Simulations of the IR/THz source at PITZ (SASE FEL and CTR)

Outline

- Introduction
- Simulations of SASE FEL
- Simulations of CTR
- Summary
- Issues for Discussion

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Mini-Workshop on THz Option at PITZ
DESY, Zeuthen
22.09.2015

HELMHOLTZ ASSOCIATION

PITZ Photo Injector Test Facility Zeuthen

DESY

Proposal for IR/THz source at PITZ

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

Considering

Development of "Intense and wide wavelength range" IR/THz source at PITZ

Motivations & Goals

European - XFEL — X-ray

PITZ-like — IR/THz

Pump & Probe experiment

PITZ is an ideal machine for development of the prototype IR/THz source

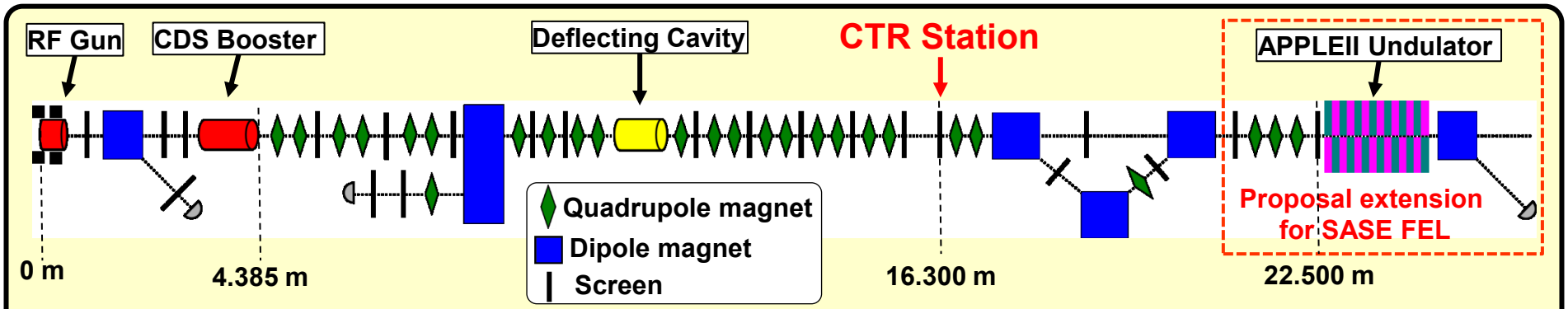
(Reference: E.A.Schneidmiller et al., WEPD55, FEL2012 conf.)

- Photon diagnostics
- Radiation based e-bunch diagnostics
- Service for light users

Case studies of radiation generation produced by the PITZ electron beam

- SASE FEL for $\lambda_{rad} \leq 100\ \mu m$ ($f \geq 3$ THz)
- Coherent Transition Radiation (CTR) for $\lambda_{rad} \geq 100\ \mu m$ ($f \leq 3$ THz)

PITZ Beamline Overview



PITZ Beamline layout including radiation stations for simulation studies

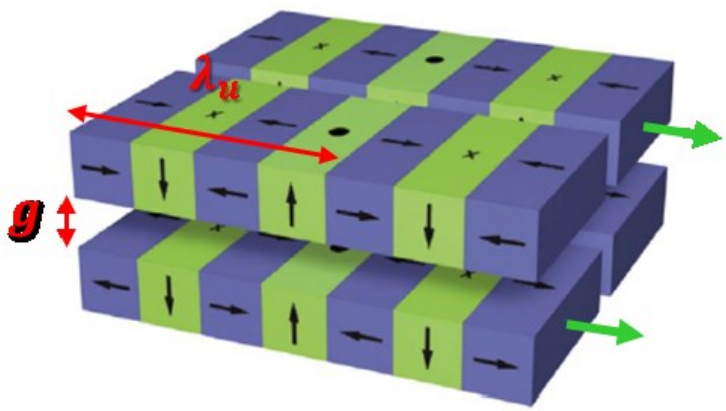
- Photocathode RF Gun
- Cut Disk Structure (CDS) Booster
- UV photocathode laser
  - Cylindrical pulse shape (Gaussian, flat-top)
  - 3D-ellipsoidal pulse shape
- Electron beam diagnostics stations
- **Radiation stations for simulations studies**
  - **CTR station**
  - **Extension for SASE FEL**

Key Parameters	
Laser temporal length	2 - 20 ps FWHM
Bunch charge	few pC … 4 nC
Maximum mean momentum $\langle P_z \rangle$	~22 MeV/c

Simulations of SASE FEL

- Consideration of undulator parameters
- Overview of FEL parameter space
- Beam dynamics simulations
- Radiation calculations
- Summary and outlook

SASE FEL: Consideration of undulator parameters



Sketch of APPLE- II Undulator*

Important Equations

The Peak magnetic field (B_{max}) :

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

where a_1, a_2, and a_3 are coefficients and $0.1 < \frac{g}{\lambda_u} < 1$.

For APPLE-II in helical mode*:

$a_1 = 0.39, a_2 = 0.42$, and $a_3 = 0.001$

Undulator Parameter (K)

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

Radiation Wavelength (λ_{rad})

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

where γ is Lorentz factor.

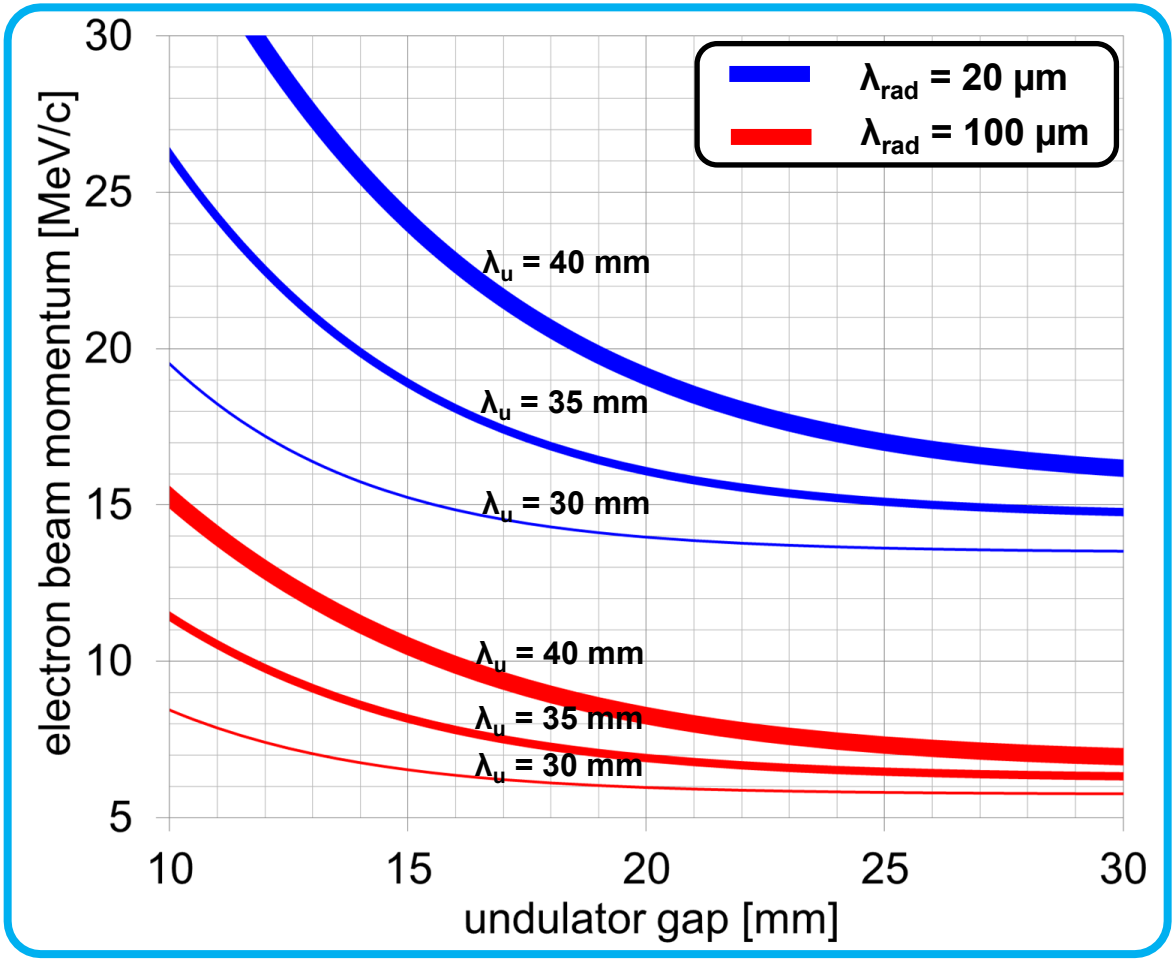
Reference:
*** Conceptual Design Report ST/F-TN-07/12, Fermi@Elettra, 2007.**
**** P. Elleaume, NIM. A., 455(2000), 503-523.**

