PHOTOCATHODES WITH OPTIMIZED QE FOR SPIN POLARIZED POSITRON SOURCES

European Workshop for Photocathodes for Accelerator Applications

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Kurt Aulenbacher

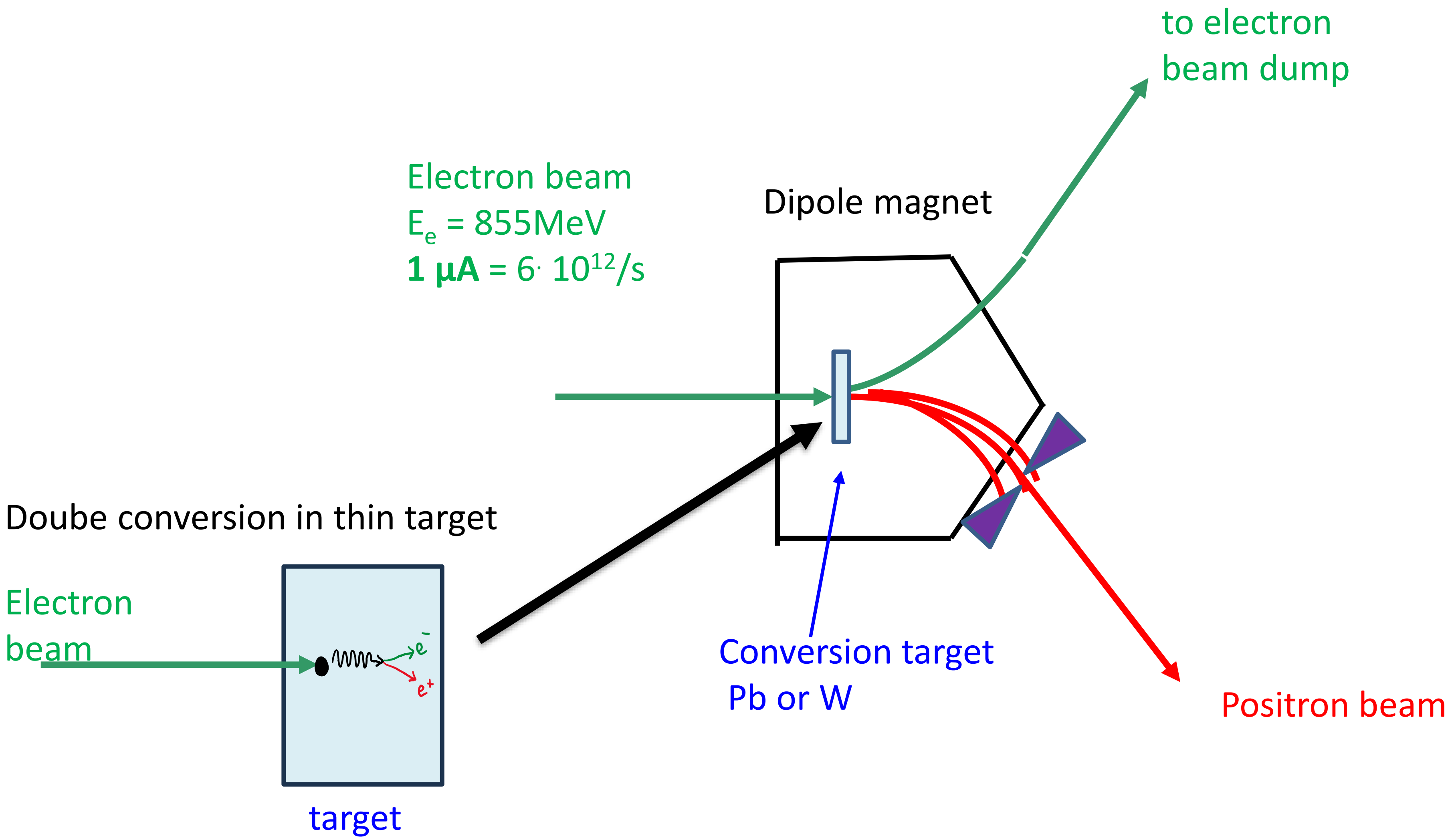
Institut für Kernphysik der Universität Mainz

