Undulators and FEL schemes in searching for ALPs

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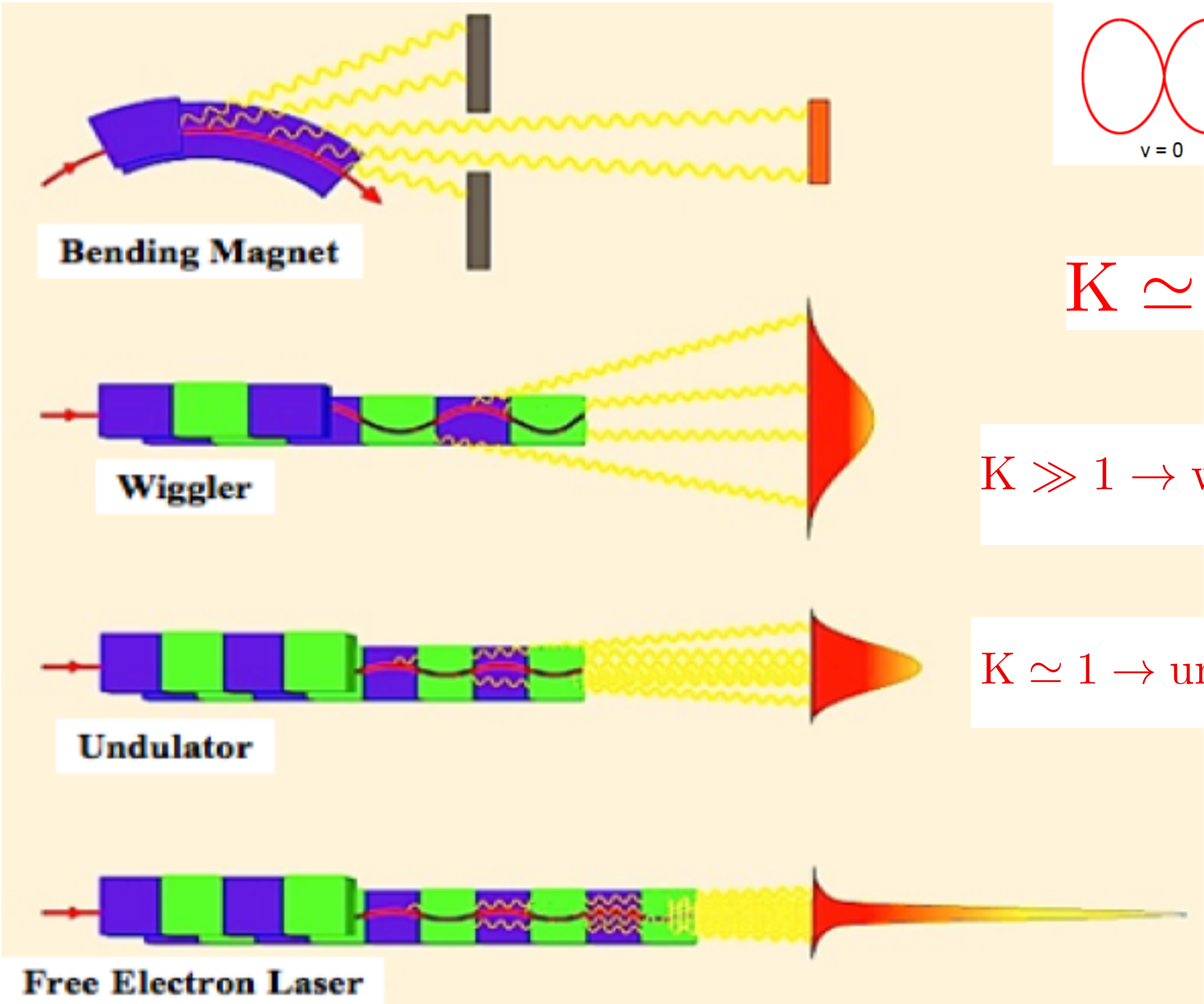
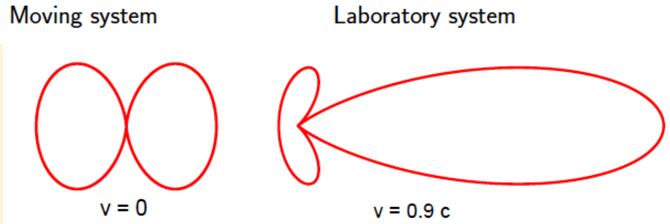
Laboratori Nazionali di Frascati, March 27th 2017

Outline

- ✓ Introduction: undulators and free electron lasers
- ✓ Light-Shining-through-Wall with undulators
- ✓ Undulator technology (for FELs): today & tomorrow
- ✓ FEL Oscillator scheme in the search for ALPs
- ✓ Conclusions

Undulator conventional use: Free Electron Laser





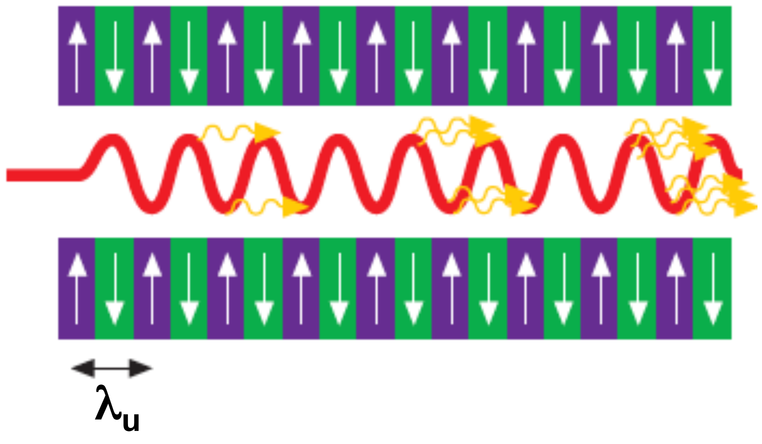
$$\mathrm{K} \simeq 0.94\ \mathrm{B[T]}\ \lambda_{\mathrm{u}}[\mathrm{cm}]$$

$$\mathrm{K} \gg 1 \rightarrow \mathrm{wiggler}: \ \ \mathrm{also}\ \theta \gtrsim \frac{1}{\gamma}$$

$$\mathrm{K} \simeq 1 \rightarrow \mathrm{undulator}: \ \ \theta \sim \frac{1}{\gamma\sqrt{\mathrm{N_u}}} < \frac{1}{\gamma}$$

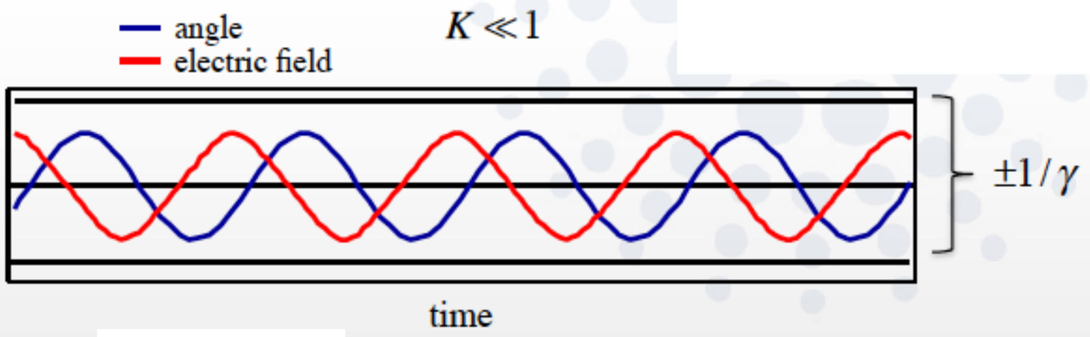
Bunching happens!

