EUROPEAN
PLASMA RESEARCH
ACCELERATOR
WITH
EXCELLENCE IN
APPLICATIONS

EuPRAXIA
Preparatory Phase

The ARIA seeded Free-Electron Laser beamline at EuPRAXIA@SPARC_LAB

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On behalf of theEuPRAXIA@SPARC_LAB collaboration

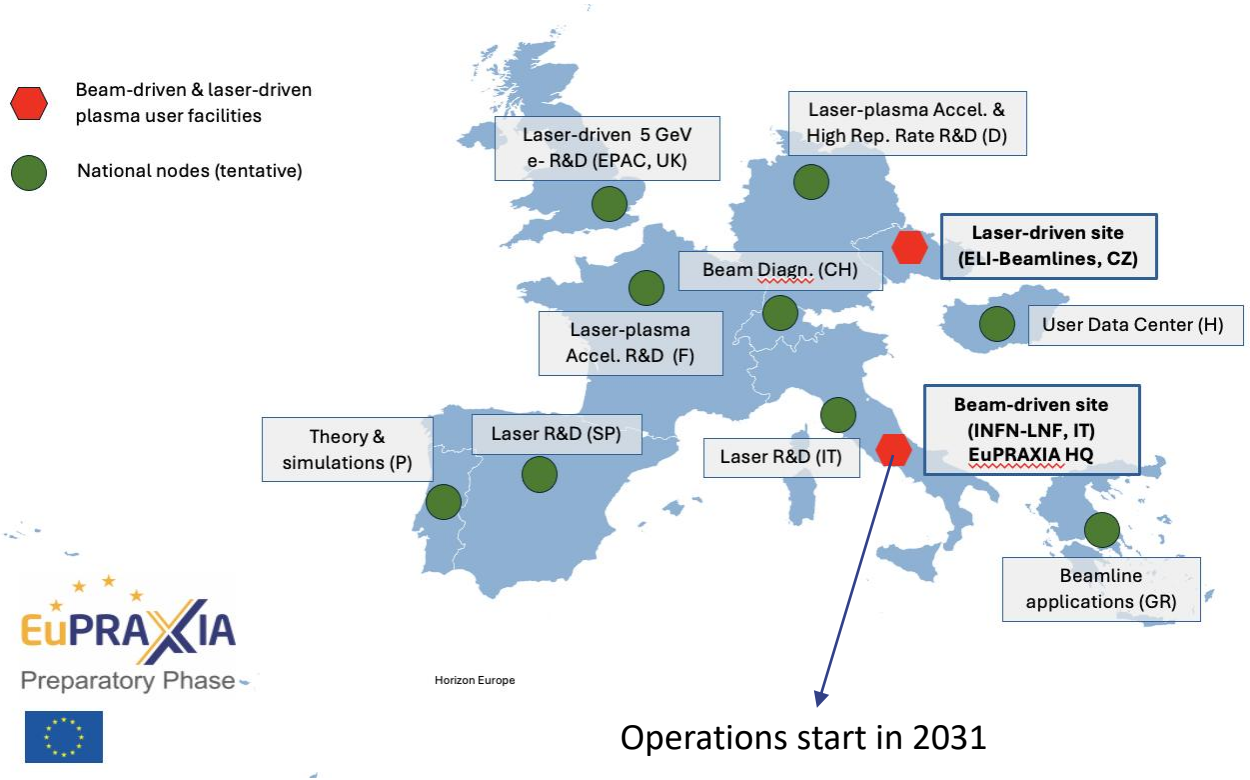
This project has received funding from the European Union´s Horizon Europe research and innovation programme under grant agreement No. 101079773

EuPRAXIA_Preparatory_Phase and EuPRAXIA_Doctoral_Network, Sep 20 – 26, 2026 Hotel Hermitage, La Biodola Bay, Isola d'Elba, Italy

EuPRAXIA Project

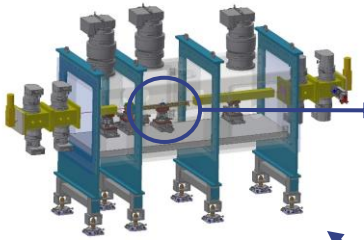
Funded by the European Union

- European project for a particle accelerator based on **plasma acceleration**.
- Wide network of institutes all over Europe
- Main goal: a shorter and cheaper machine.
- Two facilities:
  - **INFN-LNF** (Rome): beam-driven
  - **ELI Beamlines** (Prague): laser-driven

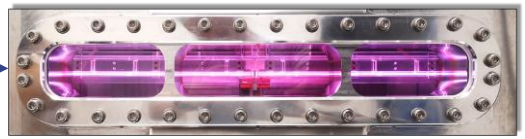


EuPRAXIA@SPARC_LAB

Plasma chamber: 3.5 m



Plasma capillary: 0.6 m



Energy doubling:
500MeV -> 1GeV

54 m

AQUA Beamline

ARIA Beamline

Photon beamlines

28.5 m

9 m

33.5 m

17.5 m

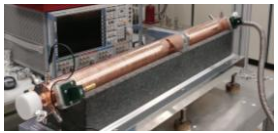
Undulators

Plasma module

X-band Linac

S-band Injector

ARIA and AQUA FEL lines



Apple-X undulators tested at SABINA

ARIA is co-funded by

REGIONE LAZIO

M. Ferrario et al.. (2026) «EuPRAXIA@SPARC_LAB Technical Design Report». oar.it. doi: 10.15161/oar.it/k57qz-5qk09.

EuPRAXIA@SPARC_LAB FEL lines

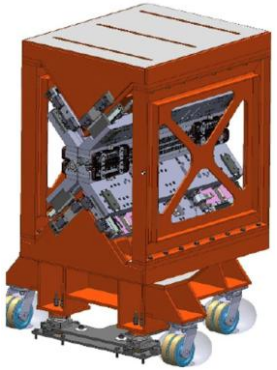
Funded by the European Union

1) AQUA: Soft-X ray SASE FEL optimized for water window

$\lambda = 4\ nm$

APPLE-X undulators

10 APPLE-X Open Permanent Magnets undulators, 1.98 m each, **1.8 cm** period
60 cm intra-undulator sections



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

$\lambda = [50, 180]\ nm$

Seed Modulator Disp. sec. Radiators

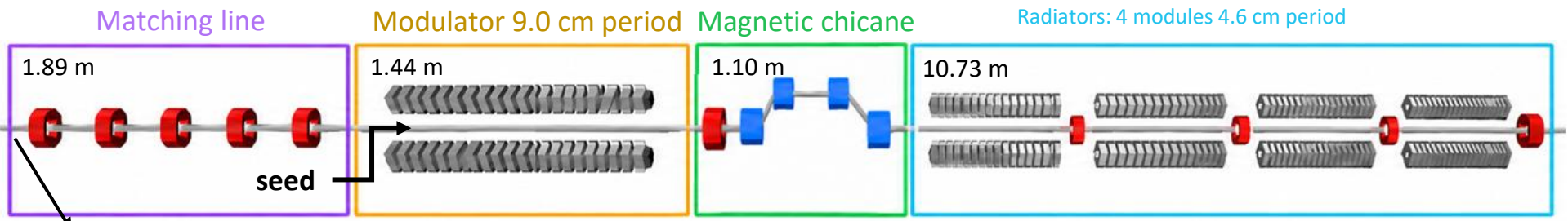
Planar modulator: 1.44 m, **9.0 cm** period
4 Radiators APPLE X: variable pol., 1.93 m each, **4.6 cm** period
Seed laser in the range [350-800] nm

Same scheme of FERMI FEL-1

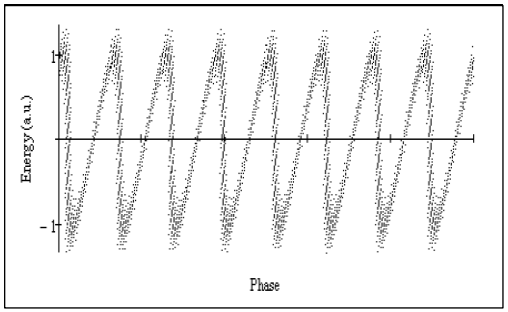
Applications

- Atomic, Molecular, and Cluster Physics
- Atmospheric Physics
- Biosciences / Chirality
- Two-Photon
- Photoemission
- Molecular
- Photodissociation

ARIA: a seeded HGHG FEL



e-bunch phase space

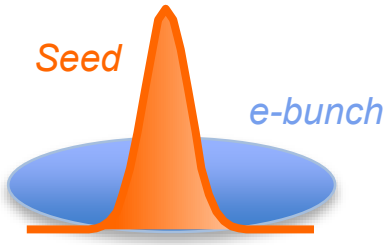


Chicane	
Dipole length	8 cm
R_{56} max	$\sim 300\,\mu m$
Total length	60 cm
Quadrupoles	
Length	25 cm
G max	35 T/m

	Modulator	Radiator
Period	**9.0 cm**	**4.6 cm**
Active length	144.0 cm	193.2 cm
Configuration	planar	planar/helical
K_{max} (700 MeV)	4.9	3.7
Model	LPU	Apple X
Wavelength	[350,800]nm	[50,180]nm

Two working configurations

Configuration 1 (LINAC only)