PRISMA+

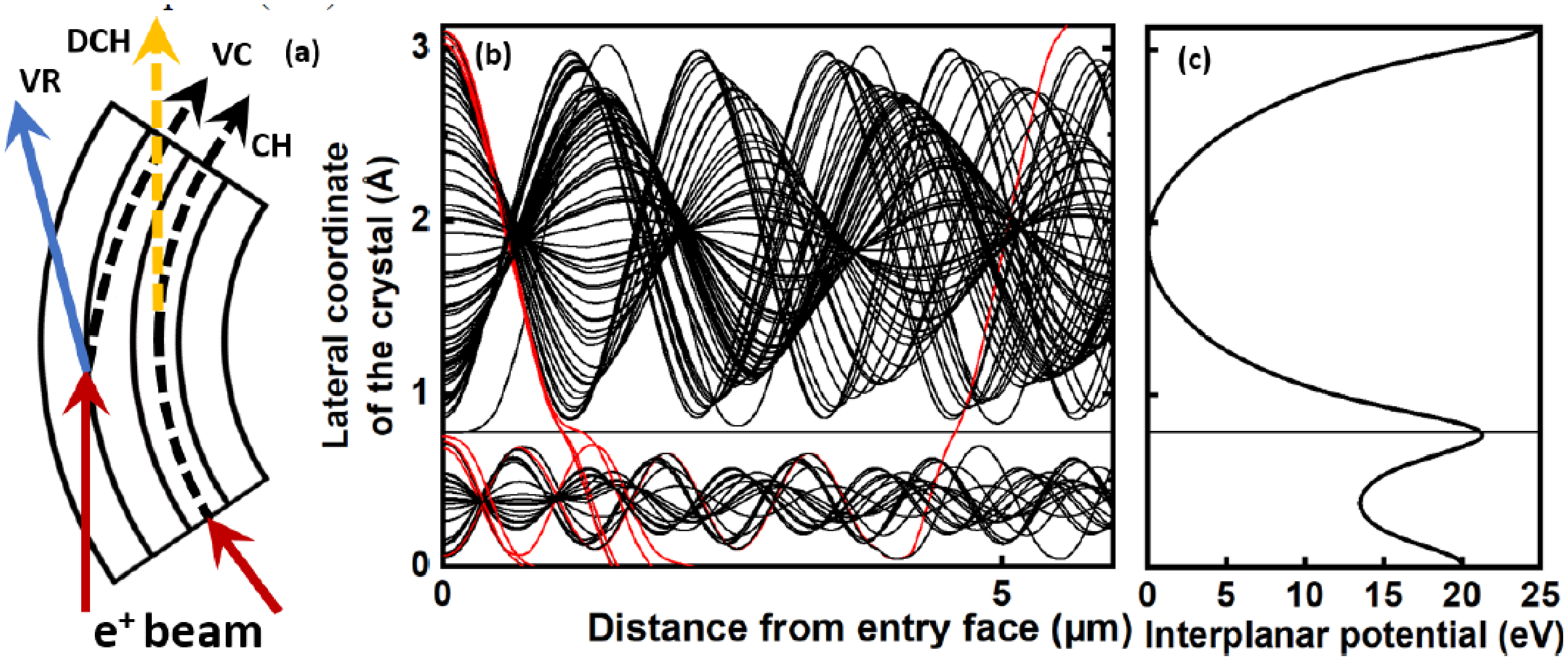
Outline-

- Spin polarized positrons – how does it work (and what for?) ?
- Demands to photocatode, technical issues→ High QE polarized photcathode
- High QE Photcathode photocathode : sustainable supply & quality control approach

Principle of the Positron source at MAMI



Why positrons of several hundred MeV?



Positrons have much better channeling properties should have *100 times longer dechanneling length
Some dream of micro-scaled undulators, leading to new radiation sources….

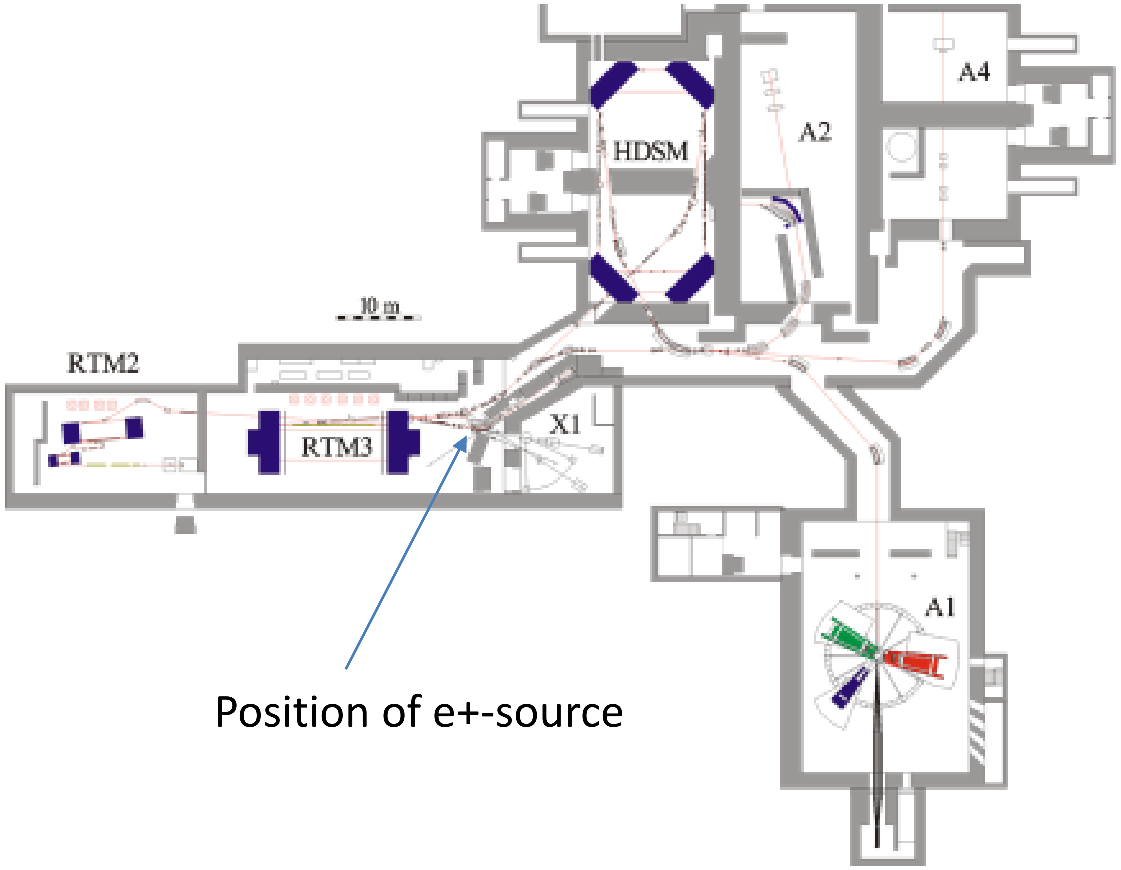
Positron Production with high power recirculating linear accelerator MAMI

MAMI: MAINZER MIKROTRON
MAMI-C –three RTM stages + „HDSM“
CW-machine
Energies: 180-1600 MeV
Beam current: few electrons/s – 100µA (150kW)
Applications:

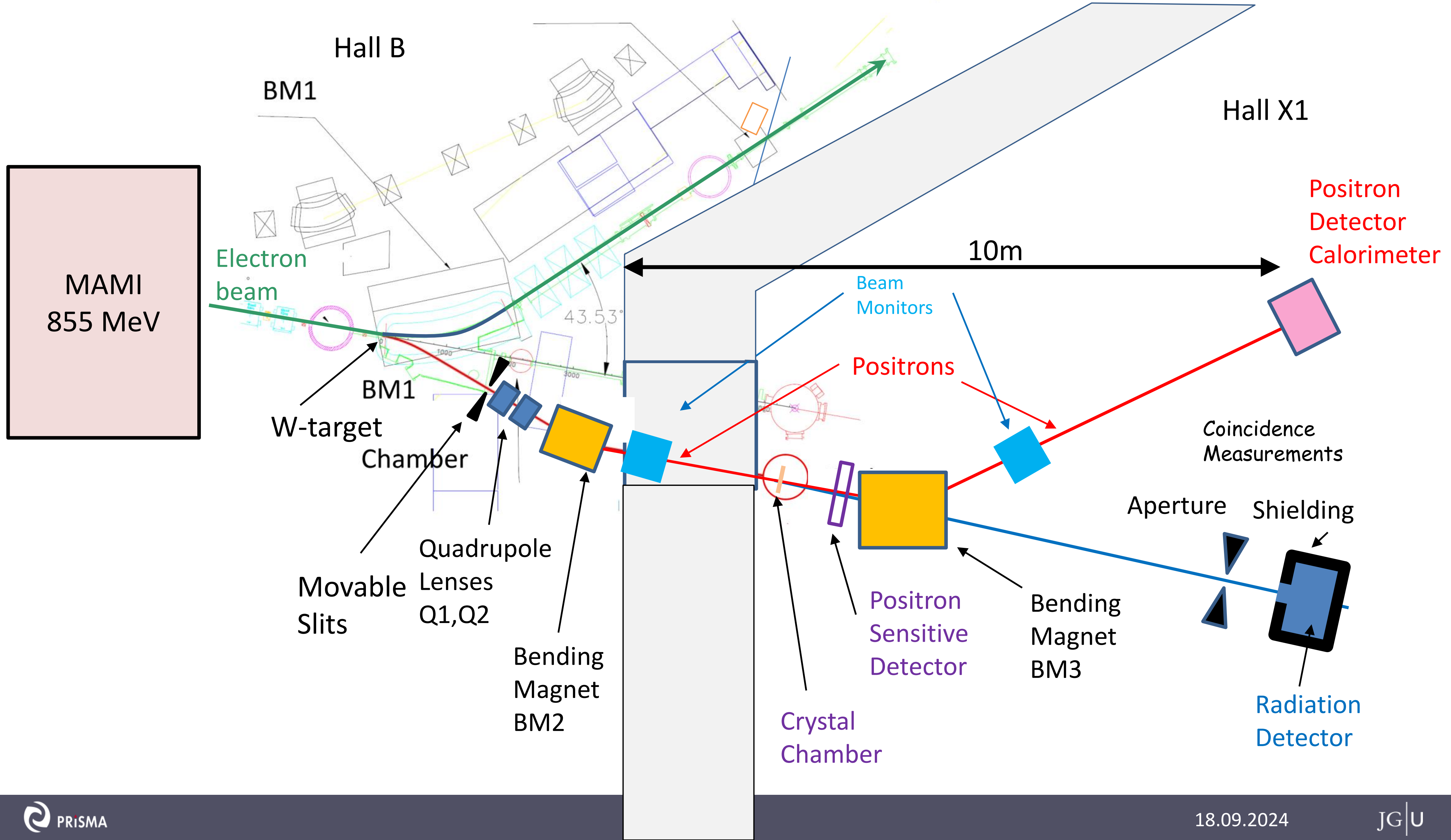
- Electron scattering (A1)
- Tagged Photon scattering (A2)
- PV-electron scattering (A4, until 2012→MESA)
- Detector/materials testing
- Secondary positron beams
- Spin polarized electron beams (A1,A2,A4)

GSI-related Collaborations:

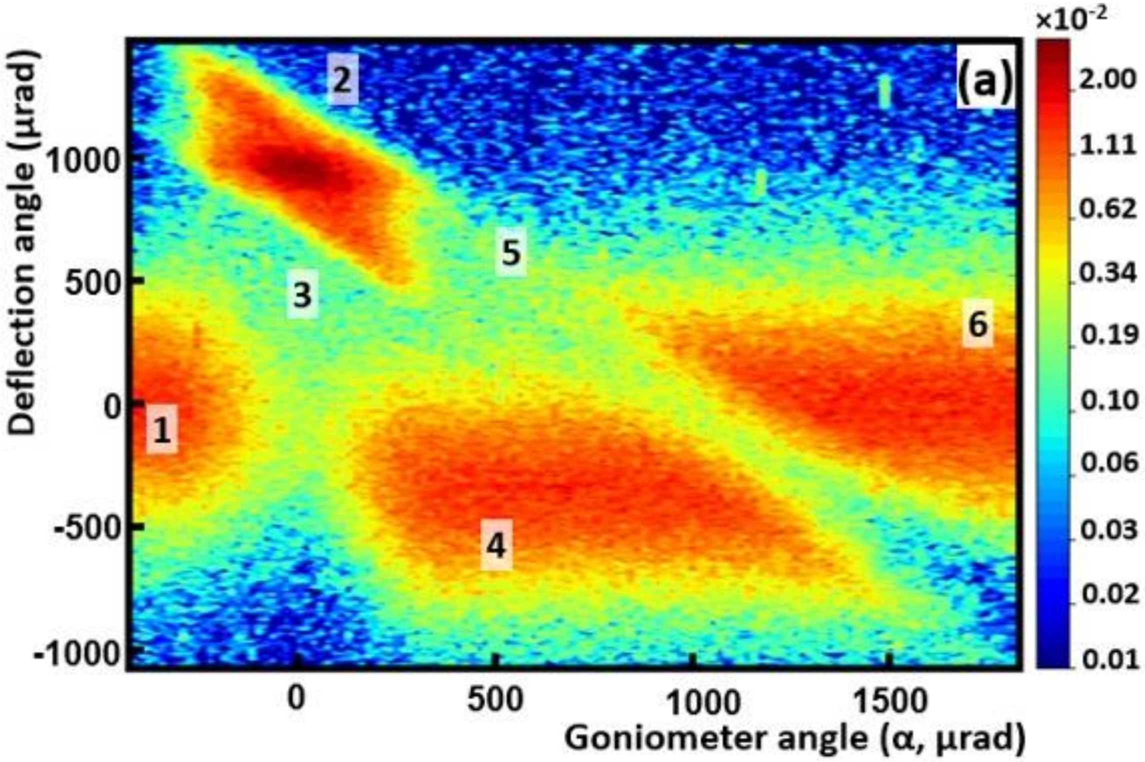
- Detector/target testing (e.g. PANDA)
- FAIR phase-0 experiment PRIMA in hall A1



