Accelerators for the future

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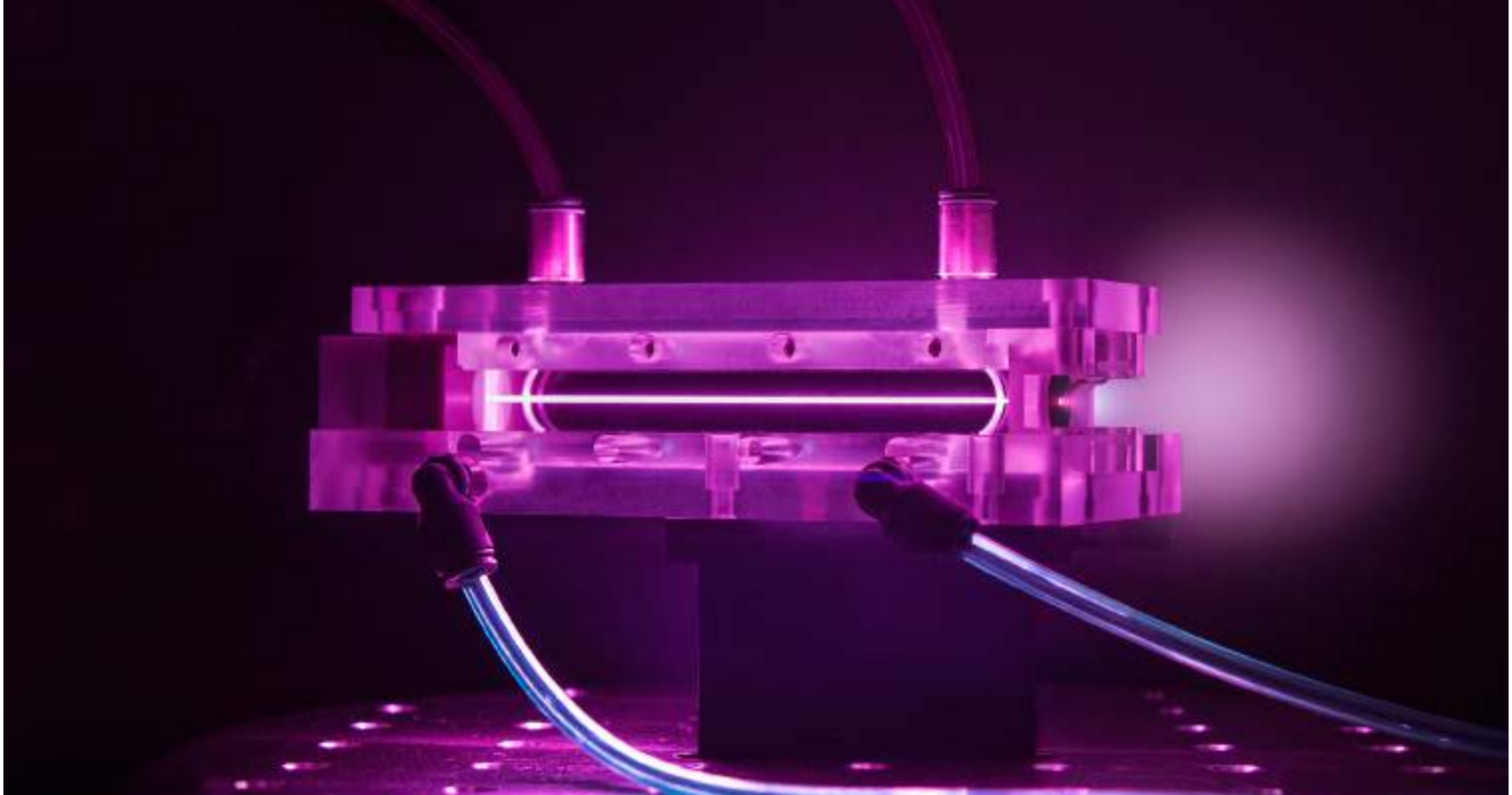


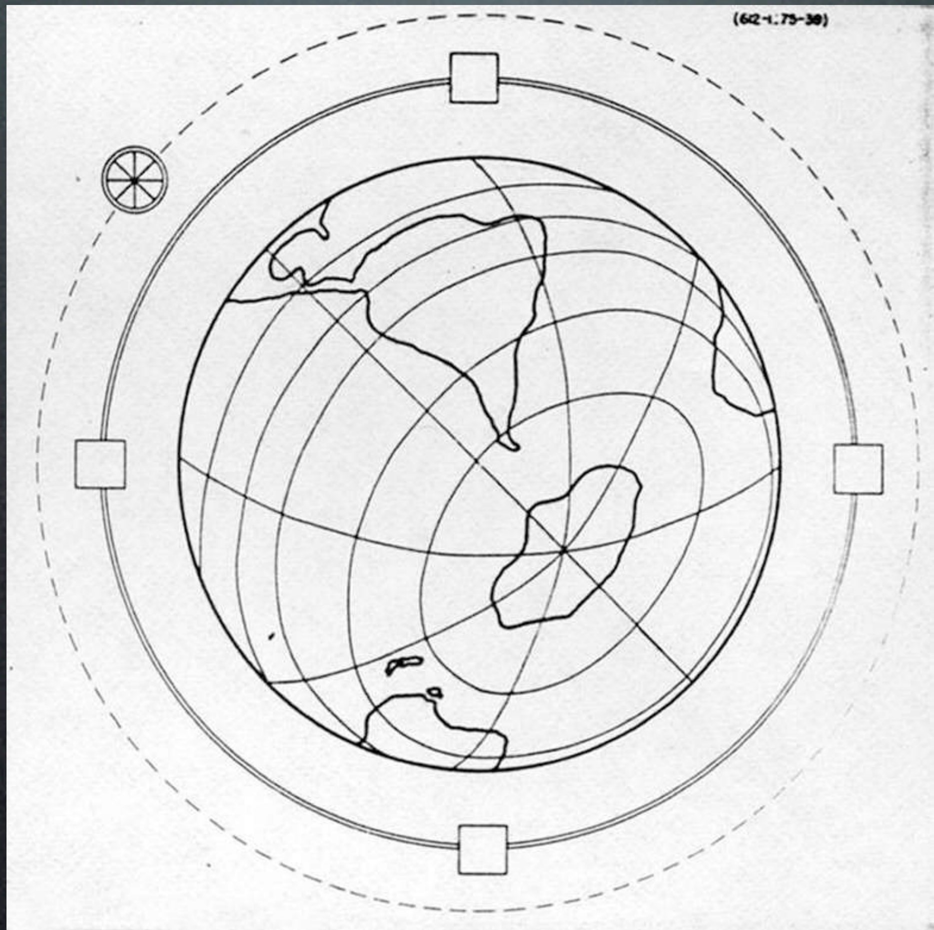
INSPYRE – LNF 15 February 2018

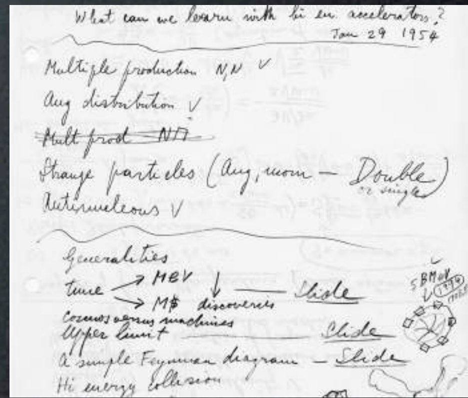
Fermi's Globatron: ~5000 TeV Proton beam

1954 the ultimate synchrotron

B_{max} 2 Tesla
ρ 8000 km
fixed target
3 TeV cm
170 G$
1994

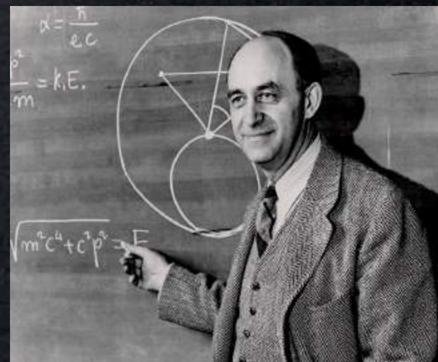
$$\rho = \frac{p}{Bq} \cong \frac{E}{cqB}$$




What can we learn with hi en accelerators?
Jan 29 1954

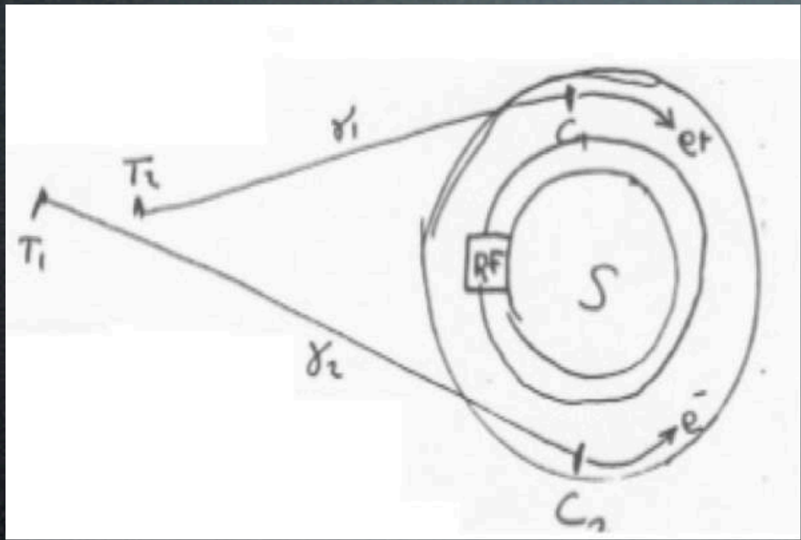
Multiple production N,N ✓
Ang distribution ✓
~~Mult prod NП~~
Strange particles (Ang, mom — Double or single)
Antinucleons ✓

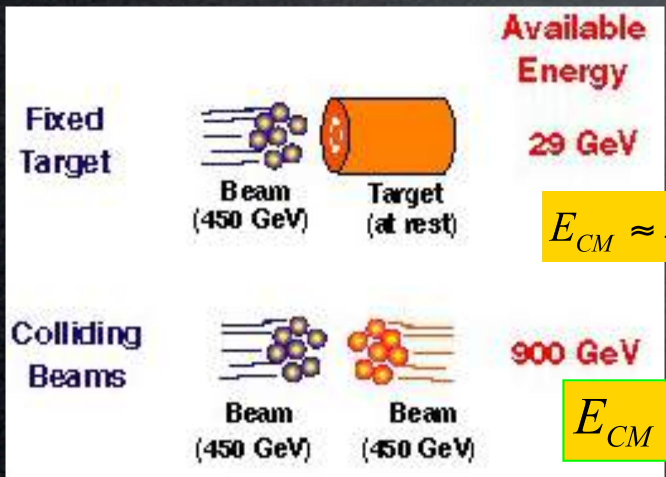
Generalities
time → MeV ↓ —— Slide
→ M$ discoveries
Cosmos versus machines
Upper limit —— Slide
A simple Feynman diagram — Slide
Hi energy collision



Touschek's Anello Di Accumulazione (ADA)

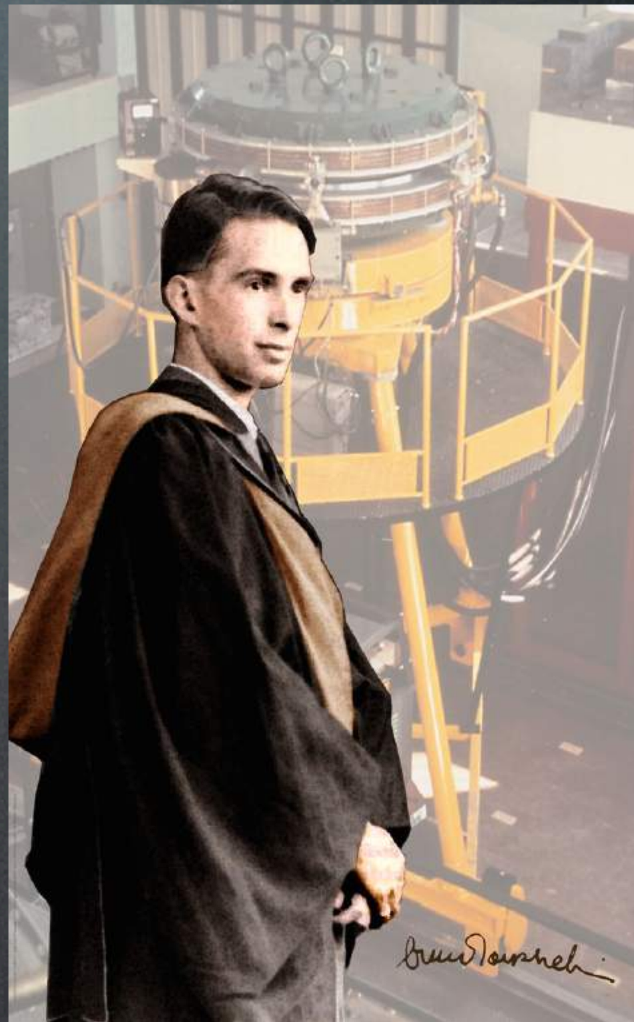
1961 the first e+e- Collider





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

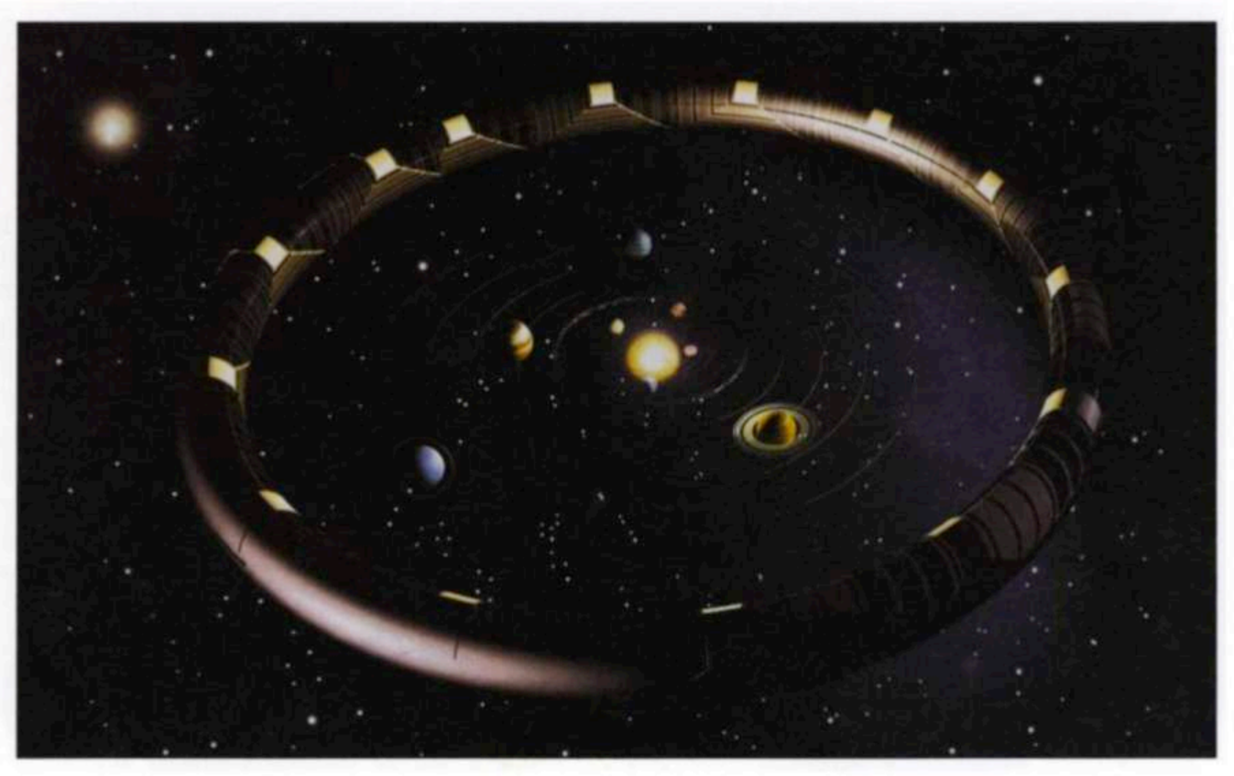
$E_{CM} \approx 2E$



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.)

Hawking: the Solartron

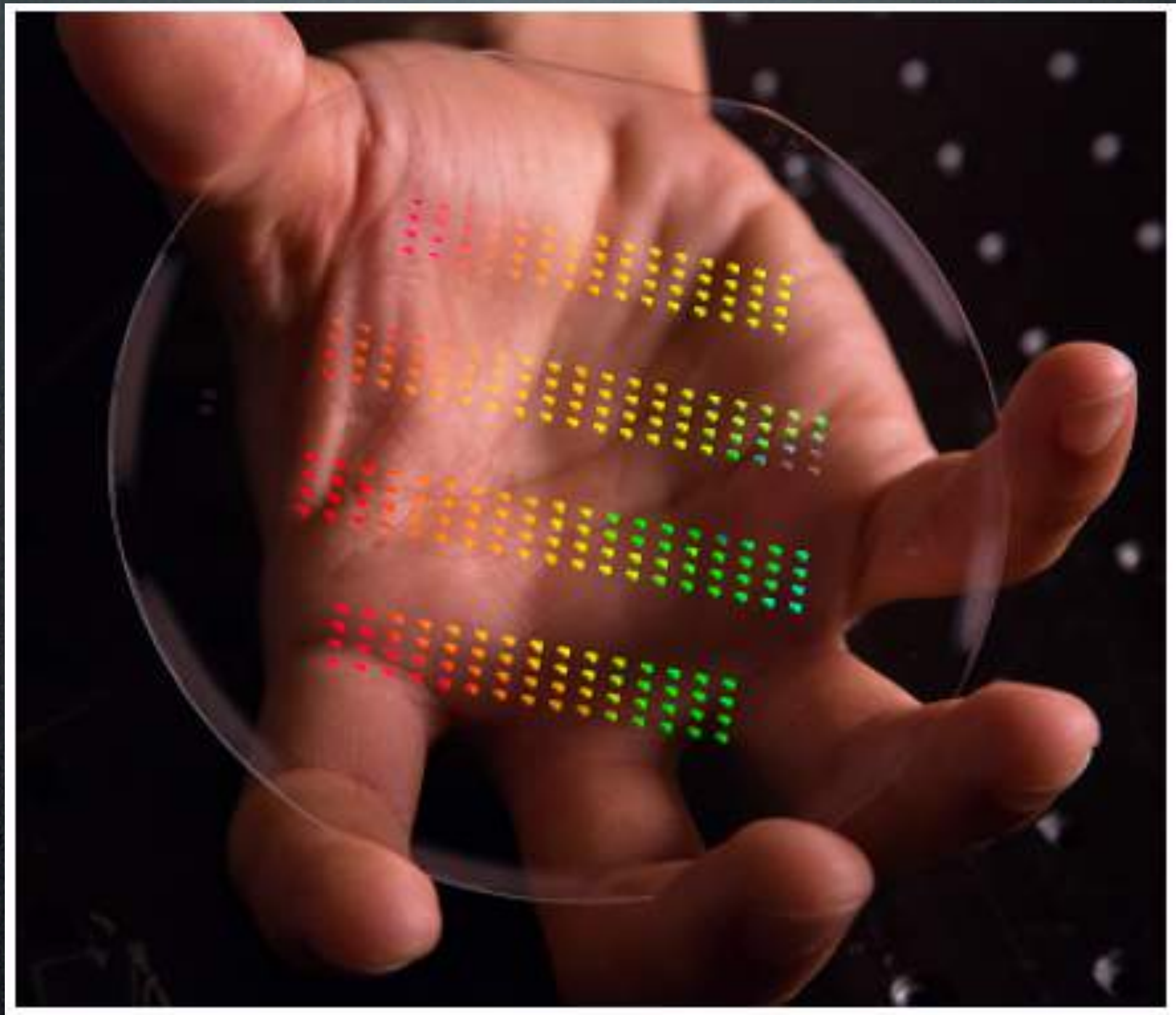
Towards the Planck scale



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

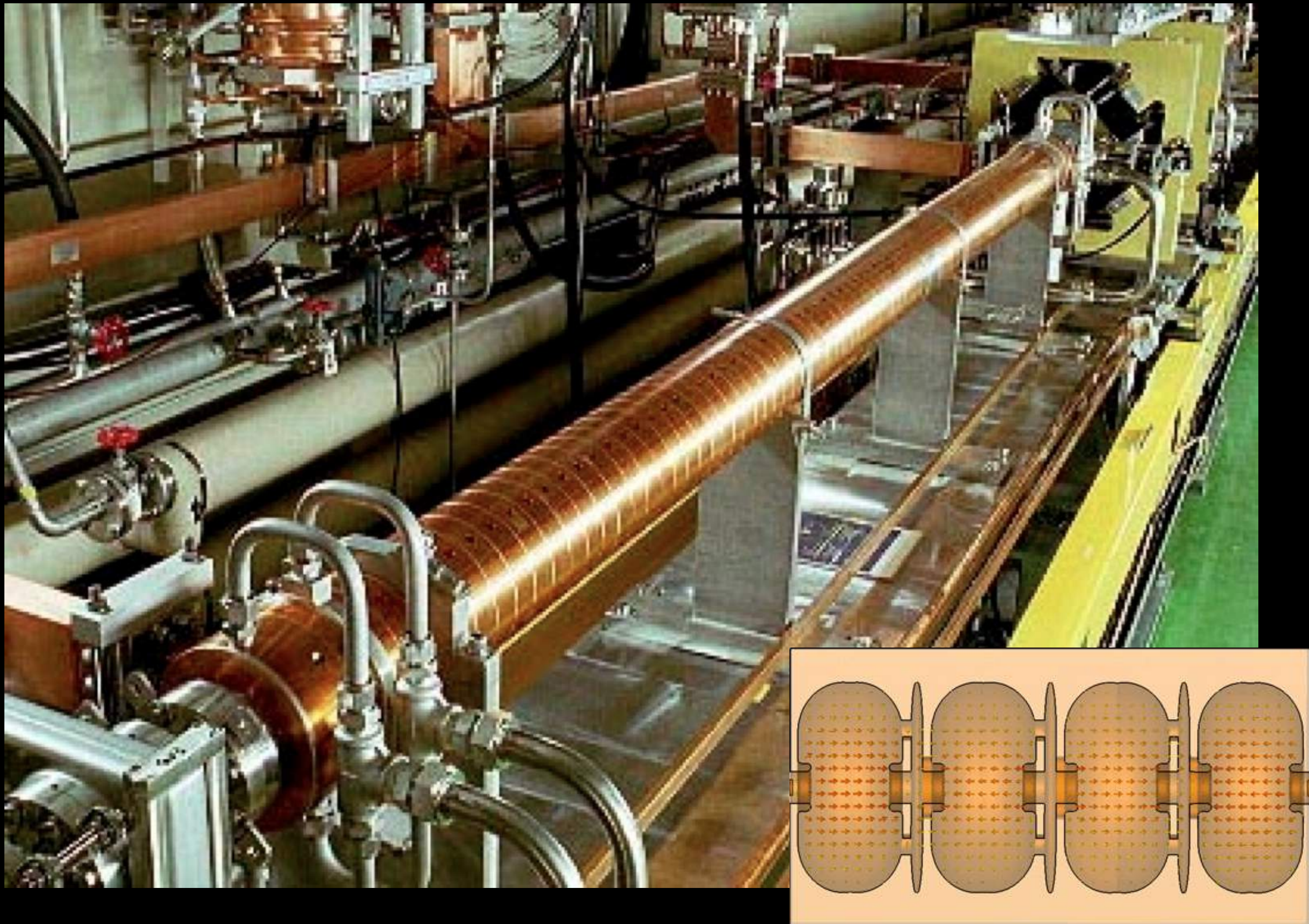
↑ $$L = \frac{N_{e+} N_{e-} f_r}{4\pi\sigma_x\sigma_y}$$

