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# Report on WIGGLE 2005
# Mini-Workshop on Wiggler optimization for emittance control

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## Abstract

A two days Mini-Workshop on WIGGLer optimization for Emittance control was held at the Frascati National Laboratories on February 22-23, 2005. About 35 participants from Europe, Japan and USA attended the meeting. A short introduction of the workshop objectives and conclusions is given in the following, focusing on the items that can be of importance for the ILC Damping Rings design. Some of the slides presented are also attached.

# Introduction

The Mini-Workshop on **WIGGL**er optimization for **E**mittance control was held at the Frascati National Laboratories on February 22-23, **2005**, under the auspices of ELAN.
The aim of the workshop was to study wiggler optimization for emittance control and understand limitations from operational and design/construction point of view, since it is particularly important to determine the optimum wiggler parameters to get the very low emittance required by the Damping Rings designs of future linear colliders in the framework of EuroTeV. Review of wiggler models and existing tools for characterizing the nonlinear dynamics in a wiggler-dominated ring and benchmarking of analysis tools with data from wiggler-dominated ring were also presented. Low emittance tuning operational experience is also an important item in order to understand possible operating problems. 34 scientists from Europe, USA and Japan presented 20 talks and discussed on the future work.

Wigglers are particularly important in the design and operation of different accelerators. They allow to:

- achieve the short damping times and ultra-low beam emittance needed in Linear Collider Damping Rings;
- increase the wavelength and/or brightness of emitted radiation in synchrotron light sources;
- increase radiation damping and control emittance in colliders.

A good wiggler design is one of the key points for the Damping Rings operation.
The Workshop was divided in 4 sessions. **Session 1** was dedicated to a review of **Wiggler Parameters & Experiences** with operating machines, colliders, synchrotron light sources and test facilities. In **Session 2** different **Wiggler Technologies** were presented. **Session 3** focused on **Nonlinear Wiggler Fields, Modeling & Beam Dynamics Studies**. Finally, **Session 4** was a general discussion on the open problems.
In the following section a very short summary of those talks more related to the Damping Rings problematic is presented. Copy of all slides is available at the Workshop web site:
http://www.lnf.infn.it/conference/wiggle2005/

# Summary

The first session was dedicated to reports on wiggler parameters choices and to experiences on operating machines. Reports from colliders, as DAΦNE (LNF) and CESR-C (Cornell), from test facilities as ATF (KEK) and from synchrotron light sources as Spring-8 (Riken) were presented. At DAΦNE (M. Biagini, M. Preger) wiggler nonlinearities were responsible for the reduction in lifetimes and dynamic aperture, as well as in the beam-beam performances. These nonlinearities have been measured with beams and cured by modifying the wiggler poles, as well as by lowering the beta functions in the wigglers and by installing 3 octupole magnets.
At ATF (J. Urakawa) measurements of beam emittances and damping times demonstrated how the wigglers have been useful in reducing their values, consistently with the calculations, and in suppressing the effect of the Intra Beam Scattering. These results are of particular interest in view of the Damping Rings parameters choice.
At CESR-c (A. Temnykh) different wiggler designs (7-pole symmetric, 8-pole asymmetric) were studied and measured with beam, for model benchmarking. The measurements demonstrated that the 8-pole wiggler had better performances in terms of systematic errors

and field quality. 12 Superferric (iron poles and super conducting coils) wigglers have been installed and are presently under operation. The beam based wiggler characterization is in good agreement with the model, meaning they have good wigglers and a reliable model. So far, the beam performances at CESR-c were not degrading due to wiggler field nonlinearities. This very positive experience is highly encouraging for the future projects.

