First studies of crystal collimation for the FCC-ee

G. Broggi[1,2,3], A. Abramov[2], M. Boscolo[3], R. Bruce[2], D. Mirarchi[2], S. Redaelli[2]

[1] Sapienza University of Rome, Italy
[2] CERN, Meyrin, Switzerland
[3] INFN-LNF, Frascati, Italy

Channeling 2024 – Riccione, Italy, 09/09/2024

Many thanks to:

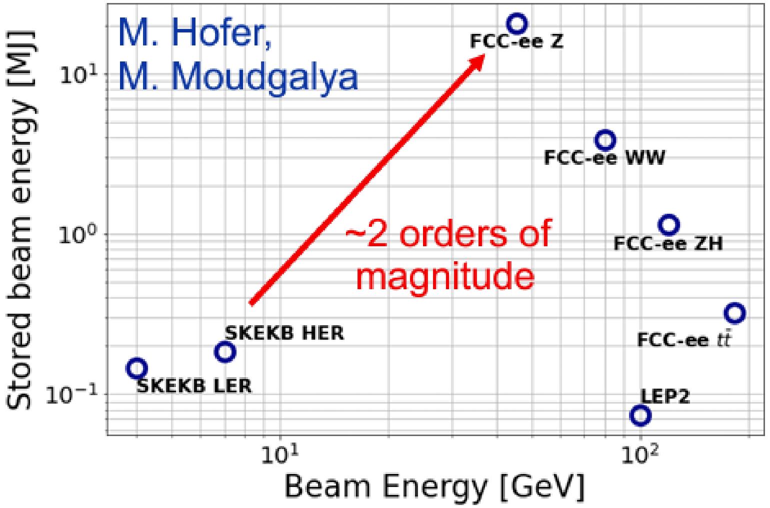
L. Bandiera, B. Lindstrom, L. Nevay, F. Zimmermann

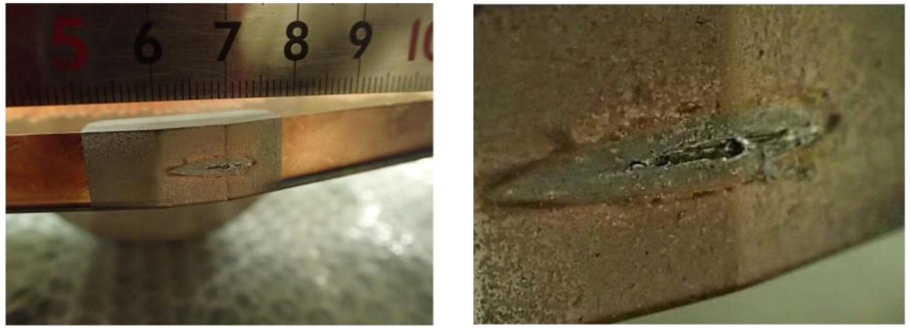
Collimation for the FCC-ee

- **FCC-ee is the FCC first stage e⁺e⁻ collider**
  - 90.7 km circumference, tunnel compatible with FCC-hh
  - 4 beam operation modes, optimized for production of different particles: ***Z*** (45.6 GeV), ***W*** (80 GeV), ***H*** (120 GeV), ***ttbar*** (182.5 GeV)

- **FCC-ee presents unique challenges**
  - Unprecedented stored beam energy for a lepton collider: up to **17.5 MJ** in the ***Z*** operation mode (45.6 GeV)
  - Highly destructive beams: **collimation system indispensable**
  - The main roles of the collimation system are:
    - Reduce background in the experiments
    - Protect the machine from unavoidable losses
  - Two types of collimation currently foreseen for the FCC-ee:
    - **Beam halo (global) collimation**
    - Synchrotron Radiation (SR) collimation – around the IPs
    - Tertiary collimators for local protection and particle shower absorbers under study

Comparison of lepton colliders

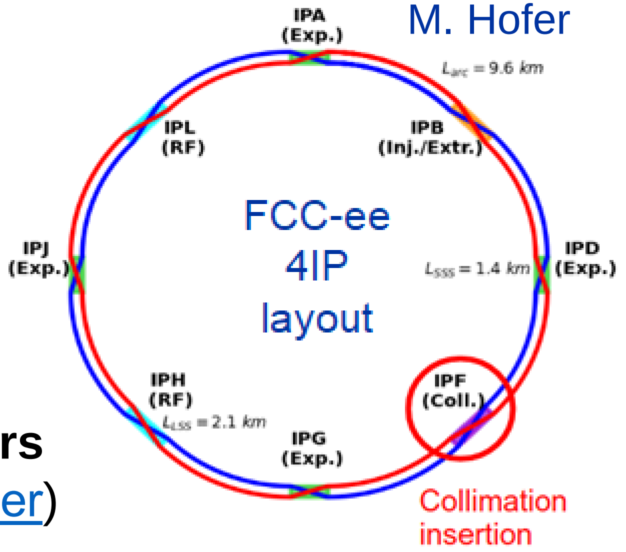




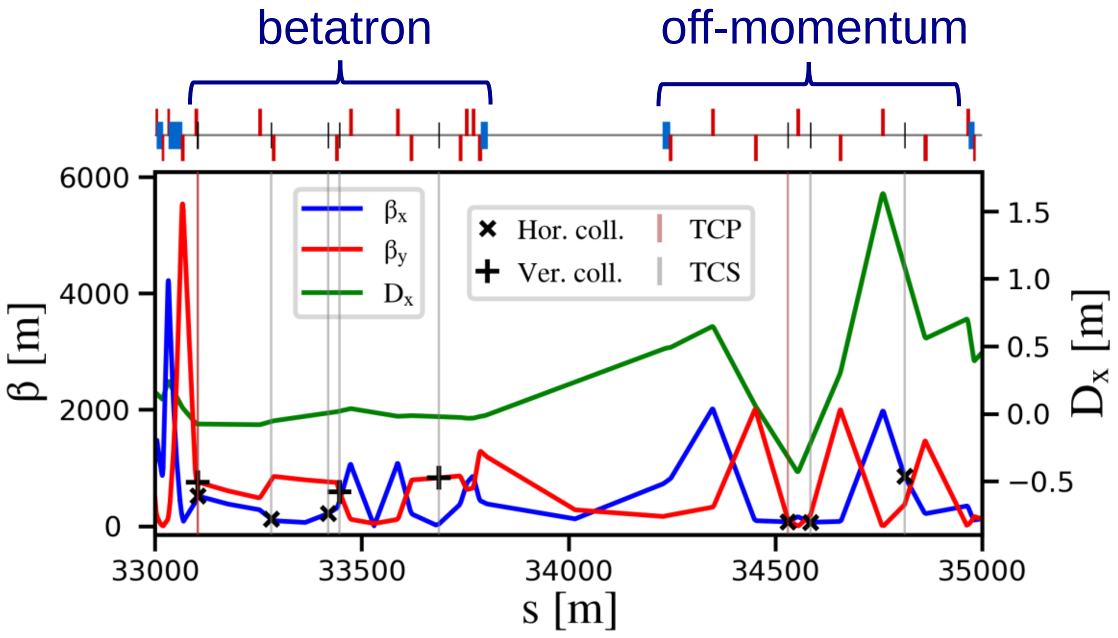
Damage to coated collimator jaw due to accidental beam loss in the SuperKEKB – T. Ishibashi (talk)

