Fisica degli Acceleratori

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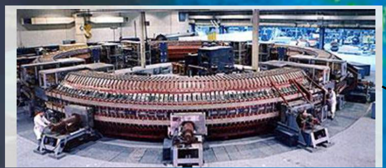
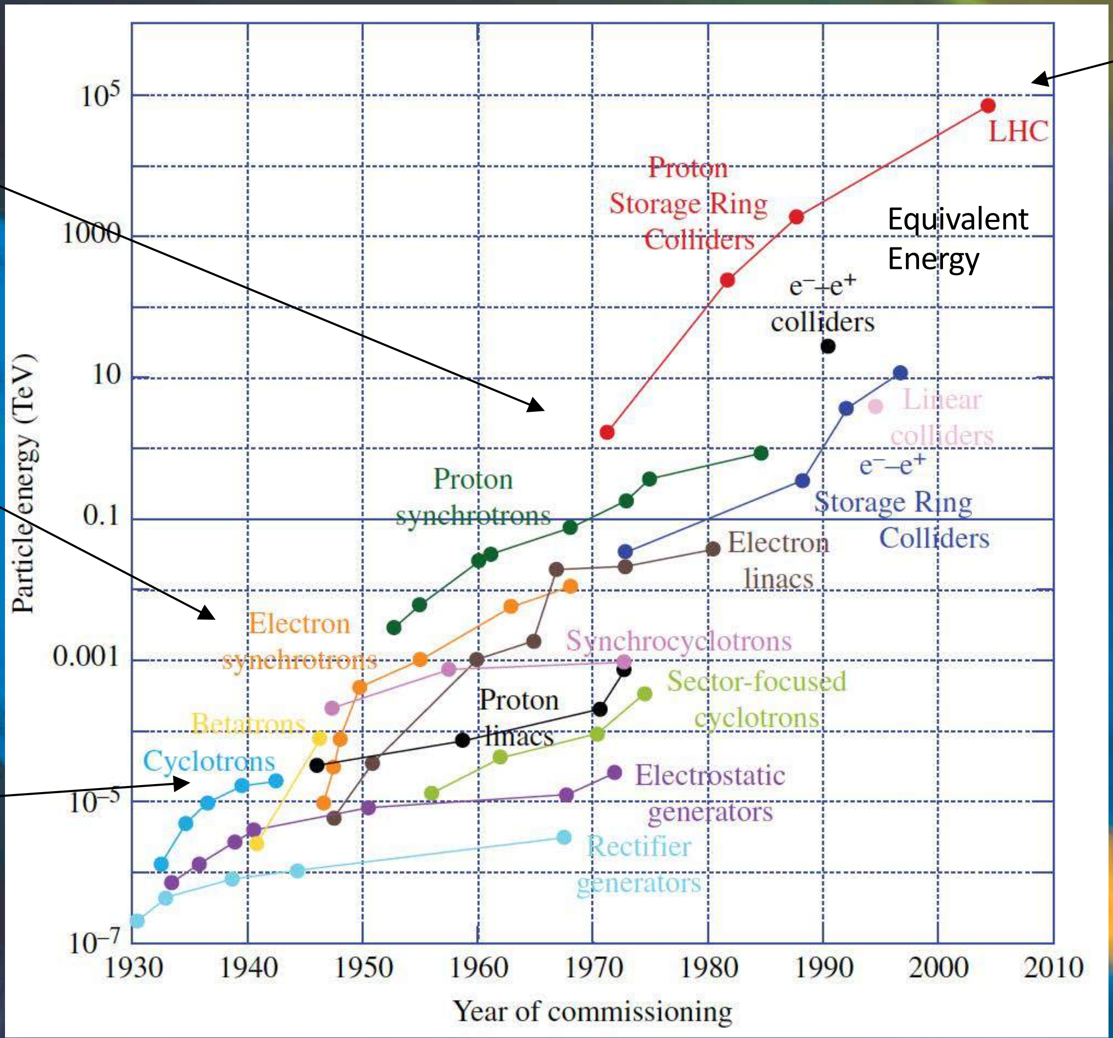
LNF– 21 Luglio 2022

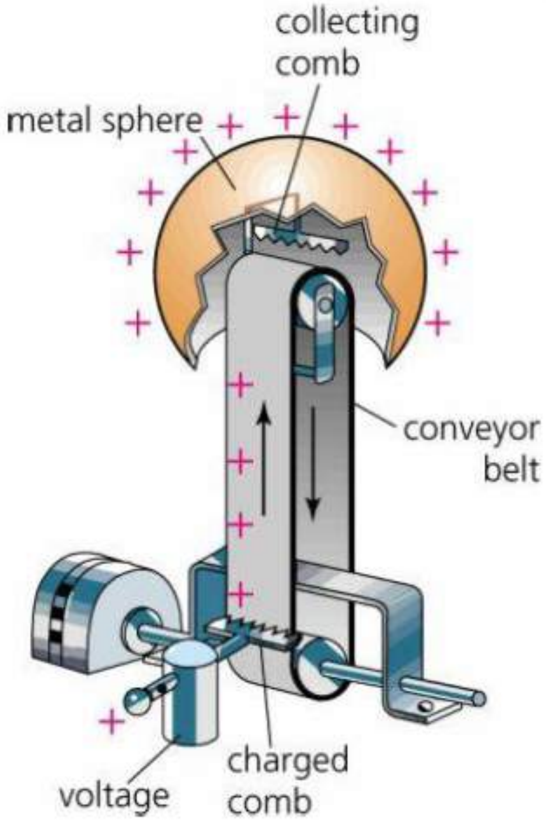
Il diagramma di Livingstone

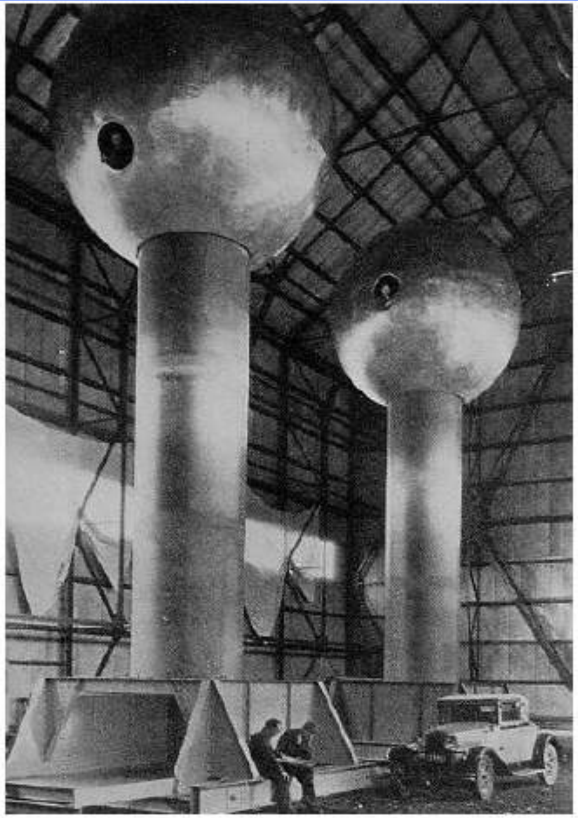




Energy of colliders is plotted in terms of the laboratory energy of particles colliding with a proton at rest to reach the same center of mass energy.

Electrostatic Accelerator: Van de Graff



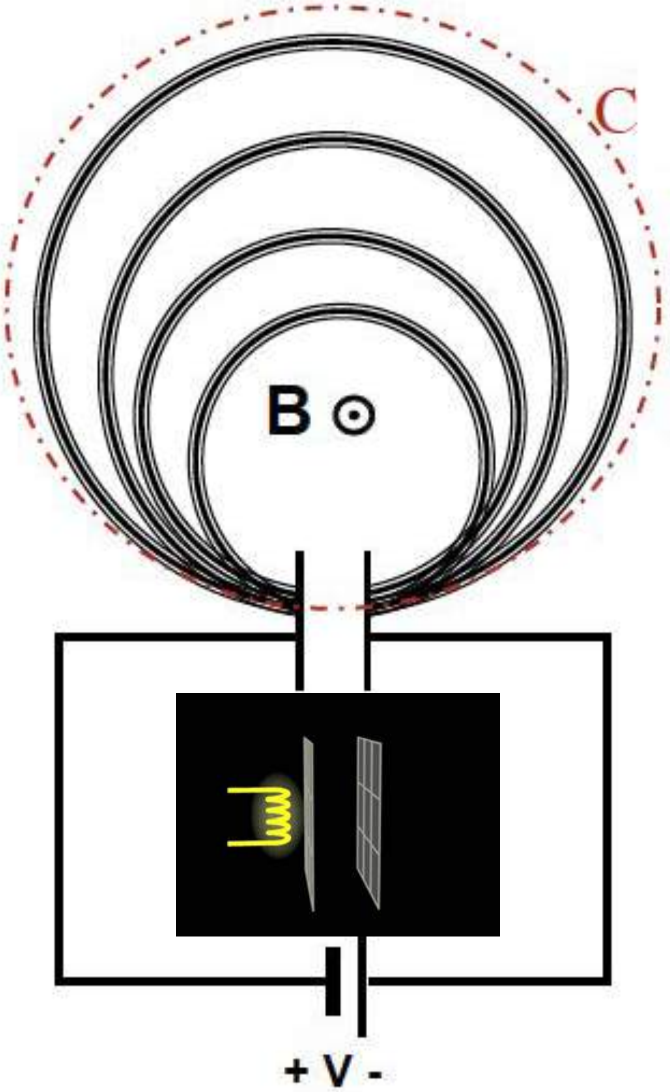


7 MV Van de Graaf at MIT (1933)

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?



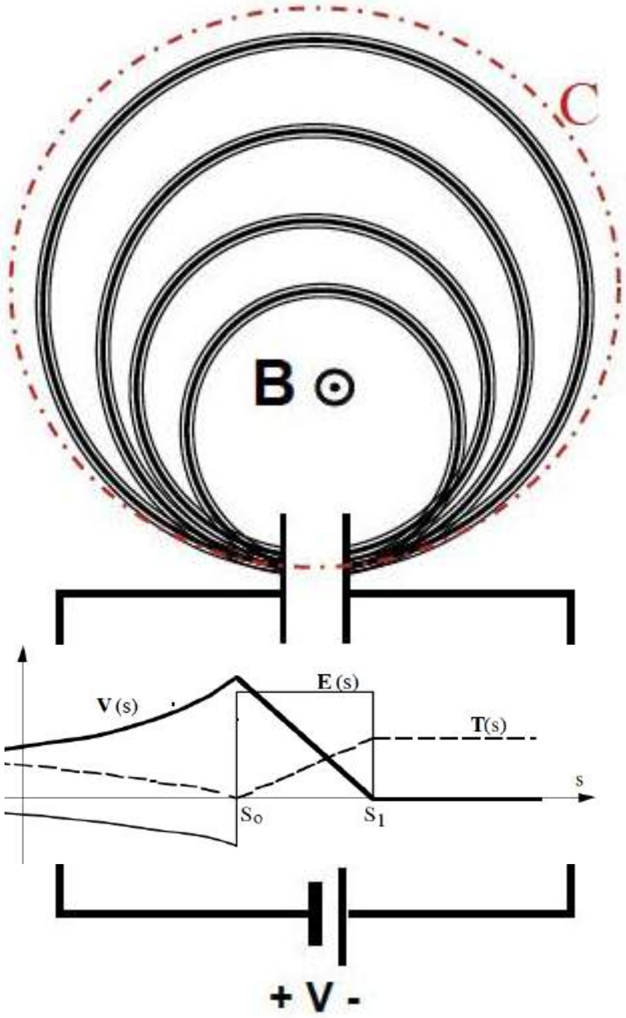
$$F_{Lorentz} = q\,v\,B = F_{centripital} = \frac{mv^2}{\rho}$$

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

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

$T = q\Delta V$

Forbidden by Maxwell



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

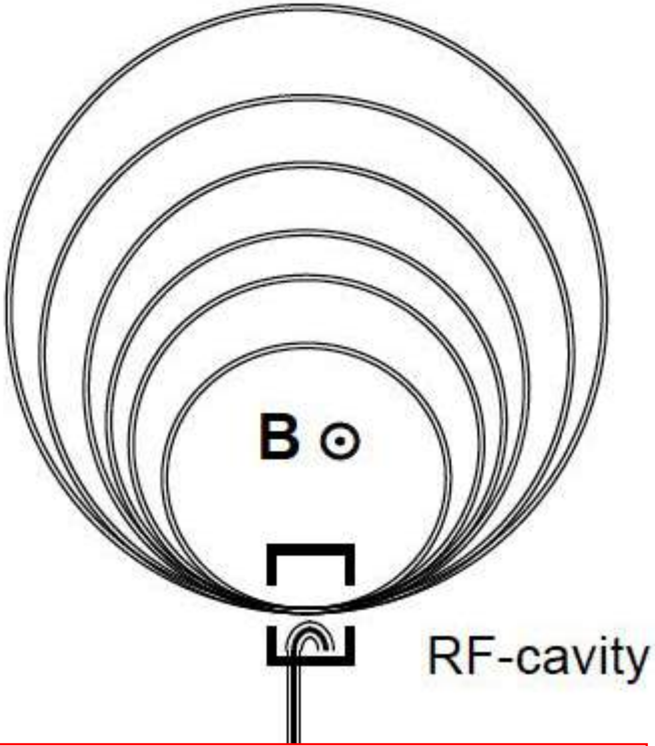
or in integral form

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

∴ There is no acceleration without time-varying magnetic flux

$\Delta V_T = 0$

B can vary in a RF cavity



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

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

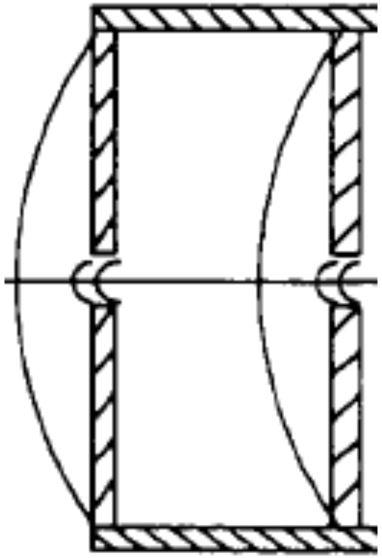
Note that inside the cavity

dB/dt ≠ 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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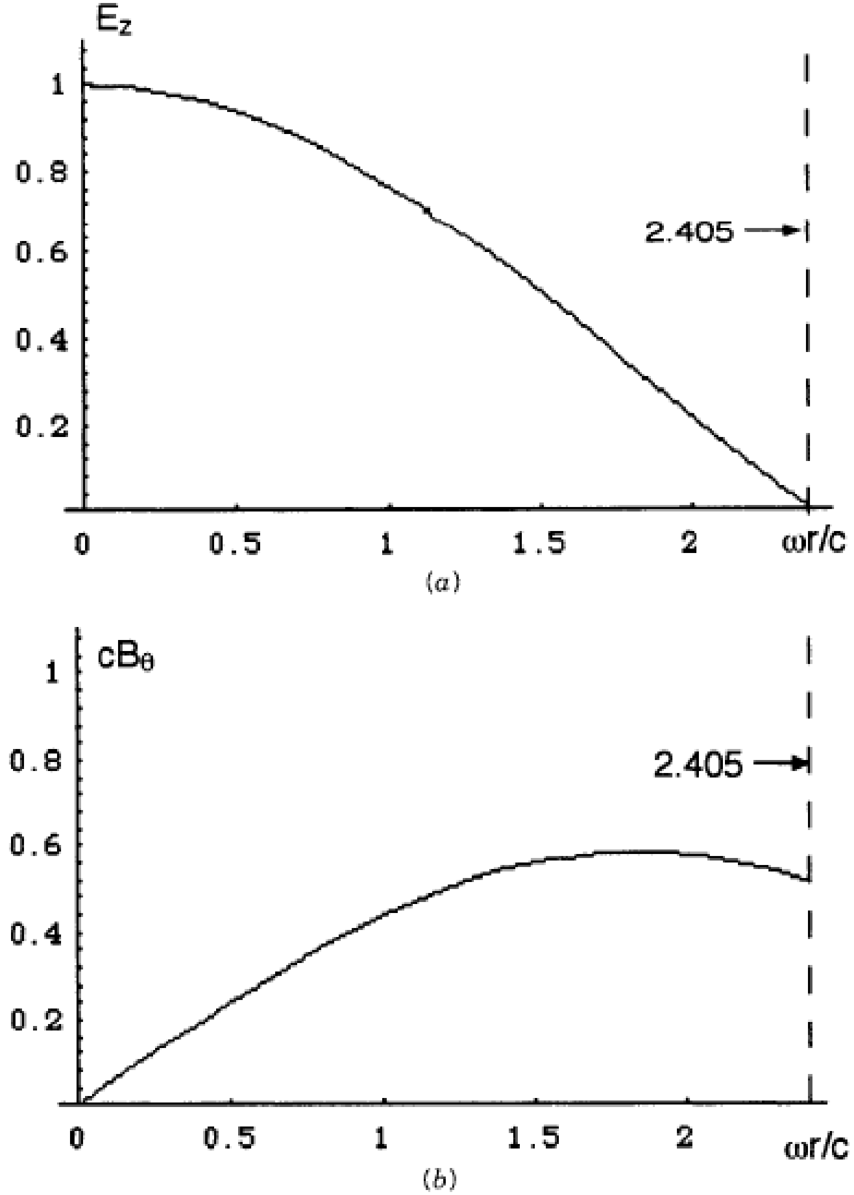
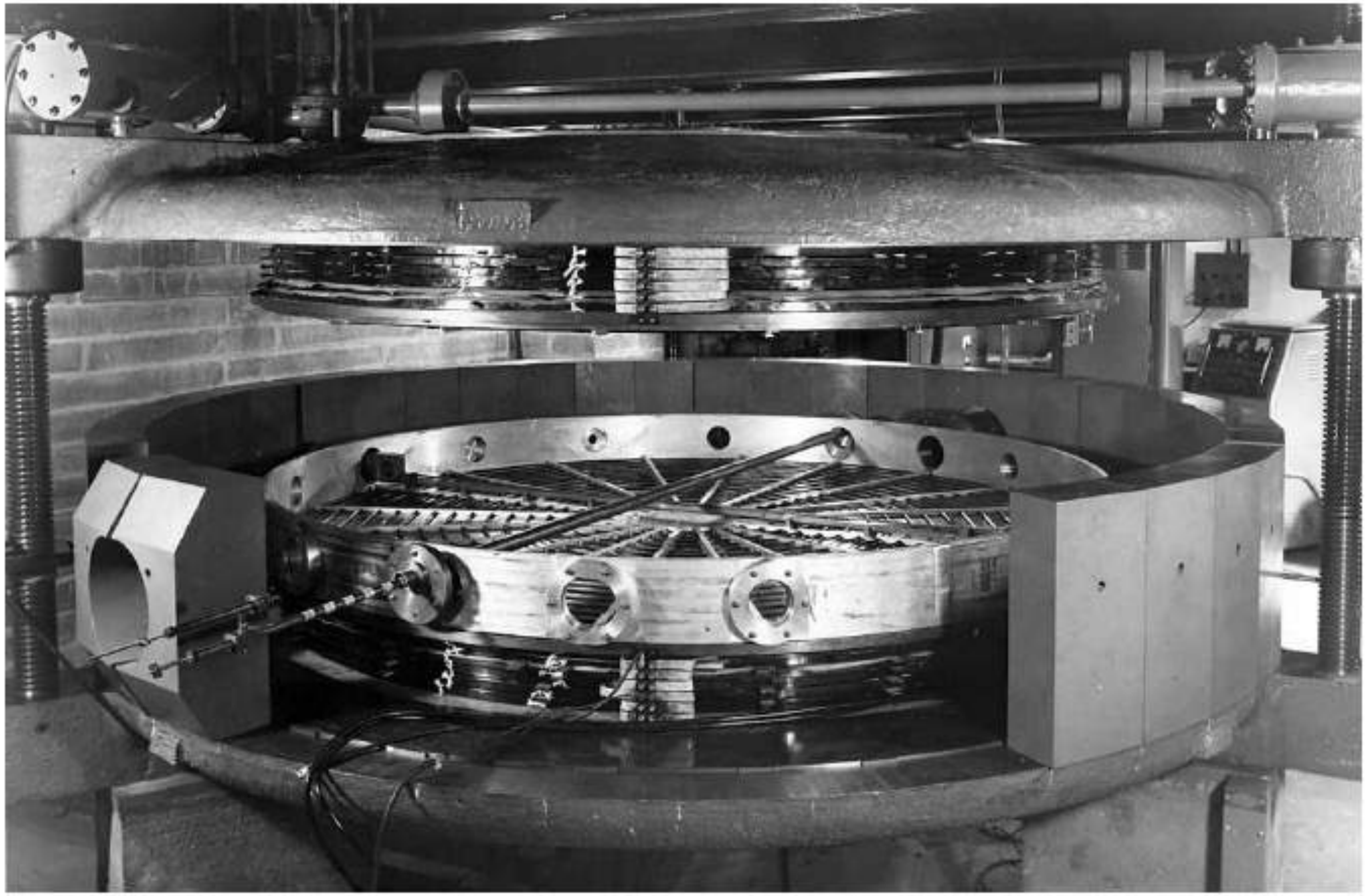
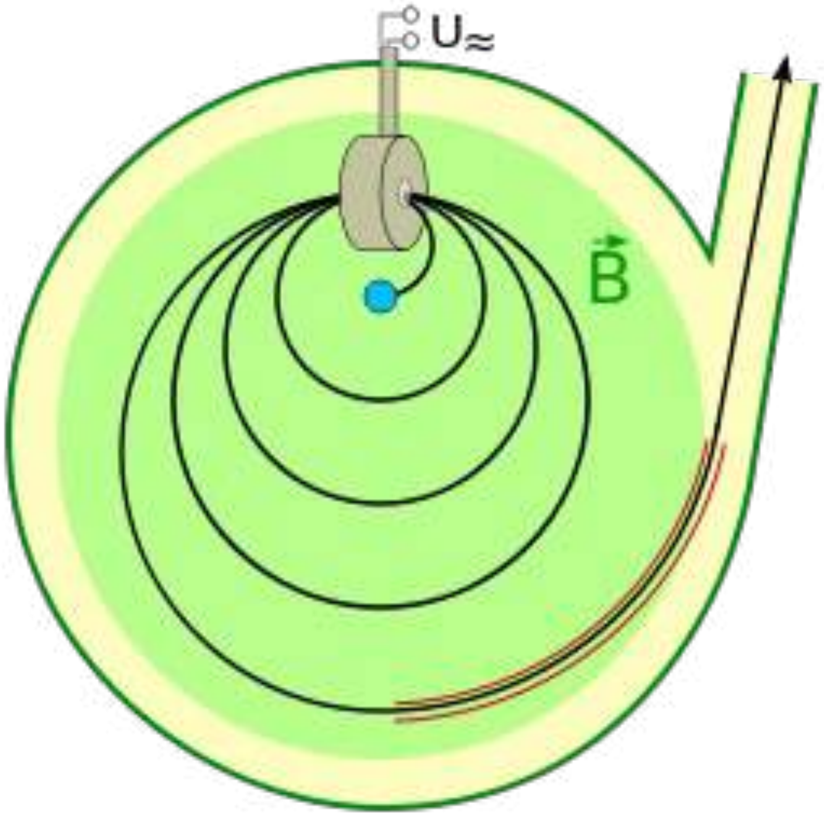


Figure 1.17 Fields for a TM_{010} mode of a cylindrical (pillbox)-cavity resonator.

