# Accelerating the future

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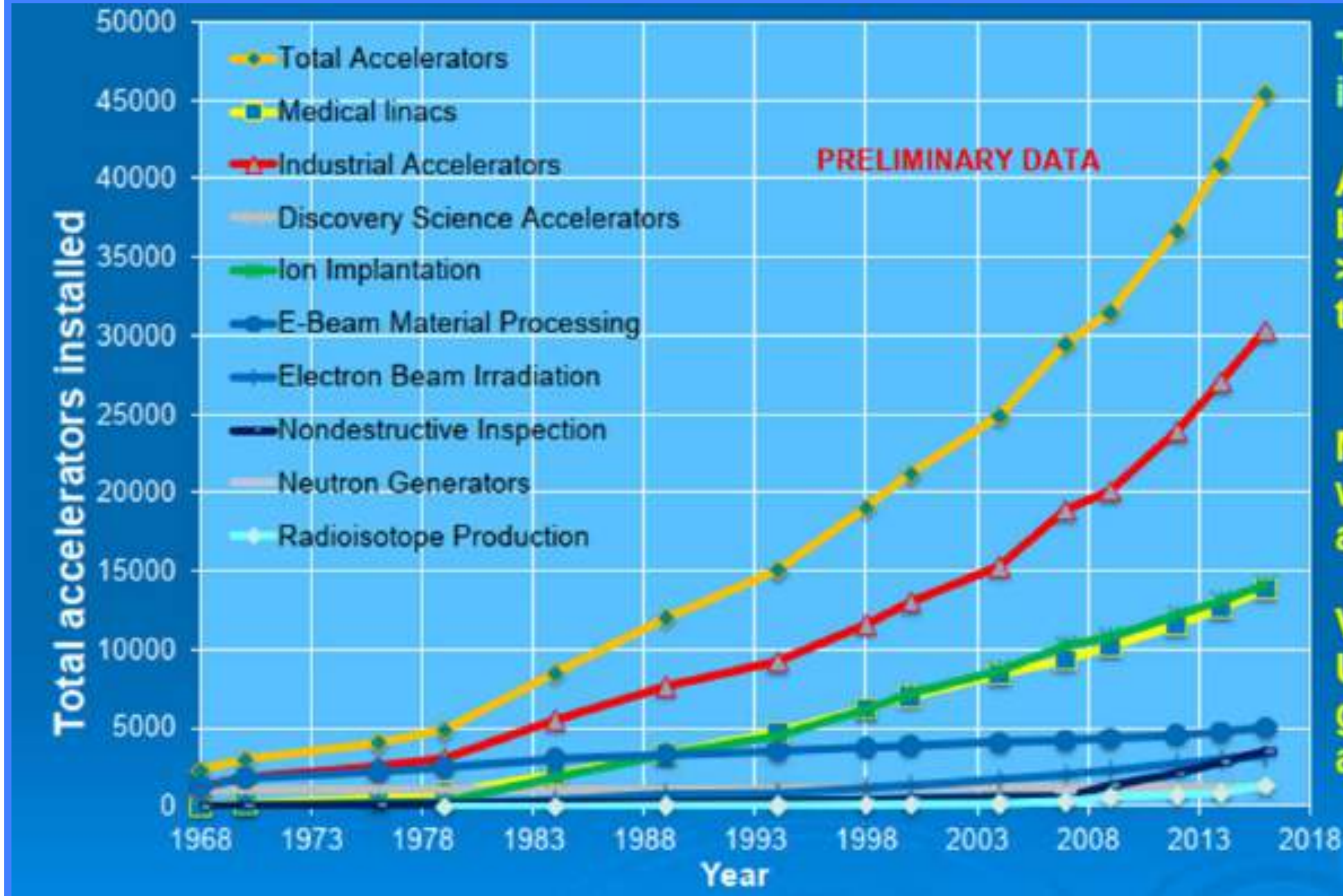
INSPYRE – LNF 2 April 2019

# Accelerators installed worldwide




Total sales of accelerators is ~US$5B annually

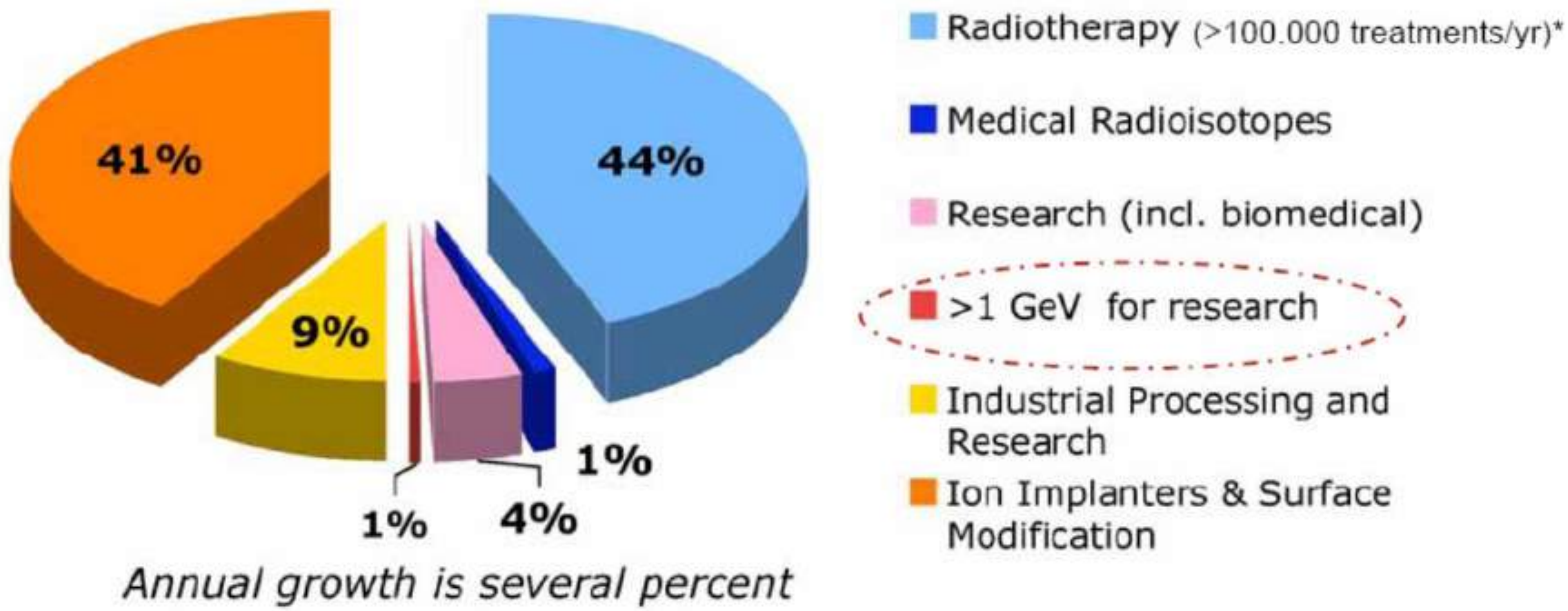
About 47,000 systems have been sold,
> 40,000 still in operation today

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

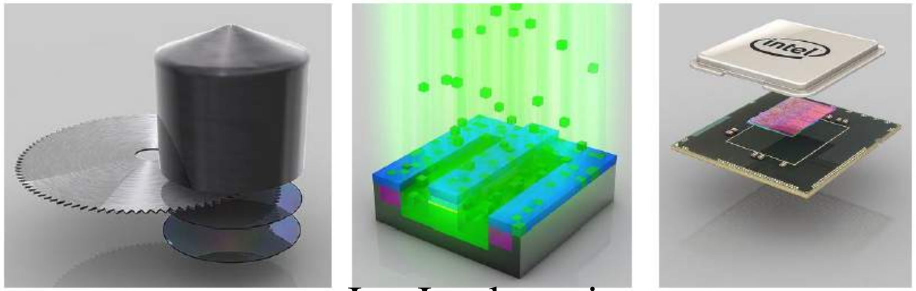
-Accelerators for Americas Future Report, pp. 4, DoE, USA, 2011

# Accelerators installed worldwide



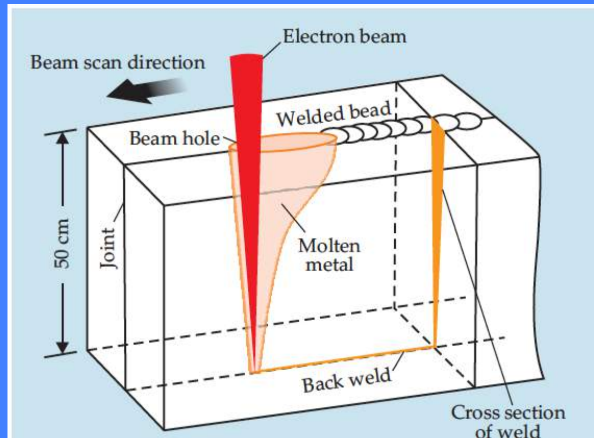

-Accelerators for Americas Future Report, pp. 4, DoE, USA, 2011

# The Beam Business



Images courtesy of Intel

Ion Implantation



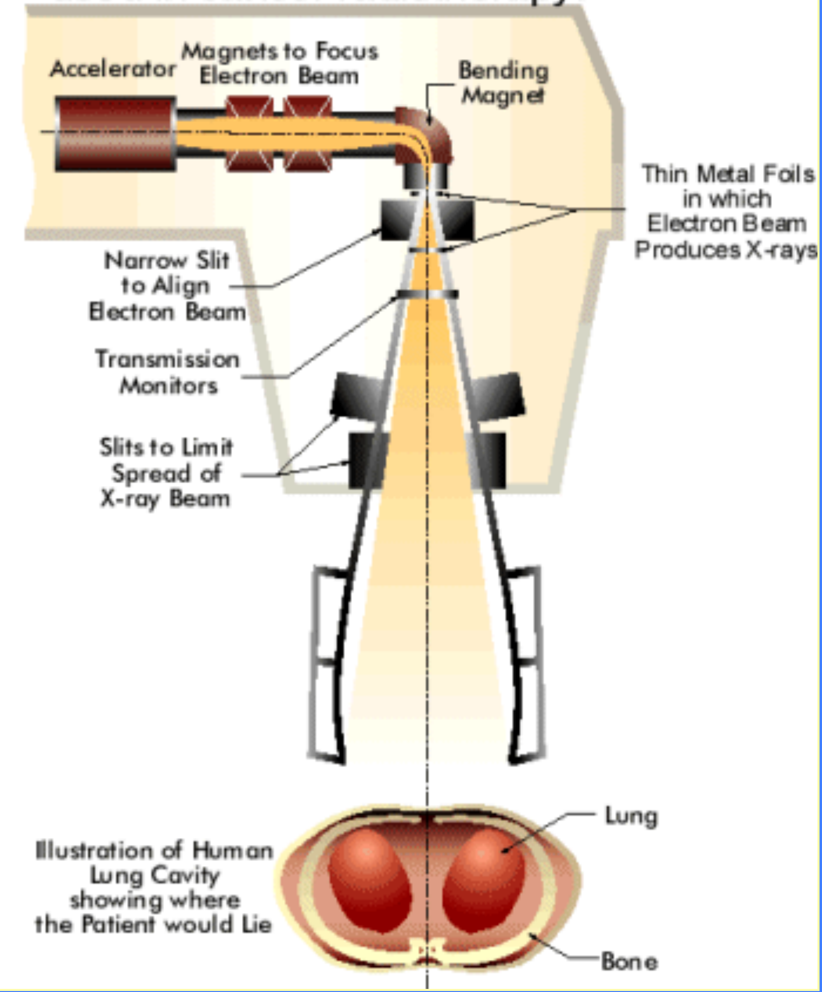

**The beam business: Accelerators in industry**

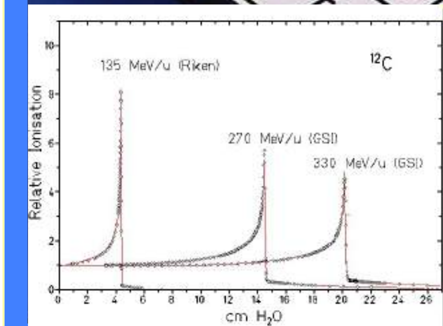
Robert W. Hamm, and Marianne E. Hamm

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

# Medical Applications

Schematic diagram of a typical medical accelerator used in cancer radiotherapy.




| Area | Application | Beam | Accelerator | Beam energy/MeV | Beam current/mA | Number |
| --- | --- | --- | --- | --- | --- | --- |
| **Medical** | Cancer therapy | e | linac | 4-20 | $10^{-2}$ | >14000 |
| | | p | cyclotron, synchrotron | 250 | $10^{-6}$ | 60 |
| | | C | synchrotron | 4800 | $10^{-7}$ | 10 |
| | Radioisotope production | p | cyclotron | 8-100 | 1 | 1600 |

# Cultural Heritage

## Why is an accelerator under the Louvre museum?

AGLAE, Accélérateur Grand Louvre d'Analyse Élémentaire in Paris, is the world's only accelerator facility fully dedicated to the study and investigation of works of art and archeological artifacts. It serves more than 1200 French museums. The 4-million-electron-volt proton beam delicately probes a large variety of materials: jewels, ceramics, glass, alloys, coins and statues, as well as paintings and drawings. These investigations provide information on the sources of the materials, the ancient formulas used to produce them, and the optimal ways to preserve these treasures.

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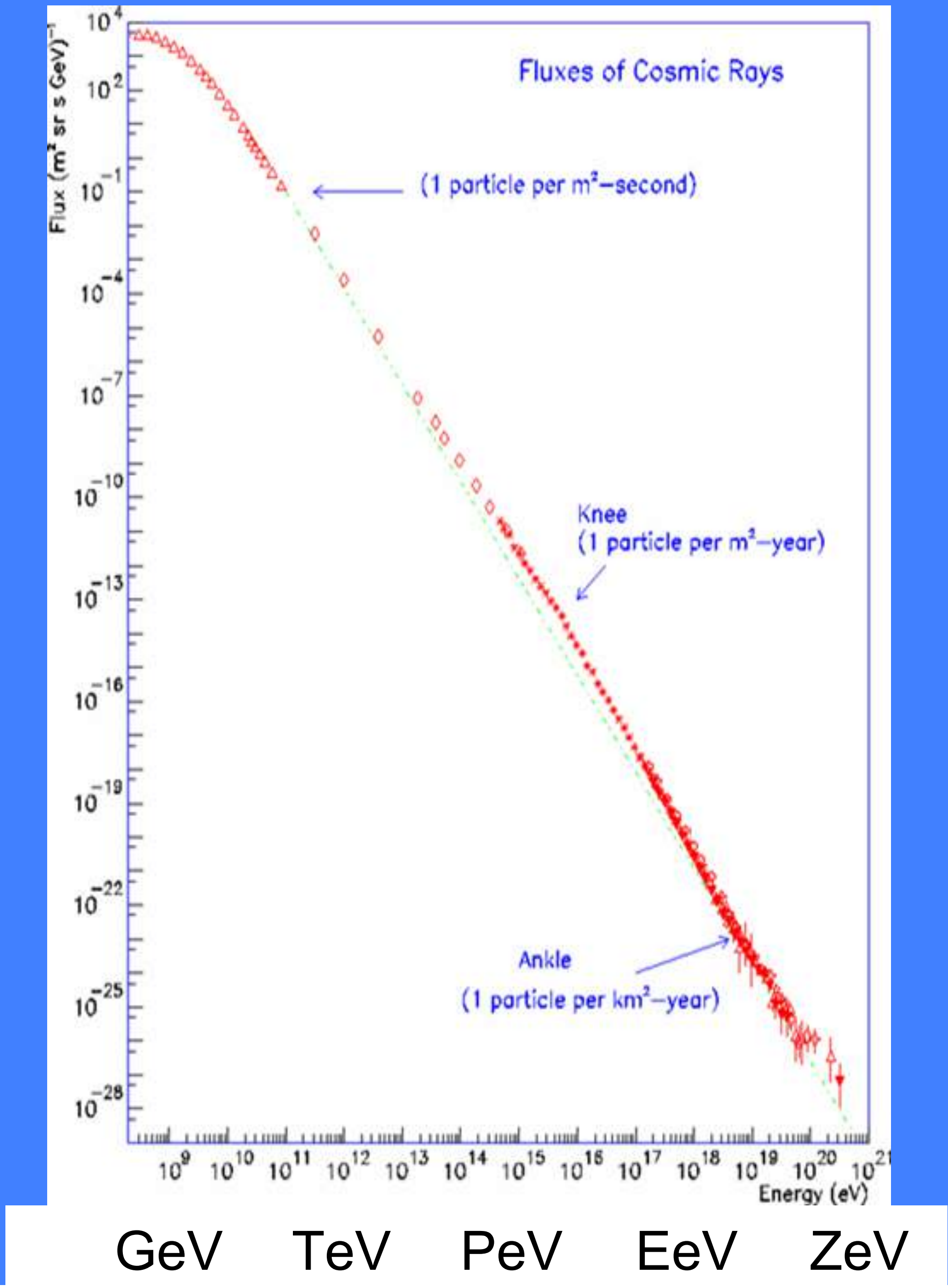
### The Story of Ishtar

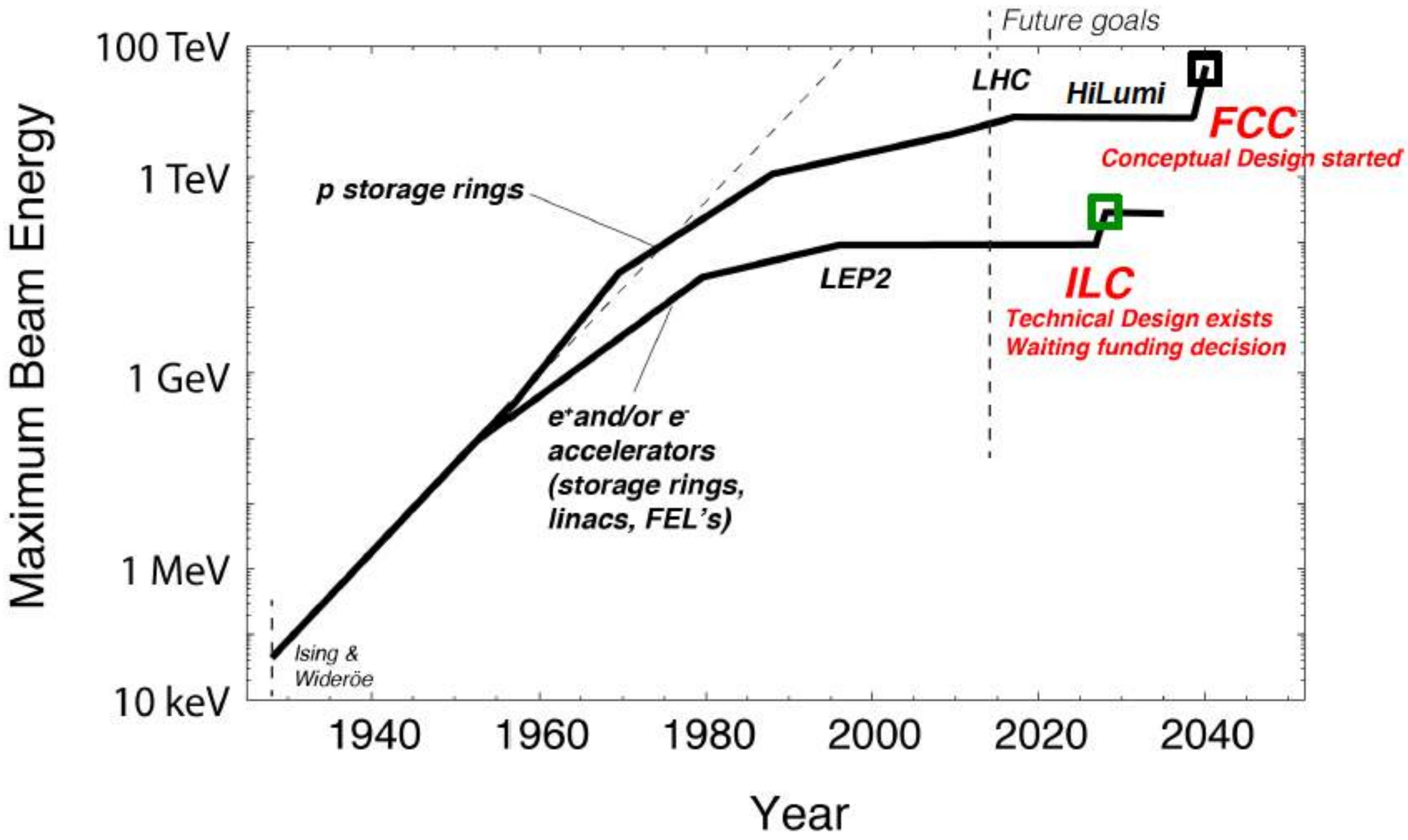
In 1863, while excavating a tomb from the ancient Parthian civilization in Mesopotamia (200 BC – 200 AD), an amateur archeologist who was the French consul in Baghdad discovered this 5-inch-tall alabaster figurine representing the goddess Ishtar. He donated it to the Louvre. Recently a Louvre curator asked the AGLAE team to analyze the figurine's red eyes and red navel. The inlays turned out to be exquisite rubies, a great mystery since rubies are only found in remote lands like India or Southeast Asia. Analysis of rubies with known provenance from Paris jewelers yielded trace-element fingerprints showing that Ishtar's rubies originated in Burma — testifying to an unreported trade network (see map), perhaps by ship, between Babylon and Southeast Asia.


MAP BY T. CALLIGARO.

PHOTO BY OLIVIA DIAZ.

# The Cosmos is able to accelerate particles …but in uncontrolled conditions




Future goals
100 TeV
1 TeV
1 GeV
1 MeV
10 keV
Maximum Beam Energy
LHC
HiLumi
FCC
Conceptual Design started
p storage rings
LEP2
ILC
Technical Design exists
Waiting funding decision
e+and/or e-
accelerators
(storage rings,
linacs, FEL's)
Ising &
Wideröe
1940
1960
1980
2000
2020
2040
Year

