BINP EXPERIENCE IN WIGGLERS DEVELOPMENT

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- Few examples of wigglers produced at BINP

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Budker Institute of Nuclear Physics

The Budker Institute of Nuclear Physics of the Siberian Branch of the Russian Academy of Science was founded in 1958. Academician G.Budker was the founder and first director of the Institute.

There are around 3000 members of the Institute's staff including 600 researchers, 400 engineers, 900 technicians and workers, and 900 machinery shop personnel.

BINP production capability

BINP Workshop consists of three divisions (Workshop-1, 2 and 3).

- Total area more than 70,000 m^2.
- Total work power more than 1,000,000 work hours per year.
- Total staff around 1000 workers/engineers.

Manufacture of wigglers at BINP

At BINP approximately 50 wigglers/undulators were designed and produced. Among them:

- Multipole 3 T superconducting wiggler (1979). Record field (10.3 T) wavelength shifter for Spring-8 (2000). Multipole superconducting wigglers for BESSY-II (2001) and Elettra (2002).
- Around 10 electromagnet wigglers/undulators including variable polarization devices for APS and PSI.
- Several permanent magnets wigglers and undulators (including undulators for the Optical Klystron-5 system).
- Presently we produce for DESY 20 4-m damping wigglers (PETRA III light source).

Damping wiggler main requirements

- Good damping performance.

- Minimisation of the weight (price) of permanent magnets.

For one CLIC damping wiggler around 150 kG of permanent magnets are required.

- Reliability and easiness of adjustment (~100 m of wigglers).

- Convenience of the radiation interception (several hundreds kW).

- Small distortion/easy correction of the beam dynamics.

Damping performance

Lattice integrals for cos-like wiggler model:

$$I_2 = \int_M \frac{ds}{\rho^2} \quad \xrightarrow{\text{wiggler}} \quad i_2 = \frac{1}{2} h_w^2 L_w$$

$$I_5 = \int_M H(s)/|\rho^3|\,ds \quad \xrightarrow{\text{wiggler}} \quad i_5 = \frac{8}{15} h_w^2 N_w \theta_m \left(5\frac{\eta_0^2}{\bar{\beta}_x} + \bar{\beta}_x \theta_m^2 \right)$$

$$H(s) = \gamma_x \eta^2 + 2\alpha_x \eta' \eta + \beta_x \eta'^2$$

h_w is the peak curvature, θ_m is the maximum deviation angle,
L_w and N_w are the total wiggler length and the total periods number.

Lattice function optimization

Precision of the residue dispersion cancellation:

$$\eta_0 << \frac{\bar{\beta}_x \cdot \theta_m}{\sqrt{5}}$$

= 4.5 mm for the CLIC damping ring.

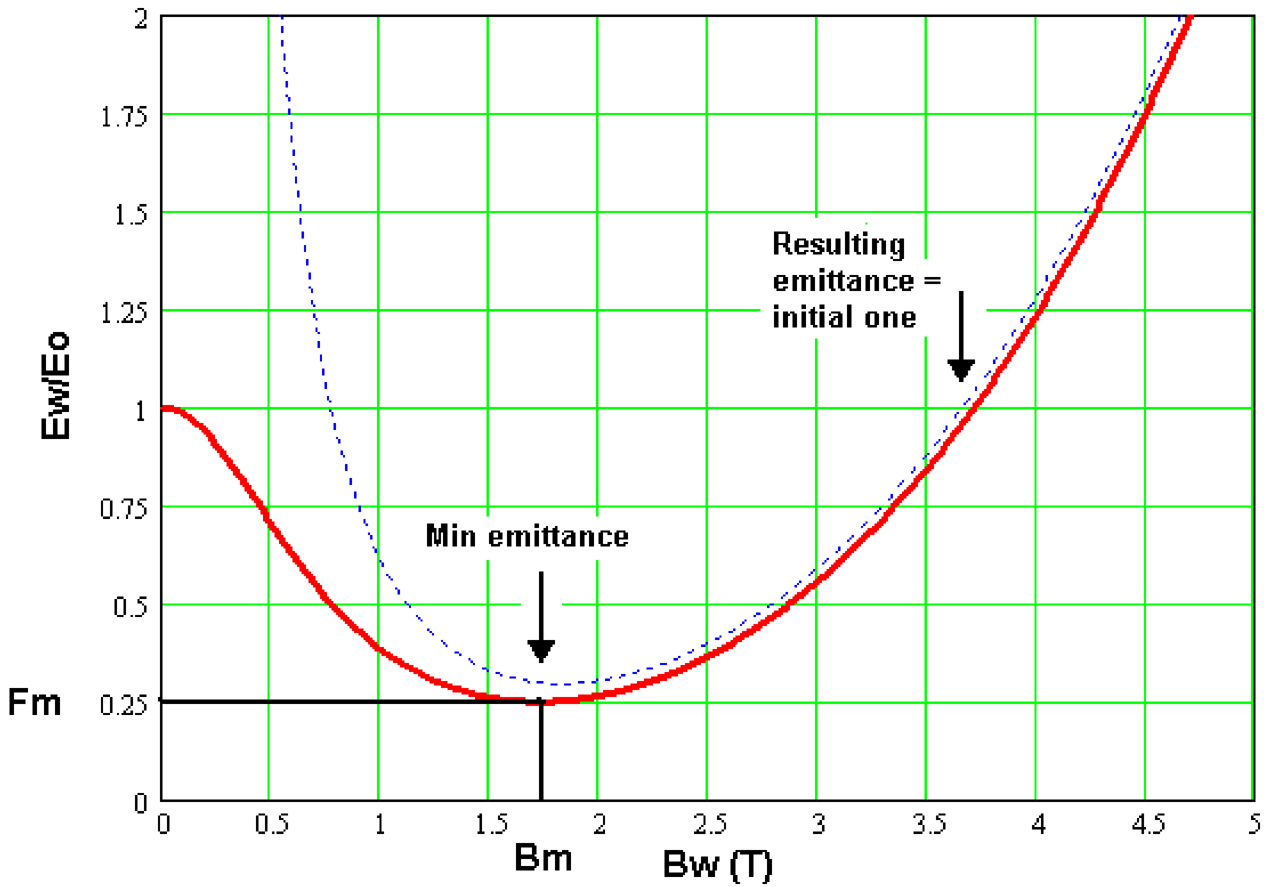
FODO beta-function optimization:

$$i_5 = \frac{16}{15\sqrt{3}} \frac{n_w \theta_m^3 \cdot L_w}{\rho_w^2}$$ = min if the "waist" FODO beta is $\breve{\beta}_x = l_w / \sqrt{3}$