FCC-ee halo collimation system

- **Dedicated halo collimation system in PF**
  - ➢ Dedicated collimation optics (M. Hofer)
  - ➢ Two-stage betatron and off-momentum collimation system in one insertion
  - ➢ Ensure protection of the aperture bottlenecks in different conditions
    - ➢ **Aperture bottleneck at *Z***: 14.6σ (H plane), 84.2σ (V plane)
  - ➢ First collimator design for cleaning performance – relies on **amorphous collimators**
    - ➢ Ongoing studies for optimizing the collimator design (G. Broggi – IPAC'24 paper)



M. Hofer



FCC-ee *Z* V23, tridodo_572 collimation optics

FCC-ee beam halo collimator parameters and settings (*Z* mode)

Name	Plane	Material	Length [cm]	Gap [σ]	Gap [mm]	δ_{cut} [%]
TCP.H.B1	H	MoGr	25	11	6.7	8.9
TCP.V.B1	V	MoGr	25	65	2.4	-
TCS.H1.B1	H	Mo	30	13	3.8	6.7
TCS.V1.B1	V	Mo	30	75	2.5	-
TCS.H2.B1	H	Mo	30	13	5.1	90.6
TCS.V2.B1	V	Mo	30	75	3.0	-
TCP.HP.B1	H	MoGr	25	18.5	4.2	1.3
TCS.HP1.B1	H	Mo	30	21.5	4.6	2.1
TCS.HP2.B1	H	Mo	30	21.5	16.8	1.6

Further materials will be studied in the future

Crystal collimation for the FCC-ee: motivation

- As an alternative to the baseline design relying on amorphous collimators, crystal collimation is also being explored:

Cleaning efficiency

Angular deflection by bent crystals increases the impact parameter of beam halo particles on the absorbers (secondary collimators)

Impedance

Short (sub-mm) bent crystals in place of tens of cm long amorphous primary collimators

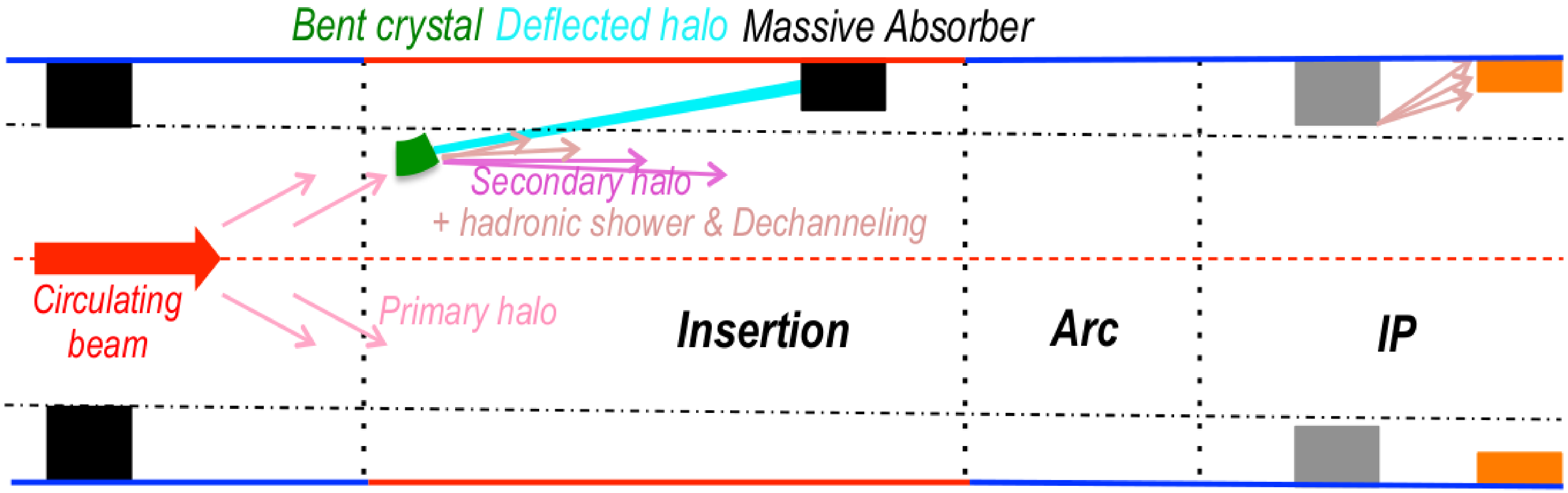
Potentially larger absorber (secondary collimator) mechanical gaps

Power deposition on collimators

Short (sub-mm) bent crystals in place of tens of cm long amorphous primary collimators

Potentially increase beam halo spot size at the absorbers employing bent crystals

Power deposition on absorber could still be challenging



Working principle of a crystal collimation system
D. Mirarchi, PhD thesis

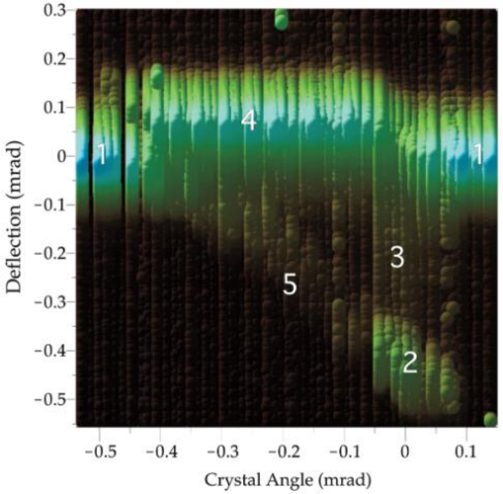
Crystal collimation for the FCC-ee: first considerations

- Particle steering exploiting channeling in bent crystals more challenging for q<0
    - First focus on e- crystal collimation exploiting planar channeling in Si (111) plane
    - Studies extended to e+ crystal collimation