SASE FEL: Consideration of undulator parameters

Conditions :
λ_{rad} of 20 – 100 µm
P_z of 15 – 22 MeV/c
g ≥ 10 mm

Selections :
λ_u of 40 mm
22 MeV/c for 20 µm
15 MeV/c for 100 µm

Plot of $P_z(g, \lambda_{rad}, \lambda_u)$

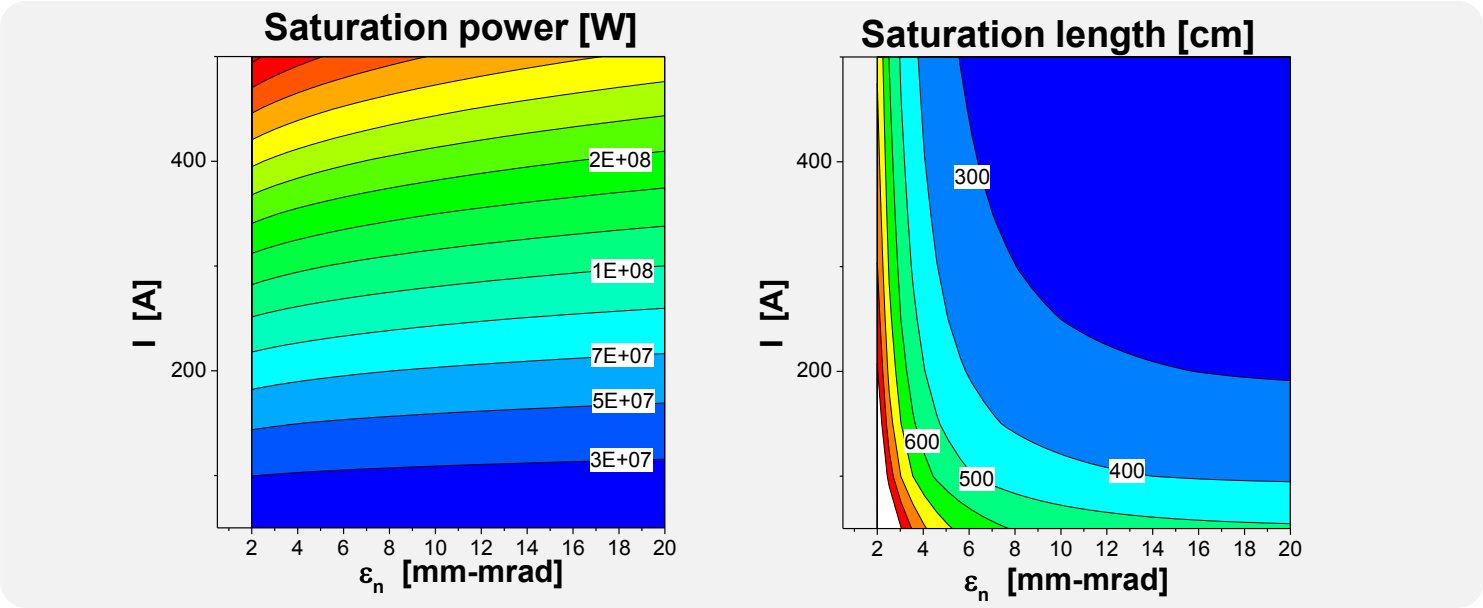


SASE FEL: Overview of FEL Parameter Space (for λ_{rad} = 100 µm)

The calculations have been performed with code FAST (Calculated by M.Yurkov & E. Schneidmiller).

Generate SASE FEL radiation wavelength of 100 µm using:

- Helical undulator with period length of **40 mm**
- Electron beam with **15 MeV/c** momentum, **4 nC** bunch charge, **~2 mm** rms bunch length



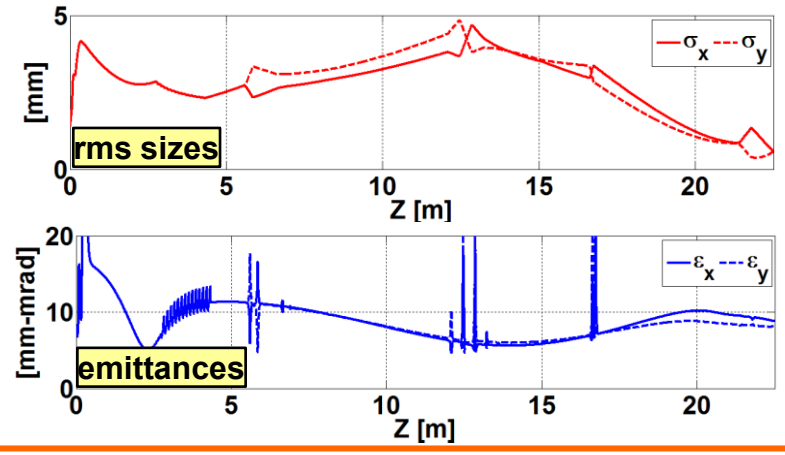
- **Transverse normalized emittance (ε_n) has almost no impact on saturation power.**
- **Higher ε_n ➔ lower saturation length.**

SASE FEL: Beam Dynamics Simulations (for λ_{rad} = 100 µm)

