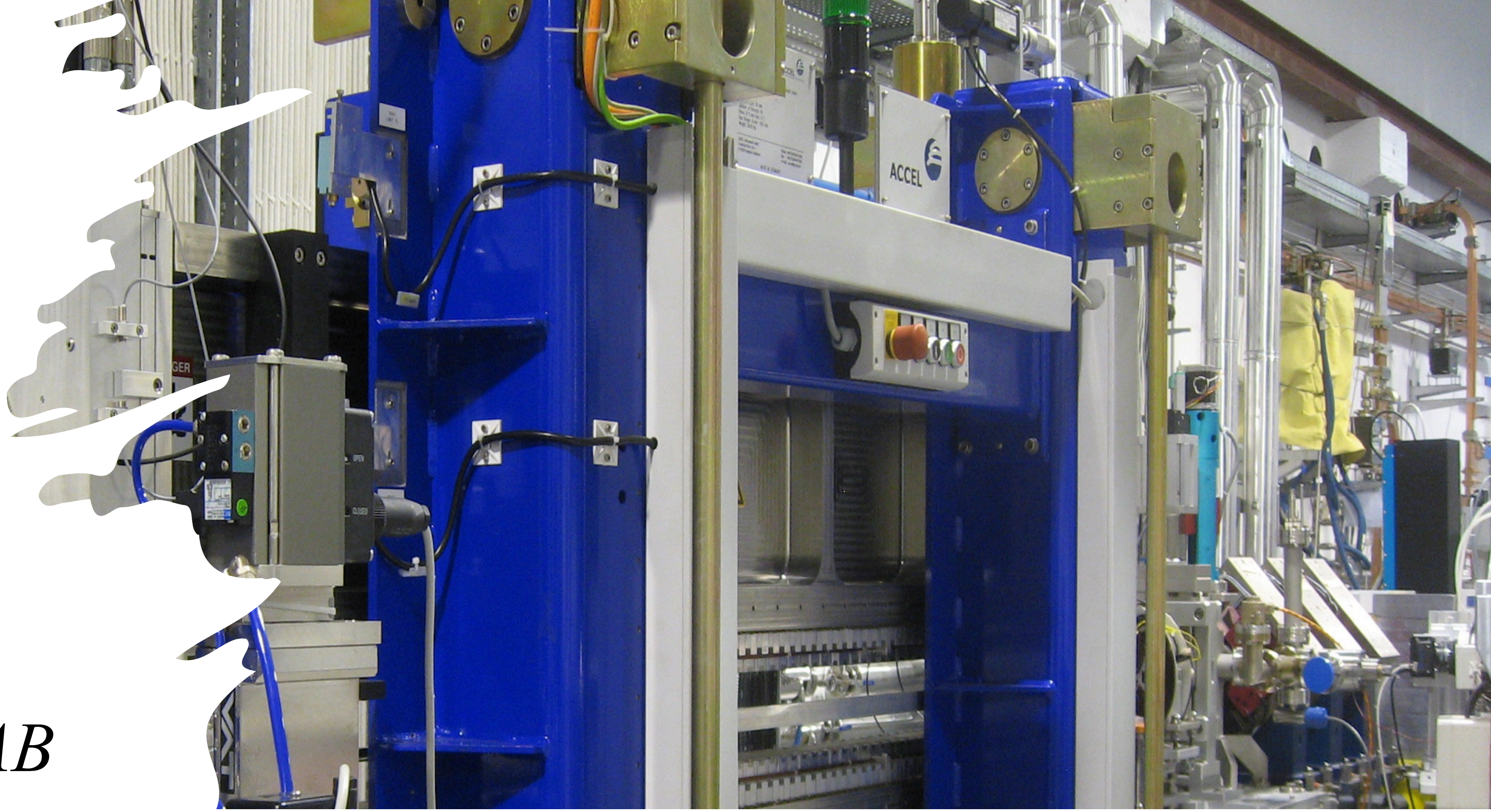
WA6 Report
FEL Schemes for *EuPRAXIA@SPARC_LAB*



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on behalf of the WA6 collaboration team

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EuPRAXIA

ENEA

TOR VERGATA Università degli Studi di Roma

Fermilab

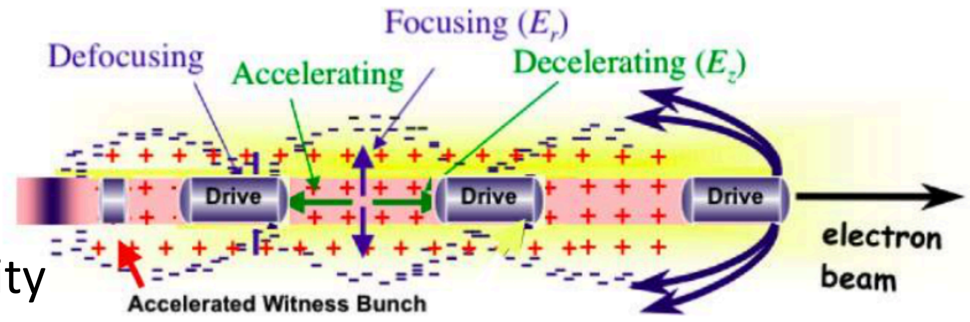
Università degli Studi di Milano

EuPRAXIA@SPARC_LAB TDR I Review Committee

Monday 22 Feb 2021, 09:00 → 18:31 Europe/Rome

EuPRAXIA at SparcLab: Mixed role of test/user facility

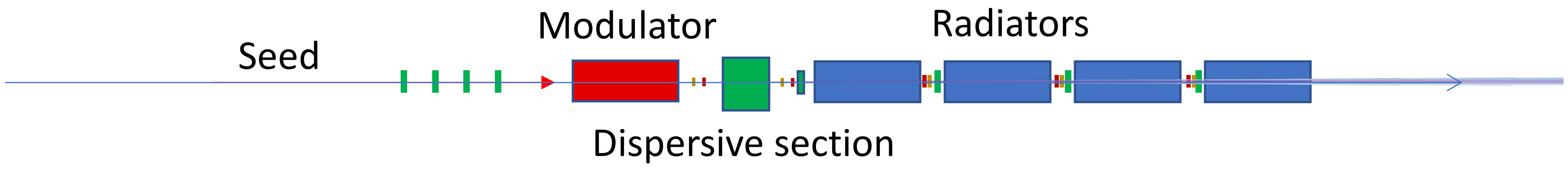
- **It's a «beam driven» choice – PWFA beam is one of the assumptions for the operation of this FEL**
- FEL lasing from a PWFA (or LWPA) is an important scientific achievement by itself
- It's also a user facility: **deliver light to experiments**. User community «grown» and «fertilized» over time by providing <u>continuous scientific opportunities.</u>



<u>Studying two FEL lines</u>:

1) AQUA: Soft-X ray SASE FEL – Water window 3 nm shortest wavelength (<u>baseline</u>)

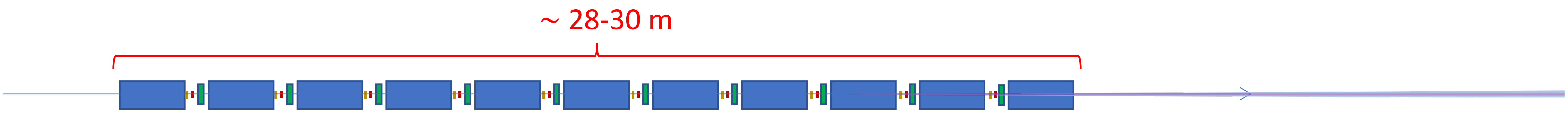
2) ARIA: VUV seeded HGHG FEL beamline for gas phase (not yet in the baseline)



OUTLINE

- **AQUA:** Constraints, choice of undulator technology & expected performances
- **ARIA:** Ready solution to cover an unexplored niche for FEL applications with a VUV seeded FEL
- **Phased Approach & commissioning**
- **Pathway to TDR**

AQUA: General constraints on FEL area



- Target wavelength 3 nm @ 1 GeV – Relatively short period required (12-20 mm)

- Total Available length ~ 28-30 m, depending on linac spreader system, matching section, e-beam diagnostics and main beam dump.