28 MeV Microtron at HEP Laboratory University College London



Microtron - Synchronization



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

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

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

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

Energy gain/revolution

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

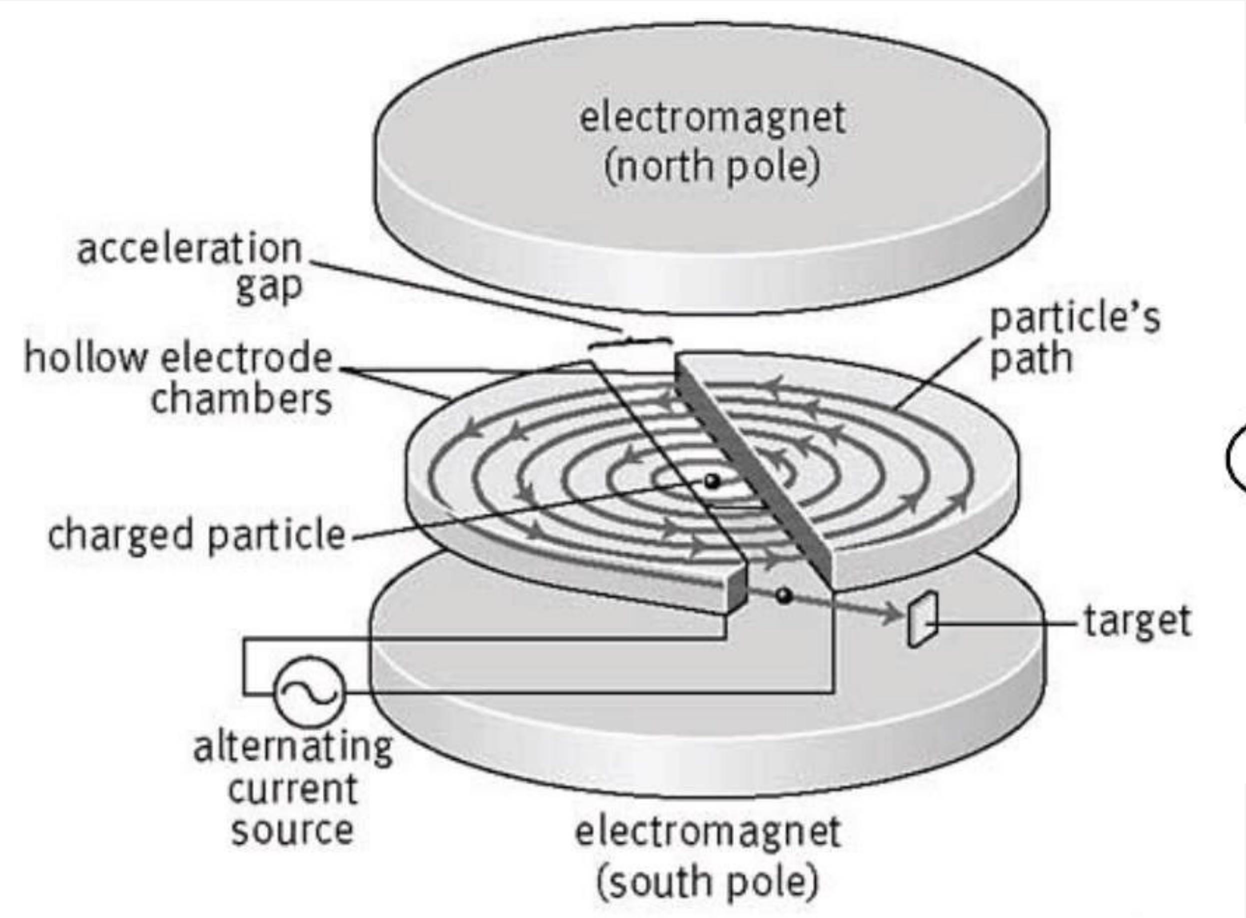
$$\Delta t = \frac{k}{\nu_{RF}} = \frac{2\pi}{ec^2 B}\Delta E$$

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

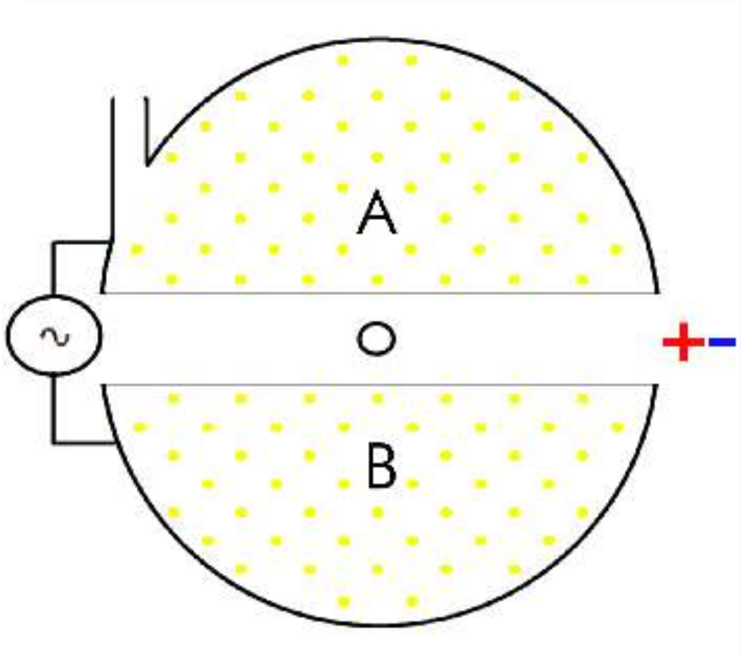
- In a microtron, due to the electrons' increasing momentum, the particle paths are different for each pass. The time needed for that must be an integer multiple k of the RF period. The allowed energy gain/pass must fulfill the above condition.

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

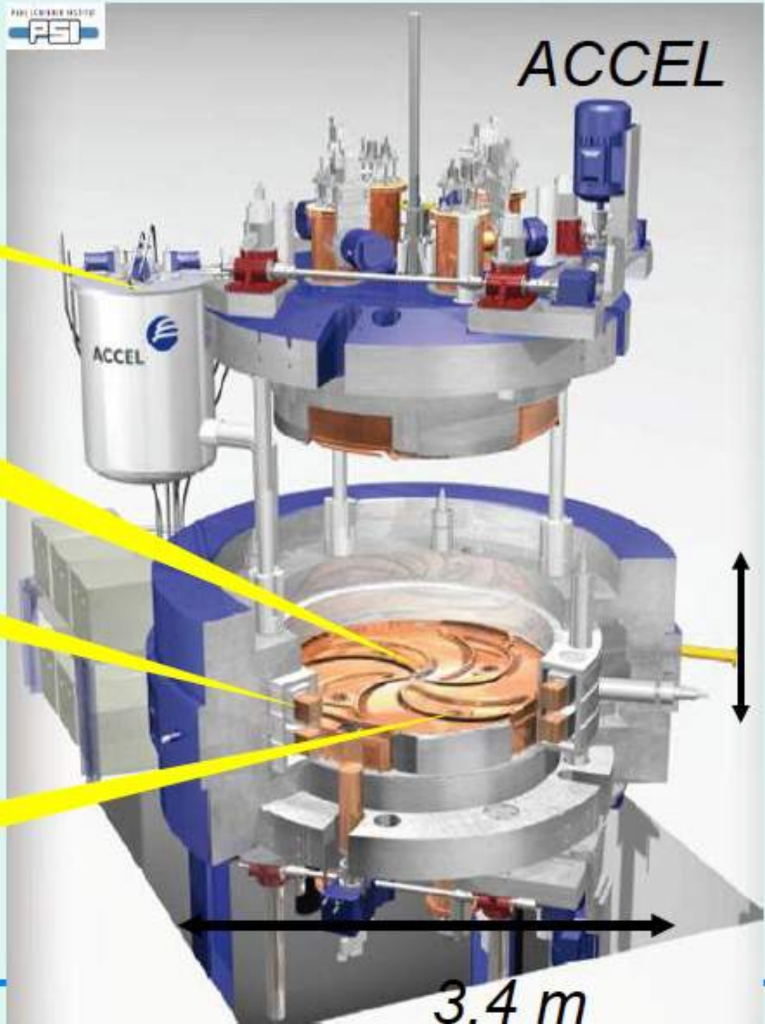
4 x 1.5 W @4K

Proton source

superconducting coils => 2.4 - 3.8 T

4 RF-cavities:

72 MHz ~80 kV

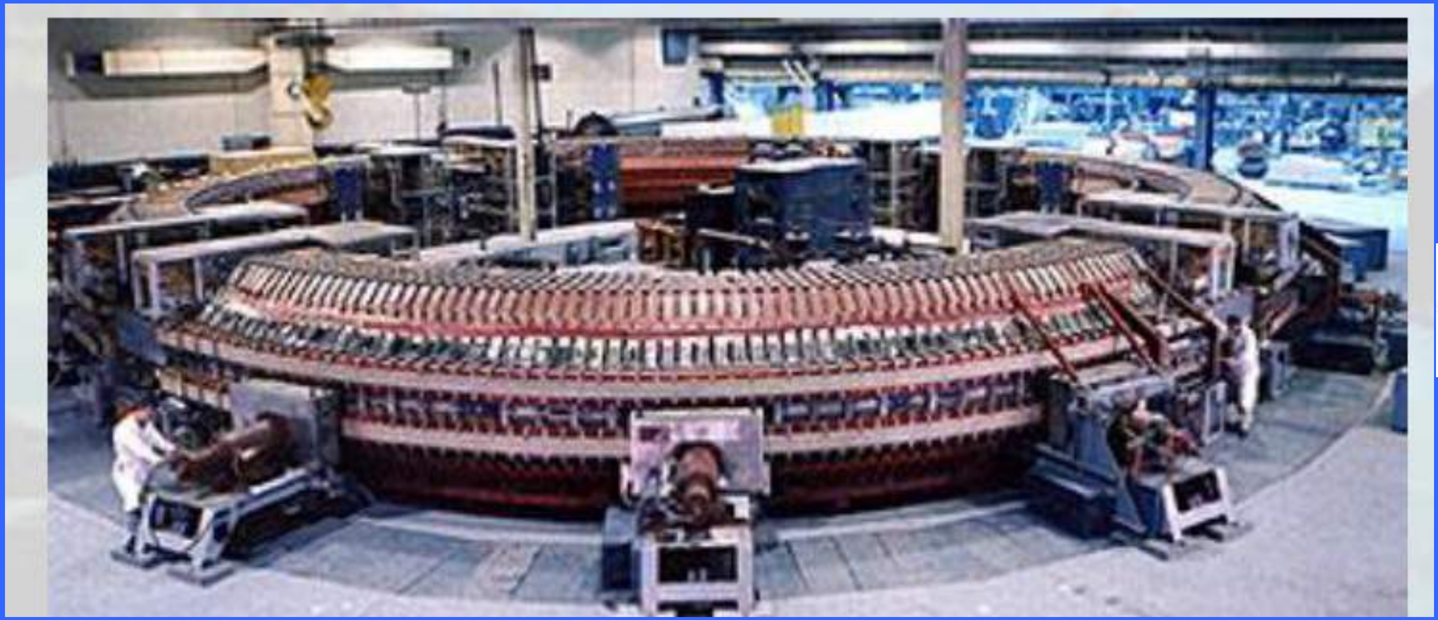


300 kW

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).

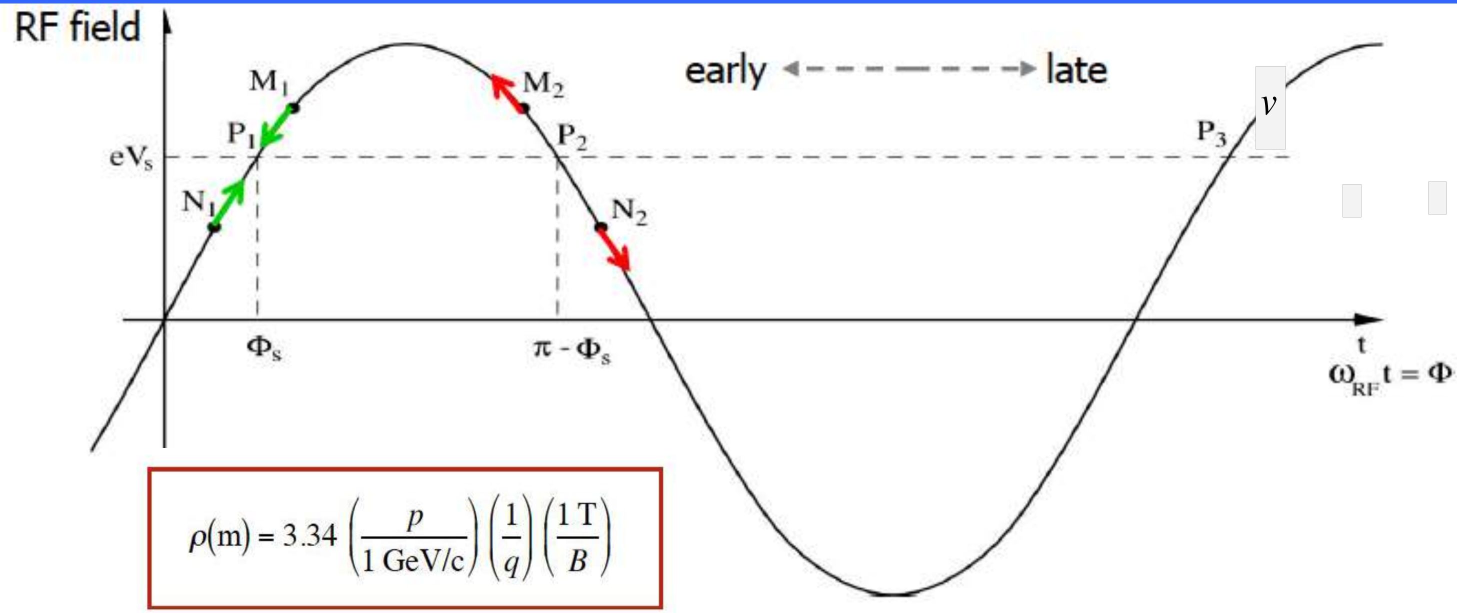


$$\rho = \frac{mvc}{qB} = \frac{pc}{qB}$$

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.

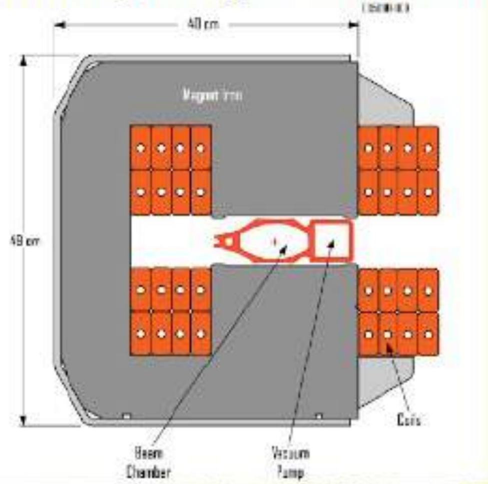
Phase stability and longitudinal focusing

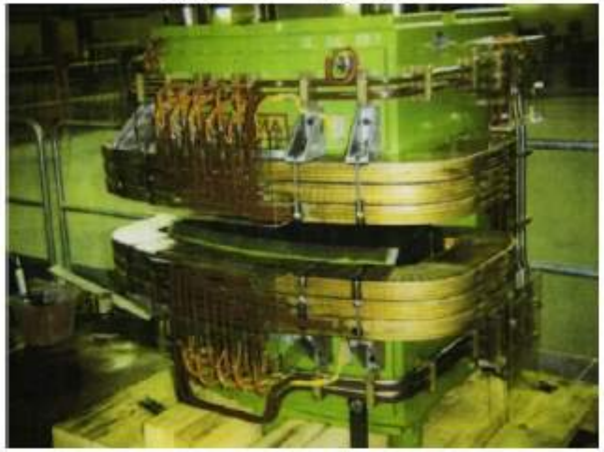


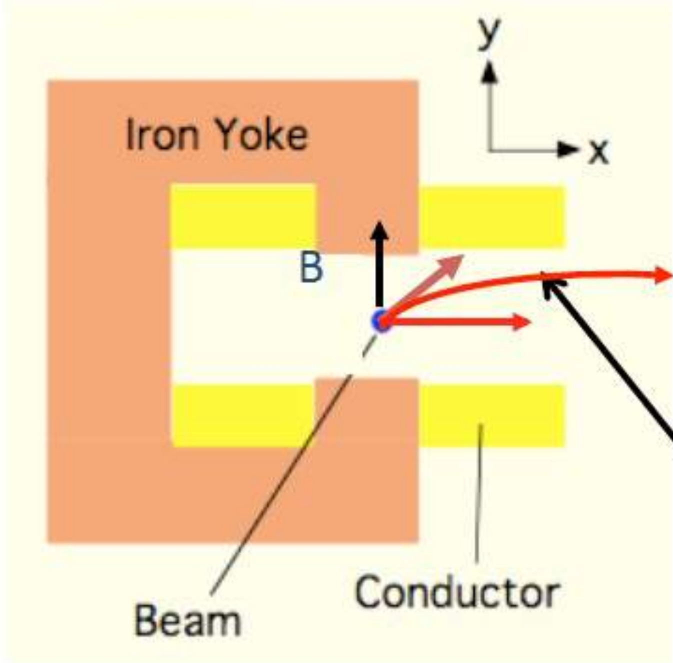
- In a certain energy range, acceleration by RF field results in early arrival of particle at next turn: for stability, this particle should undergo less acceleration
- Operating point P2 is unstable
  - Late particle N2 sees lower acceleration and gets even later
  - Early particle M2 sees higher acceleration 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 $B\rho[Tm] = \frac{p}{q} \cong \frac{W}{cq}$

Per particelle ultra-relativistiche

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

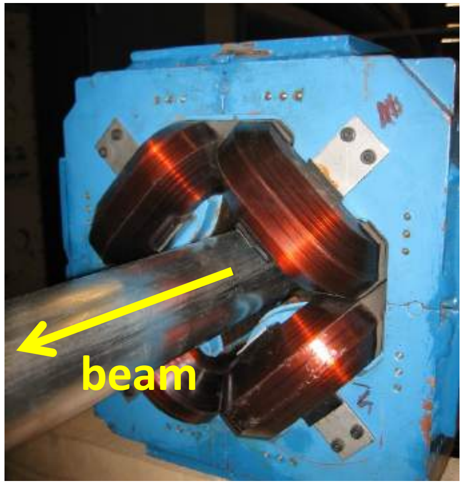
MAGNETIC QUADRUPOLE

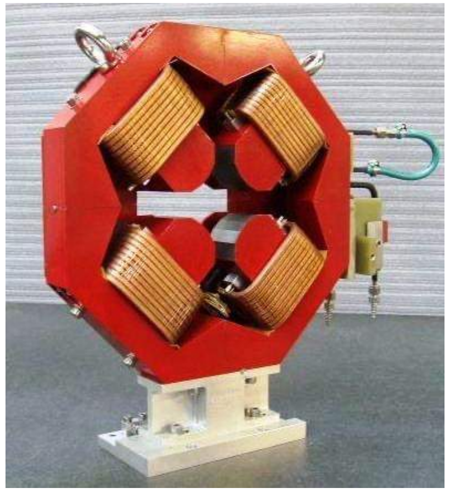
Quadrupoles are used to **focalize the beam in the transverse plane**. It is a **4 poles magnet**:

⇒**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**



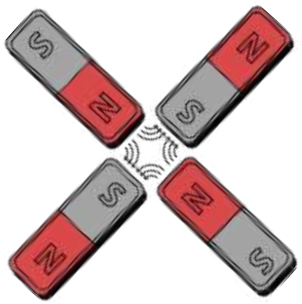


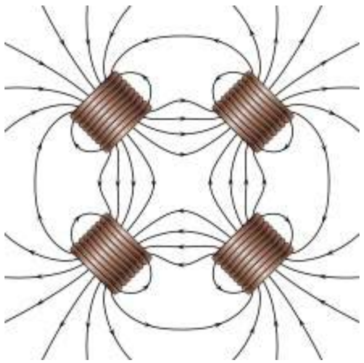
$$\begin{cases} B_x = G \cdot y \\ B_y = G \cdot x \end{cases} \Rightarrow \begin{cases} F_y = qvG \cdot y \\ F_x = -qvG \cdot x \end{cases}$$

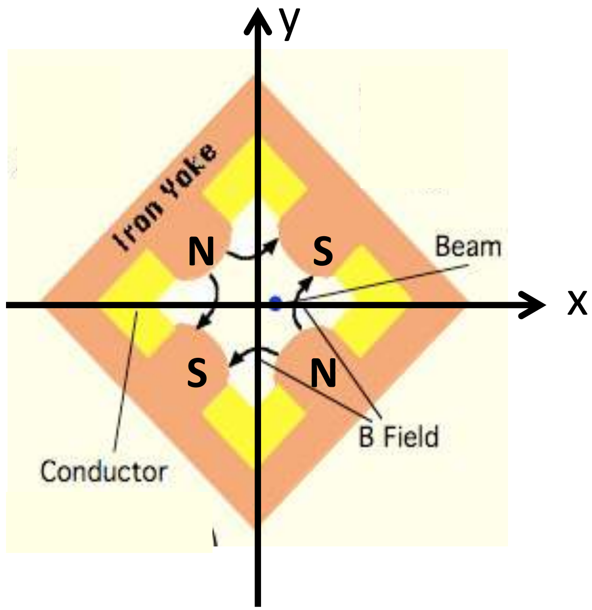
$$G = \text{quadrupole gradient} \left[\frac{T}{m} \right]$$

Electromagnetic quadrupoles G <50-100 T/m

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

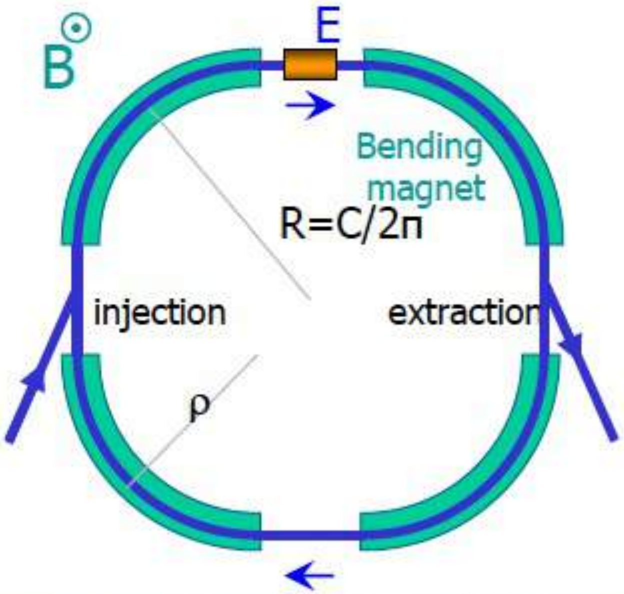






3 GeV Cosmotron at BNL

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

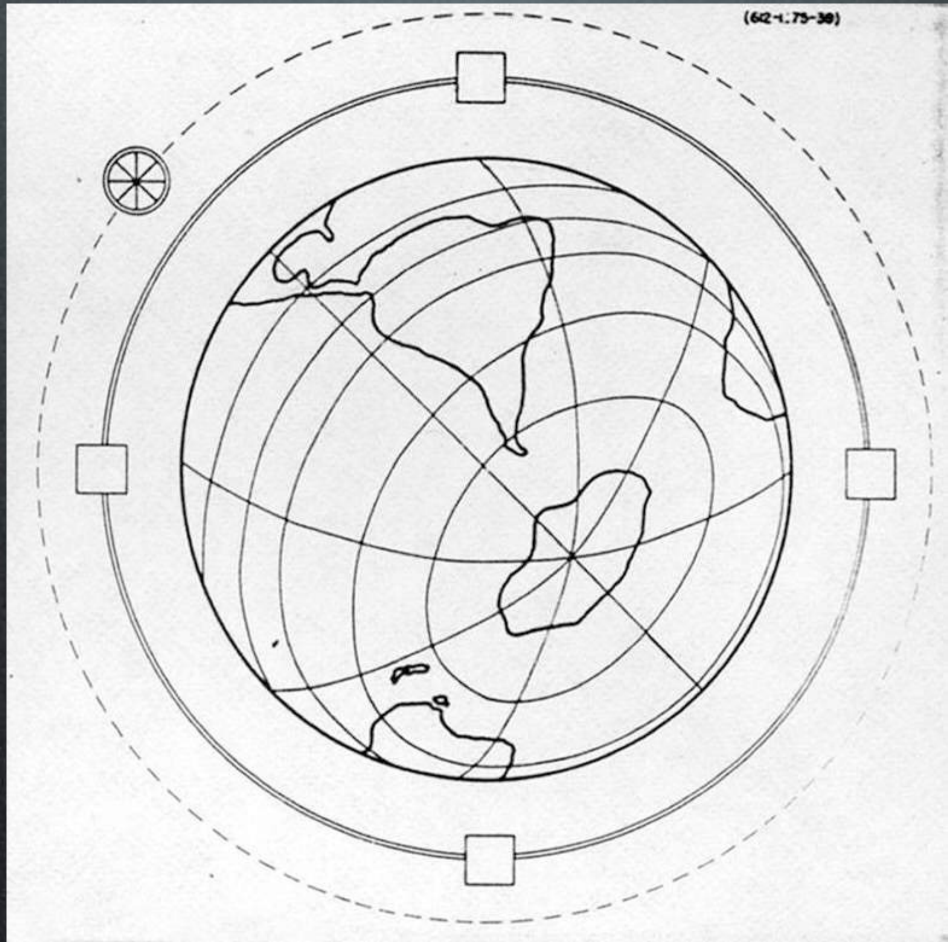
ρ 8000 km

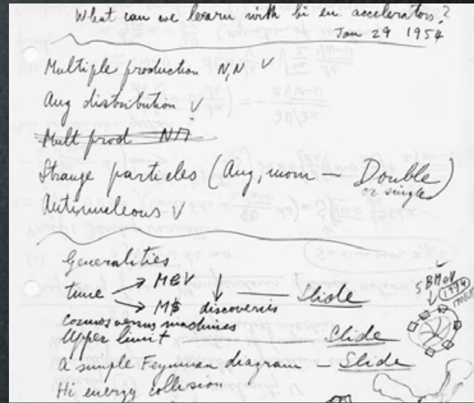
fixed target

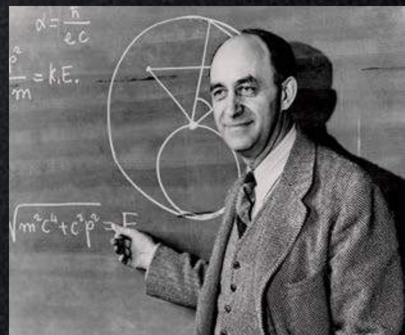
3 TeV c.m.

