Fundamental research and applications with the EuPRAXIA facility at LNF
December 4th 2024

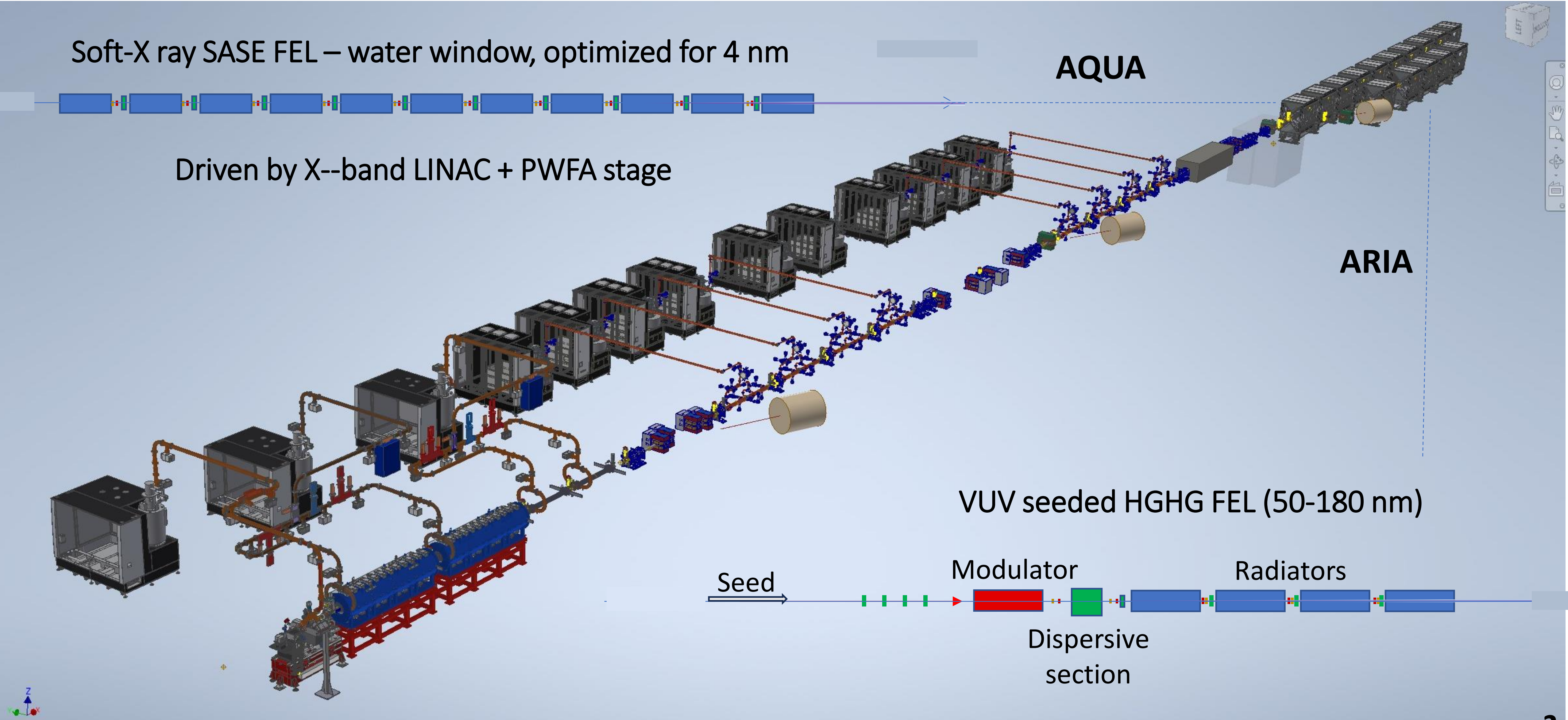
EuPRAXIA@SPARC_LAB FELs

Michele Opromolla (INFN-LNF)

on behalf of the EuPRAXIA@SPARC_LAB WA6 collabotion team

L.Giannessi, F.Nguyen, A.Petralia, V.Petrillo, L.Sabbatini, A.Selce, A.Vannozzi, F.Villa,
C.Boffo, I.Balossino, M.Del Franco, M.Galletti, A.Giribono, A.Ghigo, A.Iovine, N.Mirian, C.Vaccarezza

EuPRAXIA@SPARC_LAB Machine layout



Soft-X ray SASE FEL – water window, optimized for 4 nm

Driven by X--band LINAC + PWFA stage

VUV seeded HGHG FEL (50-180 nm)

Outline

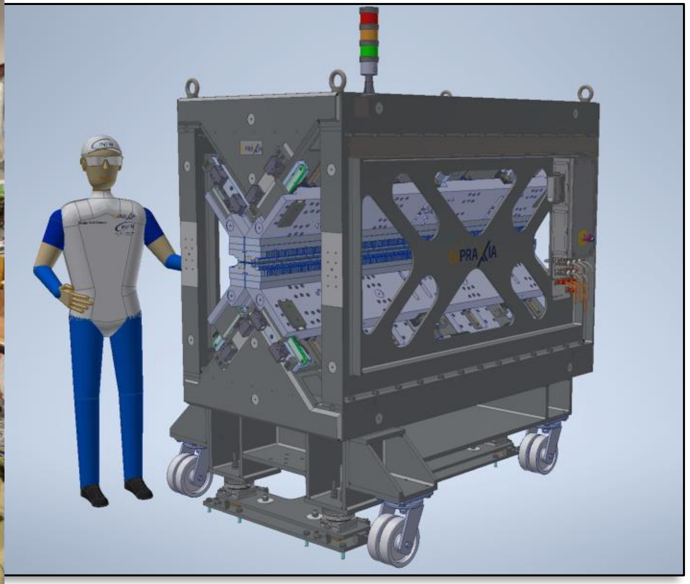
- **AQUA**
- Undulator magnetic design
- FEL tuning range
- Expected radiation performances
- Foreseen photon Diagnostics and Beamline

- **ARIA**
- Undulator line
- FEL tuning range and properties
- Expected radiation performances
- Foreseen photon Beamline

- Summary

AQUA

AQUA undulator



a) Apple-X undulator:
increased PM field through "geometry", selectable polarization

b) Superconducting undulator
collaboration agreement with FNAL for NbTi planar prototype

- **Target wavelength 3-4 nm @ 1 GeV**: relatively short period required **(12-20 mm)**
- **Total available length ~ 25-30 m,** depending on linac spreader system, matching section, beam diagnostics and main beam dump.

✓ Total **undulator magnetic length: 20 m**, 10 modules

✓ **Period length: 18 mm**
sufficient tuning range at fixed energy
reach carbon /nitrogen K-edge

✓ **Polarization : variable**
fits with the requests from the scientific case

✓ **Type: Apple-X**
substantially higher field
extended tuning range
K_{max} independent of polarization → fully symmetric

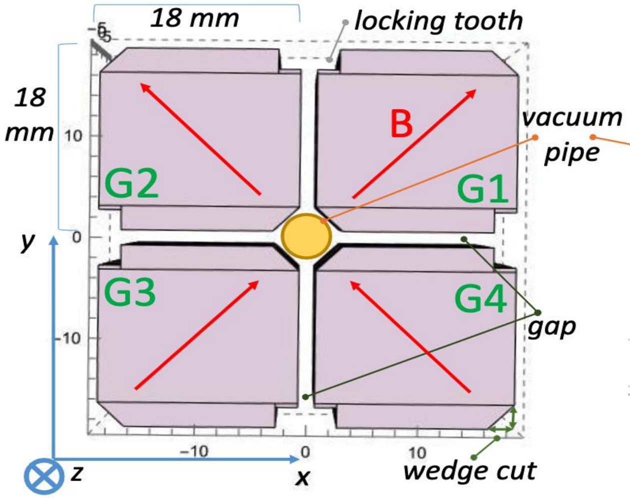
Experience from the **SABINA** Undulator @LNF (KYMA)

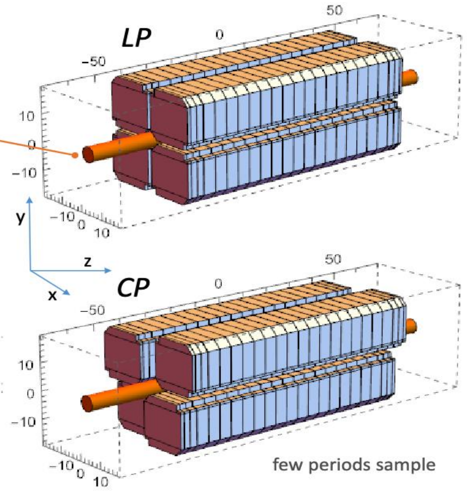
Apple-X undulator modeling and design

Modeling parameters

- Remanent field Br = 1.35 T
- Undulator period λ_u = 18 mm
- Material NdFeB
- 4 blocks / period
- # of periods (eff.) N = 110
- L_{und}= 1990.4 mm (10 modules)

Pipe ext. diam. (mm)	5.6
Pipe inner diam. (mm)	5.0
Wedge cut (mm)	2.8
ϕ aperture (mm)	6.0
B_{max} (T) in LP	0.935
K_{max} in LP	1.572
K_{rms} (max=a_w in CP)	1.111
max λ_0 (nm) @ 1 GeV	5.25





Interplay among aperture, magnetic strength, wavelength tunability and inner diameter constrained by wakefield effects on FEL performance

Electron beam parameter acceptance analysis

The undulator is engineered to amplify radiation at 4 nm from a suitable beam.

Required e-beam properties from a modified Ming-Xie model analysing the FEL performance vs. the e-beam emittance and energy spread.

This analysis assumes:

- a Gaussian beam (in current, energy, energy spread, transverse momenta and spatial distributions)
- duration 5 fs, peak current 1.5 kA, average beta functions $\beta_x = \beta_y = 10$ m, emittances $\varepsilon_x = \varepsilon_y$

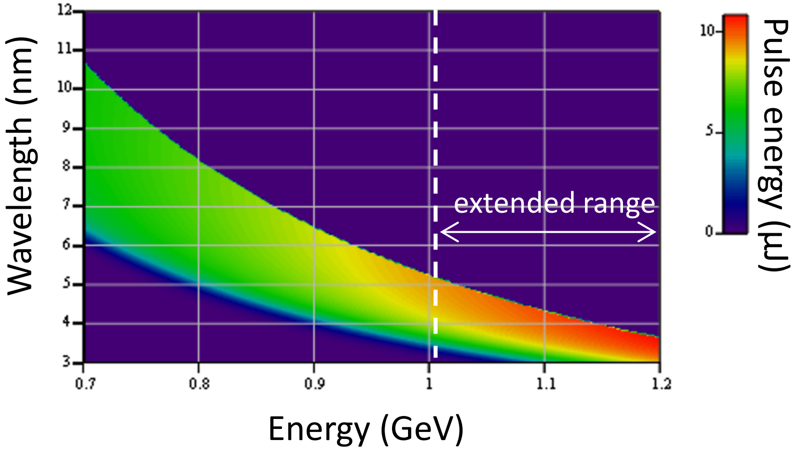
The most efficient FEL operation in both linear and circular polarization can be achieved for:

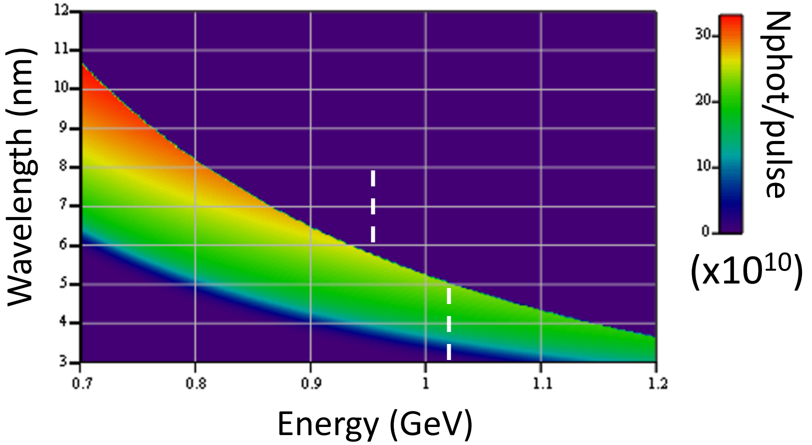
☐ Transverse slice emittances $\boldsymbol{\varepsilon_{x,y} \leq 0.6 - 0.8}$ **mm mrad**
☐ Relative slice energy spread $\boldsymbol{\Delta E/E \leq 3 \times 10^{-4}}$

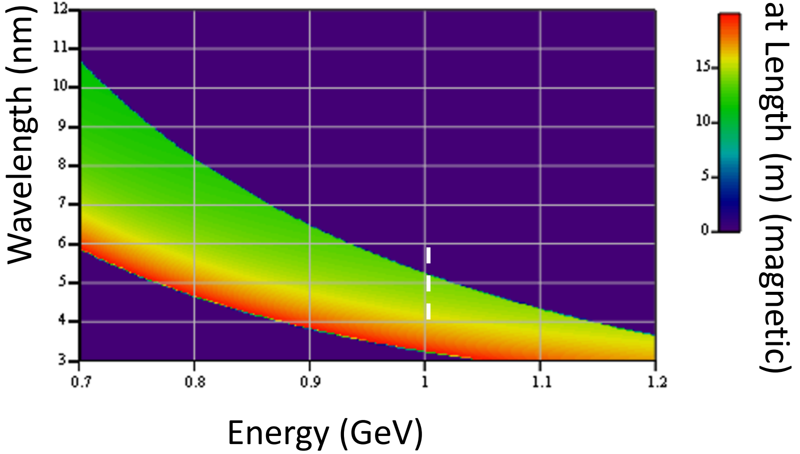
FEL tuning range – linear polarization

Analysis with a modified Ming-Xie model, assuming the reference e-beam:

Quantity	Value
Energy E_{beam}	0.7 – 1.2 GeV
Peak current I_{peak}	1.5 kA
FWHM bunch duration σ_t	5 fs
Slice normalized x, y emittance ε_n	0.7 mm × mrad
Slice fractional energy spread $\sigma_{\delta,s}$	0.03 %







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

Tunability both in beam energy $\gamma m_e c^2$ and in undulator gap g_u

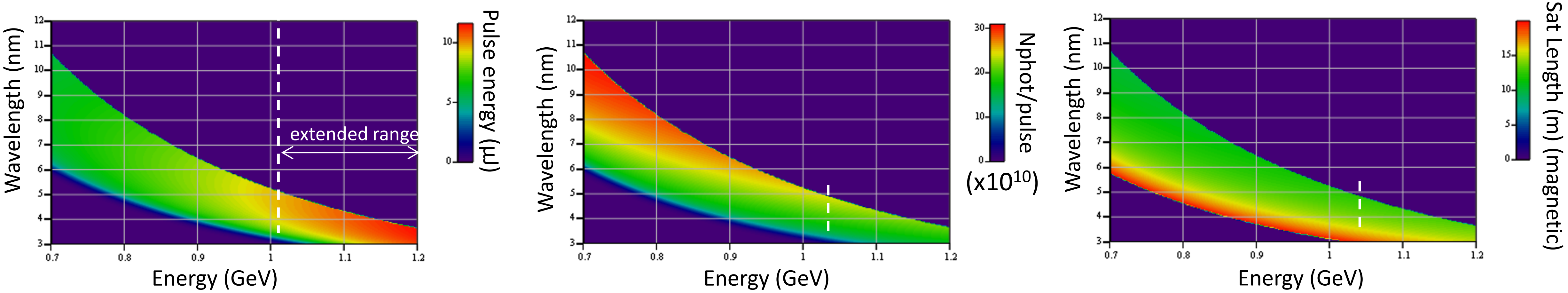
Limited lever arm in lin. Pol because of the lower gain:

shorter λ_{res} ←→ lower K values ←→ lower N_γ/pulse, longer gain length and saturation length

By increasing beam energy (other parameters constant) → chance to make 4nm with performance similar to longer wavelengths

FEL tuning range – circular polarization

Thanks to its symmetry, the Apple-X undulator provides the same Krms in both linear and circular polarizations



Wider undulator gap tunability in Circular Polarization

→ "water window" wavelengths probed with higher N_γ yield

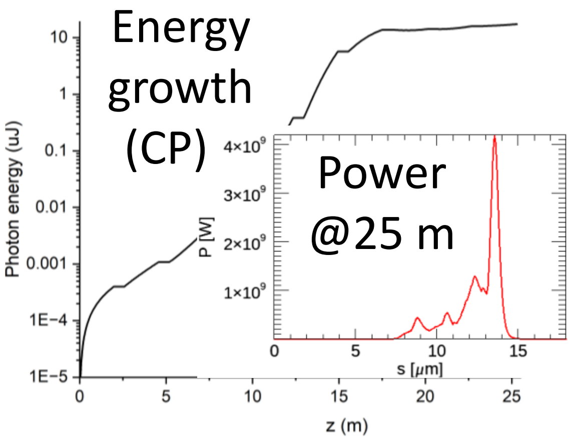
By increasing beam energy (other parameters constant)

→ saturation length below 20 m, most of the available spectrum; chance to reach for 3nm

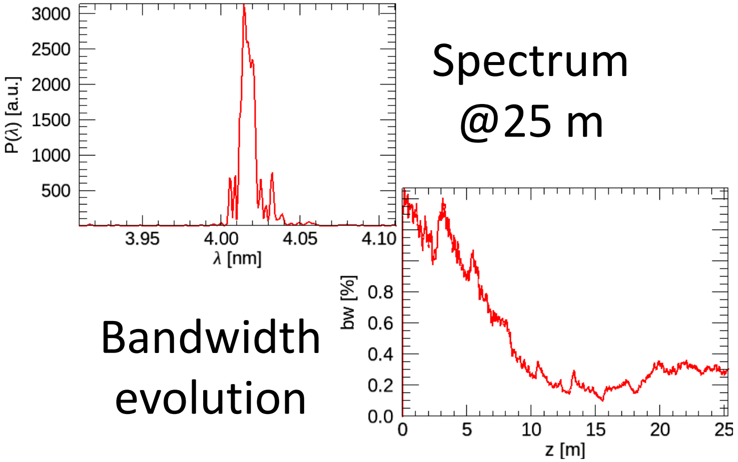
Expected electron beam and AQUA FEL performances

Desired/foreseen average e-beam parameters from PWFA

Parameter	Unit	Range	Simulated
Energy	GeV	1-1.2	1
Charge	pC	25-50	25
Rms Bunch length	μm	2-4	2
Peak current	kA	1.5-3	1.5
Slice emitX,Y	mm mrad	0.6-0.8	0.7
Slice rel. energy spread	‰	0.2-0.3	0.3


