Self-Seeding implementation at European XFEL

Shan Liu, DESY

on behalf of the HXRSS collaboration team

- **HXRSS simulations**: G. Geloni, V. Kocharyan, E. Saldin, S. Tomin, S. Serkez et al.
- **Monochromator**: H. Sinn, X. Dong, L. Samoylova, T. Wohlenberg, D. Shu (ANL), V. Blank (TISNUM), S. Terentiev (TISNUM) et al.
- **Chicane magnets and girder**: W. Decking, S. Liu, T. Wohlenberg, B. Krause, A. Petrov, N. Golubeva, C. Engling et al.

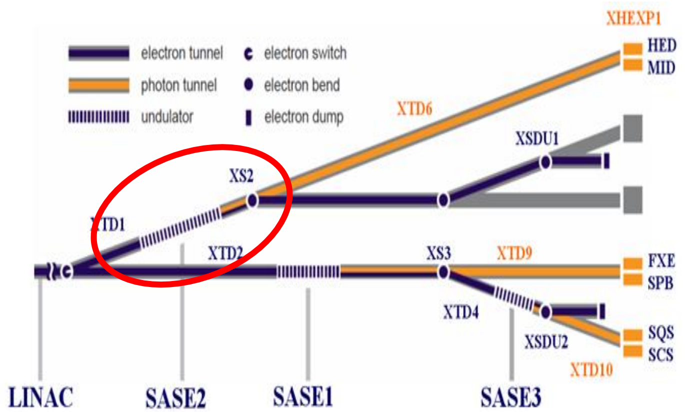
8th Hard X-ray FEL Collaboration Meeting, Pohang, Korea, 24-26 Oct. 2016

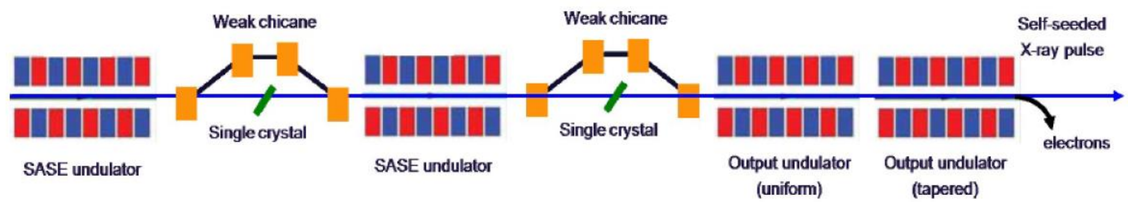
Outlines

- **Why** Hard X-Ray Self-Seeding (HXRSS) at European XFEL?
- **How** HXRSS designed at European XFEL?
- **What** are the challenges for HXRSS?
- Summary and discussions

HXRSS at European EXFEL

G. Geloni, V. Kocharyan, E. Saldin (*DESY 10-133*)





SASE2 line (3 keV -25 keV) will be first equipped with HXRSS

- High repetition-rate
- Long undulators → HXRSS+tapering

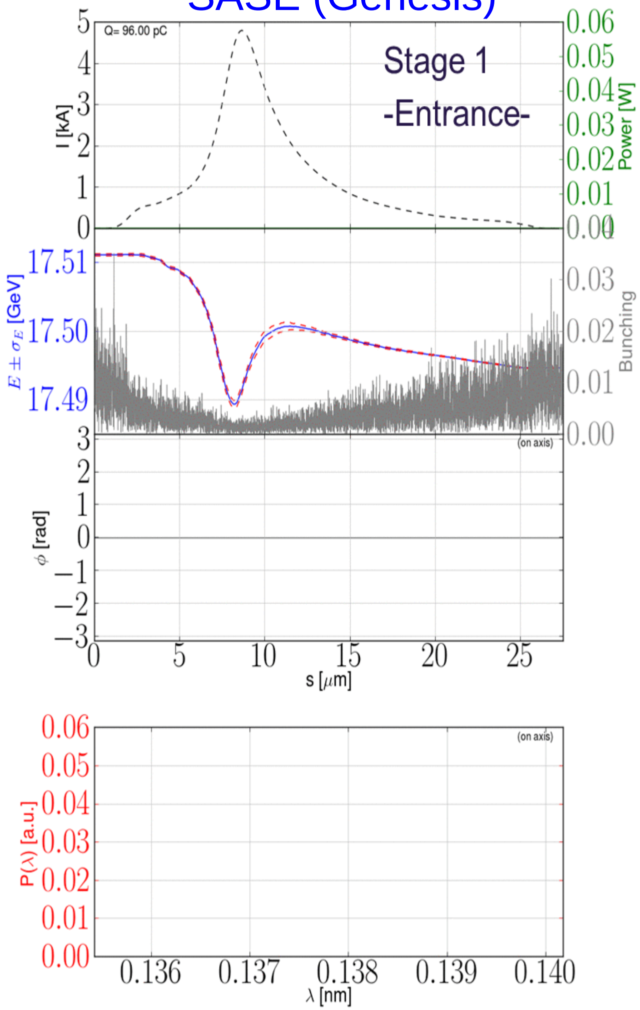
Simulations: (1) HXRSS – 9 keV – taper, (2) HXRSS – 14.4 keV- 2nd harm. bunching – taper

	Photon energy, [keV]	Integrated flux, [Ph/ pulse]	Photon pulse BW	Photon Flux, [Ph/s/meV]
w/o HXRSS	9	7e11	$\Delta\lambda/\lambda$~1.2e-3 or ~12eV	**1.5e12**
w/ HXRSS [(1)]	9	7e12	$\Delta\lambda/\lambda$~1e-4 or ~940meV	**2.1e14**
w/o HXRSS	14.4	1e11	$\Delta\lambda/\lambda$~1.6e-3 or ~20eV	**1e11**
w/ HXRSS [(2)]	14.4	9e11	$\Delta\lambda/\lambda$~7e-5 or ~1eV	**4e13**

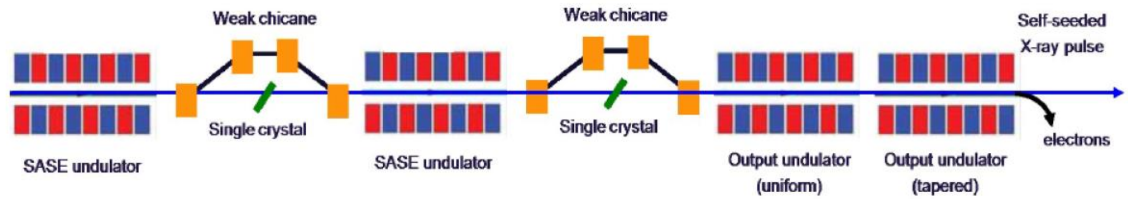
(1) G. Geloni, V. Kocharyan and E. Saldin DESY 15-141; (2) O. Chubar, G. Geloni et al. J. Synchrotron Rad. 23 (2016).

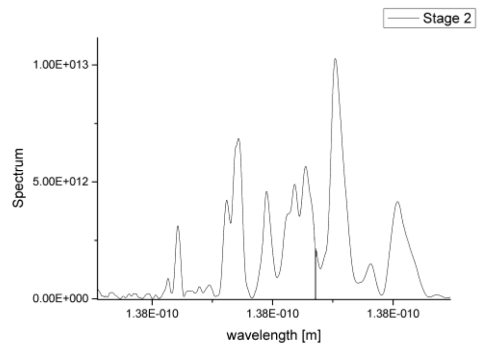
HXRSS Simulations

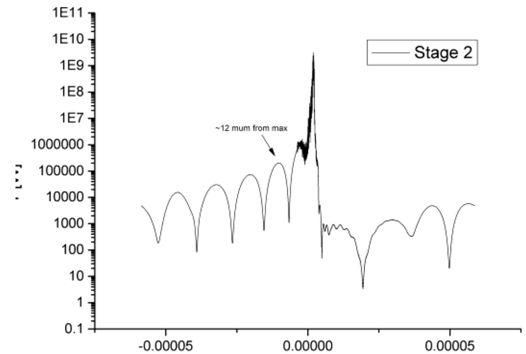
SASE (Genesis)



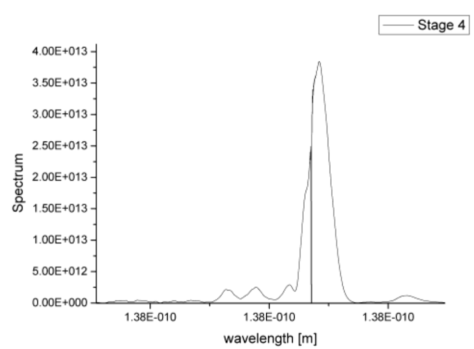
Courtesy of *G. Geloni*

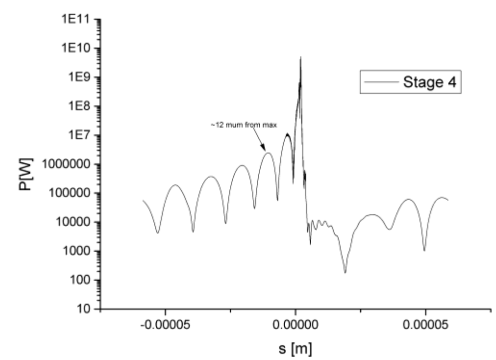






Seeding Stages (Ocelot)



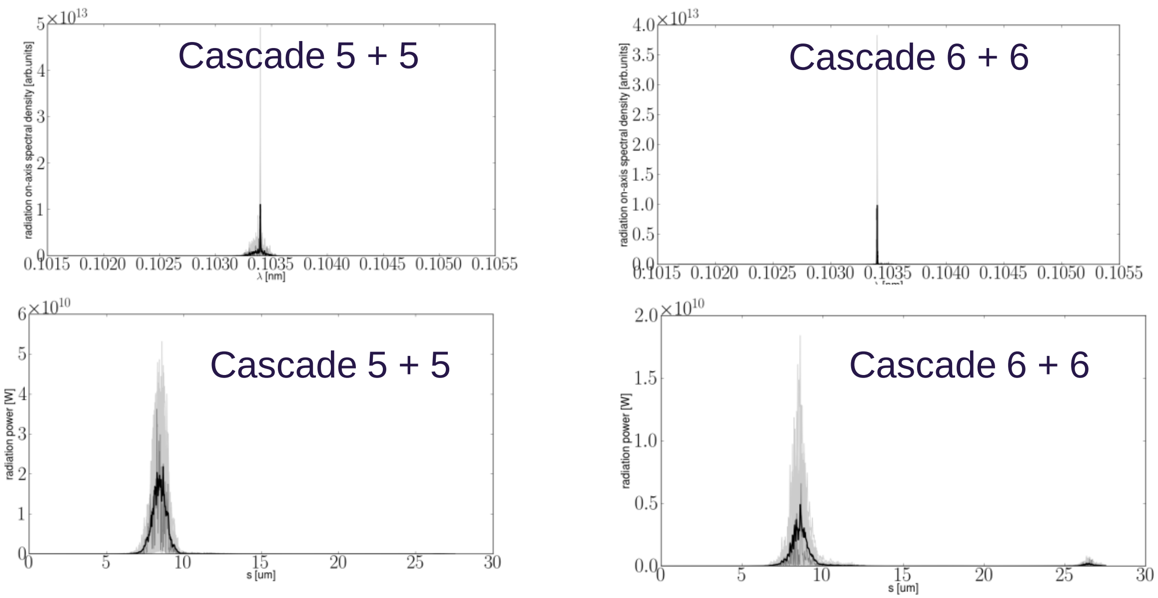


Challenges for HXRSS

HXRSS performance drops at **high energies** due to

- Spatiotemporal coupling for low Miller indexes
- Larger equivalent SASE shot noise to beat
- Longer gain length ➔increase # modules before HXRSS can improve the situation

100pC – 17.5 GeV – C004 – 12keV – 5th stage



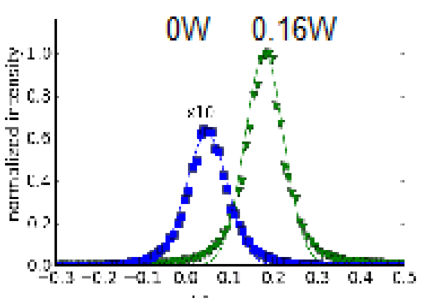
Courtesy of *G. Geloni*

Heat load on crystals by spontaneous radiation **also increases!**

Monochromator Design: pitch oscillator

High repetition rate: 27000 bunches/s Heat load is an issue!

- Spontaneous emission radiation has a broad energy spectrum, it is considered as the main source of heat load.
- Calculated total energy deposition from spontaneous emission: ~ 6 μJ.



