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INTERNATIONAL CENTRE FOR THEORETICAL PHYSICS
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SECOND SCHOOL ON THE USE OF SYNCHROTRON RADIATION IN SCIENCE AND TECHNOLOGY: *"JOHN FUGGLE MEMORIAL"*

25 October - 19 November 1993

Miramare - Trieste, Italy

INSERTION DEVICES # 2

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Second School on the Use of Synchrotron Radiation
in Science and Technology

Trieste, October 25th - November 19th, 1993

Insertion Devices # 2

R.P.Walker, Sincrotrone Trieste, Italy

1. Performance Limitations

2. Undulator and Wiggler Performance

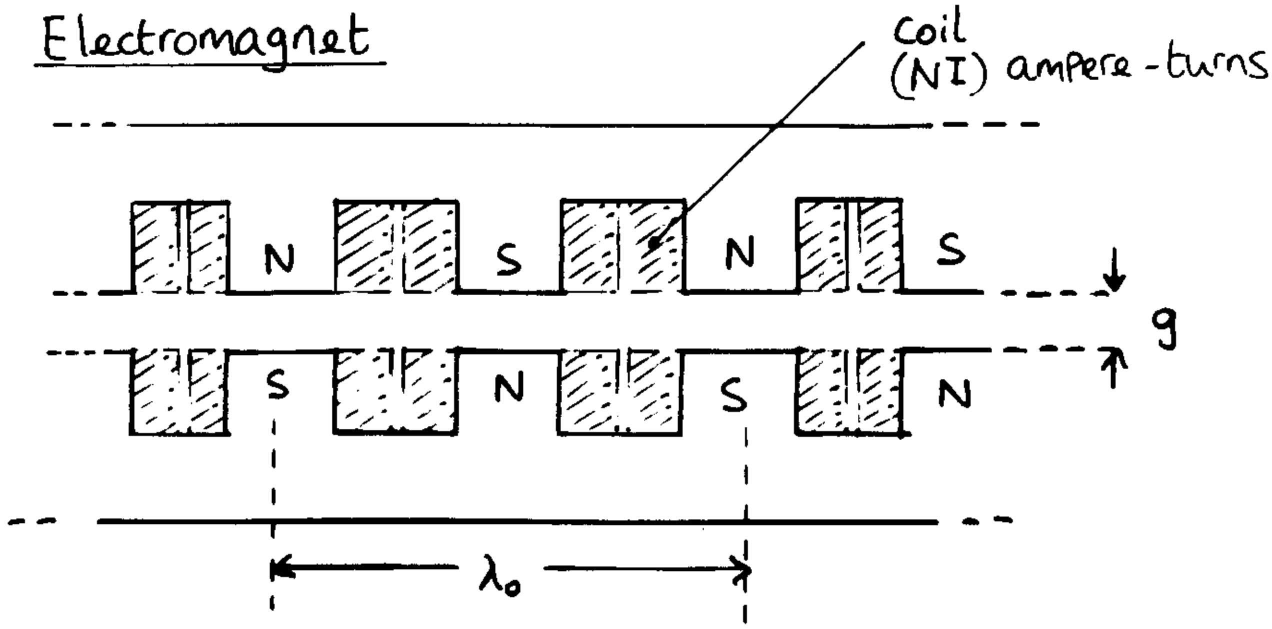
3. Construction Aspects

4. Computation of Undulator Radiation Properties

5. Undulator Field Errors

1. PERFORMANCE LIMITATIONS

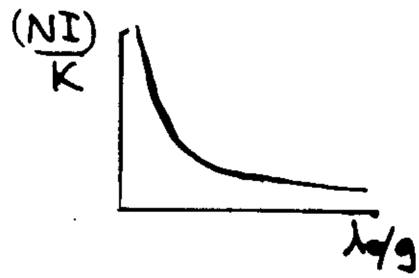
Electromagnet



simple dipole magnets:

$$\mu_0 (NI) = B_0 \frac{g}{2}$$

i.e. $$\frac{(NI)}{K} = \frac{4260}{(\lambda_0/g)}$$



current density → $$\frac{J}{K} \sim \frac{1}{(\lambda_0/g)\,\lambda_0^2}$$

Very rapid increase as λ_0 reduces

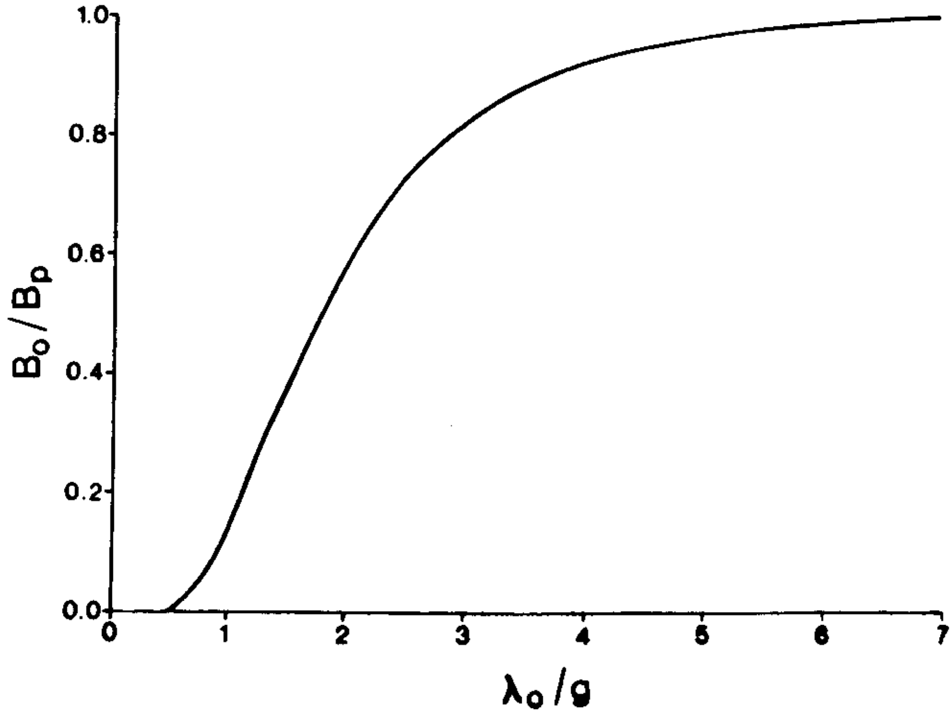
including sinusoidal field variation:

$$B_y = B_0 \cos\left(\frac{2\pi z}{\lambda_0}\right) \cosh\left(\frac{2\pi y}{\lambda_0}\right)$$

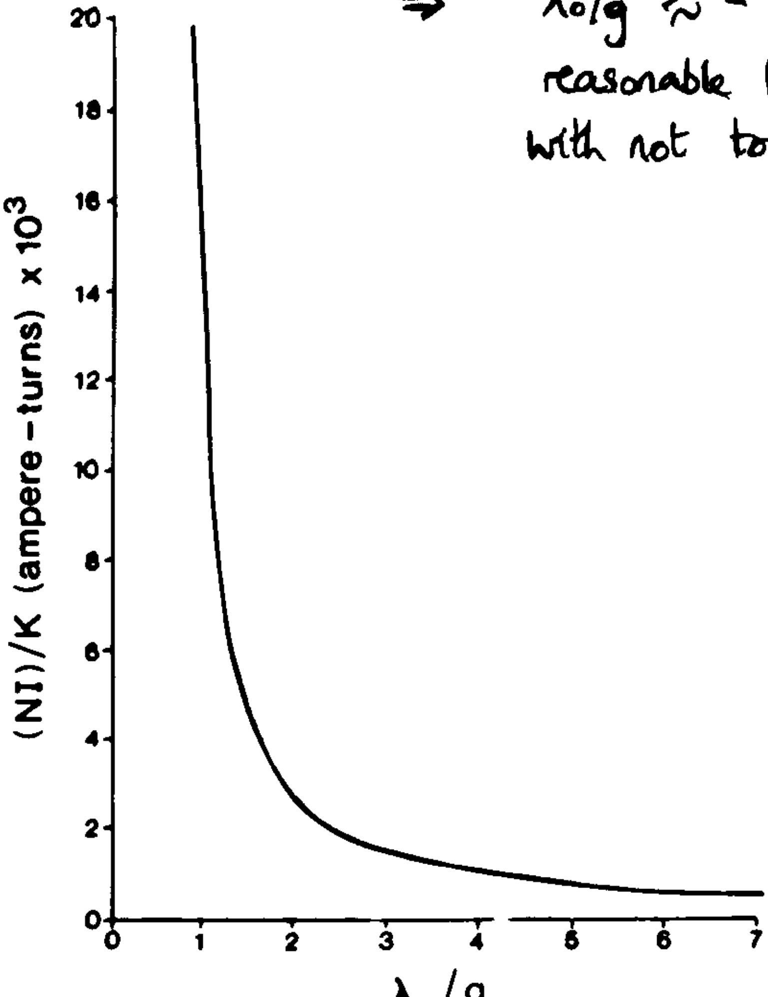
(solution of Maxwell's equations close to axis)

→ even faster increase in (NI) and J required as λ_0 decreases

→ field on axis (B_0) smaller than at pole-tip (B_P)

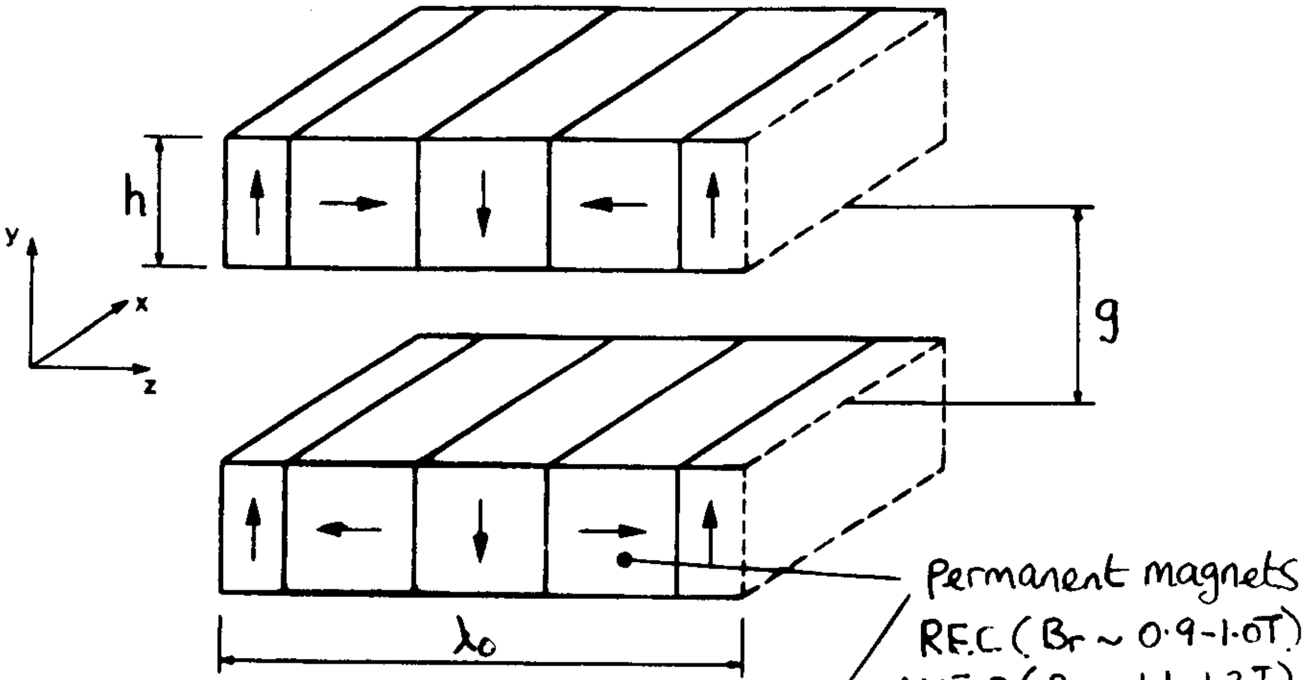


$\Rightarrow$ $\lambda_o/g \gtrsim 2$ to get a reasonable field strength with not too high current.



