Advanced Radiation Sources based on Plasma Accelerators

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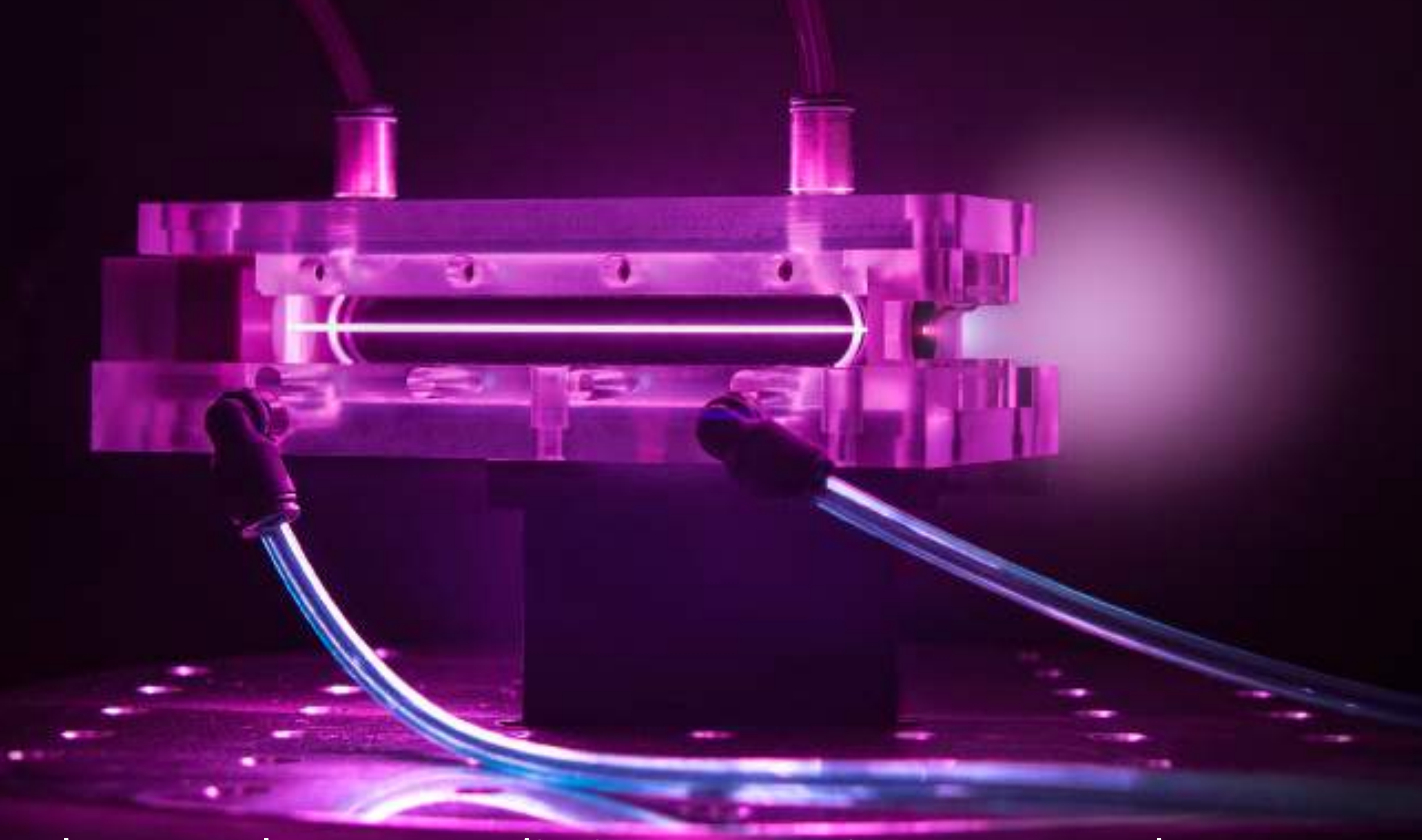
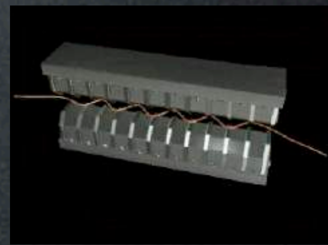
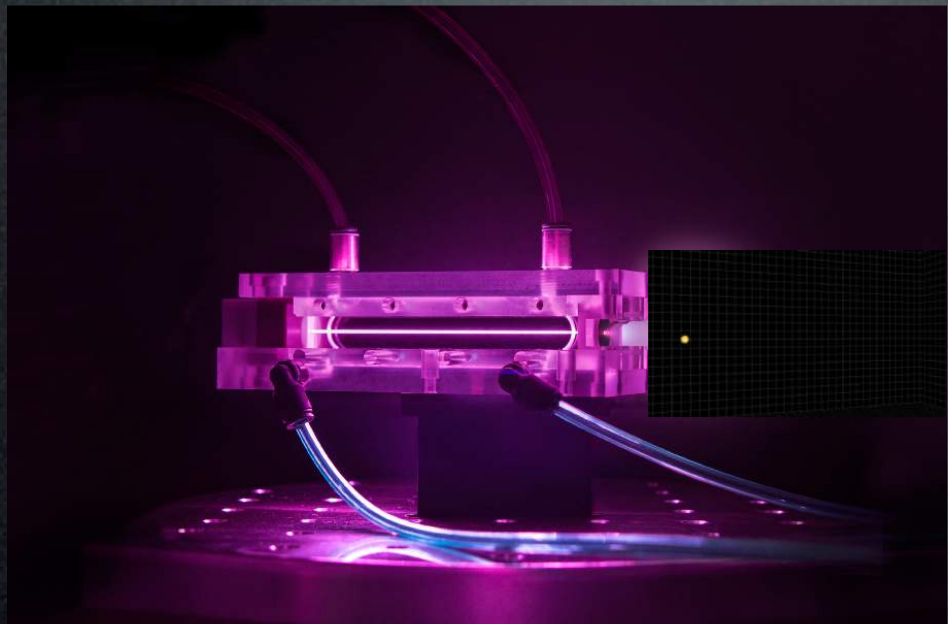


XIV School on Synchrotron Radiation – Muggia, 21 September 2017

Generations of Synchrotron Light Sources

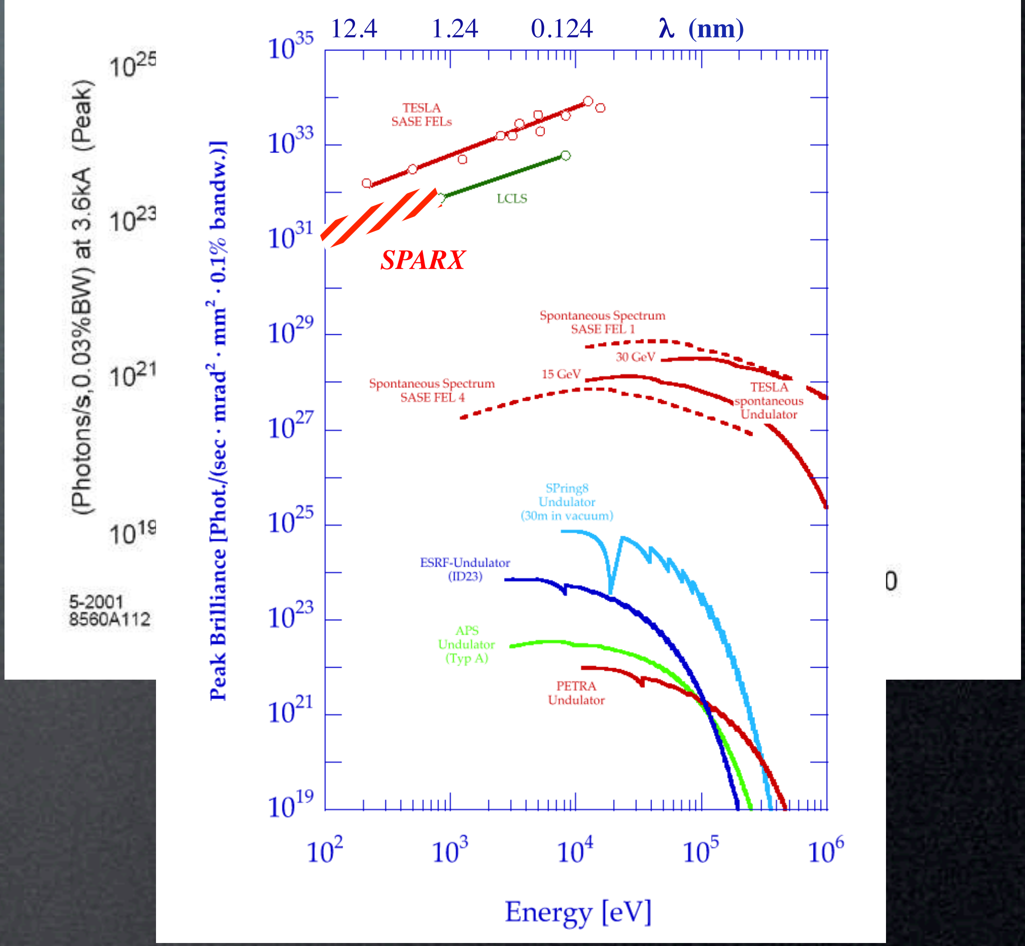
I. Bending magnets in HEP rings





V. Compact Sources

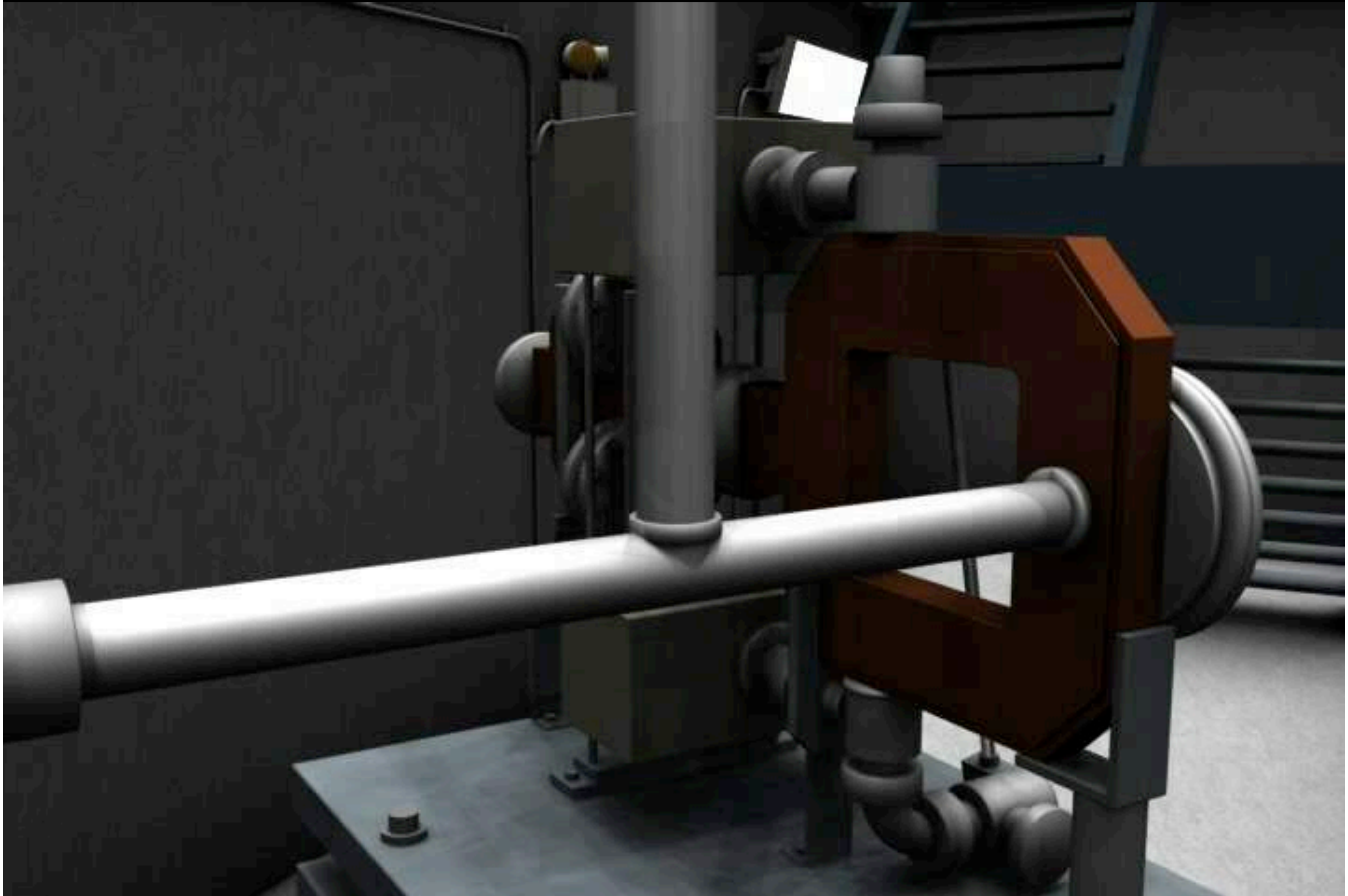
A Free Electron Laser is a device that converts a fraction of the electron kinetic energy into coherent radiation via a collective instability in a long undulator



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

(Tunability - Harmonics)

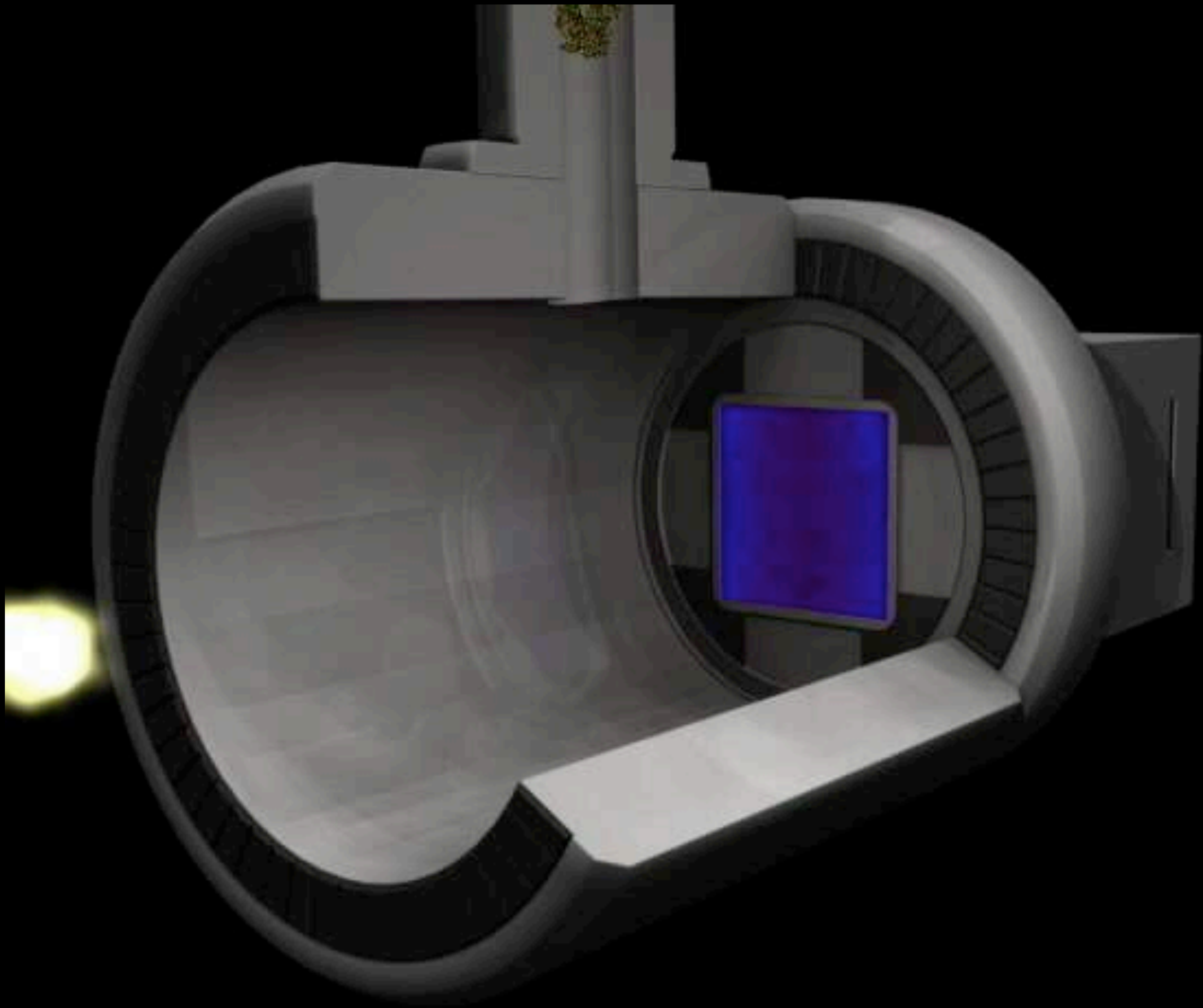
Electron source and acceleration



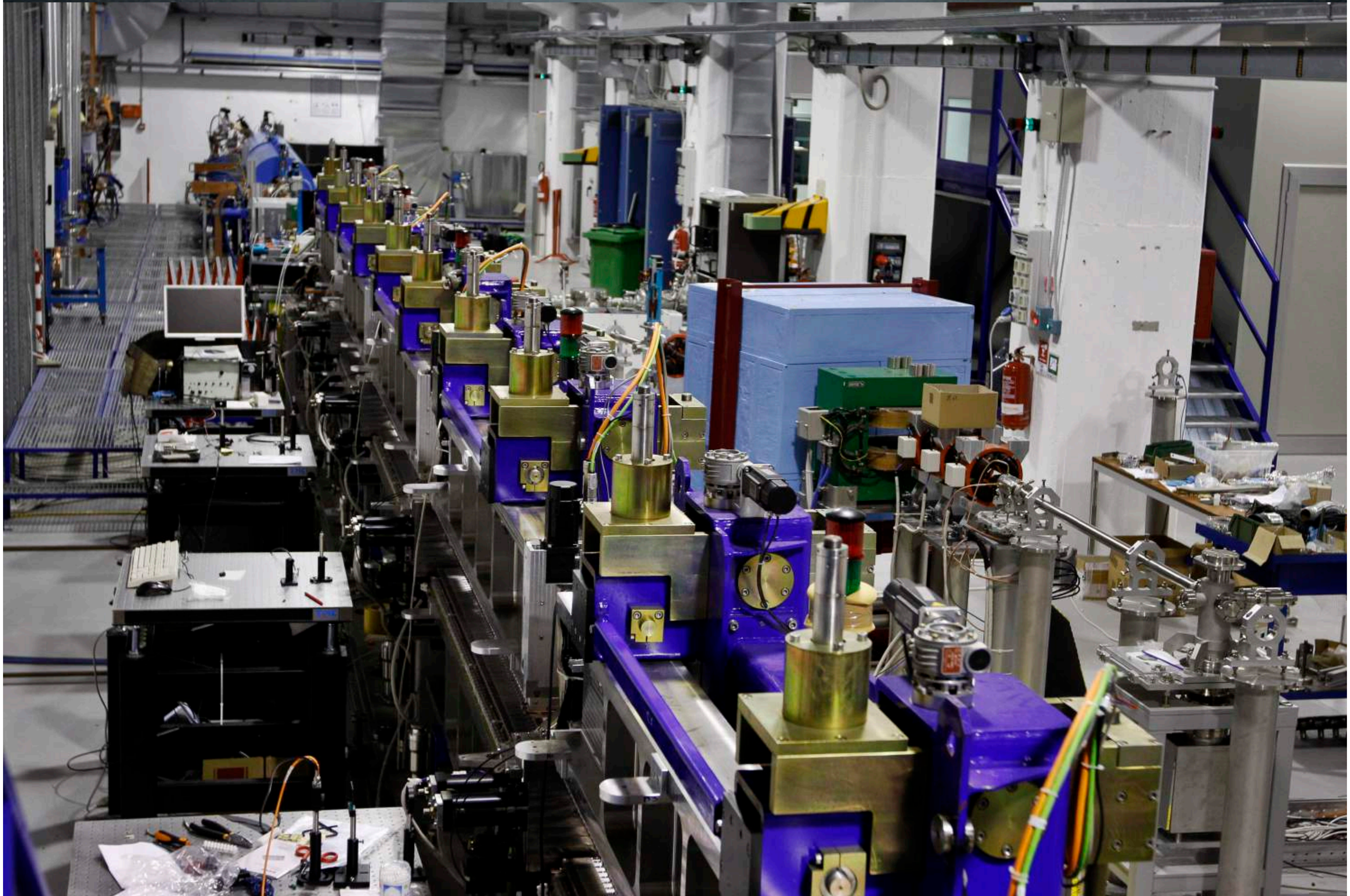
Long undulators chain

Beam separation

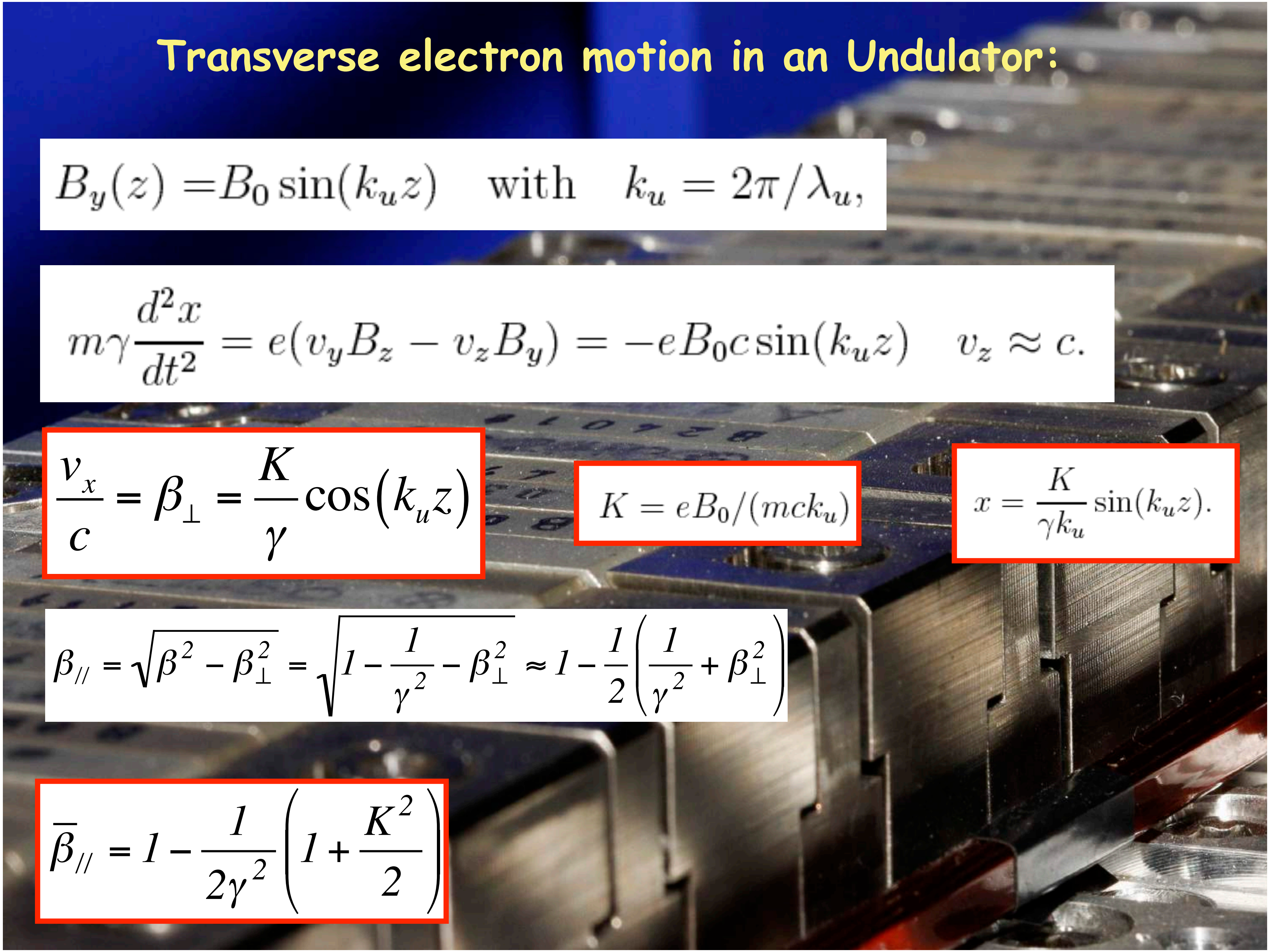
Experimental hall (Single Protein Imaging)



