$$

z-TW pattern

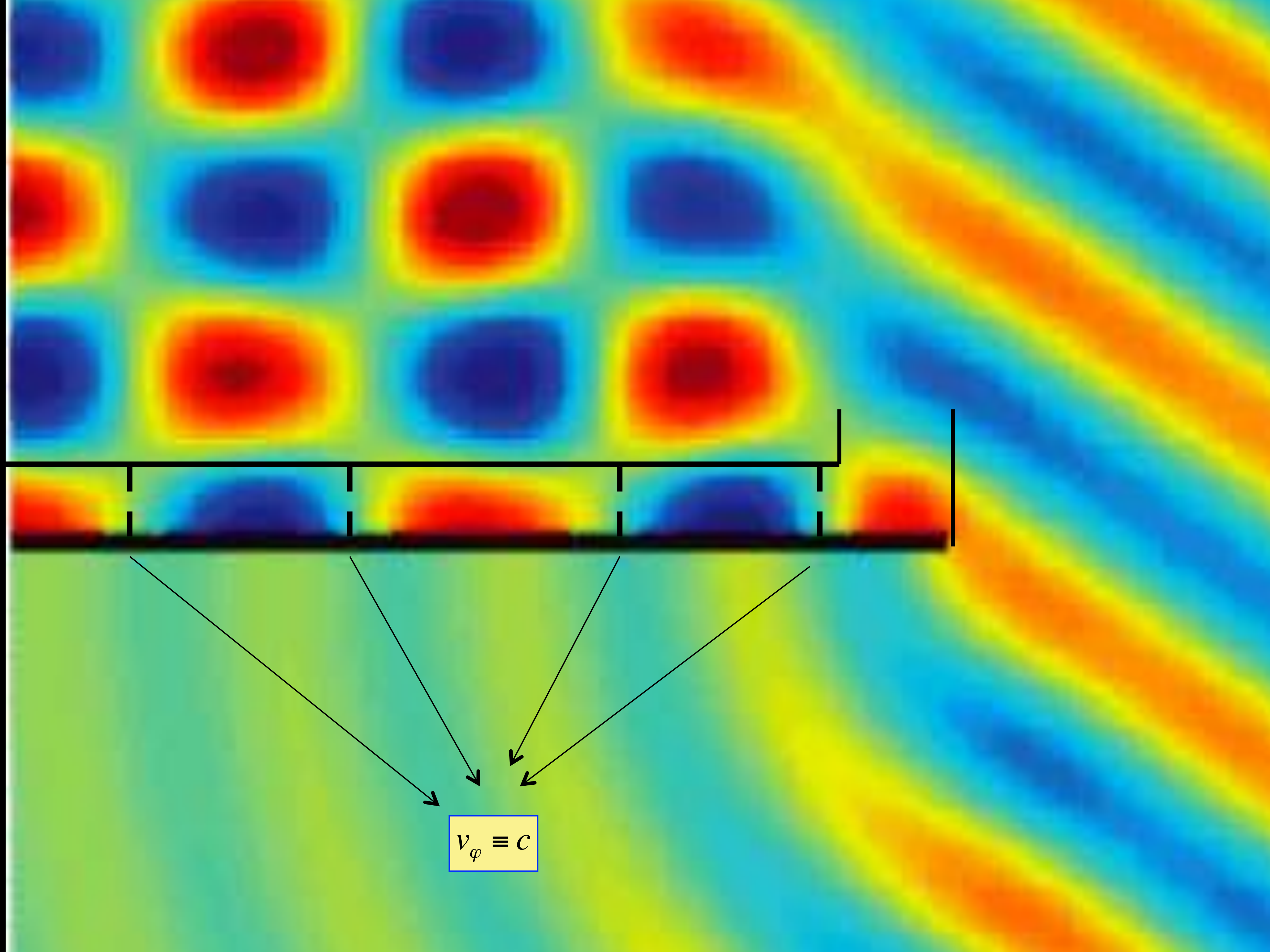


x-SW pattern





$$v_{\phi z} = \frac{\omega}{k_z} = \frac{\omega}{k\cos\theta} = \frac{c}{\cos\theta} > c$$


$v_\varphi \equiv c$

We must slow down the wave propagation

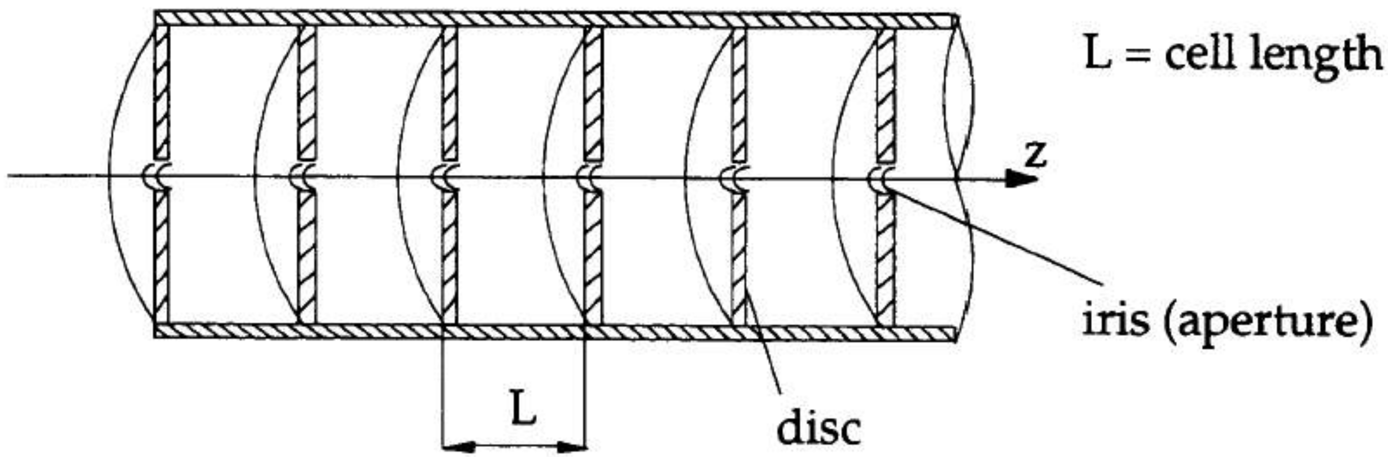
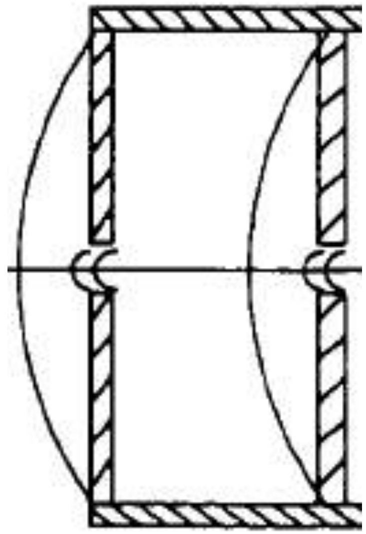


Fig. 6 Disc-loaded cavity (schematic)

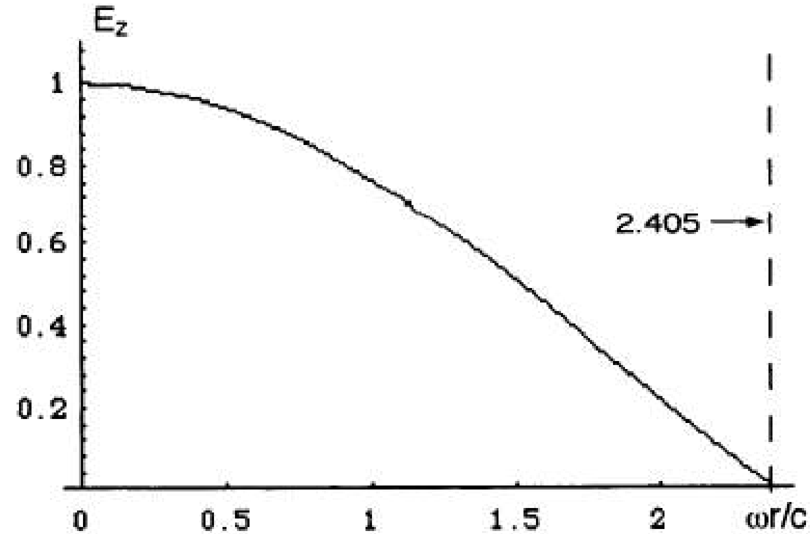
In order to slow down the waves we have to load the cavity by introducing some periodic obstacle into it

$$\frac{\partial^2 E_z}{\partial z^2} + \frac{1}{r}\frac{\partial E_z}{\partial r} + \frac{\partial^2 E_z}{\partial r^2} - \frac{1}{c^2}\frac{\partial^2 E_z}{\partial t^2} = 0$$

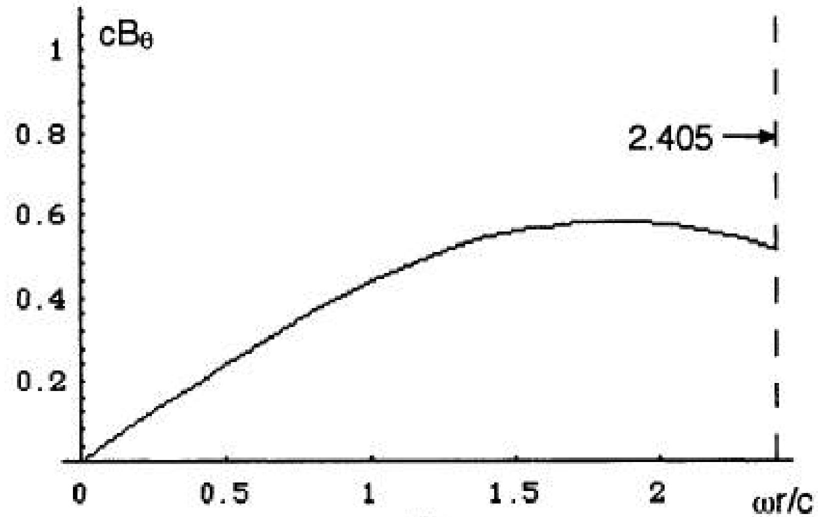


$$E_z = E_0 J_0(k_r r) \cos \omega t$$

$$B_\theta = -\frac{E_0}{c} J_1(k_r r) \sin \omega t$$



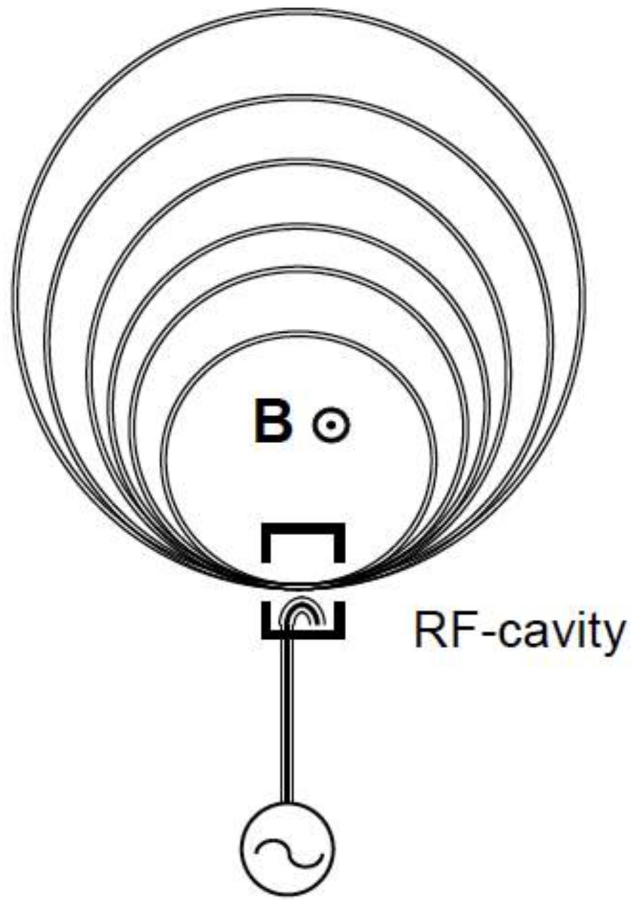
(a)



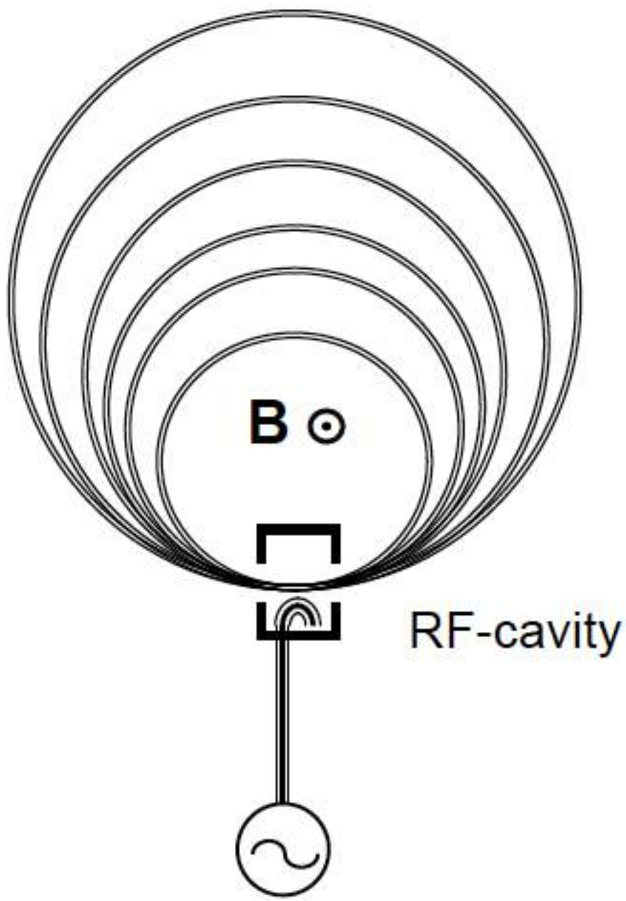
(b)

Figure 1.17 Fields for a TM_{010} mode of a cylindrical (pillbox)-cavity resonator.

Will this work?



We can vary B in an RF cavity



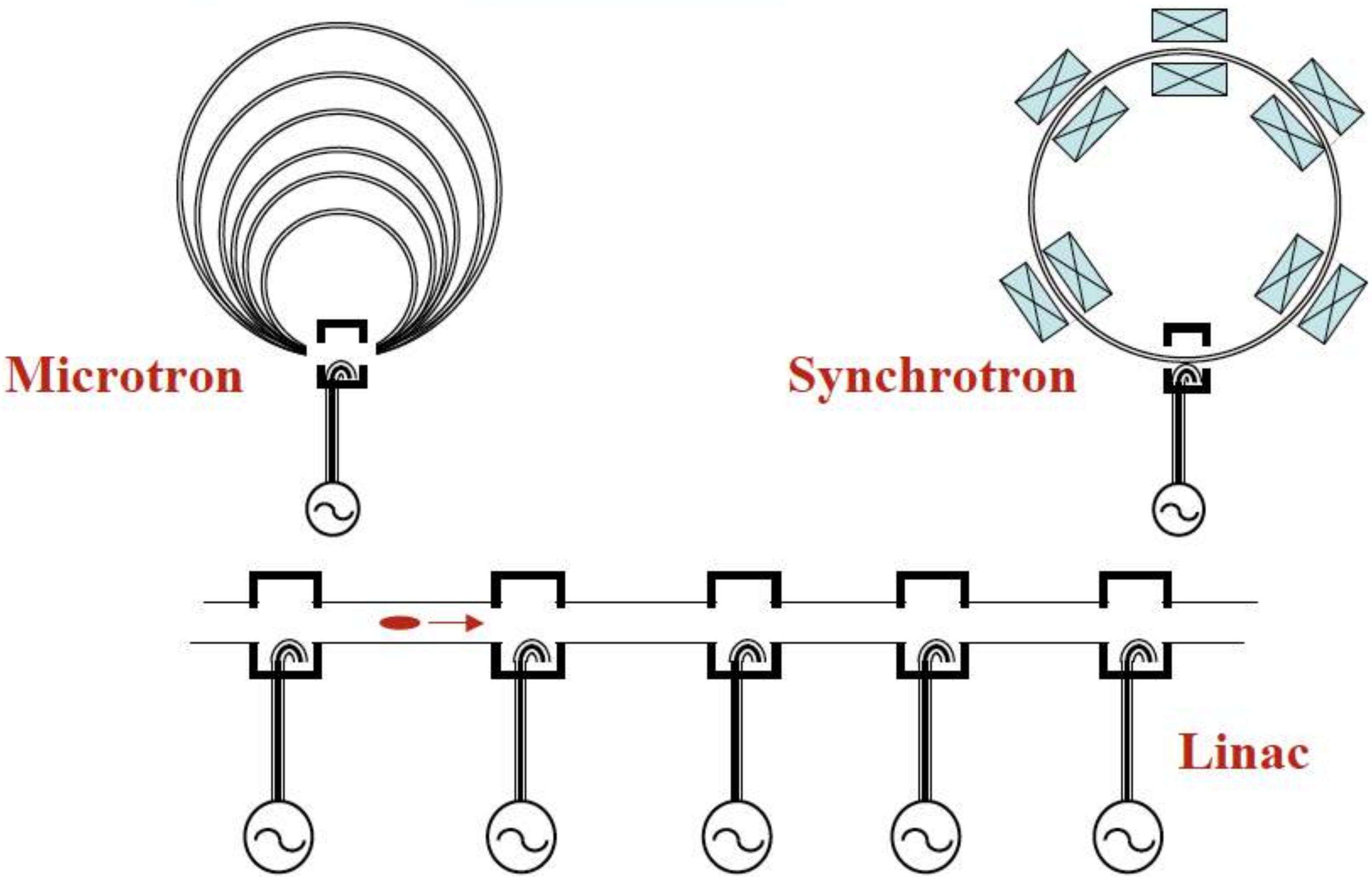
Note that inside the cavity

dB/dt ≠ 0

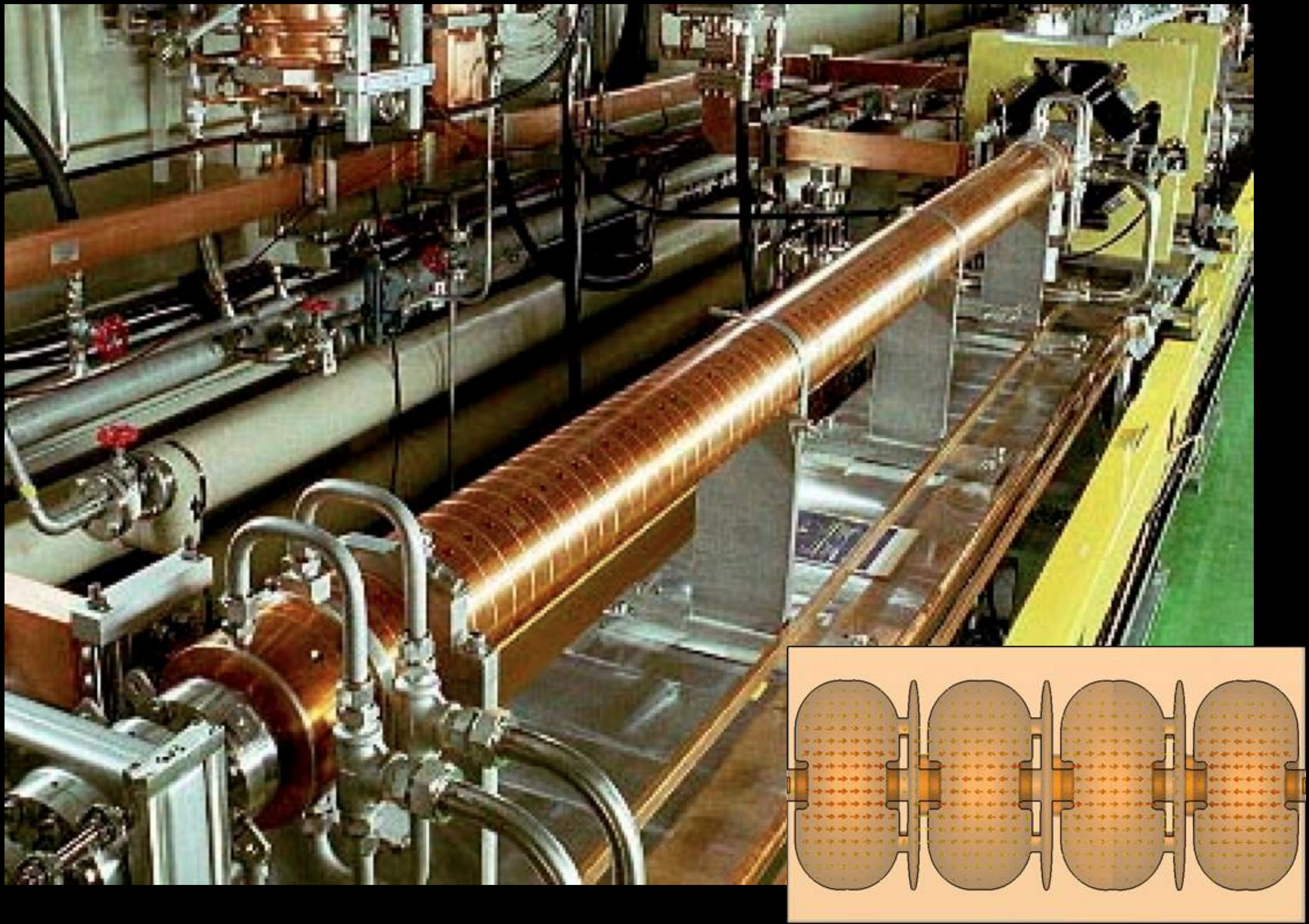
$$E_z = E_0 J_0(k_r r) \cos \omega t$$

$$B_\theta = -\frac{E_0}{c} J_1(k_r r) \sin \omega t$$

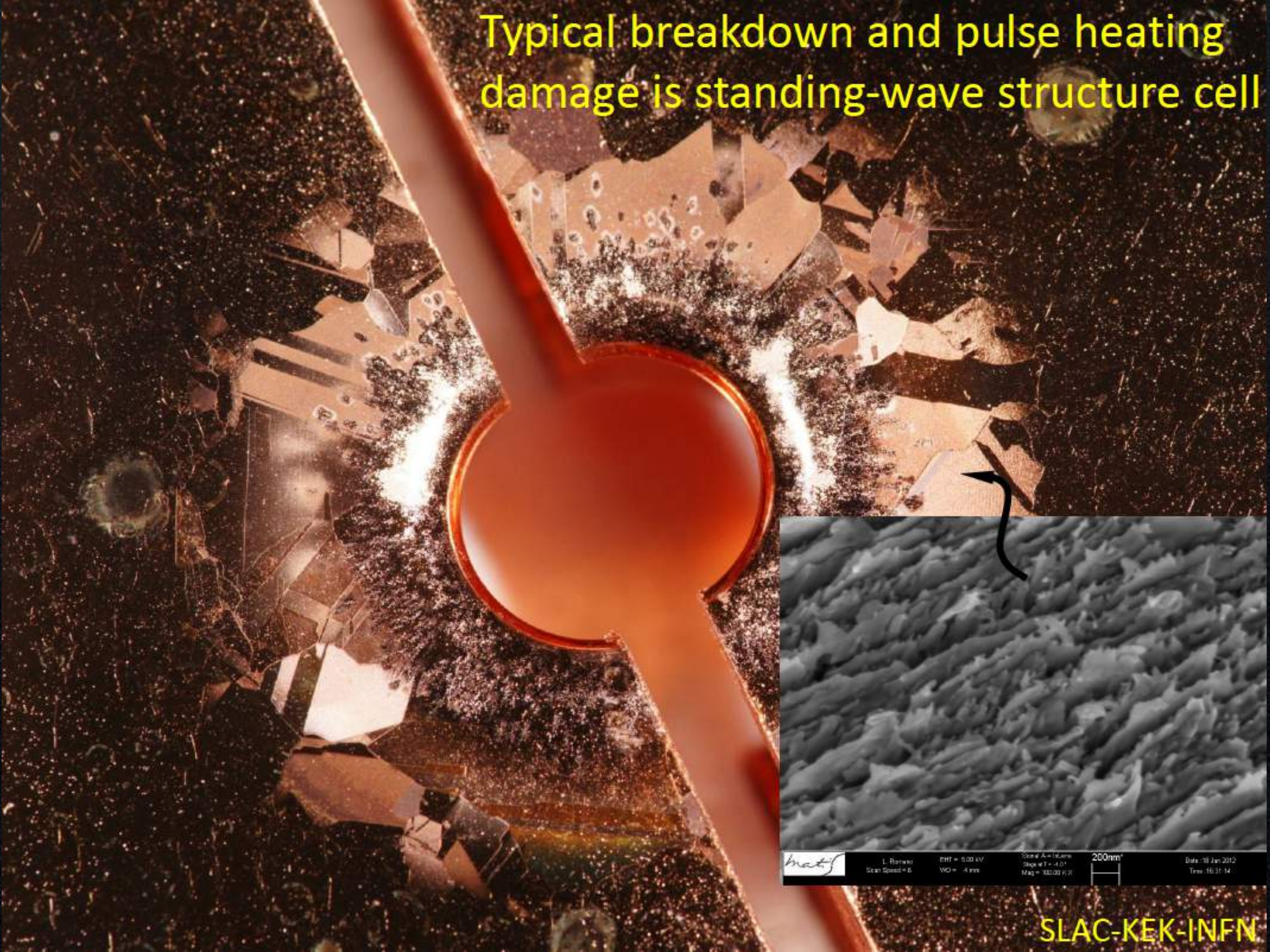
RF-cativties for acceleration

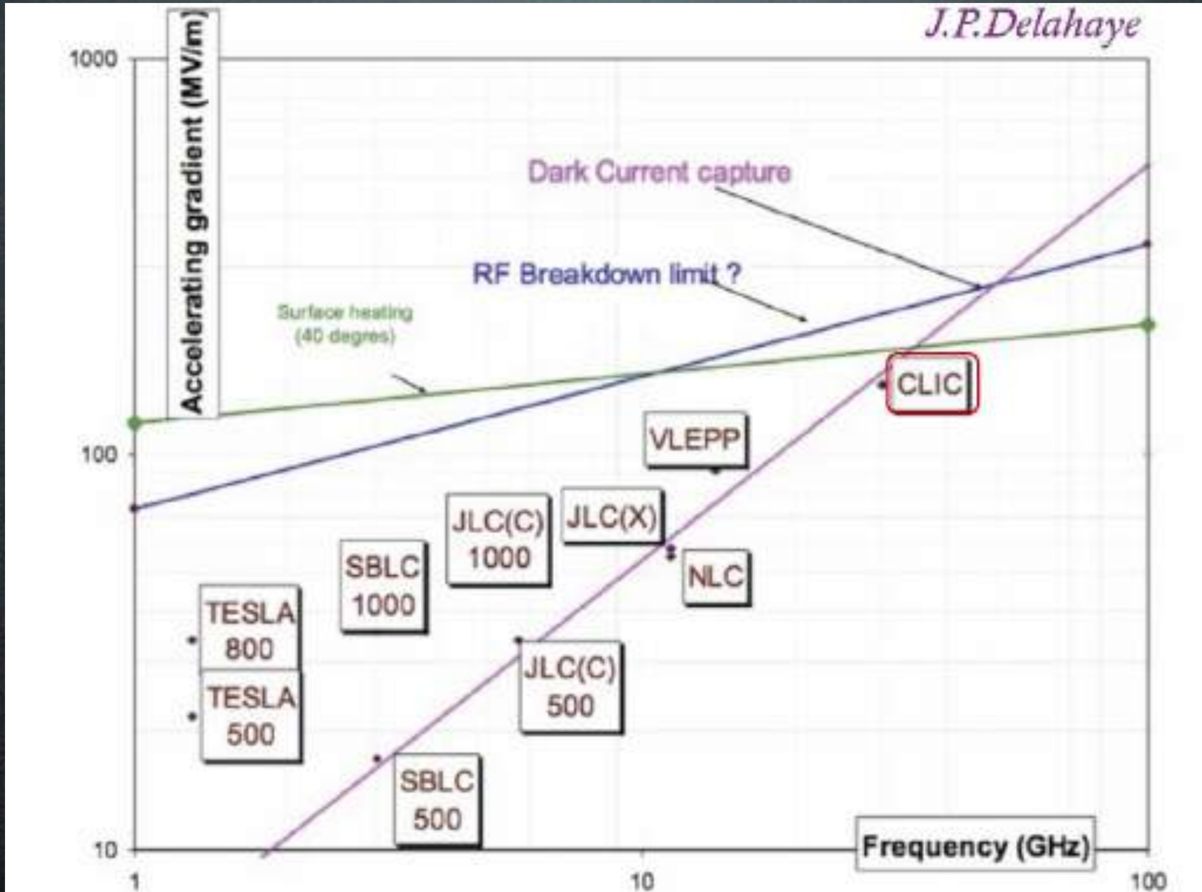


Conventional RF accelerating structures



Typical breakdown and pulse heating damage is standing-wave structure cell





Breakdown limits metal:

$$E_s = 220(f[\mathrm{GHz}])^{1/3}\ \mathrm{MV/m}$$

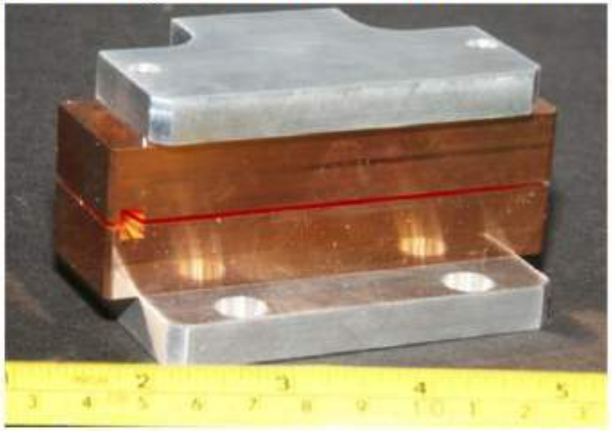
High field ->Short wavelength->ultra-short bunches-> low charge

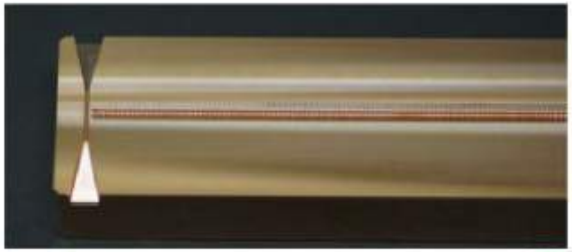
Miniaturization of the accelerating structures