FODO cell phase advance = 120°

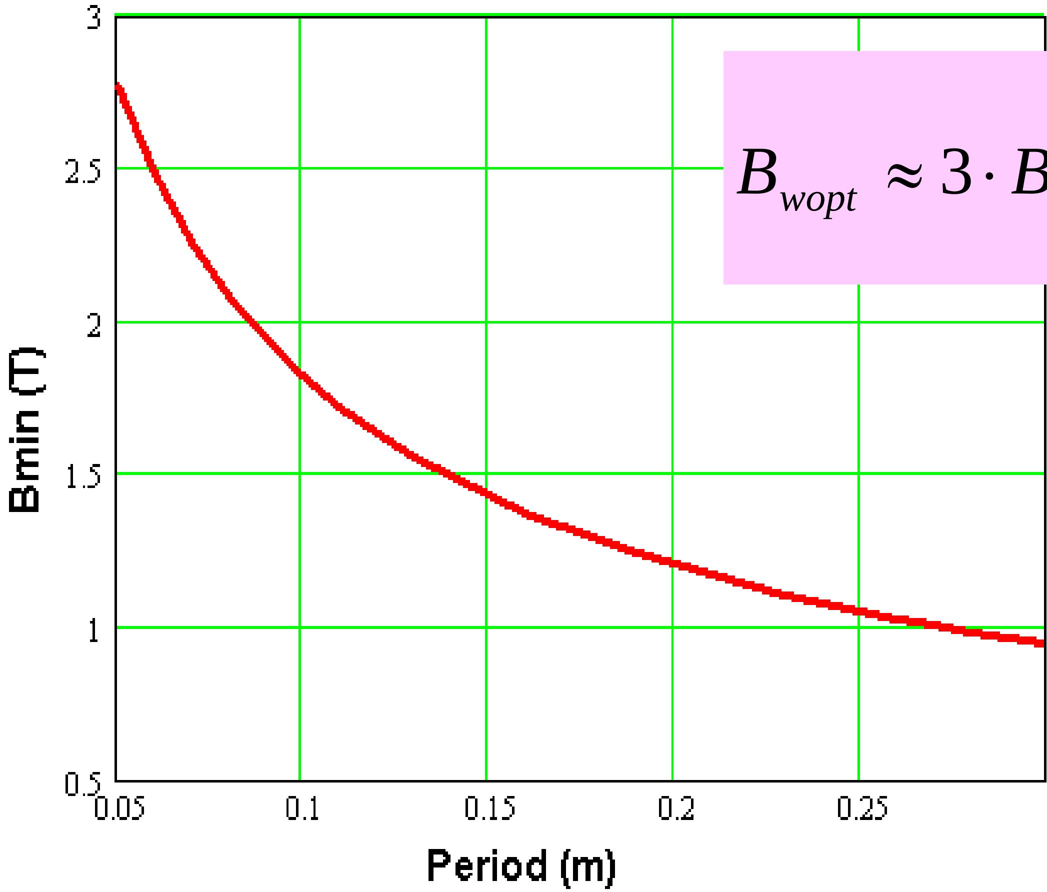
Emittance change due to the wiggler influence

$$\frac{\varepsilon_w}{\varepsilon_0} = C_q \frac{\gamma^2}{J_x} \frac{1 + i_5 / I_5}{1 + i_2 / I_2}$$



Field-period optimization

Optimum peak field for minimum emittance:

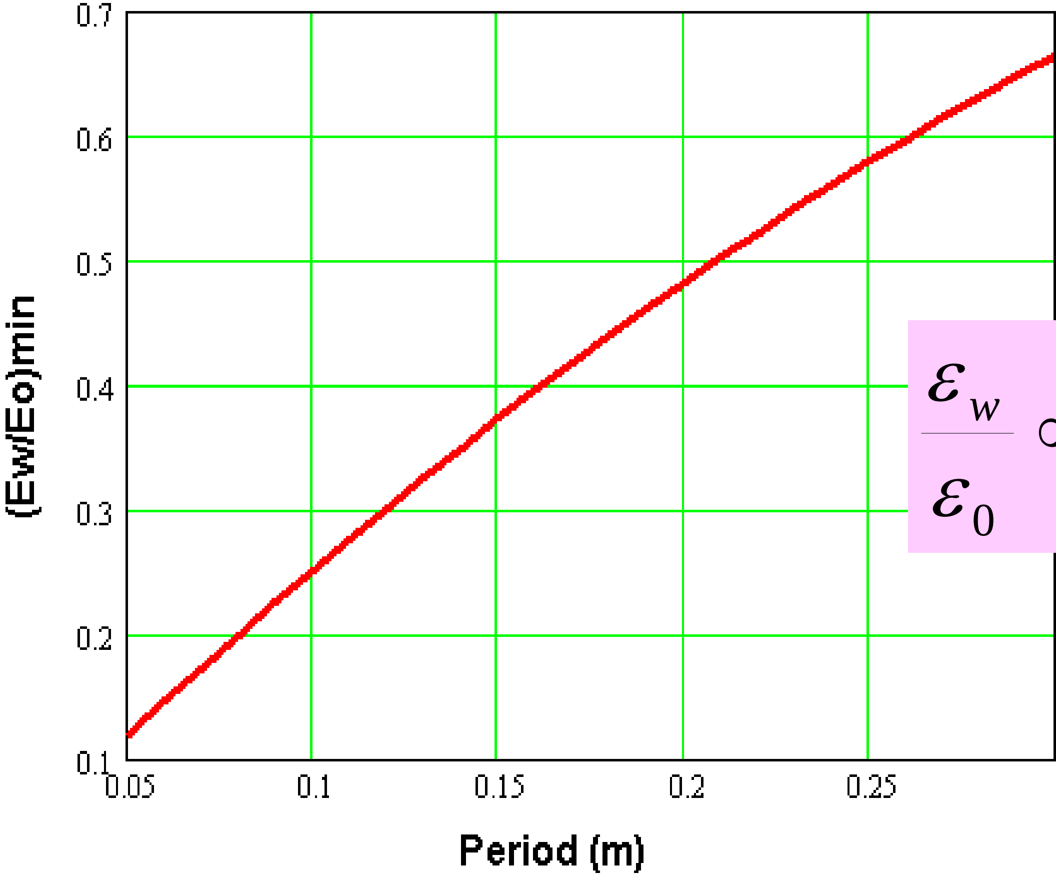


$$B_{wopt} \approx 3 \cdot B\rho \cdot \left(\frac{I_5}{L_w l_w \lambda_w^2} \right)^{1/5}$$

CLIC damping ring:
λ_w **= 0.1 m**
Bopt = 1.7…1.8 T

Emittance optimization

Resulting minimum emittance with wiggler:



$$\frac{\varepsilon_w}{\varepsilon_0} \propto l_w^{2/5} \lambda_w^{4/5}$$

Electromagnet wigglers

UNDULATOR WITH TUNABLE ELLIPTICAL POLARIZATION FOR APS

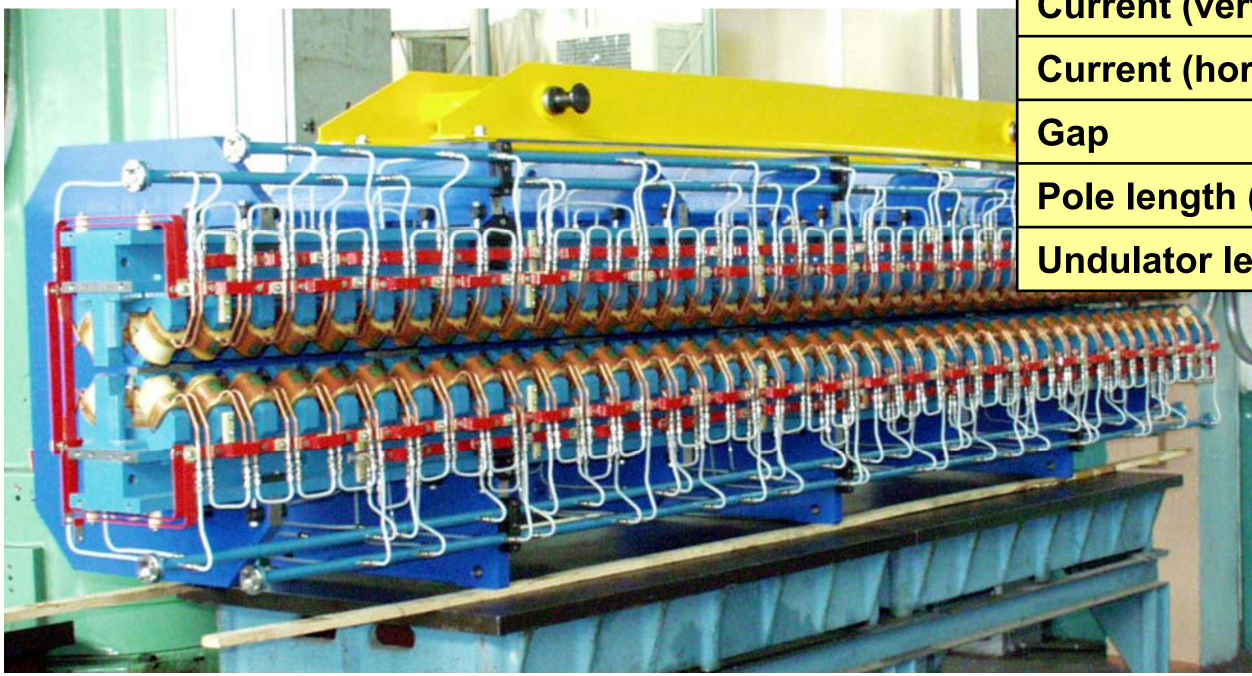
(Argonne National Laboratory, USA), 1998