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



Transverse electron motion in an Undulator:



$$B_y(z) = B_0 \sin(k_u z) \quad \text{with} \quad k_u = 2\pi/\lambda_u,$$

$$m\gamma \frac{d^2 x}{dt^2} = e(v_y B_z - v_z B_y) = -e B_0 c \sin(k_u z) \quad v_z \approx c.$$

$$\frac{v_x}{c} = \beta_\perp = \frac{K}{\gamma}\cos(k_u z)$$

$$K = eB_0/(mck_u)$$

$$x = \frac{K}{\gamma k_u}\sin(k_u z).$$

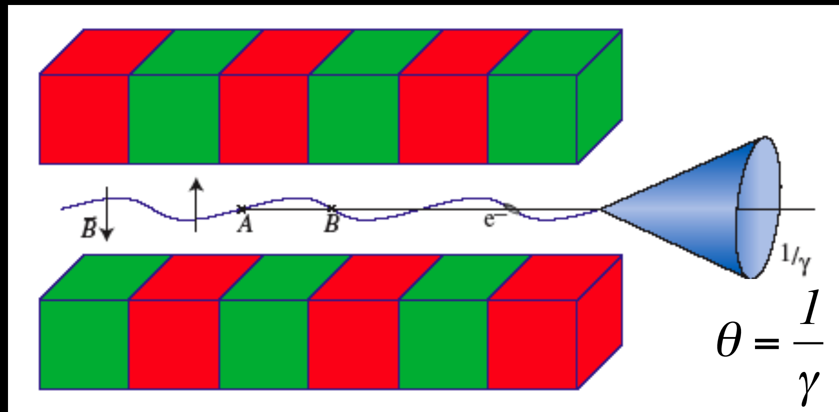
$$\beta_{//} = \sqrt{\beta^2 - \beta_\perp^2} = \sqrt{1 - \frac{1}{\gamma^2} - \beta_\perp^2} \approx 1 - \frac{1}{2}\left(\frac{1}{\gamma^2} + \beta_\perp^2\right)$$

$$\overline{\beta}_{//} = 1 - \frac{1}{2\gamma^2}\left(1 + \frac{K^2}{2}\right)$$

Undulator Radiation

$$x = \frac{K}{\gamma k_u} \sin(k_u z).$$

$$\overline{\beta}_{//} = 1 - \frac{1}{2\gamma^2}\left(1 + \frac{K^2}{2}\right)$$



$$x' = \frac{K}{\gamma}\cos(k_u z)$$

$$K = eB_0/(mck_u)$$

The electron trajectory is determined by the undulator field and the electron energy

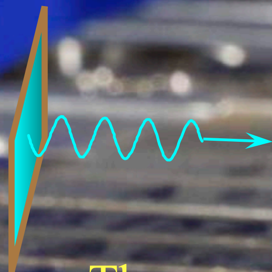
The electron trajectory is inside the radiation cone if:

$$K \le 1$$

Relativistic Mirrors

$$\lambda'_u = \frac{\lambda_u}{\gamma_{//}}$$

Counter propagating pseudo-radiation

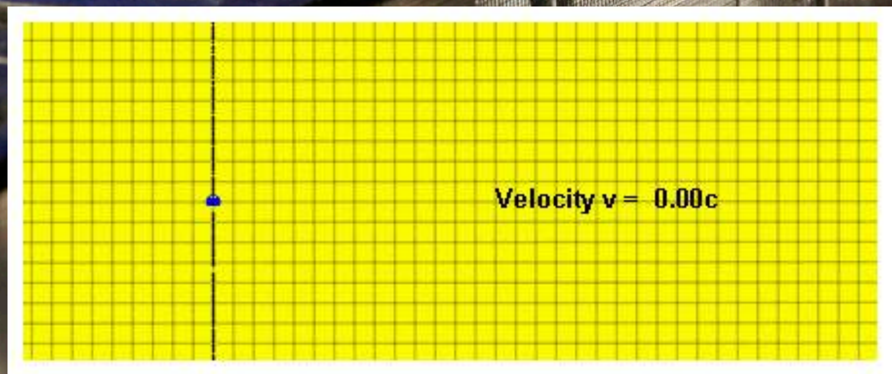


$$\lambda'_{rad} = \lambda'_u$$

Thompson back-scattered radiation in the mirror moving frame

$$\lambda_{rad} = \gamma\lambda'_{rad}\left(1-\beta\cos\vartheta\right) \approx \lambda_u\left(1-\bar{\beta}_{//}\cos\vartheta\right)$$

Doppler effect in the laboratory frame



$$\bar{\beta}_{//} = 1 - \frac{1}{2\gamma^2}\left(1+\frac{K^2}{2}\right)$$

$$\cos\vartheta \approx 1 - \frac{\vartheta^2}{2}$$

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

Tunability & Red Shift

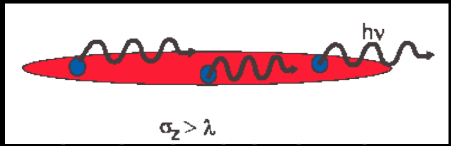
Peak power of one accelerated charge:

$$P_1 = \frac{e^2}{6\pi\varepsilon_o c^3}\gamma^4\left\langle \dot{v}_\perp^2 \right\rangle$$

Different electrons radiate indepedently hence the total power depends linearly on the number N_e of electrons per bunch:

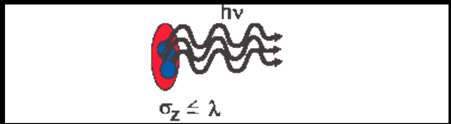
Incoherent Spontaneous Radiation Power:

$$P_T = N_e \frac{e^2}{6\pi\varepsilon_o c^3}\gamma^4\left\langle \dot{v}_\perp^2 \right\rangle$$



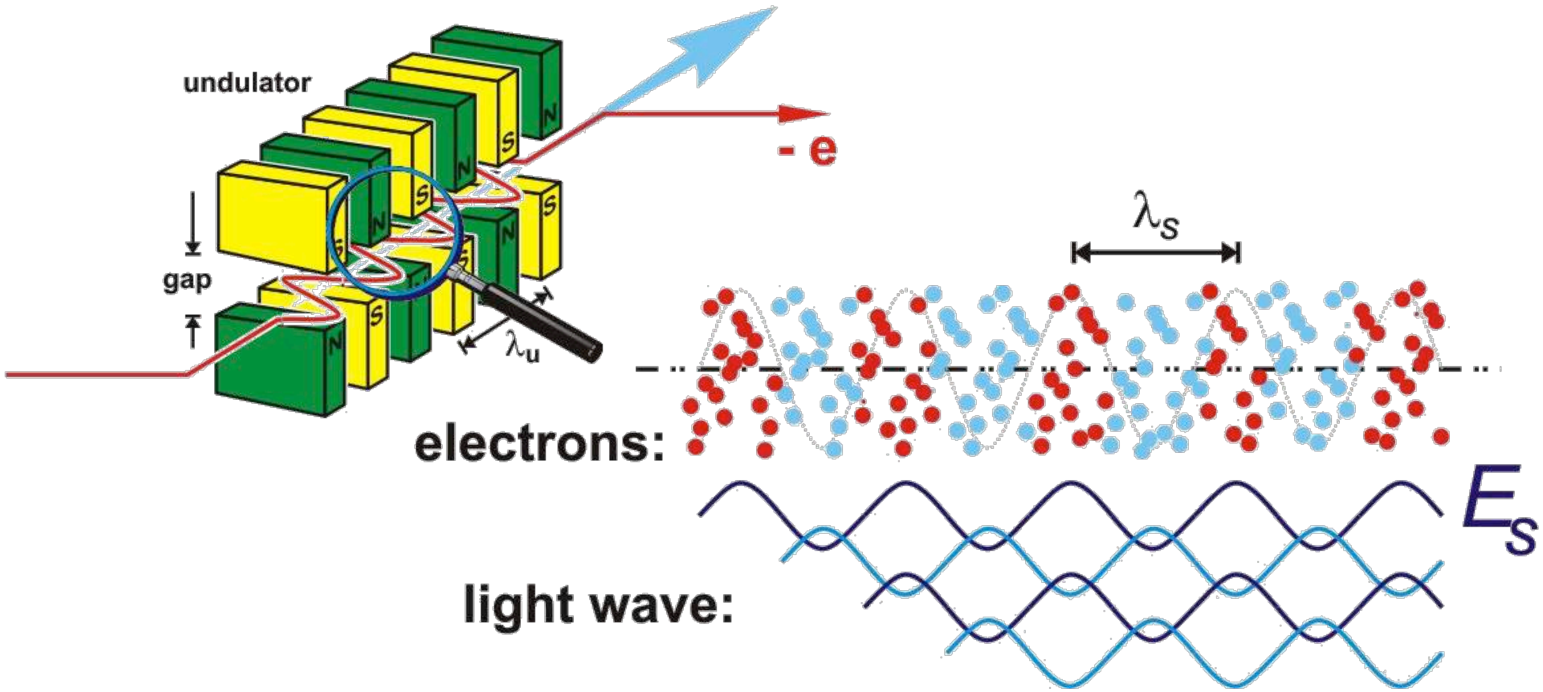
Coherent Stimulated Radiation Power:

$$P_T = \frac{N_e^2 e^2}{6\pi\varepsilon_o c^3}\gamma^4\left\langle \dot{v}_\perp^2 \right\rangle$$



Bunching on the scale of the wavelength:

Spontaneous Emission ==> Random phases



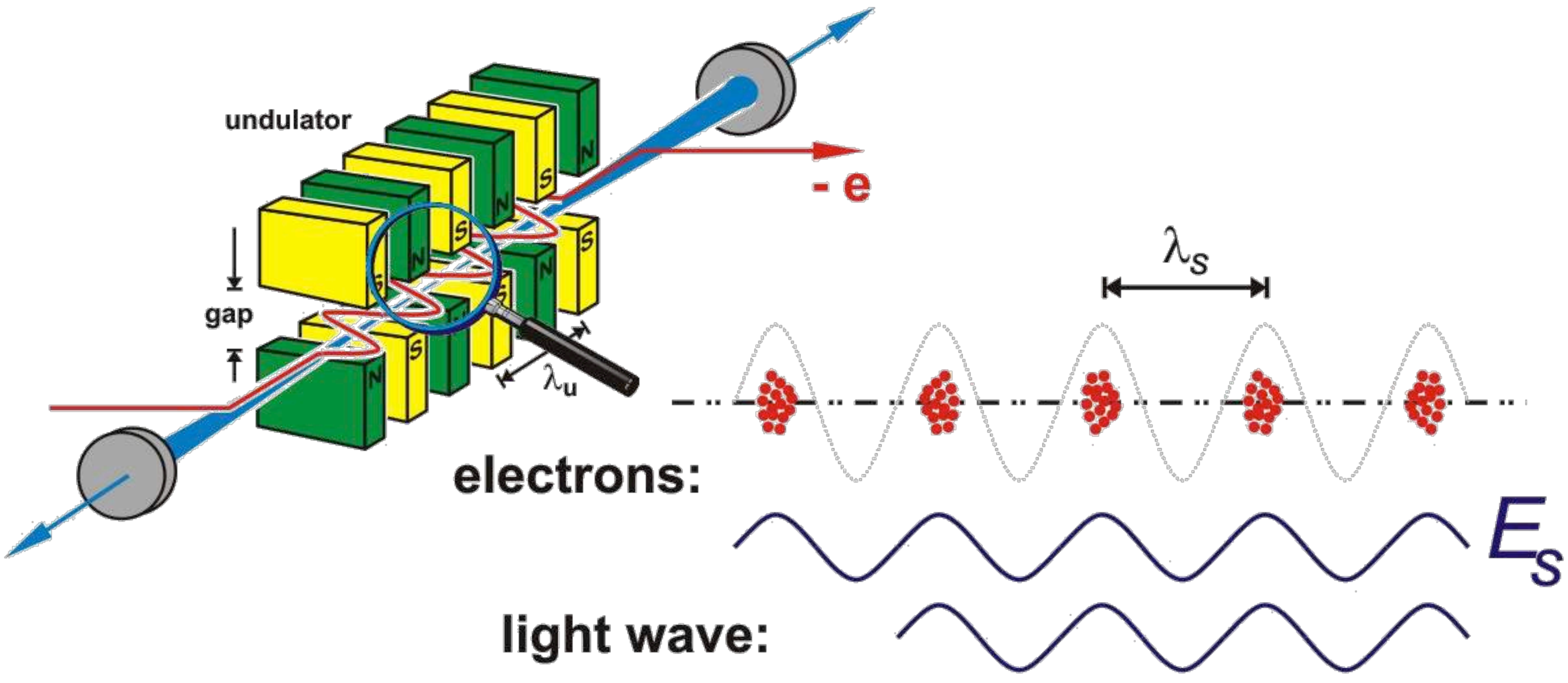
Radiated Power:

$P \propto N$

destructive interference

⟶ **shotnoise radiation**

Coherent Light ==> Stimulated Emission

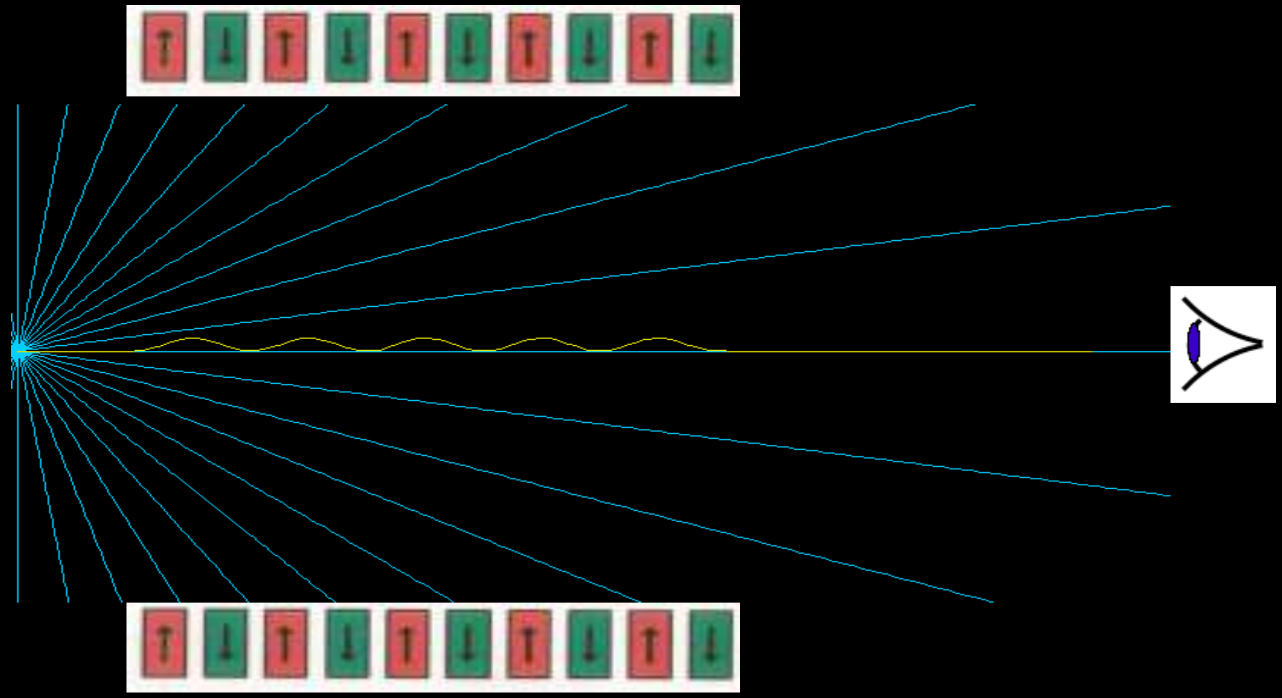


Radiated Power :

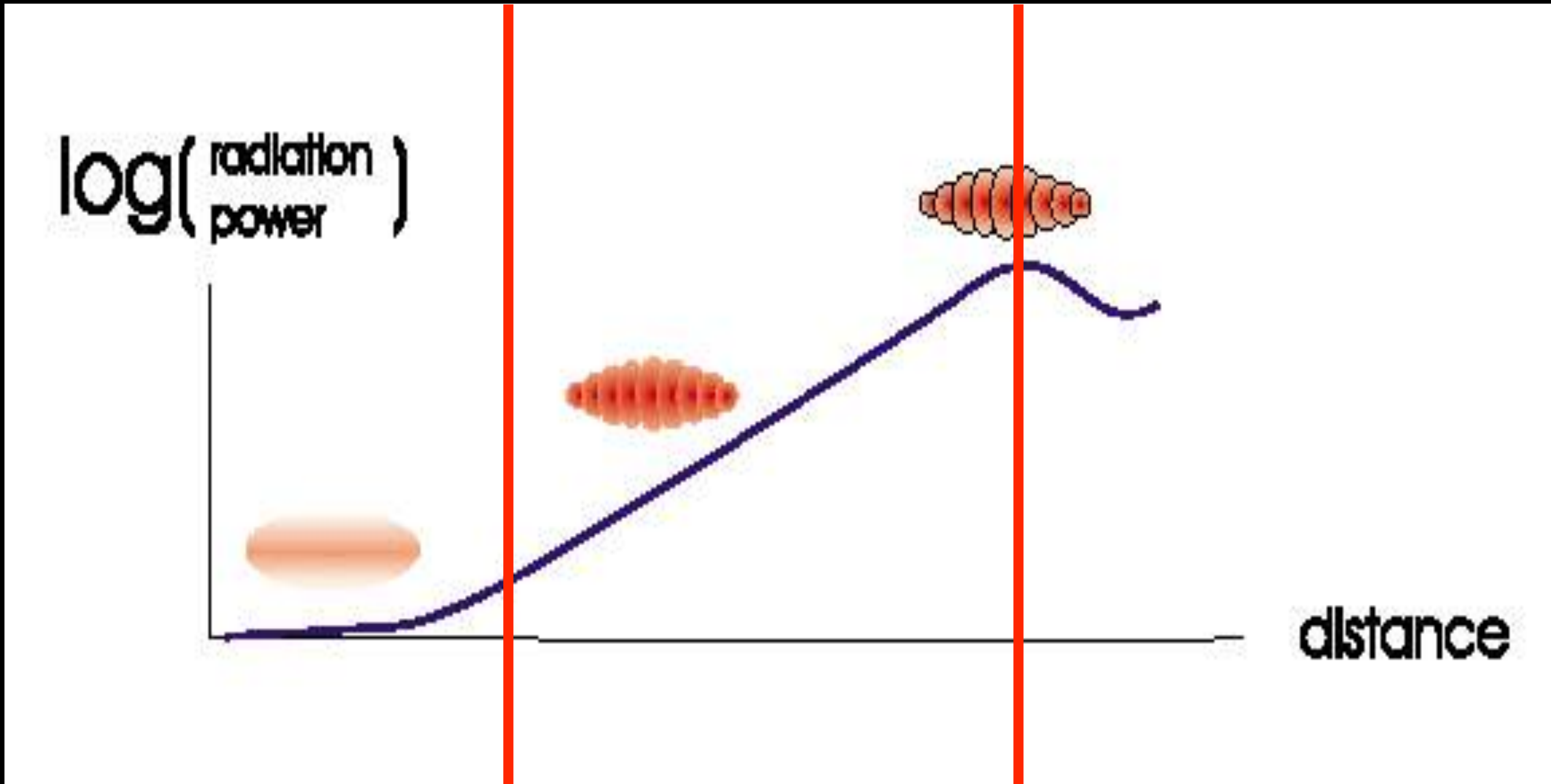
$P \propto N^2$

constructive interference

⟶ **enhanced emission**



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



Letargy

Spontaneous Emission

Low Gain

Slow Bunching

Exponential Growth

Stimulated emission

High Gain

Enhanced Bunching

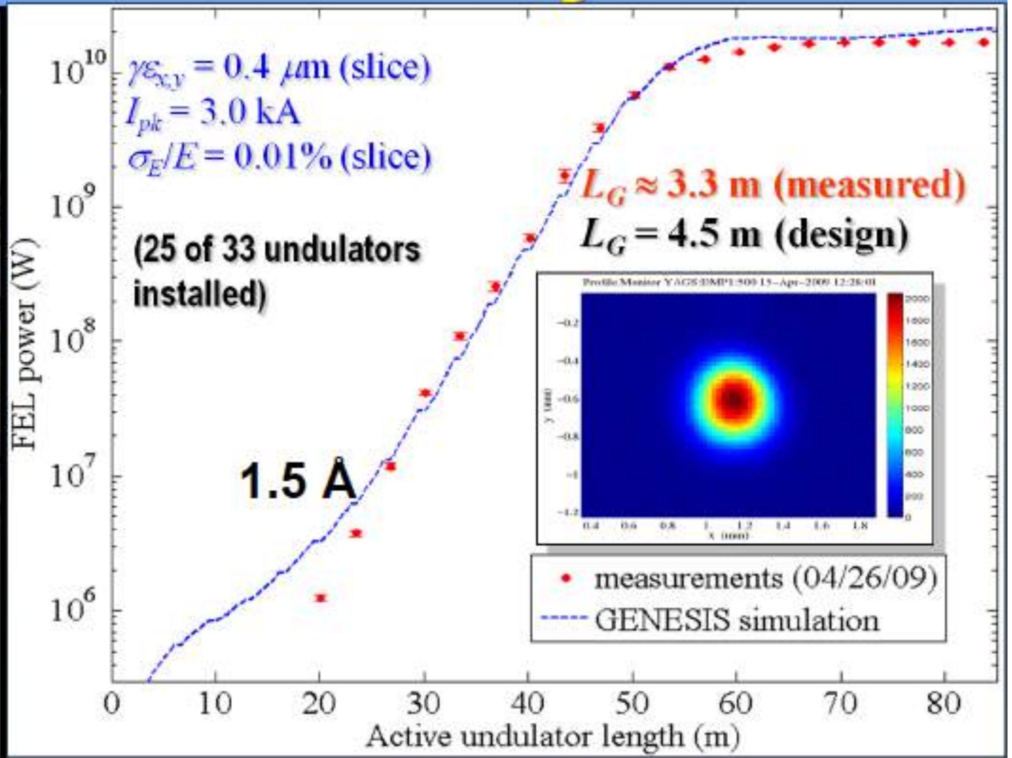
Saturation

Absorption

No Gain

Debunching

LCLS: world's first hard x-ray FEL



- SASE wavelength range: **25 – 1.2** Å
- Photon energy range: **0.5 - 10** keV
- Pulse length FWHM **5 - 500** fs (SXR only)
- Pulse energy up to **4** mJ

XFEL first lasing – Hamburg May 2017

2 WAYS COMPACT SOURCE ROAD MAP

① High gradient compact accelerating structures

② Short period undulators

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

Towards a Compact Accelerator

① Miniaturization of the accelerating structures (resonant)

② Plasma Acceleration (transient) (LWFA,PWFA,DWFA)

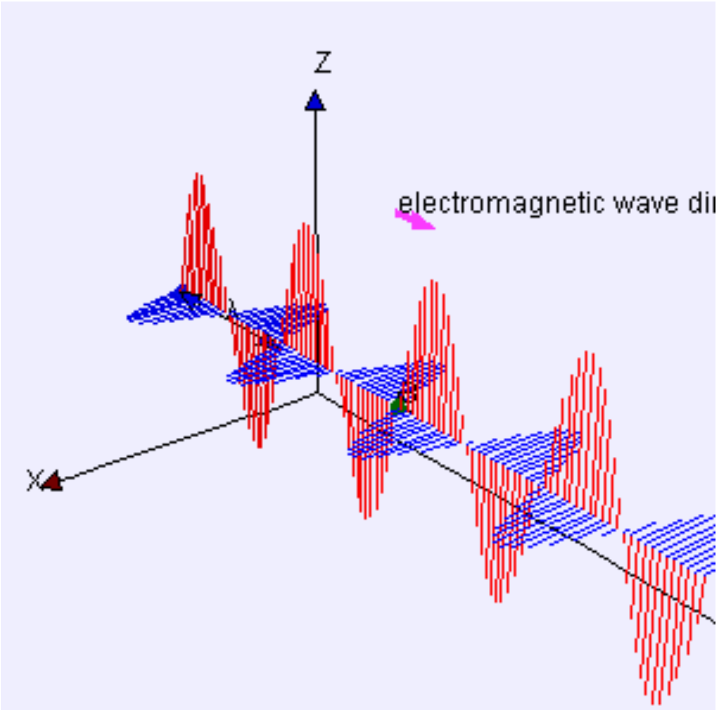
- Power sources
- Accelerating structures
- High quality beams