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

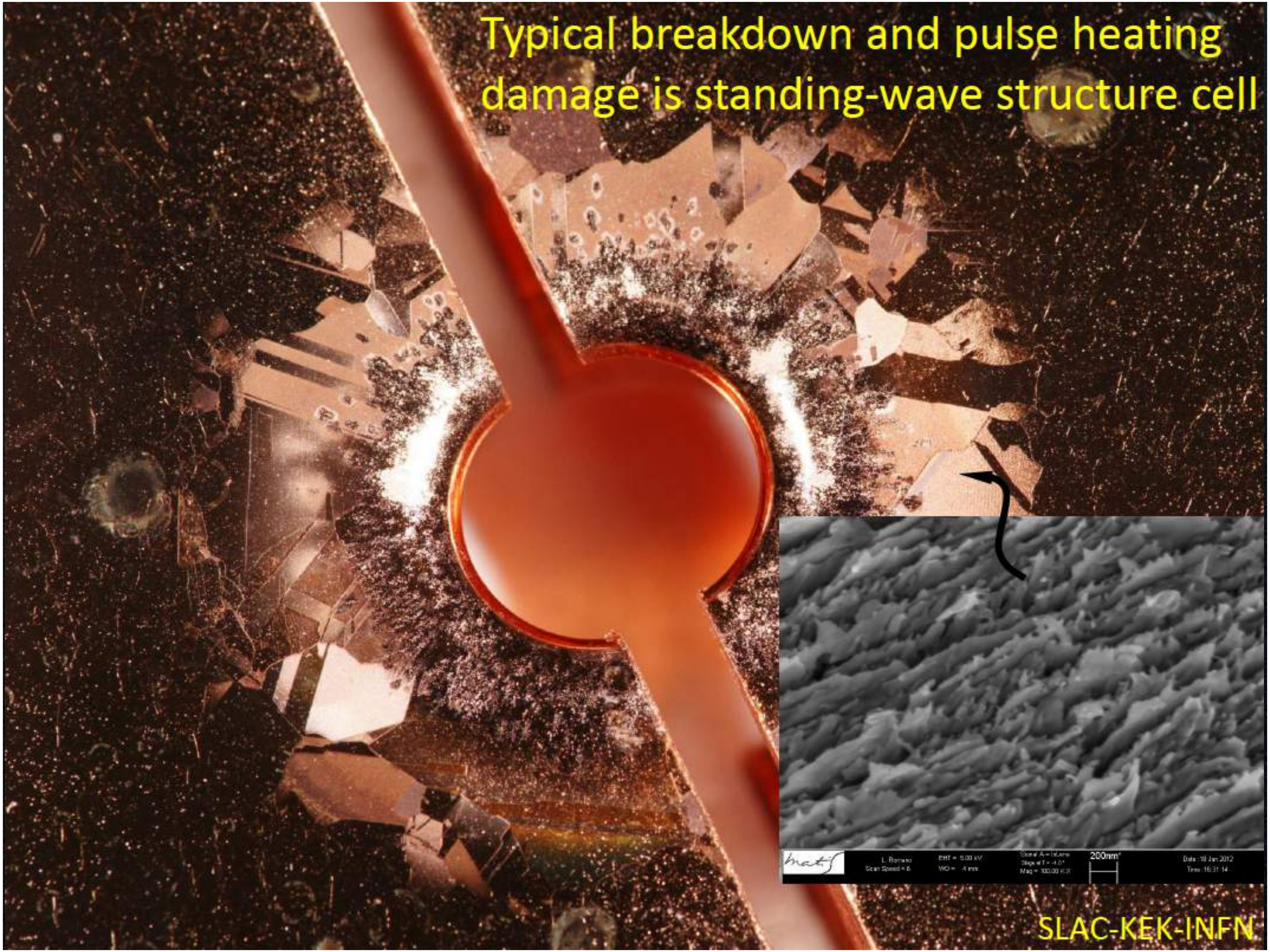
↑ $$B_n \approx \frac{2I}{\varepsilon_n^2}$$

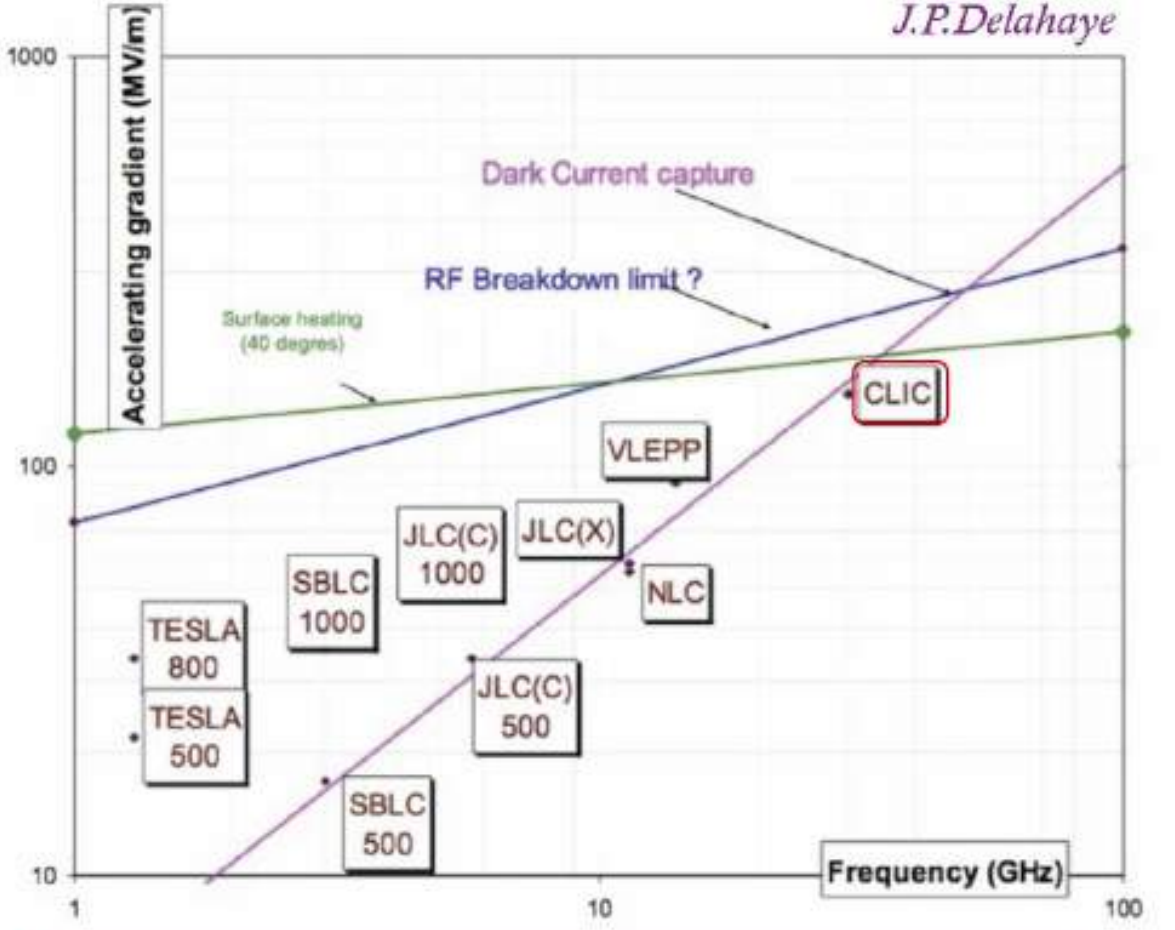
- –Short pulse (ps to fs)
- –Little spread in transverse momentum and angle => low emittance

Conventional RF accelerating structures



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





Breakdown limits metal:

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

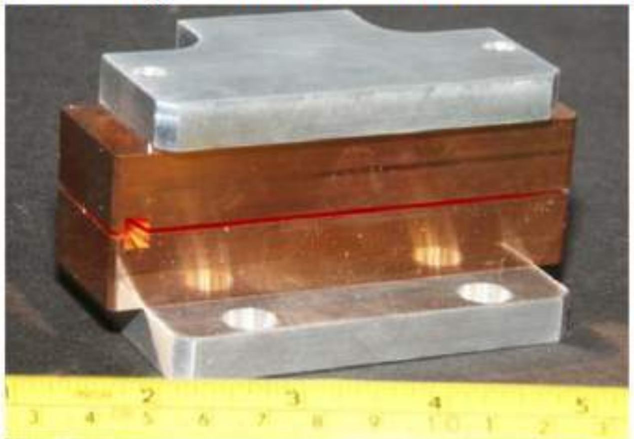
High field ->Short wavelength->ultra-short bunches-> low charge

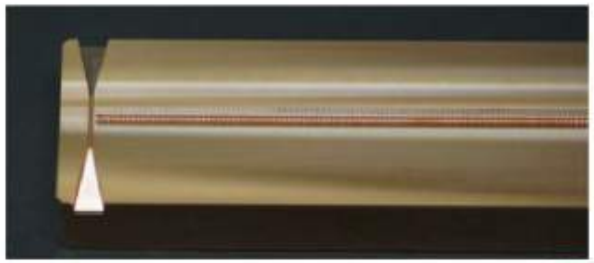
Miniaturization of the accelerating structures

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



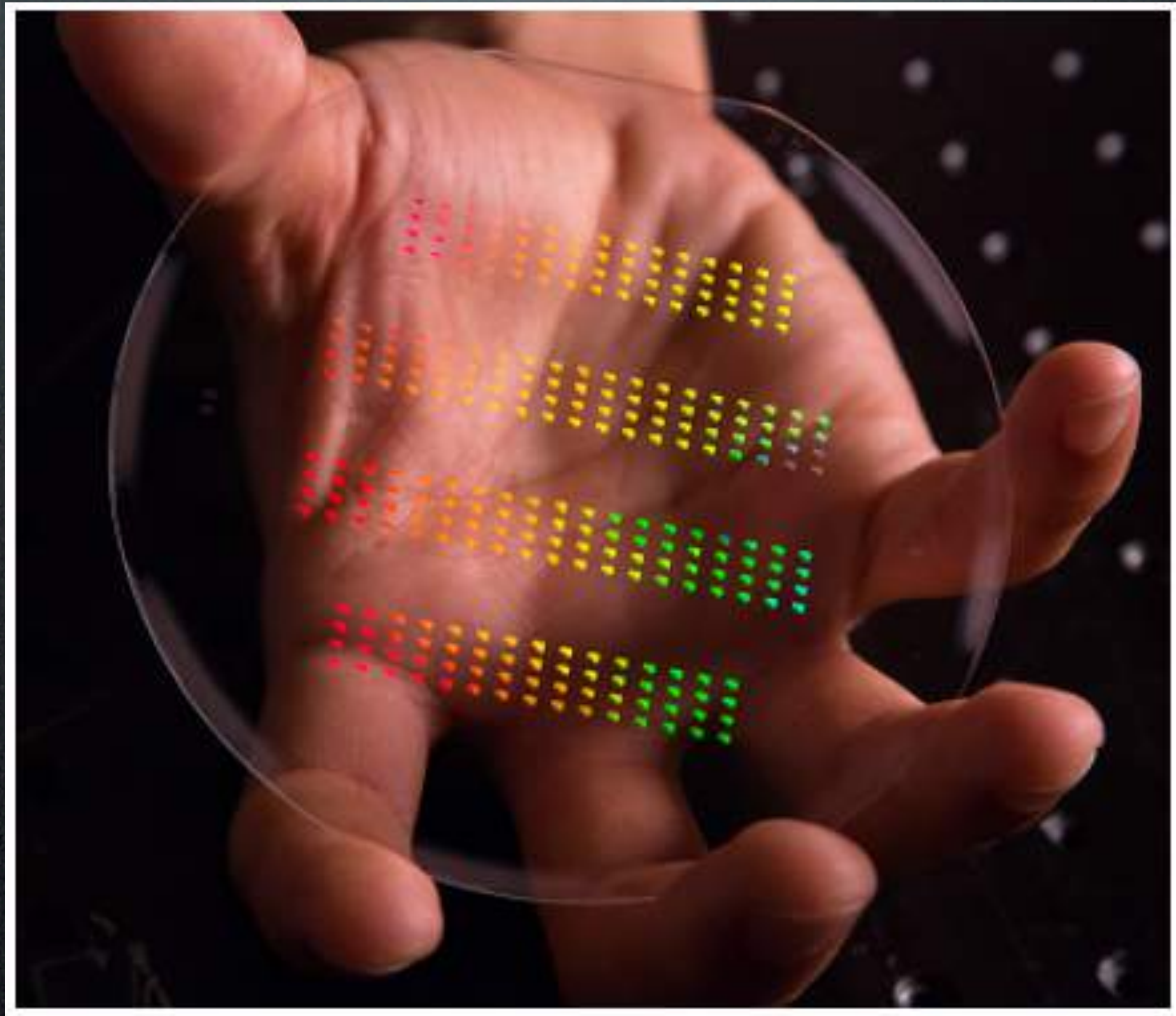


SLAC NATIONAL ACCELERATOR LABORATORY

Direct Laser Acceleration

DLA

Accelerator on a Chip?



Light Source on a Chip

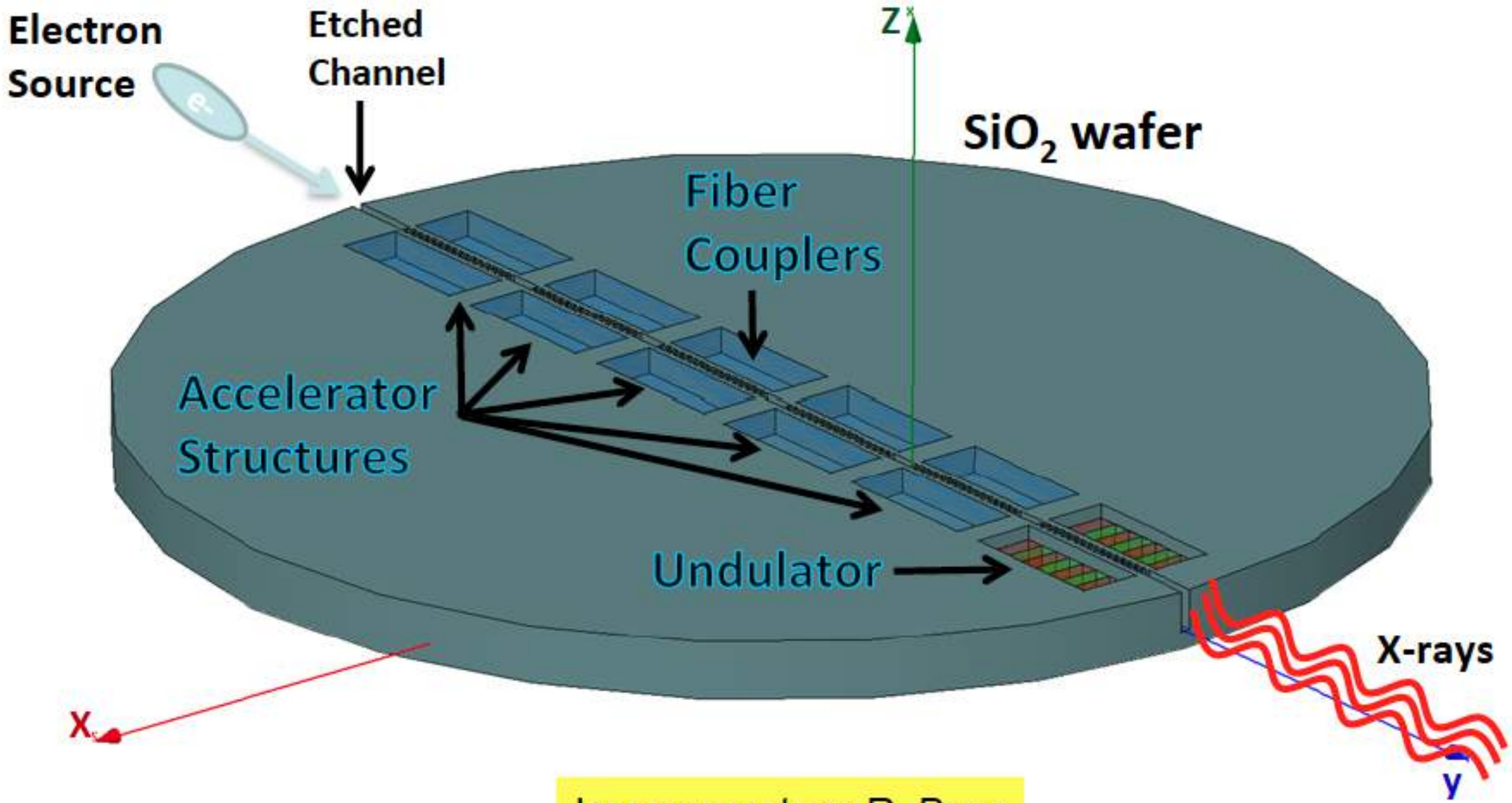
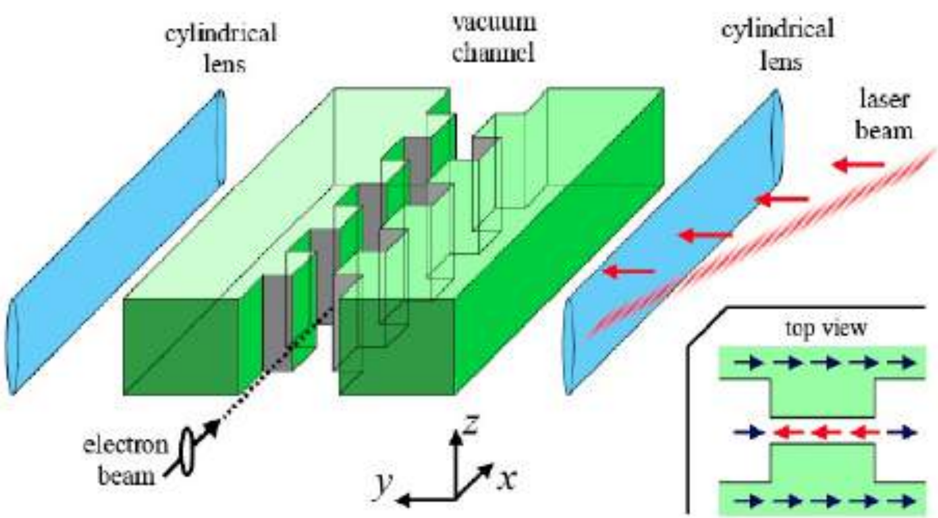
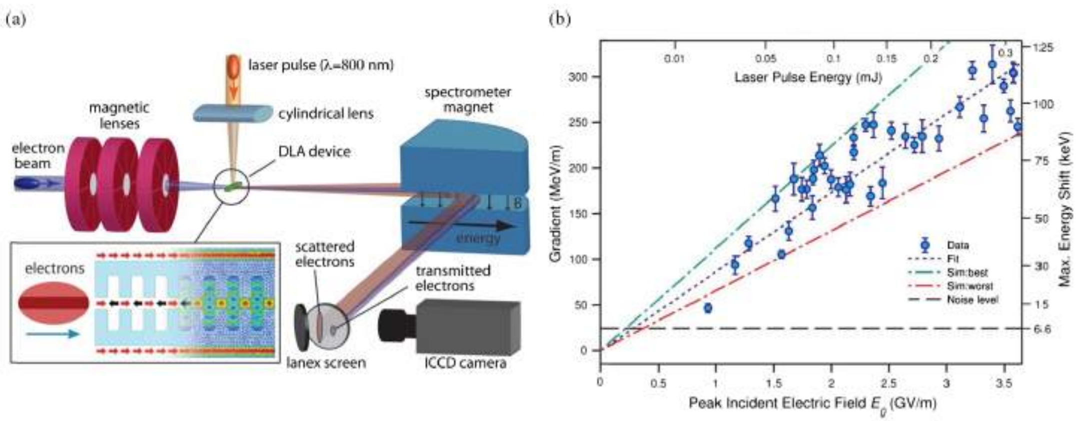


Image courtesy R. Byer

Grating-Based Planar Structure



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

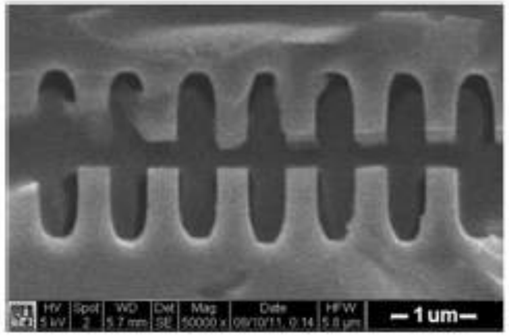


SiO_2 planar gratings with side-coupled laser and flat beam.