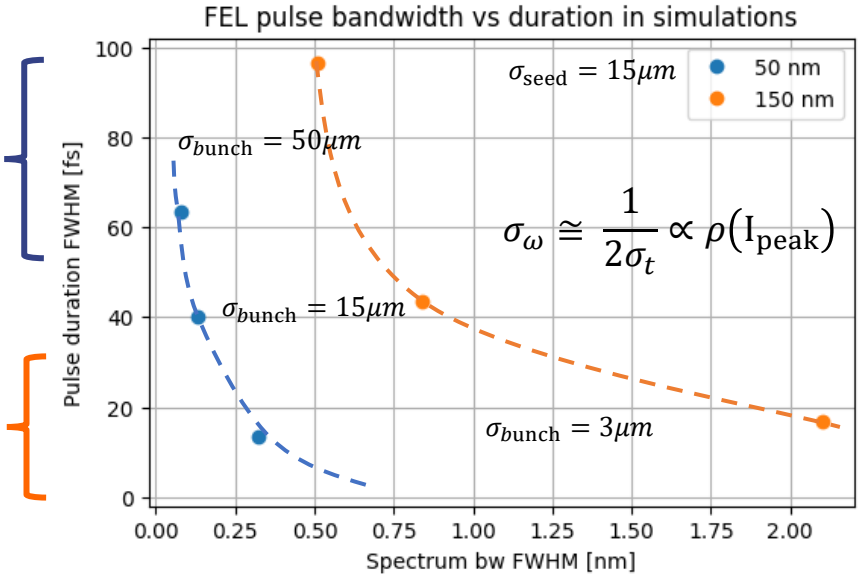


Seed + long e-bunch

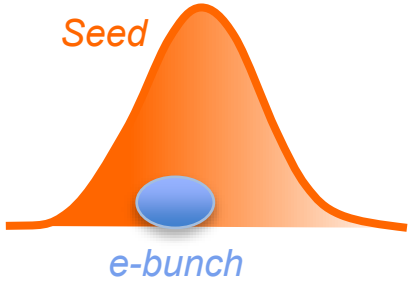
⇩

Narrow spectra

Pulse duration determined by the seed length



Configuration 2 (LINAC-plasma)



Long seed + short e-bunch

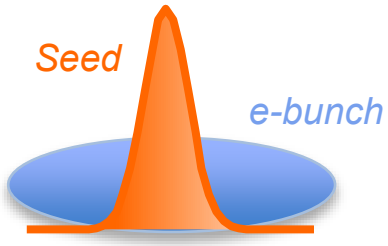
⇩

Short pulses (tens of fs)

Pulse duration determined by the e-bunch length

Long bunch configuration

Configuration 1 (LINAC only)



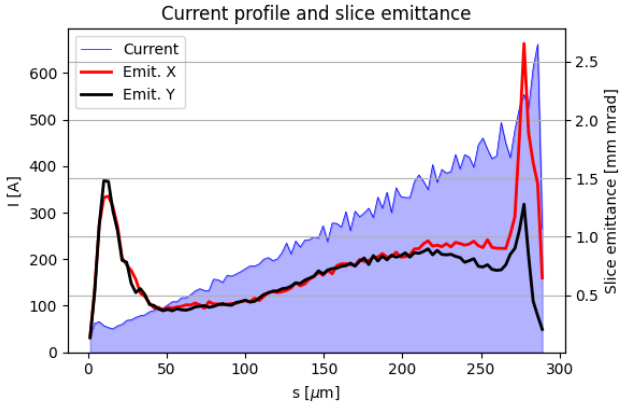
Seed + long e-bunch

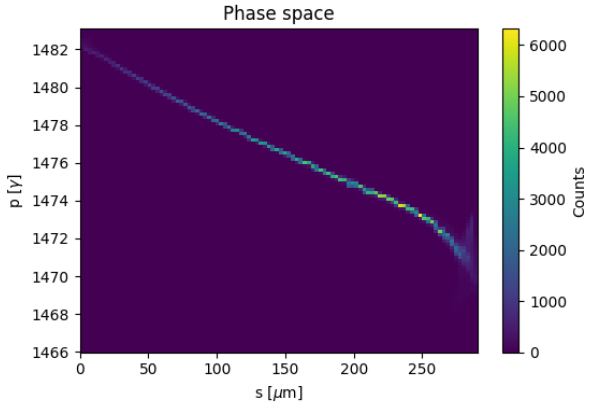
⇩

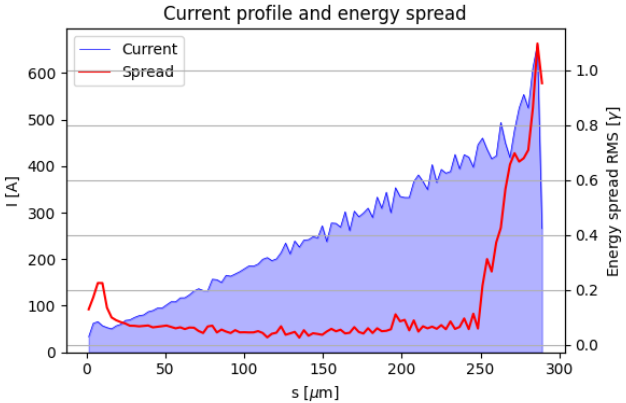
Narrow spectra

Wide range of start-to-end simulations with long e-bunches from LINAC

Parameter	Value
Time length	~ 1 ns
Average energy	754 MeV
Charge	250 pC
Slice emittance	~ 1 mm mrad
Energy spread	$\sim 7 * 10^{-5}$





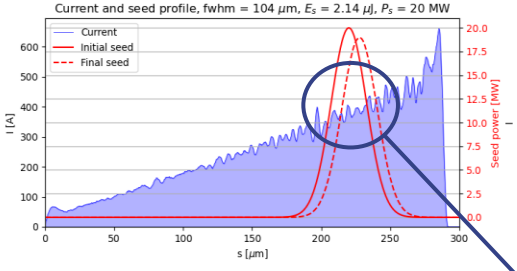


ARIA: Start to end simulations

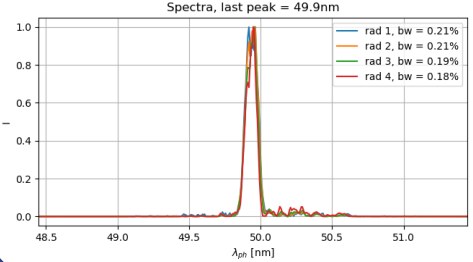
Funded by the European Union

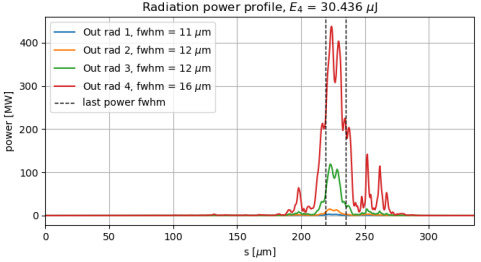
Gaussian seed 100 fs FWHM | **Narrow spectrum** | **Time profile** | **Pulse parameters**

$\lambda = 350$ nm



$\lambda = 50$ nm

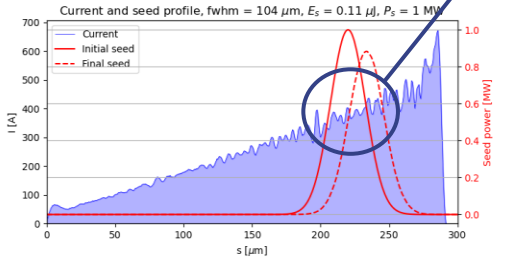




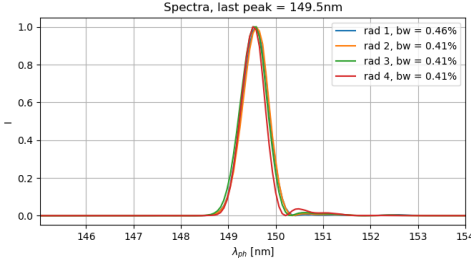
Parameter	Value
FWHM	37 fs
Energy	30.4 μJ
Wavelength	50 nm ($h = 7$)
Spectral bw	0.09 nm
N. of photons	$4.81 * 10^{13}$

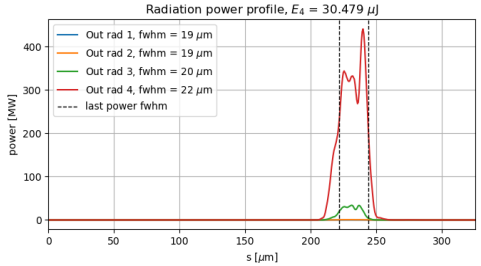
In long bunch configuration the smoothness of the seeded region is critical

$\lambda = 600$ nm



$\lambda = 150$ nm





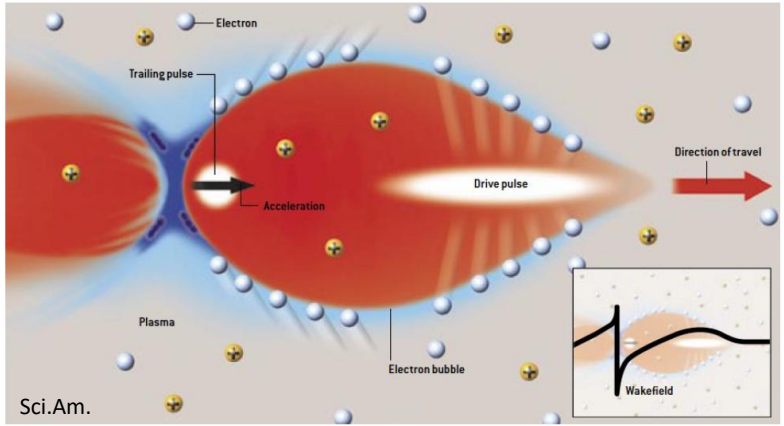
Parameter	Value
FWHM	73 fs
Energy	30.5 μJ
Wavelength	150 nm ($h = 4$)
Spectral bw	0.6 nm
N. of photons	$1.45 * 10^{14}$

