High Precision X-ray Measurements 2025

16-20 June 2025, Laboratori Nazionali di Frascati INFN

Beamlines of the EuPRAXIA@SPARC_LAB X-ray FEL facility

F. Nguyen on behalf of the EuPRAXIA@SPARC_LAB Collaboration

EuPRAXIA at SPARC_LAB

ENEA Italian National Agency for New Technologies, Energy and Sustainable Economic Development

INFN Istituto Nazionale di Fisica Nucleare

UNIVERSITÀ DEGLI STUDI DI MILANO

Fermilab

EuPRAXIA@SPARC_LAB: AQUA

1st international design of a plasma accelerator facility

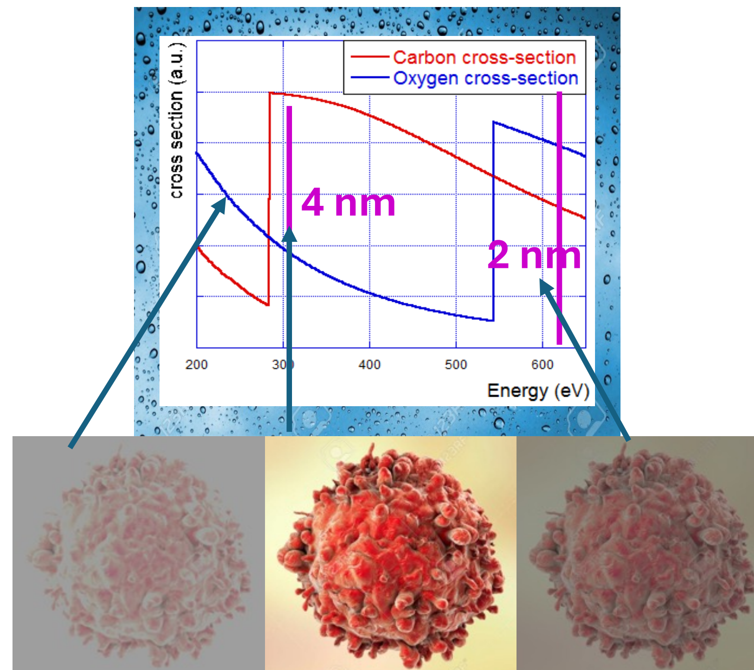
EuPRAXIA is designed to deliver at 10-100 Hz ultra-short pulses of
- Electrons (0.1-5 GeV, 30 pC)
- Positrons (0.5-10 MeV, 10^6)
- Positrons (GeV source)
- Lasers (100 J, 50 fs, 10-100 Hz)
- Betatron X rays (5-18 keV, 10^{10})
- FEL light (0.2-36 nm, 10^9-10^{13})

ESFRI certified EuPRAXIA through intermediate goals, as stated in the CDR (from R. Aßmann):

- **150 MeV → 1 GeV → 5 GeV (FEL + other applications)**
- **1 plasma stage → 2 plasma stages → multiple**
- **factor 3 facility size reduction → factor 10**
- **low charge, 10 Hz e^- beam applications (and e^+ generation)**
  → high charge, 10 Hz → 100 Hz applications (FEL)

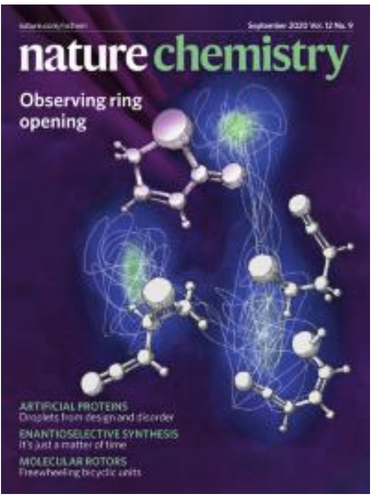
The **AQUA** (water in *Latin*) beamline of the EuPRAXIA@SPARC_LAB project is a **FEL facility** to be operated in Self-Amplified Stimulated Emission **SASE** for experiments around **4-10 nm wavelength, i.e. 120-310 eV photon energy. At 3-4 nm** we have **lower attenuation length in water** → *water window* relevant to study biological samples

See F. Stellato's talk for more details



EuPRAXIA@SPARC_LAB: ARIA

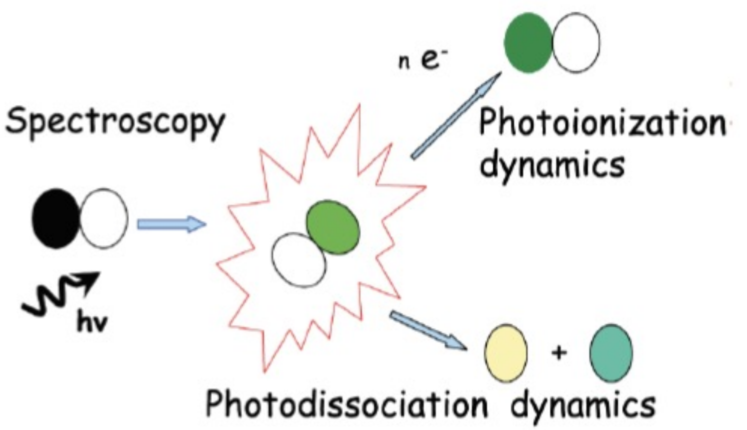
The **ARIA** (air in *Italian*) beamline of the EuPRAXIA@SPARC_LAB project is going to be an **EUV-VUV seeded HGHG FEL** facility for **gas phase (50-180 nm)**, providing longitudinal coherence **10-100 µJ** pulse energy class, with continuous tunability and **selectable polarization → less demanding** electron beam parameter space → **user** operations at **early stage**



Light induced molecule ring structure opening reactions to be studied with time resolved photoemission spectroscopy → formation of the previtamin D_3 in the skin under the sun ← absorption of UV rays

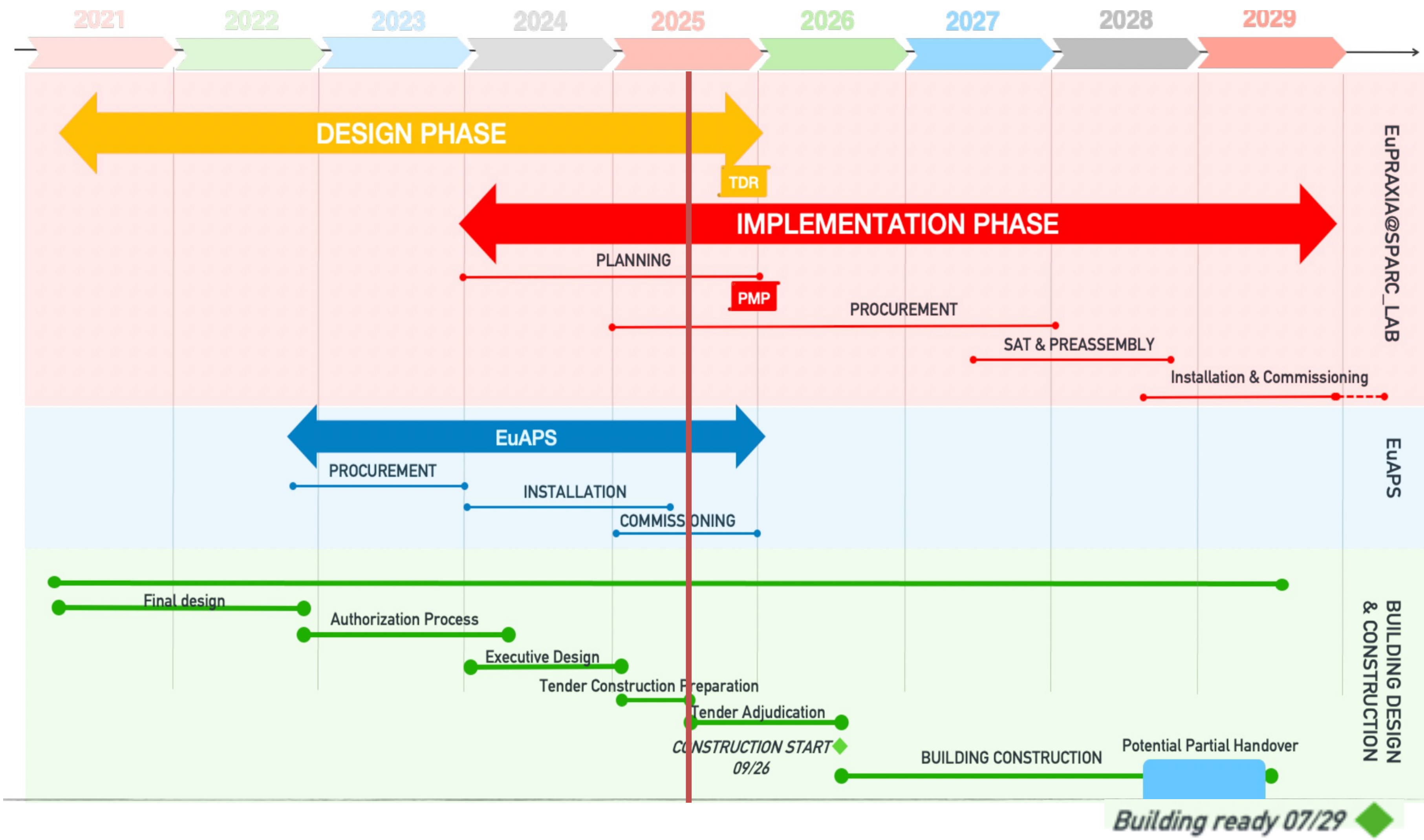
Vitamin D involves several biological functions and ring opening is an aspect