E. Levichev (BINP) reviewed the damping wigglers parameters and scaling laws, in connection with the study of a damping wiggler for CLIC (1.7 T). Wigglers of course affect beam dynamics and have both beneficial (a,b) and unwanted (c,d) effects. In particular they:

a. increase damping times proportionally to their peak field. However higher field induces a small increase in energy spread and partition numbers;
b. can reduce emittance when reducing the wiggler cell length and its period, and increasing the peak field (warning: at very high peak field the emittance blows up);
c. introduce a linear tune shift that can be cured by changing working point. However it is also possible to reduce it by decreasing the cell length and the average beta function in the cell, as well as by increasing the number of periods;
d. introduce a vertical cubic non linearity, whose effect can be minimized by increasing the wiggler period, by reducing the average beta function in the cell and by installing octupole magnets at azimuth with high $\beta_y$ and low $\beta_x$ value.

Scaling laws are particularly useful to set the wiggler parameters. For example at BINP a detailed study of the peak field *versus* the magnet gap, the period length and the pole width, and of the peak field quality *versus* the pole width has been carried out. In real life the wiggler field behavior depends on the wiggler type, material features, saturation, etc. so it seems that for every particular case scaling laws can be found by simulation only. In principle rather high quality of the wiggler transverse field can be achieved. However to take into account the influence of production tolerance, material characteristics, etc... the development and measurement of small (2-3 periods) prototypes is desirable.

In Session 2 the different magnet technologies (electro-magnetic, permanent magnet, super-conducting, superferric, hybrid, etc...) were reviewed. Some of them have been studied by performing magnetic field calculations and building prototypes. New ideas, as the “wedge-pole hybrid” scheme (P. Vobly) for CLIC and Petra III and the “equipotential bus” wigglers conceived by K.Halbach, have been discussed. Superconducting devices seem to be most effective as damping wigglers: they can achieve fields up to 3.5-4 T, but are very expensive and require complicated cryogenic equipment. Permanent magnet devices can provide 1.5-2 T and are 4-5 times cheaper compared to the SC ones and rather reliable. “Equipotential bus” wigglers reach the same parameters (and even better) as pm wigglers for approximately the same price, they need a power supply system, but they allow changing amplitude of the magnetic field in the range of 25%.

In Session 3 there were many presentations on wiggler modeling and dynamic aperture calculations. In order to predict the beam performances it is mandatory to have a good model of the wigglers, including nonlinearities. Several methods (M. Venturini, Y. Cai, M. Korostelev, J. Urban, K. Soutome) have been studied for the ILC damping rings as well as for operating accelerators. For example a hybrid symplectic integrator has been developed by Y. Cai for faster and more accurate evaluation of the dynamic aperture of the ILC lattices, while M. Venturini studied a fast, simple and accurate 3D multipole cylindrical representation of fields. Results from tracking of ILC lattices confirm that field quality in wigglers does have an impact on dynamic aperture: wiggler design should be tuned to tame nonlinearities. However the wiggler problem seems not to be a fundamental limitation of the lattices and it is solvable with more engineering efforts. Using non-interlaced sextupoles in Damping Rings seems to be a very effective way to increase the dynamic aperture. Dynamic aperture in these newly designed rings is adequate once the wigglers are improved in terms of field quality.

Finally F. Zimmermann presented a study of the e-cloud instability in wigglers for DAΦNE, ILC, CLIC. Several simulation codes for e-cloud build up have been produced. The e-cloud instability was observed at the DAΦNE positron ring, which can be a benchmark for simulation codes. In DAΦNE the e-cloud formation in the wigglers likely causes single and multi-bunch instabilities and might be responsible for the present current limitation. More precise field models in are needed in future simulations, and probably it would be wise to consider e-cloud effects in the wiggler design.

## Conclusions and open questions

Here is a brief summary of the conclusions drawn at the end of the Workshop:

- With an optimization of the field quality, harmful effects on dynamic aperture can be avoided.
- Different techniques can be used: Permanent magnets, SuperConducting, Electromagnet, Hybrid schemes, some of them are new and still being studied.
- New technologies allow to design wiggler magnets with ambitious parameters:
  - good field quality
  - high peak field
  - short period
- Many tools for wiggler modeling and DA evaluation are available, and will be extremely useful to predict effects on beam dynamics. Some of these have been successfully used for wigglers in operation and checked with beam measurements. Code benchmarking using the same lattice and field map has been proposed.
- Dynamic aperture reduction seems mainly due to field non-uniformity in the horizontal plane. Experience of operating machines has shown that good field quality wigglers do not have harmful effect on beam performances.
- Tools and technologies are available to design and build wigglers with the characteristics and field quality needed for the Damping Rings.

