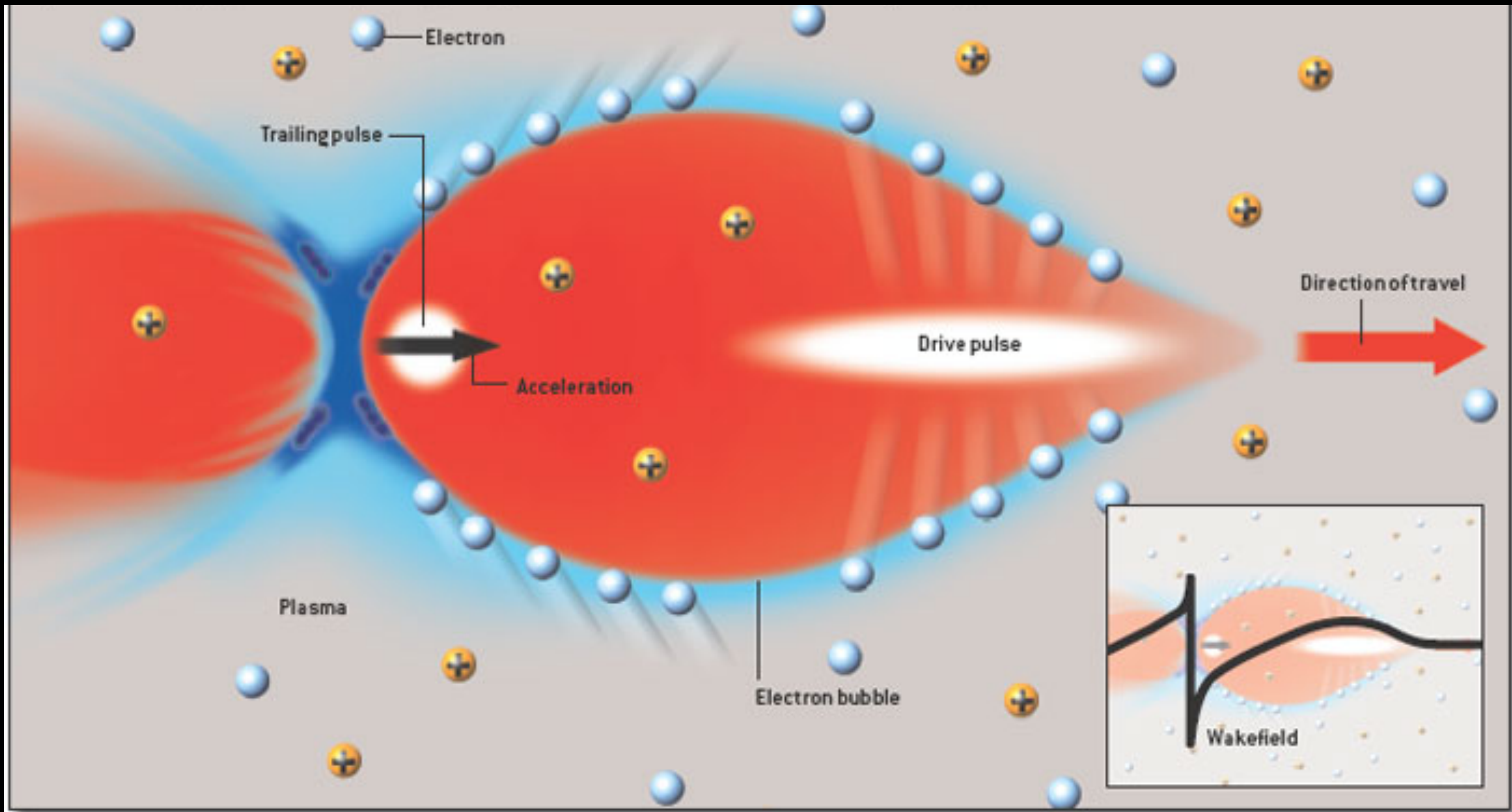
From SPARC_LAB to EuPRAXIA

Massimo.Ferrario@LNF.INFN.IT

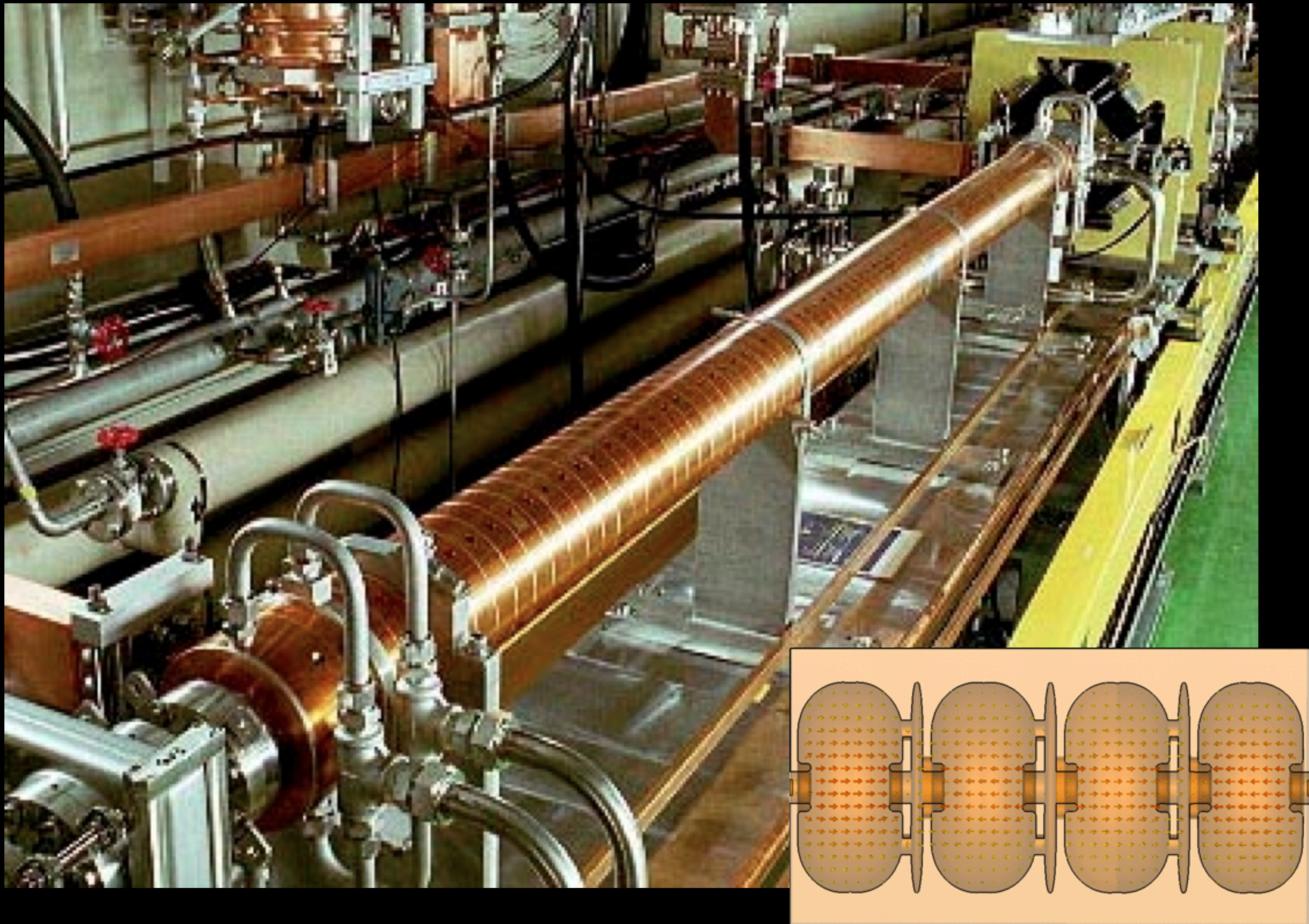
Firenze 20 February 2018

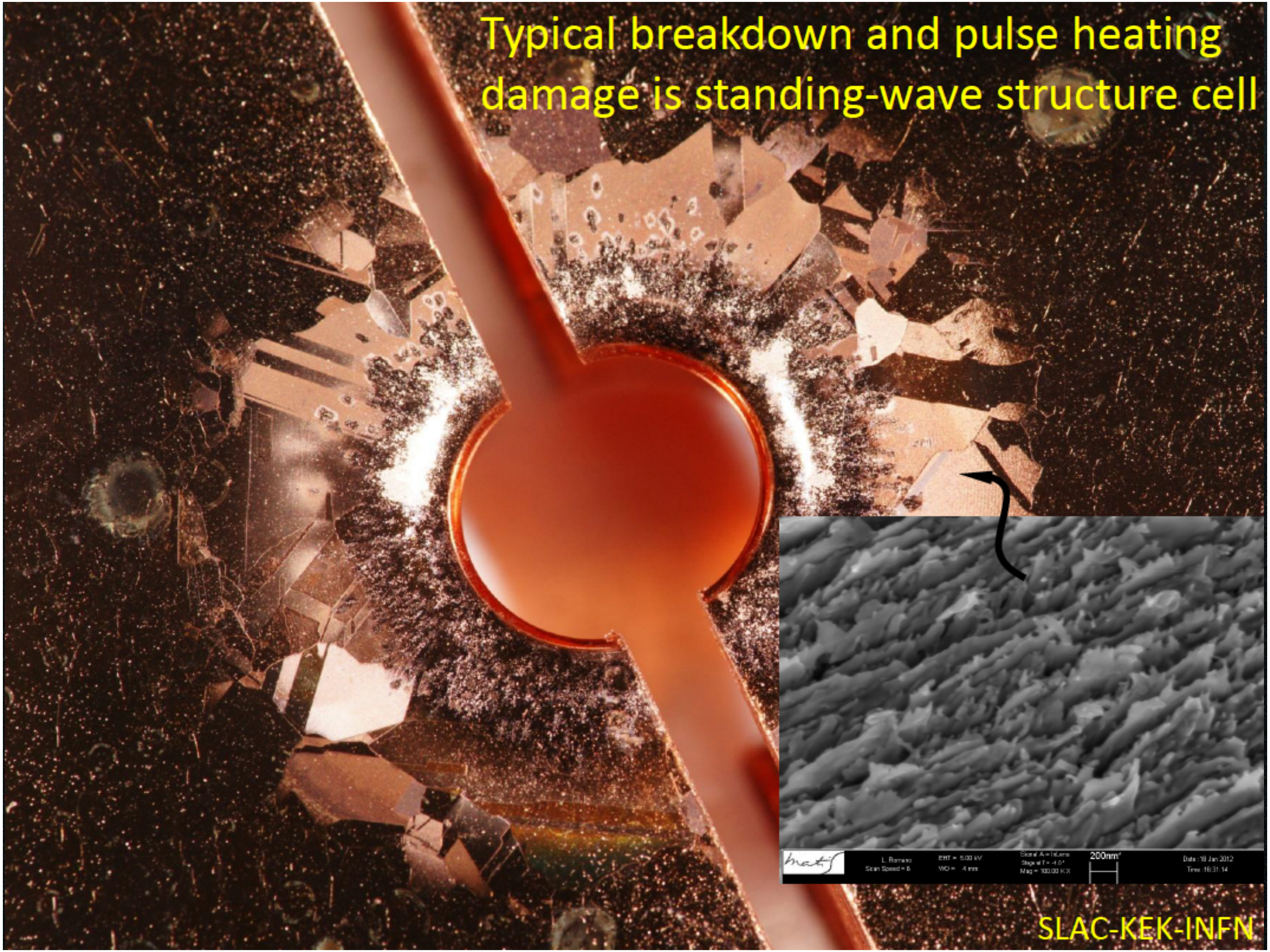


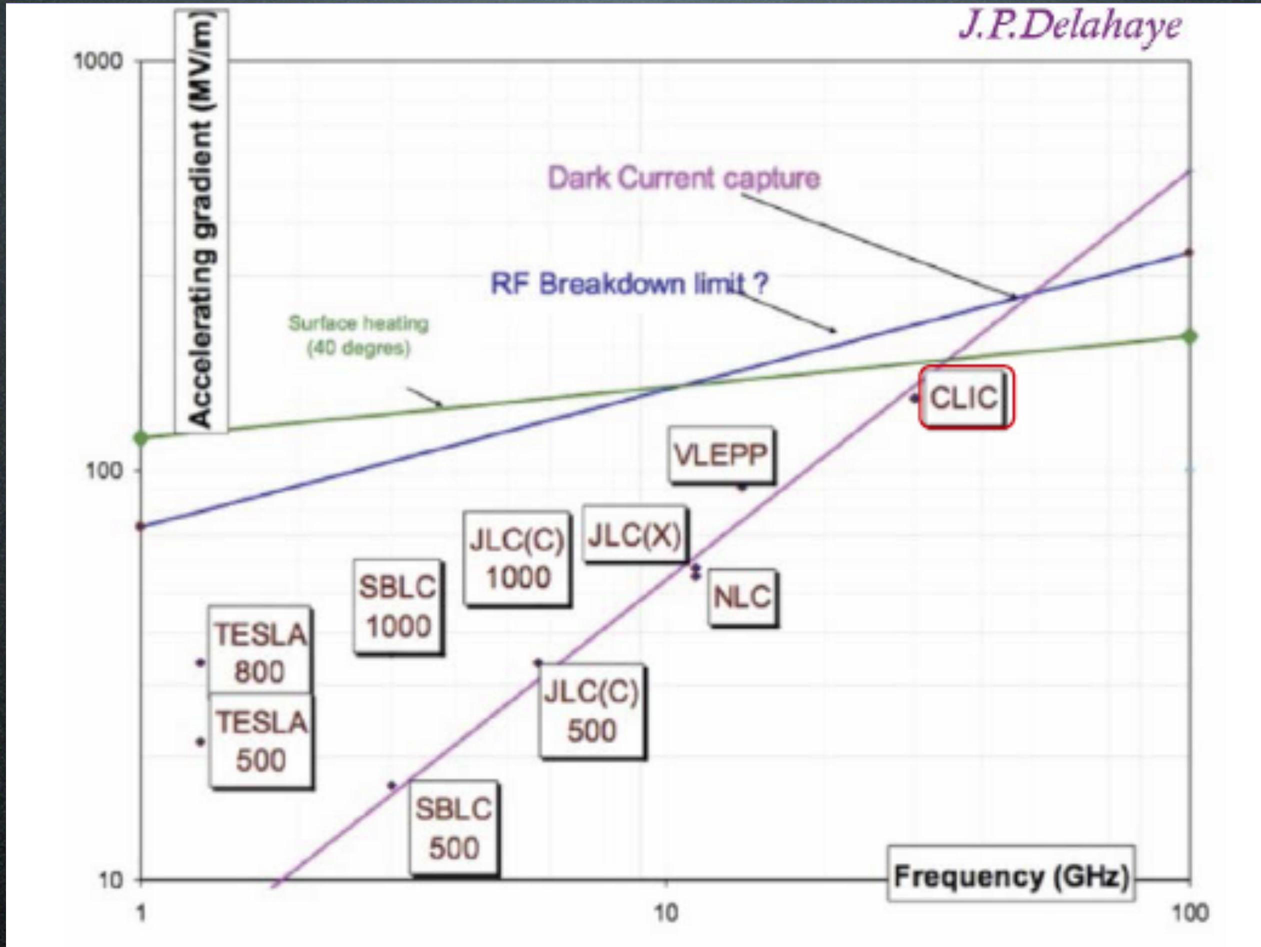
Breakdown limit?

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

Conventional RF accelerating structures




Typical breakdown and pulse heating
damage is standing-wave structure cell
L. Romano
EHT = 5.00 kV
WD = 4 mm
200nm
Date :18 Jan 2012
SLAC-KEK-INFN



Breakdown limits metal:

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

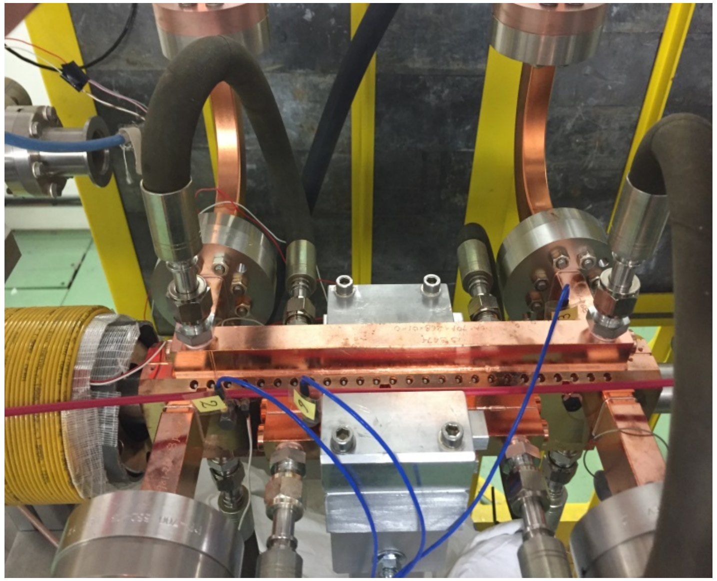
High field ->Short wavelength->ultra-short bunches-> low charge

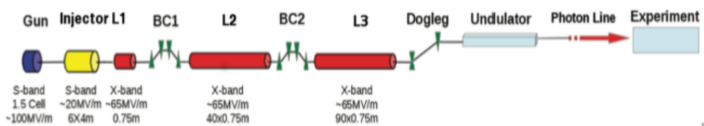
Compact

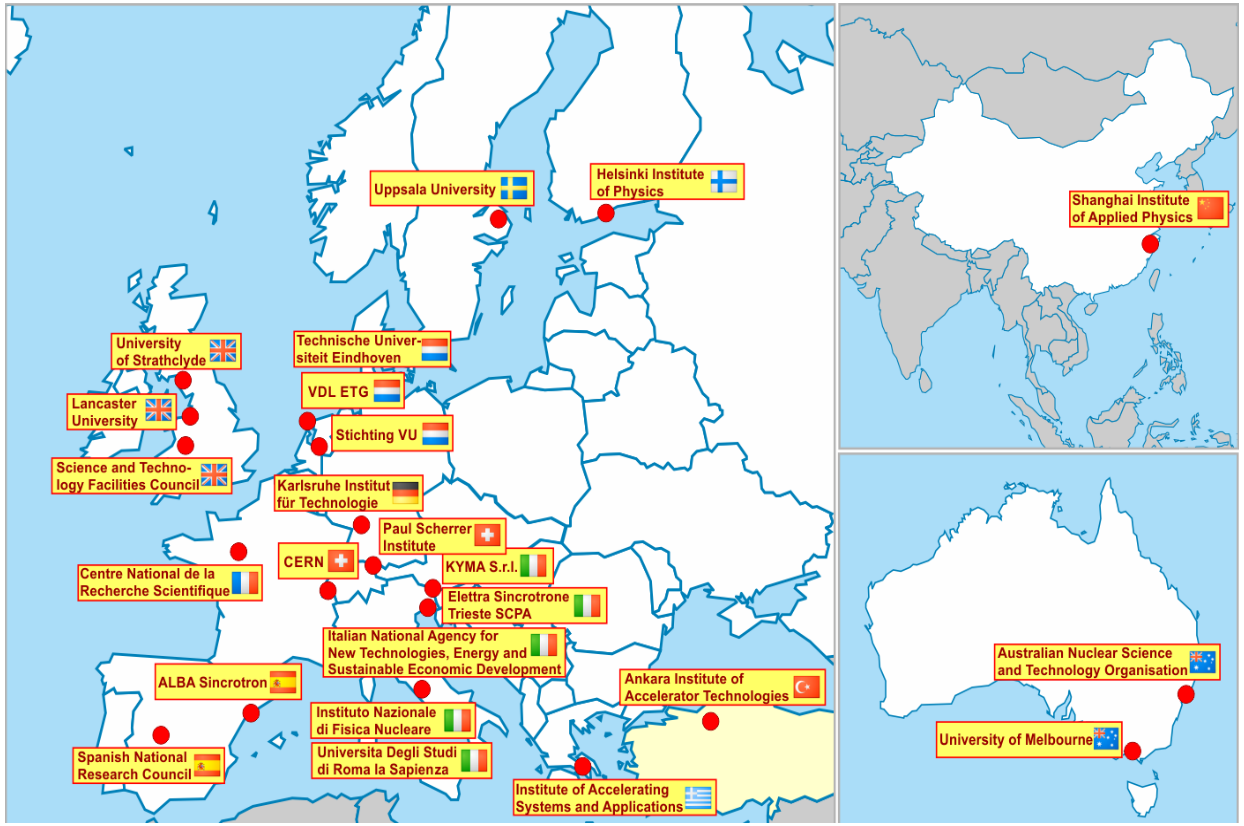
New EU Design Study Approved

3 years – 3 MEuro

Coordinator: G. D'Auria (Elettra)





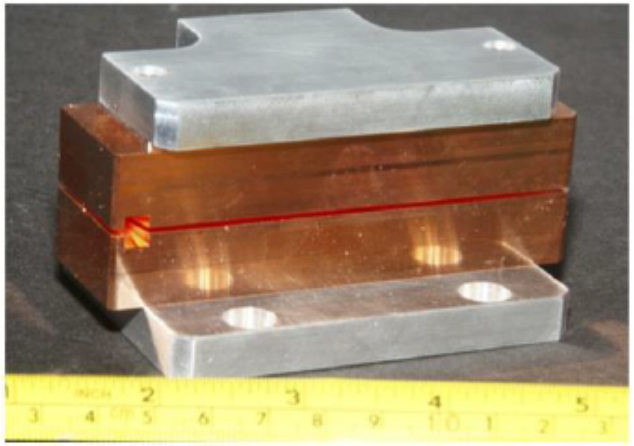


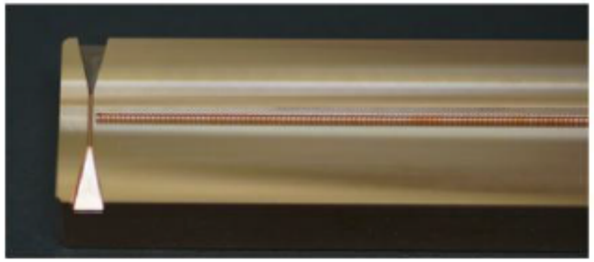
The key objective of the CompactLight Design Study is to demonstrate, through a conceptual design, the feasibility of an innovative, compact and cost effective FEL facility suited for user demands identified in the science case.

