EUROPEAN
PLASMA RESEARCH
ACCELERATOR WITH
EXCELLENCE IN
APPLICATIONS

EuPRAXIA
Preparatory Phase

WP9 – Considerations on Undulators

WP9 – RF, Magnets & Beamline Components

F. Nguyen (ENEA)

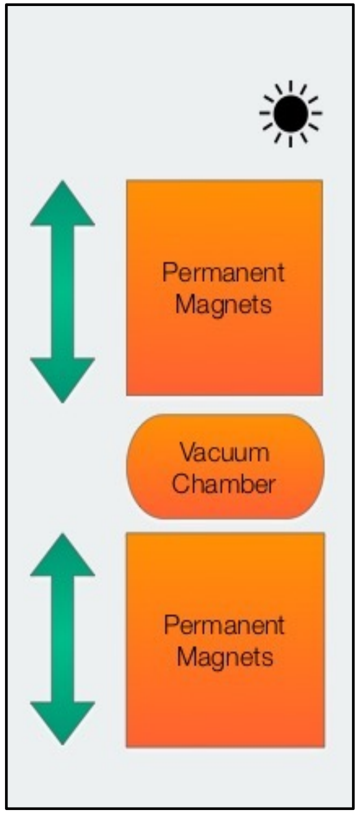
Elba Annual Meeting on September 24th, 2024

