Deliverable 5.1 – Section 2 – PM undulators

Jordi Marcos (ALBA) on behalf of WP5-PM Task

- # WP5 deliverables

Description of deliverables

D5.1: A report comparing the different technologies for the undulator, as an input for WP2, (R, PU, M18).
D5.2: Design Report of the undulator to be included in the main deliverable of CompactLight, (R, PU, M36).

D5.1 : Technologies for the CompactLight undulator [18]

Review report comparing the different technologies for the CompactLight undulator.

D5.2 : Conceptual Design Report of the undulator [36]

Design Report of the undulator to be included in the main deliverable of CompactLight

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XLS Deliverable D5.1

Technologies for the CompactLight undulator

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- # D5.1, section 2: PM undulators

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2 Permanent magnet undulators

Main editor: J. Marcos
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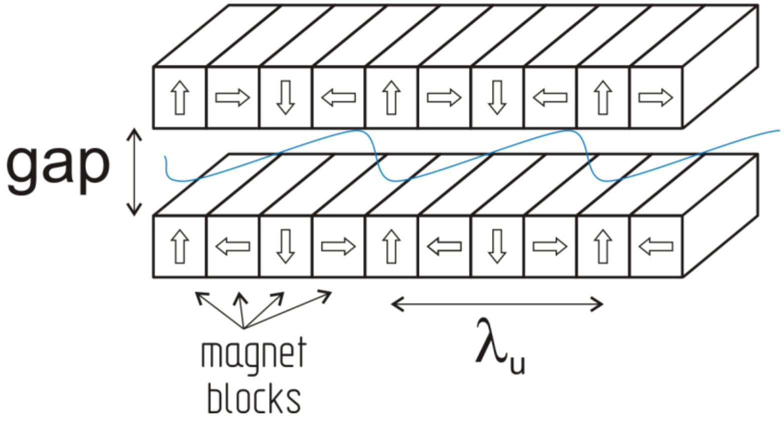
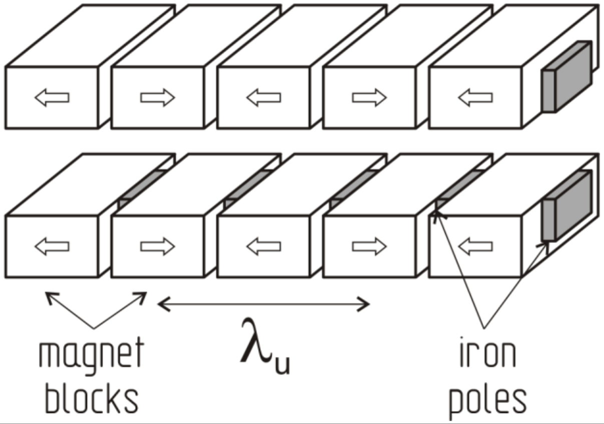
D5.1, section 2: PM undulators

- What have we done?
  - For each subcategory of PM undulators (out-of-vacuum, in-vacuum, and cryoundulators)
    - We have prepared a short introduction, explaining some generalities about the technology
    - We have established the application of that technology (as per today or foreseen in the near future) in X-ray FELs
    - We have performed a SWOT analysis
    - We have identified some recent developments that can be interesting in the context of CompactLight project





- # D5.1, section 2: Out-of-vacuum devices

Table 4: Out-of-vacuum PM devices in X-ray FEL facilities.

Facility	type	min gap [mm]	period [mm]	max K	length [m]	#	Ref
LCLS							
main line	planar hybrid	6.8 (fixed)	30.0	3.5	3.4	33	[29]
afterburner	Delta	6.6	32.0	3.37	3.2	1	[30]
LCLS II							
HXR	planar hybrid	7.2 (hor.)	26.0	>2.44	3.4	32	[31]
SXR	planar hybrid	7.2 (ver.)	39.0	>5.43	3.4	21	[31]
SXR afterburner	Delta II	?	44.0	>5.14	3.3	3	[32]
FLASH II	planar hybrid	9.0	31.4	2.87	2.5	12	[33]
European XFEL							
SASE 1/2	planar hybrid	10.0	40.0	3.9	5	35	[34]
SASE 3	planar hybrid	10.0	68.0	9.0	5	21	[34]
SASE 3 afterbur.	APPLE-X	10.0	90.0	7.8	2	4	[35]
FERMI@Elettra							
FEL-1	APPLE-II	10	55.2	–	2.4	6	[36]
FEL-2	APPLE-II	10	34.8	–	2.4	9	[37]
SwissFEL							
Athos	APPLE-X	6.5	38.0	3.8	2	16	[10]
PAL-XFEL							
HXU	planar hybrid	8.3	26.0	1.973	5	20	[38]
SXU	planar hybrid	9.0	35.0	3.321	5	7	[38]