Overview Positron beam line



First results from e+ beam



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

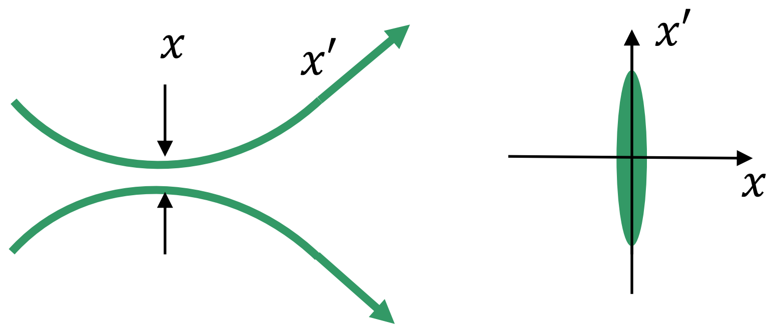
First high-efficient deflection of sub-GeV positron worldwide !!!

Fallout in :

- Crystal-Light-Source
- Channeling based technologies
- Accelerator technologies: for beam steering, extraction, focusing..

Open access paper on arXiv
Submitted to Phys. Rev. Lett.

„Good" geometrical emittance of e+ beam….



vertical

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

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

$= 10\, \mu m \cdot 0.1 mrad = 1nm$

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

Thin target for Positron production

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

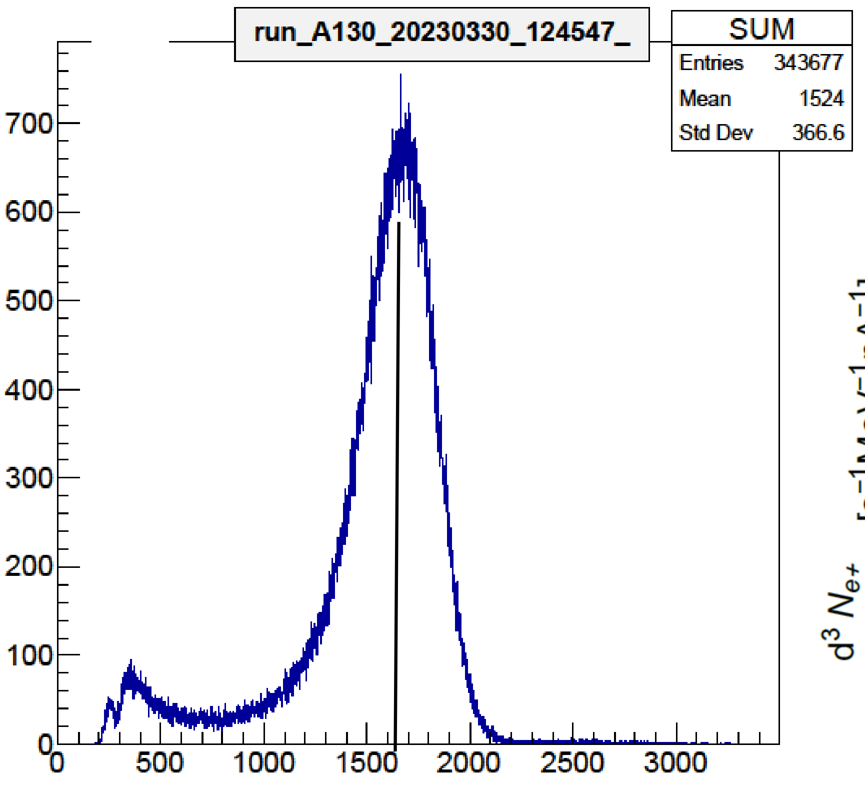
$\sigma_p = \cong \frac{1}{\gamma} = 1\ \text{mrad}\ @500\text{MeV}$

$\varepsilon_{e+} = 10\ \mu m\ \cdot\ 1.4\ mrad$

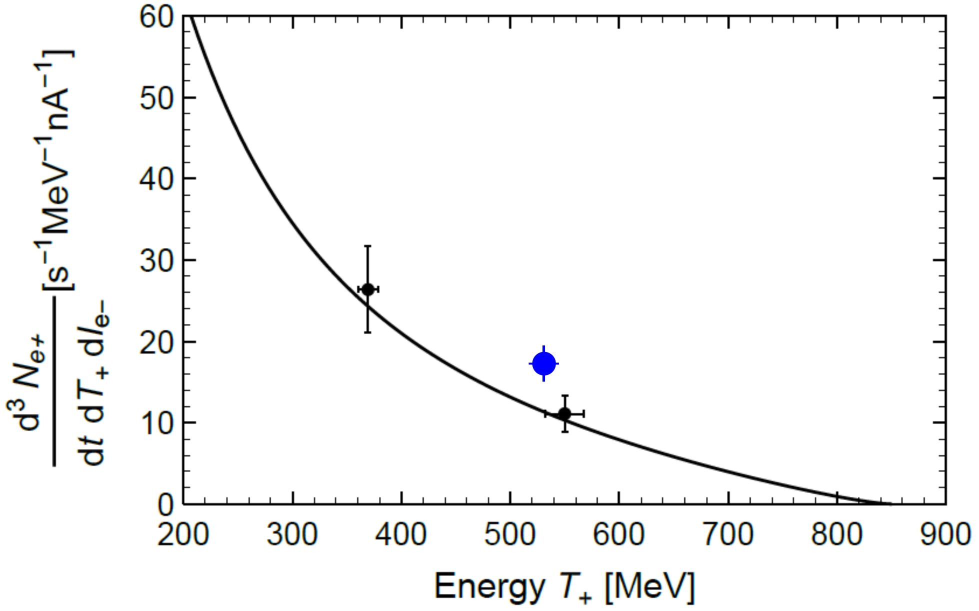
Emittance of Positrons: $= 1mm \cdot 0.014\ mrad = 14nm$