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

Undulators: technology ranking

Funded by the European Union

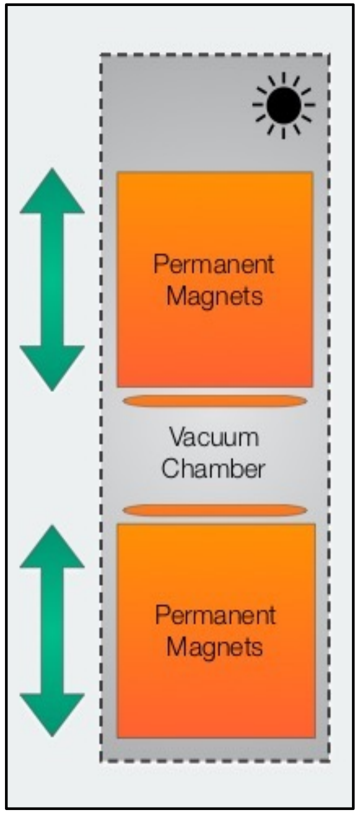
Out of vacuum PMU



Variable polarization & **cheapest** design

Good performance

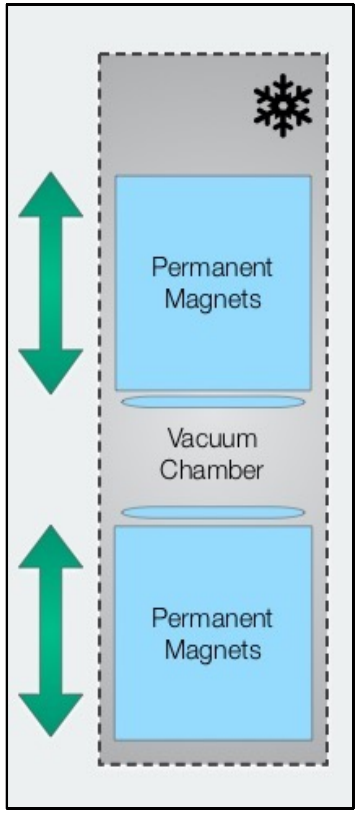
In vacuum PMU



Magnets inside VC
→ no polarization

Optimal performance

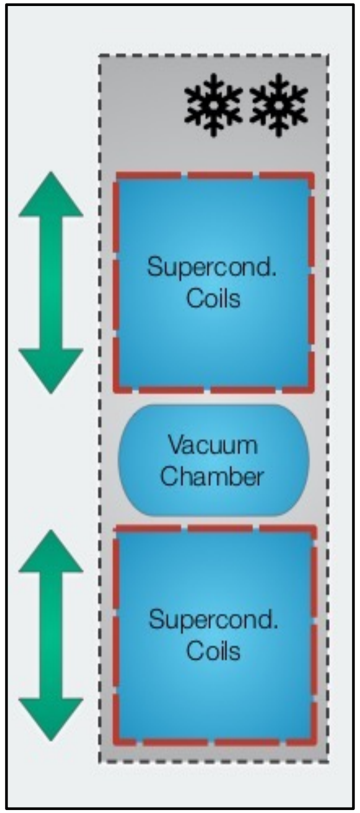
Cryogenic PMU



Improved B but
increased complexity

Better performance

Superconducting



Highest B and SC
electromagn. coils

Best performance

The AQUA beamline – EuPRAXIA@SPARC_LAB

Funded by the European Union

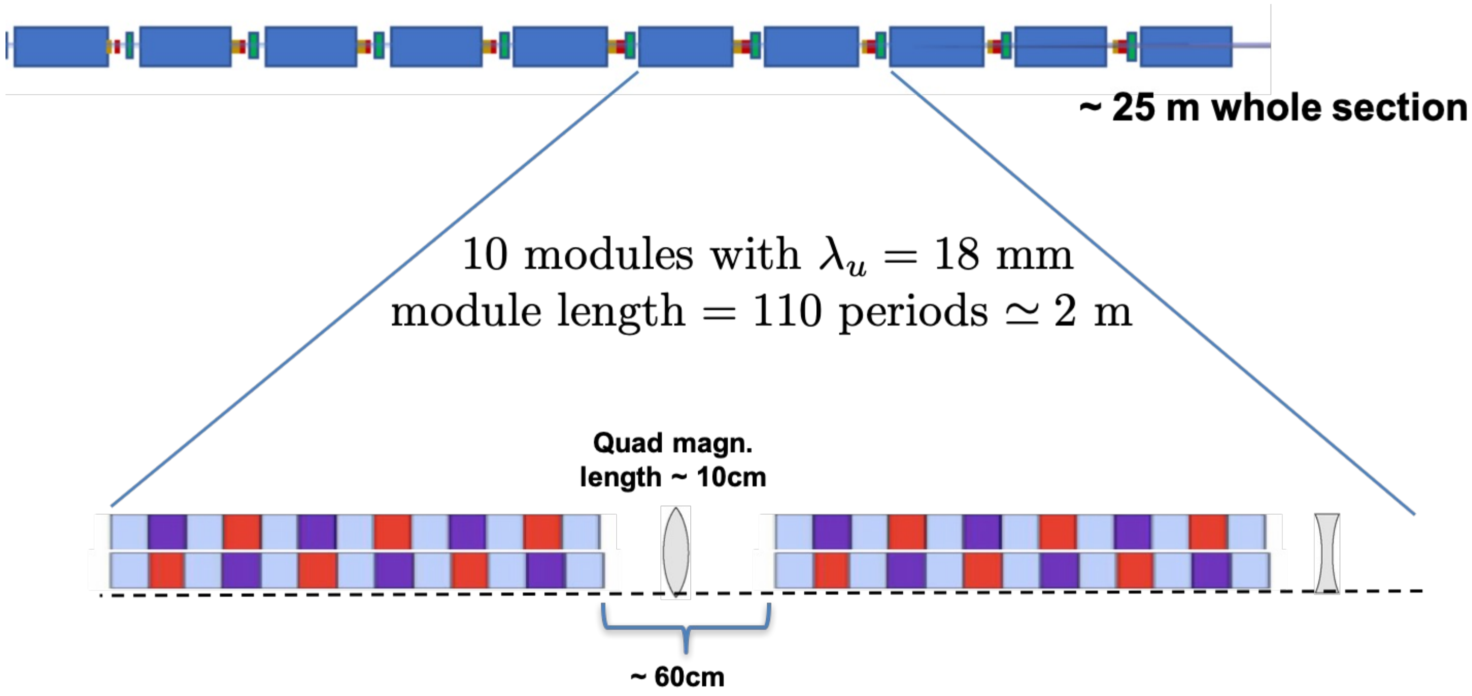
AQUA: Soft-X ray SASE FEL – Water window

- Target wavelength 3-4 nm @ 1 GeV: relatively short period required (12-20 mm)
- Total available length ~ 25-30 m ← → linac floor constraints: matching section, beam diagnostics and beam dump
- Hypotheses:
  - Optimize magnetic length/available length filling factor
  - Make sure gain length shorter than 1 undulator module length
  - 60-80 cm intra-undulator sections: Quads, BPMs, correctors, phase shifters, alignment diagnostics

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

b) SCU: collaboration agreement with FNAL for the NbTi planar prototype

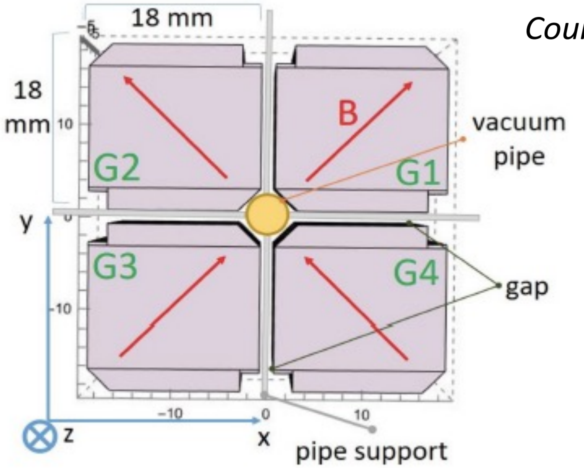
DELAYED 1 YEAR

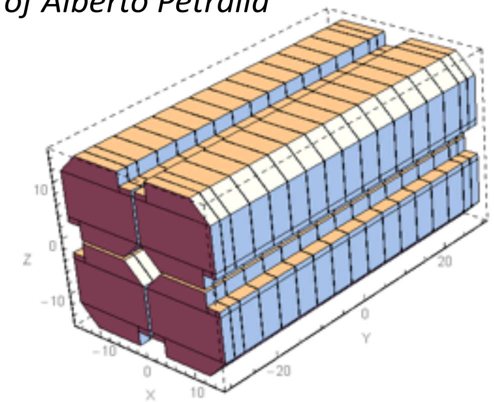


Variable polarization undulator for AQUA

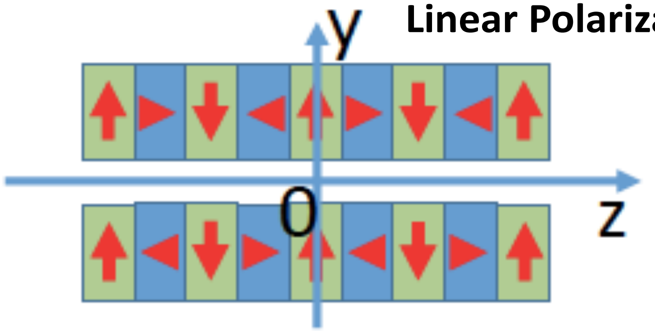
Funded by the European Union

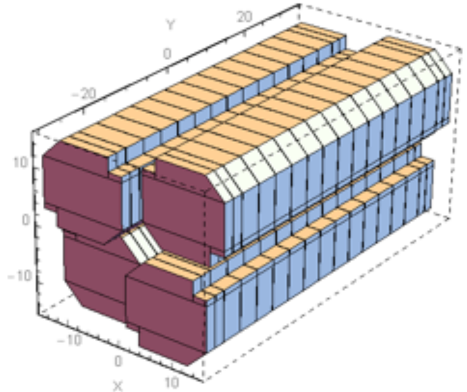
Courtesy of Alberto Petralia



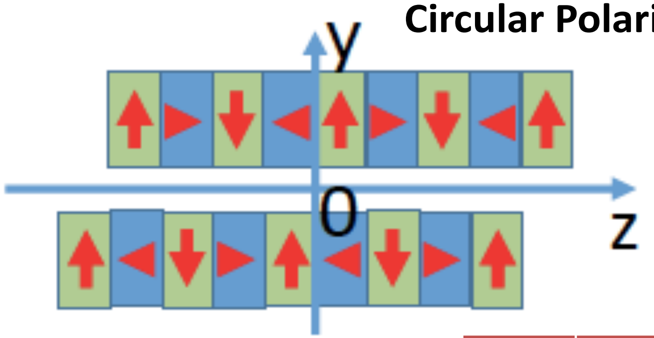


Linear Polarization





Circular Polarization



Advanced **P**lanar **P**olarized **L**ight **E**mitter-**X**

Pipe ext. diam. (mm)	5.6
Piper inner diam. *d (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_{max} (in CP)	1.111
max λ_0 (nm) (@ 1 GeV)	**5.25**