S. Pathak *et al.*, *Nat. Chem.* **12** (2020) 795

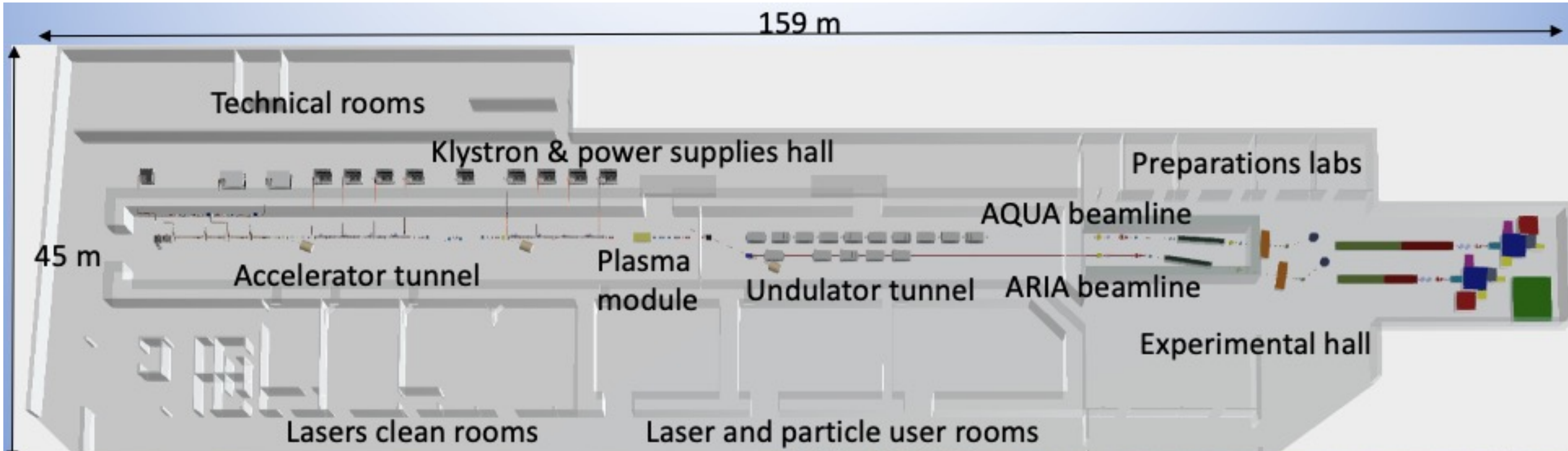


- **No other seeded FEL facility** covers the **full 50-180 nm range**, except for the DALIAN light source
- Overlap with **HHG sources**, but **without** limitations **on polarization, wavelength tuning** & **intensity**
- **Can be synchronized** with HHG sources or external lasers for **multicolor multi-pulse pump and probe operations**

