Simulation of Undulator Radiation for the THz Source Project at PITZ

Considerations for the Design of Undulator

Prach Boonpornprasert

PITZ Physics Seminar
13.03.2014

HELMHOLTZ ASSOCIATION

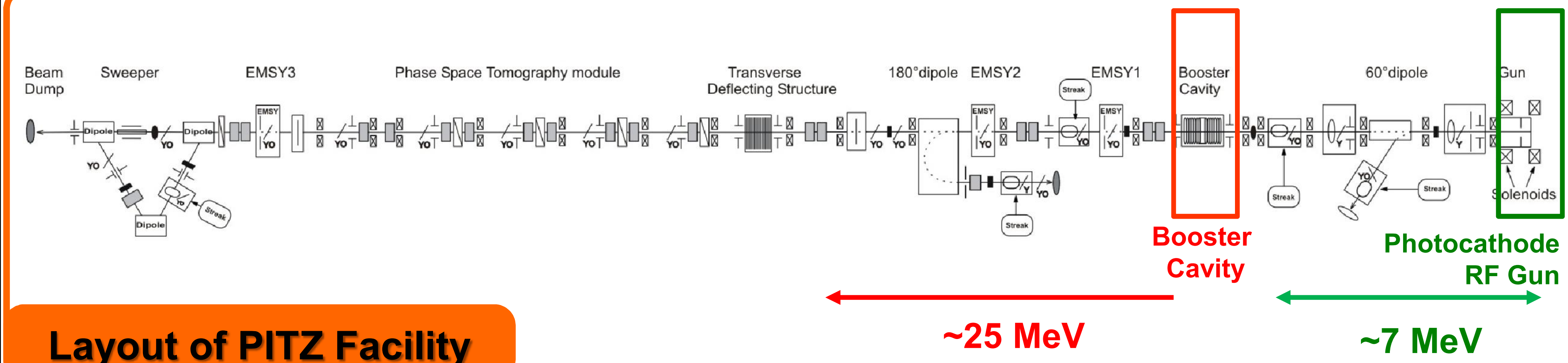
PITZ Photo Injector Test Facility Zeuthen

DESY

Outline

- PITZ Facility
- THz source Project at PITZ
- Considerations for the Design of Undulator
- Summary
- Outlook

Photo Injector Test Facility at DESY, Location Zeuthen (PITZ)



Layout of PITZ Facility

Goal

Development of high brightness electron source for linac based FELs

Highlights in 2014

> Plasma wakefield acceleration experiment
> Setup of 3D-elipsoidal laser system

Parameter	Value
RF frequency	1.3 GHz
RF repetition rate	10 Hz
Laser → Flattop → FWHM	~20 ps
e- bunch charge	20 pC – 4 nC
Maximum peak current	~200 A

THz source Project at PITZ

- The concept of an accelerator based source of THz/IR radiation for pump-probe experiment at European XFEL was presented in FEL2012 conference. (*E.A.Schiendmiller, M.Yurkov et al., WEPD55*)
- Due to the identical time structure, PITZ can be considered as a proper site for the development of a THz source prototype that could be placed at the European XFEL site.
- The preliminary simulations of SASE FEL using GENESIS code were done. The results are comparable to the benchmark results which using FAST code.
- Suggestions from E.A.Schiendmiller and M.Yurkov for FEL simulation:
  - The goal radiation wavelengths are **5 µm, 20 µm and 100 µm.**
  - Consider the design of APPLE-II type undulator.

Are all goal radiation wavelengths accessible with one undulator,
OR we need 2 undulators with different period lengths ?

Considerations for the Design of Undulator

Parameter	Corresponding study for its adjustment
Undulator Type	Polarization type of radiation field • Helical type for circular polarization • Planar type for linear polarization
Range of gap variation	• electron beam dynamics in undulator • mechanical limitation
Period Length	• radiation wavelength • electron beam momentum
Undulator length	• saturation length • Radiation properties (peak power, bandwidth) • Facility space