We concluded with a number of open questions (F. Zimmermann):

- What is minimum acceptable period, for given peak wiggler field and gap, in view of nonlinear dynamics, electron cloud, impedance, SR power removal?
- Study of thermal stability of permanent magnets; machine protection; absorber design?
- What determines the minimum gap height?
- Can we achieve sufficient orbit control inside long wiggler sections? COD tolerance due to various effects (dynamic aperture, SR fan, emittance)?
- Shaping of pole pieces for horizontal focusing? Use of ‘magic fingers’?
- Effect of radiation energy loss on wiggler nonlinear dynamics (increasing ‘wiggle’ amplitude, increasing strength of nonlinear fields, loss of symmetry)?
- Importance of path length effects?
- Limits on the maximum length of a wiggler section?
- Should beta function be matched to the wiggler natural one?
- Can we produce lower emittance operating with undulators rather than wigglers?
- Can we use coherent synchrotron radiation to damp instabilities?

## Acknowledgements

The author would like to express her gratitude to all the participants for their high interest, competence and involvement that made this Mini-Workshop very successful.
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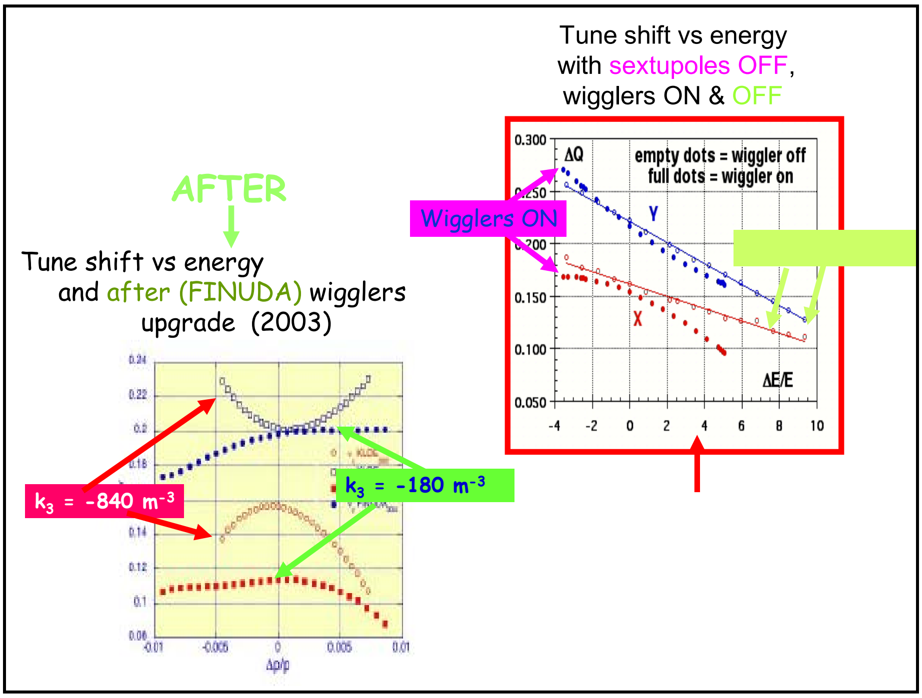
## Summary slides

