Istituto Nazionale di Fisica Nucleare

CRYSTALS FOR HYBRID TARGET

Speaker: **L. Bandiera** - INFN Ferrara
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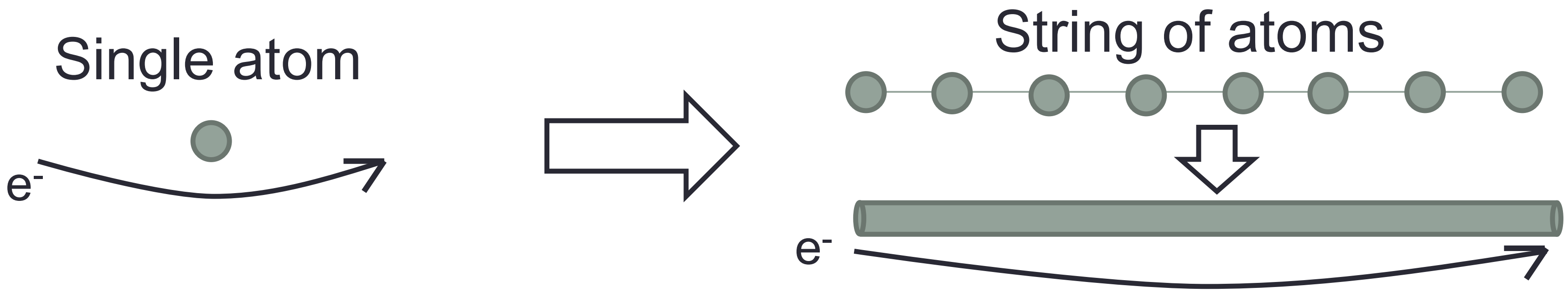
FCC-ee Injector Studies Mini Workshop
IJCLab Orsay 24-25 November 2022

25/11/2022

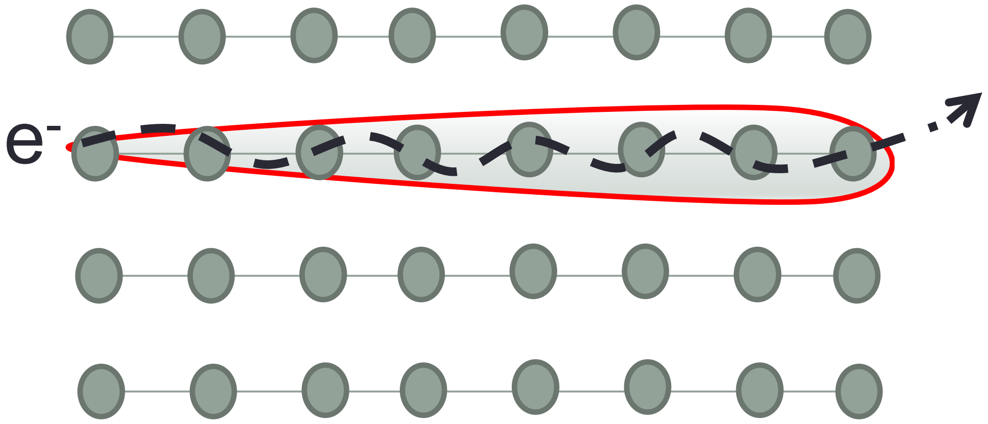
Enhancement of bremsstrahlung in aligned crystals

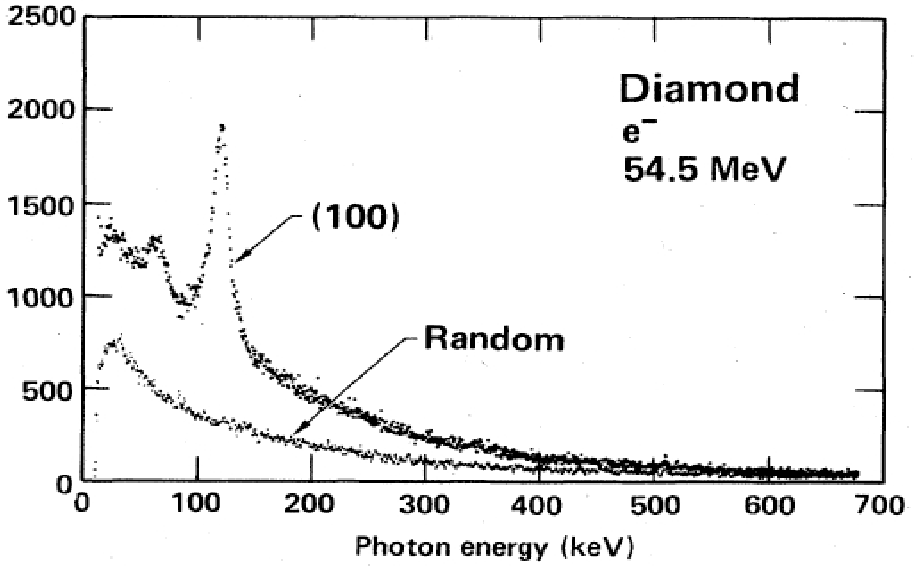


Single atom

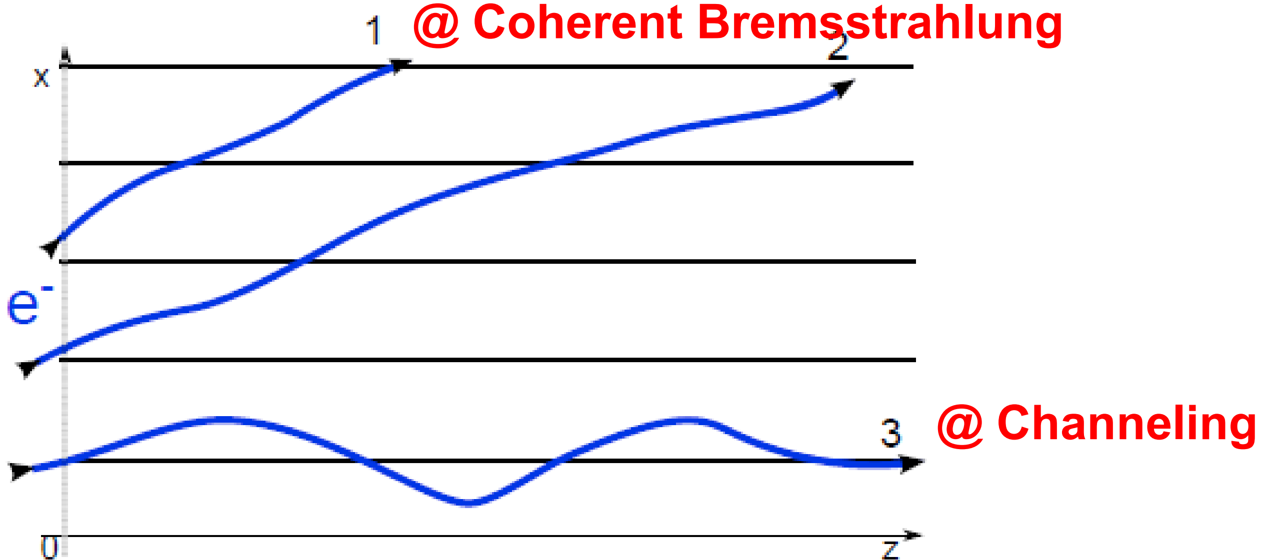
String of atoms

Channeling Radiation (1976, Kumakhov)





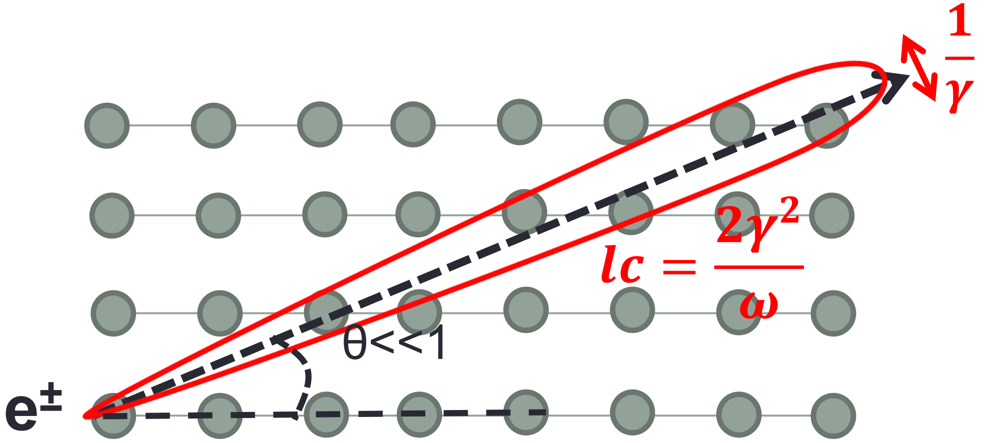
… and in nearly aligned crystals



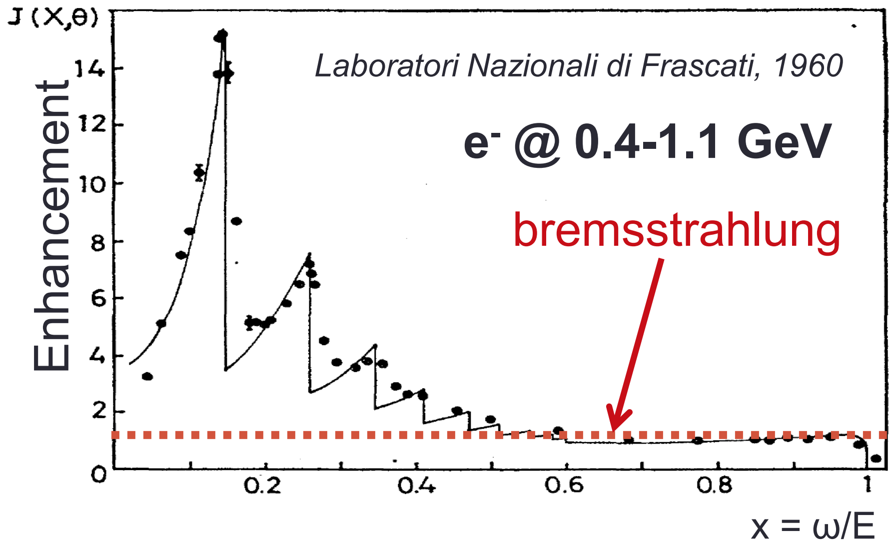
@ Coherent Bremsstrahlung

@ Channeling

Coherent Bremsstrahlung (1950s) Ter-Mikaelian, Ferretti, Dyson-Uberall



$$lc = \frac{2\gamma^2}{\omega}$$



Laboratori Nazionali di Frascati, 1960

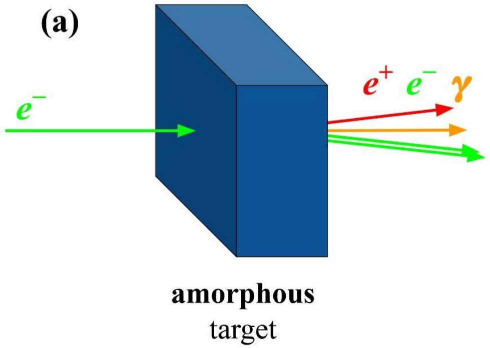
e^- @ 0.4-1.1 GeV

bremsstrahlung

Hybrid crystal based positron source for future colliders

UNPOLARIZED POSITRON SOURCES

1. Conventional



start of an electromagnetic shower in

1. **amorphous** single target

→ large output emittance (divergence, momentum spread)

→ high energy deposit ⇒ heating, thermo-mechanical stress, activation

Hybrid crystal based positron source for future colliders

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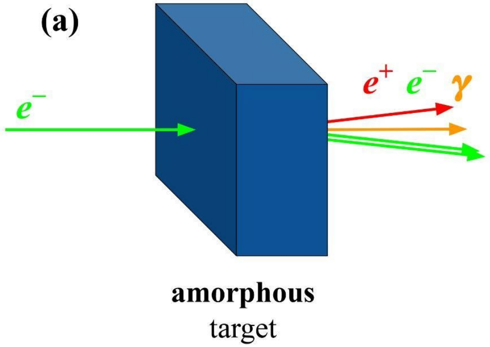

start of an electromagnetic shower in

1. **amorphous** single target
   → large output emittance (divergence, momentum spread)
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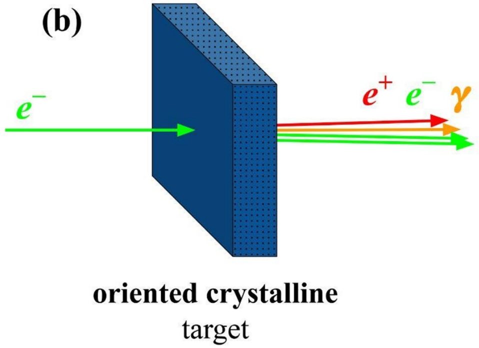
2. e+ from channeling radiation



2. **oriented crystalline** single target
   → same positron production rate
   → lower emittance
   → lower energy deposit
   → still unsatisfactory, as stress can degrade the crystalline lattice

Tests performed at CERN (WA 103) and at KEK

Hybrid crystal based positron source for future colliders

UNPOLARIZED POSITRON SOURCES

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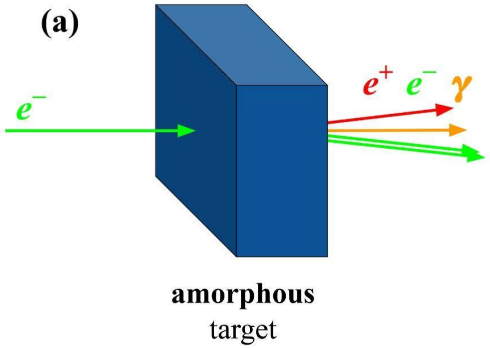

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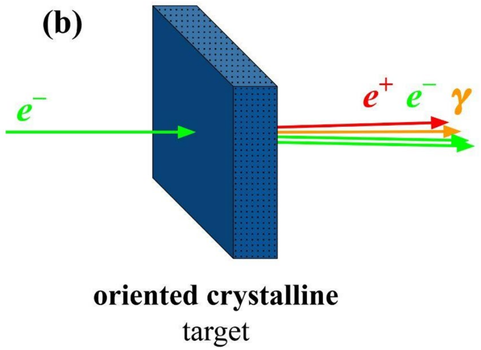
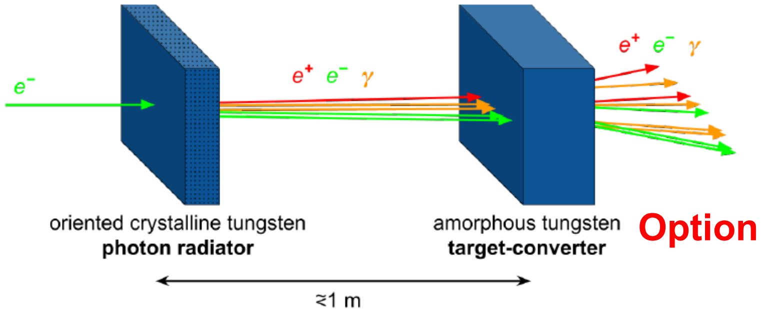


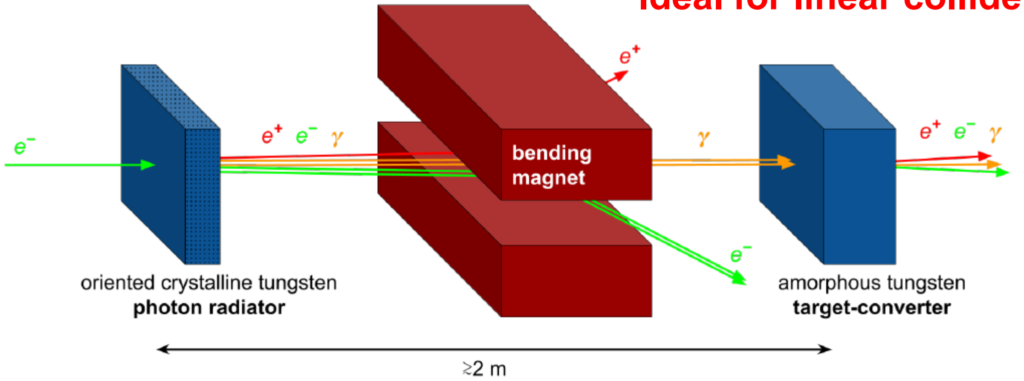
Tests performed at CERN (WA 103) and at KEK