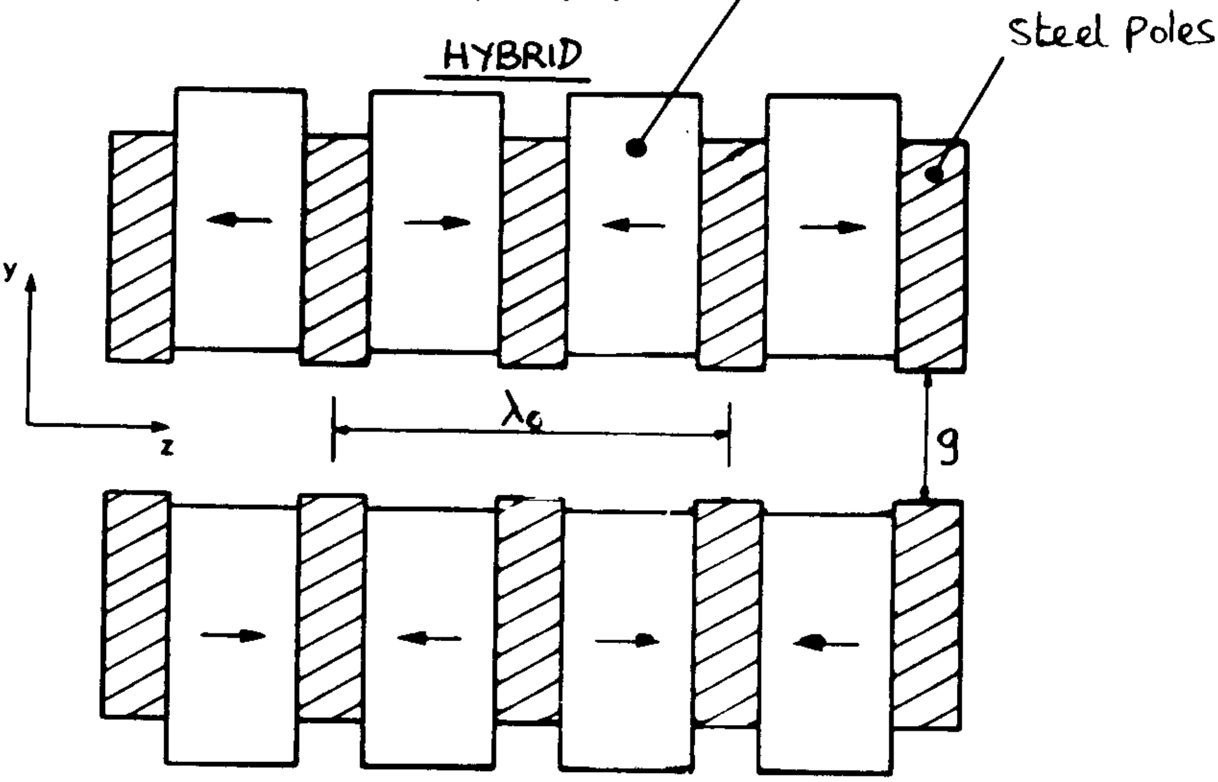
Permanent magnets

PURE PERMANENT MAGNET



$$B_0 = \frac{4\sqrt{2}}{\pi} B_r \left(1 - e^{-2\pi h/\lambda_0}\right) e^{-\pi g/\lambda_0}$$
(analytic)

HYBRID



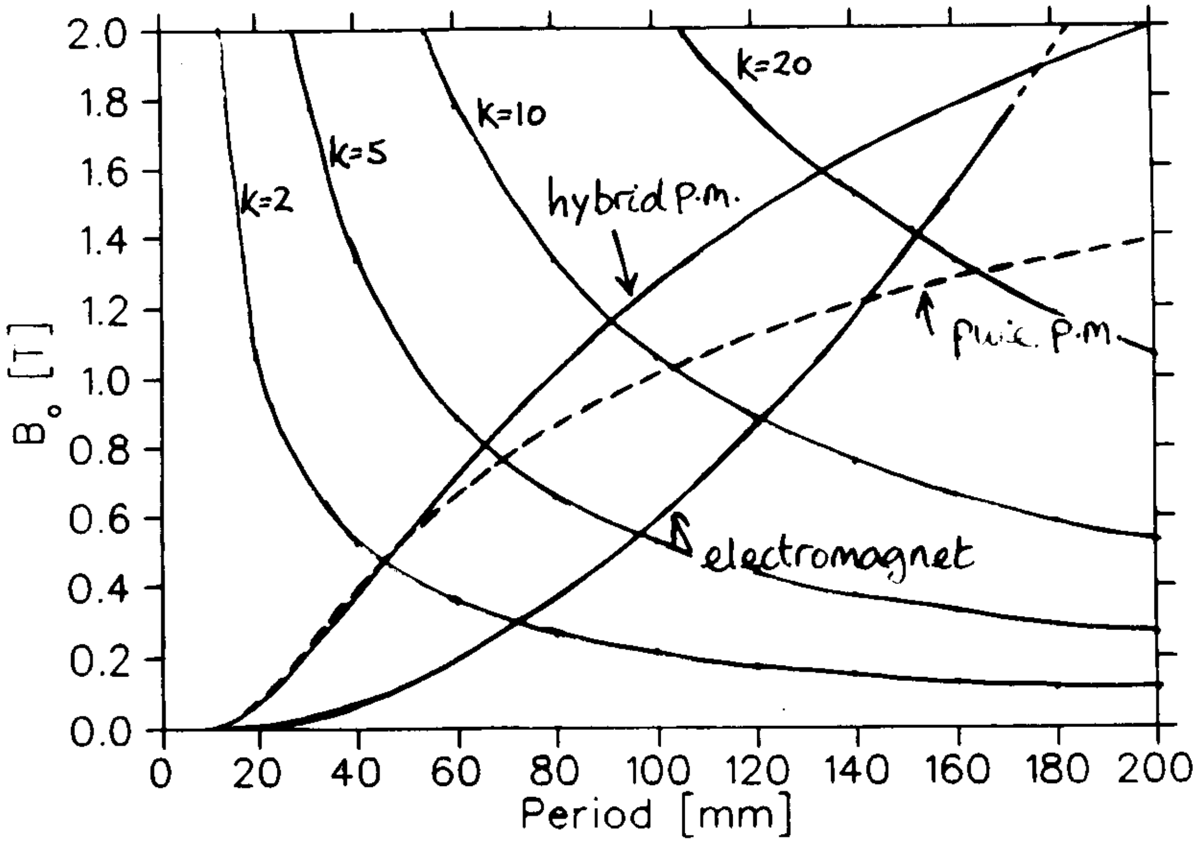
$$B_0 = 3.44\, e^{-g/\lambda_0 (5.08 - 1.54\, g/\lambda_0)}$$
(empirical)

Common features:

- scaleable to smaller dimensions, as function of (g/λ_0)
- mechanical variation of gap to change field strength

Performance comparison

gap = 20mm
(J = 15 A/mm^2, electromagnet)



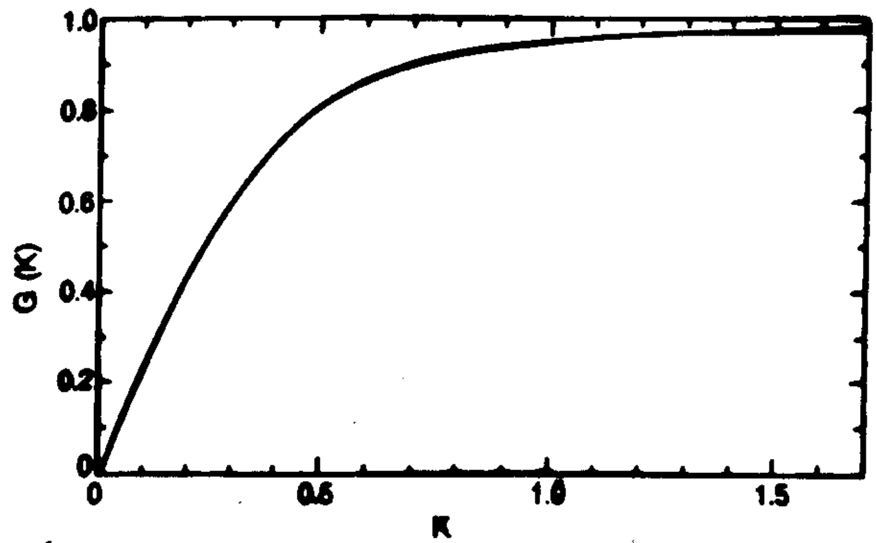
- performance at small λ_0 limited by magnet gap; in general need $\lambda_0/g \gtrsim 2$
- electromagnet only useful at small λ_0 if field required relatively small, or at very large period lengths
- for $\lambda_0/g \lesssim 3$ both permanent magnet schemes give similar performance (undulators)
- for $\lambda_0/g \gtrsim 3$ hybrid scheme becomes increasingly more powerful than PPM. (wigglers)
- maximum B_0 limited by steel saturation to ~ 2T above this limit need <u>superconducting</u> magnets

Power, and power density

for both undulators and multipole wigglers :

$$P_{tot} = 0.633\ E^2_{GeV}\ B_o^2\ L\ I_b \qquad kW$$

$$d^2P/d\Omega = 10.84\ E^4_{GeV}\ B_o\ N\ G(K)\ I_b \qquad W/mrad^2$$



e.g. L=3 m, I_b=100 mA

E (GeV)	λ_o=0.06, B_o=0.5 P_{tot}	$d^2P/d\Omega$	λ_o=0.14, B_o=1.5 P_{tot}	$d^2P/d\Omega$ (kW, kW/mrad²)
0.8	0.03	0.011	0.27	0.014
1.5	0.11	0.14	0.96	0.17
6.0	1.7	35.1	15.4	44.3

