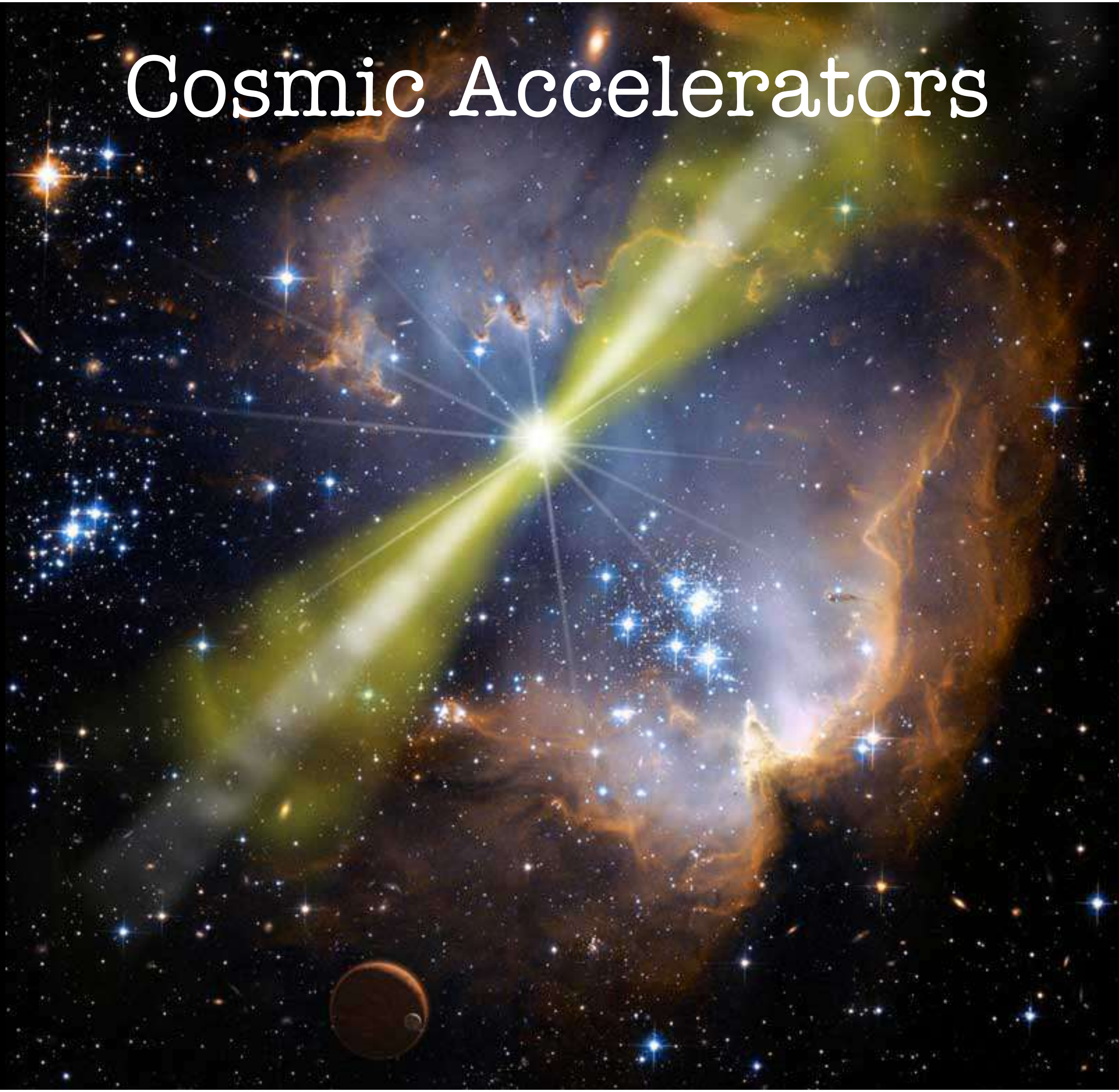
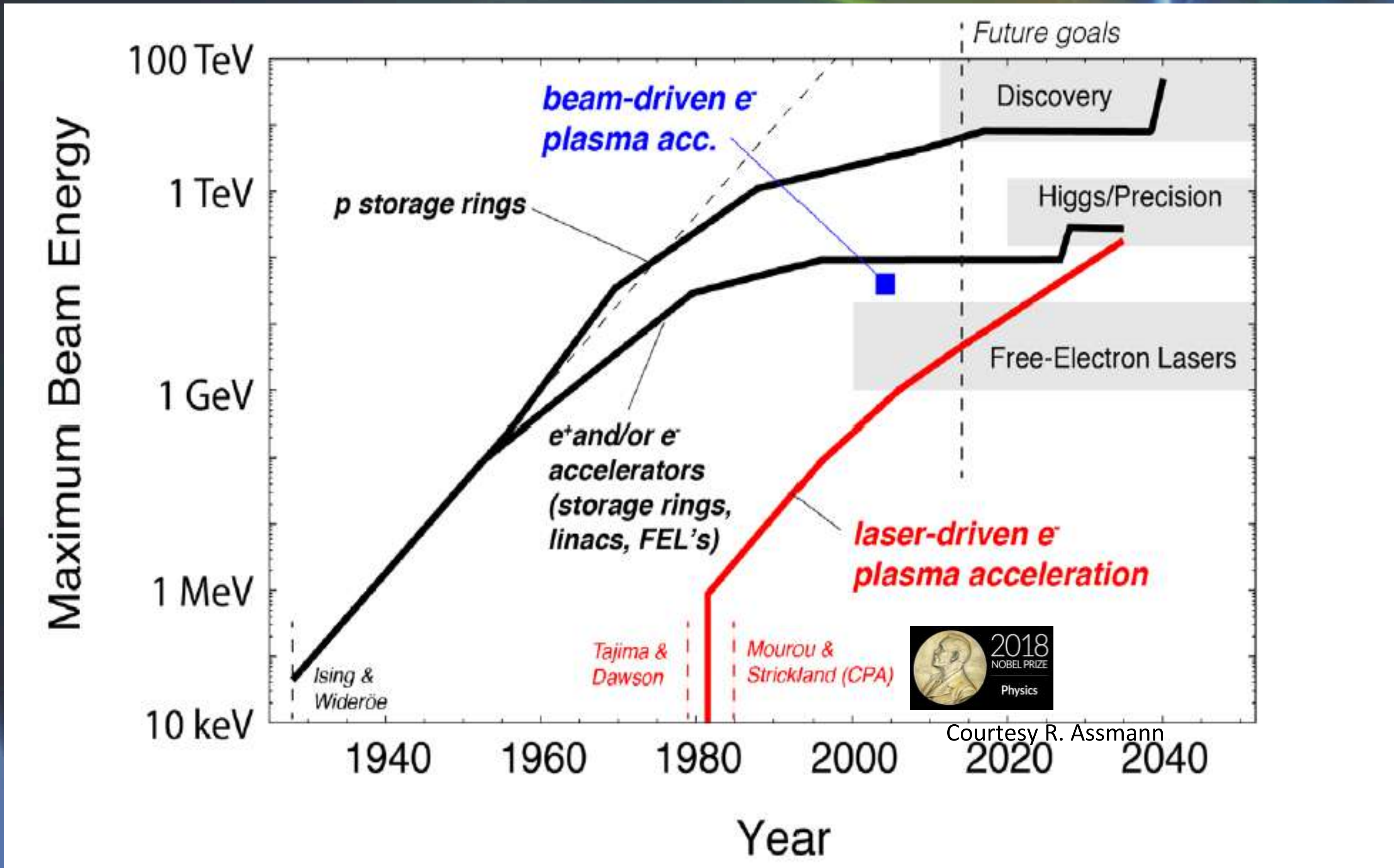
Gli acceleratori del futuro: EuPRAXIA

Massimo.Ferrario@lnf.infn.it

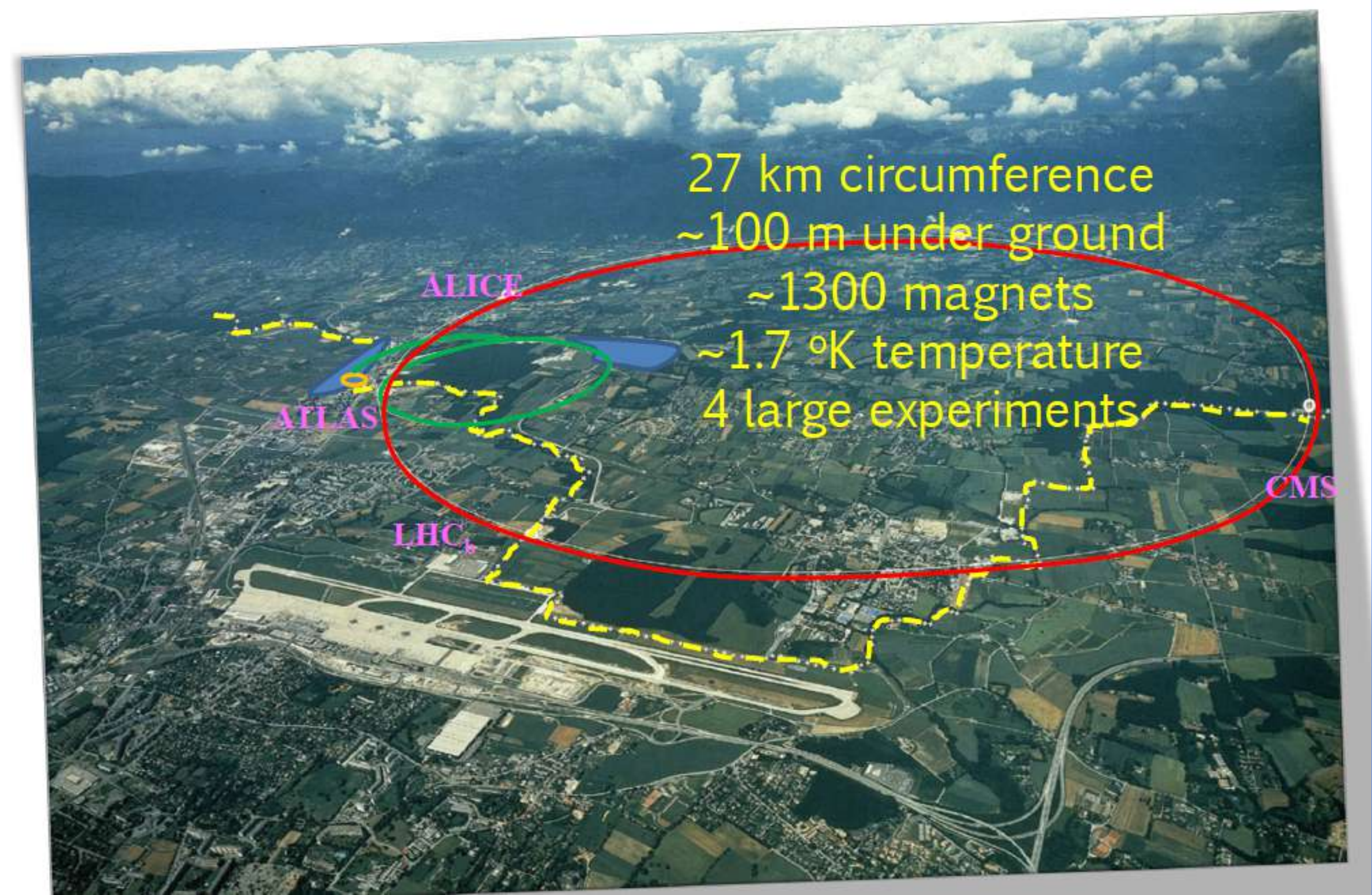
LNF Summer School - 19 Giugno 2020

Cosmic Accelerators




Future goals
100 TeV
1 TeV
1 GeV
1 MeV
10 keV
Maximum Beam Energy
beam-driven e- plasma acc.
Discovery
Higgs/Precision
p storage rings
Free-Electron Lasers
e+and/or e- accelerators (storage rings, linacs, FEL's)
laser-driven e- plasma acceleration
Ising & Wideröe
Tajima & Dawson
Mourou & Strickland (CPA)
2018 NOBEL PRIZE Physics
Courtesy R. Assmann
1940
1960
1980
2000
2020
2040
Year

LHC few data



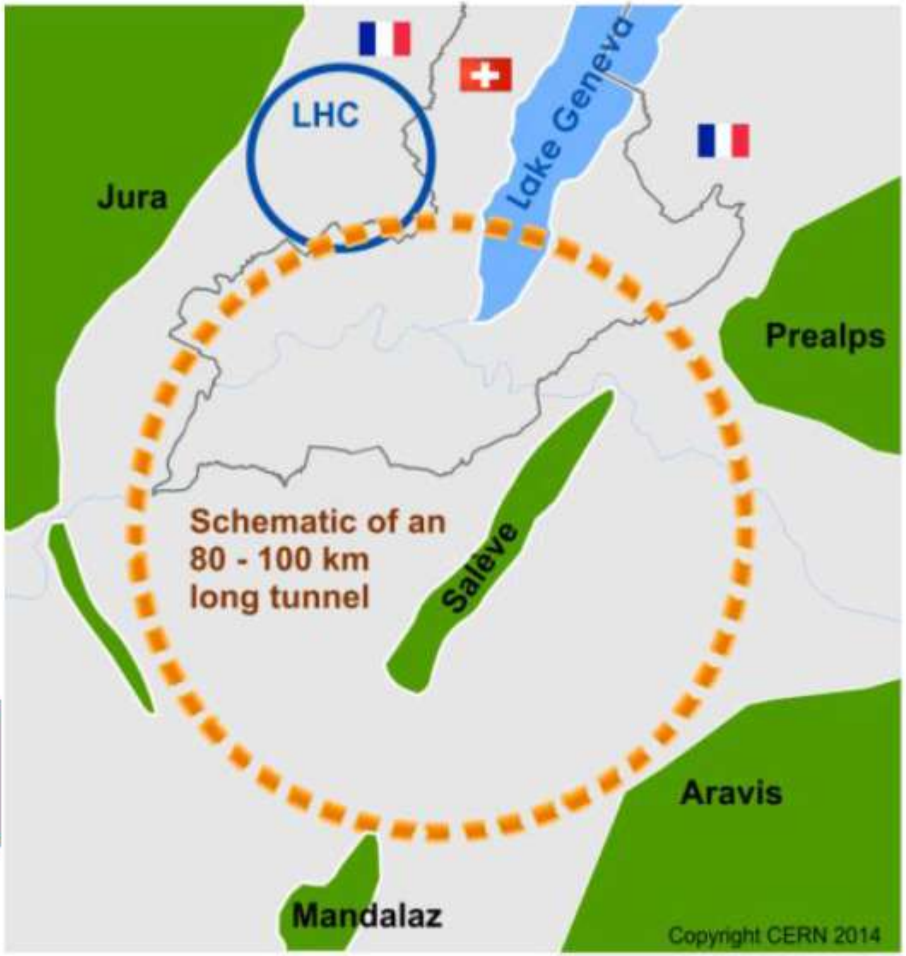
27 km circumference
~100 m under ground
~1300 magnets
~1.7 ºK temperature
4 large experiments
ALICE
ATLAS
LHCb
CMS

Today FCC (Future Circular Collider) study

International collaboration to study:

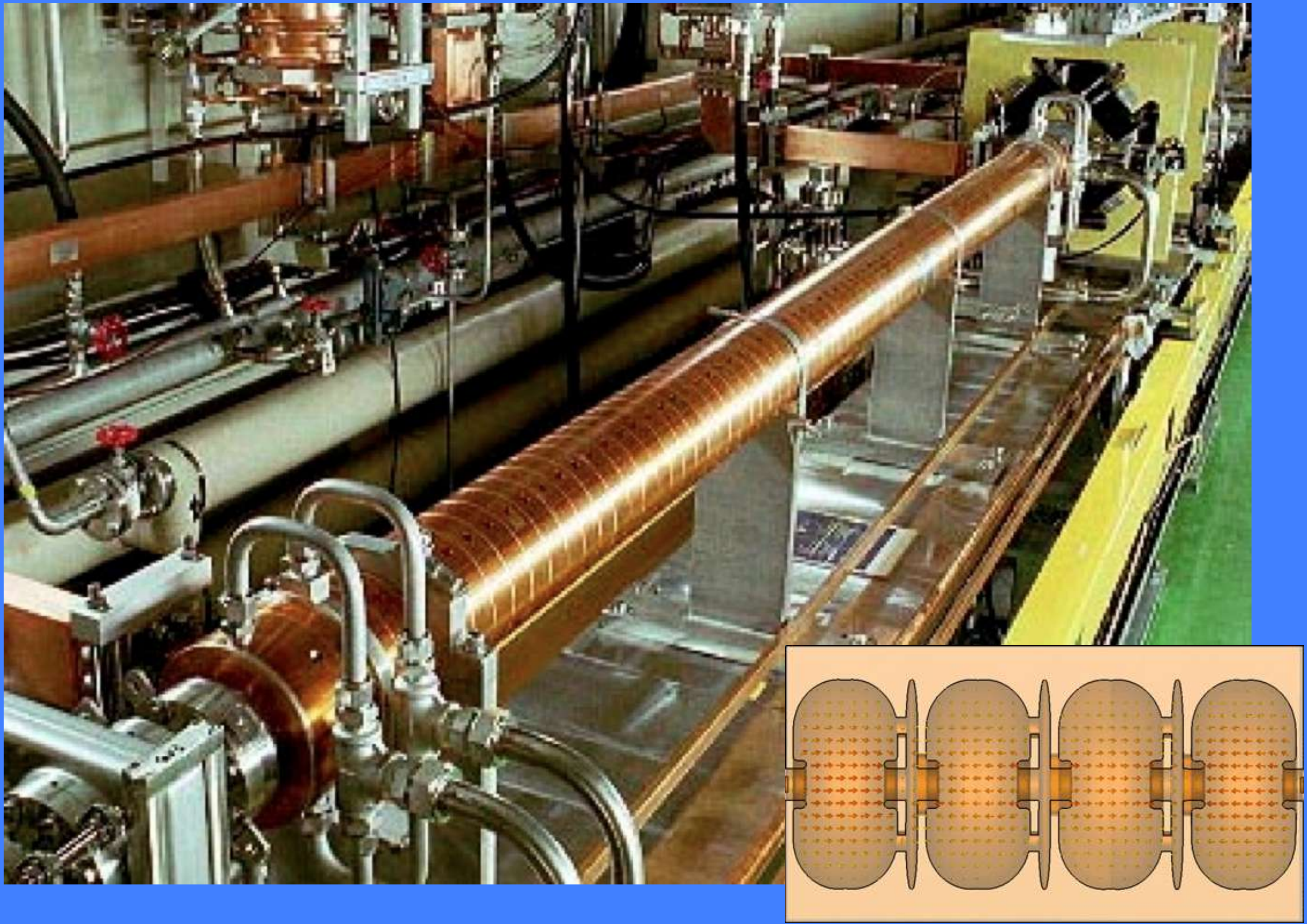
- *pp*-collider (*FCC-hh*)
- e^+e^- collider (*FCC-ee*)
  as potential intermediate step
- *p-e* (*FCC-he*)
  as an option

