# EuPRAXIA@SPARC_LAB

## design study towards a new compact FEL facility at LNF

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On behalf of the study group

Lisbon, 21 November 2017

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CDR.0 delivery expected by end of 2017

WG 0 – Project Management
- 0.1 Executive summary (M. Ferrario)

WG 1 – Electron beam design and optimization
- 1.1 Advanced High Brightness Photo-injector (E. Chiadroni)
- 1.2 HB Linac technology, (A. Gallo)
- 1.3 Linac design and parameters (C. Vaccarezza)

WG 2 – Laser design and optimization
- 2.1 FLAME upgrade (M. P. Anania)
- 2.2 Advanced Laser systems (L. Gizzi)

WG 3 – Plasma Accelerator
- 3.1 PWFA beam line (A. Marocchino)
- 3.2 LWFA beam line (A. R. Rossi)
- 3.3 Plasma and Beam Diagnostics (A. Cianchi)

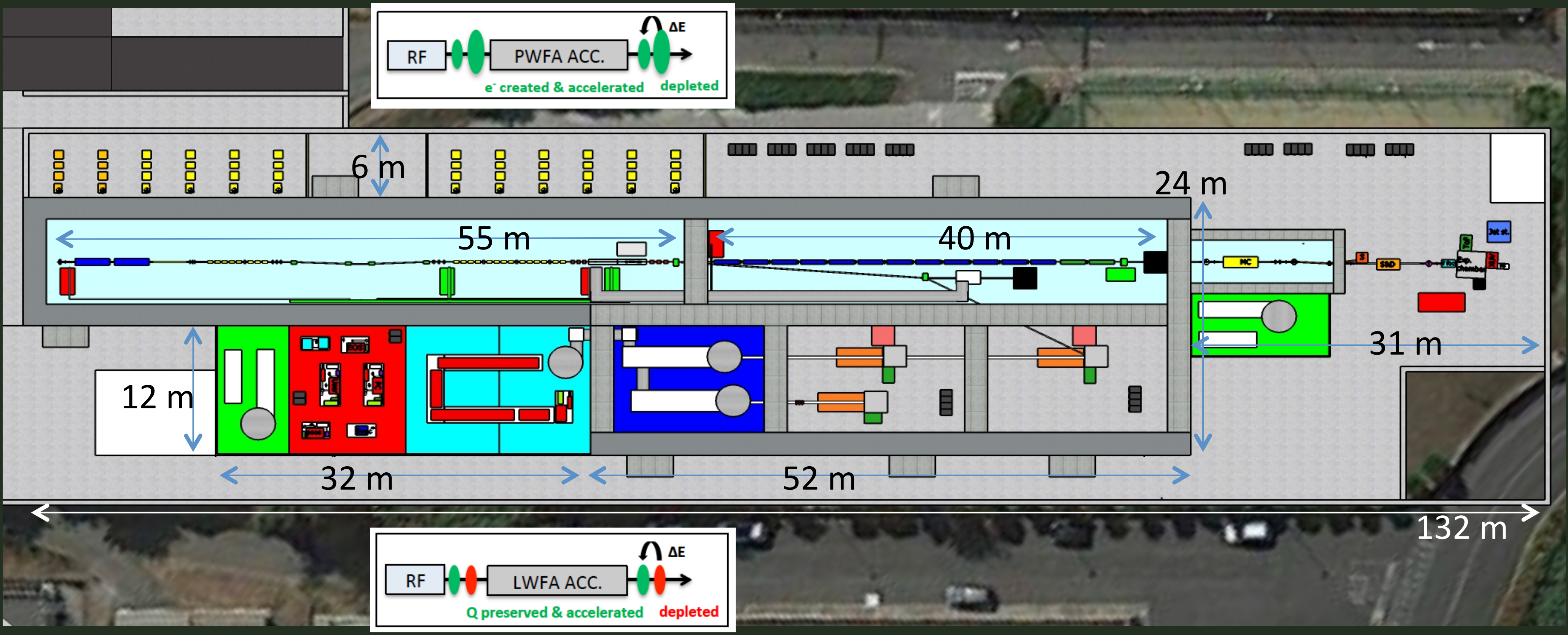
WG 4 – FEL pilot applications
- 4.1 Conventional and Plasma driven FEL (V. Petrillo)
- 4.2 Advanced FEL schemes (G. Dattoli)
- 4.3 Photon beam lines (F. Villa)
- 4.4 FEL user applications (F. Stellato)

WG 5 – Radiation sources and user beam lines
- 5.1 Advanced (dielectric) THz source (S. Lupi)
- 5.2 Compton source (C. Vaccarezza)
- 5.3 Secondary Particle Sources (LNS)?
- 5.4 Laser-driven neutron source (Cianchi)
- 5.4 User beam lines (P. Valente)

WG 6 – Low Energy Particle Physics
- 6.1 Advanced positron sources (A. Variola)
- 6.2 Fundamental physics experiments , LabAstro (C. Gatti)
- 6.3 Plasma driven photon collider (L. Serafini)

WG 7 – Infrastructure
- 7.1 Civil Engineering and conventional plants (U. Rotundo)
- 7.2 Control system (G. Di Pirro)
- 7.3 Radiation Safety (A. Esposito)
- 7.4 Machine layout

- 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

# SASE FELs at short wavelengths requirements

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

- FEL Parameter

$$\rho = 0.136\frac{1}{\gamma_r} J^{1/3} B_u^{2/3} \lambda_u^{4/3} \quad \Rightarrow \quad 10^{-3}$$

- Number of Photons at saturation

$$N_{ph} \approx 1.6 \frac{E_b}{h\nu_{ph}} \rho Q \quad \Rightarrow \quad >10^{11} \quad \Rightarrow \text{Q>30pC}$$

- Gain Length

$$L_G = \frac{\lambda_u}{4\pi\sqrt{3}\rho}$$

- Slice Length

$$L_s = \frac{\lambda_r}{4\pi\sqrt{3}\rho} \quad \Rightarrow \quad \approx 1\ \mu\text{m}$$

- Constraint on emittance

$$\varepsilon_n < \frac{\gamma\lambda_r}{4\pi} \quad \Rightarrow \quad <1\ \mu\text{m}$$

- Constraint on energy spread

$$\Delta\gamma/\gamma < 0.5\rho \quad \Rightarrow \quad <10^{-3}$$

- Relative bandwidth

$$\frac{\Delta\omega}{\omega} = \sqrt{\frac{\rho}{N_u}}$$

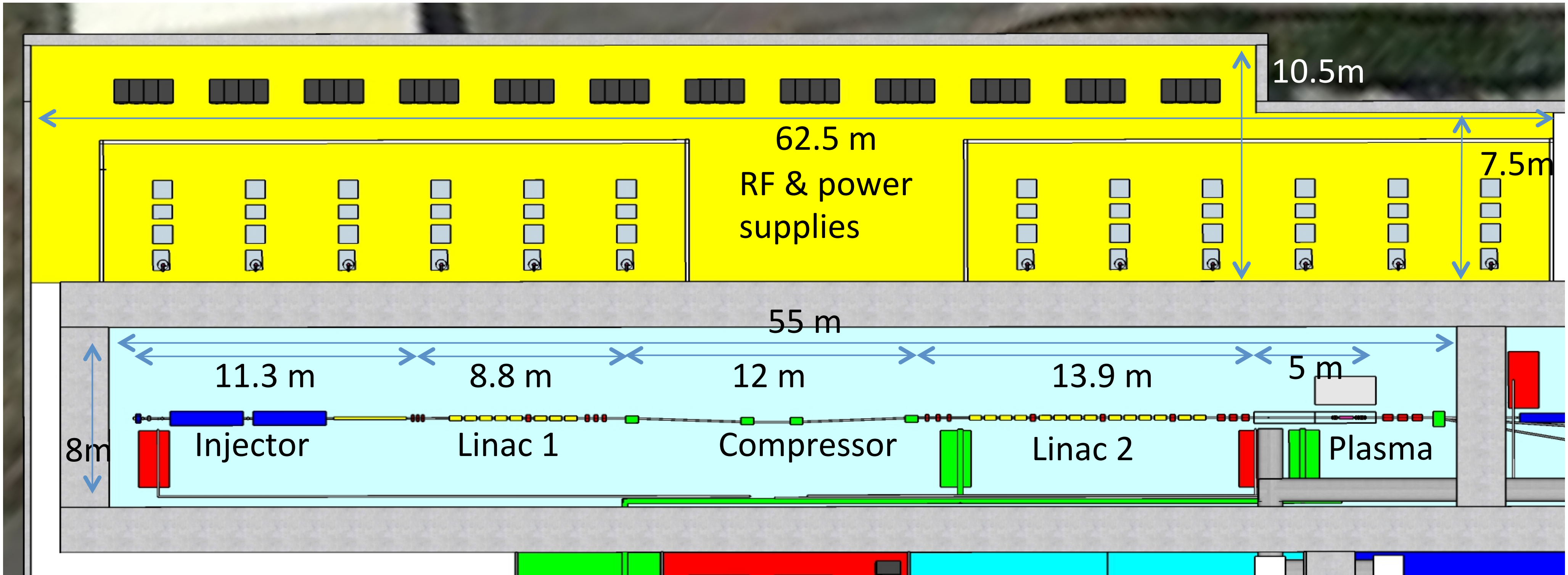
# FEL Electron Beam Requirements



## Electron beam parameters at the undulator

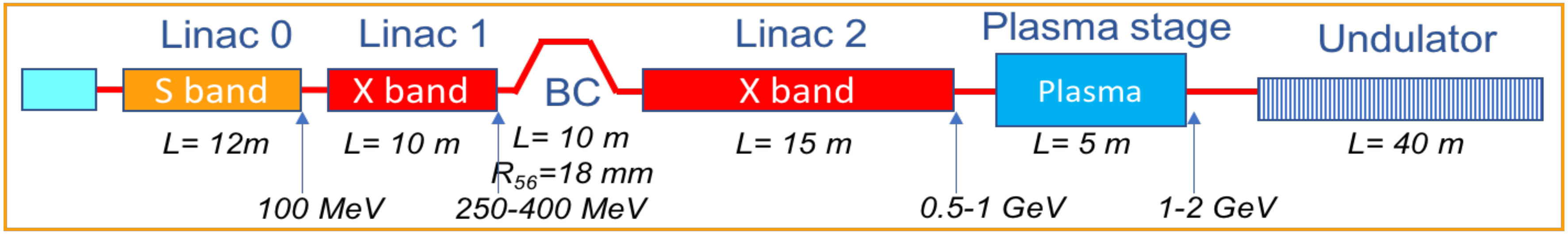
| Quantity | Symbol [Unit of Meas.] | Target parameters |
|---|---|---|
| Energy | E [GeV] | 1 - 5 |
| Charge | Q [pC] | 30 |
| Bunch length (FWHM) | $t_{FWHM}$ [fs] | 10 |
| Peak current | I [kA] | 3 |
| Repetition rate | f [Hz] | 10 |
| # of bunches | N | 1 |
| Transverse Norm. emittance | $\varepsilon_{n,x},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

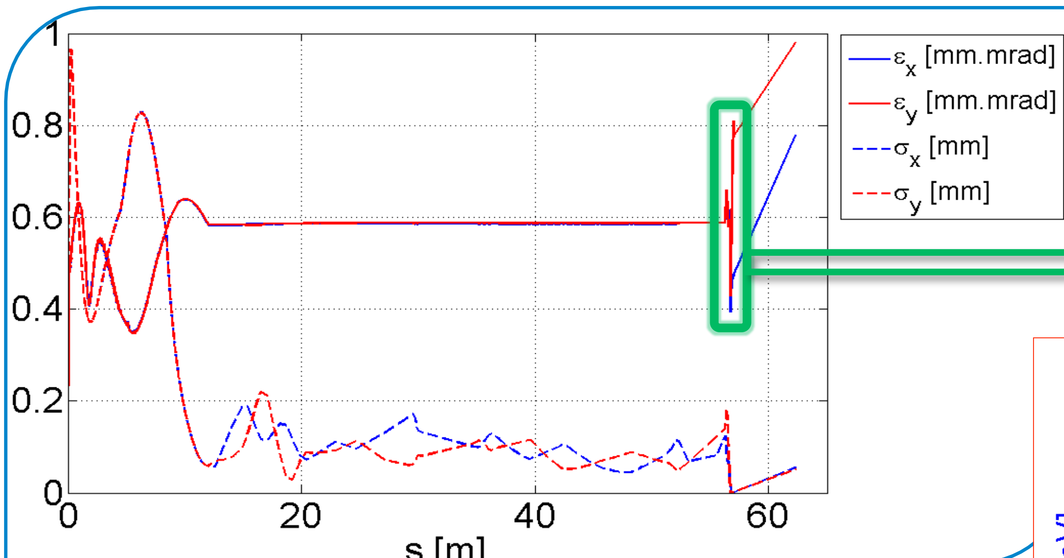
# Accelerator (X-band EU frequency – 100 Hz?)

