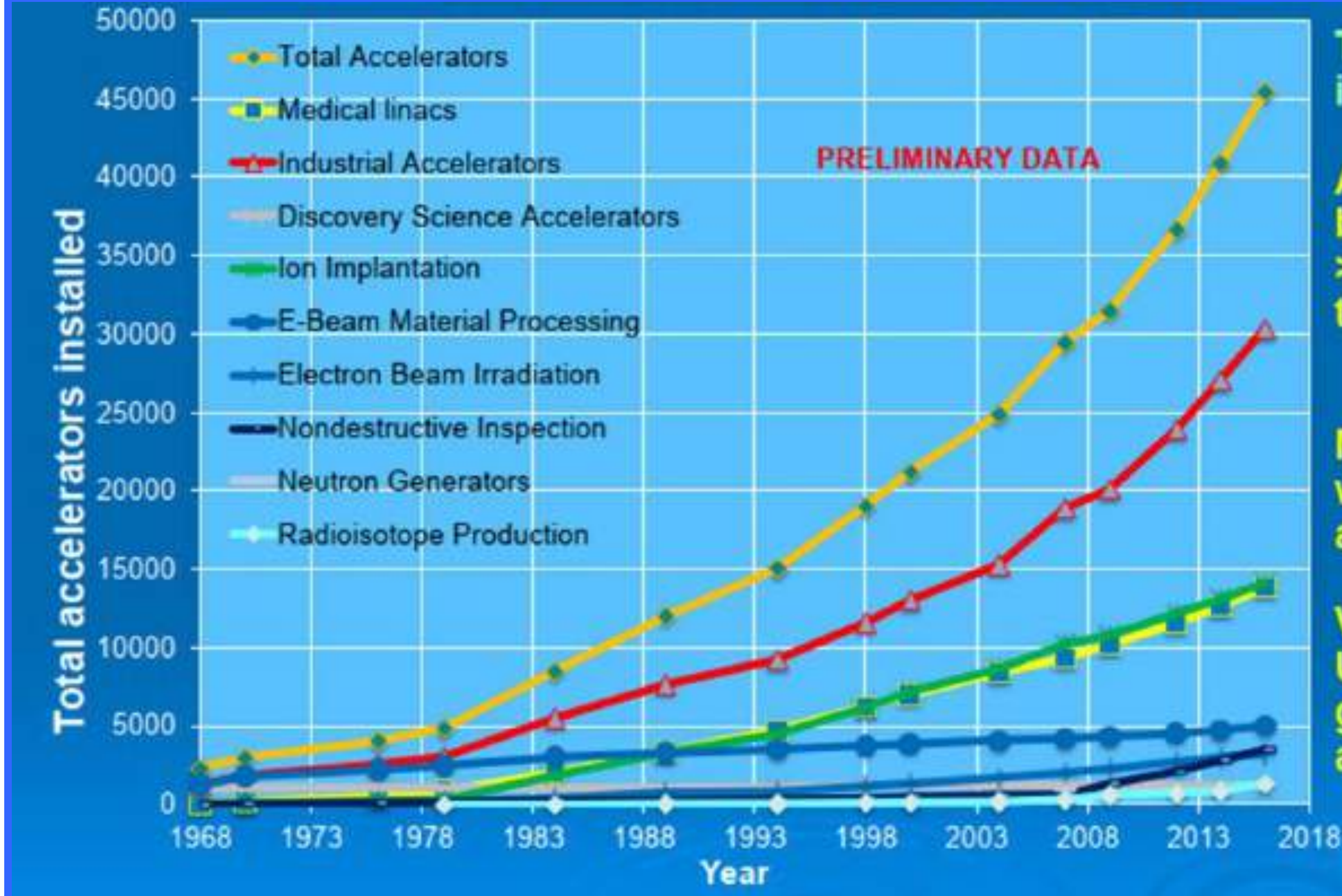
Acceleratori per il Futuro

Massimo.Ferrario@LNF.INFN.IT

Incontri di Fisica– 30 Marzo 2022

Accelerators installed worldwide



Total sales of accelerators is ~US$5B annually

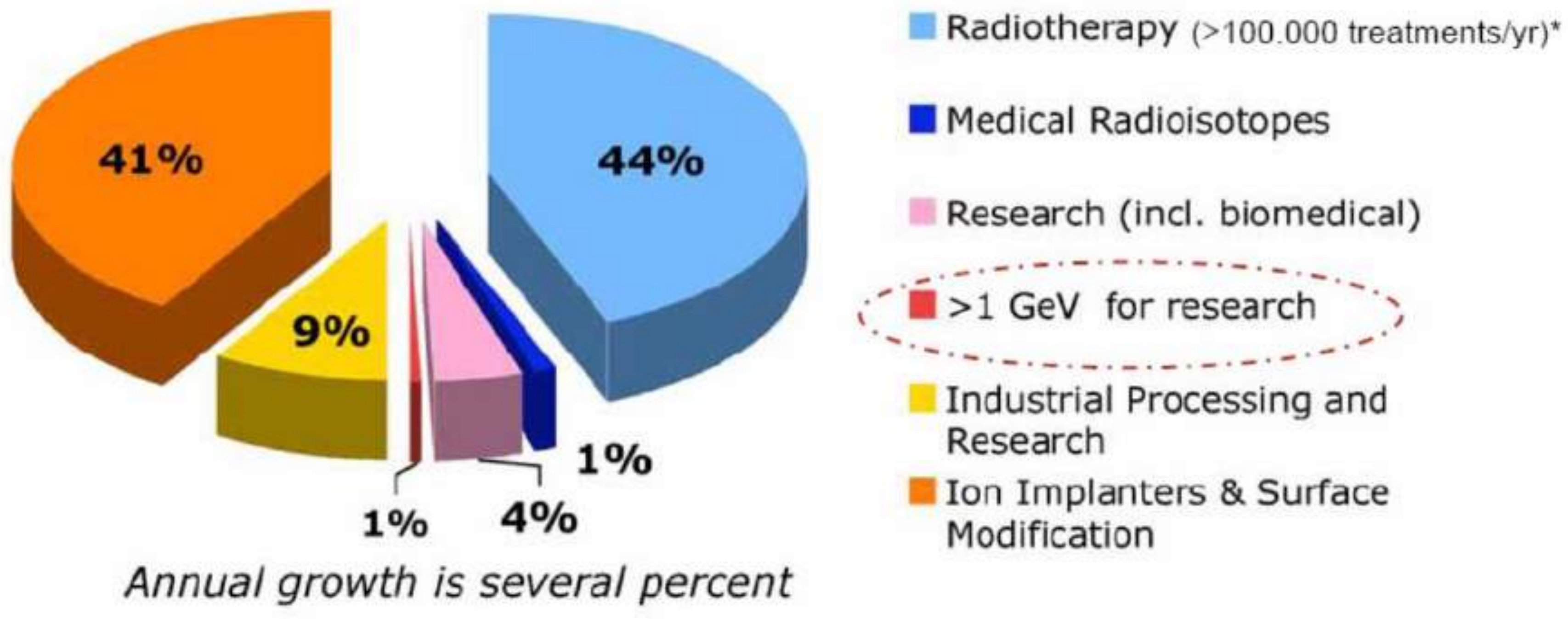
About 47,000 systems have been sold, > 40,000 still in operation today

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

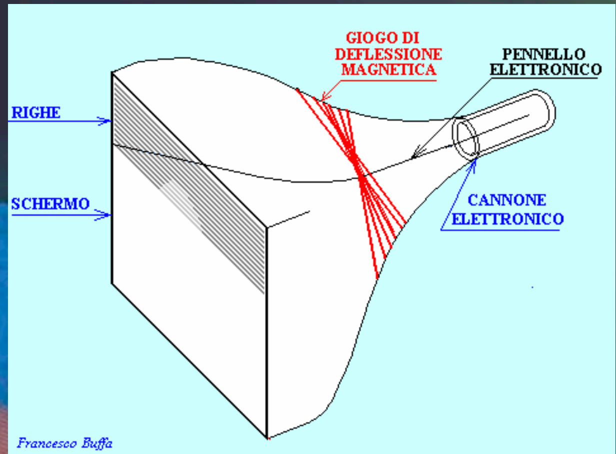
Accelerators installed worldwide

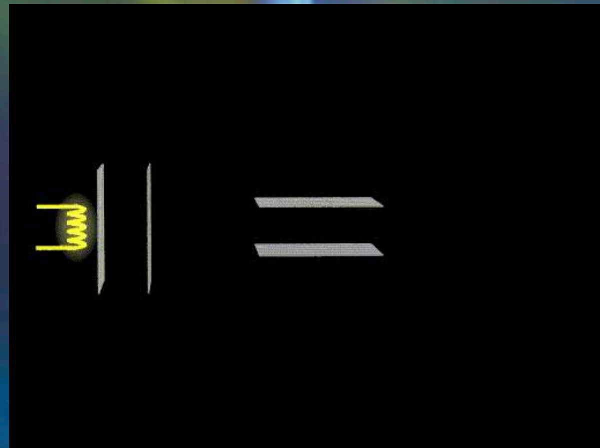


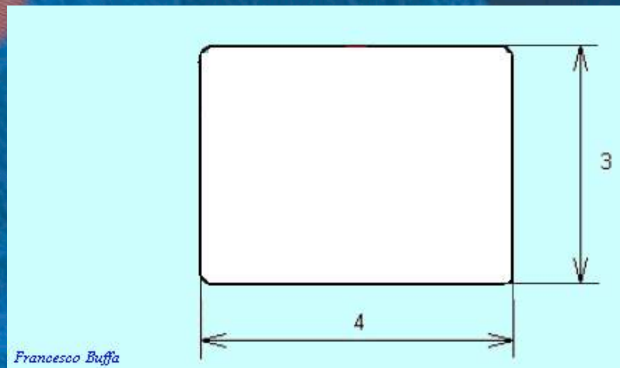
-Accelerators for Americas Future Report, pp. 4, DoE, USA, 2011

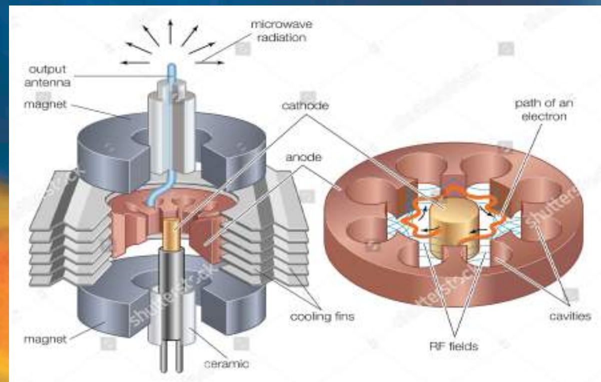
Acceleratori Domestici

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.)

