Introduzione alla Fisica degli Acceleratori di Particelle 2

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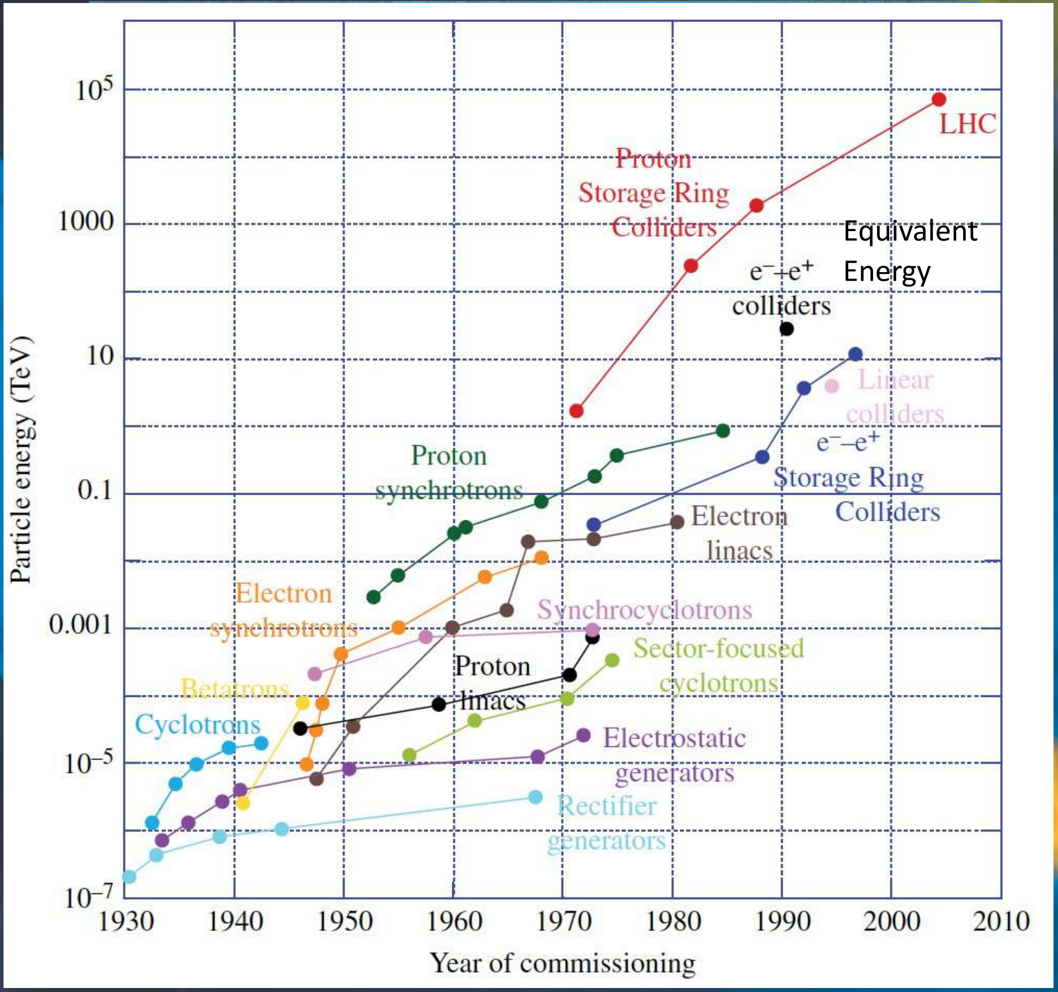
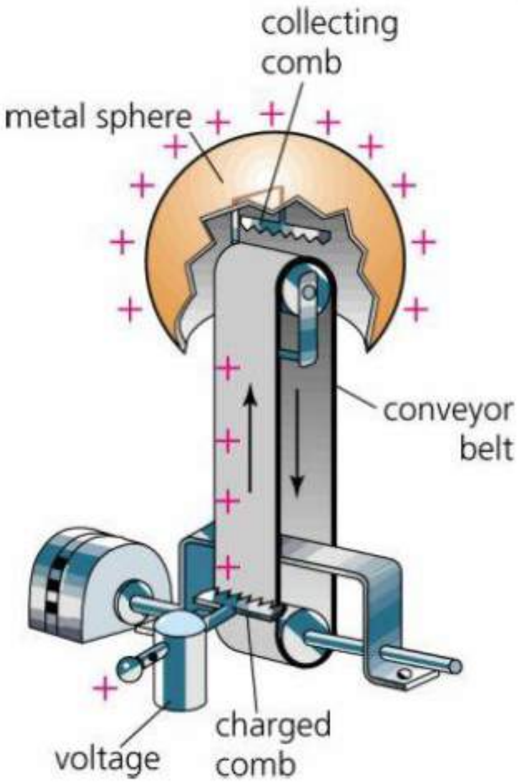
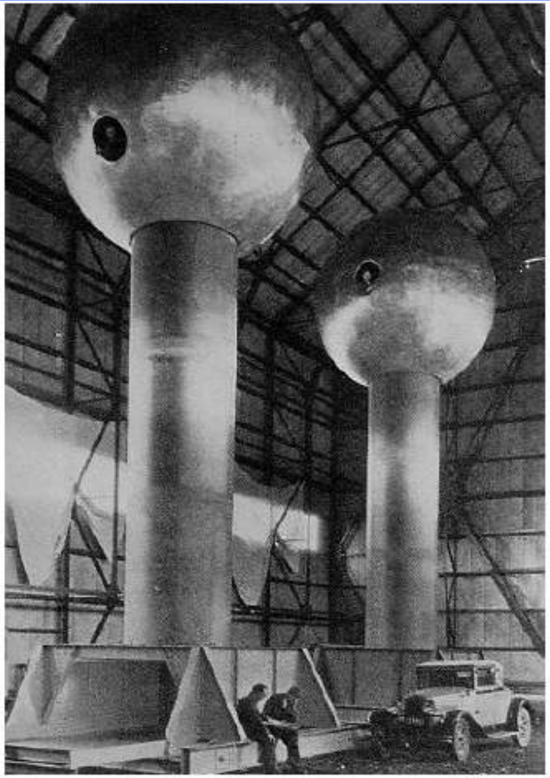


Energy of colliders is plotted in terms of the laboratory energy of particles colliding with a proton at rest to reach the same center of mass energy.

Electrostatic Accelerator: Van de Graff



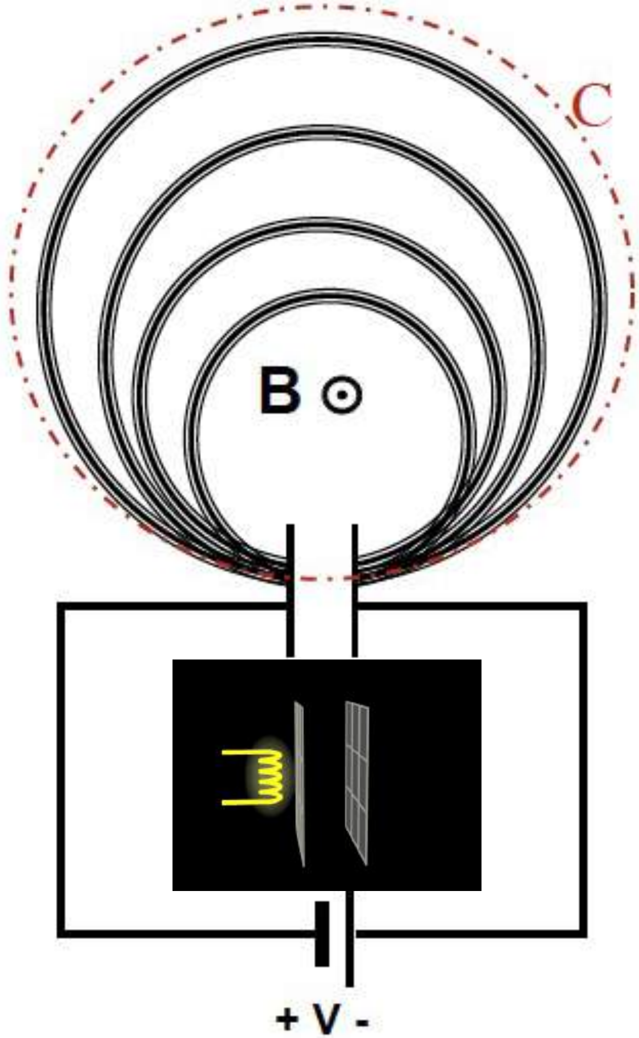


7 MV Van de Graaf at MIT
(1933)

R.J. Van de Graaf

- Electric charges are transported mechanically on an insulating belt
- Stable, continuous beams, practical limit 10 - 15 MV

Possible Higher energy DC accelerator?



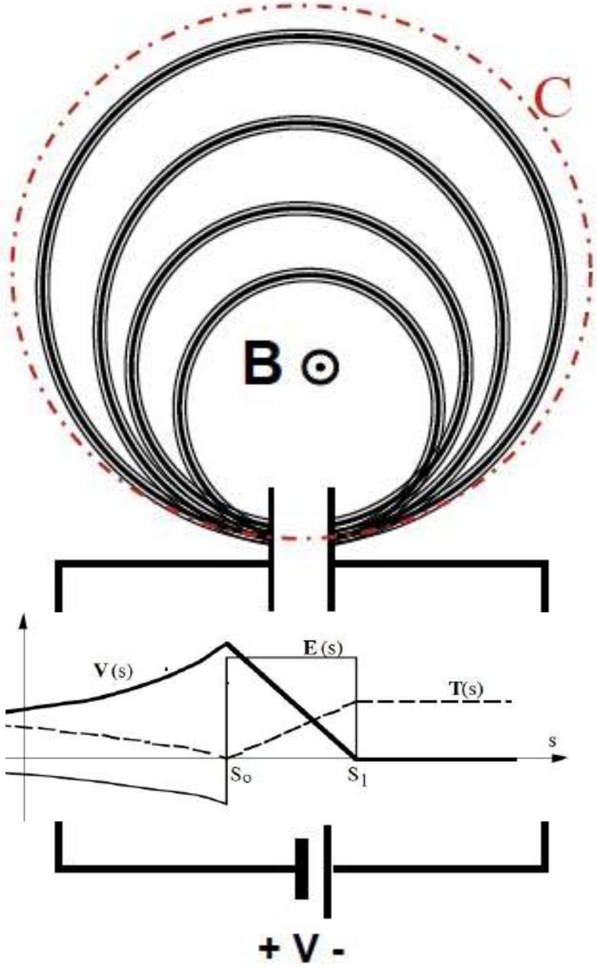
$$F_{Lorentz} = q\,v\,B = F_{centripital} = \frac{mv^2}{\rho}$$

$$\Rightarrow \rho = \frac{mv}{qB} = \frac{p}{qB}$$

$$\rho(\mathrm{m}) = 3.34\left(\frac{p}{1\ \mathrm{GeV/c}}\right)\left(\frac{1}{q}\right)\left(\frac{1\ \mathrm{T}}{B}\right)$$

$T = q\Delta V$

Forbidden by Maxwell



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

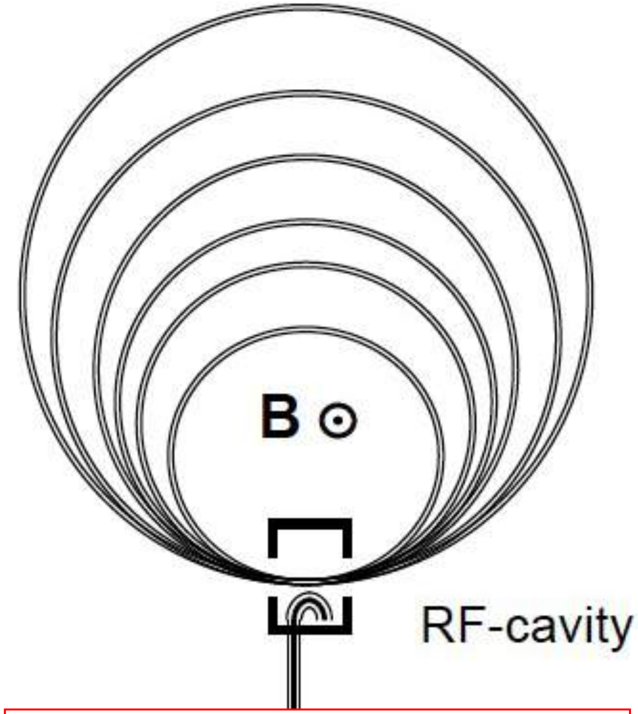
or in integral form

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

∴ There is no acceleration without time-varying magnetic flux

$\Delta V_T = 0$

B can vary in a RF cavity



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

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

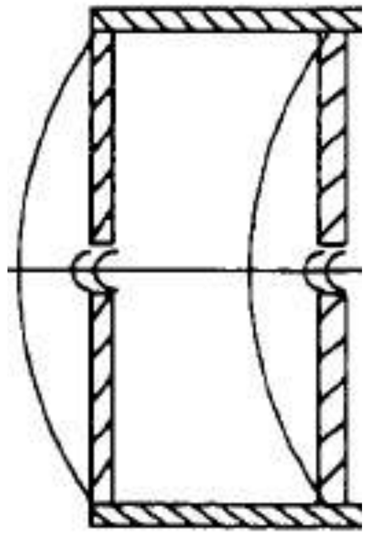
Note that inside the cavity

$dB/dt \neq 0$

However,

Synchronism condition:

$\Delta\tau_{rev} = N/f_{rf}$



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

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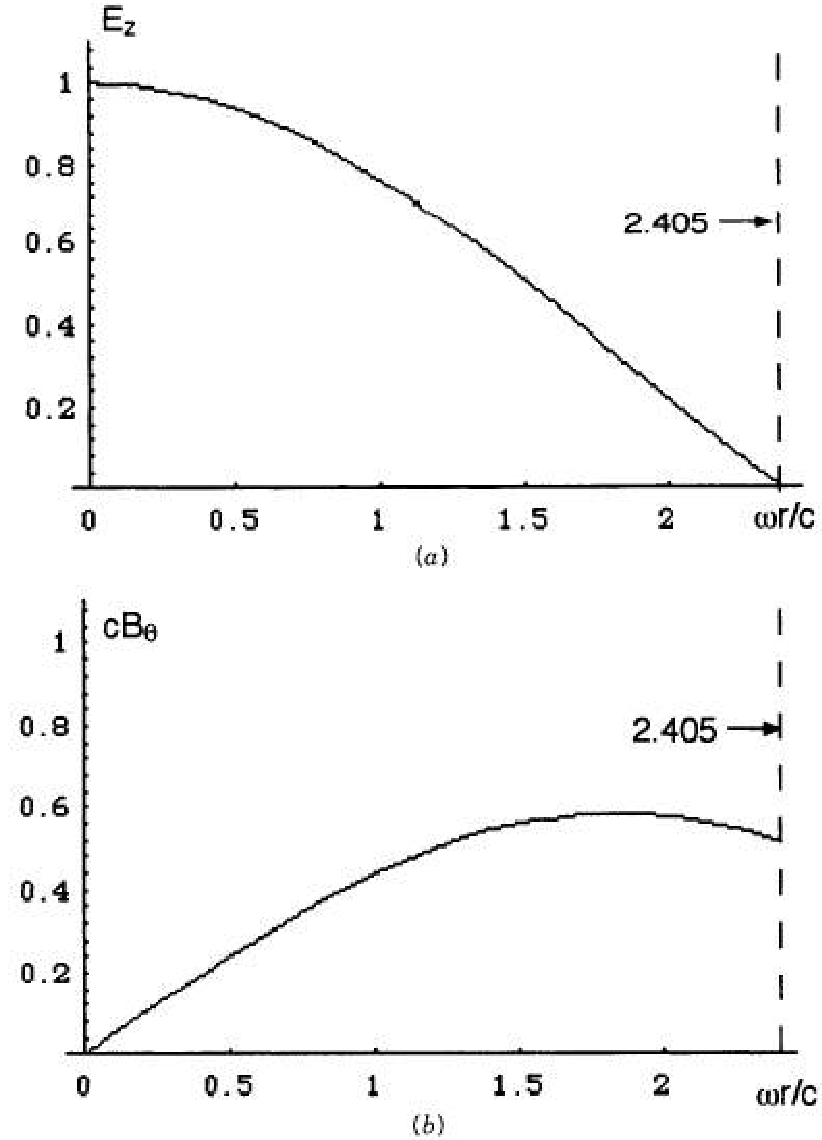
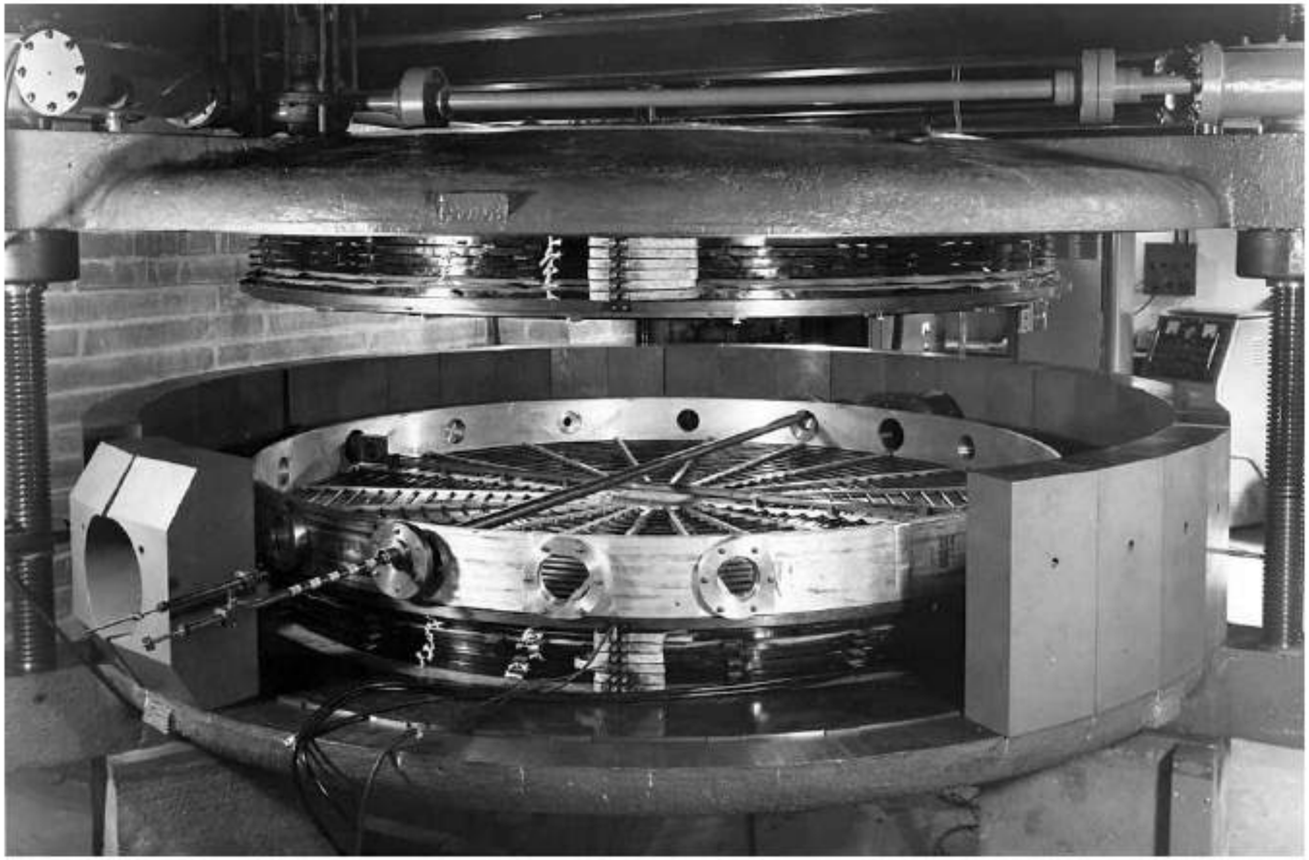
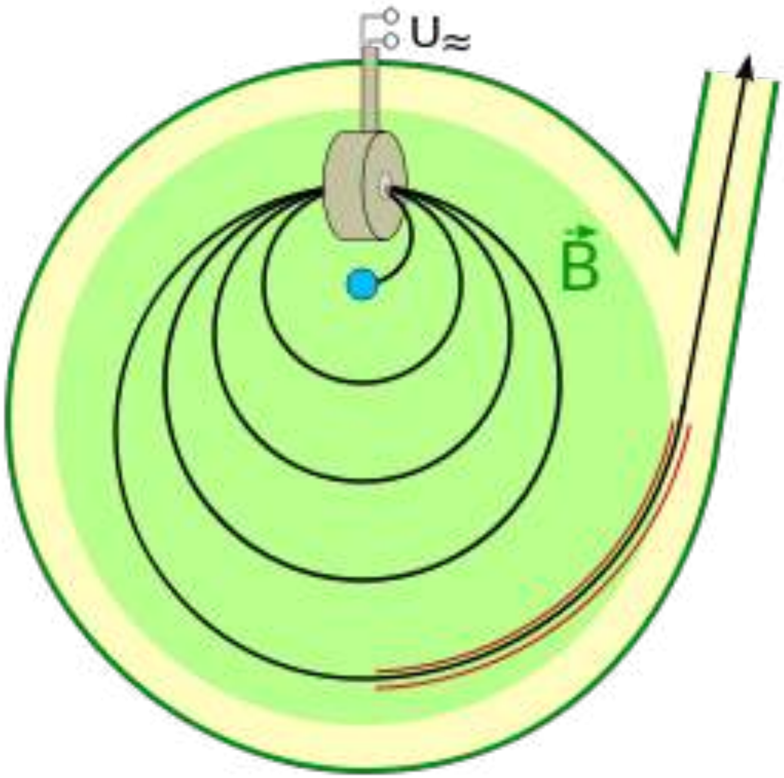


Figure 1.17 Fields for a TM_{010} mode of a cylindrical (pillbox)-cavity resonator.

28 MeV Microtron at HEP Laboratory University College London



Microtron - Synchronization



$$t_i = \frac{2\pi R_i}{v_i}$$

$$ev_i B = m_i \frac{v_i^2}{R_i}$$

$$R_i = \frac{v_i m_i c^2}{ec^2 B} = \frac{v_i}{ec^2 B} E_i$$

$$\Delta t = t_{i+1} - t_i = \frac{2\pi}{ec^2 B}\left(E_{i+1} - E_i\right) = \frac{2\pi}{ec^2 B}\Delta E$$

Energy gain/revolution

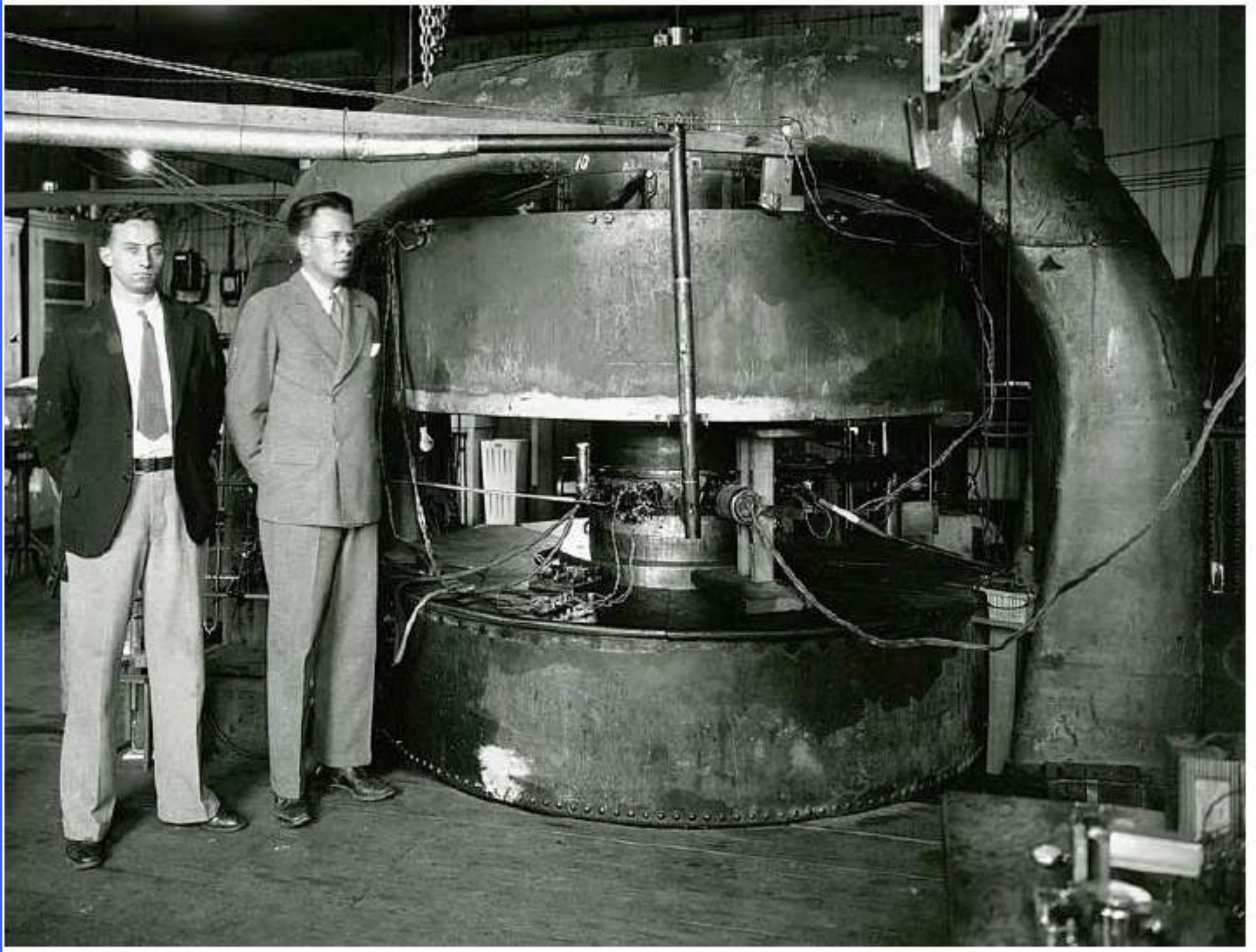
$$\Delta t = t_{i+1} - t_i = \frac{2\pi}{ec^2 B}\left(E_{i+1} - E_i\right) = \frac{2\pi}{ec^2 B}\Delta E$$

$$\Delta t = \frac{k}{\nu_{RF}} = \frac{2\pi}{ec^2 B}\Delta E$$

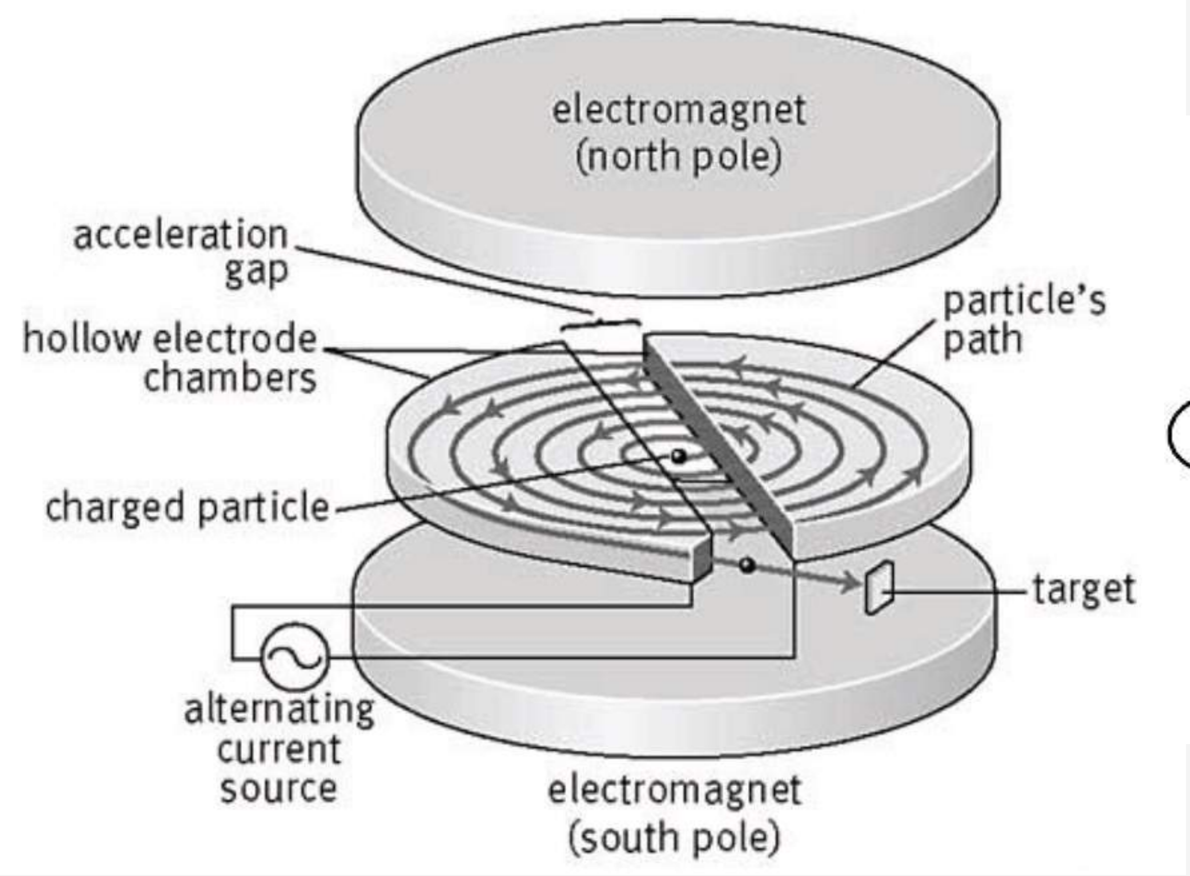
$$\boxed{\Delta E = k\frac{ec^2 B}{2\pi\nu_{RF}}}$$

- In a microtron, due to the electrons' increasing momentum, the particle paths are different for each pass. The time needed for that must be an integer multiple k of the RF period. The allowed energy gain/pass must fulfill the above condition.

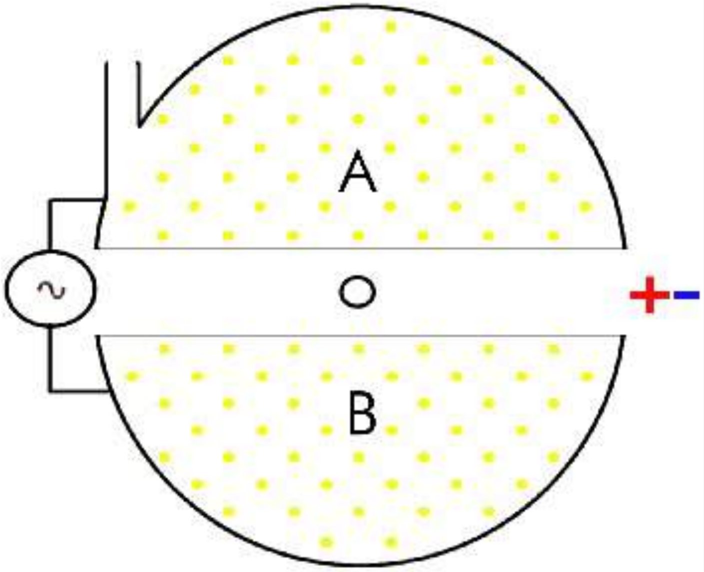
The Lawrence Cyclotron



The Cyclotron concept



$$\rho = \frac{mvc}{qB} = \frac{pc}{qB}$$



$$\omega = 2\pi f = \frac{qB}{\gamma m_0} = \frac{\omega_0}{\gamma}$$

250 MeV proton cyclotron (ACCEL/Varian)

Closed He system

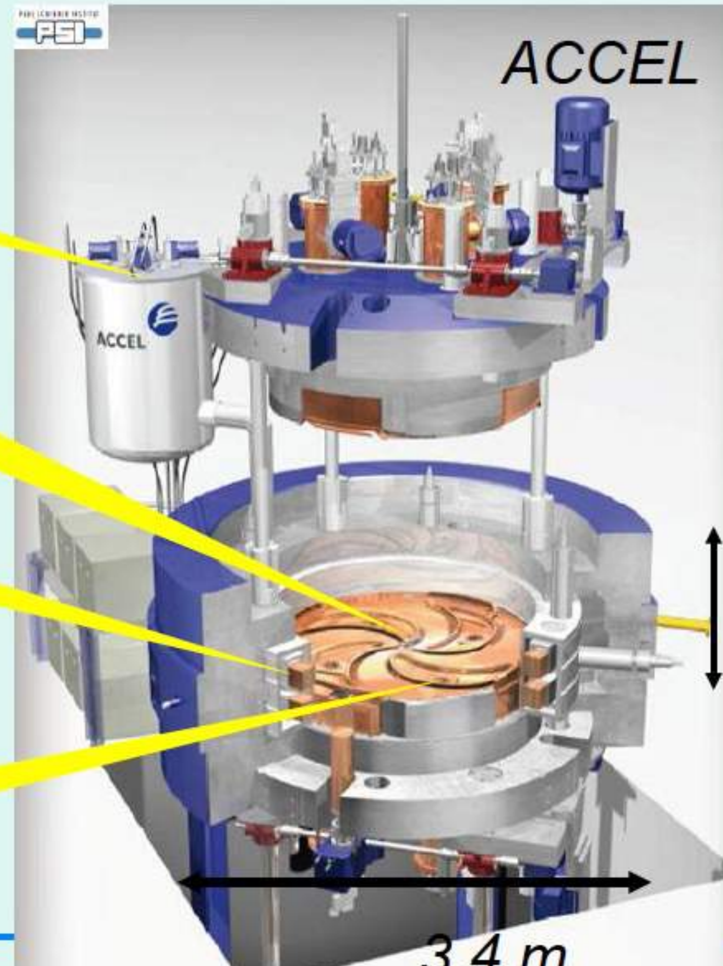
4 x 1.5 W @4K

Proton source

superconducting coils => 2.4 - 3.8 T

4 RF-cavities:

72 MHz ~80 kV

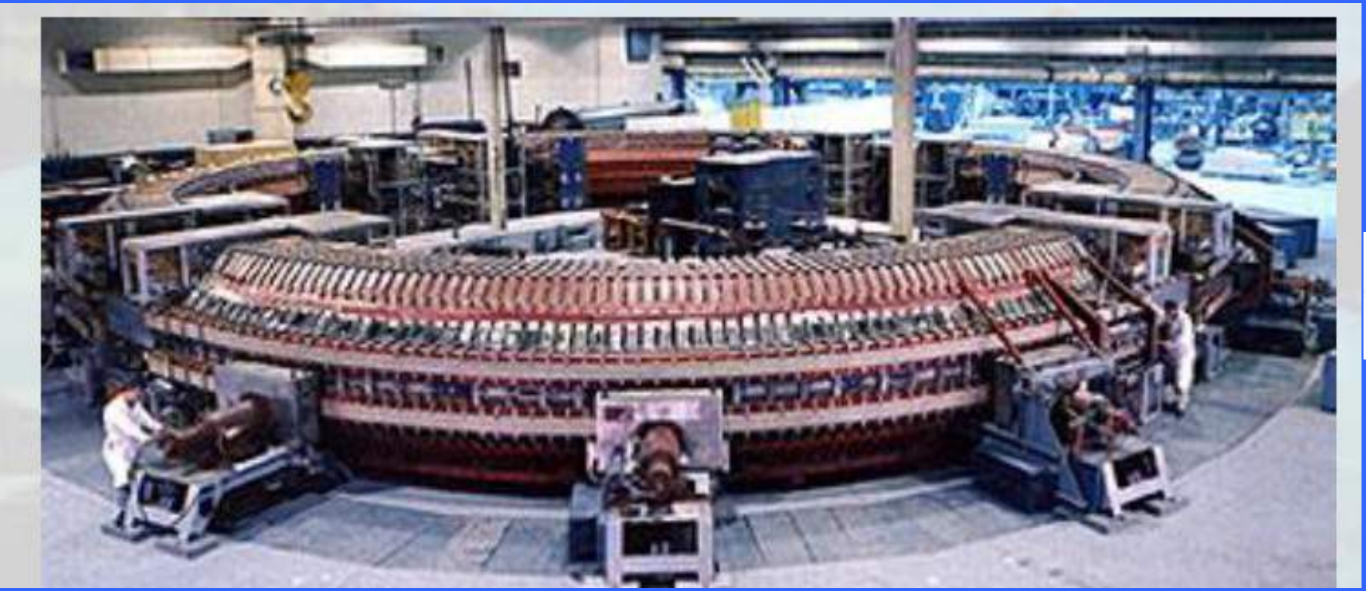


300 kW

90 tons

The Synchrotron concept

The main principle is to keep separated the bending and focusing devices (magnets of various types) from the ones that accelerates (resonant cavities).

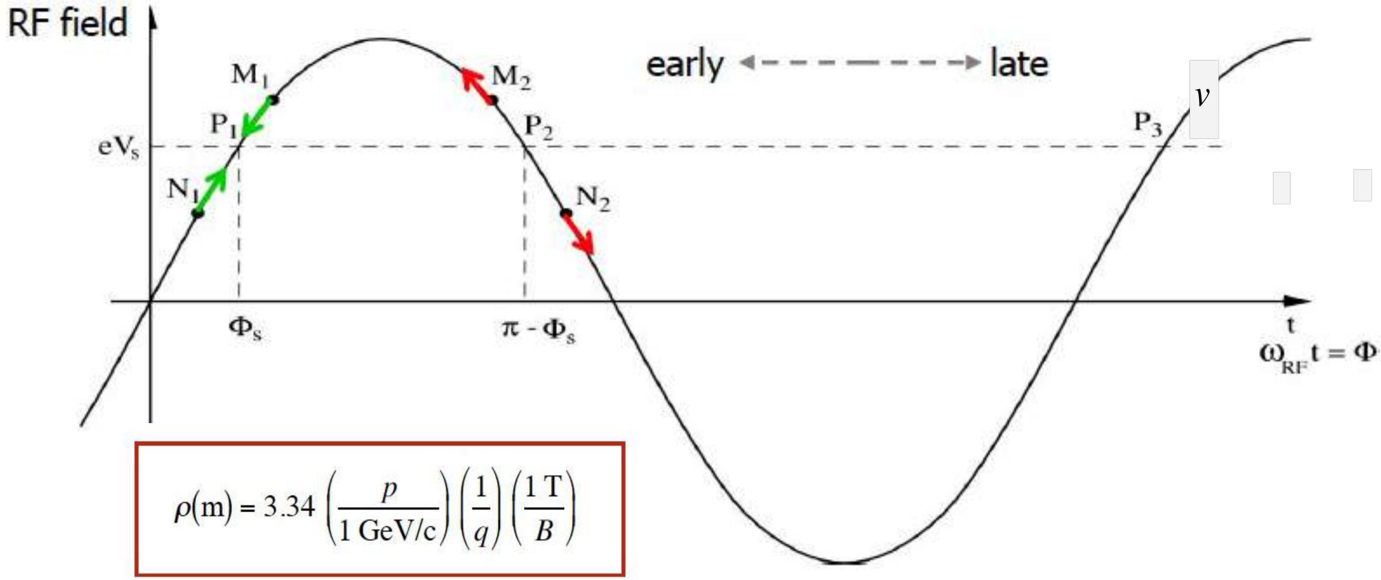


$$\rho = \frac{mvc}{qB} = \frac{pc}{qB}$$

There is main difference from cyclotrons: the particles always ride on the same orbit. Therefore:

- the cavities field must be synchronous with particle crossing and
- the bending magnet field must change in order to keep constant the radius of curvature.

Phase stability and longitudinal focusing

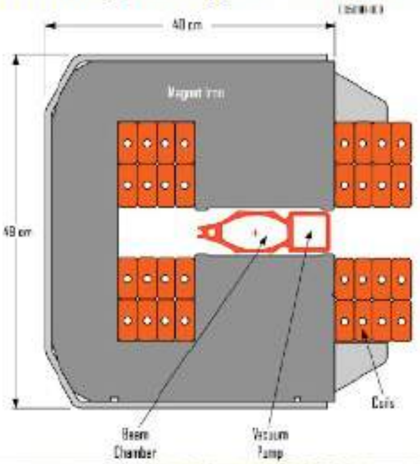


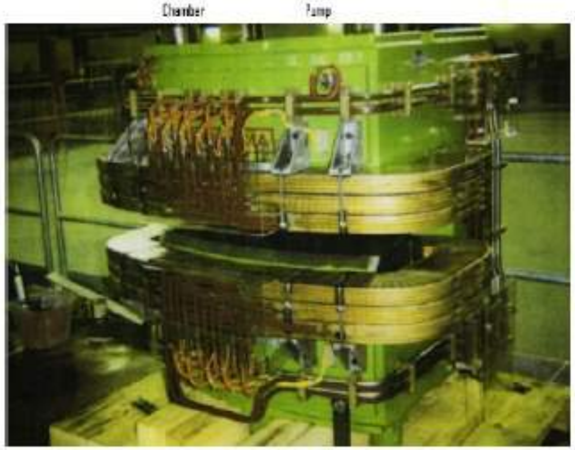
$$\rho(\mathrm{m}) = 3.34 \left(\frac{p}{1\ \mathrm{GeV/c}}\right)\left(\frac{1}{q}\right)\left(\frac{1\ \mathrm{T}}{B}\right)$$

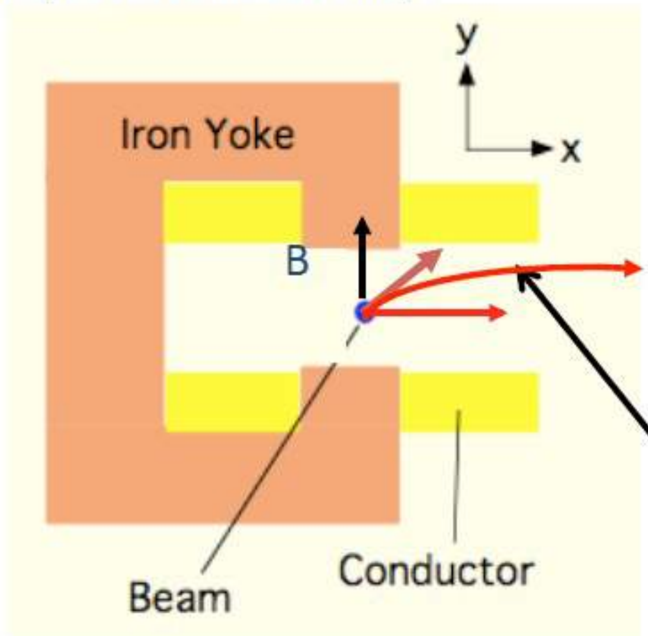
- In a certain energy range, acceleration by RF field results in early arrival of particle at next turn: for stability, this particle should undergo less acceleration
- Operating point P2 is unstable
  - Late particle N2 sees lower acceleration and gets even later
  - Early particle M2 sees higher acceleration and gets even earlier
- Operating point P1 is stable

Dipoli: deflessione

Consentono di curvare la traiettoria delle particelle. Possono essere realizzati con **magneti permanenti** o **elettromagneti** (poli ferro con avvolgimenti percorsi da corrente).