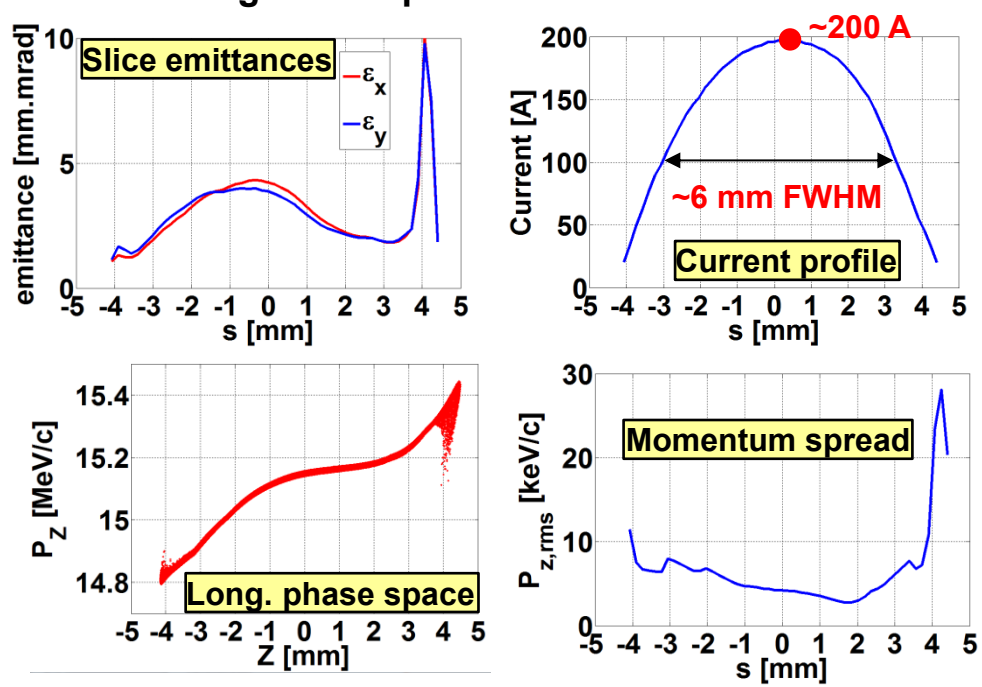
- **Simulation Tool: ASTRA code**
- **Goals of the beam transport:**
  - **<P_z> ~ 15 MeV/c** at the undulator entrance
  - Symmetric transverse beam sizes and emittances at the undulator entrance

Input for ASTRA	
Laser pulse shape	Flattop
Laser temporal length	20 ps FWHM
Rms laser spot size	1.25 mm
Bunch charge	4 nC
Z_{start} to Z_{end}	0 (cathode) to 22.500 m
Gun peak E-field	60 MV/m
Booster peak E-field	10 MV/m **(for <P_z> ~ 15 MeV/c)**
Gun phase	Optimized for: ***High peak current*** ***Low energy spread***
Booster phase	
Solenoid fields	

Evolutions of transverse beam sizes and emittances



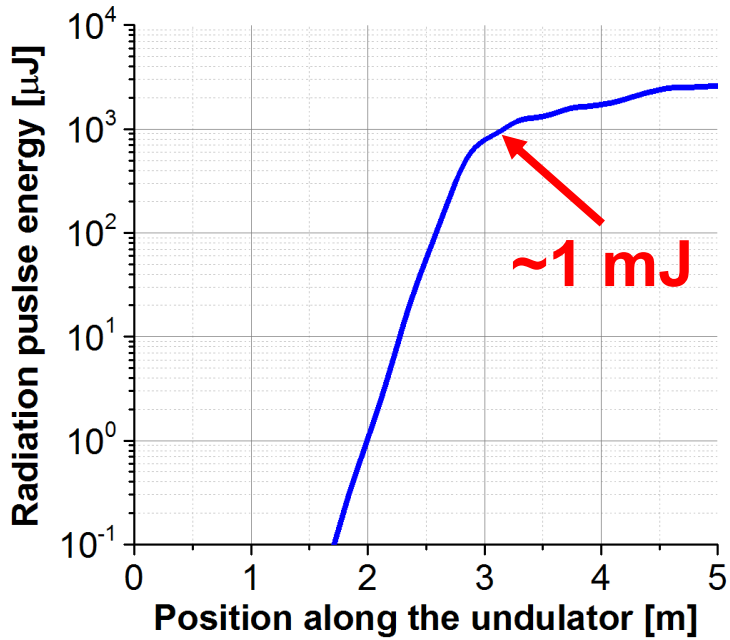
The longitudinal profiles at undulator entrance



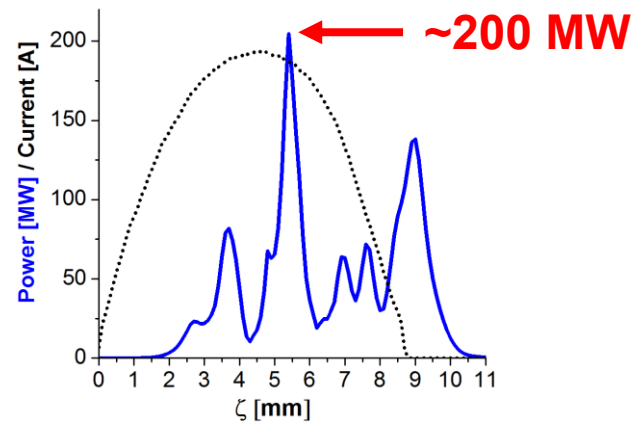
SASE FEL: Radiation Calculations (for λ_{rad} = 100 µm)

- **GENESIS 1.3 code (Version 2) was used for numerical calculations of SASE FEL.**
- **Input for GENESIS:**
  - Time-dependent mode, space-charge calculation included.
  - Helical undulator with **period length of 40 mm**
  - SASE FEL, **Radiation wavelength of 100 µm (3 THz)**

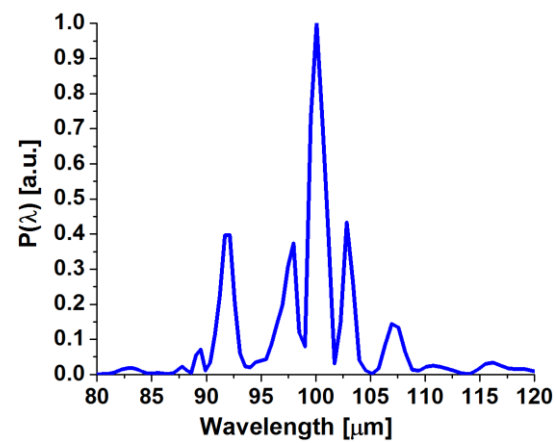
Energy in the radiation pulse as a function of Undulator length



Temporal profile of radiation pulse at the saturation



Spectral profile of radiation pulse at the saturation



SASE FEL: Summary & Outlook

Summary

- The saturation length is ~3 m (75 periods)
- The radiation has high energy (~1 mJ) and long temporal length (~20 ps).

