Accelerating the future

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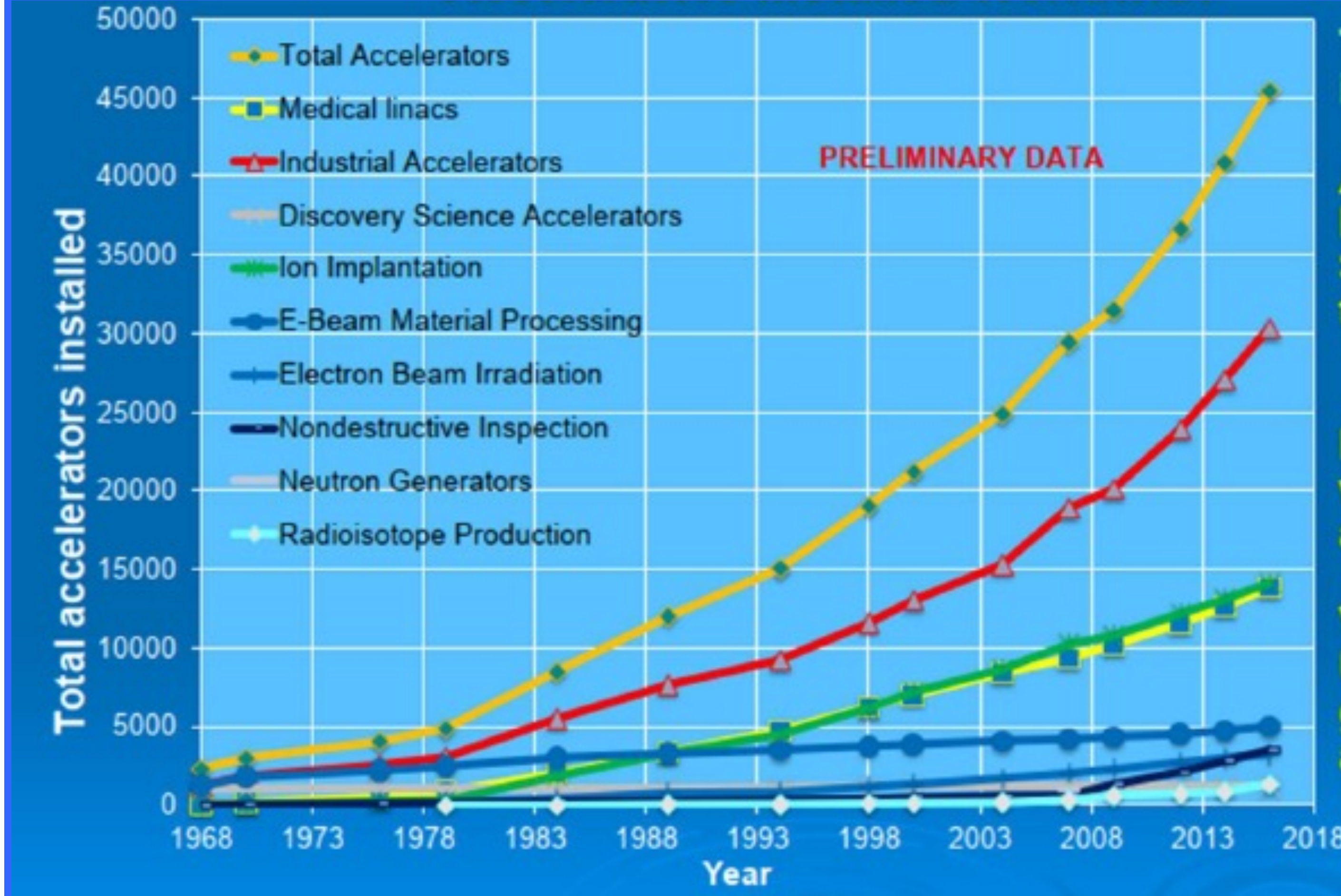
INSPYRE – 28 March 2023

Accelerators installed worldwide



Total sales of accelerators is ~US$5B annually

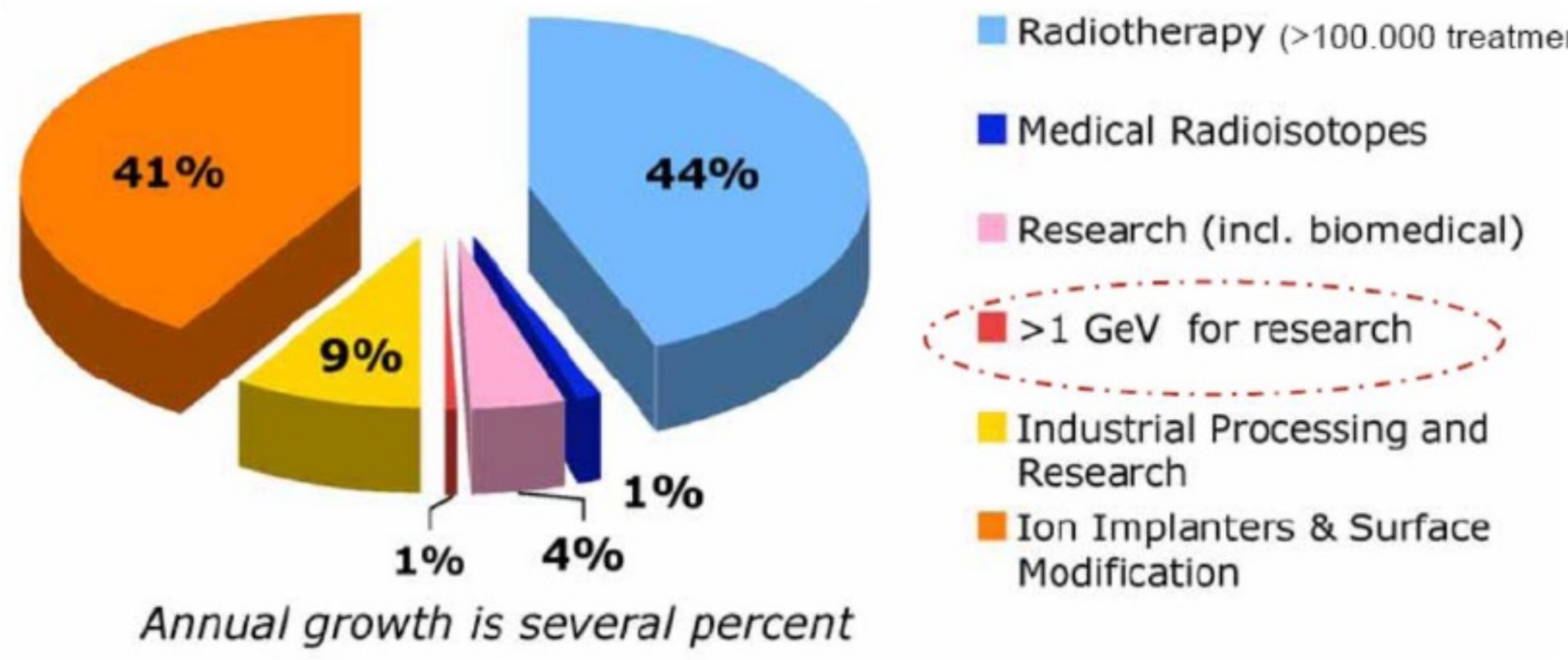
About 47,000 systems have been sold,
> 40,000 still in operation today

More than 100 vendors worldwide are in the accelerator business.

Vendors are primarily in US, Europe and Japan, but growing in China, Russia and India

-Accelerators for Americas Future Report, pp. 4, DoE, USA, 2011

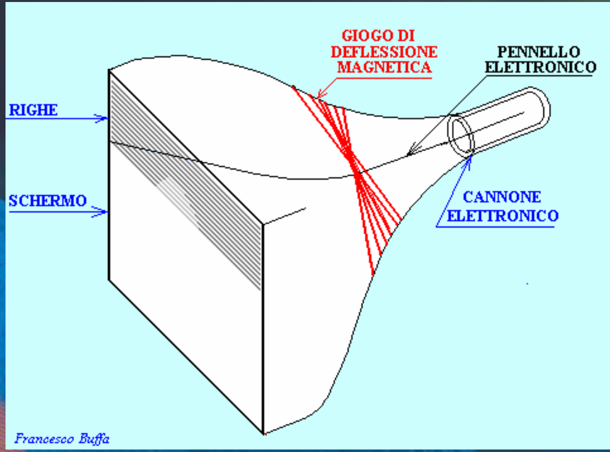
Accelerators installed worldwide

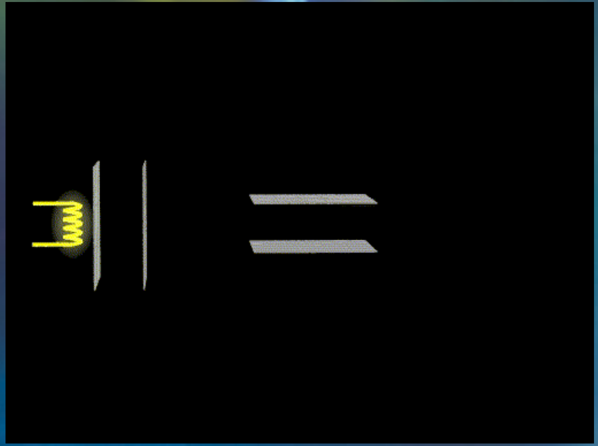


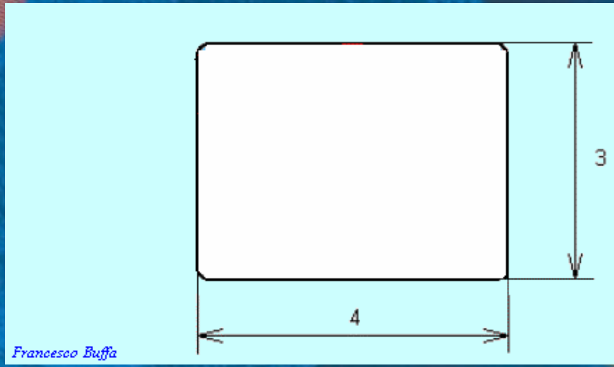
-Accelerators for Americas Future Report, pp. 4, DoE, USA, 2011

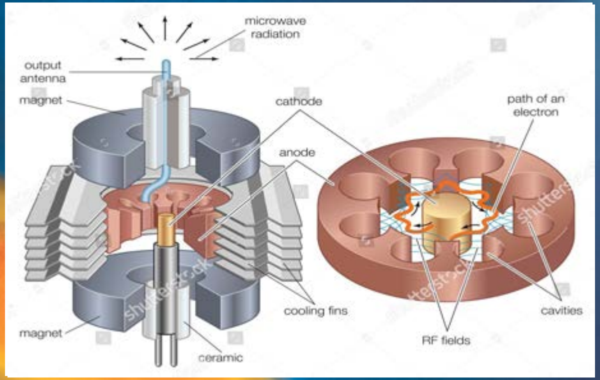
Domestic Accelerators

FIGURE 3. ERNEST LAWRENCE, EDWIN MCMILLAN, AND LUIS ALVAREZ (left to right) admire a finished Chromatron. (Ernest O. Lawrence papers, BANC MSS 2005/200c, oversize box 3. Courtesy of the Bancroft Library, University of California, Berkeley.)

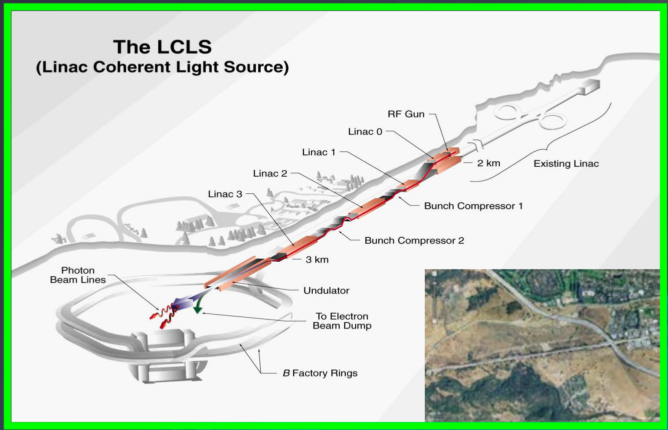


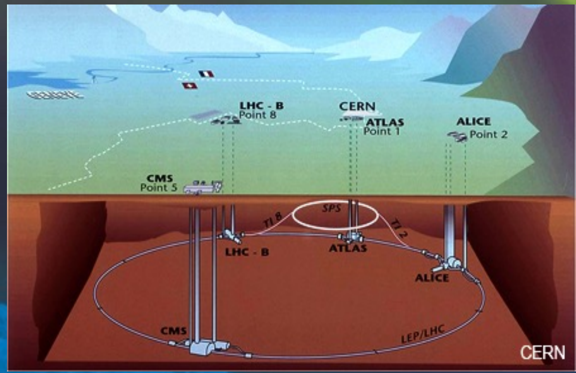


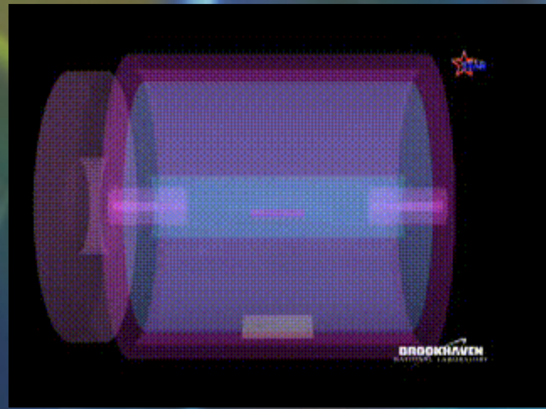


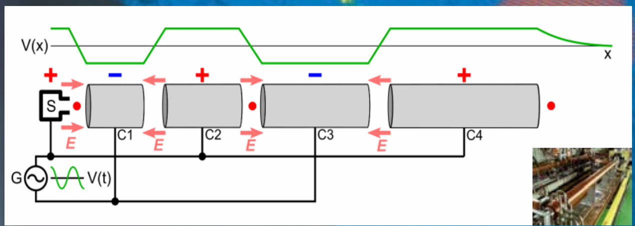


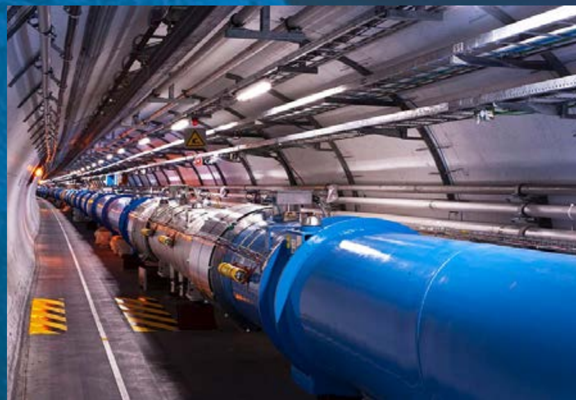
High Energy accelerators

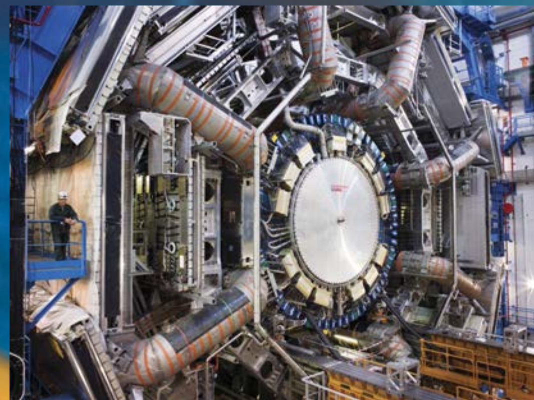












$$F_{Lorentz} = q \cdot v\,B = F_{centripital} = \frac{mv^2}{\rho}$$

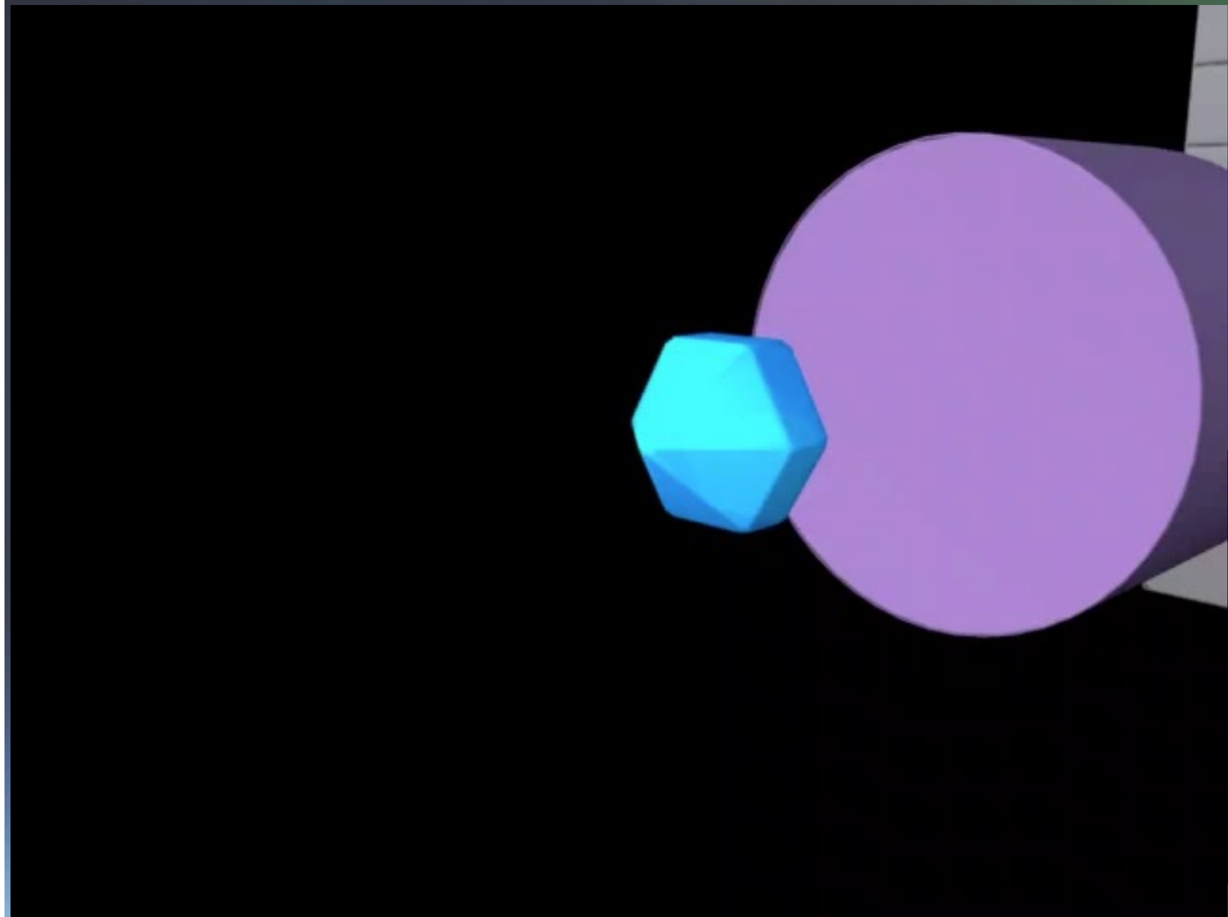
$$\Rightarrow \rho = \frac{mv}{qB} = \frac{p}{qB}$$