Traiettoria circolare

Raggio di curvatura

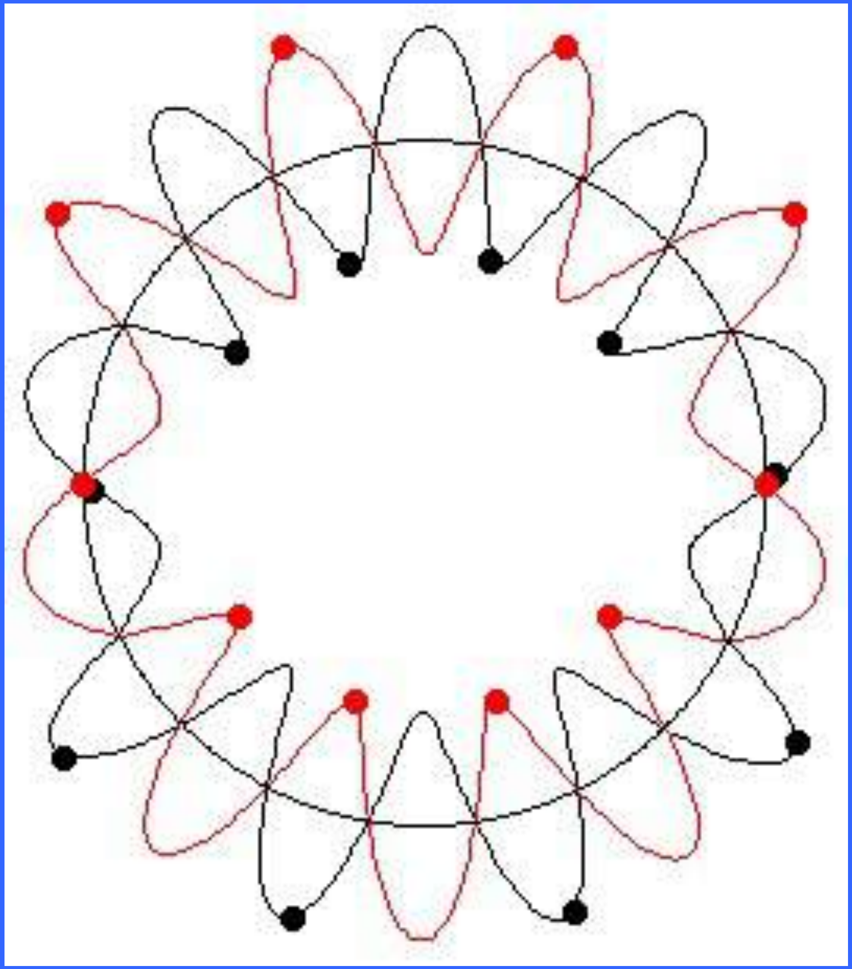
$$\rho[m] = \frac{p}{Bq} \cong \frac{W}{cqB}$$

Rigidità magnetica del fascio di particelle è definita come Bρ $B\rho[Tm] = \frac{p}{q} \cong \frac{W}{cq}$

I dipoli elettromagnetici vengono usati per produrre B non oltre 1-2 T.
Per campi magnetici più intensi si ricorre a ***magneti superconduttori***

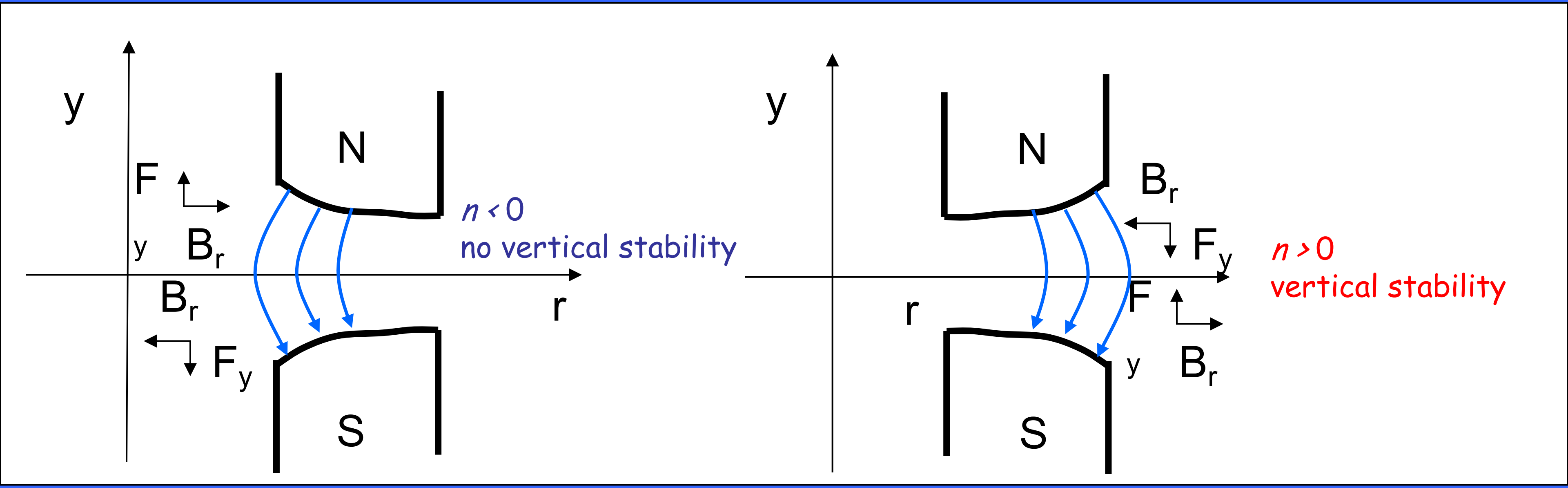
Per particelle ultra-relativistich

Betatron oscillations and transverse focusing



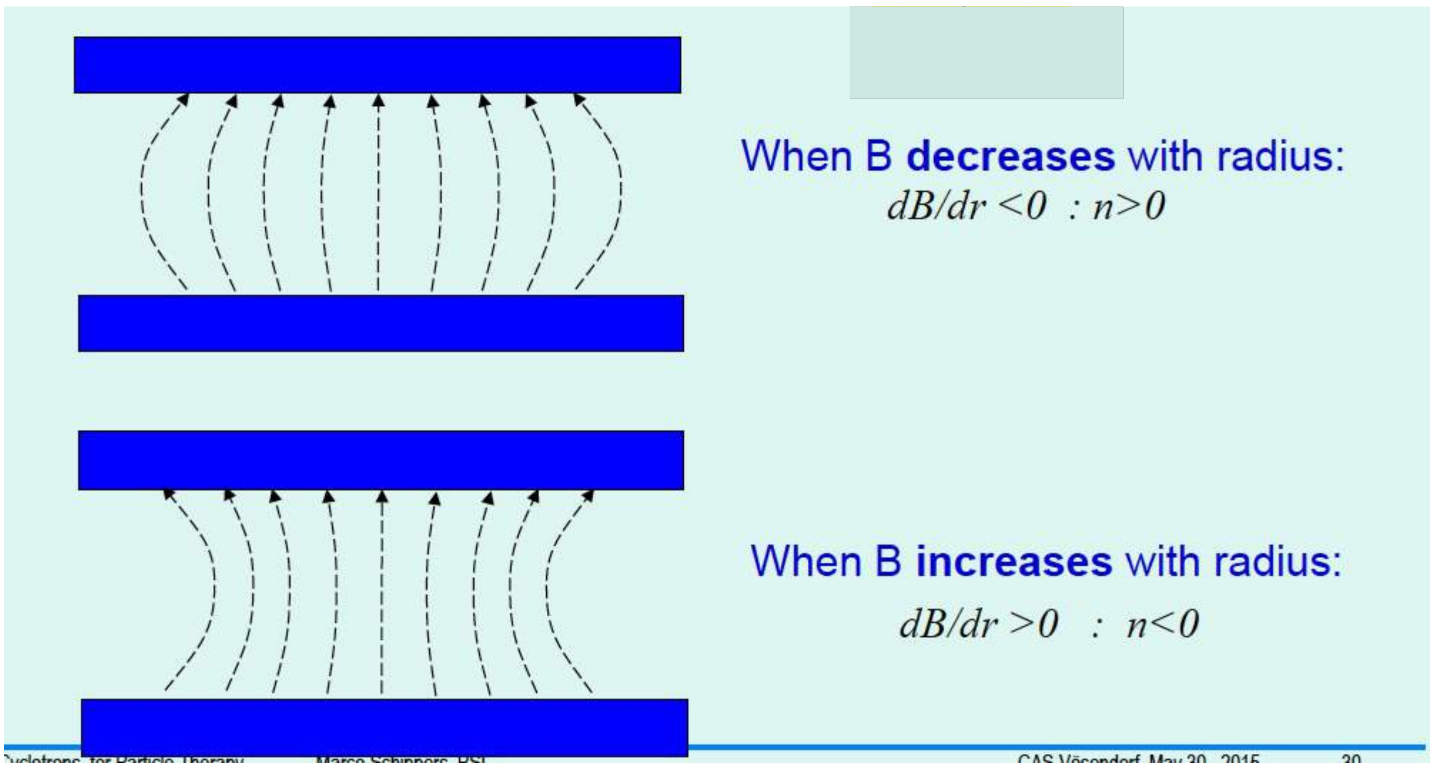
Weak focusing with combined function magnets

- to get vertical stability, the bending field should decrease with ρ, as in cyclotrons,
- to get horizontal stability the decrease of B with ρ should be moderate, so that, for $\rho > \rho_0$, the Lorenz force exceeds the centripetal force.



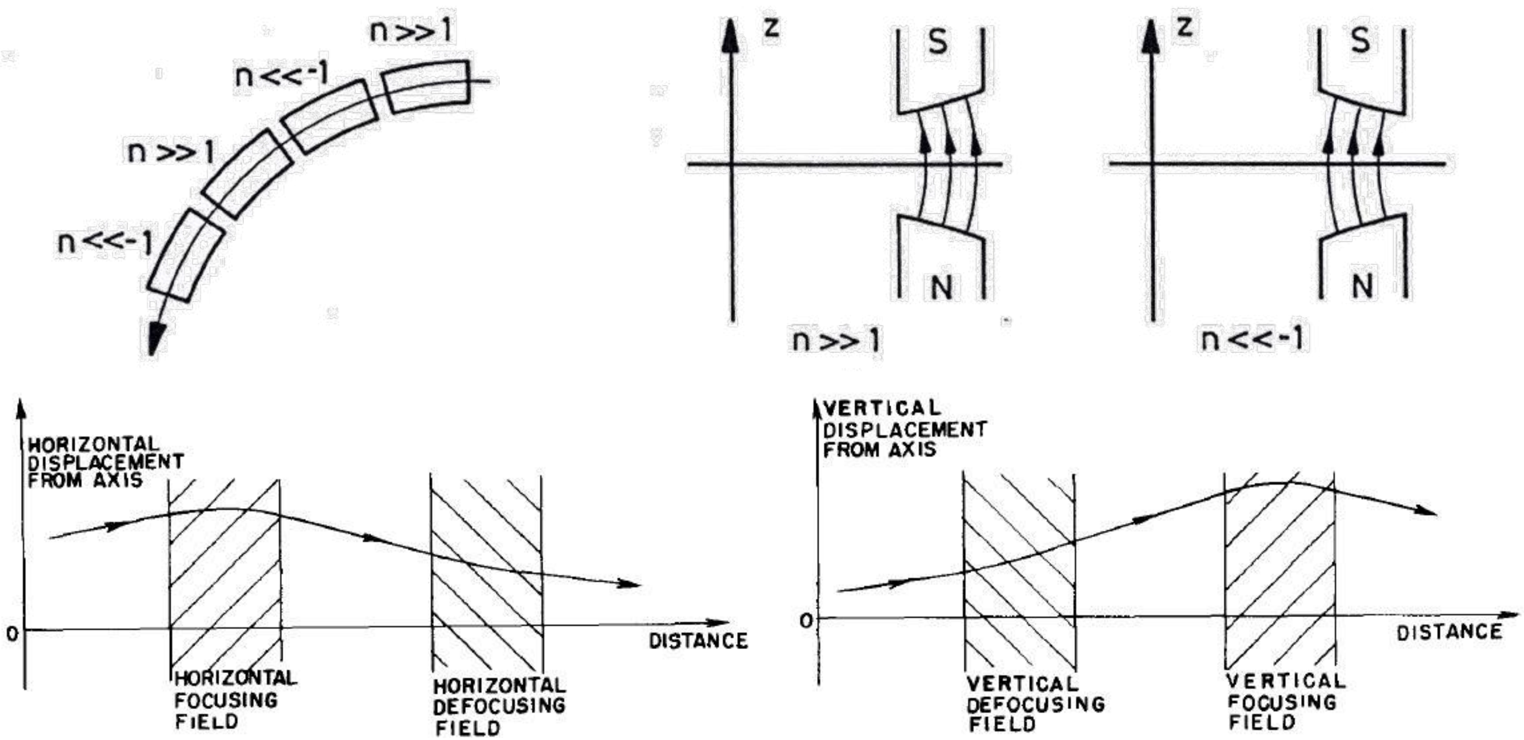
Weak focusing → Field index

$$B_y = B_{0y} + \frac{\partial B_y}{\partial x} x = B_{0y}\left(1 + \frac{R}{B_{0y}} \frac{\partial B_y}{\partial x} \frac{x}{R}\right) \qquad n = -\frac{R}{B_{0y}} \frac{\partial B_y}{\partial x}$$

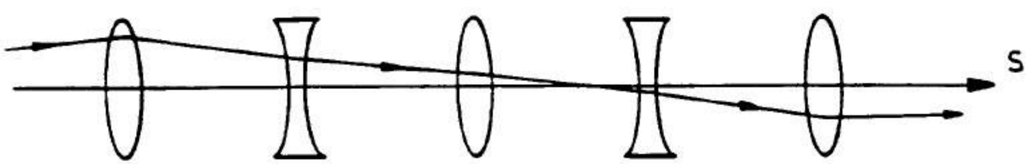


Strong focusing with combined function magnets

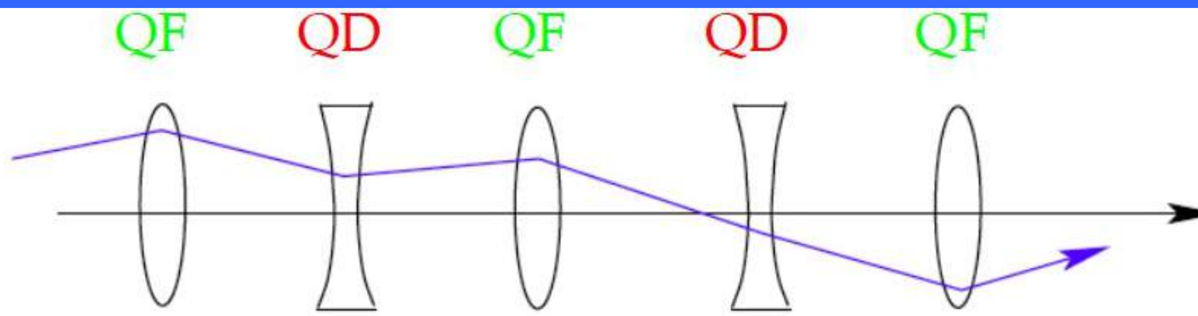
It is not possible to get strong focusing in both planes at the same time



The overall effect is focusing!!



Strong focusing with separated function magnets



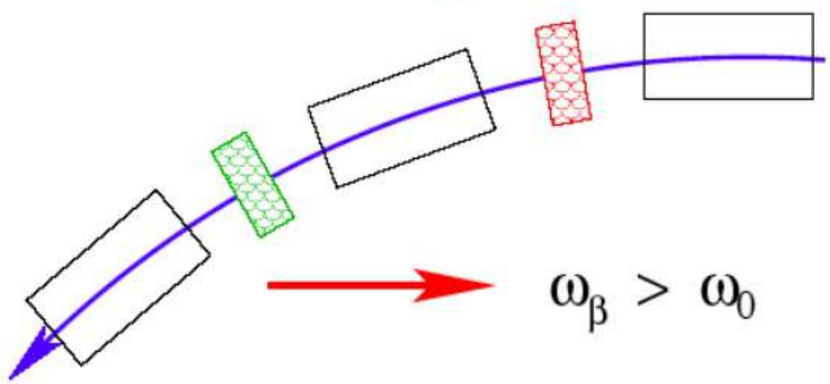
$$\frac{1}{f} = \frac{1}{f_1} + \frac{1}{f_2} - \frac{\Delta}{f_1 f_2}$$

$$\text{if} \quad f_1 = -f_2$$

$$\text{and} \quad \Delta = |f_1|$$

$$\frac{1}{f} = \frac{1}{|f_1|}$$

Idea: **cut the arc sections in *focusing* and *defocusing* elements**



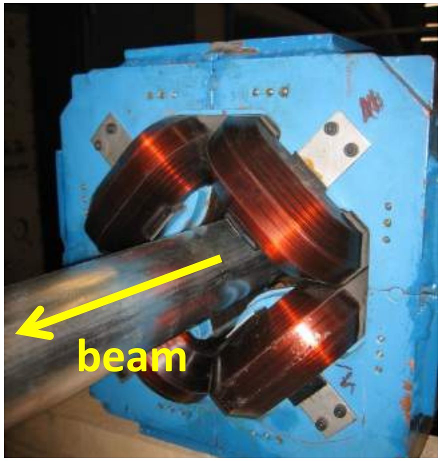
MAGNETIC QUADRUPOLE

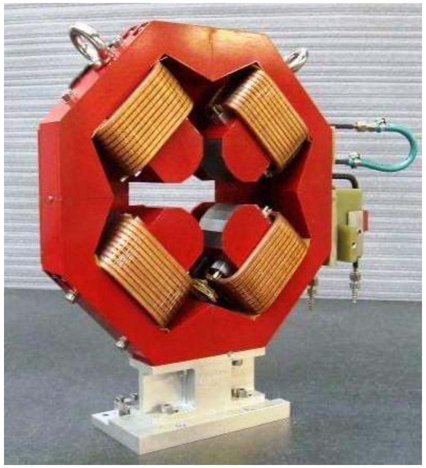
Quadrupoles are used to **focalize the beam in the transverse plane**. It is a **4 poles magnet**:

⇒**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**



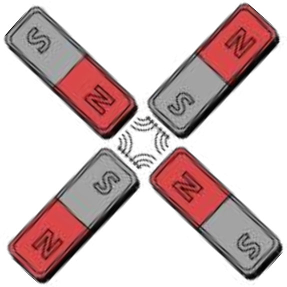


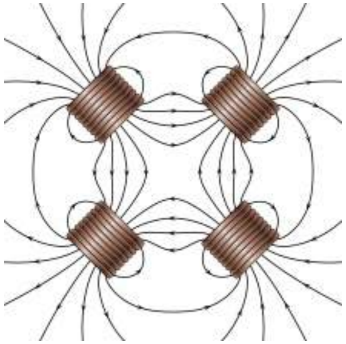
$$\begin{cases} B_x = G \cdot y \\ B_y = G \cdot x \end{cases} \Rightarrow \begin{cases} F_y = qvG \cdot y \\ F_x = -qvG \cdot x \end{cases}$$

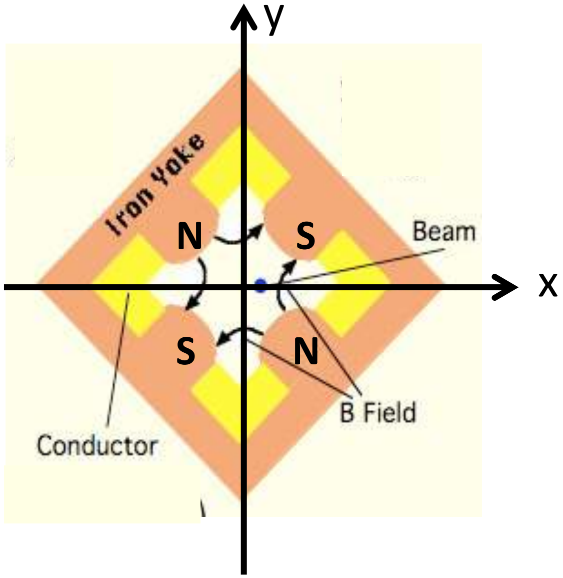
$$G = \text{quadrupole gradient} \left[\frac{T}{m} \right]$$

Electromagnetic quadrupoles G <50-100 T/m

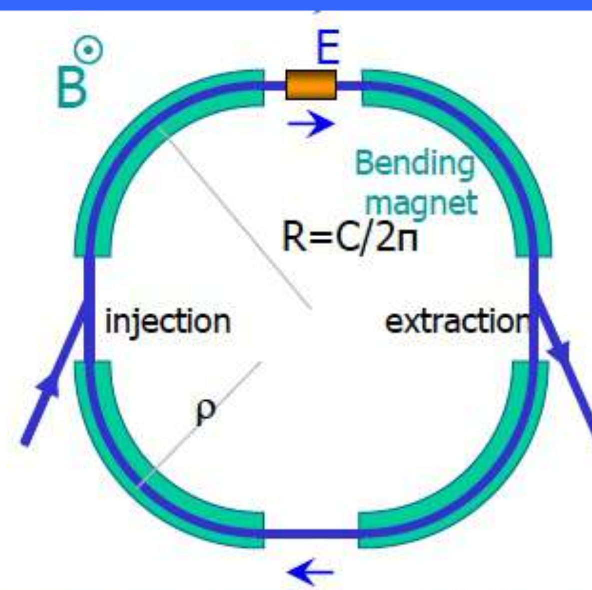
$$\frac{F_B}{F_E} = v \Rightarrow \begin{cases} F_B(1T) = F_E\left(300\frac{MV}{m}\right) @ \beta = 1 \\ F_B(1T) = F_E\left(3\frac{MV}{m}\right) @ \beta = 0.01 \end{cases}$$







3 GeV Cosmotron at BNL
weak focussing, combined function magnets



28 GeV PS at CERN
strong focussing, combined function magnets

400 GeV SPS at CERN
strong focussing, separated function magnets

Fermi's Globatron: ~5000 TeV Proton beam

1954 the ultimate synchrotron

B_{max} 2 Tesla

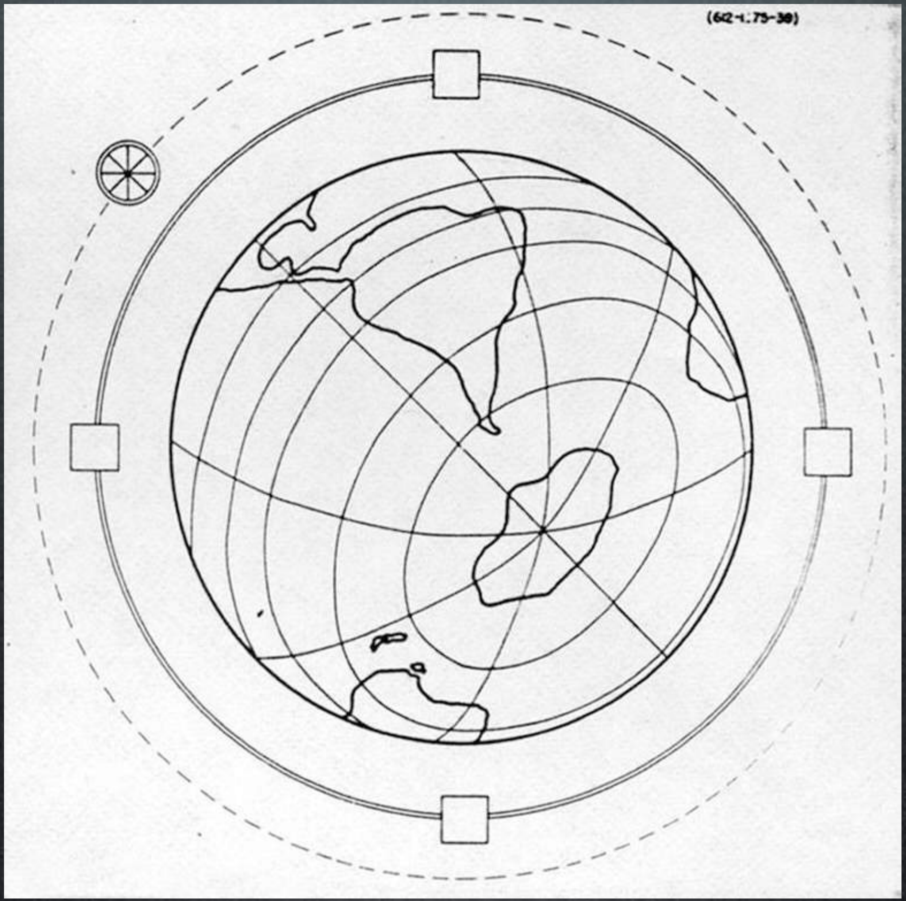
ρ 8000 km

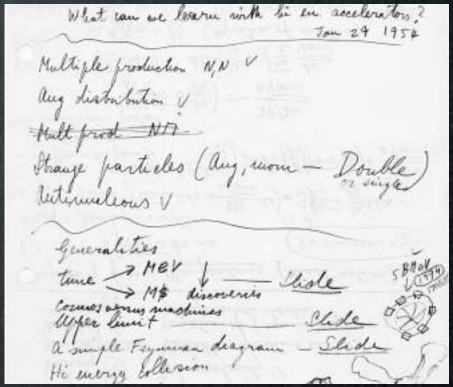
fixed target

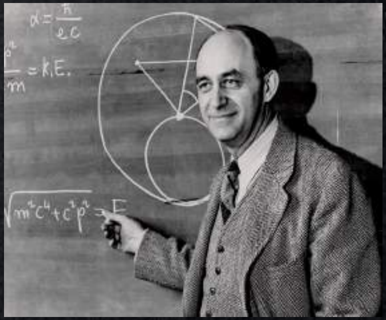
3 TeV c.m.

170 G$

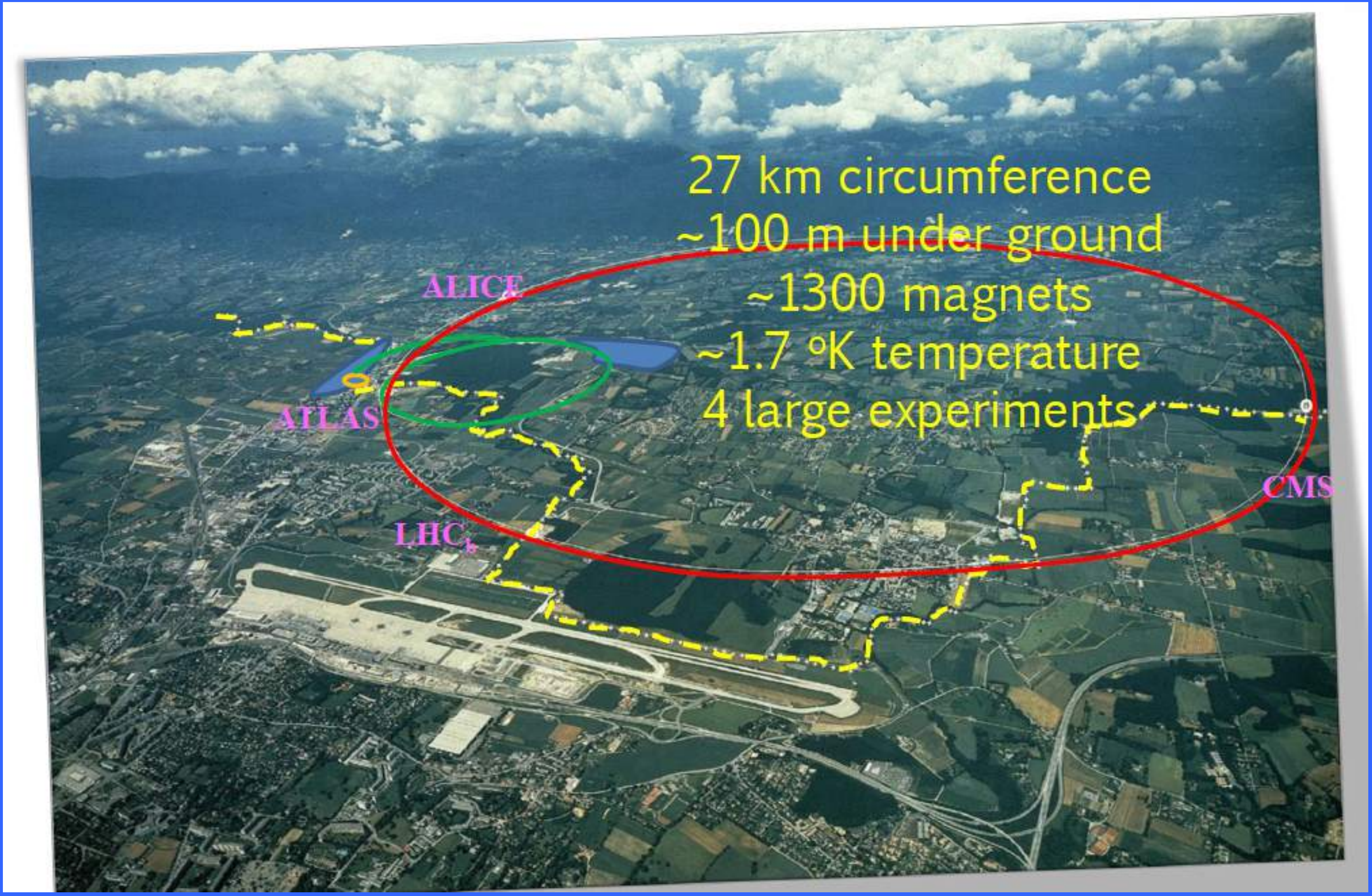
1994







LHC few data



27 km circumference
~100 m under ground
~1300 magnets
~1.7 ºK temperature
4 large experiments
ALICE
ATLAS
LHCb
CMS

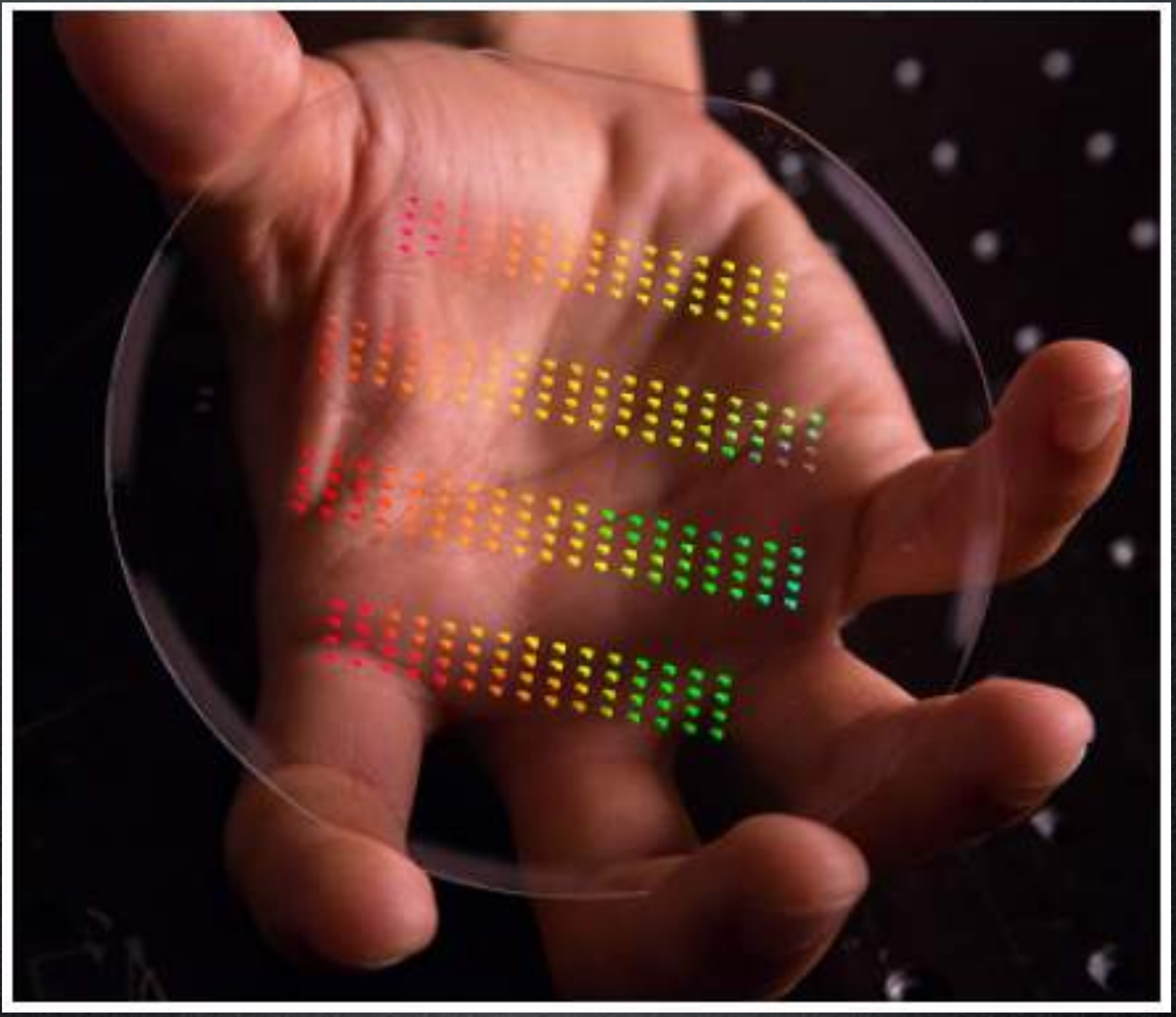
Hawking: the Solartron

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

… or accelerator on a Chip?



Advanced Accelerator Concepts

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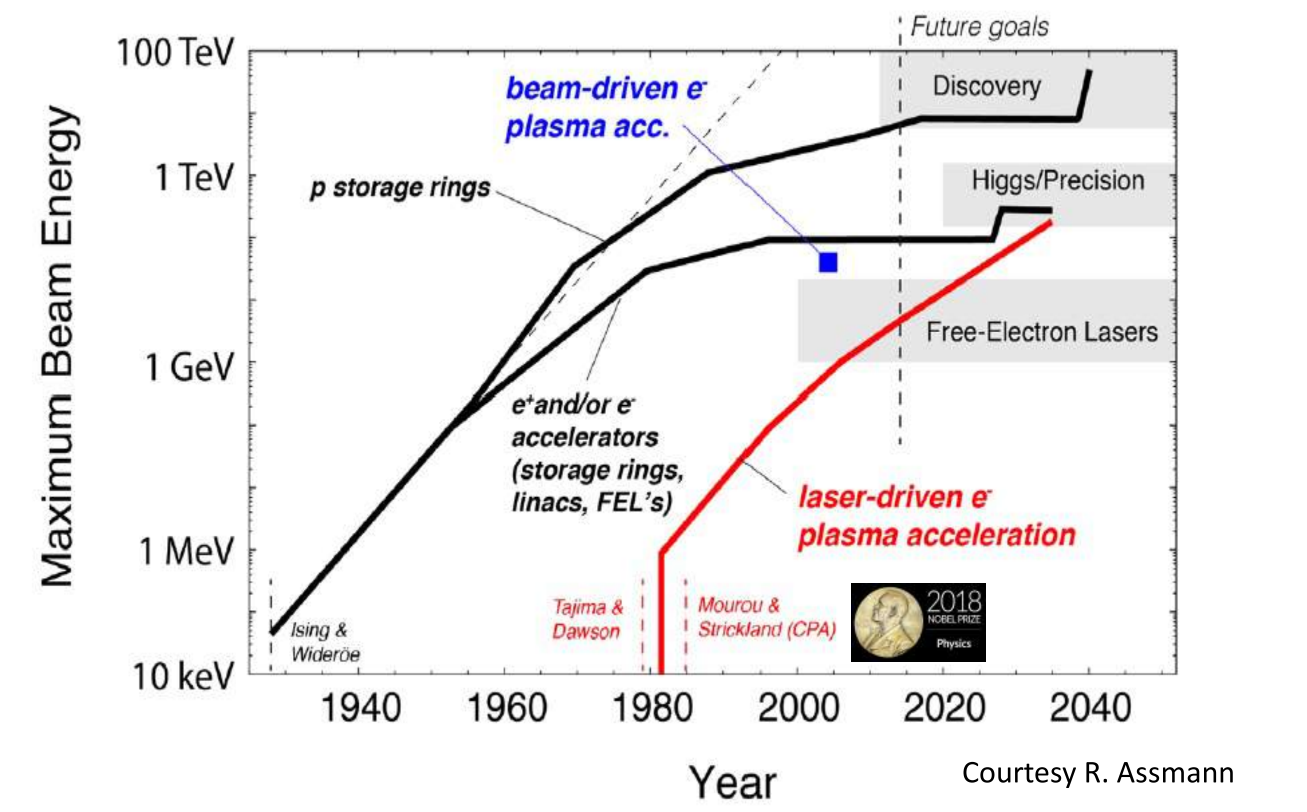


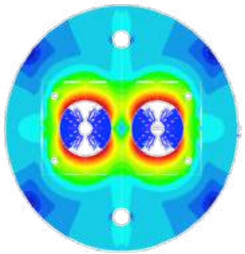
Courtesy R. Assmann

Options towards higher energies

Hadron (p) circular collider

$$p = e \cdot R \cdot B_y$$

Increase bending field
SC bend magnet work (FCC-hh)

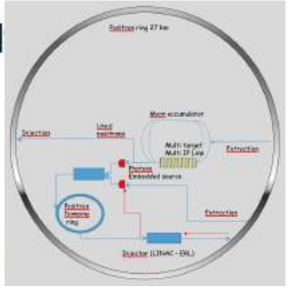


Increase radius = size (FCC-hh)

Lepton (e-,e+) circular collider

$$p \propto E_0 \cdot \sqrt[4]{\rho \cdot U_0}$$

Increase supplied RF vol
(FCC-ee)



Increase mass of acc. particle (muon)

Increase radius = size (FCC-ee)

Lepton (e-,e+) linear collider

$$p = L \cdot G_{acc}$$

Compact and Cost Effective....