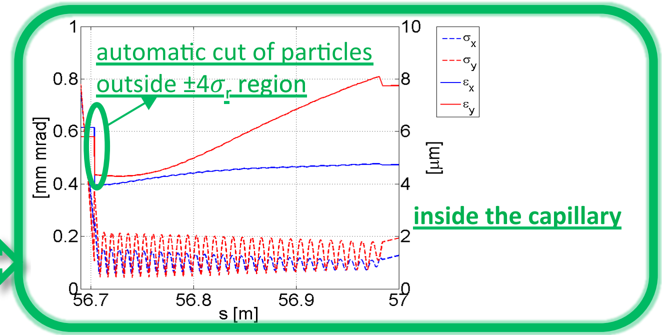


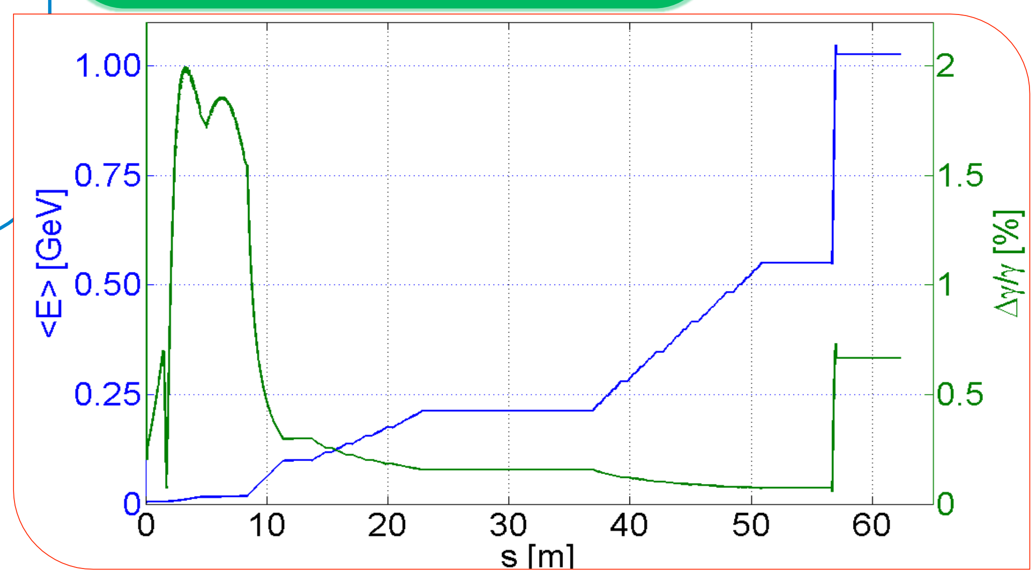

- Injector:
  - Gun+solenoid
  - 3x 3m s-band sectons
- Linac 1:
  - 8x 0.5m x-band sections
  - Matching Quads
- Compressor:
  - 2.19° deflection
- Linac 2:
  - 14x 0.5m x-band sections
  - Matching Quads
- Plasma:
  - PMQ matching
  - 0.6 m capillary

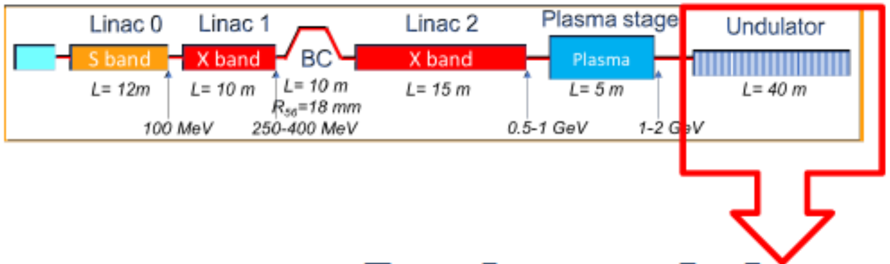
# 30 pC beam Start To End Simulations



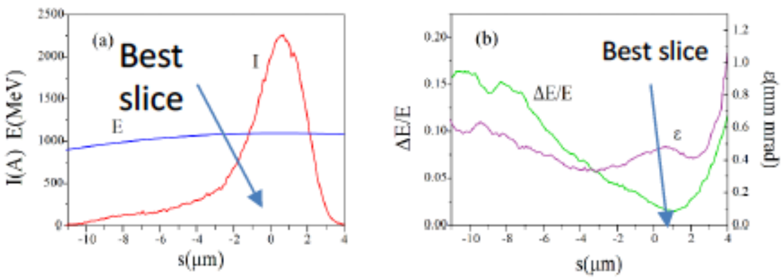





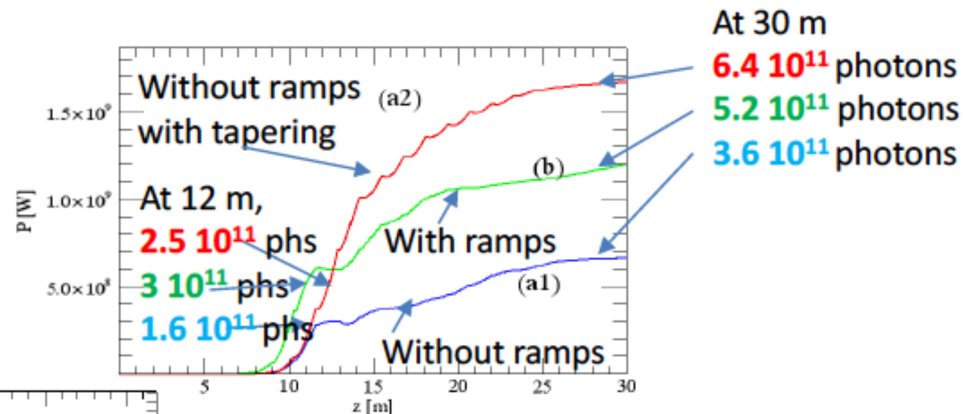

# In the undulator


Undulator $\lambda_u$=1.5 cm, $a_w$=0.8

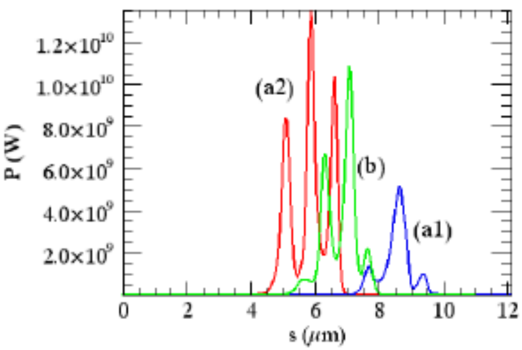
Radiation: $\lambda$=2.7 nm
$E_{phot}$=0.45 keV



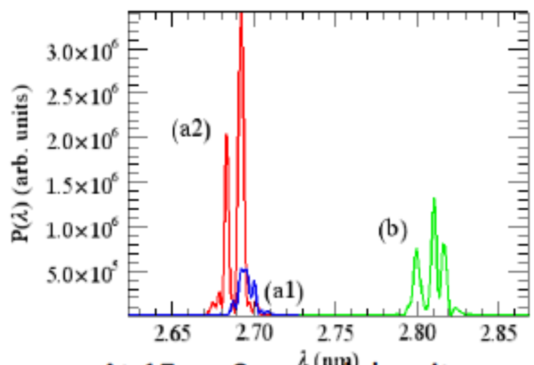

Characteristics of the electron beam, case a1




Growth of the radiation along the undulator



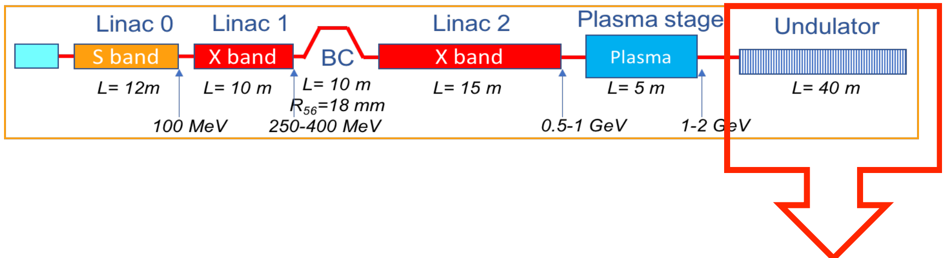

At 15 m, Power density
Quasi-single structure




At 15 m, Spectral density
Quasi-single spike structure

| | (a) |
|---|---|
| Q(pC) | 30 |
| $\varepsilon_x$ (mmmrad) | 0.45 |
| $\varepsilon_y$ (mmmrad) | 0.49 |
| $\Delta E/E$ ($10^{-4}$) | 1.54 |
| $I_{peak}$(A) | 2258 |
| $z_1$(m) | 12 |
| E($z_1$) (μJ) | 12 |
| $N_{phot}$($z_1$) ($10^{11}$) | 1.62 |
| $z_2$(m) | 30 |
| E($z_2$) (μJ) | 27. |
| $N_{phot}$($z_1$)($10^{11}$) | 3.63 |
| Bandwidth(%) | 0.15 |
| Divergence(μrad) | 50 |
| Rad. Size (μm) | 155 |

Courtesy of V. Petrillo

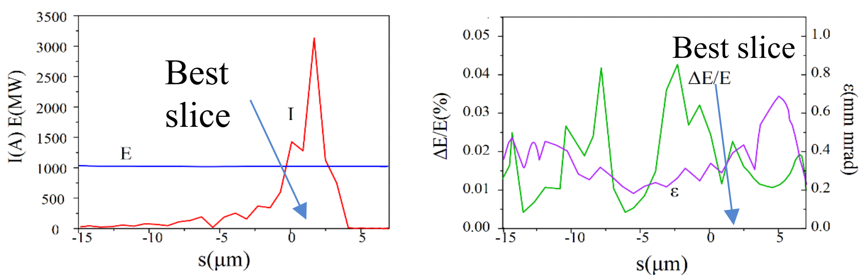




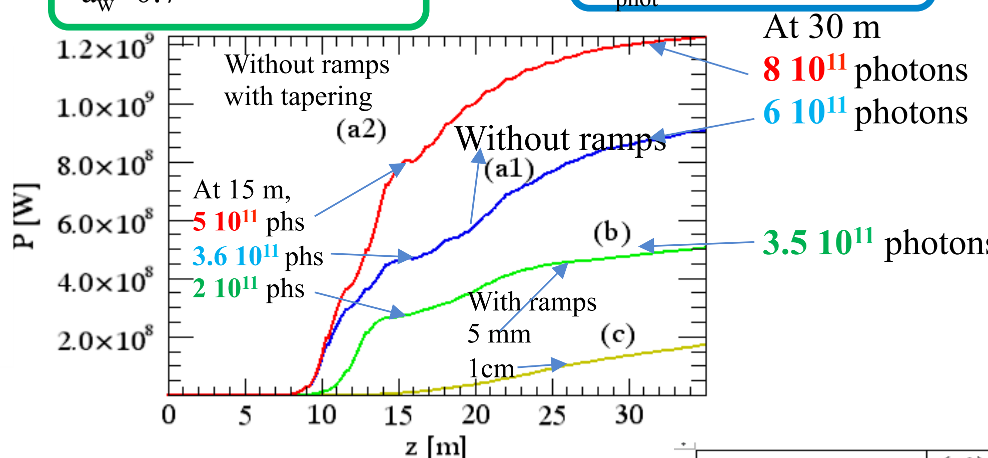
# In the undulator

Undulator $\lambda_u$=1.5 cm, $a_w$=0.7

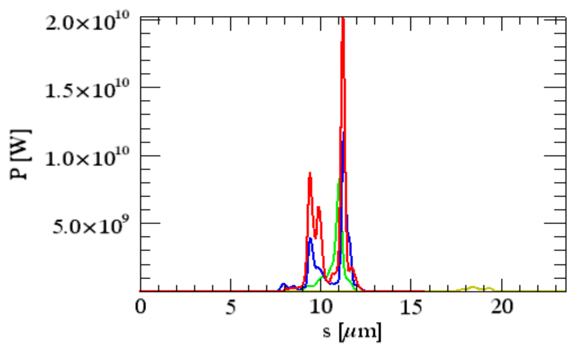
Radiation: λ=2.78 nm
$E_{phot}$=0.44 keV



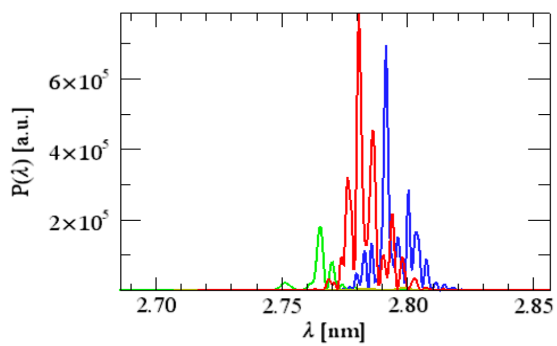

Characteristics of the electron beam




Growth of the radiation along the undulator




At 15 m, Power density
Quasi-single structure




At 15 m, Spectral density
Quasi-single spike structure

| | (a1) |
|---|---|
| Q(pC) | 30 |
| $\varepsilon_x$ (mmmrad) | 0.39 |
| $\varepsilon_y$ (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 |

