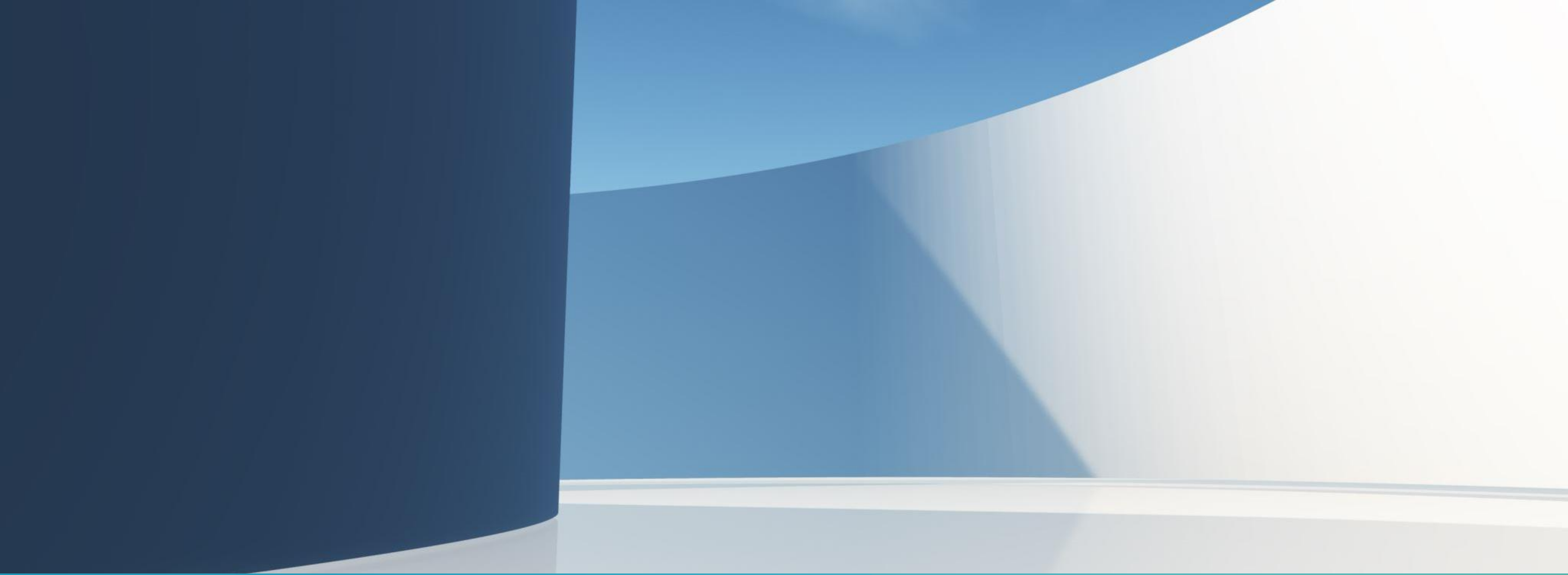


INTRODUCTION TO LINEAR PARTICLE ACCELERATORS

A. GIRIBONO, C. VACCAREZZA

OUTLINE

Introduction

Brief History

Main Components

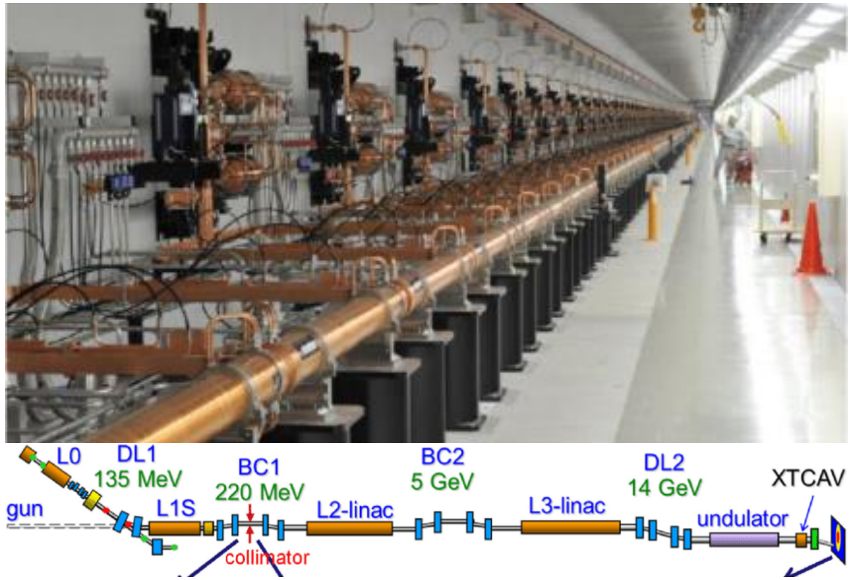
- Particle Sources
- RF cavities
- Beam Transport System

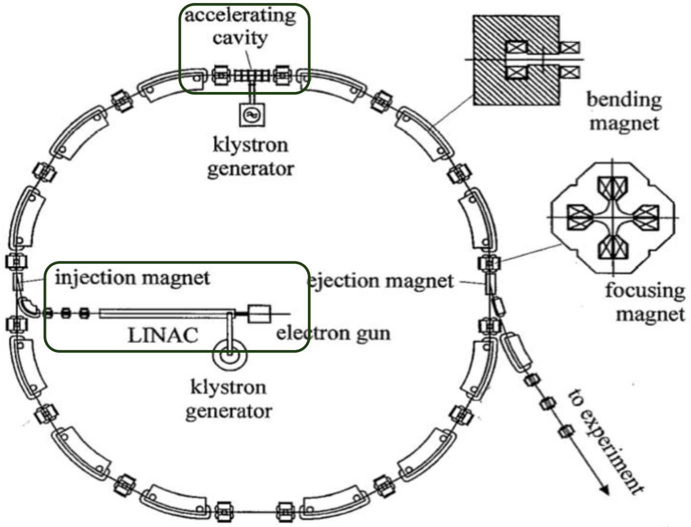
High Gradient path

- X-band Technology for FEL's (Compact Light Project)
- Plasma Acceleration (EuPRAXIA@SPARC_LAB Project)

INTRODUCTION

- ❑ An Accelerator system accelerates charged particles by means of electrical and /or magnetic fields
- ❑ Two basic categories are available:
  - ❑ Linear Accelerators
  - ❑ Circular Accelerators





LINEAR ACCELERATORS

In Linear Accelerators the particles follow a straight trajectory ending with fixed target or interaction points with co-propating or counter propagating beams, or coherent radiation sources like magnetic undulators

The longitudinal extension of a linear accelerator can range between few centimeters and some kilometers depending on the desidered final energy and the application

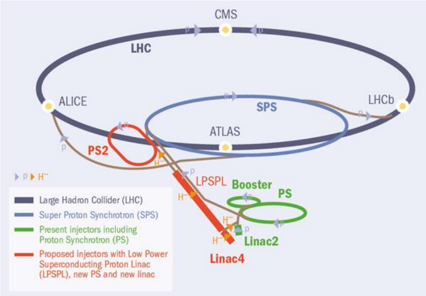
In Circular Accelerators the particles follow a circular path, typically at very high energies and can circulate for very long time

The path along a circular accelerator can be very long, up to tenths of kilometers, and particles of opposite charge travel in opposite directions, eventually colliding in specific experimental zones

CIRCULAR ACCELERATORS

LINEAR ACCELERATORS APPLICATIONS

- Colliders and Synchrotron Injectors
- Free Electron Lasers
- Spallation Sources
- Medical Applications
- National Security
- Industrial Applications:
  - Ion Implantation, Material treatment, Food Treatment
- Testing for Fusion Reactors



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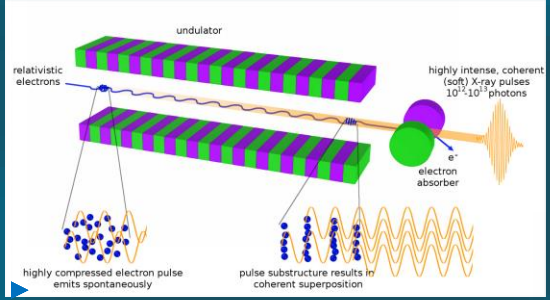

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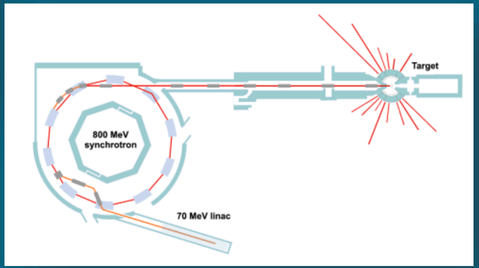

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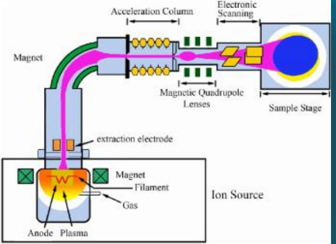

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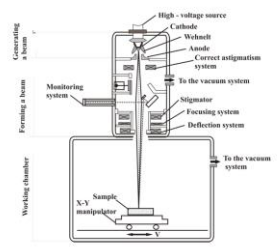

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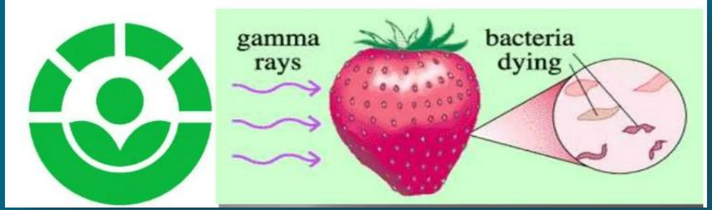

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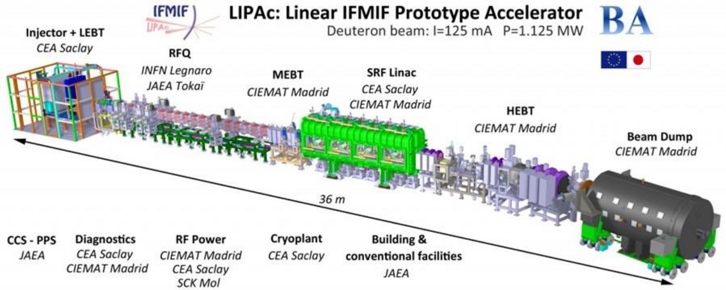

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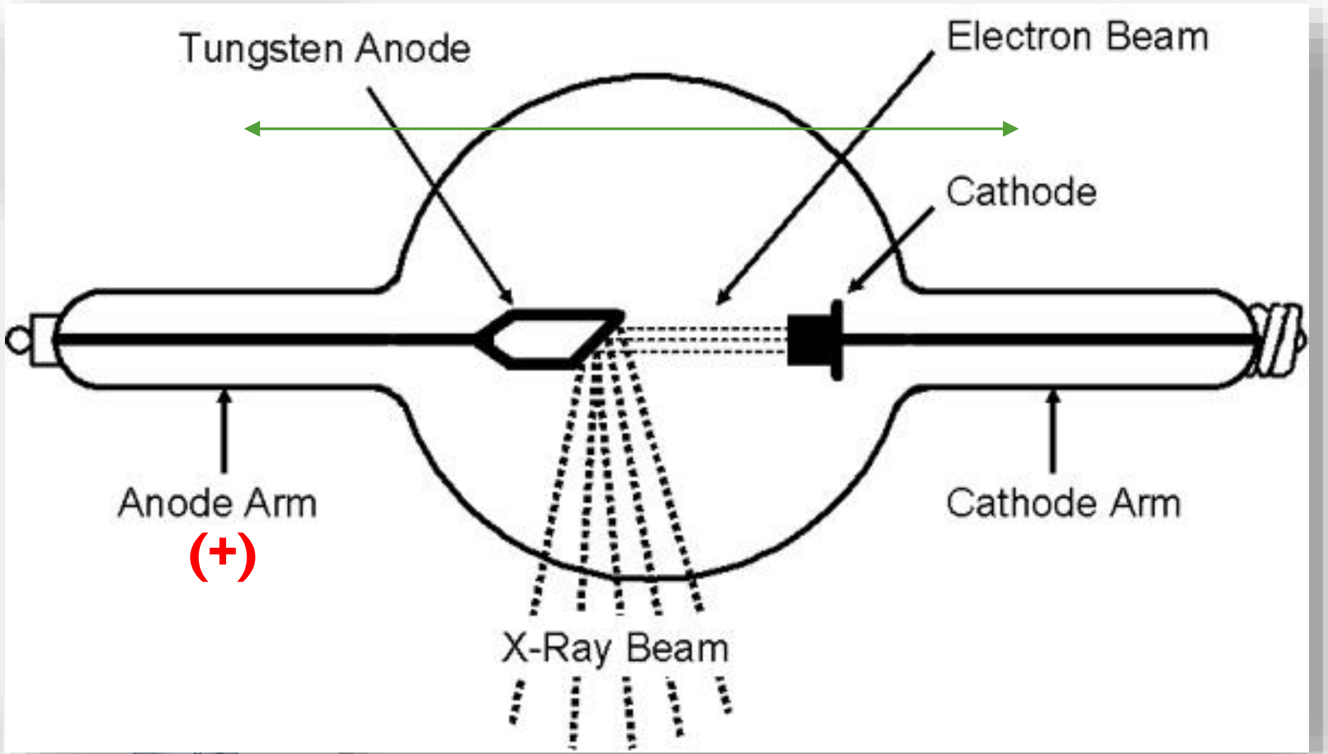
BRIEF HISTORICAL OVERVIEW

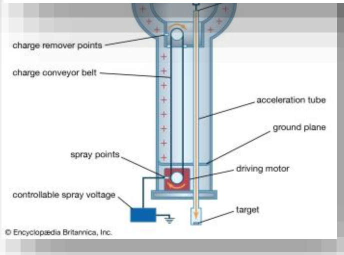
Electrostatic Accelerators

- 1926 X-ray tubes: David Coolidge achieved 900 keV electron beam energy with three X-ray tubes in series (Coolidge Tube)

- 1930 Cockroft-Walton accelerators reached 400 kV for the first nuclear man induced transmutation: $p + \mathrm{Li} \rightarrow 2\,\mathrm{He}$. Maximum achievable voltage $\approx 1MeV$

- 1931 Van de Graaff developed the electrostatic charging accelerator. Today the maximum achievable voltage is $\approx 25MeV$





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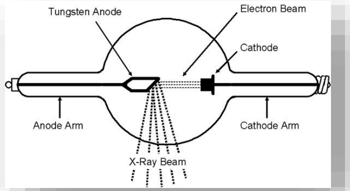

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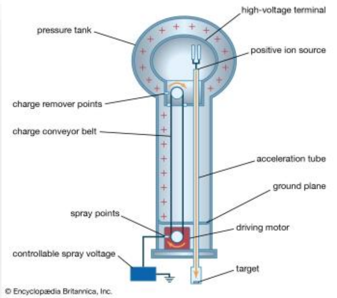

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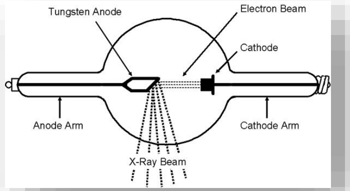

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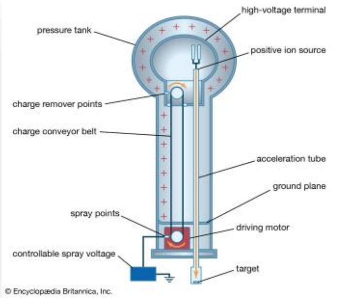
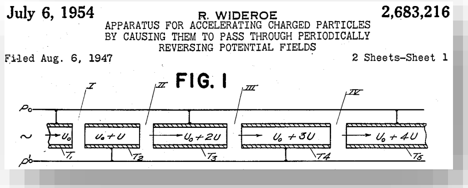
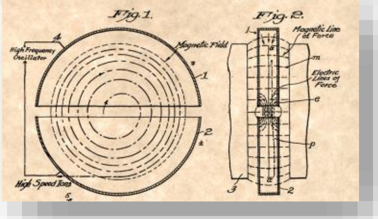


Radio-Frequency Accelerators

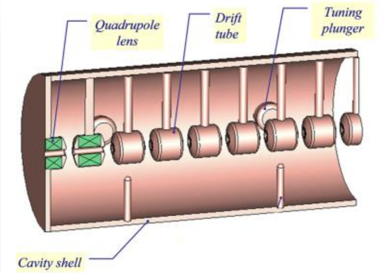
- 1928 Based on the G. Ising idea (1924) of particle accelerated by means of alternating radio-frequency fields, R.Wiederoe realised the first RF accelerator applying a sine-wave voltage to a series of drift tubes by means of a 1 MHz, 25-kV oscillator, producing 50-kV potassium ions



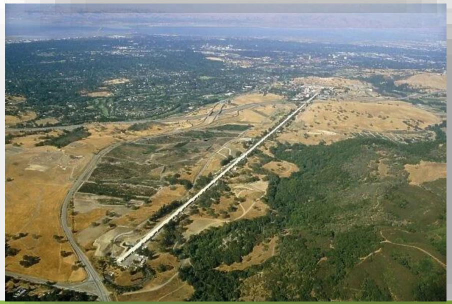
- 1932 Lawrence's cyclotron produced 1.25 MeV protons



- 1948 L. Alvarez–WKH. Panofsky constructed the first 32 MV drift-tube linac for protons



- 1950-1990 Thanks to the RF technology progress since the II World War end in producing magnetron and klystron amplifiers up to 1 MW at 3 GHz, the Stanford Linear Accelerator reached 1.2 GeV in early 1950 and with the 3.2 km linac project completed in 1966, the final energy of 50 GeV was reached in 1989



BASIC EQUATIONS: THE LORENTZ FORCE

$$\frac{d\vec{p}}{dt} = q\left(\vec{E} + \vec{v} \times \vec{B}\right)$$

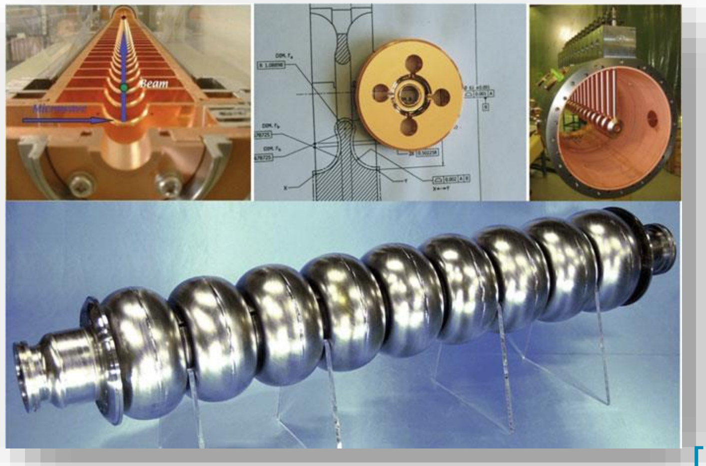
$\vec{p} = momentum$

$\vec{v} = velocity$

$m = mass$

$q = charge$

Acceleration → Longitudinal Beam Dynamics



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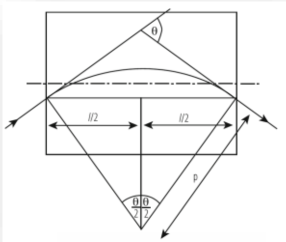
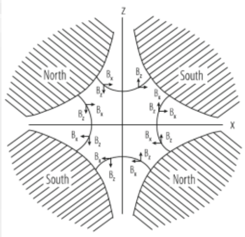
Bending/Focusing → Transverse Beam Dynamics

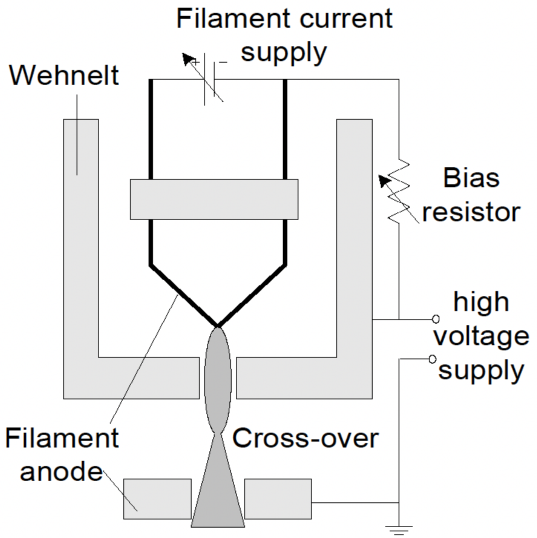




The charged particles are accelerated by means of the Electric Fields and bent/focused by means of the Magnetic Fields

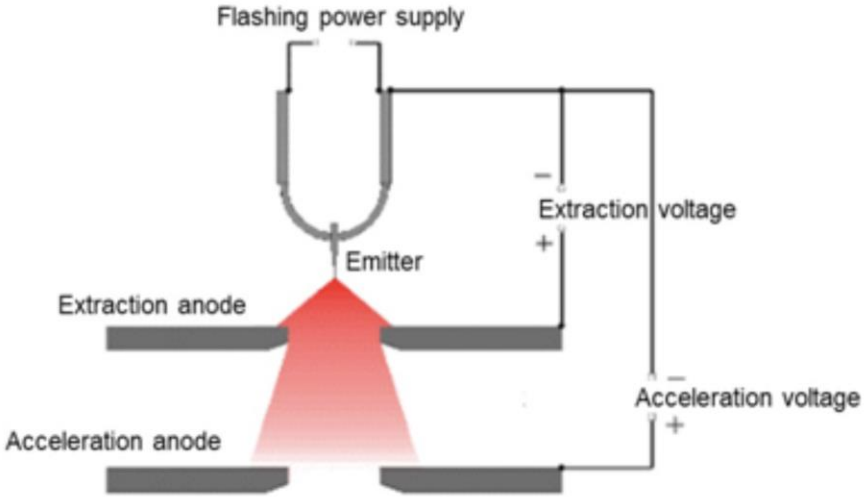
MAIN COMPONENTS 1.PARTICLE SOURCE

1.1.1 Thermionic Gun



In the simplest configuration (above) the cathode of a hairpin W filament is electrically heated (2800K) in vacuum (10^{-3} Pa) so as to emit thermoelectrons. The emitted electrons are accelerated by a high voltage applied to the anode up to a desired energy. The electric current is controlled by a bias voltage applied to the Wehnelt electrode.

1.1.2 Field Emission Gun



A single crystal W tip is used as the cathode (emitter) of the field-emission electron gun (FEG). The strong electric field is generated around the emitter tip for the electrons in the solid to emit from the solid surface. The gun is operated in an ultra-high vacuum of 10^{-8} Pa to avoid contamination of the tip due to residual gases. Since the emitter is operated at room temperature, this is called a cold-cathode emitter.