# Fermi's Globatron: ~5000 TeV Proton beam

## 1954 the ultimate synchrotron

$B_{max}$ 2 Tesla

ρ  8000 km

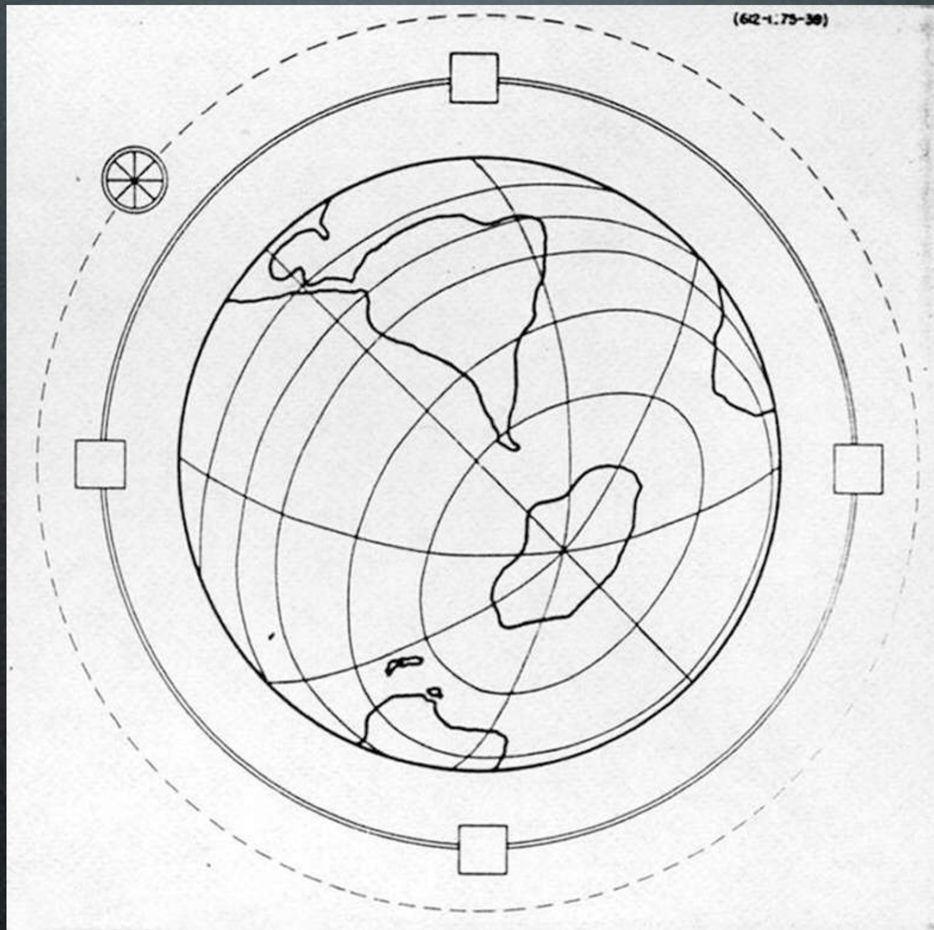
**fixed target**

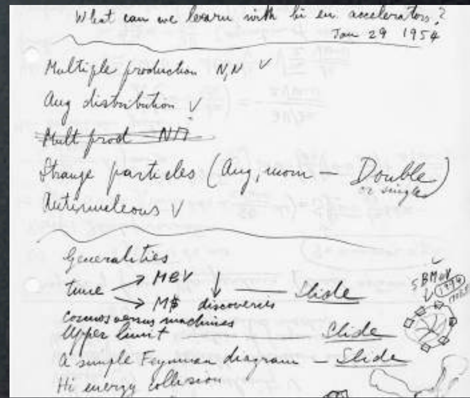
**3 TeV cm**

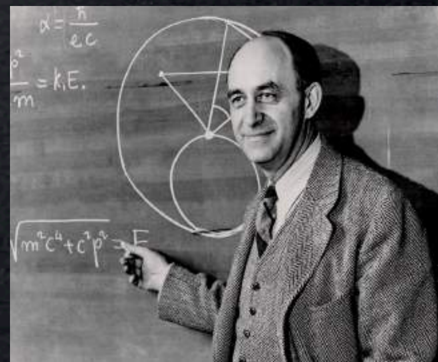
170 G$

1994

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

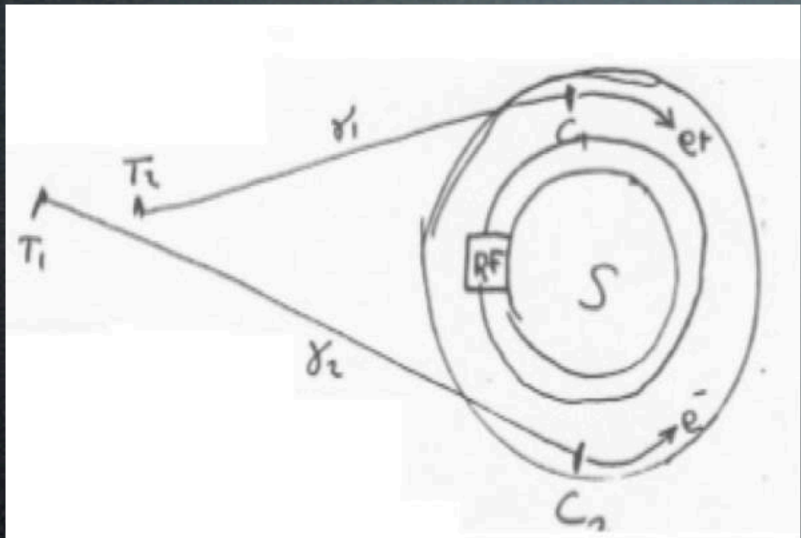




# Touschek's Anello Di Accumulazione (ADA)

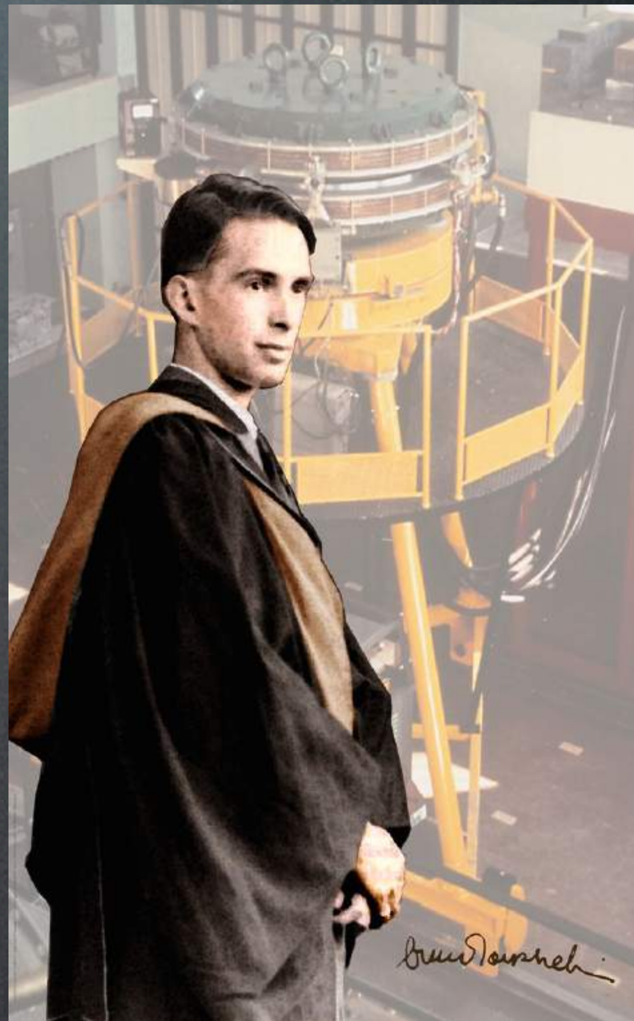
## 1961 the first e+e- Collider



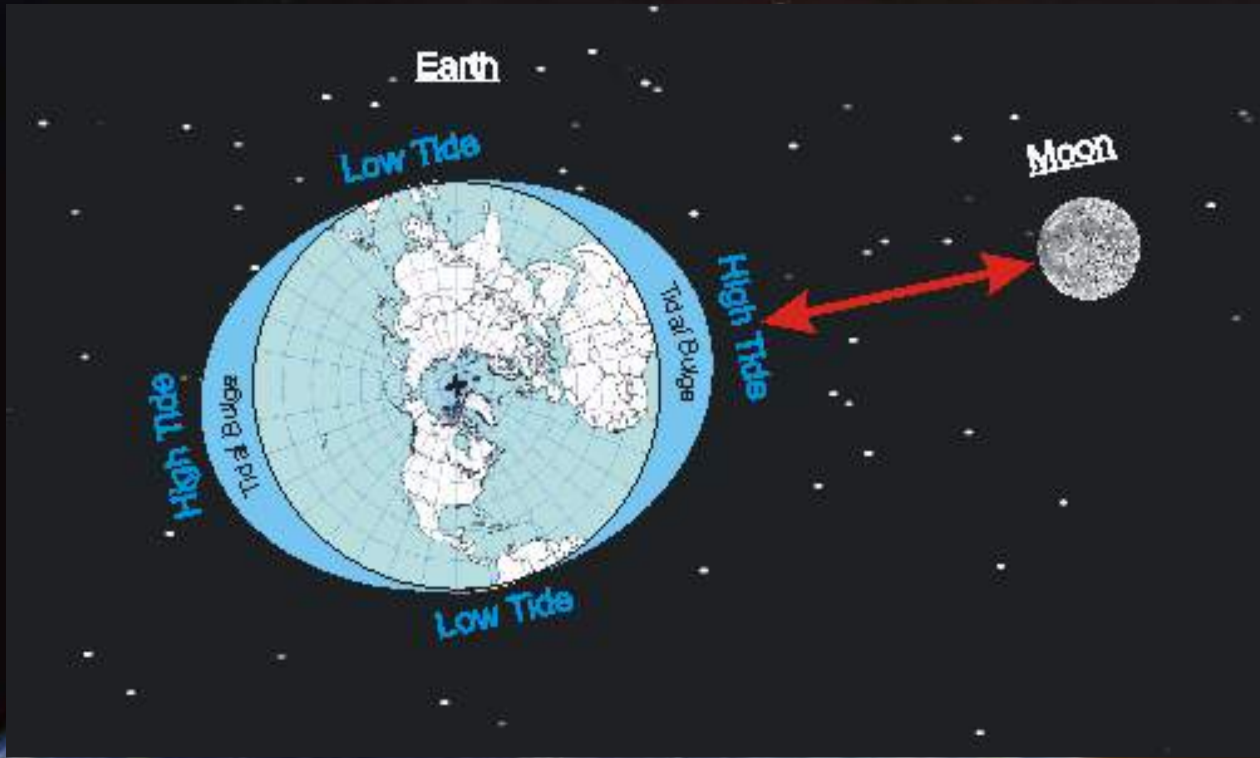


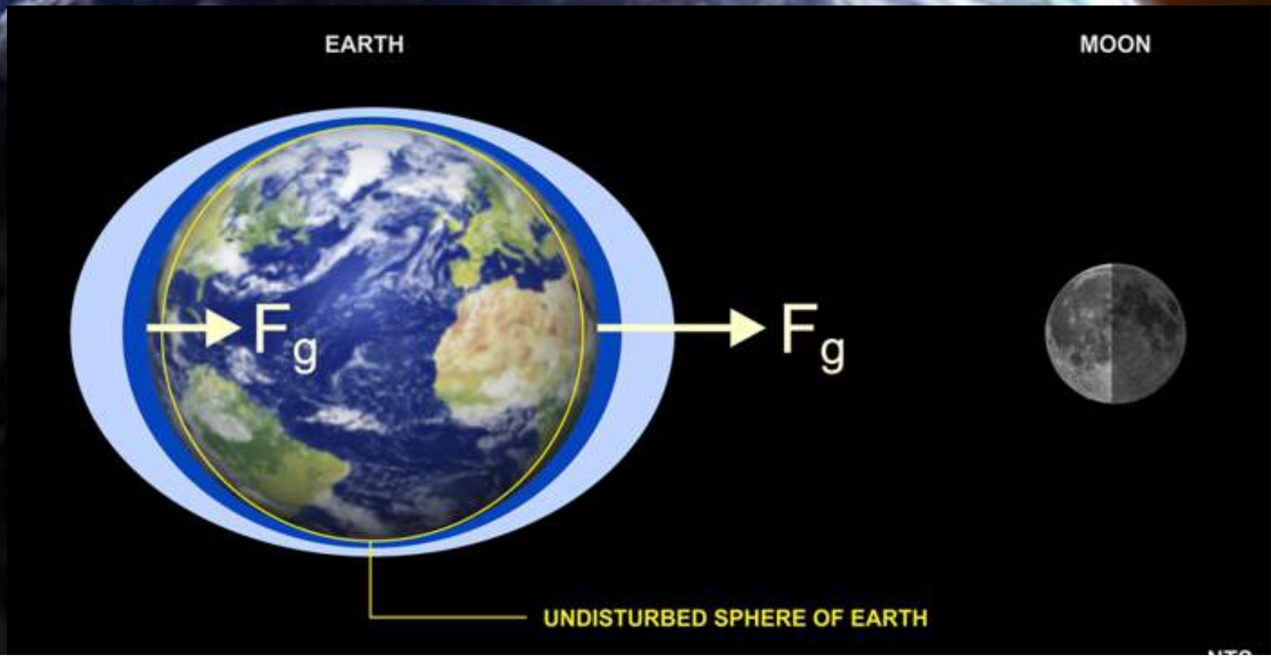
$$E_{CM} \approx \sqrt{2E_1 m_2}$$

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




| 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
Moon
Low Tide
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

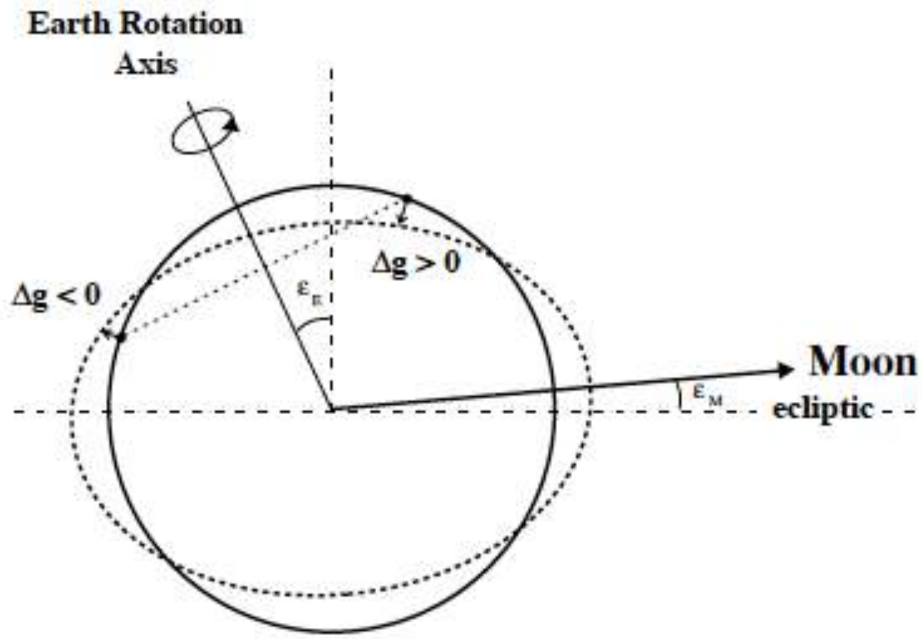



Figure 2: Tidal deformation of the Earth crust due to the presence of the moon. One tide bulge is formed in the direction of the moon and another one just opposite of it. The changes in gravity associated to the tidal deformations $\Delta g$ are indicated for an observer at a latitude of about 45°. The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

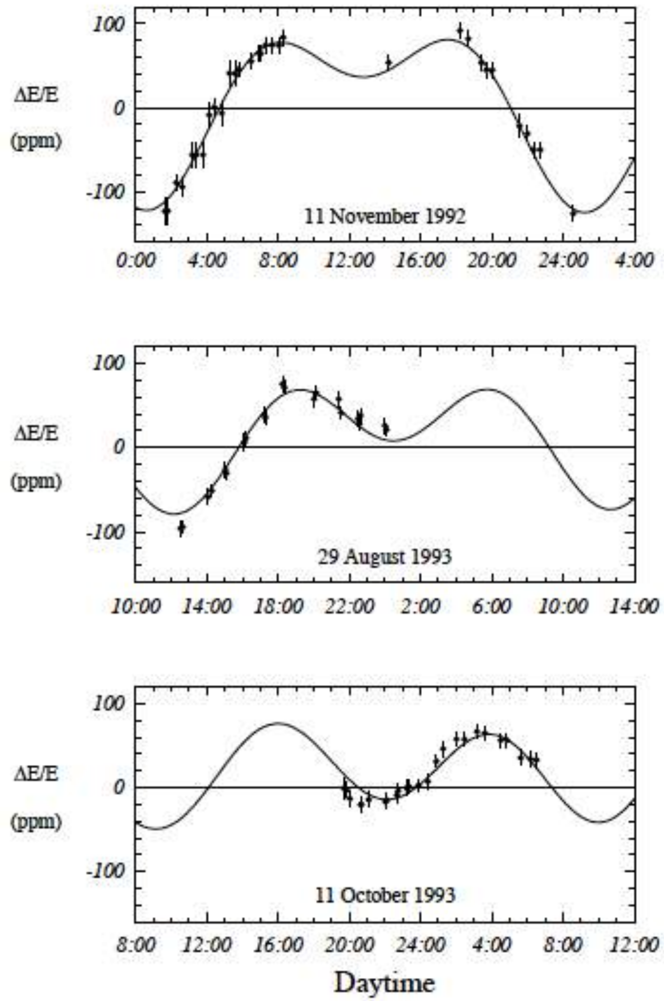
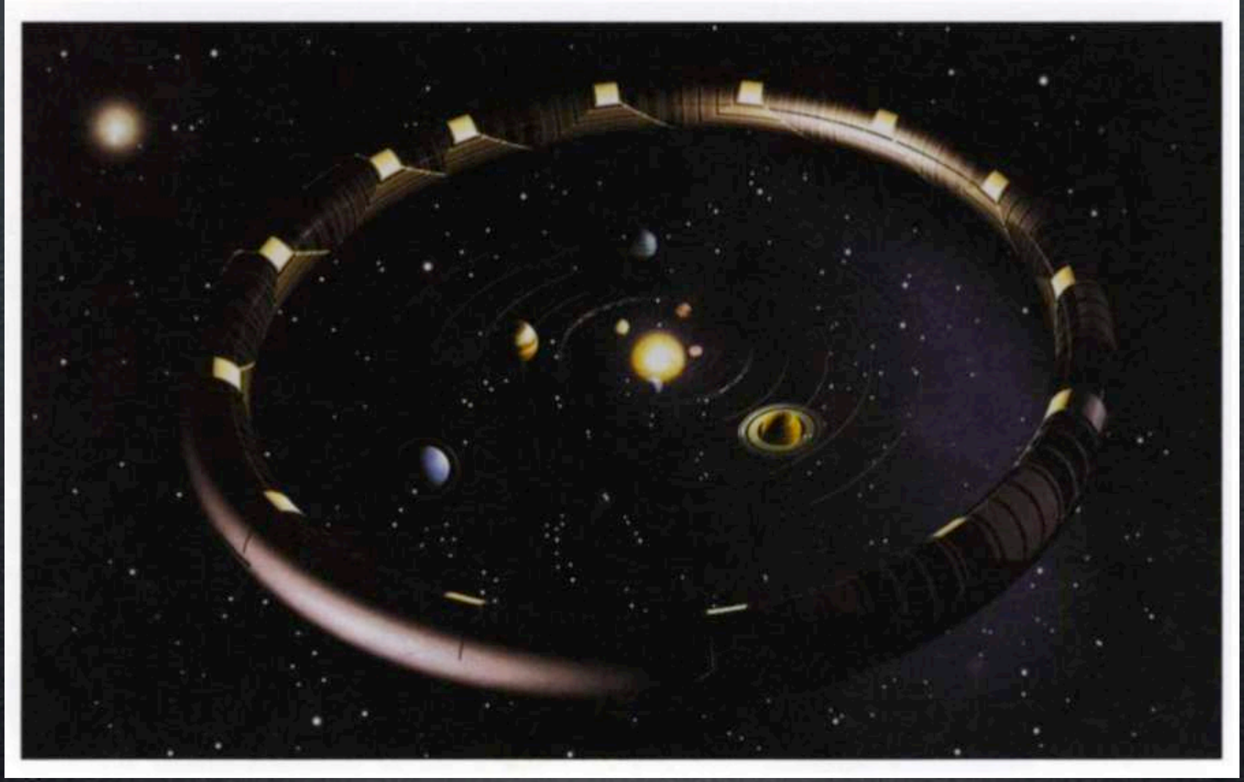



Figure 3: The evolution of the relative beam energy variation due to tides is shown as a function of time for three periods with stable beam conditions. The solid line is calculated using the CTE tide model with the average coefficient from equation 4. The top picture corresponds to full-moon, the bottom 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

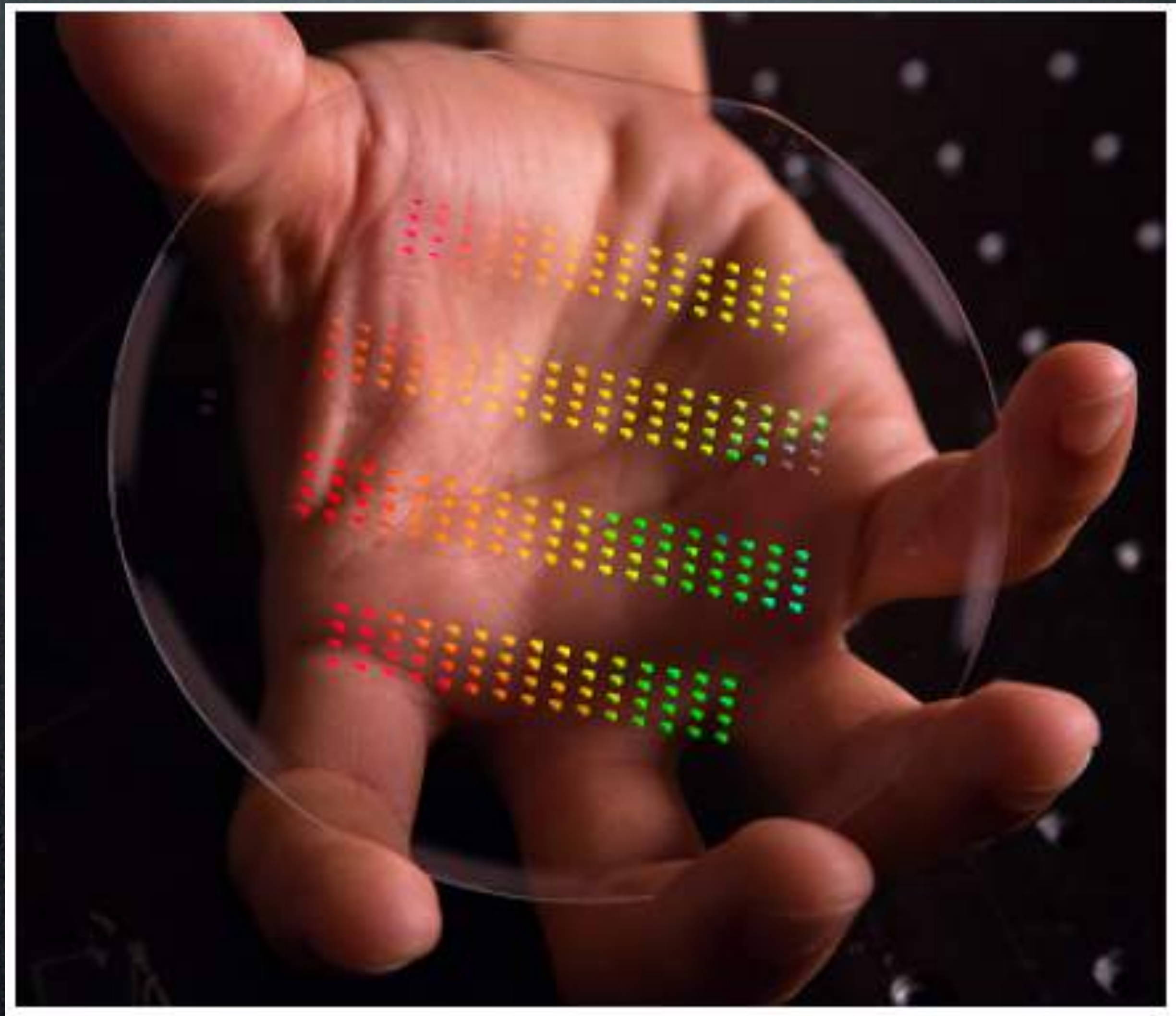
## Towards the Planck scale



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?

# HIGH GRADIENT AAC ROAD MAP

① Miniaturization of the accelerating structures (~resonant)

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

- Power sources
- Accelerating structures
- High quality beams

## Modern accelerators require high quality beams:

==> High Luminosity & High Brightness

==> High Energy & Low Energy Spread

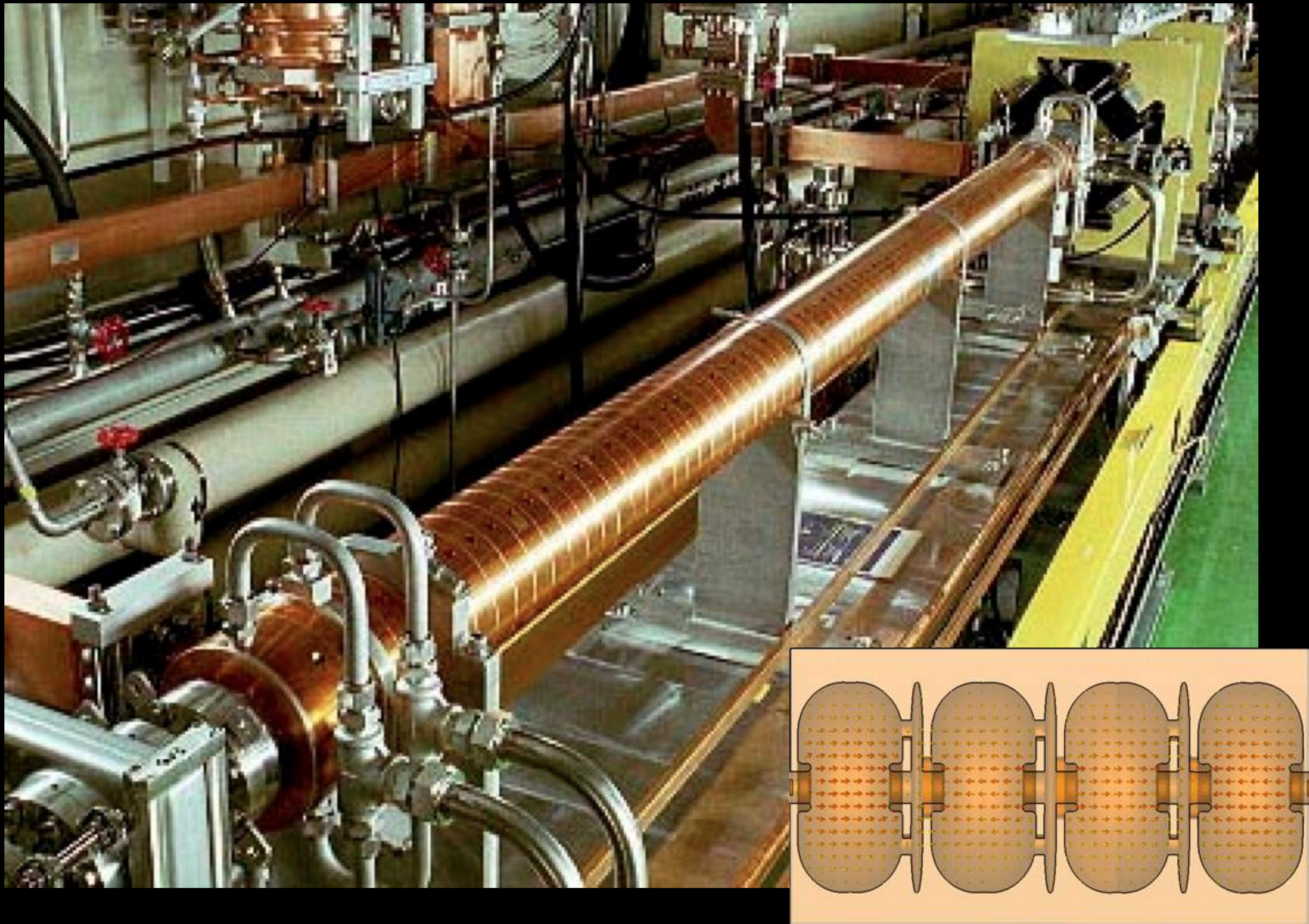
↑ $$L = \frac{N_{e+} N_{e-} f_r}{4\pi \sigma_x \sigma_y}$$