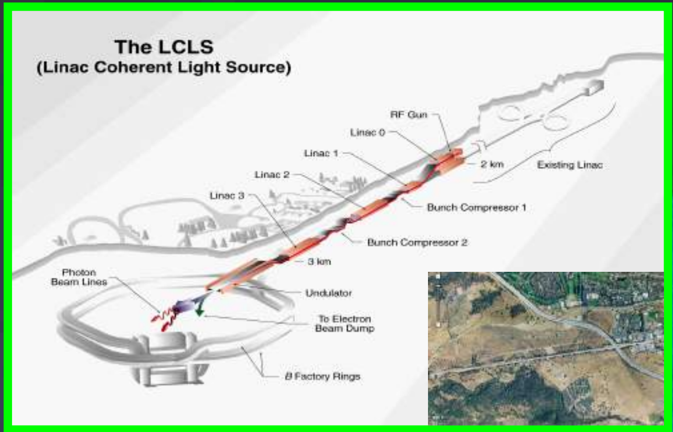


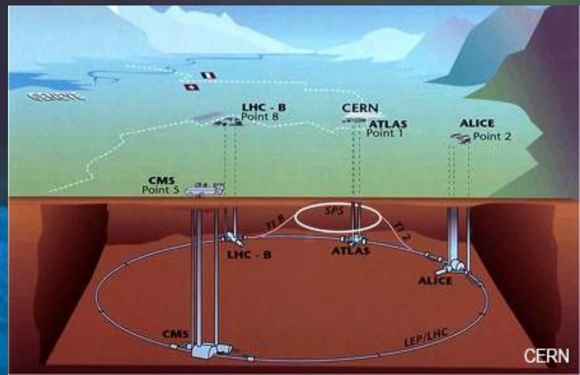


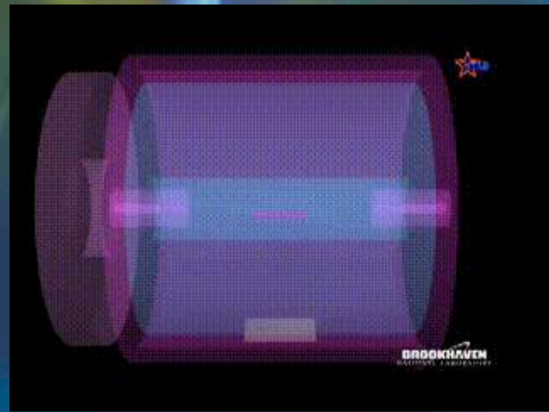


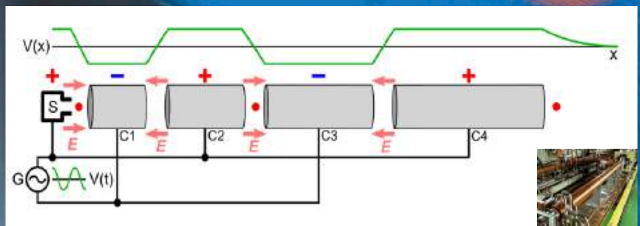


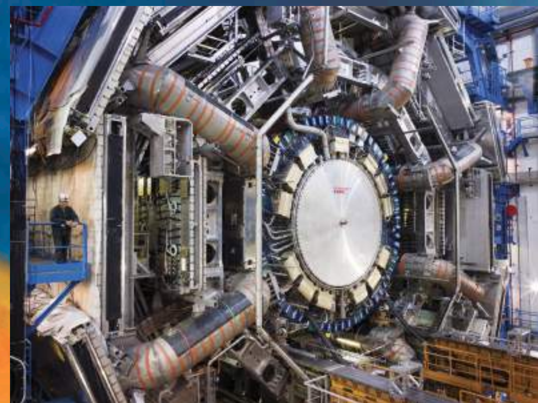
Acceleratori ad Alta Energia



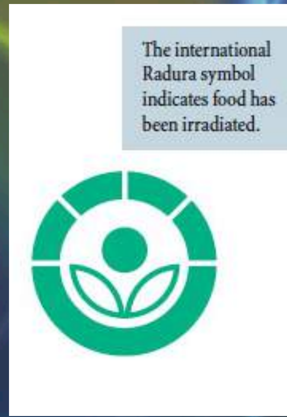


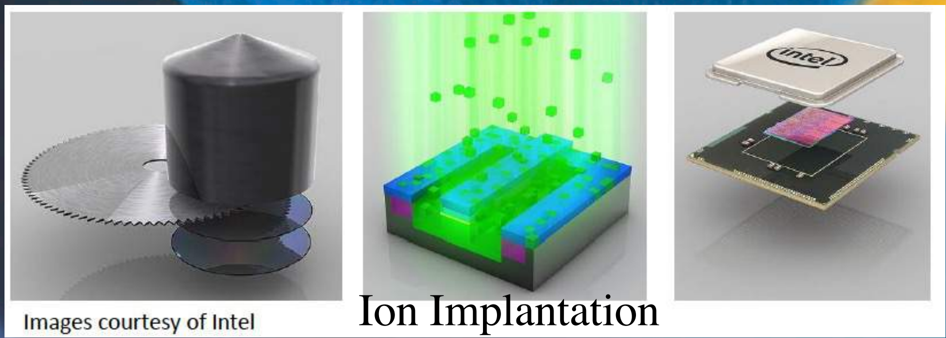


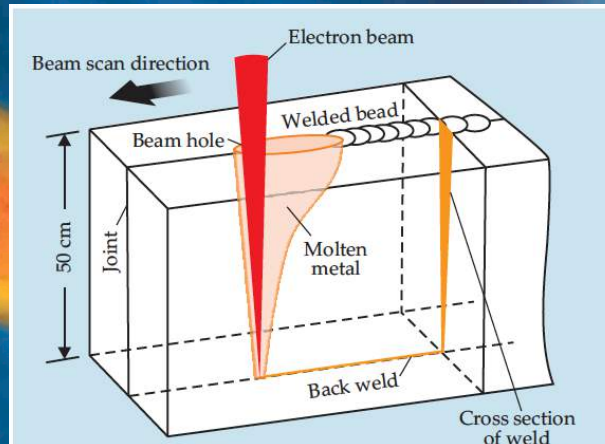




Acceleratori per l'Industria



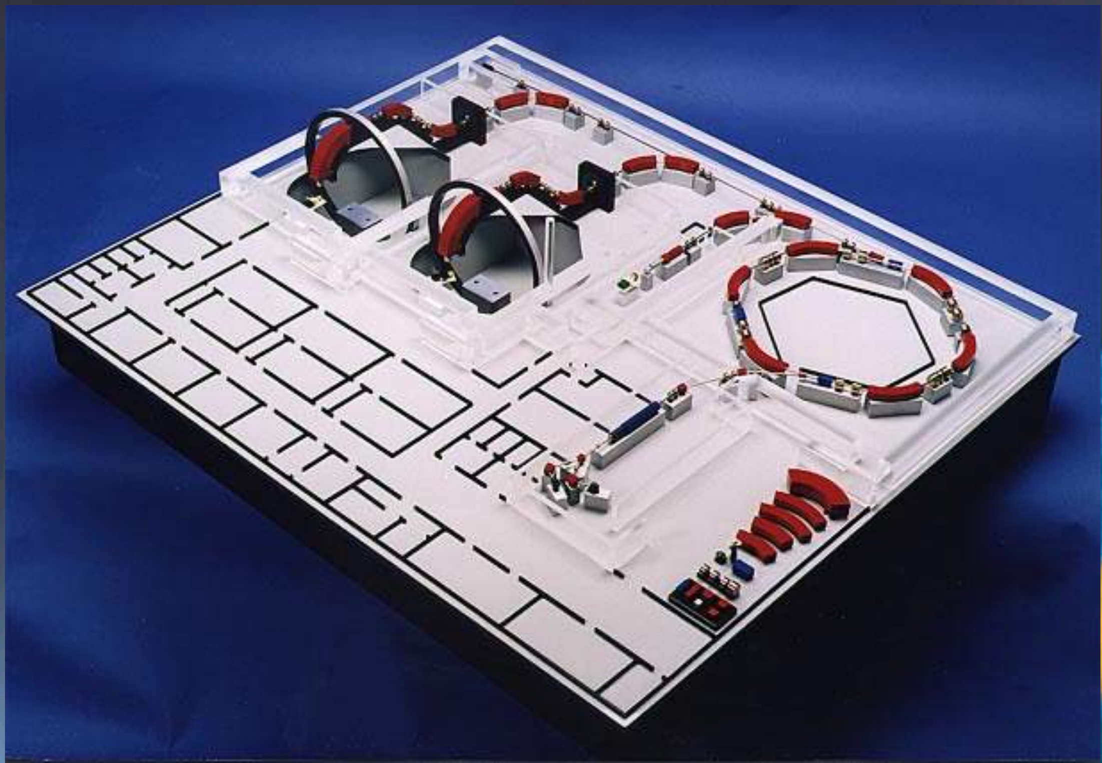


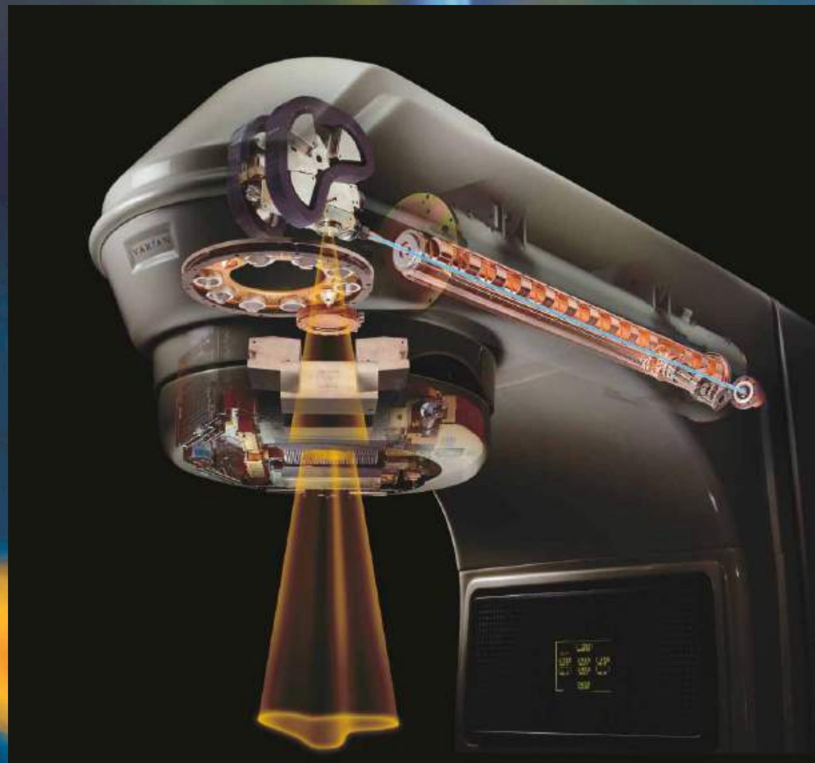


The beam business: Accelerators in industry
Robert W. Hamm, and Marianne E. Hamm

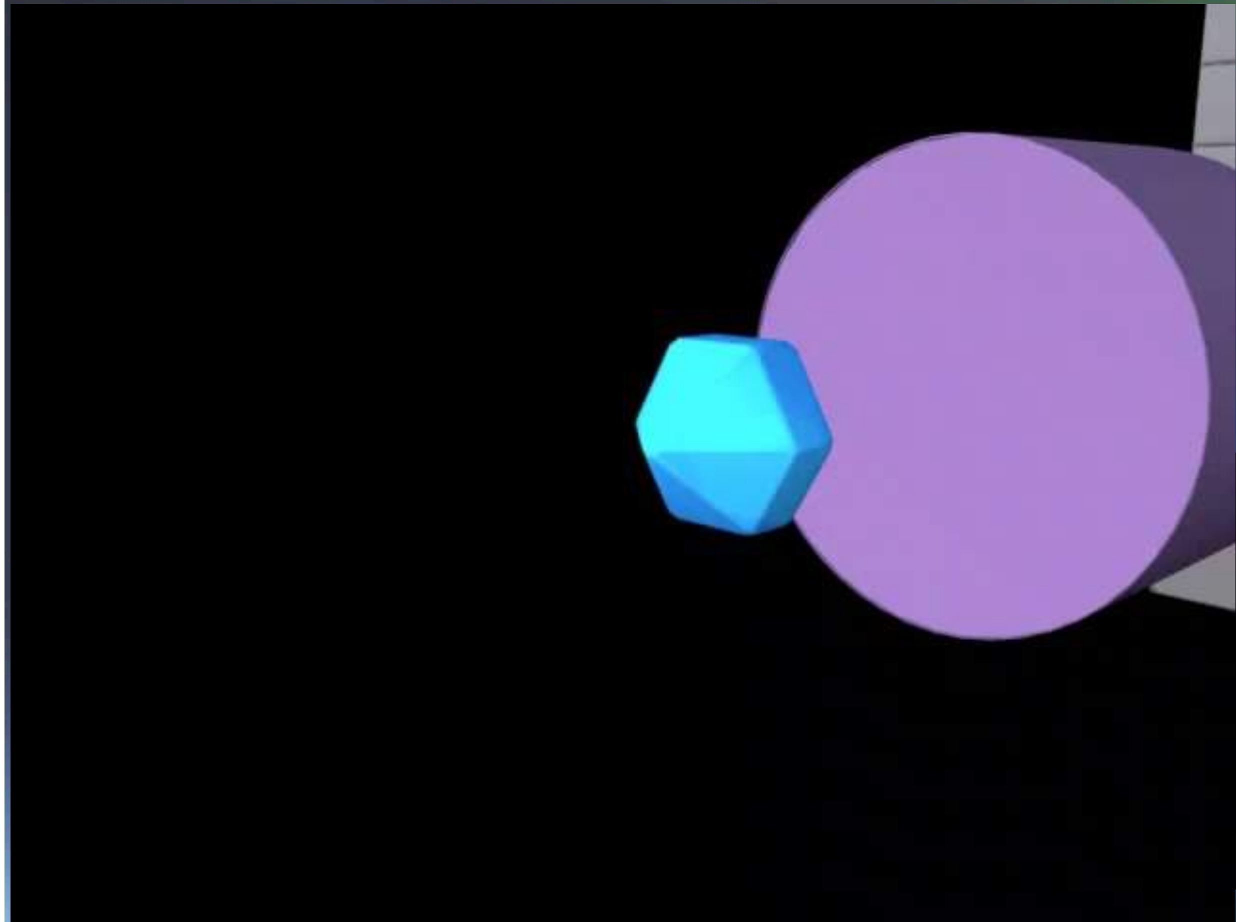
Citation: Physics Today **64**, 6, 46 (2011); doi: 10.1063/1.3603918

Acceleratori per la medicina

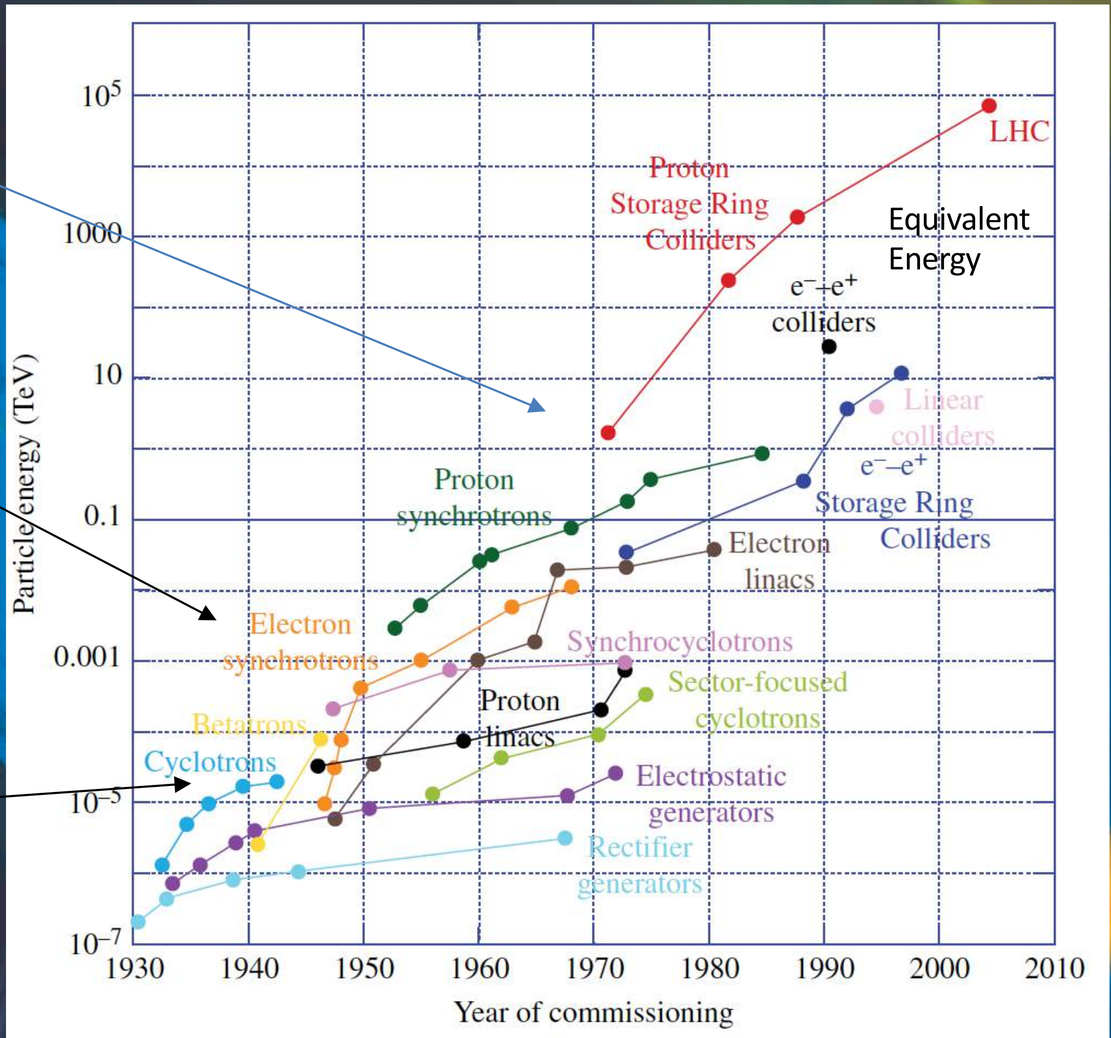




Acceleratori e Luce di Sincrotrone



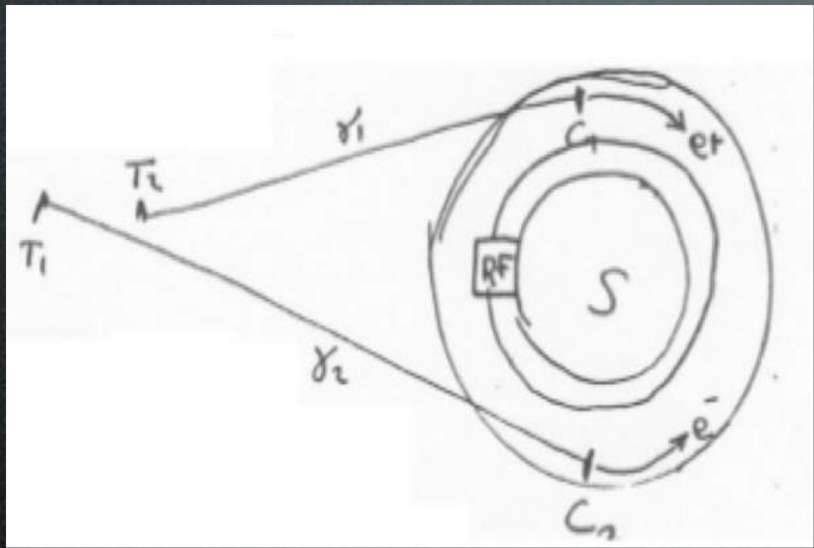
Il diagramma di Livingstone



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.

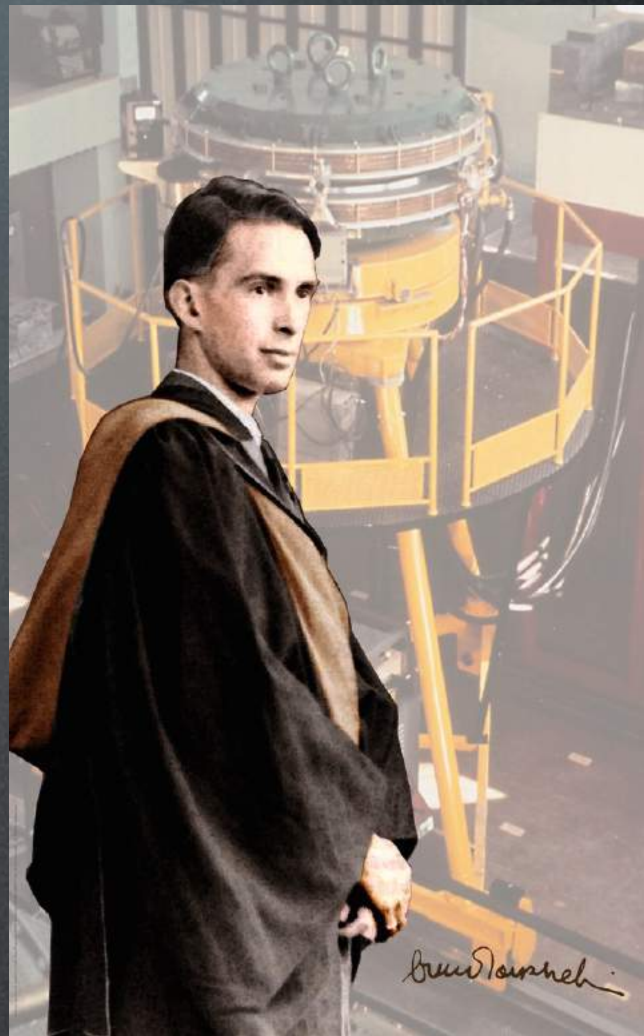
Touschek's Anello Di Accumulazione (ADA)