Increase length (ILC, CLIC)

Beam Quality Requirements

Future accelerators will require also high quality beams :

==> High Luminosity & High Brightness,

==> High Energy & Low Energy Spread

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

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

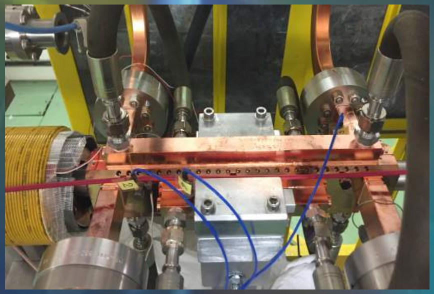
$$B_n \approx \frac{2I}{\varepsilon_n^2}$$

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

High Gradient Options

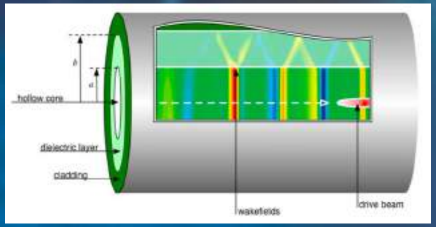
Metallic accelerating structures =>

100 MV/m < E_{acc}< 1 GV/m



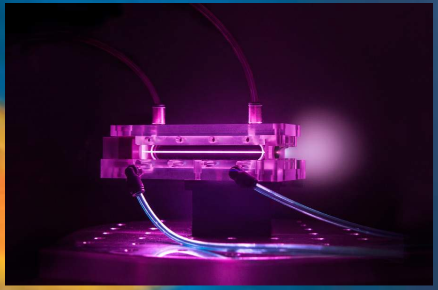
Dielectrict structures, laser or particle driven =>

E_{acc} < 10 GV/m



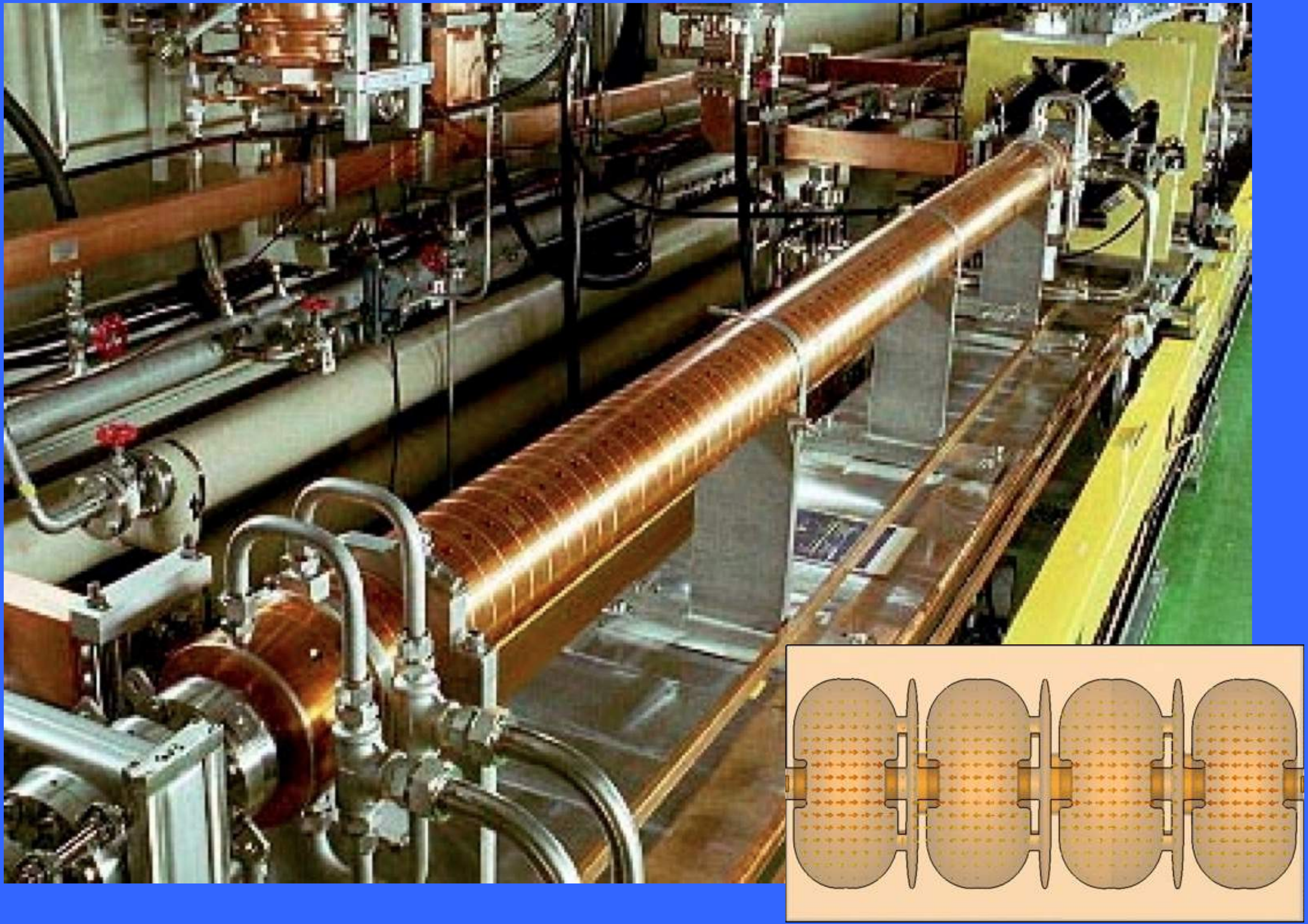
Plasma accelerator, laser or particle driven =>

E_{acc} < 100 GV/m

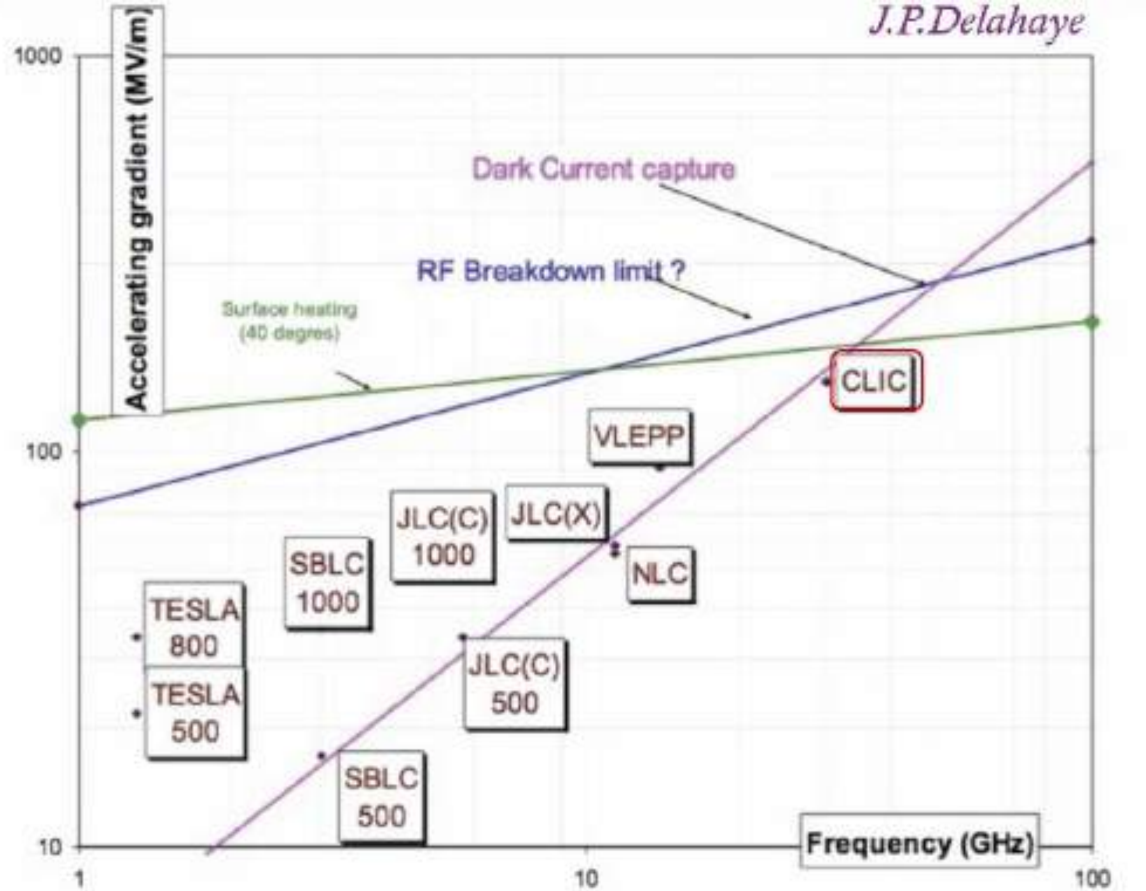


Related Issues: Power Sources and Efficiency, Stability, Reliability, Staging, Synchronization, Rep. Rate and short (fs) bunches with small (μm) spot to match high gradients

Conventional RF accelerating structures



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



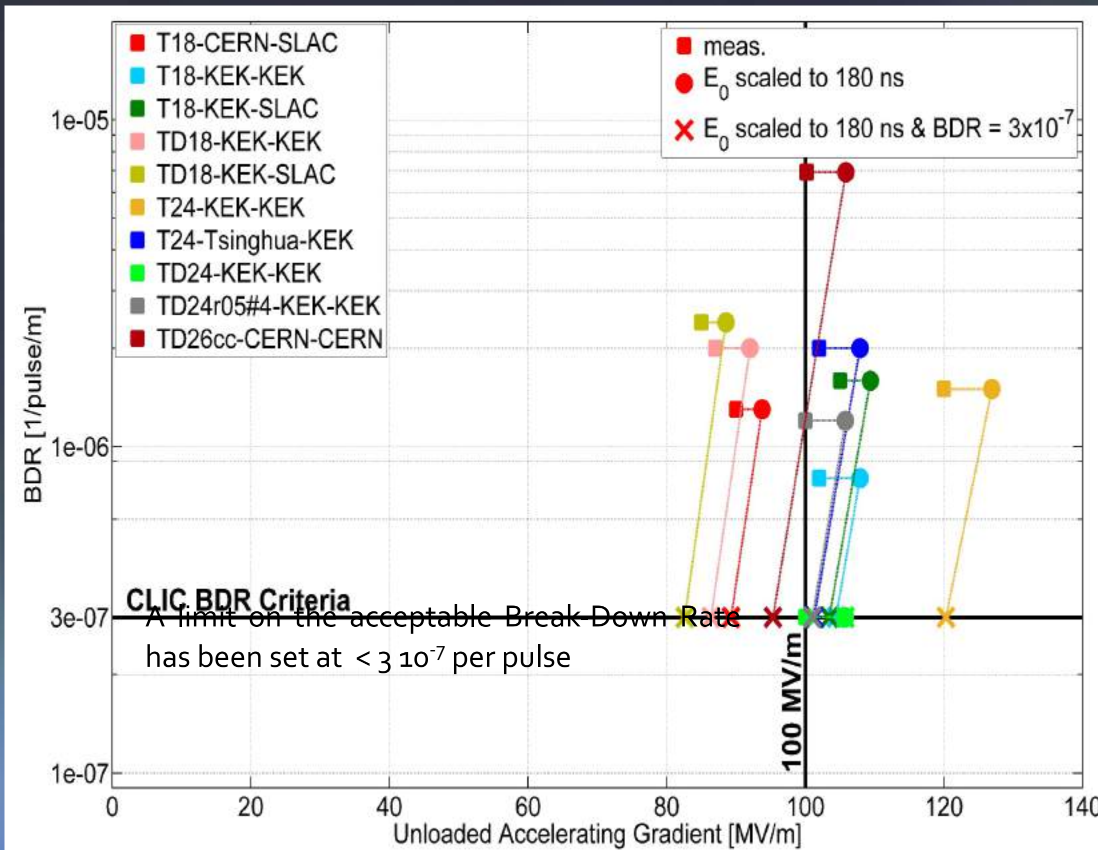
Breakdown limits metal:

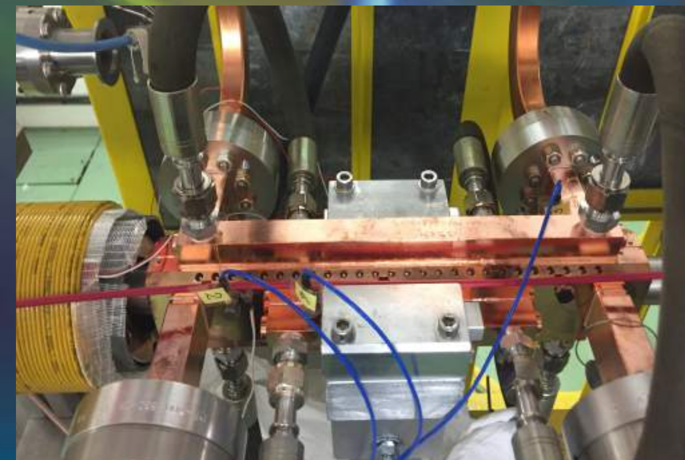
$$E_s = 220(f\,[\mathrm{GHz}])^{1/3}\ \mathrm{MV/m}$$

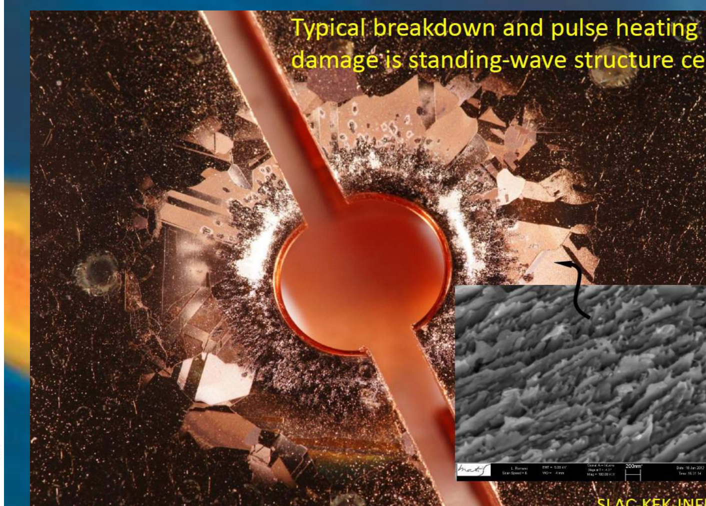
High field ->Short wavelength->ultra-short bunches-> low charge

X-band RF structures – State of the Art

Max accelerating field: $\tau_{rf}^{-1/6}$
Stored energy: f^{-3}







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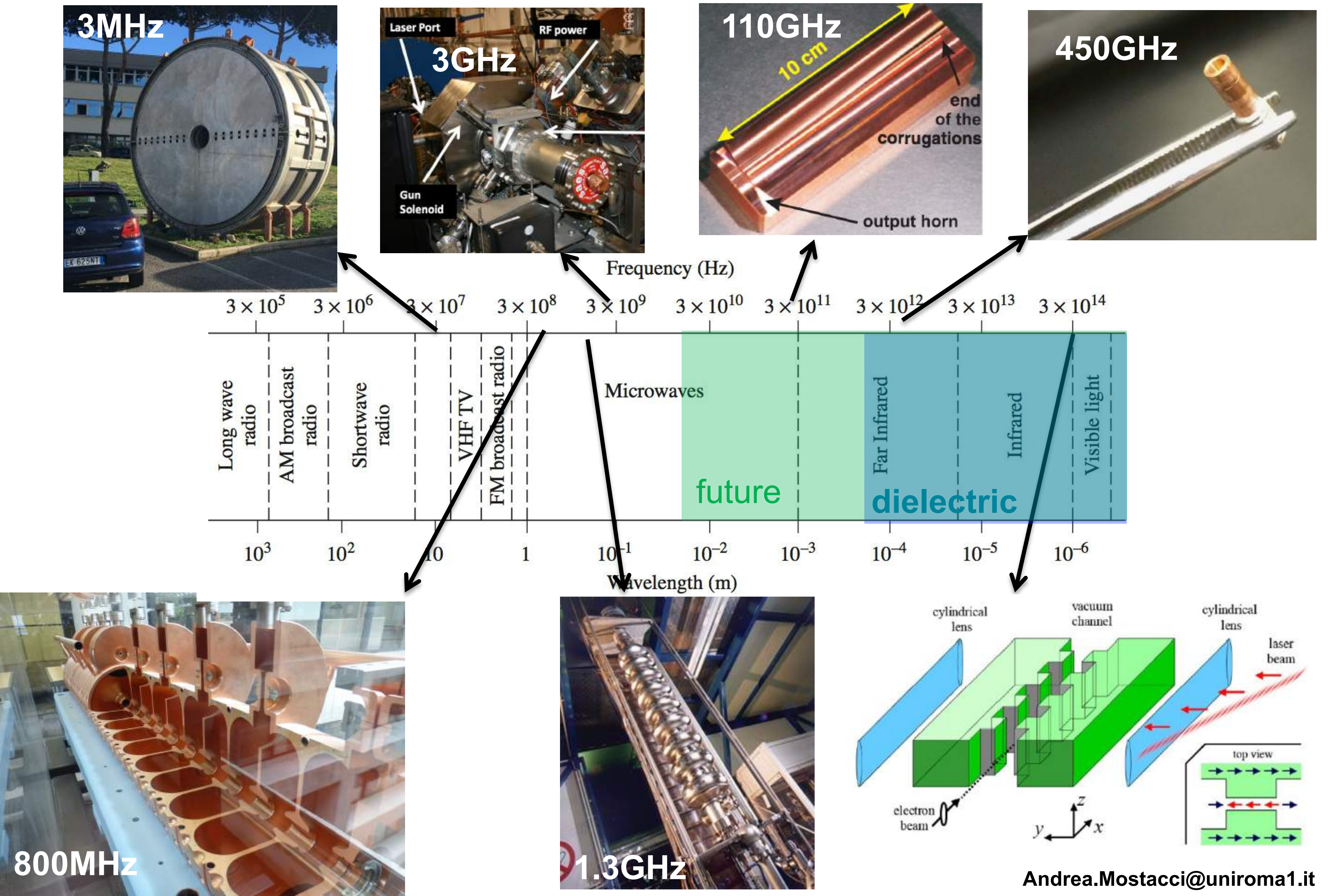
- *A. Grudiev et al, PRST-AB 12, 102001 (2009)*
- S. V. Dolgashev, et al. Appl. Phys. Lett. 97, 171501 2010.
- M. D. Forno, et al. PRAB. 19, 011301 (2016).

The E.M. Spectrum of Accelerating Structures



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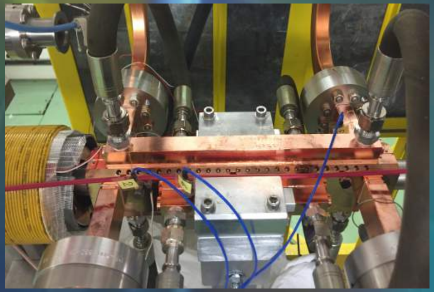
High Gradient Options

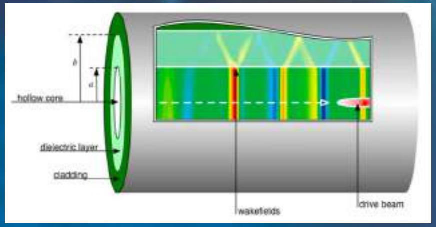
Metallic accelerating structures =>

100 MV/m < E_{acc}< 1 GV/m



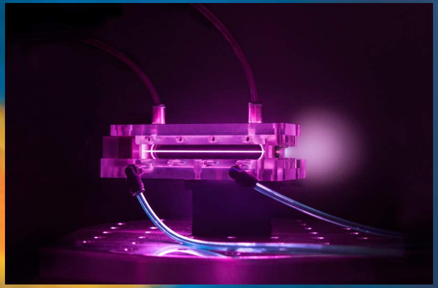
Dielectrict structures, laser or particle driven =>

E_{acc} < 10 GV/m



Plasma accelerator, laser or particle driven =>

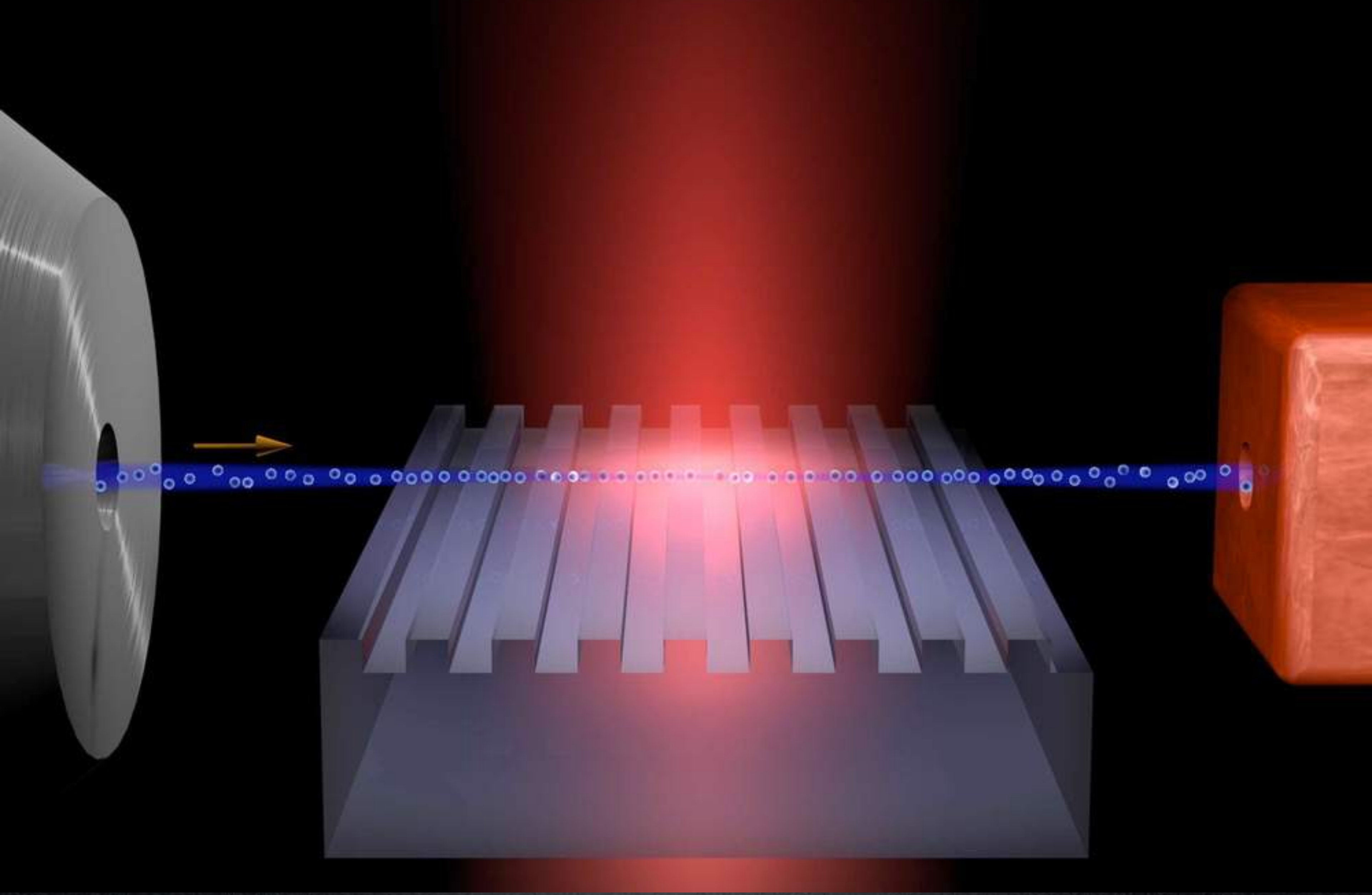
E_{acc} < 100 GV/m



Related Issues: Power Sources and Efficiency, Stability, Reliability, Staging, Synchronization, Rep. Rate and short (fs) bunches with small (μm) spot to match high gradients

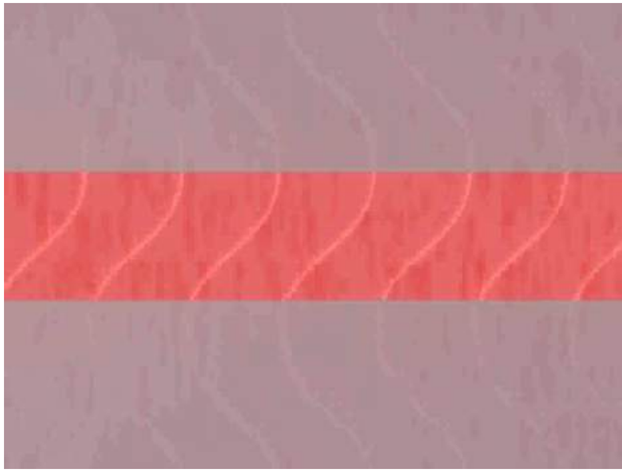
Dielectric Laser Acceleration
DLA

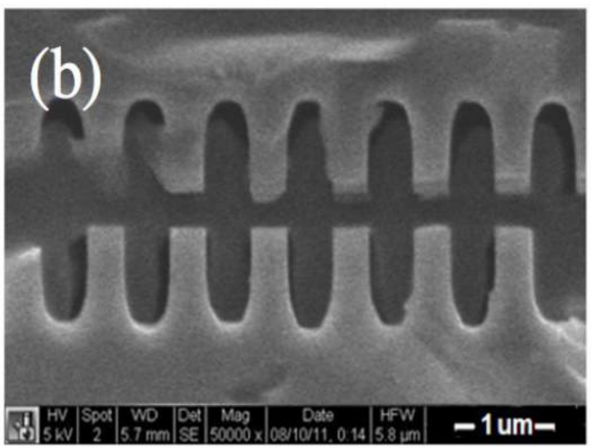
Laser based dielectric accelerator

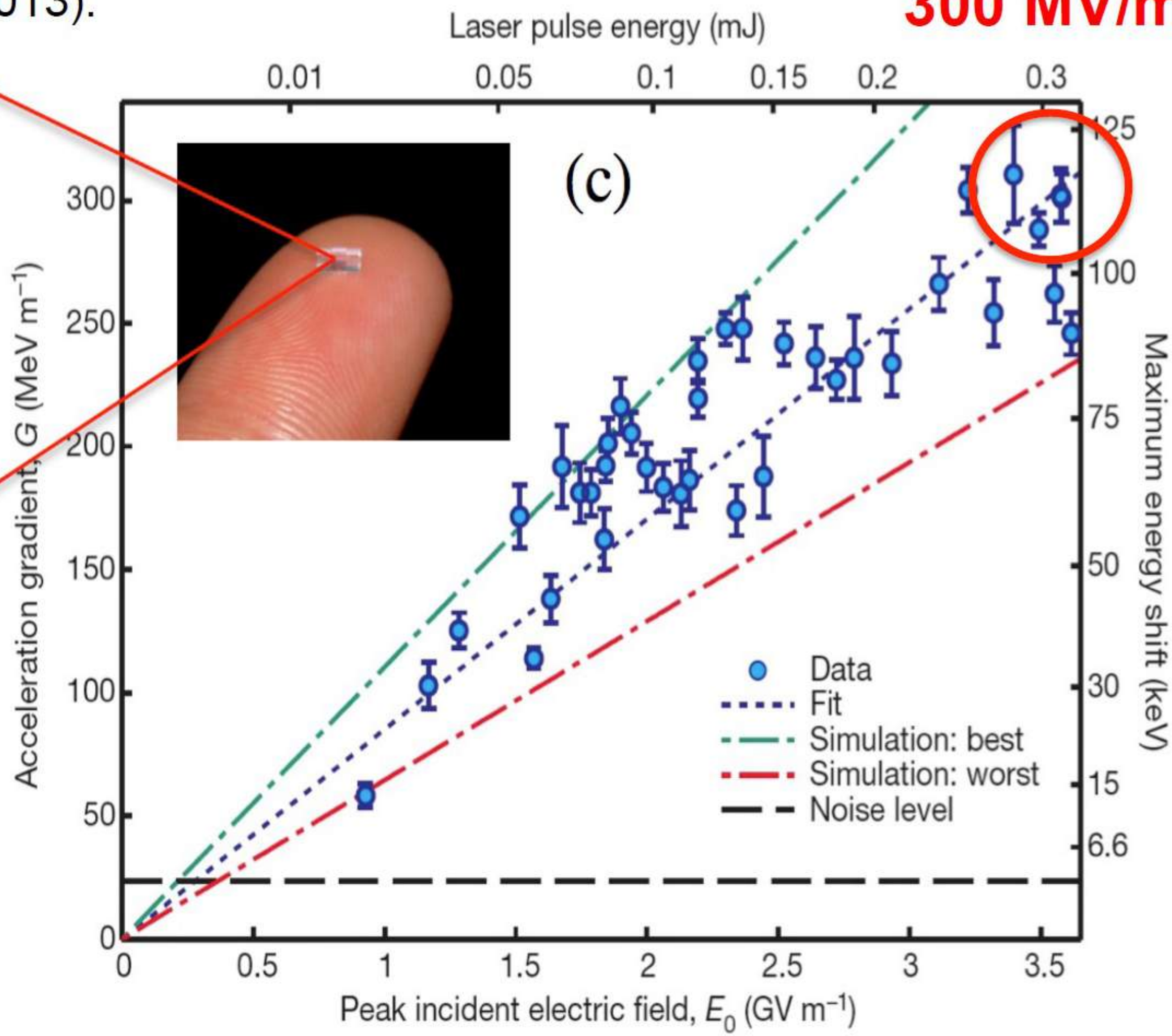


Nature **503**, 91-94 (2013).

300 MV/m

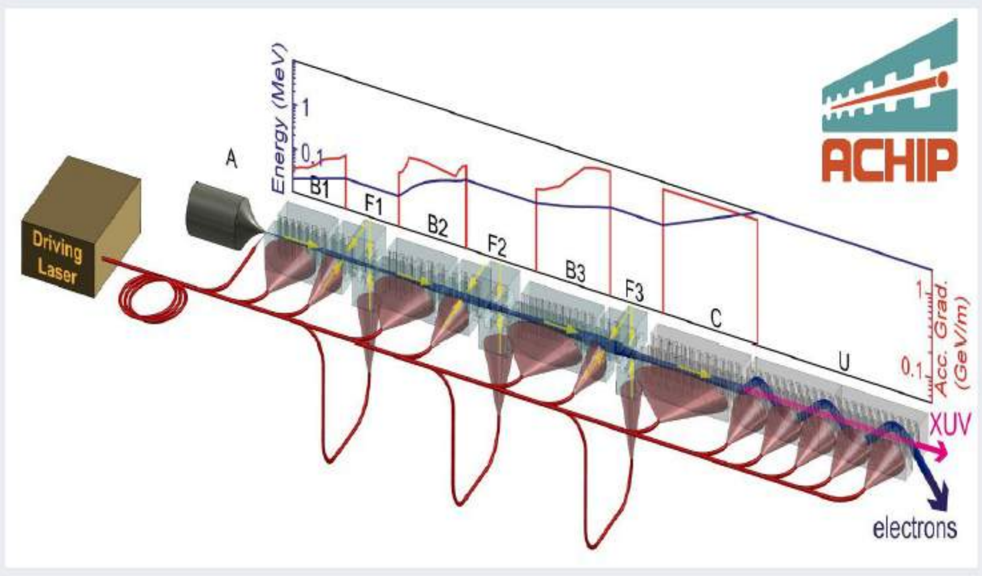




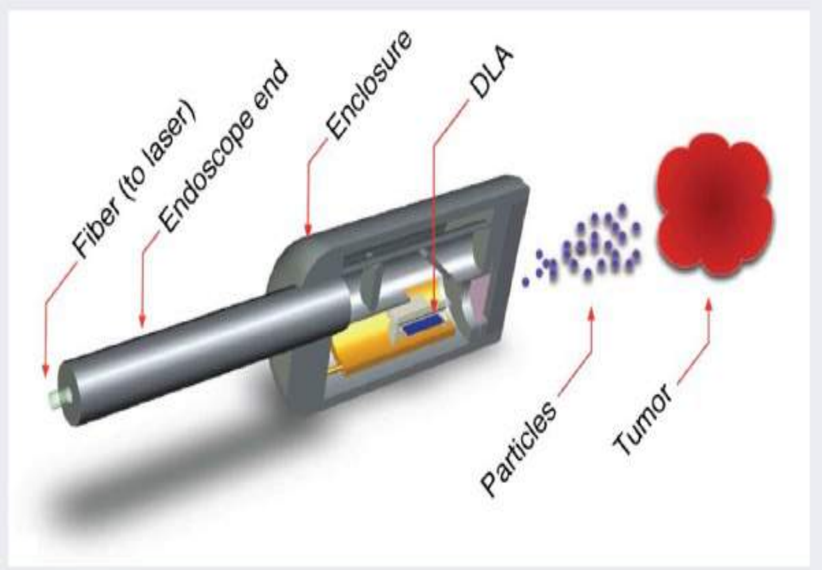


Dielectric Structures Applications

A combination of DLA modules and optical undulator allows dreaming for a compact table top FEL



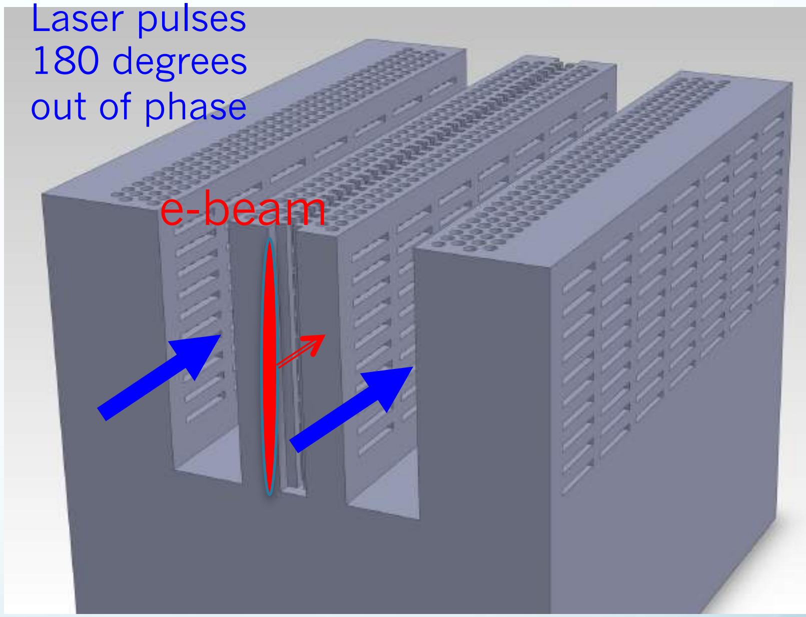
DLA module can be built onto the end of a fiber-optic catheter and attached to an endoscope, allowing to deliver controlled, high energy radiation directly to organs, tumors, or blood vessels within the body.



Electrons with 1–3MeV have a range of about a centimeter, allowing for irradiation volumes to be tightly controlled.

Dielectric Photonic Structure

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

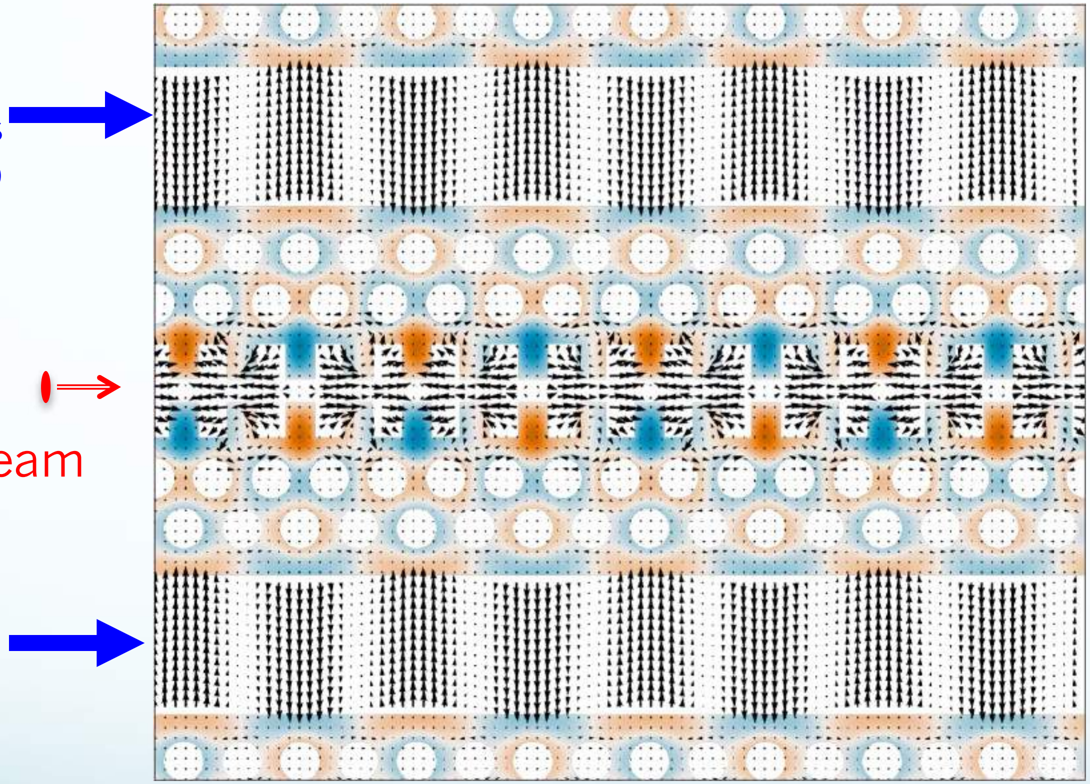


Schematic of GALAXIE monolithic photonic DLA

Laser-Structure Coupling: TW

GALAXIE Dual laser drive structure, large reservoir of power recycles

Laser pulses
(180 degrees
out of phase)

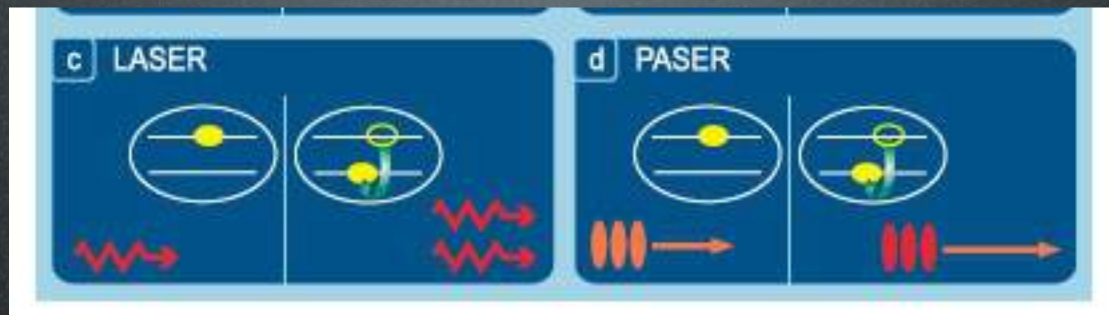


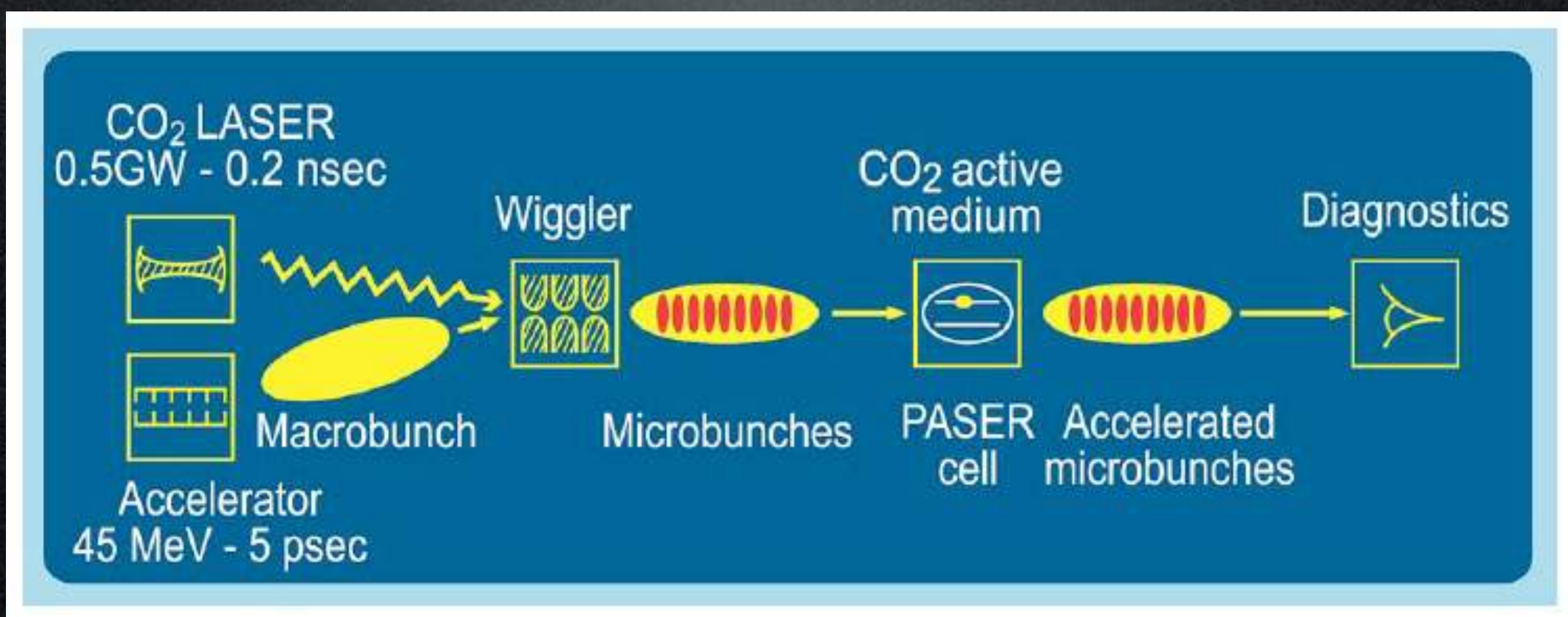
e-beam

PHYSICAL REVIEW E 74, 046501 (2006)

Particle acceleration by stimulated emission of radiation: Theory and experiment

Samer Banna,* Valery Berezovsky, and Levi Schächter
Department of Electrical Engineering, Technion, Israel Institute of Technology, Haifa 32000, Israel
(Received 28 June 2006; published 23 October 2006)





PRL 97, 134801 (2006) PHYSICAL REVIEW LETTERS week ending 29 SEPTEMBER 2006

Experimental Observation of Direct Particle Acceleration by Stimulated Emission of Radiation

Samer Banna,* Valery Berezovsky, and Levi Schächter
Department of Electrical Engineering, Technion-Israel Institute of Technology, Haifa 32000, Israel
(Received 4 June 2006; published 28 September 2006)

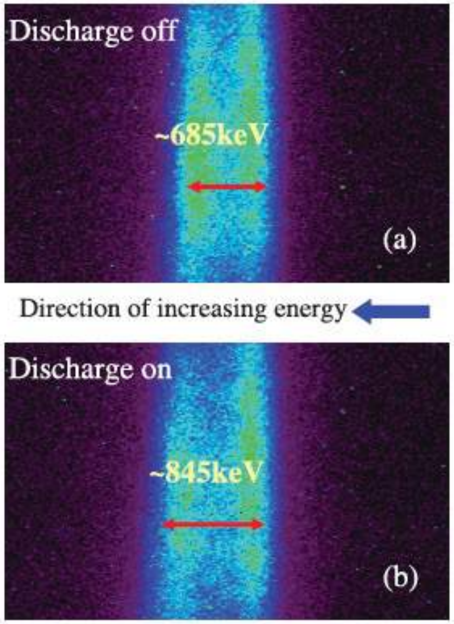
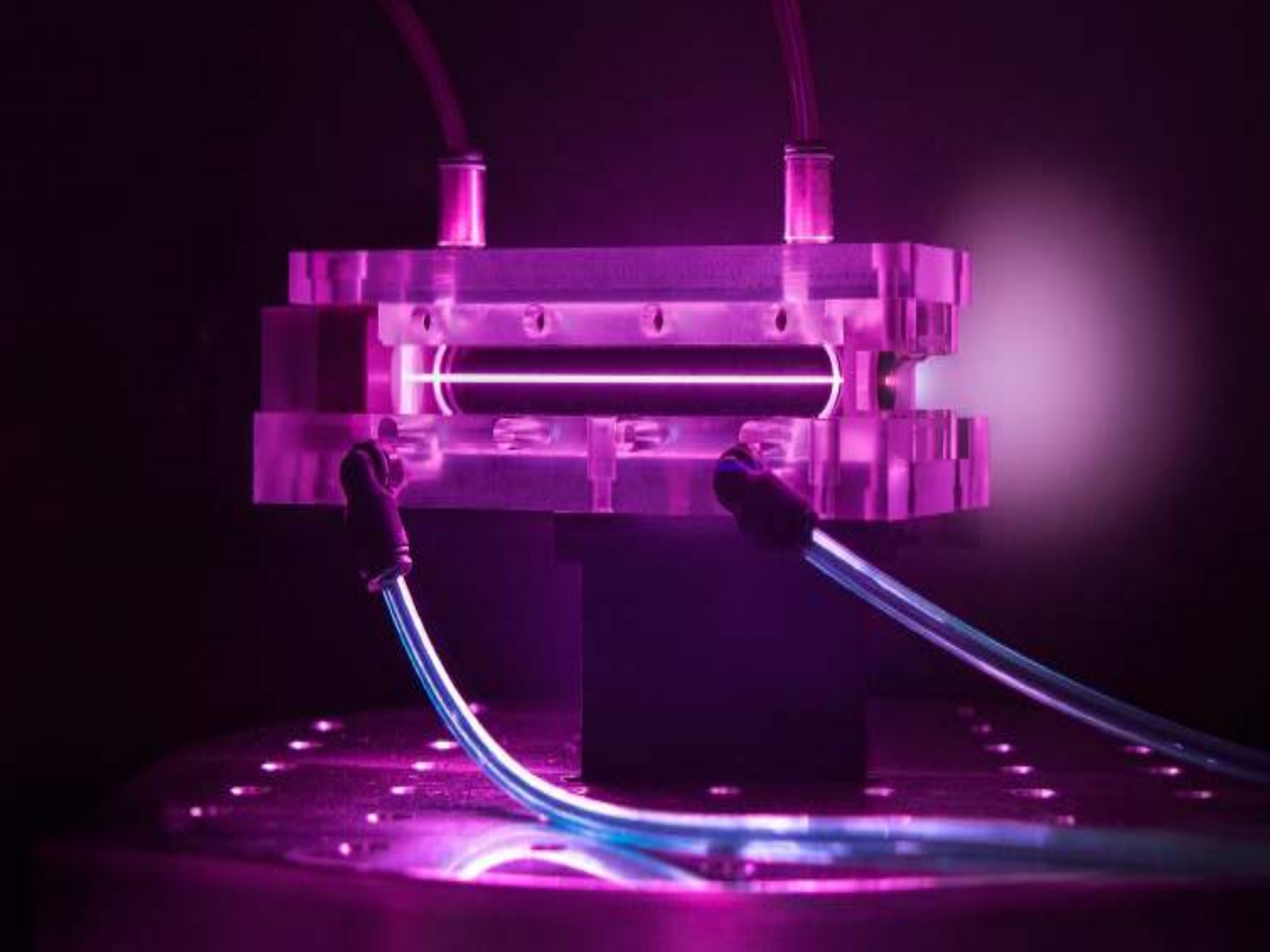
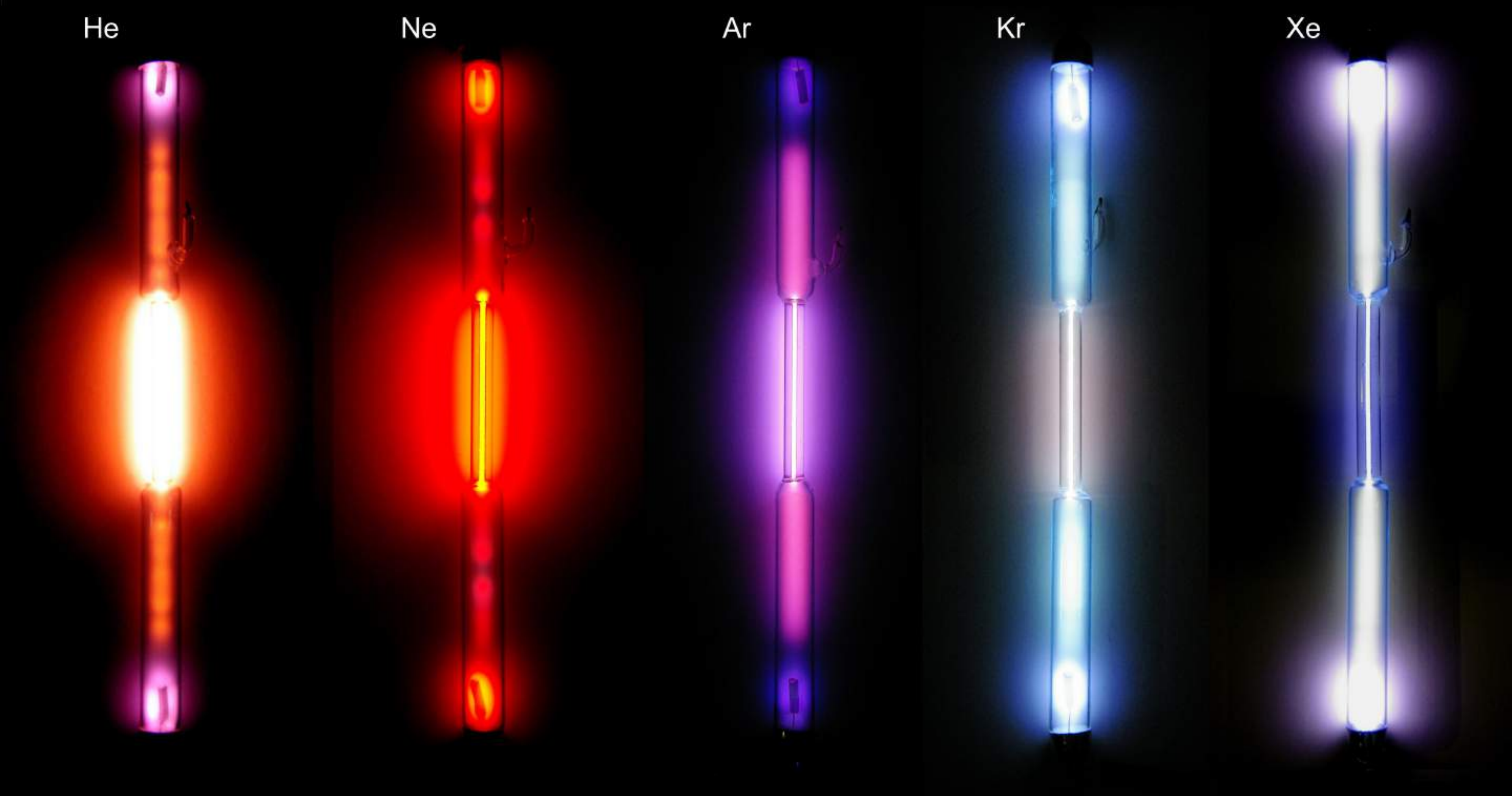


FIG. 3 (color). Raw video images from the electron energy spectrometer. Energy dispersion is in the horizontal direction. (a) Discharge is off in the PASER cell. (b) Discharge is on in the PASER cell. In both cases, ~1.5% peak-to-peak energy modulation was imparted.