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

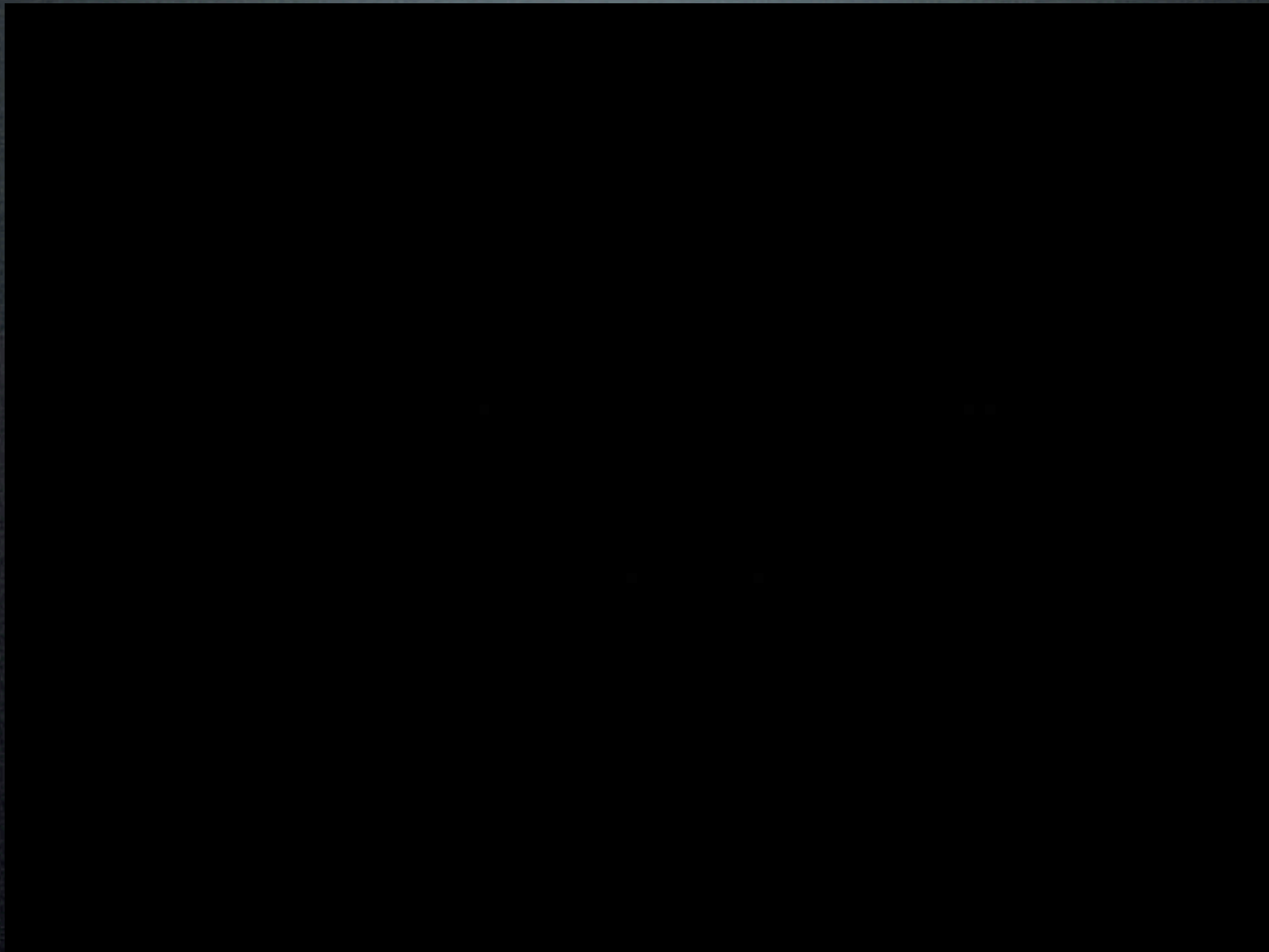
damage threshold for SiO_2 >3 GV/m @ 1ps

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



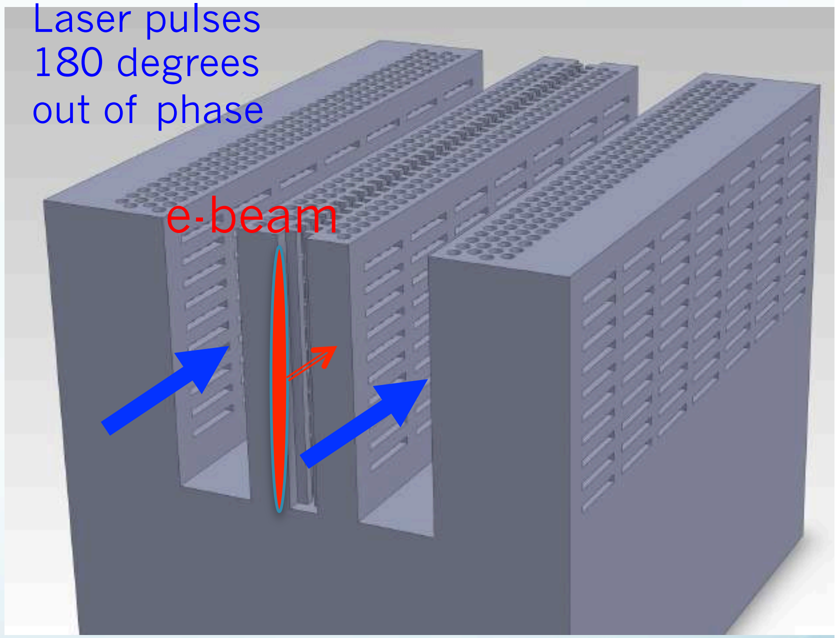
E. Peralta, recently fabricated prototype structure

Accelerator on a Chip



Dielectric Photonic Structure

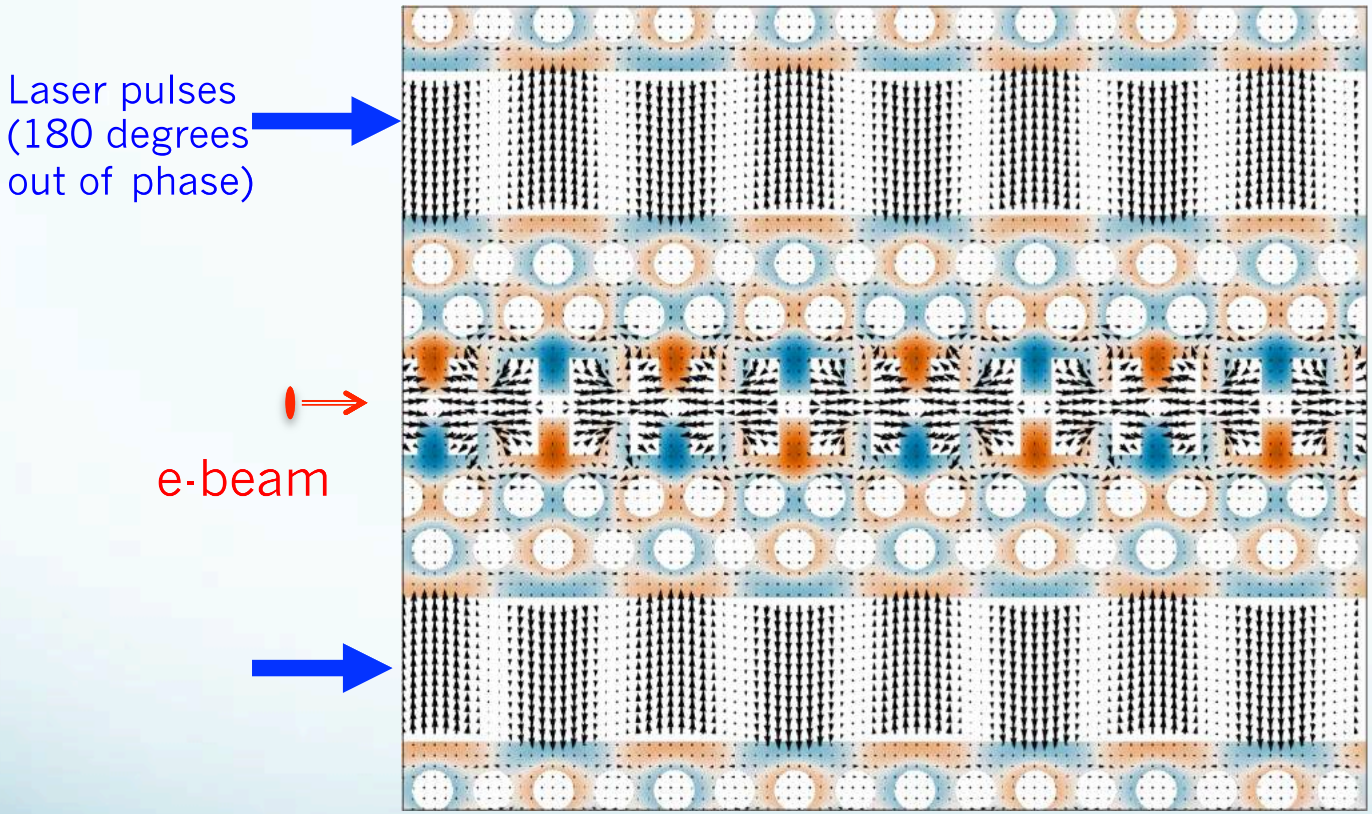
- Why photonic structures?
  - Natural in dielectric
  - Advantages of burgeoning field
    - design possibilities
    - Fabrication
- Dynamics concerns
- External coupling schemes



Schematic of GALAXIE
monolithic photonic DLA

Laser-Structure Coupling: TW

GALAXIE Dual laser drive structure, large reservoir of power recycles

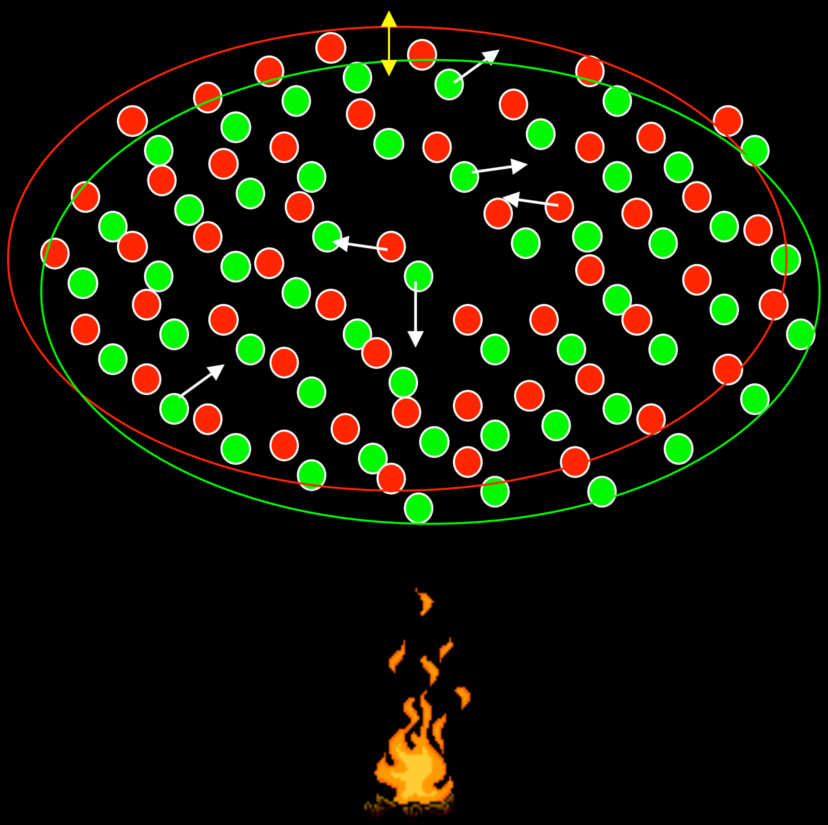


Plasma Acceleration

Surface charge density

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

δx



Surface electric field

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

Restoring force

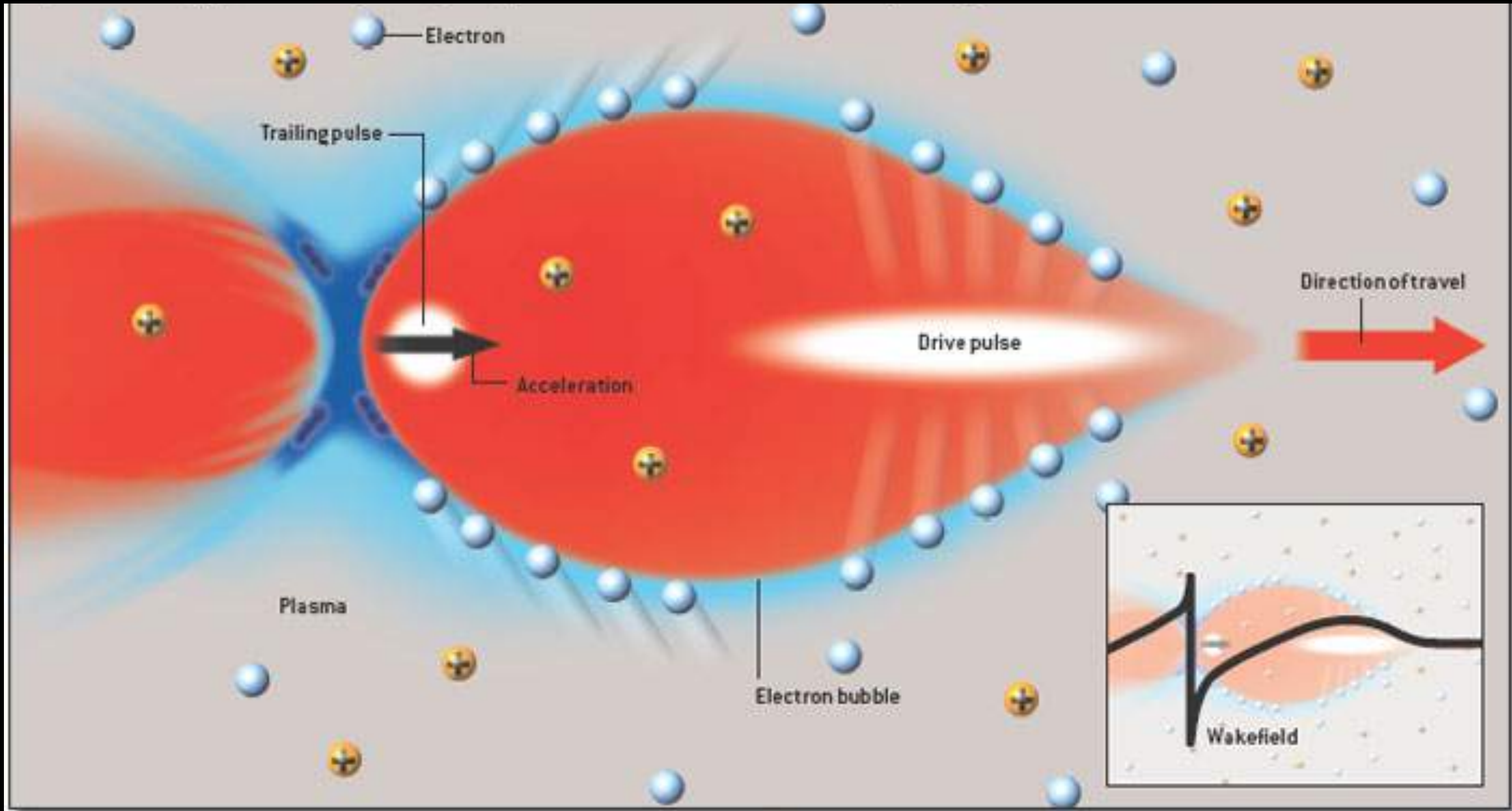
$$m\,\frac{d^2\delta x}{dt^2} = e\,E_x = -m\,\omega_p{}^2\,\delta x$$