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

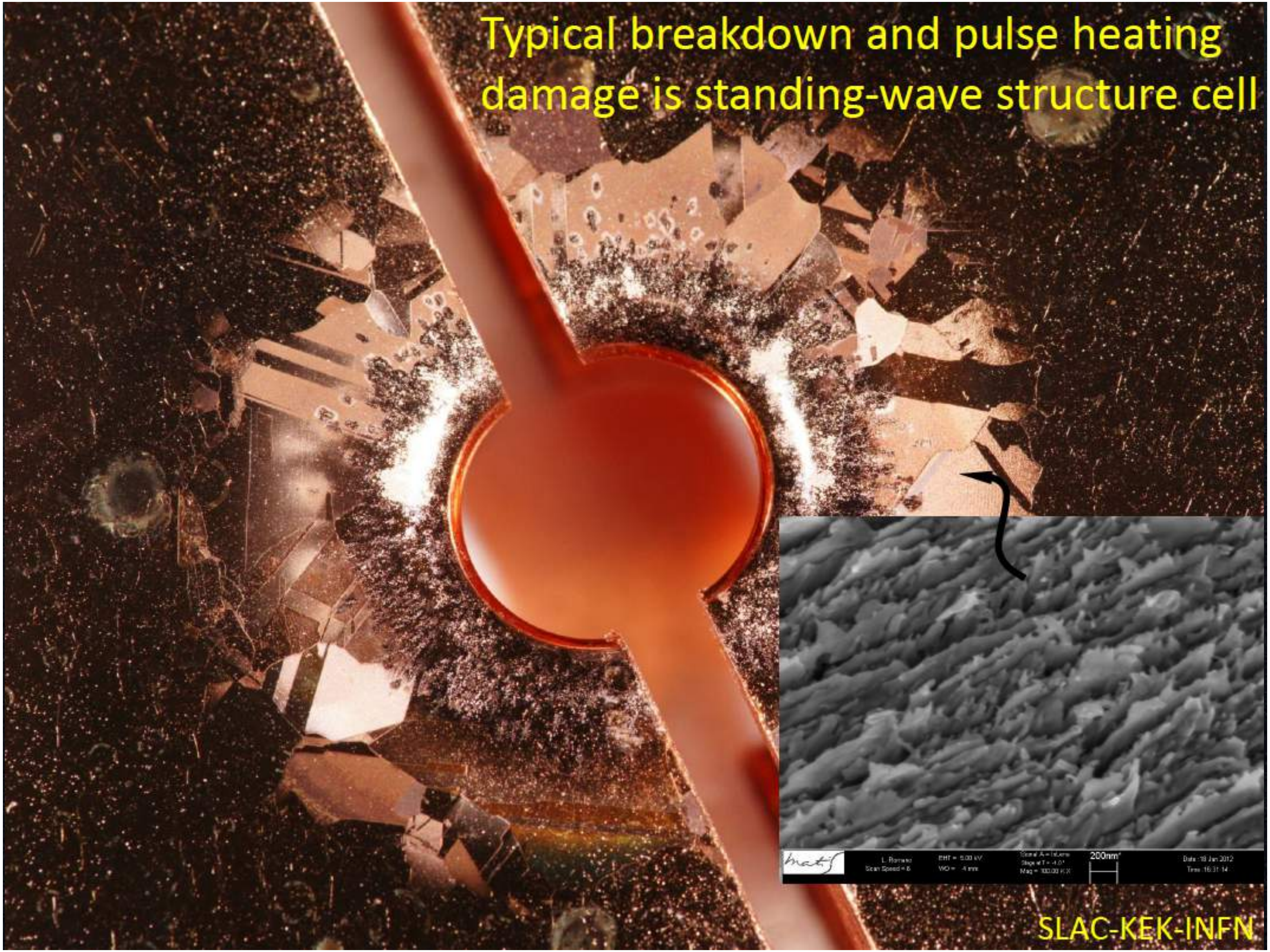
↑ $$B_n \approx \frac{2I}{\varepsilon_n^2}$$

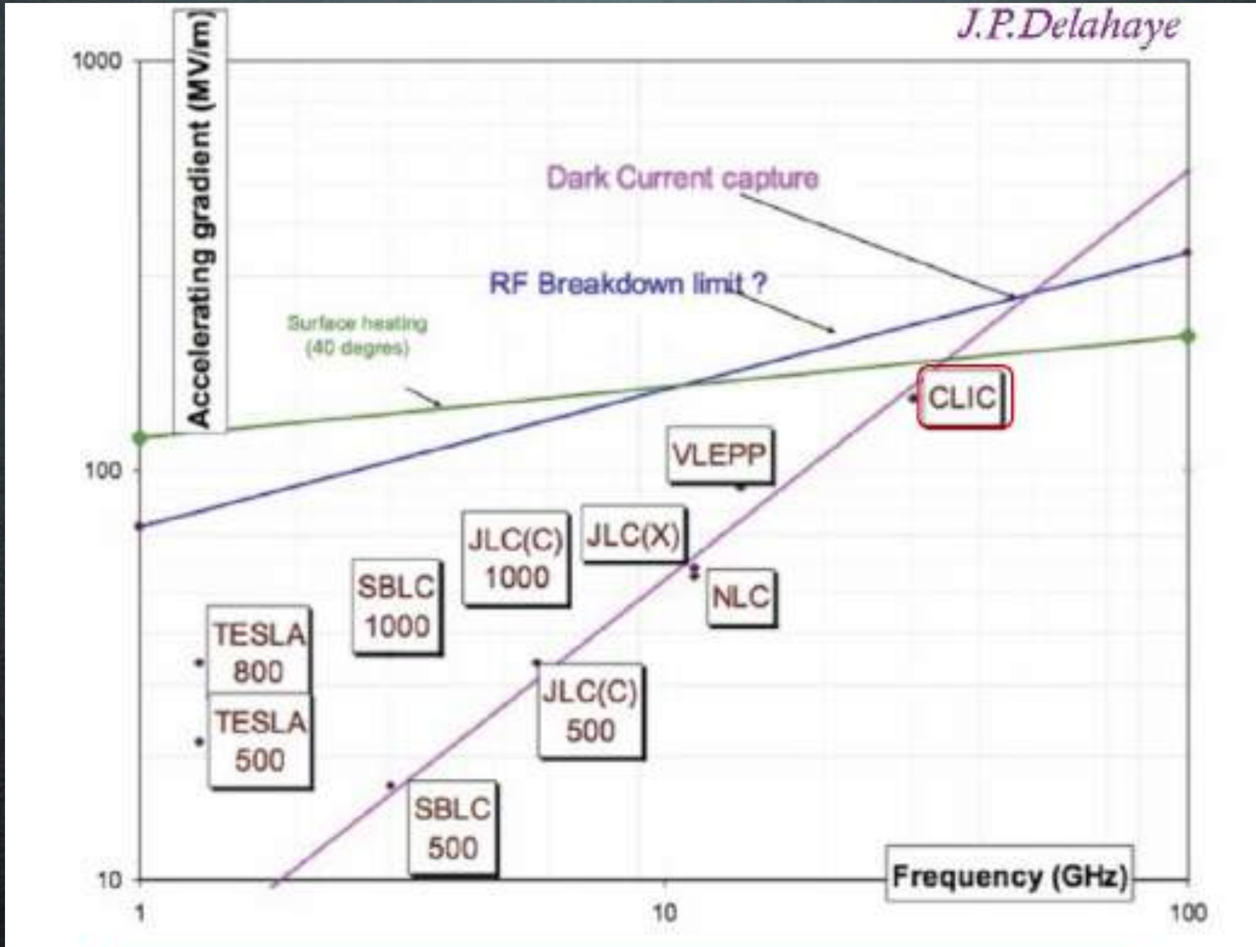
- −Short pulse (ps to fs)
- −Little spread in transverse momentum and angle => low emittance

# Conventional RF accelerating structures



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






## Breakdown limits metal:

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

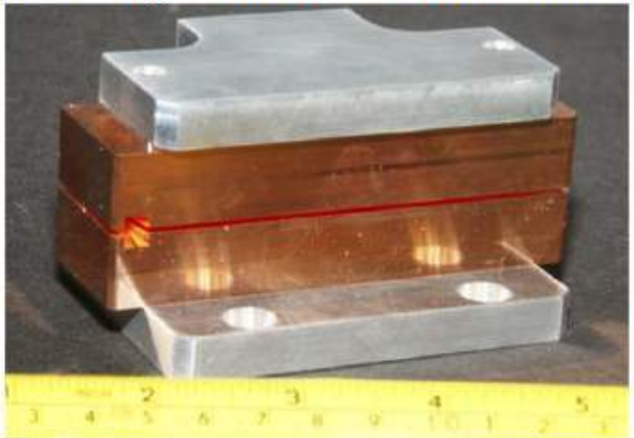
High field ->Short wavelength->ultra-short bunches-> low charge

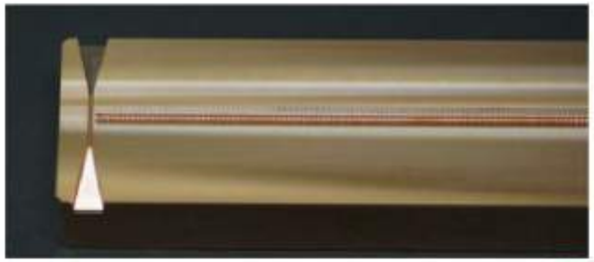
# Miniaturization of the accelerating structures

# Future plans for the high gradient collaboration

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

mm-Wave structure to be tested at FACET

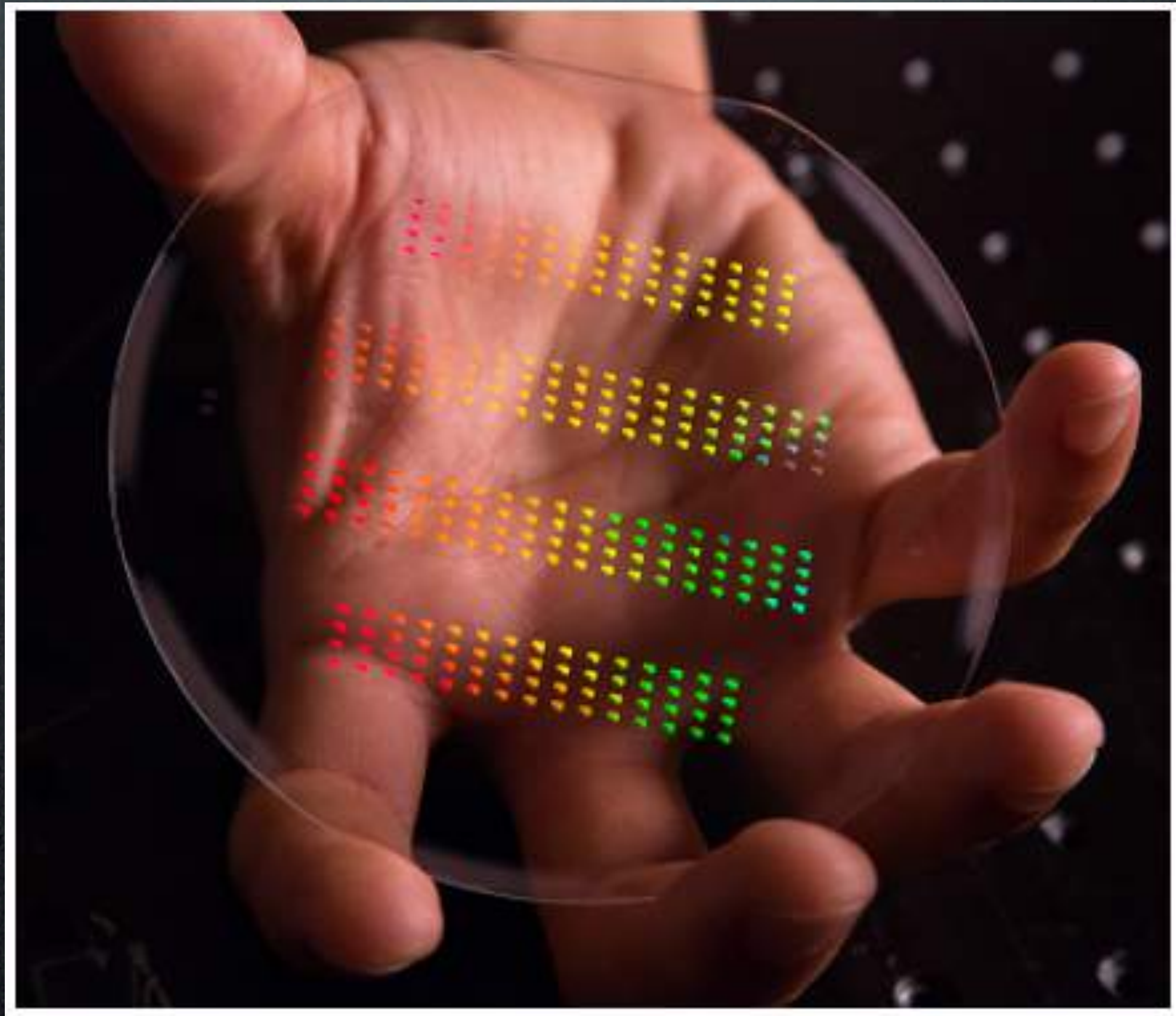




NATIONAL ACCELERATOR LABORATORY

# Direct Laser Acceleration
# DLA

# Accelerator on a Chip?



# Light Source on a Chip

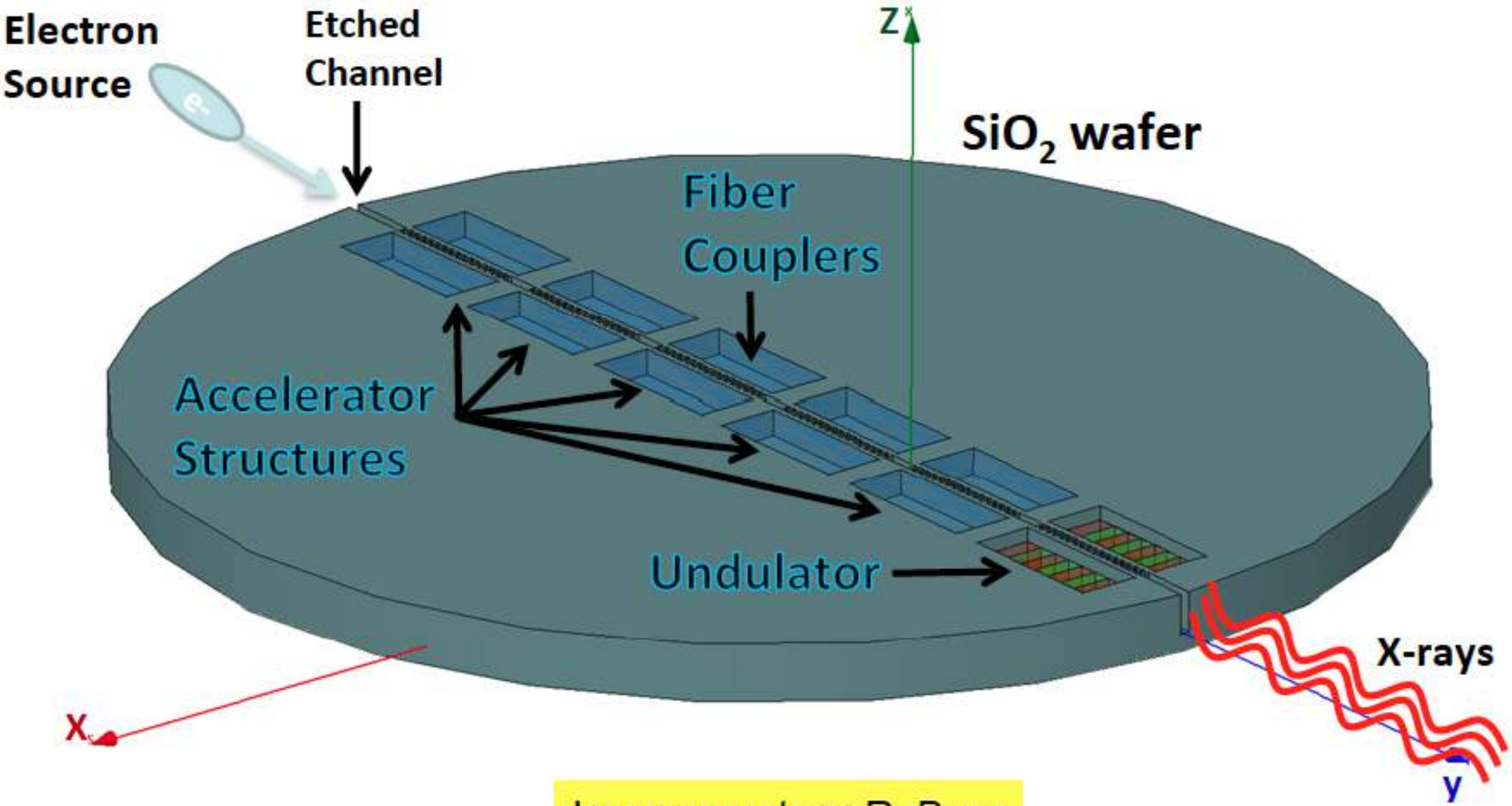
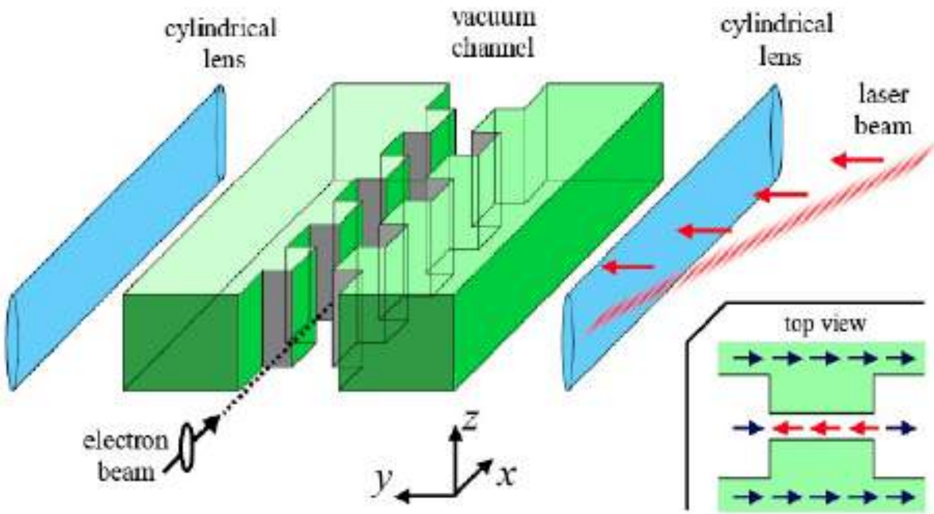
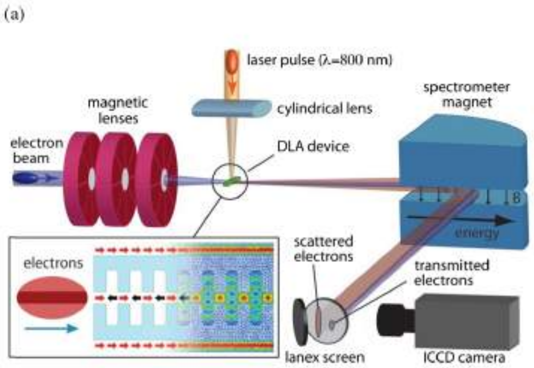


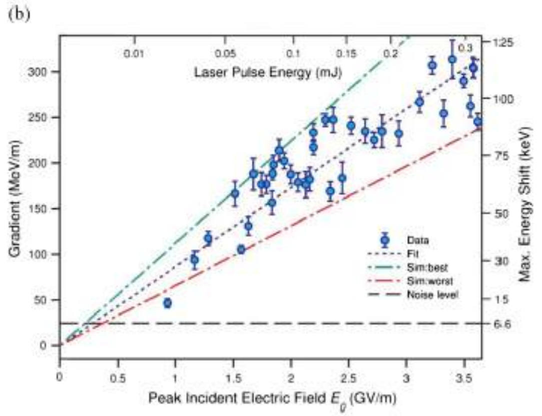

Image courtesy R. Byer

# Grating-Based Planar Structure




T. Plettner, et al. PRST-AB **9**, 111301 (2006).



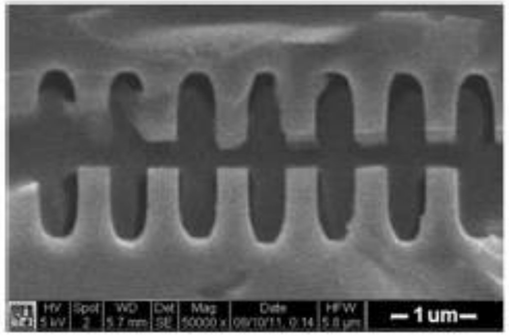




$SiO_2$ planar gratings with side-coupled laser and flat beam.

Periodic phase reset of the EM field results in a large accelerating gradient over many periods.

damage threshold for $SiO_2$ >3 GV/m @ 1ps

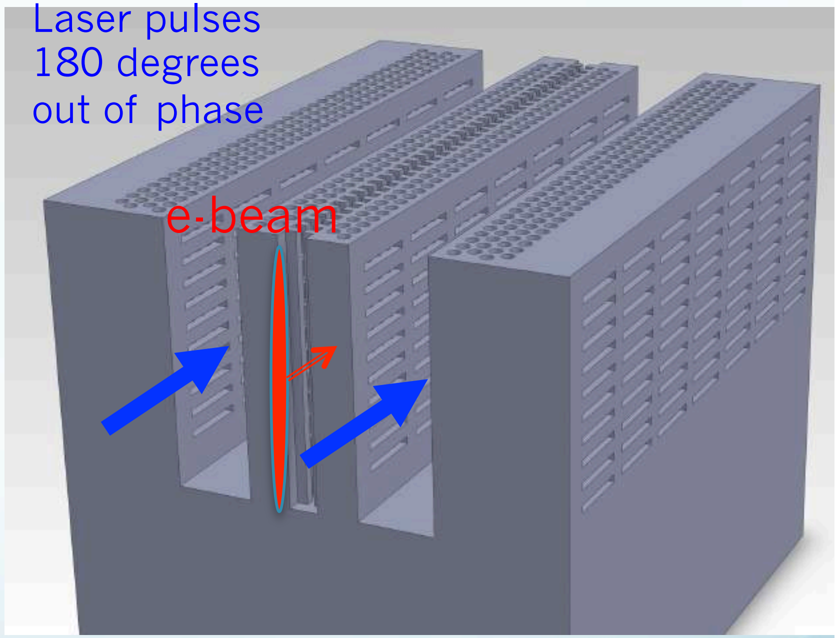
$G_{0,max}$ ~ 1GV/m




E. Peralta, recently fabricated prototype structure

# Dielectric Photonic Structure

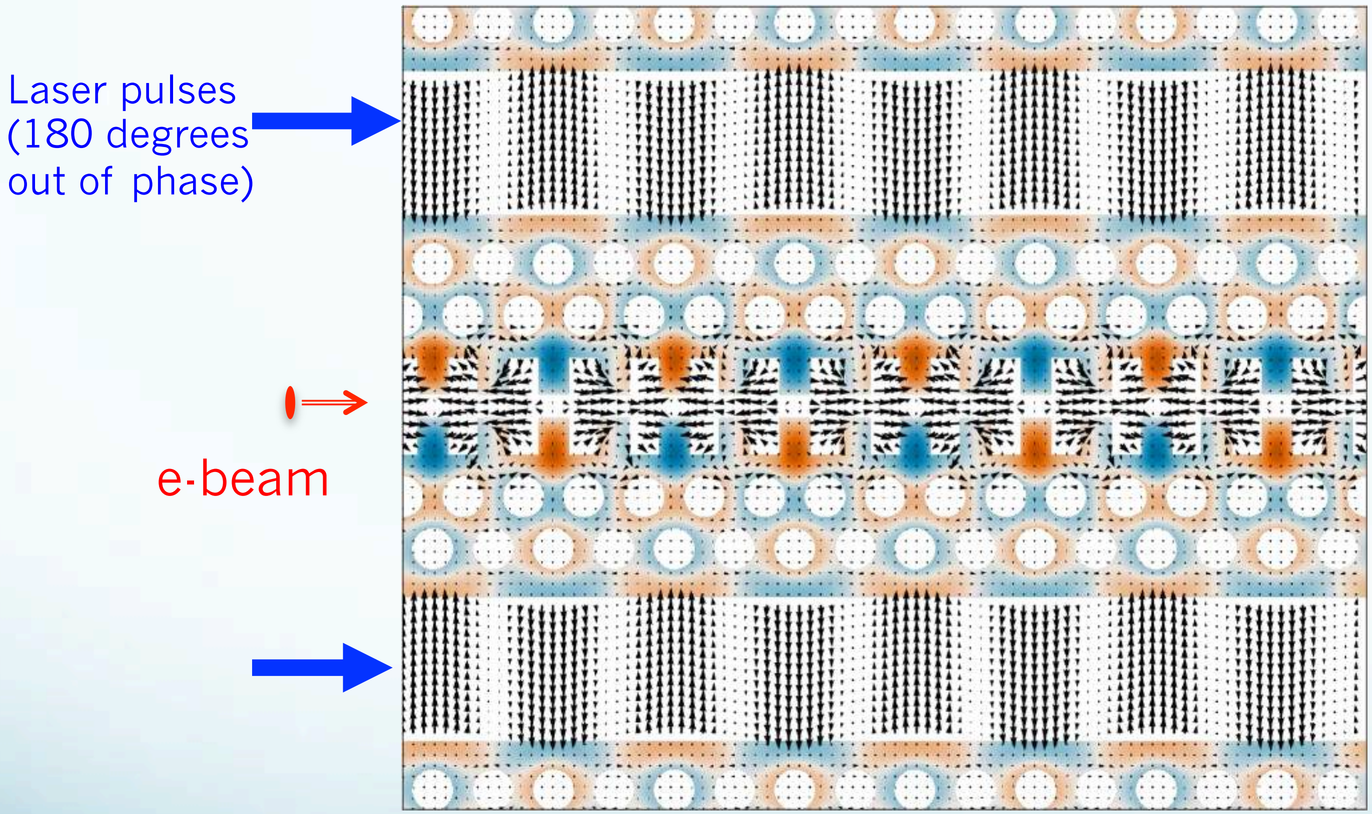
- Why photonic structures?
  - Natural in dielectric
  - Advantages of burgeoning field
    - design possibilities
    - Fabrication
- Dynamics concerns
- External coupling schemes