3. Hybrid crystal based positron source



Option for FCCee

Ideal for linear colliders



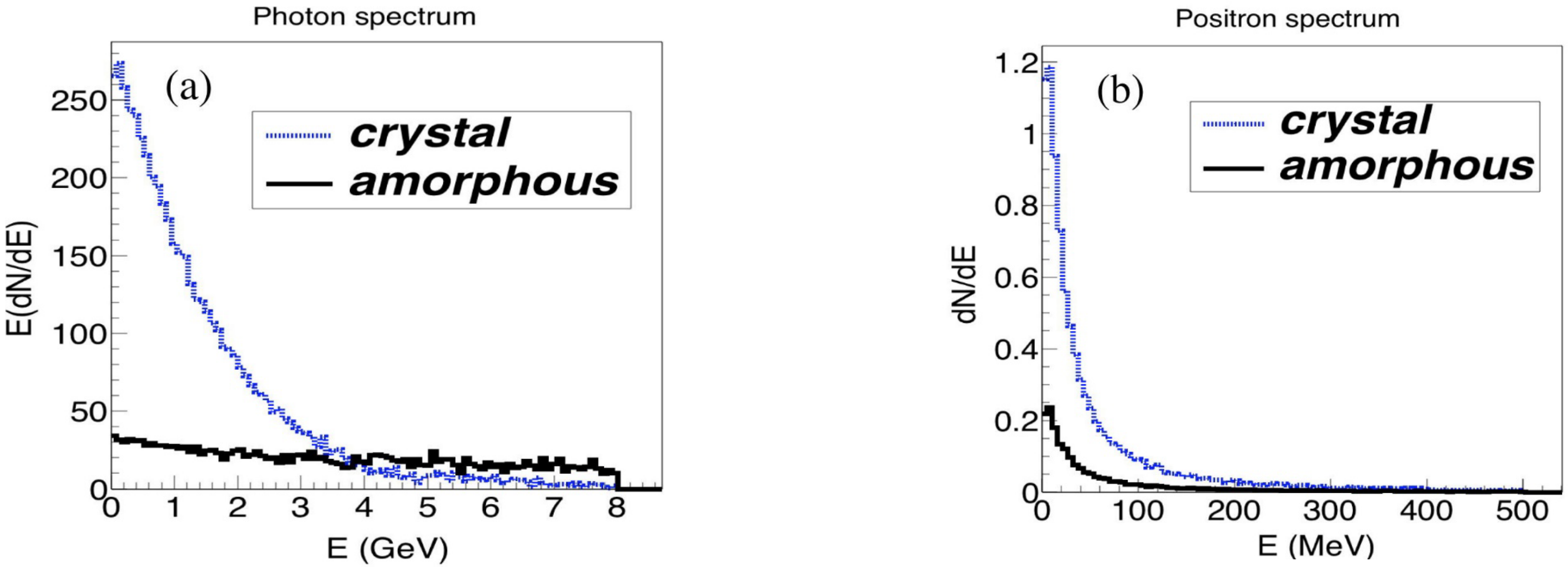
Idea of R. Chehab, V. Strakhovenko and A. Variola, NIM B 266 (2008) 3868

Hybrid crystal based positron source for future colliders

The main concern for all positron sources is not only the yield but also the energy deposition and the associated PEDD (Peak Energy Deposition Density)

Main advantages of the hybrid source:

- **Enhancement of photon generation in crystals in channeling conditions ➔ enhanchement of pair production in the converter target**
- **High rate of soft photons ➔ creation of soft e^+ easily captured in matching systems**



X. Artru, I. Chaikovska, R.Chehab et al. NIM B 355 (2015) 60

Hybrid crystal based positron source for future colliders

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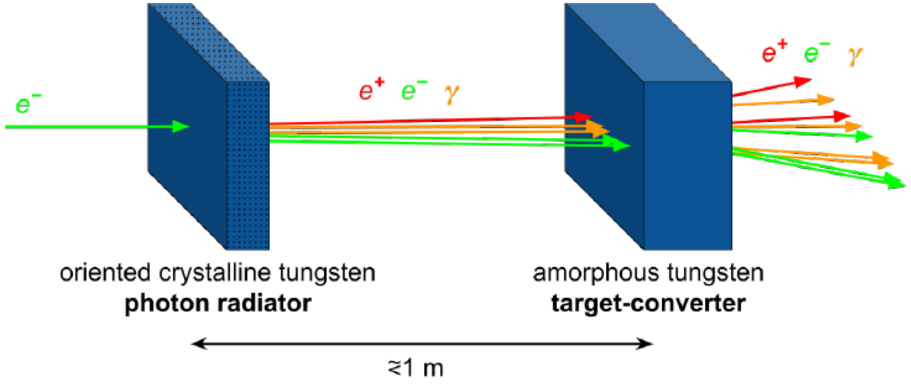
- **Enhancement of photon generation in crystals in channeling conditions ➔ enhanchement of pair production in the converter target**
- **High rate of soft photons ➔ creation of soft e^+ easily captured in matching systems**
- **Decrease of the PEDD in the converter target**

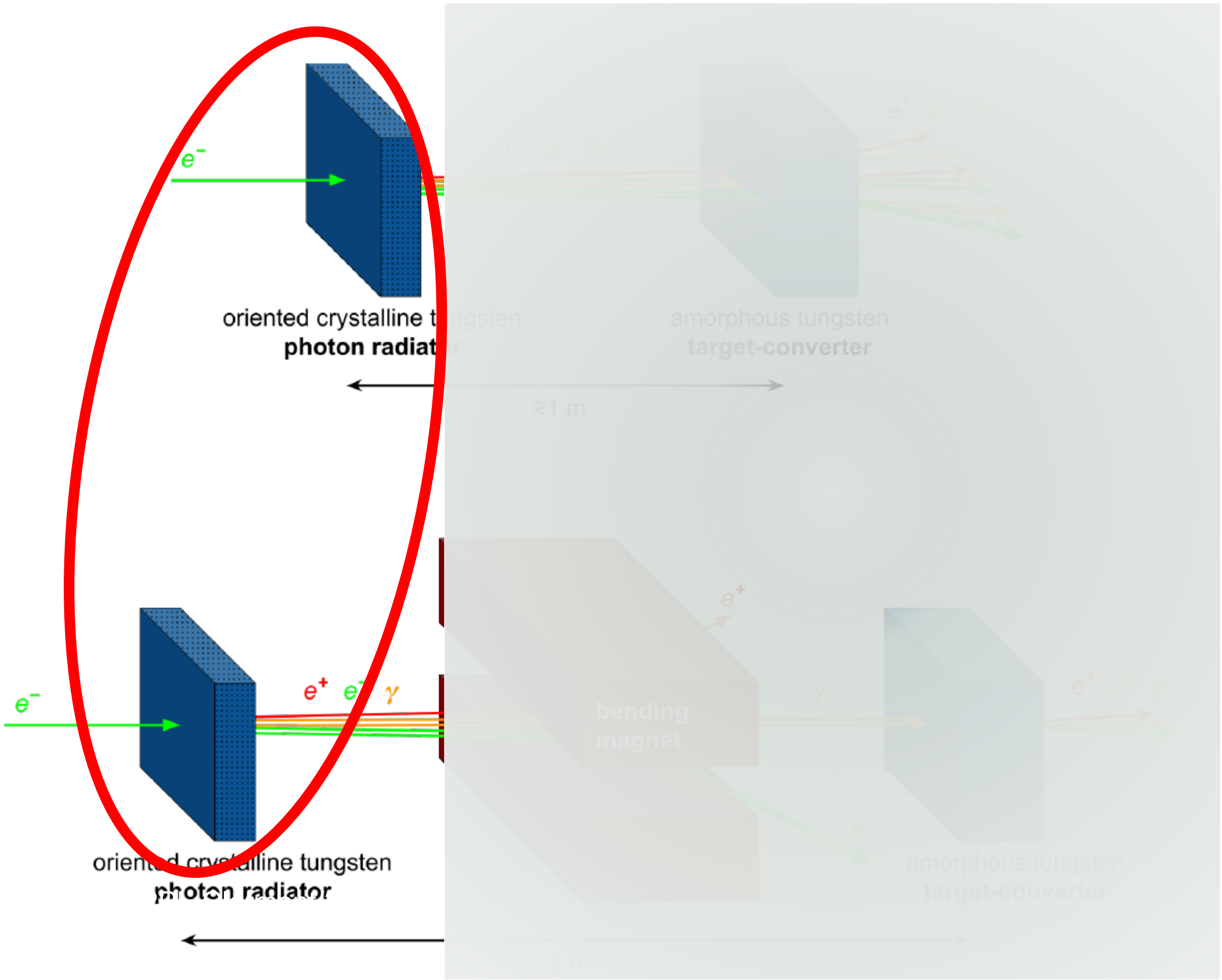


→ total energy deposit shared between the two stages ⇒ overall lower energy density

→ very low energy deposit and PEDD in radiator ⇒ very low heating and thermo-mechanical stress

Test on crystal radiator

- We focused our studies on the **“thin” crystal radiator, with thickness < X_0** , to limit both the heating/irradiation and the e± pairs production
- High-Z metallic crystals, as **tungsten (W)**, providing **the highest axial potential**
- We developed **a Monte Carlo code** to simulate the electromagnetic **processes in oriented crystals**
- We carried out **a benchmark test** at energies of interest for positron sources of future colliders



A Monte Carlo based for computation of radiation emission in oriented crystals

The electromagnetic radiated energy is evaluated with the Baier Katkov formula:

$$\frac{dE}{d^3k} = \omega \frac{dN}{d^3k} \quad \frac{\alpha}{4\pi^2} \iint dt_1 dt_2 \frac{\left[\left(E^2+E'^2\right)(v_1 v_2-1)+\omega^2/\gamma^2\right]}{2E'^2} e^{-ik'(x_1-x_2)}$$

where the integration is made over the classical trajectory.

Simulation of crystal radiator for positron source

Simulation of different physical processes:

- Multiple and single **Coulomb scattering** on nuclei and electrons.

Simulation of radiation:

- Baier-Katkov for the energies of e^+/e^- above 200 MeV.
- Bremsstrahlung by Bethe-Heitler formula for the energies of e^+/e^- below 200 MeV.

Simulation of pair production:

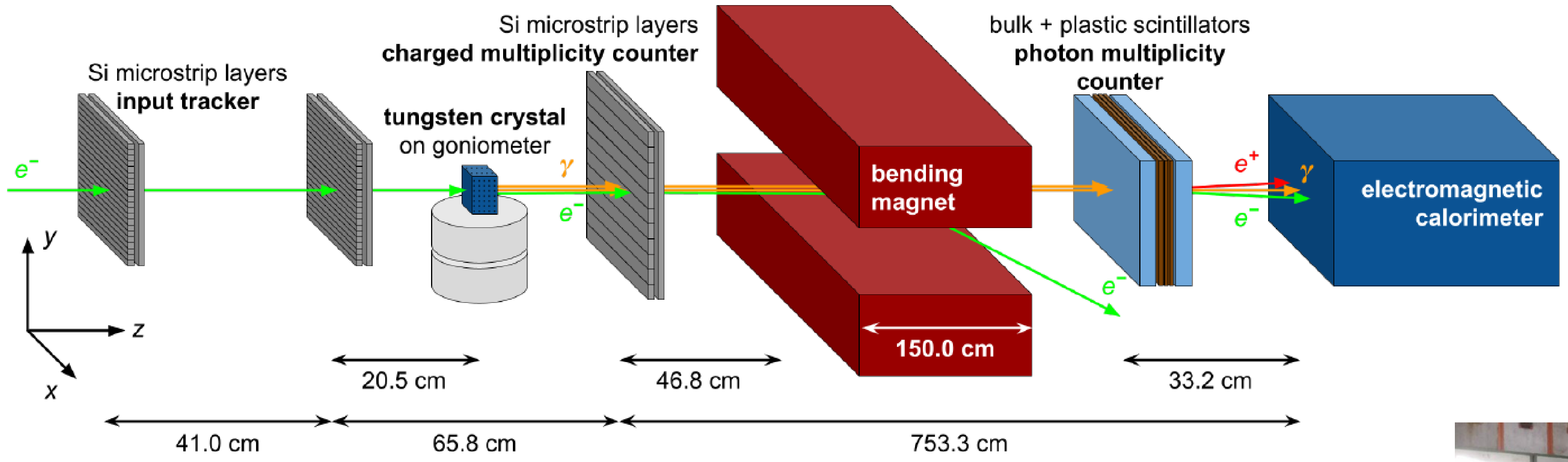
- Probabilities of pair-production pre-calculated by Baier-Katkov.
- Simulation of energies and angular distribution of e^+/e^- using the approach analogous to Geant4.

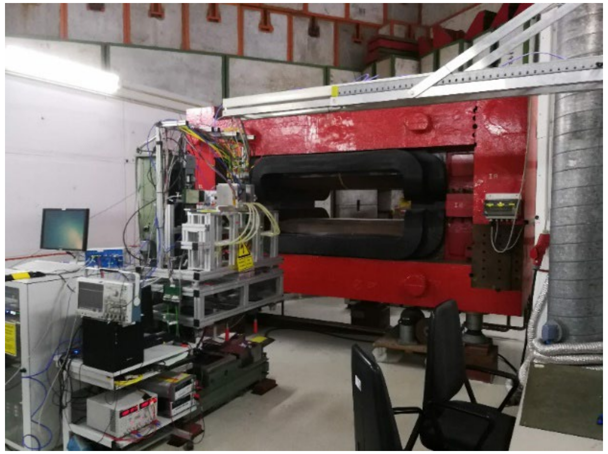
Simulation output

- Both primary and secondary particles (e^+/e^- and gamma) at the crystal exit, namely coordinates and momenta – compatible with the **Geant4 toolkit.**

[1] V. Guidi, L. Bandiera, V. Tikhomirov, Phys. Rev. A 86 (2012) 042903
[2] L. Bandiera, et al., Nucl. Instrum. Methods Phys. Res. B 355, 44 (2015).
[3] A. I. Sytov, V. V. Tikhomirov, and L. Bandiera, Phys. Rev. Accel. Beams 22, 064601 (2019).
[4] L. Bandiera, V.V.Haurylavets, V. Tikhomirov Nucl. Instrum. Methods Phys. Res. A 936 (2019) 124.