⇒ design of beamline components to handle the high power and power density

⇒ interlock system to prevent damage to vacuum chamber if beam mis-steered

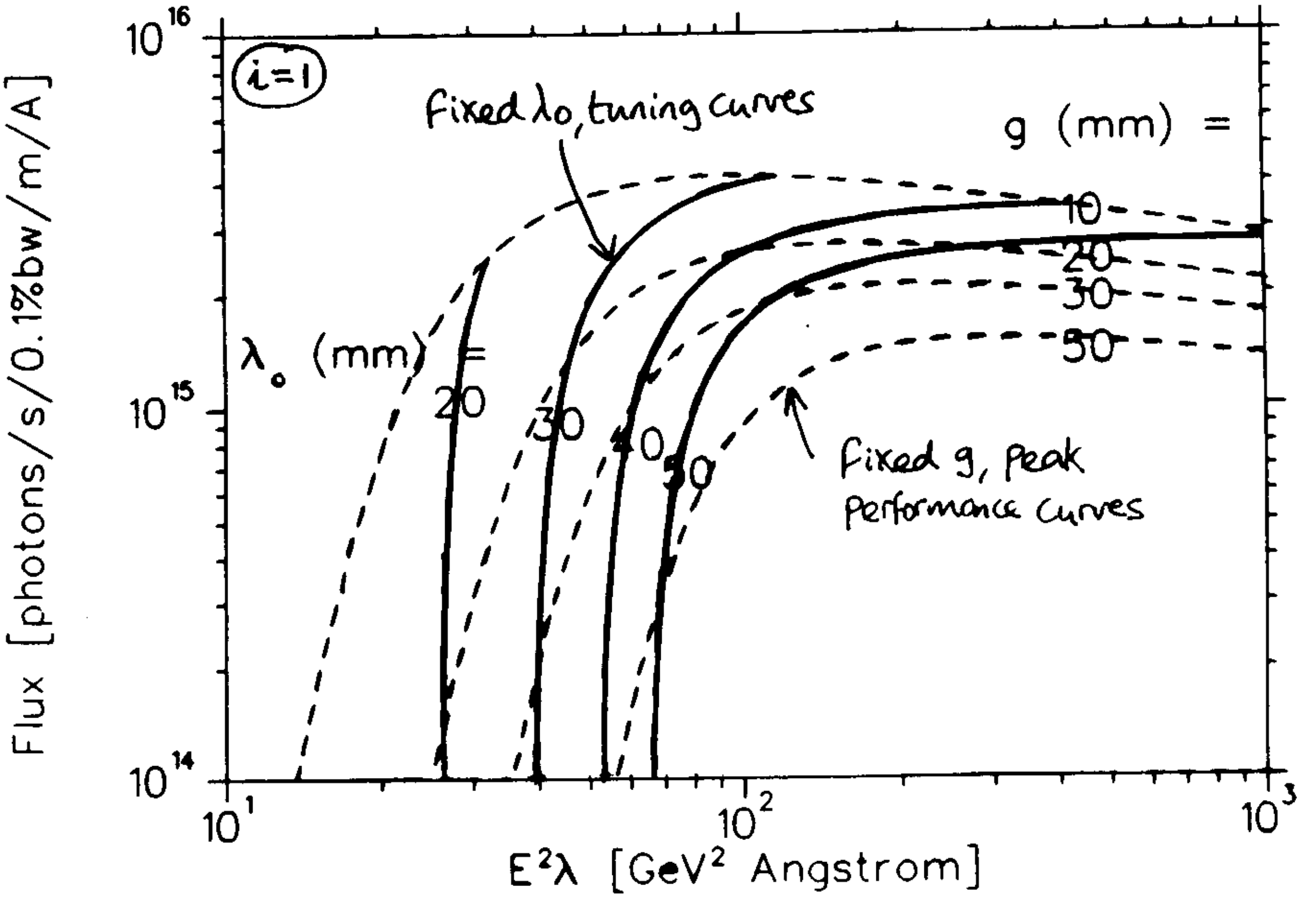
2. UNDULATOR AND WIGGLER PERFORMANCE

$$\text{Flux}/0.1\%\ \text{bandwidth}/\text{meter}/\text{Amp} = 1.43\ 10^{14}\ \frac{F_i(K)\ 1+K^2/2}{\lambda_0\ \ i}$$

$$E^2\lambda\ (\text{GeV}^2\ \text{Å}) = 1305.6\ \frac{\lambda_0\ \ 1+K^2/2}{i} \qquad \left\{ \lambda = \frac{\lambda_0}{2\gamma^2}\left(1+K^2/2\right) \right\}$$

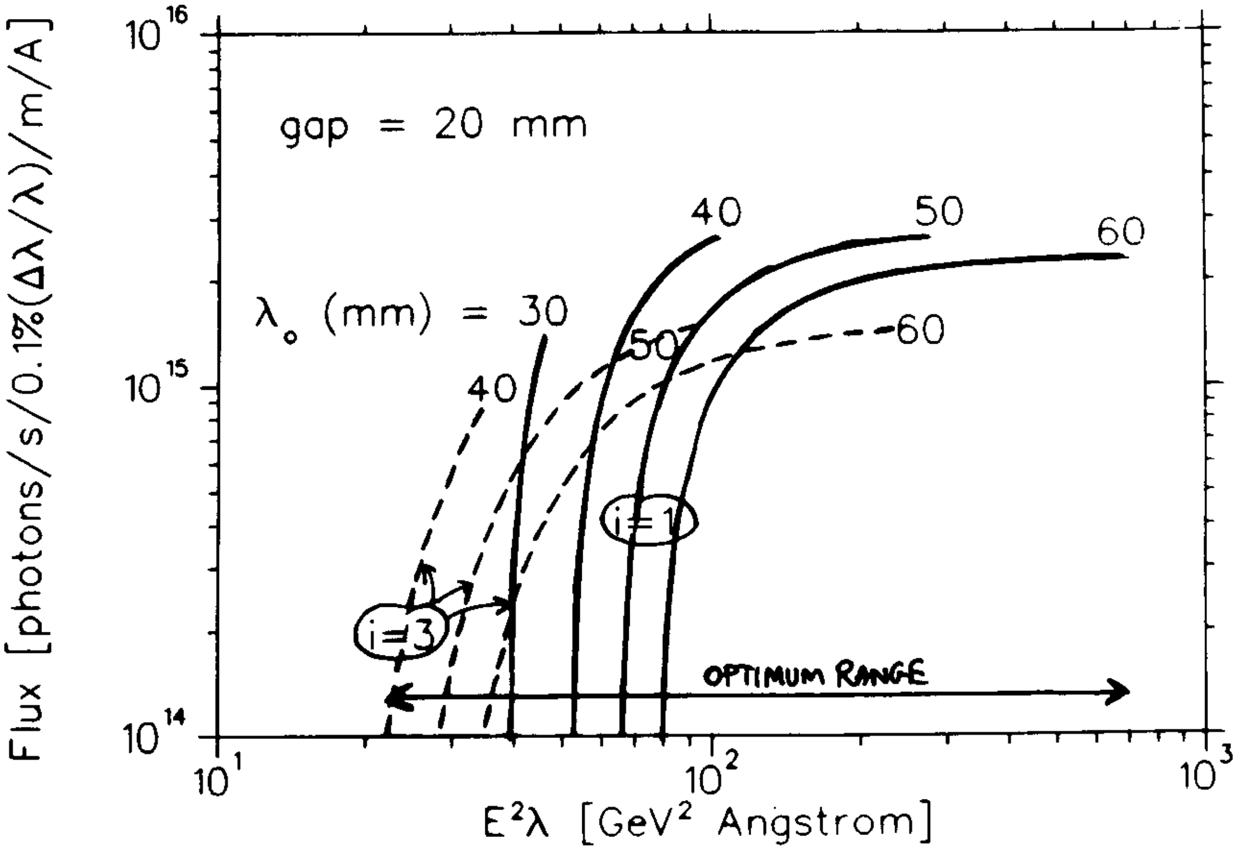
For a given magnet type (eg. hybrid p.m.) and harmonic, i, these are both functions only of period (λ_0) and gap (g)

∴ a "universal" performance curve can be drawn :-



- tuneability limited at short λ, since K small

- at long λ, K becomes very large ∴ large number of harmonics and increased power density it is possible to extend the tuning range somewhat by means of harmonics :



however, there is still an optimum range of undulator wavelength for a given Energy ($\propto$ gap)
and hence an <u>optimum ring energy to cover a given spectral range</u>:

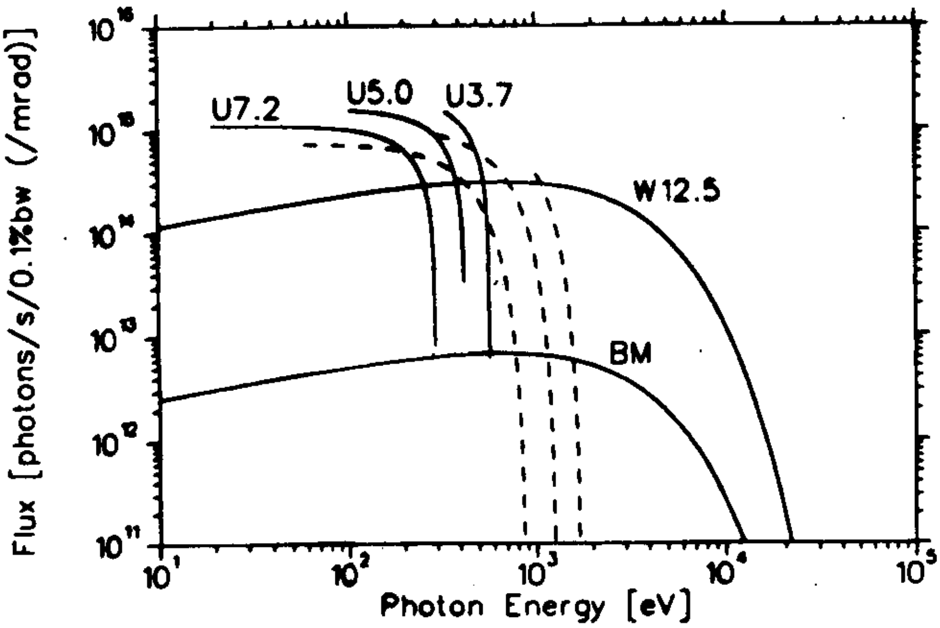
Ring energy	wavelength range	ph. energy range
0.8	35 – 1250 Å	10 – 350 eV
1.5	10 – 350 Å	35 eV – 1.2 keV
6.0	0.6 – 22 Å	0.5 – 20 keV