# FEL driven by PLASMA

| | Units | 1 GeV PWFA with Undulator Tapering | 1 GeV LWFA with Undulator Tapering |
|---|---|---|---|
| **Bunch charge** | pC | 29 | 26.5 |
| **Bunch length rms** | fs | 11.5 | 8.4 |
| **Peak current** | kA | 2.6 | 3.15 |
| **Rep. rate** | Hz | 10 | 10 |
| **Rms Energy Spread** | % | 0.73 | 0.81 |
| **Slice Energy Spread** | % | 0.022 | 0.015 |
| **Average Rms norm. emittance** | μm | 0.6 | 0.47 |
| **Slice norm. emittance** | μm | 0.39-0.309 | 0.47 |
| **Slice Length** | μm | 1.39 | 1.34 |
| | | | |
| **Radiation wavelength** | nm | 2.79 | 2.7 |
| **ρ** | x $10^{-3}$ | 2 | 2 |
| **Undulator period** | cm | 1.5 | 1.5 |
| **K** | | 0.987 | 1.13 |
| **Undulator length** | m | 30 | 30 |
| **Saturation power** | GW | 0.850-1.2 | 1.3 |
| **Energy** | μJ | 63 | 63.5 |
| **Photons/pulse** | | 8.8 x $10^{11}$ | 8.6 x $10^{11}$ |
| **Bandwidth** | % | 0.35 | 0.42 |
| **Divergence** | μrad | 49 | 56 |
| **Rad. size** | μm | 210 | 160 |
| **Brilliance per shot** | (s $mm^2$ $mrad^2$bw (‰)$)^{-1}$ | 0.83 x $10^{27}$ | 1.22 x$10^{27}$ |

# FEL simulation with **linac accelerated electron beams, high flux case**

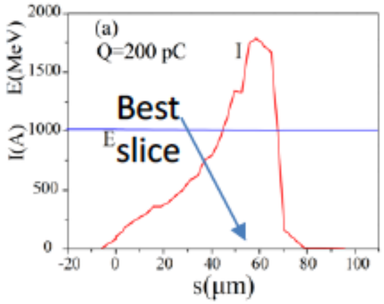
**Case with 200 pC**

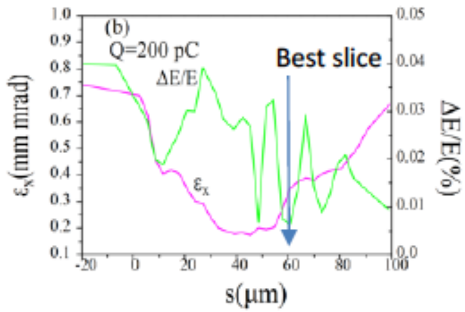
Undulator $\lambda_u$=1.5 cm, $a_w$=0.7

Radiation: $\lambda$=2.87 nm
$E_{phot}$=0.43 keV

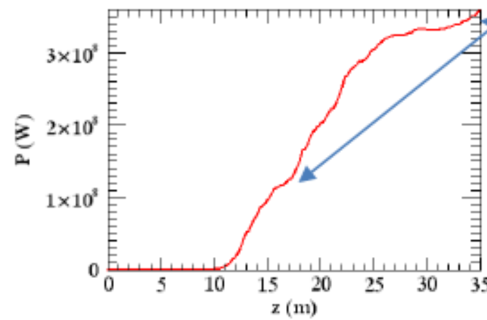
First saturation at 15 m with **9.1 $10^{11}$** photons

At 35 m, **2.7 $10^{12}$** photons

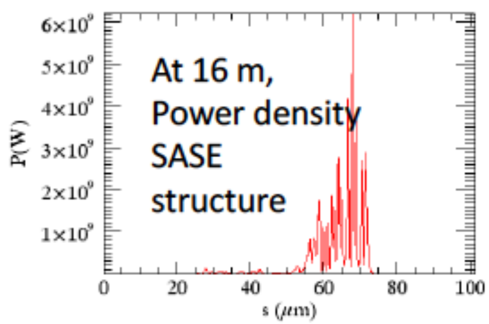


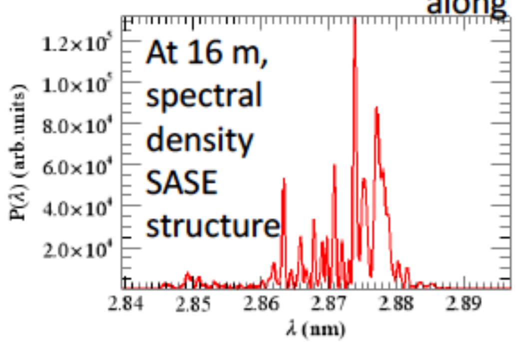




Characteristics of the electron beam




Growth of the radiation along the undulator



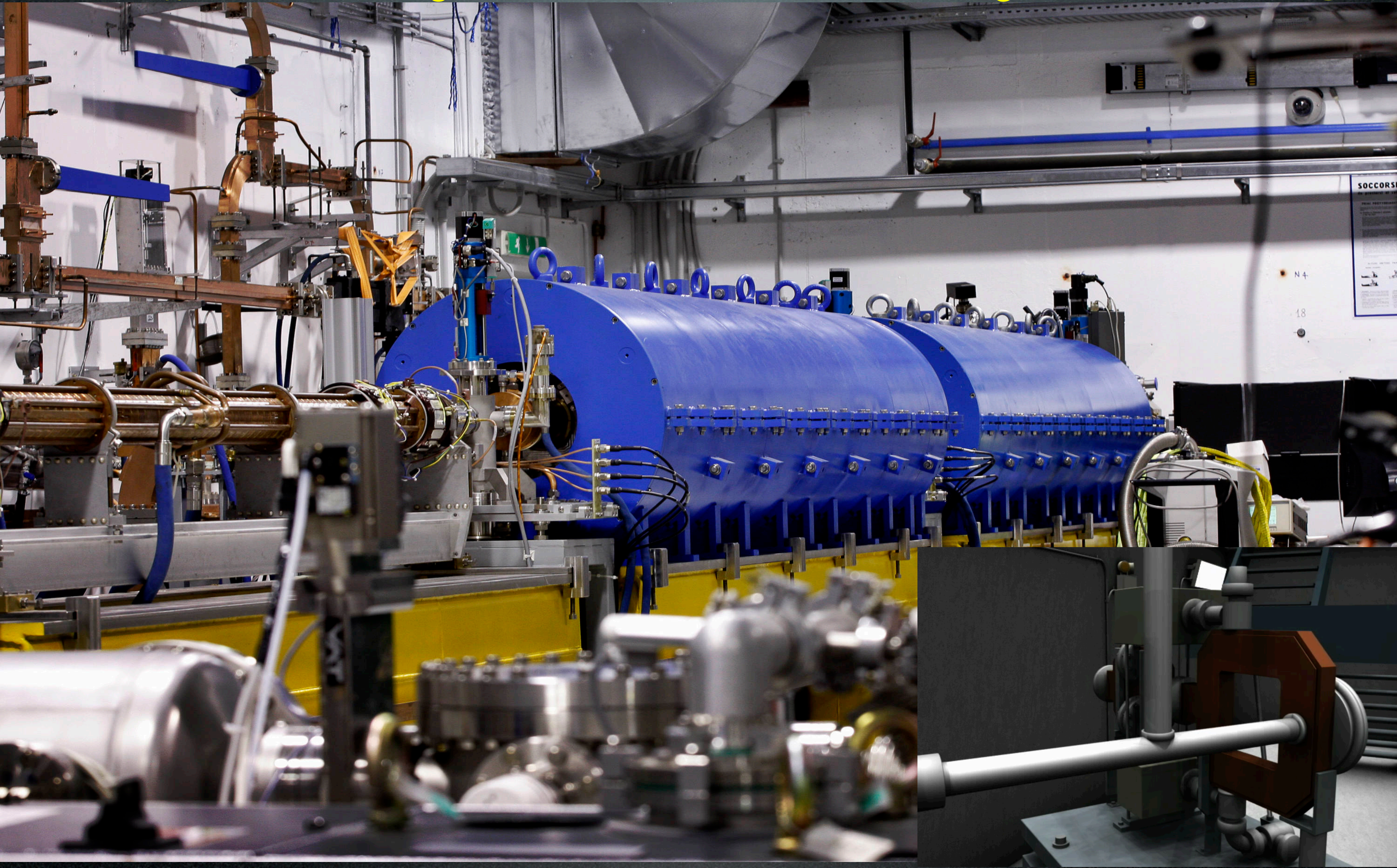

Courtesy of V. Petrillo

# FEL driven by X-band only

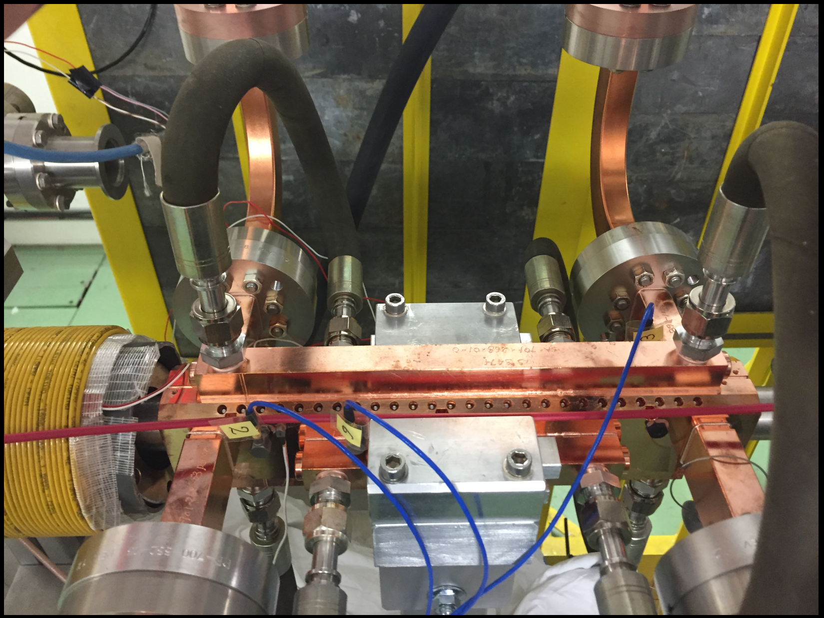
| | Units | 1 GeV with X-band linac only 100 pC | 1 GeV with X-band linac only 200 pC |
|---|---|---|---|
| **Bunch charge** | pC | 100 | 200 |
| **Bunch length rms** | fs | 38.2 | 55.6 |
| **Peak current** | kA | 2. | 1.788 |
| **Rep. rate** | Hz | 10 | 10 |
| | | | |
| **Rms Energy Spread** | % | 0.1 | 0.05 |
| **Slice Energy Spread** | % | 0.018 | 0.02 |
| **Average Rms norm. emittance** | μm | 0.5 | 0.5 |
| **Slice norm. emittance** | μm | 0.35-0.24 | 0.4-0.37 |
| **Slice Length** | μm | 1.25 | 1.66 |
| | | | |
| **Radiation wavelength** | nm | 2.4 (0.52 keV) | 2.87(0.42 keV) |
| **ρ** | $\times 10^{-3}$ | 1.9(1.7) | 1.55(1.38) |
| **Undulator period** | cm | 1.5 | 1.5 |
| **K** | | 0.987 | 0.987 |
| **Saturation length** | m | 15-25 | 16-30 |
| **Saturation power** | GW | 0.361-0.510 | 0.120-0.330 |
| **Energy** | μJ | 48-70 | 64-177 |
| **Photons/pulse** | | $5.9\text{-}8.4 \times 10^{11}$ | $9.3\text{-}25.5 \times 10^{11}$ |
| **Bandwidth** | % | 0.13-2.8 | 0.24-0.46 |
| **Divergence** | μrad | 17.5-16 | 28-27 |
| **Rad. size** | μm | 65-75 | 120-200 |
| **Brilliance per shot** | $(\text{s mm}^2 \text{ mrad}^2 \text{bw} (‰))^{-1}$ | $\text{Fx}3.8\text{-}2.2\ 10^{28}$ | $\text{Fx}2.5\text{-}1.4\ 11^{27}$ |