Schematic of GALAXIE
monolithic photonic DLA

# Laser-Structure Coupling: TW

GALAXIE Dual laser drive structure, large reservoir of power recycles

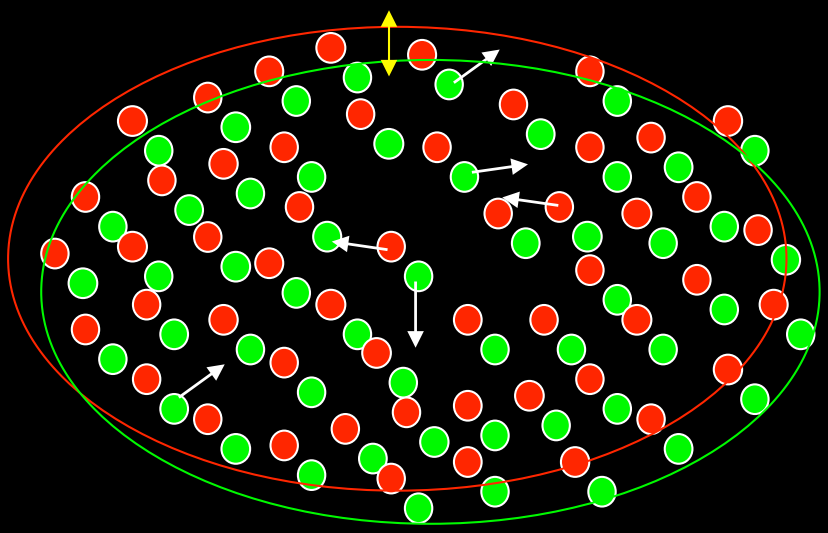


# Plasma Acceleration

Surface charge density

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

$\delta x$



Surface electric field

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

Restoring force

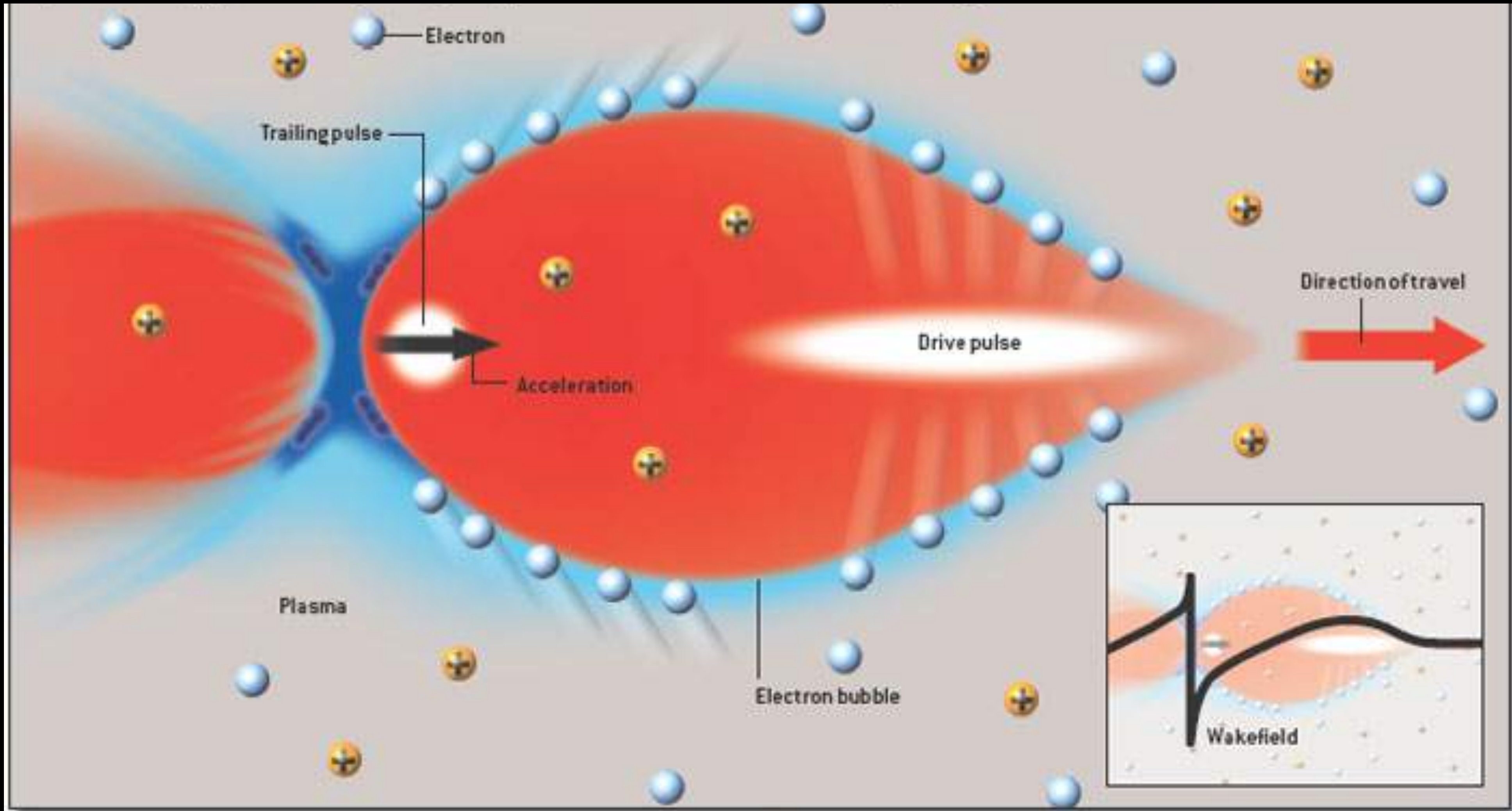
$$m\frac{d^2\delta x}{dt^2} = e\,E_x = -m\,\omega_p{}^2\,\delta x$$

Plasma frequency

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

Plasma oscillations

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

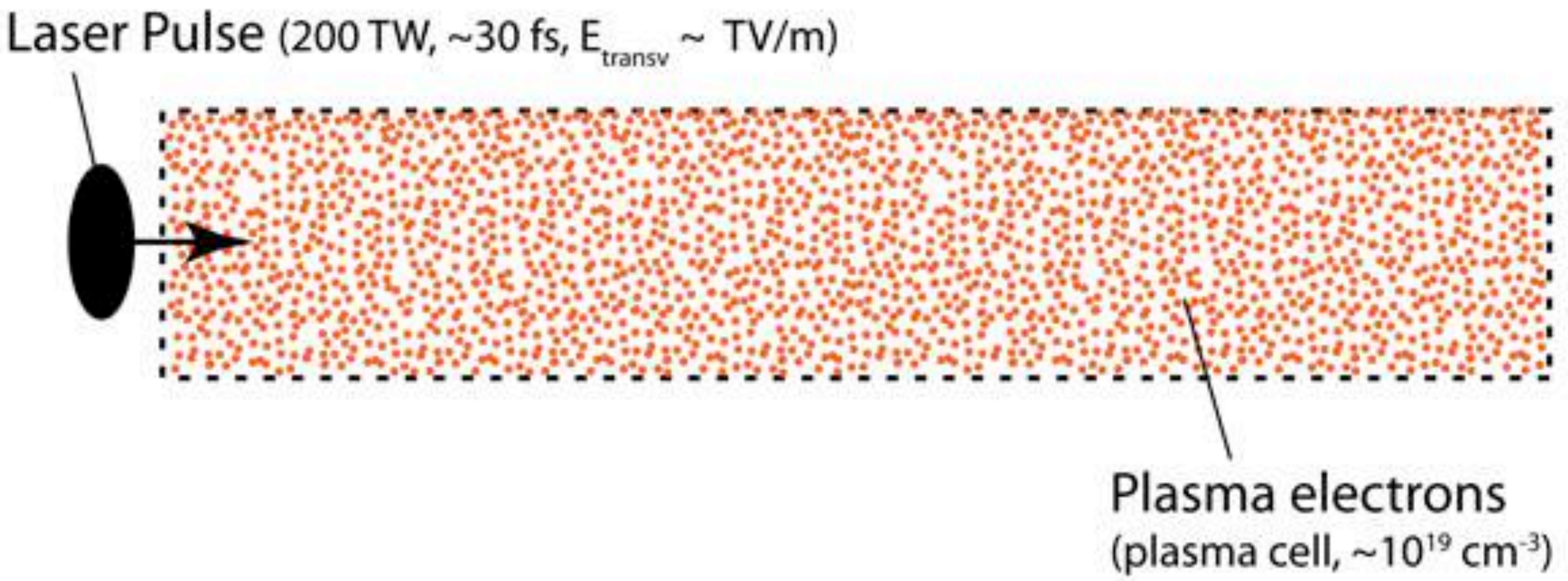



# Breakdown limit?

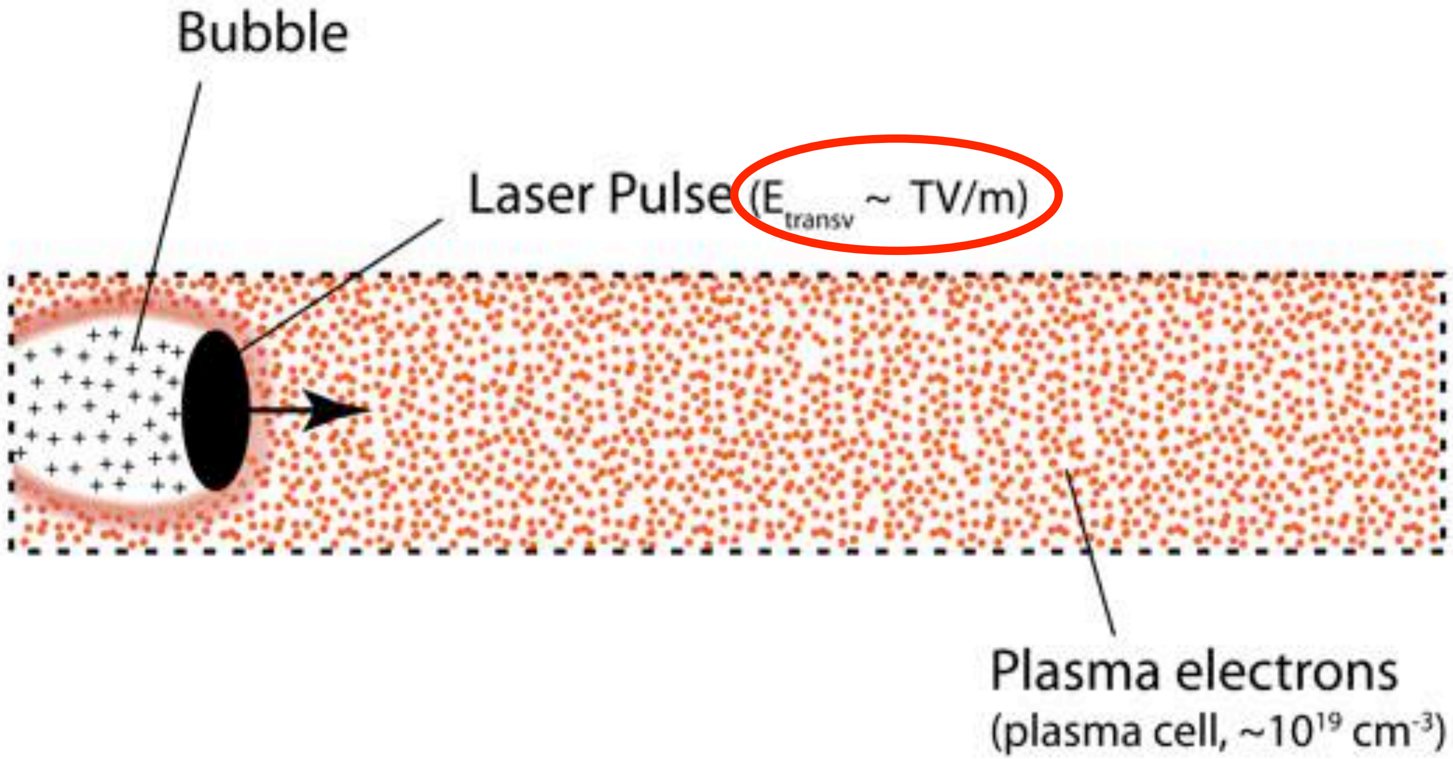
$$E_0 = \frac{m_e c \omega_p}{e} \approx 100[\frac{GeV}{m}] \cdot \sqrt{n_0[10^{18} cm^{-3}]}$$

# Laser Plasma-Acceleration
## (Internal Injection)

Horizon2020

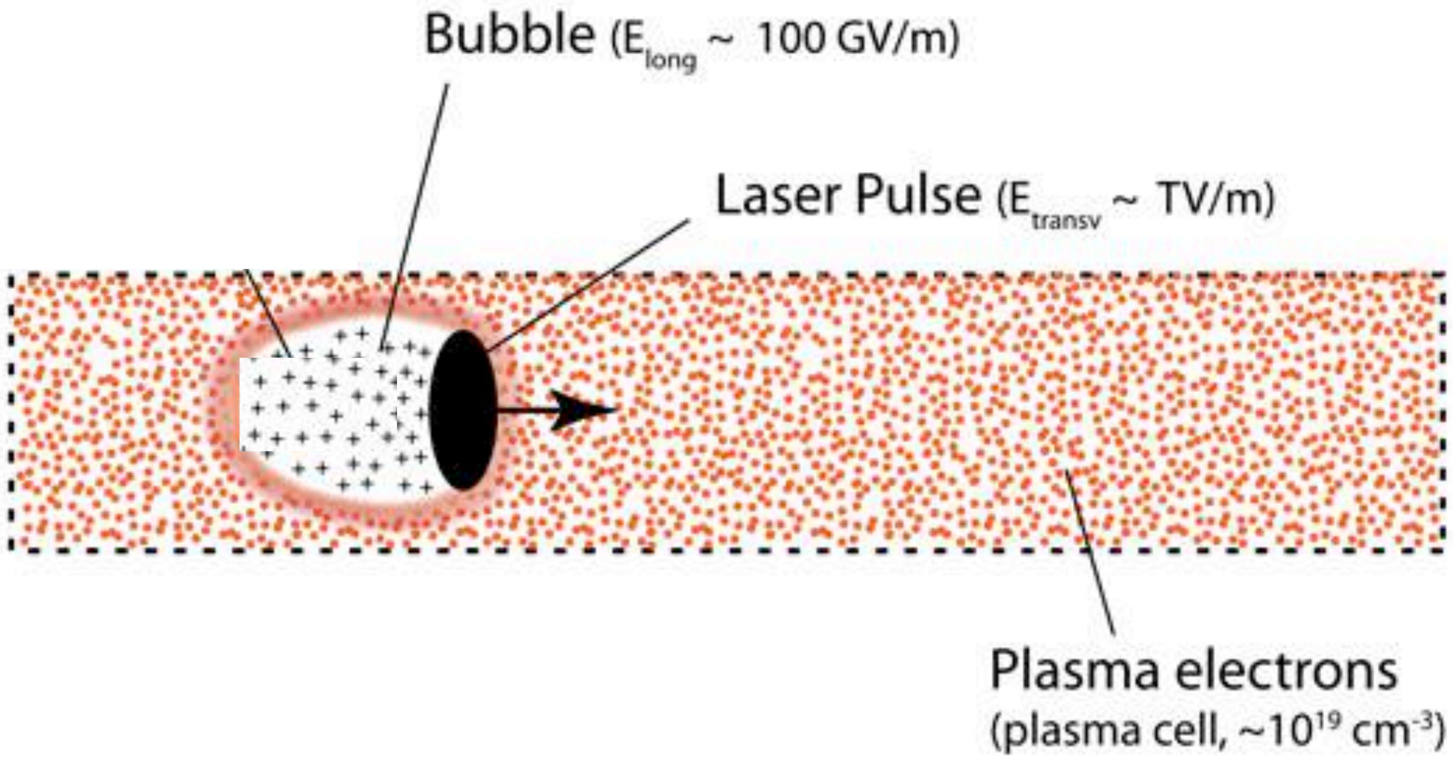


# Laser Plasma-Acceleration
## (Internal Injection)



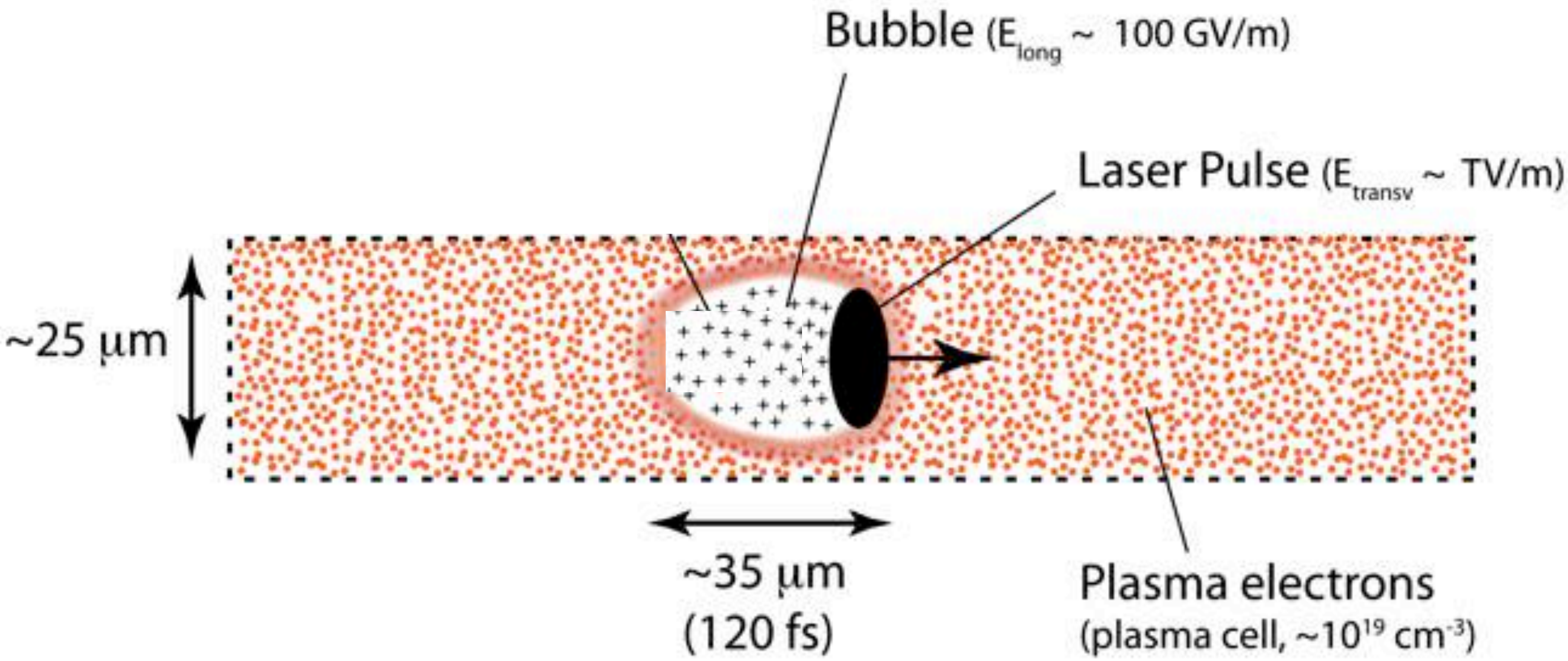
# Laser Plasma-Acceleration
## (Internal Injection)