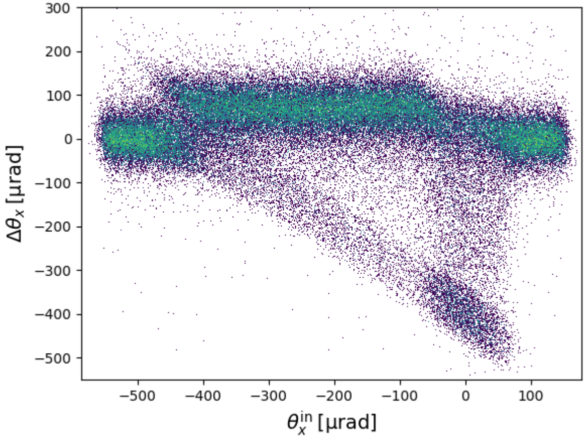
- First checks to identify possible show-stoppers
    - Beam divergence at crystal candidate location in the FCC-ee vs. critical angle
    - Crystal bending angle needed to deeply impact an absorber downstream
    - Crystal bending radius vs. critical bending radius

- First bent crystal parameters based on **optimization of channeling efficiency through channeling simulations**:
    - Geant4 (10.4.03) crystal channeling routine through the BDSIM simulation toolkit
    - Crystal data from E. Bagli, G4_MC_CHANNELING Git repository
    - Good agreement with exp. results – efficiencies agreement within few % (e.g., U. Wienands *et al.*, Observation of Deflection of a Beam of Multi-GeV Electrons by a Thin Crystal)
- **First collimation tracking simulations** with selected bent crystal parameters

experiment

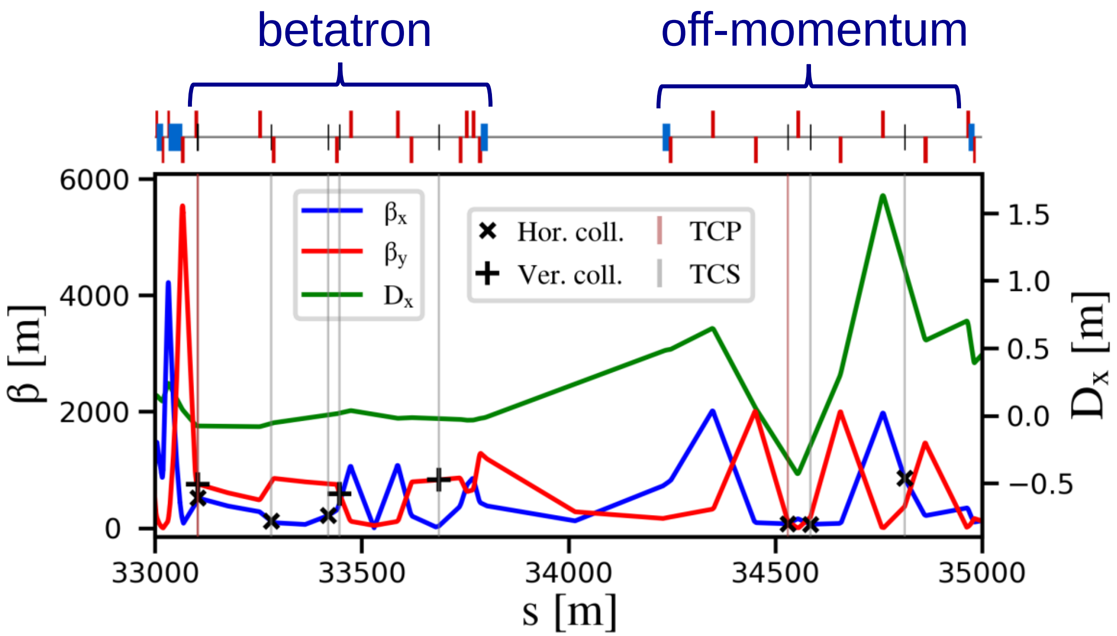


simulation (BDSIM)



Crystal candidate location: FCC-ee *Z* mode

- **Current locations of FCC-ee primary betatron collimators** (TCPs) chosen as crystal candidate locations
- At such locations: $\begin{cases} \text{relatively high } \beta\text{-functions} \leftrightarrow \text{large beam sizes} \leftrightarrow \text{large collimator half-gaps} \\ \text{small Twiss } \alpha\text{-functions} \leftrightarrow \text{small beam divergence} \end{cases}$



FCC-ee *Z* V23, tridodo_572 collimation optics

FCC-ee beam halo collimator parameters and settings

Name	Plane	Material	Length [cm]	Gap [σ]	Gap [mm]	δ_{cut} [%]
TCP.H.B1	H	MoGr	25	11	6.7	8.9
TCP.V.B1	V	MoGr	25	65	2.4	-
TCS.H1.B1	H	Mo	30	13	3.8	6.7
TCS.V1.B1	V	Mo	30	75	2.5	-
TCS.H2.B1	H	Mo	30	13	5.1	90.6
TCS.V2.B1	V	Mo	30	75	3.0	-
TCP.HP.B1	H	MoGr	25	18.5	4.2	1.3
TCS.HP1.B1	H	Mo	30	21.5	4.6	2.1
TCS.HP2.B1	H	Mo	30	21.5	16.8	1.6

- **TCP.H.B1** and **TCP.V.B1** might be replaced by **bent crystals**
- Absorber candidate locations are the same as secondary collimators (TCSs): phase advance is optimal

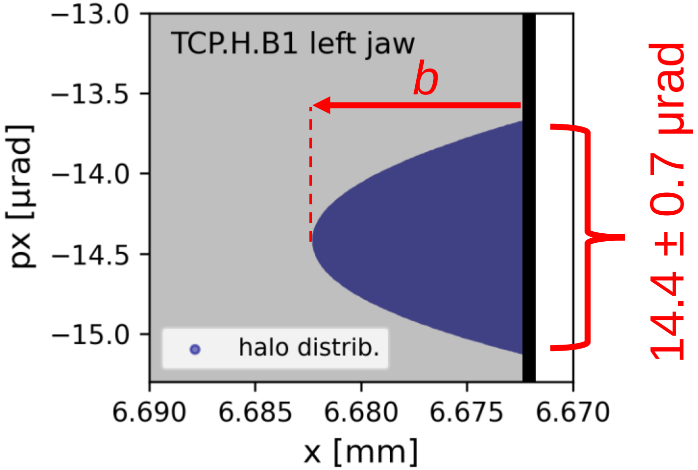
Divergence at crystal location and critical angle