# Technological Aspects

# HB photo- injector with Velocity Bunching



# X-band Linac

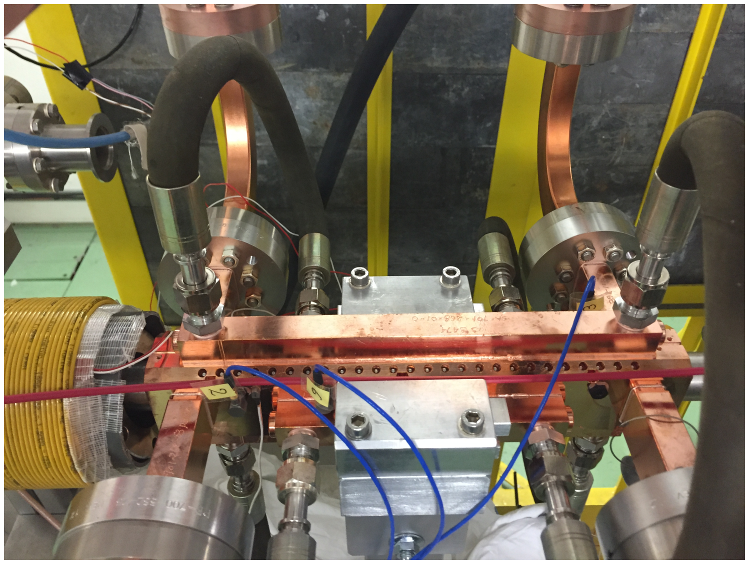


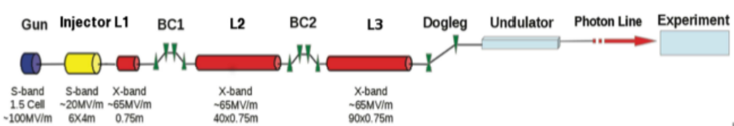
# Compact

# New EU Design Study Approved

## 3 years - 3 MEuro

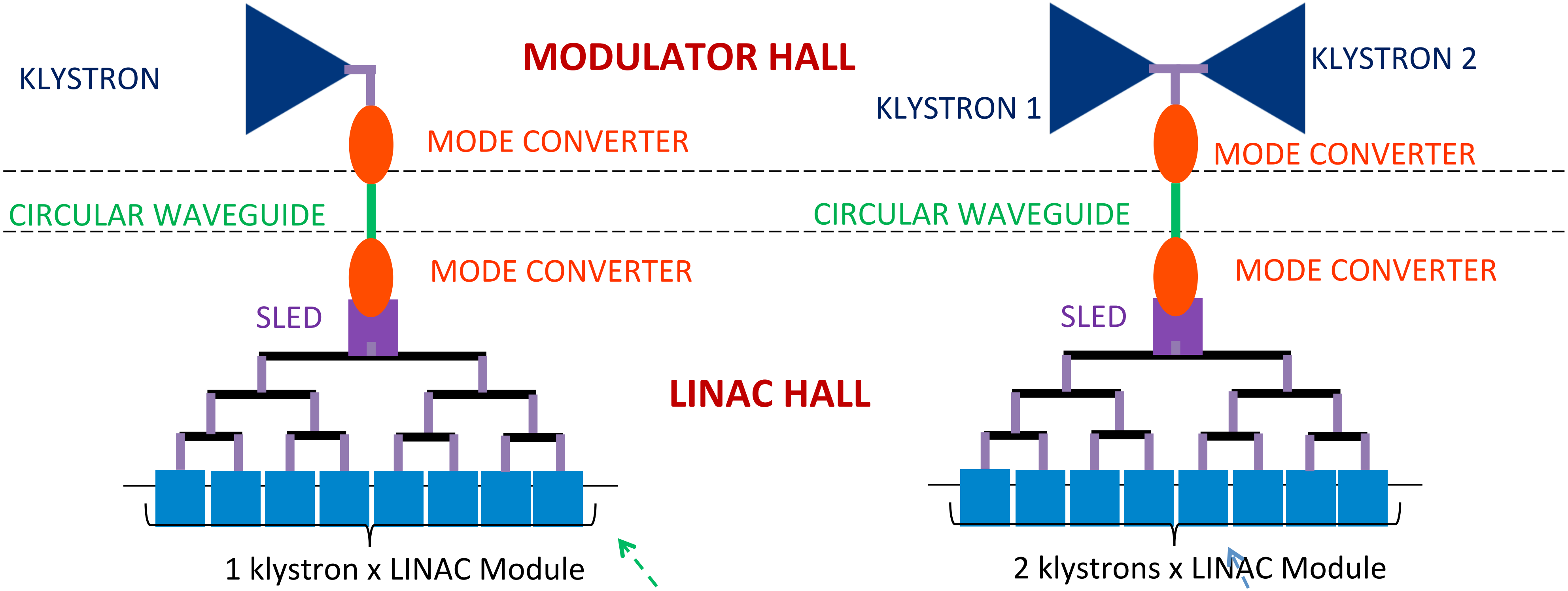
## Coordinator: G. D'Auria (Elettra)





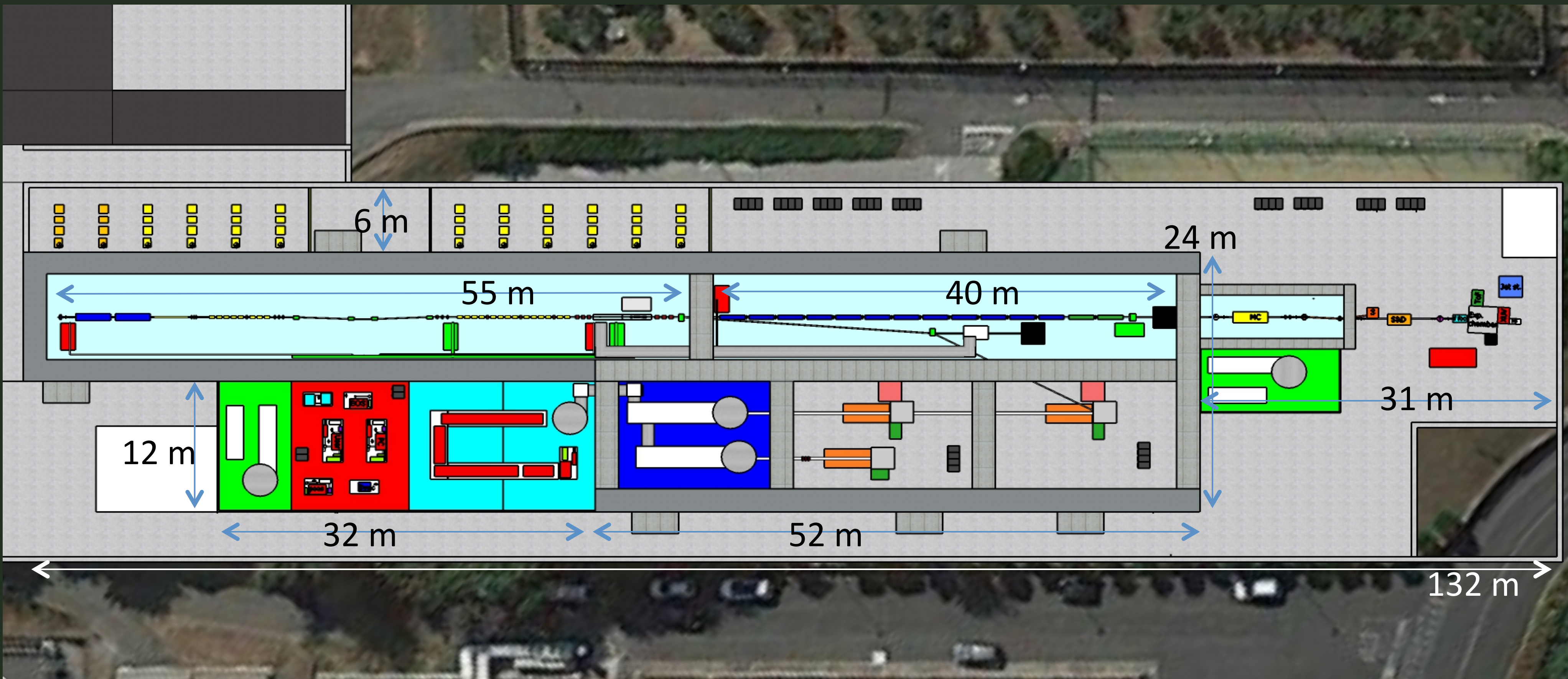


The key objective of the CompactLight Design Study is to demonstrate, through a conceptual design, the feasibility of an innovative, compact and cost effective FEL facility suited for user demands identified in the science case.

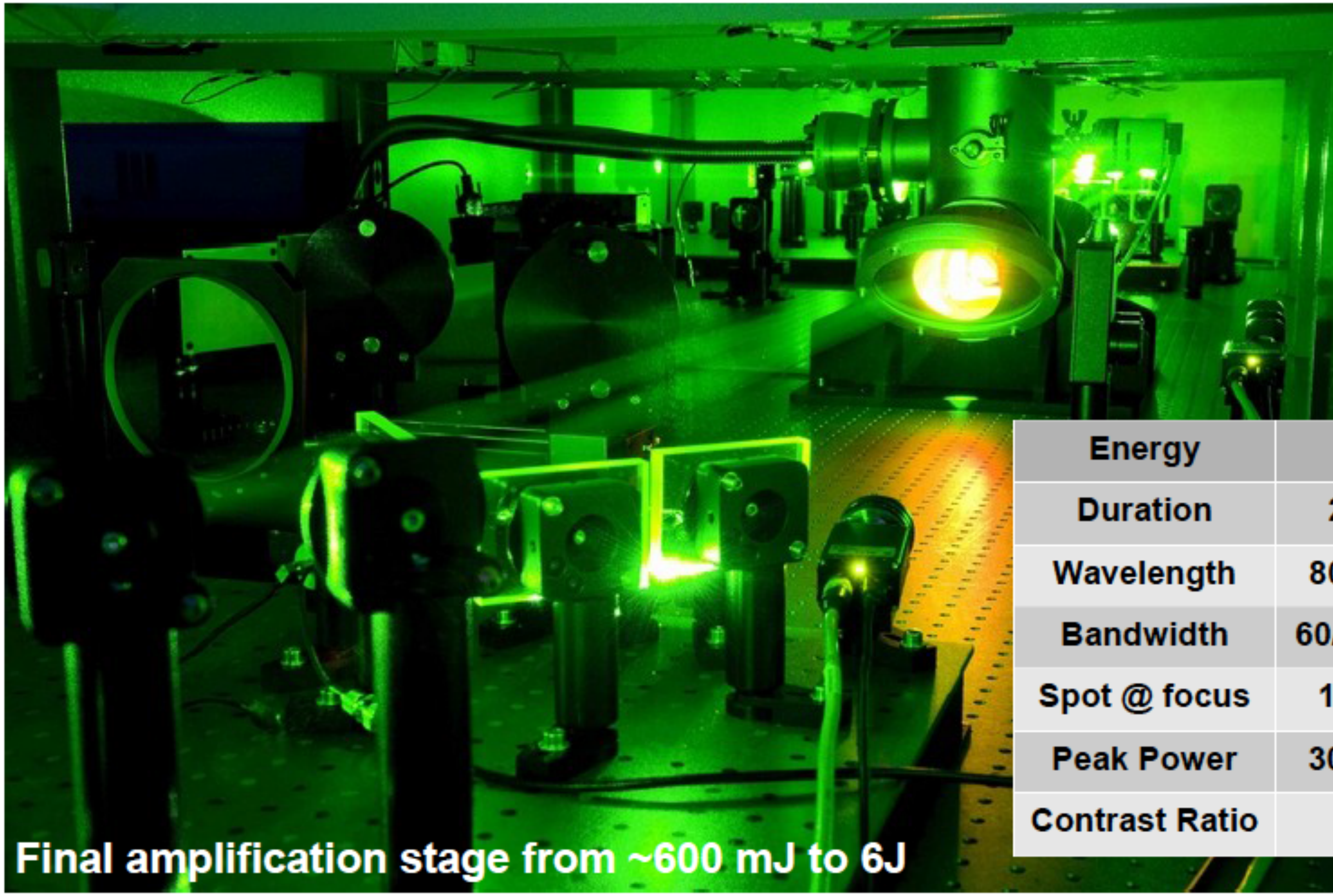



| X-Band LINAC parameters | | | |
|---|---|---|---|
| total active length $L_t$ | 16 m | | |
| Number of sections $N_s$ | 32 (4 modules x 8 sections) | | |
| available RF power | 50 MW (@klystron output coupler)<br>40 MW (@ section input couplers) | | |
| | Injection in the plasma | Injection in the undulator | Ultimate |
| linac energy gain $\Delta W_{linac}$ | 480 MeV | 910 MeV | 1280 MeV |
| average acc gradient $<E_{acc}>$ | 30 MV/m | 57 MV/m | 80 MV/m |
| total required RF power $P_{RF}$ | 44 MW | 158 MW | 310 MW |

- The High Power Laser system



# Ti:Sa FLAME laser



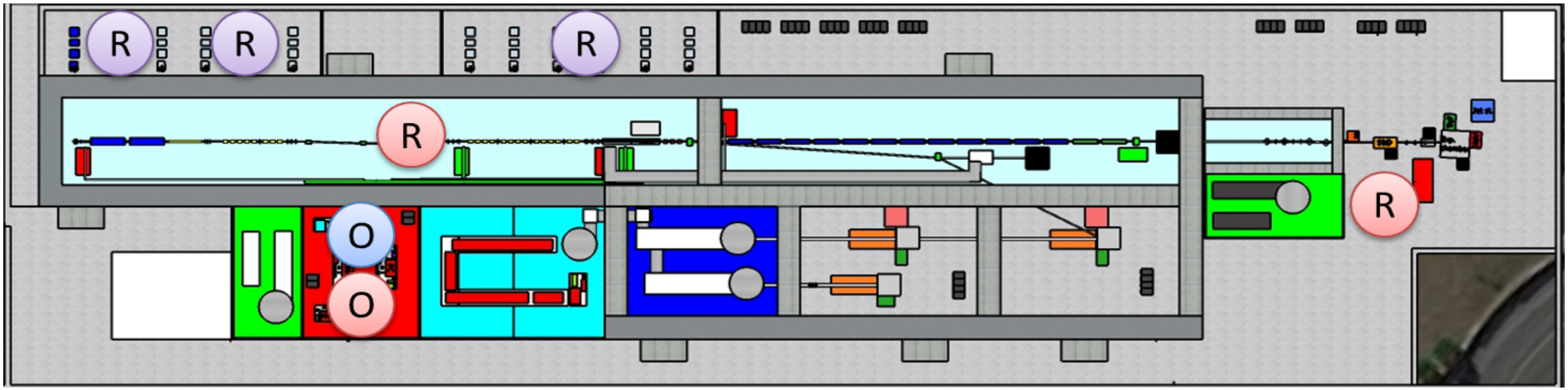

| | |
|---|---|
| Energy | 6 J |
| Duration | 23 fs |
| Wavelength | 800 nm |
| Bandwidth | 60/80 nm |
| Spot @ focus | 10 µm |
| Peak Power | 300 TW |
| Contrast Ratio | $10^{10}$ |

# Parameters of the 500 TW laser

| Parameters | FLAME today | FLAME upgrated |
|---|---|---|
| Wavelength [nm] | 800 | 800 |
| Bandwidth [nm] | 60-80 | 60-80 |
| Repetition rate [Hz] | 10 | 1-5 |
| Max energy before compression [J] | 7 | 20 |
| Max energy on target [J] | 4 | 13 |
| Min pulse length [fs] | 25 | 25 |
| Max power [TW] | 250 | 500 |
| Contrast ratio | $10^{10}$ | $10^{10}$ |

Comparison between the parameters of the actual FLAME system and the upgraded FLAME system.