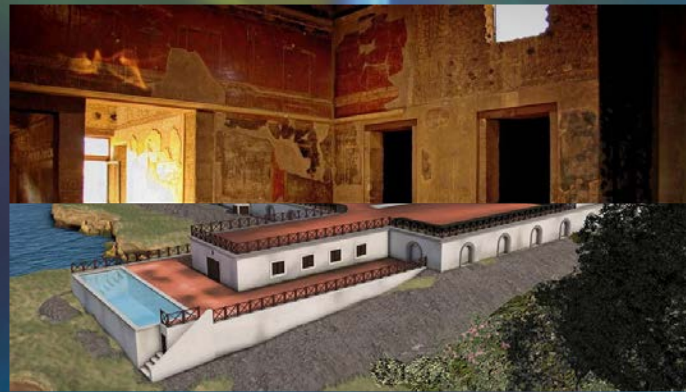
Equilibrium radius

$$\boxed{U_0 = \frac{e^2}{3\varepsilon_0}\frac{\beta^3\gamma^4}{\rho}}$$

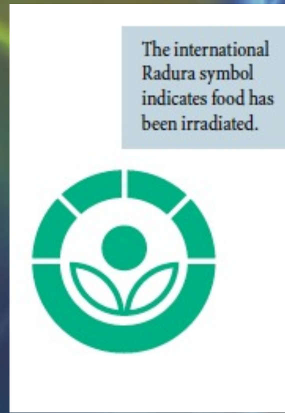
Energy lost by emission of radiation

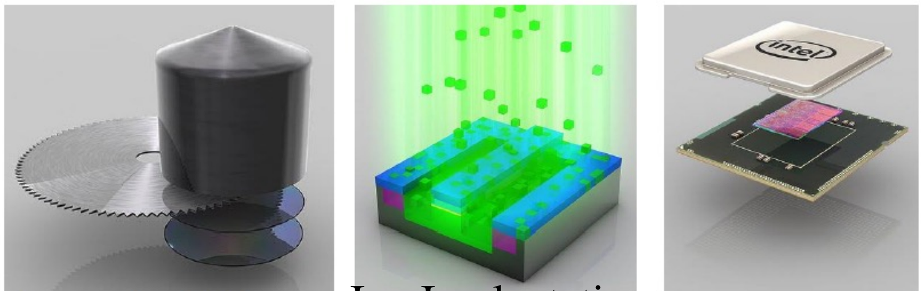
Synchrotron light sources





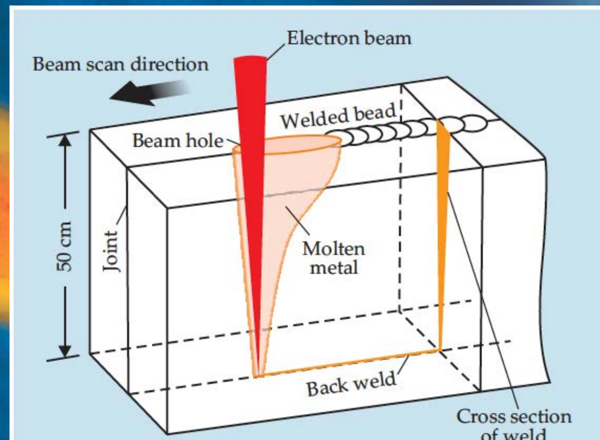
The beam business





Images courtesy of Intel

Ion Implantation

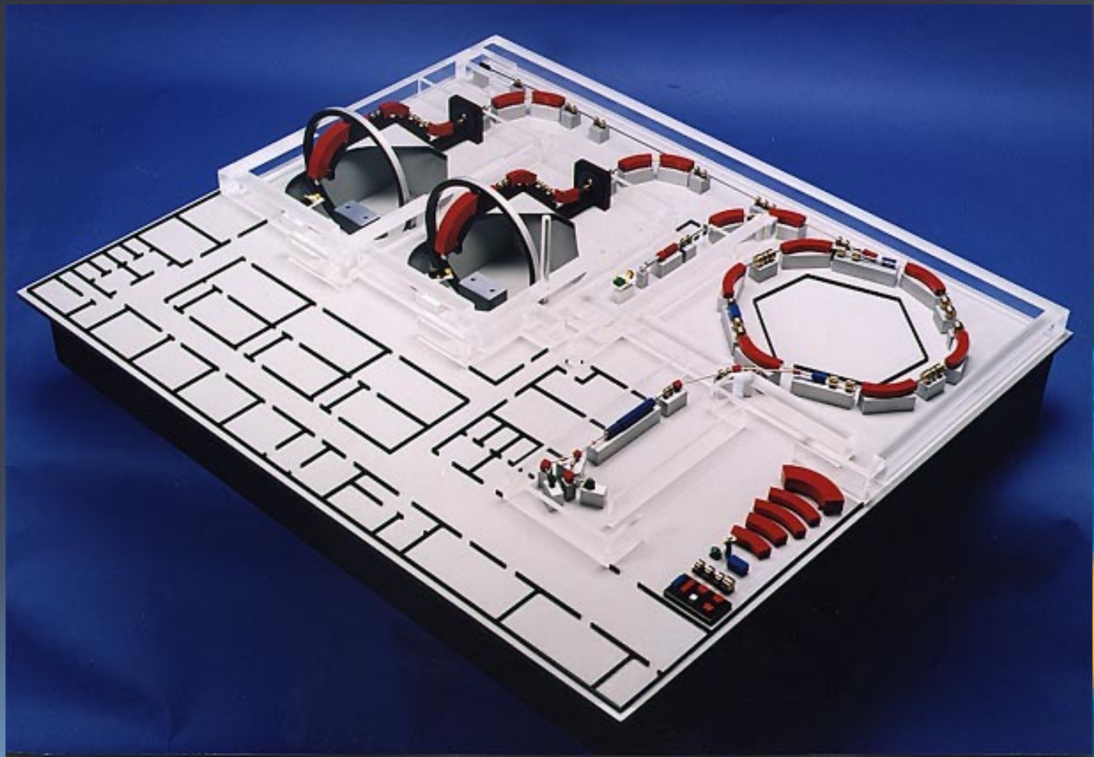


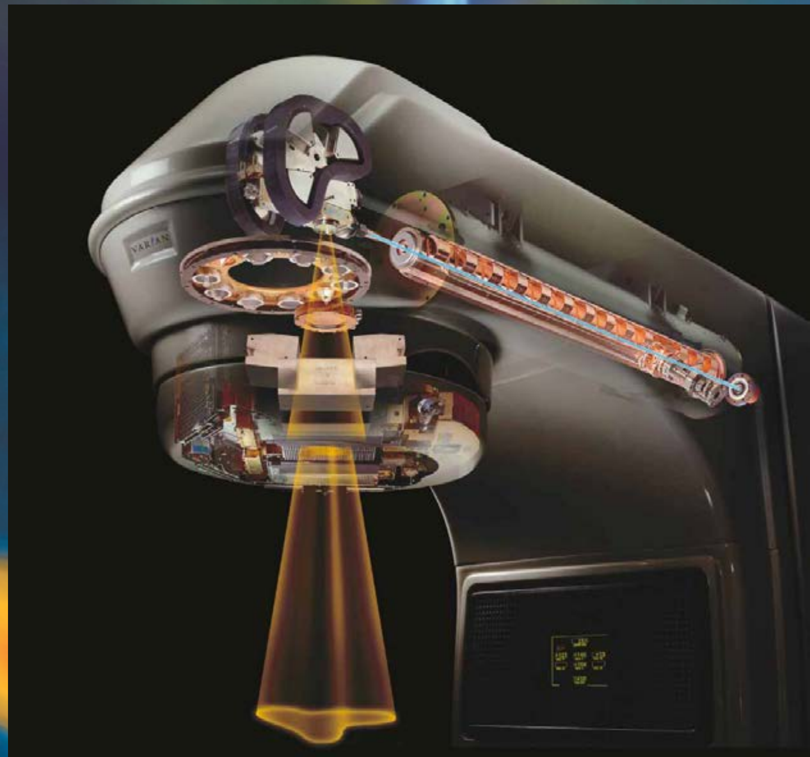
The beam business: Accelerators in industry

Robert W. Hamm, and Marianne E. Hamm

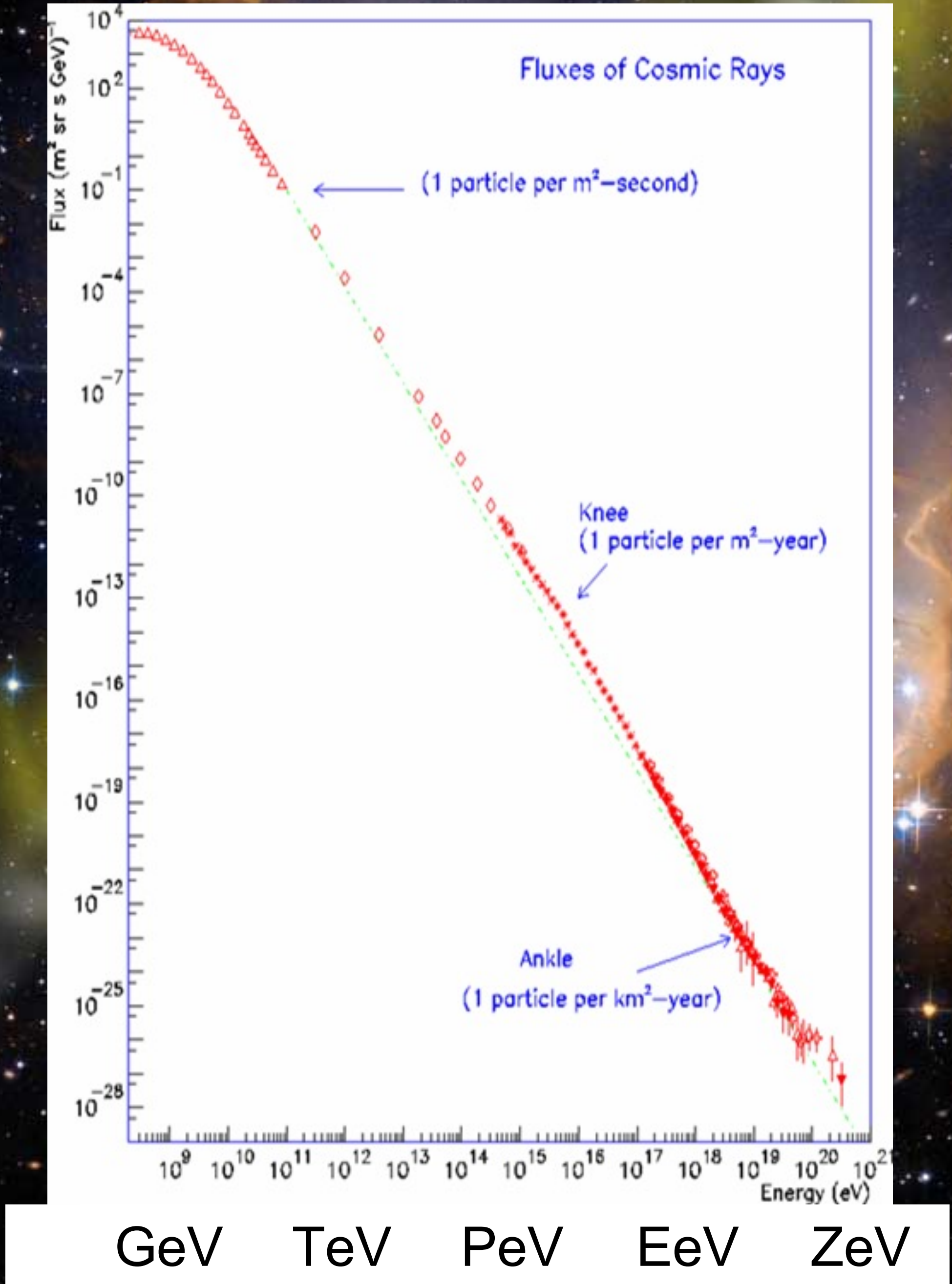
Citation: Physics Today **64**, 6, 46 (2011); doi: 10.1063/1.3603918

Medical Accelerators

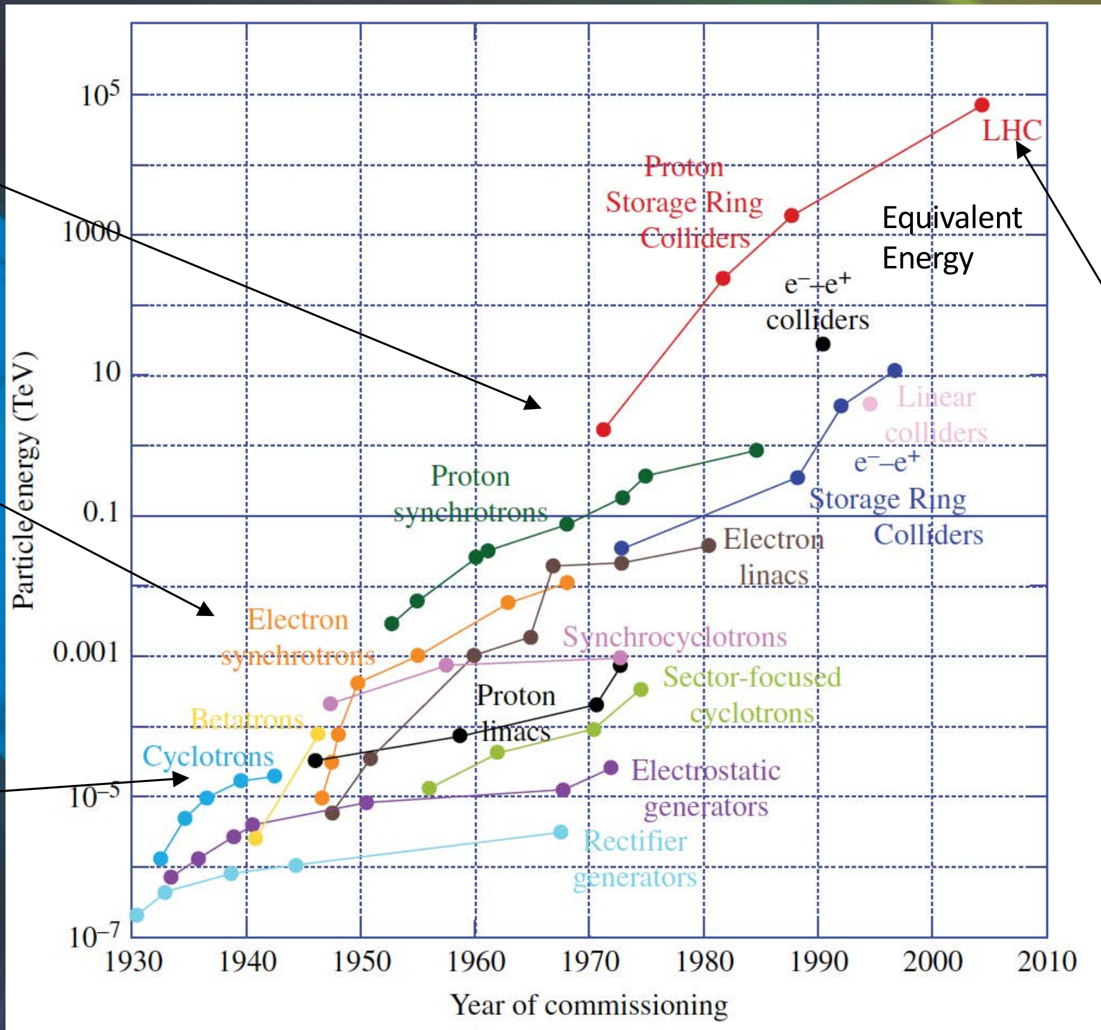


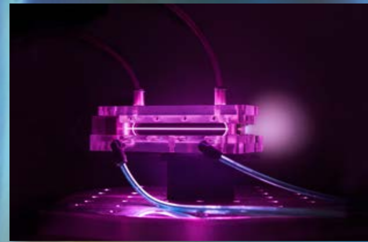


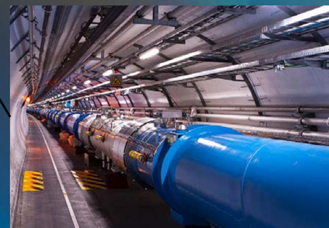
The Cosmos is a very large particle accelerator…but in uncontrolled conditions



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.

Fermi's Globatron: ~5000 TeV Proton beam

1954 the ultimate synchrotron

B_{max} 2 Tesla

ρ 8000 km

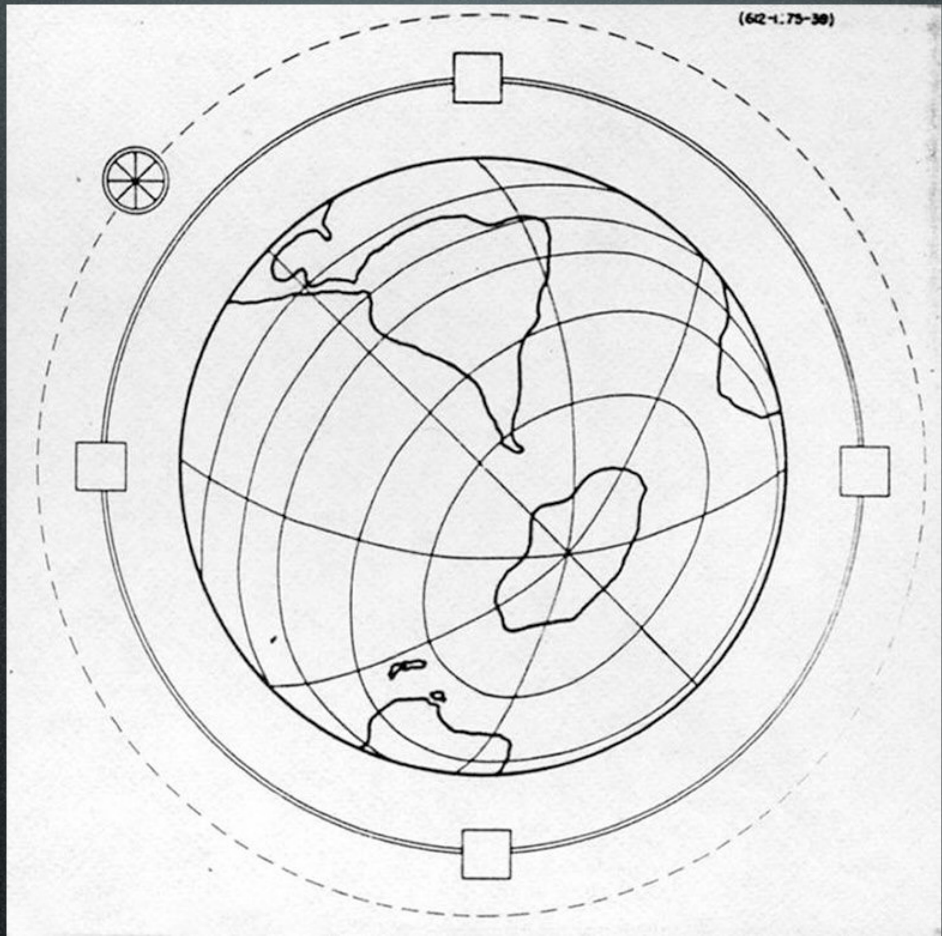
fixed target

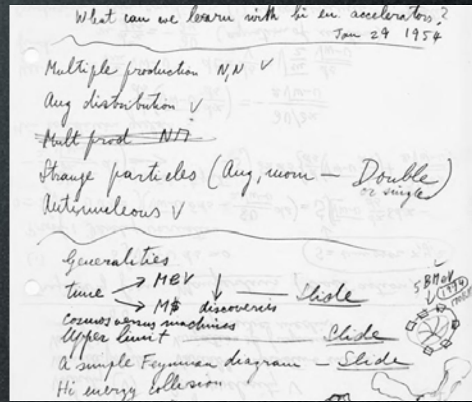
3 TeV cm

170 G$

1994

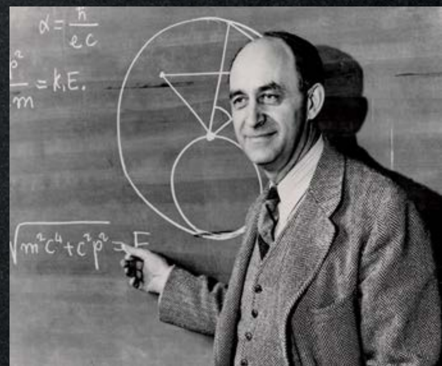
$$\rho = \frac{p}{Bq} \cong \frac{E}{cqB}$$




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

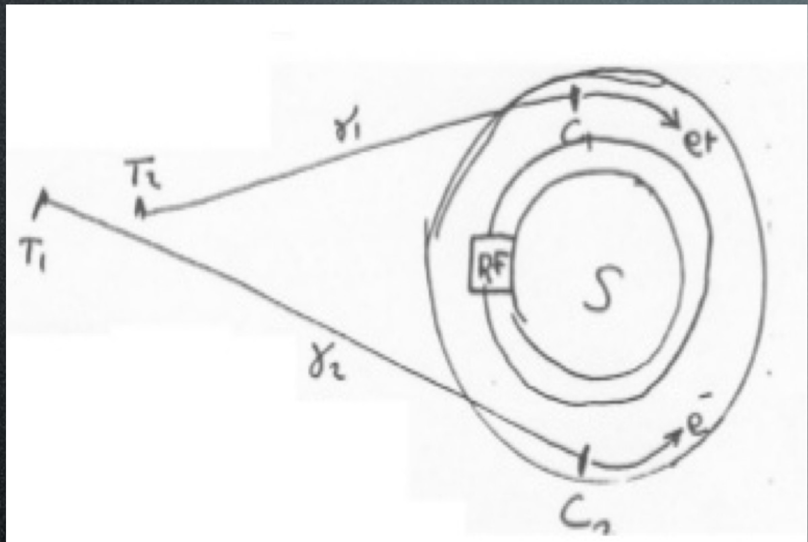
Multiple production N,N ✓
Ang distribution ✓
~~Mult prod NΠ~~
Strange particles (Ang, mom — Double or single)
Antinucleons ✓

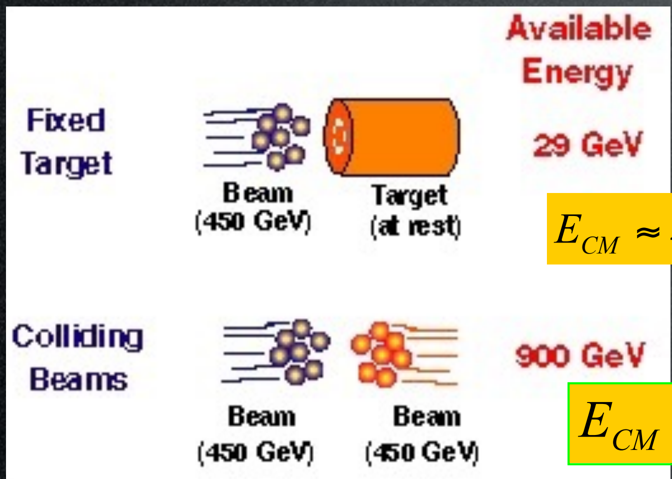
Generalities
time → MEV ↓ discoveries — Slide
time → M$
Cosmos versus machines
Upper limit — Slide
A simple Feynman diagram — Slide
Hi energy collision



Touschek's Anello Di Accumulazione (ADA)

1961 the first e+e- Collider

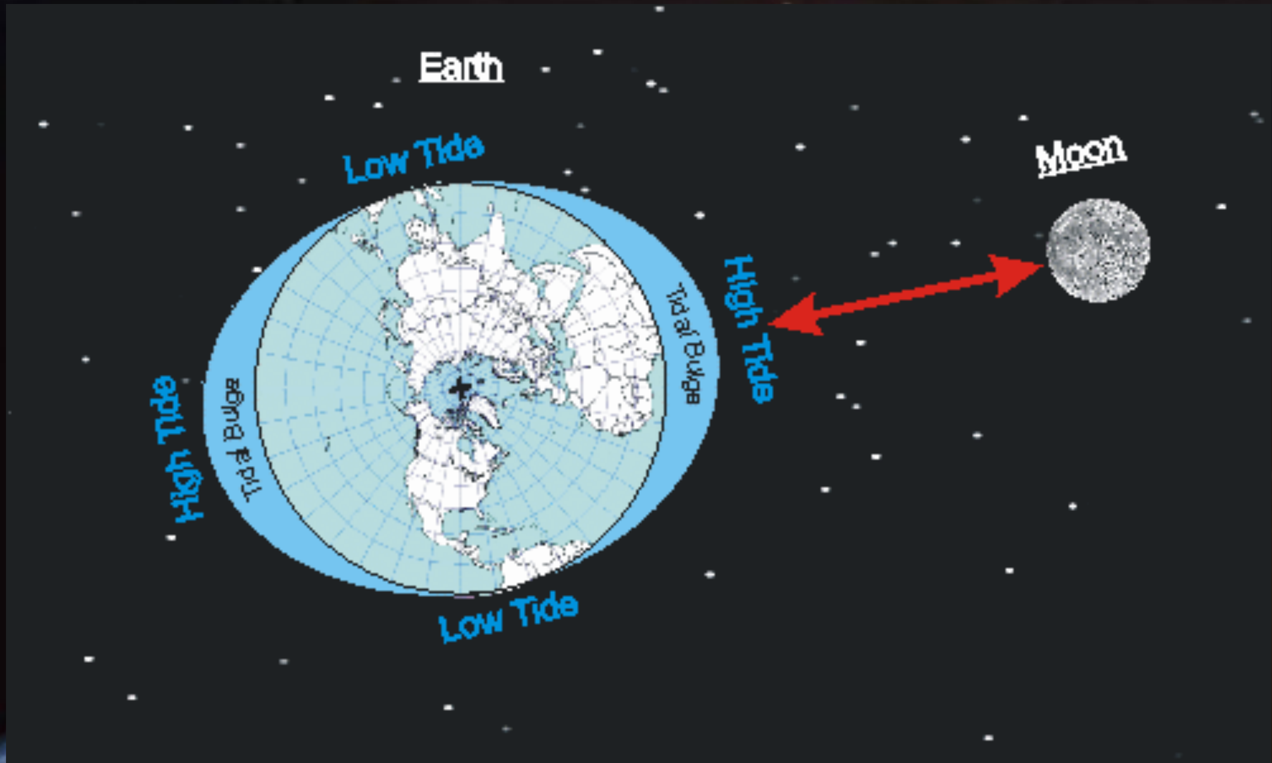


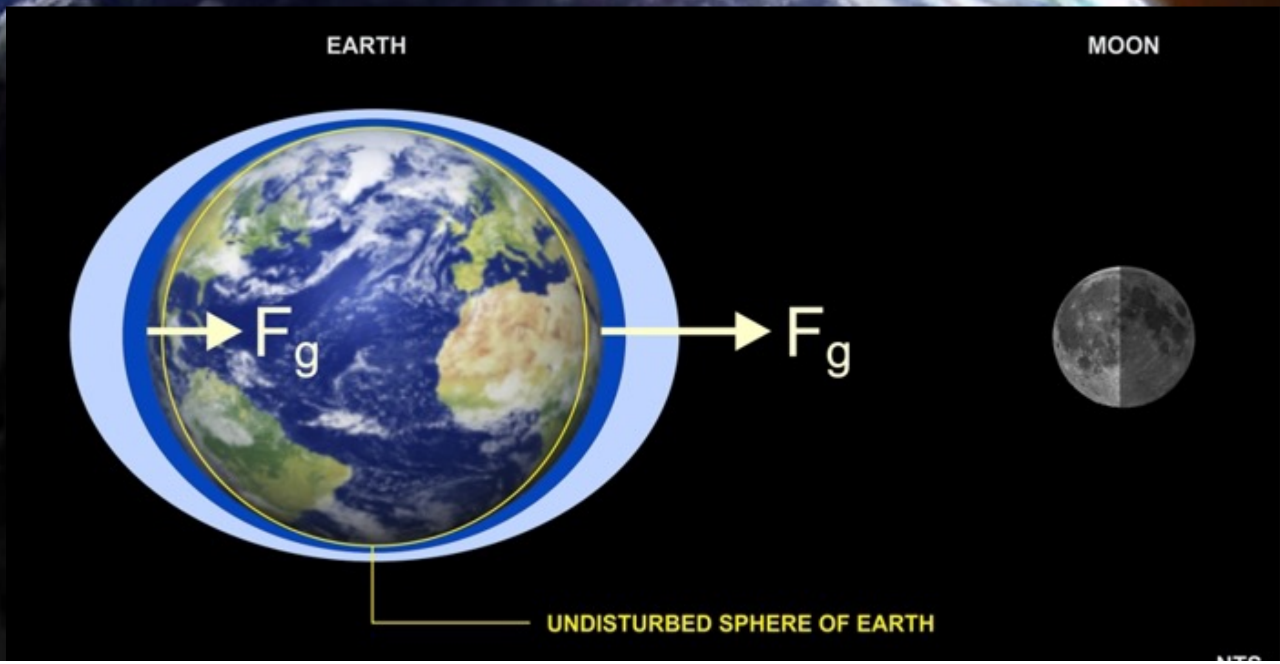


$$E_{CM} \approx \sqrt{2E_1 m_2}$$

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

LHC	HE-LHC	VHE-LHC	VHE-LHC
27 km, 8.33 T	27 km, **20 T**	80 km, **20 T**	100 km, **16 T**
14 TeV (c.o.m.)	33 TeV (c.o.m.)	100 TeV (c.o.m.)	100 TeV (c.o.m.)