~16 T ⇒ 100 TeV *pp* in 100 km
~20 T ⇒ 100 TeV *pp* in 80 km



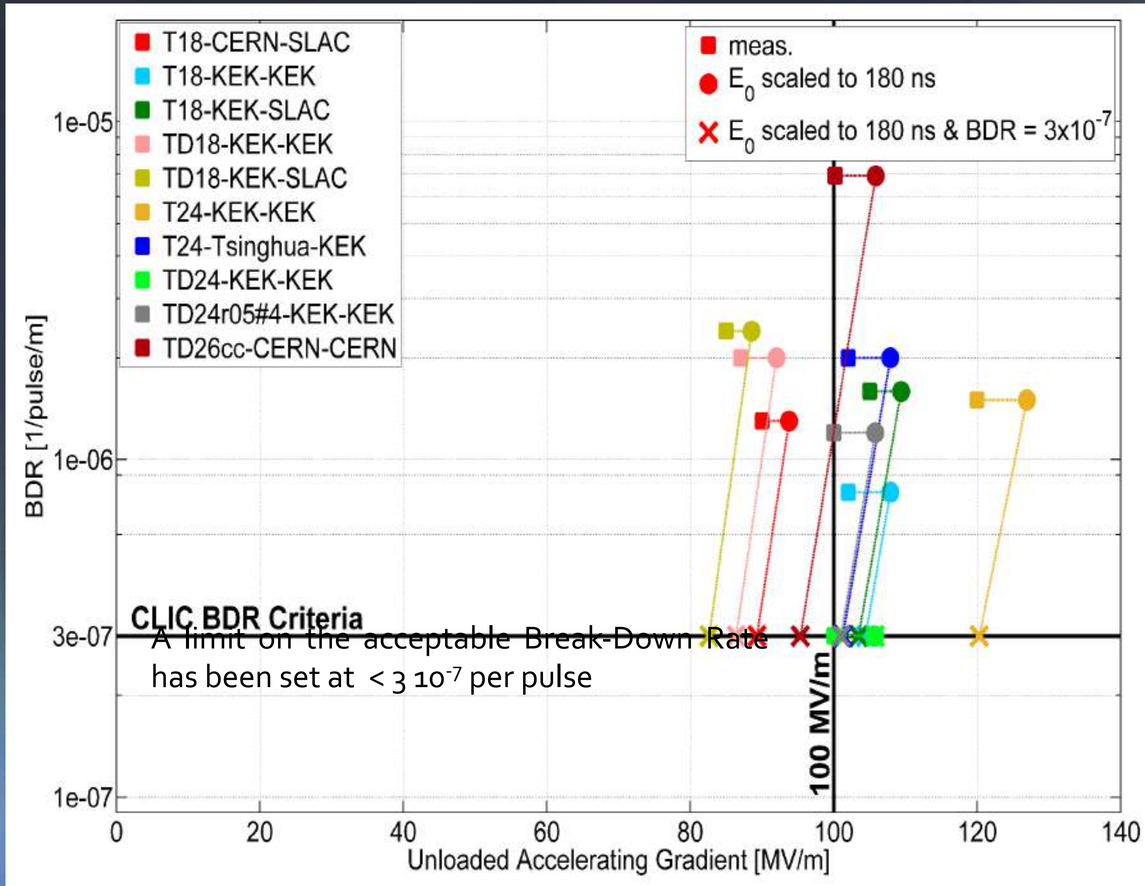
FCC: 80-100 km infrastructure in Geneva area

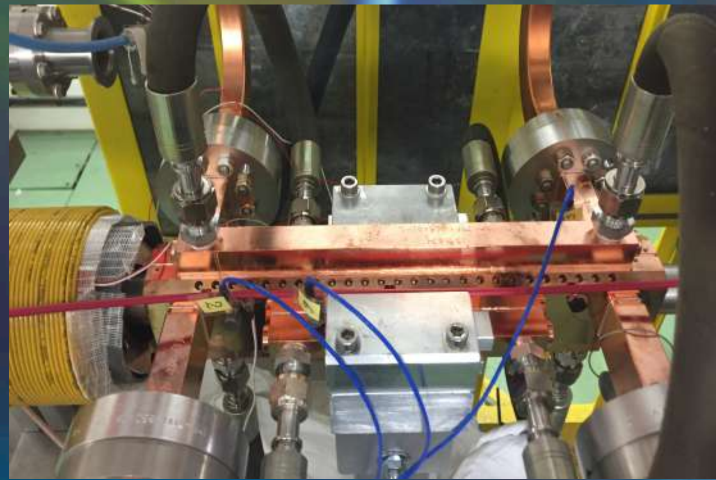
Conventional RF accelerating structures

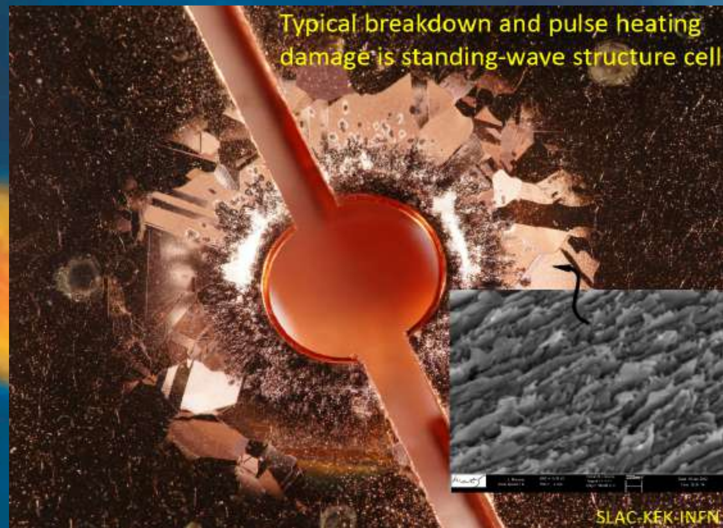


X-band RF structures – State of the Art

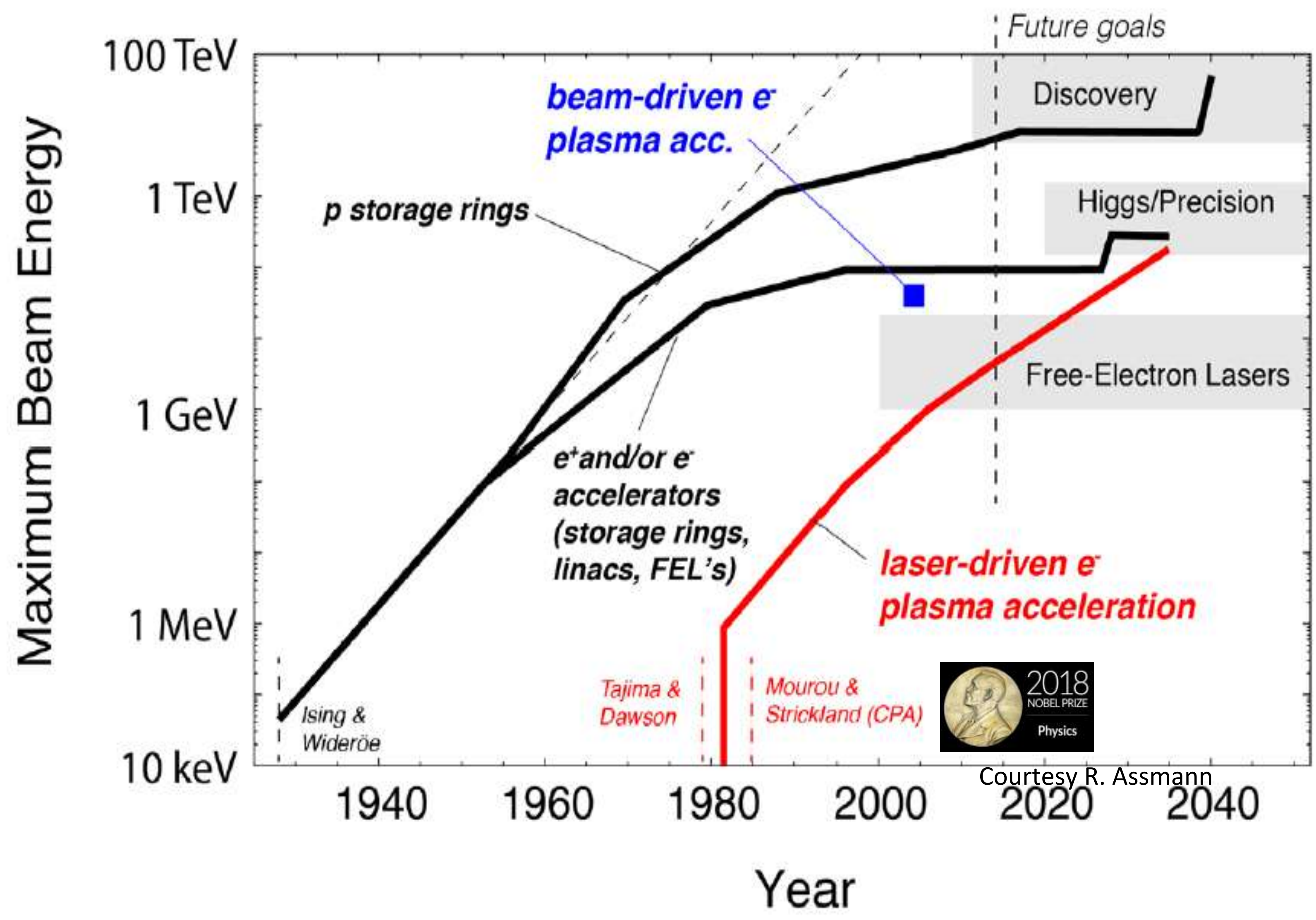
Max accelerating field: $\tau_{rf}^{-1/6}$
Stored energy: f^{-3}







- Kilpatrick, W. D., Rev. Sci. Inst. 28, 824 (1957).
- *A. Grudiev et al, PRST-AB 12, 102001 (2009)*
- S. V. Dolgashev, et al. Appl. Phys. Lett. 97, 171501 2010.
- M. D. Forno, et al. PRAB. 19, 011301 (2016).



Courtesy R. Assmann

VOLUME 43, NUMBER 4 PHYSICAL REVIEW LETTERS 23 JULY 1979

Laser Electron Accelerator

T. Tajima and J. M. Dawson
Department of Physics, University of California, Los Angeles, California 90024
(Received 9 March 1979)

An intense electromagnetic pulse can create a weak of plasma oscillations through the action of the nonlinear ponderomotive force. Electrons trapped in the wake can be accelerated to high energy. Existing glass lasers of power density 10^{18}W/cm^2 shone on plasmas of densities 10^{18} cm^{-3} can yield gigaelectronvolts of electron energy per centimeter of acceleration distance. This acceleration mechanism is demonstrated through computer simulation. Applications to accelerators and pulsers are examined.

VOLUME 54, NUMBER 7 PHYSICAL REVIEW LETTERS 18 FEBRUARY 1985

Acceleration of Electrons by the Interaction of a Bunched Electron Beam with a Plasma

Pisin Chen[a]
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305

and

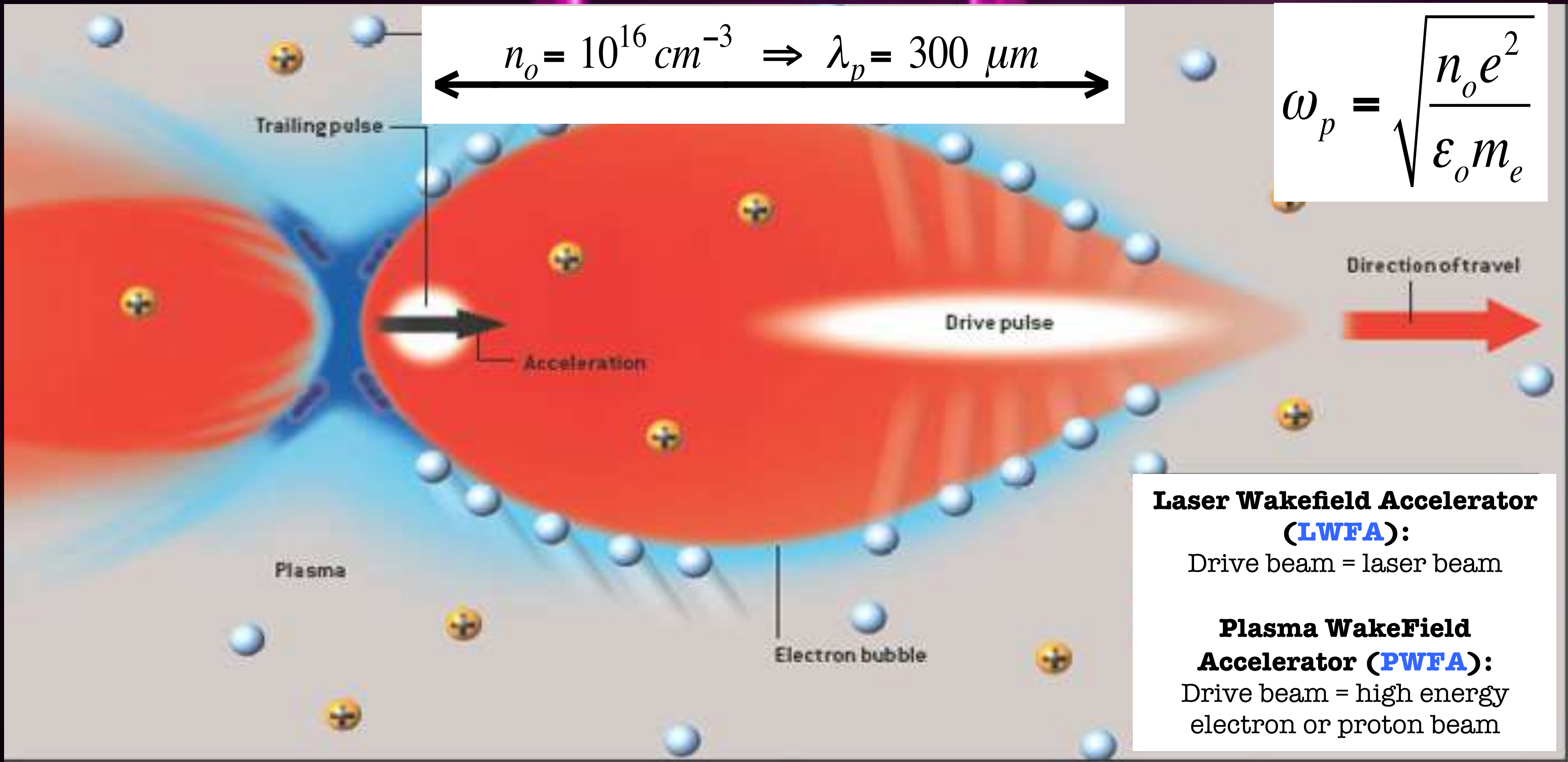
J. M. Dawson, Robert W. Huff, and T. Katsouleas
Department of Physics, University of California, Los Angeles, California 90024
(Received 20 December 1984)

A new scheme for accelerating electrons, employing a bunched relativistic electron beam in a cold plasma, is analyzed. We show that energy gradients can exceed 1 GeV/m and that the driven electrons can be accelerated from $\gamma_0 mc^2$ to $3\gamma_0 mc^2$ before the driving beam slows down enough to degrade the plasma wave. If the driving electrons are removed before they cause the collapse of the plasma wave, energies up to $4\gamma_0^6 mc^2$ are possible. A noncollinear injection scheme is suggested in order that the driving electrons can be removed.