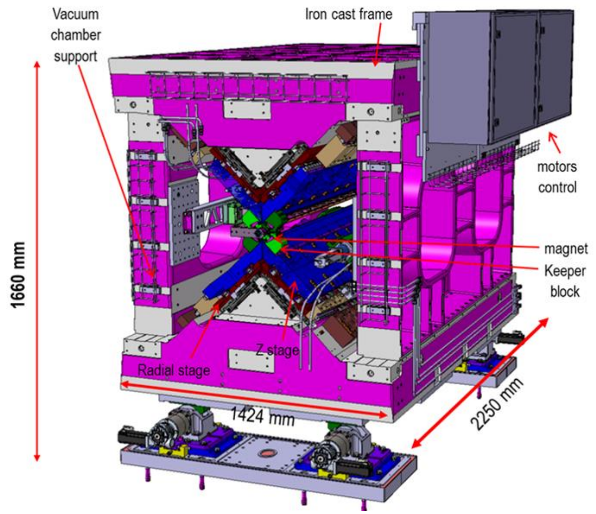
No devices with period length $\lambda_u < 25\text{mm}$

D5.1, section 2: Out-of-vacuum devices SWOT

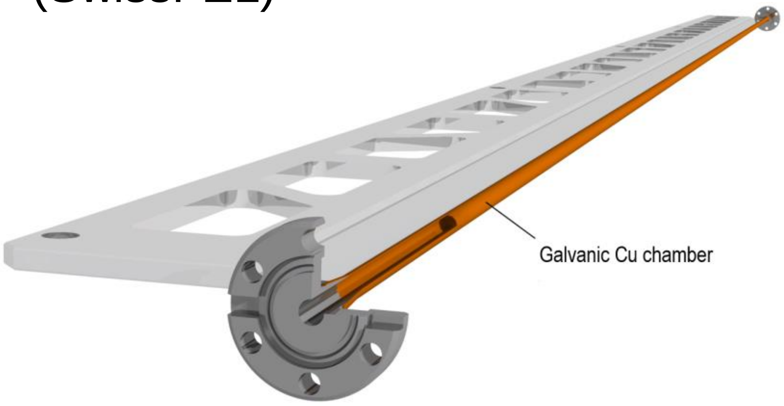
STRENGTHES	WEAKNESSES
• Technology highly mature • Many active and knowledgeable groups • Low cost • Low energy consumption • Simple associated infrastructure • Simpler mechanical and ultra-high vacuum solutions • Good accessibility for magnetic measurements • Existence of automated assembly and field tuning procedures • Availability of different schemes providing full control on the polarization of the emitted light	• Possible magnets' demagnetization • Minimum gap limited by the dimensions of the vacuum chamber • As the magnetic field decreases exponentially with g/λ_u, limitation on smaller periods • Difficult commissioning due to narrow vacuum chambers
OPPORTUNITIES	**THREADS**
• New assembly techniques for PPM • Application of improved permanent magnets • Development of automated procedures for serial production • Application of cast/extruded material for cost optimization on serial production • Adoption of compact cost-saving architectures • Further development of aggressive design (APPLE-X, Delta II…) for elliptical undulators • Optimum exploitation of round and small diameter vacuum chambers • Exploration of alternative driving systems • Development of a technology consistent with the increasing public sensitivity to environmental issues	• Magnetic field performances not satisfying CompactLight requirements • Spare PM blocks needed in case of long term magnets' demagnetization

• D5.1, section 2: Out-of-vacuum devices advances

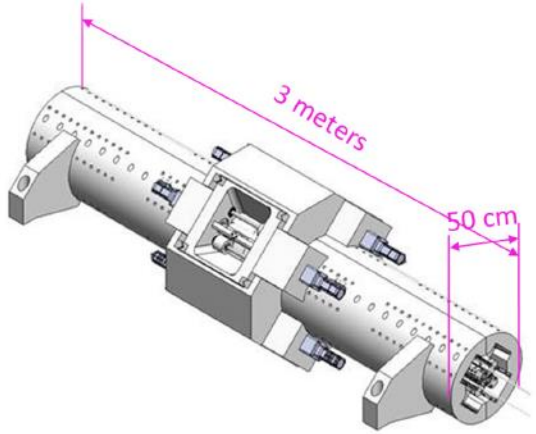
Apple X undulator (SwissFEL)