Earth
Low Tide
Moon
High Tide
Tidal Bulge
High Tide
Tidal Bulge
Low Tide


EARTH
MOON
F_g
F_g
UNDISTURBED SPHERE OF EARTH

Effects of Terrestrial Tides on the LEP Beam Energy

L. Arnaudon, R. Assmann[*], A. Blondel[†], B. Dehning,
G.E. Fischer[‡§], P. Grosse-Wiesmann, A. Hofmann,
R. Jacobsen, J.P. Koutchouk, J. Miles, R. Olsen,
M. Placidi, R. Schmidt, J. Wenninger

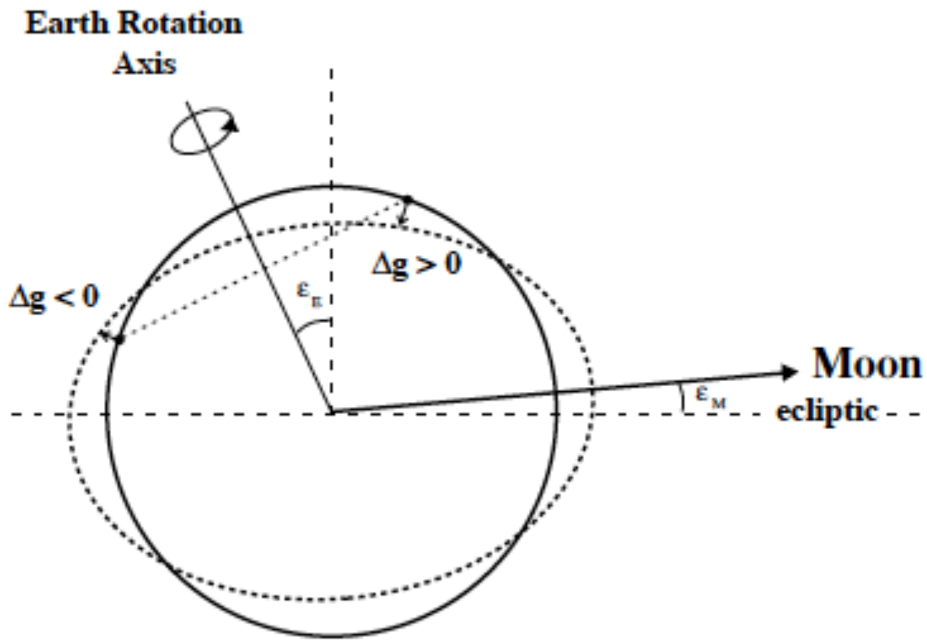


Figure 2: Tidal deformation of the Earth crust due to the presence of the moon. One tide bulge is formed in the direction of the moon and another one just opposite of it. The changes in gravity associated to the tidal deformations Δg are indicated for an observer at a latitude of about 45°. The sun tides have not been drawn. They create a tide bulge along the plane of the ecliptic. Their amplitude is 45% of the moon tides.

Beam energy daily variation

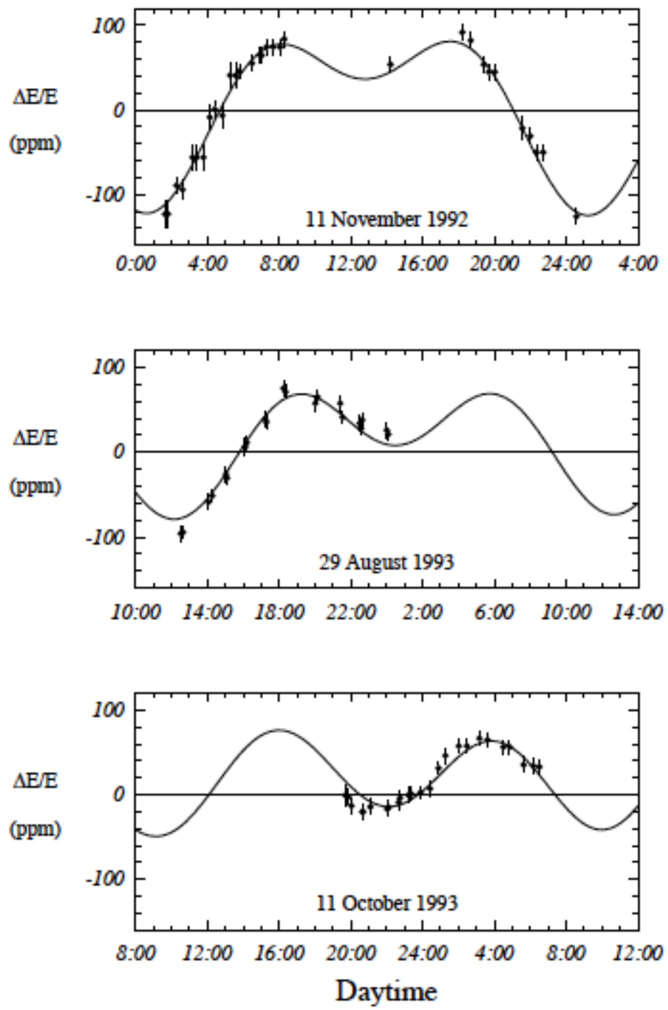


Figure 3: The evolution of the relative beam energy variation due to tides is shown as a function of time for three periods with stable beam conditions. The solid line is calculated using the CTE tide model with the average coefficient from equation 4. The top picture corresponds to full-moon, the bottom picture to a time close to half-moon. Relative beam energy variations of up to 220 ppm are observed on November 11^{th} 1992.

← Full Moon

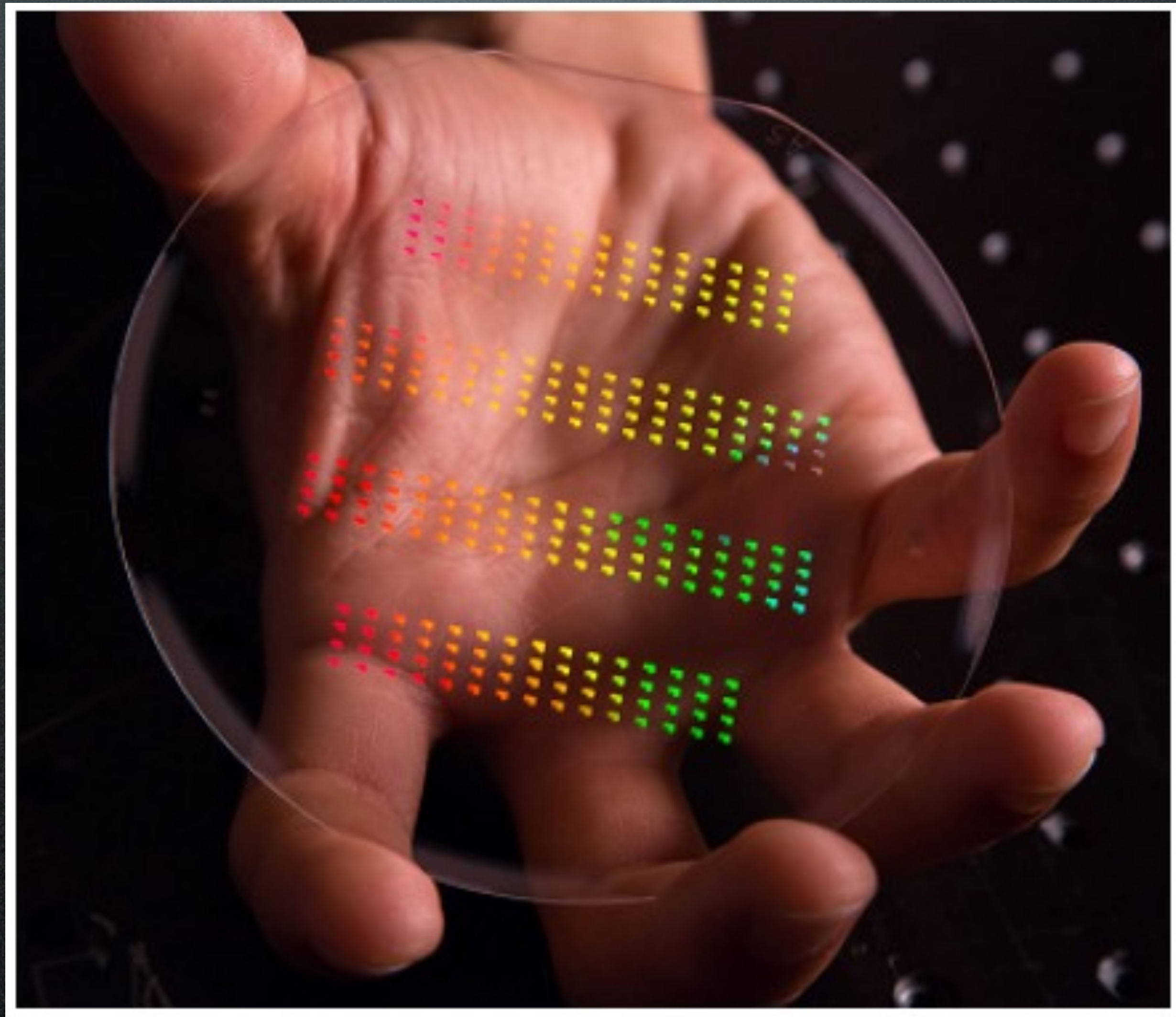
Hawking: the Solartron

Towards the Planck scale

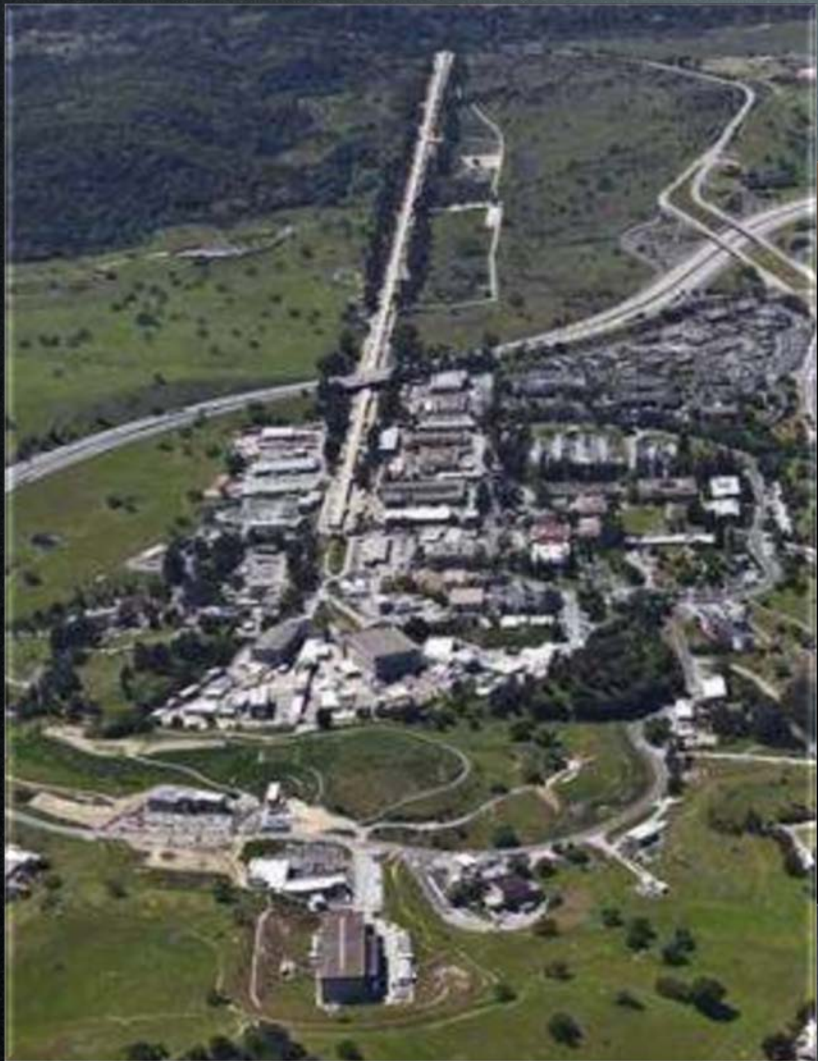
Without further novel technology, we will eventually need an accelerator as large as Hawking expected.

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

Accelerator on a Chip?

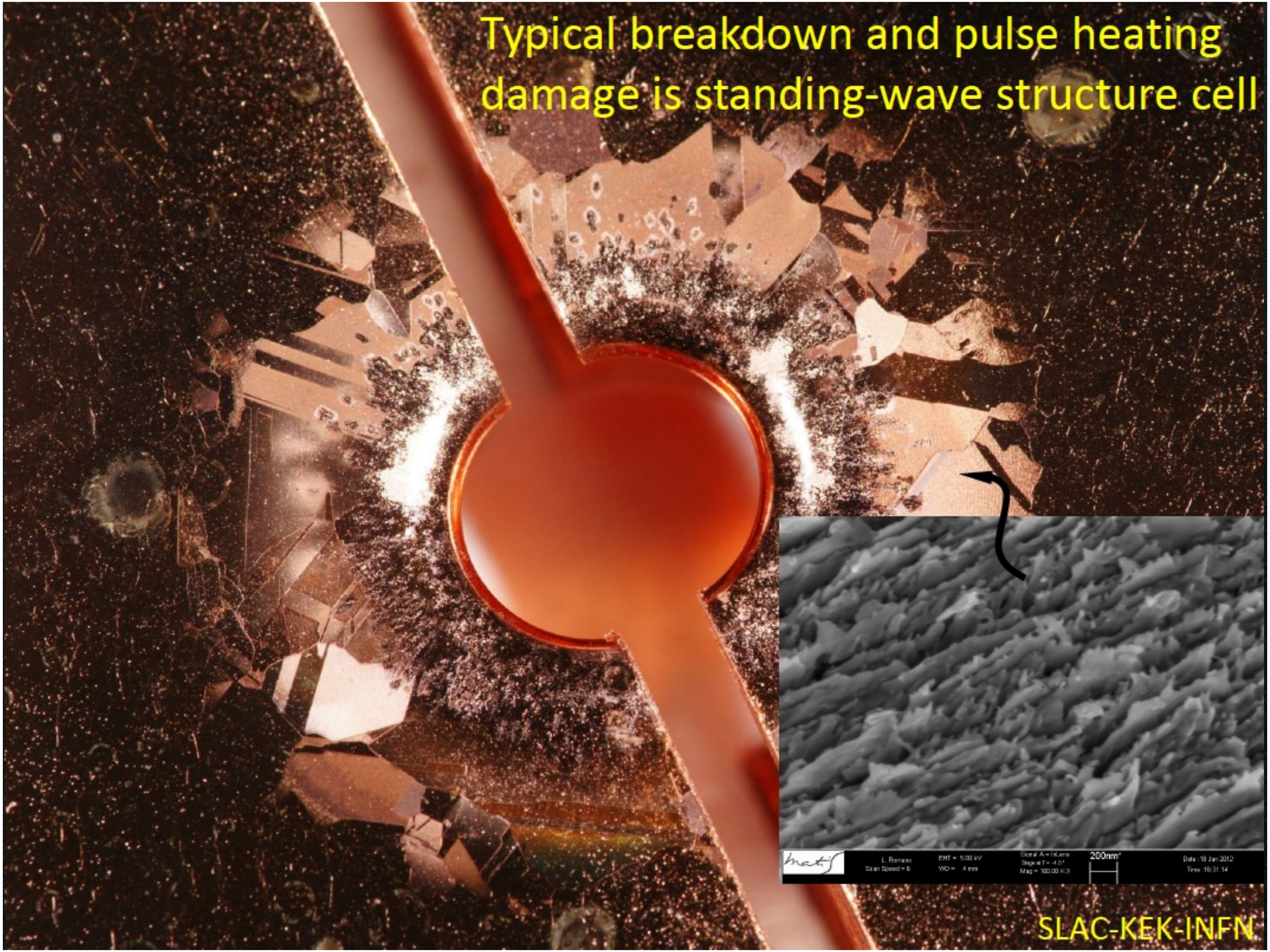


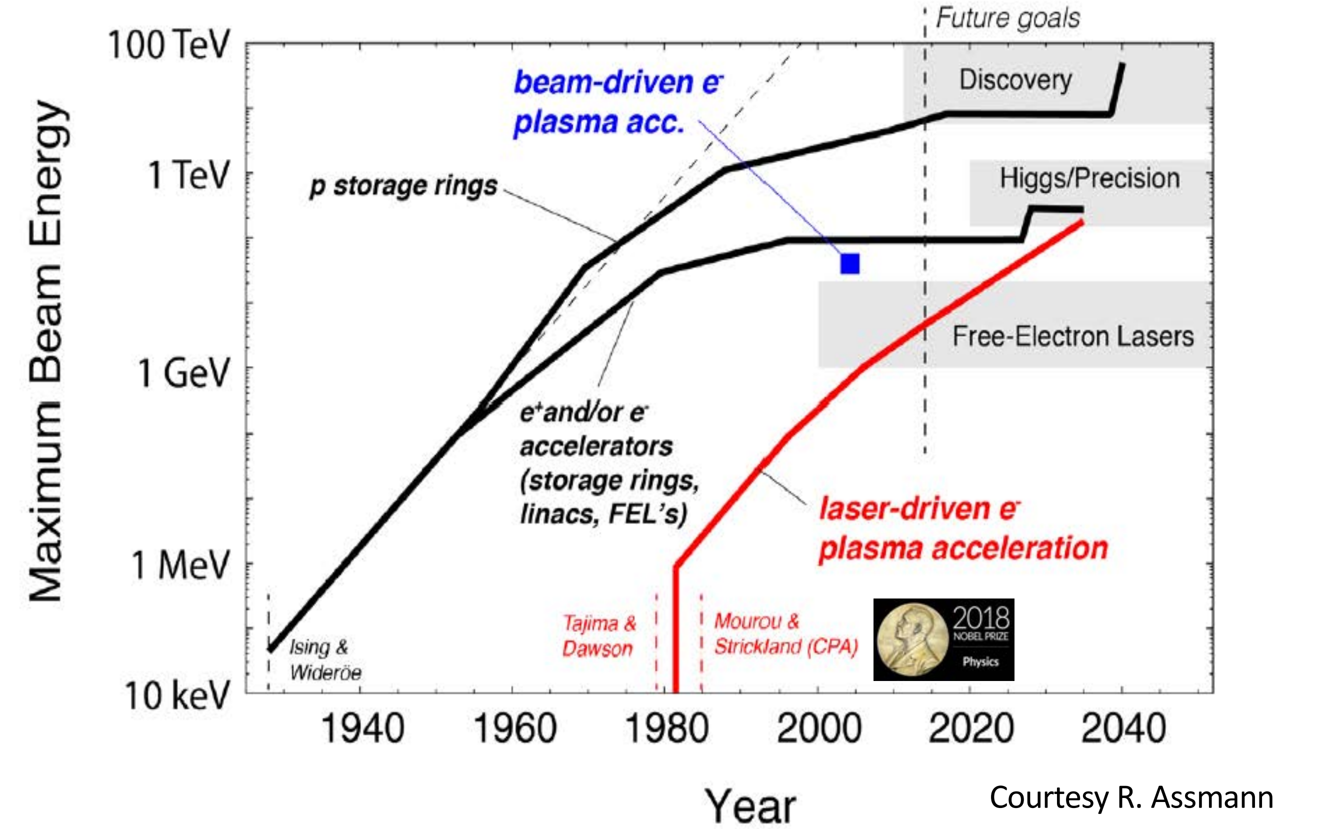
SLAC Now and Tomorrow?