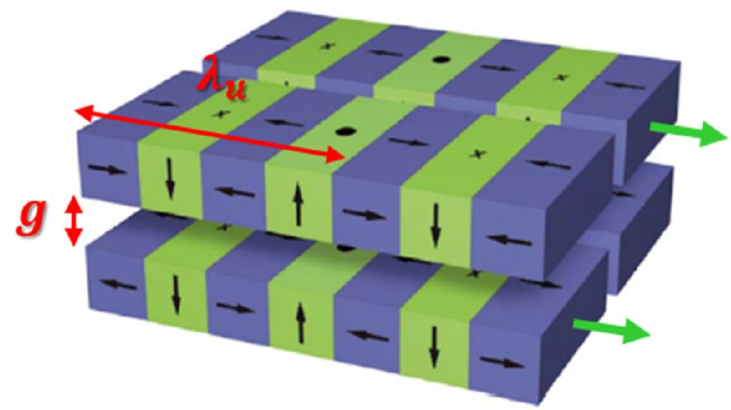
Note: In this study, we consider only the helical undulator.

Design Consideration: Undulator Type

Requirement : Variably Polarized Undulator

APPLE-II Type Undulator

- **A**dvanced **P**lanar **P**olarized **L**ight **E**mitter → **APPLE**
- The undulator is a pure permanent magnet which composed of 4 arrays.
- **The radiation** can be polarized vertically, horizontally, and circularly by moving two opposing magnet arrays.



Sketch of APPLE- II Undulator*

***Source: Conceptual Design Report ST/F-TN-07/12, Fermi@Elettra, 2007**

Decision: APPLE-II Type Undulator

Design Consideration: Undulator Type

Requirement : Variably Polarized Undulator

- **The Peak magnetic field (B_{max})** of an APPLE-II undulator can be derived from following formula:

$$B_{max}[T] = a_1 \times \exp\left[a_2 \frac{g}{\lambda_u} + a_3 \left(\frac{g}{\lambda_u}\right)^2\right] \; ; 0.1 < \frac{g}{\lambda_u} < 1.0$$

where a_1 = 1.54, a_2 = -4.46, and a_3 = 0.43 for the helical mode.

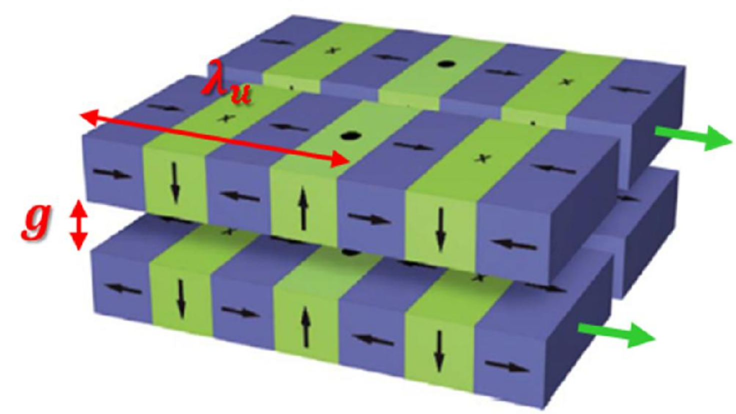
- **Undulator Parameter (K)**

$$K = 0.934 \cdot B_{max}[\mathrm{T}] \cdot \lambda_u[\mathrm{cm}]$$

- **Radiation Wavelength (λ_{rad})**

$$\lambda_{rad} = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2}\right)$$

where γ is relativistic factor.