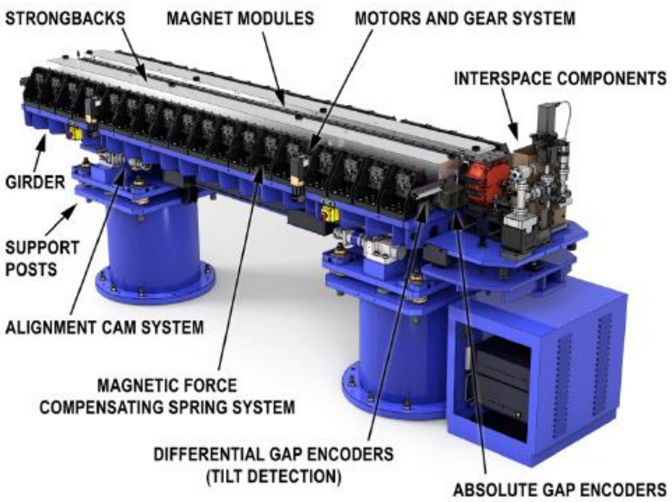
Small aperture galvanic Cu chamber (SwissFEL)



Compact Apple X undulator (MaxLab)



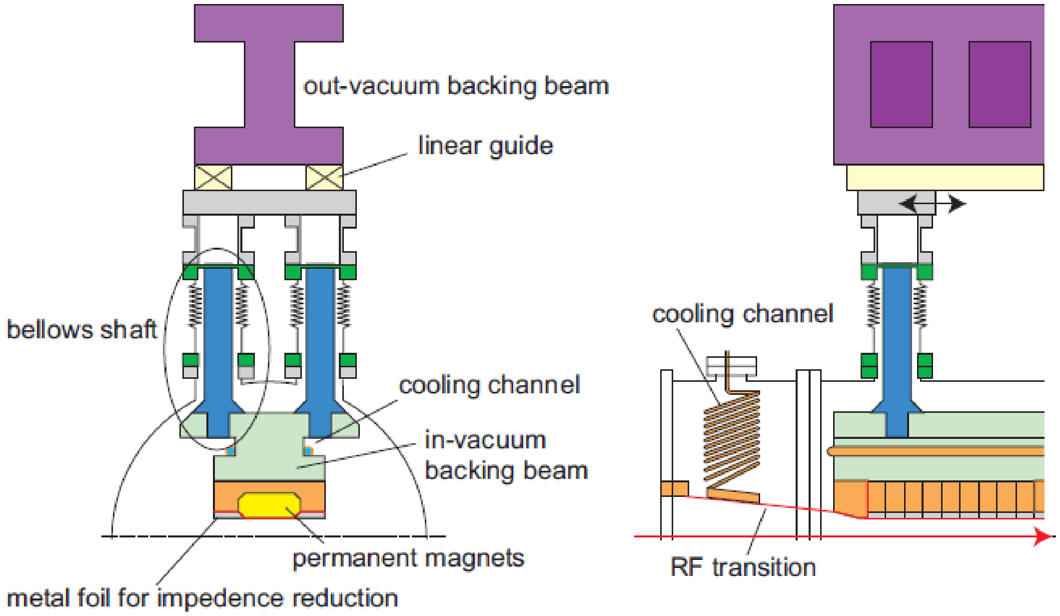
Horizontal gap undulator with force compensation (LCLS II)



D5.1, section 2: In-vacuum devices

Table 6: In-vacuum PM devices in X-ray FEL facilities.