1961 the first e+e- Collider



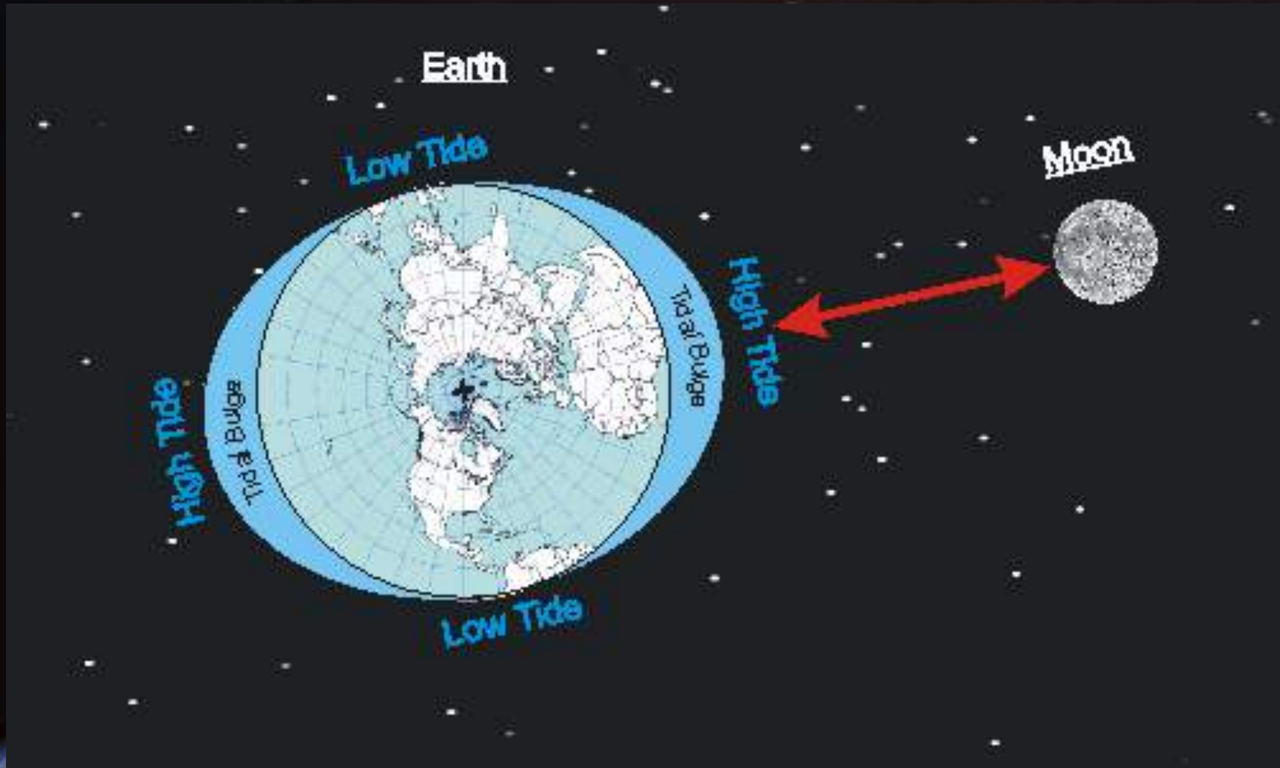
$$E_{CM} \approx \sqrt{2E_1 m_2}$$

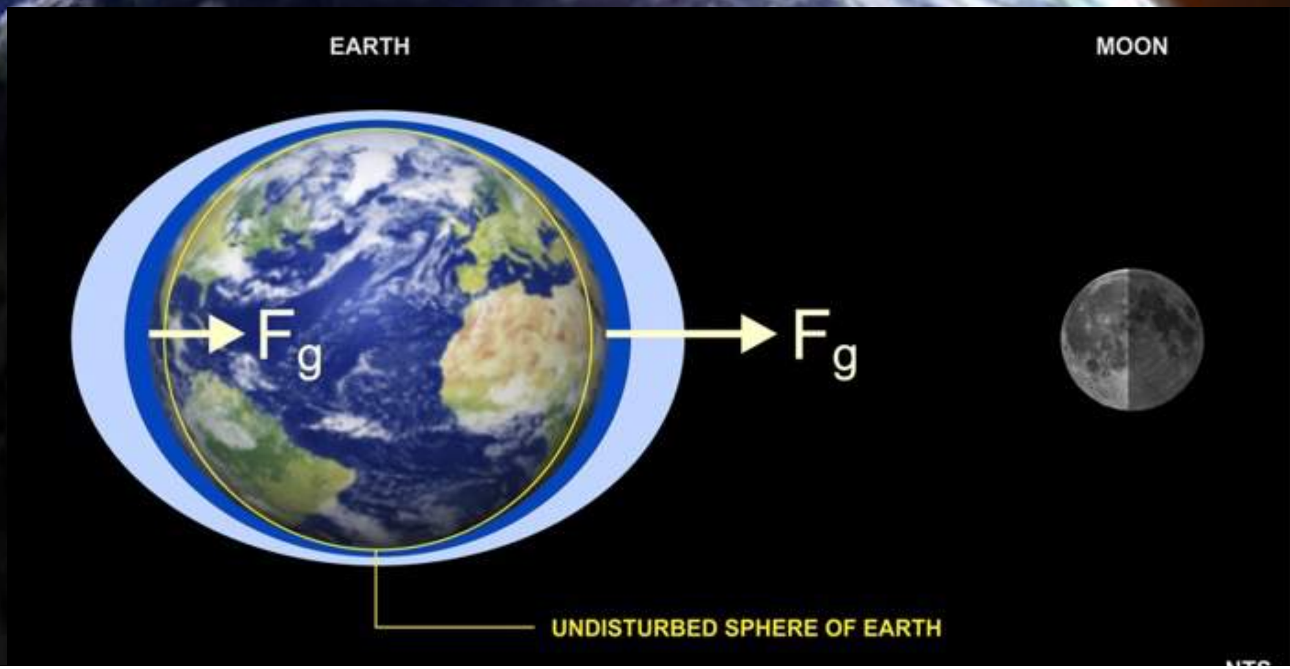
$$E_{CM} \approx 2E$$



I COLLIDERS materia-antimateria: una storia che parte e si sviluppa a Frascati

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
Moon
Low Tide
High Tide
Tidal Bulge
Tidal Bulge
High Tide
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

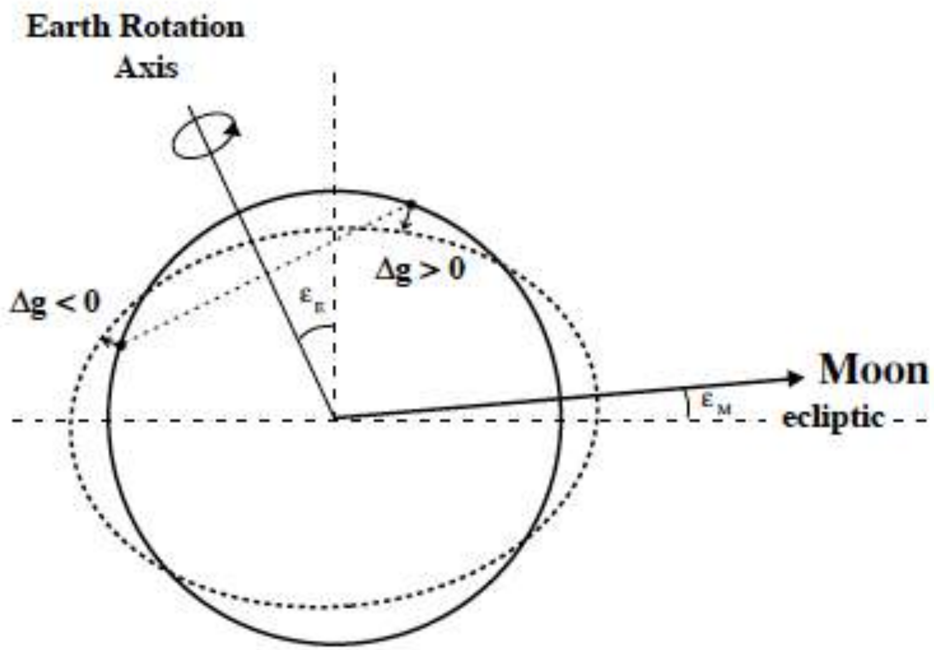


Figure 2: Tidal deformation of the Earth crust due to the presence of the moon. One tide bulge is formed in the direction of the moon and another one just opposite of it. The changes in gravity associated to the tidal deformations Δg are indicated for an observer at a latitude of about 45°. The sun tides 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

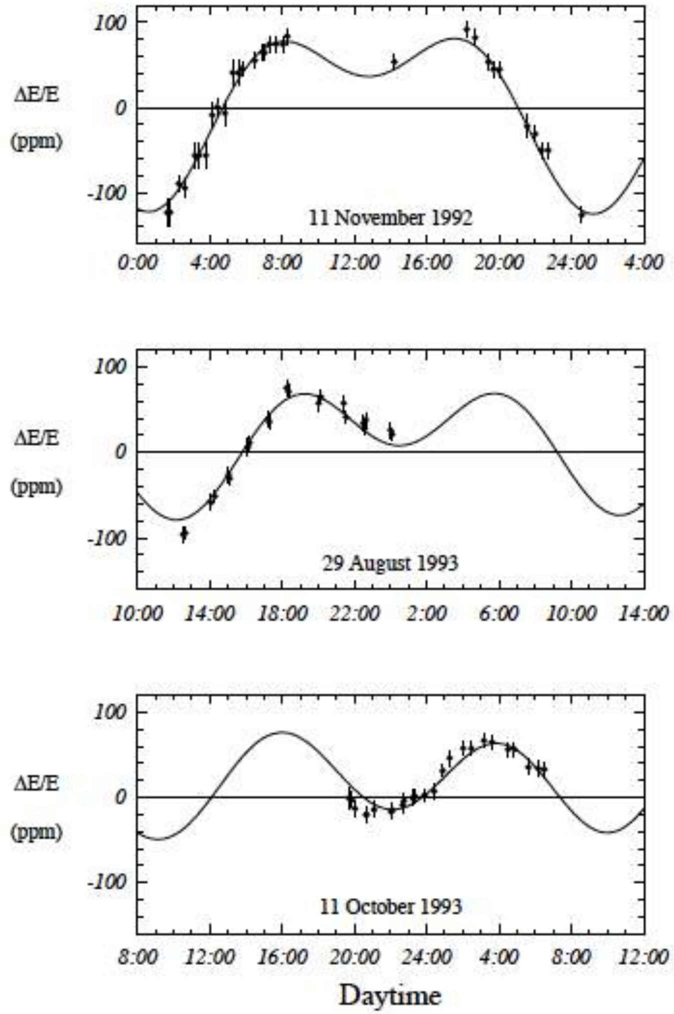
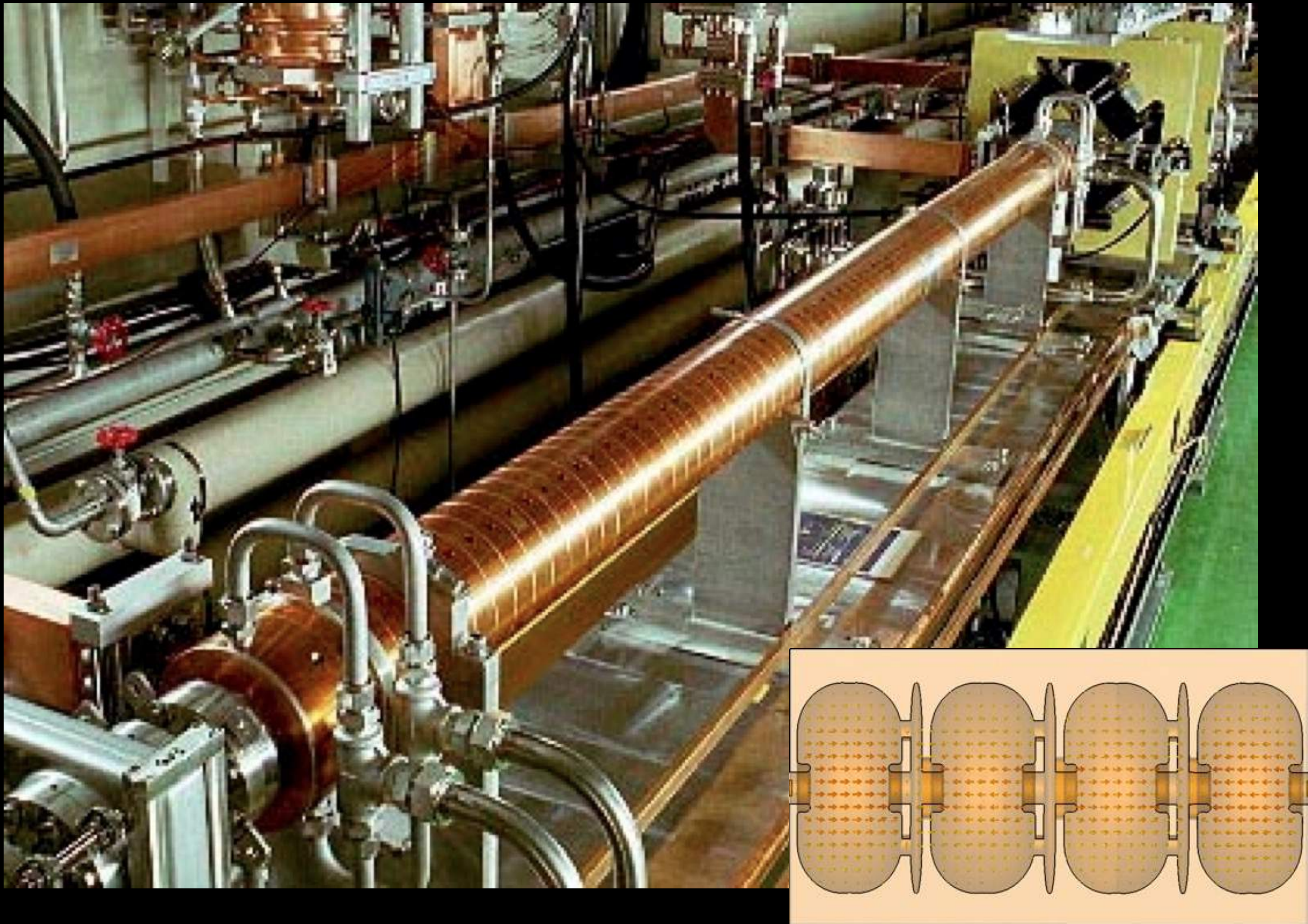
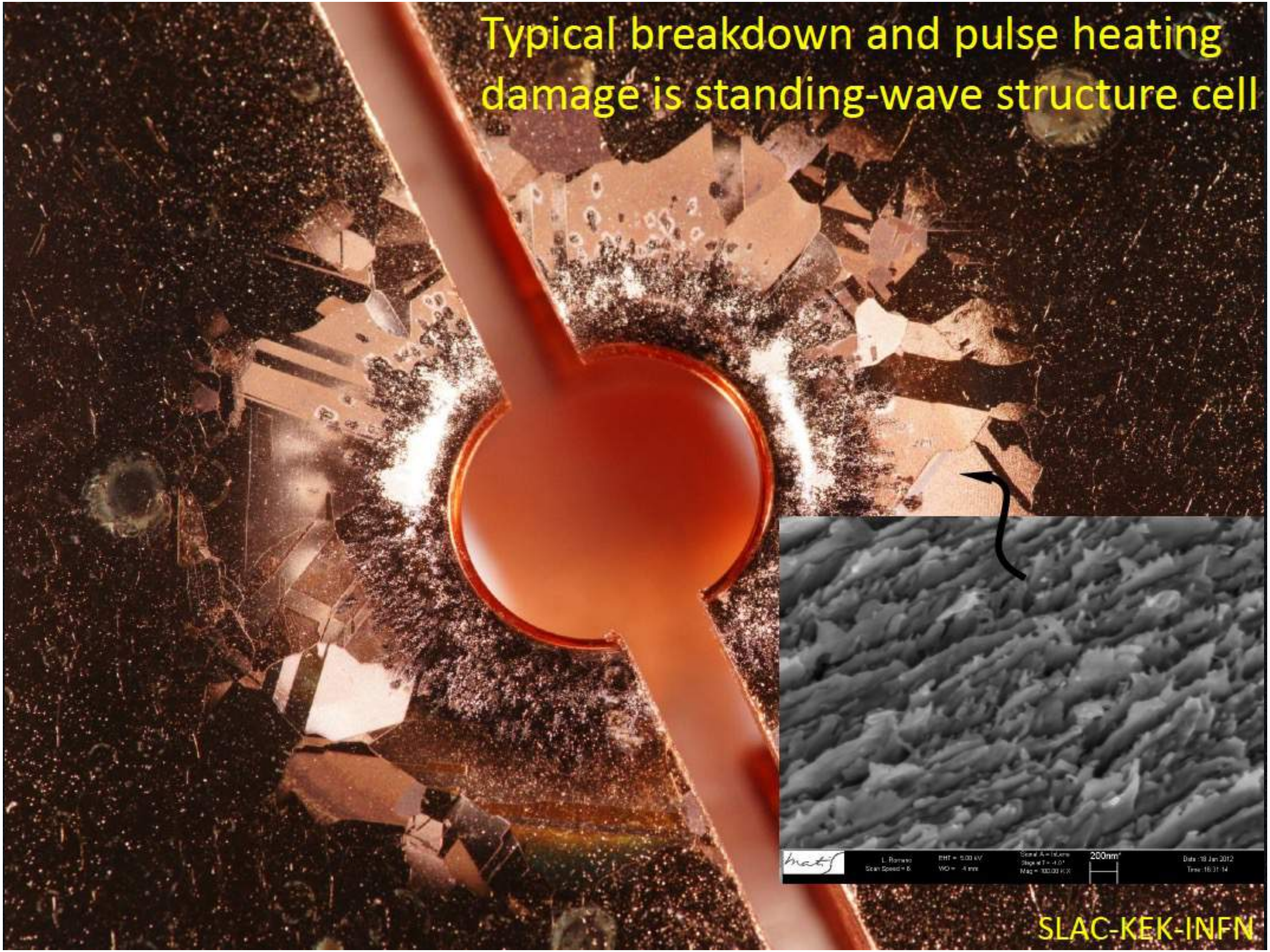


Figure 3: The evolution of the relative beam energy variation due to tides is shown as a function of time for three periods with stable beam conditions. The solid line is calculated using the CTE tide model with the average coefficient from equation 4. The top picture corresponds to full-moon, the bottom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