Sketch of APPLE- II Undulator*

*Source: Conceptual Design Report ST/F-TN-07/12, Fermi@Elettra, 2007

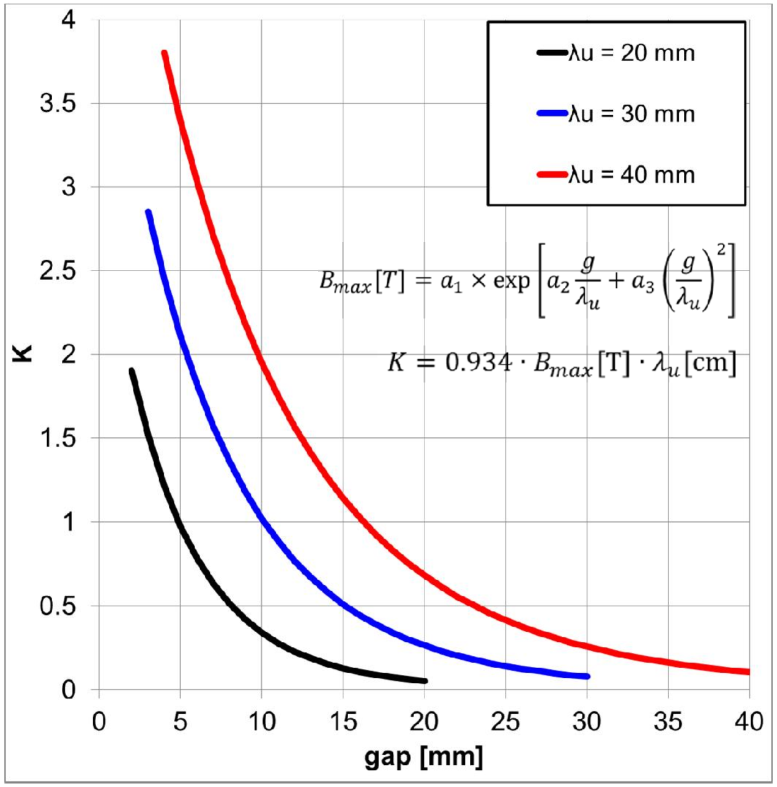
Decision: APPLE-II Type Undulator

Design Consideration: Range of Gap Variation

Requirement : e-beam dynamics aperture ~0.6mm*

***From preliminary simulation with 4nC, 15MeV/c e-beam and λ_u= 40 mm.**

- λ_u= 20mm, 30mm and 40mm were considered.
- The range is limited by the condition, $0.1 < \frac{g}{\lambda_u} < 1.0$.
- For in-vacuum undulator, the minimum gap has to be larger than
  (max beam tr size) + (tolerance)
  = 0.6 mm + 1 mm = 1.6 mm ≈ **2 mm**
- For in-air undulator, the minimum gap has to be larger than
  (max beam tr size) + (tolerance) + (vacuum chamber wall)
  = 0.6 mm + 1 mm + 2 mm = 3.6 mm ≈ **4 mm**
- The maximum gap (open gap) of APPLE-II undulator used in various FEL facility is in general **~40mm.**