Si(440) analyzer crystal scans

X-ray reflection energy shift due to heat load
ΔE/E = 3.1 e-4

Experiment by L. Samoylova

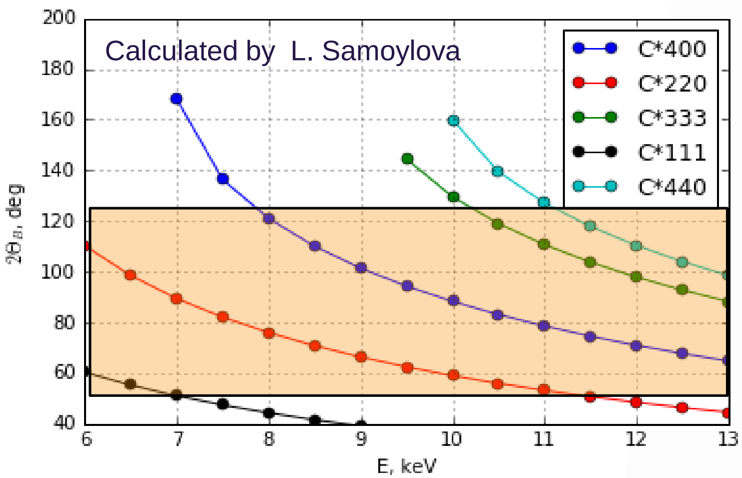
Courtesy of *H. Sinn*

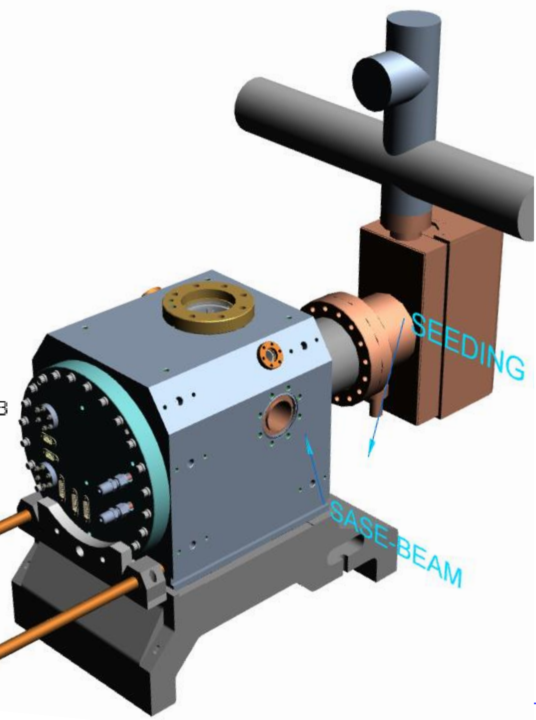
Frequency (Hz)	Angular Range (PV)
1200	70 urad
…	…
300	280 urad
…	…
10	0.48°

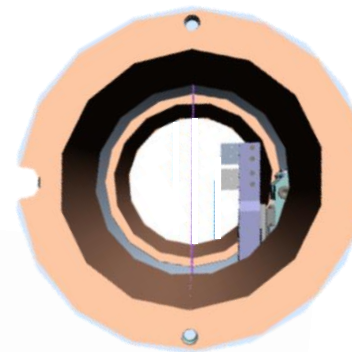
- Pitch oscillator will be treated as option (space foreseen and some development within design contract).
- Oscillate bragg angle can be used to compensate temperature cycle during pulse train.

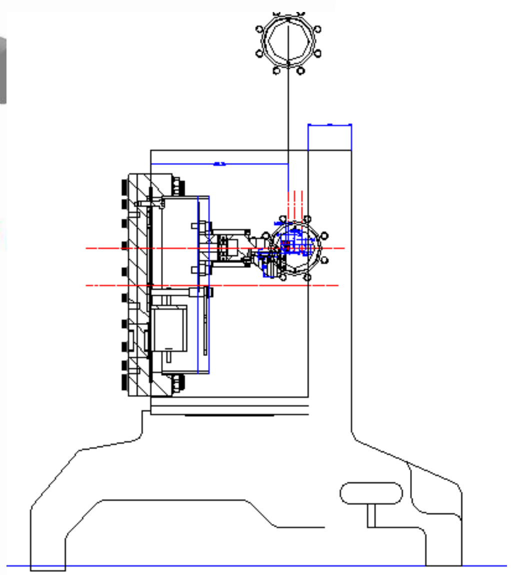
Monochromator Design

- View window for reflected signal detected by YAG screen: window angle at 90° ±33.5° view covers all the reflections
- Two crystals with different orientations on one holder



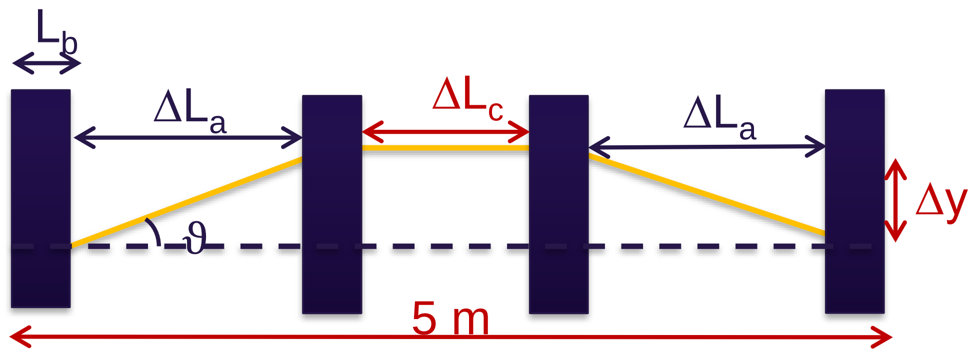




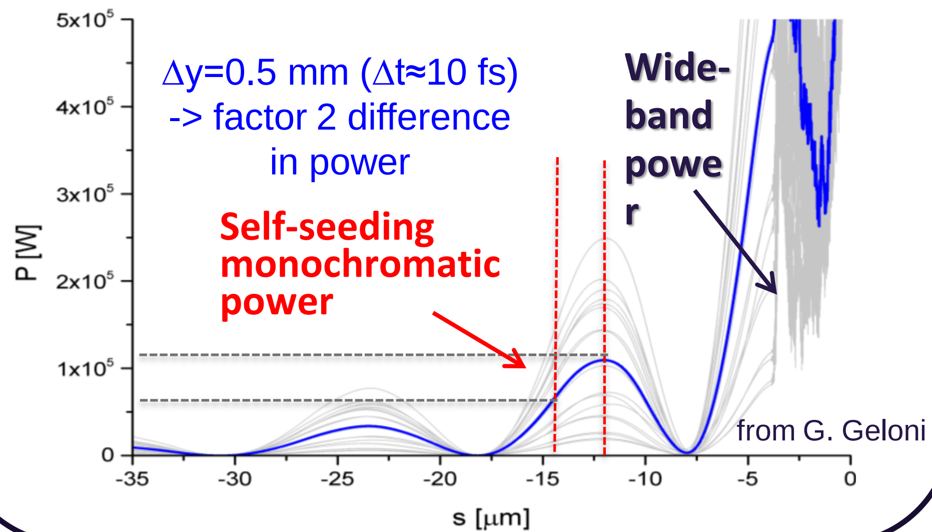


- Chamber design: *T. Wohlenberg (DESY)*
- Diamond and holder design: *D. Shu (ANL), S. Terentiev (TISNUM)*

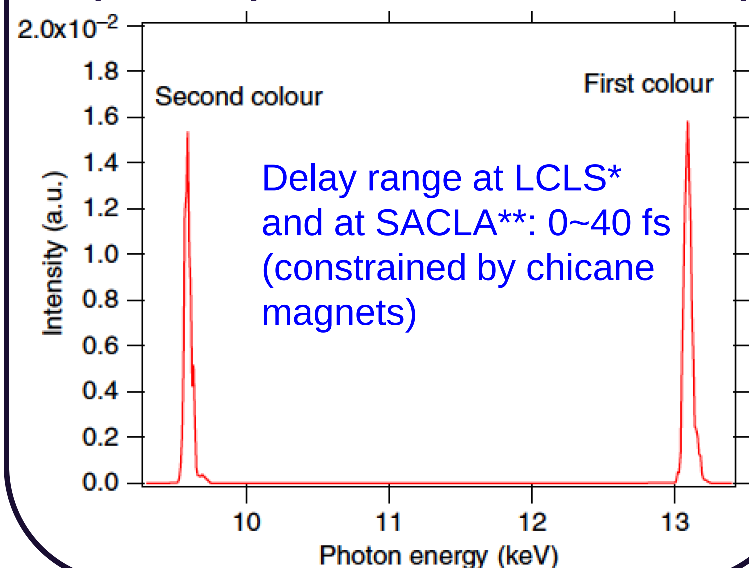
HXRSS Chicane design



Minimum delay
(<40 fs preferred, constrained by min. e- beam offset)



Maximum delay
(> 400 fs preferred for 2-colour SASE)



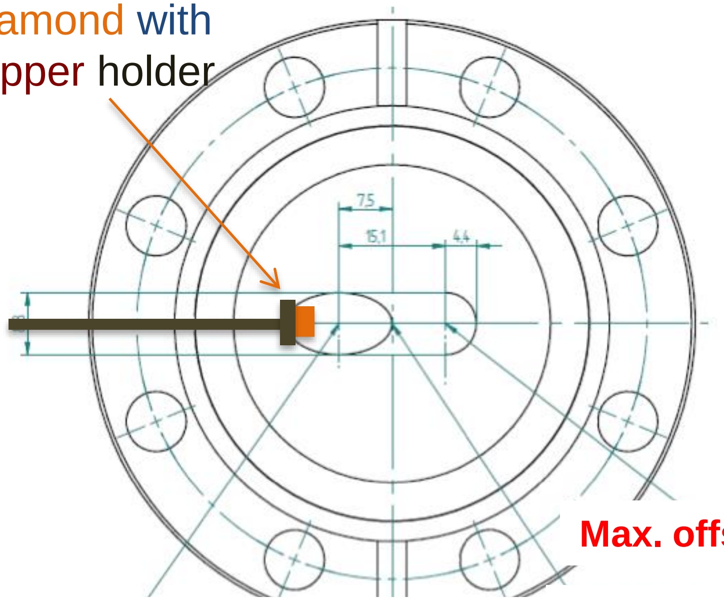
A. A. Lutman et al., PRL 110, 134801 (2013)* * Toru Hara et al., Nature communications 4 (2013)*

Chicane Design: maximum delay

Chicane chamber center is shifted to insure a maximum offset of 15 mm

436 fs max. delay can be achieved at European XFEL for <11.6 GeV beam

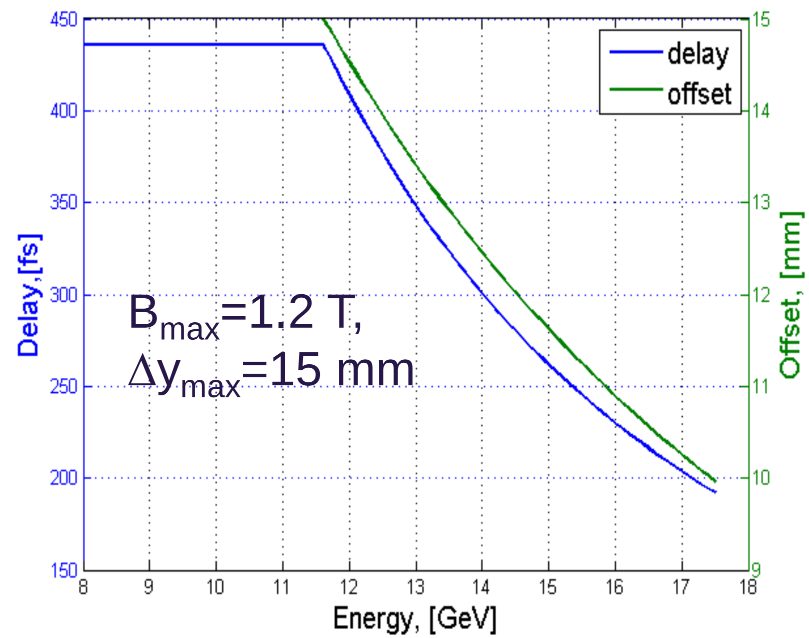
Diamond with copper holder



Max. offset of 15 mm

Center of undulator system (beam w/o seeding)