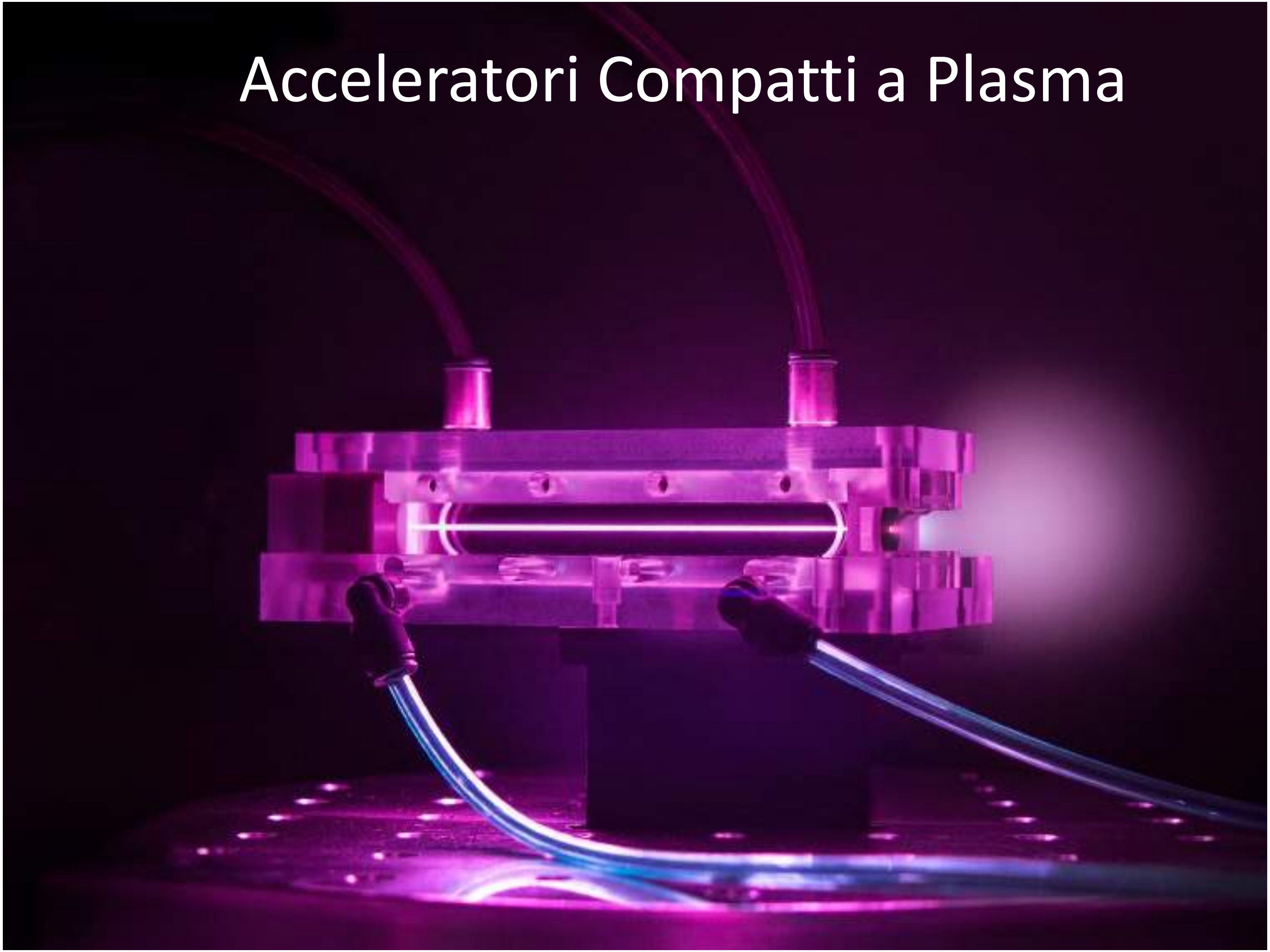
← Full Moon

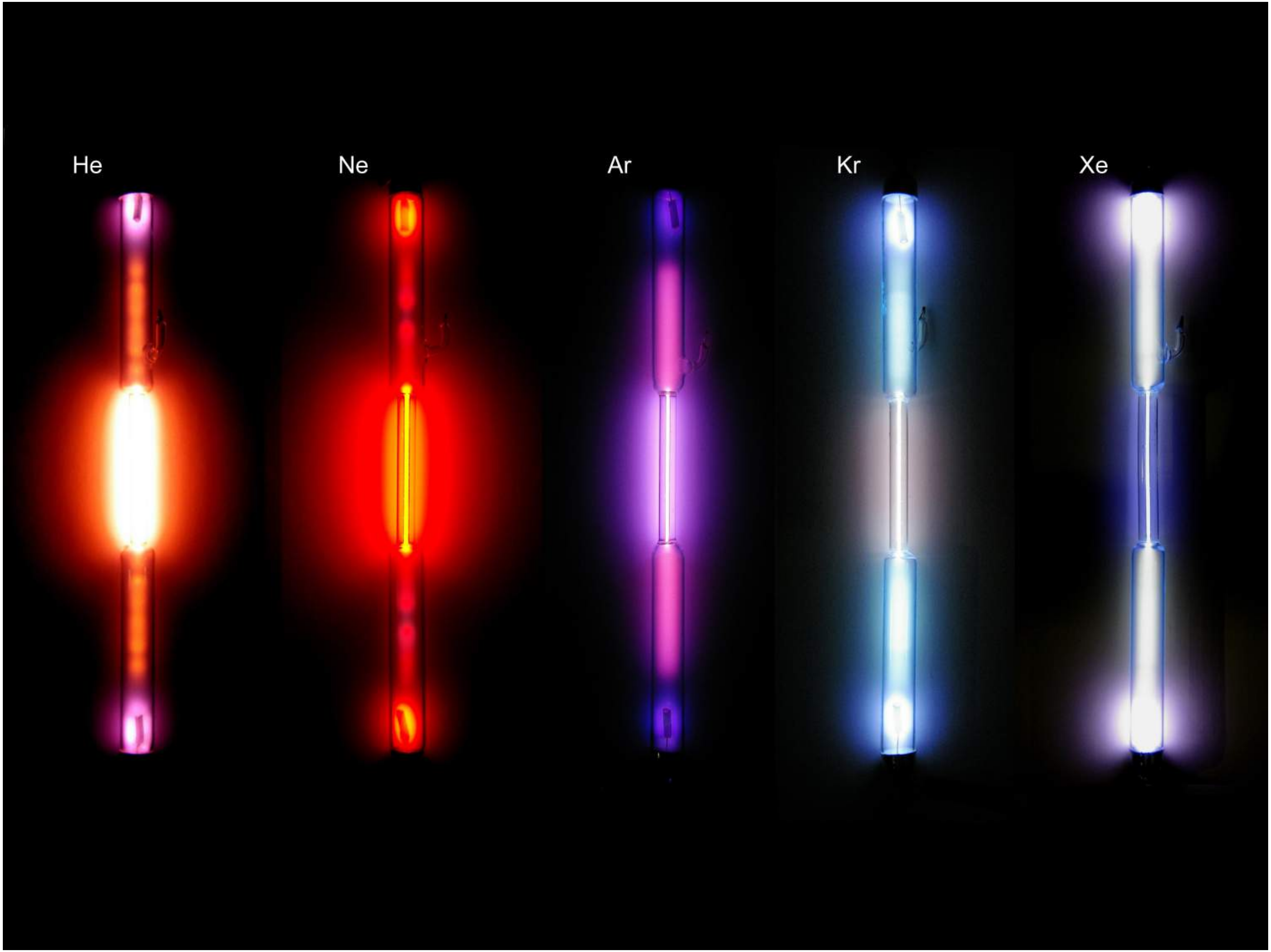
Conventional RF accelerating structures

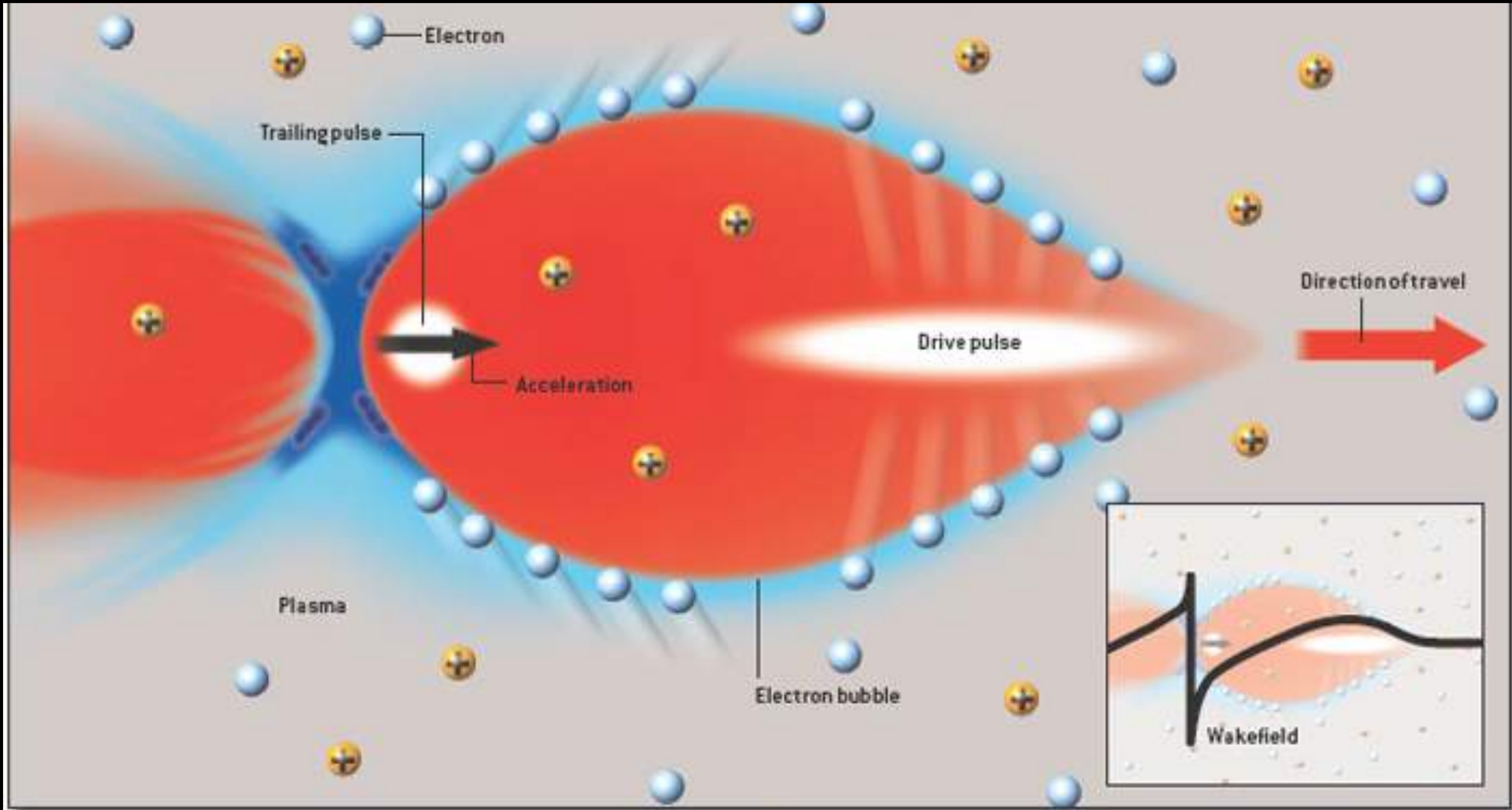



Typical breakdown and pulse heating damage is standing-wave structure cell
200nm
SLAC-KEK-INFN

Acceleratori Compatti a Plasma




He
Ne
Ar
Kr
Xe



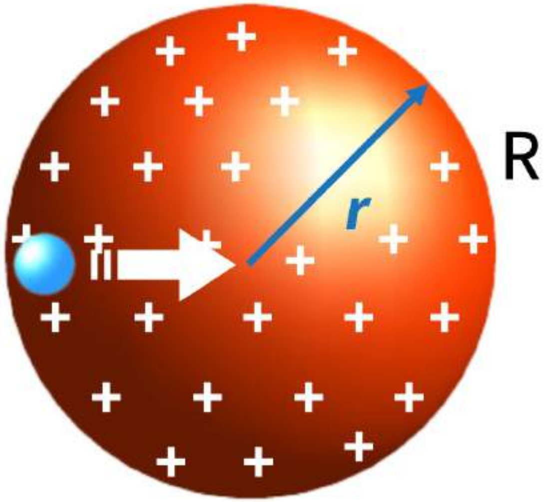
Breakdown limit?

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

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

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



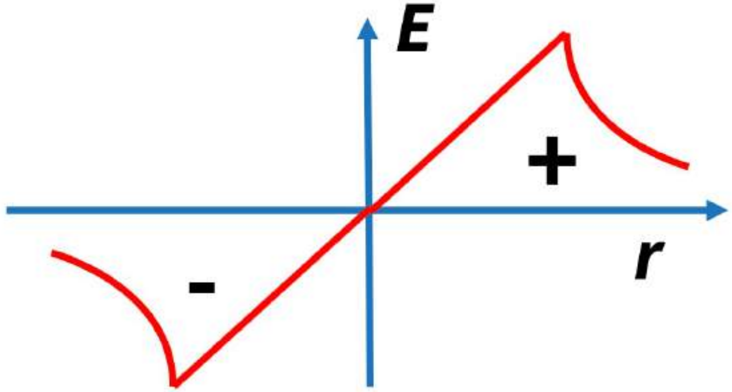
The field is **increasing** inside the sphere

Let's put some numbers

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

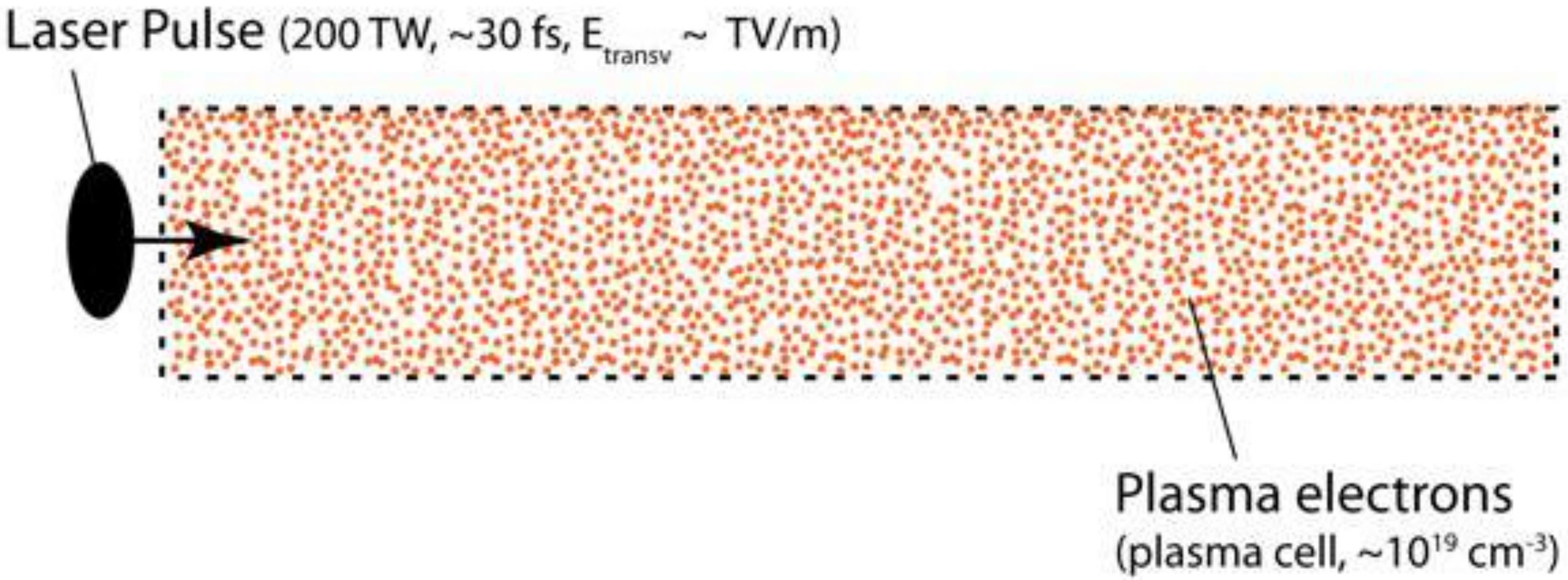
$R = 0.5$

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



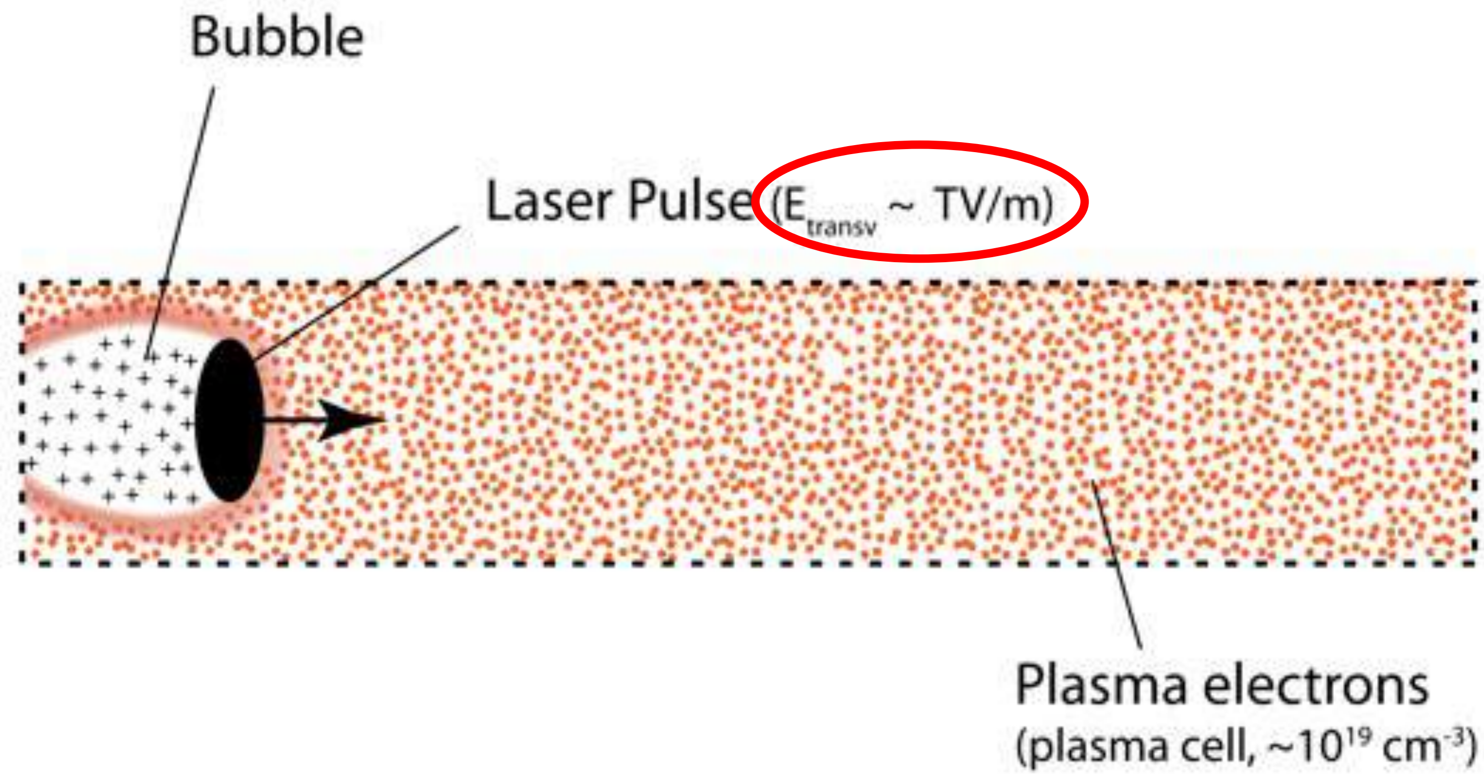
Laser Plasma-Acceleration
(Internal Injection)