Model 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)**

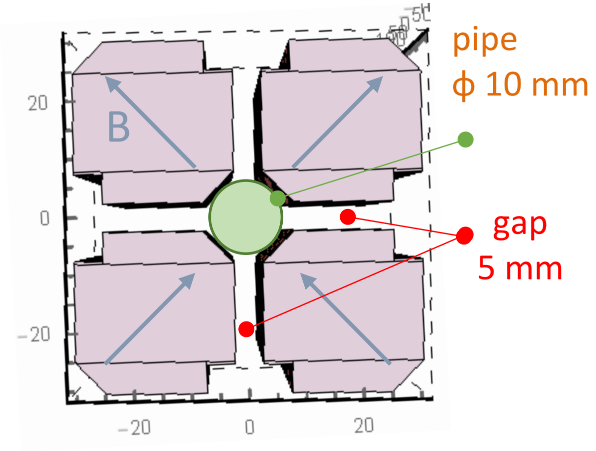
Field Integrals from RADIA

	LP (h)	CP	LP (v)	units
$\int B_x$	0	0	0	G m
$\int B_y$	0.0119	-0.0095	0.4118	G m
$\iint B_x$	0	-0.0179	-0.1322	G m^2
$\iint B_y$	0	-0.0001	0	G m^2

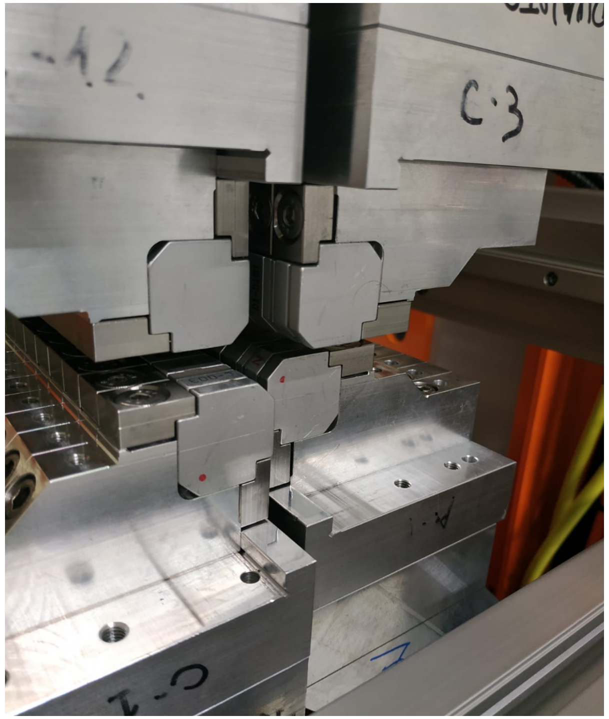
SABINA APPLE-X Undulator

Source of Advanced Beam Imaging for Novel Applications
Italian Regional Call (PI: Lucia Sabbatini)

THz user facility @ $\lambda \sim$10-100 μm – INFN-LNF
Operating at low energy e-beam - 30-100 MeV



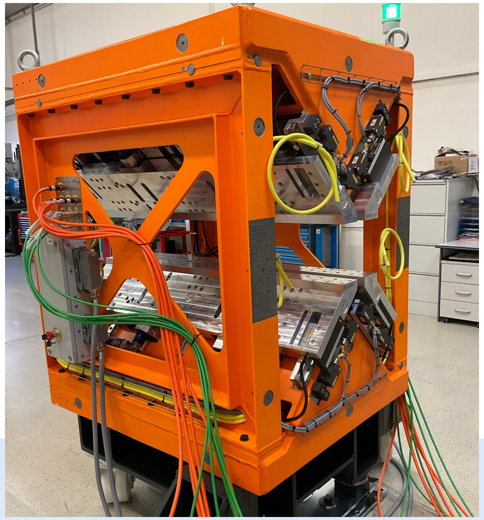
- NdFeB
- Circ./Linear pol.
- λ_u 55 mm
- Br 1.22 T
- Min gap 5 mm
- 22 periods
- Kmax 3.4 *(CP)*, 4.8 *(LP)*
- Length 1.35 m
- 3 modules



Purchased from KYMA after the tender:

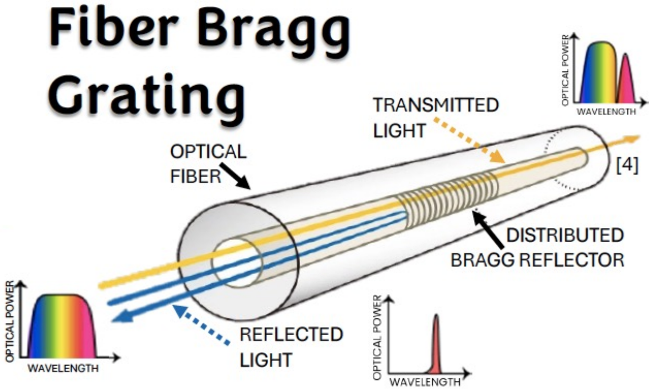
Three APPLE-X modules ←→ 1.8 M€
Each module 1.3 m long, 55mm period
—> 650 k€/module —> 500 k€/meter