MAIN COMPONENTS 1.PARTICLE SOURCE

1.2 - Photo Guns

Beam quality key Parameters:

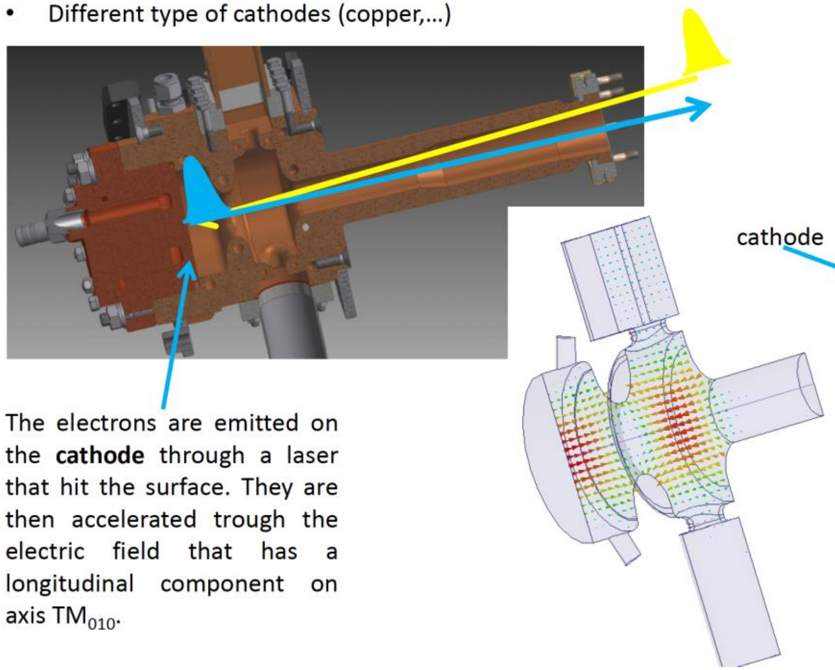
Perveance $P = \frac{I}{U_a^{3/2}}$, I is the current in A, and U_a the accelerating voltage in V

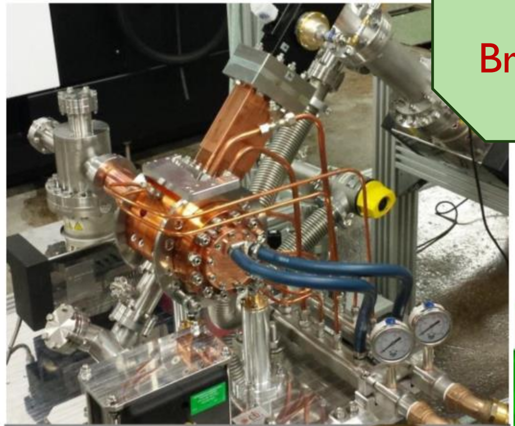
Brightness $B = \frac{2I}{\pi^2 \varepsilon^2}$, ε is the transverse space beam emittance

ELECTRON SOURCES: RF PHOTO-GUNS

RF guns are used in the first stage of electron beam generation in FEL and acceleration.

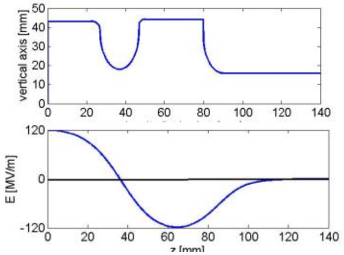
- Multi cell: typically 2-3 cells
- SW π mode cavities
- operate in the range of 60-120 MV/m cathode peak accelerating field with up to 10 MW input power.
- Typically in L-band- S-band (1-3 GHz) at 10-100 Hz.
- Single or multi bunch (L-band)
- Different type of cathodes (copper,…)



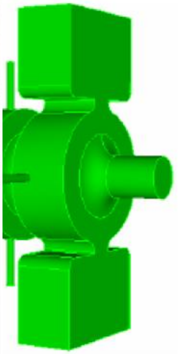


cathode

The electrons are emitted on the **cathode** through a laser that hit the surface. They are then accelerated trough the electric field that has a longitudinal component on axis TM_{010}.

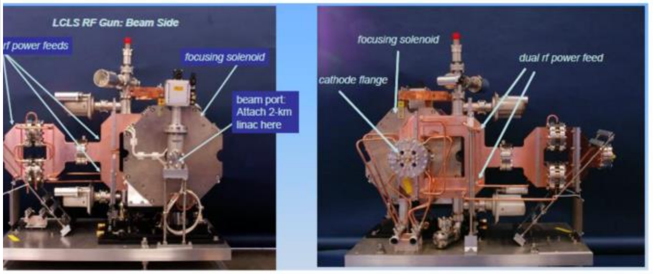


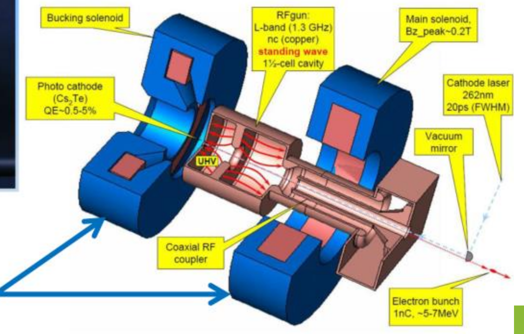
RF PHOTO-GUNS: EXAMPLES



LCLS
Frequency = 2,856 MHz
Gradient = 120 MV/m
Exit energy = 6 MeV
Copper photocathode
RF pulse length ~2 μs
Bunch repetition rate = 120 Hz
Norm. rms emittance
0.4 mm·mrad at 250 pC

PITZ L-band Gun
Frequency = 1,300 MHz
Gradient = up to 60 MV/m
Exit energy = 6.5 MeV
Rep. rate 10 Hz
Cs_2Te photocathode
RF pulse length ~1 ms
800 bunches per macropulse
Normalized rms emittance
1 nC 0.70 mm·mrad
0.1 nC 0.21 mm·mrad





Solenoids field are used to compensate the space charge effects in low energy guns. The configuration is shown in the picture

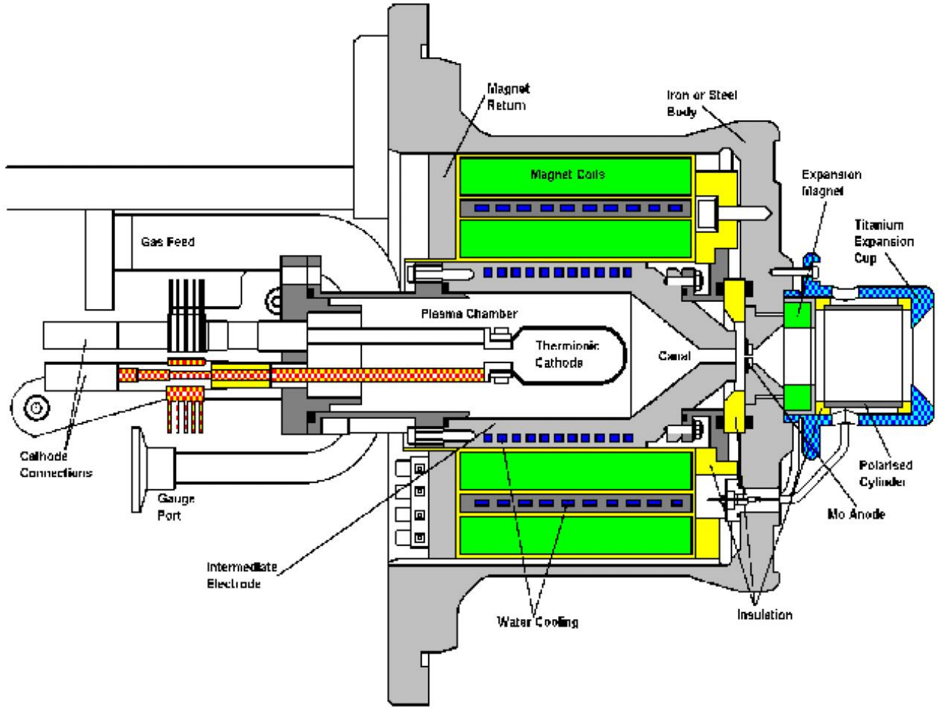
Courtesy of D. Alesini [10]

MAIN COMPONENTS 1.PARTICLE SOURCE

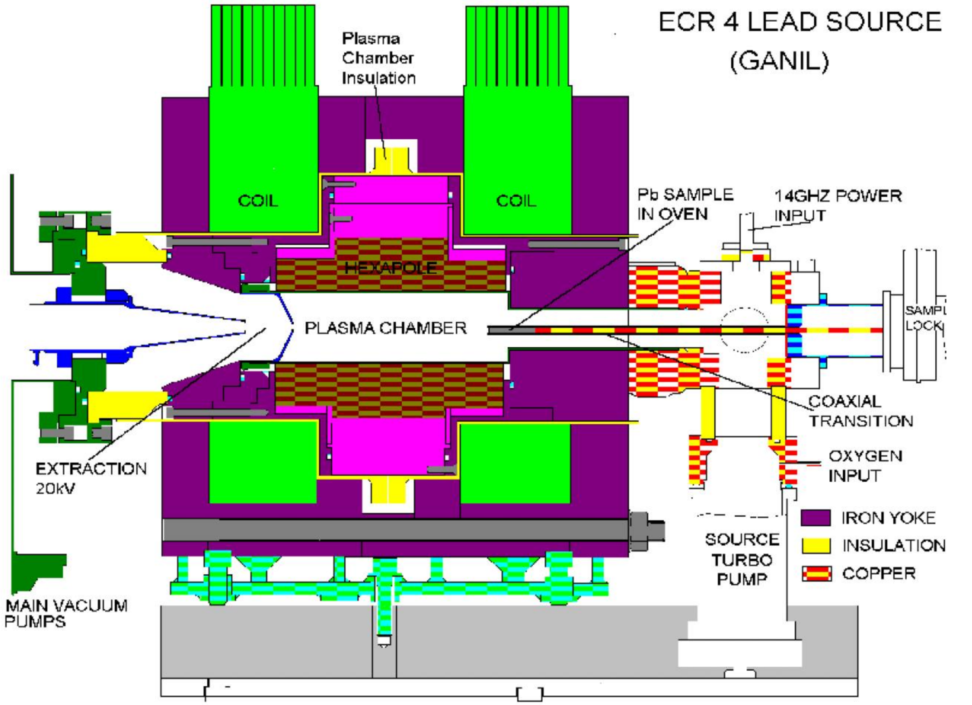
1.3 – Ion Source

Basic principle

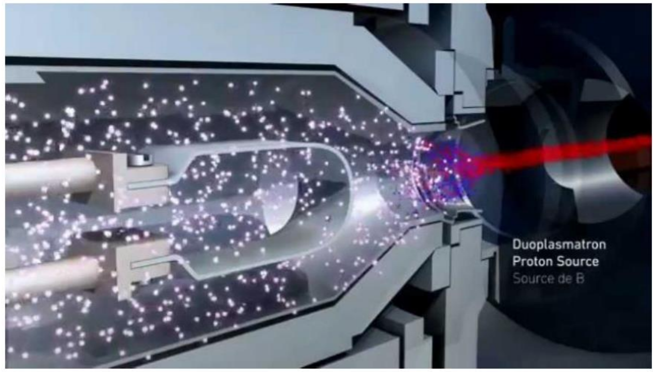
- Create a plasma and optimize its conditions (heating, confinement and loss mechanisms) to produce the desired ion type.
- Remove ions from the plasma via an aperture and strong electric field

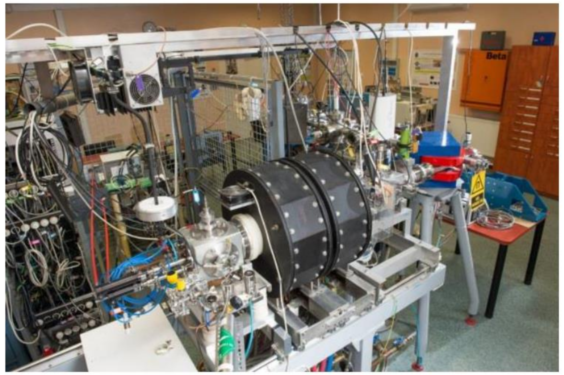


CERN Duoplasmatron proton Source



Electron Cyclotron Resonance (ECR) ECR

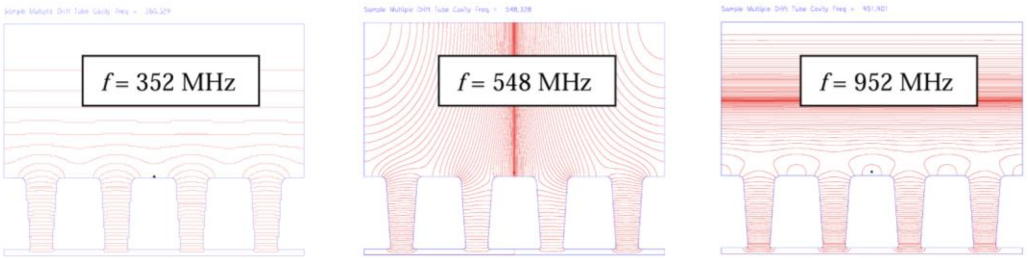




Courtesy of D. Alesini [10]

MAIN COMPONENTS 2.RF CAVITIES

Standing Wave

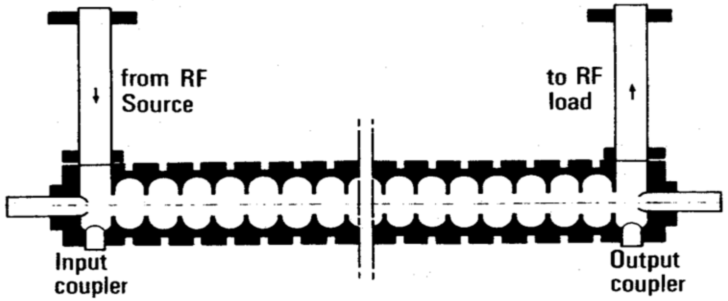


An RF cavity is a piece of conductor enclosing an empty volume. Solutions of Maxwell's equations in this volume, taking into account the boundary conditions on the conductor surface, allow the existence of electromagnetic field configurations in the cavity, i.e. the resonant modes [11]:

$$\vec{E}(\vec{r},t)=\sum e_n(t)\vec{E}(\vec{r})=\sum a_n(t)\cdot e^{j\omega_n t}\vec{E}_n\left(\vec{r}\right)$$

where a_n is a complex number and $e_n(t)$ is the field variation with time.

Travelling wave



The electric field travels through the cavity from the input to the output port. Its phase velocity is matched to the beam velocity, (as in presence of iris-loaded waveguide). The field phase is chosen to continuously accelerate the beam and the periodic field can be expanded in a Fourier series, with different wave numbers [11].

$$Ez(t,z)=\sum_{n=-\infty}^{+\infty} ez_n\cdot\exp\big(j\cdot(\omega t-k_n z)\big)$$

where ez_n are the space harmonic amplitude and k_n are the space harmonic wave numbers: $k_n=k_o+\frac{2\pi n}{d}$, being d the cell period and k_o the guide wave number

RF CAVITIES 2.1 CHOICE OF ACCELERATING STRUCTURE

In general **the choice of the accelerating structure depends on**:

⇒ **Particle type**: mass, charge, energy
⇒ **Beam current**
⇒ **Duty cycle** (pulsed, CW)
⇒ **Frequency**
⇒ **Cost** of fabrication and of operation

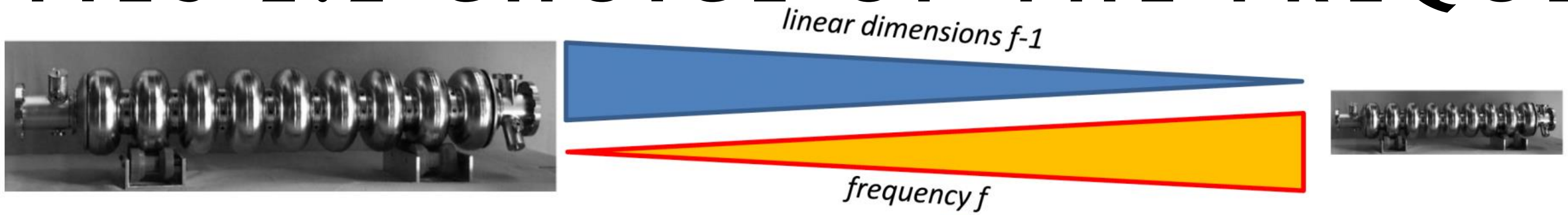
Moreover **a given accelerating structure has also a curve of efficiency** (shunt impedance) with respect to the particle energies and the choice of one structure with respect to another one depends also on this.

As example a very general scheme is given in the Table (absolutely not exhaustive).

Cavity Type	β Range	Frequency	Particles
RFQ	0.01– 0.1	40-500 MHz	Protons, Ions
DTL	0.05 – 0.5	100-400 MHz	Protons, Ions
SCL	0.5 – 1	600 MHz-3 GHz	Protons, Electrons
SC Elliptical	> 0.5-0.7	350 MHz-3 GHz	Protons, Electrons
TW	1	3-12 GHz	Electrons

Courtesy of D. Alesini [10]

RF CAVITIES 2.2 CHOICE OF THE FREQUENCY



Structure dimensions	**Scales with 1/f**
Shunt impedance (efficiency) per unit length r	**NC structures** r increases and this push to adopt **higher frequencies** $\propto f^{1/2}$
	SC structures the power losses increases with f^2 and, as a consequence, r scales with 1/f this push to adopt **lower frequencies**
Power sources	At very high frequencies (>10 GHz) **power sources** are commercially not available or expensive
Mechanical realization	Cavity fabrication at very high frequency requires **higher precision** but, on the other hand, at low frequencies one needs more material and **larger machines**/brazing oven
Bunch length	**short bunches** are easier with higher f (FEL)
RF defocusing (ion linacs)	Increases with frequency ($\propto$ f)
Cell length ($\beta\lambda$RF)	1/f
Wakefields	more critical at high frequency ($w_{//}\propto f^2$, $w_\perp\propto f^3$)

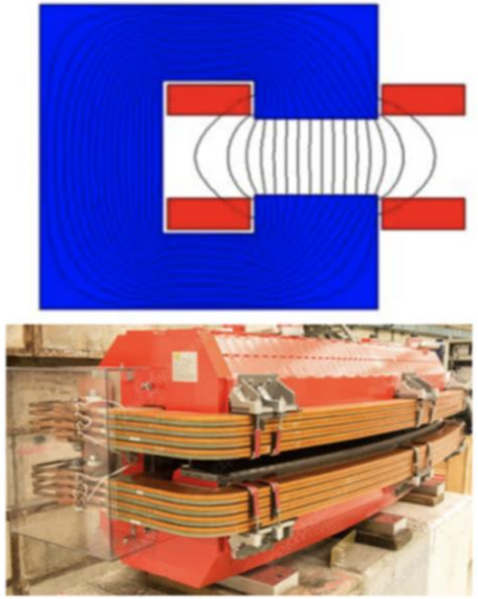
⇒**Higher frequencies** are economically convenient (shorter, less RF power, higher gradients possible) but the limitation comes from **mechanical precision** (tight tolerances are expensive!) and **beam dynamics** for ion linacs.

⇒**Electron** linacs tend to use higher frequencies (1-12 GHz) than ion linacs.
SW SC: 500 MHz-1500 MHz
TW NC: 3 GHz-12 GHz

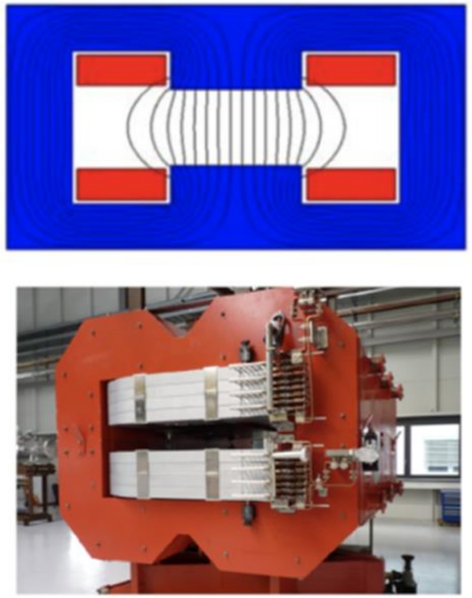
⇒**Proton** linacs use lower frequencies (100-800 MHz), increasing with energy (ex.: 350–700 MHz): compromise between focusing, cost and size.
Heavy ion linacs tend to use low frequencies (30-200 MHz),

Courtesy of D. Alesini [10]

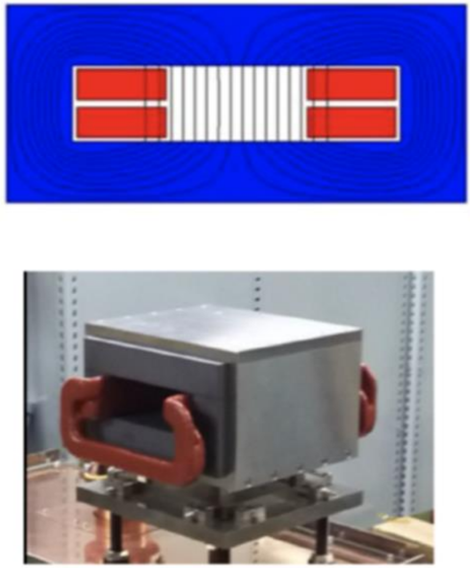
TRANSPORT SYSTEM: BENDING MAGNETS



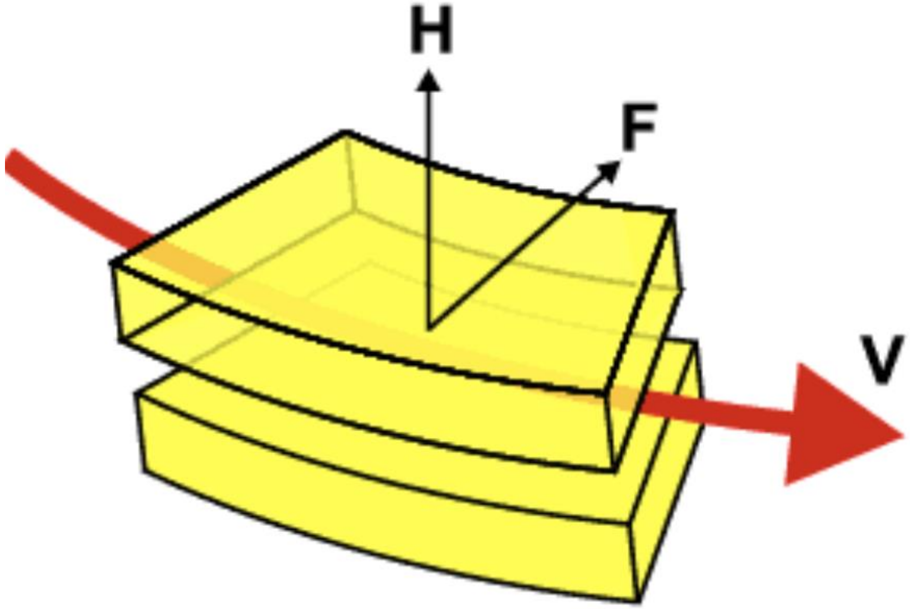
C-dipole



H-dipole

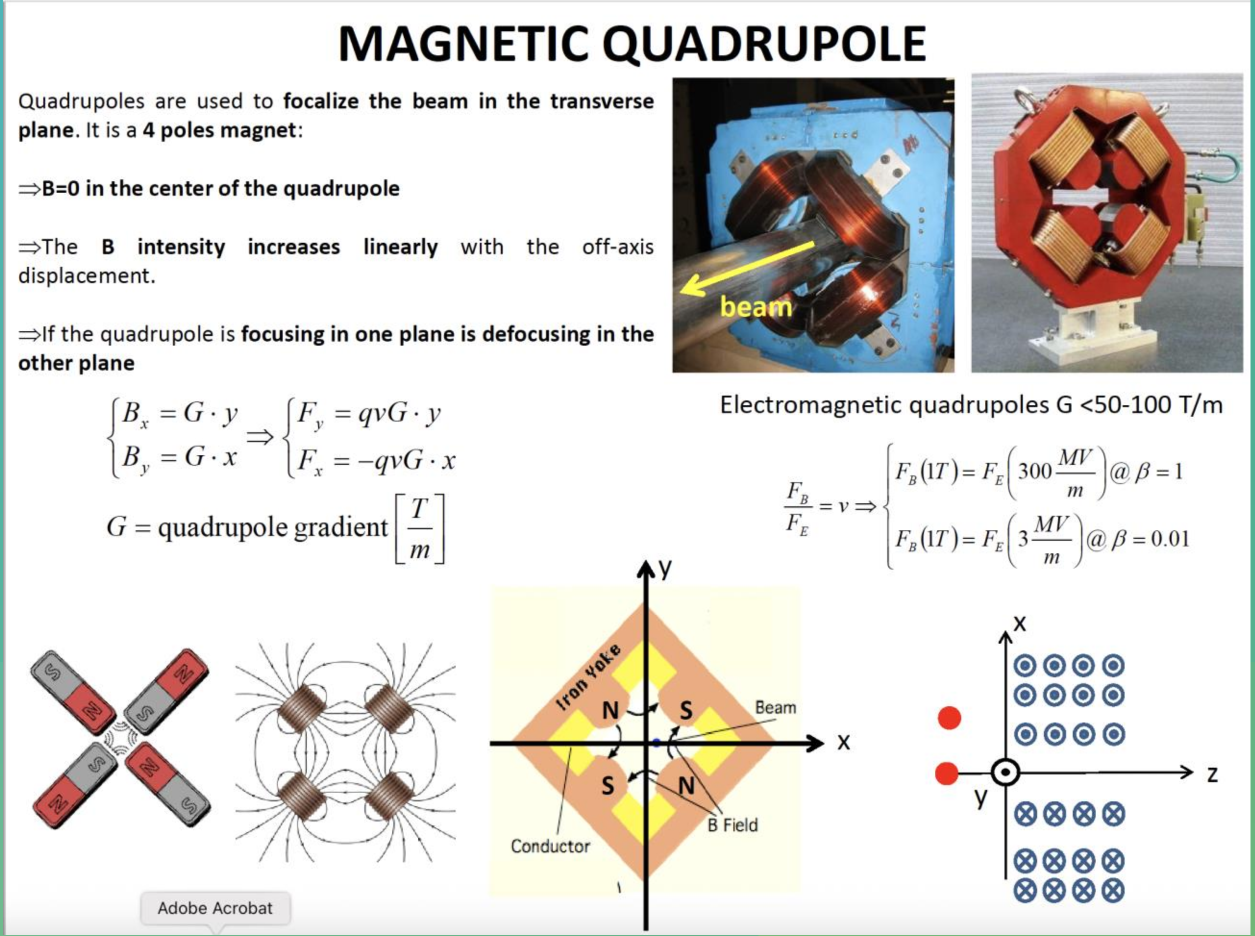


window-frame



$$B[T]\rho[m] = 3.3357\,p\left[\frac{GeV}{c}\right]$$

TRANSPORT SYSTEM: QUADRUPOLE AND SOLENOID MAGNETS



MAGNETIC QUADRUPOLE

Quadrupoles are used to **focalize the beam in the transverse plane**. It is a **4 poles magnet**:

⇒B=0 in the center of the quadrupole

⇒The **B intensity increases linearly** with the off-axis displacement.