Facility	type	min gap [mm]	period [mm]	max K	length [m]	#	Ref
SACLA	planar hybrid	3.5	18	2.2	5.0	18	[53]
SwissFEL Aramis	planar hybrid	3.2	15	1.8	4.0	13	[54]
SXFEL SASE line	planar hybrid	4.0	16	1.6	4.0	10	[55]

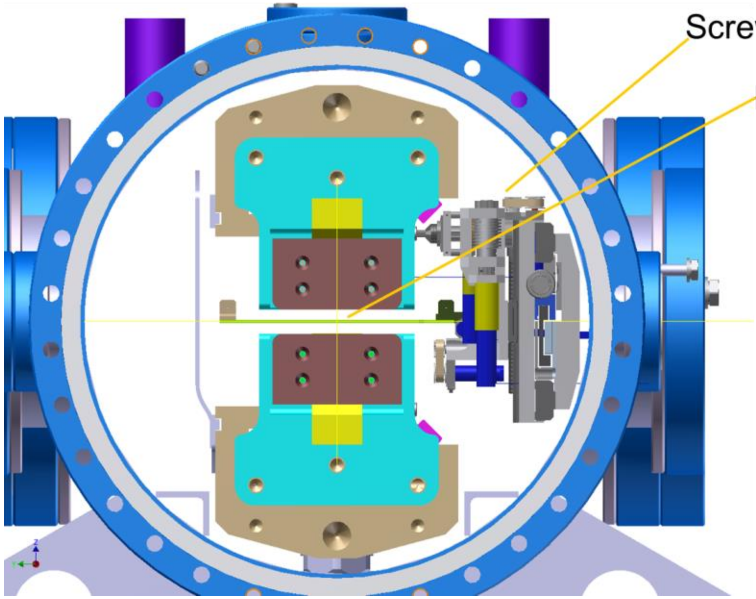


T. Tanaka et al., *In-vacuum undulators*, Proceedings of FEL2005, Stanford, California, 2005, p.370

D5.1, section 2: In-vacuum devices SWOT

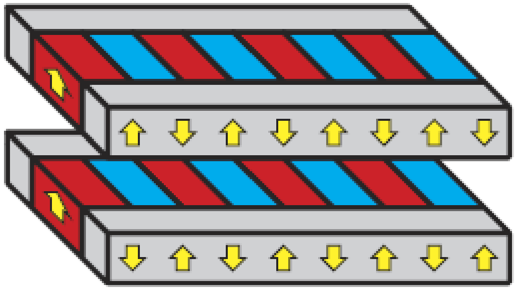
STRENGTHES • Technology mature • Well-known mechanical and ultra-high vacuum solutions • Enhanced field strength • Less limitation on smaller periods • Easier initial commissioning due the absence of the inner vacuum chambers	**WEAKNESSES** • Possible magnets' demagnetization • More complex mechanical and ultra-vacuum solutions • Schemes providing full control on the polarization of the emitted light under development • Accessibility for magnetic measurements more difficult • Required the baking of the magnetic structure
OPPORTUNITIES • Application of improved permanent magnets • Smaller periods devices • Further development of variable polarization IVUs • Further development of magnetic measurement benches for closed gap undulators	**THREADS** • Spare PM blocks needed in case of long term magnets' demagnetization • Full-scale device with variable polarization not available in the short term

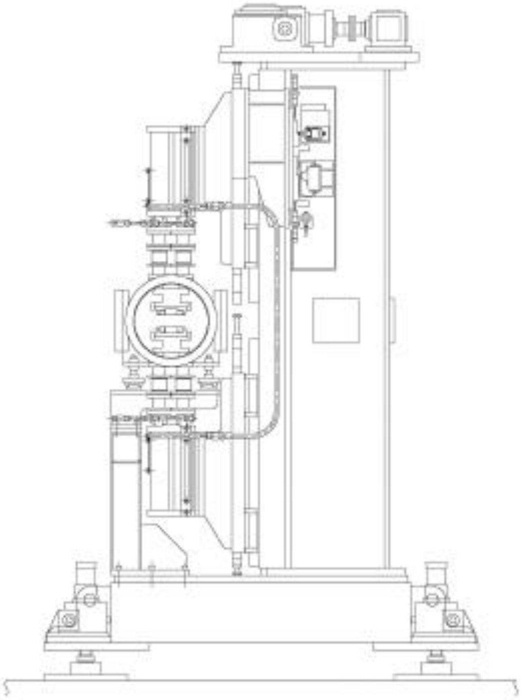
• D5.1, section 2: In-vacuum devices advances



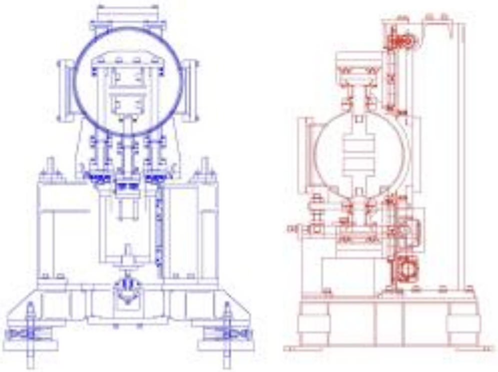
In-situ measurement and automated correction
(SwissFEL)

Undulators with force compensation
MMM (Multipole Monolithic Magnet)
(SPring-8)





Conventional IVU



Prototypes with force compensation

- # D5.1, section 2: cryogenic PM devices

Table 8: Non-exhaustive list of full-scale cryogenic PM devices in operation or being manufactured.