Future plans for the high gradient collaboration

- The collaboration during the next 5 will address 4 fundamental research efforts:
  - Continue basic physics research, materials research frequency scaling and theory efforts.
  - Put the foundations for advanced research on efficient RF sources.
  - Explore the spectrum from 90 GHz to THz
    - Sources at MIT
    - Developments of suitable sources at 90 GHz
    - Developments of THz stand alone sources
    - Utilize the FACET at SLAC and AWA at ANL
    - Address the challenges of the Muon Accelerator Project (MAP)

mm-Wave structure to be tested at FACET

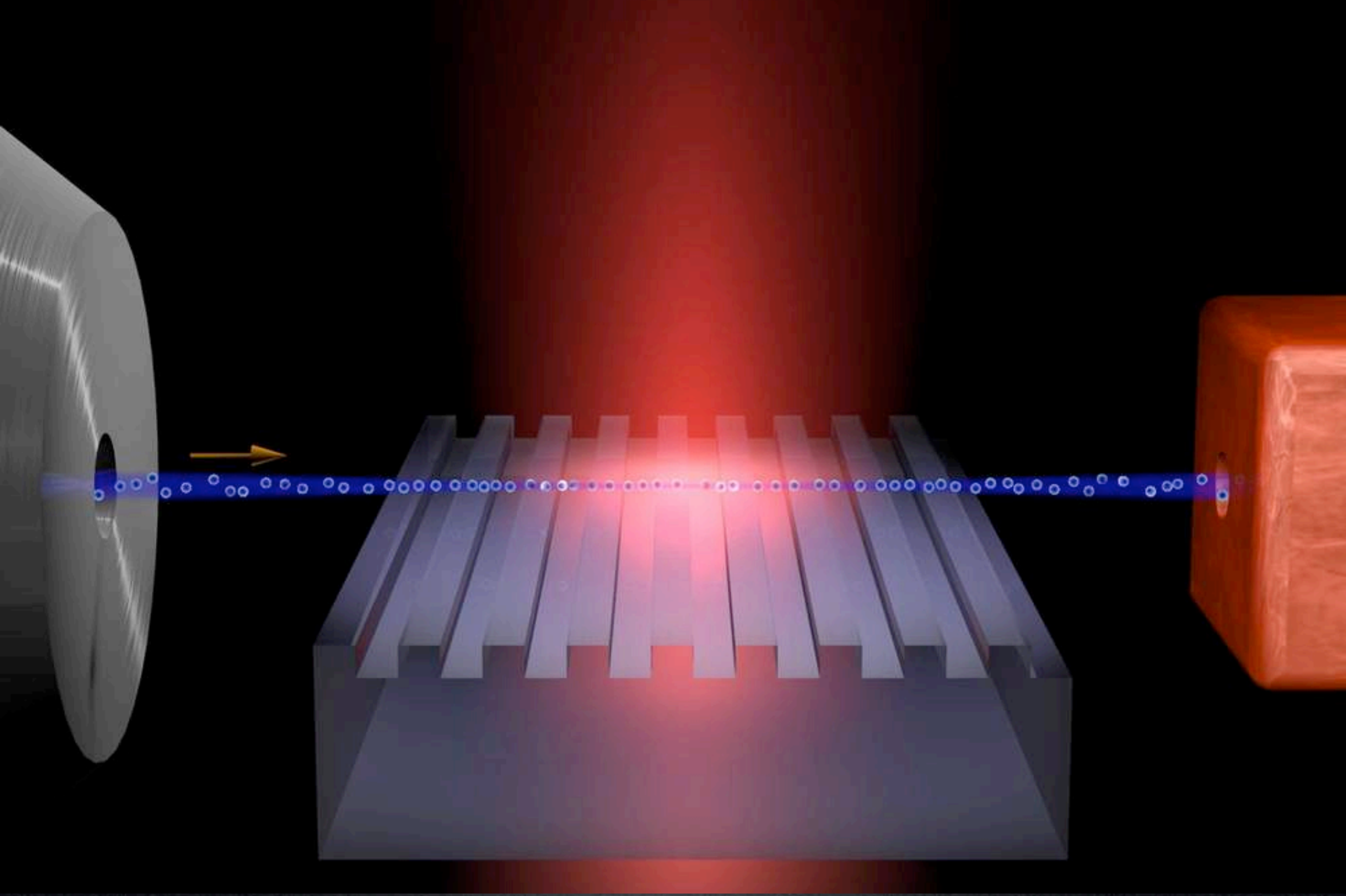




SLAC
NATIONAL ACCELERATOR LABORATORY

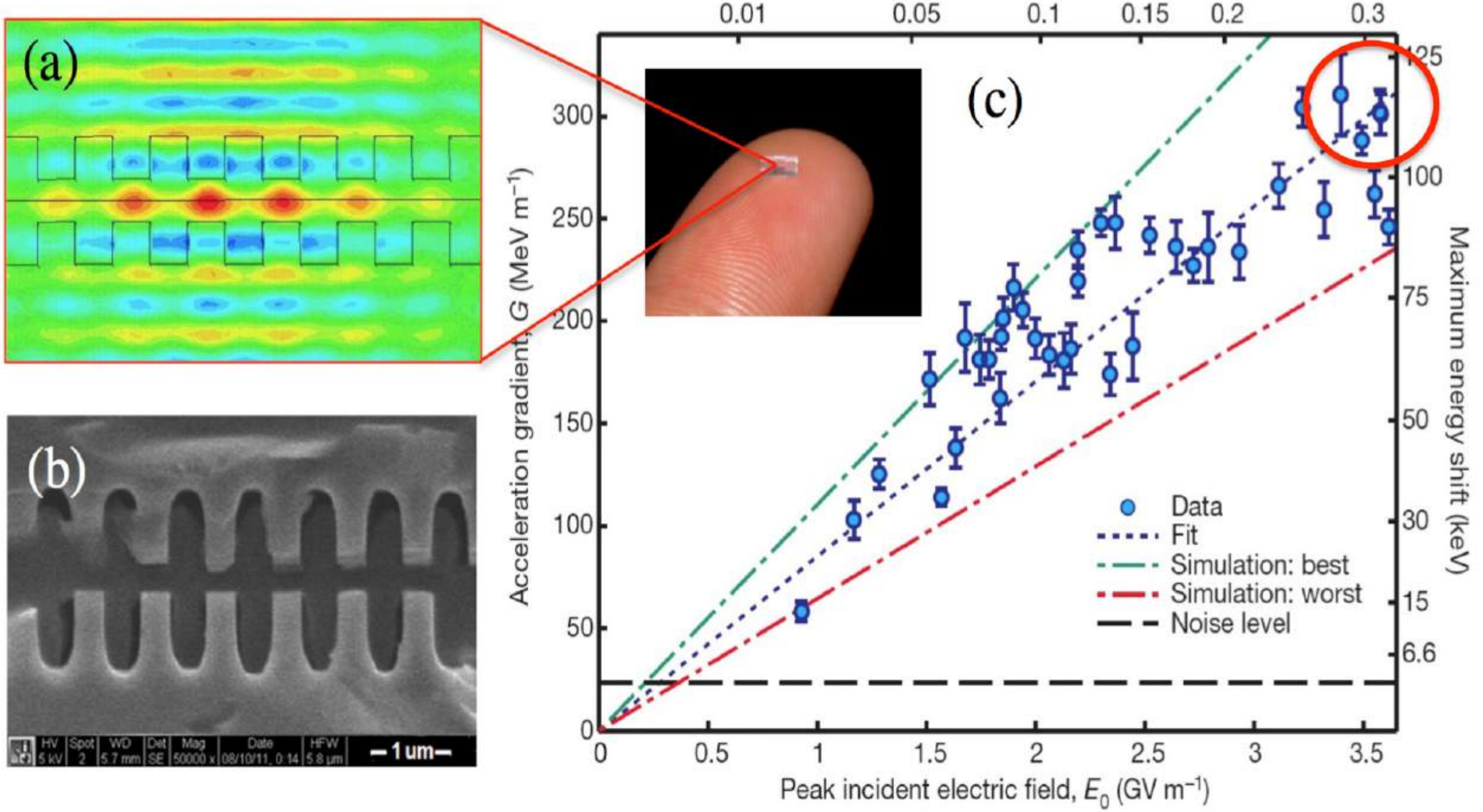
Direct Laser Acceleration
DLA

Laser based dielectric accelerator



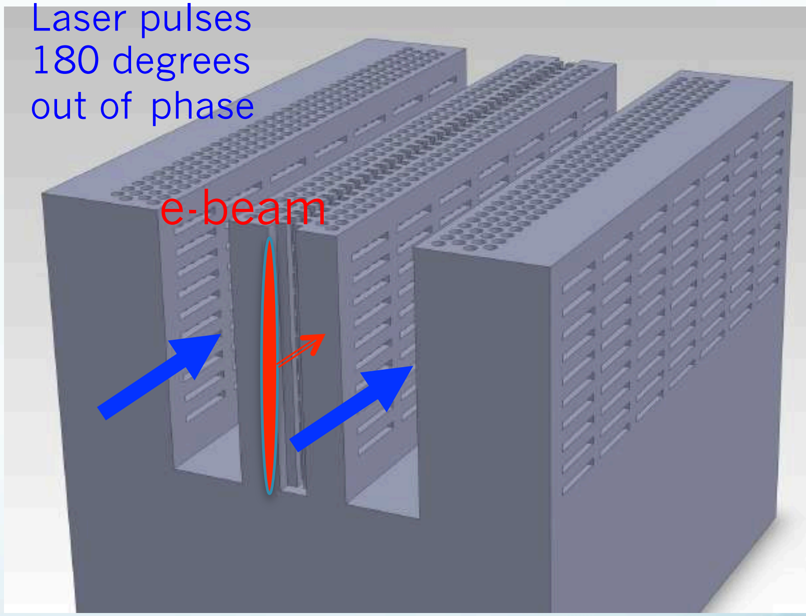
Nature **503**, 91-94 (2013).

300 MV/m



Dielectric Photonic Structure

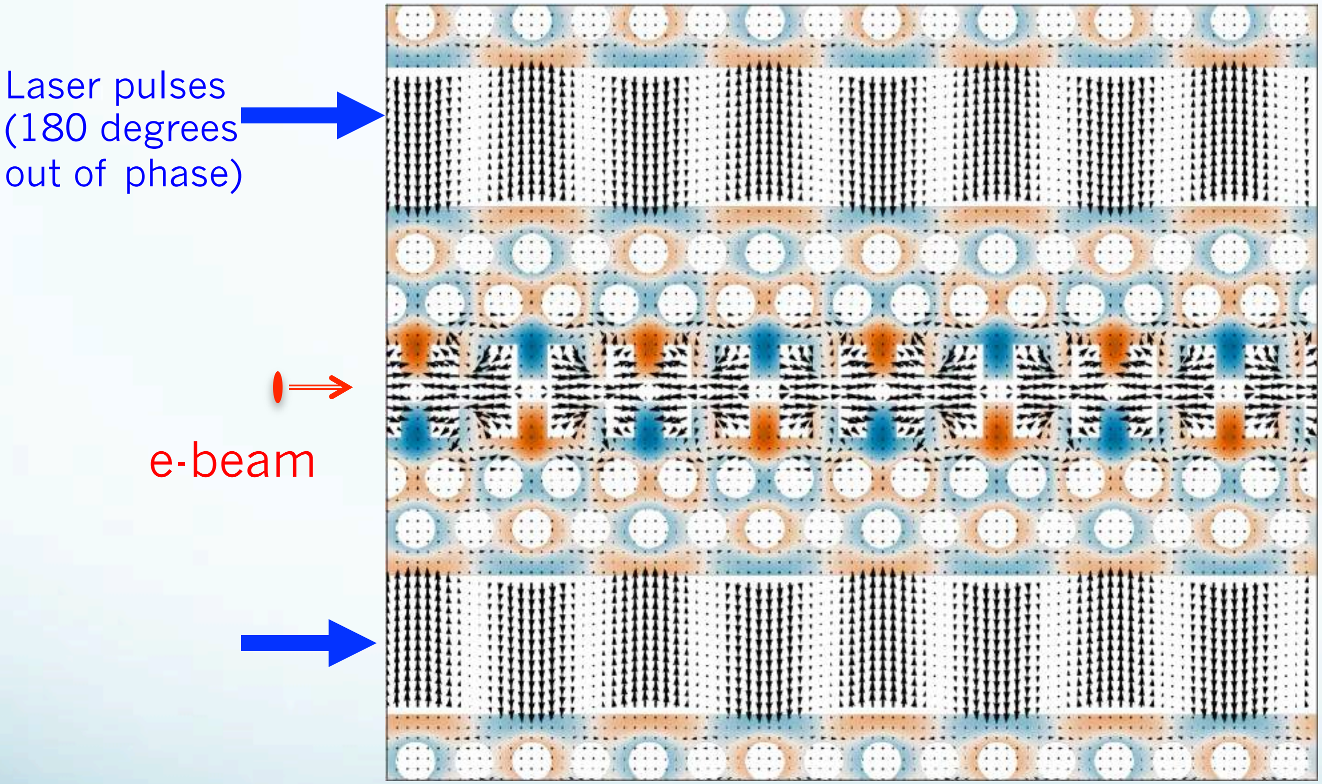
- Why photonic structures?
  - Natural in dielectric
  - Advantages of burgeoning field
    - design possibilities
    - Fabrication
- Dynamics concerns
- External coupling schemes



Schematic of GALAXIE
monolithic photonic DLA

Laser-Structure Coupling: TW

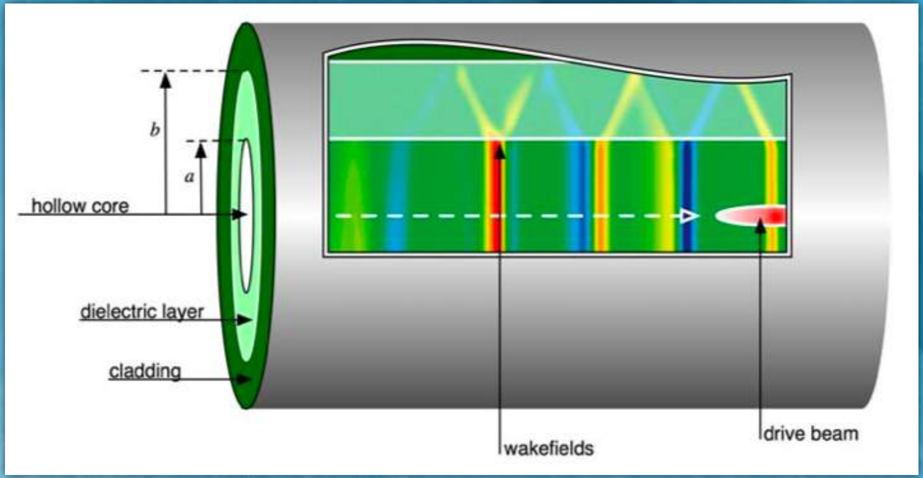
GALAXIE Dual laser drive structure, large reservoir of power recycles

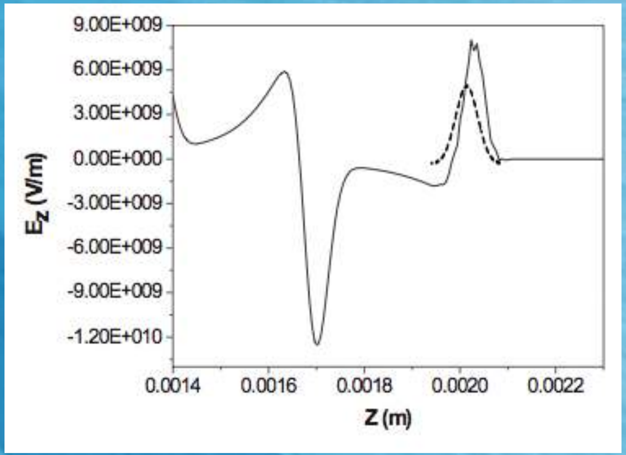


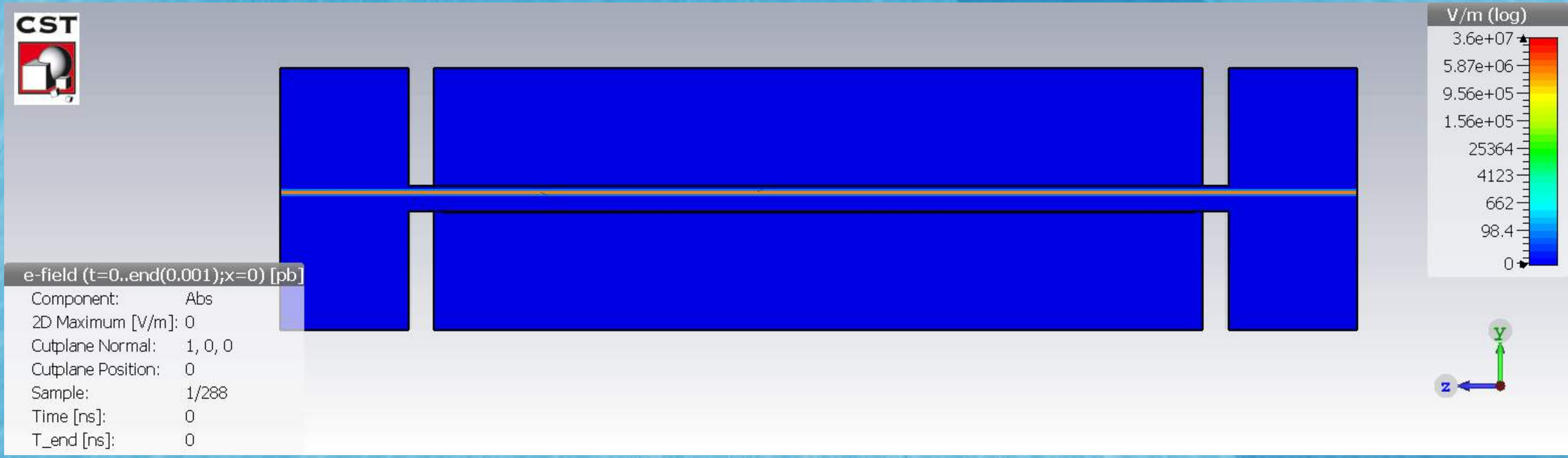
Direct Wakefield Acceleration

DWA

Dielectric Wakefield Accelerator

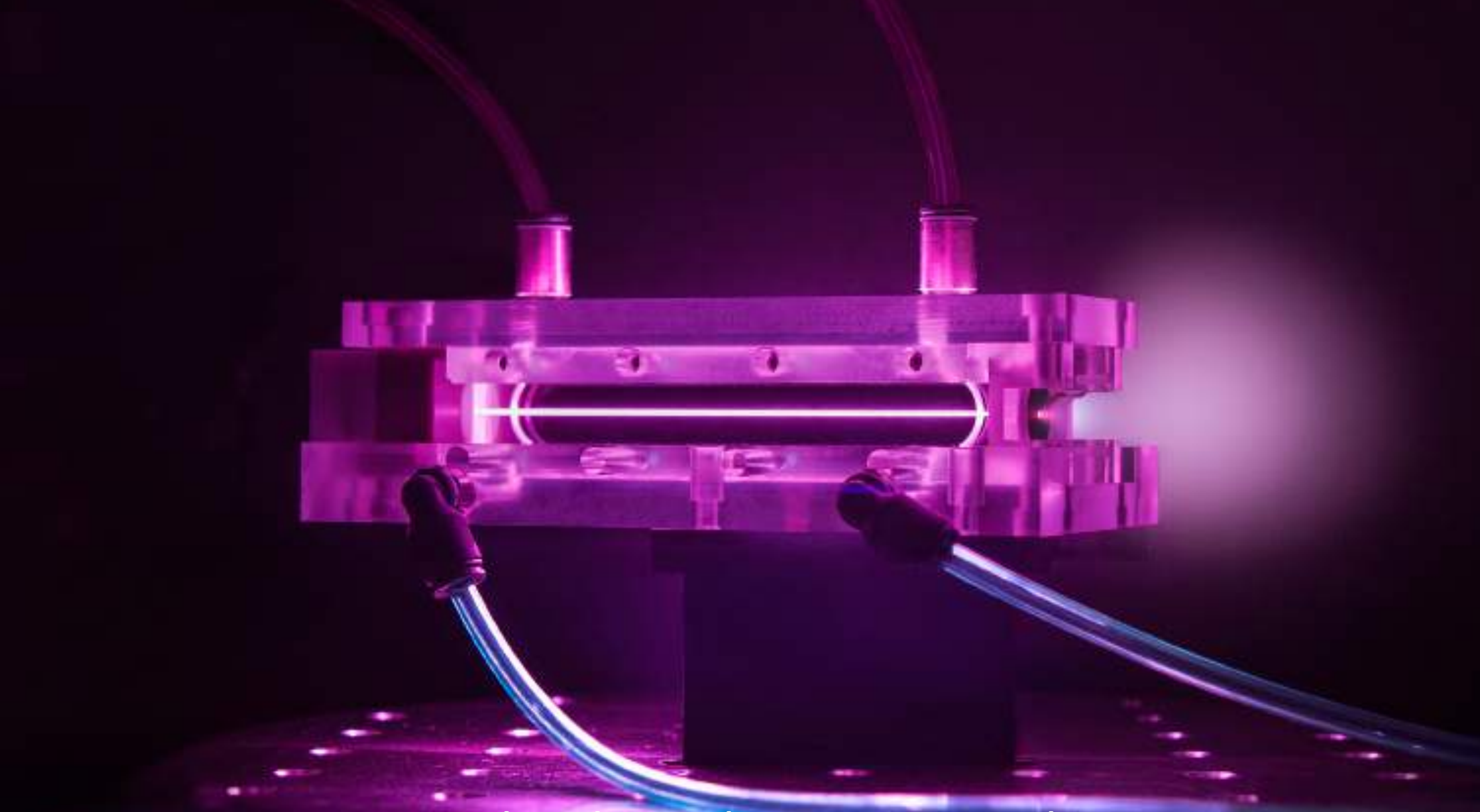






Future Accelerators – part II

Massimo.Ferrario@LNF.INFN.IT



XIV ICFA School – Habana - December 2017

Plasma Acceleration

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.

VOLUME 54, NUMBER 7 PHYSICAL REVIEW LETTERS 18 FEBRUARY 1985

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

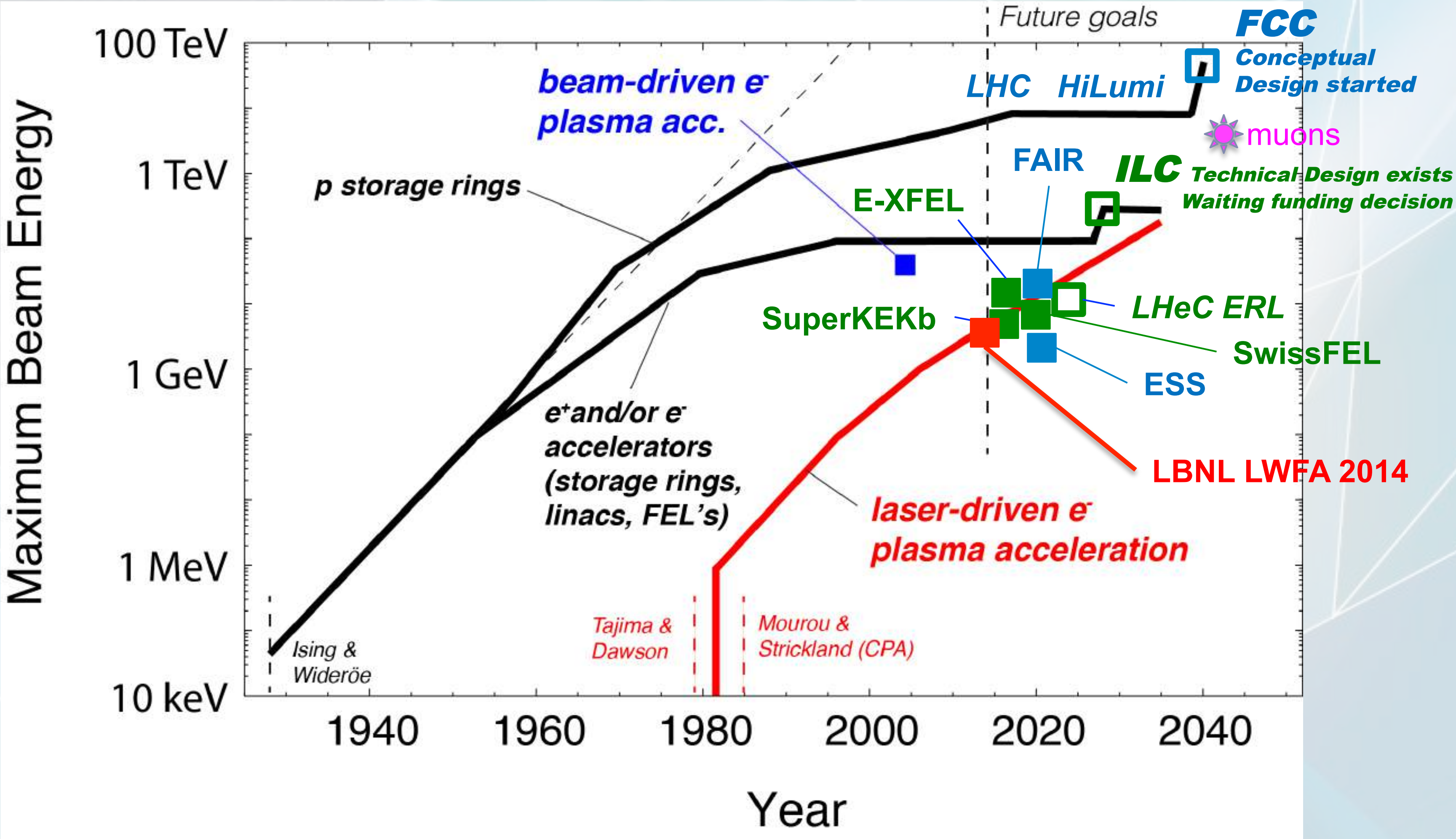
Pisin Chen[(a)]
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305

and

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

A new scheme for accelerating electrons, employing a bunched relativistic electron beam in a cold plasma, is analyzed. We show that energy gradients can exceed 1 GeV/m and that the driven electrons can be accelerated from $\gamma_0 mc^2$ to $3\gamma_0 mc^2$ before the driving beam slows down enough to degrade the plasma wave. If the driving electrons are removed before they cause the collapse of the plasma wave, energies up to $4\gamma_0^6 mc^2$ are possible. A noncollinear injection scheme is suggested in order that the driving electrons can be removed.

Future of Accelerators

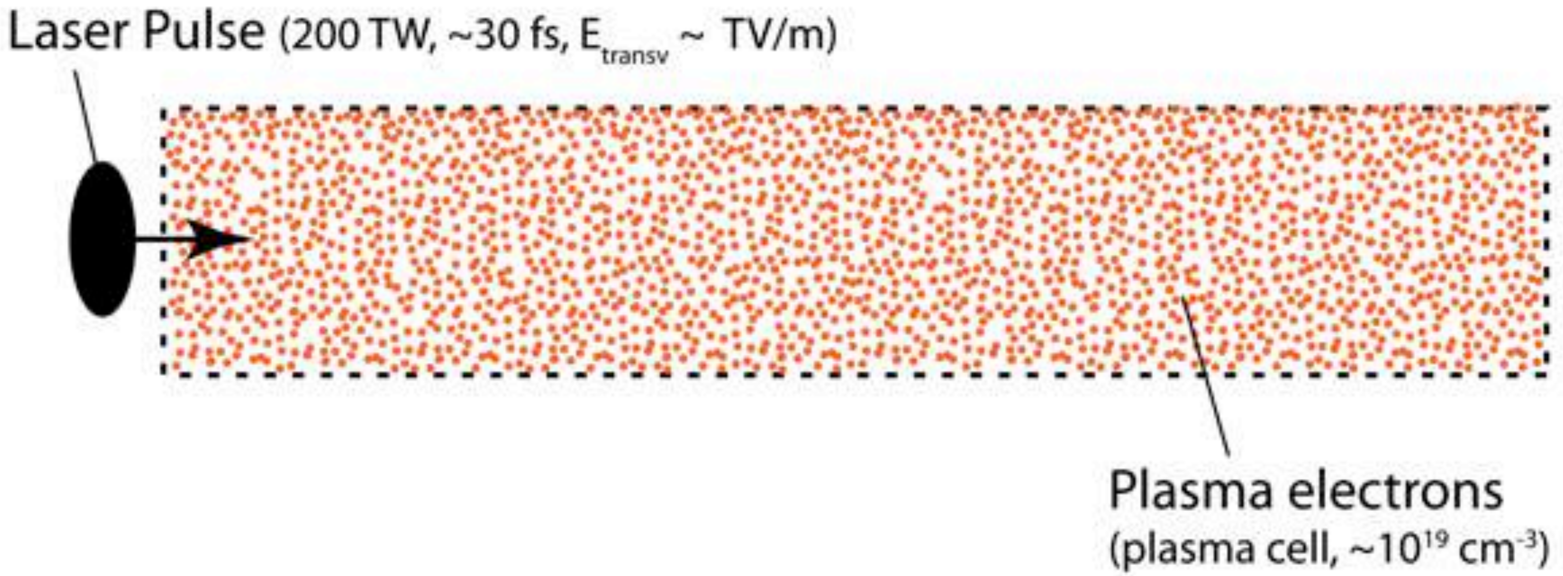


■ Hadron acc. project ■ Lepton acc. project

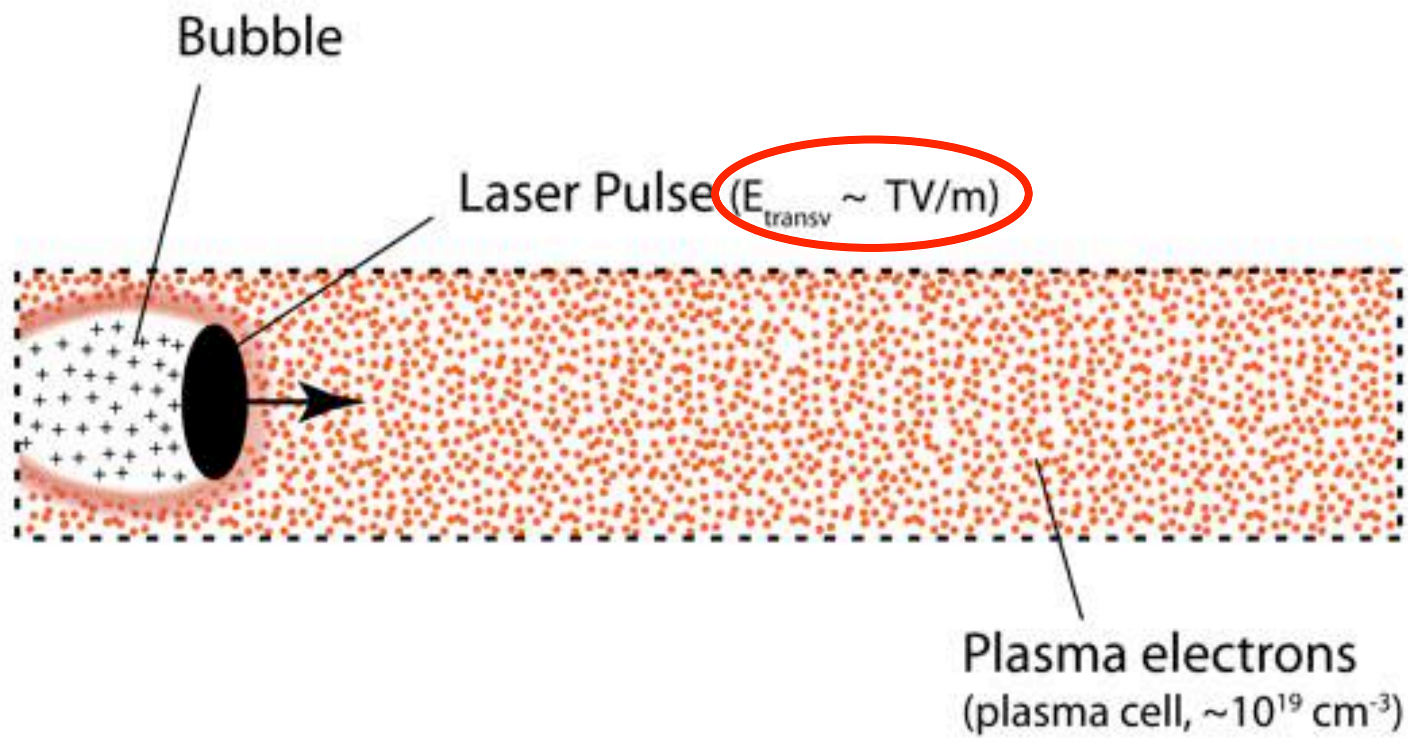
□ Hadron acc. proposal □ Lepton acc. proposal

R. Assmann, EAAC 2015, 9/2015

Laser Plasma-Acceleration
(Internal Injection)

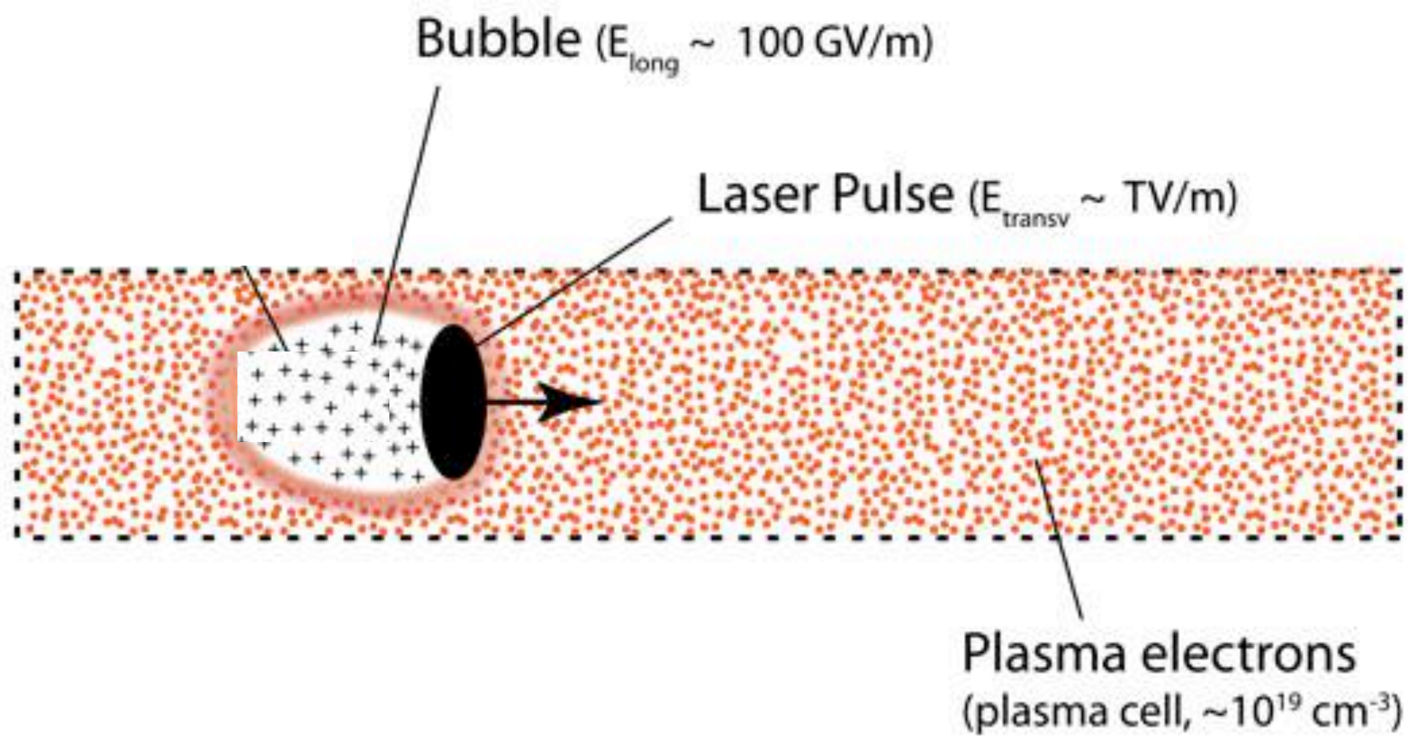


Laser Plasma-Acceleration
(Internal Injection)

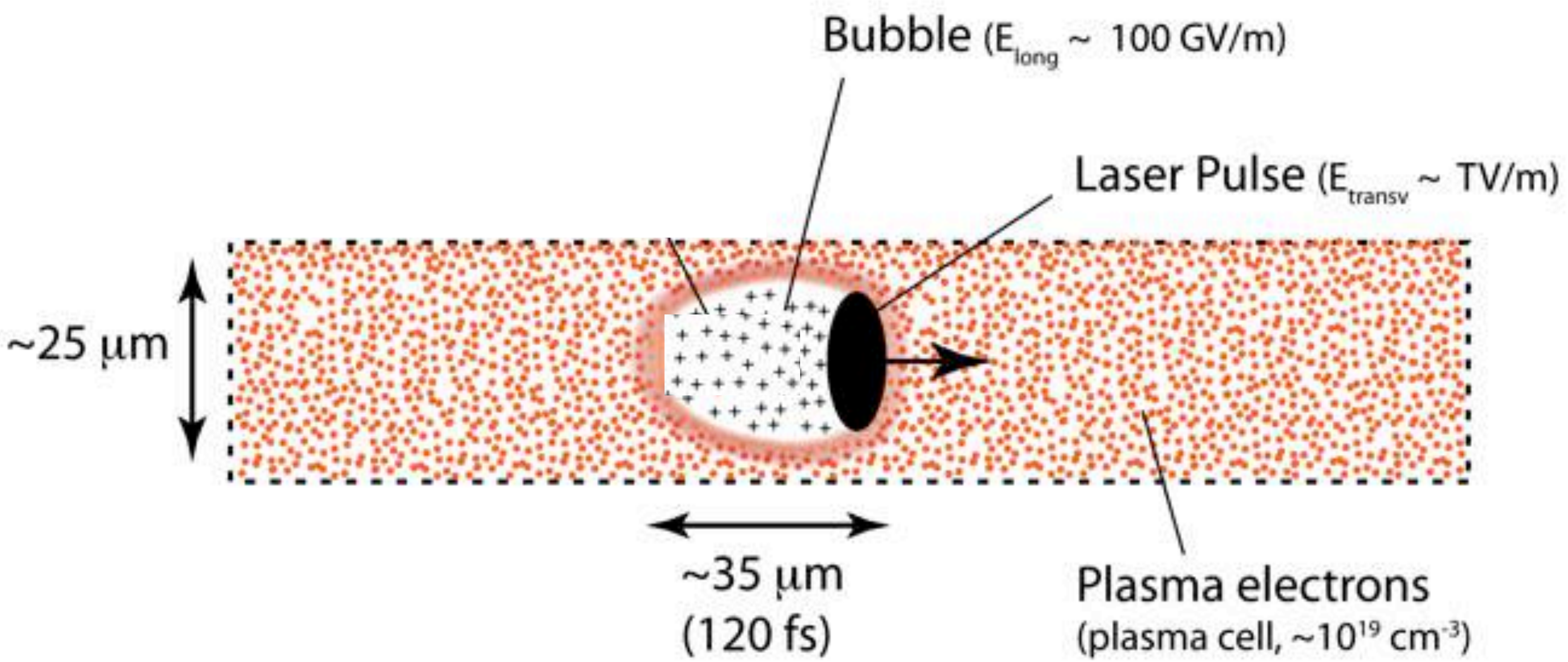


Laser Plasma-Acceleration
(Internal Injection)