Plasma frequency

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

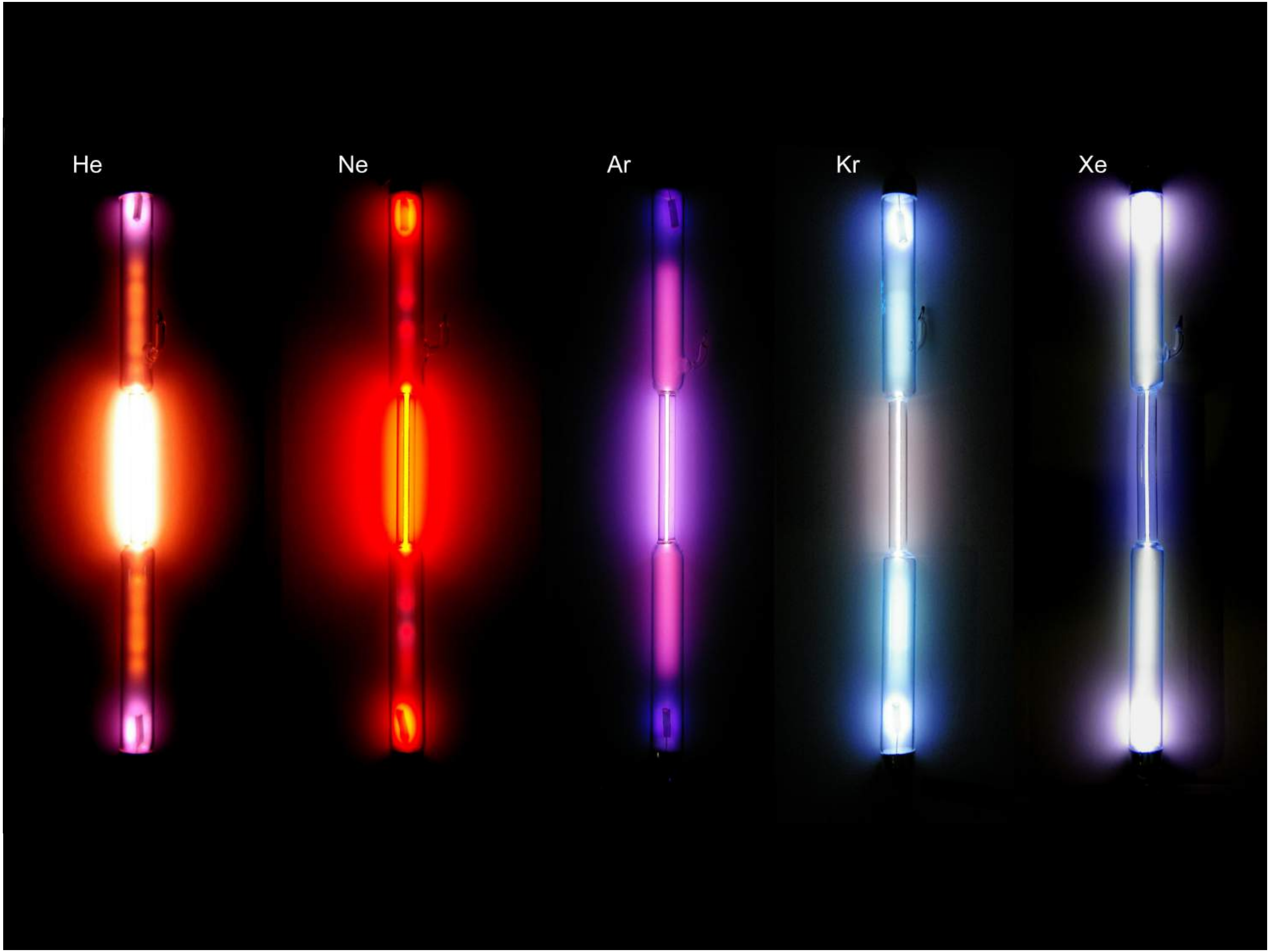
Plasma oscillations

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

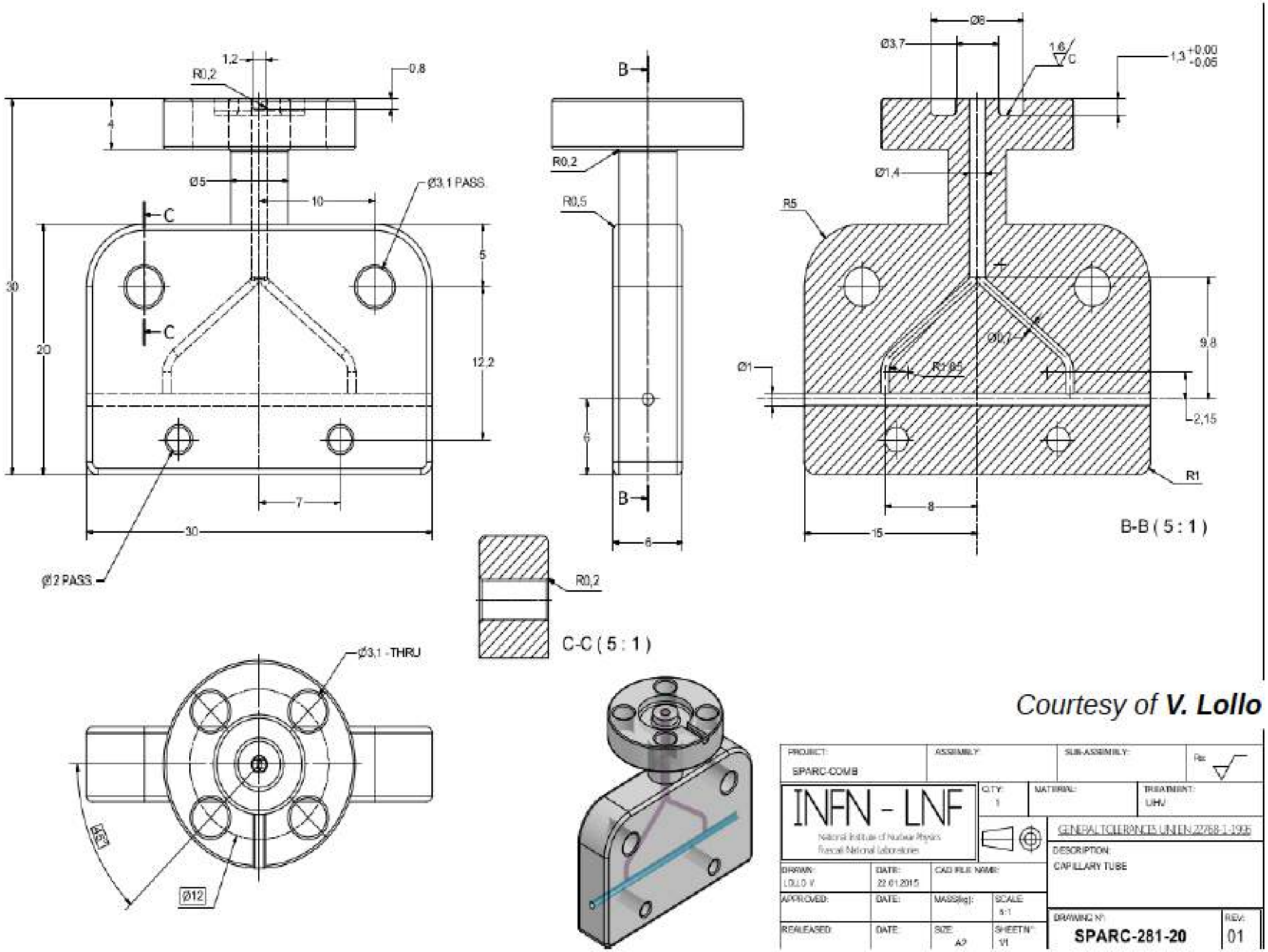


Breakdown limit?

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

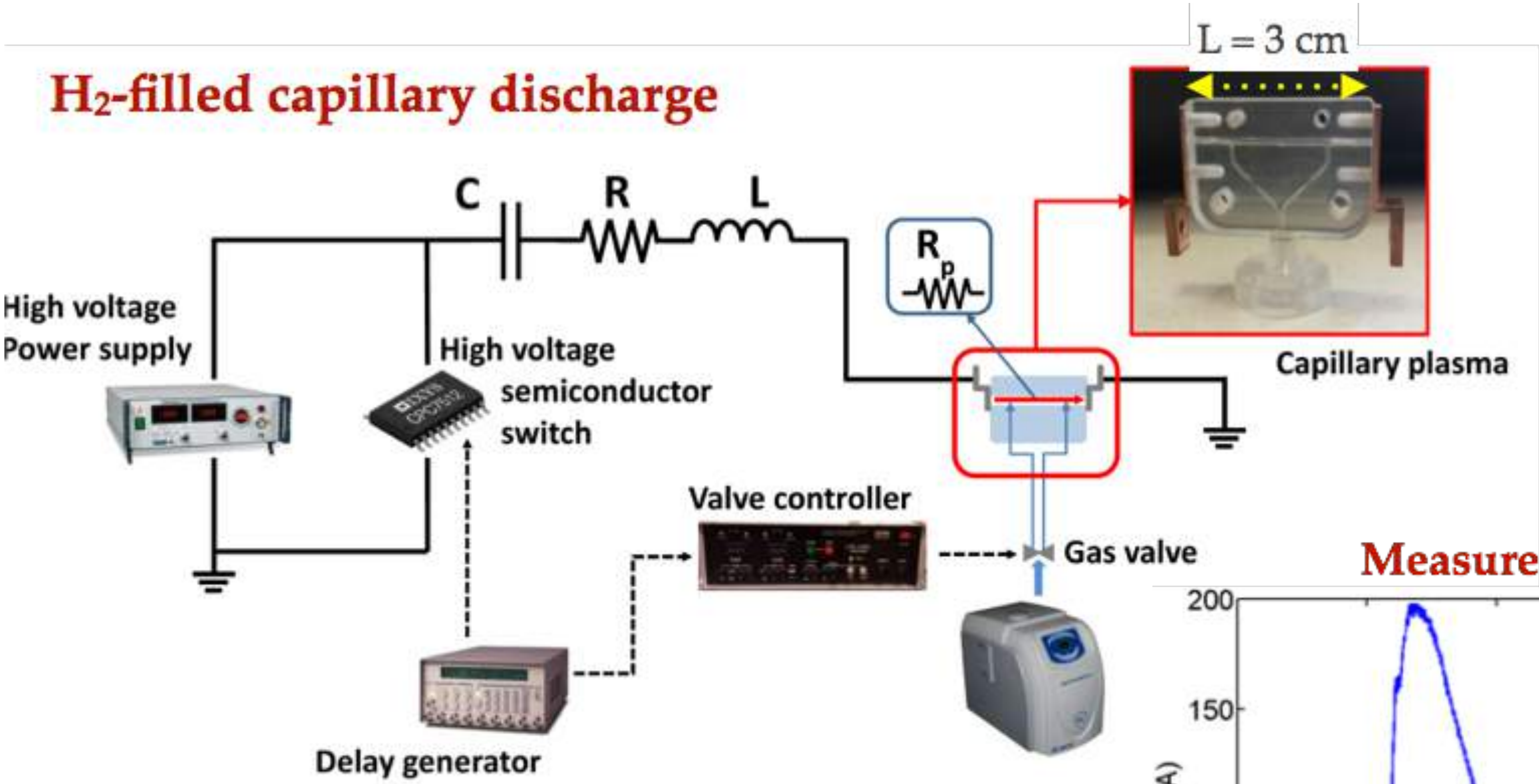

He
Ne
Ar
Kr
Xe

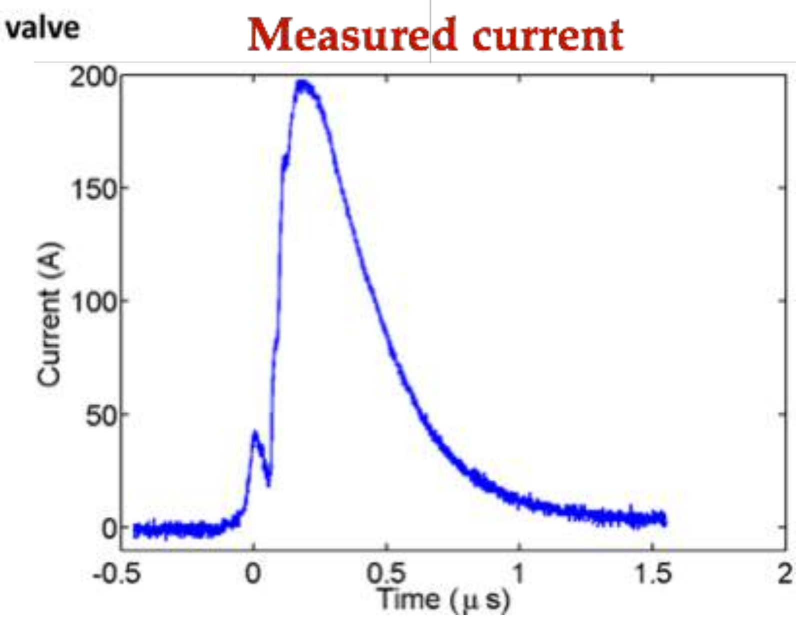
Plasma capillary



Courtesy of ***V. Lollo***

Plasma Source



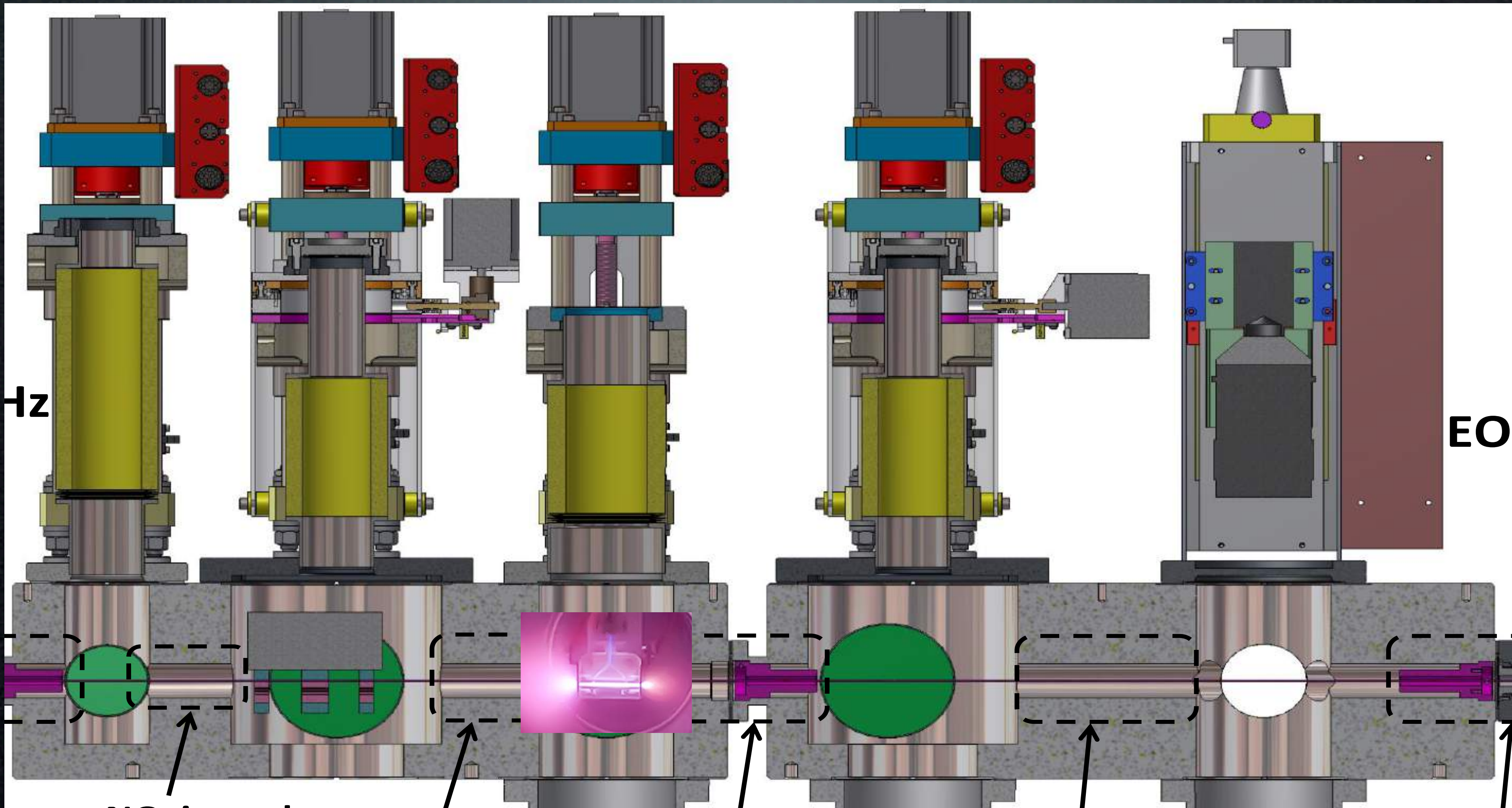


P_{H2} = 10 mbar
Total discharge duration: 800 ns
Voltage: 20 kV
Peak current: 200 A
Capacitor: 6 nF

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

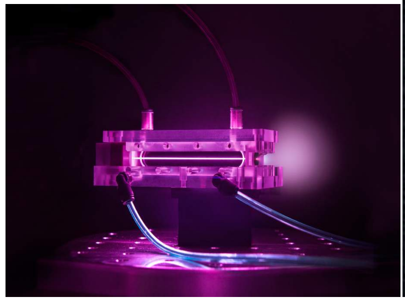
Capture PMQ

BELLA: BErkeley Lab Laser Accelerator

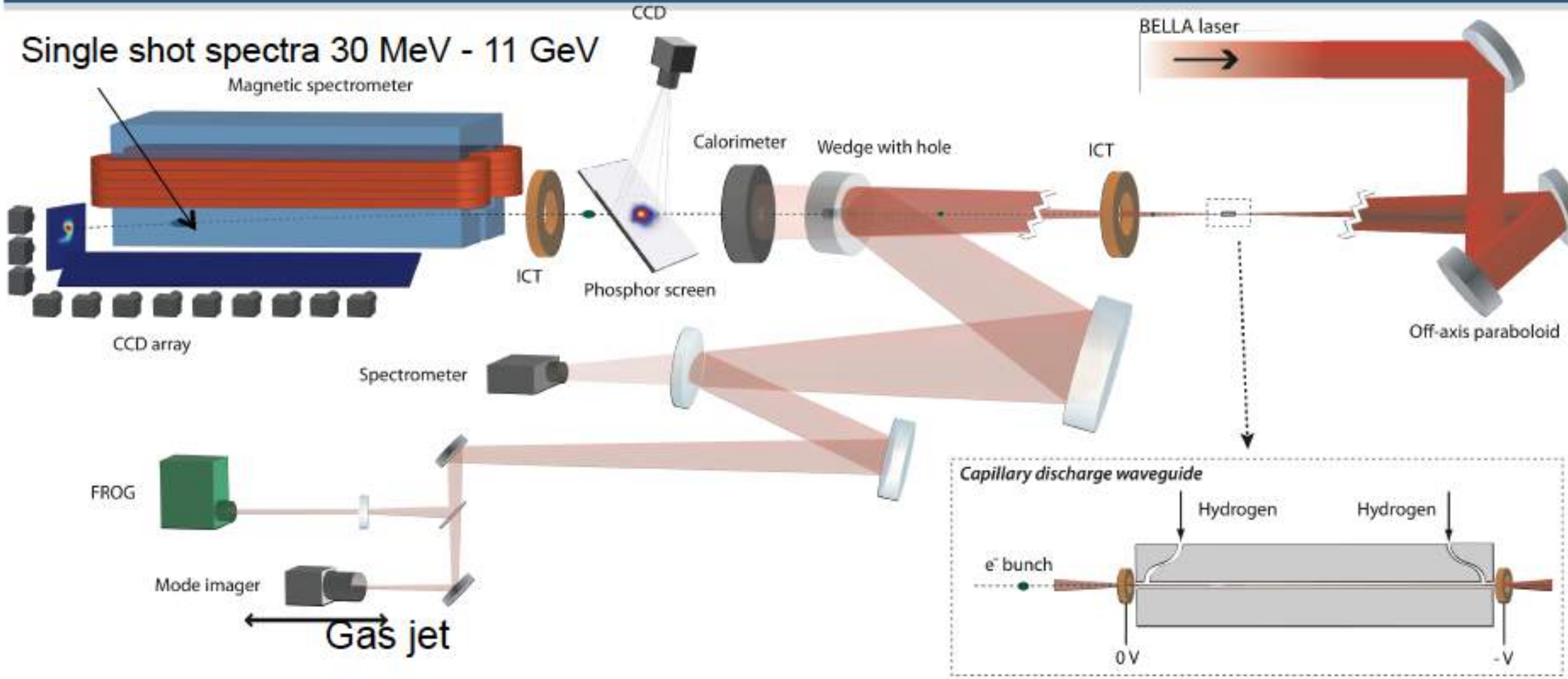
BELLA Facility: state-of-the-art 1.3 PW-laser for laser accelerator science: >42 J in <40 fs (> 1PW) at 1 Hz laser and supporting infrastructure at LBNL

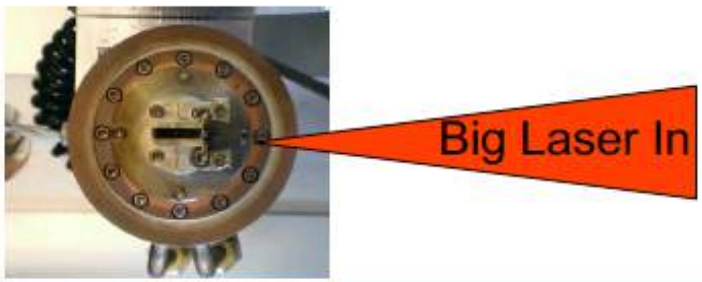
Critical HEP experiments:

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



Experiments at LBNL use the BELLA laser focused by a 14 m focal length off-axis paraboloid onto gas jet or capillary discharge targets