Lawson-Woodward Theorem

(J.D. Lawson, IEEE Trans. Nucl. Sci. NS-26, 4217, 1979)

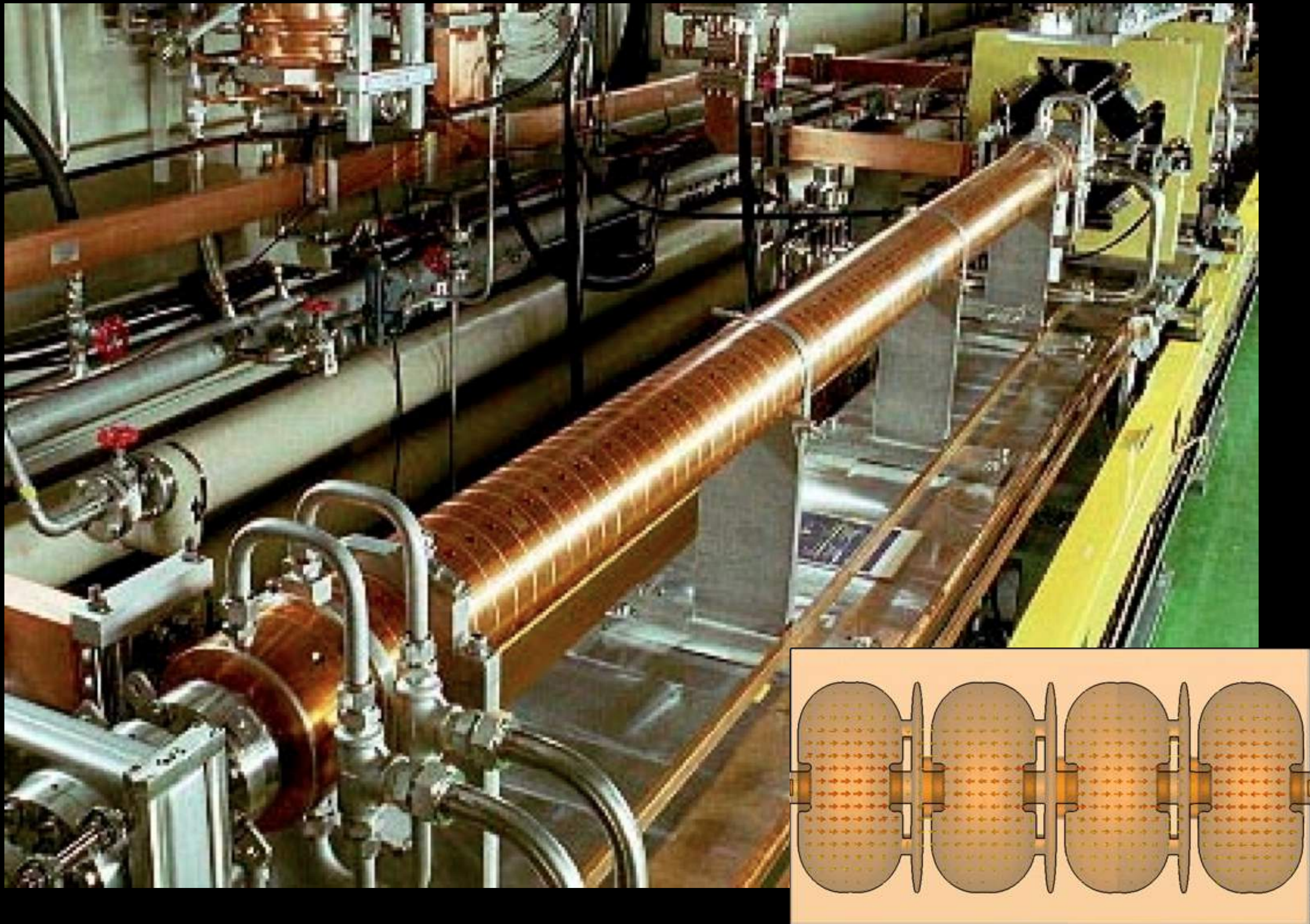
The net energy gain of a relativistic electron interacting with an electromagnetic field **in vacuum** is zero.

The theorem assumes that
(i) the laser field is in vacuum with no walls or boundaries present,
(ii) the electron is highly relativistic ($v \approx c$) along the acceleration path,
(iii) no static electric or magnetic fields are present,
(iv) the region of interaction is infinite,

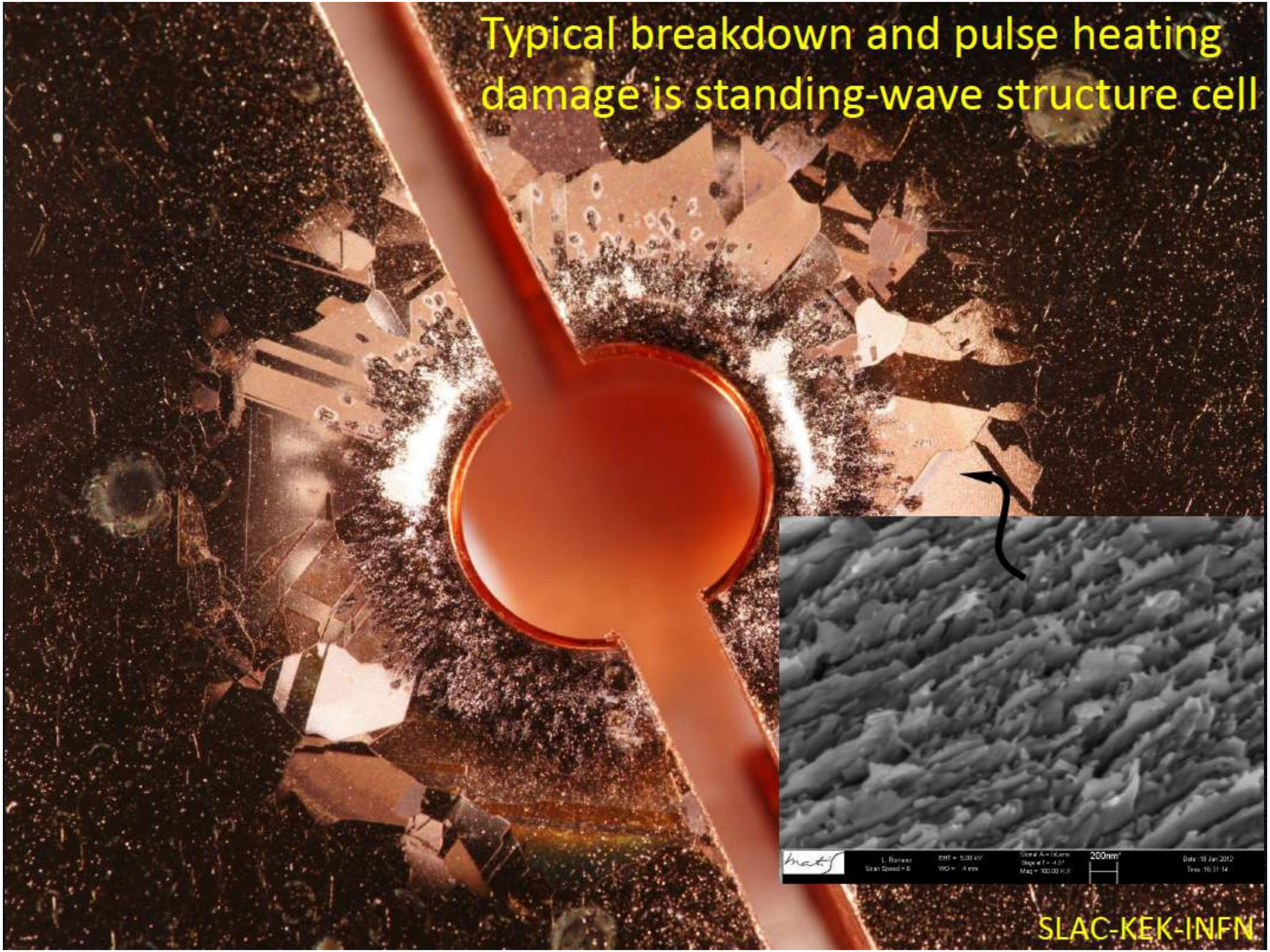


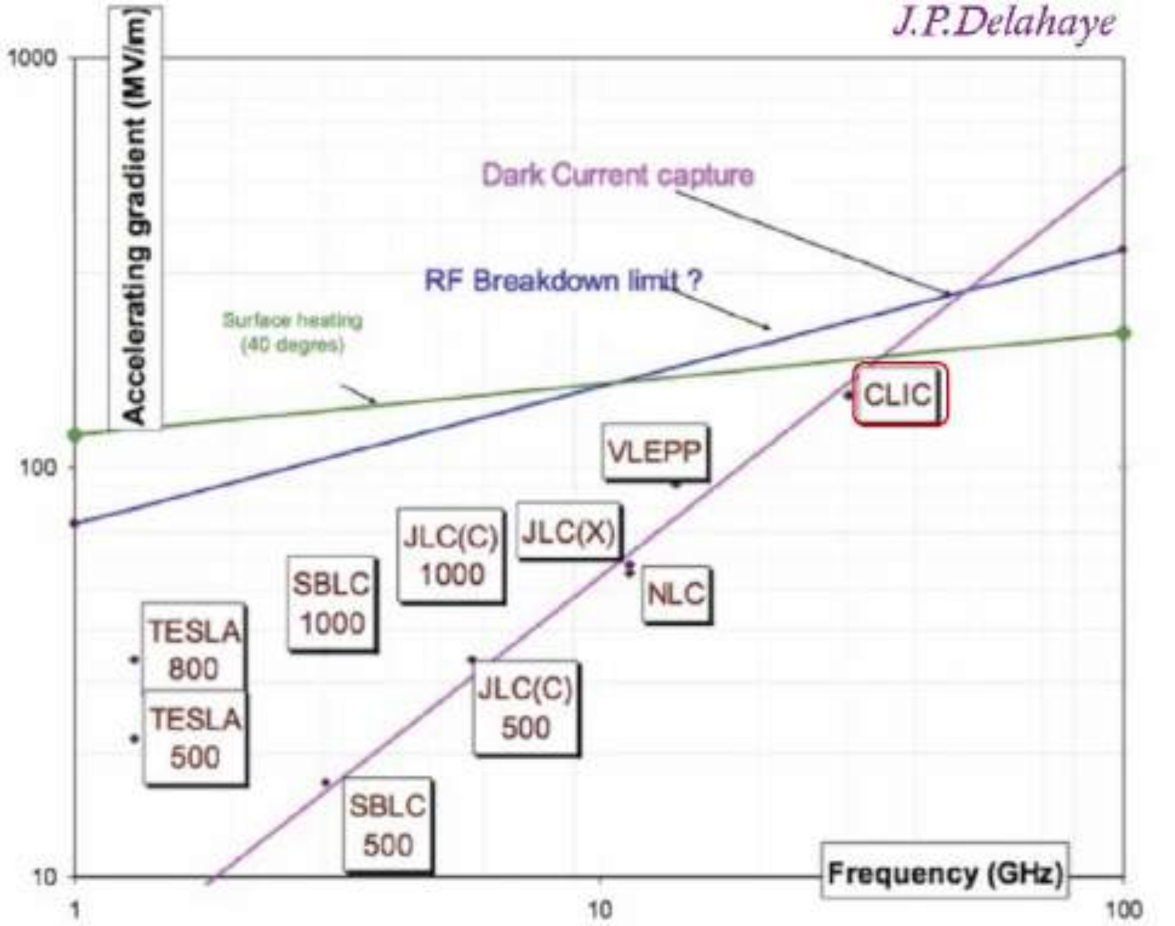
$$F_{\perp} \cong \frac{eE_x}{2\gamma^2}\cos\left(\frac{\omega t}{2\gamma^2}\right)$$

Conventional RF accelerating structures



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





Breakdown limits metal:

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

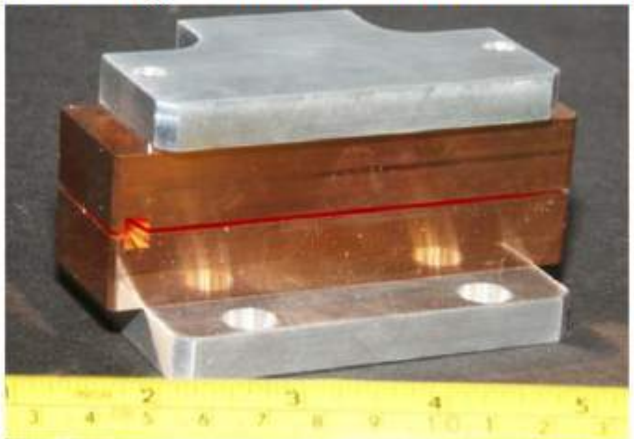
High field ->Short wavelength->ultra-short bunches-> low charge

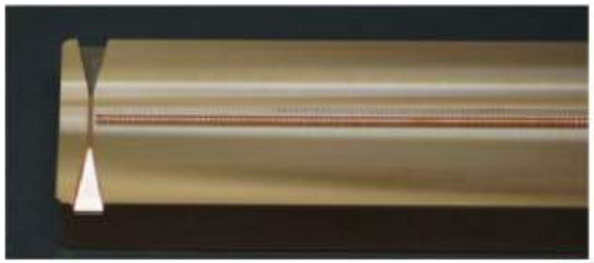
Miniaturization of the accelerating structures

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)

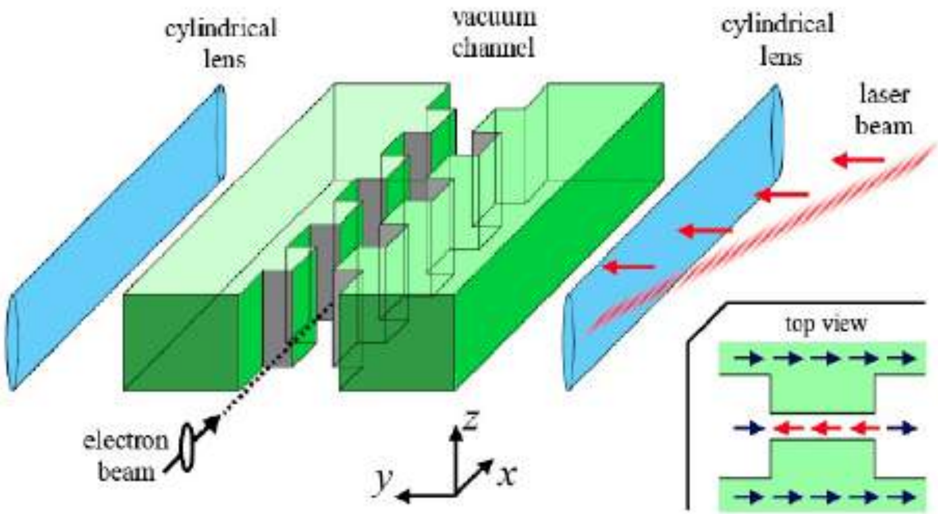
mm-Wave structure to be tested at FACET



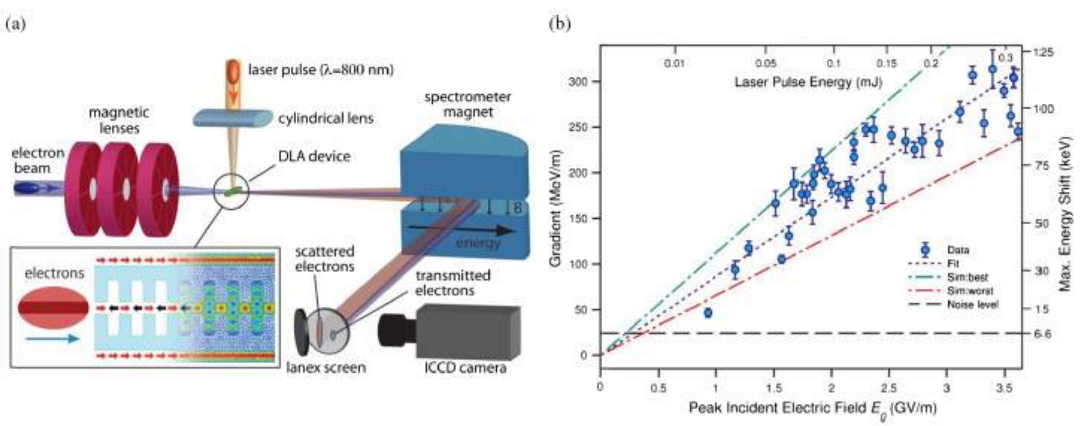


SLAC NATIONAL ACCELERATOR LABORATORY

Grating-Based Planar Structure



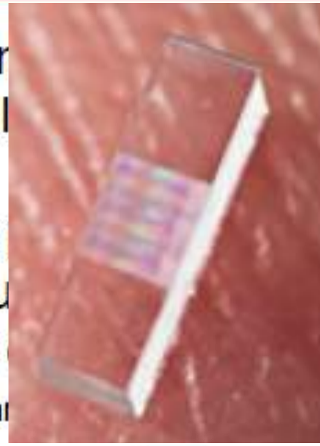
T. Plettner, et al. PRST-AB **9**, 111301 (2006).



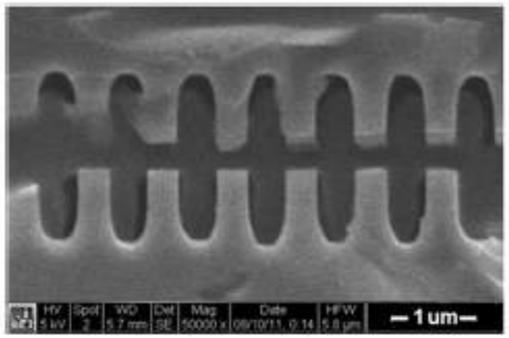
SiO_2 plar   th side-
coupled l   eam.

Periodic   the EM
field resu   ccelerating
gradient   iods.

damage thr   V/m @ 1ps

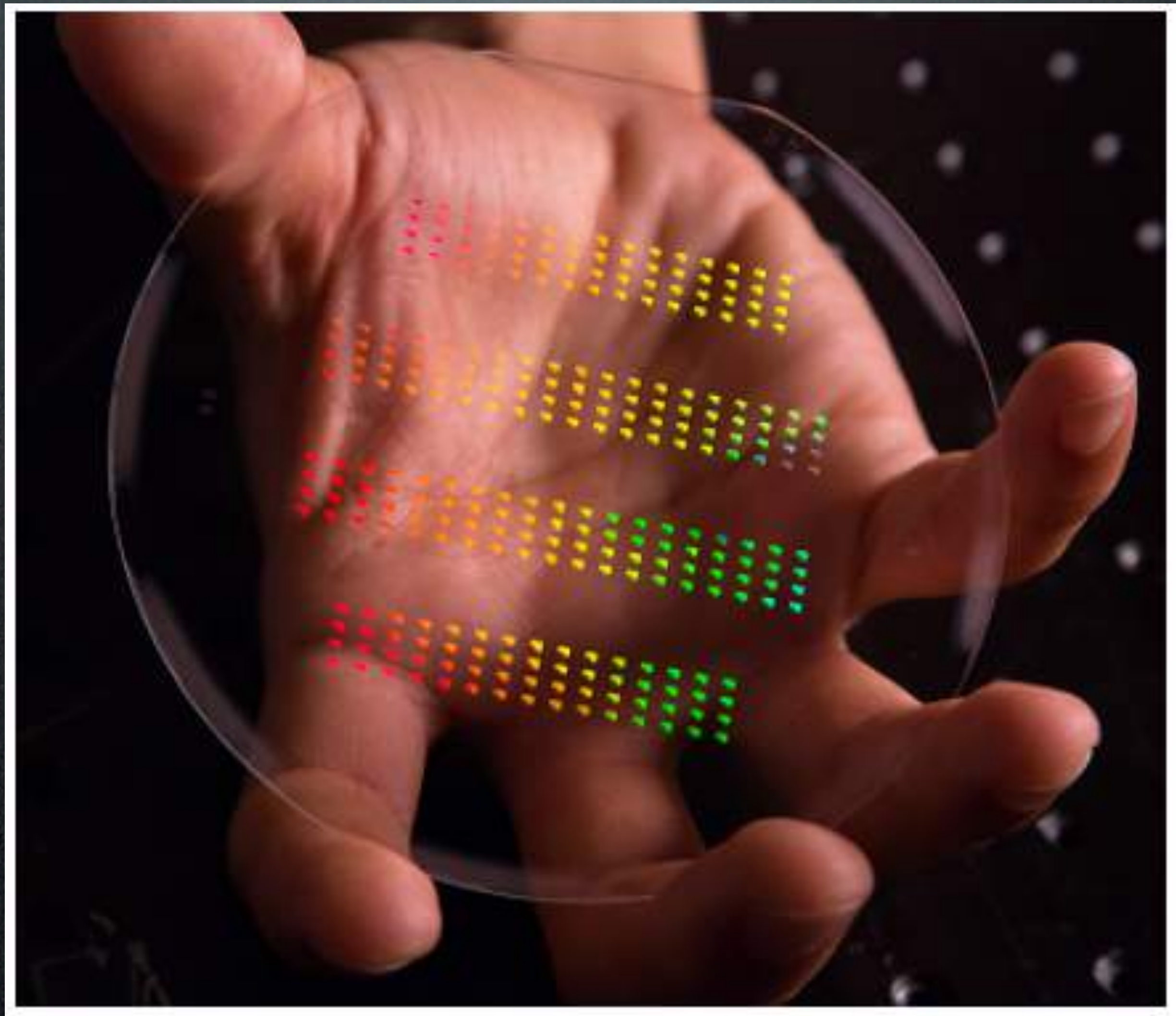


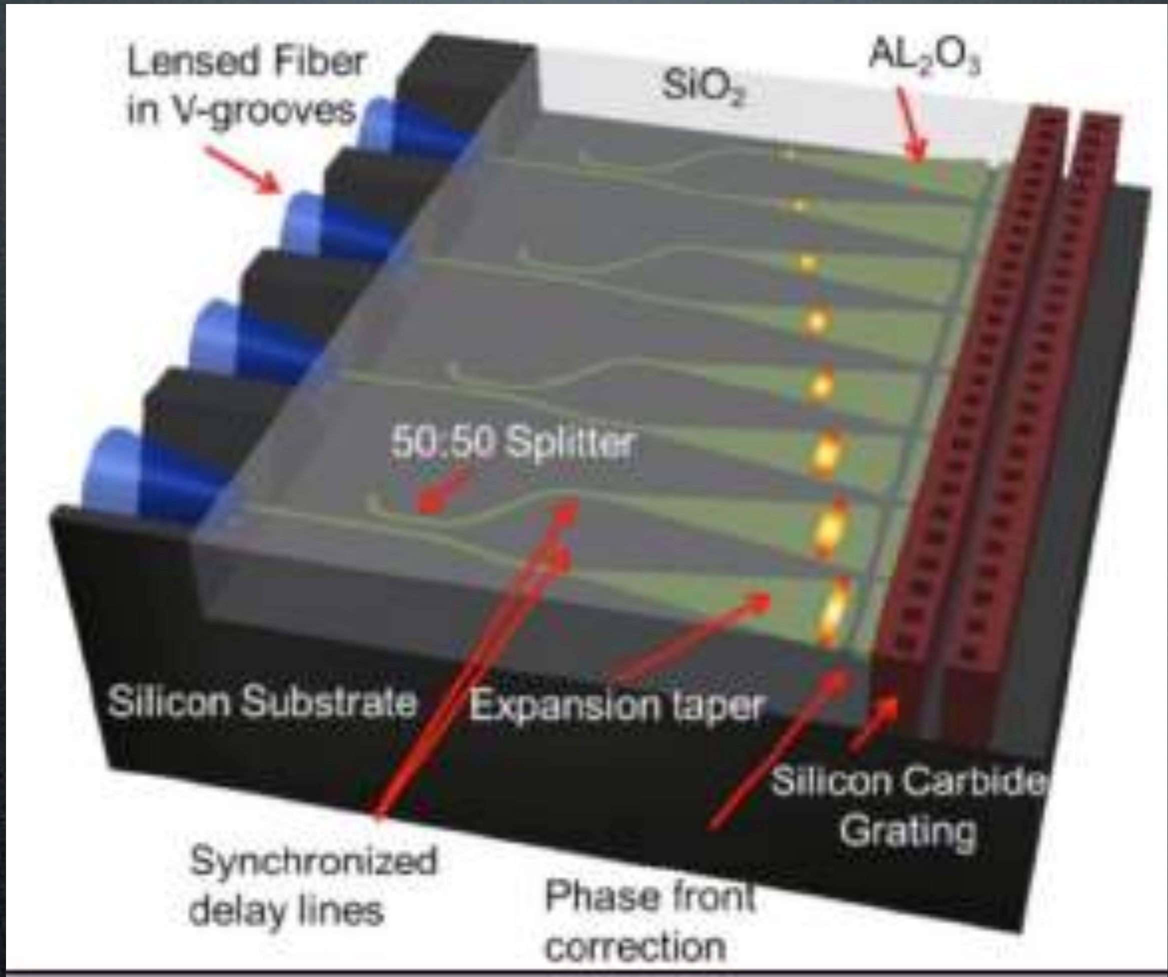
$G_{0,max}$ ~ 1GV/m



E. Peralta, recently fabricated prototype structure

Accelerator on a Chip?