Time: EuPRAXIA@SPARC_LAB timeline

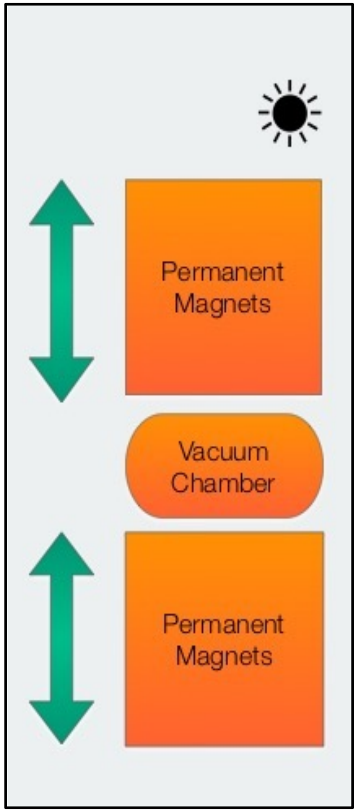


Space: EuPRAXIA@SPARC_LAB layout



Light from magnetic undulators: strength order

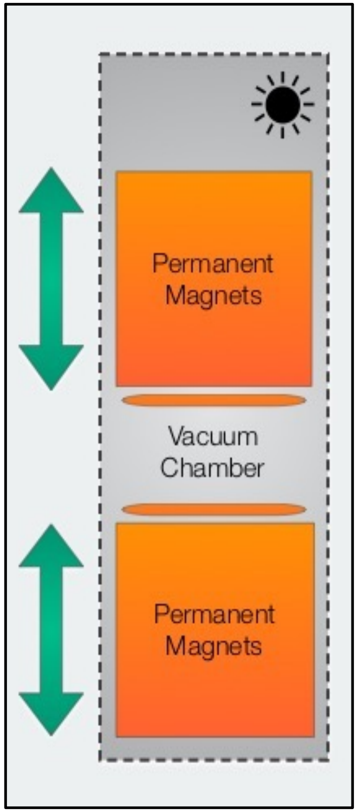
Out of vacuum PMU



Traditional and cheapest design

Selectable Polarization

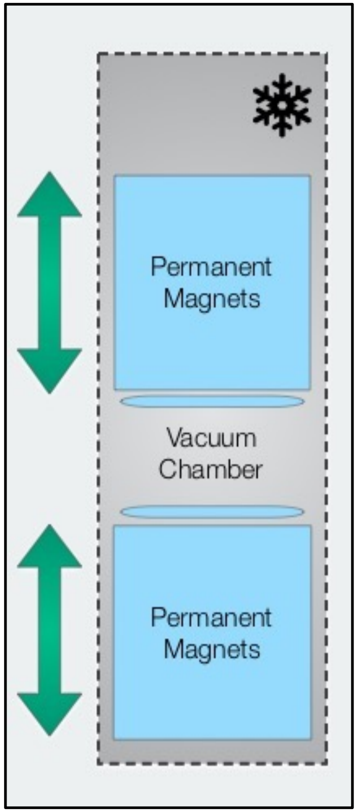
In vacuum PMU



Magnets inside vacuum but not cheap & no polarization

Good performance

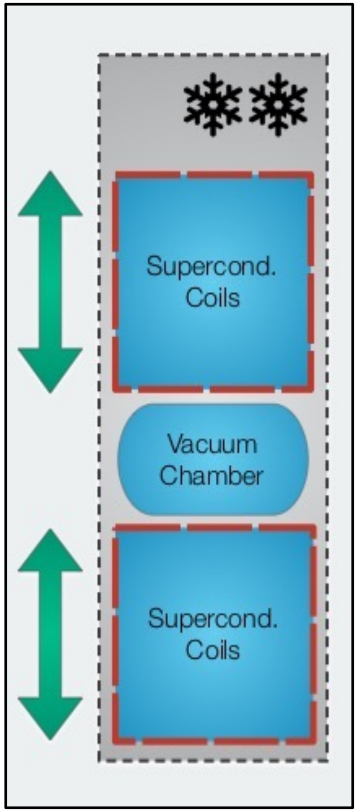
Cryogenic PMU



Improved B but not cost-effective, also increased complexity

Better performance

Superconducting

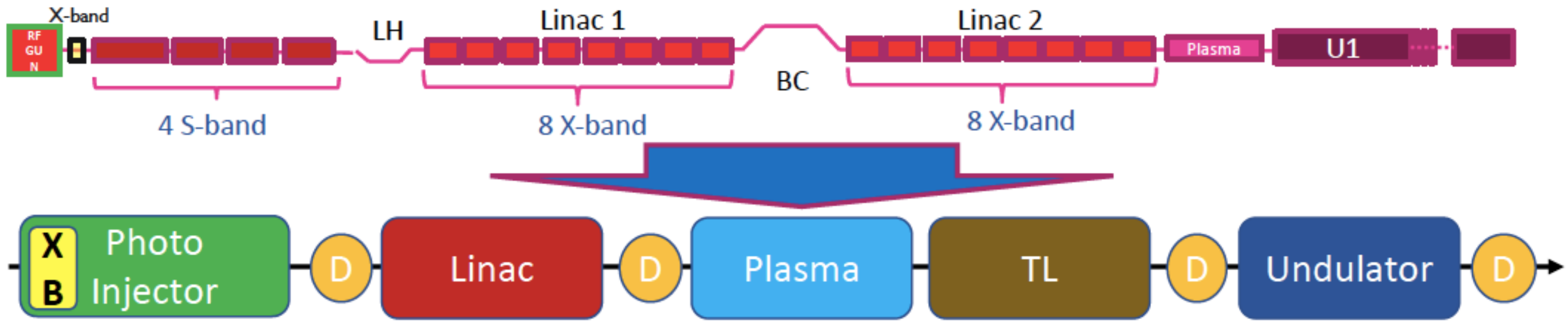


Highest B and SC electromagn. coils

Best performance

EuPRAXIA@SPARC_LAB FEL beamlines

Plasma-Beam driven site at INFN Frascati

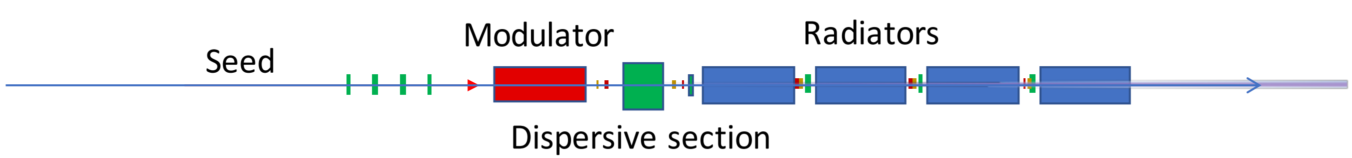


Two foreseen FEL beamlines:

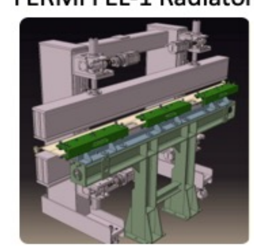
1) AQUA: Soft-X ray SASE FEL – Water window optimized for 4 nm (baseline)

SASE FEL: 10 UM Modules, 2 m each – Two technologies under study: Apple-X PMU and planar SCU

2) ARIA: VUV seeded HGHG FEL beamline for gas phase

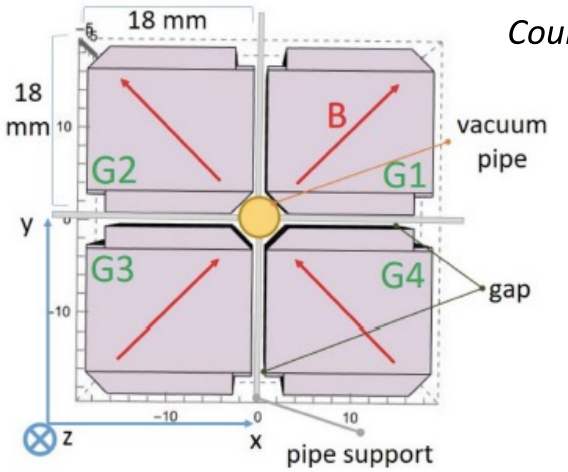


FERMI FEL-1 Radiator

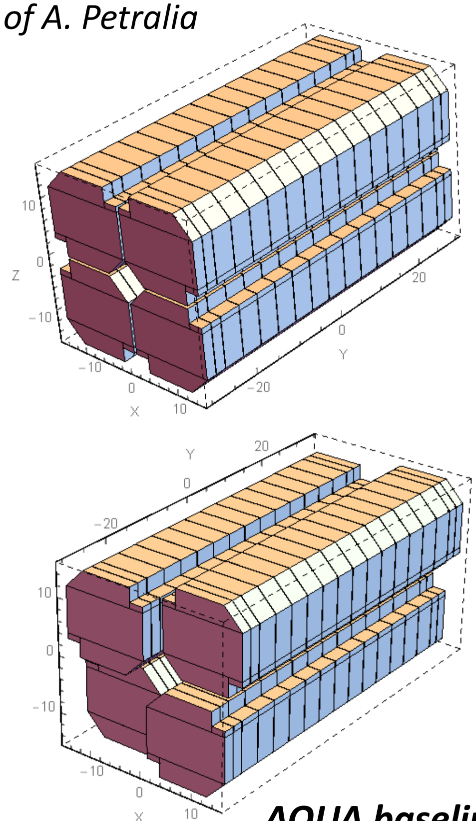


SEEDED FEL – Modulator 3 m + 4 Radiators APPLE II – variable pol. 2.2 m each – SEEDED in the range 290 – 460 nm – Undulator based on consolidated technology.

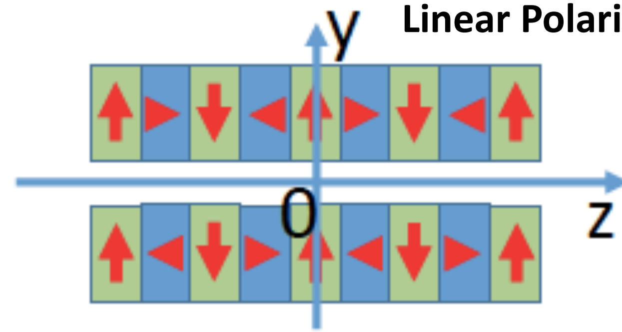
Variable polarization undulator for AQUA



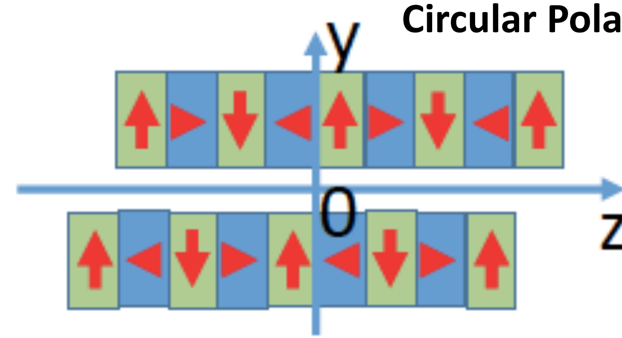
Courtesy of A. Petralia



Linear Polarization



Circular Polarization



Polarization: variable polarization meets the scientific case requests → circ. polar. guarantees high gain (~ L_{mod})

Advanced **P**lanar **P**olarized **L**ight **E**mitter**-type**: **APPLE-X** much higher field at the same undulator aperture → extended tuning range, K_{max} independent of polarization → fully symmetric