# Eupraxia@SPARC_LAB synchronization system

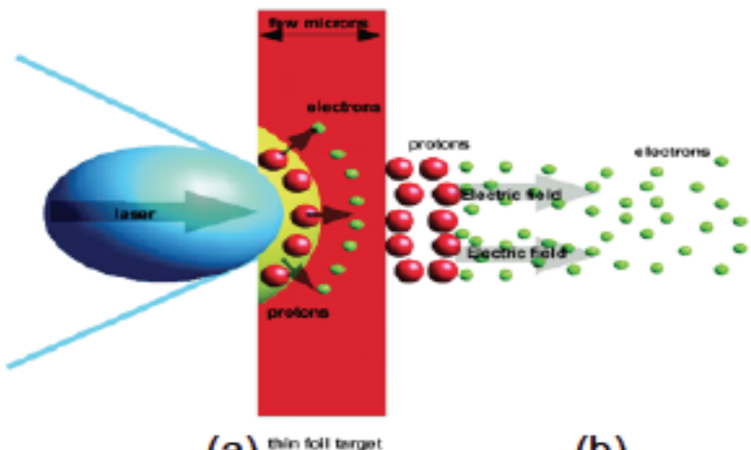


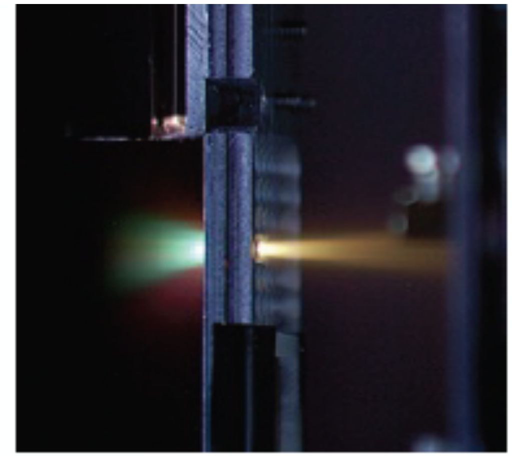

**Synchronization system:** A fine temporal alignment among all the relevant sub-system oscillators that guarantees temporal coherence of their outputs (**precision ~10fs**)

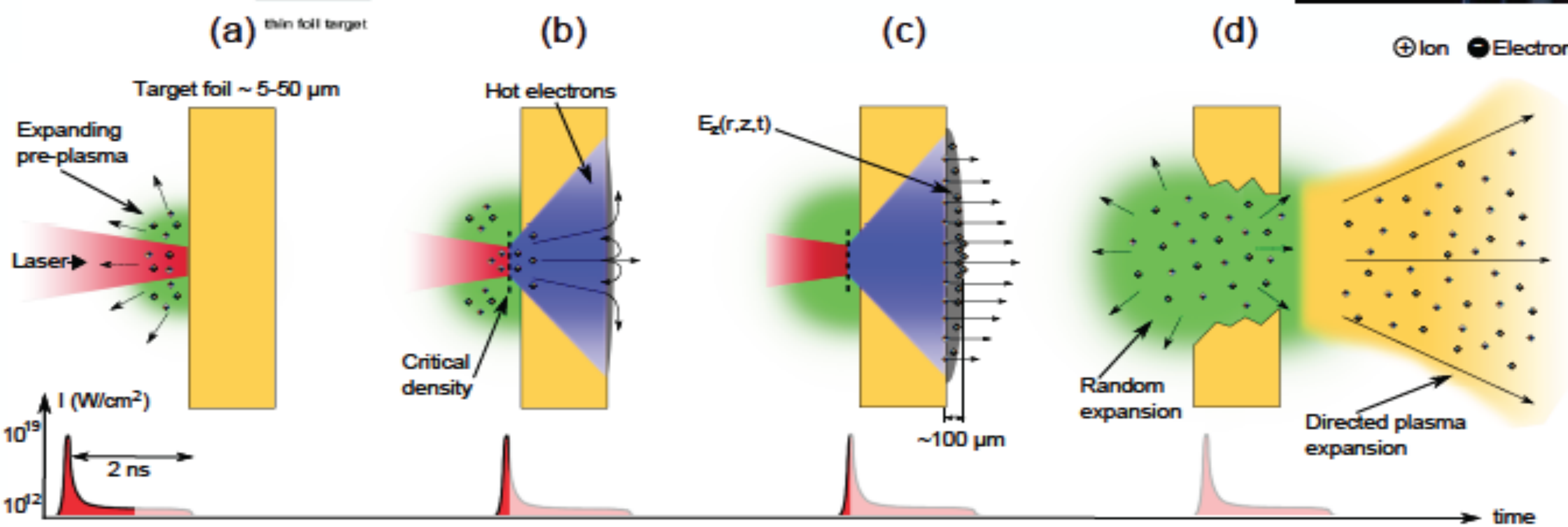
**Tasks:** triggers to sub systems (RF pulses, laser amplifiers, BPM, injection/extraction kickers), event tagging

**Layout:** 1 Electrical and 1 Optical Master Oscillator, 3 RF extractors, 2 optical link ends (diagnostics and users)

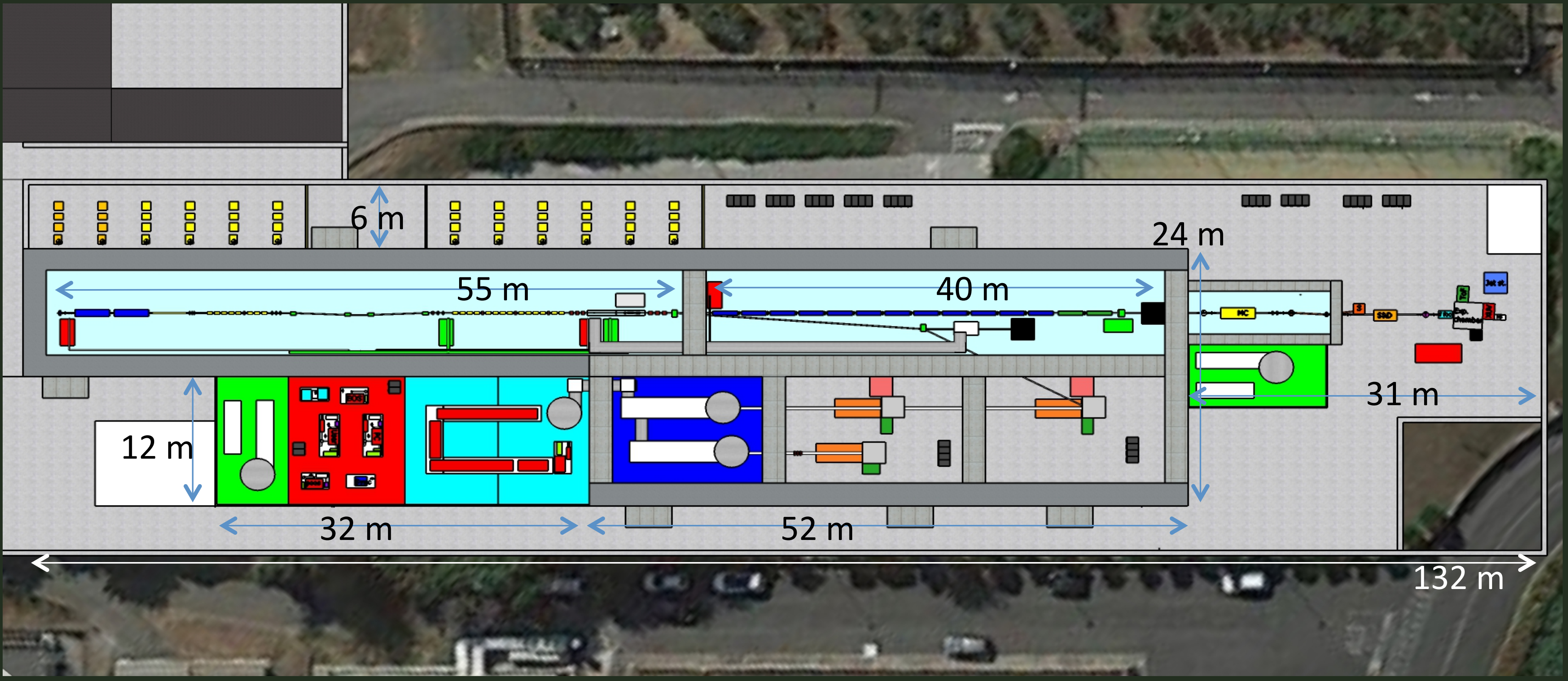
# Target Normal Sheath Acceleration





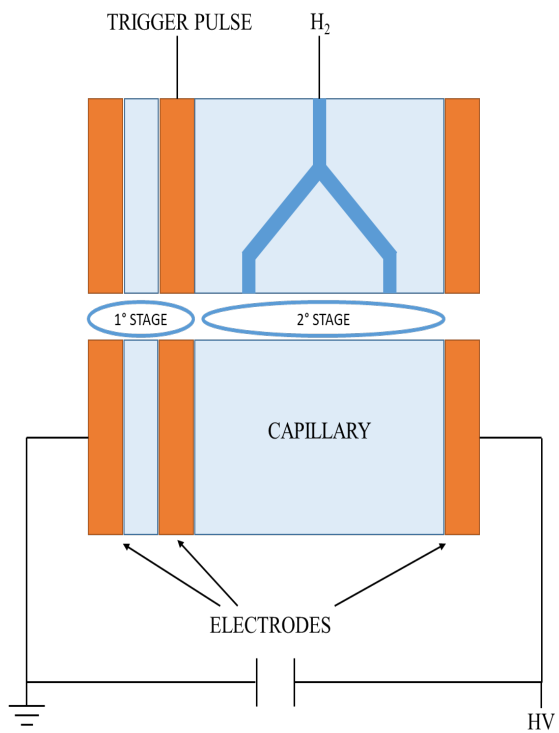
- The Plasma Accelerator Target



# Plasma source

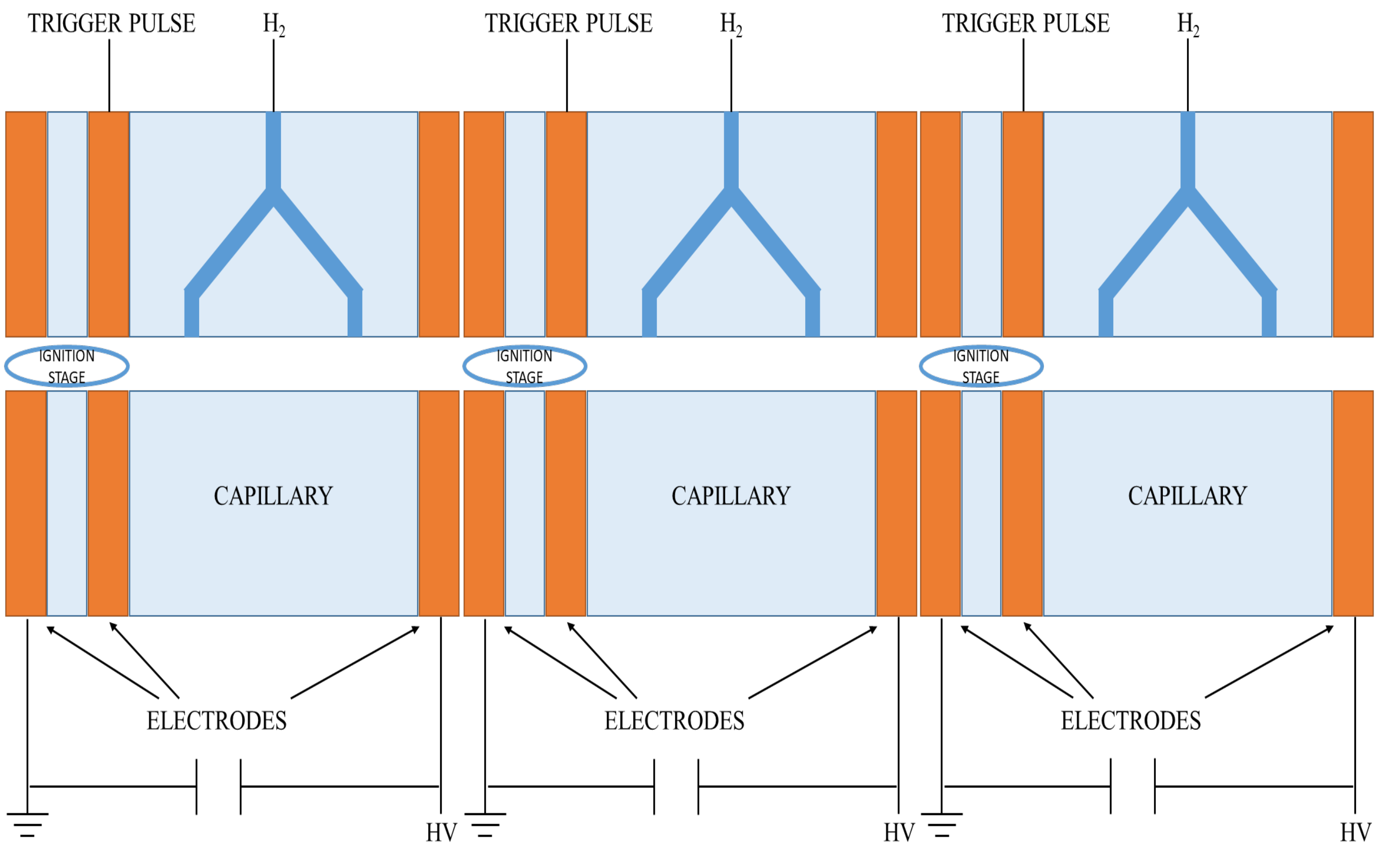
We preionize the capillary with a preformed plasma prior the main discharge. The initial plasma is formed in a short primary capillary by a high voltage pulse discharge. Part of this plasma and free electrons expanding into a long capillary that is connected to a high voltage capacitor. Since the discharge process follows the Paschen law, the breakdown threshold of the long capillary is lowered and the discharge can develop.