Plasma Wakefield Acceleration




He
Ne
Ar
Kr
Xe

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

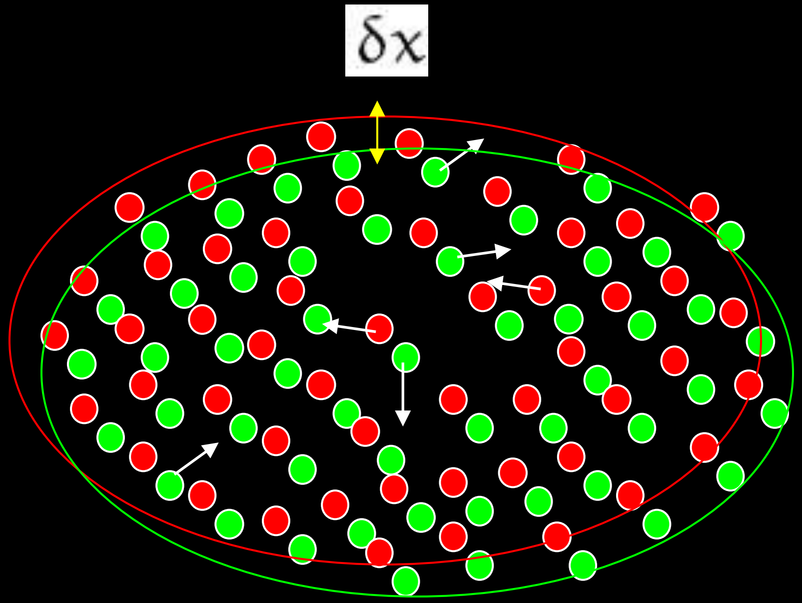
and

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 $4\gamma_0^2 mc^2$ are possible. A noncollinear injection scheme is suggested in order that the driving electrons can be removed.

Surface charge density

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



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

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

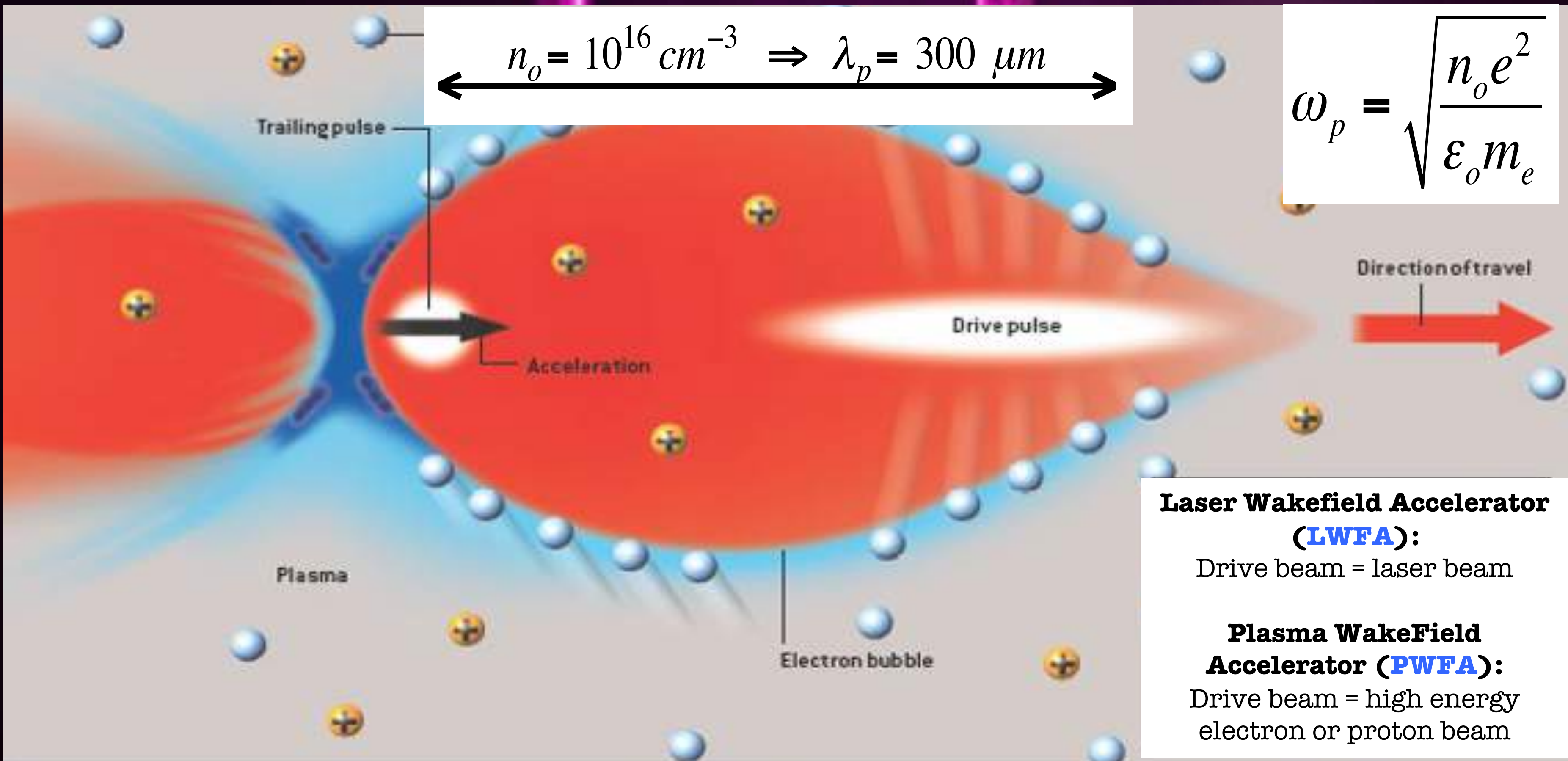
Plasma oscillations

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

Principle of plasma acceleration

$$n_o = 10^{16}\ cm^{-3} \Rightarrow \lambda_p = 300\ \mu m$$

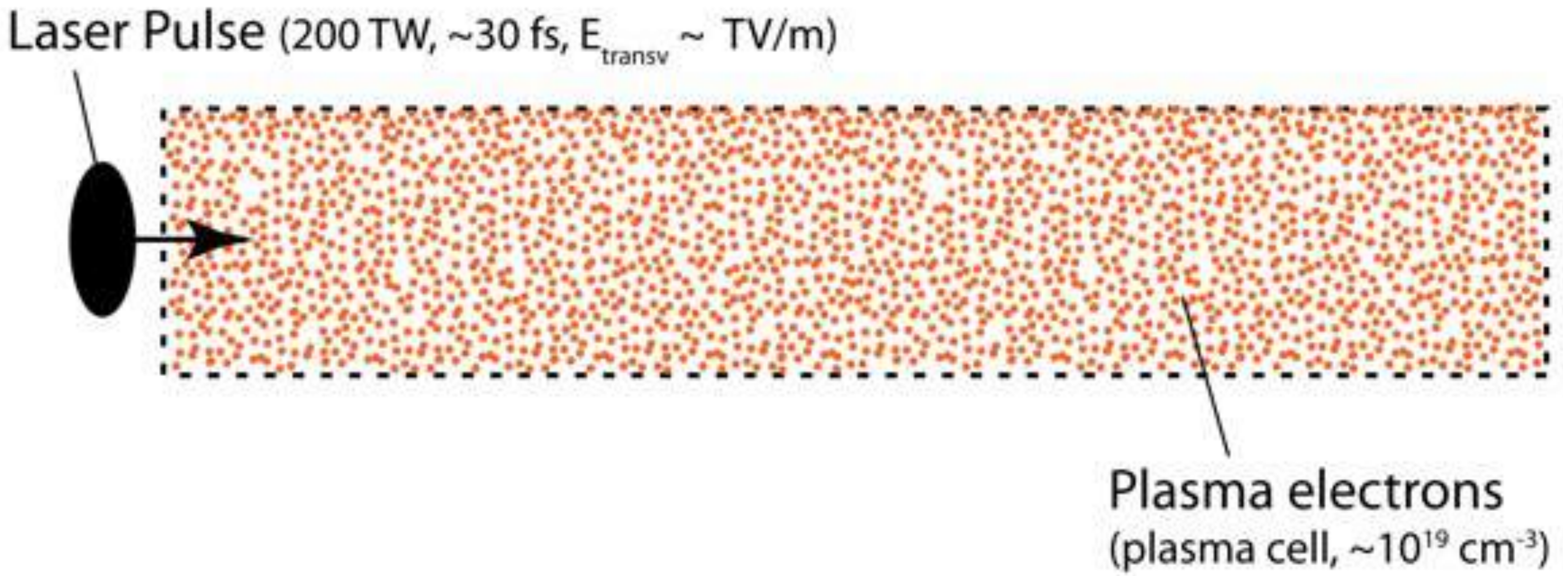
$$\omega_p = \sqrt{\frac{n_o e^2}{\varepsilon_o m_e}}$$



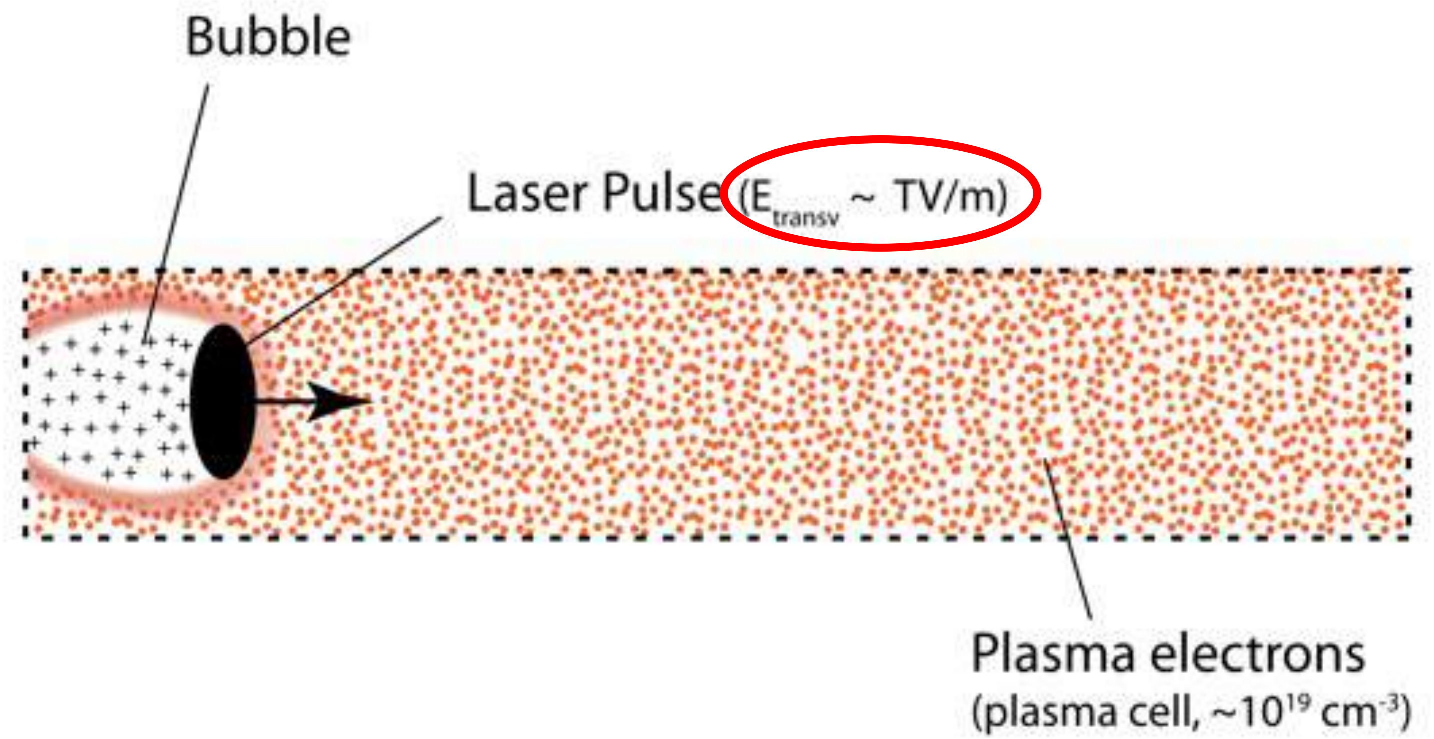
Laser Wakefield Accelerator (LWFA):
Drive beam = laser beam

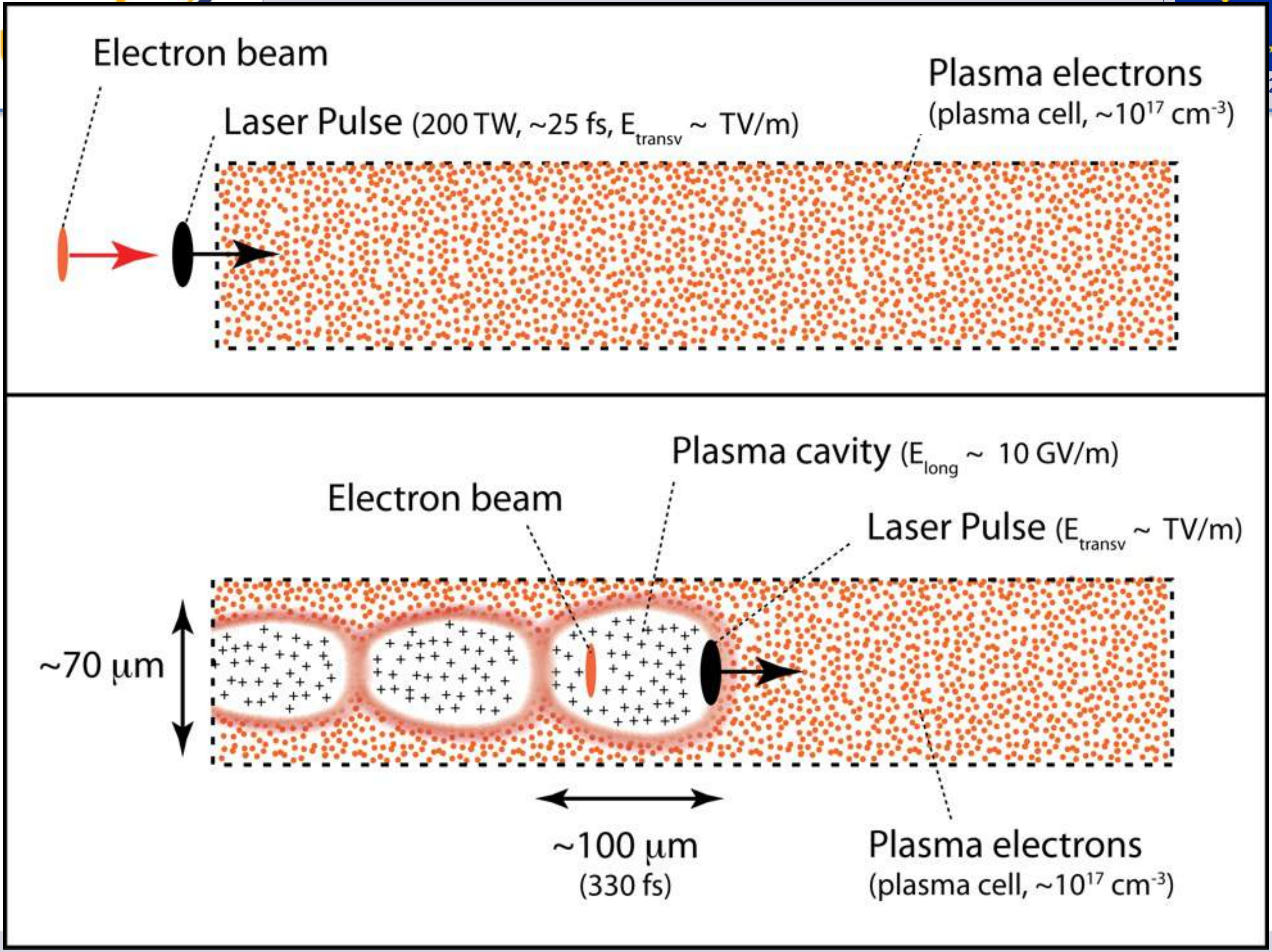
Plasma WakeField Accelerator (PWFA):
Drive beam = high energy electron or proton beam

Plasma Wake-Acceleration

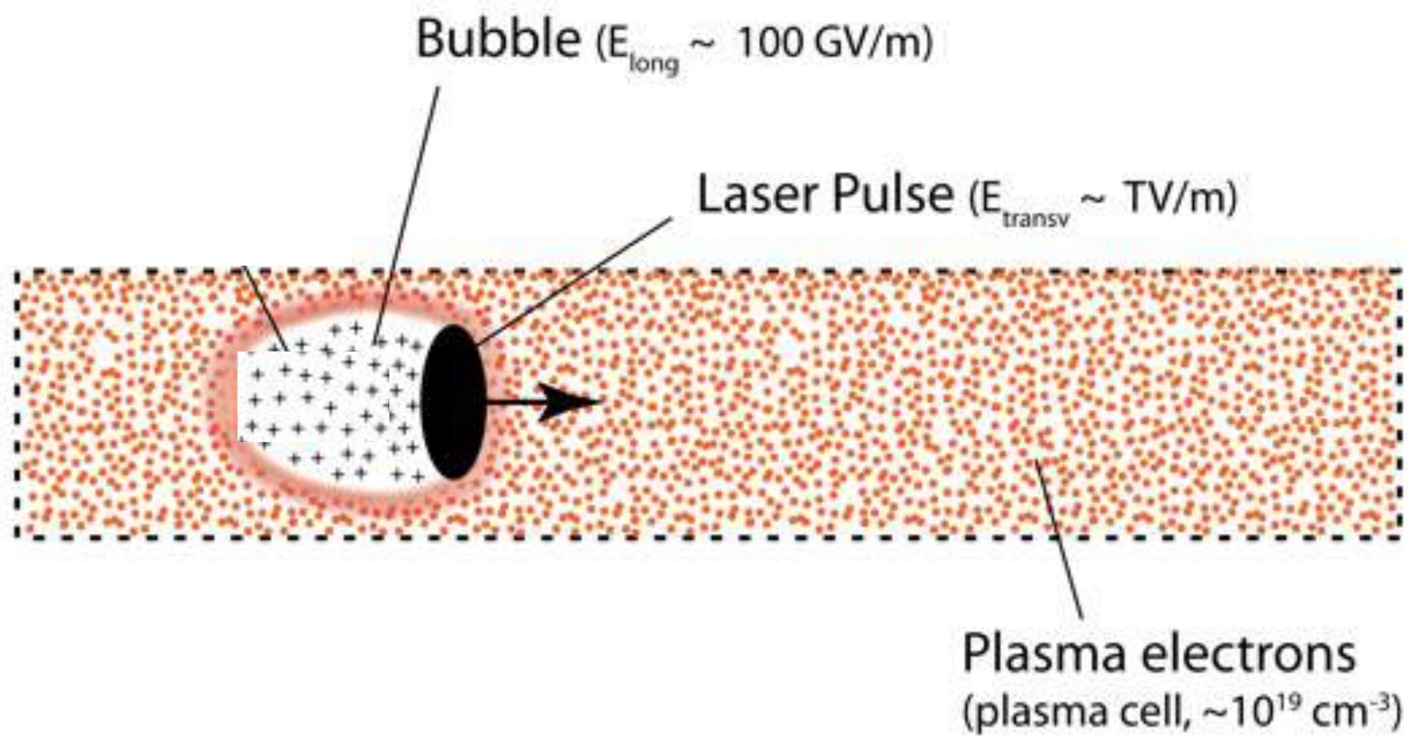


Plasma Wake-Acceleration

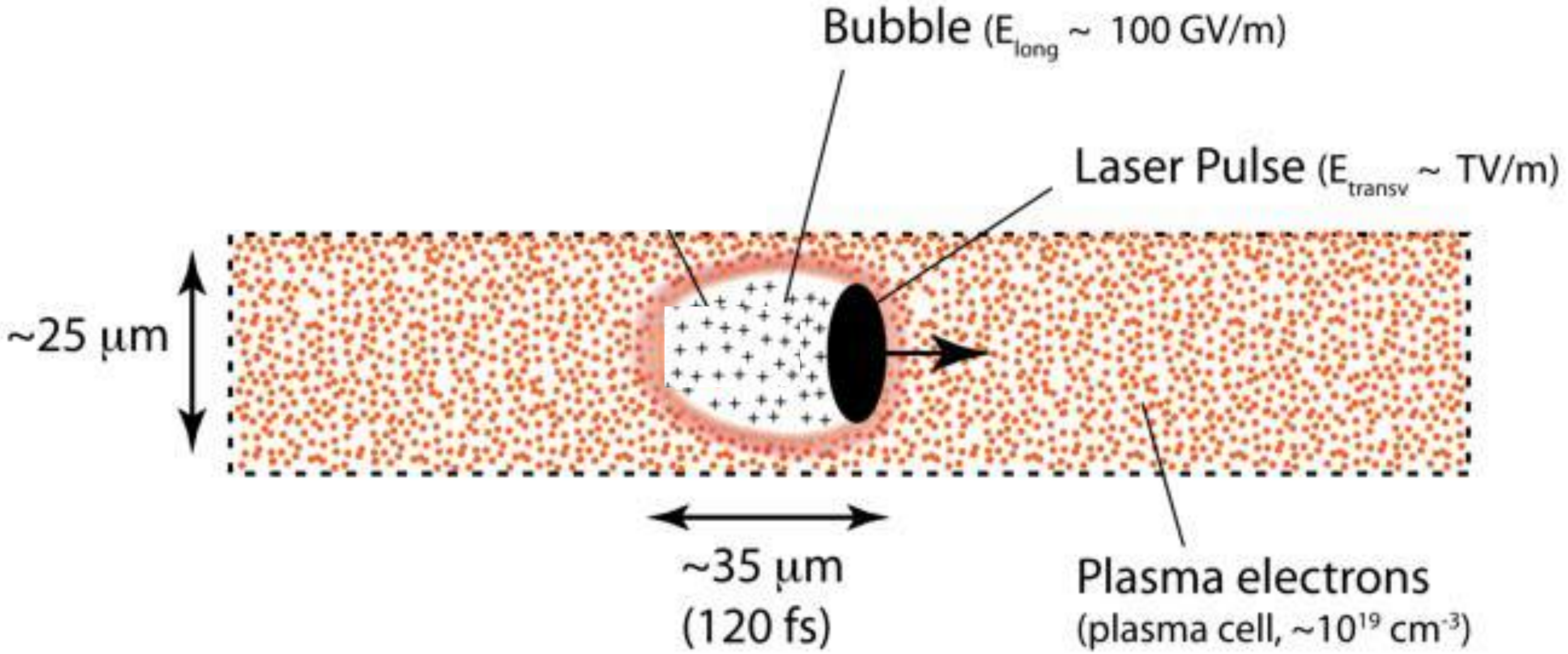



Electron beam
Laser Pulse (200 TW, ~25 fs, E$_{transv}$ ~ TV/m)
Plasma electrons
(plasma cell, ~10^{17} cm^{-3})
Plasma cavity (E$_{long}$ ~ 10 GV/m)
Electron beam
Laser Pulse (E$_{transv}$ ~ TV/m)
~70 μm
~100 μm
(330 fs)
Plasma electrons
(plasma cell, ~10^{17} cm^{-3})

Plasma Wake-Acceleration



Plasma Wake-Acceleration

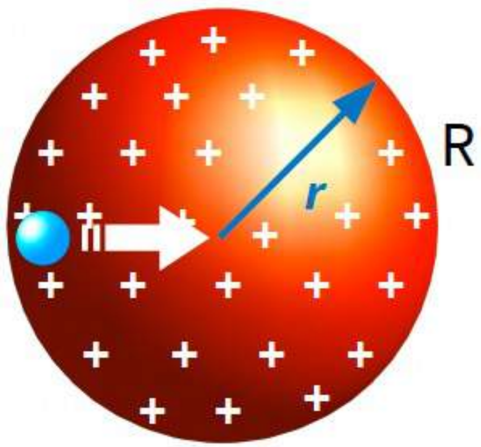


This accelerator fits into a human hair!

Principle of plasma acceleration

From Maxwell's equations, the electric field in a (positively) charged sphere with uniform density n_i at location **r** is

$$\vec{E}(r) = \frac{q_i n_i}{3\epsilon_0} r$$



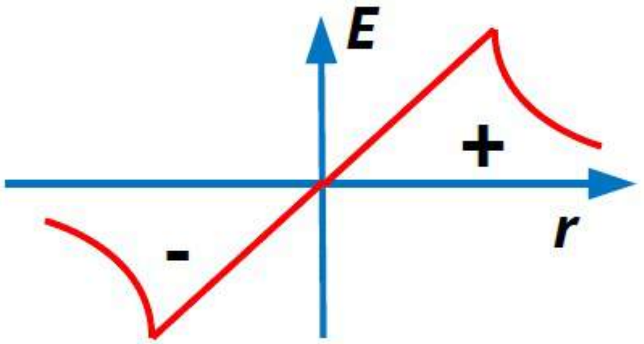
The field is **increasing** inside the sphere

Let's put some numbers

$n_i = 10^{16}\ cm^{-3}$

$r = \lambda_p/2 = 150\ \mu m$

$$\Rightarrow E \approx 10 \frac{GV}{m}$$



Break-Down Limit?
⇒ Wave-Breaking field:

$$E_{wb} \approx 100\left[GeV/m\right]\sqrt{n_o\left[cm^{-3}\right]}$$

Principle of plasma acceleration

Driven by Radiation Pressure

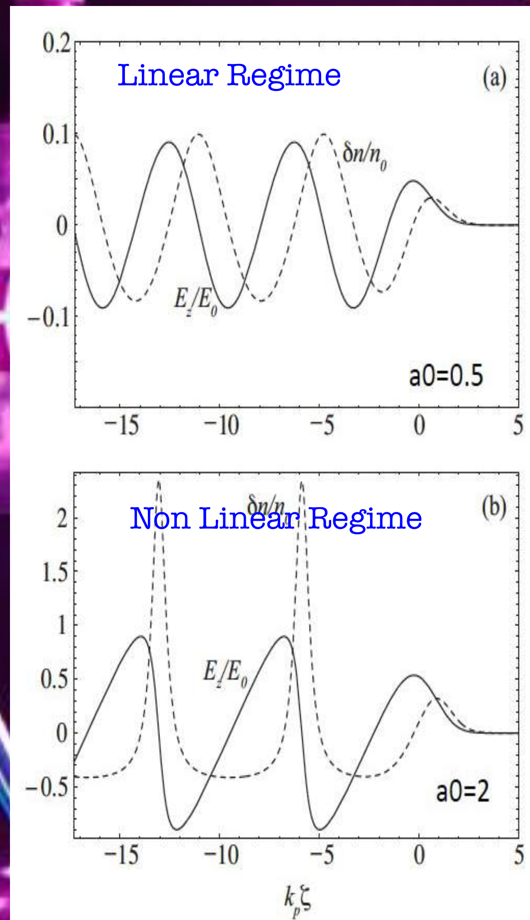
$$\left(\frac{\partial^2}{\partial t^2}+\omega_p^2\right)\frac{n}{n_o}=c^2\nabla^2\frac{a^2}{2}$$

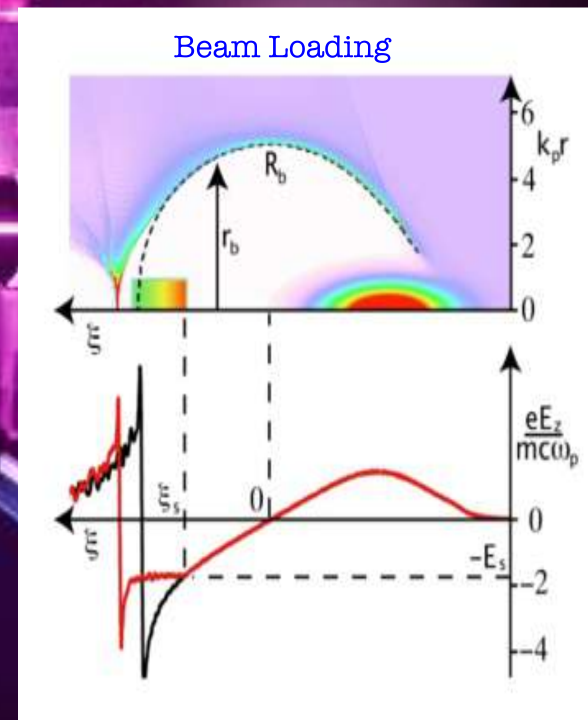
$$a=\frac{eA}{mc^2}\propto\lambda J^{1/2}$$

Driven by Space Charge

$$\left(\frac{\partial^2}{\partial t^2}+\omega_p^2\right)\frac{n}{n_o}=-\omega_p^2\frac{n_{beam}}{n_o}$$

$$n_{beam}=\frac{N}{\sqrt{(2\pi)^3}\,\sigma_r^2\sigma_z}$$



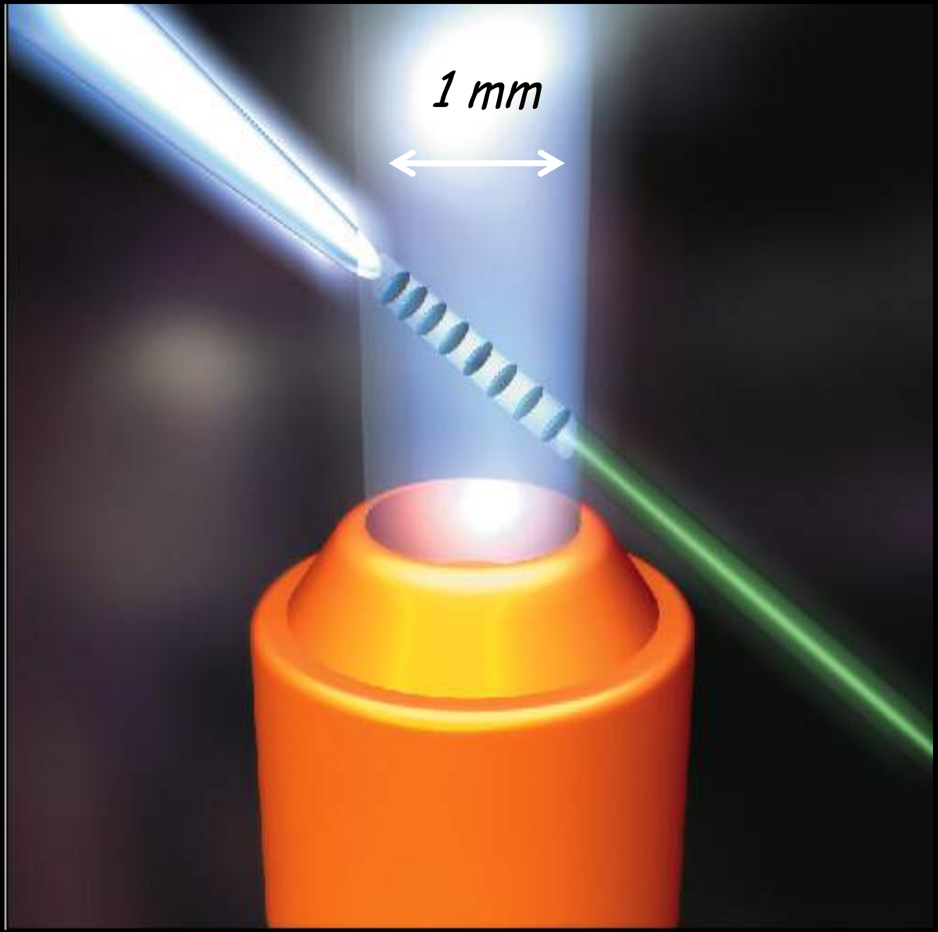


LWFA limitations: Diffraction, Dephasing, Depletion

PWFA limitations: Head Erosion, Hose Instability

Laser Driven
LWFA

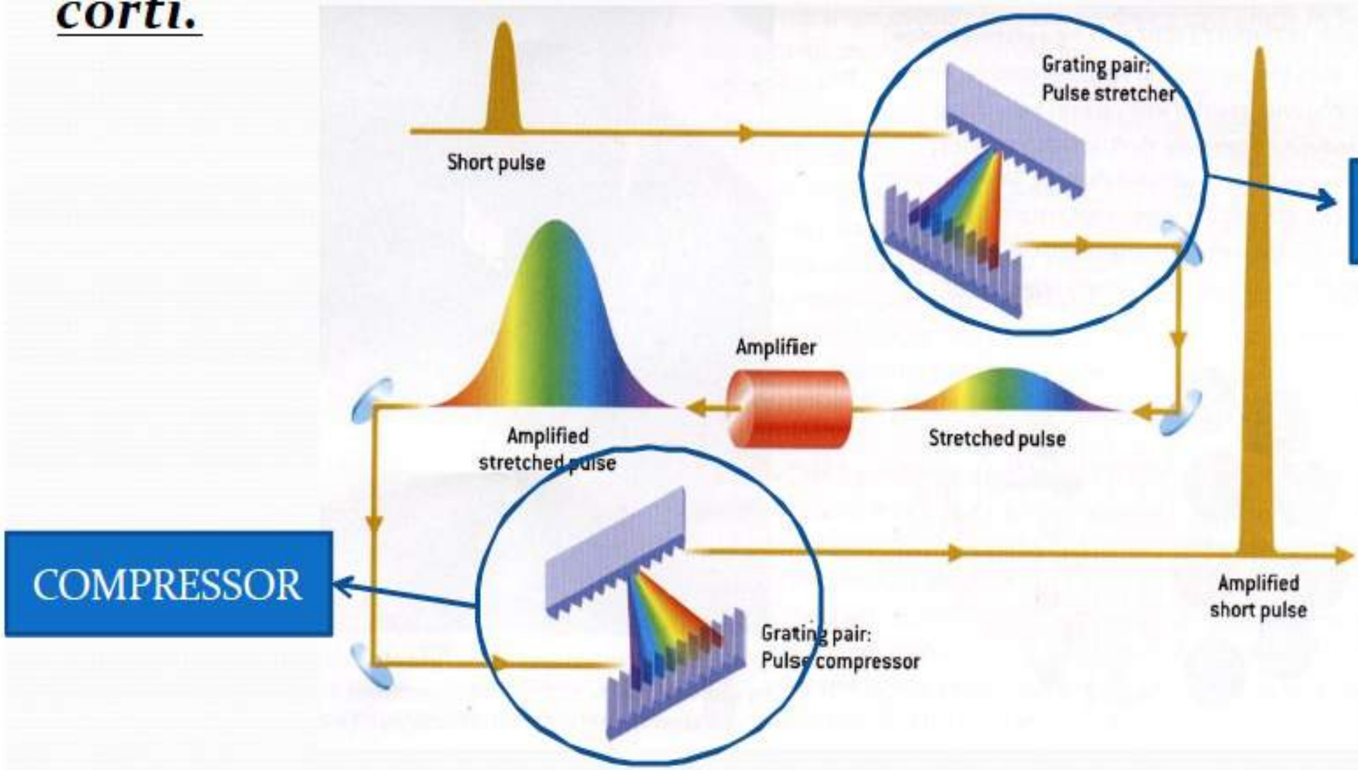
Direct production of e-beam



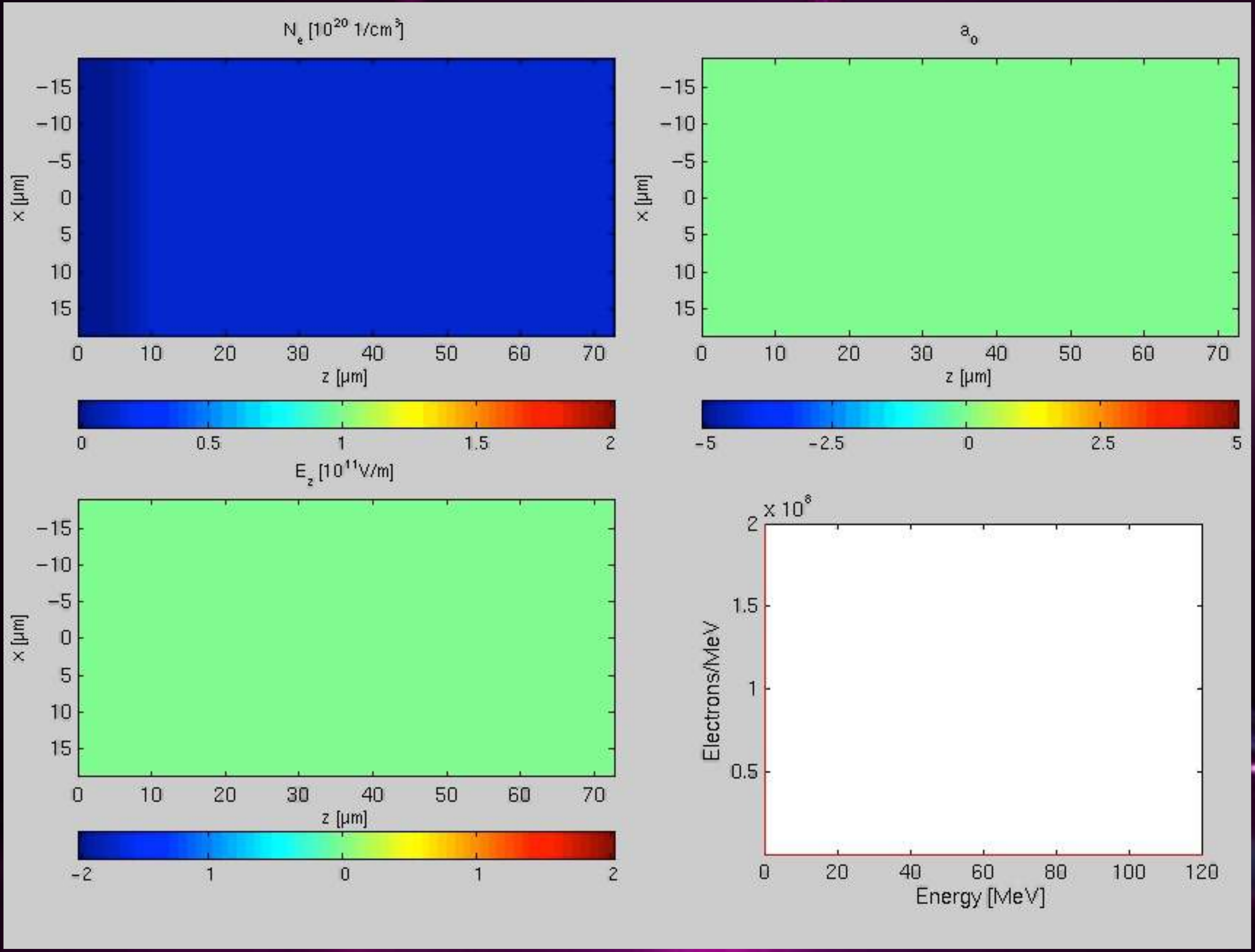
Electron beam

CPA: stretcher e compressore

La CPA – Chirped Pulse Amplification – è l'idea, semplice e geniale, suggerita nel 1985 da Strickland and Mourou, che si basa sulla manipolazione reversibile delle caratteristiche temporali del fascio laser e che permette di amplificare il fascio laser senza danneggiare le ottiche, ottenendo ***alte potenze e impulsi ultra-corti.***