Parameter	Units	Value
Max magnetic field	T	0.25
Gap	mm	9
Period	mm	128
Total length	m	2.2

Electromagnet wigglers

ELLIPTICAL QUASI-PERIODIC ELECTROMAGNETIC UNDULATOR UE212 (PSI, Switzerland), 2001

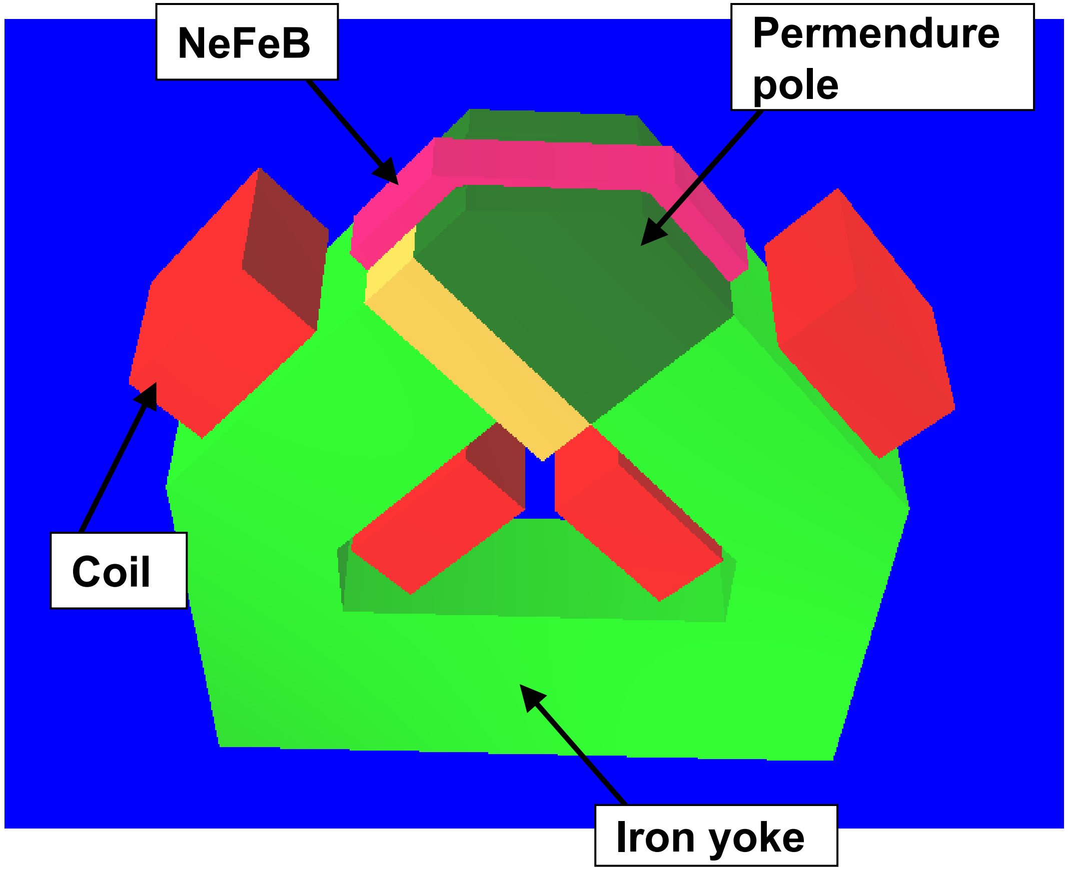
Parameter	Units	Value
Operating vertical magnetic field	T	0.5
Operating horizontal magnetic field	T	0.1
Current (vertical coils)	A	166
Current (horizontal coils)	A	120
Gap	mm	19
Pole length (period)	mm	212
Undulator length	m	4.5



Electromagnet wigglers

Usual electromagnet wigglers can not be used as damping wigglers because it is difficult to achieve high field with small period.

However combined permanent/electromagnet devices (equipotential bus wigglers, K.Halbach) can show good damping parameters.



g = 6 mm
λ_w = 25 mm
Bm = 0.45…0.7 T
L = 2 m
$\Delta B/B < 5\times10^{-4}$ at 1 cm.

FEL undulator for KAERI (1999).

g = 12 mm ← **Proposal for damping wiggler (2005)**
λ_w = 76 mm
Bm = 1.7 T

Superconducting wigglers

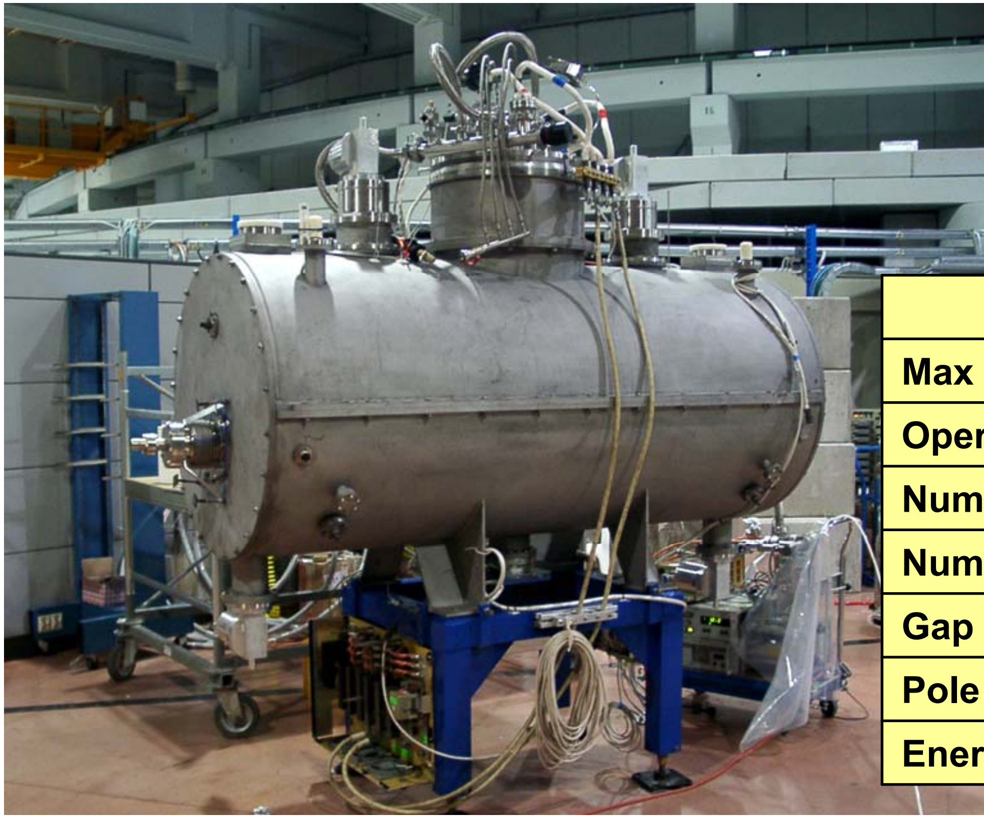
7 TESLA 17 POLE SUPERCONDUCTING WIGGLER

for BESSY-II, HMI, (Berlin, Germany), 2002

Parameter	Units	Value
Max magnetic field	T	7.45
Operating magnetic field	T	7
Number of base poles		13
Number of additional poles		4
Gap	mm	19
Pole length (period)	mm	74 (148)
Energy content	kJ	460

Superconducting wigglers

3.5 TESLA SUPERCONDUCTING WIGGLER for ST (TRIESTE, Italy), 2002



Parameter	Units	Value
Max magnetic field	T	3.62
Operating magnetic field	T	3.5
Number of base poles		45
Number of additional poles		4
Gap	mm	16.5
Pole length (period)	mm	32 (64)
Energy content	kJ	240