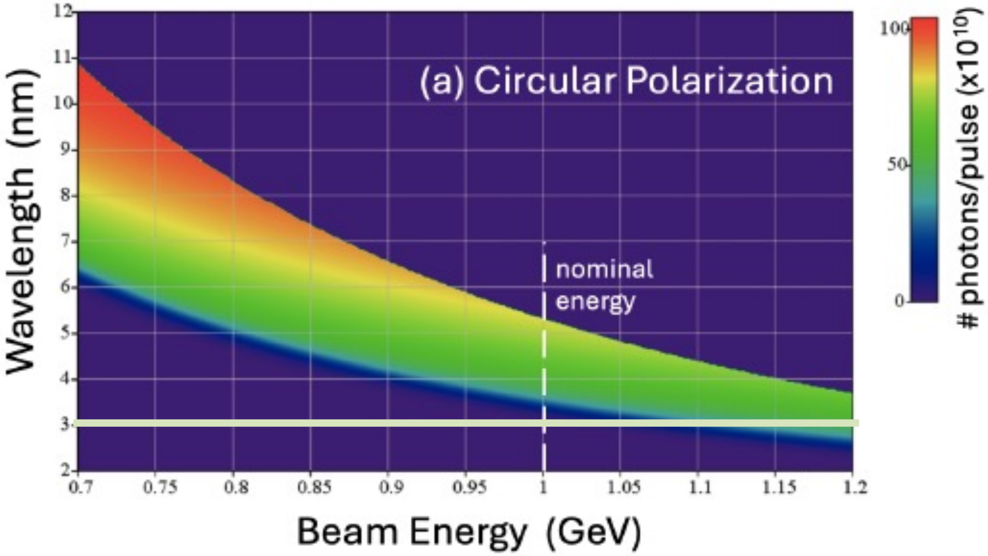
AQUA baseline radiator: 10 APPLE-X modules

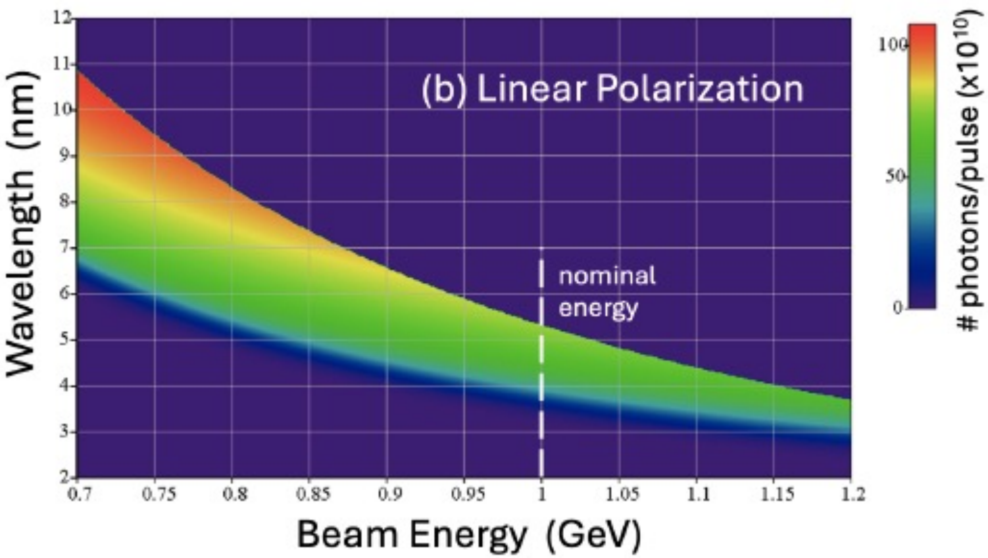
B max (T) (in LP)	0.935
K_{max} (in LP)	1.572
K_{max} (in CP)	1.111
max λ_0 (nm) (@ 1 GeV)	**5.25**

Main parameters:

- Remanent field Br = 1.35 T
- Undulator period λ_u = 18 mm
- 4 blocks / period, NdFeB
- # of periods (eff.) N = 110 (L_u=1990mm)

FEL performance vs. beam energy





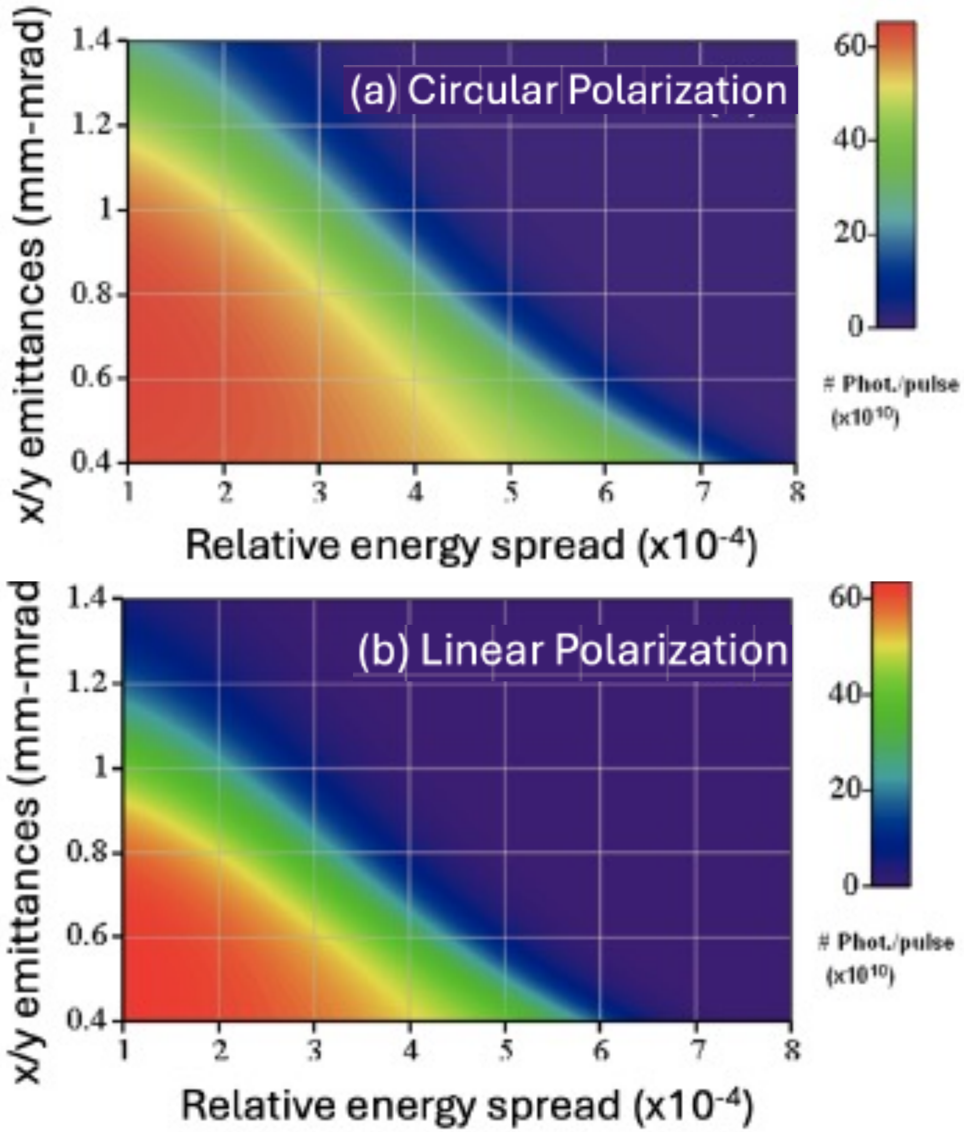
Tunability in beam energy $\gamma m_e c^2$ and in undulator gap g_u weighted in terms of photons number

$$\lambda = \frac{\lambda_u}{2\gamma^2}\left(1 + a_w^2(g_u)\right)$$

Circular Polarization:
wider undulator gap tunability than Linear → "water window" wavelengths probed with higher photon yields and shorter saturation lengths
By increasing beam energy → chance to cover 3nm wavelength
The same undulator beamline can smoothly operate in the 0.7-1.2 GeV range

Linear Polarization:
undulator gap gives limited lever arm shorter λ → lower K values → lower power and smaller tunability

