# Project Report

July 21 – September 10, 2009

on

# Modeling of Non-Linear Fields In Damping Wigglers In PETRA III

At

Deutsches Elektronen-Synchrotron (DESY), Hamburg, Germany

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# Certificate of Work

This is to certify that Rohan Mittal, M.Sc. (Final) Student at the School of Physics, Devi Ahilya University, Indore, India has worked on this Project under my guidance on Modeling of Non-Linear Fields in Damping Wigglers in PETRA III at the MPY Group, Deutsches Elektronen-Synchrotron (DESY), Hamburg, Germany as part of the DESY Summer Student Programme 2009.

The Project Work was done from July 21 – 10 September, 2009.

**Dr. Alexander Kling**
**Group - MPY, DESY**
**(Project Supervisor)**

**DESY Summer Student Programme 2009**
**at DESY, Hamburg, Germany**

**July 21 – September 10, 2009**

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# Acknowledgements

Success doesn't mean the absence of failures;
it means the attainment of ultimate objectives.
It means winning the war, not every battle.
- Edwin C. Bliss

Any accomplishment requires the effort of many people and this work is no different. I sincerely thank my parents and in particular Dr. Joachim Meyer, the Coordinator for the Summer Student Programme at DESY for giving me this opportunity, his continued support throughout the duration of the program, the wonderful lectures and assignments he gave us, for arranging the HERA and DESY Tours, and on-site accommodation for us. I also thank Andrea Schrader for answering the numerous questions I had before the start of the programme and also for expediting the documents for the visa in a short span of time. But most of all, I wish to thank my Project Supervisor, Dr. Alexander Kling who took time to teach and guide me during the course of my Project, the various exhaustive facility visits he took me on, and kudos to his "ingenious explanations, I just loved them", the patience with which he used to listen to me and we discussed, all his efforts and his interest in my work, the support and encouragement he provided me with on knowing I wanted to work on SRF Cavities and Coherent Transition Radiation at DESY for my Project, simply wonderful, I do not think anyone would have done that. Thank you so much!

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Further, I also wish to express my sincere gratitude and another special thanks to Dr. Detlef Reschke, Dr. Nicholas John Walker, Dr. Martin Dohlus, Dr. Stephan Wesch, Dr. Winfried Decking (again), and Dr. Hans Weise, with whom I interacted while I did this Project and for other ideas I had in mind for my future accelerator research.

Nevertheless, curiosity does make us ask questions. And even though we may not be familiar with those people but we still ask them our questions. Here, in particular, I wish to mention Dr. Weiming Guo from Brookhaven National Lab., Dr. Carsten Niebuhr, Dr. Joerg Rossbach, Dr. Wolf-Dietrich Moeller, Dr. Waldemar Singer, Dr. Alexey Ermakov, Dr. Denis Kostin, Dr. Sven Karstensen, Dr. Gajendra Kumar Sahoo, Dr. Dinesh Shukla, Sarika Garg, Andreas Schmidt, and other researchers working at DESY. I would also like to express my very special thanks to Dr. Rainer Gehrke from HASYLAB who guided us on the particularly long DESY Tour which lasted about three hours more than the regular ones, answering countless questions, and trying to satisfy our insatiable curiosities every now and then, I really appreciate all the patience and everything, simply wonderful!

Even though discussions were not always centered on the Project, but around on different aspects of Accelerator Physics. None the less, there were always useful inputs for the Project.

Finally, I would like to thank Steffi Killough, Regina Hoppmann, Iris Rathgeber, Marion Bierhahn, and Maja Stolper in the International Office, DESY Hostel, Central Library, and HASYLAB Library respectively for all the assistance they provided in getting us through the paperwork, making our stay at DESY comfortable, and academically enriching and useful. The overall effort of all and the exposure at DESY was sure amazing as were the great friends I made here.