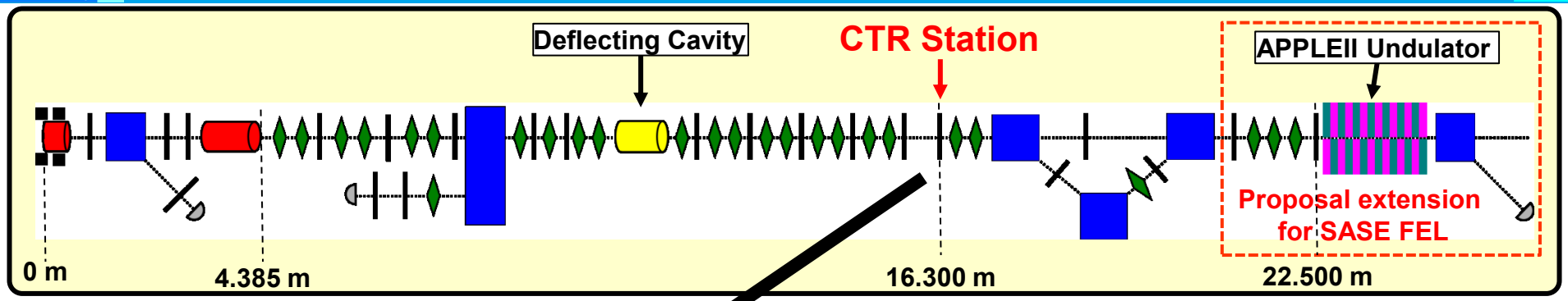
Outlook for Simulation Studies

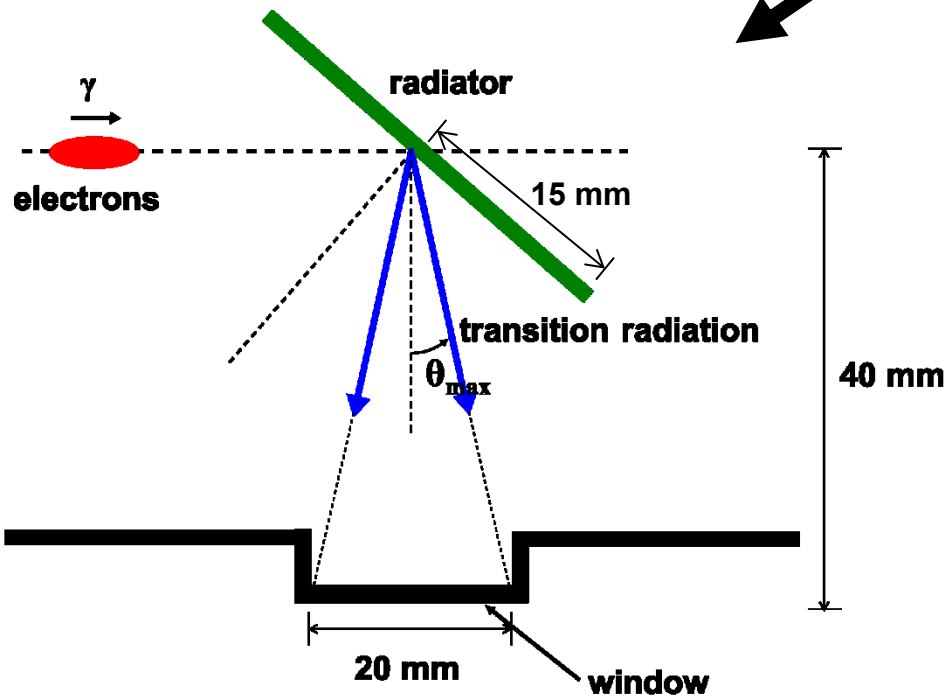
- Studies for radiation wavelength of 20 μm.
- Use hybrid undulator instead of APPLE-II (PPM) ?
- Boundary conditions in the GENESIS1.3 code
- Radiation profiles & transport

Simulations of CTR

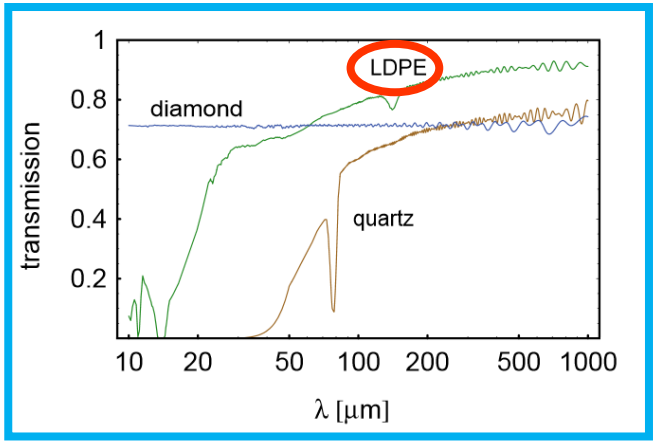
- Parameters of CTR station
- Beam dynamics simulations
- Radiation calculations
- Summary & outlook

CTR: Preliminary Design of CTR station





- $\theta_{max} = \tan\left(\frac{10\ \mathrm{mm}}{40\ \mathrm{mm}}\right) \approx 0.25$
- Expected acceptance angle: $\theta_{max} = \mathbf{6/\gamma}$
- $\gamma = \frac{6}{\theta_{max}} = \frac{6}{0.25} = 24 \rightarrow P_z \approx 12 \rightarrow$ **15 MeV/c**
- **Transm. coef. Vs λ** for 0.5 mm thick window*



* Casalbuoni et al., TESLA 2006-04

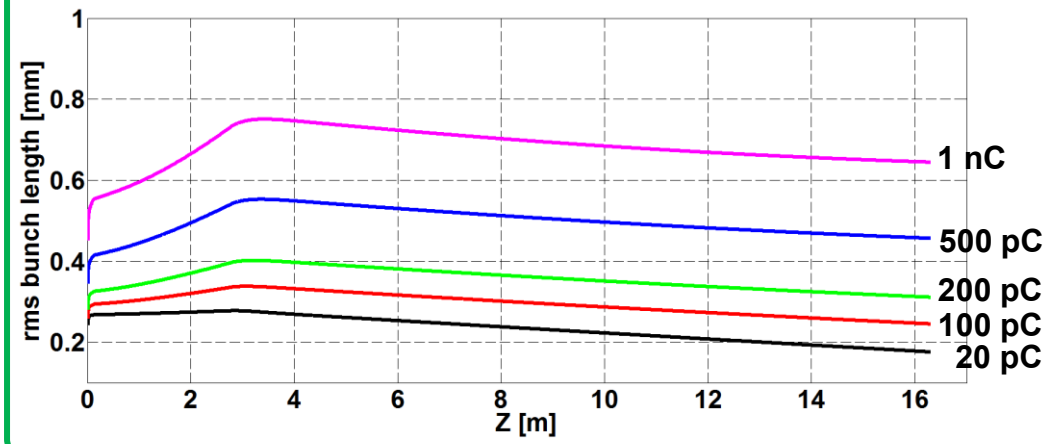
CTR: Beam Dynamics Simulations

- Simulation Tool: ASTRA code
- The bunch compressed by velocity bunching in the booster.
- Minimum <P_z> is limited to ~15 MeV/c

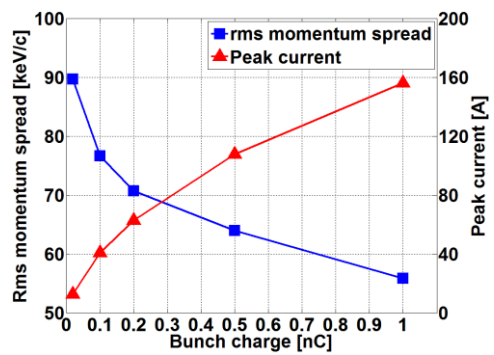
Input Parameters for ASTRA	
Laser pulse shape	Gaussian
Laser temporal time	2.43 ps (FWHM)
Rms laser spot size	1 mm
Bunch charge	20 pC to 1 nC
Z_{start} to Z_{end}	0 (cathode) to 16.30 m
Gun peak field	60 MV/m
Booster peak field	18 MV/m
Gun phase*	0°
Booster phase*	-60°