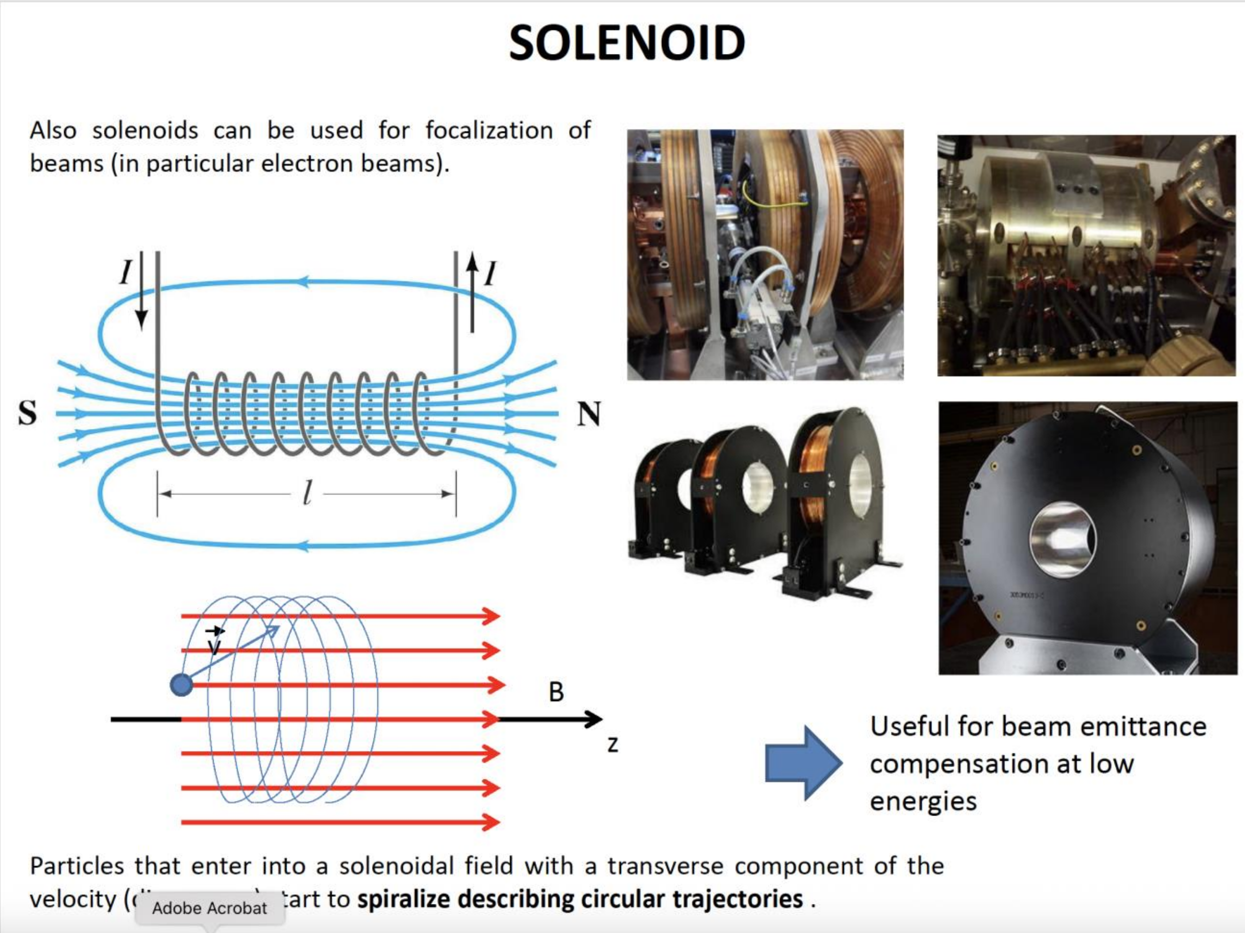
⇒If the quadrupole is **focusing in one plane is defocusing in the other plane**

$$\begin{cases} B_x = G \cdot y \\ B_y = G \cdot x \end{cases} \Rightarrow \begin{cases} F_y = qvG \cdot y \\ F_x = -qvG \cdot x \end{cases}$$

$$G = \text{quadrupole gradient}\left[\frac{T}{m}\right]$$

Electromagnetic quadrupoles G <50-100 T/m

$$\frac{F_B}{F_E} = v \Rightarrow \begin{cases} F_B(1T) = F_E\left(300\frac{MV}{m}\right) @ \beta = 1 \\ F_B(1T) = F_E\left(3\frac{MV}{m}\right) @ \beta = 0.01 \end{cases}$$



SOLENOID

Also solenoids can be used for focalization of beams (in particular electron beams).

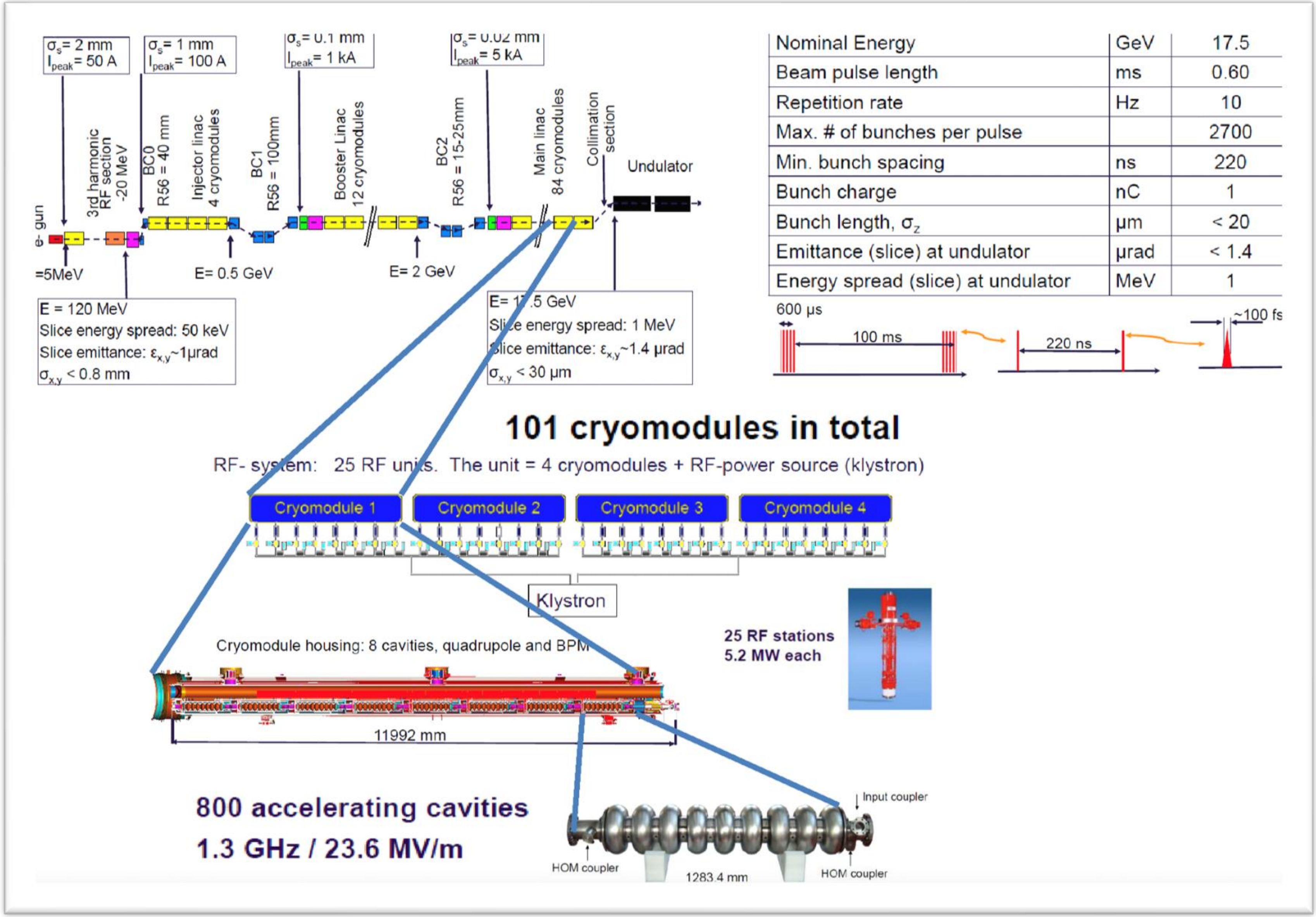
Useful for beam emittance compensation at low energies

Particles that enter into a solenoidal field with a transverse component of the velocity (tart to **spiralize describing circular trajectories** .

Courtesy of D. Alesini [10]

EUROPEAN XFEL

EXAMPLES 1: [12]



Nominal Energy	GeV	17.5
Beam pulse length	ms	0.60
Repetition rate	Hz	10
Max. # of bunches per pulse		2700
Min. bunch spacing	ns	220
Bunch charge	nC	1
Bunch length, σ_z	µm	< 20
Emittance (slice) at undulator	µrad	< 1.4
Energy spread (slice) at undulator	MeV	1

E = 120 MeV
Slice energy spread: 50 keV
Slice emittance: $\varepsilon_{x,y}$~1µrad
$\sigma_{x,y} < 0.8$ mm

E= 17.5 GeV
Slice energy spread: 1 MeV
Slice emittance: $\varepsilon_{x,y}$~1.4 µrad
$\sigma_{x,y} < 30$ µm

101 cryomodules in total

RF- system: 25 RF units. The unit = 4 cryomodules + RF-power source (klystron)

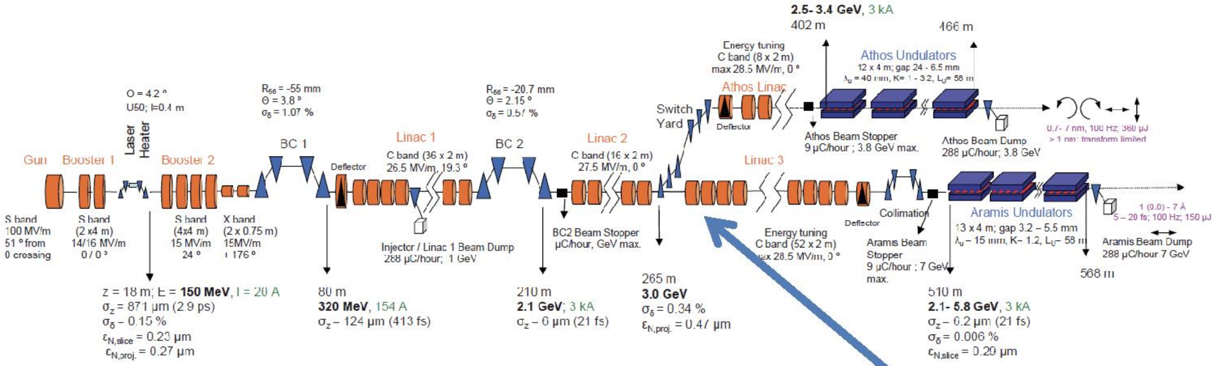
Cryomodule housing: 8 cavities, quadrupole and BPM

25 RF stations
5.2 MW each

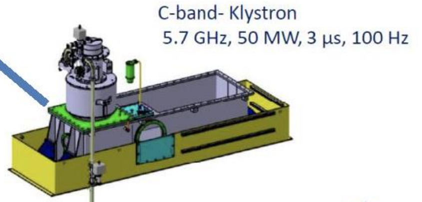
800 accelerating cavities
1.3 GHz / 23.6 MV/m

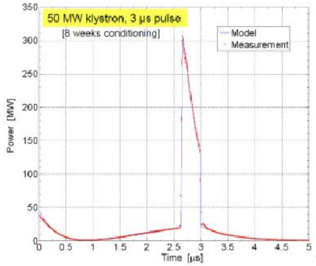
EXAMPLES 2: [13]

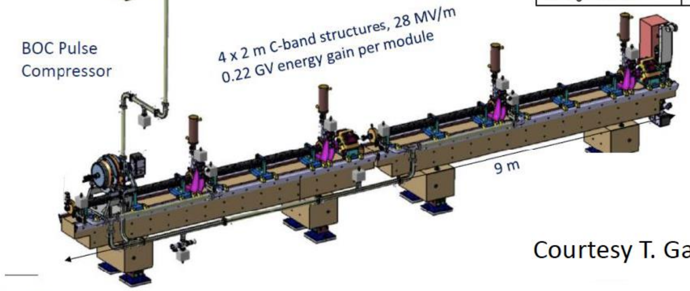
SWISSFEL LINAC (PSI)



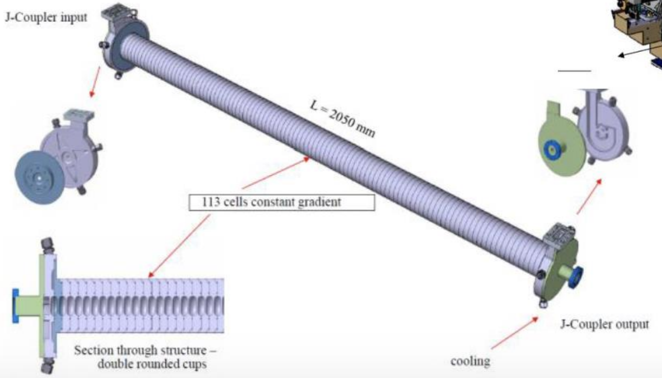
Main LINAC	#
LINAC modules	26
Modulator	26
Klystron	26
Pulse compressor	26
Accelerating structures	104
Waveguide splitter	78
Waveguide loads	104

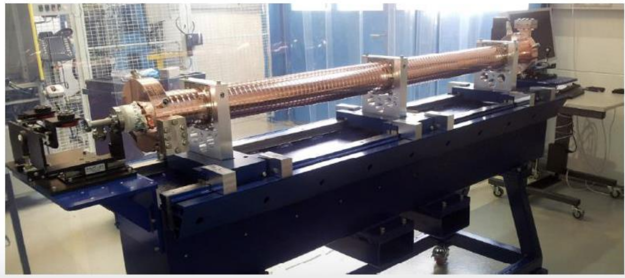






Courtesy T. Garvey





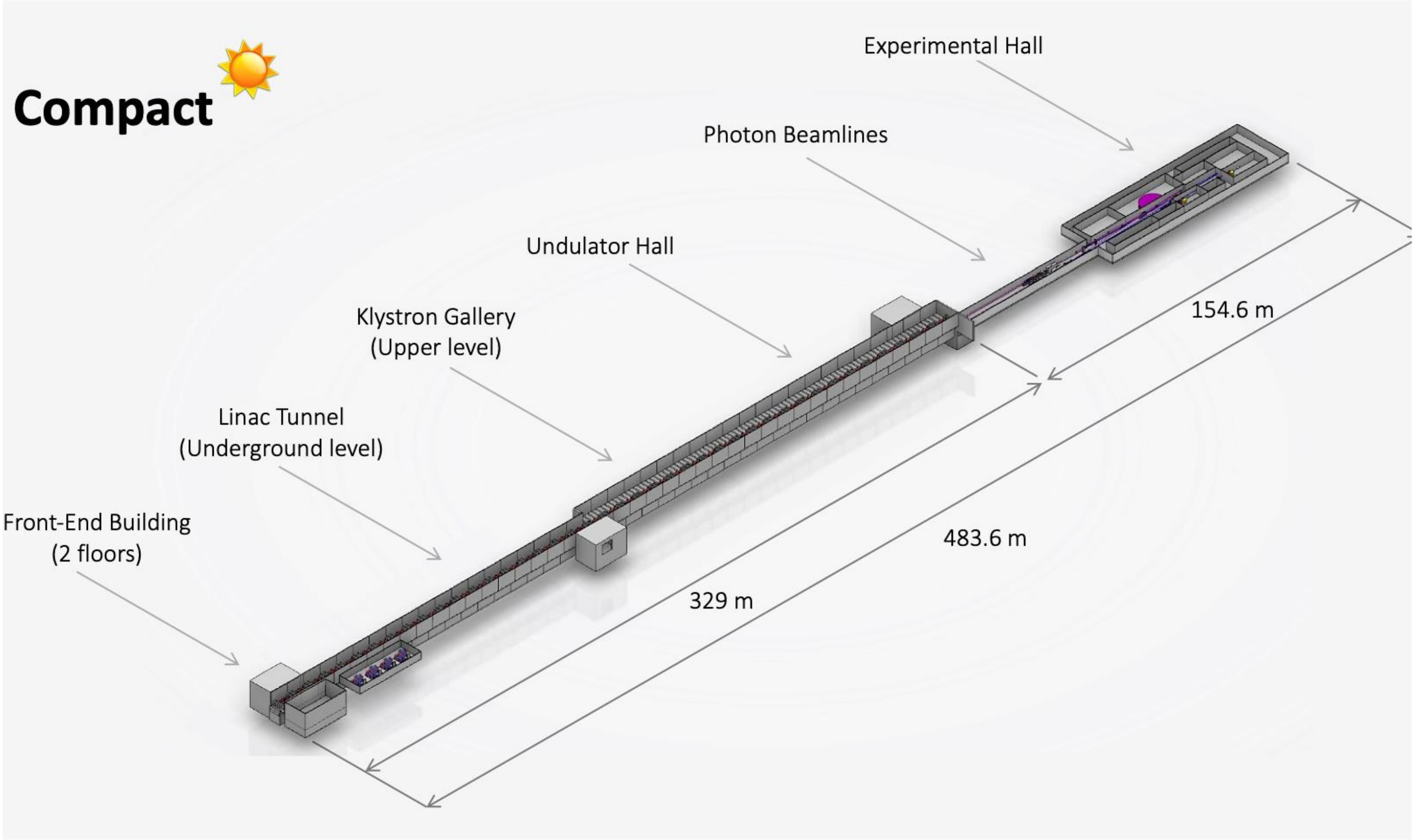
HIGH GRADIENT PATH

X- BAND TECHNOLOGY FOR FEL’S

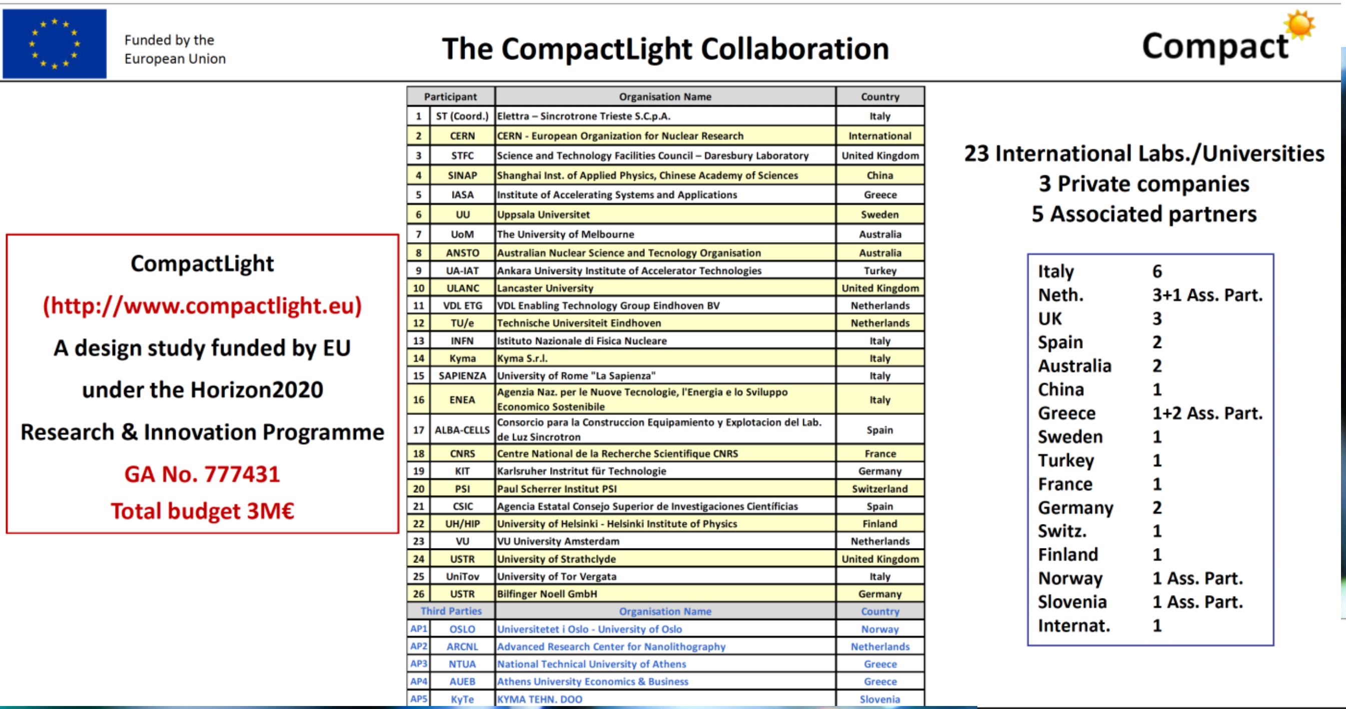
PLASMA ACCELERATION

X-BAND TECHNOLOGY FOR FEL’S

- Synchrotron Radiation (SR) is a fundamental and indispensable research tool in a wide spectrum of scientific and technological fields. The latest generation of SR sources is based on Free Electron Lasers (FELs) driven by linacs.
- These facilities, with sub-picosecond pulse-lengths and wavelengths down to the hard X-ray range, feature unprecedented performance in terms of peak brilliance, exceeding by many orders of magnitude that of third generation synchrotrons.