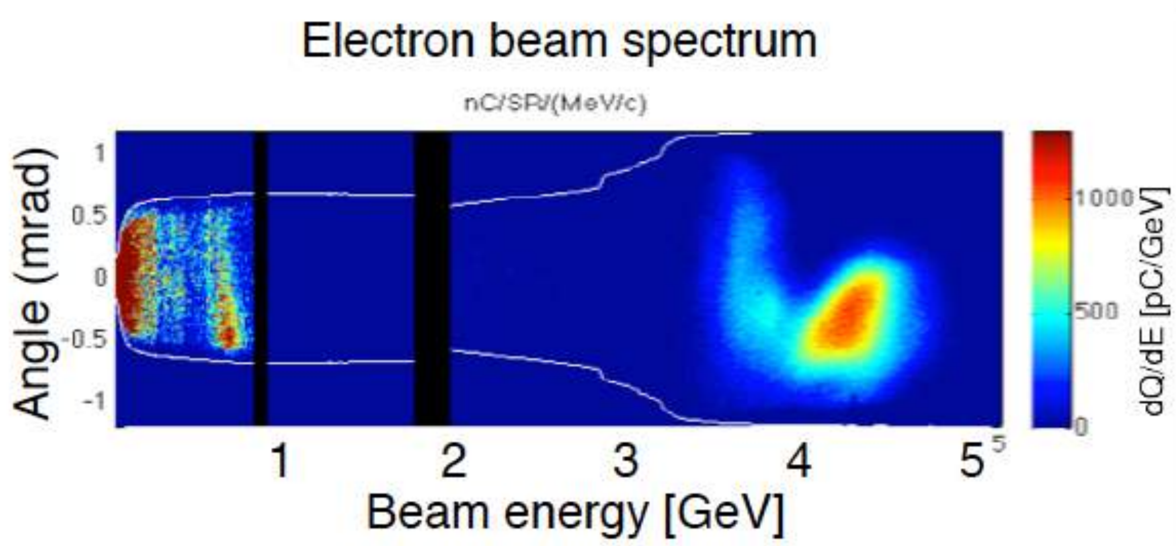


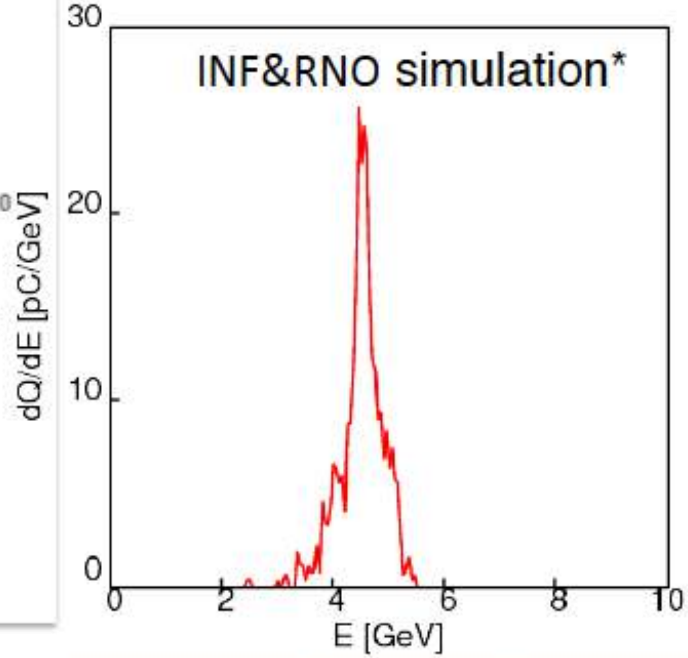


Capillary discharge

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



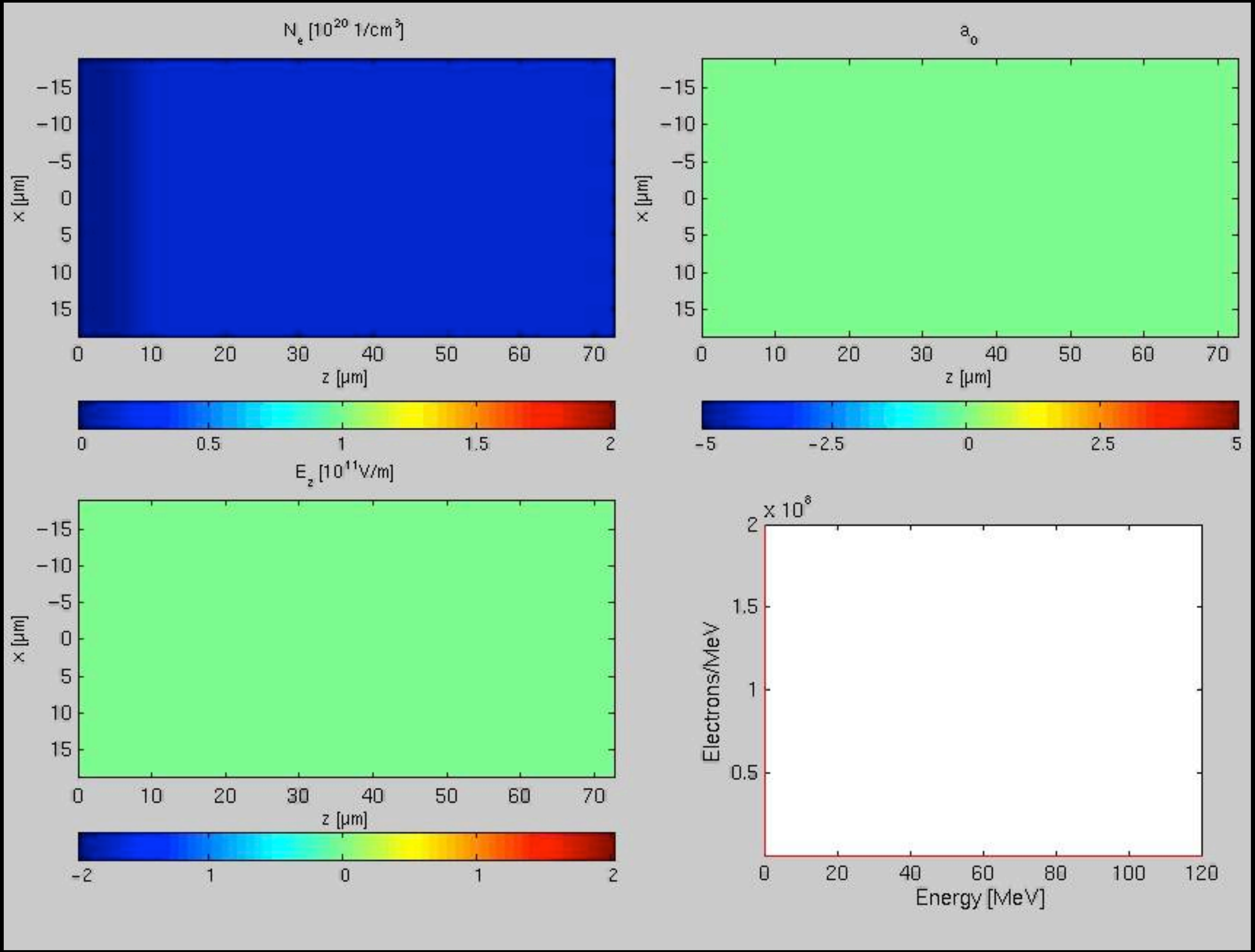


- **Laser** (E=15 J):
  - Measured) longitudinal profile (T_0= 40 fs)
  - Measured far field mode (w_0=53 µm)
- **Plasma:** parabolic plasma channel (length 9 cm, n_0~6-7x10^{17} cm^{-3})

	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

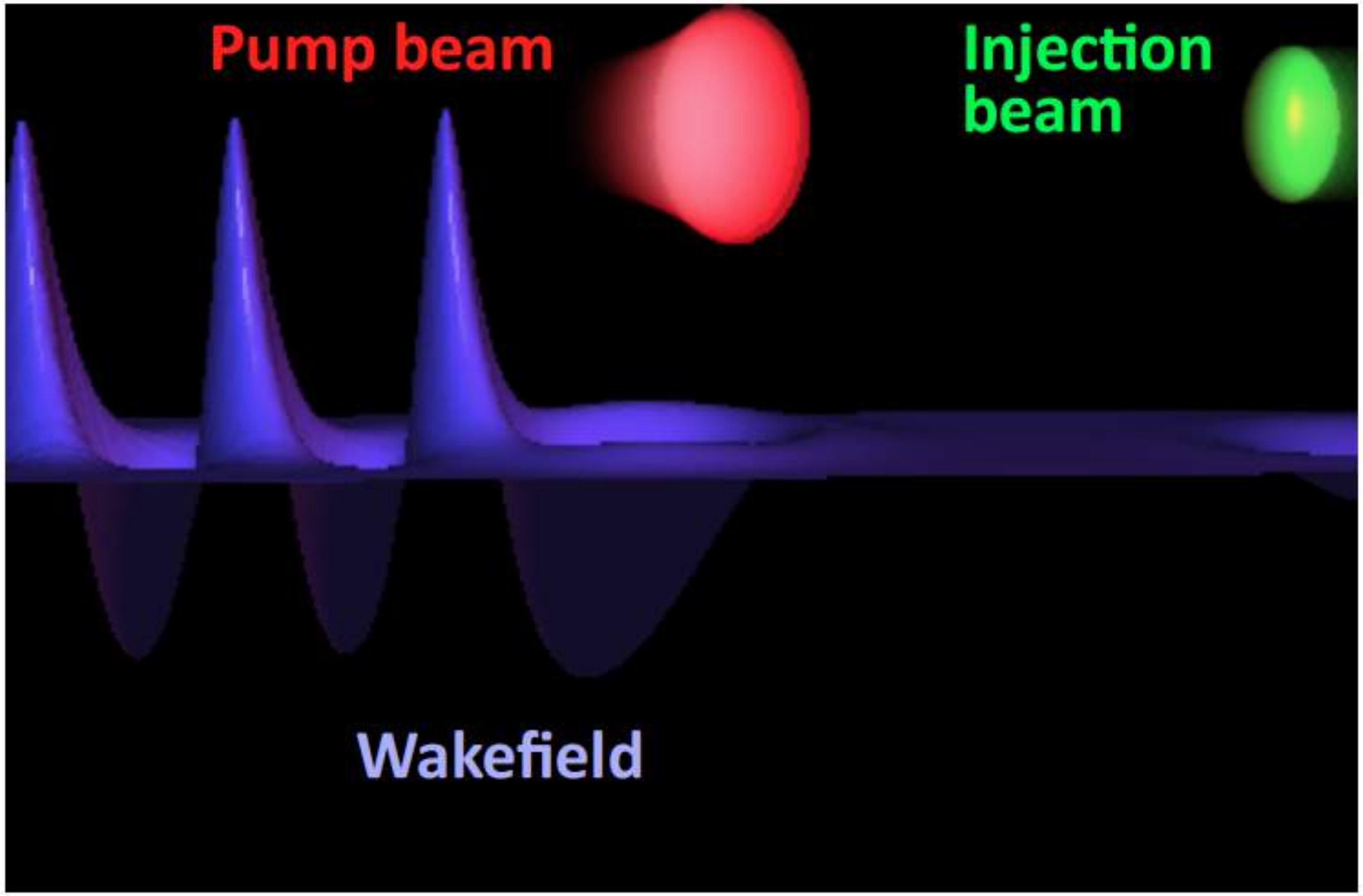
W.P. Leemans et al.,PRL 2014

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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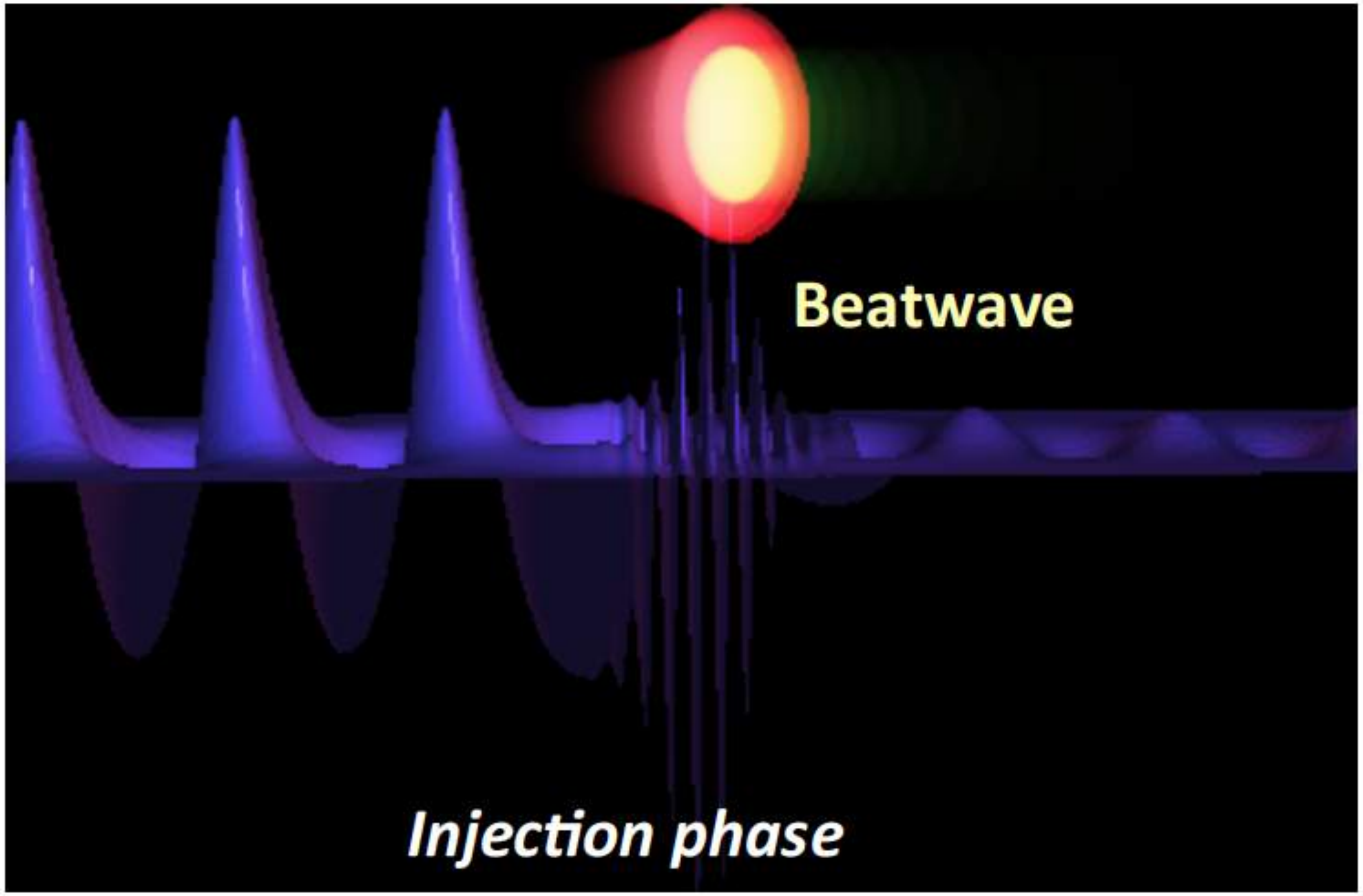

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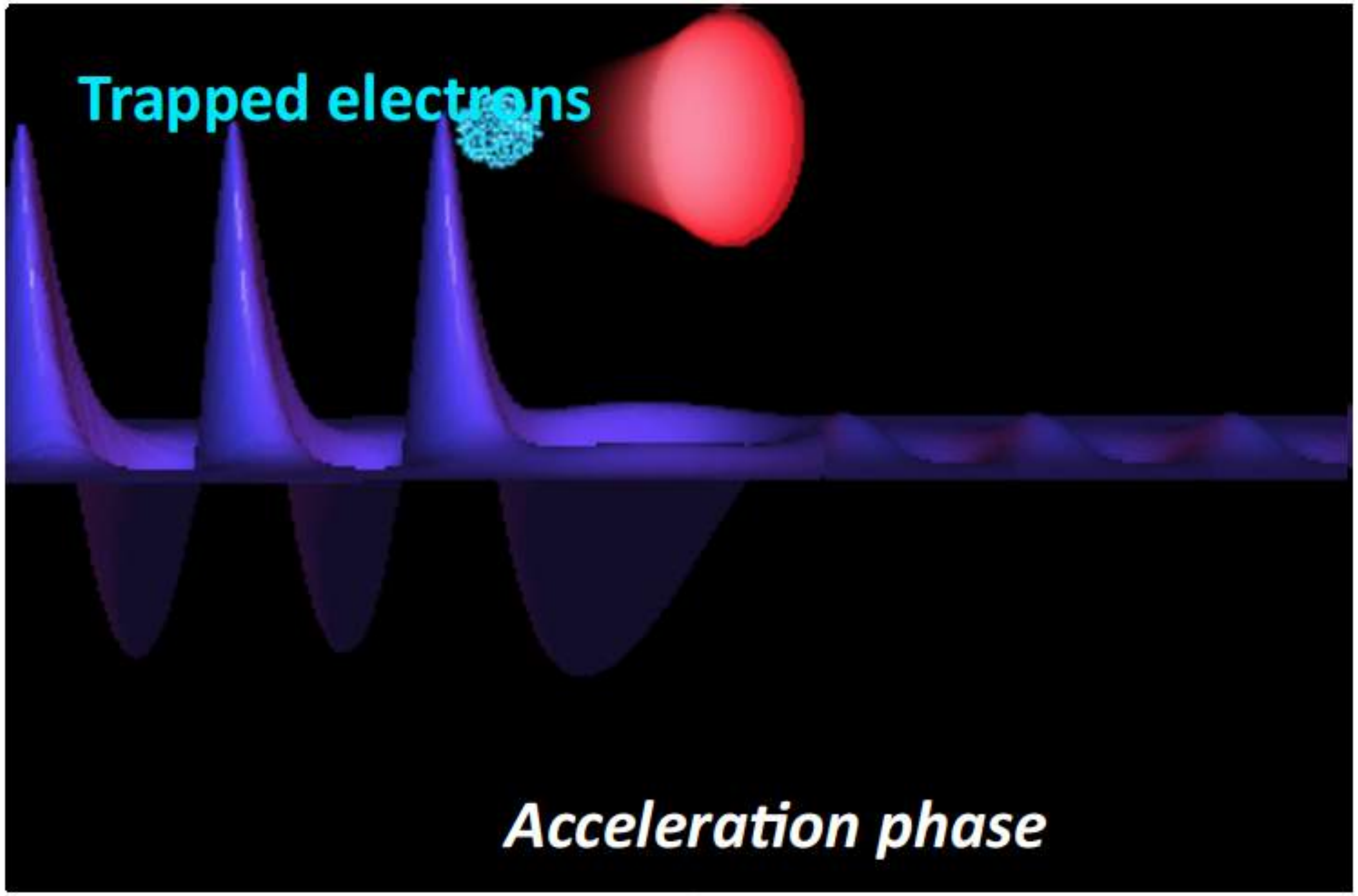

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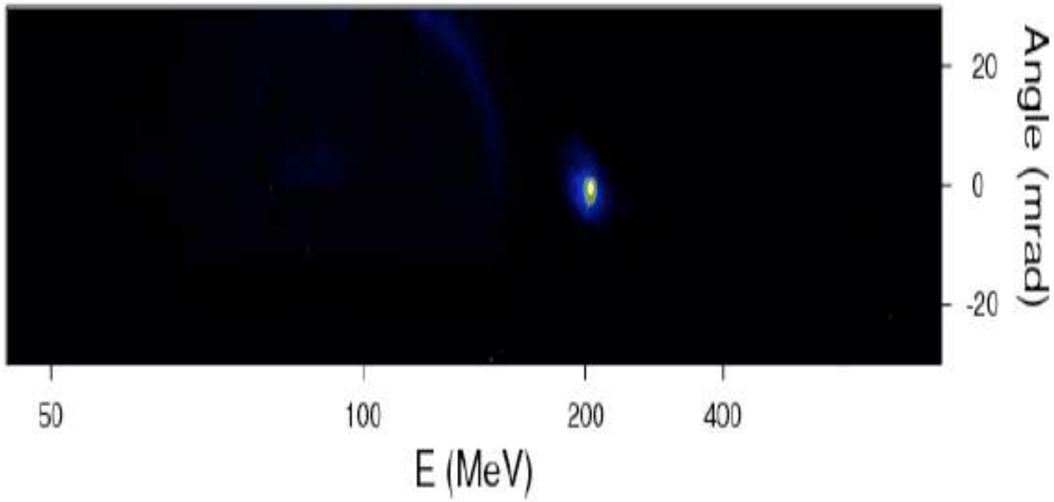
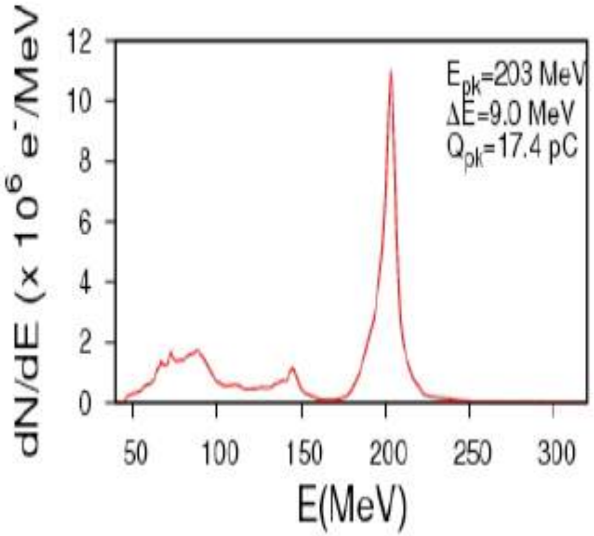
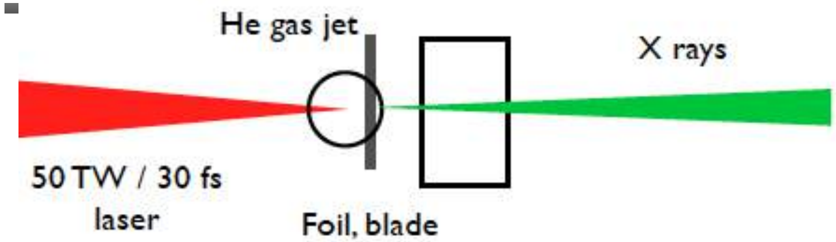
Experiments : J. Faure *et al.*, Nature **444**, 737 (2006)

