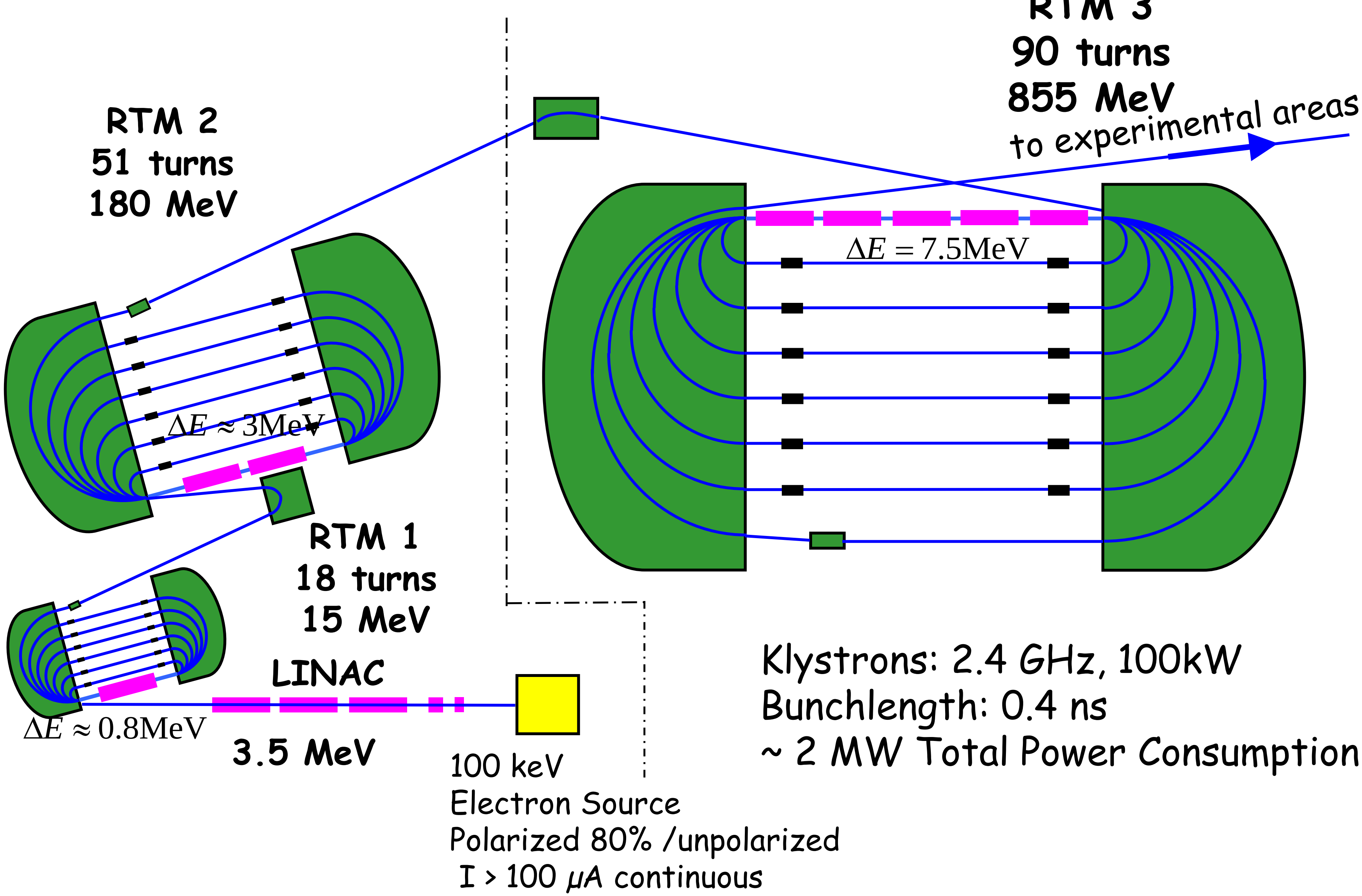
Channeling experiments at the Mainz Microtron MAMI

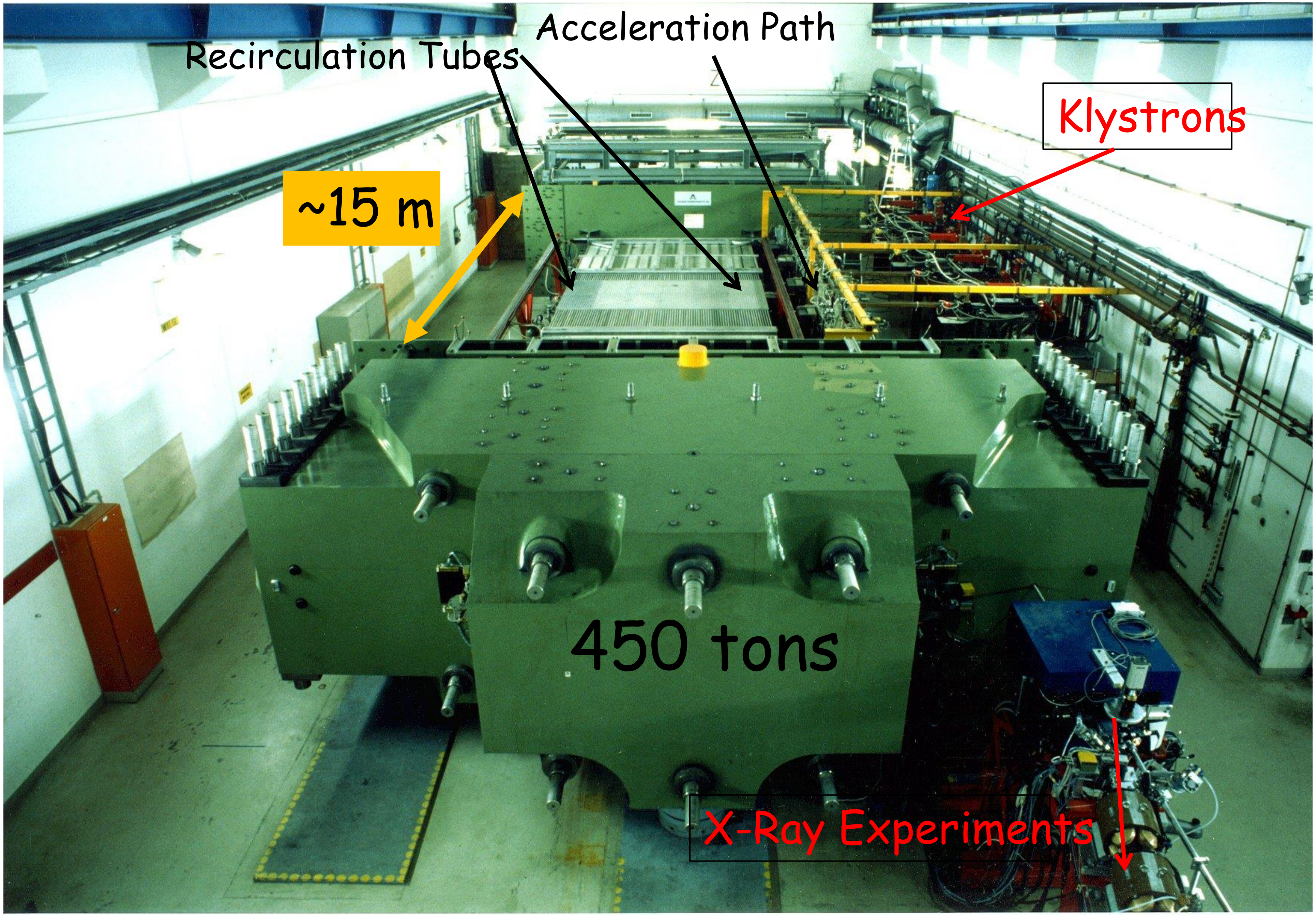
- The MAMI Accelerator
- Principal of a crystal based light source
- Experimental setup and methods
- Results
- The new Positron beamline

W. Lauth, Institute of Nuclear PhysicsUniversity of Mainz, Germany,
DESY, Hamburg, 8.-10. December 2025,
Workshop about "Relativistic Electron Beam Dynamics in Crystals and Related Electrodynamic Processes“

Mainzer Mikrotron MAMI B



Klystrons: 2.4 GHz, 100kW
Bunchlength: 0.4 ns
~ 2 MW Total Power Consumption



Acceleration Path
Recirculation Tubes
Klystrons
~15 m
450 tons
X-Ray Experiments

Ground plan of MAMI

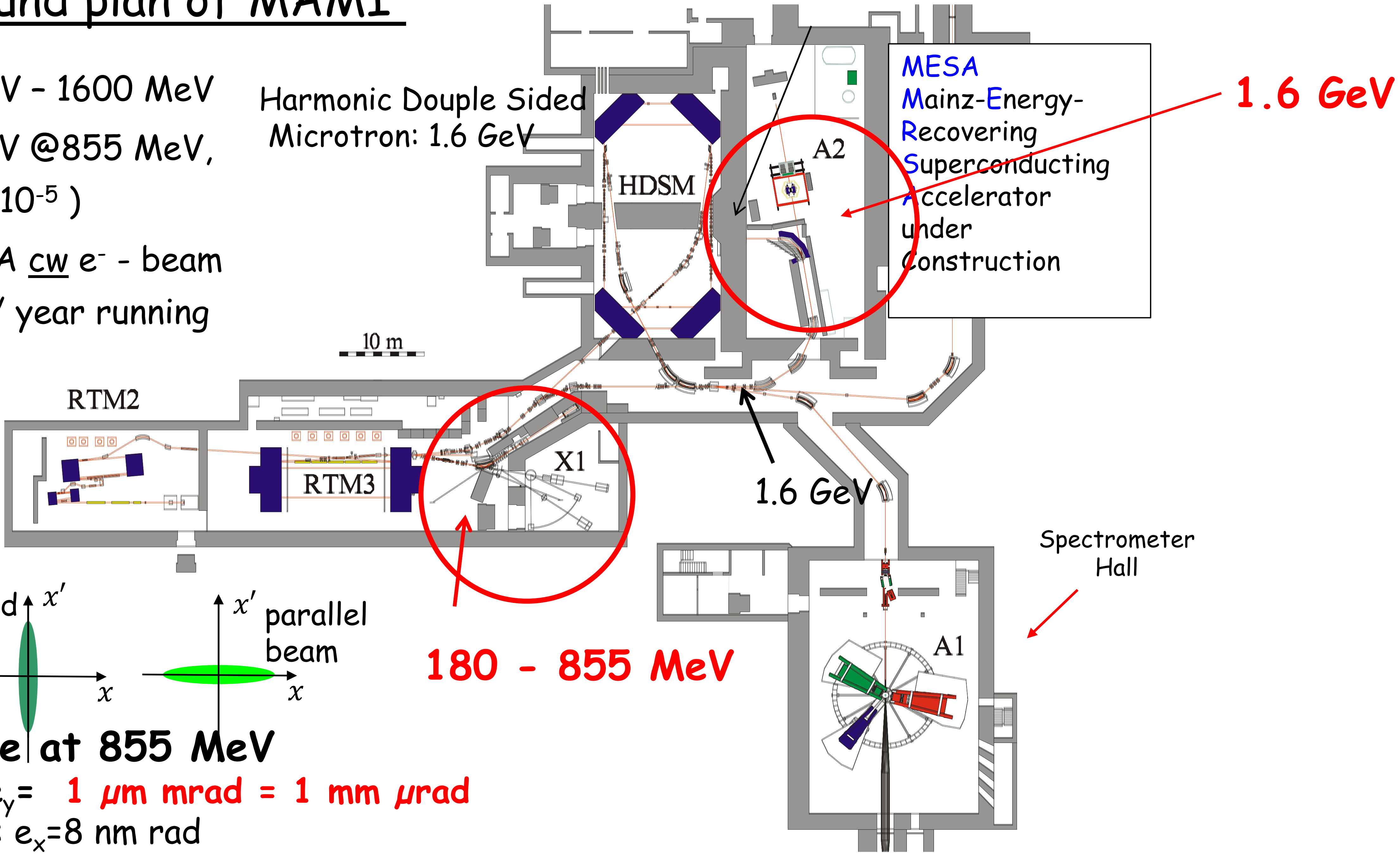
E= 180 MeV – 1600 MeV

ΔE = 13 keV @855 MeV,

$\Delta E/E = (2 \cdot 10^{-5})$

max. 100μA cw e^- - beam

~ 7000 h / year running

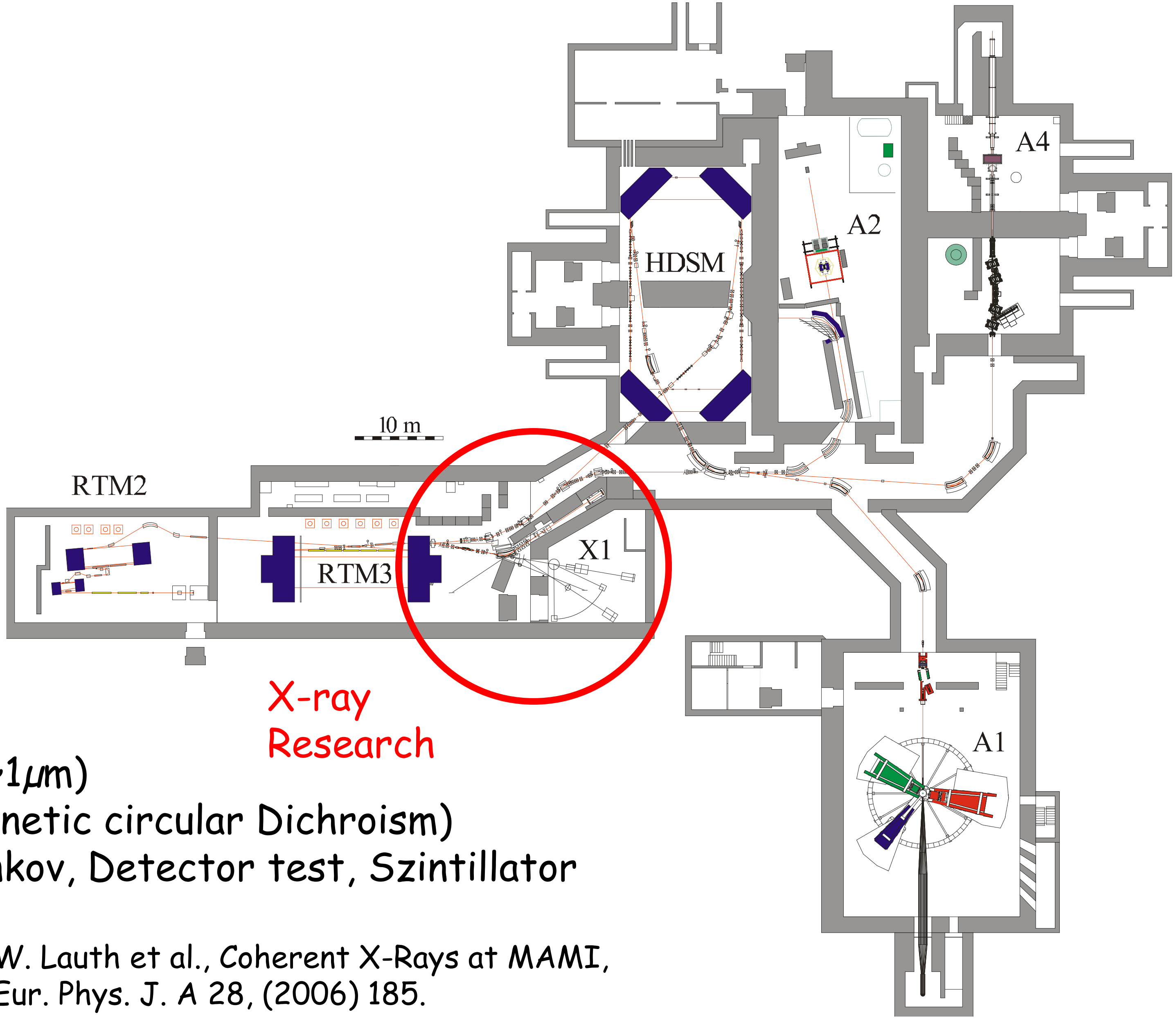


Emittance at 855 MeV

Vertical : e_y= **1 μm mrad = 1 mm μrad**

Horizontal: e_x=8 nm rad

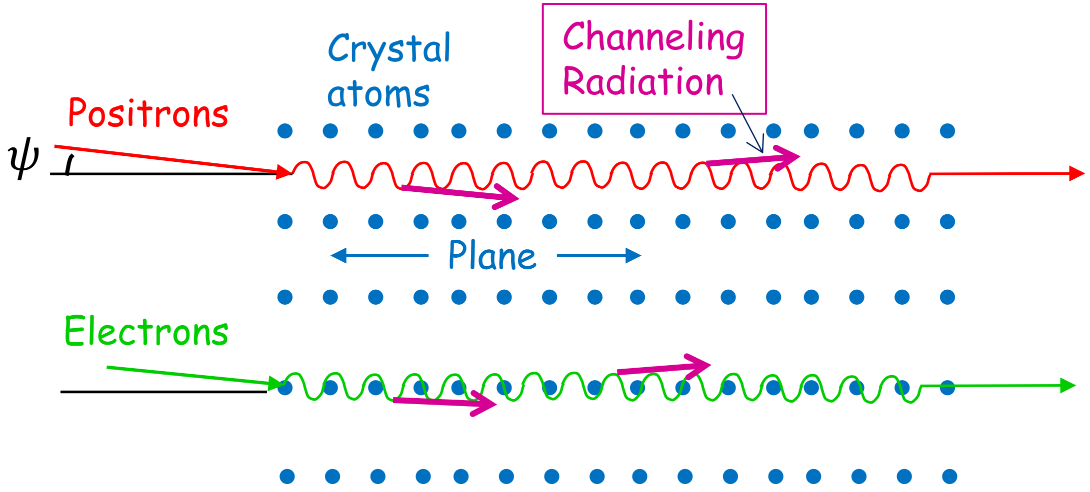
X-Ray Experiments @ MAMI

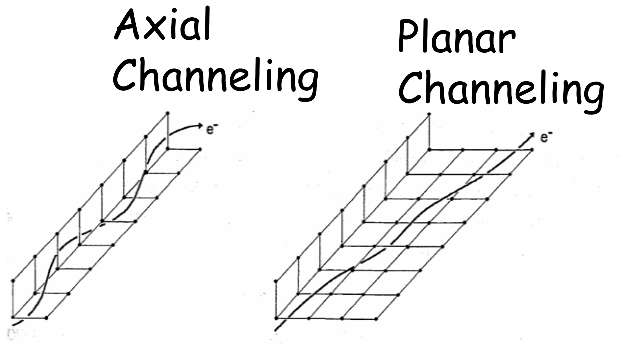


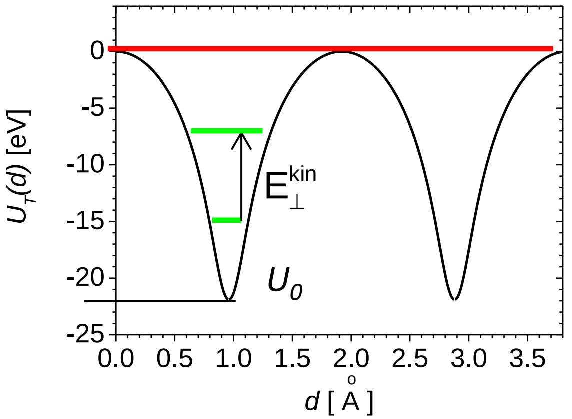
Phase Contrast (Beamspot ~1μm)
X-ray Interferometry (Magnetic circular Dichroism)
PXR, TR, Channeling, Cherenkov, Detector test, Szintillator