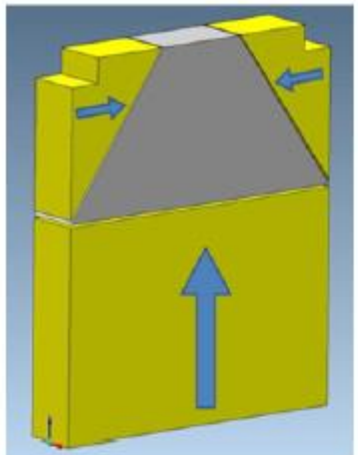
Facility	material	min gap [mm]	period [mm]	B_{peak} [Tesla]	K_{max}	length [m]	Temperature [K]	Year	Ref.
ESRF	NdFeB	6.0	18.0	0.88	1.48	2.0	150-175	2008	[70]
SLS	NdFeB	3.0	14.0	1.186	1.551	1.7	135	2009	[72]
Diamond	NdFeB	5.0	17.7	1.04	1.72	2.0	155	2010	[80]
SOLEIL	PrFeB	5.5	18.0	1.152	1.94	2.0	77	2011	[24]
SOLEIL	PrFeB	5.5	18.0	1.152	1.94	2.0	77	2015	[78]
SOLEIL	PrFeB	5.5	18.0	1.152	1.94	2.0	77	2017	[78]
ESRF	(Pr,Nd)FeB	5.0	14.4	1.0	1.35	2.0	80	2016	[81]
SSRF	NdFeB	6.0	20.0	1.03	1.92	1.6	140	2016	[82]
SSRF	PrFeB	6.0	18.0	0.91	1.53	2.6	80	2017	[82]
BESSY-II	(Pr,Nd)FeB	5.5	17.0	1.17	1.85	1.6	80	2018	[83]
SOLEIL	PrFeB	3.0	15.0	1.735	2.34	3.0	77	—-	[78]
TPS	PrFeB	3.0	15.0	1.77	2.48	2.0	77	—-	[69]
Diamond	(Pr,Nd)FeB	5.0	17.6	1.20	1.97	2.0	77	—-	[84]

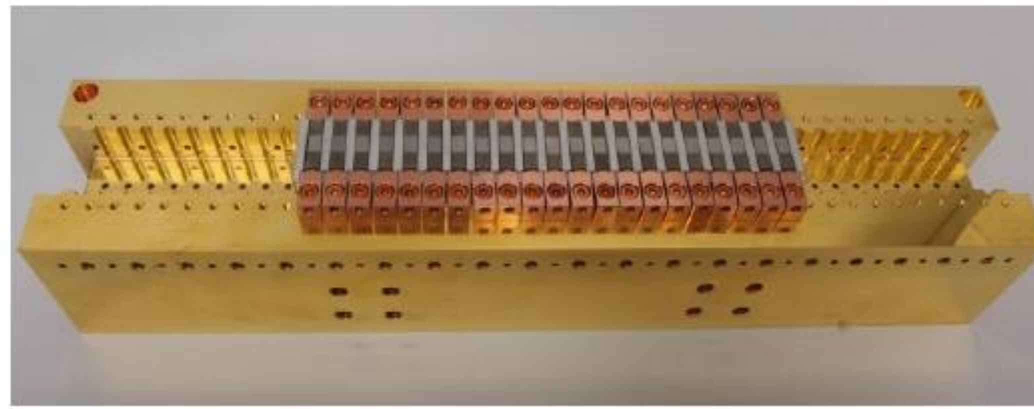
- D5.1, section 2: cryogenic PM devices SWOT