K-band RF Structures

- 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

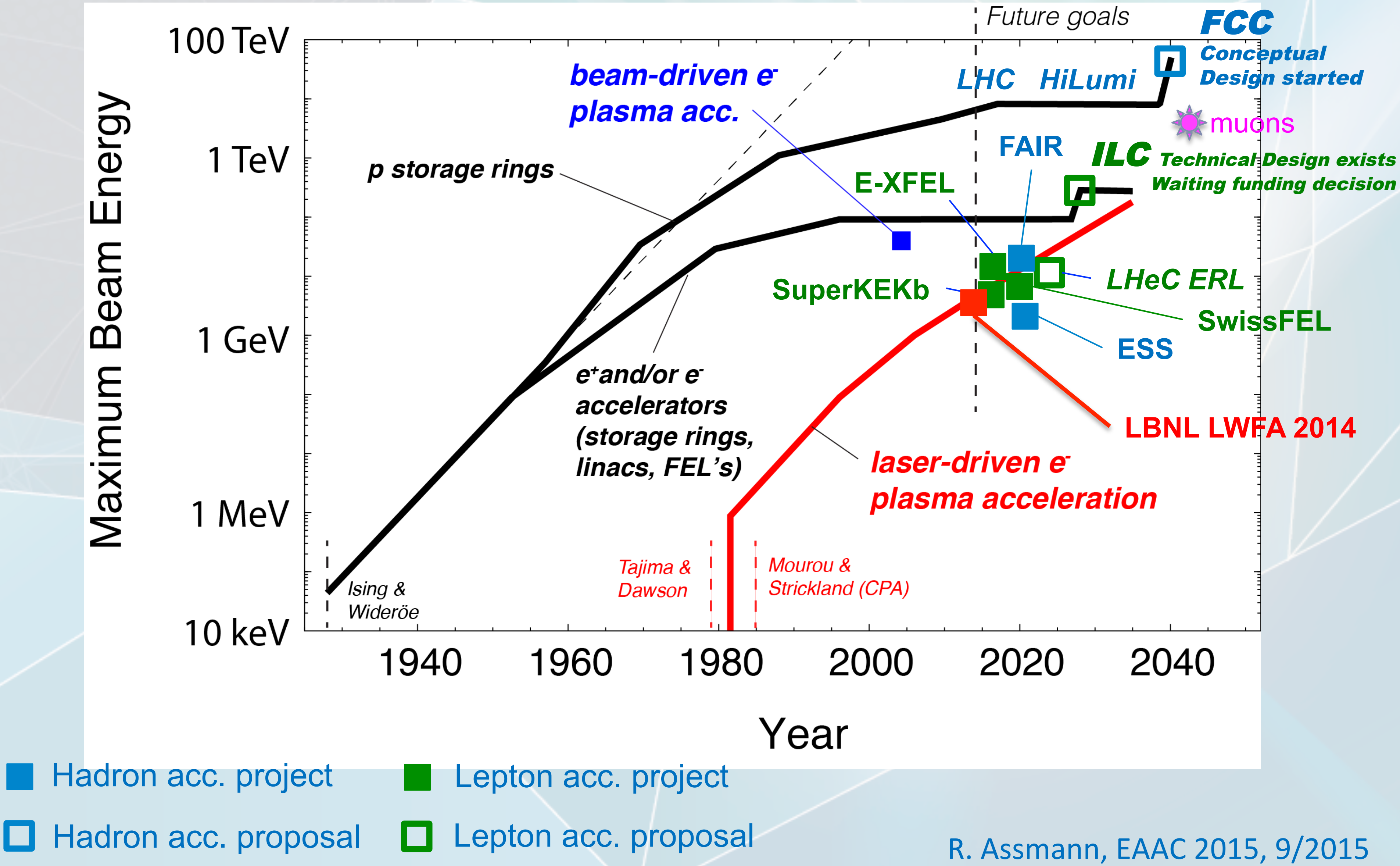




SLAC NATIONAL ACCELERATOR LABORATORY

INFN

Future of Accelerators



R. Assmann, EAAC 2015, 9/2015

Modern accelerators require high quality beams:

==> High Luminosity & High Brightness

==> High Energy & Low Energy Spread

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

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

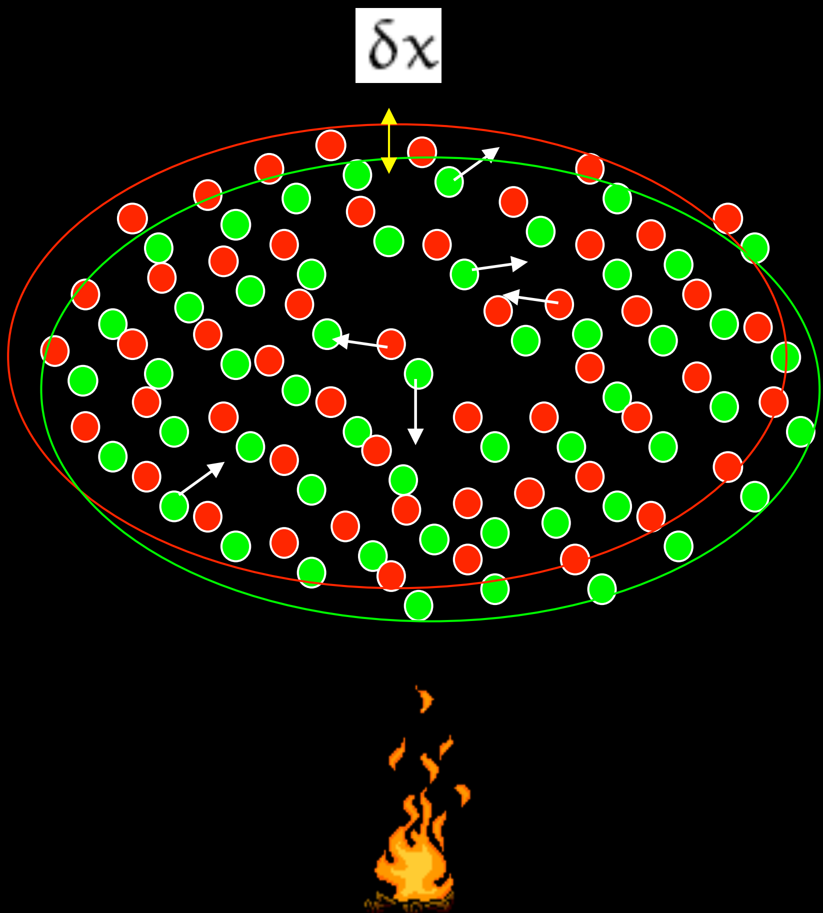
$$\uparrow B_n \approx \frac{2I}{\varepsilon_n^2}$$

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

Plasma Acceleration

Surface charge density

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



Surface electric field

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

Restoring force

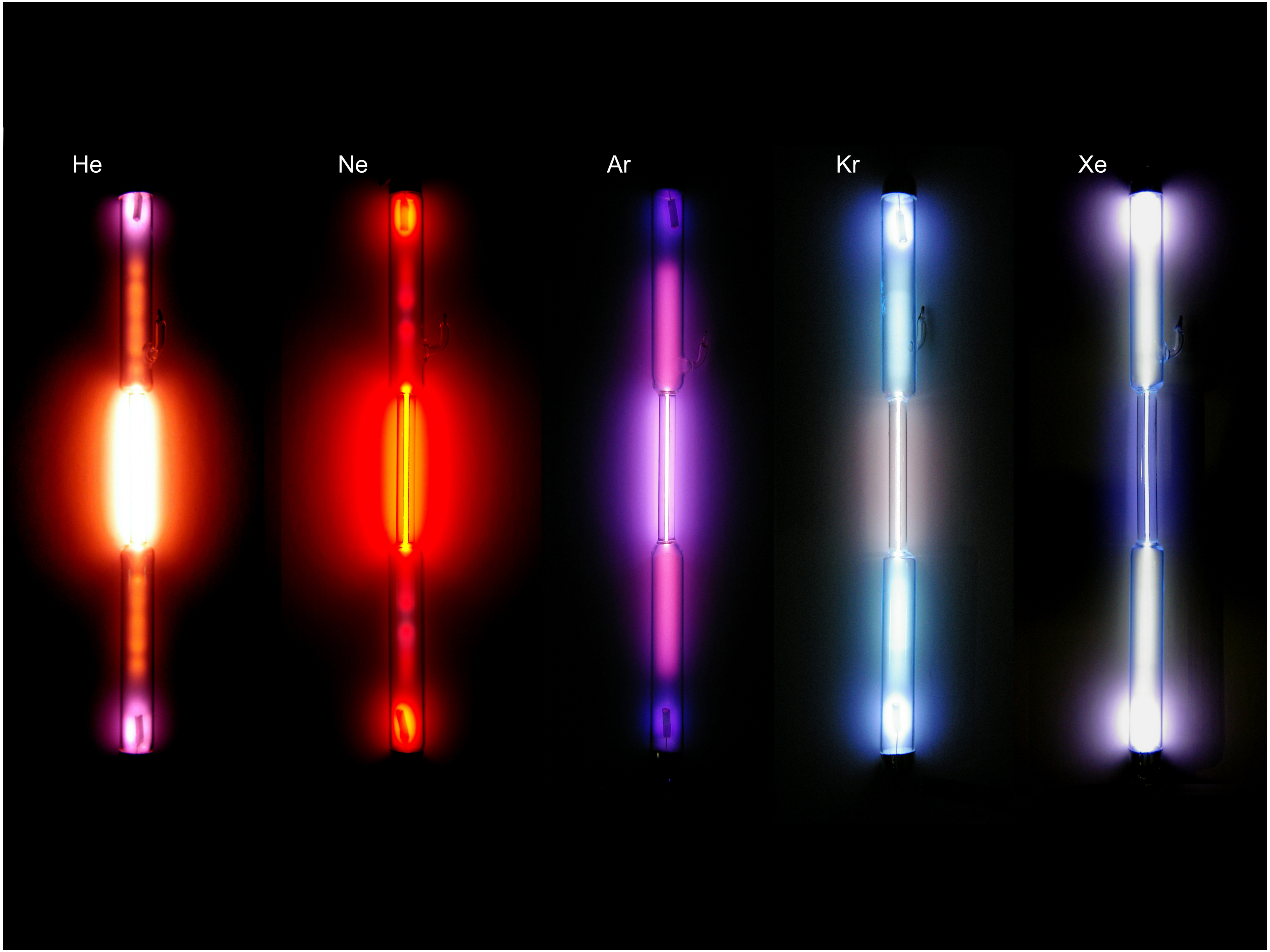
$$m\,\frac{d^2\delta x}{dt^2} = e\,E_x = -m\,\omega_p{}^2\,\delta x$$

Plasma frequency

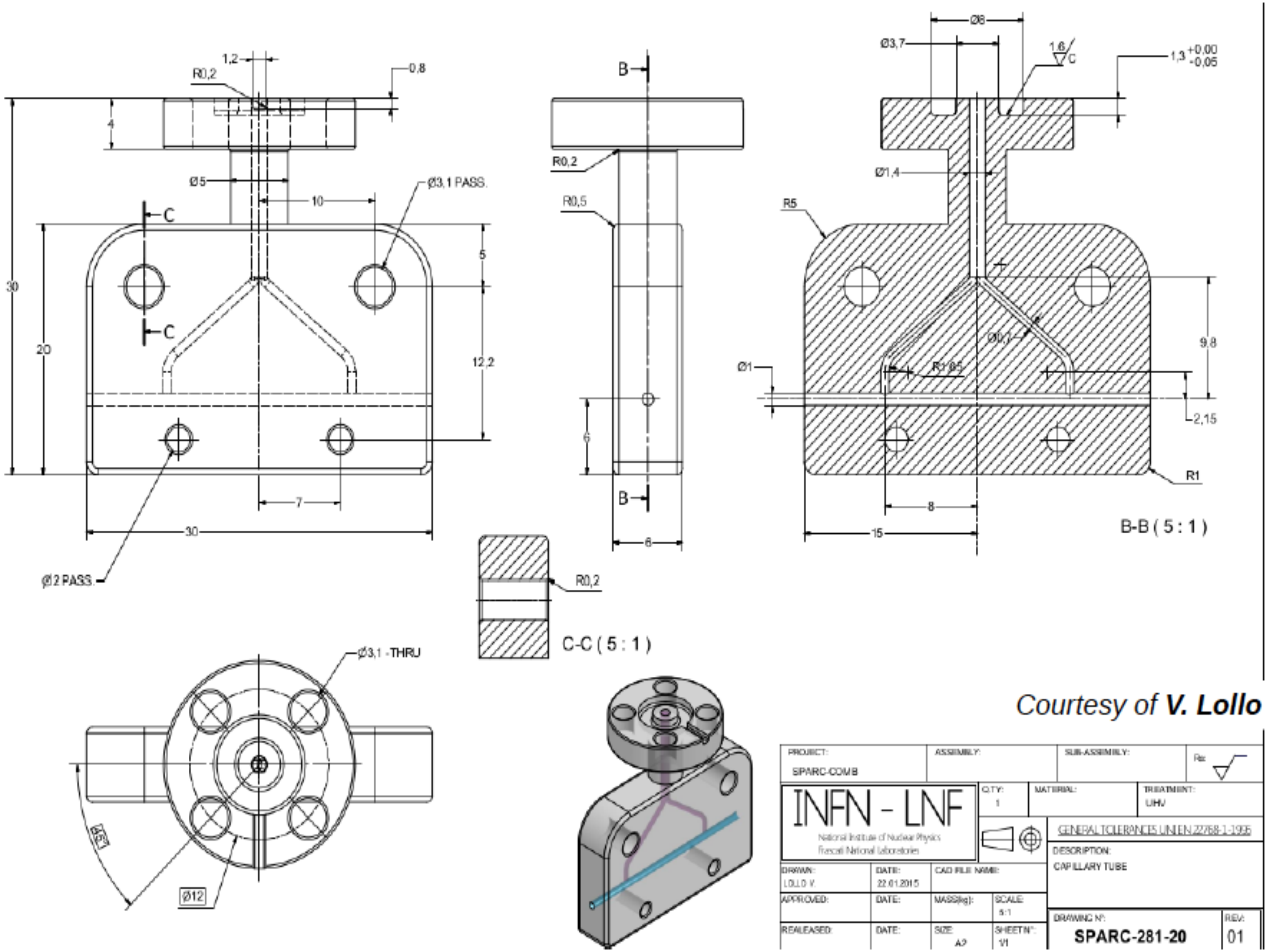
$$\omega_p{}^2 = \frac{n\,e^2}{\epsilon_0\,m}$$