Short bunch configuration

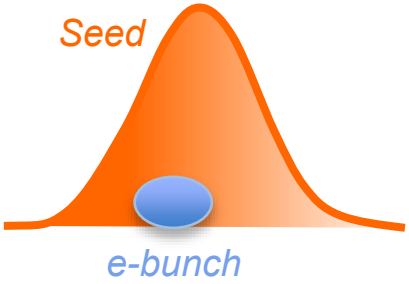
Plasma wake field acceleration at
EuPRAXIA@SPARC_LAB

Very **short** (tens of fs) and **intense** (kA) e-bunches

$$\sigma_\omega \cong \frac{1}{2\sigma_t} \propto \rho(\mathrm{I_{peak}})$$

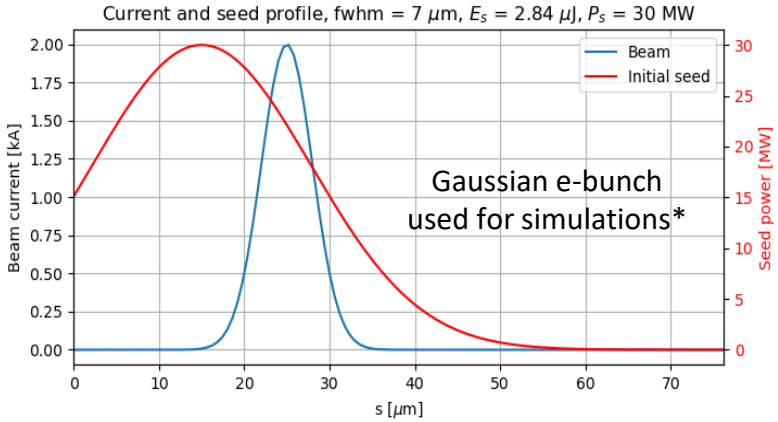


Configuration 2 (LINAC-plasma)



Long seed + short e-bunch

Short pulses (tens of fs)



*Genesis-1.3-Version4, developed by Sven Reiche

Multicolor pulse generation

Funded by the European Union

1 Proven at FERMI

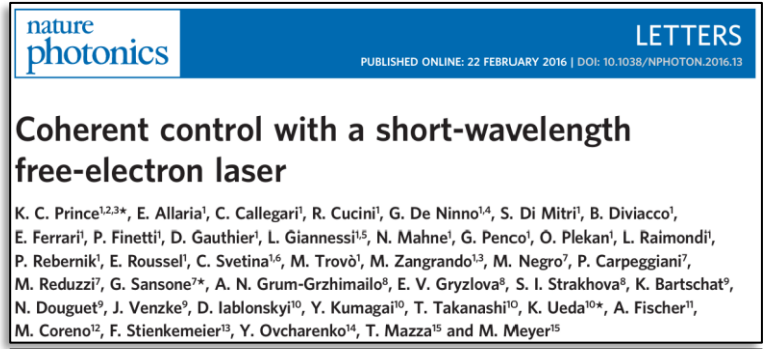
Multicolor generation has been widely studied at FERMI. Time-superimposed pulses can create **attosecond pulse trains**.

2 Transfer to ARIA

All techniques implemented at FERMI also apply to ARIA, in the **long bunch configuration**.

3 The short e-bunch case

ARIA operates at longer wavelength than FERMI → larger **slippage**: $\Delta = N \cdot \lambda,\ N = 42$ in each undulator.
A short e-bunch may generate **short pulses separated in time**.
The temporal separation can be tuned via the gap of an off-resonance undulator.



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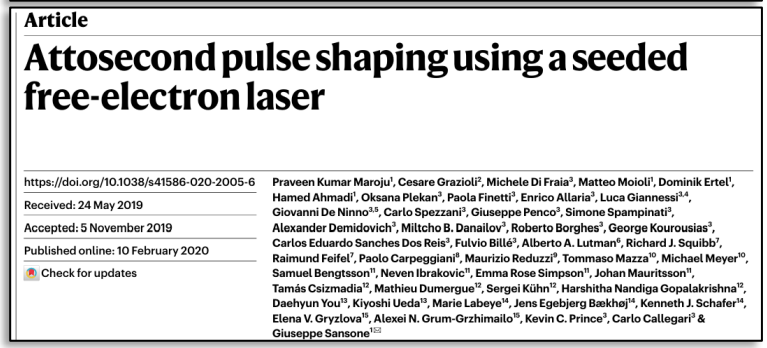
Coherent control with a short-wavelength free-electron laser

K. C. Prince[1,2,3]*, E. Allaria[1], C. Callegari[1], R. Cucini[1], G. De Ninno[1,4], S. Di Mitri[1], B. Diviacco[1], E. Ferrari[1], P. Finetti[1], D. Gauthier[1], L. Giannessi[1,5], N. Mahne[1], G. Penco[1], O. Plekan[1], L. Raimondi[1], P. Rebernik[1], E. Roussel[1], C. Svetina[1,6], M. Trovò[1], M. Zangrando[1,3], M. Negro[7], P. Carpeggiani[7], M. Reduzzi[7], G. Sansone[7]*, A. N. Grum-Grzhimailo[8], E. V. Gryzlova[8], S. I. Strakhova[8], K. Bartschat[9], N. Douguet[9], J. Venzke[9], D. Iablonskyi[10], Y. Kumagai[10], T. Takanashi[10], K. Ueda[10]*, A. Fischer[11], M. Coreno[12], F. Stienkemeier[13], Y. Ovcharenko[14], T. Mazza[15] and M. Meyer[15]



Article

Attosecond pulse shaping using a seeded free-electron laser

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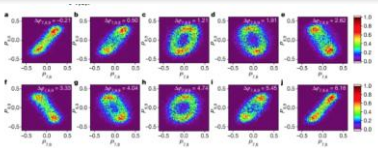
Check for updates

Praveen Kumar Maroju[1], Cesare Grazioli[2], Michele Di Fraia[3], Matteo Moioli[1], Dominik Ertel[1], Hamed Ahmadi[1], Oksana Plekan[3], Paola Finetti[3], Enrico Allaria[3], Luca Giannessi[3,4], Giovanni De Ninno[3,5], Carlo Spezzani[3], Giuseppe Penco[3], Simone Spampinati[3], Alexander Demidovich[3], Miltcho B. Danailov[3], Roberto Borghes[3], George Kourousias[3], Carlos Eduardo Sanches Dos Reis[3], Fulvio Billé[3], Alberto A. Lutman[6], Richard J. Squibb[7], Raimund Feifel[7], Paolo Carpeggiani[8], Maurizio Reduzzi[8], Tommaso Mazza[10], Michael Meyer[10], Samuel Bengtsson[11], Neven Ibrakovic[11], Emma Rose Simpson[11], Johan Mauritsson[11], Tamás Csizmadia[12], Mathieu Dumergue[12], Sergei Kühn[12], Harshitha Nandiga Gopalakrishna[12], Daehyun You[13], Kiyoshi Ueda[13], Marie Labeye[14], Jens Egebjerg Bækhøj[14], Kenneth J. Schafer[14], Elena V. Gryzlova[15], Alexei N. Grum-Grzhimailo[15], Kevin C. Prince[3], Carlo Callegari[3] & Giuseppe Sansone[1]✉