- Magnetic studies and design performed by A. Petralia (ENEA)
- Undulator realization and mechanical structure by KYMA
- Detailed inspection performed at the KYMA factory
- All 3 modules already on site → learn magnetic errors in view of AQUA



Lessons learned from the SABINA APPLE-X

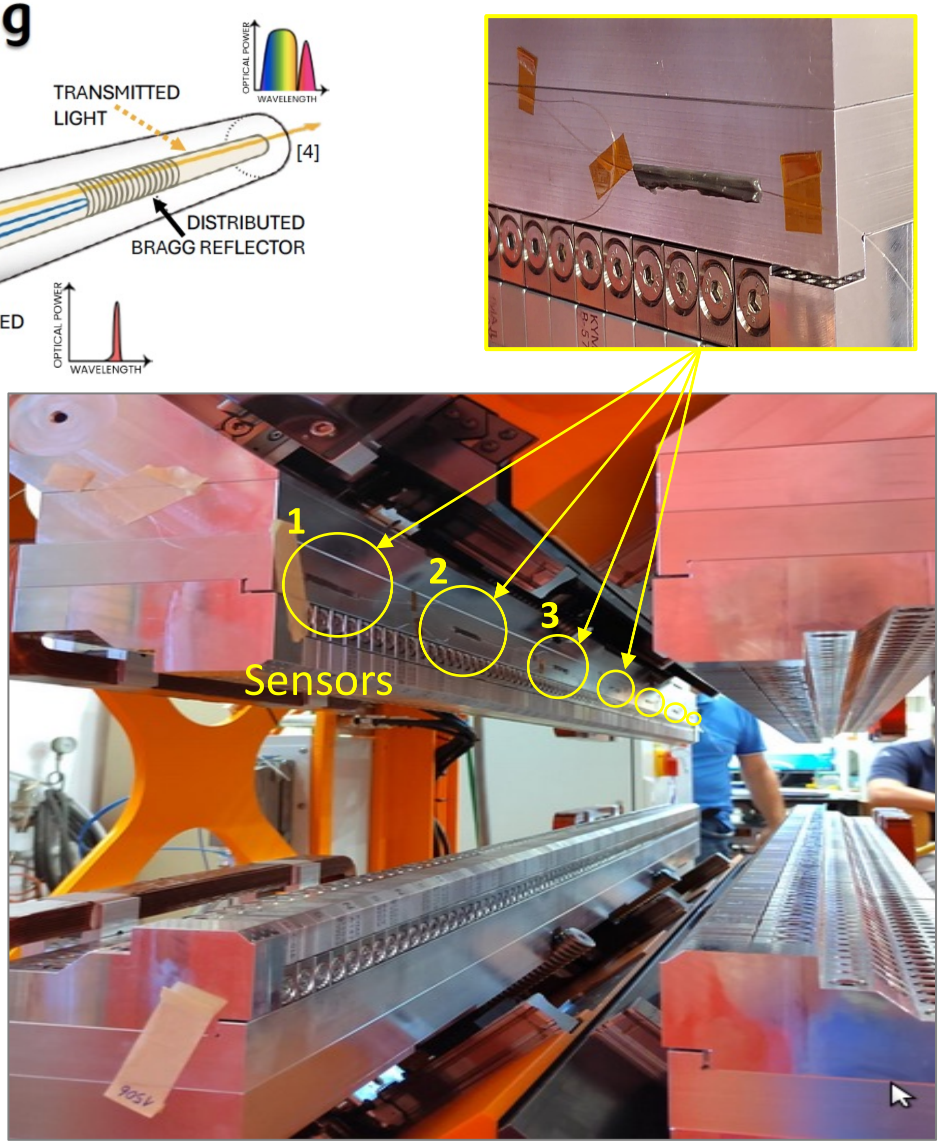
Thanks to the **Holographic Interferometry** & **Fibre Optic Sensors (HIFOS) Laboratory at *ENEA*** we measured the APPLE-X mechanical structure deformations → **negligible B field impact!**
A diffraction grating is produced by the refraction index variation of the fiber core (FBG Sensors) → any movement generates wavelength spectrum modification



APPLE-X module tested for

- Temperature dependence over a dynamic range of 3 °C
- Magnetic forces: gap – phase variations opening. Sensors were used in two different ways:
  1. as **strain measurement**, by gluing the fiber fully adhered to the surface of the magnet holder-plates;
  2. as **gap measurement** devices, by placing the sensors between adjacent plates.