Principle of plasma acceleration

$n_o = 10^{16}\ cm^{-3} \Rightarrow \lambda_p = 300\ \mu m$

$$\omega_p = \sqrt{\frac{n_o e^2}{\varepsilon_o m_e}}$$



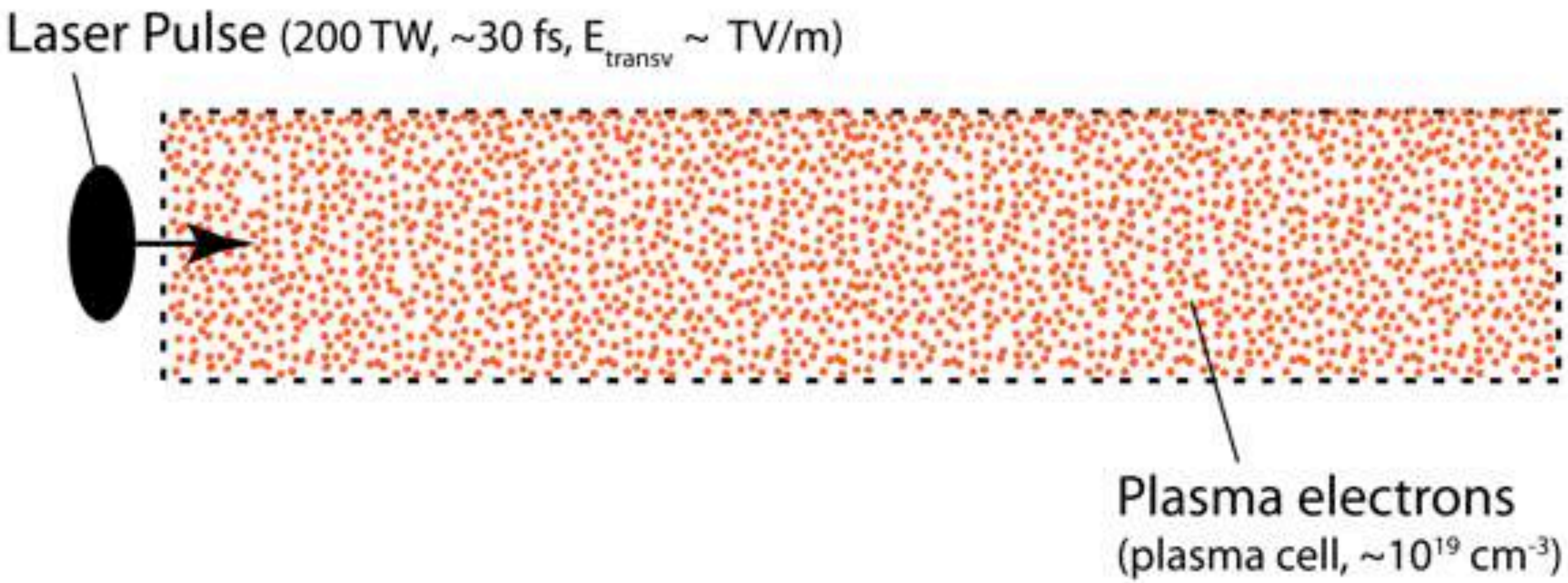
Laser Wakefield Accelerator (LWFA):
Drive beam = laser beam

Plasma WakeField Accelerator (PWFA):
Drive beam = high energy electron or proton beam

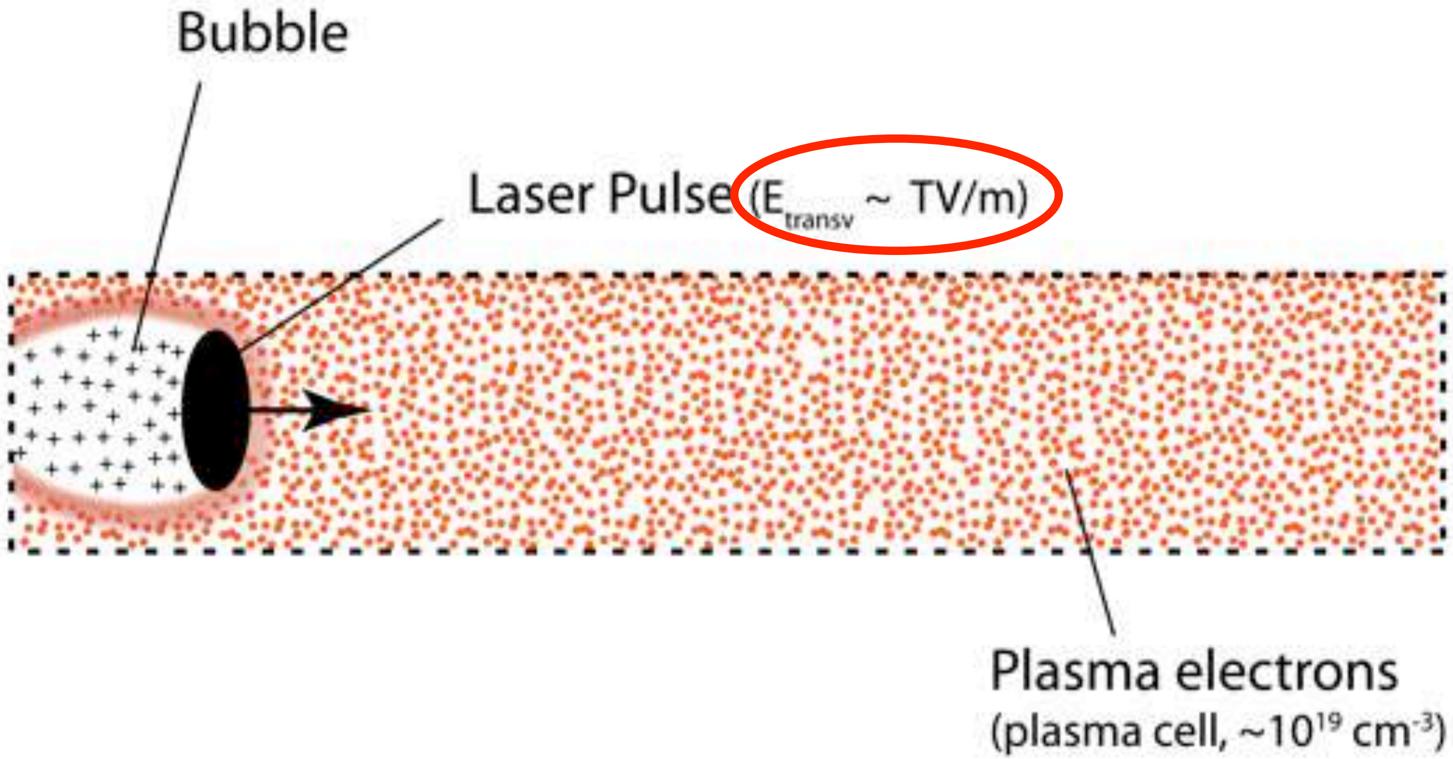
Break-Down Limit?
⇒ Wave-Breaking field:

$$E_{wb} \approx 100\left[GeV/m\right]\sqrt{n_o\left[cm^{-3}\right]}$$

Plasma Wake-Acceleration

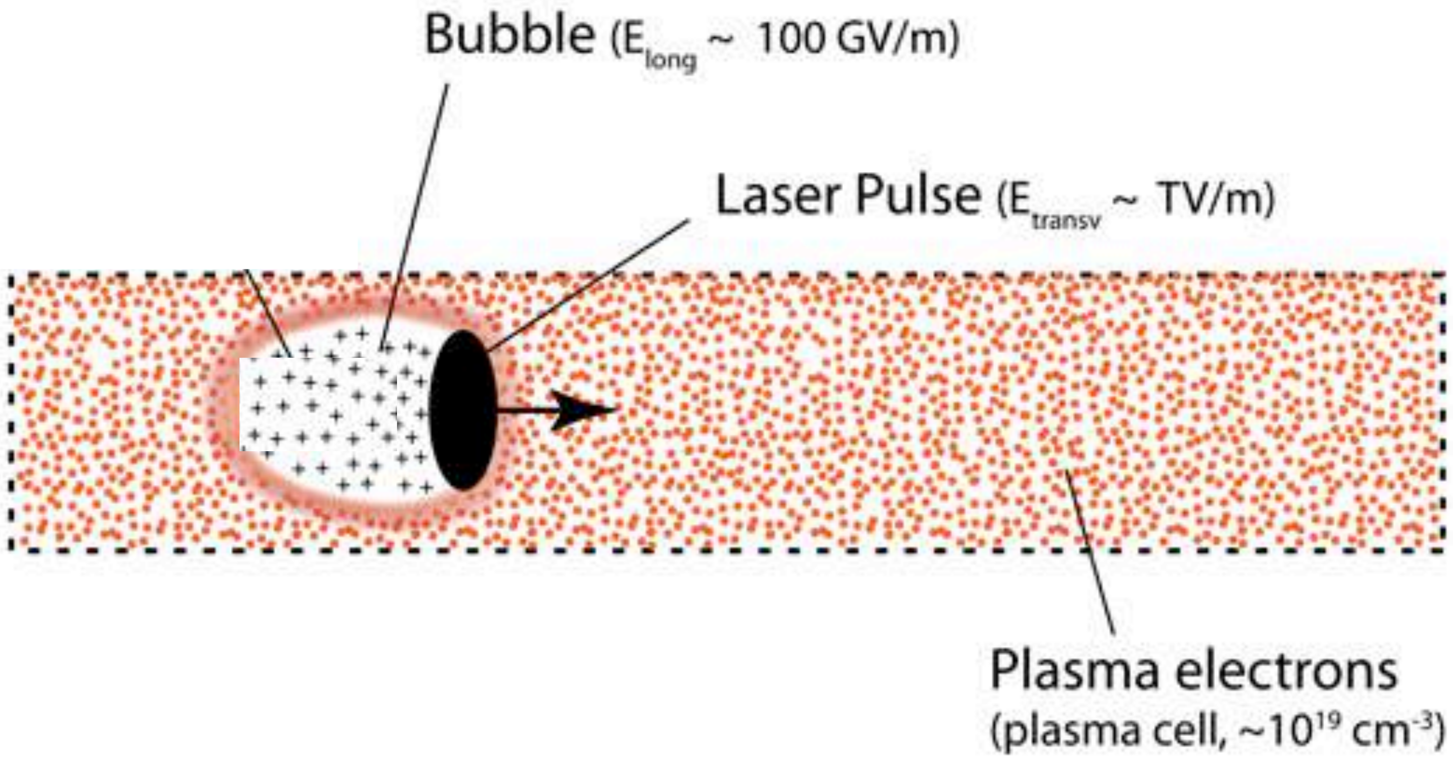


Plasma Wake-Acceleration

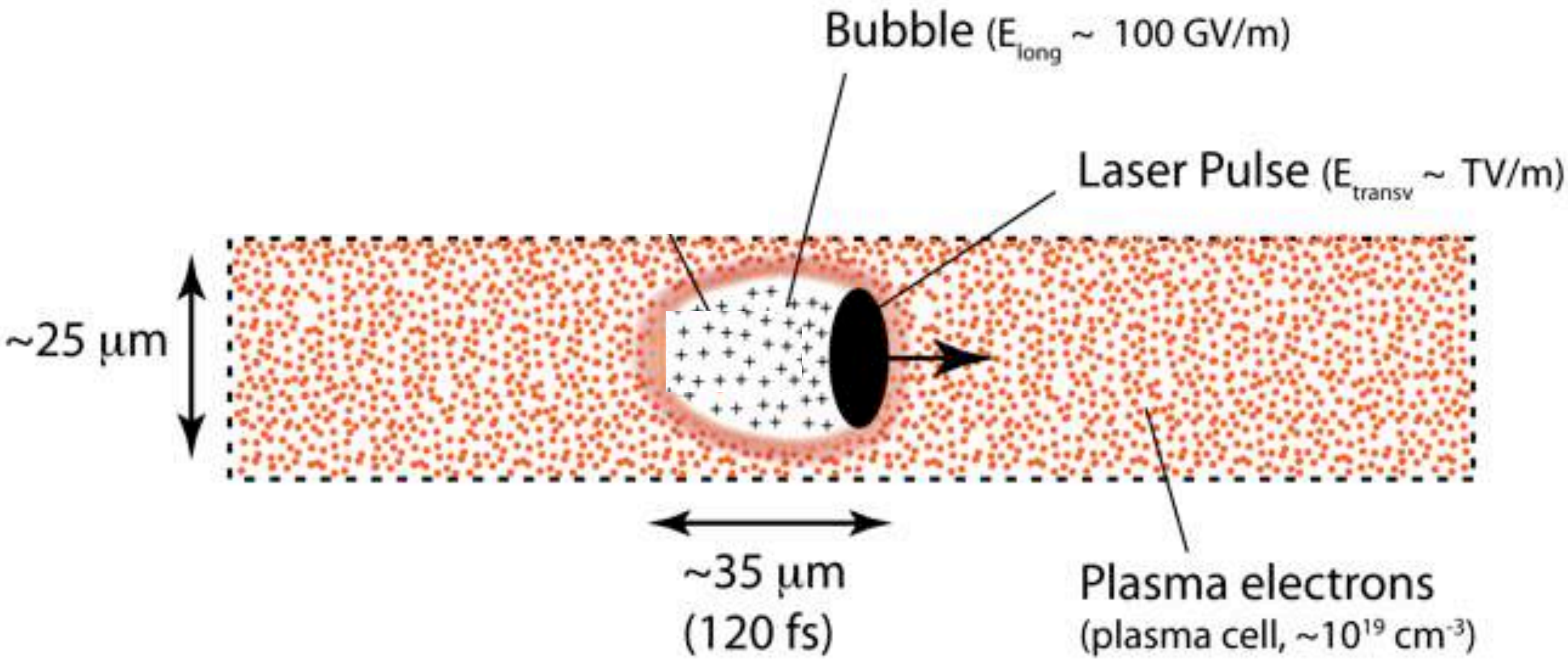


Plasma Wake-Acceleration

Horizon2020

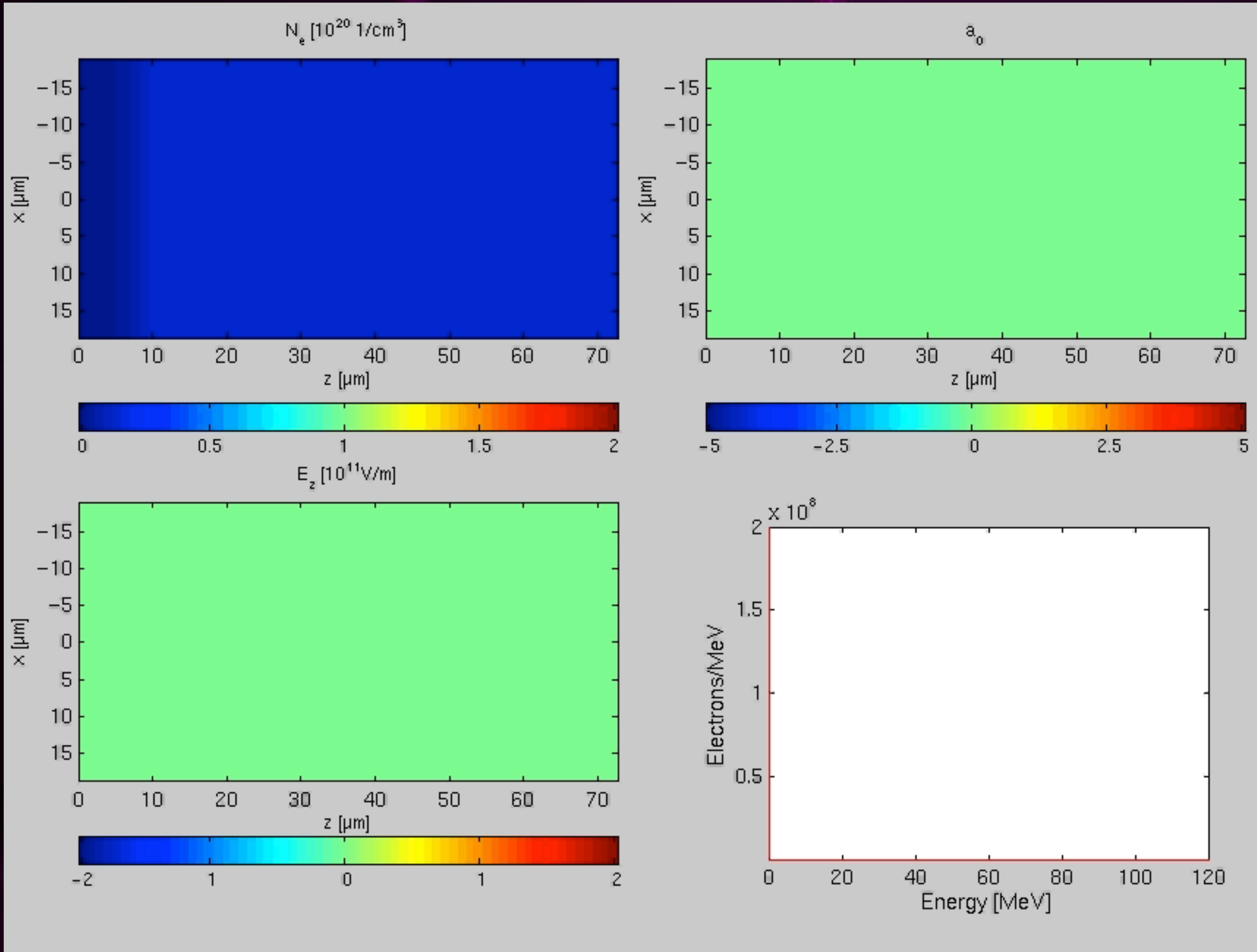


Plasma Wake-Acceleration



This accelerator fits into a human hair!