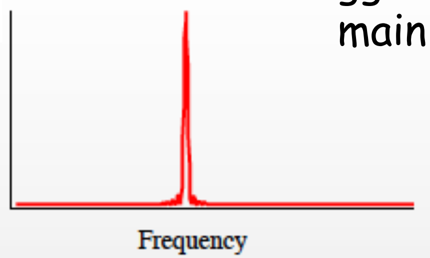
Undulator conventional use: Free Electron Laser



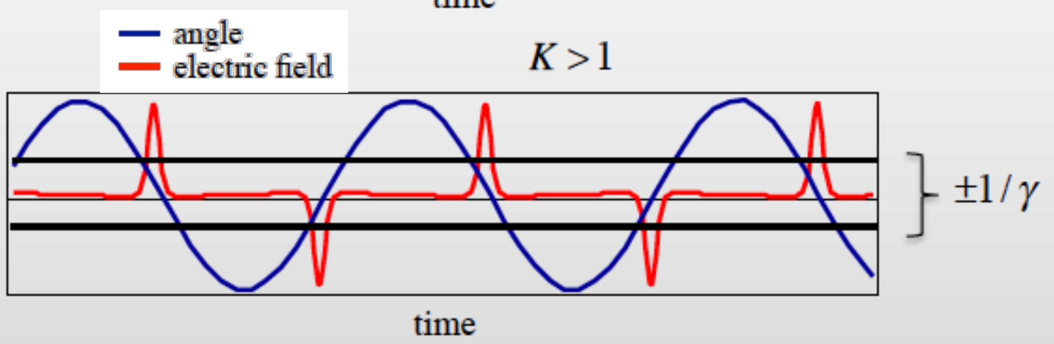
$$\lambda_{FEL} = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K_u^2}{2} + \gamma^2\theta^2\right)$$

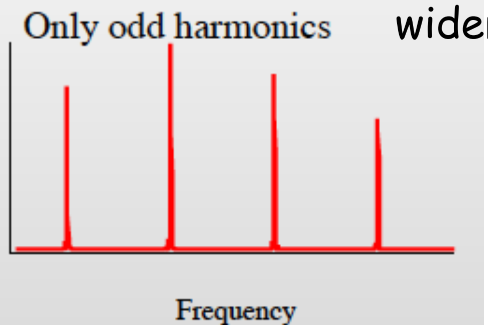
deflection parameter: $K \simeq 0.94\ B[T]\ \lambda_u[cm]$





wiggler radiation:
main frequency

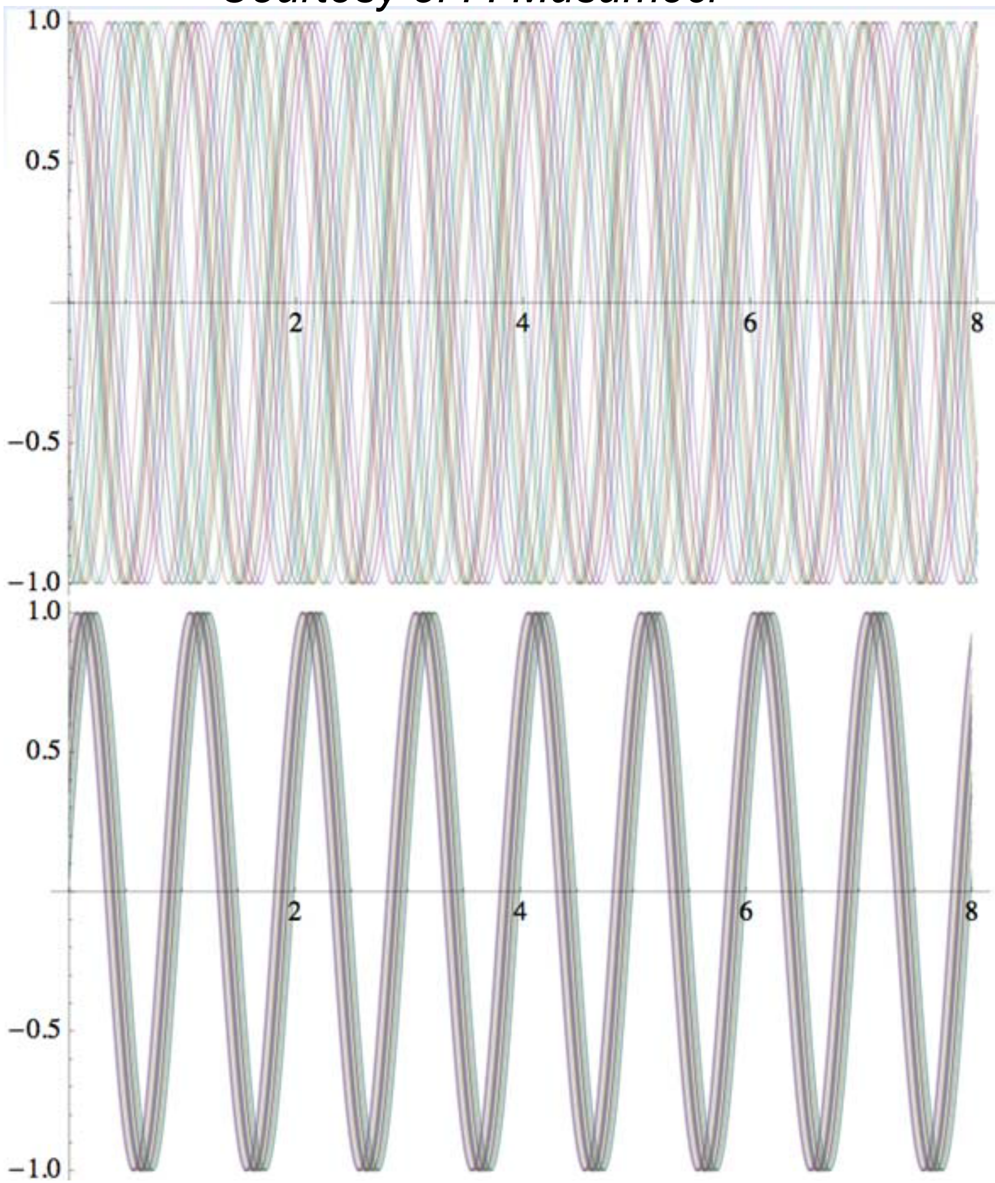




undulator radiation:
wider hν content

FEL: undulator + bunching

Courtesy of P. Musumeci



Disordered system: **single electron wave trains superimpose with random phases: noise.** ***Intensity*** $\propto N_e$

$$B = \frac{1}{N_e}\sum_{n=1}^{N_e}\exp(i\phi_n)$$

B=1 ***is the perfect order***

Ordered system: **all single wave trains are in phase.** ***Intensity*** $\propto N_e^2$