Plasma oscillations

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

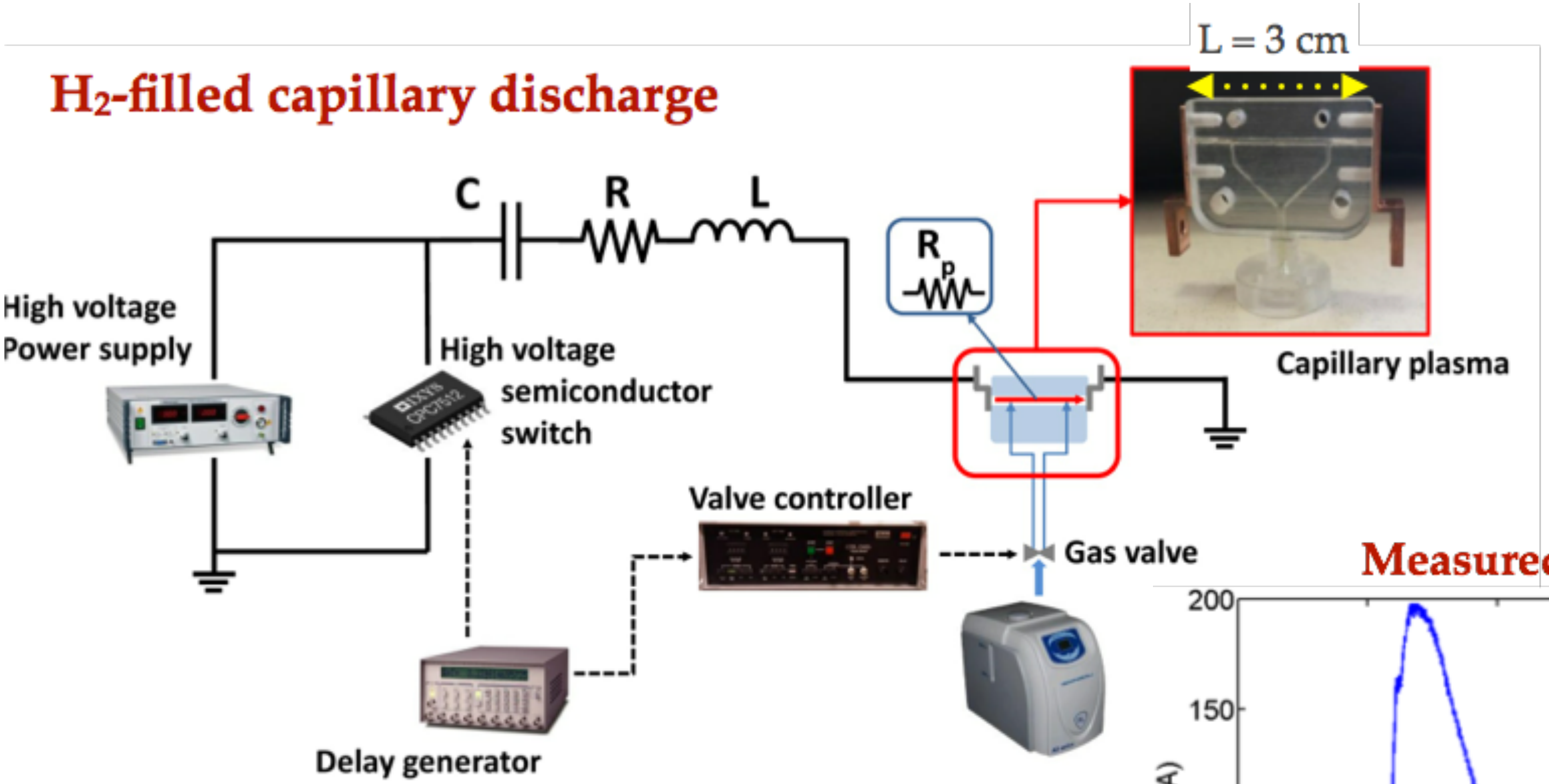

He
Ne
Ar
Kr
Xe

Plasma capillary

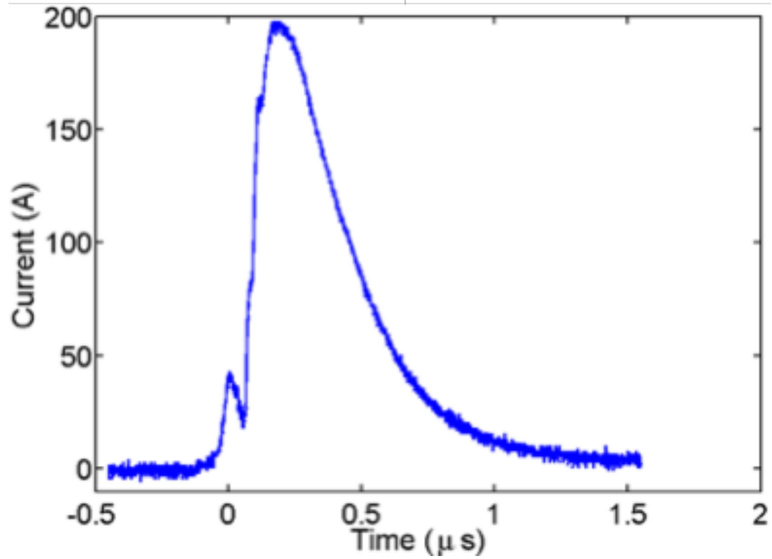


Courtesy of ***V. Lollo***

Plasma Source



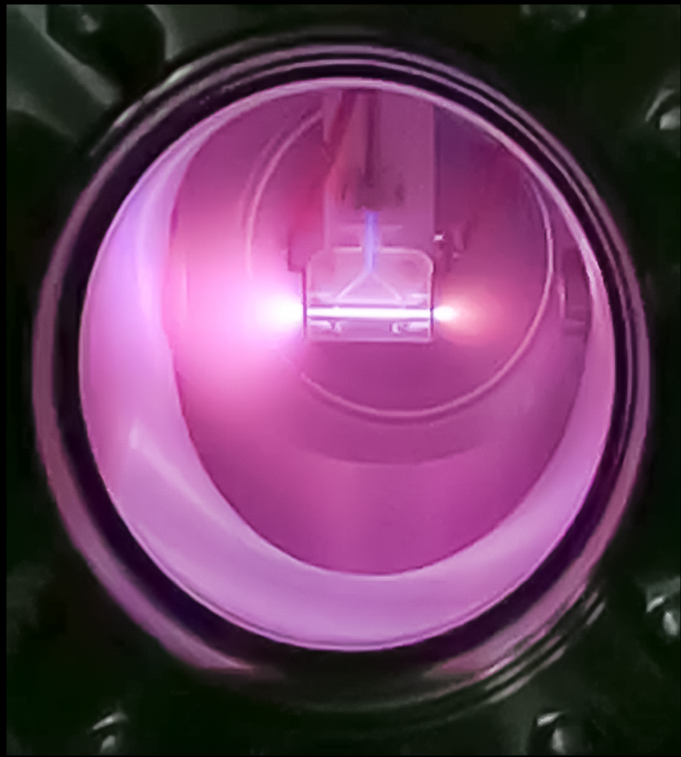
Measured current



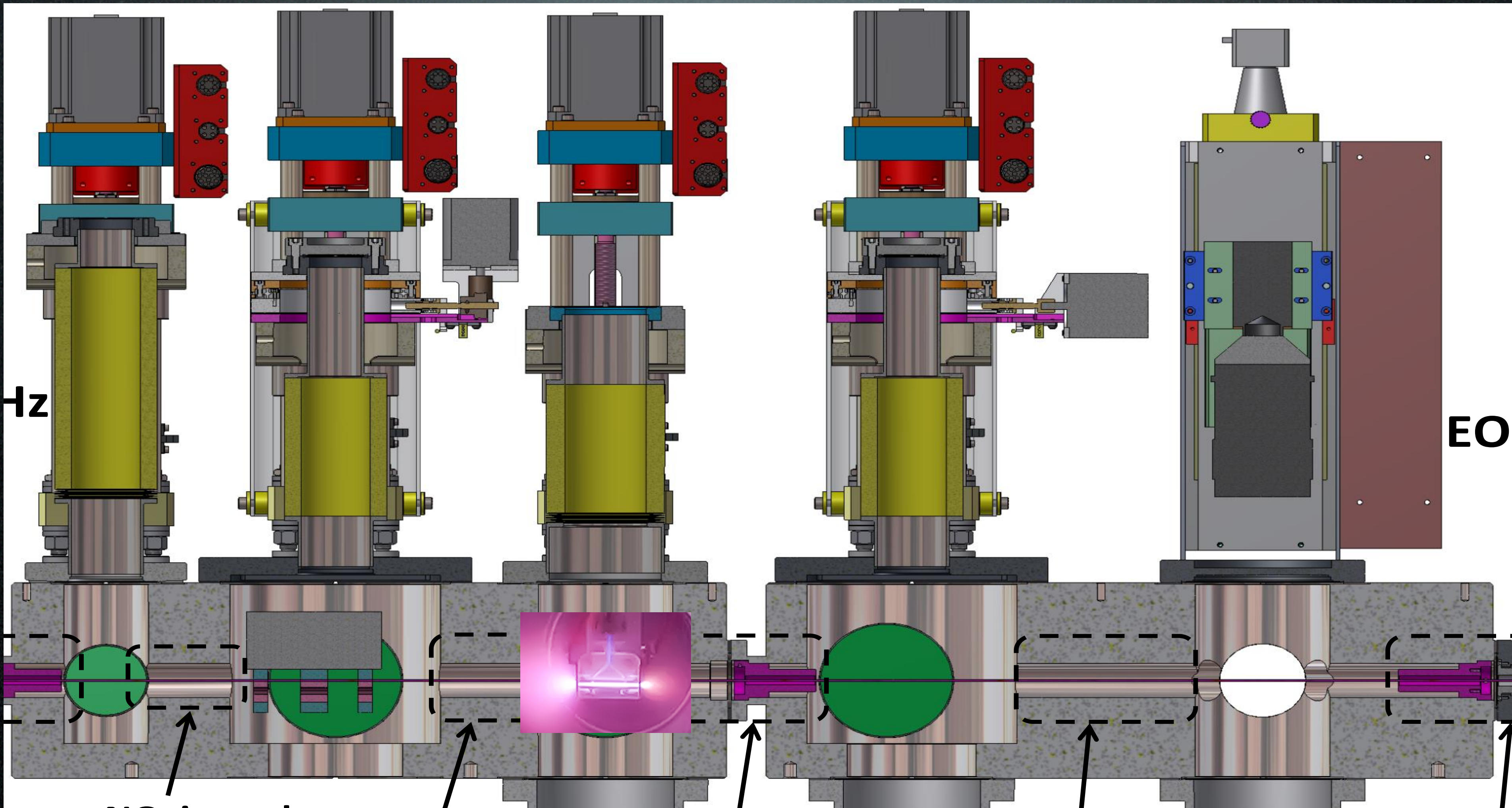
P_{H2} = 10 mbar
Total discharge duration: 800 ns
Voltage: 20 kV
Peak current: 200 A
Capacitor: 6 nF

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

Capillary Discharge



SPARC_LAB Plasma Vacuum Chamber



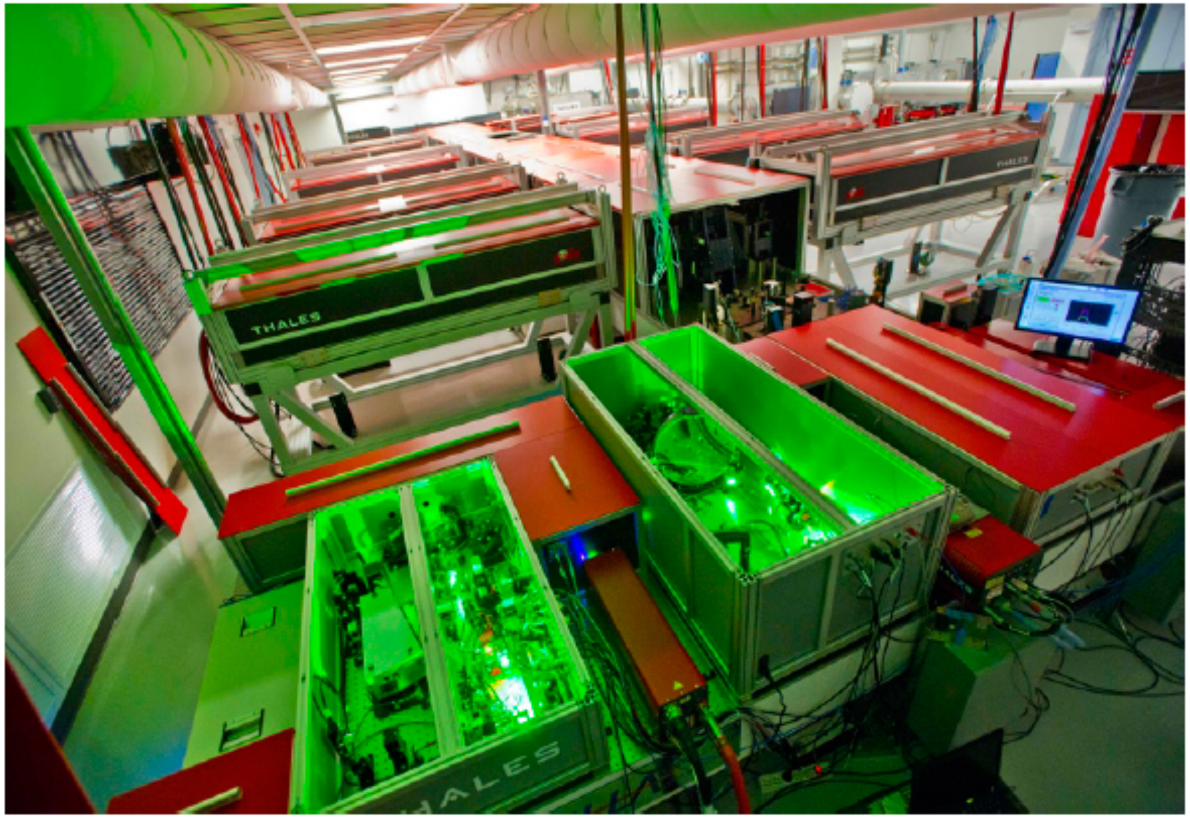
Focusing PMQ

PWFA module

Capture PMQ

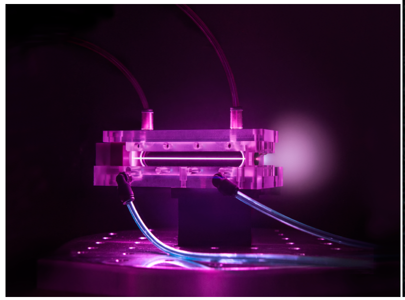
BELLA: BErkeley Lab Laser Accelerator

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

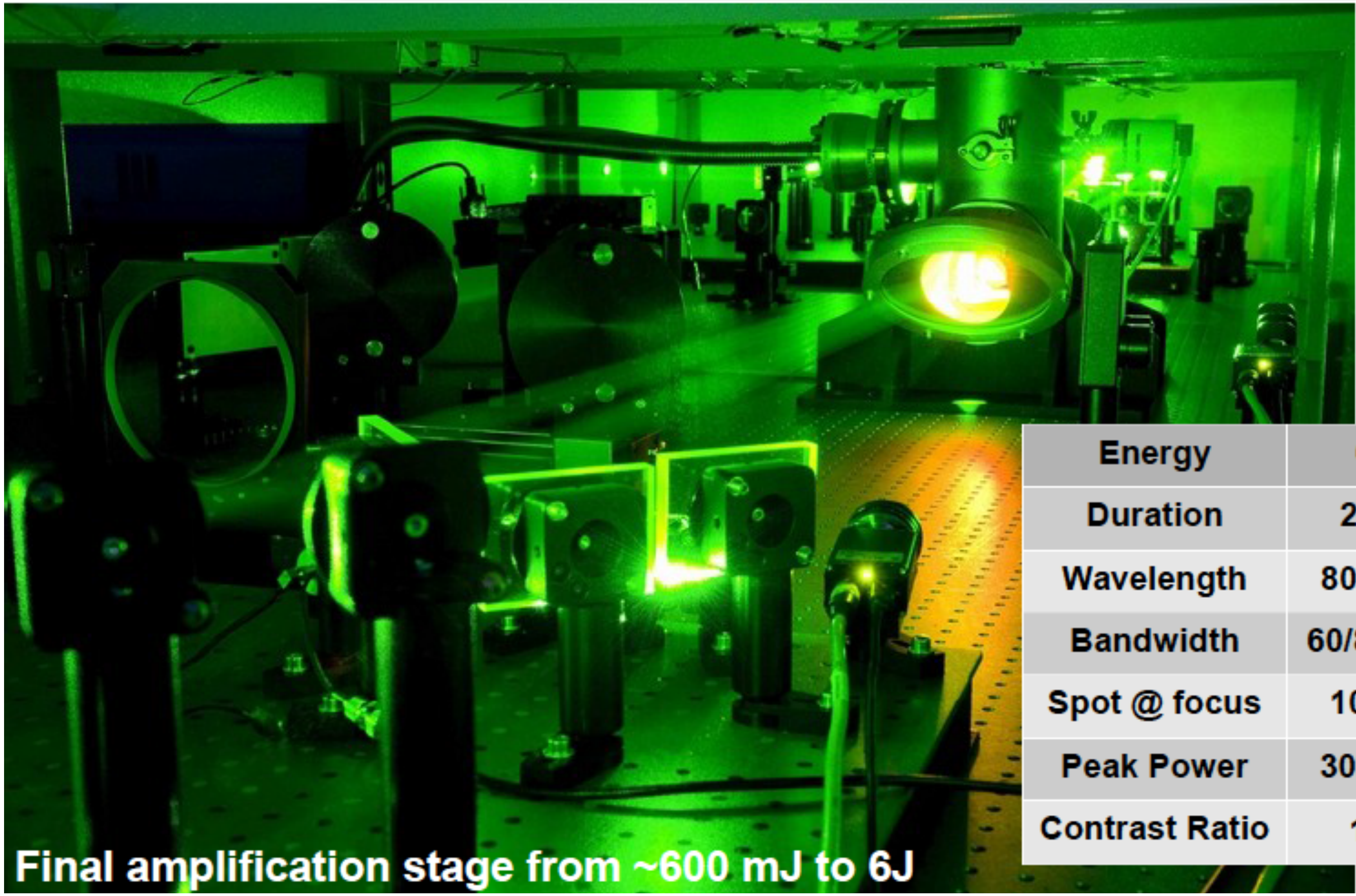


Critical HEP experiments:

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

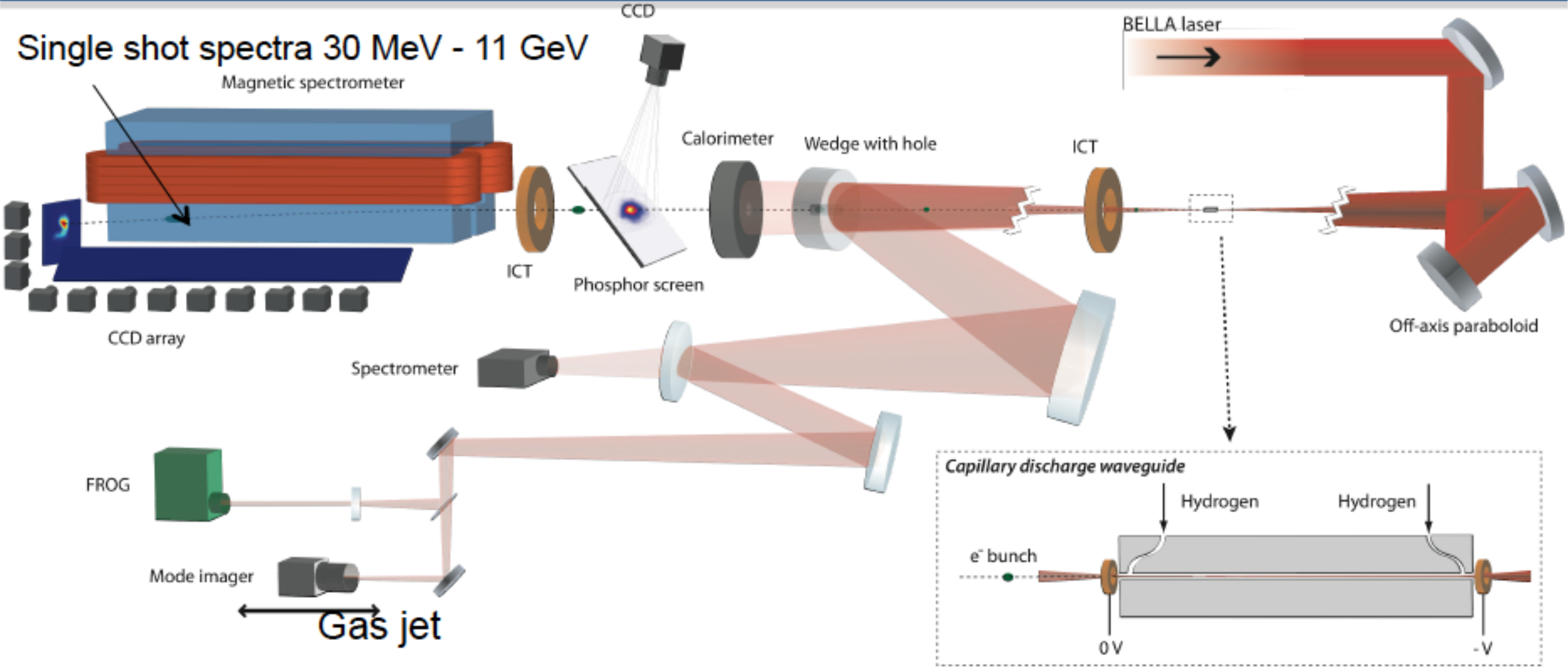


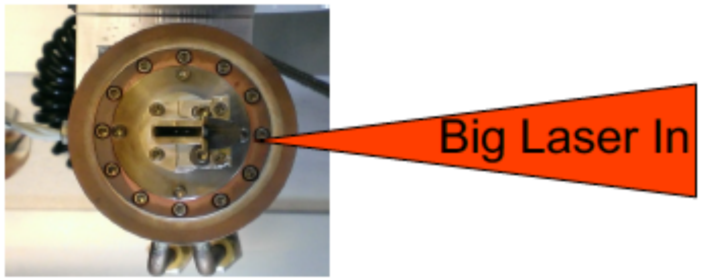
High power laser FLAME



Energy	6 J
Duration	23 fs
Wavelength	800 nm
Bandwidth	60/80 nm
Spot @ focus	10 µm
Peak Power	300 TW
Contrast Ratio	10^{10}