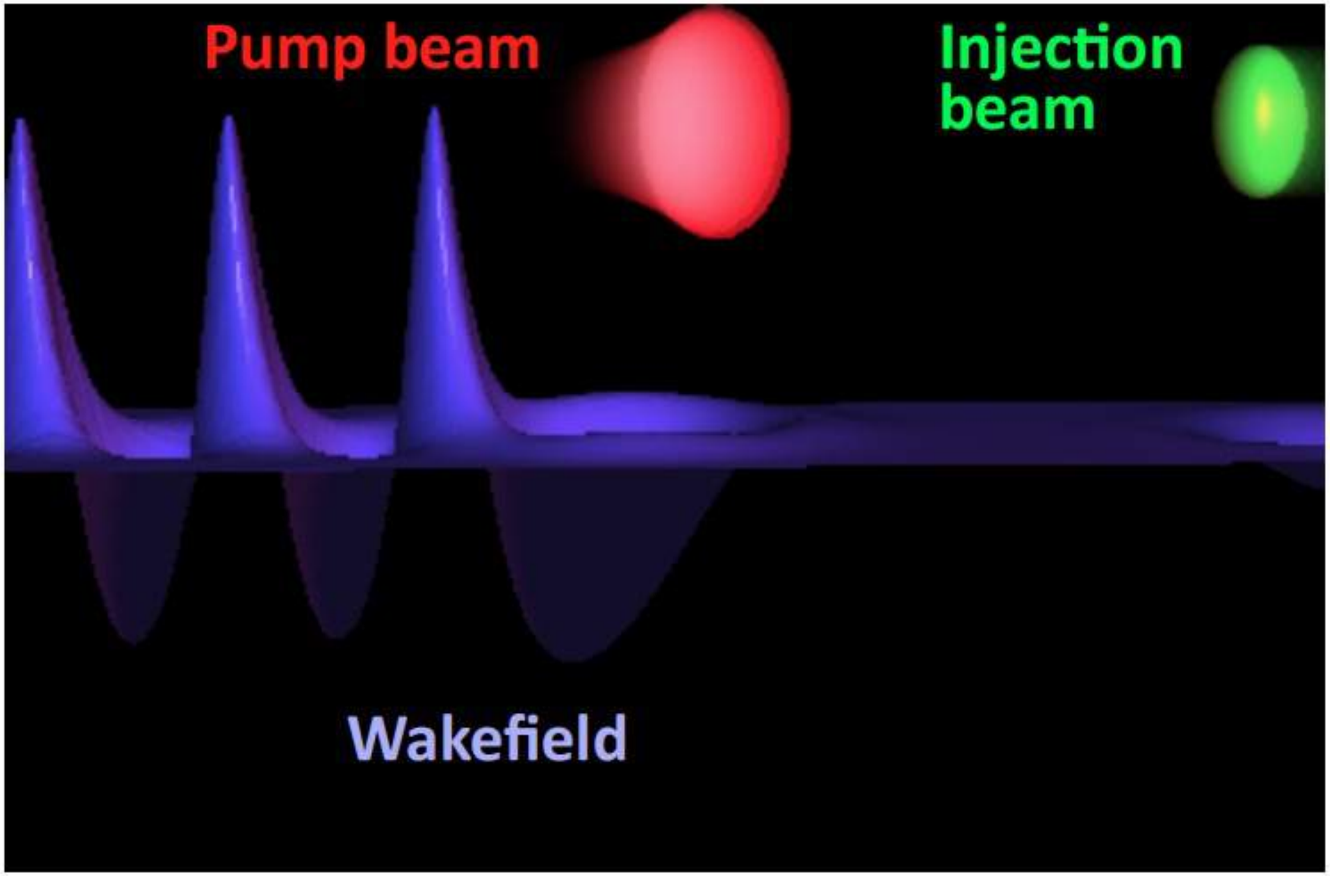


Diffraction - Self injection - Dephasing – Depletion



Colliding Laser Pulses Scheme

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



Break-Down Limit?
⇒ Wave-Breaking field: $E_{wb} \approx 100\left[GeV/m\right]\sqrt{n_o\left[cm^{-3}\right]}$

Colliding Laser Pulses Scheme

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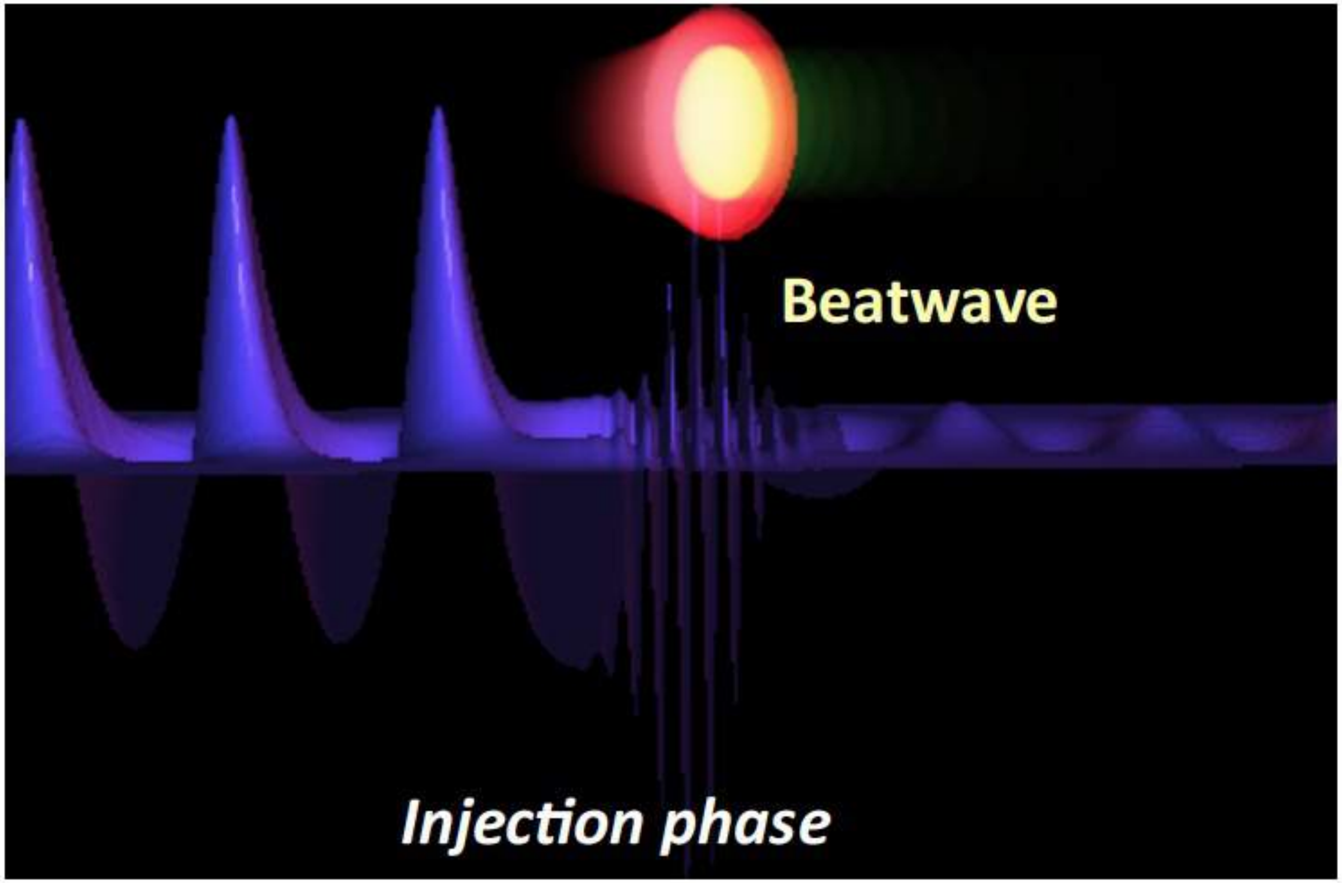

Theory : E. Esarey *et al.*, PRL **79**, 2682 (1997), H. Kotaki *et al.*, PoP **11** (2004)
Experiments : J. Faure *et al.*, Nature **444**, 737 (2006)

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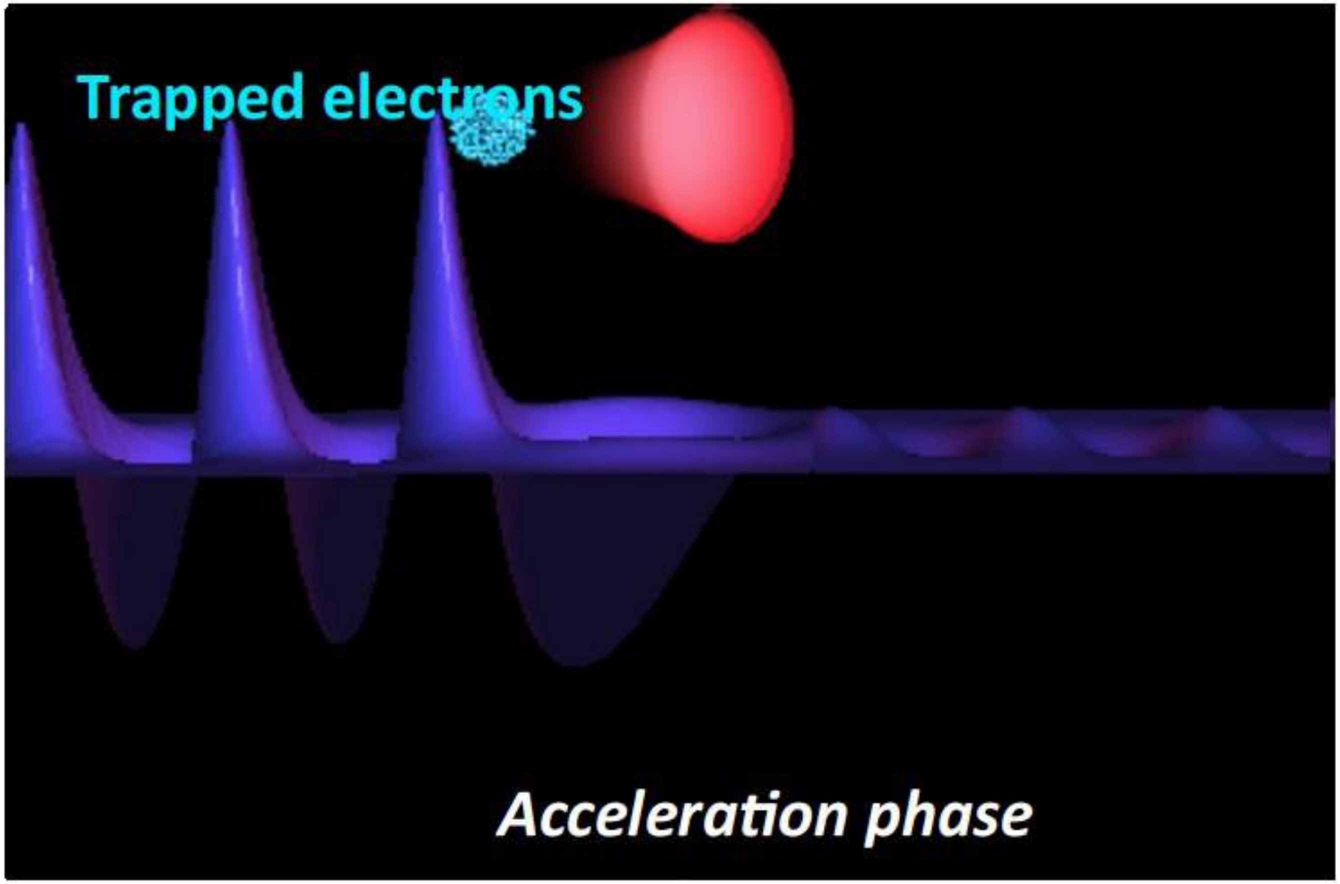
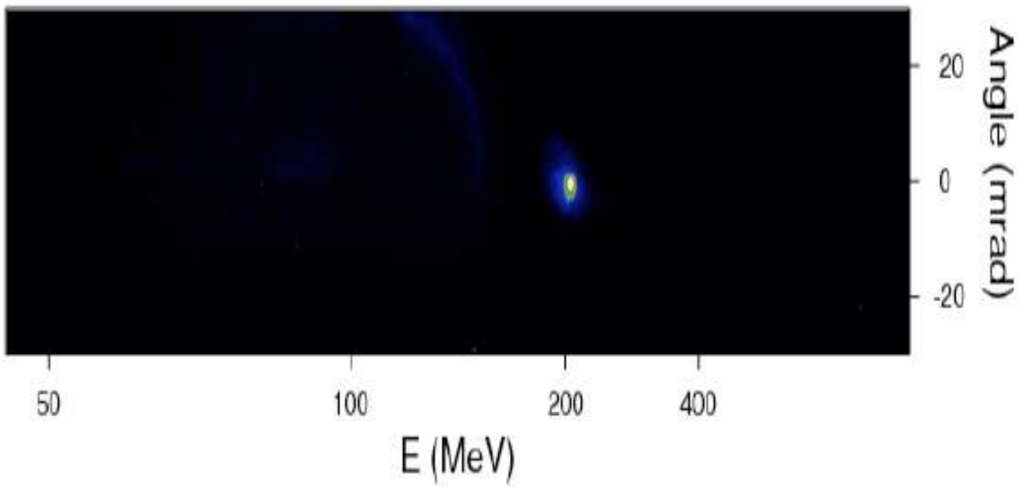
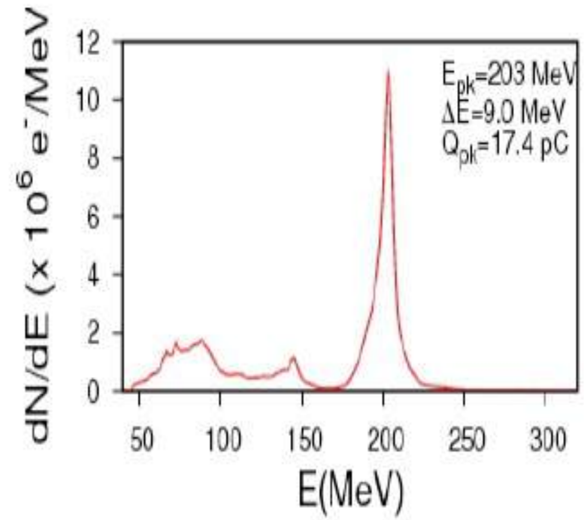


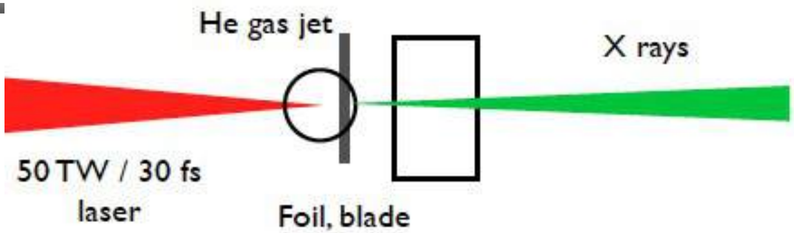
Theory : E. Esarey *et al.*, PRL **79**, 2682 (1997), H. Kotaki *et al.*, PoP **11** (2004)
Experiments : J. Faure *et al.*, Nature **444**, 737 (2006)

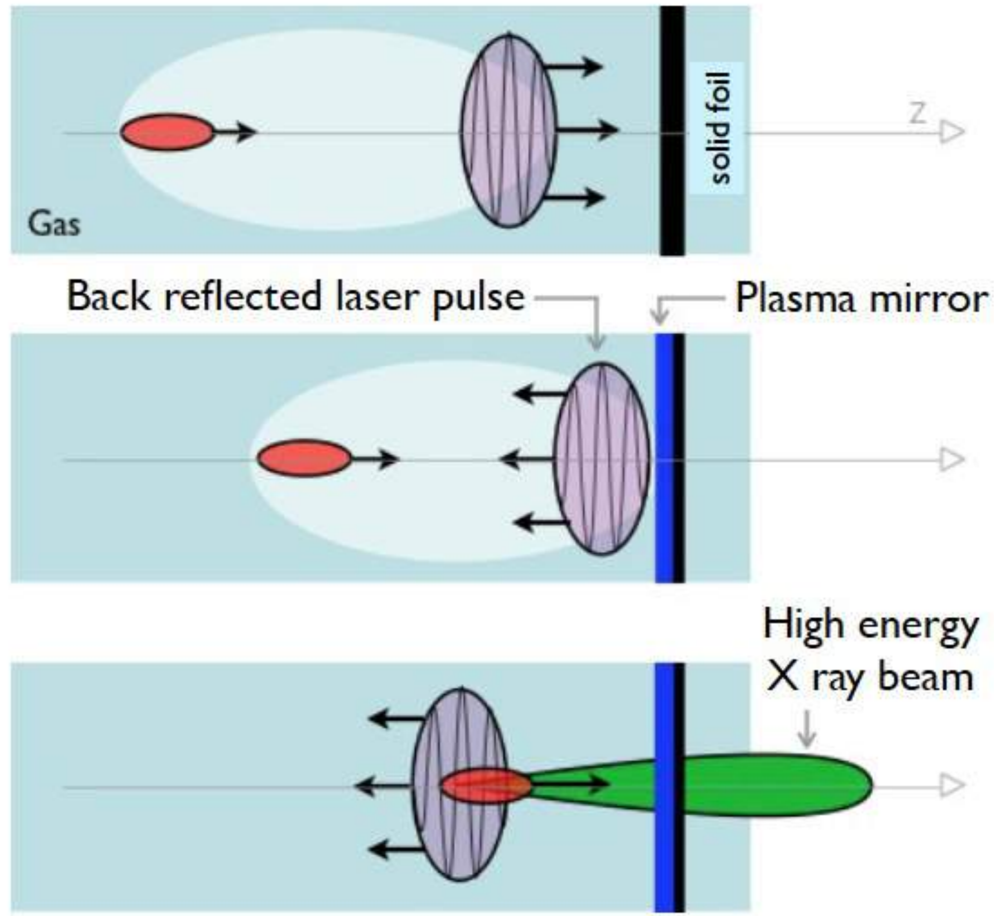
Stable Laser Plasma Accelerators





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

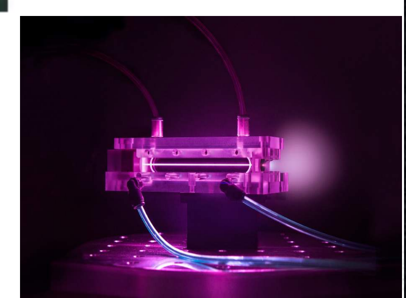
Save the laser energy !

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

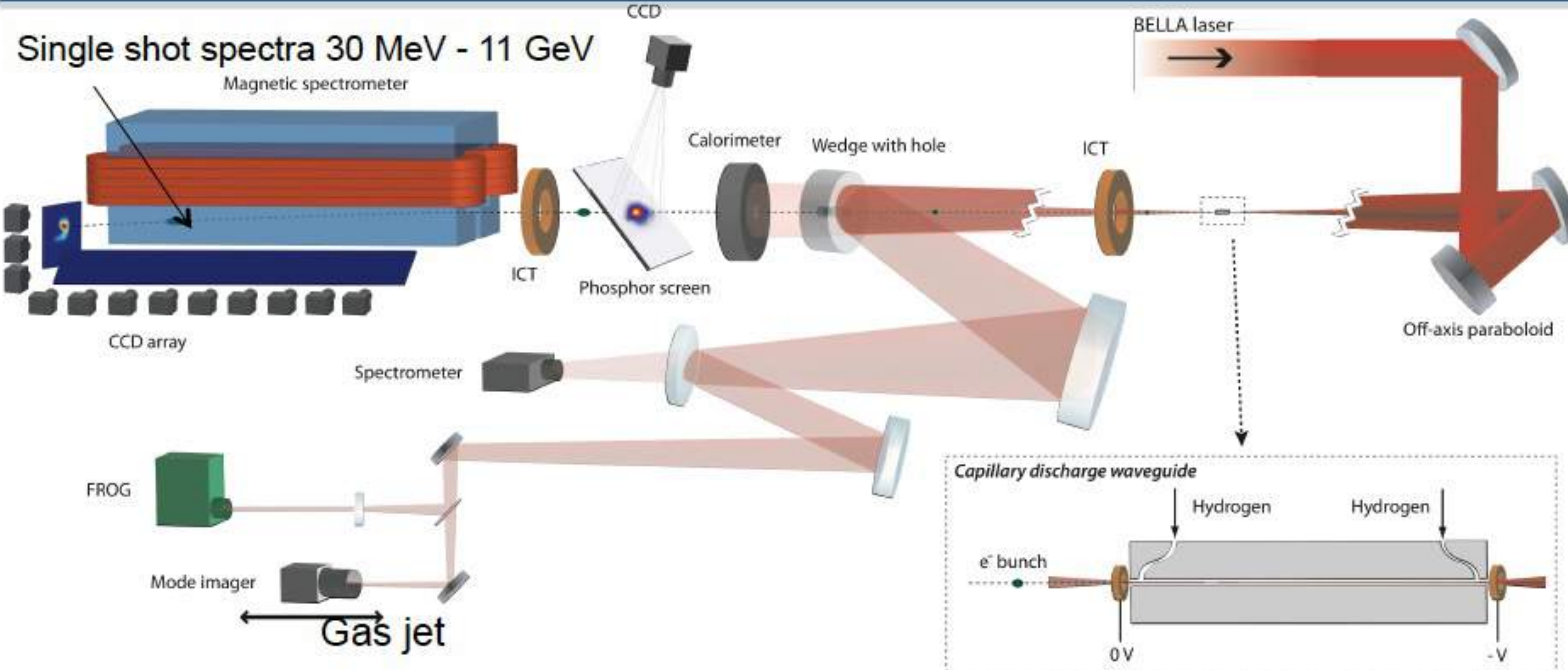
Critical HEP experiments:

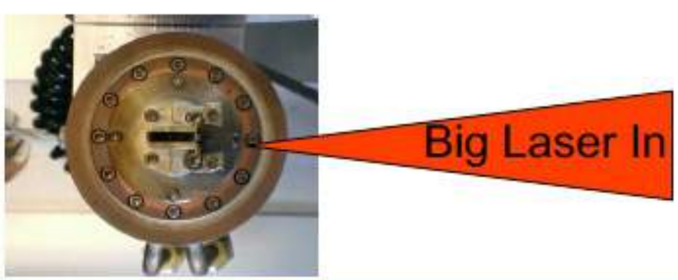
- 10 GeV electron beam from <1 m LPA
- Staging LPAs
- Positron acceleration



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

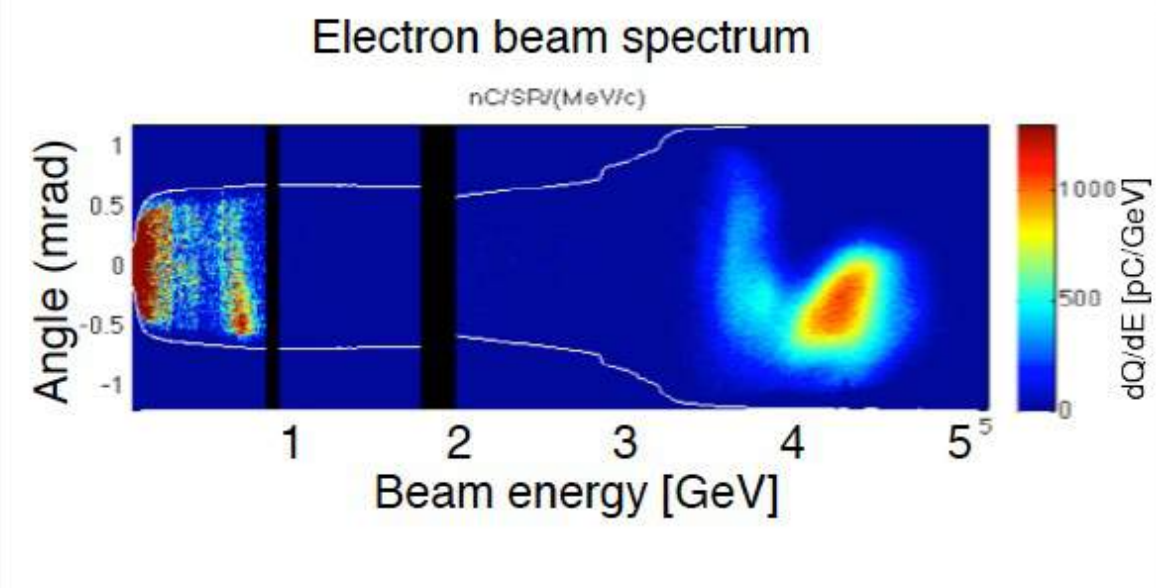


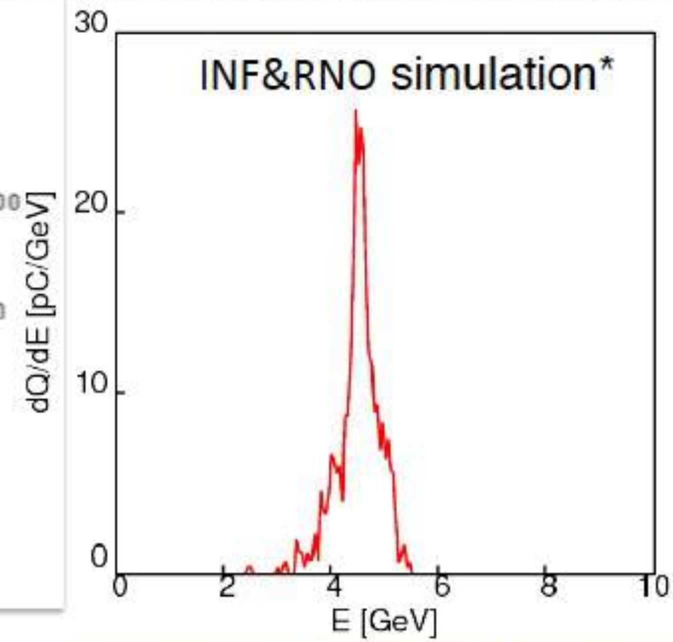


Capillary discharge

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



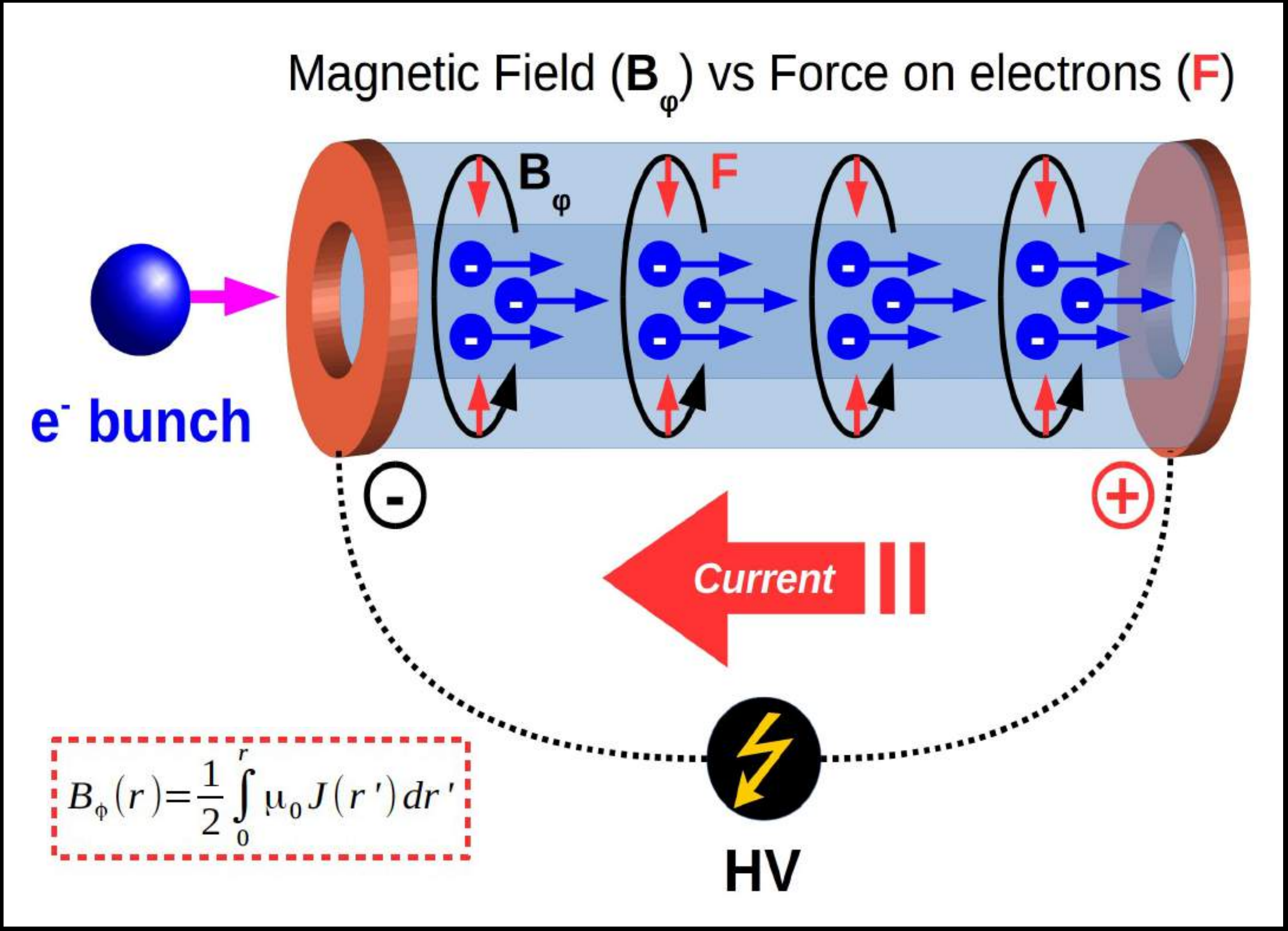


	Exp.	Sim.
Energy	4.25 GeV	4.5 GeV
ΔE/E	5%	3.2%
Charge	~20 pC	23 pC
Divergence	0.3 mrad	0.6 mrad

- **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})

W.P. Leemans et al.,PRL 2014

Active Plasma Lens

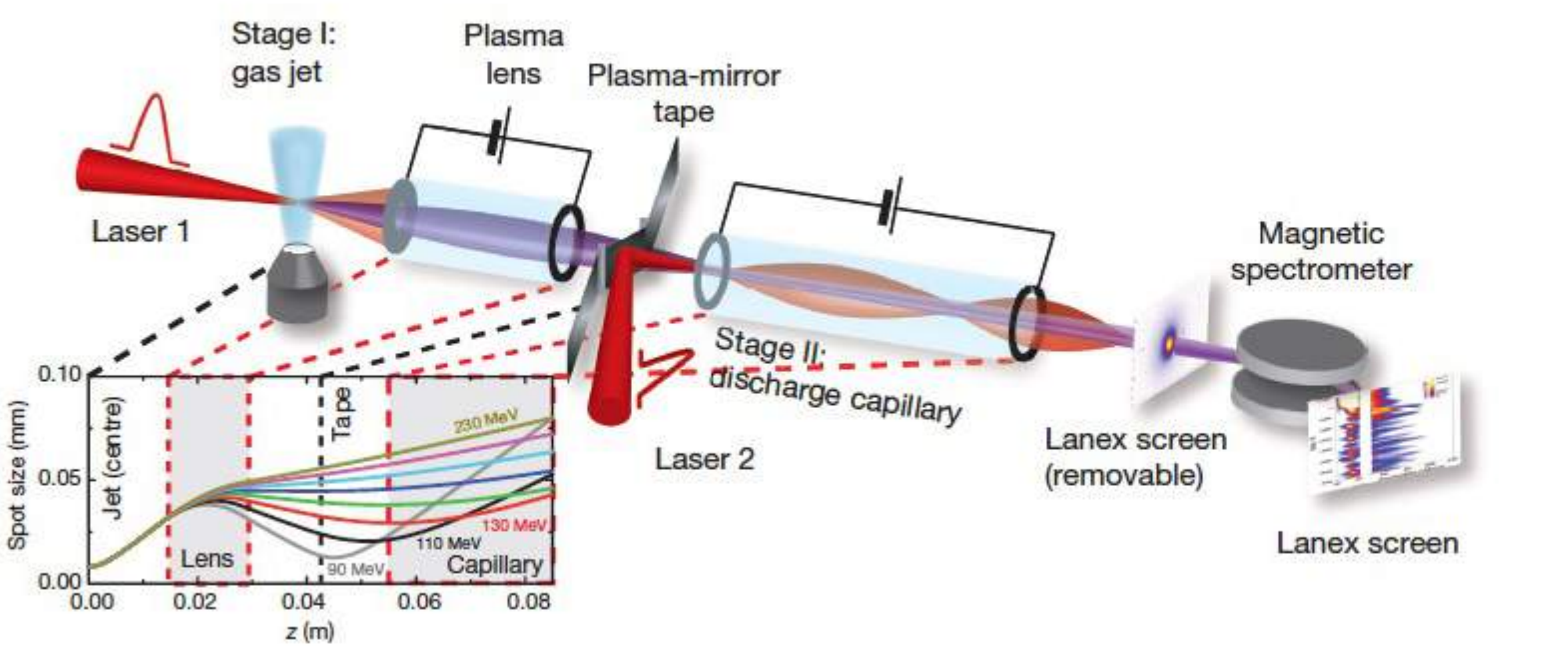


LETTER

doi:10.1038/nature16525

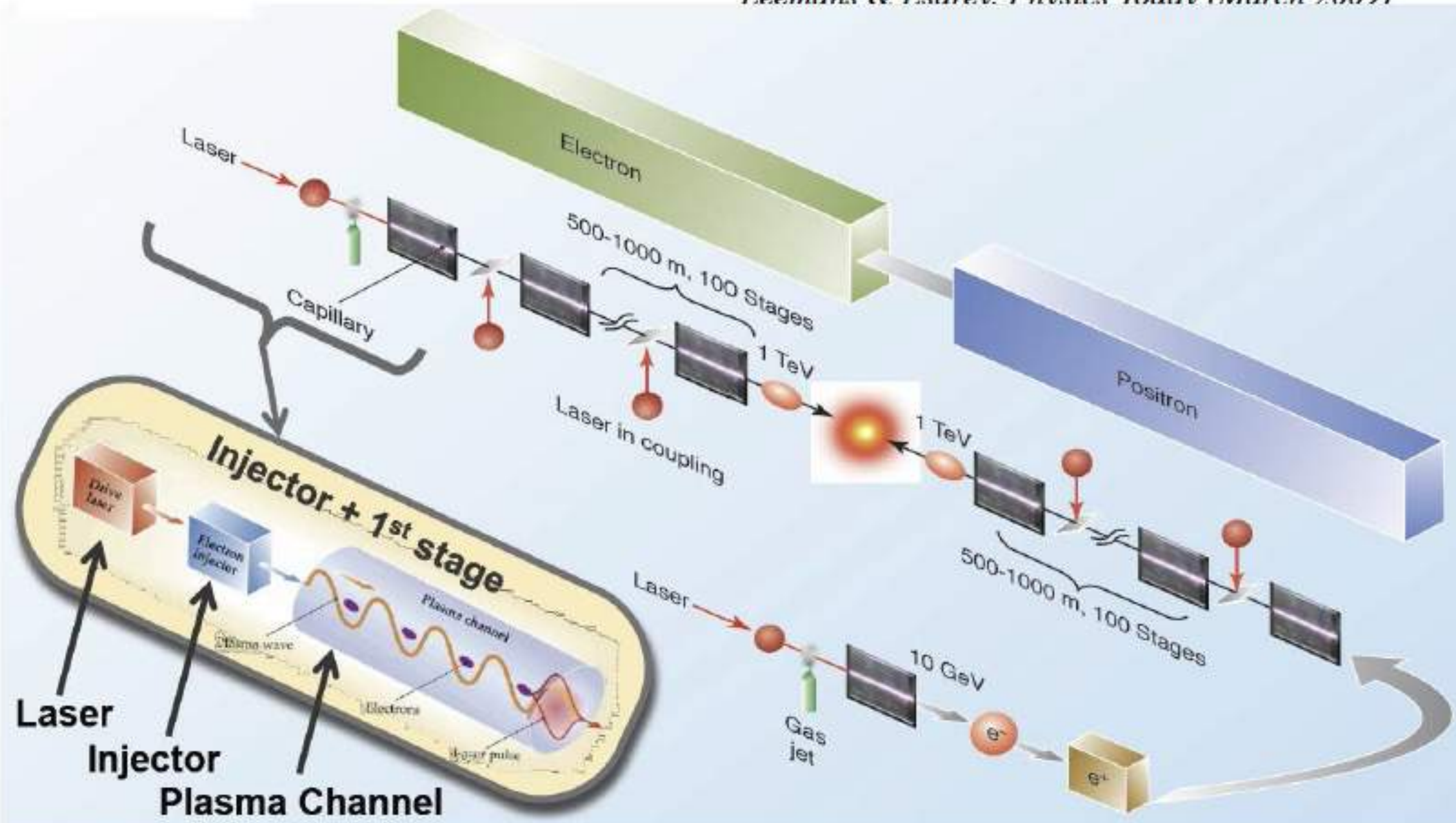
Multistage coupling of independent laser–plasma accelerators

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]



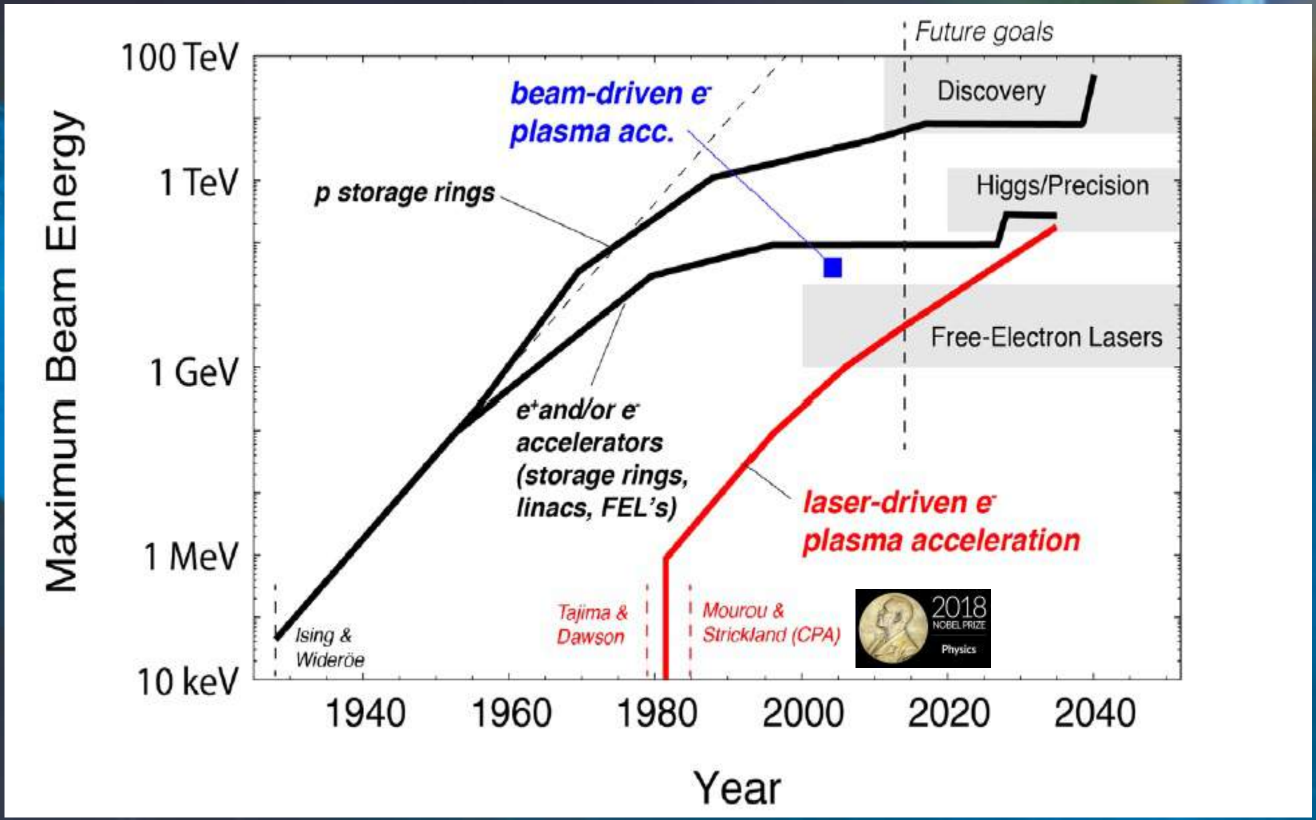
Laser-Plasma-Accelerator LC

Leemans & Esarey, Physics Today (March 2009)