### Wiggler Parameters & Experiences

**DAΦNE**

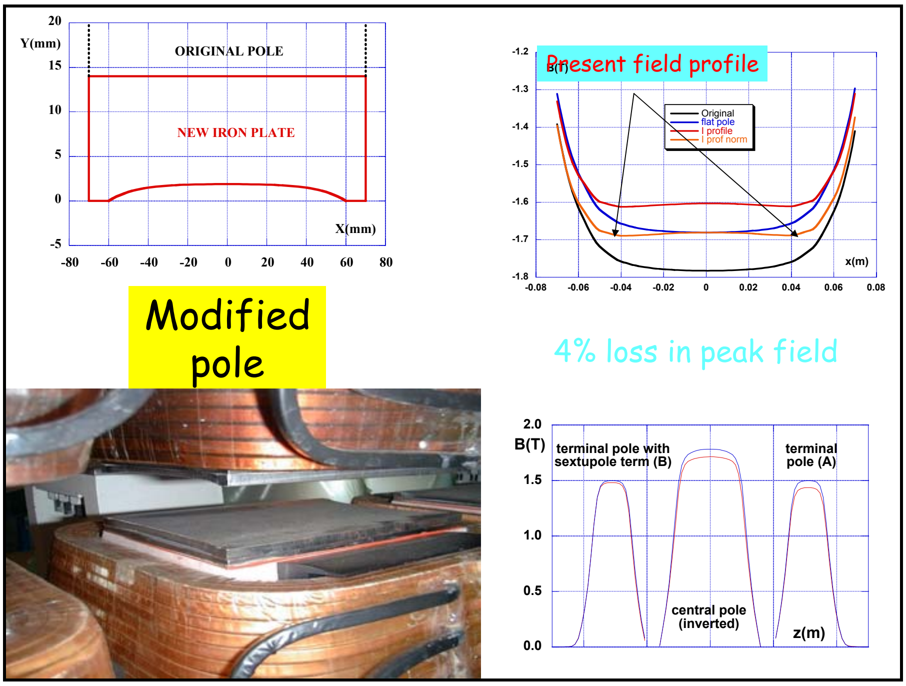
- Nonlinear wiggler field terms associated with wiggling trajectory responsible for tune shift with particle amplitude and momentum (octupole-like effect).
- Installation of octupoles and tuning were able to decrease tune shift, however it was necessary to change the pole shape to correct the effect.
- For an easier chromaticity correction, it was required to create an additional sextupole term in one of the two terminal poles. Dynamic aperture after magnet reshaping was increased, with beneficial effects on tune shifts and beam lifetimes.



# DAΦNE wiggler modification (M. Preger)

- 11 mm thick spacers were inserted between the two halves of the “C” supports to increase the wiggler gap
- 7 mm thick flat iron plates were glued on the pole faces
- Iron plates were machined to compensate the field fall off at large distance from the wiggler axis according to:

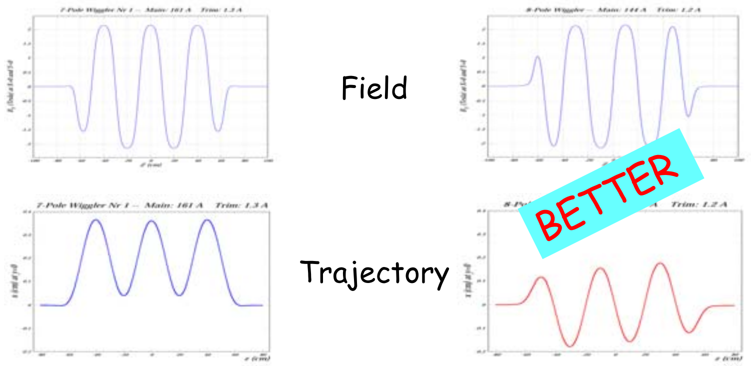
$$gap(x)/B_{meas}(x) = const$$



# CESR-c wigglers (A. Temnykh)

- 2.1 T peak field, 40cm period, 20cm pole width, 7.62cm gap
- 8 poles (asymmetric magnetic design)
- Iron poles & superconductive coils (superferric technology)