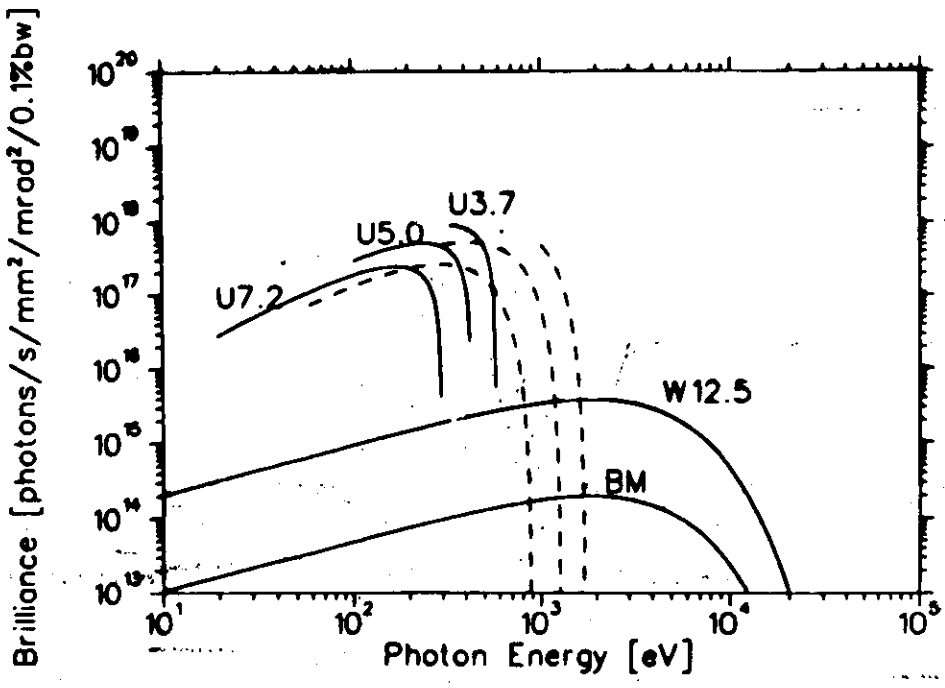
(based on 20mm gap)

Example : Insertion Devices for a 1.5 GeV ring

Type	λ_o (cm)	N	B_o (T)	K	P_{tot} (W)	P_{den} (W/mrad^2)
U	7.2	41	0.79	5.3	526	355
U	5.0	60	0.54	2.5	248	351
U	3.7	81	0.35	1.2	103	296
W	12.5	23	1.5	17.5	1821	378

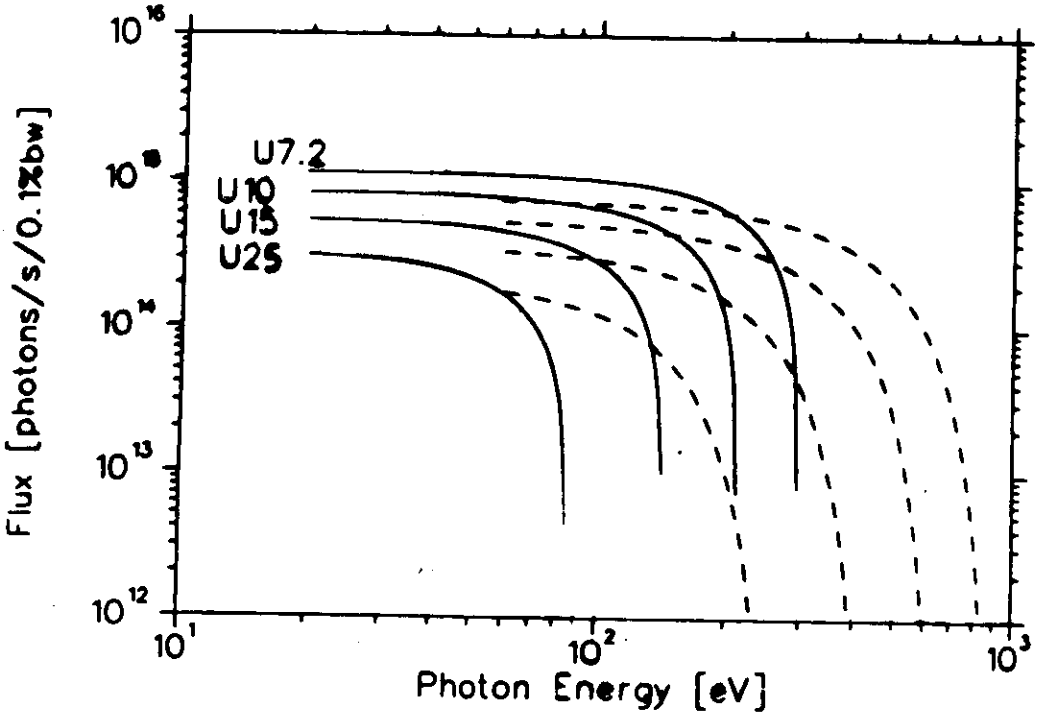
NB] assumes $\varepsilon_x = 10^{-8}$, $\varepsilon_y = 10^{-9}$, g_{min}=20 mm, L=3m, I_b=200 mA



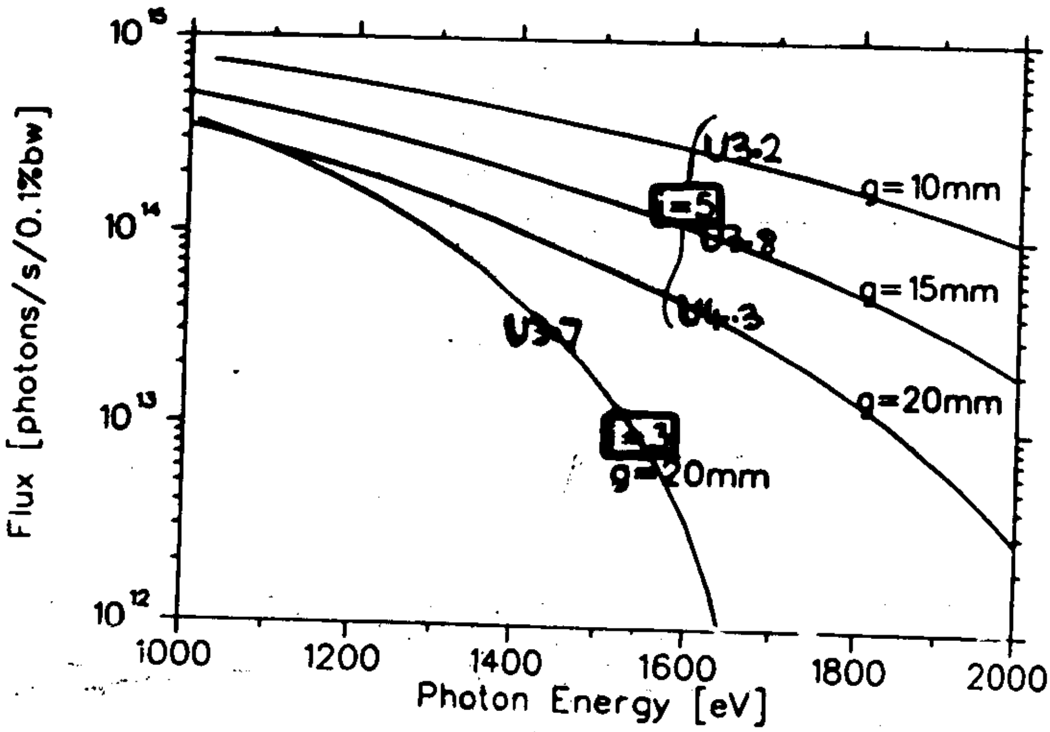


Low energy undulator (ε_{min} = 20 eV)

λ_o (cm)	N	B_o (T)	K	P_{tot} (W)	P_{den} (W/mrad2)
7.2	41	0.79	5.3	526	355
10.0	30	0.47	4.4	190	155
15.0	20	0.25	3.5	53	55
25.0	12	0.11	2.6	10	14



High energy undulator (ε_{min} = 1 keV)



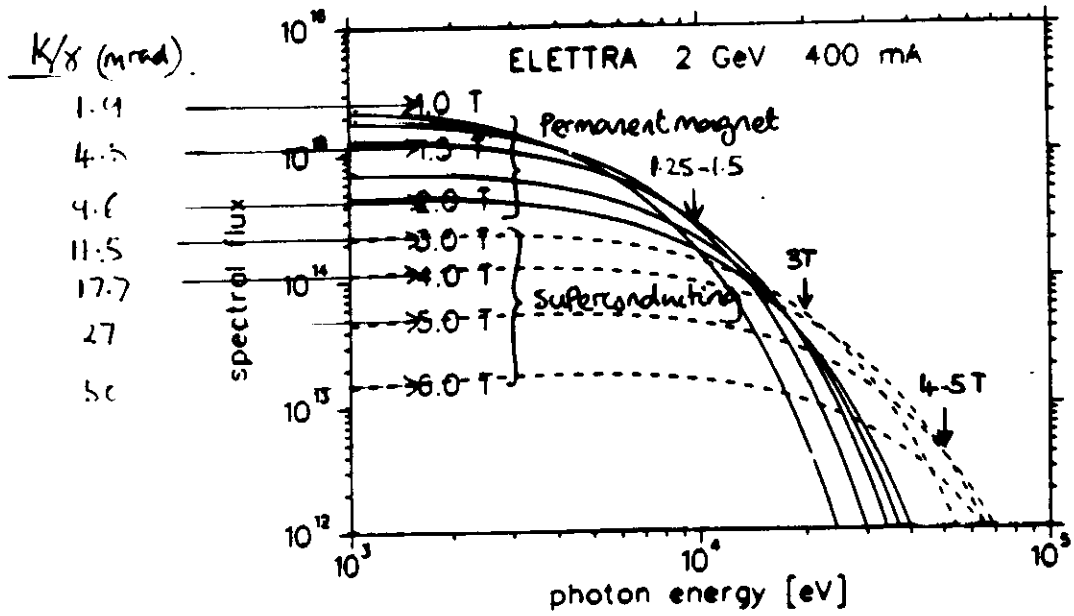
Multipole Wiggler Performance

Usually the aim is to enhance the intensity at high photon energy by increasing the field strength and the number of poles

Limitations :

- minimum magnet gap
- radiation power (and power density)
- opening angle of the radiation (K/γ)
- effects on the electron beam (focusing, emittance)

Trade-off between number of poles and field strength for constant total power, e.g. ELETTRA : $P_{max.} = 10\,kW$



⇒ there is an optimum field strength for a given photon energy

However, the radiation opening angle may also be restricted to reduce the power incident on the vacuum chamber walls :

ELETTRA - ± 4.5 mrad

SRS, 5 T wiggler - ± 32 mrad, shorter straight section, wider vacuum vessel

3. CONSTRUCTION ASPECTS

• choice of length :

flux ~ N

angular flux density ~ N^2 (ideal) - N (emittance dominated)

brilliance ~ N, both ideal and emittance dominated

power, power density ~ N

⇒ no strong reason to increase length; 3-5 m typical

[unless very long, e.g. Tristan Super Light Facility - 70 m !]