For an electron Gaussian bunch with rms length σ_0

$$N_e^2|B|^2 = N_e + N_e(N_e - 1)e^{-\omega^2\sigma_0^2/c^2}$$

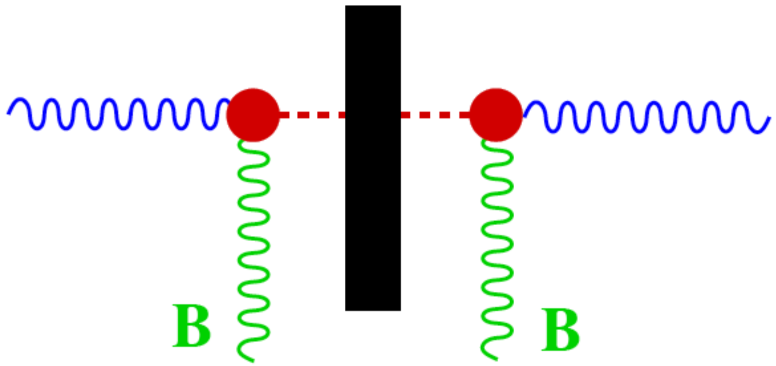
Bunching happens if

$$\sigma_0 \ll c/\omega = \lambda/(2\pi)$$

LSW through an undulator

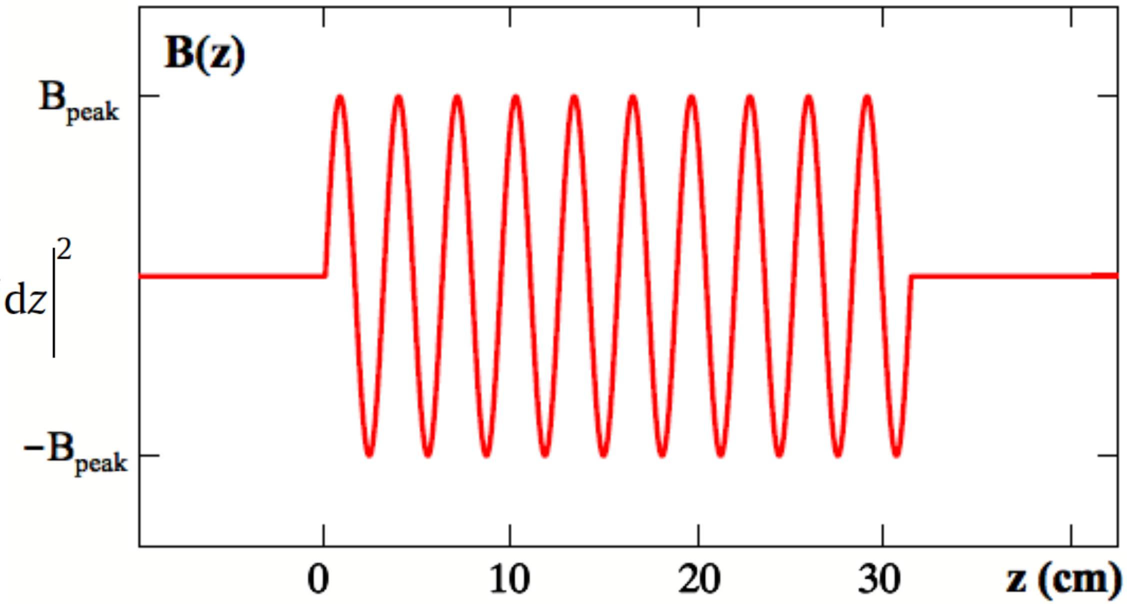
Light Shining through the Wall, LSW concept:

EM radiation propagates subject to a magnetic field in vacuum, if radiation emerges after proper shielding & noise treatment (and assuming QED nonlinearities are tiny)
→ some non-standard dynamics is going on



Inhomogeneous B field case:

$$P(a \leftrightarrow \gamma) = \frac{g_{a\gamma\gamma}^2}{4} \frac{\omega}{\sqrt{\omega^2 - m_a^2}} \left| \int_0^L B(z) e^{iqz} \mathrm{d}z \right|^2$$



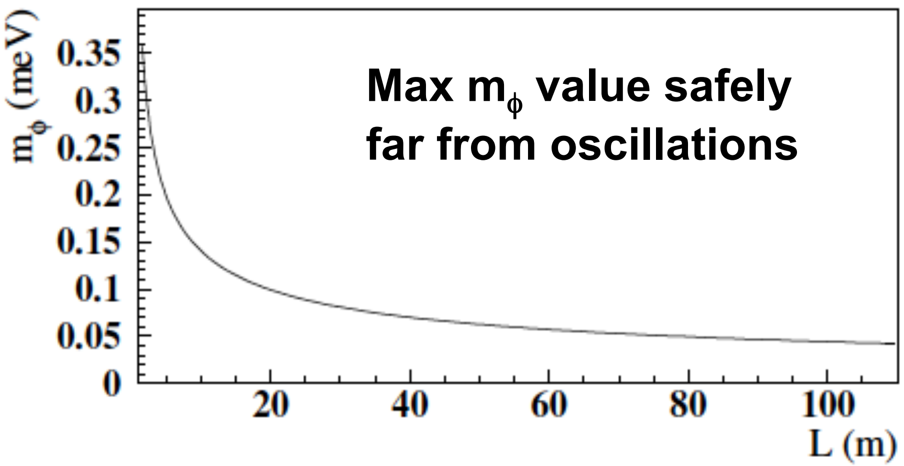
Dipole vs. undulator: probability to produce ALPs

$$P_{\gamma\to\phi} = \frac{g_{\phi\gamma\gamma}^2 B^2}{q_B^2} \sin^2 \frac{q_B L}{2}$$

$$q_B = \omega - q_\phi \simeq \frac{m_\phi^2}{2\omega}$$

✓ allows to smoothly probe all mass values up to the oscillations onset, depending on L

✓ high magnetic field values available

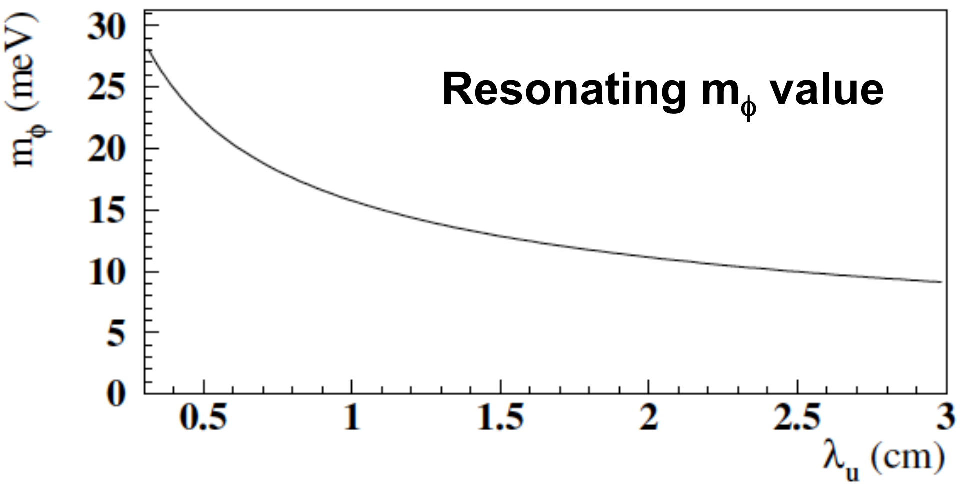


$$P_{\gamma\to\phi} = \frac{g_{\phi\gamma\gamma}^2 B^2}{4} \frac{\sin^2 \frac{\zeta L}{2}}{\zeta^2}$$