Energy growth (CP)

Power @25 m


Spectrum @25 m

Bandwidth evolution

AQUA FEL theoretical performances

working point	LP K_{max}	LP 4nm	CP K_{max}	CP 4nm
resonant λ [nm]	5.75	4.01	5.75	4.01
photon energy [eV]	215	309	215	309
matching $\langle\beta\rangle$ [m]	6	8	6	8
Pierce ρ_{1D} [10^{-3}]	1.81	1.35	2.04	1.46
gain length$_{1D}$ [m]	0.559	0.788	0.405	0.566
satur. length [m]	16.78	23.40	14.33	20.81
satur. $\langle$power$\rangle$ [GW]	0.394	0.236	0.486	0.277
exit E_{pulse} [μJ]	23.90	11.56	32.95	13.73
exit bandwidth [%]	0.154	0.088	0.223	0.117
exit pulse length$_{\mathrm{RMS}}$ [fs]	6.10	3.50	6.12	3.76
exit divergence [mrad]	0.032	0.023	0.031	0.022
exit trans. size [μm]	195	133	190	132
exit N$_\gamma$/pulse [10^{11}]	6.93	2.33	9.53	2.77

On average, photon briliiance of about 10^{29}- 10^{30} ph/s/mm²/mrad²/0.1% BW

AQUA FEL performances

FEL performance in CP: ideal case of the Tested beam with Gaussian current profile

Average pulse properties at the undulator exit

<Energy> (μJ)	**λ (nm)**	<BW> (%)	<Photon number>	<Size> (μm)	<Div.> (μrad)	L_{sat} (m)	$<L_{rad}^{FWHM}>$ (fs)
17	4	0.3	3.4×10^{11}	90	100	22	15

Sources of **FEL radiation instabilities**

FEL single-spike regime → intensity fluctuations

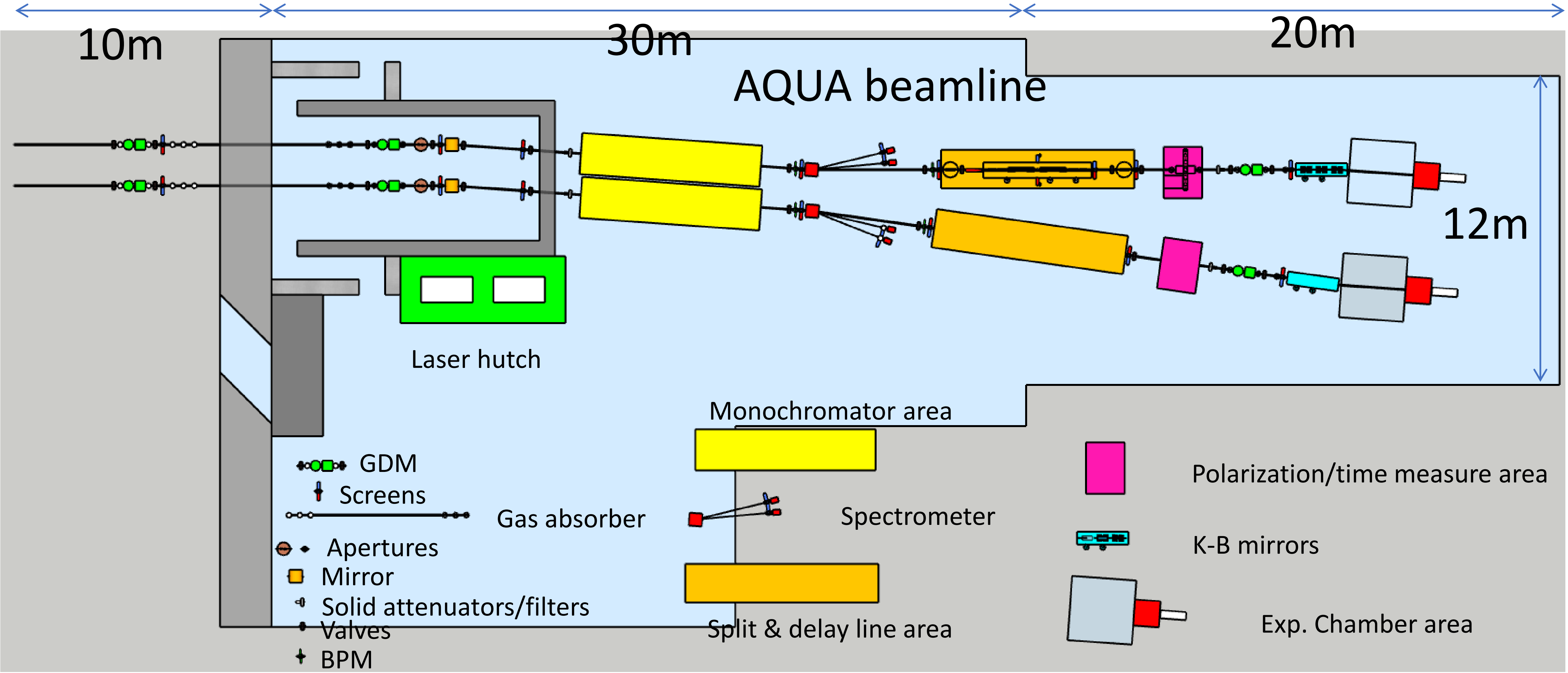
E-beam energy jitter → resonant wavelength jitter

Expected FEL performance and stability from start2end EuPRAXIA@SPARC_LAB beams

- **>80% successful (>10^{11}N$_\gamma$ /pulse) shots are expected**

FEL radiation @und. exit	**Unit**	**Range ± error%**
Wavelength λ	nm	4 ± 2%
Energy at 25 m	**μJ**	5-20 ± 50%
FWHM Pulse length	**fs**	10 ± 15%
Photon number	$\times 10^{11}$	2-4 ± 45%
Bandwidth	%	0.2-0.4

FEL Beamline

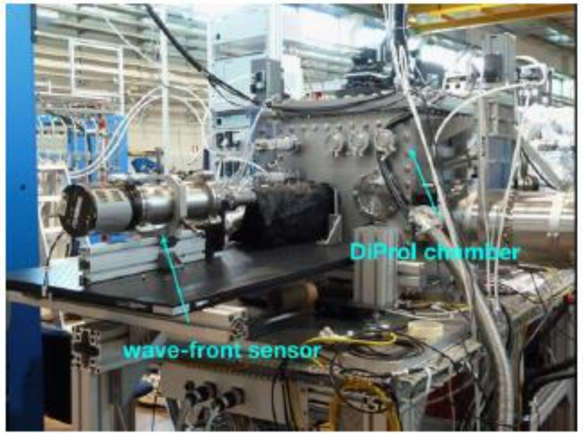


Courtesy of F. Villa

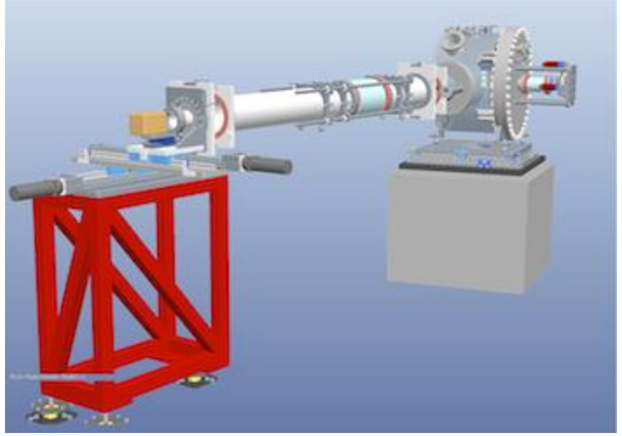
FEL Photon diagnostics

Courtesy of F. Villa

Wavefront sensors

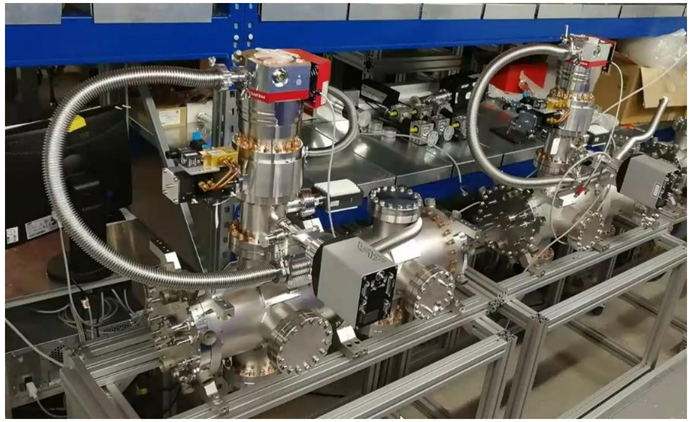


Grating spectrometer

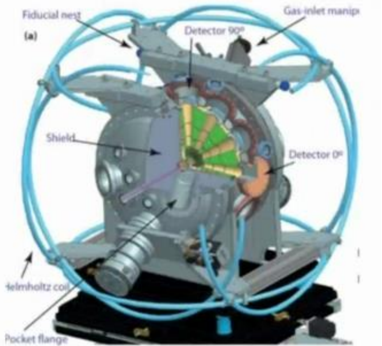


YAG screen

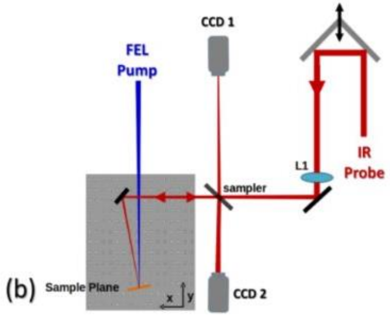
Gas Intensity Monitors and BPMs



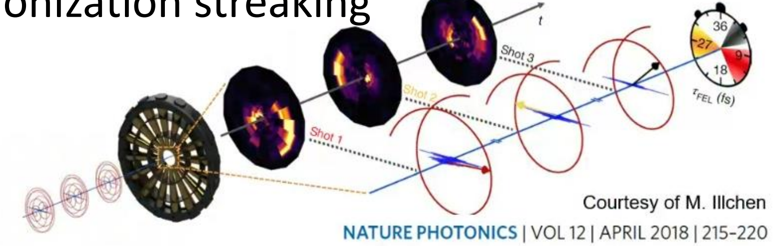
Longitudinal measurements



Ionization streaking



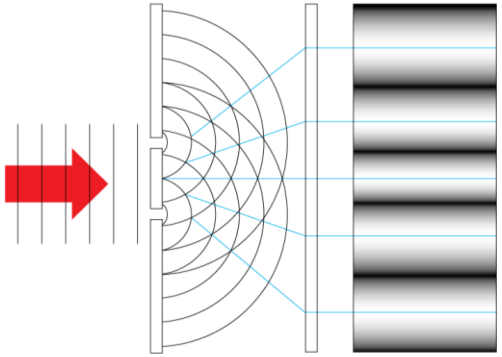
Transient reflectivity

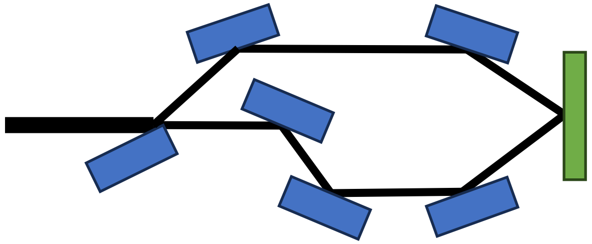


Courtesy of M. Illchen

NATURE PHOTONICS | VOL 12 | APRIL 2018 | 215-220

Coherence measurements (**transverse** and **longitudinal**)





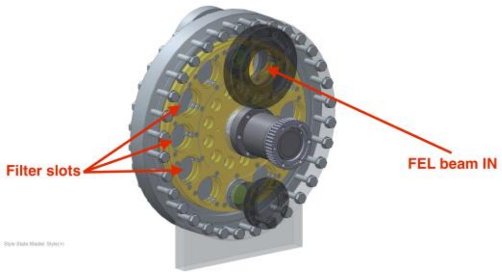
Single-shot diagnostics

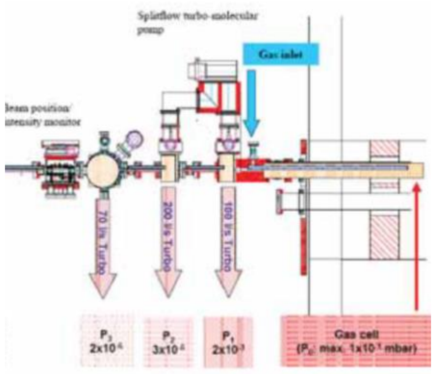
Multi-shot diagnostics

Intercepting diagnostics

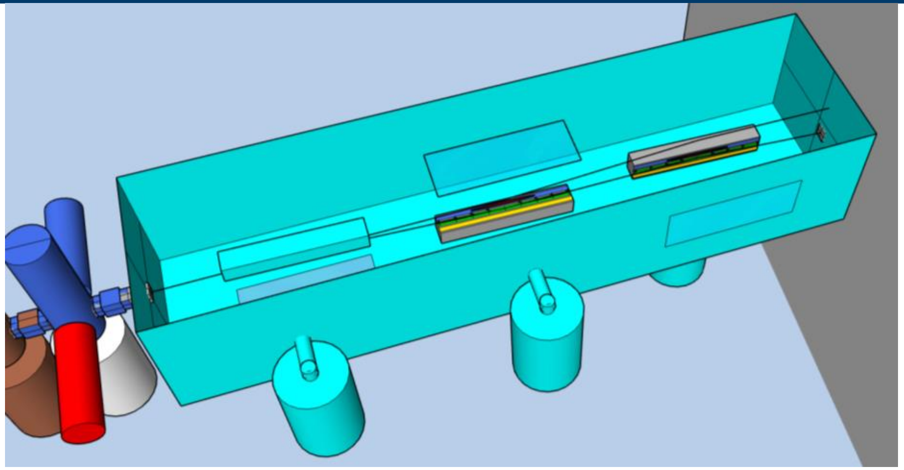
Bladed BPM

FEL optics and transport



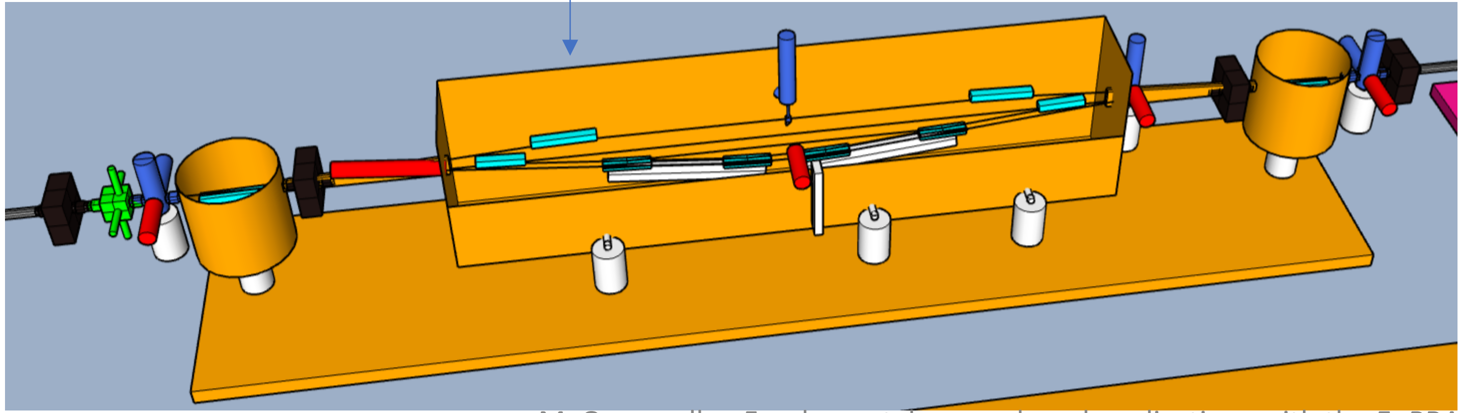


Filters (solids and gas attenuators)

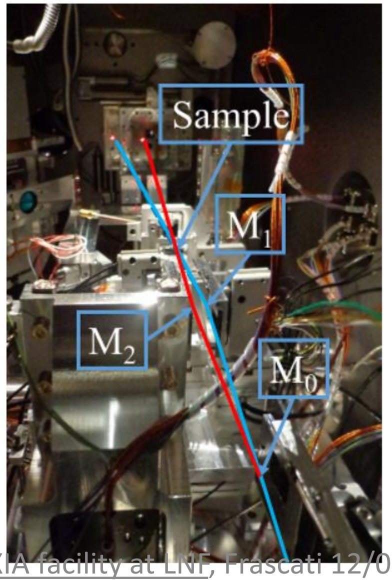


Bendable mirror in K-B configuration
for tunable final focus

Split and delay systems (10s ps or 100s fs range)



MiniTIMER compact delay line



Courtesy of F. Villa

Preliminary estimations on losses

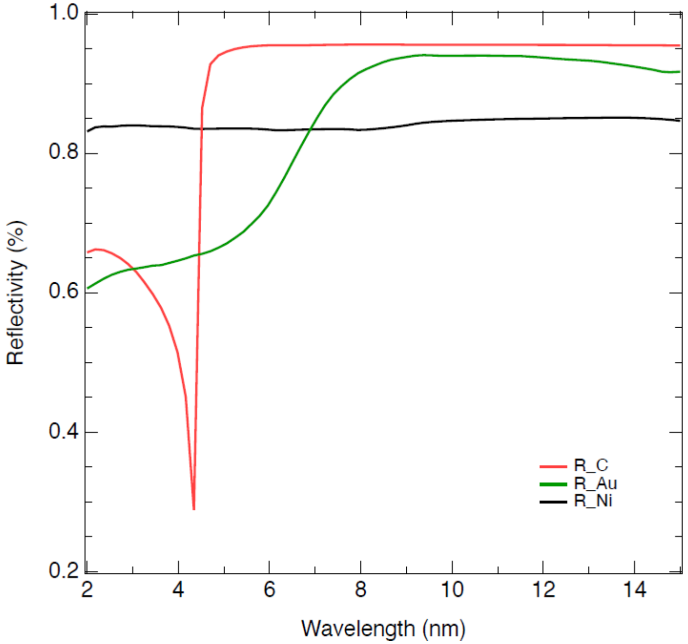
AQUA FEL parameters

	Linear Pol.	Circular Pol.
Central wavelength range	4.0 nm, 310eV	4.0 nm
Spectral bandwidth (rms, % to central wavelength)	0.088%	0.117%
Beam length (rms)	3.50 fs	3.76 fs
Beam transverse size (rms)	133 um	132 um
Beam divergence (half angle)	0.023 mrad	0.022 mrad
Photons per pulse	2.33*10^11	2.77*10^11
Polarization (direction)	H	C
Repetition rate	100 Hz	100 Hz