- Hypothesis:
  - 10 modules ~2 m each
    - Optimize magnetic length/available length filling factor
    - Ensure gain length shorter than UM length
  - 80 cm intra-undulator sections:
    1. Quadrupole
    2. Beam position monitor
    3. Corrector
    4. Phase Shifter
    5. Vacuum components
    6. Diagnostics/alignment

Electron beam parameters

- **Linac layout definition still in progress.** Parameters for this analysis from *«EuPRAXIA@SPARC_LAB Conceptual Design Report» D. Alesini et al. - LNF–18/03 May 7, 2018*
- **The cases A, B are considered.**
- FEL performances analyzed with Xie Scaling like relations *Ming Xie, IEEE Proceedings for Pac95, No. 95CH3584, 183, (1996)* – **Work in progress to extend the validity to large values of Energy spread/Pierce parameter** (Ref. M. Opromolla, V. Petrillo)

- **Remarks:**
  - **Energy spread plays an important role on FEL performances**
  - Peak current ~ 2kA from a S-band injector with gradient of 100-110 MeV/m implies a **relatively large compression factor (>35-40)**
  - Final energy spread ~ 200 keV (Case A) -> **before compression uncorrelated energy spread < 5 keV.** Initial incoherent energy spread evaluation.
  - Risk of energy spread growth by LSC driven microbunching instability. Still to be investigated.
  - Low beta functions, constraints on undulator module length and alignment tolerances - relaxed to 8 m in the present analysis
  - 5% contingency in the gain length estimates

76 Chapter 4. Start to end simulation results

	Units	Full RF case (A)	LWFA case	PWFA case (B)
Electron Energy	GeV	1	1	1
RMS Energy Spread	%	0.05	2.3	1.1
Peak Current	kA	1.79	2.26	2.0
Bunch Charge	pC	200	30	30
RMS Bunch Length	µm (fs)	16.7 (55.6)	2.14 (7.1)	3.82 (12.7)
RMS normalized Emittance	mm mrad	0.5	0.47	1.1
Slice Length	µm	1.66	0.5	1.2
Slice Charge	pC	6.67	18.7	8
Slice Energy Spread	%	0.02	0.03	0.034
Slice normalized Emittance (x/y)	mm mrad	0.35/0.24	0.45/0.465	0.57/0.615
Undulator Period	mm	15	15	15
Undulator Strength $K(a_w)$		0.978 (0.7)	1.13 (0.8)	1.13 (0.8)
Undulator Length	m	30	30	30
Pierce parameter ρ **(1D/3D)**	$\times 10^{-3}$	1.55/1.38	2/1.68	2.5/1.8
Radiation Wavelength	nm (keV)	2.87 (0.43)	2.8 (0.44)	2.98 (0.42)
Photon Energy	µJ	177	40	6.5
Photon per pulse	$\times 10^{10}$	255	43	10
Photon Bandwidth	%	0.46	0.4	0.9
Photon RMS Transverse Size	µm	200	145	10
Photon Brilliance per shot	(s mm^2 mrad^2 bw(0.1%))$^{-1}$	1.4 $\times 10^{27}$	1.7 $\times 10^{27}$	0.8 $\times 10^{27}$

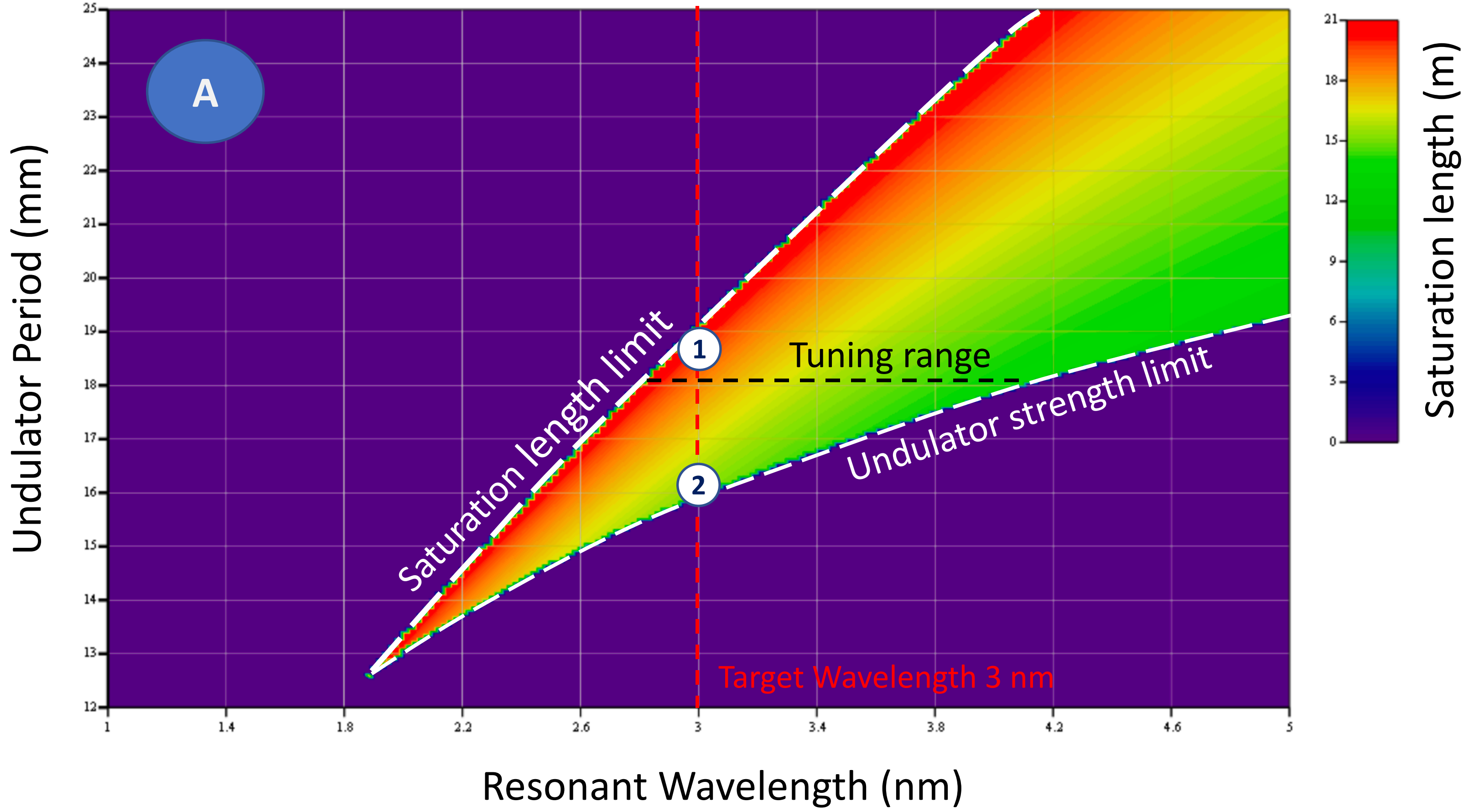
Table 4.1: Beam parameters from start-to-end simulations for full RF and for plasma wakefield acceleration cases with electron (PWFA) or laser (LWFA) driver beam

A X-band conventional linac

B X-band conventional linac + PWFA

Period – central resonance map

Planar permanent magnet undulator (PMU) Br=1.2 T – 1 GeV



Undulator strength limit: **set by design** (predictable)

Saturation length limit: **depends on effective beam parameters** (less predictable)

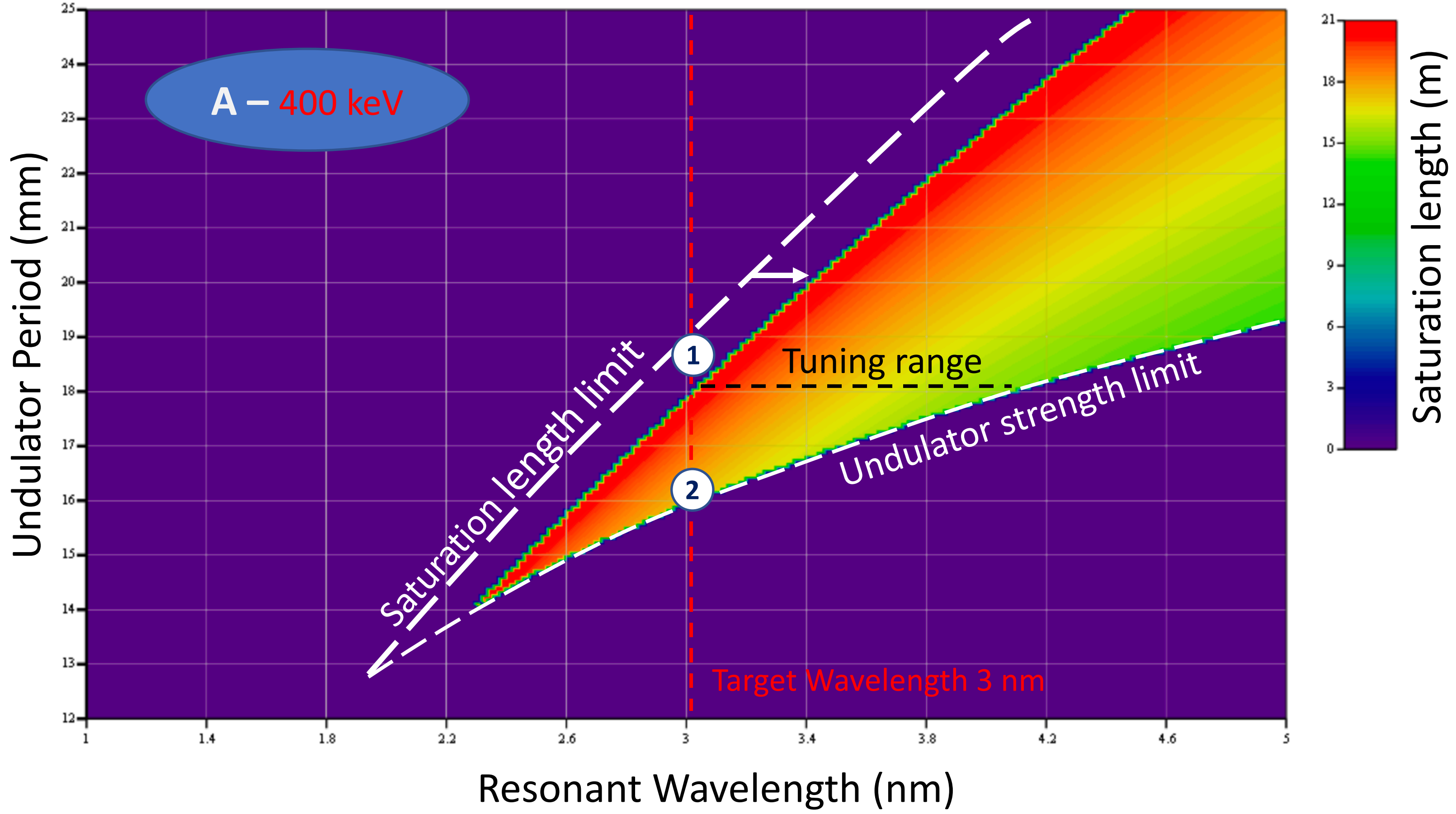
Choices:

1. Tuning range suggests 18-19 mm period length, **but no saturation length contingency**

2. Sat. length "contingency" suggests 16 mm, **but no tuning range**

Period – central resonance map – doubling energy spread

Planar permanent magnet undulator (PMU) Br=1.2 T – Magnetic gap 6 mm



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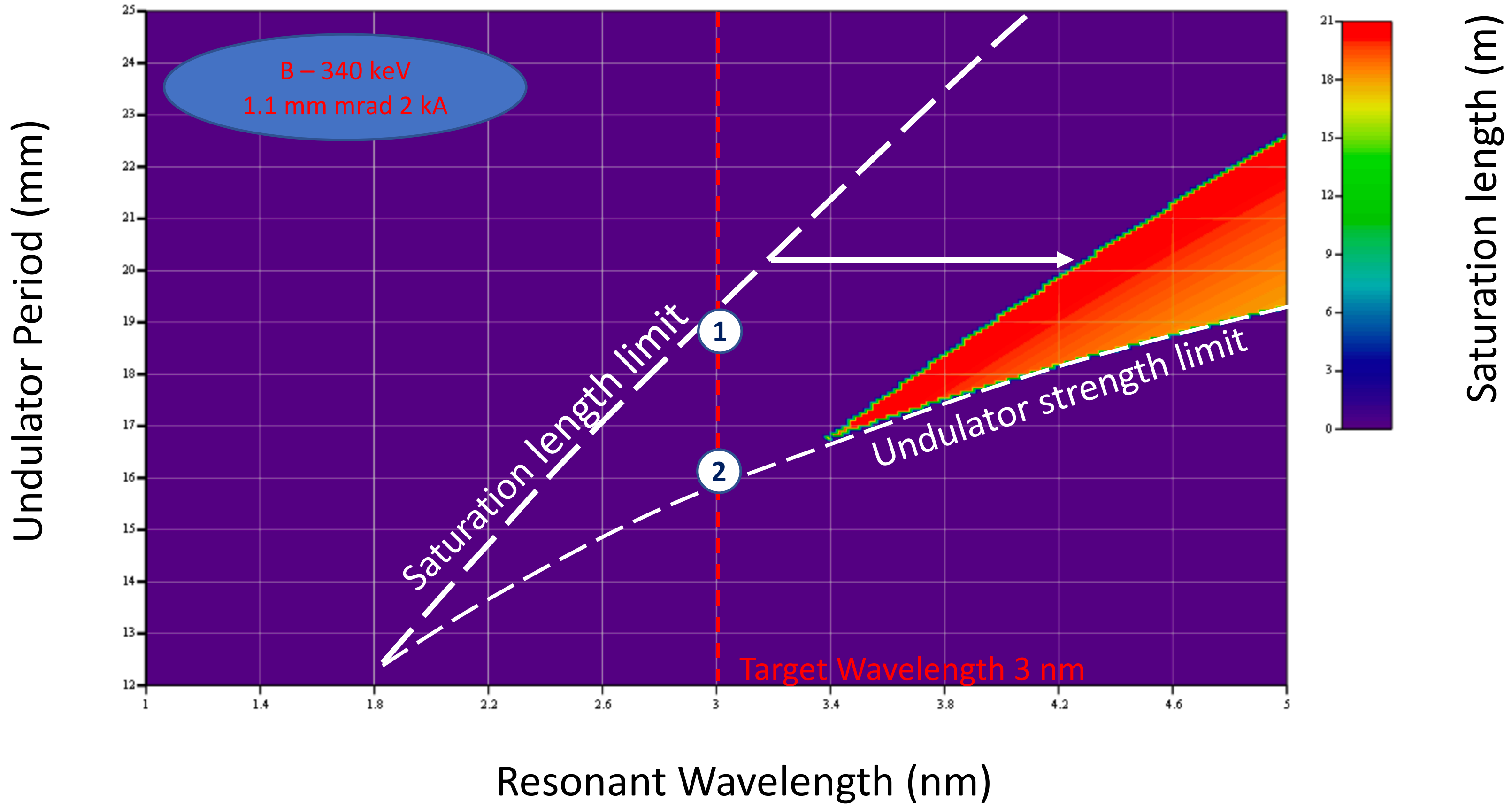
An increased energy spread will cause a shift of (1) out of the saturation region

Period – central resonance map – Beam (B) PWA with proj. emit.

Planar permanent magnet undulator (PMU) Br=1.2 T – Magnetic gap 6 mm



Undulator strength limit: **set by design** (predictable)

Saturation length limit: **depends on effective beam parameters** (less predictable)

Choices:

1. Tuning range suggests 18-19 mm period length, **but no saturation length contingency**
2. Sat. length "contingency" suggests 16 mm, **but no tuning range**

An increased energy spread will cause a shift of (1&2) out of the saturation region

Undulator technology

- **Best: period close to 16 mm**, with the possibility to increase the peak magnetic field to maintain some tuning range.

- Space of parameters explored by **CompactLight design study (Ref. F. Nguyen)**. We are implementing the UM parametrization in our calculation models.
- Preliminary contacts with ind. representatives for costs analysis and technical challenges.

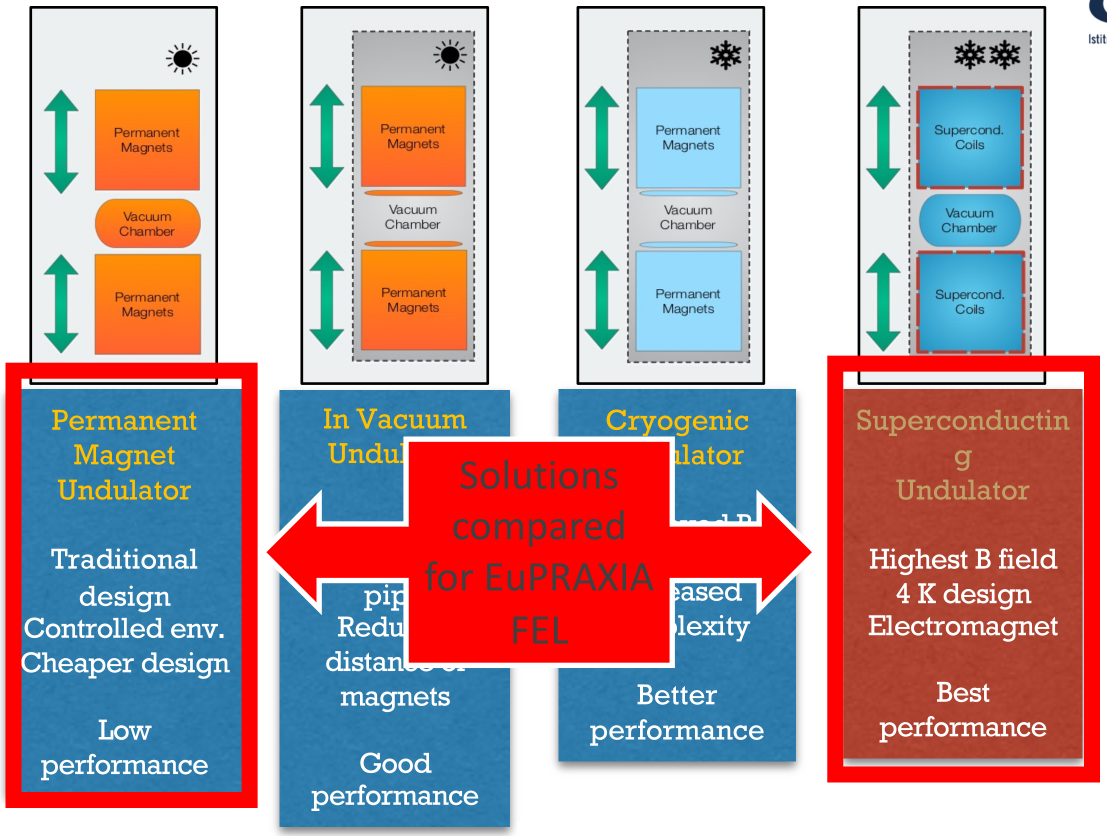
- Main options under consideration:

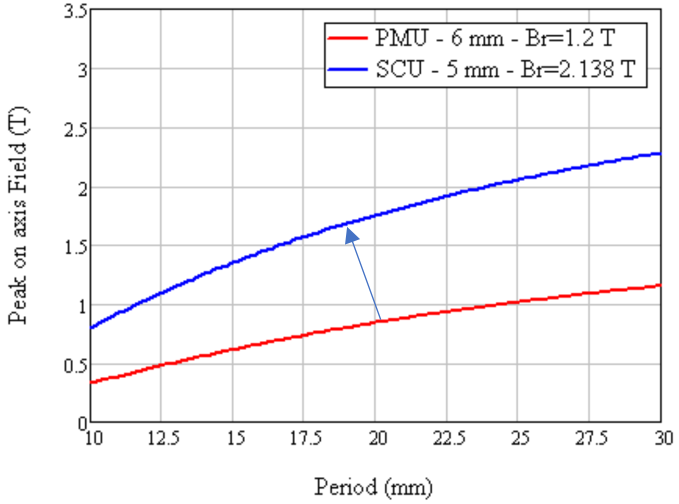
  1. **Apple X undulator**, increased PM field by "geometry"