• segmented or in one piece ?

segmented - easier construction, measurement etc.; flexibility but attention has to be paid to phase differences between sections and also magnetic interaction effects.

• "C"-frame or "H-frame" ?

C-frame has easier access for magnetic measurements, and for installation, but H-frame more rigid; depends on the length.

• pure permanent magnet or hybrid ?

- good results can be achieved with either - with sufficient care

• obtaining the minimum gap

- standard construction, external to fixed vacuum chamber :

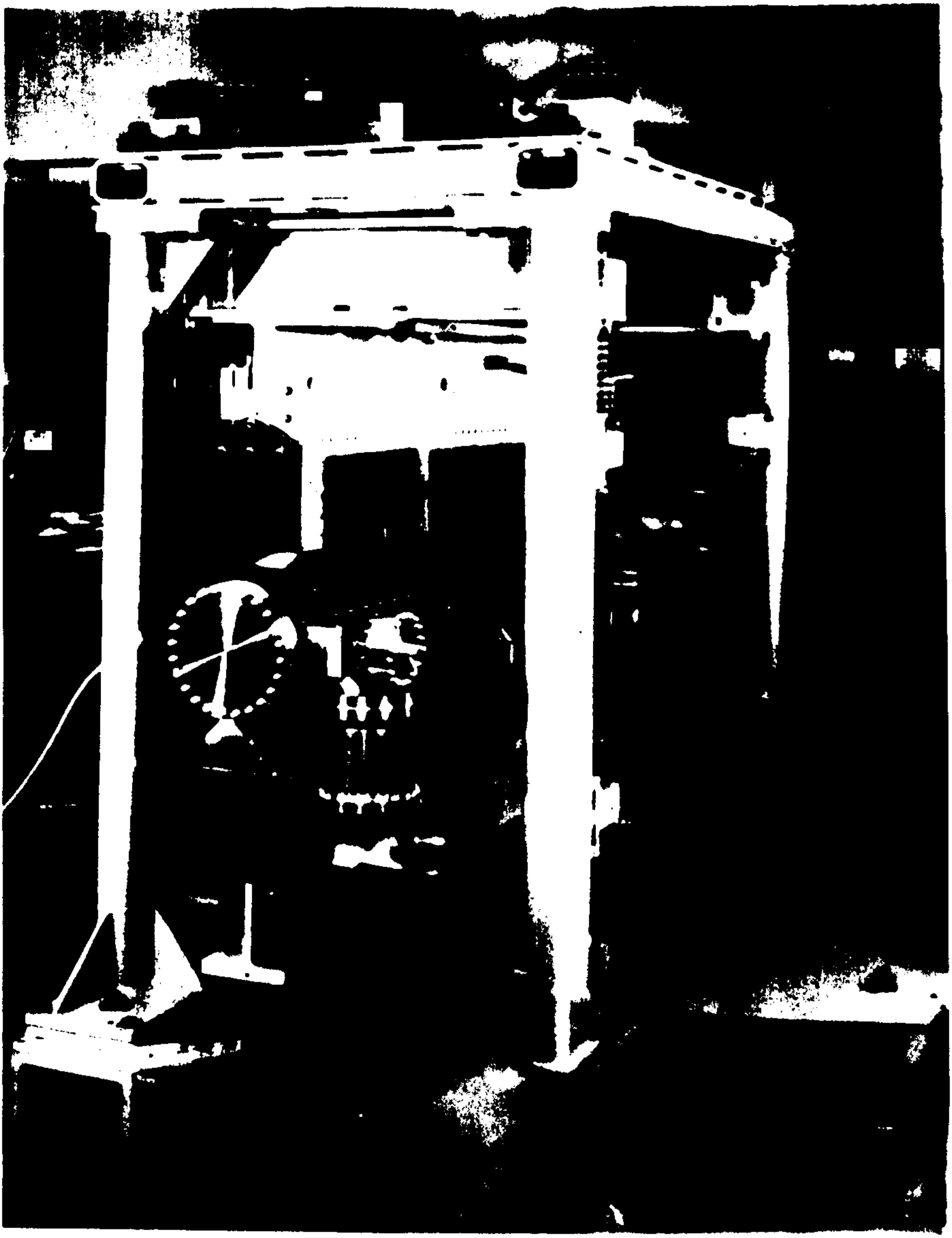
  $g_{ID} = g_{int} + 4$ mm

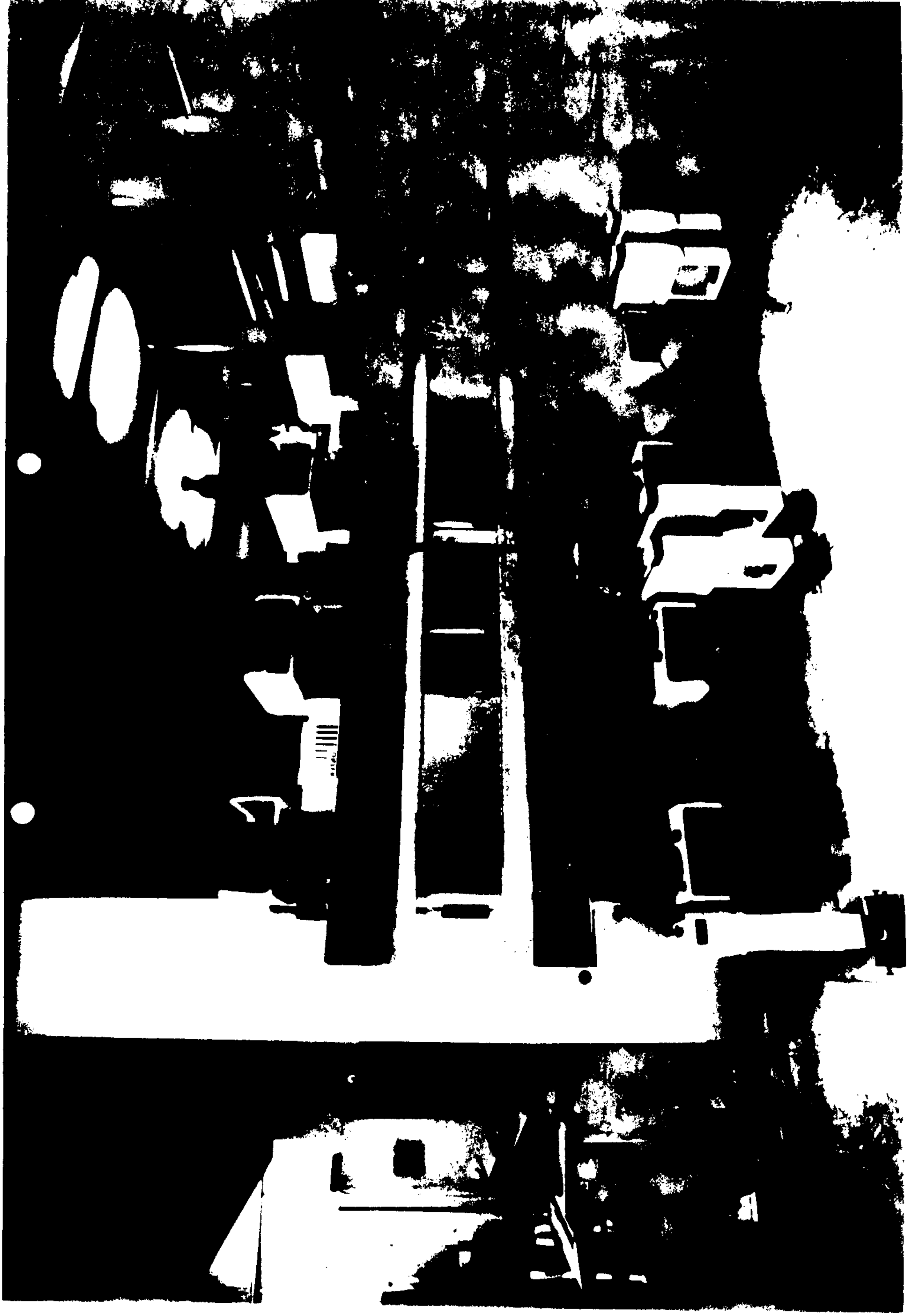
- minimum thickness chamber, at the position of the poles :

  $g_{ID} = g_{int} + 1$ mm

- variable gap vacuum chamber, can be adjusted after beam injected and stored in the ring