- $\theta_c = \sqrt{\frac{2U_0}{pv}} \approx \sqrt{\frac{2U_0}{E}}$

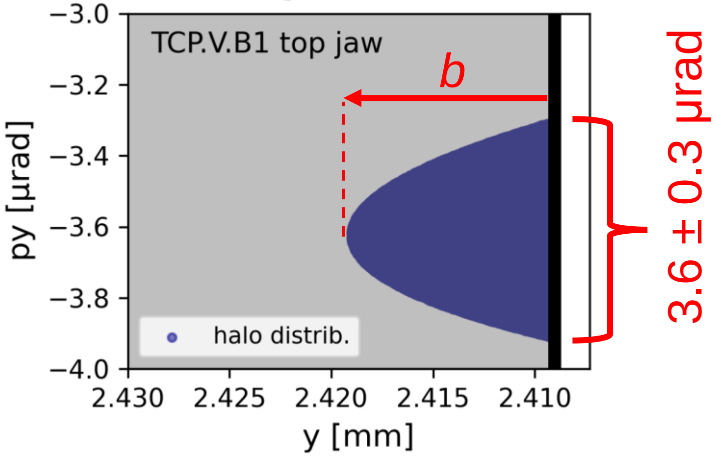
U_0: potential well depth of the planar/axial channel [eV]
E: particle energy [eV]

- Angular spread of a beam halo distributions with impact parameter b=10 µm at crystal candidate locations:

H plane



V plane



FCC-ee *Z* mode (*E* = 45.6 GeV)

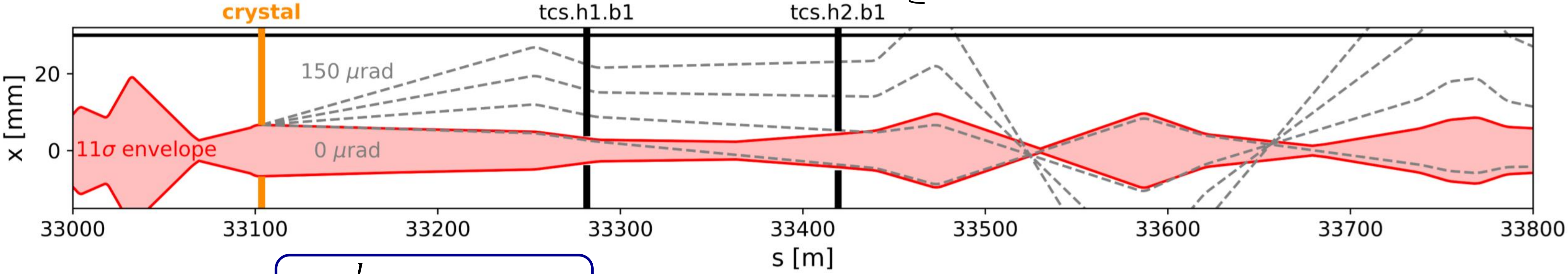
Si planar channel	U_0 [eV]	θ_c [µrad]
(111)	25.6	33.5
(110)	22.8	31.6
(100)	12.9	23.8

NOTE: At the highest FCC-ee beam energy of 182.5 GeV (*ttbar* mode) the critical angles reduce by about a factor 2 w.r.t FCC-ee Z beam energy

NO show stoppers identified

Crystal bending angle, bending radius and length

- First focus on H plane – the study will then be extended to the V plane
- Different **bending angles** scanned (50 µrad, 100 µrad, 150 µrad) – maximize impact parameter on absorber; safety margin w.r.t mechanical aperture (30 mm)

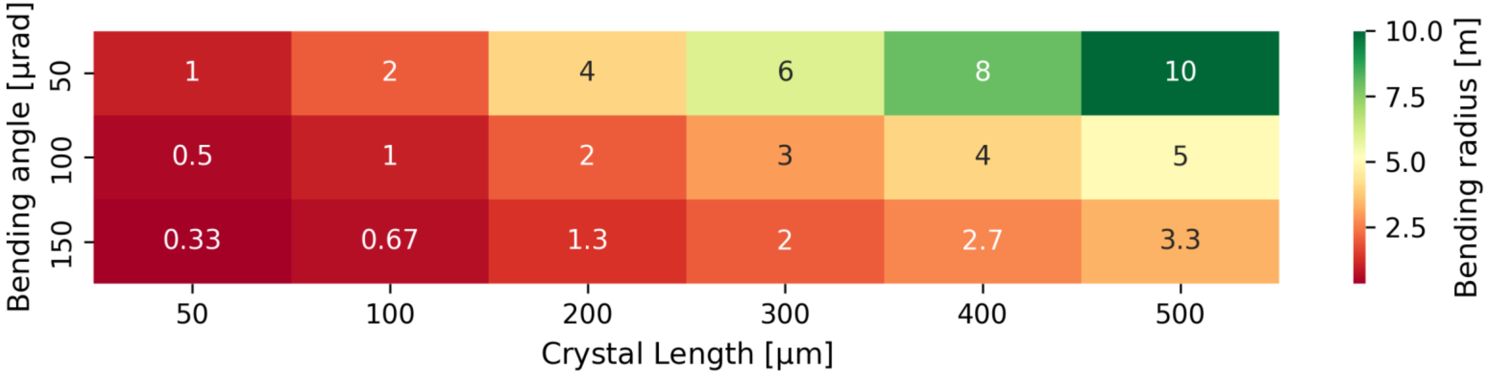


- **Bending radius R**: $\boxed{R = \frac{l}{\theta} > 3R_c = 0.3\ m}$ to ensure smooth particle steering and enhance channeling efficiency

Critical bending radius (Si, E = 45.6 GeV)

$$\boxed{R_c = \frac{pv}{U'(x_{max})} \approx \frac{E}{U'(x_{max})} \approx 9\ cm}$$

$U'(x_{max})$: maximum potential gradient [eV/cm]



Bending angle [µrad] \ Crystal Length [µm]	50	100	200	300	400	500
50	1	2	4	6	8	10
100	0.5	1	2	3	4	5
150	0.33	0.67	1.3	2	2.7	3.3