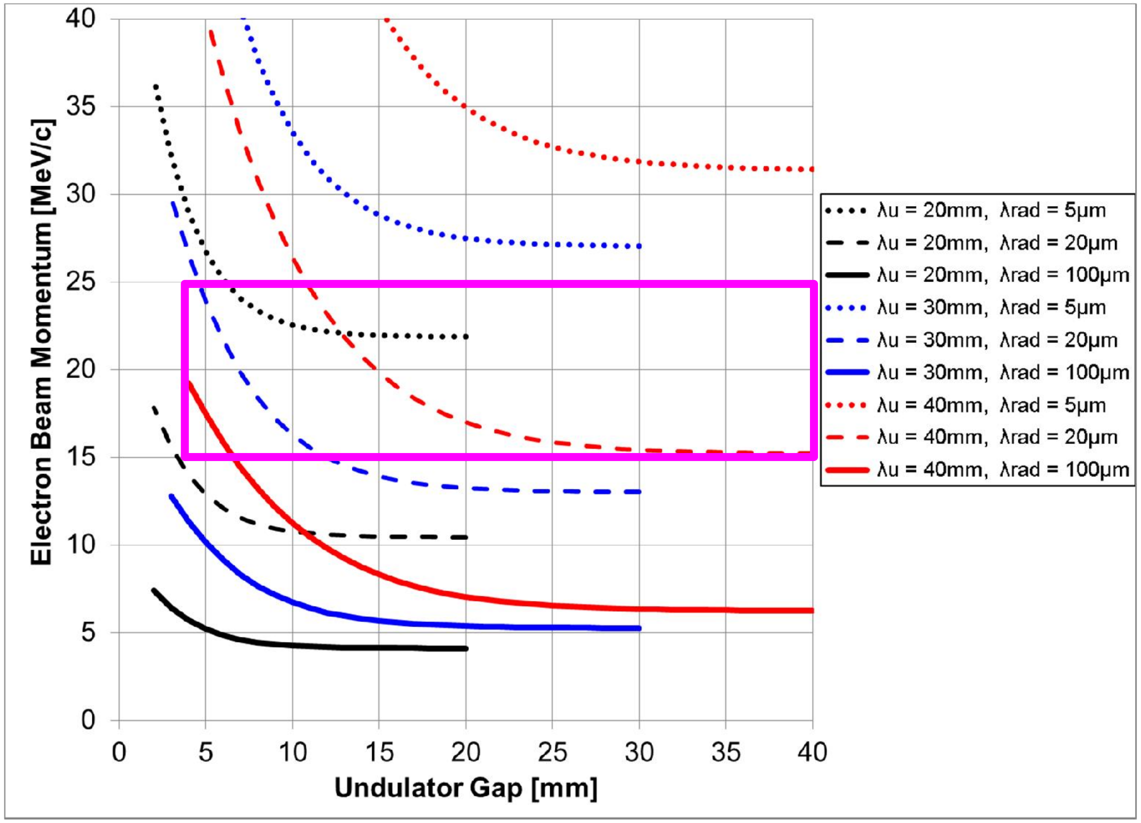


Decision: 2mm to 40mm for in-vacuum undulator
4mm to 40mm for in-air undulator

Design Consideration: Undulator Period Length

Requirement : in-air undulator, range of e-beam momentum is 15 -25 MeV/c

- λ_u= 20mm, 30mm and 40mm were considered.
- λ_{rad} = 5µm, 20µm and 100µm were considered.
- purple box shows the possible operation region.



Decision: λ_u **= 20 mm for** λ_{rad} **= 5 µm**
λ_u **= 40 mm for** λ_{rad} **= 20 µm and 100 µm**

Design Consideration: Undulator Length

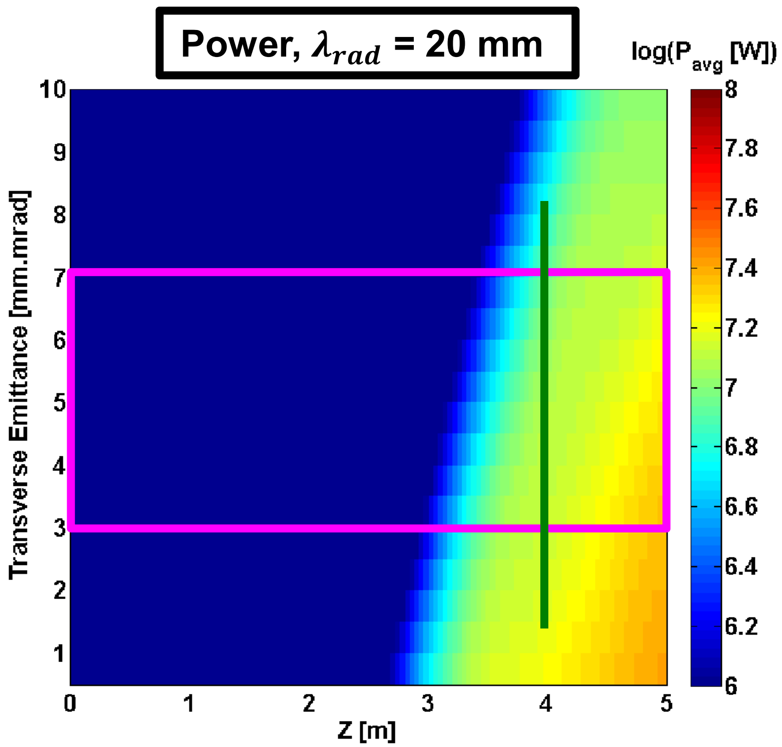
Requirements: **maximum undulator length of 5 m,**
radiation bandwidth ~5%, peak power in MW level