170 G$

1994

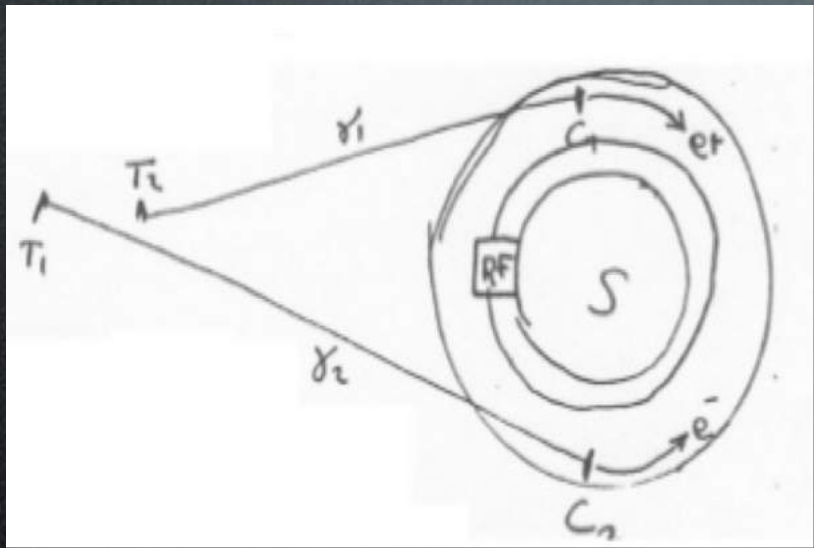






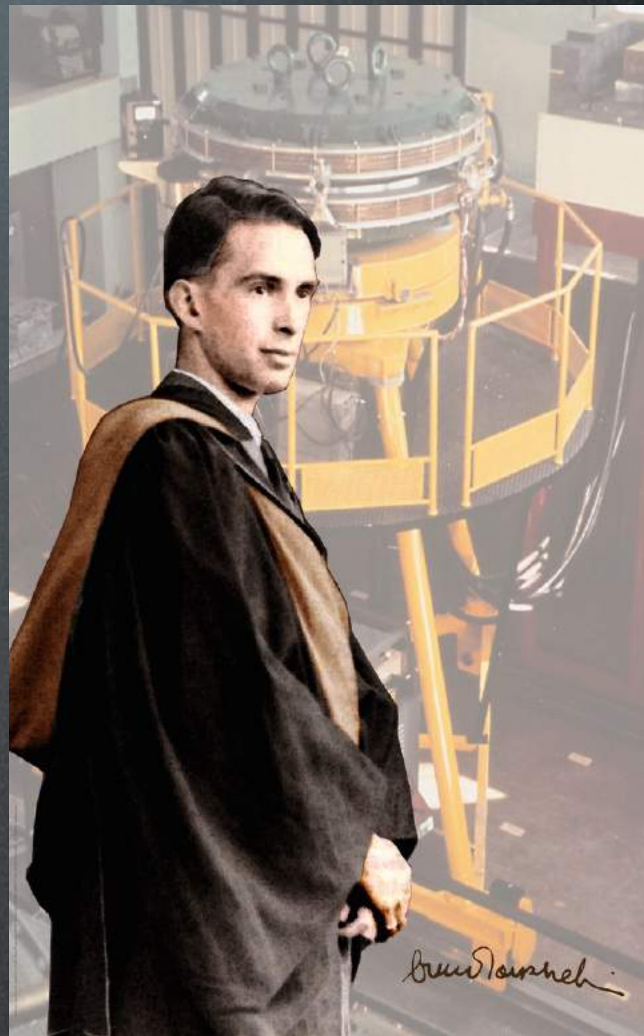
Touschek's Anello Di Accumulazione (ADA)

1961 the first e+e- Collider

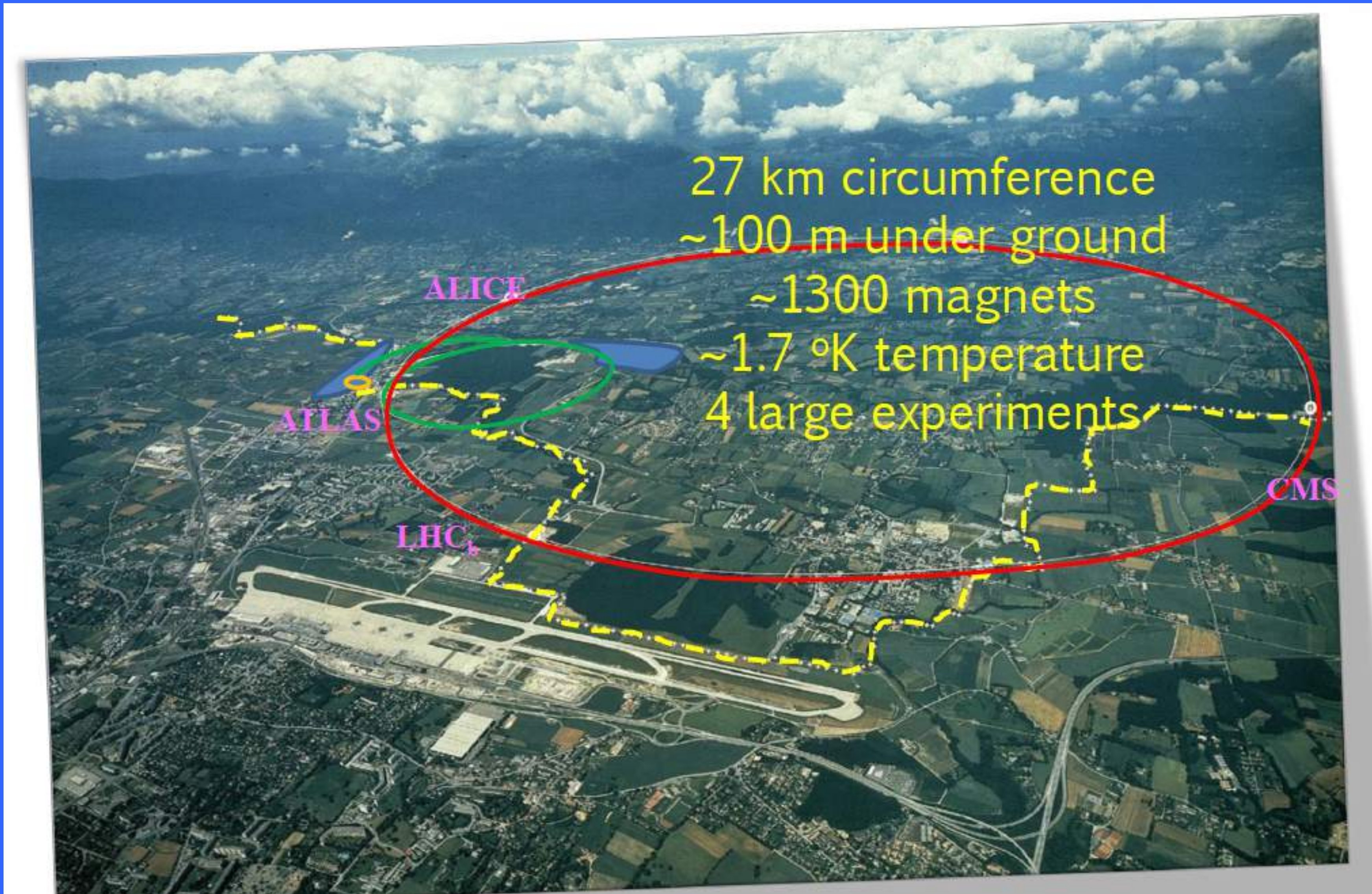


$$E_{CM} \approx \sqrt{2E_1 m_2}$$

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

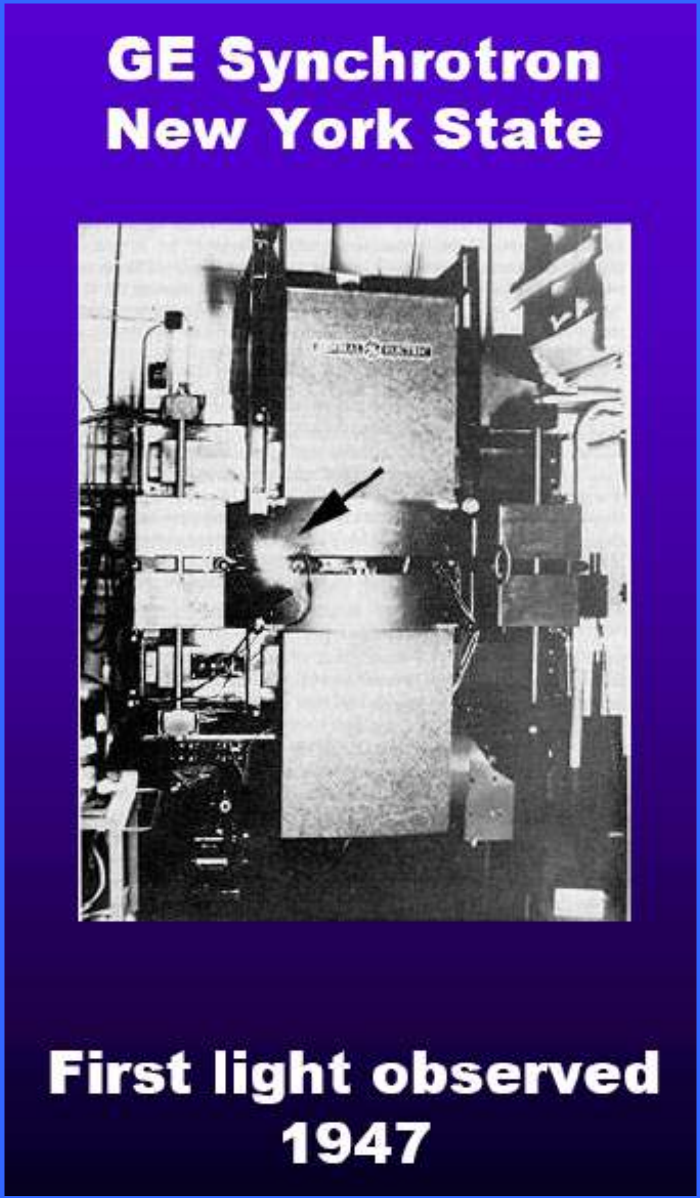


LHC few data

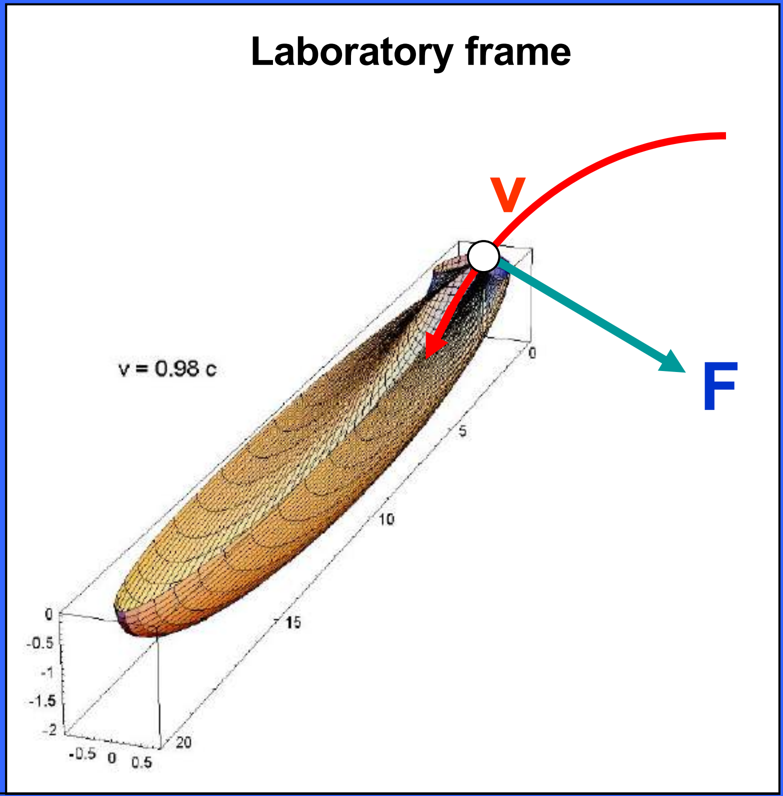


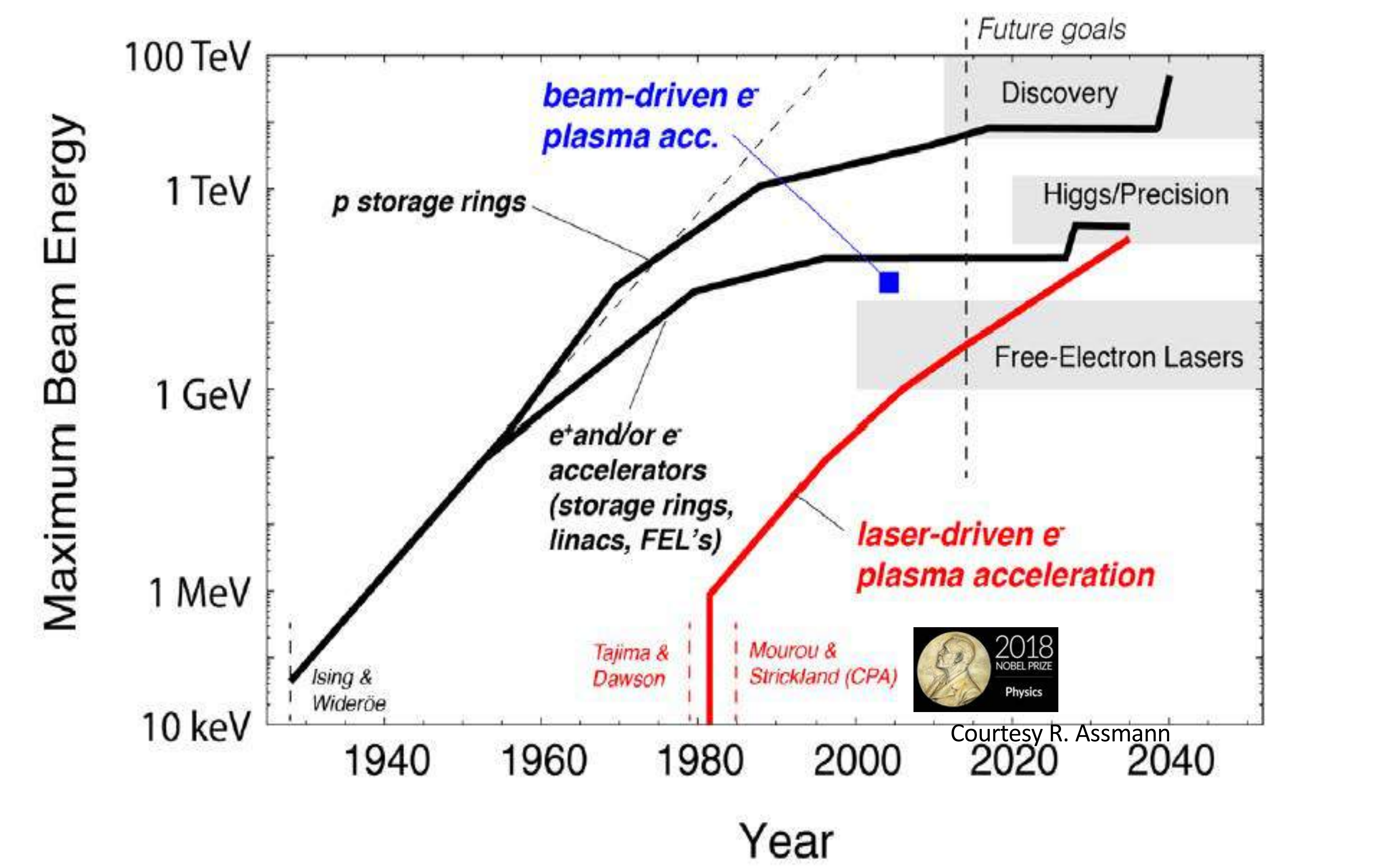
27 km circumference
~100 m under ground
~1300 magnets
~1.7 ºK temperature
4 large experiments
ALICE
ATLAS
LHCb
CMS

Synchrotron Radiation



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





Courtesy R. Assmann

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

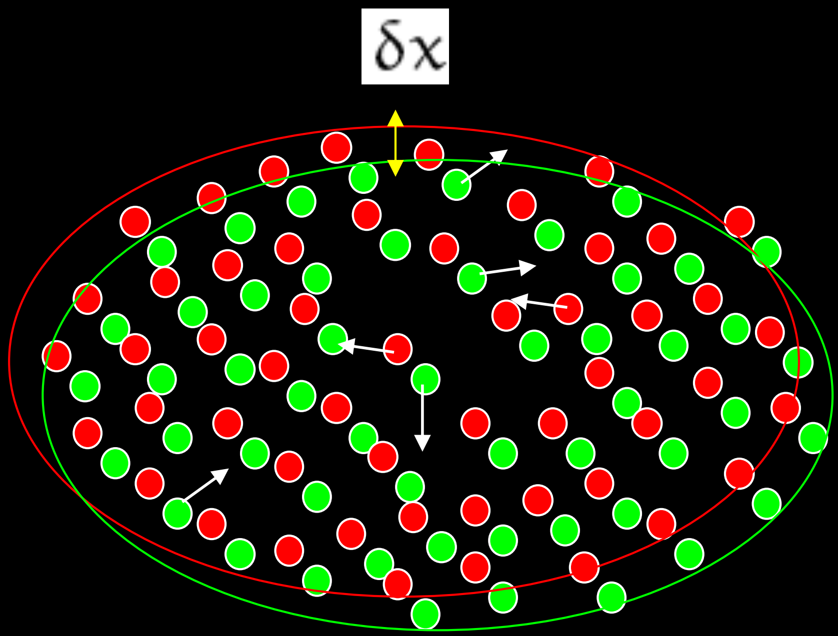
and

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 $4\gamma_0^c mc^2$ 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

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

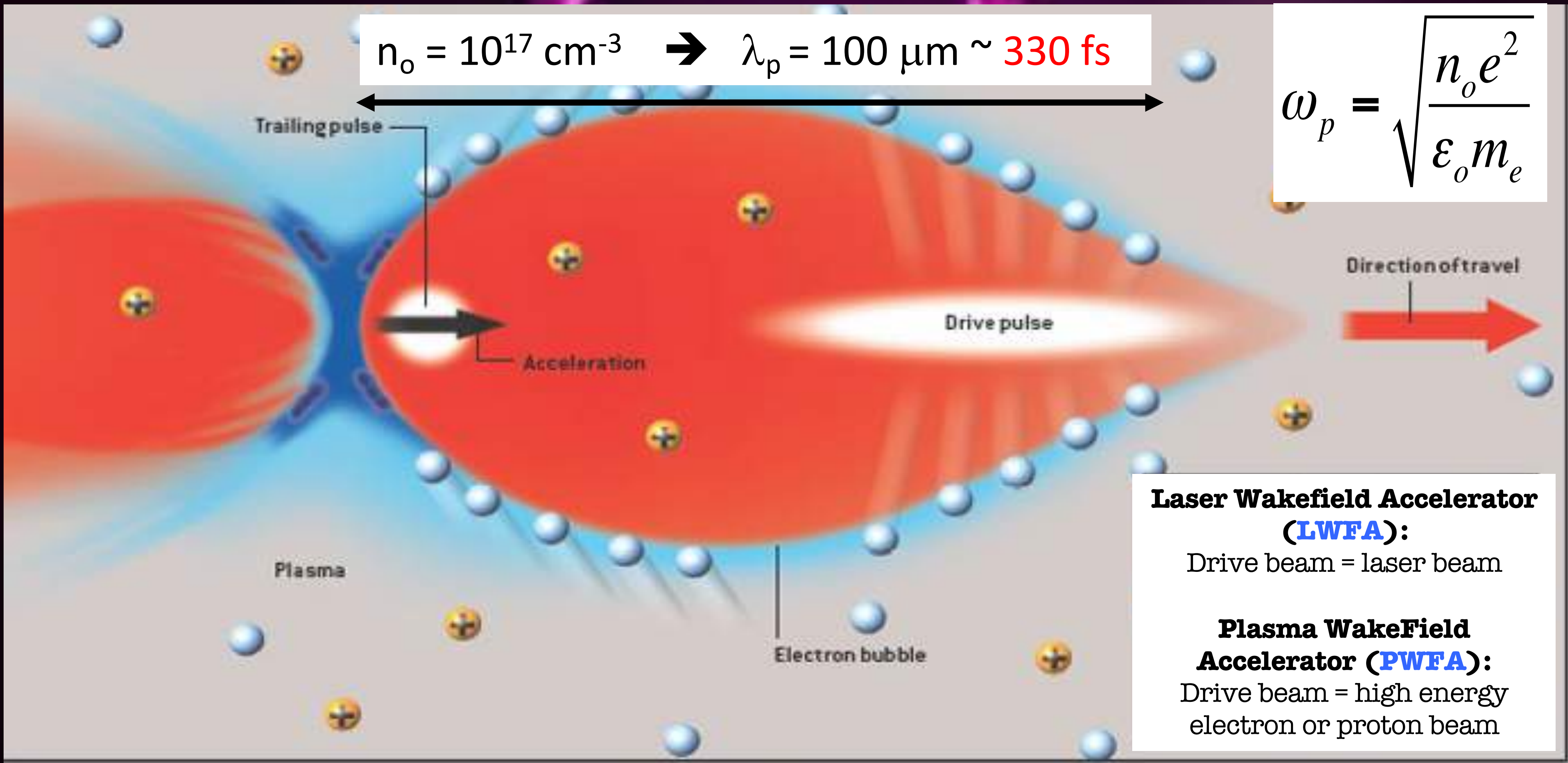
Plasma frequency

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

Plasma oscillations

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

Principle of plasma acceleration



$n_o = 10^{17}\ cm^{-3} \rightarrow \lambda_p = 100\ \mu m \sim 330\ fs$

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

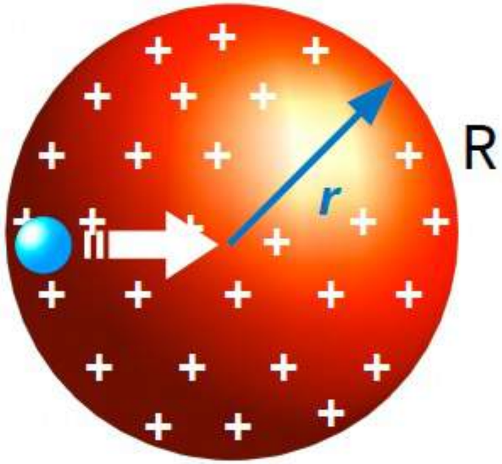
Laser Wakefield Accelerator (LWFA):
Drive beam = laser beam

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

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

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



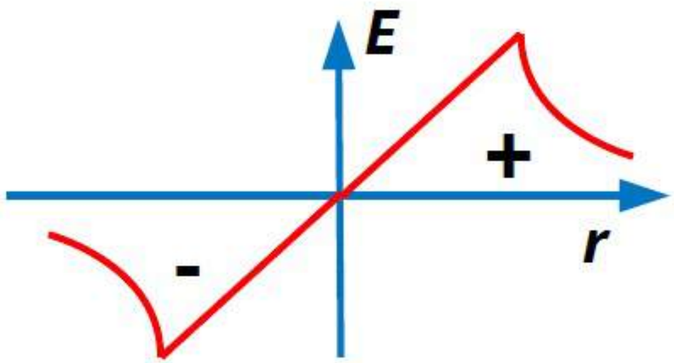
The field is **increasing** inside the sphere

Let's put some numbers

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

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

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

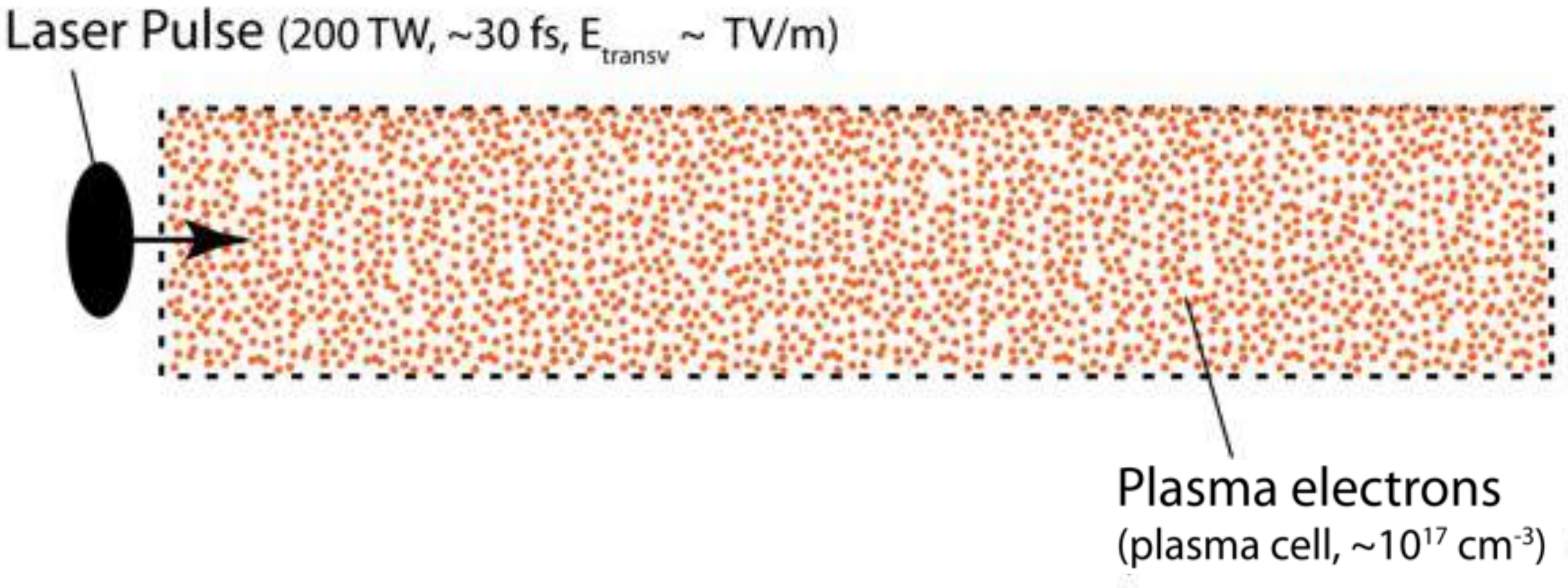


Break-Down Limit?
⇒ Wave-Breaking field:

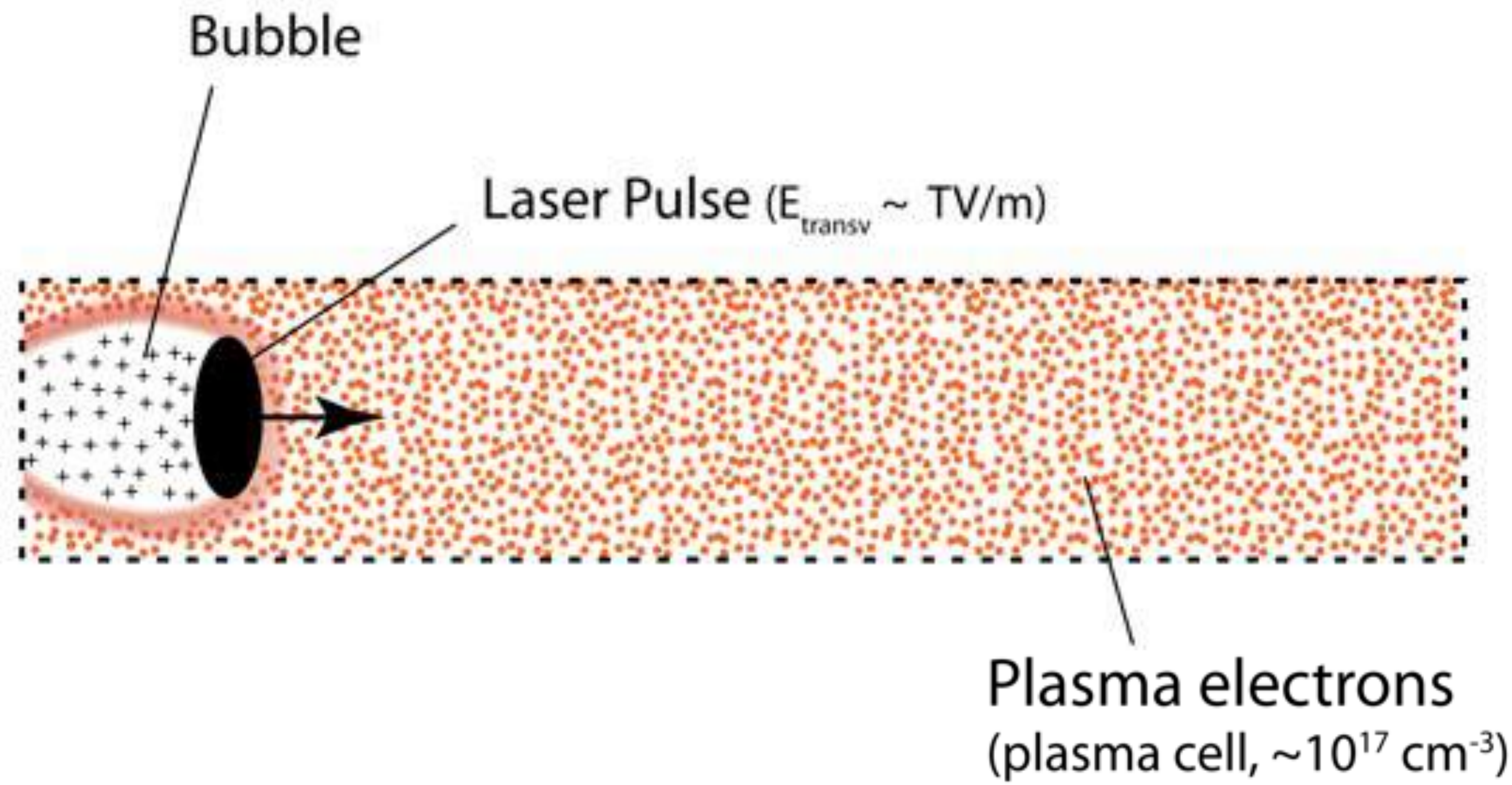
$$E_{wb}\approx 100\left[GeV/m\right]\sqrt{n_o\left[cm^{-3}\right]}$$

Plasma Wake-Acceleration

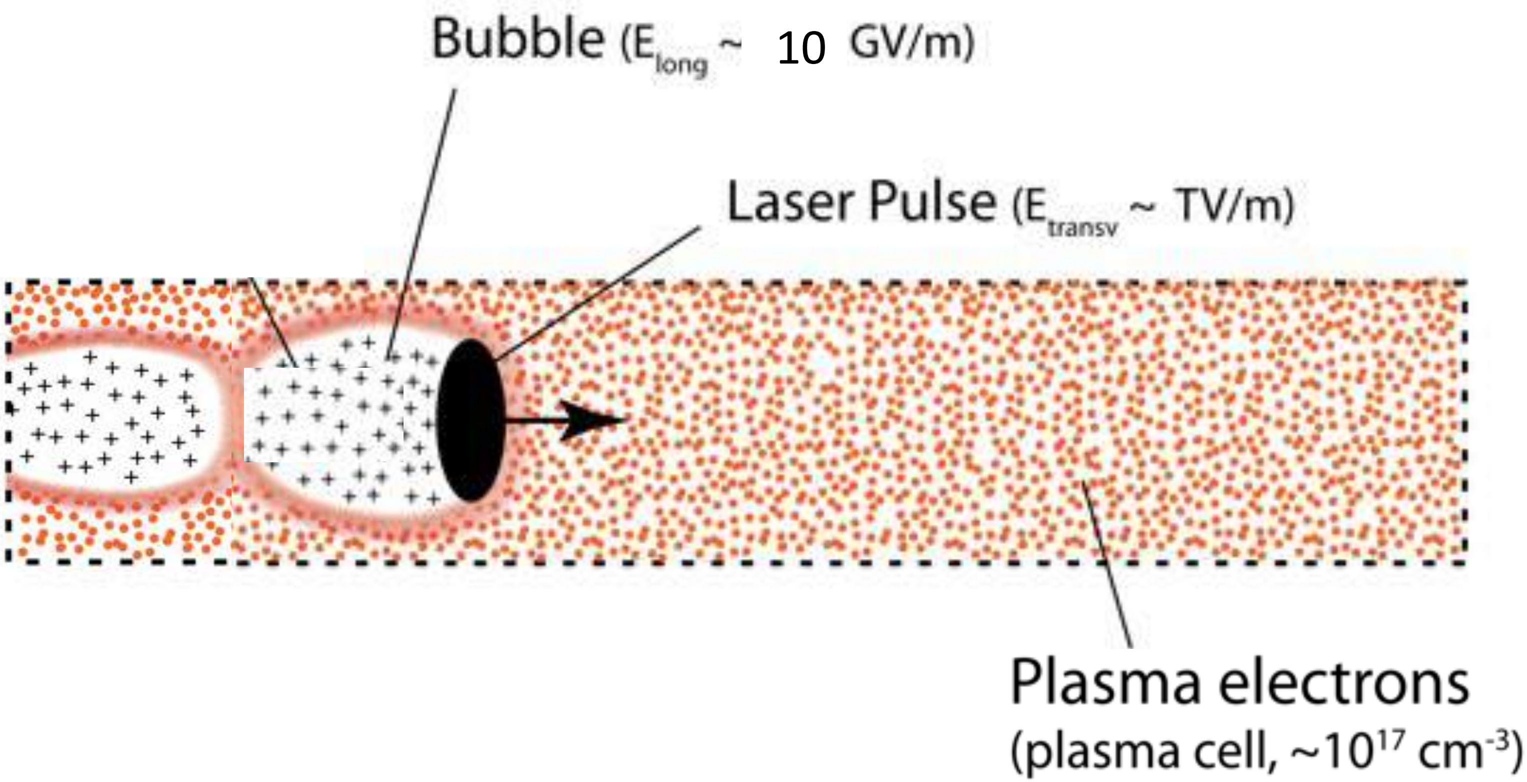
Horizon2020



Plasma Wake-Acceleration

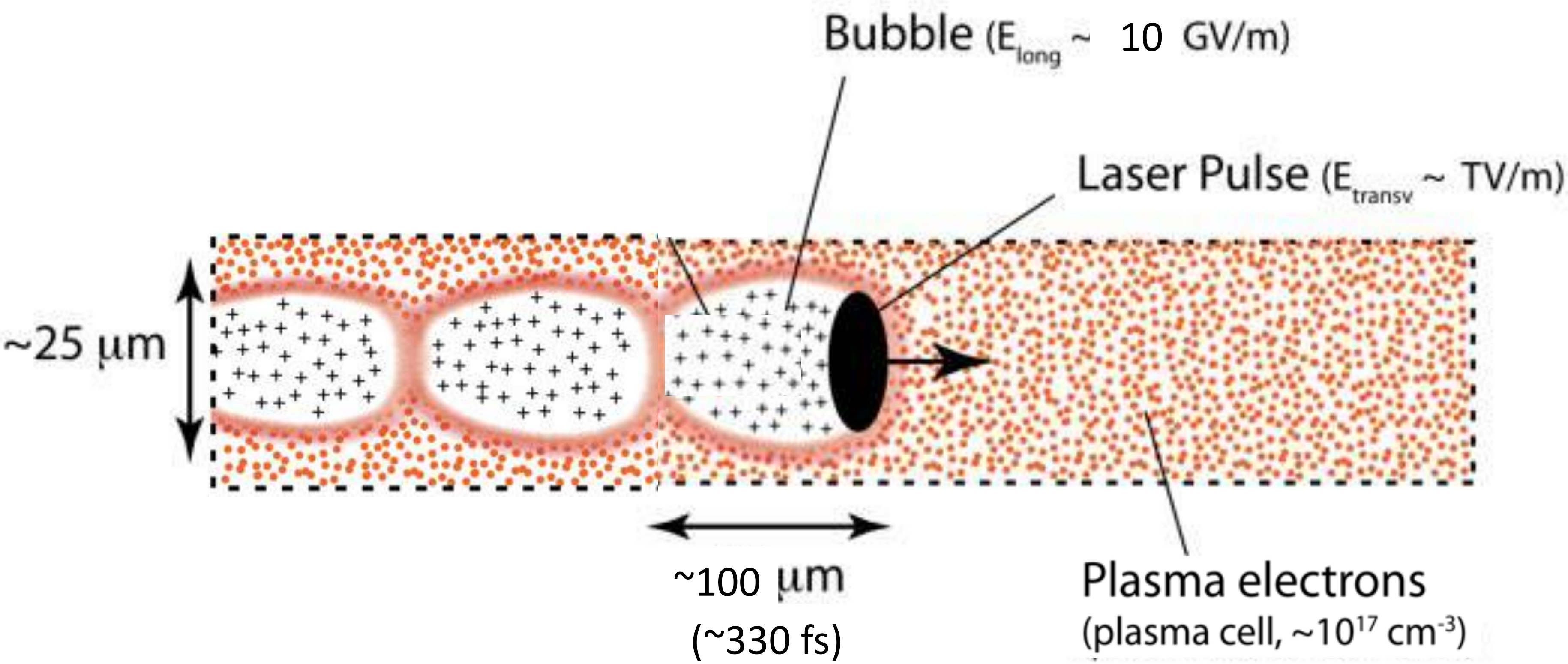


Plasma Wake-Acceleration

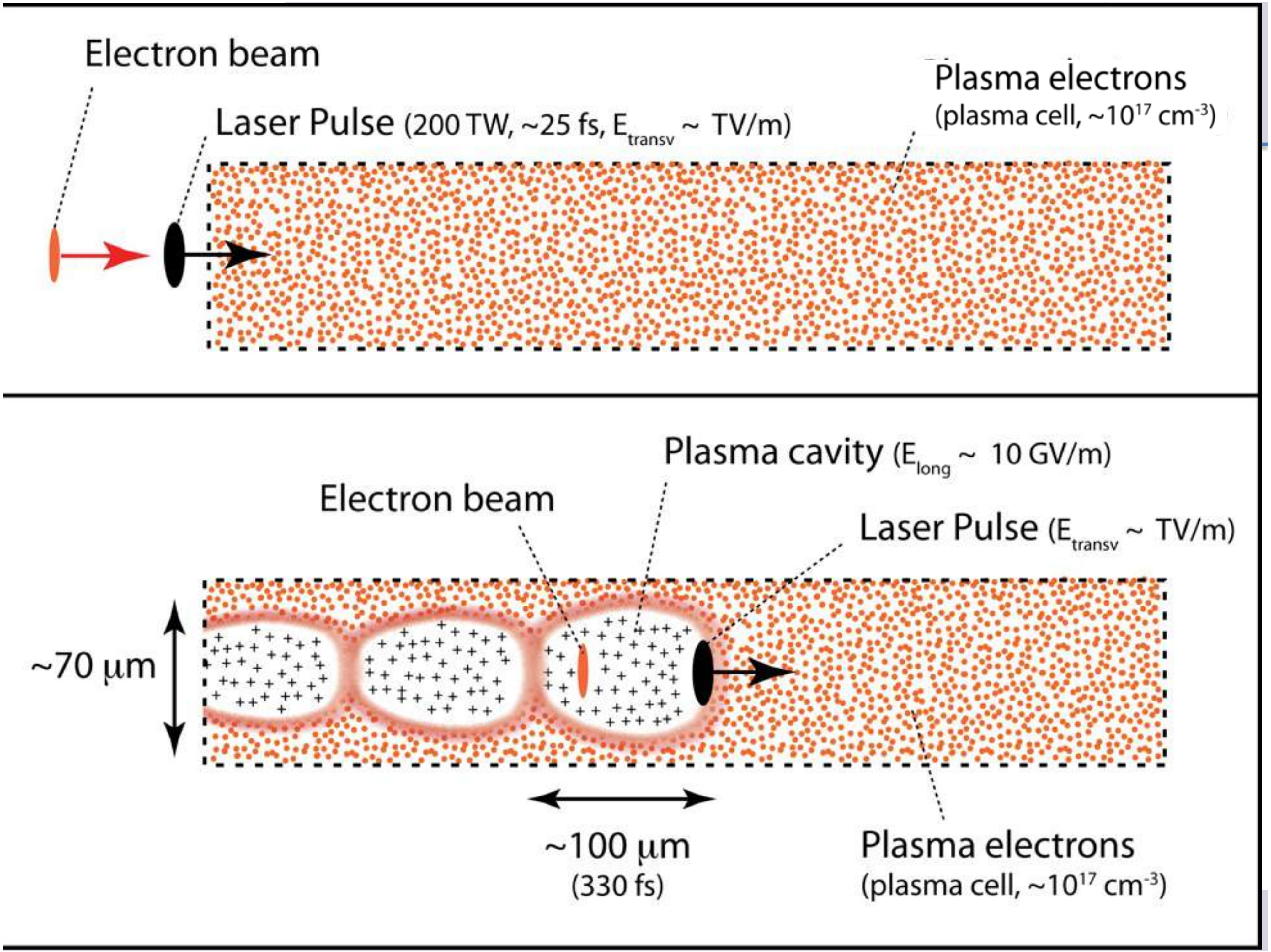


Plasma Wake-Acceleration

Horizon2020



This accelerator fits into a human hair!


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})

Principle of plasma acceleration

Driven by Radiation Pressure

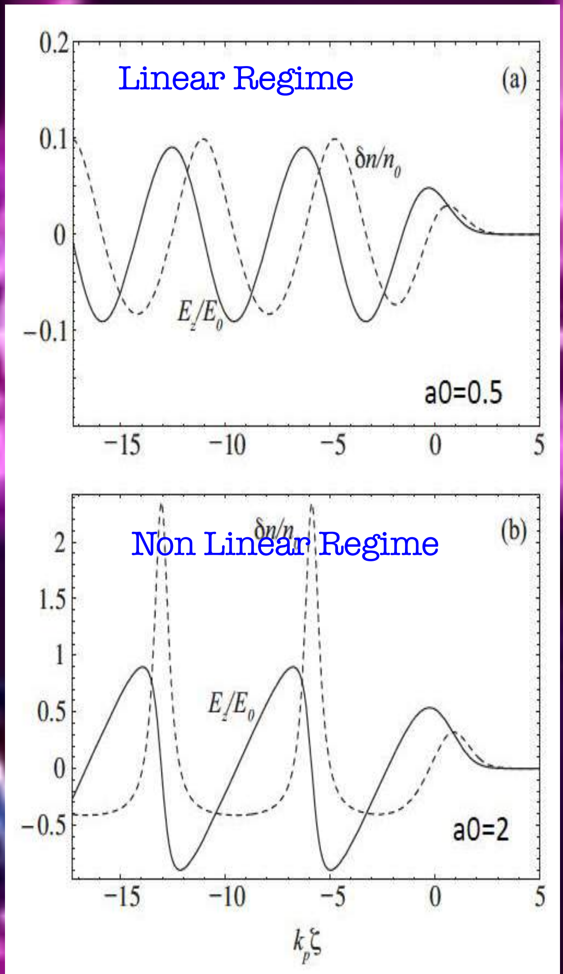
$$\left(\frac{\partial^2}{\partial t^2}+\omega_p^2\right)\frac{n}{n_o}=c^2\nabla^2\frac{a^2}{2}$$

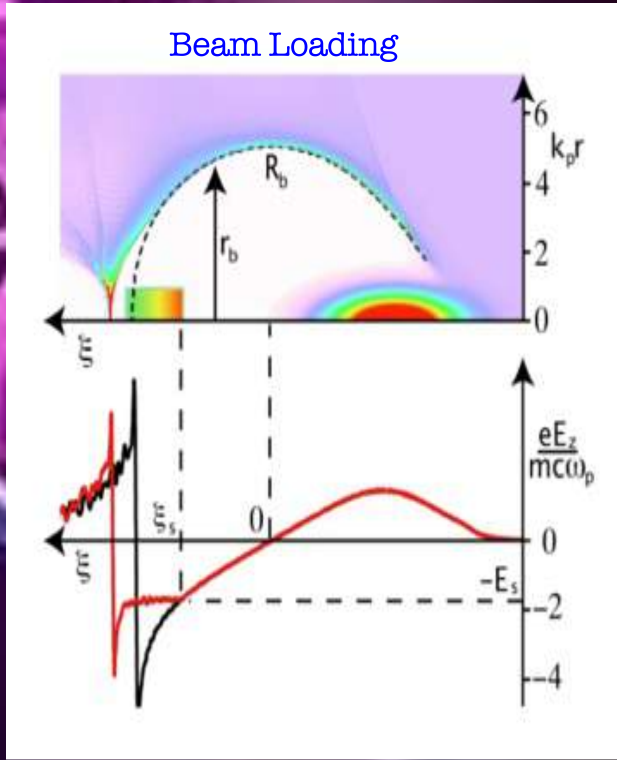
$$a=\frac{eA}{mc^2}\propto\lambda J^{1/2}$$

Driven by Space Charge

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

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

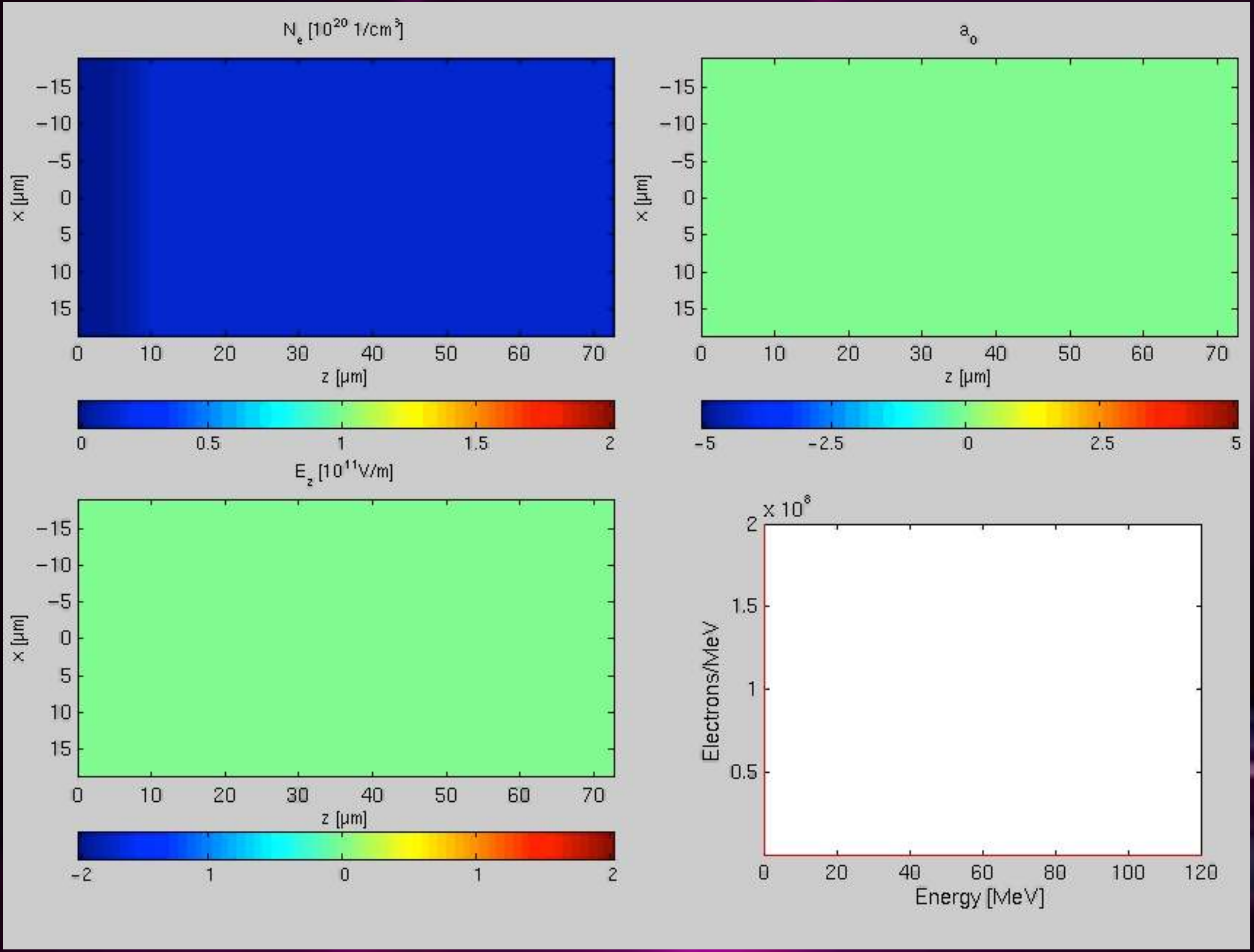




LWFA limitations: Diffraction, Dephasing, Depletion

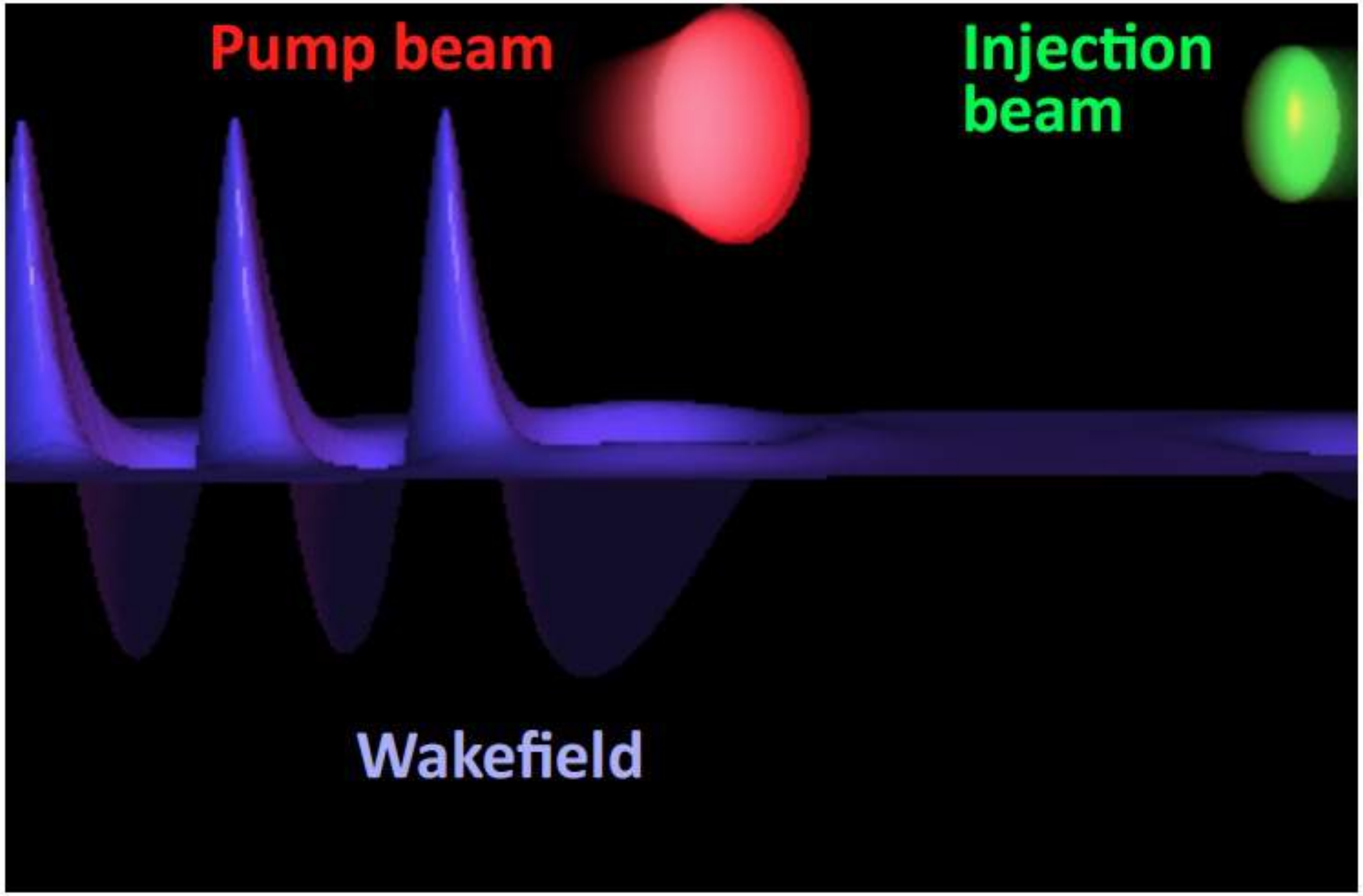
PWFA limitations: Head Erosion, Hose Instability