Diffraction - Self injection - Dephasing – Depletion

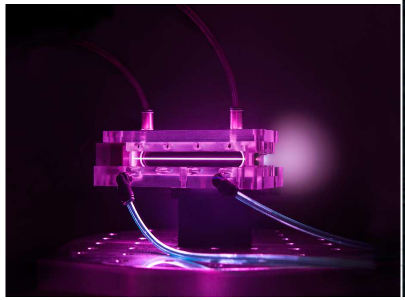


BELLA: BErkeley Lab Laser Accelerator

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

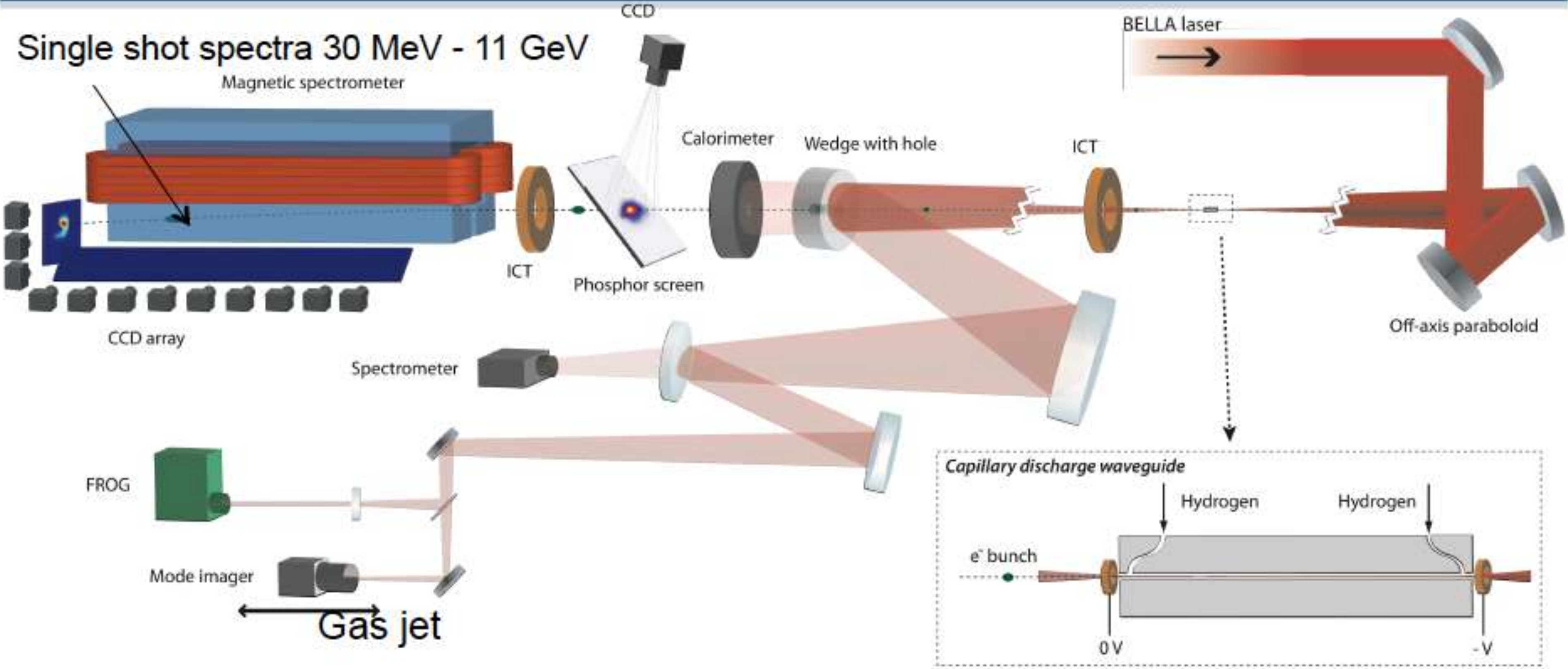
Critical HEP experiments:

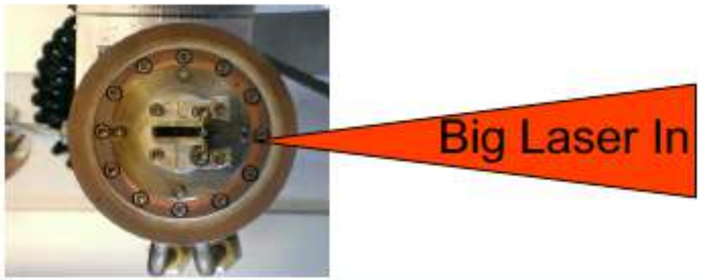
- 10 GeV electron beam from <1 m LPA
- Staging LPAs
- Positron acceleration



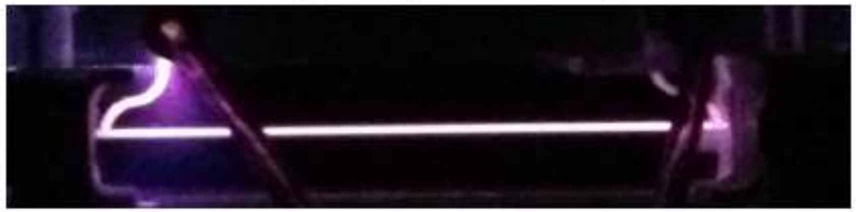
BELLA

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



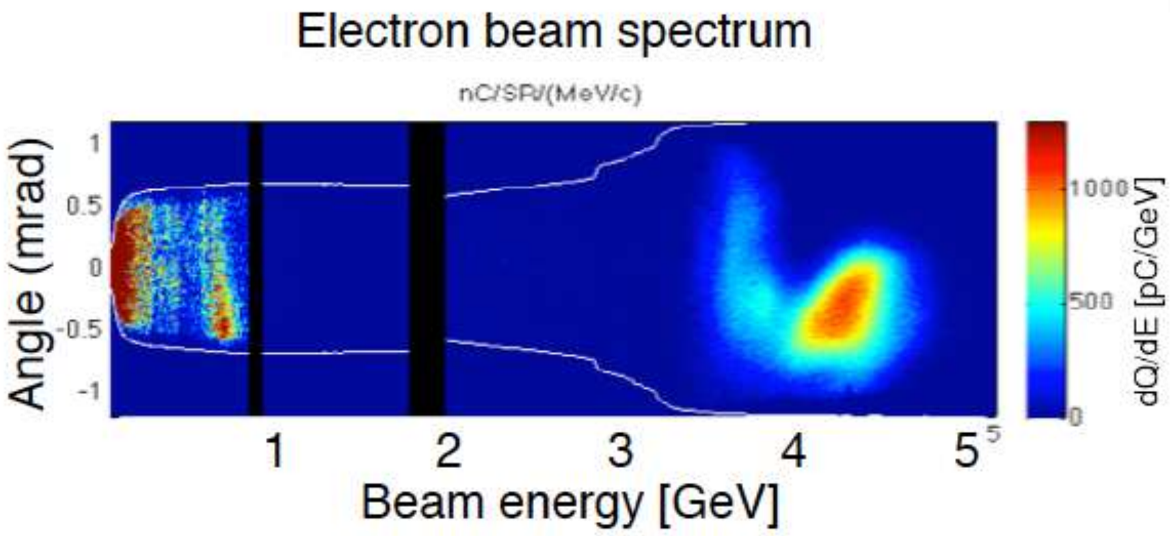


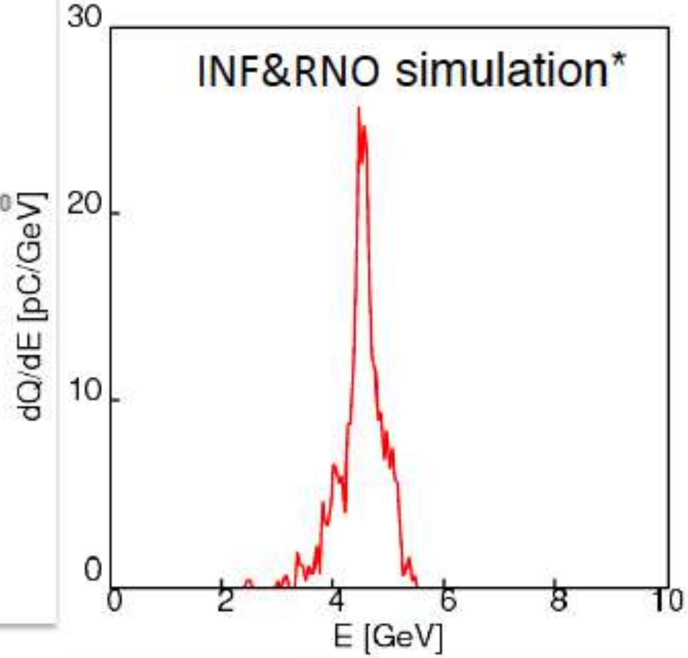
Capillary discharge



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_0~6-7x10^{17} cm^{-3})

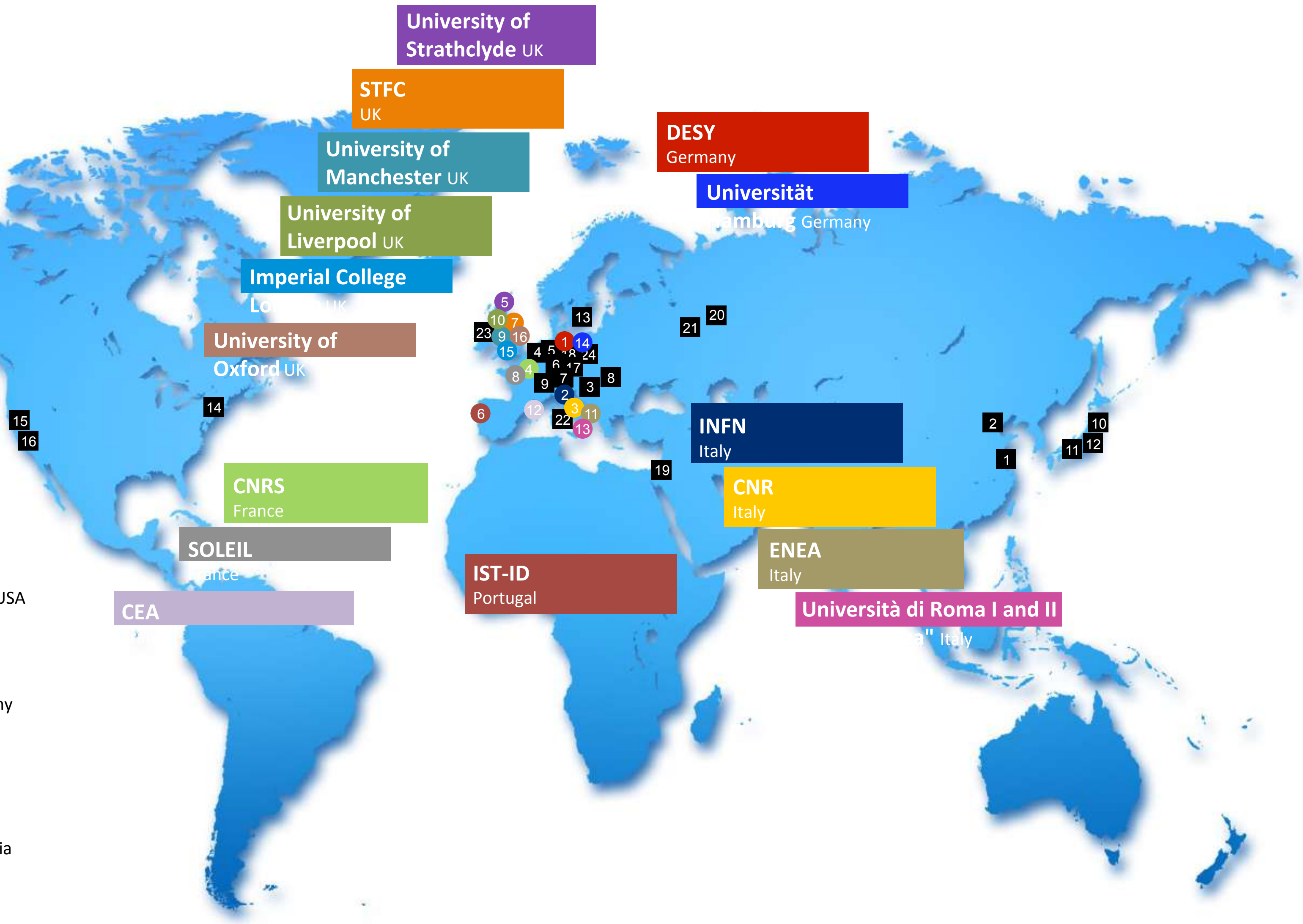
	Exp.	Sim.
Energy	4.25 GeV	4.5 GeV
ΔE/E	5%	3.2%
Charge	~20 pC	23 pC
Divergence	0.3 mrad	0.6 mrad

W.P. Leemans et al.,PRL 2014

Worldwide effort towards high quality plasma beams

Associated Partners
(as of December 2017)

1. **Shanghai Jiao Tong-University**, China
2. **Tsinghua University Beijing**, China
3. **ELI Beamlines**, International
4. **PHLAM, Université de Lille,** France
5. **Helmholtz-Institut Jena**, Germany
6. **HZDR (Helmholtz)**, Germany
7. **LMU München**, Germany
8. **Wigner Fizikai Kutatóközpont**, Hungary
9. **CERN**, International
10. **Kansai Photon Science Institute**, Japan
11. **Osaka University**, Japan
12. **RIKEN SPring-8**, Japan
13. **Lunds Universitet**, Sweden
14. **Stony Brook University & Brookhaven NL**, USA
15. **LBNL**, USA
16. **UCLA**, USA
17. **Karlsruher Institut für Technologie**, Germany
18. **Forschungszentrum Jülich**, Germany
19. **Hebrew University of Jerusalem**, Israel
20. **Institute of Applied Physics**, Russia
21. **Joint Institute for High Temperatures**, Russia
22. **Università di Roma 'Tor Vergata'**, Italy
23. **Queen's University Belfast**, UK
24. **Ferdinand-Braun-Institut**, Germany



EUROPEAN
PLASMA RESEARCH
ACCELERATOR WITH
EXCELLENCE IN
APPLICATIONS

EuPRAXIA

EuPRAXIA Design Study started on Novemebr 2015

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.

http://eupraxia-project.eu

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

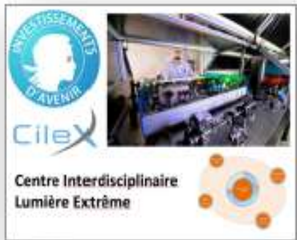
Medical, industrial applications soon

Courtesy R. Assmann

Location of possible sites within EU

EuPRAXIA site studies:

- Design study is site independent
- Five possible sites have been discussed so far
- We invite the suggestions of additional sites



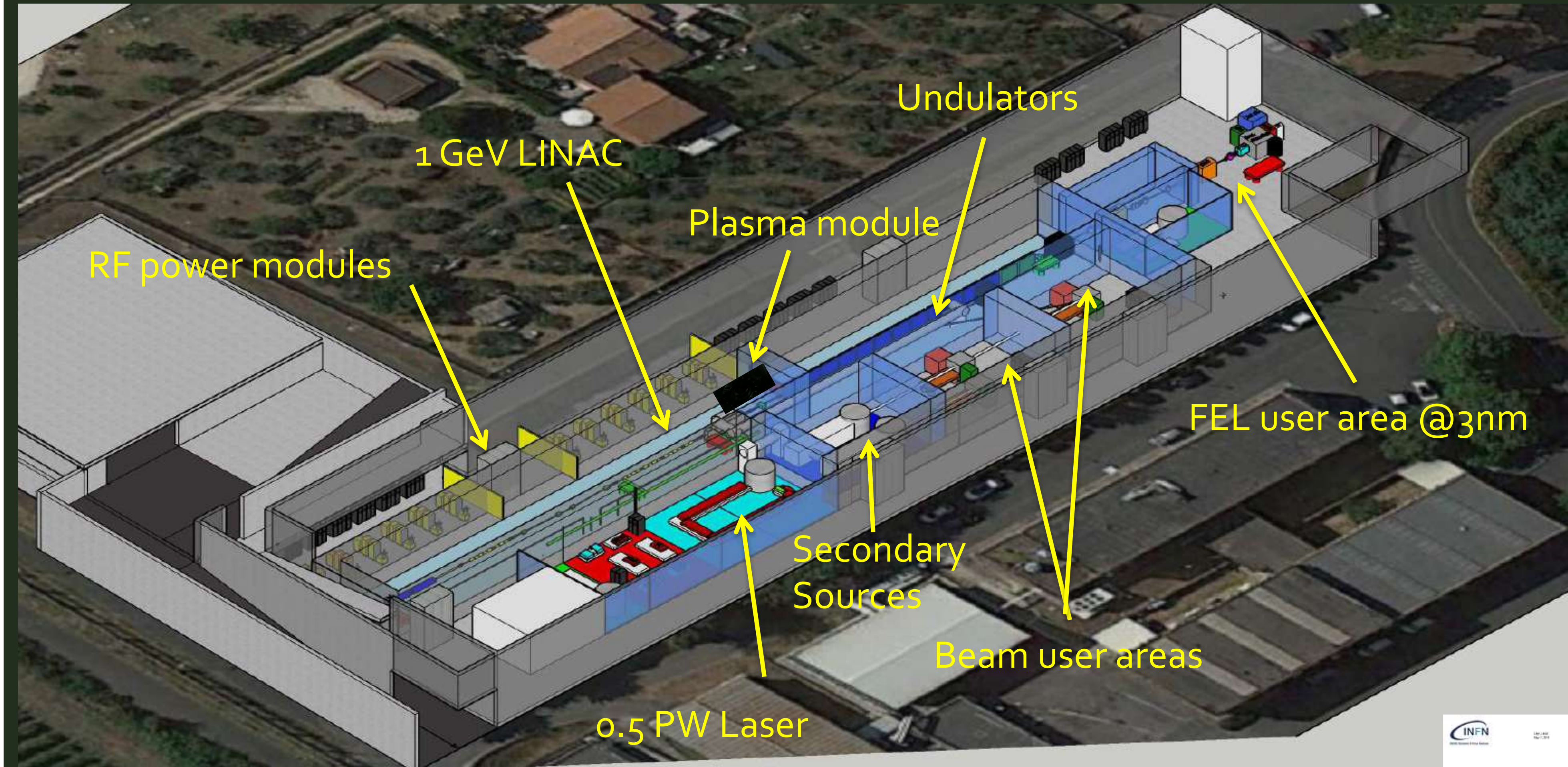
Central Laser Facility
Didcot, United Kingdom