7 poles symmetric 8 poles asymmetric




# CESR-c wiggler characterization with beam and model benchmarking (A. Temnykh)

- Bunch length and beam energy spread
- Tune variation with wiggler field
- Tune variation with beam position in wiggler
- Tune variation with amplitude (octupole moment)

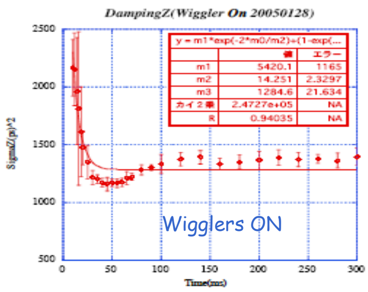
- 12 superferric wigglers installed and under operation
- Beam based wiggler characterization in good agreement with model:
- So far, beam performances not degrading due to wiggler field nonlinearities:

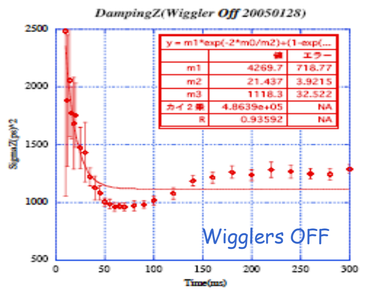
## ATF (J.Urakawa)

- Four wigglers (2m long) turned on
- Damping times and emittances were measured and found consistent with calculations
- Horizontal beam size, bunch length and energy spread growth, due to IBS effects after damping, was observed.
- Reduction of the damping time and suppression of IBS effect with wiggler operation observed
- Reduction of emittance with wigglers ON also observed

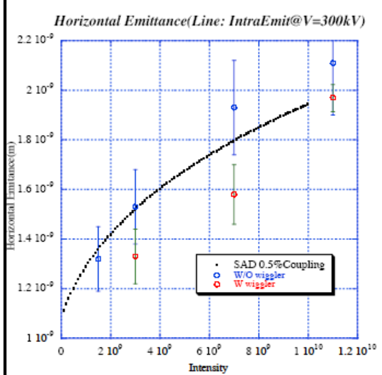
## ATF Damping times

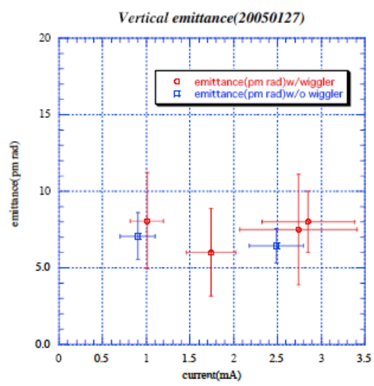
| Damping Time | Cal.,wiggler off | Cal.,wiggler on | Meas.wiggler off | Meas.wiggler on |
|---|---|---|---|---|
| Horizontal $\tau_x$ | 17.5 ms | 15.0 ms | 19.3+/-0.63 ms | 15.7+/-0.38 ms |
| Vertical $\tau_y$ | 28.5 ms | 23.0 ms | 28.8+/-1.5 ms | 25.4+/-0.67 ms |
| Longitudinal $\tau_z$ | 20.5 ms | 15.5 ms | 21.4+/-3.9 ms | 14.2+/-2.4 ms |




## ATF- Emittance measurements




| | Cal.wiggler OFF | Cal.wiggler ON | Meas.wiggler OFF | Meas.wiggler ON |
|---|---|---|---|---|
| $\varepsilon_0$ | 1.03 nm | 0.87 nm | (1.1+/-0.2) nm | (0.9+/-0.2) nm |

## Damping wiggler parameters **(E. Levichev)**

Damping effect depends on the wiggler length and squared field amplitude.

♦ To minimize the resulting emittance the shortest period length and the high field are desired. But very high field provides emittance blow-up.