Introduzione alla Fisica degli Acceleratori di Particelle
3

Massimo.Ferrario@LNF.INFN.IT



Principle of plasma acceleration

Driven by Radiation Pressure

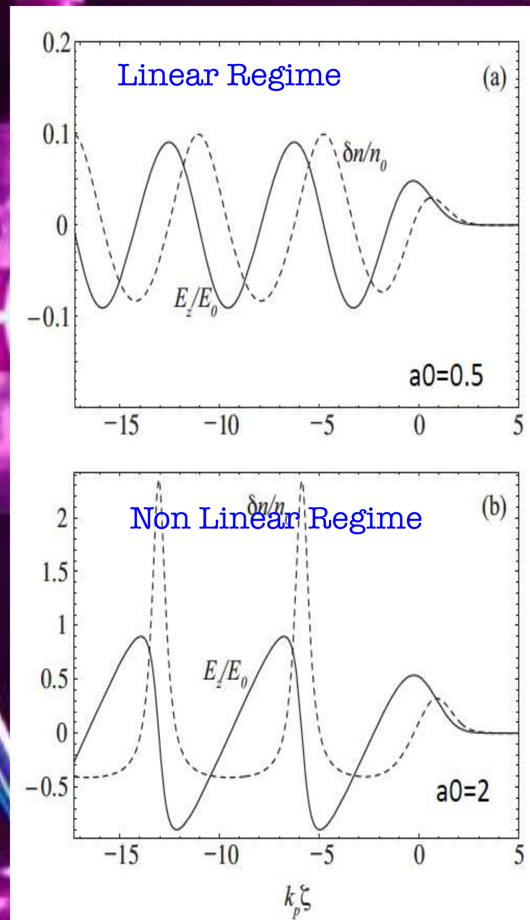
$$\left(\frac{\partial^2}{\partial t^2}+\omega_p^2\right)\frac{n}{n_o}=c^2\nabla^2\frac{a^2}{2}$$

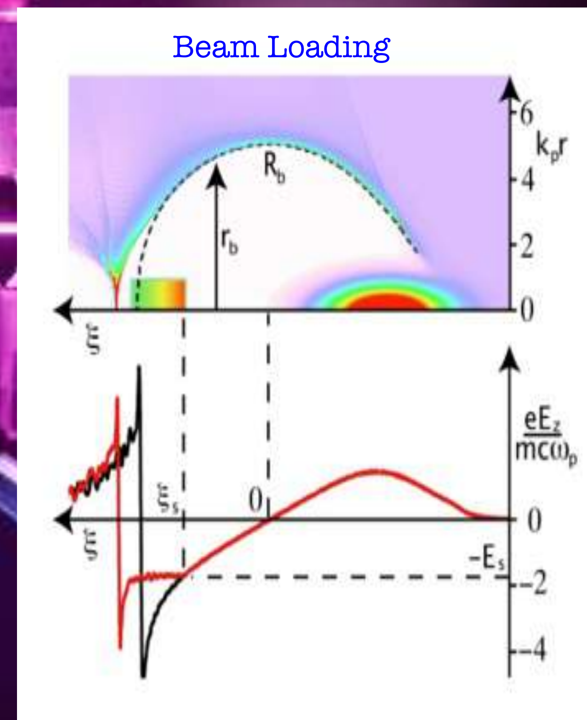
$$a=\frac{eA}{mc^2}\propto \lambda J^{1/2}$$

Driven by Space Charge

$$\left(\frac{\partial^2}{\partial t^2}+\omega_p^2\right)\frac{n}{n_o}=-\omega_p^2\frac{n_{beam}}{n_o}$$

$$n_{beam}=\frac{N}{\sqrt{(2\pi)^3}\sigma_r^2\sigma_z}$$

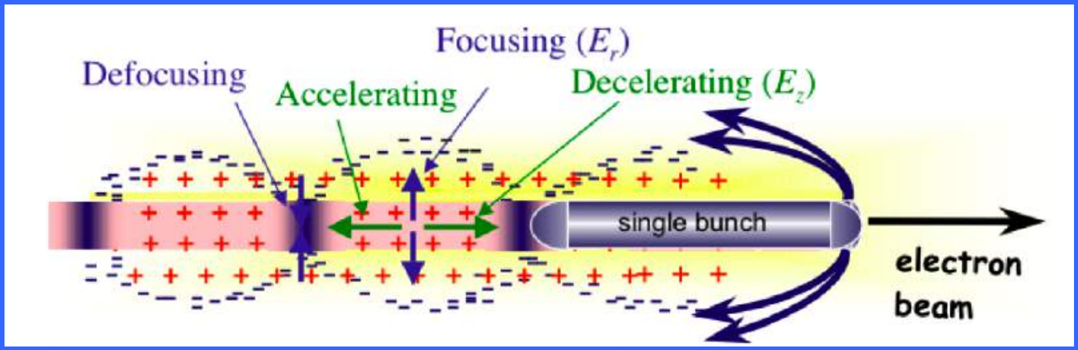


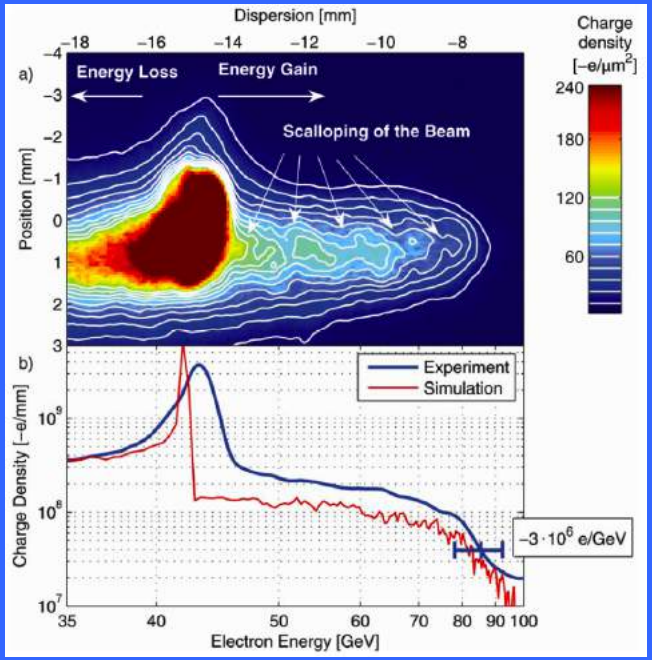


LWFA limitations: Diffraction, Dephasing, Depletion

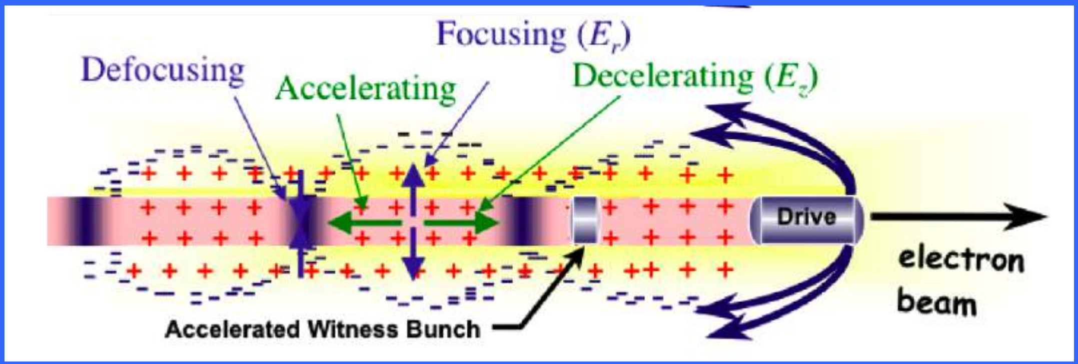
PWFA limitations: Head Erosion, Hose Instability

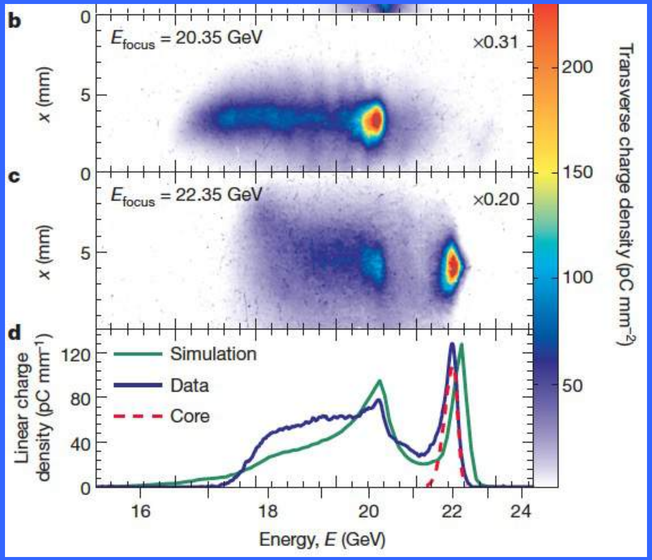
Beam Driven
PWFA





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).

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

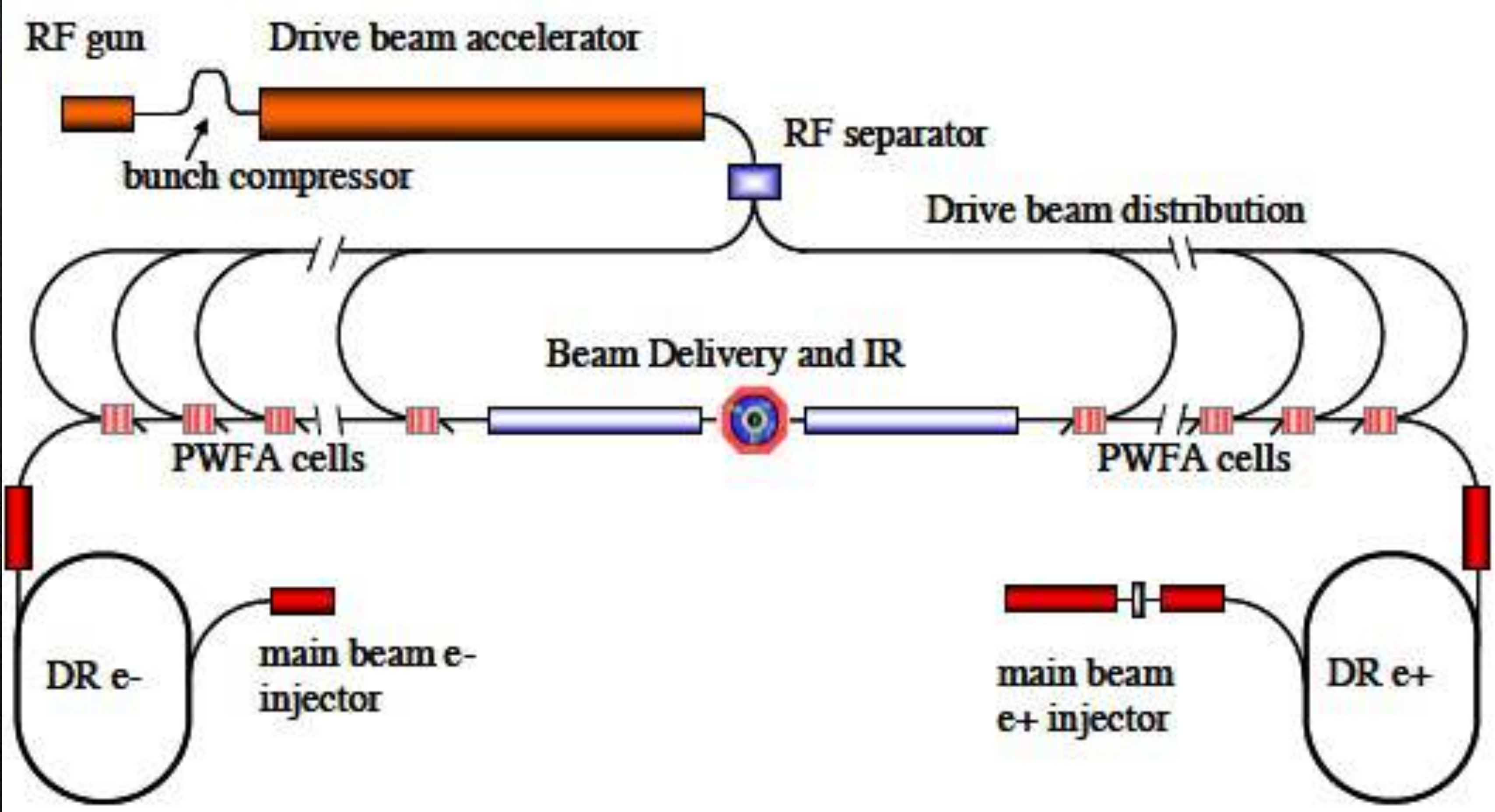
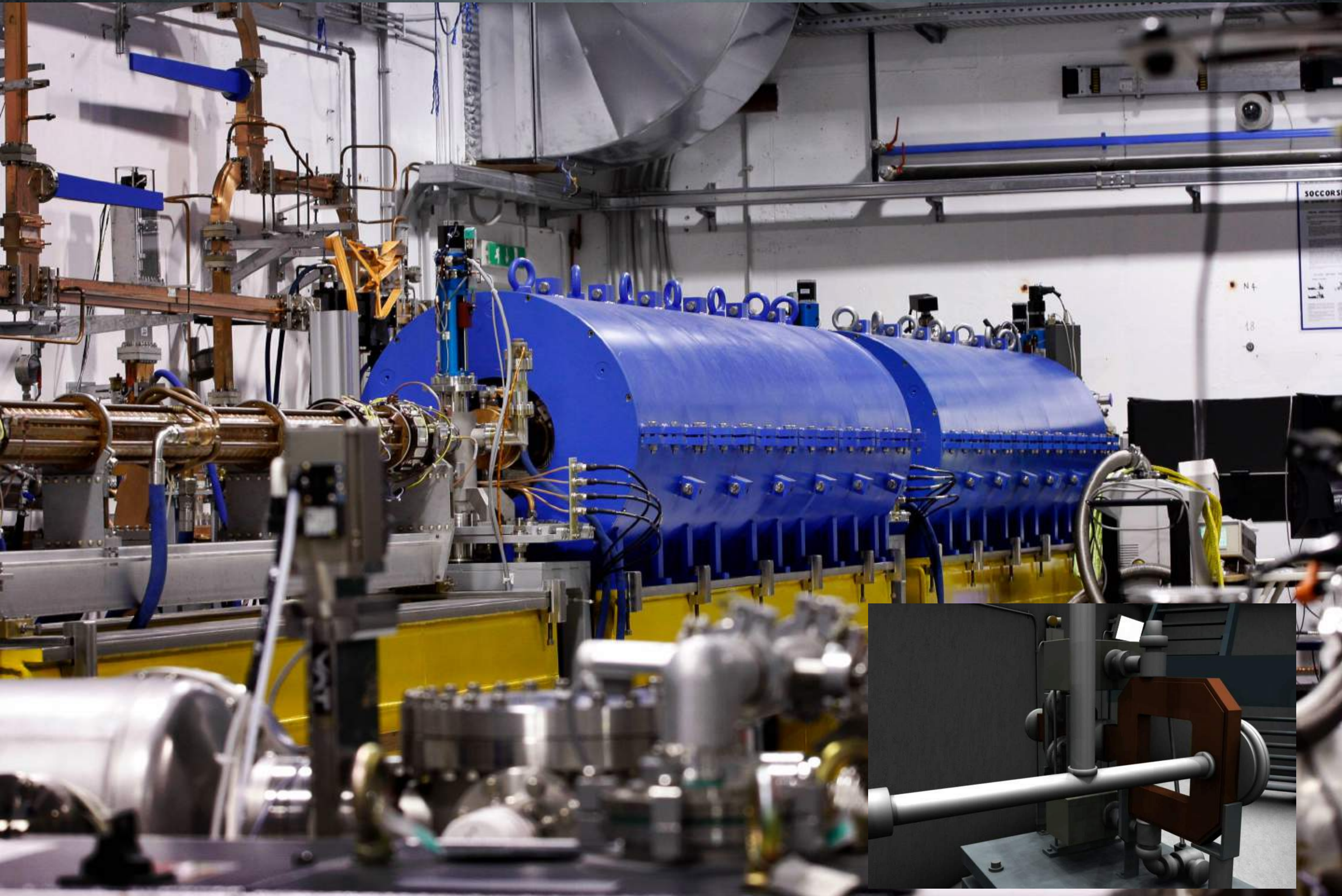


Fig. 1: Concept for a multi-stage PWFA Linear Collider.

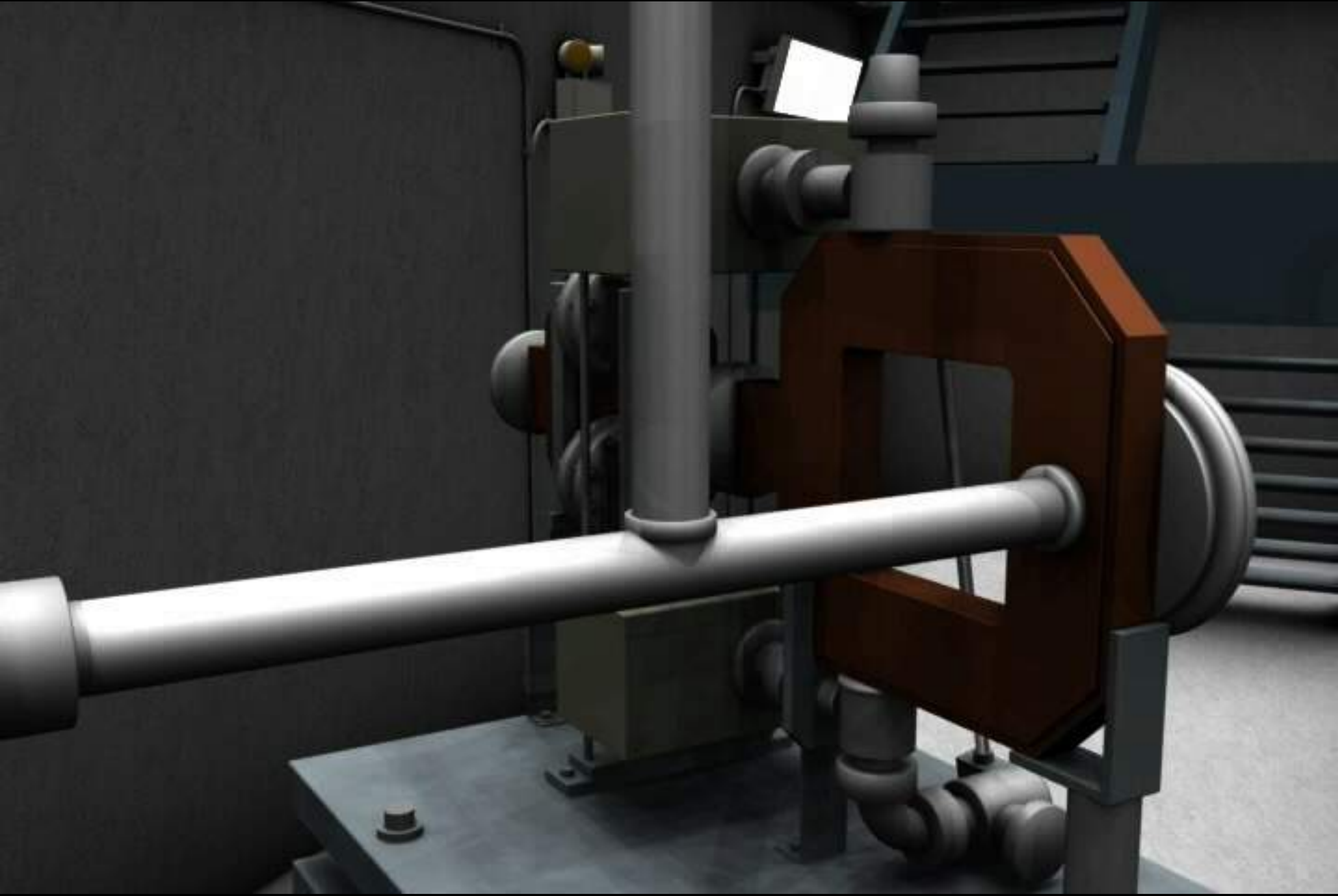
SPARC_LAB is the test and training facility at LNF for Advanced Accelerator Developments (since 2005)


High harmonics in a single pass seeded FEL amplifier

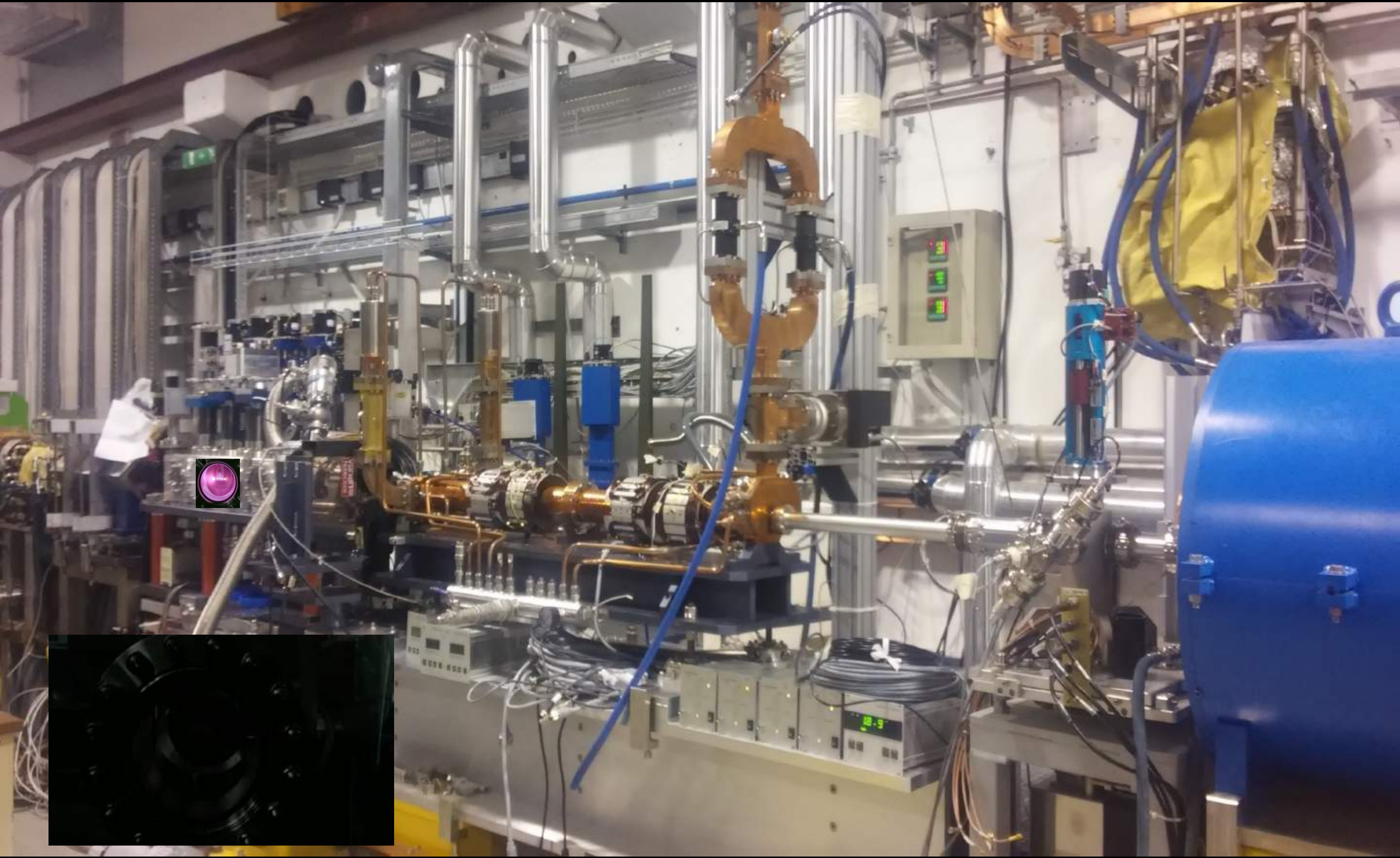
High Brightness Photo-injector with Velocity Bunching

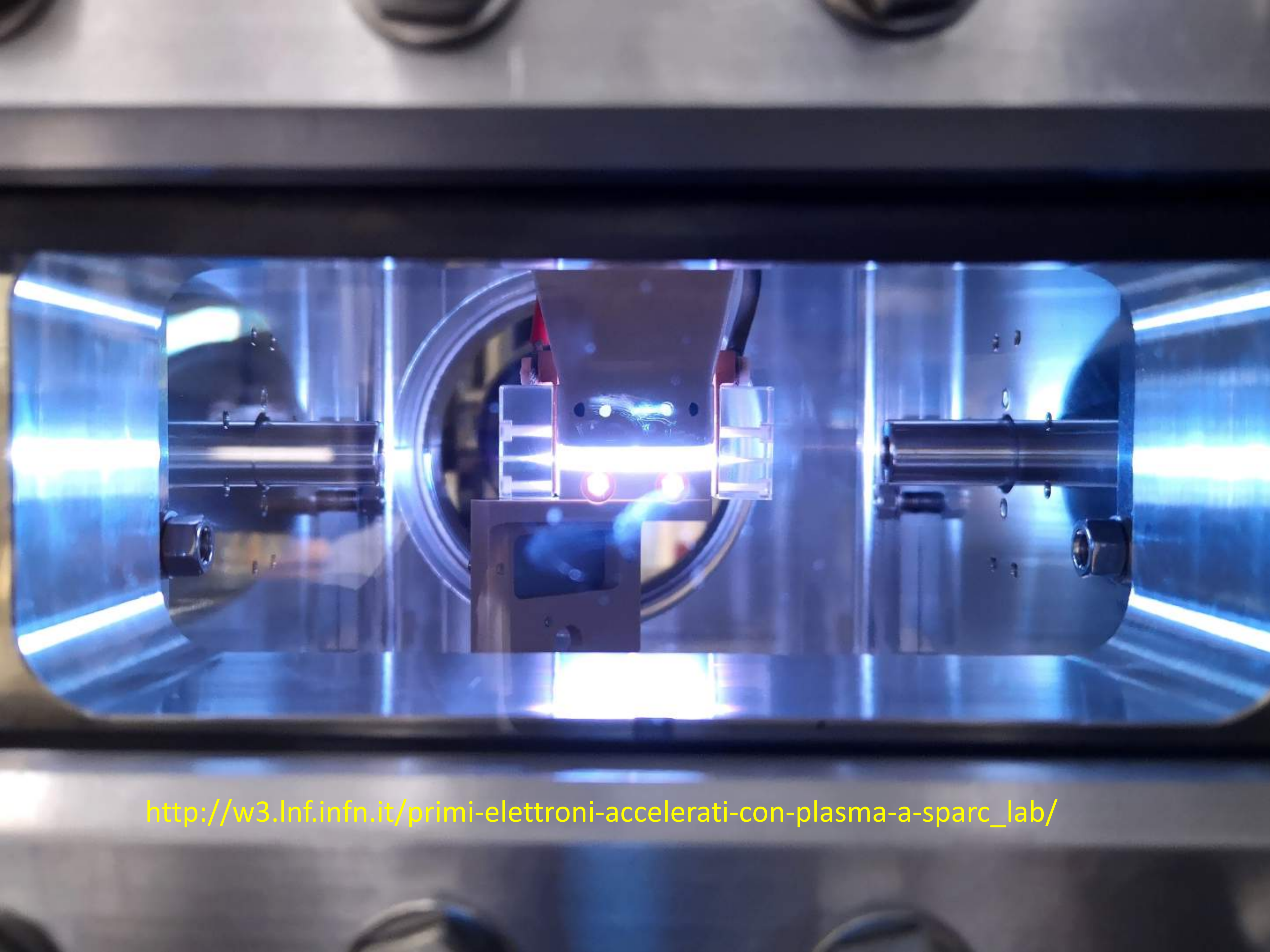


Electron source and acceleration



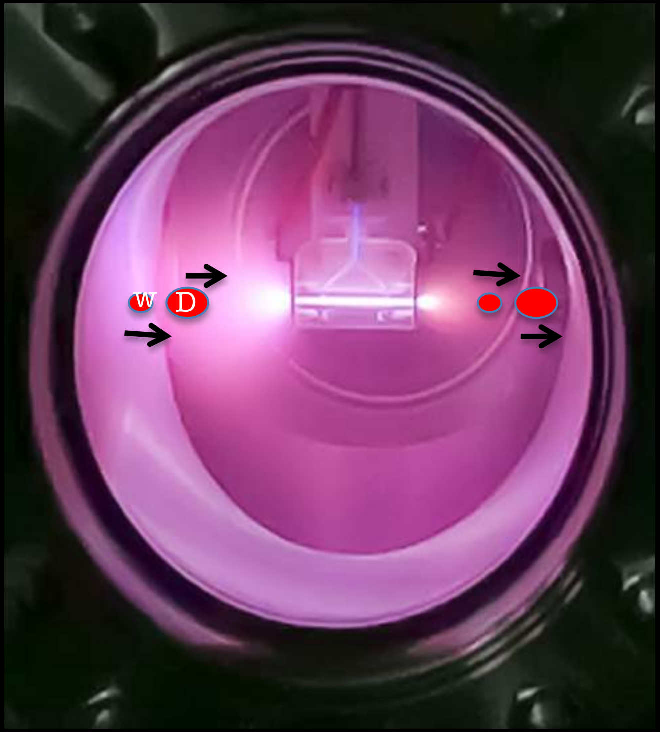
PWFA vacuum chamber at SPARC_LAB



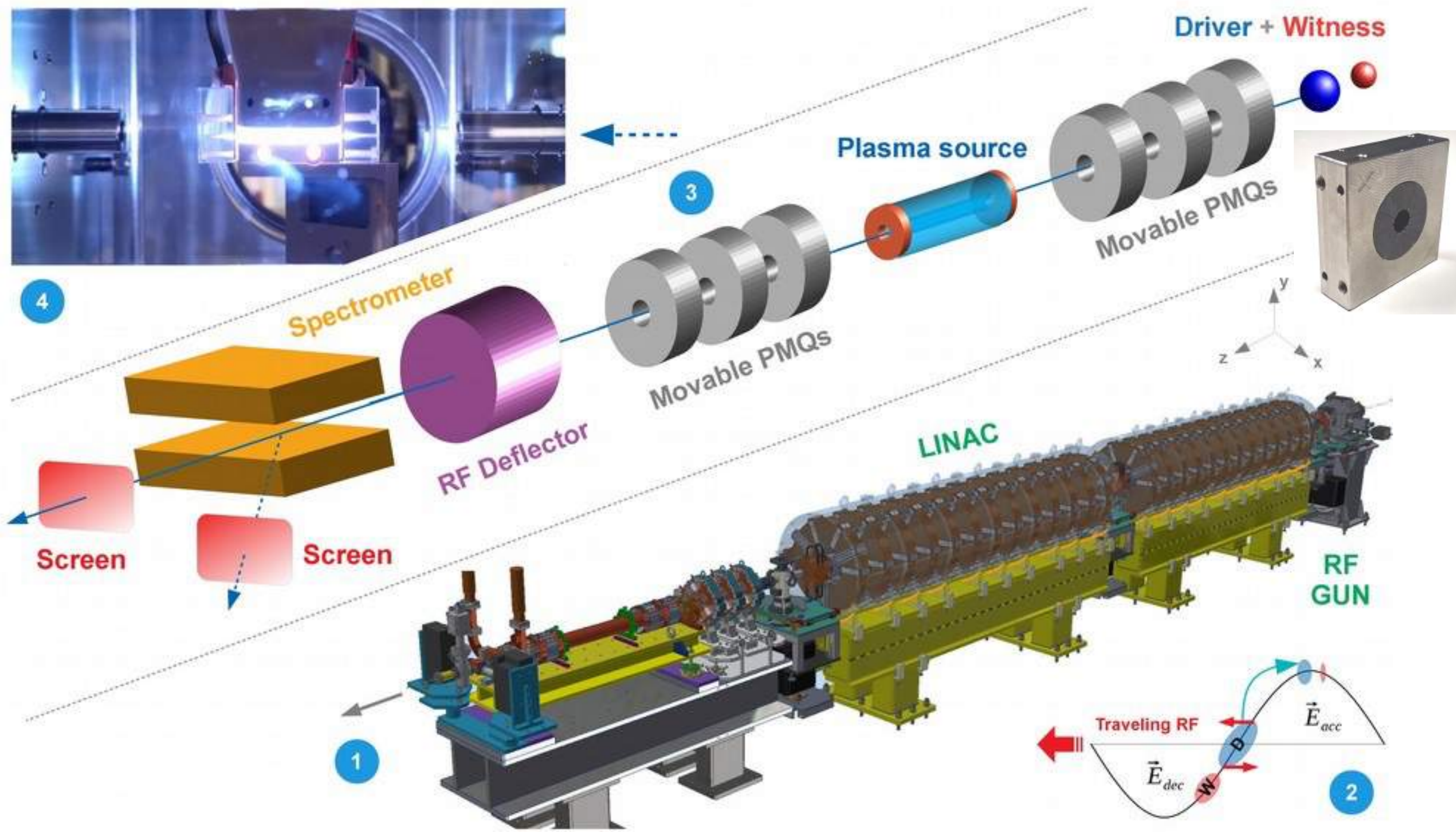


http://w3.lnf.infn.it/primi-elettroni-accelerati-con-plasma-a-sparc_lab/

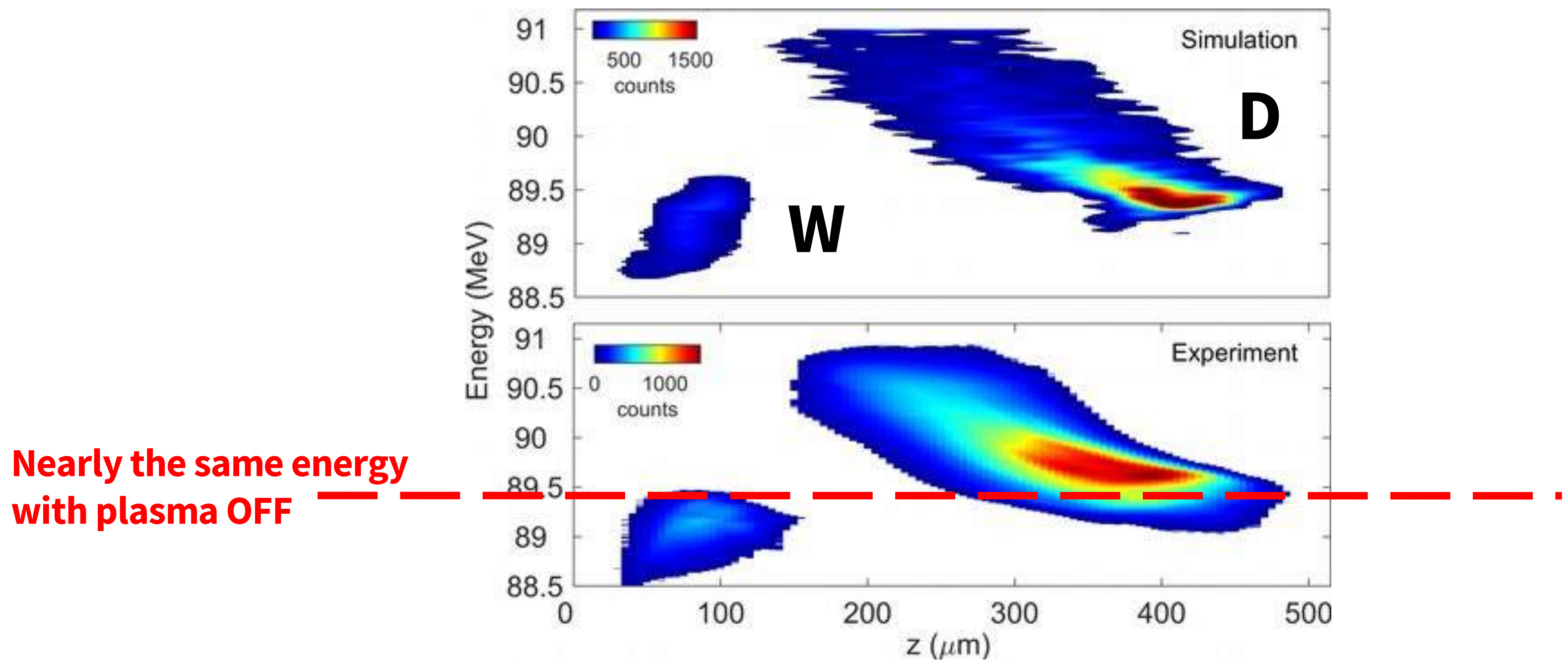
Beam Driven



Plasma acceleration experiment



Beam configuration



Two-bunches configuration produced directly at the cathode with laser-comb technique

200 pC driver (charge increased up to 350 pC) followed by witness bunch (20 pC)

Ultra-short durations (200 fs + 30 fs)

Separation approximately equal to ¾ of the plasma wavelength (~1 ps)

By increasing the driver charge a **larger ion bubble is produced**

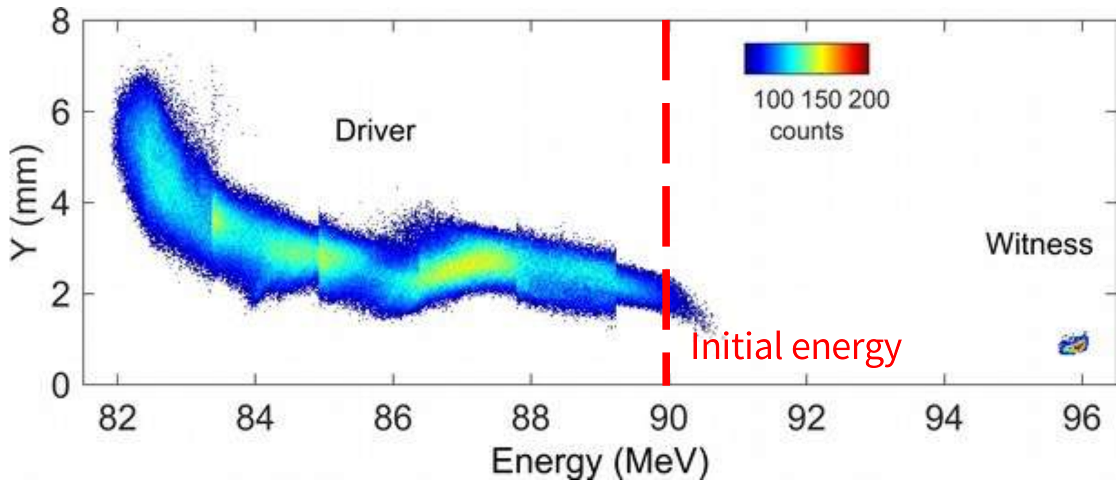
Achieved 7 MeV acceleration in 3 cm plasma with 350 pC driver

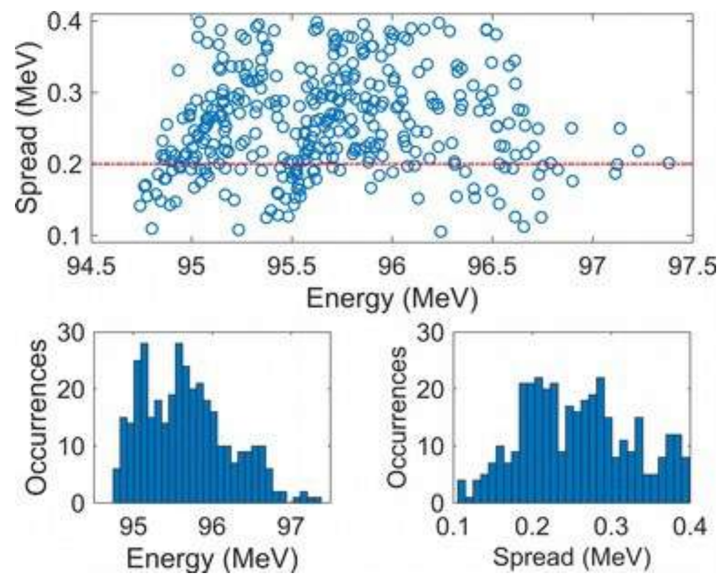
- *~233 MV/m accelerating gradient*
- *2×10^{15} cm^{-3} plasma density*

Energy spread of the accelerated beam slightly increased

- *Energy spread from 0.2% to 0.26%*

Still order of magnitudes lower spread with respect to previous experiments





The near future

Beam Quality Requirements

Future accelerators will require also high quality beams :