  2. **Superconducting undulator (SCU)**

     - **Collaboration agreement with FNAL (Ref. C. Boffo) for the realization of a first SCU prototype in preparation**

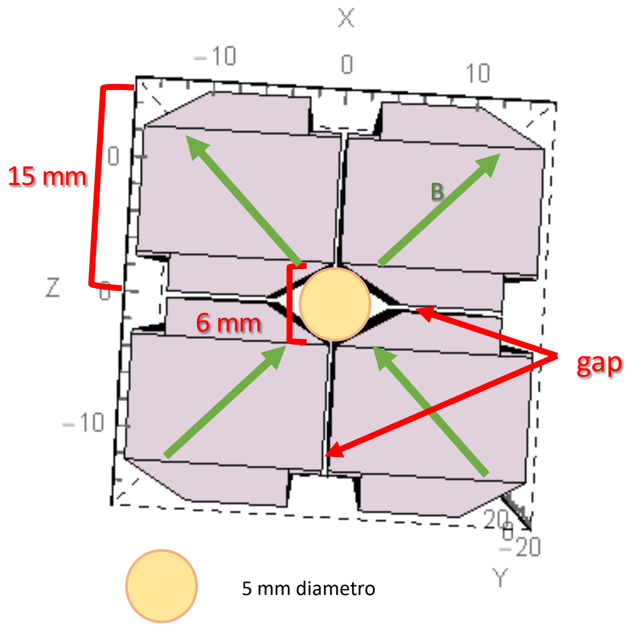
     - "Equivalent"remanent field 2.138 T for the SCU. Beam clearance of 5 mm



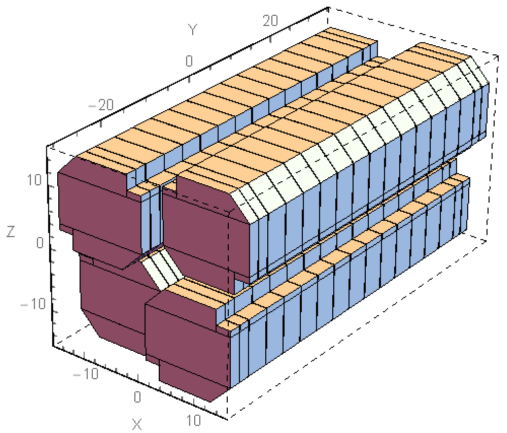


Apple X – PMU: study in progress – RADIA Model

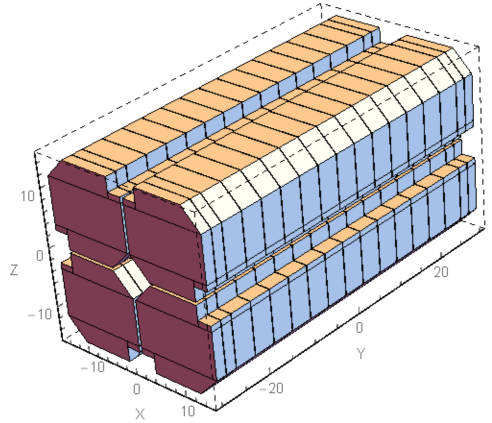
Period = 16 mm
Gap min = 0.5 mm – Beam stay clear 5 mm
Br = 1.3 T
Block/Periods = 4
Magnets heights = 15 mm
Material: NeFeBo, Br =1.3 T



Linear



Helical



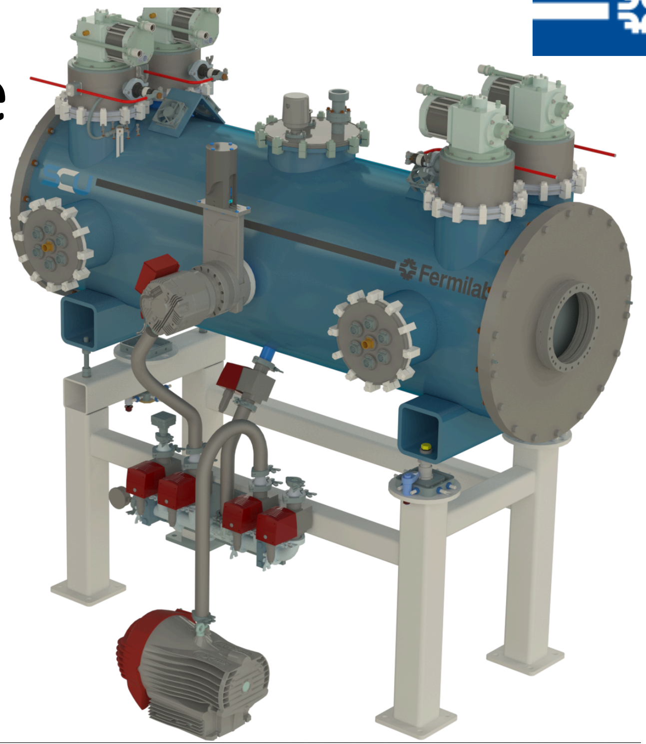
	Pipe 6 mm			Pipe 5 mm		
λu (mm)	14	15	16	14	15	16
K max	1.07	1.24	1.42	1.32	1.5	1.7
Max wl (nm)	2.88	3.47	4.20	3.42	4.18	5.11
Min wl (K=0.9)	2.57	2.75	2.93	2.57	2.75	2.93

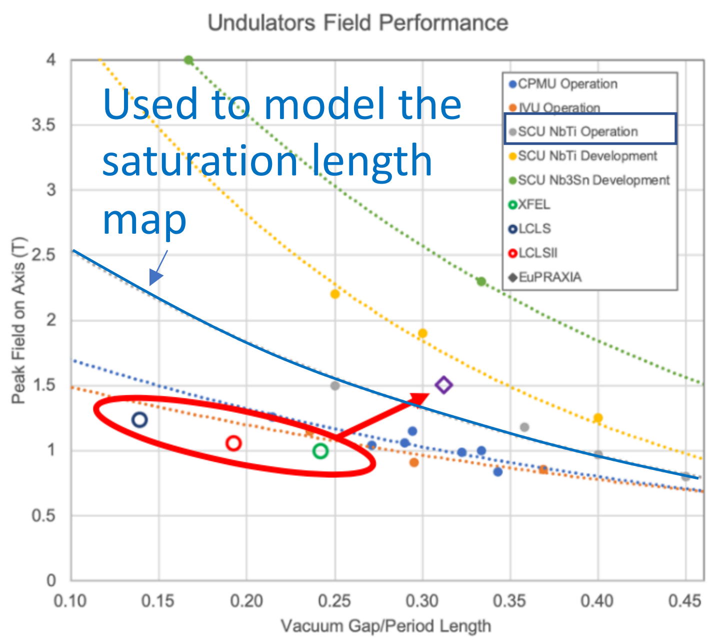
	Pipe 6 mm			Pipe 5 mm		
λu (mm)	14	15	16	14	15	16
K max	0.54	0.63	0.72	0.66	0.76	0.86
Max wl (nm)	2.36	2.73	3.16	2.63	3.09	3.62

Courtesy of A. Petralia

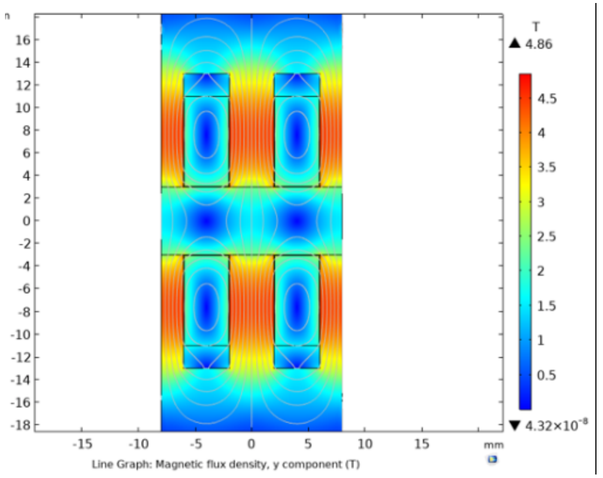
Realization of SCU prototype

- **Collaboration agreement with FNAL in preparation**
- Design based on improved NbTi technology to further increase field explored.
- Final specs to be defined after mockup phase.
- Helical polarization would provide a further advantage, a flexible design to allow replacement of cold mass is foreseen.
- Integration of SC correctors/quadrupoles in the cold mass to increase the filling factor.