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

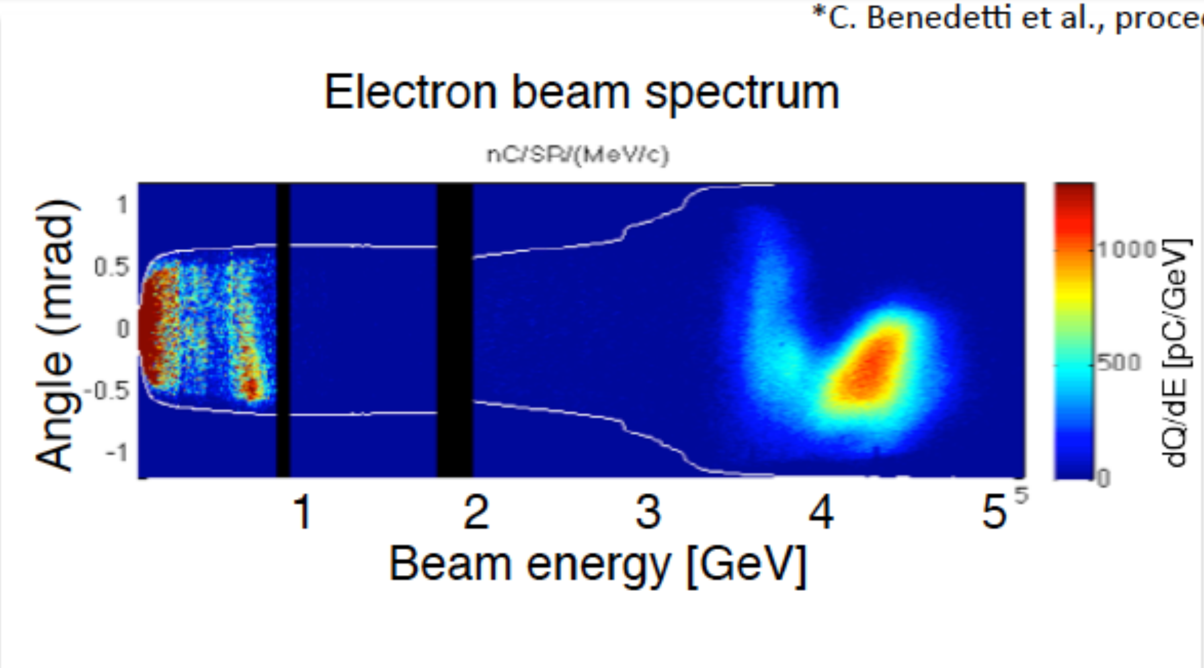


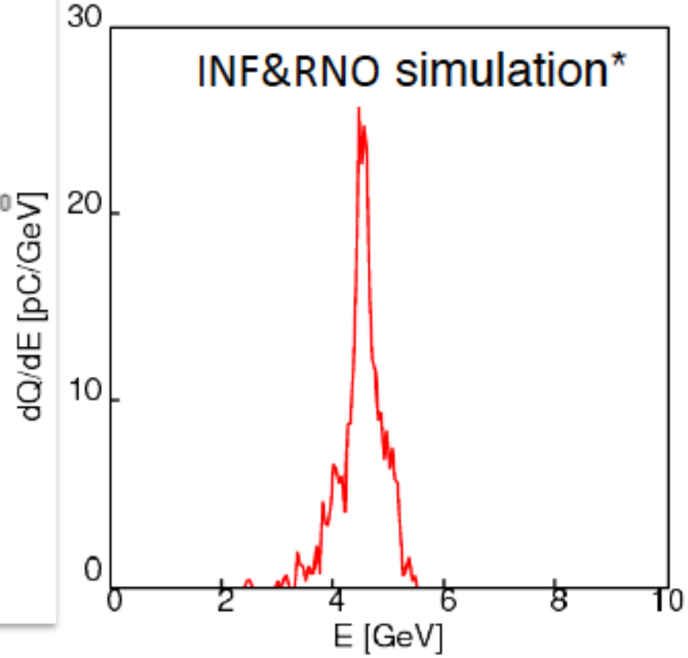


Capillary discharge

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



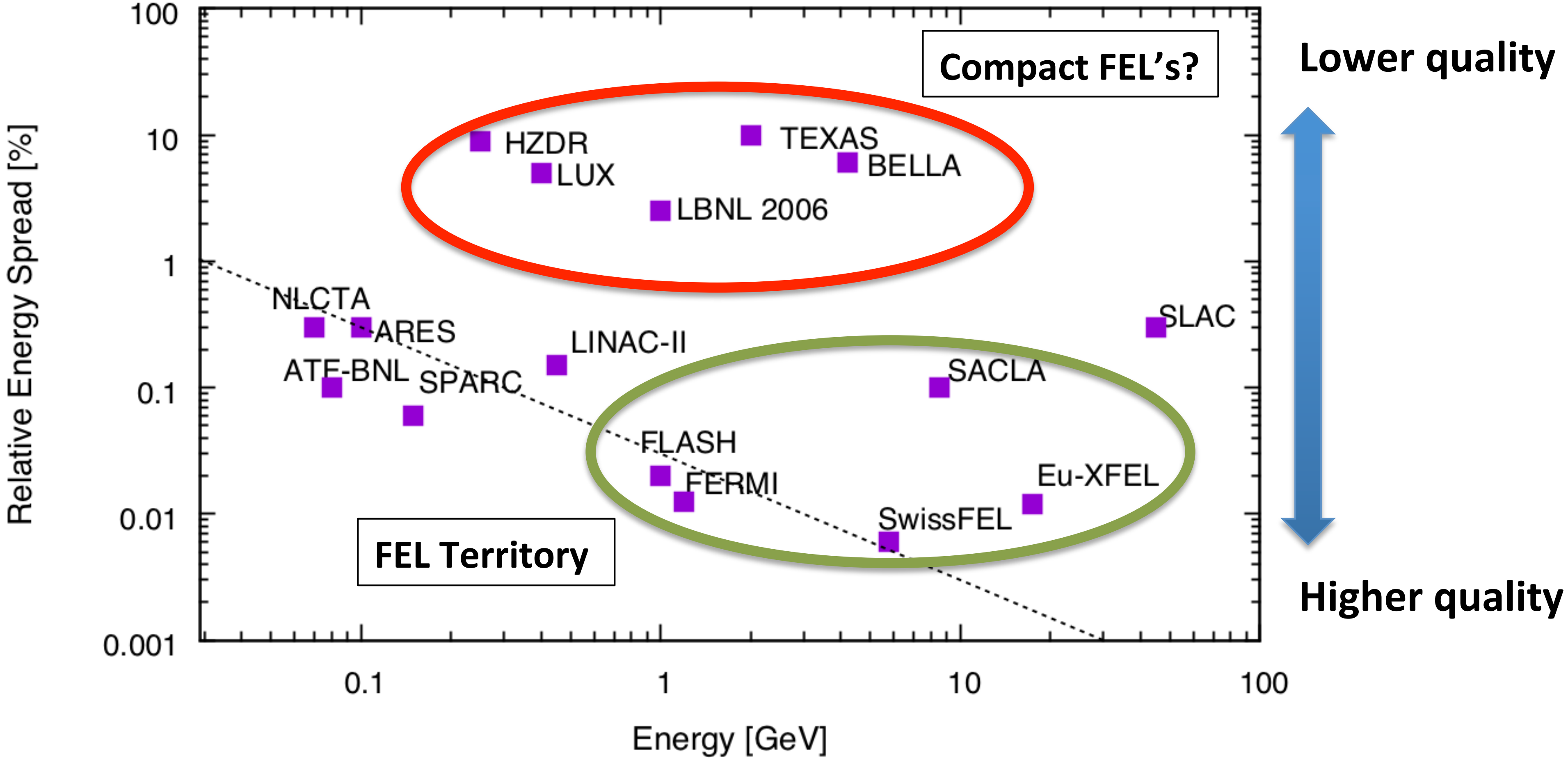


	Exp.	Sim.
Energy	4.25 GeV	4.5 GeV
ΔE/E	5%	3.2%
Charge	~20 pC	23 pC
Divergence	0.3 mrad	0.6 mrad

- **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})

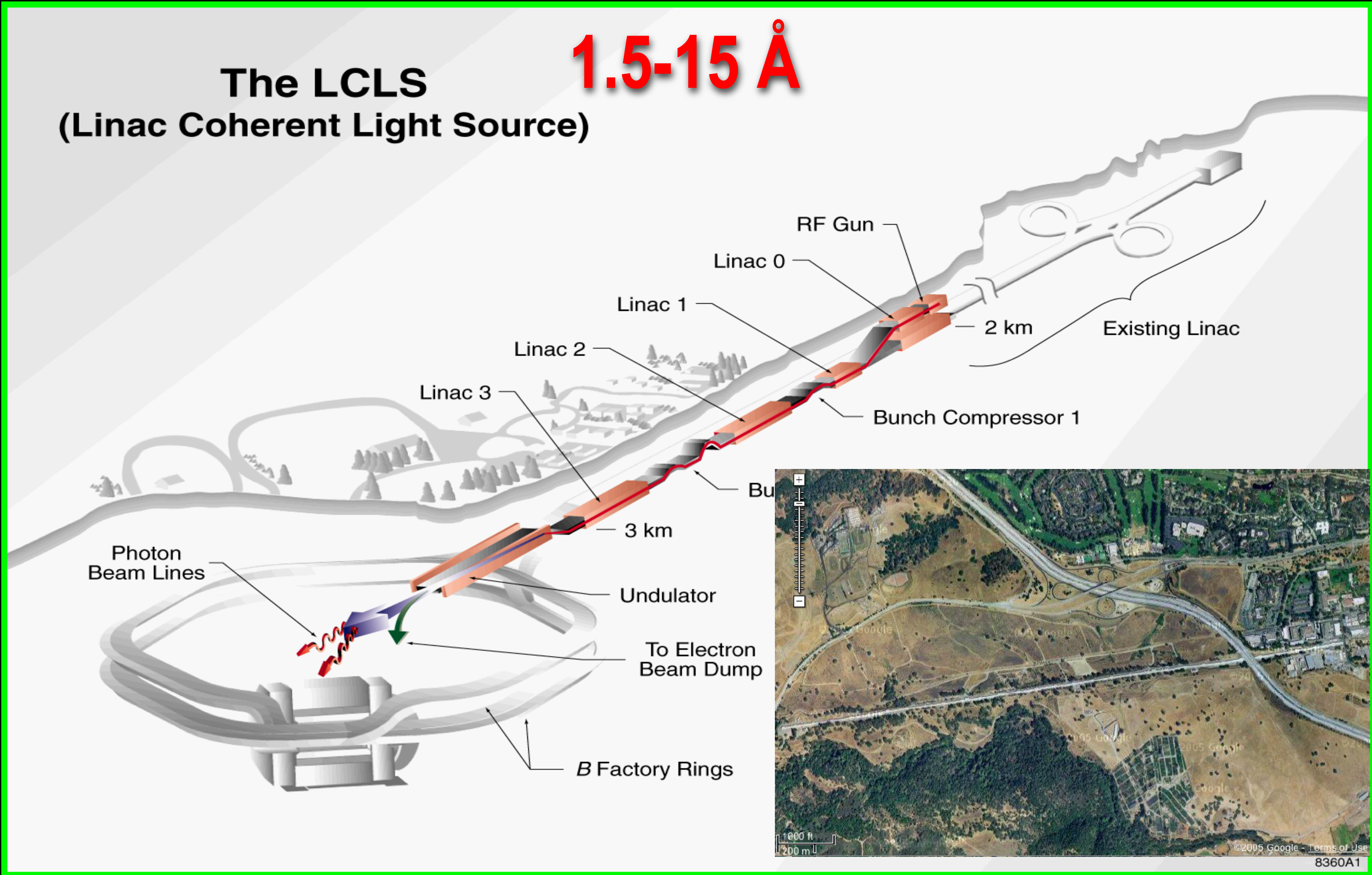
W.P. Leemans et al.,PRL 2014

Quality: Example Energy Spread



FELs require energy spread < 0.1 %

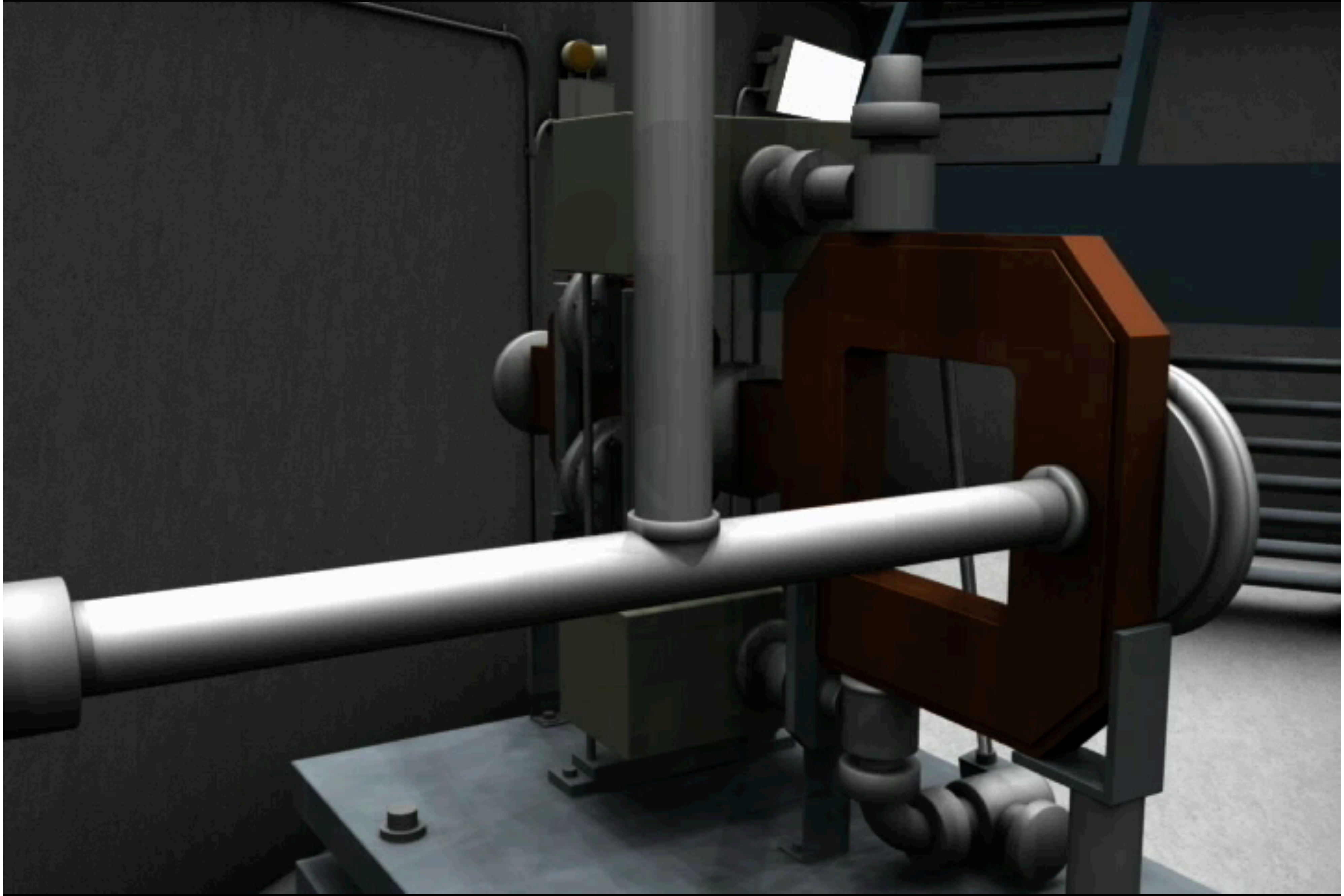
LCLS at *SLAC*



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

XFEL first lasing – Hamburg May 2017

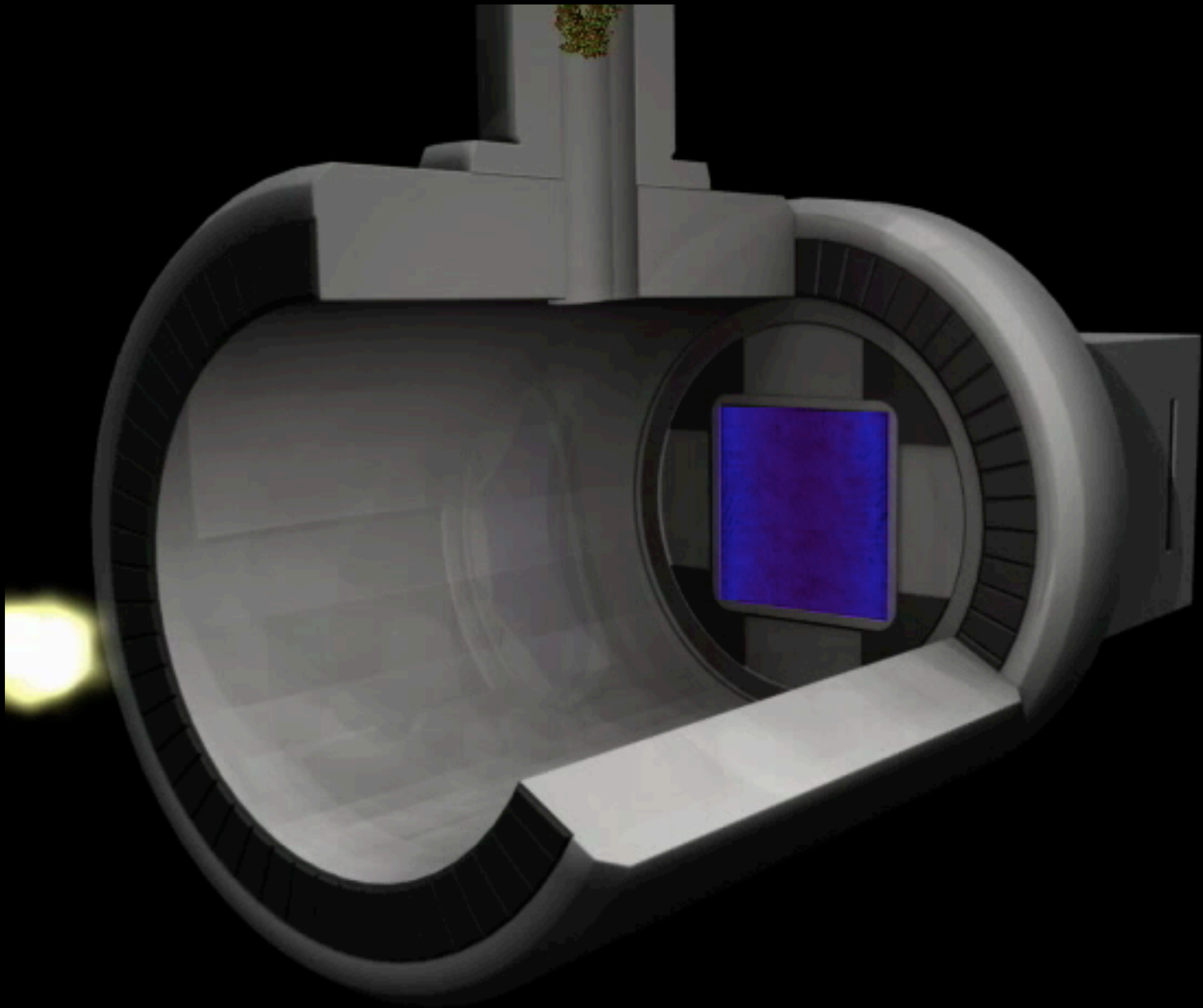
Electron source and acceleration



Long undulators chain

Beam separation

Experimental hall (Single Protein Imaging)



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

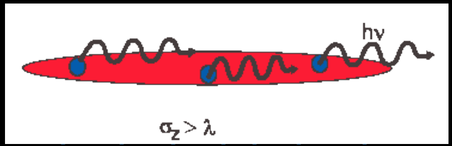
Peak power of one accelerated charge:

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

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

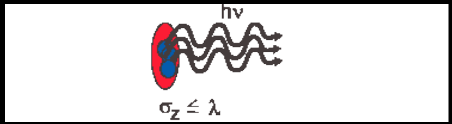
Incoherent Spontaneous Radiation Power:

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

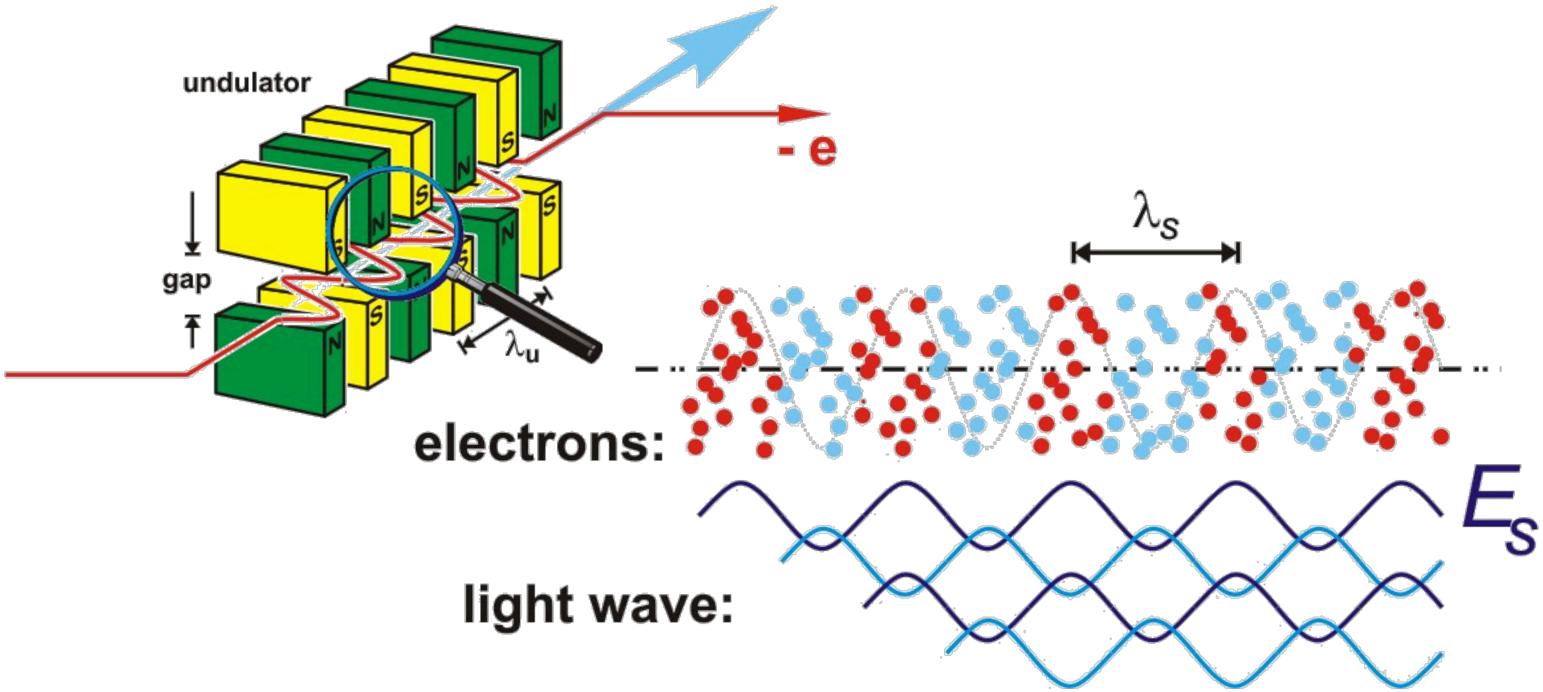


Coherent Stimulated Radiation Power:

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



Bunching on the scale of the wavelength:

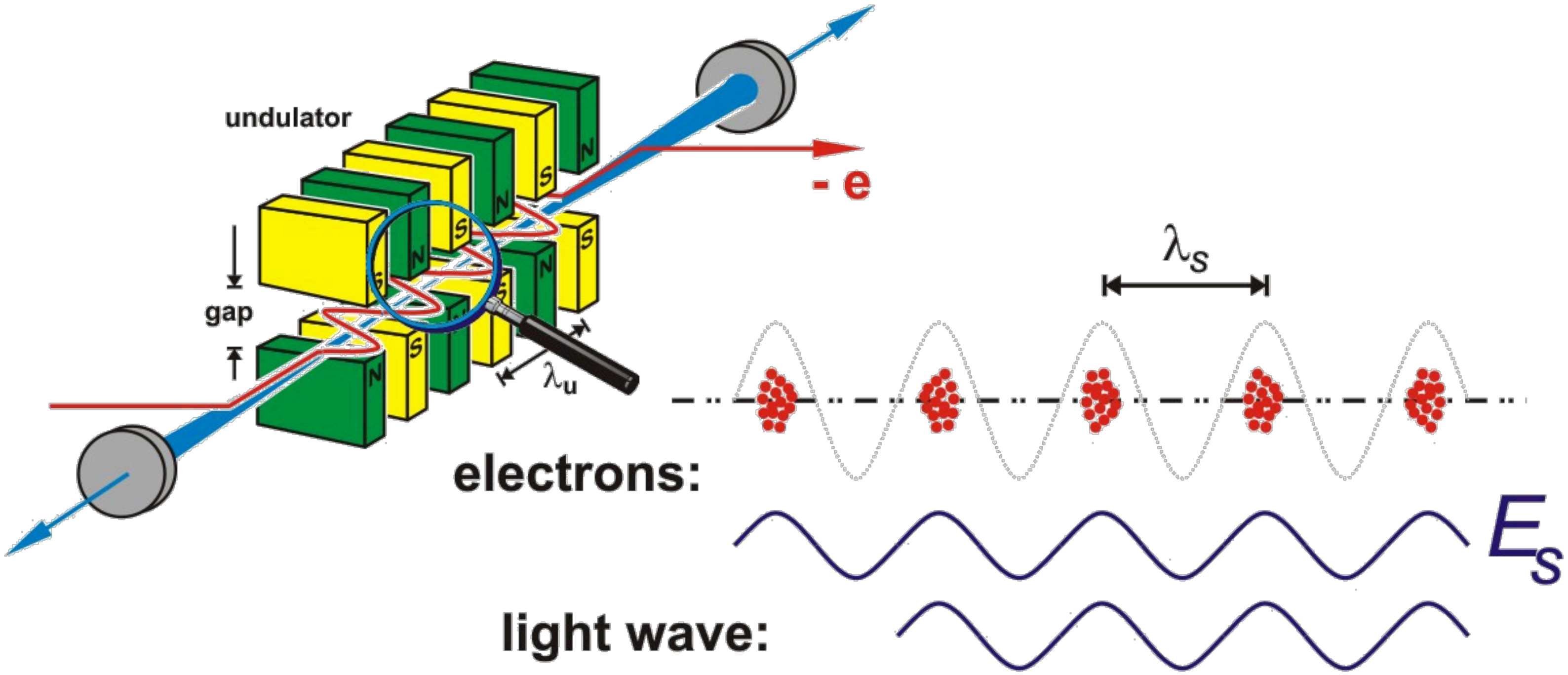


Radiated Power :

$P \propto n_e$ (number of electrons)

destructive interference

⟶ **shotnoise radiation**

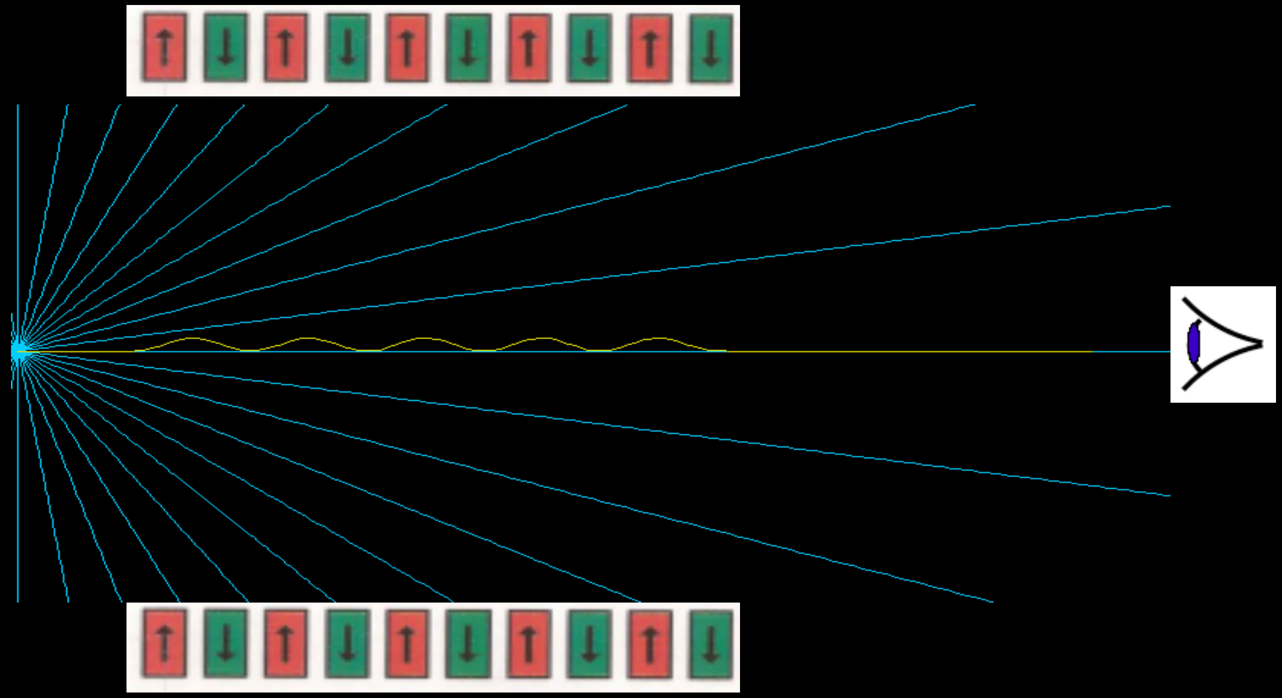


Radiated Power :

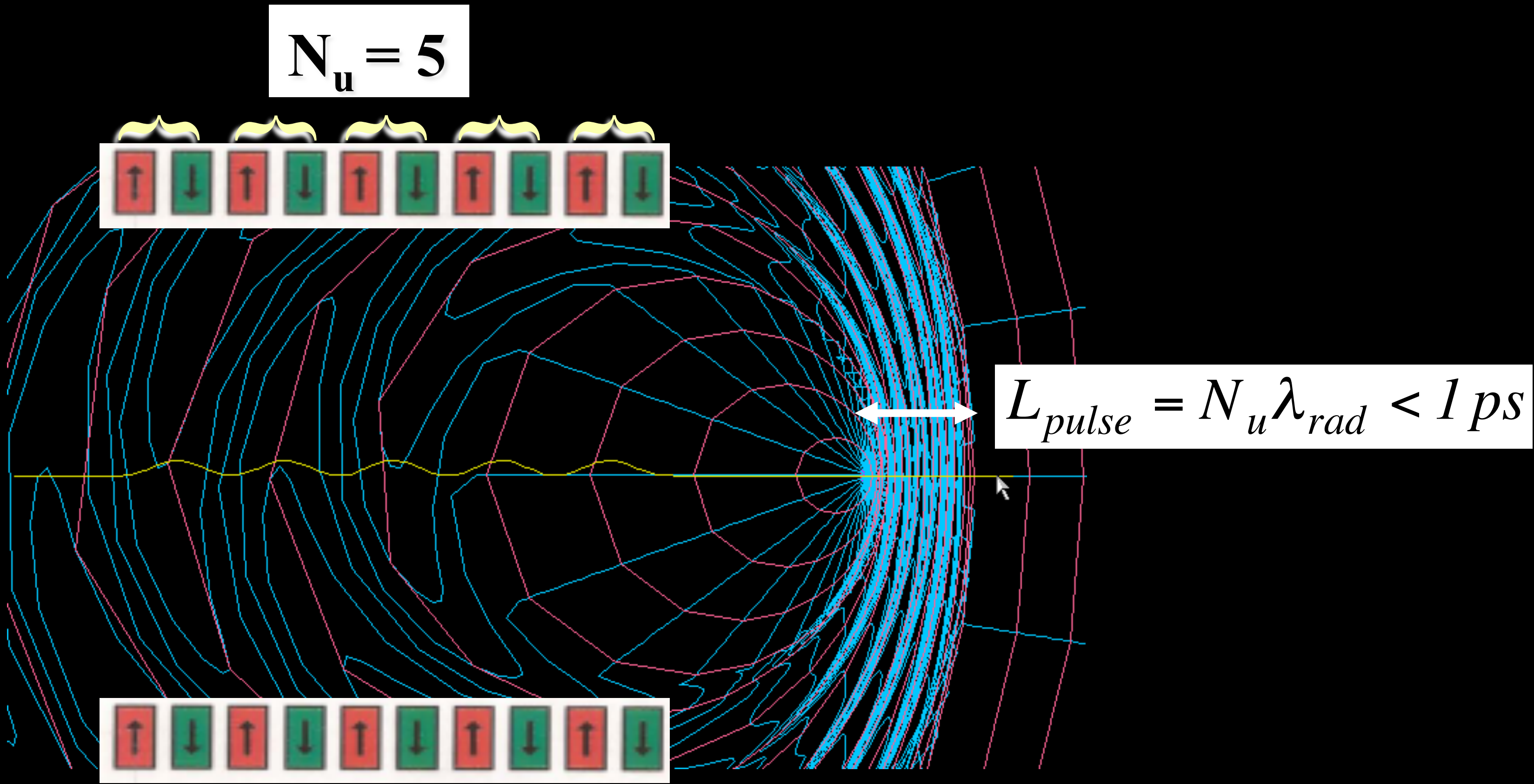
$$P \propto n_e^2 \begin{pmatrix} \text{number of electrons} \\ n_e \sim 10^6 - 10^9 \end{pmatrix}$$

constructive interference

⟶ **<u>enhanced emission</u>**

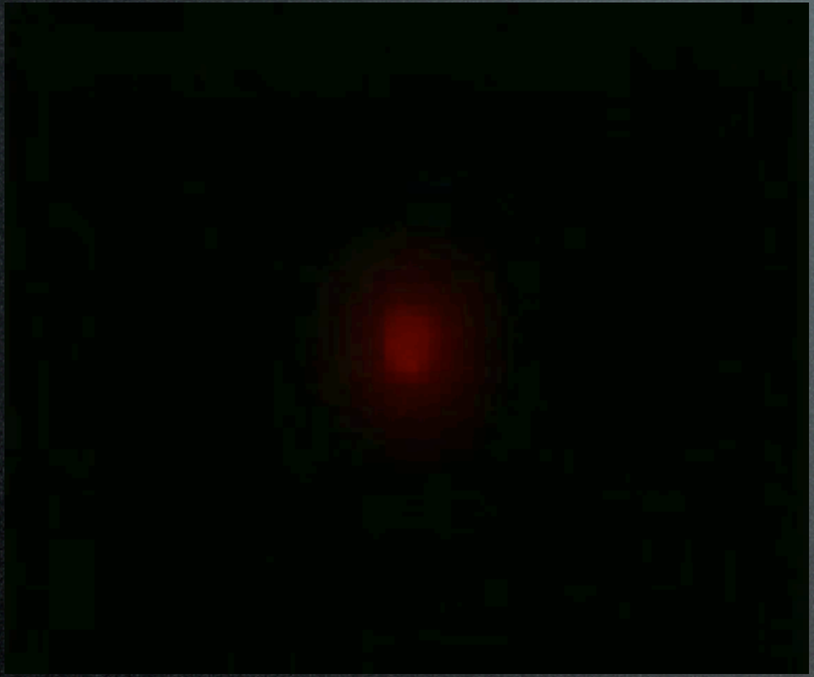


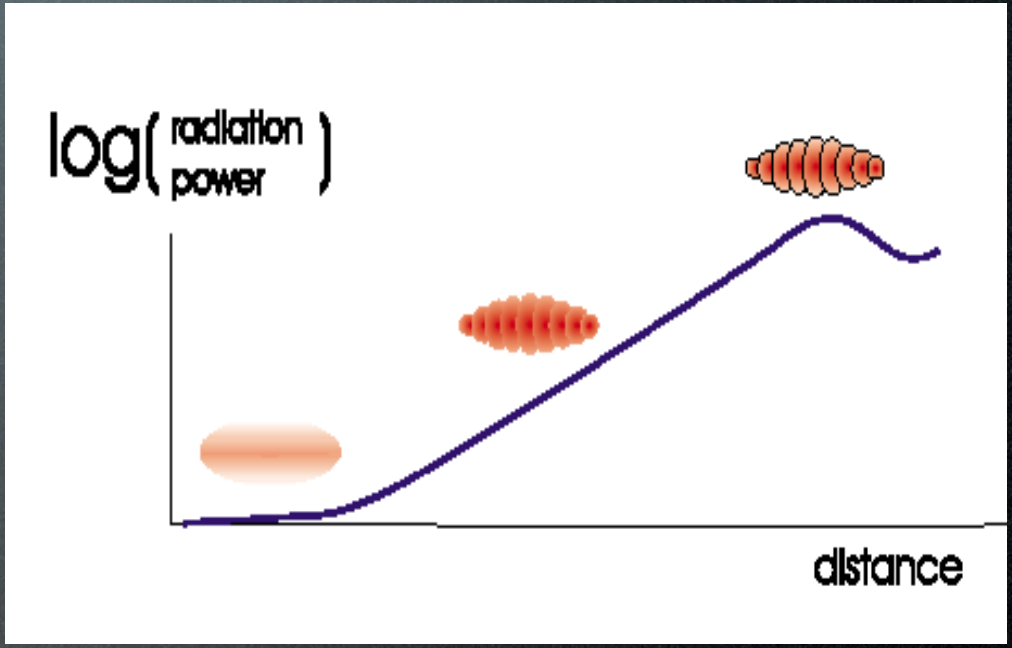
Radiation Simulator – T. Shintake, @ http://www-xfel.spring8.or.jp/Index.htm



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

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)

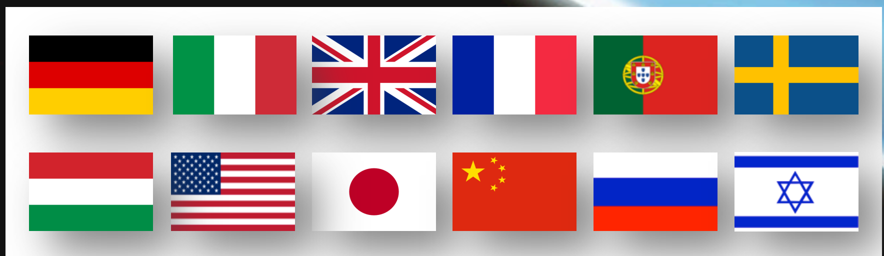
EUROPEAN
PLASMA RESEARCH
ACCELERATOR WITH
EXCELLENCE IN
APPLICATIONS

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

EuPRAXIA

Consortium

Horizon 2020

16 Participants

24 Associated Partners

(as of December 2017)