Diffraction - Self injection - Dephasing – Depletion



Colliding Laser Pulses Scheme

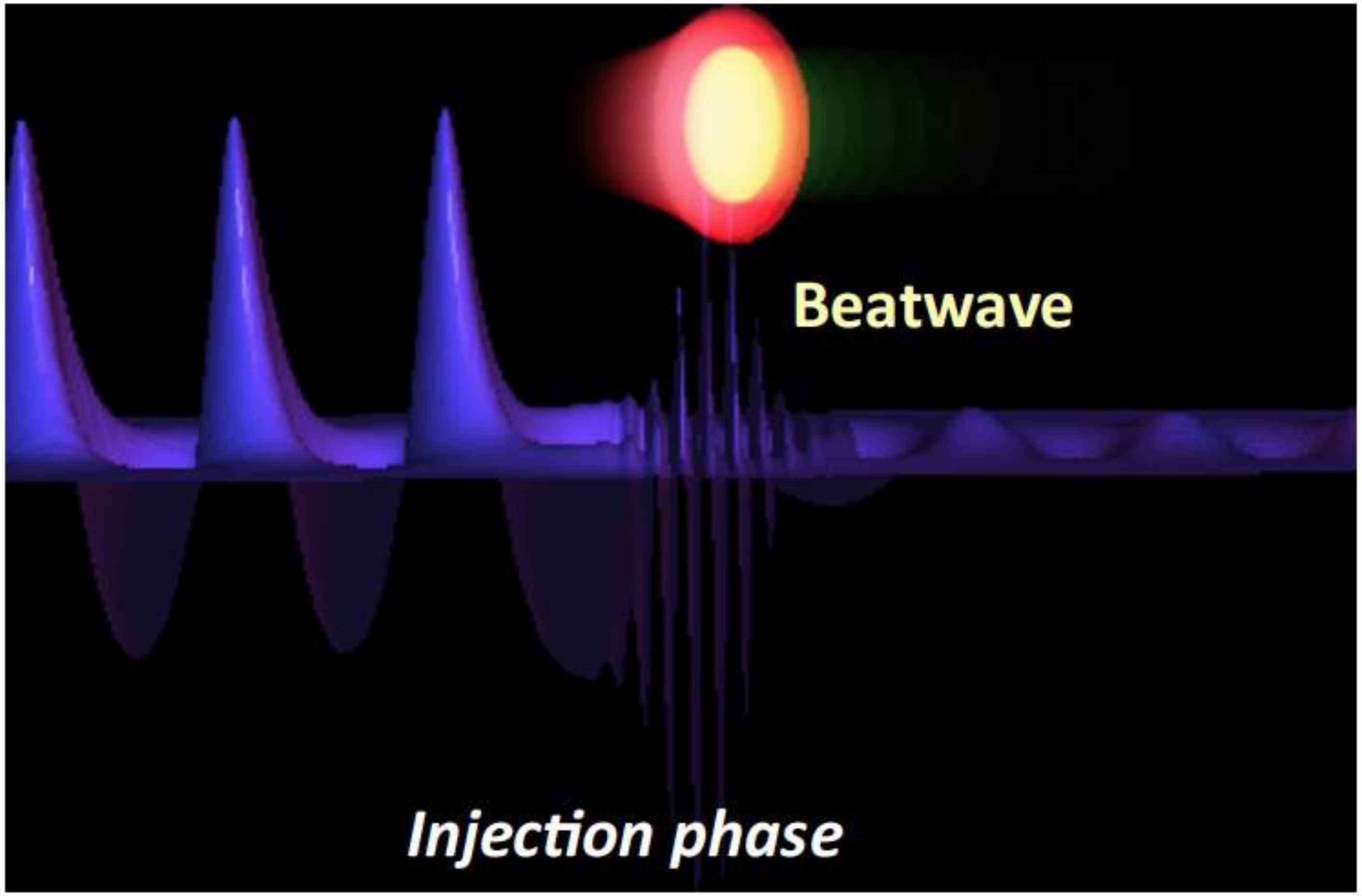
The first laser creates the accelerating structure, a second laser beam is used to heat electrons



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

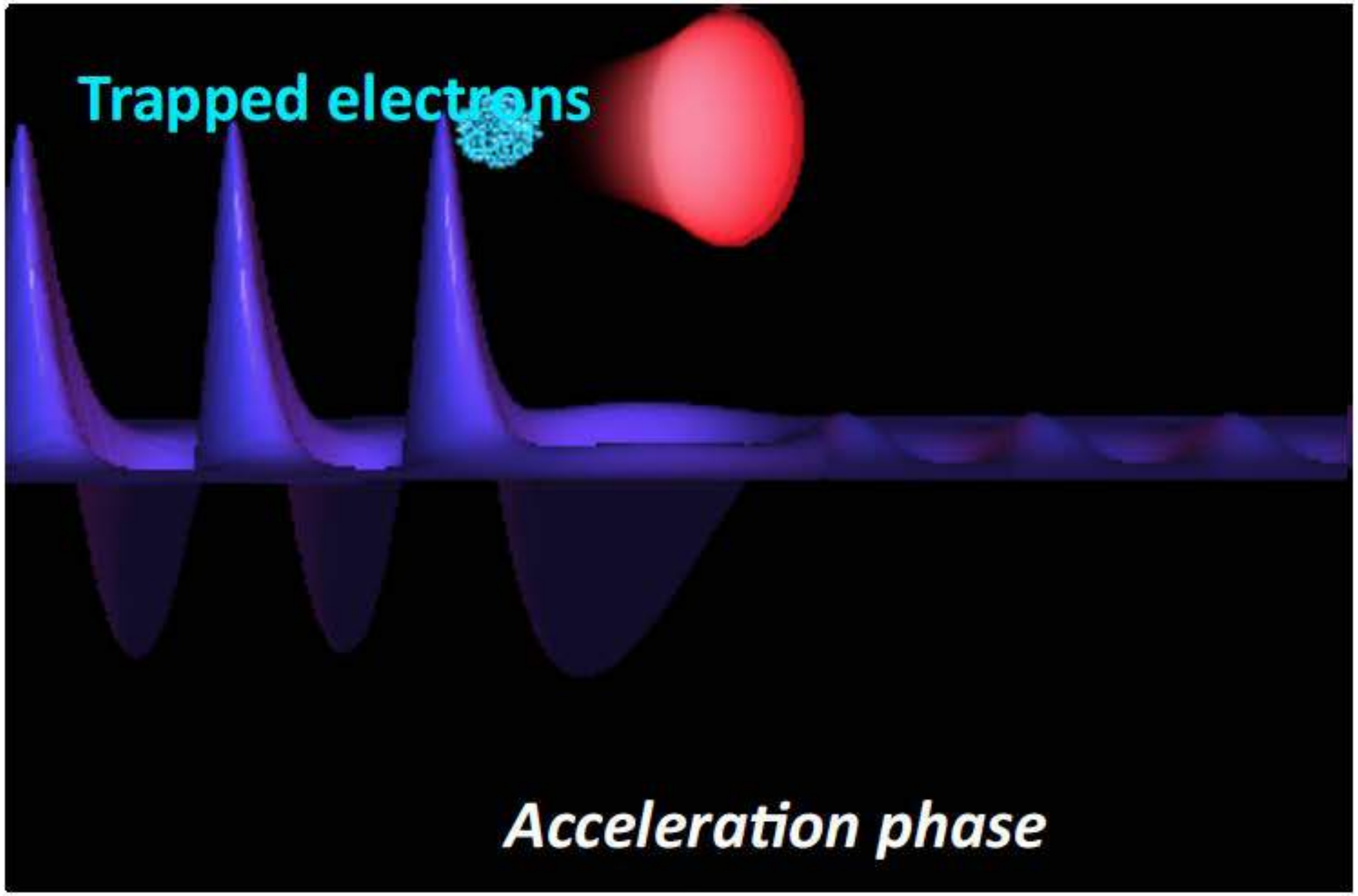
The first laser creates the accelerating structure, a second laser beam is used to heat electrons



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)

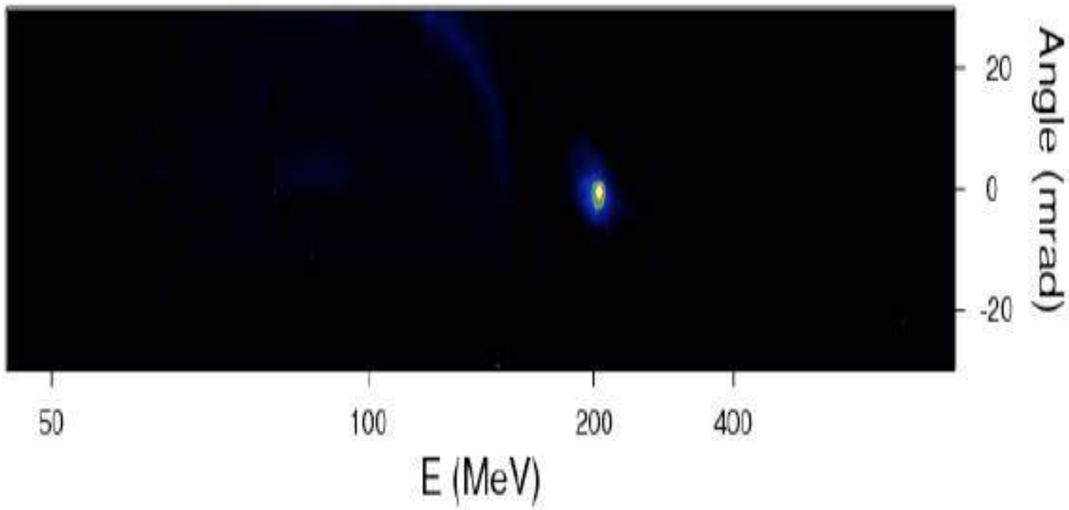
Colliding Laser Pulses Scheme

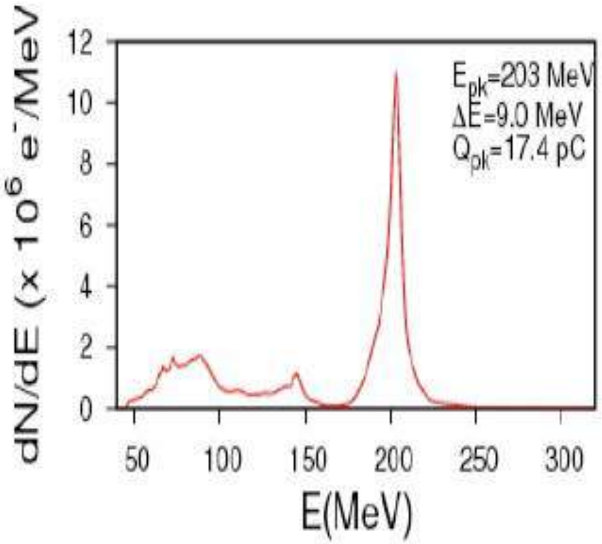
The first laser creates the accelerating structure, a second laser beam is used to heat electrons



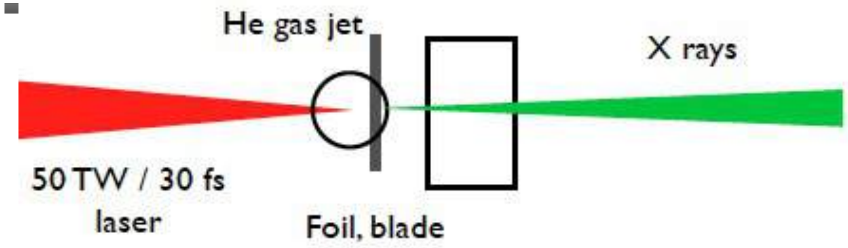
Theory : E. Esarey *et al.*, PRL **79**, 2682 (1997), H. Kotaki *et al.*, PoP **11** (2004)
Experiments : J. Faure *et al.*, Nature **444**, 737 (2006)

Stable Laser Plasma Accelerators





Inverse Compton Scattering : New scheme



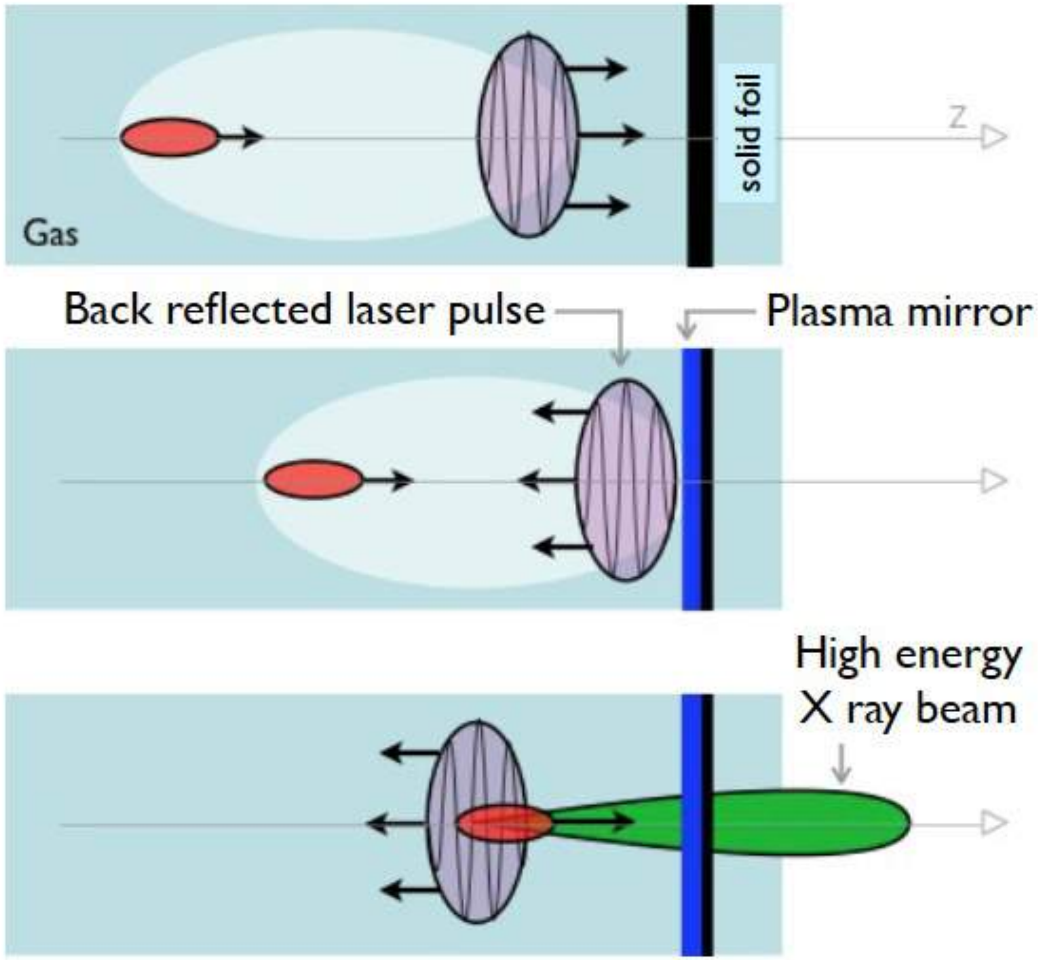
A single laser pulse

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 !

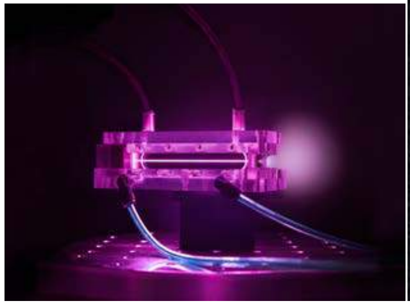


BELLA: BErkeley Lab Laser Accelerator

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

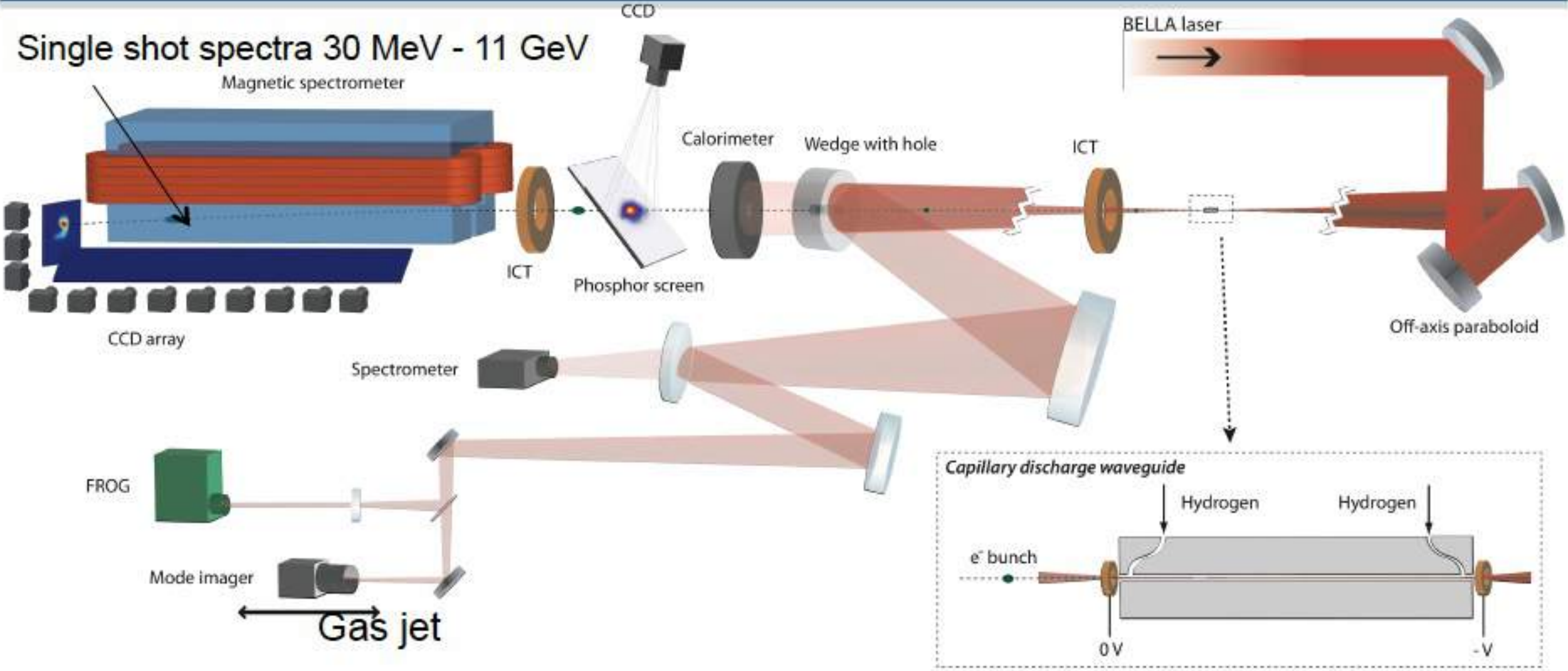
Critical HEP experiments:

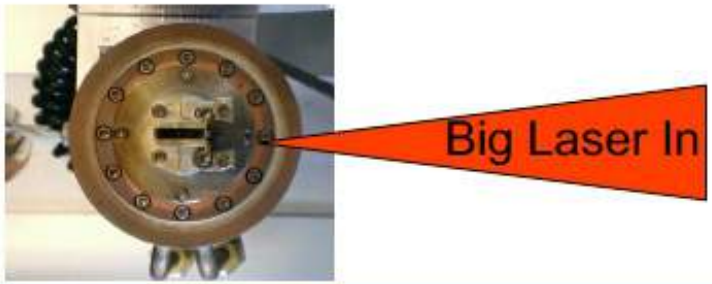
- 10 GeV electron beam from <1 m LPA
- Staging LPAs
- Positron acceleration



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

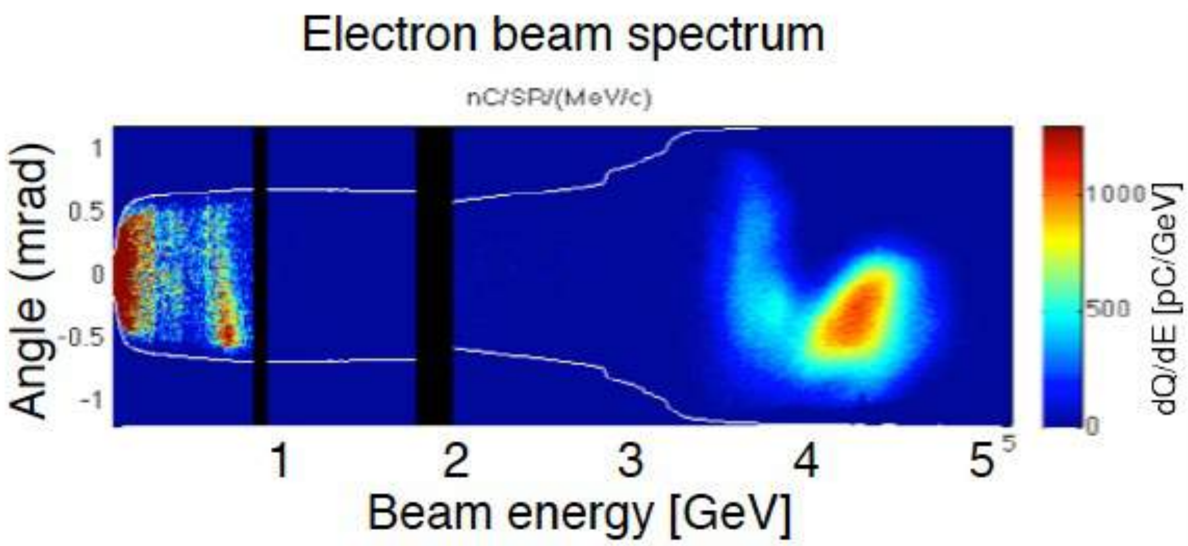


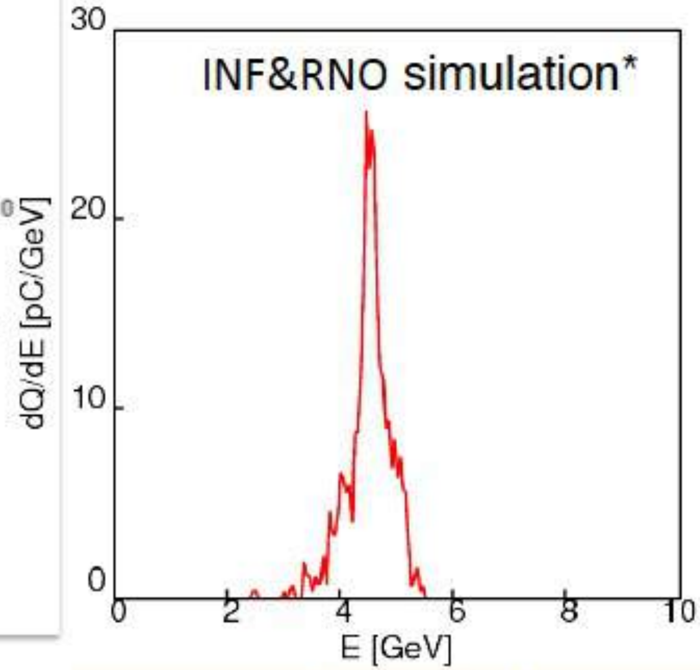


Capillary discharge

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

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

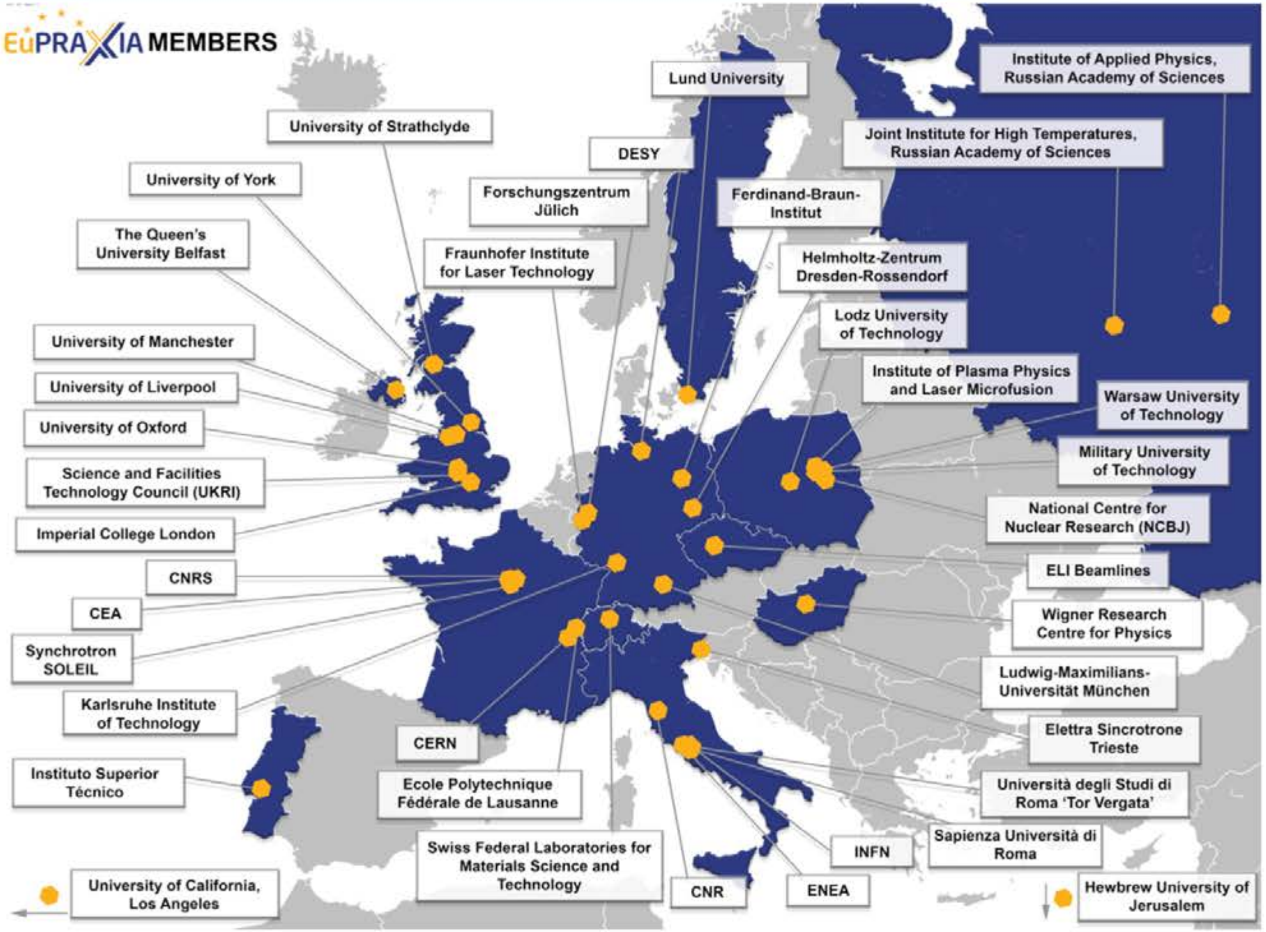
Medical, industrial applications soon

Courtesy R. Assmann

The Consortium Members for the Next Phase

(from 16 to 40)