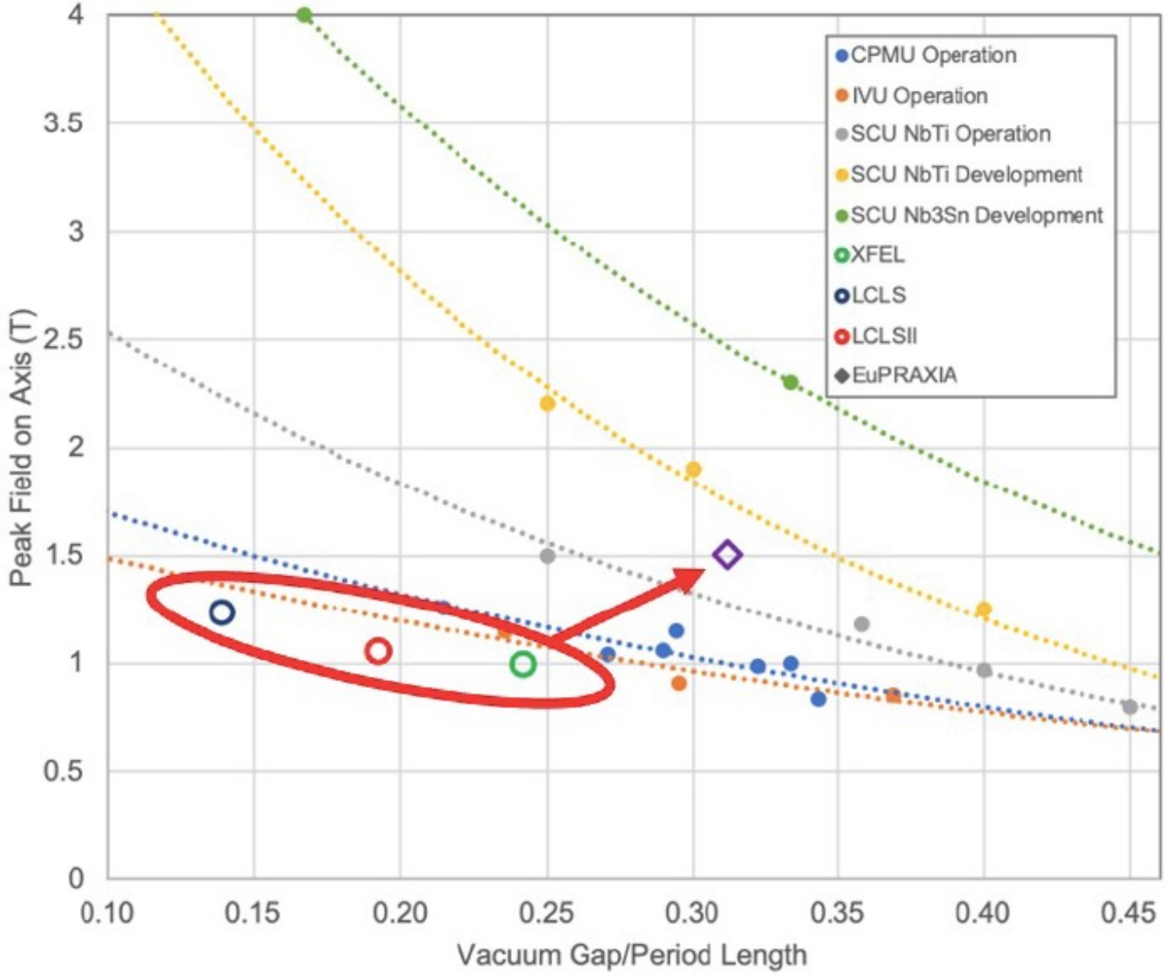
- No hysteresis or distortions independent of a gap macroscopic movement were observed → max wavelength shift of 0.2nm observed by gap sensor;
- Max wavelength shift of 0.12nm over 2.7°C/15 hours



I. Balossino, A. Selce, A. Polimadei, M. Del Franco, A. Petralia
M. Caponero, L. Giannessi, A. Vannozzi, L. Sabbatini & myself

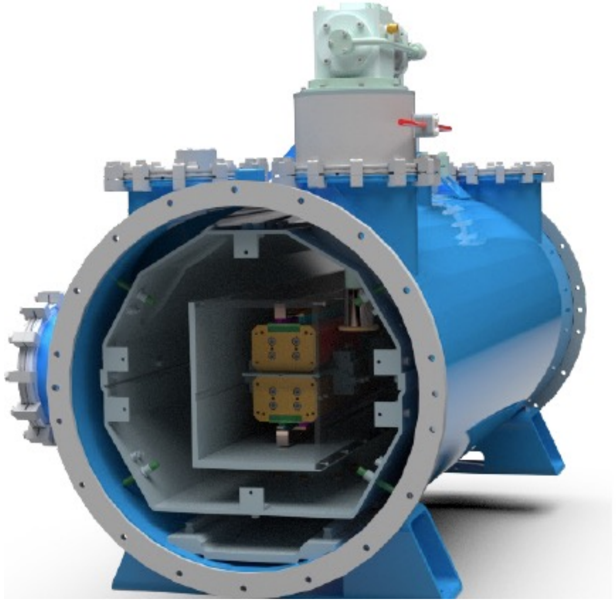
TUP220-THB @ FEL2024
THPS21 @ IPAC2024

Planar SCU prototype from FNAL



One year delay wrt the schedule:

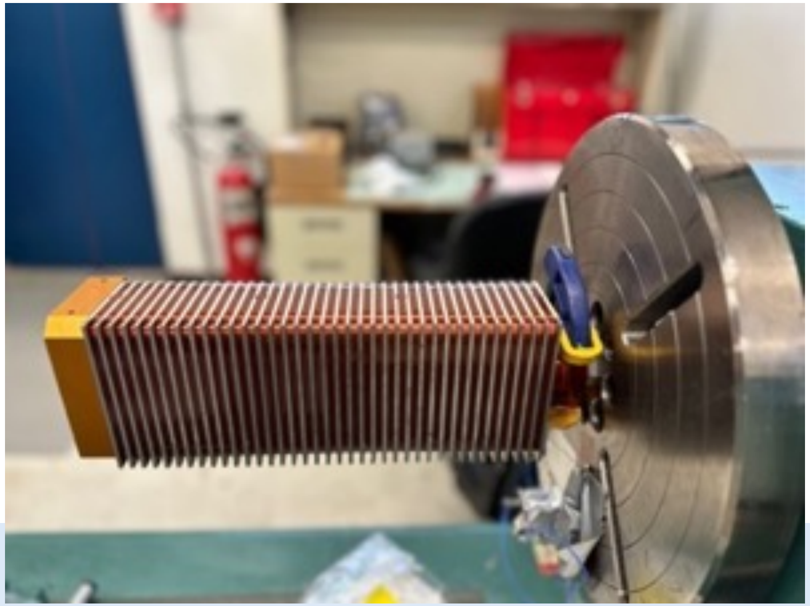
- Prototype completed → tested during 2024
- Vacuum vessel in final stages of manufacturing
- Thermal shield in procurement
- Assembly to be completed not before September 2024



Courtesy of Cristian Boffo

NbTi prototype to be deployed upstream of the APPLE-X modules
To be delivered from FNAL to INFN as a result of equipment exchange