*with respect to maximum momentum gain phase

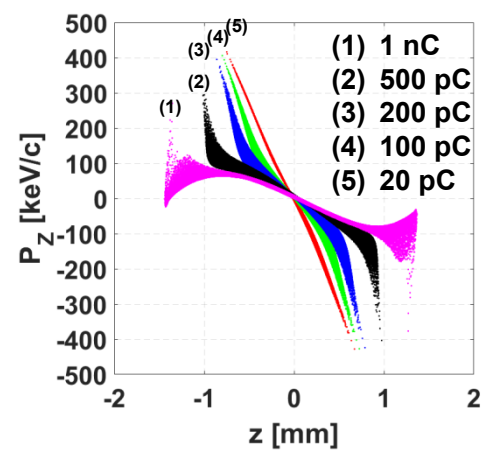
Evolutions of simulated rms bunch length



Rms momentum spread and peak current VS bunch charges at the CTR station



Long. phase spaces at the CTR station



CTR: Radiation Calculations

- CTR calculations were performed by using **Generalized Ginzburg-Frank Formula** [Casalbuoni et al., TESLA 2005-15].
- Assume:
  - The radiation screen is a finite circular metallic screen with the radius $\boldsymbol{a}$.
  - Electron beam with transverse radius of $\boldsymbol{r_b}$ impinges normally on the screen.
- The spectral and spatial radiation energy in the far-field regime for backward CTR are given by

$$\frac{d^2U_{\text{bunch}}}{d\omega d\Omega} = \frac{e^2}{4\pi^3\varepsilon_0 c}\frac{\beta^2\sin^2\theta}{(1-\beta^2\cos^2\theta)^2}\cdot N^2\left|F_{long}(\omega)\right|^2\cdot\left[\frac{2c}{\omega r_b\sin\theta}J_0\left(\frac{\omega r_b\sin\theta}{c}\right)-\frac{2c\beta\gamma}{\omega r_b}I_0\left(\frac{\omega r_b}{c\beta\gamma}\right)T(\gamma,\omega a,\theta)\right]^2$$

Longitudinal Form factor of the e-beam

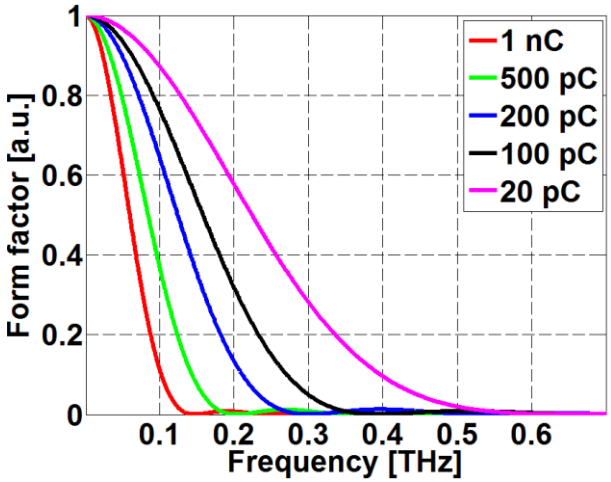
$$F_{long}(\omega) = \int_{-\infty}^{+\infty}\rho_{long}(t)e^{-i\omega t}dt$$

$$T(\gamma,\omega a,\theta) = \frac{\omega a}{c\beta\gamma}J_0\left(\frac{\omega a\sin\theta}{c}\right)K_1\left(\frac{\omega a}{c\beta\gamma}\right)+\frac{\omega a\sin\theta}{c\beta^2\gamma^2\sin\theta}J_1\left(\frac{\omega a\sin\theta}{c}\right)K_0\left(\frac{\omega a}{c\beta\gamma}\right)$$

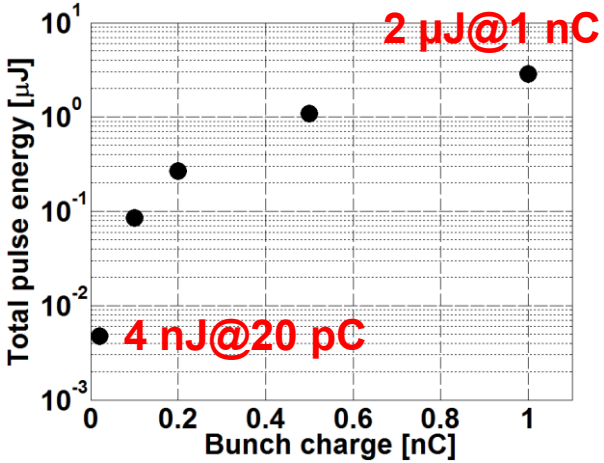
CTR: Radiation Calculations

- **CTR calculations were performed by using Generalized Ginzburg-Frank Formula** [Casalbuoni et al., TESLA 2005-15].
- **Assumptions and input:**
  - Perfect conductor and **circular screen with radius of 15 mm.**
  - Backward radiation, far-field regime calculation
  - **E-beam with radius of 0.5 mm** is normal incident to the screen.

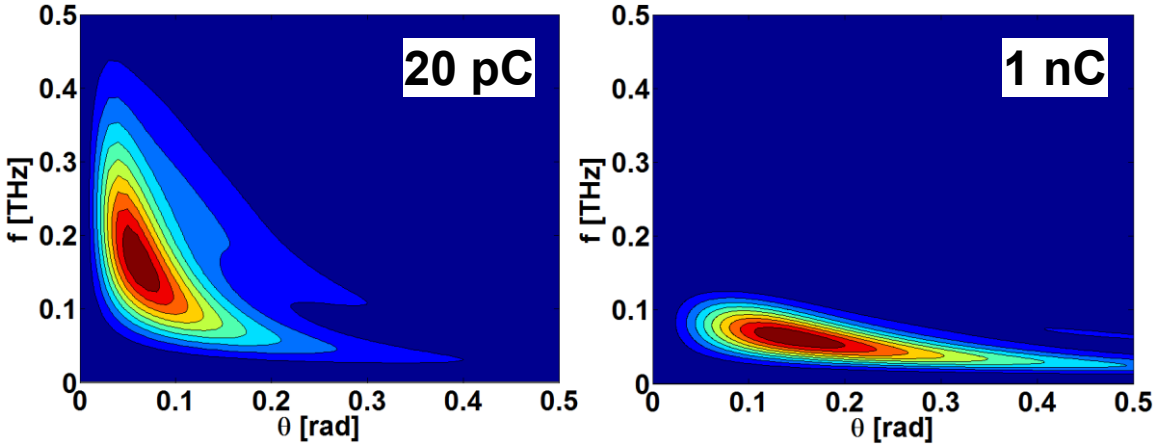
Form factors of the compressed bunch at the CTR station



Total radiation energy VS bunch charge



Normalized radiation energy VS frequency (f) and the emission angle (θ)



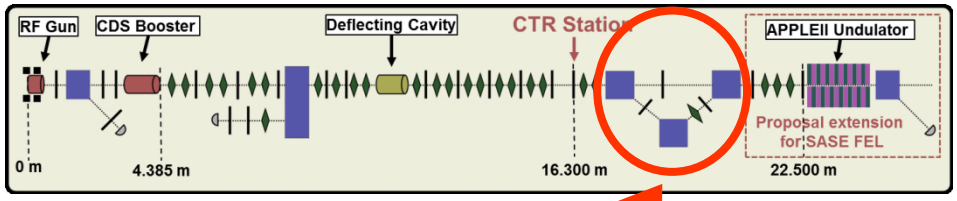
CTR: Summary & Outlook

Summary

- FWHM bunch length reaches only **~0.5 mm (1.6 ps)** when compressed by velocity bunching using the booster.
- The radiation has low energy (**nJ - µJ**) and low frequency (**0.01-0.5 THz**).