Experiment@DESY Test Beam facility



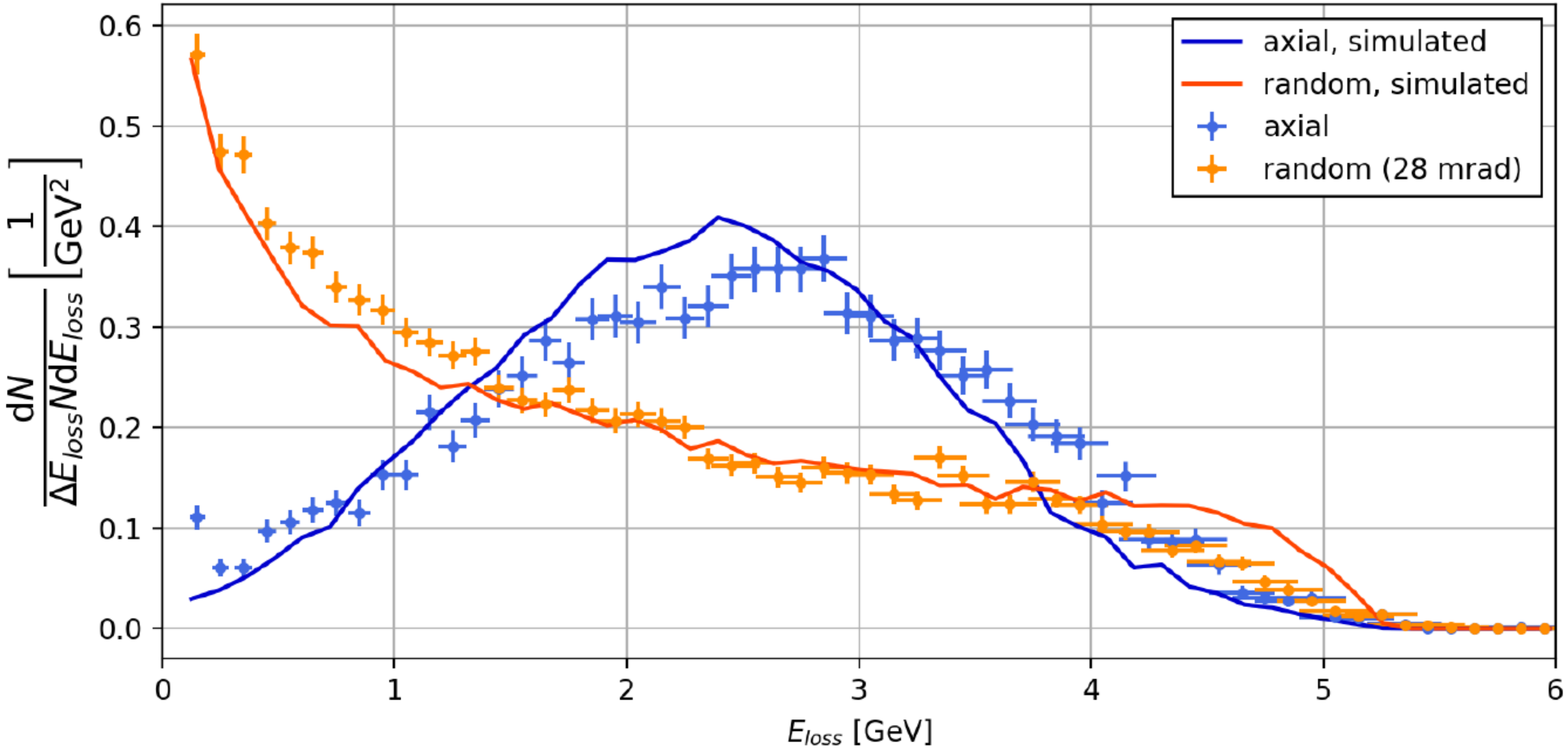


Investigation of radiation enhancement **in an axially oriented tungsten crystal**:

- e^- beam energy = 5.6 GeV
- beam divergence ≈ 0.7 mrad
- W crystal, <001> oriented, 2.24 mm thick (≈$0.65X_0$) – Manifactured by the Laboratory of Materials Science (LMS), Institute of Solid State Physics RAS (coord. V. Glebovsky)

We acknowledge the support of the DESY TB facility staff

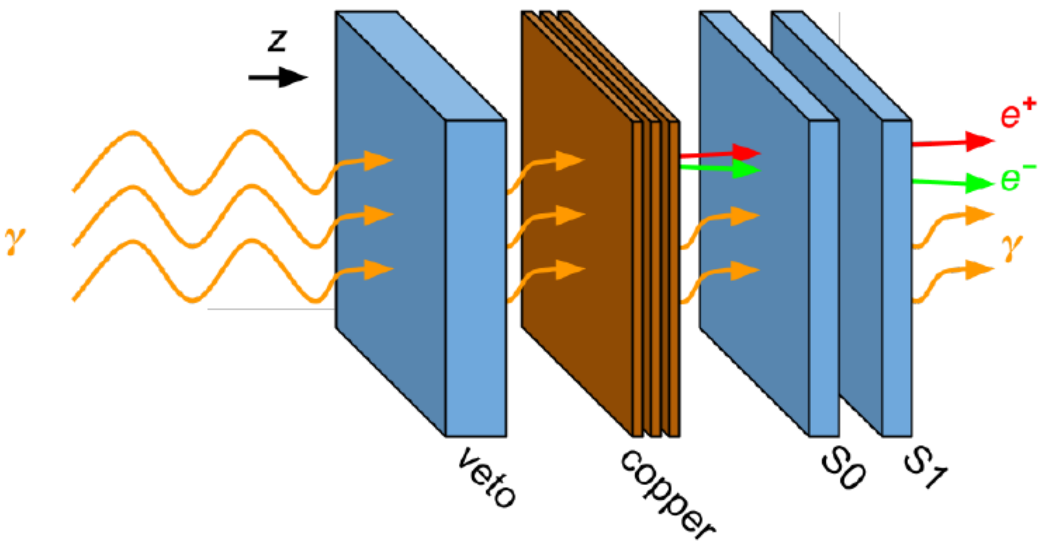
DESY results: calorimeter signal



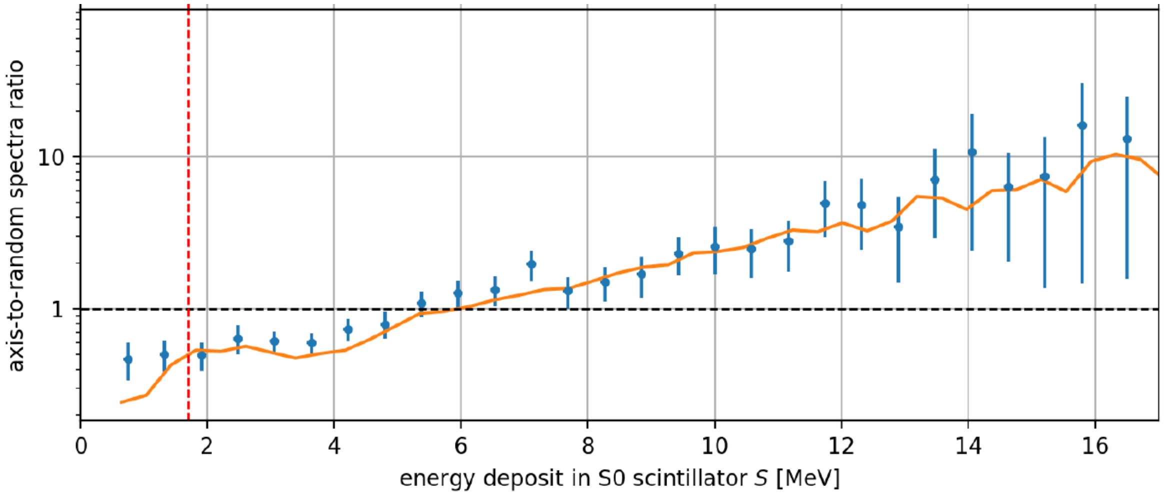
- For the 2.24 mm long W aligned along the **<001> axes** the maximum energy loss in the emission of photons **is peaked at 2.5 GeV**, while for the **random case is close to 0** as typical for Bremsstrahlung.
- Good agreement with Monte Carlo simulations including the whole experimental setup.

L. Bandiera et al., Eur. Phys. J. C 82, 699 (2022), Crystal-based pair production for a lepton collider positron source

Results on photo emission enhancement



Enhancement of energy deposited in downstream scintillator S0 in case of axial orientation of the crystal related to the random orientation



- An **estimate of the number of photons that emerge from the crystal was obtained via a photon multiplicity counter**, which consisted of plastic scintillators placed upstream (for photon veto) and downstream (for electron-positron pair multiplicity measurement) with respect to a converter layer (0.2-0.4 radiation lengths of copper).

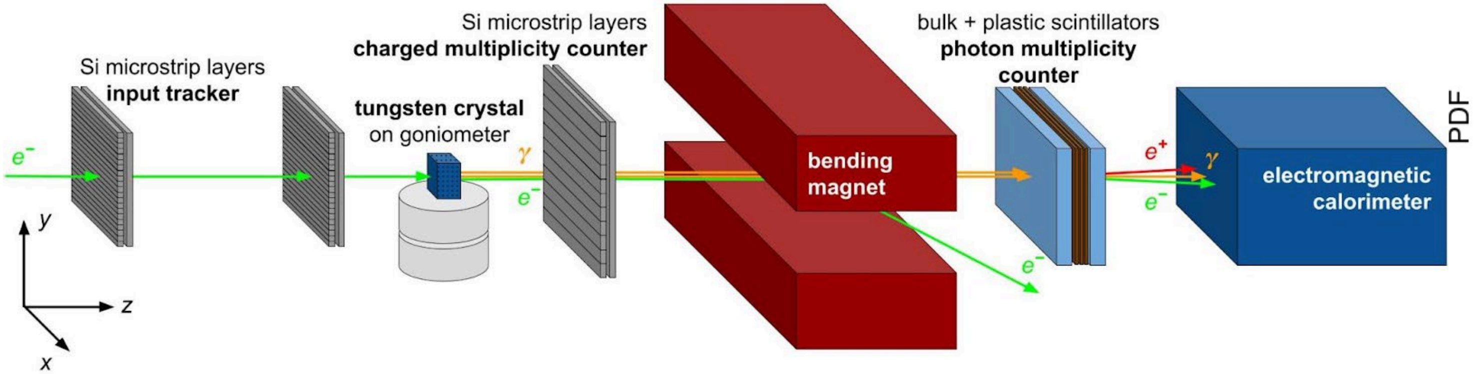
- **Increase** in the average number of high-energy deposit events (i.e. **in the average number of events featuring many output photons — more than 2) in case of axial alignment if compared to random**.

- **Good agreement with Monte Carlo simulations!**

L. Bandiera et al., Eur. Phys. J. C 82, 699 (2022), **Crystal-based pair production for a lepton collider positron source**

CERN PS t9 beam test – AUGUST 2022 RADITATION MEASUREMENT

Setup @CERN PS T9 beamline

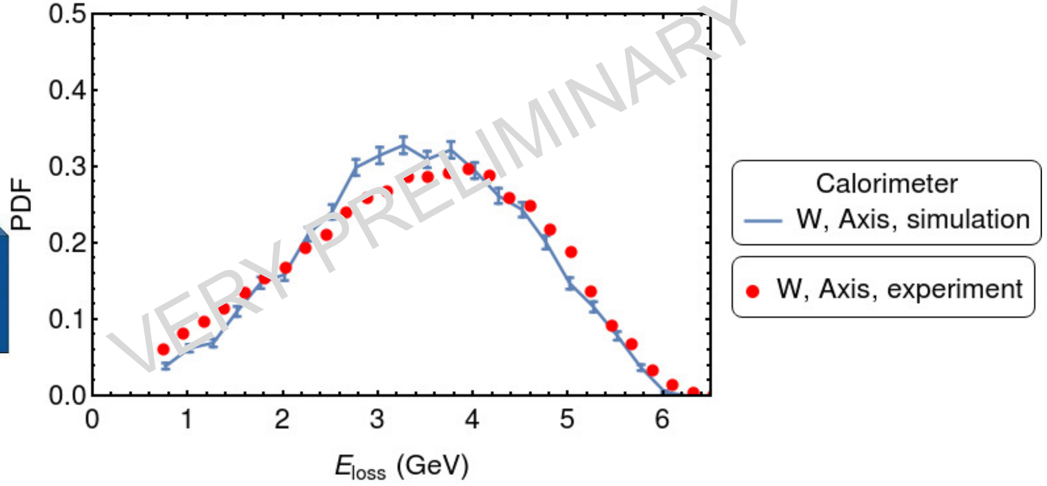


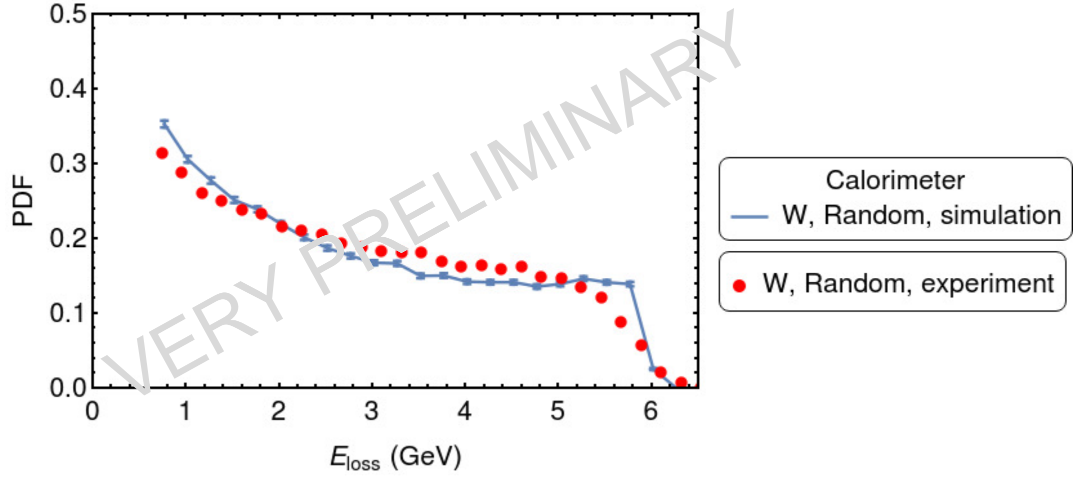
Electron beam energy: 6 GeV
Crystal target: W <111>, 2 mm long

Parameters chosen in agreement with the Geant4 optimization: *L. Bandiera et al., Eur. Phys. J. C 82, 699 (2022), Crystal-based pair production for a lepton collider positron source. https://doi.org/10.1140/epjc/s10052-022-10666-6*

We also tested a Iridium and diamond crystals with 6 GeV and a W target with 20 GeV – analysis ongoing

Radiative energy loss measured by the Ecal



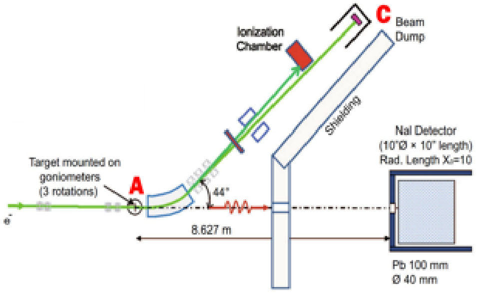


Target studies @MAMI for intense positron sourceS for future colliders

IPAC 2022: ***F. Alharthi*** *, I. Chaikovska , R. Chehab , S. Ogur , S. Wallon , , A. Ushakov , V. Mytrochenko , Y. Zhao , P. Sievers , L. Bandiera , A. Mazzolari , M. Romagnoni , A. I. Sytov , M. Soldani , W. Lauth , O. Khomyshyn , D. Klekots*

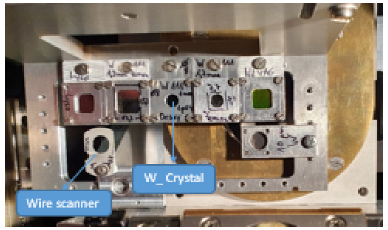
MAMI experiment layout:

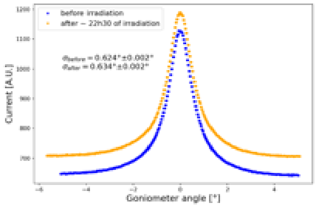
- Measurements were performed with low-emittance, high-intensity, 855 MeV electron beam on different samples.
- Two positions are chosen to place the samples: position (A) & (C).
- Samples are placed on target holders.



Preliminary results at position (A):

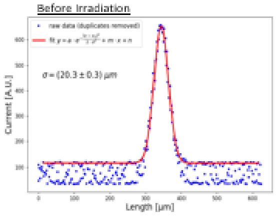
- Beam is highly focused and crystalline target is placed on a goniometer.
- **Several angular scans were performed to align the crystal <111> axis with respect to the beam direction using Ionization chamber.**





No significant variation in the width of the axial angular ranges has been observed.

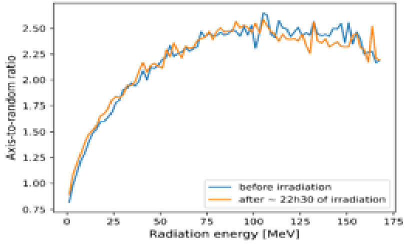
Vertical beam size



Stable beam size for the whole radiation cycle, σ_{after} =(20.4μm)

- **Measurement of the integral energy spectrum was performed by NaI detector.**

Target	Dimensions	Beam current	Irradiation time	Preliminary Fluence
W-crystal	1mm thick, 8mm diameter	8-10nA CW	~22.5h	6.11e17 [e-/mm²]



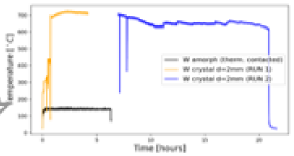
Crystalline structure of the target wasn't affected by the irradiation.

Preliminary results at position (C):

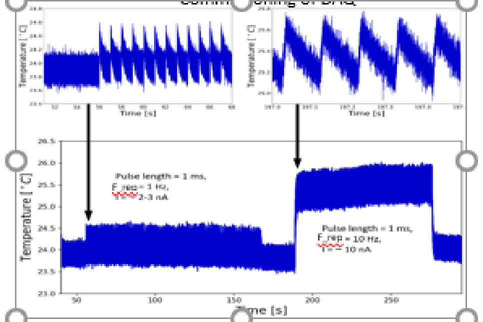
The main goal : target irradiation, under the precise temperature control.

- Three W targets were installed(crystal + 2 amorphous).
- Thermocouples (K-type) were readout by DAQ (Ametek VTI Instruments EX1401).
- Observables: target steady state temperature and temperature jump per pulse.
- No beam monitoring installed at this position but an attempted was done to measure the beam size using the thermocouples.
- Crystal and amorphous thermally contacted targets were irradiated.