Lensed Fiber
in V-grooves
SiO_2
AL_2O_3
50:50 Splitter
Silicon Substrate
Expansion taper
Silicon Carbide
Grating
Synchronized
delay lines
Phase front
correction

Light Source on a Chip

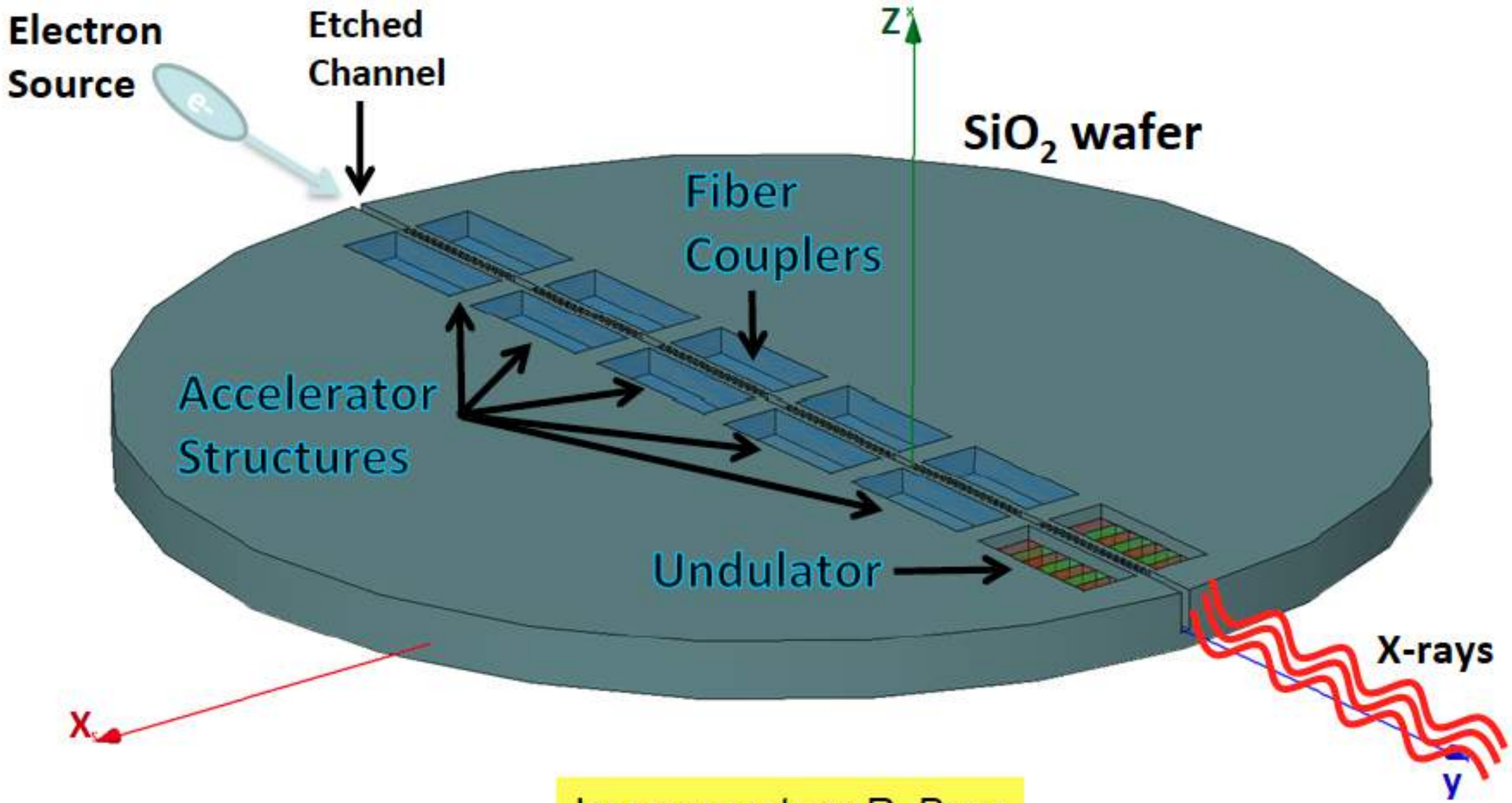
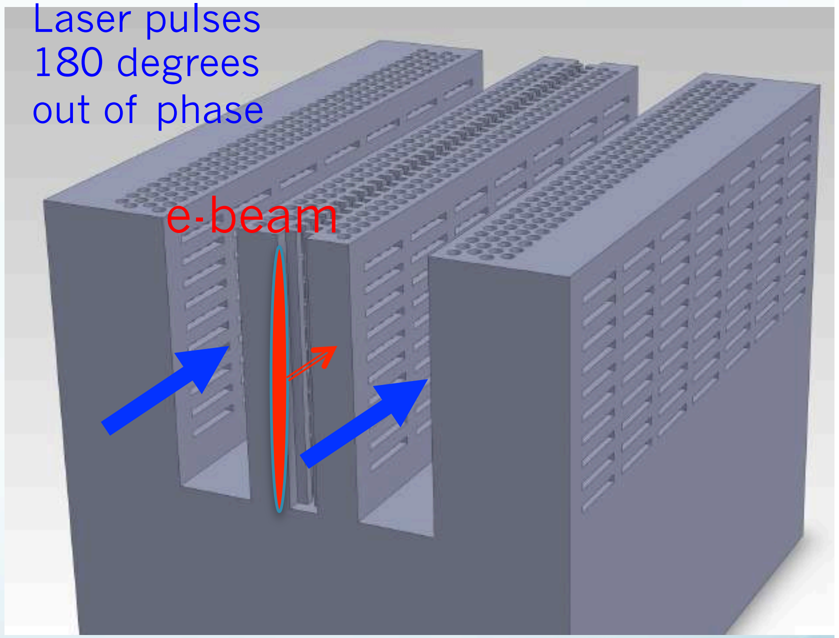


Image courtesy R. Byer

Dielectric Photonic Structure

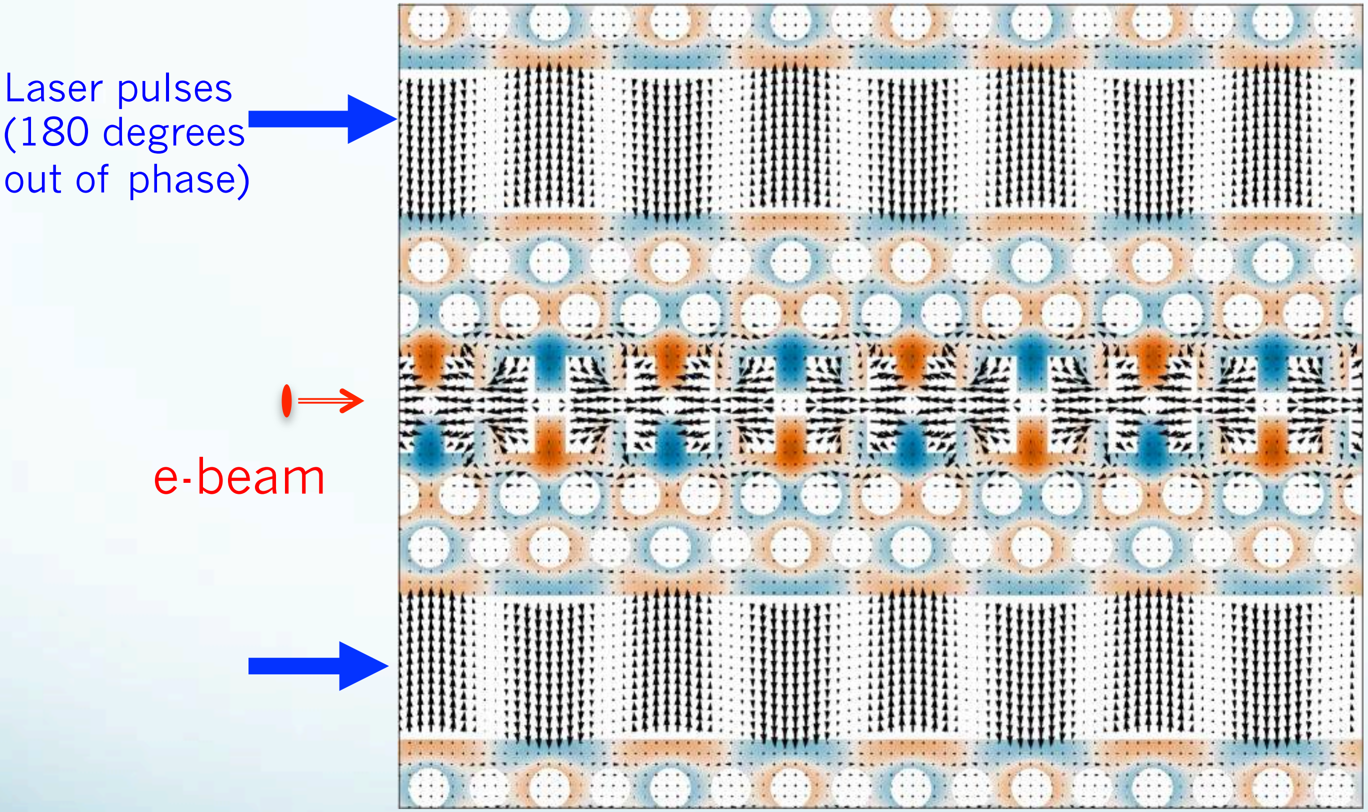
- Why photonic structures?
  - Natural in dielectric
  - Advantages of burgeoning field
    - design possibilities
    - Fabrication
- Dynamics concerns
- External coupling schemes



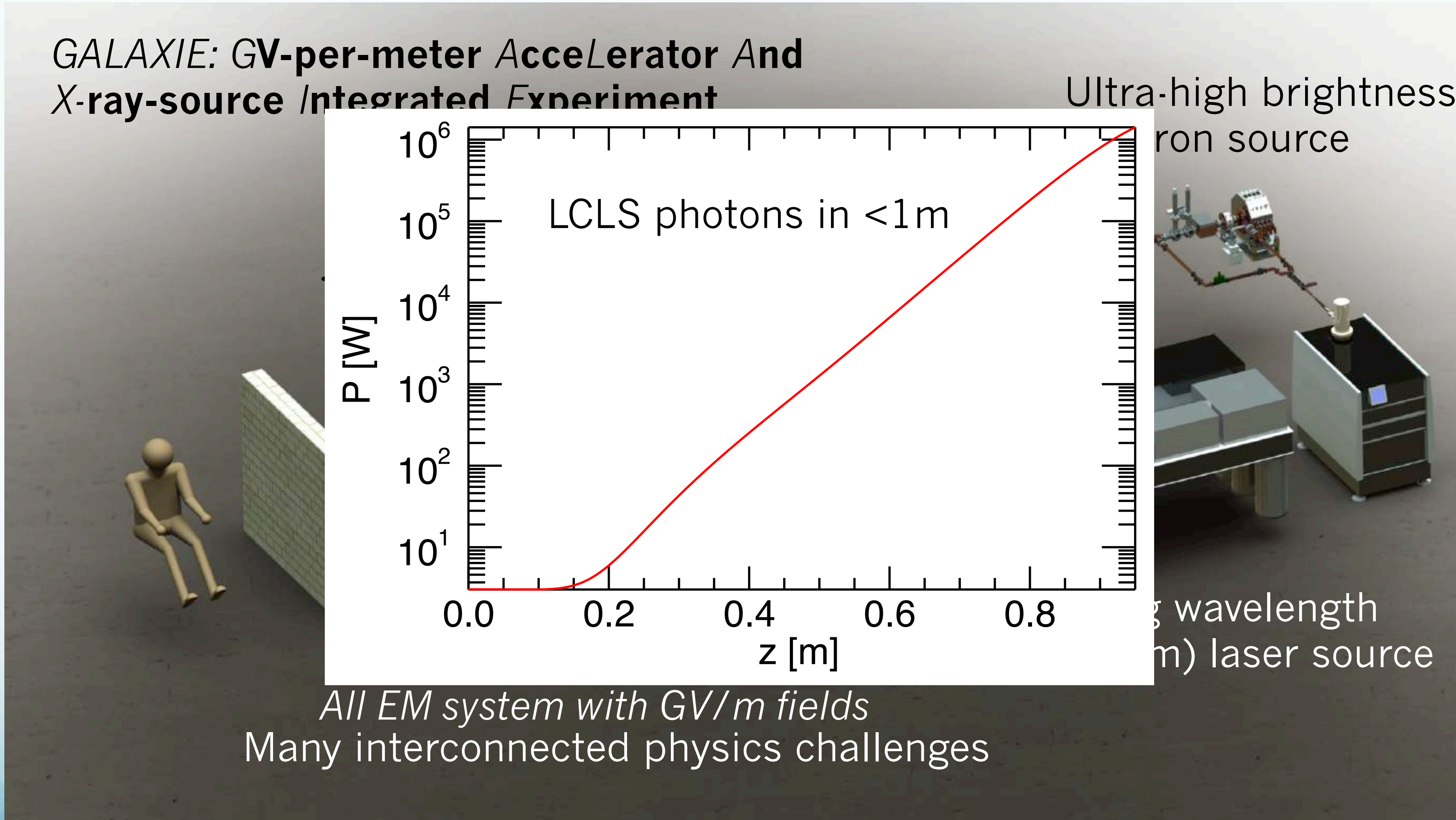
Schematic of GALAXIE
monolithic photonic DLA

Laser-Structure Coupling: TW

GALAXIE Dual laser drive structure, large reservoir of power recycles



5th Gen Light Source: A Table-top X-ray FEL

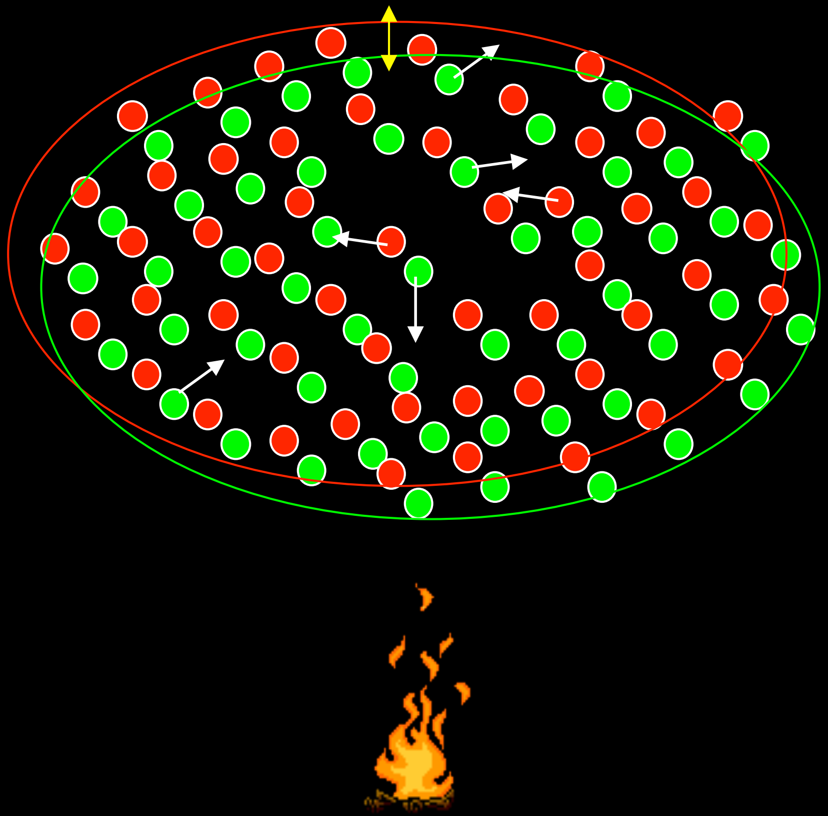


Plasma Acceleration 1
Laser Driven
LWFA

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

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

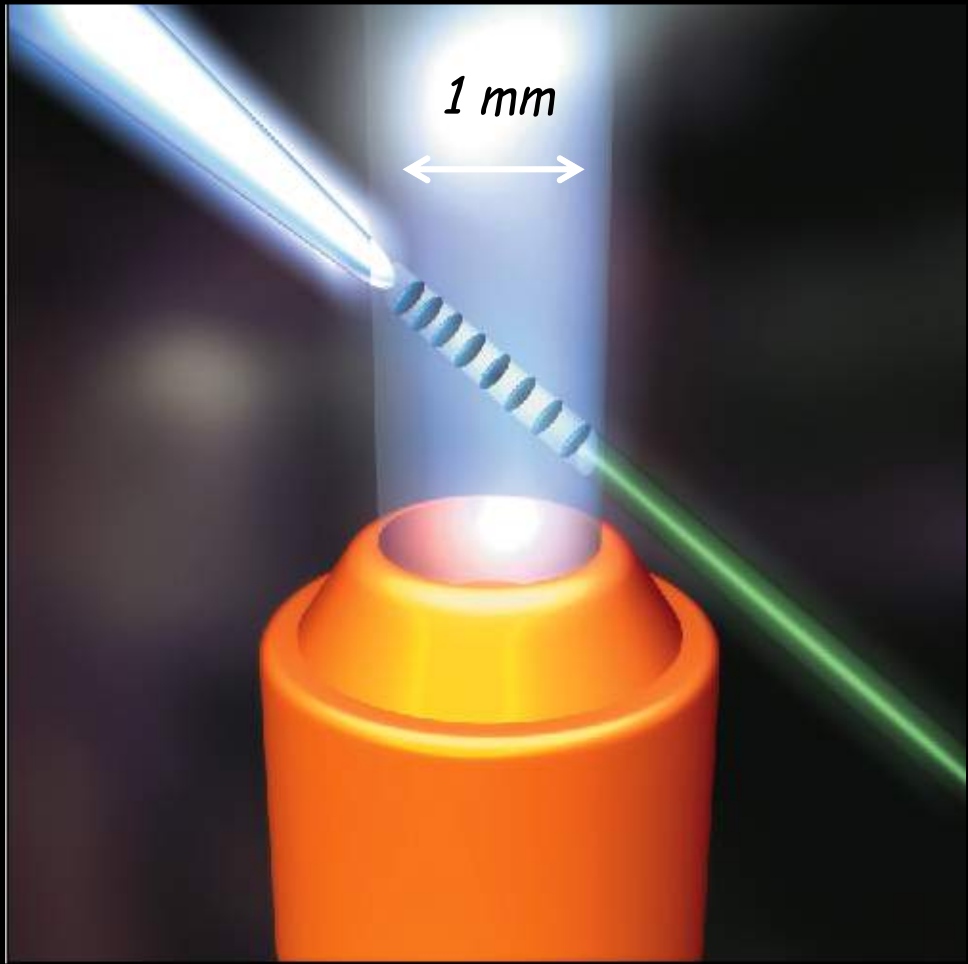
Plasma frequency

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

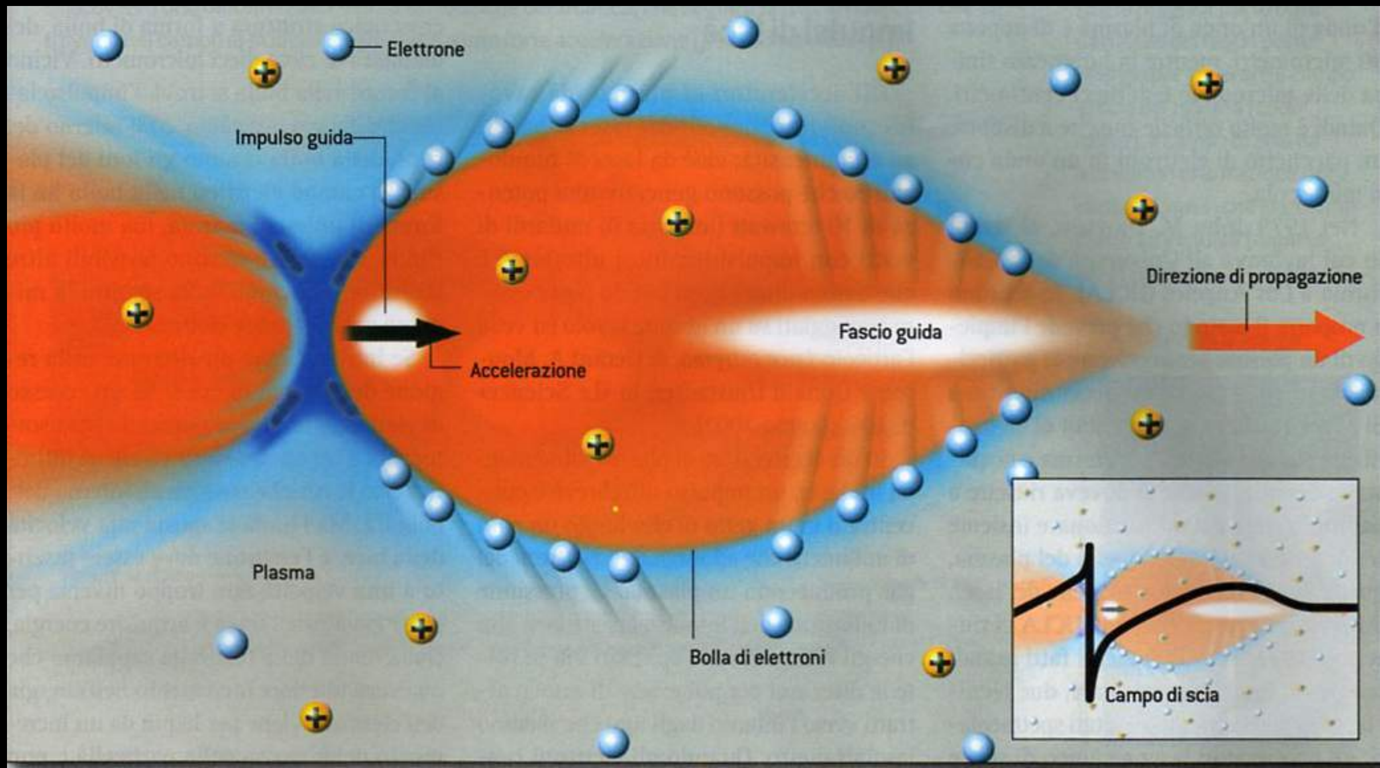
Plasma oscillations

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

Direct production of e-beam

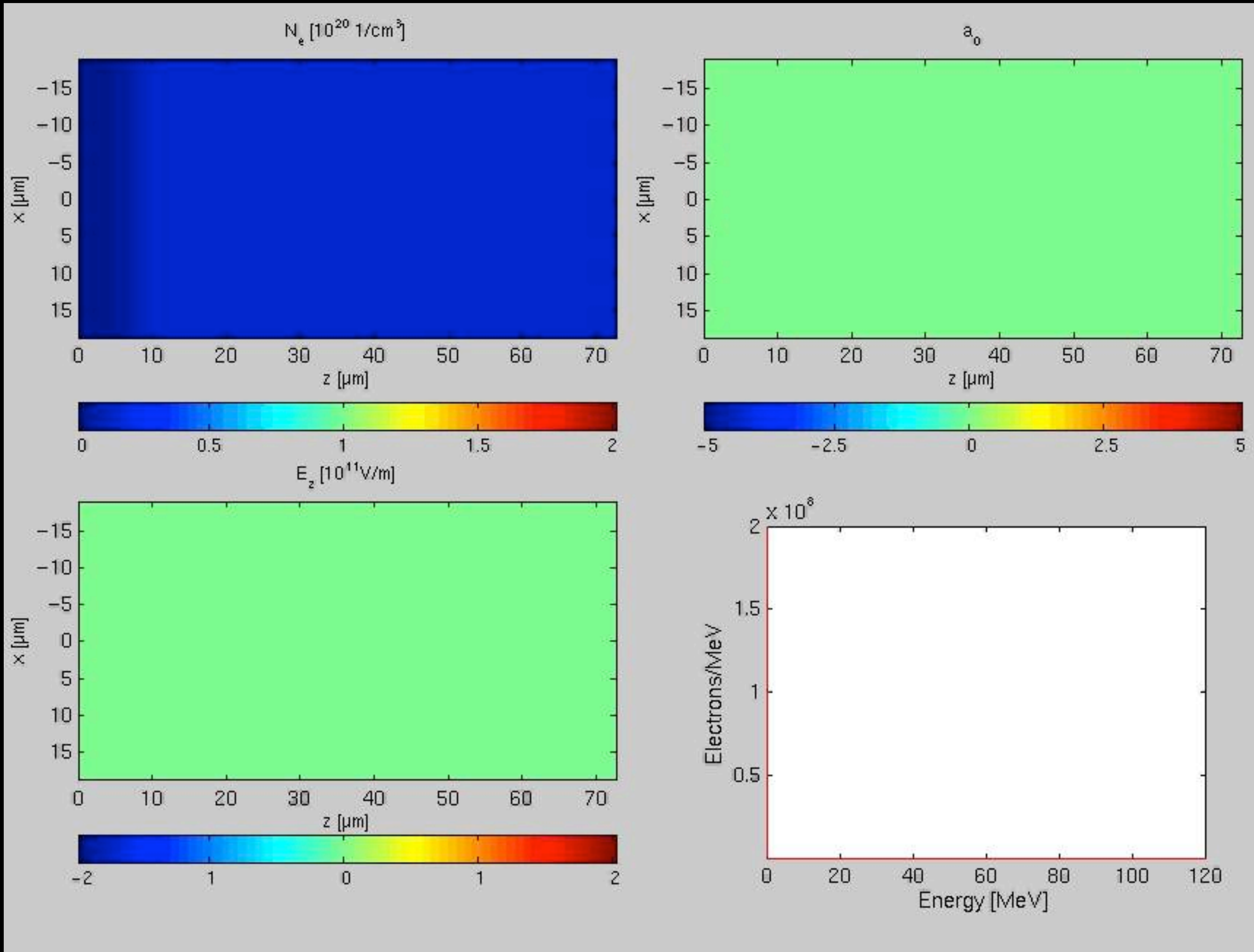


High quality beam Plasma Acceleration



Breakdown limit?