Parameter	Value	Unit
Period	< 16	Mm
Beam stay clear	5	mm
FEL wavelength	~3	Nm
K-value	>1.2	-
Beam heat load	TBD	W
Ramp to operating field	<600	s
Cooling	Cryocoolers	-
Operating temperature	4.2	K
Magnet length	1.5-1.6	m
Flange to flange length	2.0-2.5	m
Beam height	TBD	m
Vacuum vessel diameter	<1	m
Insulation vacuum	1*10^{-5}	mbar
Cooldown time	<7	days

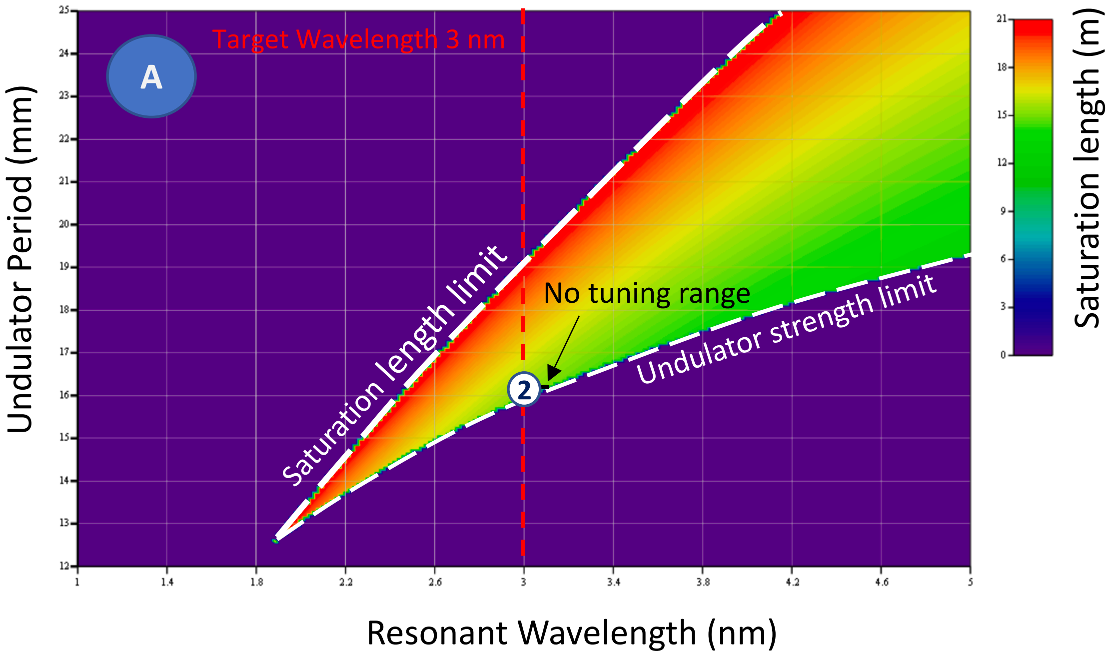


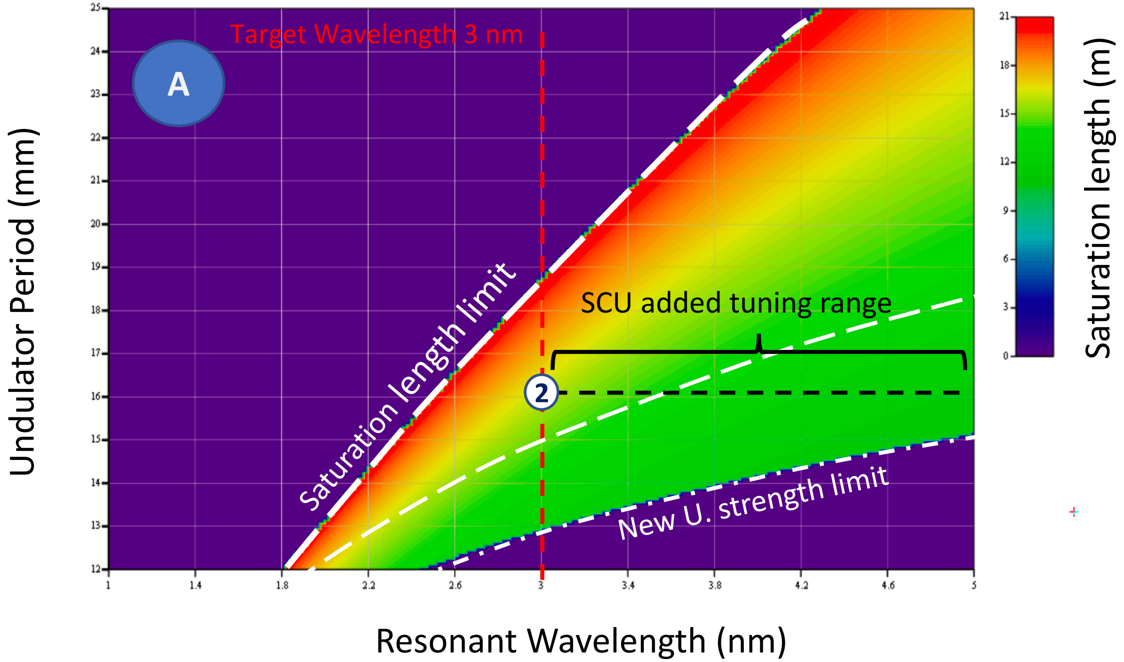
Courtesy of C. Boffo

SCU solution: Extended tuning range

- PMU 16 mm period
- Magnetic gap 6 mm; beam stay clear 5 mm

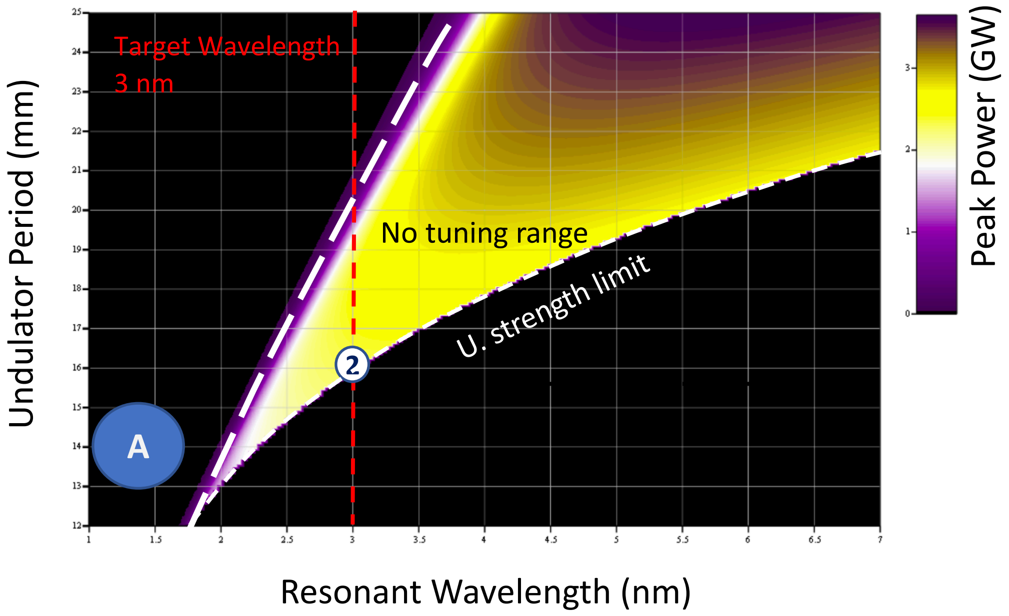
- SCU Nb Ti operation parameters, beam stay clear aperture 5 mm