Target irradiation



Commissioning of DAQ

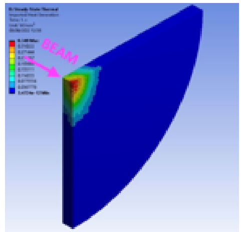


The detailed simulation studies for the PEDD are on the way

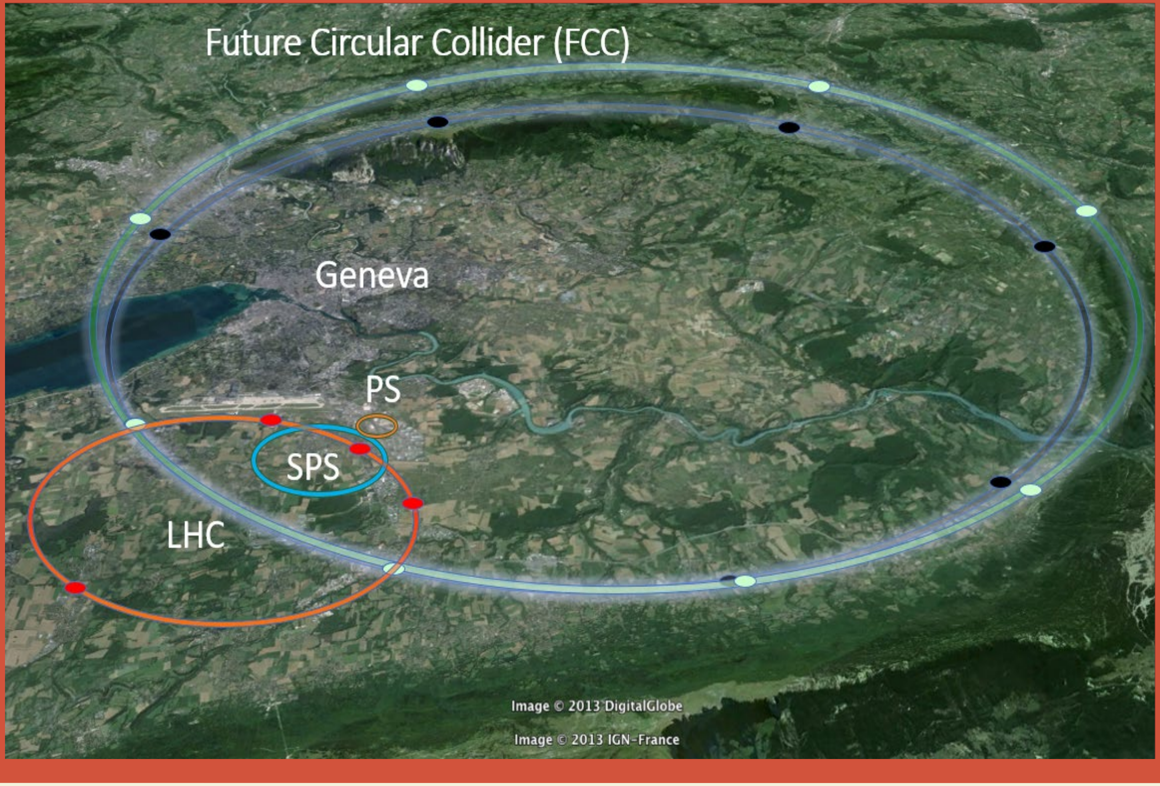
Target	Dimensions (Thickness, diameter)	Beam current	Irradiation Time	Preliminary Fluence [e-/mm²]
W-amorphous	(2mm, 50mm)	1-3μA	~23 hours	~1.3e18
W-crystal	(2mm, 8mm)		~21 hours	~1.1e18

Thermal simulation and analysis:

- ANSYS thermal simulations are under way to assess the target behavior during the beam tests
- It allows useful comparison with temperature measurements in order to:
    - check the beam power deposition and PEDD in the target, therefore giving an "overall" check of beam parameters..



The results of this work is based on the collaboration between CNRS, University of paris saclay, INFN-FERRARA and MAINZ.

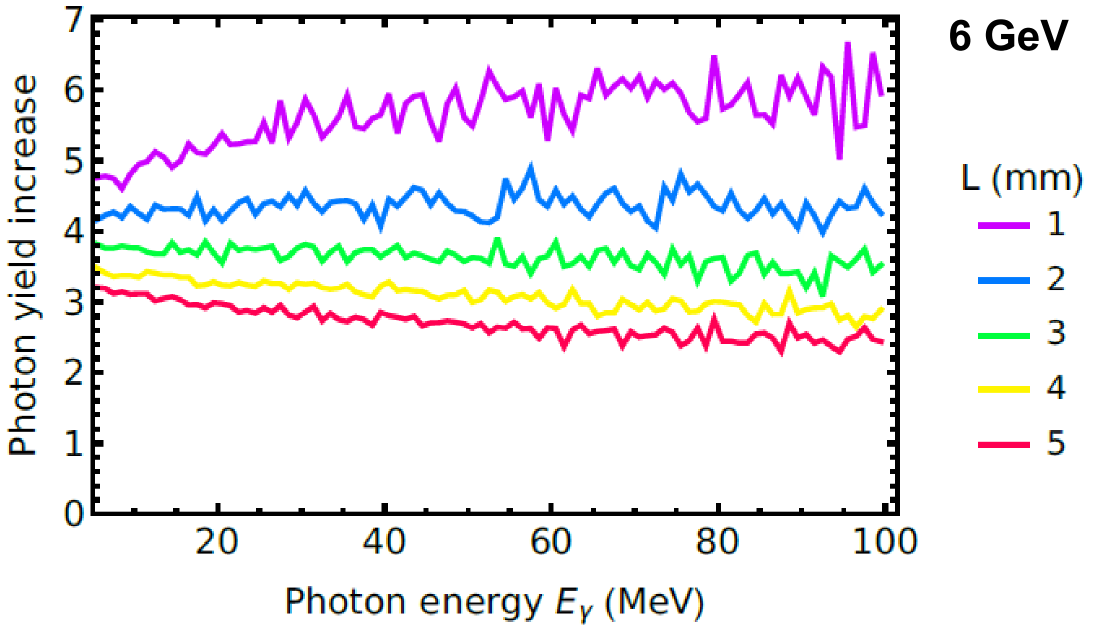


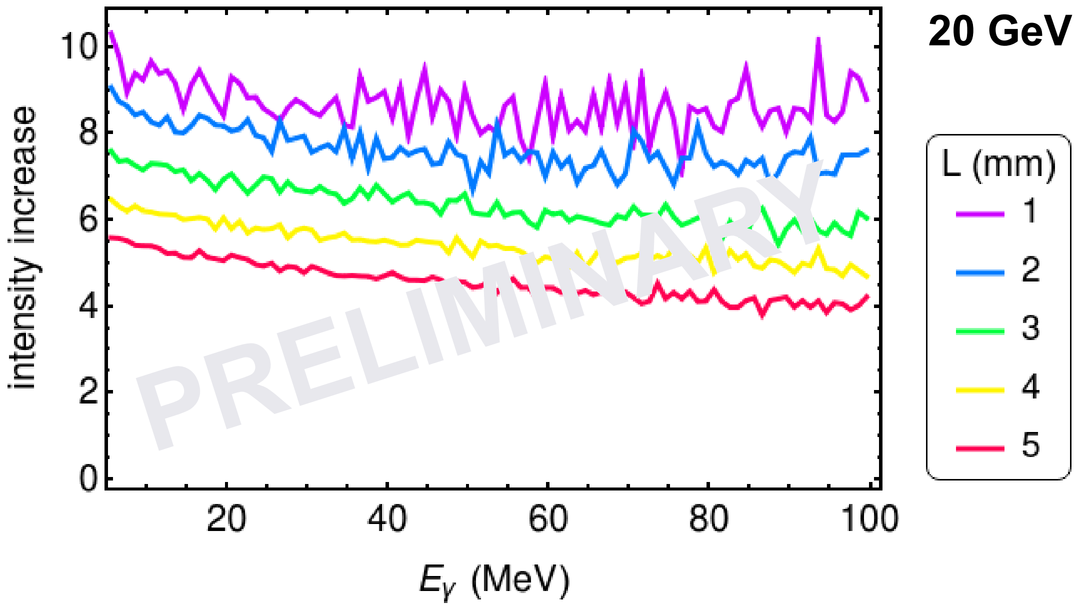
HYBRID SOURCE OPTIMIZATION FOR THE FCC-EE E+ SOURCE

joint effort by INFN Ferrara (Italy) and IJCLab (France)

A. Sytov (INFN-Ferrara), V. Tikhomirov (INP)

Radiation emitted by electrons in an axially oriented <111> W crystal





Photon yield for the case e- @6 GeV

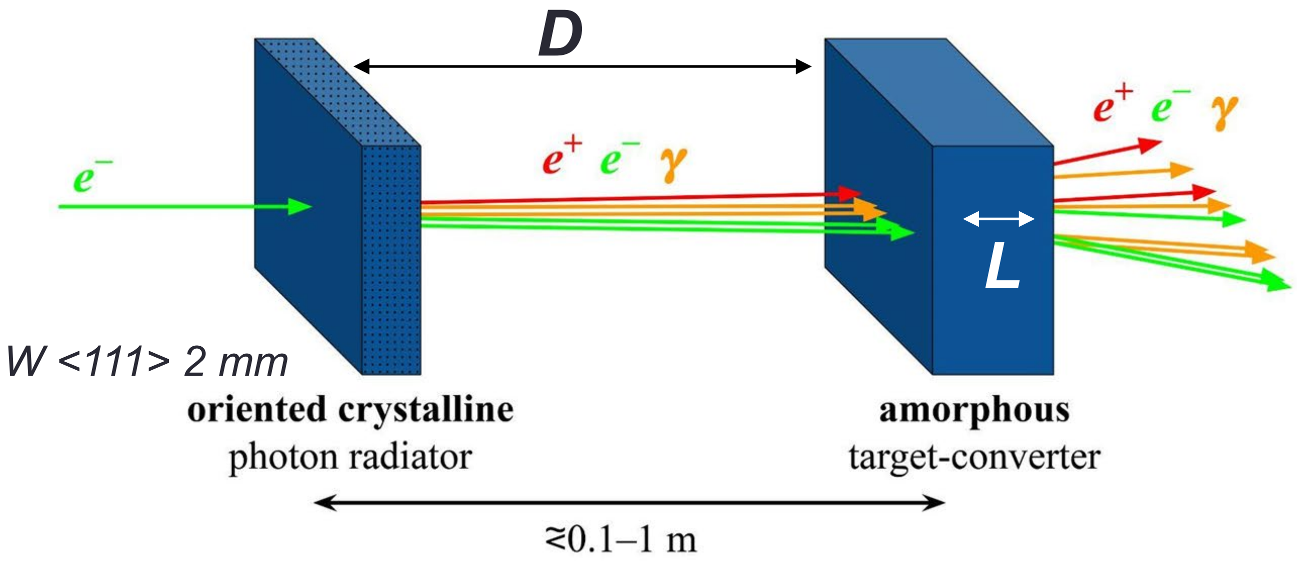
Photon energy < 100 MeV since these photons are responsible for the production of positrons within the typical capture system acceptance

crystal thickness [mm]	1	2	3	4	5
N_γ					
$<$ 100 MeV, amorphous	1.1	2.6	4.6	7.4	10.9
$<$ 100 MeV, $\langle 111 \rangle$ axis	6.1	11.3	17.2	24.0	31.8
full spectrum, amorphous	2.3	4.7	7.5	11.0	15.1
full spectrum, $\langle 111 \rangle$ axis	11.0	17.6	24.0	31.0	38.8

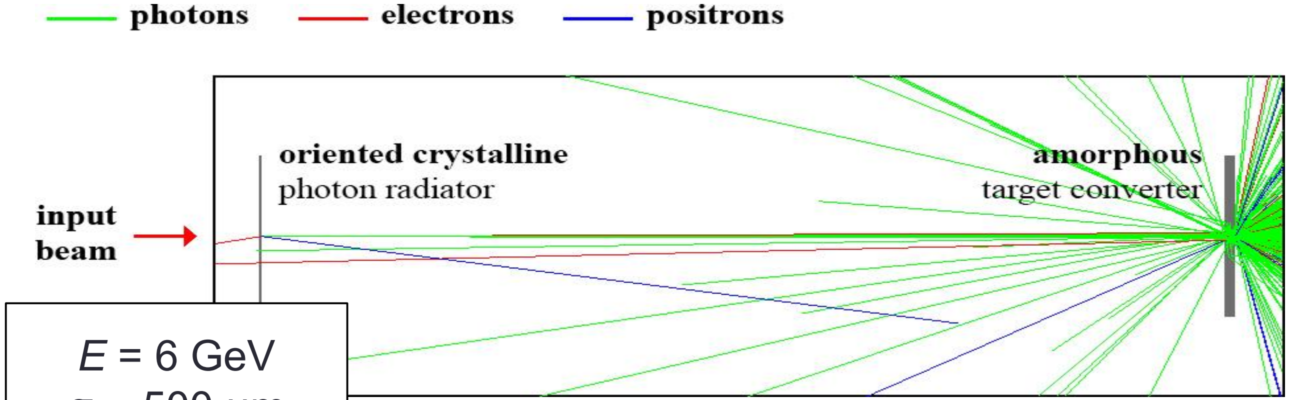
L. Bandiera *et al.*, **EPJC 82**, 699 (2022) **Crystal-based pair production for a lepton collider positron source**

M. Soldani (INFN-Ferrara)

Hybrid source optimization



energy deposit and PEDD in amorphous converter can be reduced by tuning ***L*** (while keeping the radiator thickness fixed to maximise EM enhancement) and ***D***



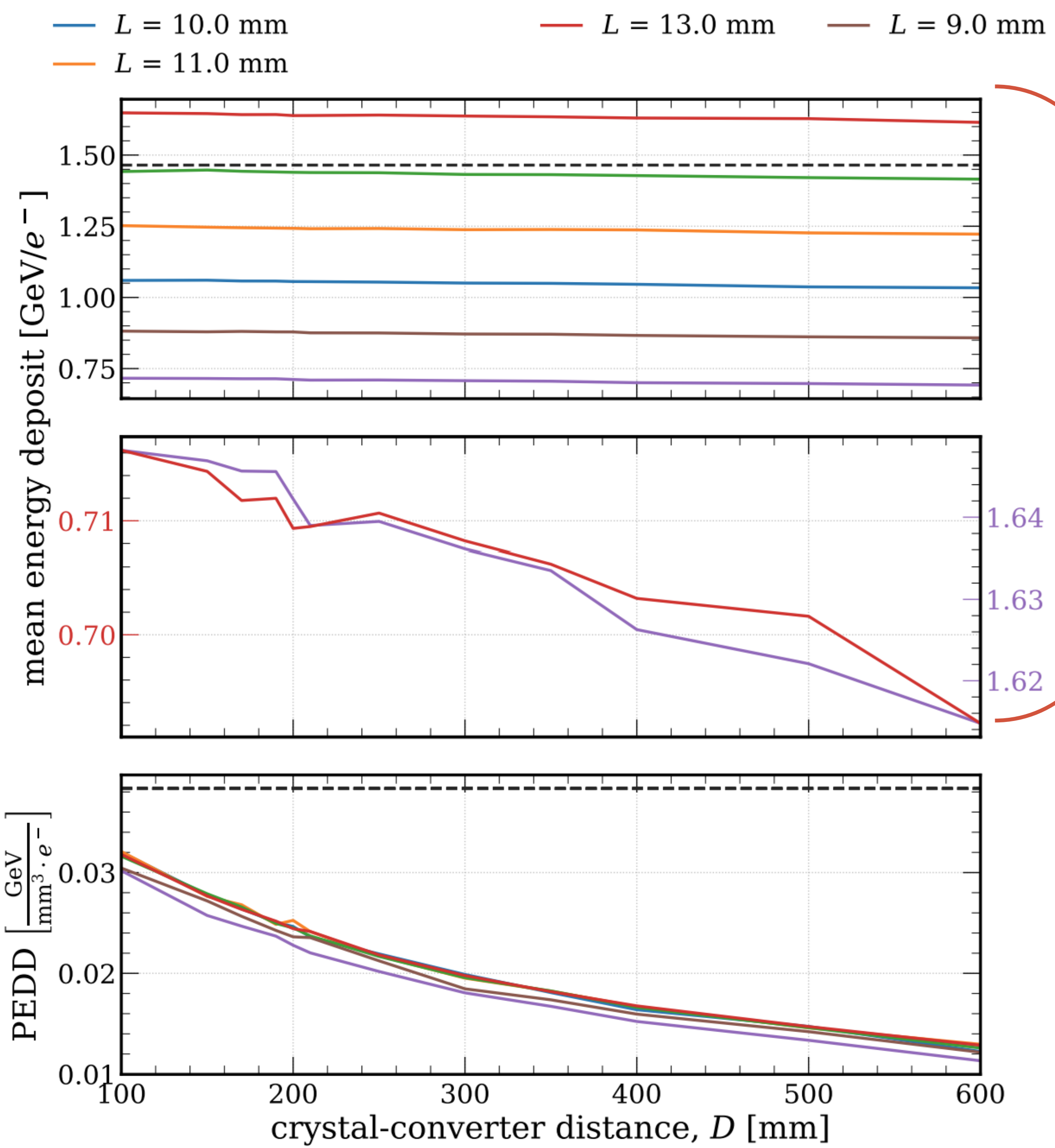
E = 6 GeV
σ = 500 μm
σ’ = 100 μrad

Geant4 simulation of the downstream stage…

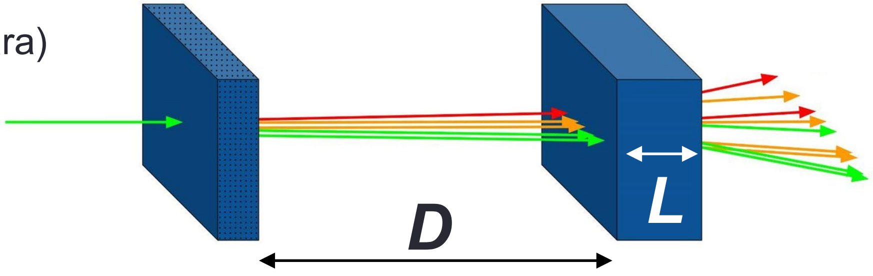
(upstream stage already optimised with dedicated code and experimental data→ dedicated input files)