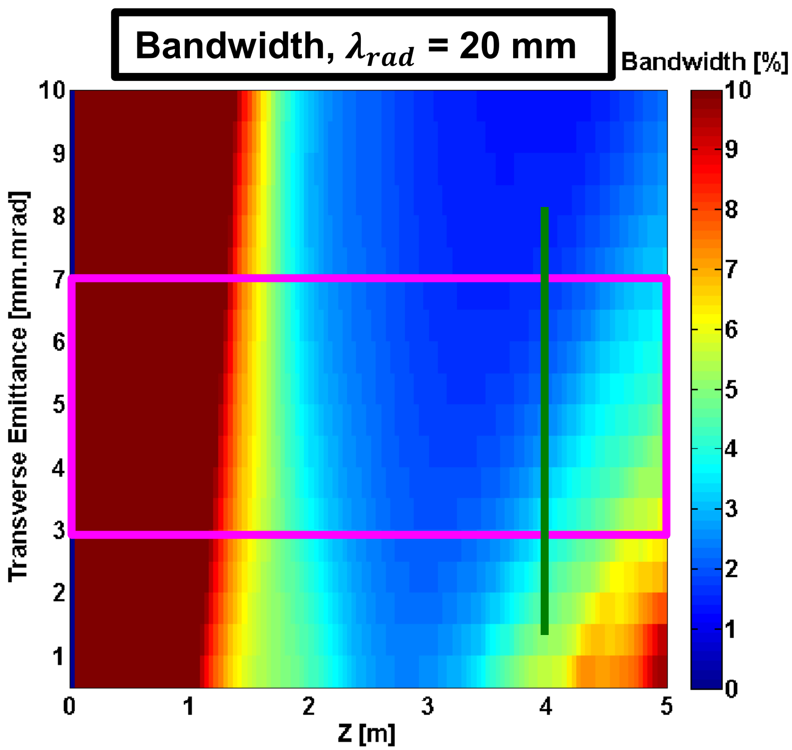
- The undulator length is determined from saturation length of SASE FEL radiation.
- GENESIS1.3 code was used for FEL simulation.
- The space charge calculation is excluded in the simulation.
- In this presentation, only **20 µm** and **100 µm** cases were studied. For **5 µm** case, which different period length has to be used, will be studied later.
- The model Gaussian electron beam with parameters in the right hand side table were used in the simulations.
- From preliminary beam dynamics simulations, The possible range of $\varepsilon_{tr,rms}$ is **3 to 7 mm.mrad**.

Parameter	Detail	
undulator type	Helical	
undulator period length (λ_u)	40 mm	
number of period	125	
radiation wavelength (λ_{rad})	20 µm	100 µm
undulator gap (g)	14 mm	6 mm
$K / \sqrt{2}$	0.90	2.10
$\langle P_z \rangle$	21 MeV/c	16 MeV/c
$P_{z,rms}/\langle P_z \rangle$	0.1%	
bunch charge	4 nC	
rms current length	2.4 mm	
peak current	200 A	
α_x, α_y	0	
σ_x, σ_y	0.2178 mm	

Design Consideration: Undulator Length (2)

Requirements: maximum undulator length of 5 m, radiation bandwidth ~5%, peak power in MW level



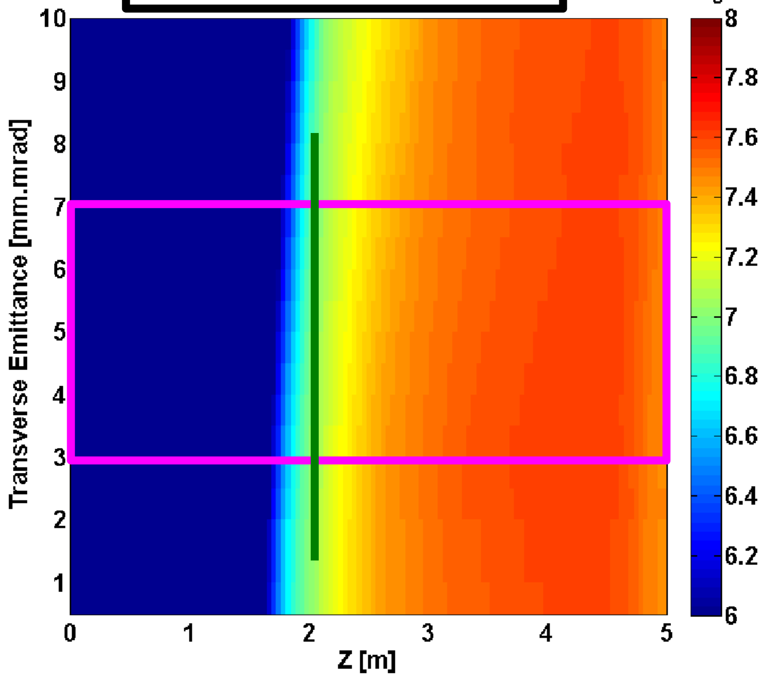


By neglecting the space charge effect, the expected peak power and bandwidth correspond to z = 4 m for λ_{rad} = 20 μm