- in-vacuum insertion device : $g_{ID} = g_{int}$

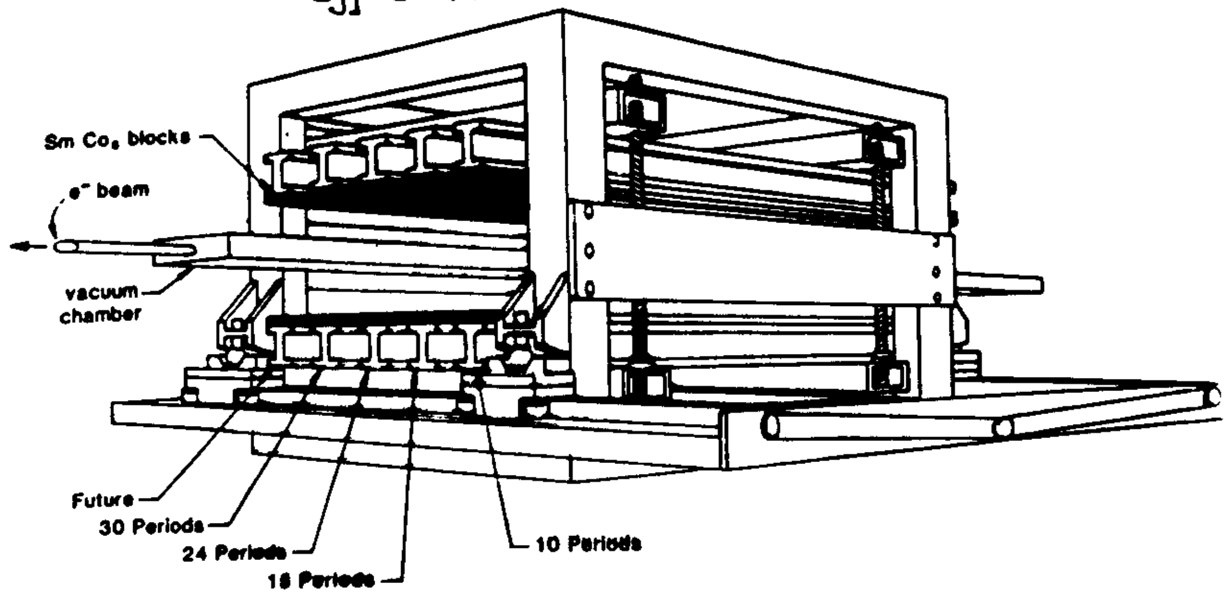




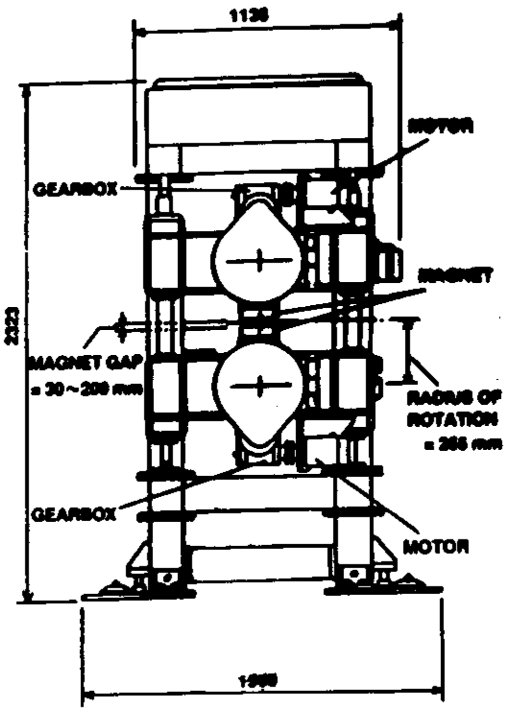
Multi-undulators

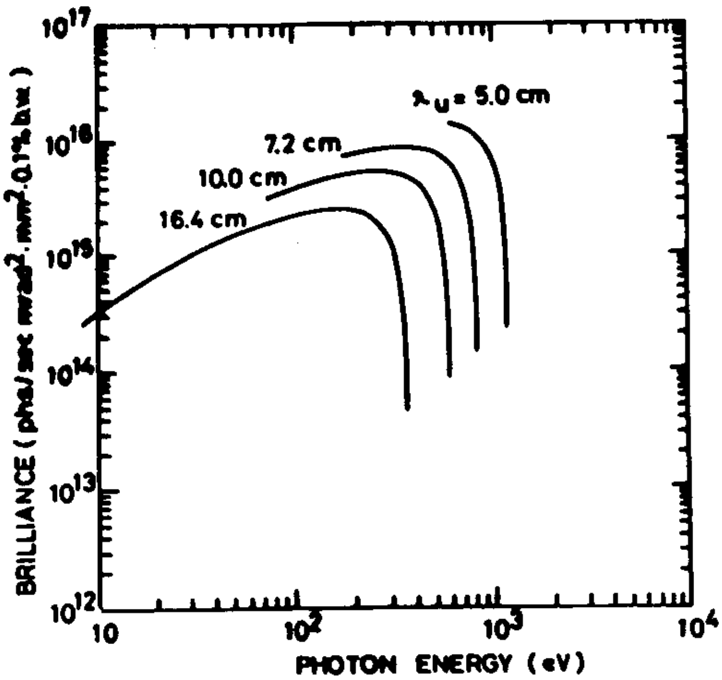
- coverage of a wide spectral range using several magnet arrays

eg] SSRL :



Photon Factory ("Revolver") :





Short period undulators

"short"	≤ 30 mm
"mini-undulator"	~ 1-10 mm
"micro-undulator"	< 1 mm

Aim : higher photon energies with given electron beam energy.

Much effort has gone into the development of short period devices for use in FELs, based on permanent magnets, pulsed electromagnets and superconducting magnets.

Limited application so far in storage rings, because of the need for small gaps :

⇒ variable vacuum vessel gap or in-vacuum
⇒ possible changes to ring optics to reduce the vertical beam size (β_y) at the undulator location

examples :

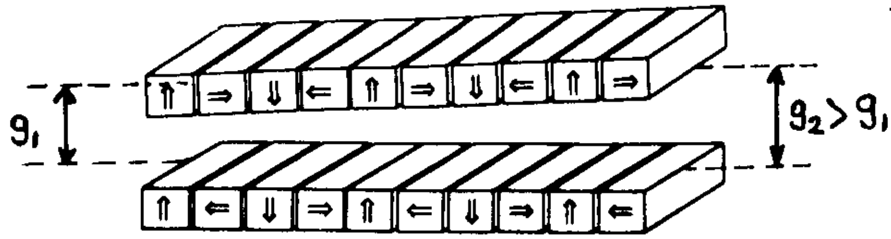
• smallest period in routine use (?), MAX, λ_o = 24 mm, PM
K=1.9 at g=7 mm (6 mm for e- beam) - variable vac. vessel

• PSGU under construction at NSLS, λ_o = 16 mm, PM
K=1.0 at g=6 mm (4 mm for e- beam) - variable vac. vessel

• constructed for FEL at NSLS, λ_o = 8.8 mm, SC
K=0.36 at g=4.4 mm

NB] reduced tuneability, due to small K value

Tapered undulators



variation of magnet gap along undulator axis :
⇒ variation in the output wavelength
⇒ broadened linewidth

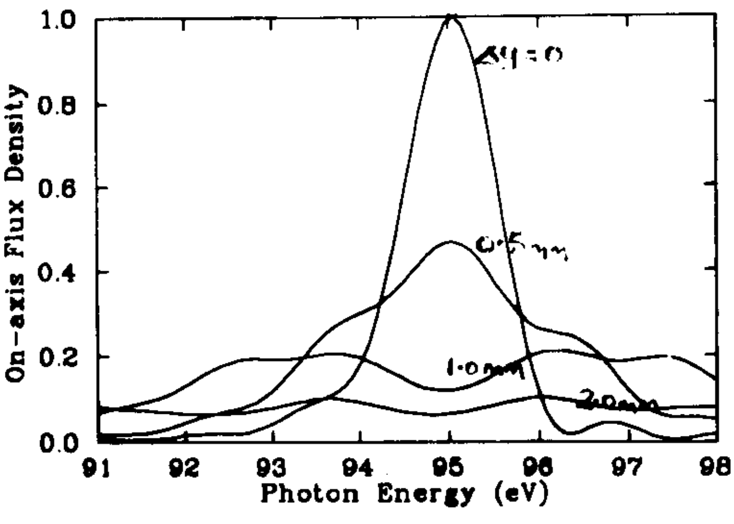
⇑ possibility to perform experiments over a range of wavelengths (~ 10-20 %) without changing the undulator

⇓ reduced intensity compared to standard case

gap variation required varies with **K** and λ_0 :

$$\frac{\Delta\lambda}{\lambda} = \frac{K^2}{1+K^2/2}\,\frac{\Delta B_0}{B_0} = \frac{K^2}{1+K^2/2}\,\frac{\pi}{\lambda_0}\,\Delta g$$

e.g. for $\Delta\lambda/\lambda$=10% with λ_0=50 mm, Δg ranges from 1-7 mm K=2.5-0.5



e.g.]
ELETTRA
U5.6
K = 3.5
i = 1
emittance included

NB] the spectrum is not smooth, particularly with low emittance and low **photon energy** e.g. Measurement of the APS prototype undulator carried out at CESR (Cornell) :

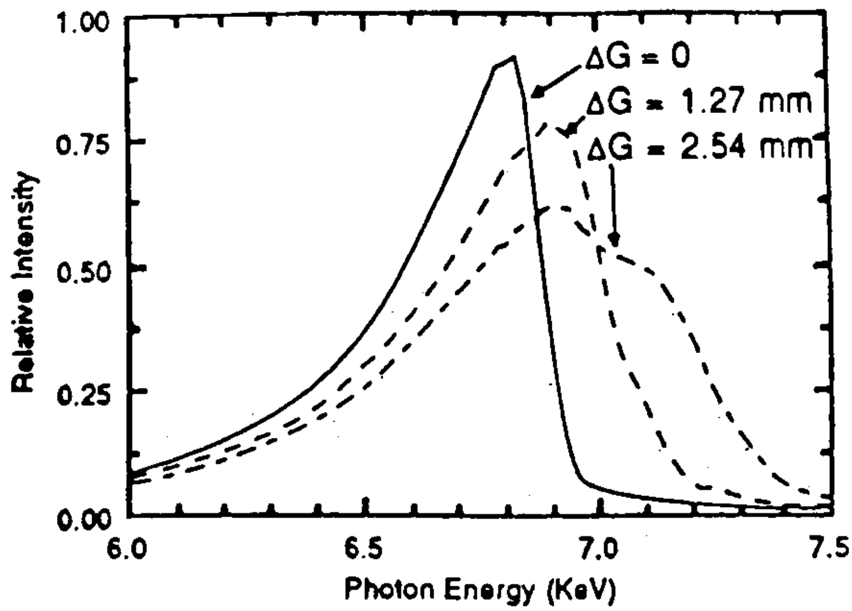


FIG. 2. On-axis spectra measured during the first undulator run.

4. COMPUTATION OF UNDULATOR RADIATION PROPERTIES

Why ?

- more precise determination of peak angular flux density, by correct convolution of ideal angular distribution and electron beam divergence
- calculation of integrated flux over finite aperture ("pinhole")
  → define required aperture for given fraction of total flux
- calculation of power density and integrated power over finite apertures, as a function of photon energy
  → power loading on optical elements
  NB the spectral and angular distribution can be important
- input for optical element design

etc. etc.

How ?

Various computer codes exist; two main types :

(1) ideal trajectory, plane sinusoidal or general elliptical, in the far field → analytic expressions (Bessel functions)