Horizon2020



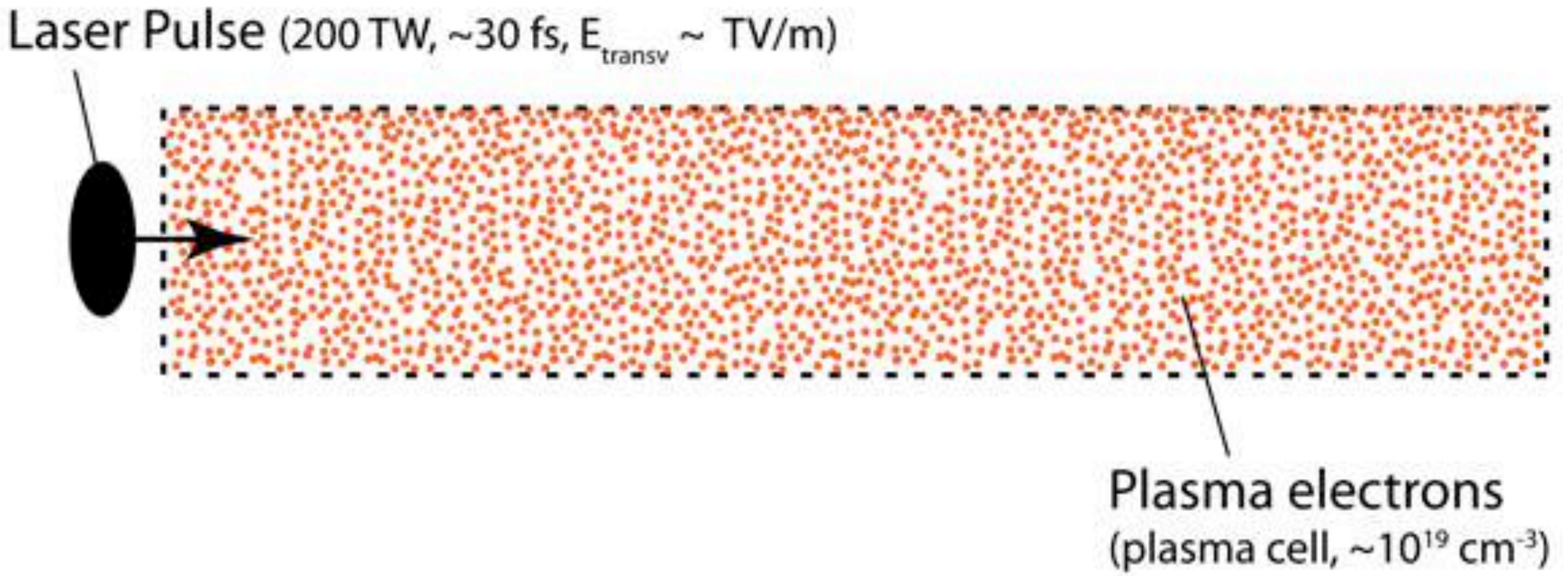
Laser Plasma-Acceleration
(Internal Injection)



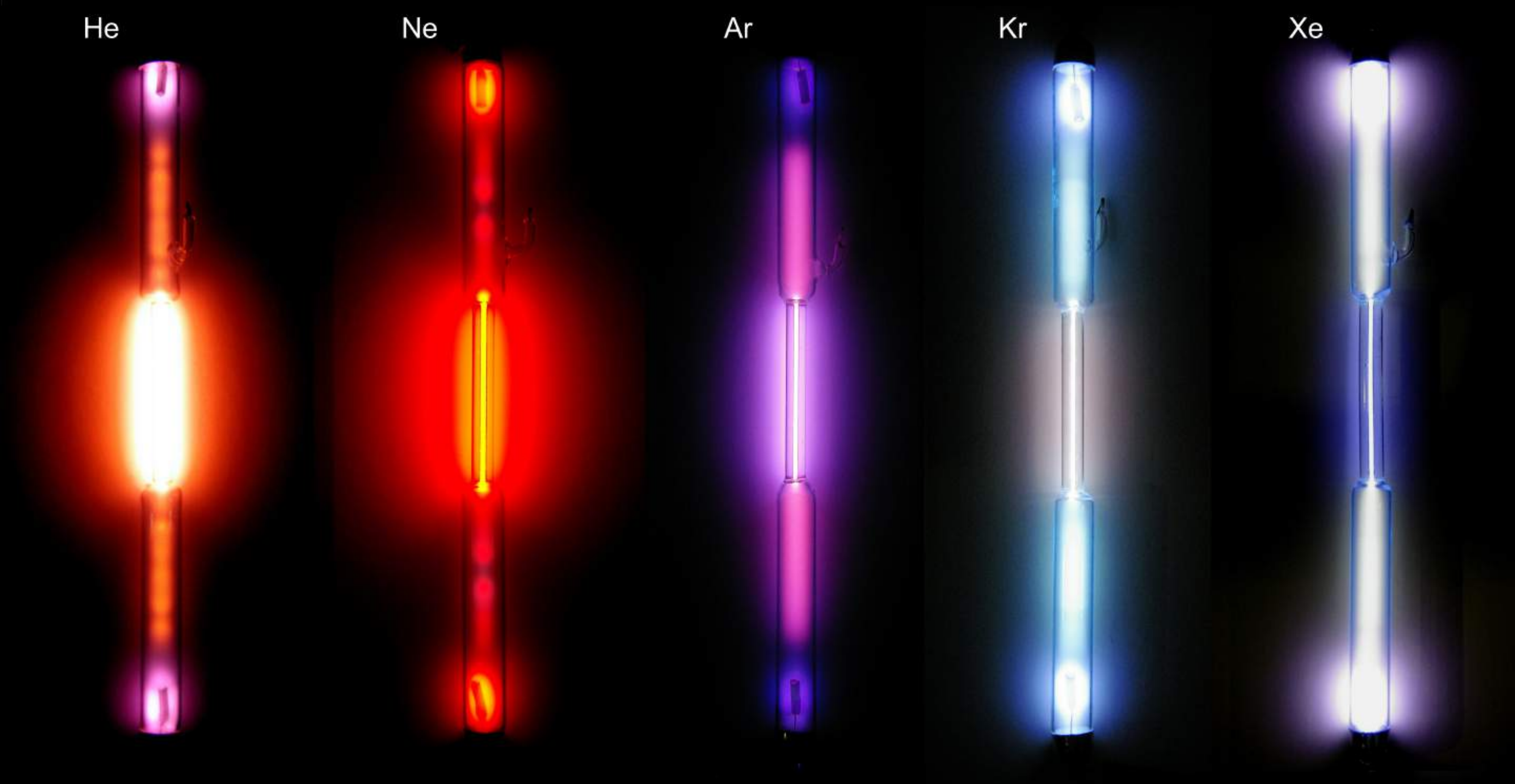
This accelerator fits into a human hair!

External-injection

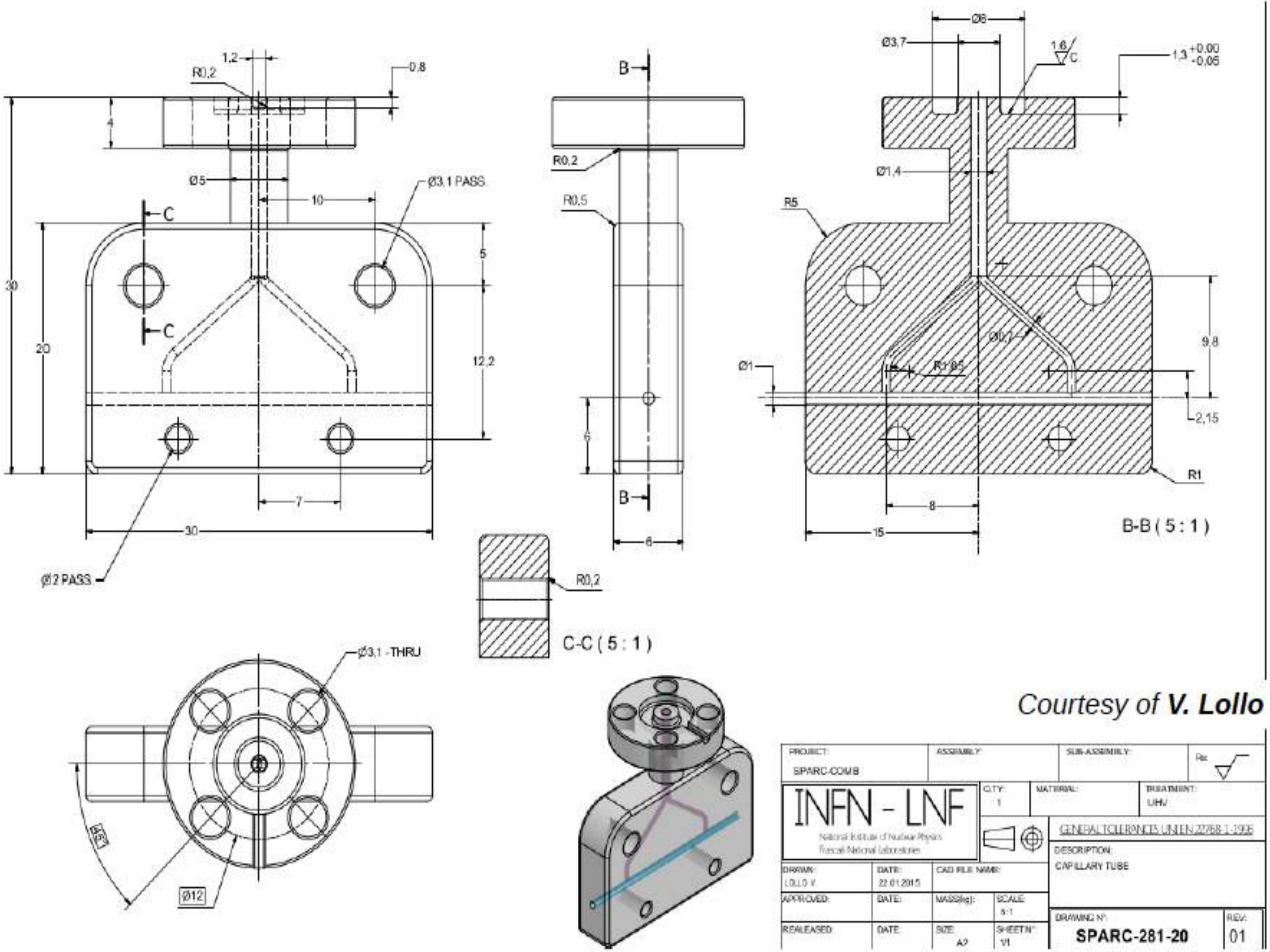
Laser Plasma-Acceleration
(Internal Injection)



Capillary Discharge

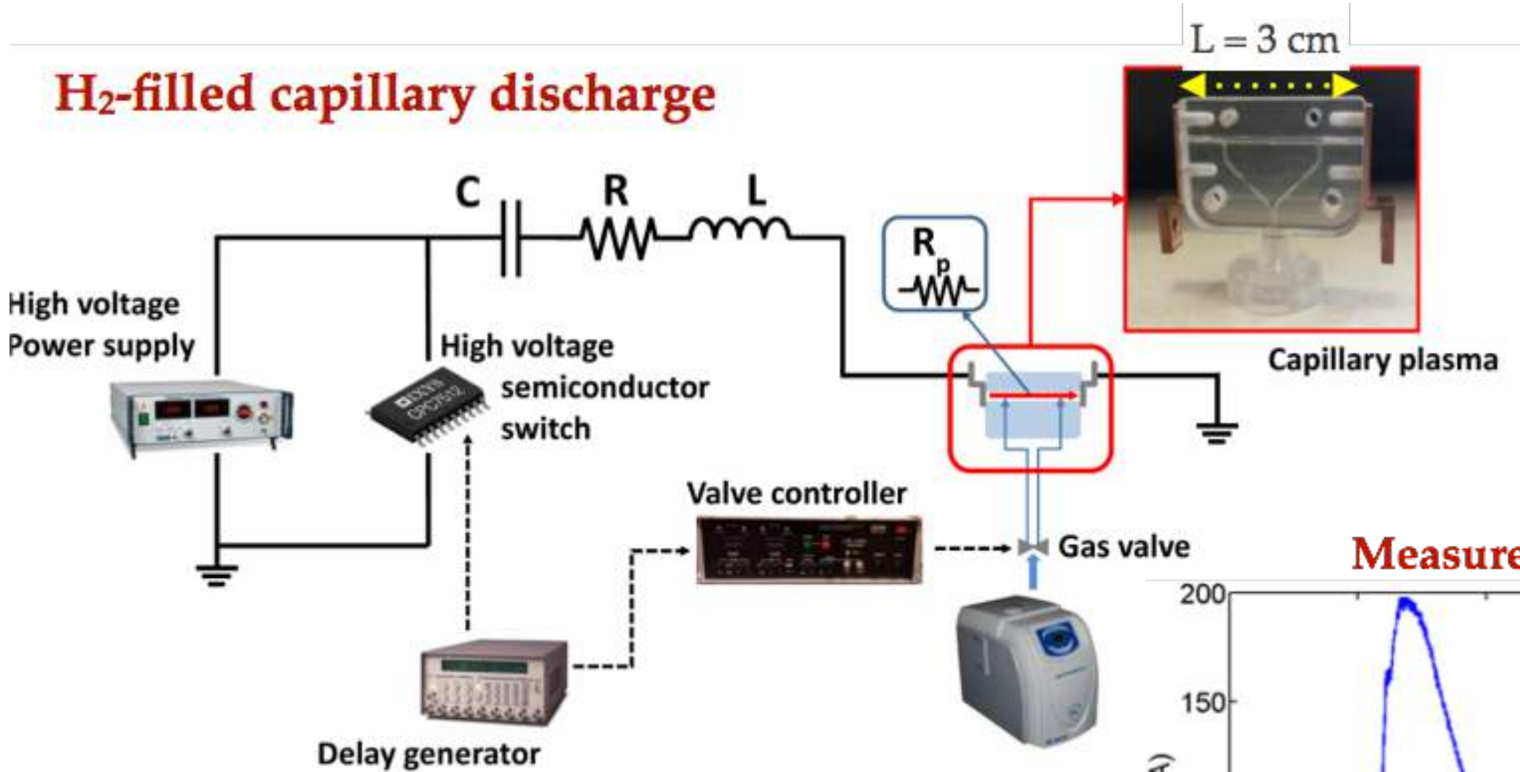

He
Ne
Ar
Kr
Xe

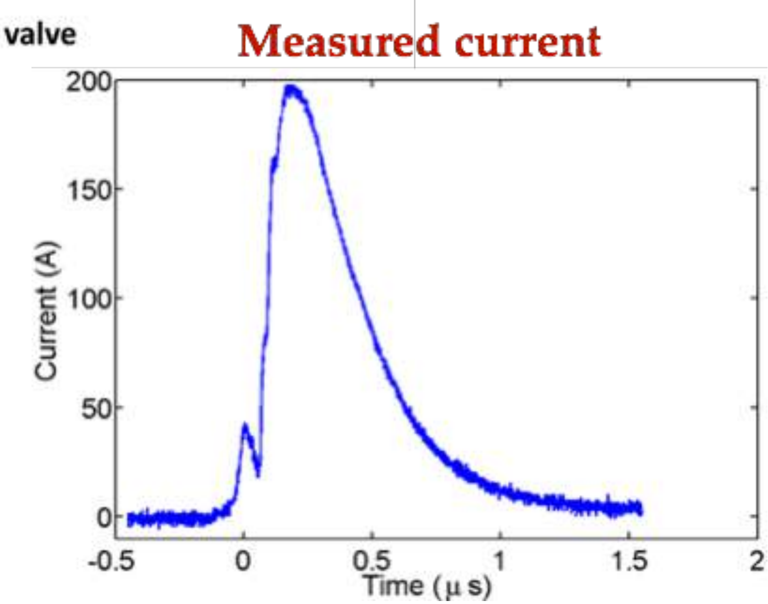
Plasma capillary



Courtesy of ***V. Lollo***

Plasma Source

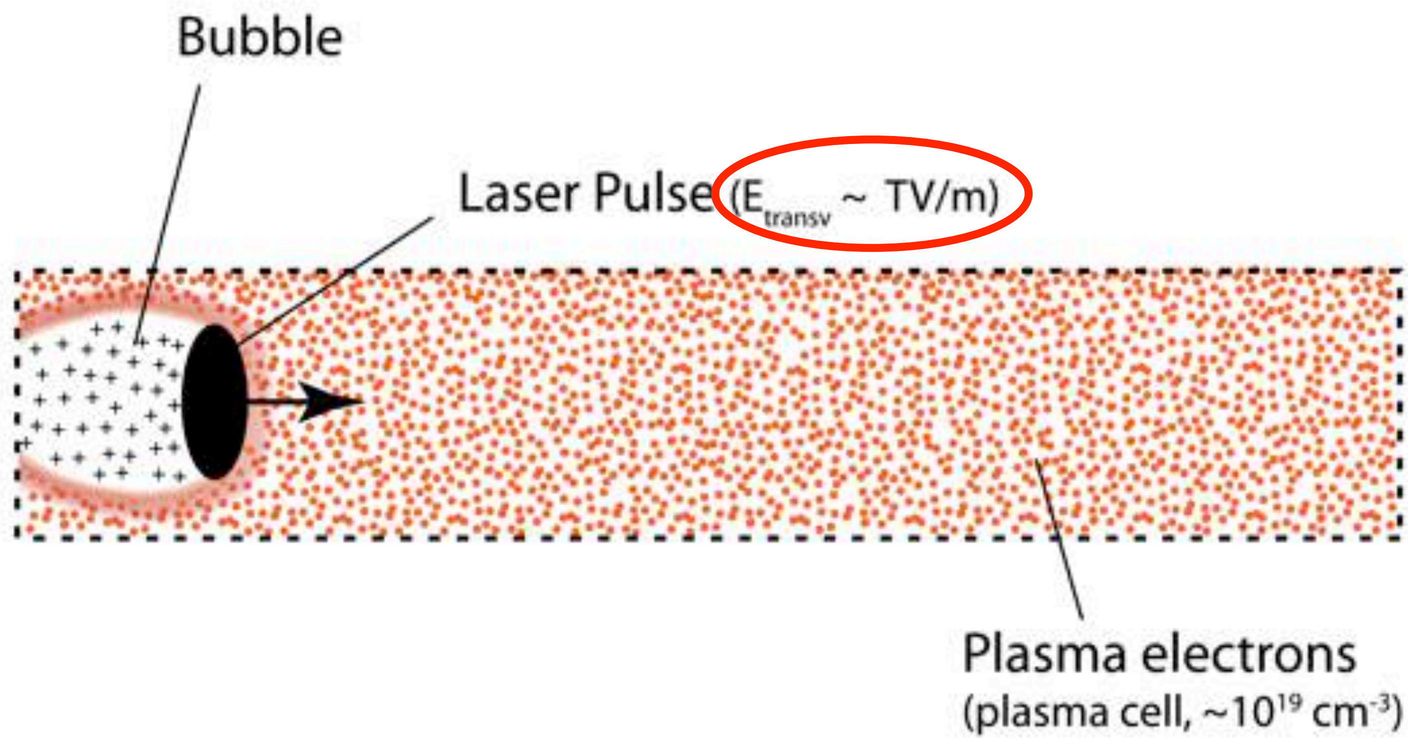




P_{H2} = 10 mbar
Total discharge duration: 800 ns
Voltage: 20 kV
Peak current: 200 A
Capacitor: 6 nF

Courtesy of M. P. Anania, A. Biagioni, D. Di Giovenale, F. Filippi, S. Pella

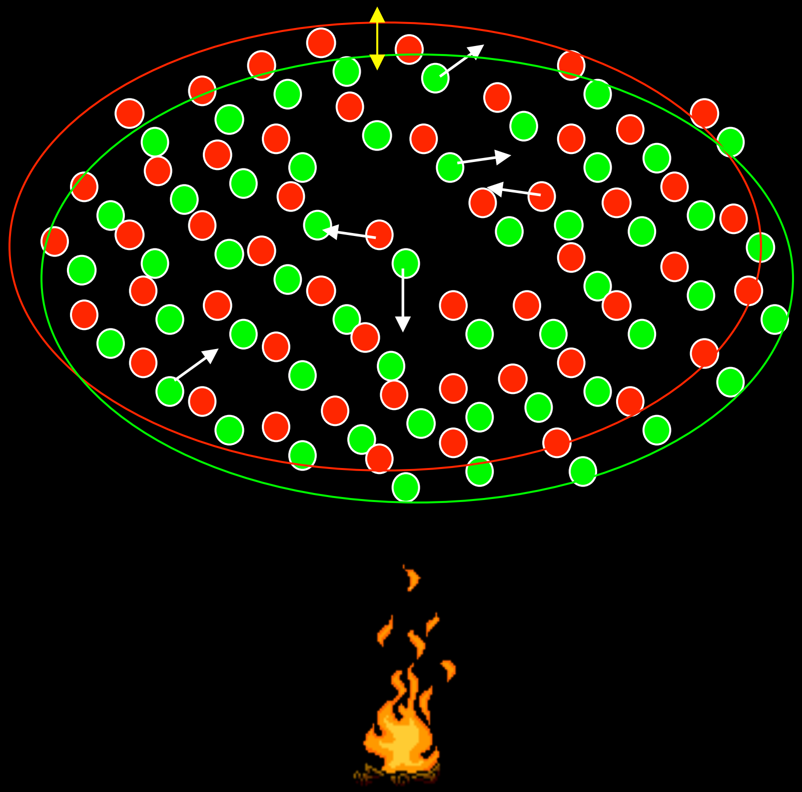
Laser Plasma-Acceleration
(Internal Injection)



Surface charge density

$$\sigma = e\, n\, \delta x$$

$$\delta x$$



Surface electric field

$$E_x = -\sigma/\epsilon_0 = -e\, n\, \delta x/\epsilon_0$$

Restoring force

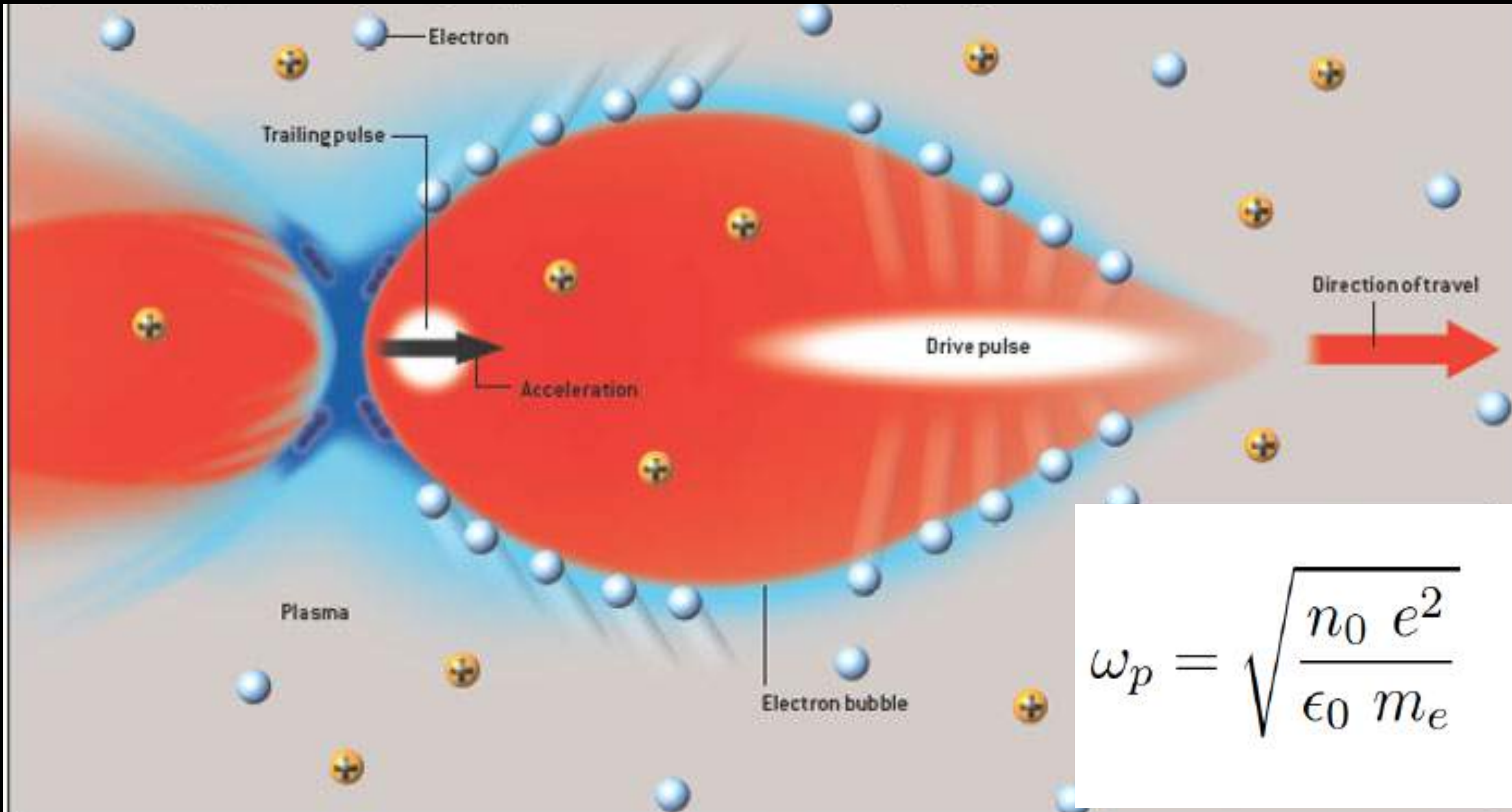
$$m \frac{d^2 \delta x}{dt^2} = e\, E_x = -m\, \omega_p^{\,2}\, \delta x$$

Plasma frequency

$$\omega_p^{\,2} = \frac{n\, e^2}{\epsilon_0\, m}$$

Plasma oscillations

$$\delta x = (\delta x)_0 \cos(\omega_p t)$$



$$\omega_p = \sqrt{\frac{n_0\ e^2}{\epsilon_0\ m_e}}$$

$$\lambda_p \approx 1\text{mm} \cdot \sqrt{\frac{10^{15}\text{cm}^{-3}}{n_0}}$$

0.3 mm for $n_0 = 10^{16}\ \text{cm}^{-3}$

Linear Wakefields
(R. Ruth / P. Chen 1986)

Accelerating field

Depends on radial position r

Changes between accelerating and decelerating as function of longitudinal position z