STRENGTHES	WEAKNESSES
• Lowest period achievable • Enhanced field strength • Improved radiation resistance • No baking of the magnetic structure needed at high temperature • Higher coercive force of the magnets • More resistant to demagnetization effects • Higher magnets' remanence • Increased undulators' peak field	• Technology not mature • Few active and knowledgeable groups • Minimum industrial involvement • More expensive • Challenging magnetic field characterization • Complex mechanical, ultra-vacuum and cryo solutions • No schemes providing full control on the polarization of the emitted • Magnetic measurements more difficult and under development
OPPORTUNITIES	**THREADS**
• Application of improved permanent magnets • Smaller periods devices • Longer durability of magnetic structures • Higher performance achievable • Further developments of magnetic measurement benches for closed gap undulators • More stable operation due to large cooling capacity • Possible application for future FEL	• Serial productions are far to being feasible • Full-scale device with variable polarization not available

- D5.1, section 2: cryogenic PM devices advances

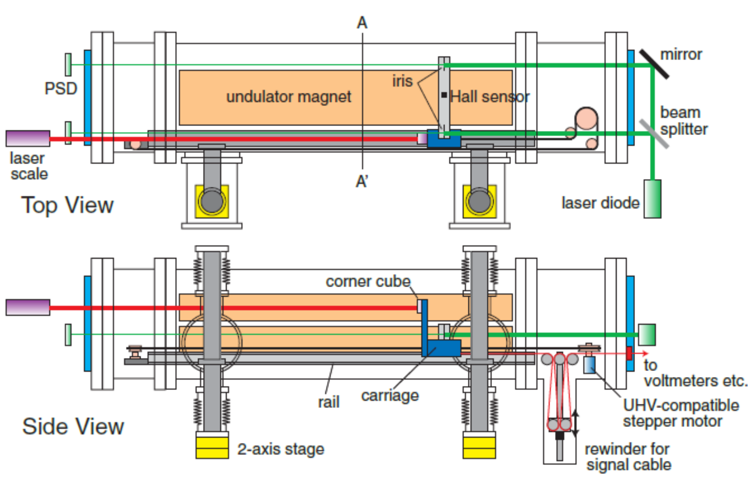
Compound poles and short period ($\lambda_u = 9$mm) devices (HZB)

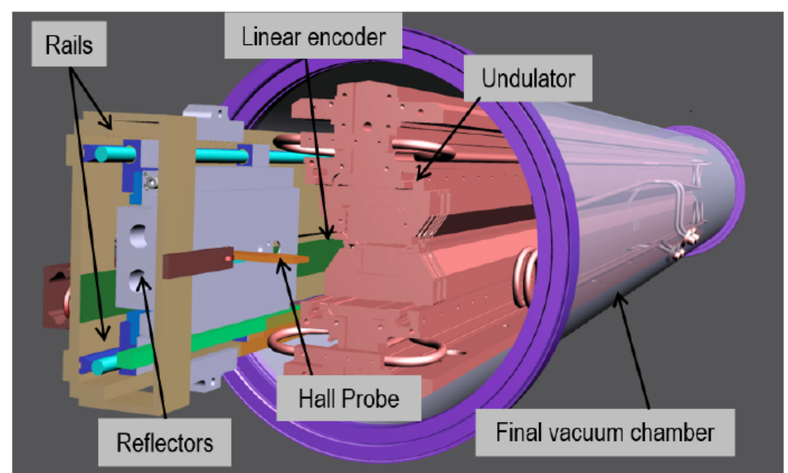




In-situ measurement benches at low temperature

Spring-8





ESRF

- # D5.1, section 2: summary

	Out-of-vacuum	Room Temp. IVU	CPMU
Price	🙂	😐	🙁
Complexity	🙂	😐	🙁
Period	🙁	😐	🙂
Field strength	🙁	😐	🙂
Radiation resistance	😐	🙁	🙂
Degree of maturity	🙂	🙂	🙁
Polarization control	🙂	🙁	🙁

- # D5.1, section 2: scaling laws

$$B = a\exp\left[b\left(\frac{g}{\lambda_u}\right) + c\left(\frac{g}{\lambda_u}\right)^2\right]$$

Table 10: Scaling law parameters for the magnetic field (either peak or effective value) as a function of the gap over period ratio for different types of PM undulators.