.....but low efficiency

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**

1. Why polarized positrons?

1. Particle physics: e-/e+ colliders (especially, but not only, linear colliders) (100 GeV scale)
2. Hadron Physics: 2 photon processes „deeply virtual Compton scattering“ (GeV scale)
3. Applied science: in particular magnetic nanostructures (eV scale)

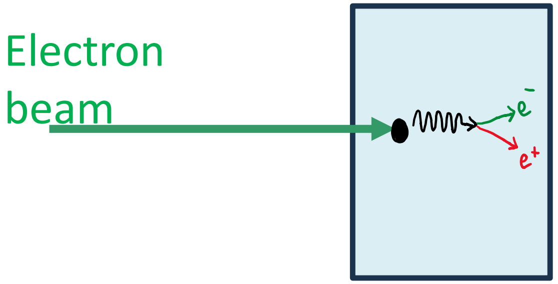
Can we use a polarized electron beam for a e+ source ?

Yes we can ! 20 μA with >80% Polarization is possible for long user runs at MAMI.

But will the positrons be polarized too?

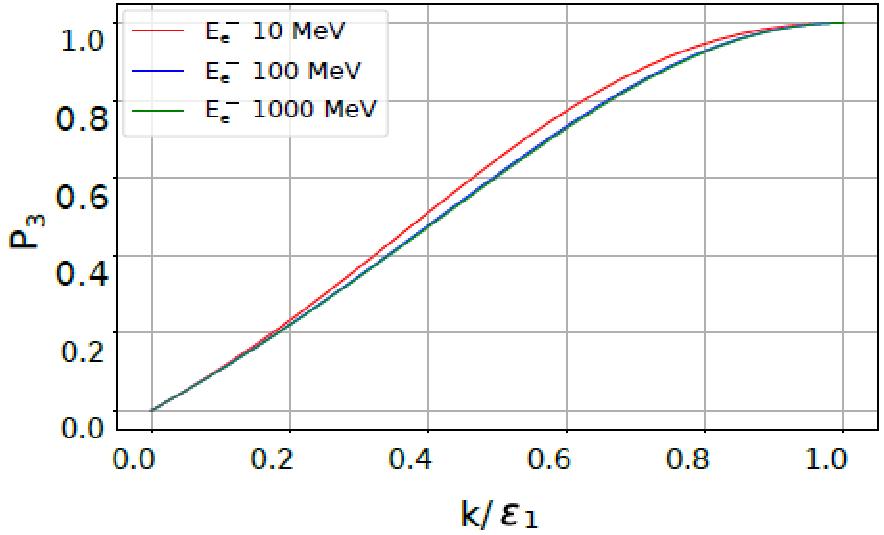
But will the positrons be polarized too –yes!

Doube conversion in thin target

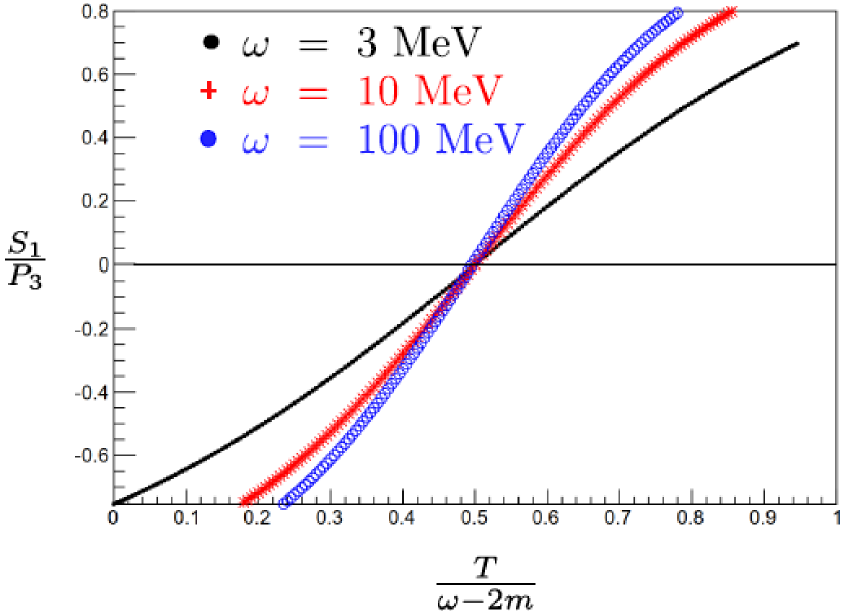


Principle first tested by SLAC/DESY collaboration for ILC in 2006.
Cross sections and multiple scattering must be taken into Account→ PhD work by S. Habet at ORSAY for JLAB

Figures after QED calculations by Olsen et al, taken from:
S. Habet: Concept of a polarized electron source for CEBAF, PhD Thesis, Université Paris-Saclay, CNRS, IJCLab, 91405, Orsay, France. (2023)