Period	16	mm
Beam stay clear	5	mm
FEL wavelength	4	nm
Peak field on axis at 5 mm beam stay clear	1.5	T

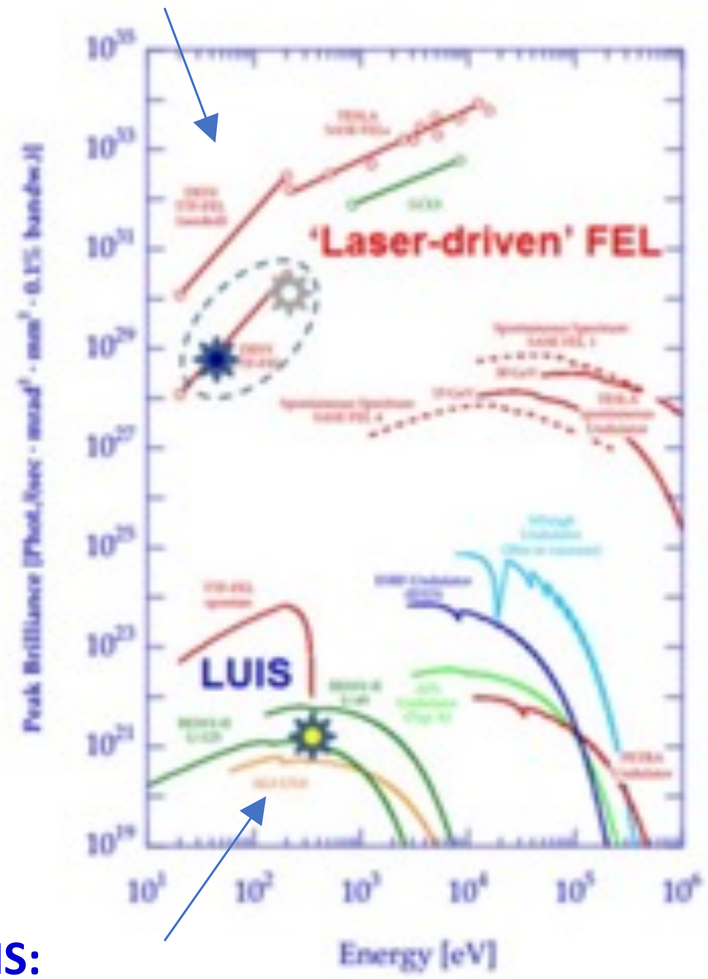


Undulator activities at ELI-ERIC

Funded by the European Union

LUIS:
coherent regime

Courtesy of Alexander Molodozhentsev



LUIS:
Incoherent regime

Plans based on the novel L2-DUHA laser system (200TW/20-100 Hz):

- **Demonstration of an LPA driven SASE-FEL at beam energy = 350 MeV, within an undulator module 4m long, next in line → seeded FEL**
- **Compact FEL operation in the "water window" at beam energy = 1.2 GeV**

Parameter	Unit	HPMU/ Swiss-FEL Aramis type [14]	SCU [16]
Undulator period	mm	15	13
Undulator gap	mm	5.5	5.2
Remanent/pole magnetic field	Tesla	1.38	2.12
On-axis magnetic field	Tesla	0.75	1.03
Undulator parameter	-	1.06	1.26
Average transverse beta-function in Undulator	m	8.9	6.4

XLS FEL beamlines cost breakdown

Funded by the European Union

PBS_CODE	PBS_MULTIPLICITY	TOTAL Cost	PROPORTIONAL_COST
6. FEL 1 and FEL 2	1	39450000	39450000
6.1. Undulators 1 and 2	1	28190000	28190000
6.1.1. Undulator units	32	24960000	780000
6.1.1.1. Cryomodule	1	650000	650000
6.1.1.2. Power supply set	1	100000	100000
6.1.1.3. Magnet and Cryostat instrumentation	1	30000	30000
6.1.2. End unit	4	800000	200000
6.1.3. Beam Instrumentation	1	2430000	2430000
6.1.3.1. Beam Current Transformer	2	40000	20000
6.1.3.2. Cavity Beam Position Monitor	34	680000	20000
6.1.3.3. View Screen	2	30000	15000
6.1.3.4. Polarix	2	1600000	800000
6.1.3.5. Arrival Monitor	1	40000	40000
6.1.3.6. Beam Loss Monitor	2	40000	20000
6.2. Afterburners 1 and 2	1	7200000	7200000
6.2.1. Afterburner units	6	7200000	1200000
6.3. FEL1 & FEL2 Vacuum System	1	1440000	1440000
6.3.1. Vacuum Pumps and Connecting Elements	36	720000	20000
6.3.2. Vacuum Instrumentation System	36	720000	20000
6.4. FEL1 & FEL2 Cryo System	1	2500000	2500000
6.4.1. Cryoplant and Ancillaries	1	2500000	2500000
6.5. FEL1 & FEL2 Control System Integration	1	20000	20000
6.5.1. Control system	1	20000	20000

2×16 helical 13mm NbTi undulators

2×3 APPLE-X 19mm undulators

Courtesy of Carlo Rossi (CERN) – beginning of 2020

D'Auria, G., Adli, E.,... Nguyen, F. *et al.* **The CompactLight Design Study** *Eur. Phys. J. Spec. Top.* **233**, 1–208 (2024). https://doi.org/10.1140/epjs/s11734-023-01076-0

Conclusions

- Undulator decisions on the 1st site: APPLE type technologies for variable and selectable polarization FEL experiments
- One planar NbTi SCU prototype module to be deployed in collaboration with Fermilab
- LPA 2nd site example case: ELI-ERIC plans to operate a water-window FEL, driven by 1.2 GeV beam energy, with SCU modules
- Undulators drive the facility cost → the final choice of the undulator technology shall depend on the particular application → specific facility budget, timeframe and wishlist

Thank you for your attention!