L. Bandiera *et al.*, **EPJC 82**, 699 (2022)

energy deposit & PEDD



M. Soldani (INFN-Ferrara)



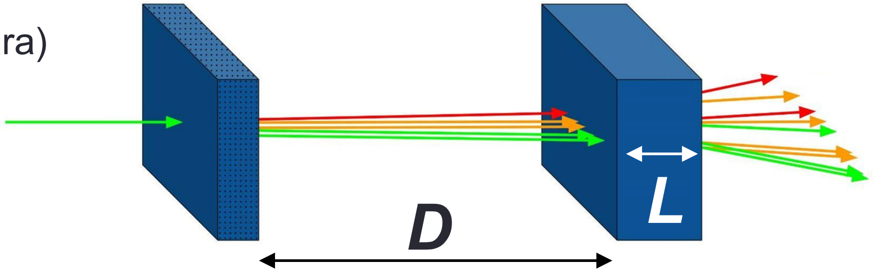
energy deposit heavily depends on *L* and slightly on *D*

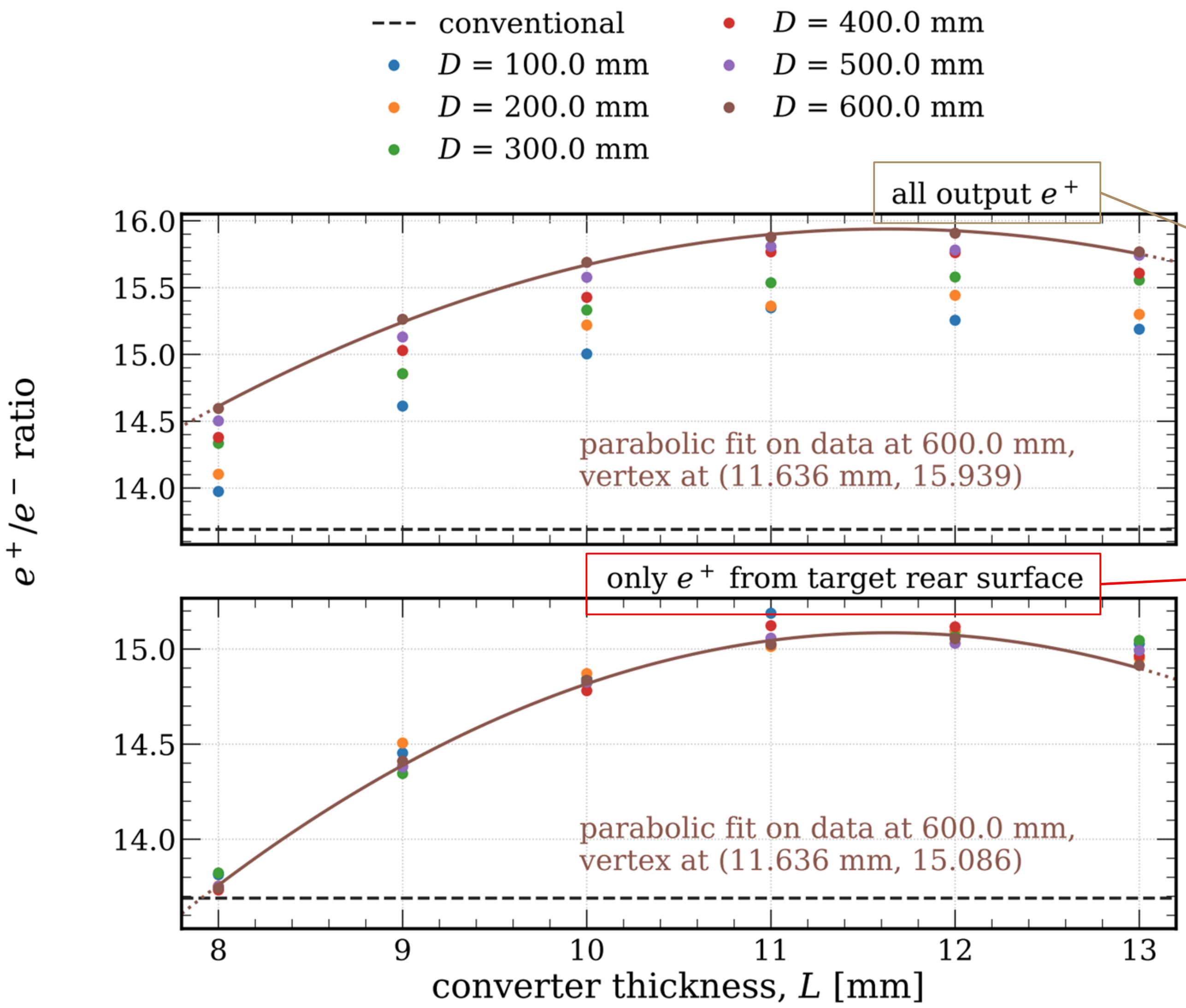
in general, it is better than in the conventional case (but for very thick converter target → inconvenient)

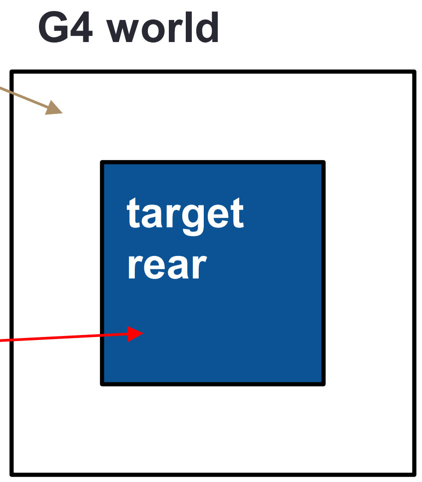
PEDD: essentially independent on *L*, heavily depends on *D* → crystal-target distance has to be as high as possible (bound by output beam aperture requirements)

positron production rate

M. Soldani (INFN-Ferrara)





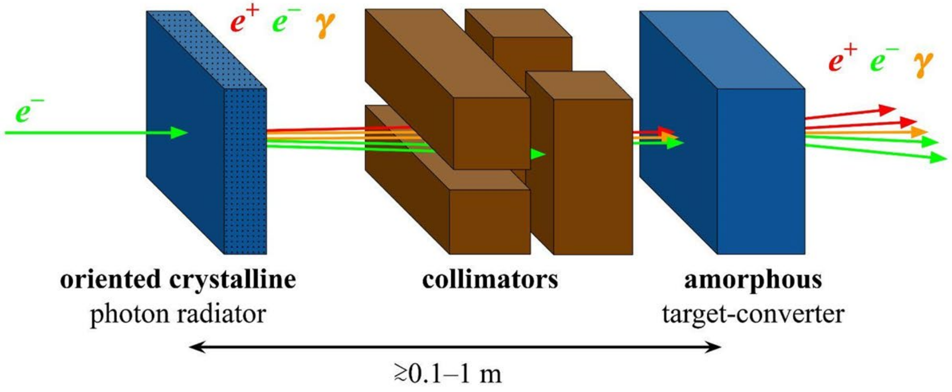


transition curve has a maximum at L ~ 11.6 mm, which corresponds to an integral energy deposit lower than the conventional case

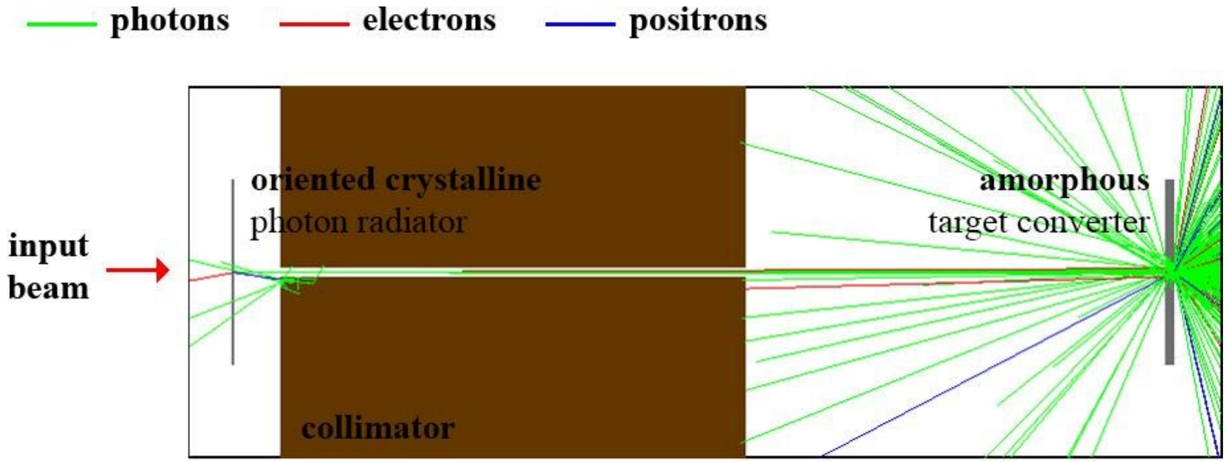
improving the hybrid scheme…

L = 11.6 D = 600, 1000, 2000 mm

…with **collimator**

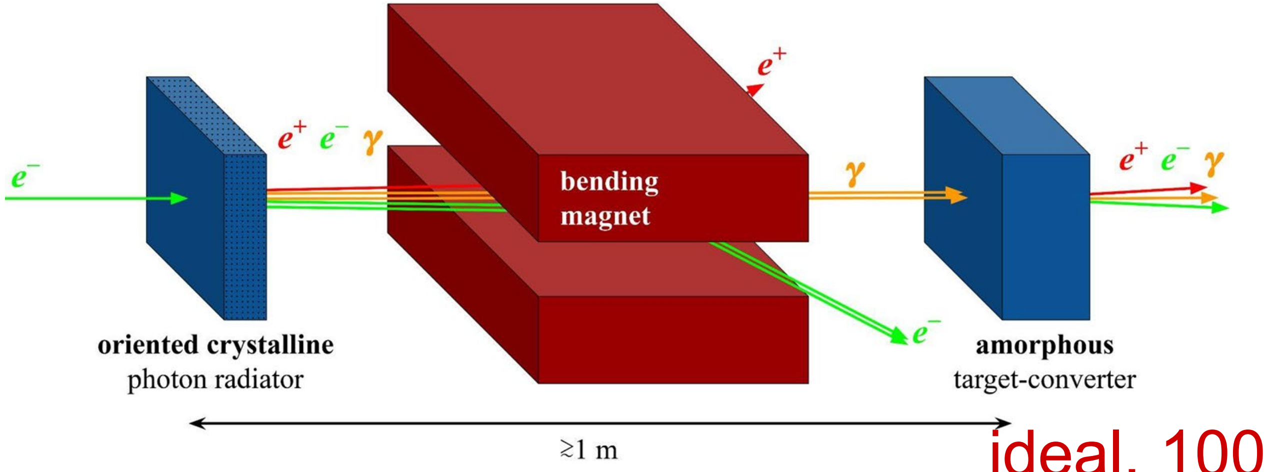


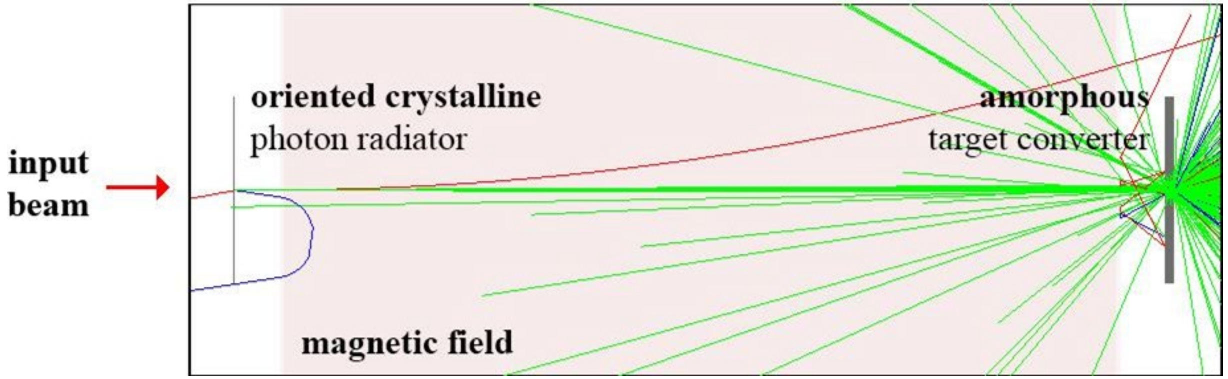
M. Soldani (INFN-Ferrara)