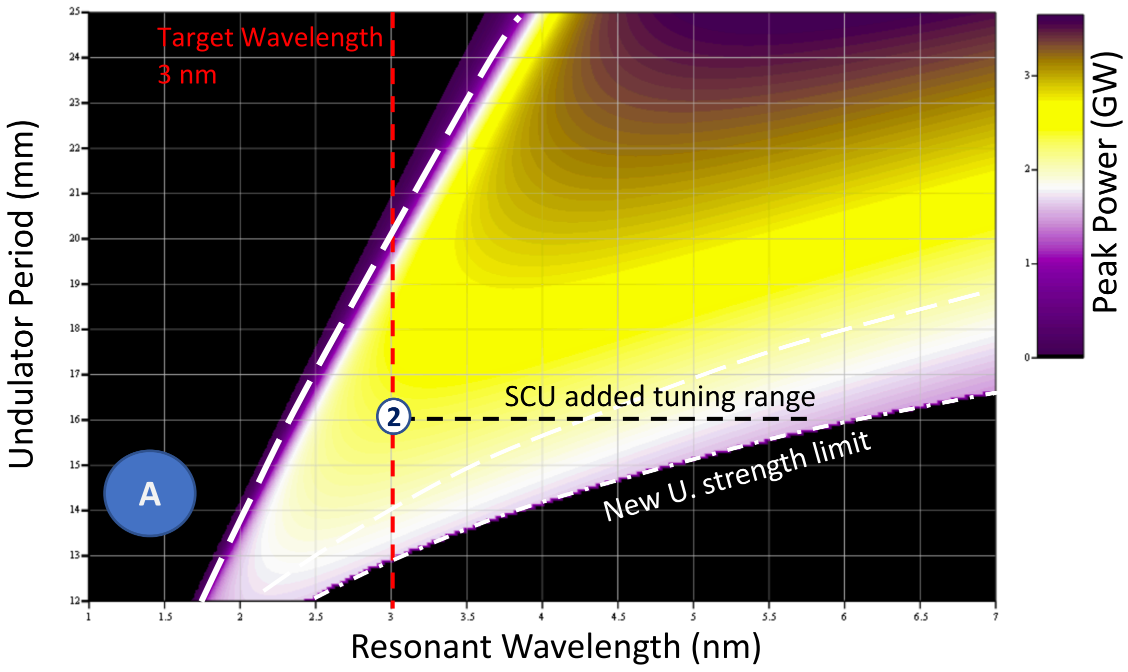


FEL Performances – PMU vs SCU

- **PMU** Br = 1.2 T - Planar polarization – 6 mm gap – beam stay clear 5 mm

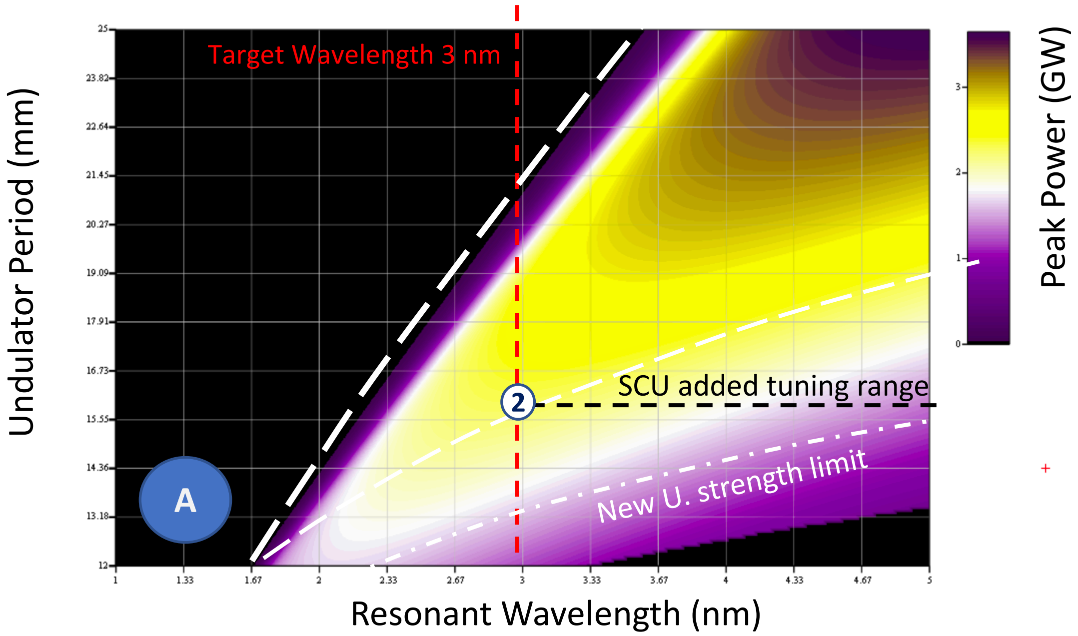


- **SCU** - Planar polarization – equivalent beam stay clear 5 mm

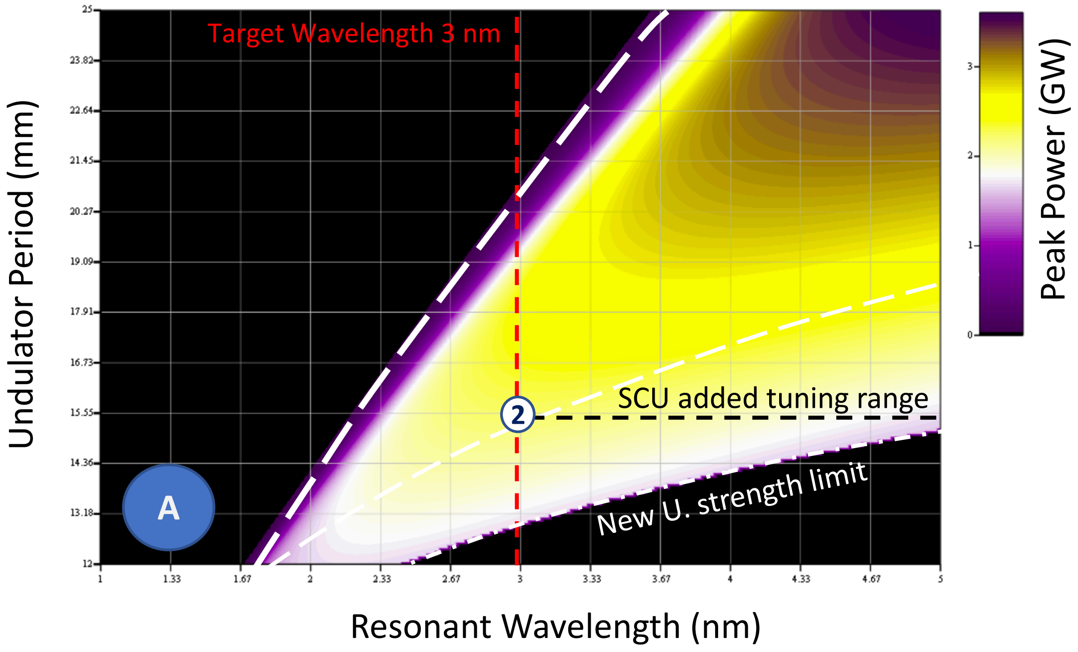


FEL Performances – SCU linear vs. SCU helical

- **SCU** Nb Ti operation parameters, beam stay clear aperture 5 mm – Helical polarization

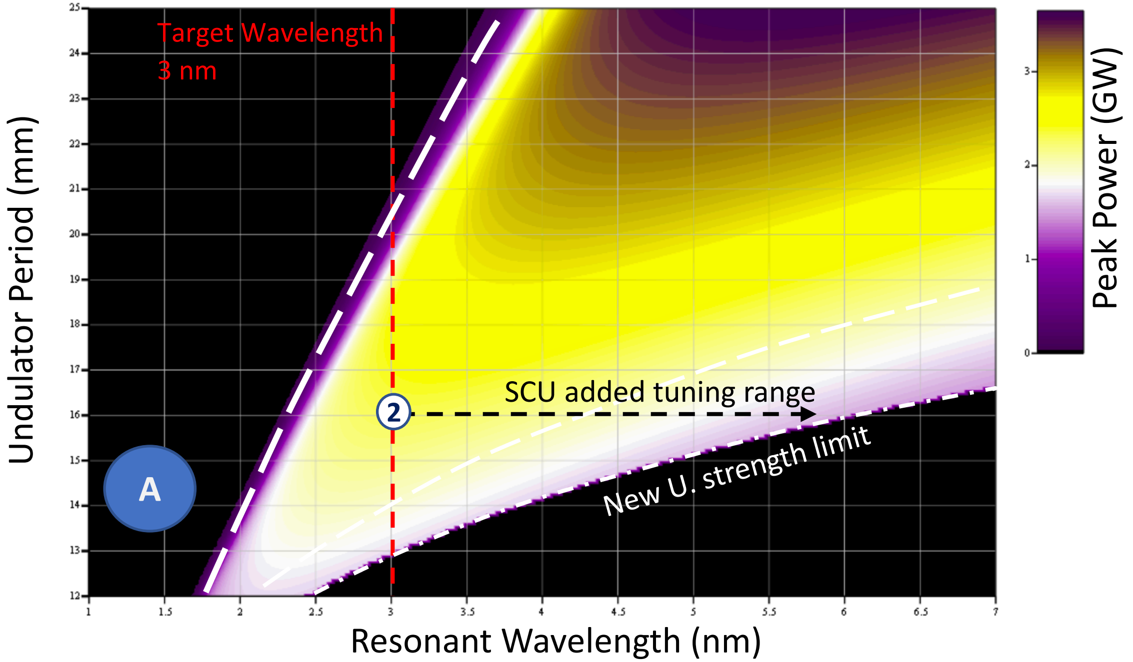


- SCU Nb Ti operation parameters, beam stay clear aperture 5 mm

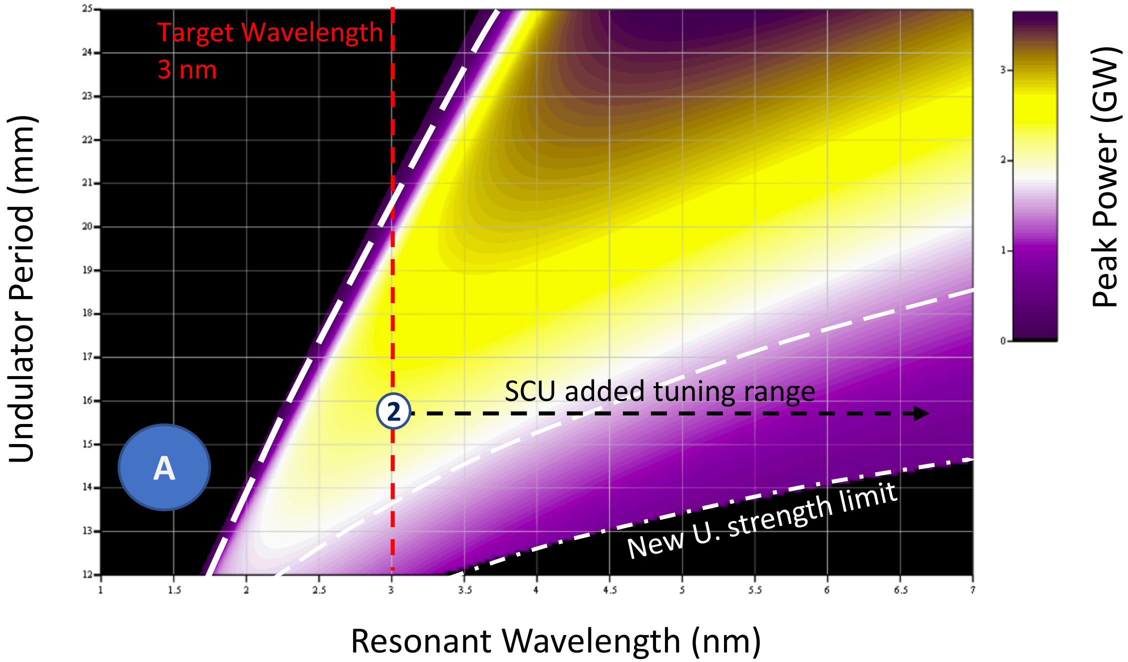


FEL Performances – PMU vs SCU

- SCU - Planar polarization – equivalent beam stay clear 5 mm



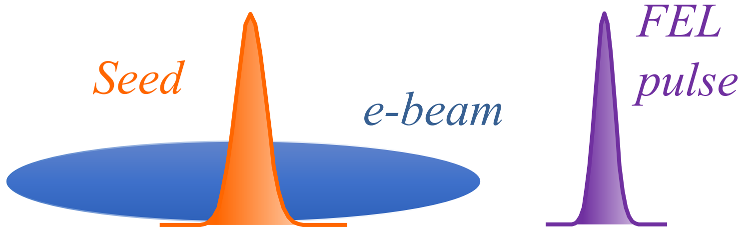
- SCU - <u>Helical polarization</u> – equivalent beam stay clear 5 mm