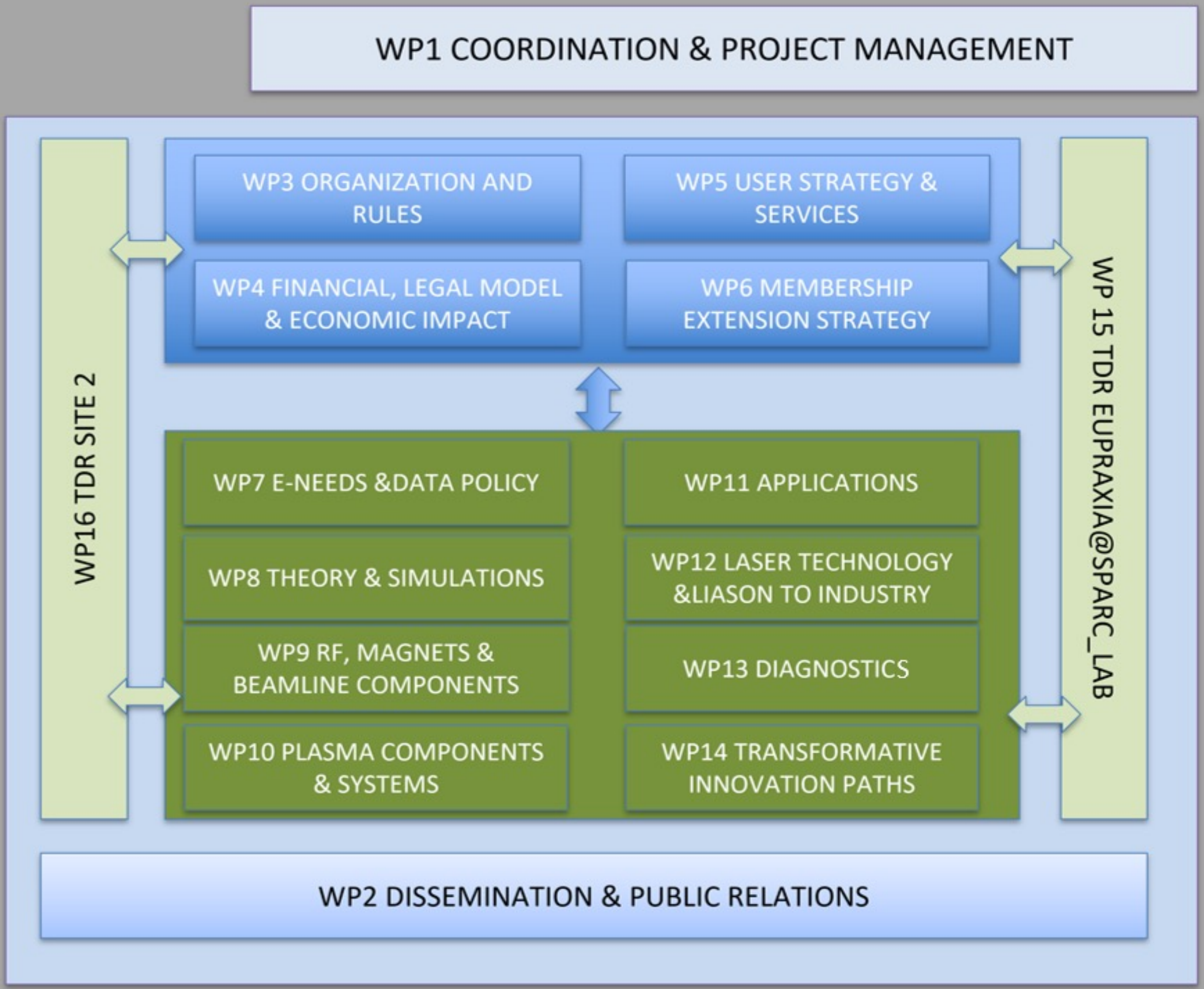
EuPRAXIA-PP Consortium

Funded by the European Union

Coordinator

EuPRAXIA-PP Structure

Funded by the European Union



Selected Committees and Boards

GOVERNING BOARD
(decision-making body, 1 representative per institute)

Steering Committee
(coordinator plus WP leaders plus experts)

Scientific/Technical Advisory Board
(external experts in user services, RI implement-tation, ESFRI aspects and technical themes)

Board of Financial Sponsors
(connection to decision makers and funding authorities)

Acknowledgements

- EuPRAXIA Preparatory Phase

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- EuPRAXIA Doctoral Network

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- EuAPS

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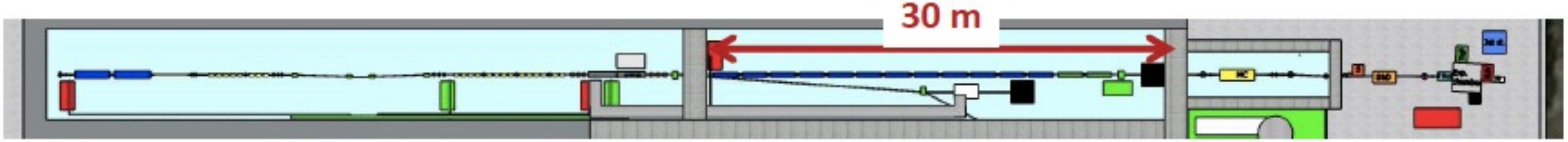
FEL Beamlines for EuPRAXIA@SPARC_LAB

Funded by the European Union

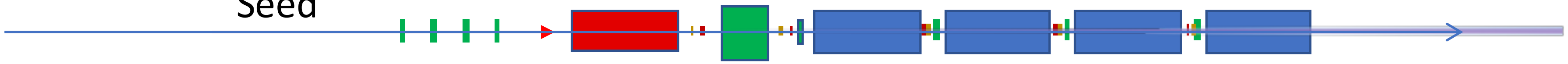


Two foreseen FEL beamlines:

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
18mm **16mm**

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 – 430 nm – Undulator based on consolidated technology.