$$\mathcal{E}_z \simeq -A\left(1-\frac{r^2}{a^2}\right)\cos(k_p z-\omega_p t)$$

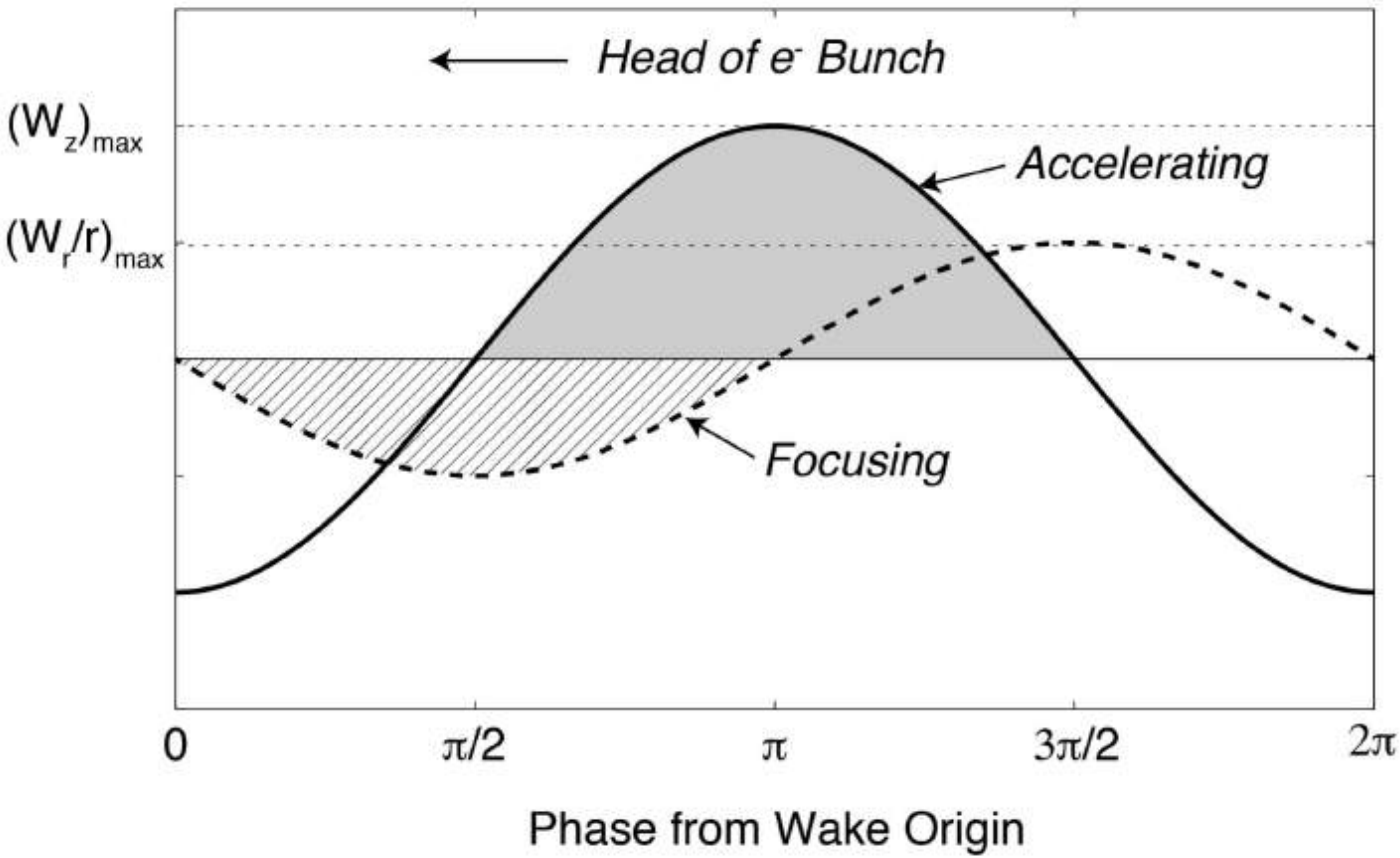
$\pi/2$ out of phase

$$\mathcal{E}_r \simeq \; 2A\frac{r}{k_p a^2}\sin(k_p z-\omega_p t)$$

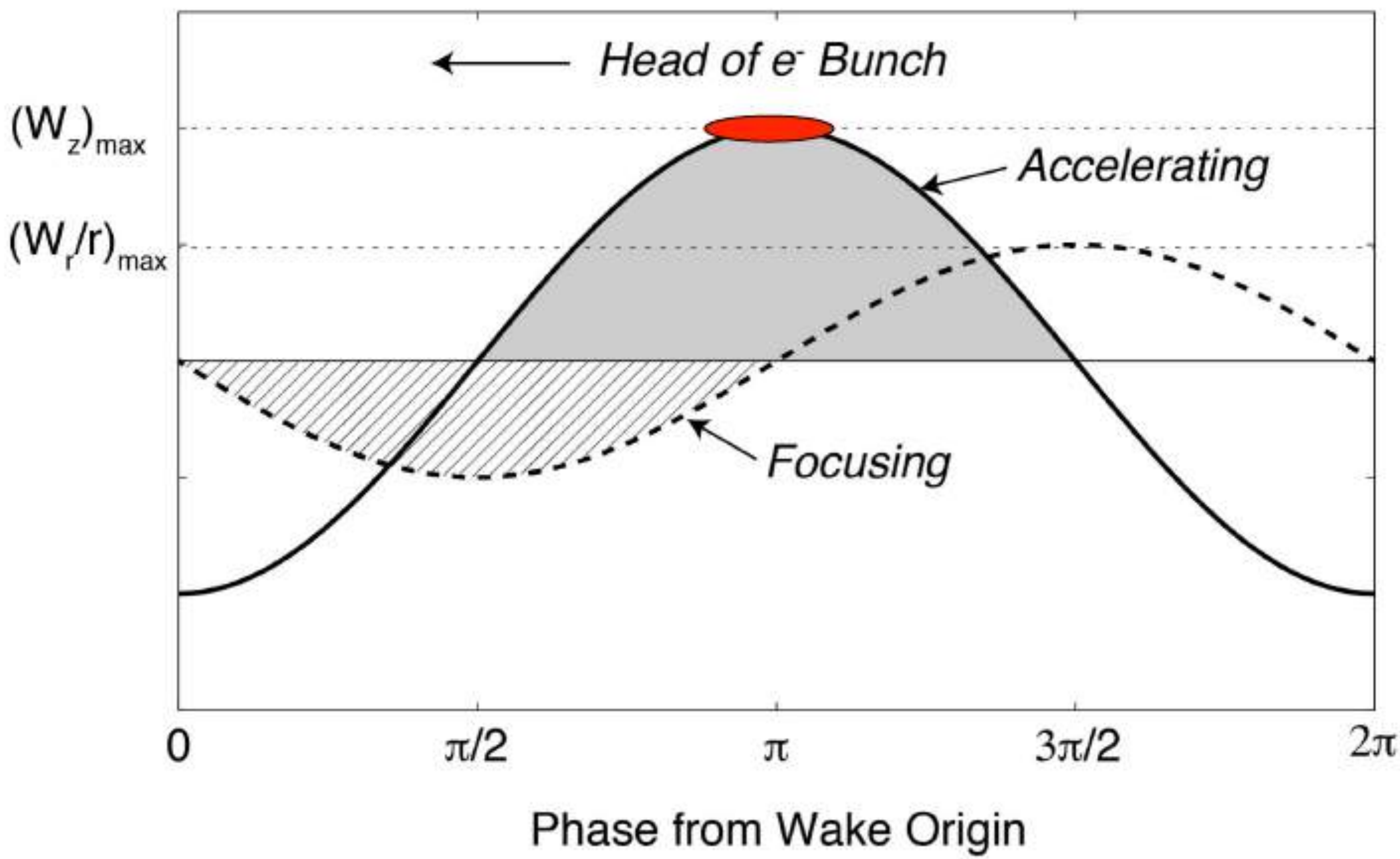
Transverse field

Depends on radial position r

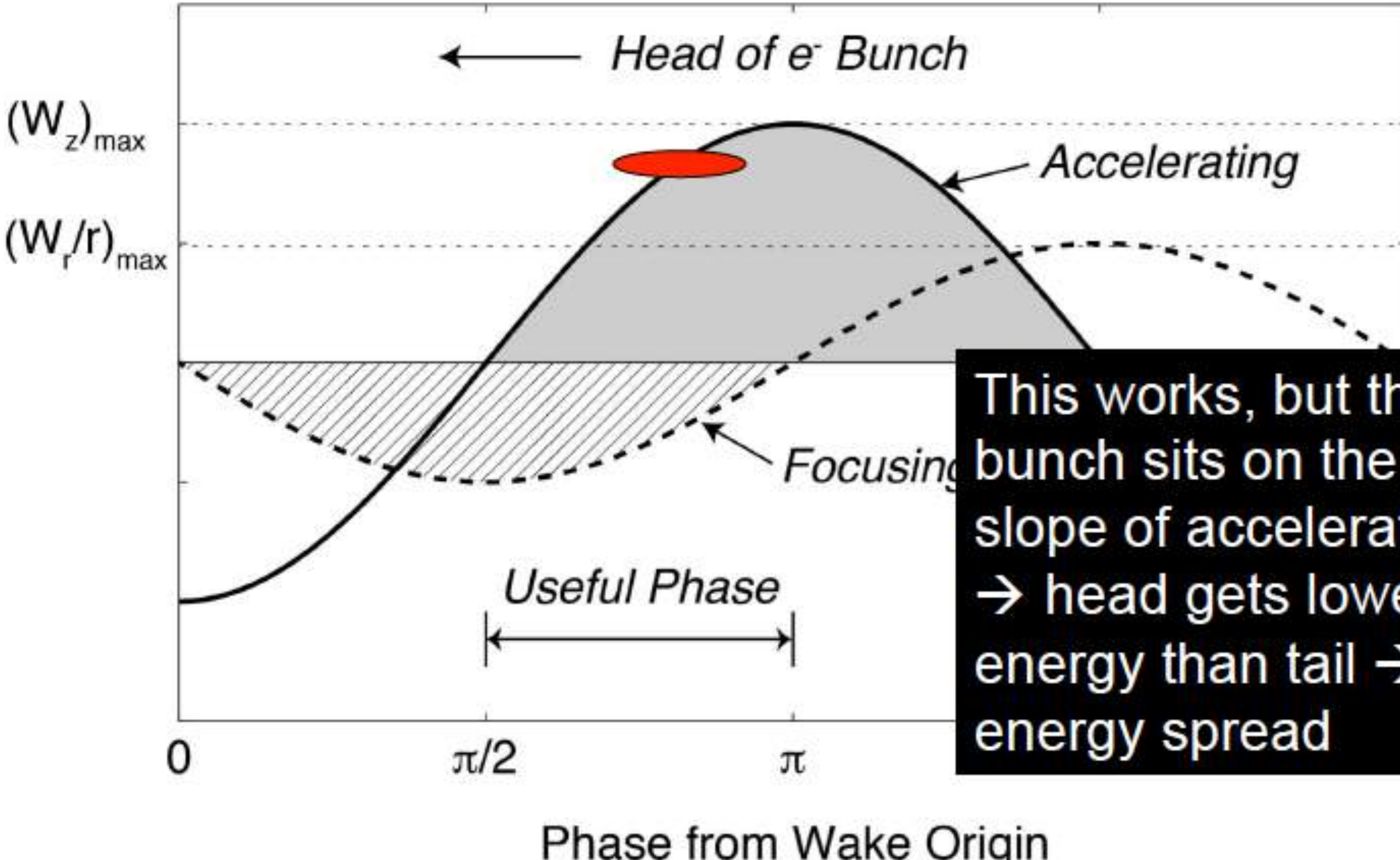
Changes between focusing and defo-cusing as function of longitudinal position z



Head of e⁻ Bunch
$(W_z)_{max}$
$(W_r/r)_{max}$
Accelerating
Focusing
0
π/2
π
3π/2
2π
Phase from Wake Origin



Head of e- Bunch
(Wz)max
(Wr/r)max
Accelerating
Focusing
0
π/2
π
3π/2
2π
Phase from Wake Origin



This works, but the bunch sits on the slope of acceleration → head gets lower energy than tail → energy spread

Energy spread compensation with beam loading

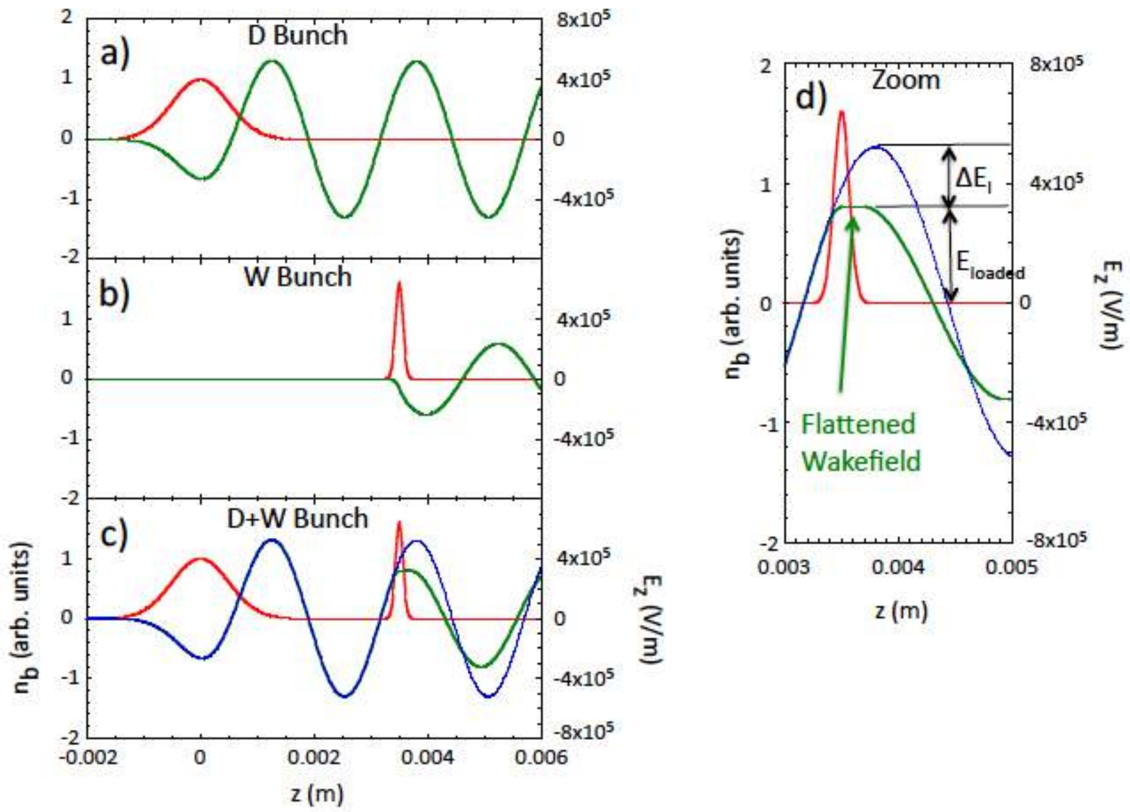


Fig. 5: Linear beam loading example: (a) drive bunch density profile (red line) and longitudinal wakefield E_z (green line), (b) same for the witness bunch, (c) same for the drive and witness bunches together. The field of the drive bunch only is shown as the blue line in panel (c). A zoom around the witness bunch is shown in panel (d). The bunches move to the left.

Regimes: Linear & Non-Linear

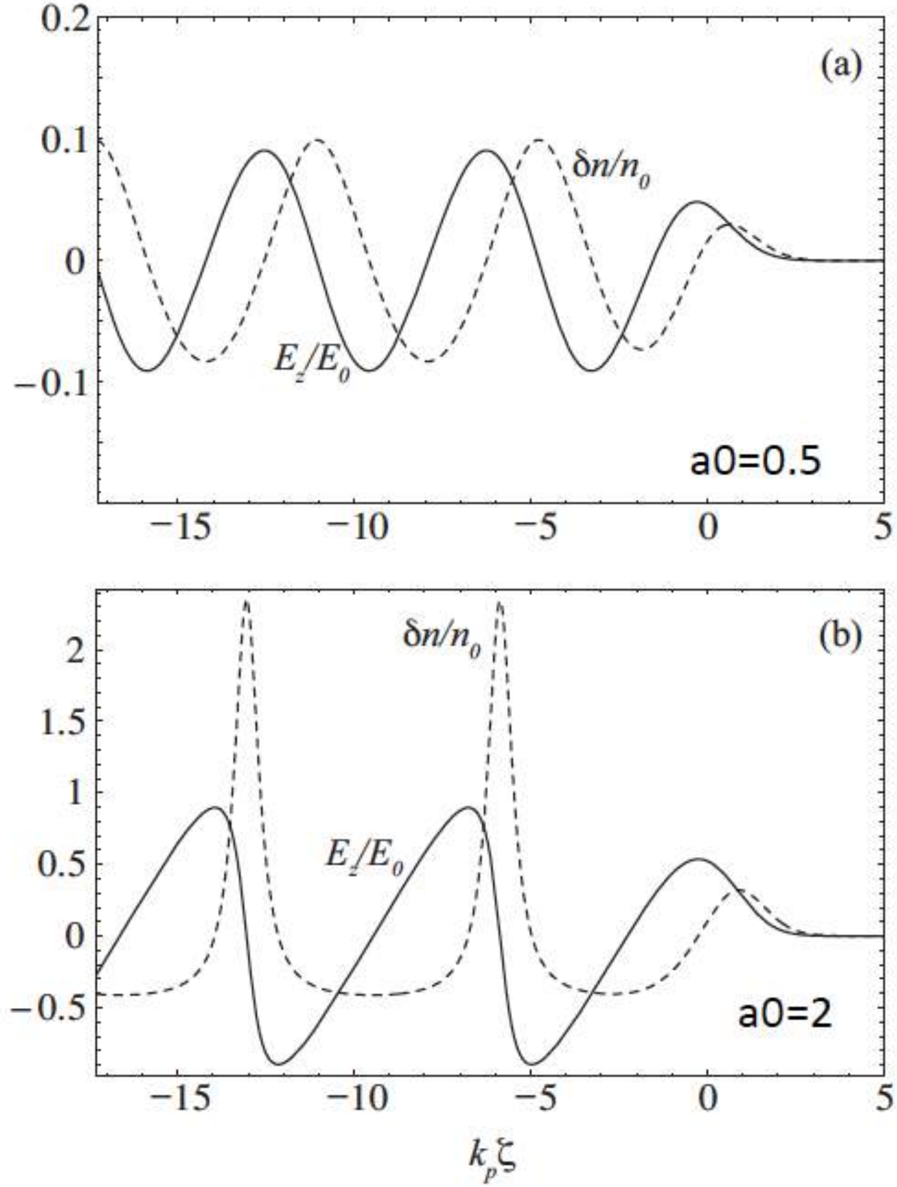
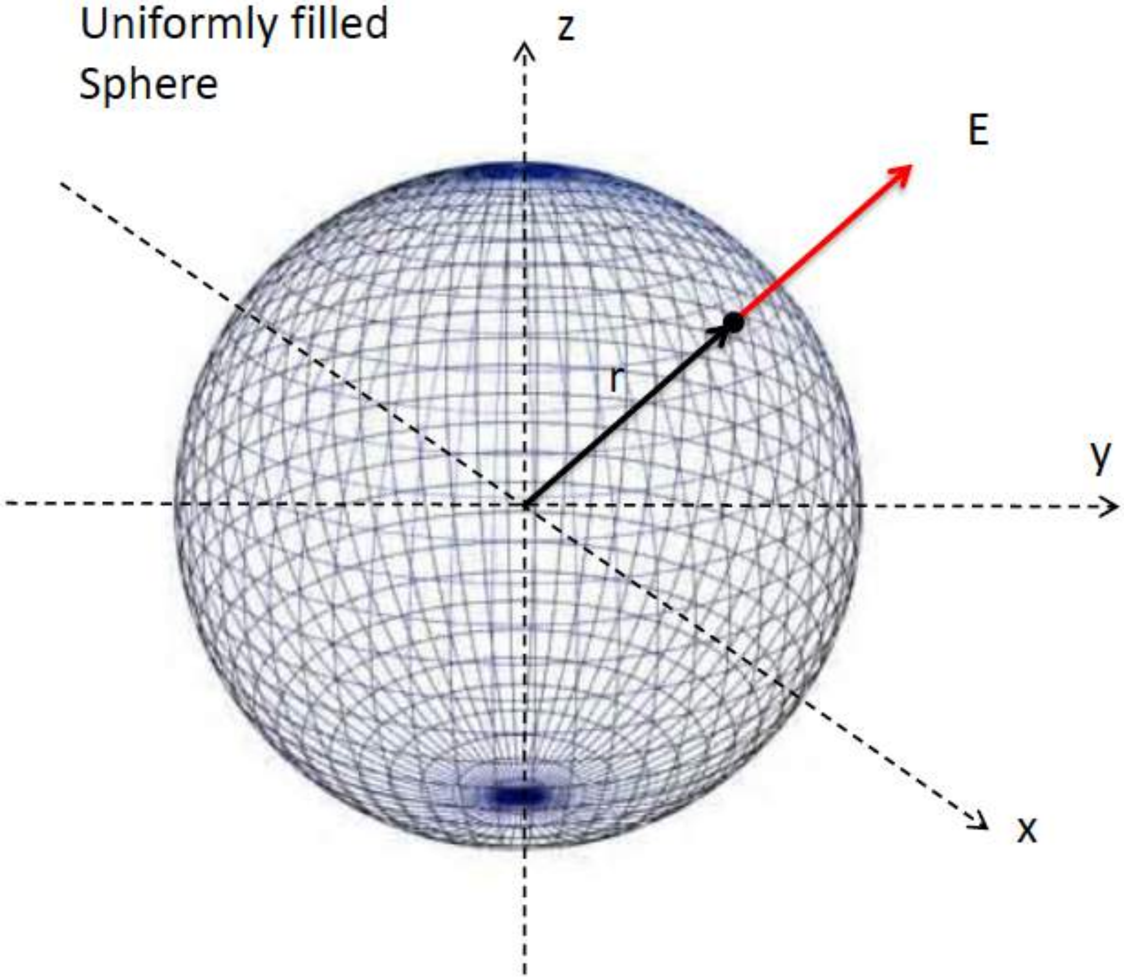


FIG. 8. Time-averaged density variation $\delta n/n_0$ (dashed curve) and axial electric field E_z/E_0 (solid curve) in an LWFA driven by a Gaussian laser pulse (pulse is moving to the right, centered at $k_p\zeta=0$ with rms intensity length $L_{\mathrm{rms}}=k_p^{-1}$) for (a) $a_0=0.5$ and (b) $a_0=2.0$.

Linear

Non-Linear

Coulomb Forces



Inside the sphere

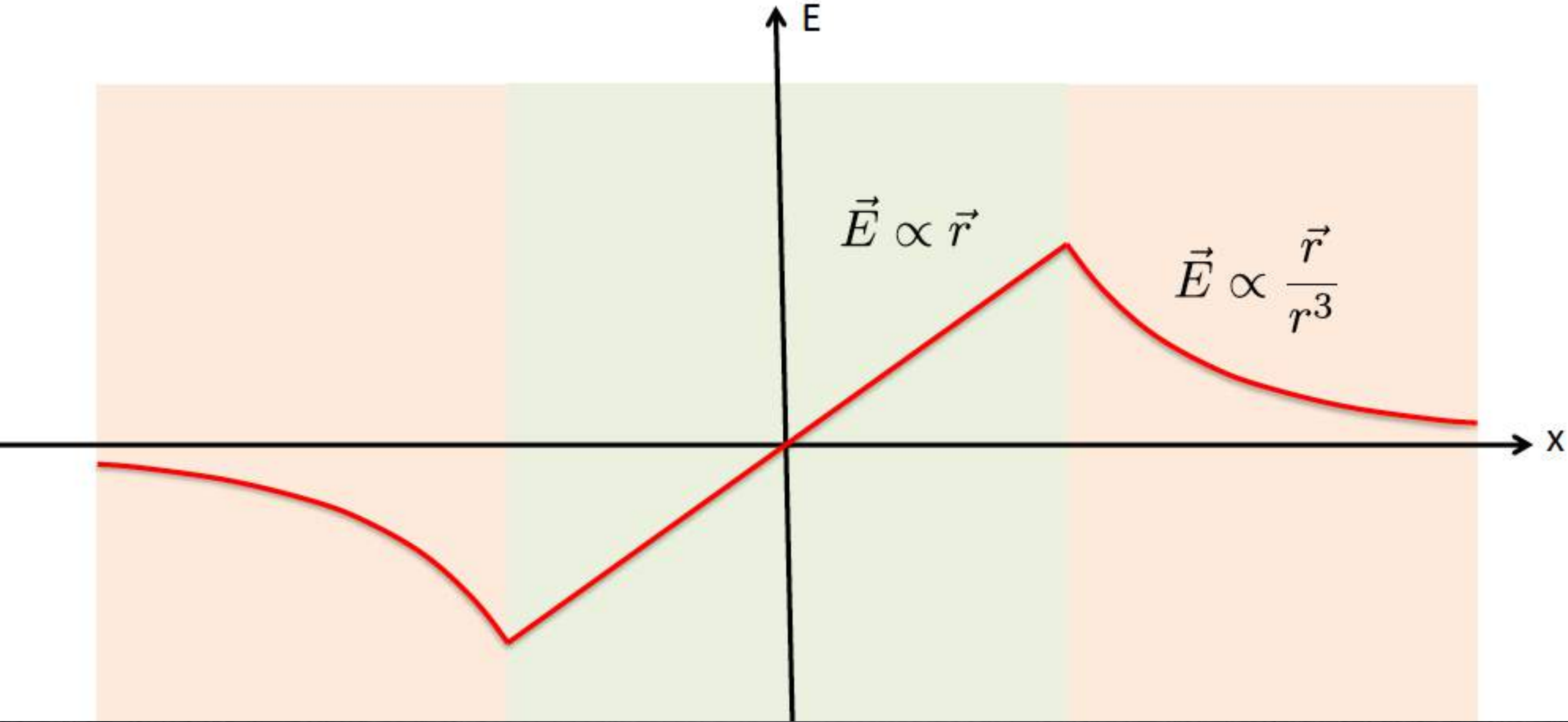
$$E = \frac{\rho}{3\epsilon_0} r$$

ρ = charge density

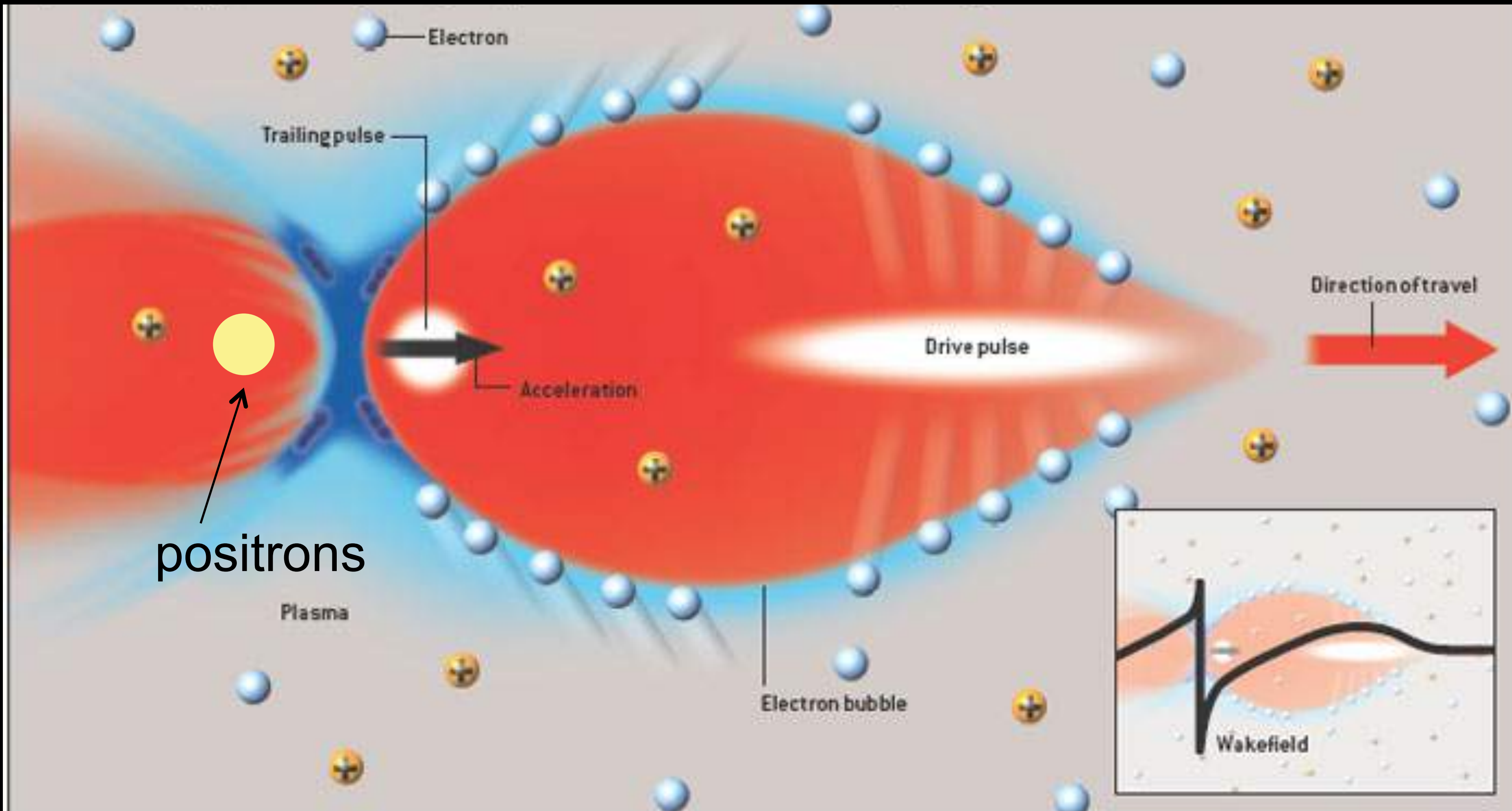
Outside the sphere

$$E = \frac{R^3}{3\epsilon_0} \frac{\rho}{r^2}$$

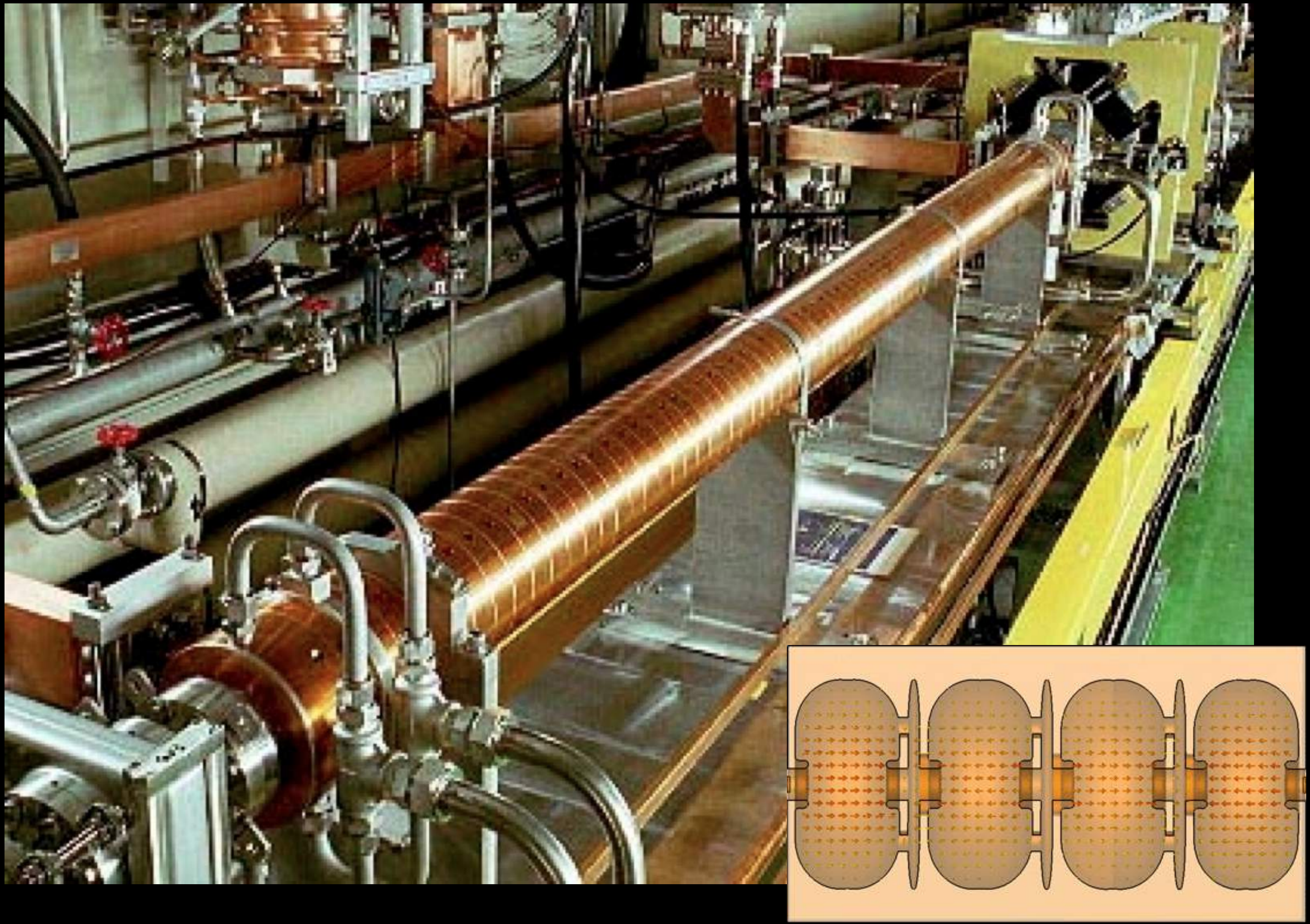
Radial Electric field (along x)



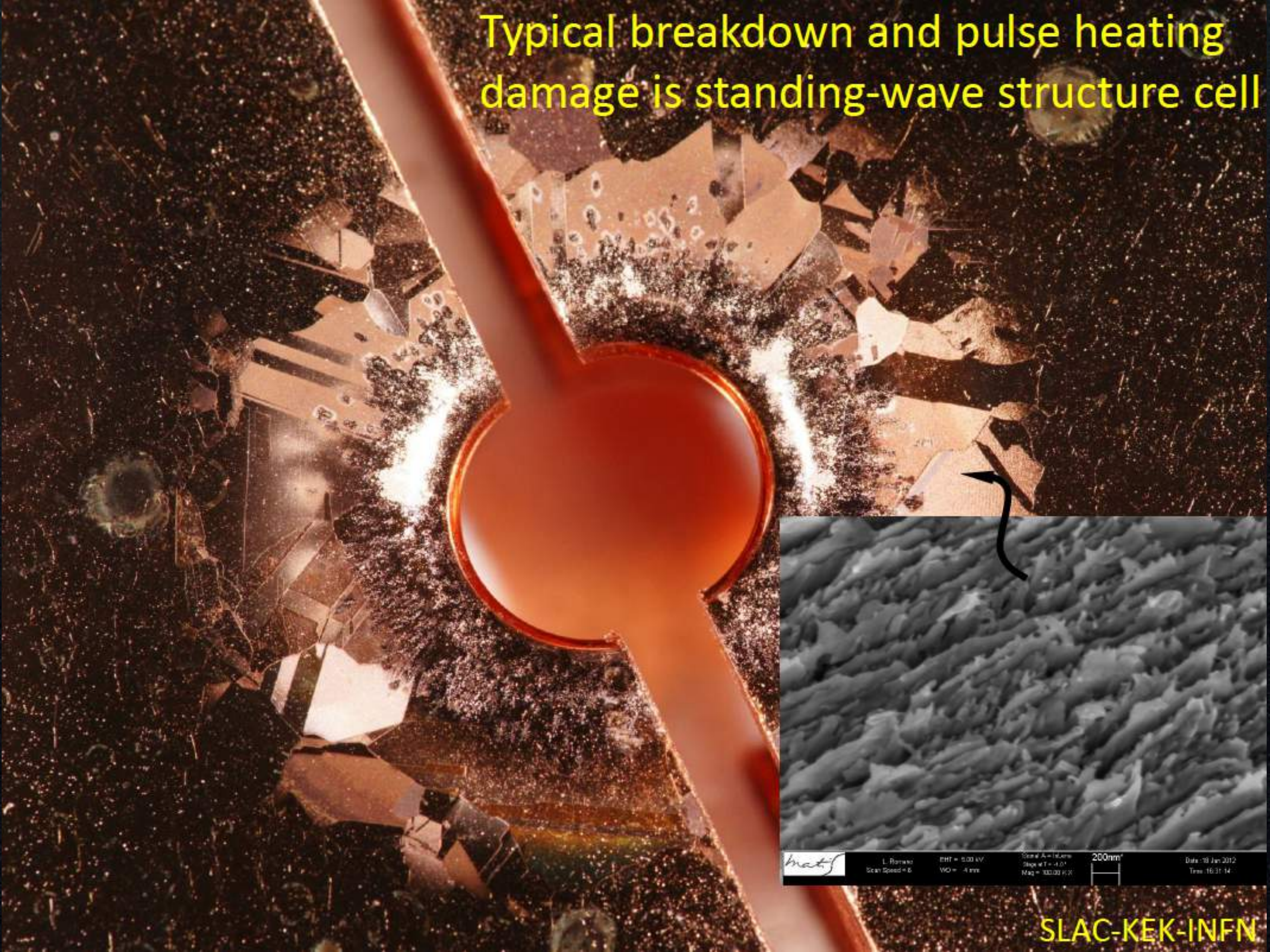
What about positrons?