Eli Beamlines
Prague, Czech Republic

EuPRAXIA@SPARC_LAB

Istituto Nazionale di Fisica Nucleare

EuPRAXIA@SPARC_LAB

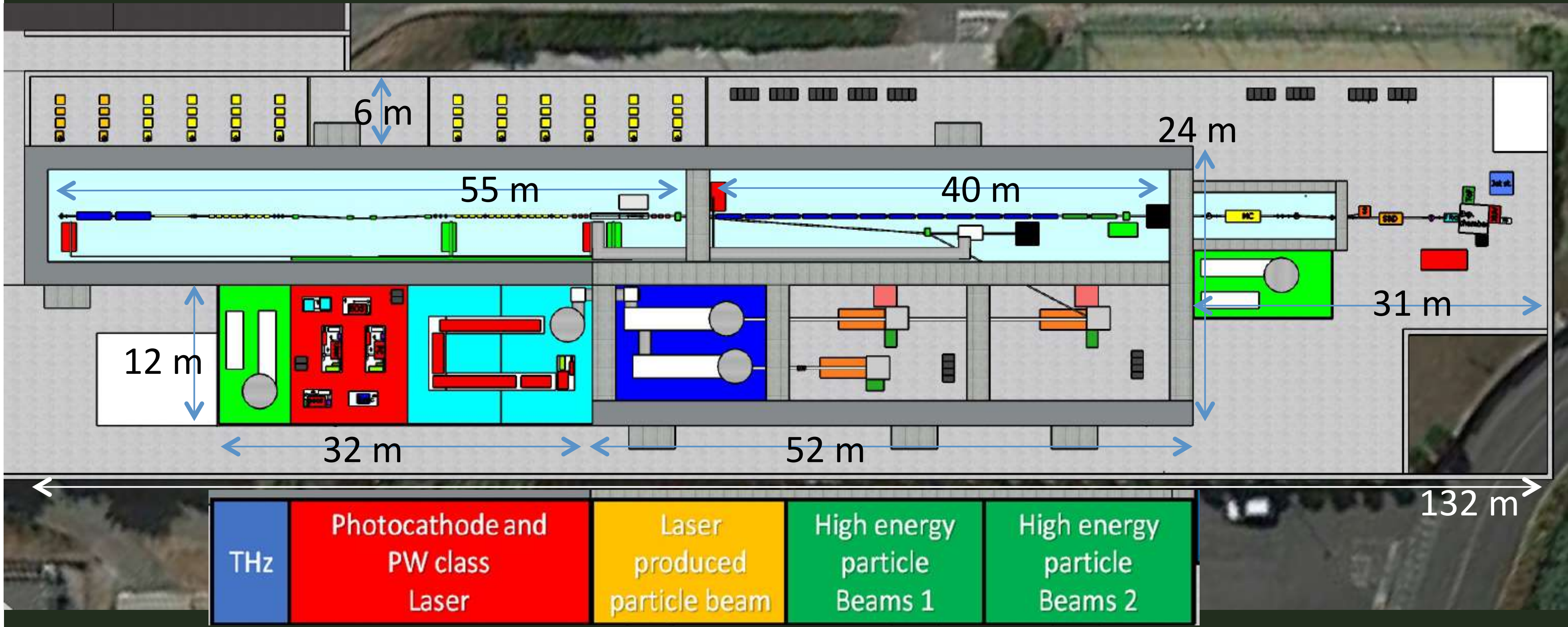


http://www.lnf.infn.it/sis/preprint/pdf/getfile.php?filename=INFN-18-03-LNF.pdf

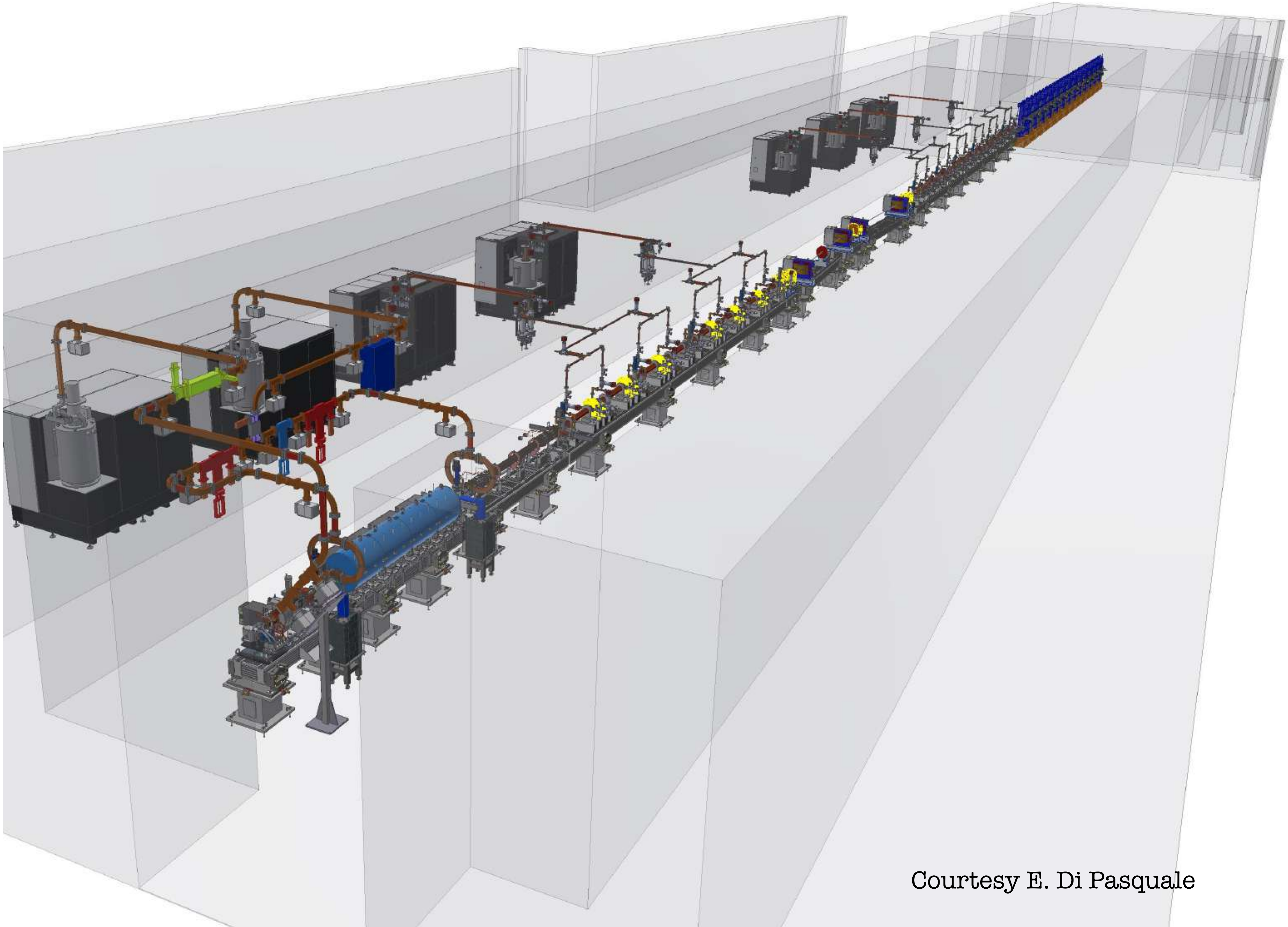
- D. Alesini, M. P. Anania, R. Bedogni, M. Bellaveglia, A. Biagioni, F. Bisesto, E. Brentegani, B. Buonomo, P.L. Campana, G. Campogiani, S. Cantarella, F. Cardelli, M. Castellano, E. Chiadroni, R. Cimino, R. Clementi, M. Croia, A. Curcio, G. Costa, S. Dabagov, M. Diomede, A. Drago, D. Di Giovenale, G. Di Pirro, A. Esposito, M. Ferrario, F. Filippi, O. Frasciello, A. Gallo, A. Ghigo, A. Giribono, S. Guiducci, S. Incremona, F. Iungo, V. Lollo, A. Marcelli, A. Marocchino, V. Martinelli, A. Michelotti, C. Milardi, L. Pellegrino, L. Piersanti, S. Pioli, R. Pompili, R. Ricci, S. Romeo, U. Rotundo, L. Sabbatini, O. Sans Plannell, J. Scifo, B. Spataro, A. Stecchi, A. Stella, V. Shpakov, C. Vaccarezza, A. Vannozzi, A. Variola, F. Villa, M. Zobov.
- **INFN - Laboratori Nazionali di Frascati**
- A. Bacci, F. Broggi, C. Curatolo, I. Debrot, A. R. Rossi, L. Serafini. **INFN - Sezione di Milano**
- D. Cirrincione, A.Vacchi. **INFN - Sezione di Trieste**
- G. A. P. Cirrone, G. Cuttone, V. Scudieri. **INFN - Laboratori Nazionali del Sud**
- M. Artioli, M.Carpanese, F.Ciocci, D.Dattoli, S.Licciardi, F.Nguyen, S. Pagnutti, A.Petralia, E. Sabia. **ENEA – Frascati and Bologna**
- L. Gizzi, L. Labate. **CNR - INO, Pisa**
- R. Corsini, A. Grudiev, N. Catalan Lasheras, A. Latina, D. Schulte, W. Wuensch. **CERN, Geneva**
- C. Andreani, A. Cianchi, G. Festa,V. Minicozzi, S. Morante, R. Senesi, F. Stellato. **Universita' degli Studi di Roma Tor Vergata and Sezione INFN**
- V. Petrillo, M. Rossetti. **Universita' degli Studi di Milano and Sezione INFN**
- G. Castorina, L. Ficcadenti, S. Lupi, M. Marongiu, F. Mira, A. Mostacci. **Universita' degli Studi di Roma Sapienza and Sezione INFN**
- S. Bartocci, C. Cannaos, M. Faiferri, R. Manca, M. Marini, C. Mastino, D. Polese, F. Pusceddu, E. Turco. **Università degli Studi di Sassari, Dip. di Architettura, Design e Urbanistica ad Alghero**
- M. Coreno, G. D'Auria, S. Di Mitri, L. Giannessi, C. Masciovecchio. **ELETTRA Sincrotrone Trieste**
- A. Ricci. **RICMASS, Rome International Center for Materials Science Superstripes**

✓ Candidate LNF to host EuPRAXIA (1-5 GeV)

- FEL user facility (1 GeV – 3nm)
- Advanced Accelerator Test facility (LC) + CERN

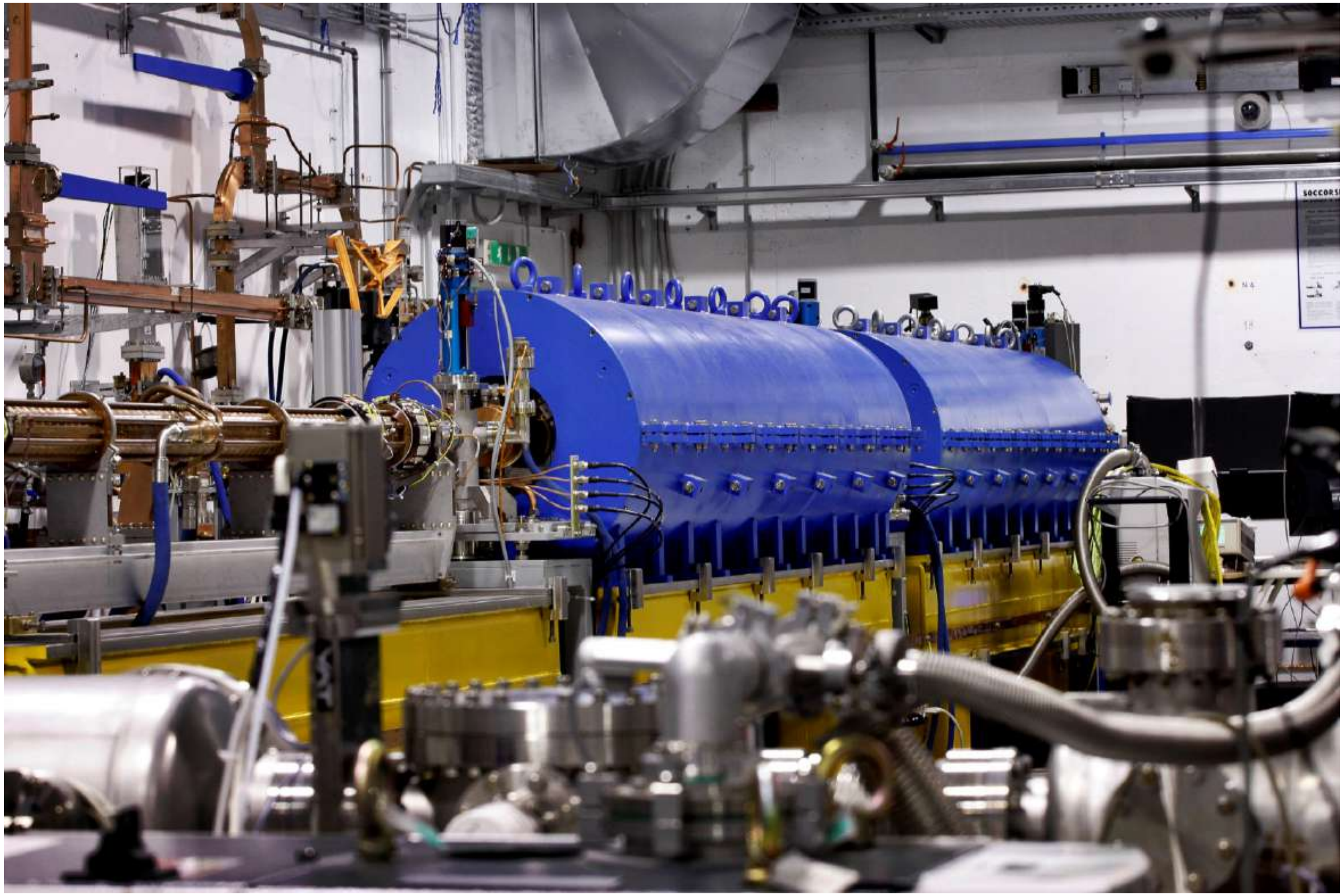


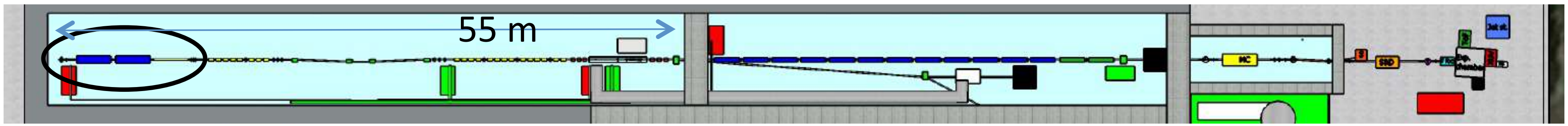
- 500 MeV by RF Linac + 500 MeV by Plasma (LWFA or PWFA)
- 1 GeV by X-band RF Linac only
- Final goal compact 5 GeV accelerator