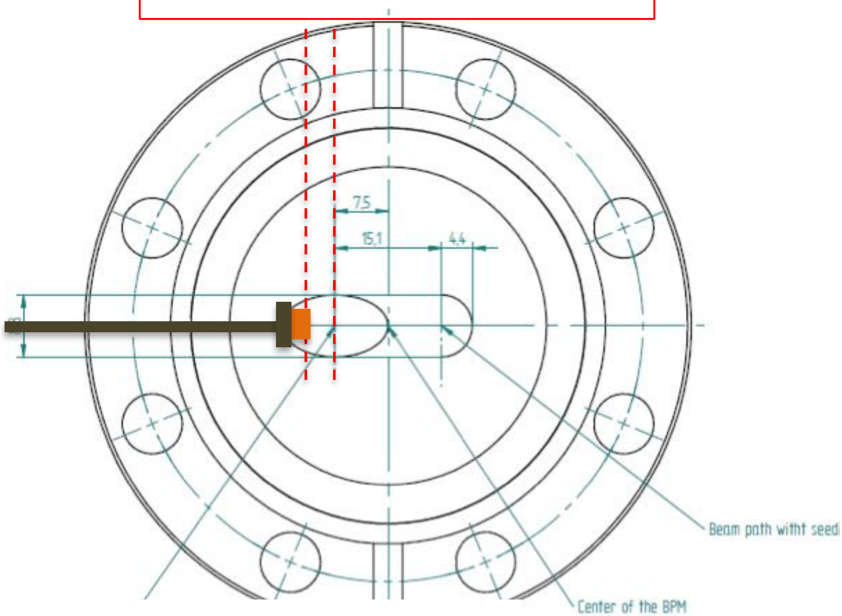
Center of chicane (dipole magnets, BPM and Monochromator)



Chicane Design: minimum delay

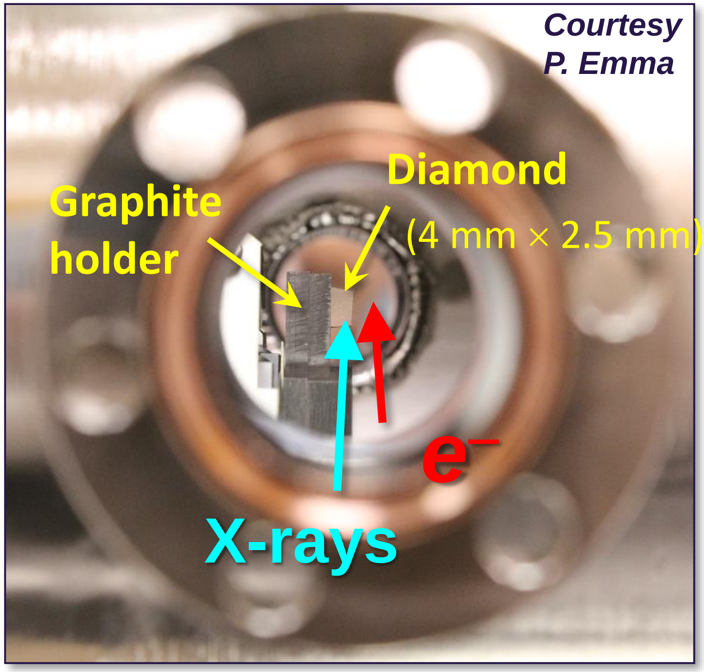
European XFEL HXRSS with
450 times higher duty cycle than LCLS

minimum offset: ? mm



Center of undulator system (beam w/o seeding)

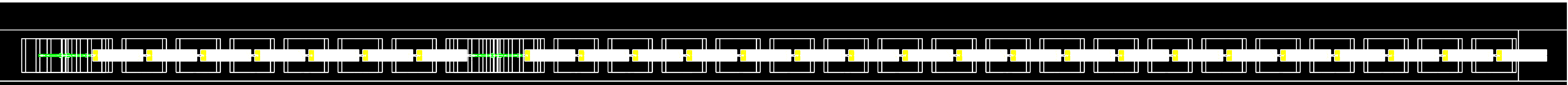
LCLS HXRSS: diamond is 2.5 mm from beam center

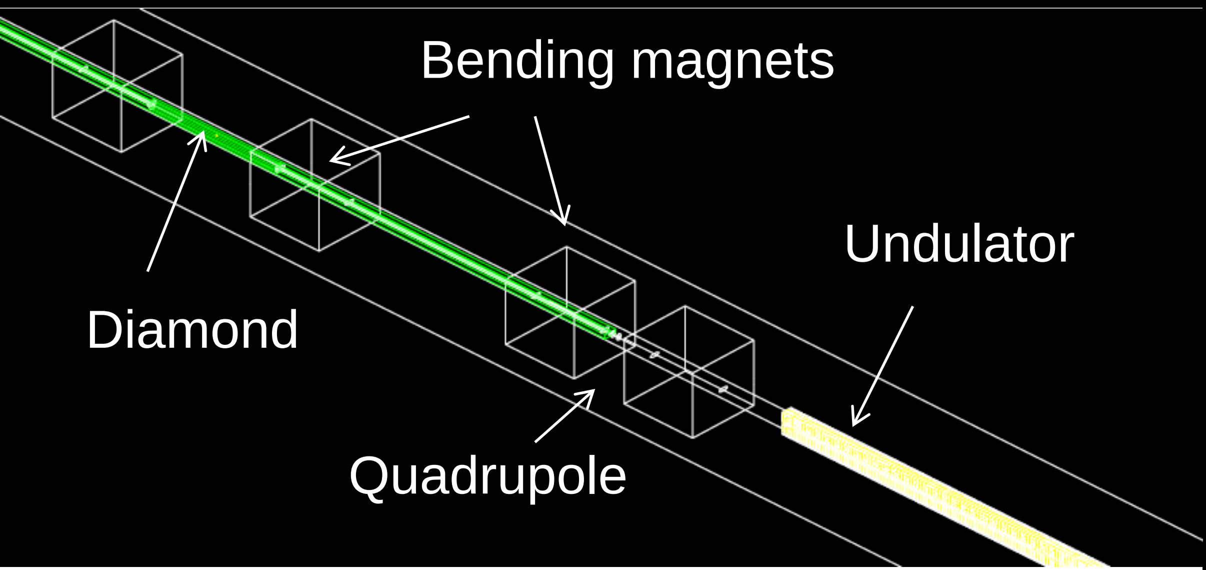


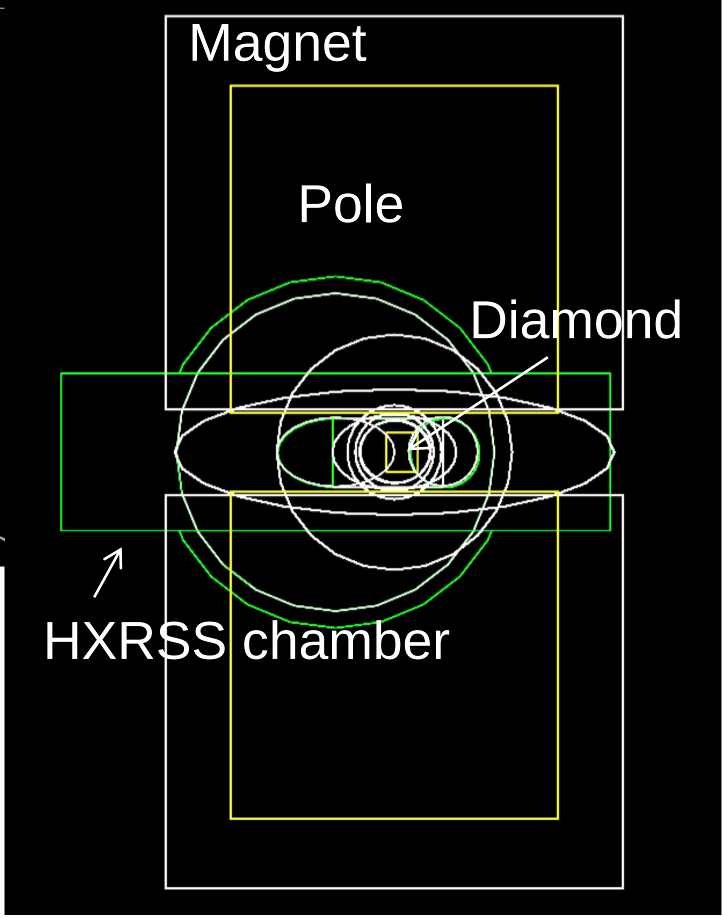
Seeding Power ⟷ VS ⟷ Undulator Damage

Undulator damage: GEANT4 simulations

- HXRSS+7 undulators+HXRSS+18 undulators





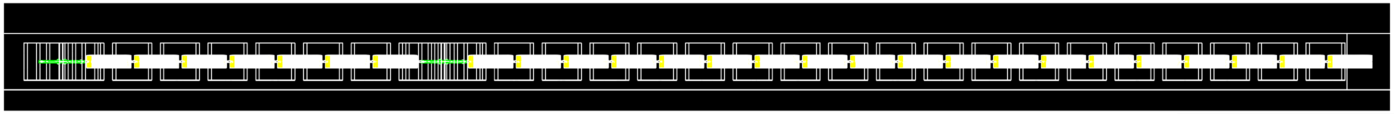


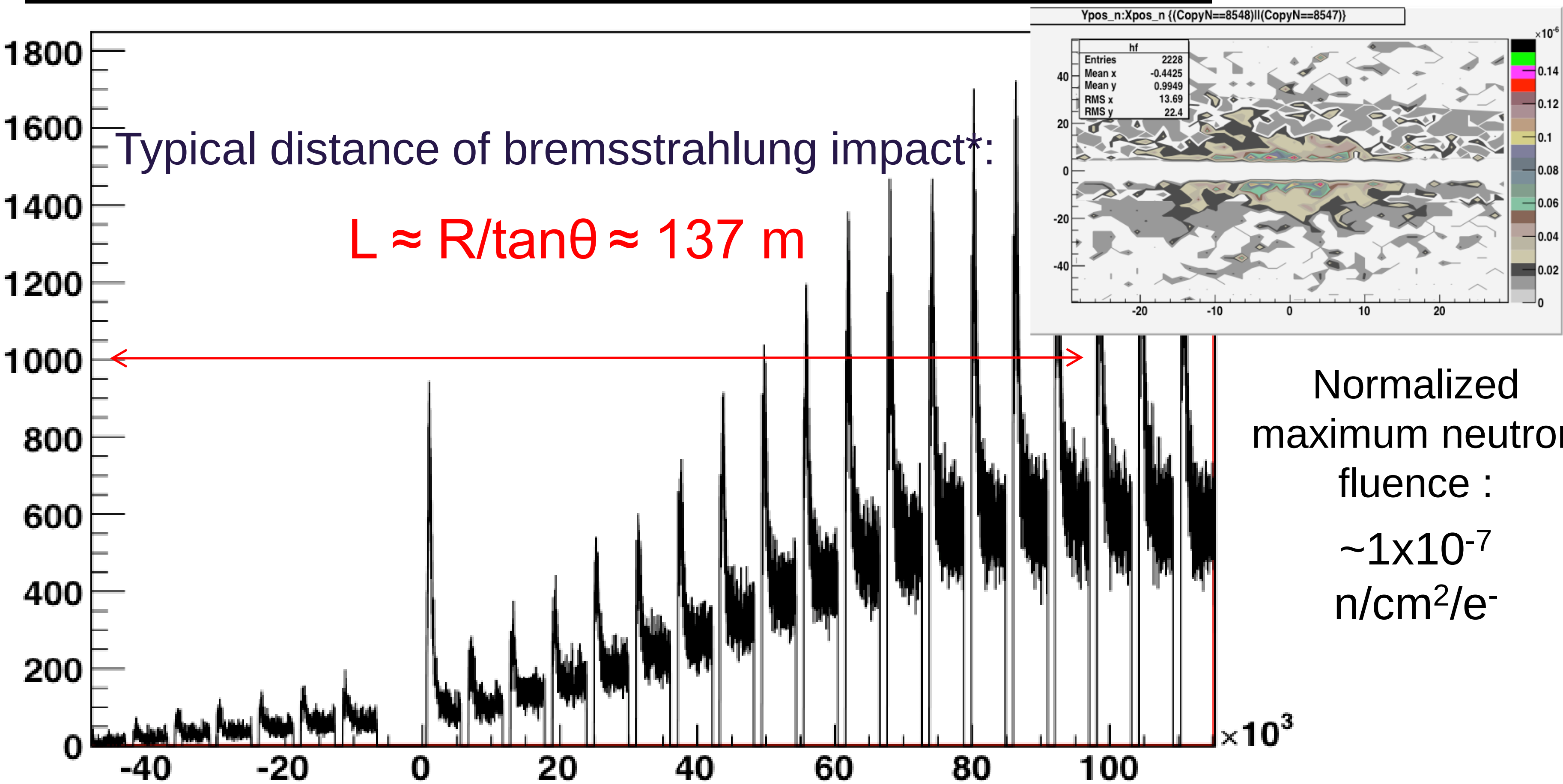
- Dipoles and quadruples are simplified as boxes with elliptical apertures

- Input beam: 10^6 e^- with 17.5 GeV energy hitting the crystal with 90° angle

European XFEL

Neutron fluence along undulator line





Typical distance of bremsstrahlung impact*:

$L \approx R/\tan\theta \approx 137$ m

Normalized maximum neutron fluence :

~$1\text{x}10^{-7}$ $n/cm^2/e^-$

* A. Fasso, Dose Absorbed in LCLS Undulator Magnets, I. Effect of a 100 µm Diamond Profile Monitor, RP-05-05, May 2005.