Conventional RF accelerating structures

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



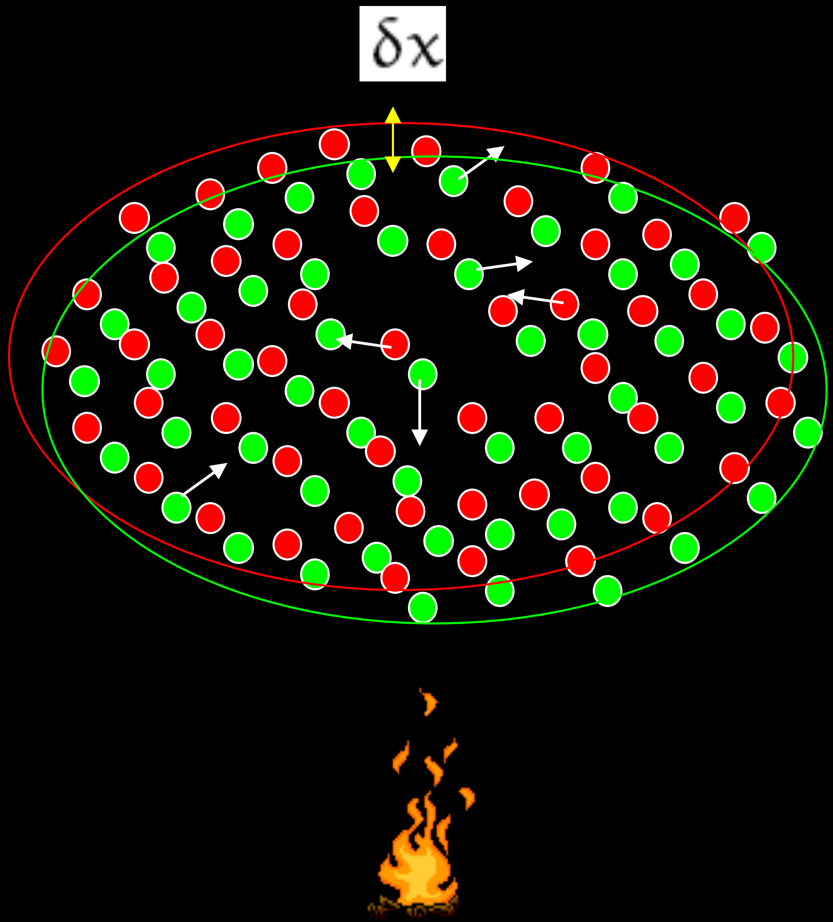


Courtesy R. Assmann

Plasma Acceleration

Surface charge density

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



Surface electric field

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

Restoring force

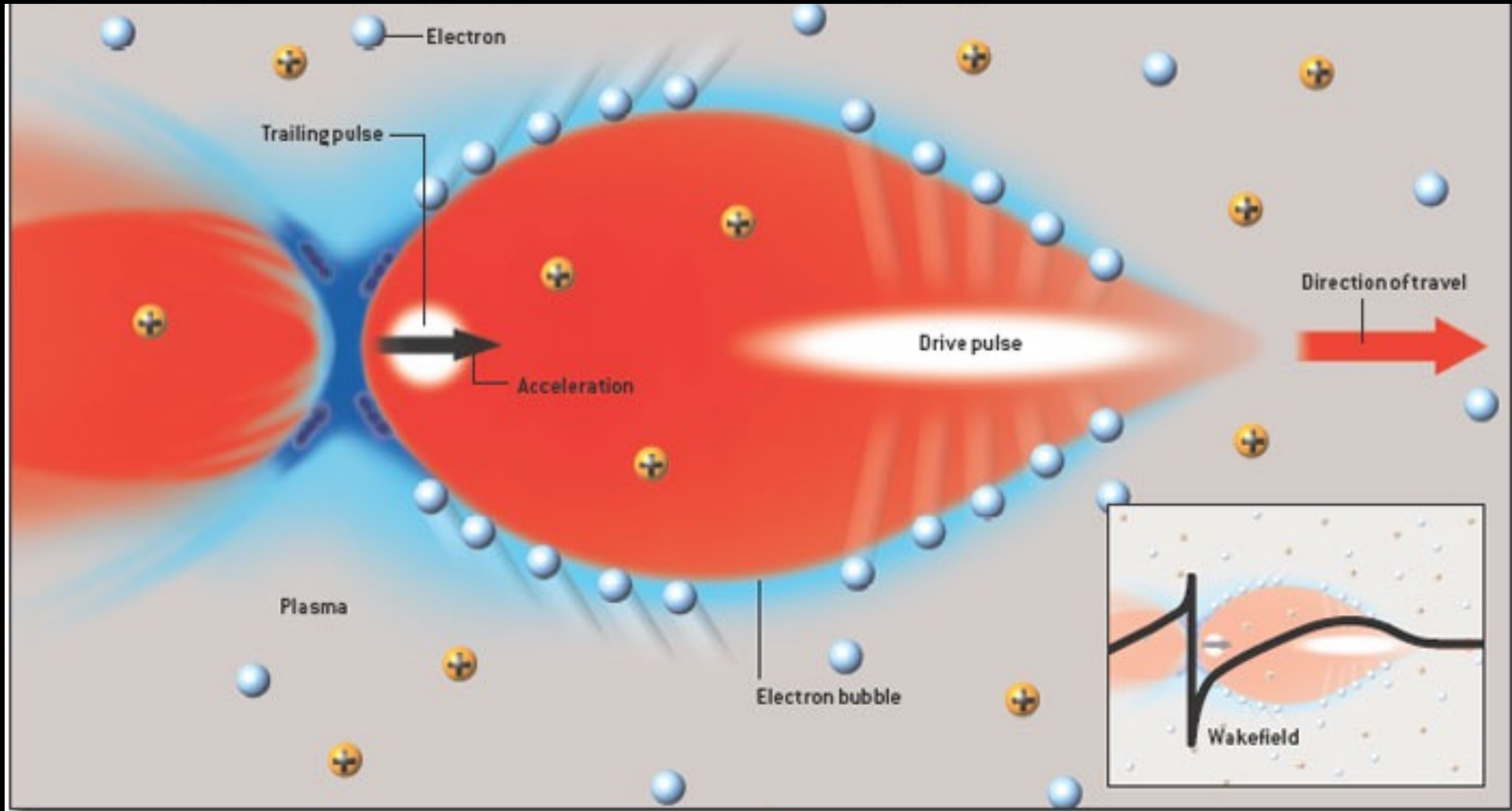
$$m \frac{d^2 \delta x}{dt^2} = e\, E_x = -m\, \omega_p^{\,2}\, \delta x$$

Plasma frequency

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

Plasma oscillations

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

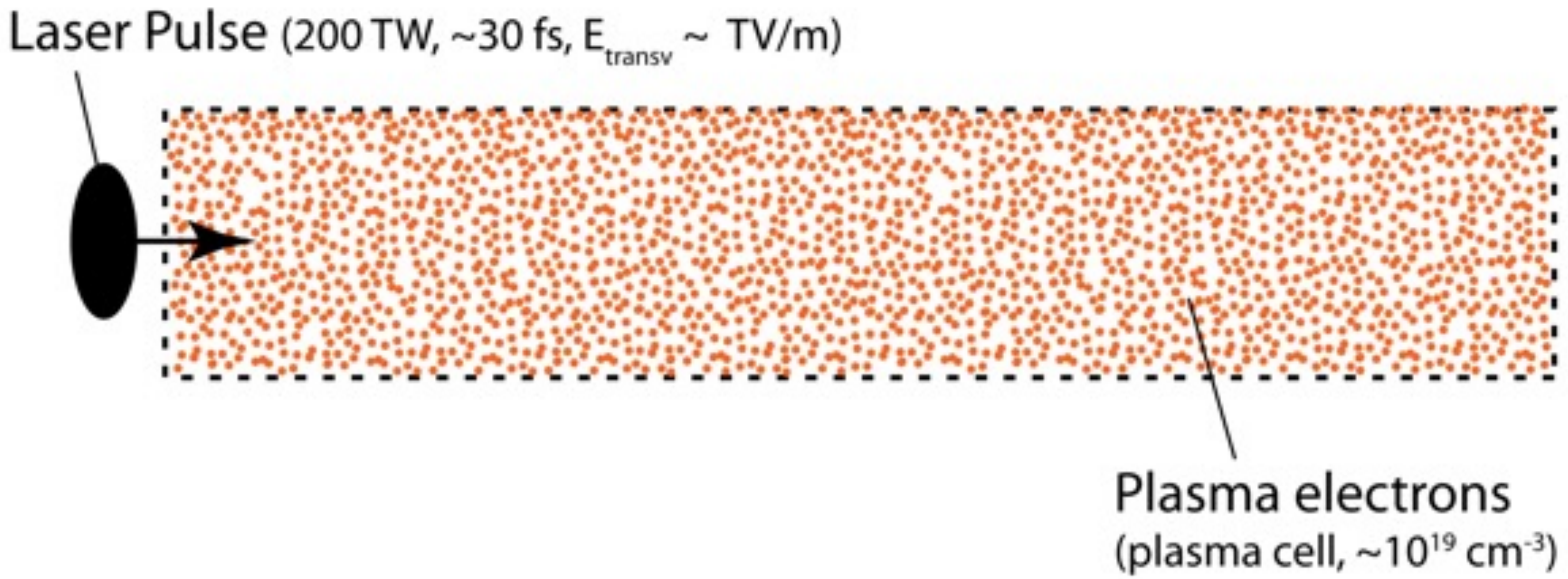


Breakdown limit?

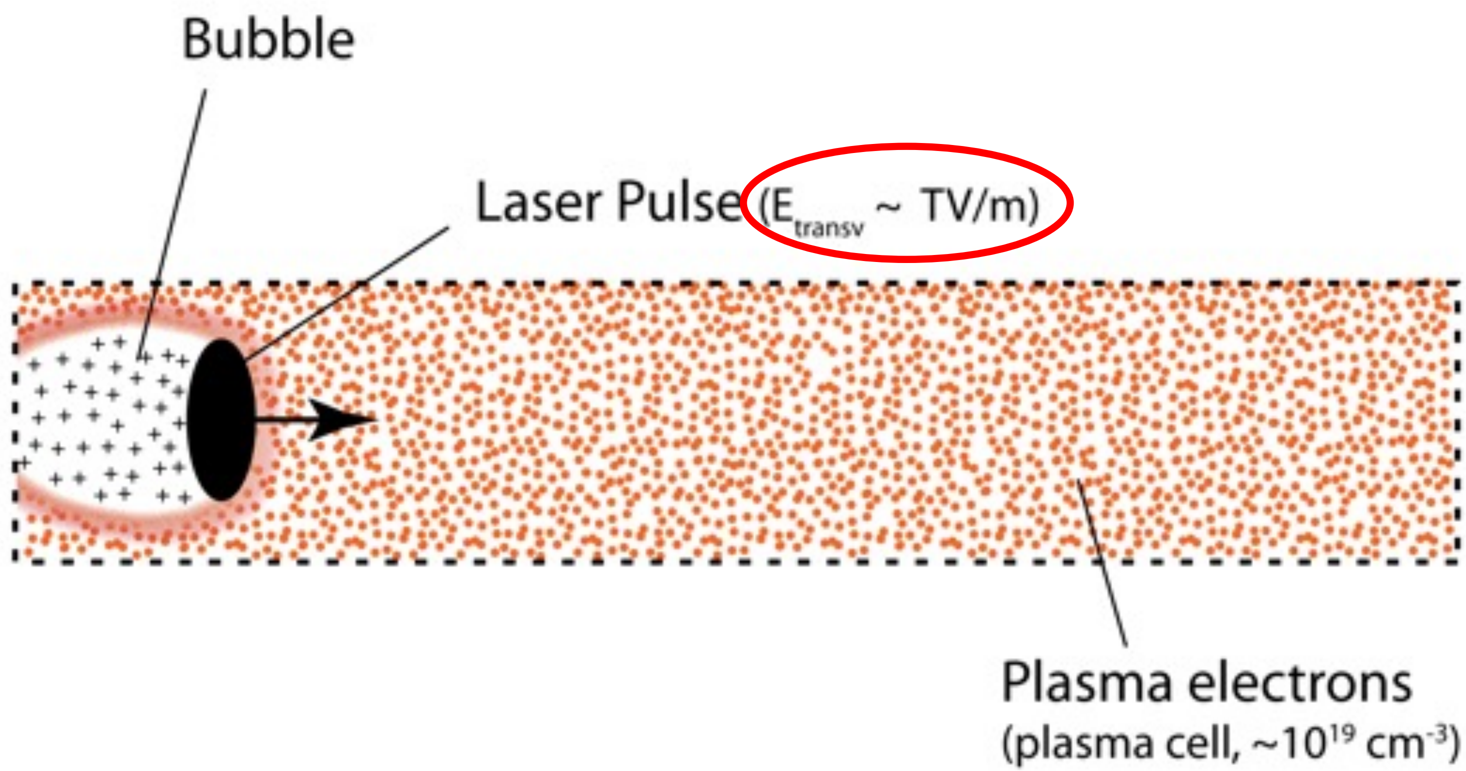
$$E_0 = \frac{m_e c \omega_p}{e} \approx 100[\frac{GeV}{m}] \cdot \sqrt{n_0[10^{18} cm^{-3}]}$$

Laser Plasma-Acceleration
(Internal Injection)

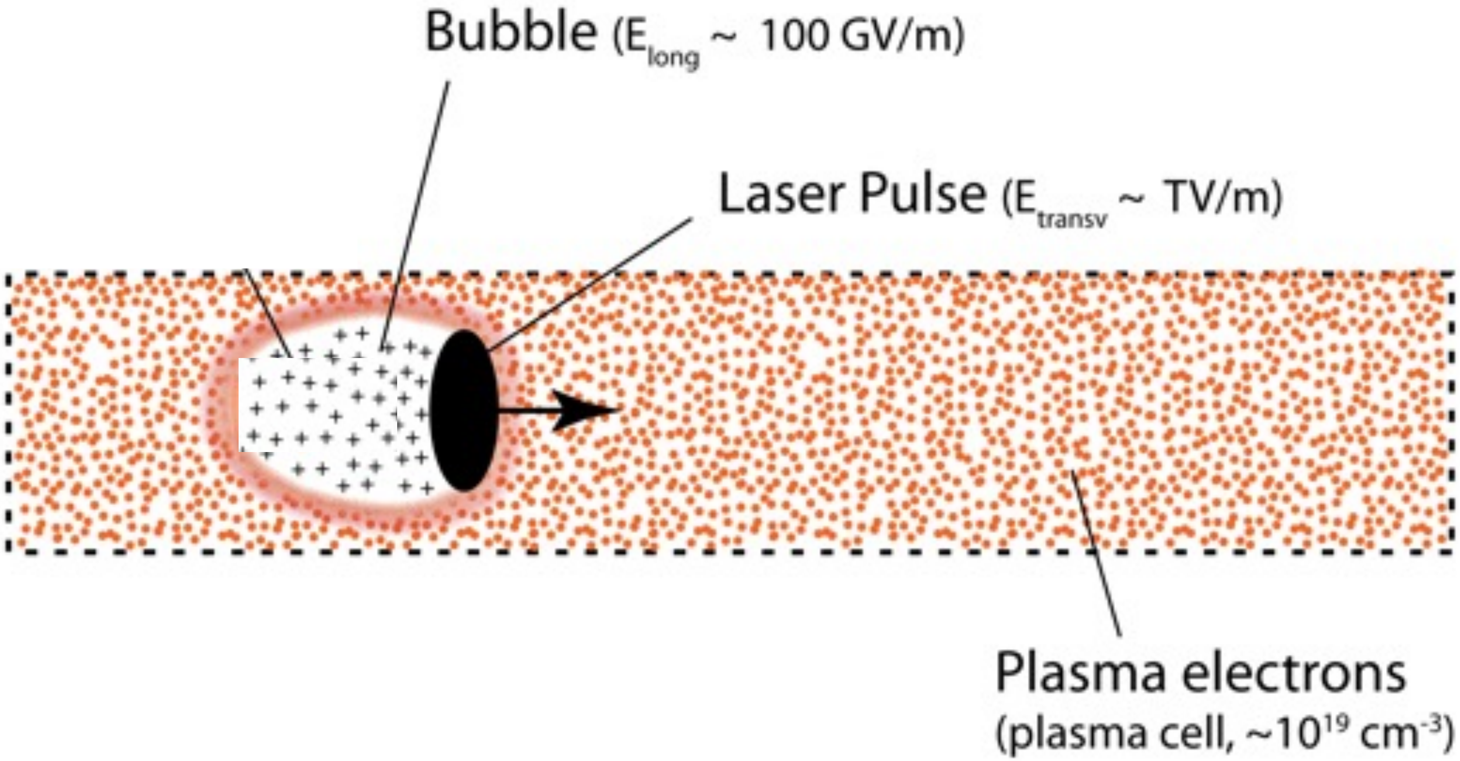
Horizon2020



Laser Plasma-Acceleration
(Internal Injection)

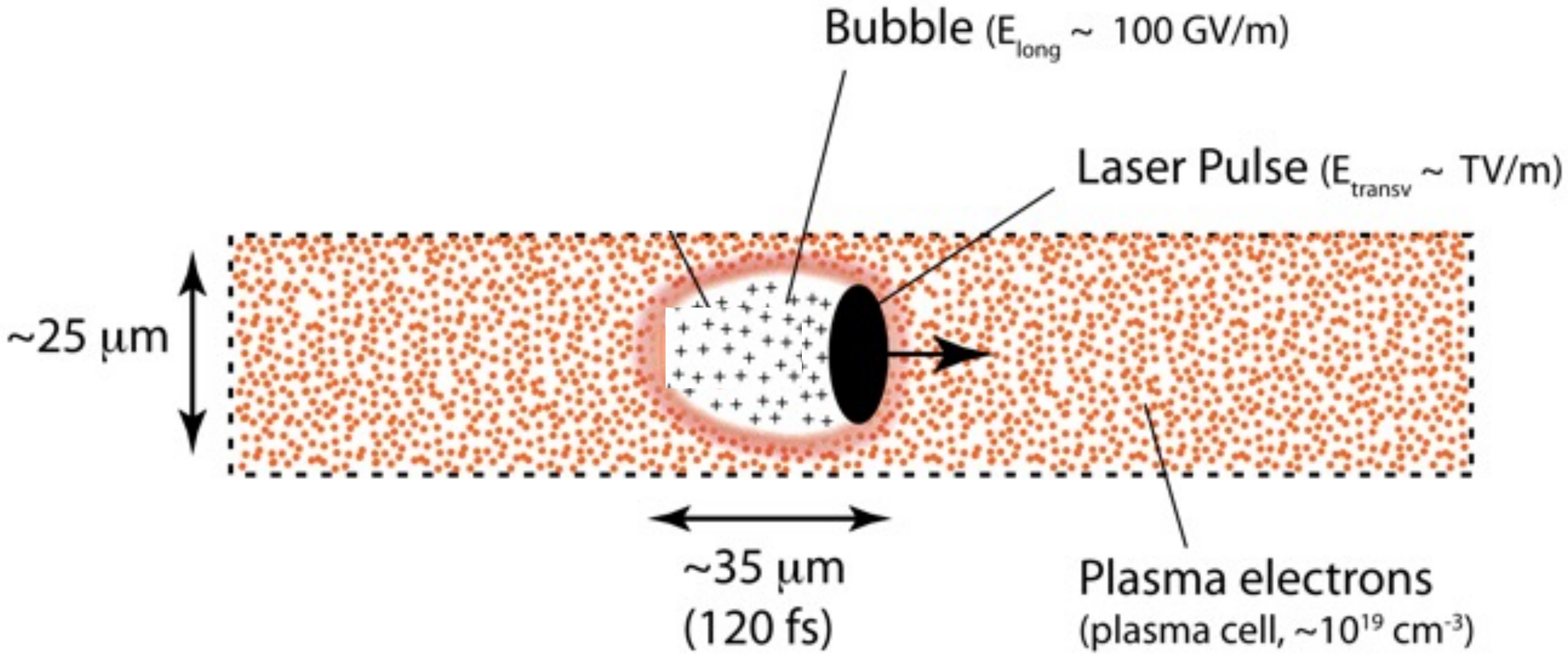


Laser Plasma-Acceleration
(Internal Injection)

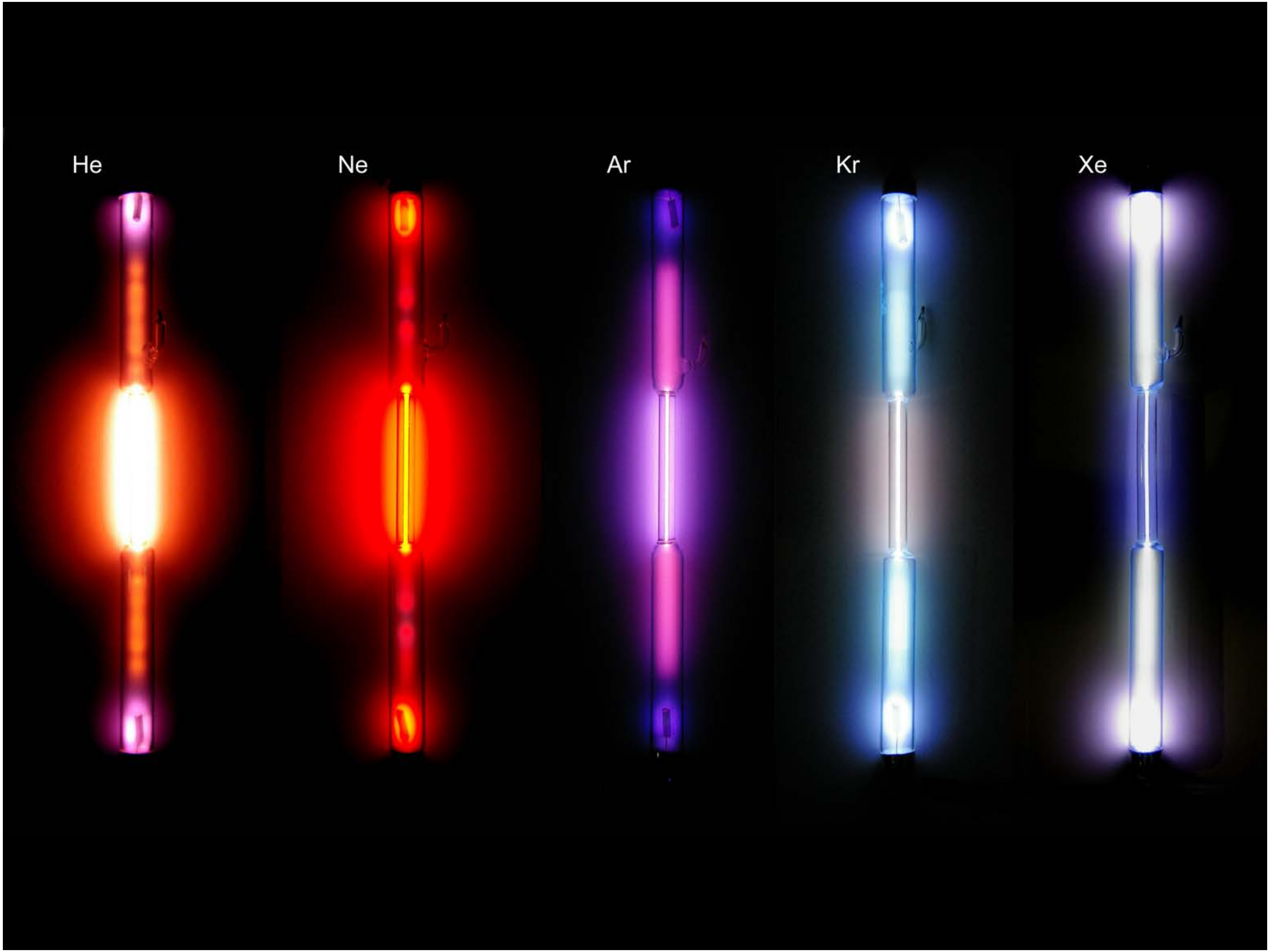


Laser Plasma-Acceleration
(Internal Injection)