And sure, I cannot forget my supervisors Dr. Brajesh C. Choudhary, University of Delhi for recommending this Summer Programme to me and Dr. Juhao Wu, SLAC for his support in my endeavors. Unfortunately, sources were not always noted or available; hence, it became impractical to provide an accurate acknowledgement. Regardless of the source, I wish to express my sincere thanks to those who may have contributed to this work, even though anonymously. This Project is a result of my work and I undertake that the mistakes, if any are my own.

Before coming here, I was told at various Indian labs., LBNL, SLAC, and FNAL that "DESY is a very nice place to work…" and "So it was…!". Thank you.

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**Devi Ahilya Universtiy, Indore, India**

Date: September 10, 2009

# Contents

# Chapter 1

# Introduction

An attempt to model the experimentally measured magnetic field in the damping wigglers in PETRA III has been made in this project. A fit function has been generated with multiple harmonics and the residual of the two fields i.e., one due to the fit function and the other due to the available data is minimized using Least Square Non Linear Fitting function in Matlab R2007b. Many improvements were made to the program during the course of the project which also led to some very good results with even a few harmonics. Also, many observations were made which can help reduce the processing time for minimizing the residual with some of them listed in this report.

**The equations of motion applicable in the fields calculated with this method are integrated numerically since a large number of harmonics are involved.**

# Chapter 2

# Insertion Devices

A wiggler is an Insertion Device (ID) usually used in a storage ring. It is a series of magnets designed to periodically laterally deflect ('wiggle') a beam of charged particles (invariably electrons or positrons) inside the storage ring of a synchrotron. These deflections produce emission of broadband synchrotron radiation much like that of a bending magnet, but the intensity is higher due to the contribution of many magnet dipoles in the wiggler.

Wigglers and undulators are used for the production of synchrotron radiation or to **control beam sizes** in storage rings. Their introduction in the lattices of storage rings cause some problems due to the **strong nonlinearities of the magnetic fields**. Hence the analysis of the particle dynamics under the influence of the wiggler magnetic fields.

**Some properties of Synchrotron Radiation:**

1- Continuous Spectrum: Synchrotron radiation is emitted in a broad continuous spectrum from **infrared to hard X-rays**.
2- High Flux: The flux of photons in a given frequency interval is usually higher than from any other light source (X-ray tube or LASER) available.
3- High Brightness: The strong forward emission of synchrotron radiation and the small size of the source (electron beam) allows for high brightness.
4- Time Structure: The bunched structure of a stored beam leads to the same time structure of the synchrotron radiation which enables time resolved experiements.

A wiggler typically has a broader spectrum of radiation than an undulator. Undulators are preferred for photon science experiements though.

**Technical Parameters - PETRA III**

| Parameter | Value |
|---|---|
| Energy | 6 GeV |
| Emittance | 1 nm rad |
| Positron/Electron Current | 100(200) mA |

In reference to the emittance of 1 nm rad, it may be noted that such an emittance is achieved with the help of 80 m of damping wigglers. Also, in an experiment, it is not only the wavelength which allows the observation of a certain object but the resolution of an experiement using light is determined by the brilliance of the light source i.e., amount of light which is emitted within a certain area and solid angle, giving the spot size and photon flux on the probe. Hence the importance of such a small emittance like that in PETRA III.

In damping wigglers electrons emit very intense synchrotron radiation into a very small solid angle in longitudinal direction. The energy the electrons lose when emitting radiation is completely returned to them in the cavities by a forward momentum. On average, the transverse expansion of the beam can thus be reduced.

Wigglers are magnetic structures (similar to undulators) with a periodically alternating vertical field in which the electrons oscillate in the horiontal plane. This leads to intense synchrotron radiation in the X-ray range which is emitted in forward direction. Damping wigglers for PETRA III are built in permanent magnet technology with a length of four metres. The radiation power generated in the damping wigglers has to be absorbed by intensely cooled apertures and must not impinge other components of the beamline.

There will be two damping wigglers in the straight sections of the PETRA III storage ring. They consist of a continuous sequence of wigglers, absorbers and focussing magnets. Two stretches with ten damping wigglers each will be built and will generate a radiation power of up to 2 x 420 kW, thus reducing the emittance of the electron beam by factor of four.