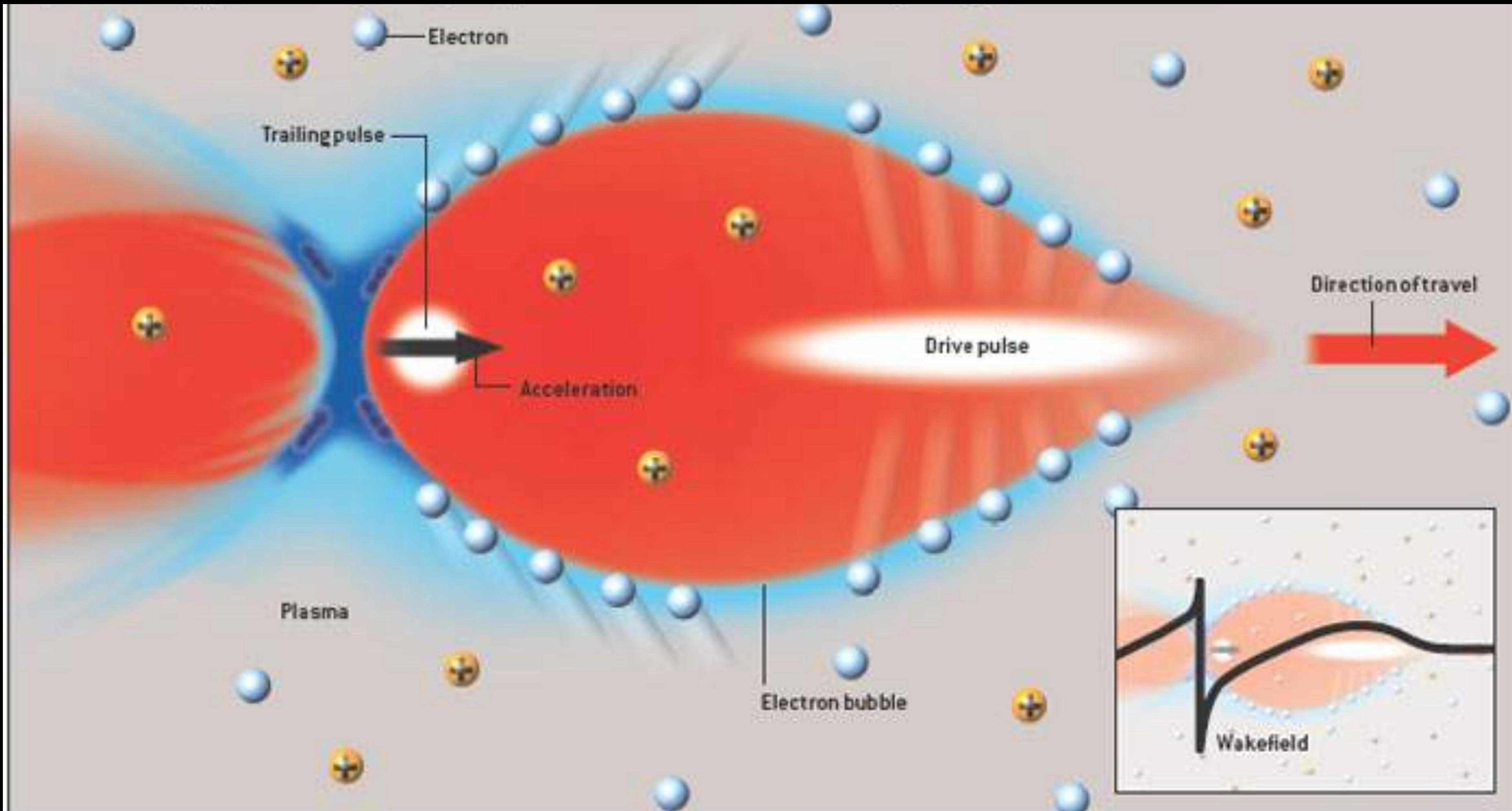


Conventional RF accelerating structures



Typical breakdown and pulse heating damage is standing-wave structure cell

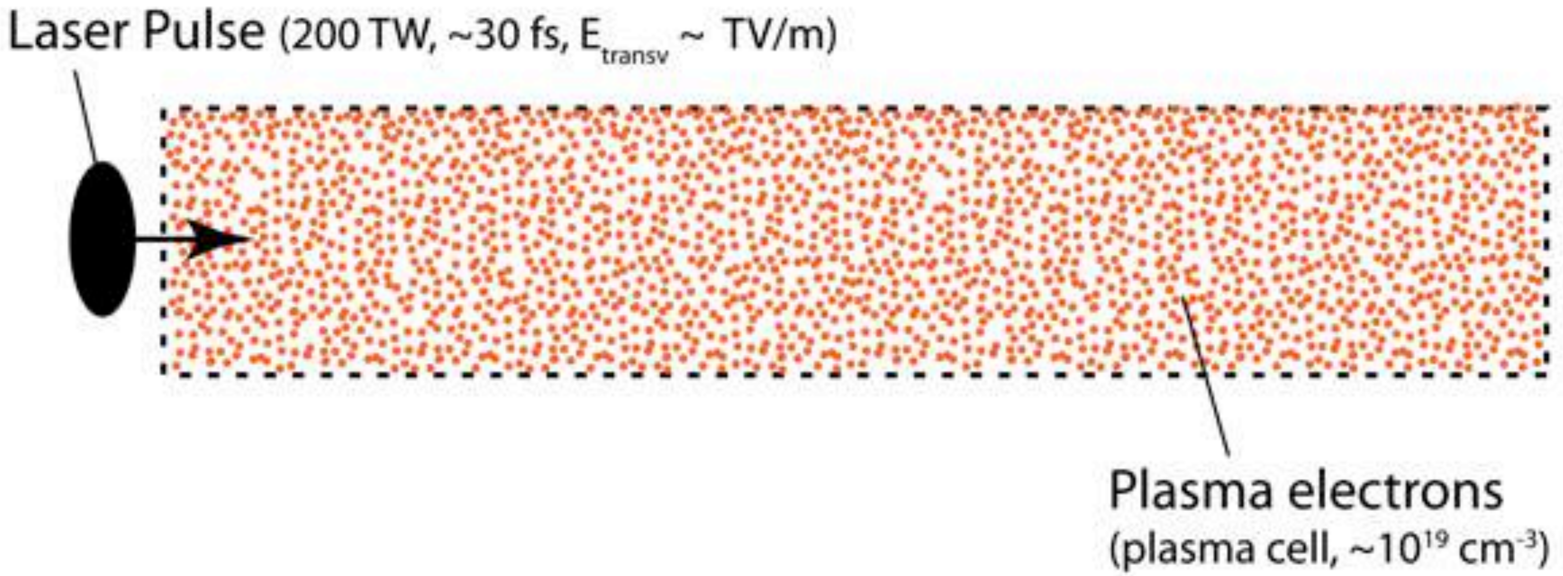




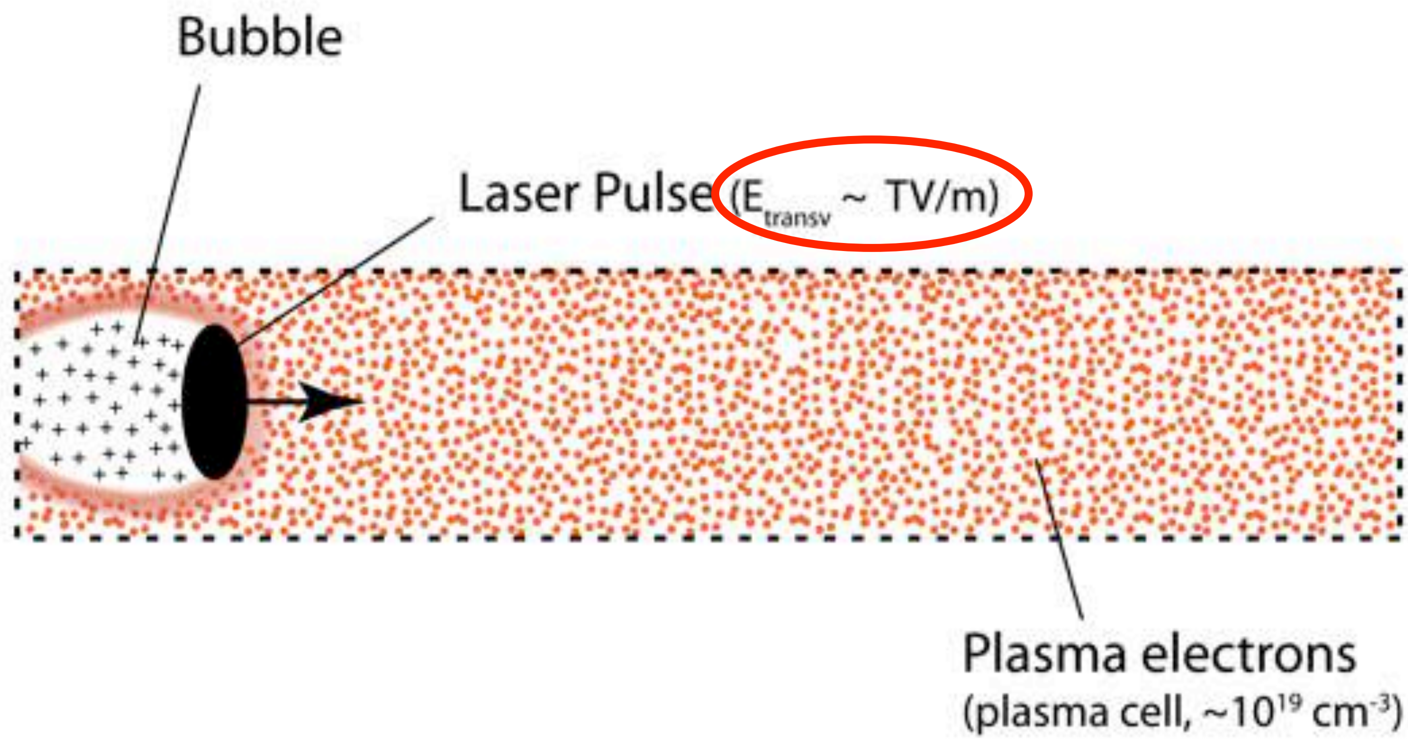
Breakdown limit?

$$E_0 = \frac{m_e c \omega_p}{e} \approx 100[\frac{GeV}{m}] \cdot \sqrt{n_0[10^{18} cm^{-3}]}$$

Laser Plasma-Acceleration
(Internal Injection)



Laser Plasma-Acceleration
(Internal Injection)



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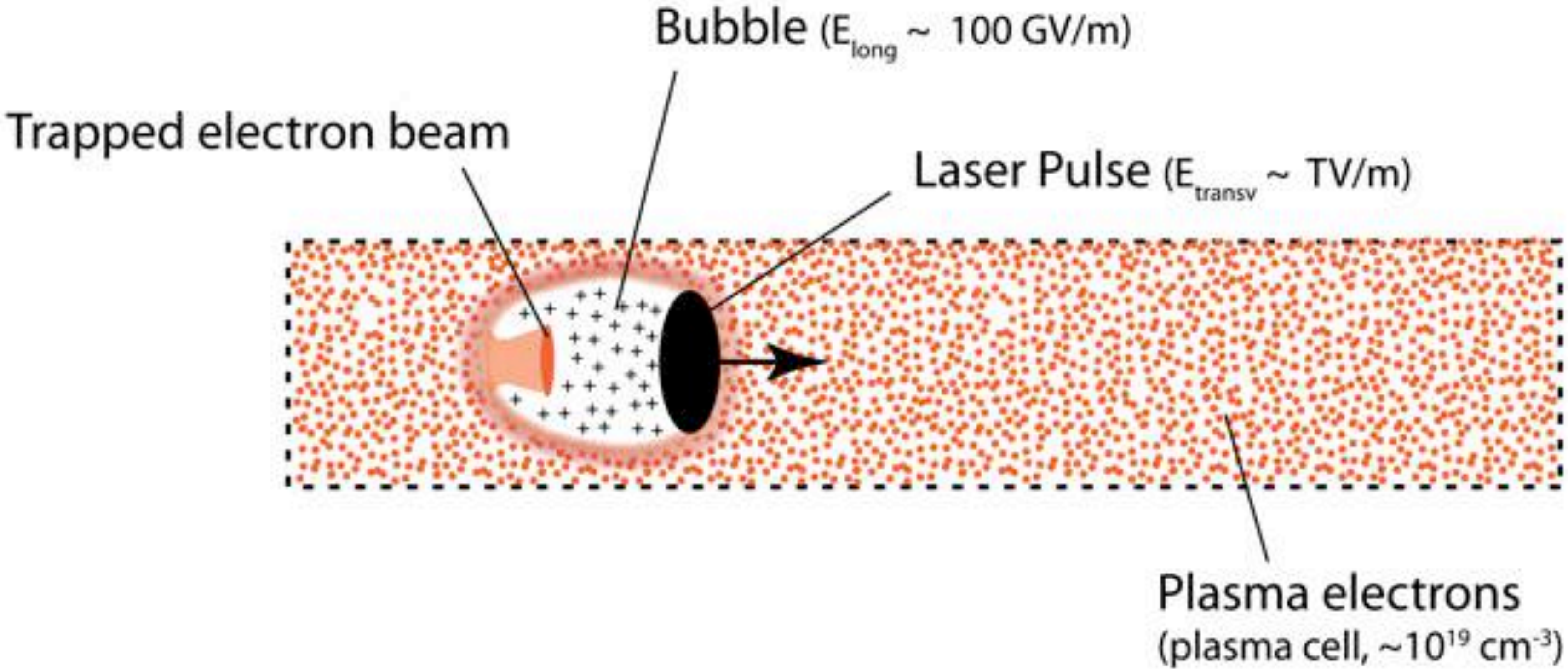

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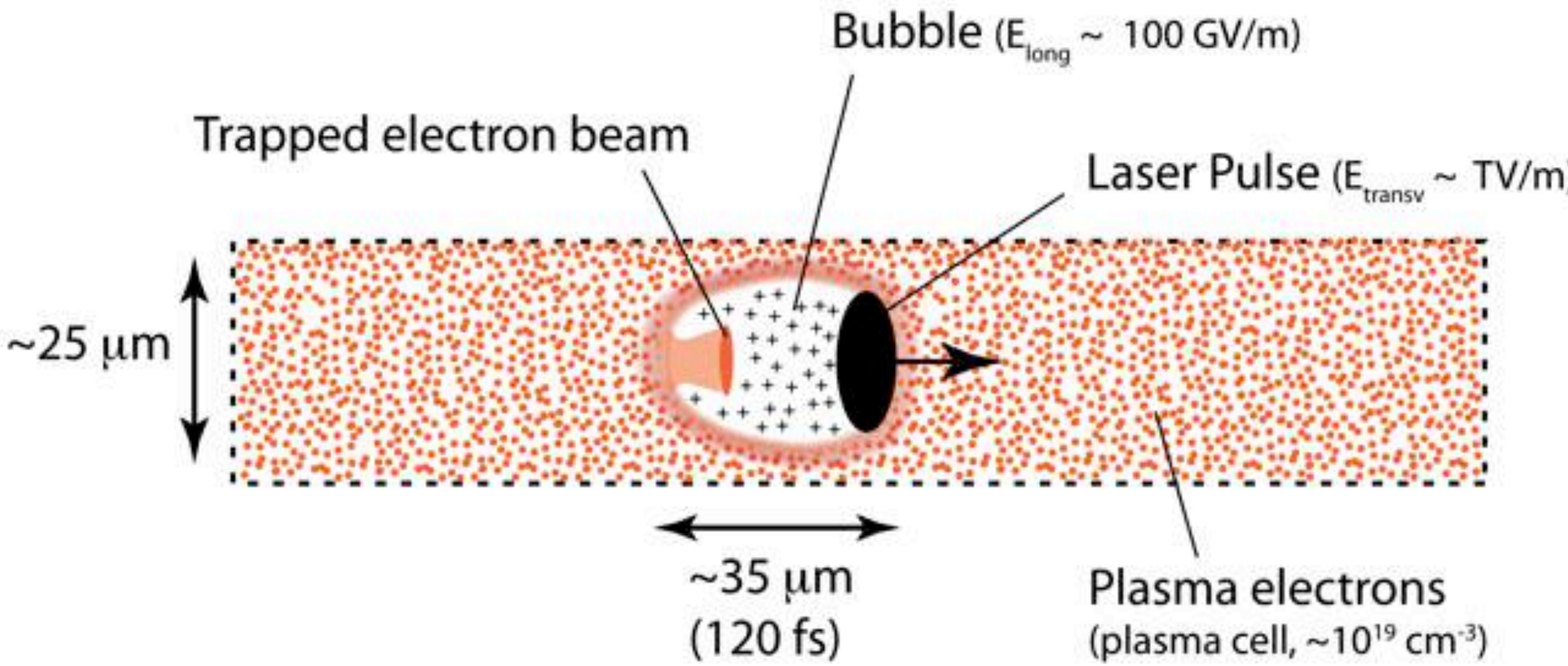
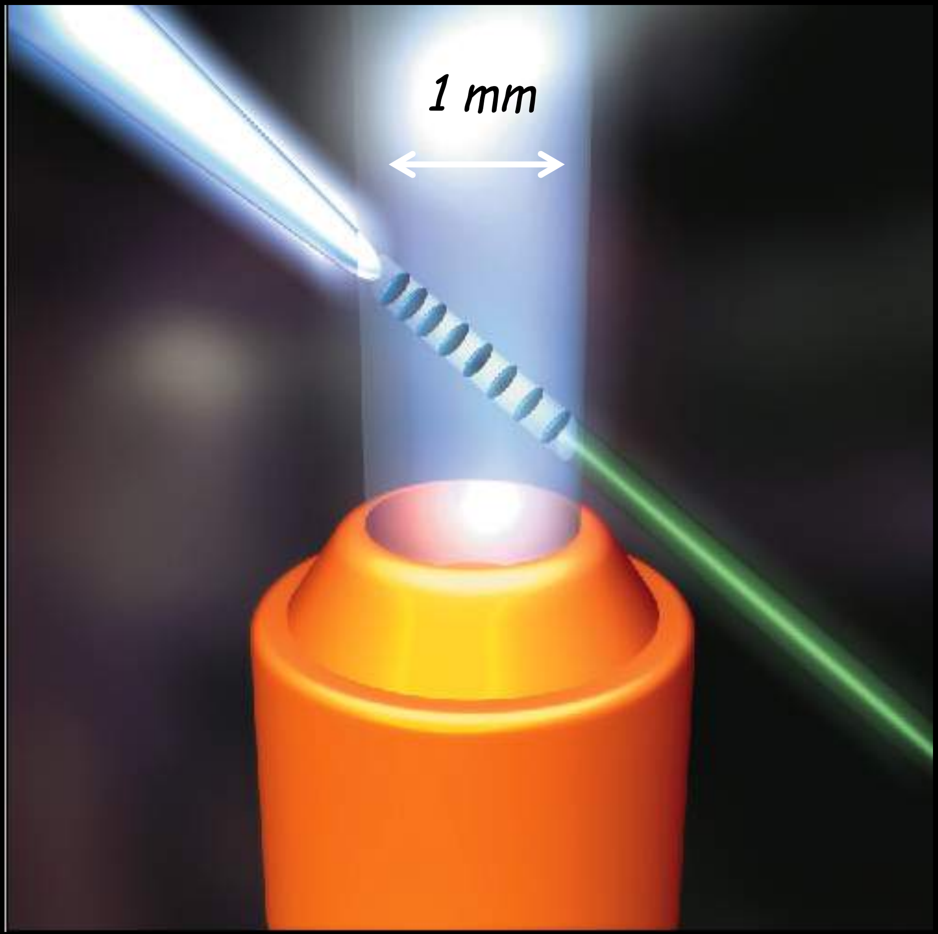


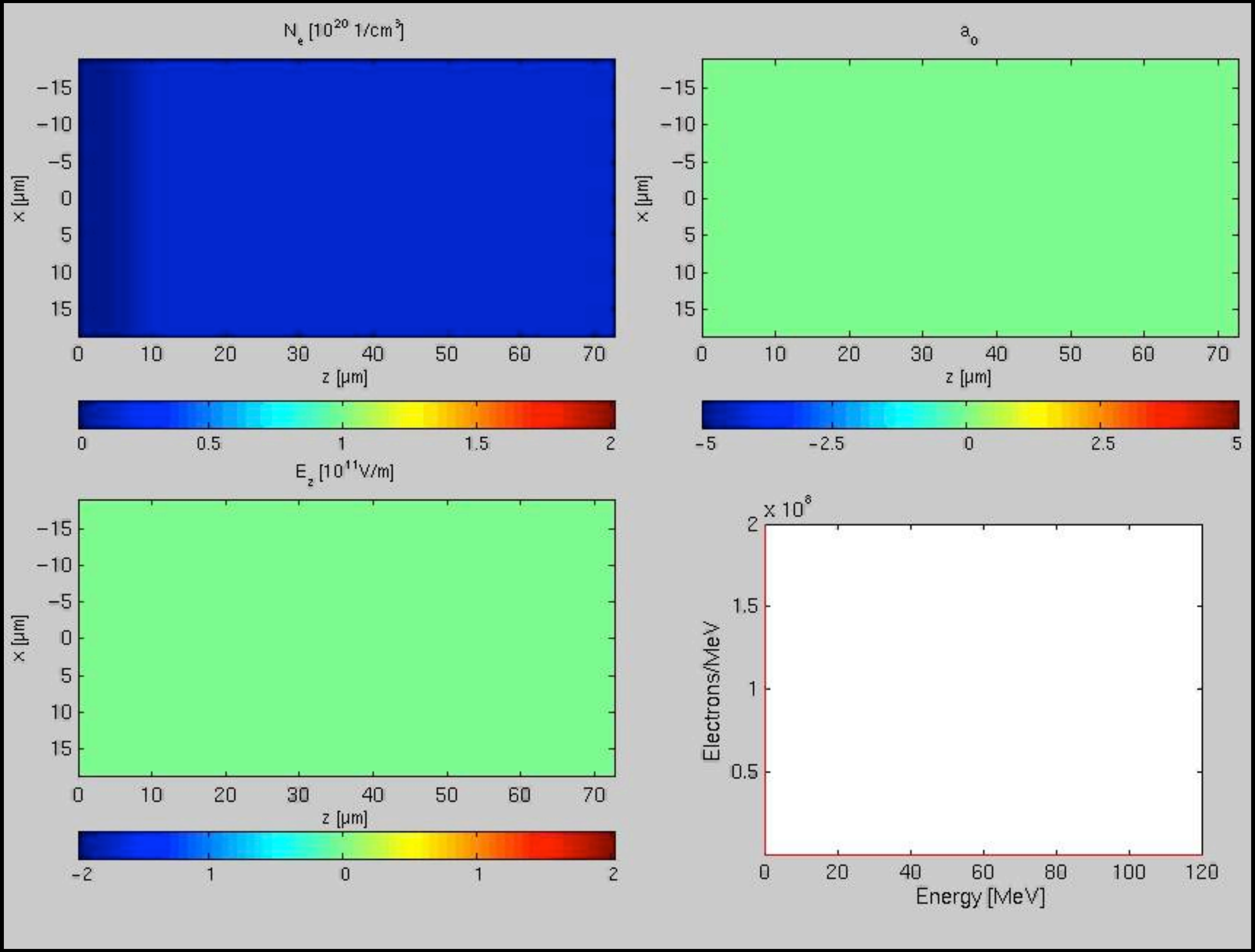
This accelerator fits into a human hair!

Wake Field Acceleration 1
Laser Driven
LWFA

Direct production of e-beam

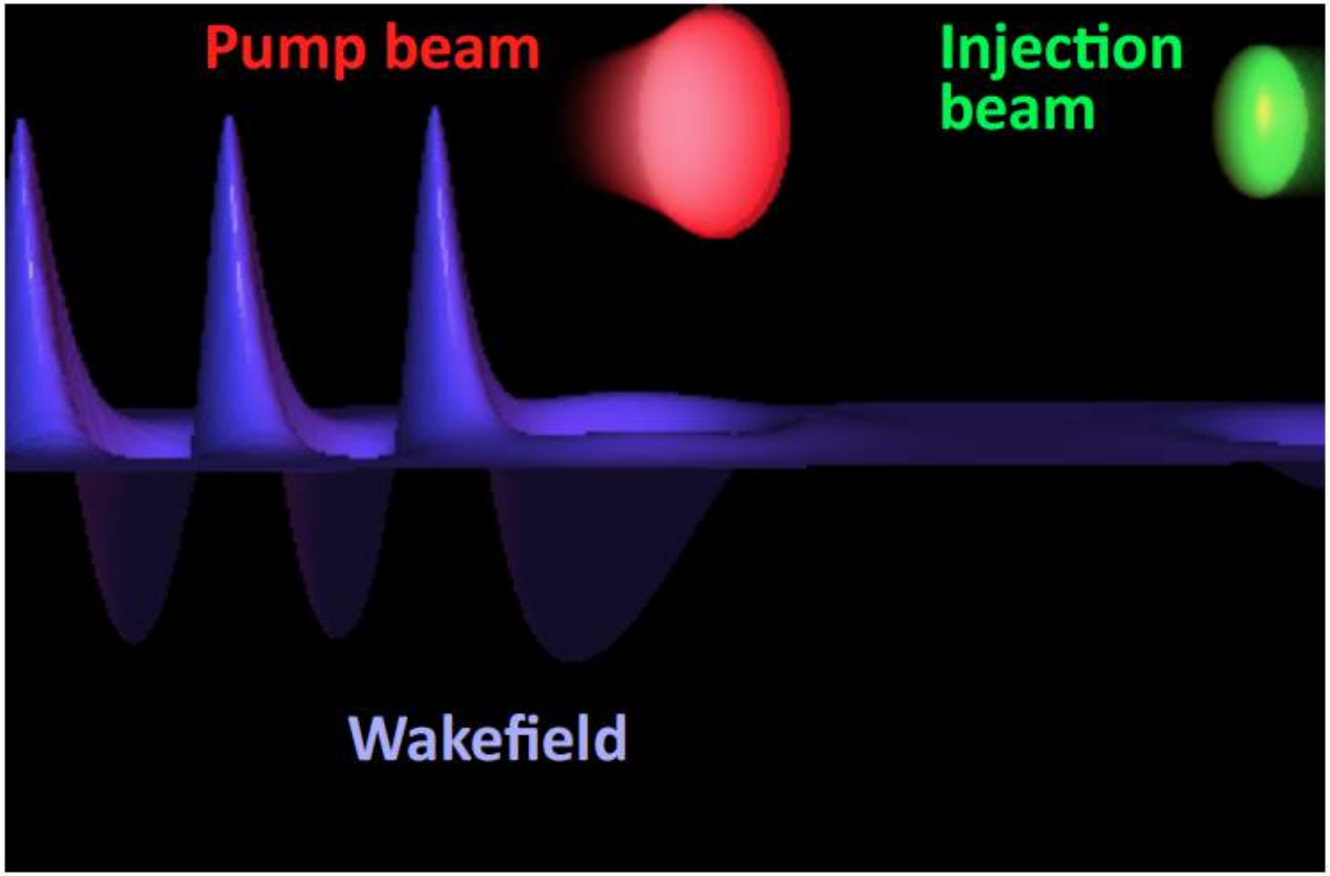


Diffraction - Self injection - Dephasing – Depletion



Colliding Laser Pulses Scheme

The first laser creates the accelerating structure, a second laser beam is used to heat electrons



Theory : E. Esarey *et al.*, PRL **79**, 2682 (1997), H. Kotaki *et al.*, PoP **11** (2004)
Experiments : J. Faure *et al.*, Nature **444**, 737 (2006)

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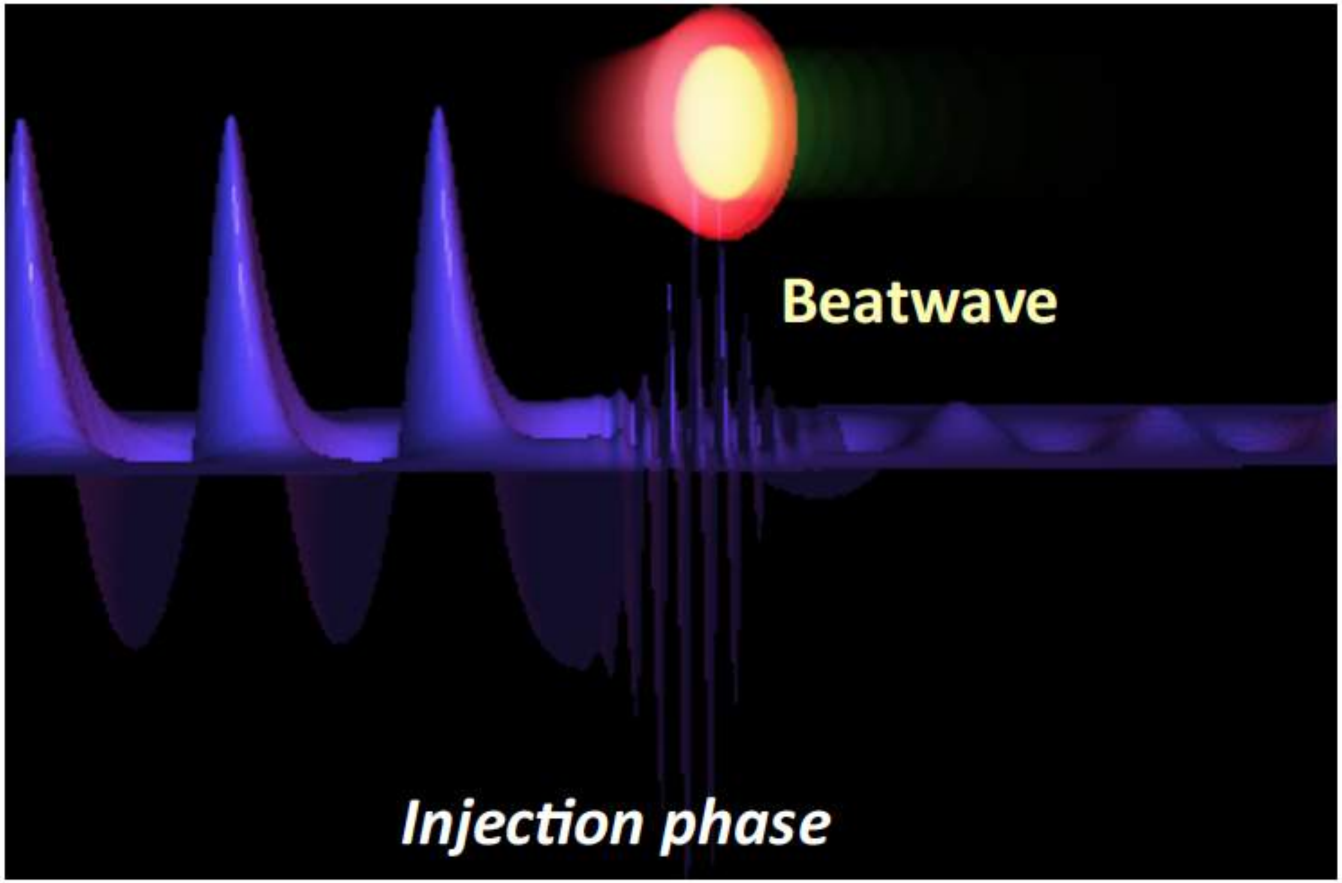

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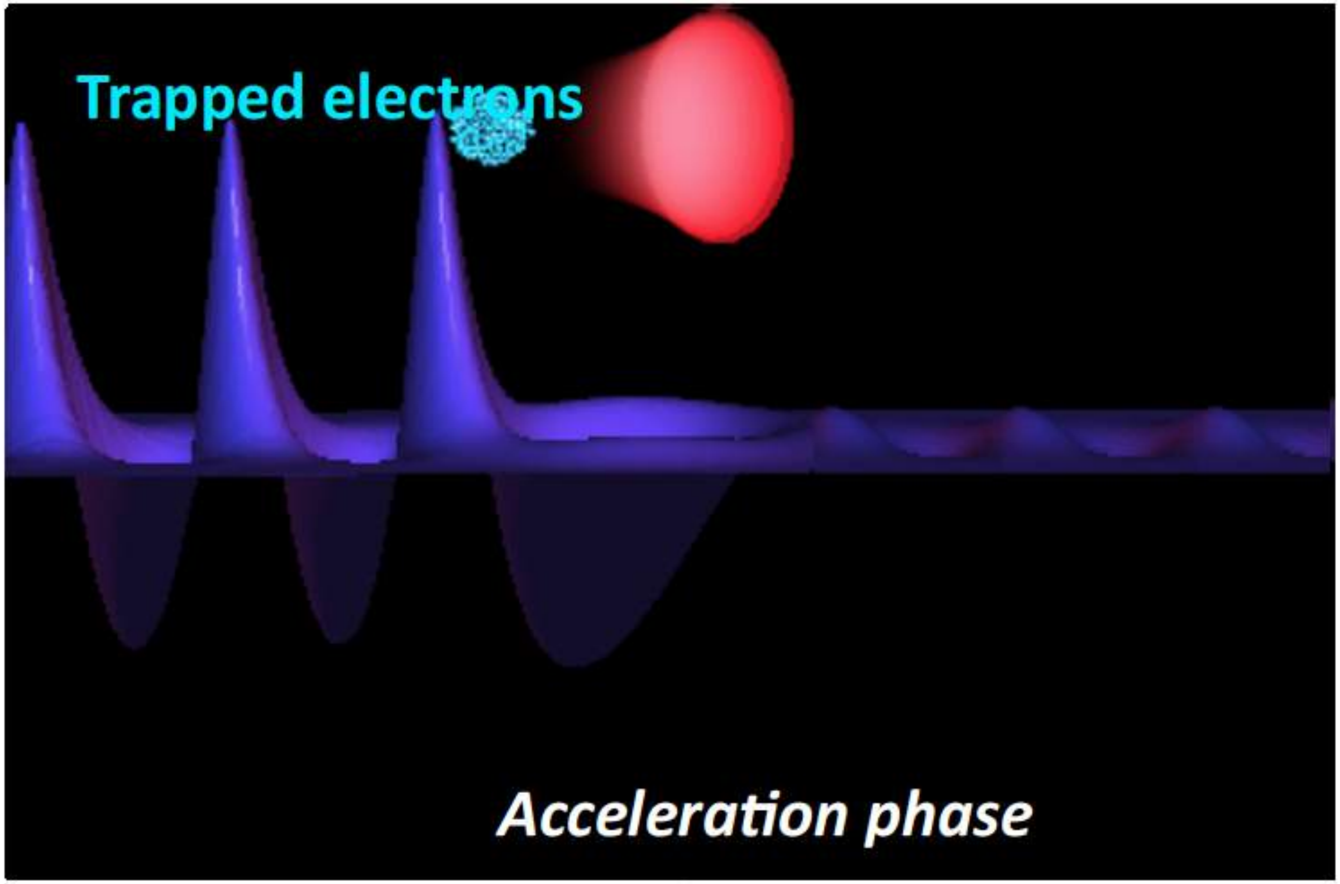
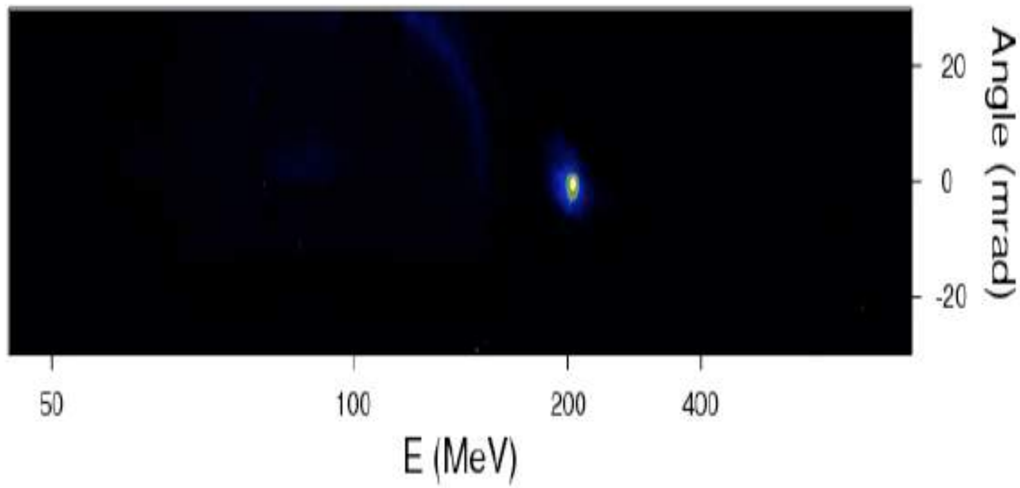
Colliding Laser Pulses Scheme

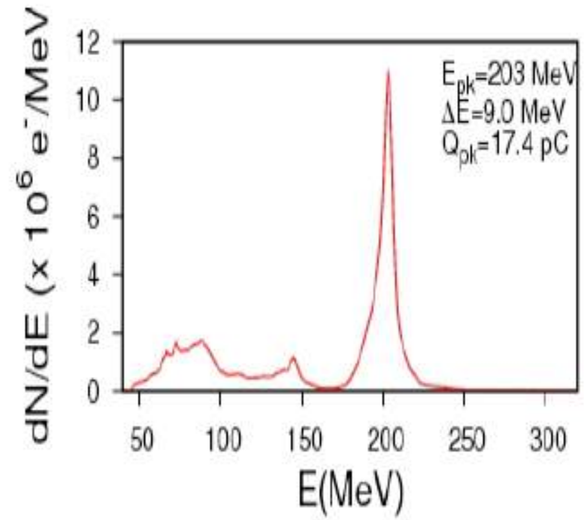
The first laser creates the accelerating structure, a second laser beam is used to heat electrons



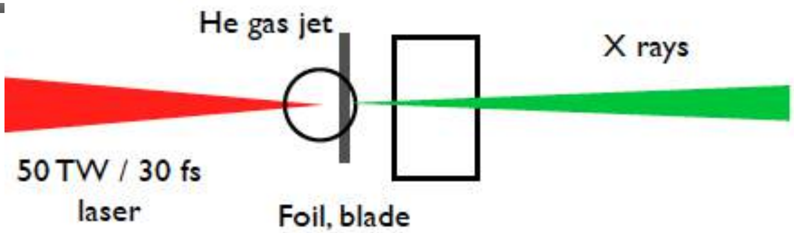
Theory : E. Esarey *et al.*, PRL **79**, 2682 (1997), H. Kotaki *et al.*, PoP **11** (2004)
Experiments : J. Faure *et al.*, Nature **444**, 737 (2006)

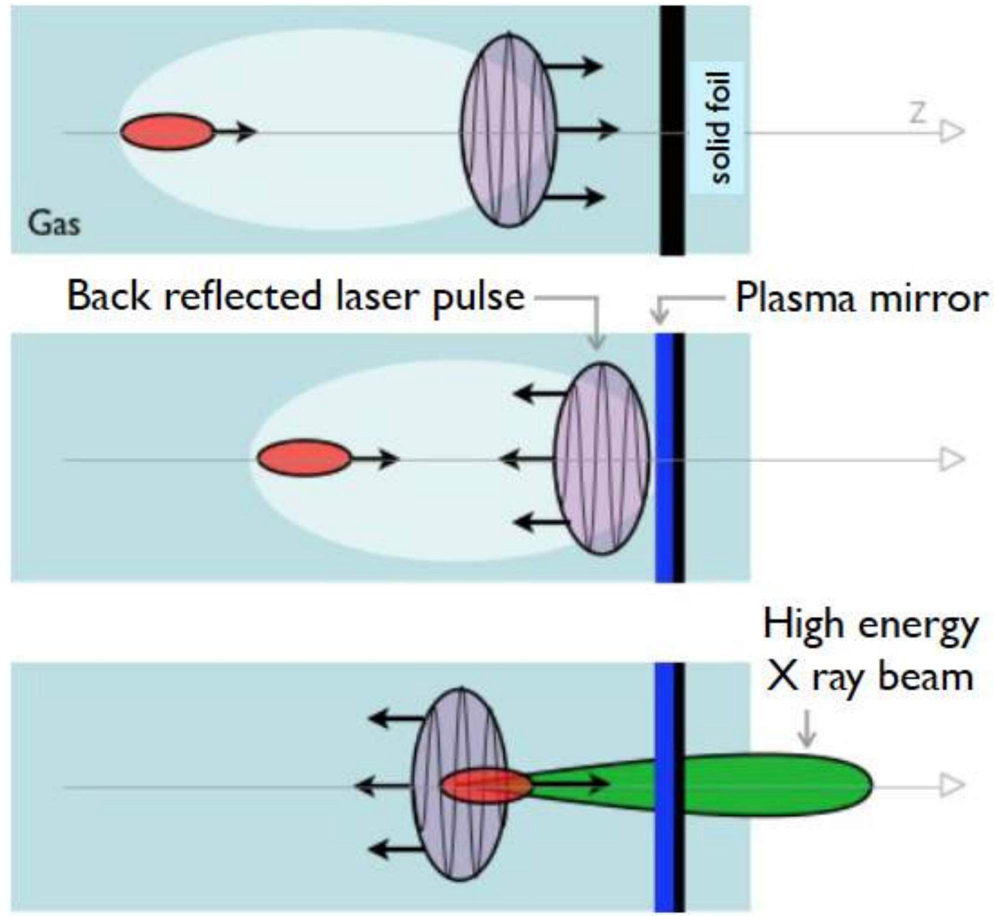
Stable Laser Plasma Accelerators





Inverse Compton Scattering : New scheme





A single laser pulse

A plasma mirror reflects the laser beam

The back reflected laser collides with the accelerated electrons

No alignment : the laser and the electron beams naturally overlap

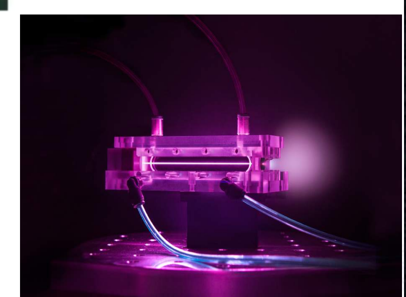
Save the laser energy !