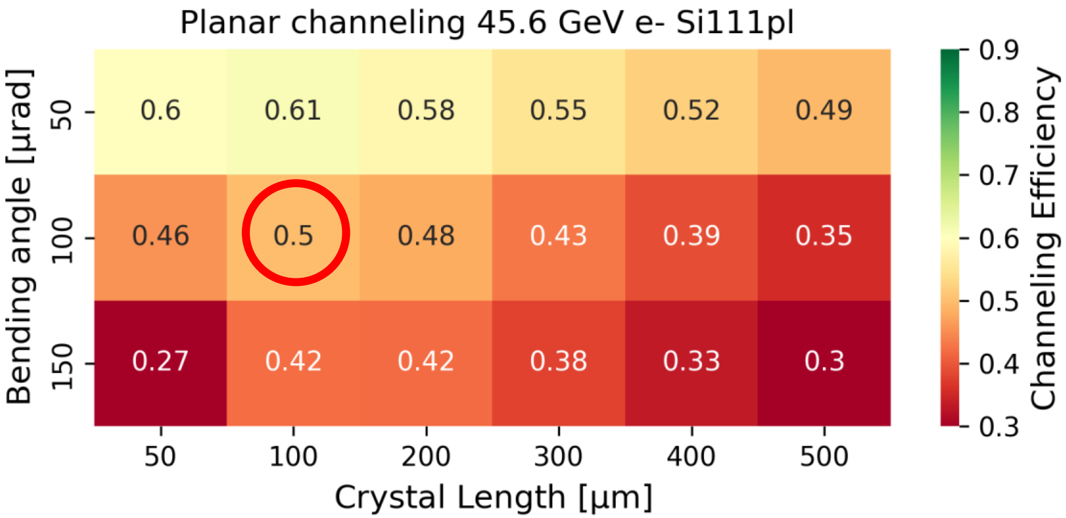
Channeling efficiency

Particles are considered channeled if:

$$\boxed{\Delta x_p \in [\theta_b - \theta_c,\ \theta_b + \theta_c]}$$

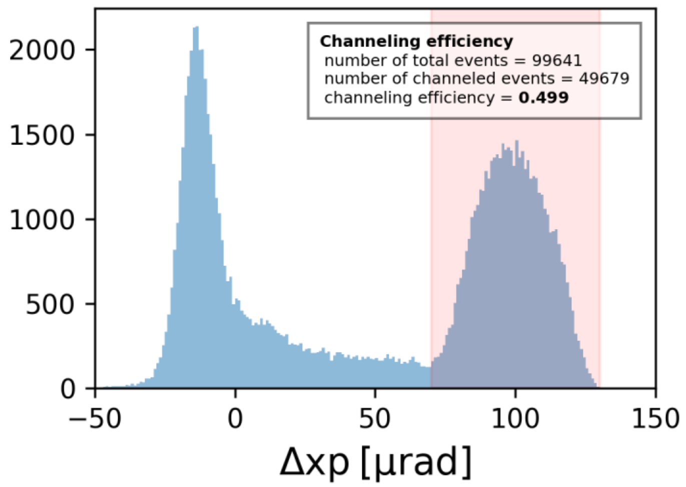
θ_b: bending angle

θ_c: critical angle



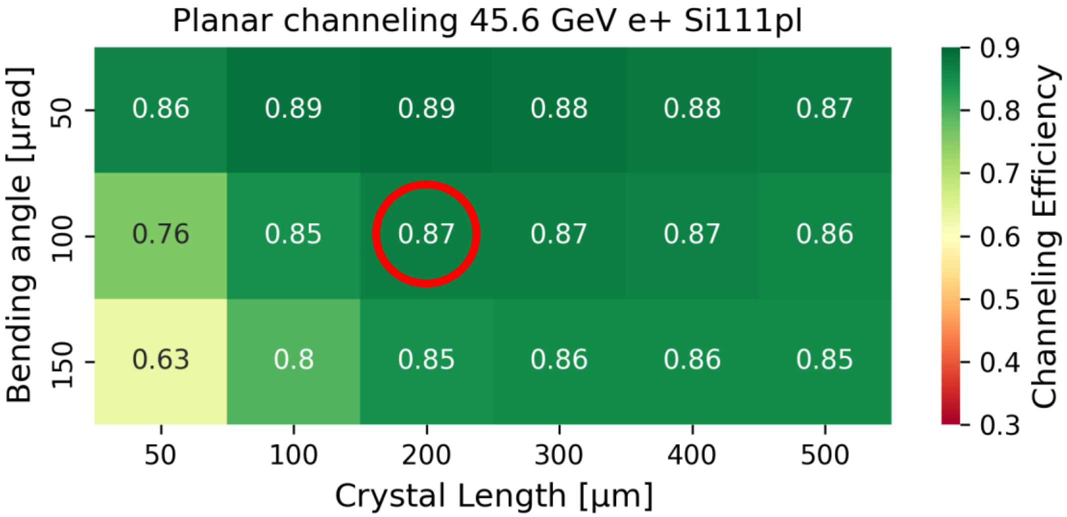
Planar channeling 45.6 GeV e- Si111pl

Bending angle [µrad] \ Crystal Length [µm]	50	100	200	300	400	500
50	0.6	0.61	0.58	0.55	0.52	0.49
100	0.46	0.5	0.48	0.43	0.39	0.35
150	0.27	0.42	0.42	0.38	0.33	0.3



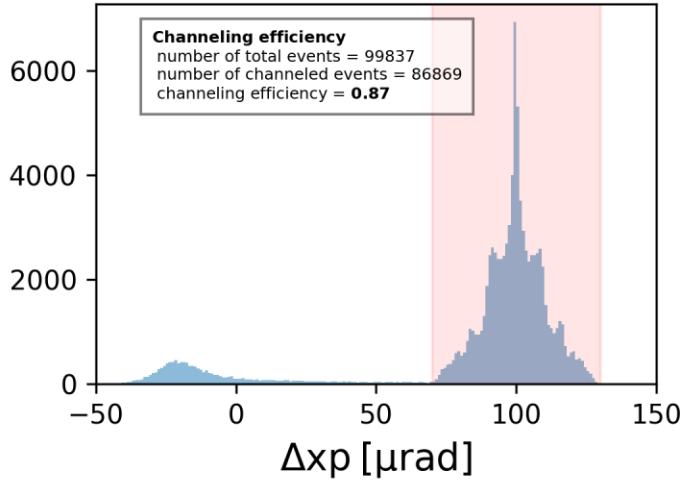
Channeling efficiency
number of total events = 99641
number of channeled events = 49679
channeling efficiency = **0.499**

Deflection of 100 µrad of 45.6 GeV e- using the Si (111) planar potential of a 100 µm long Si crystal.