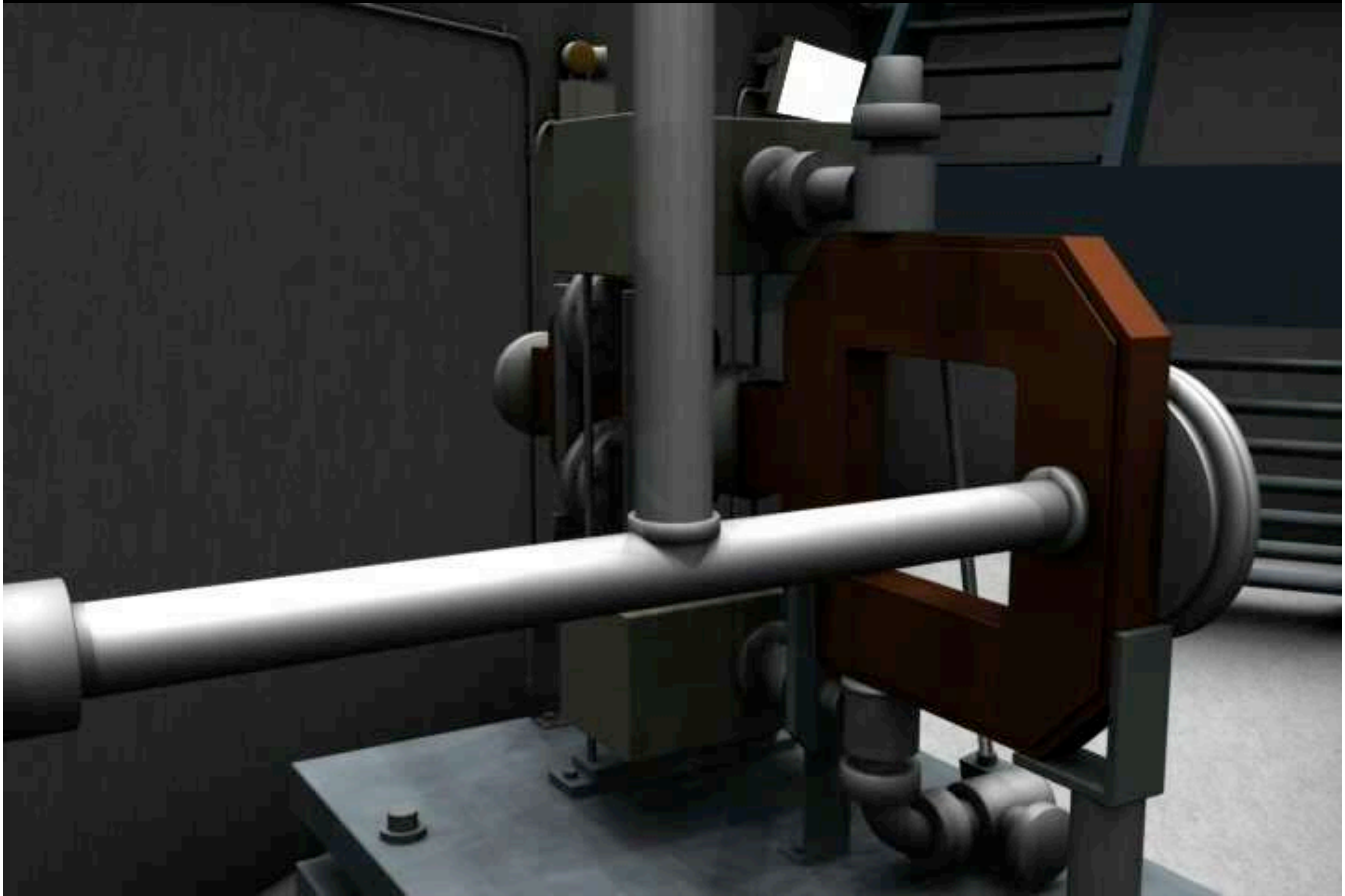
Courtesy E. Di Pasquale

SPARC_LAB HB photo- injector

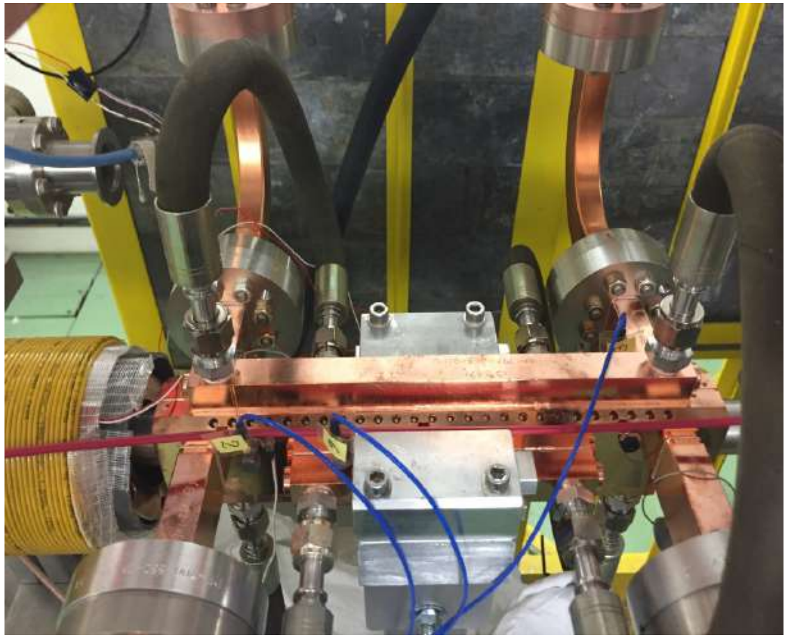


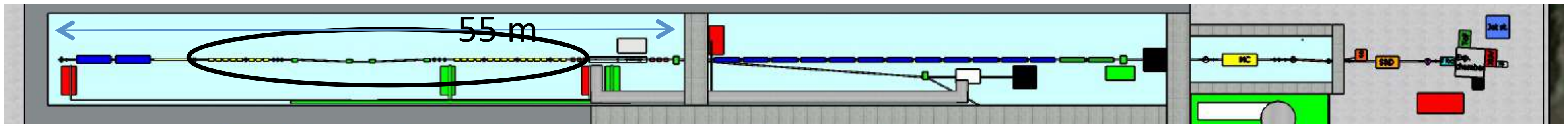


Electron source and acceleration

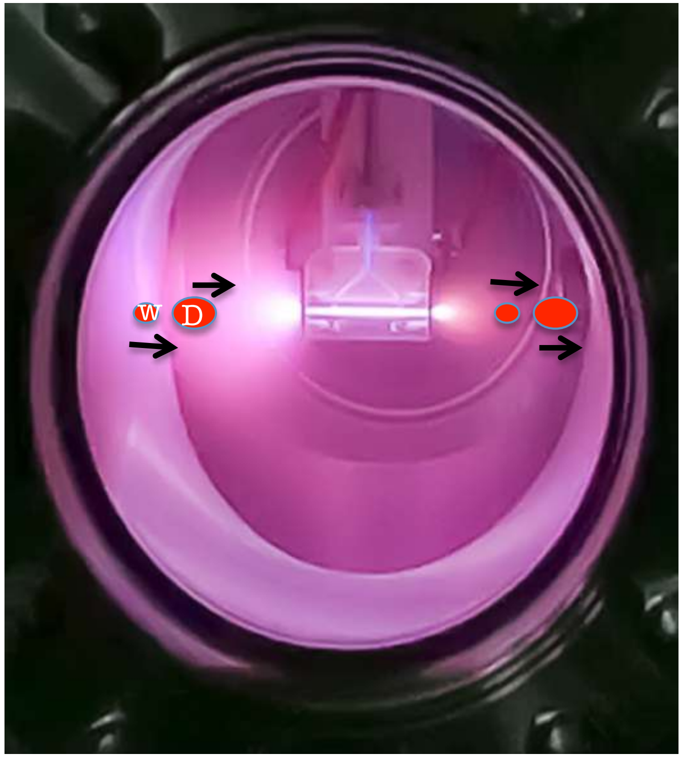


X-band Linac

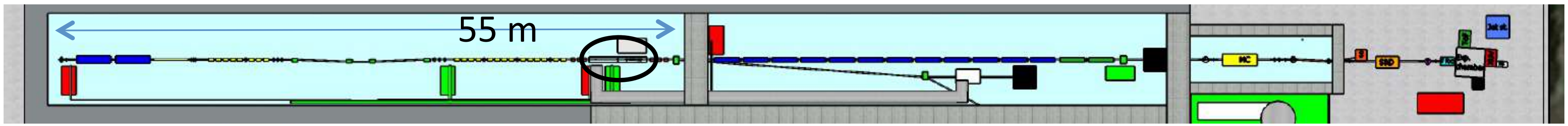




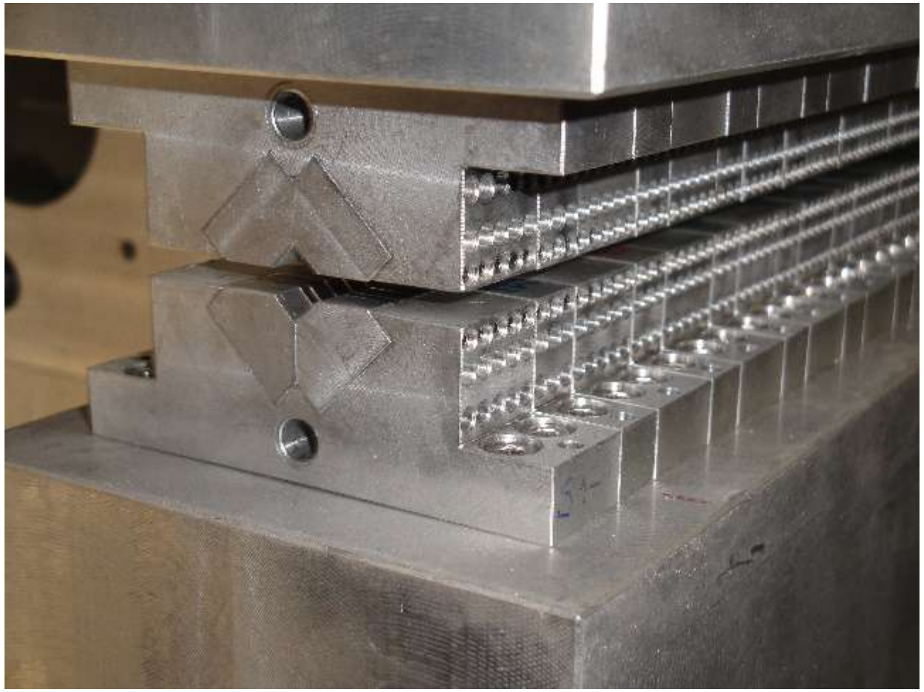
Plasma WakeField Acceleration



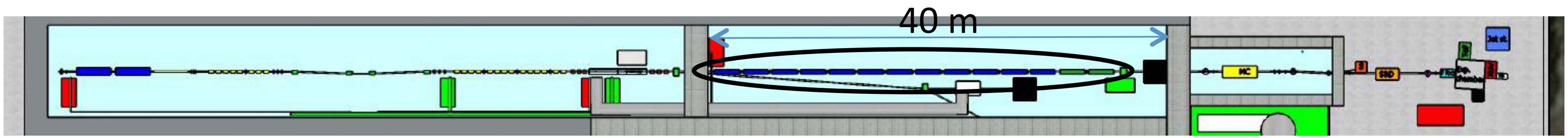
Capillary discharge at SPARC_LAB



Undulators

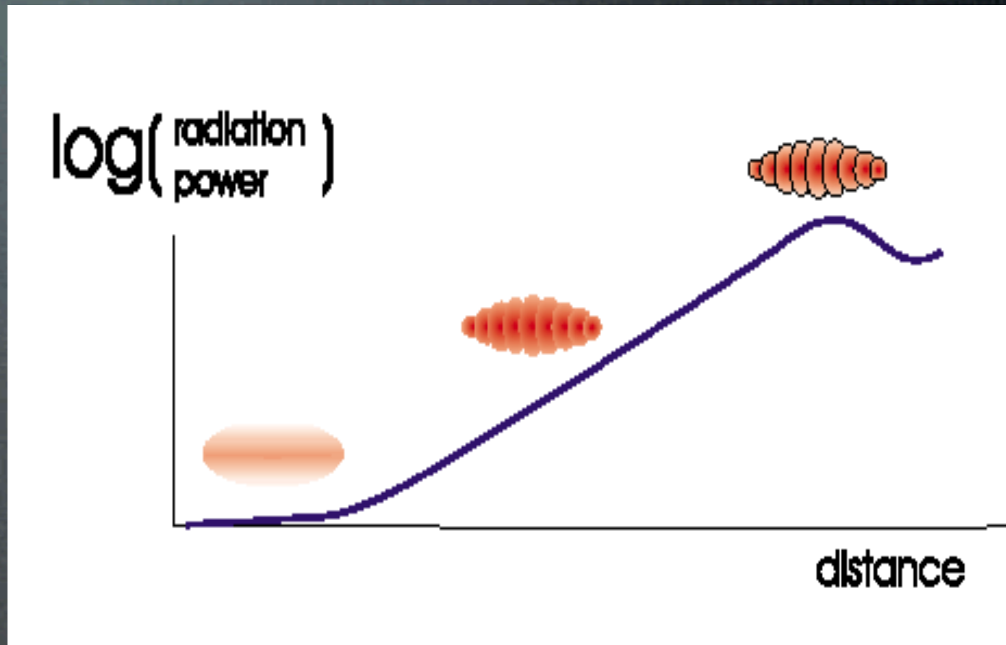


KYMA Δ udulator at SPARC_LAB: λ=1.4 cm, K1



Long undulators chain

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

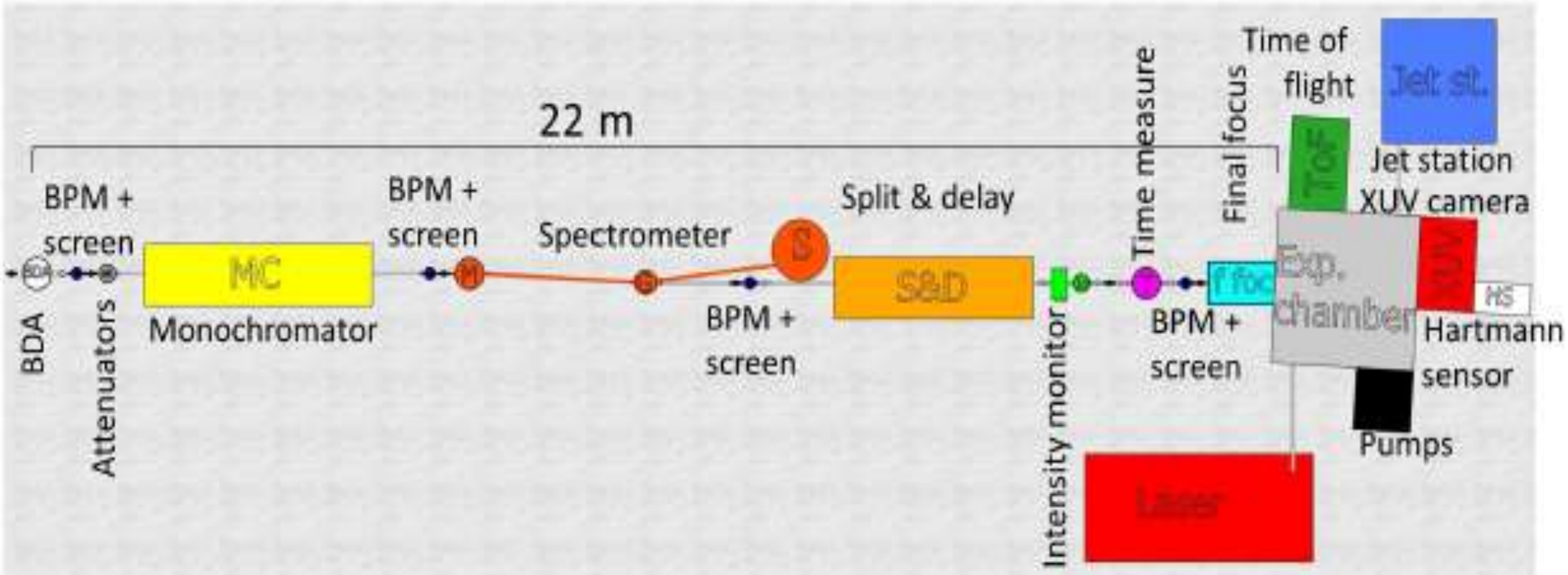


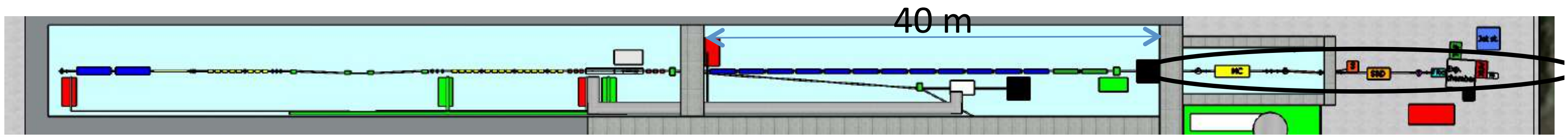
$$\lambda_{rad} \approx \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2} + \gamma^2\vartheta^2\right)$$

(Tunability - Harmonics)