==> High Luminosity & High Brightness,

==> High Energy & Low Energy Spread

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

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

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

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

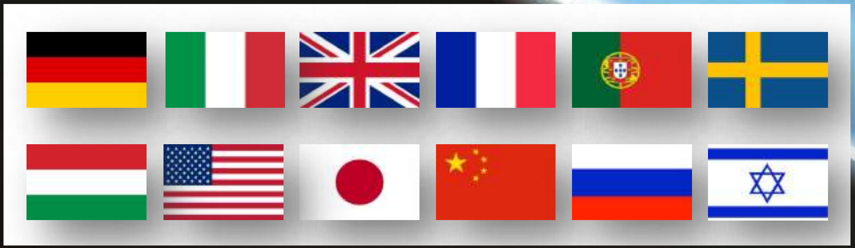
EUROPEAN
PLASMA RESEARCH
ACCELERATOR WITH
EXCELLENCE IN
APPLICATIONS

EuPRAXIA

EuPRAXIA Design Study started on Novemebr 2015

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.

http://eupraxia-project.eu

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

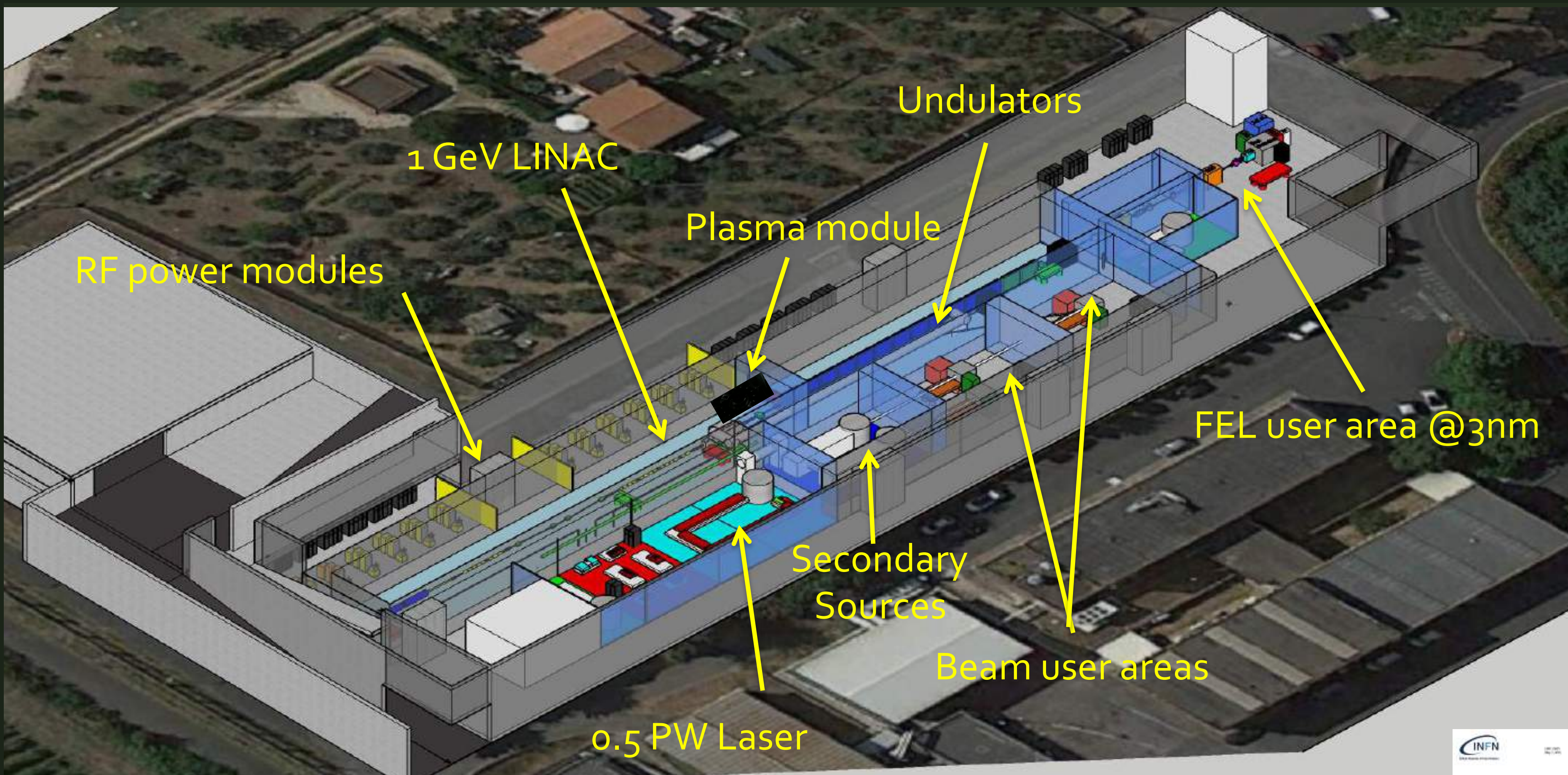
Courtesy R. Assmann

Location of possible sites within EU

Horizon 2020

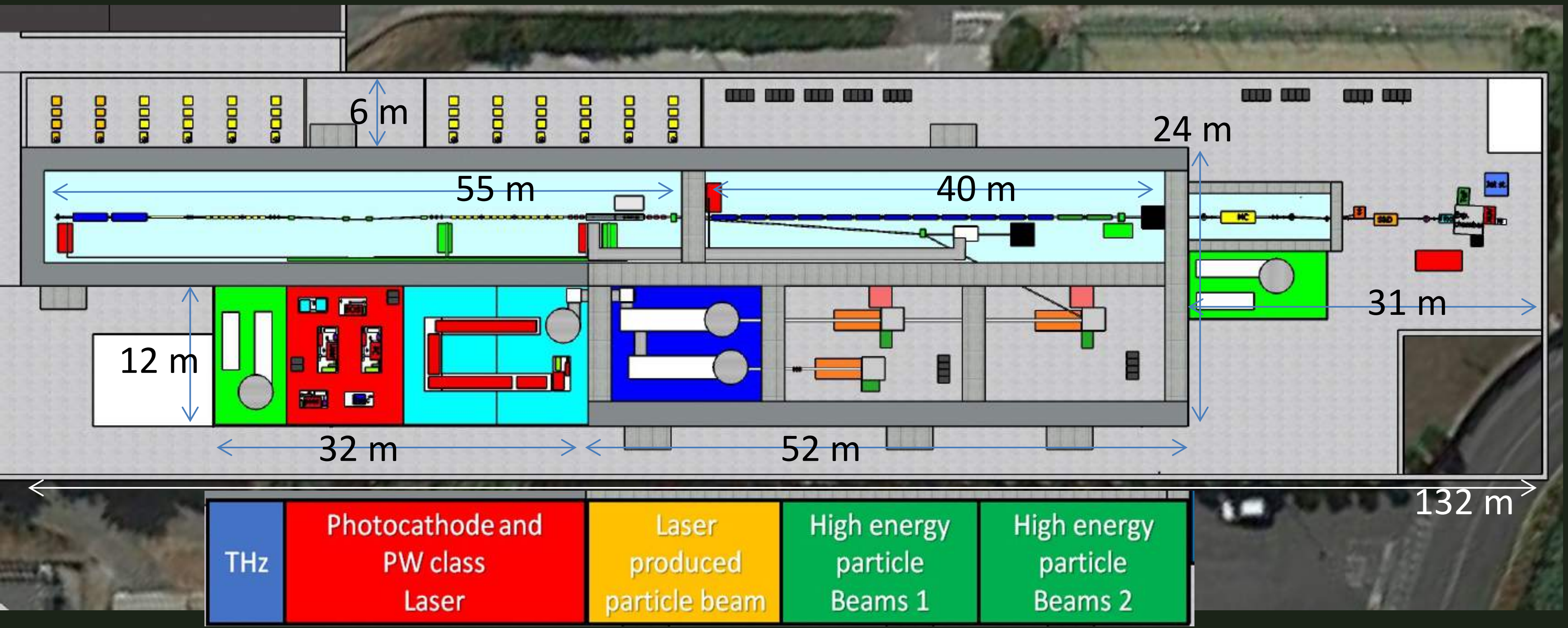
EuPRAXIA site studies:
- Design study is site independent
- Five possible sites have been discussed so far
- We invite the suggestions of additional sites

EuPRAXIA@SPARC_LAB



http://www.lnf.infn.it/sis/preprint/pdf/getfile.php?filename=INFN-18-03-LNF.pdf

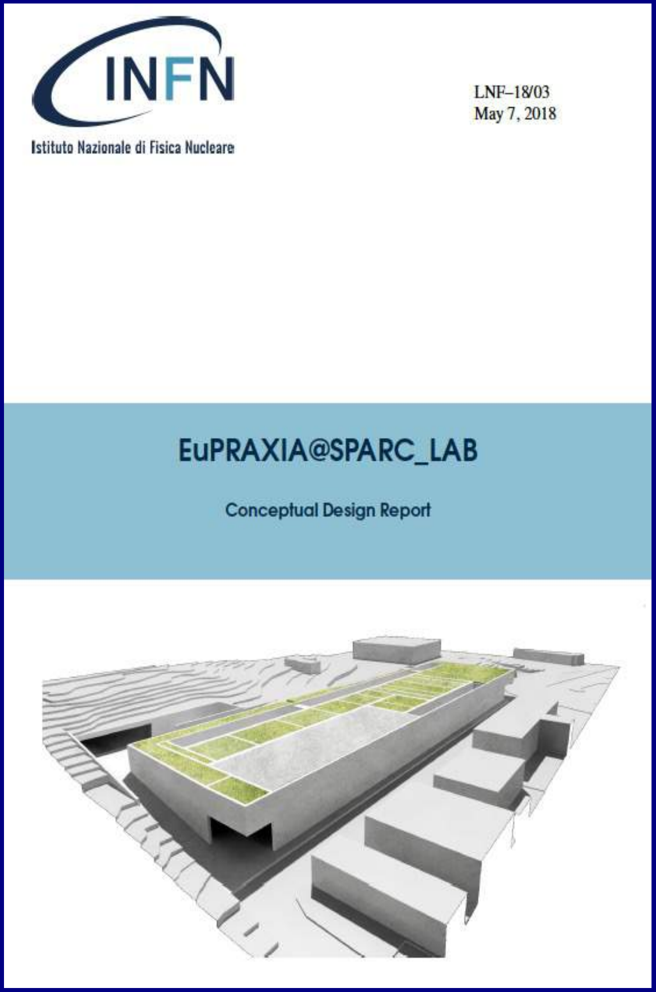
- Candidate LNF to host EuPRAXIA (1-5 GeV)
- FEL user facility (1 GeV – 3nm)
- Advanced Accelerator Test facility (LC) + CERN



- 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

Free Electron Laser

Conceptual Design Report Ready for the LNF site



INFN
Istituto Nazionale di Fisica Nucleare

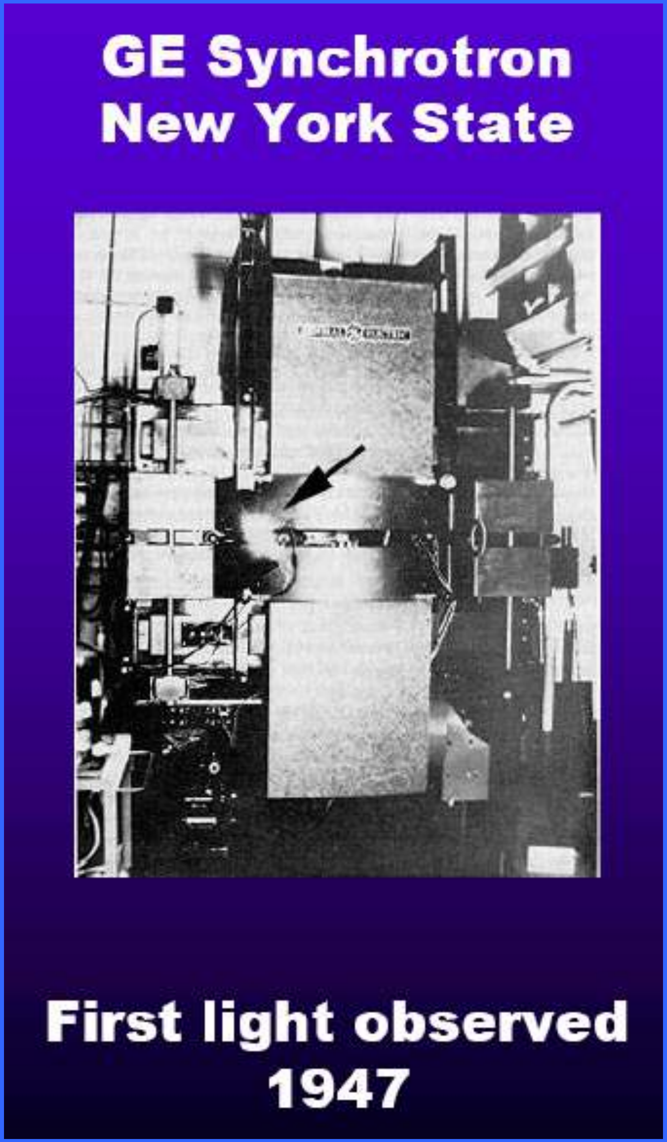
LNF–18/03
May 7, 2018

EuPRAXIA@SPARC_LAB

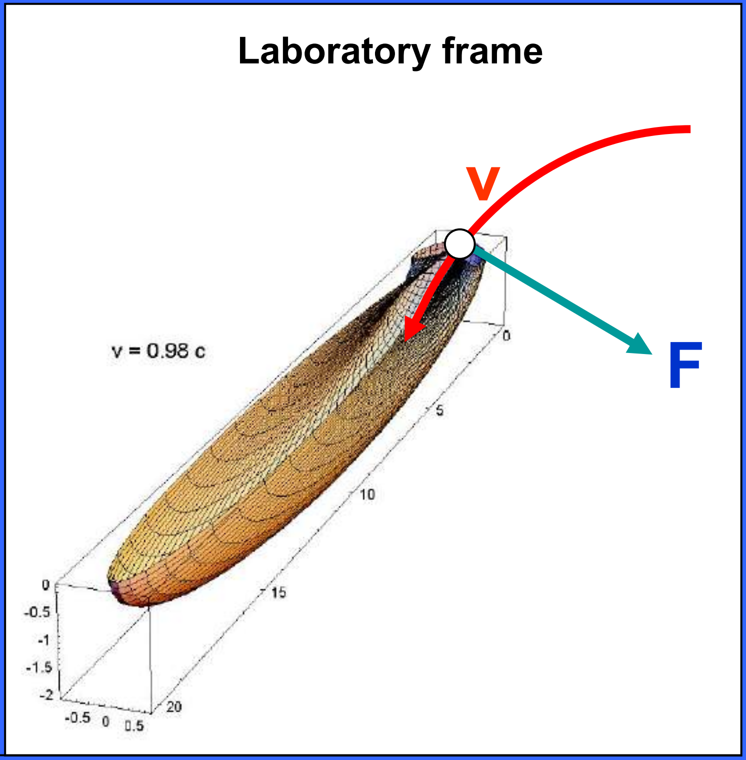
Conceptual Design Report

http://www.lnf.infn.it/sis/preprint/pdf/getfile.php?filename=INFN-18-03-LNF.pdf

Synchrotron Radiation

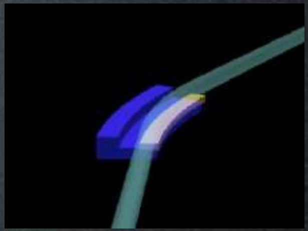


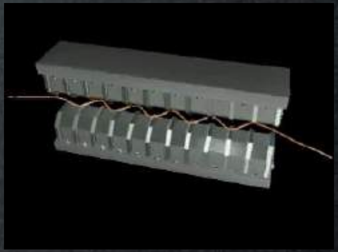
$$P_\gamma = \frac{cC_\gamma}{2\pi} \cdot \frac{E^4}{\rho^2}$$

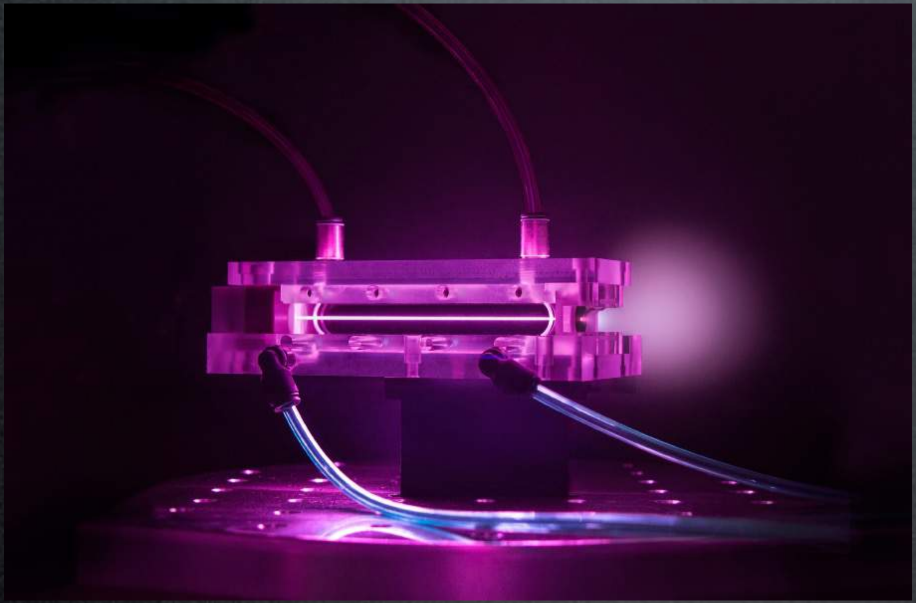


Generations of Synchrotron Light Sources

I. Bending magnets in HEP rings

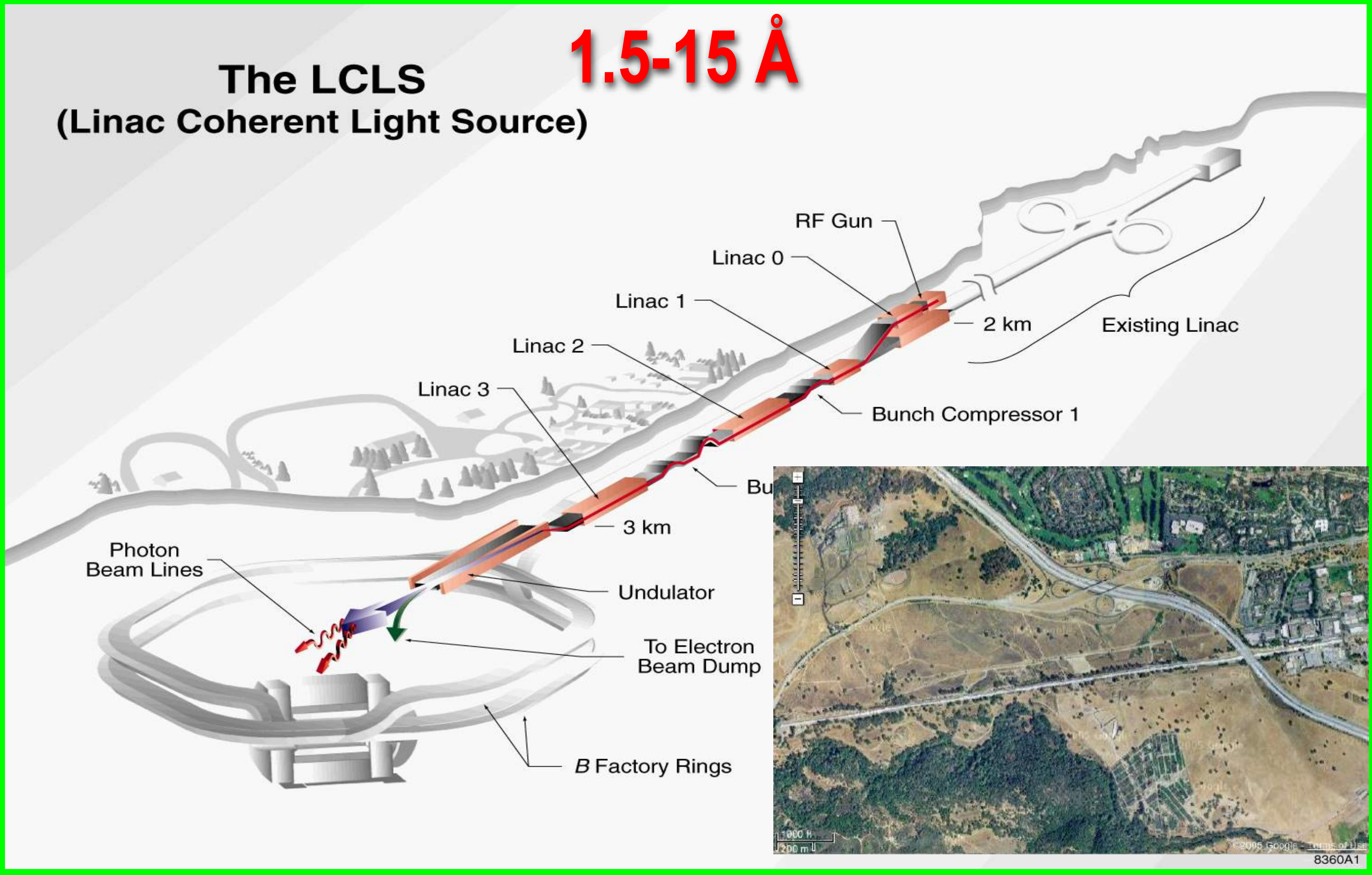






II. Compact Sources

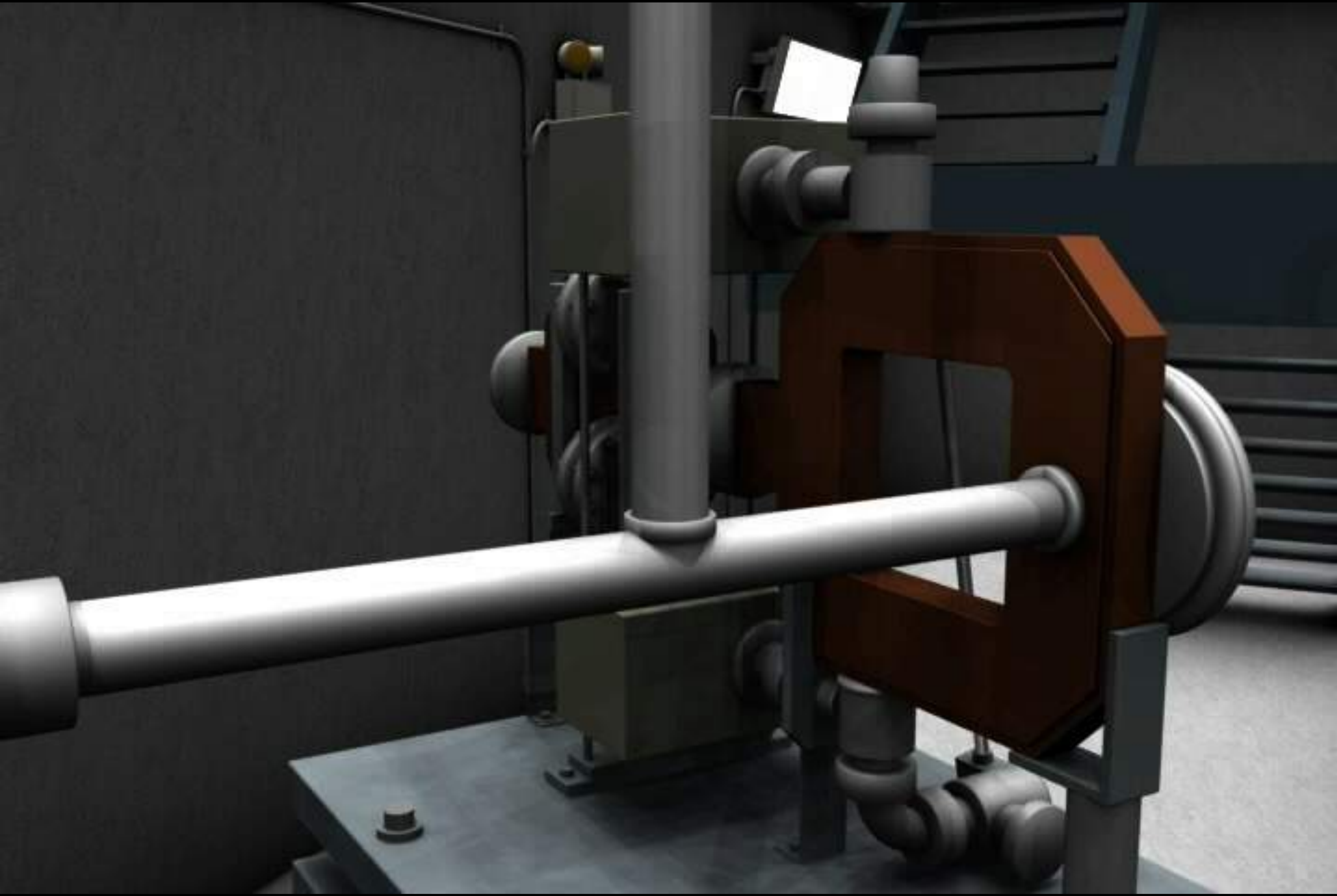
LCLS at *SLAC- First Lasing 2009*



X-FEL based on last 1-km of existing *SLAC* linac

XFEL first lasing – Hamburg May 2017

Electron source and acceleration



Long undulators chain

Beam separation

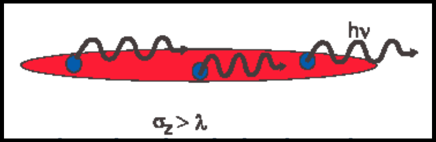
Peak power of one accelerated charge:

$$P_1 = \frac{e^2}{6\pi\varepsilon_o c^3}\gamma^4\left\langle \dot{v}_\perp^2 \right\rangle$$

Different electrons radiate indepedently hence the total power depends linearly on the number N_e of electrons per bunch:

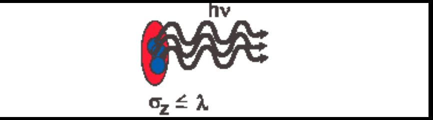
Incoherent Spontaneous Radiation Power:

$$P_T = N_e \frac{e^2}{6\pi\varepsilon_o c^3}\gamma^4\left\langle \dot{v}_\perp^2 \right\rangle$$



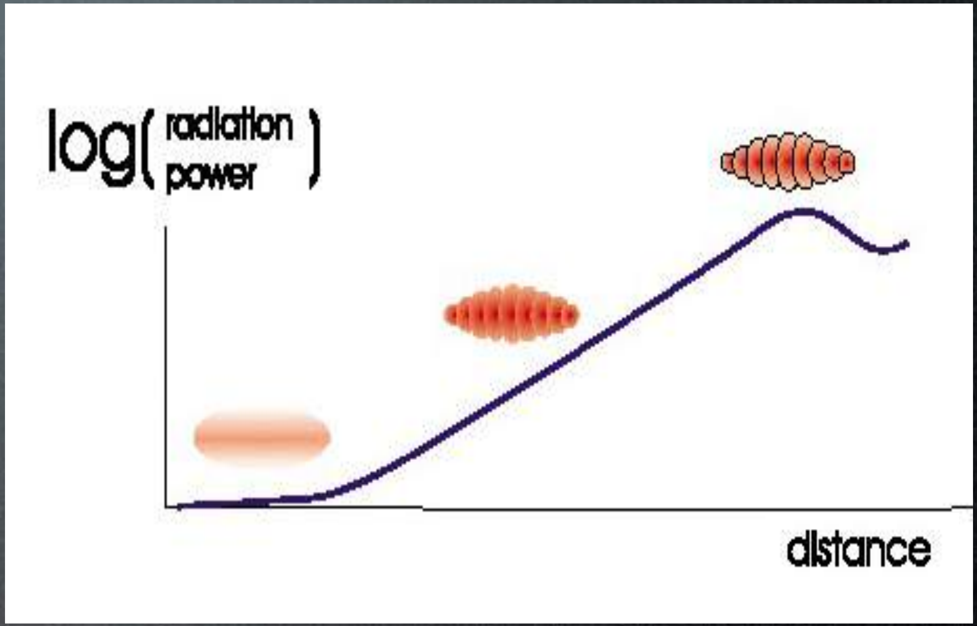
Coherent Stimulated Radiation Power:

$$P_T = \frac{N_e^2 e^2}{6\pi\varepsilon_o c^3}\gamma^4\left\langle \dot{v}_\perp^2 \right\rangle$$



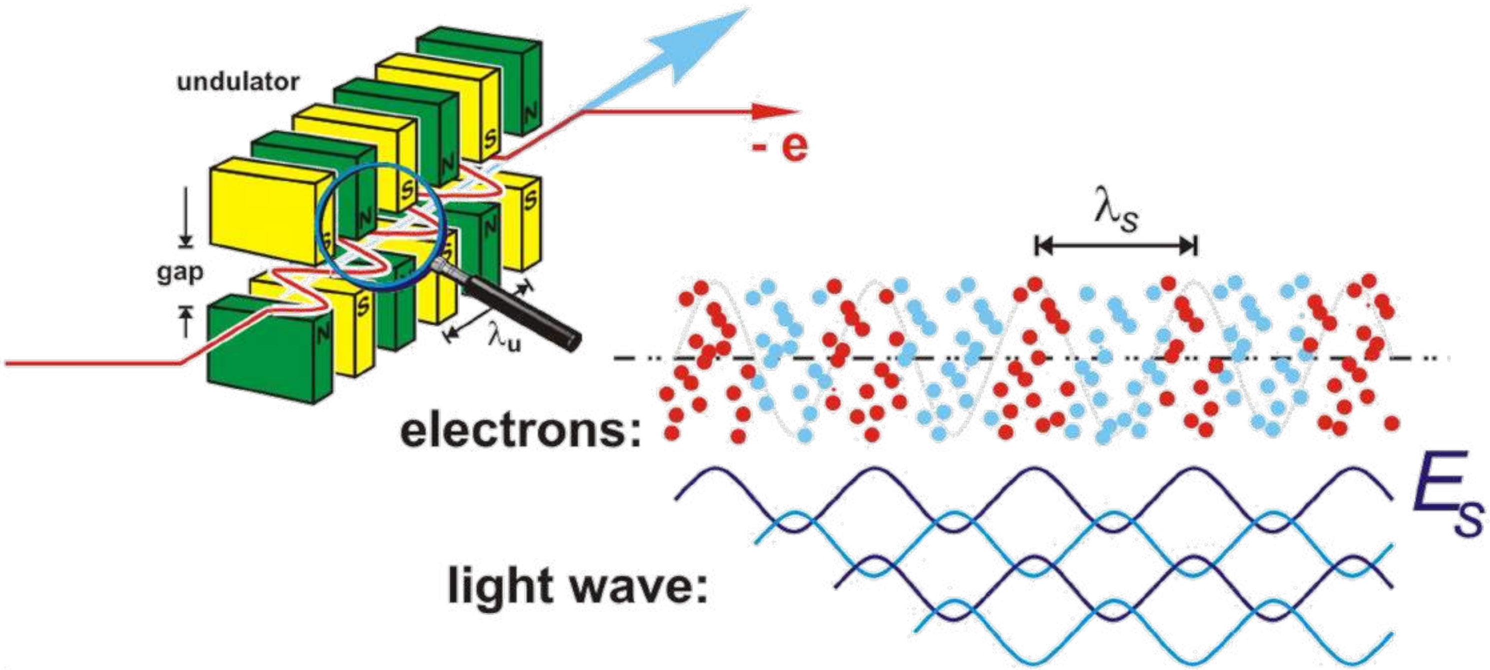
Bunching on the scale of the wavelength:

A Free Electron Laser is a device that converts a fraction of the electron kinetic energy into coherent radiation via a collective instability in a long undulator



$$\lambda_{rad} \approx \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2} + \gamma^2\vartheta^2\right)$$

(Tunability - Harmonics)

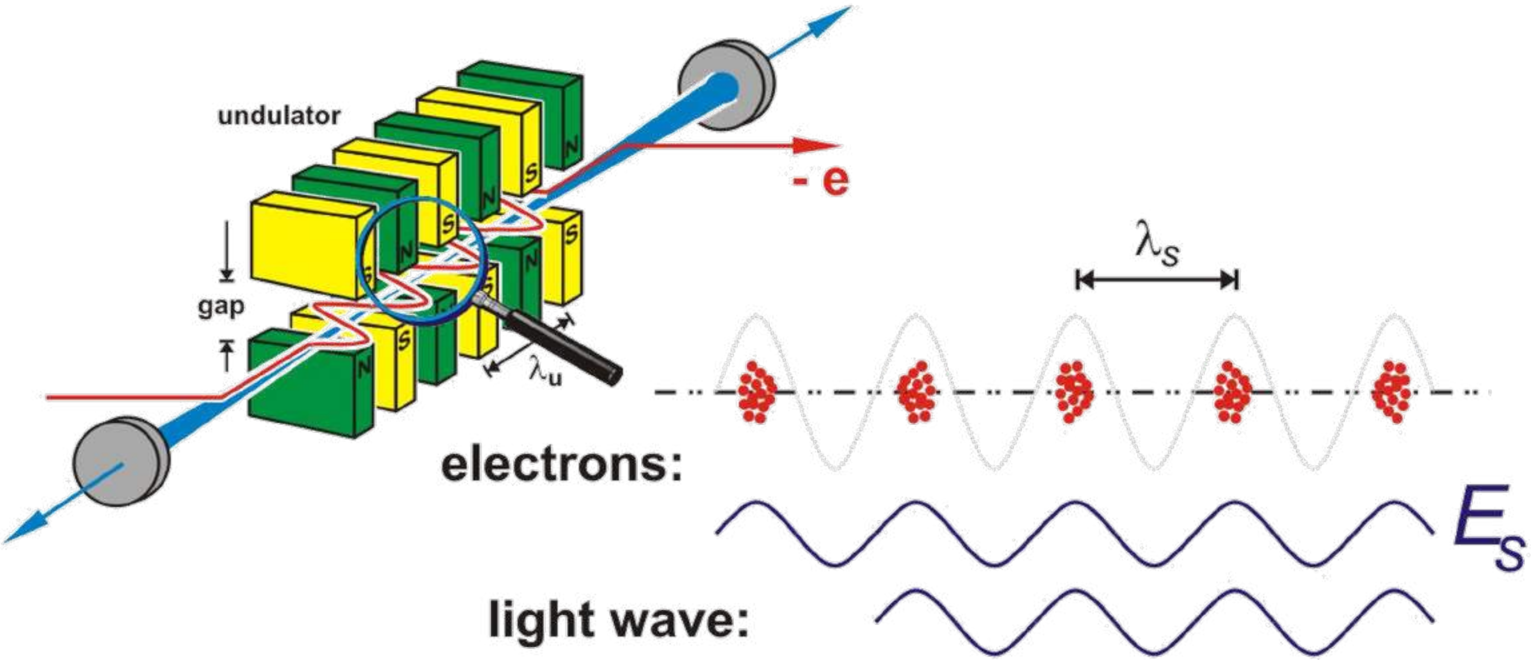


Radiated Power:

$P \propto n_e$ (number of electrons)

destructive interference

⟶ **shotnoise radiation**

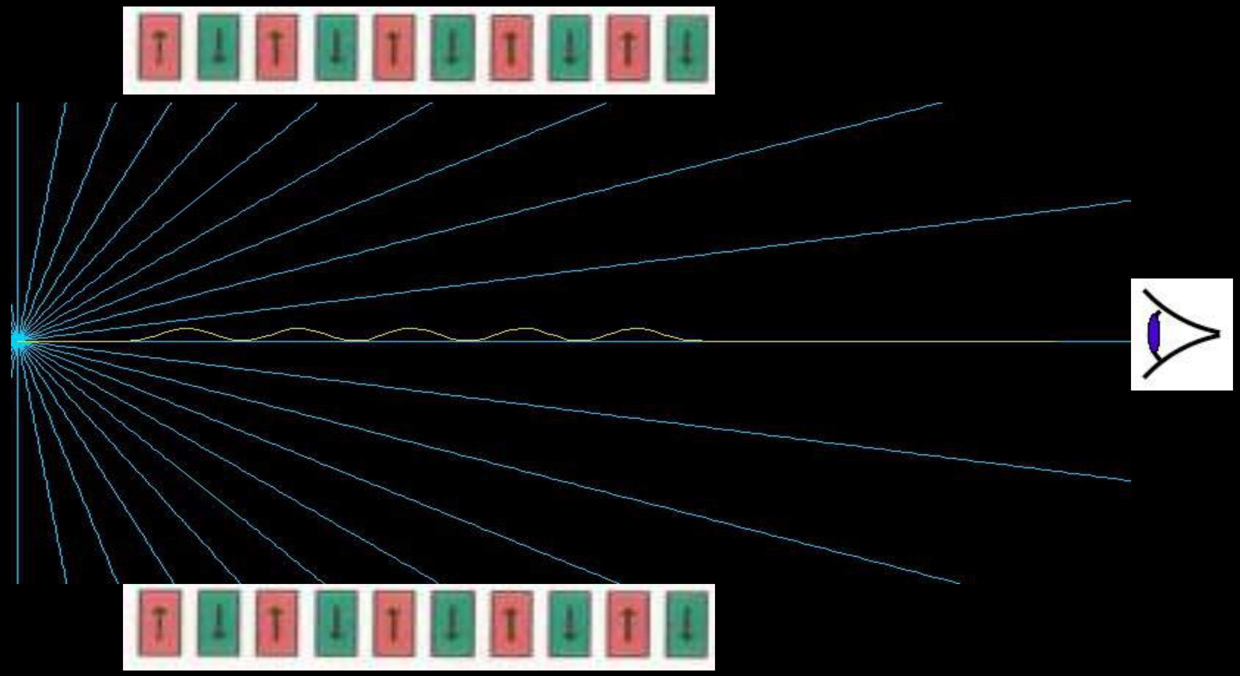


Radiated Power :