tungsten block of thickness 50 cm with square hole of side ***a***

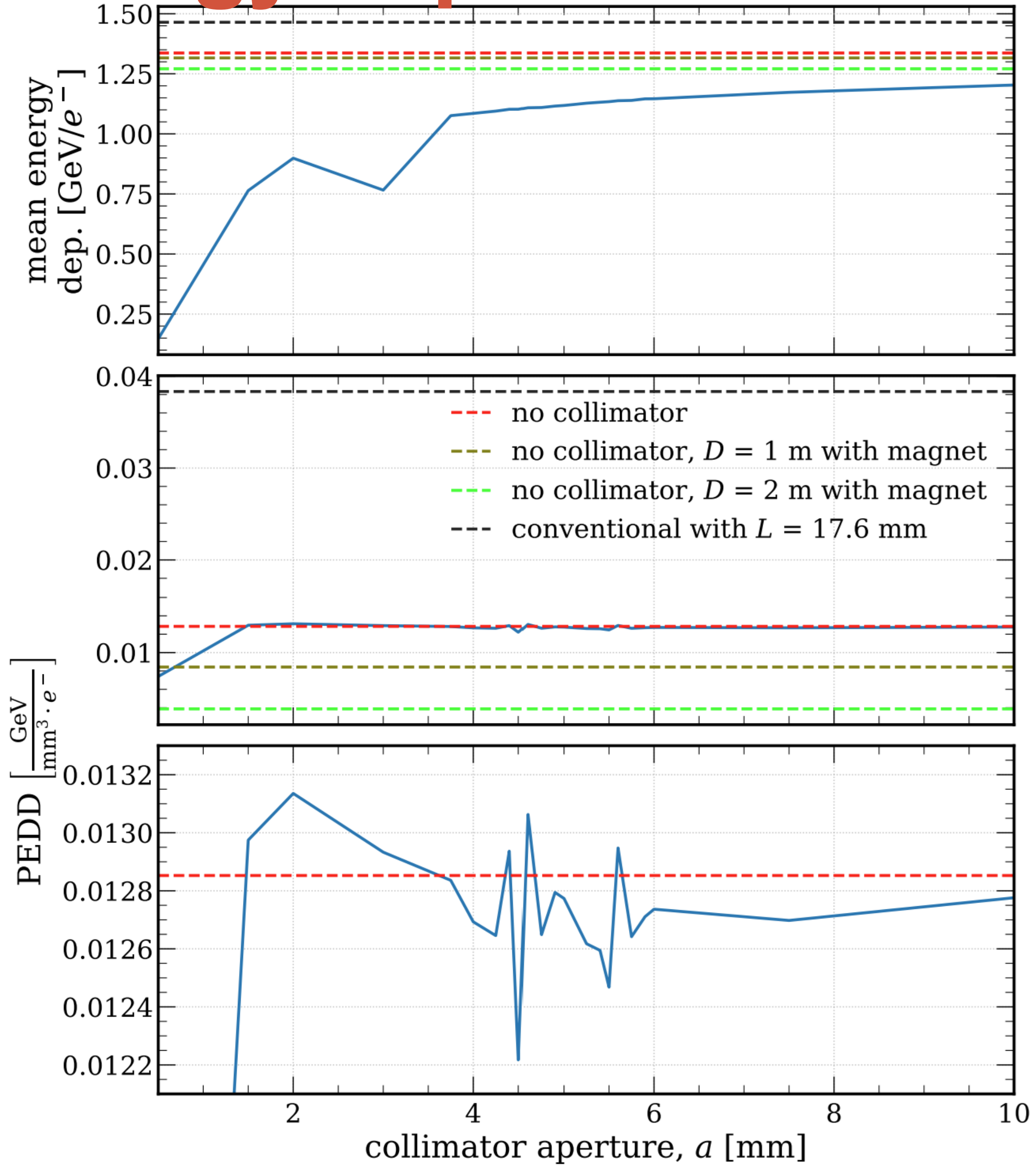
…with **magnet**

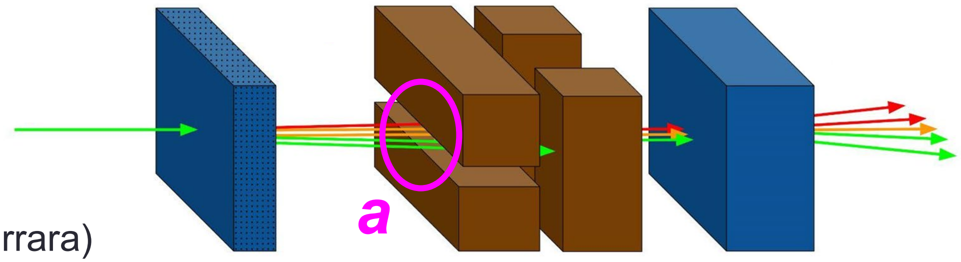




ideal, 100 T field to swipe all charged particles away

energy deposit & PEDD





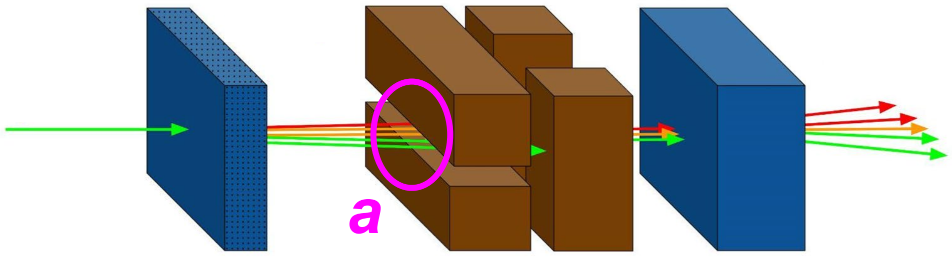
M. Soldani (INFN-Ferrara)

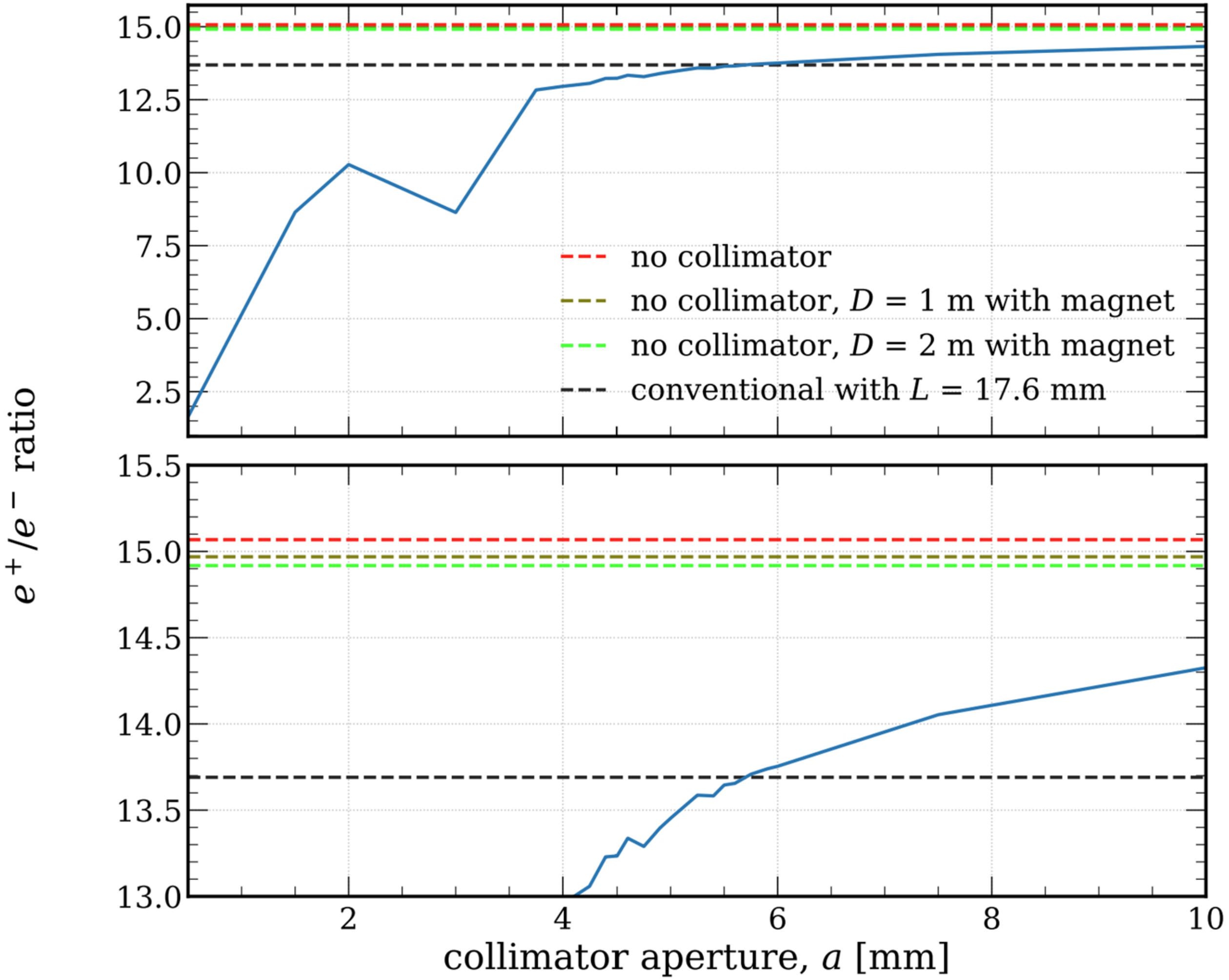
in general, **energy deposit** is lower (much lower) with magnet (collimator) wrt normal hybrid case, and it grows with *a* → better to keep *a* as low as possible

PEDD with collimator is similar to normal hybrid case, only a slight reduction for *a* with minimum around 7 mm is observed

PEDD with magnet (with larger *D*) is lower

positron production rate





output positron rate with collimator improves as *a* increases

⇒ conventional value is obtained at *a* ~ 5.5 mm, hybrid (without and with magnet) value is obtained asymptotically

M. Soldani (INFN-Ferrara)

All together…

M. Soldani (INFN-Ferrara)

conventional (amorphous)
collimator
magnet

$a = 5.5$ mm

Scheme	conv.	hybrid						
L_{crys} [mm]	–	2						
D [m]	–	0.6	1			2		
L [mm]	17.6	11.6						
Collimator?	no	no	no	yes	no	no	yes	no
Magnet?	no	no	no	no	yes	no	no	yes
E_{dep} [GeV/e^-]	1.46	1.34	1.32	1.13	1.32	1.27	1.11	1.27
PEDD [MeV/(mm$^3 \cdot e^-$)]	38.3	12.8	8.4	8.2	8.4	4.1	3.8	3.9
Out. e^+/e^-	13.7	15.1	15.1	13.6	15	14.9	13.7	14.9
Out. e^+ beam size [mm]	0.7	1	1.2	1.2	1.2	1.5	1.5	1.5
Out. e^+ beam div. [mrad]	25.9	27.4	26.8	27.7	28.9	29.2	25.6	27.1
Out. e^+ mean energy [MeV]	48.7	46.2	45.6	47.4	45.9	46.1	47.7	46.3
Out. n/e^-	0.37	0.31	0.31	0.27	0.29	0.29	0.26	0.3
Out. γ/e^-	299	310	308	270	307	301	268	301

Joint effort between INFN-Fe and IJCLab

Summary

- **Crystal radiator**
  - DESY and CERN tests in agreement with MC with two different W crystals;
  - Other test with Ir, diamond and W at different energies are under analysis;
  - Currently A. Sytov (INFN-Fe) is including the e.m. processes in oriented crystal inside the Geant4 toolkit within his MSCA IF project TRILLION.
  - Irradiation tests to measure the heating/radiation resistance started in MAMI (A past test at SLAC with a thin W crystal (0.3 mm thick) showed no damages up to a fluence of $2\text{x}10^{20}$ e^{-}/cm^{2}).

- **FCC-ee hybrid source optimization**
  - Different configurations under study (with or without collimators/magnet): each of them has its own strengths and caveats ⇒ choosing the final configuration will require additional info concerning the downstream stages…
  - indeed output tracks can be fed to the magnetic capture system simulations ⇒ work in synergy to optimise the whole chain

Joint effort between INFN-Fe and IJCLab

What to do in future…

Experiment

- Other crystalline materials with different thicknesses have been purchased and will be tested in the near future to select the final configuration for the crystal radiator: in particular 1.5 mm & 2.5 mm W and 2 mm Ir crystals.
- Test of the two target setup (crystal+converter) to measure directly the e+ yield.
- Continue irradiation tests on crystal and converter targets. Also evaluating the possibility to use more sophisticated targets (granular, rotating)

Simulation

- The simulation environment has now been fully developed and can be used for more sophisticated studies (capture system etc…)
- Future full inclusion in G4 will permit to change also the crystal radiator parameters. For now, different input files will be prepared for different thicknesses and materials.

THANK YOU FOR THE ATTENTION!

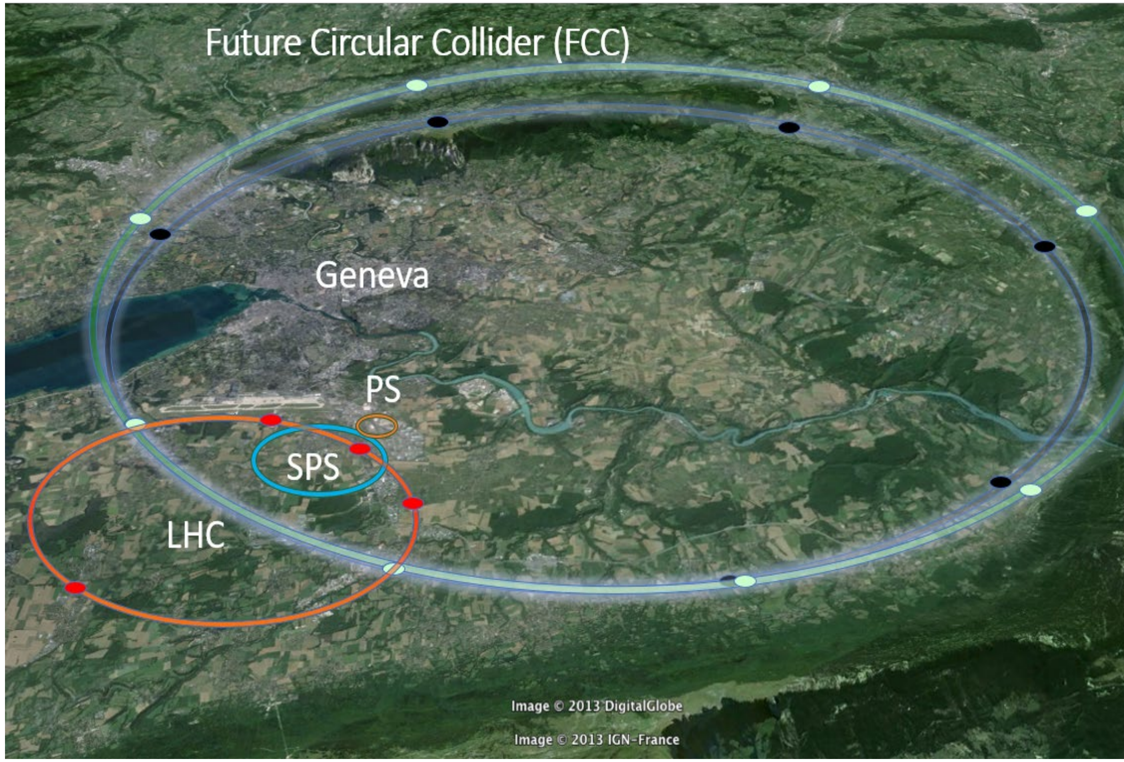
FCC-ee positron source

- The positron source is one of the key elements of the FCC-ee. To ensure high reliability of the positron source, conventional and hybrid targets are currently under study. The final choice of the positron target will be based on the estimated performances.

- A positron bunch intensity of 2.1×10^{10} particles is required at the injection into a pre-booster ring allowing for a positron yield of 0.5 Ne+/Ne−. These constraints about intensity and emittance results in a strong heat load, with constraints in the reliability of the targets.

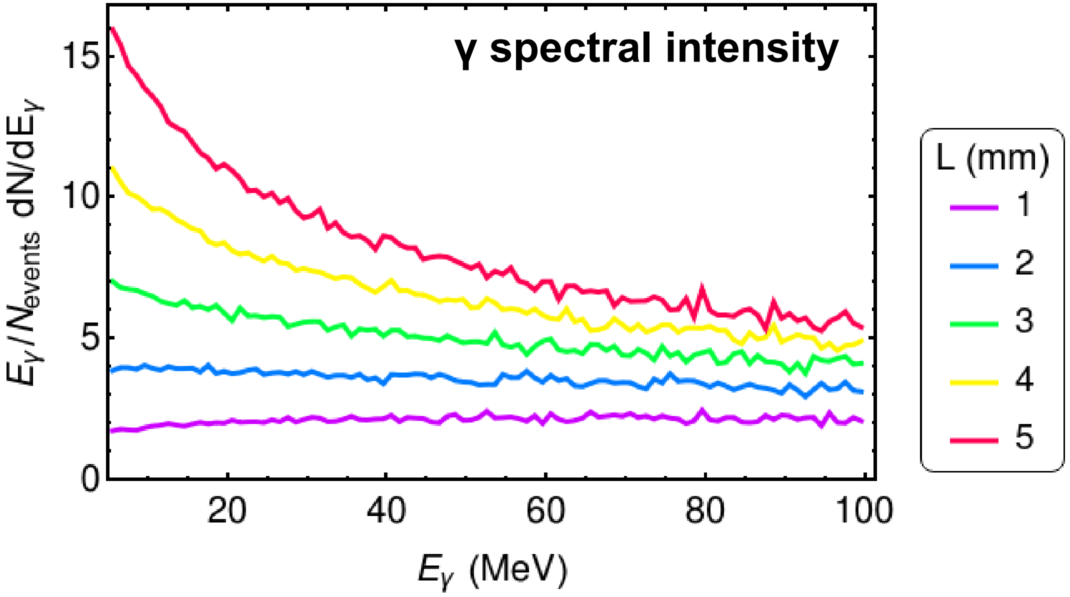
- The **injector complex for the FCC-ee consists of a 6** GeV linac and then the beams are accelerated from 6 to 20 GeV in the pre-booster synchrotron ring and then to full energy in the booster synchrotron ring. **The positron source could be inserted at the injection (6 GeV).**

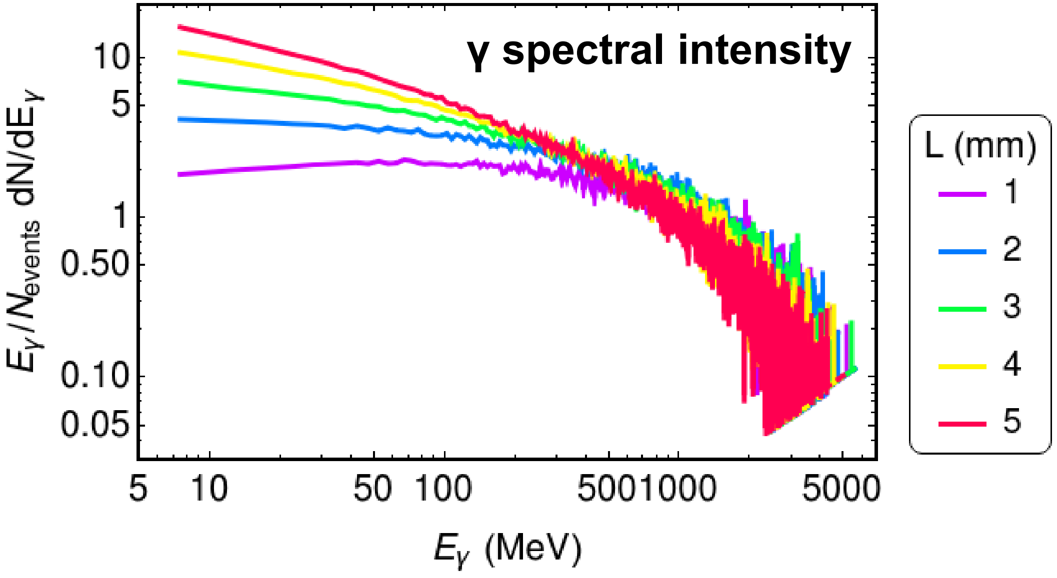
- As an alternative option for the FCC-ee injector, **a 20 GeV linac is proposed** to provide the direct injection into the booster ring.