**Technical Parameters - Damping Wigglers in PETRA III**

| Parameter | Value |
|---|---|
| Maximum Field | 1.5 T |
| Total Length | 80 m |
| Total Radiated Power (200 $mA$) | 820 kW |
| Energy Loss in one 40 m segment | 2.05 MeV |

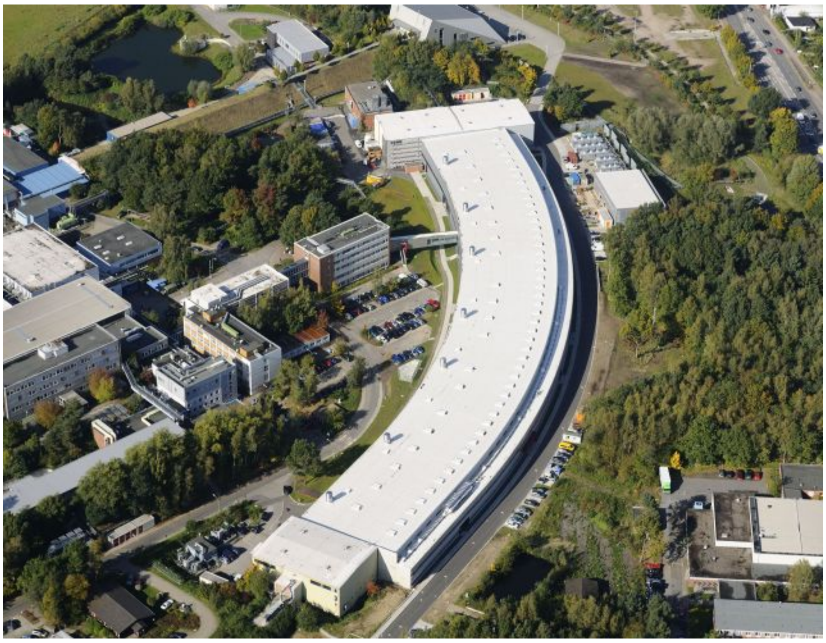

Figure 2.1: Aerial view of the PETRA III experimental hall. The insertion devices are installed in the smaller arc of the building.

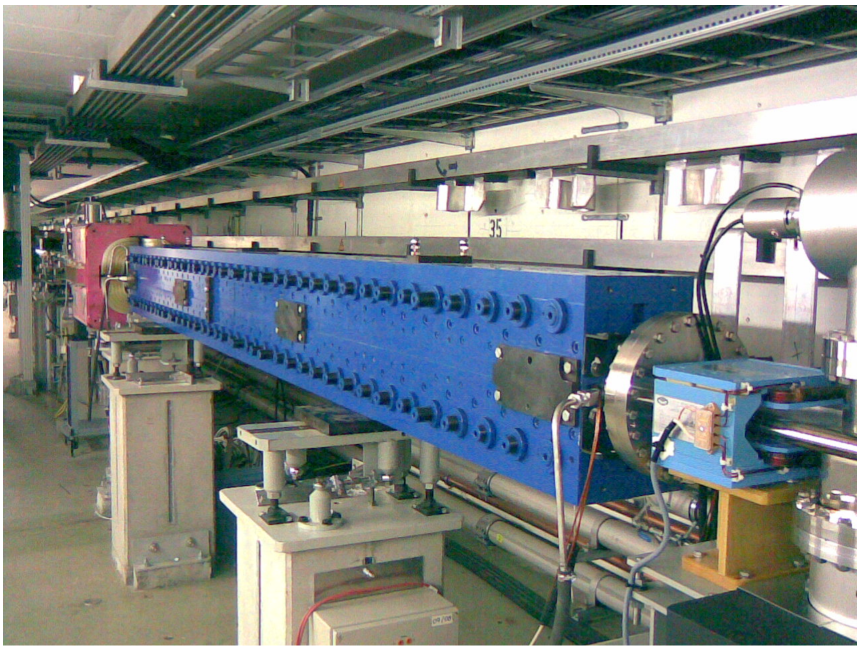

Figure 2.2: External view of one of the wiggler installed in PETRA III.