W. Lauth et al., Coherent X-Rays at MAMI,
Eur. Phys. J. A 28, (2006) 185.

Channeling Radiation







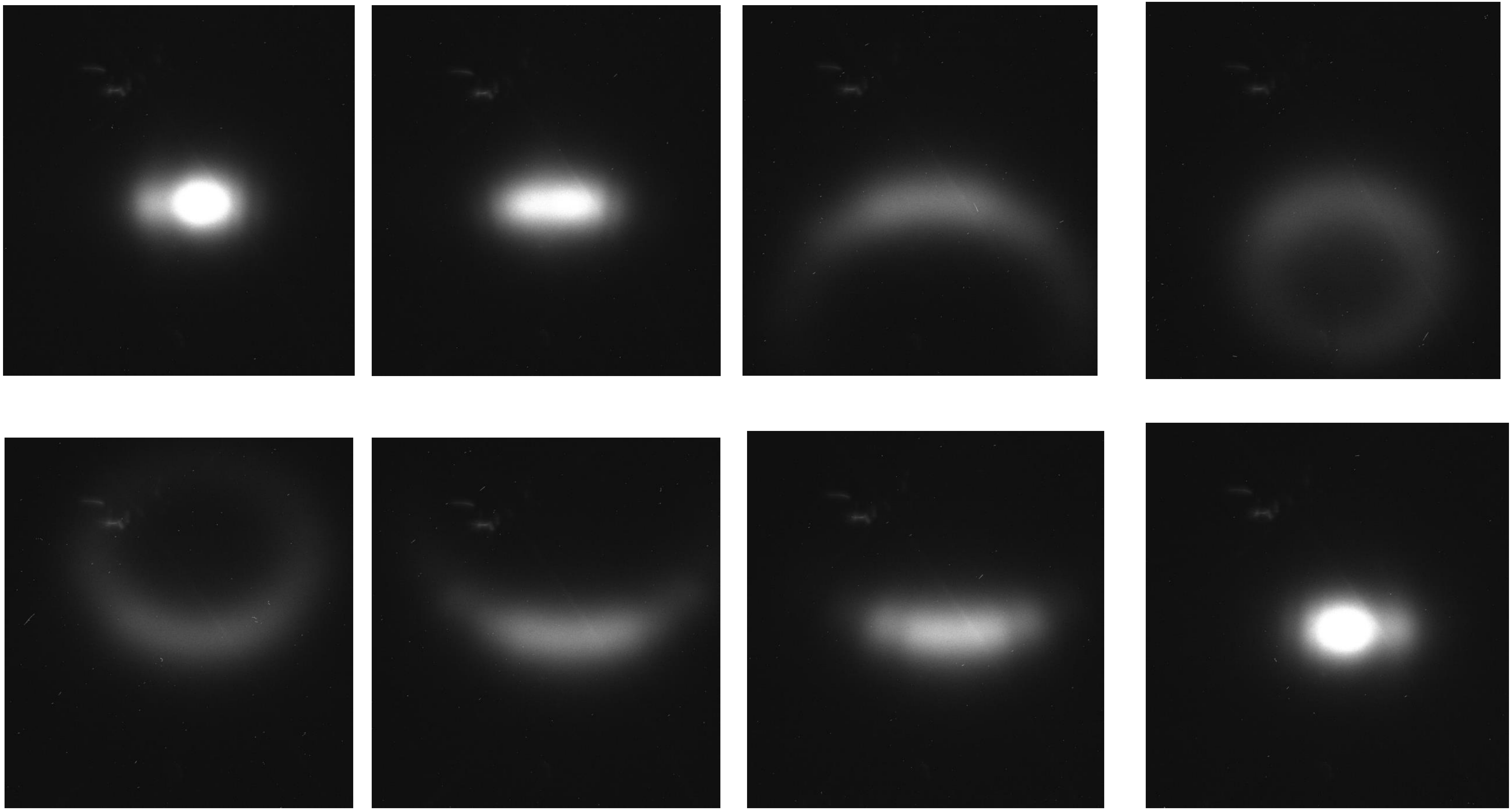
$$E_\perp^{kin} = \frac{p_\perp^2 c^2}{2mc^2} \approx \frac{E\psi^2}{2}$$

$$E_\perp^{kin} < U_0 \;\rightarrow$$

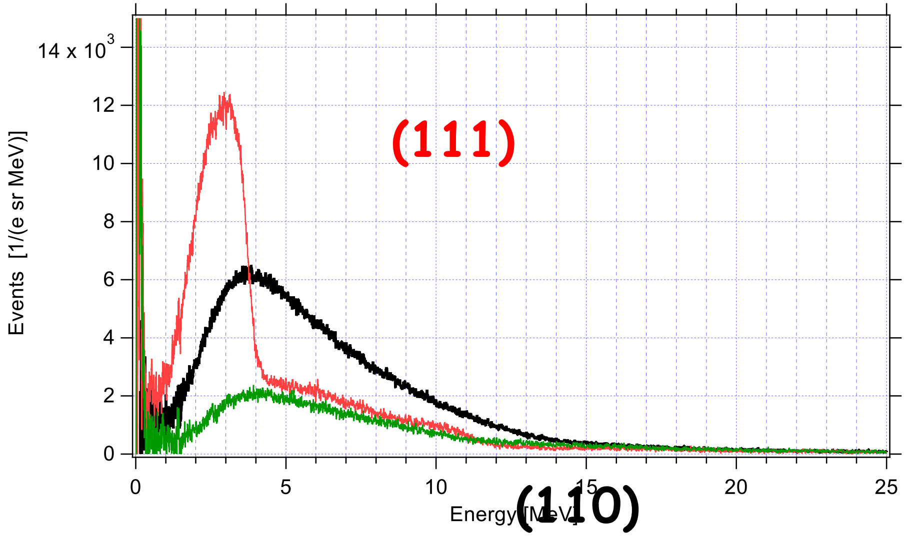
Lindhard critical angle

$$\psi < \sqrt{\frac{2U_0}{E}} \approx \sqrt{\frac{2 \cdot 20eV}{1\;GeV}}$$

$$\boxed{\psi < 0.2\;mrad}$$



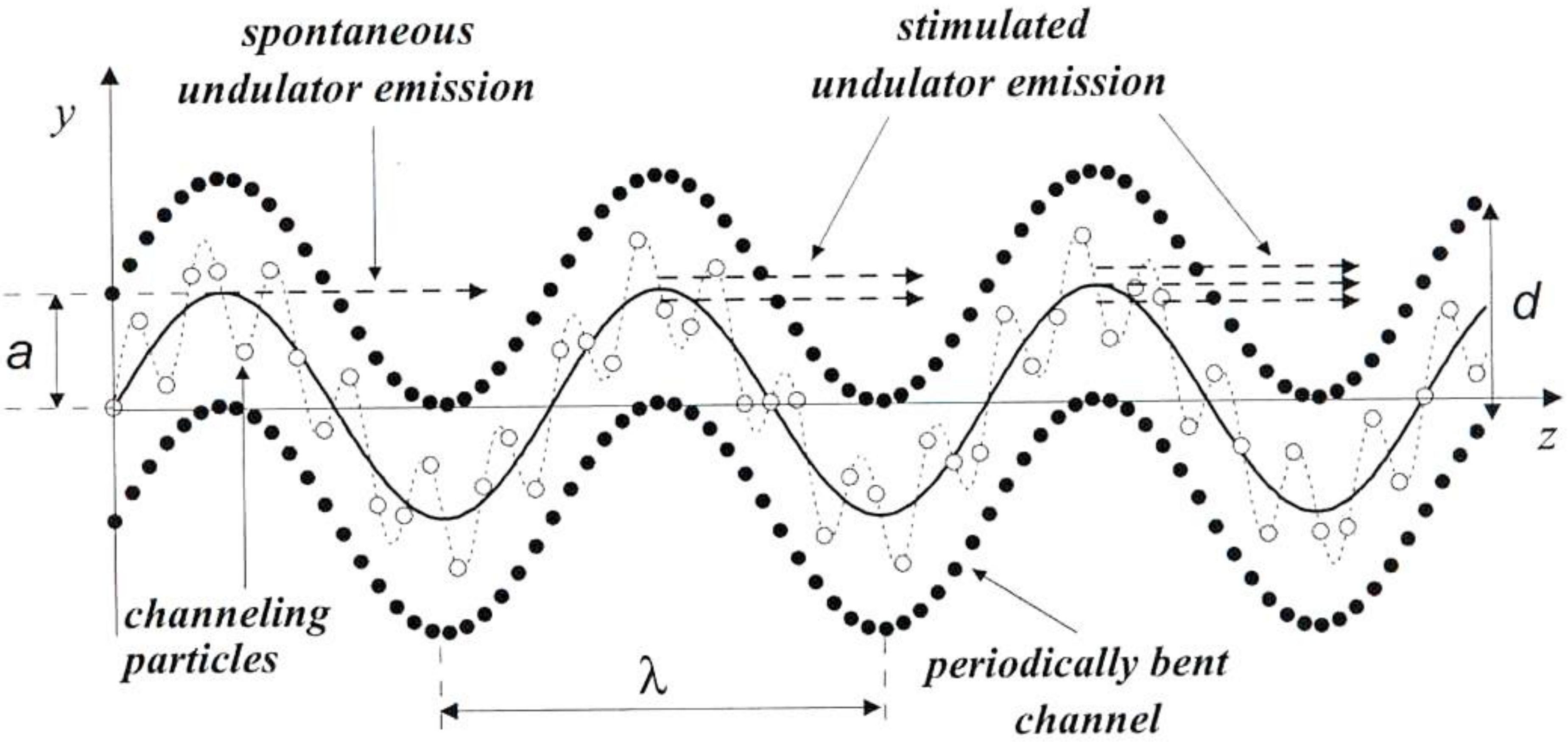
Channeling radiation of electrons in a flat diamond crystal



(100)

Undulator Radiation at Positron/Electron Channeling in a Single Crystal

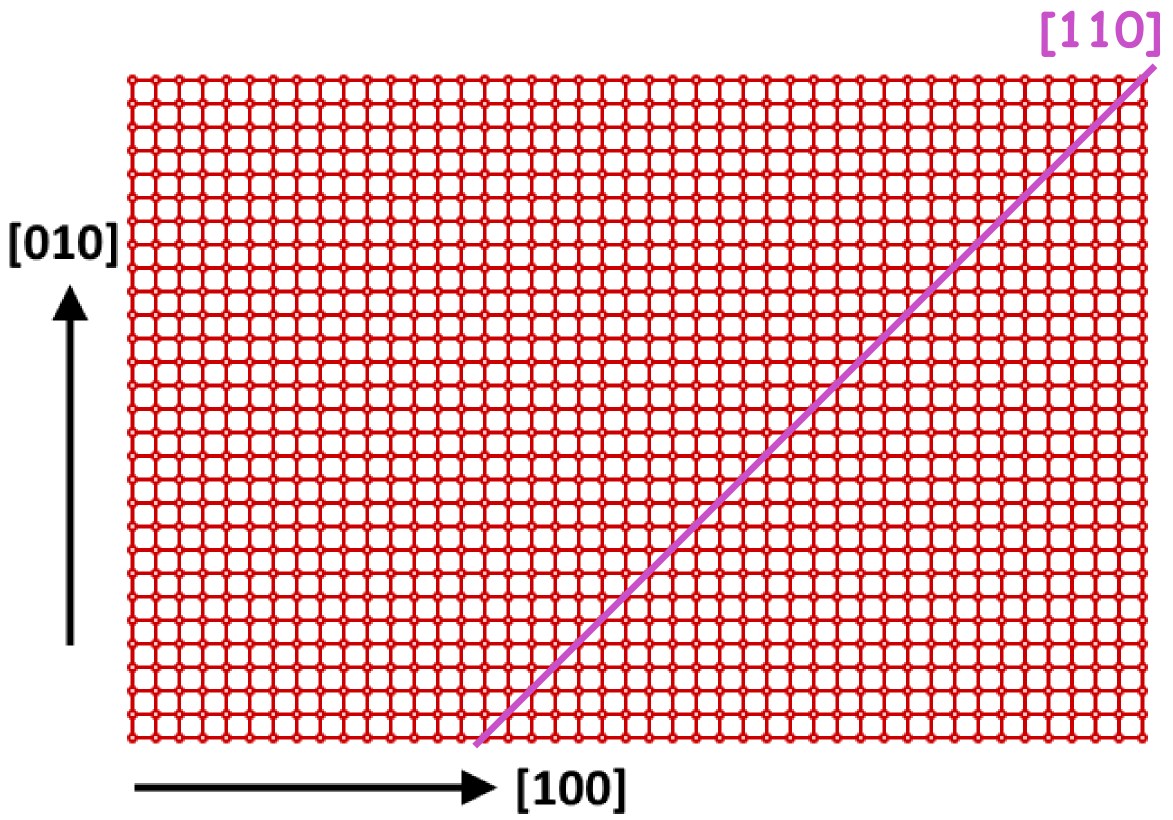
A. Solov'yov, A. Korol, W. Greiner *et al.*



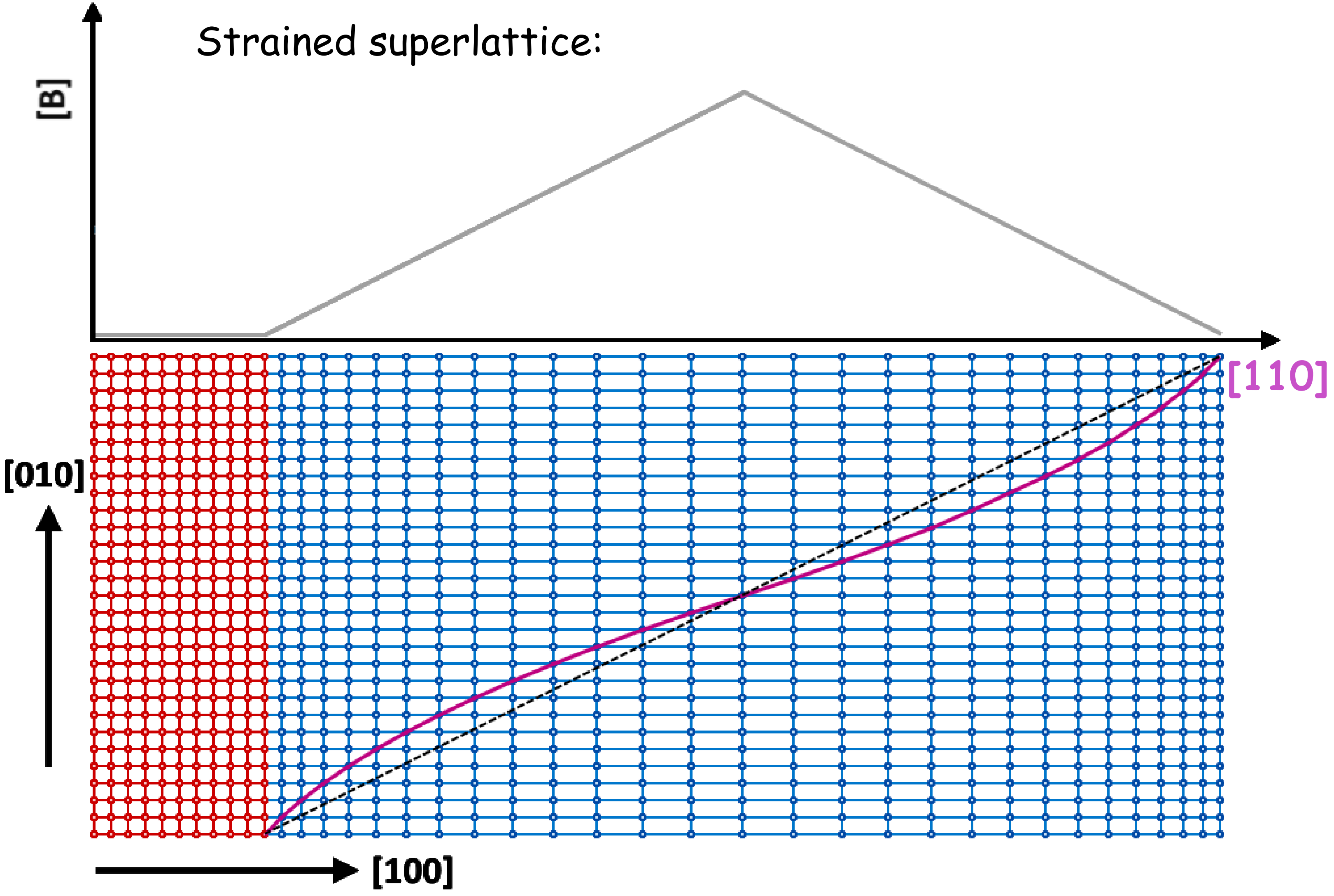
$$\hbar\omega = n\frac{4\pi\gamma^2\hbar c}{\lambda(1+K^2/2+\gamma^2(\delta-\theta_x)^2)}$$

Superlattice principles

Normal cubic crystal: flat planes



Superlattice principles



Undoped substrate

Growth with increasing doping
= increase in crystal parameter along [100].

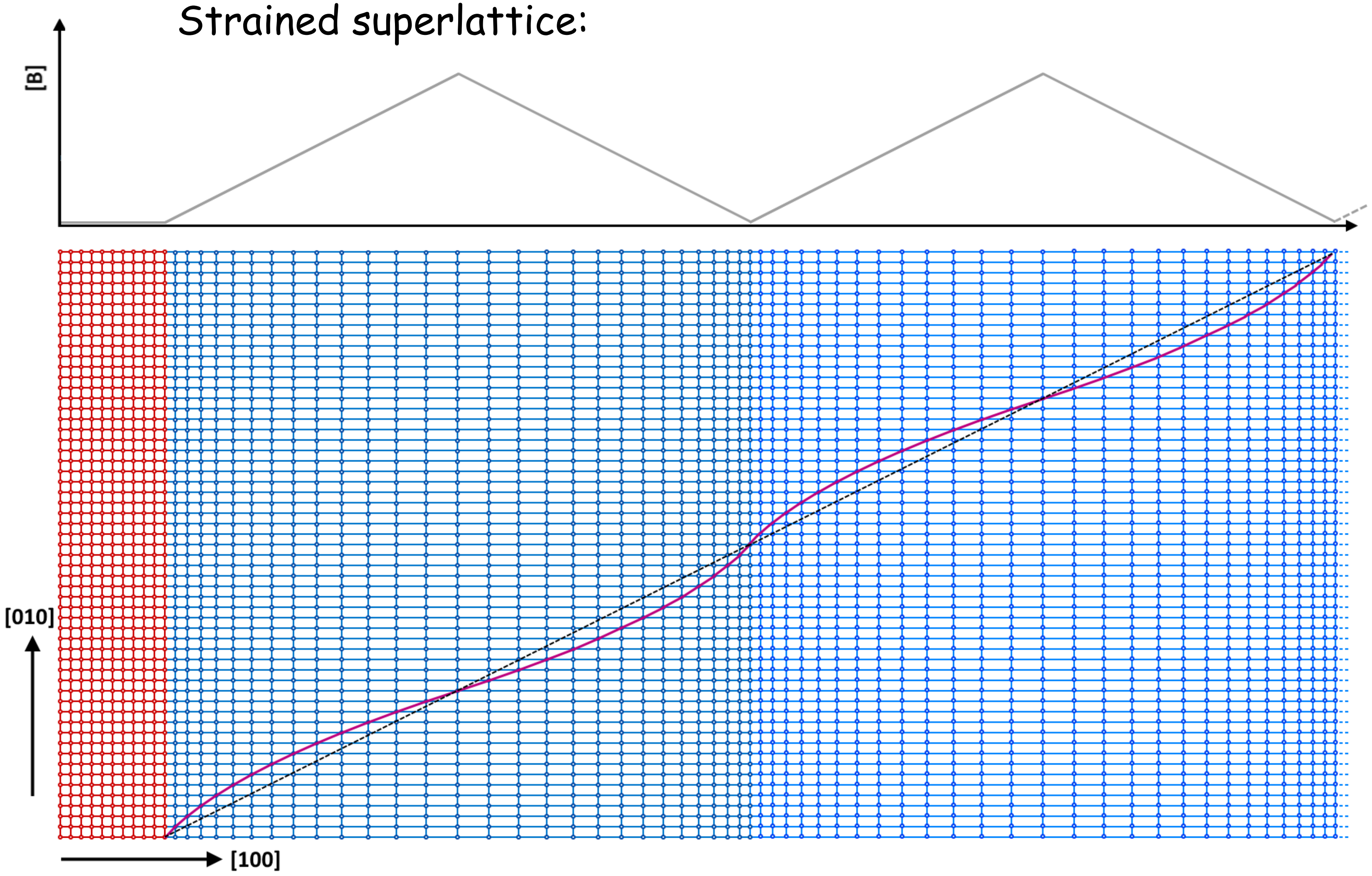
Growth with decreasing doping
= decrease in crystal parameter along [100]

Channeling along [110]: undulation

Superlattice principles

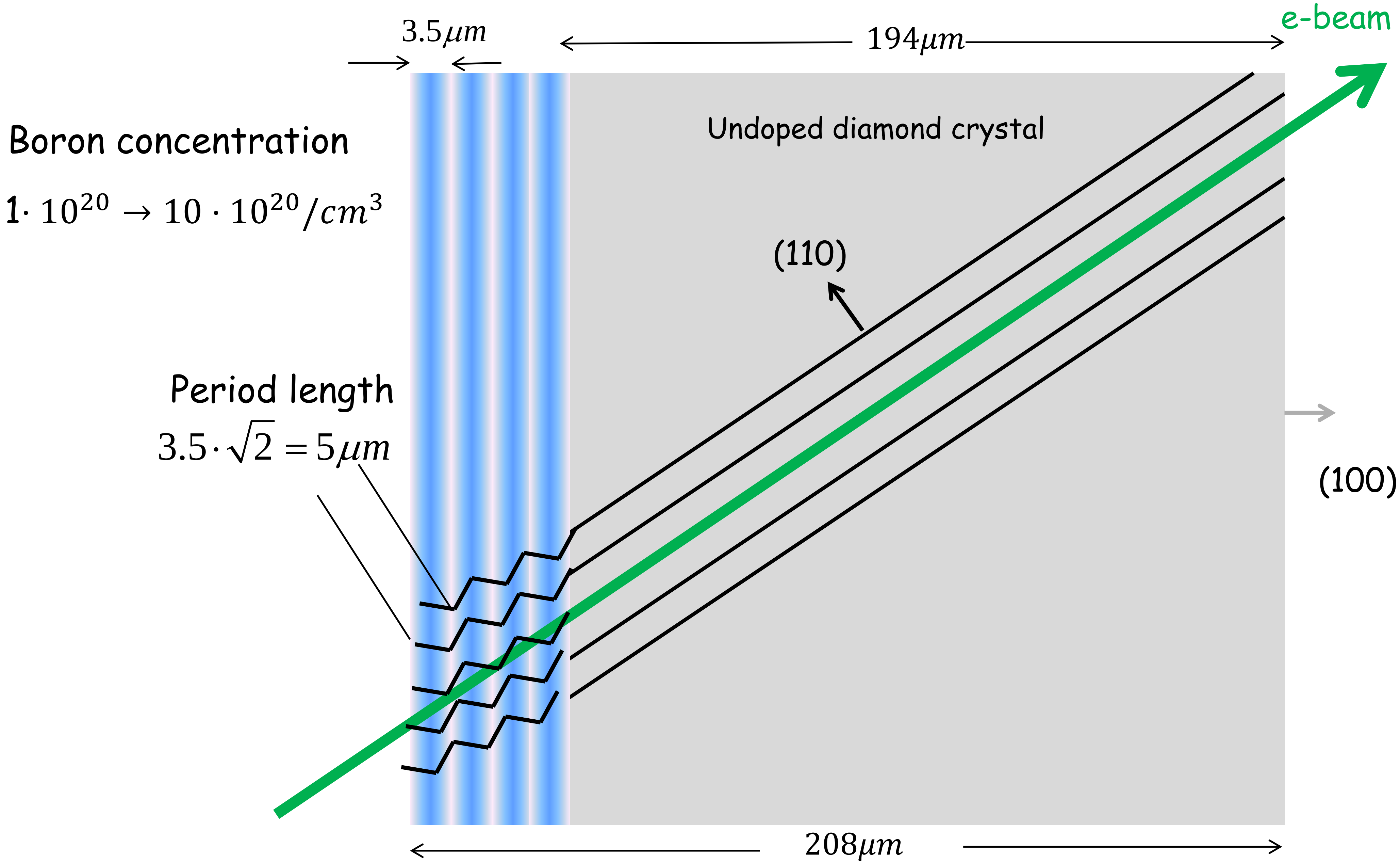
PBCs

Strained superlattice:

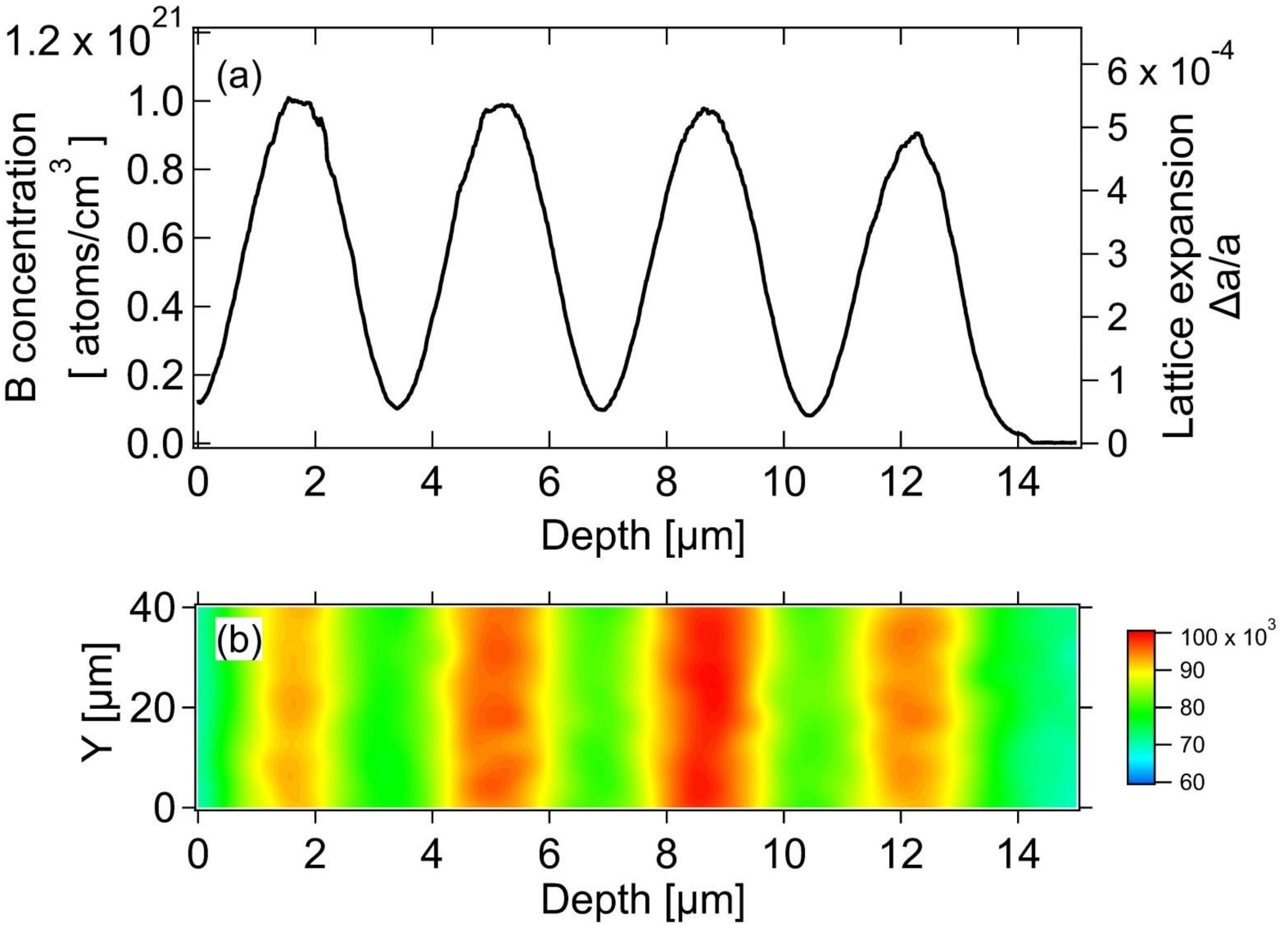


On several successive doped layers = periods

4 Period Diamond Undulator



SIMS Profile - Bor concentration



Rocking Curve Imaging

SIMS hole

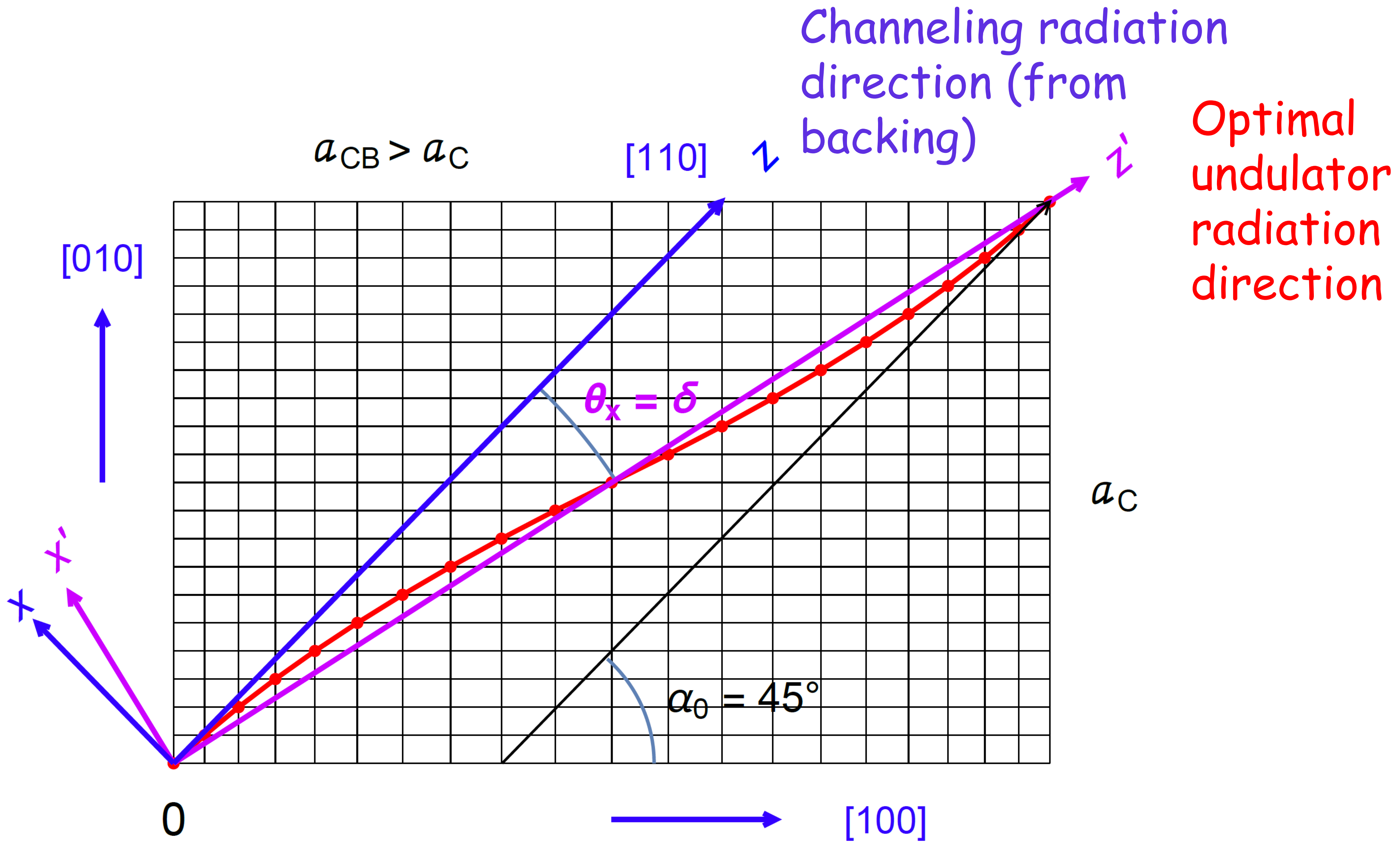
4 Period Diamond crystal, 855 MeV

$\lambda_U = 3.5\sqrt{2}\,\mu m = 5\ \mu m,$ A= 0.138 nm, K=0.291, γ=1673

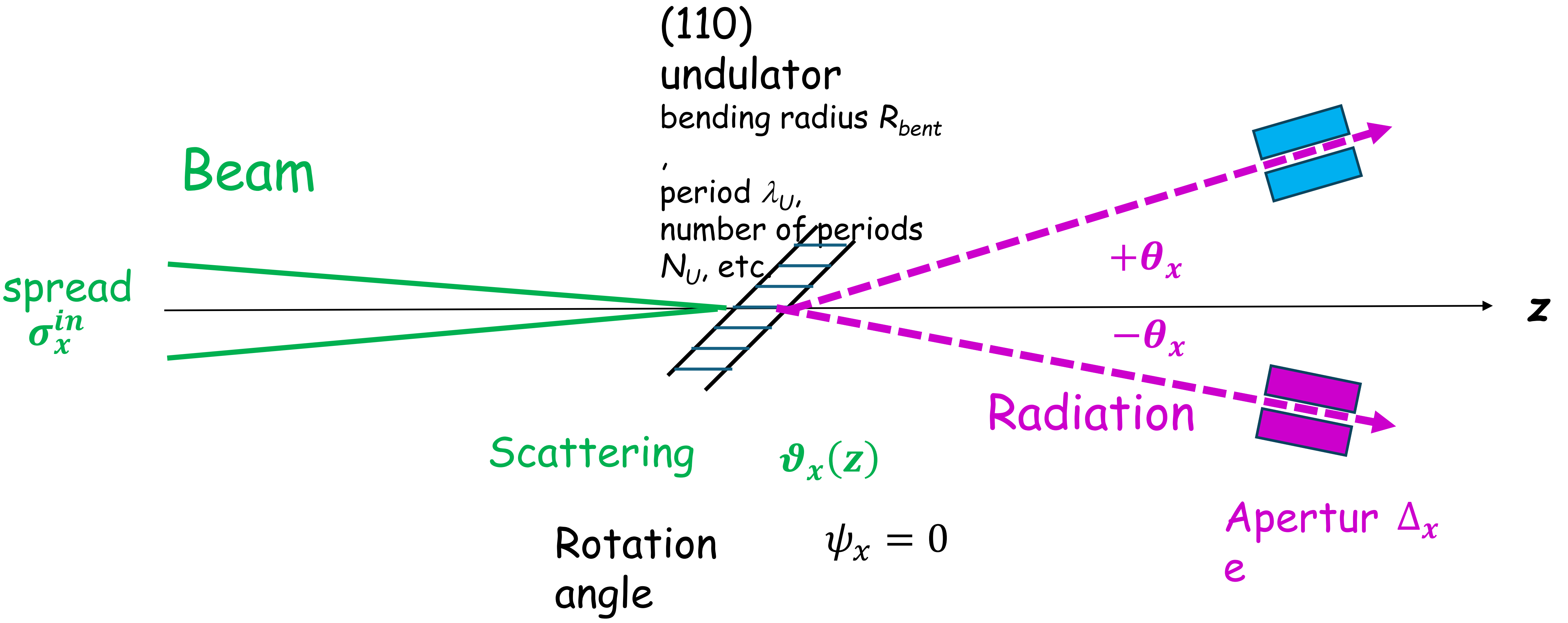
$$\hbar\omega = n\frac{4\pi\gamma^2\hbar c}{\lambda(1\ + K^2/2 + \ \gamma^2(\delta\ -\ \theta_x)^2)} = 1.33\ MeV$$

at $(\delta\ -\ \theta_x)$ = θ_y= 0 and first order n=1

Definition of Observation Directions

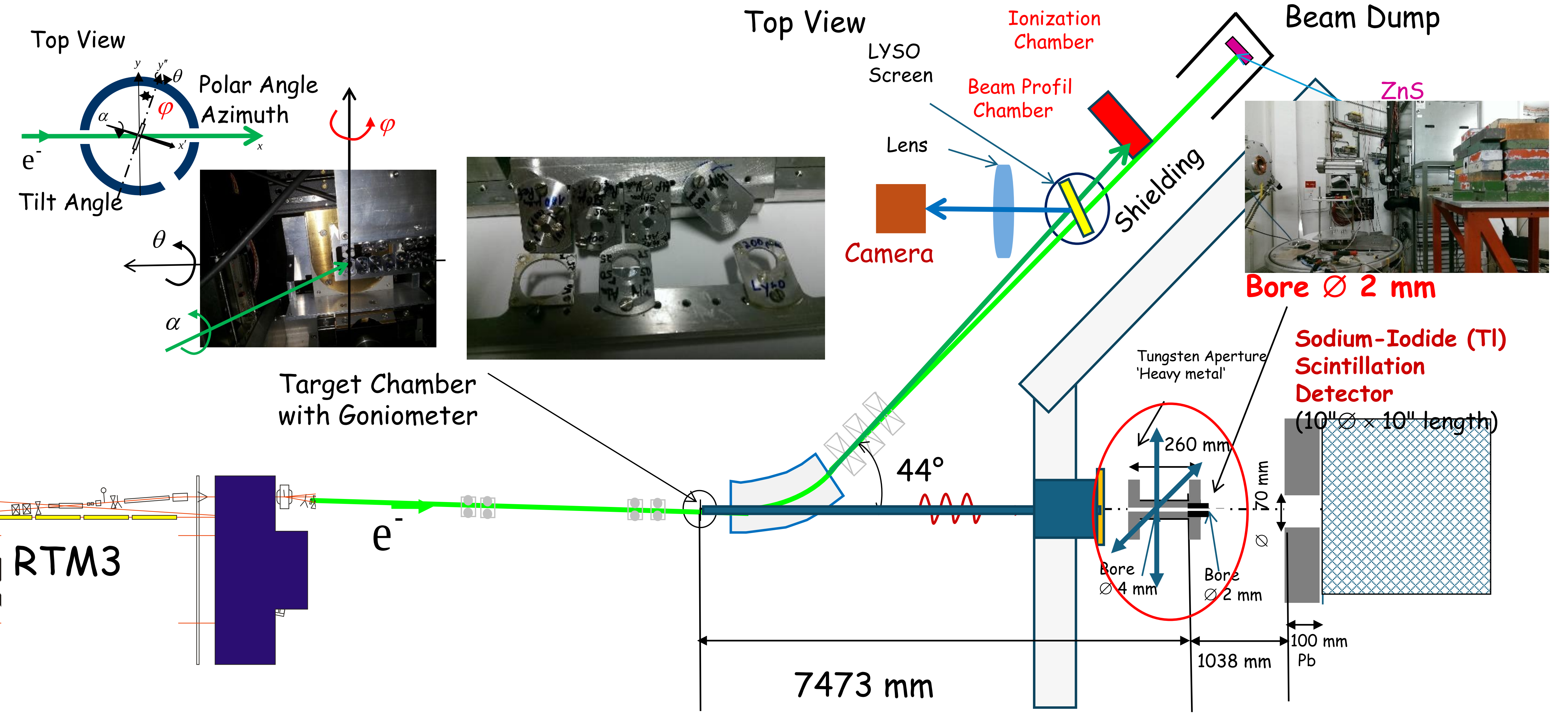


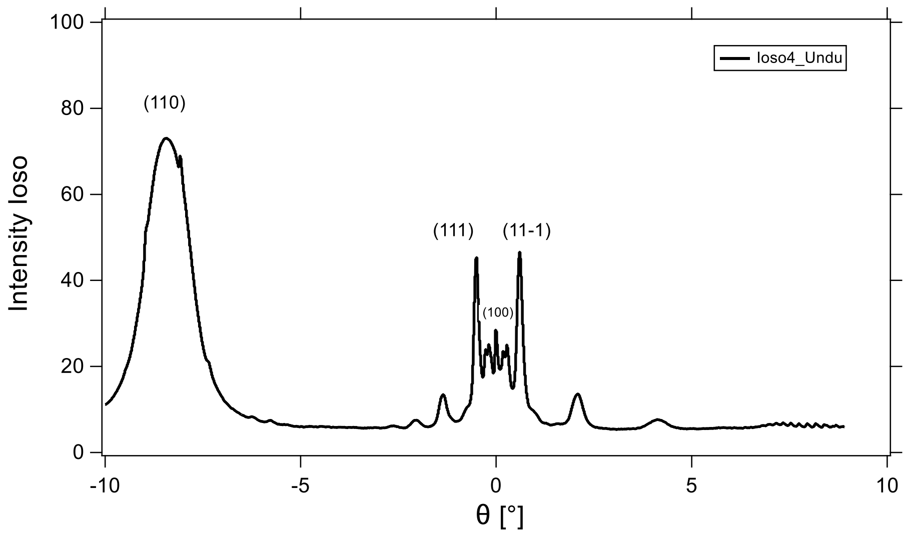
Principle of Peak Search



H. Backe et al. Nuclear Instruments and Methods in Physics Research A 1073 (2025) 170236.
https://doi.org/10.1016/j.nima.2025.170236 and arXiv:2404.15376

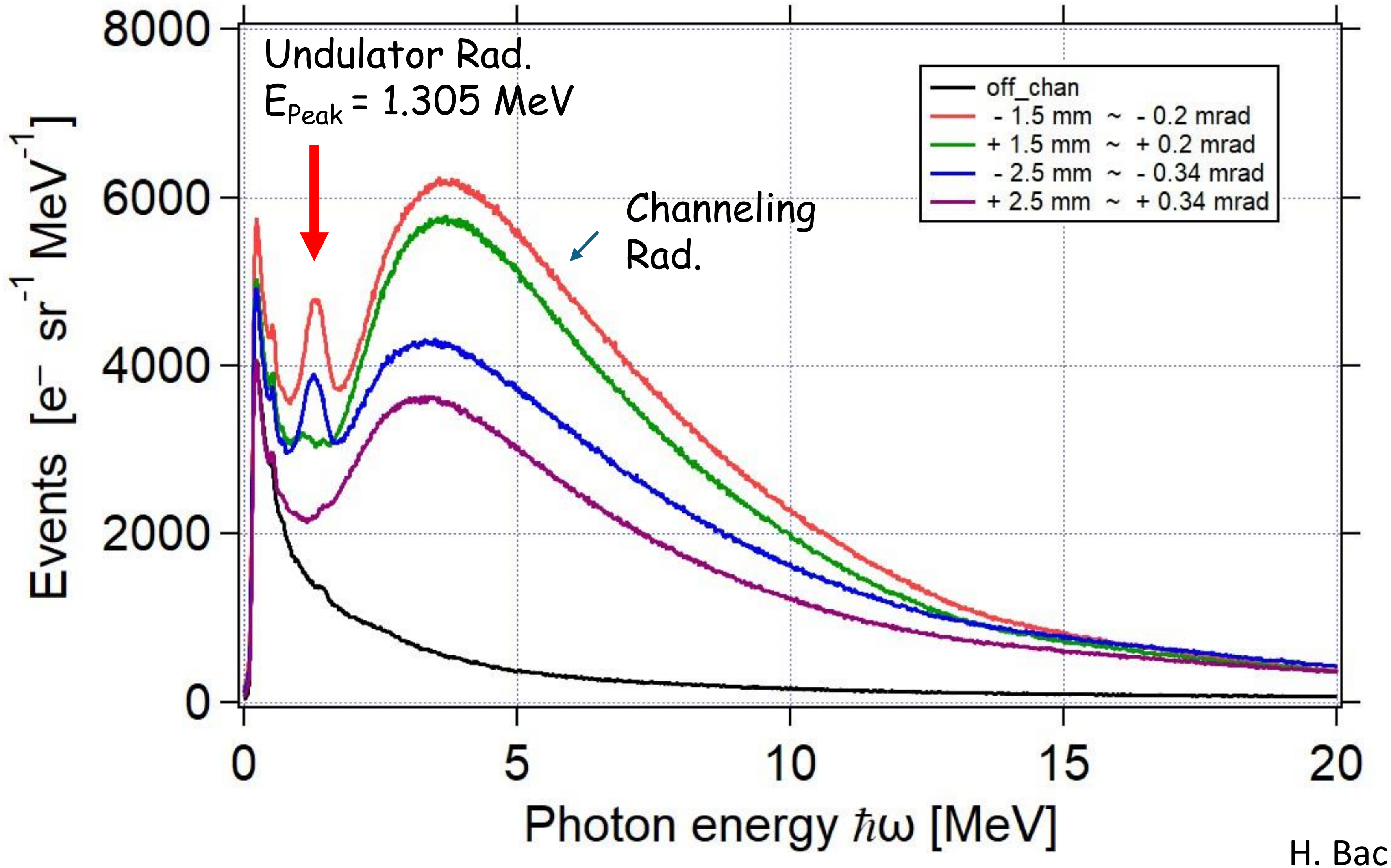
Experimental Setup (855) MeV e^-





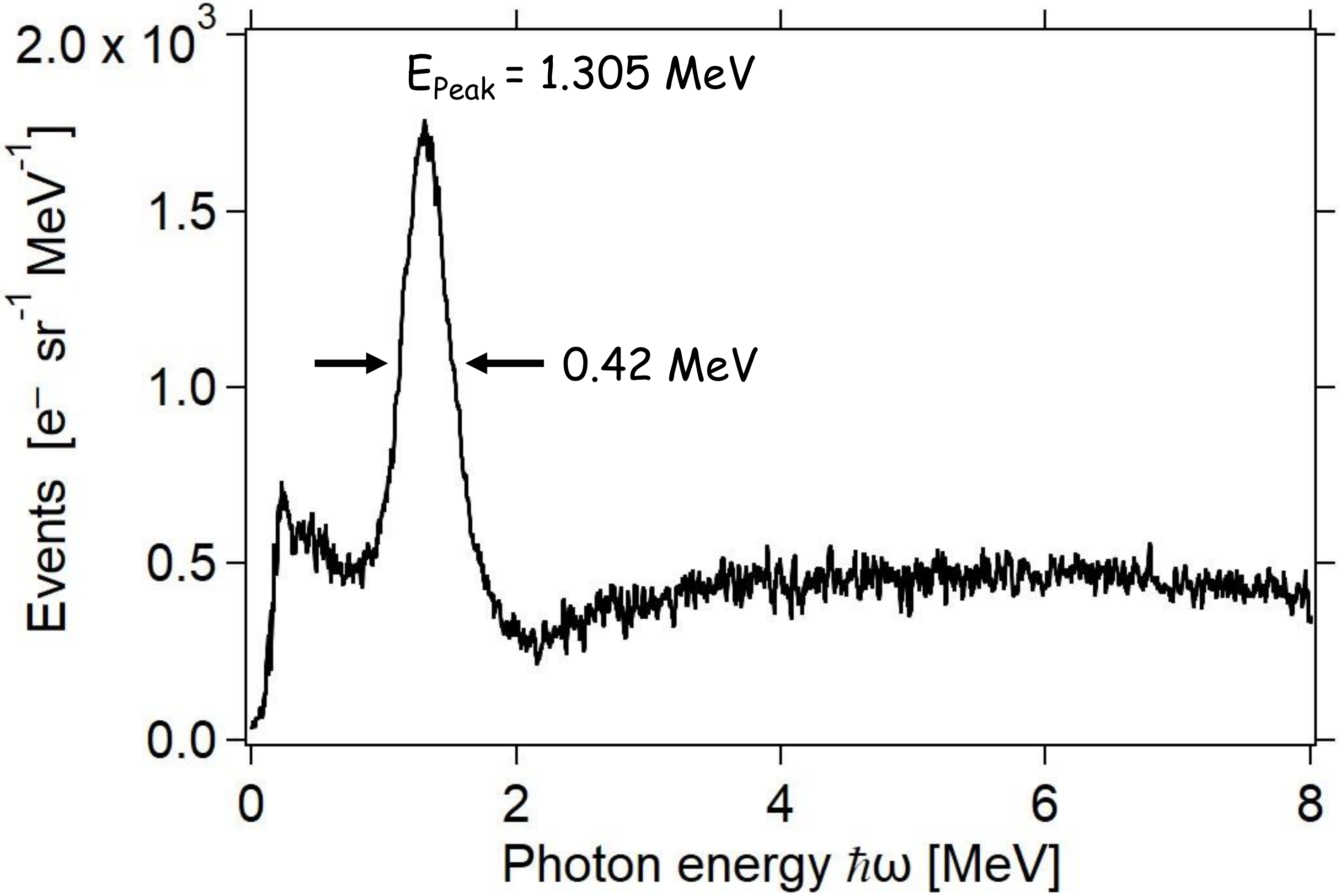
Ioso4_Undu
(110)
(111)
(11-1)
(100)
Intensity Ioso
θ [°]
100
80
60
40
20
0
-10
-5
0
5
10