Horizon2020

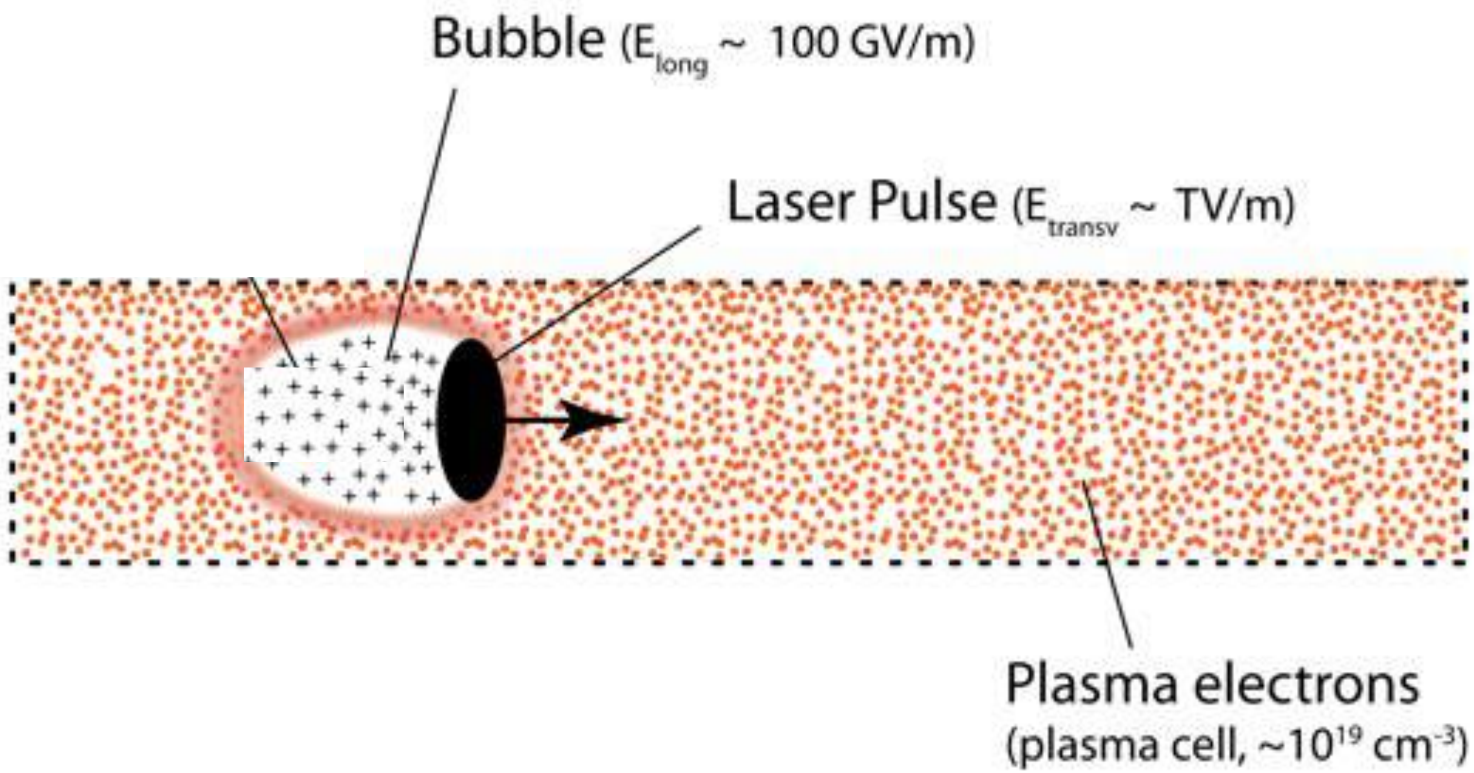


Laser Plasma-Acceleration
(Internal Injection)

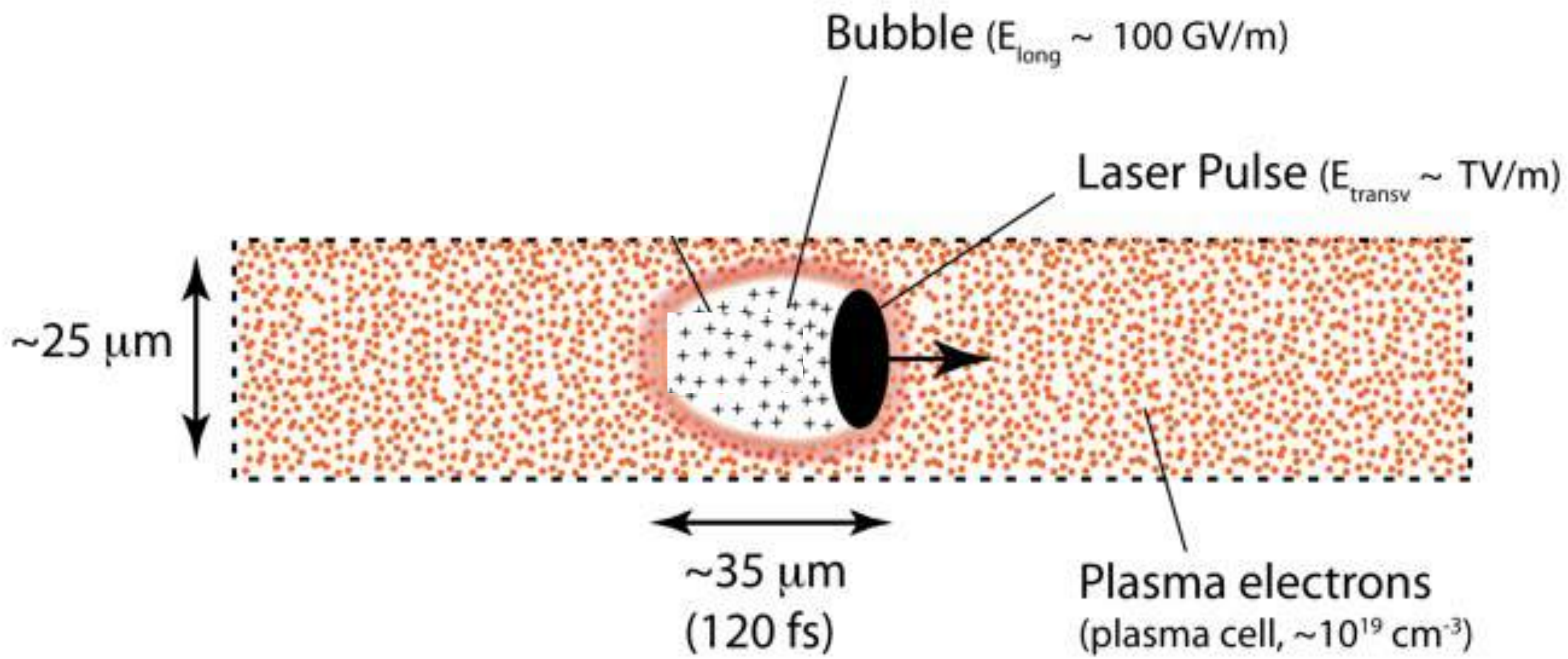
Horizon2020



Laser Plasma-Acceleration
(Internal Injection)

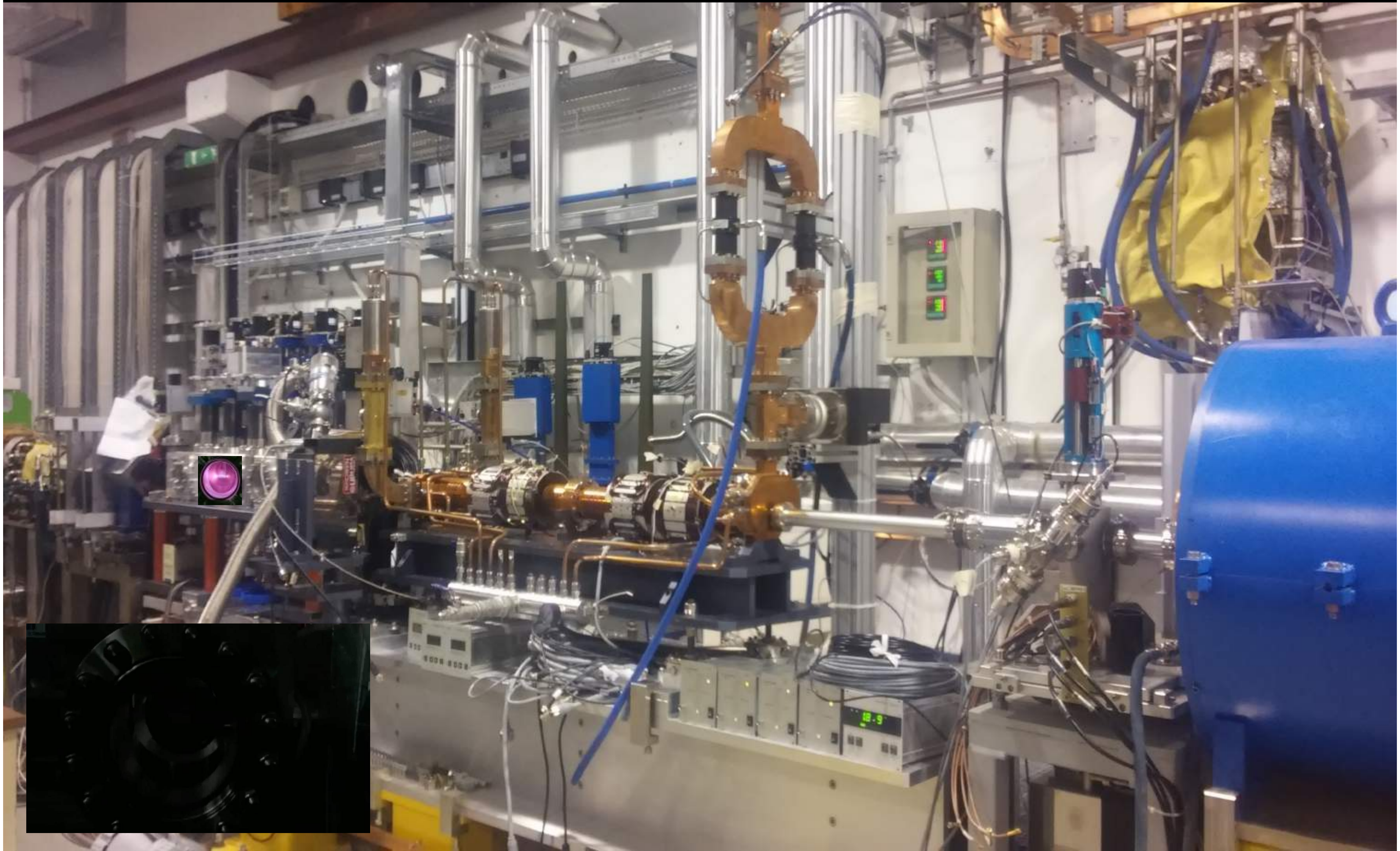


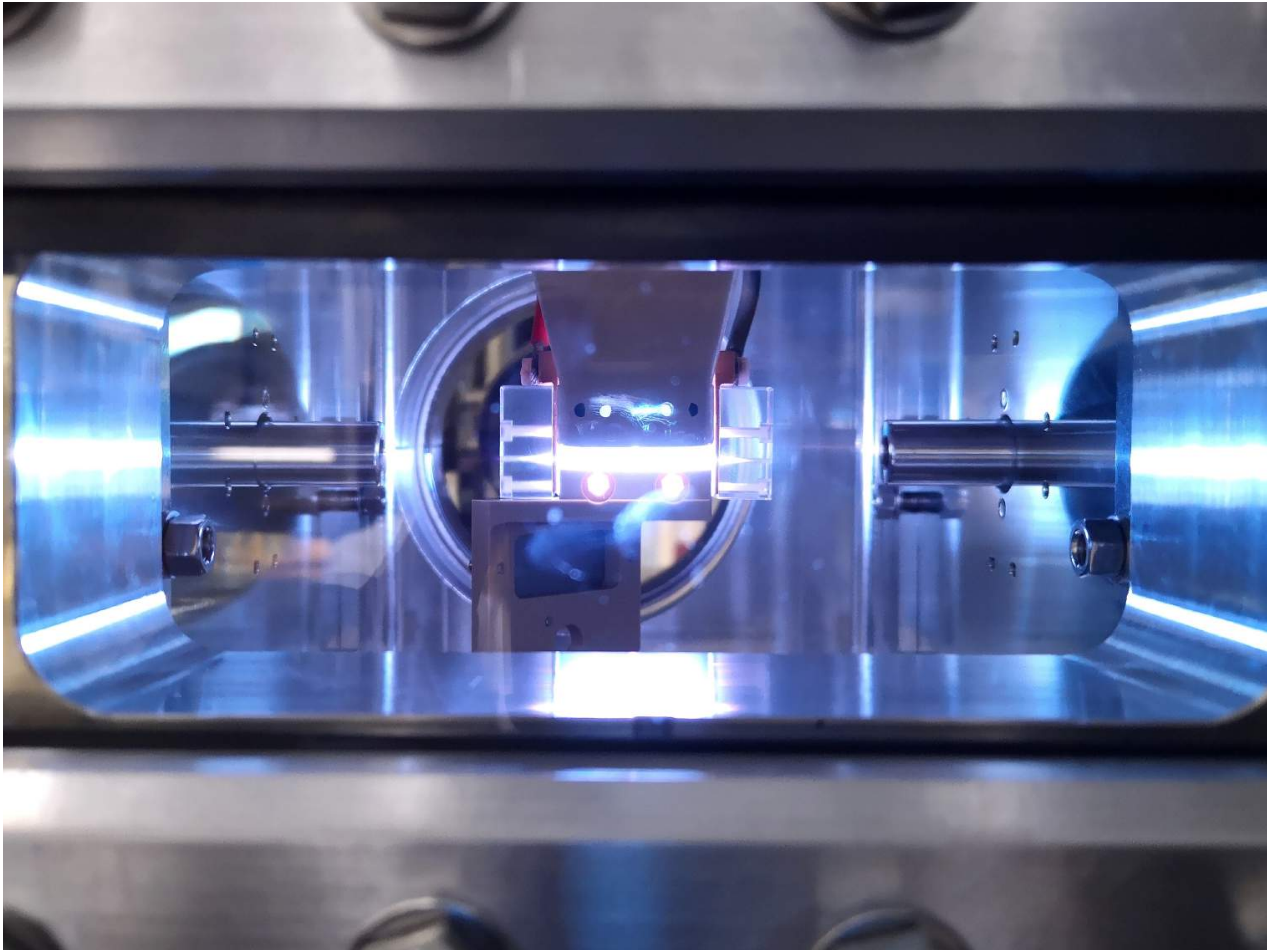
Laser Plasma-Acceleration
(Internal Injection)



This accelerator fits into a human hair!

Accelerazione a Plasma a Frascati



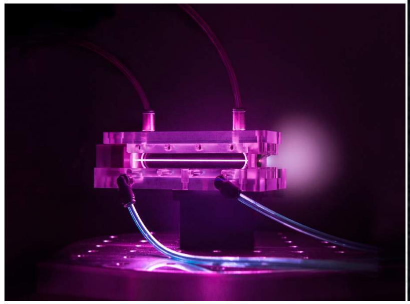


BELLA: BErkeley Lab Laser Accelerator

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

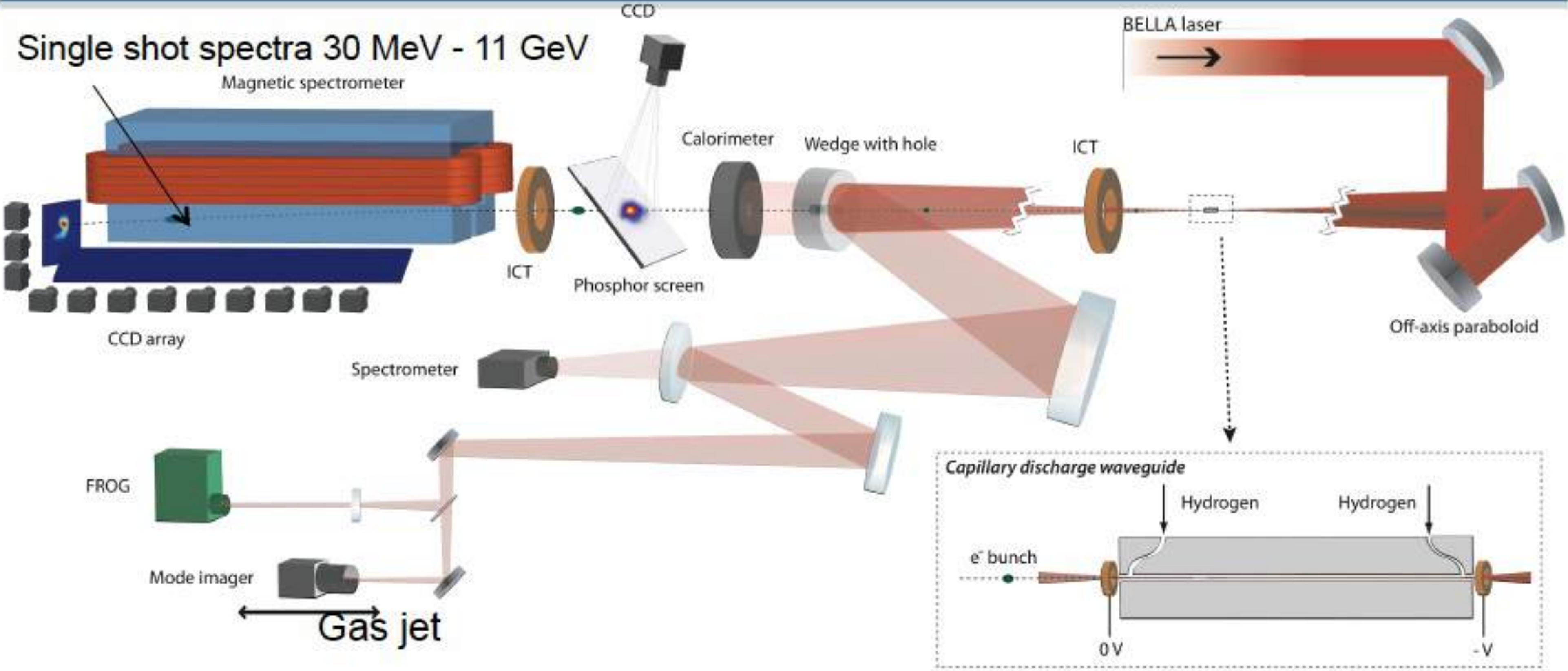
Critical HEP experiments:

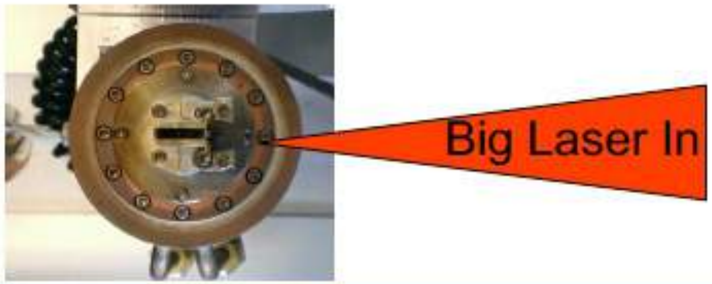
- 10 GeV electron beam from <1 m LPA
- Staging LPAs
- Positron acceleration



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

EUROPEAN PLASMA RESEARCH ACCELERATOR WITH EXCELLENCE IN APPLICATIONS

EuPRAXIA Design Study

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

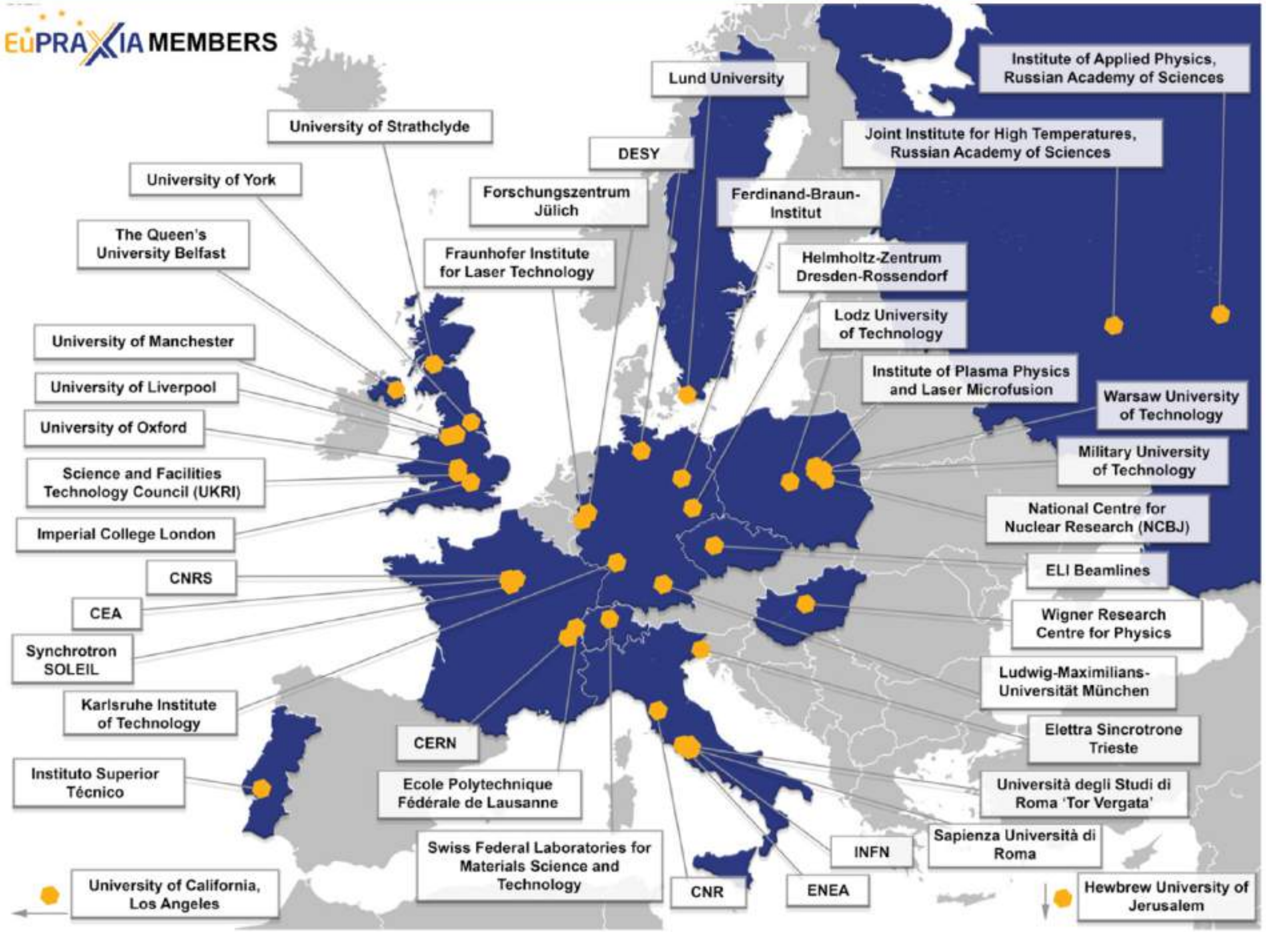
Coordinator: Ralph Assmann (DESY)

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

The Consortium Members for the Next Phase

(from 16 to 40)

Horizon 2020

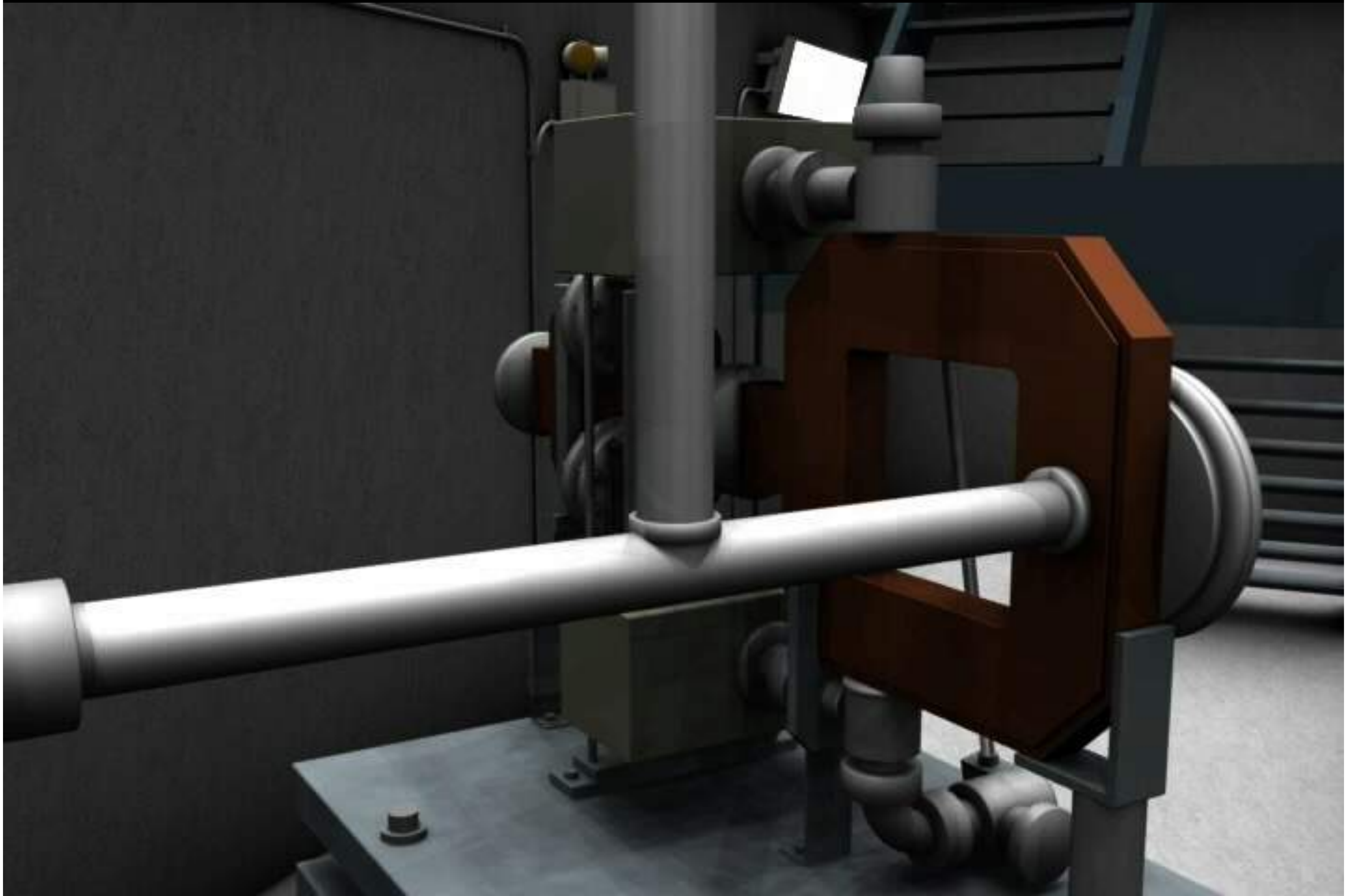


40 Member institutions in:

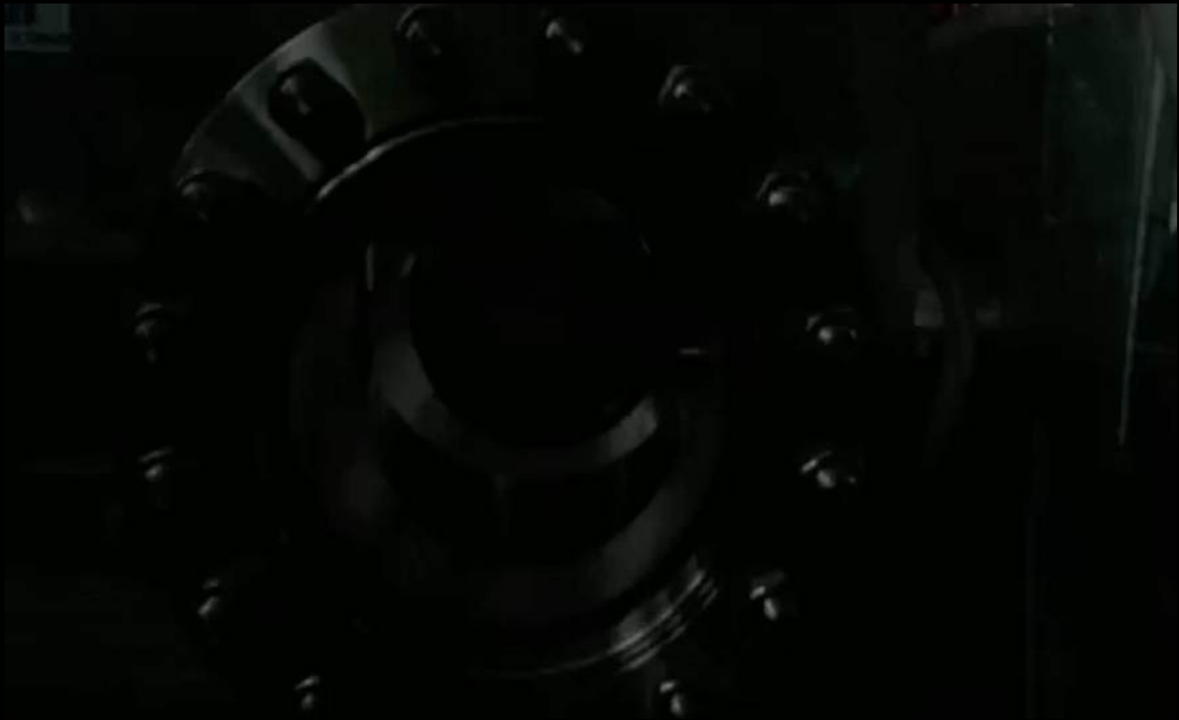
- **Italy** (INFN, CNR, Elettra, ENEA, Sapienza Università di Roma, Università degli Studi di Roma "Tor Vergata")
- **France** (CEA, SOLEIL, CNRS)
- **Switzerland** (EMPA, Ecole Polytechnique Fédérale de Lausanne)
- **Germany** (DESY, Ferdinand-Braun-Institut, Fraunhofer Institute for Laser Technology, 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**

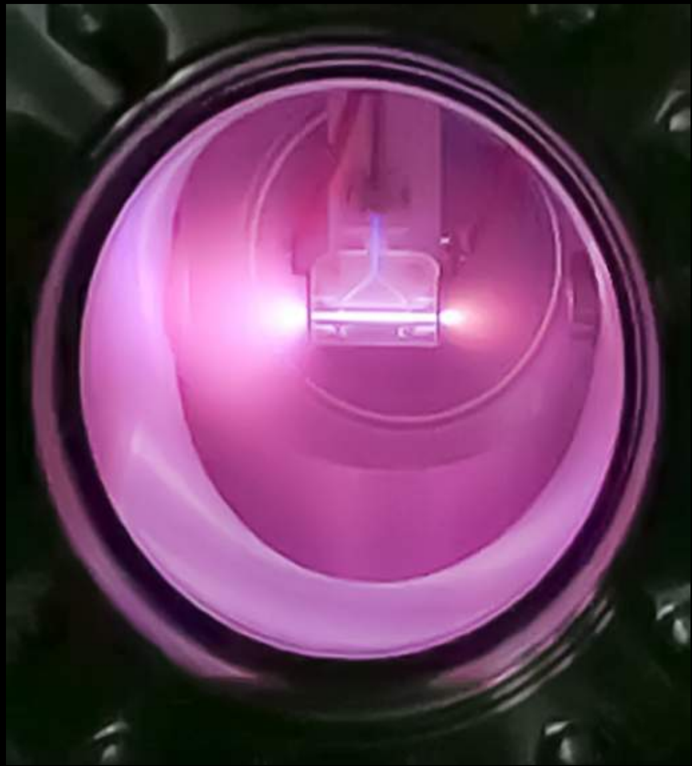
Il Progetto EuPRAXIA ai Laboratori Nazionali di Frascati

Electron source and acceleration



Capillary Discharge

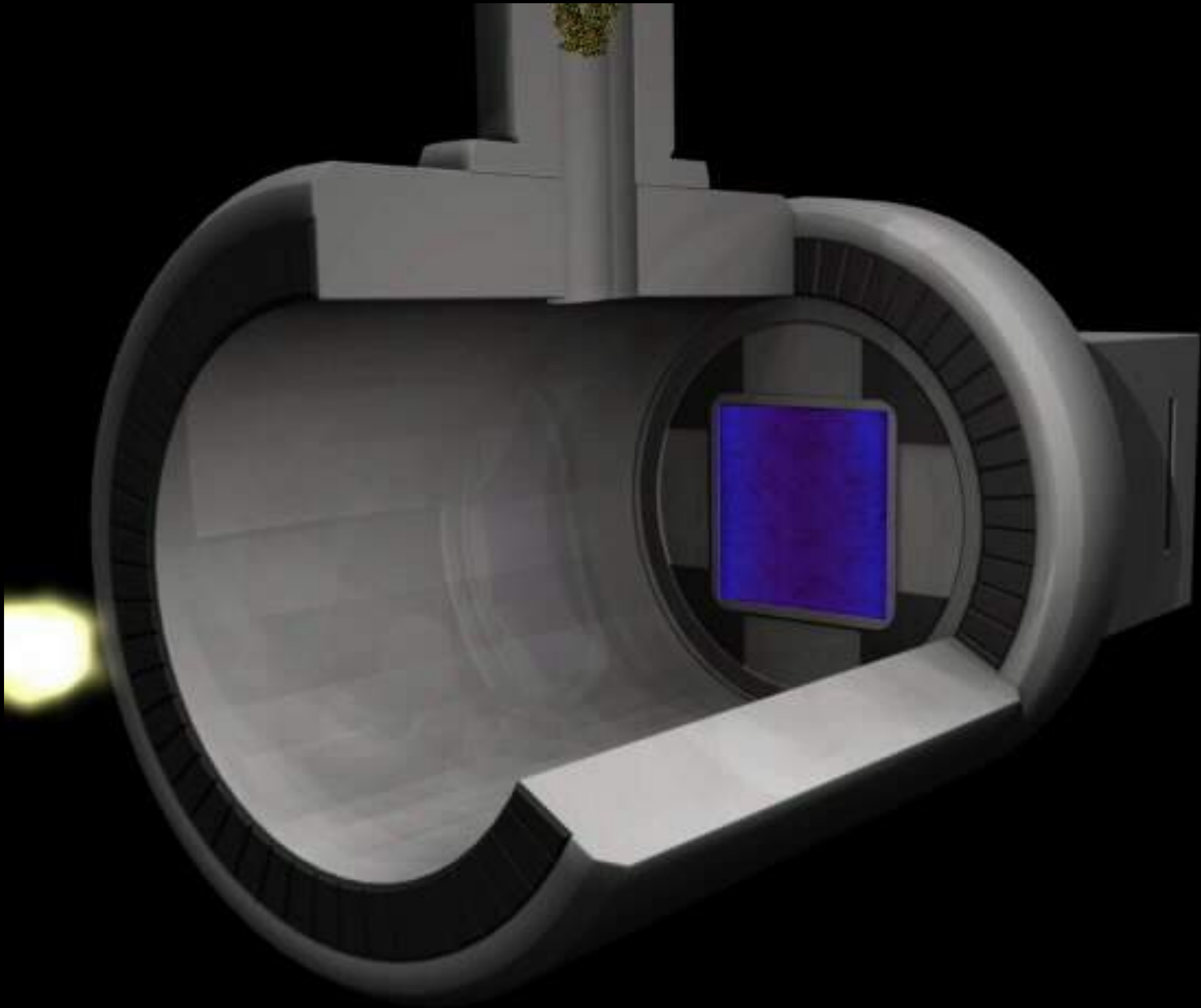




Laser ad Elettroni Liberi (FEL)