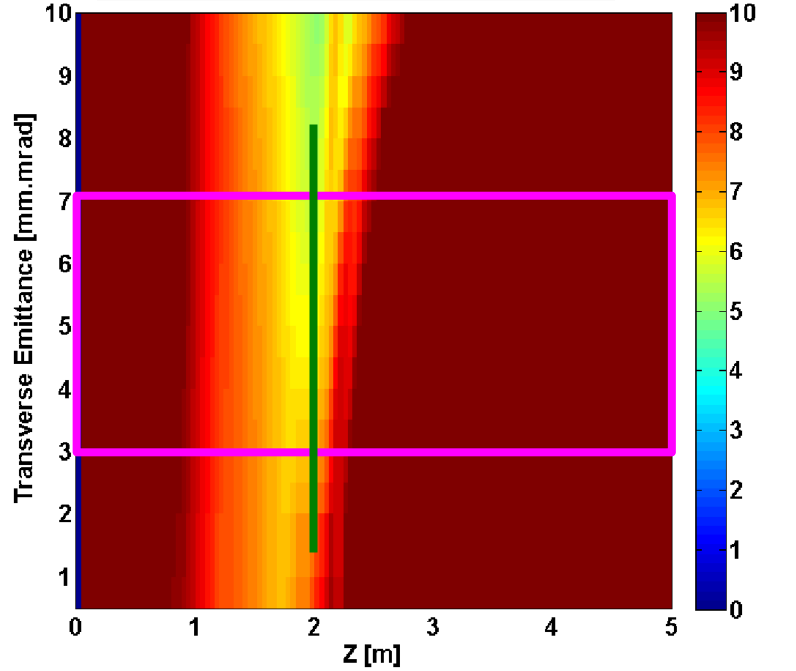
Design Consideration: Undulator Length (3)

Requirements: maximum undulator length of 5 m,
radiation bandwidth ~5%, peak power in MW level

Power, λ_{rad} = 100 mm



Bandwidth, λ_{rad} = 100 mm



By neglecting the space charge effect, the expected peak power and bandwidth correspond to z = 2 m for λ_{rad} = 100 μm

Summary

The considered undulator parameters are shown in following table:

Specification	Decision
Undulator Type	APPLE-II type undulator, in-air
Range of gap variation	4mm to 40mm
Period Length	λ_u = 20 mm for λ_{rad} = 5 µm λ_u = 40 mm for λ_{rad} = 20 µm λ_u = 40 mm for λ_{rad} = 100 µm
Undulator length	under study…

Outlook

- Repeat the scans concerning the power and bandwidth as a function of emittance of the electron bunch including space charge effect.
- Perform the same scan for λ_{rad} = 5 μm.
- Start to End (S2E) simulation for SASE FEL

- Simulation of the production of THz radiation using Coherent Transition Radiation.

This point only for PPS

Publish paper in topic,
"Start-to-End Simulation of THz Source Project at PITZ"

Thanks for your attention !

Backup: more information of APPLE-II

APPLE-II Type Undulator*

- **The Peak magnetic field (B_{max})** of an APPLE-II undulator can be derived from the formula:

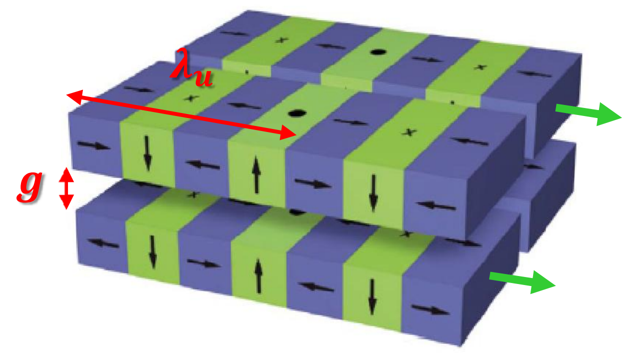
$$B_{max}[T] = a_1 \times \exp\left[a_2 \frac{g}{\lambda_u} + a_3 \left(\frac{g}{\lambda_u}\right)^2\right] ,$$