Energy spectra, central position, 855 MeV



H. Backe, et al. arXiv:2504.17988

Difference Spectra, ± 0.2mrad, 855 MeV



E_{Peak} = 1.305 MeV

Sigma = 0.18 MeV

FWHM = 0.42 MeV

Relative bandwidth

Measured $\frac{\Delta E}{E} = \frac{0.42}{1.31} = 0.32$

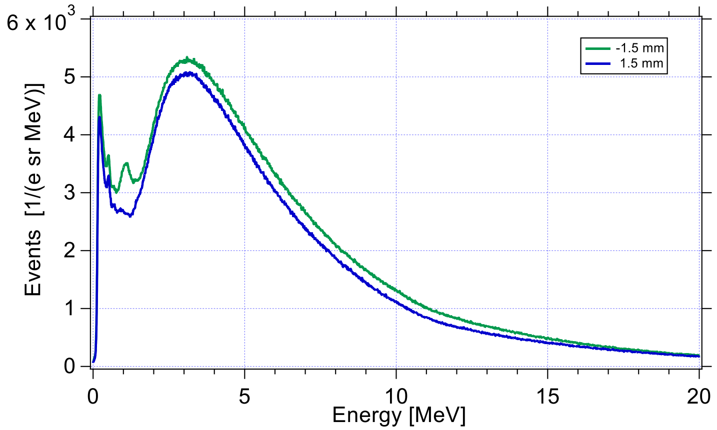
With $(\sin x/x)^2$

$$\frac{\Delta E}{E} = \frac{0.886}{N}$$

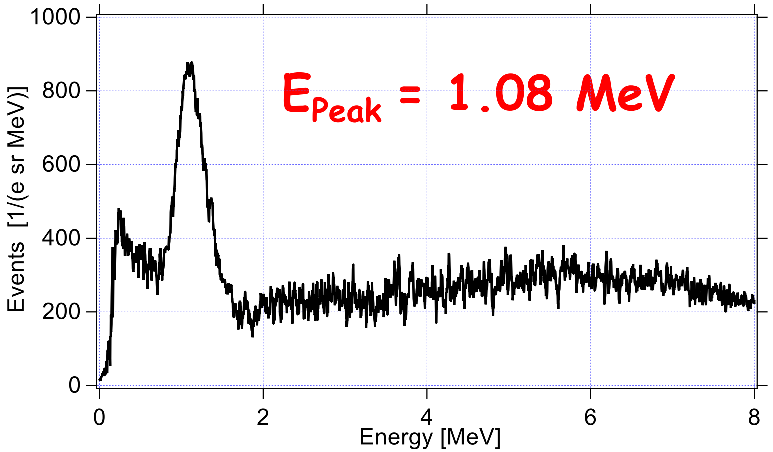
For N=4 -> = 0.22
For N=3 -> = 0.29

Spectra at electron beam Energy 765 MeV

$$\hbar\omega = n\frac{4\pi\gamma^2\hbar c}{\lambda\left(1 + K^2/2 + \gamma^2(\delta - \theta_x)^2\right)} = 1.06\ MeV$$



Difference Spectra (765 MeV)



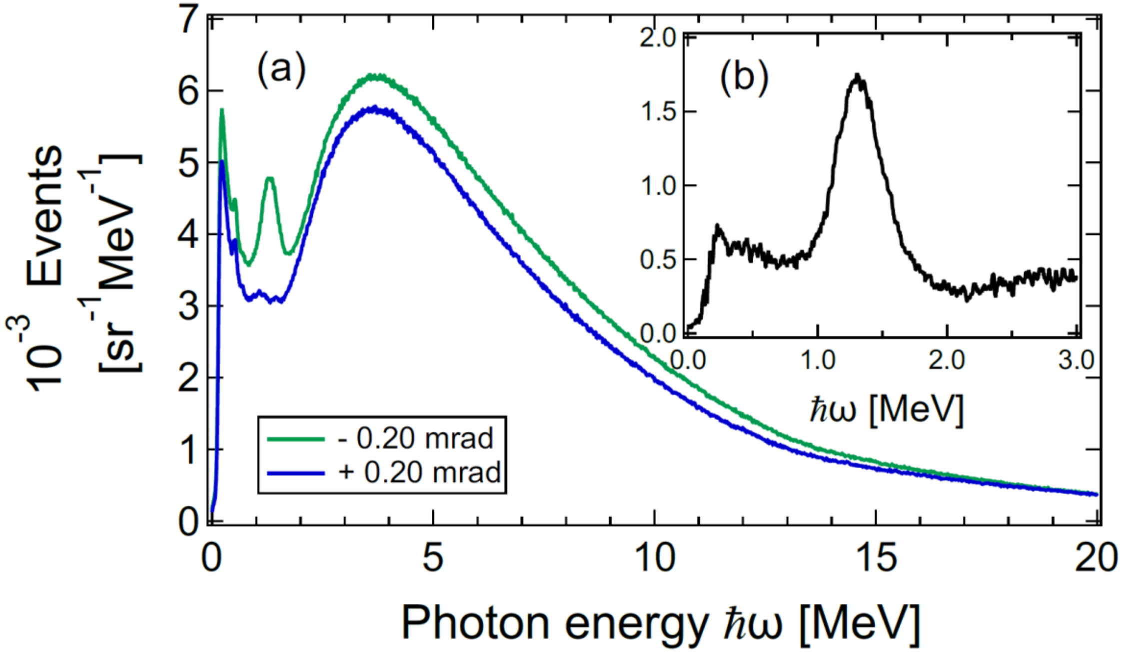
Energy scaling

Electron energy $$\left(\frac{855\ MeV}{765\ MeV}\right)^2 = 1.25$$

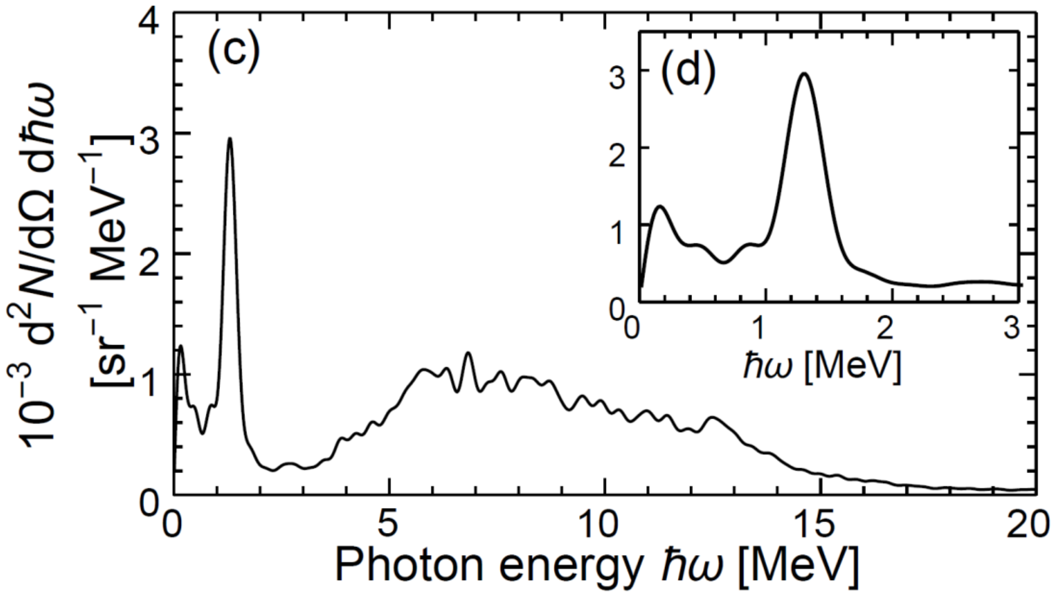
Measured peak energy $$\left(\frac{1.3\ MeV}{1.1\ MeV}\right) = 1.25$$

Comparison with simulation calculations

Experiment



Calculations



H. Backe, et al. arXiv:2504.17988

A.V. Korol, A.V. Solov'yov, arXiv:2405.20037 (2025)

First Conclusion

- First observation of crystalline undulator radiation.
  Peak energy, peak width and intensity agree
  with predictions.

- Undulator radiation at (110) and (111) planes

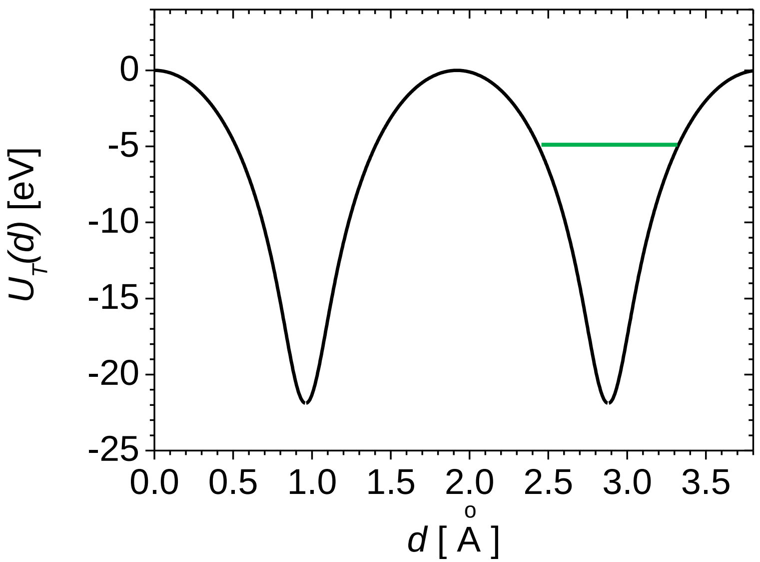
- New sensitive experimental method for the peak detection
  supported with simulation calculations

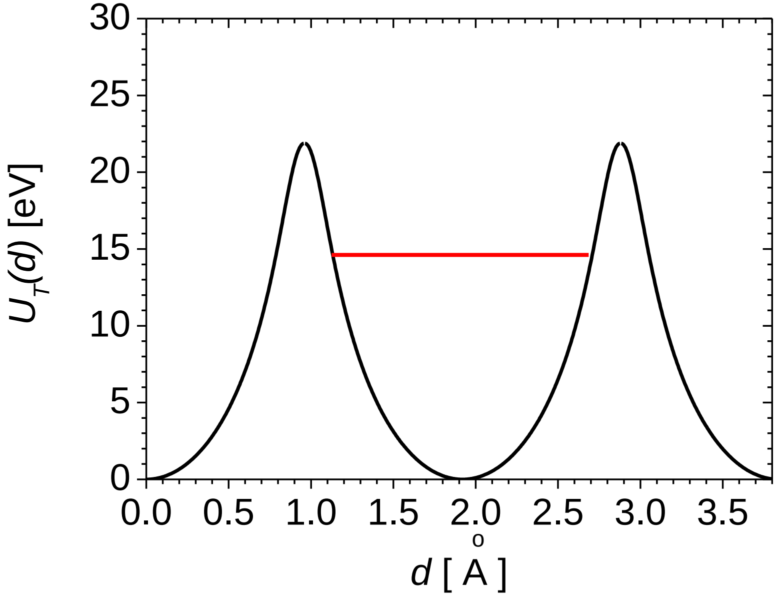
- High quality diamond crystals for the backing

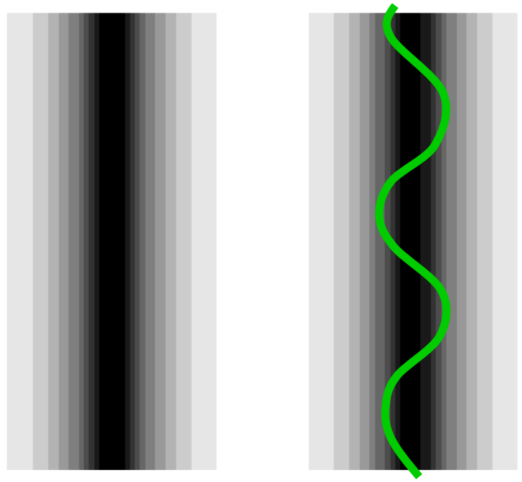
- Production of new crystals with smaller period length -> higher energy

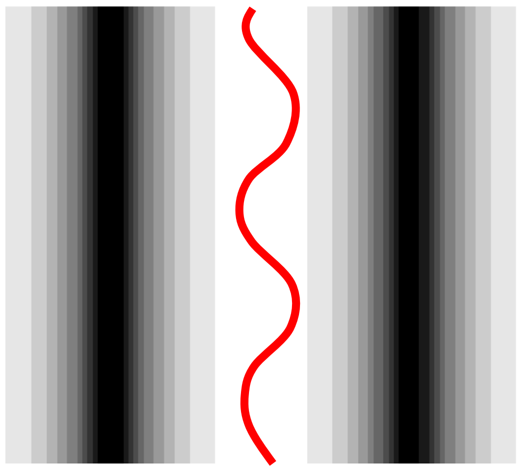
- γ-ray source for nuclear physics

Electrons versus Positrons

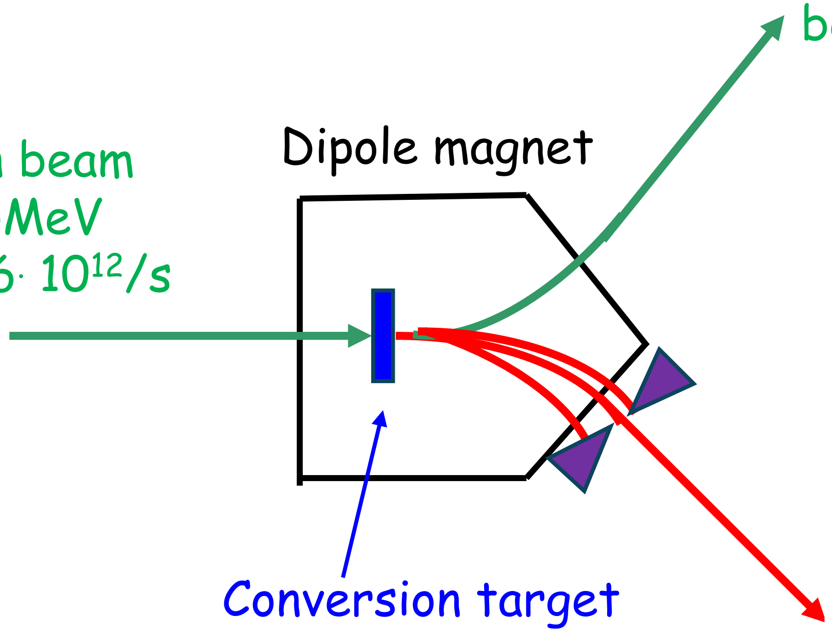


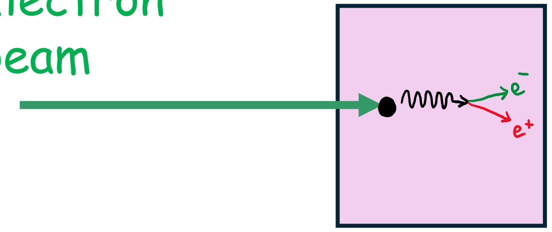




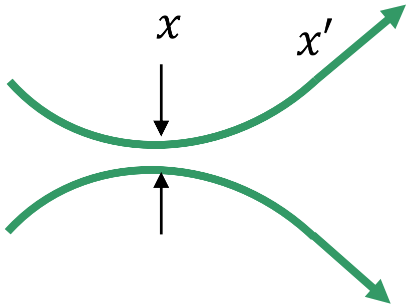


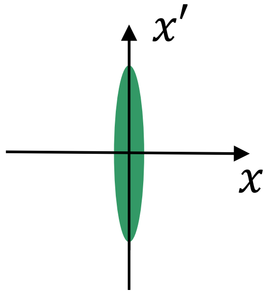
Pair production with the MAMI beam in combination with a monochromator





High quality Positron beam @ MAMI





vertical

MAMI: $\varepsilon_x = x \cdot x'$

$= 1\, mm \cdot \mu rad$

$= 10\ \mu m \cdot 0.1 mrad$

Emittance $\varepsilon_x = x \cdot x' = \frac{F}{\pi} = const$

Thin target for Positron production

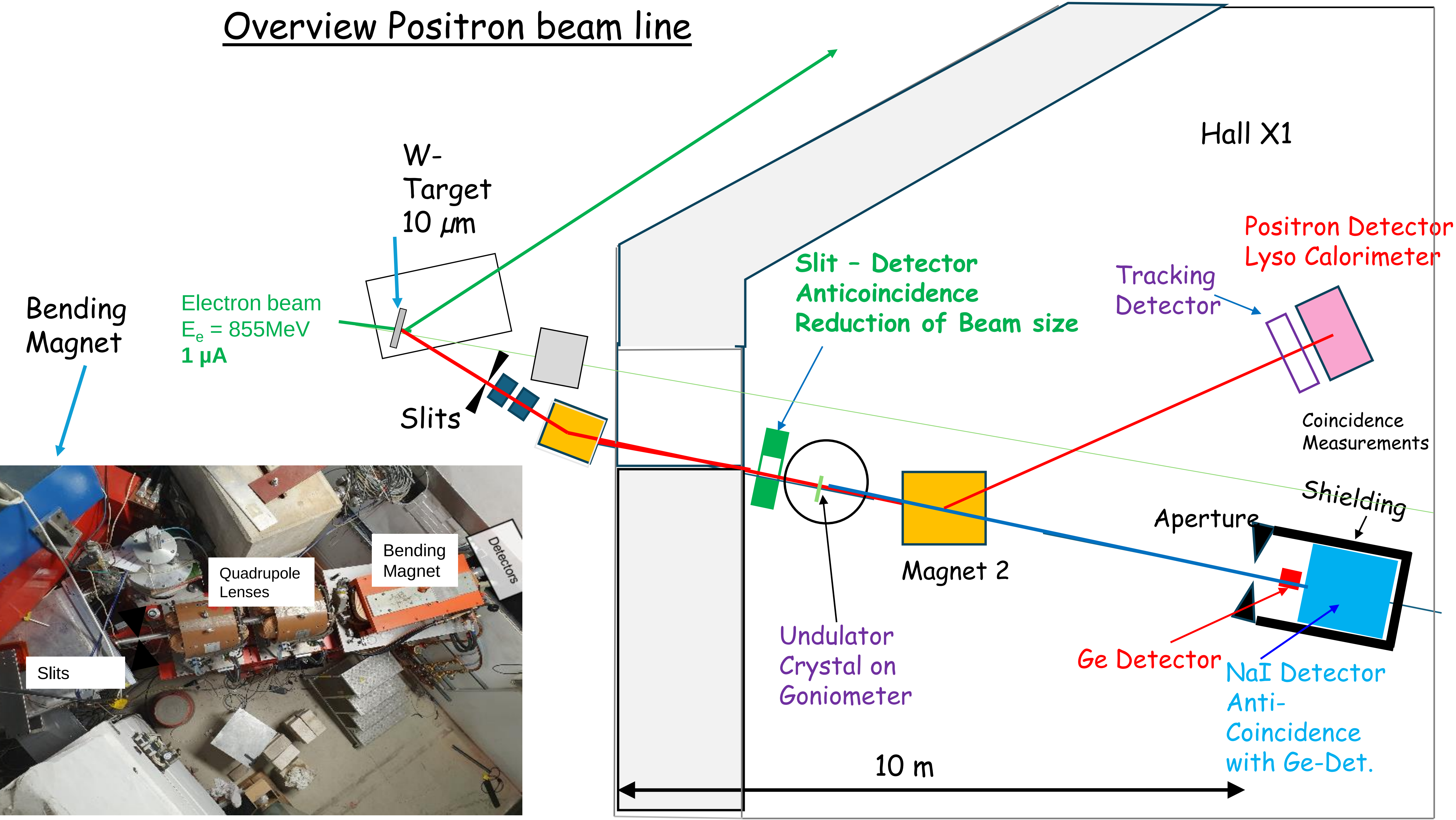
$10\ \mu m\ \ W \ \rightarrow Scattering\ \sigma_S = 0.94\ \mathrm{mrad}$

$$\sigma_p = \cong \frac{1}{\gamma} = 1\ \mathrm{mrad}\ @500\mathrm{MeV}$$

Emittance of Positrons: $\varepsilon_{e+} = 10\ \mu m\ \cdot\ 1.4\, mrad$

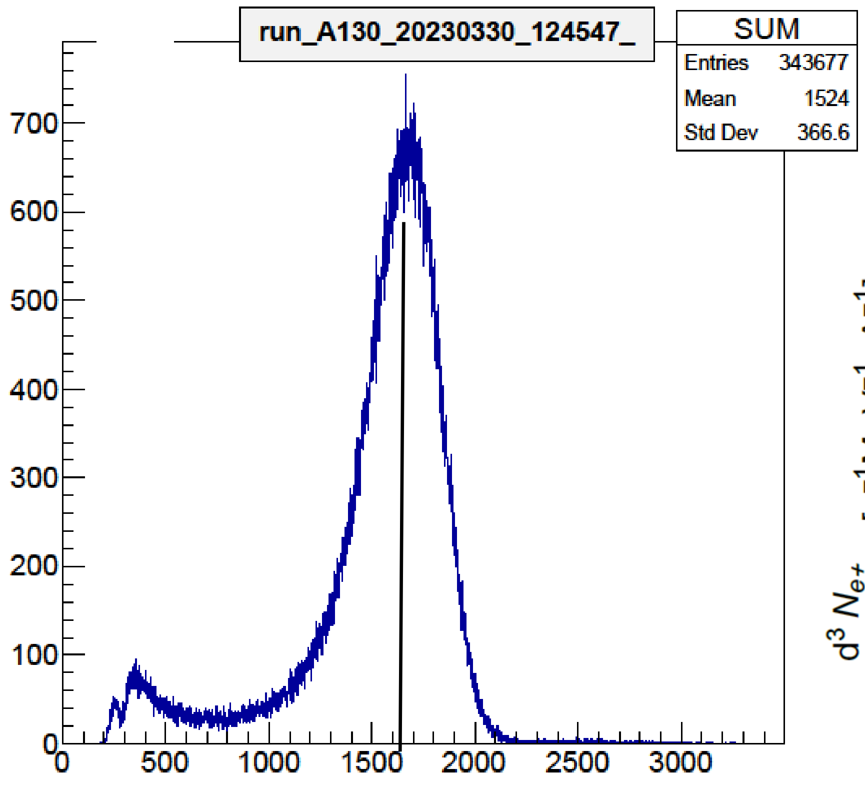
$= \ \ 1 mm \cdot 0.014\, mrad$

Overview Positron beam line

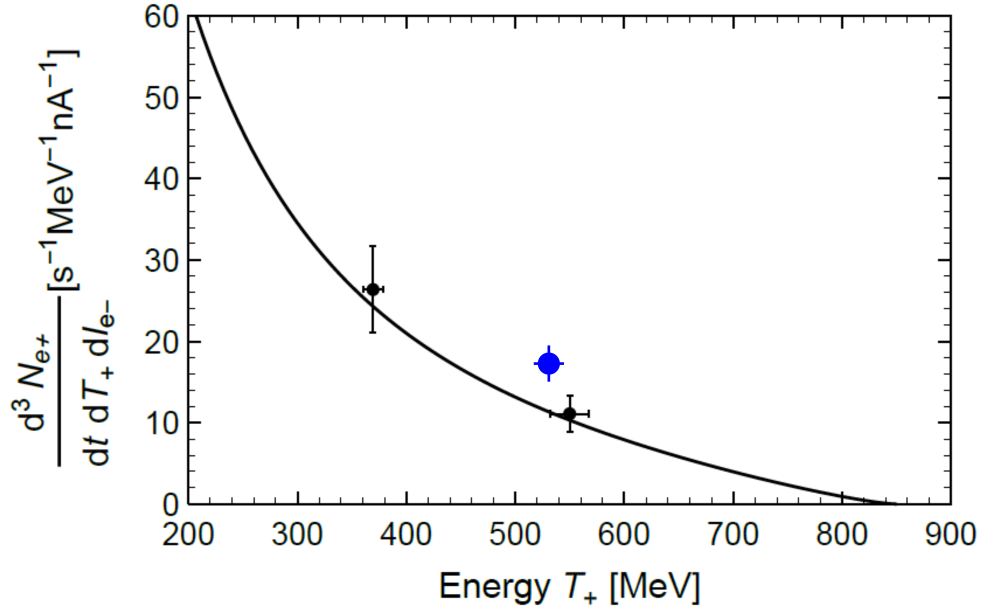


Production Rate

10 μm W Target
Slit width 3mm
~4.5 MeV



530 MeV



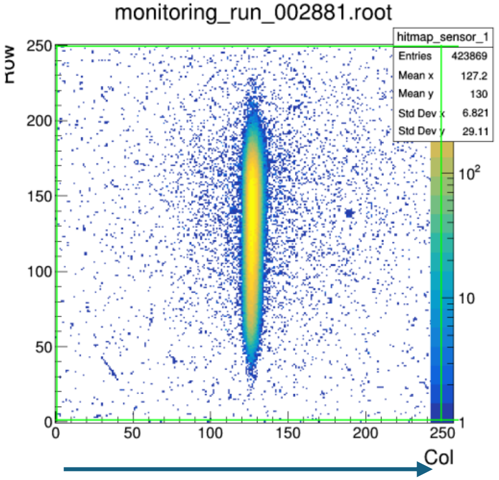
$$17.3 \frac{1}{s \cdot nA \cdot MeV}$$

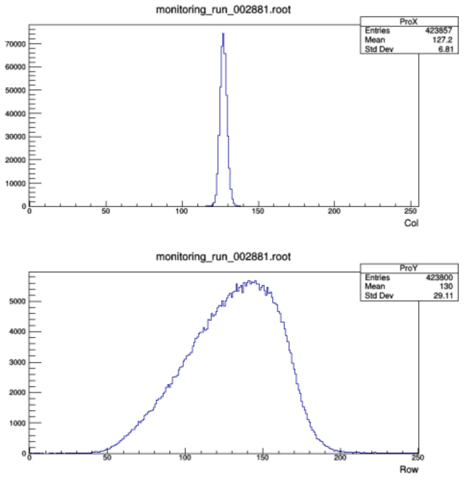
Max. e-current (without shielding) ~1 μA ->
Max. positron rate **20 kHz**