Critical number of electrons

- Maximum neutron flux allowed for 0.01 % demagnetization of Nd-Fe-B magnets: $1x10^{11}$ n/cm^2 *.
- Assuming 0.01% demagnetization in 20 years with 10 shifts (8 hours each) /month for HXRSS operation, the maximum allowed number of e$^-$ /bunch (with 27000 bunches/s):

$$N_{max} = 1x10^{11}/20x12x10x8x60x60x27000x10^{-7} \approx 5x10^5 \ e^-/bunch$$

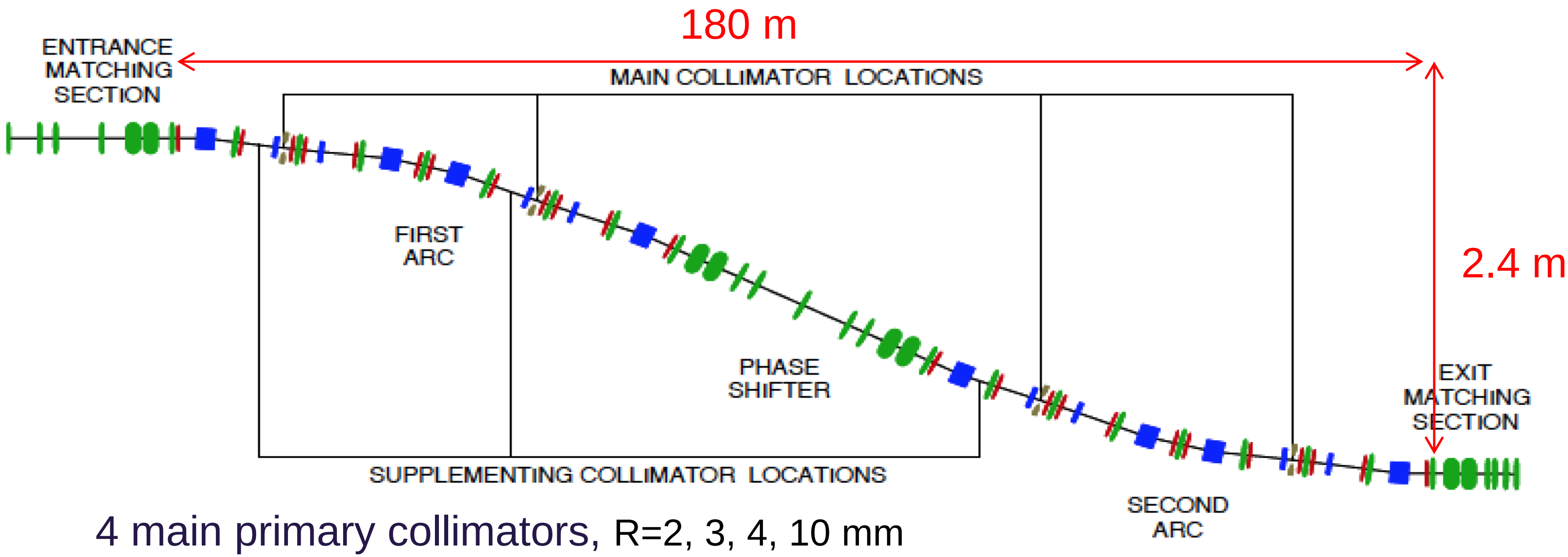
- Maximum charge per bunch: 1nC $\approx 6.25x10^9$ e$^-$/bunch
- Maximum horizontal beam size in undulator section: $\sigma_x \approx 50$ µm

If there is no halo, the crystal can enter as close as $\sim 4\sigma_x \approx 200$ µm to a gaussian beam core with above mentioned conditions!

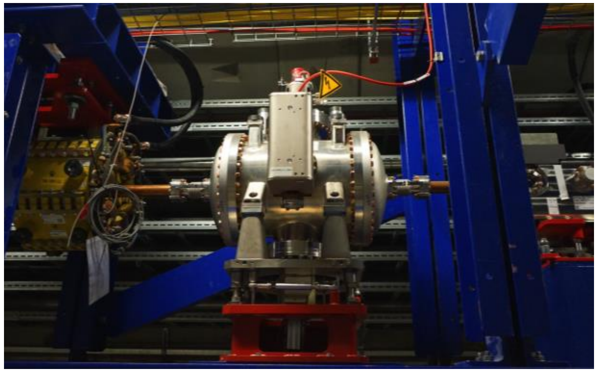
What if there is 100 σ_x of halo?

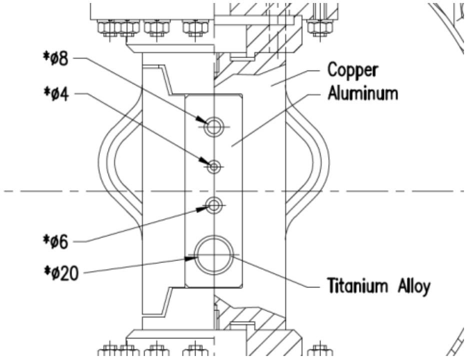
*M. Santana Leitner, et al, Radiation Protection Studies for LCLS Tune Up Dump, SLAC-PUB-14020, 2010.
*J. Alderman, P.K. Job, R.C. Martin, C.M. Simmons, G.D. Owen, and 0 J. Puhl, Radiation-Induced Demagnetization of Nd-Fe-B Permanent Magnets, Advanced Photon Source Report LS-290 (2000).

Collimation System Design

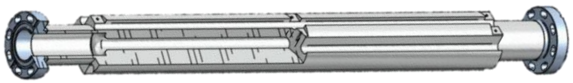


4 main primary collimators, R=2, 3, 4, 10 mm
(Titanium alloy+Aluminum+Copper)





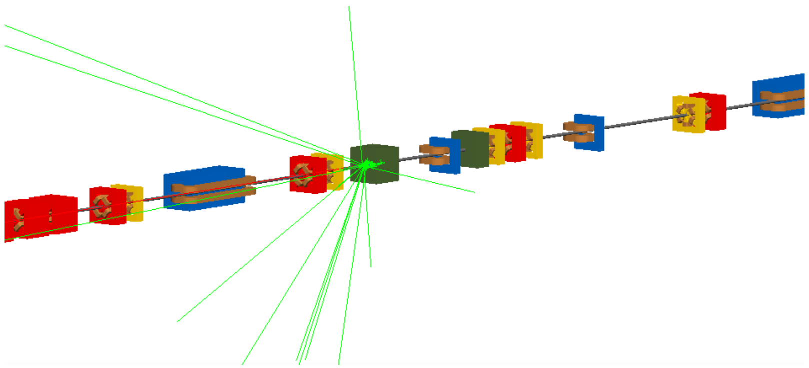
Supplementary collimator aperture: R=10 mm (Aluminum)

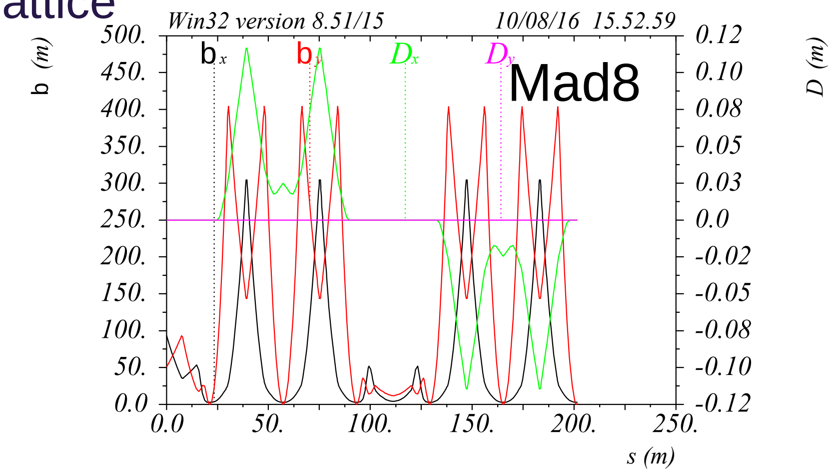


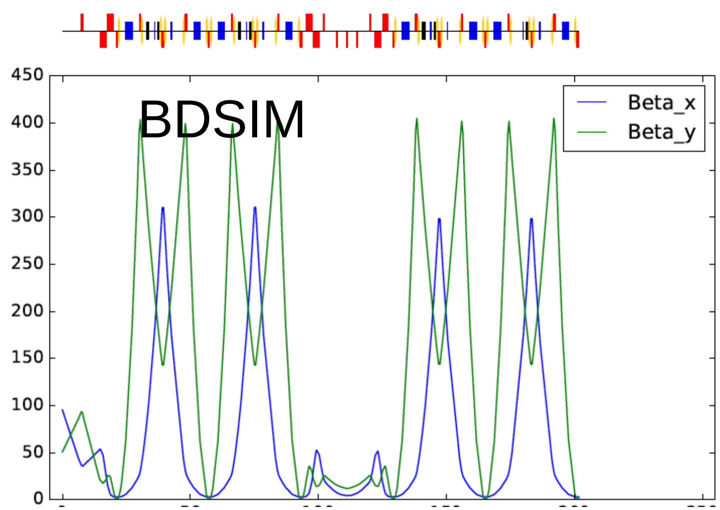
*** V.Balandin, R.Brinkmann, W.Decking, N.Golubeva, TESLA-FEL 2007-05**

Beam Delivery Simulation (BDSIM) and Optics Comparison

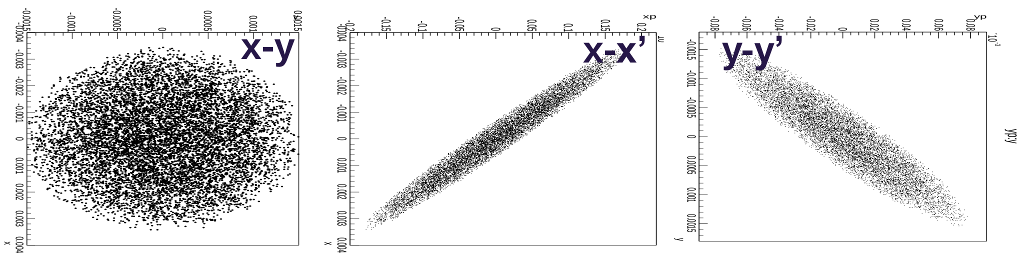
BDSIM*: GEANT4 simulation with accelerator lattice