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



N_e [10^20 1/cm^3]
a_0
E_z [10^11V/m]
x [μm]
z [μm]
0 0.5 1 1.5 2
-5 -2.5 0 2.5 5
-2 1 0 1 2
x 10^8
Electrons/MeV
Energy [MeV]

2005 The Dream Beam

Monoenergetic beams of relativistic electrons from intense laser–plasma interactions

S. P. D. Mangles[1], C. D. Murphy[1,2], Z. Najmudin[1], A. G. R. Thomas[1], J. L. Collier[2], A. E. Dangor[1], E. J. Divall[2], P. S. Foster[2], J. G. Gallacher[3], C. J. Hooker[2], D. A. Jaroszynski[3], A. J. Langley[2], W. B. Mori[4], P. A. Norreys[2], F. S. Tsung[4], R. Viskup[3], B. R. Walton[1] & K. Krushelnick[1]

[1]The Blackett Laboratory, Imperial College London, London SW7 2AZ, UK
[2]Central Laser Facility, Rutherford Appleton Laboratory, Chilton, Didcot, Oxon, OX11 0QX, UK
[3]Department of Physics, University of Strathclyde, Glasgow G4 0NG, UK
[4]Department of Physics and Astronomy, UCLA, Los Angeles, California 90095, USA

High-quality electron beams from a laser wakefield accelerator using plasma-channel guiding

C. G. R. Geddes[1,2], Cs. Toth[1], J. van Tilborg[1,3], E. Esarey[1], C. B. Schroeder[1], D. Bruhwiler[4], C. Nieter[4], J. Cary[4,5] & W. P. Leemans[1]

[1]Lawrence Berkeley National Laboratory, 1 Cyclotron Road, Berkeley, California 94720, USA
[2]University of California, Berkeley, California 94720, USA
[3]Technische Universiteit Eindhoven, Postbus 513, 5600 MB Eindhoven, the Netherlands
[4]Tech-X Corporation, 5621 Arapahoe Ave. Suite A, Boulder, Colorado 80303, USA
[5]University of Colorado, Boulder, Colorado 80309, USA

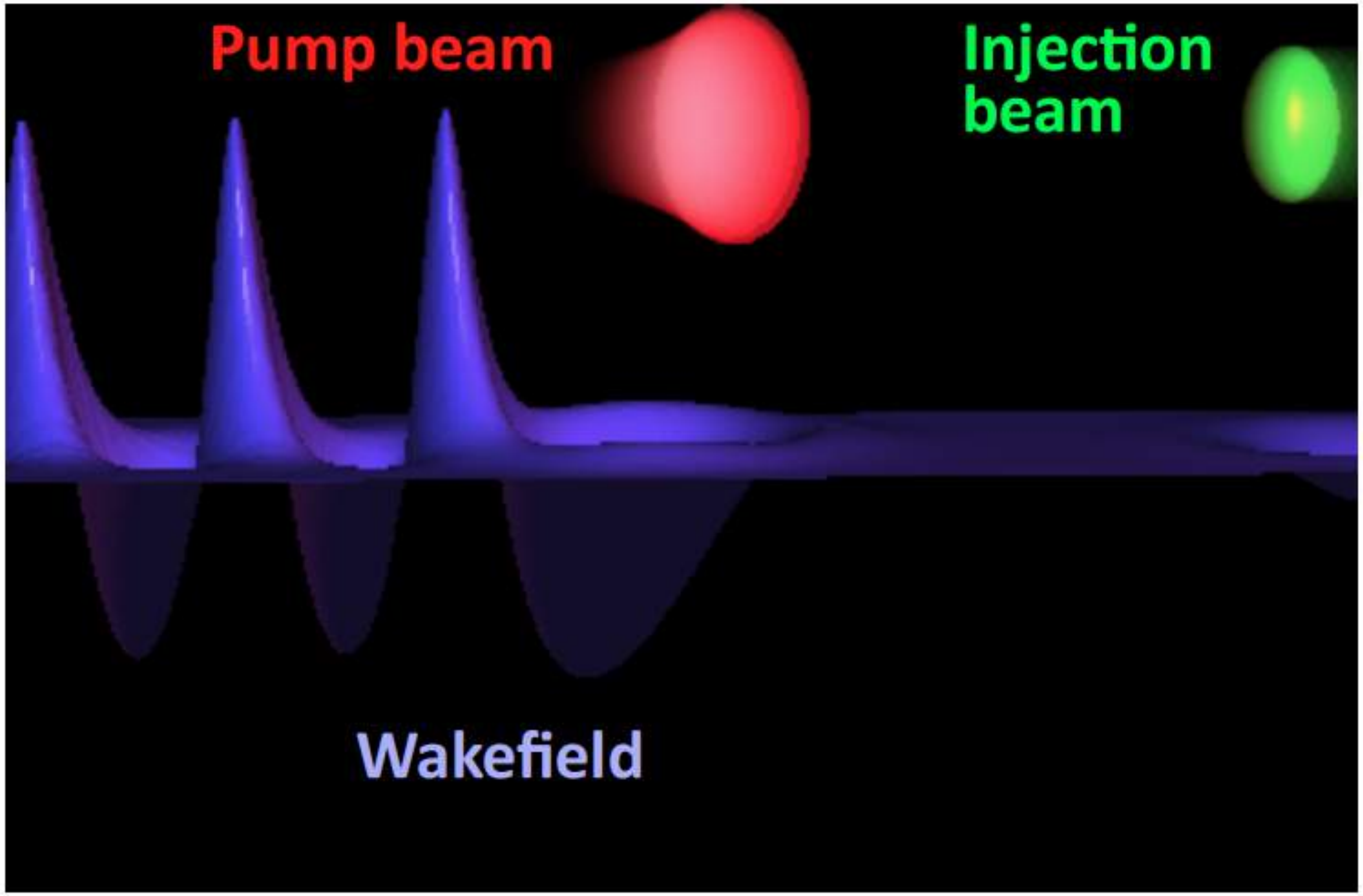
A laser–plasma accelerator producing monoenergetic electron beams

J. Faure[1], Y. Glinec[1], A. Pukhov[2], S. Kiselev[2], S. Gordienko[2], E. Lefebvre[3], J.-P. Rousseau[1], F. Burgy[1] & V. Malka[1]

[1]Laboratoire d'Optique Appliquée, Ecole Polytechnique, ENSTA, CNRS, UMR 7639, 91761 Palaiseau, France
[2]Institut fur Theoretische Physik, 1, Heinrich-Heine-Universitat Duesseldorf, 40225 Duesseldorf, Germany
[3]Département de Physique Théorique et Appliquée, CEA/DAM Ile-de-France, 91680 Bruyères-le-Châtel, France

Colliding Laser Pulses Scheme

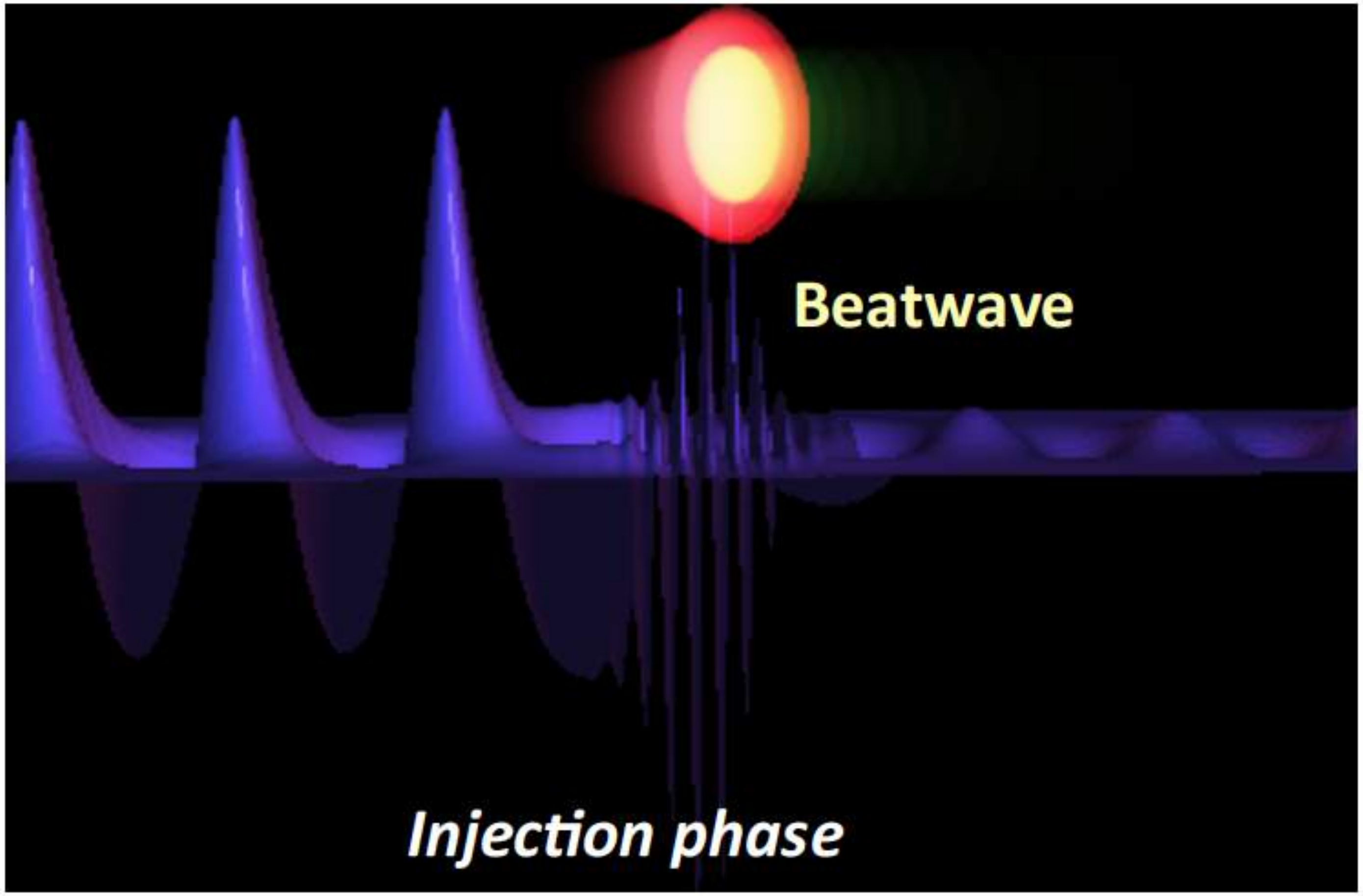
The first laser creates the accelerating structure, a second laser beam is used to heat electrons



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

Colliding Laser Pulses Scheme

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



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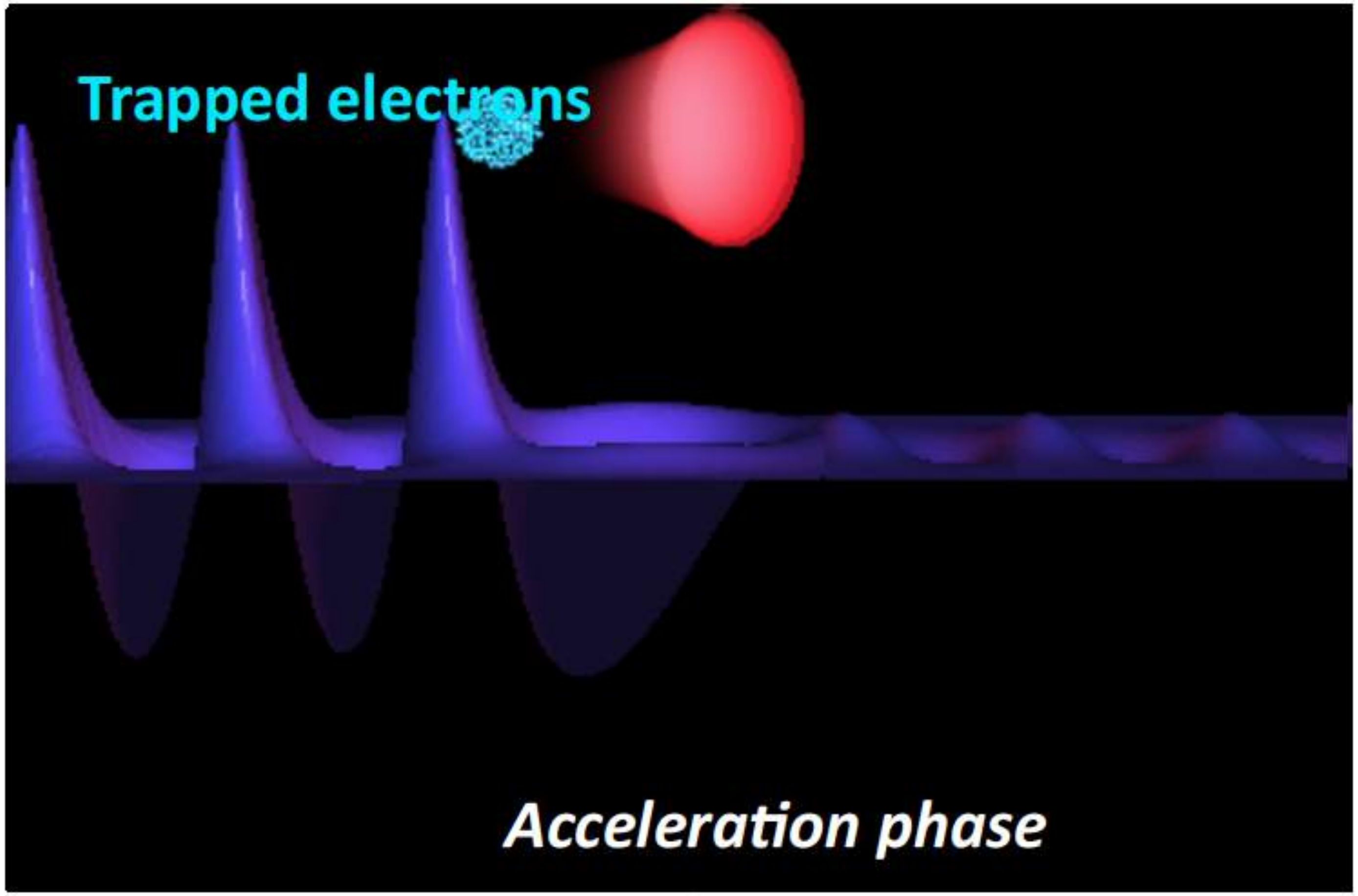

Theory : E. Esarey *et al.*, PRL **79**, 2682 (1997), H. Kotaki *et al.*, PoP **11** (2004)
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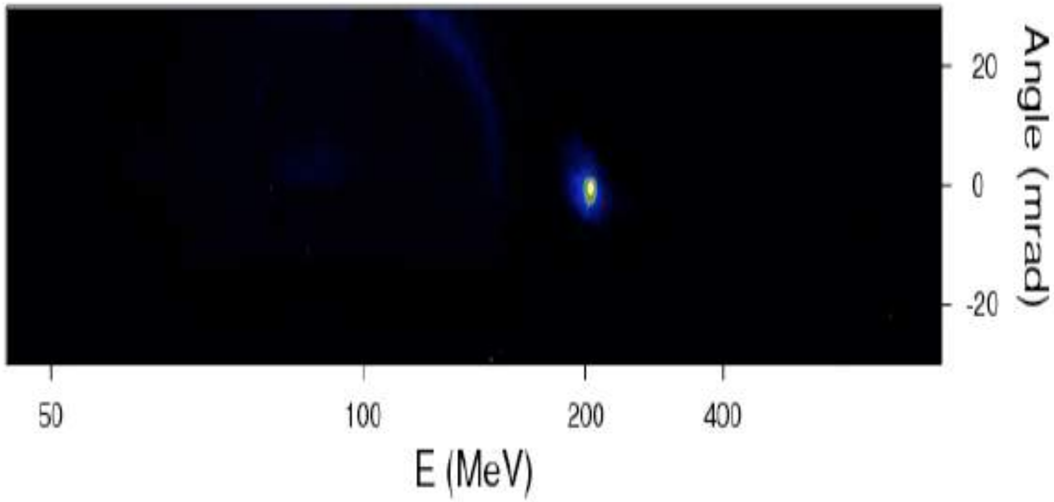
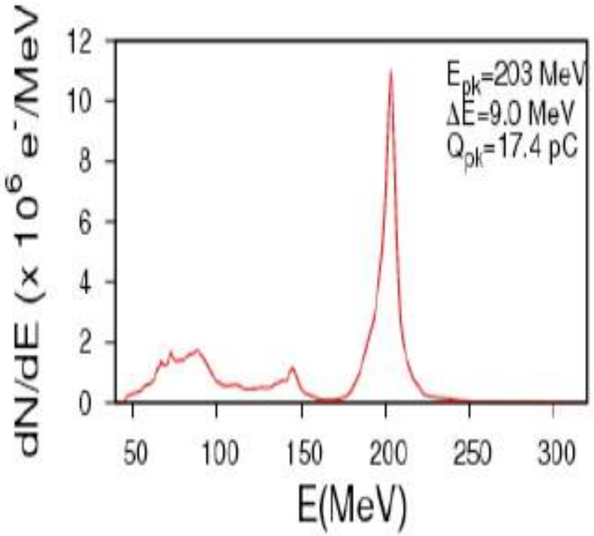
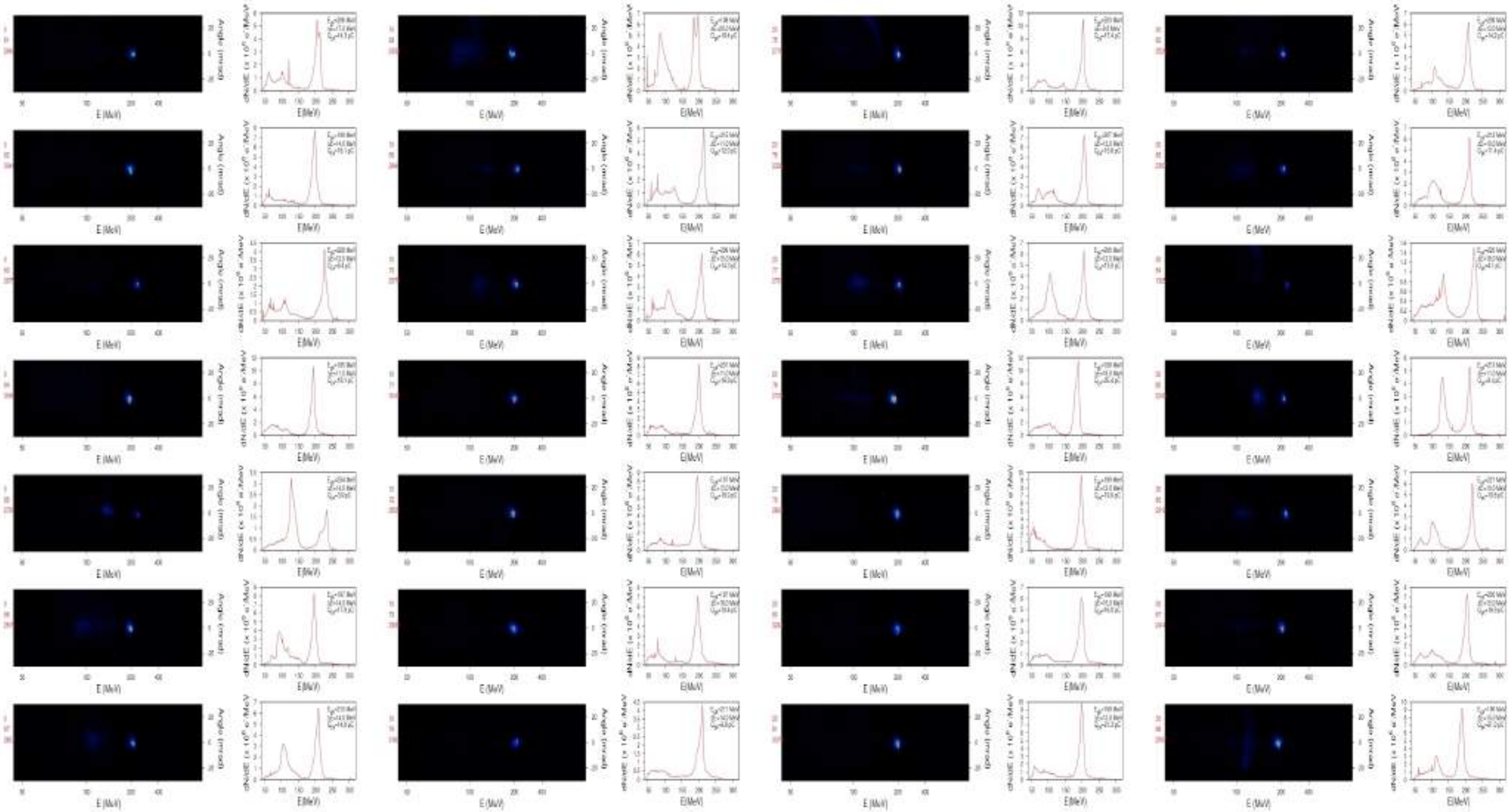
Stable Laser Plasma Accelerators