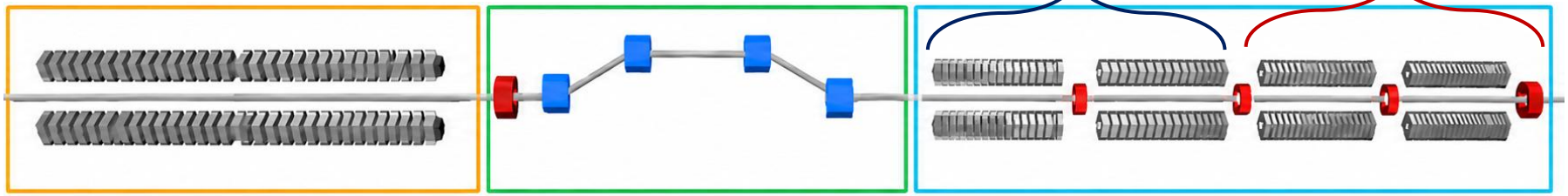
and many others…

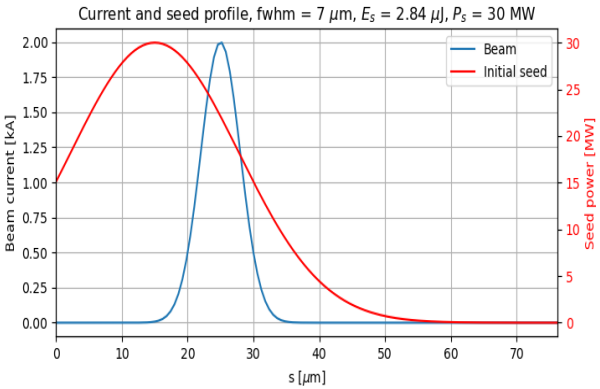
ARIA: two colors

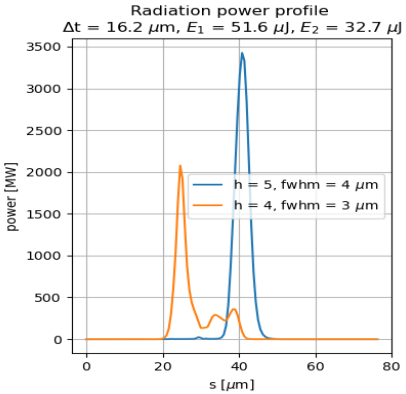
Seeding at 600 nm

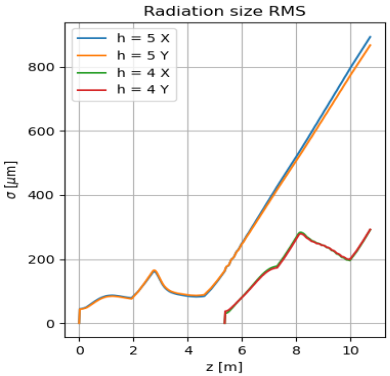
2 radiators tuned at harmonic 5: 120 nm

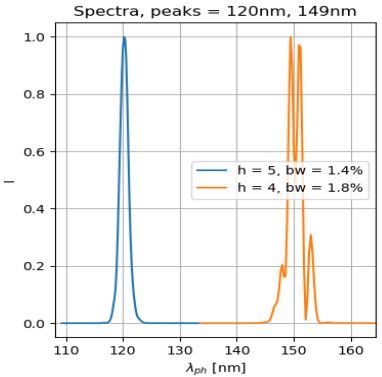
2 radiators tuned at harmonic 4: 150 nm







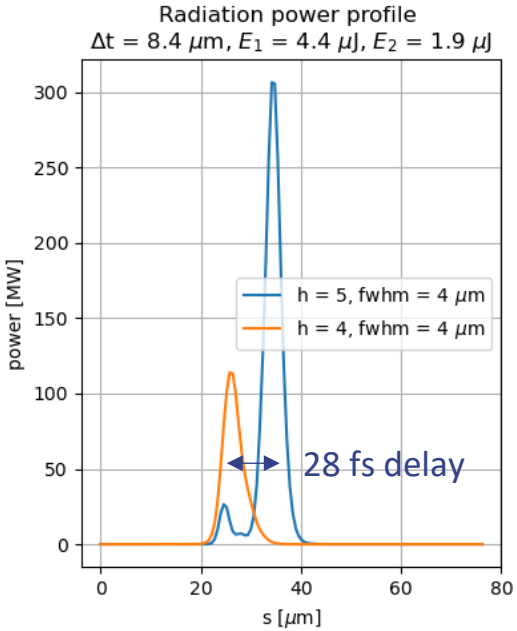




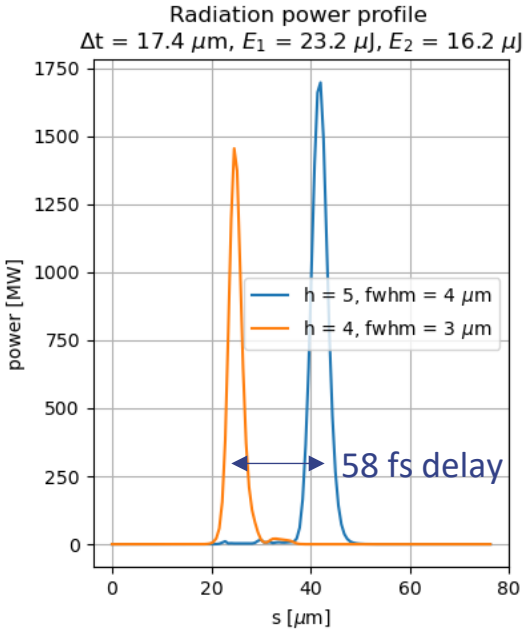
Short pulses **separated in time**

Two colors delayed

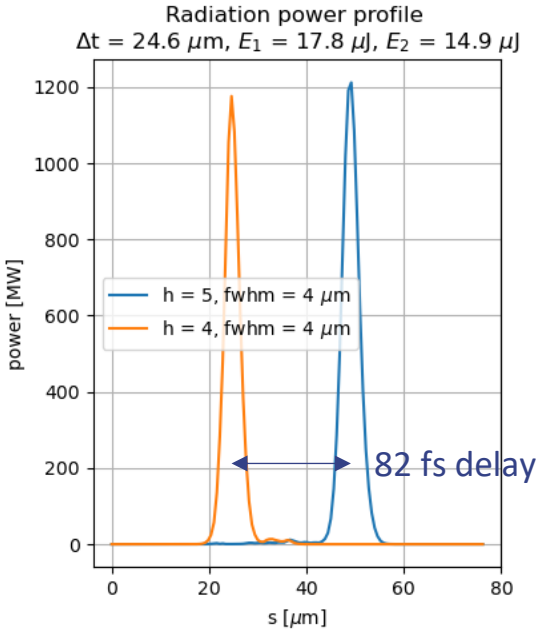
Undulator 3 at **K=0**



Undulator 3 at **maximum K**

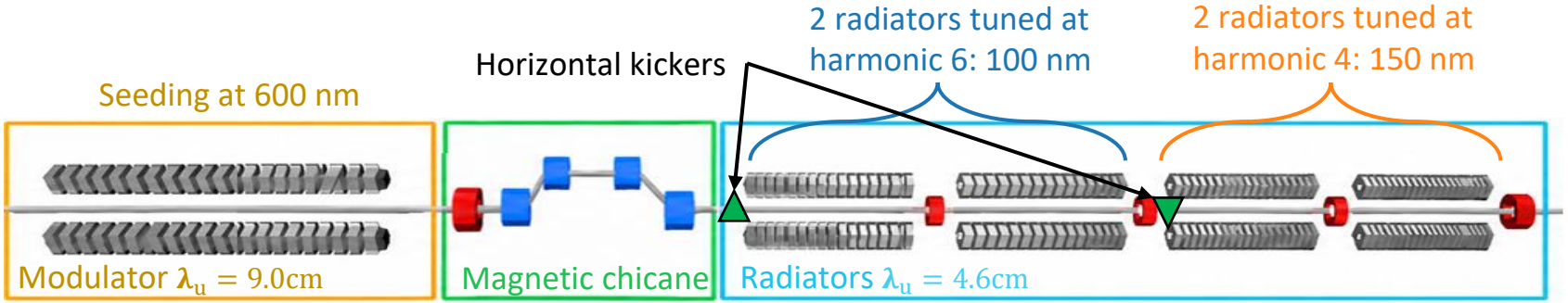


Undulator **2 and 3** at maximum K

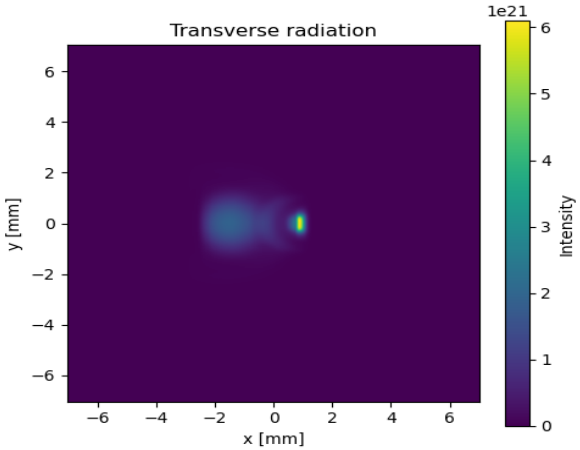


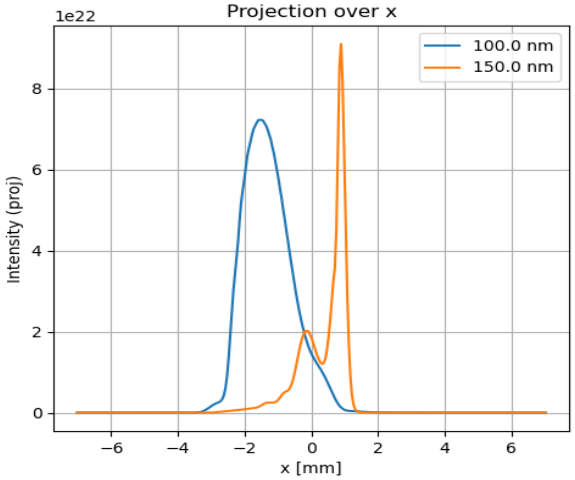
- Changing the gap of the third undulator we can vary the time delay between colors of 30 fs
- Detuning the second too we can reach 54 fs

Two colors delayed



- For a bigger delay we can use a **split and delay line***
- spatial color separation is possible.