COMPACT LIGHT XLS PROJECT



Funded by the European Union

The CompactLight Collaboration

Compact

CompactLight

(http://www.compactlight.eu)

A design study funded by EU under the Horizon2020 Research & Innovation Programme

GA No. 777431

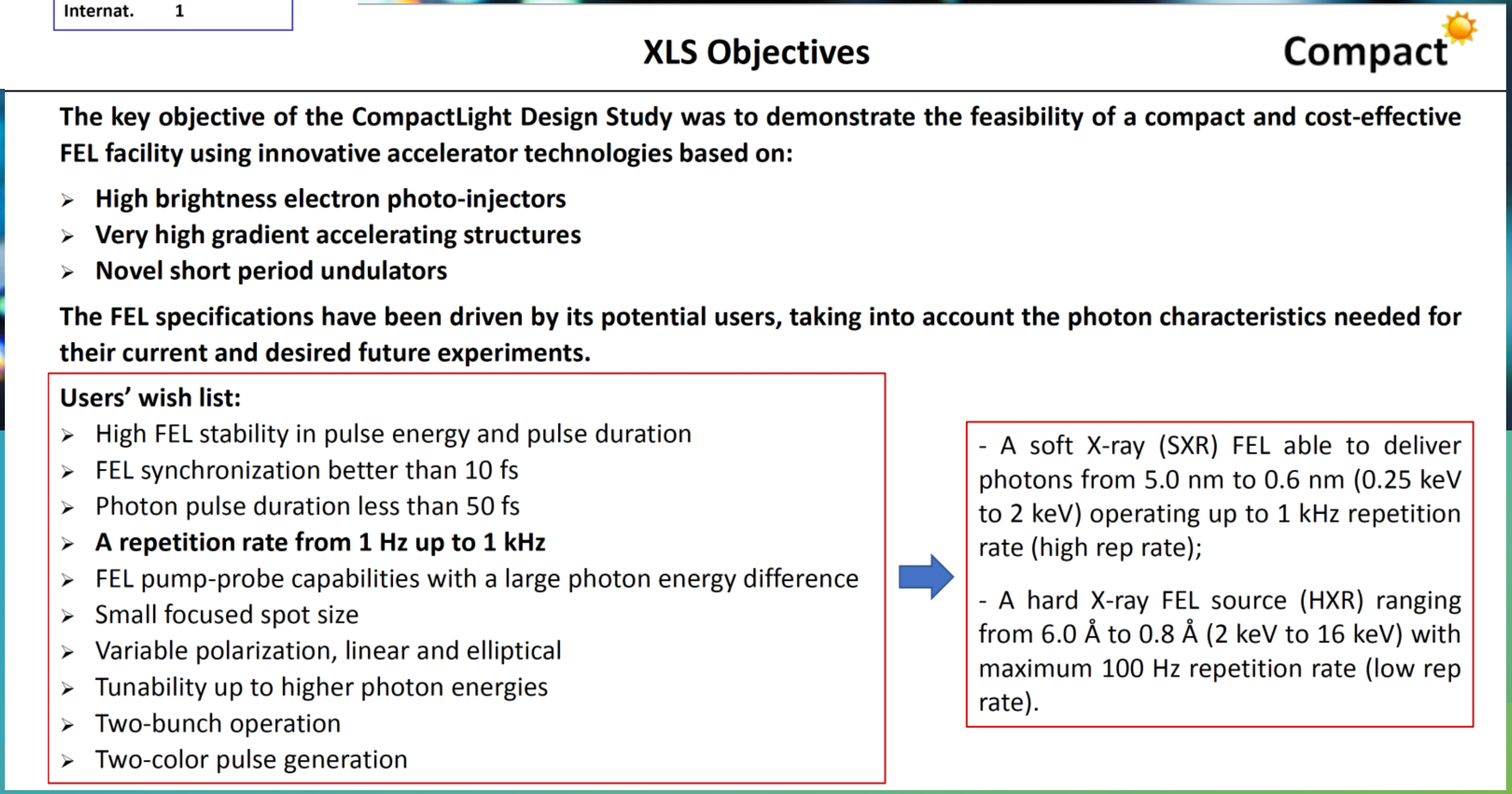
Total budget 3M€

Participant		Organisation Name	Country
1	ST (Coord.)	Elettra – Sincrotrone Trieste S.C.p.A.	Italy
2	CERN	CERN - European Organization for Nuclear Research	International
3	STFC	Science and Technology Facilities Council – Daresbury Laboratory	United Kingdom
4	SINAP	Shanghai Inst. of Applied Physics, Chinese Academy of Sciences	China
5	IASA	Institute of Accelerating Systems and Applications	Greece
6	UU	Uppsala Universitet	Sweden
7	UoM	The University of Melbourne	Australia
8	ANSTO	Australian Nuclear Science and Tecnology Organisation	Australia
9	UA-IAT	Ankara University Institute of Accelerator Technologies	Turkey
10	ULANC	Lancaster University	United Kingdom
11	VDL ETG	VDL Enabling Technology Group Eindhoven BV	Netherlands
12	TU/e	Technische Universiteit Eindhoven	Netherlands
13	INFN	Istituto Nazionale di Fisica Nucleare	Italy
14	Kyma	Kyma S.r.l.	Italy
15	SAPIENZA	University of Rome "La Sapienza"	Italy
16	ENEA	Agenzia Naz. per le Nuove Tecnologie, l'Energia e lo Sviluppo Economico Sostenibile	Italy
17	ALBA-CELLS	Consorcio para la Construccion Equipamiento y Explotacion del Lab. de Luz Sincrotron	Spain
18	CNRS	Centre National de la Recherche Scientifique CNRS	France
19	KIT	Karlsruher Instritut für Technologie	Germany
20	PSI	Paul Scherrer Institut PSI	Switzerland
21	CSIC	Agencia Estatal Consejo Superior de Investigaciones Científicias	Spain
22	UH/HIP	University of Helsinki - Helsinki Institute of Physics	Finland
23	VU	VU University Amsterdam	Netherlands
24	USTR	University of Strathclyde	United Kingdom
25	UniTov	University of Tor Vergata	Italy
26	USTR	Bilfinger Noell GmbH	Germany
Third Parties		Organisation Name	Country
AP1	OSLO	Universitetet i Oslo - University of Oslo	Norway
AP2	ARCNL	Advanced Research Center for Nanolithography	Netherlands
AP3	NTUA	National Technical University of Athens	Greece
AP4	AUEB	Athens University Economics & Business	Greece
AP5	KyTe	KYMA TEHN. DOO	Slovenia

23 International Labs./Universities
3 Private companies
5 Associated partners

Italy	6
Neth.	3+1 Ass. Part.
UK	3
Spain	2
Australia	2
China	1
Greece	1+2 Ass. Part.
Sweden	1
Turkey	1
France	1
Germany	2
Switz.	1
Finland	1
Norway	1 Ass. Part.
Slovenia	1 Ass. Part.
Internat.	1

Courtesy of G. D'Auria
https://indico.elettra.eu/event/29/overview



XLS Objectives

Compact

The key objective of the CompactLight Design Study was to demonstrate the feasibility of a compact and cost-effective FEL facility using innovative accelerator technologies based on:

- **High brightness electron photo-injectors**
- **Very high gradient accelerating structures**
- **Novel short period undulators**

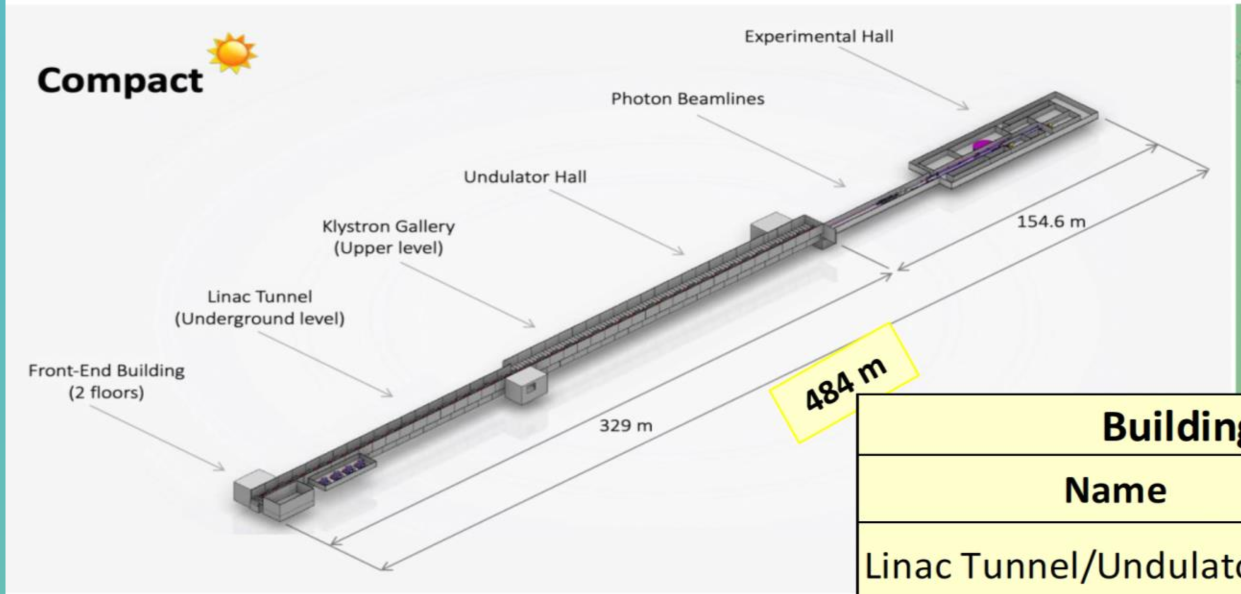
The FEL specifications have been driven by its potential users, taking into account the photon characteristics needed for their current and desired future experiments.

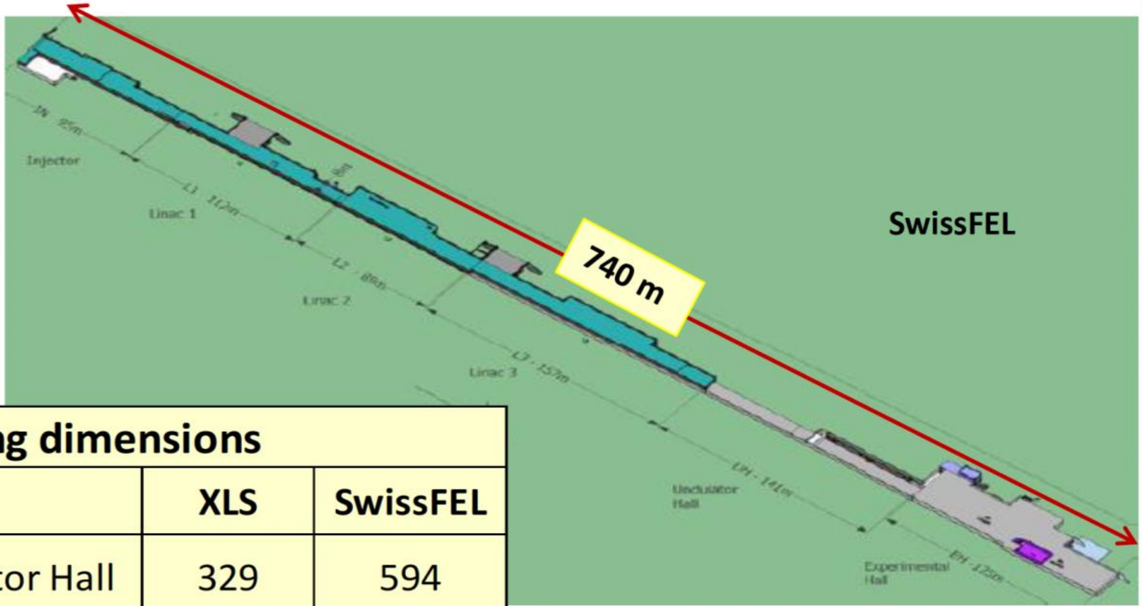
Users' wish list:

- High FEL stability in pulse energy and pulse duration
- FEL synchronization better than 10 fs
- Photon pulse duration less than 50 fs
- **A repetition rate from 1 Hz up to 1 kHz**
- FEL pump-probe capabilities with a large photon energy difference
- Small focused spot size
- Variable polarization, linear and elliptical
- Tunability up to higher photon energies
- Two-bunch operation
- Two-color pulse generation

- A soft X-ray (SXR) FEL able to deliver photons from 5.0 nm to 0.6 nm (0.25 keV to 2 keV) operating up to 1 kHz repetition rate (high rep rate);
- A hard X-ray FEL source (HXR) ranging from 6.0 Å to 0.8 Å (2 keV to 16 keV) with maximum 100 Hz repetition rate (low rep rate).

Facility dimensions & costs





Building dimensions

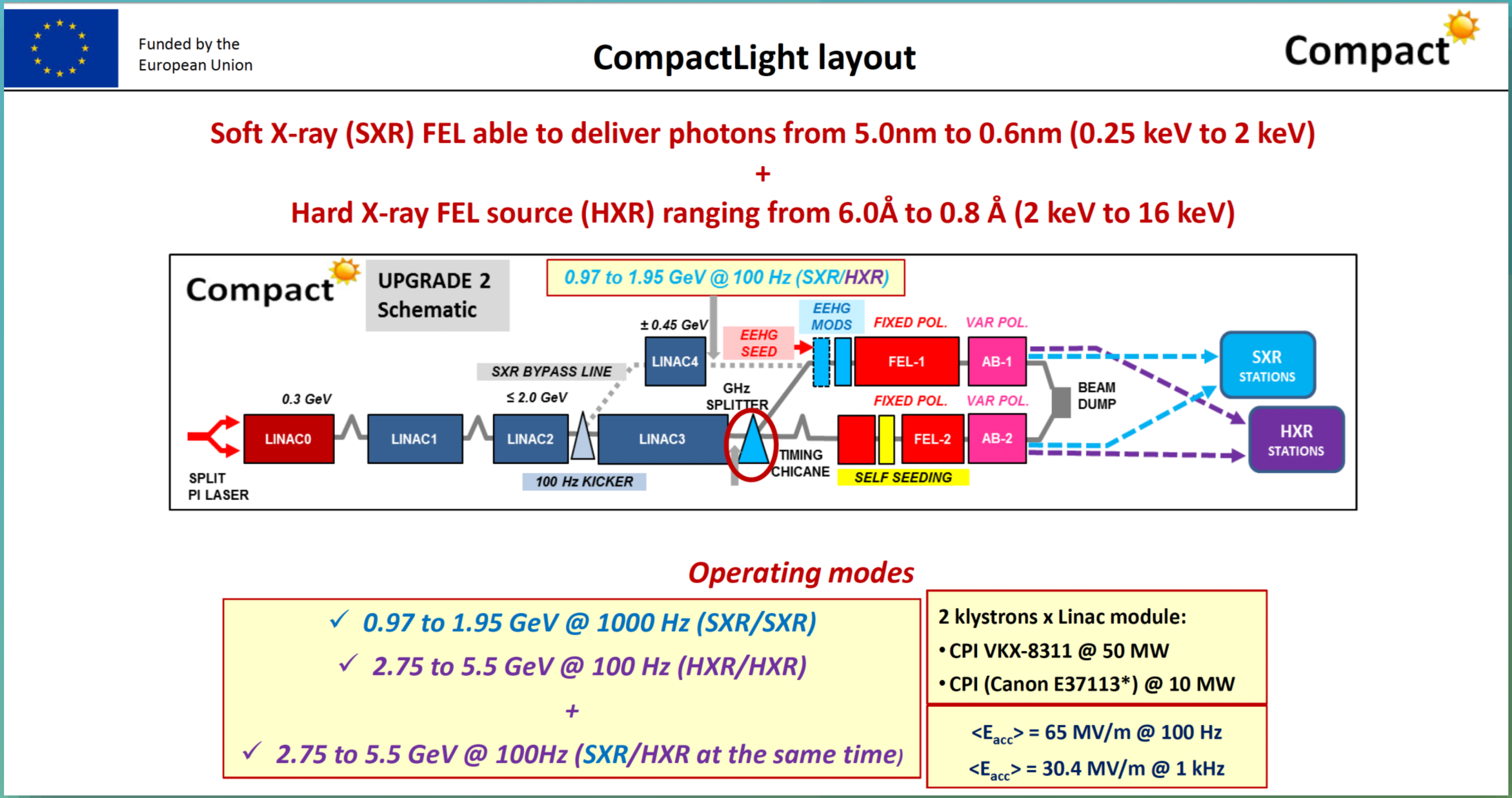
Name	XLS	SwissFEL
Linac Tunnel/Undulator Hall	329	594
Experimental Hall	155	146
TOTAL	**484**	**740**

Footprint → ≈ 35% shorter than SwissFEL

Complexity → macro-components design as ”building blocks” or ”standard units” to assemble for a vast number of applications

Efficiency → normal-conducting facilities that can operate at high rep. rates, (kHz regimes)

Cost → ≈ 25% cost reduction



Funded by the
European Union

CompactLight layout

Compact

Soft X-ray (SXR) FEL able to deliver photons from 5.0nm to 0.6nm (0.25 keV to 2 keV)

+

Hard X-ray FEL source (HXR) ranging from 6.0Å to 0.8 Å (2 keV to 16 keV)

Operating modes

- ✓ *0.97 to 1.95 GeV @ 1000 Hz (SXR/SXR)*
- ✓ *2.75 to 5.5 GeV @ 100 Hz (HXR/HXR)*

+

- ✓ *2.75 to 5.5 GeV @ 100Hz (SXR/HXR at the same time)*

2 klystrons x Linac module:

- **CPI VKX-8311 @ 50 MW**
- **CPI (Canon E37113*) @ 10 MW**

$\langle E_{acc} \rangle$ = 65 MV/m @ 100 Hz
$\langle E_{acc} \rangle$ = 30.4 MV/m @ 1 kHz

G. D'Auria
"The CompactLight(XLS) Project Objectives & Results", LEDS 2023, 03–05 ott 2023, ENEA Frascati, Rome

Funded by the
European Union

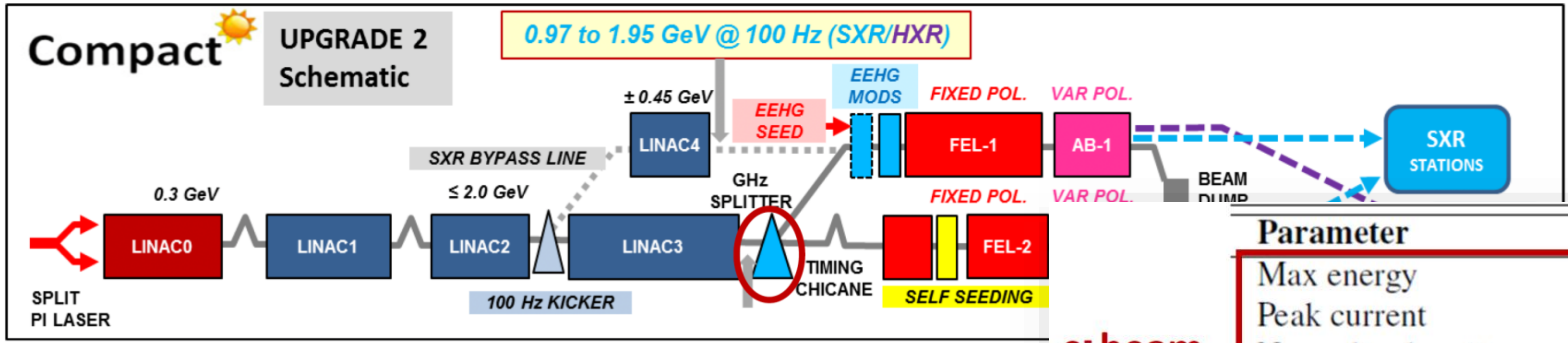
CompactLight layout

Compact

Soft X-ray (SXR) FEL able to deliver photons from 5.0nm to 0.6nm (0.25 keV to 2 keV)

+

Hard X-ray FEL source (HXR) ranging from 6.0Å to 0.8 Å (2 keV to 16 keV)



Operating modes

- ✓ *0.97 to 1.95 GeV @ 1000 Hz (SXR/SXR)*
- ✓ *2.75 to 5.5 GeV @ 100 Hz (HXR/HXR)*

+

- ✓ *2.75 to 5.5 GeV @ 100Hz (SXR/HXR at the same time)*

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e⁻ beam (HXR)

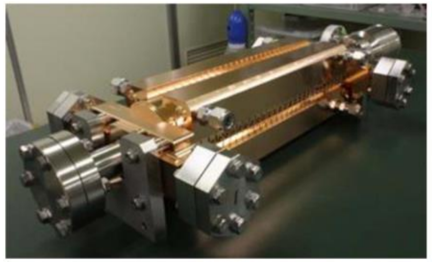
Parameter	Value
Max energy	5.5 GeV @100 Hz
Peak current	5 kA
Normalised emittance	0.2 mm.mrad
Bunch charge	< 100 pC
RMS slice energy spread	10^{-4}
Max photon energy	16 keV
FEL tuning range at fixed energy	×2
Peak spectral brightness @16 keV	10^{33} ph/s/mm^2/mrad^2/0.1%bw

FEL

Parameter	Unit	Soft-x-ray FEL	Hard-x-ray FEL
Photon energy	keV	0.25 – 2.0	2.0 – 16.0
Wavelength	nm	5.0 – 0.6	0.6 – 0.08
Repetition rate	Hz	1000	100
Pulse duration	fs	0.1 – 50	1 – 50
Polarization		Variable, selectable	Variable, selectable
Two-pulse delay	fs	±100	±100
Two-colour separation	%	20	10
Synchronization	fs	<10	<10

NEW SUB-SYSTEMS DESIGN

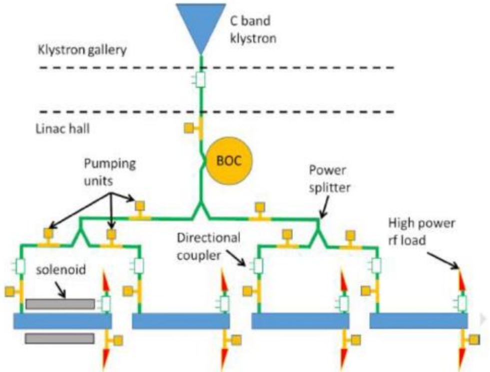
C-band photoinjector



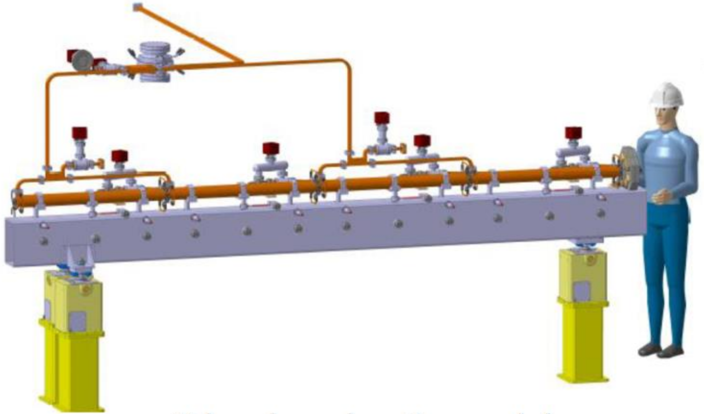
C- and X-band accelerating structures

Two prototypes under construction in the context of the I.FAST project

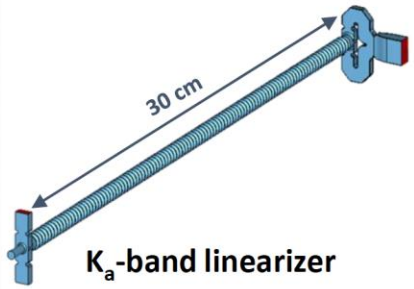
Helical SC Undulator 30 cm model



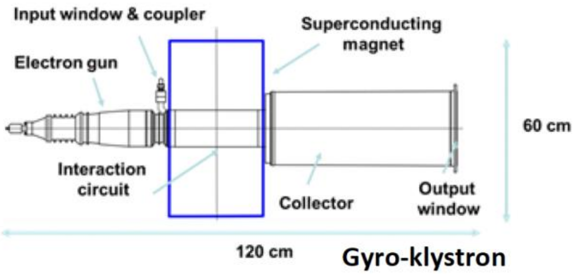
C-band accelerating module



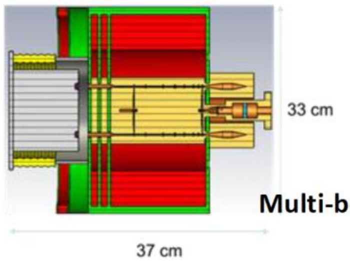
X-band accelerating module



K_a-band linearizer



Gyro-klystron



Multi-beam klystron

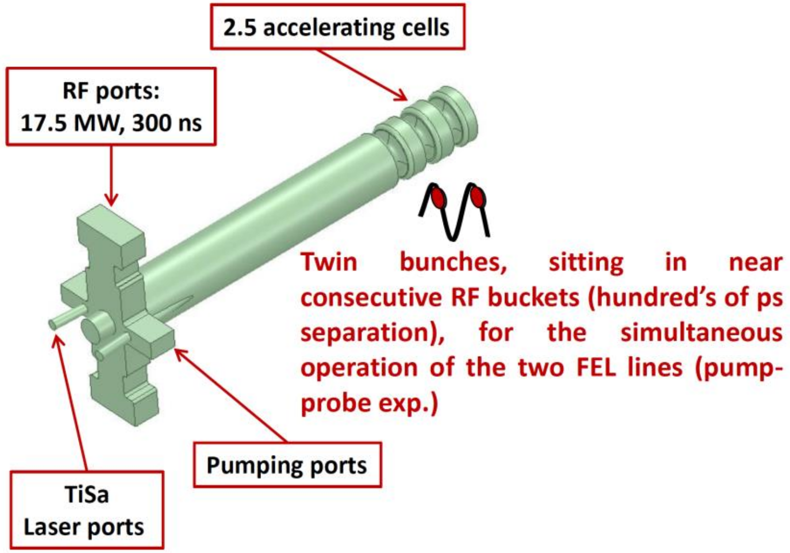
K_a-band RF sources

The XLS Collaboration is also strongly promoting with industry the development of C- and X-band high power RF sources that can operate up to 1 KHz

Funded by the European Union

XLS C-band photoinjector

Compact



Twin bunches, sitting in near consecutive RF buckets (hundred's of ps separation), for the simultaneous operation of the two FEL lines (pump-probe exp.)