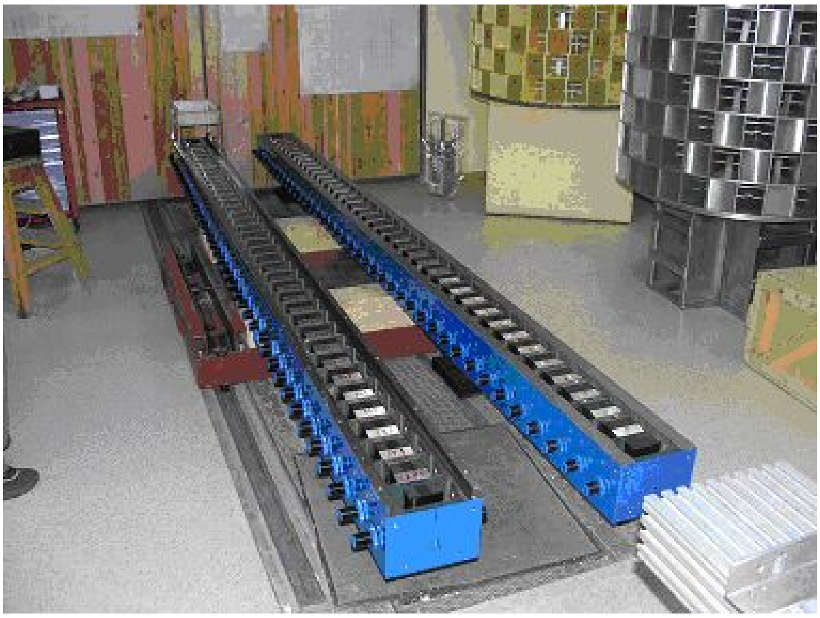

Figure 2.3: Inside view of one of the wiggler installed in PETRA III.

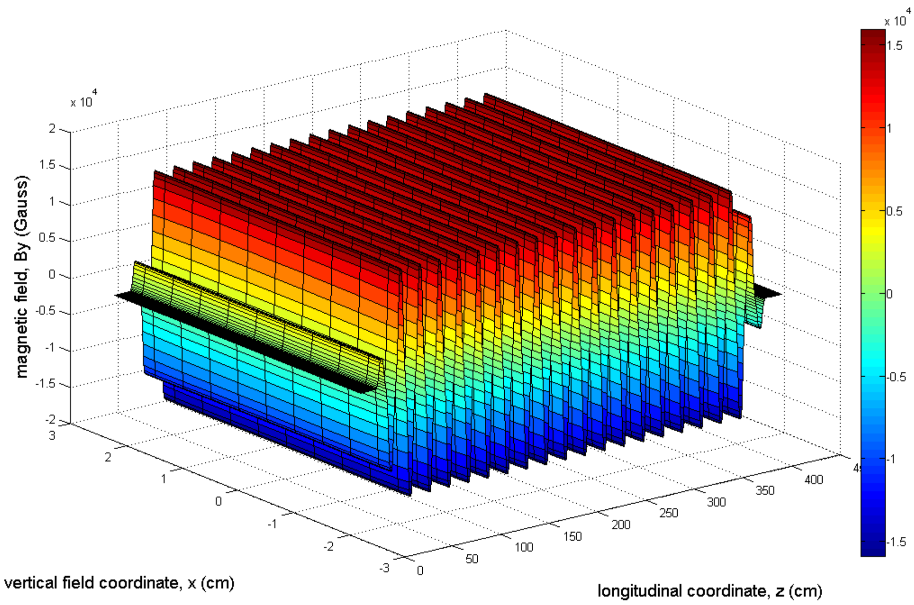


Figure 2.4: 3D field map of the wiggler # 11. The data points from the actual field measurements taken using Hall probes have been used here.