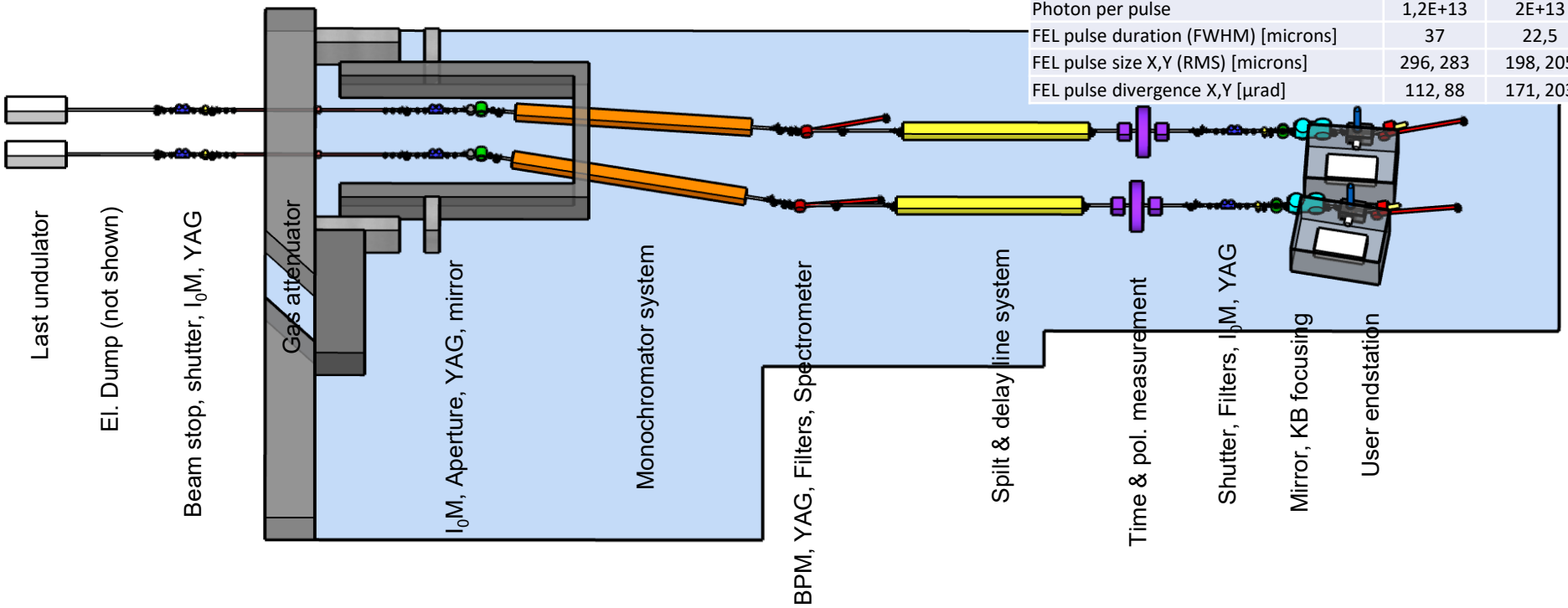


ARIA Photon beamline

Funded by the European Union

A phased realization of the full beamline is foreseen

Parameters at undulators' end		
Wavelength [nm]	49,9	149,5
Bandwidth (FWHM) [nm]	0,054	0,59
Photon per pulse	1,2E+13	2E+13
FEL pulse duration (FWHM) [microns]	37	22,5
FEL pulse size X,Y (RMS) [microns]	296, 283	198, 205
FEL pulse divergence X,Y [µrad]	112, 88	171, 203



ARIA's applications

Funded by the European Union

1 Atomic, Molecular, and Cluster Physics

Pump-probe techniques to study the structure and formation of free clusters of varying chemical nature following the evolution of matter from a single isolated particle up to condensed surface and bulk phases.

2 Atmospheric Physics

Access to photoionization thresholds and valence ionic states of **atmospheric and combustion-relevant species**, studying light-induced dynamics via mass/electron spectrometry and monochromatic VUV photo-emission techniques.

3 Biosciences / Chirality

By varying the FEL light polarization from linear to circular, it is possible to **correlate chirality** and natural dichroism in biotic media **with the electronic structure** of their basic constituents.

4 Two-Photon Photoemission

Time-resolved study of **excited states** (excitons, polarons, spin-charge-orbital ordering) in confined structures, organic-inorganic hetero-junctions (organic solar cells), doped semiconductor heterostructures, and spintronics devices.

5 Molecular Photodissociation

Dissociation of molecules via tunable FEL pulses, with fragment analysis by **time-of-flight spectroscopy** (pilot measurements already performed at the Dalian Coherent Light Source*).

*Chang, Y et al. Tunable VUV photochemistry using vacuum ultraviolet free electron laser combined with H-atom Rydberg tagging time-of-flight spectroscopy. Rev. Sci. Instrum. 1 June 2018; 89 (6): 063113. https://doi.org/10.1063/1.5017757

Summary and next steps

- **Summary:**
  1. ARIA will be the second FEL line of EuPRAXIA@SPARC_LAB.
  2. It aims to produce FEL light pulses in the **gas ionization range** (50-150) nm.
  3. It can operate in **two regimes**: long beams for narrow spectra or short beams for short light pulses.
  4. A wide set of **start-to-end simulations** have been done in long beam mode and could fill a niche in the world scientific scenario.
  5. In short beams mode we investigated the **multi-color** emission and the delay tunability between two pulses at different wavelengths.
- **Next steps:**
  1. Start-to-end simulations in short beam mode.
  2. Split and delay line design and optimization.

Thanks for your attention!

Acknowledgements

M. Ferrario, D. Alesini, L. Giannessi, V. Petrillo, F. Nguyen, A. Petralia, A. Giribono, G.J. Silvi, A. Biagioni, G. Campri, E. Chiadroni, A. Del Dotto, F. Demurtas, M. Galletti, G. Griseri. G. Parise, R. Pompili, S. Romeo, A.R. Rossi, L. Sabbatini, C. Vaccarezza, F. Villa

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EuPRAXIA Preparatory Phase

Funded by
the European Union

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EuPRAXIA Doctoral Network

Funded by
the European Union

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EuAPS

Co-funded by
the European Union

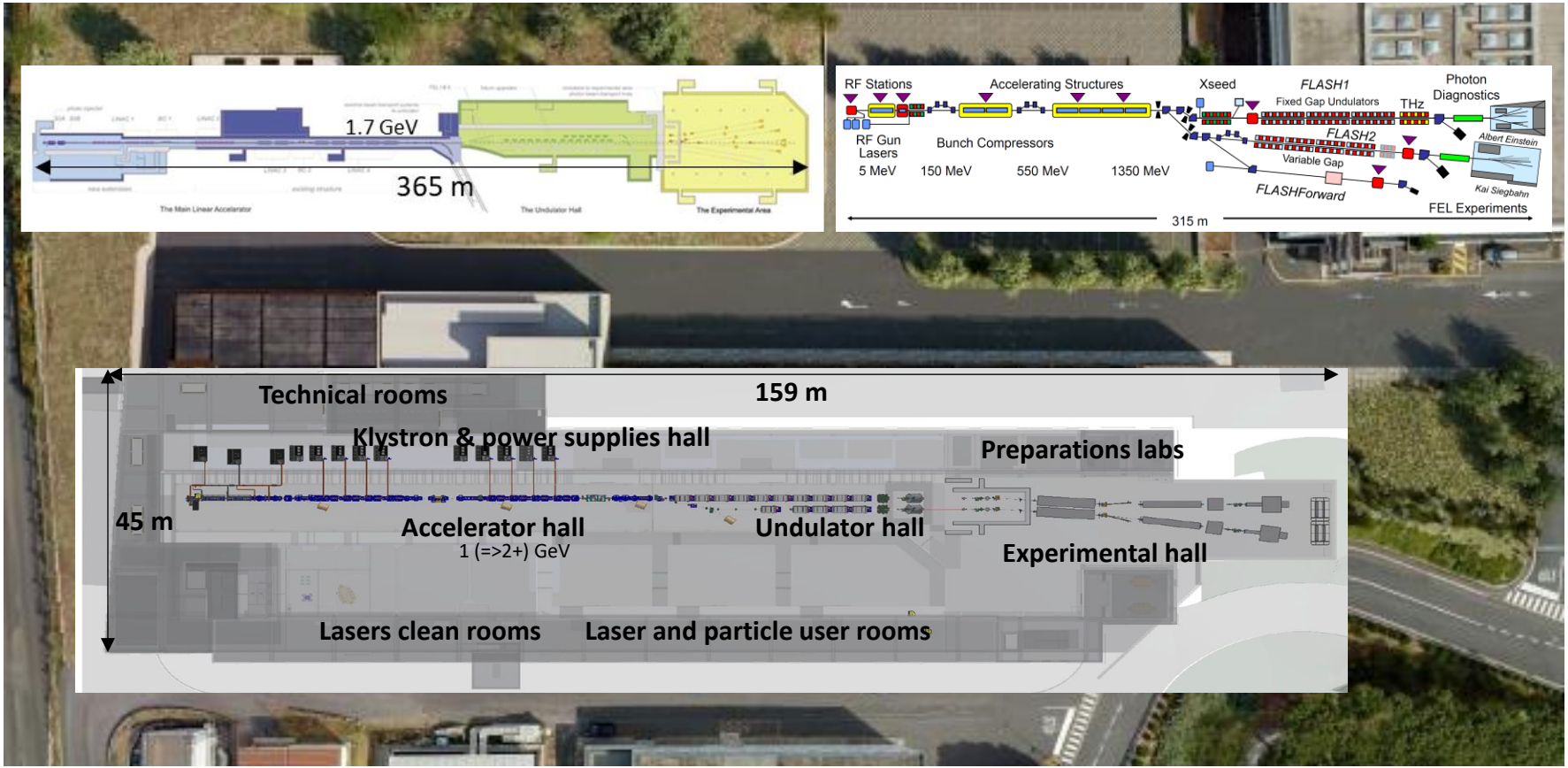
This publication has been made with the co-funding of European Union Next Generation EU.