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

FEL Electron Beam Requirements

Horizon 2020

Electron beam parameters at the undulator

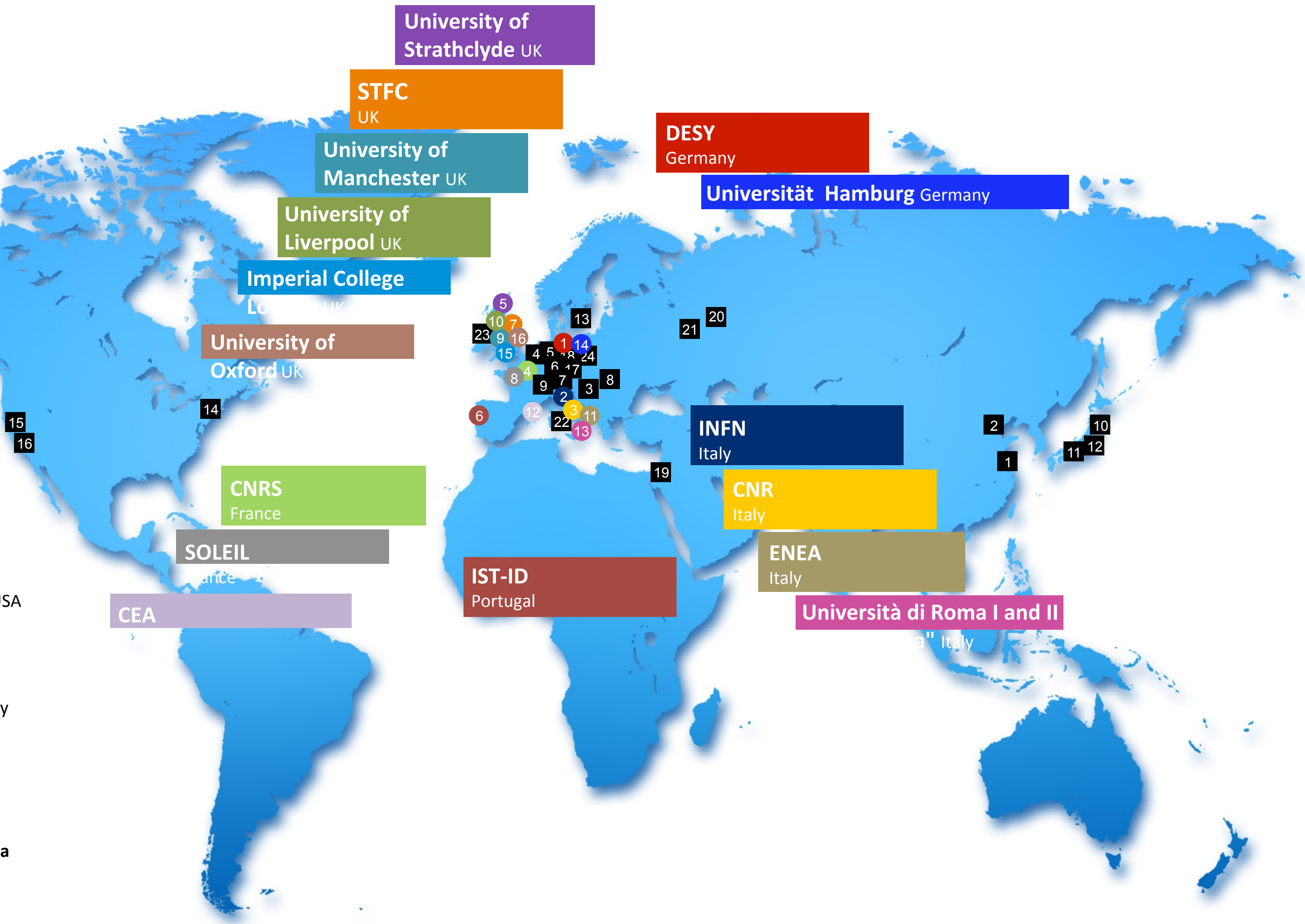
Quantity	Symbol [Unit of Meas.]	Target parameters
Energy	E [GeV]	1 - 5
Charge	Q [pC]	30
Bunch length (FWHM)	t_{FWHM} [fs]	10
Peak current	I [kA]	3
Repetition rate	f [Hz]	10
# of bunches	N	1
Transverse Norm. emittance	$\varepsilon_{n,x}, \varepsilon_{n,y}$ [mm mrad]	<1
Total energy spread	σ_E/E [%]	1
Slice Norm. emittance	$\varepsilon_{n,x}, \varepsilon_{n,y}$ [mm mrad]	<<1
Slice energy spread	$\sigma_{E,s}/E$ [%]	~0.1
Slice length	L_{Slice} [μm]	0.75 - 0.12

Participating Institutions

Horizon 2020

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



Industrial Participation

Industry: involved through workshops and Scientific Advisory Board

Contacts still evolving, several cooperations under discussion

Thales group (France): Number of employees: 62,194 (2015)
Sales 14.06 B€ (2015)

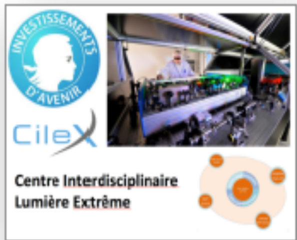
Amplitude (France): Number of employees: 80 (2015)
Sales 17.4 M€ (2015)

Trumpf group (Germany): Number of employees: 11,181 (2016)
Sales 2.81 B€ (2016)

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

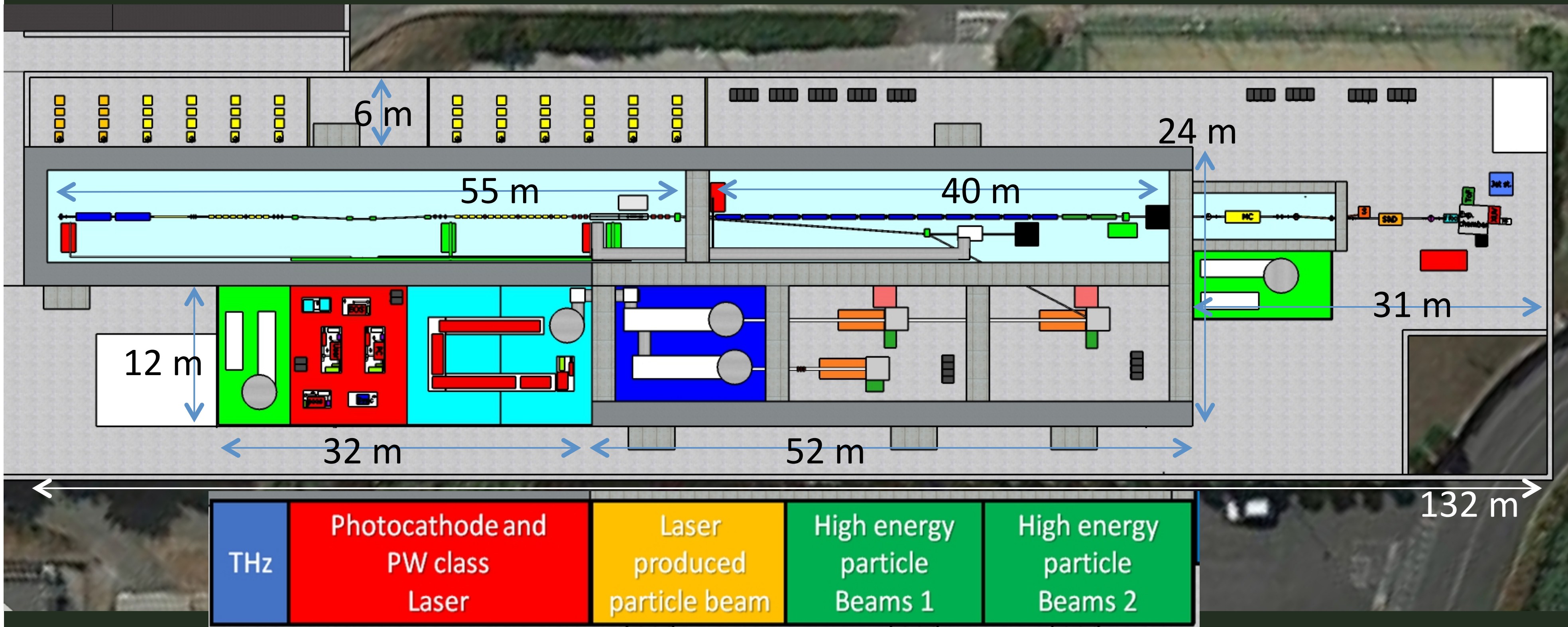


Central Laser Facility
Didcot, United Kingdom

Eli Beamlines
Prague, Czech Republic

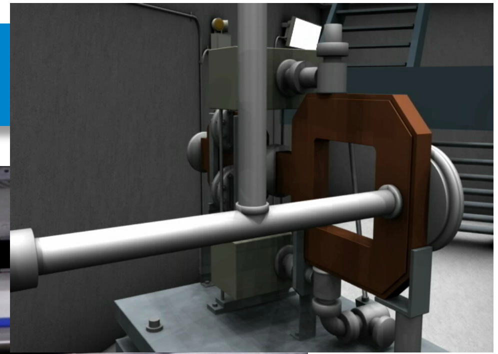
EuPRAXIA@SPARC_LAB

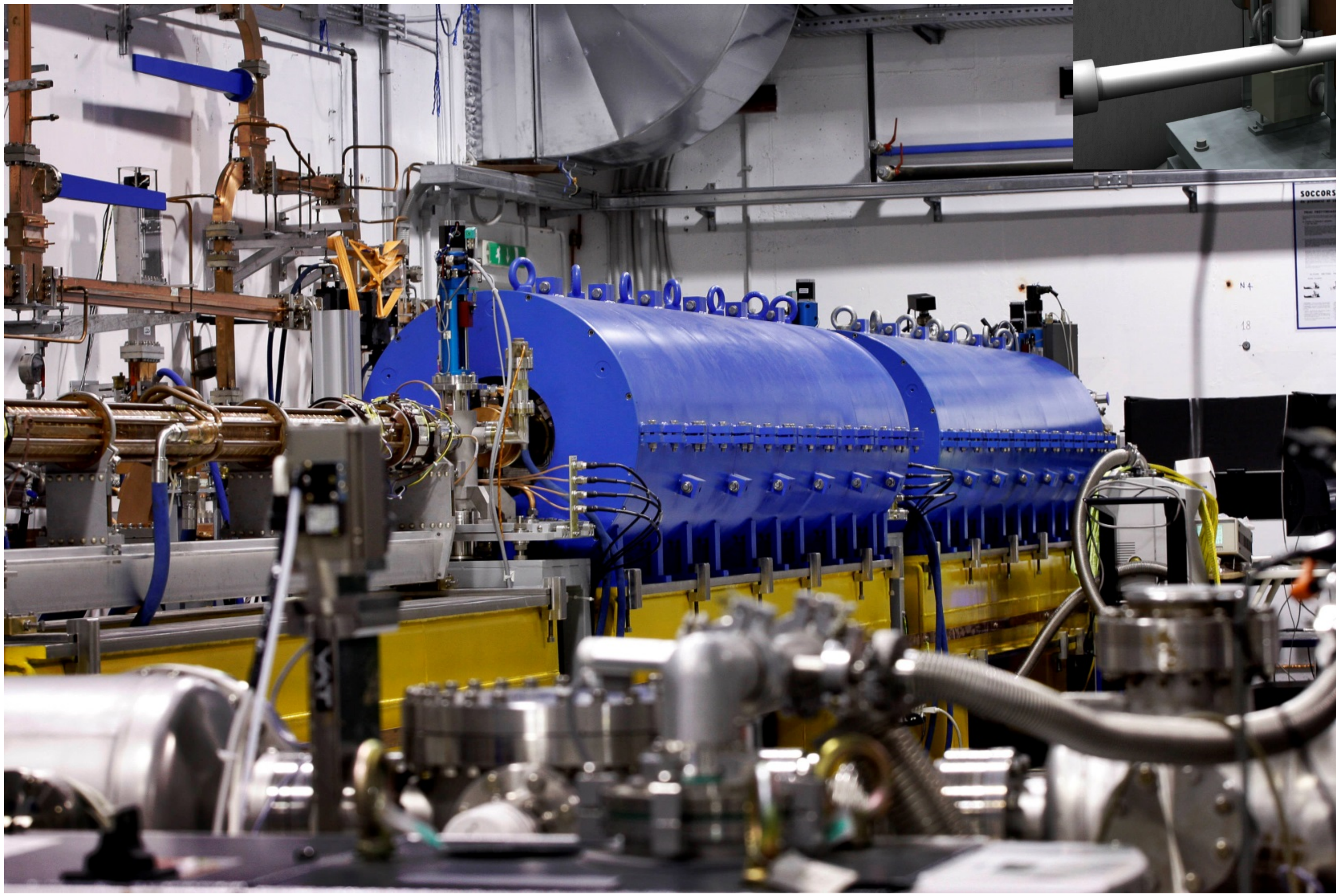
- Candidate LNF to host EuPRAXIA (1-5 GeV)
- FEL user facility (1 GeV – 3nm)
- Advanced Accelerator Test facility (LC) + CERN

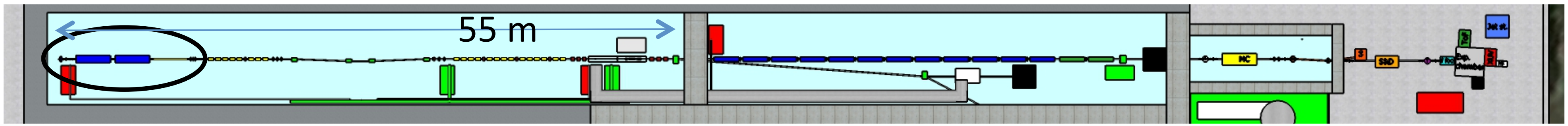


- 500 MeV by RF Linac + 500 MeV by Plasma (LWFA or PWFA)
- 1 GeV by X-band RF Linac only
- Final goal compact 5 GeV accelerator

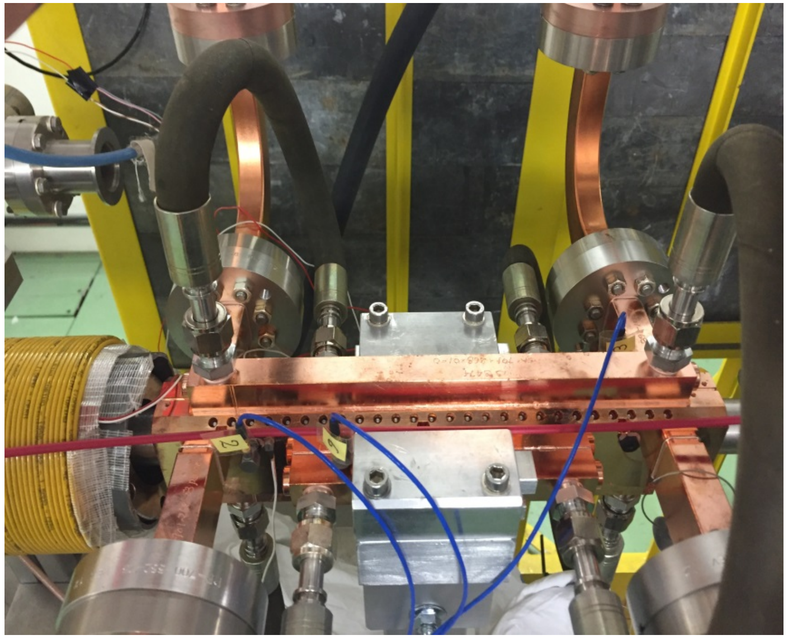
SPARC_LAB HB photo- injector

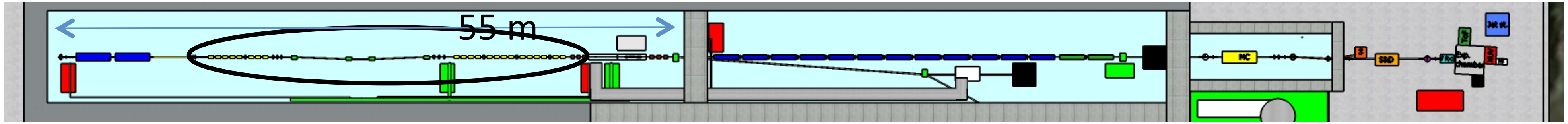




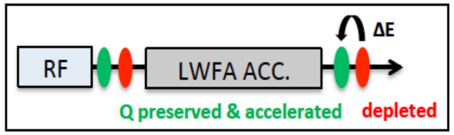


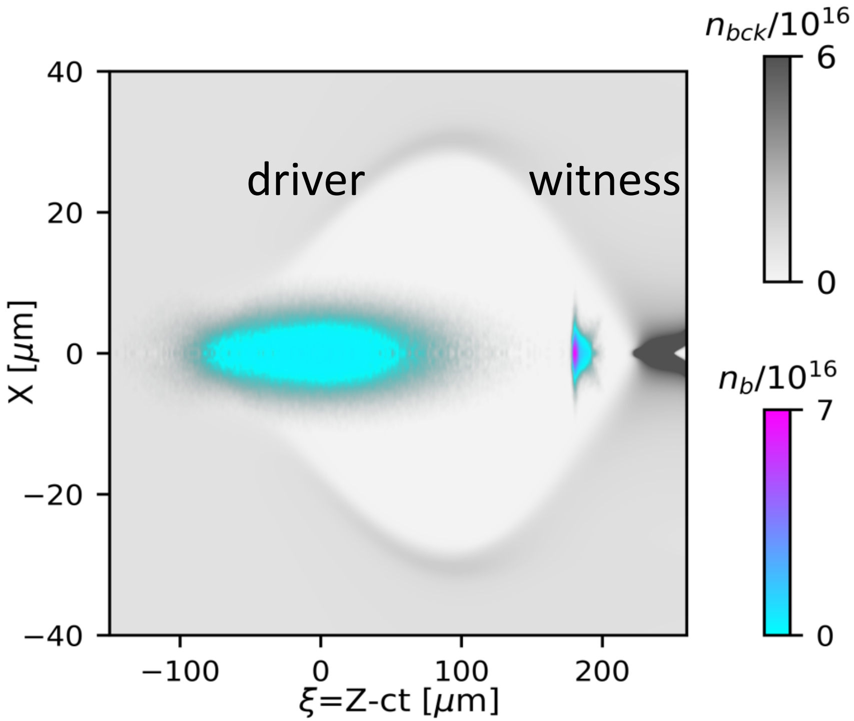
X-band Linac





Plasma WakeField Acceleration – External Injection





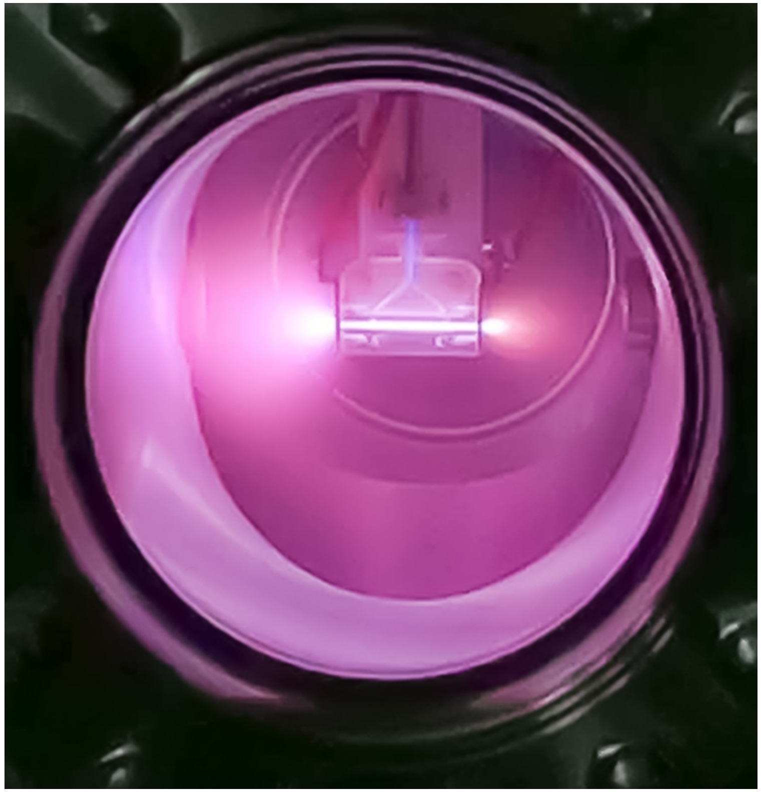
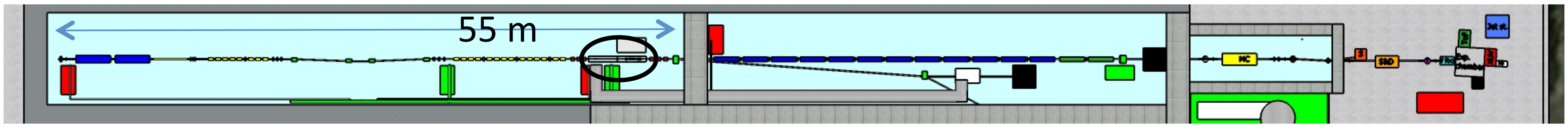
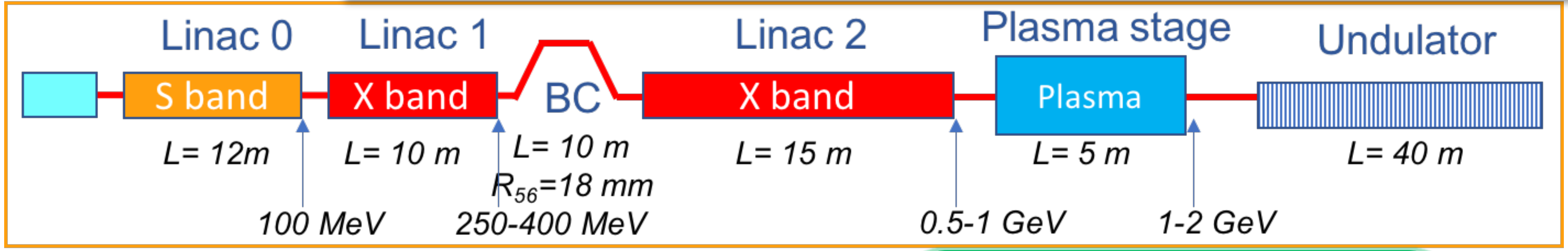
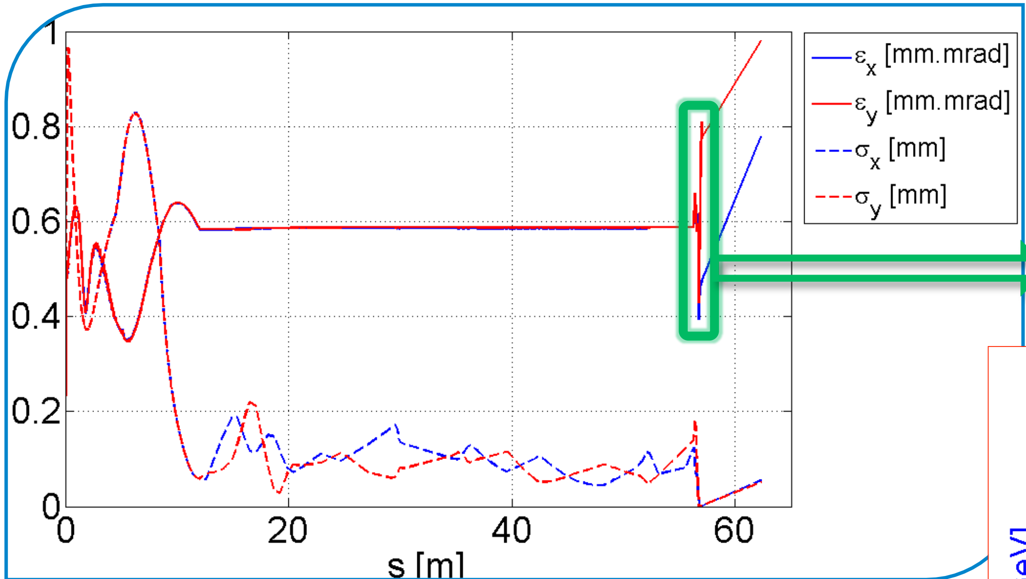