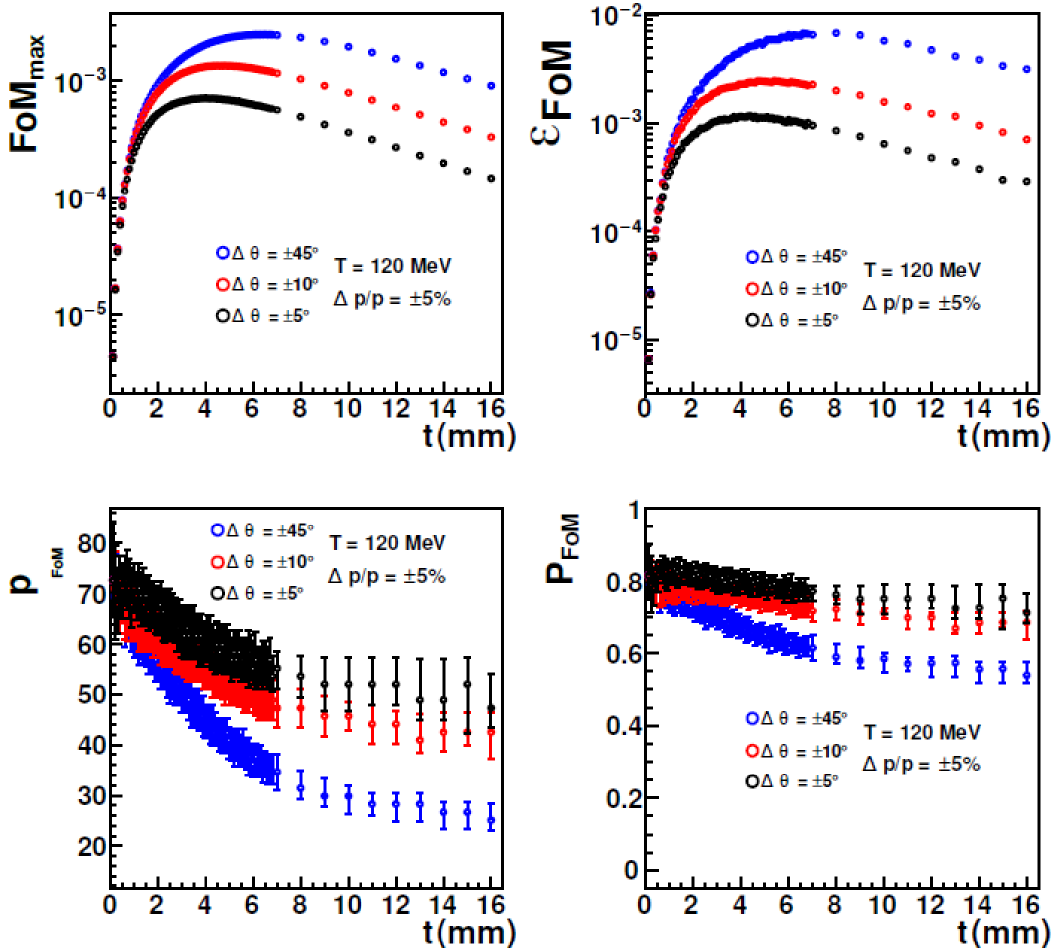


Transfer of electron polarization to photon circ. pol.



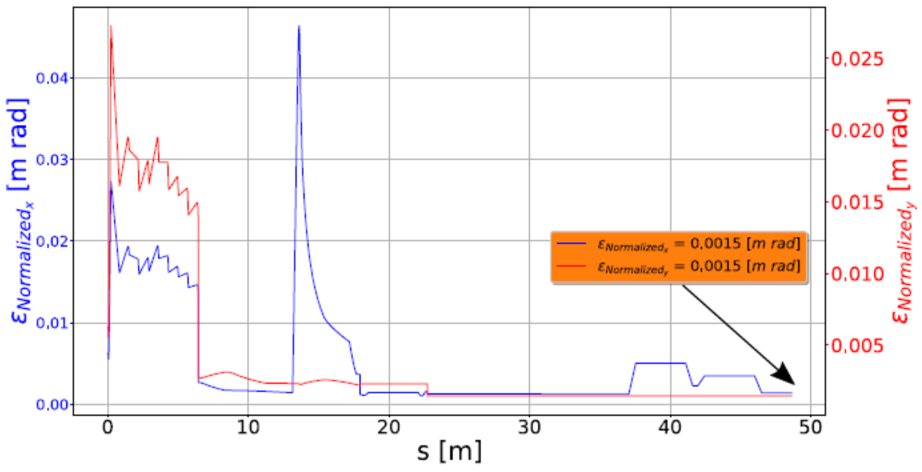
Transfer of photon circ. pol. To positron pol

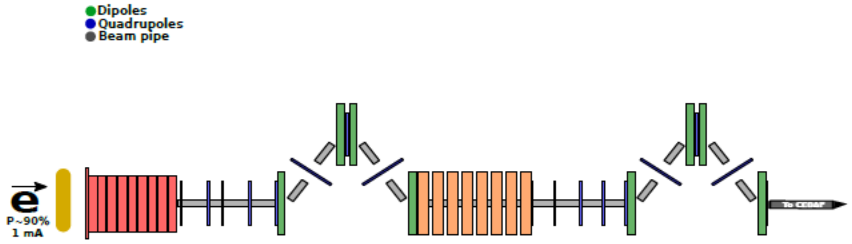
Simulations for CE⁺BAF with 126 MeV pol drive beam



Figures/Data taken from:
S. Habet: Concept of a polarized electron source for CEBAF, PhD Thesis, Université Paris-Saclay, CNRS, IJCLab, 91405, Orsay, France. (2023)

Simulations for CE⁺BAF with 126 MeV pol drive beam





Predicted parameters:

Predicted Parameters	
E- beam current/Energy/Polarization	1mA/120 MeV/0.9
Positron beam current	0.17 μA
Positron Polarization	0.65
Energy width /bunch length	0.6%/ 2ps
Positron normalized emittance	1500 μm

Figures/Data taken from:
S. Habet: Concept of a polarized electron source for CEBAF, PhD Thesis, Université Paris-Saclay, CNRS, IJCLab, 91405, Orsay, France. (2023)

Low efficiency!