BELLA: BErkeley Lab Laser Accelerator

BELLA Facility: state-of-the-art 1.3 PW-laser for laser accelerator science: >42 J in <40 fs (> 1PW) at 1 Hz laser and supporting infrastructure at LBNL

Critical HEP experiments:

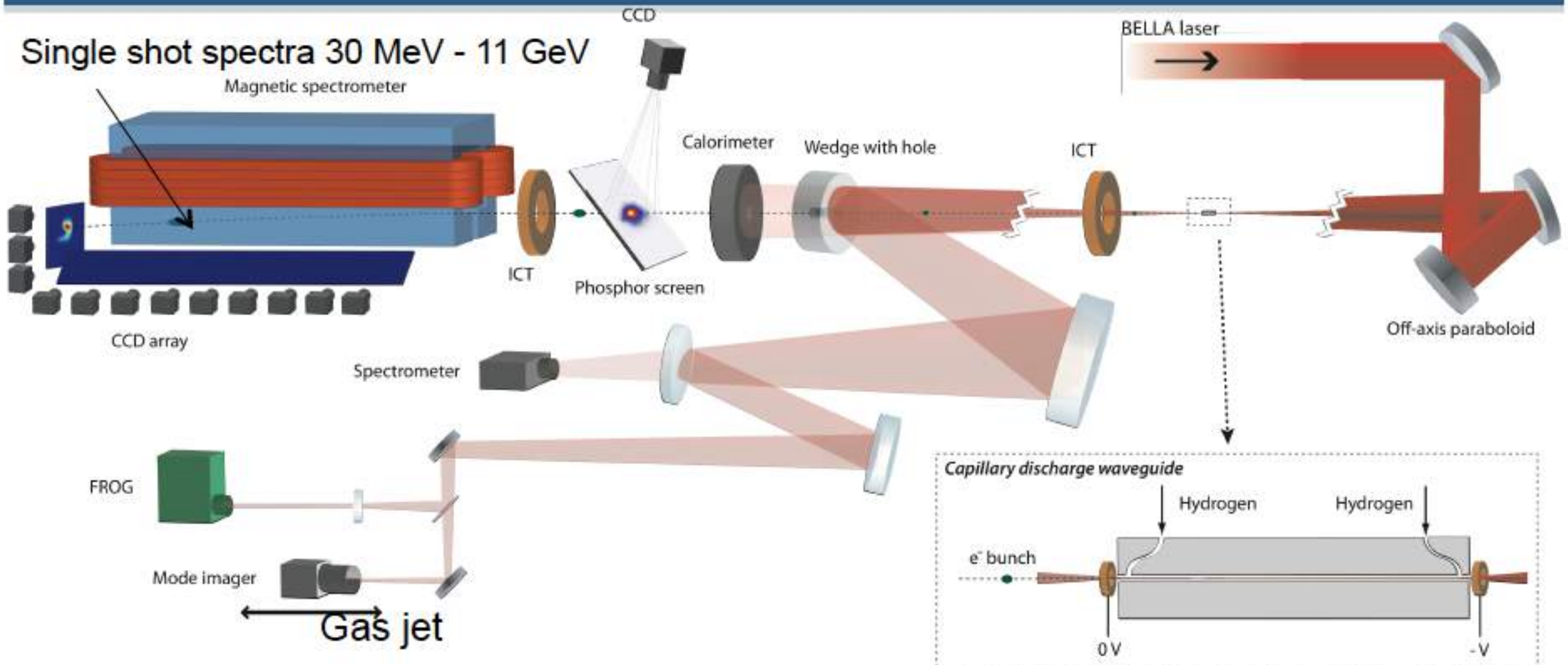
- 10 GeV electron beam from <1 m LPA
- Staging LPAs
- Positron acceleration



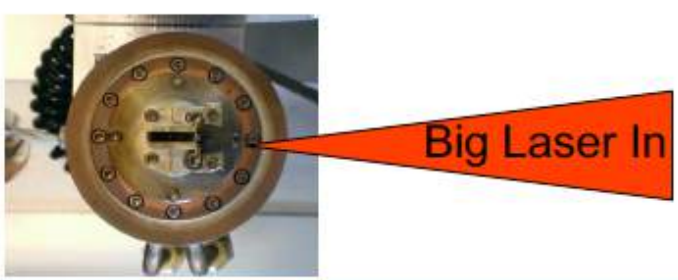
BELLA

Experiments at LBNL use the BELLA laser focused by a 14 m focal length off-axis paraboloid onto gas jet or capillary discharge targets

Single shot spectra 30 MeV - 11 GeV



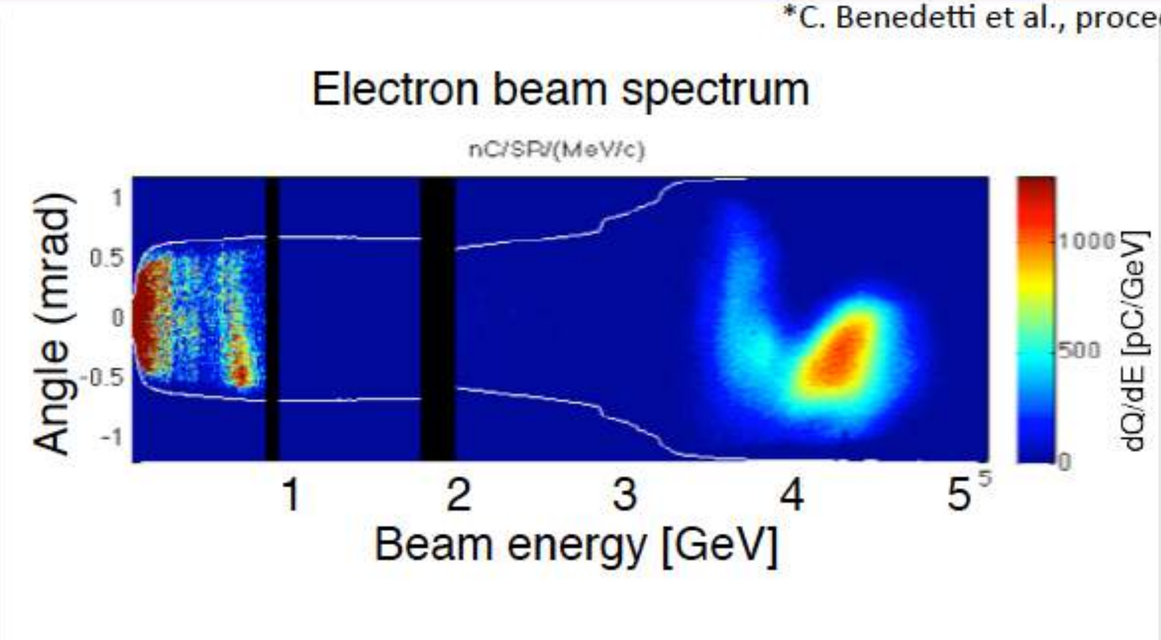
Gas jet

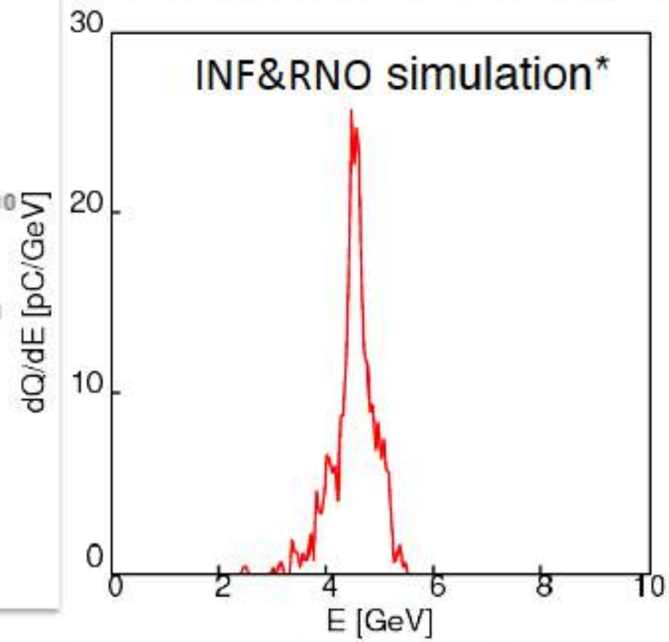


Capillary discharge

4.25 GeV beams have been obtained from 9 cm plasma channel powered by 310 TW laser pulses (15 J)

*C. Benedetti et al., proceedings of AAC2010, proceedings of ICAP2012





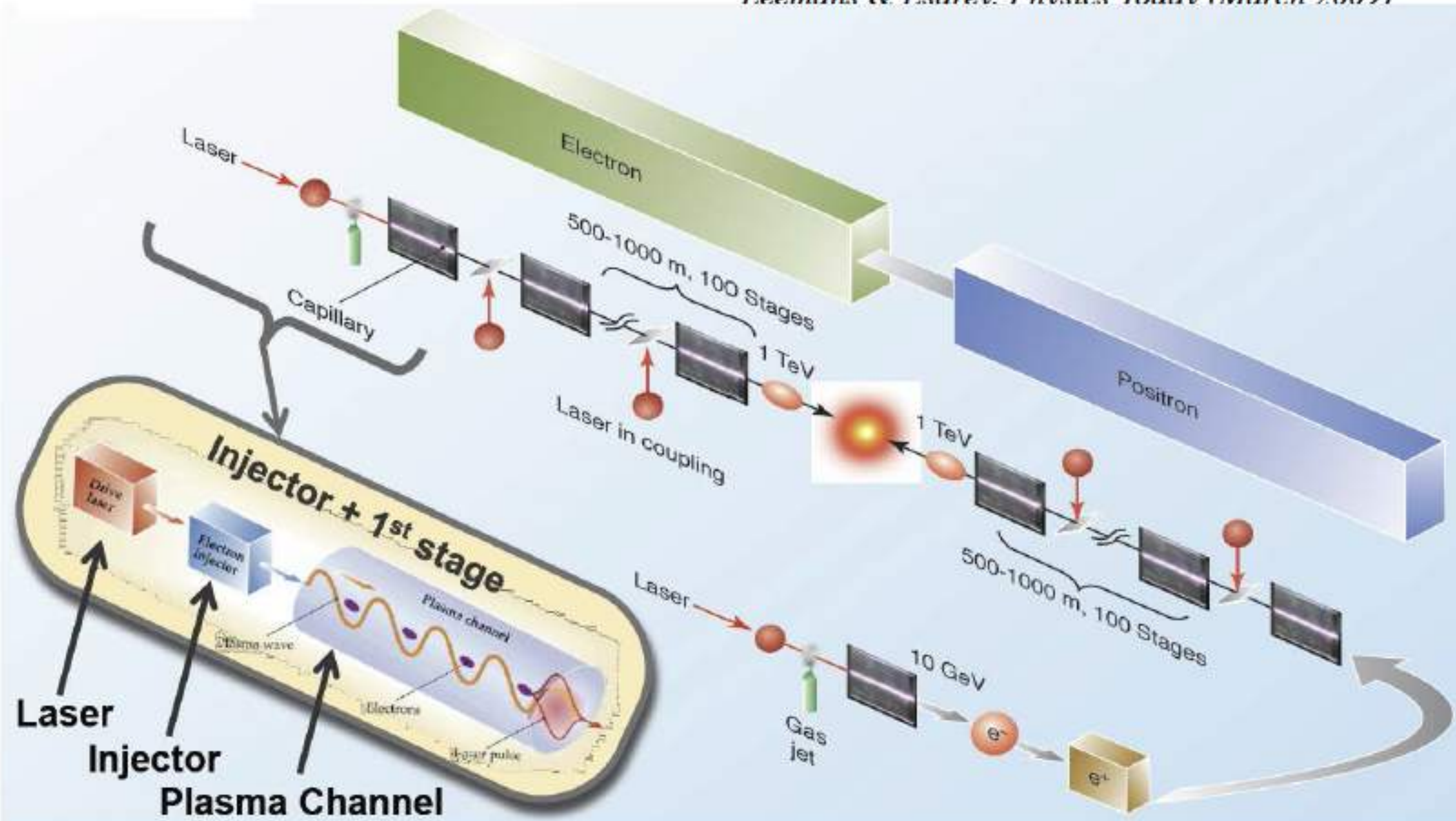
- **Laser** (E=15 J):
  - Measured) longitudinal profile (T_0= 40 fs)
  - Measured far field mode (w_0=53 µm)
- **Plasma:** parabolic plasma channel (length 9 cm, n_0~6-7x10^{17} cm^{-3})

	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

W.P. Leemans et al.,PRL 2014

Laser-Plasma-Accelerator LC

Leemans & Esarey, Physics Today (March 2009)



Parameter Set for LPWA LC

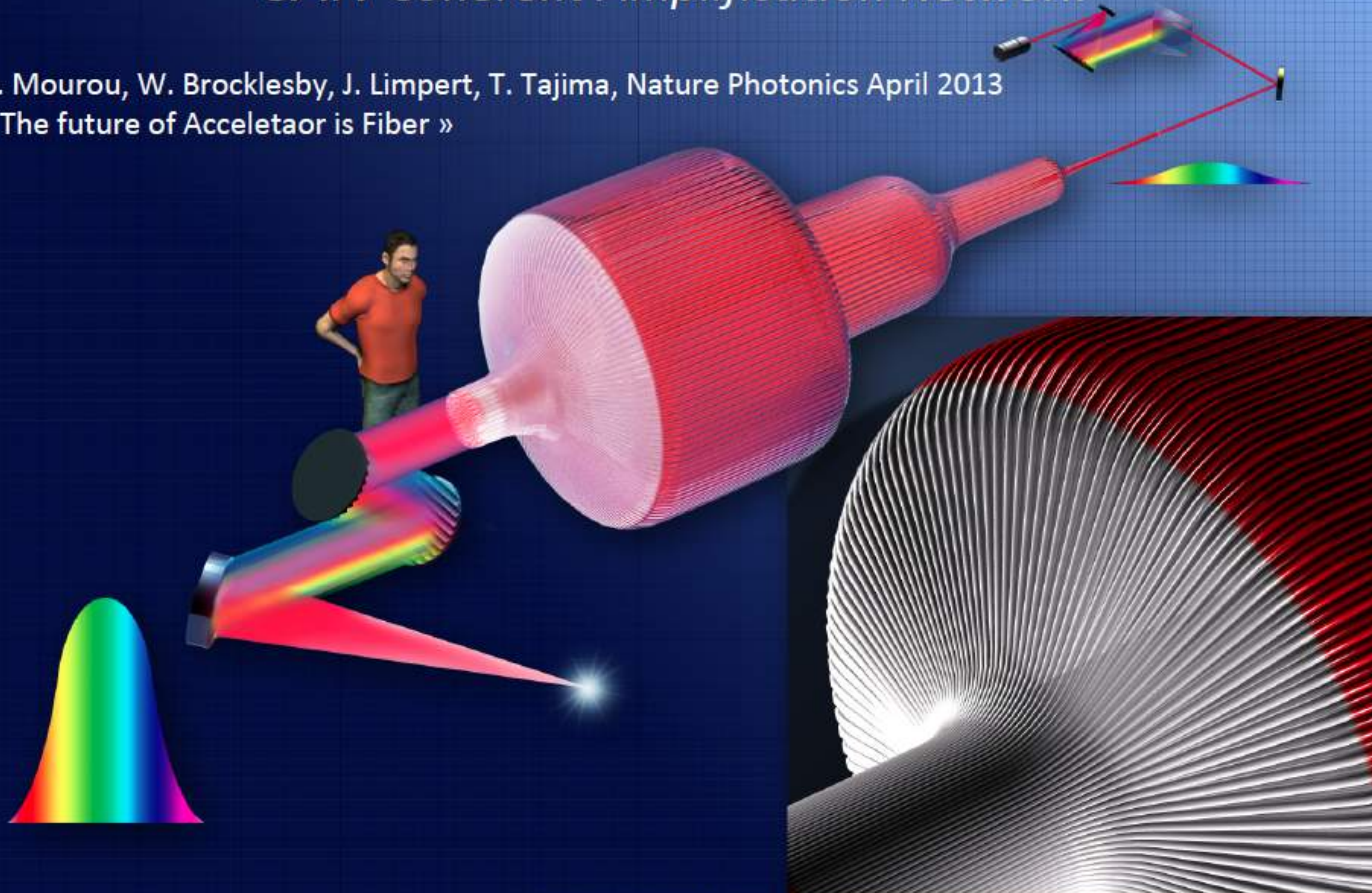
Case: CoM Energy (Plasma density)	1 TeV (10^{17} cm^{-3})	1 TeV (2×10^{15} cm^{-3})	10 TeV (10^{17} cm^{-3})	10 TeV (2×10^{15} cm^{-3})
Energy per beam (TeV)	0.5	0.5	5	5
Luminosity (10^{34} cm^{-2}s^{-1})	2	2	200	200
Electrons per bunch ($\times10^{10}$)	0.4	2.8	0.4	2.8
Bunch repetition rate (kHz)	15	0.3	15	0.3
Horizontal emittance $\gamma\varepsilon_x$ (nm-rad)	100	100	50	50
Vertical emittance $\gamma\varepsilon_y$ (nm-rad)	100	100	50	50
β^* (mm)	1	1	0.2	0.2
Horizontal beam size at IP σ^*_x (nm)	10	10	1	1
Vertical beam size at IP σ^*_y (nm)	10	10	1	1
Disruption parameter	0.12	5.6	1.2	56
Bunch length σ_z (μm)	1	7	1	7
Beamstrahlung parameter Υ	180	180	18,000	18,000
Beamstrahlung photons per e, n_γ	1.4	10	3.2	22
Beamstrahlung energy loss δ_E (%)	42	100	95	100
Accelerating gradient (GV/m)	10	1.4	10	1.4
Average beam power (MW)	5	0.7	50	7
Wall plug to beam efficiency (%)	6	6	10	10
One linac length (km)	0.1	0.5	1.0	5

×2+FF

ICAN (European Project)

CAN Coherent Amplification Network

G. Mourou, W. Brocklesby, J. Limpert, T. Tajima, Nature Photonics April 2013
« The future of Acceletaor is Fiber »



Gerard Mourou S.L Chin, Laval

Beam Manipulation

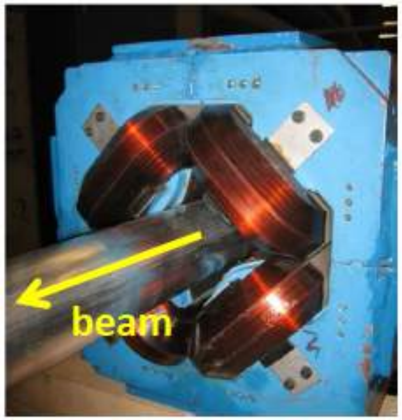
MAGNETIC QUADRUPOLE

Quadrupoles are used to focalize the beam in the transverse plane. It is a 4 poles magnet:

⇒B=0 in the center of the quadrupole

⇒The B intensity increases linearly with the off-axis displacement.

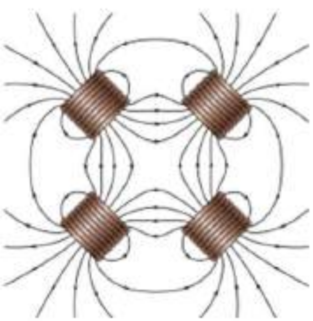
⇒If the quadrupole is focusing in one plane is defocusing in the other plane



Electromagnetic quadrupoles G <100 T/m

$$\begin{cases} B_x = G \cdot y \\ B_y = G \cdot x \end{cases} \Rightarrow \begin{cases} F_y = qvG \cdot y \\ F_x = -qvG \cdot x \end{cases}$$

$$G = \text{quadrupole gradient} \left[\frac{T}{m} \right]$$



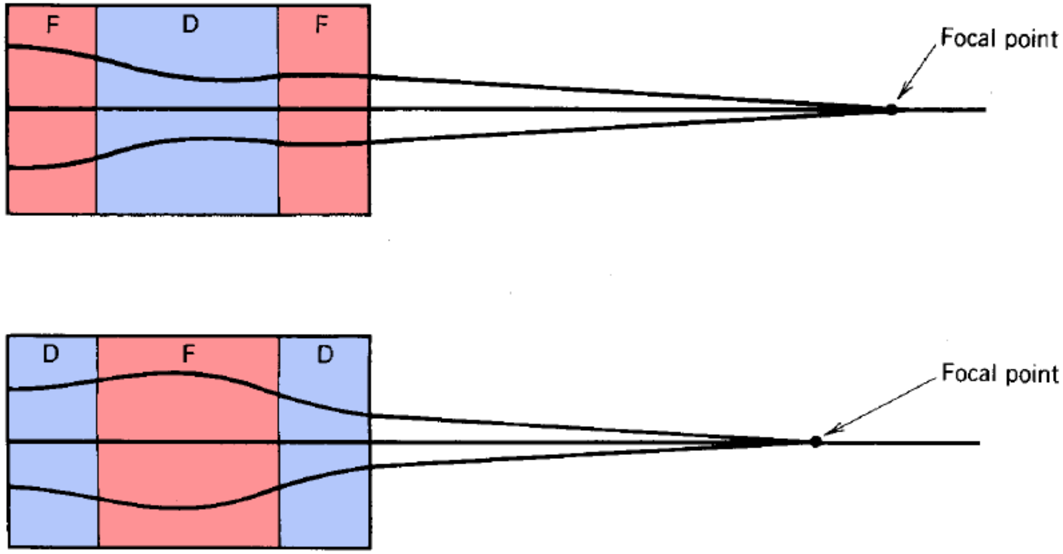
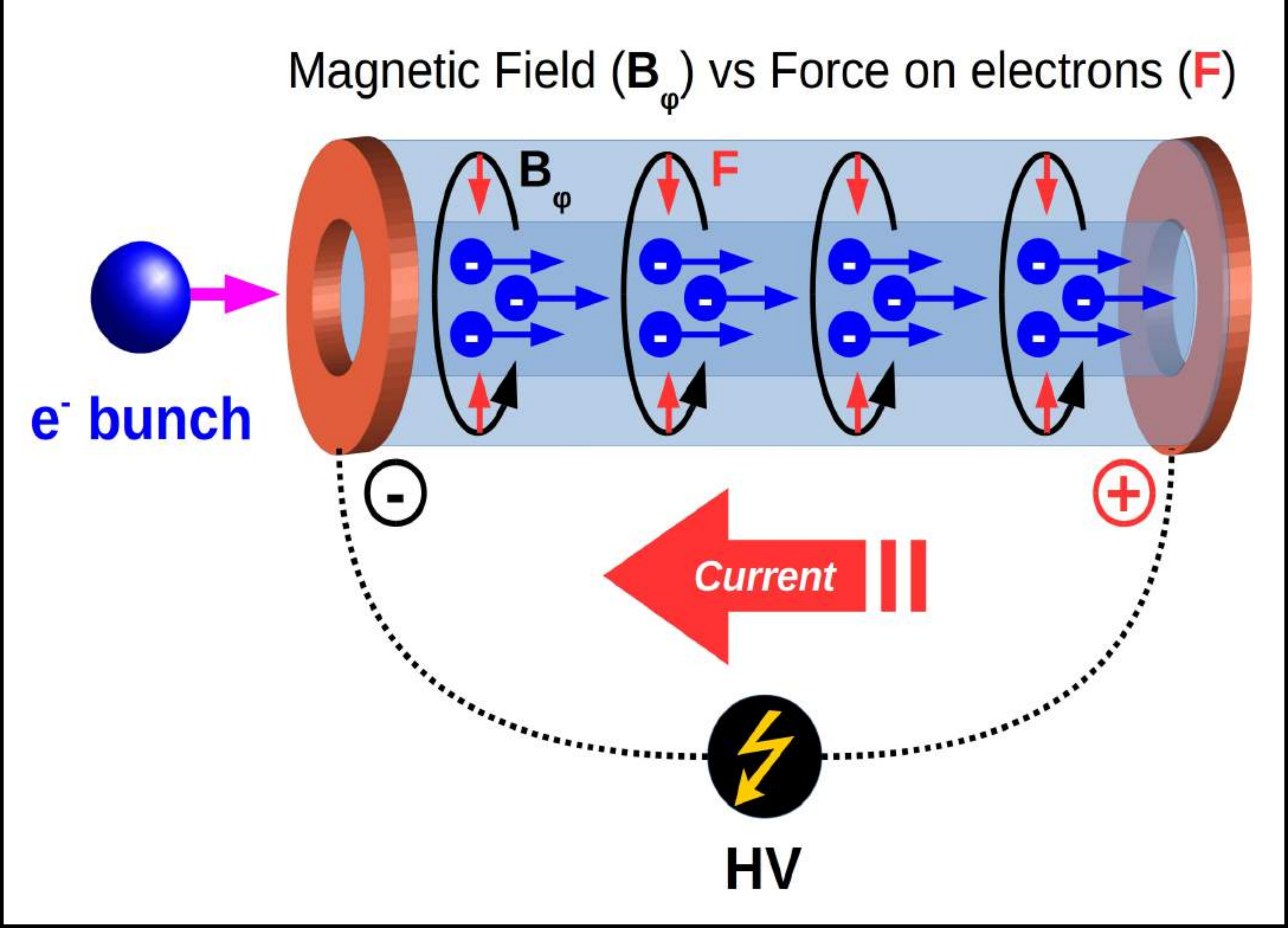


Figure 8.8 Improved stigmatic properties of a quadrupole triplet lens. Orbits of particles initially parallel to the axis projected in the x and y planes.

Capillary Discharge

Active Plasma Lens

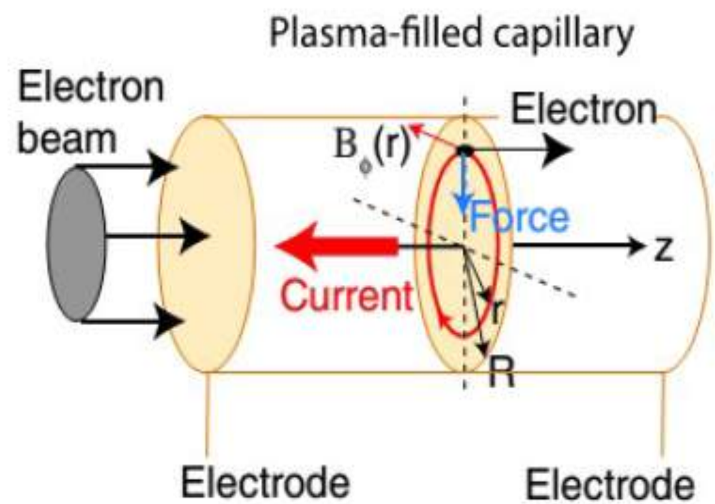


Active plasma lens

- Focusing field produced by electric discharge in a plasma-filled capillary
  - *Focusing field produced, according to Ampere's law, by the discharge current*

$$B_{\phi}(r)=\frac{1}{2}\int_{0}^{r}\mu_0 J(r')\,dr'$$

- ✔ Radial focusing
  - *X/Y planes are not dependent as in quads*
- ✔ Weak chromaticity
  - *Focusing force scales linearly with energy*
- ✔ Compactness
  - *Higher integrated field than quad triplets*
- ✔ Independent from beam distribution
  - *Not sensitive to longitudinal/transverse charge profile as in passive plasma lenses*



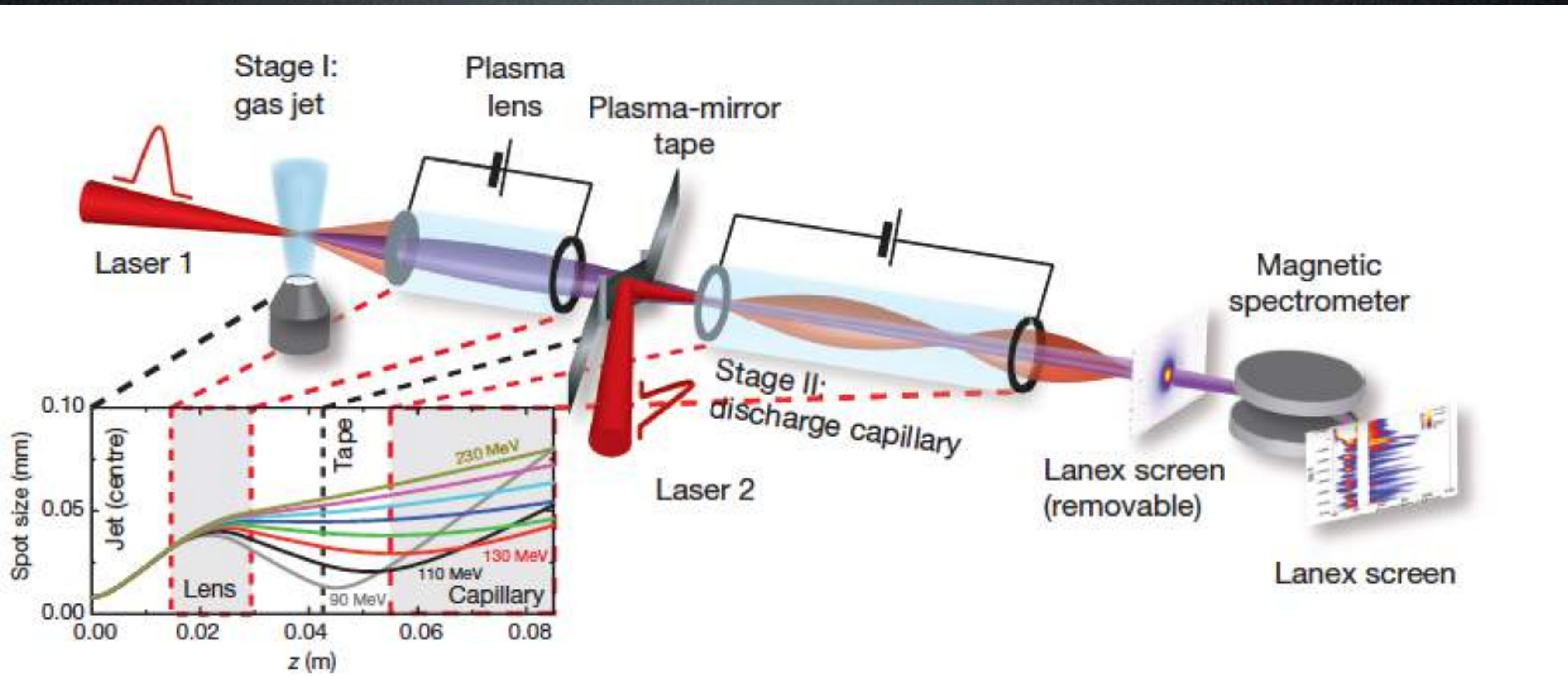
Van Tilborg, J., et al. "Active plasma lensing for relativistic laser-plasma-accelerated electron beams." Physical review letters 115.18 (2015): 184802.