Type	Material	Field	a	b	c	Range ($x = g/\lambda_u$)	Ref
planar PM ver. field	SmCo ($B_r = 1.1$ T)	B_{peak}	1.87	-3.01	-0.14	$0.3 < x < 3$	[D5_1]
planar PM ver. field	NdFeB ($B_r = 1.25$ T)	B_{peak}	2.13	-3.01	-0.14	$0.3 < x < 3$	[D5_1]
planar PM ver. field	NdFeB ($B_r = 1.42$ T)	B_{peak}	2.42	-3.01	-0.14	$0.3 < x < 3$	[D5_1]
CPMU planar PM ver. field	PrNdFeB ($B_r = 1.7$ T)	B_{peak}	2.89	-3.01	-0.14	$0.3 < x < 3$	[D5_1]
Hybrid	SmCo ($B_r = 1.1$ T)	B_{peak}	3.50	-4.75	0.89	$0.3 < x < 3$	[D5_1]
Hybrid	NdFeB ($B_r = 1.25$ T)	B_{peak}	3.60	-4.45	0.67	$0.3 < x < 3$	[D5_1]
Hybrid	NdFeB ($B_r = 1.42$ T)	B_{peak}	3.70	-4.18	0.49	$0.3 < x < 3$	[D5_1]
CPMU Hybrid	PrNdFeB ($B_r = 1.7$ T)	B_{peak}	3.88	-3.87	0.26	$0.3 < x < 3$	[D5_1]
APPLE-II ver. field	NdFeB ($B_r = 1.42$ T)	B_{peak}	1.76	-2.62	-0.55	$0.3 < x < 3$	[D5_1]
APPLE-II circular	NdFeB ($B_r = 1.42$ T)	B_{peak}	1.36	-2.98	-0.28	$0.3 < x < 3$	[D5_1]
APPLE-X ver. field	NdFeB ($B_r = 1.42$ T)	B_{peak}	3.25	-4.11	0.35	$0.3 < x < 3$	[D5_1]
APPLE-X circular	NdFeB ($B_r = 1.42$ T)	B_{peak}	2.41	-4.27	0.40	$0.3 < x < 3$	[D5_1]
planar PM ver. field	NdFeB	B_{peak}	2.076	-3.24	0	$0.1 < x < 1$	[90]
planar PM hor. field	NdFeB	B_{peak}	2.400	-5.69	1.46	$0.1 < x < 1$	[90]
planar PM circular	NdFeB	B_{peak}	1.614	-4.67	0.62	$0.1 < x < 1$	[90]
APPLE-II ver. field	NdFeB	B_{peak}	1.76	-2.77	-0.37	n/a	[91]
APPLE-II hor. field	NdFeB	B_{peak}	2.22	-5.19	0.88	n/a	[91]
APPLE-II circular	NdFeB	B_{peak}	1.54	-4.46	0.43	n/a	[91]
Delta ver./hor. field	NdFeB ($B_r = 1.26$ T)	B_{peak}	1.96	-0.82	-3.31	$0.2 < x < 0.32$	[9]
Delta circular field	NdFeB ($B_r = 1.26$ T)	B_{peak}	1.45	-1.28	-2.24	$0.2 < x < 0.32$	[9]
Hybrid	SmCo	B_{peak}	3.33	-5.47	1.8	$0.07 < x < 0.7$	[5]
Hybrid	NdFeB/permendur	B_{peak}	3.694	-5.068	1.520	$0.1 < x < 1$	[90]
Hybrid	NdFeB ($B_r = 1.1$ T)	B_{peak}	3.44	-5.08	1.54	$0.07 < x < 0.7$	[92]
Hybrid	NdFeB ($B_r = 1.3$ T)	B_{peak}	4.3	-6.45	1.00	$0.04 < x < 0.2$	[92]
Hybrid	SmCo ($B_r = 1.12$ T)	B_{eff}	2.94	-4.62	1.37	$0.1 < x < 0.6$	[93]
Hybrid	NdFeB ($B_r = 1.22$ T)	B_{eff}	3.276	-4.51	1.20	$0.1 < x < 0.6$	[93]
CPMU hybrid	NdFeB ($B_r = 1.5$ T @150K)	B_{peak}	3.121	-3.204	-0.193	$0.2 < x < 0.6$	[27]
CPMU hybrid	PrFeB ($B_r = 1.67$ T @77K)	B_{peak}	3.198	-3.062	-0.332	$0.2 < x < 0.6$	[27]
CPMU hybrid	(Nd,Pr)FeB ($B_r = 1.62$ T @77K)	B_{eff}	3.177	-3.111	-0.495	$0.14 < x < 0.8$	[67]

Dedicated simulations for this project (rows referenced [D5_1])

Data from literature (remaining rows)

PM undulator design: next steps

- Define a balance between the different driving conditions:
  - Compactness
  - Feasibility
  - Cost
  - State of the art
  - Aggressive solutions
- Previous balance will have an impact on parameters such as minimum gap value, usage of in-vacuum/out-of-vacuum solutions, configuration for variable polarization devices, etc.
- Look for two or three design alternatives for each energy range

Thank you!