This strategy allow to ionize long capillaries with reasonable applied voltage in controlled and homogeneous way.



# Plasma source

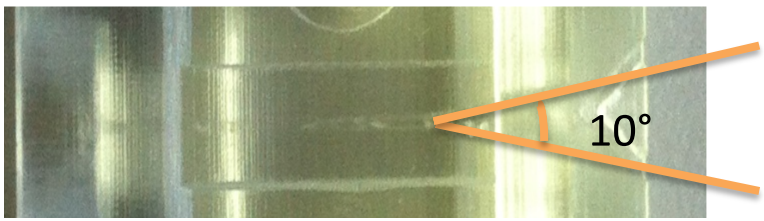
This scheme can be reproduced for tens-of-centimetre capillaries. This single unit can be integrated simply by adding more units obtaining up to tens of centimetre capillaries homogenously ionized and controlled independently one to each other, leading to the desired length of plasma (almost 30 cm) with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



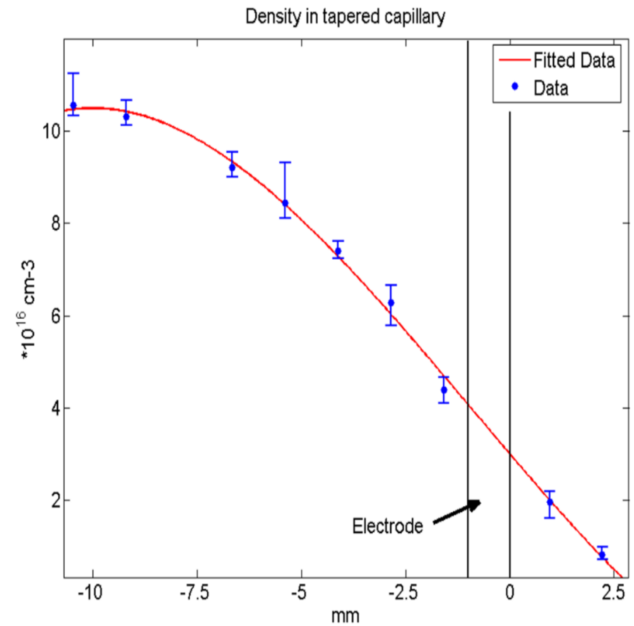
# Tapered capillaries

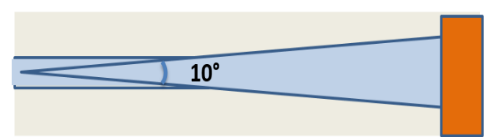
Local control of the plasma density is required to match the laser/electron beam into the plasma. Tapering the capillary diameter is the easiest way to change locally the density.

By monotonically varying the radius of the capillary it is possible to change the density using the empirical formula.




**Kaganovich et al., Appl. Phys. Lett. 75, 772–774 (1999).**




Studies on plasma tapering are currently in progress in the Plasma lab.

# Tapered capillaries

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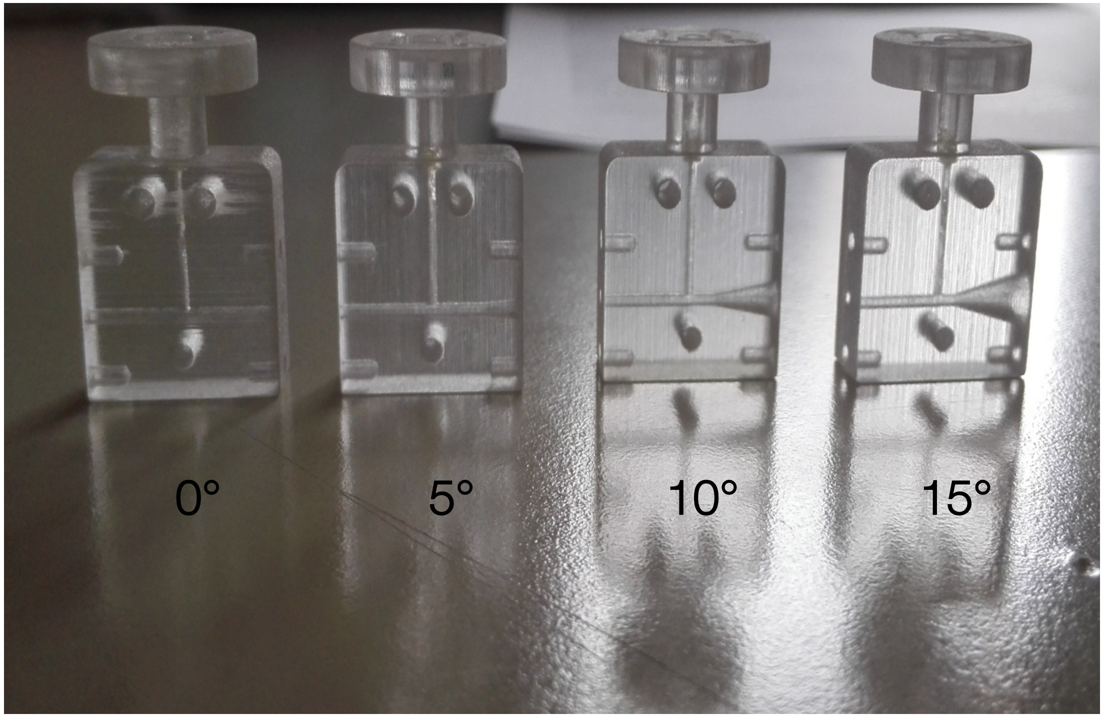
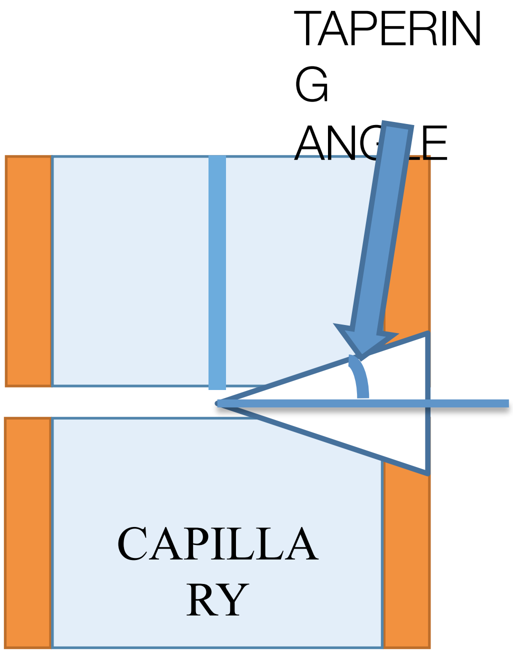


# 3. Simulations: preliminary results of 2D simulations

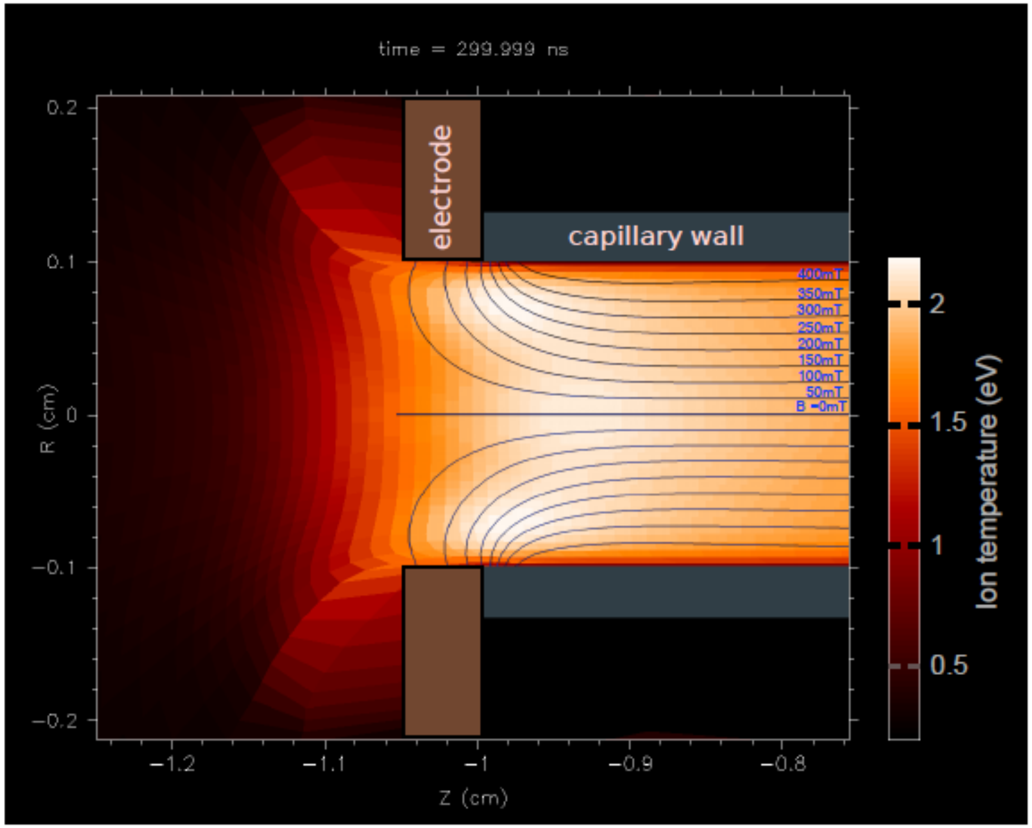
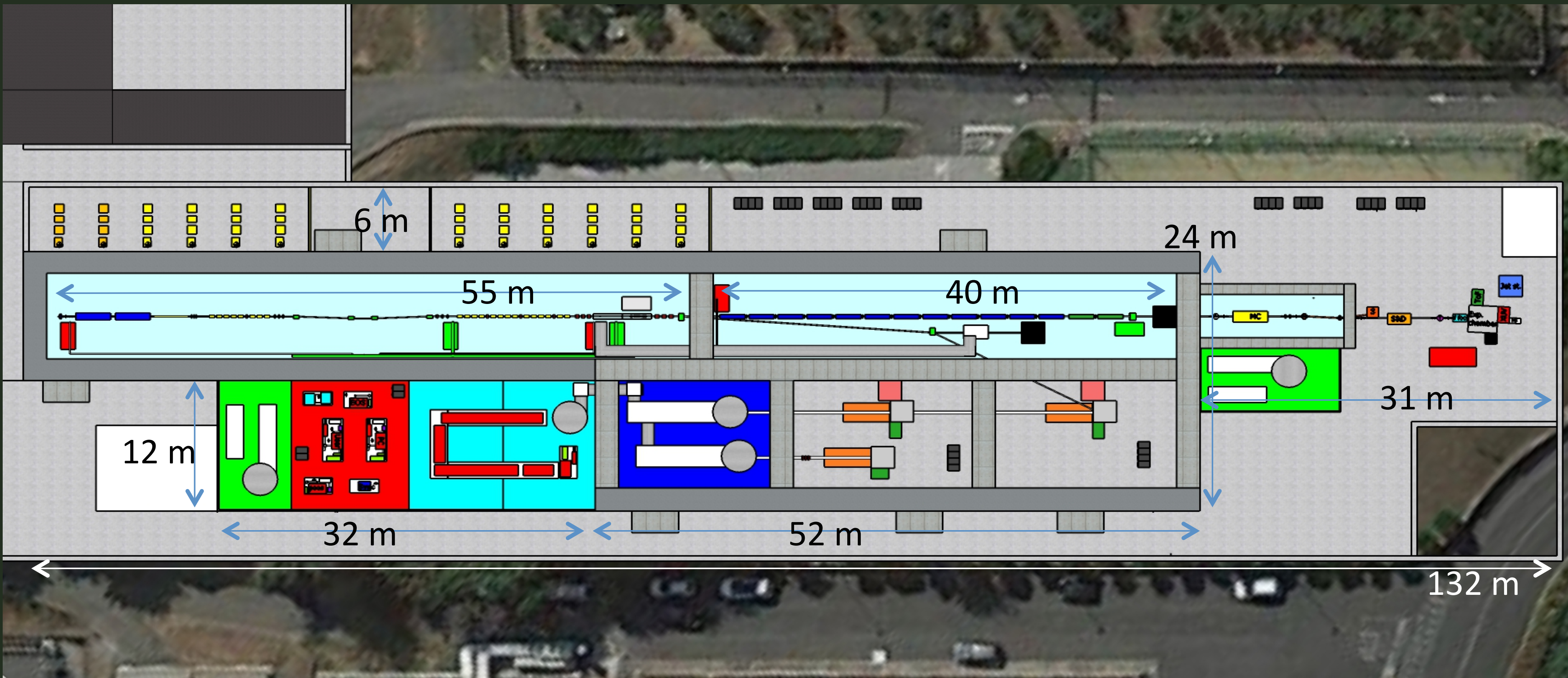



Figure: Particular of the plasma temperature (colored map) and azimuthal magnetic field (contour lines) in proximity of the left electrode at 300ns from the start of the discharge.