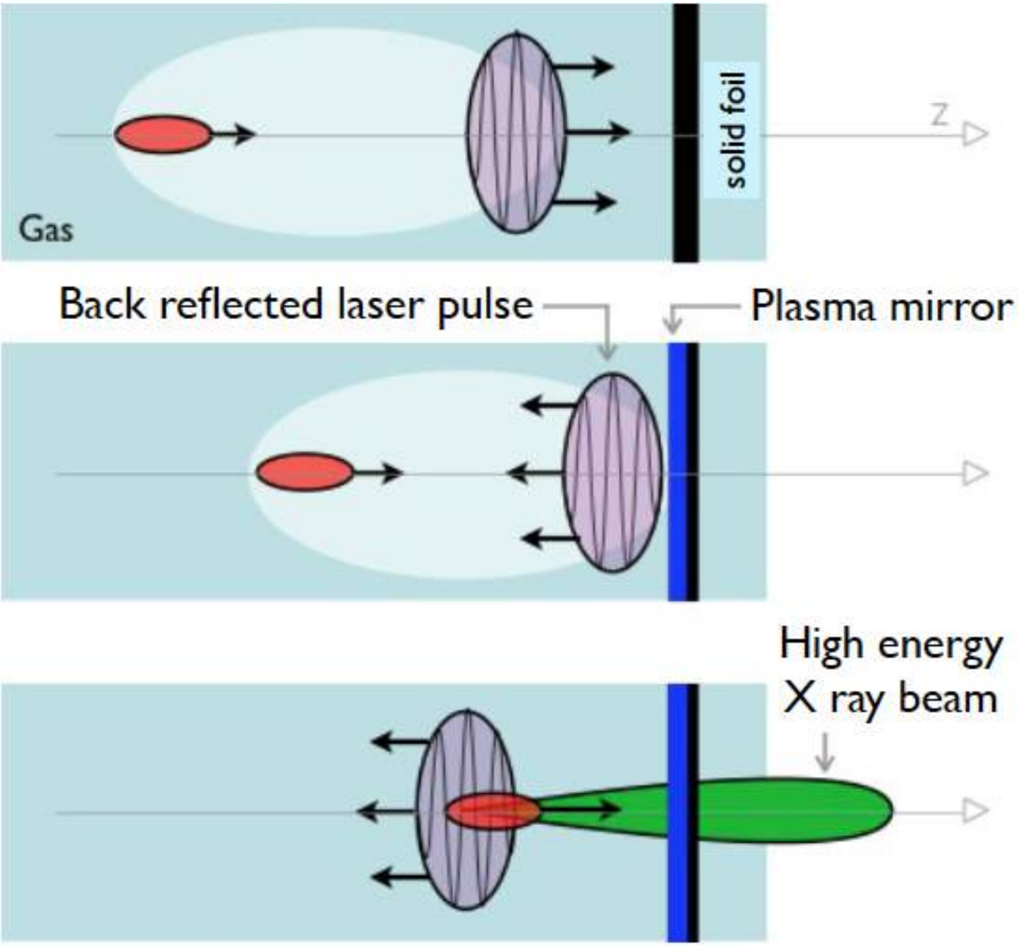
Stable Laser Plasma Accelerators





Inverse Compton Scattering : New scheme





A single laser pulse

A plasma mirror reflects the laser beam

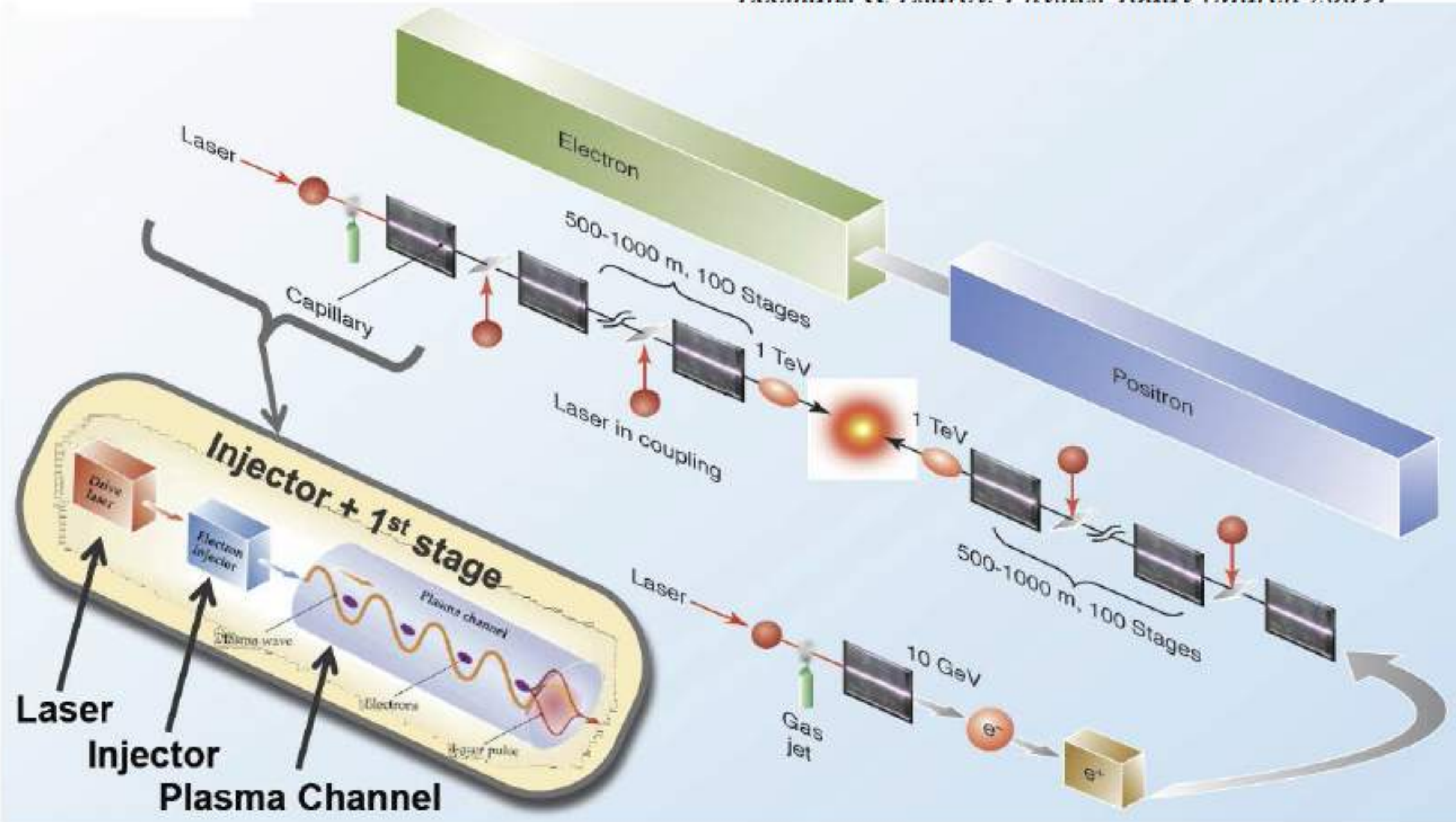
The back reflected laser collides with the accelerated electrons

No alignment : the laser and the electron beams naturally overlap

Save the laser energy !

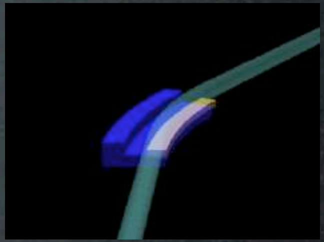
Laser-Plasma-Accelerator LC

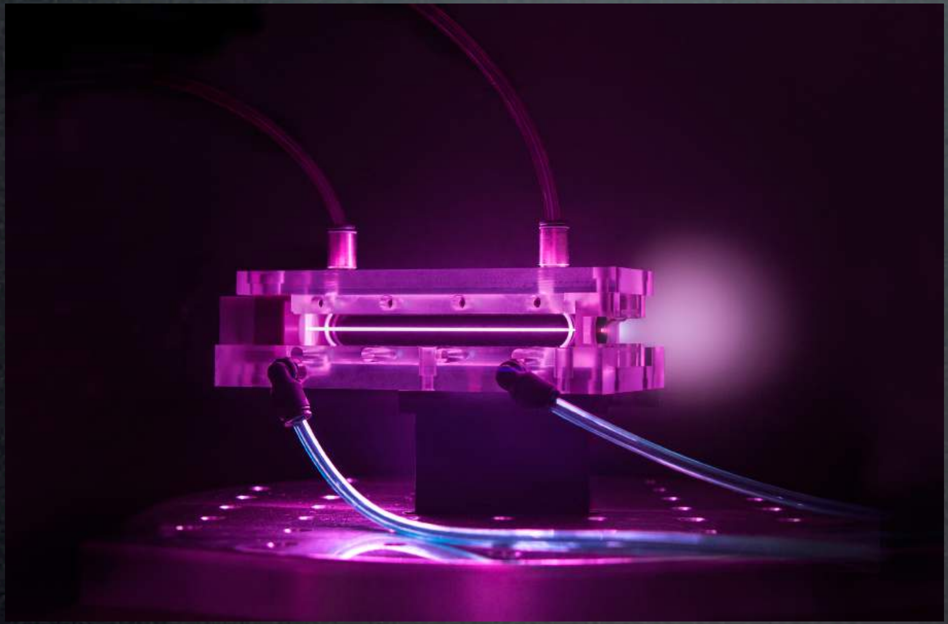
Leemans & Esarey, Physics Today (March 2009)

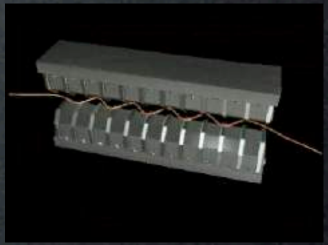


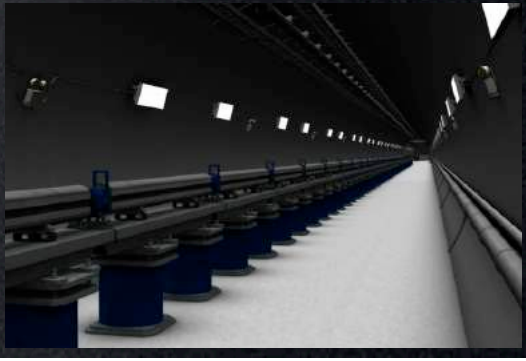
Generations of Synchrotron Light Sources

I. Bending magnets in HEP rings



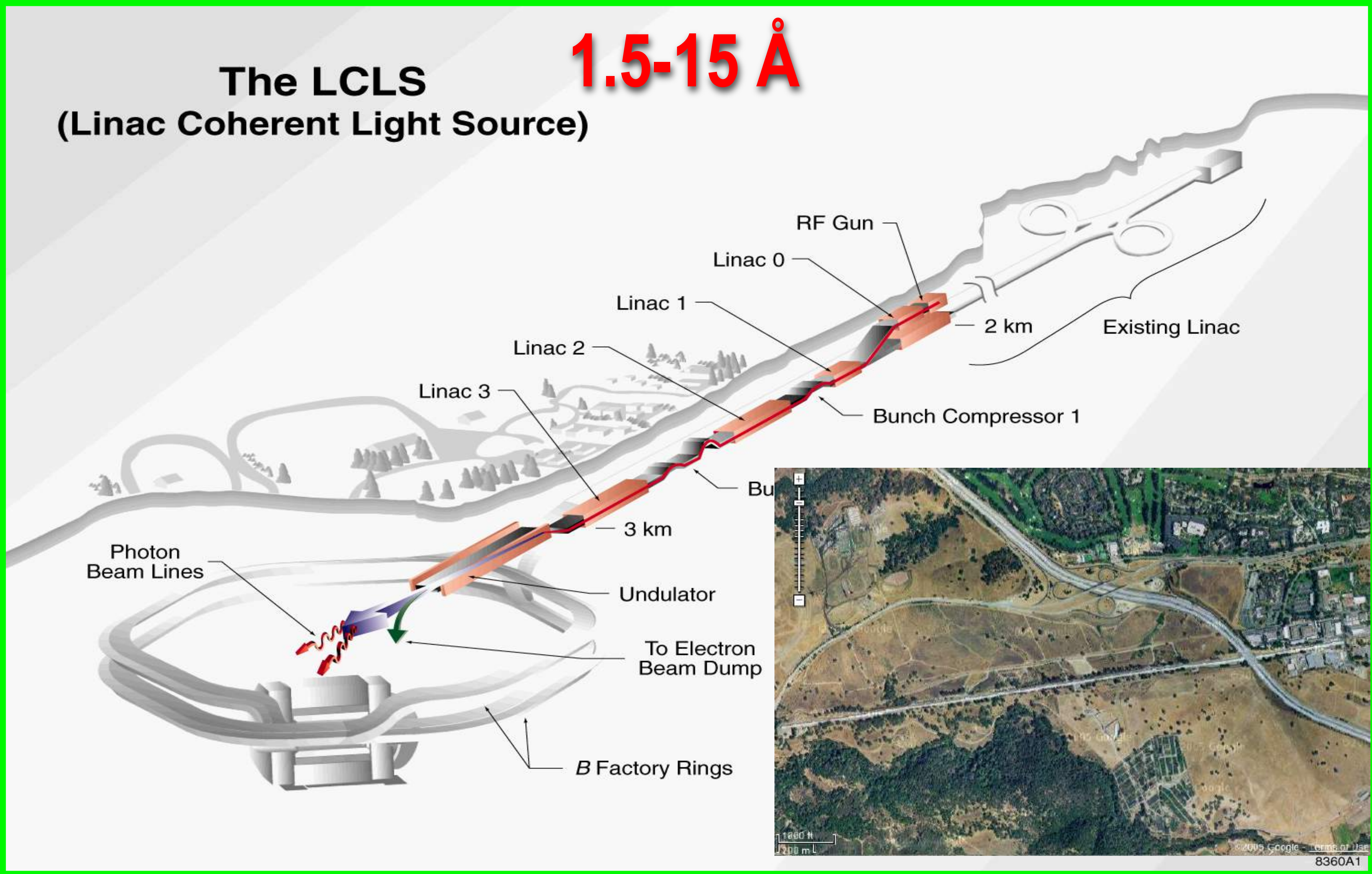






V. Compact Sources

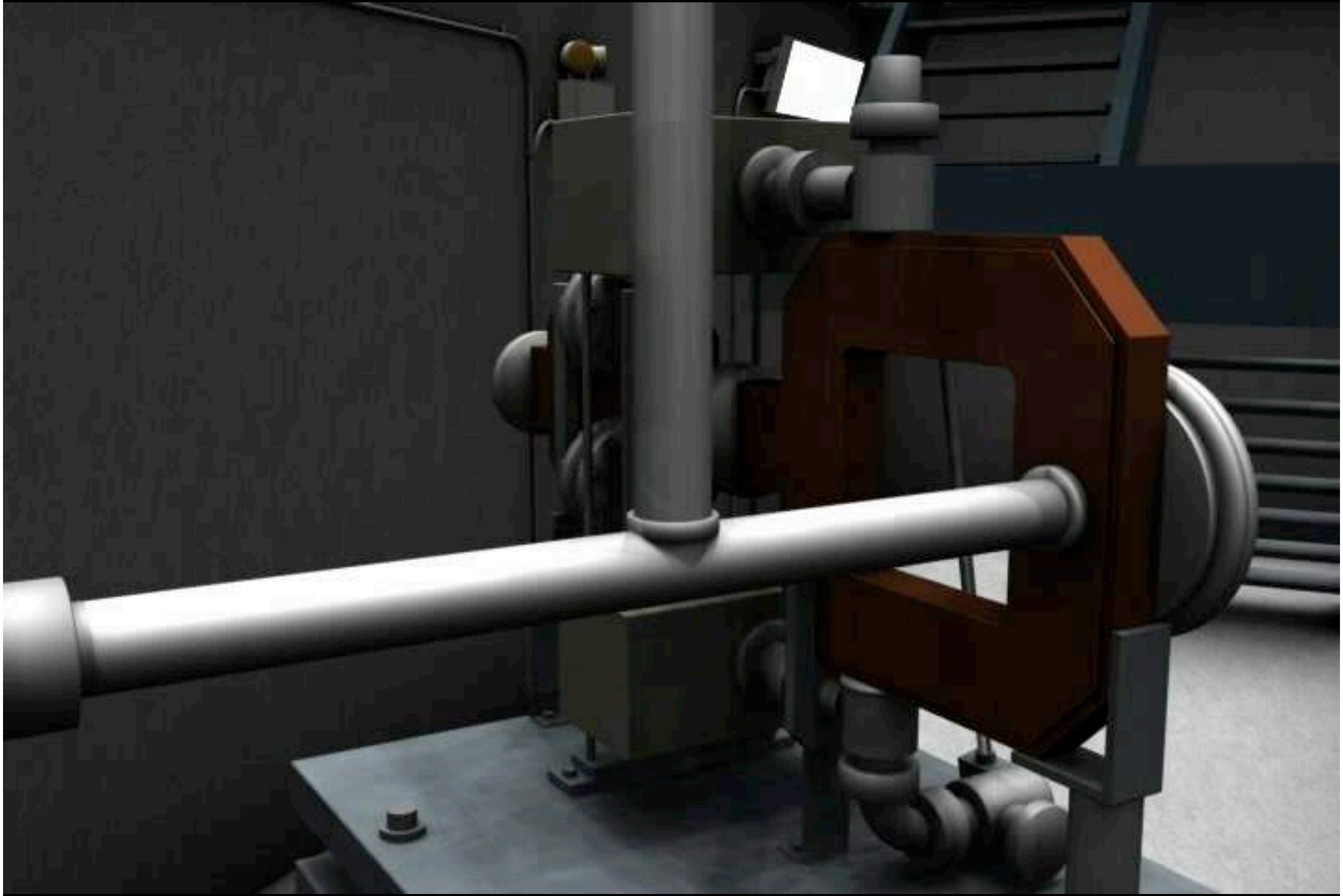
LCLS at *SLAC*



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

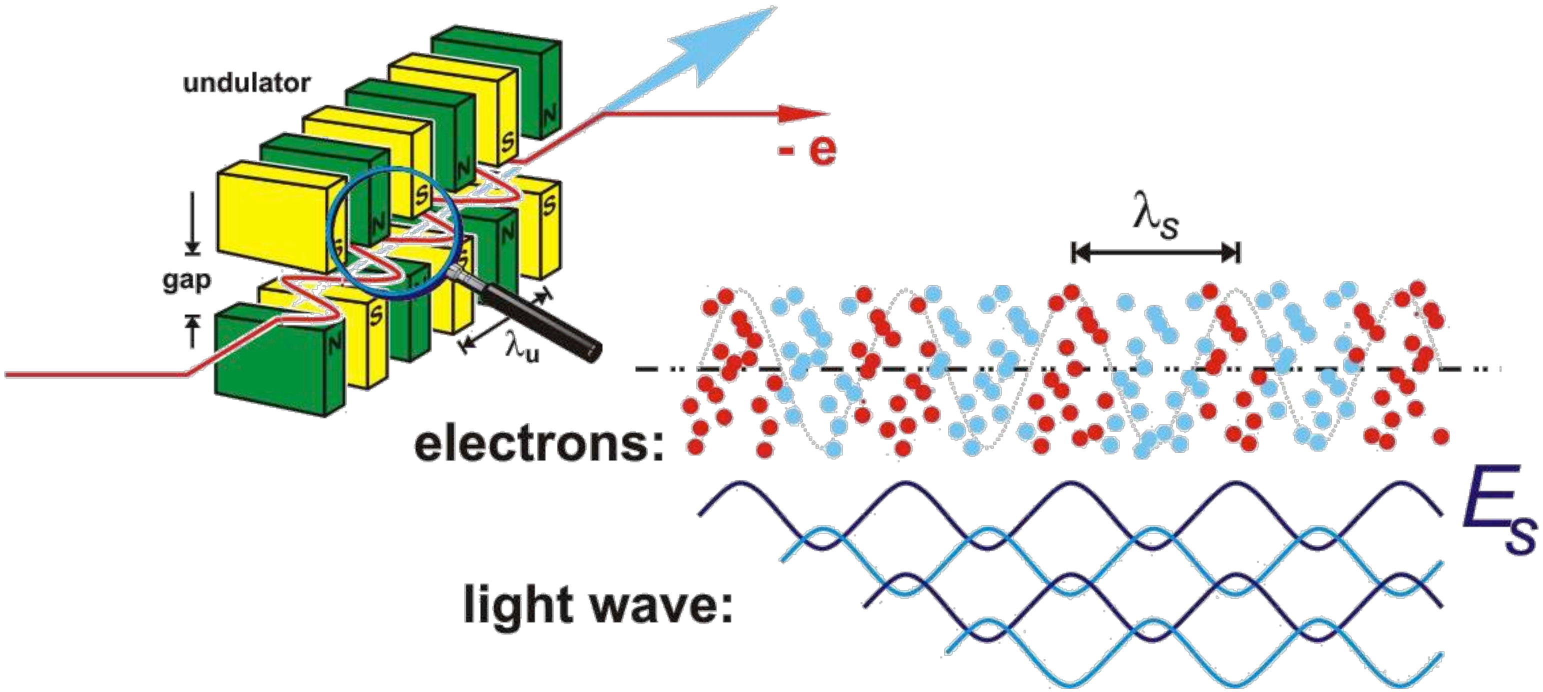
XFEL first lasing – Hamburg May 2017

Electron source and acceleration



Long undulators chain

Beam separation

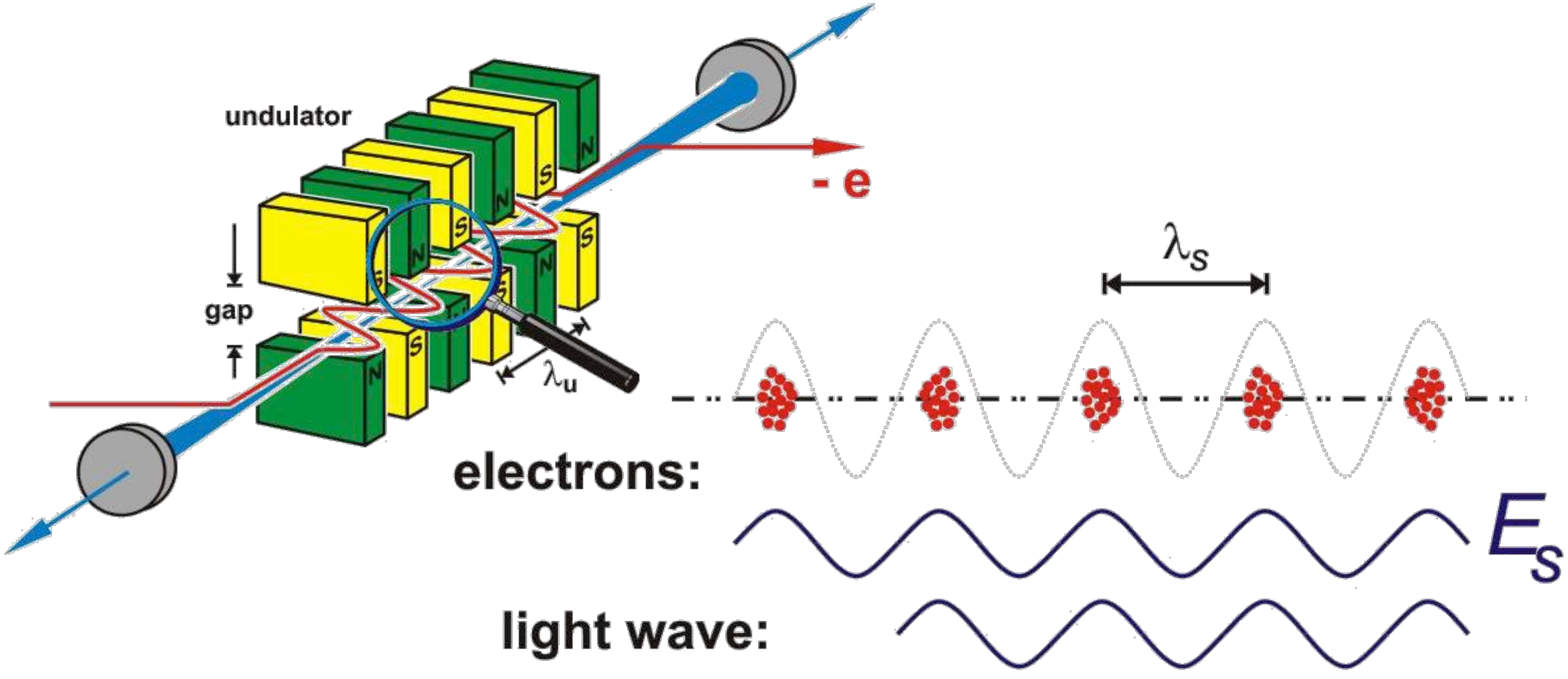


Radiated Power :