Planar channeling 45.6 GeV e+ Si111pl

Bending angle [µrad] \ Crystal Length [µm]	50	100	200	300	400	500
50	0.86	0.89	0.89	0.88	0.88	0.87
100	0.76	0.85	0.87	0.87	0.87	0.86
150	0.63	0.8	0.85	0.86	0.86	0.85



Channeling efficiency
number of total events = 99837
number of channeled events = 86869
channeling efficiency = **0.87**

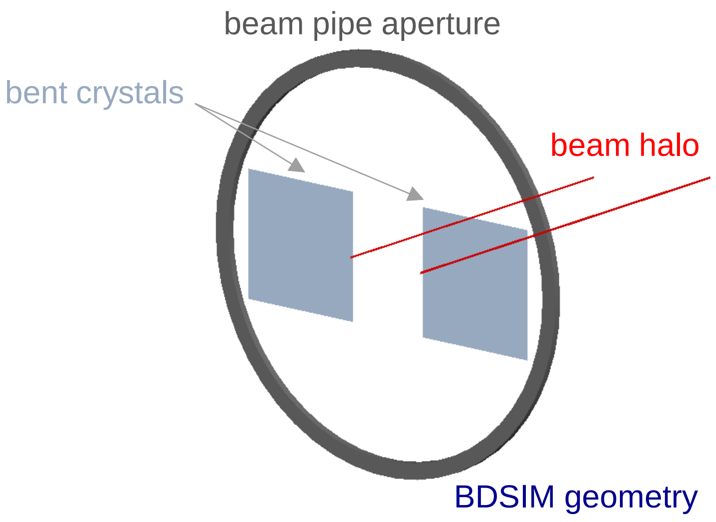
Deflection of 100 µrad of 45.6 GeV e+ using the Si (111) planar potential of a 200 µm long Si crystal.

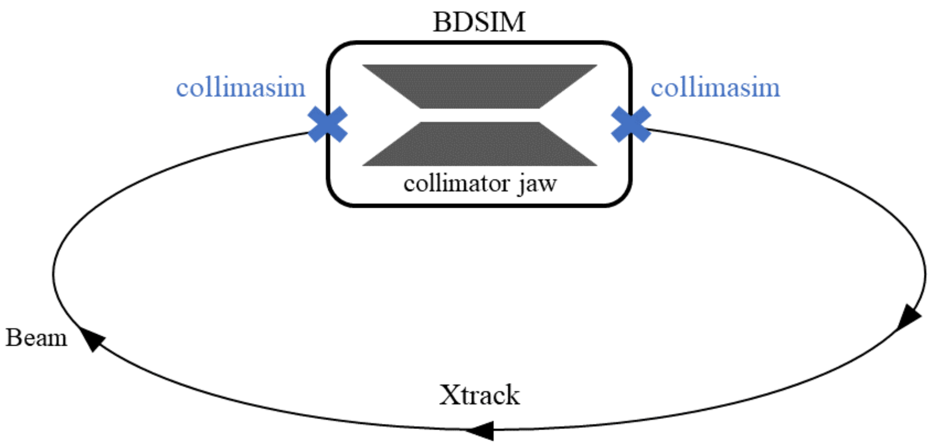
NOTE: safety margin w.r.t mechanical aperture for 150 urad angular kick is tight.

Collimation tracking simulations

- **Simulation workflow**:
  - Stand-alone BDSIM simulation for FCC-ee (Z) beam halo interacting with bent crystal
  - Channelled halo distributions used as input for Xsuite-BDSIM
  - 5x10^6 macroparticles (45.6 GeV) tracked through the FCC-ee lattice - including:
    - Nonlinearities
    - Synchrotron Radiation (mean model)
    - RF cavities
    - magnet tapering
    - detailed aperture model
    - halo and SR collimators

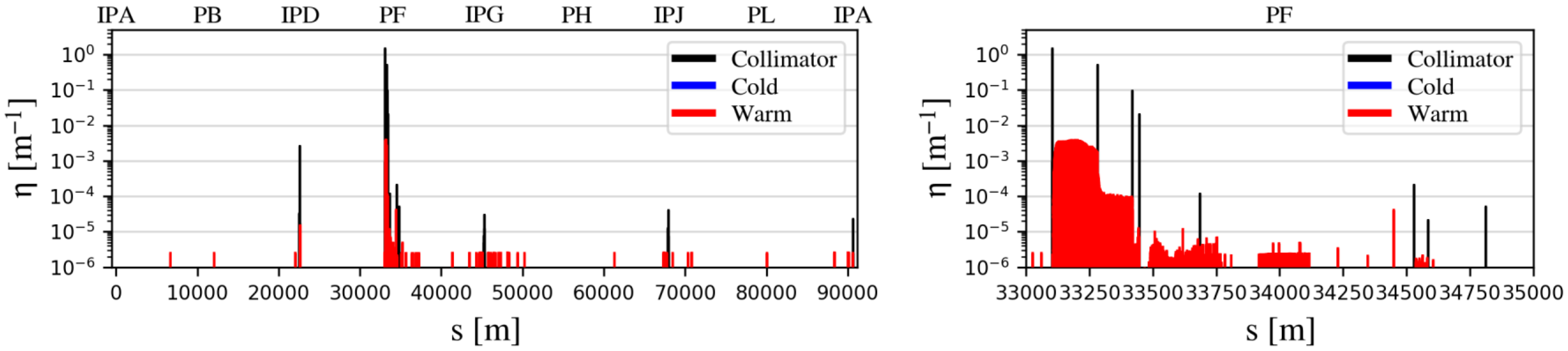
    For 1 machine turn.
- Results compared with standard (amorphous) collimation system one-turn cleaning



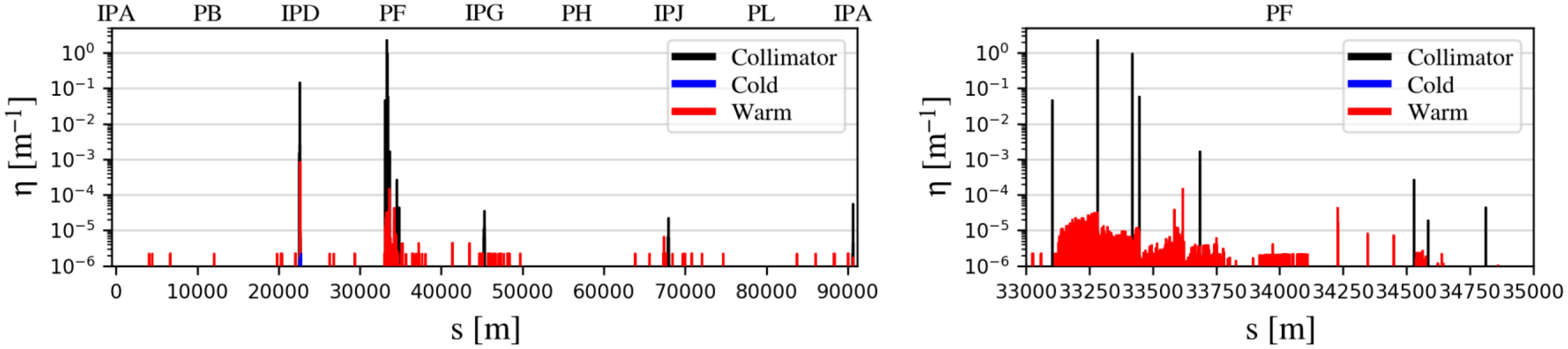


One-turn cleaning of the e- beam

- Replacement of primary collimators with 100 µm bent Si crystals (100 µrad bending angle)