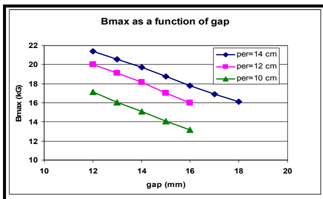
♦ Short period length yields increasing of the vertical cubic nonlinearity.
For VEPP-3 optical klystron undulator (1983) and for the VEPP-4M dipole wiggler it was controlled by properly placed octupole magnets.

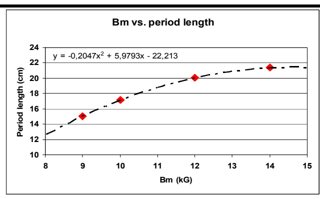
♦ Transverse nonlinearity can be kept small (<0.5…1x$10^{-3}$ at ±1 cm) by proper pole design.
Odd number transverse multipoles (sextupole, …) integral values are cancelled because of wiggler periodicity.

## Scaling laws (E. Levichev)

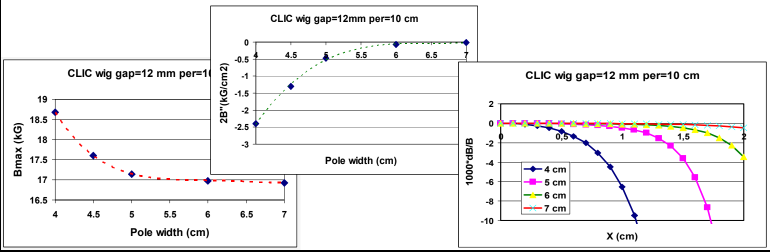
- Scaling laws are useful to select wigglers parameters. In real life the wiggler field behaviour depends on wiggler type, material features, saturation, etc. so it seems that for every particular case scaling laws can be found by simulation only.

- In principle rather high quality of the wiggler transverse field can be achieved. However to take into account influence of production tolerance, material characteristics, etc. small (2-3 periods) prototypes development and measurement is desirable.



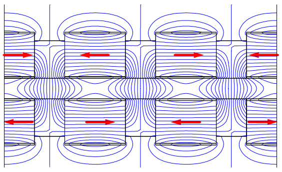

- B peak is linear for reasonably small change of pole gap
- B peak tends to be saturated with increasing of the period length
- B peak has to be compromised with acceptable transverse field quality
- By choosing proper pole size and shimming rather good transverse field quality can be achieved



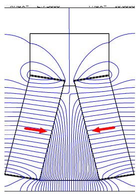
## Choice of technology

- em wigglers
- pm wigglers
- SC wigglers
- Superferric (iron poles + SC coils)
- Hybrid
- Wedge pole hybrid
- pm+em (Halbach)

## Hybrid wedge-pole (P. Vobly)



Hybrid w. with rectangular poles

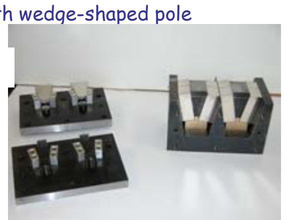


- Magnetic symmetry leads to magnetic potential of wedge-like plate equals zero
- Reduction of the magnet volume compared to the common design of hybrid wiggler
- No coupling between poles