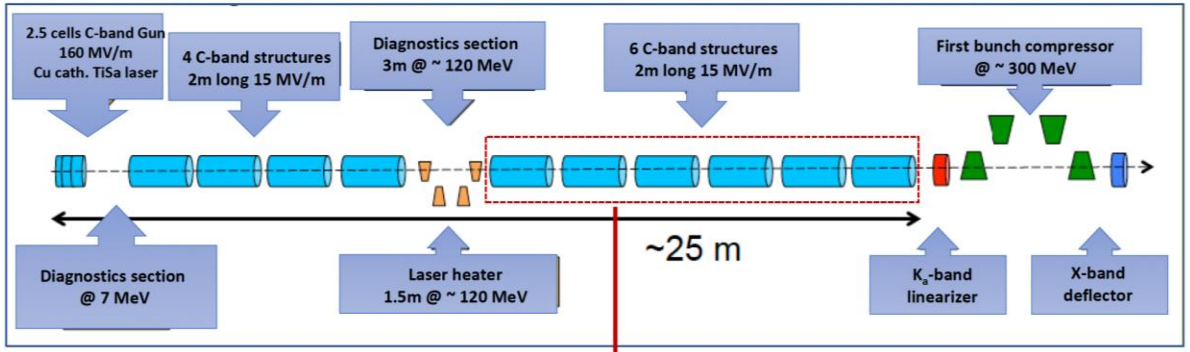
E_{cath}	160 MV/m
$\Delta f_{\pi/2-\pi}$	≈ 52 MHz
Q_0	11600
β	3
Filling time (τ_F)	160 ns
P_{diss} @160MV/m	9.7 MW
$E_{CAT}/\sqrt{P_{diss}}$	51.4 [MV/m/(MW)$^{0.5}$]
Rep. Rate	1000 Hz
Peak Input power P_{IN}	17.5 MW
Pulsed heating (T_{puls})	<20 °C
RF pulse length (T_{RF})	300 ns
Av diss power (P_{av})	2300 W

KEY SUB-SYSTEMS 1.

Full C-band injector

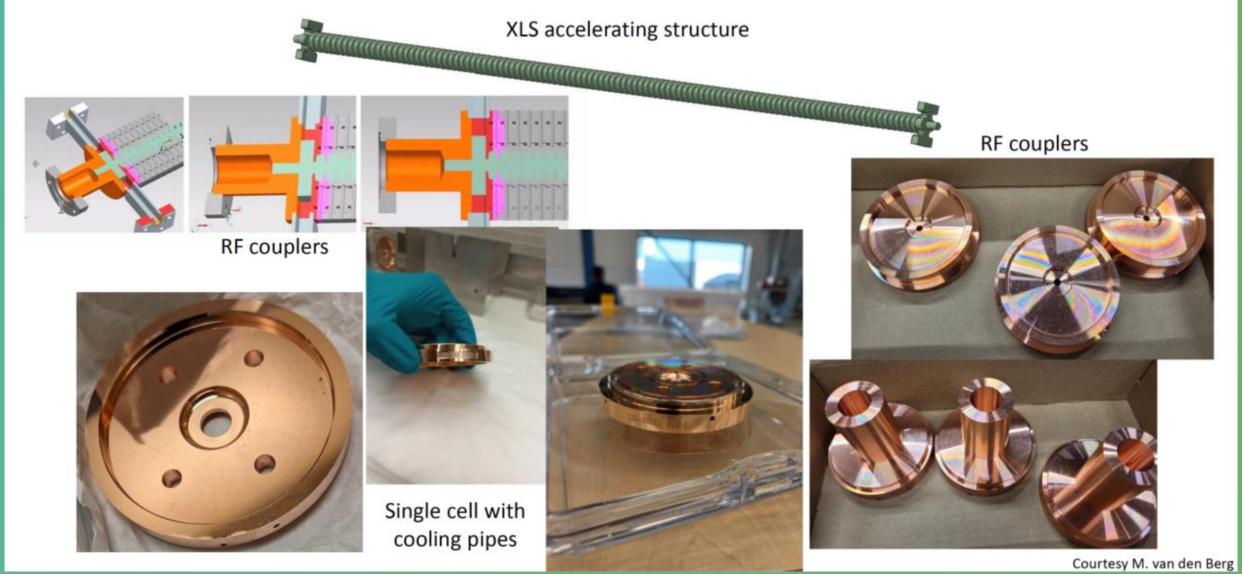
Courtesy D. Alesini

Same injector for High and Low repetition rate operations (1 KHz and 100 Hz)

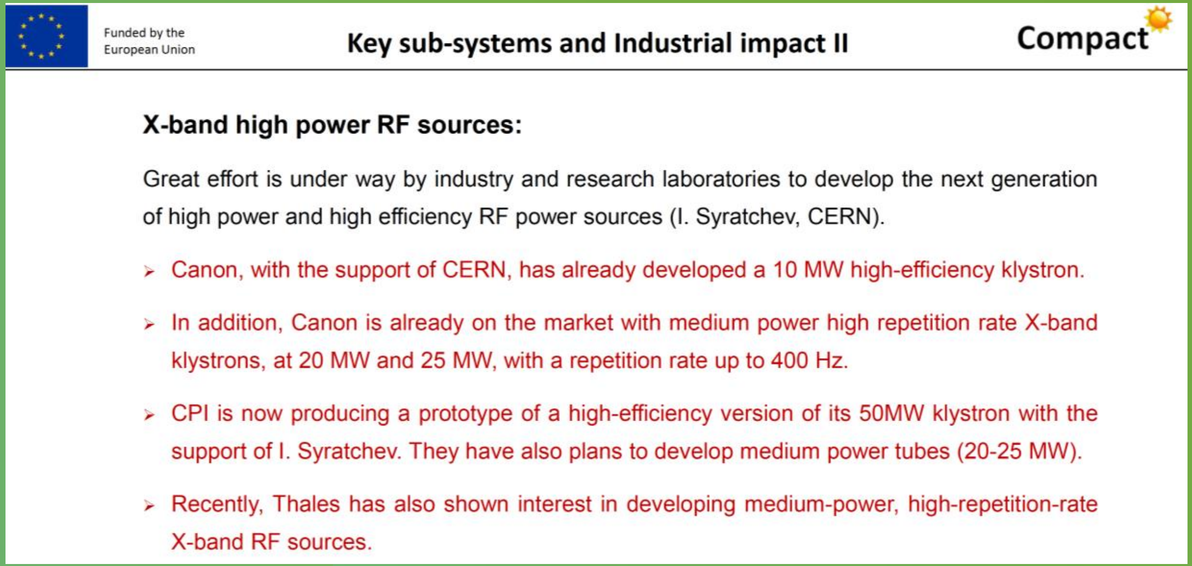


Possible replacement of the last 6 C-band stuctures
with 4 X-band structures @30 MV/m for the 1 KHz operation

KEY SUB-SYSTEMS 2.



Courtesy M. van den Berg


Funded by the European Union

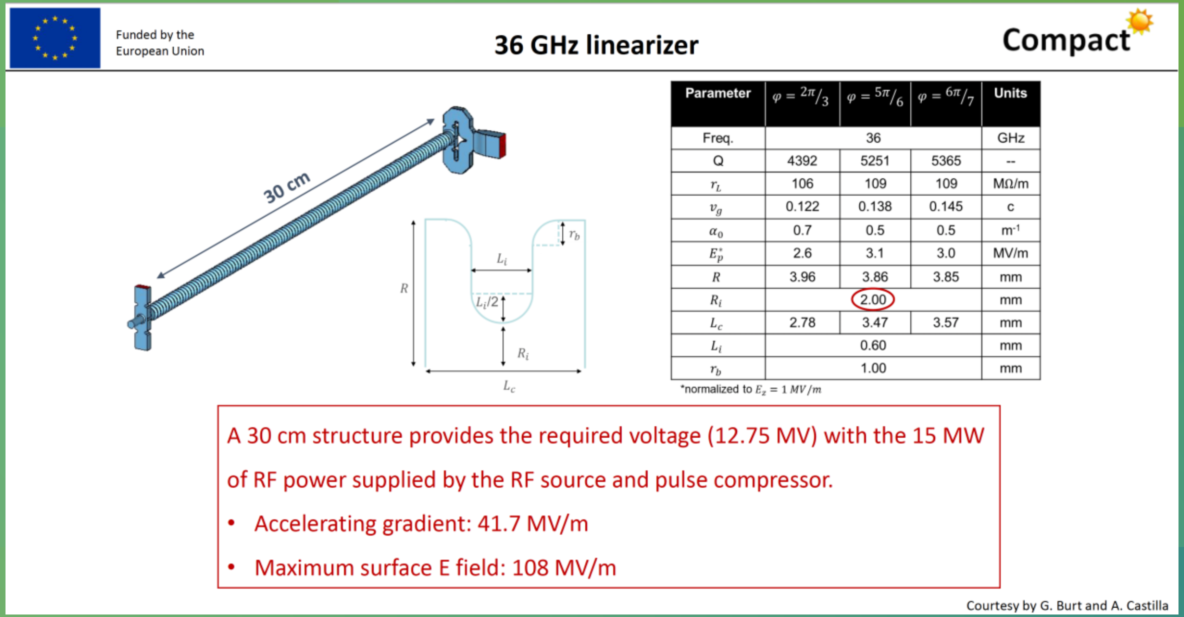
Key sub-systems and Industrial impact II

Compact

X-band high power RF sources:

Great effort is under way by industry and research laboratories to develop the next generation of high power and high efficiency RF power sources (I. Syratchev, CERN).

- Canon, with the support of CERN, has already developed a 10 MW high-efficiency klystron.
- In addition, Canon is already on the market with medium power high repetition rate X-band klystrons, at 20 MW and 25 MW, with a repetition rate up to 400 Hz.
- CPI is now producing a prototype of a high-efficiency version of its 50MW klystron with the support of I. Syratchev. They have also plans to develop medium power tubes (20-25 MW).
- Recently, Thales has also shown interest in developing medium-power, high-repetition-rate X-band RF sources.


Funded by the European Union

36 GHz linearizer

Compact

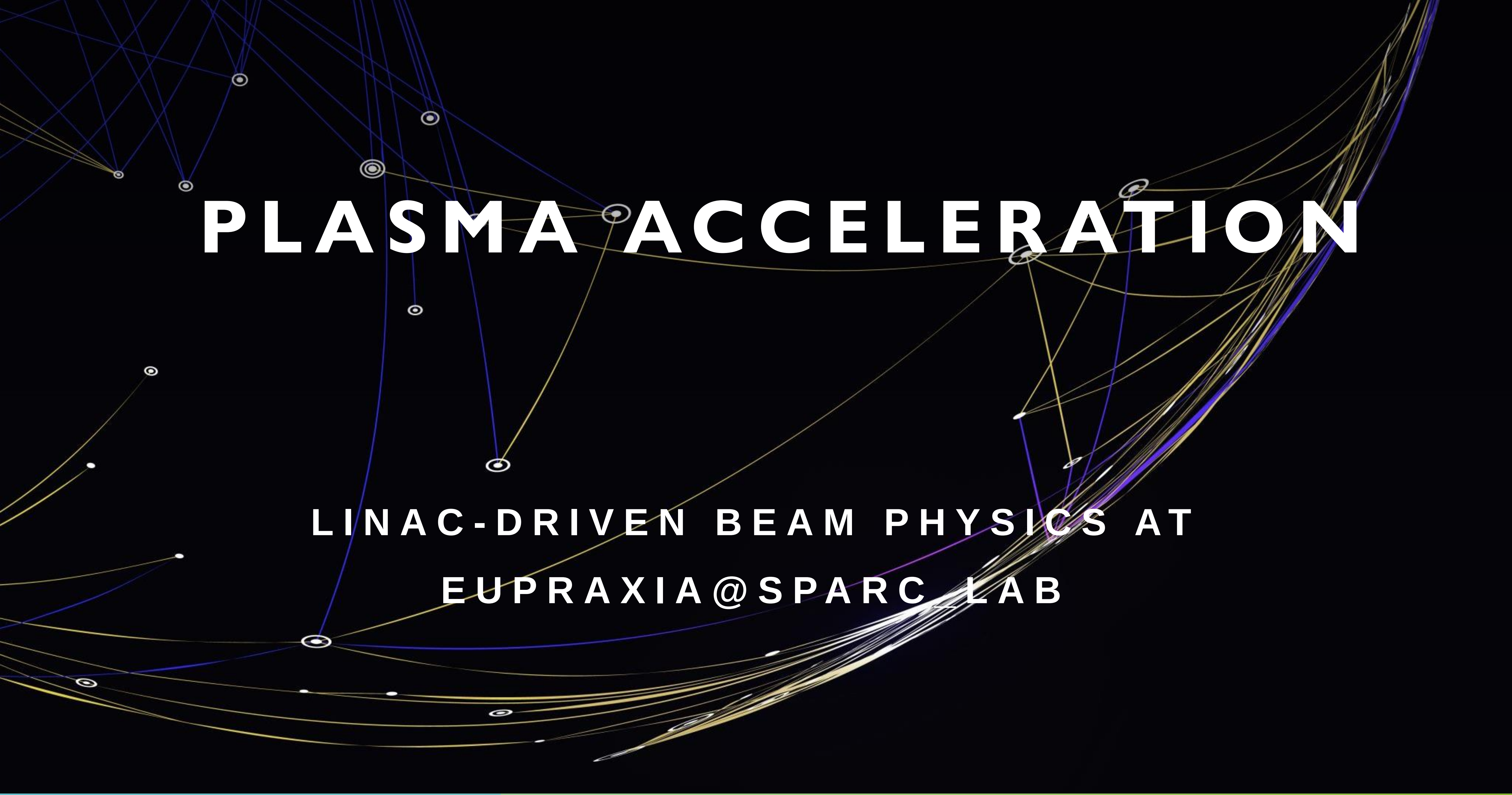
Parameter	$\varphi = {}^{2\pi}/_{3}$	$\varphi = {}^{5\pi}/_{6}$	$\varphi = {}^{6\pi}/_{7}$	Units
Freq.	36			GHz
Q	4392	5251	5365	--
r_L	106	109	109	MΩ/m
v_g	0.122	0.138	0.145	c
α_0	0.7	0.5	0.5	m^{-1}
E_p^*	2.6	3.1	3.0	MV/m
R	3.96	3.86	3.85	mm
R_i	2.00			mm
L_c	2.78	3.47	3.57	mm
L_i	0.60			mm
r_b	1.00			mm

*normalized to $E_z = 1\ MV/m$

A 30 cm structure provides the required voltage (12.75 MV) with the 15 MW of RF power supplied by the RF source and pulse compressor.

- Accelerating gradient: 41.7 MV/m
- Maximum surface E field: 108 MV/m

Courtesy by G. Burt and A. Castilla



PLASMA ACCELERATION

LINAC-DRIVEN BEAM PHYSICS AT EUPRAXIA@SPARC_LAB

A New European High-Tech User Facility

European Plasma Research Accelerator With Excellence In Applications

a European project “which aims to develop the first dedicated research infrastructure based on novel plasma-acceleration concepts”

Building a facility with very high field plasma accelerators, driven by lasers or beams

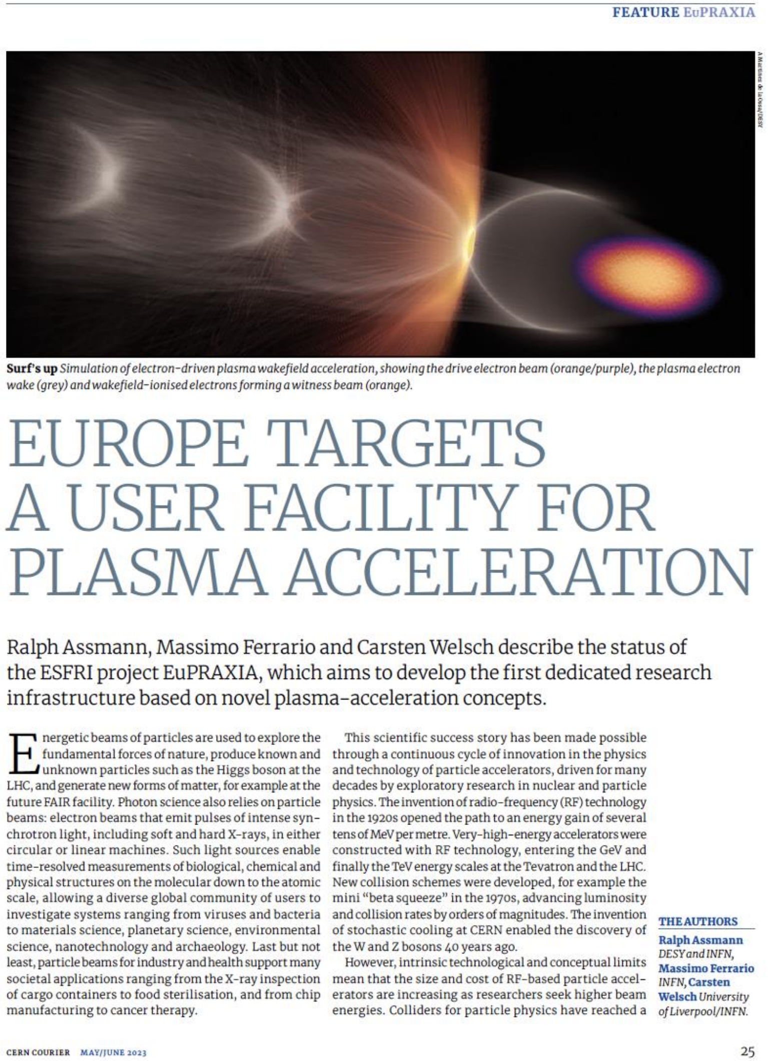
1 – 100 GV/m accelerating field

Shrink down the facility size

↓

Provide a practical path **to more research facilities** and ultimately to **higher beam energies** for the same investment in terms of size and costs

Enable frontier science in new regions and parameter regimes



FEATURE EuPRAXIA

A Martinez de la Ossa/DESY

Surf’s up *Simulation of electron-driven plasma wakefield acceleration, showing the drive electron beam (orange/purple), the plasma electron wake (grey) and wakefield-ionised electrons forming a witness beam (orange).*

EUROPE TARGETS A USER FACILITY FOR PLASMA ACCELERATION

Ralph Assmann, Massimo Ferrario and Carsten Welsch describe the status of the ESFRI project EuPRAXIA, which aims to develop the first dedicated research infrastructure based on novel plasma-acceleration concepts.

Energetic beams of particles are used to explore the fundamental forces of nature, produce known and unknown particles such as the Higgs boson at the LHC, and generate new forms of matter, for example at the future FAIR facility. Photon science also relies on particle beams: electron beams that emit pulses of intense synchrotron light, including soft and hard X-rays, in either circular or linear machines. Such light sources enable time-resolved measurements of biological, chemical and physical structures on the molecular down to the atomic scale, allowing a diverse global community of users to investigate systems ranging from viruses and bacteria to materials science, planetary science, environmental science, nanotechnology and archaeology. Last but not least, particle beams for industry and health support many societal applications ranging from the X-ray inspection of cargo containers to food sterilisation, and from chip manufacturing to cancer therapy.

This scientific success story has been made possible through a continuous cycle of innovation in the physics and technology of particle accelerators, driven for many decades by exploratory research in nuclear and particle physics. The invention of radio-frequency (RF) technology in the 1920s opened the path to an energy gain of several tens of MeV per metre. Very-high-energy accelerators were constructed with RF technology, entering the GeV and finally the TeV energy scales at the Tevatron and the LHC. New collision schemes were developed, for example the mini “beta squeeze” in the 1970s, advancing luminosity and collision rates by orders of magnitudes. The invention of stochastic cooling at CERN enabled the discovery of the W and Z bosons 40 years ago.