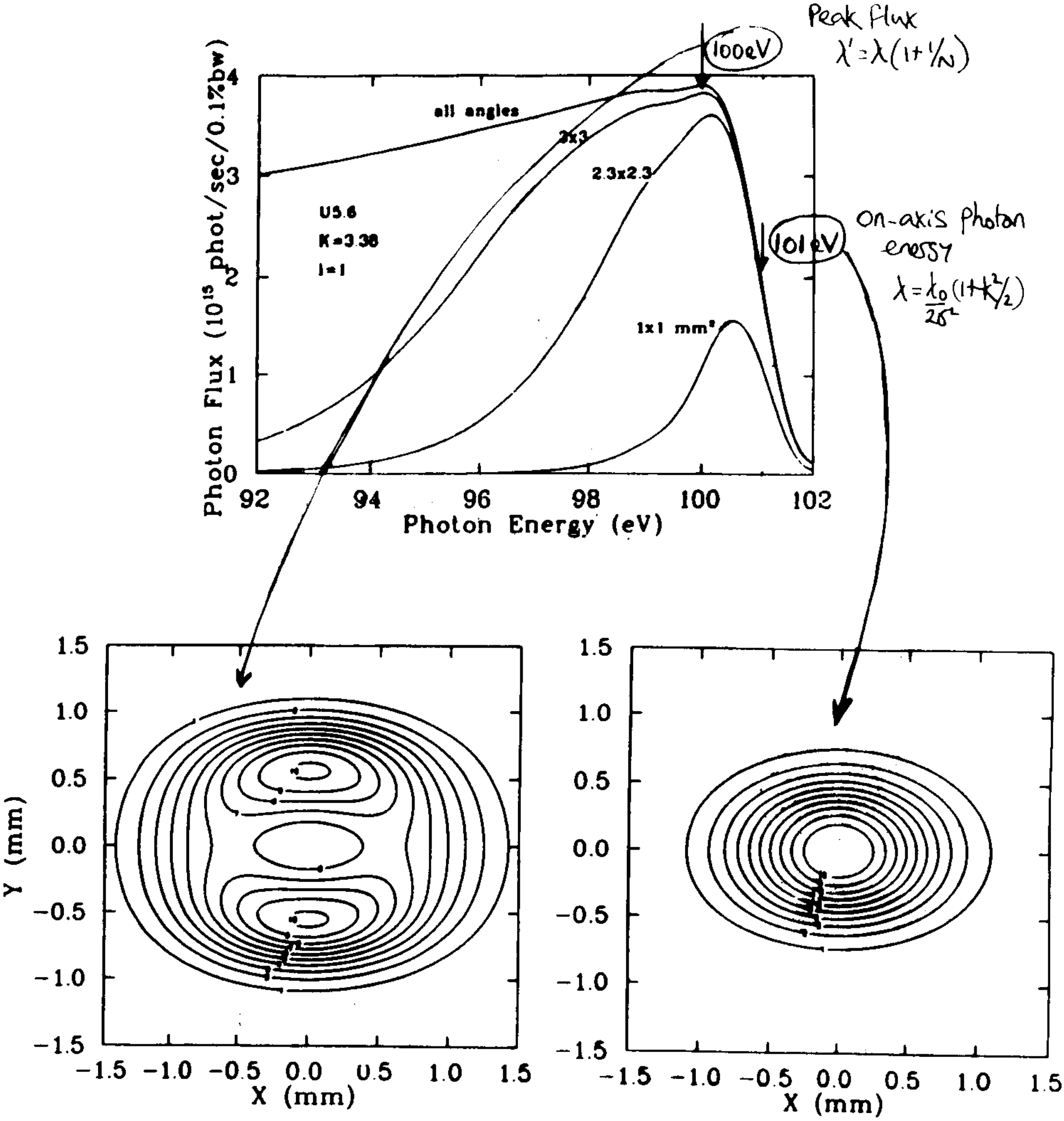
(2) arbitrary field distribution and trajectory, and/or near field → numerical integration, or FFT

options for - inclusion of emittance, energy spread
calculation of polarization properties

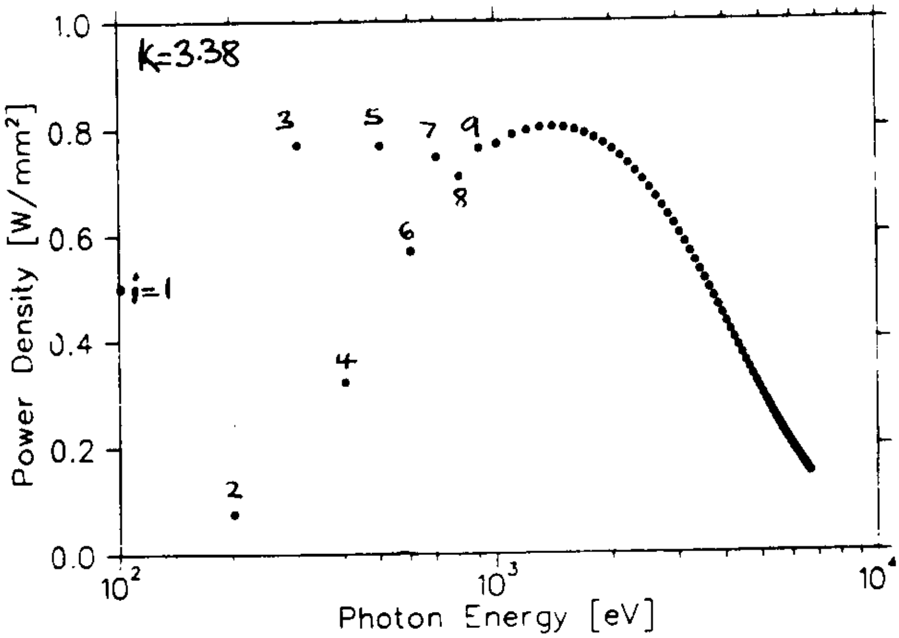
For design work, the most important effects can be calculated using the first approach; e.g. URGENT

To evaluate the magnetic measurement results on real devices requires the second approach.

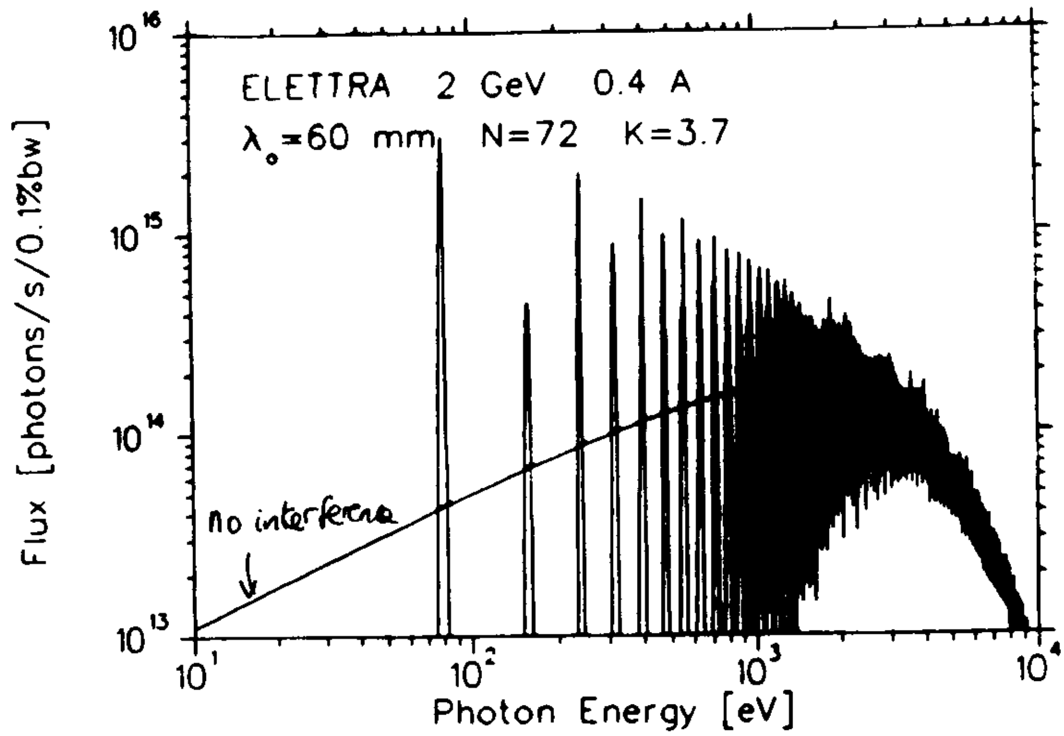
Examples of flux transmitted by various pinholes and angular distributions of flux for an undulator on ELETTRA, calculated with URGENT.



Power densities for each individual harmonic for the same case as above :



Another example, showing the spectrum of flux transmitted through a pinhole up to very high harmonic numbers :



- solid line = wiggler approximation (no interference)

5. UNDULATOR FIELD ERRORS

- permanent magnet magnetization errors :

- variations from block-to-block of total magnetization strength (± 2.5 %) and angle (±2 °),
- inhomogeneity (up to 20 % between opposite faces of the same block)

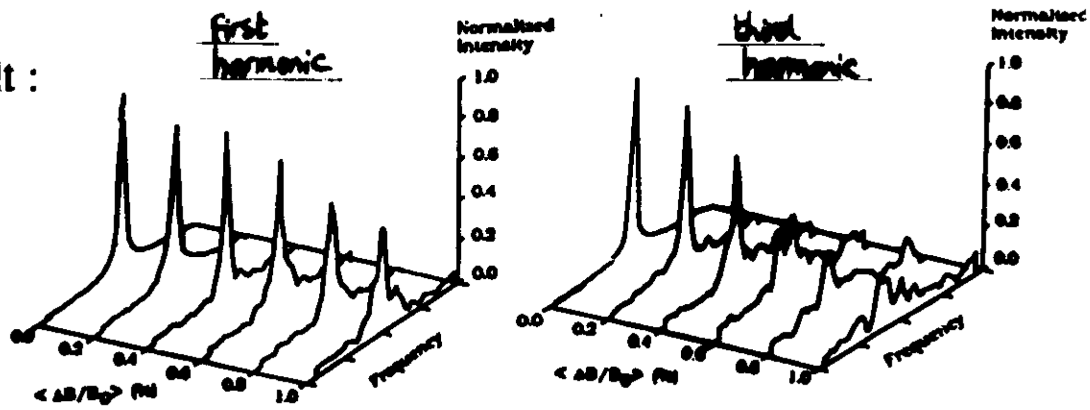
- mechanical tolerances

two effects :

(i/ deflection of the electron beam away from the axis
equivalent to observing the radiation off-axis
⇒ introduction of even harmonics

(ii/ random phase errors
⇒ loss of constructive interference

result :



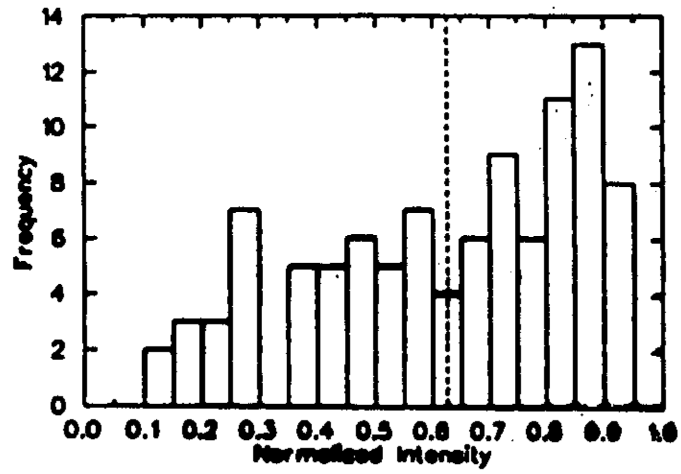
- reduced peak angular flux density and brilliance

- deterioration gets worse with increasing harmonic number
- limits the tuning range : for the new Synchrotron Radiation Sources, up to the 5th harmonic was generally considered useful....