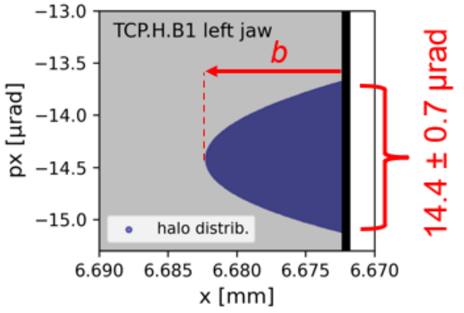
Standard collimation



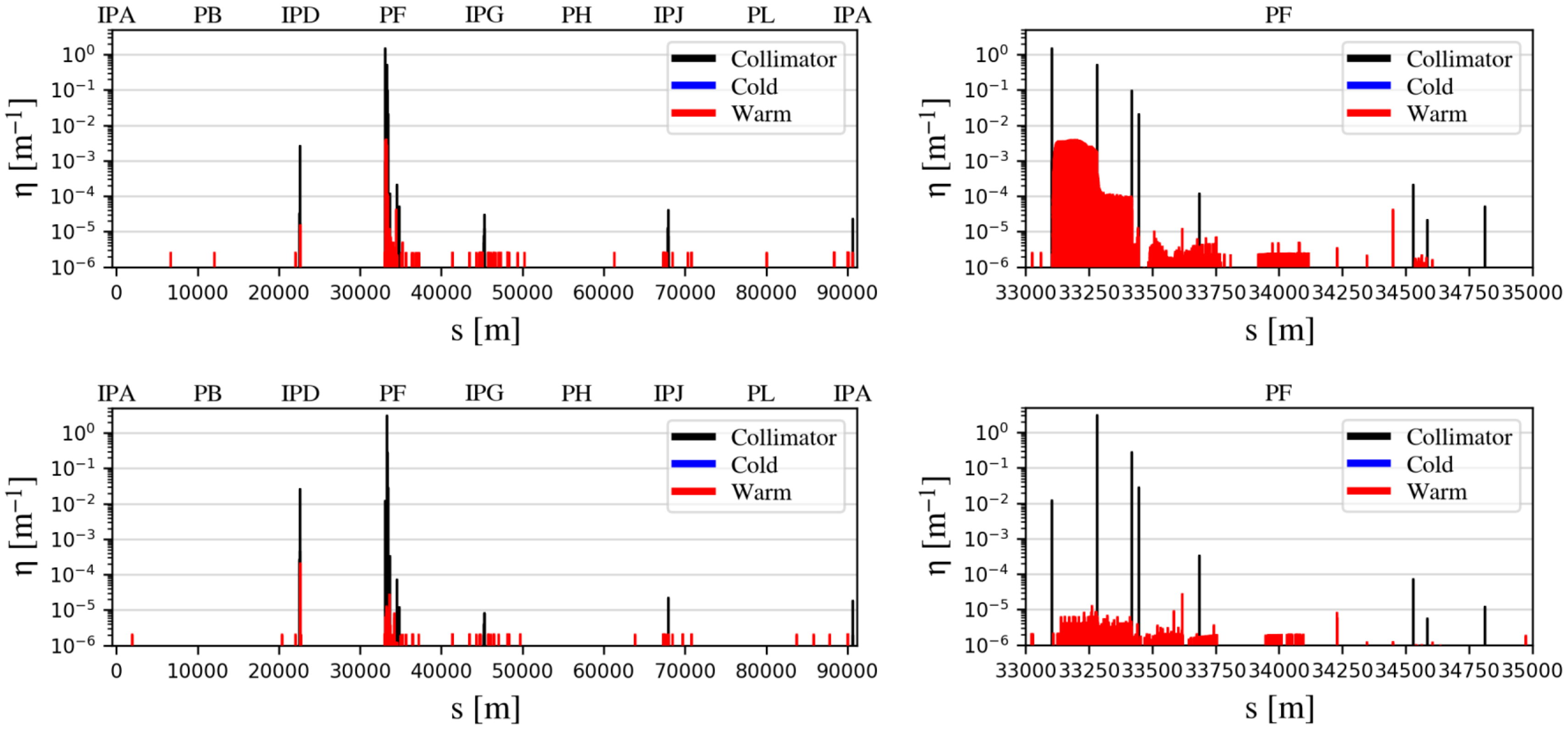
Crystal collimation

- One-turn cleaning is comparable
- In the crystal collimation case:
  - Most beam halo losses end up on the absorbers – as expected
  - Significant reduction (up to a factor >100) of local losses in PF
  - Increase of losses on a vertical SR collimator upstream IPD – to be investigated

One-turn cleaning of the e+ beam



- Replacement of primary collimators with 200 μm bent Si crystals (100 μrad bending angle)



Standard collimation

Crystal collimation

- One-turn cleaning is comparable – compare again the performance considering smaller impact parameters *b*
- In the crystal collimation case:
  - Most beam halo losses end up on the absorbers – as expected
  - Significant reduction (up to a factor >100) of local losses in PF
  - Increase of losses on a vertical SR collimator upstream IPD – to be investigated

Summary

- **Crystal collimation might be an interesting solution for FCC-ee collimation**
  - Feasibility studies have started: no show-stoppers identified
  - **First crystal parameter optimization studies performed**
    - Planar channeling of e- and e+ in Si (111)
    - 100/200 µm Si crystals with 100 µrad bending angle
- **First collimation tracking simulations with crystals performed**: **performance gain over standard collimation cannot be demonstrated yet** – further studies are needed (e.g., considering smaller impact parameters)

Next steps

- Extend the analysis using **more complete channeling routines** including { radiation emission / strong field effects }
- Extend the analysis for studying **crystal collimation in the V plane**
- Possibly extend the current analysis to:
  - **Axial channeling** – potentially more promising for the e- beam
  - **(Multiple) volume reflection**
- **Optimize absorber parameters** (materials, length, retraction, etc.)
- Extend the capabilities of the Xsuite-BDSIM simulation tool to allow for multi-turn collimation tracking with crystals

Thank you!