Horizon 2020



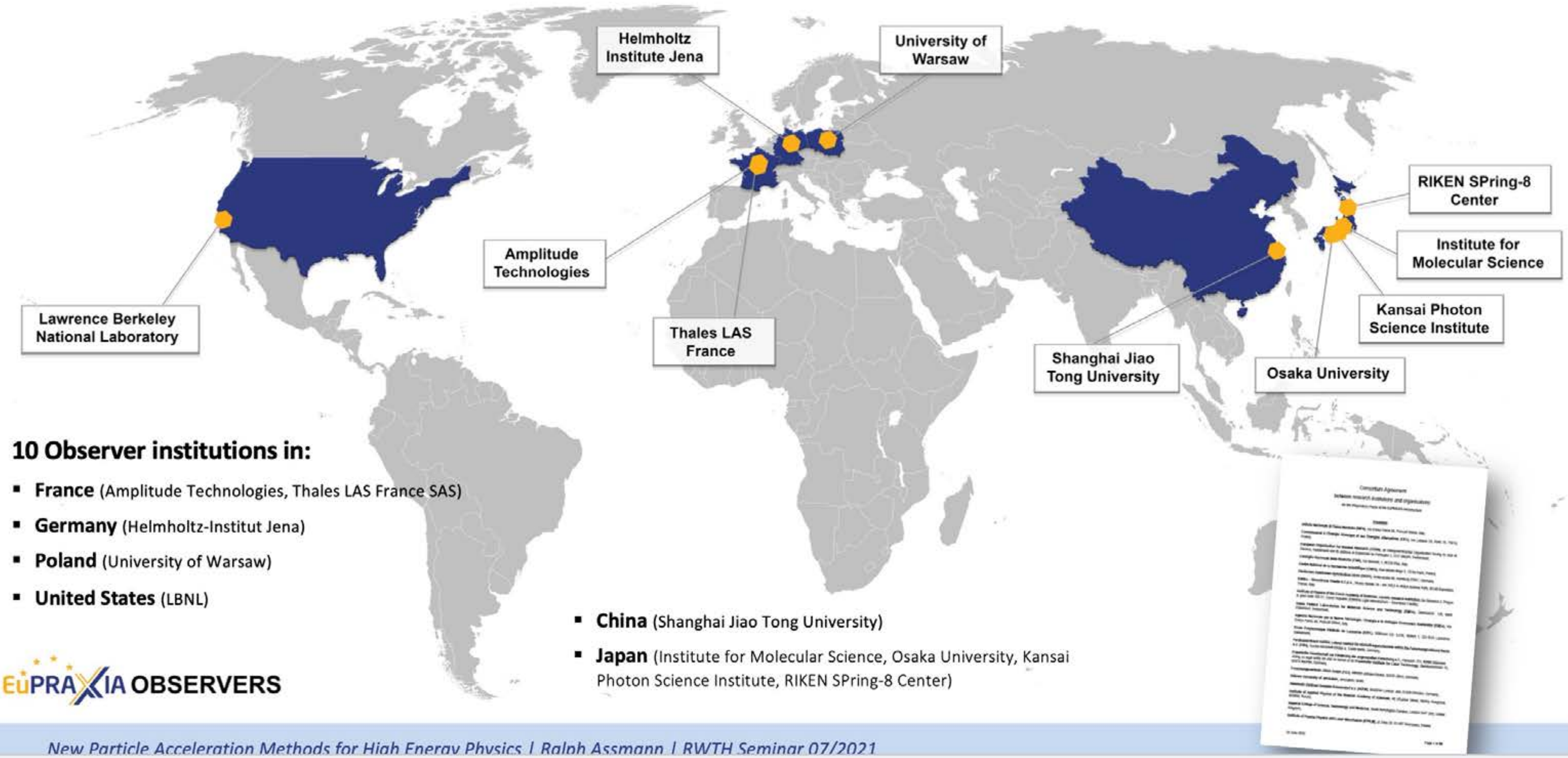
40 Member institutions in:

- **Italy** (INFN, CNR, Elettra, ENEA, Sapienza Università di Roma, Università degli Studi di Roma "Tor Vergata")
- **France** (CEA, SOLEIL, CNRS)
- **Switzerland** (EMPA, Ecole Polytechnique Fédérale de Lausanne)
- **Germany** (DESY, Ferdinand-Braun-Institut, Fraunhofer Institute for Laser Technology, Forschungszentrum Jülich, HZDR, KIT, LMU München)
- **United Kingdom** (Imperial College London, Queen's University of Belfast, STFC, University of Liverpool, University of Manchester, University of Oxford, University of Strathclyde, University of York)
- **Poland** (Institute of Plasma Physics and Laser Microfusion, Lodz University of Technology, Military University of Technology, NCBJ, Warsaw University of Technology)
- **Portugal** (IST)
- **Hungary** (Wigner Research Centre for Physics)
- **Sweden** (Lund University)
- **Israel** (Hebrew University of Jerusalem)
- **Russia** (Institute of Applied Physics, Joint Institute for High Temperatures)
- ***United States*** (UCLA)
- **CERN**
- **ELI Beamlines**

The Consortium Observers for the Next Phase

(from 25 to 10, Consortium Agreement signed)

Horizon 2020



10 Observer institutions in:

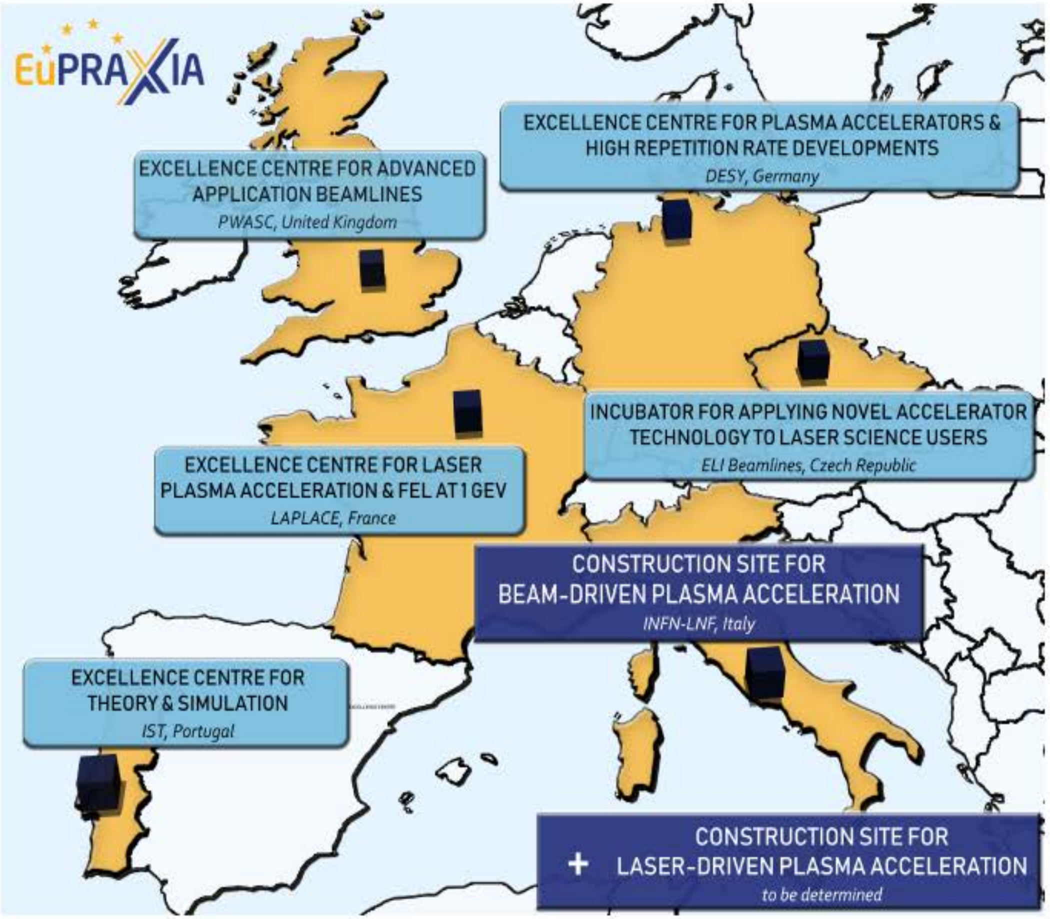
- **France** (Amplitude Technologies, Thales LAS France SAS)
- **Germany** (Helmholtz-Institut Jena)
- **Poland** (University of Warsaw)
- **United States** (LBNL)
- **China** (Shanghai Jiao Tong University)
- **Japan** (Institute for Molecular Science, Osaka University, Kansai Photon Science Institute, RIKEN SPring-8 Center)

EuPRAXIA OBSERVERS

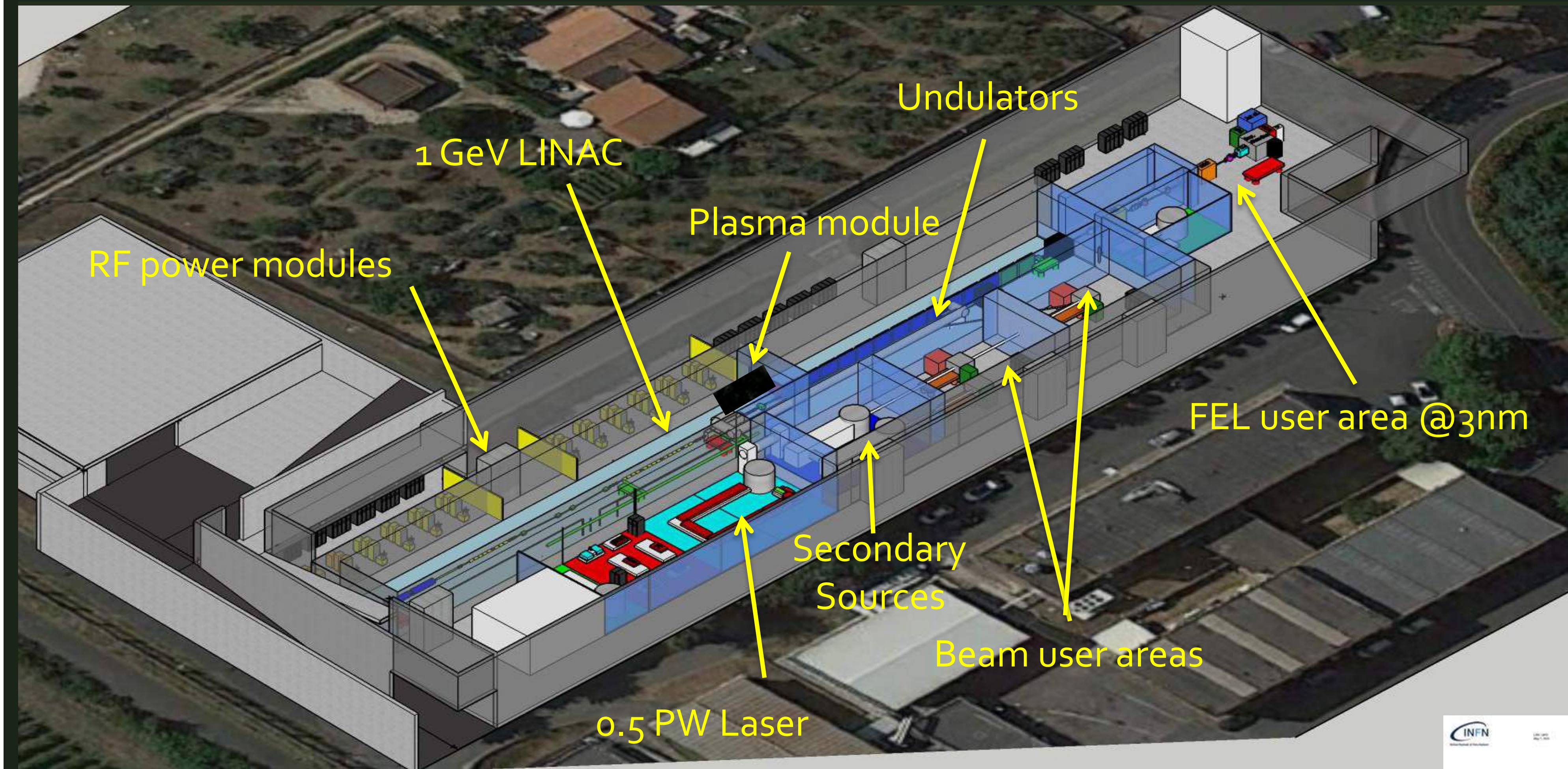
… and Builds a European Distributed Facility

Position Europe as a Leader in the Global Context

1. Lean overall **EuPRAXIA management**
2. **Ten clusters:** Collaborations of institutes on specific problems, developing solutions, technical designs, driving developments with EuPRAXIA generated funding → **expertise of Helmholtz centers required - opportunities**
3. **Five excellence centers** at existing facilities: Using pre-investment, support tests, prototyping, production with EuPRAXIA generated funding → **DESY excellence center**
4. **One or two construction sites** at existing facilities with EuPRAXIA generated funding:
   - **Beam-driven** at Frascati (Italy).
   - **Laser-driven** at CLF/STFC (UK), CNR/ INFN (Italy) or ELI-Beamlines.



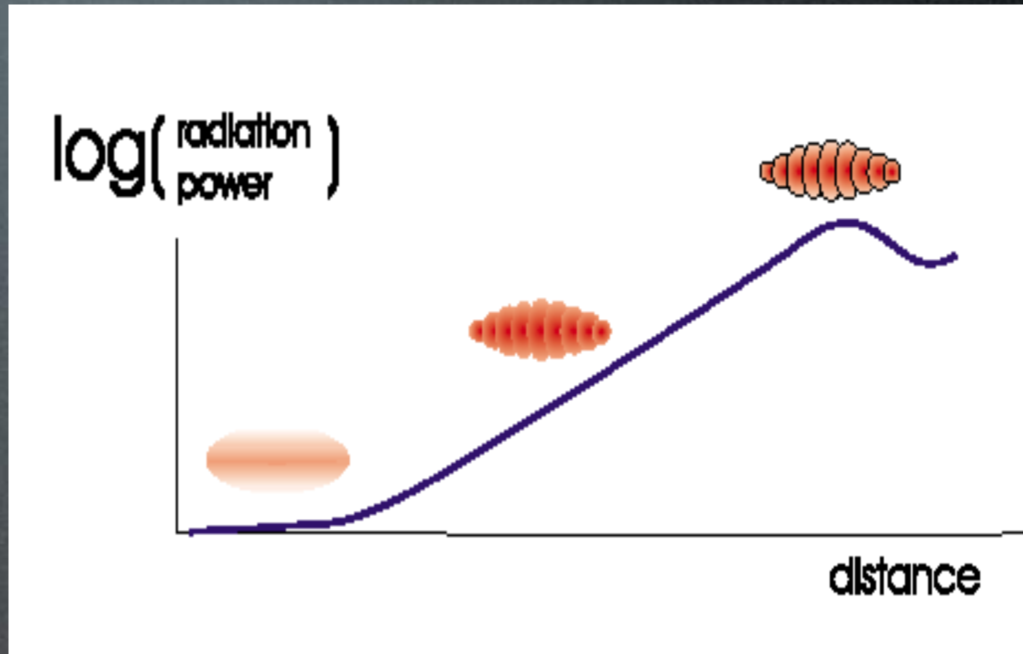
EuPRAXIA@SPARC_LAB



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

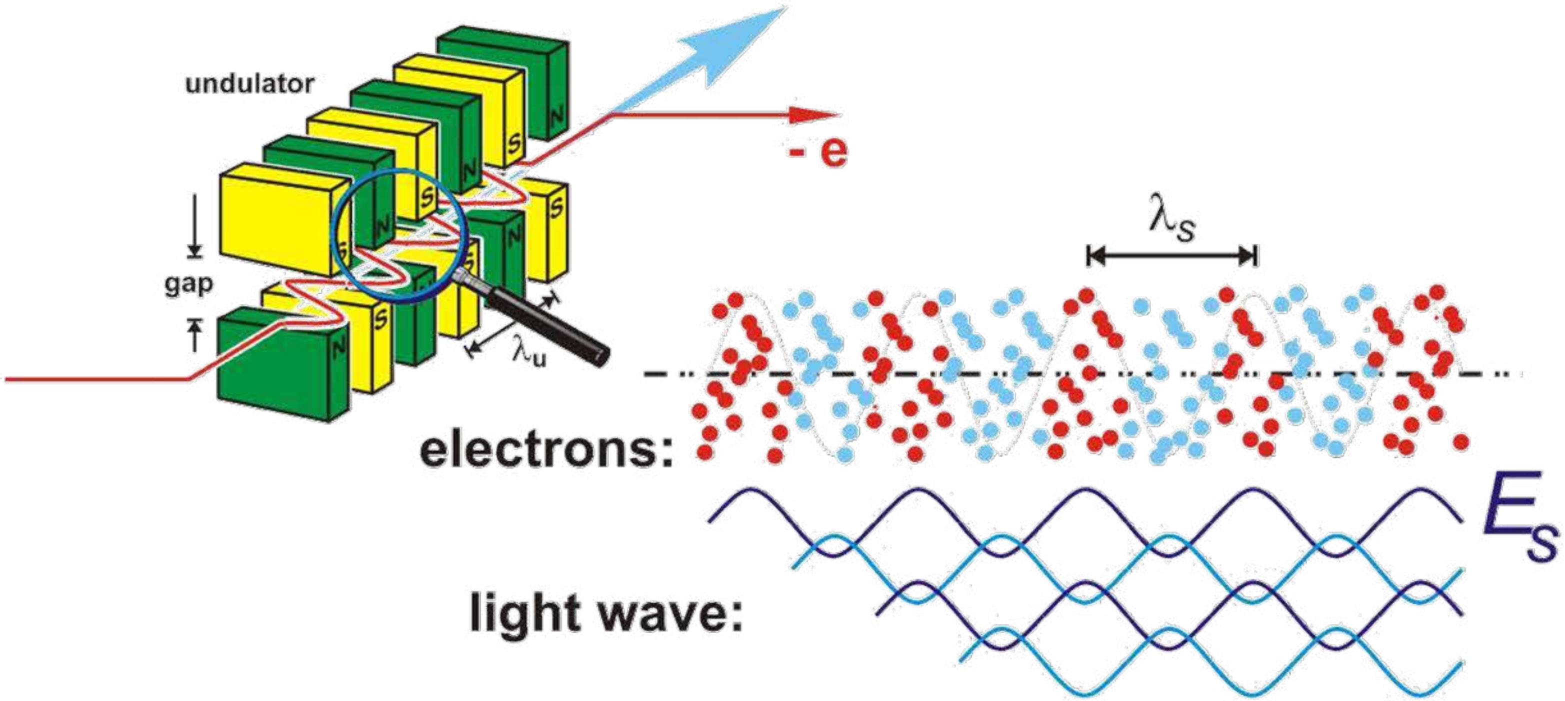
Long undulators chain

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)

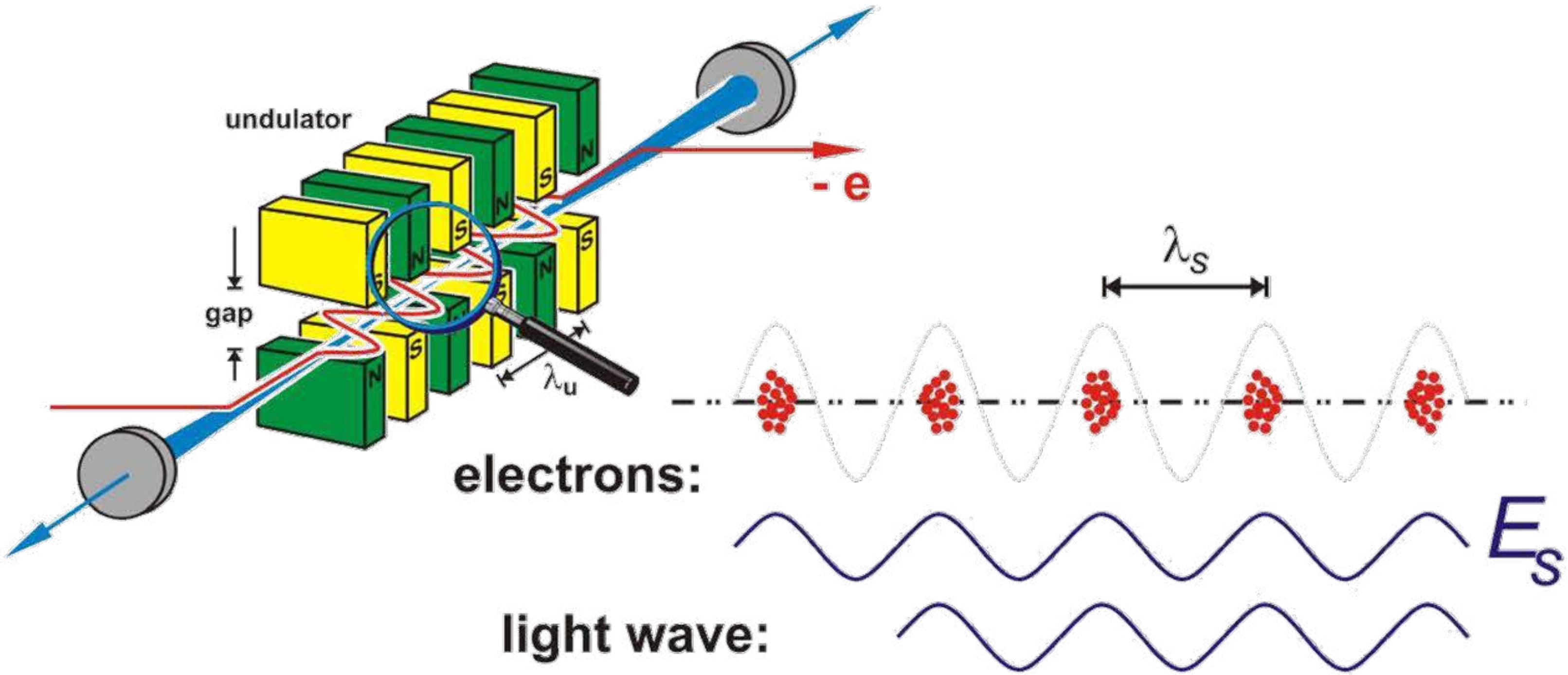


Radiated Power:

$P \propto n_e$ (number of electrons)

destructive interference

⟶ **shotnoise radiation**

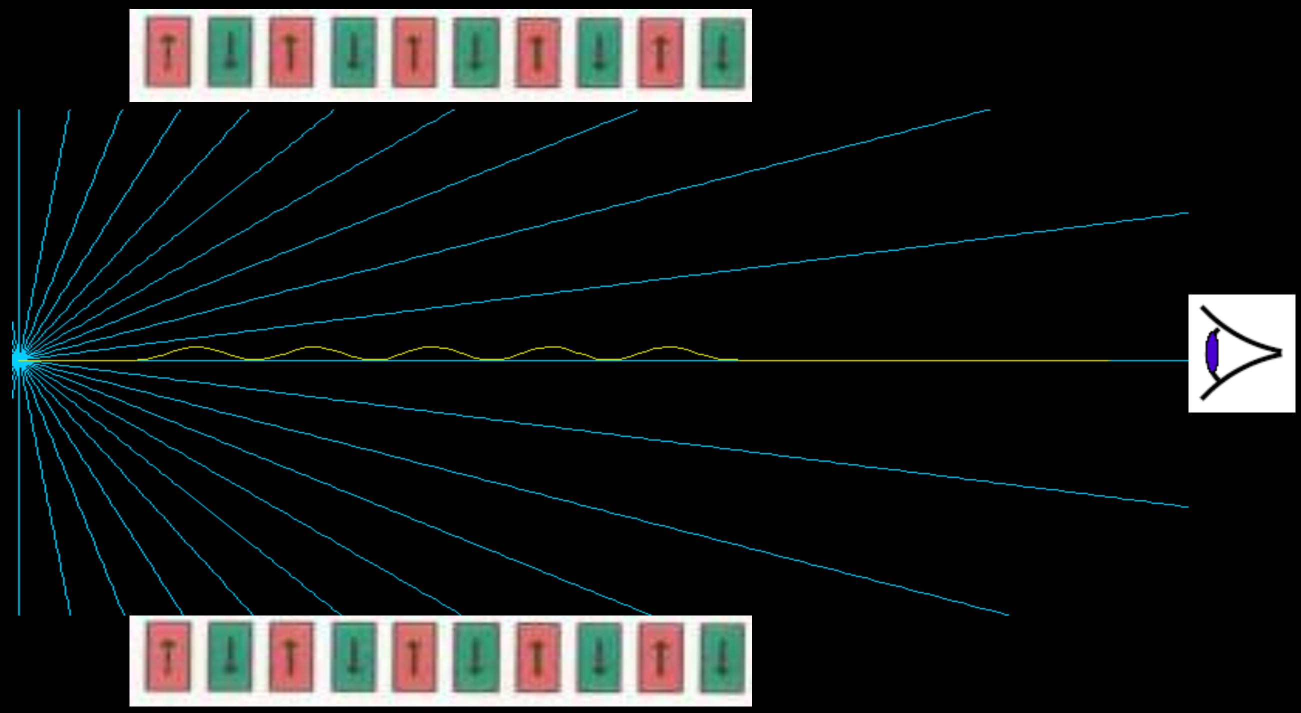


Radiated Power :

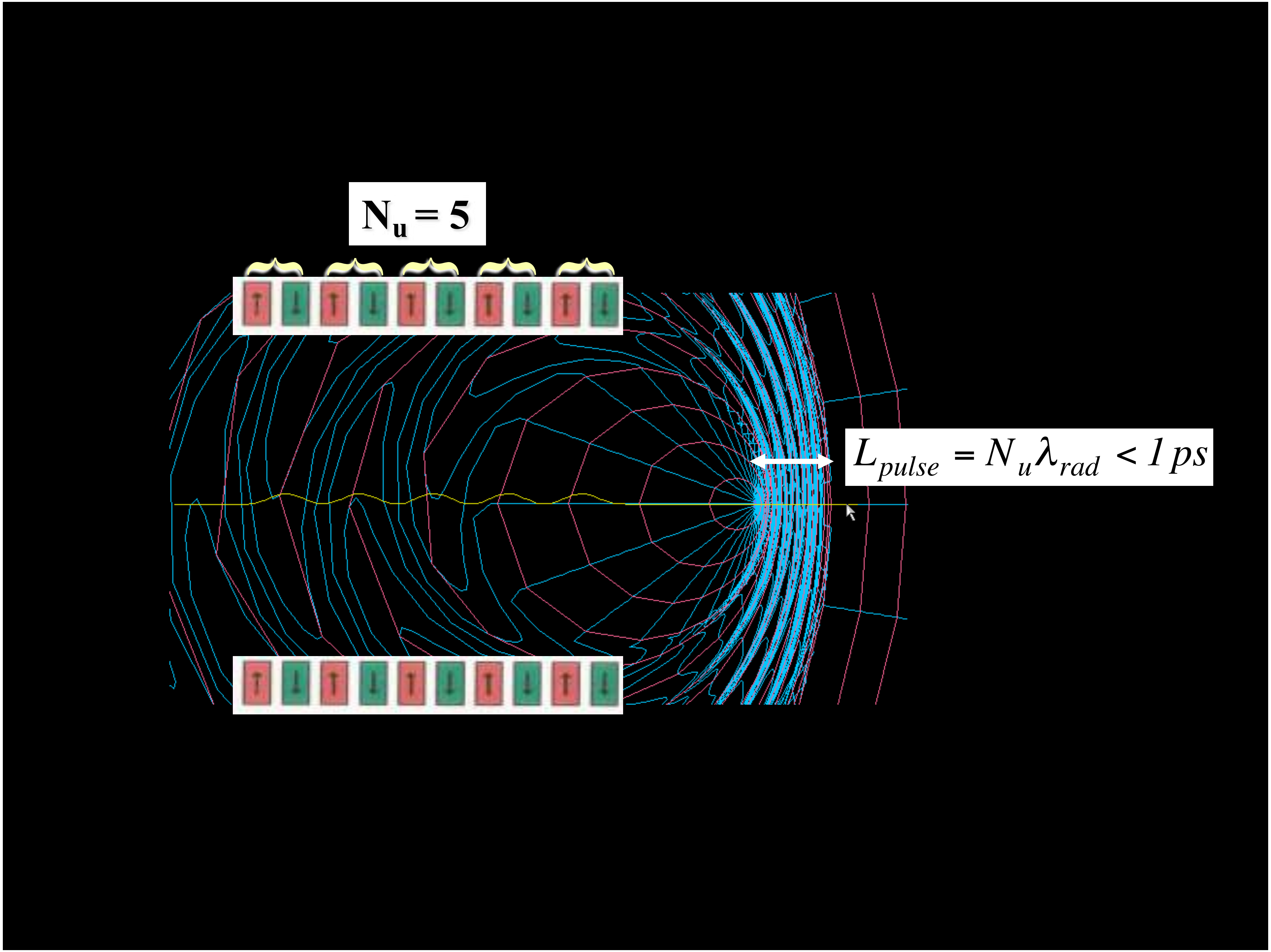
$$P \propto n_e^2 \begin{pmatrix} \text{number of electrons} \\ n_e \sim 10^6 - 10^9 \end{pmatrix}$$

constructive interference

$\longrightarrow$ **enhanced emission**

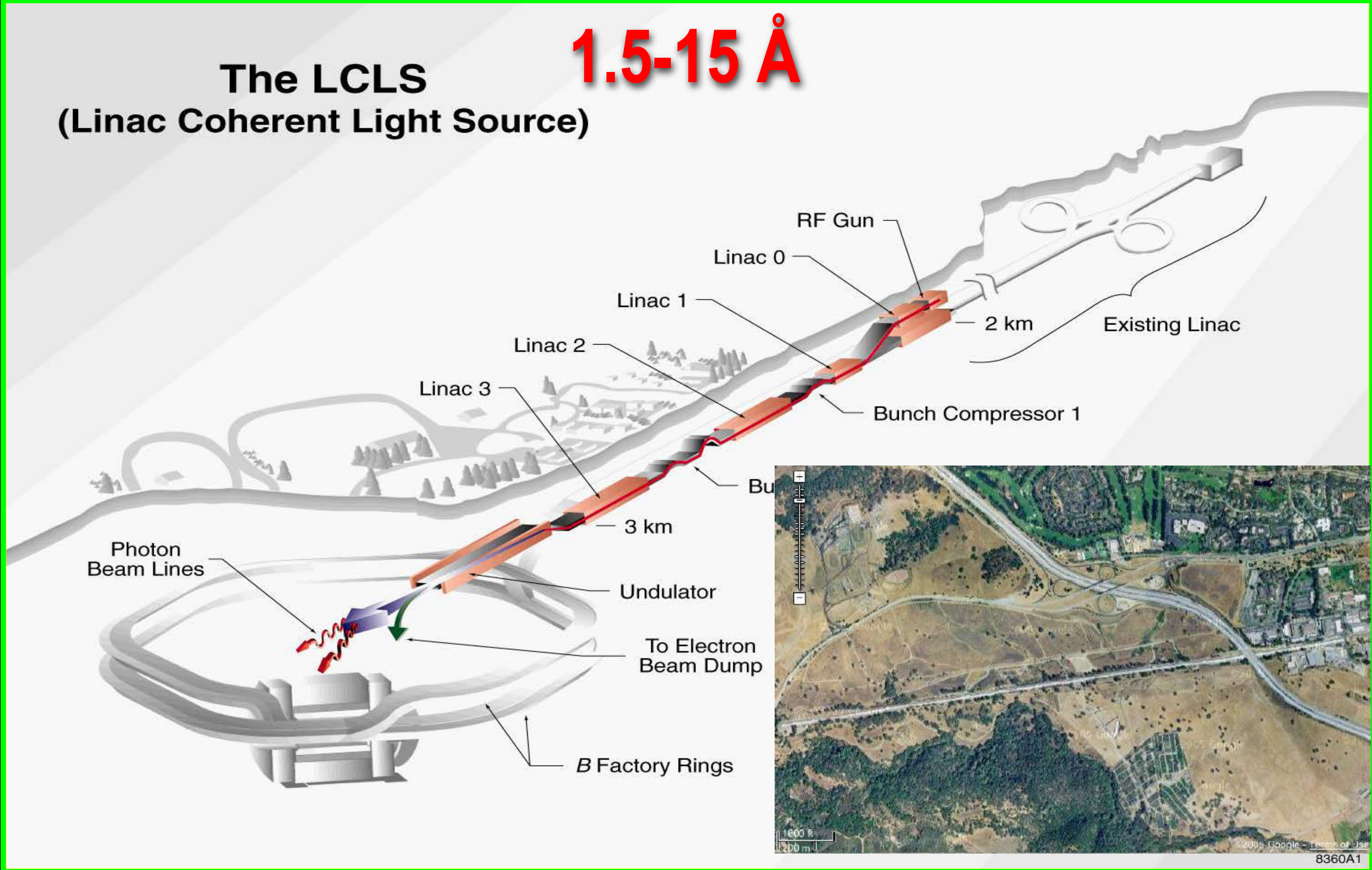


Radiation Simulator – T. Shintake, @ http://www-xfel.spring8.or.jp/Index.htm



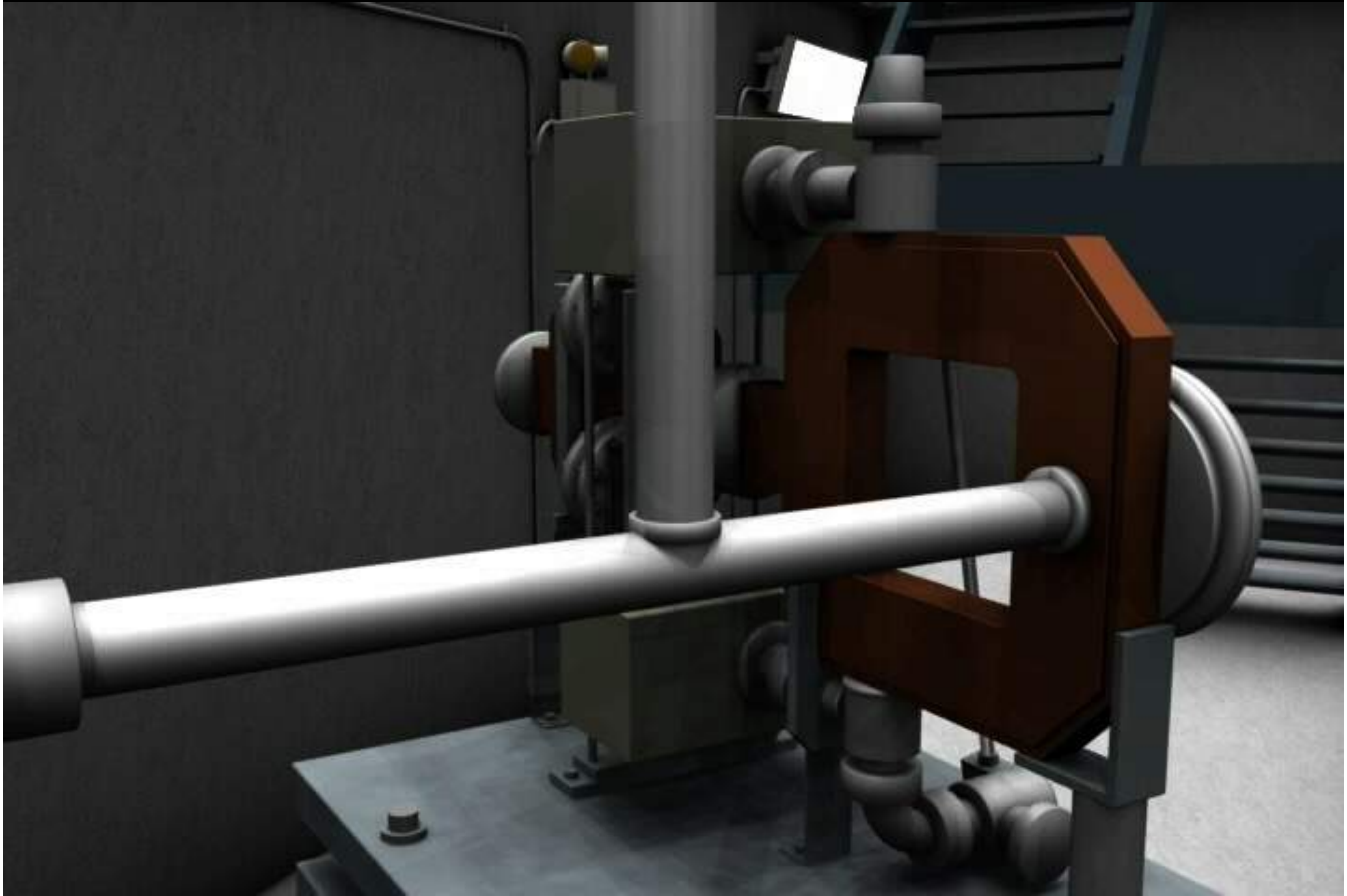
$N_u = 5$
$L_{pulse} = N_u \lambda_{rad} < 1\, ps$

LCLS at *SLAC- First Lasing 2009*

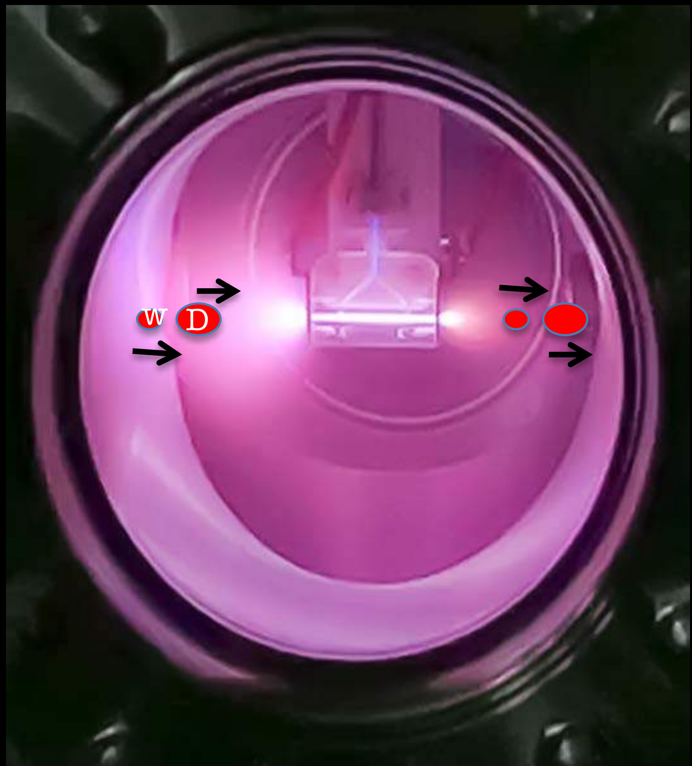


X-FEL based on last 1-km of existing *SLAC* linac

Electron source and acceleration



Beam Driven



March 2022 - First discharge in EuPRAXIA @ SPARC_LAB plasma acceleration module turned on

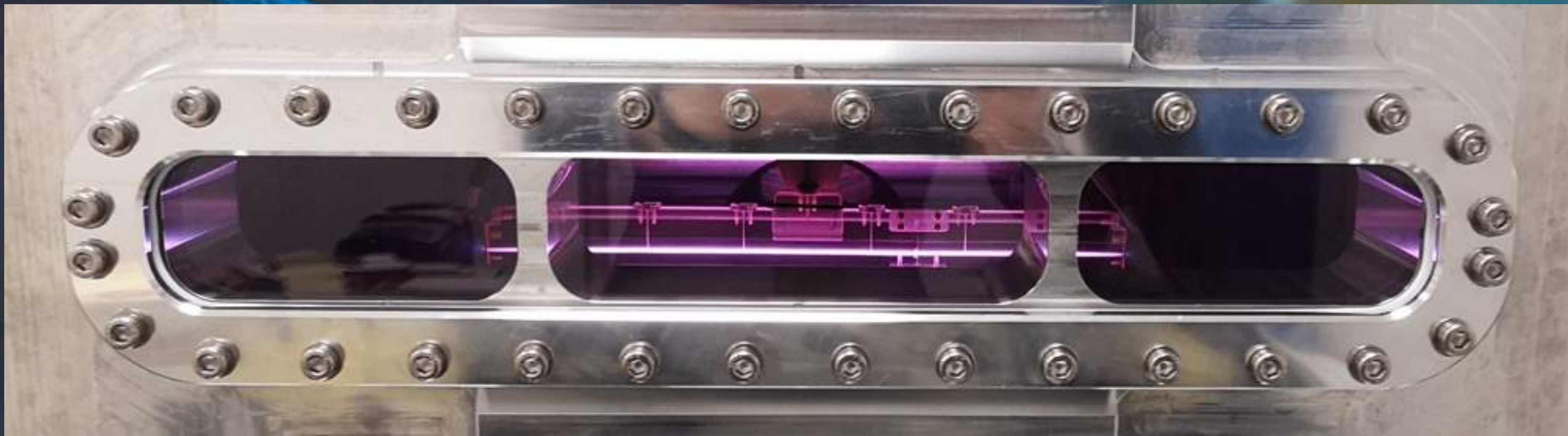


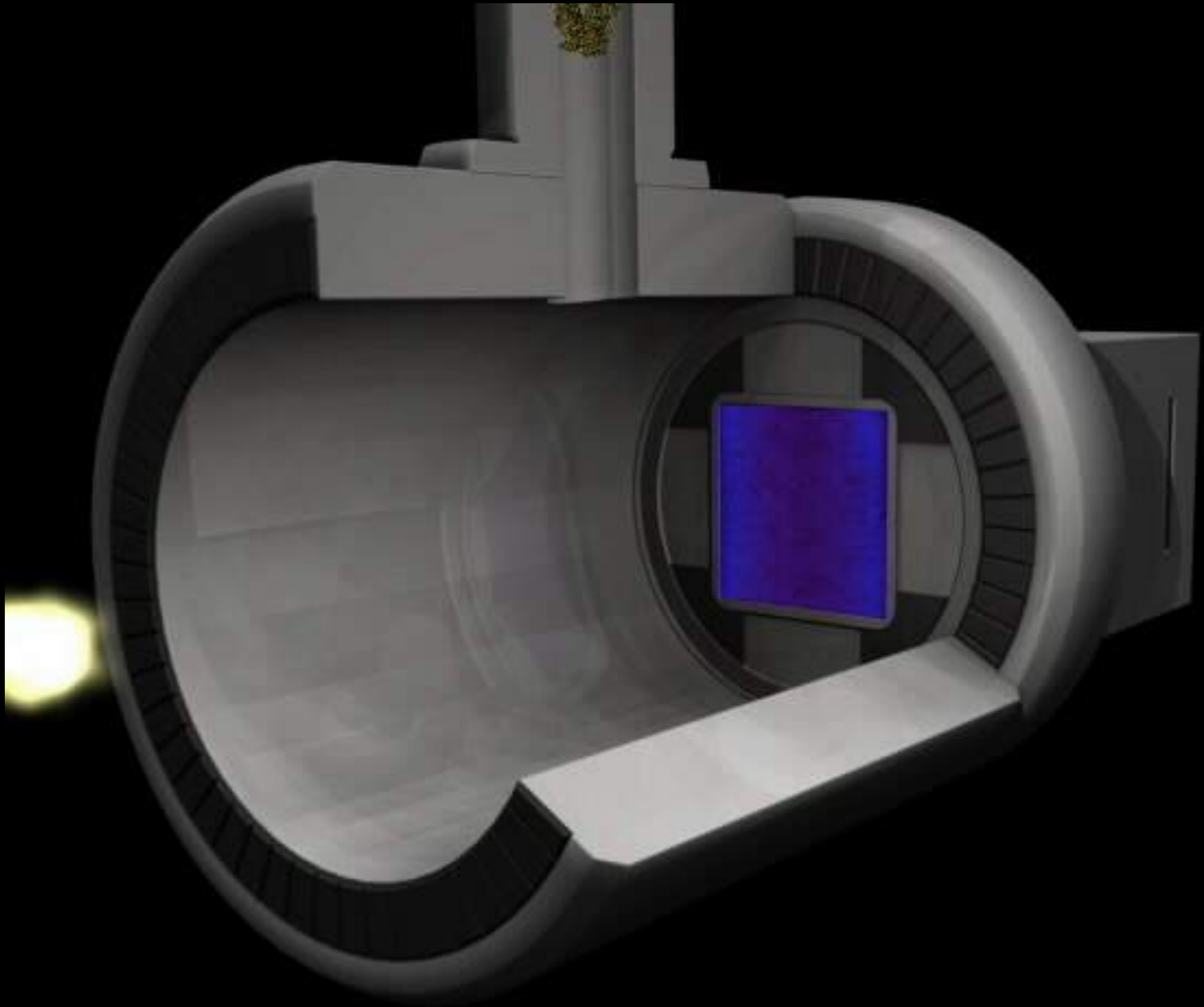
Image captured during the formation of plasma in the capillary 40 cm long and 2 mm in diameter, installed inside a vacuum chamber specially created to accommodate large plasma sources. The applied voltage pulse is 9 kV and the peak current reaches about 500 A.