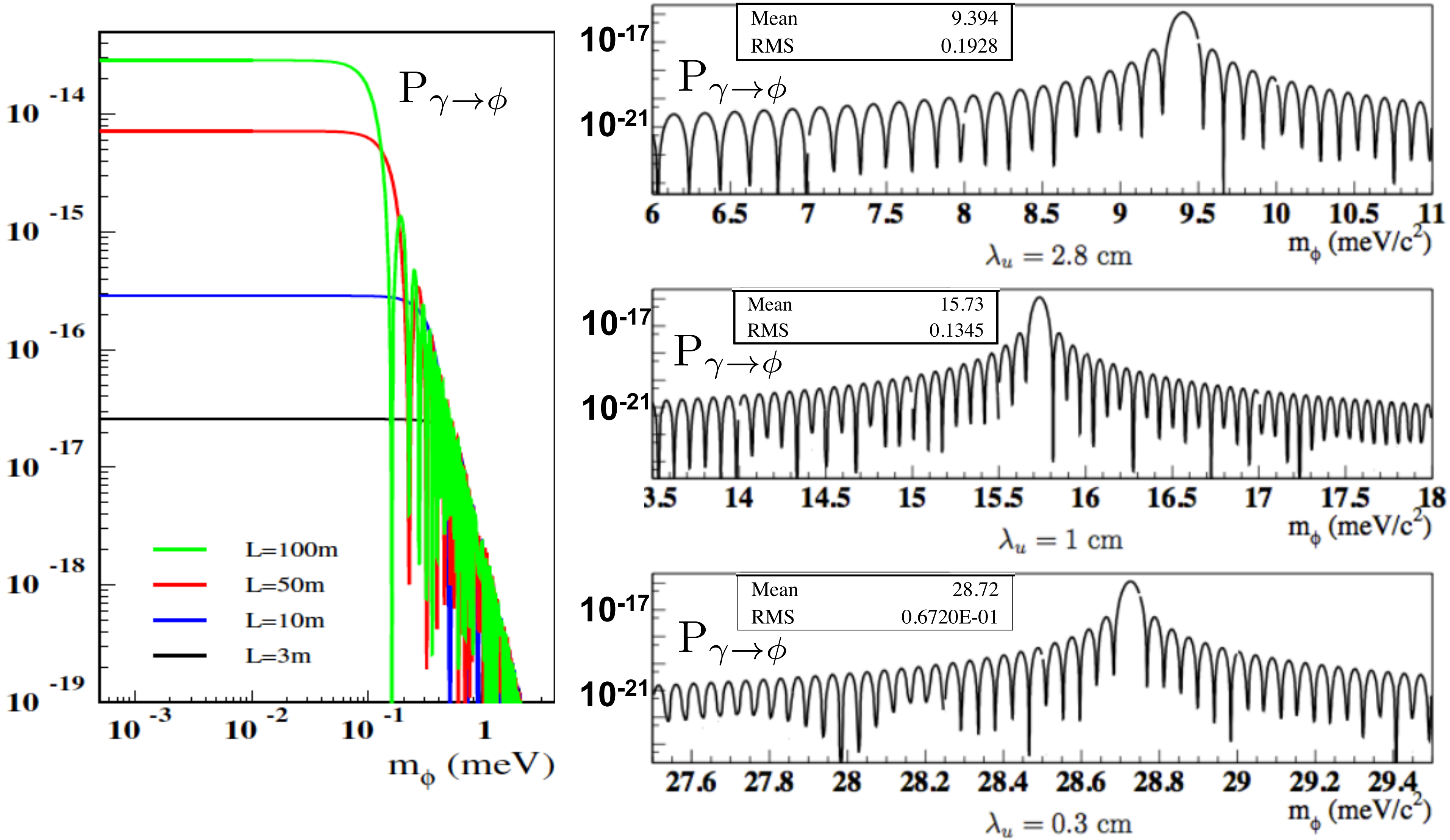
$$\zeta = \frac{m_\phi^2}{2\omega} - \frac{2\pi}{\lambda_U}$$

✓ resonates at discrete values as a function of λ_U and ω, independent of L

✓ hard to have high B fields



Dipole vs. undulator: probability to produce ALPs



shorter λ_u → higher m_ϕ & narrower signal shape

FEL drivers in undulator technology

✓ for the shortest possible wavelength at a fixed *e*-beam energy, undulator period and K have to be small

$$\lambda_{FEL} = \frac{\lambda_u}{2\gamma^2}\left(1+\frac{K_u^2}{2}+\gamma^2\theta^2\right)$$

✓ we can't accept too small K values ➔ too low FEL coupling ➔ FEL power growth occurs after too long a path (must have: $K \geq 1$)

✓ *e*-beam energy is the major cost driver for a FEL facility: better to change undulator period, B field, or K to tune wavelength

$$\mathrm{B} \approx \mathrm{B_{peak}}\,\mathrm{e}^{-\mathrm{b}\left(\frac{\mathrm{g}}{\lambda_\mathrm{u}}\right)}$$

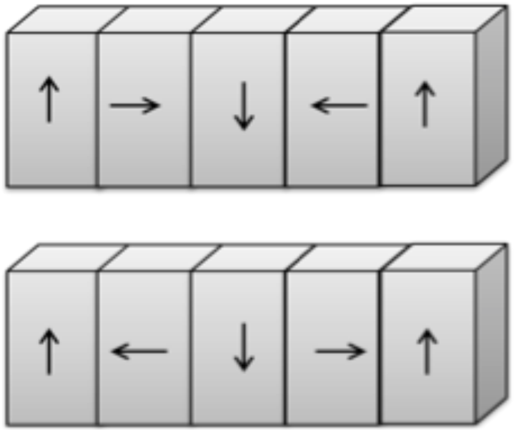
✓ at fixed gap **g** between poles, shorter λ_u imply smaller K values

✓ at fixed λ_u, higher B fields demand for smaller gap values, but narrow gaps increase the wakefields which can disrupt lasing, increase the risk of radiation damage to the magnets, and make vacuum harder to achieve

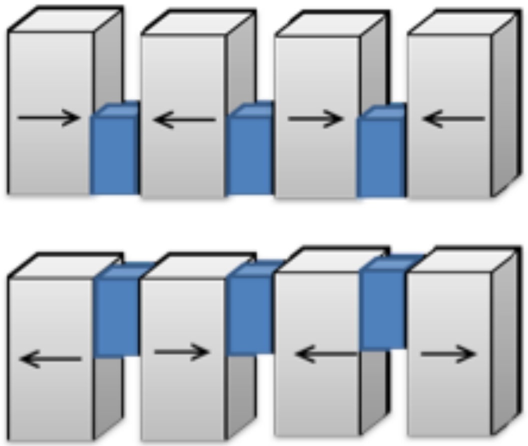
$$\mathrm{K} \simeq 0.94\ \mathrm{B[T]}\ \lambda_\mathrm{u}[\mathrm{cm}]$$

Existing technologies: permanent magnets

Permanent magnet-based undulators dominate FELs: able to generate high fields at short periods with acceptable magnet gaps



pure permanent magnet in Hallbach configuration



hybrid permanent magnet: poles in permendur are added to concentrate flux and increase B_{peak}