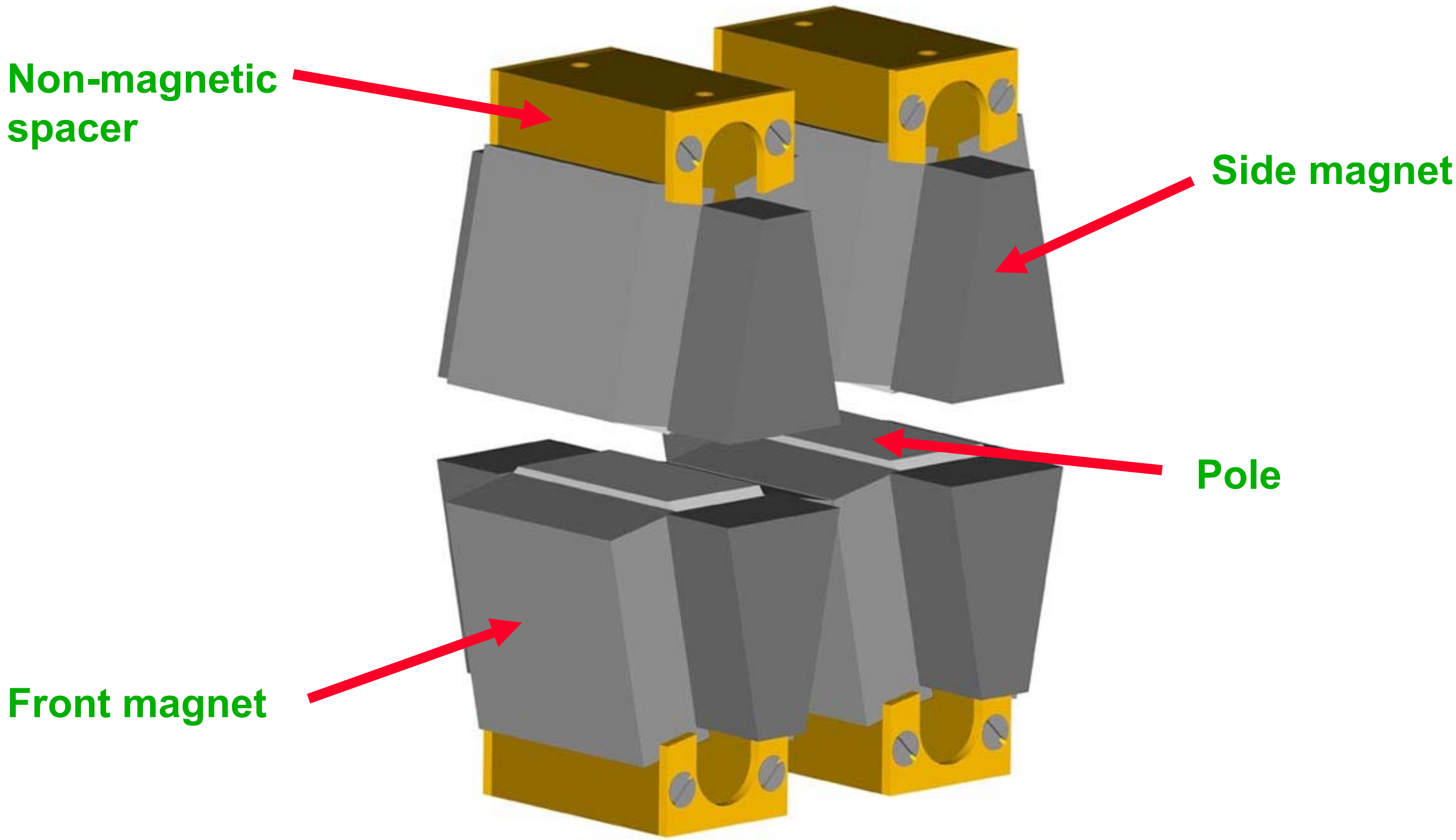
Permanent magnet PETRA III damping wiggler

20 4-m-long NdFeB damping wigglers will be made at BINP for the PETRA III light source.

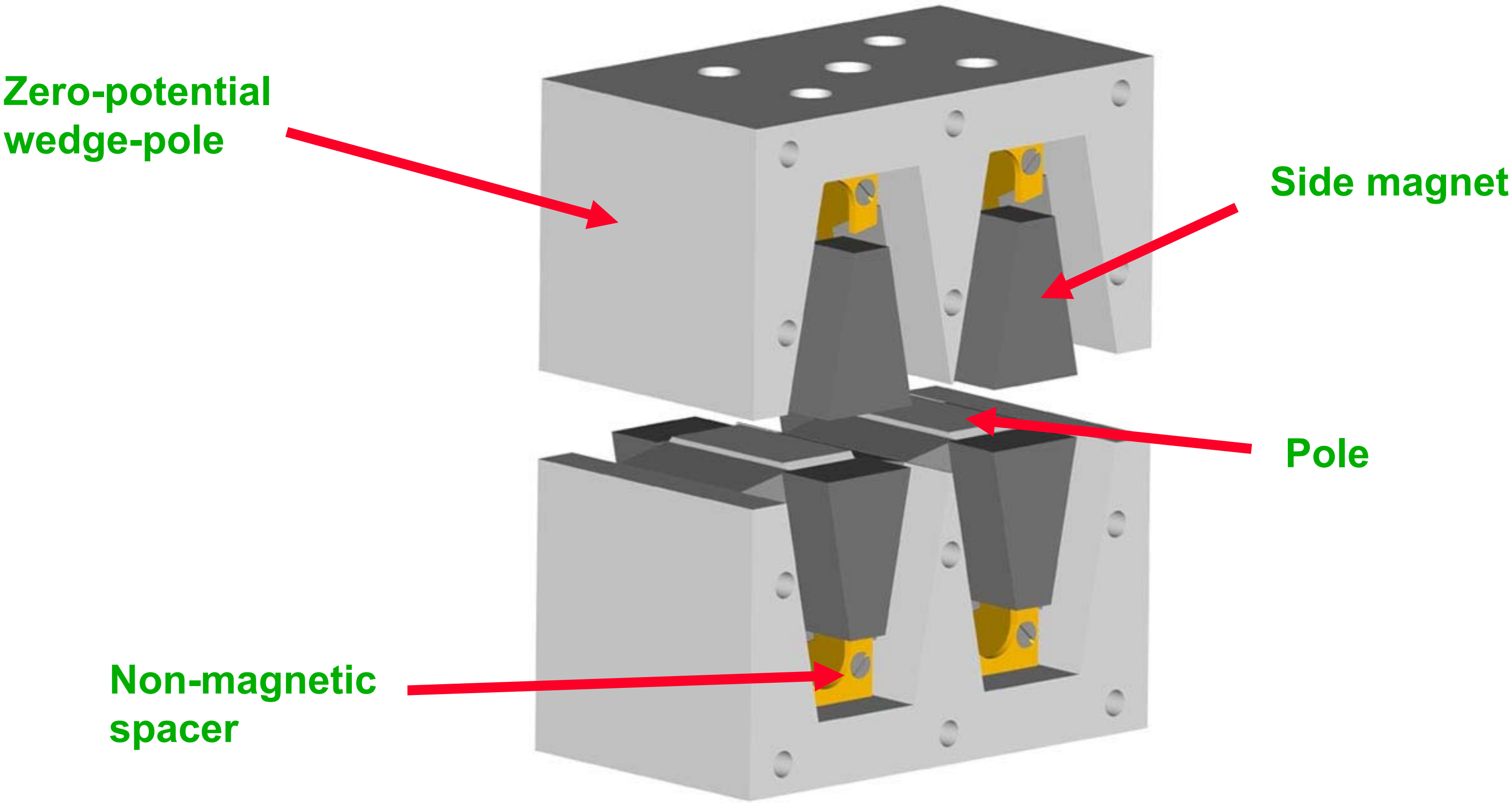
Main parameters of the PETRA III wiggler

Period:	20 cm
Field amplitude:	1.5 T
Field quality @ 1 cm:	10^{-3}
Total length:	80 m
Total radiation power:	887 kW