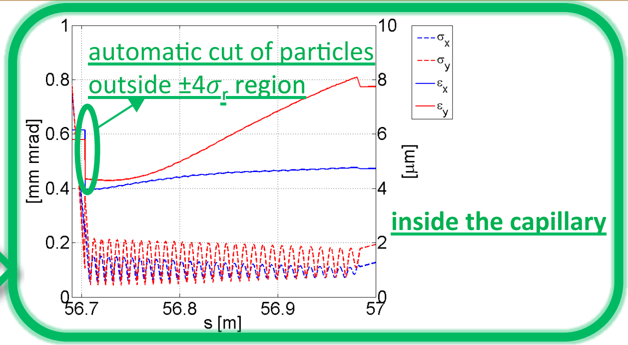
Photo of capillary discharge at SPARC_LAB

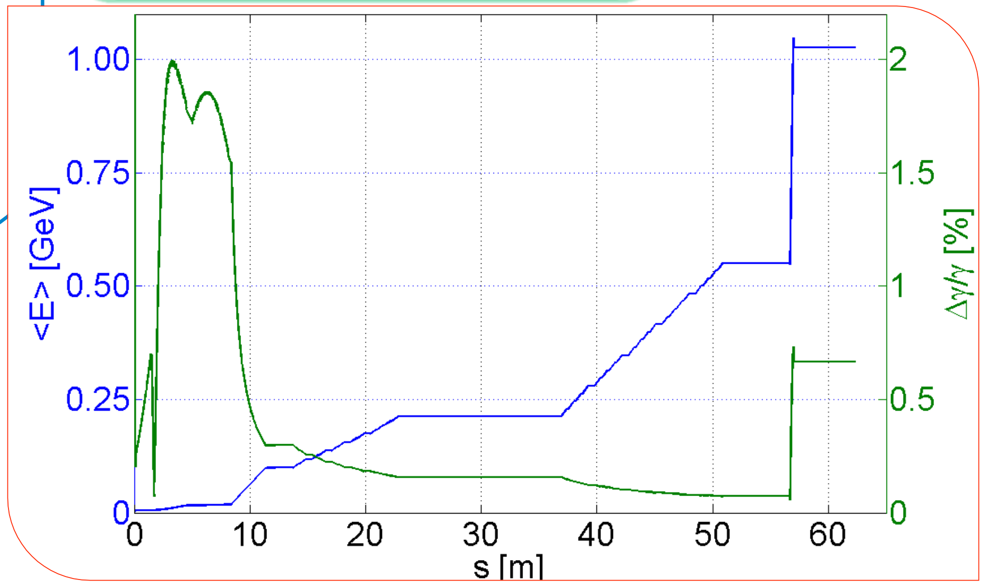


Start-to-end simulations with particle driven PWFA



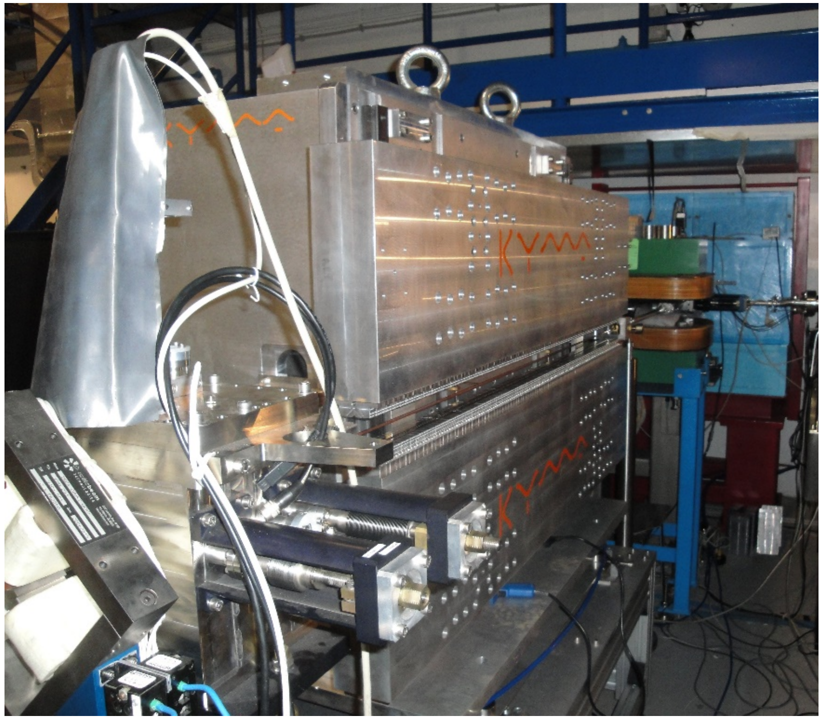


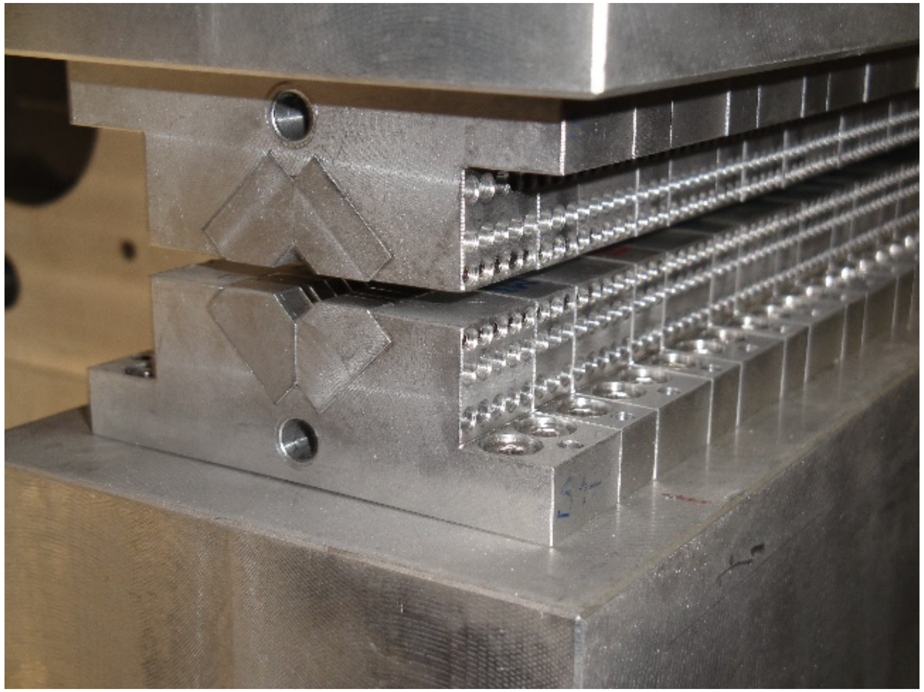




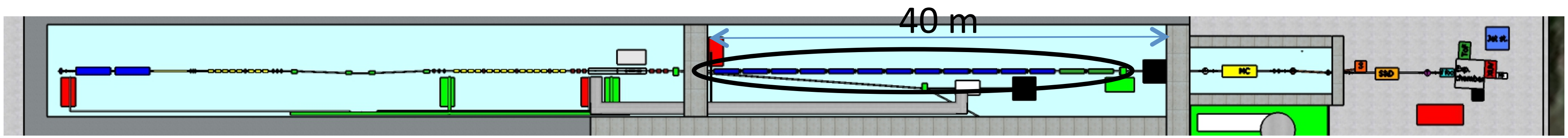
preliminary

Undulators

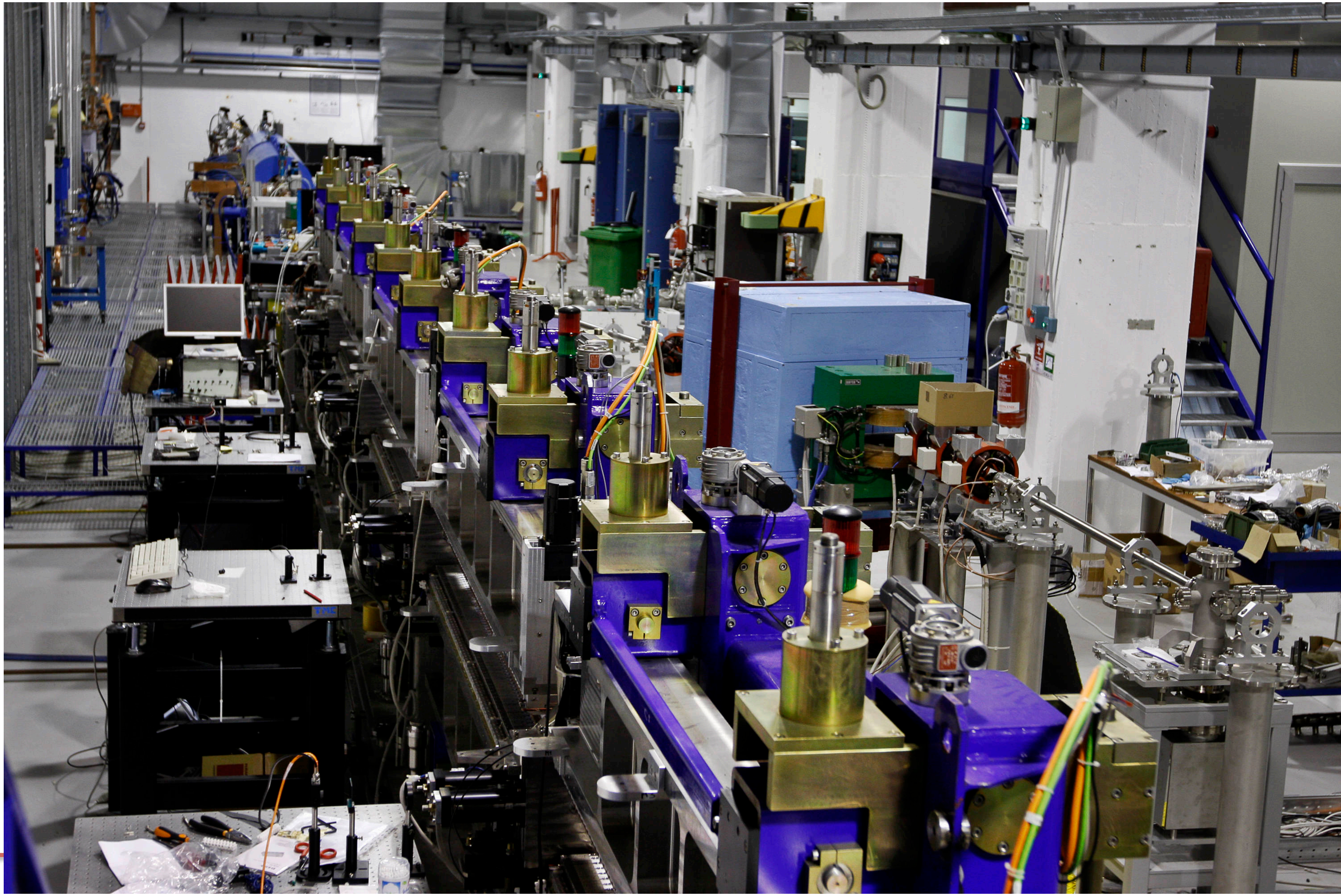




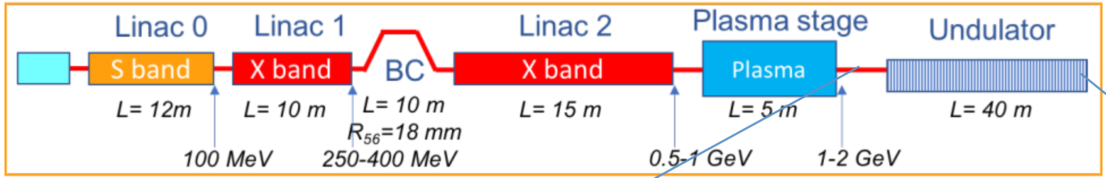
Photos of KYMA Δ udulator at SPARC_LAB: λ=1.4 cm, K1

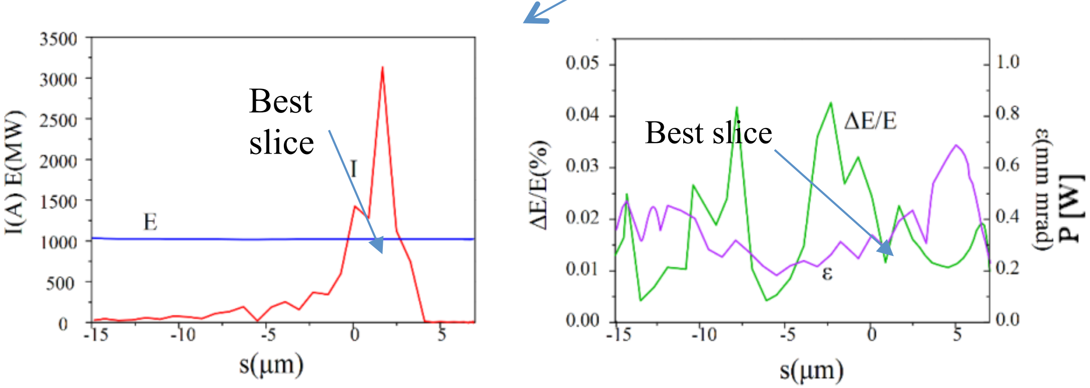


SPARC FEL

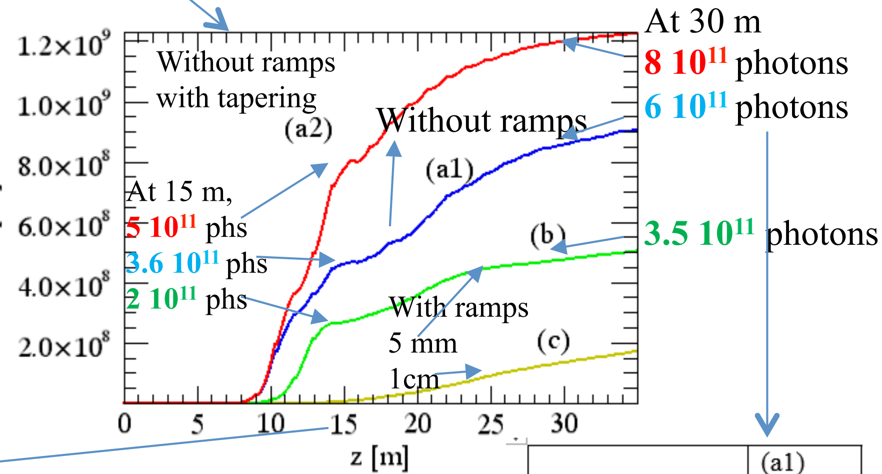


Start-to-end simulations with particle driven PWFA





Characteristics of the electron beam

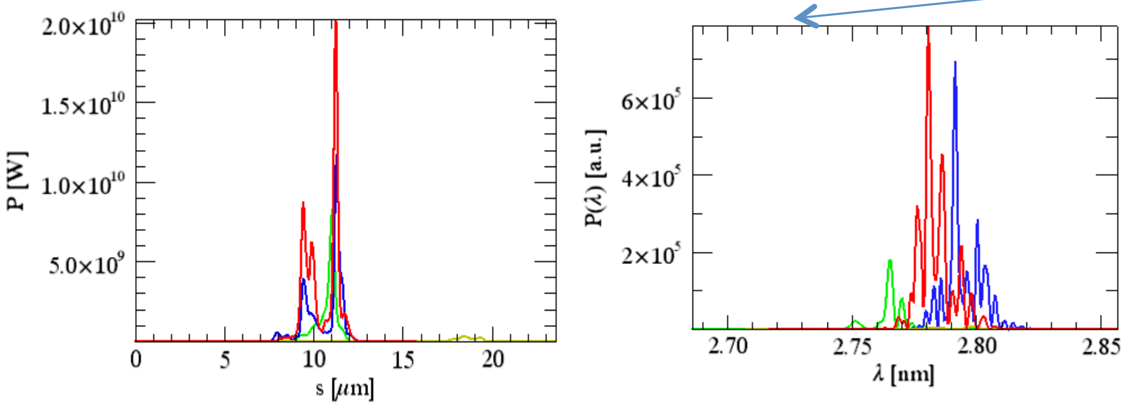


Growth of the radiation along the undulator

Undulator λ_u=1.5 cm, a_w=0.7

Radiation: λ=2.78 nm
E_{phot}=0.44 keV

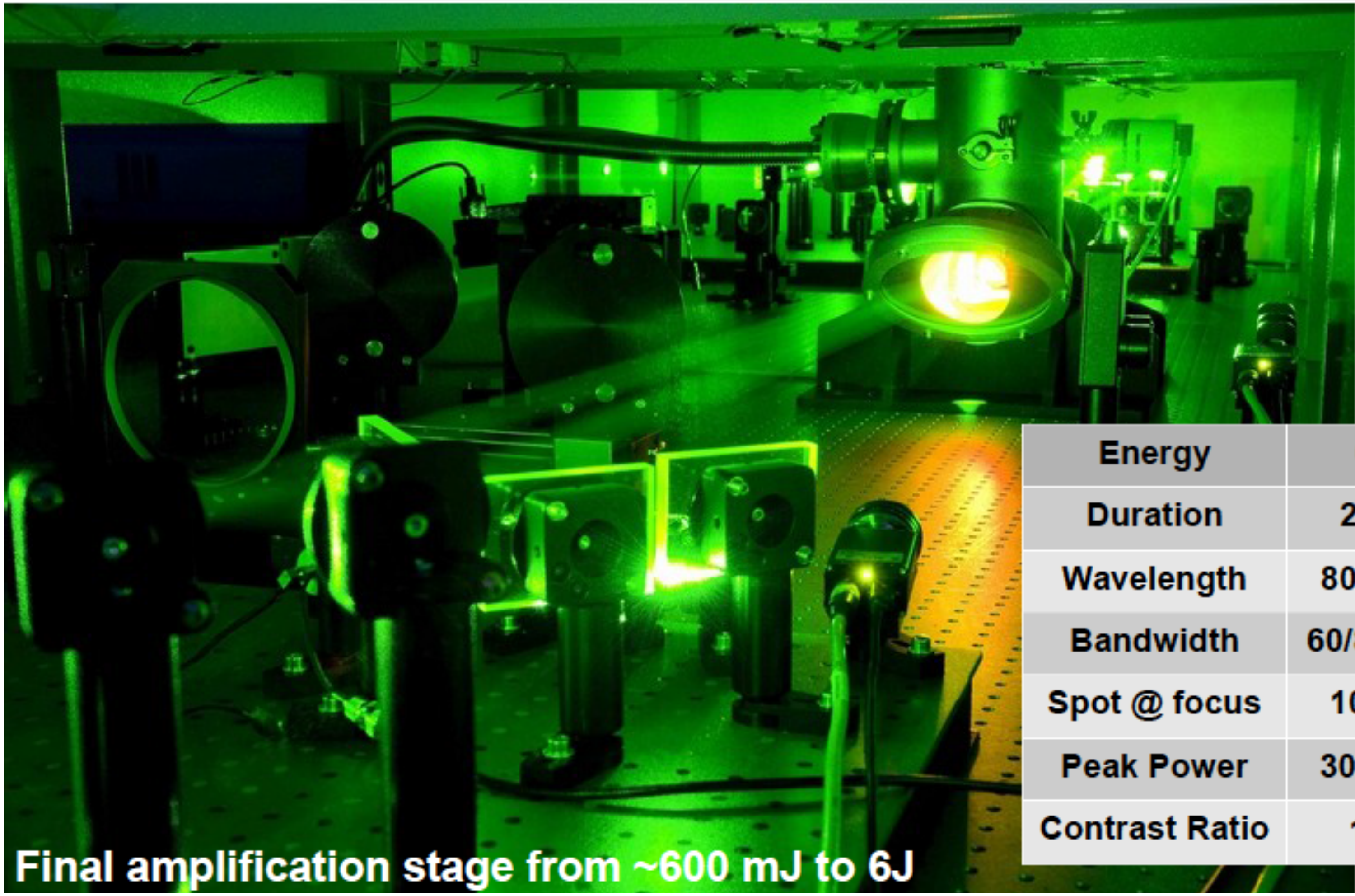
	(a1)
Q(pC)	30
ε_x (mmmrad)	0.39
ε_y (mmmrad)	0.309
ΔE/E (10^{-4})	2.49
I_{peak}(A)	3131
z_1(m)	15
$E(z_1)$ (μJ)	25.8
$N_{phot}(z_1)$ (10^{11})	3.61
z_2(m)	30
$E(z_2)$ (μJ)	43.9
$N_{phot}(z_1)$(10^{11})	6.1
Bandwidth(%)	0.15
Divergence(μrad)	40
Rad. Size (μm)	195