Flat 30 μm Si crystal (100)

Direct beam

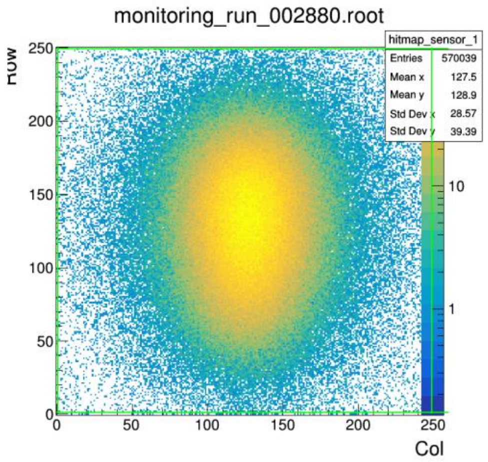
20 mm horizontal

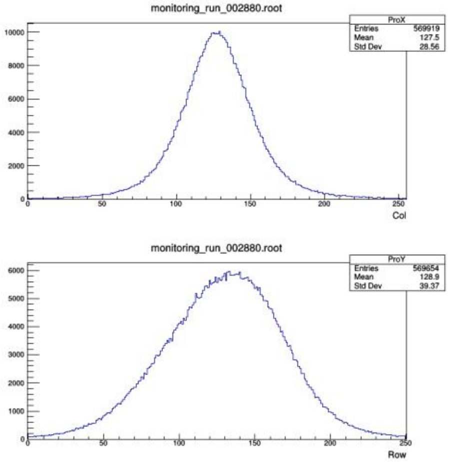


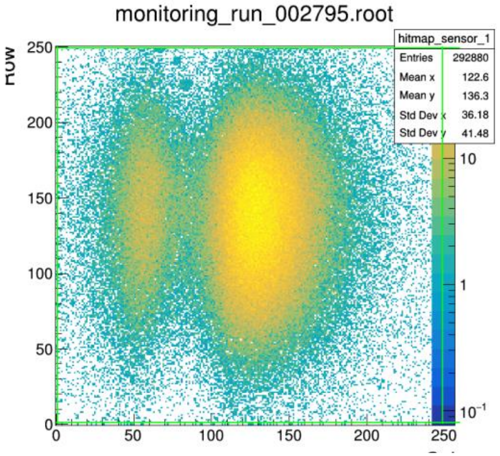


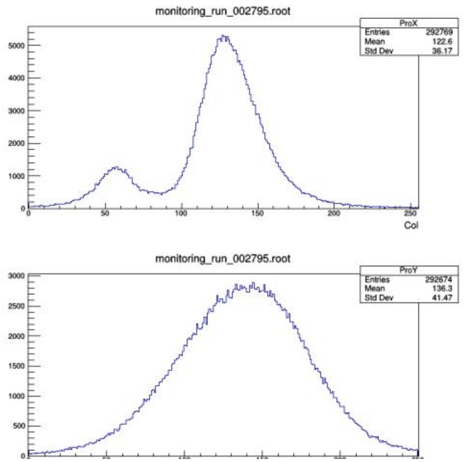
20 mm vertical

900









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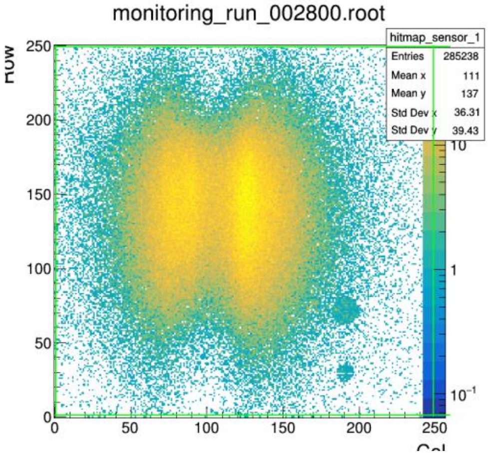

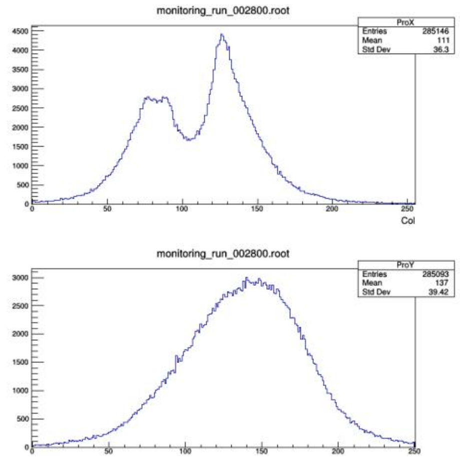

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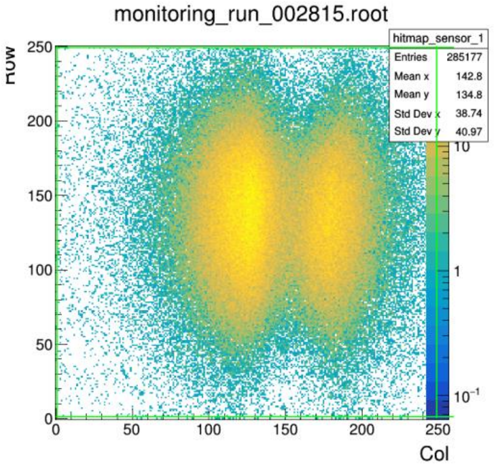
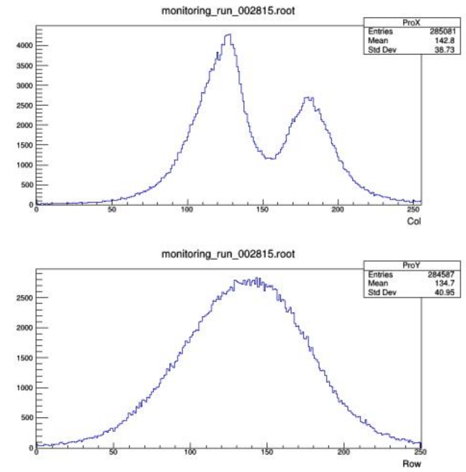
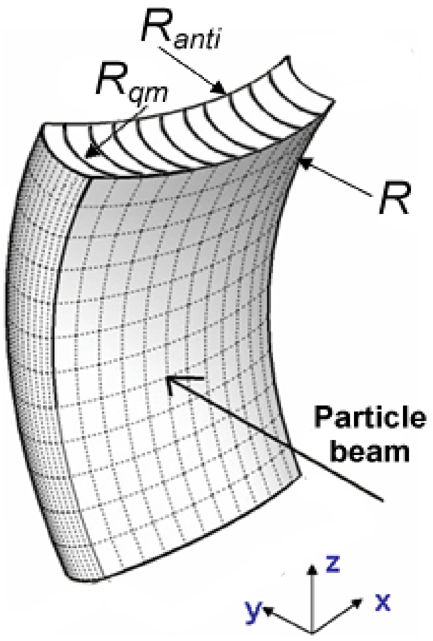
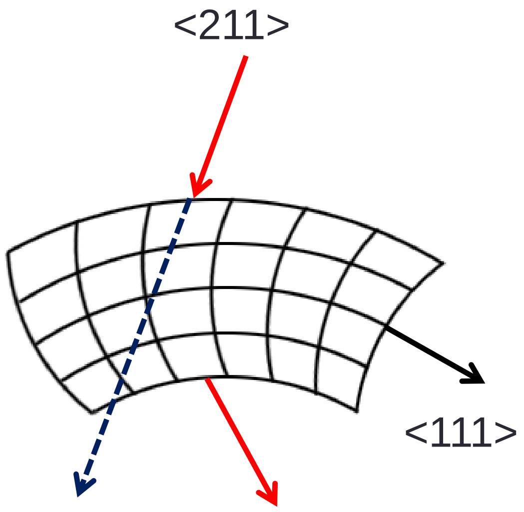




345

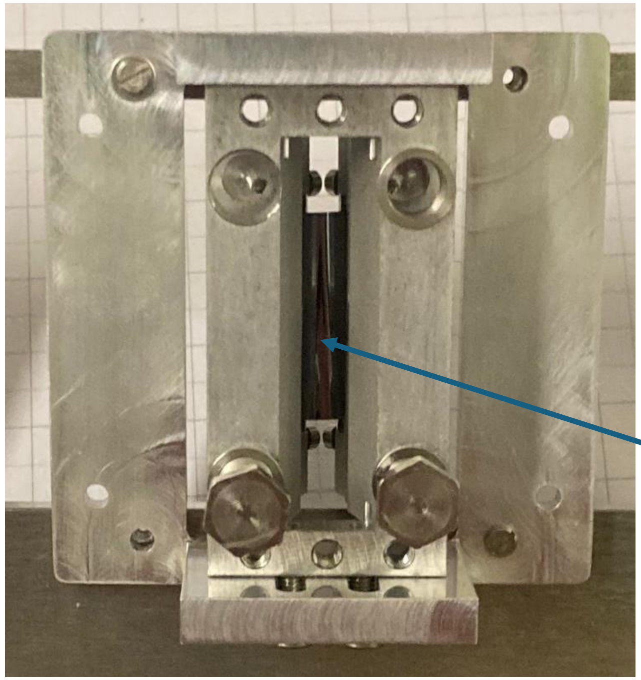
Positron beam steering in bent crystals

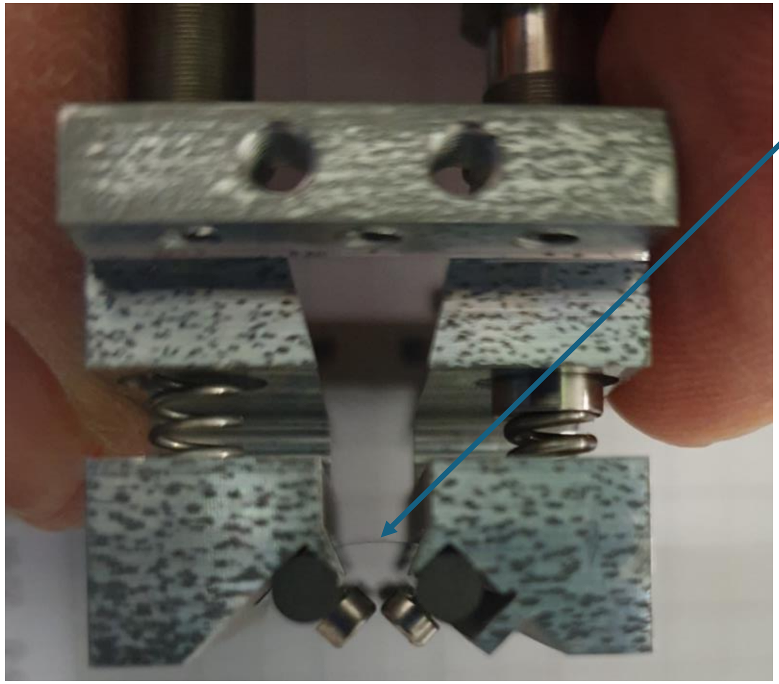


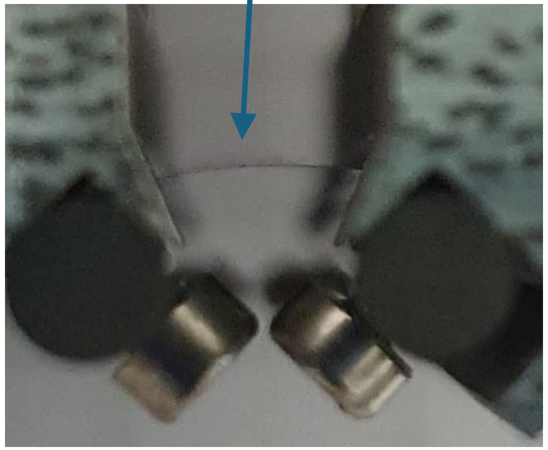


Guidi, V., et al.,, 2009. Journal of Physics D Applied Physics42(18).
Germogli, G.,NIM B, 2015. 355: p. 81-85

Thickness along the beam: 29.9±0.1 μm Bent planes, exploiting quasimosaic effect (111)
Bending angle: 970±10 μrad

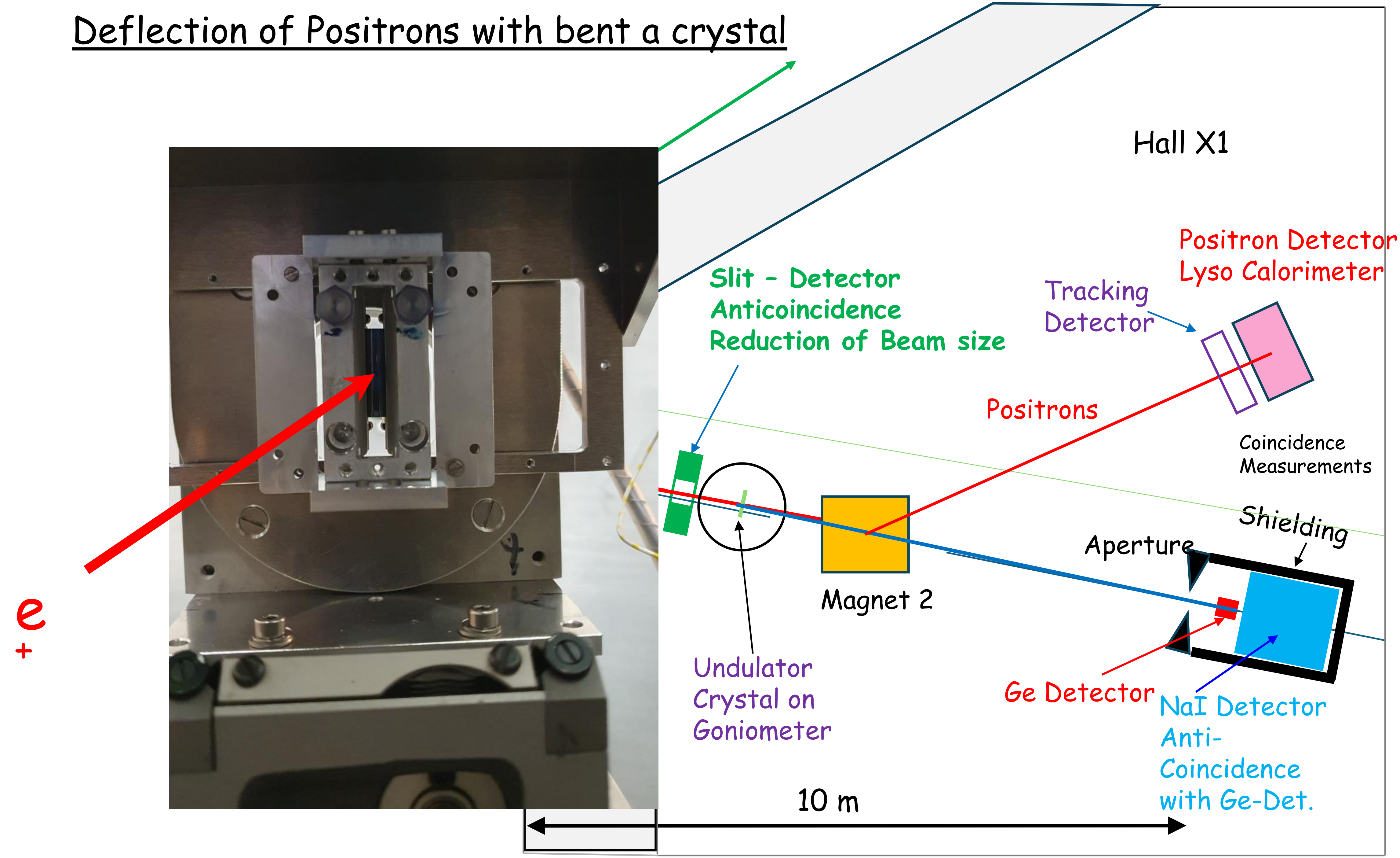






Bent crystal

Deflection of Positrons with bent a crystal

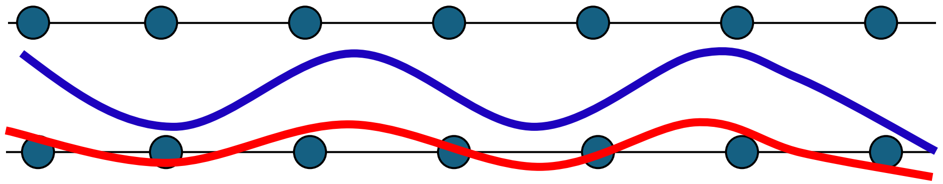


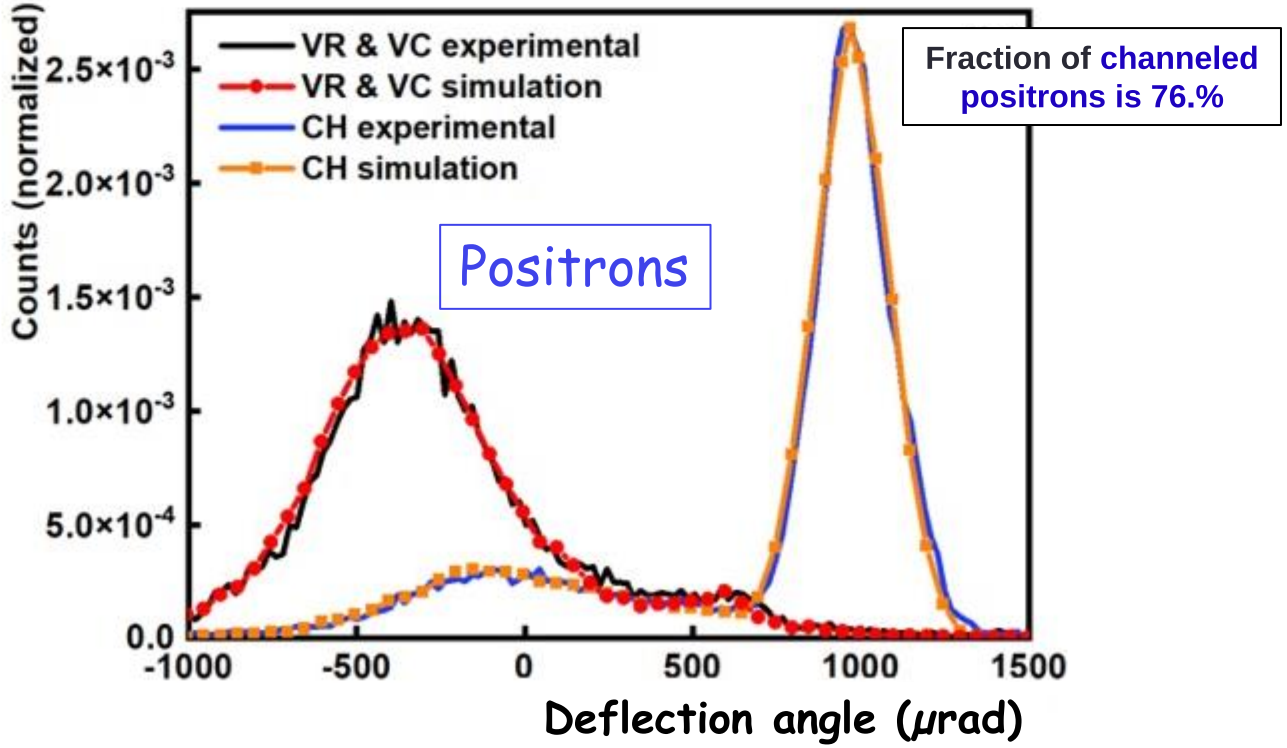
Channeling efficiency e+ vs e-

Advantage of positrons for CLS –> higher channeling efficiency!