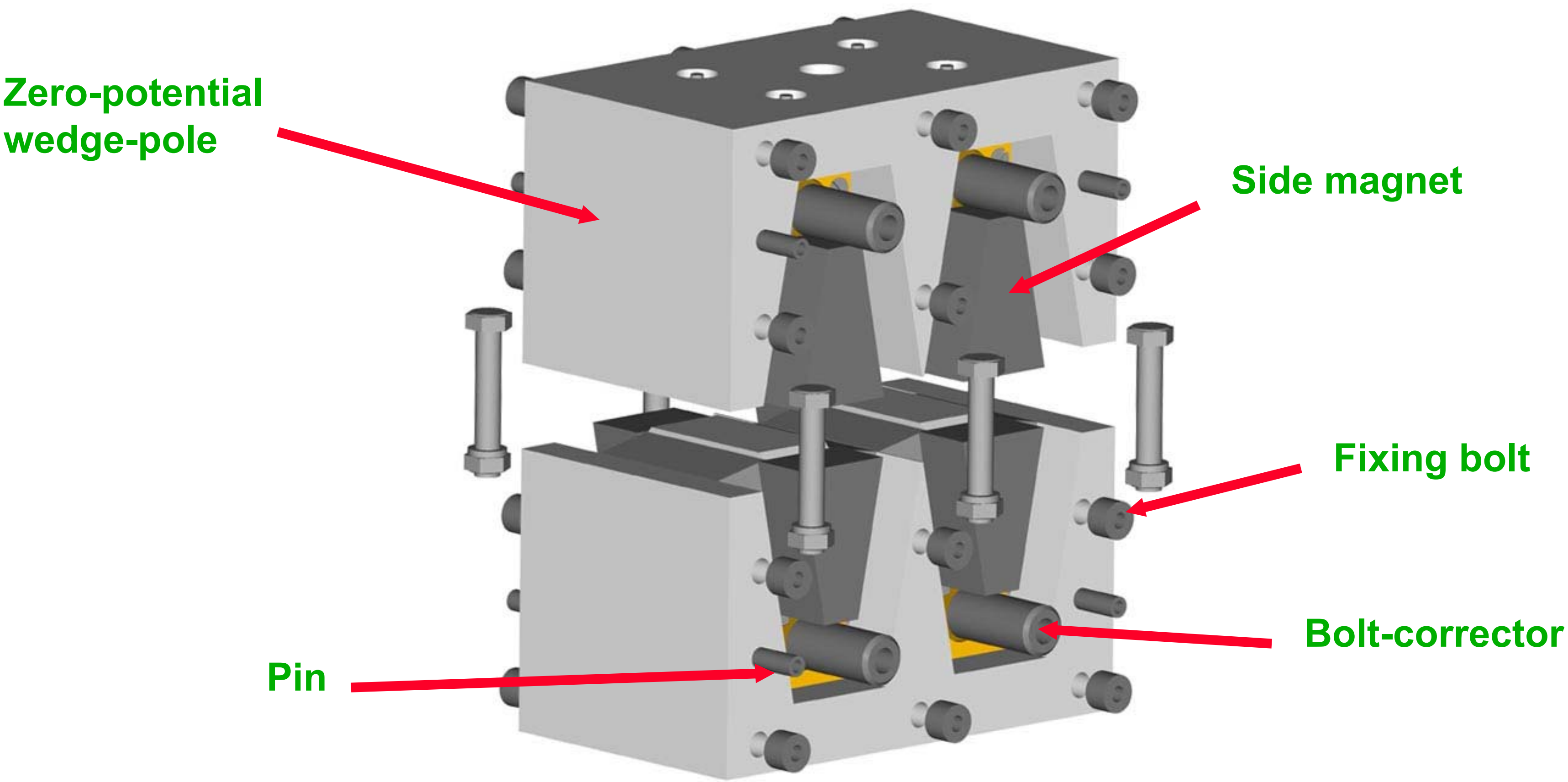
Wiggler period (1)



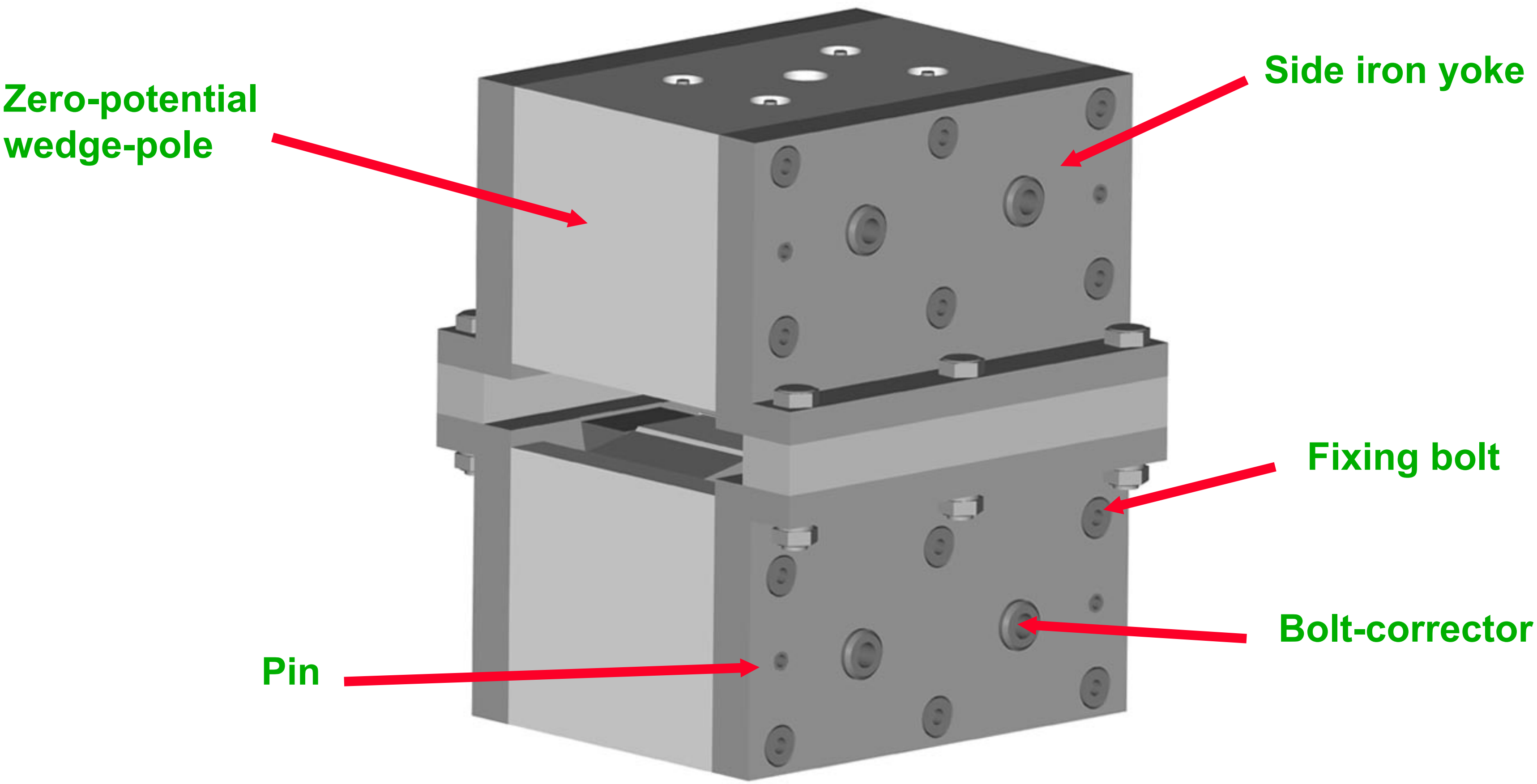
Wiggler period (2)



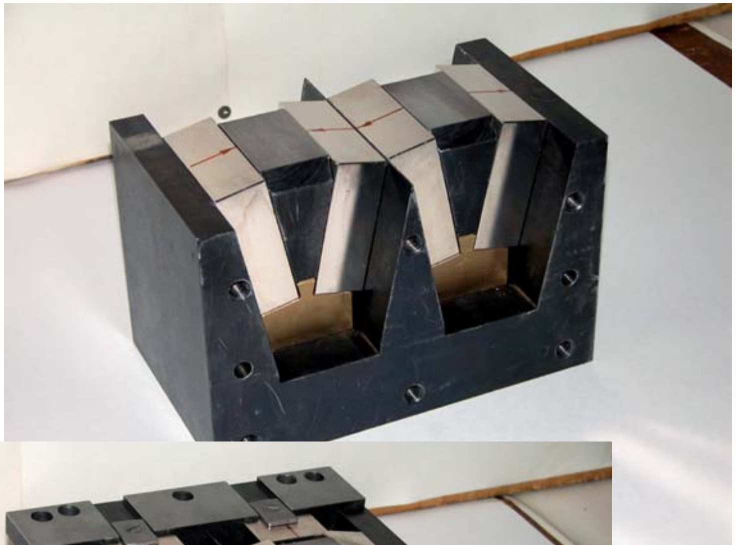
Wiggler period (3)