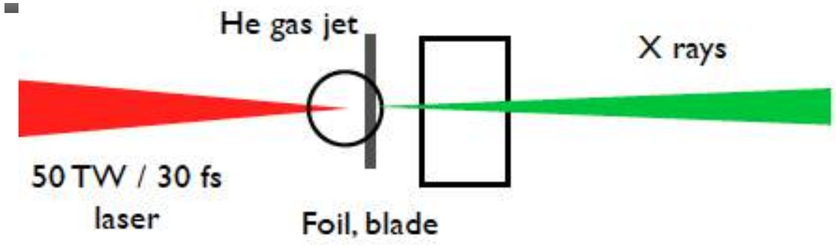
Stable Laser Plasma Accelerators

Series of 28 consecutive shots with : $a_0=1.5$, $a_1=0.4$, $n_e=5.7\times10^{18}cm^{-3}$



loa

Inverse Compton Scattering : New scheme



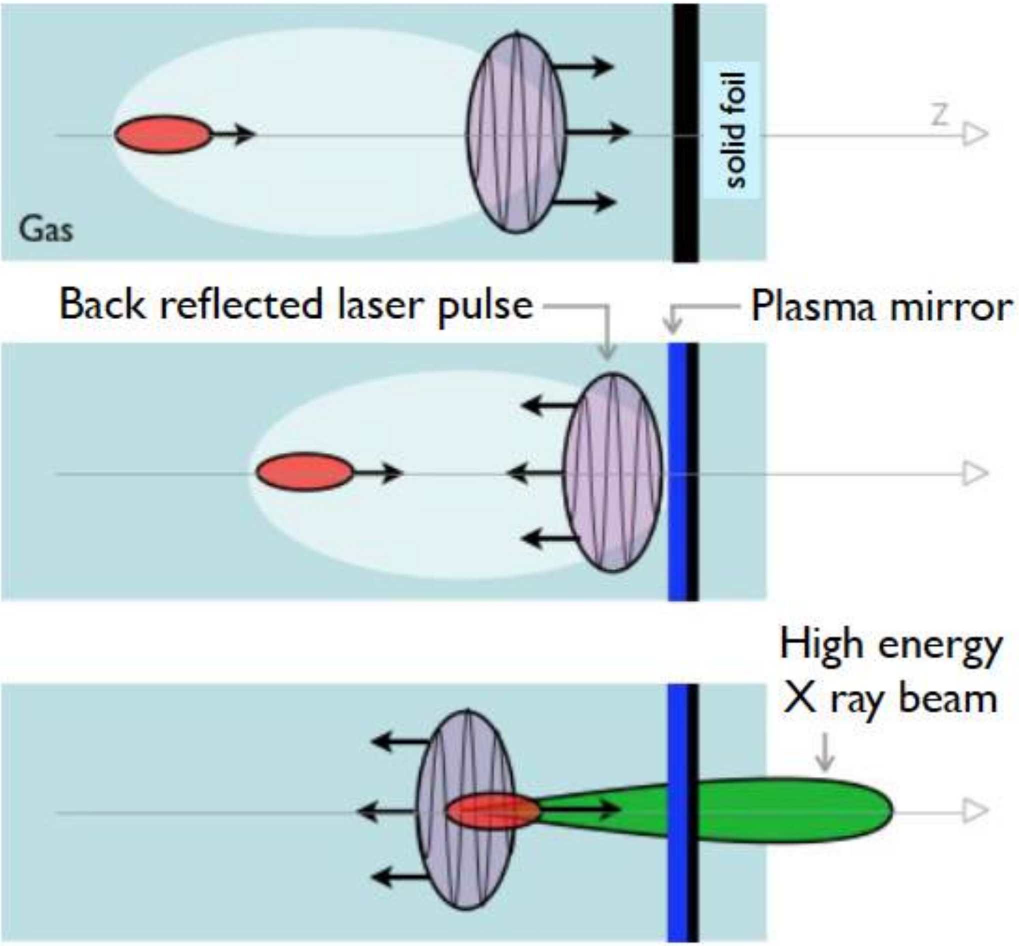
A single laser pulse

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 !

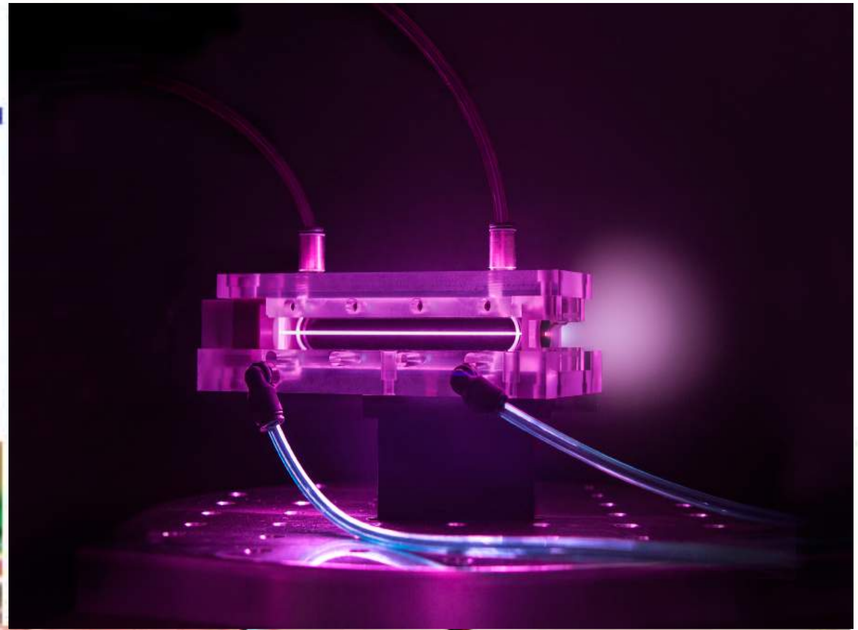


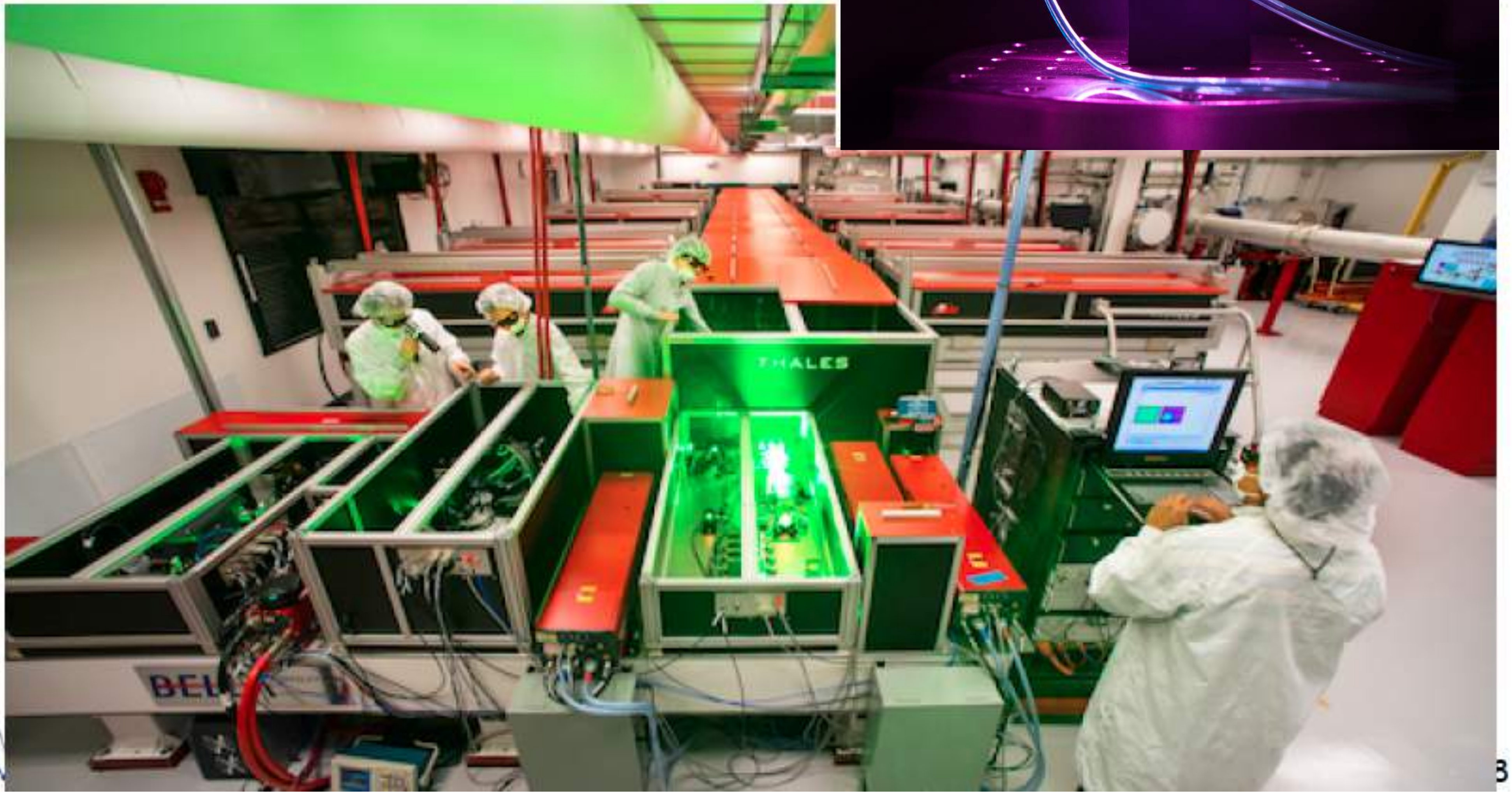
World Leader

BELLA LPWA facility:

3 cm 1 GeV 40 TW laser ~1Hz

10-30 cm 5-10 GeV PW laser, ~1 Hz



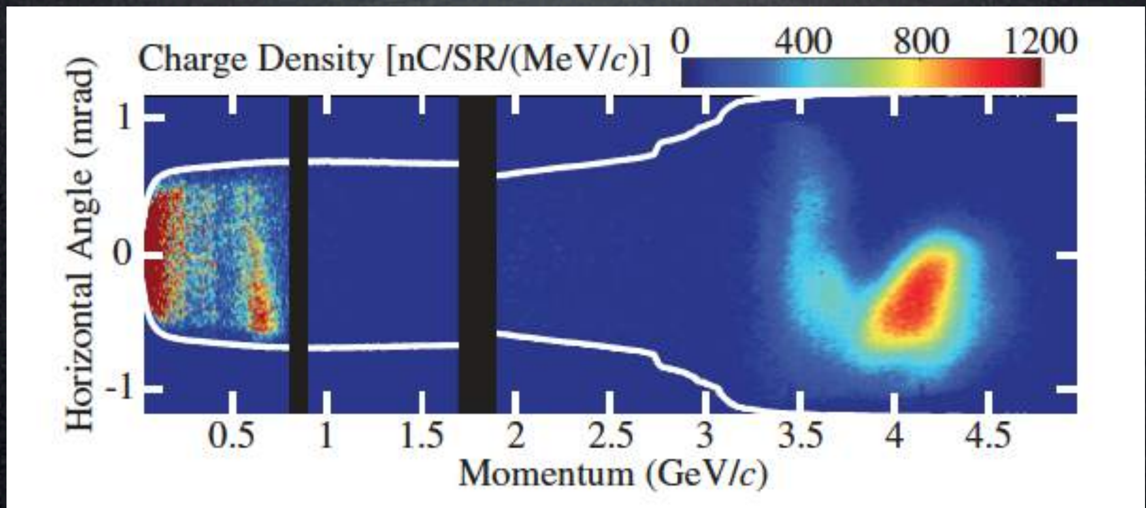


PRL 113, 245002 (2014) Selected for a Viewpoint in *Physics* PHYSICAL REVIEW LETTERS week ending 12 DECEMBER 2014

Multi-GeV Electron Beams from Capillary-Discharge-Guided Subpetawatt Laser Pulses in the Self-Trapping Regime

W. P. Leemans,[1,2,*] A. J. Gonsalves,[1] H.-S. Mao,[1] K. Nakamura,[1] C. Benedetti,[1] C. B. Schroeder,[1] Cs. Tóth,[1] J. Daniels,[1] D. E. Mittelberger,[2,1] S. S. Bulanov,[2,1] J.-L. Vay,[1] C. G. R. Geddes,[1] and E. Esarey[1]
[1]*Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA*
[2]*Department of Physics, University of California, Berkeley, California 94720, USA*
(Received 3 July 2014; revised manuscript received 11 September 2014; published 8 December 2014)

Multi-GeV electron beams with energy up to 4.2 GeV, 6% rms energy spread, 6 pC charge, and 0.3 mrad rms divergence have been produced from a 9-cm-long capillary discharge waveguide with a plasma density of $\approx 7 \times 10^{17}$ cm^{-3}, powered by laser pulses with peak power up to 0.3 PW. Preformed plasma waveguides allow the use of lower laser power compared to unguided plasma structures to achieve the same electron beam energy. A detailed comparison between experiment and simulation indicates the sensitivity in this regime of the guiding and acceleration in the plasma structure to input intensity, density, and near-field laser mode profile.



ICAN (European Project)

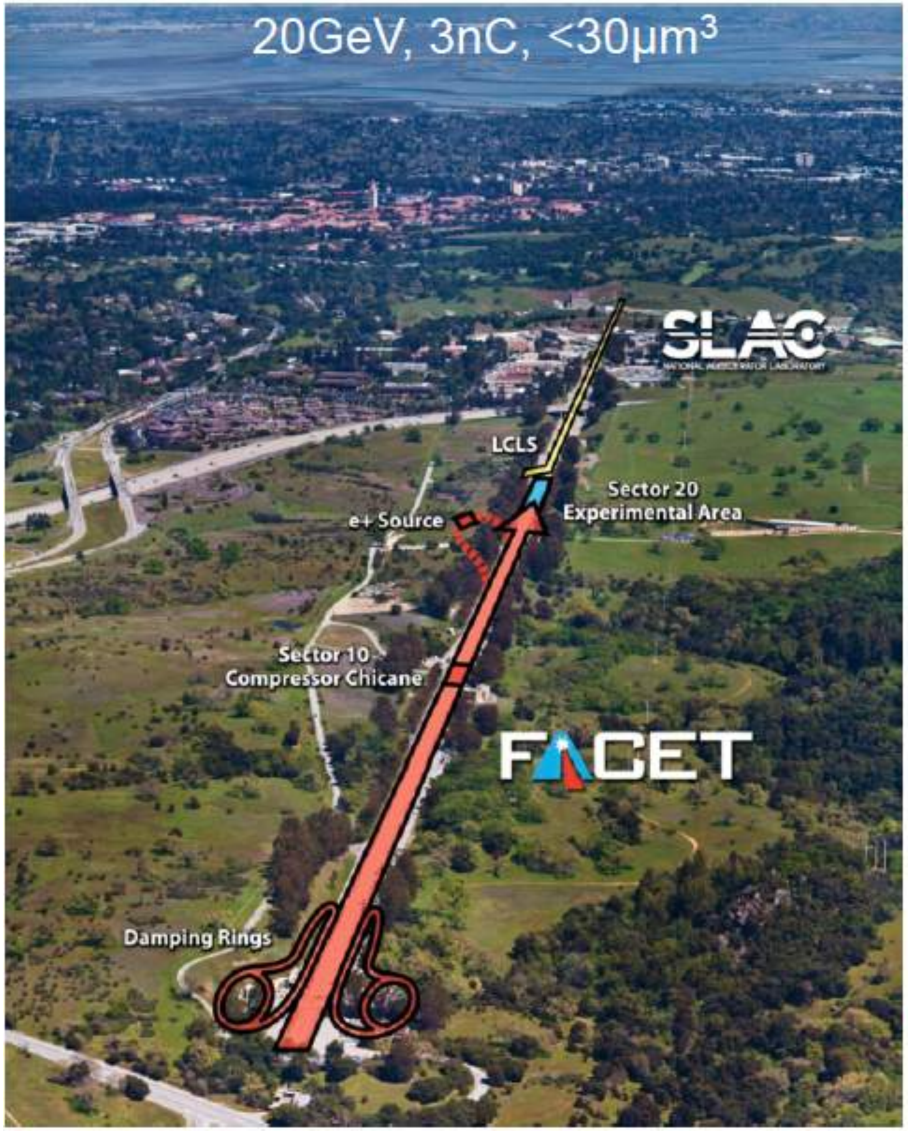
CAN Coherent Amplification Network

G. Mourou, W. Brocklesby, J. Limpert, T. Tajima, Nature Photonics April 2013
« The future of Acceletaor is Fiber »

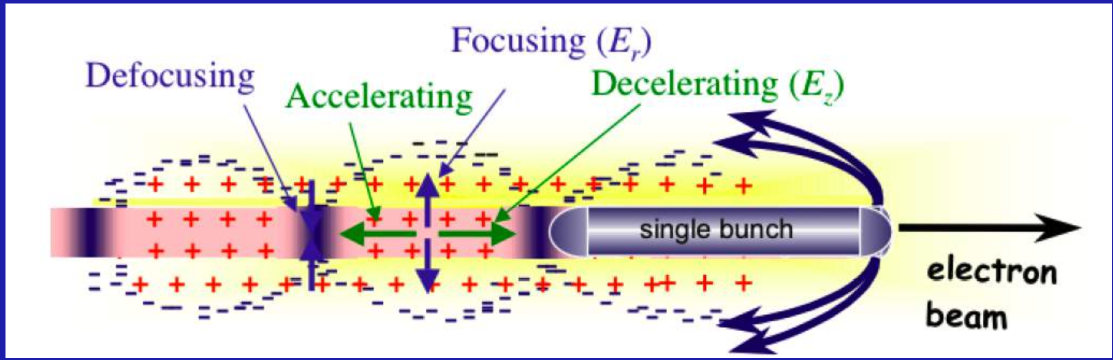
Plasma Acceleration 2
Beam Driven
PWFA

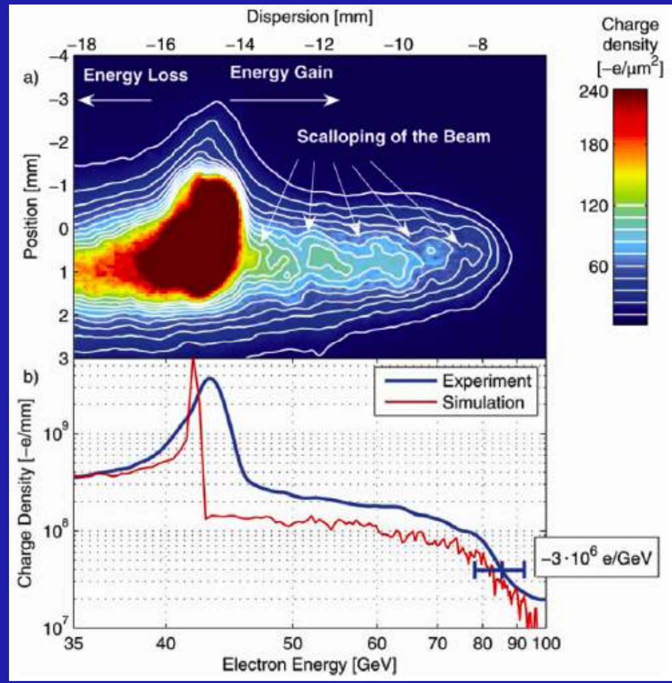
FACET Has a Multi-year Program to Study PWFA

SLAC

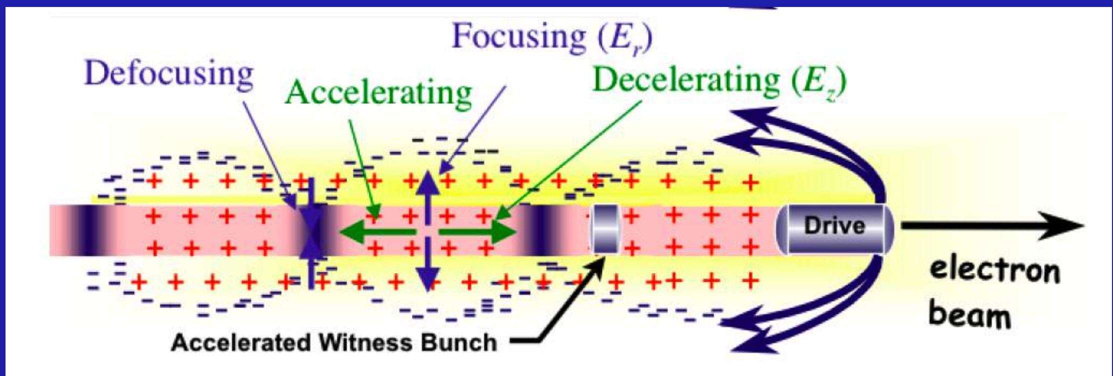


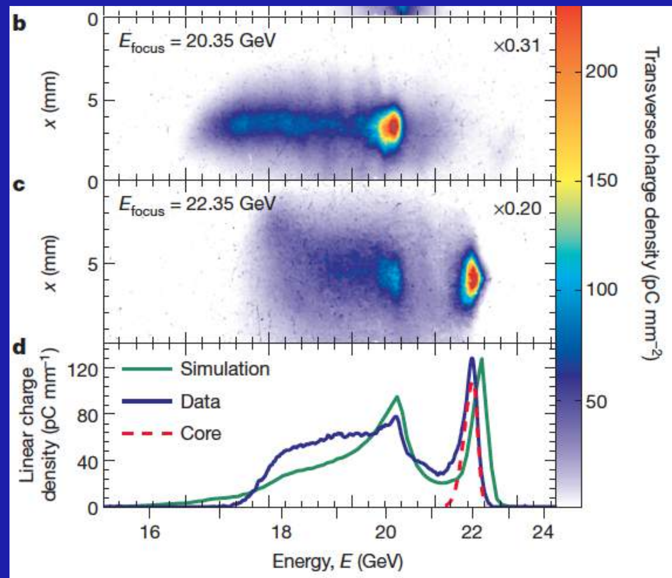
- Demonstrate a single-stage high-energy plasma accelerator for electrons
- Meter scale, high gradient, preserved emittance, low energy spread, and high efficiency
  - Commission beam, diagnostics and plasma source (2012)
  - Produce independent drive & witness bunch (2012-2013)
  - Pre-ionized plasmas and tailored profiles to maximize single stage performance: total energy gain, emittance, efficiency (2013-2015)
- First experiments with compressed positrons
  - Identify optimum technique/regime for positron PWFA (2014-2016)





Blumenfeld, I. et al. *Energy doubling of 42 GeV electrons in a metre-scale plasma wakefield accelerator*. **Nature** 445, 741–744 (2007).





Litos, M. et al. *High-efficiency acceleration of an electron beamin a plasma wakefield accelerator*. **Nature** 515, 92–95 (2014).

EUROPEAN PLASMA RESEARCH ACCELERATOR WITH EXCELLENCE IN APPLICATIONS

R. Assmann
coordinator

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

EuPRAXIA

Motivations

Horizon2020

PRESENT EXPERIMENTS

Demonstrating **100 GV/m** routinely

Demonstrating **GeV** electron beams

Demonstrating basic **quality**

EuPRAXIA INFRASTRUCTURE

Engineering a high quality, compact plasma accelerator

5 GeV electron beam for the 2020's

Demonstrating user readiness

Pilot users from FEL, HEP, medicine, ...