Funded by the European Union

EXTRA SLIDES

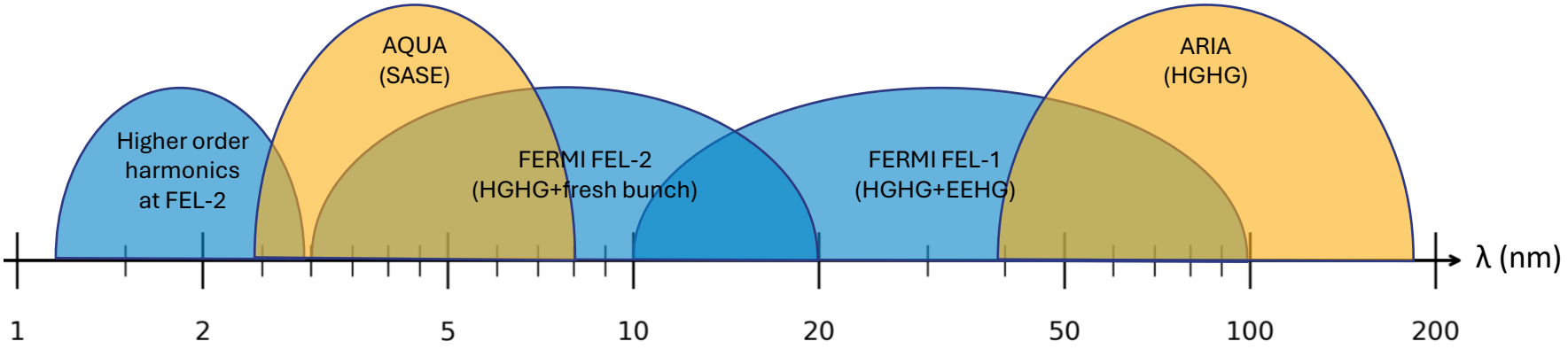
EuPRAXIA@SPARC_LAB

Funded by the European Union



ARIA Complementary with FERMI

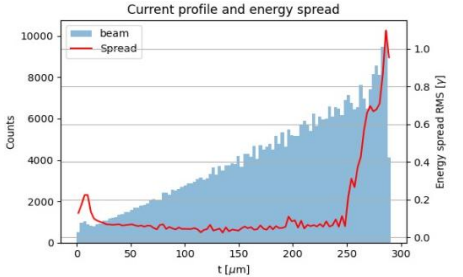
Elettra Sincrotrone Trieste

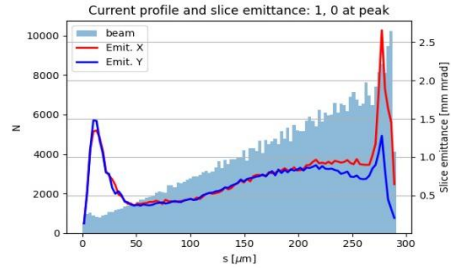


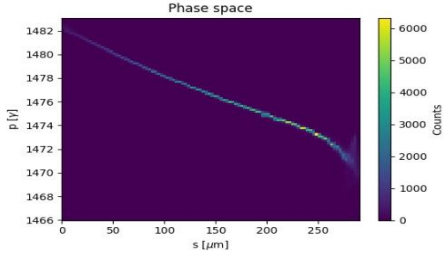
Start to end simulations

Funded by the European Union

S2E beam 250 pC @750 MeV

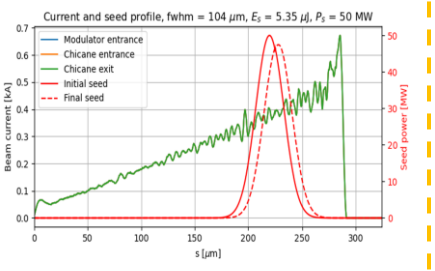




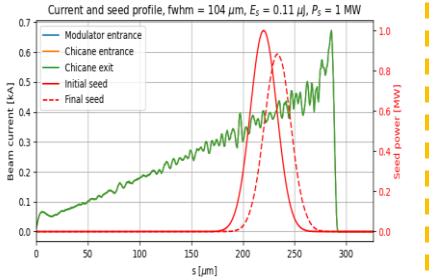


Gaussian seed 100 fs FWHM

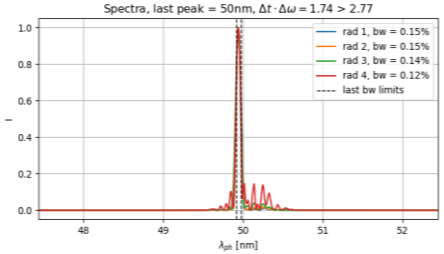
λ = 350 nm

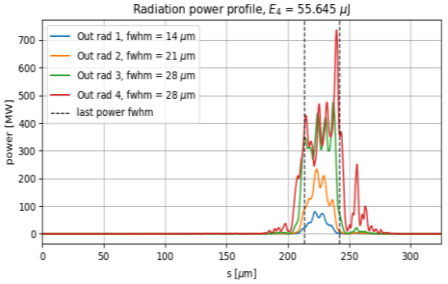


λ = 600 nm



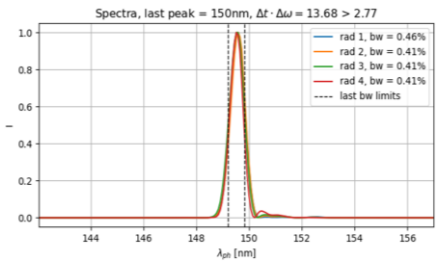
50 nm emission

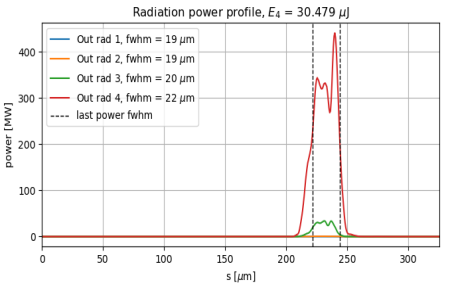




Parameter	Value
FWHM	93 fs
Energy	55.6 μJ
Wavelength	50 nm ($h = 7$)
Spectral bw	0.06 nm
N. of photon	$8.79 * 10^{13}$

150 nm emission



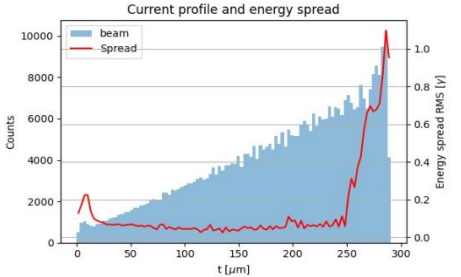


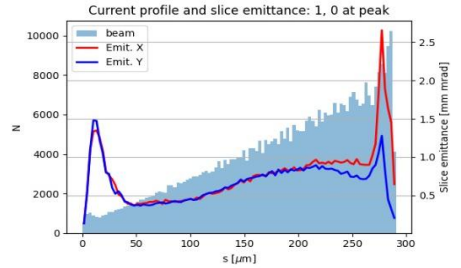
Parameter	Value
FWHM	73 fs
Energy	30.5 μJ
Wavelength	150 nm ($h = 4$)
Spectral bw	0.6 nm
N. of photon	$1.45 * 10^{14}$

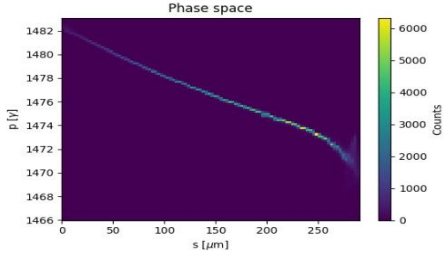
Start to end simulations

Funded by the European Union

S2E beam 250 pC @750 MeV

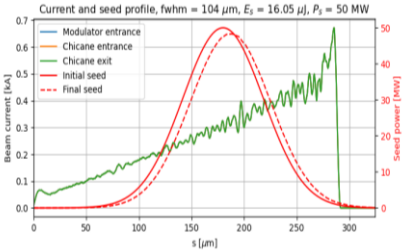




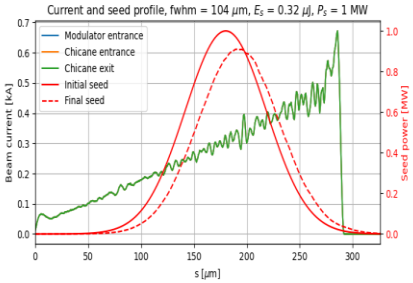


Gaussian seed 300 fs FWHM

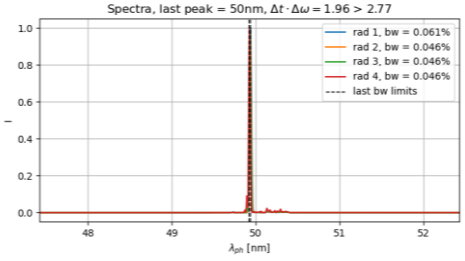
λ = 350 nm

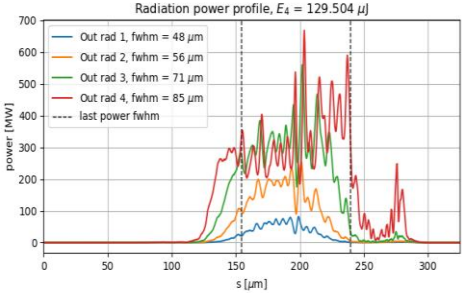


λ = 600 nm



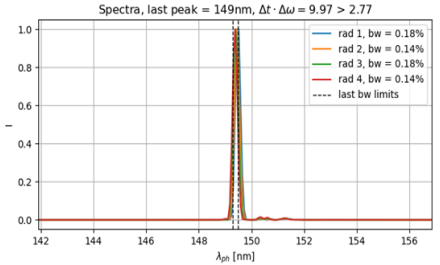
50 nm emission

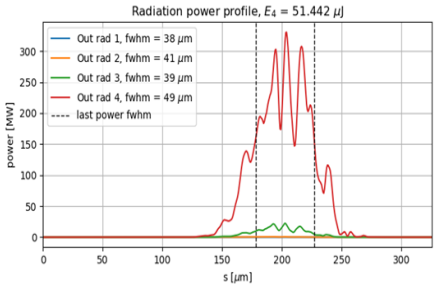




Parameter	Value
FWHM	283 fs
Energy	129.5 μJ
Wavelength	50 nm ($h = 7$)
Spectral bw	0.023 nm
N. of photon	$2.05 * 10^{14}$