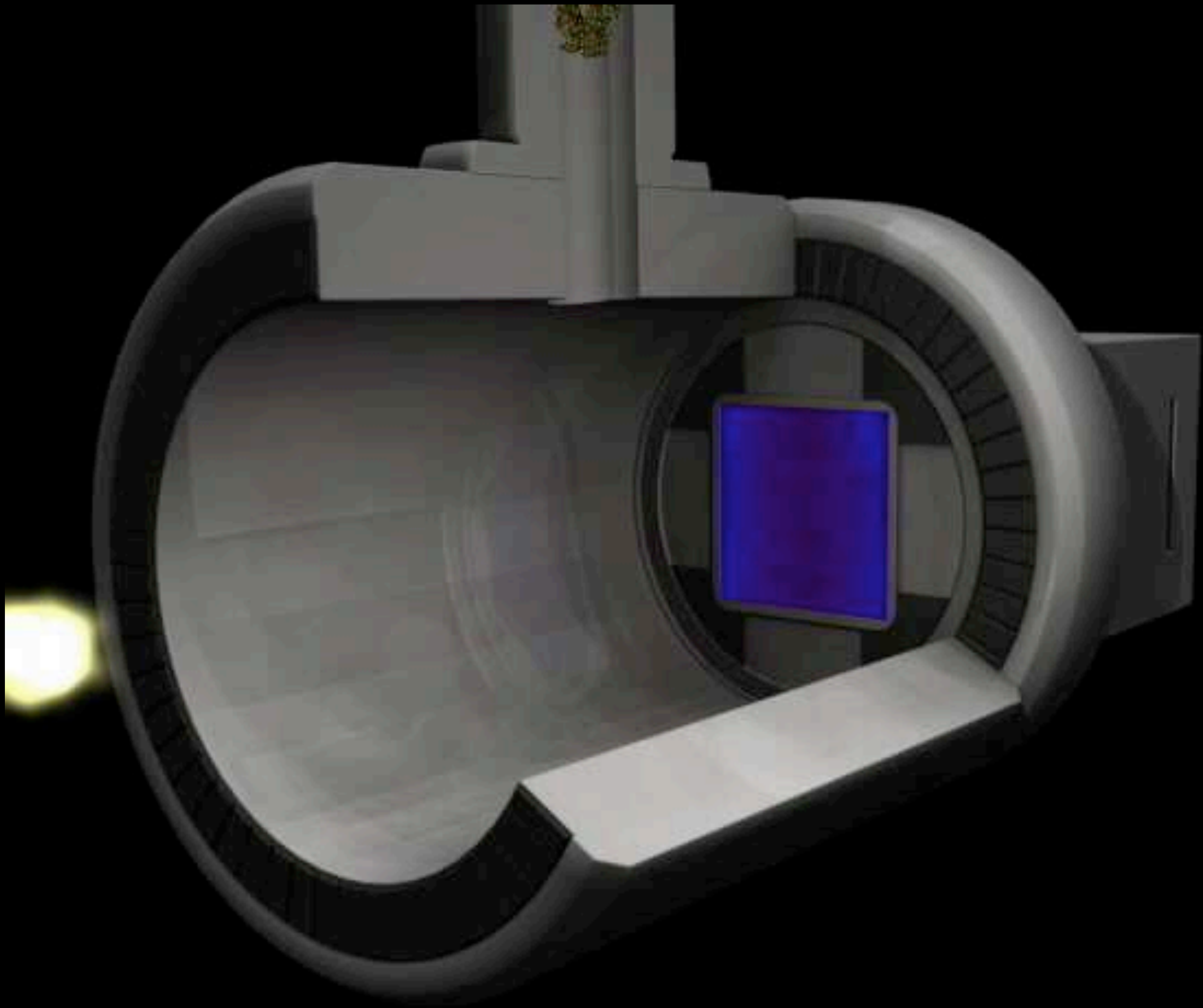
Beam separation

Photon beam line

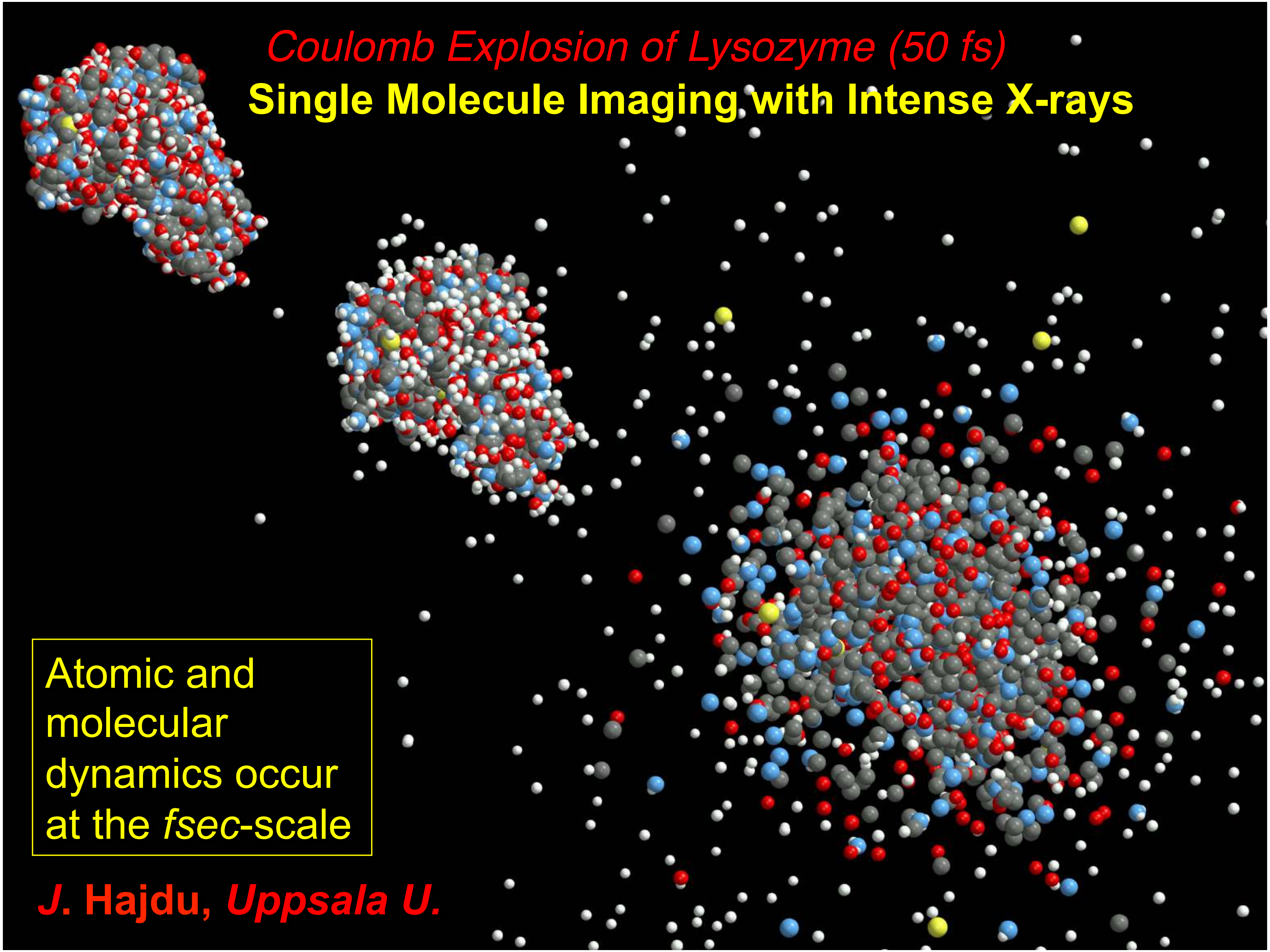




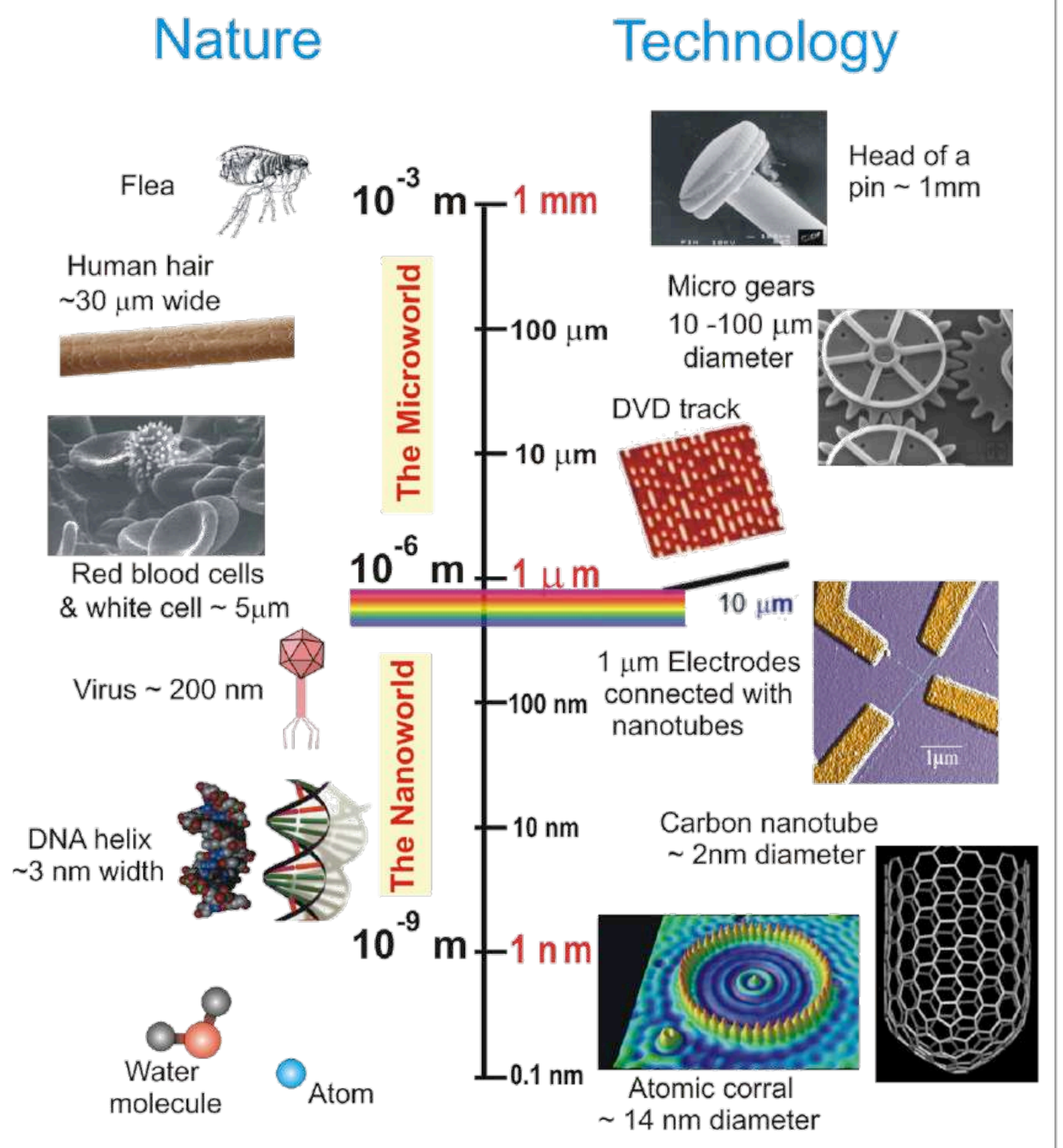
Experimental hall (Single Protein Imaging)



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.

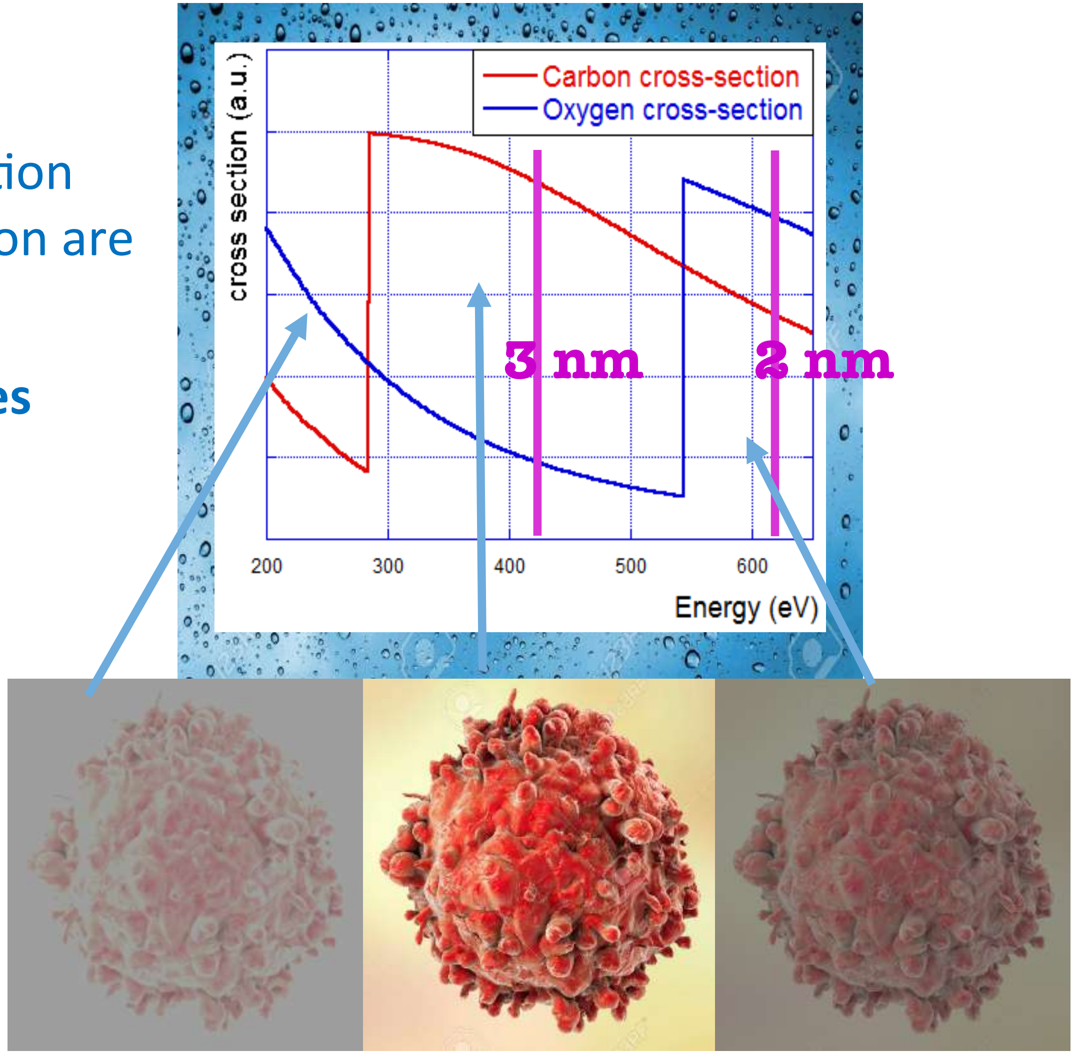
Ultra-Small



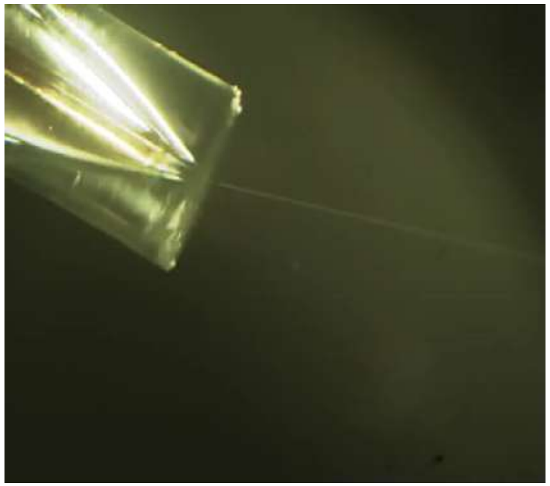
Nature
Technology
Flea
10^{-3} m
1 mm
Head of a pin ~ 1mm
Human hair ~30 µm wide
Micro gears 10 -100 µm diameter
100 µm
The Microworld
DVD track
10 µm
Red blood cells & white cell ~ 5µm
10^{-6} m
1 µm
10 µm
1 µm Electrodes connected with nanotubes
Virus ~ 200 nm
100 nm
The Nanoworld
1µm
DNA helix ~3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

Water Window Coherent Imaging

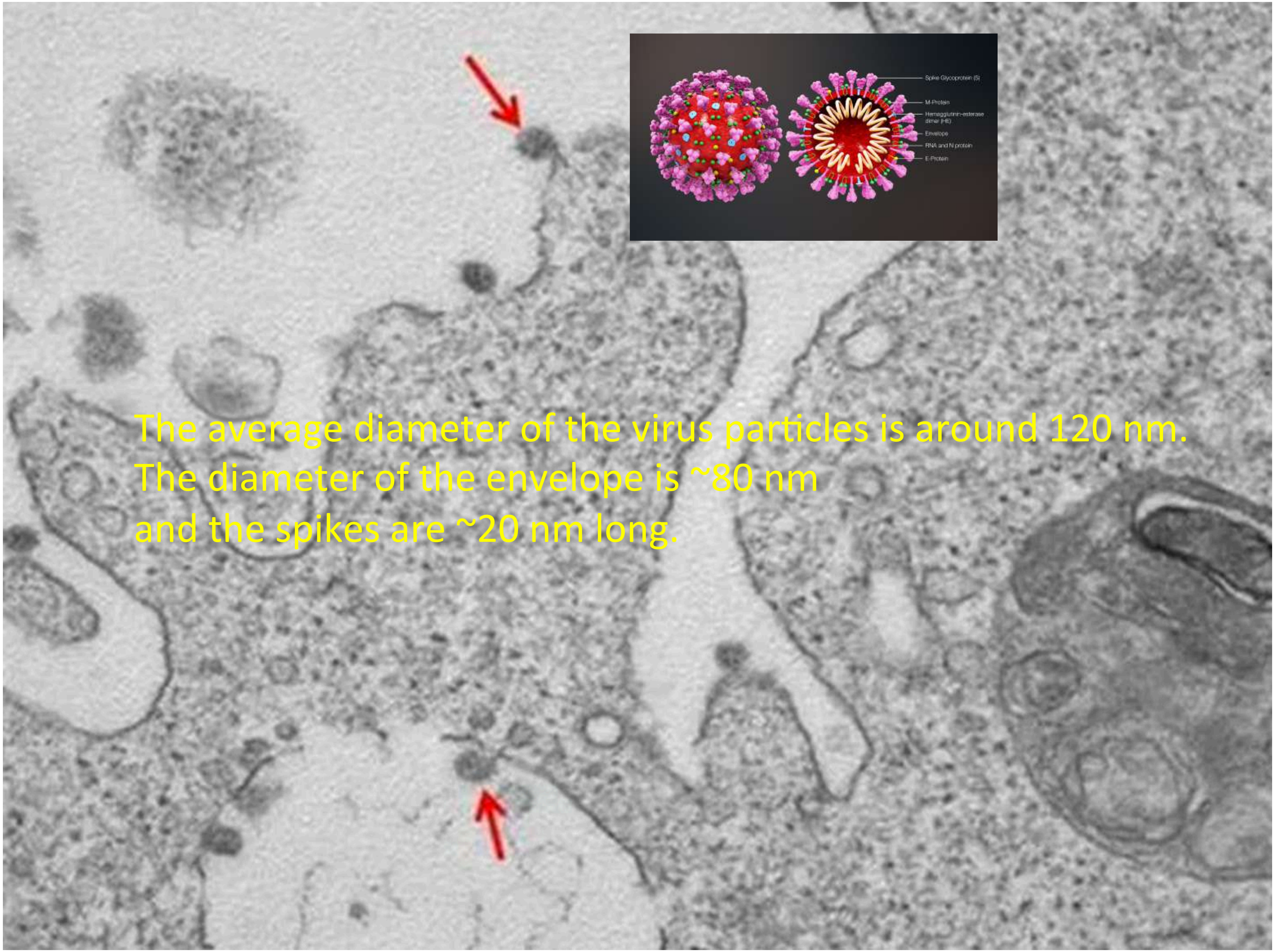
Energy region between Oxygen and
Carbon K-edge 2.34 nm – 4.4 nm
(530 eV -280 eV)
Water is almost transparent to radiation
in this range while nitrogen and carbon are
absorbing (and scattering)



Coherent Imaging of biological samples
protein clusters, VIRUSES and cells
living in their native state
Possibility to study dynamics
~10^{11} photons/pulse needed



Courtesy F. Stellato, UniToV


Spike Glycoprotein (S)
M-Protein
Hemagglutinin-esterase dimer (HE)
Envelope
RNA and N protein
E-Protein
The average diameter of the virus particles is around 120 nm.
The diameter of the envelope is ~80 nm
and the spikes are ~20 nm long.