PRODUCTION FACILITIES

Plasma-based **linear collider** in 2040's

Plasma-based **FEL** in 2030's

Medical, industrial applications soon

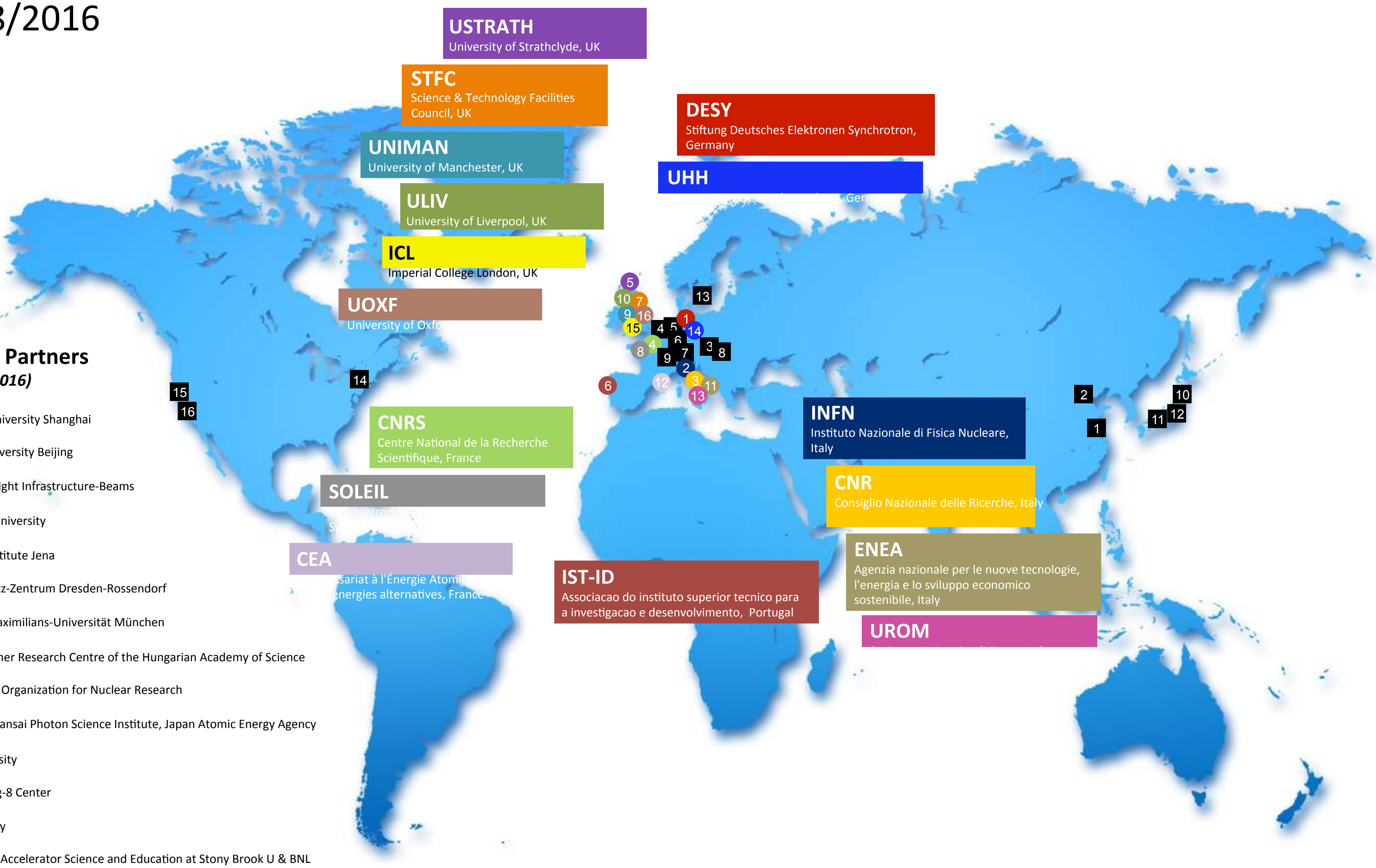
Courtesy R. Assmann

Participating Institutions

16 beneficiaries, 16 associated partners

Horizon2020

Status 8/2016



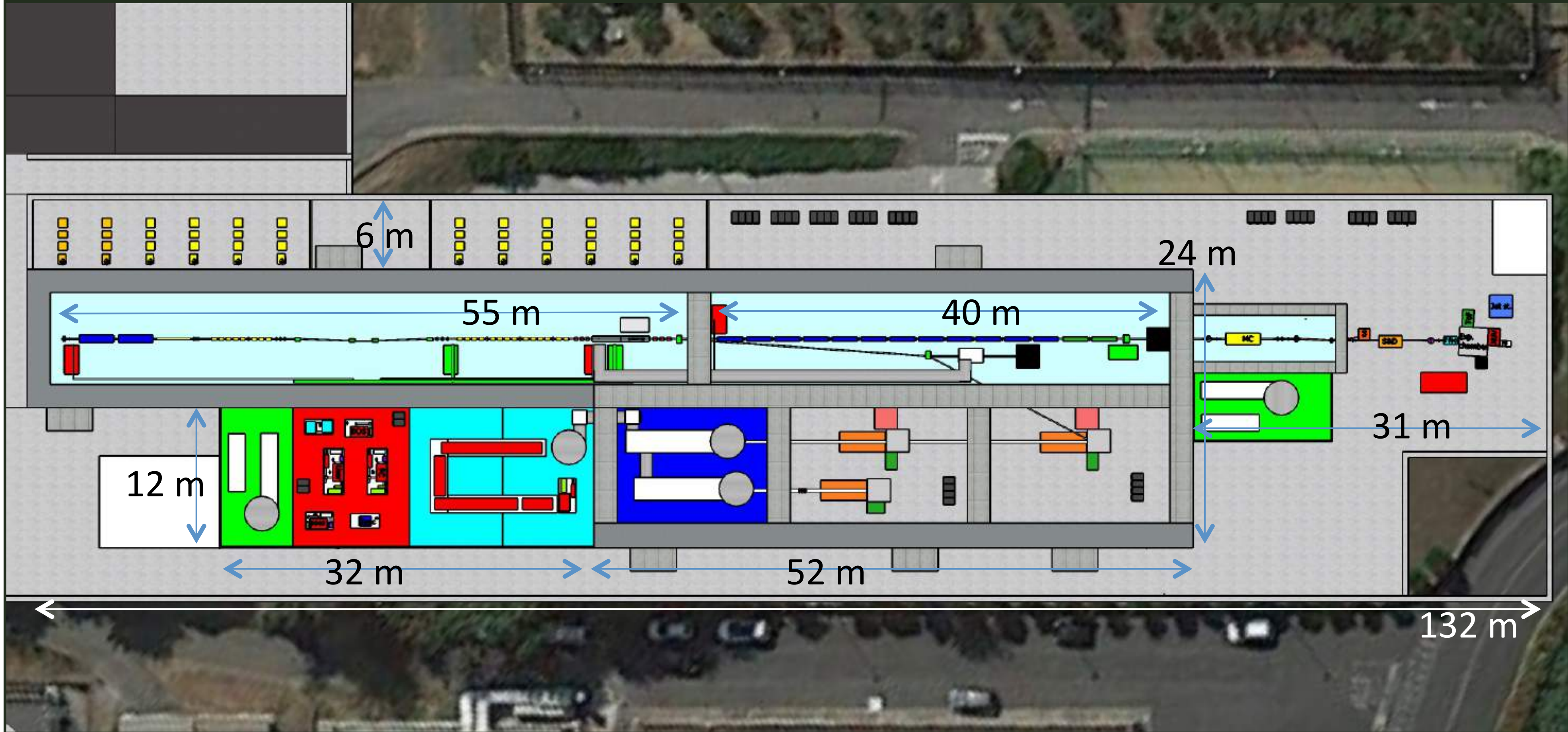
Associated Partners

(as of August 2016)

1. **JUS** Jiao Tong-University Shanghai
2. **TUB** Tsingua University Beijing
3. **ELI-B** Extreme Light Infrastructure-Beams
4. **PHLAM** Lille University
5. **HIJ** Helmholtz Institute Jena
6. **HZDR** Helmholtz-Zentrum Dresden-Rossendorf
7. **LMU** Ludwig-Maximilians-Universität München
8. **WIGNER** Wigner Research Centre of the Hungarian Academy of Science
9. **CERN** European Organization for Nuclear Research
10. **KPSI/JAEA** Kansai Photon Science Institute, Japan Atomic Energy Agency
11. **OU** Osaka University
12. **RSC** RIKEN SPring-8 Center
13. **LU** Lund University
14. **CASE** Center for Accelerator Science and Education at Stony Brook U & BNL
15. **LBNL** Lawrence Berkeley National Laboratory
16. **UCLA** University of California, Los Angeles

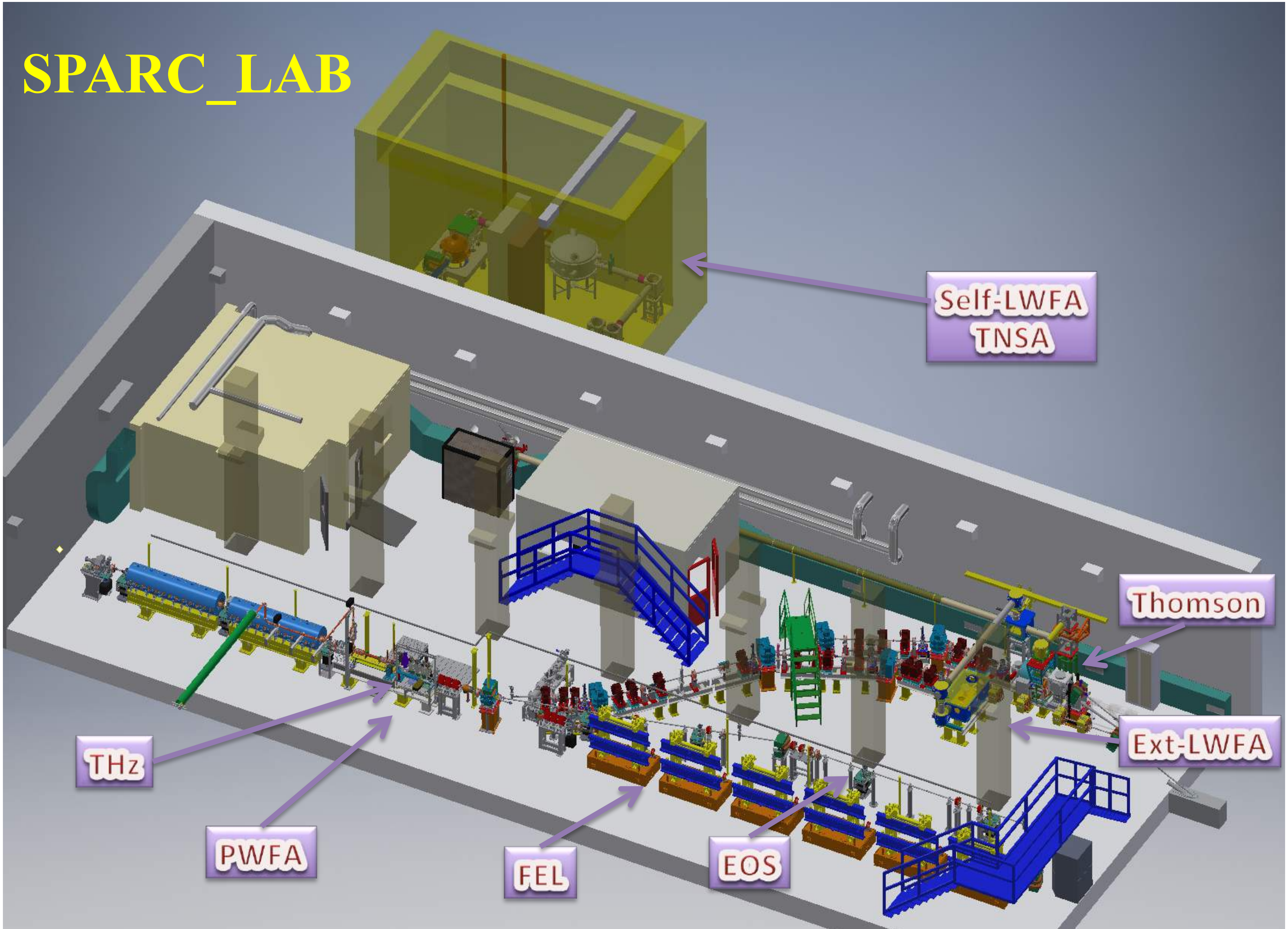
EuPRAXIA@SPARC_LAB

- Candidate LNF to host EuPRAXIA (1-5 GeV)
- FEL user facility (1 GeV – 3nm)
- Advanced Accelerator Test facility (LC) + CERN



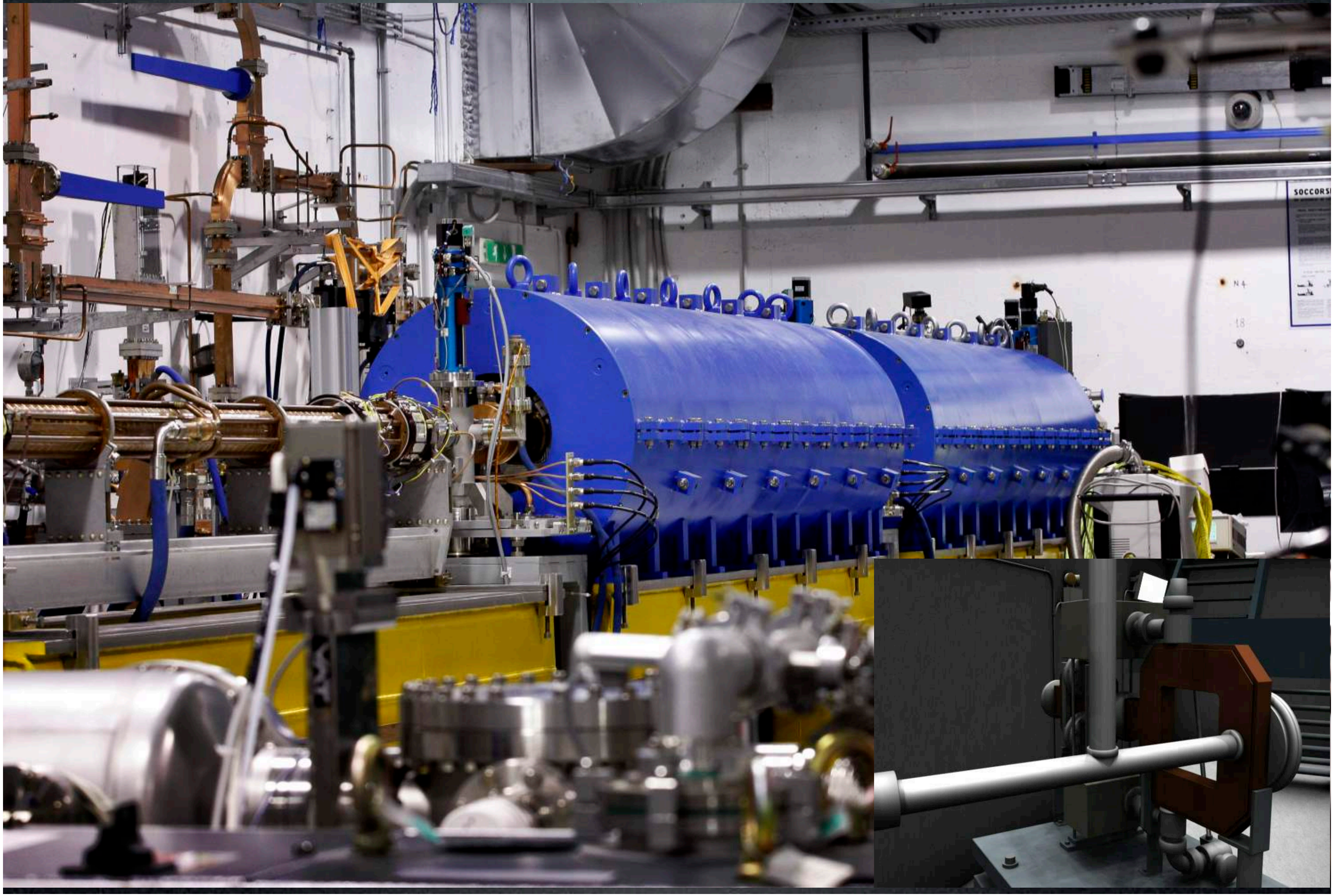
- 500 MeV by RF Linac + 500 MeV by Plasma (LWFA or PWFA)
- 1 GeV by X-band RF Linac only
- Final goal compact 5 GeV accelerator

SPARC_LAB

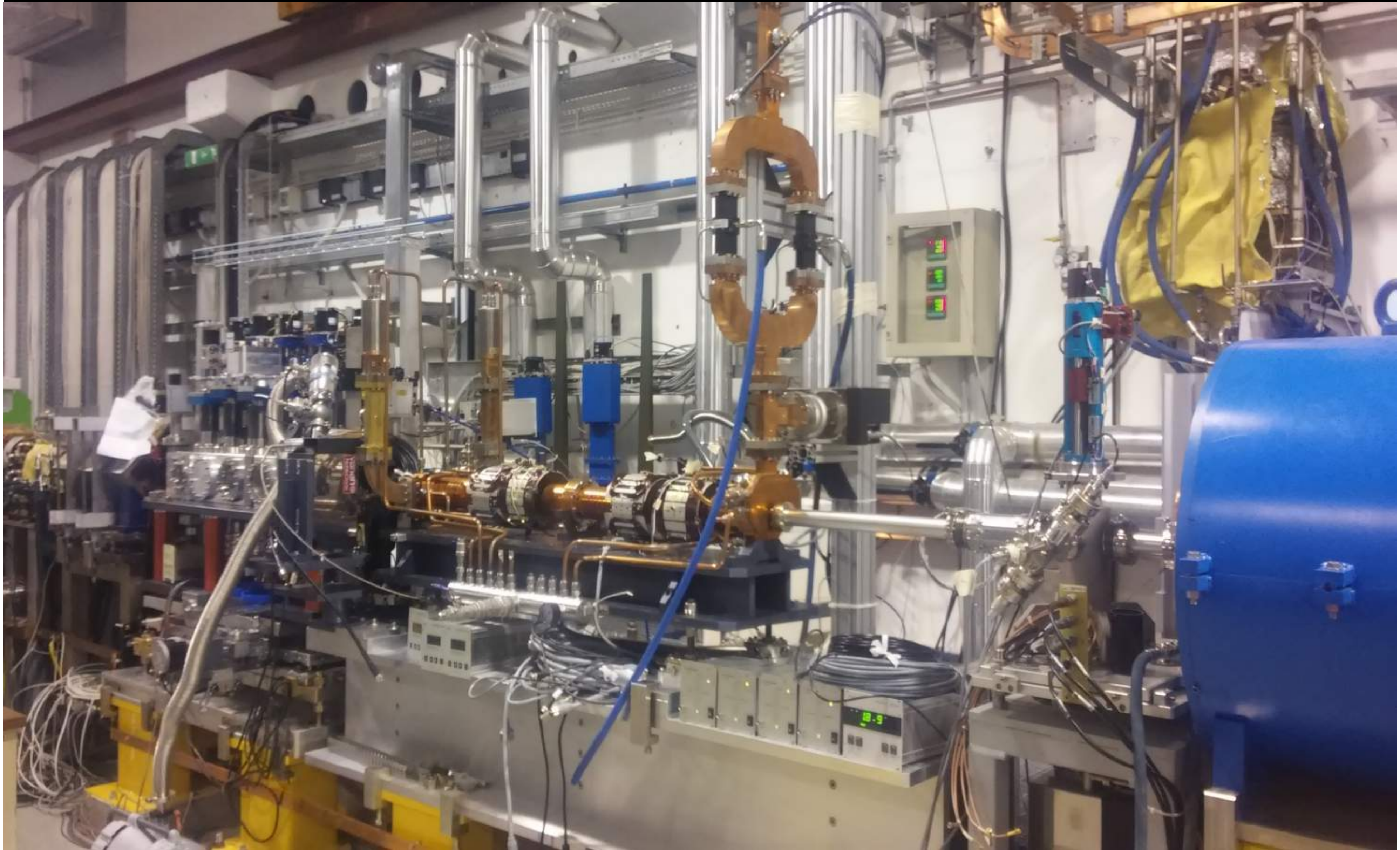


Ferrario, M., et al. "SPARC_LAB present and future." NIMB 309 (2013): 183-188.

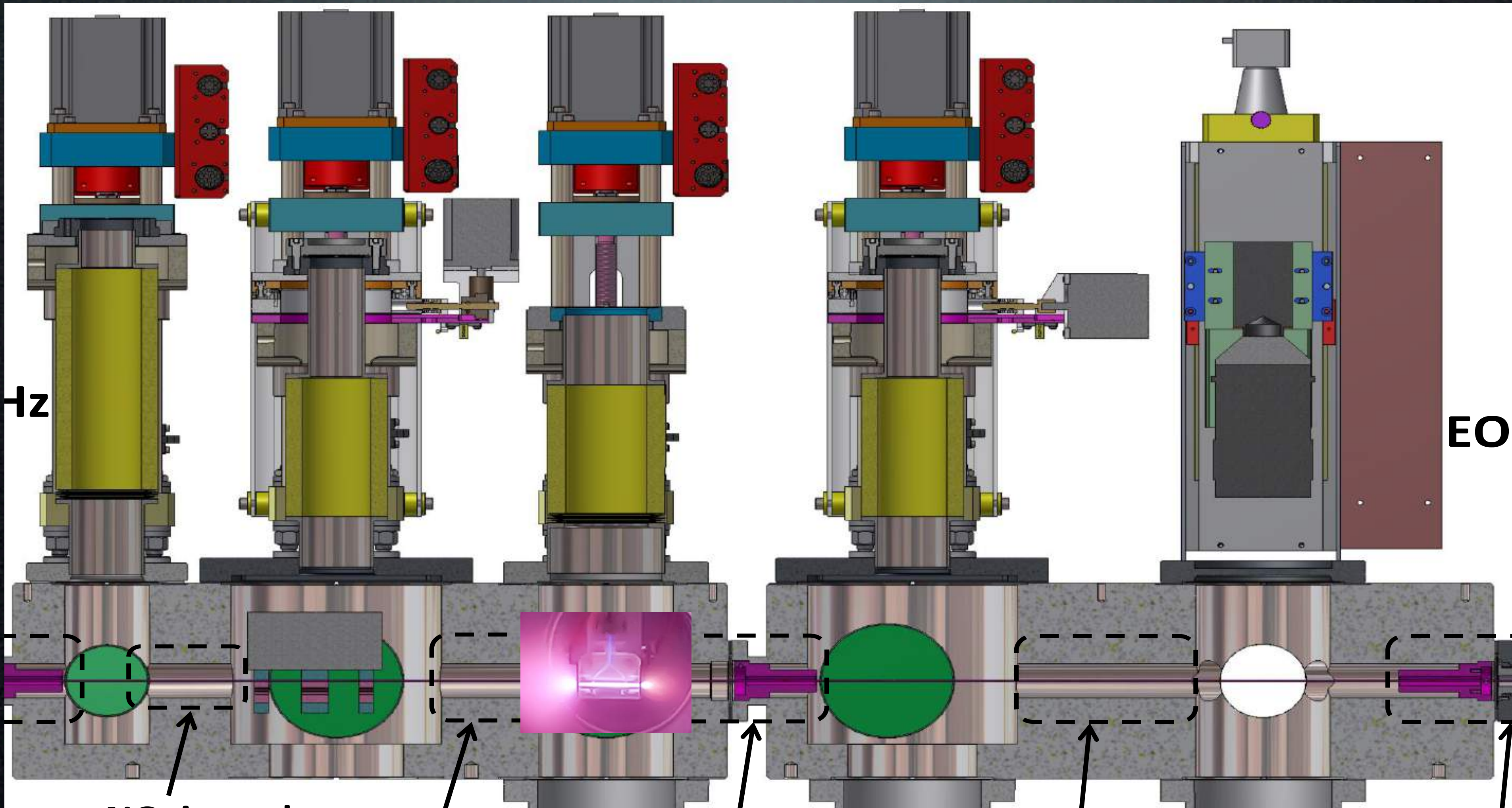
HB photo- injector with Velocity Bunching