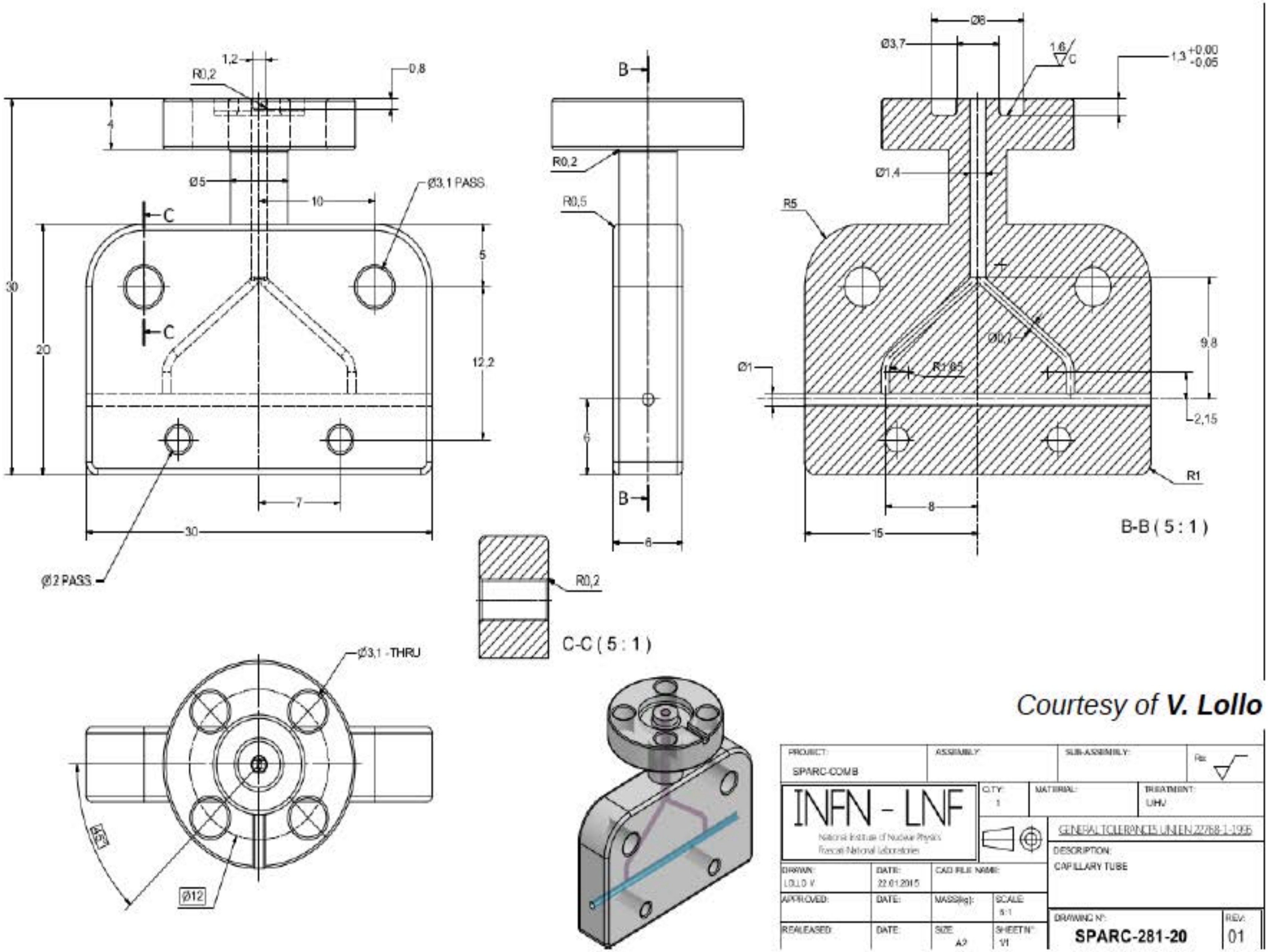
Horizon2020



This accelerator fits into a human hair!

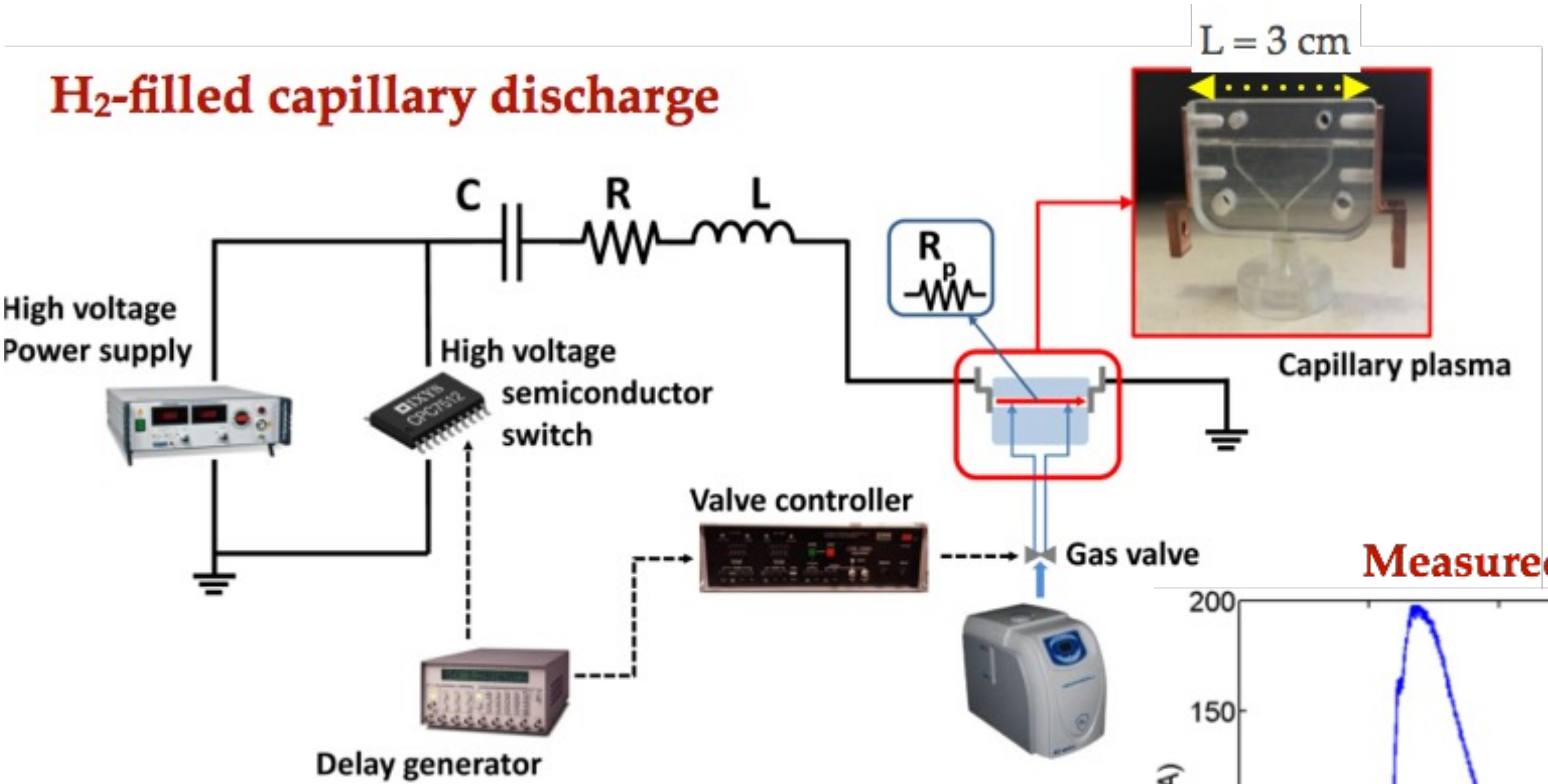

He
Ne
Ar
Kr
Xe

Plasma capillary

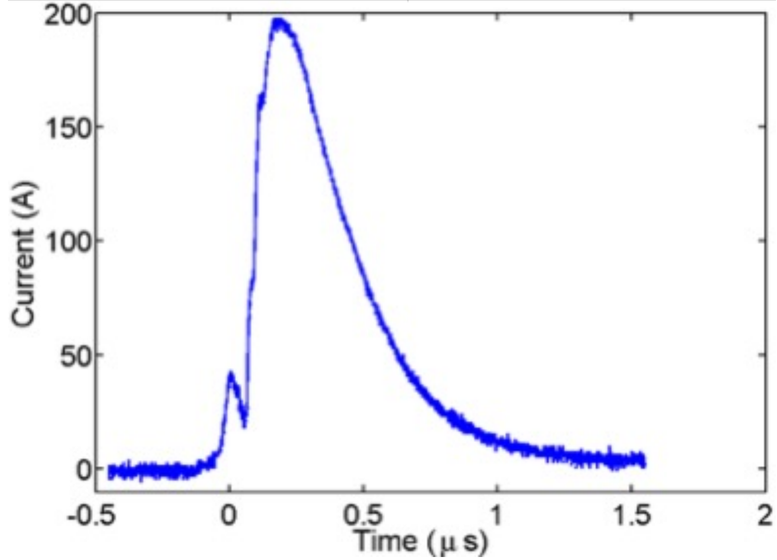


*Courtesy of **V. Lollo***

Plasma Source



Measured current

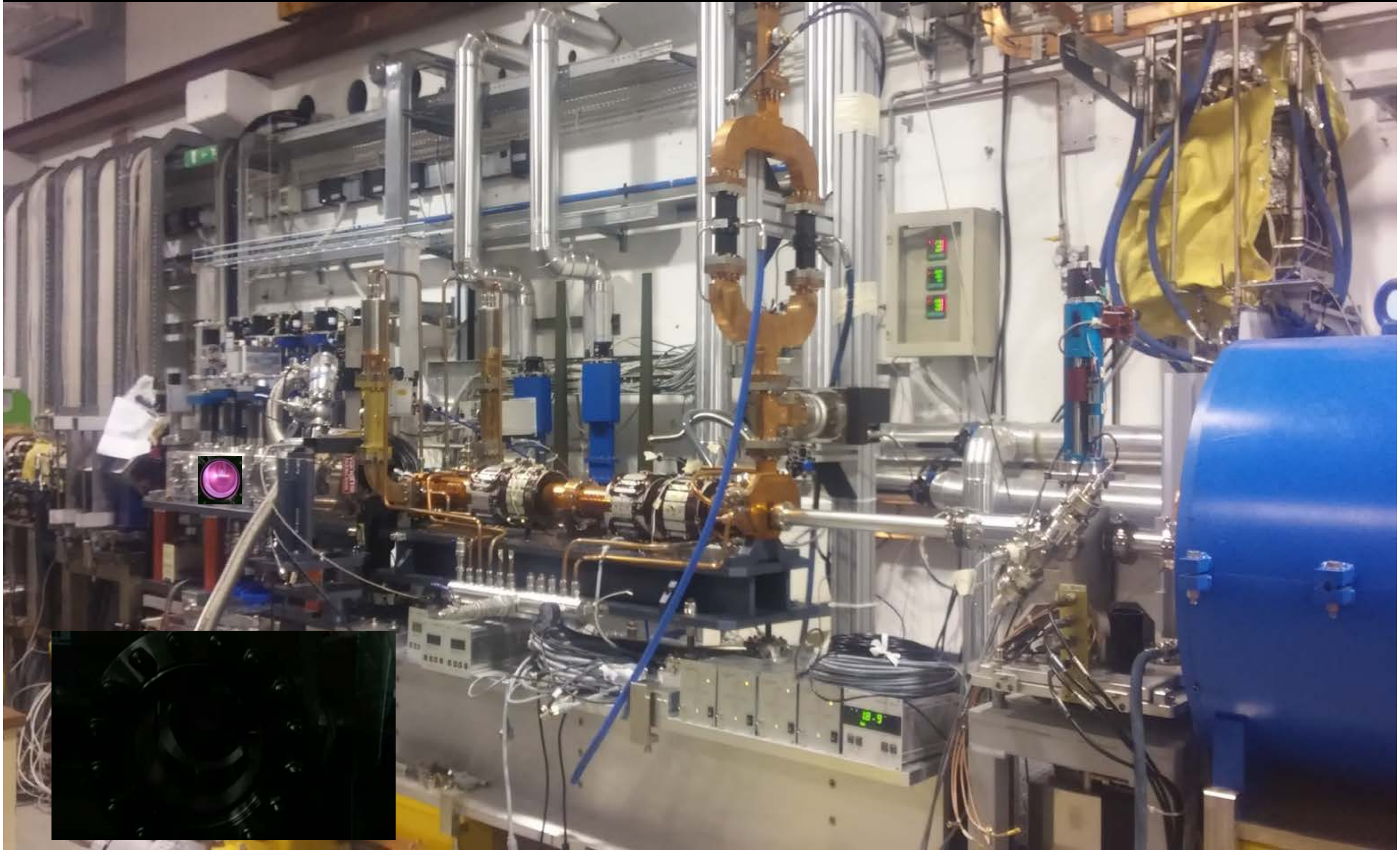


P_{H2} = 10 mbar
Total discharge duration: 800 ns
Voltage: 20 kV
Peak current: 200 A
Capacitor: 6 nF

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

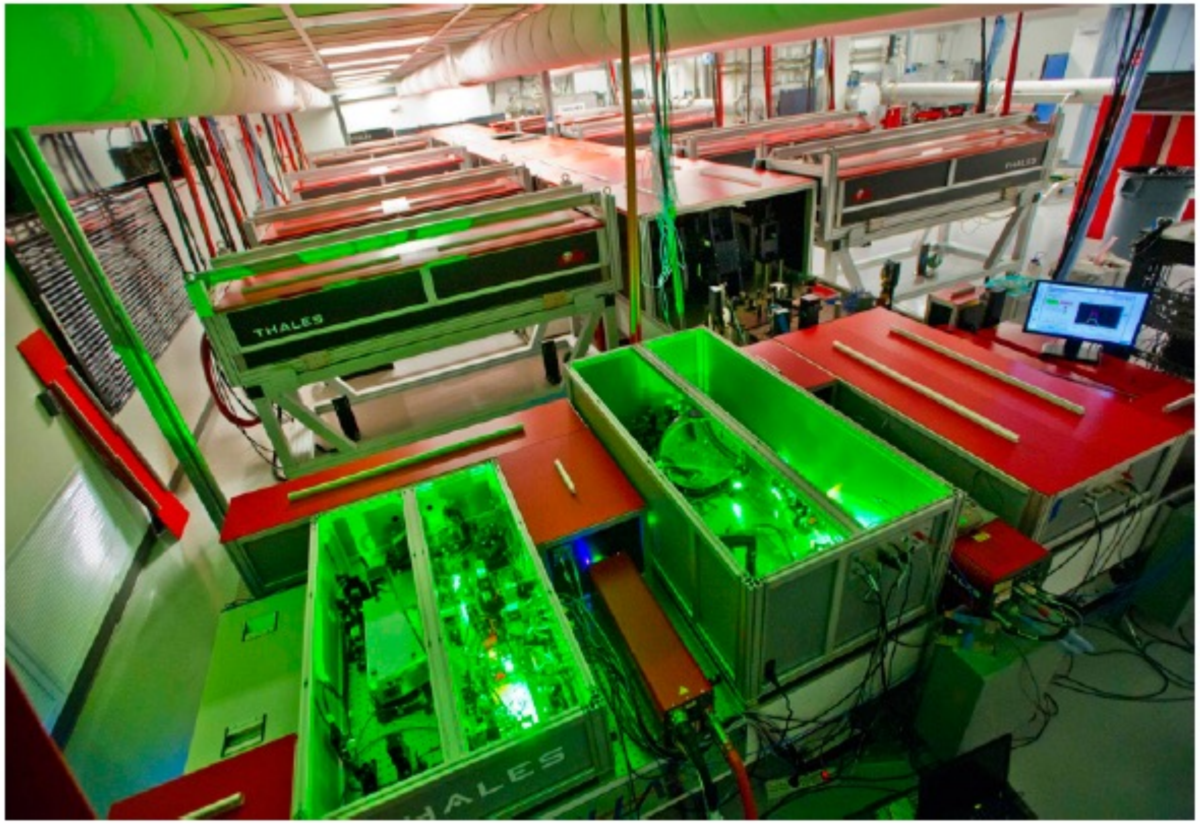
Capillary Discharge

PWFA vacuum chamber at SPARC_LAB



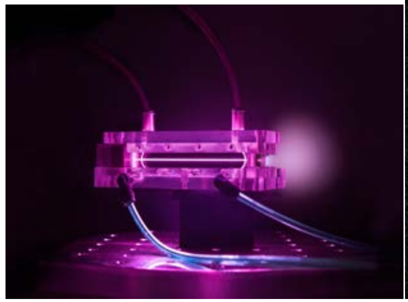
BELLA: BErkeley Lab Laser Accelerator

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



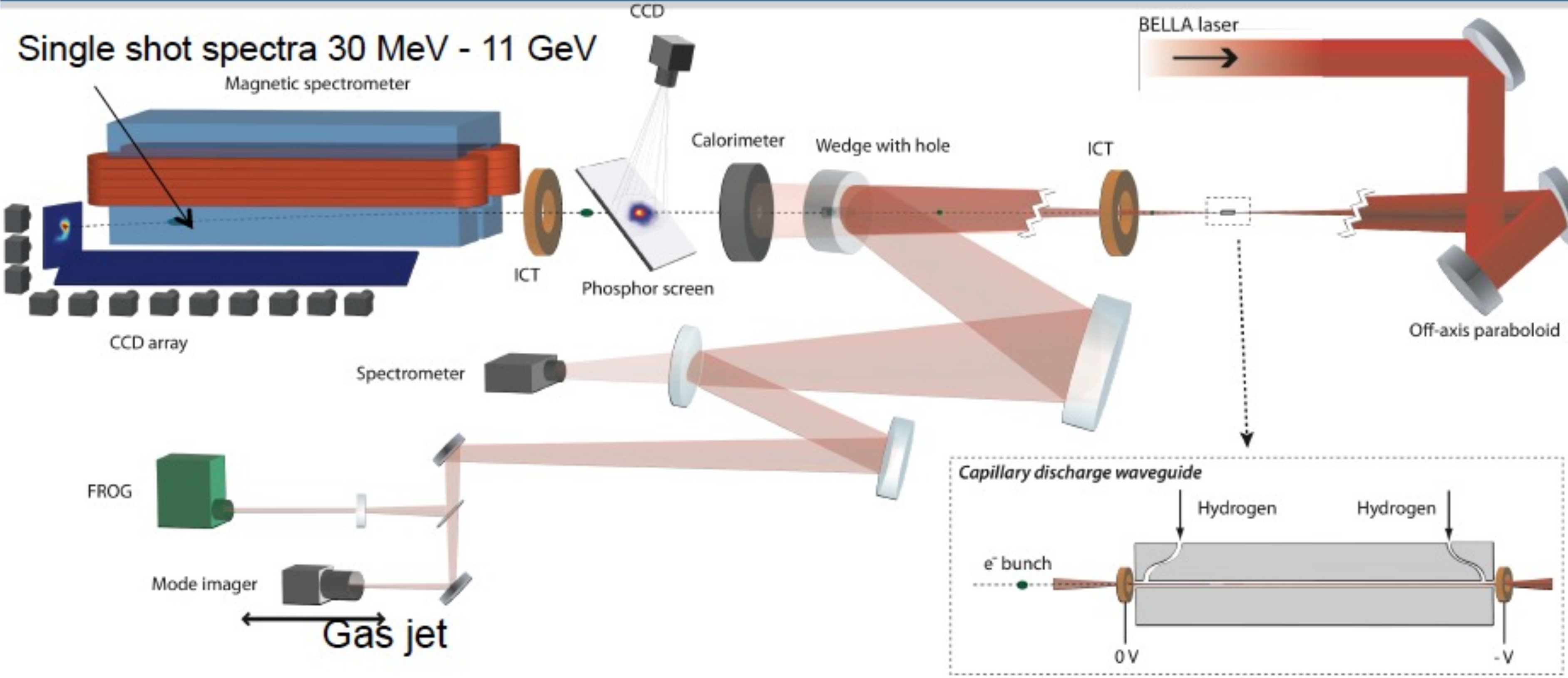
Critical HEP experiments:

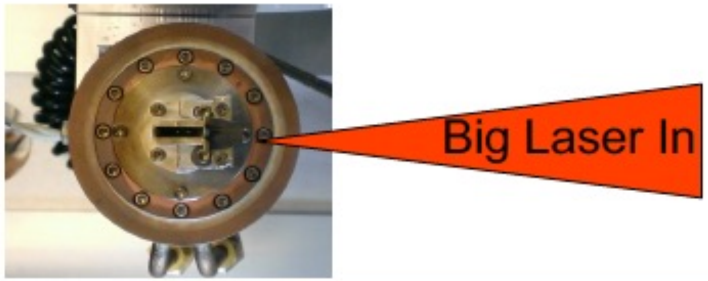
- 10 GeV electron beam from <1 m LPA
- Staging LPAs
- Positron acceleration