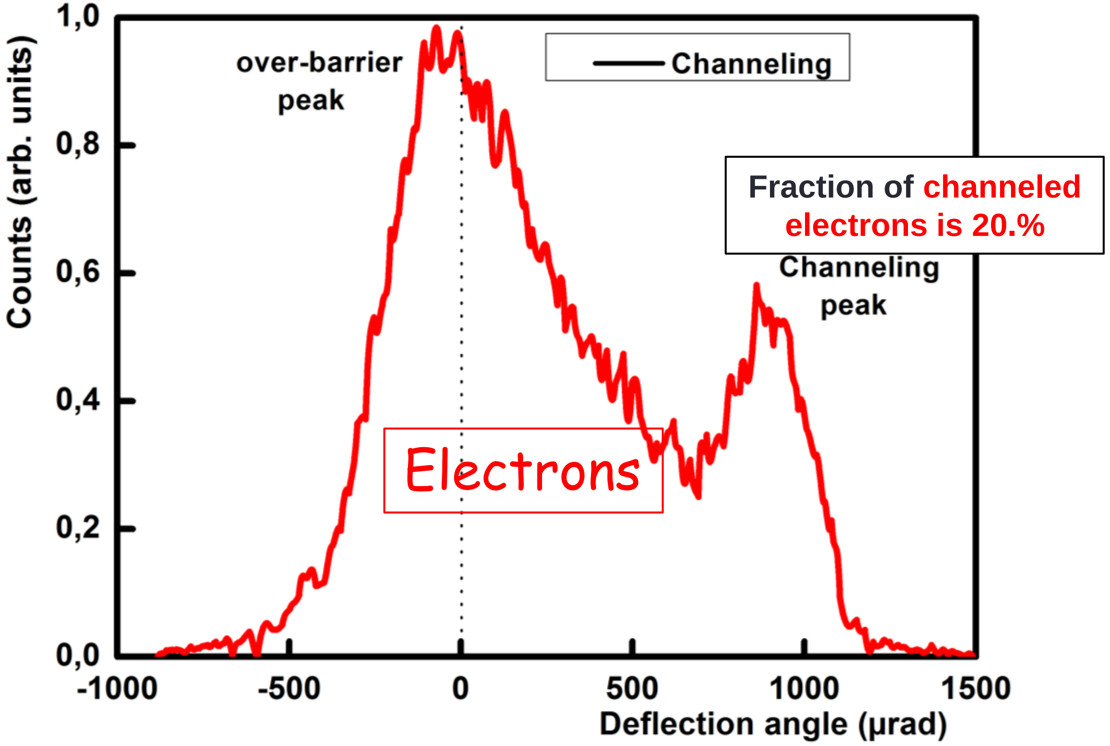
positron

electron



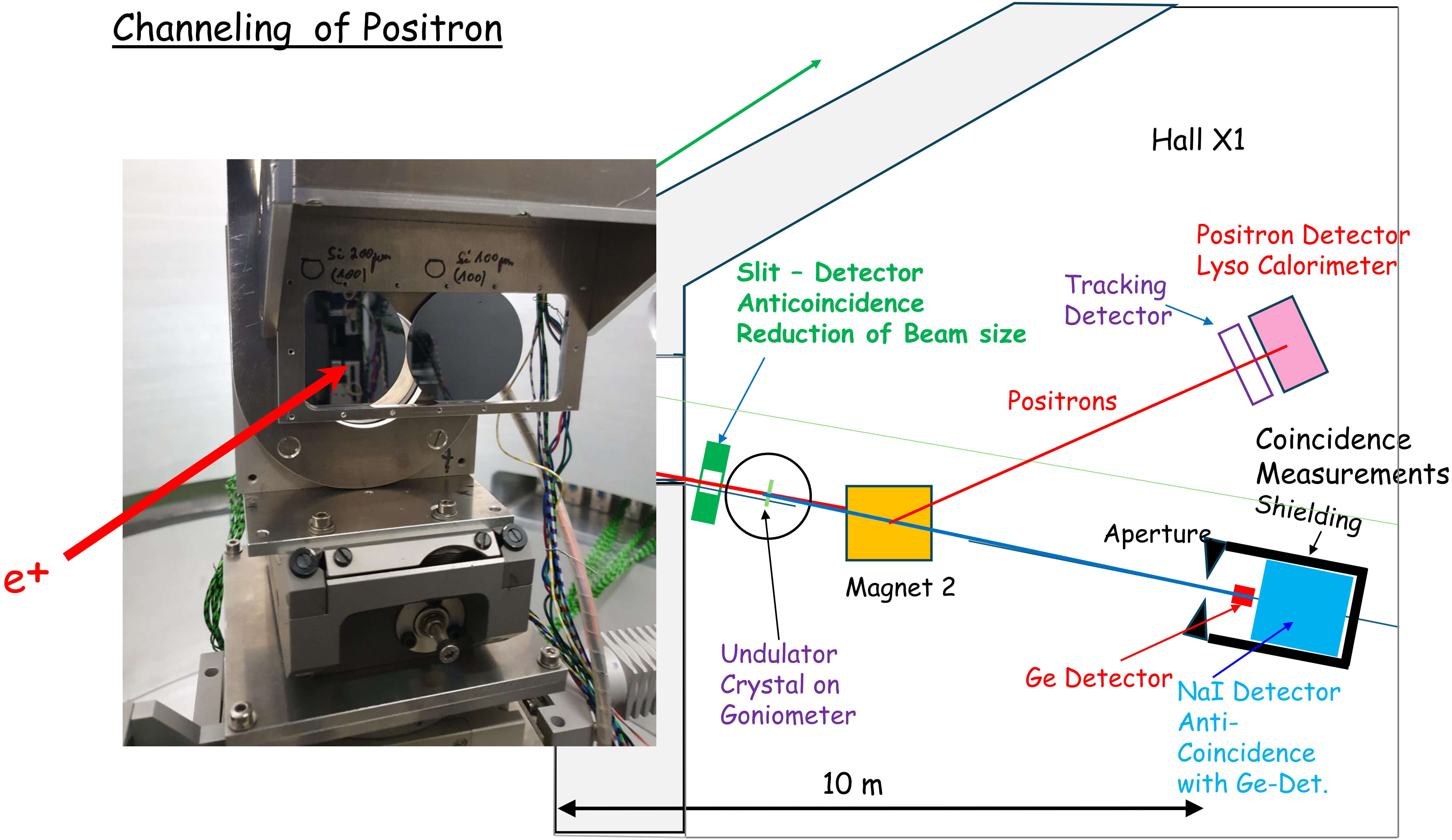


Mazzolari, A., Backe, H., Bandiera, L., et al., Phys. Rev. Lett. 135, 205002 (2025)



Mazzolari A., Bagli E., Bandiera L., et al., Phys. Rev. Lett. 112,135503, (2014)

Channeling of Positron

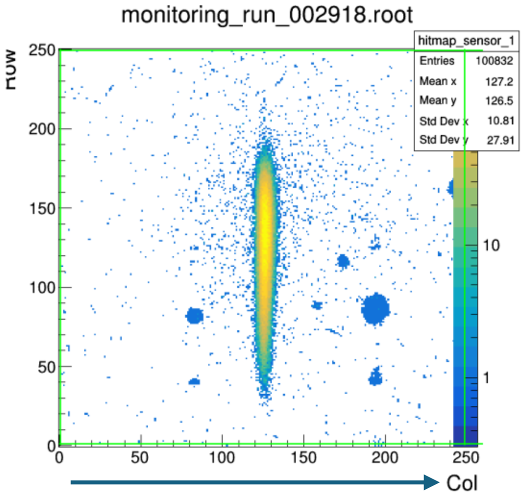


200 μm (100) Si crystal

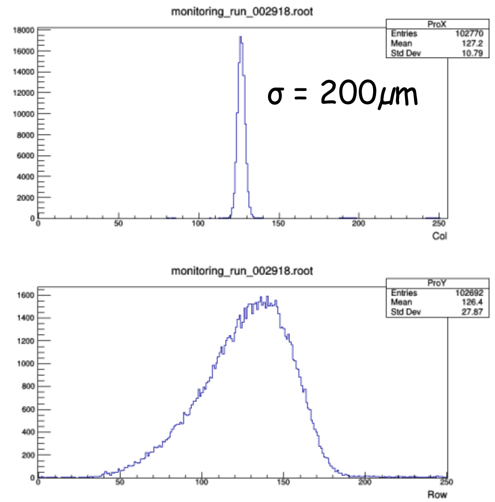
With oriented crystal

Without crystal, direct beam

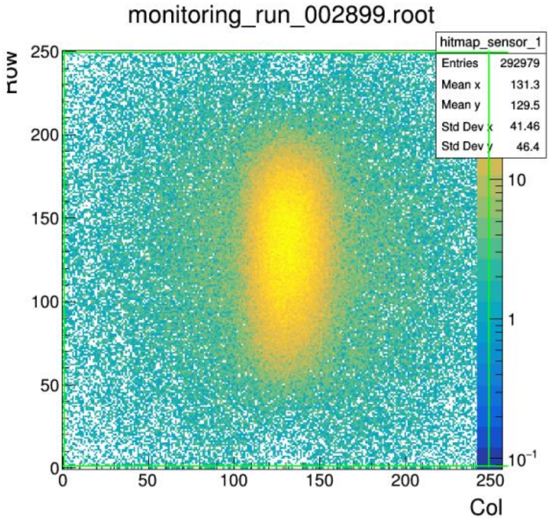
20 mm horizontal

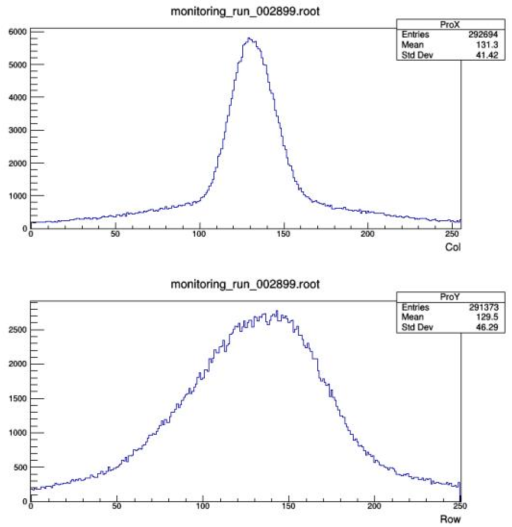


20 mm vertical



Detunig 0mrad

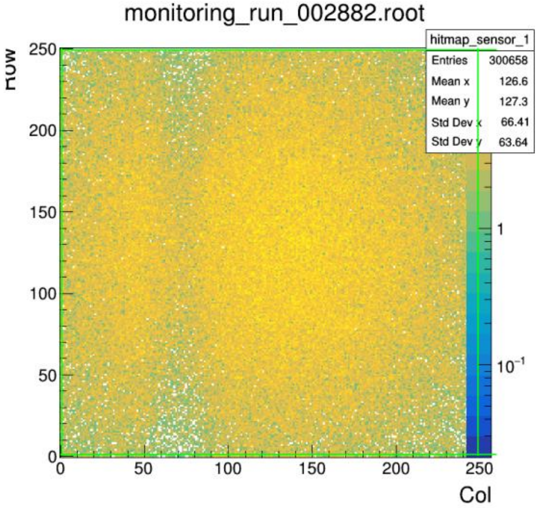


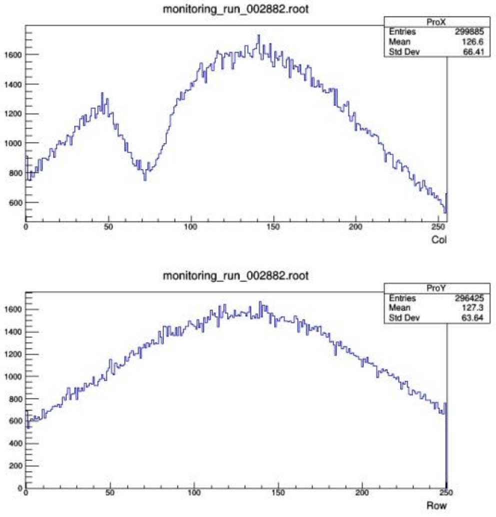


Cradle = 0.547° ,

"Random" orientation of crystal

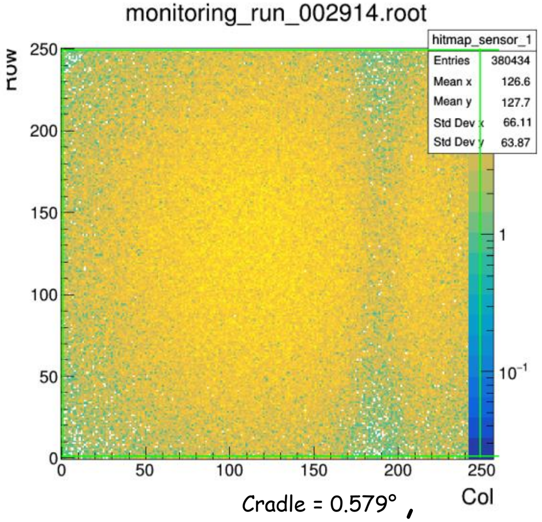
Detunig -0.56 mrad

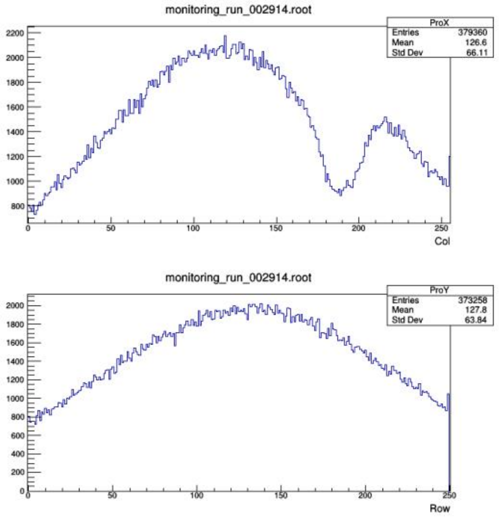




Cradle = 0.515° ,

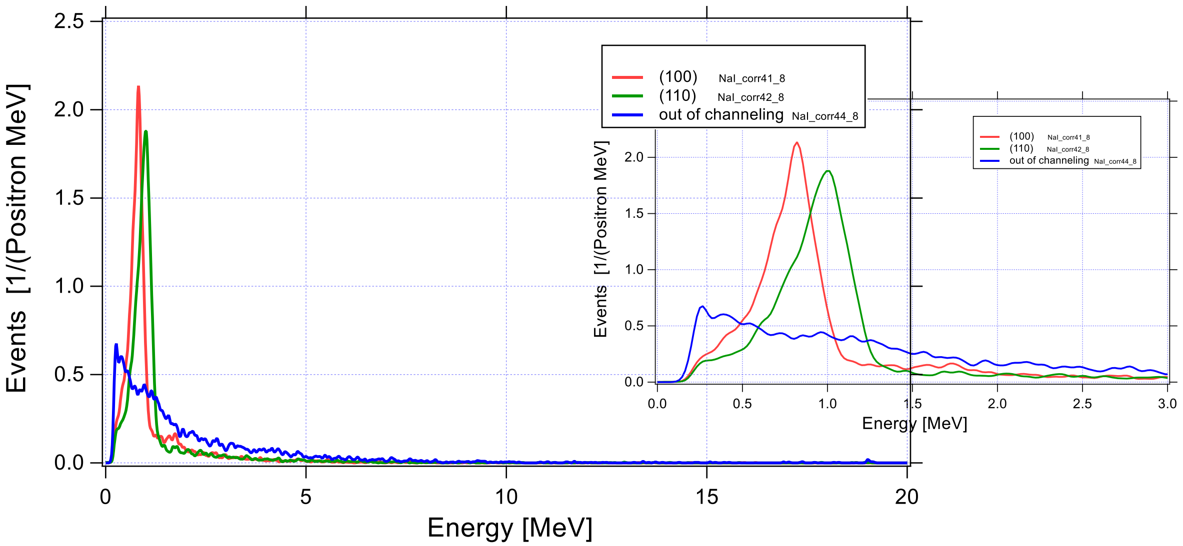
Detunig 0.56 mrad





Cradle = 0.579° ,

Channeling radiation with 530 MeV Positrons



200 µm Si

Coincidence measurements

Aperture:
Diameter 10 mm
 in 9m distance

Observation angle 0.55mrad

Conclusion positron beam

- Positron beamline is available.
- About 20 kHz Positrons with 530 MeV
- Experiments with the deflection in bent crystals
  Fine structure
- First Channeling Radiation measurements
- Ready for Channeling experiments
-

Thanks for your attention

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INFN, Section of Ferrara,
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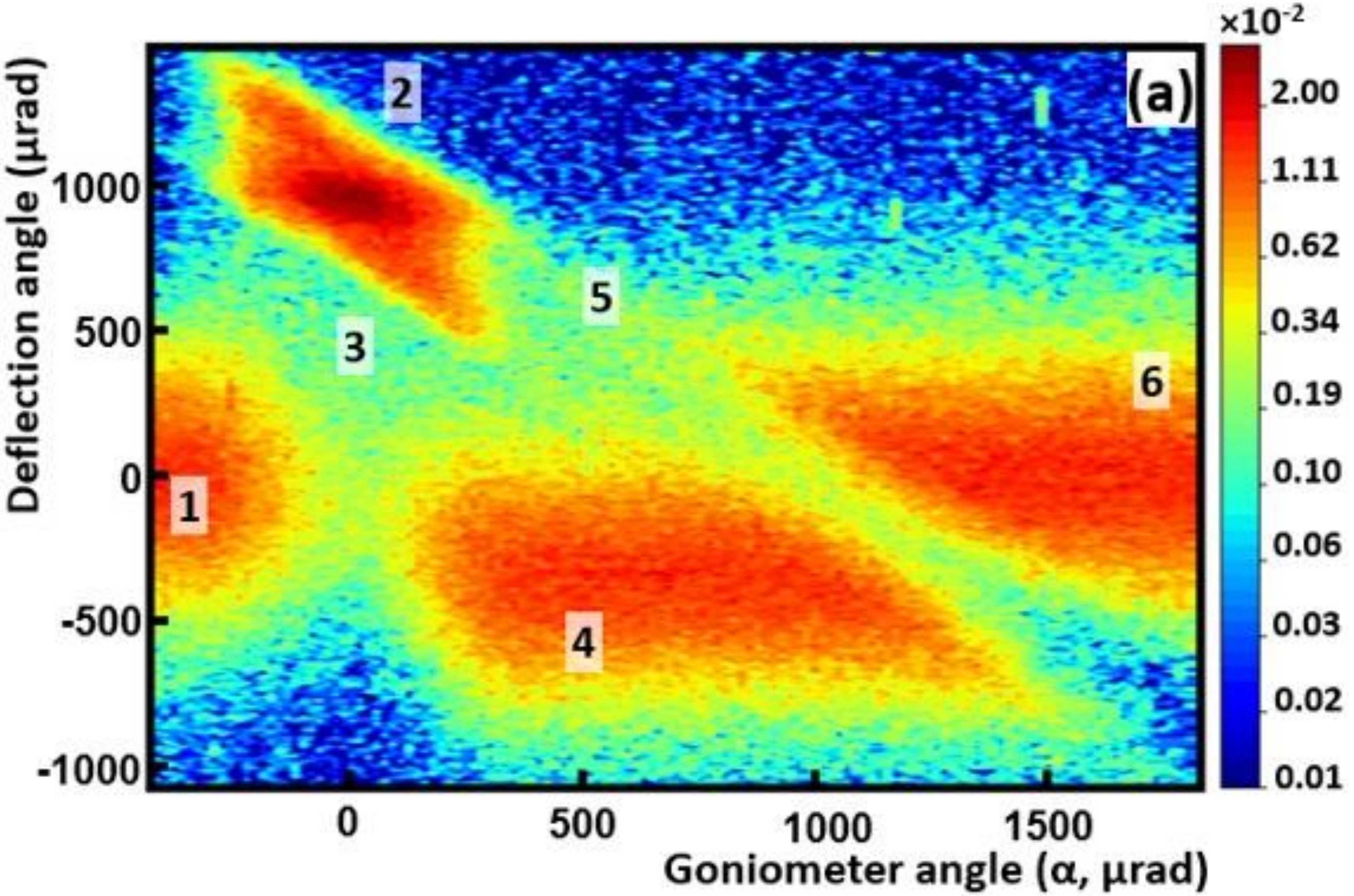
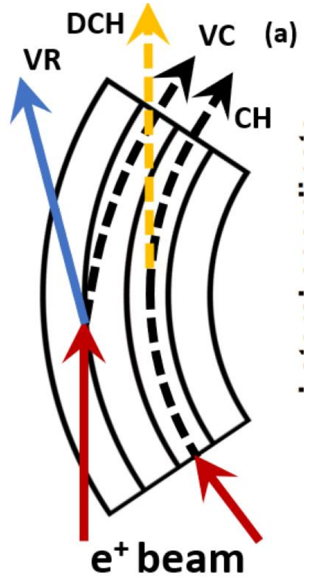
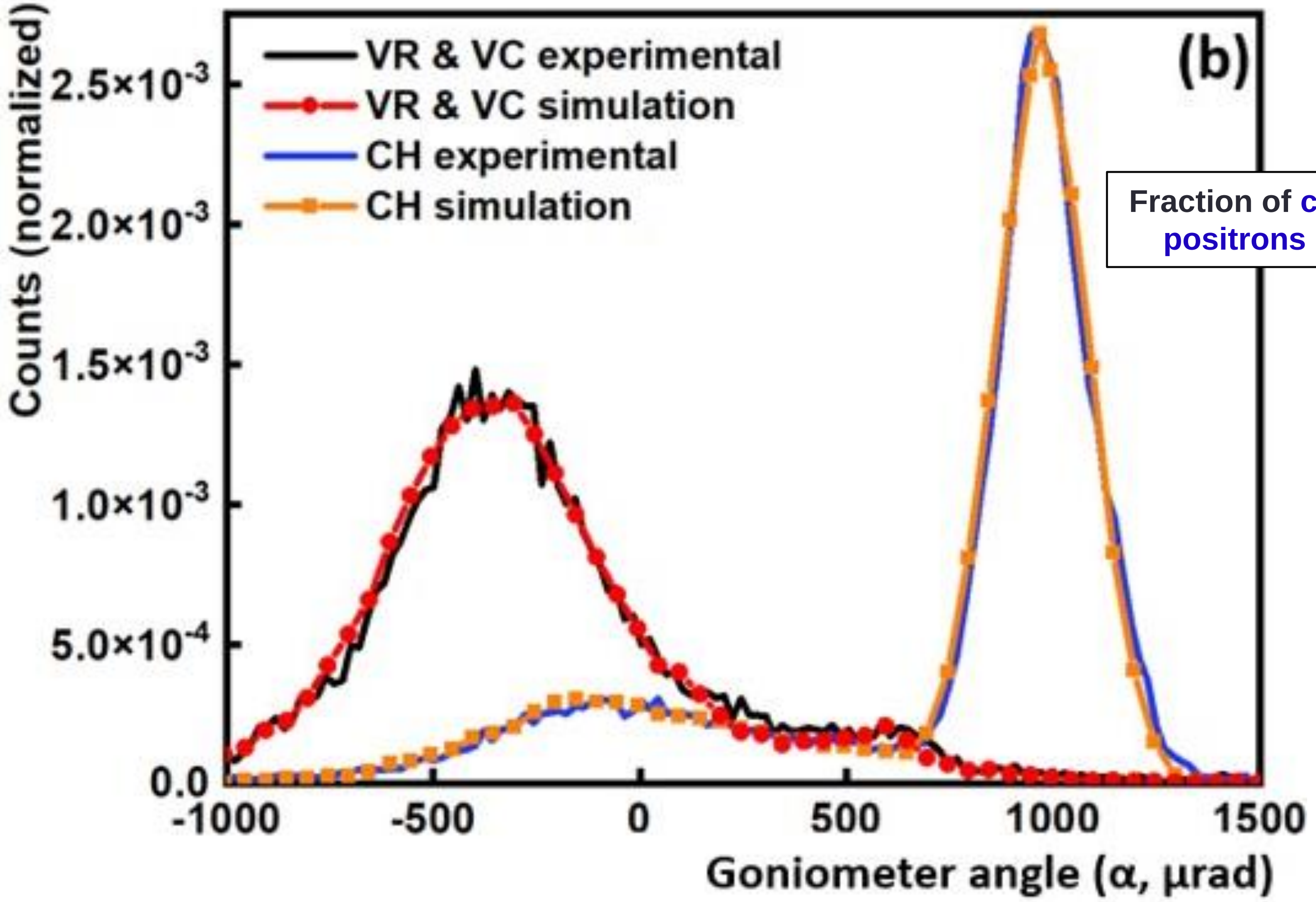
Experimental results on beam steering of 530 MeV positrons