Outlook

- Bunch compressor is needed.
  - New bunch compressor ?
  - Try to use HEDA2 section



- Simulations:
  - an oblique screen, Near-field regime
  - Radiation profiles & transport
- The first CTR experiment is foreseen to take place in 2016.

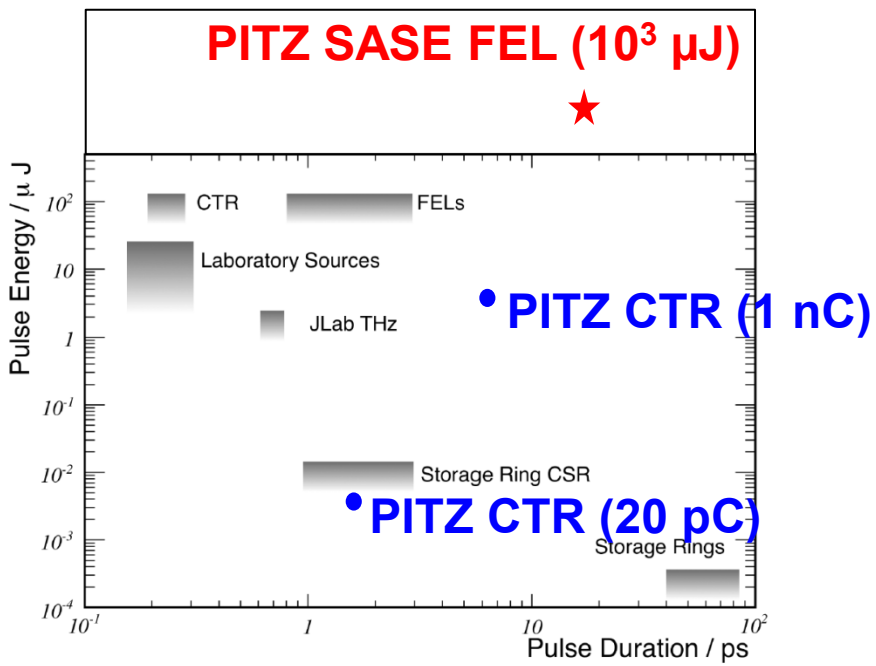
Summary

- Preliminary S2E simulations for the SASE FEL and the CTR using the PITZ accelerator were studied.

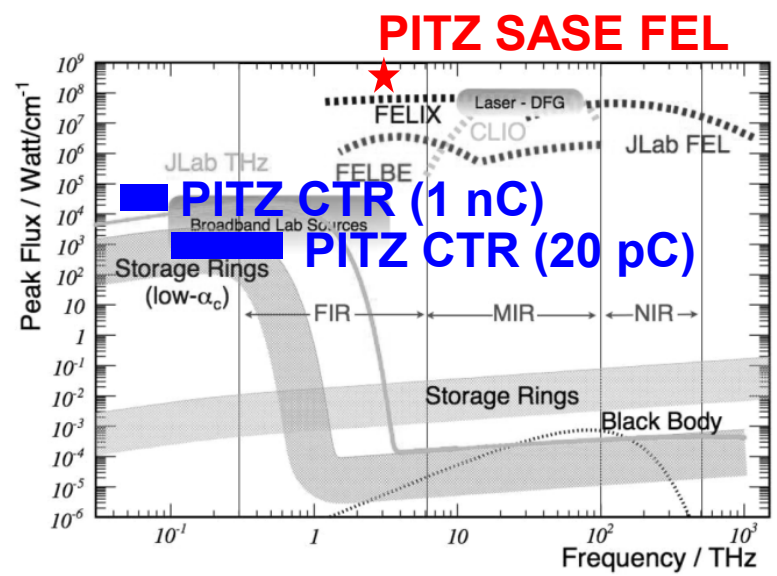
Comparison to the other IR/THz sources

(the radiation from the PITZ sources are just estimation)

Pulse energy VS FWHM of the generating bunch for the various sources



Spectral peak power density VS frequency



Reference: Anke-Susanne Müller, Rev. Accl. Sci. Tech., 03, 165 (2010)

Issues for Discussion

- **Comments from DESY Beschleuniger Ideenmarkt September 2015**

Kommentar und Empfehlung

Combining a PITZ-like accelerator with the XFEL as has been suggested by Schneidmiller et al. could be promising for THz pump-XFEL probe experiments. Following this suggestion the options to generate intense THz-radiation with a PITZ-like accelerator have been simulated which is certainly a good idea. So far the simulations show very intense THz pulses for a 75-period undulator as a radiation source albeit at the expense of generating very long pulses. For single cycle pulses from CTR the calculations show fairly low pulse energies. It should be investigated whether such a source would actually serve the user demands for THz pump-XFEL probe experiments.

- **Interesting and remarkable <u>experiments</u> those can be done at PITZ within time frame of 1 year from now.**
  - CTR
  - SASE FEL
  - Etc.,
- **In this starting step, research activities at PITZ concerning this proposal should be focused on**

Optimization of e-beam parameters ? ⟷ **quality of generated radiations** ? ⟷ **Radiation based e-bunch diagnostics**

Acknowledgement

PITZ Team

- M. Yurkov, Y. Schneidmiller, B. Marchetti — **DESY, Hamburg**
- C. Thongbai, S. Rimjaem — **CMU, Thailand**

Thank you for your attention!