- It is possible to compute the magnetic field as post-processing
- Maps of other relevant quantities can be obtained
- The temperature reached by the plasma seems to be in qualitative agreement with what expected

- The FEL Undulators

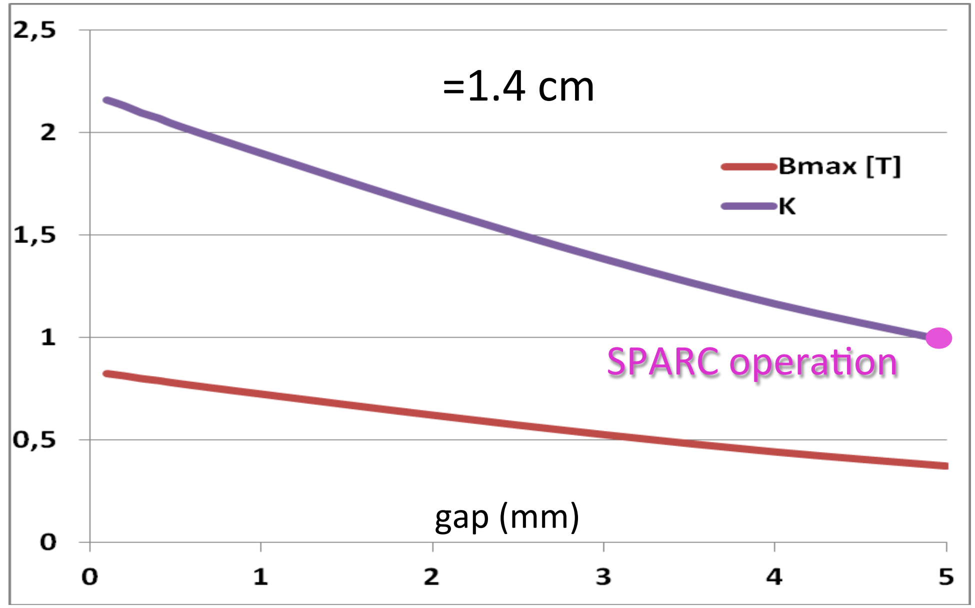


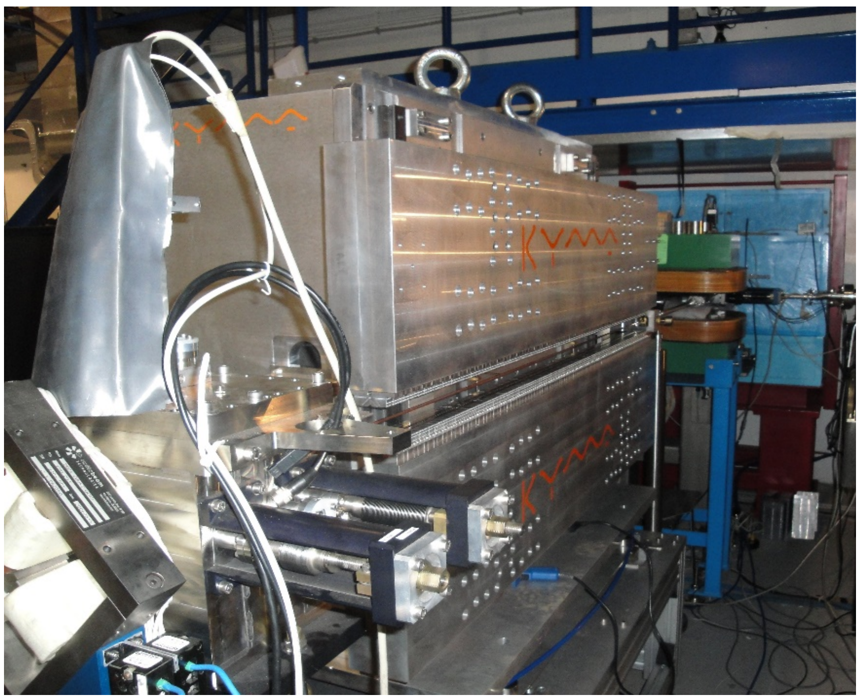

- 500 MeV by RF Linac + 500 MeV by Plasma
- 1 GeV by RF Linac only (EuSPARC)

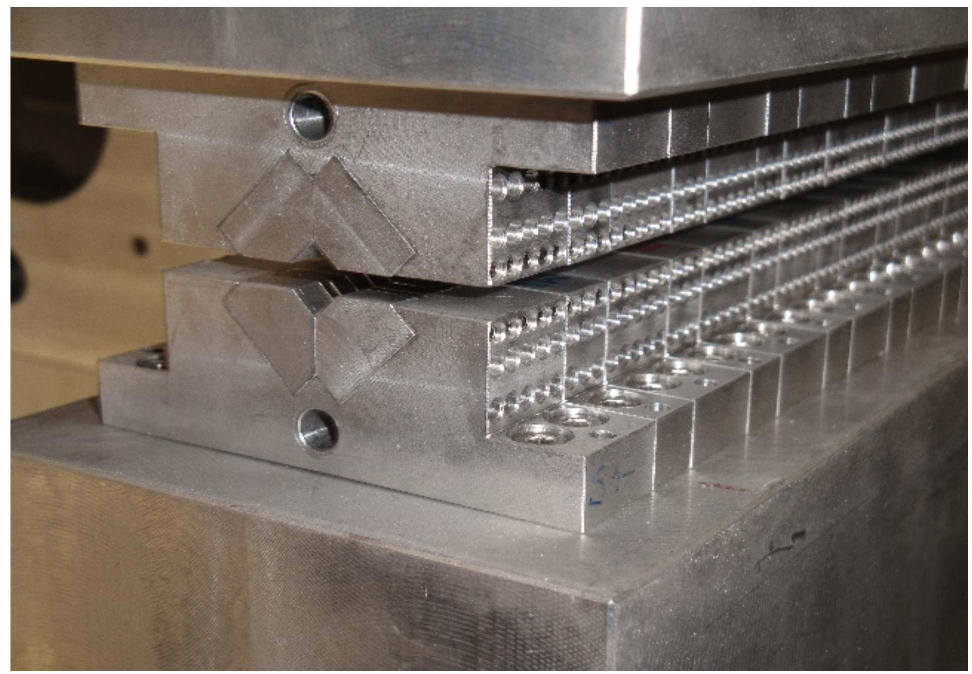
# **KYMA Δ undulator:**
designed by ENEA Frascati,
constructed by Kyma Trieste,
tested on beam at SPARC_LAB

- DELTA like undulator
  $\lambda_u$ = 1.4 cm, gap g = 5mm, Br = 1.22T.

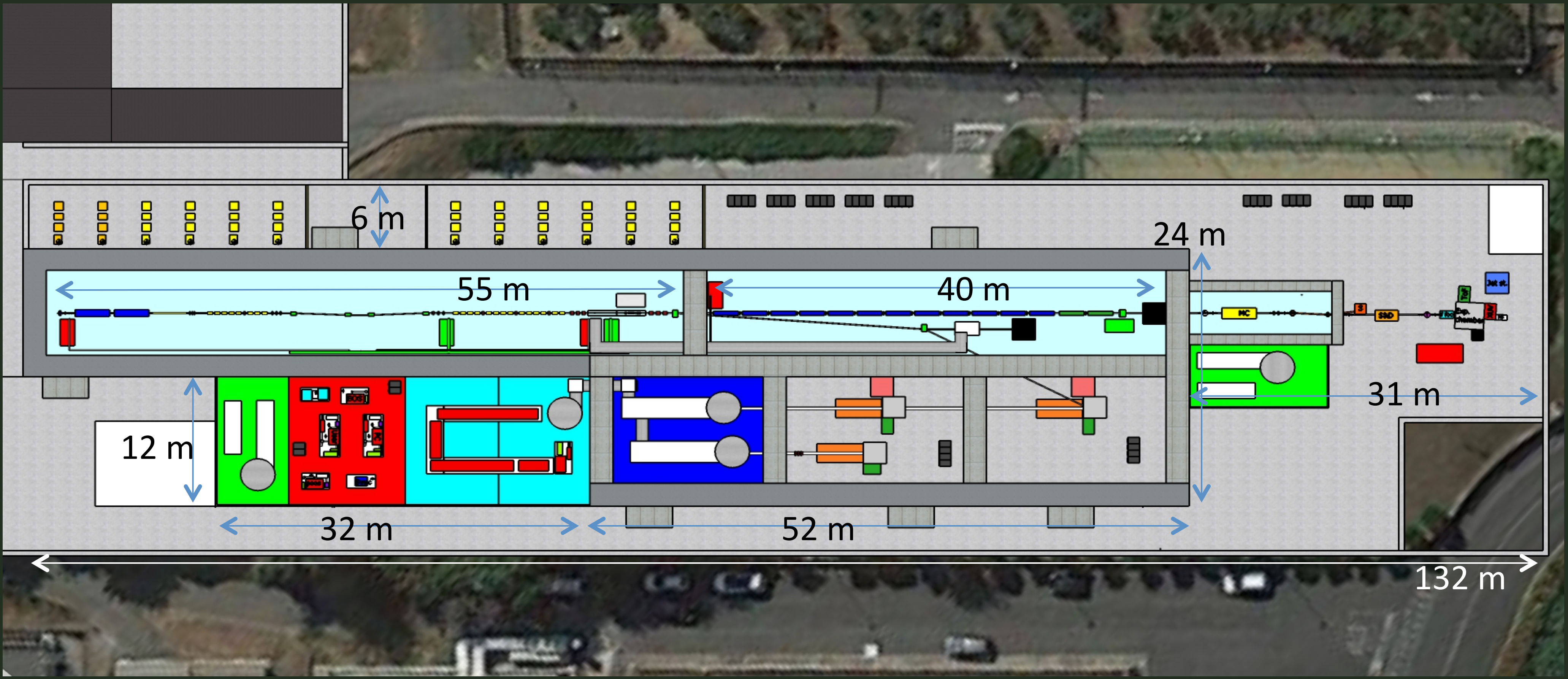
Undulator tested in two stage SASE-FEL:
630nm  to 315 nm