Horizon2020

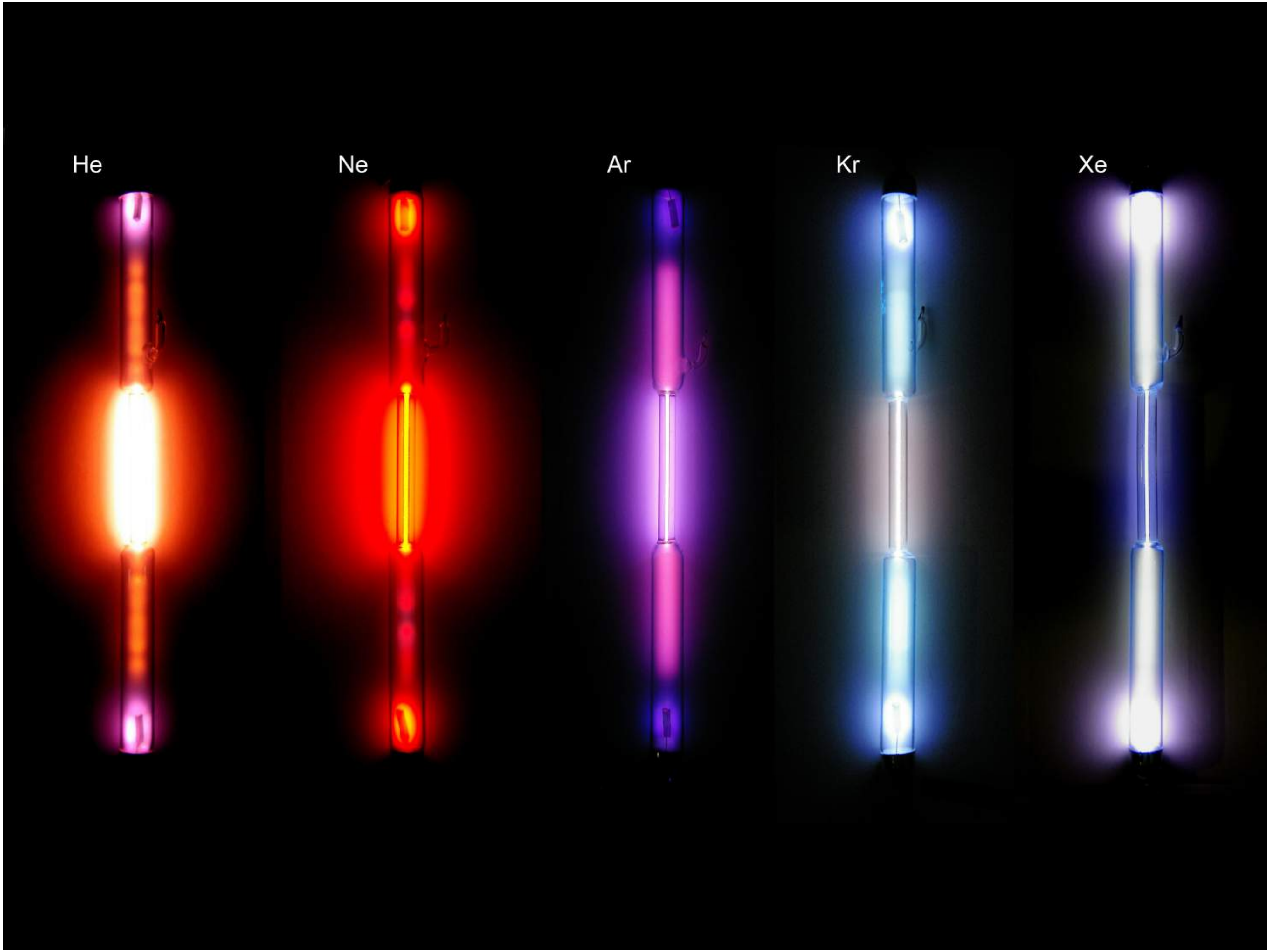


# Laser Plasma-Acceleration
## (Internal Injection)

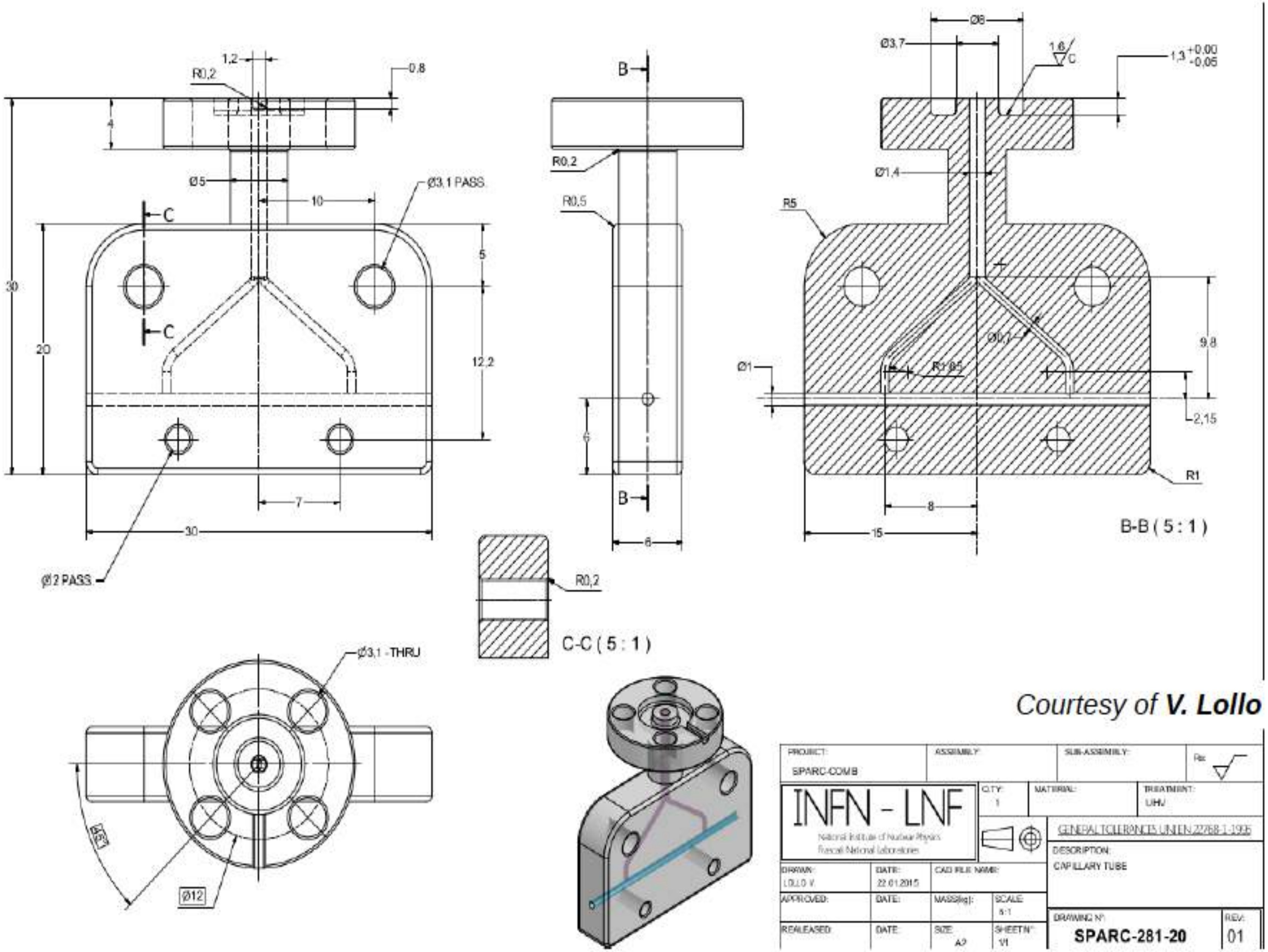
Horizon2020




**This accelerator fits into a human hair!**

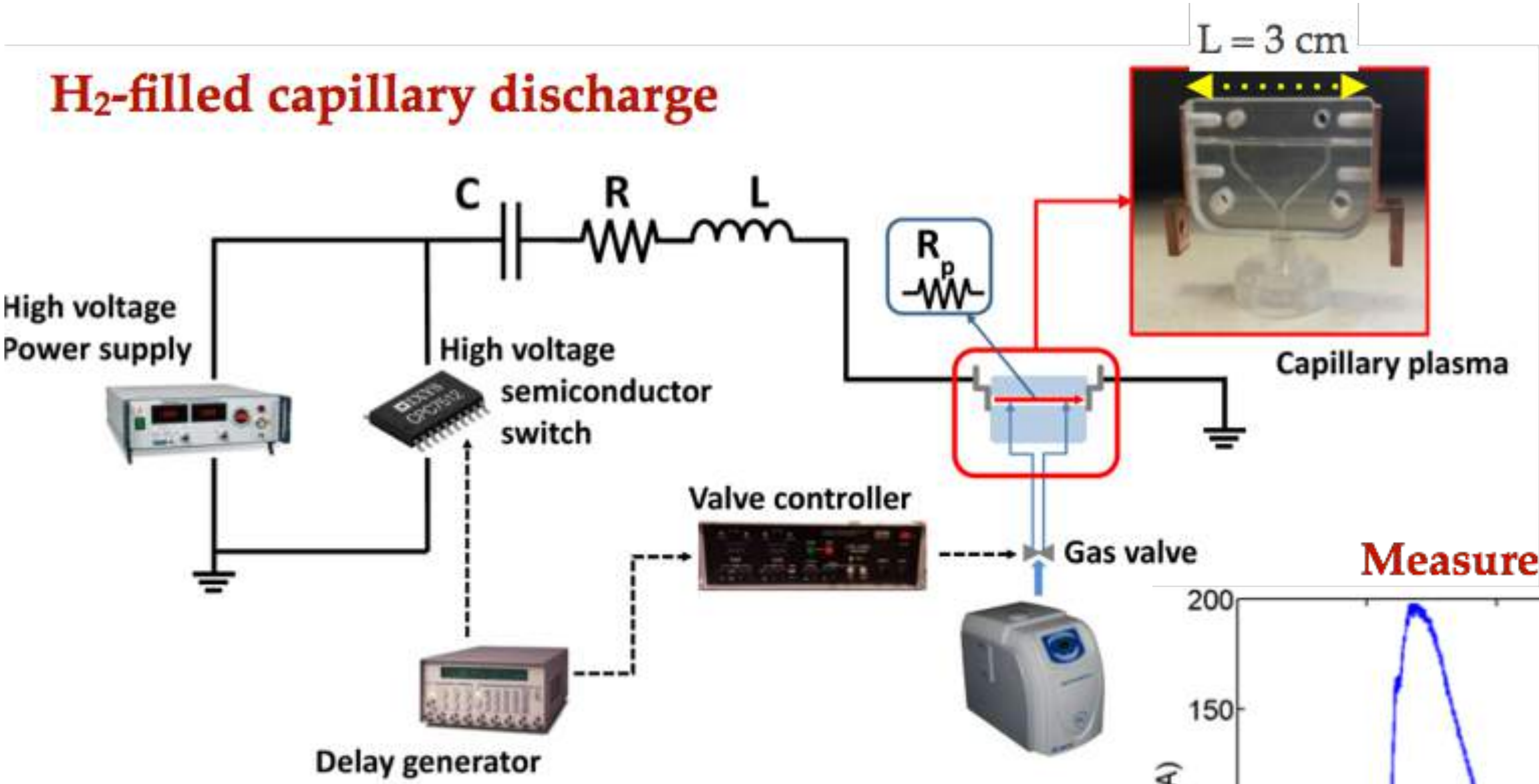

He
Ne
Ar
Kr
Xe

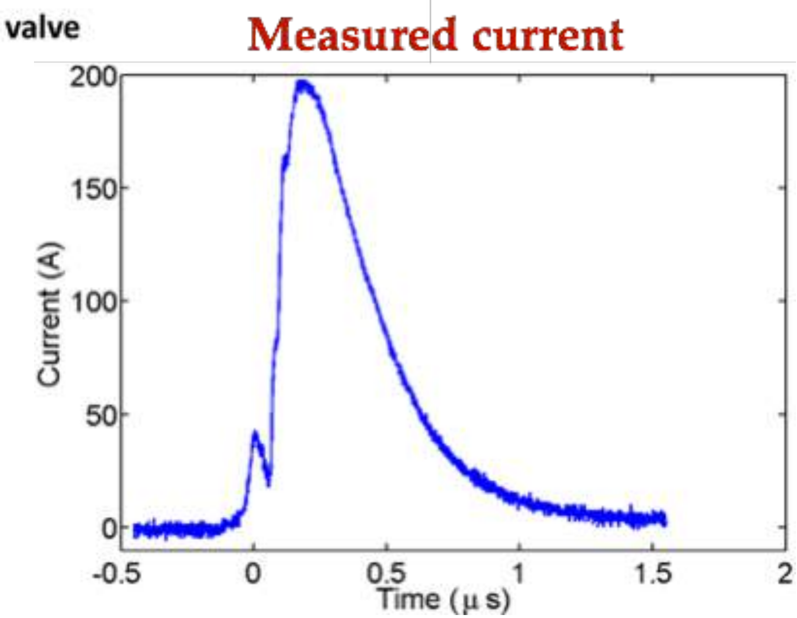
# Plasma capillary




Courtesy of ***V. Lollo***

# Plasma Source



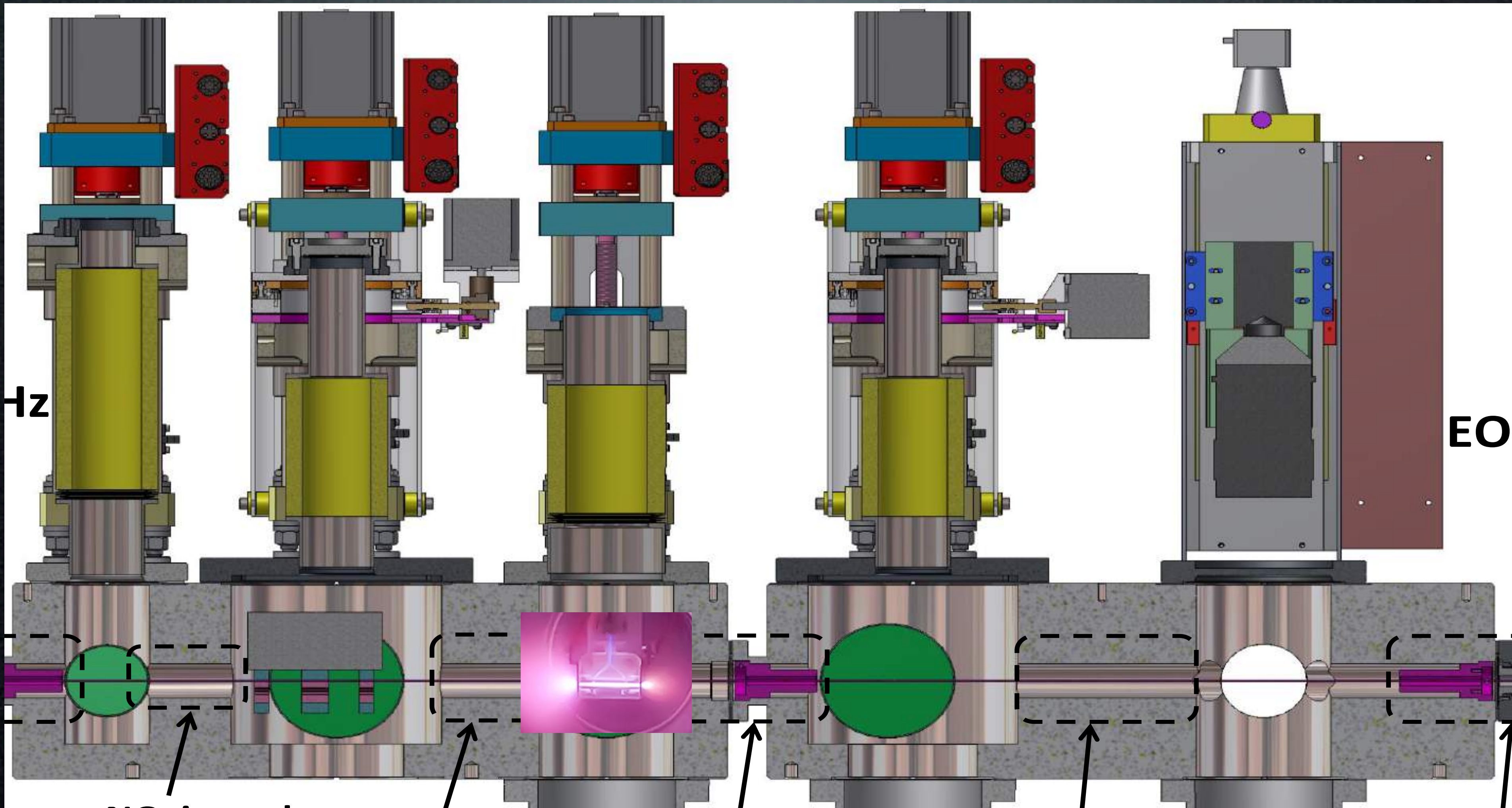




$P_{H2}$ = 10 mbar
Total discharge duration: 800 ns
Voltage: 20 kV
Peak current: 200 A
Capacitor: 6 nF

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

# Capillary Discharge

# SPARC_LAB Plasma Vacuum Chamber




Focusing PMQ

PWFA module

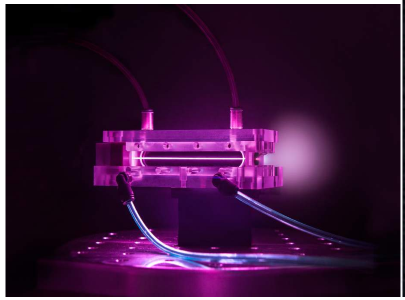
Capture PMQ

# 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

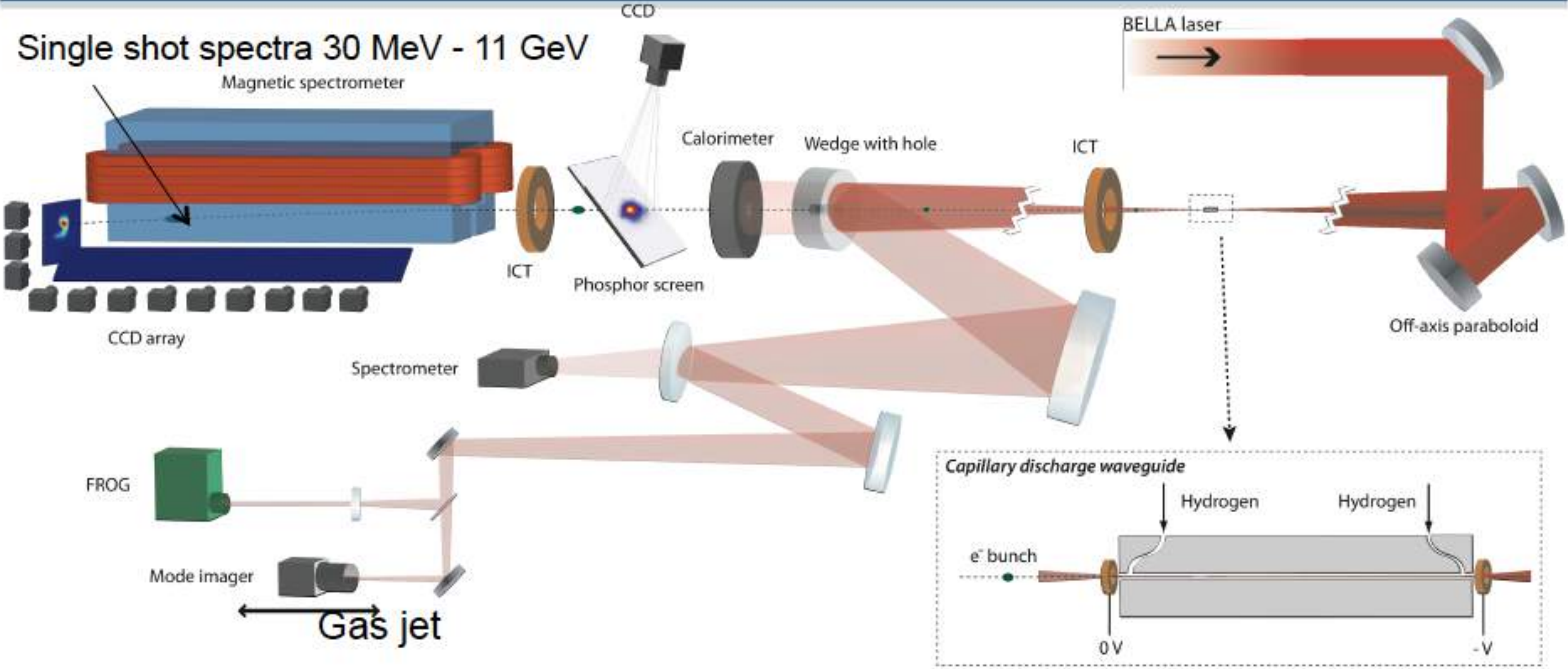

Critical HEP experiments:

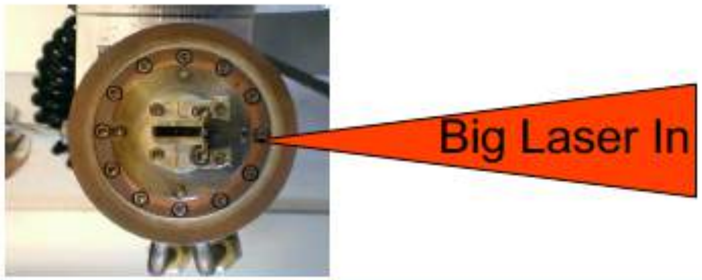
- 10 GeV electron beam from <1 m LPA
- Staging LPAs
- Positron acceleration



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

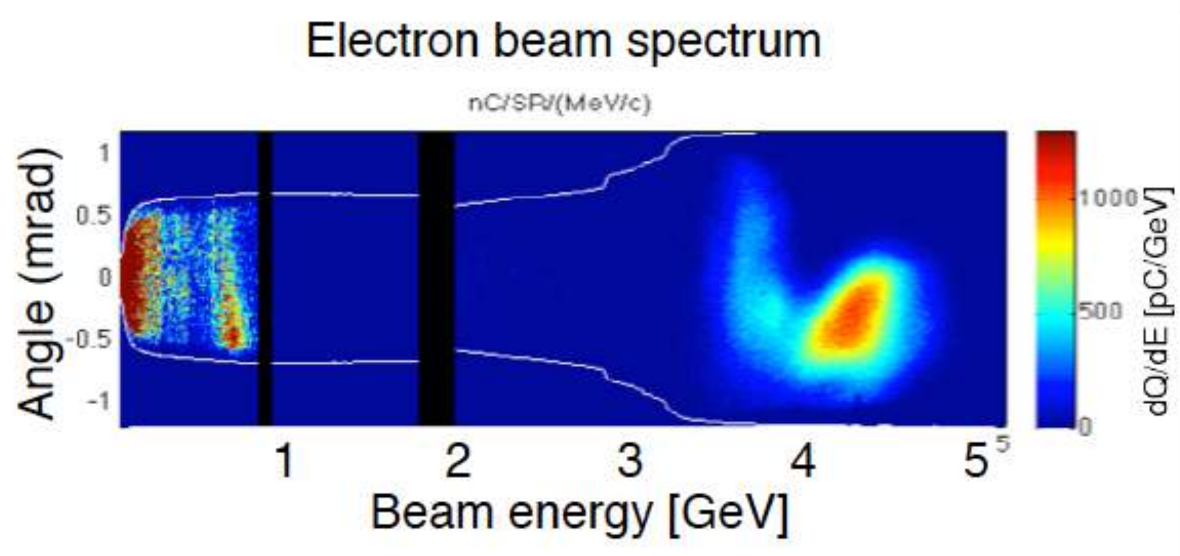


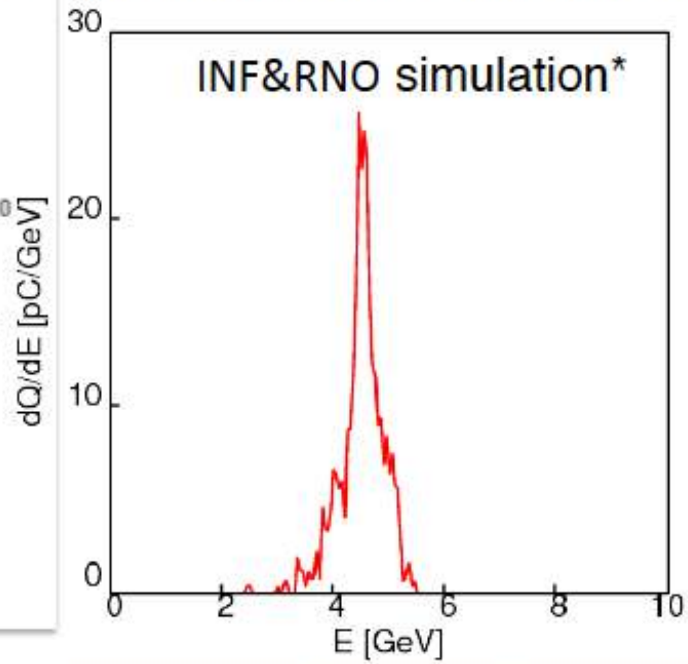




Capillary discharge

# 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



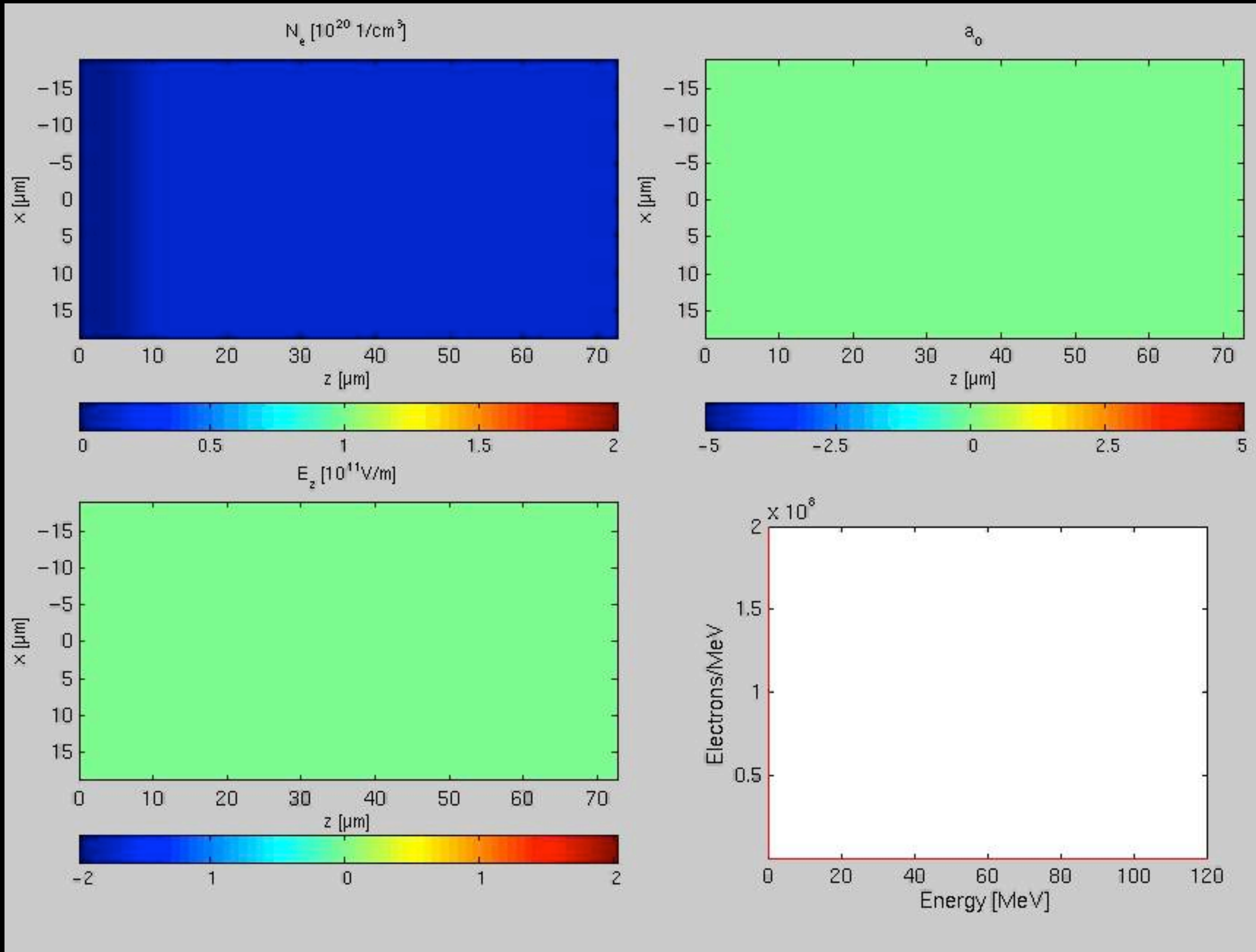




- **Laser** (E=15 J):
  - Measured) longitudinal profile ($T_0$= 40 fs)
  - Measured far field mode ($w_0$=53 μm)
- **Plasma:** parabolic plasma channel (length 9 cm, $n_0$~6-7x$10^{17}$ $cm^{-3}$)