EuPRAXIA@SPARC_LAB: undulator costs

Funded by the European Union

AQUA	Q	Unit Cost (k€)	Cost (k€)
Undulator	10	1700	17000
Phase shifters	9	150	1350
Vacuum Section	10	10	100
Quadrupole	10	15	150
Q. Power supply	10	15	150
Diag.chamber	10	50	500
Ion pump	10	15	150
BPM	10	15	150
Screen	10	12	120
CCD	10	15	150
Corrector	10	5	50
C. Power supply	10	10	100
Total			**19970**

Courtesy of Luca Giannessi

ARIA	Q	Unit Cost (k€)	Cost (k€)
Seed Laser	1	1200	1200
Optics/supports	1	400	400
Modulator	1	600	600
Radiators	4	800	3200
Phase shifters	3	150	450
Vacuum Section	5	25	125
Quadrupole	5	15	75
Q. Power supply	5	15	75
Diag.chamber	5	50	250
Ion pump	5	15	75
BPM	5	15	75
Screen	5	12	60
CCD	10	15	150
Corrector	5	10	50
C. Power supply	10	10	100
Total			**6885**

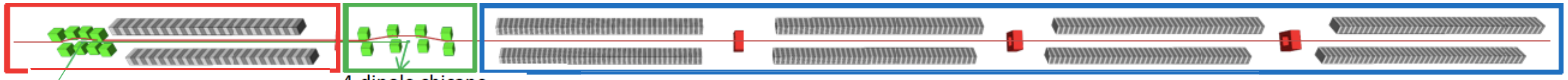
Disclaimer: **very preliminary cost values, subject to significant variations**

ARIA has no granted funds yet

ARIA baseline layout

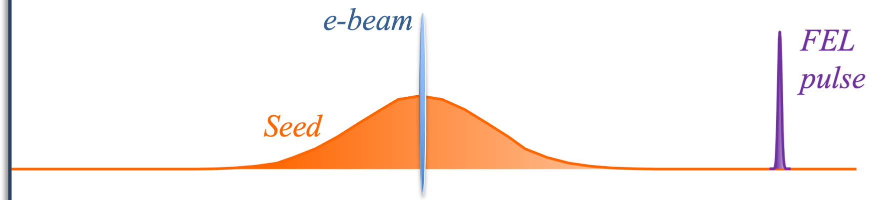
Funded by the European Union

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



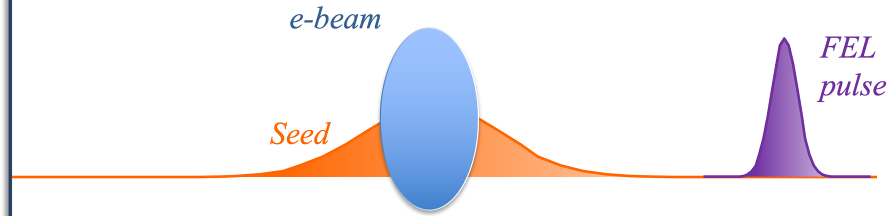
Converts electron energy modulation to spatial bunching in harmonics

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



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

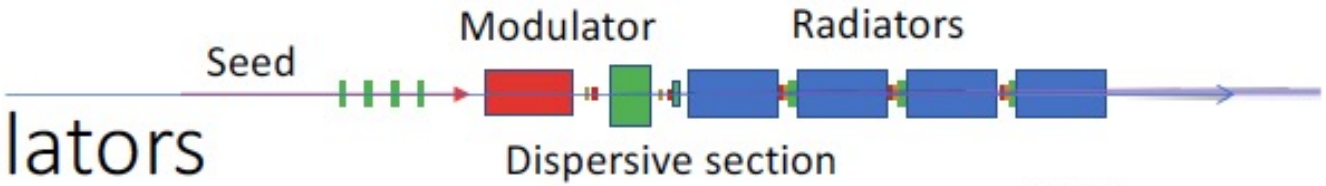
Different and complementary to long-e bunch, low current and short seed (FERMI style)



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

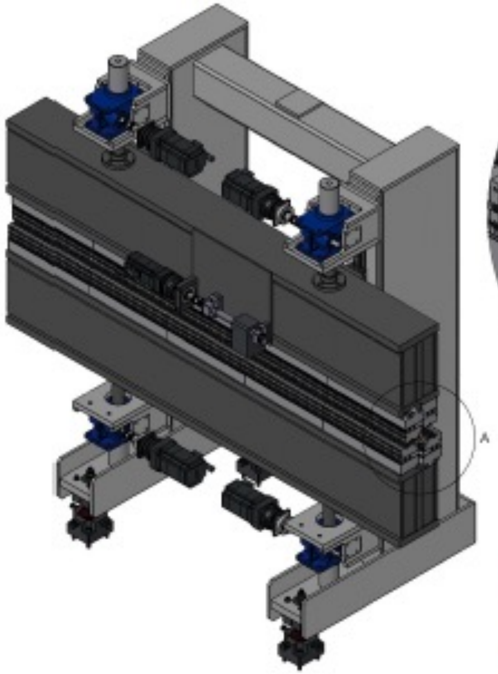
Undulators for ARIA

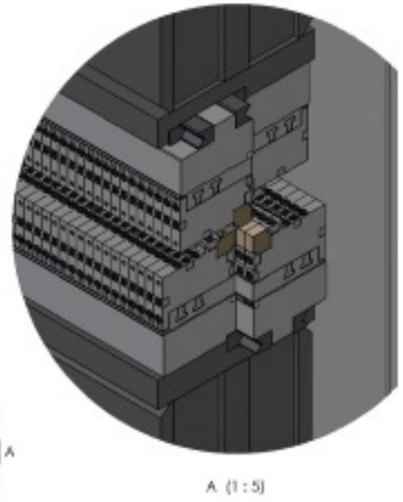
ARIA
Radiator Undulators



Main features:

- variable gap, variable phase for adjustable polarization (EPU) (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 for FERMI FEL-1

<u>Main Physical Specifications:</u>

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

Courtesy of Bruno Diviacco