- smoothing out of spectrum at high harmonics (→ wiggler)

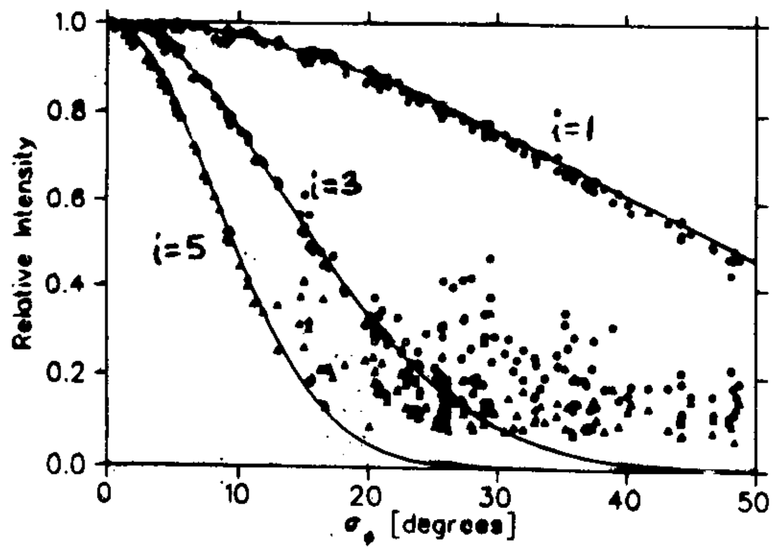
Initial work examined the effect in terms of the (rms) variation in field amplitude from pole to pole.

However, it was later shown that the intensity is not well correlated with this parameter :



for 1% rms field errors ($\sigma_B = 1\%$)

The intensities are however well correlated to the rms phase error at the emitting poles :



$\sigma_B = 0-5\%$

The phase of emission (ϕ) at any point is given by :

$$\phi = \omega\left(t - \underline{n}\cdot\underline{r}/c\right)$$

On-axis ($\underline{n} = 0$) the expression becomes :

$$\phi = \frac{2\pi}{\lambda}\left(\frac{z}{2\gamma^2} + \int \frac{x'^2}{2}\,dz\right)$$

Simple model for effect of random phase errors.

Radiation amplitude for a series of N dipole magnets :

$$A \sim e^{i\phi_1} + e^{i\phi_2} + e^{i\phi_3} \dots e^{i\phi_N}$$

where ϕ_i are the phase errors at each pole.

The intensity is therefore :

$$|A|^2 \sim \sum_{n=1}^{N} \sum_{m=1}^{N} e^{i(\phi_n - \phi_m)}$$

$$\sim N + (N^2 - N) e^{-\sigma_\phi^2}$$

since

$$\langle e^{i\phi} \rangle = e^{-\sigma_\phi^2/2}$$

In the ideal case ($\sigma_\phi = 0$) i.e. $|A|^2 = N^2$

and hence the ratio of intensity to the ideal case is :

$$R = \frac{N + (N^2 - N) e^{-\sigma_\phi^2}}{N^2}$$

Thus, for no errors ($\sigma_\phi = 0$) $R = 1$

large errors ($\sigma_\phi \to \infty$) $R \to 1/N$ (wiggler)

In most cases N large, and if σ_ϕ not too large, we have simply :

$$\boxed{R = e^{-\sigma_\phi^2}}$$

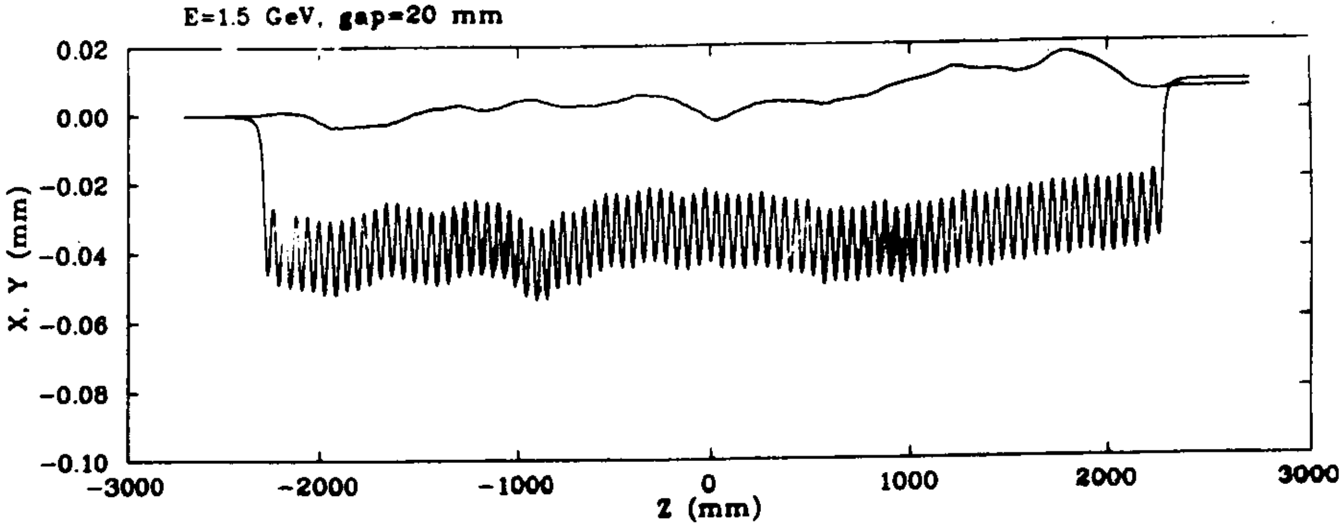
Note that σ_ϕ is linearly proportional to the frequency, so intensity reduces with harmonic number :

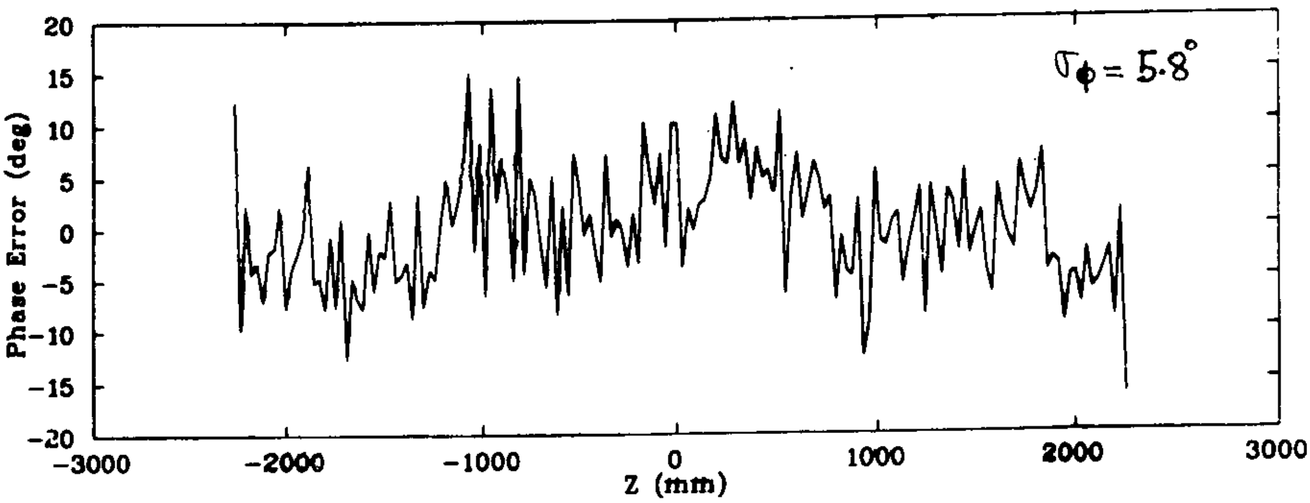
e.g. $\sigma_\phi = 5^\circ$

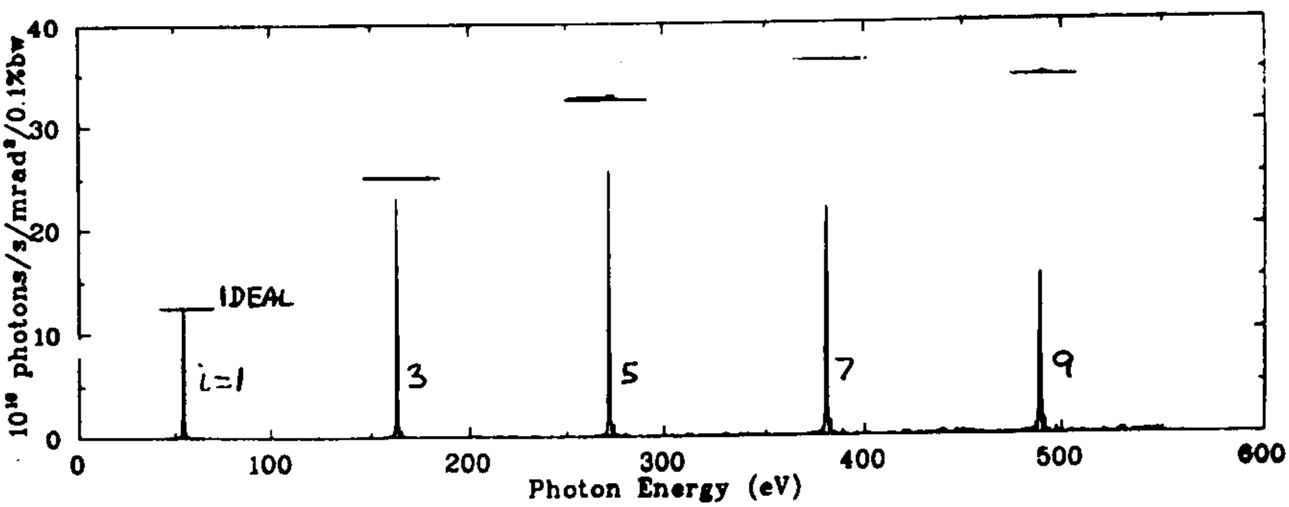
i	1	3	5	7	9	11
R	0.99	0.93	0.83	0.67	0.54	0.40

Experience shows that careful construction can result in rms phase errors of 5° or less, and hence even higher harmonics can be used than thought previously :

e.g. ELETTRA Undulator U5.6







Combination of phase errors, emittance and energy spread

The effects of electron beam emittance (i.e. beam divergence), energy spread, and undulator phase errors on the peak angular flux density are to a good approximation independent :

$$\boxed{R_{tot} = R_{\varepsilon} \times R_{\Delta E/E} \times R_{\phi}}$$

e.g. ELETTRA (1.5 GeV) U5.6, N=81

	i=1	i=3	i=5	i=7	i=9
phase error, R_{ϕ}	0.97	0.91	0.76	0.59	0.41
emittance, R_{ε}	0.98	0.84	0.71	0.62	0.54
energy spread, $R_{\Delta E/E}$	0.97	0.79	0.60	0.48	0.39

i.e. effect of energy spread (often neglected) is important, particularly for higher harmonics

NB]

R_{ϕ} depends on undulator quality; independent of ring energy

R_{ε} depends on ratio between beam divergence and natural radiation opening angle, $(\lambda/L)^{1/2}$

$R_{\Delta E/E}$ depends on ratio between energy spread and natural linewidth, $1/iN$