| | 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 |

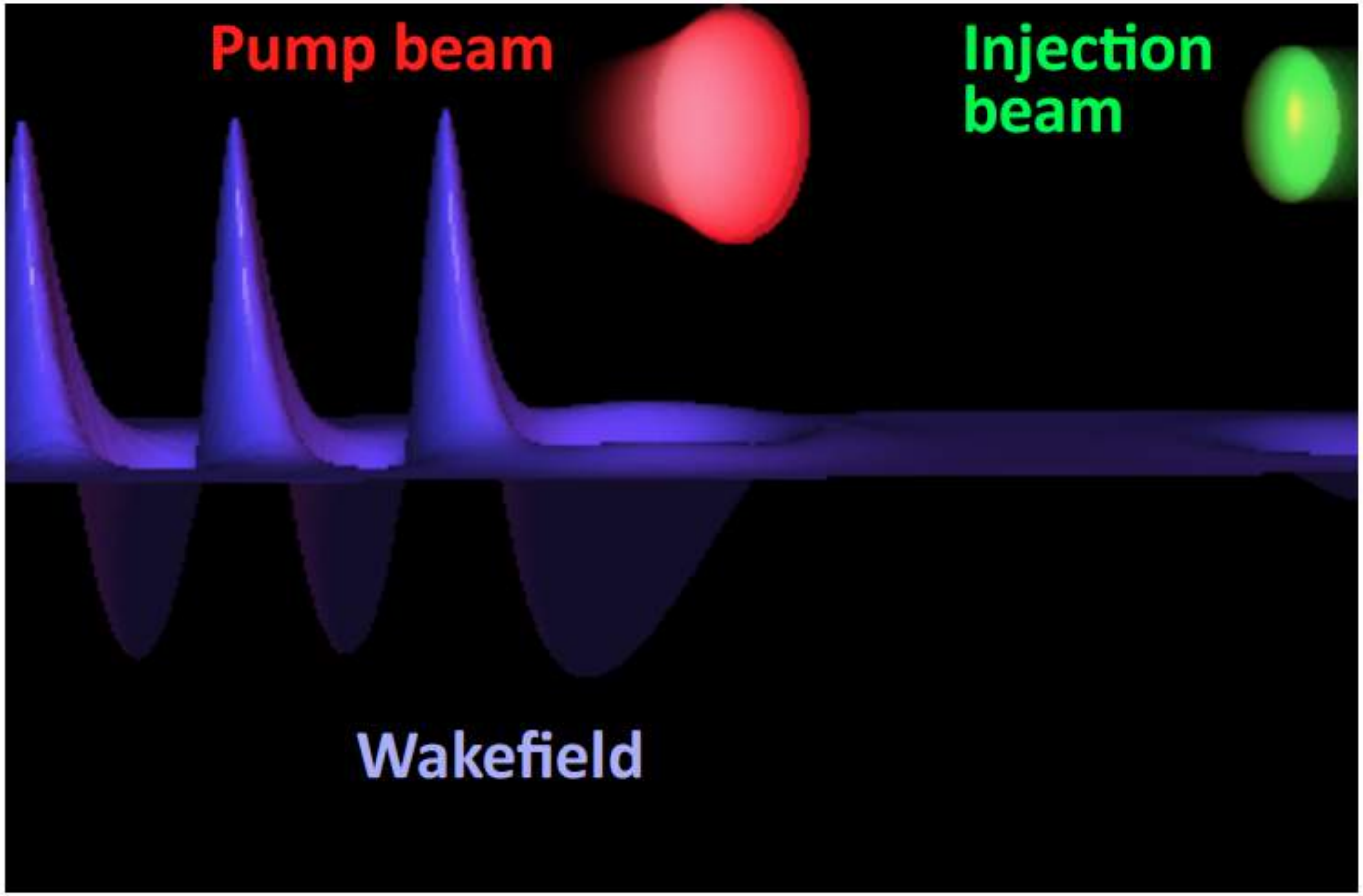
W.P. Leemans et al.,PRL 2014

# 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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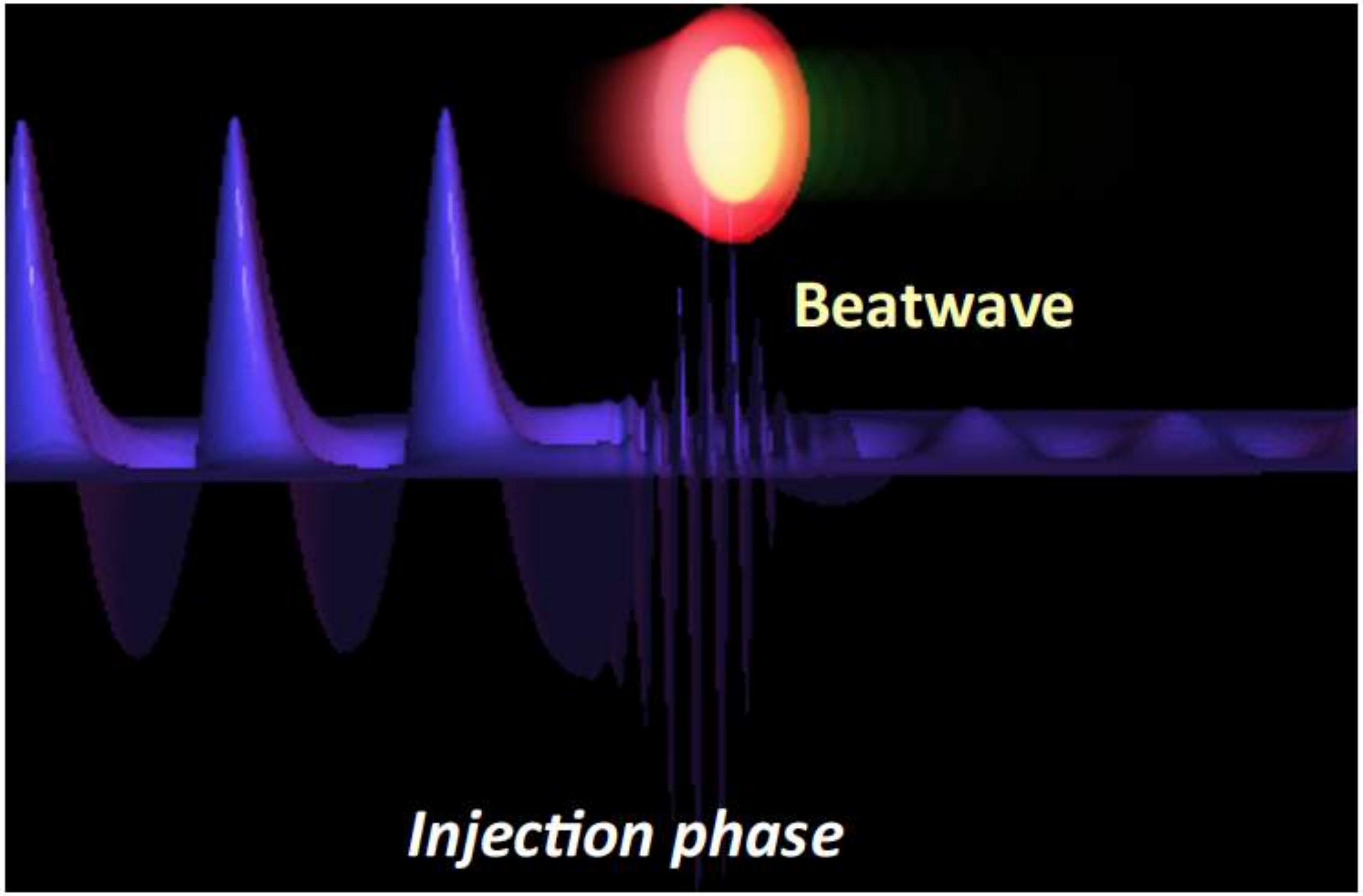


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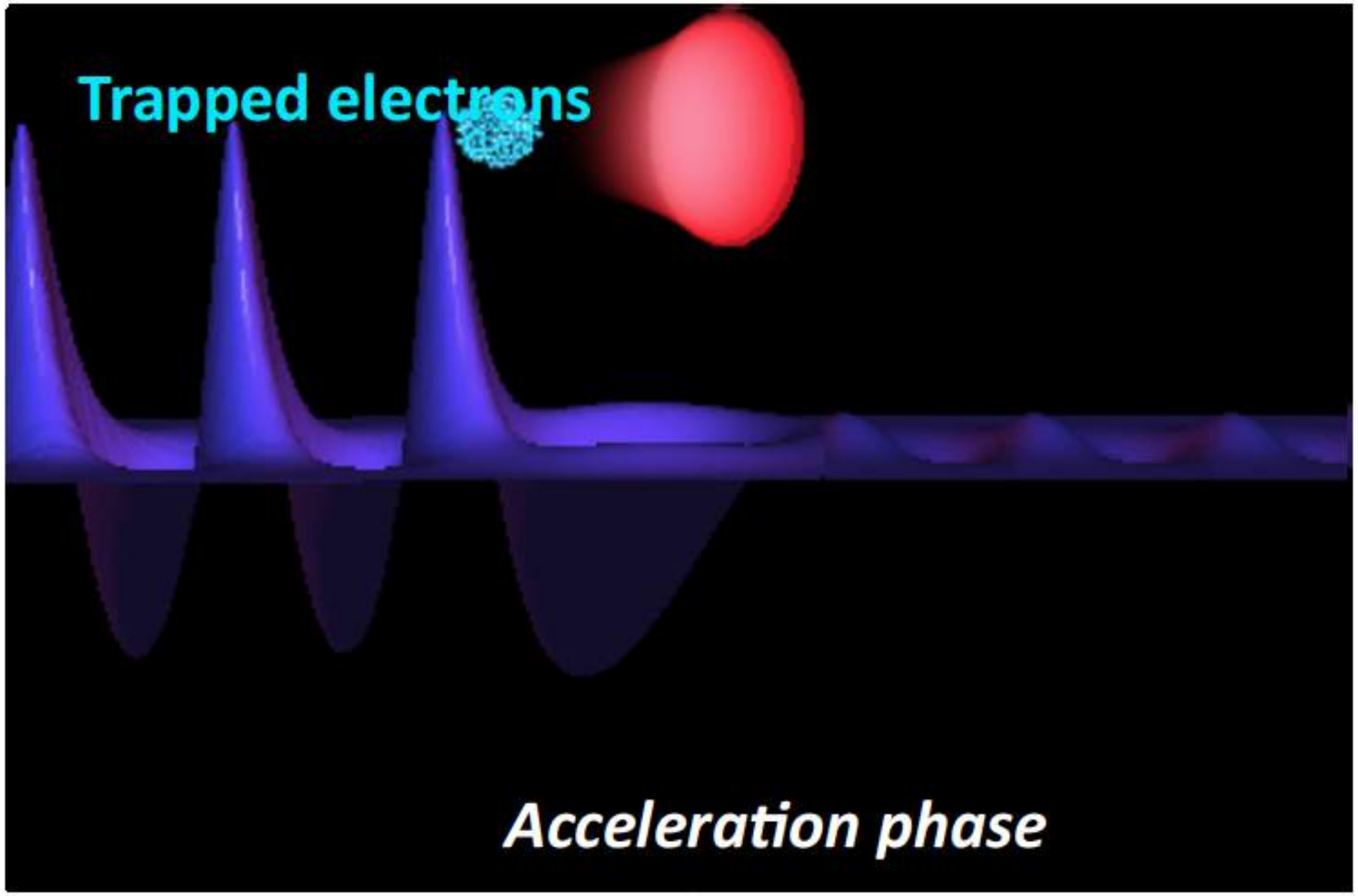
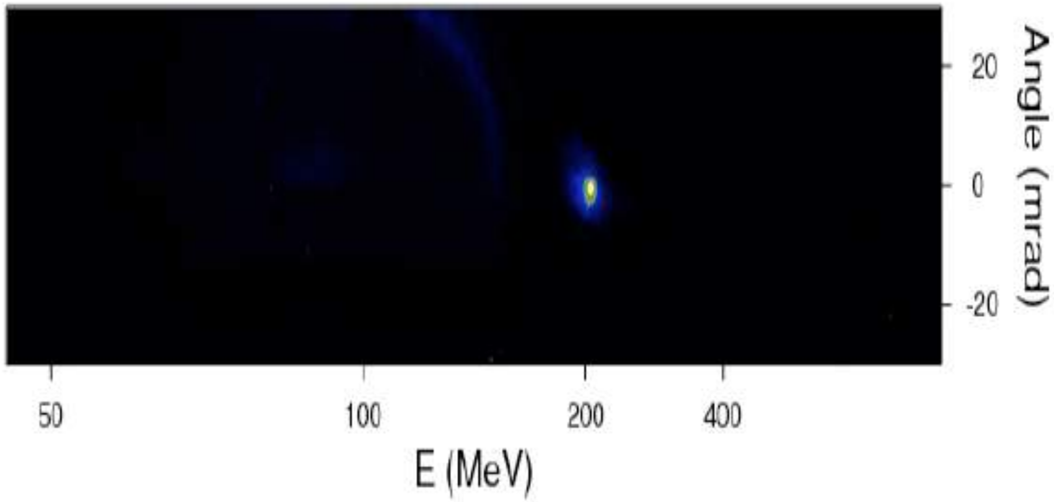
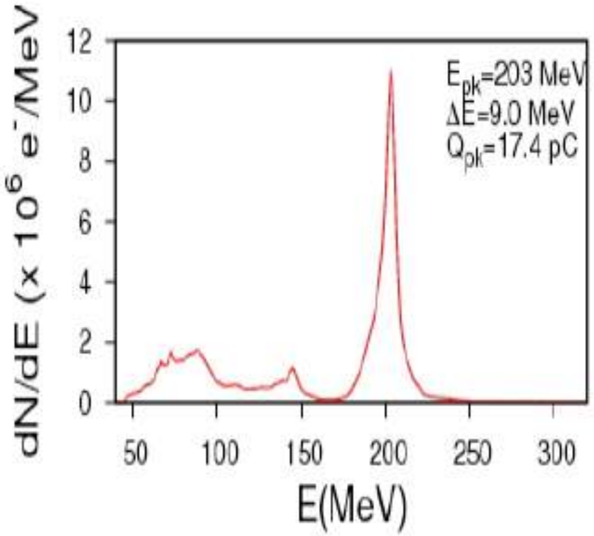


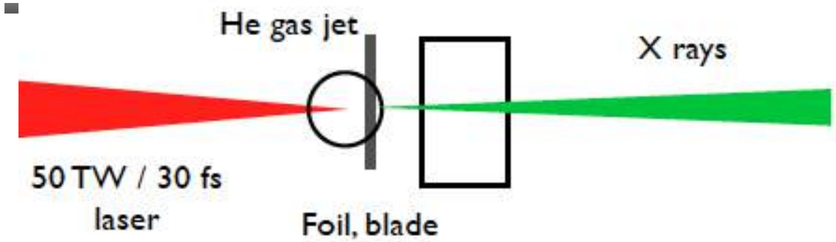

Theory : E. Esarey *et al.*, PRL **79**, 2682 (1997), H. Kotaki *et al.*, PoP **11** (2004)
Experiments : J. Faure *et al.*, Nature **444**, 737 (2006)

# Stable Laser Plasma Accelerators



# Inverse Compton Scattering : New scheme



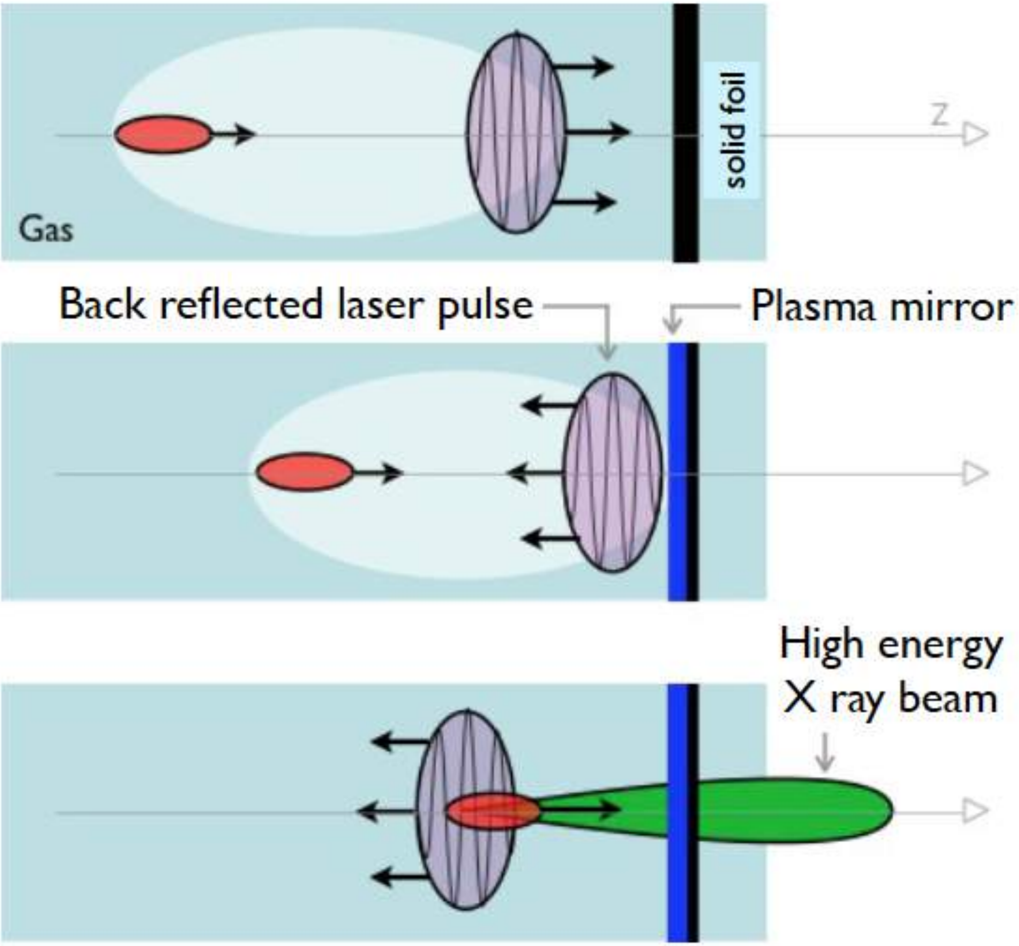

A single laser pulse

A plasma mirror reflects the laser beam

The back reflected laser collides with the accelerated electrons

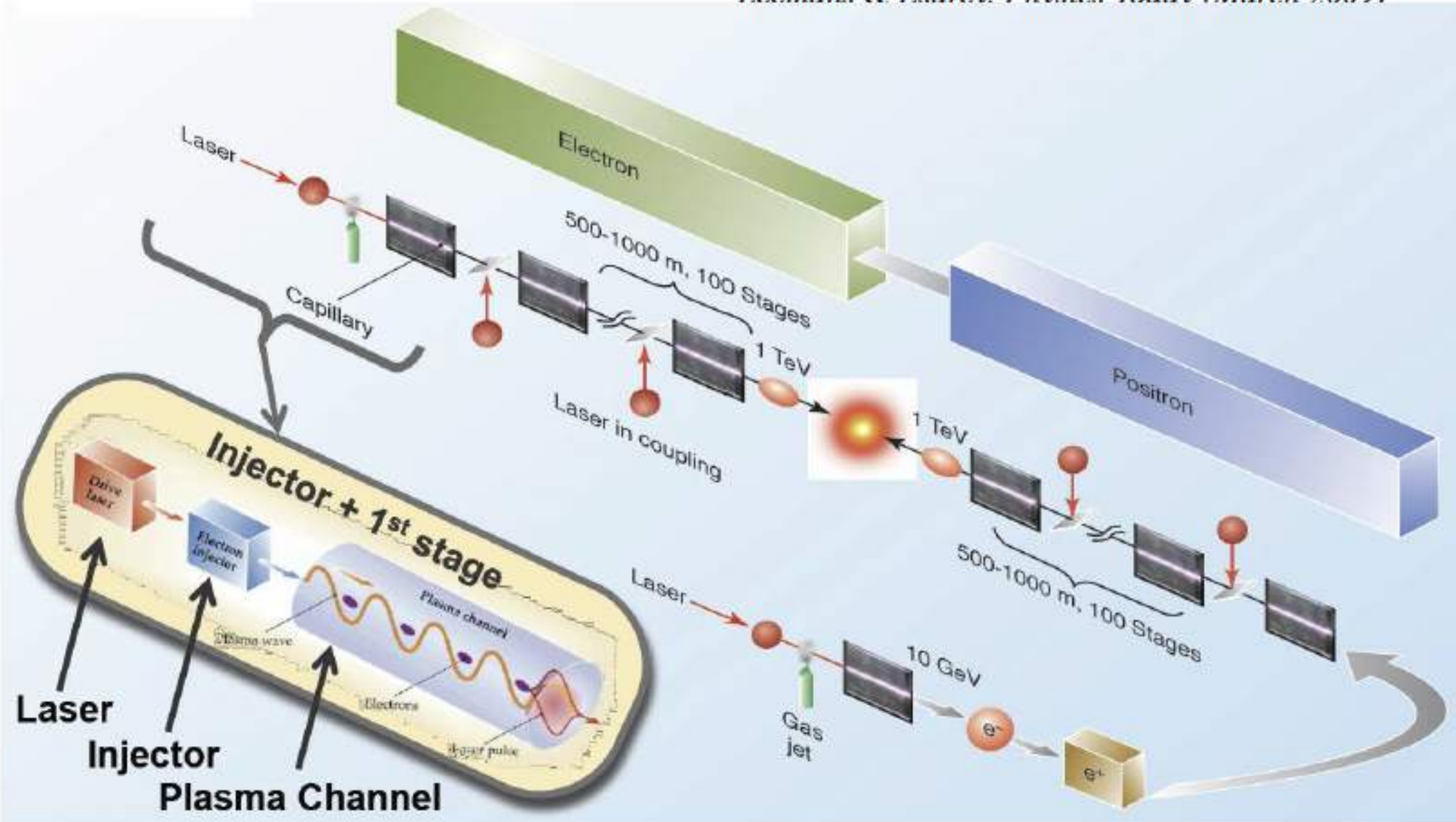
No alignment : the laser and the electron beams naturally overlap

Save the laser energy !



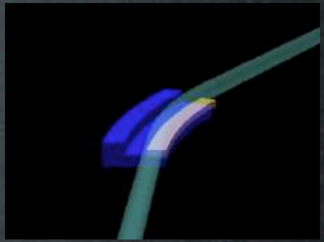
# Laser-Plasma-Accelerator LC

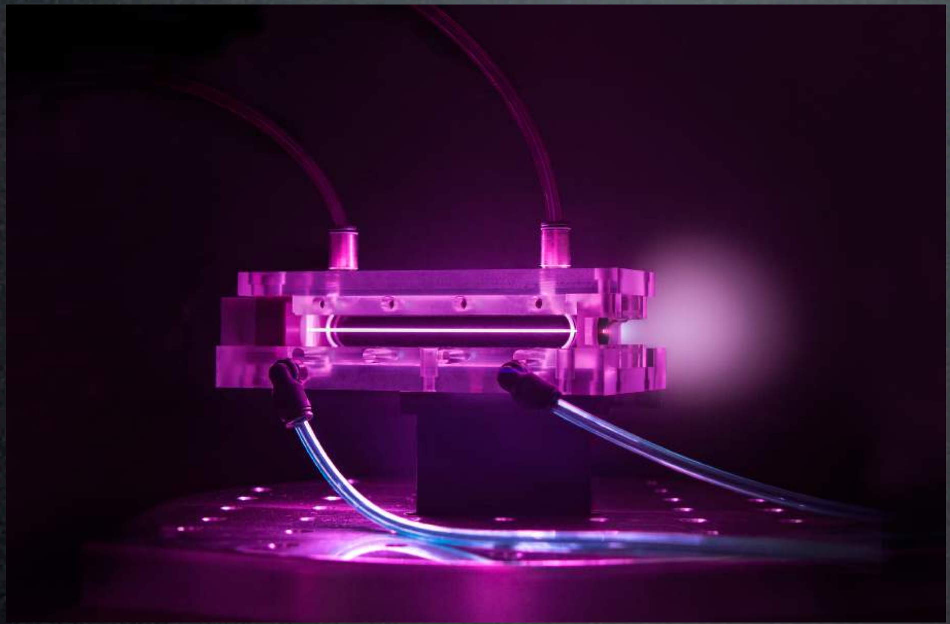
*Leemans & Esarey, Physics Today (March 2009)*