LETTER

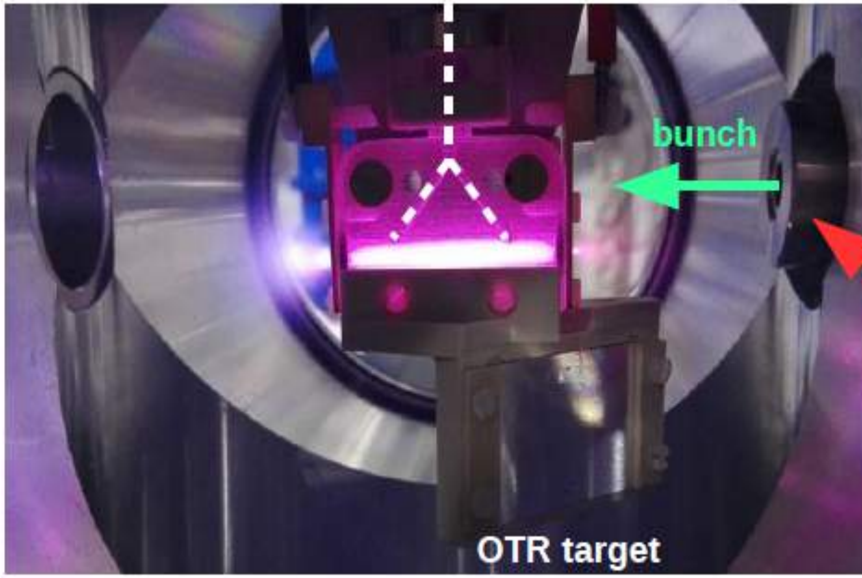
doi:10.1038/nature16525

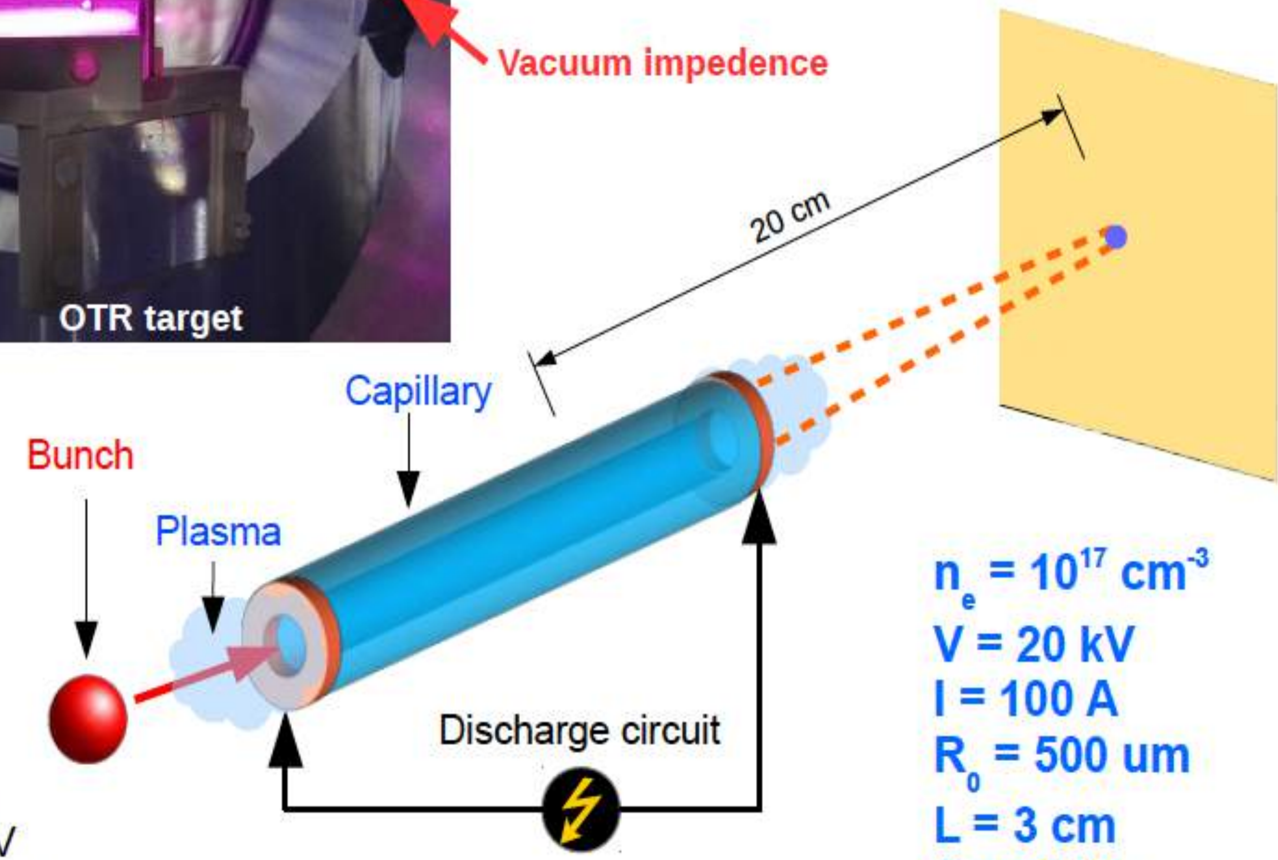
Multistage coupling of independent laser–plasma accelerators

S. Steinke[1], J. van Tilborg[1], C. Benedetti[1], C. G. R. Geddes[1], C. B. Schroeder[1], J. Daniels[1,3], K. K. Swanson[1,2], A. J. Gonsalves[1], K. Nakamura[1], N. H. Matlis[1], B. H. Shaw[1,2], E. Esarey[1] & W. P. Leemans[1,2]



Experimental layout

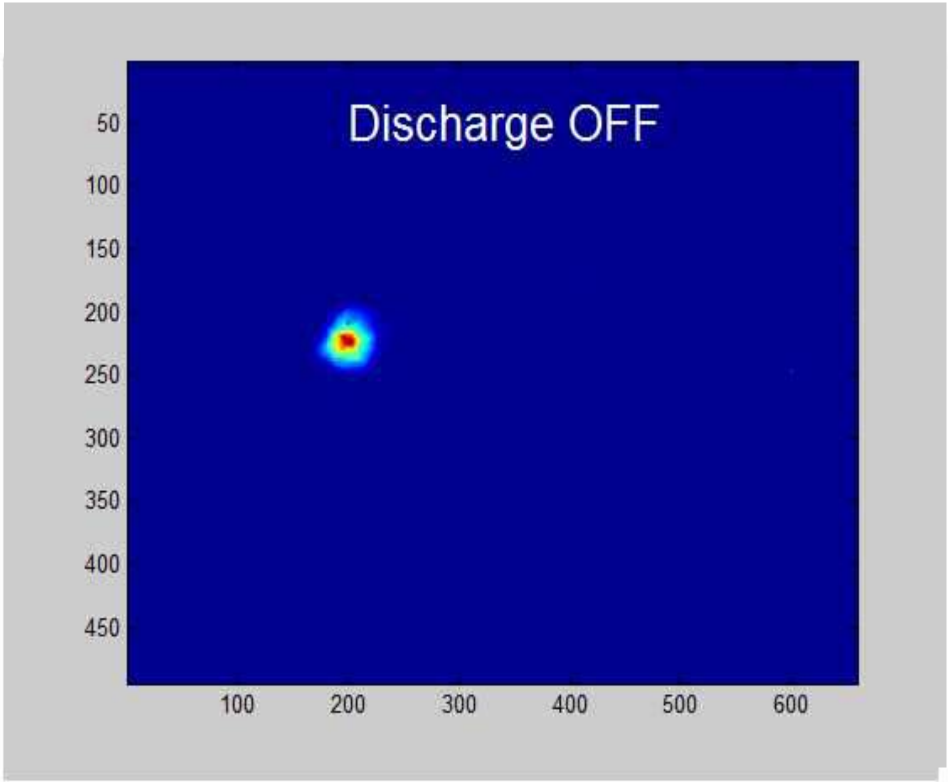


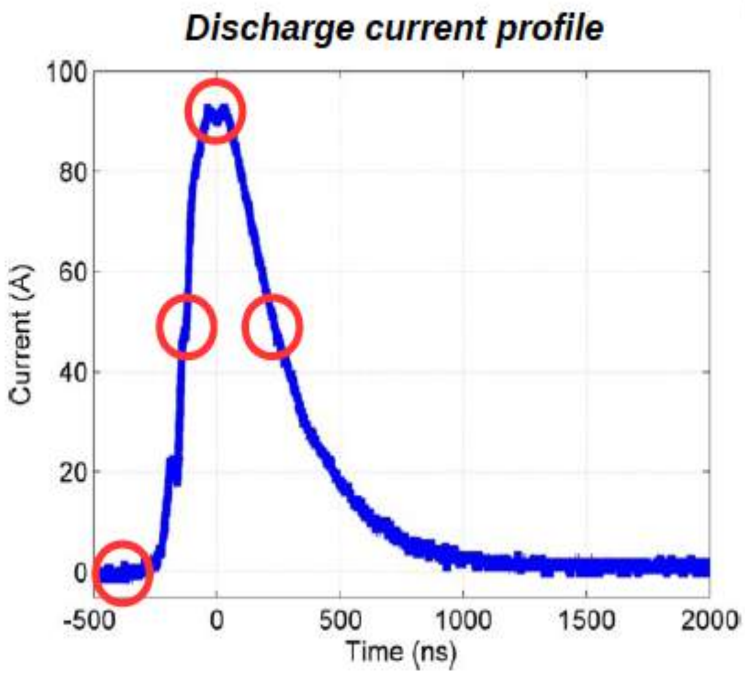


50 pC
1 ps
130 um
120 MeV
1 mm mrad

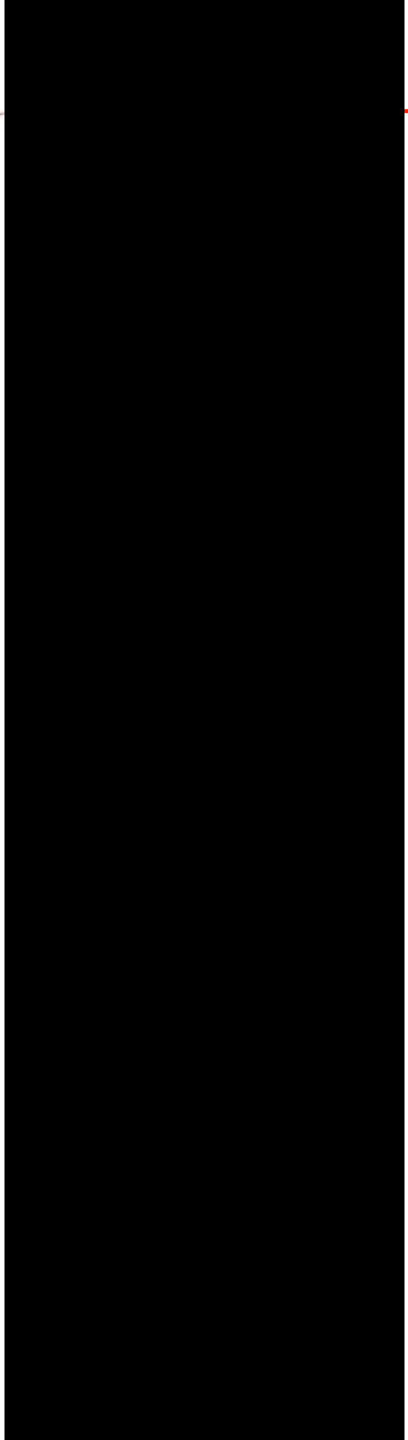
$n_e = 10^{17}$ cm^{-3}
V = 20 kV
I = 100 A
R_0 = 500 um
L = 3 cm
Sapphire

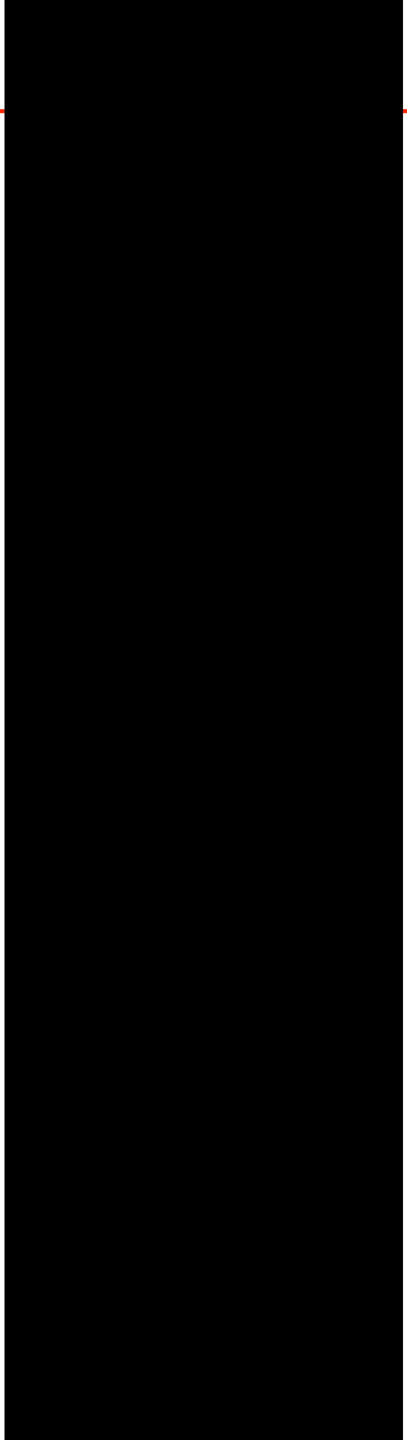
Preliminary results





velocity of plasma



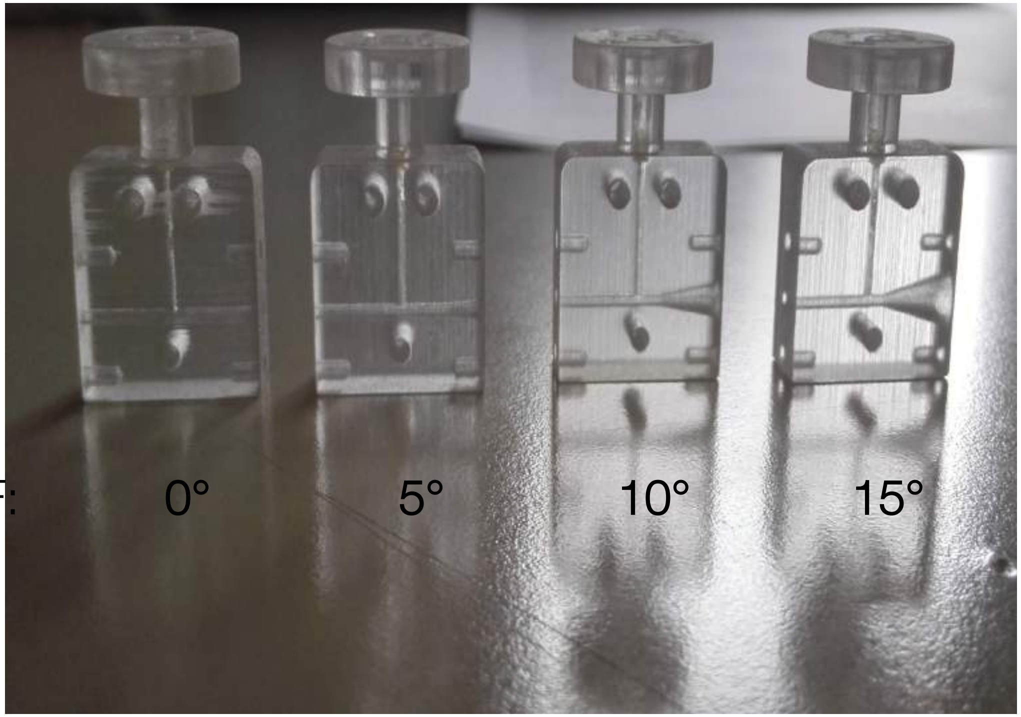


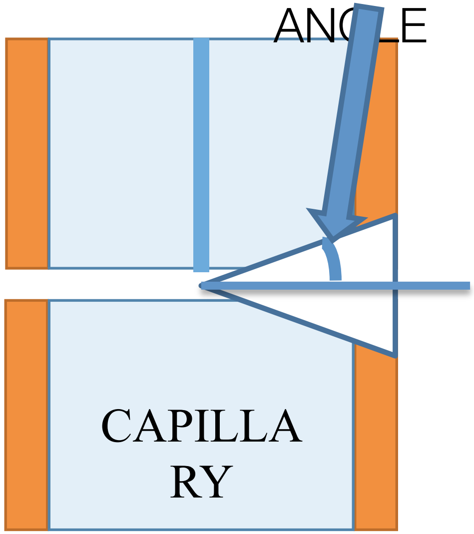
Delay: 20 images separated by 100 ns = 2 µs
Gate: 10 ns
Area: 1000 x 500 pixel

Tapered capillaries

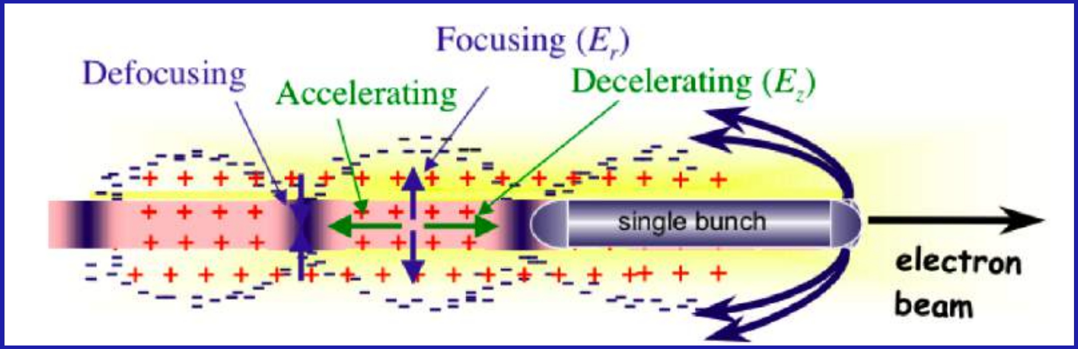
Local control of the plasma density is required to match the laser/electron beam into the plasma.
Tapering the capillary diameter is the easiest way to change locally the density.

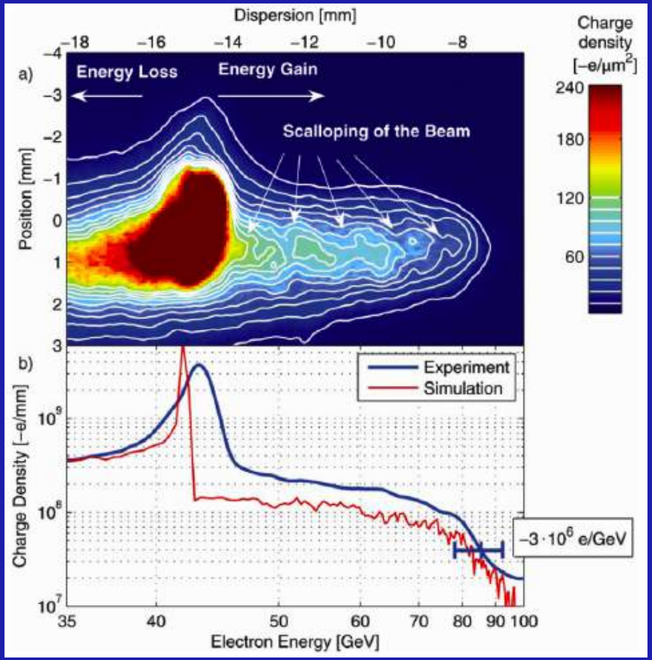
TAPERING OF:



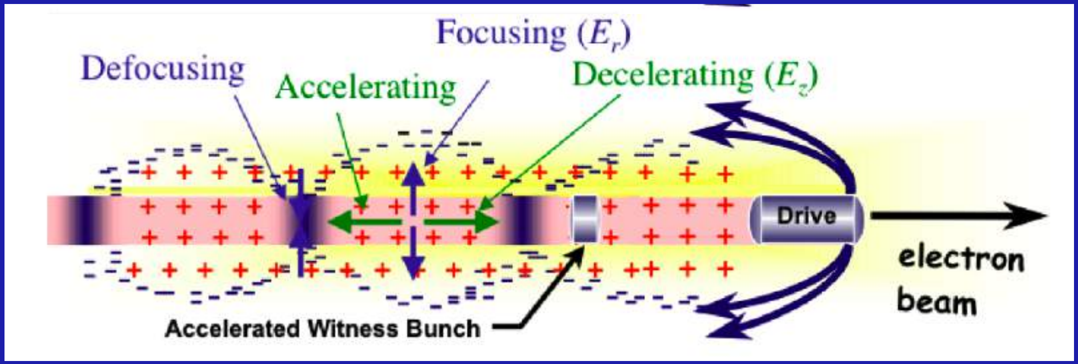


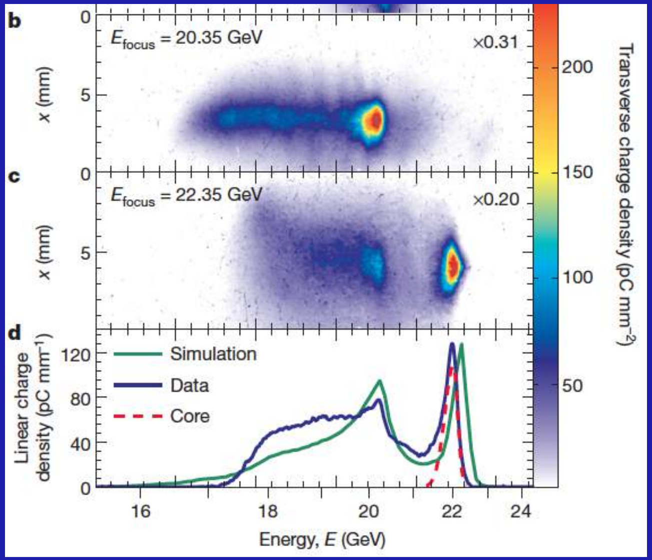
Wake Field Acceleration 2
Beam Driven
PWFA





Blumenfeld, I. et al. *Energy doubling of 42 GeV electrons in a metre-scale plasma wakefield accelerator*. **Nature** 445, 741–744 (2007).



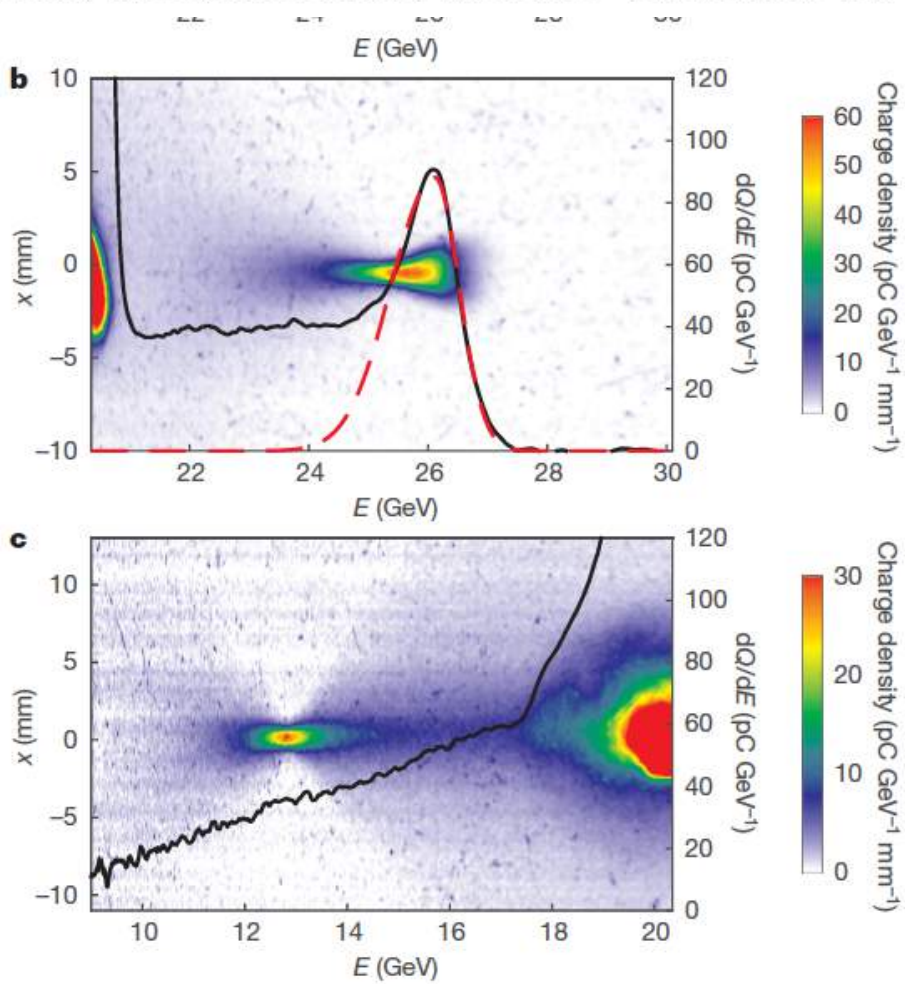


Litos, M. et al. *High-efficiency acceleration of an electron beam in a plasma wakefield accelerator*. **Nature** 515, 92–95 (2014).

doi:10.1038/nature14890

Multi-gigaelectronvolt acceleration of positrons in a self-loaded plasma wakefield

S. Corde[1,2], E. Adli[1,3], J. M. Allen[1], W. An[4,5], C. I. Clarke[1], C. E. Clayton[4], J. P. Delahaye[1], J. Frederico[1], S. Gessner[1], S. Z. Green[1], M. J. Hogan[1], C. Joshi[4], N. Lipkowitz[1], M. Litos[1], W. Lu[6], K. A. Marsh[4], W. B. Mori[4,5], M. Schmeltz[1], N. Vafaei-Najafabadi[4], D. Walz[1], V. Yakimenko[1] & G. Yocky[1]



CONCEPTUAL DESIGN OF THE DRIVE BEAM FOR A PWFA-LC*

S. Pei[#], M. J. Hogan, T. O. Raubenheimer, A. Seryi, SLAC, CA 94025, U.S.A.
H. H. Braun, R. Corsini, J. P. Delahaye, CERN, Geneva

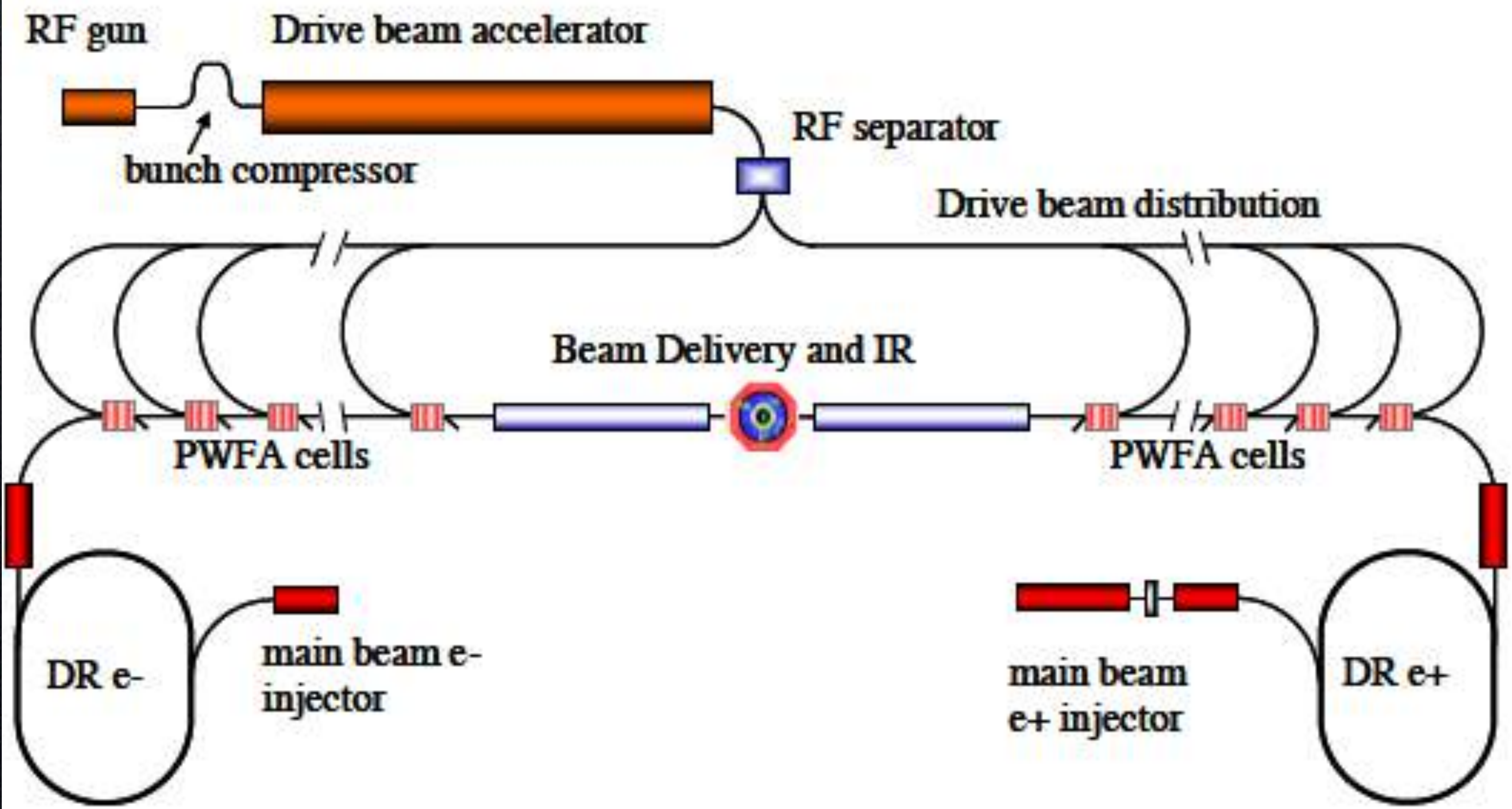


Fig. 1: Concept for a multi-stage PWFA Linear Collider.

Table 1: Key Parameters of the Conceptual Multi-Stage PWFA-based Linear Collider

Main beam: bunch population, bunches per train, rate	1×10^{10}, 125, 100 Hz
Total power of two main beams	20 MW
Drive beam: energy, peak current and active pulse length	25 GeV, 2.3 A, 10 μs
Average power of the drive beam	58 MW
Plasma density, accelerating gradient and plasma cell length	1×10^{17}cm^{-3}, 25 GV/m, 1 m
Power transfer efficiency drive beam=>plasma =>main beam	35%
Efficiency: Wall plug=>RF=>drive beam	50% × 90% = 45%
Overall efficiency and wall plug power for acceleration	15.7%, 127 MW
Site power estimate (with 40MW for other subsystems)	170 MW
Main beam emittances, x, y	2, 0.05 mm-mrad
Main beam sizes at Interaction Point, x, y, z	0.14, 0.0032, 10 μm
Luminosity	3.5×10^{34} cm^{-2}s^{-1}
Luminosity in 1% of energy	1.3×10^{34} cm^{-2}s^{-1}

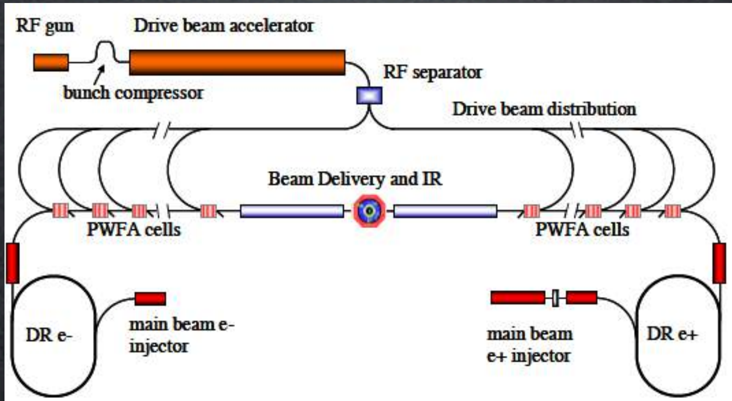


Fig. 1: Concept for a multi-stage PWFA Linear Collider.