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

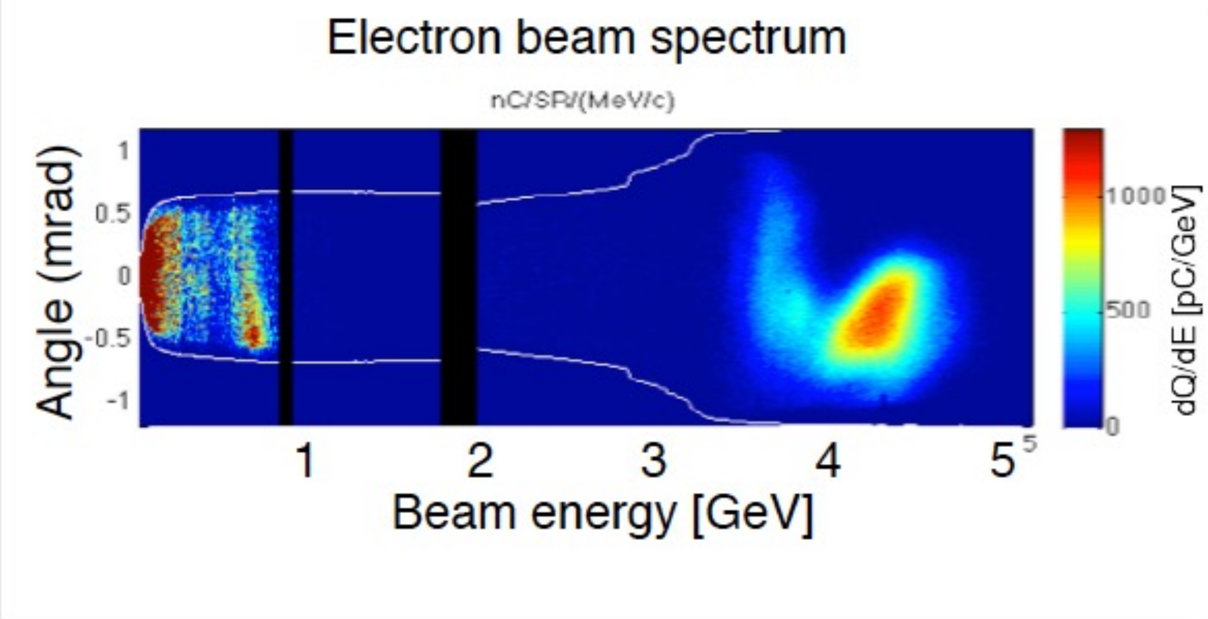


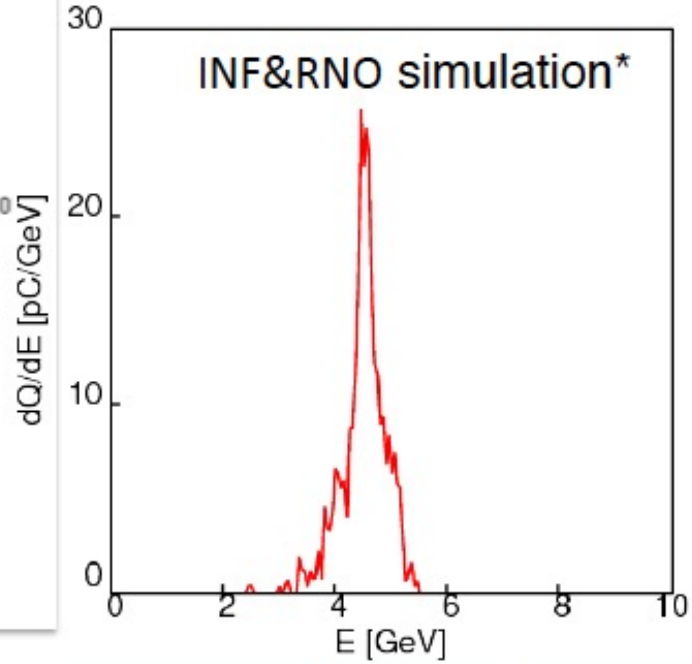


Capillary discharge

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



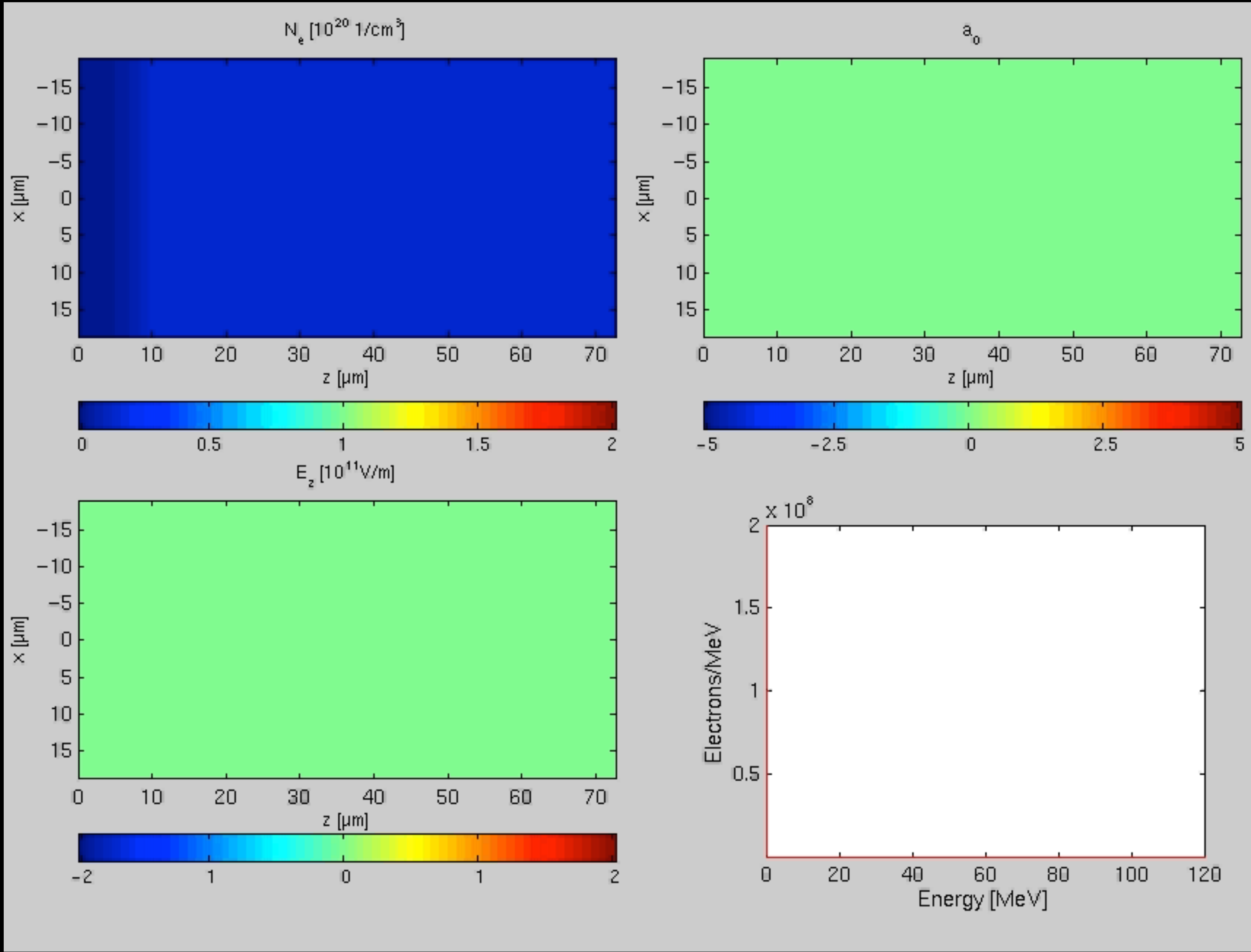


	Exp.	Sim.
Energy	4.25 GeV	4.5 GeV
ΔE/E	5%	3.2%
Charge	~20 pC	23 pC
Divergence	0.3 mrad	0.6 mrad

- **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})

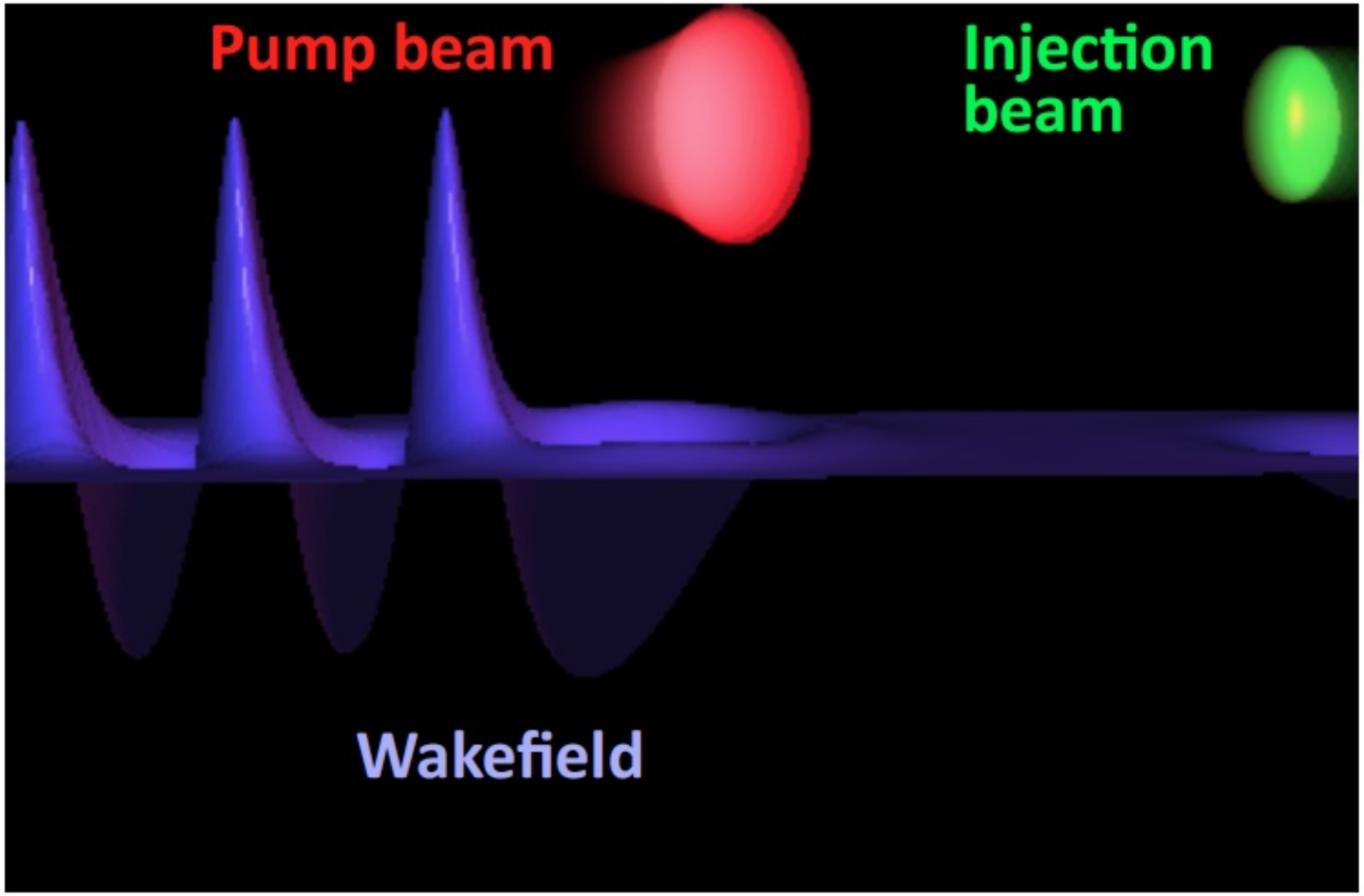
W.P. Leemans et al.,PRL 2014

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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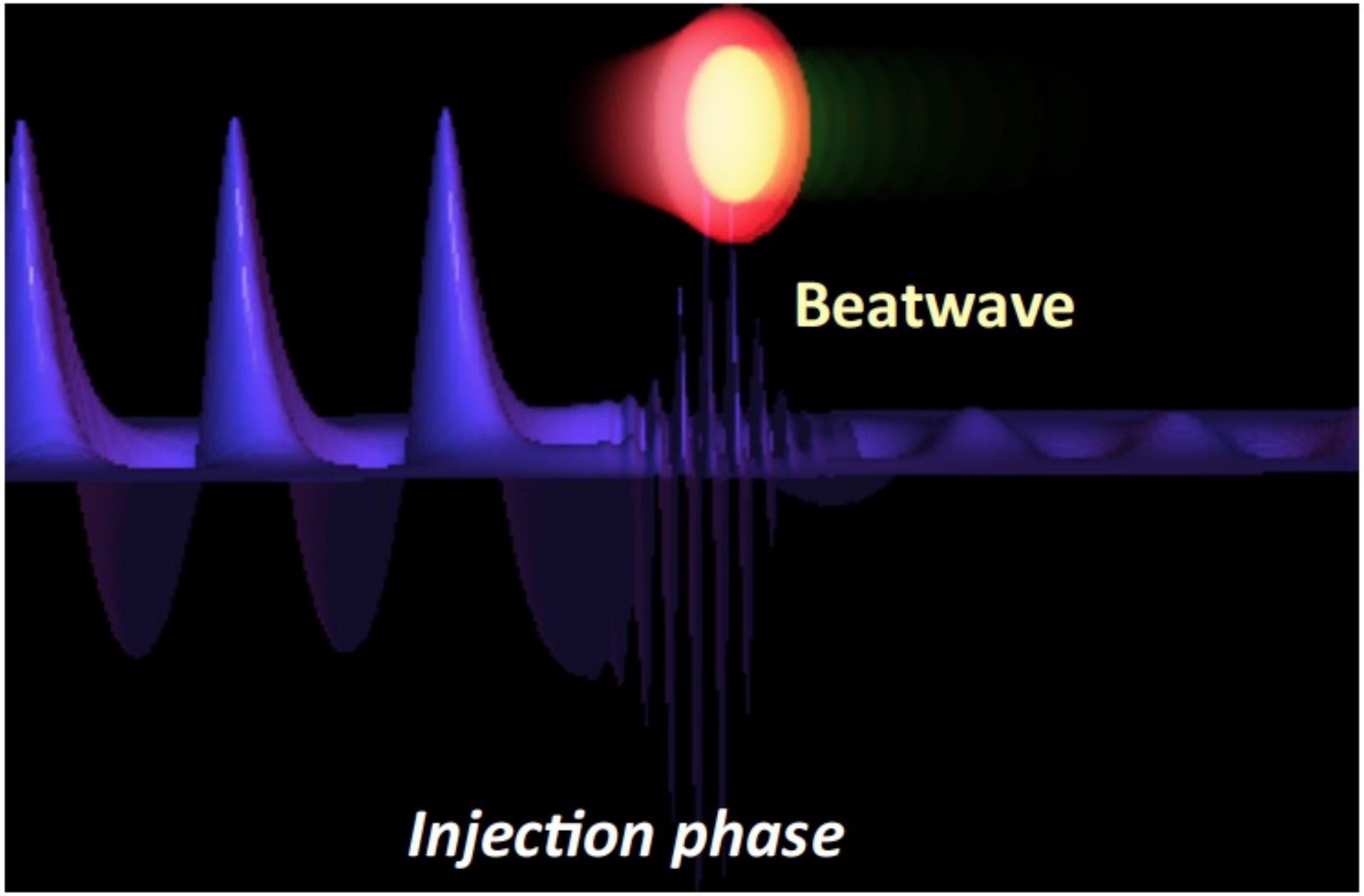

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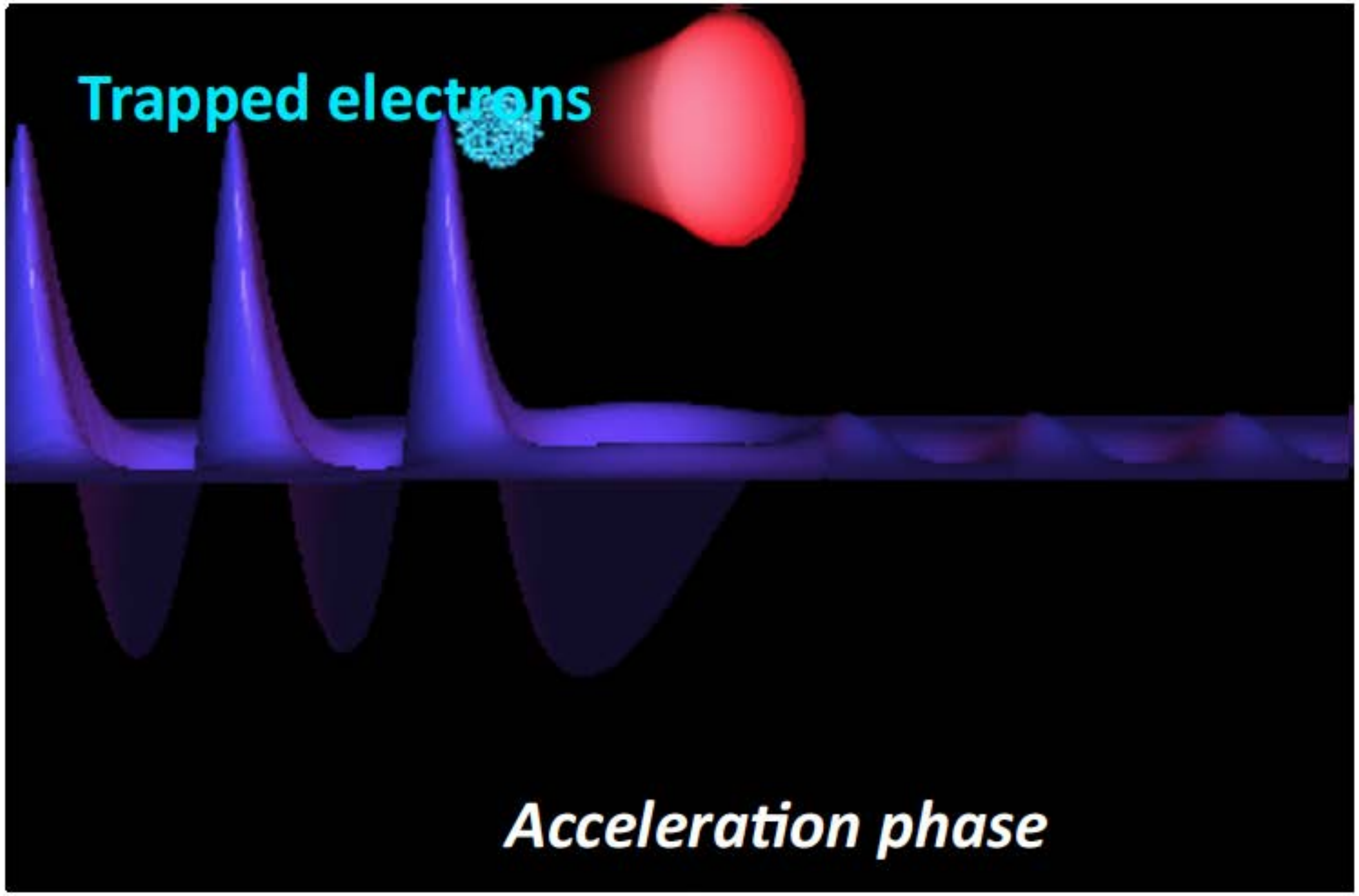
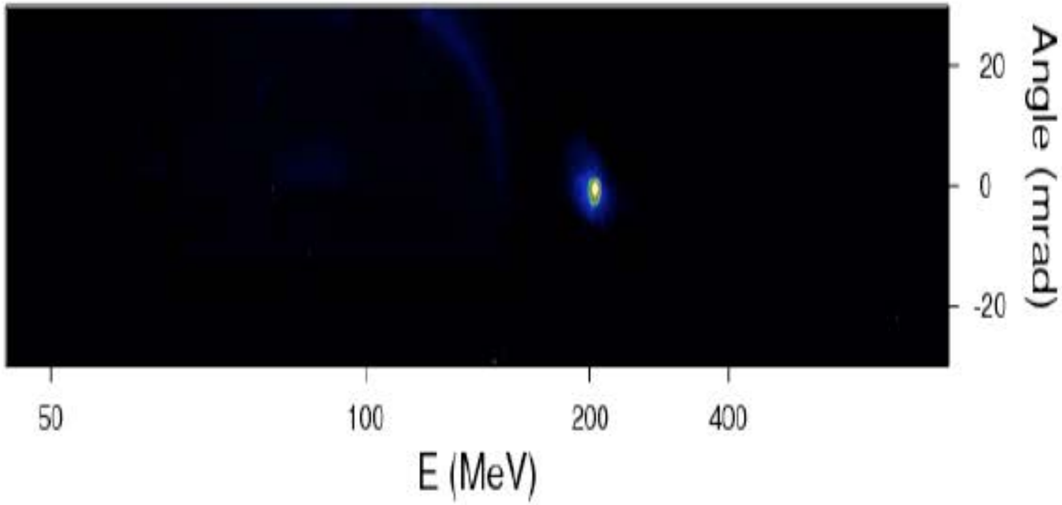
Colliding Laser Pulses Scheme

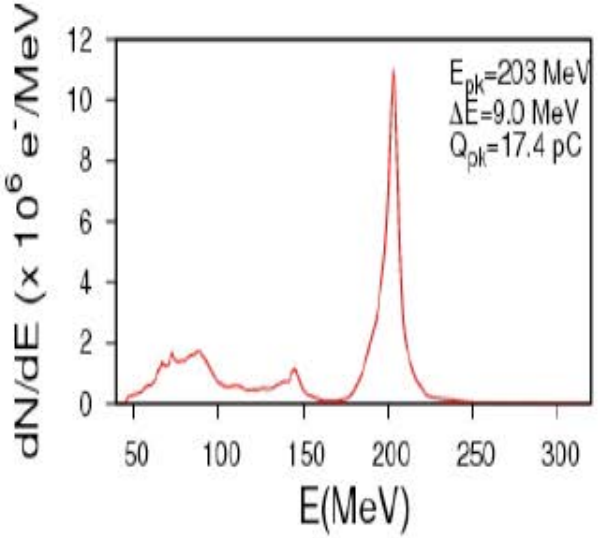
The first laser creates the accelerating structure, a second laser beam is used to heat electrons



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)