At 15 m, Power and spectral density. Quasi-single spike structure

Courtesy V. Petrillo

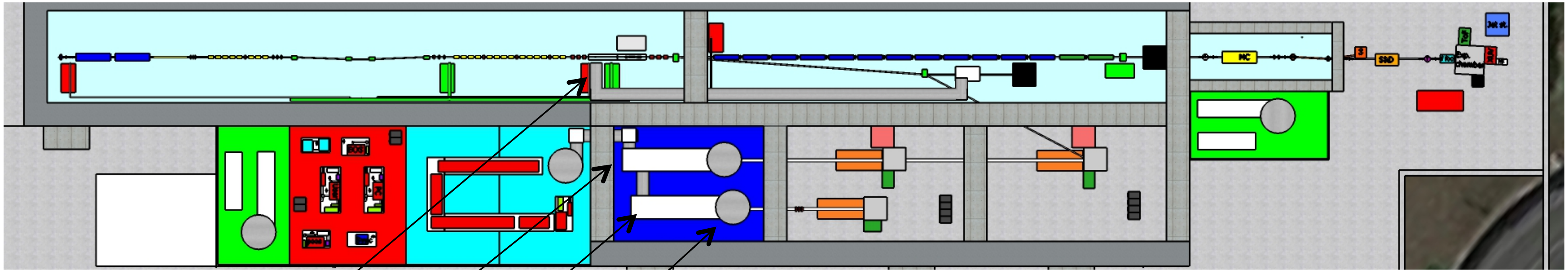
High power laser FLAME



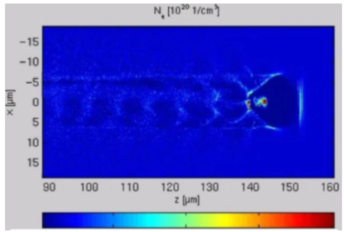
Final amplification stage from ~600 mJ to 6J

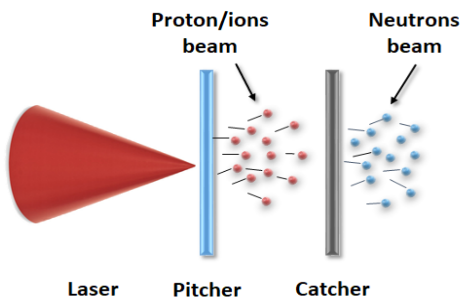
Energy	6 J
Duration	23 fs
Wavelength	800 nm
Bandwidth	60/80 nm
Spot @ focus	10 µm
Peak Power	300 TW
Contrast Ratio	10^{10}

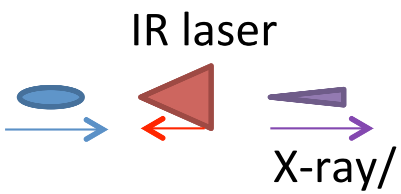
High power laser



- Laser wakefield acceleration in plasma
  - External injection
  - Self injection
- Protons (ions) acceleration
- Neutron source
- Compton scattering



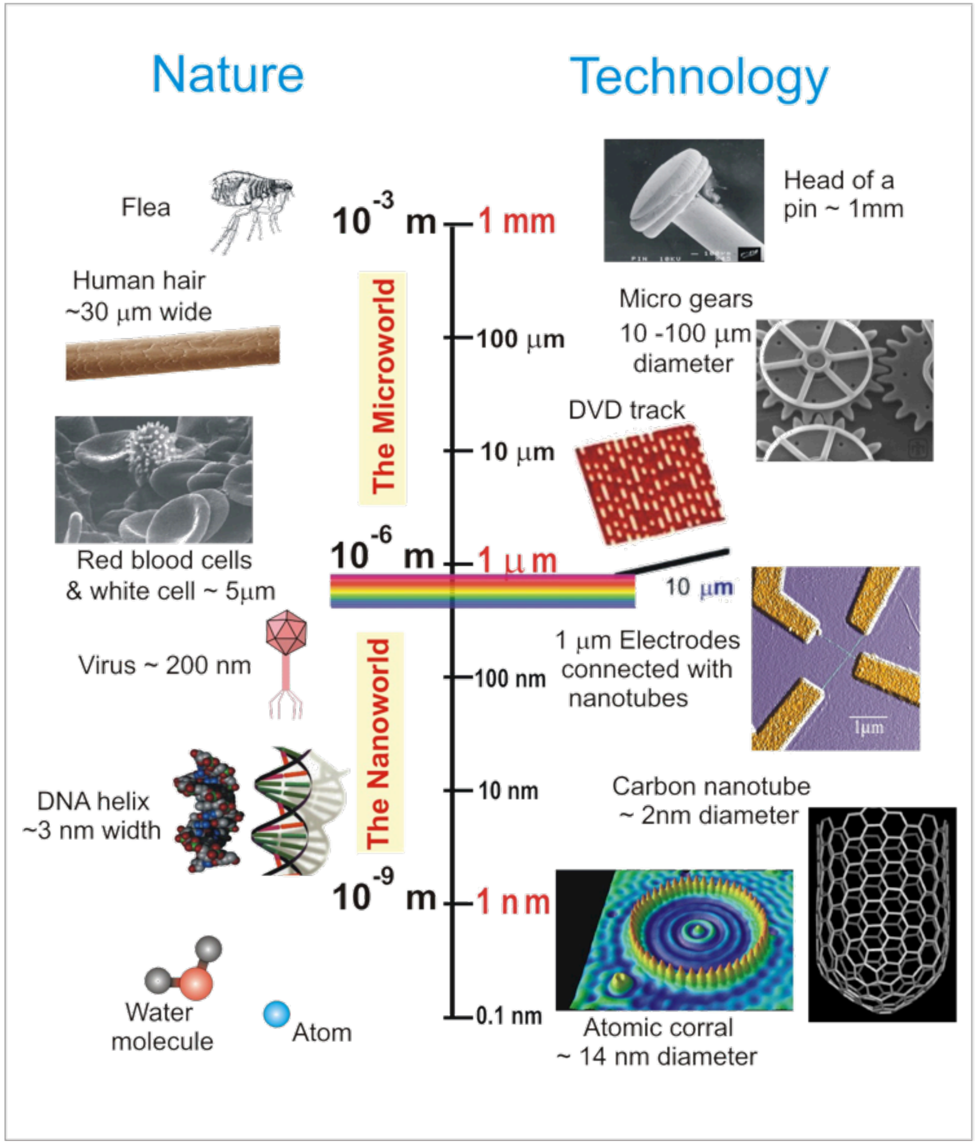




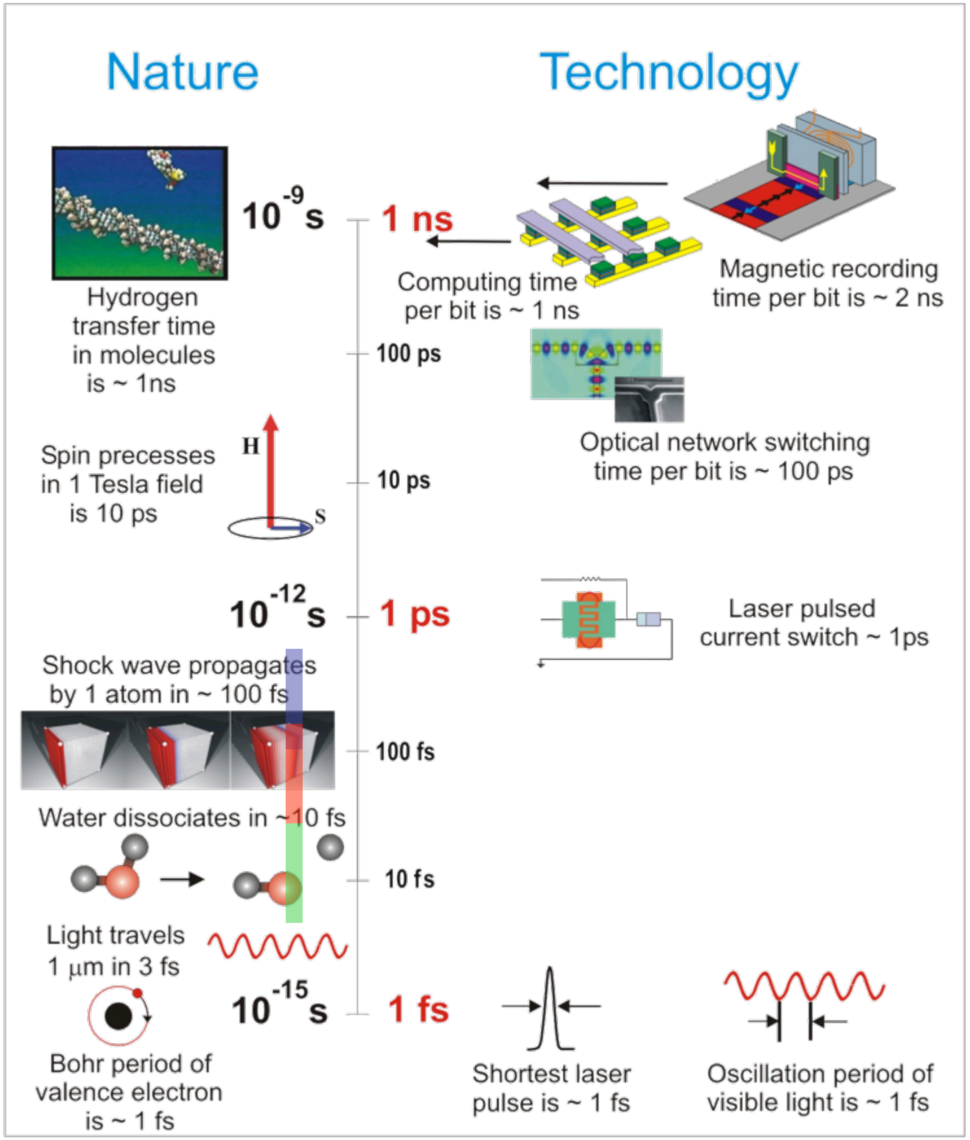
The FEL Applications

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

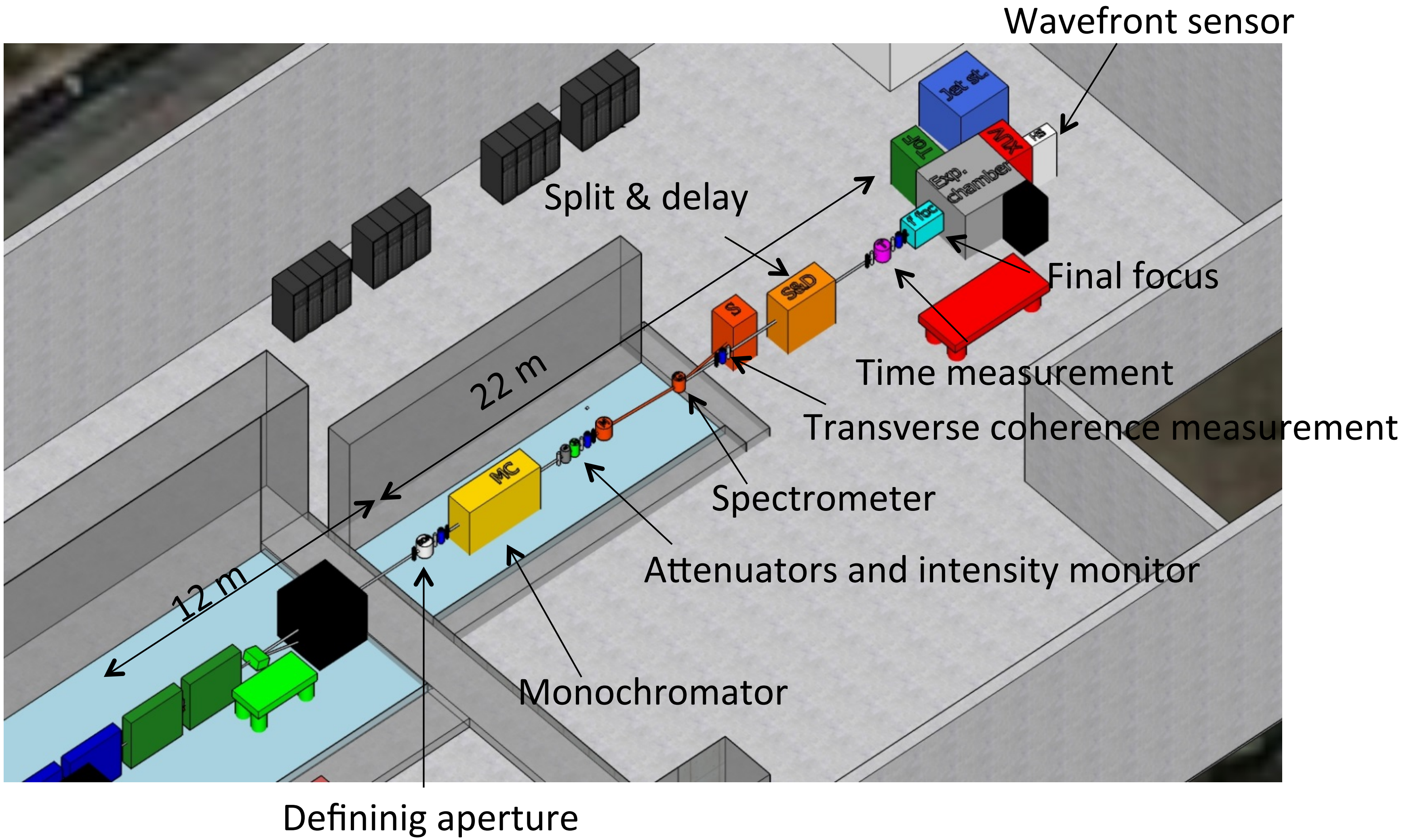
Ultra-Small



Ultra-Fast

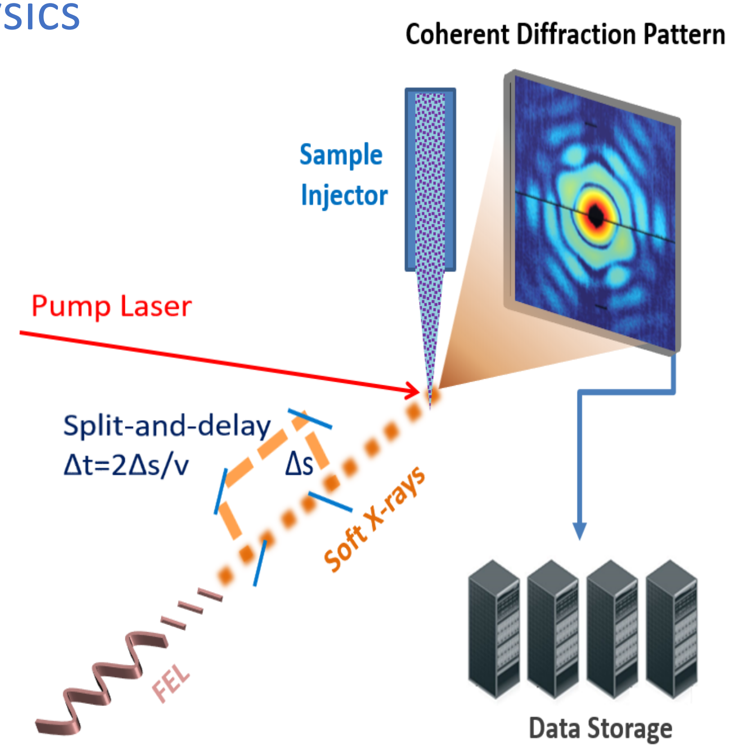


Photon beam line



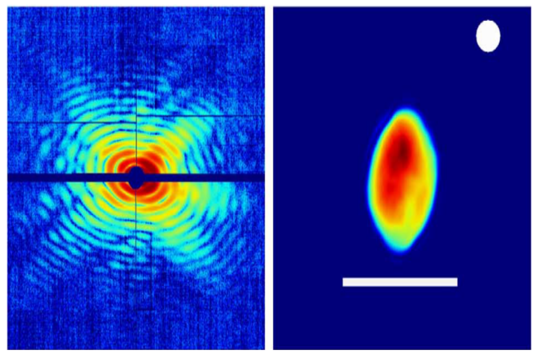
Coherent Imaging at EuPRAXIA@SPARC_LAB

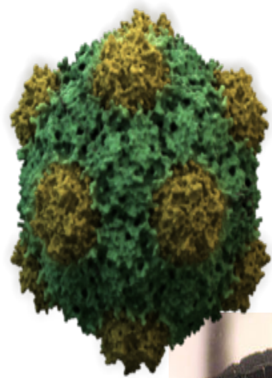
2 key issues: brilliance and coherence of the FEL radiation
1 experimental station performing coherent imaging experiments
Many applications, ranging from biological systems to condensed matter physics



Courtesy F. Stellato

Water Window Coherent Imaging of biological systems
Energy region between oxygen and carbon K-edge
2D and 3D images of biological samples: viruses, cells, organelles, protein fibrils…





Condensed matter
Cluster and nanoparticles
Laser ablation plasma
Metal-insulating transitions
Colossal magnetoresistance phenomena
Pump-probe in stimulated Raman or four wave mixing spectroscopy

Colossal Magnetoresistance
3d Orbital Types