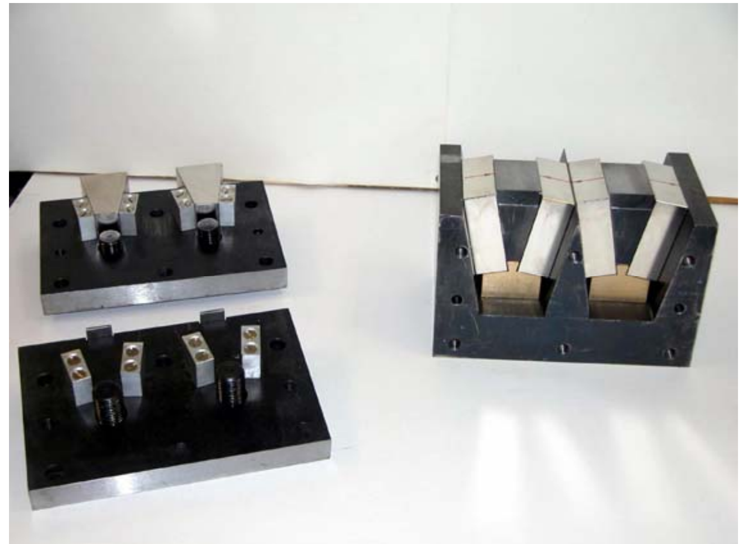


Wiggler period (4)