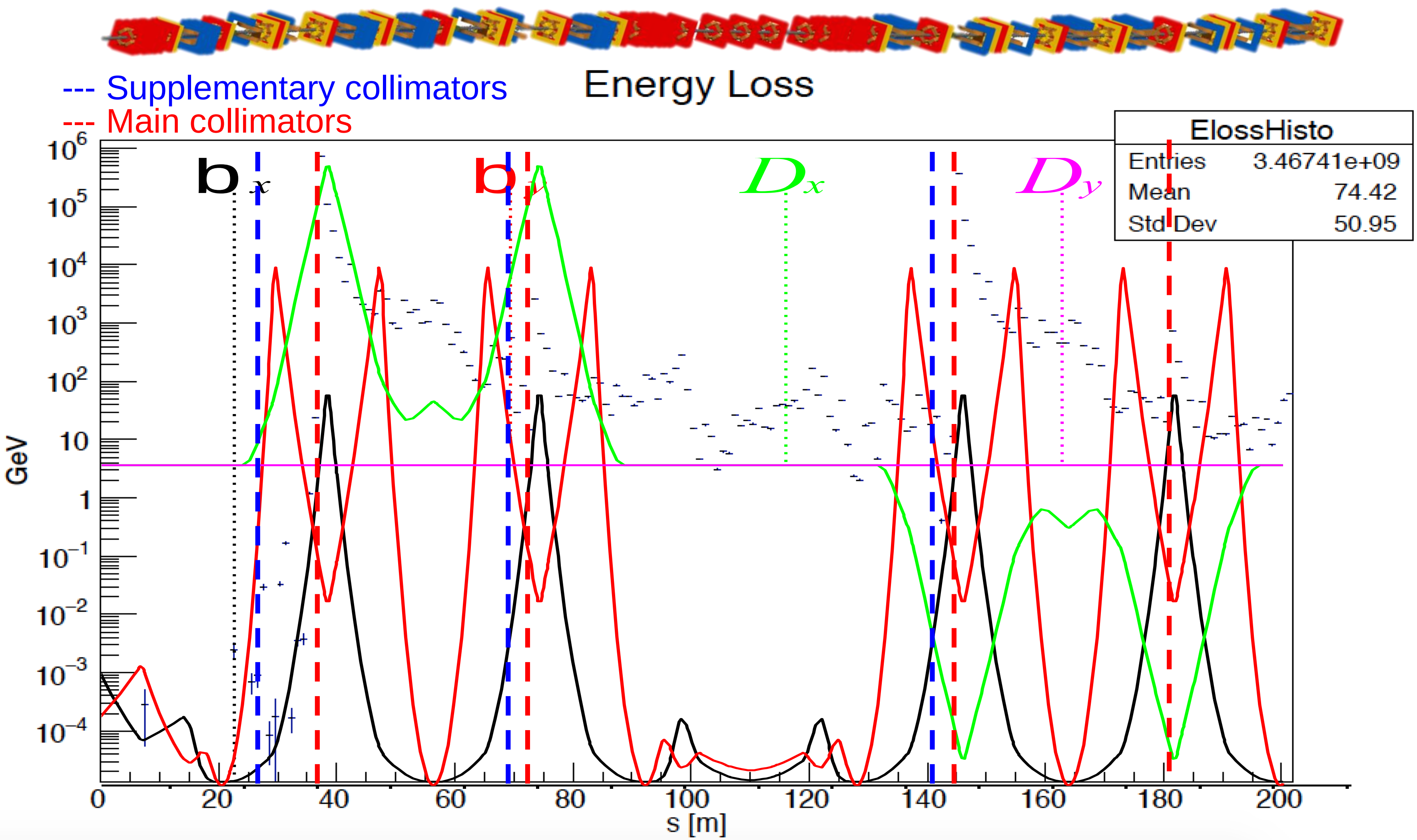
First simulations are performed with 10^5 e- with ±50σ uniform distribution in (x,x',y, y') phase space and with R=2 mm collimator aperture



- Effects from sextuples are not considered for the first simulations.
- X and Y coordinate are exchanged in the simulations.

*I. Agapov, et al, NIMA:606.3 (2009): 708-712.

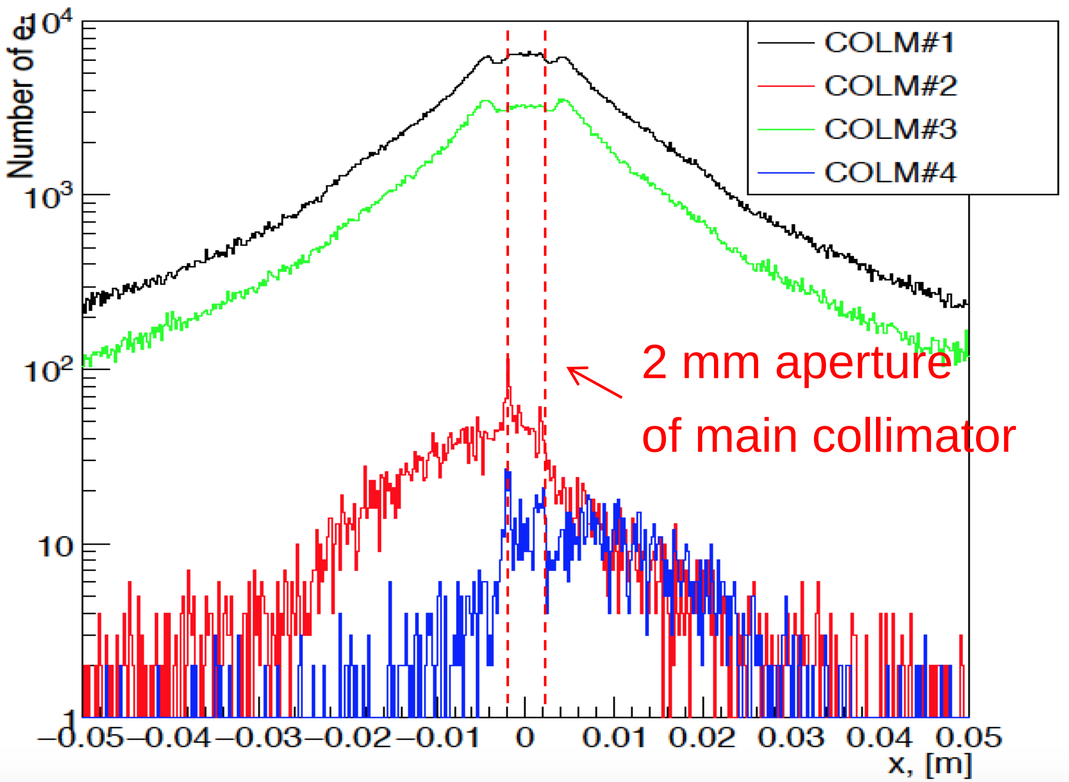
Energy loss along the collimation line



-> can be compared with the BLM measured results in the upcoming commissioning.

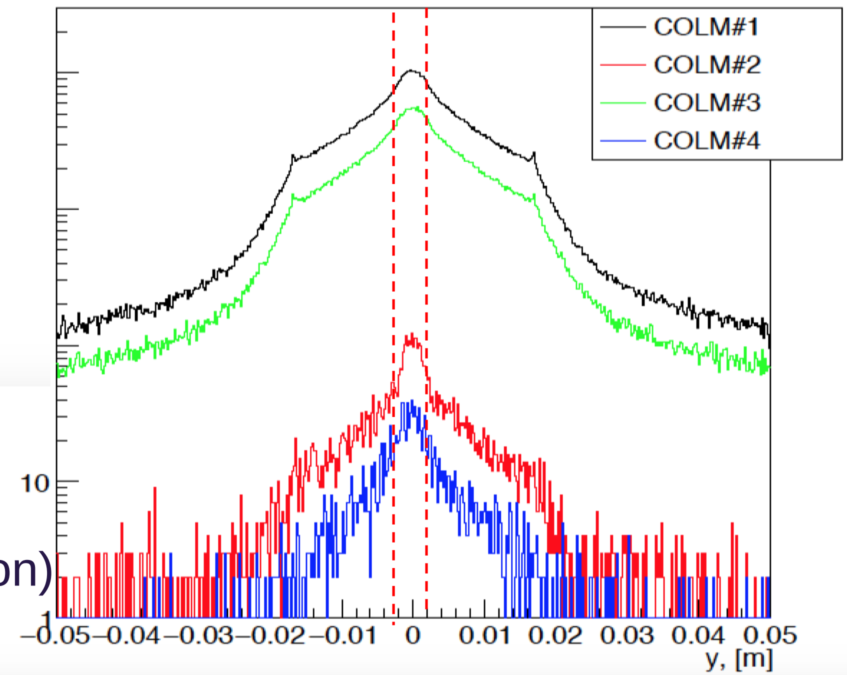
Secondary e- @ main collimators

Horizontal distribution



- Primary particles beyond 2 mm aperture are collimated mainly by the first main collimator in the two arcs: COLM#1 (black) and COLM#3 (green)

Vertical distribution

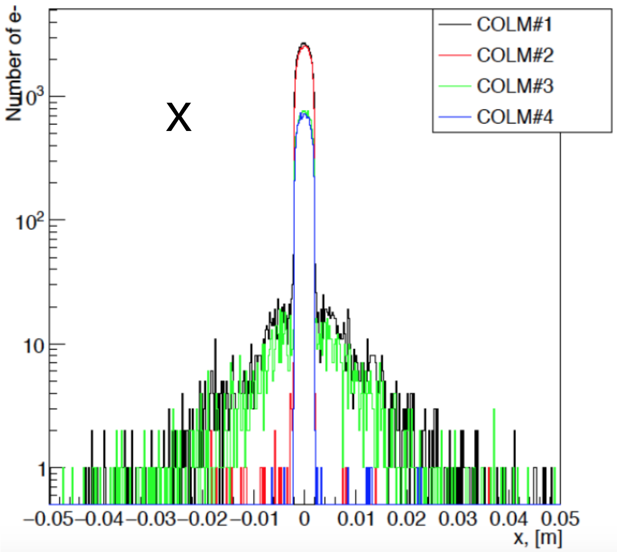


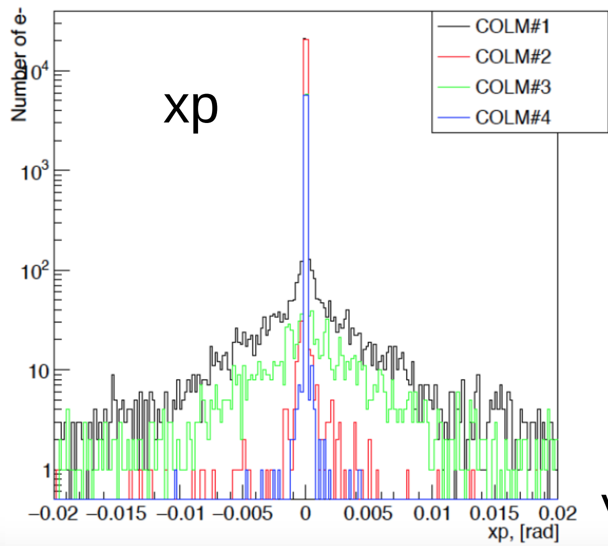
- Secondary particles and residual primary particles beyond 2 mm are collimated by COLM#2 and COLM#4 (the asymmetric distributions in x indicate the bending direction)

European XFEL

Primary e- distributions @ main collimators

Horizontal distribution

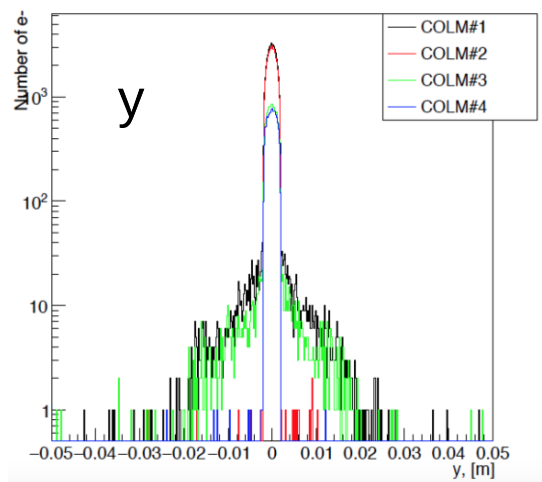


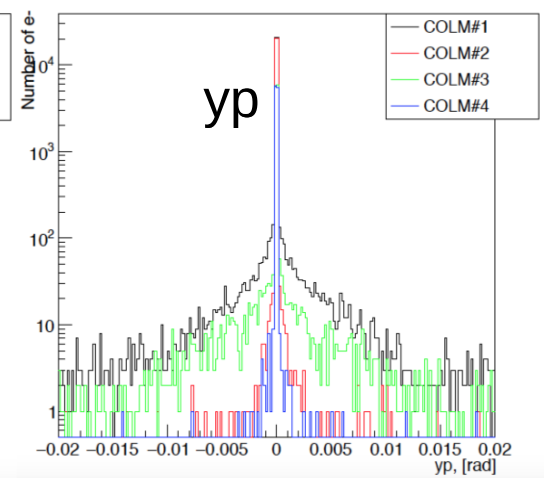


- Primary particles within ~ ± 20$\sigma_{x,xp}$ & ~ ±35$\sigma_{y,yp}$ can pass the collimators with 2 mm apertures freely;

Vertical distribution

- Almost no primary halo particles left beyond the 2 mm aperture after the 4th collimator-> in this case, **the crystal** can be inserted up to a distance of **~2 mm** to the beam core **(~13 fs of minimum delay)** !