$P \propto n_e$ (number of electrons)

destructive interference

⟶ **shotnoise radiation**

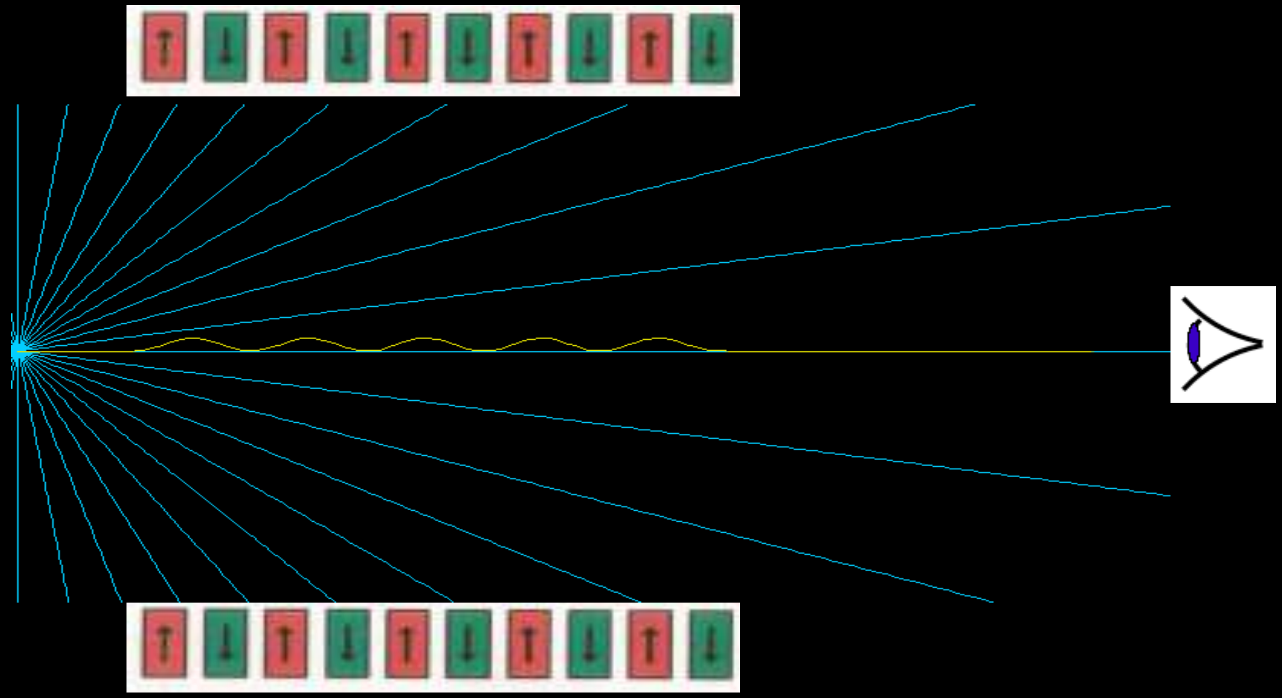


Radiated Power :

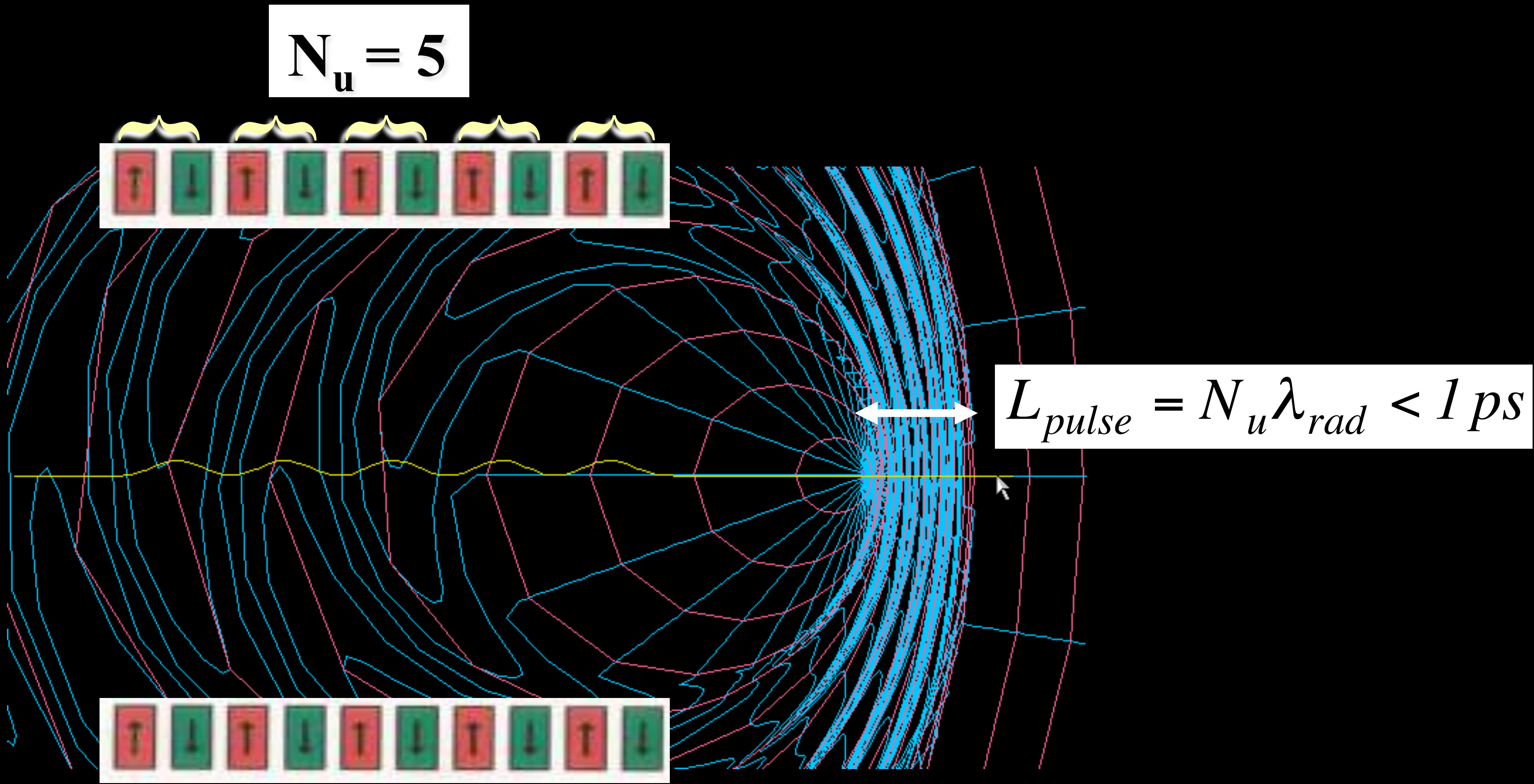
$$P \propto n_e^2 \begin{pmatrix} \text{number of electrons} \\ n_e \sim 10^6 - 10^9 \end{pmatrix}$$

constructive interference

⟶ **enhanced emission**

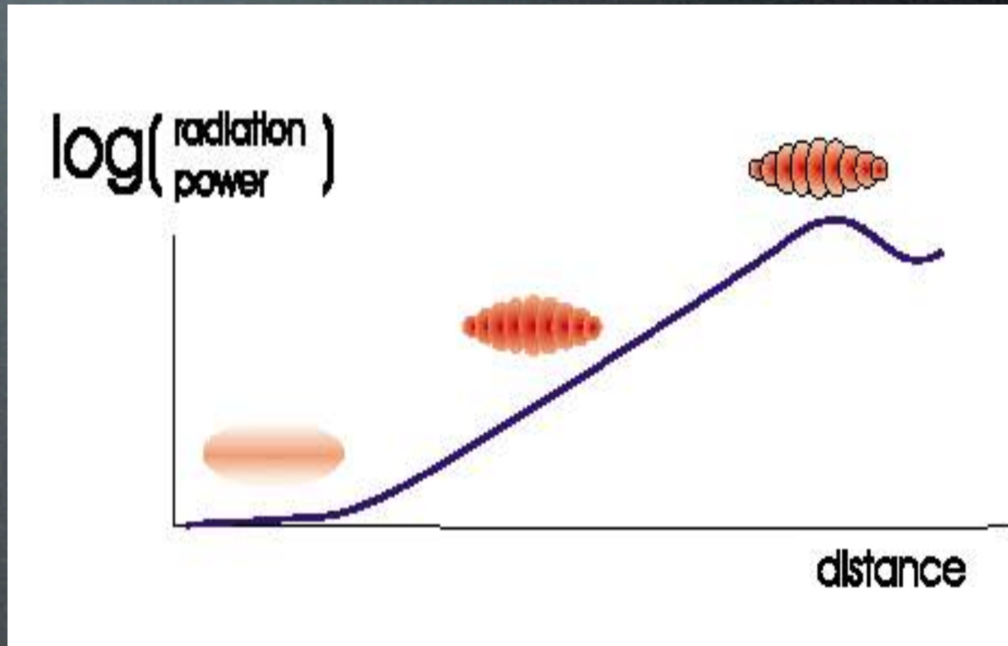


Radiation Simulator – T. Shintake, @ http://www-xfel.spring8.or.jp/Index.htm



Nu = 5
Lpulse = Nuλrad < 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



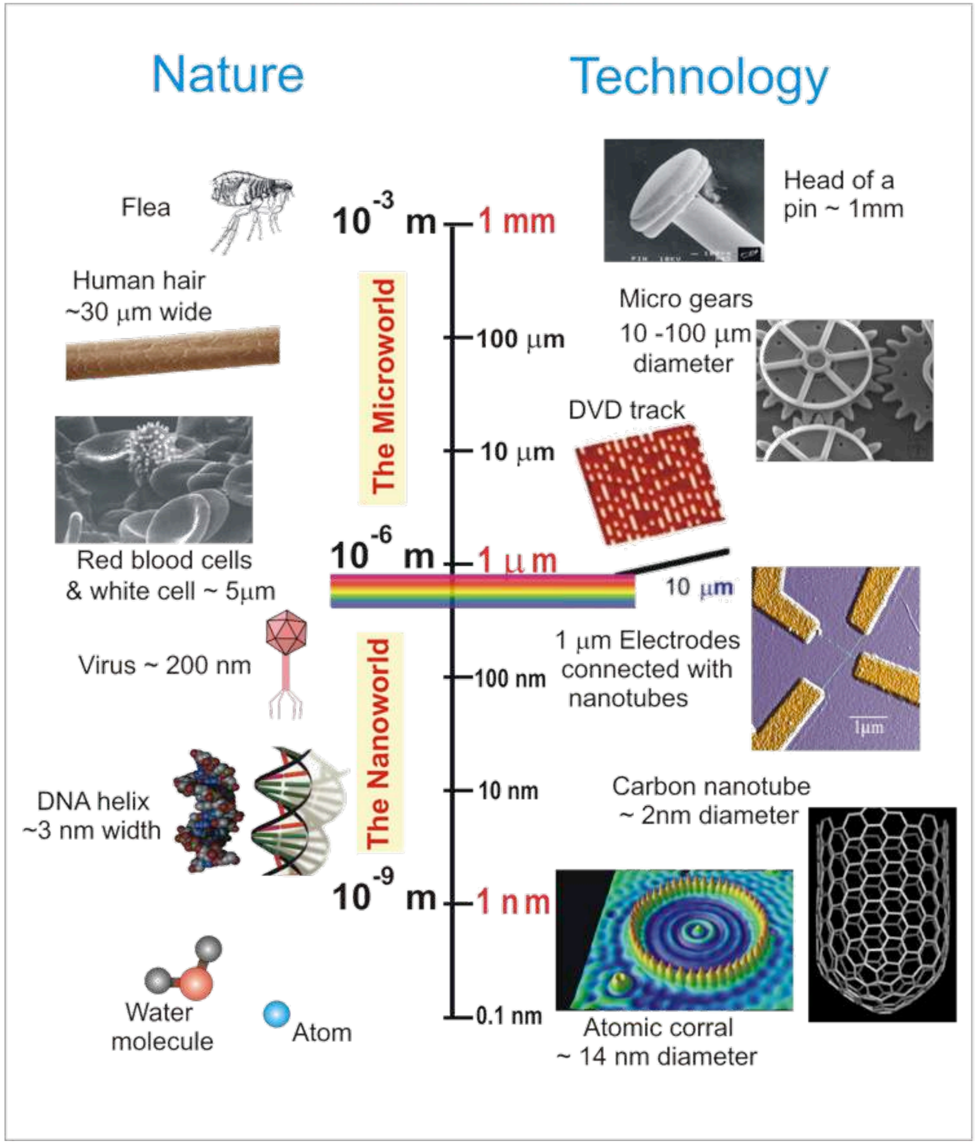
$$\lambda_{rad} \approx \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2} + \gamma^2\vartheta^2\right)$$

(Tunability - Harmonics)