FEL acceptance on other parameters



- **Modified Ming Xie-Dattoli model to analyze the FEL performance**
- **Working point: photon energy of 4 nm = 310 eV at 1 GeV**
- **Gaussian beam in current, energy, energy spread, transverse momenta and spatial distributions**
- **Peak current 1.5 kA, FWHM bunch duration 15 fs, average $\beta_x = \beta_y$ =10 m, and $\varepsilon_x = \varepsilon_y$.**

Circular polarization operations can be sustained even with non-optimal beam parameters

Effects of non-optimal parameters can be partially compensated by decreasing the Twiss β values

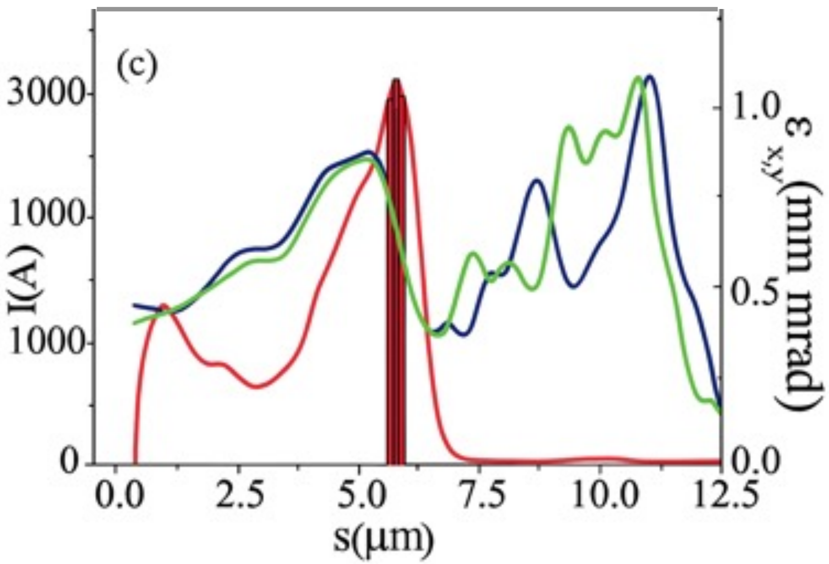
FEL performance from realistic beam distributions

electron beam parameter	Value
charge [pC]	29.5
beam energy [GeV] ([Lorentz γ])	0.995 (1946)
peak current [kA]	3.3
slice (proj.) rel. energy spread [%]	0.2 (0.5)
slice emittance x,y [mm $\times$ mrad]	0.69, 0.66

AQUA @ 4 nm wavelength

with undulators set in circular polarization

FEL light yield	Value
E_{pulse} [μJ]	19.6
N_γ [10^{11}]	3.93
L_{sat} [m]	21
peak λ [nm]	4.011
bandwidth [%]	0.16
trans. size [μm]	165
divergence [μrad]	32

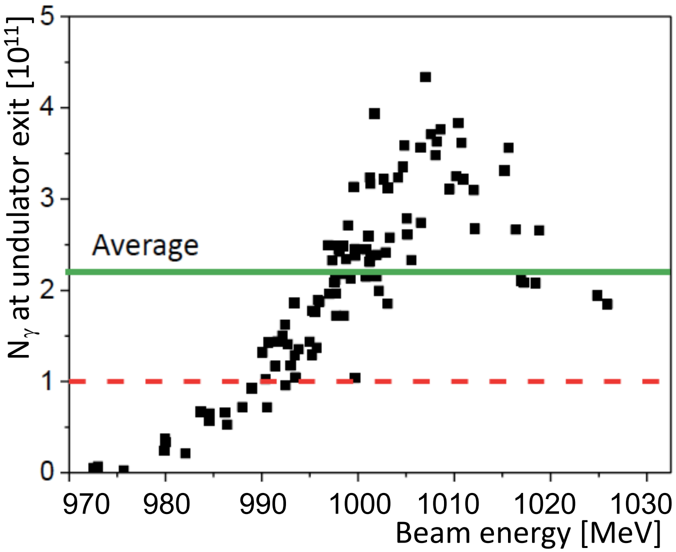


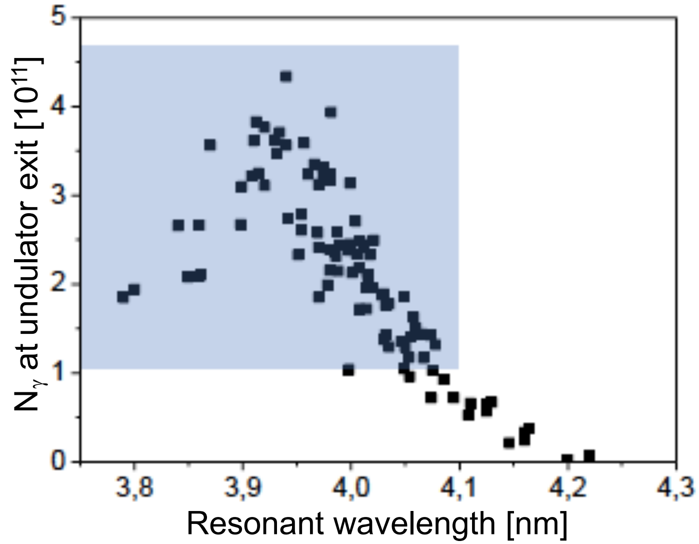
Start-2-end electron beam current and emittance profiles: the best slice is shown

100 replicas of the machine are generated via an MC approach, randomly sampling from below distributions → produced e^- bunches are transferred to the FEL

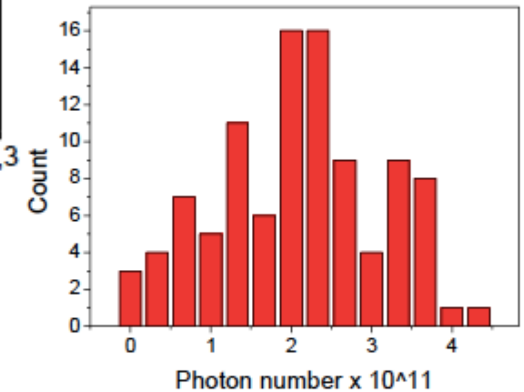
Subsystem	Parameter	Jitter (RMS)
S-band Gun and Accelerating Sections	RF Voltage	±0.02 %
	RF Phase	±0.02°
X-band Accelerating Sections	RF Voltage	±0.02 %
	RF Phase	±0.10°
Cathode Laser System	Charge	±1 %
	Time of arrival	±20 fs
	Spot size	±1 %
Plasma Accelerator	Density	±1%

Linac jitter effects on the FEL performance

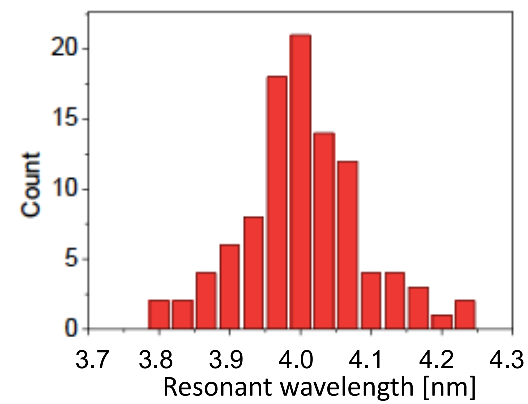




84% of the sample with:
$N_\gamma > 10^{11}$ photons and
3.80 nm < λ < 4.05 nm

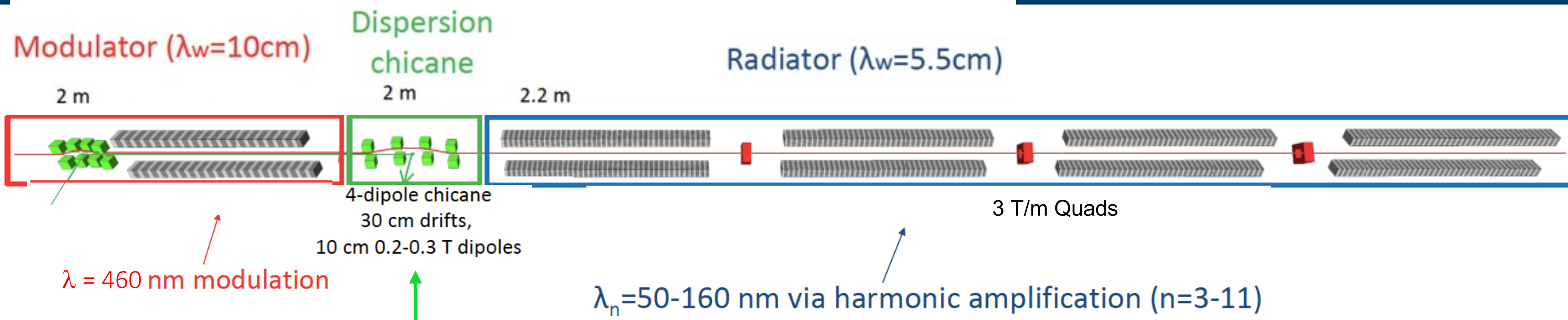


quantity at undulator exit	average value	relative deviation
Pulse energy	11 μJ	49%
Photon number	2×10^{11}	48%
Wavelength	4.00 nm	2%