European XFEL

Summary and discussions

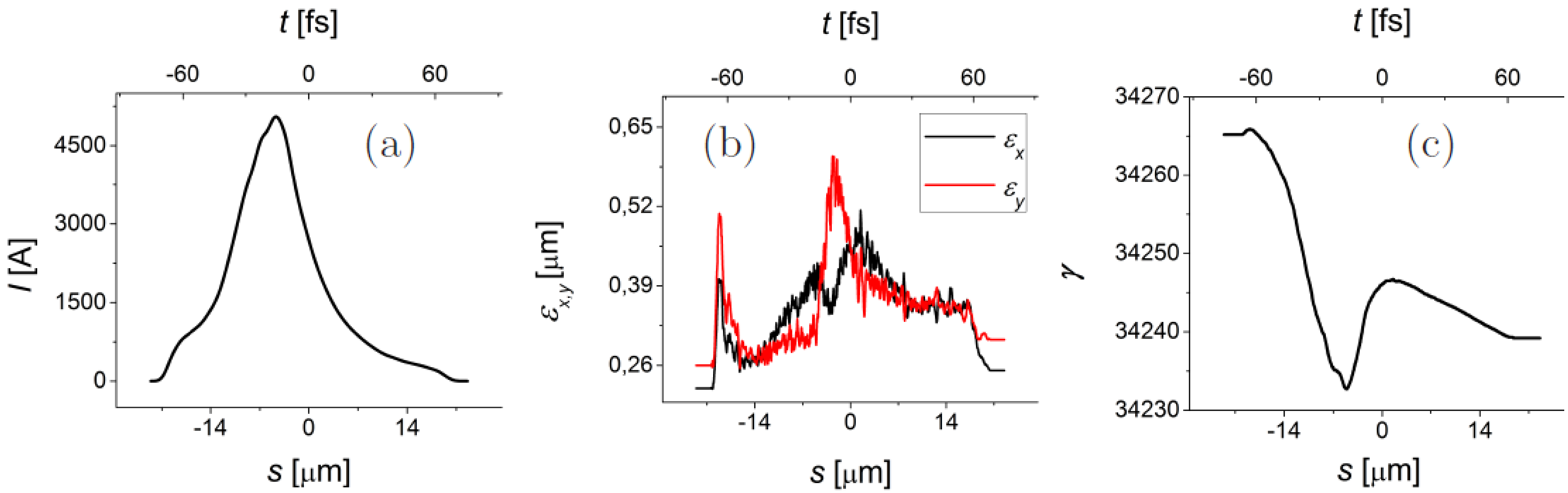
- HXRSS + tapering enable specific high-brightness applications -> simulations are on-going to finalize the location of the 2 HXRSS stages;
- Energy shift due to heat load on diamond -> can be compensated by pitch oscillator
- Issue of beam halo and radiation damage-> can be studied by simulations with different beam halo distributions and compared with beam loss/halo monitors measured results in the future -> **important for HXRSS**, **corrugated structure** with very small gaps (~1.4 mm planed at European XFEL) similar for LCLS-II.
- HXRSS project Schedule:
  - Present status: chicane (magnets, vacuum chamber, girder) and monochromator chamber design completed, components ordered
  - End 2016: final design of monochromator
  - End 2017: Two HXRSS mono ready for installation
  - 2018- Installation

Thank You!

- Thanks to I. Agapov, V. Balandin, W. Decking, G. Feng, L. Froehlich, G. Geloni, N.Golubeva et al. for helpful information and discussions!
- Thanks to colleagues from LCLS for sharing the HXRSS design and operation experiences!
- Thanks to S. Boogert and L. Nevay (RHUL) for the support on BDSIM!

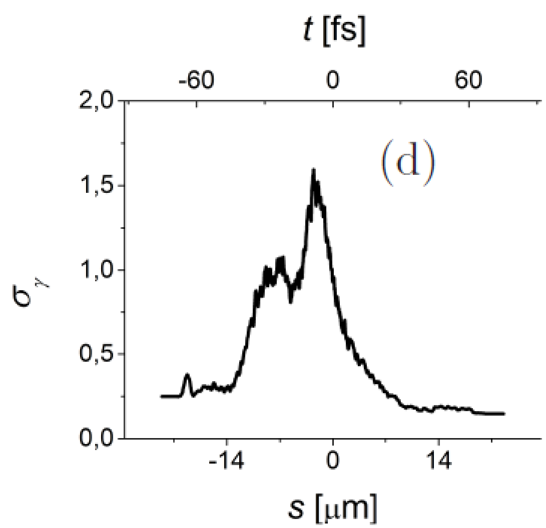
Back Up…

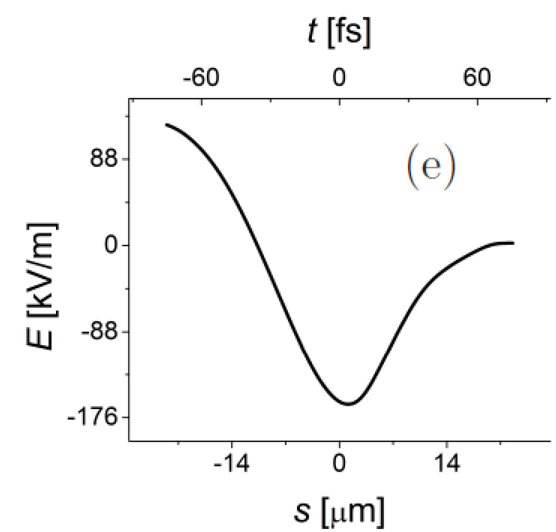
Ultra-High Resolution Inelastic X-ray Scattering UHRIX at 9 keV



Start-to-end simulations by the DESY/MPY Group

(Standard mode of operation of European XFEL at 250pC)

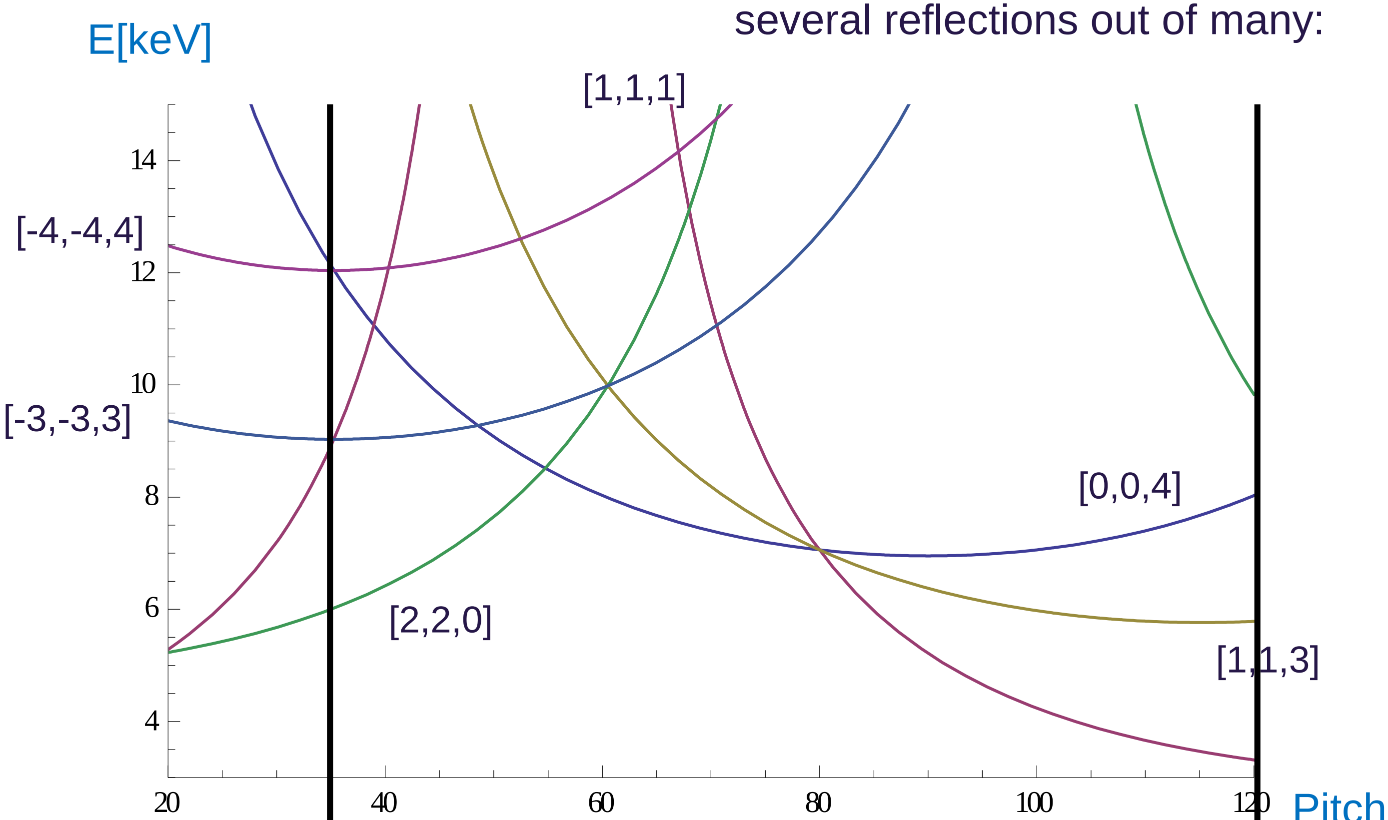




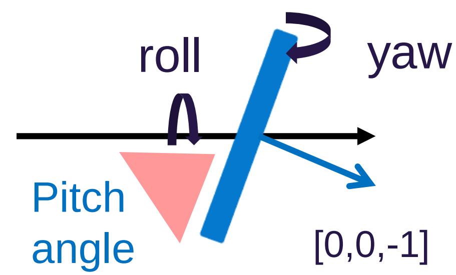
European XFEL

Energy Range and Reflections

We can cover the range from 3keV up to >12keV using only a several reflections out of many:



hkl	Min. Energy (keV)
111	3.01034
311	5.76401
400	6.95161
333	9.03035
444	12.0404



Min and Max Pitch
30deg-120deg
in 2 murad steps

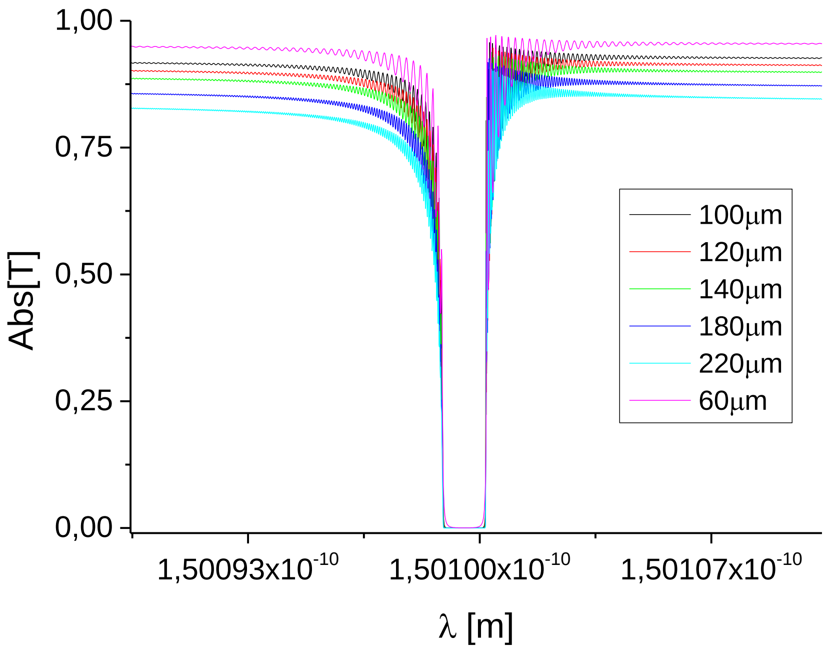
We should cover the FEL BW with +/- 3 degrees in yaw (and roll) with angular steps of 20murad