LCLS undulators

Planar hybrid (PM + iron poles), NdFeB

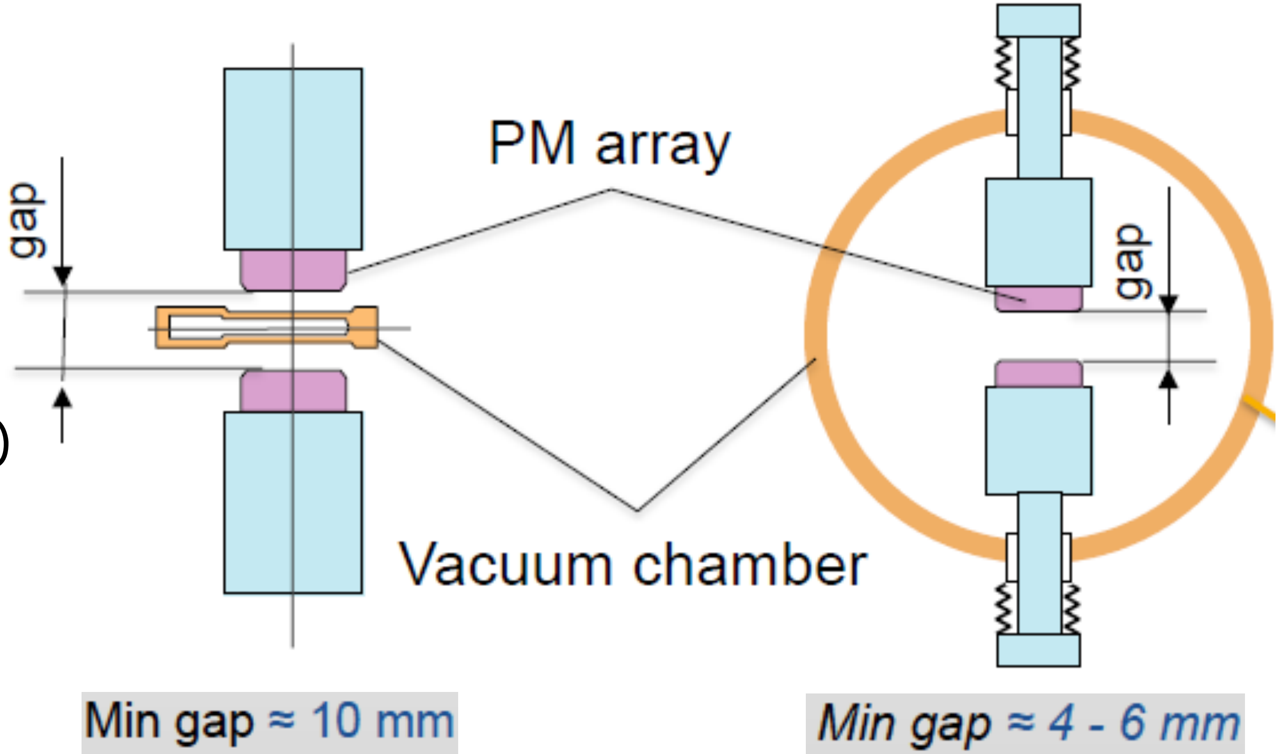
6.8mm magnet gap, B_{peak} ~ 1.25 T

30mm period, K = 3.5

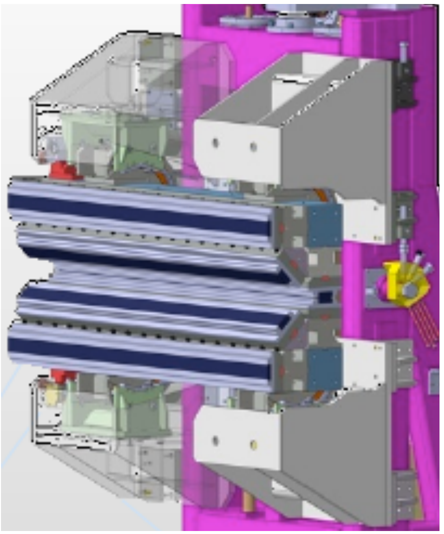
33 x 3.4m modules, 131.5m total length

Existing technologies: in-air vs. in-vacuum

Key-point is the undulator inserted in the vacuum chamber → shrink the magnetic gap (*that can't be reduced much w/o affecting the beam quality*)



Courtesy of J. Chavanne



Revolver in-vacuum undulator (INVRUM)

6mm x 133, 10mm x 100, 15mm x 66, 20mm x 50; min gap = 3.2 mm, B=0.74, 1.07, 1.32, 1.44 T

Emerging technologies

- **“Emerging”** means that there are examples already proven on storage rings or FEL but they are relatively recent developments

- Cryogenic Permanent Magnet Undulator (CPMU)
- Superconducting Undulator (SCU)

IVU= in-vacuum undulator
CPMU= cryogenic permanent magnet
SCU=superconducting undulator

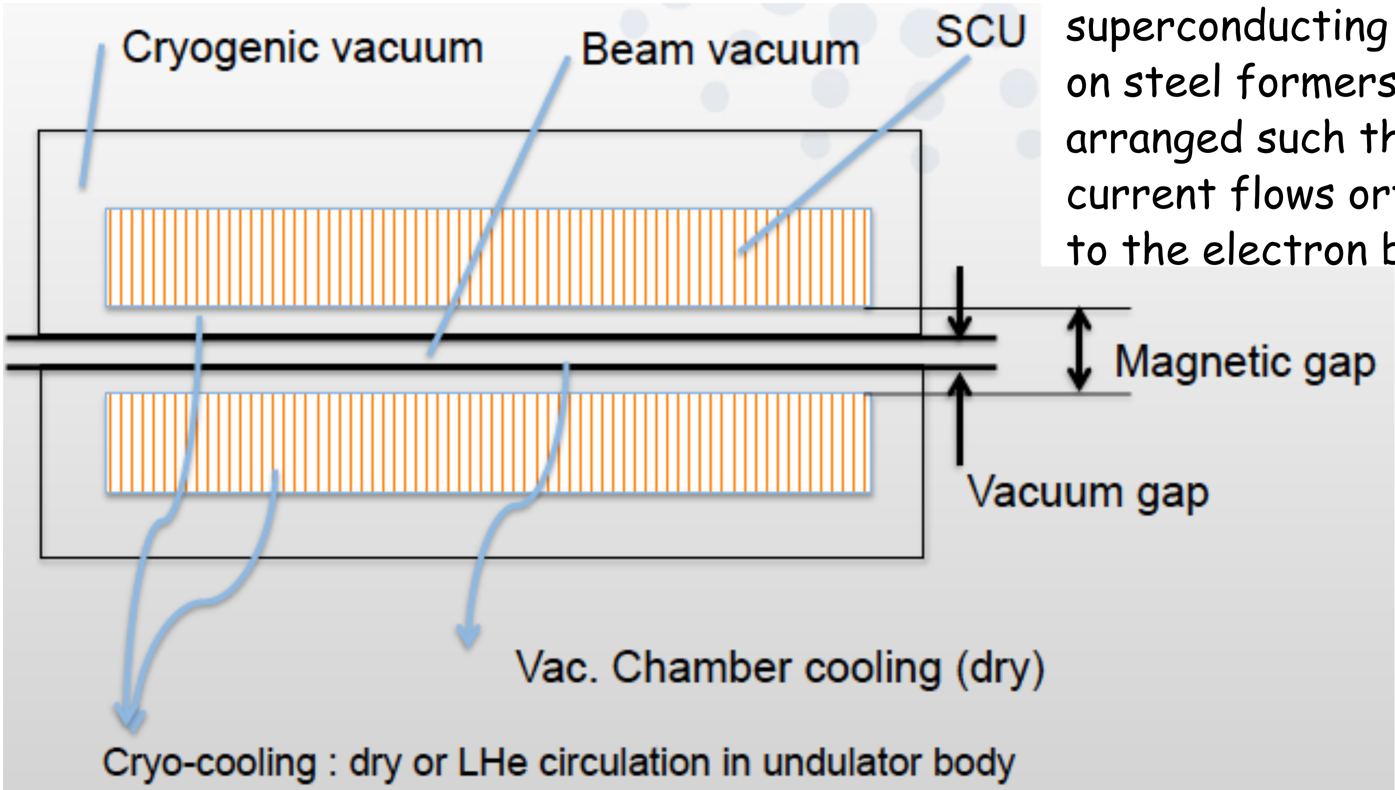
	IVU[*] (SLS)	CPMU[†] (DLS)	CPMU PrFeB[#]	SCU NbTi wire[**]	SCU NbTi APC[††]
λ_u [mm]	19	17.7	15	15	15
# of periods	105	112	133	133	133
magn. gap [mm]	5	5.2	5.2	6	6
B [T]	0.86	1.04	1.00	1.18	1.46
K	1.53	1.72	1.4	1.65	2.05

[*]F. Bødker et al., EPAC06
[†]C.W. Ostenfeld & M. Pedersen, IPAC10
[#]M.E. Couprie et al., FLS2012
[**]D. Saez de Jauregui et al., IPAC11
[††]T. Holubek et al, IPAC11

Simulations performed with SPECTRA[§]

[§]T.Tanaka & H.Kitamura, J. Synchrotron Rad. 8,1221 (2001)