where $0.1 < \frac{g}{\lambda_u} < 1.$

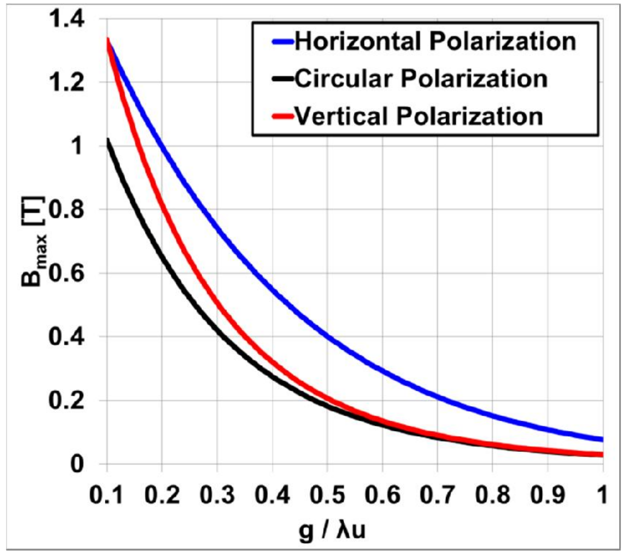
- The coefficients for each mode of APPLE-II are listed in the following table:

Polarization	a_1	a_2	a_3
Horizontal	1.76	-2.77	-0.37
Circular	1.54	-4.46	0.43
Vertical	2.22	-5.19	0.88