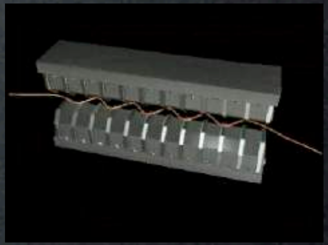


# Generations of Synchrotron Light Sources

I. Bending magnets in HEP rings

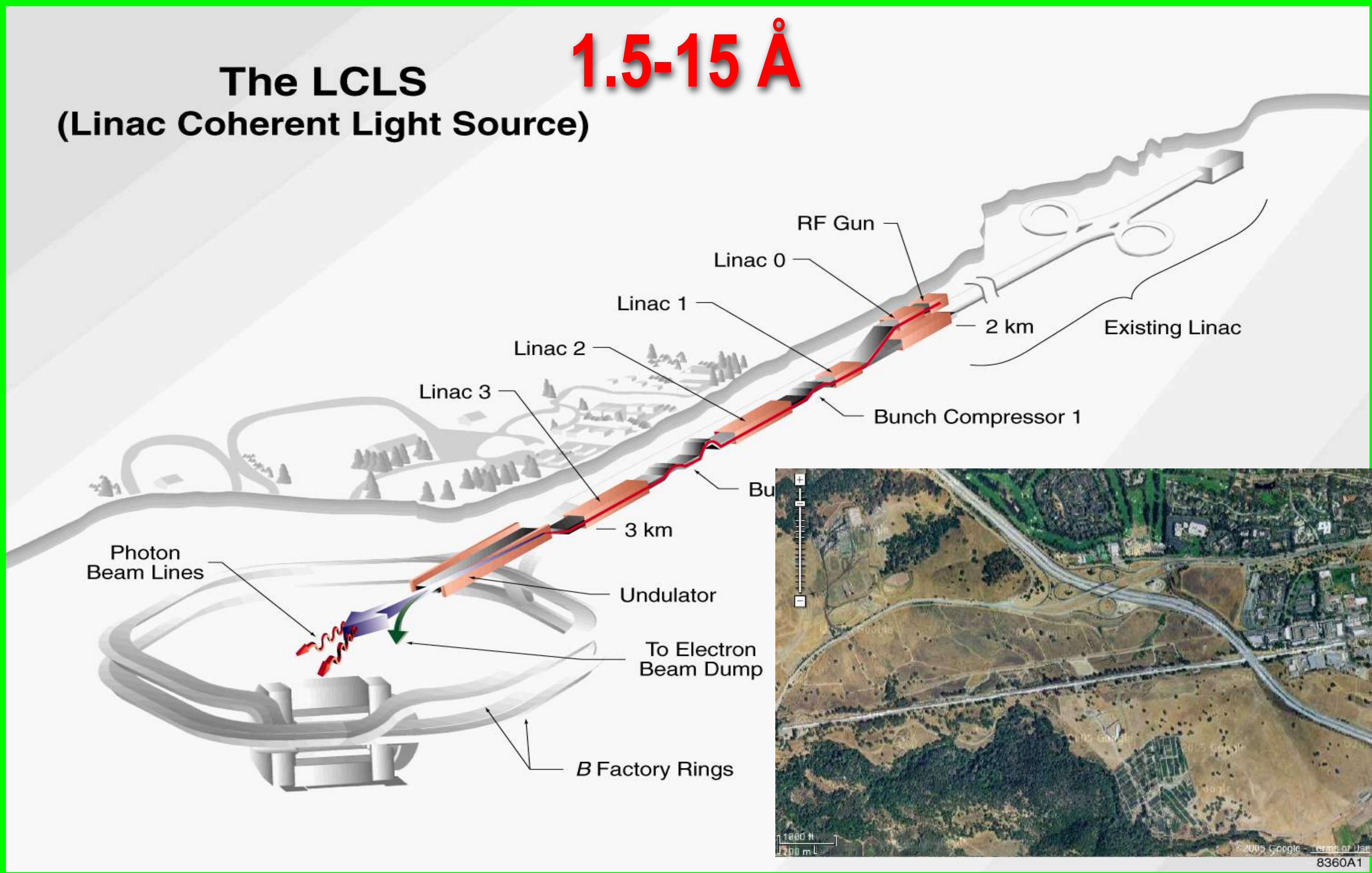






V. Compact Sources

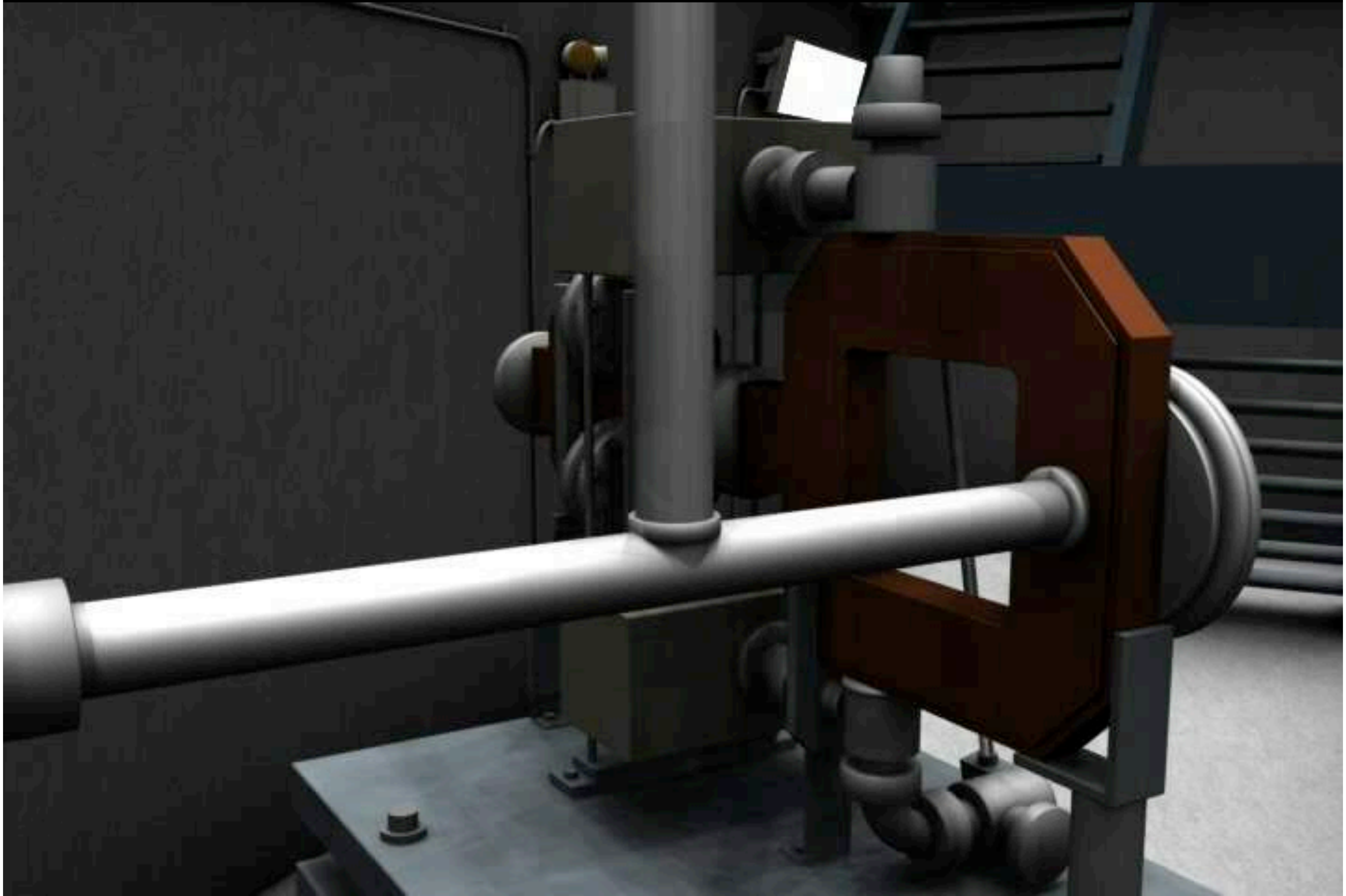
# LCLS at *SLAC*




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

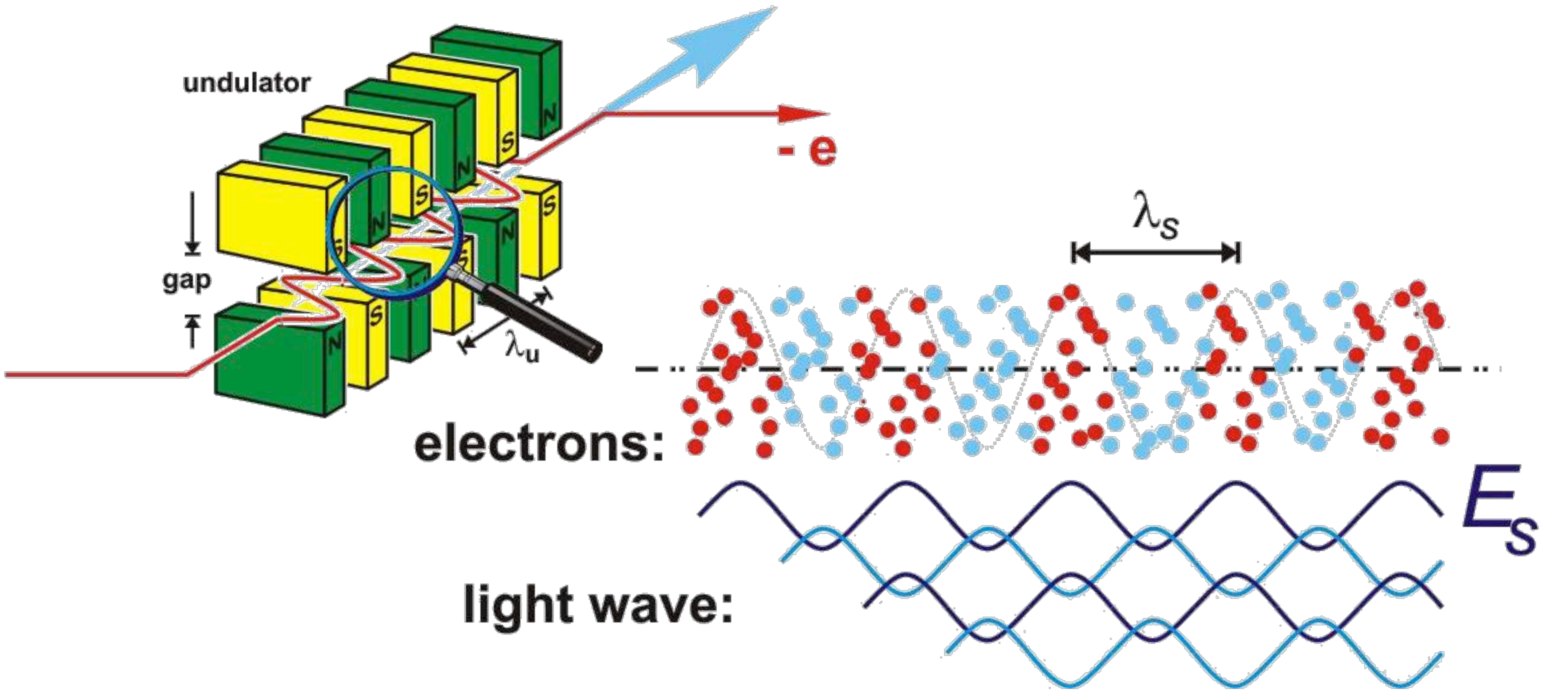
# XFEL first lasing – Hamburg May 2017

# Electron source and acceleration



# Long undulators chain

# Beam separation

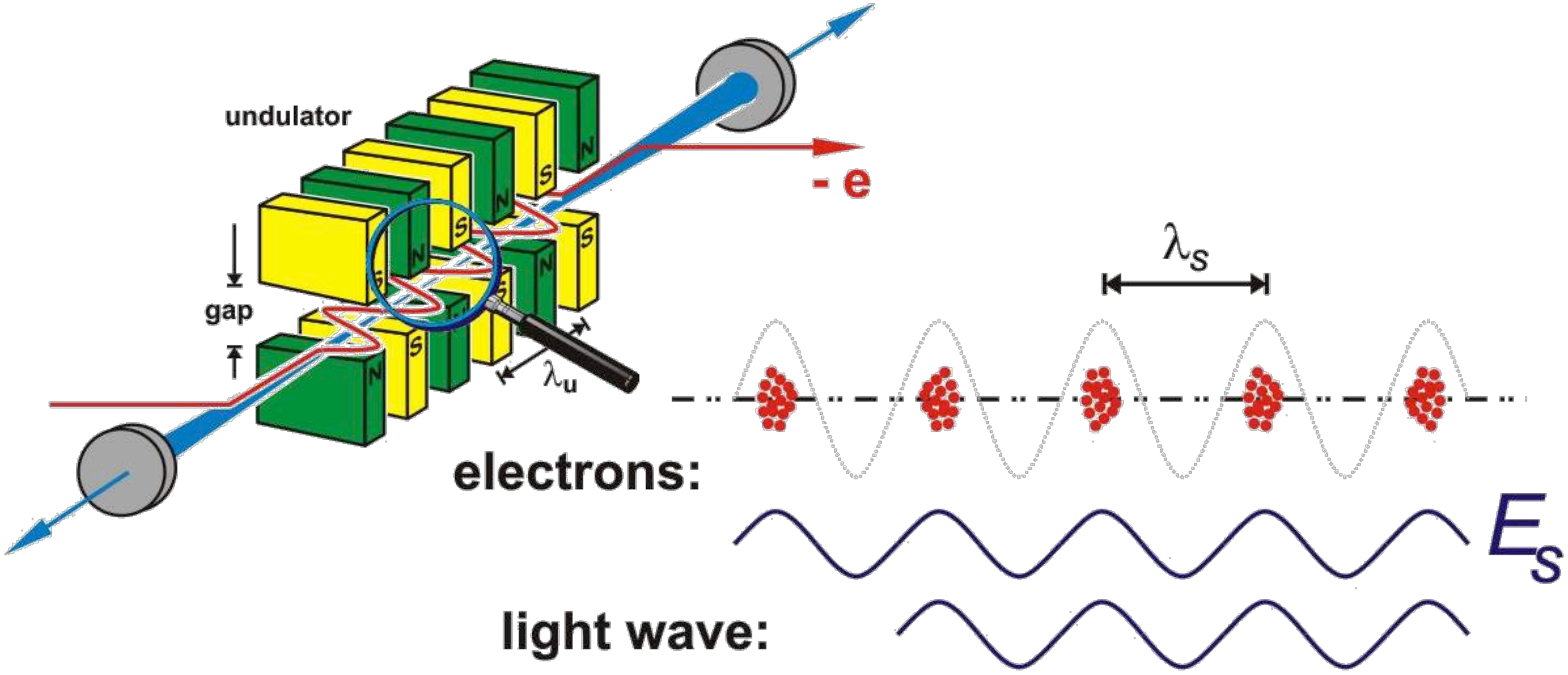



Radiated Power :

$P \propto n_e$ (number of electrons)

destructive interference

⟶ **shotnoise radiation**

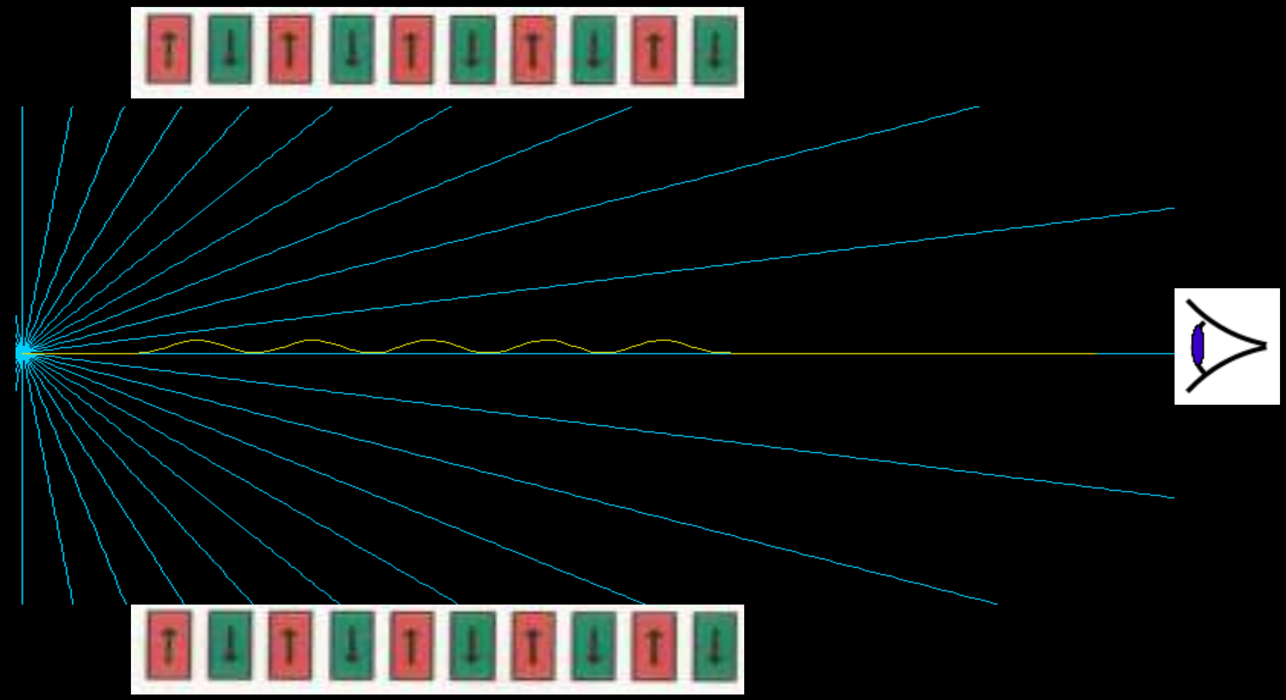



Radiated Power :

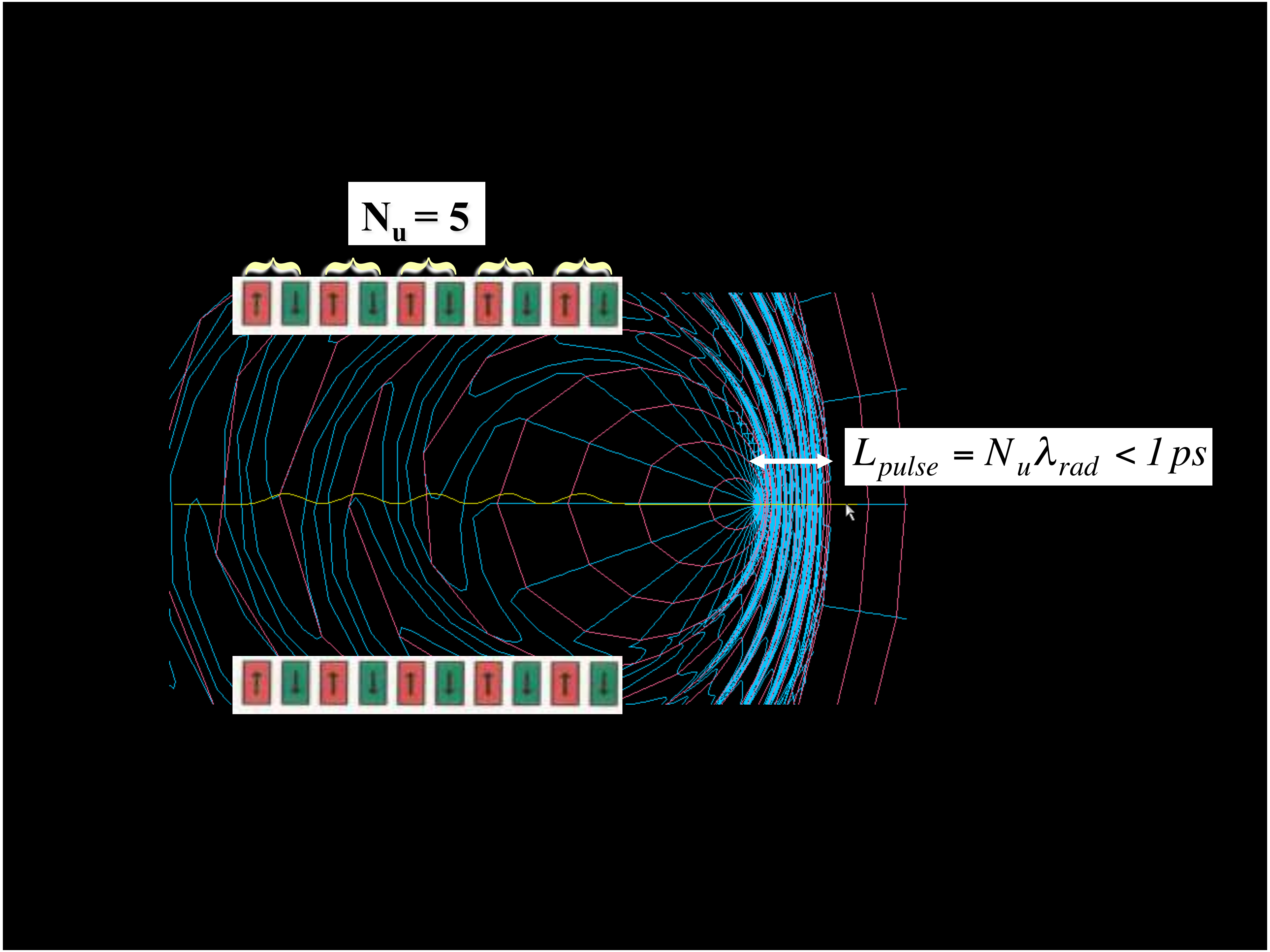
$$P \propto n_e^2 \left( \begin{matrix} \text{number of electrons} \\ n_e \sim 10^6 - 10^9 \end{matrix} \right)$$

constructive interference

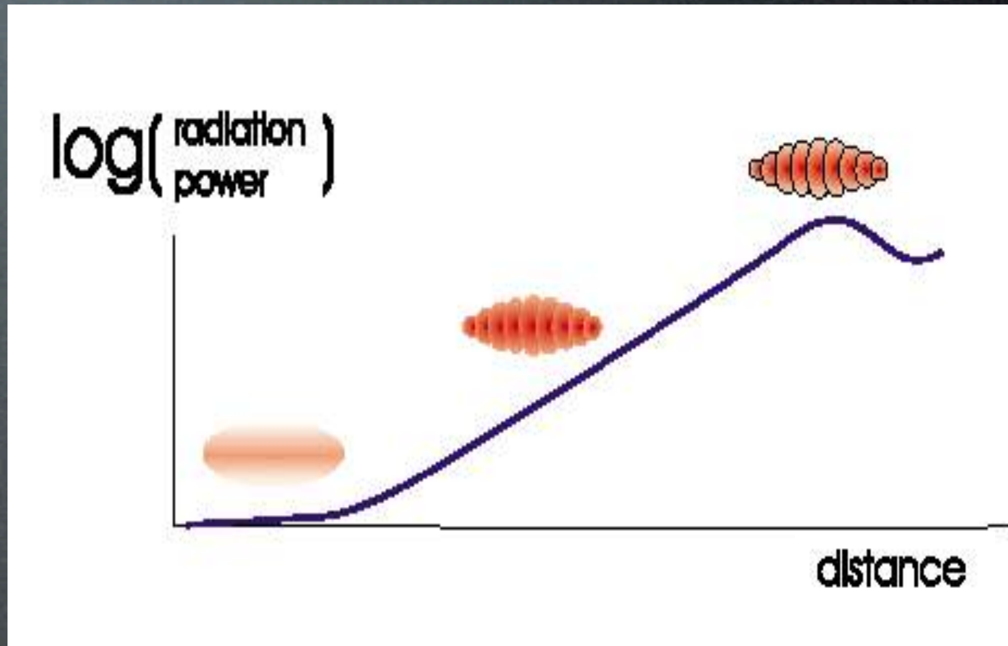
⟶ **enhanced emission**



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


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

**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**



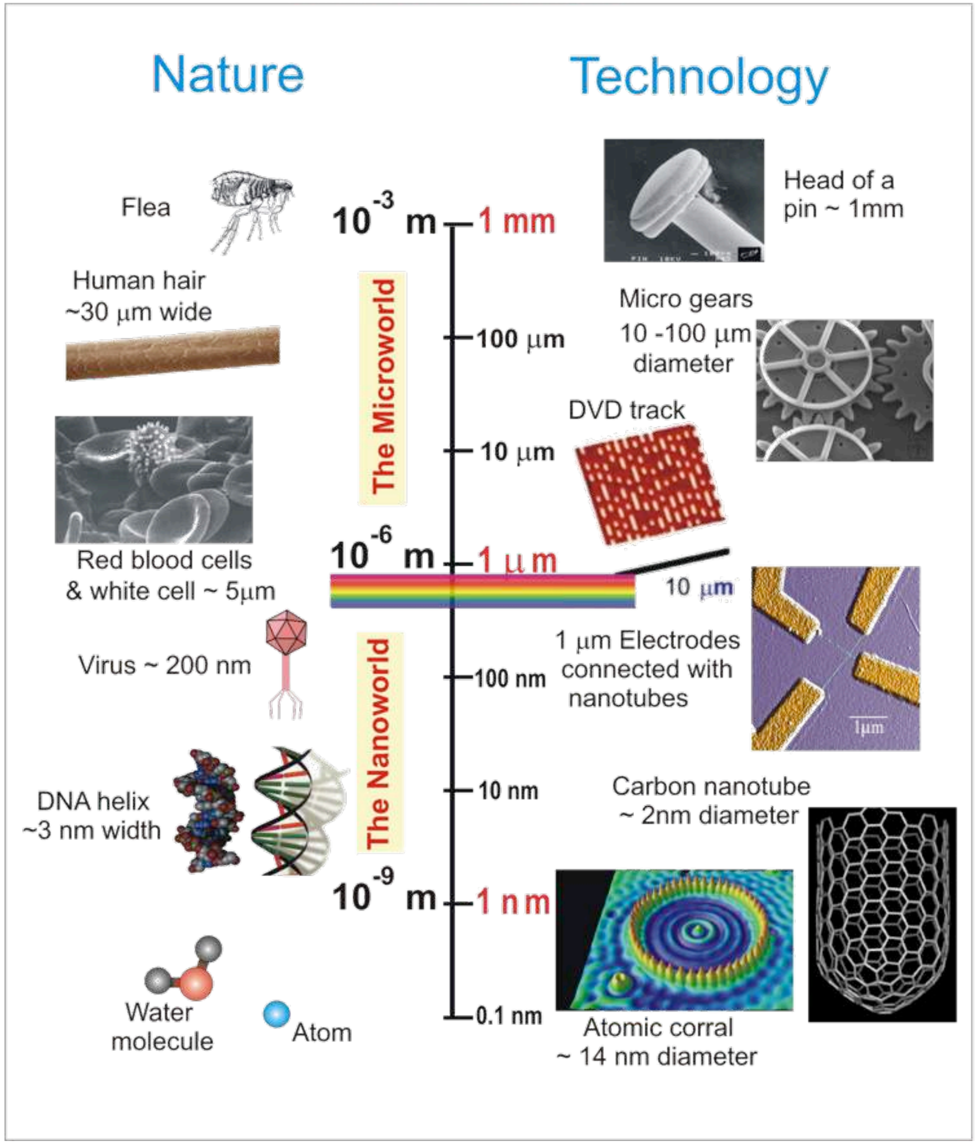

$$\lambda_{rad} \approx \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2} + \gamma^2\vartheta^2\right)$$