FCC-ee Injection Group - positron source task Leader I. Chaikovska (IJCLab)

Radiation emitted by 6 GeV e$^-$ in an axially oriented <111> W crystal

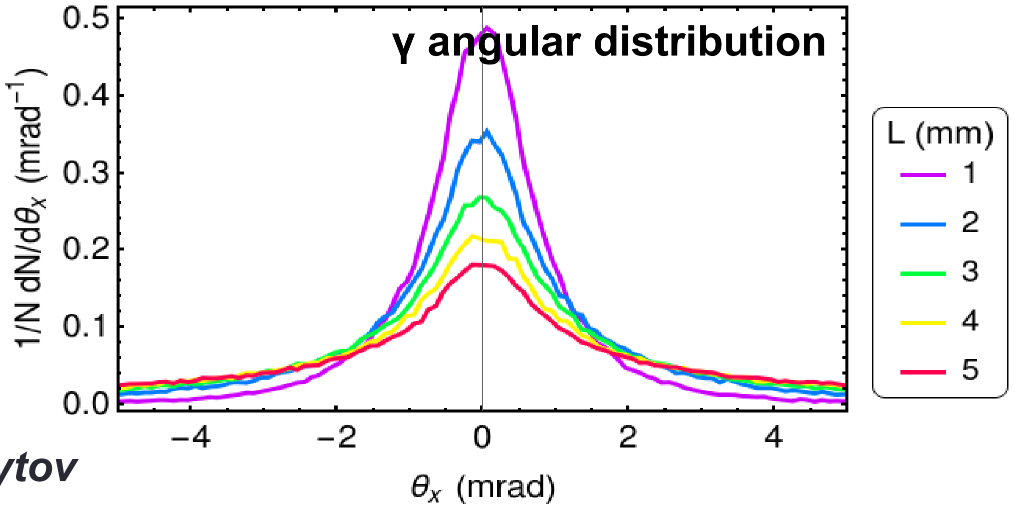




Low energy cut for gamma in simulation: 5 MeV

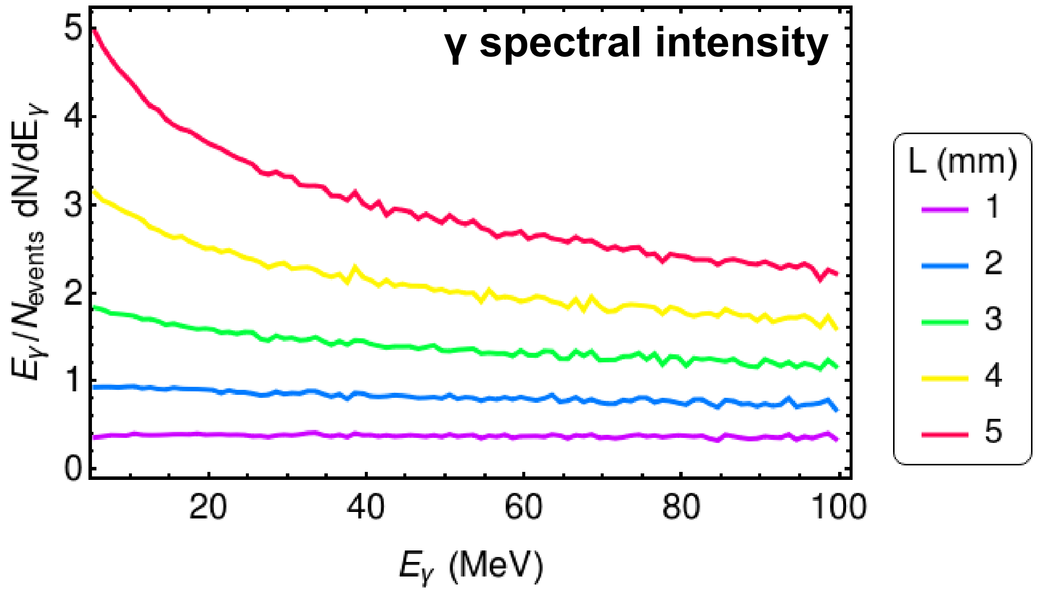
Initial beam:

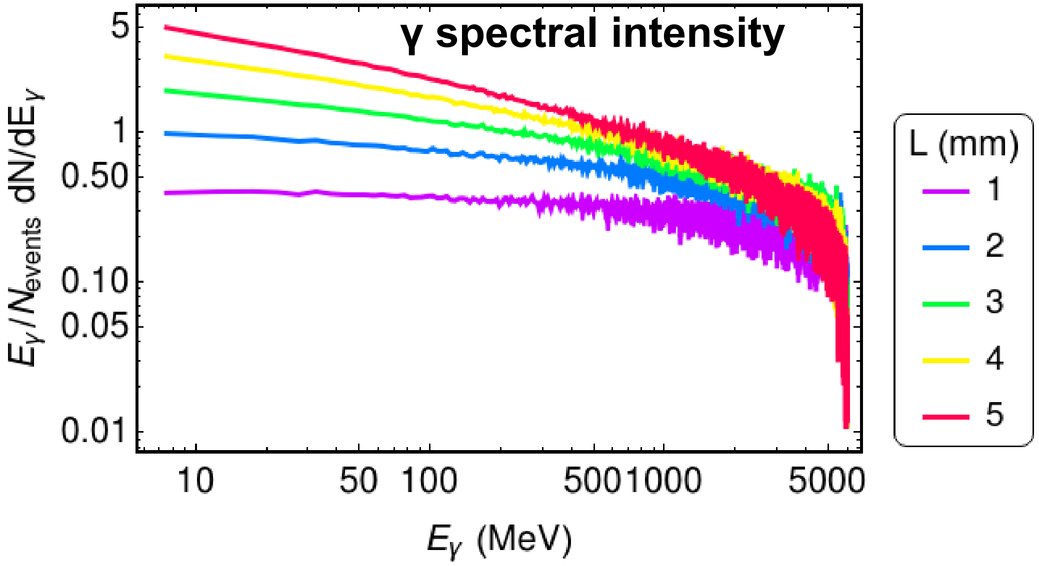
- electrons
- beam energy **6 GeV**
- angular divergence **100 μrad**
- beam size **0.5 mm**



V. Tikhomirov, A. Sytov

Radiation emitted by 6 GeV e- in an amorphous W



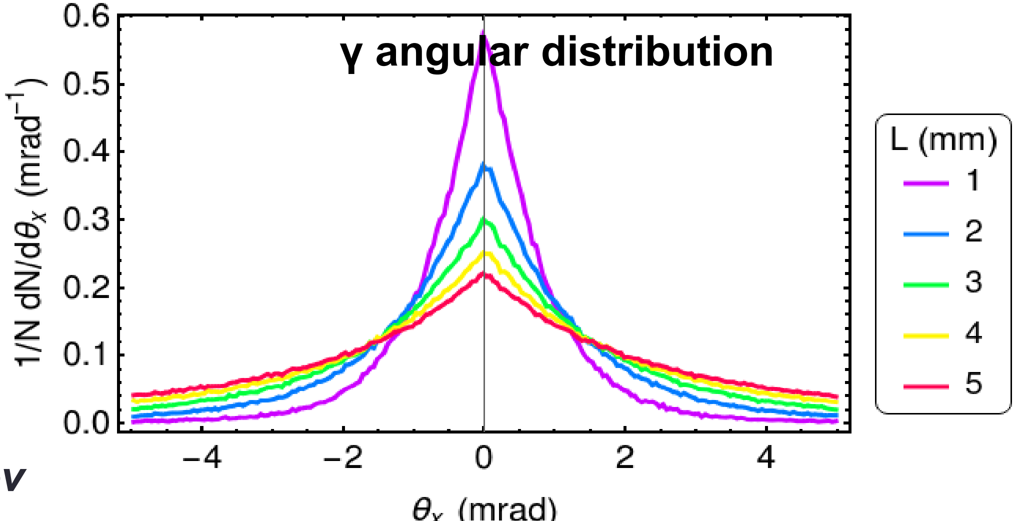


Low energy cut for gamma in simulation: 5 MeV

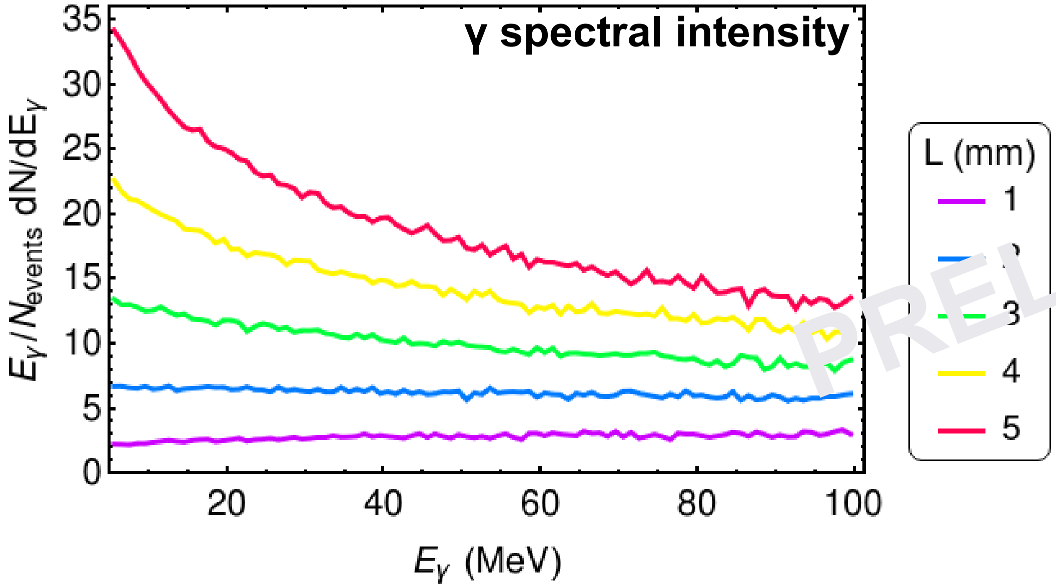
Initial beam:

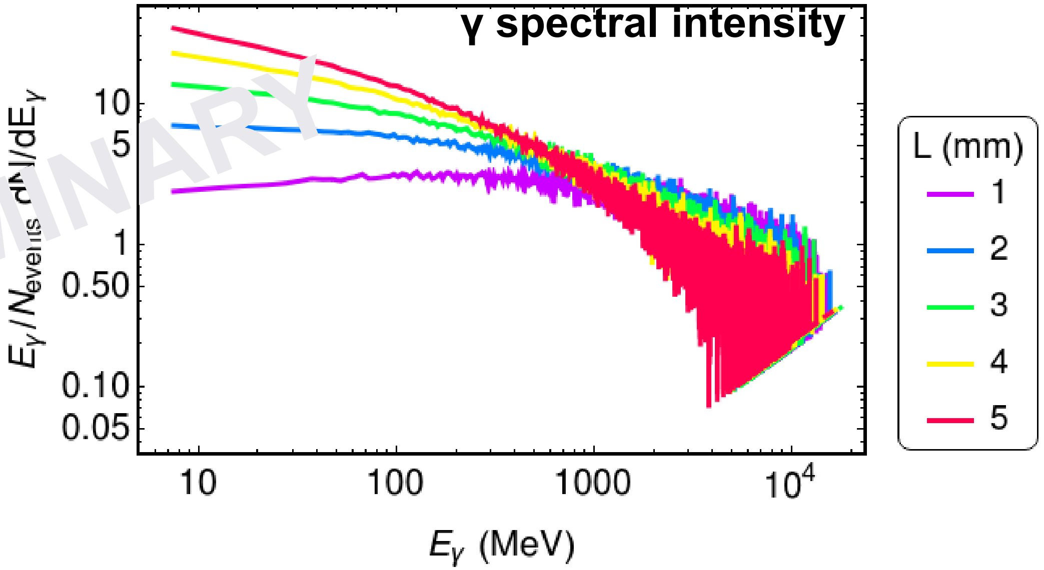
- electrons
- beam energy **6 GeV**

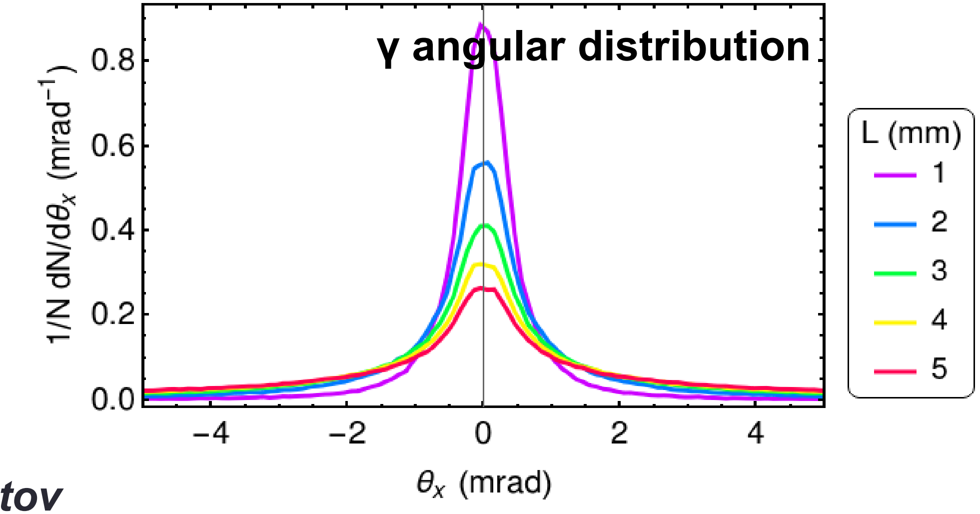
V. Tikhomirov, A. Sytov



Radiation emitted by 20 GeV e$^-$ in an axially oriented <111> W crystal





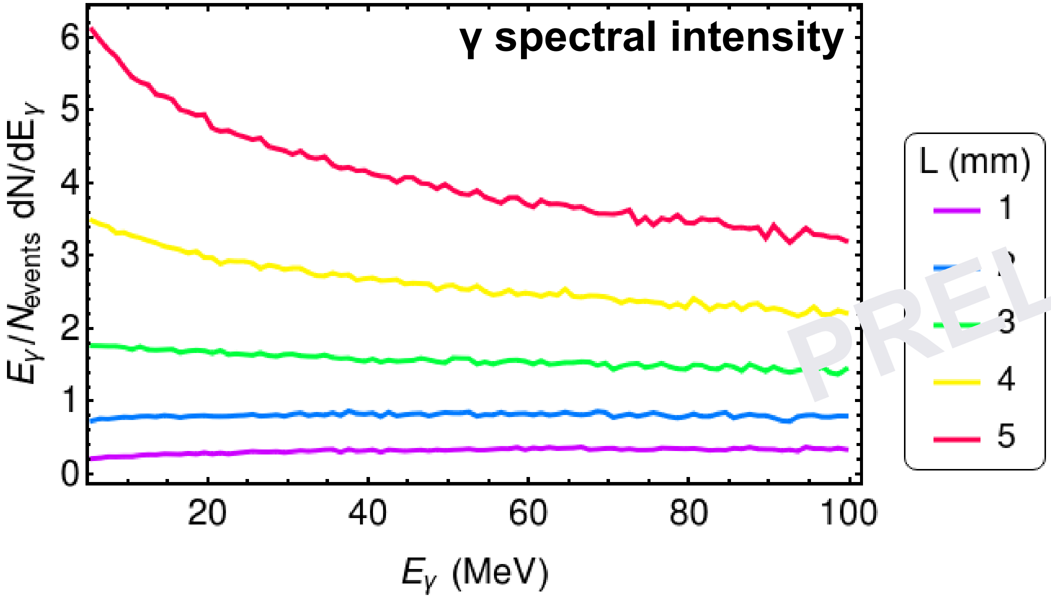


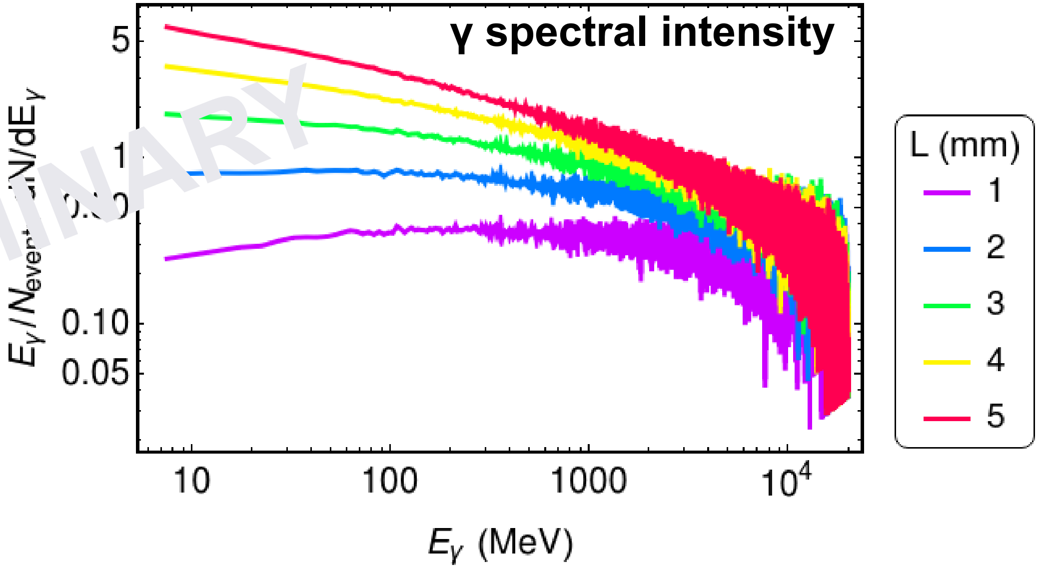
Low energy cut for gamma in simulation: 5 MeV

Initial beam:
- electrons
- beam energy **20 GeV**
- angular divergence **100 μrad**
- beam size **0.5 mm**

V. Tikhomirov, A. Sytov

Radiation emitted by 20 GeV e$^-$ in an amorphous W

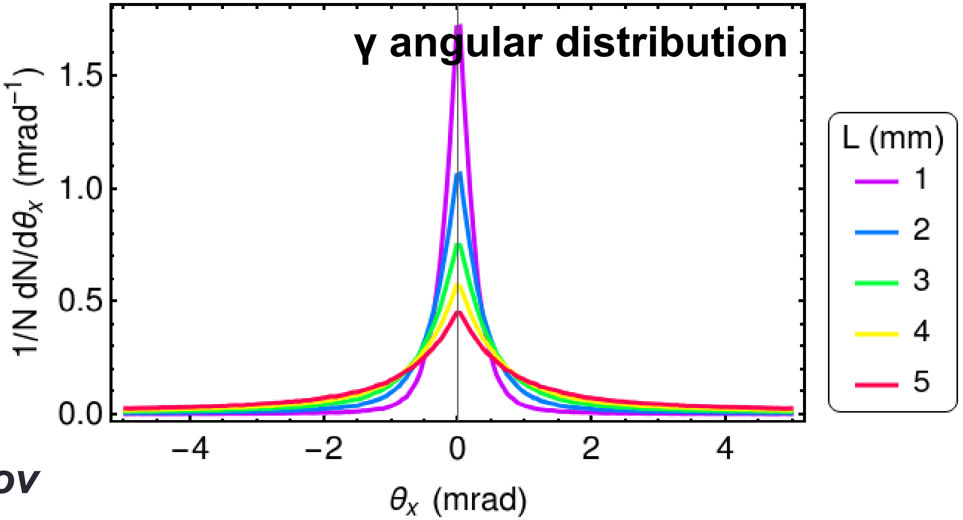




Low energy cut for gamma in simulation: 5 MeV

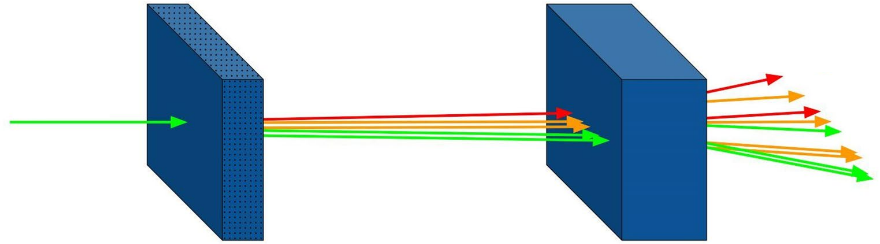
Initial beam:

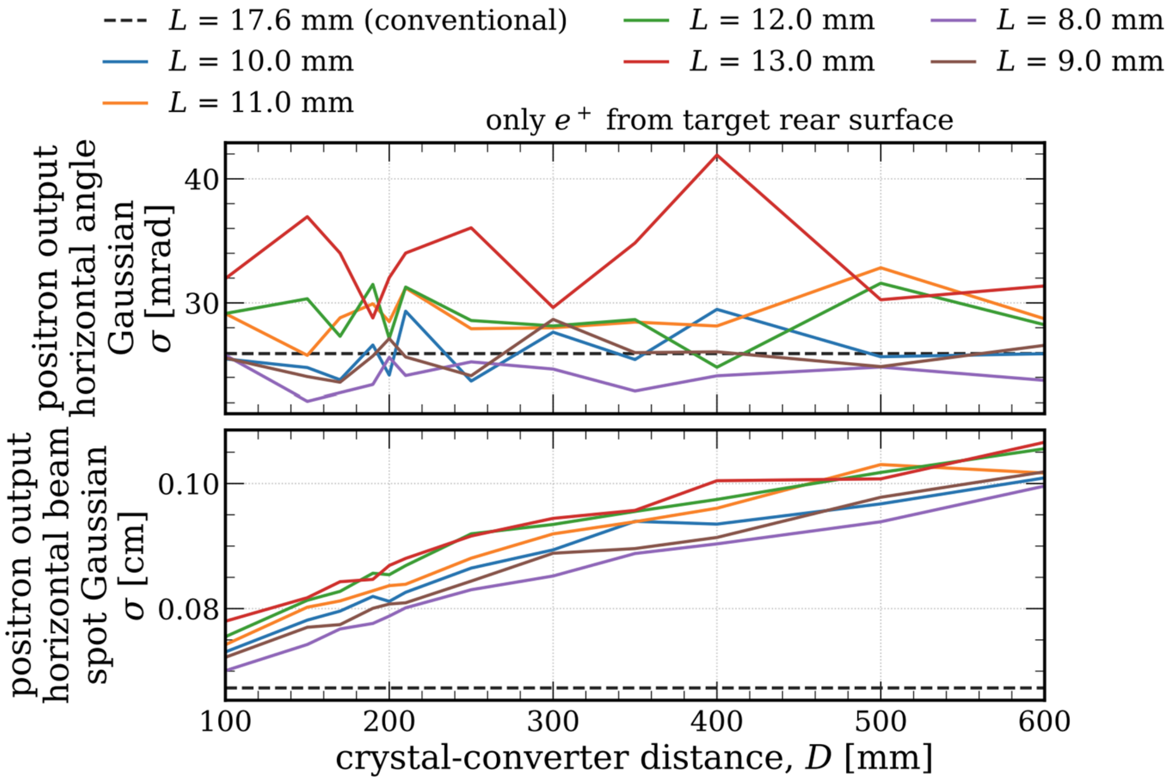
- electrons
- beam energy **20 GeV**

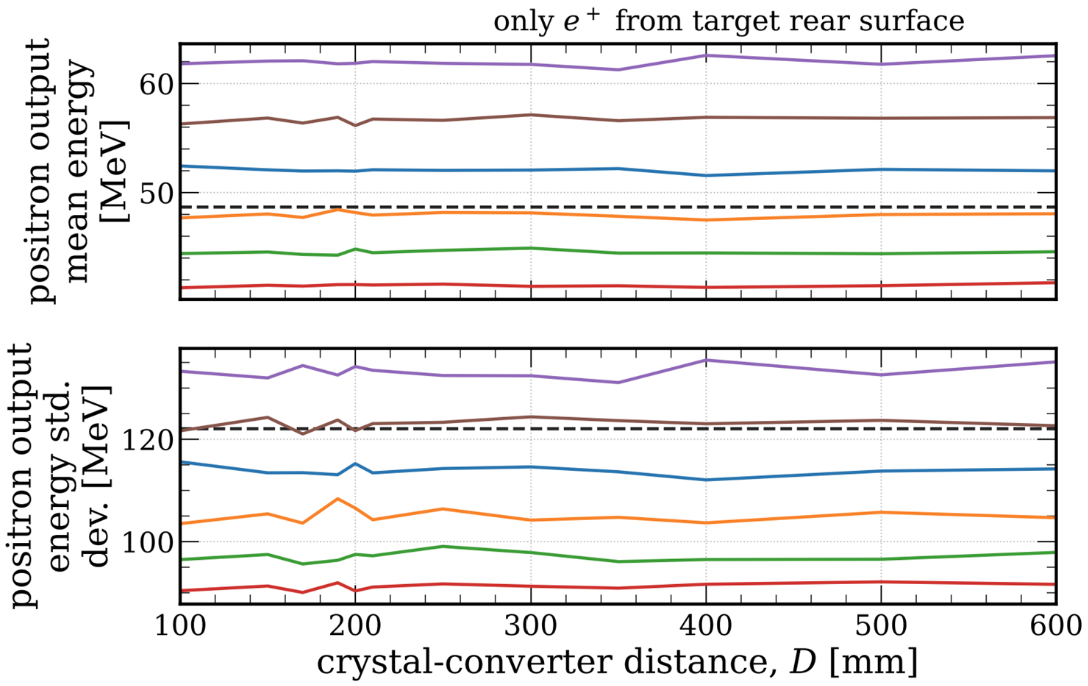


V. Tikhomirov, A. Sytov

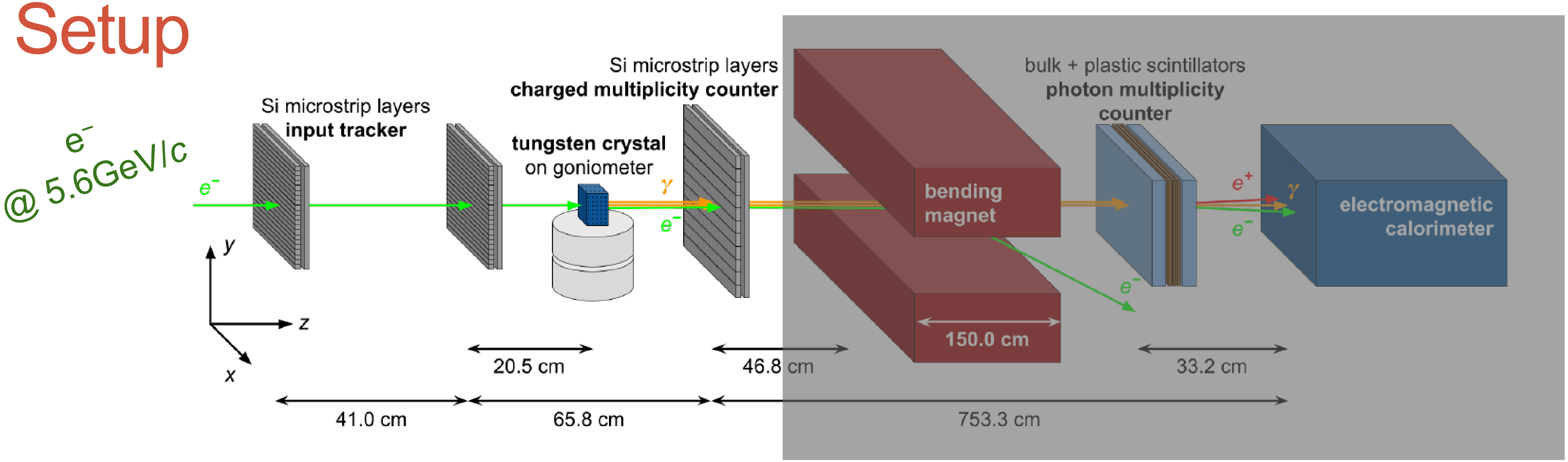
output positron emittance







Setup



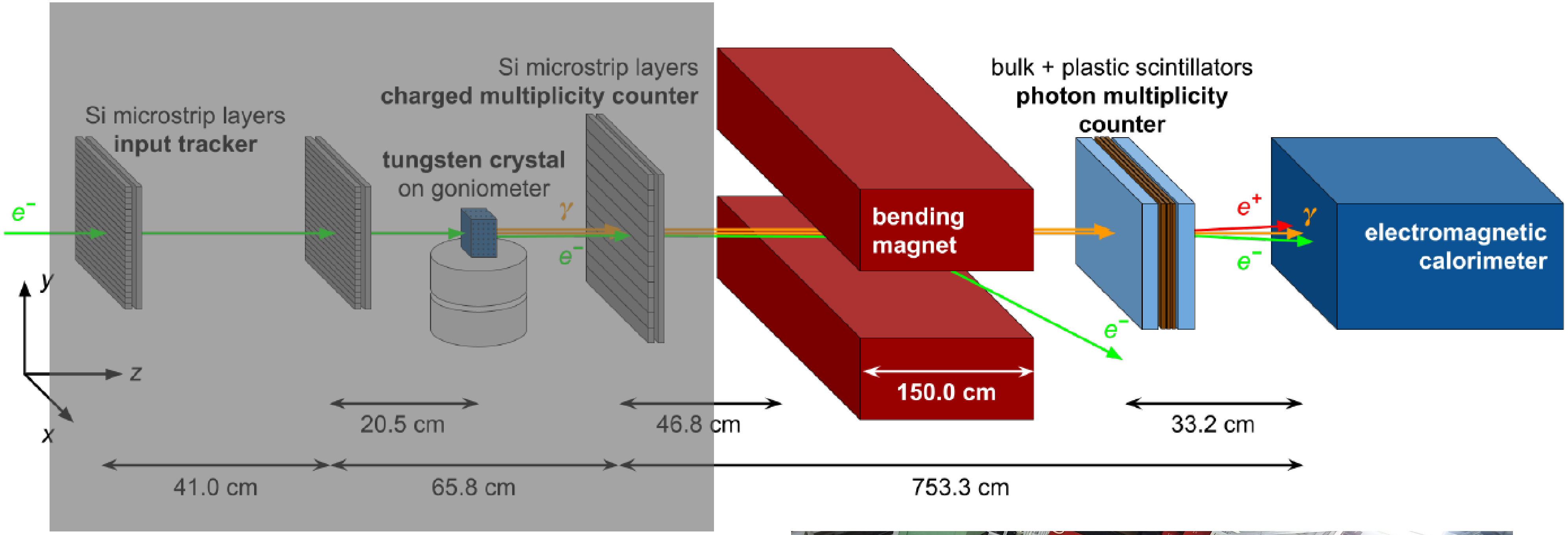
input tracking via 2 *xy* Si microstrip telescopes, with ~2×2cm^2 active area and ~10μm spatial resolution

output charged state multiplicity measurement via a pair of ~10×10cm^2 Si microstrip sensors (BC1), with double-hit resolution power of (at least) ~500μm

DESY.

Setup

e^- @ 5.6GeV/c



output charged/photon radiation separation via a magnetic spectrometer

photon energy measurement via an electromagnetic calorimeter: ~20.5 X_0 long BGO crystals arranged in a 3×3 matrix with transverse acceptance of ~7cm; PMT-based readout (Courtesy of L. Foggetta)

measurement of the output photon number via a **photon multiplicity counter...**