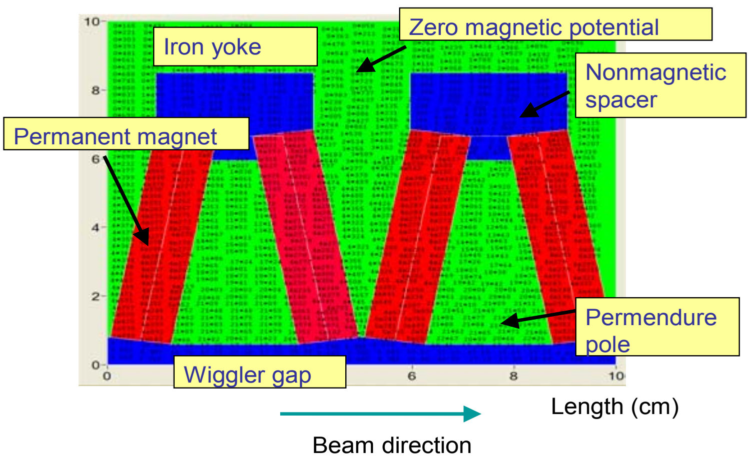
Hybrid w. with wedge-shaped pole

**Design of PetraIII wiggler**

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

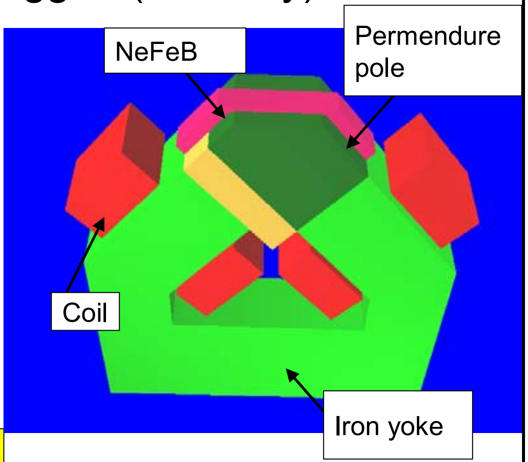


## CLIC damping wiggler configuration



## Electromagnet wiggler (P. Vobly)

Usual e.m. wigglers cannot be used as damping wigglers because it is difficult to achieve high field with small period. Combined pm/em devices (equipotential bus wigglers, K.Halbach) show good damping parameters, substantial decre-ase in period with simultaneous decrease in magnetic material volume can be achieved.




FEL undulator for KAERI (1999):
g = 6 mm
$\lambda_w$ = 25 mm
B = 0.45 -> 0.7 T
L = 2 m
$\Delta B/B < 5\times10^{-4}$ @ 1 cm

Proposal for CLIC wiggler:
g = 12 mm
$\lambda_w$ = 76 mm
B = 1.7 T

## Conclusions on technology (E. Levichev)

- Superconducting devices seem to be most effective as damping wigglers. The field up to 3.5-4 T can be achieved for 60-70 mm period and 15-20 mm gap.
  They are very expensive and require complicated cryogenic equipment.

- Permanent magnet devices can provide 1.5-2 T in gap 20-10 mm for period ~10…15 cm.
  Such wigglers are 4-5 times cheaper compared to the SC ones and rather reliable.

- Equipotential bus wigglers reach same parameters as pm wigglers and even better for approximately the same price.
  They need power supply system.
  They allow to change amplitude of the magnetic field in the range ±25%.

## Modeling and Beam Dynamics Studies

- A realistic wiggler model is mandatory
- Include non linear terms to compute dynamic aperture
- New integration techniques to increase computing speed
- DA aperture is an issue with ILC-DR lattices Dominant nonlinearities are from chromatic sextupoles
- Fast dynamic aperture tracking including errors needed to compare different lattices and make a choice for ILC

## Modeling of Wiggler Fields for Tracking (M. Venturini)

- A 3D multipole (cylindrical representation) of fields is fast, simple and accurate
- Wiggler nonlinearities appear to play a smaller role but should be kept under control. Two examples considered:

  with NLC-MDR LBL wiggler prototype. Impact of wigglers is

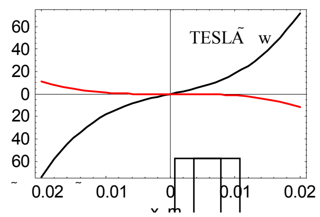
  dog-bone lattice with TESLA wiggler prototype. Impact of wiggler is

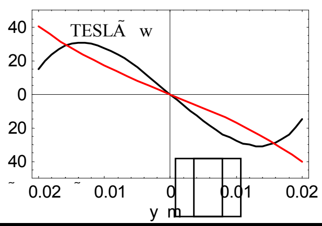
- Results from tracking of ILC lattices confirm that field quality in wigglers does have an impact on dynamic aperture. Wiggler design should be tuned to tame nonlinearities

## DA and transfer functions: NLC MDR *vs.* TESLA DR wiggler

**Transfer functions for 1 period**

- TESLA wigglers model nonlinearities are considerably larger than those from the NLC wiggler model.
- Relative strong feed-down from decapole field component present in TESLA wiggler.