System	Transmission	#
Mirror chamber	0.80 (0.85)	1
BDA	0.99	2
BPM	0.98	2
Spectrometer	0.75 (0.80)	1
Monochromator	0.08 to 0.02	1
Intensity monitor	0.99	2
Time measurement	0.99	1
Split & delay	0.41 (0.52)	1
attenuators	1 to 0	3
YAG screens	1 or 0	13
K-B focusing	0.64 (0.72)	1

Total transmission

- without monochromator and S&D: **34%** (with R=85% mirrors: **44%**)
- with Split & Delay: **14% (23%)**
- with monochr. 1-g: **2.6%** (3.3%) **x $\delta\lambda/\Delta\lambda$**
- with monochr. 2-g: **0.8%** (1.0%) **x $\delta\lambda/\Delta\lambda$**
- with monochr. 2-g + S&D: **0.32% (0.52%) x $\delta\lambda/\Delta\lambda$**

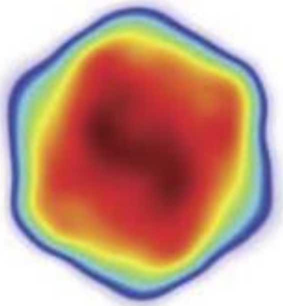


Courtesy of F. Villa

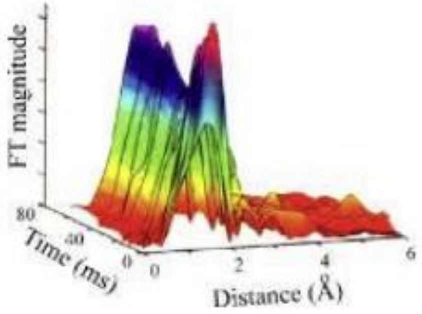
AQUA Beamline Scientific Case

Experimental techniques and typology of samples

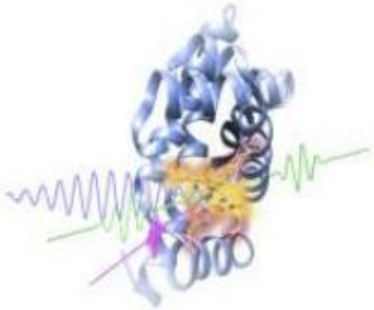
- Coherent imaging



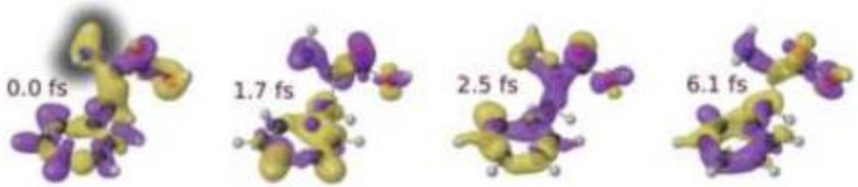
- X-ray spectroscopy



- Raman spectroscopy



- Photo-fragmentation of molecules



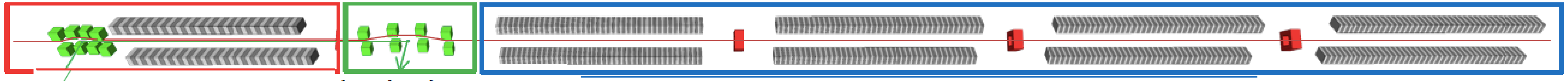
(Large) Viruses
Organelles
Bacteria/Cells
Metals
Semiconductors
Superconductors
Magnetic materials
Organic molecules

Courtesy of F. Stellato

ARIA

Baseline layout

M. Opromolla *et al.*, FEL2022 TUP75 Proceedings



Modulator (λw=10cm)

2 m

Dispersion chicane

2 m

2.2 m

Radiator (λw=5.5cm)

Laser seed:
λ_0=500 nm

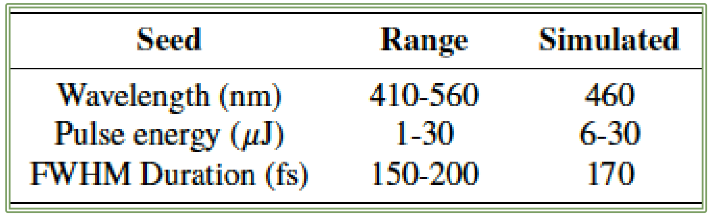
λ_0=500 nm modulation

4-dipole chicane
30 cm drifts,
10 cm 0.2-0.3 T dipoles

2 T/m quads

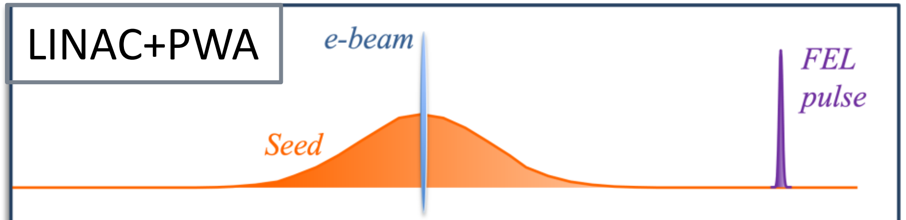
λ_n=50-160 nm via harmonic amplification (n=3-11)

Converts electron energy modulation to spatial bunching in harmonics



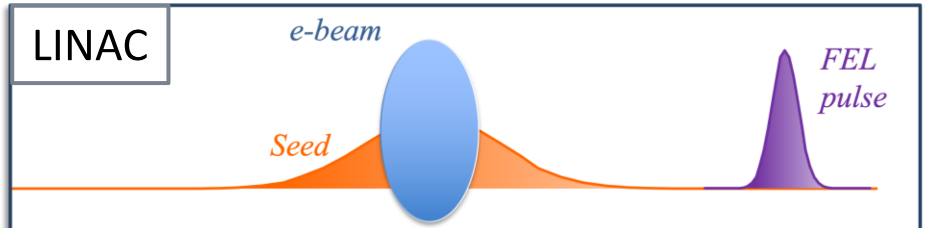
Seed	Range	Simulated
Wavelength (nm)	410-560	460
Pulse energy (μJ)	1-30	6-30
FWHM Duration (fs)	150-200	170

LINAC+PWA



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

LINAC



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

Target Eupraxia e-beam
E= 1-1.2 GeV
I_{peak}= 0.7-1.8 kA
L_{beam}= 2-34 μm rms
ε= 0.7 mm mrad
σ_e= 0.05%

Different and complementary to long-e bunch, low current and short seed (FERMI style)

Radiator Undulators

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

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

Main Physical Specifications:

• Phase error σ_Φ	< 5 º rms
• Trajectory offset error	< 20 μm rms
• Trajectory tilt error	< 25 μrad rms
• Peak-to-peak field error $\Delta B/B$	< 0.5% rms
• Integrated Quadrupole (N/S)	< 100 G
• Integrated Sextupole (N/S)	< 100 G/cm

a) **Apple-II undulator, FERMI-style:** linear/circular polarization

a) **Apple-X undulator, AQUA-style:** selectable polarization, optimal control

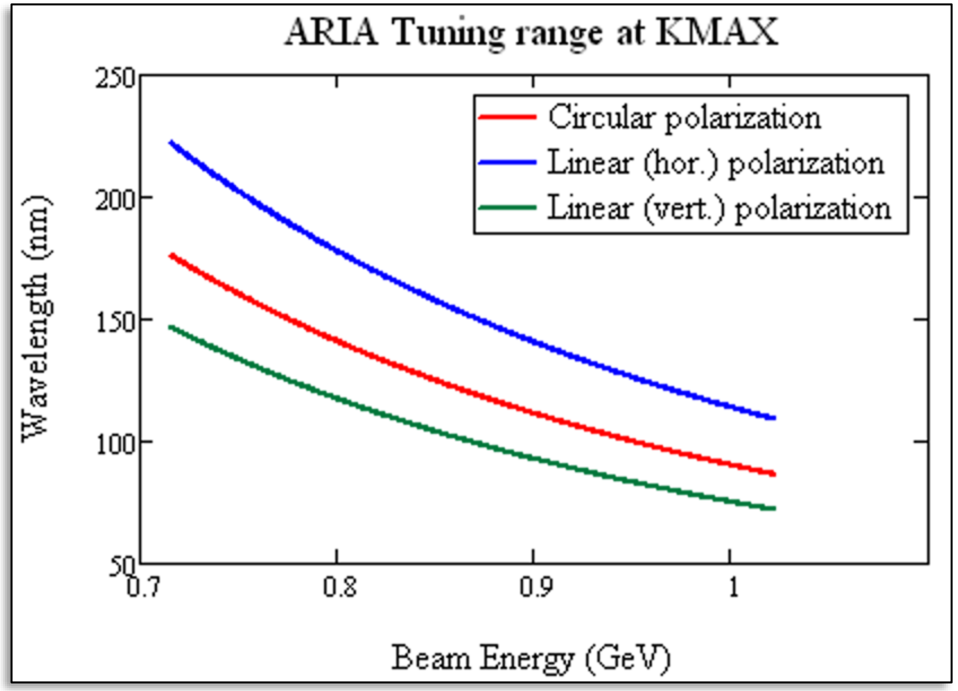
FEL tuning range

FEL:

- Max harmonic = 10
- Undulator K-range from FERMI FEL-1: K_{max} = 3.4 (CR), 4.35 (LV), 5.45 (LH)

Electron beam parameters:

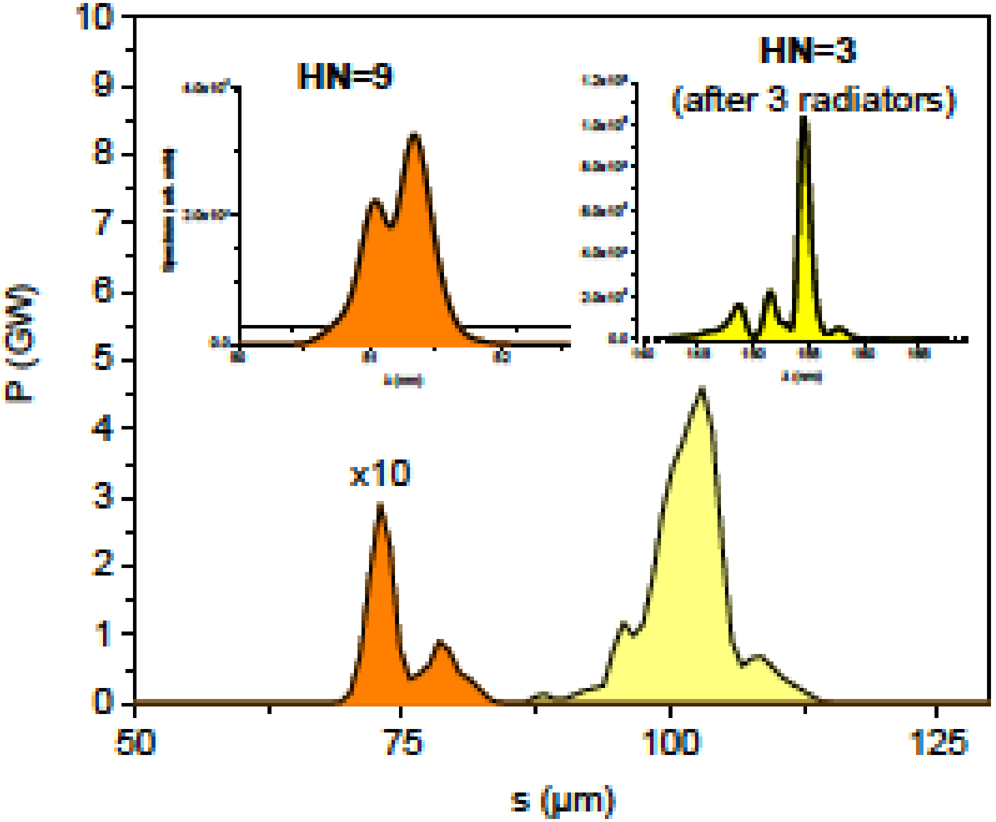
- Energy 1.0 -> 0.7 GeV
- Energy spread 200 keV @ 0.8 kA -> 400 keV@1.5 kA
- Duration: > 100 fs (long bunch mode, 200 pC)
  -> 8 fs (short bunch mode, 30 pC)
- Emittance 2 mm mrad in long bunch mode
  0.8 mm mrad in short bunch mode
- Beta function 10 m



Seed laser:

- minimum seed energy of 20 uJ
- average seed spot size of 0.5 mm^2
  independent on the wavelength
- seed duration 400 fs (long seed)
  -> 200 fs (short seed), possibly
  no frequency chirp –spectral width close to FTL

ARIA with short bunch & high current from LINAC+PWA



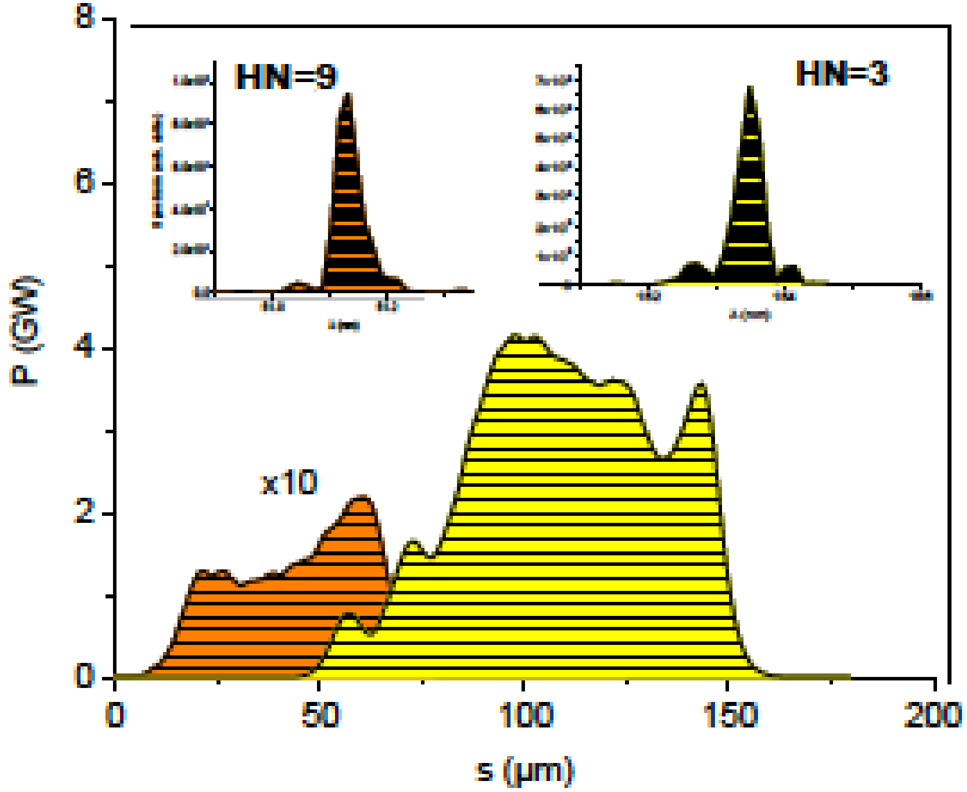
Seed: 460nm, 170 fs FWHM

Output pulse	HN=3	HN=9
λ (nm)	153	51
τ (FWHM, fs)	21	10
E (μJ)	100	5
Size (mm)	0.74	0.43
Div. (mrad)	0.1	0.04
Time-BW product ()	2	0.69

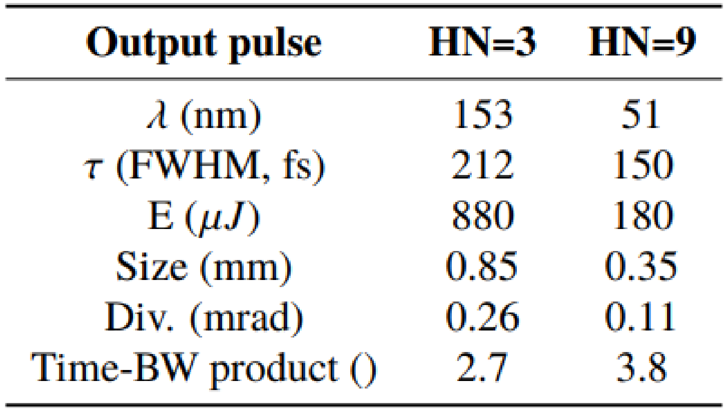
Lower harmonics (≤ 5) saturate after two or three radiators only.