Based on the simulations by Habet we could assume the following requirement for the palarized electron beam with 90% Polarization at 120 MeV:

$$I_{\vec{e}^-}[mA] = 6 I_{\vec{e}^+}[\mu A] \frac{1500}{\varepsilon_{norm}[\mu m]}$$

Note that 1mA means 120 kW beam power on the target.

For the „rotating rim technology“ for cooling, MAMI experiments (*) at 3.5 MeV may suggest that materials can withstand such loads regarding radiation damage for very long time :
→ lower energies may be better, at least to handle high beam powers….
→ But high QE cathodes required because of cathode heating!

T. Lengler et al., "Characterization of radiation damages to positron source materials",
in Proc. IPAC'24, Nashville, TN, May 2024, pp. 1206-1209. doi:10.18429/JACoW-IPAC2024-TUPC81

State of the art Superlattice cathodes

GaAs	5 nm	p=5 × 10^{19} cm^{-3}
GaAs/GaAsP SL	(3.8/2.8 nm) ×14	p=5 × 10^{17} cm^{-3}
$GaAsP_{0.35}$	2750 nm	p=5 × 10^{18} cm^{-3}
Graded $GaAsP_x$ (x = 0~0.35)	5000 nm	p=5 × 10^{18} cm^{-3}
GaAs buffer	200 nm	p=2 × 10^{18} cm^{-3}
p-GaAs substrate (p>10^{18} cm^{-3})		

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GaAs/GaAsP SL	(3.8/2.8 nm) ×14	p=5 · 10^{17} cm^{-3}
$GaAsP_{0.35}$	750 nm	p=5 × 10^{18} cm^{-3}
$GaAsP_{0.35}$/ $AlAsP_{0.4}$ DBR	(54/64 nm) ×12	p=5 × 10^{18} cm^{-3}
$GaAsP_{0.35}$	2000 nm	p=5 × 10^{18} cm^{-3}
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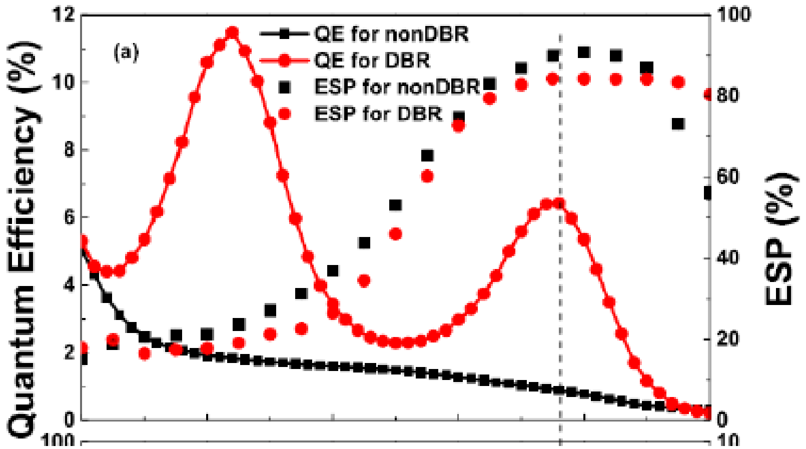

JLAB/SVT cooperation

Table and plot takenfrom: Liu et al. Appl. Phys. Lett. **109**, 252104 (2016); doi: 10.1063/1.4972180

1%QE at 780nm = 6mA/Watt!

Prepare for lifetimes effects → Present (upper) limit of charge lifetime ~200 Coulombs at MAMI correponds to 60hours.

For currents at multi-milliampere scale DBR based superlattices are mandatory!

The issue with vendors….

1. The old vendor does not want to deliver samples any more.
2. GaAsP not very attractive for mass fabrication (contrast to the 1990 „epitaxy“ peak)
3. Handling Phosphorus diffcult and blocks production
4. → an issue of „world wide“ interest. Stakeholders: Particle physicists (EIC, EICC, LHEC,..), e+ source developers …and MAMI/MESA at Mainz.

Mainz/MESA has contacts to several national semiconductor research institutes (from the Fraunhofer and Leibnizinstitutes).

Production offer & services by federal lab:

Teil A - Fertigung des Puffers

Detailliertes Verfahren (Ausschreibung 3.2 a)

1. Epitaxieentwicklung auf p-leitenden GaAs-Substraten eines 5000 nm dicken Stufenpuffers (graded buffer) von GaAs hin zu $GaAs_{0.65}P_{0.35}$
2. inklusive Kalibrierung der Gasquellen-Regelparameter für As und P
3. inklusive Charakterisierung der Schichten mittels optischer Mikroskopie, hochauflösender Röntgenbeugung (HRXRD) und reciprocal space maps (RSM) sowie Sekundärionen-Massenspektroskopie (SIMS)
4. inklusive der Entwicklung und Analyse der in-situ-Messung der Substratkrümmung und Schichtverspannung (EZcurve) für den graded buffer
5. Epitaxieentwicklung metamorpher $GaAs_{0.65}P_{0.35}$-Puffer auf vorher entwickelten Stufenpuffer mit Variation der Wachstumstemperaturen für reduzierte AFM- (atomic force microscopy) Rauigkeit
6. inklusive Charakterisierung mittels Mikroskopie, AFM, EZcurve, HRXRD mit RSM
7. inklusive der Entwicklung und Analyse der in-situ-Messung der Substratkrümmung und Schichtverspannung (EZcurve) für den graded buffer
8. inklusive Charakterisierung mittels Transmissionselektronenmikroskopie (TEM) zur Bestimmung von Versetzungsdichten

The text on the left is only the number of steps required
to make the buffer layer!