However, intrinsic technological and conceptual limits mean that the size and cost of RF-based particle accelerators are increasing as researchers seek higher beam energies. Colliders for particle physics have reached a

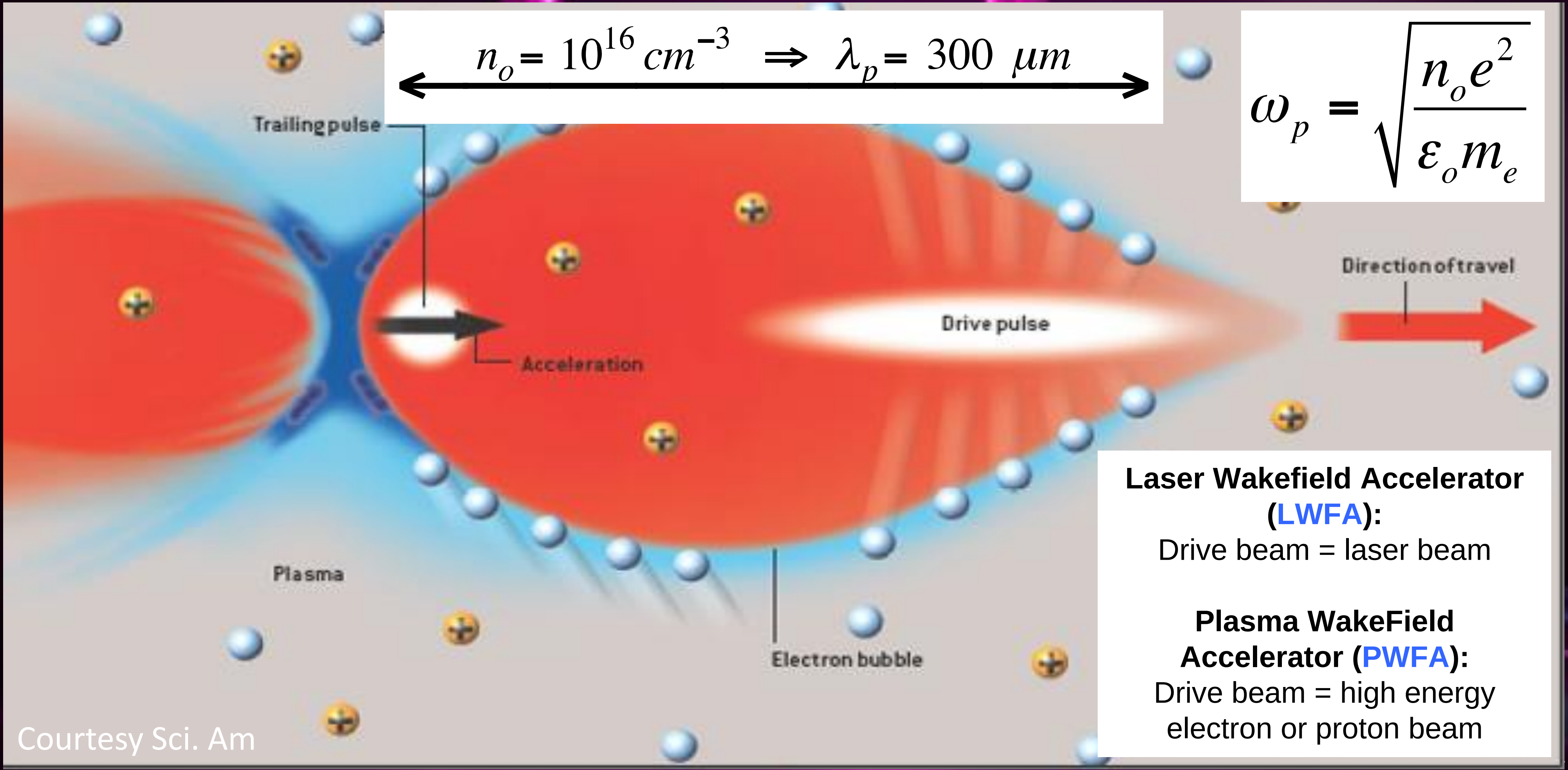
THE AUTHORS

Ralph Assmann *DESY and INFN,* **Massimo Ferrario** *INFN,* **Carsten Welsch** *University of Liverpool/INFN.*

CERN COURIER MAY/JUNE 2023 25

https://cerncourier.com/a/europe-targets-a-user-facility-for-plasma-acceleration/

Principle of plasma acceleration



$$\longleftarrow \quad n_o = 10^{16}\,cm^{-3} \;\Rightarrow\; \lambda_p = 300\ \mu m \quad \longrightarrow$$

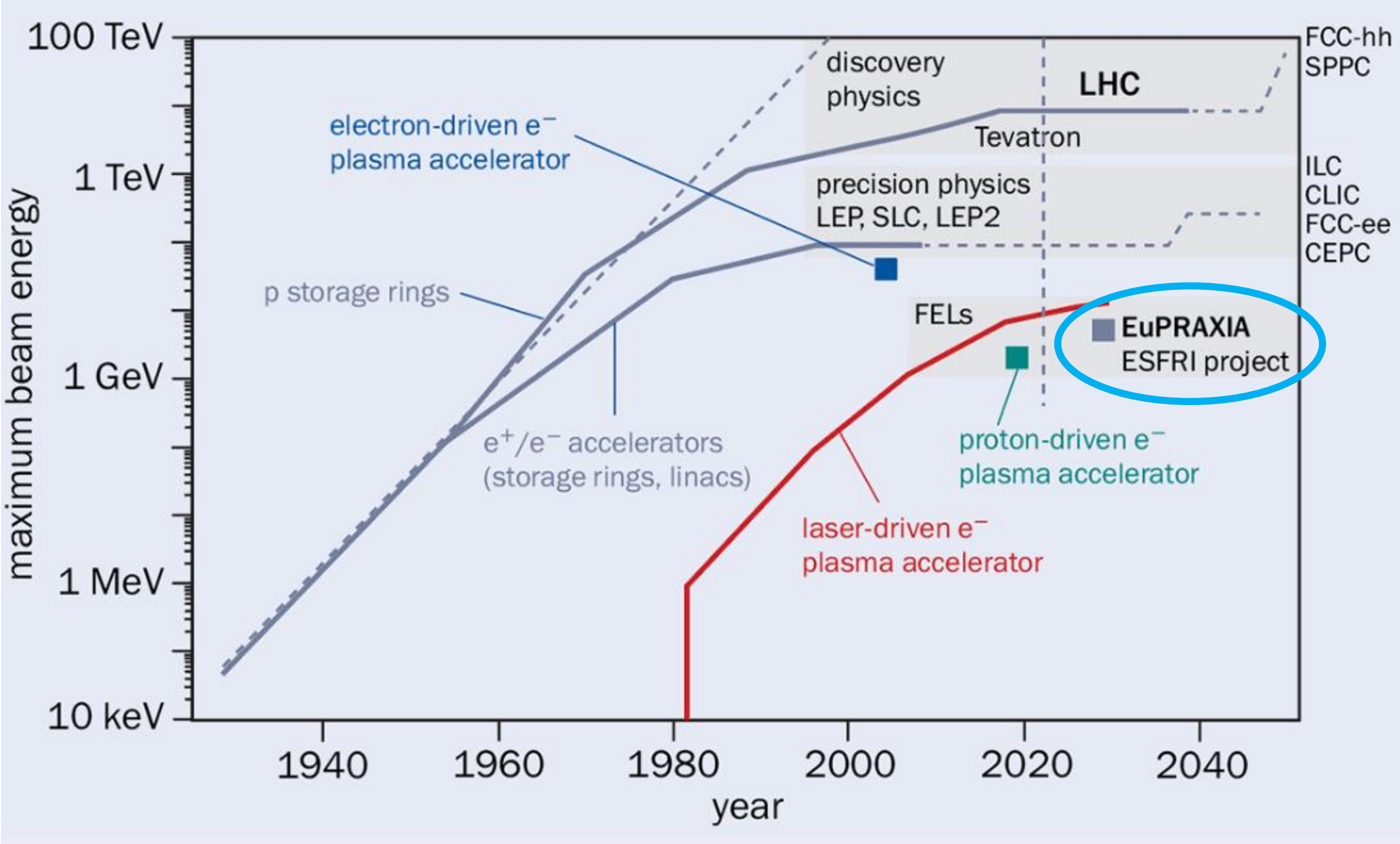
$$\omega_p = \sqrt{\frac{n_o e^2}{\varepsilon_o m_e}}$$

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

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

Courtesy Sci. Am

The Livingstone Diagram



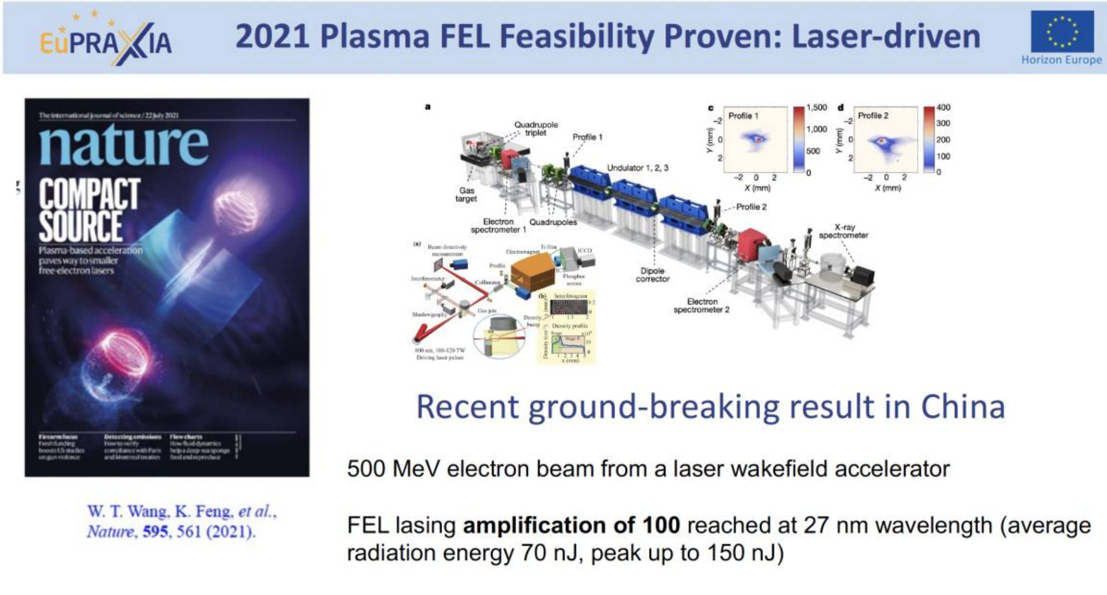
Updated Livingston plot for accelerators, showing the maximum reach in beam energy versus time. Grey bands visualize accelerator applications

Plasma Accelerator Achievements

- Gradients up to **100 GV/m**
- Acceleration > 10 **GeV** of electron beams
- Basic beam **quality for FEL** demonstrated

The most demanding in terms of beam brightness, stability and control

Basic beam quality achieved in pilot FEL experiments



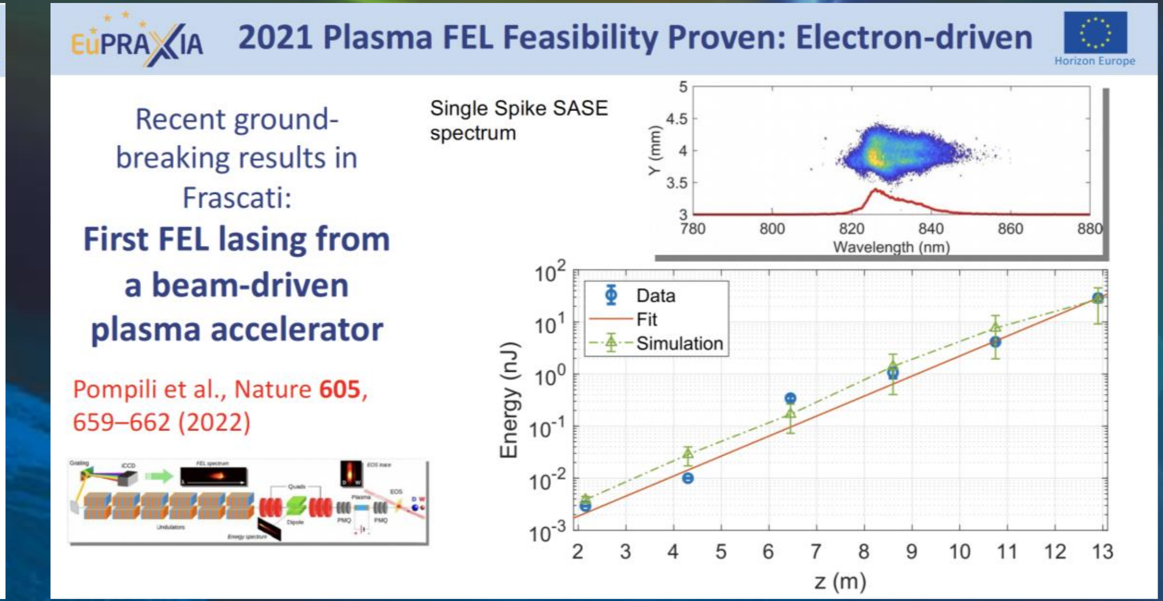
2021 Plasma FEL Feasibility Proven: Laser-driven

W. T. Wang, K. Feng, *et al.*, *Nature*, **595**, 561 (2021).

Recent ground-breaking result in China

500 MeV electron beam from a laser wakefield accelerator

FEL lasing **amplification of 100** reached at 27 nm wavelength (average radiation energy 70 nJ, peak up to 150 nJ)

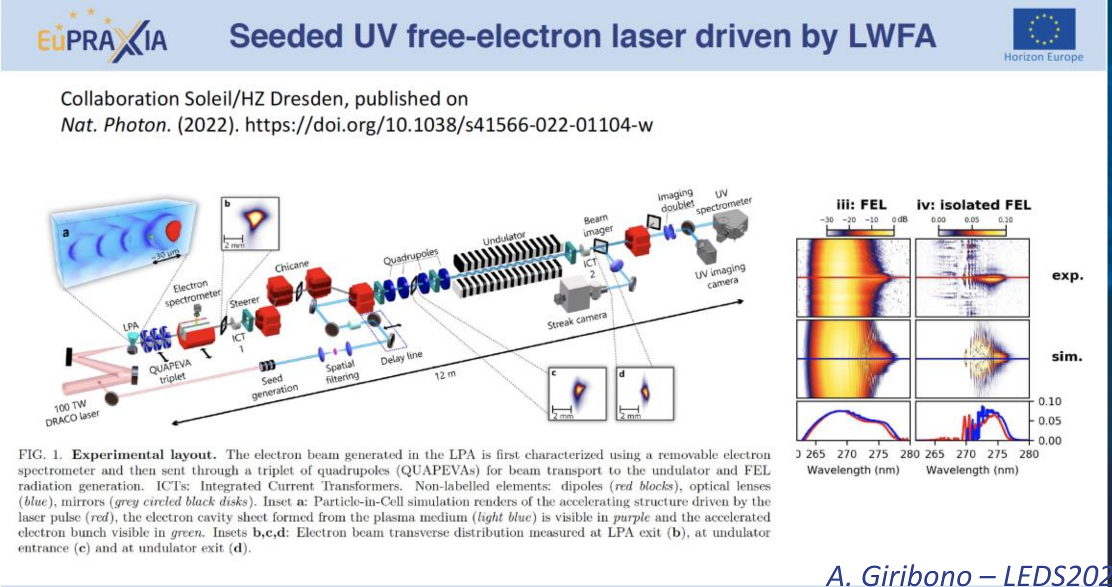


2021 Plasma FEL Feasibility Proven: Electron-driven

Recent ground-breaking results in Frascati:

First FEL lasing from a beam-driven plasma accelerator

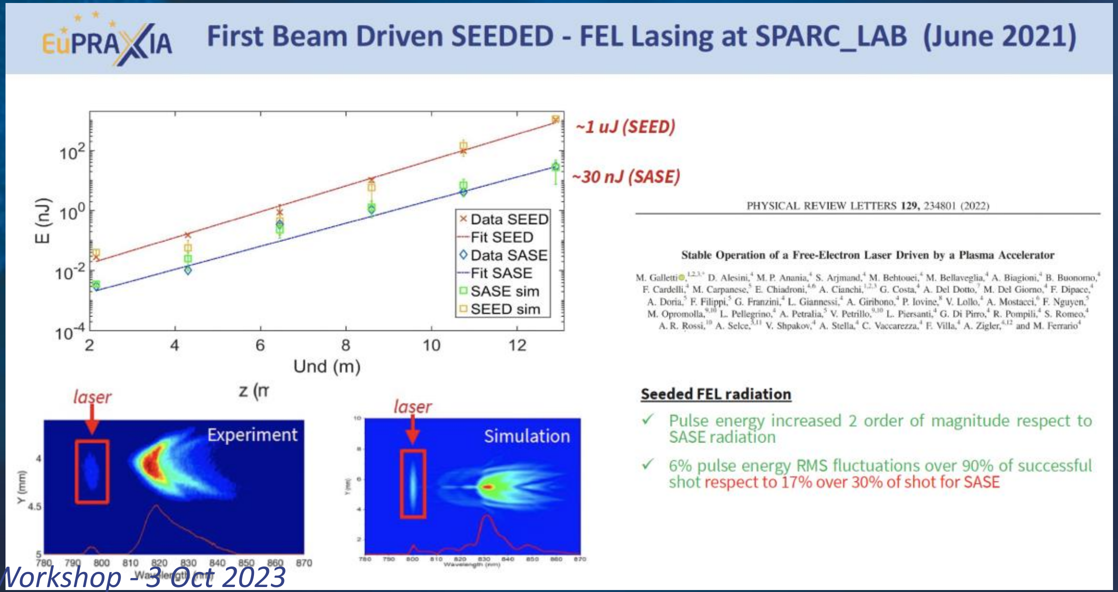
Pompili et al., Nature **605**, 659–662 (2022)



Seeded UV free-electron laser driven by LWFA

Collaboration Soleil/HZ Dresden, published on *Nat. Photon.* (2022). https://doi.org/10.1038/s41566-022-01104-w

FIG. 1. **Experimental layout.** The electron beam generated in the LPA is first characterized using a removable electron spectrometer and then sent through a triplet of quadrupoles (QUAPEVAs) for beam transport to the undulator and FEL radiation generation. ICTs: Integrated Current Transformers. Non-labelled elements: dipoles (*red blocks*), optical lenses (*blue*), mirrors (*grey circled black disks*). Inset **a**: Particle-in-Cell simulation renders of the accelerating structure driven by the laser pulse (*red*), the electron cavity sheet formed from the plasma medium (*light blue*) is visible in *purple* and the accelerated electron bunch visible in *green*. Insets **b,c,d**: Electron beam transverse distribution measured at LPA exit (**b**), at undulator entrance (**c**) and at undulator exit (**d**).



First Beam Driven SEEDED - FEL Lasing at SPARC_LAB (June 2021)

PHYSICAL REVIEW LETTERS **129**, 234801 (2022)

Stable Operation of a Free-Electron Laser Driven by a Plasma Accelerator

M. Galletti,[1,2,3,*] D. Alesini,[4] M. P. Anania,[4] S. Arjmand,[4] M. Behtouei,[4] M. Bellaveglia,[4] A. Biagioni,[4] B. Buonomo,[4] F. Cardelli,[4] M. Carpanese,[5] E. Chiadroni,[4,6] A. Cianchi,[1,2,3] G. Costa,[4] A. Del Dotto,[7] M. Del Giorno,[4] F. Dipace,[4] A. Doria,[5] F. Filippi,[5] G. Franzini,[4] L. Giannessi,[4] A. Giribono,[4] P. Iovine,[8] V. Lollo,[4] A. Mostacci,[6] F. Nguyen,[5] M. Opromolla,[9,10] L. Pellegrino,[4] A. Petralia,[5] V. Petrillo,[9,10] L. Piersanti,[4] G. Di Pirro,[4] R. Pompili,[4] S. Romeo,[4] A. R. Rossi,[10] A. Selce,[5,11] V. Shpakov,[4] A. Stella,[4] C. Vaccarezza,[4] F. Villa,[4] A. Zigler,[4,12] and M. Ferrario[4]

Seeded FEL radiation

- ✓ Pulse energy increased 2 order of magnitude respect to SASE radiation
- ✓ 6% pulse energy RMS fluctuations over 90% of successful shot respect to 17% over 30% of shot for SASE

Headquarter and Site 1: EuPRAXIA@SPARC_LAB

Frascati`s future facility

- > 130 M€ invest funding
- Beam-driven plasma accelerator - *PWFA*
- Europe`s most compact and most southern FEL
- The world`s most compact RF accelerator **X band with CERN**

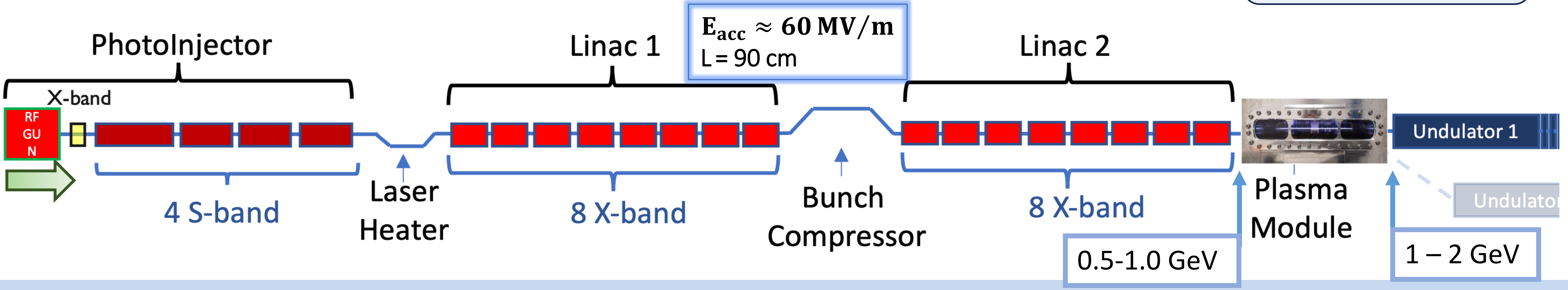
Credit: INFN and Mythos – consorzio stabile s.c.a.r.l.