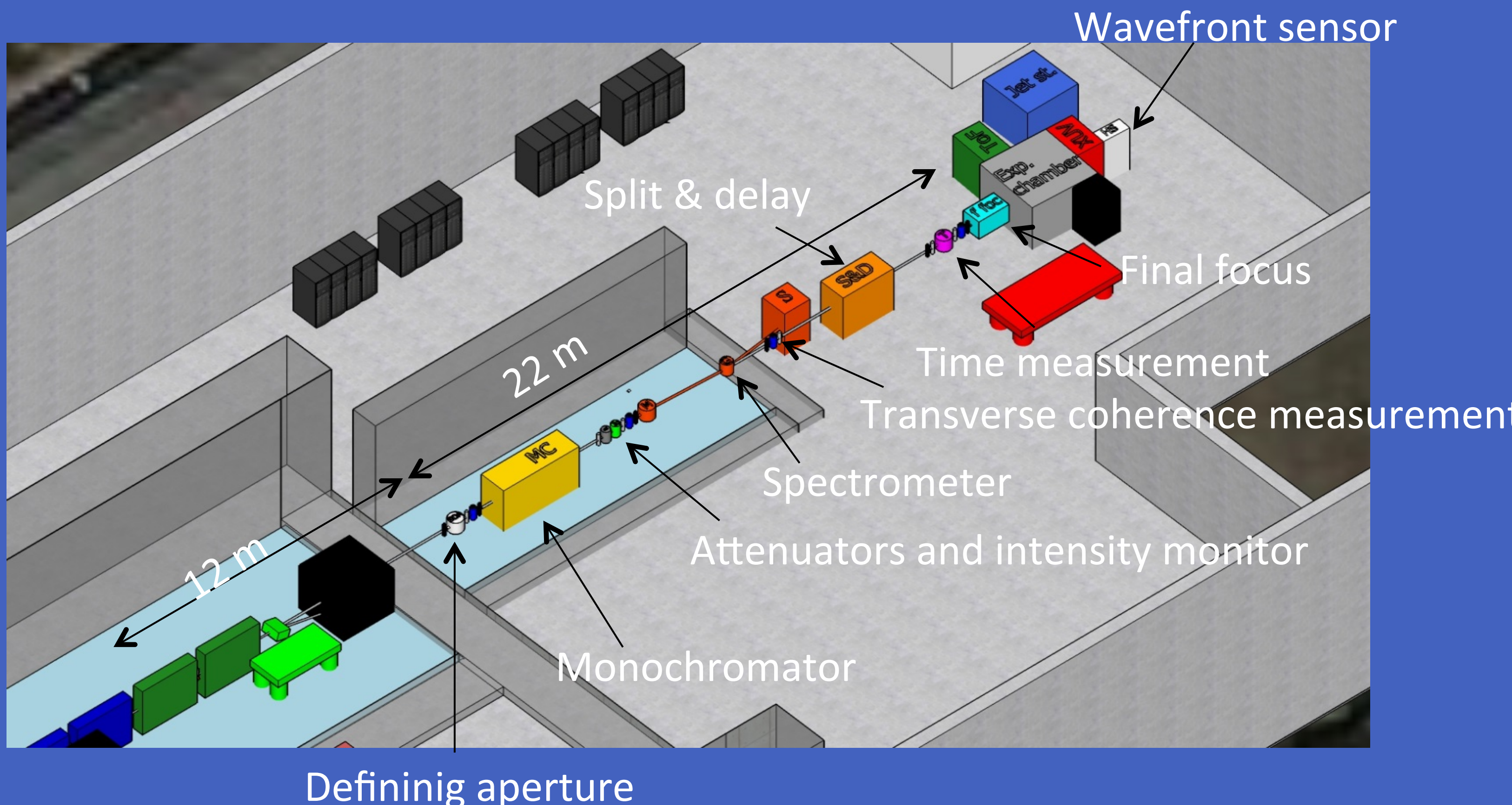





- The User Beam Line



# Photon beam line

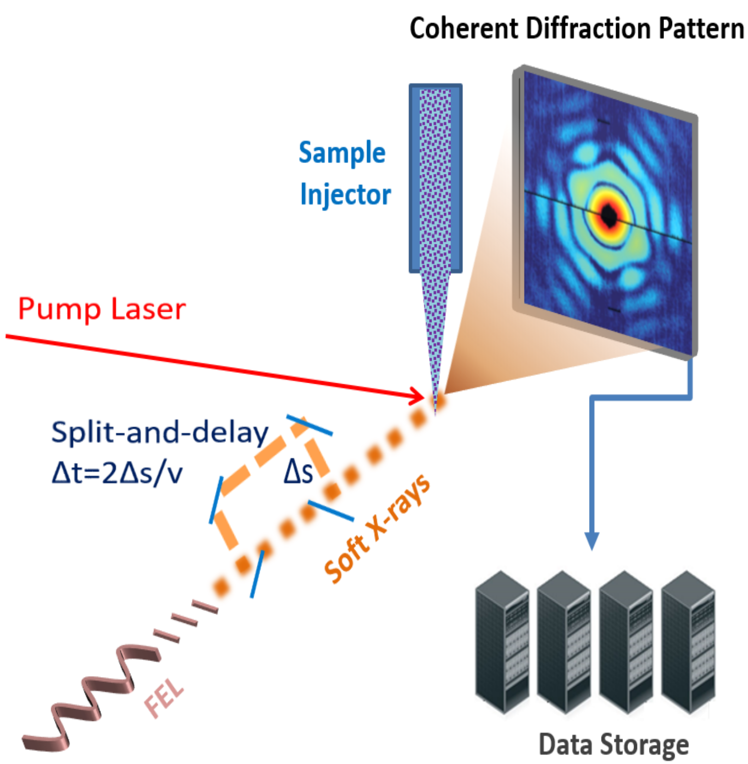


# Coherent Imaging @ EuSPARC/EuPRAXA

**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

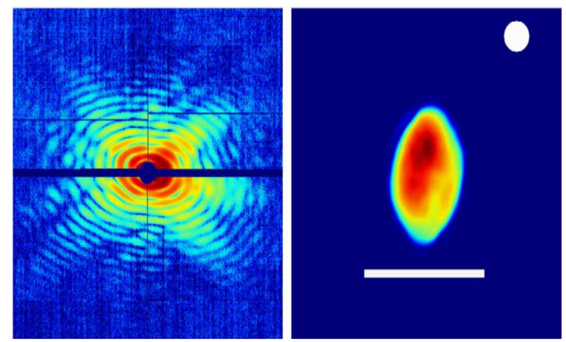


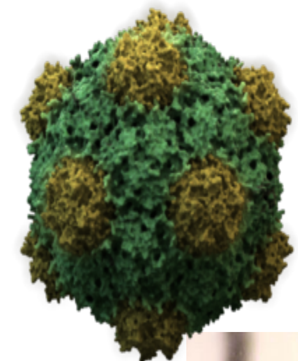

**Water Window Coherent Imaging of biological systems**

Energy region between oxygen and carbon K-edge

2D and 3D images of biological samples will be obtained

viruses, cells, organelles, protein fibrils…





**Condensed-matter**

High Temperature superconductors

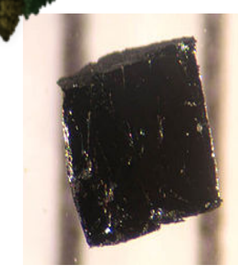
Metal-insulating transitions

Colossal magnetoresistance phenomena

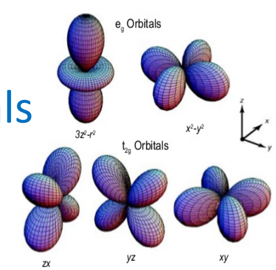
Ferroelectrics & multiferroics materials

Skyrmions, spintronics

Nanoparticles and plasma



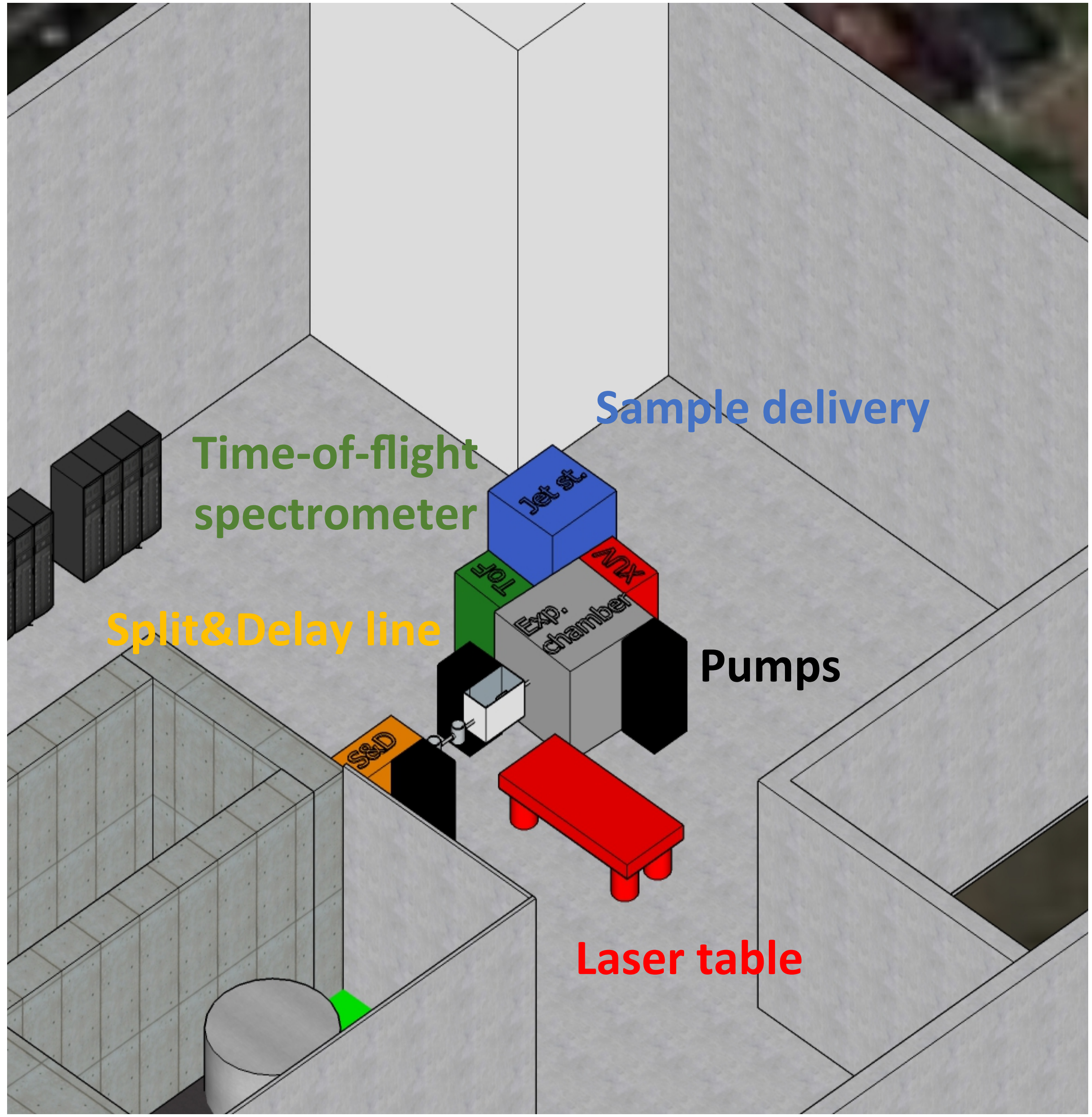
Colossal Magnetoresistance
*3d* Orbital Types



# The Experimental Endstation

| Parameters | Expected values |
|---|---|
| Radiation wavelength | 2-4 nm (310-620 eV) |
| Photons per pulse* | 1-7 x $10^{11}$ |
| Pulse length (FWHM) | 10-50 fs |
| Repetition rate | 10-100 Hz |
| Bandwidth (FWHM) | 1 eV |

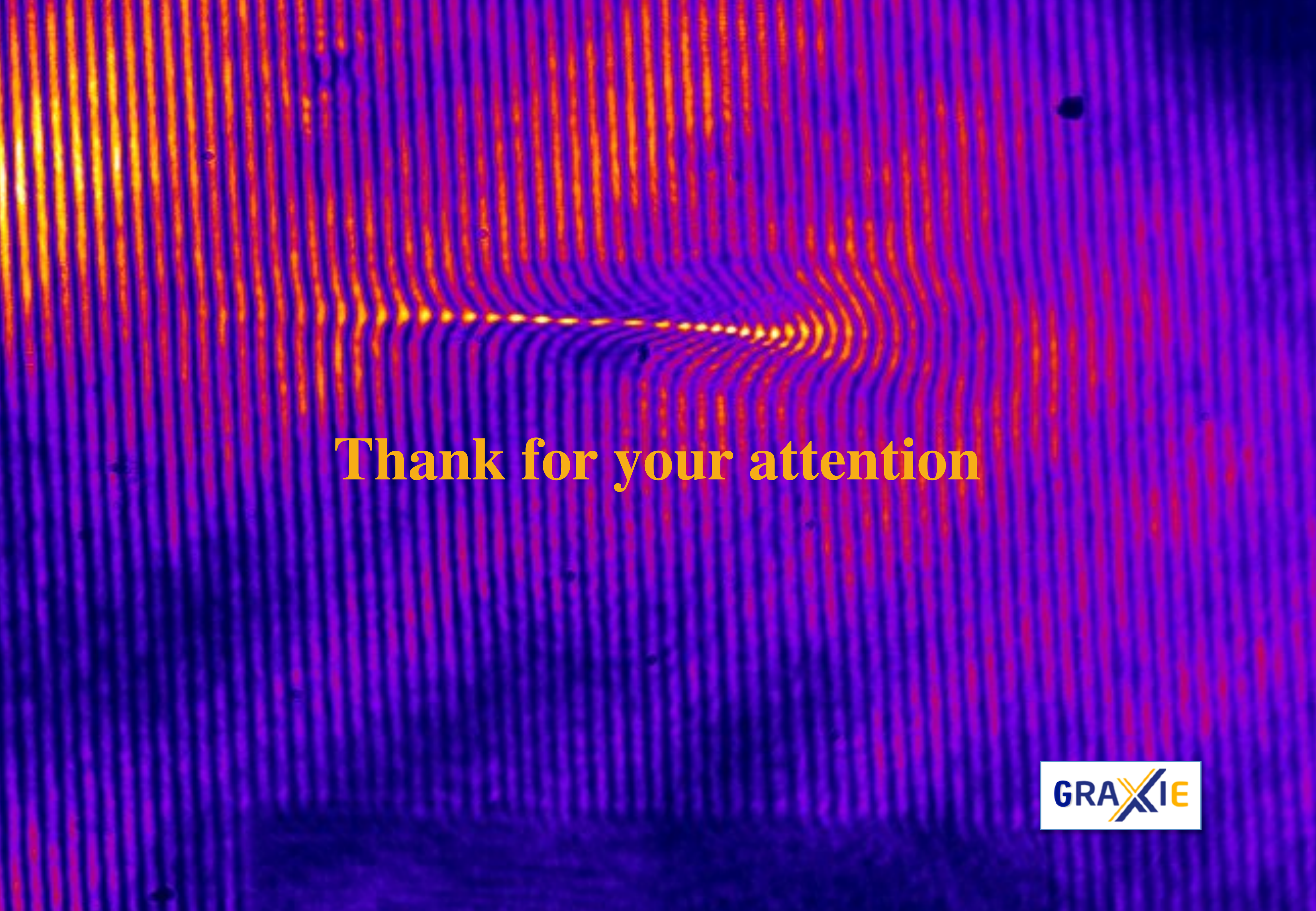
**A versatile, state-of-the art, fully equipped experimental station (and a transport line) will be necessary to exploit the brilliant, ultra-short and coherent FEL pulses**



# EuPRAXIA@SPARC_LAB

# EuPRAXIA@SPARC_LAB

- X-band RF technology implementation,➔ CompactLight
- Science with short wavelength Free Electron Laser (FEL)
- Physics with high power lasers and secondary particle source
- R&D on compact radiation sources for medical applications
- Detector development and test for X-ray FEL and HEP
- Science with THz radiation sources
- Nuclear photonics with $\gamma$-rays Compton sources
- R&D on polarized positron sources
- Quantum aspects of beam physics, Quantum-FEL development
-
- R&D in accelerator physics and industrial spin – off



# Thank for your attention