*Reference: Conceptual Design Report ST/F-TN-07/12, Fermi@Elettra, 2007



Sketch of APPLE- II Undulator

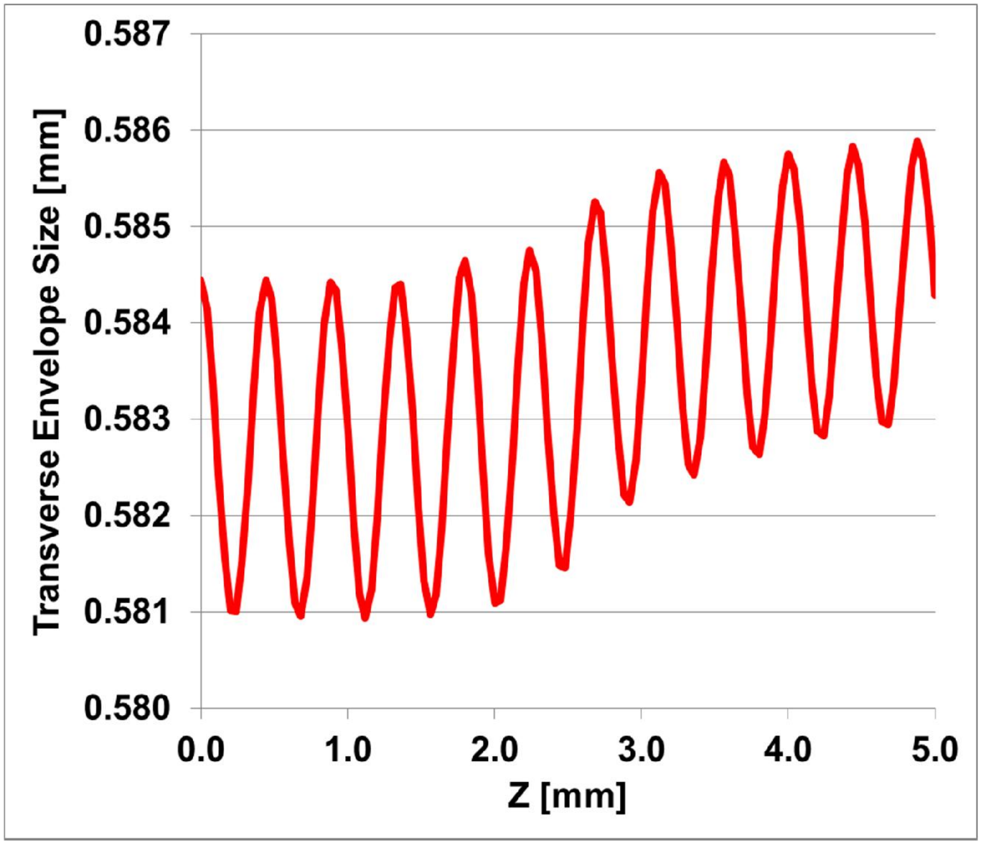


B_{max} from Various Polarization Mode

Backup: Preliminary results of beam dynamics along the undulator

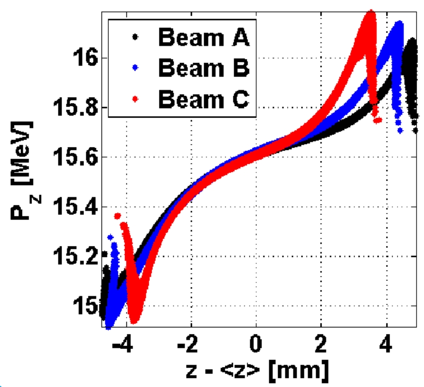
Transverse envelope size = $6*\sigma_{x,y}$

Parameter	Detail
undulator type	Helical
$K / \sqrt{2}$	1.9092
undulator period length (λ_u)	4 cm
number of period	125
radiation wavelength (λ_{rad})	100 µm
bunch charge	4 nC
rms current length	2.4 mm
peak current	200 A
e-beam energy	15 MeV
energy spread	20 keV
β_x, β_y	14.4 cm
ε_x, ε_y	10 mm.mrad
α_x, α_y	0

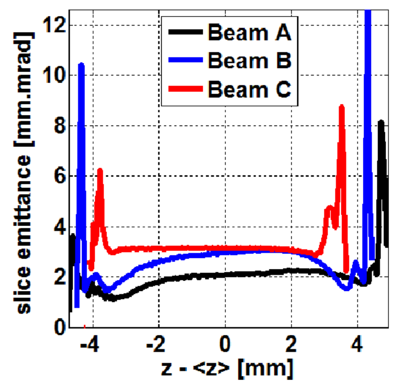


Backup: Preliminary Beam Dynamics simulations

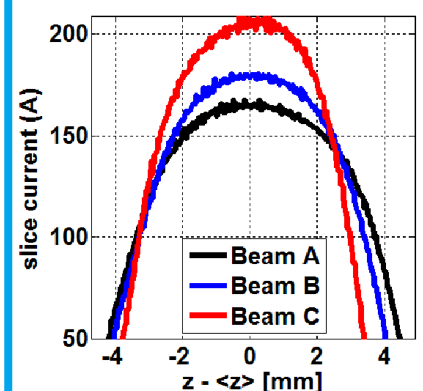
Long. Phase Space



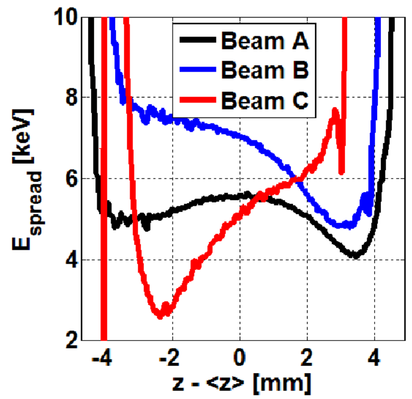
Slice Tr. Emittance



Beam Current



Slice Energy Spread



ASTRA input parameters

Parameter	Beam A	Beam B	Beam C
rms laser spot size (mm)	1.092	1.455	3.500
I_{main} (A)	378	380	340
Φ_{gun} (degree)	-1.404	-1.404	-1.404
$E_{max,booster}$ (MV/m)	10.2	10.2	10.2

Beam parameters after matching

Parameter	Beam A	Beam B	Beam C
$\varepsilon_{tr,n}$ (mm.mrad)	2.66	4.99	7.01
$\langle\varepsilon_{slice}\rangle$ (mm.mrad)	2.06	2.74	3.33
$\langle E_{spread,slice}\rangle$ (keV)	7.35	9.23	9.60
I_{peak} (A)	160	170	205