150 nm emission





Parameter	Value
FWHM	163 fs
Energy	51.4 μJ
Wavelength	150 nm ($h = 4$)
Spectral bw	0.2 nm
N. of photon	$2.44 * 10^{14}$

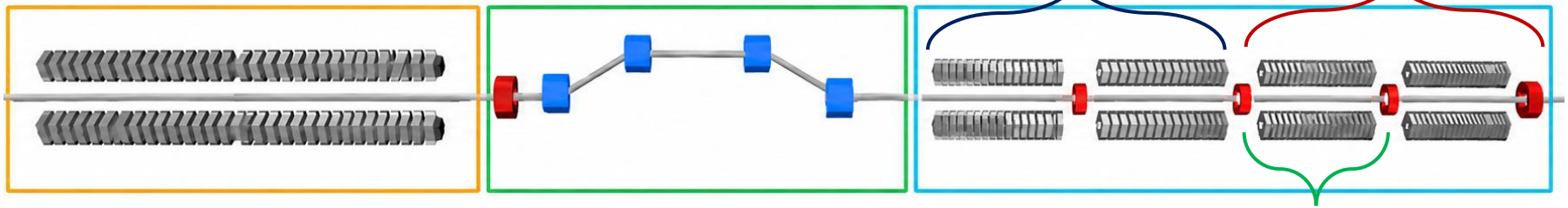
ARIA: two colors

Funded by the European Union

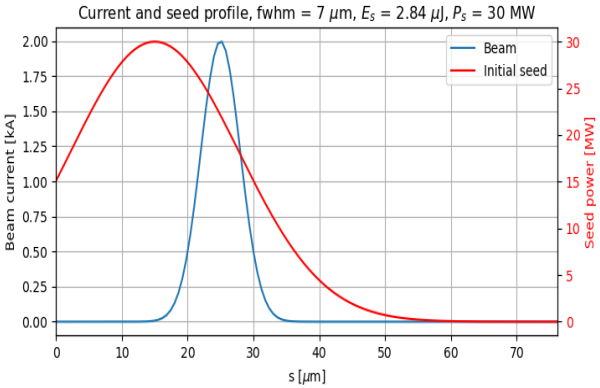
Seeding at 600 nm

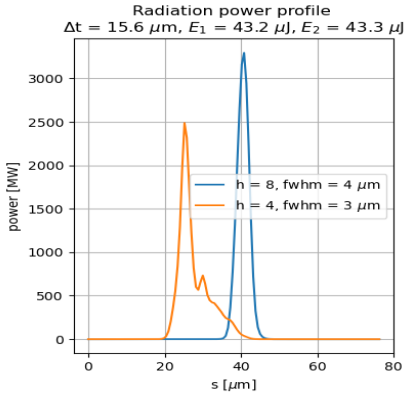
2 radiators tuned at harmonic 8: 75 nm

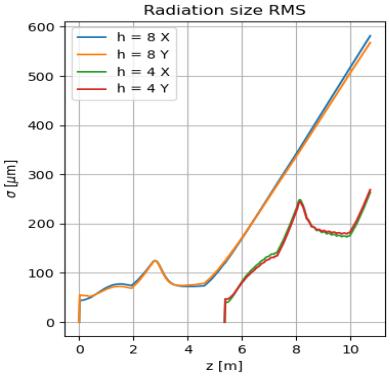
2 radiators tuned at harmonic 4: 150 nm

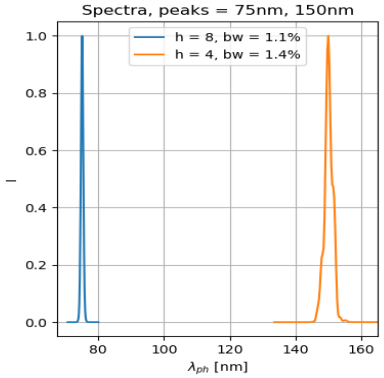


Detuned

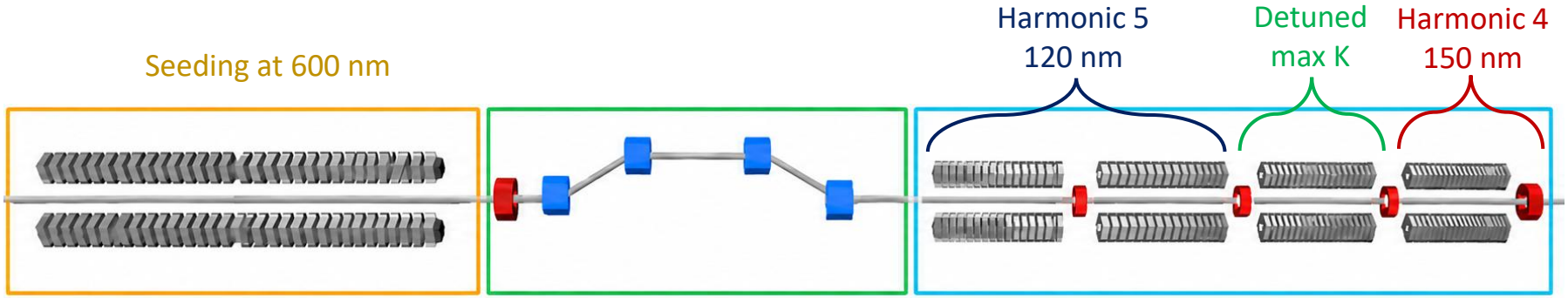


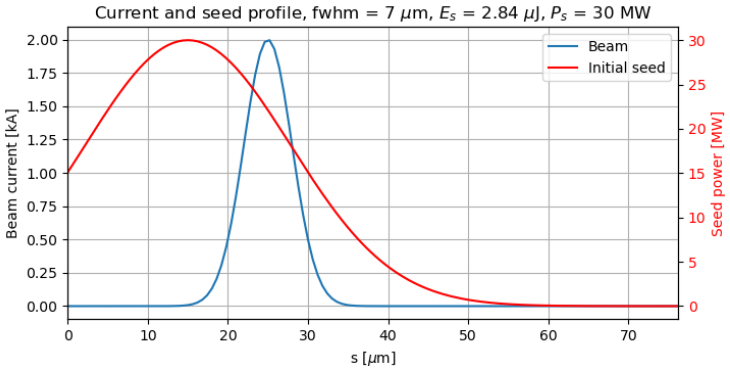


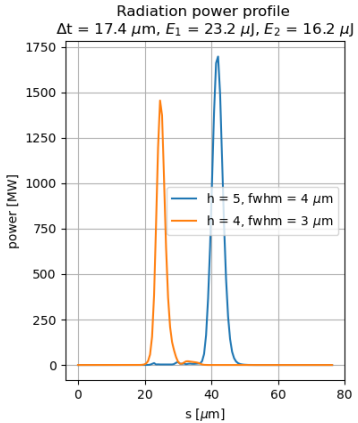


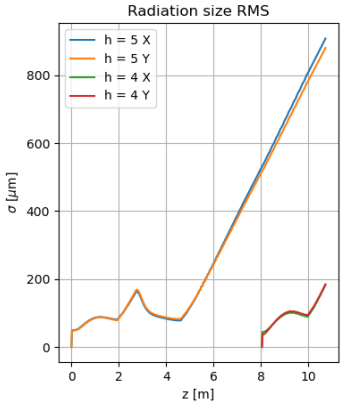


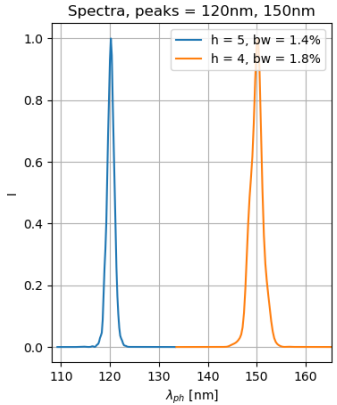
ARIA: two colors delayed



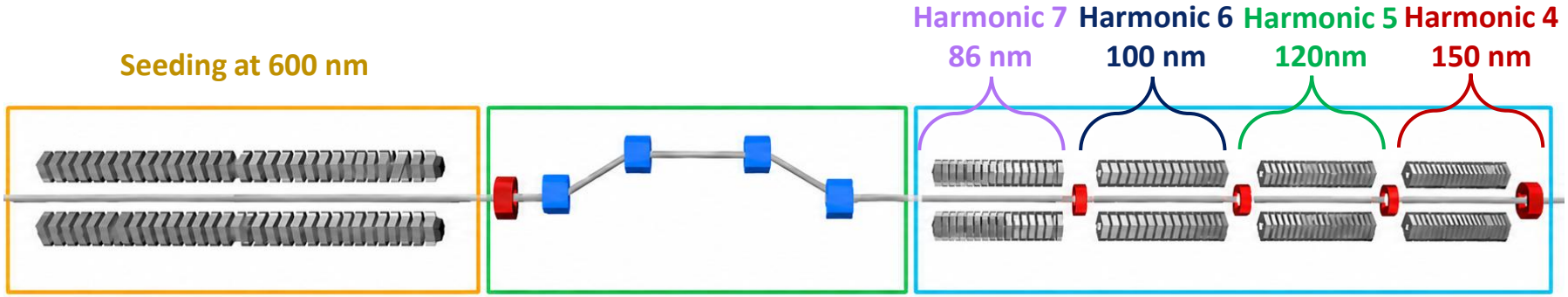




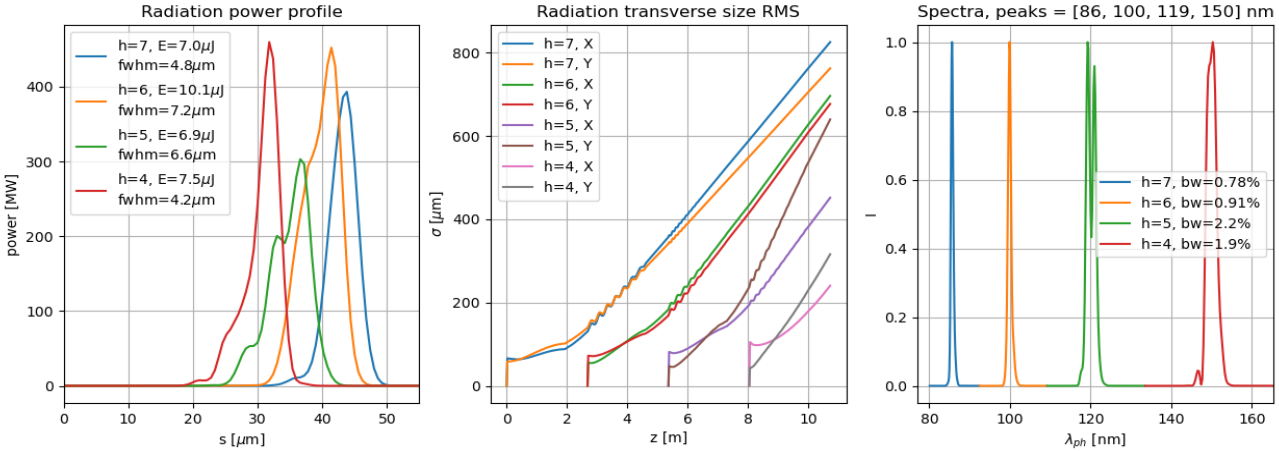




ARIA: four colors



Four radiators can produce up to 4 colors, in whatever order



FEL optical propagation

Funded by the European Union

250pC crest

Parameters at undulators' end		
Wavelength [nm]	49,9	149,5
Bandwidth (FWHM) [nm]	0,0539	0,5917
Photon per pulse	1,21E+13	2,05E+13
FEL pulse duration (FWHM) [microns]	37,3	22,53
FEL pulse size X (RMS) [microns]	295,8	198,3
FEL pulse size Y (RMS) [microns]	282,9	205,4
FEL pulse divergence X [µrad]	112,1	171
FEL pulse divergence Y [µrad]	88,3	202,9

		Envelope ph.beam				projection on the optics			
		50 nm (sigma, um)		150 nm (sigma, um)		50 nm (6sigma, mm)		150 nm (6sigma, mm)	
element	Dist. (m)	H	V	H	V	H	V	H	V
undulator end	0	315	338	250	226				
1st yag	5.9	777	908	1217	1061	4.7	5.4	7.3	6.4
steering mirror (H)	16.8	1752	2073	3161	2752	120.2	12.4	216.8	16.5