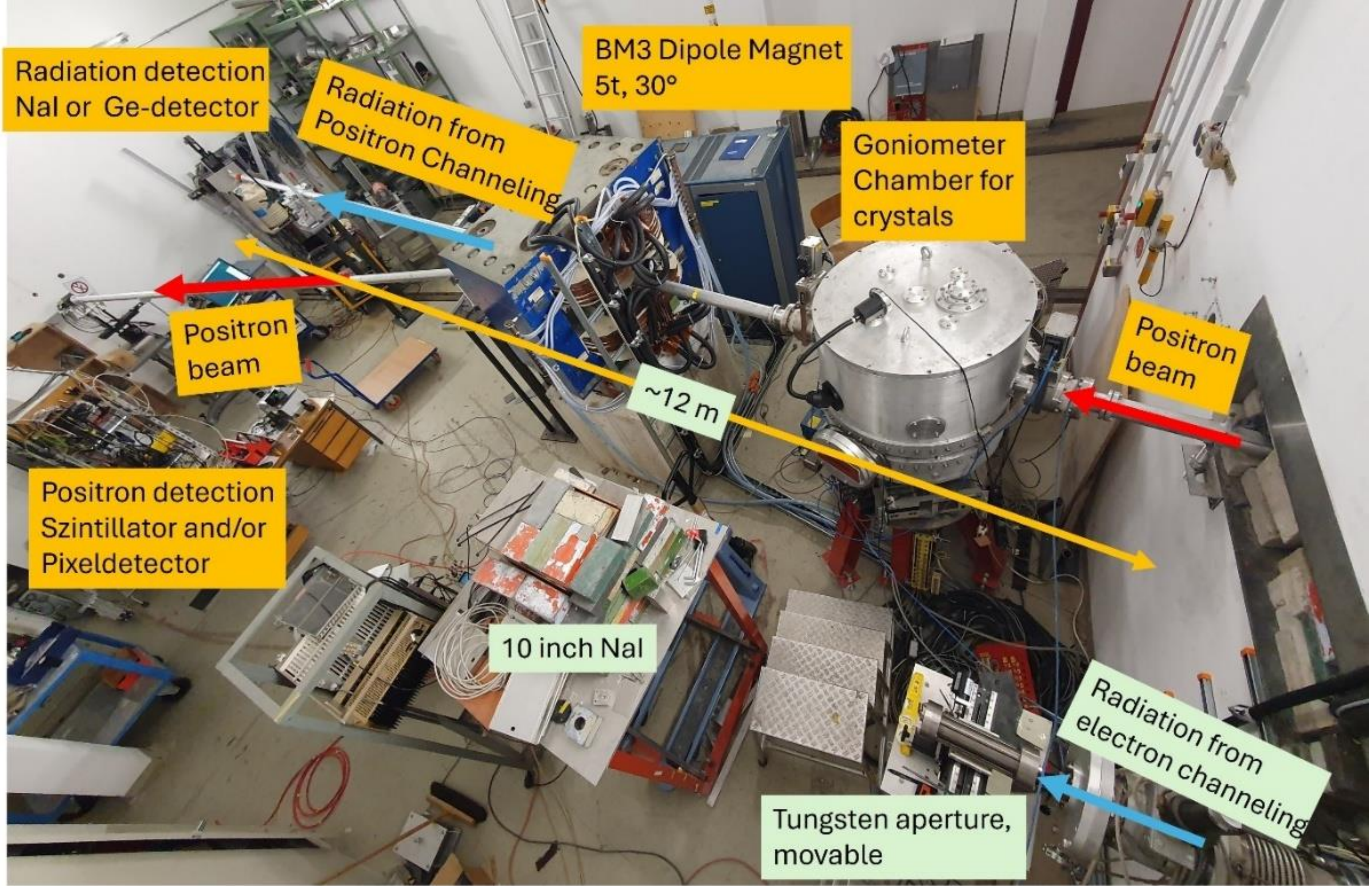
Mazzolari, A., Backe, H., Bandiera, L., et al., (2024)
arXiv:2404.08459

Channeling of Positrons in a bent crystal

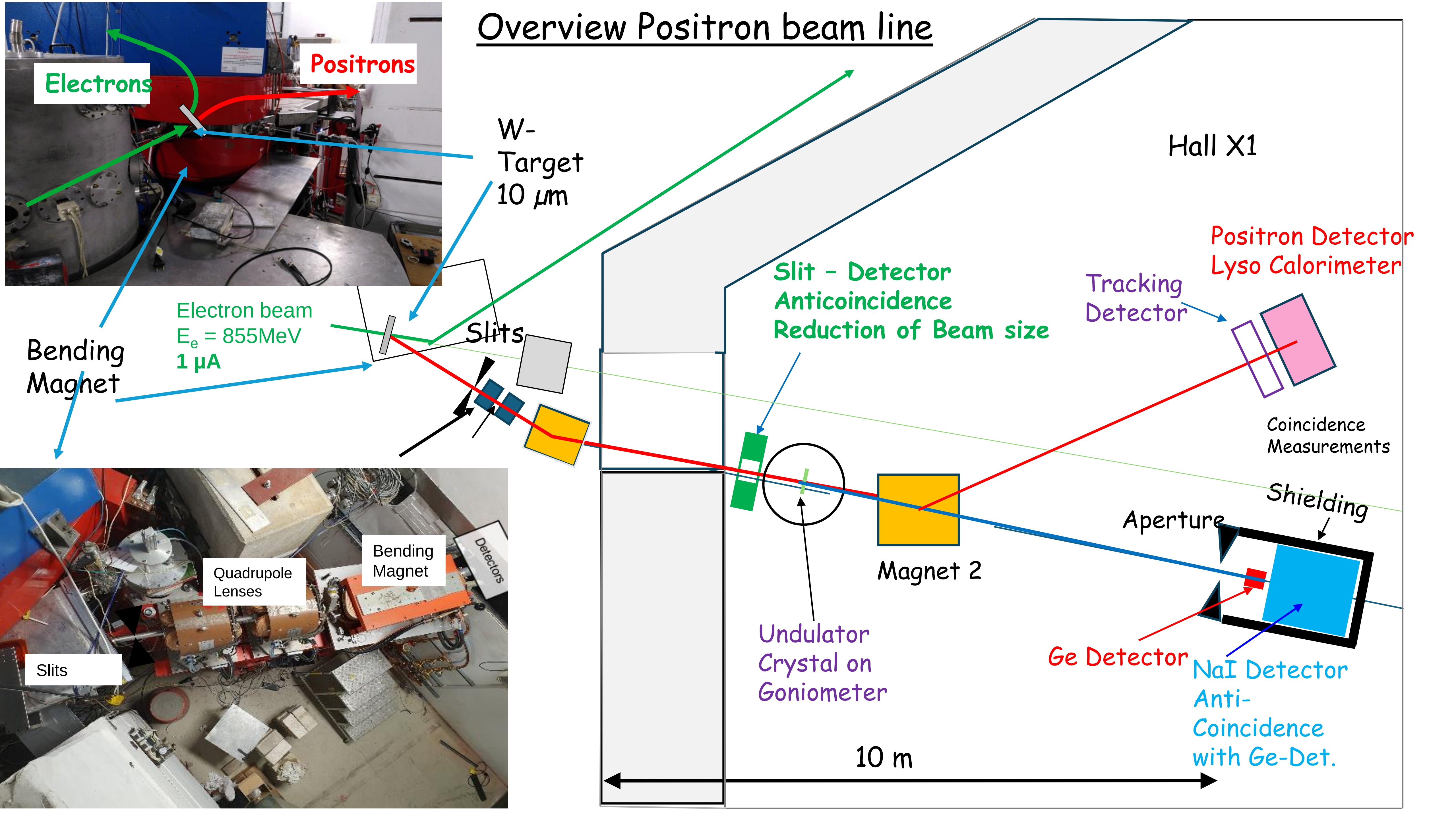


Fraction of channeled positrons is 76.%

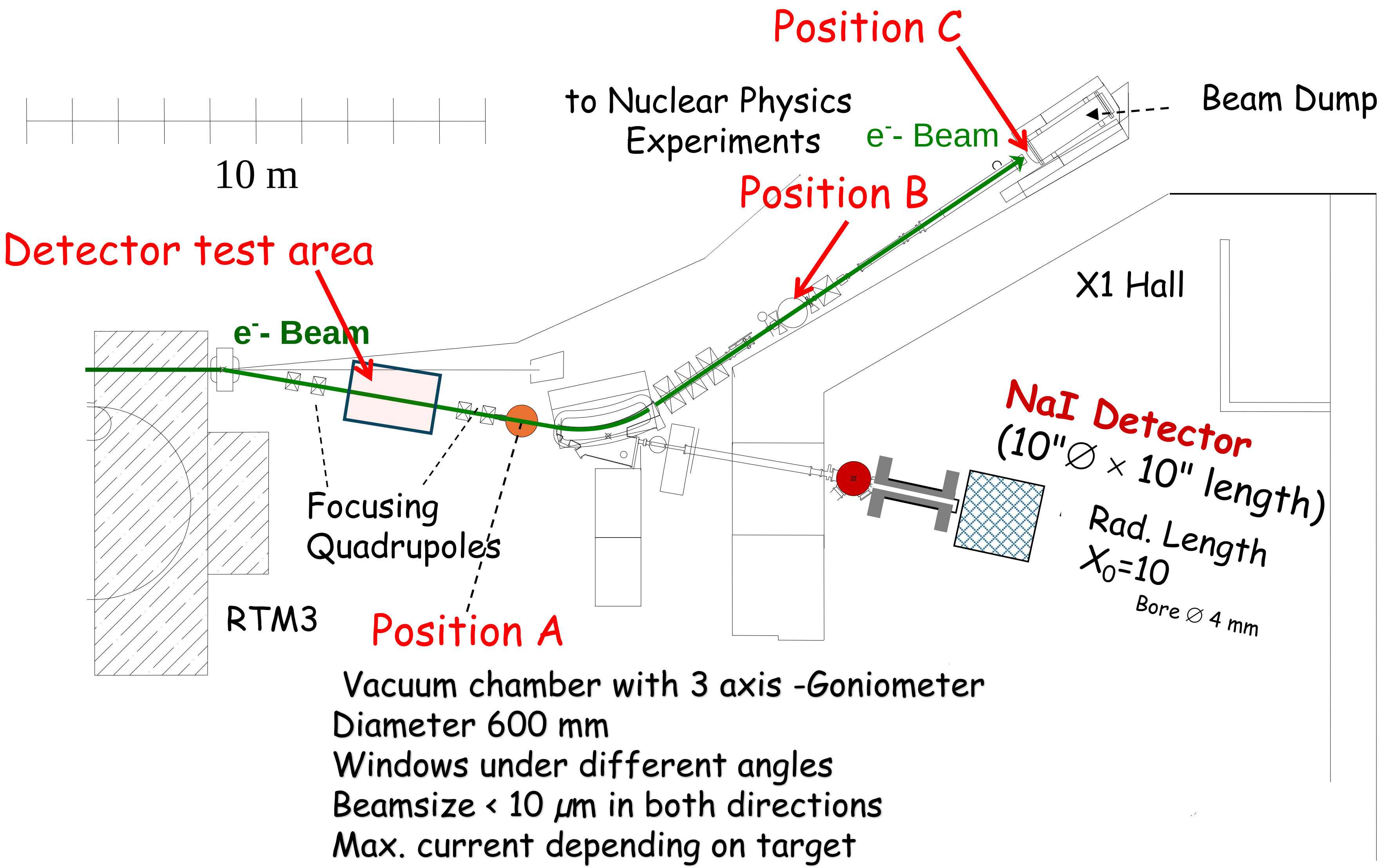
*Mazzolari, A., Backe, H., Bandiera, L., et al., (2024) arXiv:2404.08459


Radiation detection
NaI or Ge-detector
Radiation from
Positron Channeling
BM3 Dipole Magnet
5t, 30°
Goniometer
Chamber for
crystals
Positron
beam
~12 m
Positron
beam
Positron detection
Szintillator and/or
Pixeldetector
10 inch NaI
Radiation from
electron channeling
Tungsten aperture,
movable

Overview Positron beam line

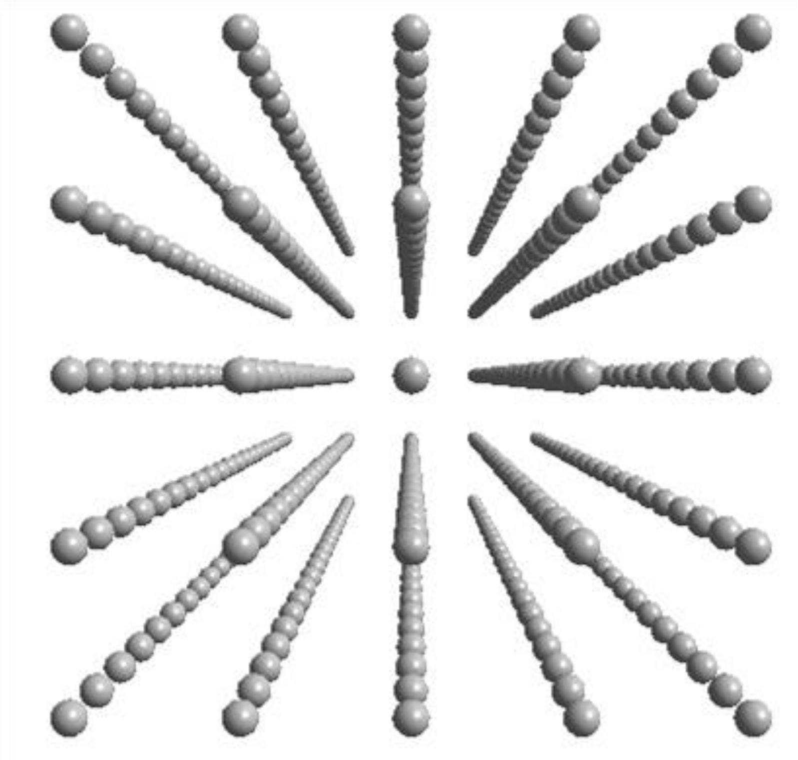


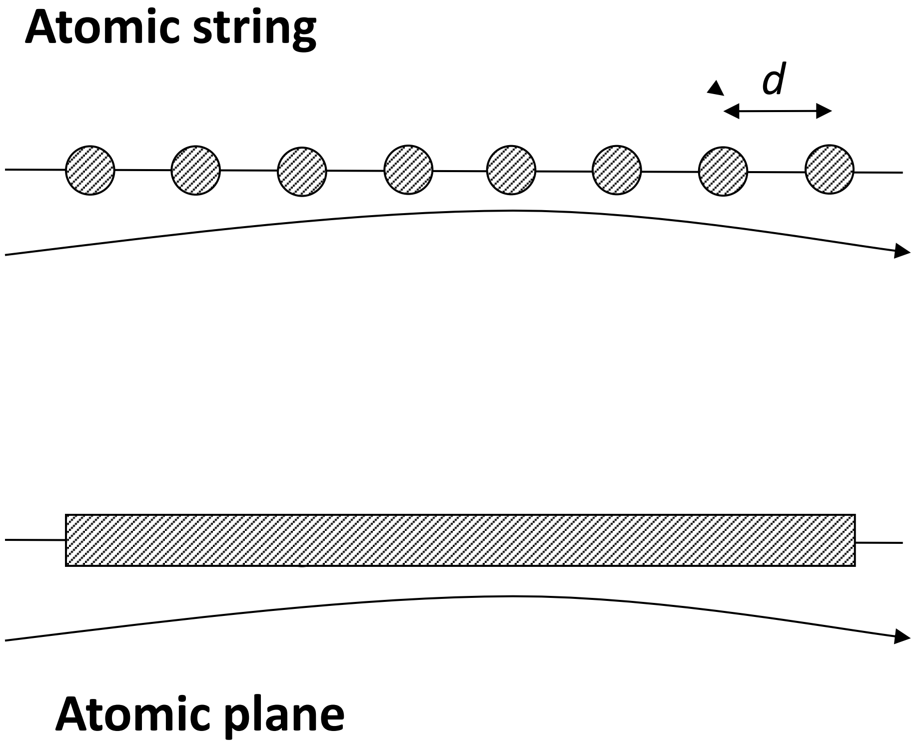
Floor Plan at MAMI for X-ray Experiments



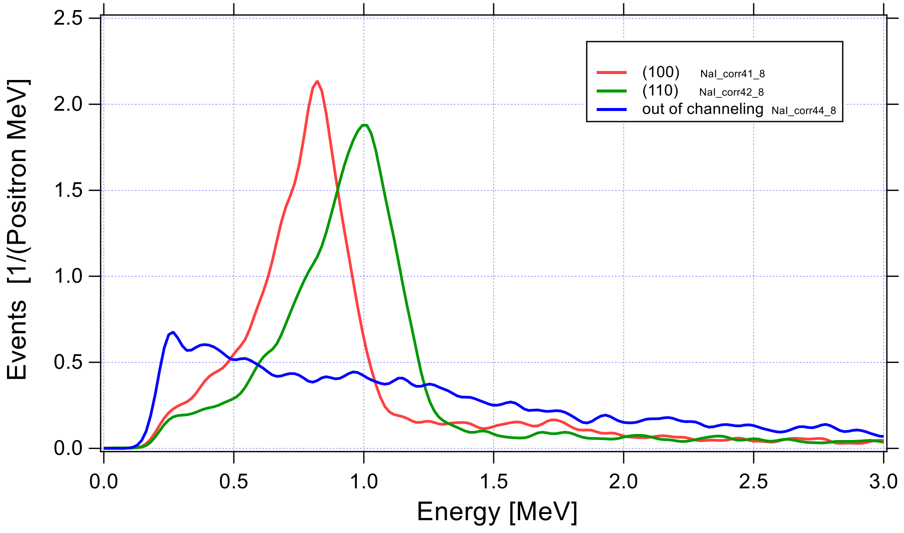
Vacuum chamber with 3 axis -Goniometer
Diameter 600 mm
Windows under different angles
Beamsize < 10 μm in both directions
Max. current depending on target
For thick targets (1mm Tungsten) I < ~nA

How Channeling Comes About



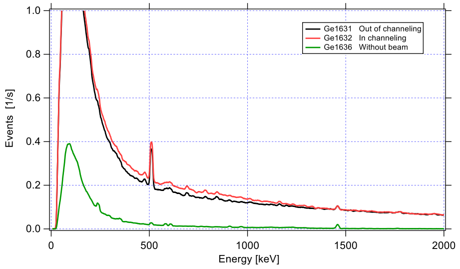


Channeling radiation with 530 MeV Positrons



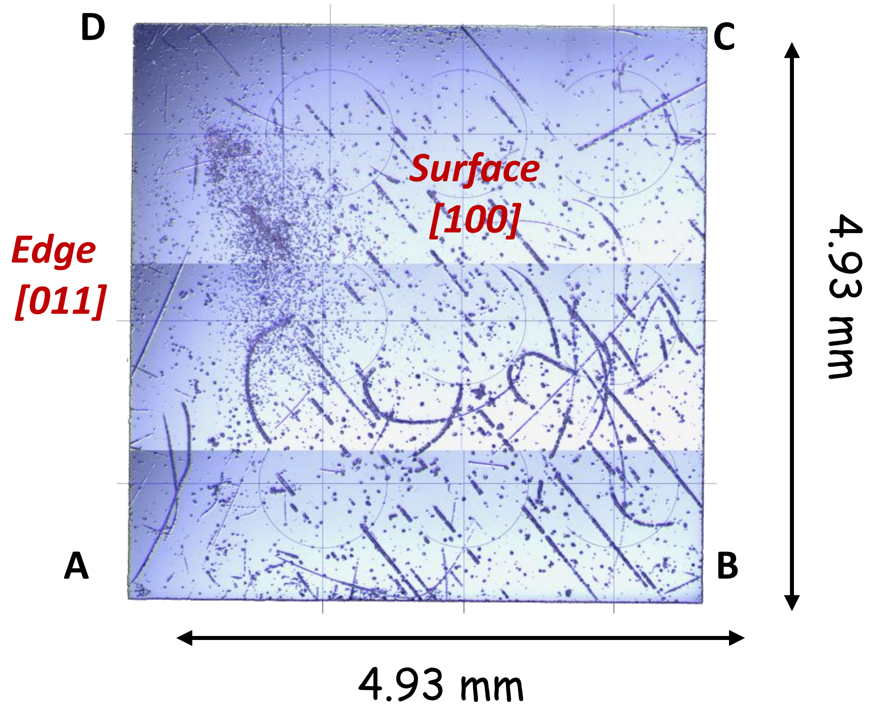
200 μm Si
Coincidence measurements
Aperture:
Diameter 10 mm in 9m distance
Observation angle 0.55mrad