GaAs	5 nm	p=5 × 10^{19} cm^{-3}
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p-GaAs substrate (p>10^{18} cm^{-3})		

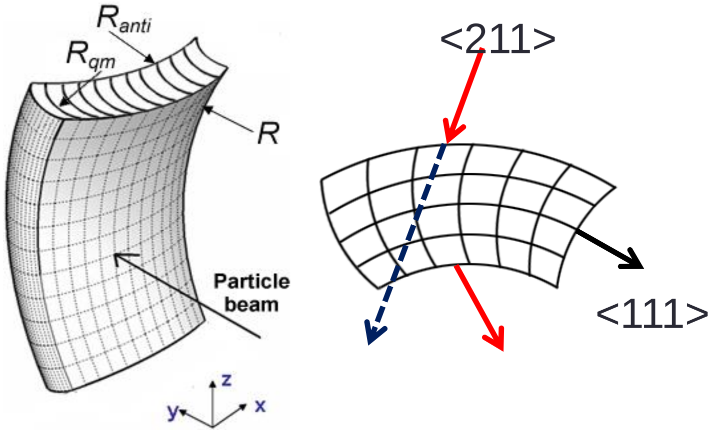
Even if the production produces non-optimal results, the information about the growth will be transferred to us!

Conclusion

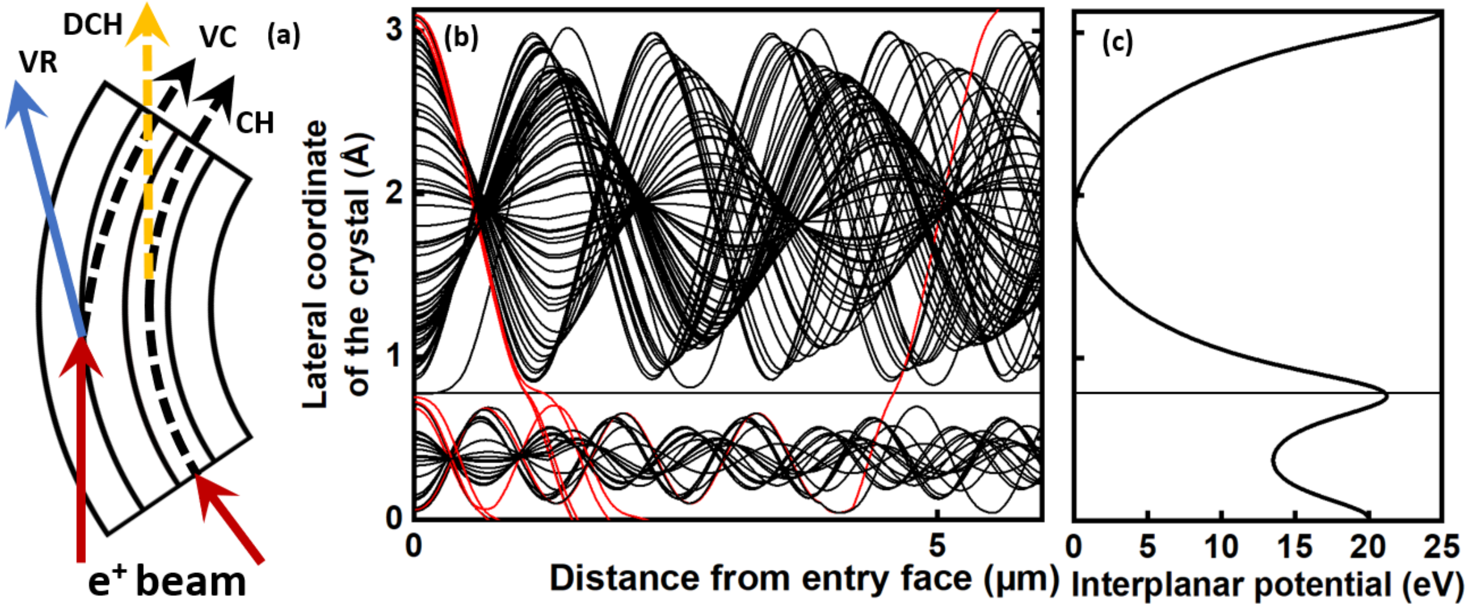
- Production of spin polarized positron beams well understood , they may be generated from spin polarized electrons beams in the Multi-MeV regime
- mA polarized electron beams required to produce a few nA polarized positron beams with good beam quality
- Not adressed here, but perhaps important: decelleration/moderation of beam without depolarisation→ 10 MeV class drive beams perhaps better to produce „thermal“ pol. e+
- Sustainable supply of GaAs/GaAsP superlattice photocathodes is of vital importance
- It is likely that wafer production runs will take place in 2025. Tests of the structures concerning QE and Polarization at Mainz (high current) and TU-Darmstadt (spectrally resolved Polarization and QE)

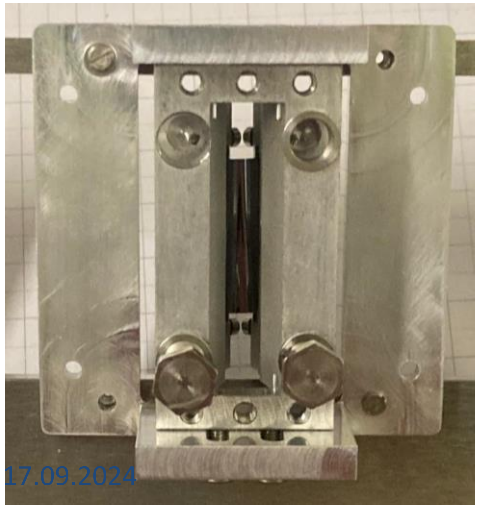
Thank you!

Beam deflection of 530 MeV positrons with mechanically bent Si crystal



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

Crystal available from a previous project @

Overview Positron beam line