Superconducting undulators



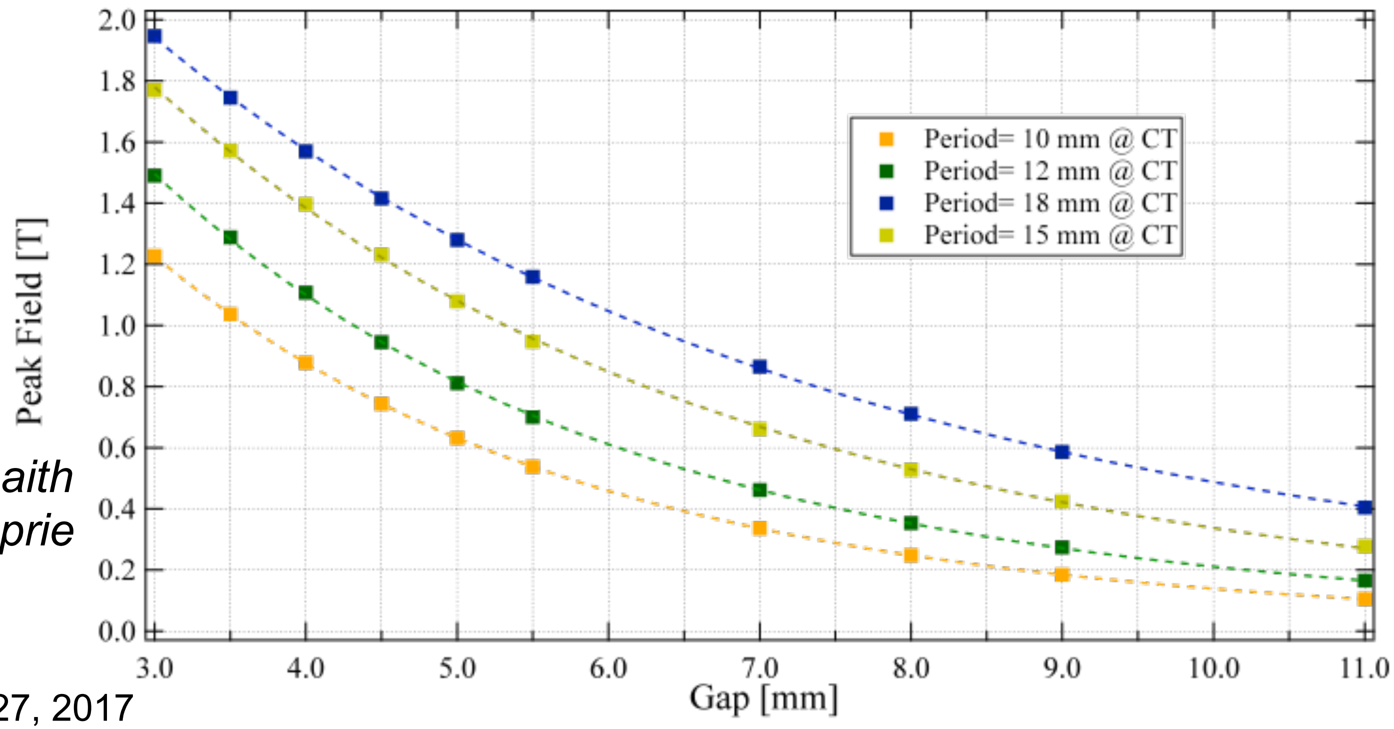
Two independent sets of superconducting windings on steel formers are arranged such that the current flows orthogonal to the electron beam

- Plans to use Nb_3Sn instead of NbTi as superconducting materials for SCUs
- Present limitations for SCUs:
  1) gap can't be squeezed because of the vacuum chamber
  2) very sensitive to synchrotron and wakefield radiations

Cryogenic permanent magnet undulators

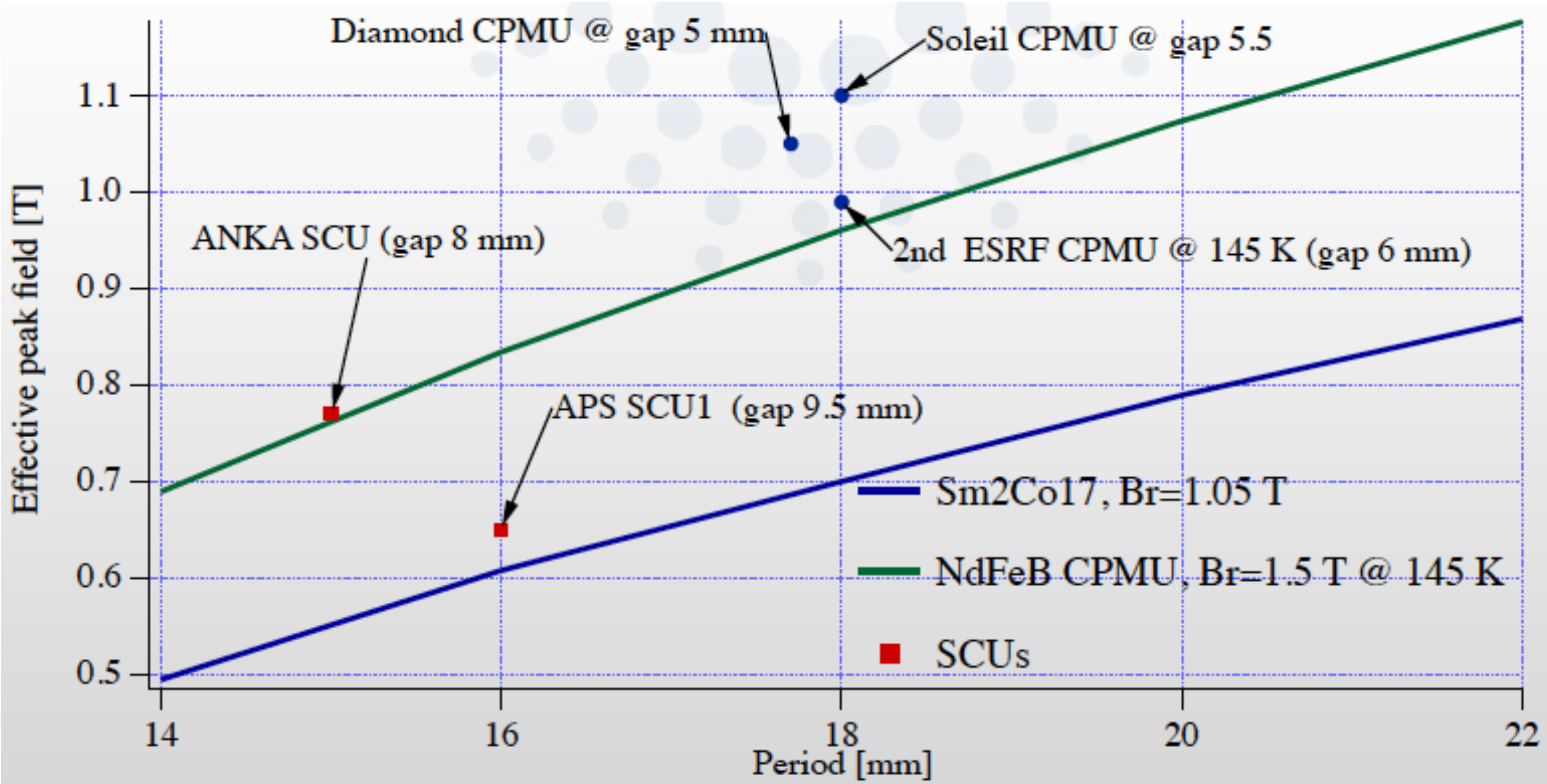
Cryogenic cooling of permanent magnet arrays:

- ✓ natural evolution of in-vacuum undulators
- ✓ higher resistance to demagnetization: PM magnetization increases at lower temperature → cooling down to T ~ 70-80K (liquid N_2) kept stable
- ✓ ~ 40-50 % gain in peak field vs standard IVUs
- ✓ better vacuum performance because cold, and better radiation damage resistance
- ✓ positive feedback from CPMUs operational experience with *e*-beams



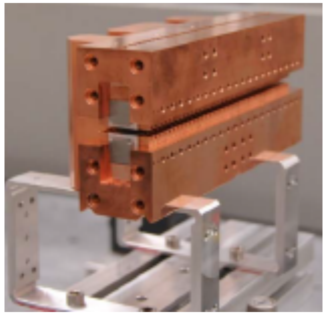
Courtesy of A. Ghaith & M.E. Couprie

CPMUs vs. SCUs



Under study @ BESSY, UCLA

- 9mm period hybrid
- 2.5mm gap, K=0.97
- $(Nd_{0.2}\ Pr_{0.8})_2\ Fe_{14}B$ magnets, B_{peak} = 1.69T