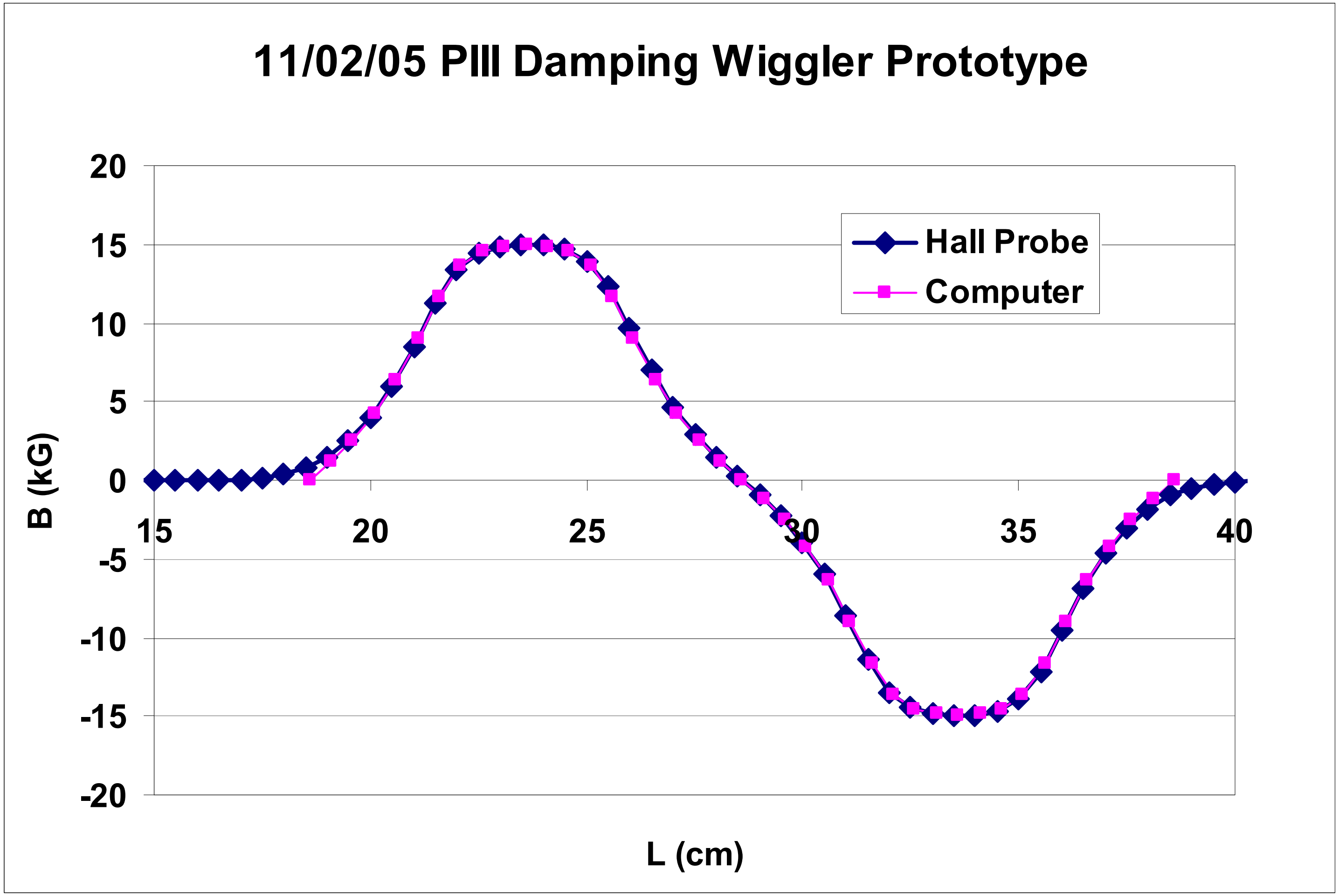


Wiggler period prototype





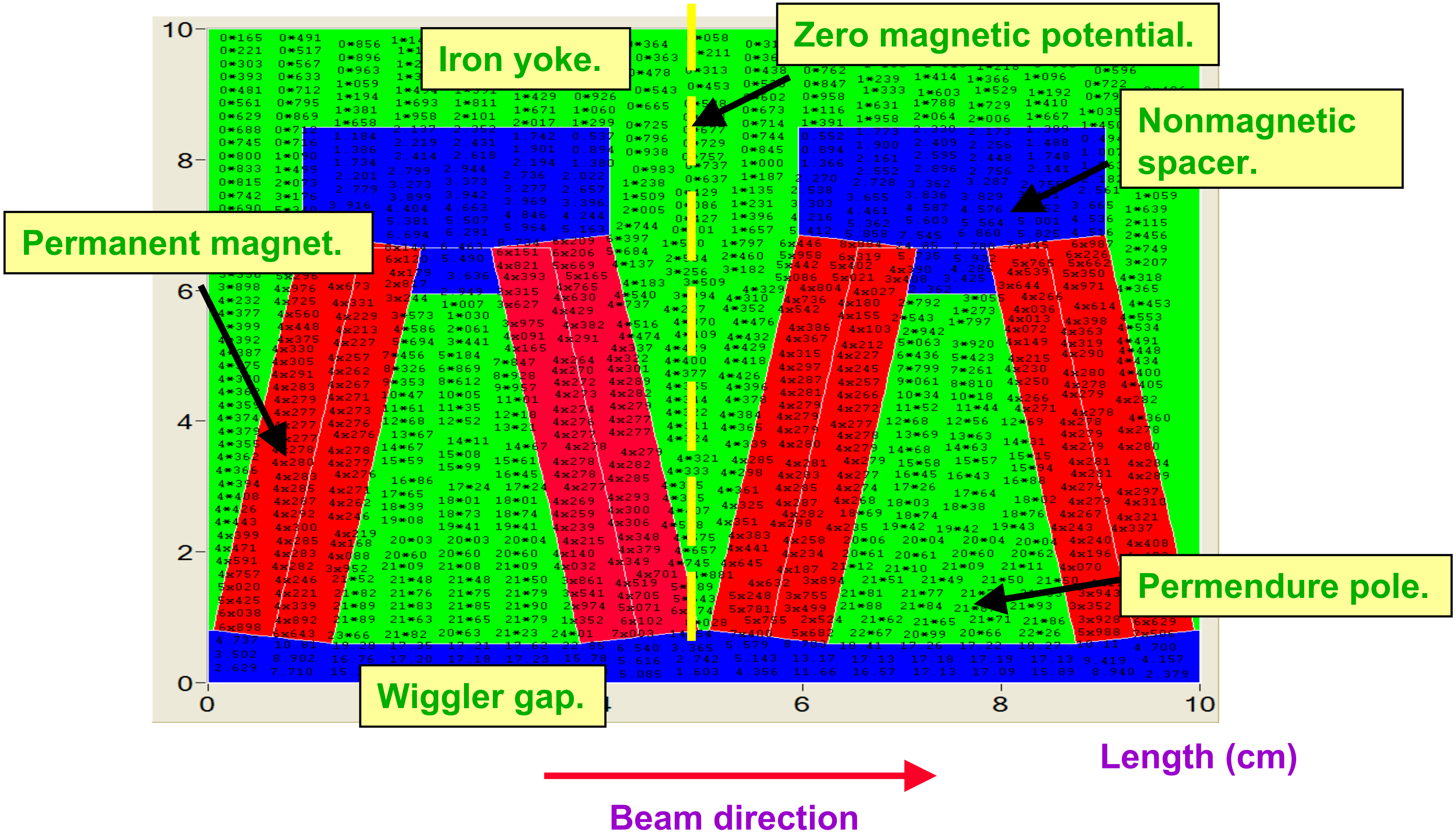
Wiggler period field



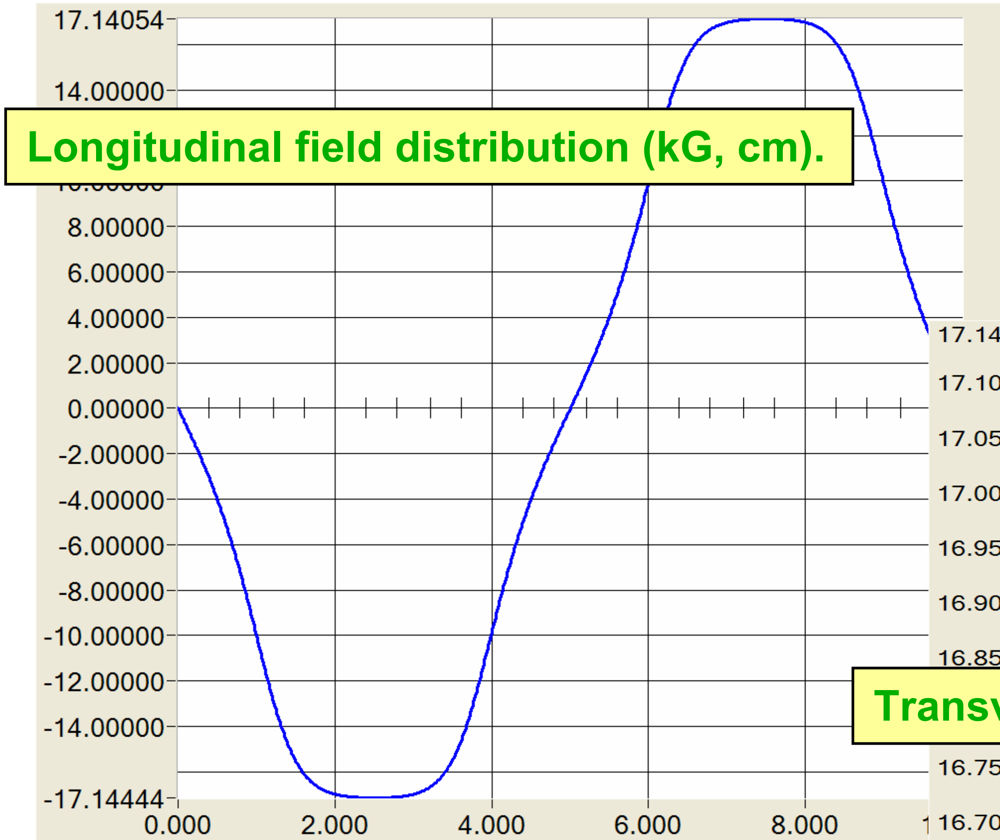
CLIC damping wiggler parameters

Period:	10 cm	12 cm	14 cm
Gap:	12 mm	14 mm	16 mm
Pole width:	50 mm	60 mm	60 mm
Length:	2 m		
Field amplitude:	1.7 T	1.8 T	1.69 T
Field quality @ ±1 cm:	10^{-3}		
Total length:	160 m		
Total radiation power:	1.7 MV at 1 A current		

CLIC damping wiggler configuration

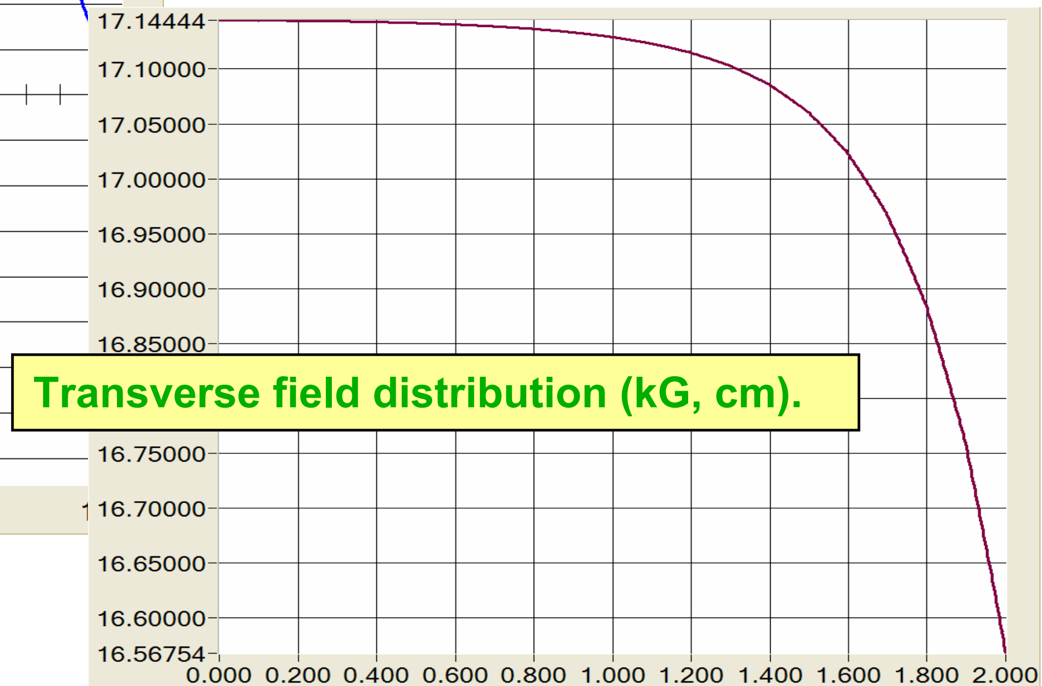


CLIC damping wiggler field distribution



Bmax = 17.1 kG

$\Delta B/B < 5 \times 10^{-3}$ at 1 cm.



Problems

► Assembling

The force between upper and lower parts of the CLIC wiggler is about 10 tons.

For the PETRA prototype easy procedure of halves joint is developed and tested.

► Field tuning

More than 6000 poles have to be tuned.

Zero magnetic potential between poles and corrector-bolts allows fast tuning procedure separately for each pole.

► Radiation

More than 1.5 MW (at 1 A beam current) of radiation power has to be intercepted.

(!) This aspect should be studied including possible COD.

► Wiggler nonlinearities

Strong wiggler nonlinearity can influence the beam dynamics.

(!) It is interesting to include damping effects in particle tracking procedure.