ILC – International Linear Collider

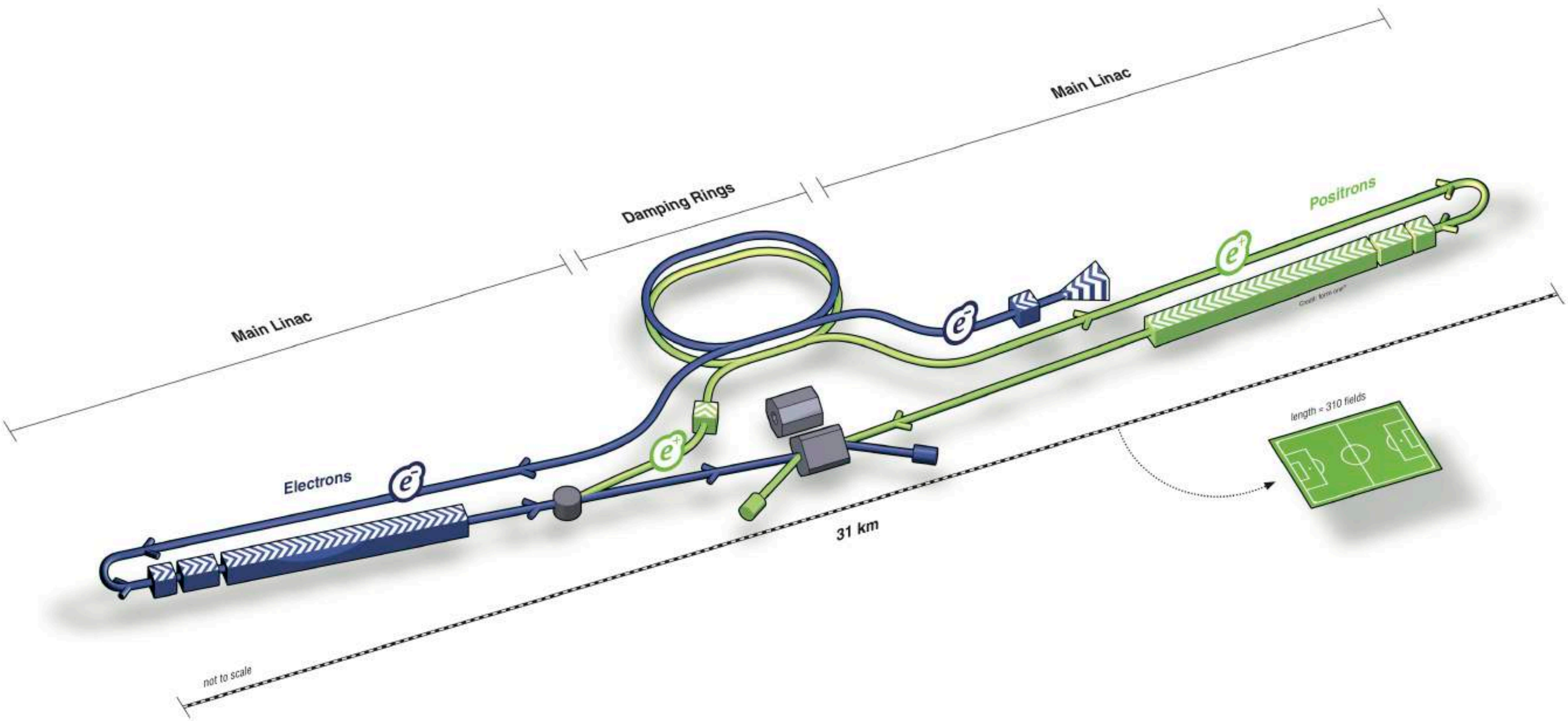


Table 2: ILC energy upgrade by PWFA after-burner

Parameter	Unit	ILC	ILC	ILC + PWFA
Energy (cm)	GeV	500	1000	PFWA = 500 to 1000
Luminosity (per IP)	$10^{34}cm^{-2}s^{-1}$	1.5	4.9	2.6
Peak (1%)Lum(/IP)	$10^{34}cm^{-2}s^{-1}$	0.88	2.2	1.3
# IP	-	1	1	1
Length	km	30	52	30
Power (wall plug)	MW	128	300	175
Lin. Acc. grad.(p/eff)	MV/m	31.5/25	36/30	7600/1000
# particles/bunch	10^{10}	2	1.74	0.66
# bunches/pulse	-	1312	2450	2450
Bunch interval	ns	554	366	366
Pulse repetition rate	Hz	5	4	15
Beam power/beam	MW	5.2	13.8	13.8
Norm Emitt (X/Y)	$10^{-6}/10^{-9}$radm	10/35	10/30	10/30
Sx, Sy, Sz at IP	nm,nm,µm	474/5.9/300	335/2.7/225	286/2.7/20
Crossing angle	mrad	14	14	14
Av # photons	-	1.70	2.0	0.7
δb beam-beam	%	3.89	9.1	9.3
Upsilon	-	0.03	0.09	0.52

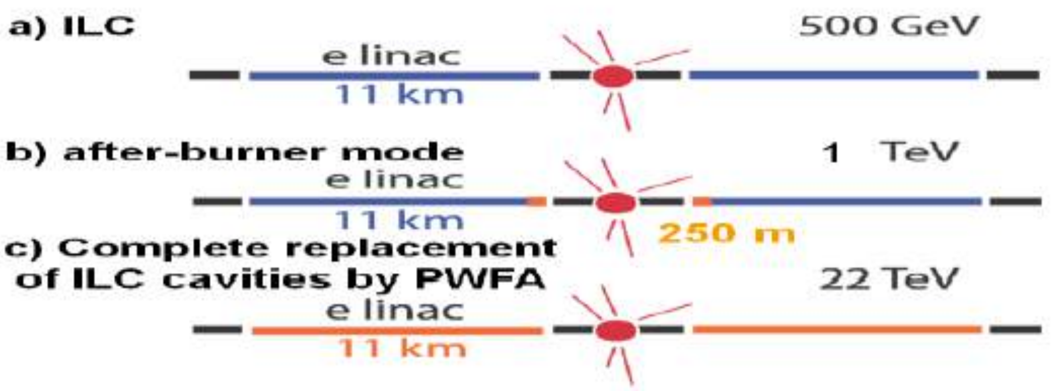


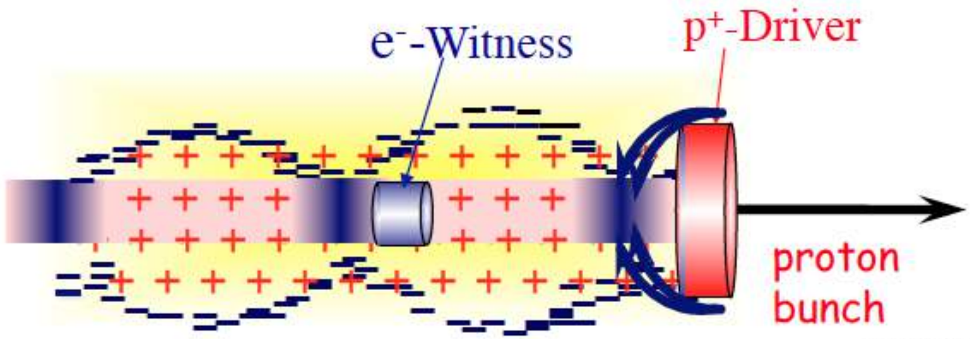
Figure 3: ILC energy upgrade by PWFA technology in the 500 GeV ILC tunnel (a), in after-burner mode (b), in the extreme case of PWFA technology use only (c).

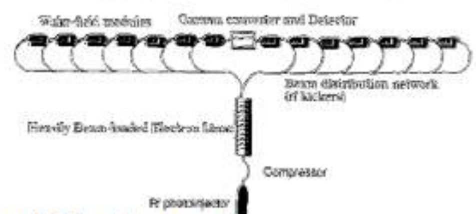
MAX-PLANCK-GESELLSCHAFT

AWAKE

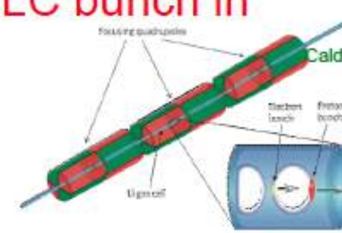
Proton-driven
Plasma Wakefield Acceleration
Collaboration:
Accelerating e^- on the wake of a p^+ bunch

WHY p+-DRIVEN PWFA?





- ✧ILC, 0.5TeV bunch with $2\times10^{10}e^-$ ~1.6kJ
- ✧SLAC, 20GeV bunch with $2\times10^{10}e^-$ ~60J
- ✧SLAC-like driver for staging (FACET= 1 stage, collider 10^+ stages)
- ✧SPS, 400GeV bunch with $10^{11}p^+$ ~6.4kJ
  LHC, 7TeV bunch with $10^{11}p^+$ ~112kJ
- ✧A single SPS or LHC bunch could produce an ILC bunch in a single PWFA stage!
- ✧Large average gradient! (≥1GeV/m, 100's m)

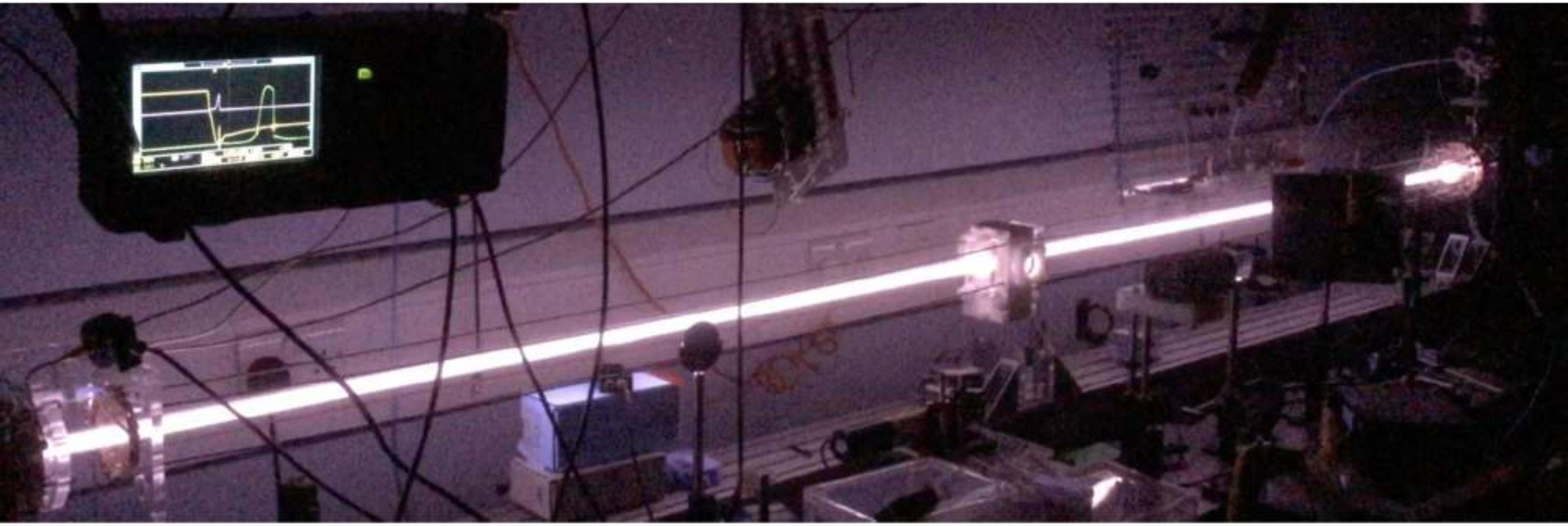


Caldwell, Nat. Phys. 5, 363, (2009)

P. Muggli, 06/04/2013, EAAC 2103

Discharge configuration II

preliminary tests with the AWAKE 3 meter test tube at IC - 2016



very promising results

… reliable, low jitter plasma formation

scalability of electric circuit for plasmas > 10 m seem achievable…

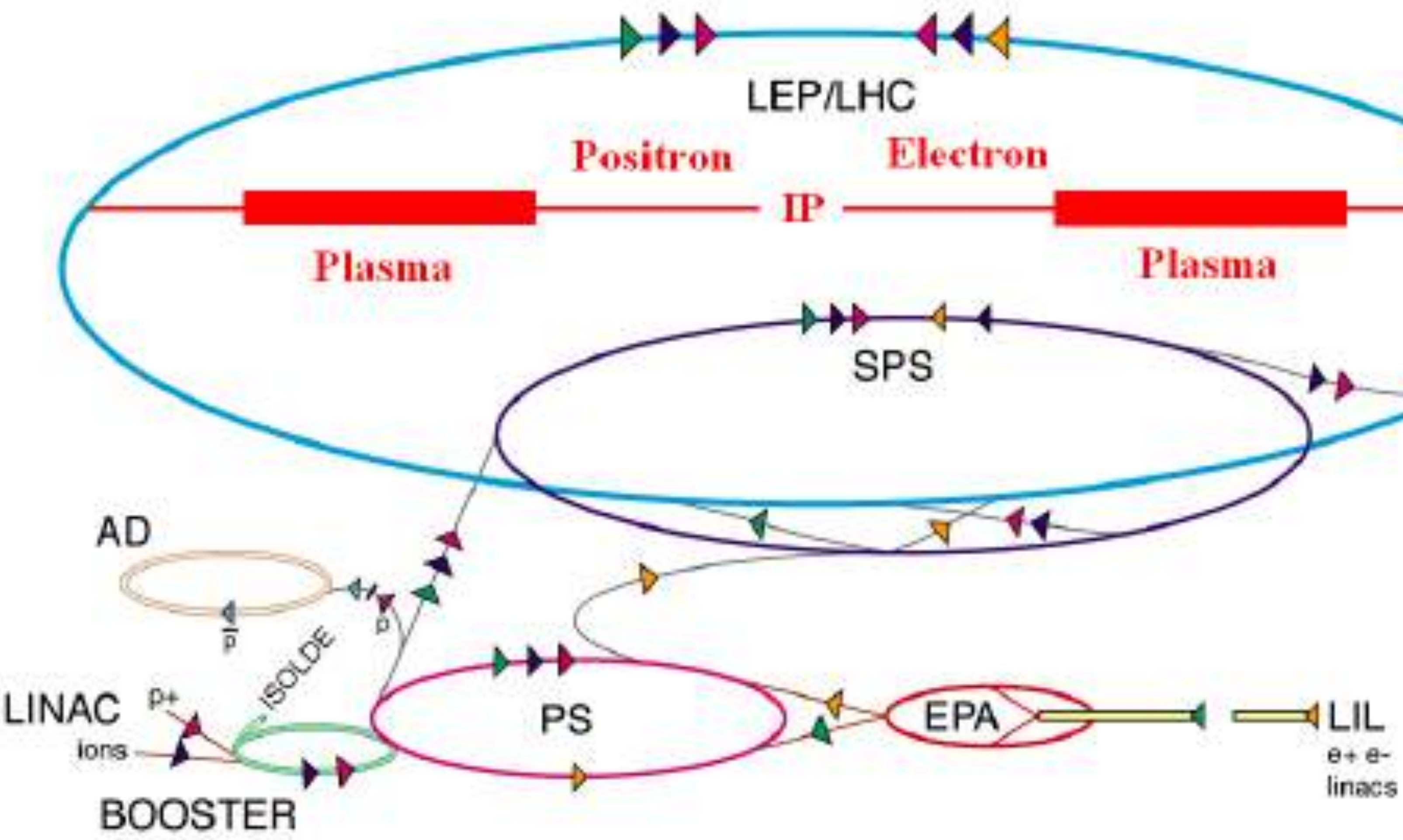


Figure 1: Schematic layout of a 2 TeV CoM electron-positron linear collider based on a modulated proton-driven plasma wakefield acceleration.

Protons and Ions

Protons and ions are too slow to catch the wave - only indirect acceleration via electrons

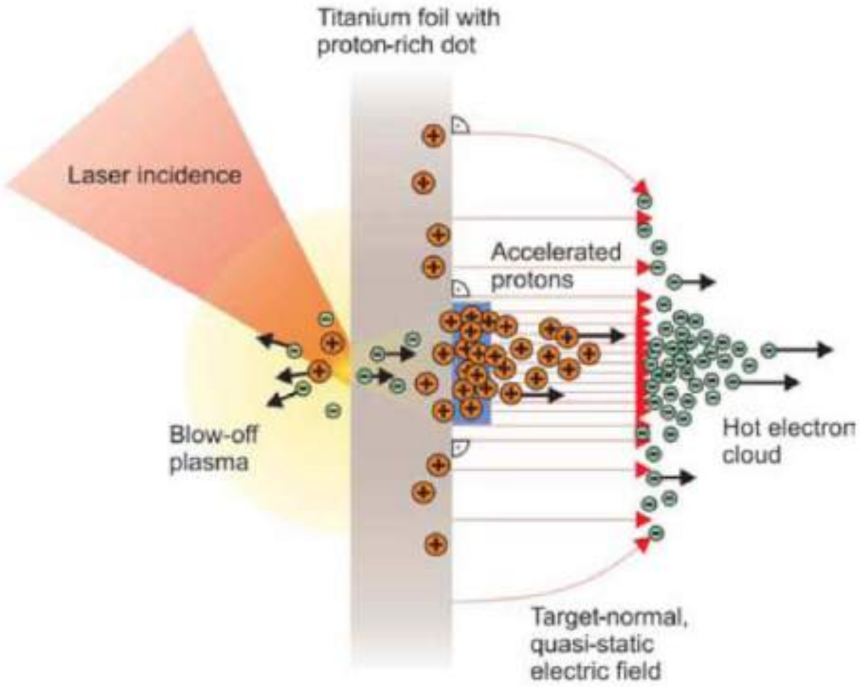
Laser Driven Acceleration of Protons

- Direct acceleration in laser field > 10^{25} W/cm² far beyond current lasers
- Plasma wakefield phase velocity too fast for protons & ions
- → only indirect ways

Need typically:
50 J 500 fs → 100 TW
30 μm radius → 10^{19} W/cm²

Target Normal Sheath Acceleration
"best understood" candidate:

- laser creates blow-off plasma on front surface
- backside expansion accelerated electrons ionize hydrogen
- hot electrons create electric field (by space charge)
- causes acceleration of protons (electrons slowing down – end of acceleration)
- neutralized bunch of comoving p and e generated



3 Steps towards a reliable PWA

① High Gradient – Low e- Beam Quality

② High e+e- Beam Quality – Low Gradient

③ High e+e- Beam Quality - High Gradient

EuPRAXIA

EUROPEAN
PLASMA RESEARCH
ACCELERATOR WITH
EXCELLENCE IN
APPLICATIONS

EuPRAXIA Design Study

Approved as HORIZON 2020 INFRADEV, 4 years, 3 M€

Coordinator: Ralph Assmann (DESY)

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

Motivations

Horizon2020

PRESENT EXPERIMENTS

Demonstrating **100 GV/m** routinely

Demonstrating **GeV** electron beams

Demonstrating basic **quality**

EuPRAXIA INFRASTRUCTURE

Engineering a high quality, compact plasma accelerator

5 GeV electron beam for the 2020's

Demonstrating user readiness

Pilot users from FEL, HEP, medicine, ...

PRODUCTION FACILITIES

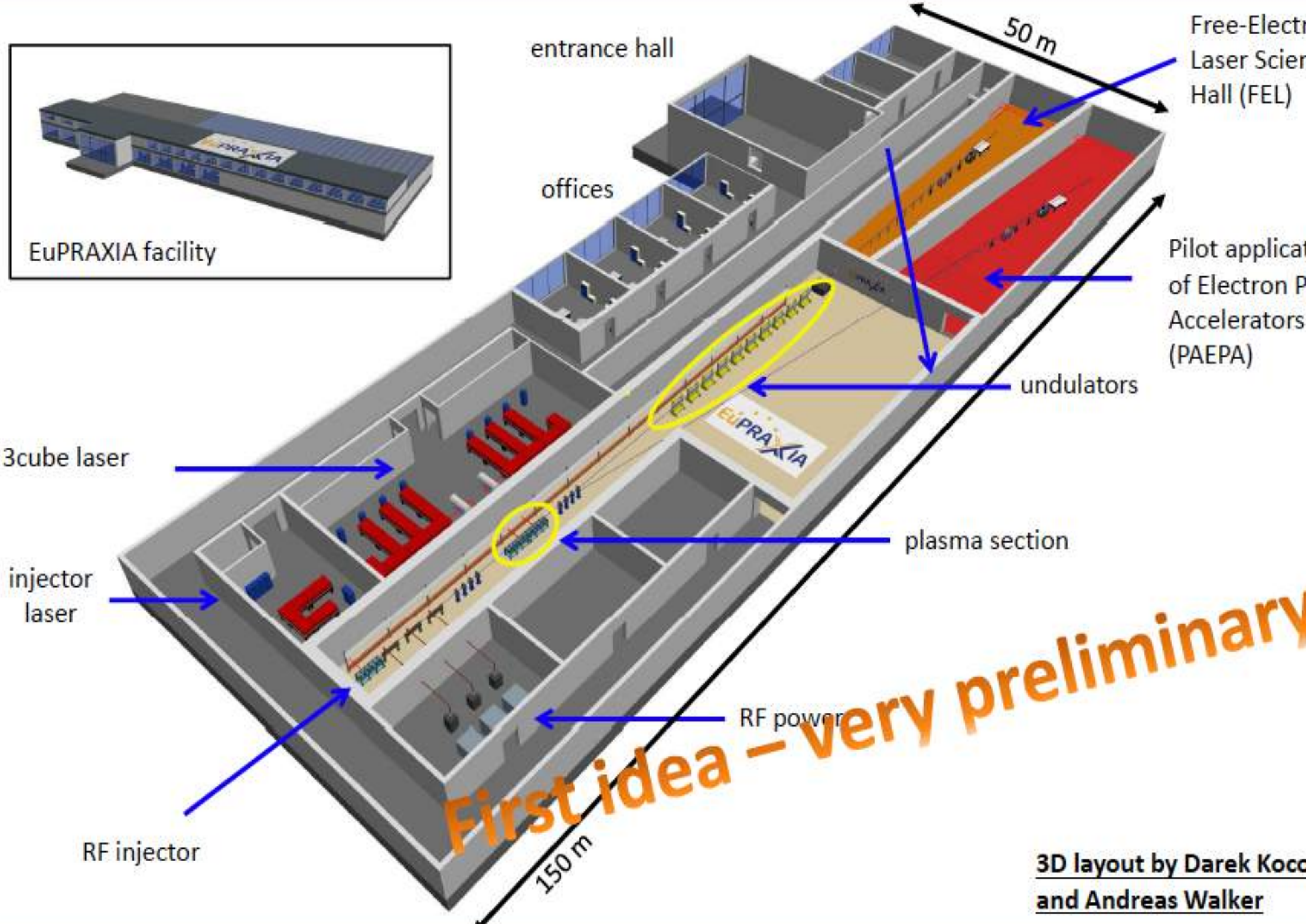
Plasma-based **linear collider** in 2040's

Plasma-based **FEL** in 2030's

Medical, industrial applications soon

Courtesy R. Assmann

draft of facility layout



3D layout by Darek Kocon and Andreas Walker

EuPRAXIA

Participating Institutions

16 beneficiaries, 16 associated partners

Horizon2020

Status 8/2016

Associated Partners

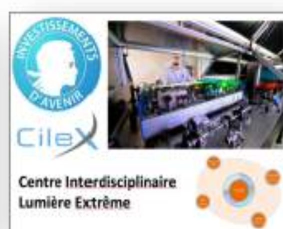
(as of August 2016)

1. **JUS** Jiao Tong-University Shanghai
2. **TUB** Tsingua University Beijing
3. **ELI-B** Extreme Light Infrastructure-Beams
4. **PHLAM** Lille University
5. **HIJ** Helmholtz Institute Jena
6. **HZDR** Helmholtz-Zentrum Dresden-Rossendorf
7. **LMU** Ludwig-Maximilians-Universität München
8. **WIGNER** Wigner Research Centre of the Hungarian Academy of Science
9. **CERN** European Organization for Nuclear Research
10. **KPSI/JAEA** Kansai Photon Science Institute, Japan Atomic Energy Agency
11. **OU** Osaka University
12. **RSC** RIKEN SPring-8 Center
13. **LU** Lund University
14. **CASE** Center for Accelerator Science and Education at Stony Brook U & BNL
15. **LBNL** Lawrence Berkeley National Laboratory
16. **UCLA** University of California, Los Angeles

Location of possible sites within EU

EuPRAXIA site studies:

- Design study is site independent
- Five possible sites have been discussed so far
- We invite the suggestions of additional sites

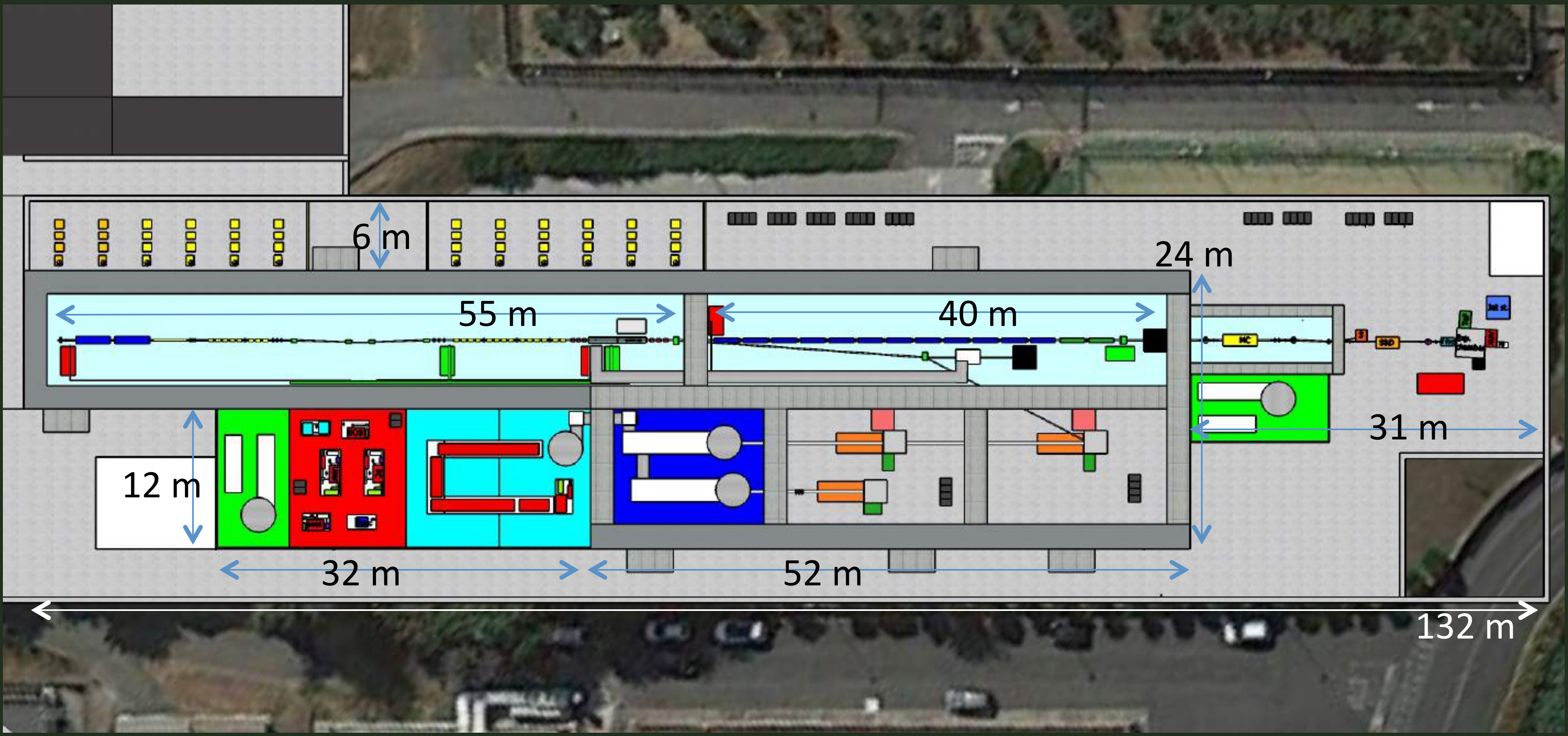


Central Laser Facility
Didcot, United Kingdom

Eli Beamlines
Prague, Czech Republic

EuPRAXIA@SPARC_LAB

- Candidate LNF to host EuPRAXIA (1-5 GeV)
- FEL user facility (1 GeV – 3nm)
- Advanced Accelerator Test facility (LC) + CERN



- 500 MeV by RF Linac + 500 MeV by Plasma (LWFA or PWFA)
- 1 GeV by X-band RF Linac only
- Final goal compact 5 GeV accelerator

Conclusions

Short term perspective (< 10 years):

Relevant applications in medicine, radiobology, material science

Compact FEL with moderate average power (10 Hz system)

Designing future accelerators

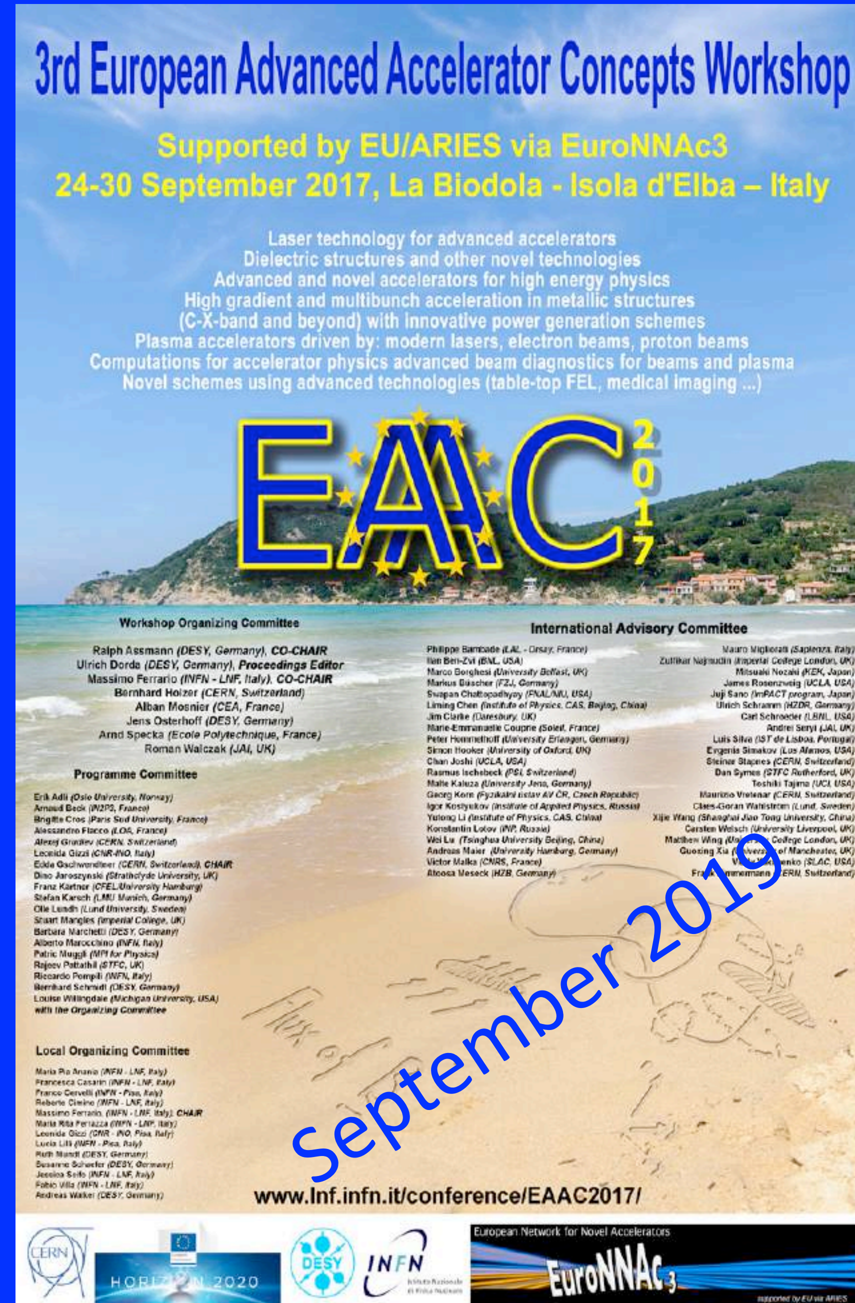
Compact X ray source (Thomson, Compton, Betatron, or FEL)

mJ-kHz laser plasma accelerators for fs electron diffraction (J. Faure' talk)

Long term possible applications

High energy physics that will depend on the laser technology evolution, on laser to electron transfer efficiency, on progress of multistage design, guiding over logn distance (energy dissipation, robustness), acceleration of positron, etc...


The CERN Accelerator School is organizing a course on
PLASMA WAKE ACCELERATION
23-29 November, 2014
CERN, Geneva, Switzerland
The course will be of interest to staff and students in accelerator laboratories, university departments and companies working in or having an interest in the field of new acceleration techniques.
Following introductory lectures on plasma and laser physics, the course will cover the different components of a plasma wake accelerator and plasma beam systems. An overview of the experimental studies, diagnostic tools and state of the art wake acceleration facilities, both present and planned, will complement the theoretical part. Topical seminars and a visit of CERN will complete the programme.
Spring 2019
Beatwave
Contact: Barbara Strasser
CERN Accelerator School
CH - 1211 Geneva 23
Tel.: +41 22 767 8607 / Fax: +41 22 767 5460
email: barbara.strasser@cern.ch
http://cas.web.cern.ch/cas
CERN


3rd European Advanced Accelerator Concepts Workshop
Supported by EU/ARIES via EuroNNAc3
24-30 September 2017, La Biodola - Isola d'Elba – Italy
Laser technology for advanced accelerators
Dielectric structures and other novel technologies
Advanced and novel accelerators for high energy physics
High gradient and multibunch acceleration in metallic structures
(C-X-band and beyond) with innovative power generation schemes
Plasma accelerators driven by: modern lasers, electron beams, proton beams
Computations for accelerator physics advanced beam diagnostics for beams and plasma
Novel schemes using advanced technologies (table-top FEL, medical imaging ...)
EAAC 2017
Workshop Organizing Committee
Ralph Assmann (DESY, Germany), CO-CHAIR
Ulrich Dorda (DESY, Germany), Proceedings Editor
Massimo Ferrario (INFN - LNF, Italy), CO-CHAIR
Bernhard Holzer (CERN, Switzerland)
Alban Mosnier (CEA, France)
Jens Osterhoff (DESY, Germany)
Arnd Specka (Ecole Polytechnique, France)
Roman Walczak (JAI, UK)
International Advisory Committee
Programme Committee
Local Organizing Committee
September 2019
www.lnf.infn.it/conference/EAAC2017/
CERN
HORIZON 2020
DESY
INFN
European Network for Novel Accelerators
EuroNNAc3


4rth EAAC 15-20 September, 2019
Isola d’Elba
TALKS
DINNER
BREAKFAST
COFFEE
LUNCH
DISCUSSIONS
WAVE-BREAKING