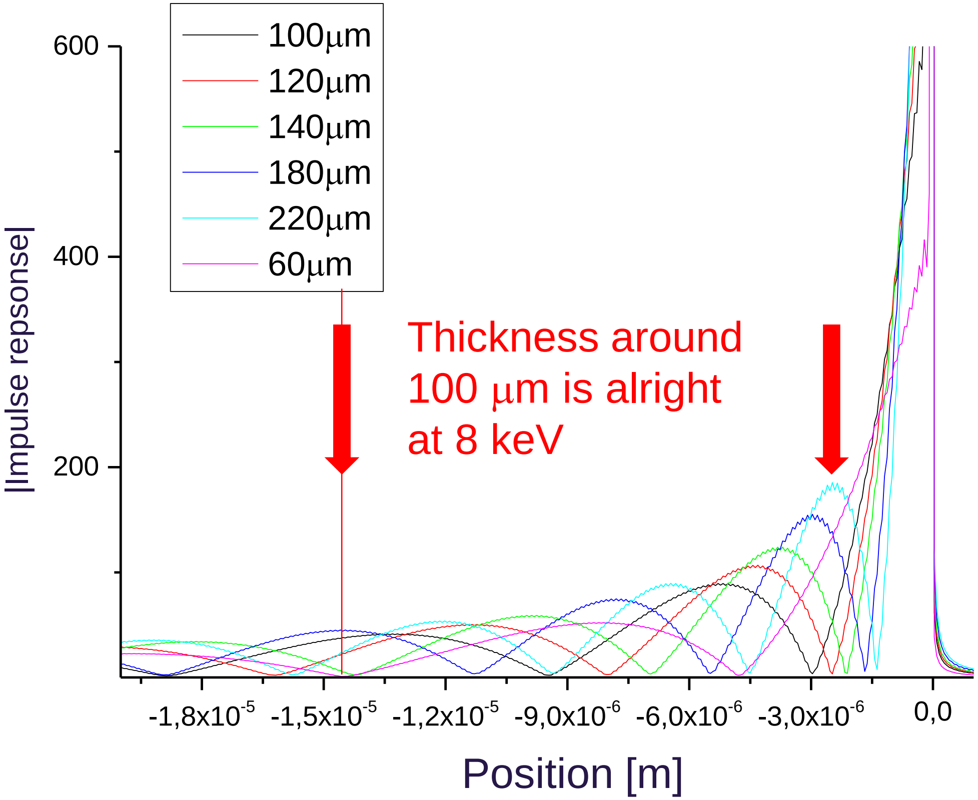
Courtesy of *G. Geloni*

Crystal Thickness

Courtesy of *G. Geloni*

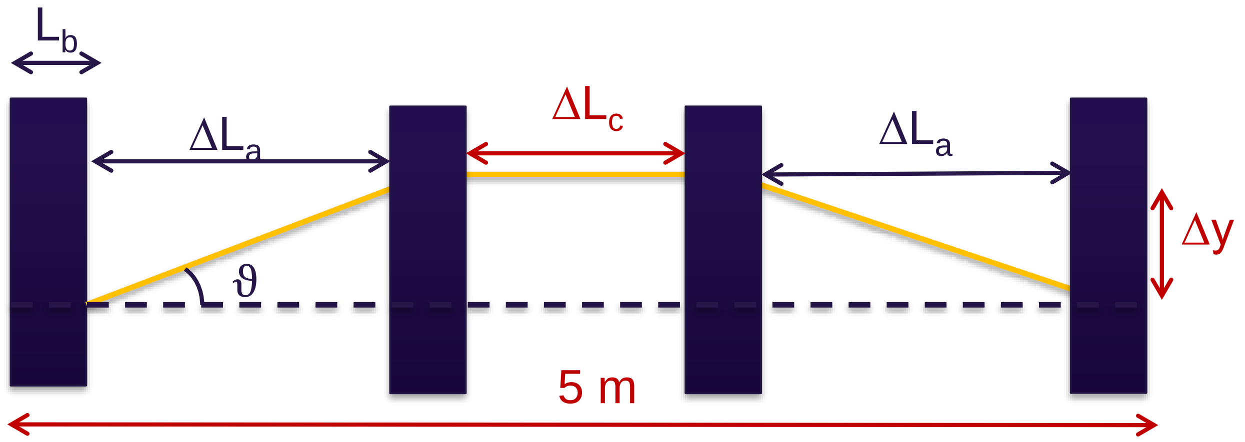
Thickness optimization relates to
1) **Crystal impulse response**
2) **Minimal delay achievable**
3) **Heat loading issues (due to absorption)**





C400 at 8.26keV

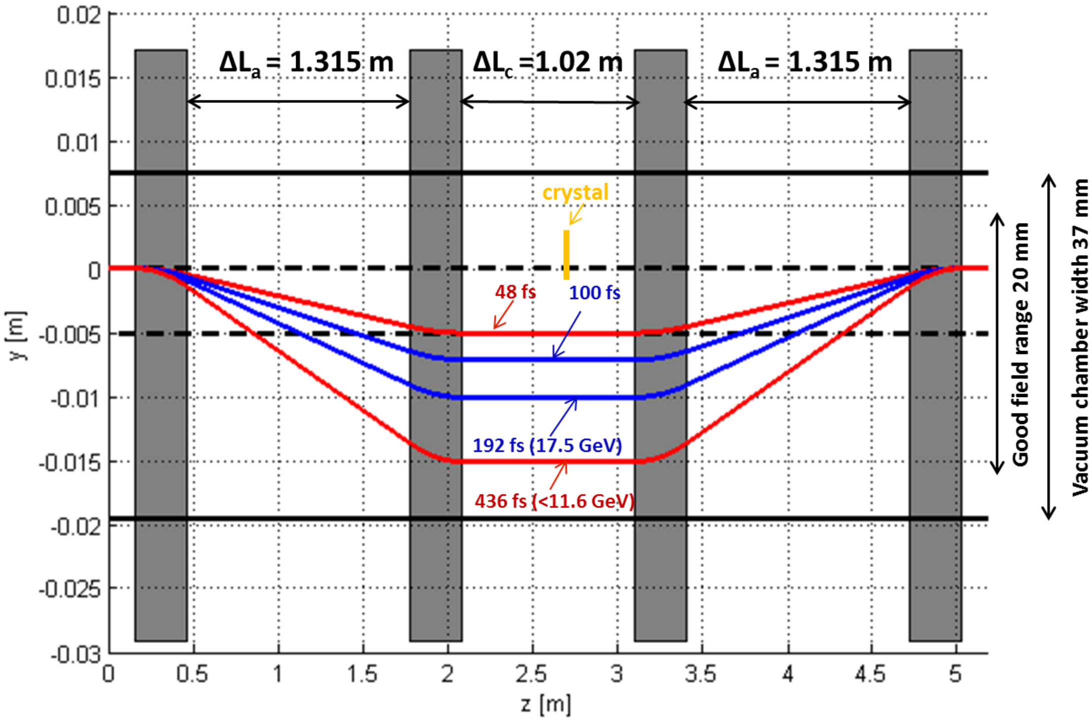
Chicane Design: Functions



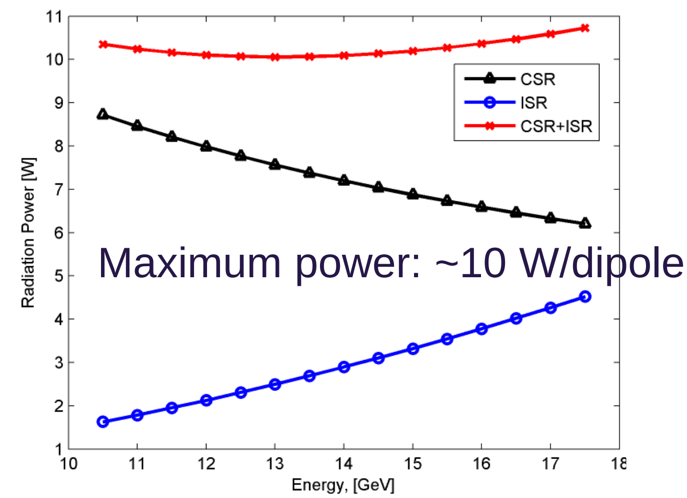
Functions of chicane:

- Create an offset between the electron bunch and the monochromator
- Wash out the SASE micro-bunching produced by the upstream undulators
- Produce an adjustable delay for the electron bunch to match the seed x-ray
- Correcting the phase error introduced by removing one undulator segment
- Scan the FEL photon pulse to obtain the length of the pulse
- Produce two color SASE pulses

Chicane Layout and Radiation Issues

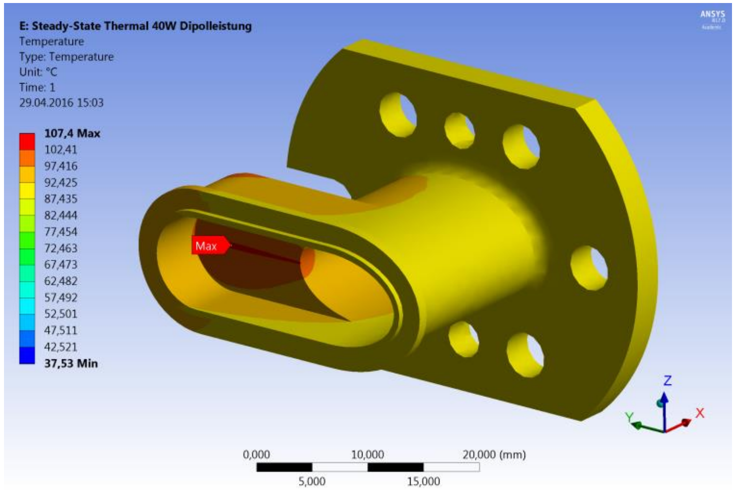


Radiation Power



Maximum power: ~10 W/dipole

Max. Temperature: 107 degree



- Worst case scenario with 27000 bunches with 1 nC at 17.5 GeV
- Planned operation far below the dump power threshold (300 kW) : max. 13500 bunches with1 nC at 17.5 GeV.
- Water cooling may be added

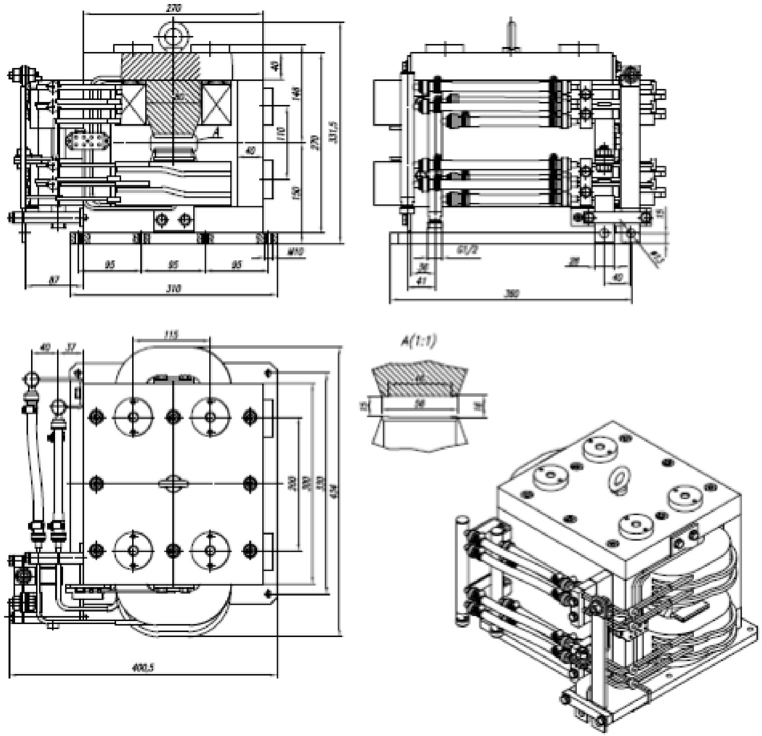
Chicane Main Parameters

Parameters*	Symbol	Normal	Minimum	Maximum	Unit
Electron beam delay	Δt	48.4 –100	0	192.2	fs
Electron beam offset	Δy	5 – 7.2	0	10	mm
Width of good field range	w_g	20	10	-	mm
Deflection angle	ϑ	3.1 – 4.4	0	6.2	mrad
R56	R_{56}	29 – 60	0	115.3	µm
Dipole field	B_0	0.60 – 0.87	0	1.2	T
Integrated field strength	$\int Bdl$	0.18 – 0.26	0	0.36	T·m
Magnet yoke length	L_b	0.3	-	-	m
Magnet vertical gap	g	16	-	-	mm
Vacuum chamber width	w	27	-	-	mm
Distance between outer and inner magnets	ΔL_a	1.315	-	-	m
Distance between inner magnets	ΔL_c	1.02	-	-	m
Nominal current	I	175	-	-	A

***Parameters for 17.5 GeV beam**

Chicane Design: Dipoles and Girder

Provided by B. Krause



TECHNICAL PARAMETERS

Basic parameters

PARAMETERS	VALUE
1. Magnetic field, T	1,2
2. Air gap height, mm	16
3. Yoke length, m	0,3
4. Integral field strength, Tm	0,36
5. Field quality ΔB/Bo (GFR– H8xW10)	≤±1x10 $^{-3}$

Excitation parameters

PARAMETERS	VALUE	
	Main winding	Correcting winding
1. Nominal current, A	175	10
2. Nominal voltage , V	10,3	1,1
3. Resistance (t=293 K), Ohm	0,059	0,11
4. Operation mode – continuous		

Winding parameters

PARAMETERS	VALUE	
	Main winding	Correcting winding
1. Number of coils per magnet	2	2
2. Number of turns per coil	48	21
3. Number of turns per magnet	96	42
4. Average turn length, m	0,92	0,91
5. Conductor dimensions, mm	6x6–Ø3,5	1,8x3,55/1,9x3,65
6. Conductor cross–section area, mm²	25,8	6,03
7. Static inductance at nominal current, H	0,021	
8. Electrical strength of coil system, kV	2,0	