filter wheels 1	29.8	2936	3479	5489	4778	17.6	20.9	32.9	28.7
spectrometer grating	30.8	3027	3588	5668	4934	207.6	21.5	388.7	29.6
filter wheels 2	47	4508	5345	8571	7462	27.0	32.1	51.4	44.8
last yag	49.1	4700	5573	8948	7789	28.2	33.4	53.7	46.7
steering mirror (V)	49.95	4778	5666	9100	7922	28.7	388.6	54.6	543.3
kb mirror (V)	50.75	4851	5753	9243	8053	29.1	394.6	55.5	552.2
kb mirror (H)	51.55	4925	3752	9403	5252	337.8	22.5	644.9	31.5
target position	53.05	6.9	10.7	5.9	8.5				

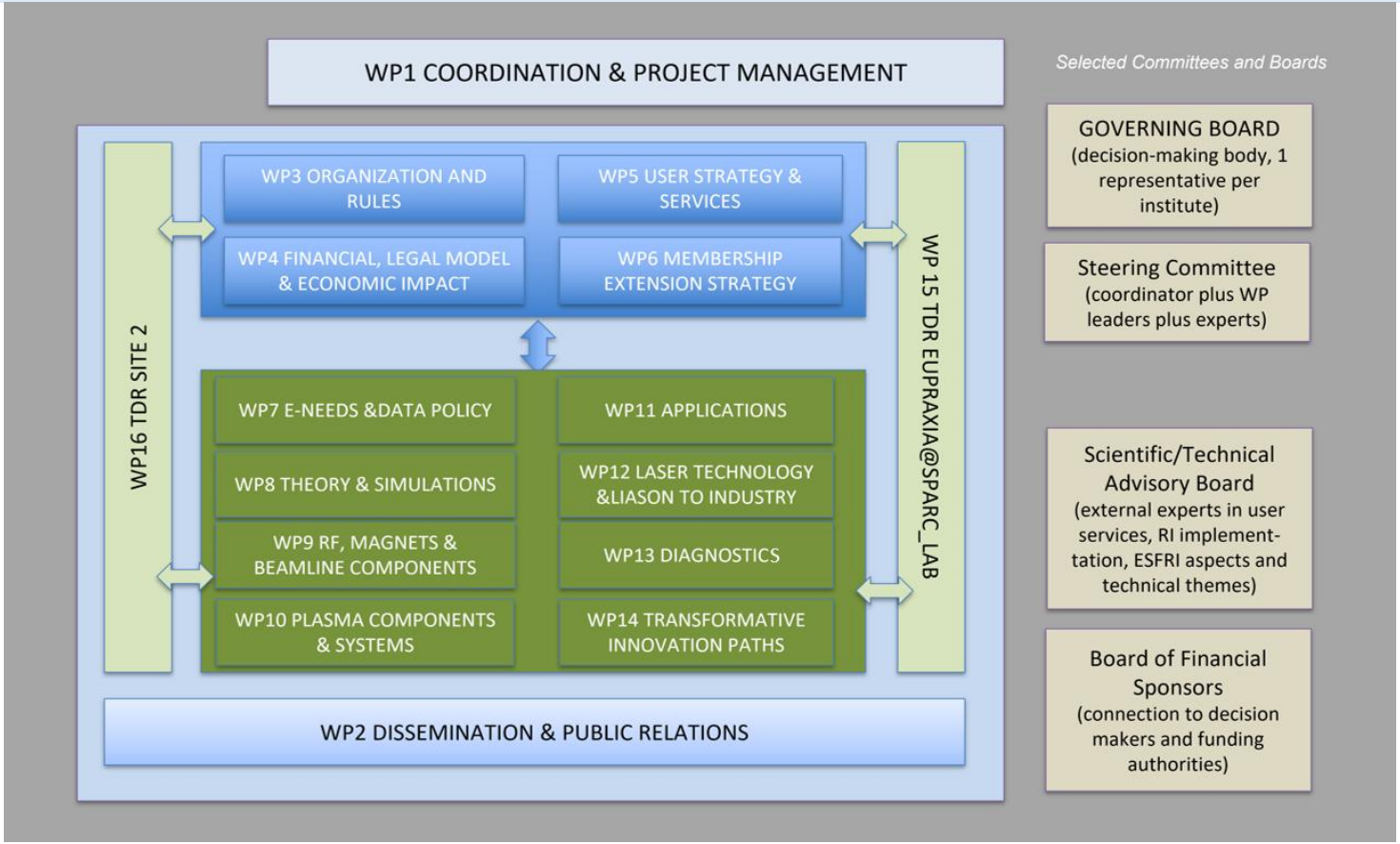
200pC VB

Parameters at undulators' end		
Wavelength [nm]	49,9	149,8
Bandwidth (FWHM) [nm]	0,0582	0,5692
Photon per pulse	1,38E+13	2,29E+13
FEL pulse duration (FWHM) [microns]	35,36	23,68
FEL pulse size X (RMS) [microns]	320,6	233,4
FEL pulse size Y (RMS) [microns]	332,6	238,7
FEL pulse divergence X [µrad]	9,18	18
FEL pulse divergence Y [µrad]	10,89	15,65

undulator end	0	334	343	255	252				
1st yag	5.9	887	929	1041	955	5.3	5.6	6.2	5.7
steering mirror (H)	16.8	1965	2064	2681	2448	134.8	12.4	183.8	14.7
filter wheels 1	29.8	3260	3425	4650	4244	19.6	20.6	27.9	25.5
spectrometer grating	30.8	3360	3530	4801	4382	230.4	21.2	329.3	26.3
filter wheels 2	47	4976	5229	7258	6624	29.9	31.4	43.6	39.7
last yag	49.1	5186	5450	7577	6914	31.1	32.7	45.5	41.5
steering mirror (V)	49.95	5271	5539	7706	7032	31.6	379.8	46.2	482.3
kb mirror (V)	50.75	5351	5624	7827	7147	32.1	385.7	47.0	490.1
kb mirror (H)	51.55	5433	3667	7960	4661	372.6	22.0	545.9	28.0
target position	53.05	5.1	7.7	6.4	10.1				

EuPRAXIA-PP Consortium

Funded by the European Union

Coordinator

EuPRAXIA-PP Structure