A Beam-Driven Plasma Wake-field Accelerator

- **EuPRAXIA@SPARC_LAB** is a multi-GeV plasma-based accelerator with outstanding beam quality to drive a user facility whose main application concerns the operation of a soft X-ray FEL (3-5 nm)
- The FEL is driven by a 1 GeV high brightness electron beam, that turns into less than 1 mm-mrad emittance and up to 2 kAmps peak current.
- The accelerator is based on the unique combination of an advanced high-brightness RF injector and a plasma-beam driven accelerator
- Beam dynamics in the EuPRAXIA@SPARC_LAB machine has been studied by means of **start to end simulations** from the cathode including the FEL emission

RMS e- beam parameters @plasma module entrance

	Single bunch (WoP2)	Comb beam operation (WoP1)	
		Witness	Driver
Q (pC)	200 - 500	30 -50	200 -500
E (GeV)	up to 1.0	Up to 0.650 GeV	
Δγ/γ (%)	< 0.10		
$\varepsilon_{nx,y}$ (mm·mrad)	< 1.0	0.5 - 1.0	2.0 -5.0
$\sigma_{z\text{-rms}}$ (μm)	20 - 50	< 6	< 65
$I_{peak\text{-slice}}$ (kA)	1.0 – 2.0	> 1.5	



$E_{acc} \approx 60\ \mathrm{MV/m}$

L = 90 cm

PhotoInjector

X-band

RF GUN

4 S-band

Laser Heater

Linac 1

8 X-band

Bunch Compressor

Linac 2

8 X-band

0.5-1.0 GeV

Plasma Module

Undulator 1

Undulator

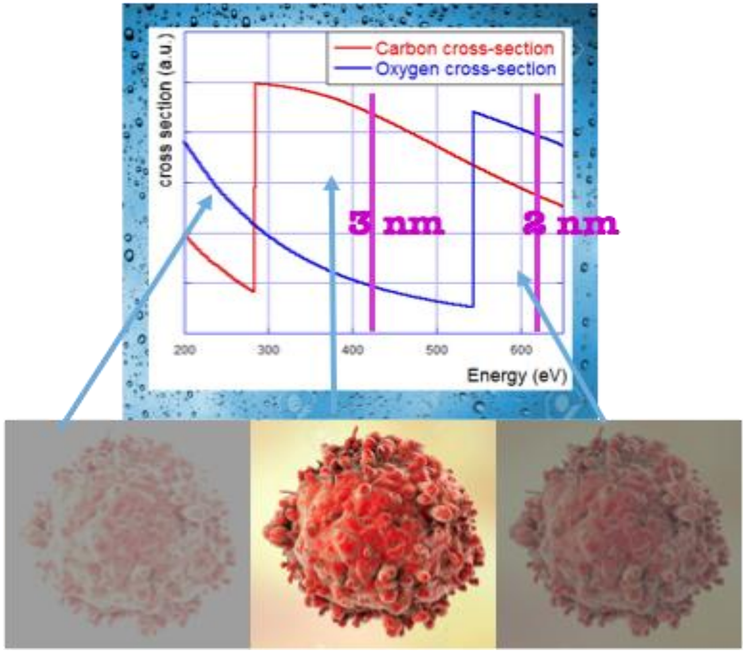
1 – 2 GeV

Expected SASE FEL performances

Radiation Parameter	**Unit**	PWFA	Full X-band
Radiation Wavelength	nm	**3-4**	4
Photons per Pulse	$\times 10^{12}$	**0.1-0.25**	1
Photon Bandwith	%	**0.1**	0.5
Undulator Area Length	m	30	
ρ(1D/3D)	$\times 10^{-3}$	**2**	2
Photon Brilliance per shot	$mm^2 mrad\ bw(0.1\%)$	$\mathbf{1-2 \times 10^{28}}$	1×10^{27}

Electron Beam Parameter	**Unit**	PWFA	Full X-band
Electron Energy	GeV	**1-*1.2***	1
Bunch Charge	pC	**30-50**	200-*500*
Peak Current	kA	**1-2**	1-2
RMS Energy Spread	%	**0.1**	0.1
RMS Bunch Length	μm	**6-3**	24-20
RMS norm. Emittance	μm	**1**	1
Slice Energy Spread	%	**≤0.05**	≤0.05
Slice norm Emittance	mm-mrad	**0.5**	0.5

In the energy region between Oxygen and Carbon K-edge 2.34 nm – 4.4 nm (530 eV -280 eV) water is almost transparent to radiation 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

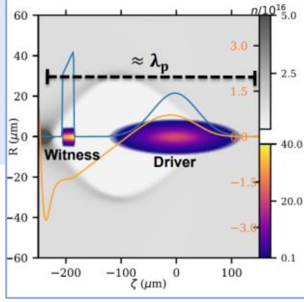
~10 ^{11} photons/pulse needed

Courtesy C. Vaccarezza

Courtesy F. Stellato (UniTov)

The PWFA operation: WoP1

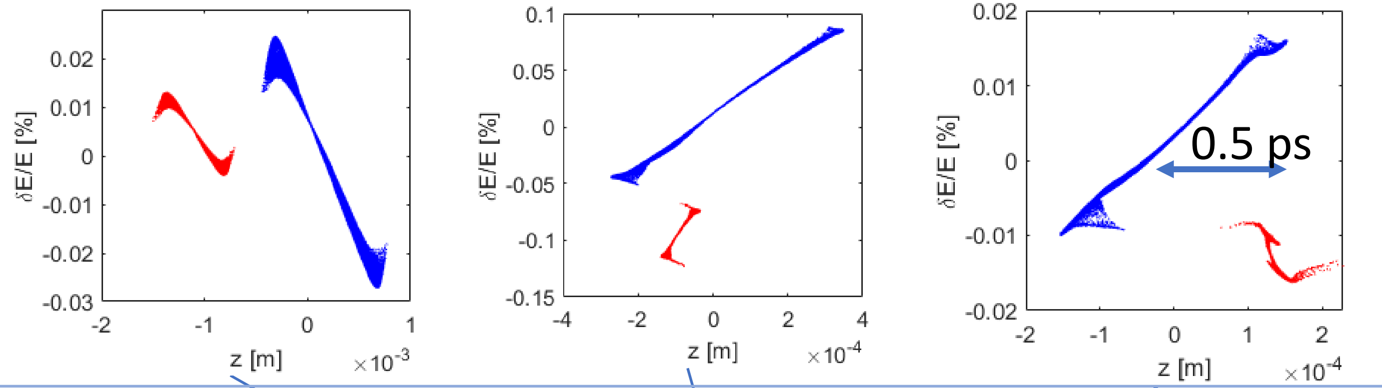
The PWFA Working Point



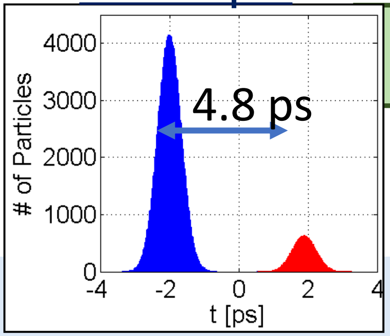
- Beside the FEL specifications, the **reference working point** has been determined by the plasma module
  - Accelerating gradient of the order of GV/m
  - Weakly non-linear regime (bubble with resonant behaviour)

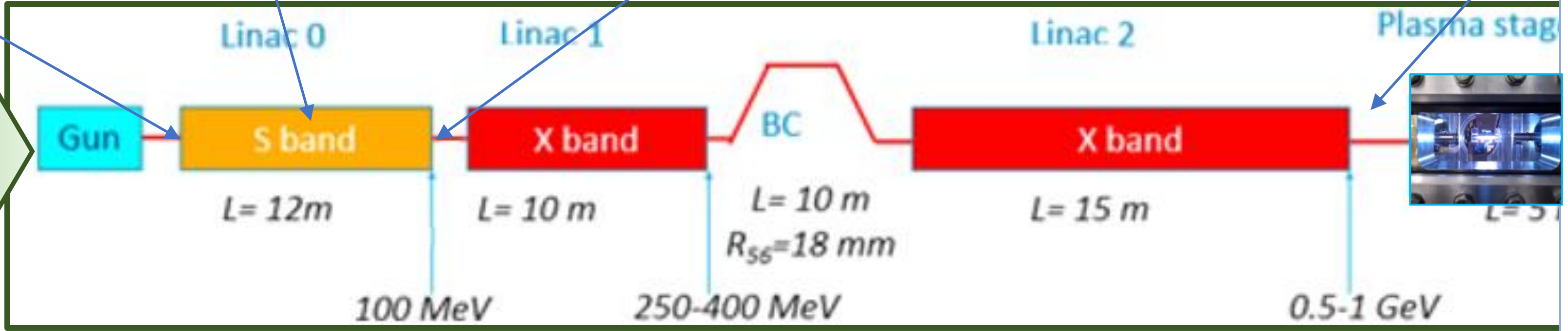
1. 200-500 pC driver + 30-50 pC witness
2. plasma density of the order of $10^{16} cm^{-3}$ (λ_p = 334 μm)
3. Driver-witness separation of around 0.5 ps (i.e. λ_p /2)
4. Driver and witness bunches of 200 fs and 10 fs rms
5. Driver and witness spot size of 4 and 1 μm with α=1

Velocity bunching technique

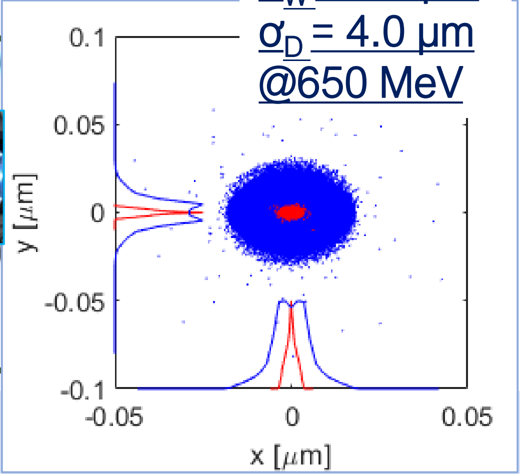


Laser comb technique





Strong focusing system

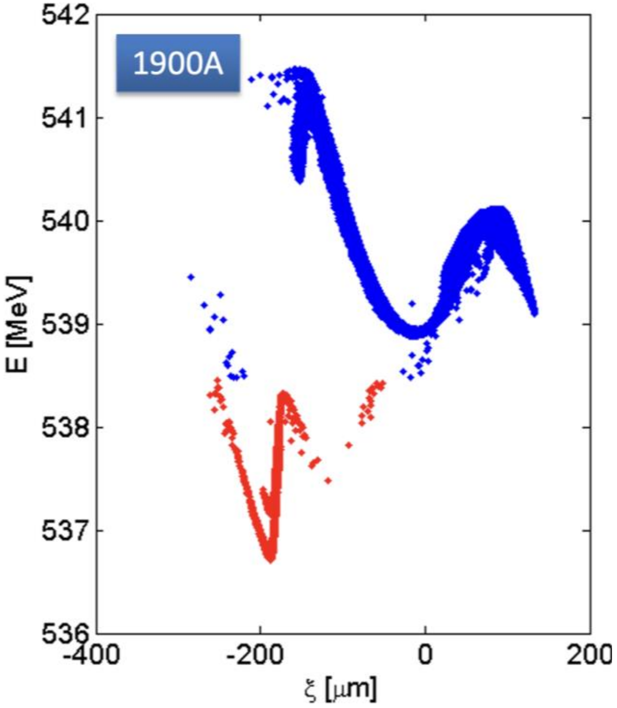


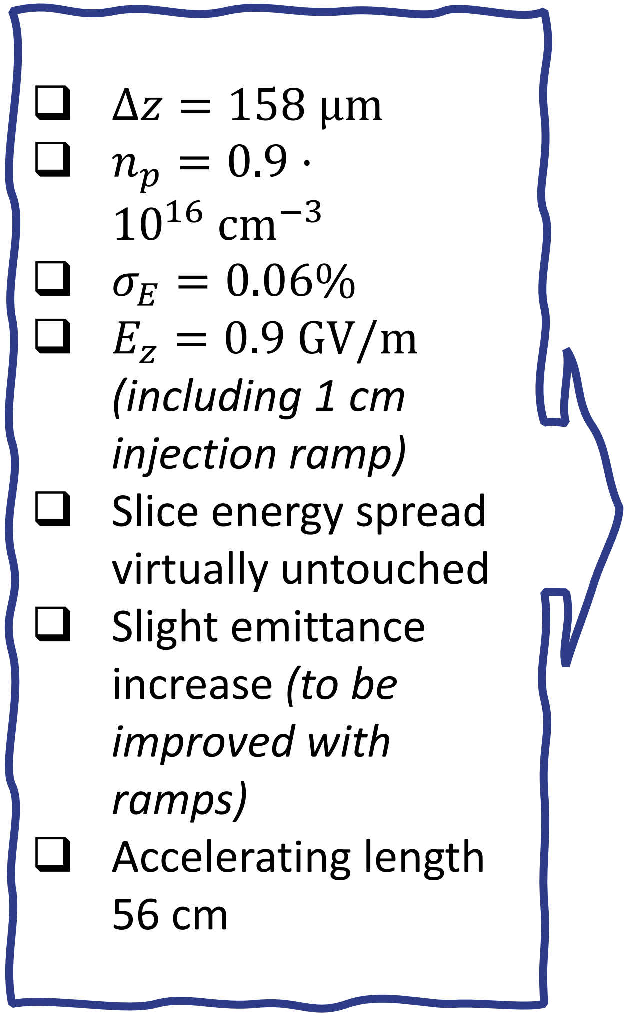
σ_W = 1.0 μm
σ_D = 4.0 μm
@650 MeV

The Plasma

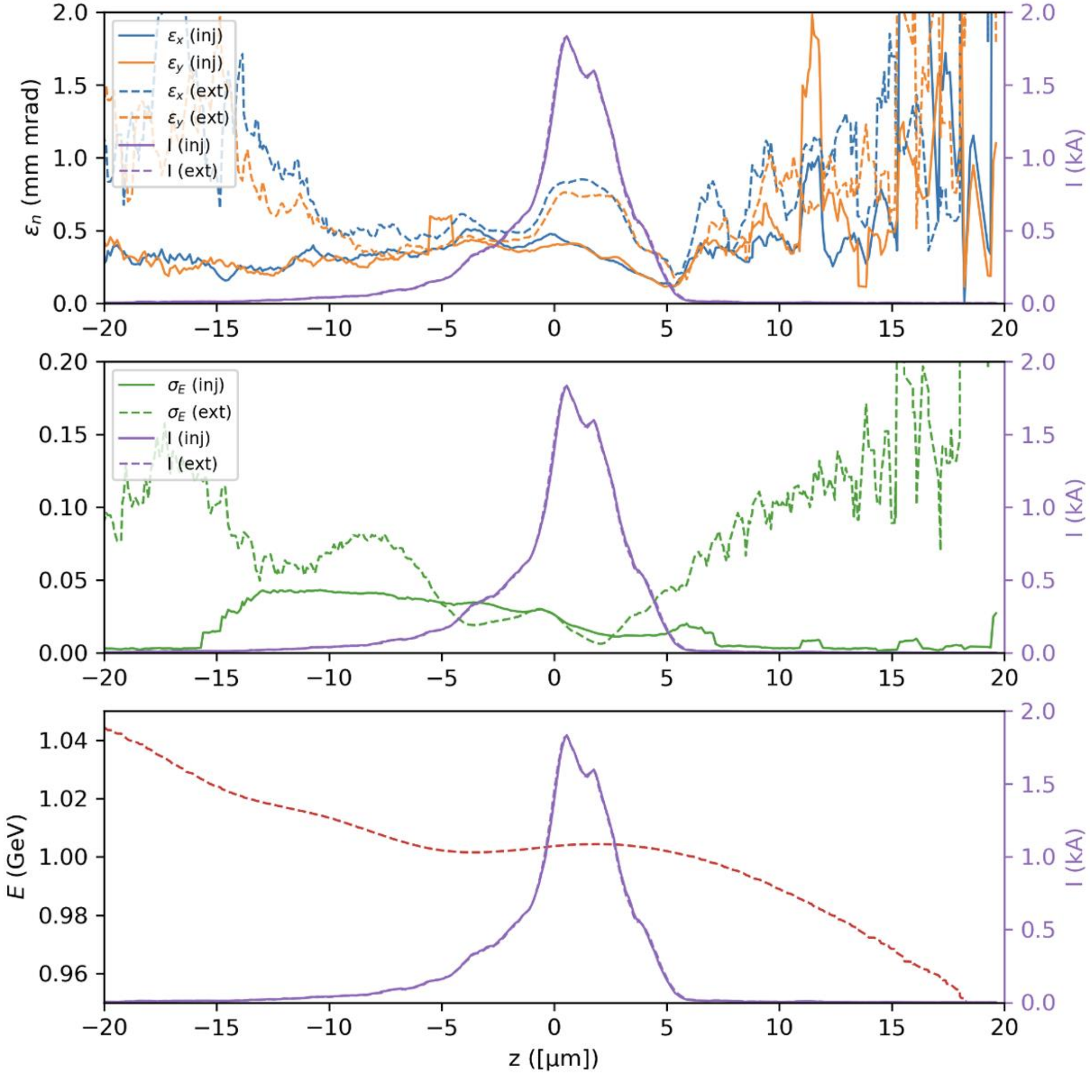
(Architect)

@plasma entrance





- ☐ $\Delta z = 158\ \mu\text{m}$
- ☐ $n_p = 0.9 \cdot 10^{16}\ \text{cm}^{-3}$
- ☐ $\sigma_E = 0.06\%$
- ☐ $E_z = 0.9\ \text{GV/m}$ *(including 1 cm injection ramp)*
- ☐ Slice energy spread virtually untouched
- ☐ Slight emittance increase *(to be improved with ramps)*
- ☐ Accelerating length 56 cm



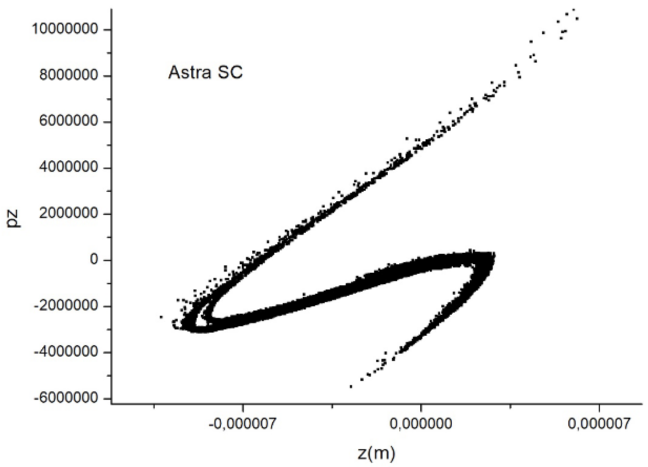
Witness slice analysis @plasma exit

Courtesy S. Romeo- A. Del Dotto

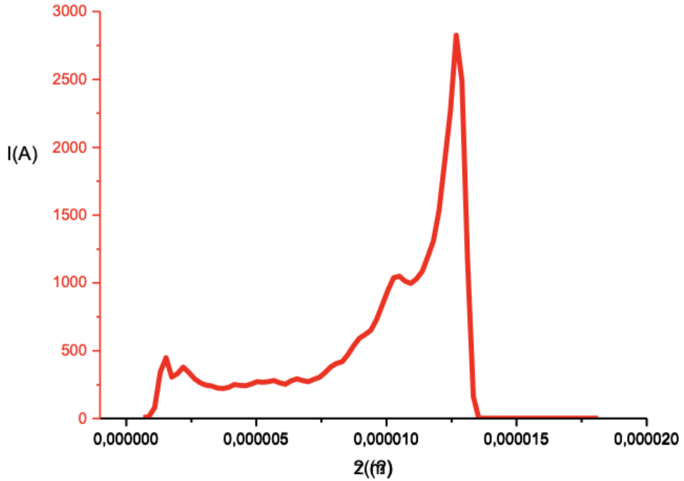
The FEL
(Genesis 3D)

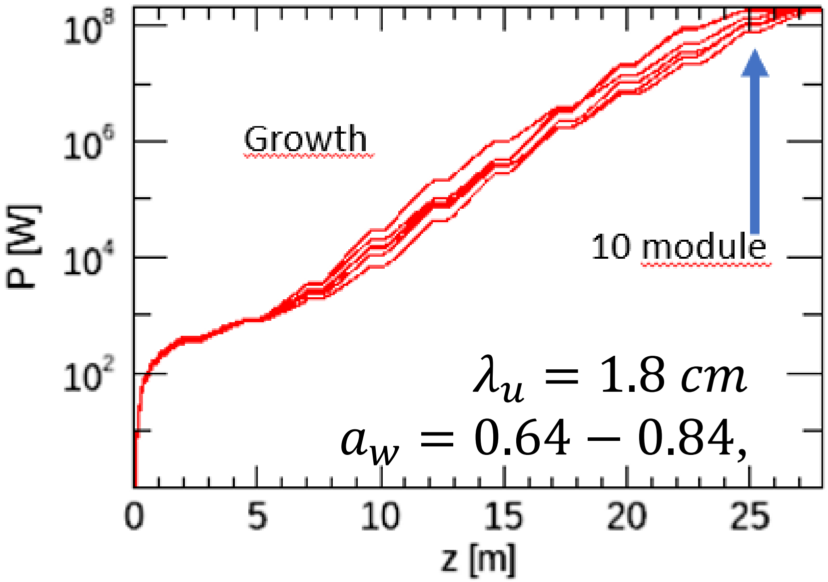
Electron beam at undulator entrance

Phase space

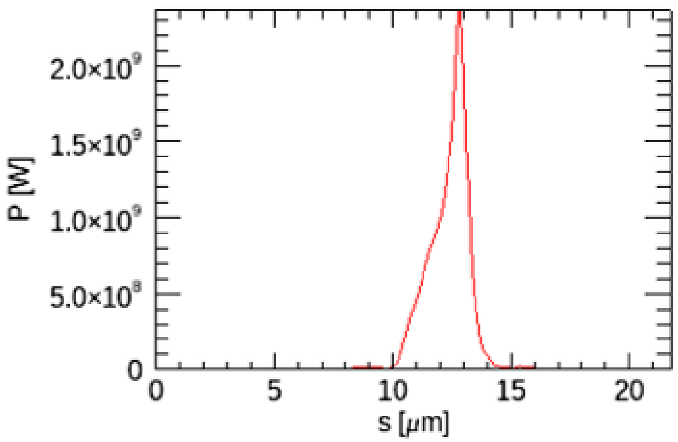


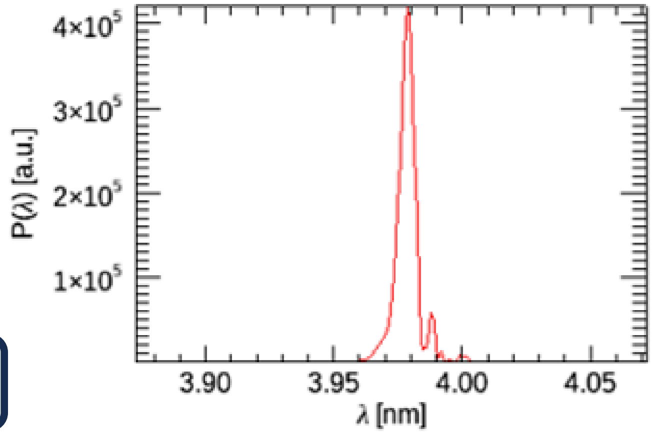
Current





Clean single spike at 25 m





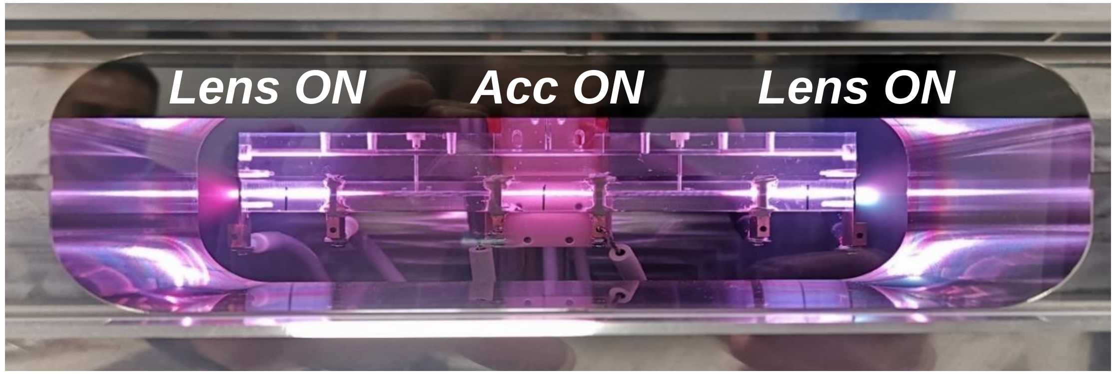
Energy at 25 m	**J**	**$11.5\ 10^{-6}$**
bandwidth	%	0.1
size	m	$1.4\ 10^{-4}$
div	rad	$1.7\ 10^{-5}$
Photon number		**$2.2\ 10^{11}$**
wavelength	nm	3.975

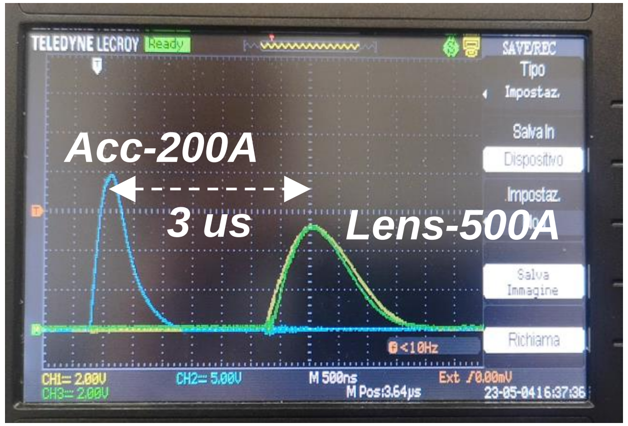
Electron beam energy : 1 GeV, matching at 4 nm. Top,left: growth of the radiation power along the undulator. Bottom, left: table with main parameters of the radiation. Right: power and spectral distribution of the radiation.