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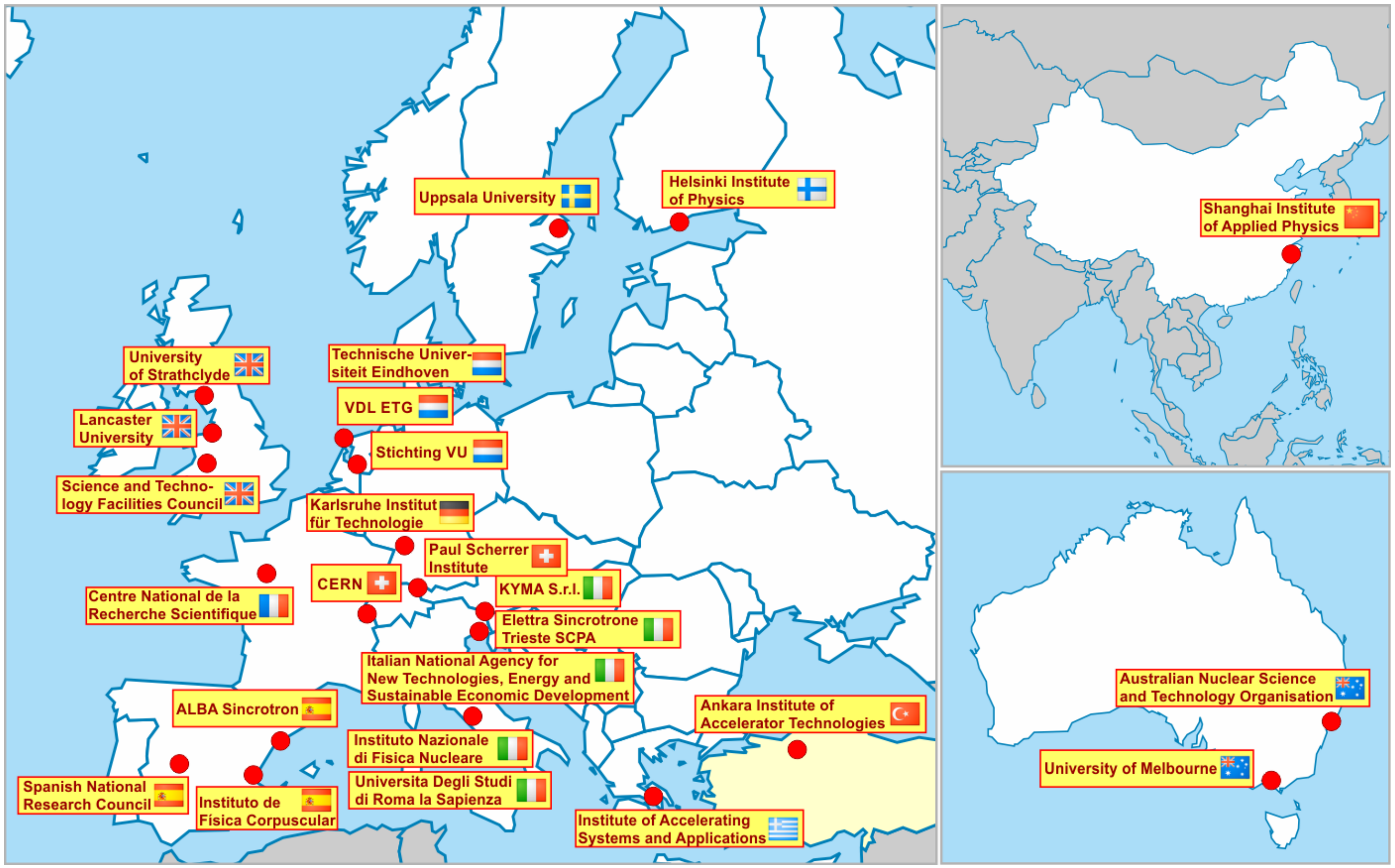

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