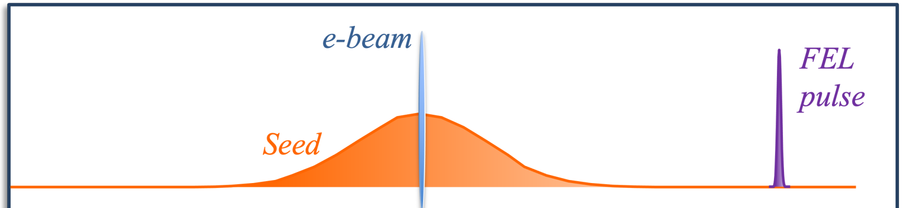


Linac jitter effects ~ 50% on N_γ – To compare with SASE fluctuations

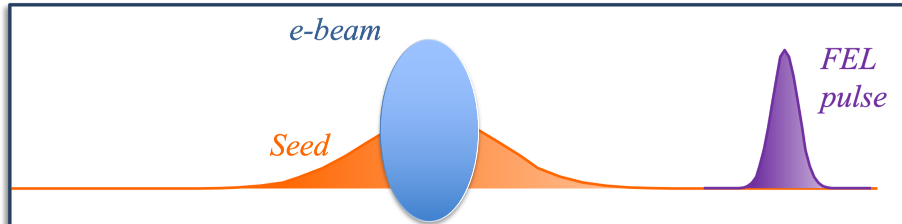
ARIA baseline layout



Converts electron energy modulation to spatial bunching in harmonics



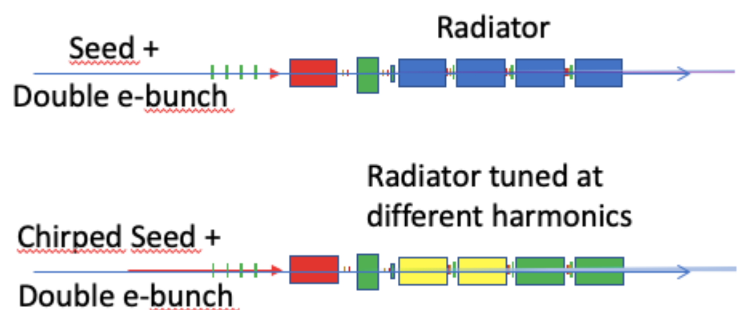
Short & high current e-bunch, long seed.
Pulse duration limited by **e-bunch duration** & large **gain bandwidth**



Long & low current e-bunch, long seed.
Pulse spectral width limited by **e-bunch energy correlation → wavelength linewidth stability by seed coherence**

Different and complementary to long e-bunch, low current and short seed (à la FERMI@Elettra)

Plus other 2-colors schemes



Radiator undulators for ARIA

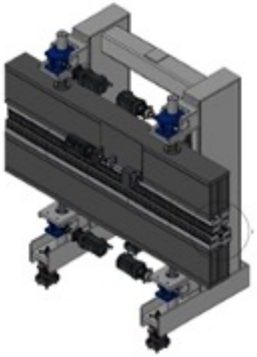
Two options under scrutiny

(1)

APPLE-II Similar to FERMI FEL-1 radiators built by KYMA in 2009-2010

Main features:

- variable gap, variable phase for adjustable polarization (six motors)
- $\lambda_u = 55.2\ mm,\ Np=42,\ L_u=2.4\ m$
- working gap: 10 ÷ 32 mm



(2)

APPLE X Similar to AQUA radiators built by KYMA in 2022-2024 for SABINA

Main features:

- variable gap, variable phase for adjustable polarization – K_{RMS} **independent of polarization**
- $\lambda_u = 48\ mm,\ Np=41,\ L_u=2.0\ m$
- working gap: 10 ÷ 32 mm

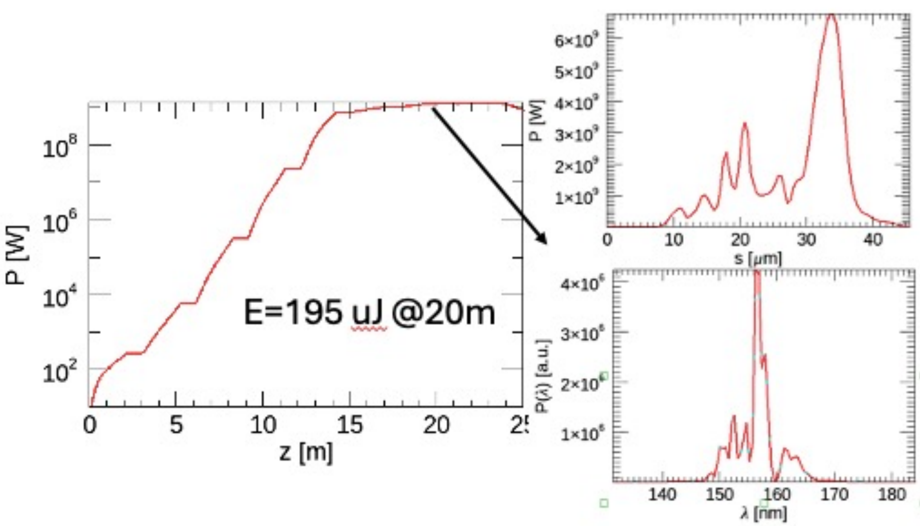
ARIA performance with realistic beam distributions

From 10 replicas of 50 pC charge electron beams	
beam parameter	average value
beam energy [MeV]	1001
peak current [kA]	2.16
proj. energy spread [MeV]	4
slice energy spread [keV]	76
slice emittance x,y [mm × mrad]	1.24, 0.98

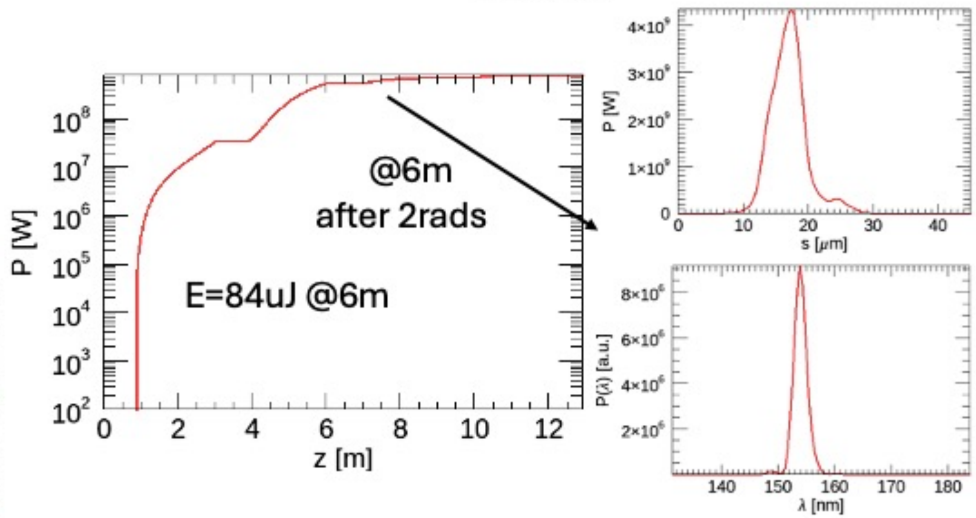
FEL light yield	$n = 3$, $\lambda = 153$ nm after 3 modules	$n = 9$, $\lambda = 51$ nm after 4 modules
rel. λ deviation [%]	1.0	1.2
pulse energy [μJ]	127	53
bandwidth [%]	1.5	0.6
FWHM duration [fs]	18	17
trans. size [mm]	0.8	0.4
divergence [mrad]	0.3	0.08
saturation length [m]	2.9	5.5