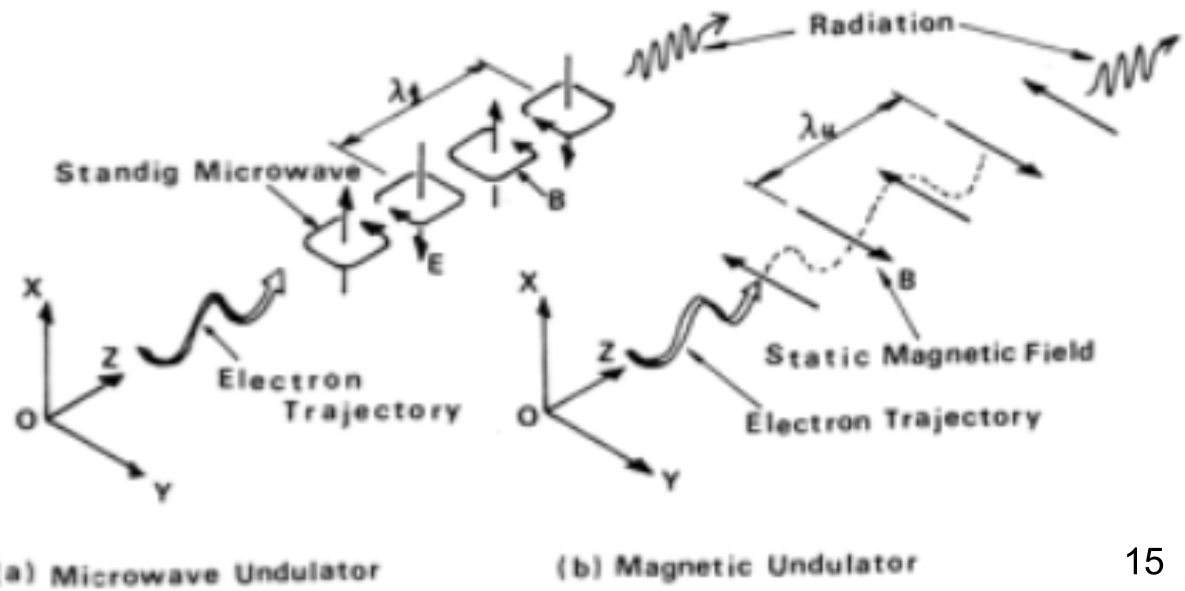
Novel short period undulators (SPUs): *e.g.* RFUs

SPUs: still too low a magnetic field (and too small a K parameter for FEL) to be widespread

- Use conventional RF system to generate deflecting fields
- Can generate short period (~10 - 15mm) with large gap (~15 - 20mm) and reasonable K~1
- Variable polarization (with fast switching) is possible (kHz)
- Normal conducting or superconducting RF could be used
- Requires high power multi-GHz RF source (see I. Spassovsky's talk)

General remark on Undulators:

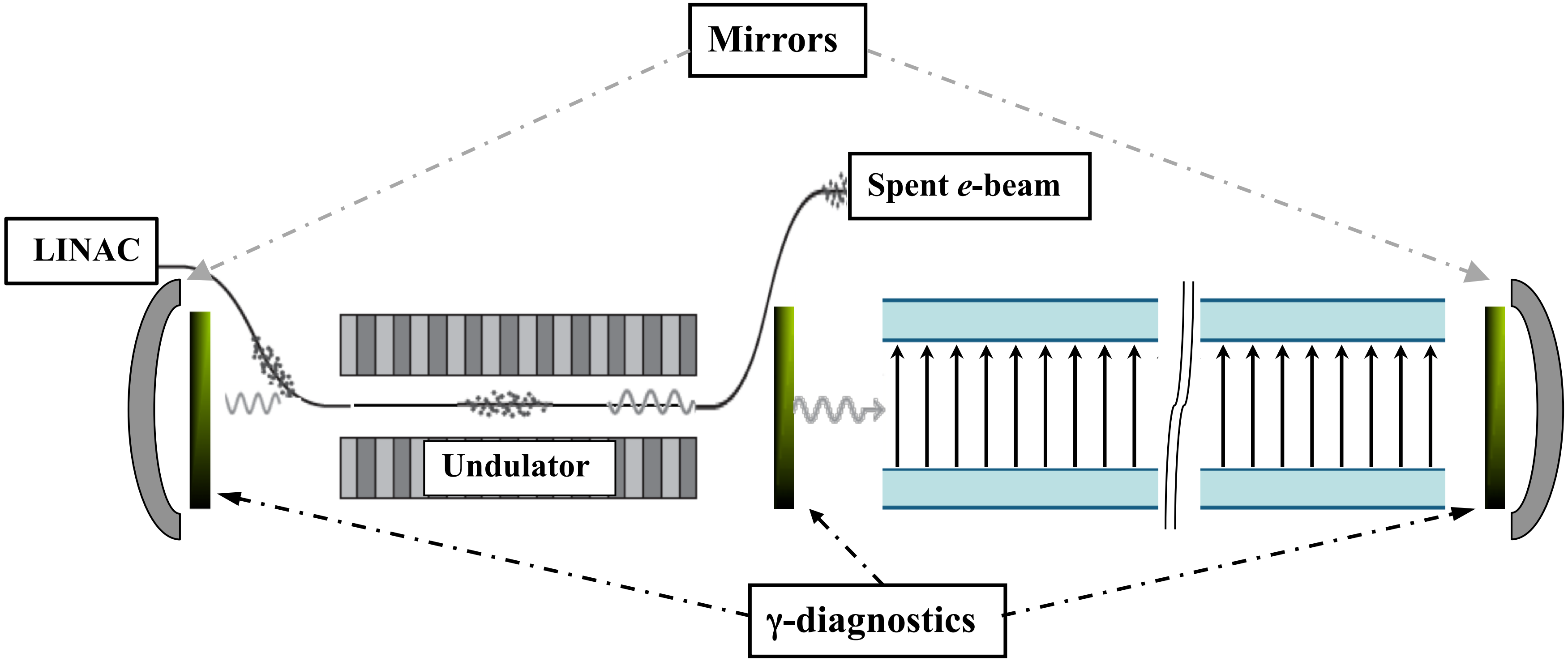
The concept as a regeneration photon-2-ALP medium should modify a bit the present undulator design paradigm



(a) Microwave Undulator (b) Magnetic Undulator

FEL Oscillator as an ALP source

We consider an FEL Oscillator (crucial device as increasing hν into the XUV/X-ray realm), as a possible source + build-up of radiation regenerating into an ALP



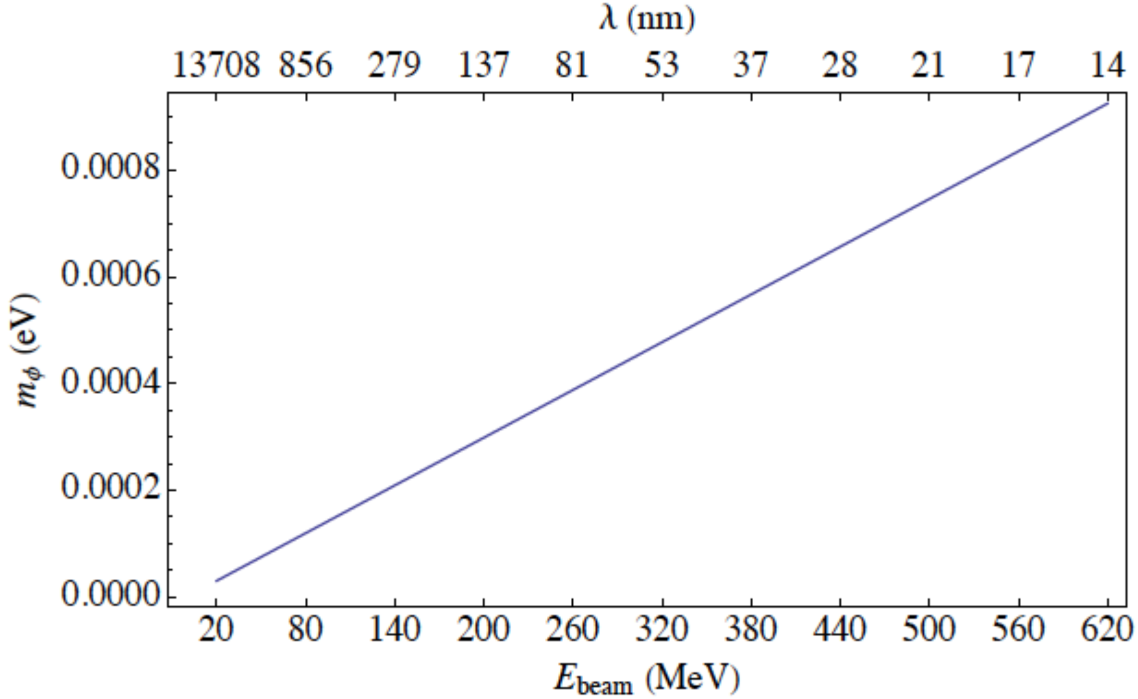
$$\omega = 2.48 \times 10^{-6}\text{eV}\ \frac{\gamma^2}{\lambda_u[\text{m}]}\left(1 + \frac{K^2}{2}\right)^{-1}$$