# Chapter 3

# Field Modeling[2]

The idea is to incorportate the effect of wiggler magnets in calculations of beam dynamics of storage rings. An analytic model of wiggler fields can be used with simplectic integration to evaluate such effects. Coefficients needed by the model are generated by fitting to the results of a finite-element field calculation which is usually obtained from a Hall probe array which is used for measurement of the field map. In contrast to models based on Fourier transforms, the model presented here uses a relatively small number of terms, leading to correspondingly fast integration times. Fringe fields are included and no assumption about the periodicity of the field is made.

Now, a prerequisite for the study of particle dynamics is the ability to calculate transfer maps for each element in a storage ring. This is difficult for wigglers since analytic formulas do not exist except in the most simplified cases. Wigglers can have strong nonlinear components which can be a major limitation on the dynamnic aperture and also impose stringent conditions on any analytic approximations.

Simplectic integration is an excellent technique for doing tracking and for constructing transfer maps. In order to do simplectic integration through a wiggler, however, one needs to know the field as well as the gradient and higher derivatives. This generally precludes simply using data from a measurement or a calculation since the discrete nature of the data will make the higher derivatives inaccurate. What we need is a model functional form that fits the data and can be quickly differentiated. This model has the advantage that the end fields are easily incorportated into the model.

The form of the field used is:

$$B_x = \sum_{n=1}^{N}\sum_{m=1}^{M} -C_{mn}\frac{k_{xm}}{k_y}\sin(k_{xm}x)\sinh(k_y y)\cos(k_{zn}z+\phi_{zn}) \tag{3.1}$$

$$B_y = \sum_{n=1}^{N}\sum_{m=1}^{M} C_{mn}\cos(k_{xm}x)\cosh(k_y y)\cos(k_{zn}z+\phi_{zn}) \tag{3.2}$$

$$B_z = \sum_{n=1}^{N}\sum_{m=1}^{M} -C_{mn}\frac{k_{zn}}{k_y}\cos(k_{xm}x)\sinh(k_y y)\sin(k_{zn}z+\phi_{zn}) \tag{3.3}$$

with,

$$k_{ymn}^{2} = k_{xm}^{2} + k_{zn}^{2} \tag{3.4}$$

$k_y$ is considered to be a function of $k_x$ and $k_s$ and the relationship between them ensures that Maxwell's equations are satisfied.

At present, for the generalized simplistic case where $x = 0$ and $y = 0$, we have,

$$B_y = \sum_{n=1}^{N} -C_n\cos(k_{zn}z+\phi_{zn}) \tag{3.5}$$

Now, given a calculation or measurement of the field at a set of points $B_{data}$, the problem is to find a set of $N$ terms such that $B_{fit}$ and $B_{data}$ agree to some given precision set by how accurately one needs to be able to track through a wiggler. This is a standard problem in nonlinear optimization. The solution is to minimize a merit function $M$ where,

$$M = \sum_{data\ points} |B_{data} - B_{fit}|^2 + w_c\sum_{n=1}^{N}|C_n| \tag{3.6}$$

The second term in $M$ is to help preclude solutions with degenerate terms that tend to cancel one another. The weight $w_c$ should be just large enough to prevent this but not so large as to unduly distort the fit. At present, this term has not been included in the minimization code. We would like to include it in the next couple of days.

The minimization of $M$ can be done by any of the well known algorithms and we use the **lsqnonlin** function in **MATLAB 7.5.0 (R2007b)** for executing our minimization code.