Circular polarization ARIA

SASE



HGHG



Conclusions

- ✓ The undulator adopted for the AQUA beamline consists of an out-of-vacuum APPLE-X: a well-known technology that allows selectable polarization and fine tuning in the water window → the same LINAC+undulator line is able to sustain E > 1 GeV beam energies and the target FEL performance is stable against variations on energy spread and transverse emittance

- ✓ Full time-dependent results with realistic electron beam distributions (from the cathode to the undulator entrance) even accounting for jitters from the reference values show that AQUA will be able to deliver 10^{11} photons/pulse with narrow bandwidth and small deviations from the target performance

- ✓ Feasibility and expected performance of a flexible and cost-effective EUV user facility delivering 15-100 fs duration FEL pulses close to Fourier transform limit are investigated, also making use of the plasma beam driven realistic distributions → selectable polarization VUV light will allow to explore chirality and dichroism in biotic media

Please, stay FEL-tuned!

Acknowledgements

Many thanks to

I. Balossino, F. Curciarello, A. Del Dotto, M. Del Franco, A. Ghigo, L. Giannessi, A. Giribono, A. Liedl, M. Opromolla, A. Petralia, V. Petrillo, S. Romeo, A.R. Rossi, L. Sabbatini, A. Selce, G. Silvi, C. Vaccarezza

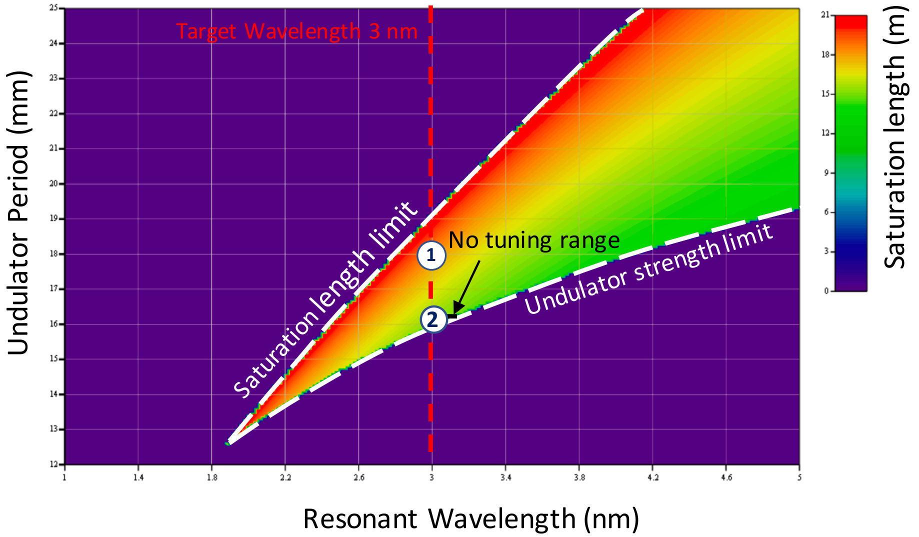
Thank you 4 your attention

AQUA tuning range: choice of the period λ_u

FEL performance evaluated with Ming Xie-Dattoli scaling formulae accounting for 60% filling factor

- **Target wavelength 3-4 nm @ 1 GeV: relatively short period required (12-20 mm)**
- **Beta function constrains alignment tolerance and undulator module length (~ gain length)**

Parameter	Symbol	Units	D (CDR)
Charge	Q	pC	30
Energy	E	GeV	1
Peak current	I_{peak}	kA	**1.8**
Bunch length	σ_z	μm	**2**
Proj. norm. emittances (x/y)	$\varepsilon_{n,x,y}$	mm-mrad	**1.7**
Slice, norm. emittances (x/y)	$\varepsilon_{n,x,y}$	mm-mrad	0.8
Proj. energy spread	$\sigma_{\delta p}$	%	0.95
Slice Energy spread	$\sigma_{\delta s}$	%	**0.05**



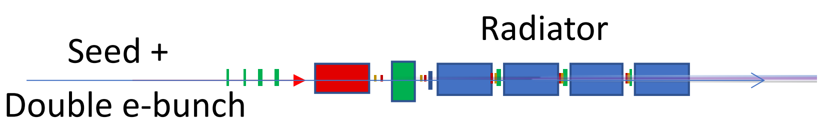
$$\lambda_{res} = \frac{\lambda_u}{2\gamma^2}\left[1 + \frac{K^2(g_u)}{2}\right]$$

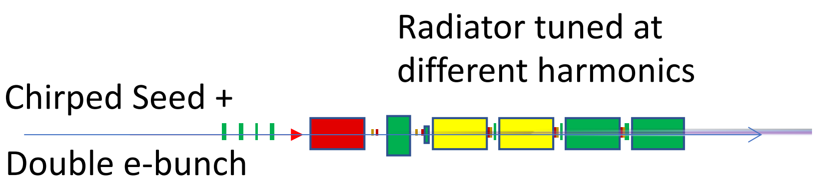
From the K vs. gap formulae of a planar PMU with remanent B_r = 1.2T, magnetic gap=6 mm, beam stay clear=5 mm:

1) **18mm implies tuning range, plus saturation length contingency if operating at 4nm wavelength;**
2) **16mm improves the saturation length limit, but almost no tuning range**

ARIA: other flavors of two-color operations

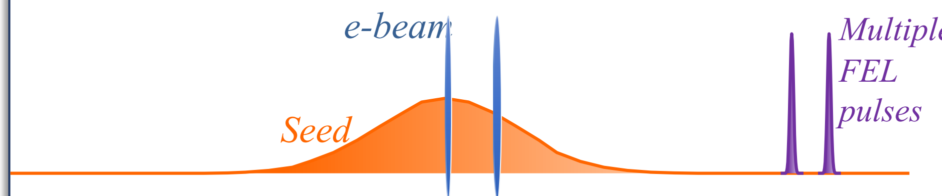
The flexibility of this source can be used in a number of ways





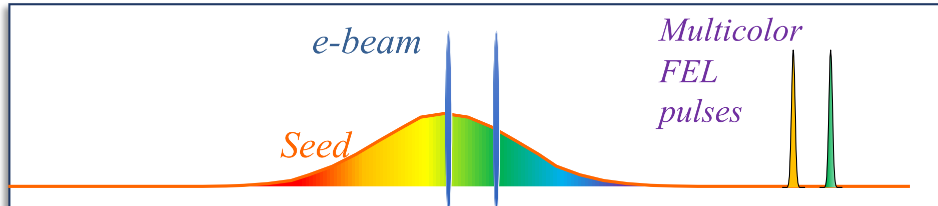
Some already explored !!