Radiation power

SR critical energy	$\varepsilon_c[keV] = 0.655 E^2[GeV] B_w[T]$	6.54 keV	
K-parameter	$K = 0.934 \lambda_w(cm) B_w(T)$	15.88	
Wiggler length	$L = N\lambda_w$	2 m	
Wiggler SR power	$P_\gamma[kW] = 0.633 E^2[GeV] B_w^2[T] L[m] I[A]$	21.5 kW	(!) 1.7 MW for 80 wig.
Relativistic factor	$\gamma = E/(mc^2)$	4747	
Vertical SR spread	$\theta_v = \gamma^{-1}$	0.21 mrad	
Horizontal SR spread	$\theta_h = 2K/\gamma$	6.69 mrad	

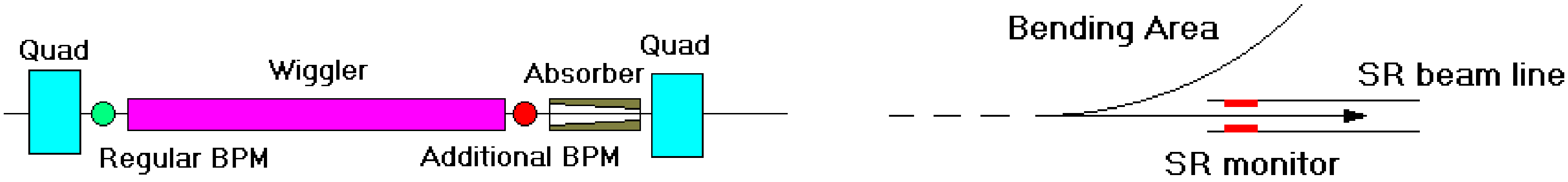
Radiation spot size in 150-m-distance:

► ± 31 mm in vertical direction

► 1000 mm in horizontal direction

Effective collimation system is very important.

Wiggler cell arrangement



► Two BPMs and two steering magnets per cell provide the COD correction with high accuracy.

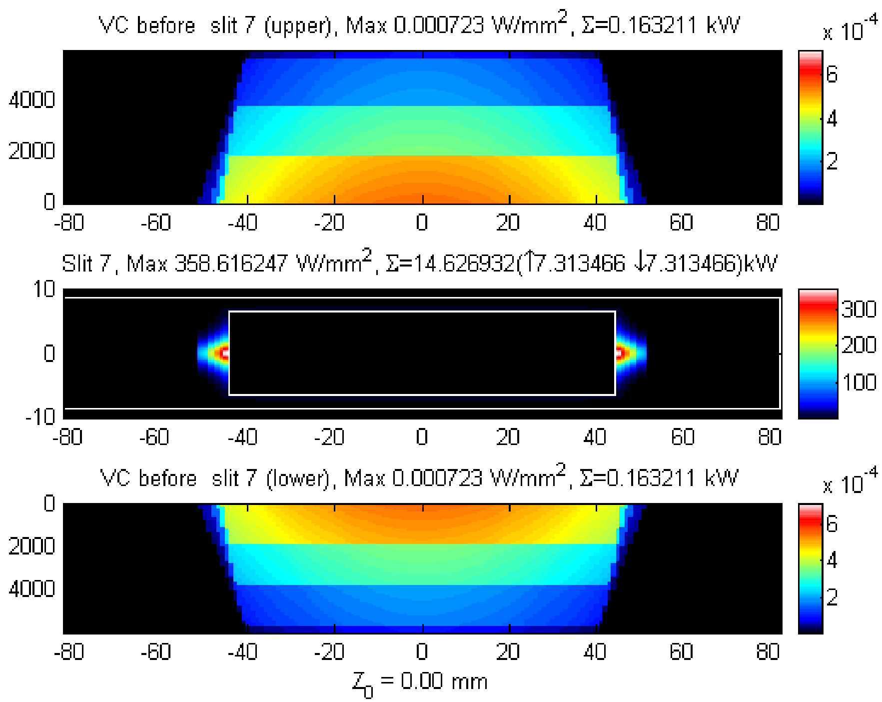
► Some fraction of the radiation power is absorbed in the regular (distributed) absorbers and the rest is intercepted by lump absorber behind the first bend.

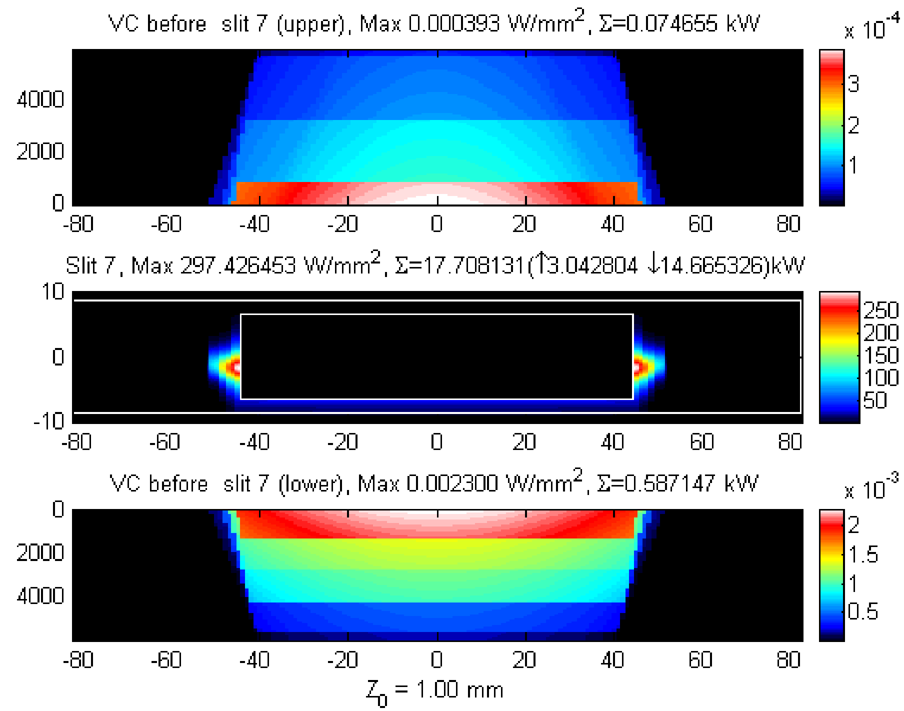
► Vacuum chamber has to be cooled for all the wiggler straight section.

► Sophisticated safety system and fast beam dump have to be foreseen.

Vertical COD

The vertical COD tolerance is a crucial problem.





In case of PETRA III 13-mm-height collimators and 1-mm COD provides 600 W heating of the wiggler vacuum chamber lower part.

Wiggler nonlinearities

► Intrinsic wiggler nonlinearity due to the orbit angle in the wiggler fringe field.

► Sextupole (and other multipole) components due to the transverse field roll-off. (a) Can be made small by proper pole design. (b) Averaged to zero for highly periodic structures.

► Field errors.

1D vertical cubic nonlinearity

For standard octupole Hamiltonian:

$$\Delta H = \frac{1}{24} n(s) y^3$$

effective cubic nonlinearity integrated over one period is

$$(n \cdot l) = \frac{B''' \cdot \lambda_w}{B\rho} = \frac{8\pi^2}{\lambda_w \rho_w^2}$$

and relevant amplitude-dependent tune shift is given by

$$\Delta \nu_y (J_y) = \left(\frac{\pi \cdot L_w \overline{\beta}_y^2}{\lambda_w^2 \rho_w^2} \right) \cdot J_y$$

Dynamic aperture

► Usually wigglers provide small reduction of the dynamic aperture defined by strong sextupole magnets because the cubic nonlinearity (even large) is the next to sextupole perturbation term.
For particular case this statement has to be checked by computer simulation starting from simple wiggler model and ending by symplectic integration in the realistic field.

► Wiggler cubic nonlinearity can be reduced by properly located octupole magnets.
Successfully applied at VEPP-3 optical klystron undulator (1983) and VEPP-4M dipole wigglers (2001).

► Other ideas of the cubic nonlinearity rejection are possible.
For instance, wiggler with sector magnets and so on.

Conclusions

► For 12 mm gap a 10-cm-period permanent magnet wiggler with the peak field up to 1.7 T is developed.

► Because of the huge radiated power the radiation interception strategy has to be considered carefully including possible errors such as COD, manufacturing and alignment tolerance, etc.

► Injection beam losses can degrade permanent magnets and have to be investigated in details.

► Nonlinear beam behaviour in the realistic wiggler field has to be studied by computer simulation (including damping?).