Light Source research on SARS-CoV-2

https://lightsources.org/2020/04/03/lightsource-research-and-sars-cov-2/

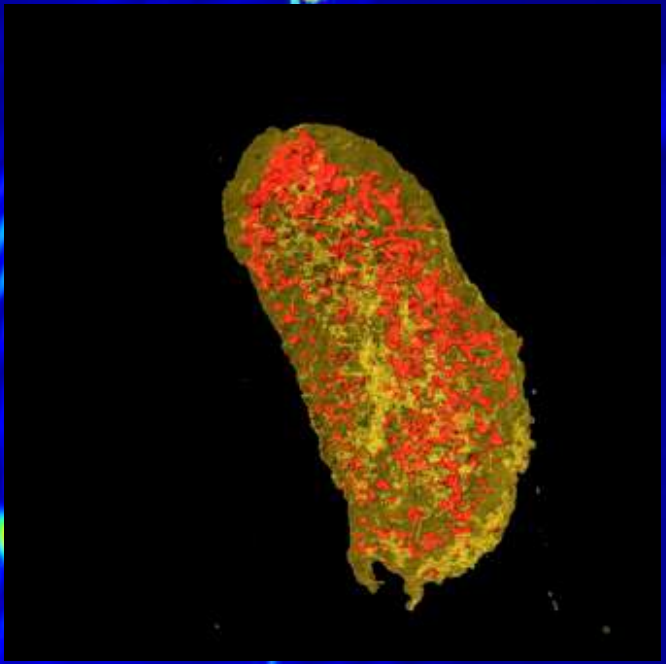
https://www.diamond.ac.uk/covid-19.html

The crystal structure of COVID-19 main protease in complex with an inhibitor N3

Electron density at the active site of the SARS-CoV-2 protease, revealing a fragment bound
https://lightsources.org/2020/03/14/lightsource-research-and-sars-cov-2/

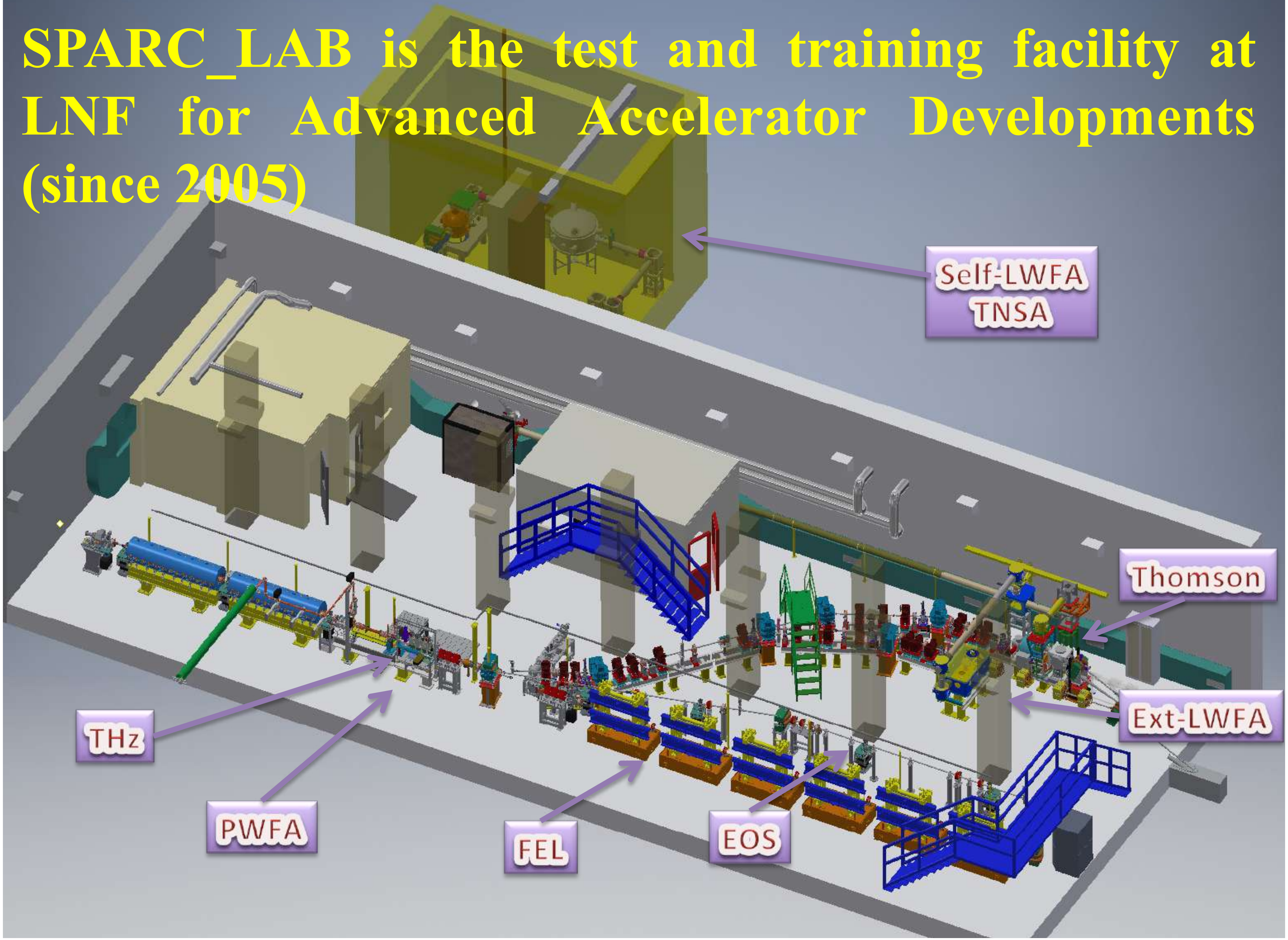
Cell Membrane Proteins Imaged in 3-D

Using lanthanide-binding tags is possible to image proteins at the level of a cell membrane, opening new doors for studies on health and medicine

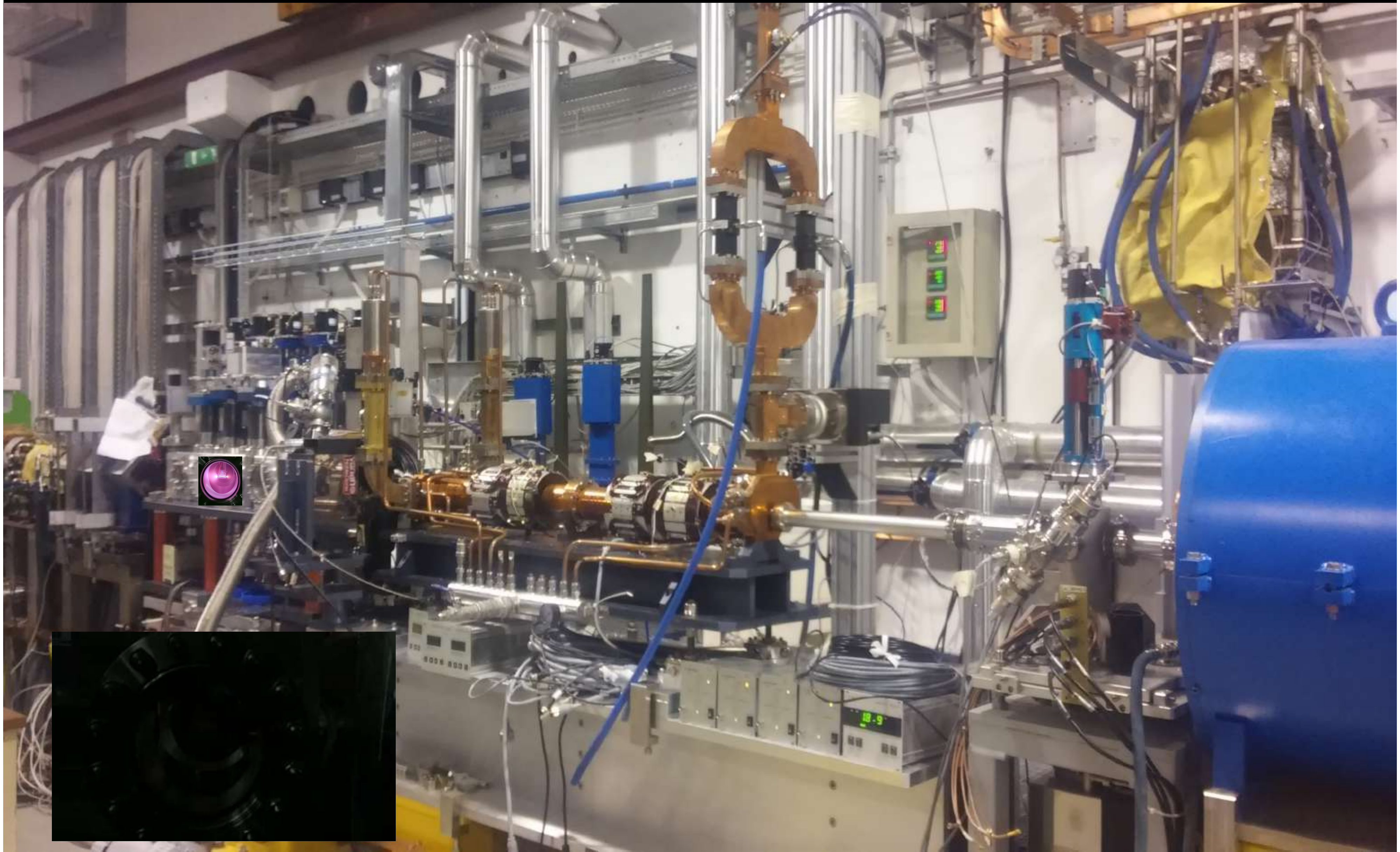


Ultrabright x-rays revealed the concentration of erbium and zinc in a single E.coli cell expressing a lanthanide-binding tag and incubated with erbium.

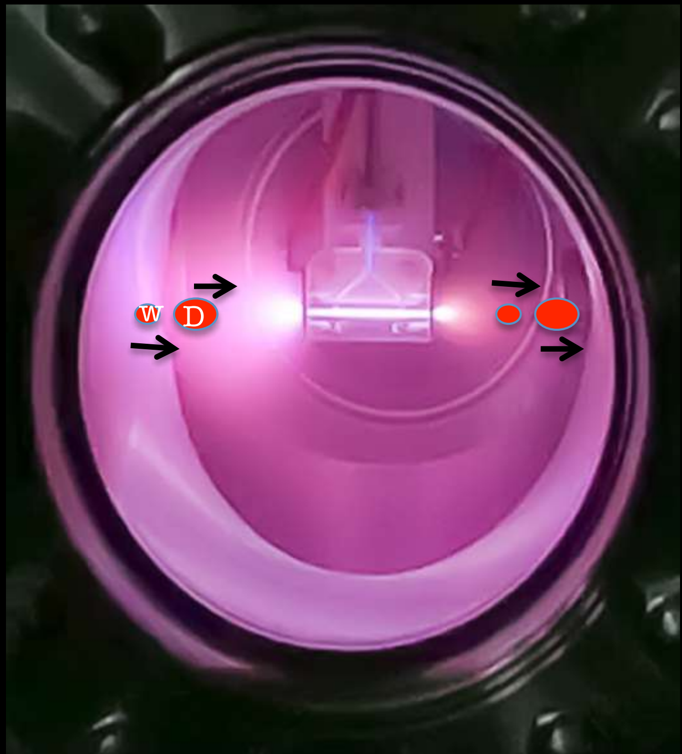
SPARC_LAB is the test and training facility at LNF for Advanced Accelerator Developments (since 2005)



PWFA vacuum chamber at SPARC_LAB



External Injection



$$\Delta T_w = \left(R - \frac{q}{Q}\right)\left|\Delta T_D\right|$$

$$R \cong 2$$

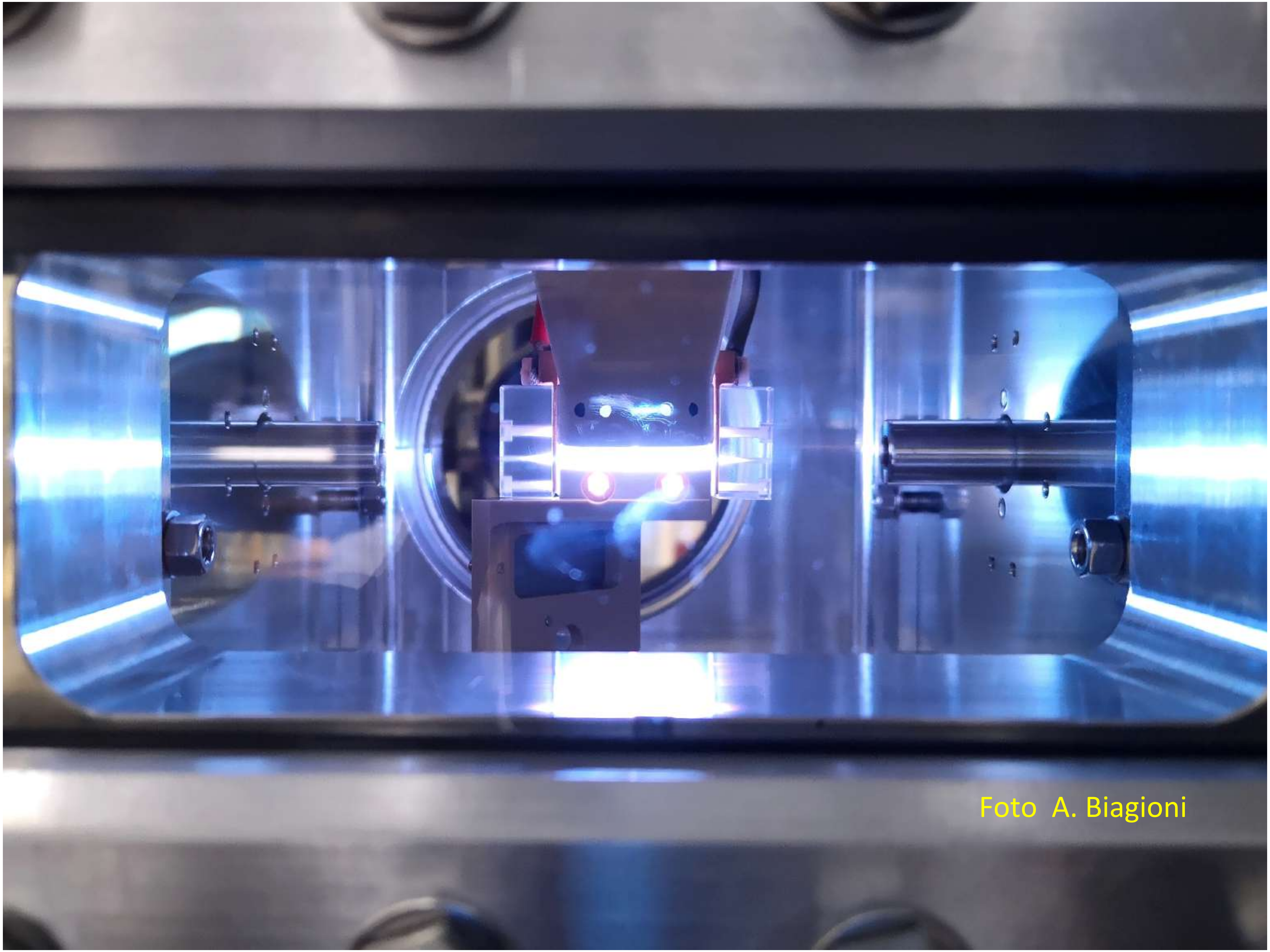


Foto A. Biagioni

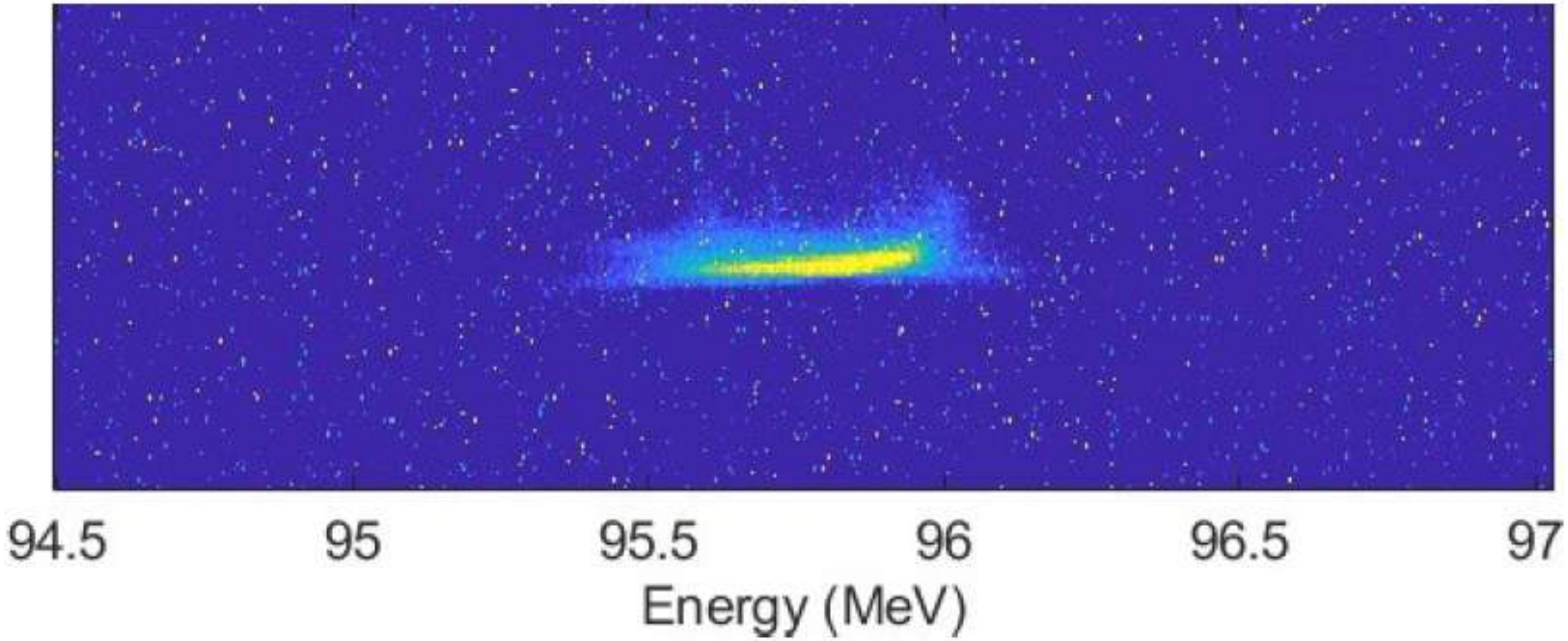


Figura 2: fascio witness accelerato a SPARC_LAB. Immagine acquisita sulla targhetta a valle dello spettrometro magnetico. L'energia iniziale (senza plasma) è di 89.8 MeV. Accendendo il plasma, il witness guadagna 6 MeV lungo i 3 cm del capillare, arrivando a 95.8 MeV.

http://w3.lnf.infn.it/primi-elettroni-accelerati-con-plasma-a-sparc_lab/


Grazie per l'attenzione