Oscillation period

- Si crystal
- $\lambda = \pi d_p \sqrt{\frac{pv}{2U_{max}}} \approx \pi d_p \sqrt{\frac{E}{2U_{max}}}$

dp: interplanar distance [Ang]
Umax: maximum potential well depth [eV]
E: particle energy [eV]

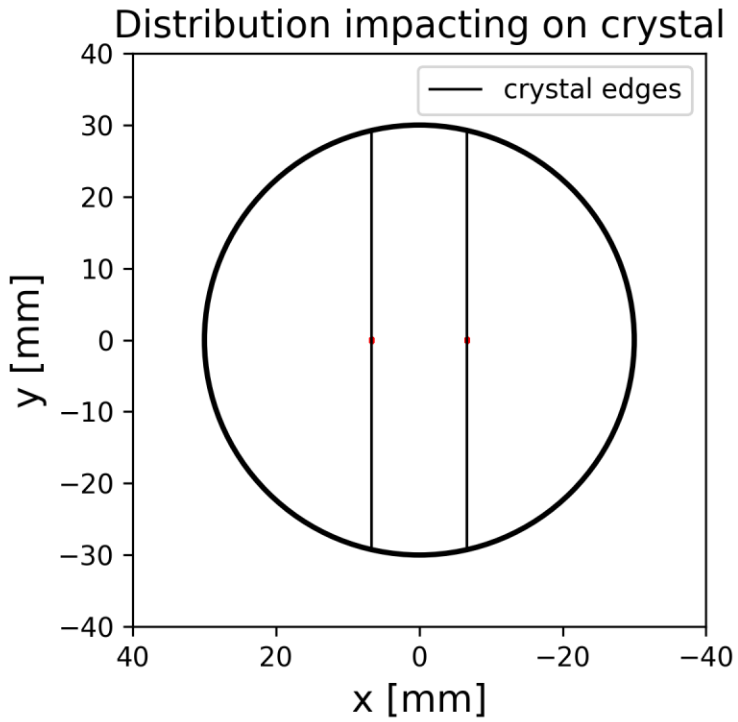
Z mode (E=45.6 GeV)

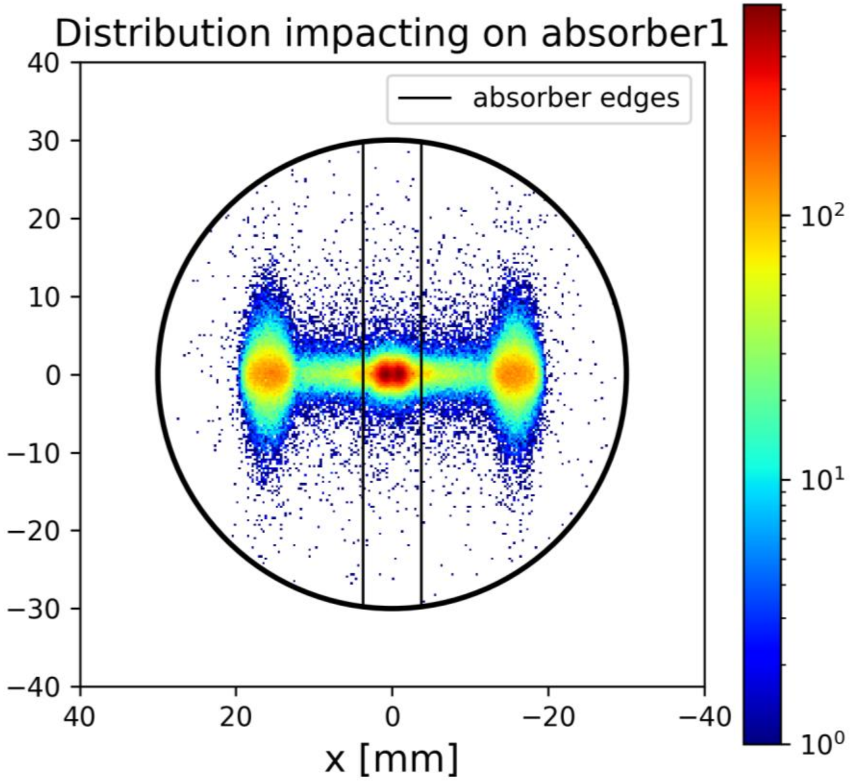
Planar channel	dp [A]	Umax [eV]	λ [um]
(111)	2.35 (0.78)	25.6	22.0
(110)	1.92	22.8	19.1
(100)	1.36	12.9	18.0

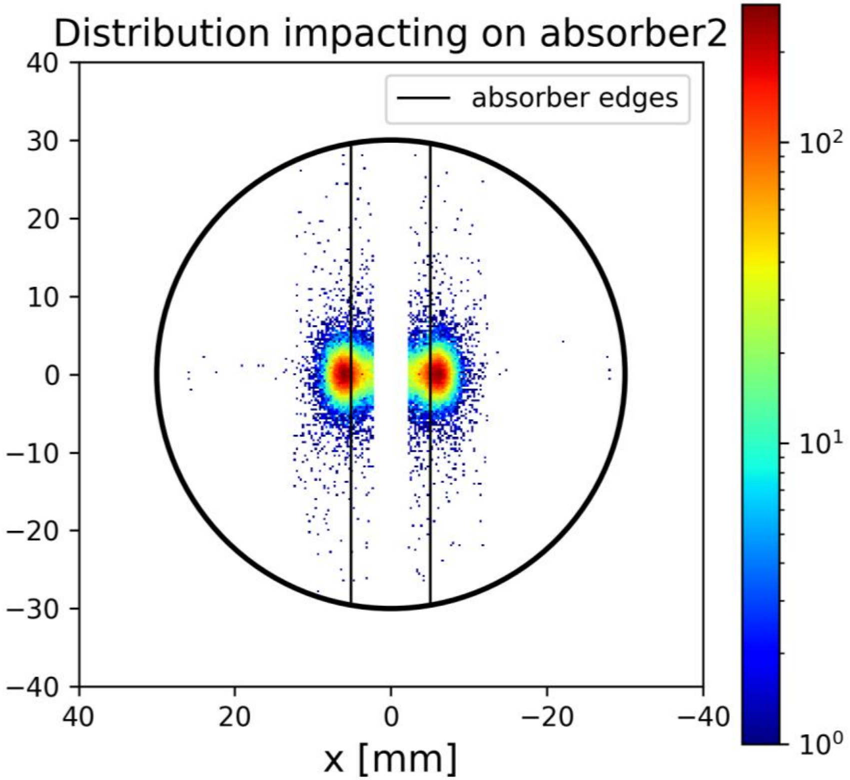
ttbar mode (E=182.5 GeV)

Planar channel	dp [A]	Umax [eV]	λ [um]
(111)	2.35 (0.78)	25.6	44.1
(110)	1.92	22.8	38.2
(100)	1.36	12.9	36.0

Electron beam distribution impacting absorbers


Distribution impacting on crystal


Distribution impacting on absorber1


Distribution impacting on absorber2