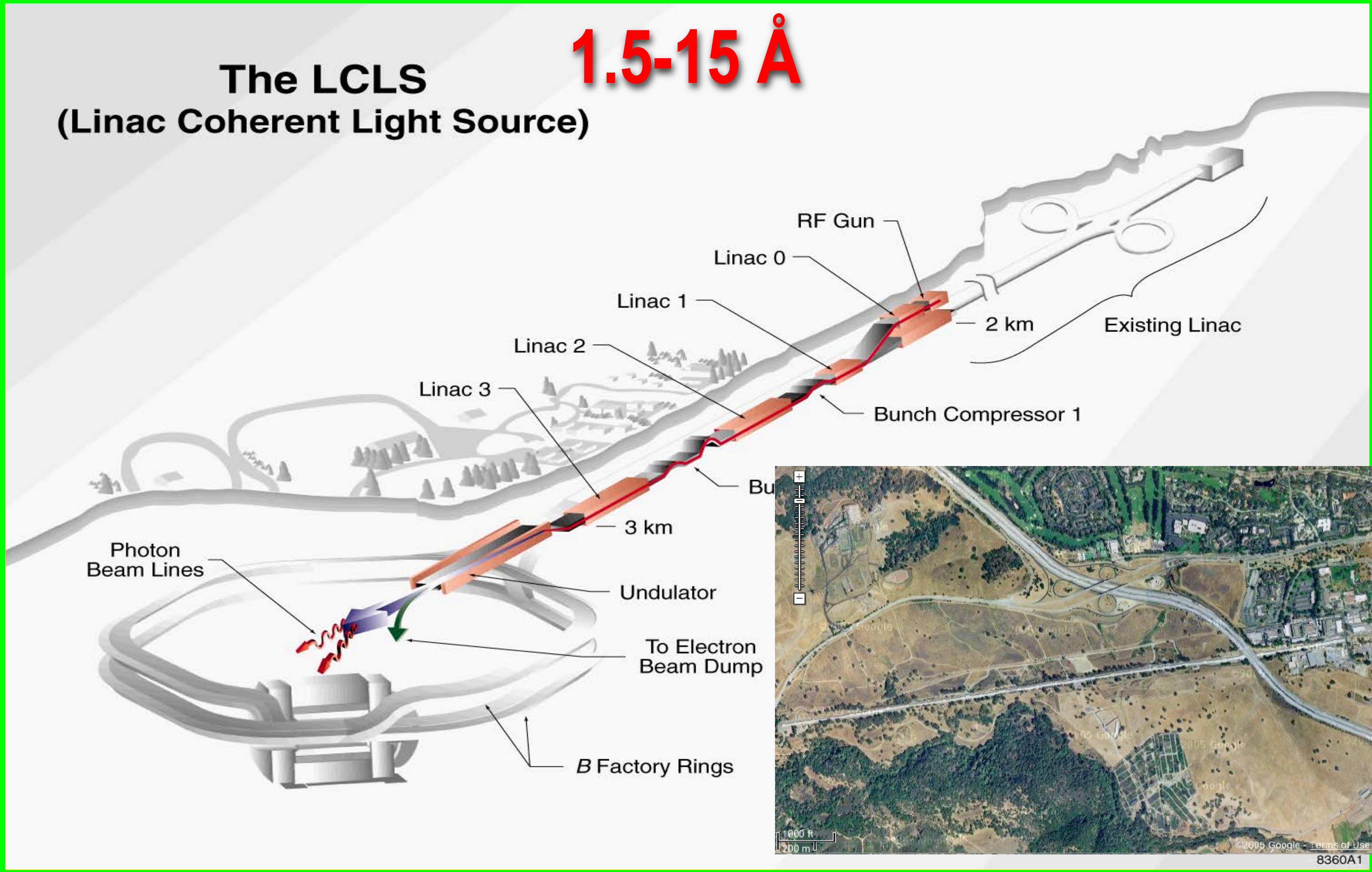
Stable Laser Plasma Accelerators





Free Electron Laser

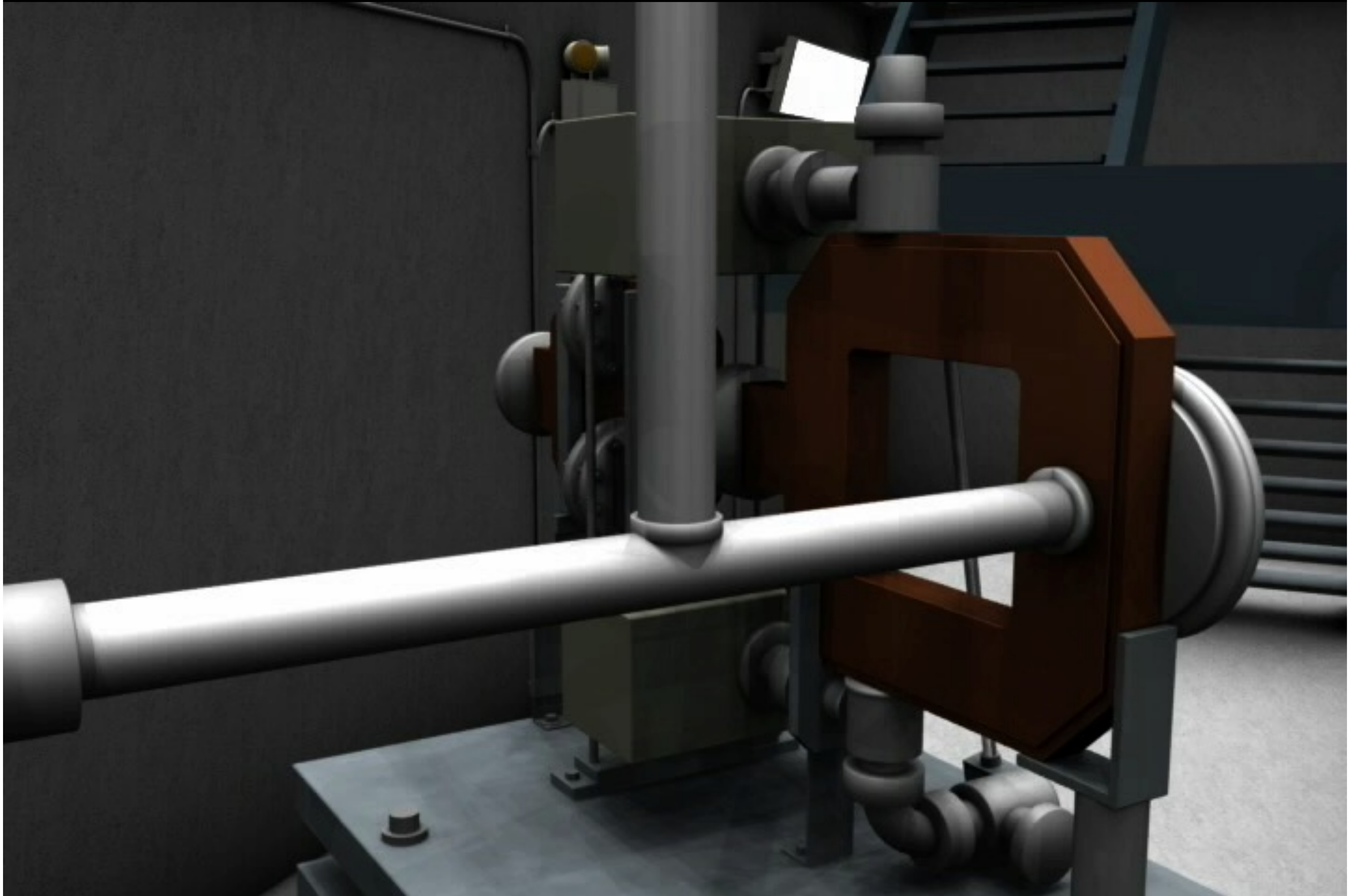
LCLS at *SLAC*



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

XFEL first lasing – Hamburg May 2017

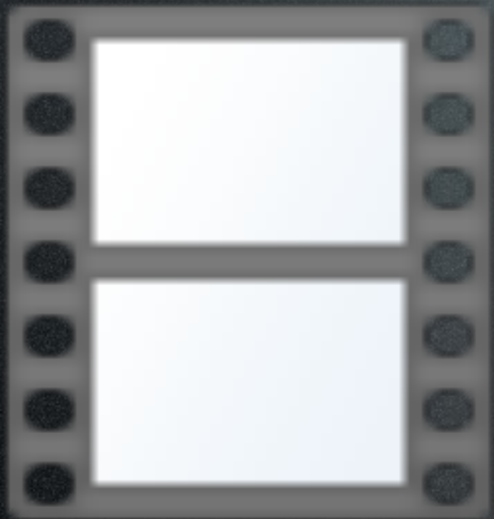
Electron source and acceleration

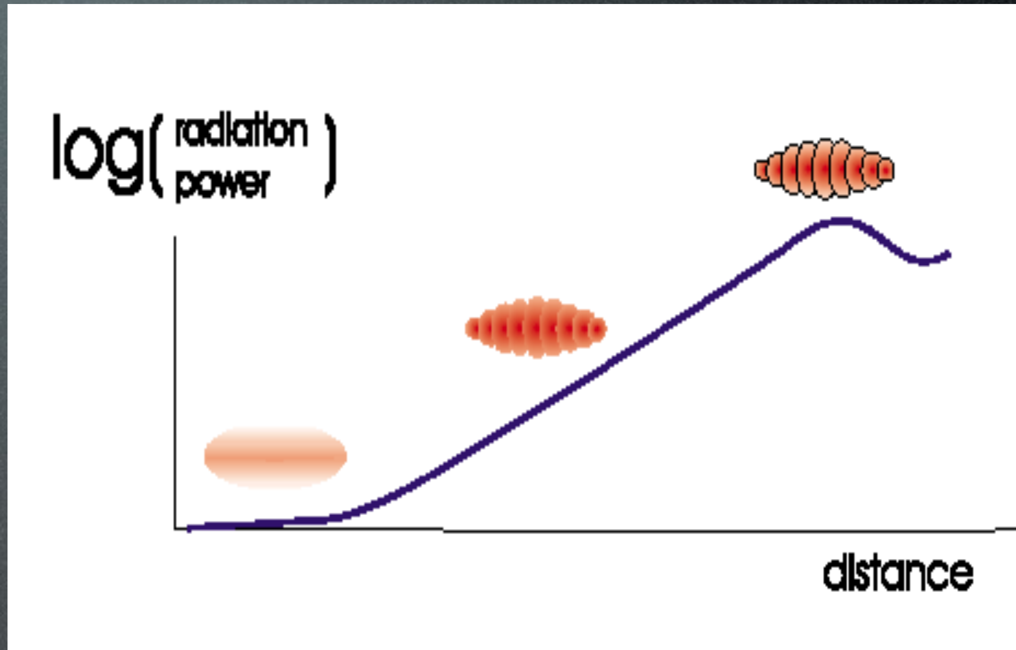


Long undulators chain

Beam separation

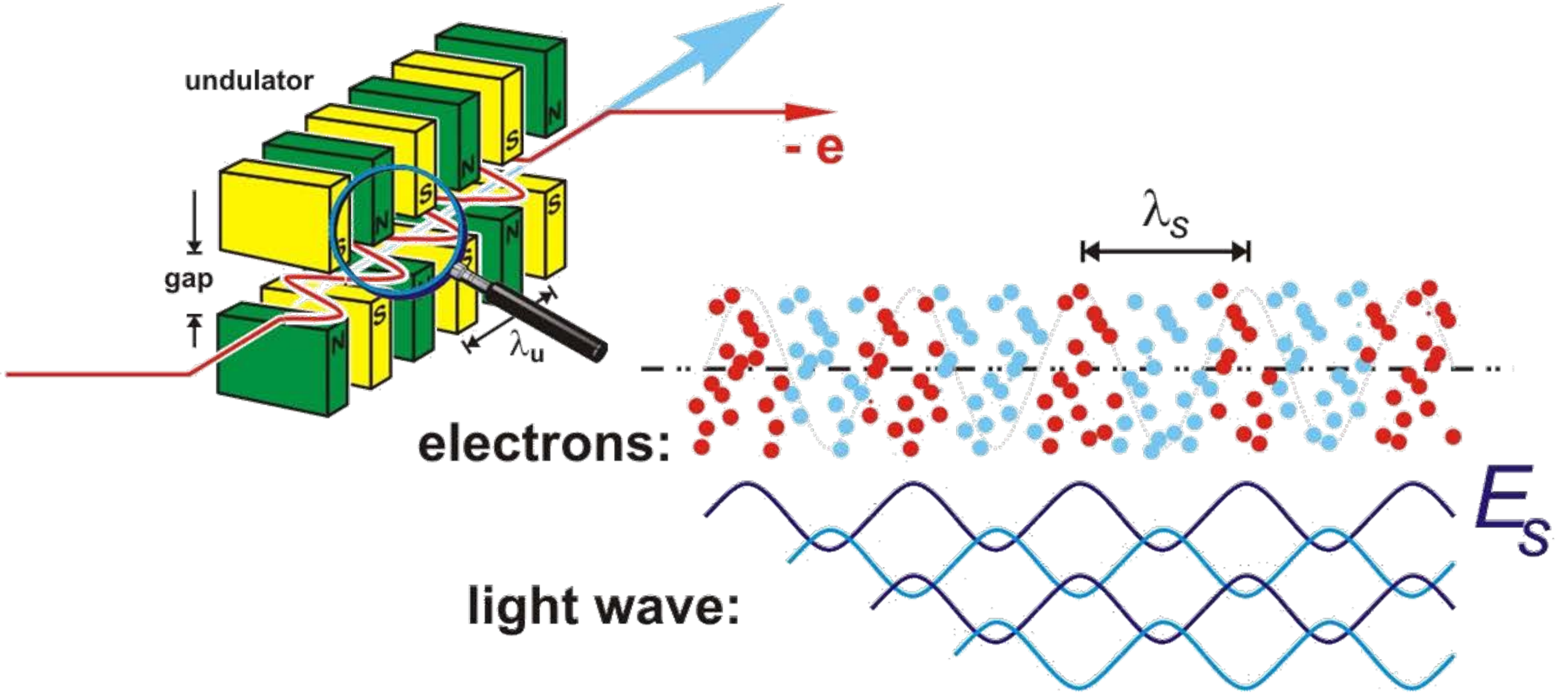
A Free Electron Laser is a device that converts a fraction of the electron kinetic energy into coherent radiation via a collective instability in a long undulator





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

(Tunability - Harmonics)

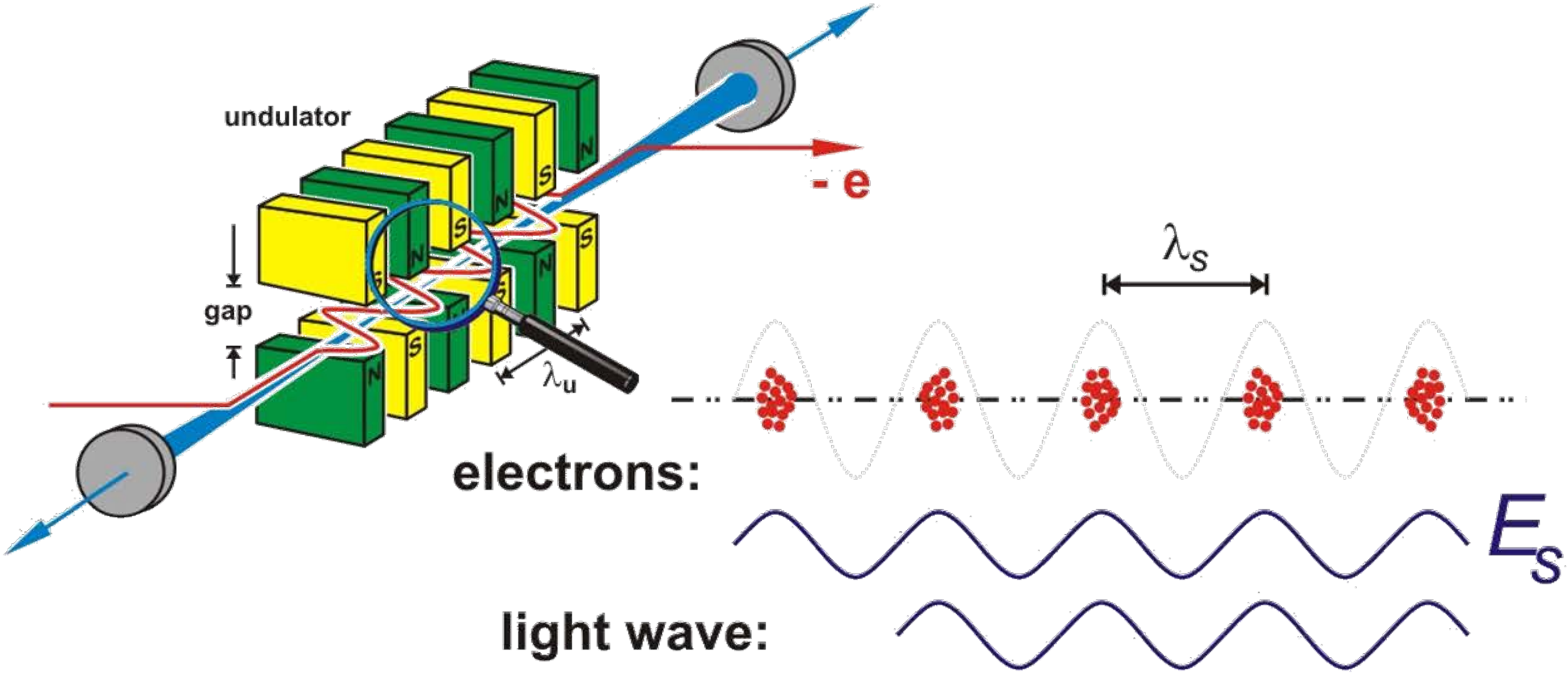


Radiated Power:

$$P \propto n_e \text{ (number of electrons)}$$

destructive interference

$\longrightarrow$ **shotnoise radiation**

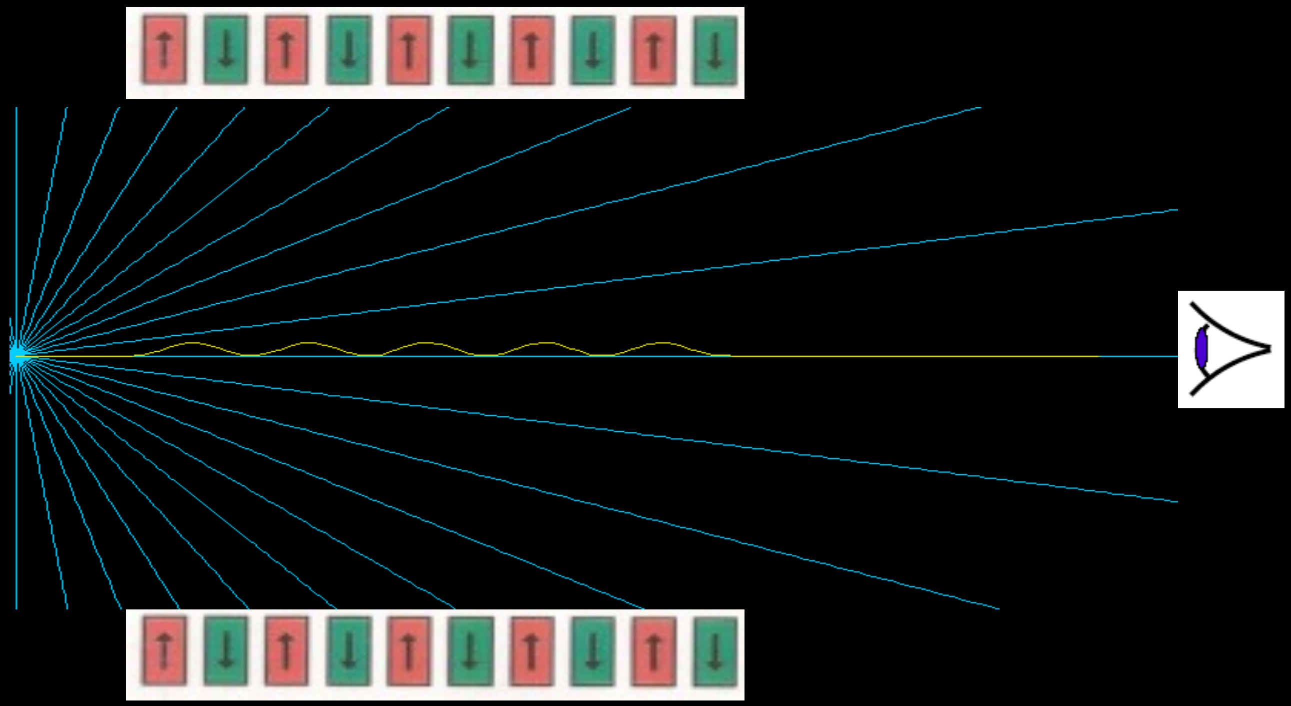


Radiated Power :