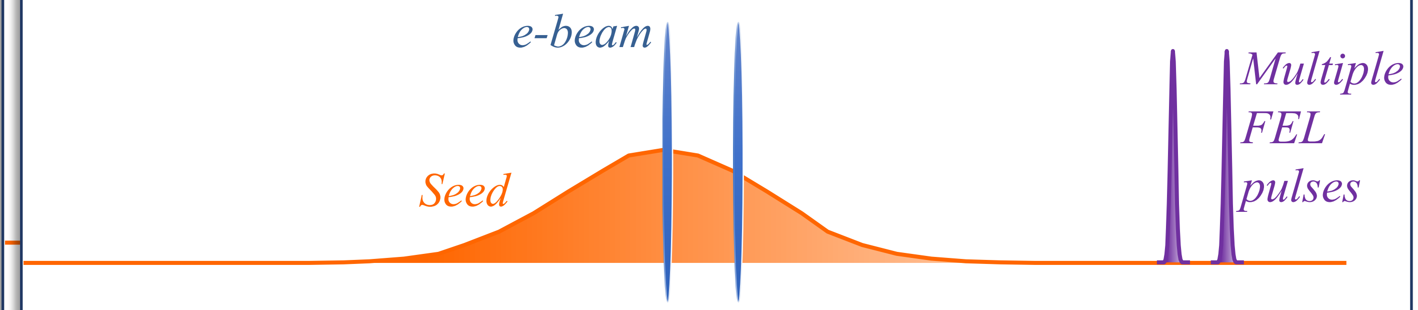
EuPRAXIA @ SparcLab: some special features

1) **E-bunch shape flexibility**: low charge short pulse operation mode – high charge long bunch mode – <u>double pulses</u>
2) **Synchronization** with external lasers
3) Very **low e-beam temporal jitter** (a pre-requisite for PWA and LWA acceleration)

We propose a «Special» SEEDED FEL line in the long wavelength range (50-180 nm)



Long-e bunch, low current – short seed.
Pulse duration at "long wavelengths" limited by **narrow gain bandwidth** (***FERMI*** like)



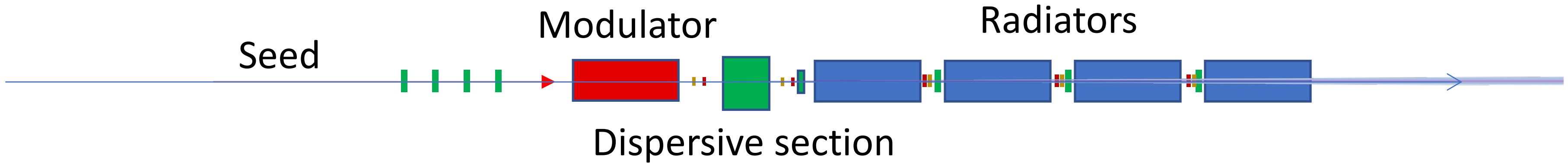
Short & high current e-bunch, long seed.
Pulse duration limited by **e-bunch duration** & large **gain bandwidth**

(Flexible: can produce multiple phase-locked pulses)

- **No other seeded FEL facility** covers the range **50-180 nm**, except fo the DALIAN light source (specialized in long pulses)
- Superposition with HHG sources, but **without their limitations on POLARIZATION, phot. energy tuning & intensity**
- **Can be synchronized** with HHG sources or external lasers for **multicolor multi-pulse pump and probe operation**

Second FEL line: ARIA

SEEDED FEL line – Full coherence = laser-like statistics



- Wavelength range 50 – 180 nm – continuously tunable – 10-100 uJ pulse energy
- Total physical length 20 m (not just magnetic) modulator – dispersive section – 4 radiators
- Variable polarization (circular left/right, horizontal and vertical)
- Design almost readily available. Could be ready for users since the first commissioning phase. Would contribute to establish a user community for the EuPRAXIA at SparcLab user facility
- Undulator cost estimate 3.5 M€ - not yet in the baseline

ARIA performances analysis

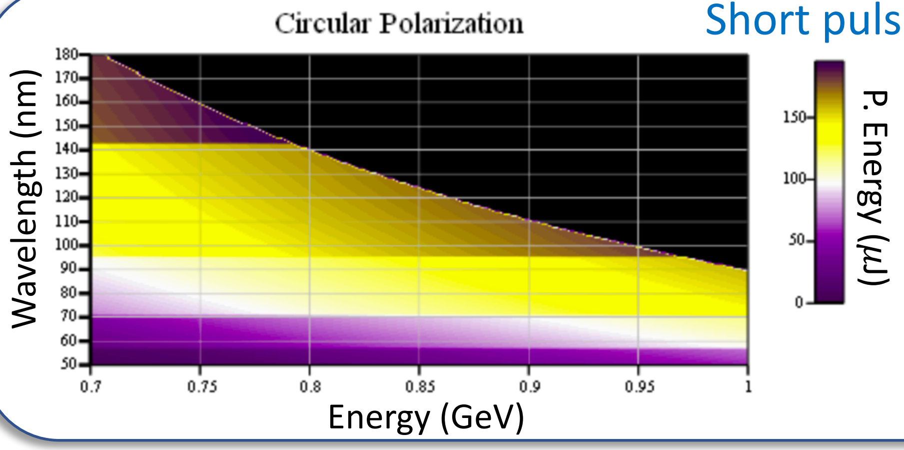
Same Xie model used for AQUA, with more relaxed beam parameters

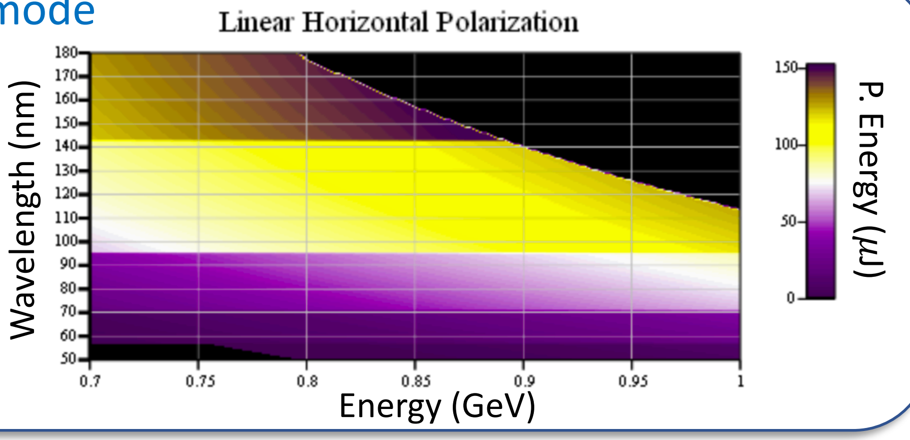
Undulator	
Modulator length	3 m
Mod. period length	10.5 cm
Dispersion	150 μm
Undulator Type	Apple - II
Radiator period length	5.5 cm
Radiator length	4 x 2.1 m

A = Long pulse mode
B = Short pulse mode

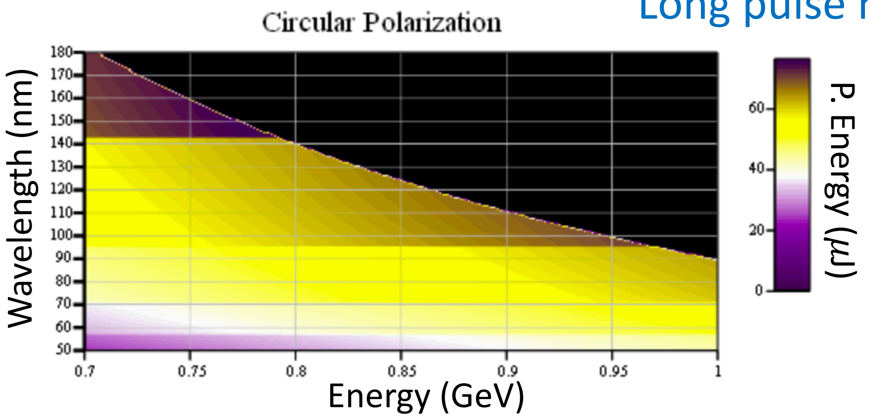
e-beam	
Energy	0.7 -> 1 GeV
Peak current (A - B)	700 – 1500 A
E-bunch charge (A - B)	200 - 30 pC
Emittances (A - B)	1.5 - 2 mm - mrad
Energy spread (A - B)	1 – 3 (x10^{-4})