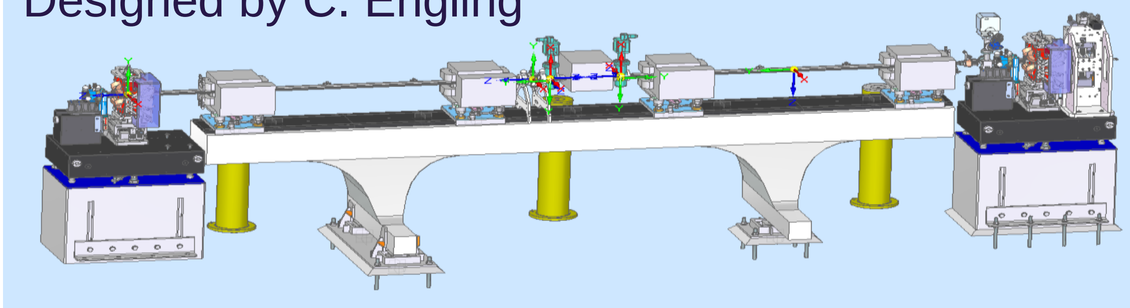
Cooling parameters

PARAMETERS	VALUE
1. Water overheating, °C	6,5
2. Cooling water pressure drop, MPa (bar)	0,4(4)
3. Cooling water requirements, l/min	4,1
4. Number of cooling circuits	4

Weight

PARAMETERS	VALUE	
	Main winding	Correcting winding
1. Yoke steel weight, kg	116	
2. Winding copper weight, kg	20,4	2,2

Designed by C. Engling

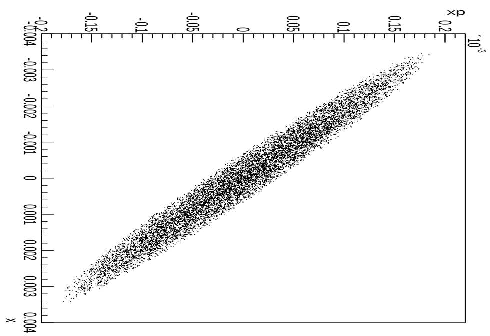


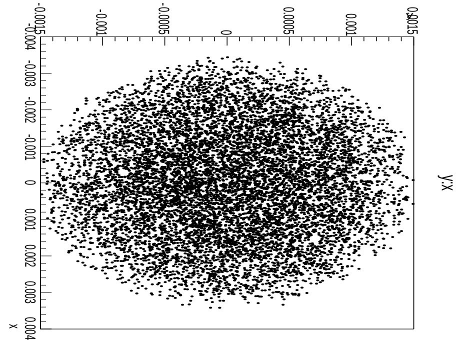
- 8 H-type dipole magnets will be delivered in March 2017
- Girder design completed -> ordered for fabrication

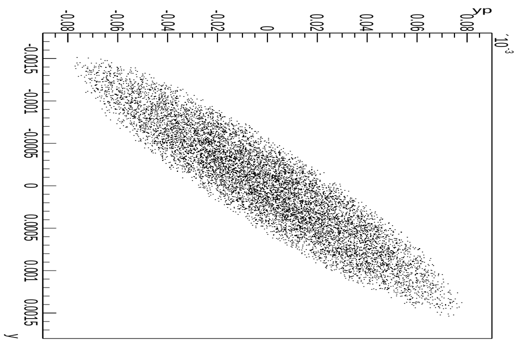
European XFEL

Input electron beam distribution

uniform distributions







betx=93.554;
bety=50.482;
alfx=4.857;
alfy=-2.389;
ex=2*Nsig*5.31e-11;
ey=2*Nsig*1.89e-11;
deltaE/E=1.5%.

- The Courant-Snyder invariant can be expressed as:

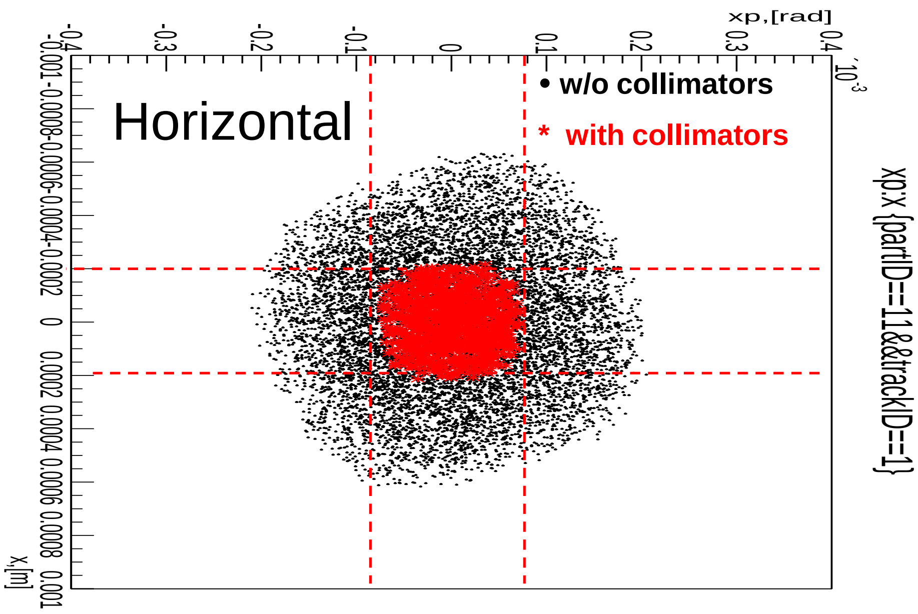
$$\tilde{x}^2 + \tilde{x}'^2 = \gamma x^2 + 2\alpha x x' + \beta x'^2 = \frac{\varepsilon}{\pi}$$

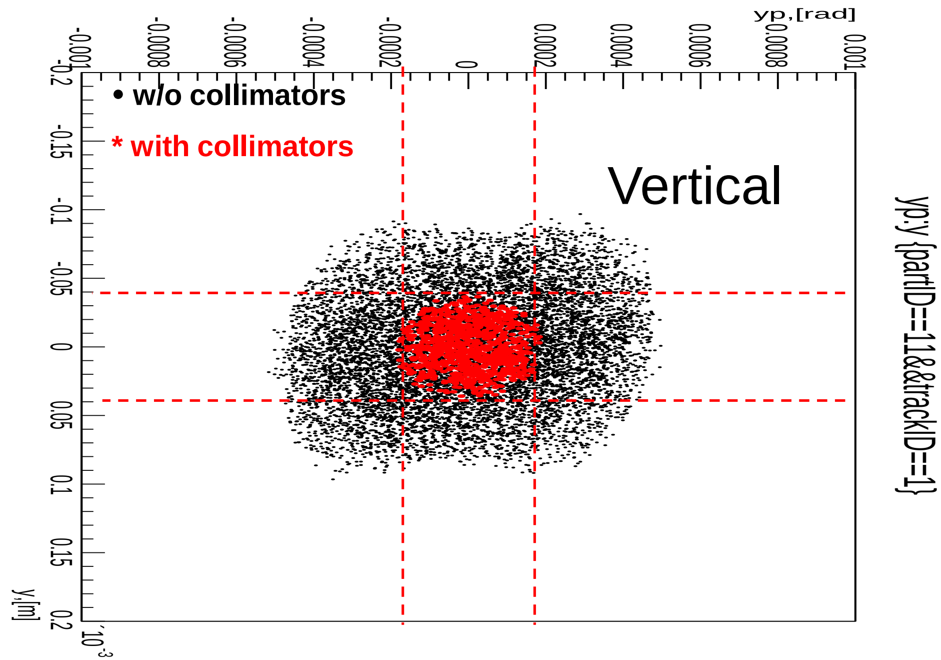
with the normalized variables:

$$\tilde{x} = \frac{x}{\sqrt{\beta}} \text{ and } \tilde{x}' = \frac{d\tilde{x}}{d\phi} = \sqrt{\beta}x' + x\frac{\alpha}{\sqrt{\beta}},$$

$(\tilde{X}, \tilde{X}')$ and $(\tilde{Y}, \tilde{Y}')$ are enlarged by N times with uniform distributions.

Phase space @ end of collimation section



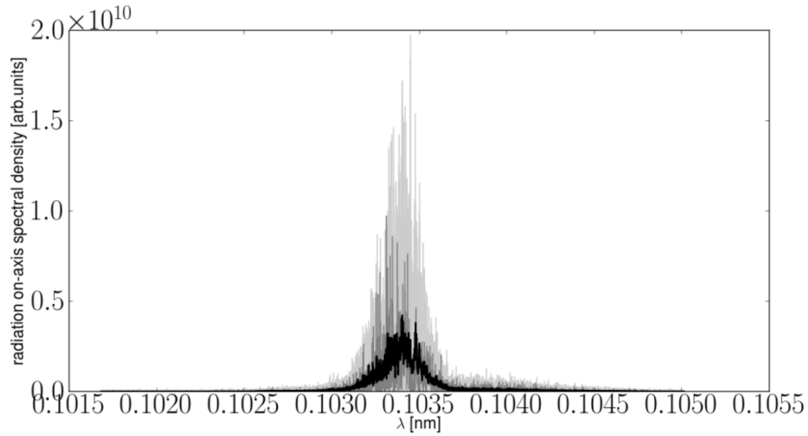


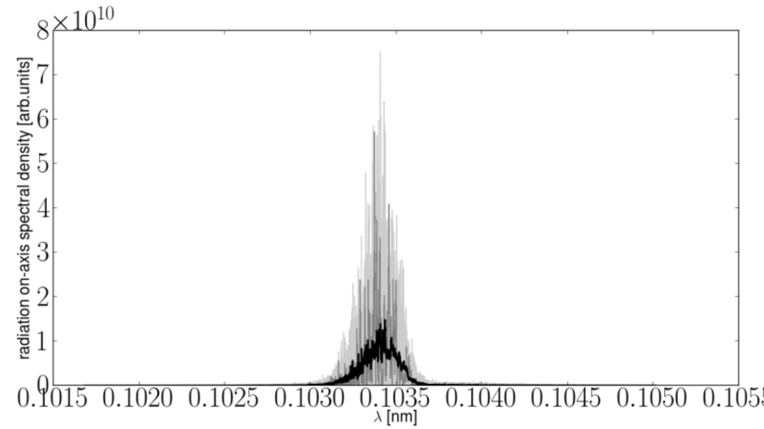
* Keep in mind that horizontal and vertical planes are exchanged in the simulation

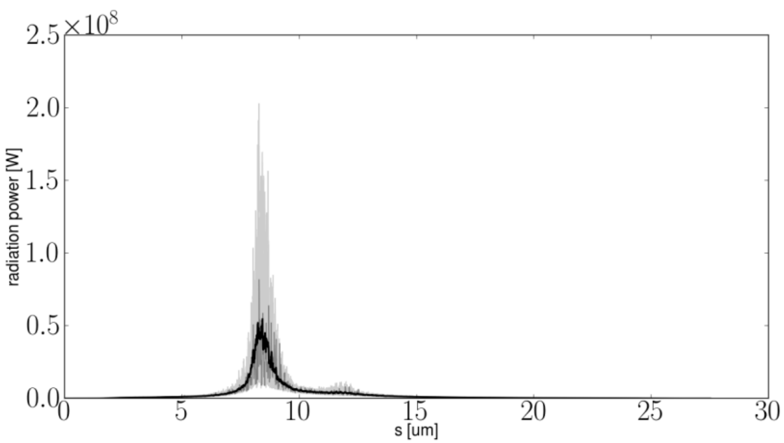
100pC – 17.5 GeV – C004 – 12keV – 1st stage

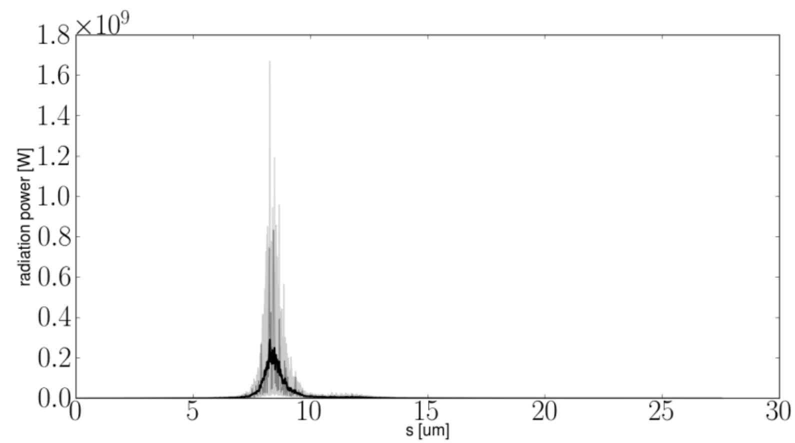
Cascade 5 + 5

Cascade 6 + 6









100pC – 17.5 GeV – C004 – 12keV – 3rd stage

Cascade 5 + 5

Cascade 6 + 6