The relevant key-point is the presence of low loss reflectors for the wavelength considered in searching for the ALP

FEL Oscillator: cavity and power considerations

Maximum m_ϕ value safely far from oscillations onset

$$2.6 \times 10^{-6}\,\mathrm{eV}\ \frac{\gamma}{\sqrt{\mathrm{L[m]}}}$$



The beam current density is matched to the transverse section of the optical cavity

$$\Sigma_{fc} = 2\pi\sigma_{x,y}^2\left(1 + \frac{W_0^2}{2\sigma_{x,y}^2}\right)$$

$$2\pi \mathrm{W}_0^2 = \lambda_{\mathrm{FEL}}\,\mathrm{L}_{\mathrm{cavity}}$$

The saturation and equilibrium intensity are:

$$\mathcal{I}_s\left[\frac{MW}{cm^2}\right] = 348\left(\frac{\gamma}{N_u}\right)^4[\lambda_u[cm]K f_B(K)]^{-2}$$

$$\mathcal{I}_e = \left(\sqrt{2}+1\right)\left(\sqrt{G_M\frac{1-\eta}{\eta}} - 1\right)\mathcal{I}_s$$

FEL Oscillator beam parameters

Small signal gain coefficient g_0
→ Max gain $G_M(g_0)$

$$g_0 = \frac{2\pi}{\Sigma_{fc}} \frac{I}{I_A} \left(\frac{N_u}{\gamma}\right)^3 [\lambda_u K f_B(K)]^2$$

beam energy [MeV]	50	270
FEL wavelength [nm]	1350	47
norm. emittance [mm×mrad]	3	1
cavity waist [mm]	1.85	0.34
transverse r.m.s. size [mm]	0.2	0.06
beam current [A]	54	106
small signal gain coefficient	2	0.7
maximum gain	2.5	0.7
cavity global loss [%]	0.03	15
average equilibrium power [kW]	16	13
intracavity rise time τ_r [μs]	0.5	1
photons stored in cavity [pulse^{-1}]	9×10^{15}	2.5×10^{14}

$$\bar{P}_{eq} = 2\pi\sigma_{x,y}^2 \mathcal{I}_e (\tau_p - \tau_r) f_R$$

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beam energy [MeV]		
FEL wavelength [nm]		
norm. emittance [mm×r		
cavity waist [mm]		
transverse r.m.s. size [m		
beam current [A]		
small signal gain coeffici		
maximum gain	[illegible]	[illegible]
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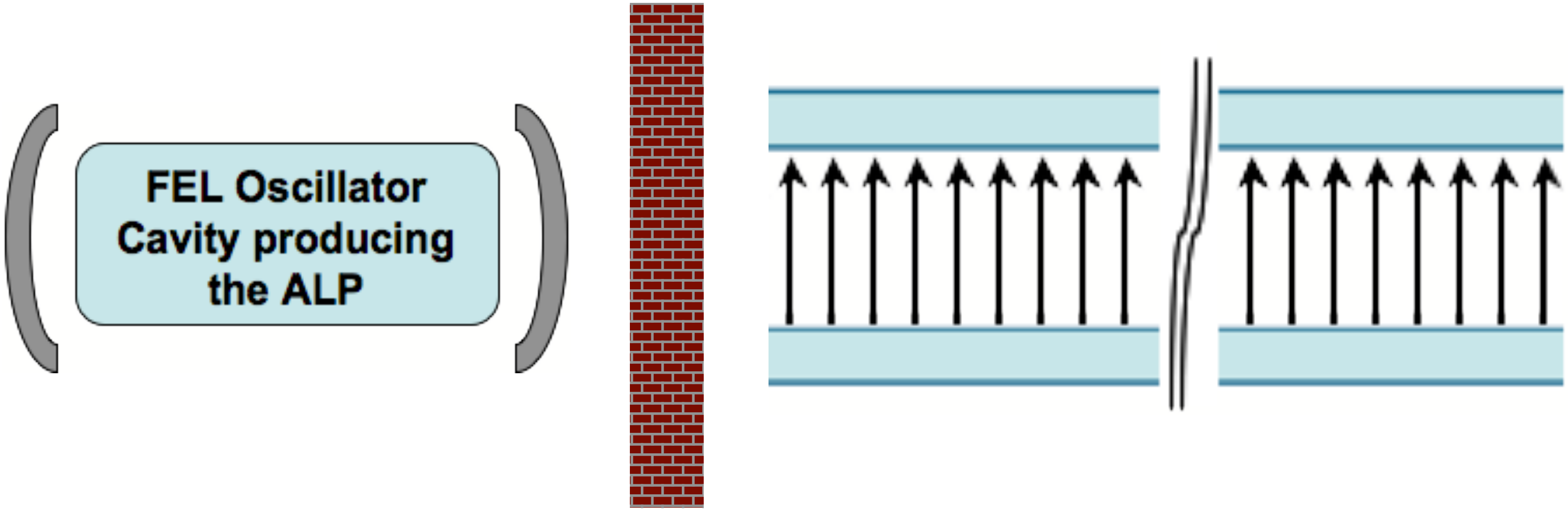
Common parameters	
overall cavity length [m]	16
macropulse duration τ_p [μs]	10
repetition rate f_R [Hz]	20
undulator periods number	160
undulator magnetic field [T]	1
dipole length in cavity [m]	12

$$\bar{P}_{eq} = 2\pi\sigma^2_{x,y}\mathcal{I}_e(\tau_p - \tau_r) f_R$$

Light from FEL Oscillator through the wall



$$N_{\gamma\text{-reg}}^{1\text{ year}} = 1.5 \times 10^{27} \frac{\varepsilon_{\text{global}}\, \bar{P}_{\text{eq}}}{\omega} g_{\phi\gamma\gamma}^{4} \left(B_{\text{CD}}\, L_{\text{dipole}}\right)^2 \left(B_{\text{ED}}\, L_{\text{extern}}\right)^2$$

ε_{global} = 80% External dipole: B_{ED} = 15T, L_{extern} = 20 m, external Q ~ 10^3

e-beam energy	m_ϕ coverage	95% CL limit on $g_{\phi\gamma\gamma}$ [GeV^{-1}]
50 MeV	$m_\phi < 0.08$ meV	2.5×10^{-10}
270 MeV	$m_\phi < 0.42$ meV	6×10^{-10}

Preliminary results

Improving over past LSW searches in such an m_ϕ range

Conclusions

- ✓ A couple of undulator technologies and FEL schemes has been reviewed, possibly adapted for the ALP search case

- ✓ Undulators technology: so far designed for other goals, *i.e.* beams of charged particles → intense and broadband interacting radiation sources demand to modify a bit the paradigm: CPMUs perhaps the best candidate for investigating

- ✓ A possible FEL Oscillator scheme has been sketched as a *source + resonator* facility in searching for ALPs, making use of present technologies for reflectors and sensible values for current intensity and delivered power → with special impact at lower wavelengths

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Please, stay tuned…