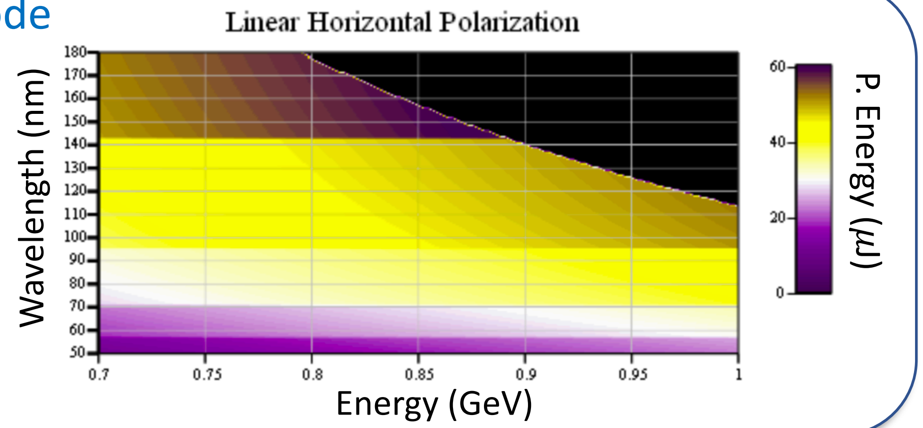
Short pulse mode





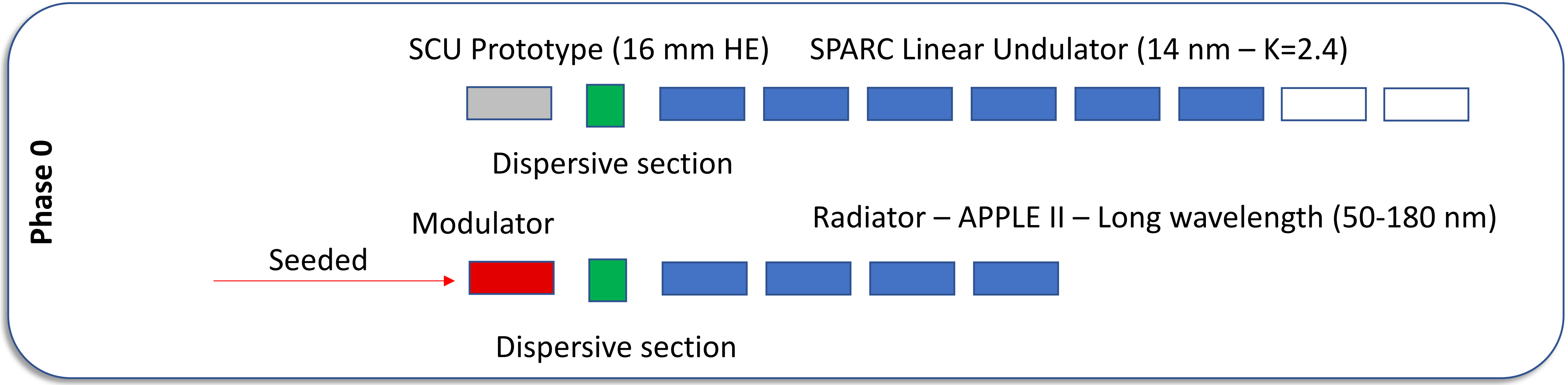
Long pulse mode





Phased Approach – Phase 0

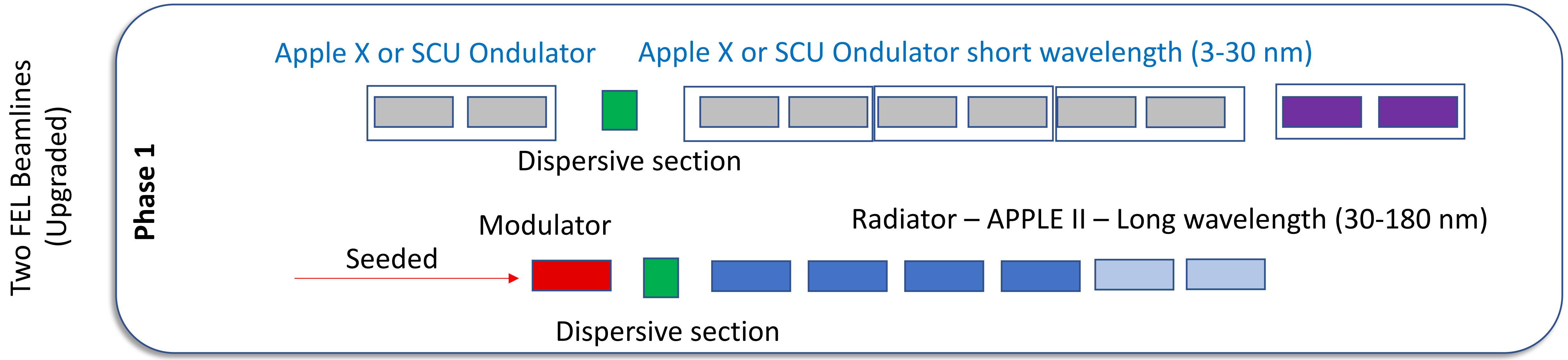
Two FEL Beamlines



- First beamline dedicated to **SCU Undulator & accelerator commissioning**
- SCU prototype + PMU optimized for short gain length, **regardless of the output wavelength**
- Dispersive section to measure slice energy spread & amplification performances *G. Penco et al. PRL 114, 013901 (2015)*
- SPARC Undulator is available for light amplification @ 10-14 nm
- Second beamline **ARIA** ready for user operation:
  - grow and strengthen a user community
  - broaden the photon energy offer of the final facility

Phased Approach – Phase 1

- **AQUA** based on advanced undulator technology with the water window target
- **ARIA** based on the same Phase 0 layout could host two additional modules for improved multi-color multi-pulses performances



Pathway to TDR

- Work in progress, starting date assumed: **Jan. 1st**
- In green the items in progress
- **24 FTE assumed in preparing the schedule**, with many workpackages involved
- **Important support from external institutions** (ENEA – FERMILAB & Universities). Reaching mutual agreements is important
- **Only magnetic design & FEL performances included**
- **Industrial realization depends on design complexity and tolerances and requires external partners involvement** (or large investments for in-house undulator realization). In particular for the SCU option.

Phase 0

	AQUA PHASE 0 (10-14 nm SPARC LIKE)		
0.1	PARAMETERS DEFINITION AGREEMENT FNAL	FNAL-WA6	
0.2	REFERENCE PARAMETERS SIMULATIONS	WG3	giu-21
0.3	S2E SIMULATIONS	WG3-WG18	dic-21
0.4	TOLERANCE ANALYSIS	WG3	giu-22
0.5	SPECS. DEFINITION	WG3-WG18	dic-22
0.6	INTRAUNDULATOR SECTIONS DEFINITION	WG13	dic-22
0.7	FINAL DESIGN	WG18-WG18-WG19	dic-23
	ARIA 50-180 nm		
1.1	Seed Parameters – range of operation	WA6-WG3	giu-21
1.2	UNDULATOR PARAMETERS DEFINITION	WG3-WG18	giu-21
1.3	REFERENCE PARAMETERS SIMULATIONS	WG3-WG18	set-21
1.4	S2E SIMULATIONS	WG3	mar-22
1.5	TOLERANCE ANALYSIS	WG3	ago-22
1.6	SPECS. DEFINITION	WG3-WG18	dic-22
1.7	INTRAUNDULATOR SECTIONS DEFINITION	WG13	giu-23
1.8	Laser SYSTEM – Transport & diagnostics	WG11	giu-23
1.9	Optical beamlines	WG4	dic-23
1.10	FINAL DESIGN	WG18-WG18-WG19	dic-23

Phase 1

	AQUA FINAL (3 nm)		
2.1	UNDULATOR PARAMETERS DEFINITION	WA6	giu-21
2.2	APPLE X study (Sabina like)	WG18	set-21
2.3	FINAL SCU Parameters definition	FNAL-WG3	dic-21
2.4	REFERENCE PARAMETERS SIMULATIONS	WG3	dic-21
2.5	S2E SIMULATIONS	WG3	giu-22
2.6	TOLERANCE ANALYSIS	WG3	dic-22
2.7	SPECS. DEFINITION	WG3-WG18	giu-23
2.8	INTRAUNDULATOR SECTIONS DEFINITION	WG13	giu-23
2.9	Optical beamlines	WG4	dic-23
2.10	FINAL DESIGN	WG18-WG18-WG19	

Conclusions

- **AQUA FEL based on a SC undulator and with e-beam parameters as listed in the EuPRAXIA at SparcLab CDR should ensure lasing with both the PWA and X-band Linac beams.**

- **The AQUA beamline requires however an advanced undulator design.** Options as SCU/Apple X technology are under study.
  - SCUs can produce higher photon flux and can cover a wider photon energy range at fixed energy compared to permanent magnet undulators (PMUs) with the same vacuum gap and period length.
  - Superior radiation hardness and therefore long-term stability in comparison to PMUs.

- **The ARIA beamline** based on Apple II PMU technology ensures FEL lasing from the commissioning of the facility, **fills a niche in the world FELs scenario** and is a fundamental resource to **build a user community** from the initial startup of the facility

- **ARIA is not yet in the baseline.**

- **A pathway to the preparation of the TDR was defined**, the schedule relys on important resources in terms of manpower.