Beam separation

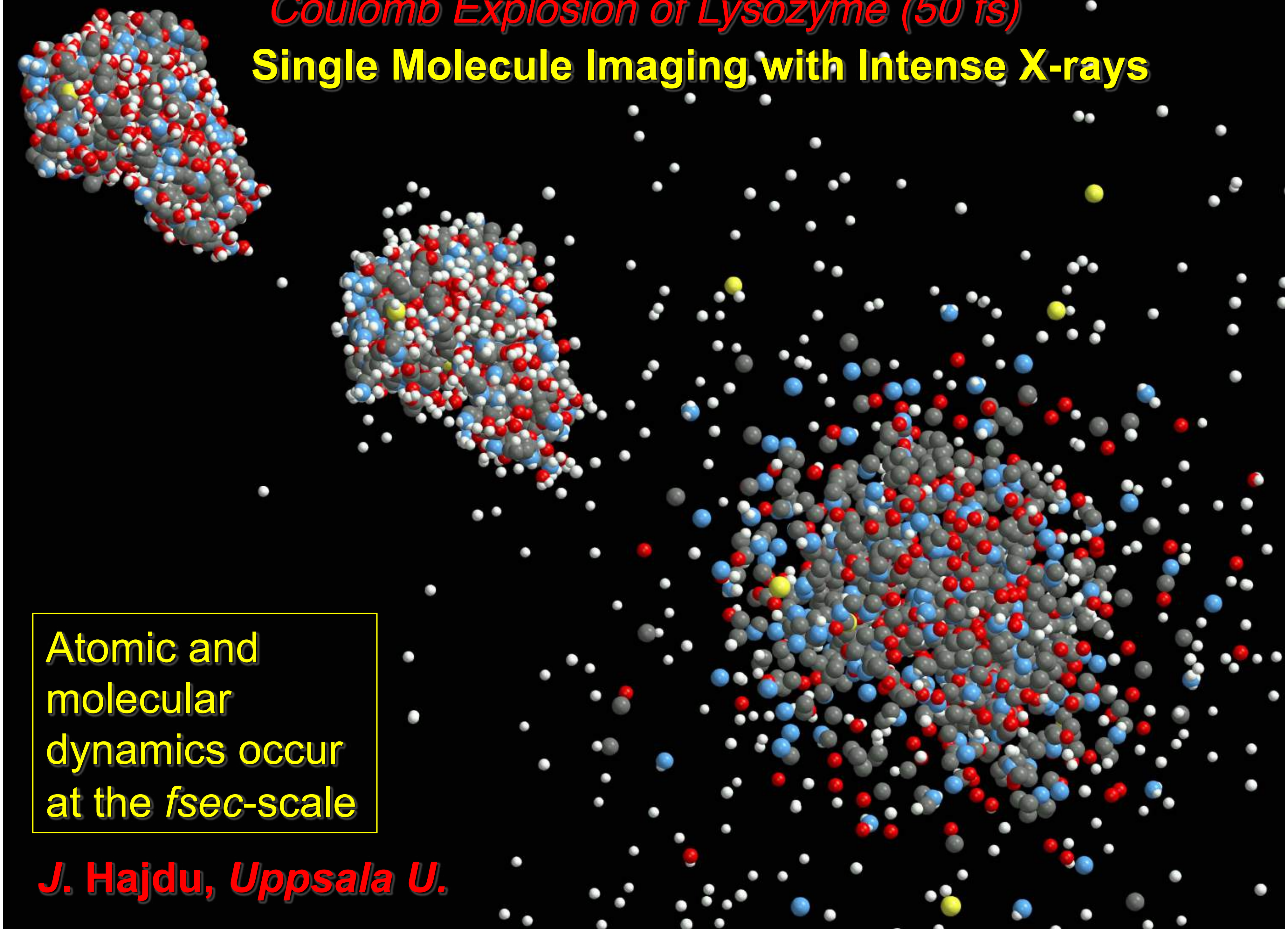
Experimental hall (Single Protein Imaging)



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

Coulomb Explosion of Lysozyme (50 fs)

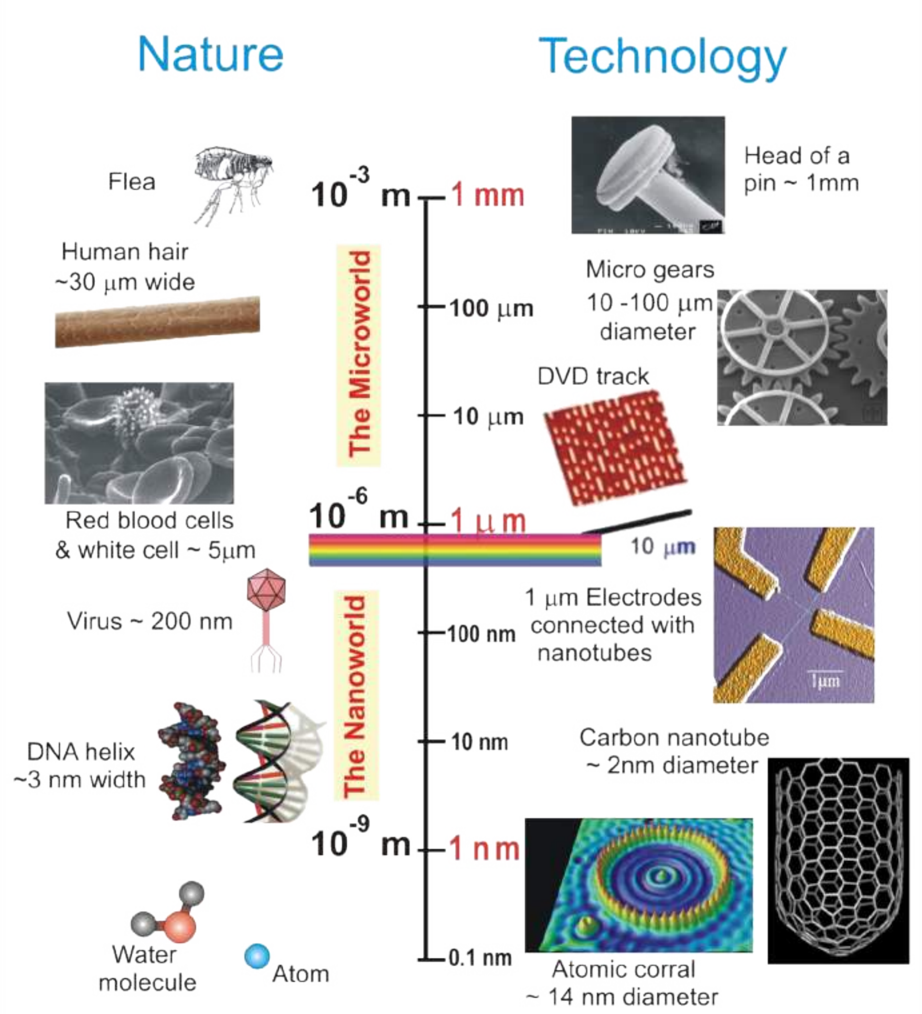
Single Molecule Imaging with Intense X-rays



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

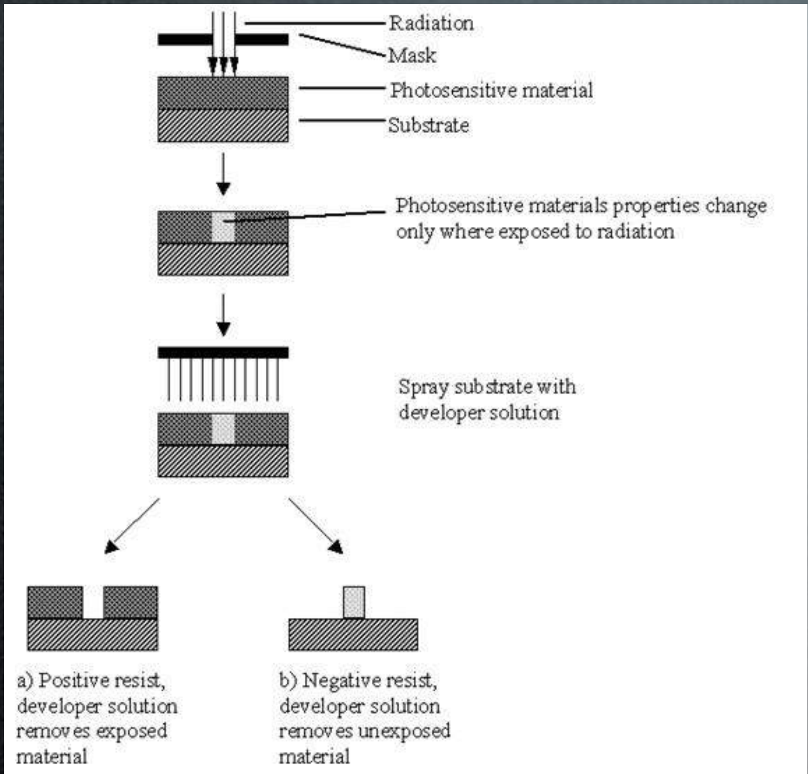
J. Hajdu, Uppsala U.

Ultra-Small

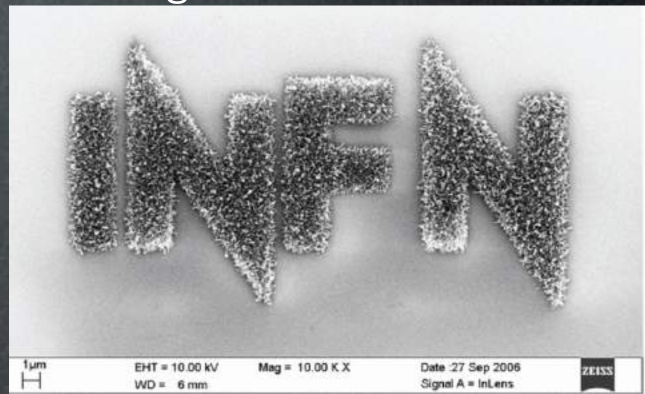


Nature
Technology
Flea
10^{-3} m
1 mm
Head of a pin ~ 1mm
Human hair ~30 μm wide
The Microworld
100 μm
Micro gears 10 -100 μm diameter
DVD track
10 μm
Red blood cells & white cell ~ 5μm
10^{-6} m
1 μm
10 μm
1 μm Electrodes connected with nanotubes
1μm
Virus ~ 200 nm
100 nm
The Nanoworld
10 nm
Carbon nanotube ~ 2nm diameter
DNA helix ~3 nm width
10^{-9} m
1 nm
0.1 nm
Water molecule
Atom
Atomic corral ~ 14 nm diameter

nano lithography



Michelangelo Ambrosio INFN-GINT



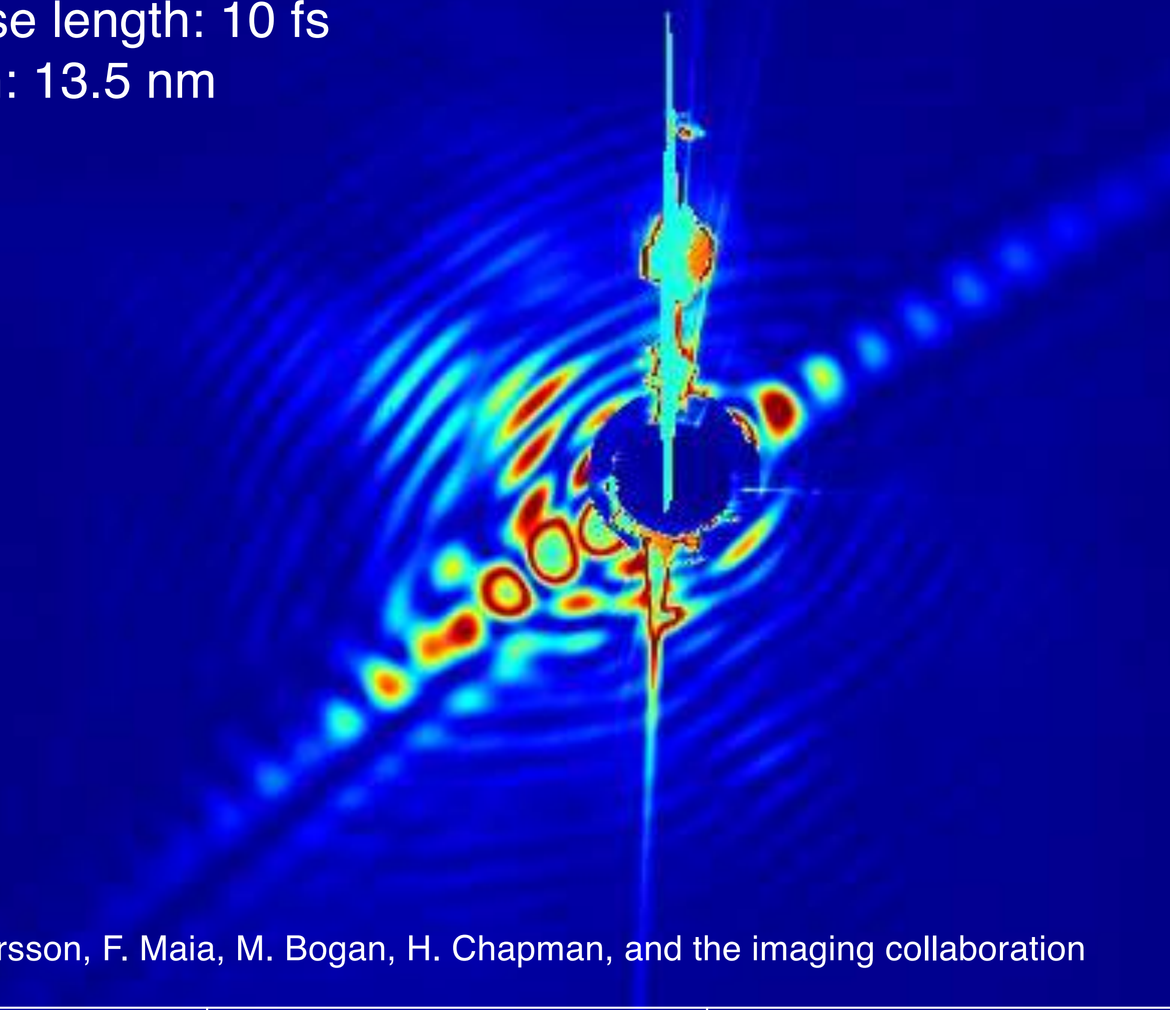
- Extreme UV Lithographt is the candidate technology with <50-35 nm

- Cost effective solutions based on FEL sources can be foreseen

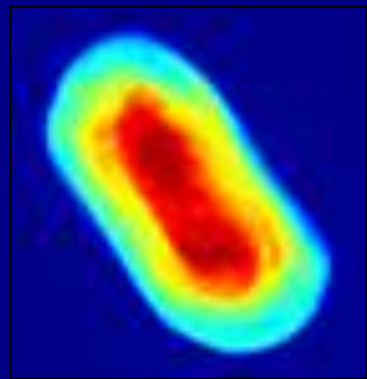
FIRST FLASH DIFFRACTION IMAGE OF A LIVING CELL

FLASH soft X-ray laser, Hamburg, Germany

FLASH pulse length: 10 fs
Wavelength: 13.5 nm



RECONSTRUCTED
CELL STRUCTURE



Filipe Maia, Uppsala

J. Hajdu, I. Andersson, F. Maia, M. Bogan, H. Chapman, and the imaging collaboration

30 | 60 | ∞ | 60 | 3

Resolution length on the detector (nm)

cluster and nanoparticle

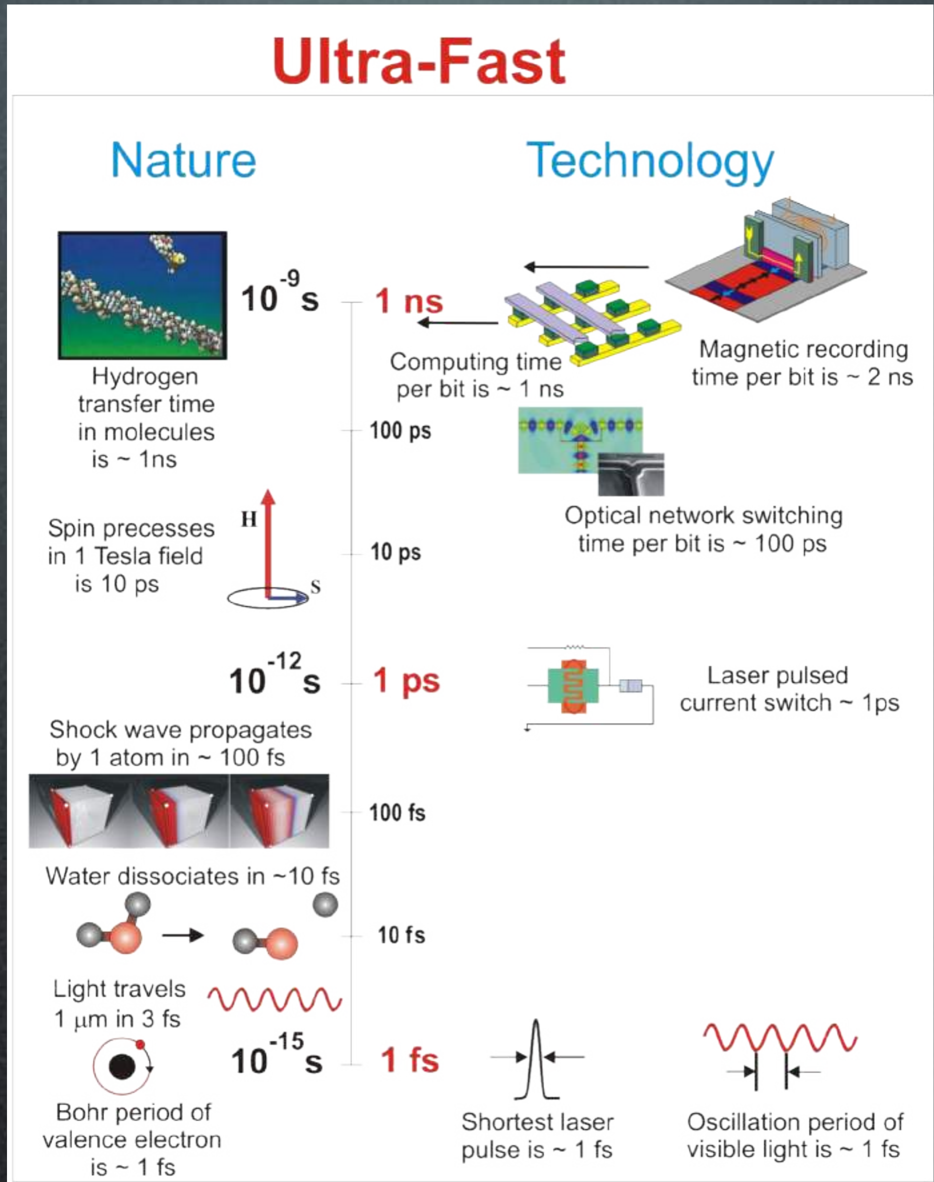
Clusters are small bits of matter composed of anywhere from a few to tens of thousands of atoms.