BACKUP SLIDES

SASE FEL: APPLE-II undulator

APPLE-II Type Undulator*

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

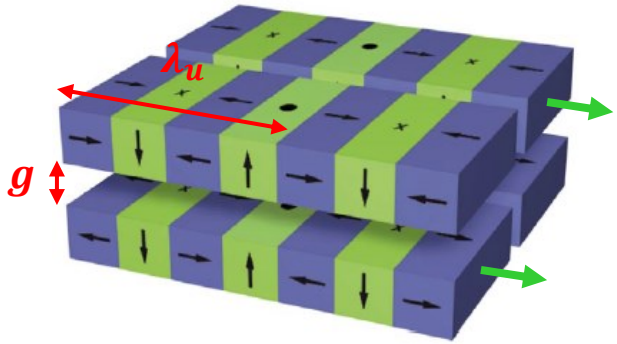
Polarization	a_1	a_2	a_3
Horizontal	1.76	-2.77	-0.37
Circular	1.54	-4.46	0.43
Vertical	2.22	-5.19	0.88

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

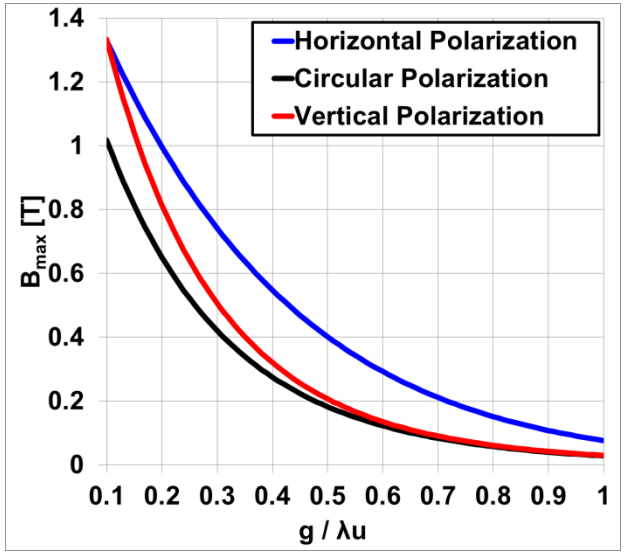
Example of APPLE-II Parameters

	UE40**
gap (magnetic)	6.5 – 25 mm
gap (vacuum)	5.0 mm
period length	40 mm
undulator length	4 m

**T.Schmidt, Undulators for SwissFEL, FEL2009, Liverpool



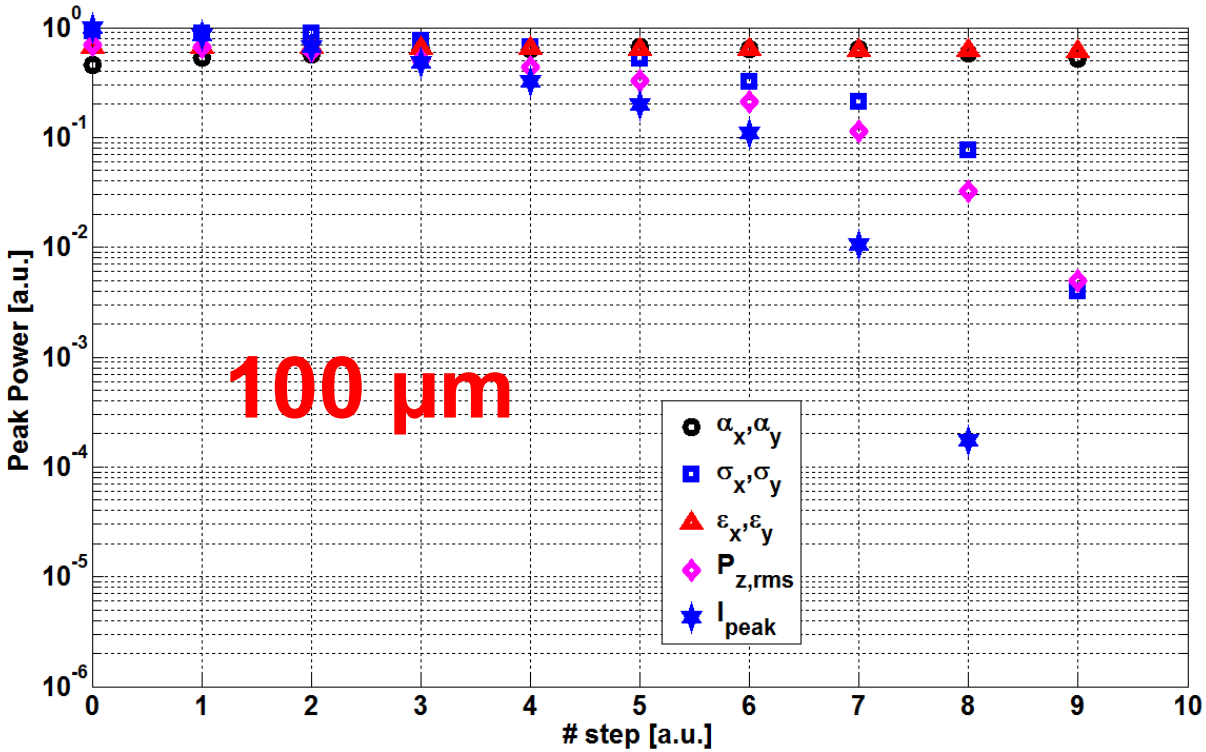
Sketch of APPLE- II Undulator



B_{max} from Various Polarization Mode

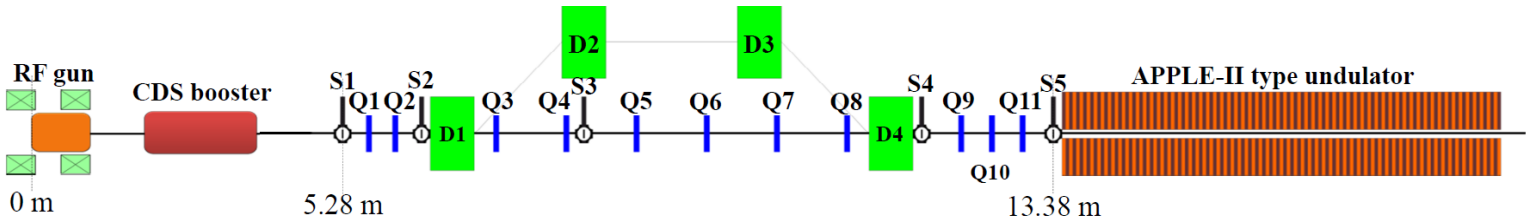
SASE FEL: Sensitivities to the electron beam parameters

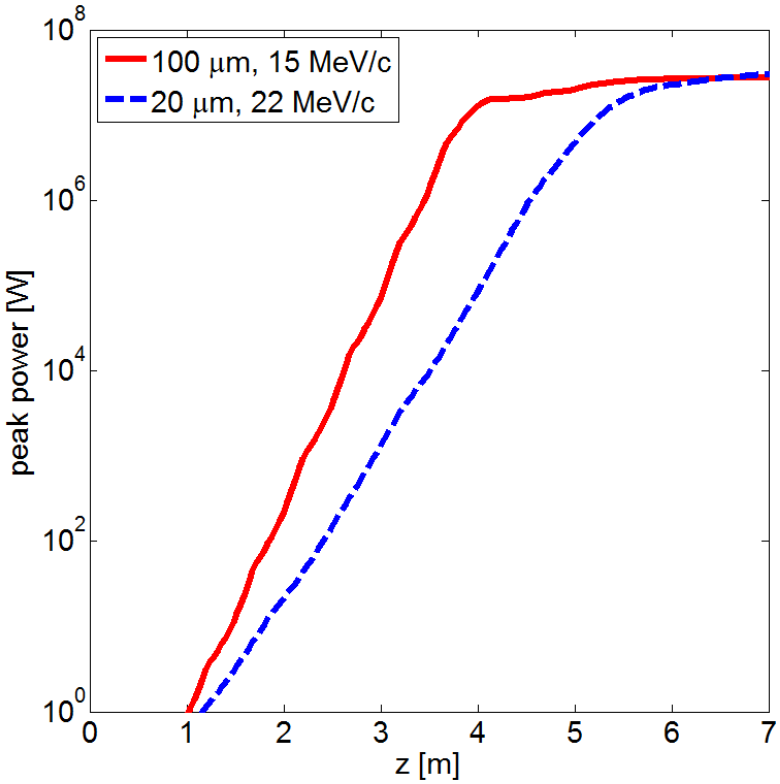
Parameter	Fixed	Varied	
	Value	Initial	Iteration
α_x, α_y	0	-10	+2
σ_x, σ_y [mm]	0.5	0.1	+0.1
ϵ_x, ϵ_y [um]	2	1	+1
I_{peak} [A]	160	200	-10
$P_{z,rms}$ / $P_{z,avg}$ [%]	0.2	0.1	+0.1