C-Band accelerating structure and PWFA chamber



SPARC_LAB Plasma Vacuum Chamber



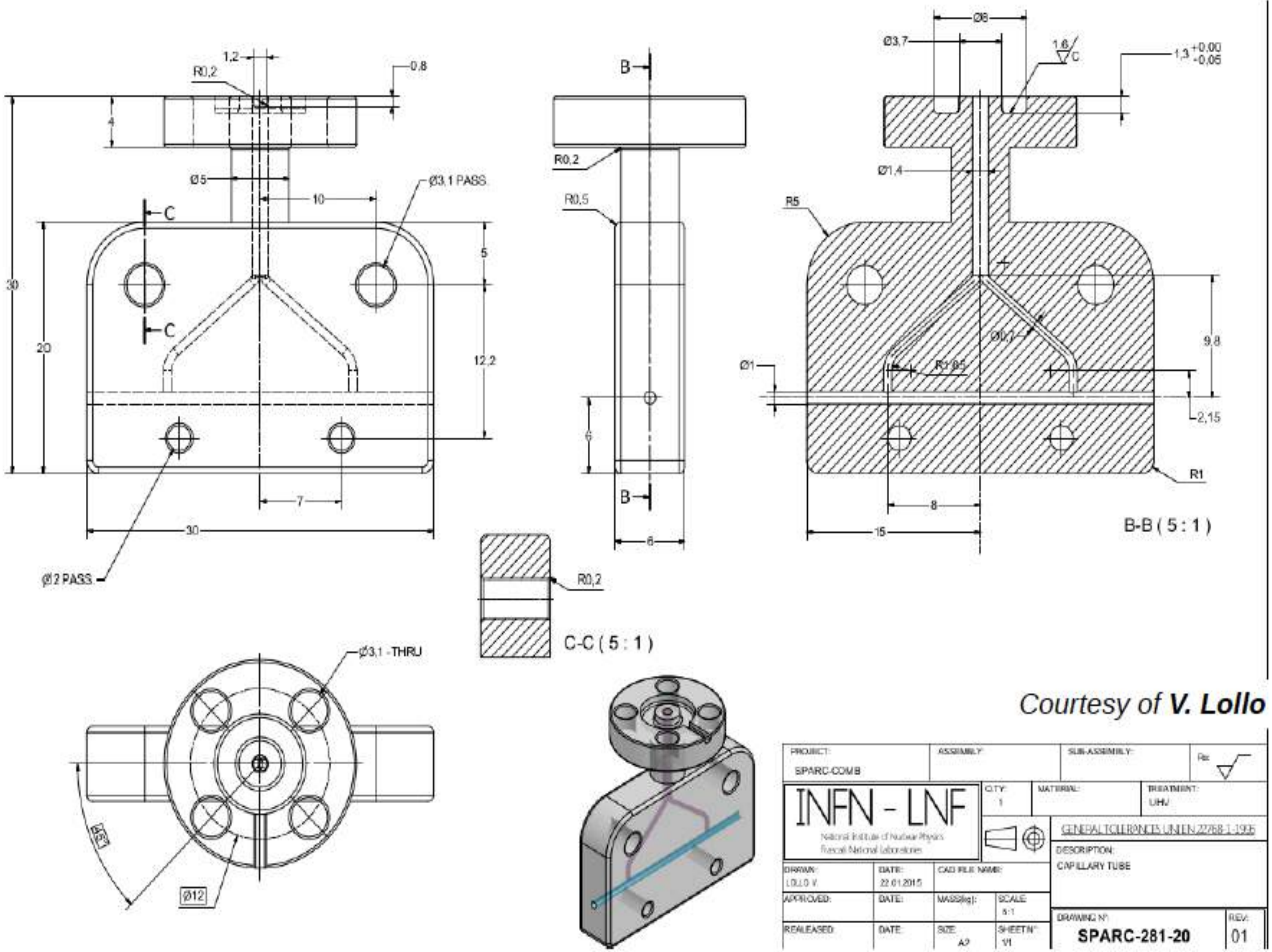
Focusing PMQ

PWFA module

Capture PMQ

Capillary Discharge at SPARC_LAB

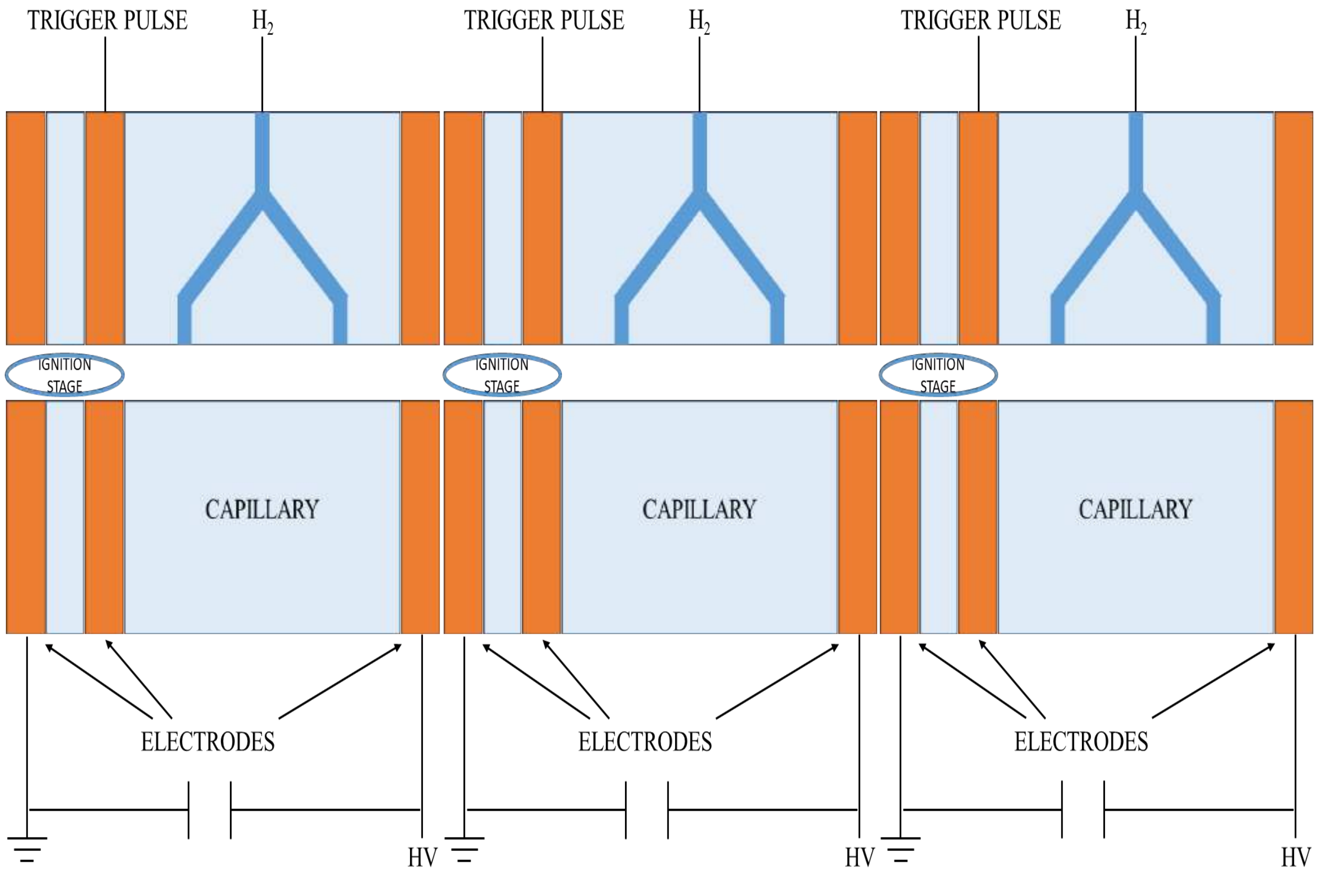
Plasma capillary



Courtesy of ***V. Lollo***

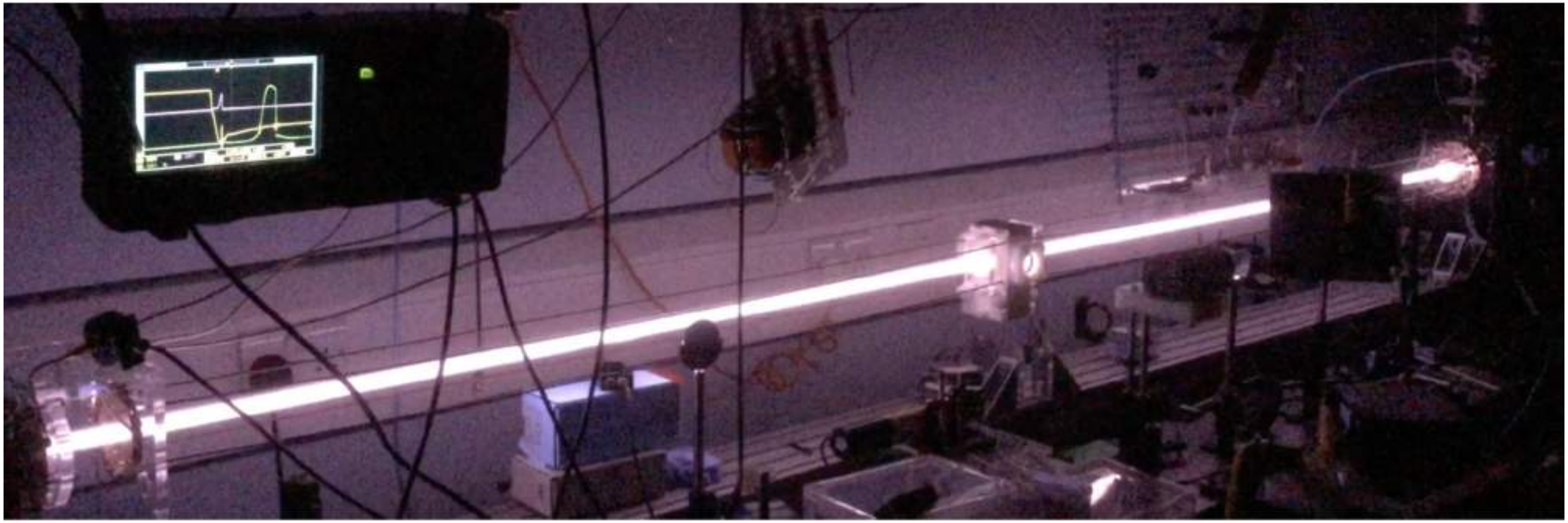
Plasma source

This scheme can be reproduced for tens-of-centimetre capillaries. This single unit can be integrated simply by adding more units obtaining up to tens of centimetre capillaries homogenously ionized and controlled independently one to each other, leading to the desired length of plasma (almost 30 cm) with the proper density (10^{17} cm^{-3}) required for this project.



Discharge configuration II

preliminary tests with the AWAKE 3 meter test tube at IC - 2016

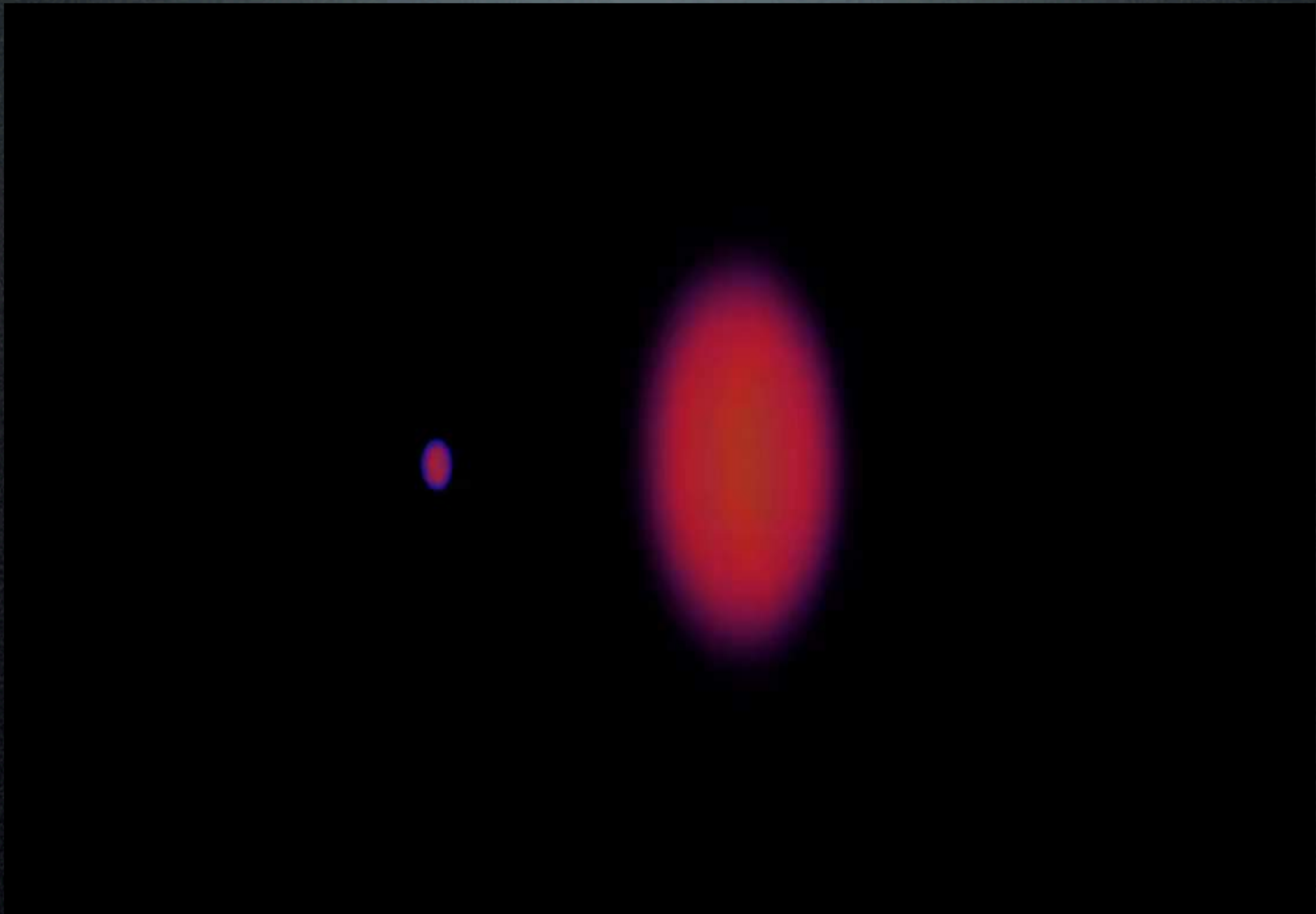


very promising results

… reliable, low jitter plasma formation

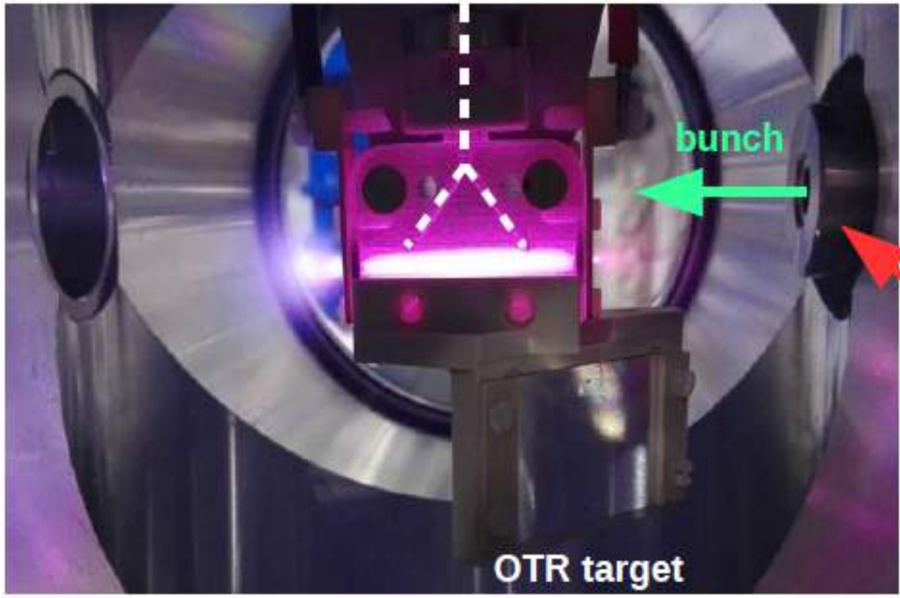
scalability of electric circuit for plasmas > 10 m seem achievable…

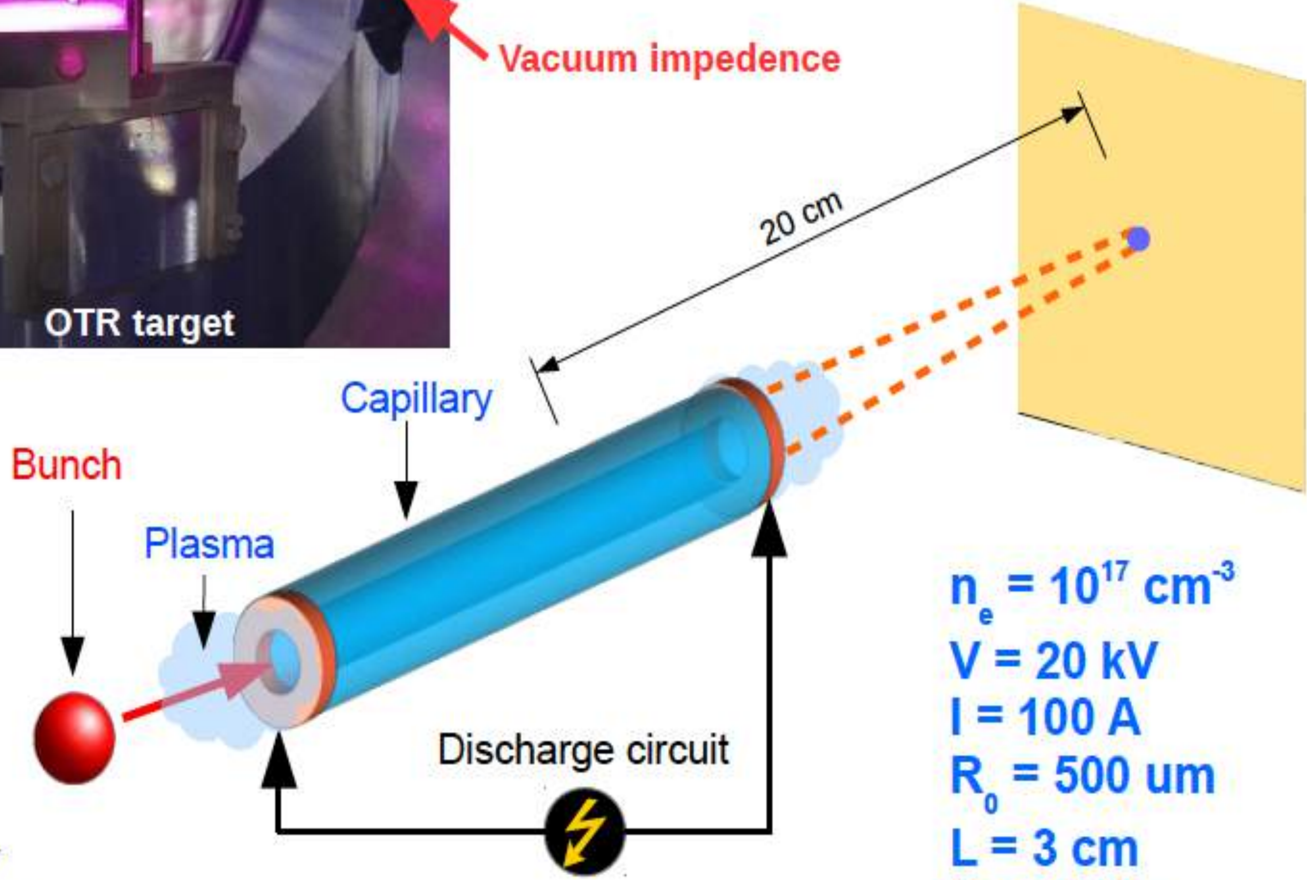
External Injection (LWFA or PWFA)



Beam Manipulation

Experimental layout

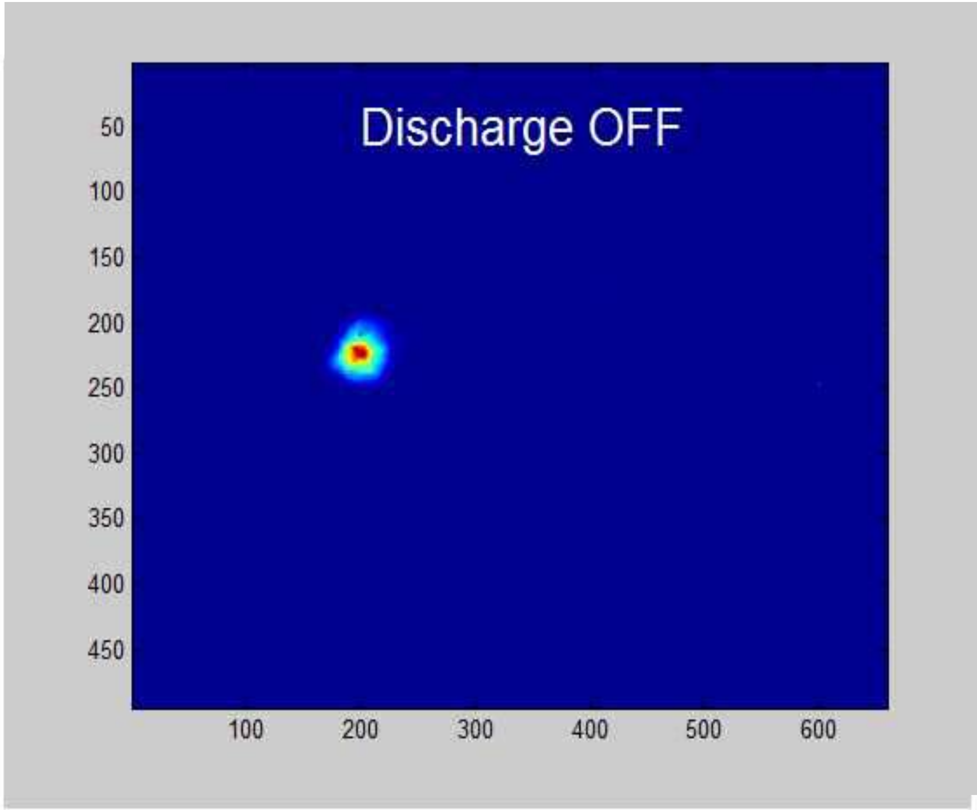


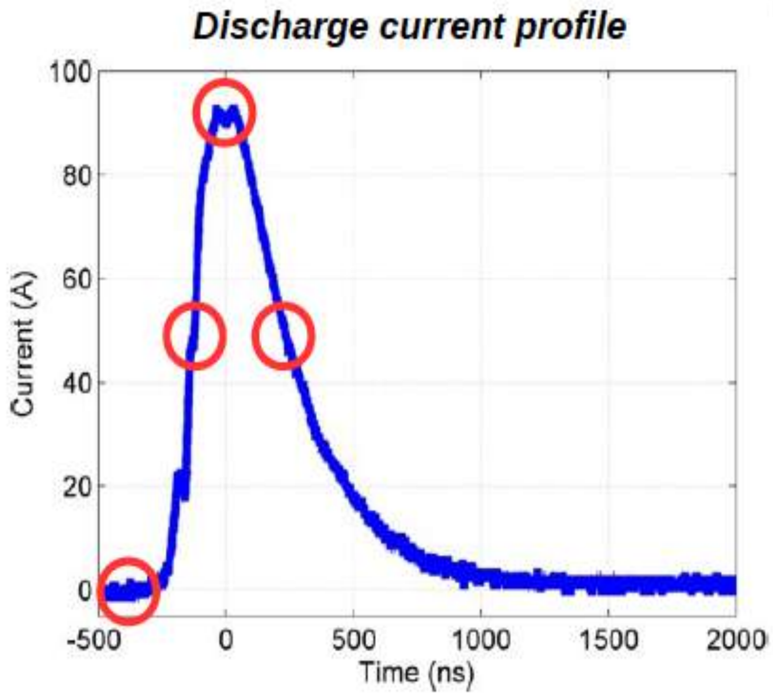


50 pC
1 ps
130 um
120 MeV
1 mm mrad

n_e = 10^{17} cm^{-3}
V = 20 kV
I = 100 A
R_0 = 500 um
L = 3 cm
Sapphire

Preliminary results






Thank you