Small particles are different from bulk matter; finite size effects influence all properties of matter.

Examples are tiny carbon spheres and carbon tubes that are considered promising candidates for use as nanotechnological components.
(17 000 copper atoms in the picture on the right).

Limited photon energy of standard laser systems prevents measuring the full valence electron structure as well or performing photon energy dependent spectroscopy across shallow core edges

The beam intensities available at 3rd generation synchrotron radiation facilities are still far below what is required for meaningful gas phase experiments.

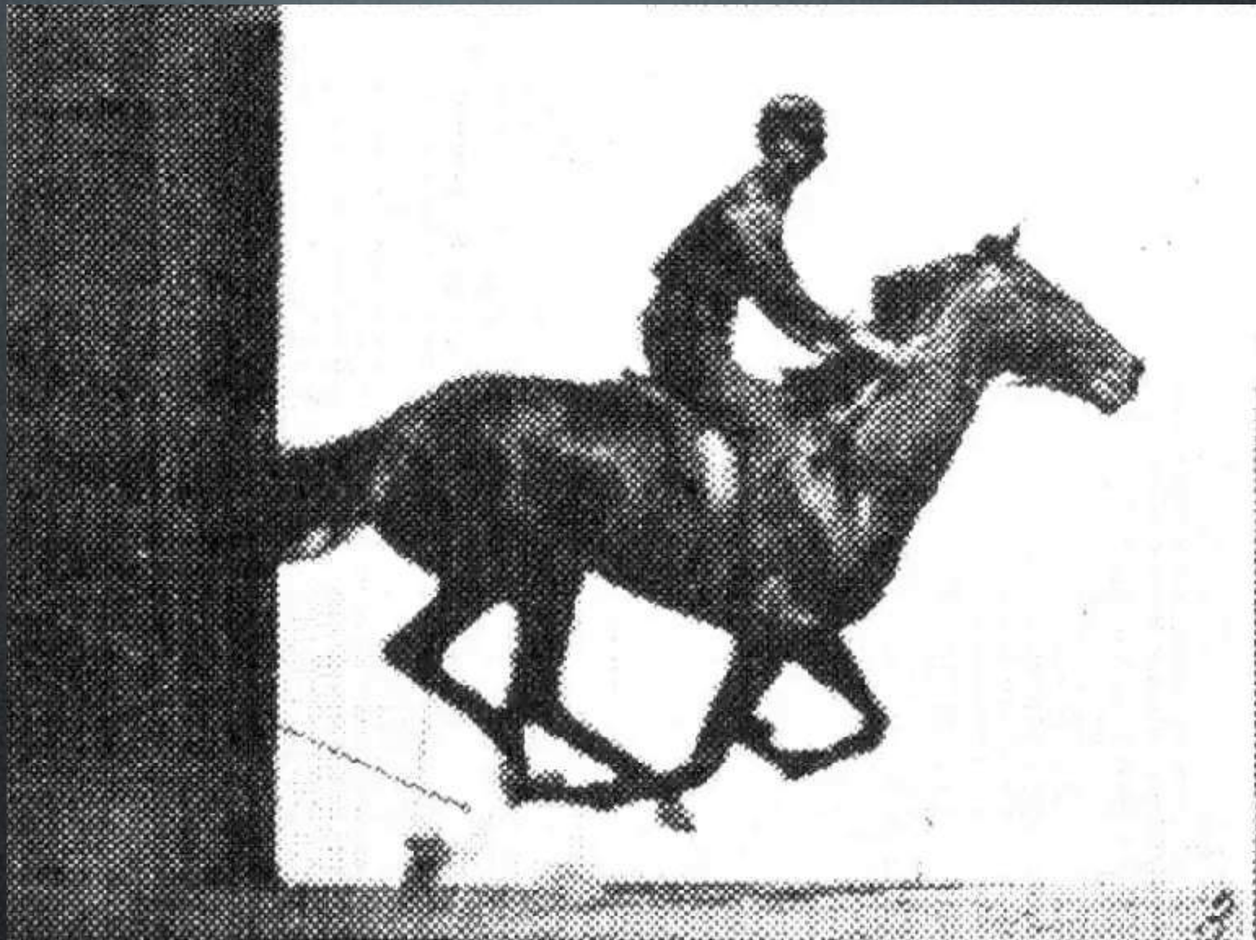


Ultra-Fast
Nature
Technology
10^{-9} s
1 ns
Hydrogen transfer time in molecules is ~ 1ns
Computing time per bit is ~ 1 ns
Magnetic recording time per bit is ~ 2 ns
100 ps
Optical network switching time per bit is ~ 100 ps
Spin precesses in 1 Tesla field is 10 ps
H
S
10 ps
10^{-12} s
1 ps
Laser pulsed current switch ~ 1ps
Shock wave propagates by 1 atom in ~ 100 fs
100 fs
Water dissociates in ~10 fs
10 fs
Light travels 1 μm in 3 fs
10^{-15} s
1 fs
Bohr period of valence electron is ~ 1 fs
Shortest laser pulse is ~ 1 fs
Oscillation period of visible light is ~ 1 fs

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

E. Muybridge

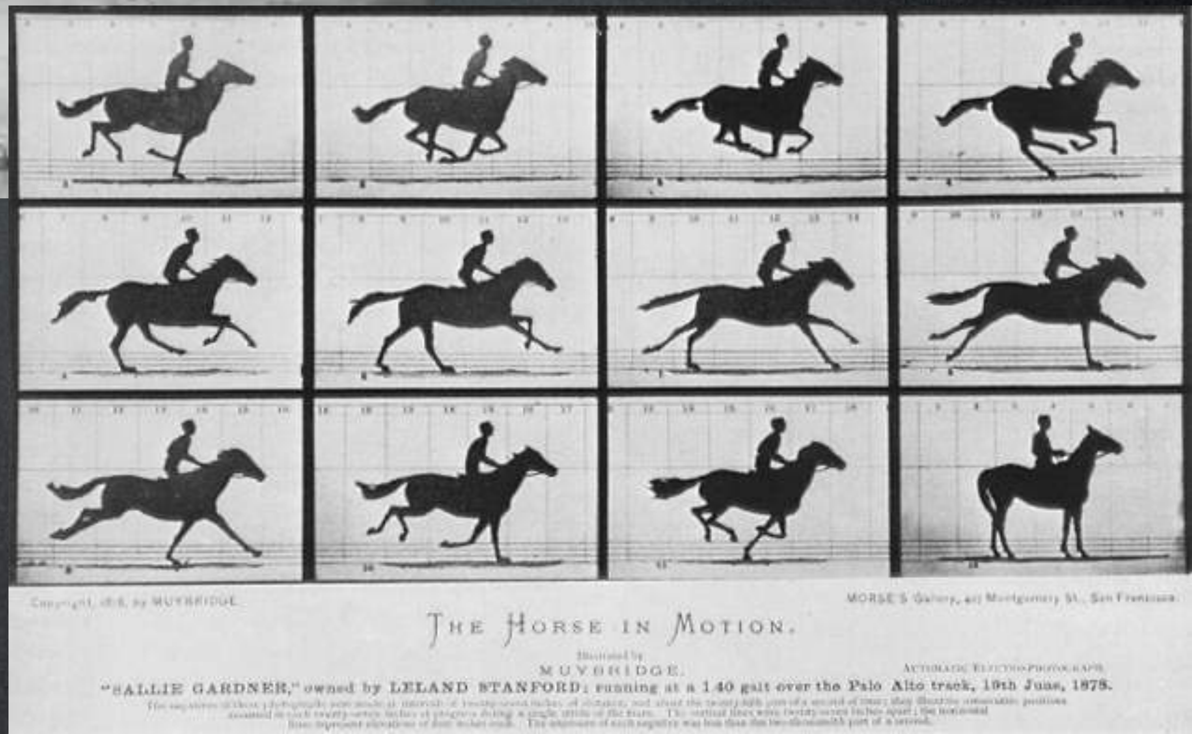
disagree whether all feet leave the ground during gallop...



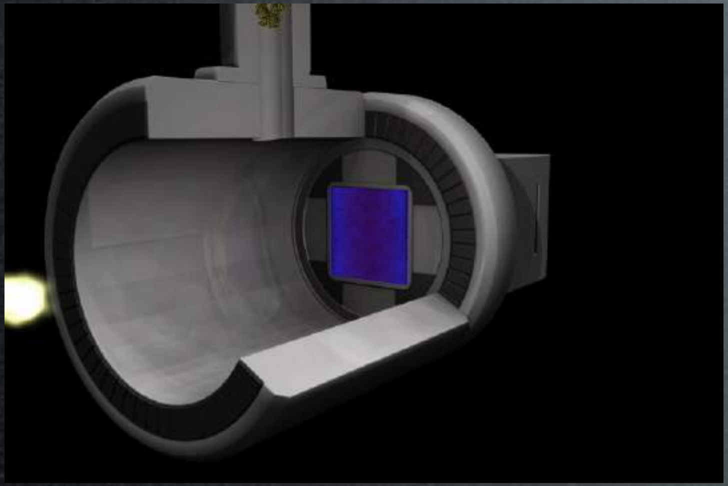
used spark photography to freeze this 'ultra-fast' process

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


FILM


MORSE'S Gallery, 417 Montgomery St., San Francisco.
THE HORSE IN MOTION.
MUYBRIDGE.
AUTOMATIC ELECTRO-PHOTOGRAPH.
"SALLIE GARDNER," owned by LELAND STANFORD; running at a 1.40 gait over the Palo Alto track, 19th June, 1878.

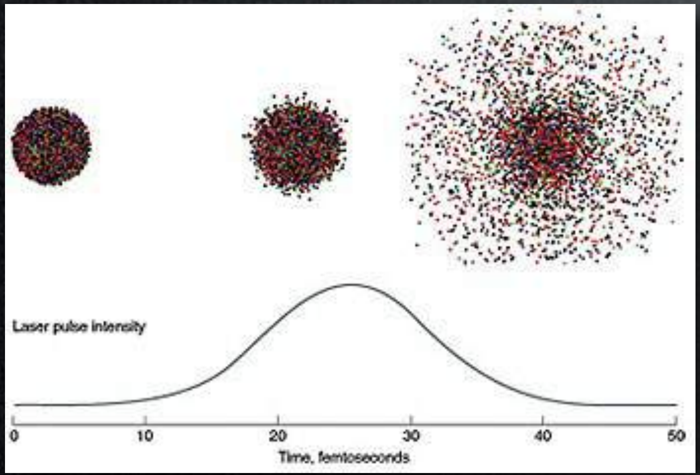
Protein imaging



Using extremely short and intense X-ray pulses to capture images of objects such as proteins before the X-rays destroy the sample.

Single-molecule diffractive imaging with an X-ray free-electron laser.

Individual biological molecules will be made to fall through the X-ray beam, one at a time, and their structural information recorded in the form of a diffraction pattern.



Lawrence Livermore National Laboratory (LLNL)

The pulse will ultimately destroy each molecule, but not before the pulse has diffracted from the undamaged structure.

The patterns are combined to form an atomic-resolution image of the molecule.

The speed record of 25 femtoseconds for flash imaging was achieved.

Models indicate that atomic-resolution imaging can be achieved with pulses shorter than 20 femtoseconds.

make a movie of chemical reactions

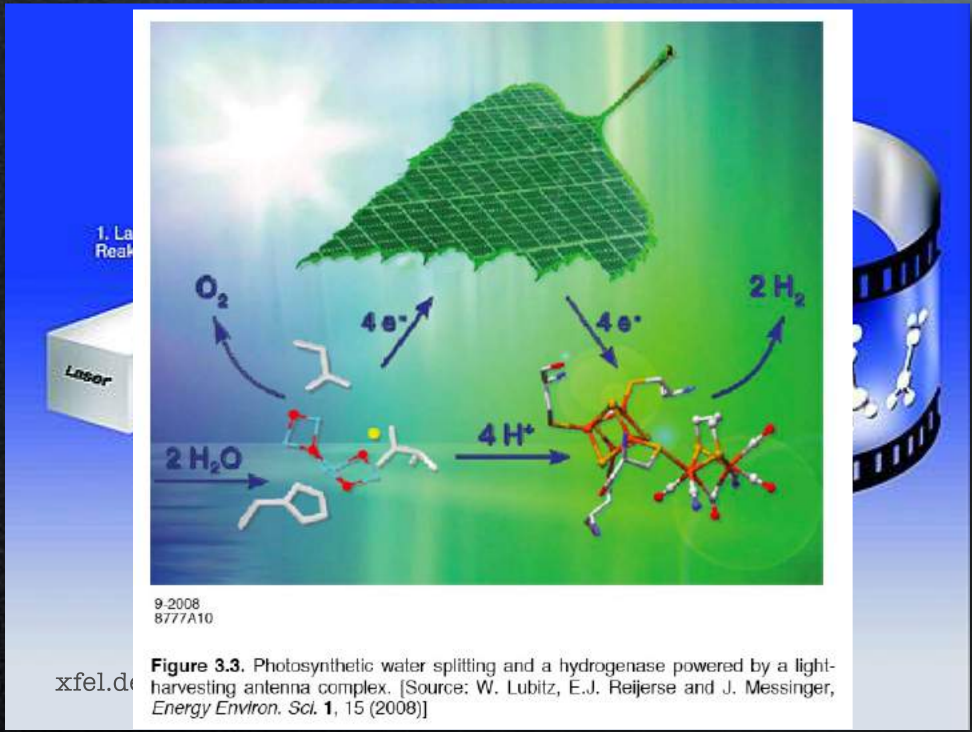


Figure 3.3. Photosynthetic water splitting and a hydrogenase powered by a light-harvesting antenna complex. [Source: W. Lubitz, E.J. Reijerse and J. Messinger, *Energy Environ. Sci.* **1**, 15 (2008)]

Chemical reactions often take place incredibly quickly: orders of magnitude of femtosecond are not rare. The atomic changes that occur when molecules react with one another take place in moments that brief.

The XFEL X-ray laser flashes make it possible to film these rapid processes with an unprecedented level of quality.

Since the flash duration is less than 100 femtoseconds, images can be made in which the movements of detail are not blurred.

And thanks to the short wavelength, atomic details become visible in the films.

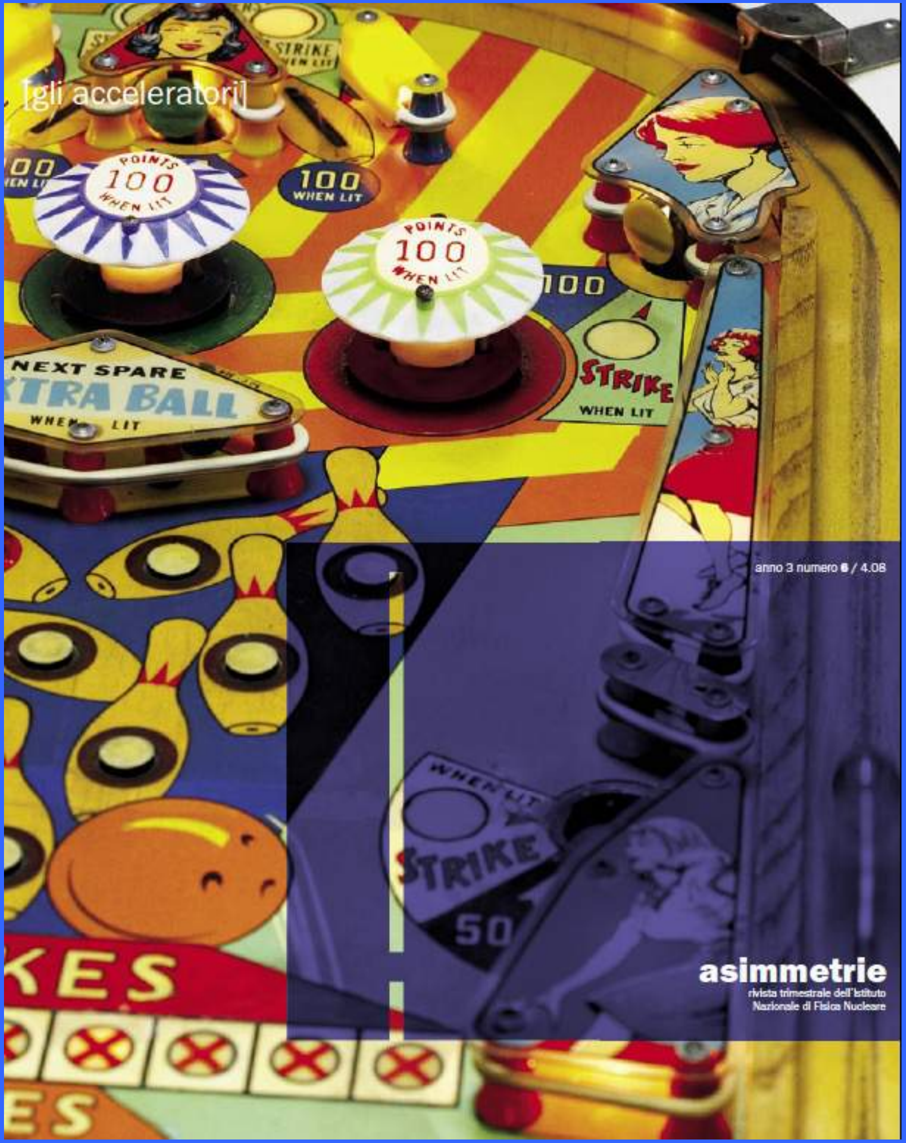
To film a chemical reaction, one needs a series of pairs of X-ray laser flashes.

The first flash in each pair triggers the chemical reaction. With the second flash, a snapshot is then made.

The delay between the two flashes can be precisely modified to within femtosecond and a series of snapshots can be made at various times following the start of the reaction.

In each case, the images are of different molecules, but these images can be combined into a film.

https://www.asimmetrie.it/



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