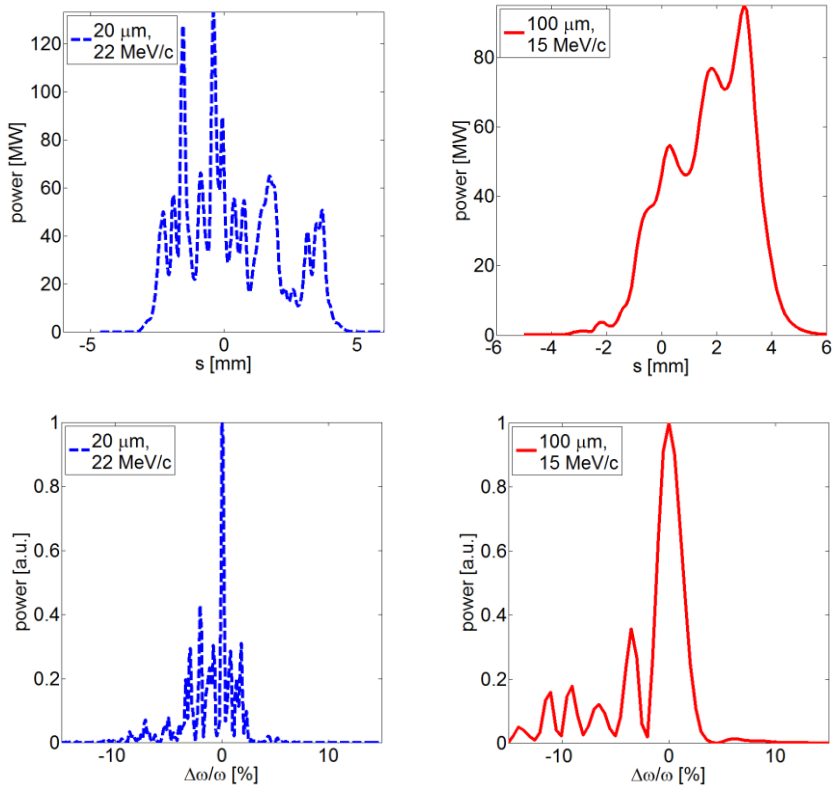


SASE FEL using a model beamline*

* P.Boonpornprasert et al., MOP055. FEL2013

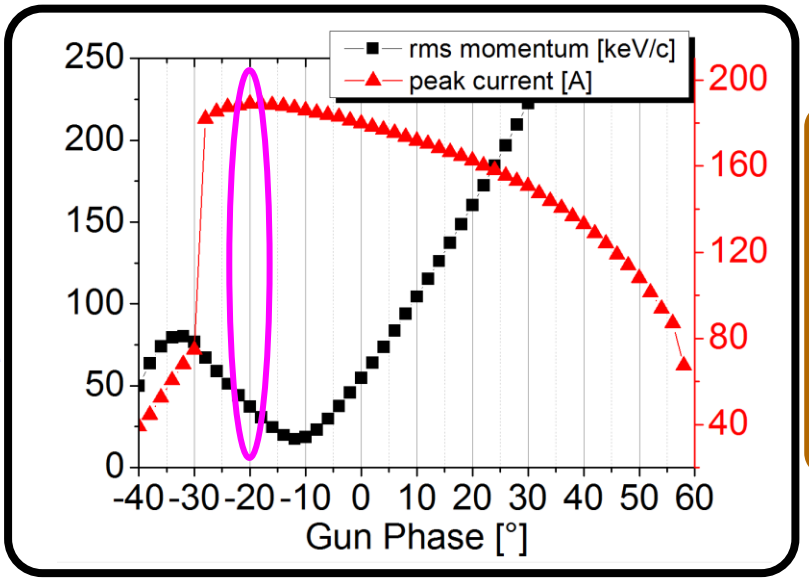






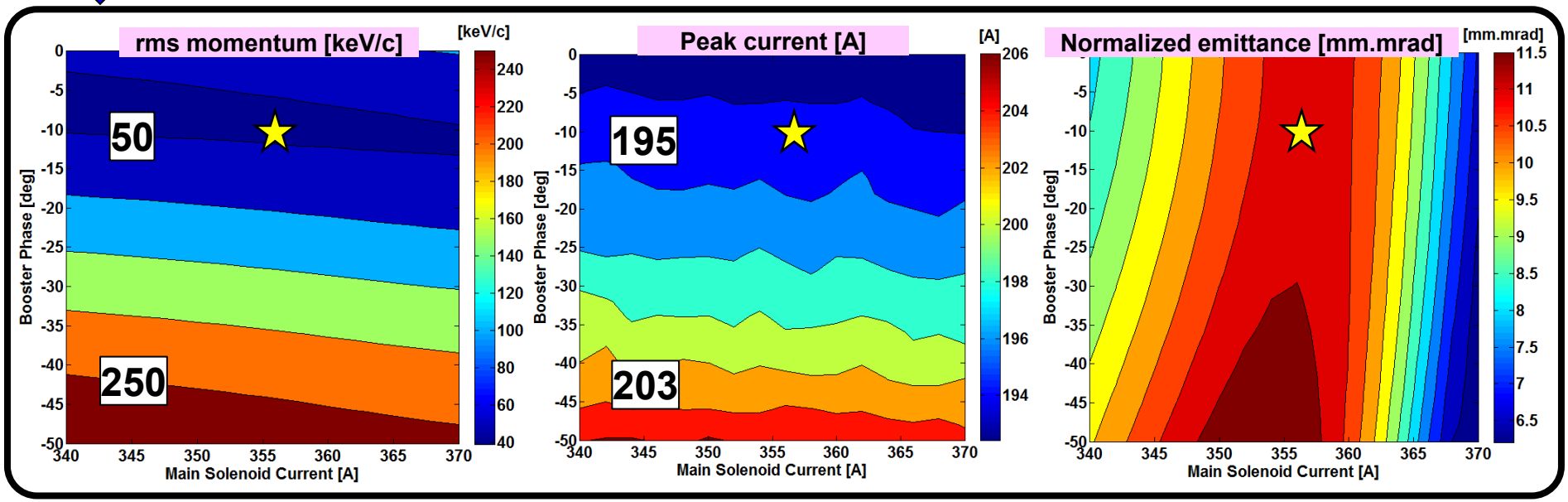
SASE FEL: Parameter Optimizations

Fixed gun phase to -20°



The optimized parameters are:

- **Gun phase = -20°**
- **Booster phase = -10°**
- **Main solenoid current = 356 A**



CTR: Other approach for RF compression