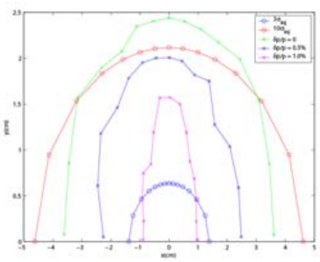



## Dynamic Aperture in Damping Rings with Realistic Wigglers (Y. Cai)

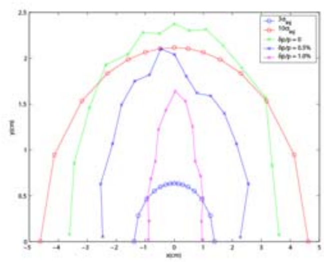
- Hybrid symplectic integrators are developed to integrate through wiggler magnets. They are much simpler and therefore much faster for tracking.
- Full nonlinear wiggler designed at DESY degrades the dynamic aperture in the lattices of damping rings designed for ILC. However the wiggler problem seems not to be a fundamental limitation of the lattices and it is solvable with more engineering efforts.
- Using non-interlaced sextupoles in damping rings is a very effective way to increase the dynamic aperture. Dynamic aperture in these newly designed rings are adequate once the wigglers are improved in terms of field quality.

## Dynamic Apertures with/without an Ideal Wiggler (Y. Cai)

Linear wiggler

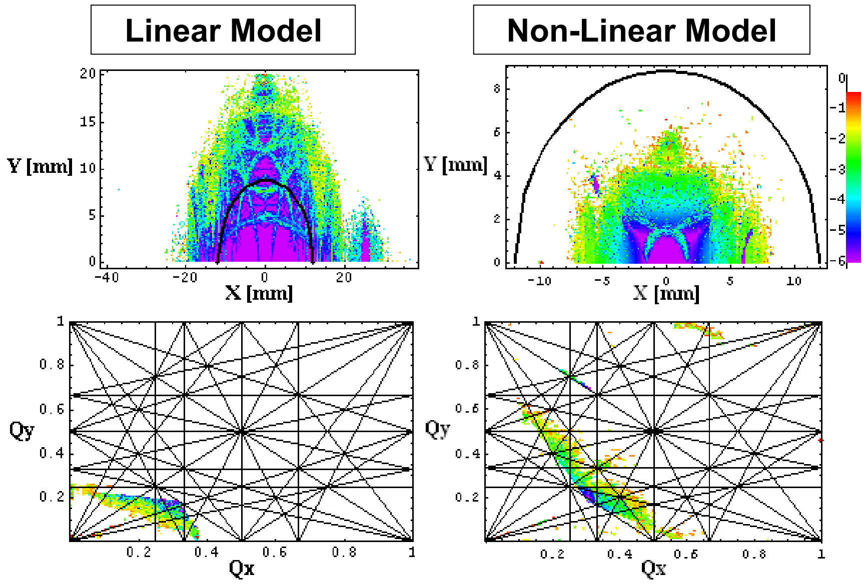


Ideal nonlinear wiggler



Impact on the dynamic aperture is barely noticeable for an ideal but nonlinear wiggler.

## Impact of Non-Linear Wiggler in ILC Dogbone ring (J. Urban)




## e-cloud in wigglers (F. Zimmermann)

- Study of e-cloud in wigglers for DAΦNE, ILC, CLIC
- Several simulation codes for e-cloud build up
- e-cloud observed at DAΦNE ➔ benchmark for simulation codes
- e-cloud in the wiggler likely causes single & multi-bunch instabilities; e-cloud might be responsible for present current limitation in DAΦNE e+ ring
- More precise field models in future simulations
- e-cloud effects must be considered in wiggler design