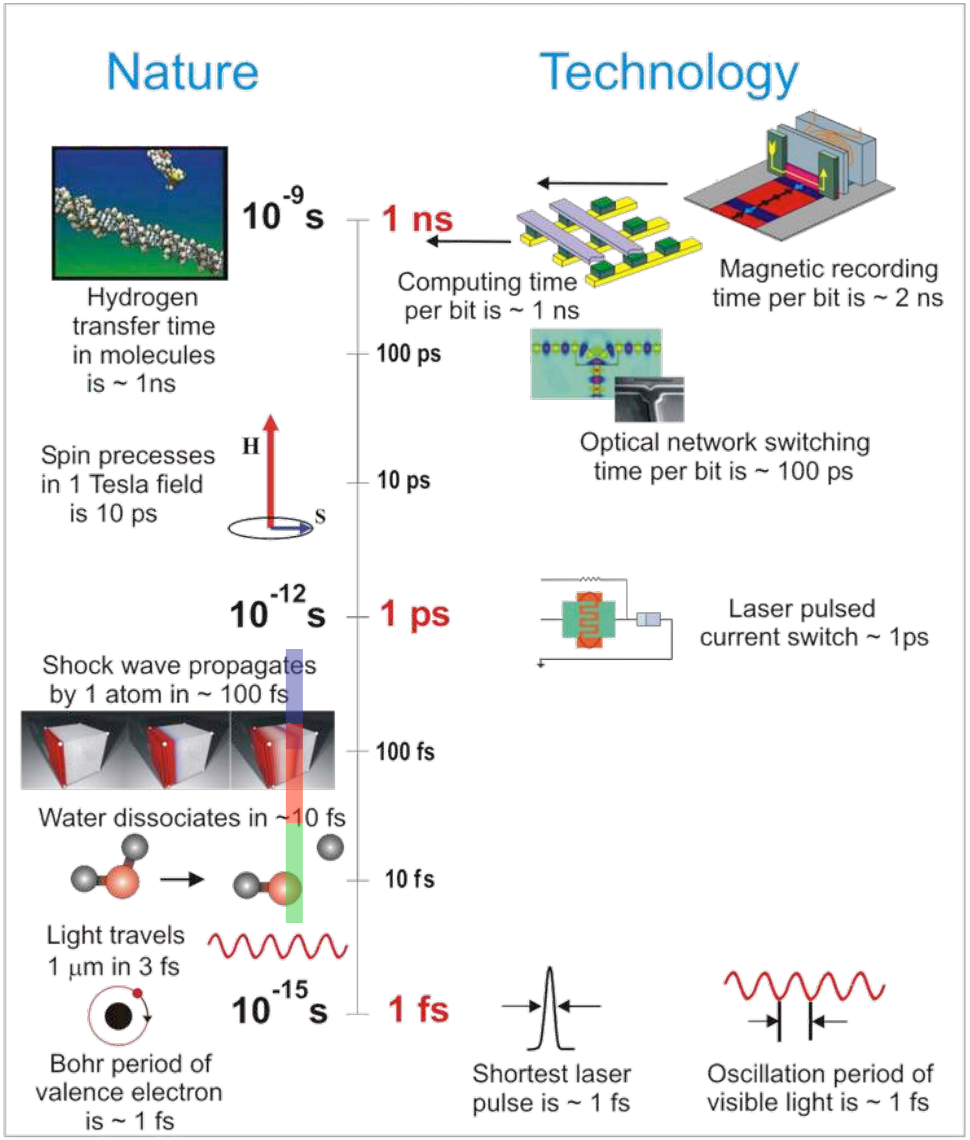
The FEL Applications

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

Ultra-Small



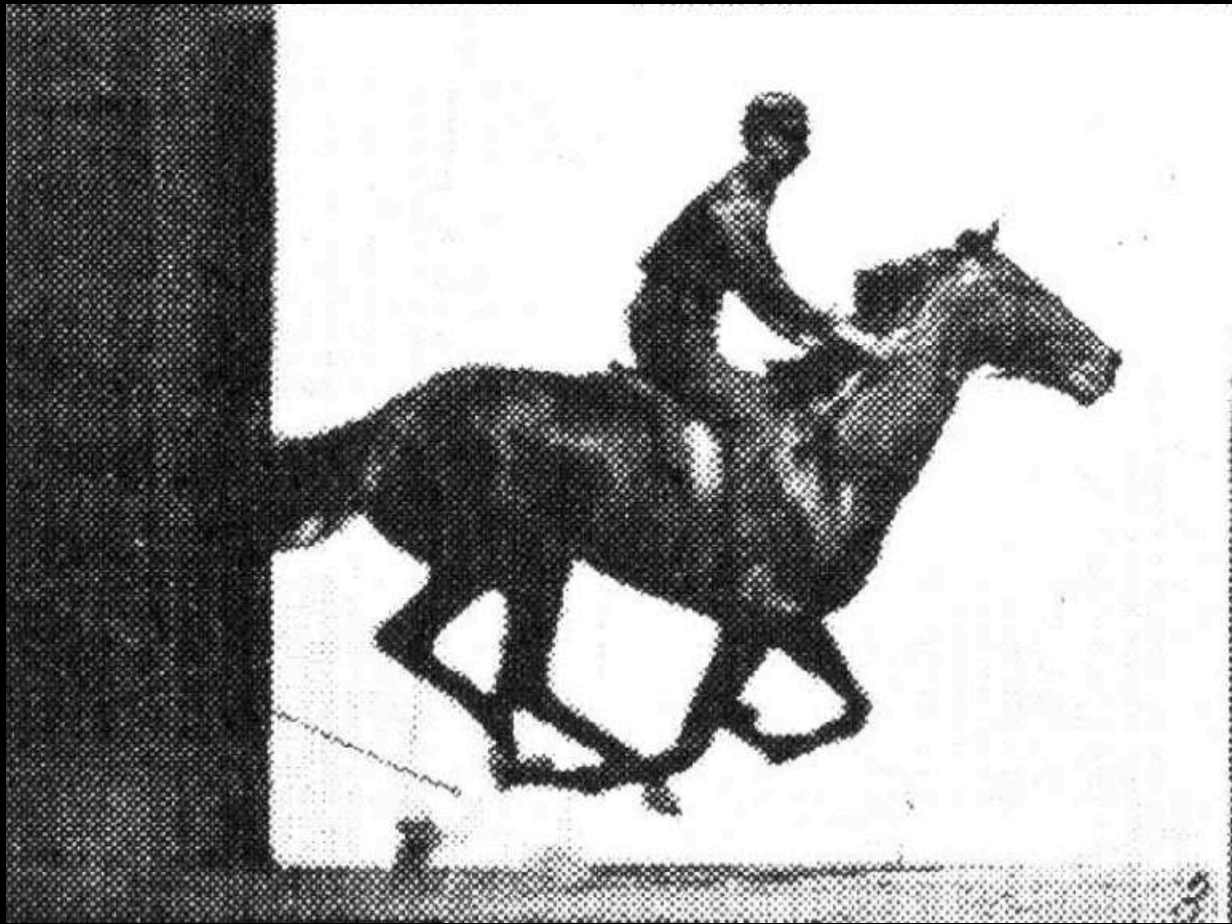
Ultra-Fast



E. Muybridge

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

disagree whether all feet leave the ground during gallop…

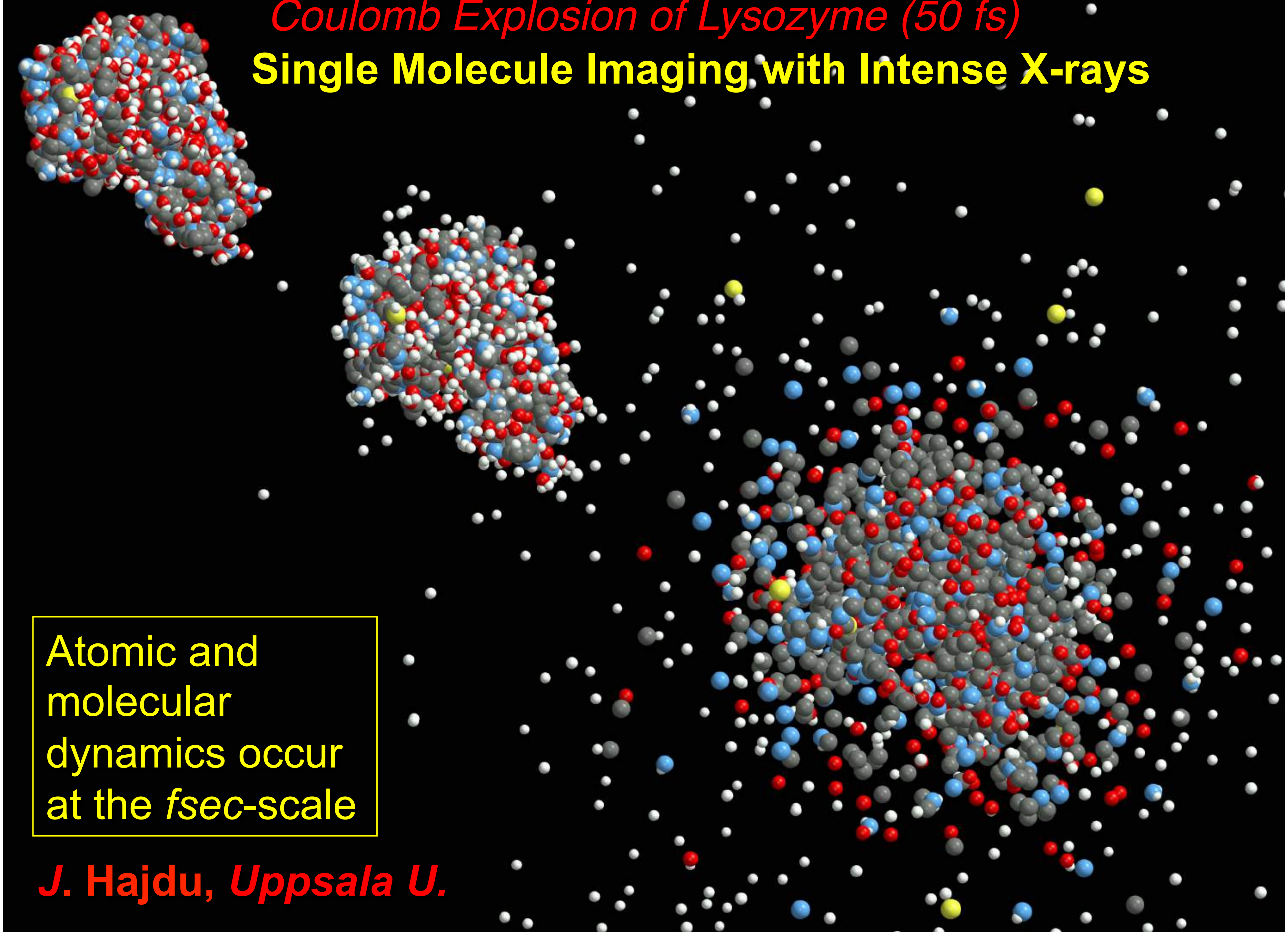


used spark photography to freeze this 'ultra-fast' process

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

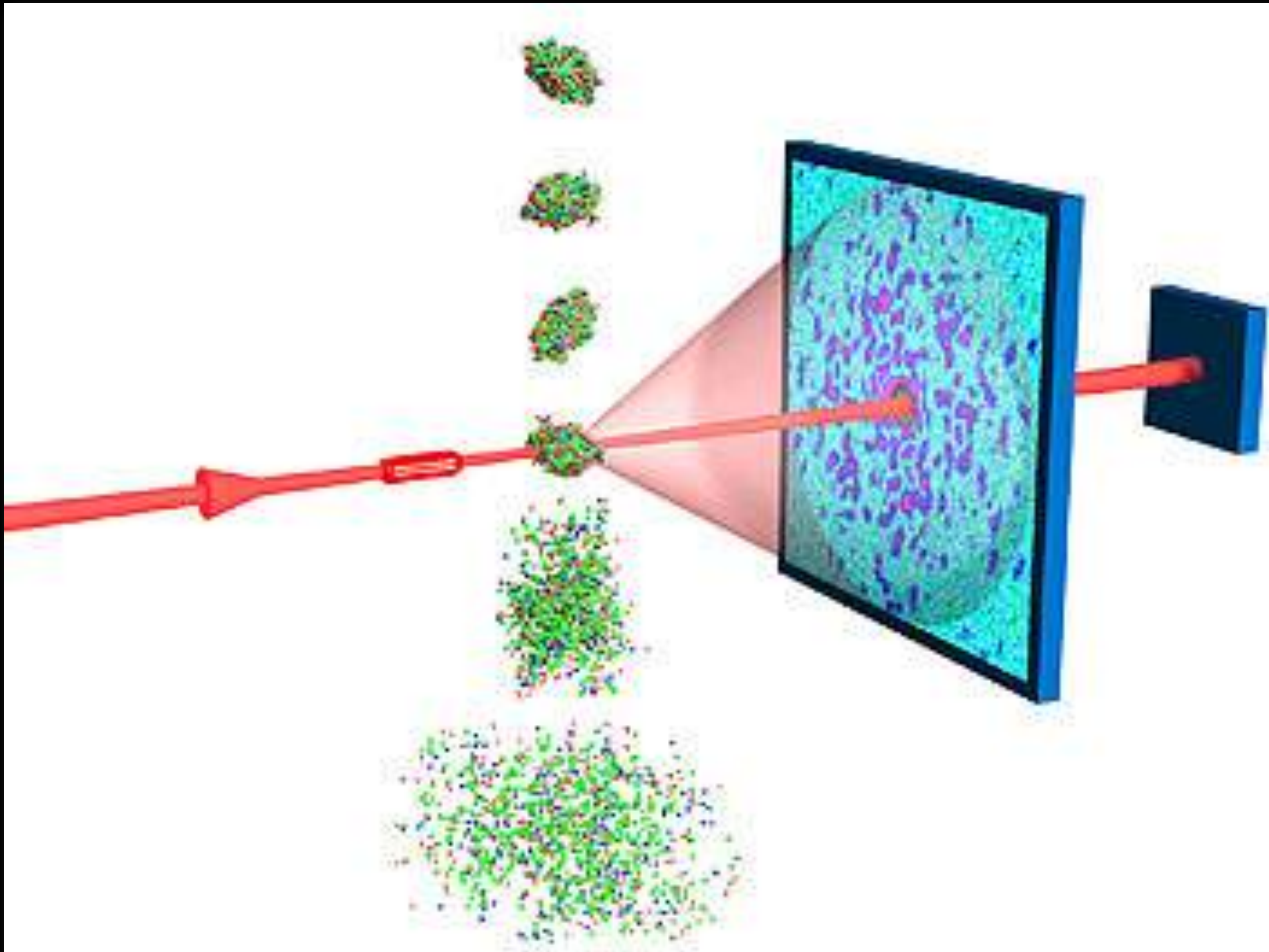
Coulomb Explosion of Lysozyme (50 fs)

Single Molecule Imaging with Intense X-rays

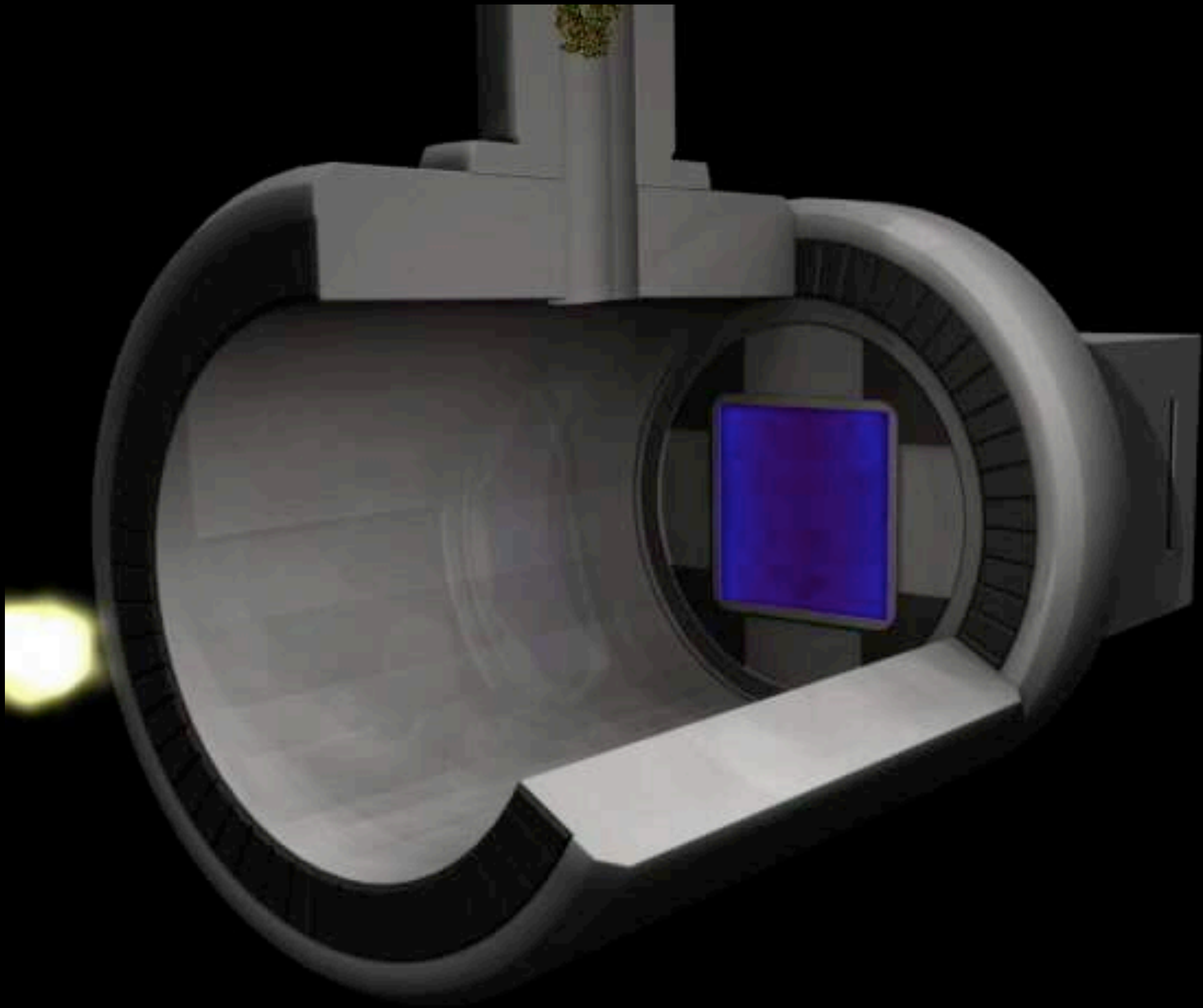


Atomic and molecular dynamics occur at the *fsec*-scale

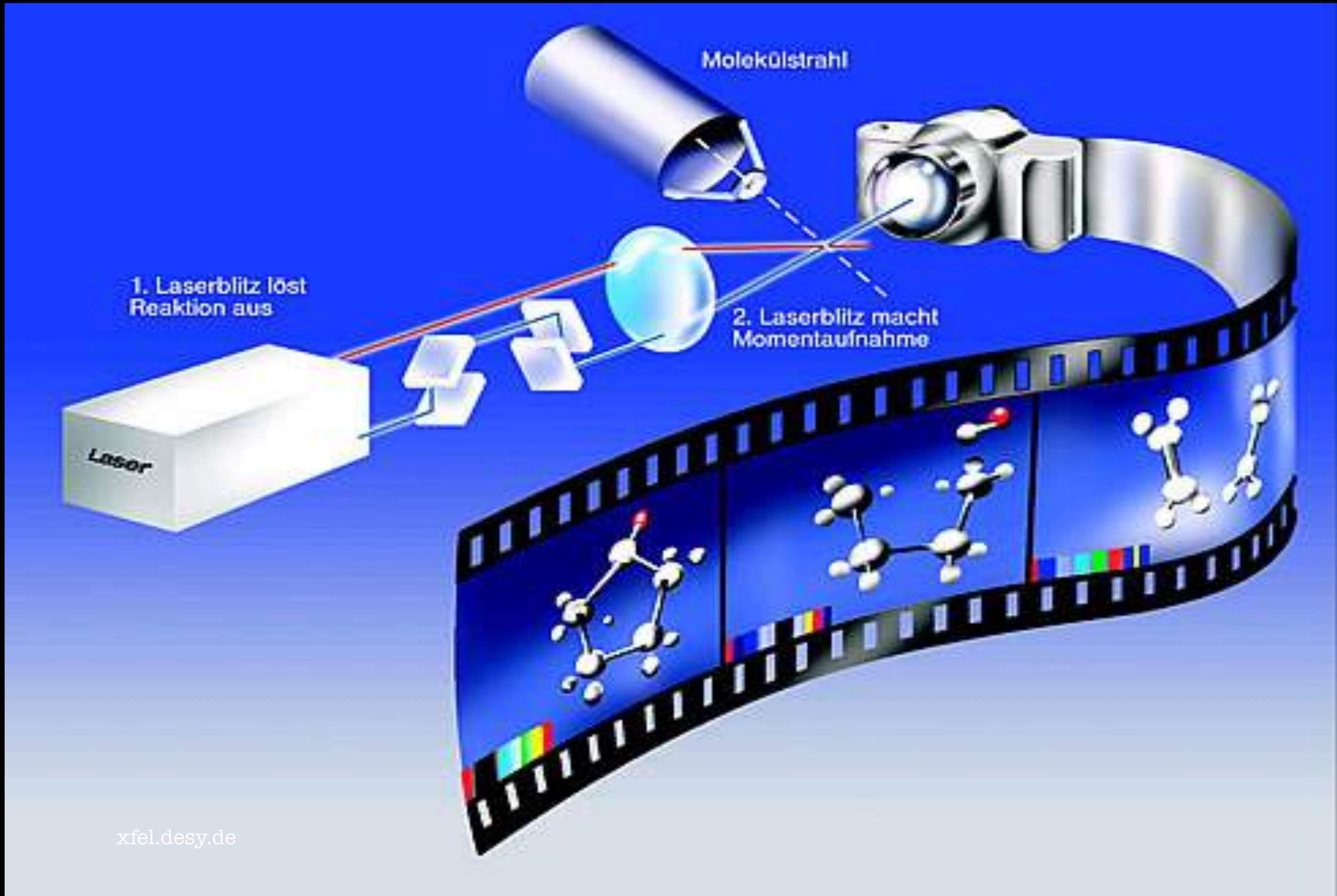
J*. Hajdu, *Uppsala U.



Experimental hall (Single Protein Imaging)



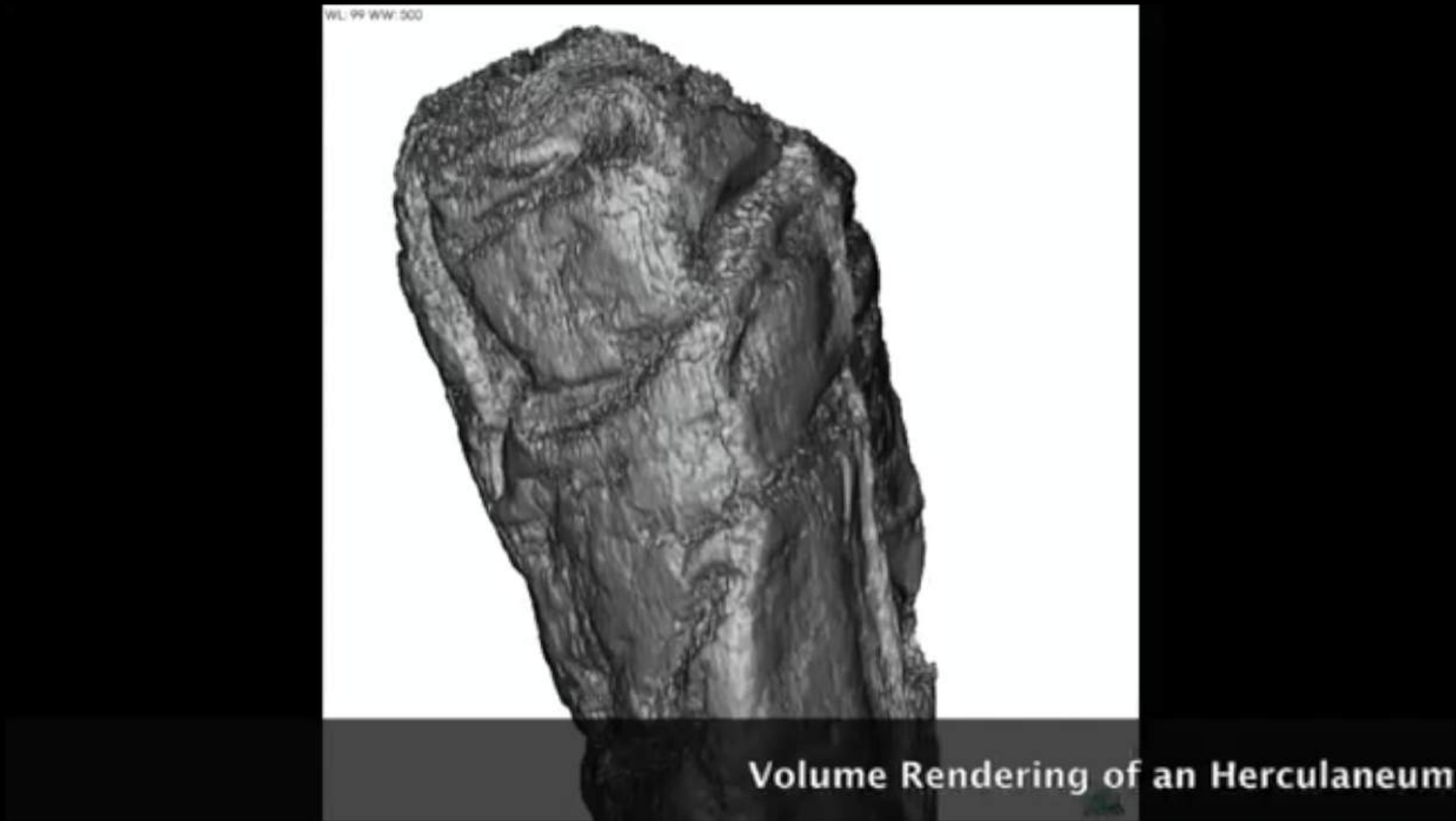
http://lcls.slac.stanford.edu/AnimationViewLCLS.aspx


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