Courtesy V. Petrillo

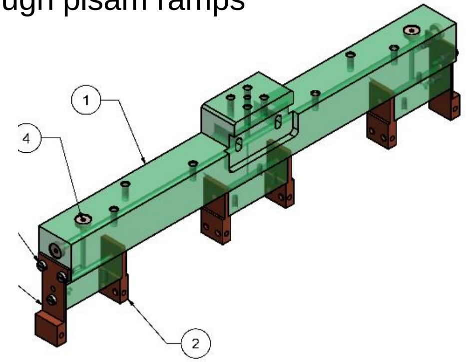
EuPRAXIA@SPARC_LAB: Plasma sources

1. Integrated capillary

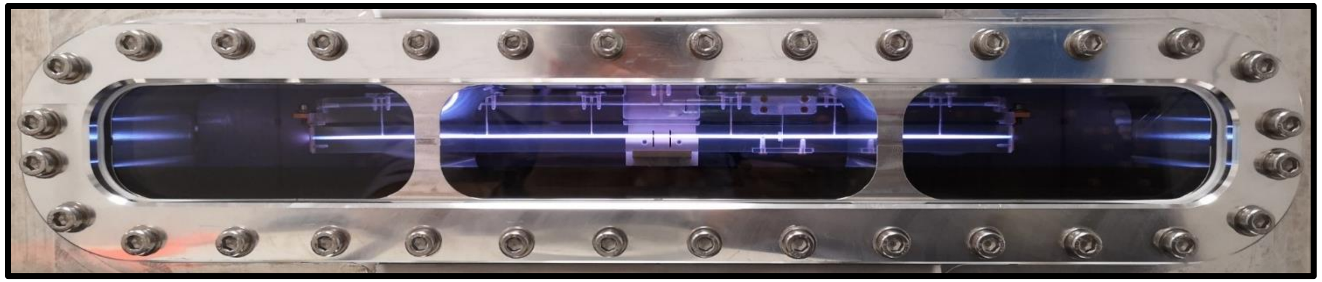




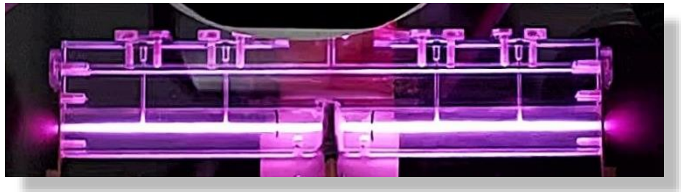
Studies on cross-talk effects:
Design of electrodes and HV-circuits to reduce the interaction among discharges through plsam ramps



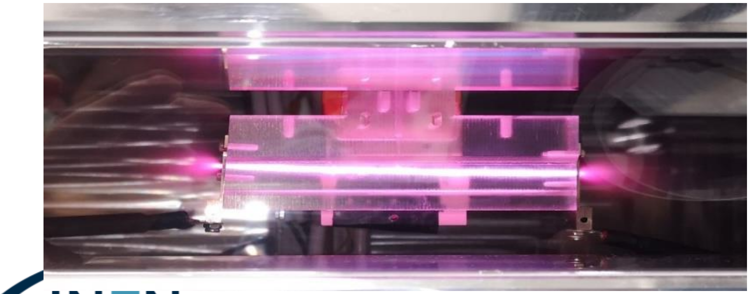
2. Very long capillary



Design of m-scale capillaries for EuPRAXIA project by using segmented capillaries: design of HV-voltage circuits and discharge synchronization



3. Curved capillary for APD



Design of new geometries for curved channels:
HV-circuits to allow high current pulses

Courtesy of A. Biagioni 6th EuPRAXIA@SPARC_LAB TDR Review Committee *21-22November 2023*

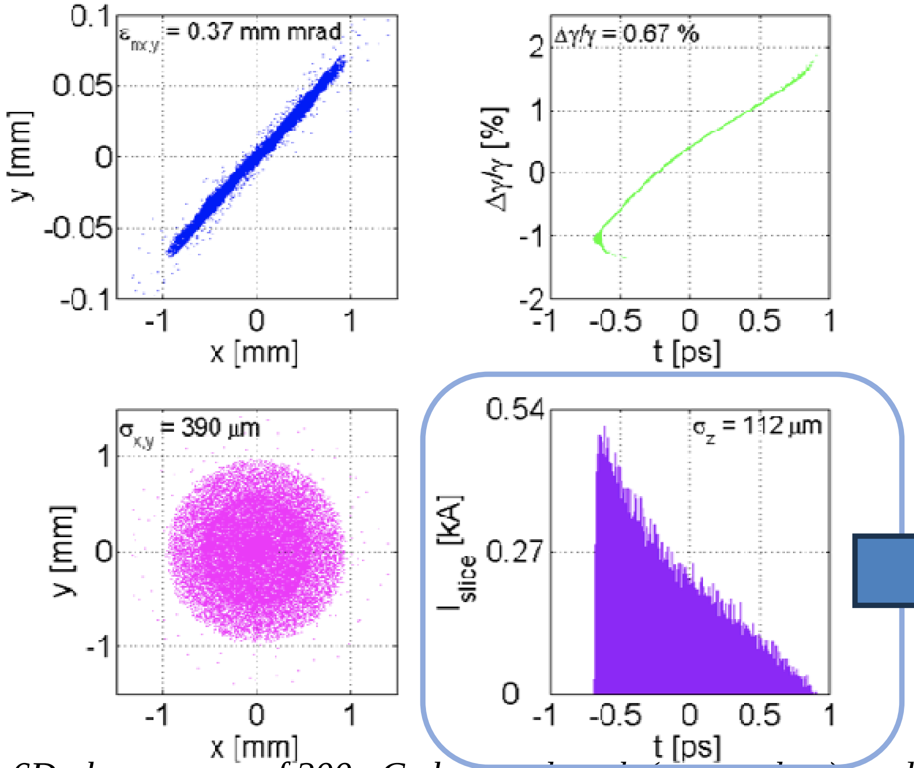
The full X-band operation: WoP2

The Photoinjector

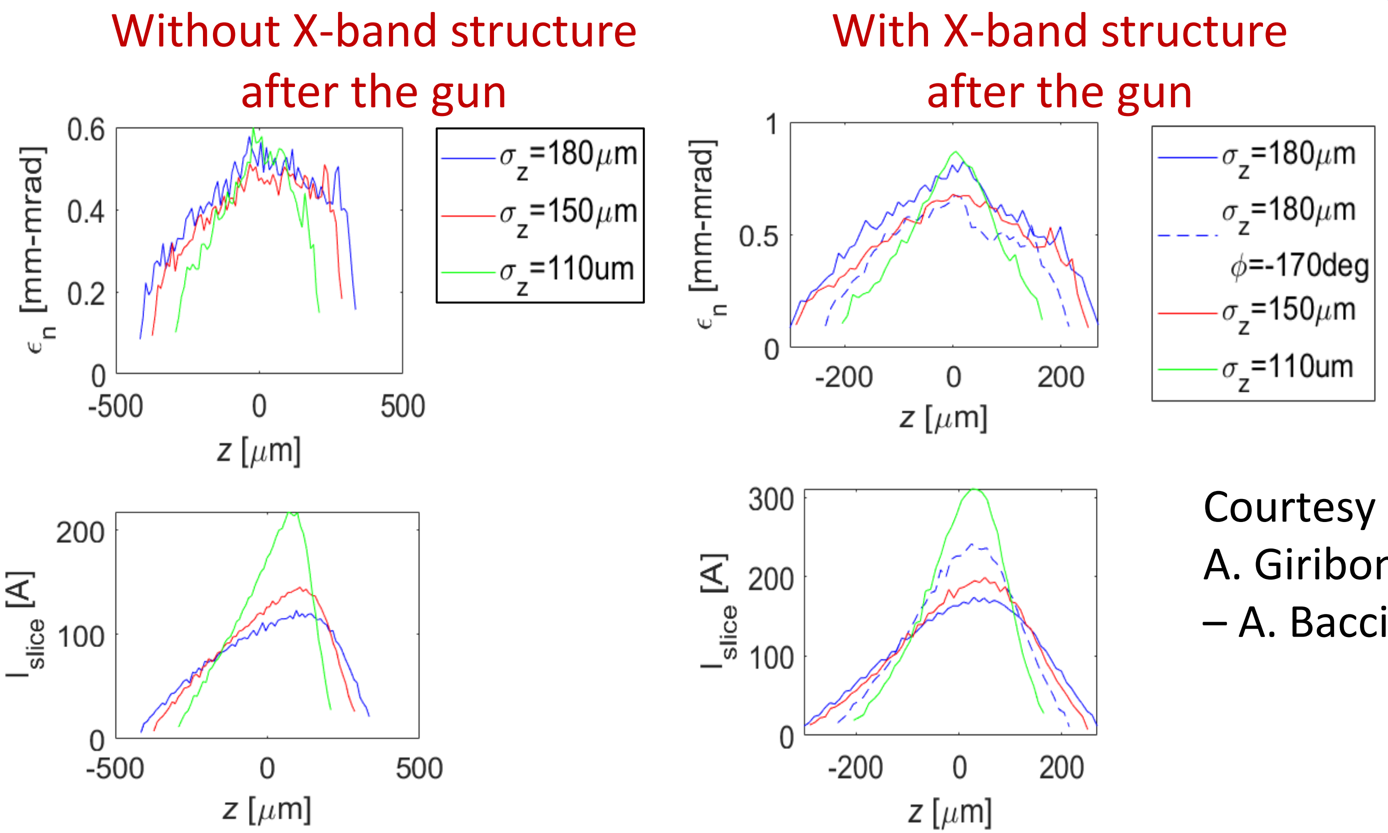
(Tstep,ASTRA)

- **The beam dynamics has been studied by means of simulations with the TStep (*and ASTRA)* code**
- The photoinjector in this case is operated in a milder velocity bunching scheme in the first S-band cavity to shorten the RMS beam length from 270 to ≈ 110 μm

@170 MeV



6D phase space of 200 pC electron bunch (upper plots), and transverse distribution and current profile (lower plots) at the Photoinjector exit.



Courtesy A. Giribono – A. Bacci

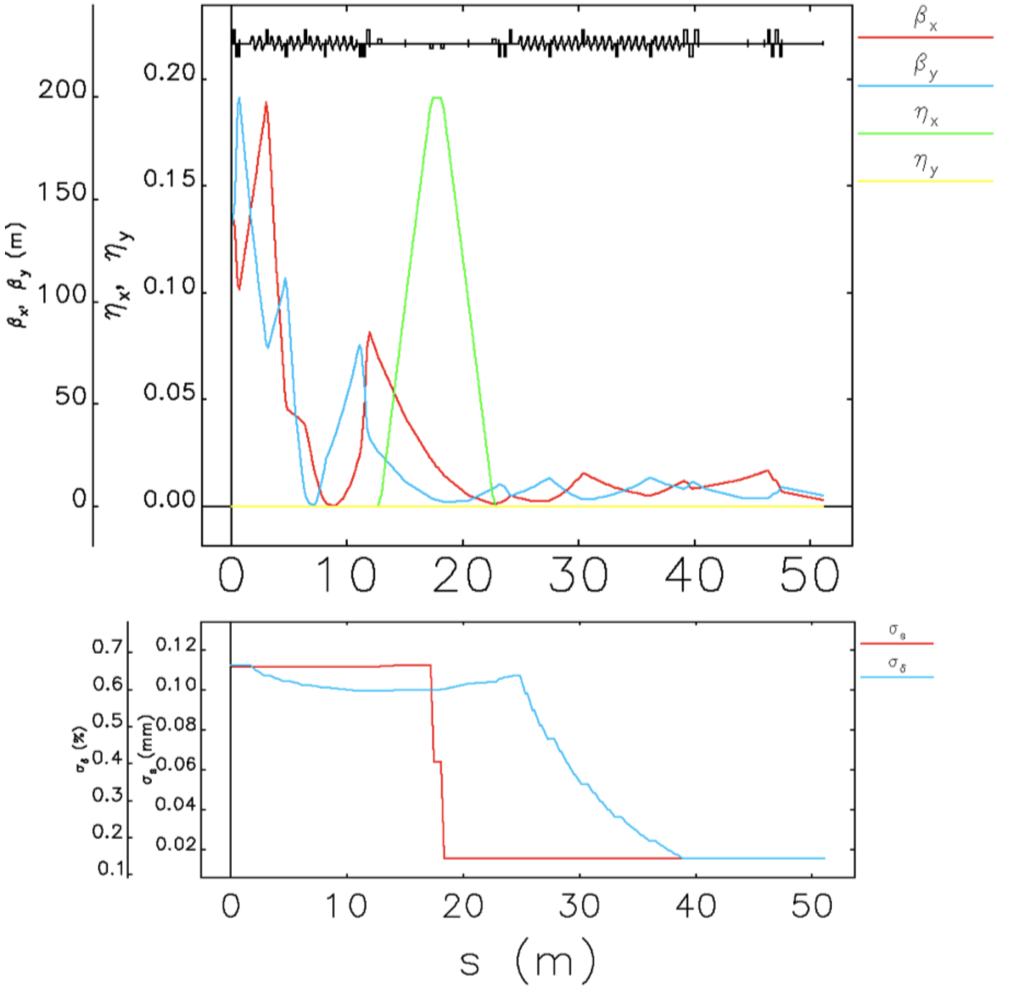
Slice analysis at the Photoinjector exit for different compression factor and introducing an X-band cavity after the gun

The X-band Linac

(Elegant)

- The beam dynamics in the X-band linac has been studied by means of Elegant simulations
  - The beam length at photoinjector exit is set to avoid the energy spread dilution due to RF curvature degradation effects in the linac
  - The X-band linac is set slightly off-crest to control and recover the correlated energy spread needed for the compression in the magnetic chicane
  - No phase space linearization is applied at this time prior the bunch compression in the chicane since the residual curvature of the longitudinal phase space distribution of the electron beam present at the photo-injector exit appears negligible and is quite completely recovered at the linac L1 exit

Linac2 Exit Parameters	
Charge (pC)	200
Spot Size (μm)	20-30
Bunch length (μm)	16
Emittance (mm-mrad)	0.5
Energy (GeV)	1.03
Energy Spread (%)	0.06

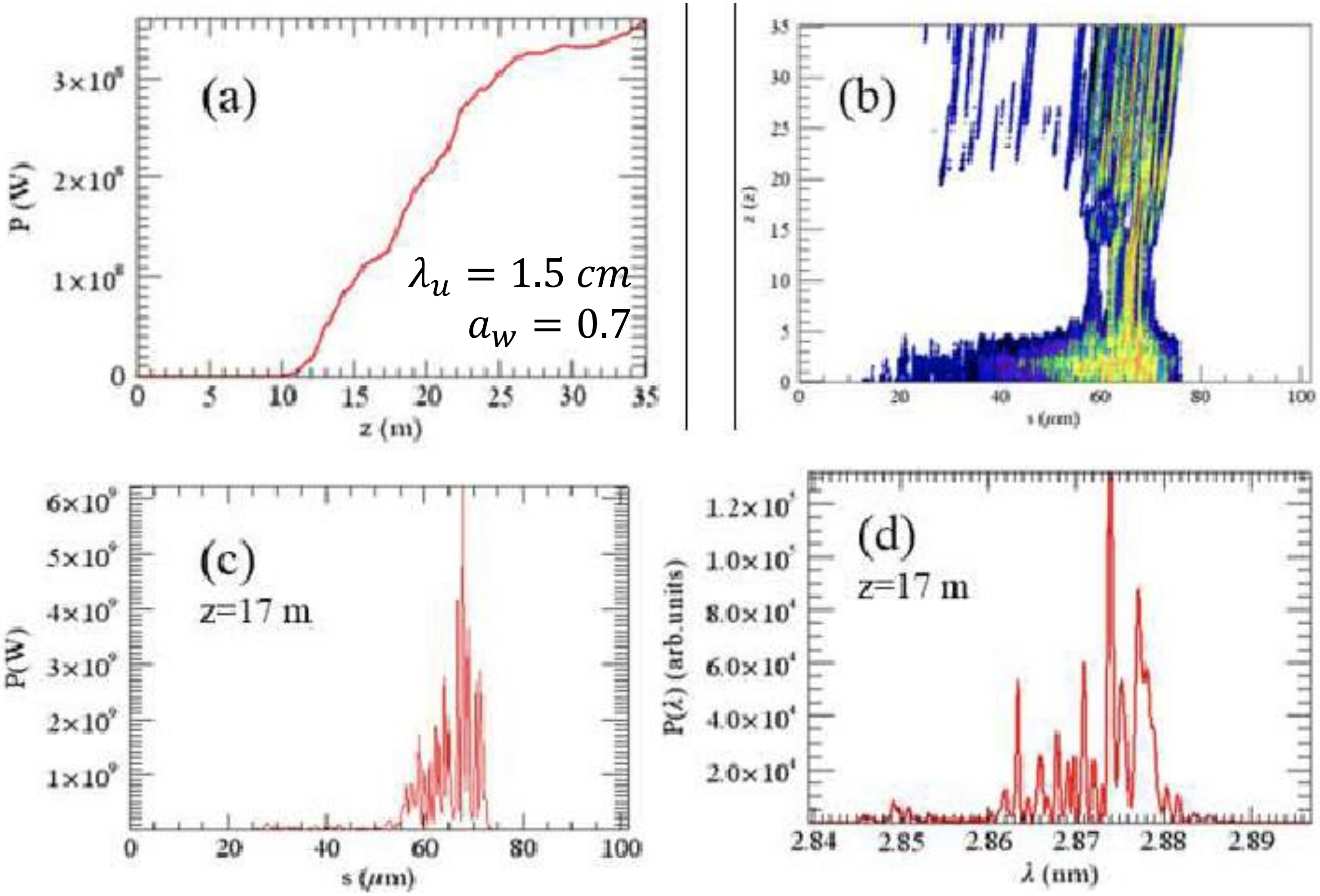


Upper plot: Twiss parameters and dispersion function through all the Linac, from photo-injector exit to the undulator entrance. Lower plot: Nominal RMS energy spread (blue) and RMS bunch length (red) along the entire Linac from photo-injector exit at 171 MeV to undulator entrance at 1 GeV

Courtesy C. Vaccarezza

The FEL
(Genesis 3D)

Parameter	Unit	Full X-band
Radiation Wavelength	nm	4
Photons per Pulse	$\times 10^{12}$	1
Photon Bandwith	%	0.5
Undulator Area Length	m	30
ρ(1D/3D)	$\times 10^{-3}$	2
Photon Brilliance per shot	$\left(\frac{s\ mm^2 mrad^2}{bw(0.1\%)}\right)$	1×10^{27}



Electron beam energy : 1 GeV, matching at 4 nm. SASE radiation simulation for the 200 pC beam (WoP2): (a) power growth P(W) as function of the undulator coordinate z(m). (b): contour plot of the radiated power in the (s; z) plane, with s (mm) coordinate along the electron beam, (c) power and (d) spectral density at z = 17 m.

Courtesy V. Petrillo

Conclusions and Perspectives

➢ Conclusions

- The EuPRAXIA@SPARC_LAB project aims to design and build
  - world’s most compact RF accelerator → 1 GeV X-band RF linac
  - First ever FEL user facility driven by a high gradient plasma accelerator module (Europe`s most compact and most southern FEL)
- The beam physics has been shown by means of start to end simulations (including the radiation generation)
- The studies show a relatively stable accelerator able to drive a radiation source
- The research activity performed at the SPARC_LAB test facility is crucial for the forthcoming EuPRAXIA@SPARC_LAB project

➢ Perspectives

- *Further manipulation and technology is under investigation for the EuPRAXIA@SPARC_LAB facility to stabilize the* e^- *beam energy and enable a stable FEL emission*
- *Further beam phase space manipulation is under investigation for the full X-band case*
- *On the road for the Technical Design Report*

This project has received funding from the European Union's Horizon 2020 Research and Innovation programme under grant agreement No 777431 and No. 653782.

EuPRAXIA Advanced Photon Sources (EuAPS)

- Supported by PNRR funding
- Collaboration among INFN, CNR, University of Tor Vergata
- EuPRAXIA → *laser-driven betatron radiation source @SPARC_LAB*
  → development of high power (up to 1 PW at LNS) and high repetition rate (up to 100 Hz at CNR Pisa) laser
  → pre-cursor for user-facility

1) **Ultrafast** - laser pulse duration tens of fs useful for **time resolved experiments** (XFEL tens of fs, synchrotron tens to 100 ps).
2) **Broad energy spectrum -** important for **X-ray spectroscopy**.
3) **High brightness** - small source size and high photon flux for **fast processes**
4) **Large market -** 50 synchrotron light sources worldwide, 6 hard XFEL's and 3 soft-ray ones (many accelerators operational and some under construction).

Electron beam Energy [MeV]	50-800
Plasma Density [cm^{-3}]	10^{17} - 10^{19}
Photon Critical Energy [keV]	1 - 10
Nuber of Photons/pulse	10^6 – 10^9

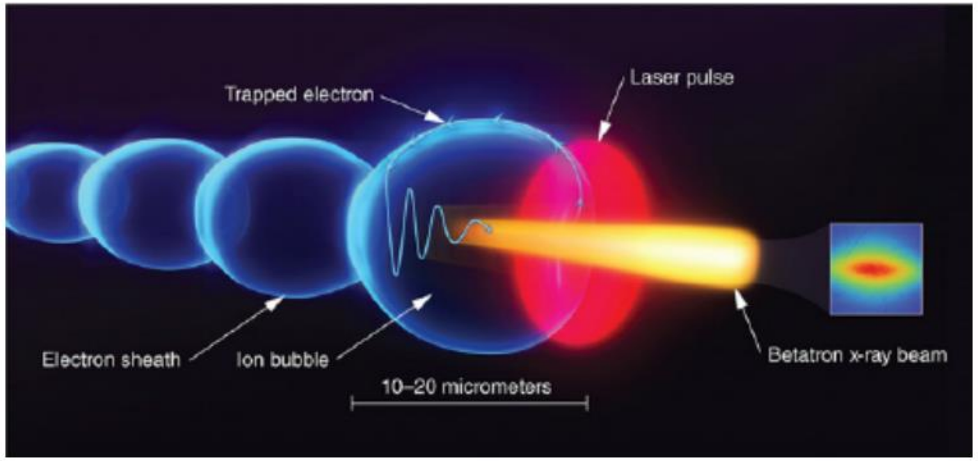


Figure 3: Principle of betatron X-ray emission from a LWFA. Electrons trapped at the back of the wakefield are subject to transverse and longitudinal electrical forces; subsequentlythey are accelerated and wiggled to produce broadband, synchrotron-like radiation in keV energy range [6].

Next Step: 'plasma-based compact undulators'

'EuPRAXIA Advanced Photon Sources PNRR_EuAPS Project', M. Ferrario et al. INFN-23-12-LNF (2023)

Thank for your attention

REFERENCES

1. https://home.cern/science/accelerators/large-hadron-collider
2. https://nux.ethz.ch/research/x-ray-free-electron-laser-science.html
3. http://pd.chem.ucl.ac.uk/pdnn/inst3/pulsed.htm
4. https://www.iaea.org/newscenter/news/what-is-radiation-therapy
5. https://lasers.llnl.gov/science/photon-science/mega-ray
6. Xuening Wang, Wenjing Wan, Shaohua Shen, Hengyi Wu, Huizhou Zhong, Changzhong Jiang, Feng Ren; Application of ion beam technology in (photo)electrocatalytic materials for renewable energy. *Appl. Phys. Rev.* 1 December 2020; 7 (4): 041303. https://doi.org/10.1063/5.0021322
7. https://www.linkedin.com/pulse/cold-pasteurization-food-irradiation-u%C4%9Furcan-kartal/
8. https://www.iter.org/newsline/-/2360
9. Valkov, S.; Ormanova, M.; Petrov, P. Electron-Beam Surface Treatment of Metals and Alloys: Techniques and Trends. *Metals* **2020**, *10*, 1219. https://doi.org/10.3390/met10091219
10. https://cas.web.cern.ch/sites/default/files/lectures/-27%20March%202022/Alesini_LINEAR_ACCELERATORS_2021.pdf
11. Seeman, J. *et al.* (2020). Design and Principles of Linear Accelerators and Colliders. In: Myers, S., Schopper, H. (eds) Particle Physics Reference Library . Springer, Cham. https://doi.org/10.1007/978-3-030-34245-6_7
12. https://www.xfel.eu/
13. https://www.psi.ch/en/swissfel/accelerator