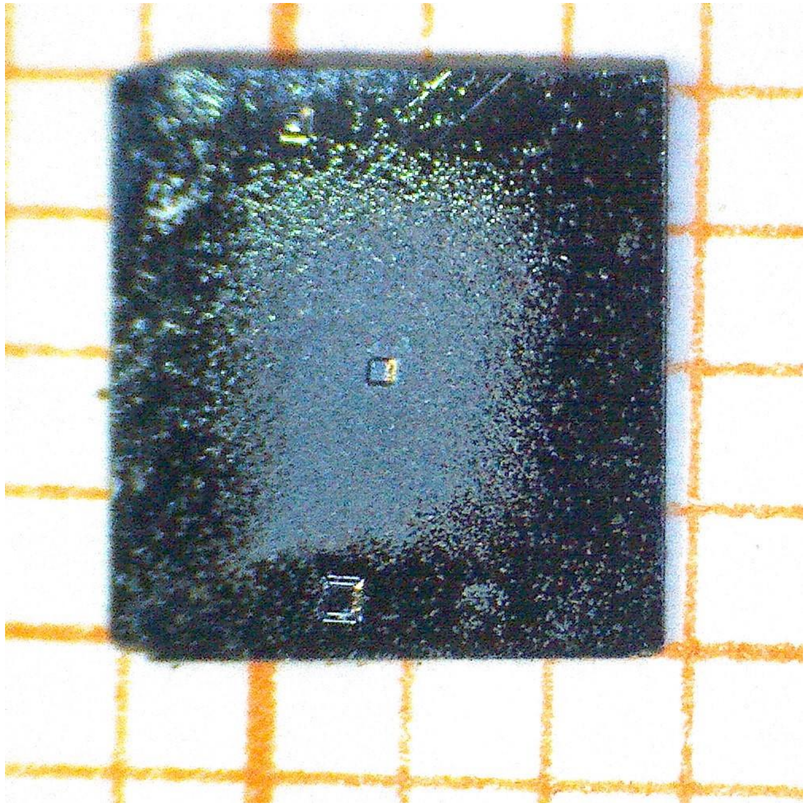
Radiation detection with Ge-Detector

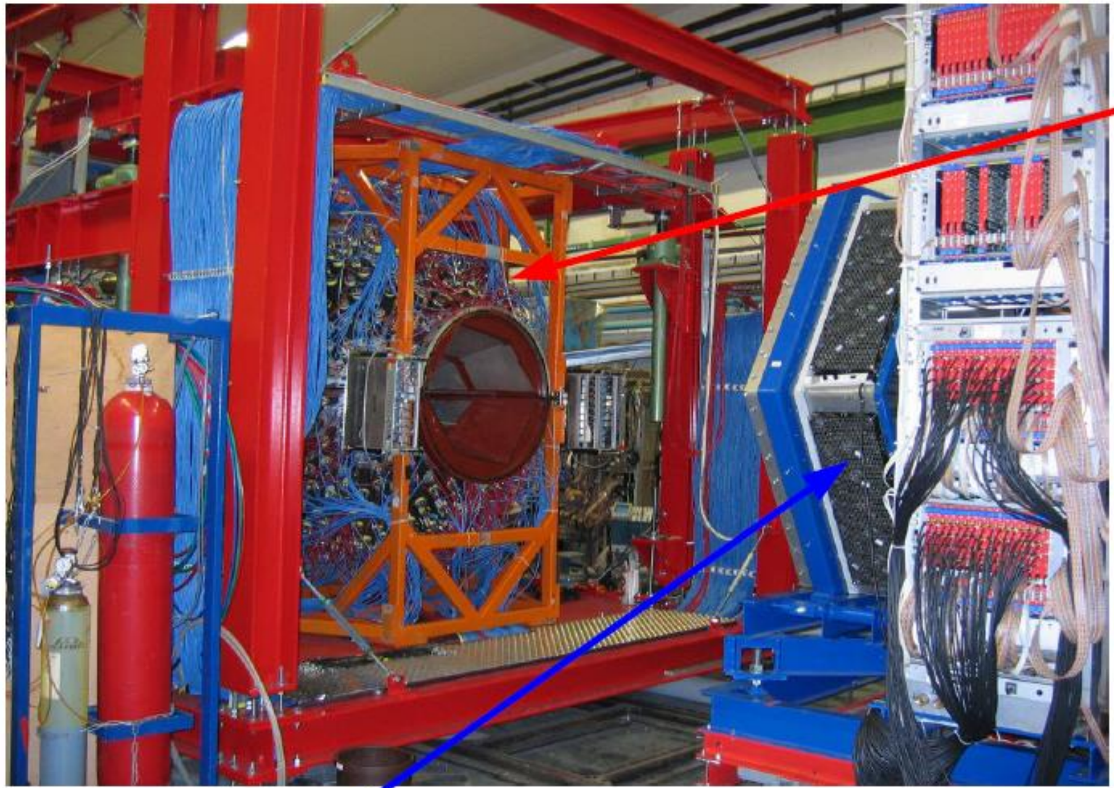


200 µm
Si crystal

Si crystal target in, Channeling
Si crystal target in, random


D
C
Surface
[100]
Edge
[011]
A
B
4.93 mm
4.93 mm





Crystal Ball:

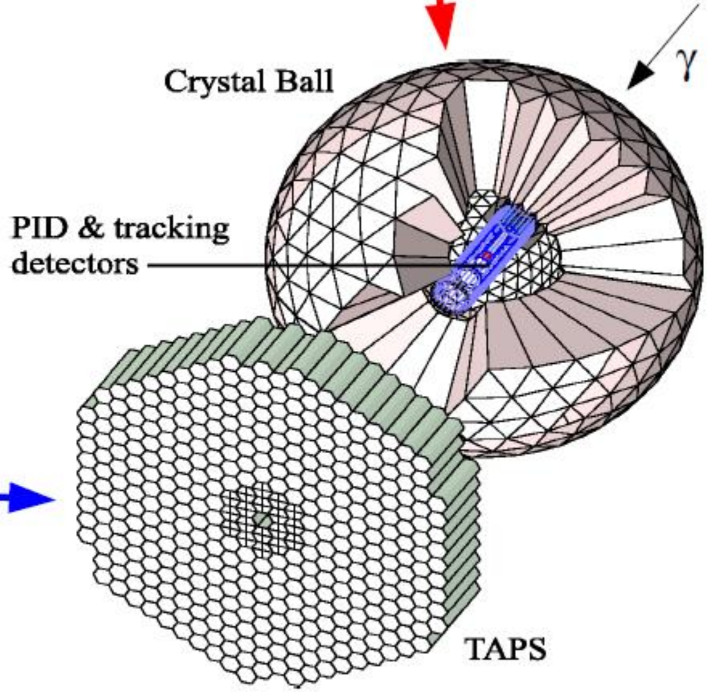
672 NaI(Tl) crystals

93,3% of total solid angle

Each crystal equipped with PMT

$$\frac{\sigma}{E_\gamma} = \frac{2\%}{(E_\gamma/GeV)^{0.25}} \qquad \sigma(\theta) = 2^\circ \ldots 3^\circ$$

$$\Delta t = 2.5 \text{ ns FWHM} \qquad \sigma(\phi) = \frac{2^\circ \ldots 3^\circ}{\sin(\theta)}$$

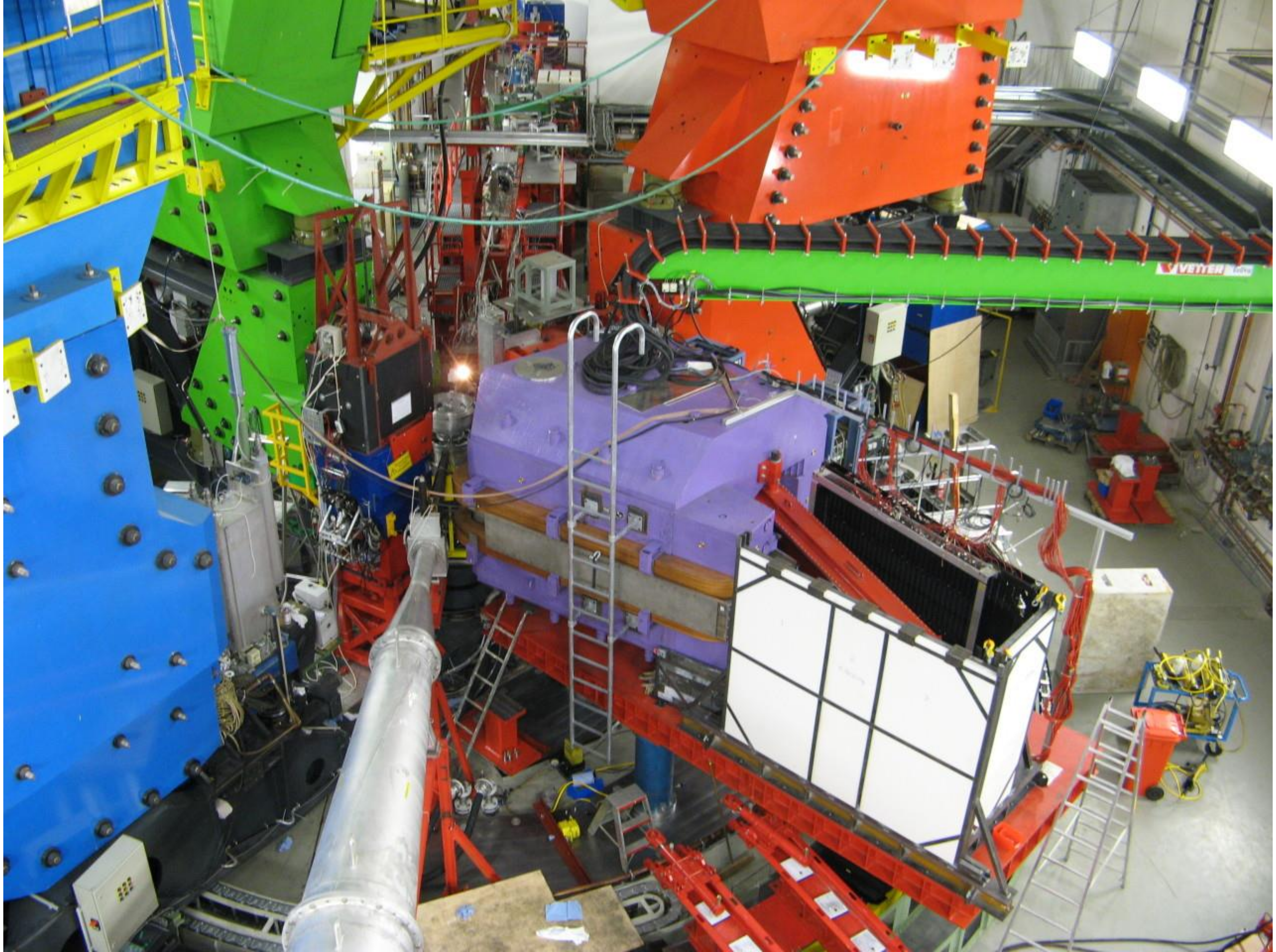


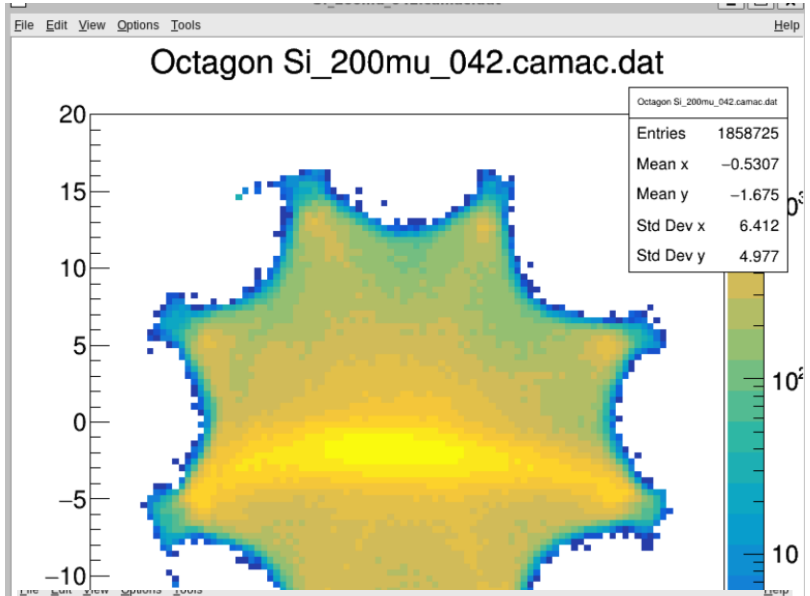
TAPS:

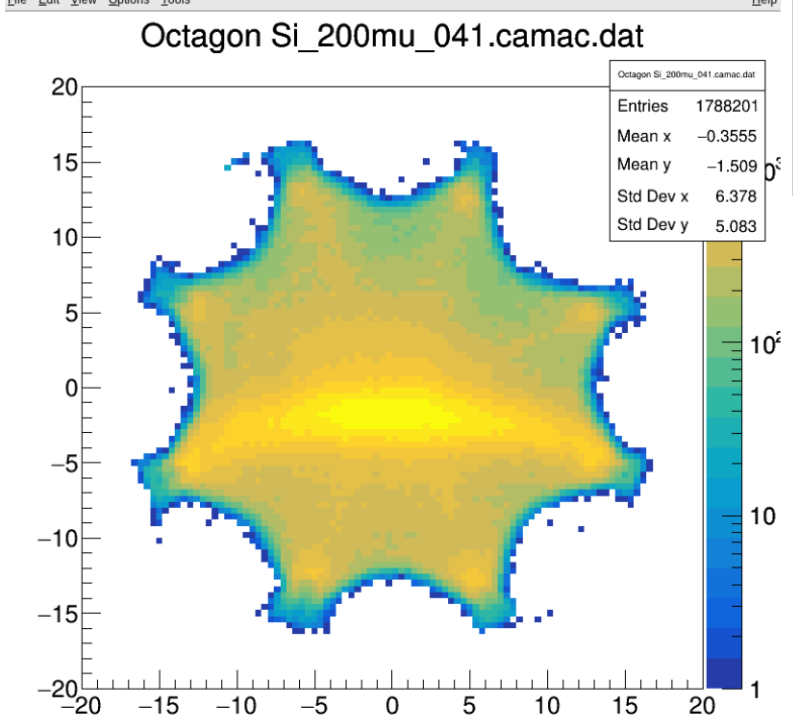
Up to 510 BaF_2 crystals

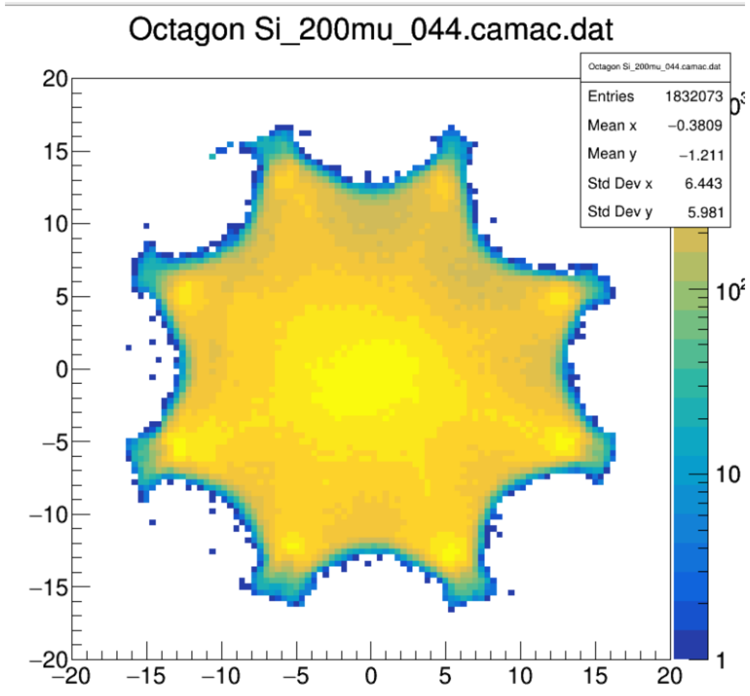
Polar acceptance: 4-20°

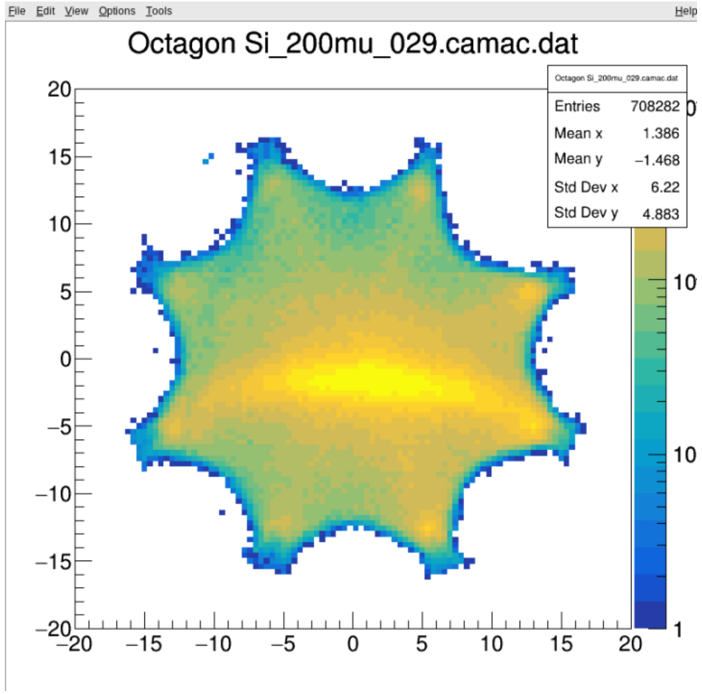
$$\Delta t = 0.5 \text{ ns FWHM} \qquad \frac{\sigma}{E_\gamma} = \frac{0{,}79\%}{\sqrt{E_\gamma/GeV}} + 1{,}8\%$$


VETTER

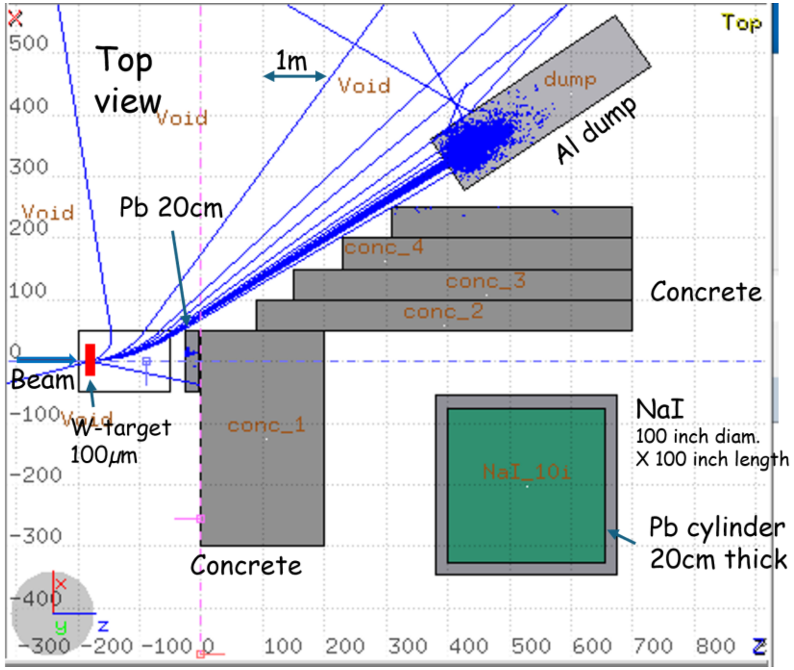

Octagon Si_200mu_042.camac.dat
Entries 1858725
Mean x −0.5307
Mean y −1.675
Std Dev x 6.412
Std Dev y 4.977


Octagon Si_200mu_041.camac.dat
Entries 1788201
Mean x −0.3555
Mean y −1.509
Std Dev x 6.378
Std Dev y 5.083

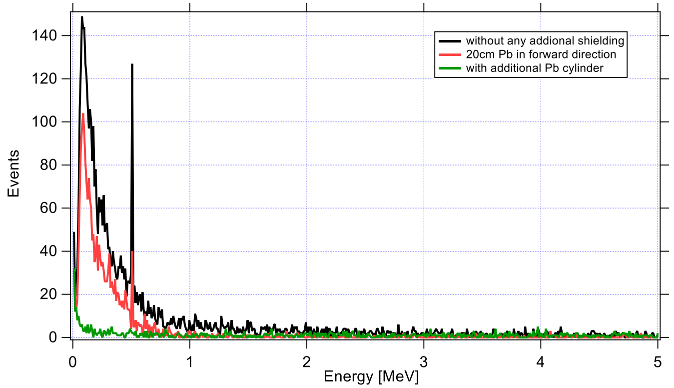

Octagon Si_200mu_044.camac.dat
Entries 1832073
Mean x −0.3809
Mean y −1.211
Std Dev x 6.443
Std Dev y 5.981


Octagon Si_200mu_029.camac.dat
Entries 708282
Mean x 1.386
Mean y −1.468
Std Dev x 6.22
Std Dev y 4.883

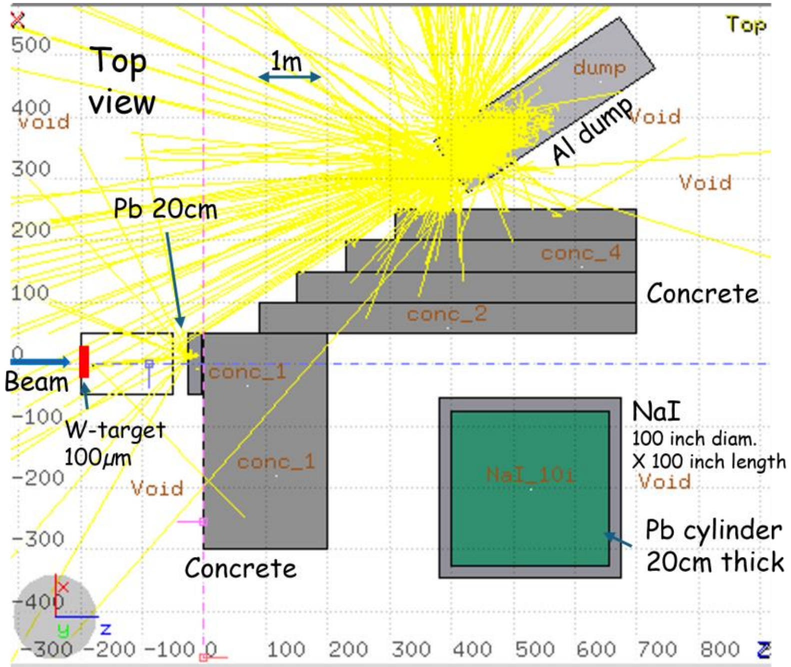
Simulation calculations of background in hall X1 with Fluka



Primary Electrons (100)



$8{\cdot}10^6$ electrons



Photon shower from 100 primary electrons

TECHNO-CLS

TECHNO-CLS consortium

MBN Research Center

MBN Research Center

INFN

Istituto Nazionale di Fisica Nucleare

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