Radiation can be extracted beforehand, using the last radiator for multi-pulse/2-color generation

ARIA with long bunch & low current from LINAC



Seed: 460nm, 170 fs FWHM



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

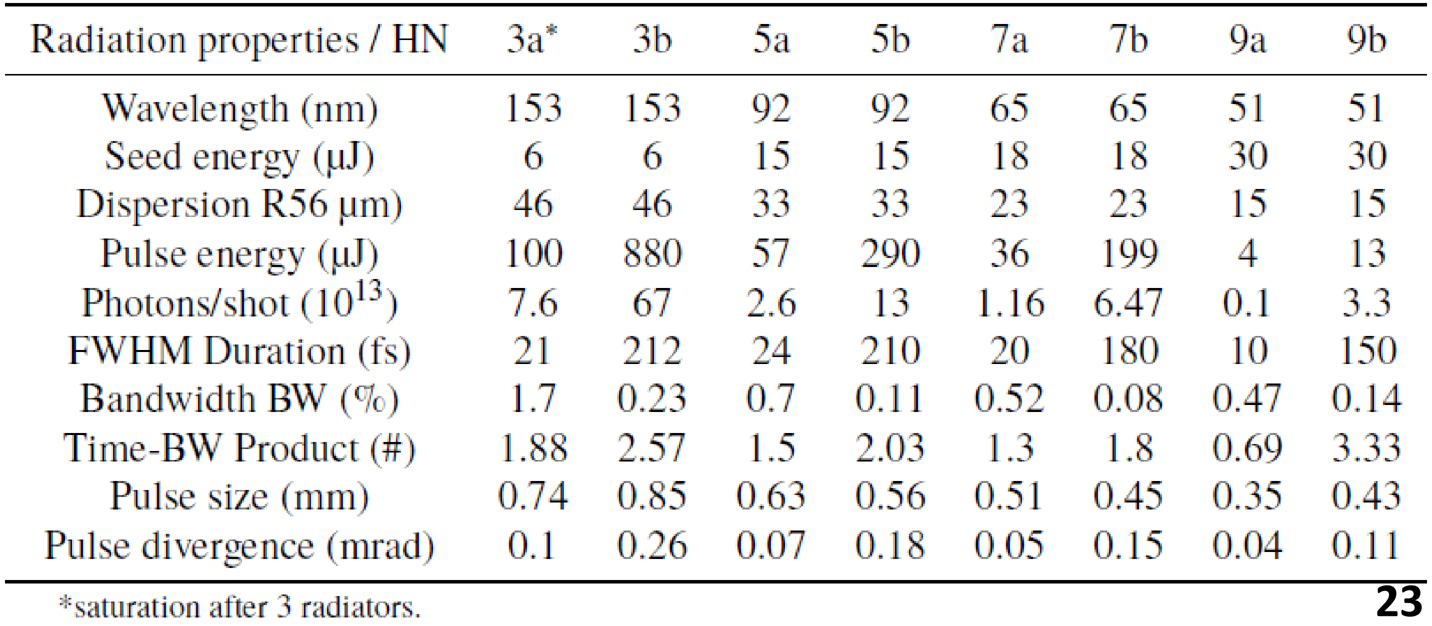
ARIA short summary

- **ARIA** operates in **High Gain Harmonic Generation** and may cover the VUV spectral range down to 50 nm with an undulator similar to the one of FERMI FEL-1. Contrary to FERMI it uses a **seed longer than the electron bunch** and uses the electron bunch shaping and control capabilities of Eupraxia@SPARC_LAB for controlling the light pulse properties.
- A commercial laser based on an Optical Parametric Amplifier should have the correct pulse energy and features to seed ARIA.

It fills a niche in the world FELs scenario:

- ✓ No other seeded FEL facility covers the full range 50-180 nm, except for the DALIAN light source
- ✓ Superposition with HHG sources, but without limitations on polarization, photon energy tuning & intensity
- ✓ Synchronization with HHG sources or external lasers for multicolor pump-probe operation.

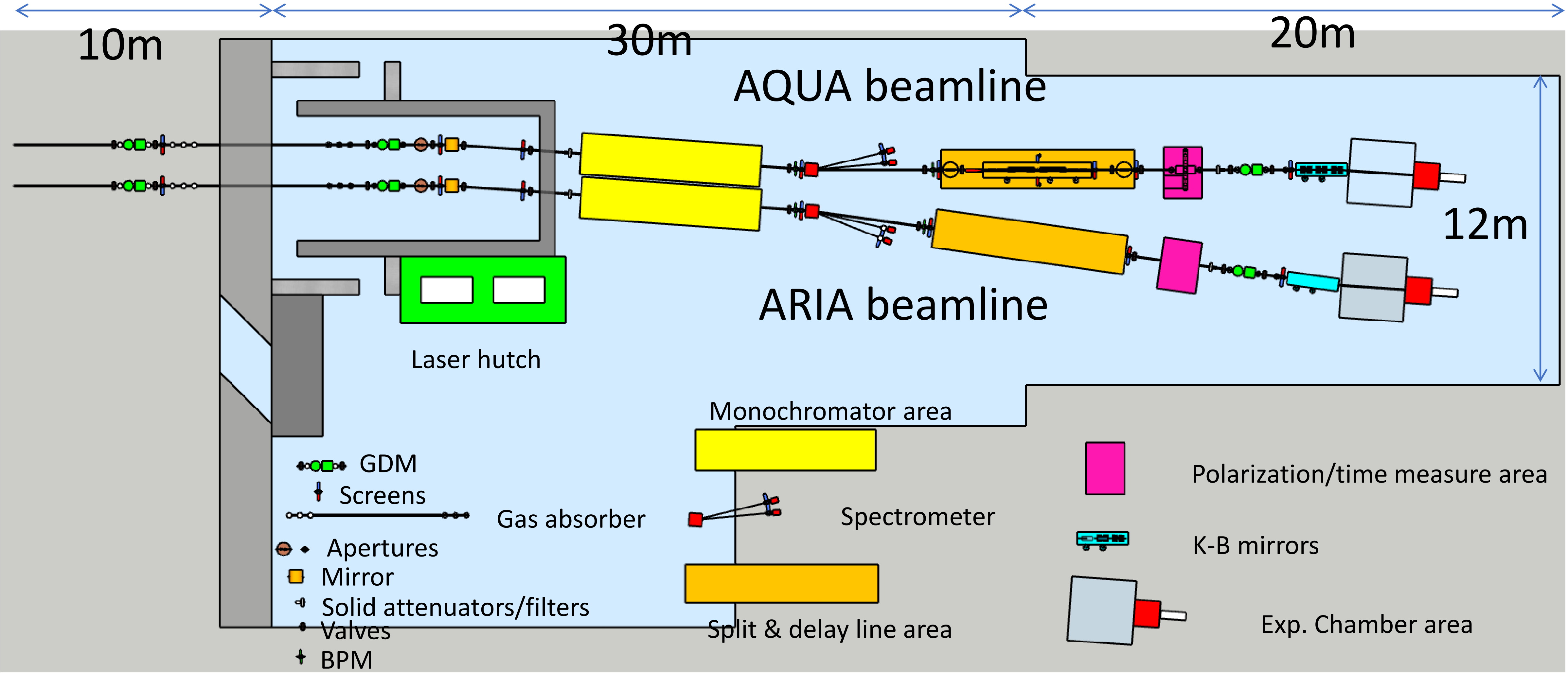
Radiation properties at saturation
Short beam (a) and Long beam (b) case



Radiation properties / HN	3a*	3b	5a	5b	7a	7b	9a	9b
Wavelength (nm)	153	153	92	92	65	65	51	51
Seed energy (μJ)	6	6	15	15	18	18	30	30
Dispersion R56 μm)	46	46	33	33	23	23	15	15
Pulse energy (μJ)	100	880	57	290	36	199	4	13
Photons/shot (10^{13})	7.6	67	2.6	13	1.16	6.47	0.1	3.3
FWHM Duration (fs)	21	212	24	210	20	180	10	150
Bandwidth BW (%)	1.7	0.23	0.7	0.11	0.52	0.08	0.47	0.14
Time-BW Product (#)	1.88	2.57	1.5	2.03	1.3	1.8	0.69	3.33
Pulse size (mm)	0.74	0.85	0.63	0.56	0.51	0.45	0.35	0.43
Pulse divergence (mrad)	0.1	0.26	0.07	0.18	0.05	0.15	0.04	0.11

*saturation after 3 radiators.

FEL Beamline



10m

30m

20m

AQUA beamline

ARIA beamline

12m

Laser hutch

Monochromator area

GDM

Screens

Gas absorber

Apertures

Mirror

Solid attenuators/filters

Valves

BPM

Spectrometer

Split & delay line area

Polarization/time measure area

K-B mirrors

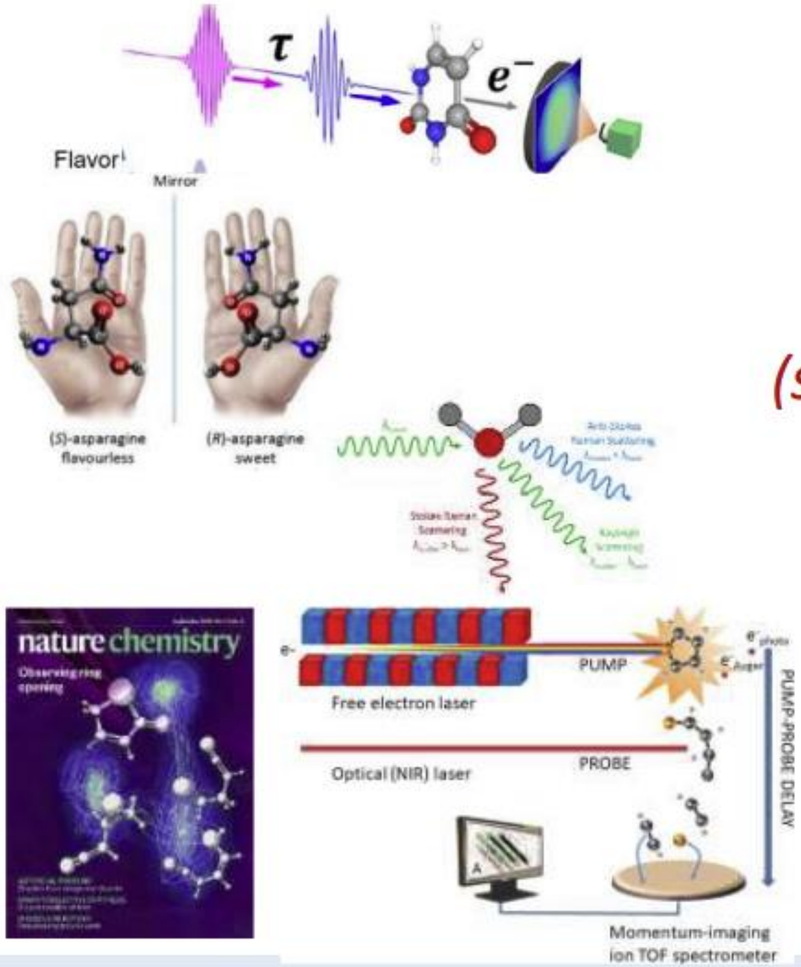
Exp. Chamber area

Courtesy of F. Villa

ARIA Beamline Scientific Case

Experimental techniques and typology of samples

- Photoemission spectroscopy
- Photoelectron Circular Dichroism
- Raman spectroscopy
- Photo-fragmentation of molecules
- Time of Flight Spectroscopy



Gas phase & Atmosphere
(Earth & Planets)
Aerosols
(Pollution, nanoparticles)
Molecules & gases
(spectroscopies, time-of-flight)
Proteins
(spectroscopies)
Surfaces
(ablation & deposition)

Courtesy of F. Stellato

Conclusions

The AQUA undulator line is optimized for 4nm-5.7nm → extended spectral range by tuning beam energy.

- ✓ **Ideal reference electron beam values as well as start-to-end beams from the EuPRAXIA@SPARC_LAB accelerator were used to perform 3D time dependent FEL simulations:**

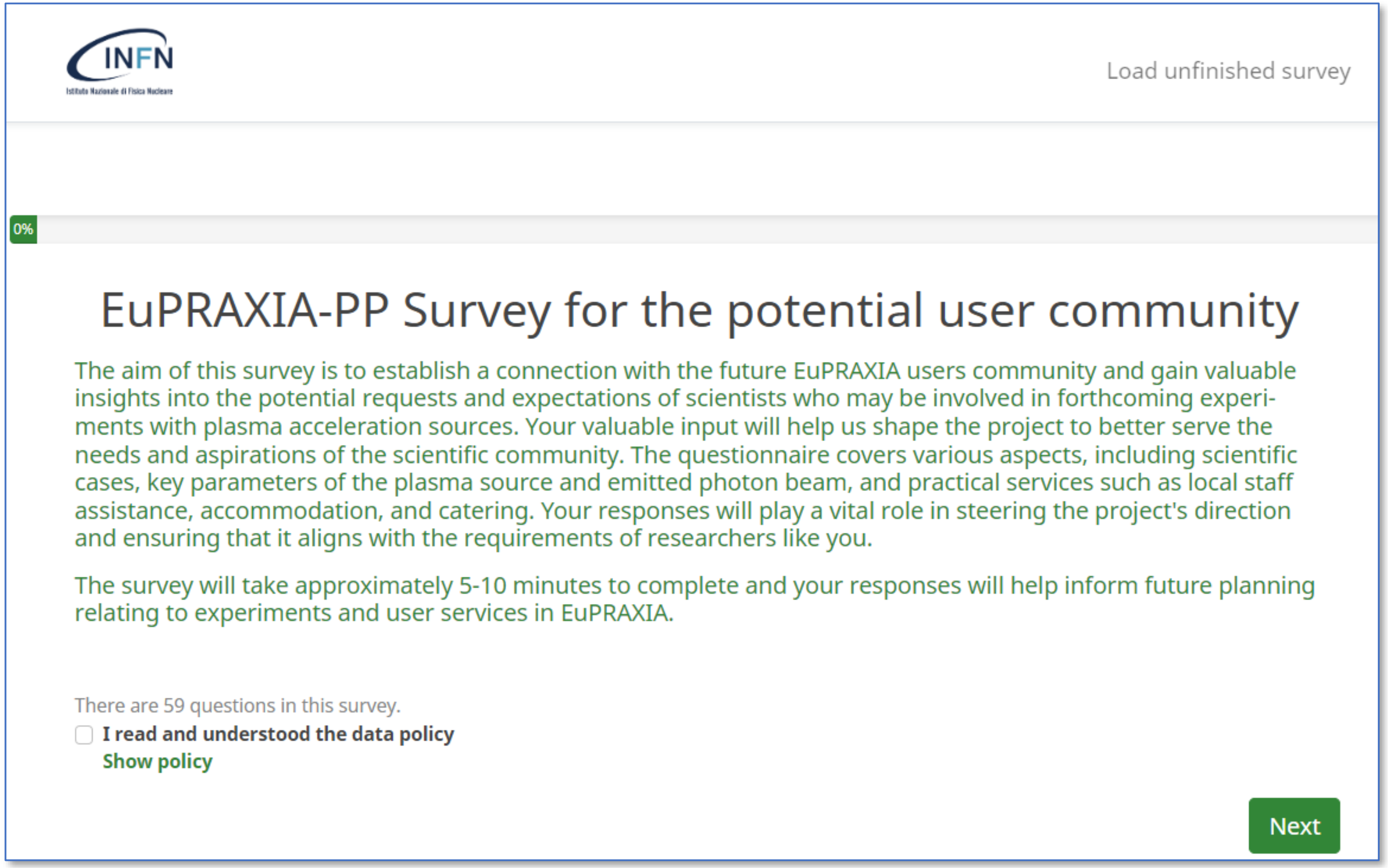
  O(10) fs-long, O(10) µJ pulses with O(10^{11}) N_{γ}/pulse at 4nm were obtained
- ✓ **The FEL radiation stability has been discussed, shorter λ with higher E_{beam} or improved e-beam quality**
- ✓ **Studies of new electron beam working points as well as stabilization methods are in progress**

The ARIA FEL line is under study: this line will extend to VUV the spectral range covered by EuPRAXIA@SPARC_LAB

- ✓ **Feasibility and expected performance of such flexible and cost-effective VUV user facility delivering 15-100 fs-long FEL pulses close to Fourier transform limit are investigated**
- ✓ **Selectable polarization VUV light allows to explore chirality and dichroism in biotic media**

More detailed studies of photon diagnostics and experimental beamlines are in progress

EuPRAXIA_PP Survey



EuPRAXIA-PP Survey for the potential user community

The aim of this survey is to establish a connection with the future EuPRAXIA users community and gain valuable insights into the potential requests and expectations of scientists who may be involved in forthcoming experiments with plasma acceleration sources. Your valuable input will help us shape the project to better serve the needs and aspirations of the scientific community. The questionnaire covers various aspects, including scientific cases, key parameters of the plasma source and emitted photon beam, and practical services such as local staff assistance, accommodation, and catering. Your responses will play a vital role in steering the project's direction and ensuring that it aligns with the requirements of researchers like you.

The survey will take approximately 5-10 minutes to complete and your responses will help inform future planning relating to experiments and user services in EuPRAXIA.

There are 59 questions in this survey.

☐ **I read and understood the data policy**

Show policy

https://surveys.infn.it/index.php/718177

Courtesy of E. Principi

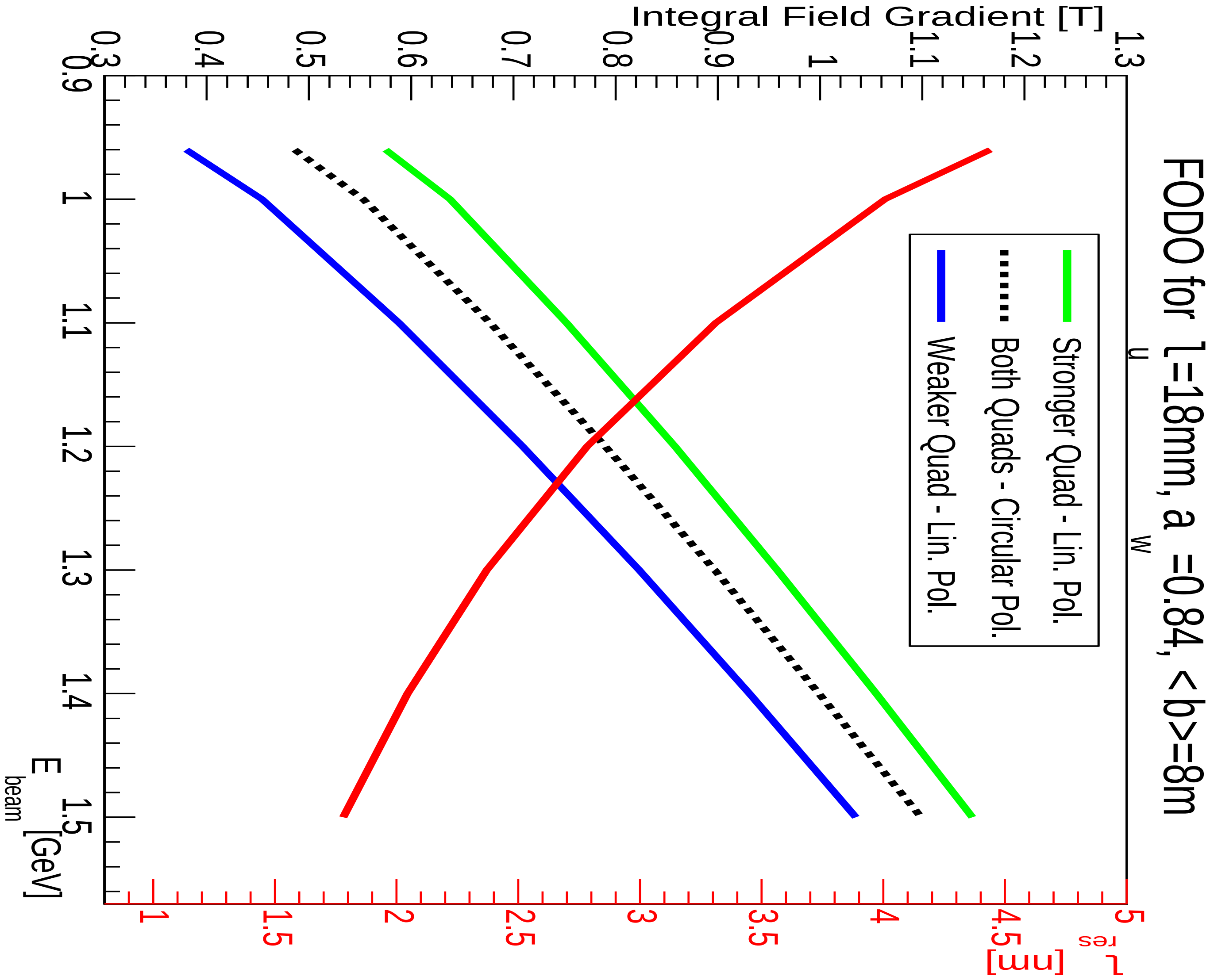
Thank you for the attention!