**(Tunability - Harmonics)**

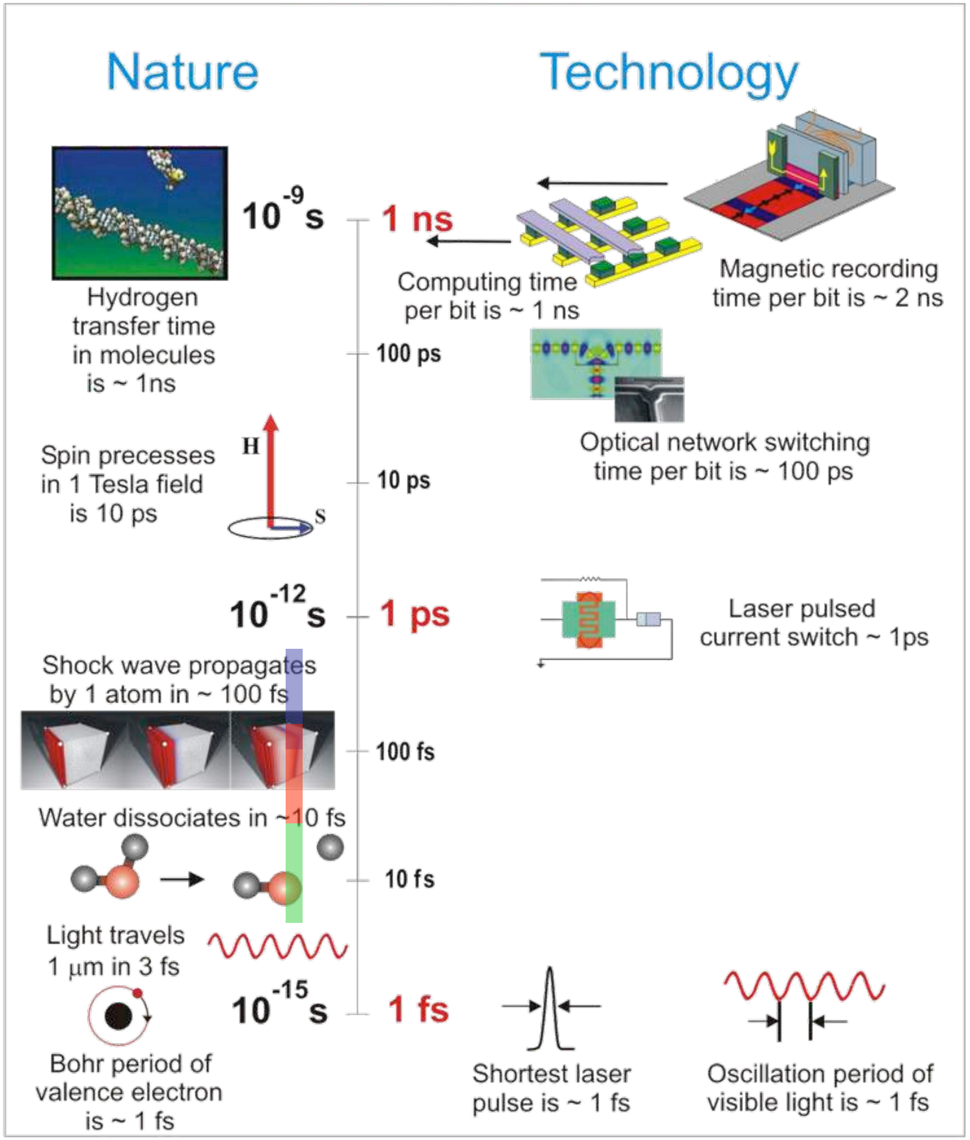
# The FEL Applications

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

## Ultra-Small



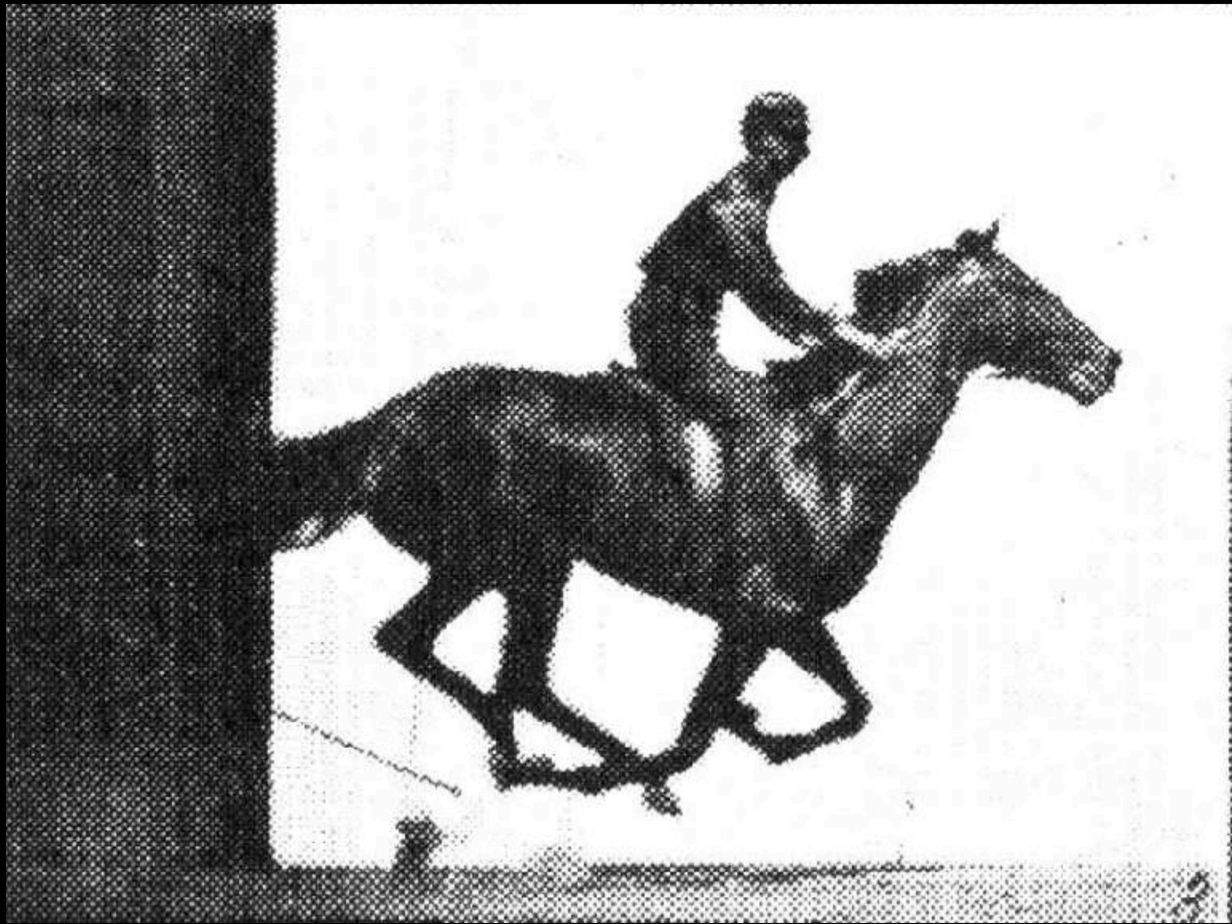

## Ultra-Fast



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

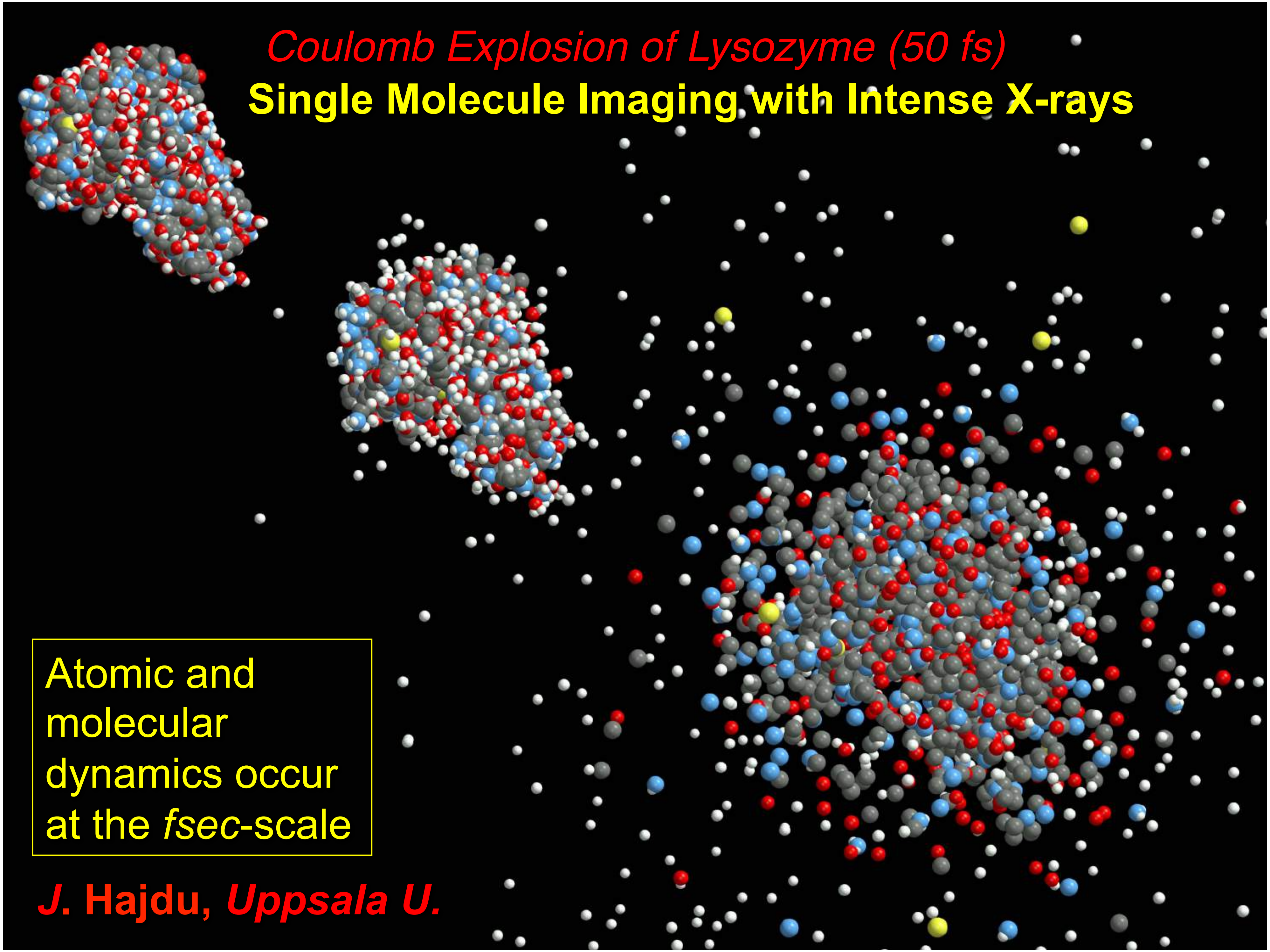
disagree whether all feet leave the ground during gallop…

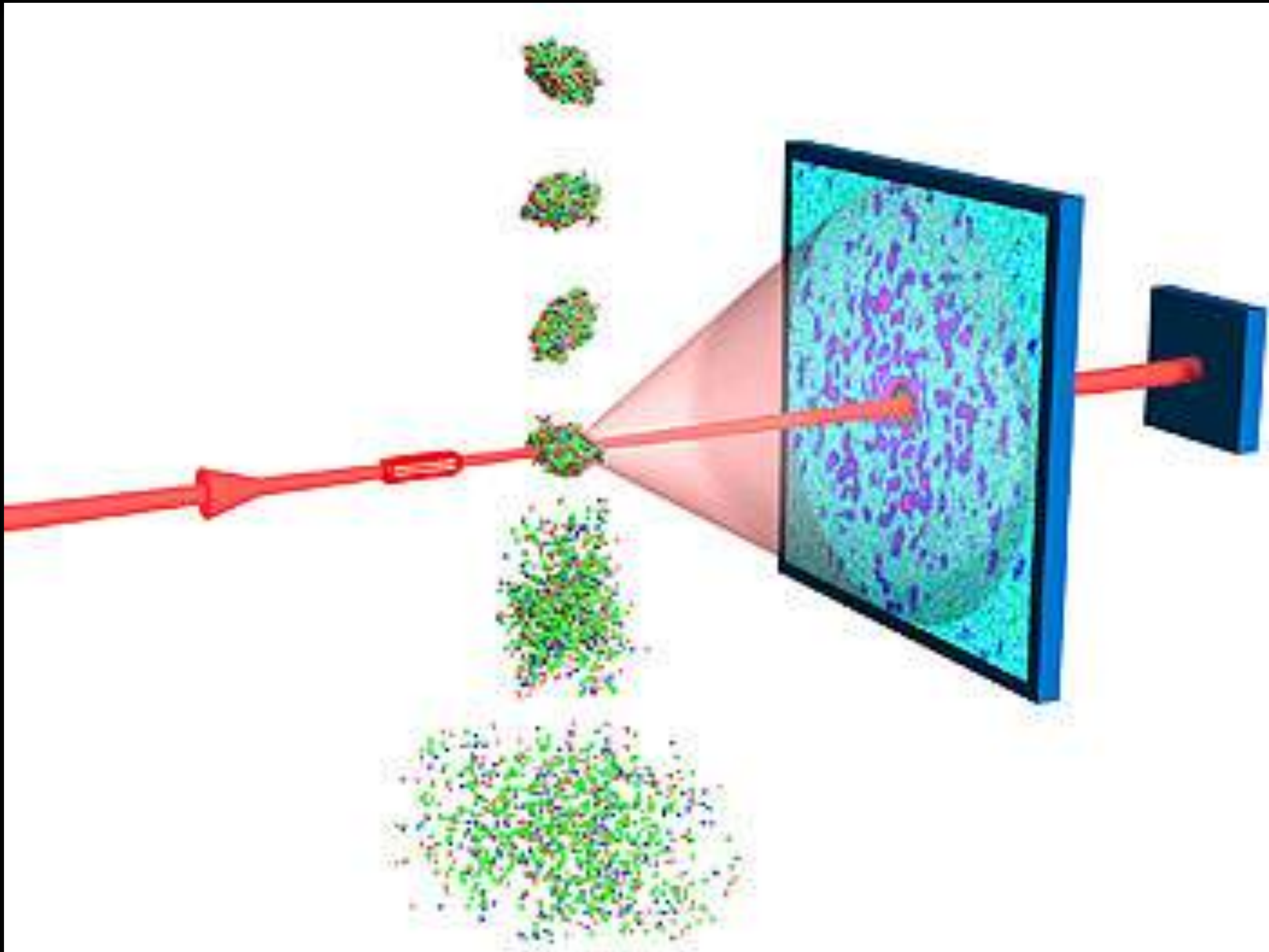
E. Muybridge



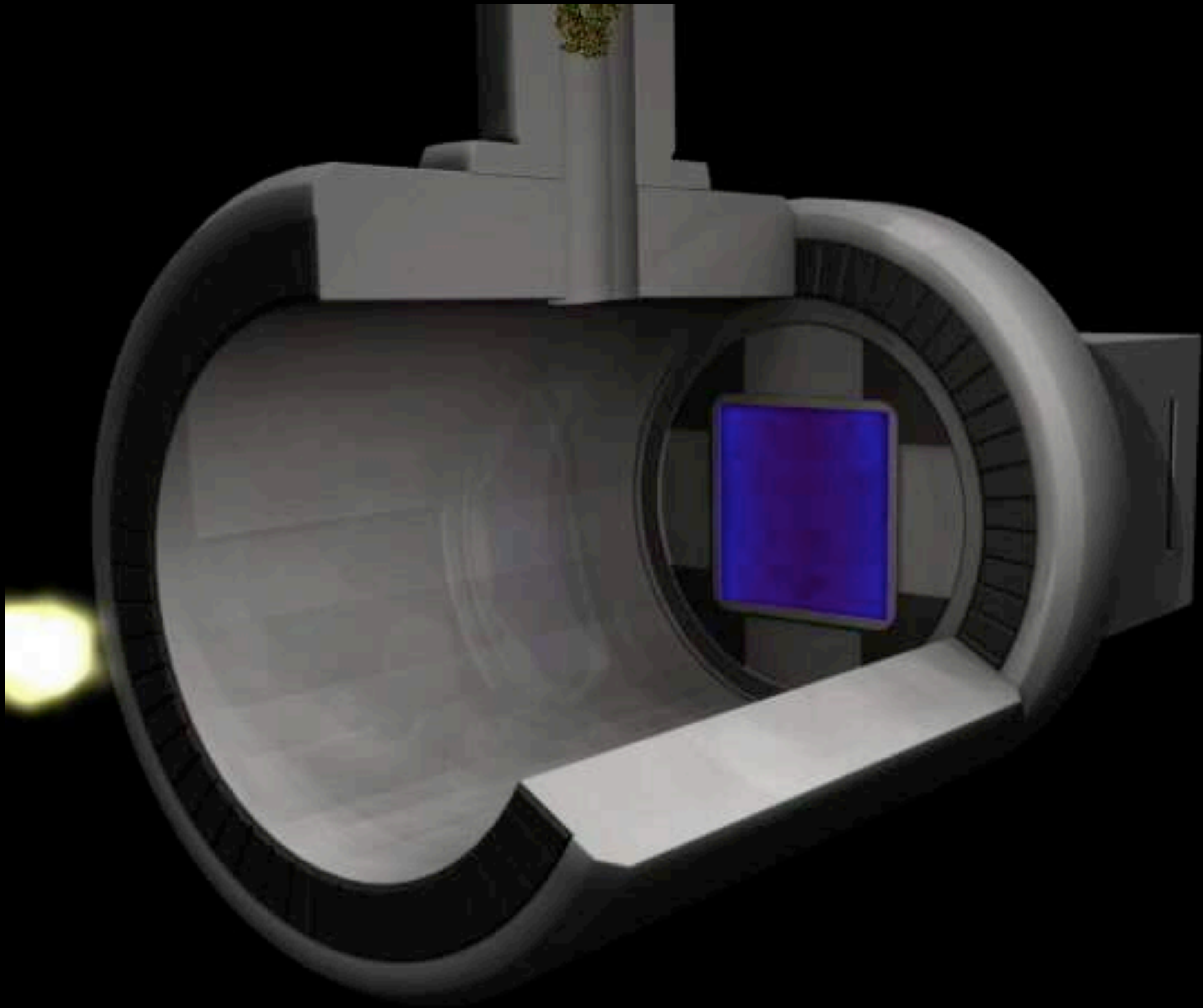
**used spark photography to freeze this ‘ultra-fast’ process**

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

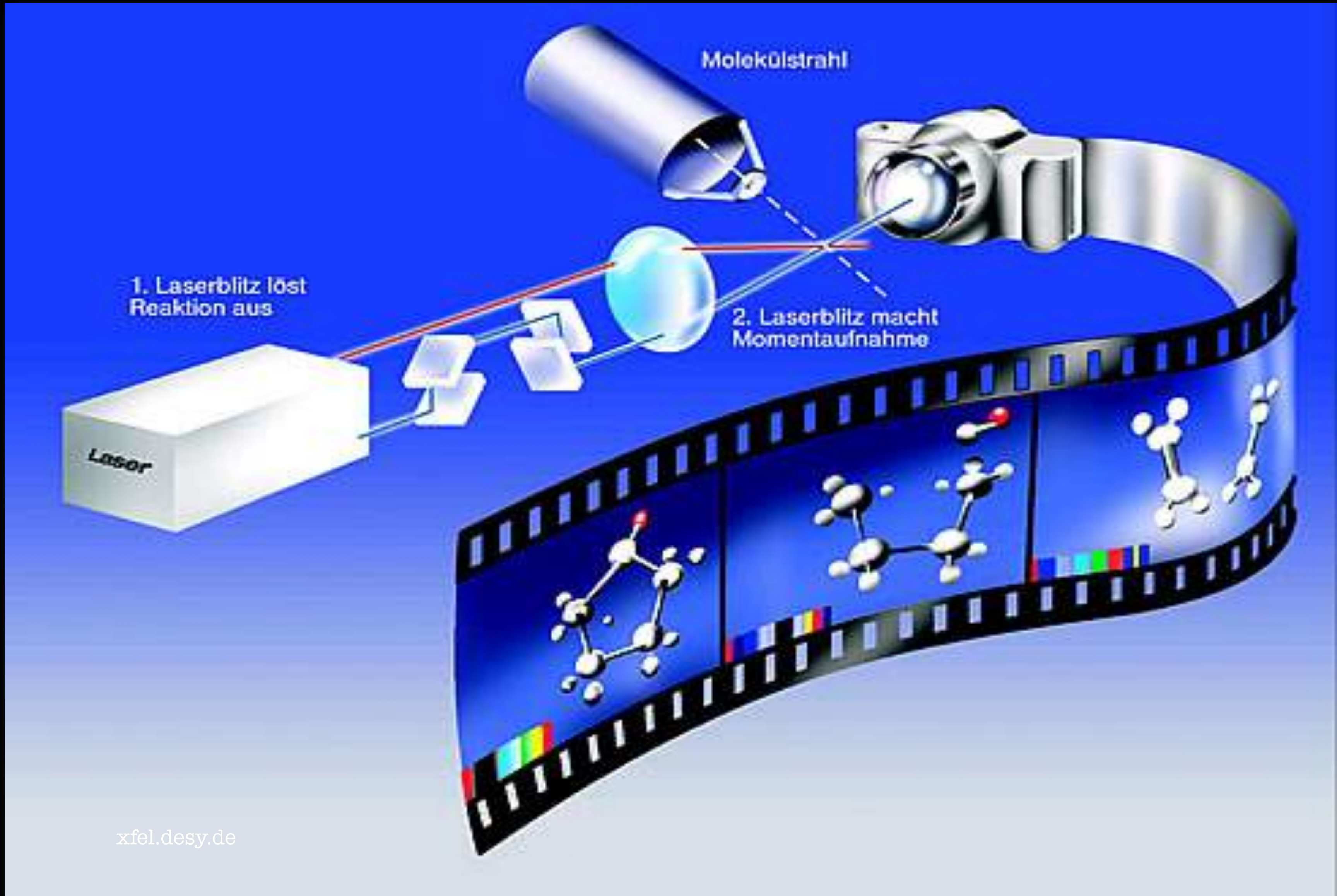

Coulomb Explosion of Lysozyme (50 fs)
Single Molecule Imaging with Intense X-rays
Atomic and molecular dynamics occur at the fsec-scale
J. Hajdu, Uppsala U.



# Experimental hall (Single Protein Imaging)



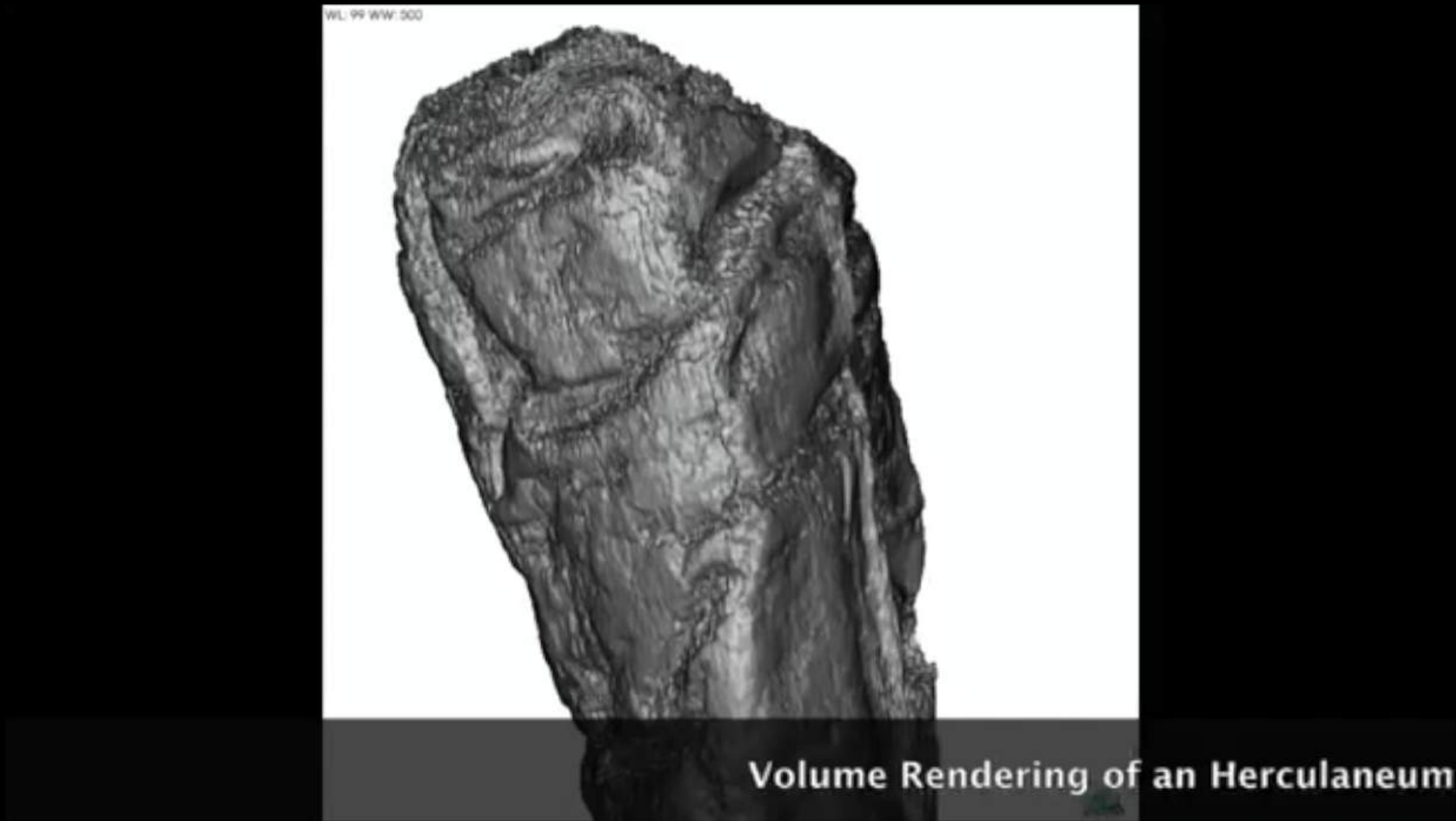
http://lcls.slac.stanford.edu/AnimationViewLCLS.aspx


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

# 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




θανκ φορ ιουρ αττεντιον


Thank for your attention