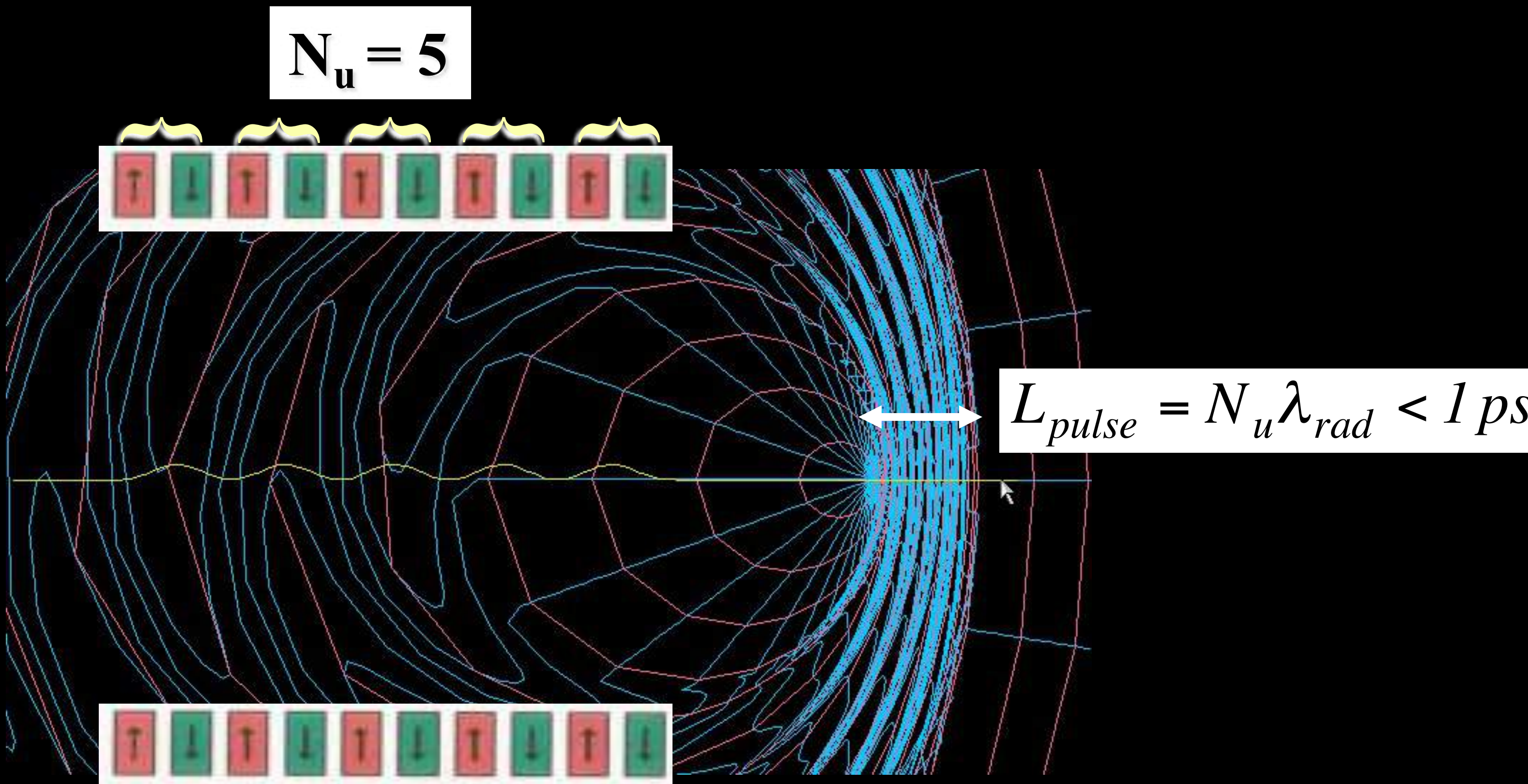
$$P \propto n_e^2 \left(\begin{array}{c} \text{number of electrons} \\ n_e \sim 10^6 - 10^9 \end{array} \right)$$

constructive interference

⟶ **enhanced emission**

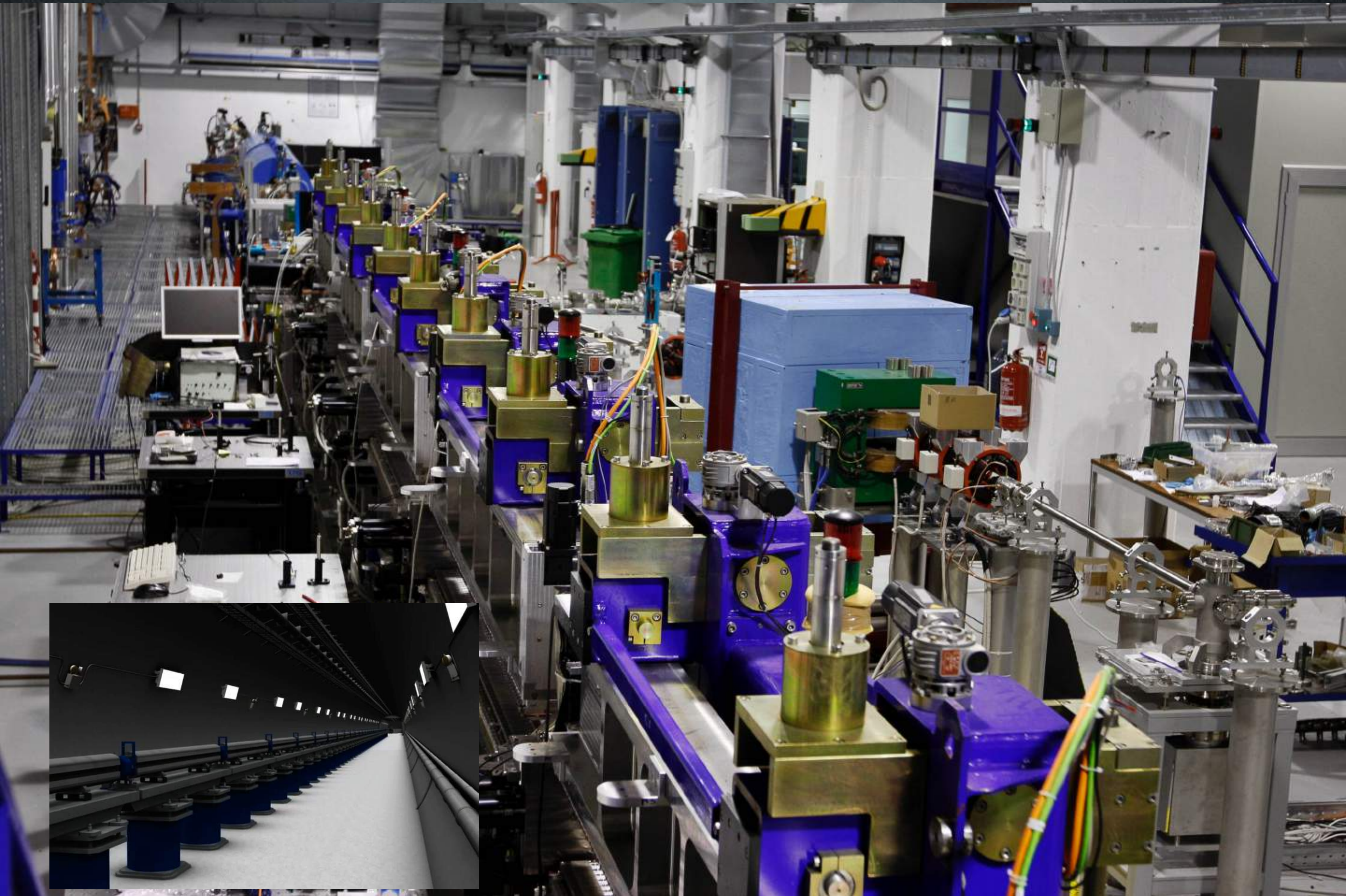


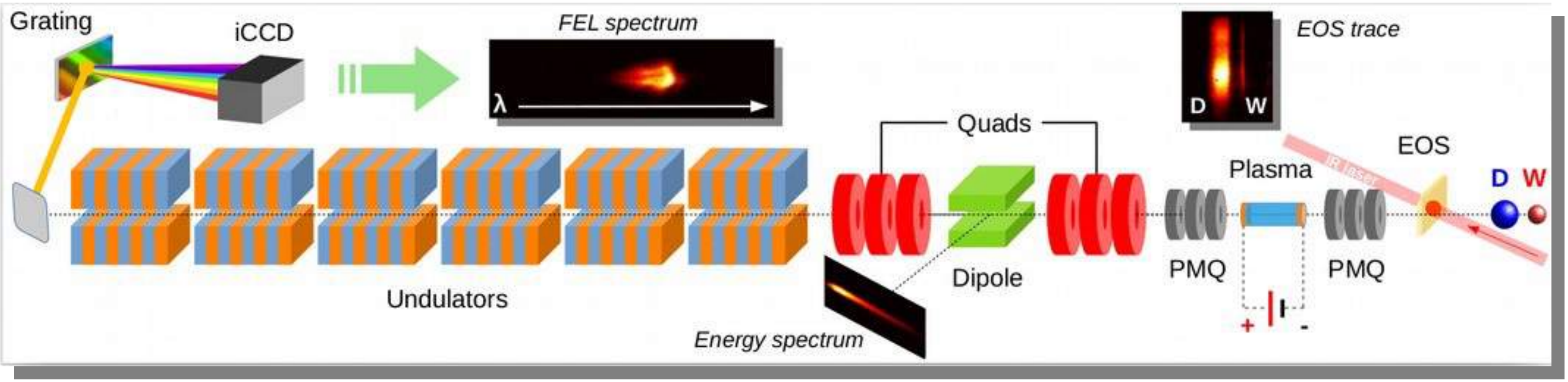
Radiation Simulator – T. Shintake, @ http://www-xfel.spring8.or.jp/Index.htm



$N_u = 5$
$L_{pulse} = N_u \lambda_{rad} < 1\,ps$

Free Electron Laser

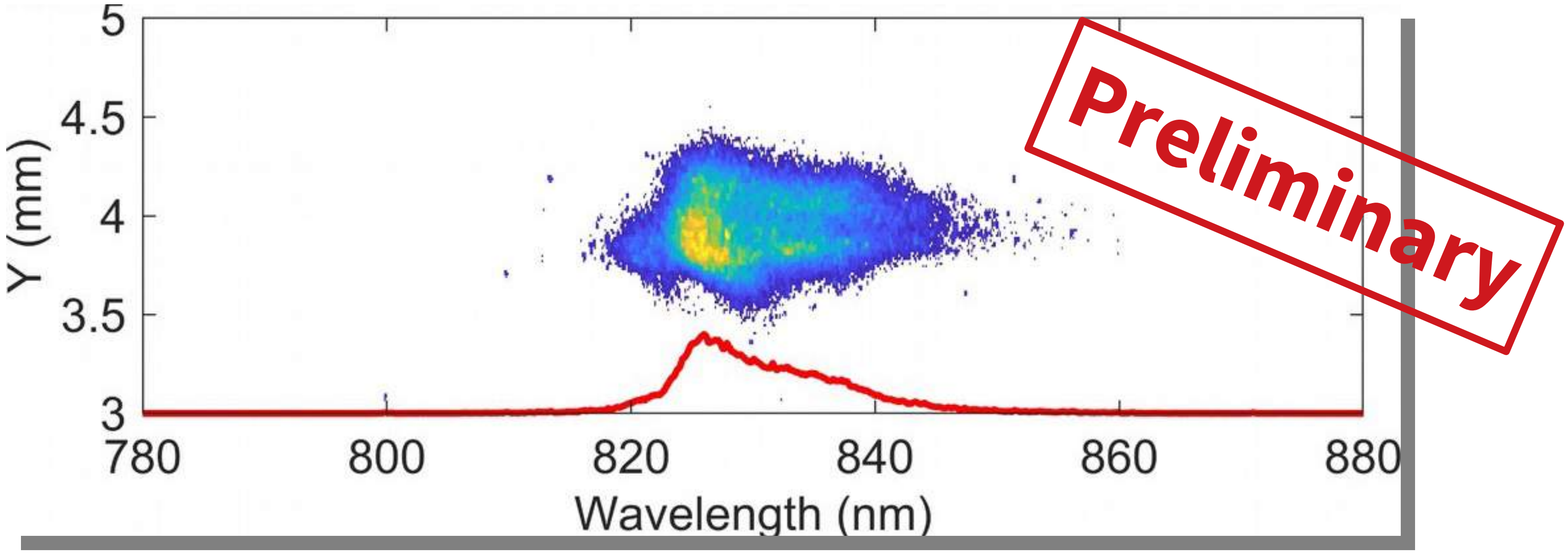




Proof-of-principle experiment to demonstrate high-quality PWFA acceleration able to drive a Free-Electron Laser

- *Witness is completely characterized (energy, spread, X/Y emittance) allowing to match it into the undulators beamline*
- *Jitter is online monitored with Electro-Optical Sampling (EOS) diagnostics*
- *Imaging spectrometer with iCCD used to detect FEL radiation*

In collaboration with

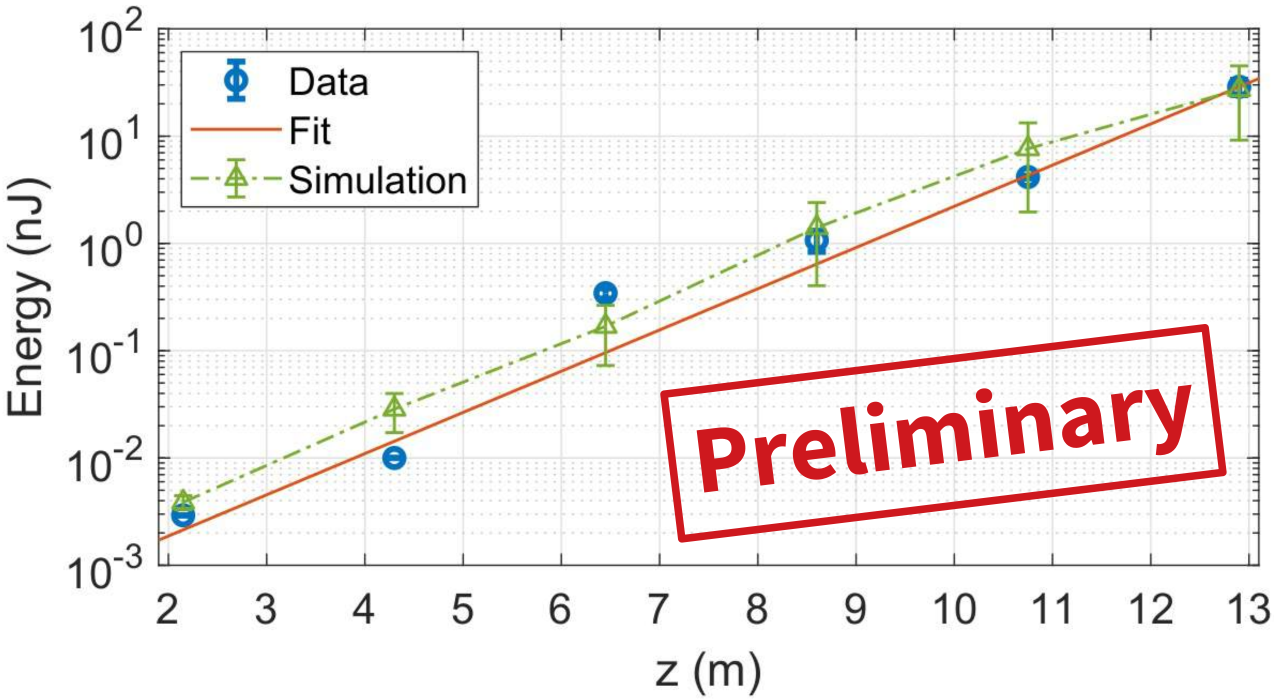


Single-shot spectrum of SASE FEL radiation emitted at 830 nm

6 undulators matched on the plasma accelerated witness bunch

Clear signals, reproducible and stable (<10% disregarded shots)

FEL driven by PWFA: exponential gain

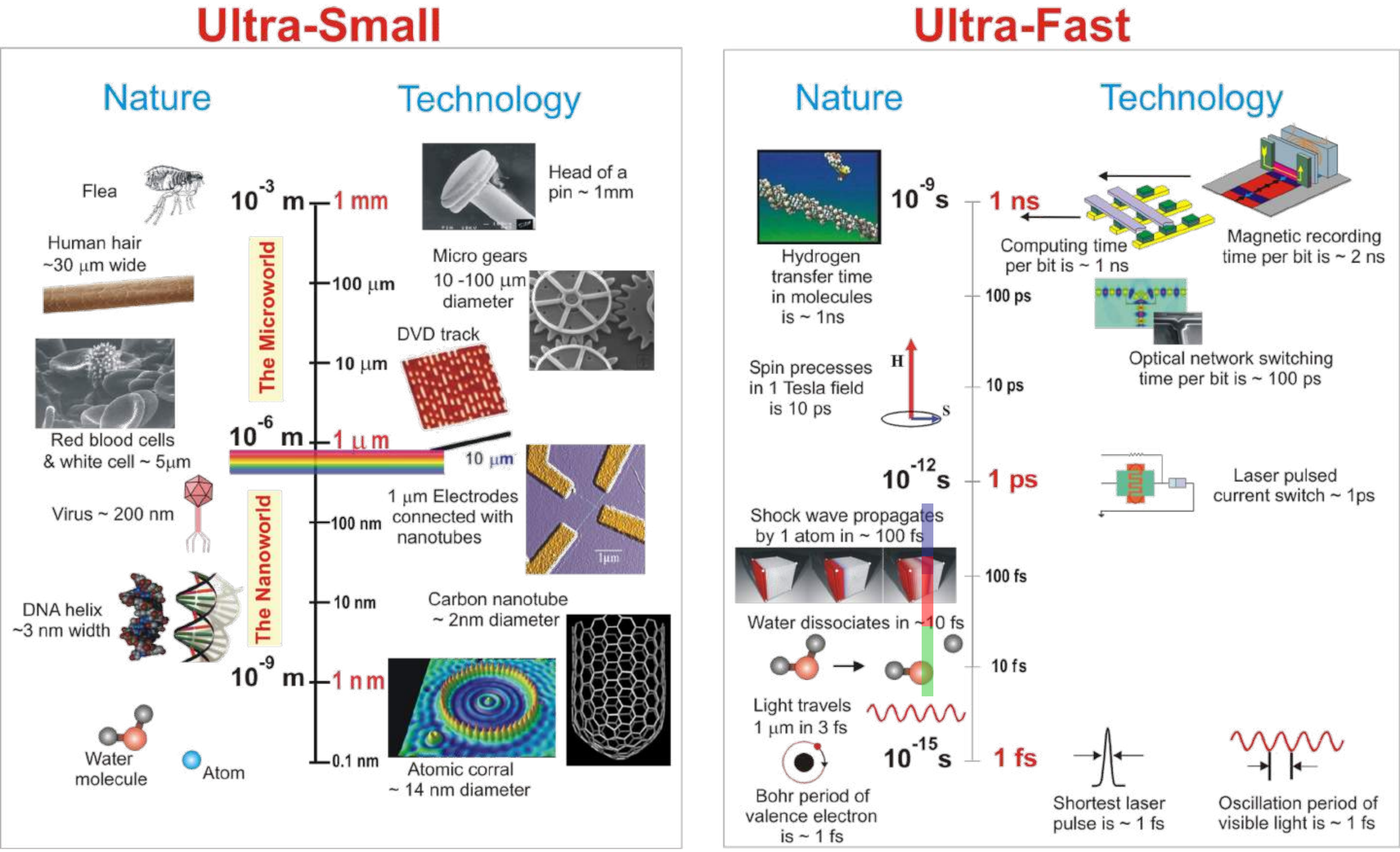


Exponential gain of FEL radiation energy

Data taken with 6 (Si) photo-diodes downstream the undulators

The FEL Applications

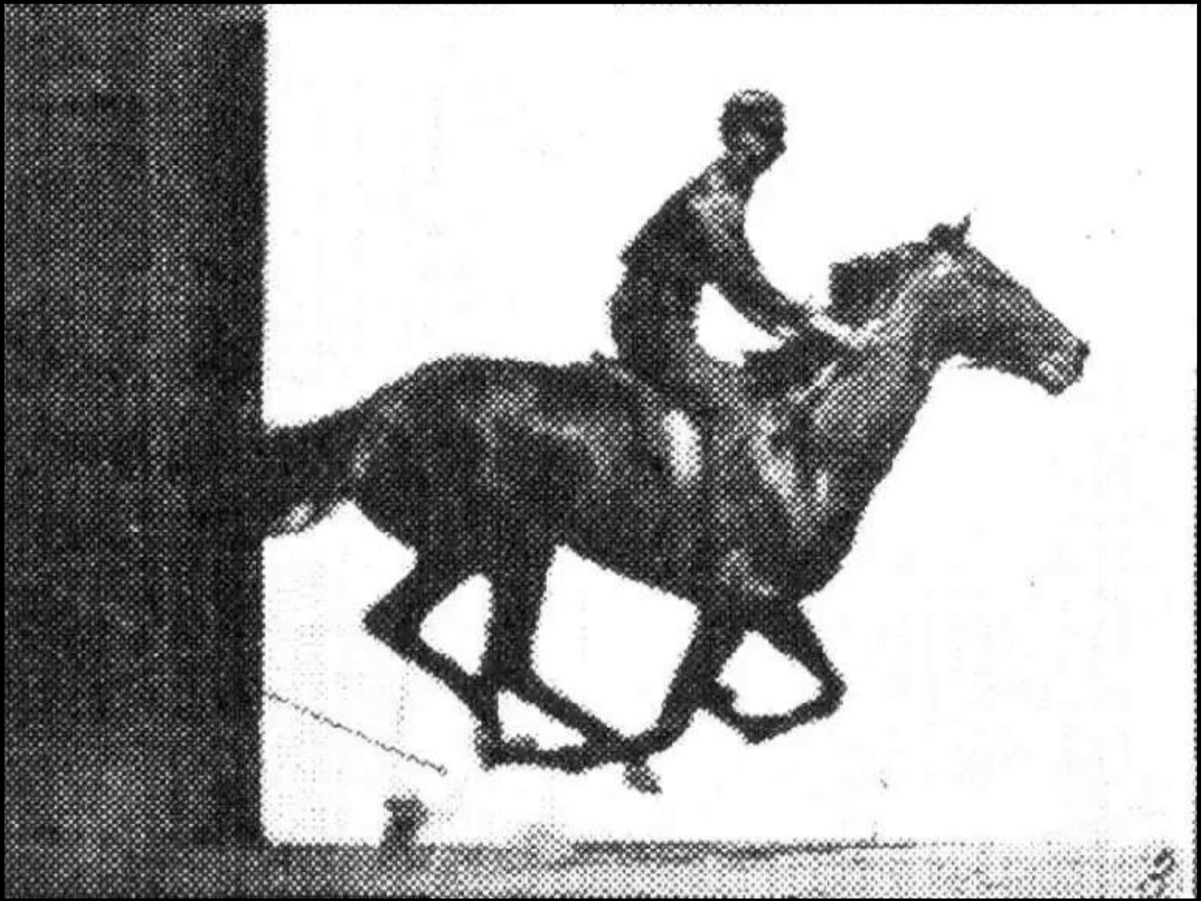
X-Rays have opened the Ultra-Small World
X-FELs open the Ultra-Small and Ultra-Fast Worlds



E. Muybridge

E. Muybridge at L. Stanford in **1878**

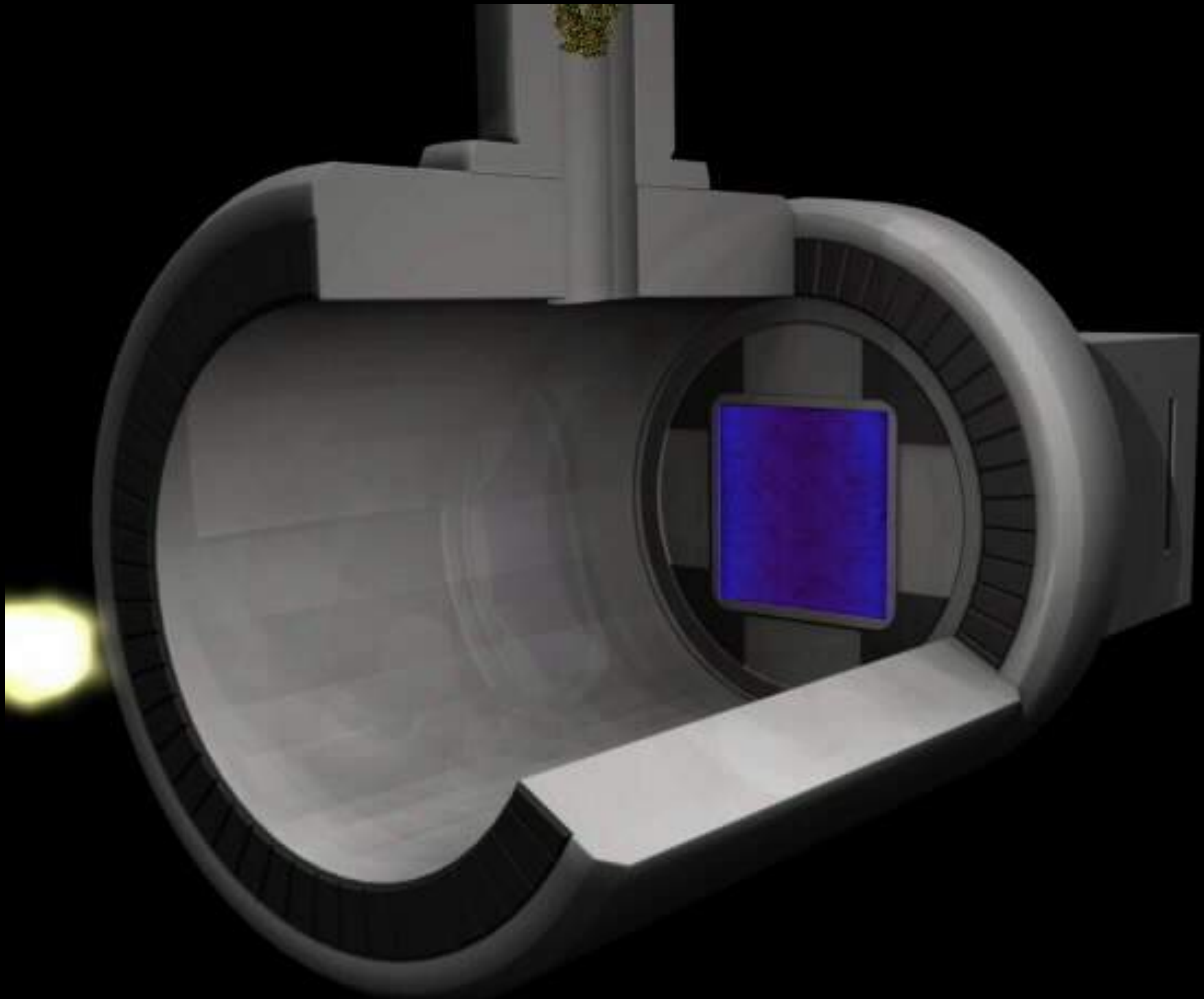
disagree whether all feet leave the ground during gallop…



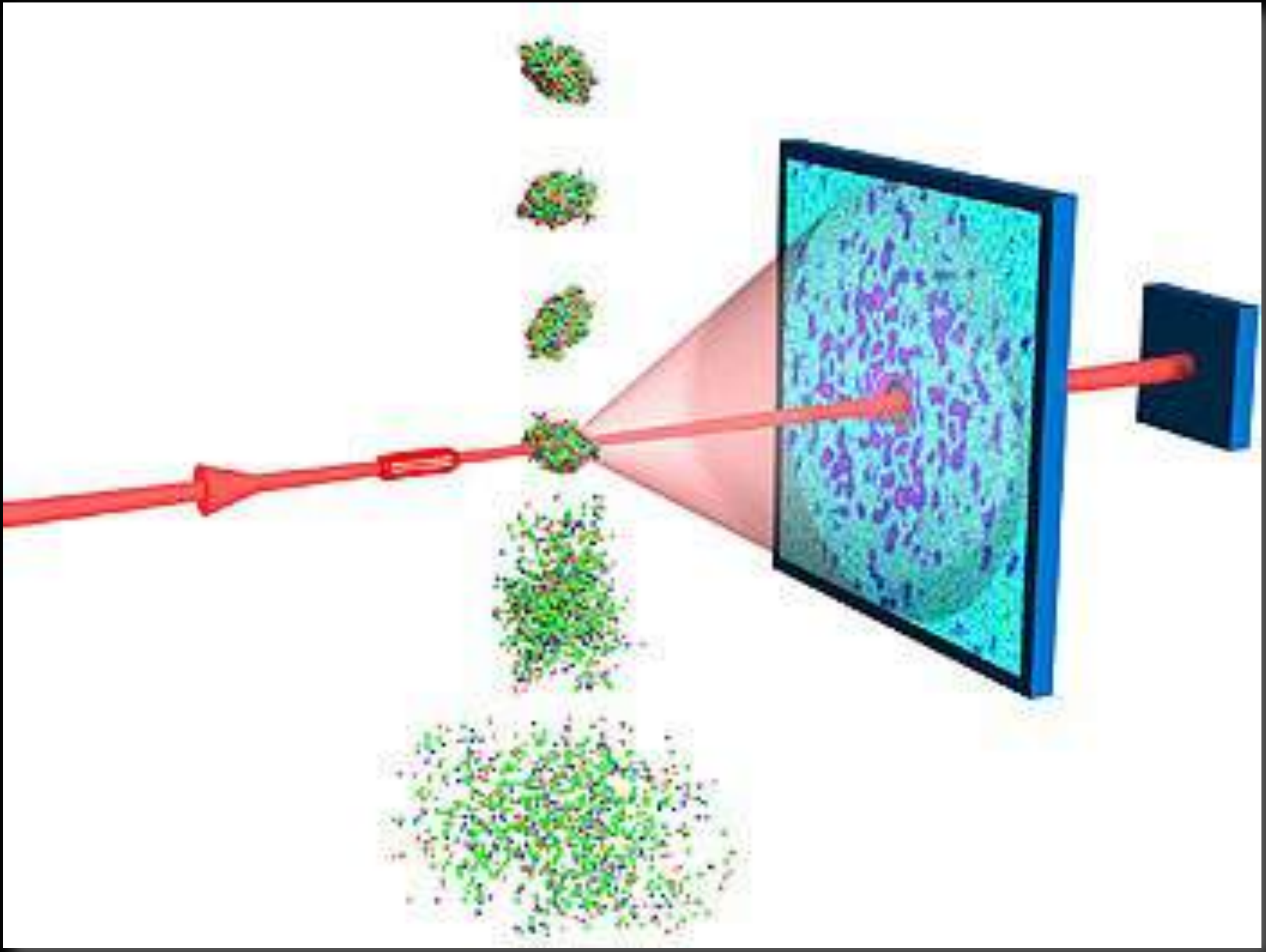
used spark photography to freeze this ‘ultra-fast’ process

E. Muybridge, *Animals in Motion*, ed. L. S. Brown (Dover Pub. Co., New York 1957)
Courtesy Paul Emma (SLAC).

Experimental hall (Single Protein Imaging)

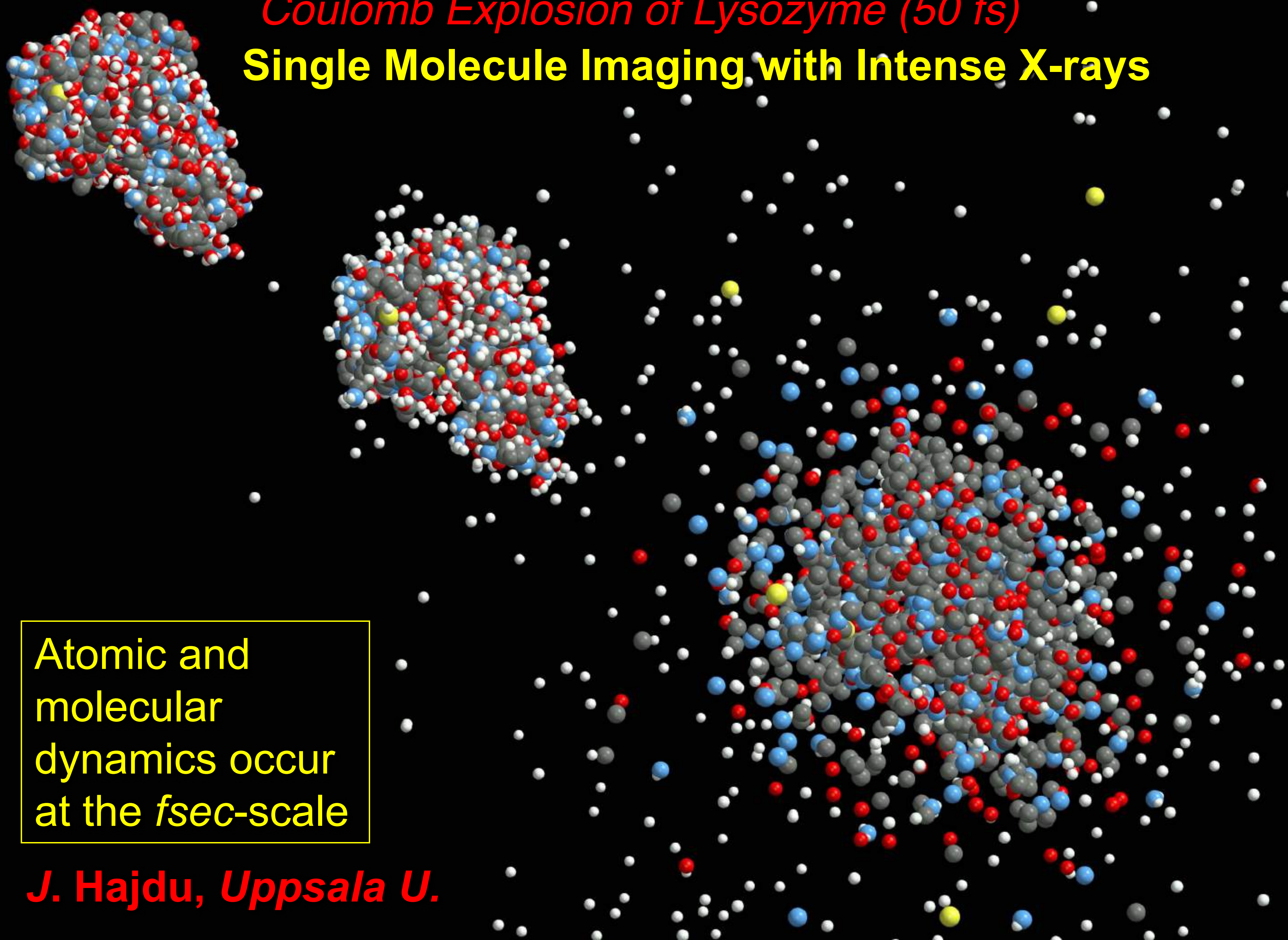


http://lcls.slac.stanford.edu/AnimationViewLCLS.aspx



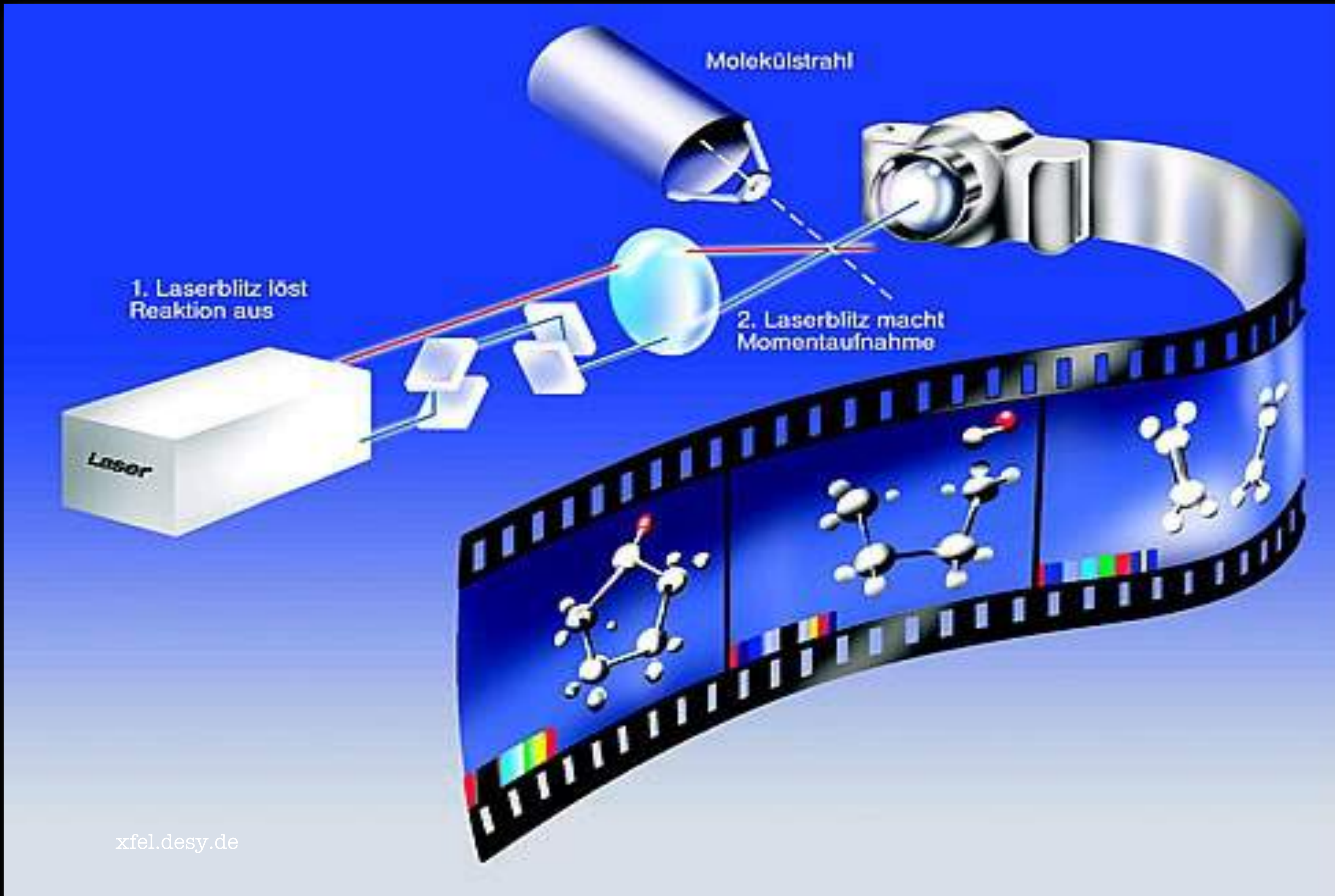
Coulomb Explosion of Lysozyme (50 fs)

Single Molecule Imaging with Intense X-rays



Atomic and molecular dynamics occur at the *fsec*-scale

J. Hajdu, *Uppsala U.*

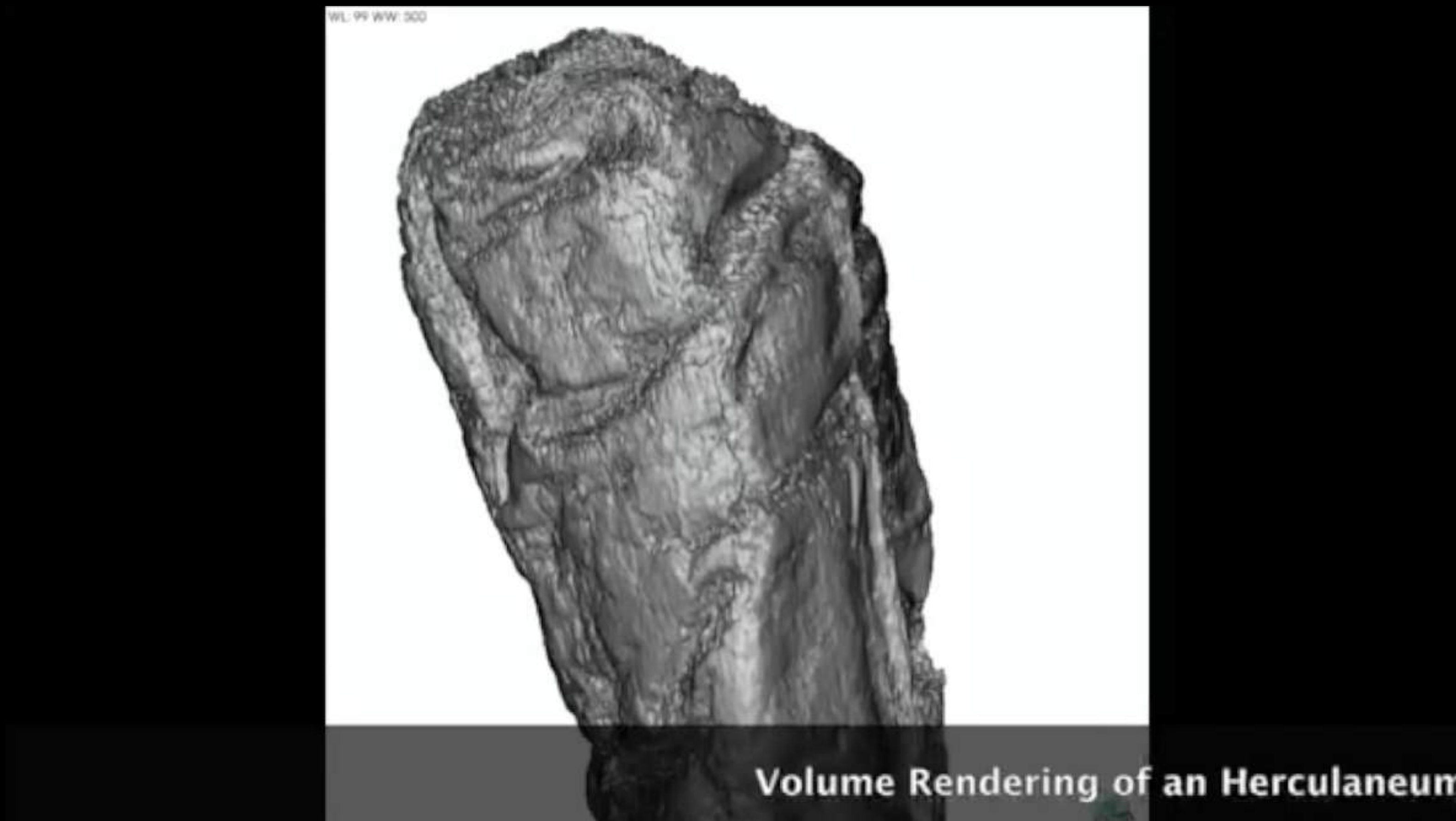

Molekülstrahl
1. Laserblitz löst
Reaktion aus
2. Laserblitz macht
Momentaufnahme
Laser

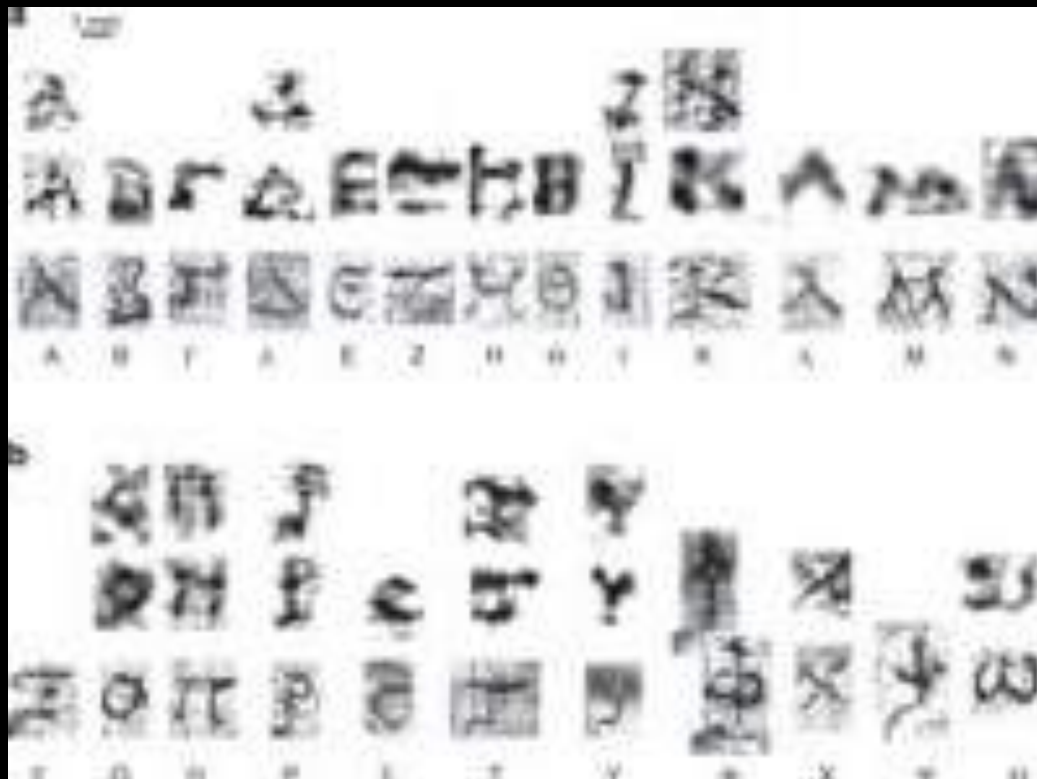
House of Papyrus Scrolls - Ercolano – 79 A. D.




Tomografia a raggi X in contrasto di fase

Vito Mocella del CNR-IMM di Napoli in collaborazione con E.Brun e C. Ferrero dell'ESRF





Conclusions

- Accelerator-based High Energy Physics will at some point become practically limited by the size and cost of the proposed e^+e^- colliders for the energy frontier.
- **Novel Acceleration Techniques and Plasma-based, high gradient accelerators open the realistic vision of very compact accelerators for scientific, commercial and medical applications.**

- The R&D now concentrates on **beam quality, stability, staging and continuous operation**. These are necessary steps towards various technological applications.
- The progress in advanced accelerators benefits from strong synergy with general advances in technology, for example in the laser and/or high gradient RF structures industry.

- **A major milestone is an operational, 1 GeV compact accelerator. Challenges in repetition rate and stability must be addressed. This unit could become a stage in a high-energy accelerator..**
- **➔ PILOT USER FACILITIES Needed**


Thank for your attention