Supplementary slides

AQUA

Magnetic design & tuning range -> vacuum chamber geometry
Longitudinal and transverse wake-fields
Analysis of SABINA Undulator and first lessons for the AQUA undulator
Magnetic: field quality, field integrals, trajectory and FEL amplification
Mechanical: stability and reproducibility tests

FODO analysis for both polarizations vs. Ebeam



Solving for the quad strengths at each beam energy

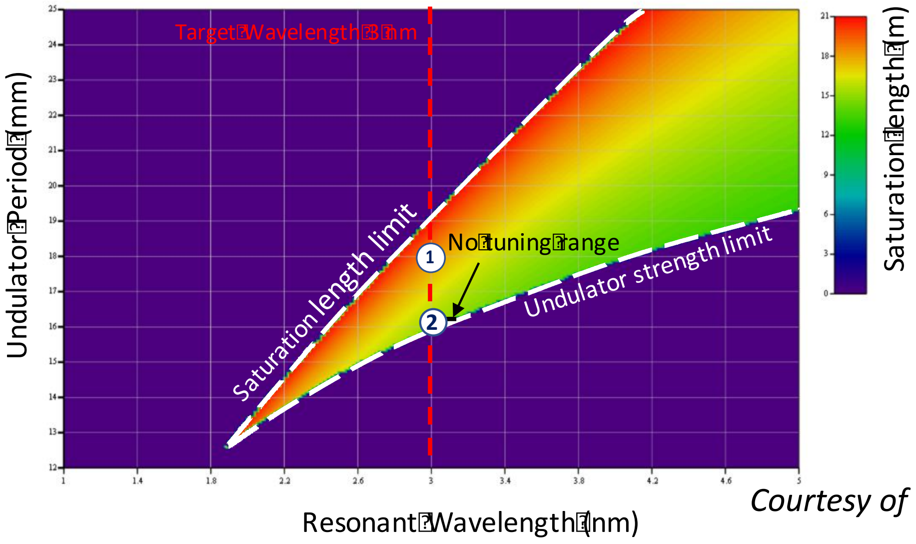
Quad (~ 10 cm magn. length) integral field gradients are such to sustain even higher beam energies →

Possible to reach for 3nm with the same undulator and quadrupole devices, if $E_{beam} \geq 1.2$ GeV

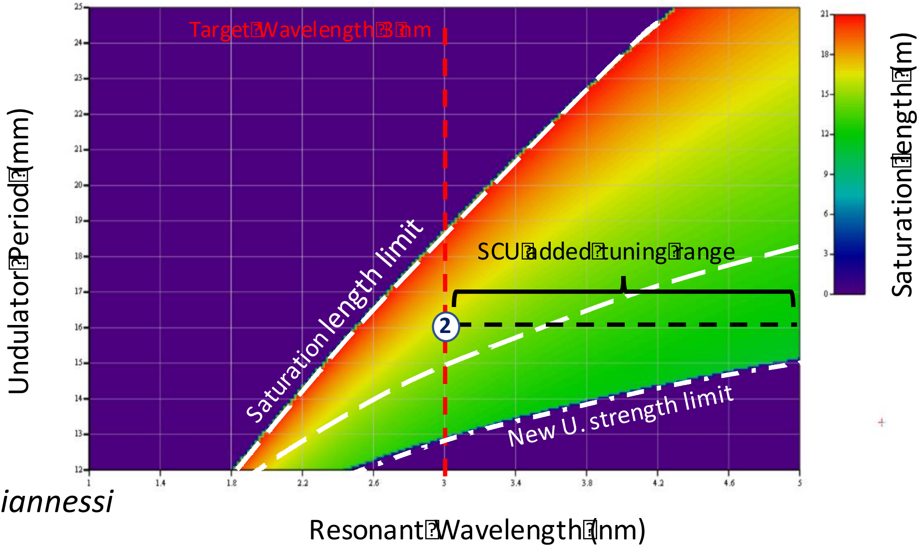
Courtesy of F. Nguyen

Tuning range: choice of the undulator period

FEL performance analyzed with Xie's scaling formulae accounting for 60% filling factor



Courtesy of L. Giannessi



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

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**

From the K vs. gap formulae of a planar NbTi SCU with beam stay clear=5mm:

2) 16mm improves the saturation length limit, and tuning range is granted as well

Courtesy of F. Nguyen

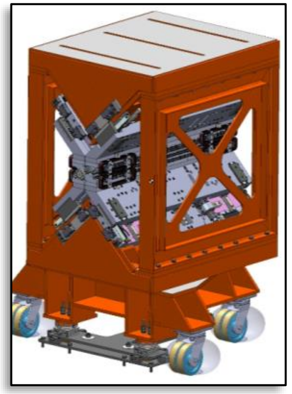
Undulator specs

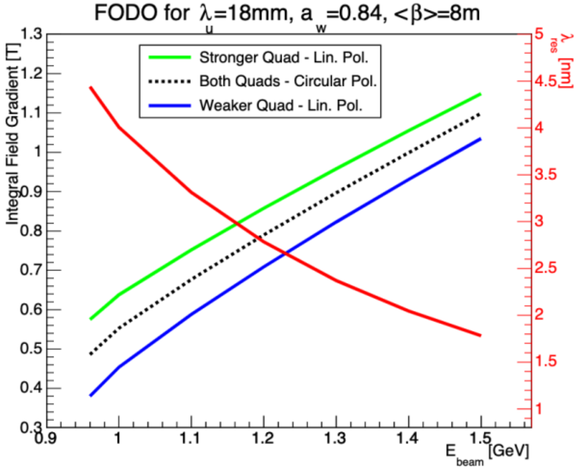
Table 1.1: Undulator basic parameters

Parameter	**Value**
Material	NdFeB
Remanent field B_r	1.35
Period λ_u	18 mm
Blocks per period	4
Block magnet x,y,z size	18 mm x 18 mm x 4.4 mm
Aperture diameter ϕ	6 mm
Minimum gap	1.5 mm
B_{max} (in LP)	0.93 T
K_{max} (in LP)	1.57
K_{rms} range	1.11 - 0.6
Resonance tuning range	3.5 - 5.24 nm
N periods	110
Module length	2 m

Table 1.2: Offsets and angles at the exit of the undulator for an electron entering with null offset and angle. The values are reported for the radial (x) and vertical (y) coordinate in both Linear (LP) and Circular (CP) polarization mode, at minimum gap of operation.

	units	**LP**	**CP**
$offset\ x$	μm	-0.23	0.56
$angle\ x$	μrad	-0.1	0.25
$offset\ y$	μm	0	-0.56
$angle\ y$	μrad	0	-0.34





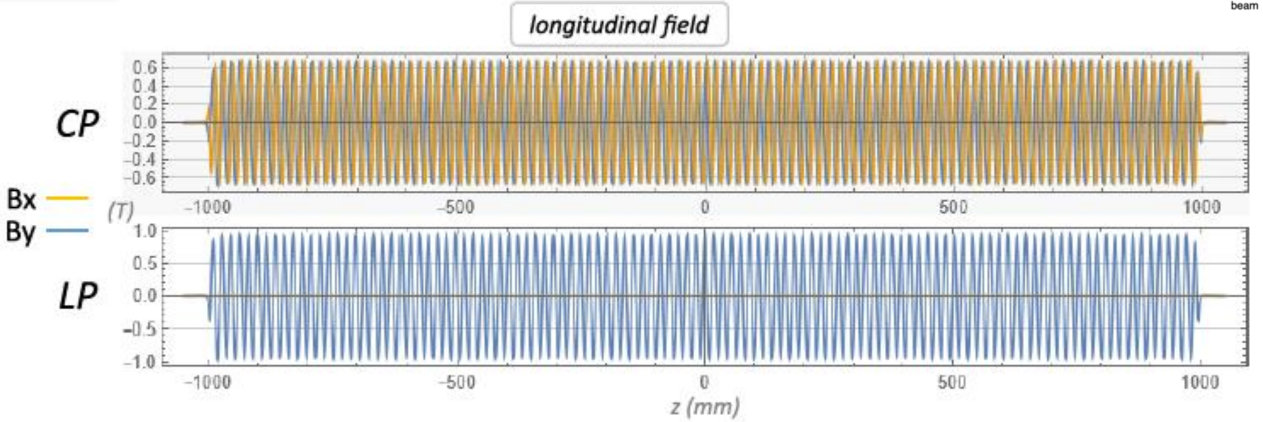


Figure 1.10: Longitudinal field profile of the AQUA undulator in Linear (LP) and Circular (CP) polarization.

Transverse resistive wall wakefields

Transverse RW wakefields induced inside the cylindrical Cu vacuum chamber of radius *a*=2… 3 mm affect the electron bunch orbit along the undulator line, depending on the initial transverse offset at entrance.

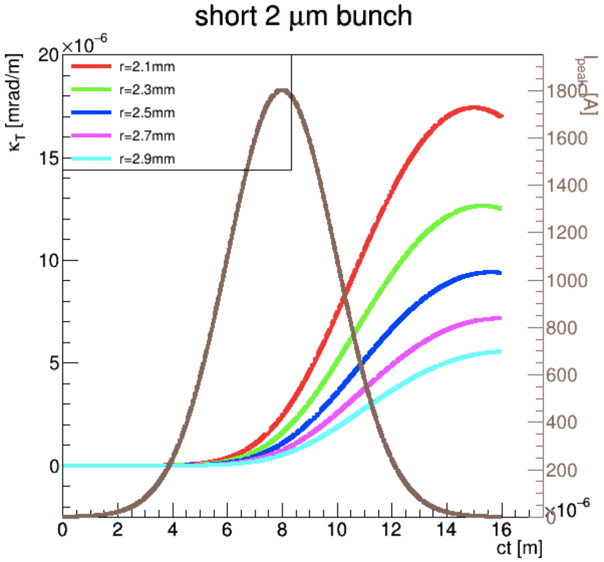
Analytical treatment based on K. Bane & G. Stupakov formulae and the relationship between transverse and longitudinal RW impedances are used to estimate the kick angle k_T parameter

$$W_t(s) = \frac{2}{a^2}\int_0^s W_\ell(s')\mathrm{d}s', \quad Z_t(k) = \frac{2}{a^2}\frac{Z_\ell(k)}{k}$$

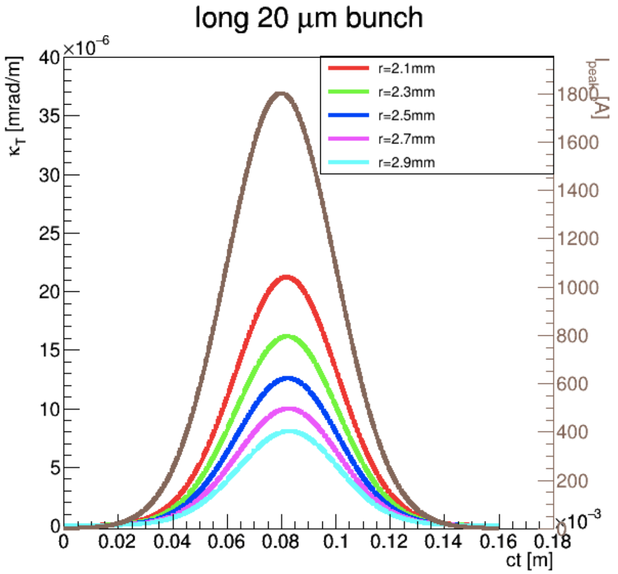
$$W_z(s) = \frac{Z_0 c}{\pi a^2} e^{-s/4c\tau} \cos\left[\sqrt{\frac{2\omega_p}{ac}} s\right]$$

$$\varkappa_T = \frac{\text{kick angle [rad]}}{\text{unit path length [m]} \times \text{unit vertical offset [m]}}$$

short 2 μm bunch



long 20 μm bunch



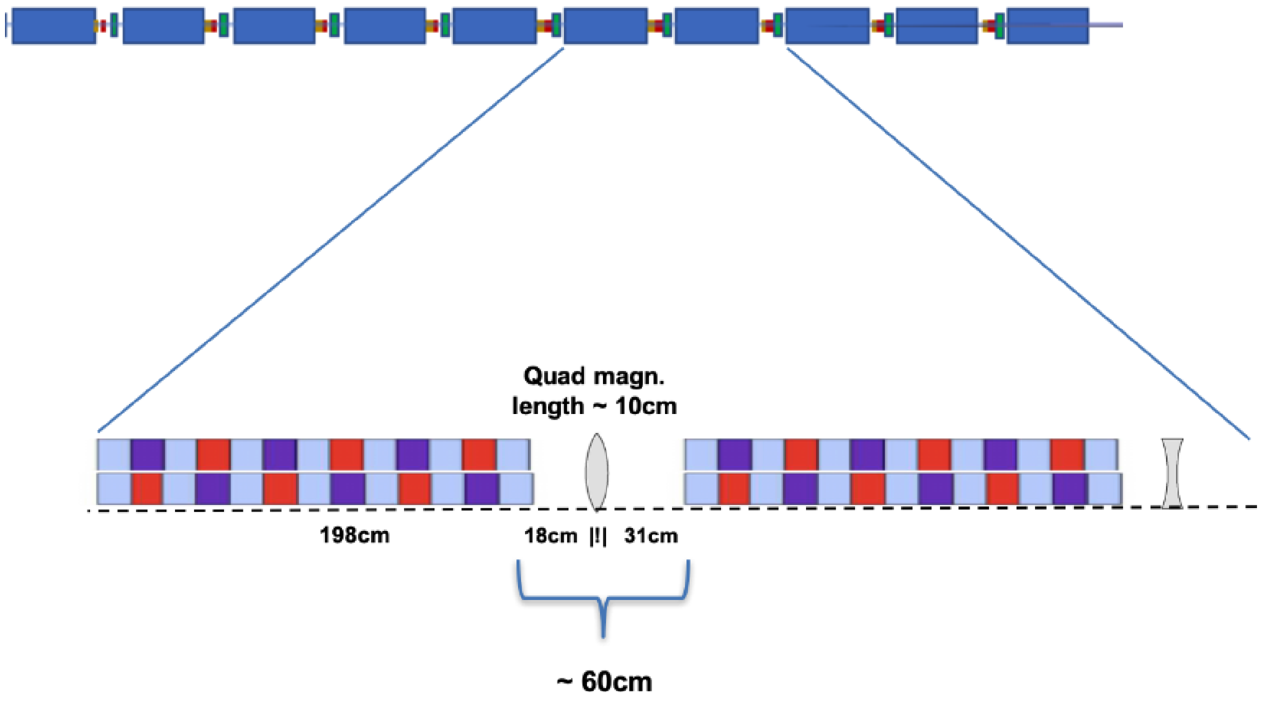
Preliminary conclusions

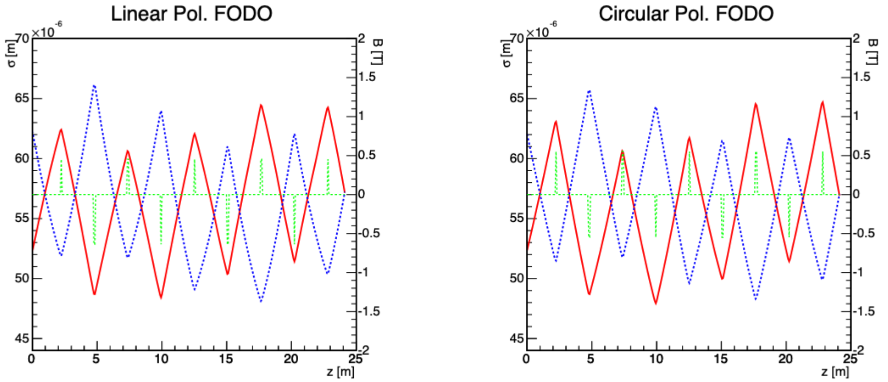
Short bunch: Max kick: 2×10^{-5} mrad/m but outside the current peak

Long bunch: same order of magnitude, but superimposed to the current profile

Courtesy of F. Nguyen

Trajectory, matching





Examples of FODO matching

Quadrupole offset errors up to qx,y ≈ 80 µm do not hamper FEL lasing.
Quadrupole offset errors up to qx,y = 400 µm lead to an off-axis beam wander which can be pre-corrected with a corrector magnet (less than 10 mT if 3.6 cm-long), to ensure FEL amplification.
(Ideal correction is when correctors are embedded into the quadrupole, share same iron)

Summary of Apple-X undulator tolerance studies

- The physical parameters and specification of the AQUA undulator system are established, most of the sensitivity studies have been carried out.

RW wakefields

- ✓ Longitudinal RW wakefields do not hamper the FEL lasing
- ✓ $\pm 150\ \mu\mathrm{m}$ transverse offset -> ≈60 nrad kick

Transverse alignments

Symmetric (x=y)	off-axis injection
Offset	$\pm 25\ \mu\mathrm{m}$
Tilt	$\pm 10\ \mu\mathrm{rad}$

Magnetic field errors

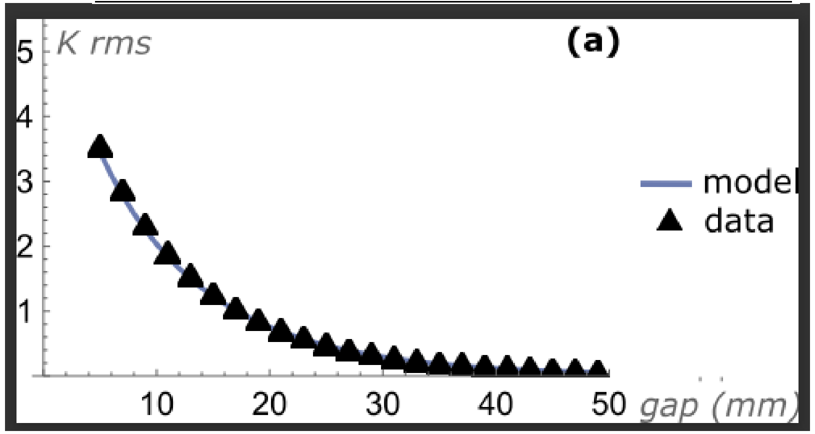
- ✓ Rms field errors of few mT
- ✓ 1st (2nd) field error integrals $\leq 5\ 10^{-5}\ Tm\ (Tm^2)$

- Mechanical stability tests of the SABINA APPLE-X modules were performed.