Courtesy Angelo Biagioni

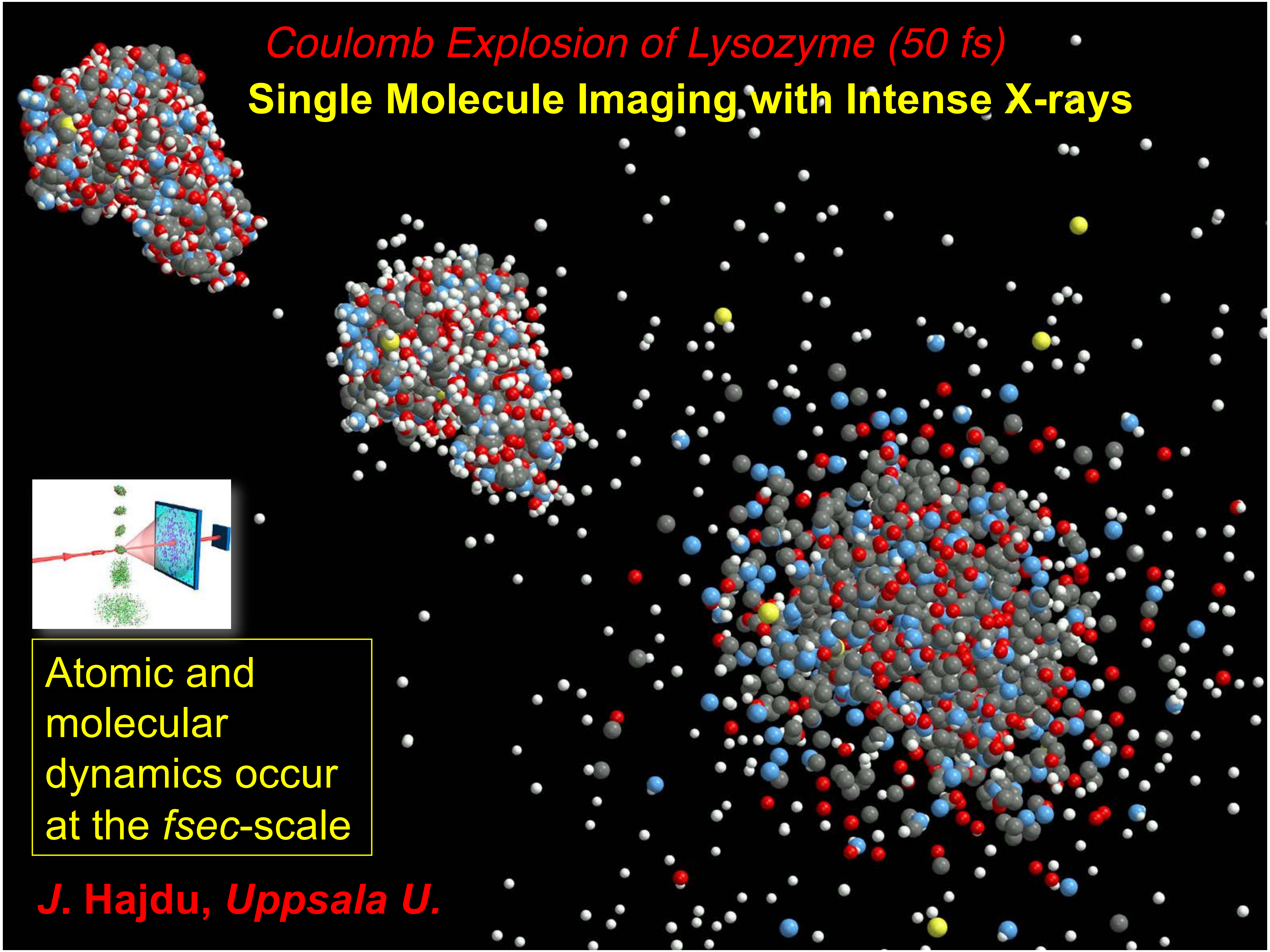
Long undulators chain

Beam separation

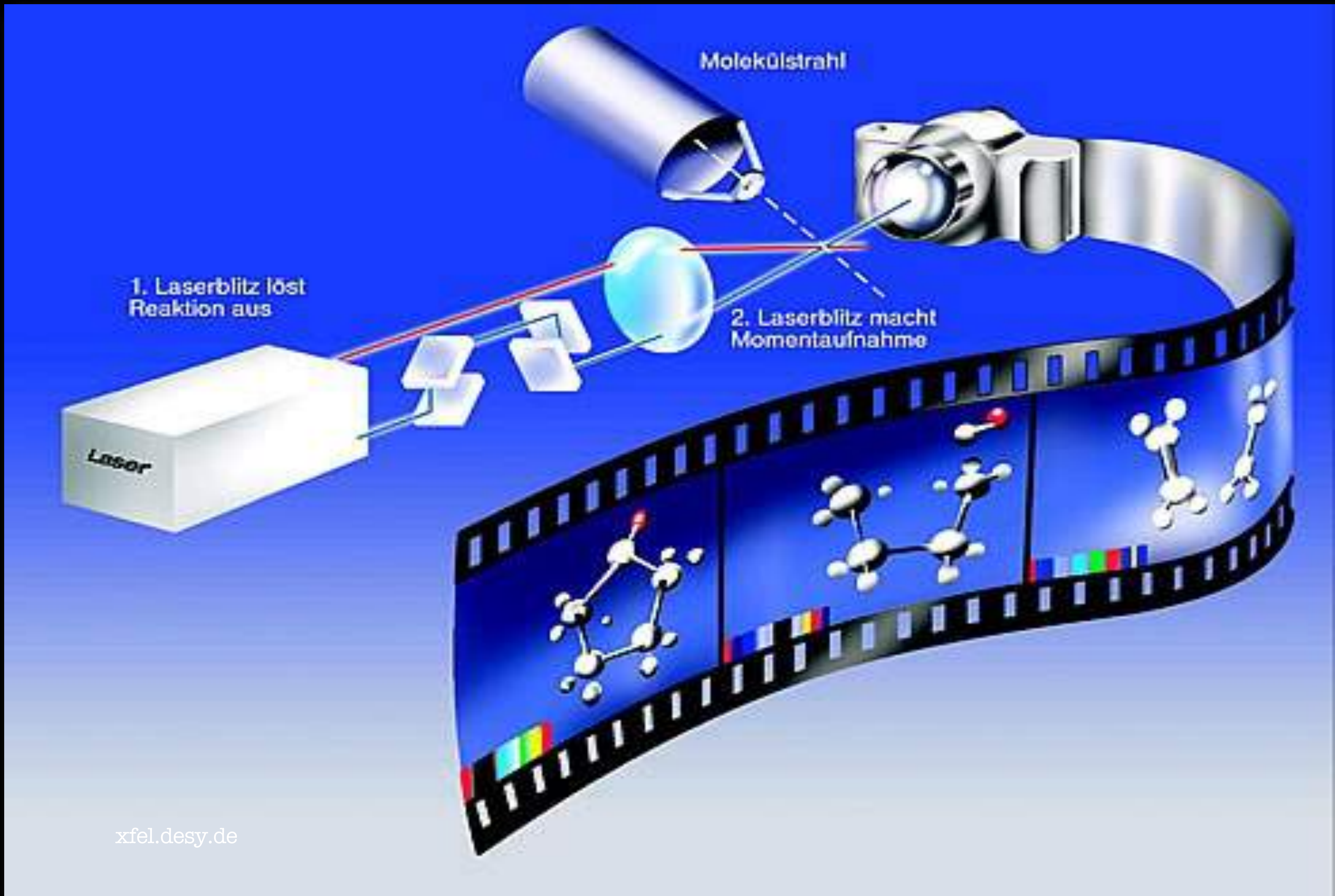
Experimental hall (Single Protein Imaging)



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

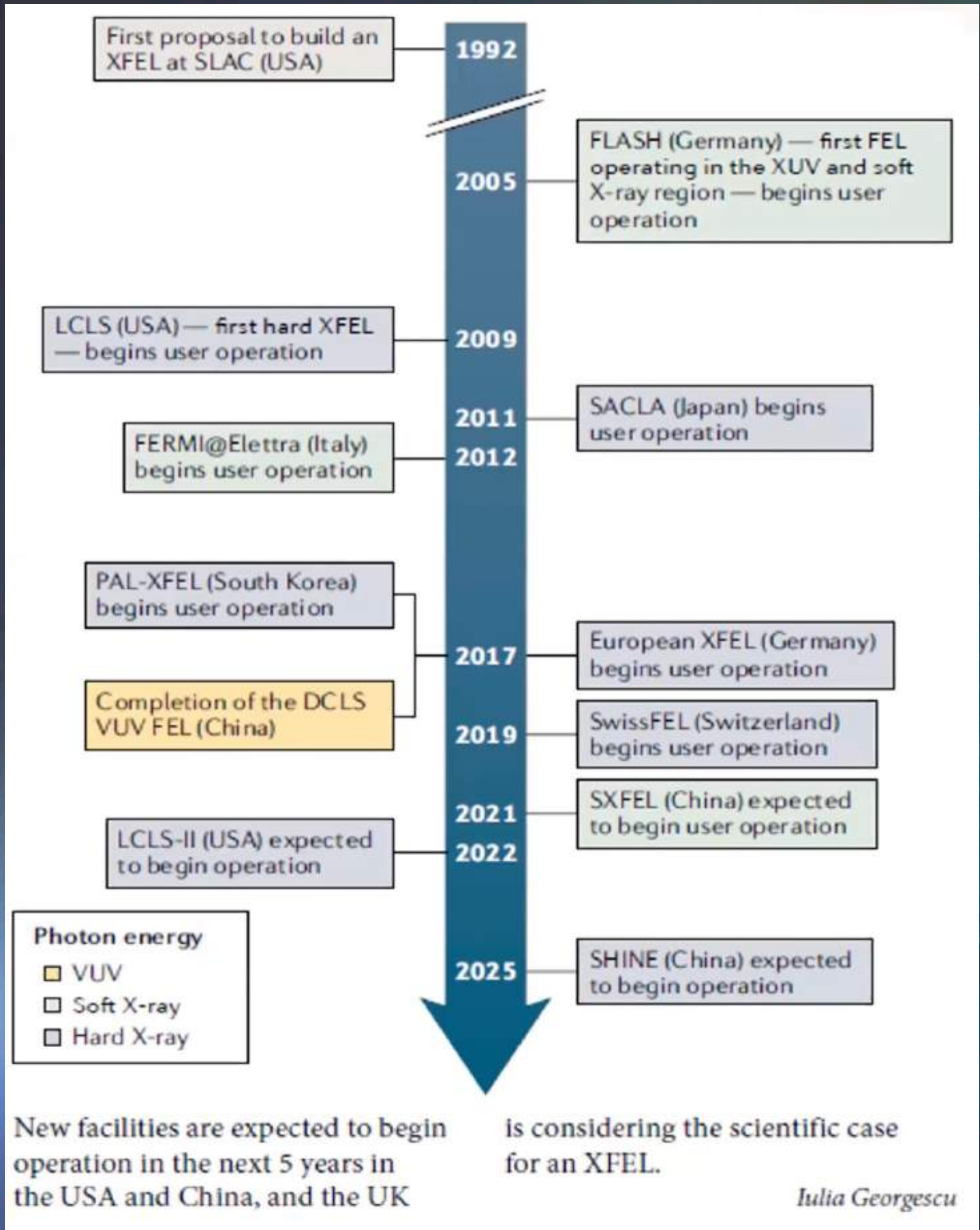

Coulomb Explosion of Lysozyme (50 fs)
Single Molecule Imaging with Intense X-rays
Atomic and molecular dynamics occur at the fsec-scale
J. Hajdu, Uppsala U.

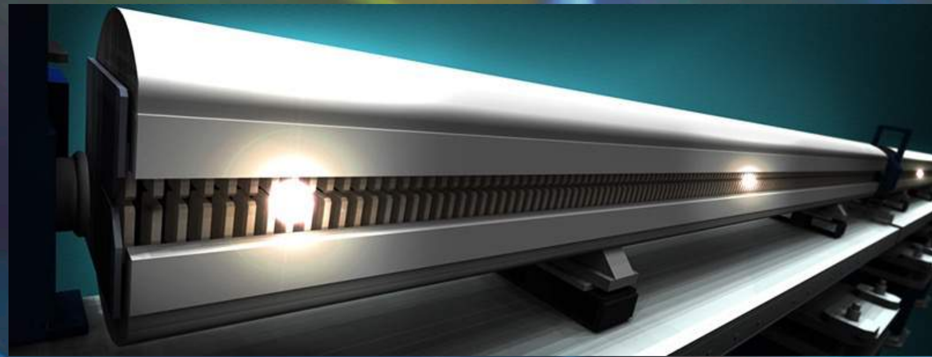
XFEL first lasing – Hamburg May 2017

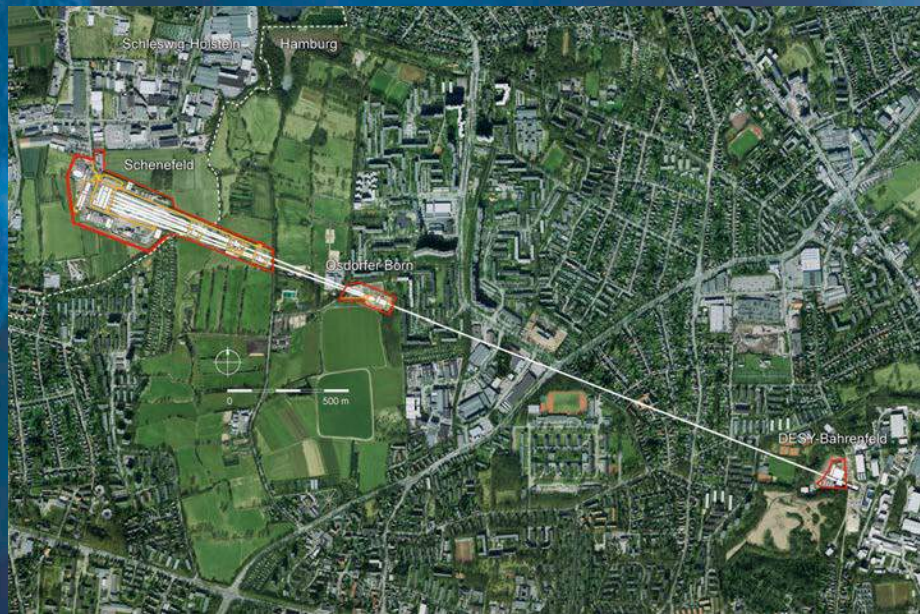

Molekülstrahl
1. Laserblitz löst
Reaktion aus
2. Laserblitz macht
Momentaufnahme
Laser
xfel.desy.de

FEL is a well established technology

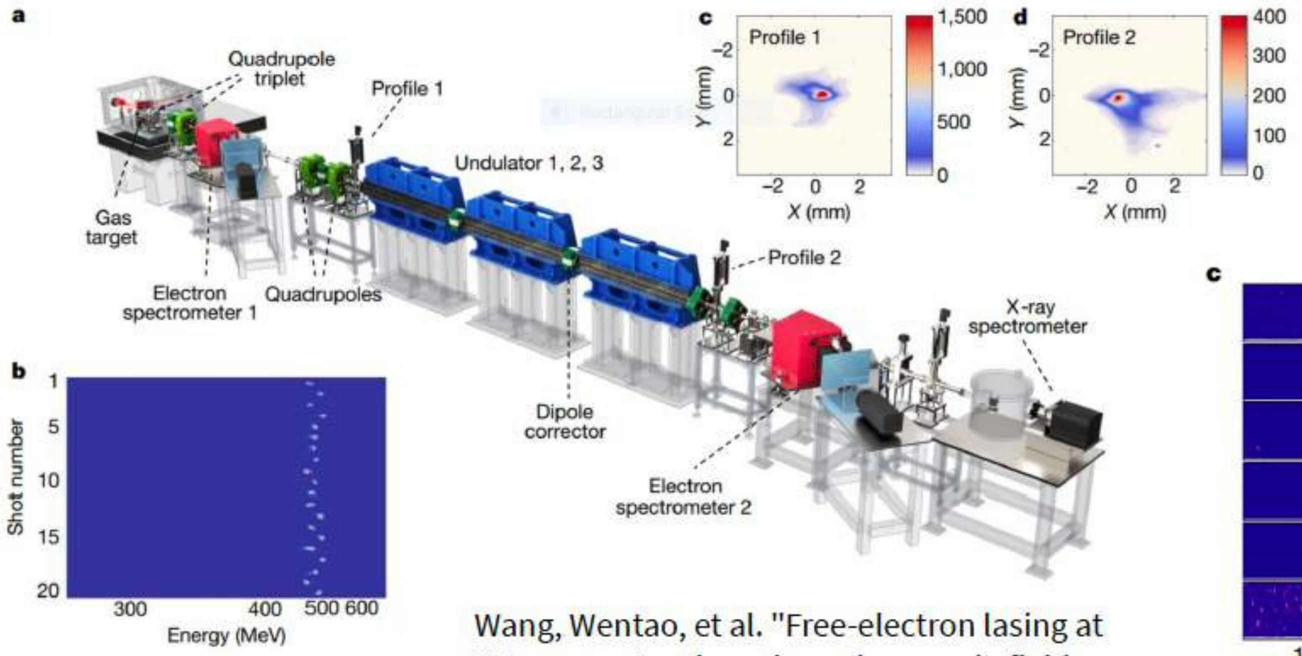
(But a widespread use of FEL is partially limited by size and costs)



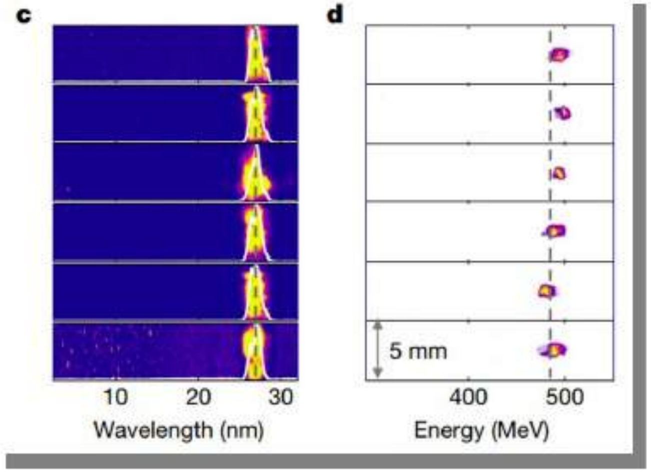




First Lasing with LWFA at SIOM



Wang, Wentao, et al. "Free-electron lasing at 27 nanometres based on a laser wakefield accelerator." Nature 595.7868 (2021): 516-520.



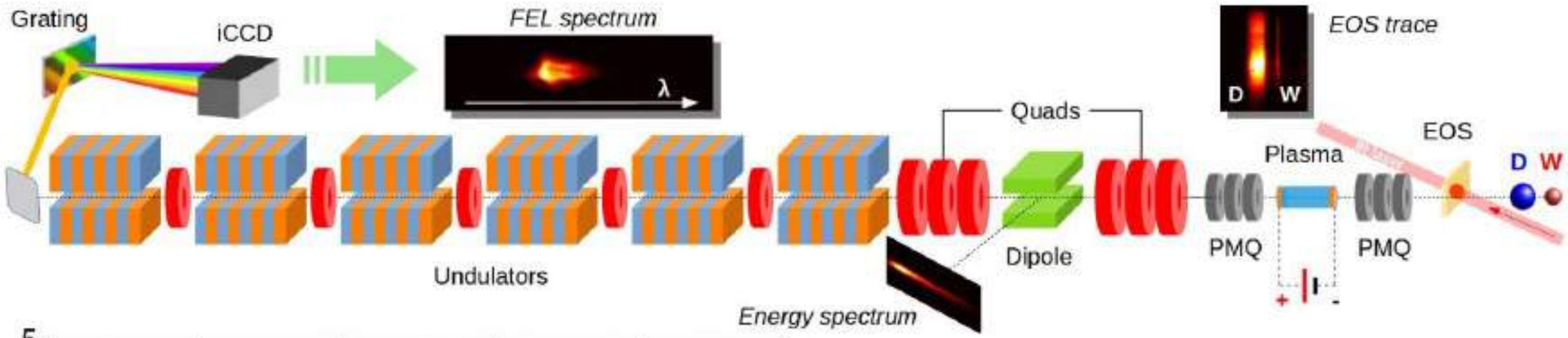
Observation of FEL radiation @ 27 nm using LWFA

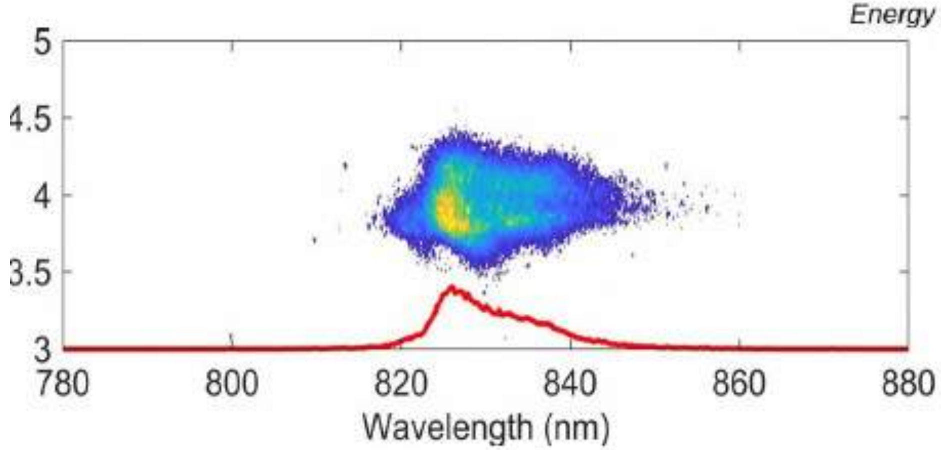
Electron beam generated from a 200 TW (I~4x10[18] W/cm[2]) laser focused on a gas-jet

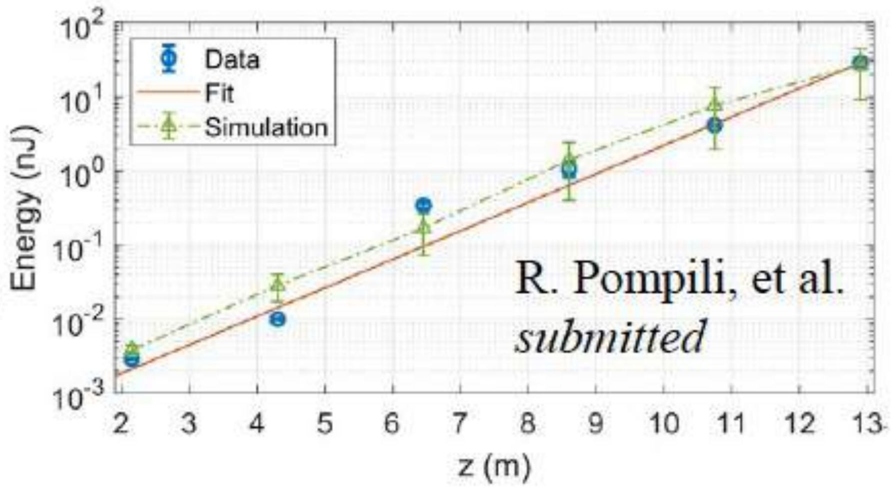
Peak energy ~ 490 MeV, 0.5% spread (measured), emittance 0.5 um (estimated)

Radiation energy from 0.5 to 150 nJ

First Beam Driven SASE-FEL Lasing at SPARC_LAB (May 2021)







SASE FEL radiation:

- peak at 830 nm;
- 6 undulators, ~ 15 m;
- data taken with 6 (Si) photo-diodes, after each undulator.

Exponential gain of FEL radiation energy

Accepted by Nature

Betatron Radiation Source

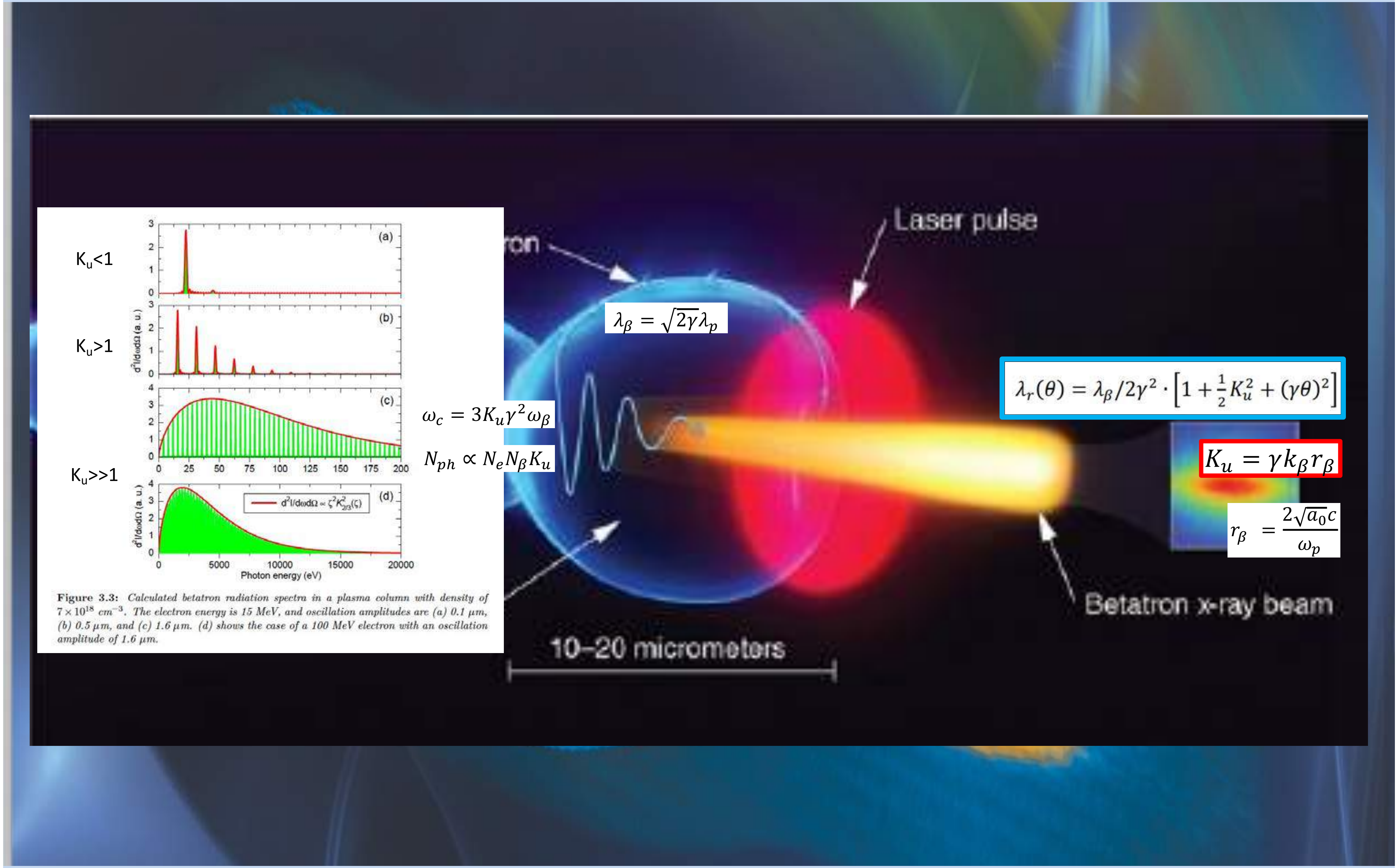


Figure 3.3: *Calculated betatron radiation spectra in a plasma column with density of 7×10^{18} cm^{-3}. The electron energy is 15 MeV, and oscillation amplitudes are (a) 0.1 µm, (b) 0.5 µm, and (c) 1.6 µm. (d) shows the case of a 100 MeV electron with an oscillation amplitude of 1.6 µm.*


Thank for your attention