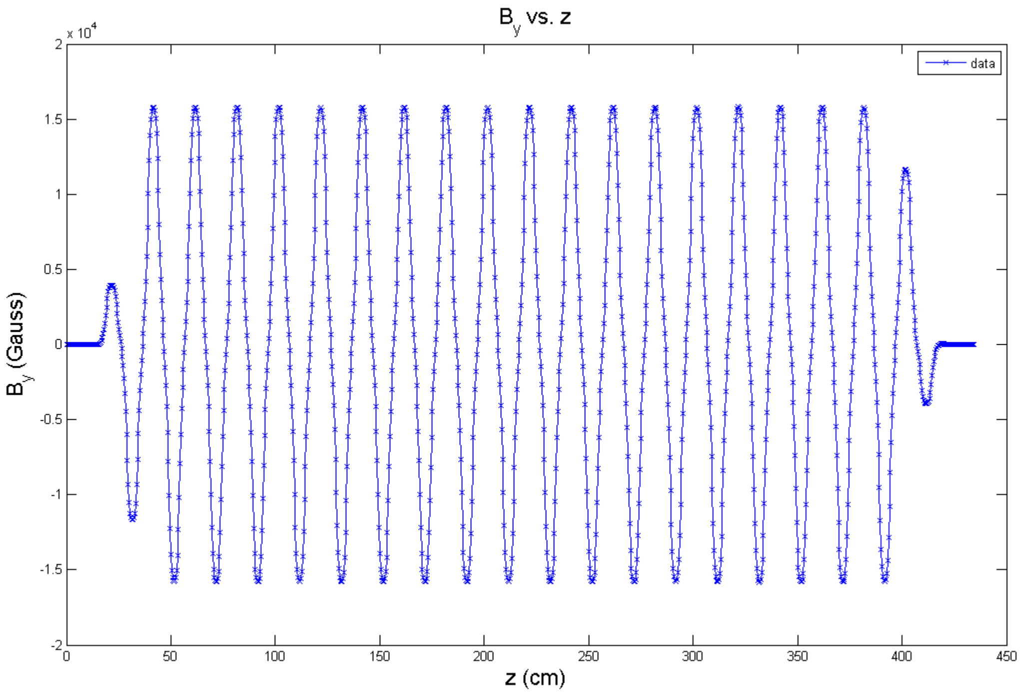


Figure 3.1: $B_y$ as a function of z at x = y = 0. The data points are from the actual field measurements taken using Hall probes.

# Chapter 4

# Matlab Work

It was found that the residual was different if the fitting was done in Matlab R2009a and Matlab R2007b using the same code. What obviously made me look into it was the vast difference in the quality of the fit that I got when I used the Matlab R2007b where I saw a dramatic improvement. The word dramatic is not an exaggeration here.

# Chapter 5

# Suggested Improvements

1- Program should ask for the path of the data file instead of the datafile so that it is more generalized. e.g. using uigetfile ('*.xls')
2- It should be able to save plot in a file with an appropriate name.
3- Interpretation of the By vs. x plot.
4- Currently, it fits only four harmonics without any phase. The program should be generalised for N harmonics and the phase component should be incorportated.
5- Fitting a function to the 3D map instead so the different vertical coordinate values are also accomodated for.
6- $B_0$ is currently assigned a value that is the maximum of all local maxima field values. Instead, it should be the average of all the local maxima and minima.
7- Optimization of the processing time of the code by looking at the improvement in the fitting parameters wrt the number of iterations including successive iterations.
8- Fitting the full field instead of fitting any particular period including the end fields. The following point may generate useful initial values for full field fitting.
9- Generation of more meaningful initial values for $k_{z0}$ possible by FFT of the data and then looking at the coefficients. One can then make use of the dominant coefficients as initial values for $k_{z0}$.
10- Generating a linear transport map by integrating the equations of motion.
11- The code should be properly and more appropriately commented for easy comprehension.
12- Mention of simplectic integration technique.
13- The differences when using different versions of Matlab to be illustrated with actual plots that were taken and the same should also be mentioned in the report. Also, the changes made in the parameters for the lsqnonlin for R2007B should be mentioned and the importance of the different parameters which help achieve the dramatic improvement clearly specified.

Thus, my main contribution was in quality improvement of the minimizing code so the fit is much better than it was earlier and in time improvement for processing on inspection of the the intermediate parameters using diagnostic tools in Matlab which reduced minimization time by more than 1/25 times.

# Bibliography

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[2] D. Sagan, J. A. Crittenden, D. Rubin, Cornell University, Ithaca, NY, USA; E. Forest, 1-1 Oho, Tsukaba, Ibaraki, Japan - A Magnetic Field Model For Wigglers and Undulators