- The constructive design of the components requires engineering development and design support from industry.
- Future studies will include tolerance of undulator&bpm misalignments, specs of phase shifters.

SABINA

Parameter	Value
Material	NdFeB
Remanent field B_r	1.28-1.31
Period λ_u	55 mm
Blocks per period	4
Block magnet x,y,z size	28 mm x 28 mm x 13.65 mm
Aperture diameter ϕ	14.84 mm
Minimum gap	5 mm
B_{max} (in LP)	0.97 T
K_{max} (in LP)	4.9
K_{rms} max	3.5
Tuning range @ 30 MeV	20 - 100 μm
Tuning range @ 100 MeV	2 - 10 μm
N periods	22 (23.5)
Module length	1.35 m



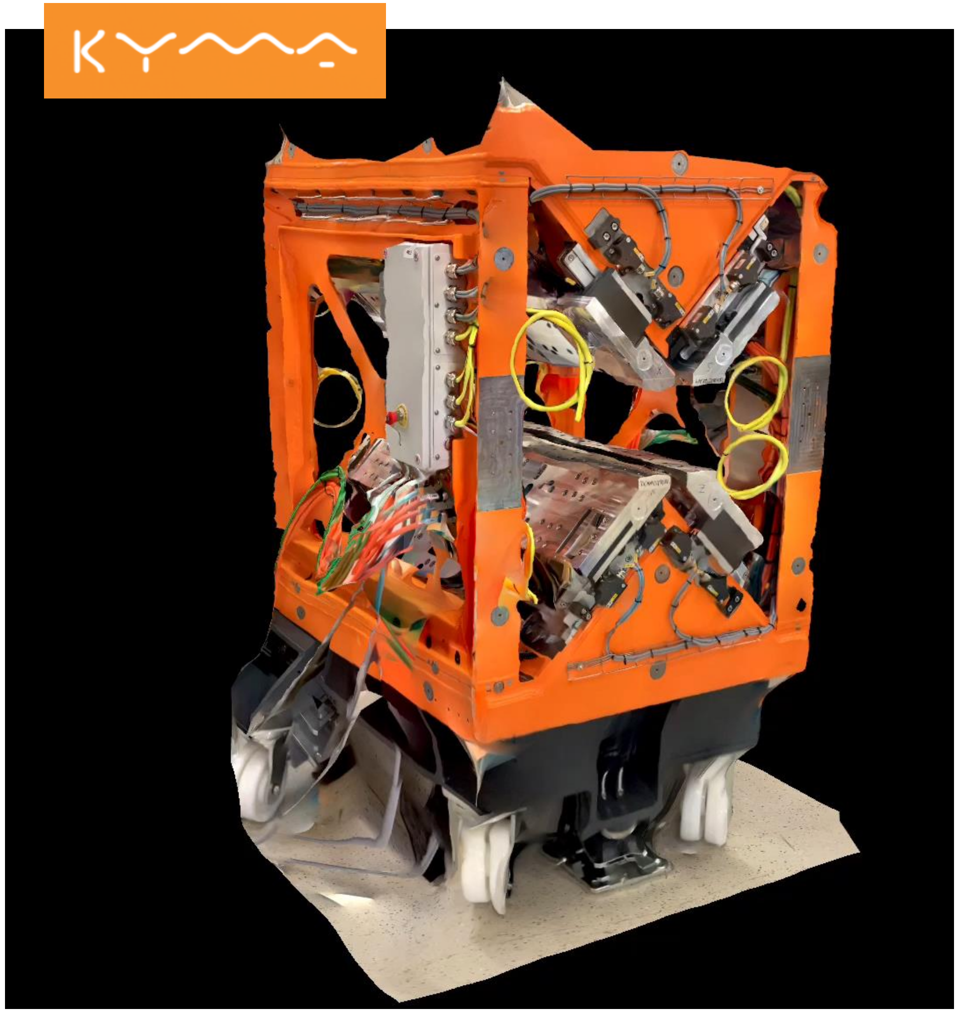
Lessons learned from the SABINA Undulator

Mechanical stability and reproducibility

In collaboraton with the **Holographyc Interferometry & Fibre Optic Sensors (HIFOS) Laboratory at *ENEA*** (ref. M. Caponero) we measured the deformations of the undulator guilders

Magnetic error analysis

Indication on the undulator feasibility comparing the SABINA undulator and the ideal RADIA model to reconstruct magnetic dipolar errors along the undulator

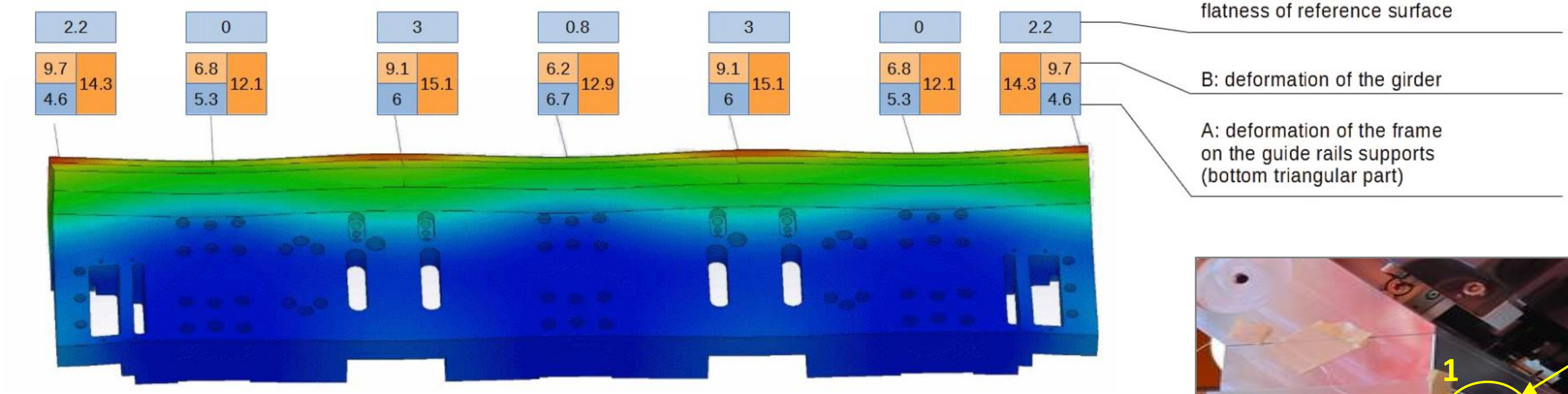


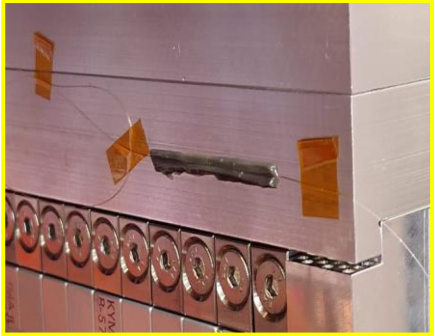
Undulator Mechanical tests on the SABINA undulator

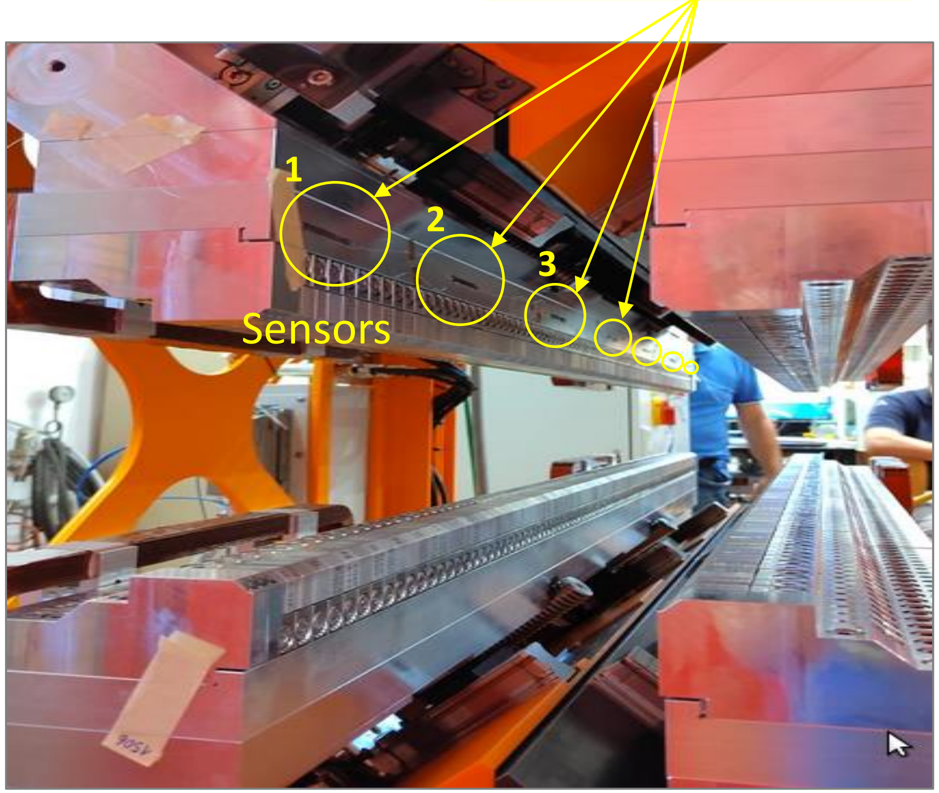
FBG measurements

deformations **in µm**

CAD model by KYMA







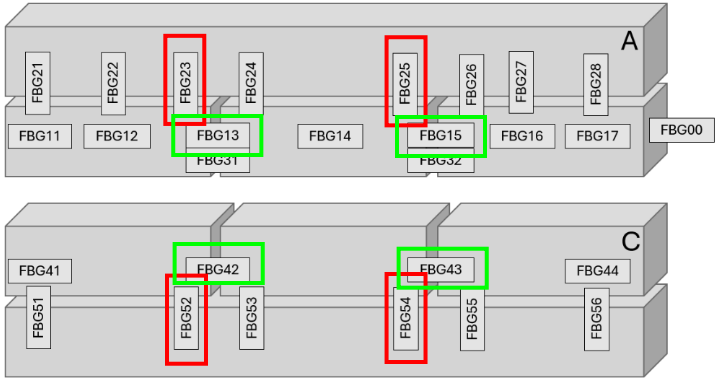
A diffraction grating is produced by modifying the refraction index of the core of a fiber (FBG Sensors).
Rough approximation: the refractive index has a sinusoidal modulation along the axis of the fibre.
The sensor length is 10 mm, temperature and strain sensing at the level 0.1K - $1/10^6$ relative elongation sensitivity

Courtesy of I. Balossino, A. Selce, A. Polimadei, A. Vannozzi, M. Del Franco, L. Sabbatini, M. Caponero

Brief summary of FBG strain measurements

- **Temperature dependence:**

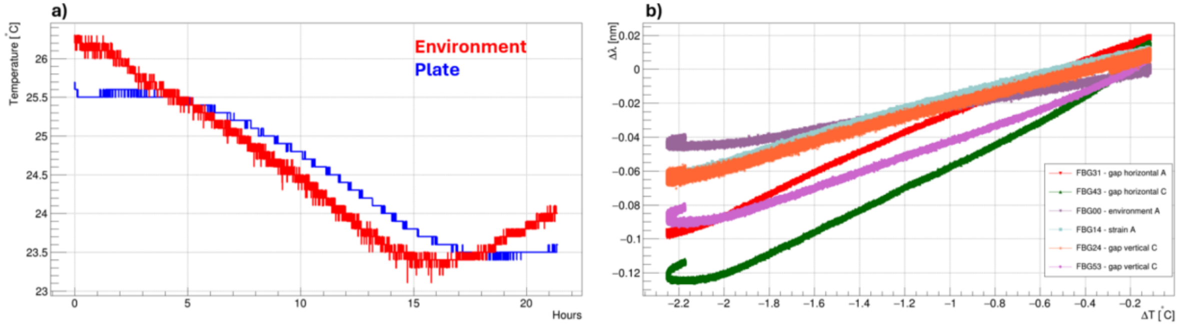
\- max deformation of 0.12 nm over 2.7 °C/15 hours

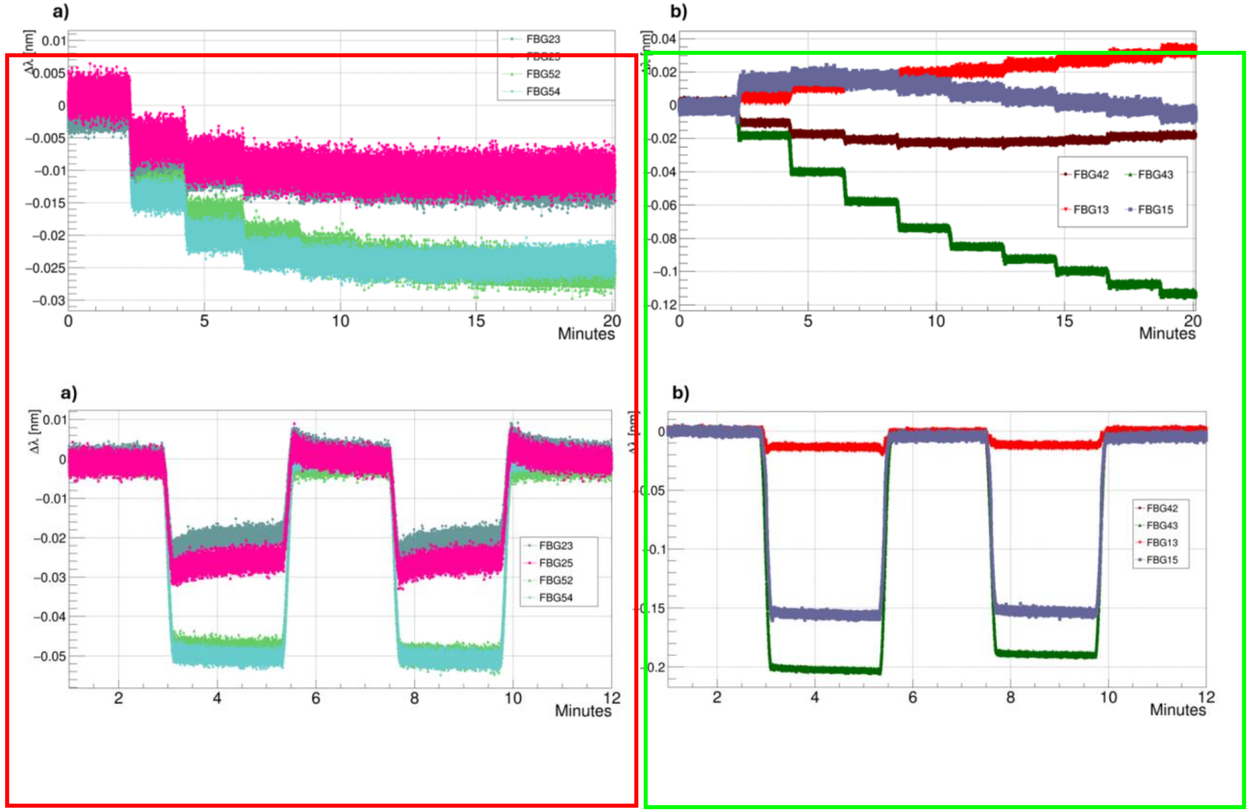


- **Mechanical**

\- by moving the four arrays all together from the minimum gap to the maximum gap, and in small steps from minimum gap to 50 mm of gap opening

\- by shifting the phase at different undulator gaps. In Fig. (right) the effect of a phase shift with the undulator tuned at minimum gap is shown





FBG strain measurement conclusions

- **The wavelength shifts are perfectly reproducible. No hysteresis or values not correlated to a gap macroscopic movement were observed, except for the temperature dependence**
- The largest observed wavelength shift is **∼0.2 nm for the gap sensors** and a factor **2-5 lower for the strain sensor** devices
- **Gap sensors,** the reference length is the plates separation. The plate sepatation cannot be measured an is virtually zero. In order to estimate an upper limit, we may consider that over an hypothetical 1 mm gap, the variation would be ∽ **150 nm. This has a negligible effect on the undulator field**
- **Strain sensors,** the reference length is the sensor length: **the local deformation is ∽300 nm/cm.**
- These deformation values are compatible or lower than those calculated by finite elements methods and **confirm the reliability of the undulator mechanical structure**
- **A finite element model of the long AQUA undulator module should provide a suitable estimate of the expected structure deformation under the effect of magnetic forces**

Undulator Mechanical tests on the SABINA undulator

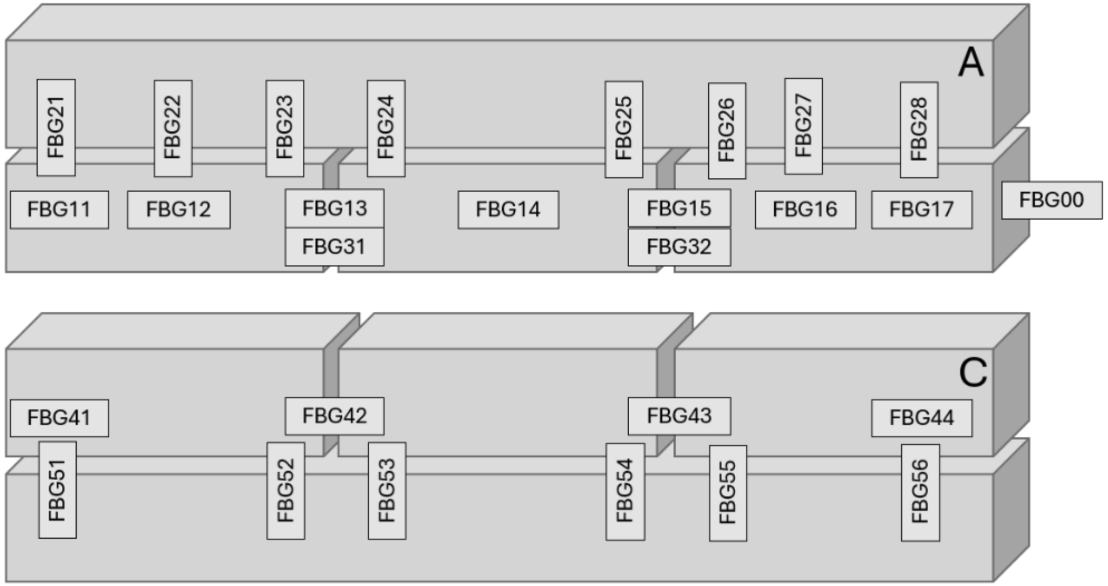
FBG measurements

Undulator tested for:

- Temperature dependence over a rance of 3 °C
- Magnetic forces: gap – phase variations opening
- Sensors were used in two different ways:

- as **strain measurement**, by gluing the fiber fully adhered to the surface of the magnet holder-plates;
- as **gap measurement** devices, by placing the sensors between adjacent plates.