1. *V. Petrillo, et al., Phys. Rev. Lett. 111, 114802 (2013)* <- SPARC experiment in 2012
2. *Ferrari, E., et al. Widely tunable two-colour seeded free-electron laser source for resonant-pump resonant-probe magnetic scattering. Nat Commun. 7, 10343 (2016).*



Short & high current e-bunch, long seed.
Pulse duration limited by **e-bunch duration** & large **gain bandwidth**

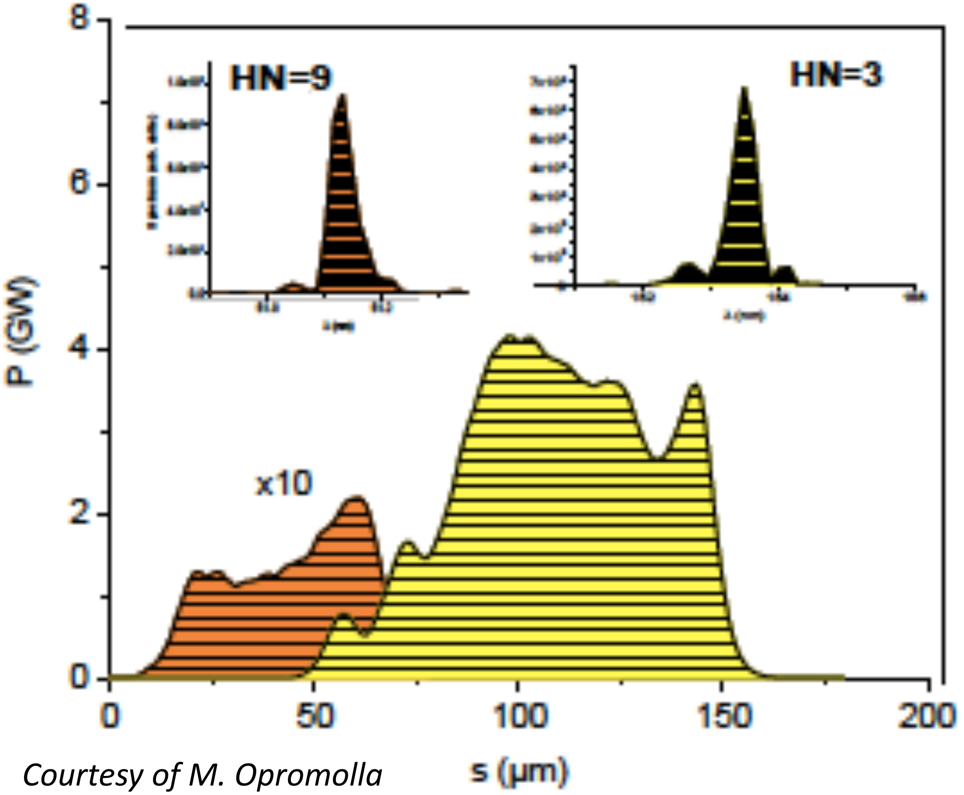
(Flexible: can produce multiple phase-locked pulses)



Multiple pulses on a chirped seed: amplification of separated colors. Different colors can be **further separated by amplification of different harmonics** in the modulator (see ref. 3)

ARIA with long bunch & low current

Long e-beam	From LINAC
Charge (pC)	200
Bunch length (rms, μm)	34
Energy (GeV)	0.8–1.2
Peak current (kA)	0.7
Slice energy spread (%)	0.01
Slice norm. emittance (mm mrad)	0.5



Courtesy of M. Opromolla

Output pulse	HN=3	HN=9
λ (nm)	153	51
τ (FWHM, fs)	212	150
E (μJ)	880	180
Size (mm)	0.85	0.35
Div. (mrad)	0.26	0.11
Time-BW product ()	2.7	3.8

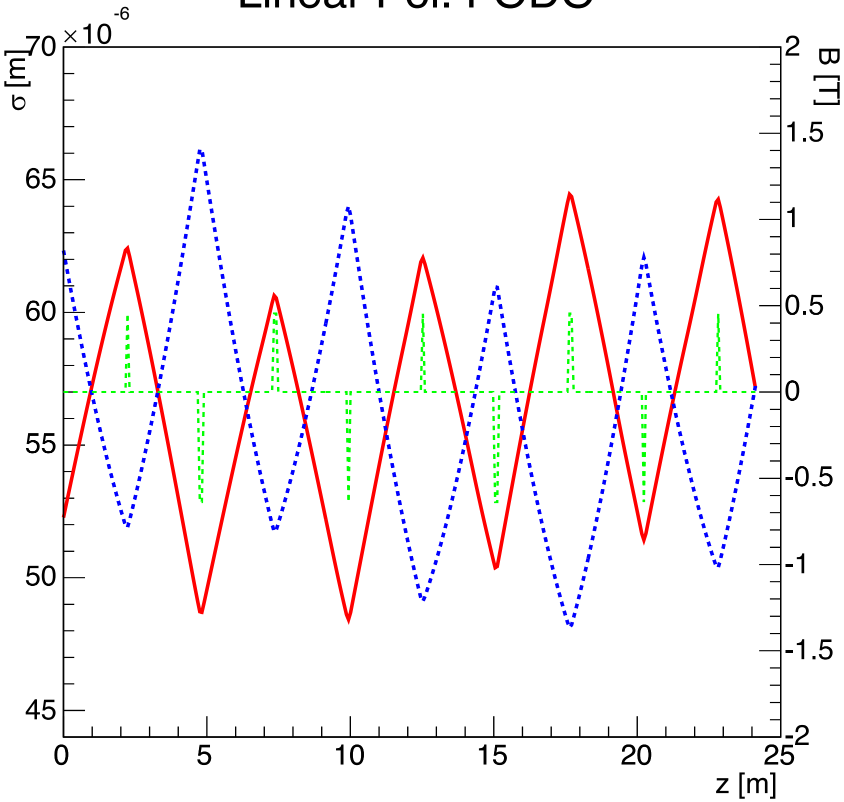
Intensity and spectrum stable, ultra-narrow bandwidth pulses are produced with longer electron bunches → high intensity allows monochromator for spectrum enhancement

AQUA @4nm with APPLE-X: selectable polarization

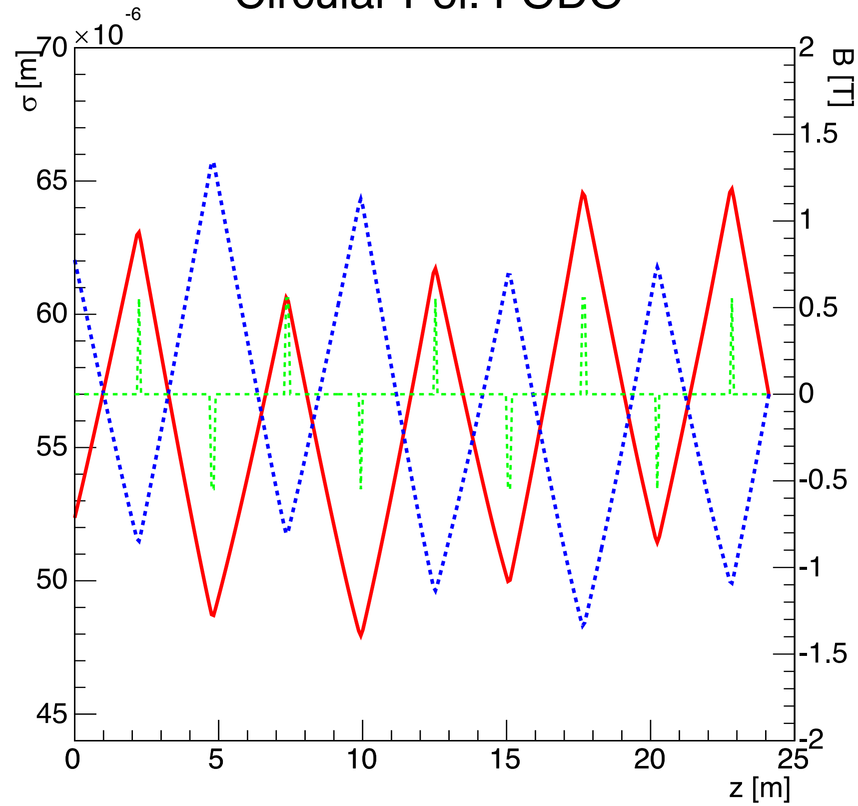
focusing: $h_x = 2.3,\ h_y = -0.3$

focusing: $h_x = h_y = 1$

Linear Pol. FODO



Circular Pol. FODO



$K = 1.189$

$a_w = 0.84$

- **Slightly asymmetric Quad field strengths in Linear**
- **Twiss values at und. entrance for the electron beam to match → constrain the upstream transfer line**

$K = a_w = 0.84$

$\lambda_R = 4\,\mathrm{nm}$