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

constructive interference

$\longrightarrow$ **enhanced emission**

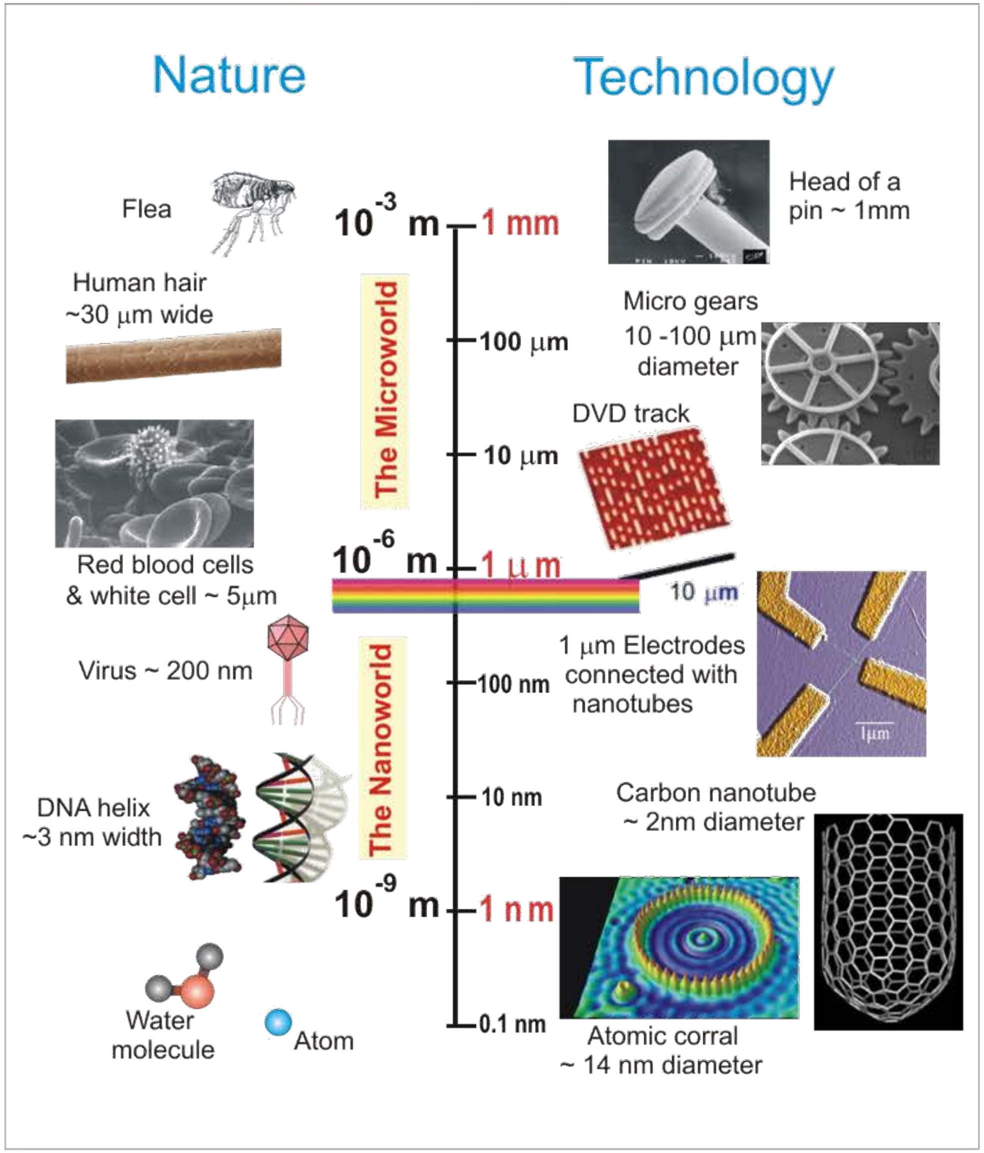


Radiation Simulator – T. Shintake, @ http://www-xfel.spring8.or.jp/Index.htm

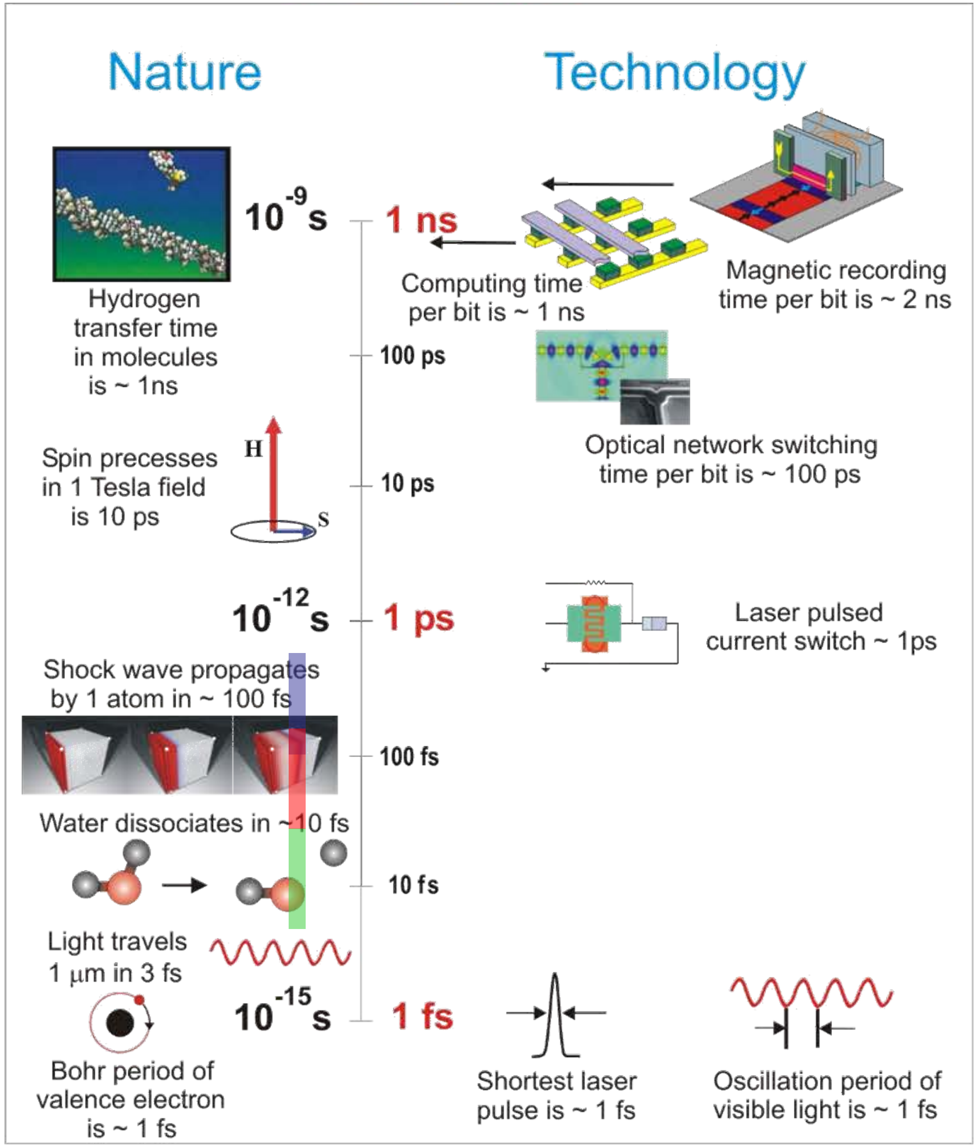
The FEL Applications

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

Ultra-Small



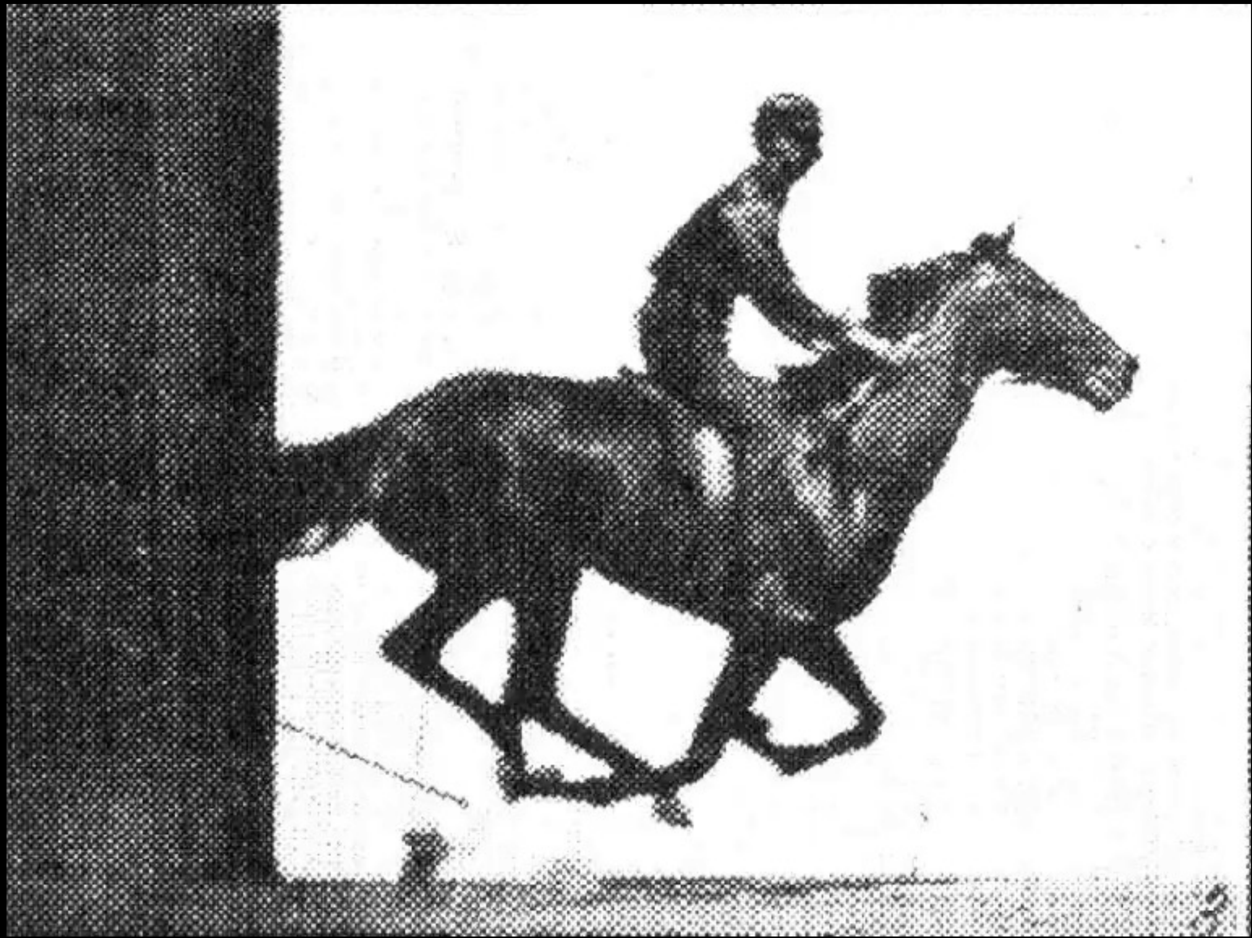
Ultra-Fast



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

disagree whether all feet leave the ground during gallop…

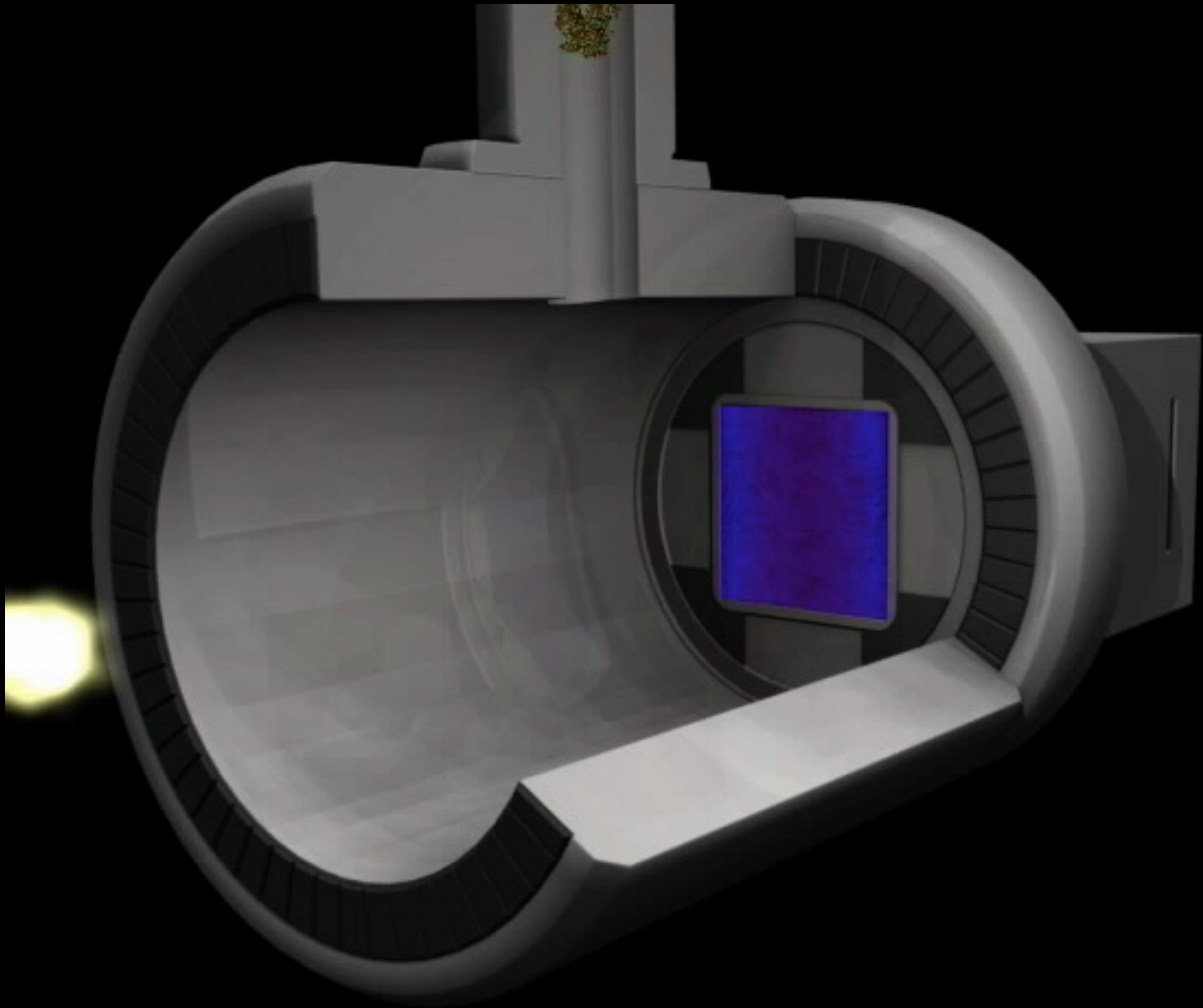
E. Muybridge



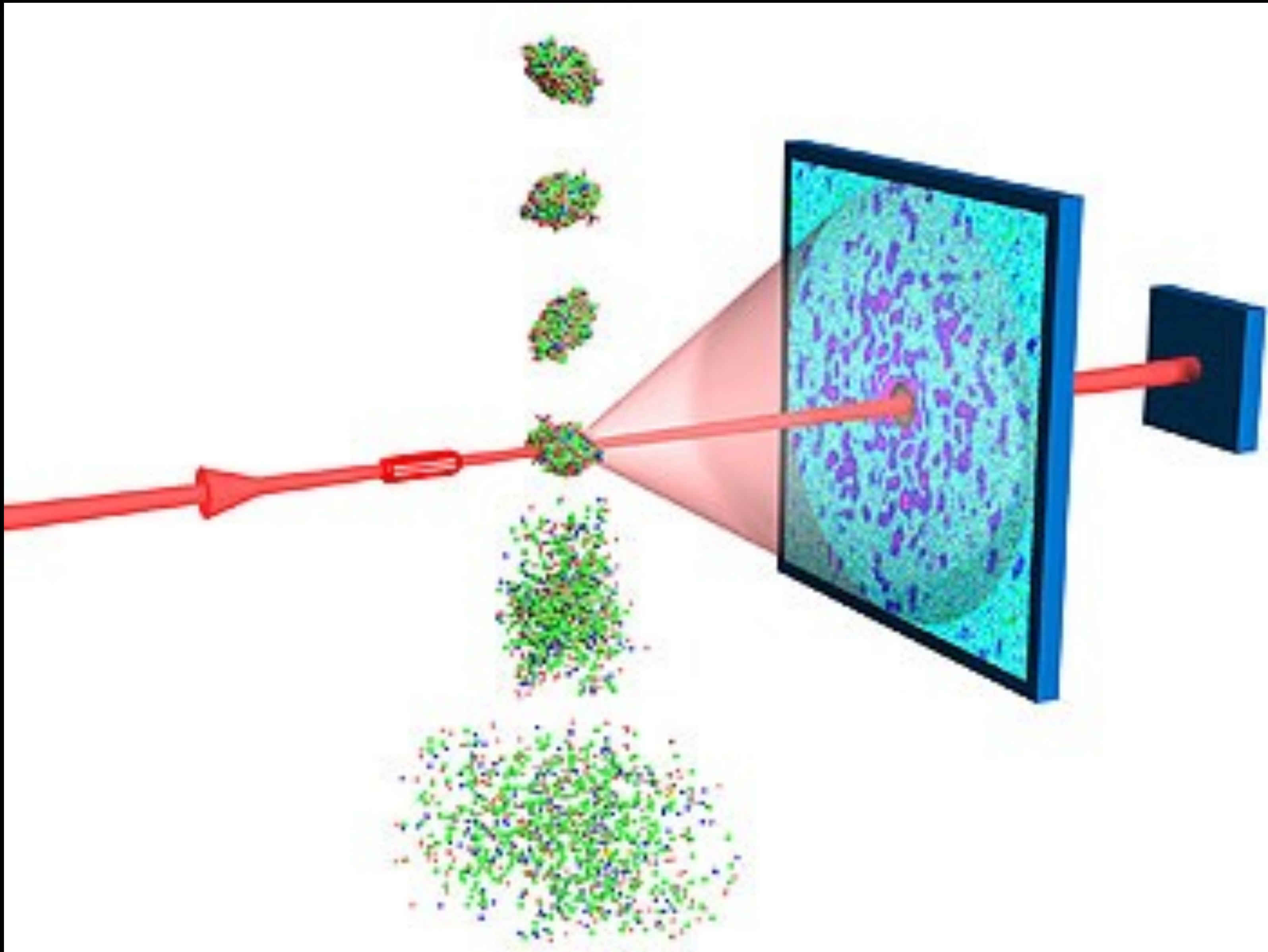
used spark photography to freeze this 'ultra-fast' process

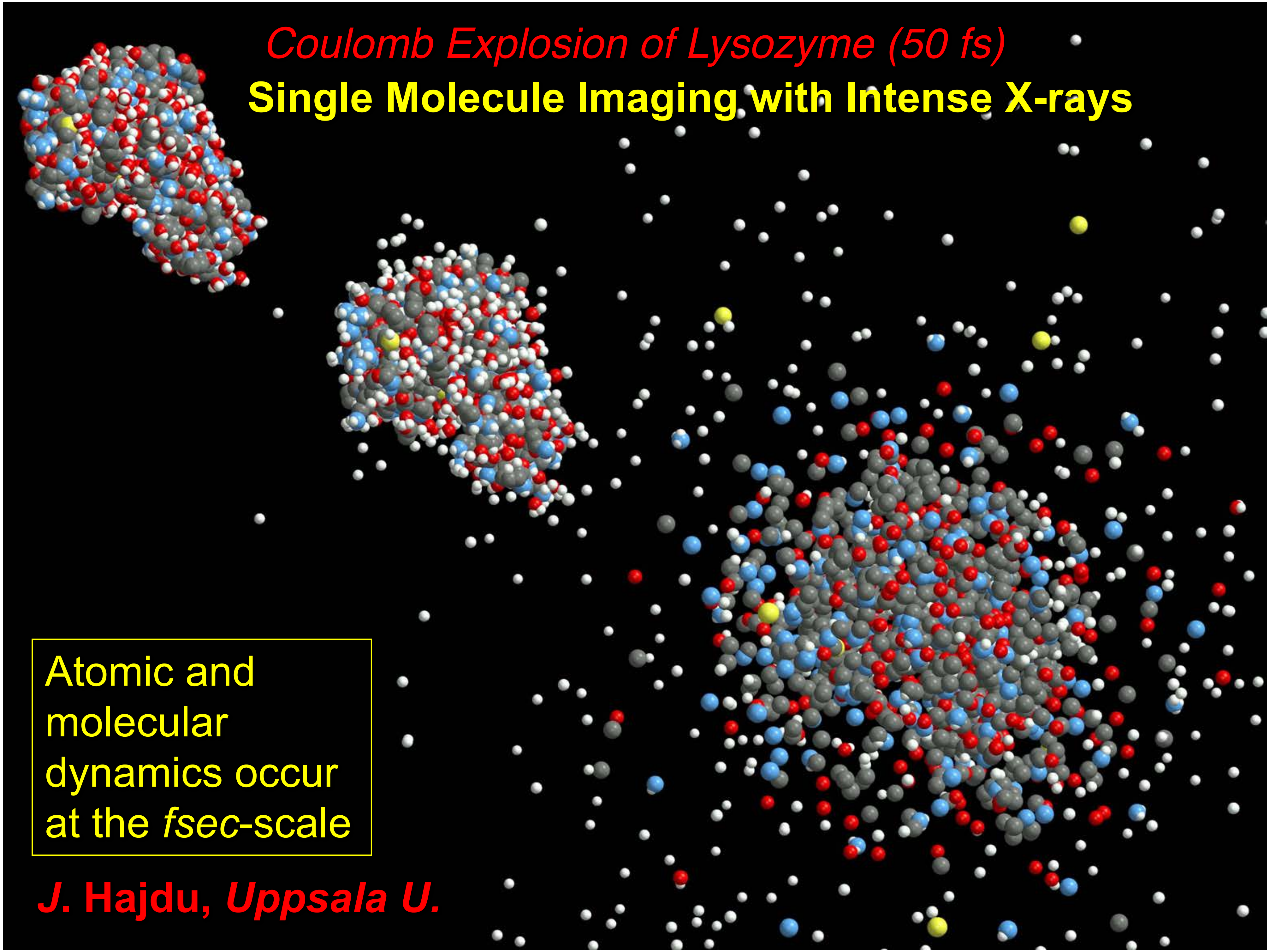
E. Muybridge, *Animals in Motion*, ed. L. S. Brown (Dover Pub. Co., New York 1957)
Courtesy Paul Emma (SLAC).

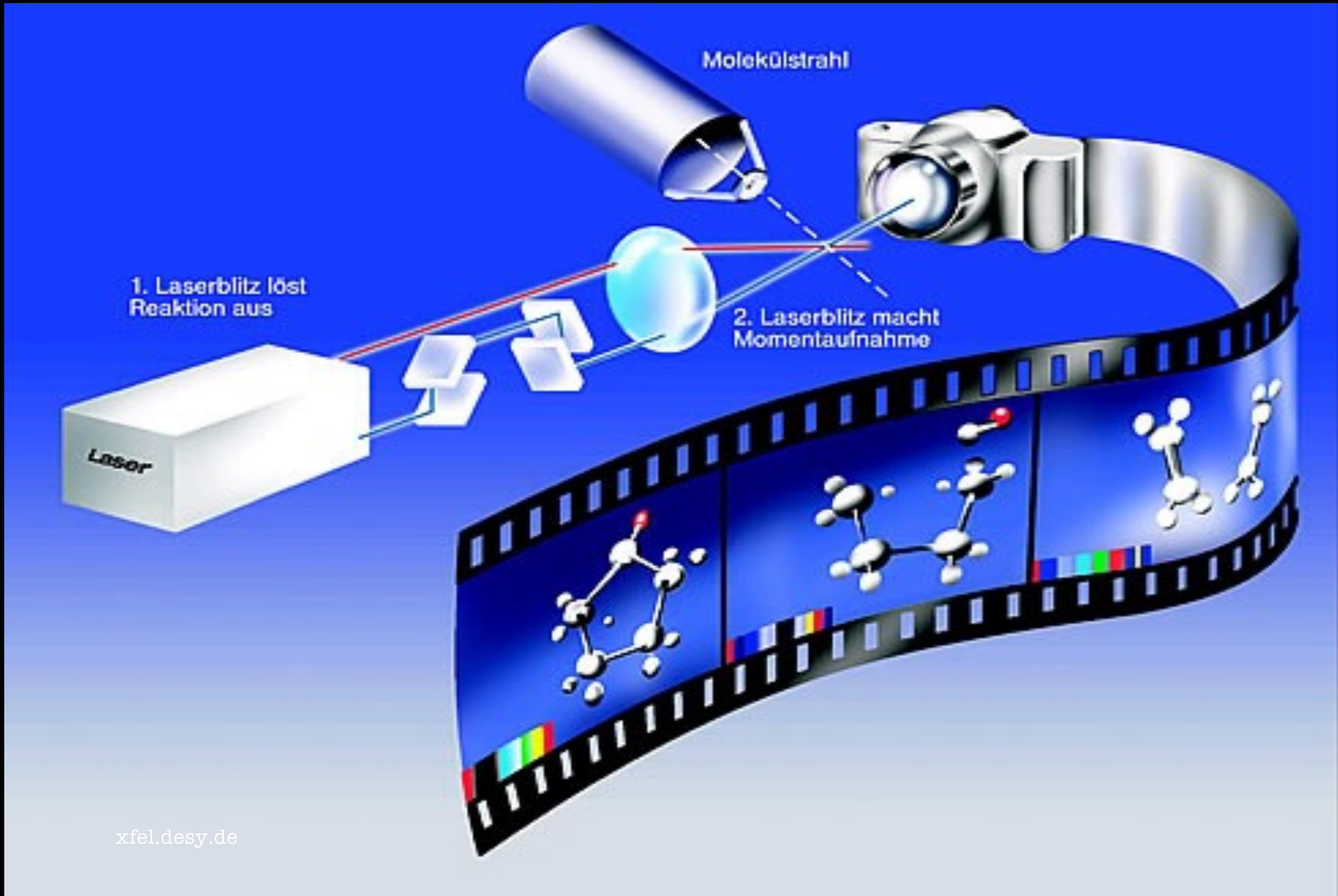
Experimental hall (Single Protein Imaging)



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
xfel.desy.de

https://www.asimmetrie.it/images/stories/archivio-numeri-passati-pdf/asimmetrie-6-HR.pdf


Thank for your attention