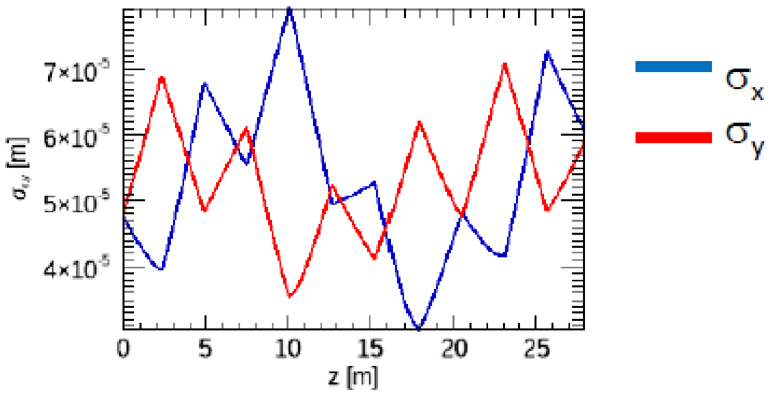
Distribution of sensors



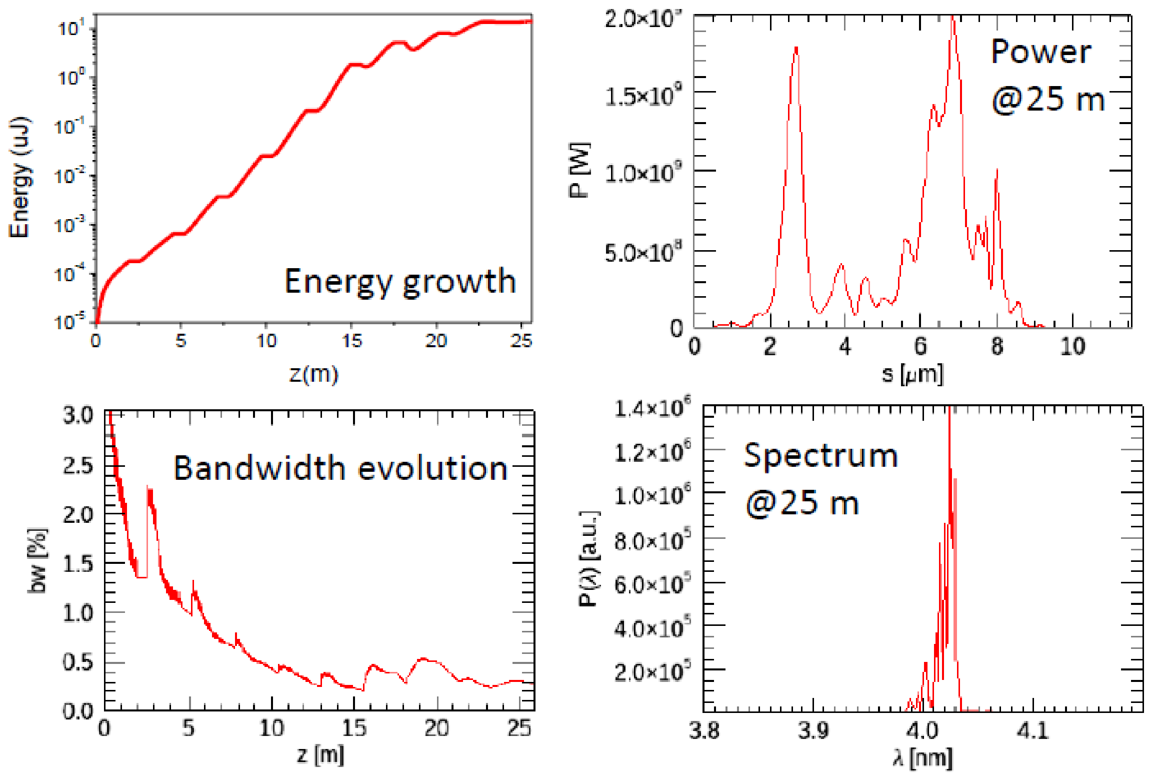
EuPRAXIA@SPARC_LAB electron beam and AQUA FEL performances

Last start2end electron beam working point with jitters

Witness @undulator	Average	Std. Dev.
Energy (GeV)	1	0.0107
Charge (pC)	29.8	0.2
Peak current (kA)	2.5	
Proj. emitX (mm mrad)	0.69	0.02
Proj. emitY (mm mrad)	0.67	0.02
Proj. dE/E (%)	0.44	0.015



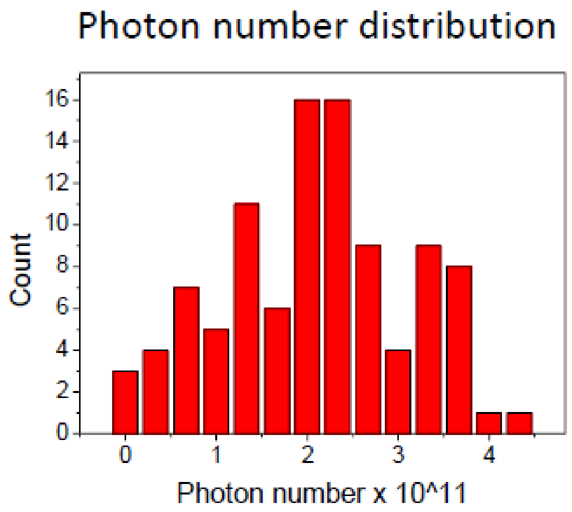
FEL simulation of a single shot

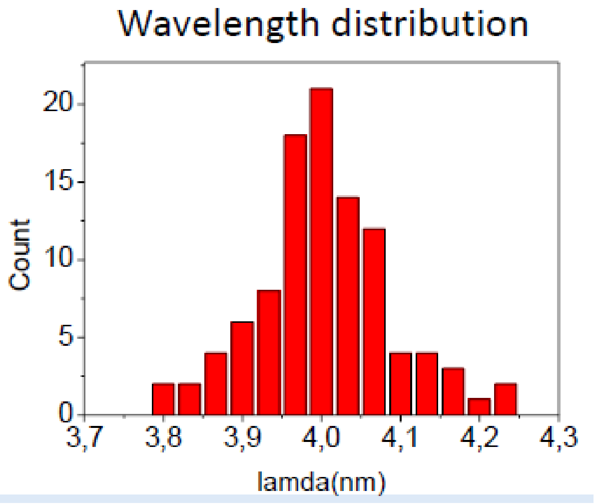


Energy (μJ)	λ (nm)	BW (%)	Photon number	Size (μm)	Div. (μrad)	Lsat (m)	Lrad (fs) FWHM
13.54	4.004	0.3	2.7×10^{11}	170	27	23	15

AQUA FEL performances: preliminary results from FEL statistics

FEL simulation statistics from the last simulated start2end e-beam working point, with jitters included





- 85/101 shots withphoton number per pulse $> 10^{11}$
- E-beam energy jitter → Radiation wavelength jitter

	Unit	Average	Error	Relative error
Wavelength λ	nm	**4.0037**	**0.084**	**0.02**
Energy at 25 m	**µJ**	**10.54**	**5.2**	**0.49**
Photon number	$\times 10^{11}$	**2.092**	**1.01**	**0.48**

- The FEL wavelength jitter reduces to ~0.05 nm if only the photon pulses with $>10^{11}$ photons are considered.

Work in progress …

ARIA

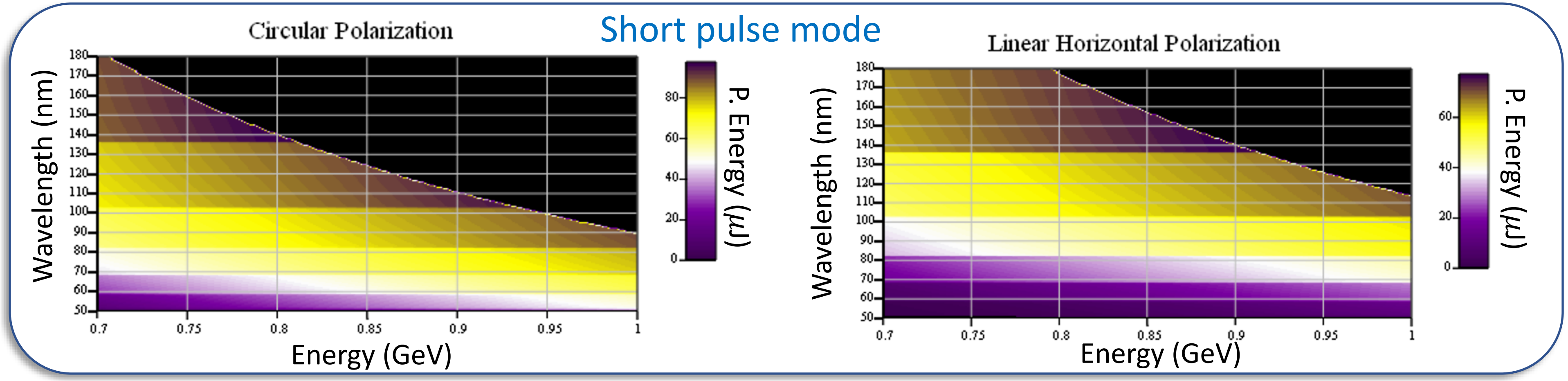
Undulators, seed and tuning range

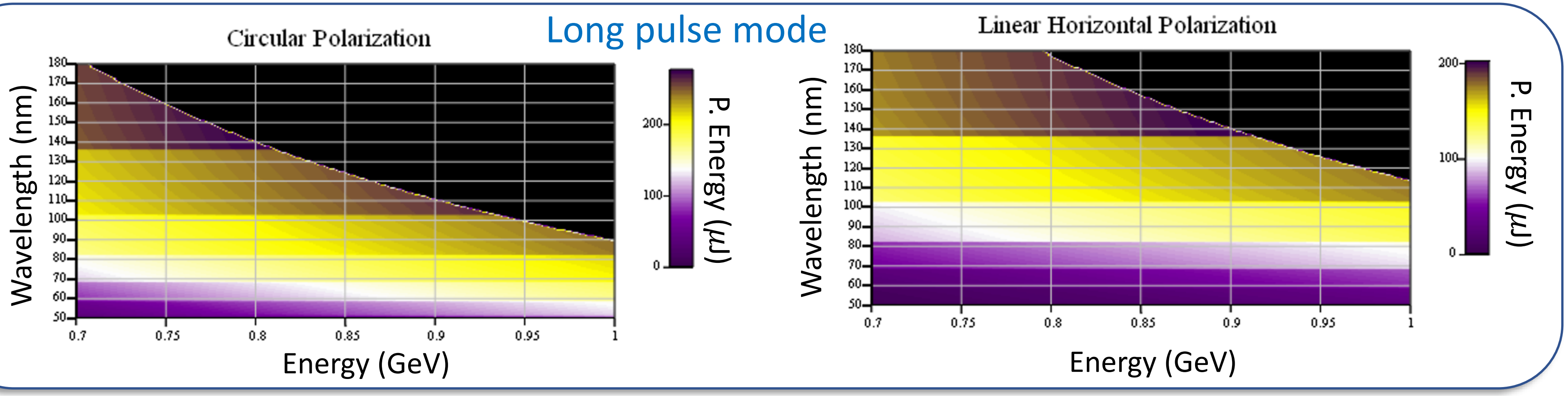
ARIA performances analysis

Based on Xie model

A = Long pulse mode
B = Short pulse mode

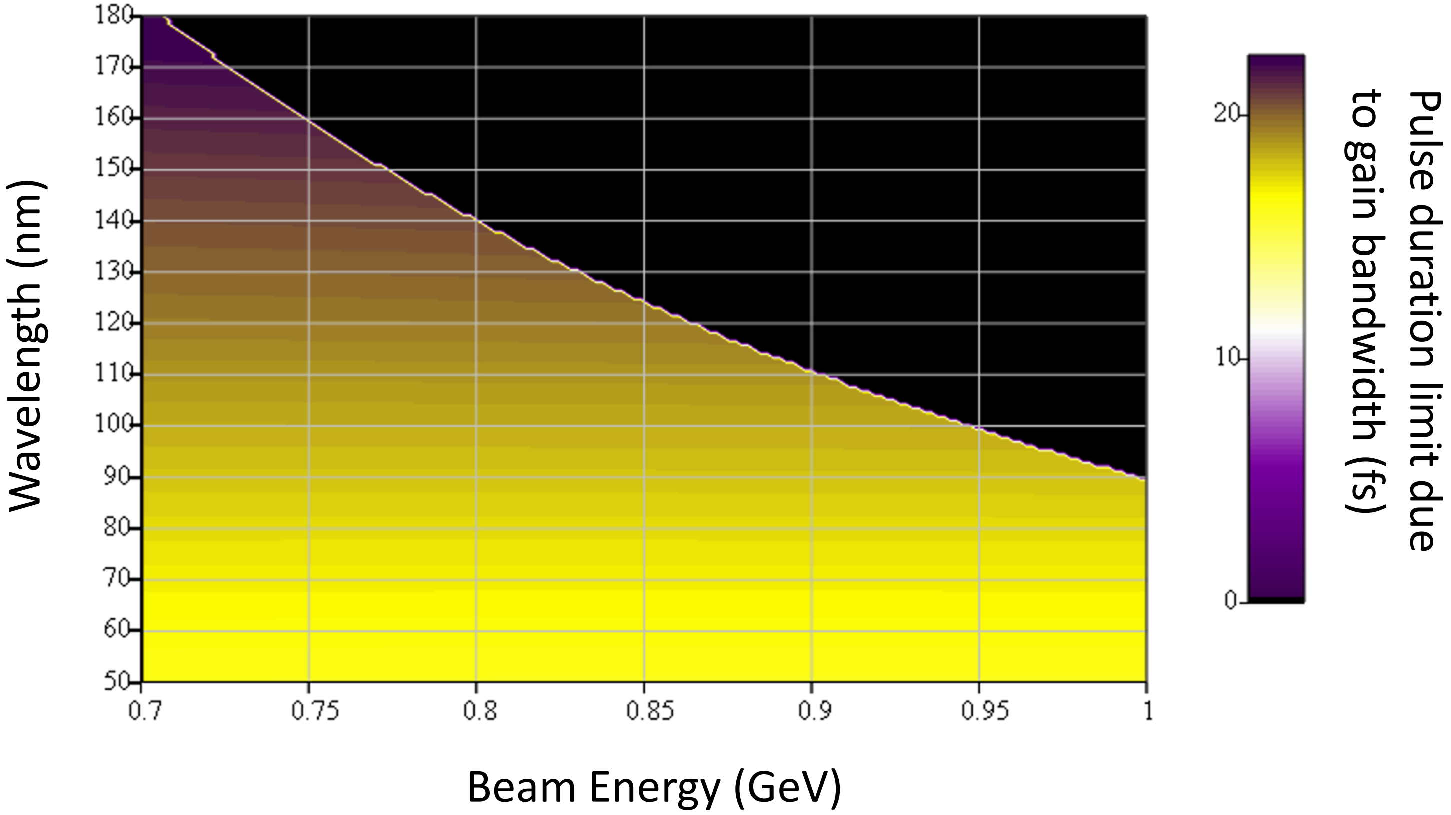
e-beam	
Energy	0.7 -> 1 GeV
Peak current (A - B)	500 – 1500 A
E-bunch charge (A - B)	200 - 30 pC
Emittances (A - B)	0.8 mm - mrad
Energy spread (A - B)	1.5 – 3.5 (x10^{-4})


Short pulse mode


Long pulse mode

Pulse duration

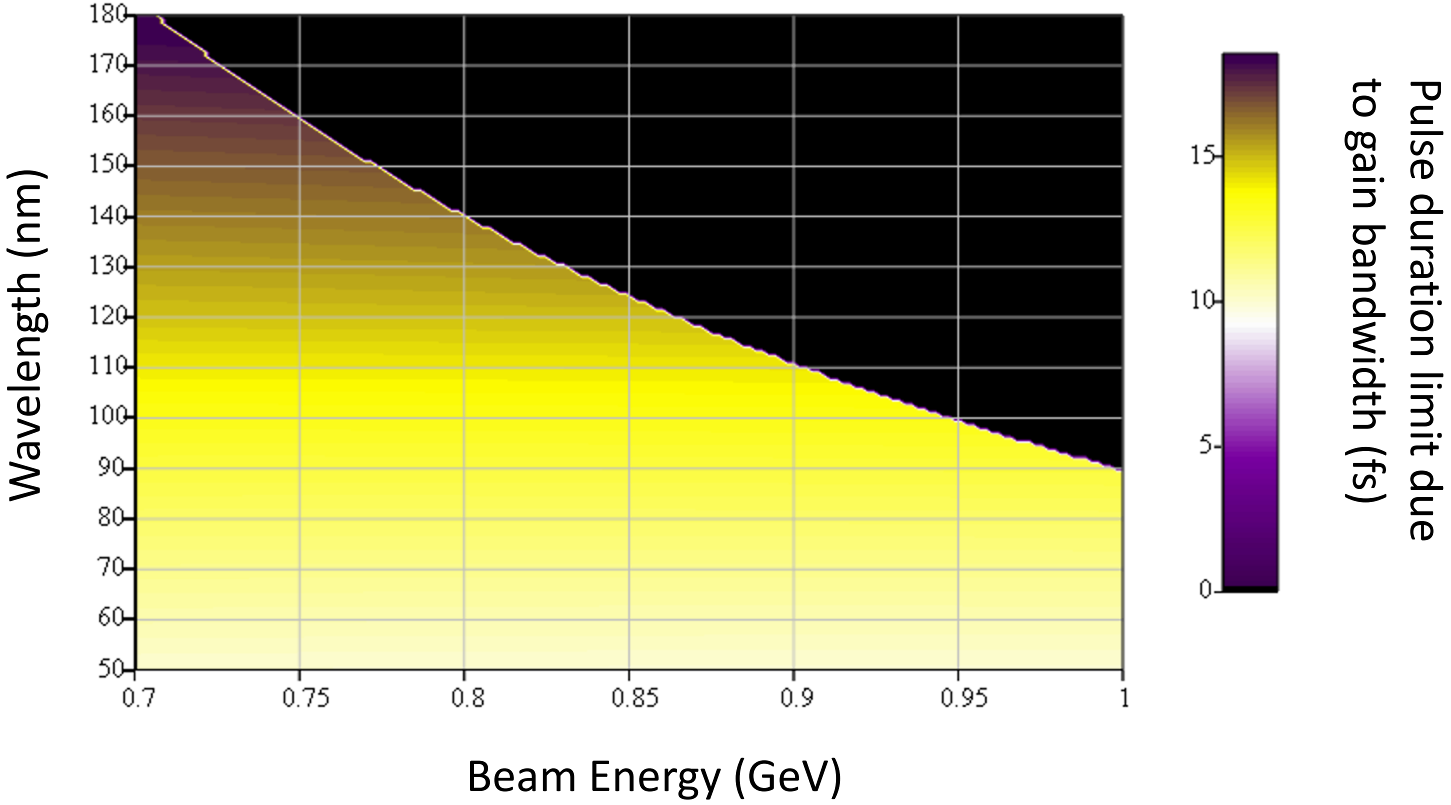
Estimated as the FT Limit of the bandwidth calculated with the Xie scaling relations



e-bunch duration 15 fs – **circular polarization** – Aria beam parameters

Pulse duration

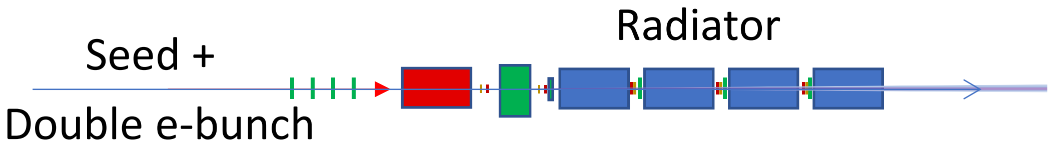
Estimated as the FT Limit of the bandwidth calculated with the Xie scaling relations

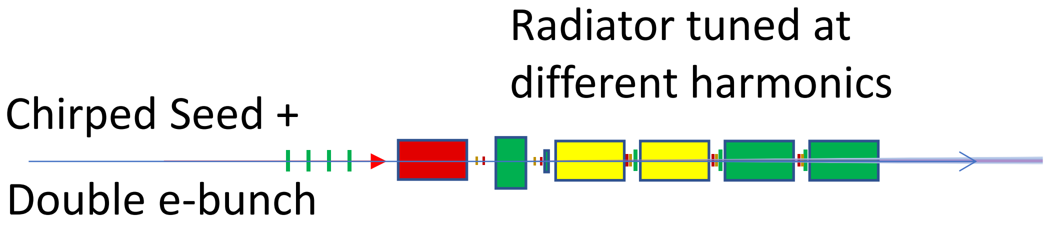


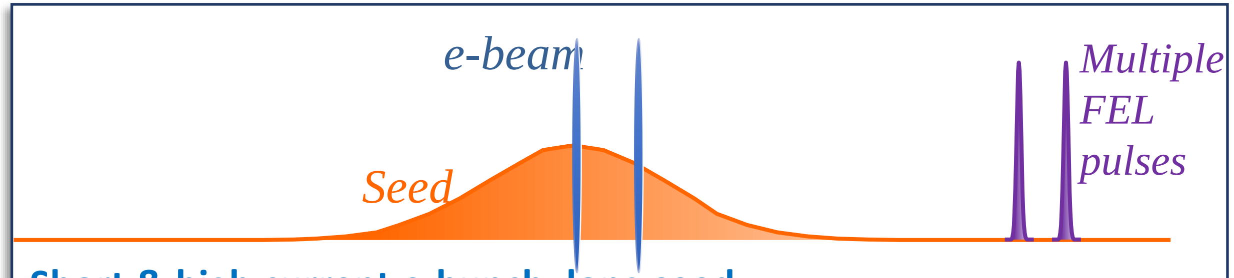
e-bunch duration 8 fs – **circular polarization** – Aria beam parameters

Special modes of operation

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

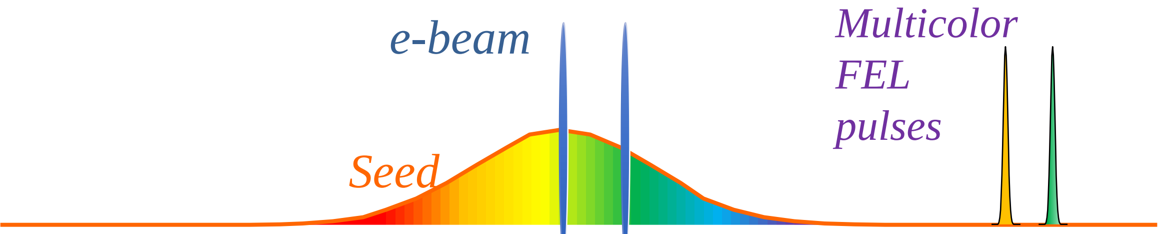






Short & high current e-bunch, long seed.
Pulse duration limited by **e-bunch duration** & large **gain bandwidth**

(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)

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).*

ARIA FEL performances

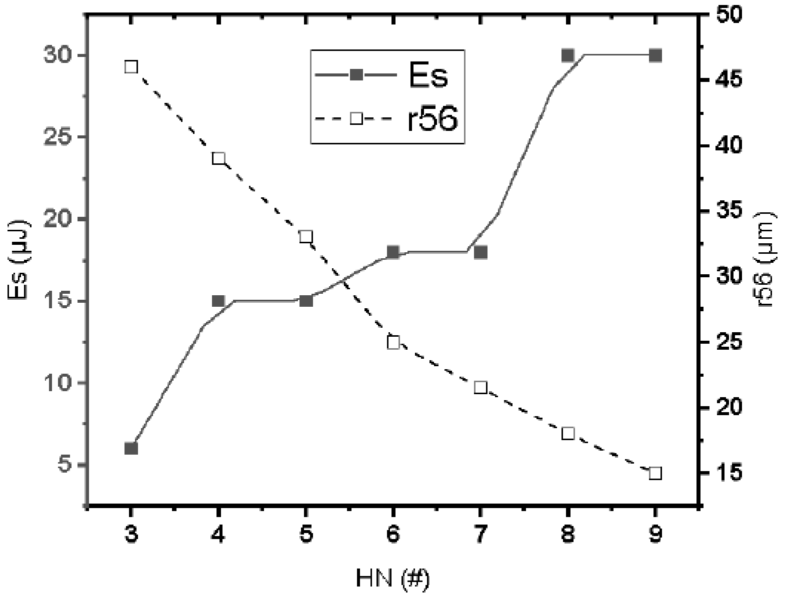


Figure 3: Seed energy Es (solid line, black squares) and dispersion strength R_{56} (dashed line, white circles) vs harmonic number HN of the 460 nm seed.

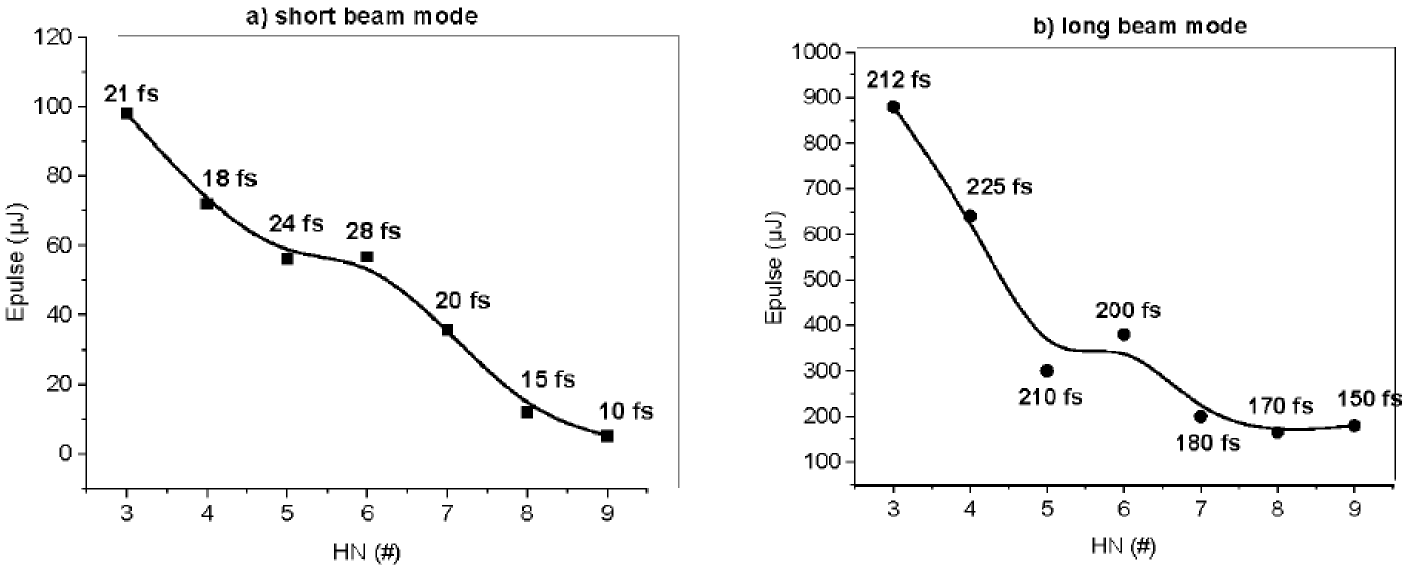
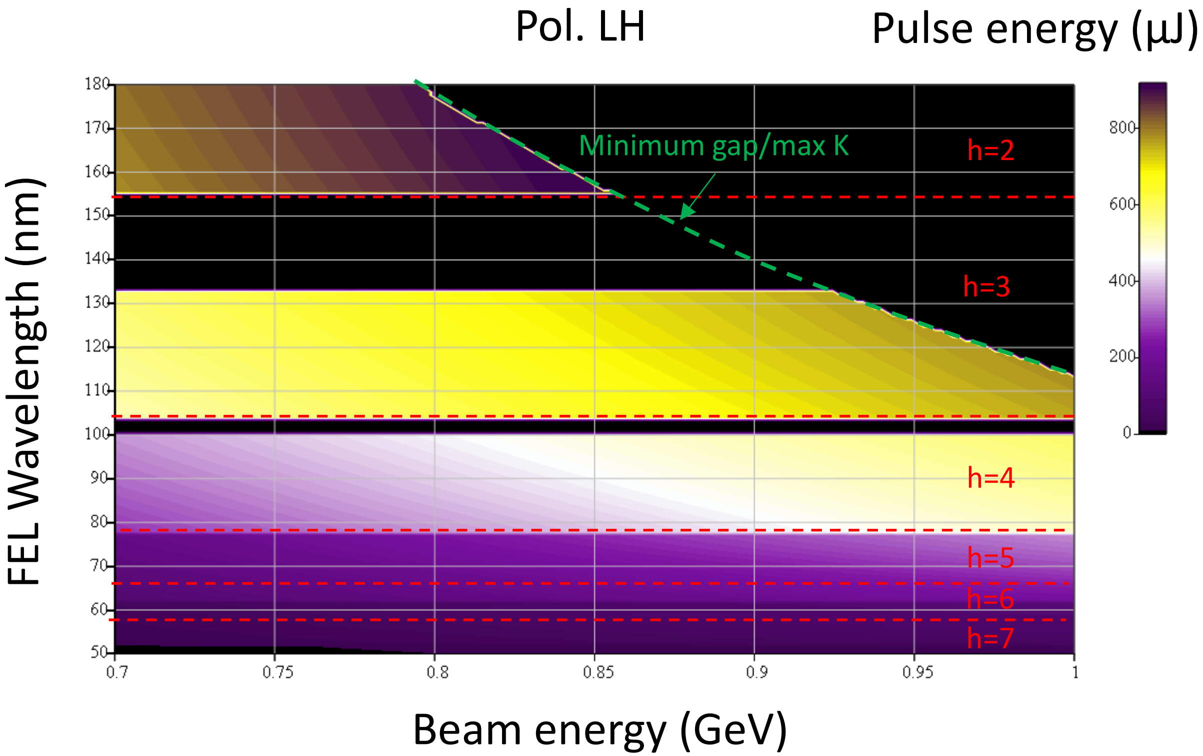


Figure 4: Output pulse energy at saturation vs harmonic number, starting from the 460 nm seed pulse. Top plot a): short beam mode, 30 pC case. Bottom plot b): long beam mode, 200 pC case. The FWHM pulse duration is specified on top of each point.

Long-bunch long-seed mode Linear Polarization

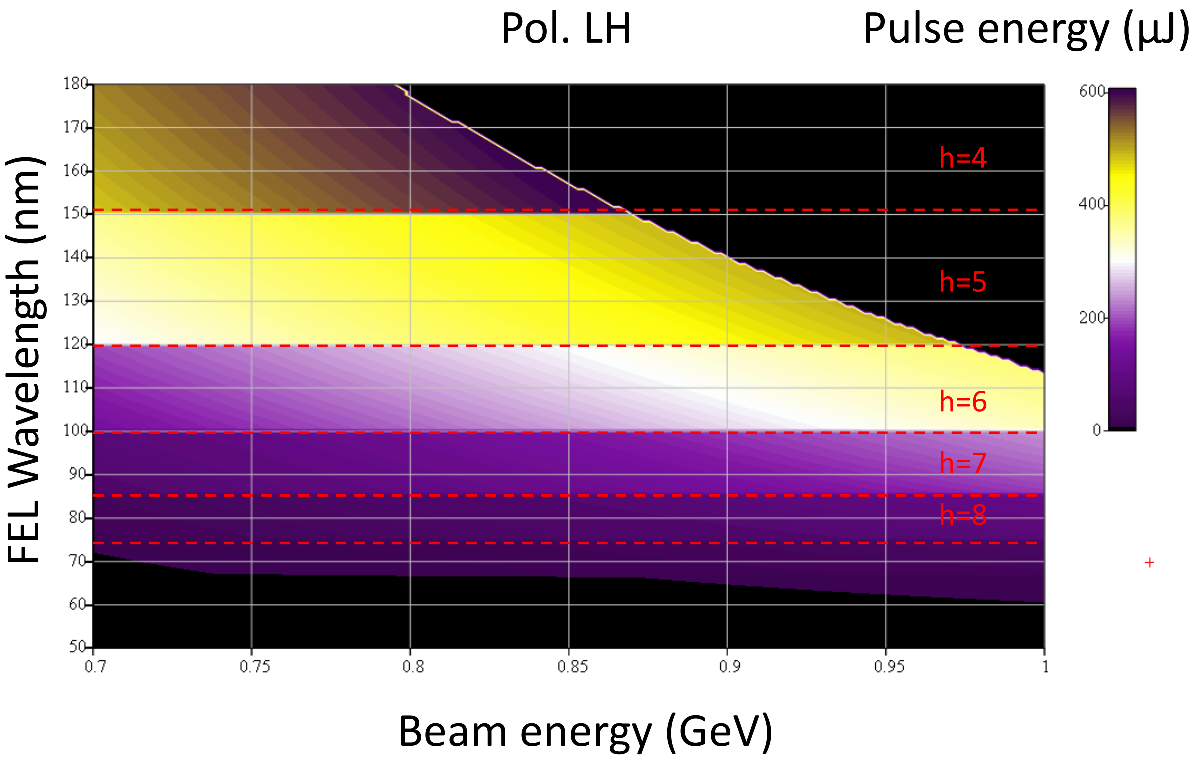
A: Seed range 320-400 nm

High energy range 100-50 nm – higher power



B: Seed range 600-800 nm

Continuous tuning in the range 60-180 nm



An OPA such as the TOPAS can seed the ARIA FEL line covering the spectral range 200-50 nm with a single OPA process 2HG (B). Improved performances below 100 nm can be achieved with the 4th HG process (A)

Courtesy of L. Giannessi

EuPRAXIA@SPARC_LAB FELs in the international panorama

FEL facility	Wavelength (nm)	Energy (μJ)	Photon # (10^{11})	Length (fs)	Rep rate (Hz)
AQUA	**4-10**	**10-20**	**1-5**	**10-20**	**100-400**
FERMI	4-100	10-500	1-50	50-100	50
FLASH	4–60	10–500	1-100	10-200	10^6
LCLS	0.12-4.5	10-3000	1-1000	1-100	100-10^6
SACLA	0.6-4.5	10-20	1-2	10-50	60
Swiss-FEL	0.7-7	10-100	1-10	1-100	100
PAL XFEL	0.6-6.5	10-1000	1-1000	10-50	60

ARIA	**50-180**	**1-500**	**100**	**1-200**	**100-400**
FERMI	20-100	10-500	1-10	50-100	50
FLASH	4-60	10-500	1-10	10-200	10^6
Swiss-FEL	30-100	10-200	0.5-5	1-100	100
DCLS	50-150	50-500	5-50	100	50

Summary of experimental techniques and samples

Technique	Samples
Coherent imaging	Cells, organelles, nanomaterials *Water window for high-contrast hydrated samples*
Photon scattering	Molecules, nanoparticles *Structural and dynamical characterization*
X-ray Spectroscopy	Warm-dense matter, organo-metallic compounds, magnetic materials *K, L and M edges falling in the FEL energy range*
Photoelectron Spectroscopy	Carbon-based materials, batteries, biomolecules *Chemical dynamics*
Ion Spectroscopy	Astrochemistry, biomolecules *Radiation-matter interaction dynamics*

This is a general overview and, ***besides coherent imaging***, these techniques are possible both at the baseline AQUA beamline and at the "beyond-the-baseline" ARIA

Pump-probe experiments to perform **time-resolved** measurements

Courtesy of F. Stellato