Crystal-assisted positron source

X. Artru, **I. Chaikovska**, R. Chehab, M. Chevallier, Y. Han

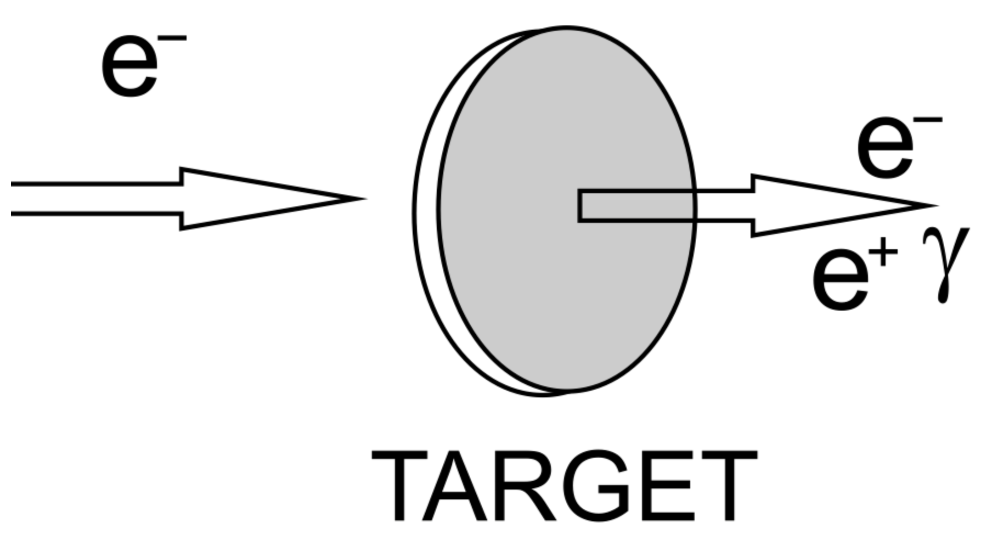
Why e+ sources are critical components of the FC

$$L = \frac{N_1 N_2 f n_b}{4\pi \sigma_x \sigma_y}$$

High luminosity at the future colliders => needs **high average and peak e- and e+ currents and small emittances.**

☞ **e+ are produced within large 6D phase space (e+/e- pairs produced in a target-converter).**

- **Current** => limited in conventional way by the target characteristics
  - Average energy deposition => target heating/melting
  - Peak Energy Deposition Density (PEDD): inhomogeneous and instantaneous energy deposition => thermo mechanical stresses due to temperature gradient
  - Thermal dynamics and shock waves
  - Fatigue limit resulting from cycling loading.
- **Emittance** => at the production 6D phase space is very large
  - After defined by the e+ capture system acceptance.

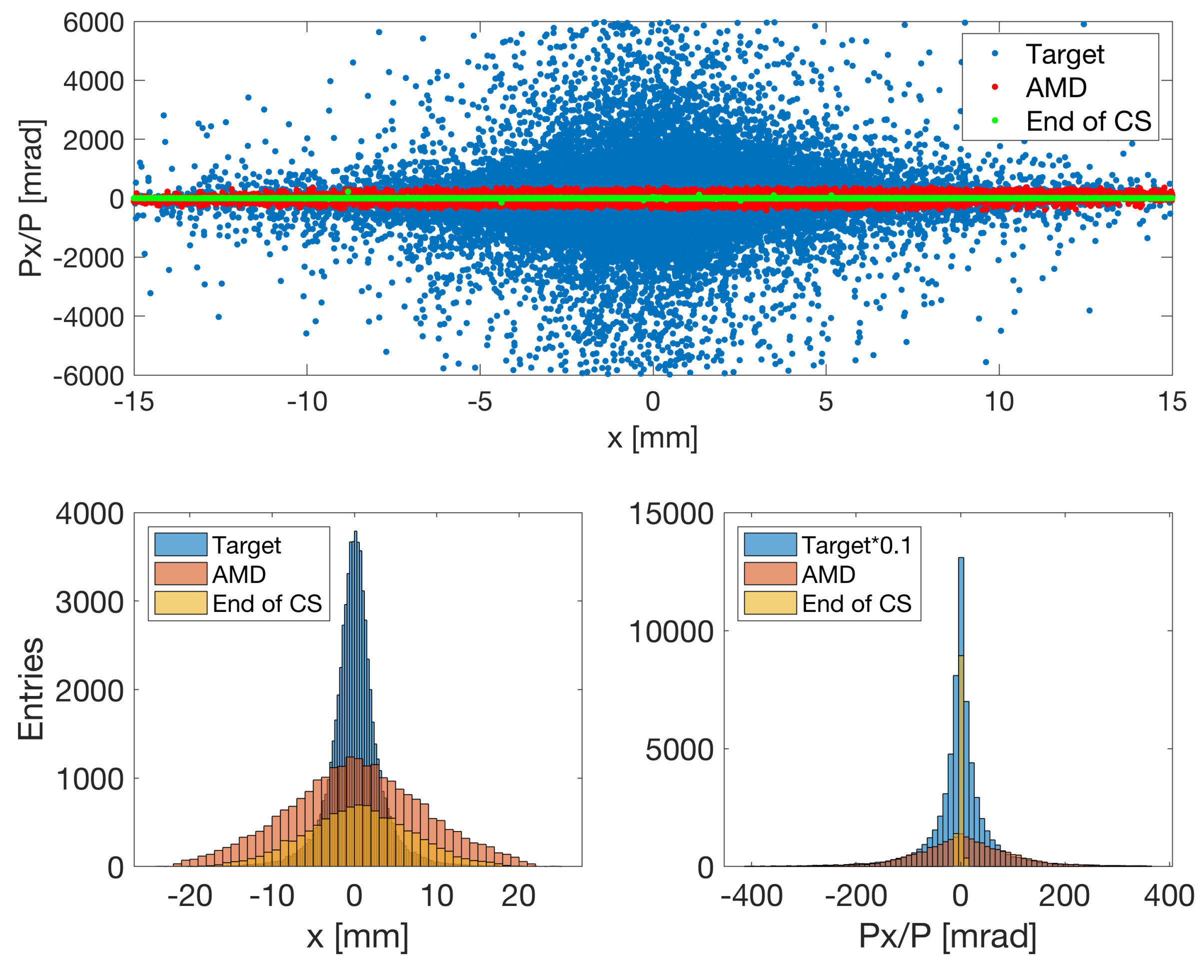


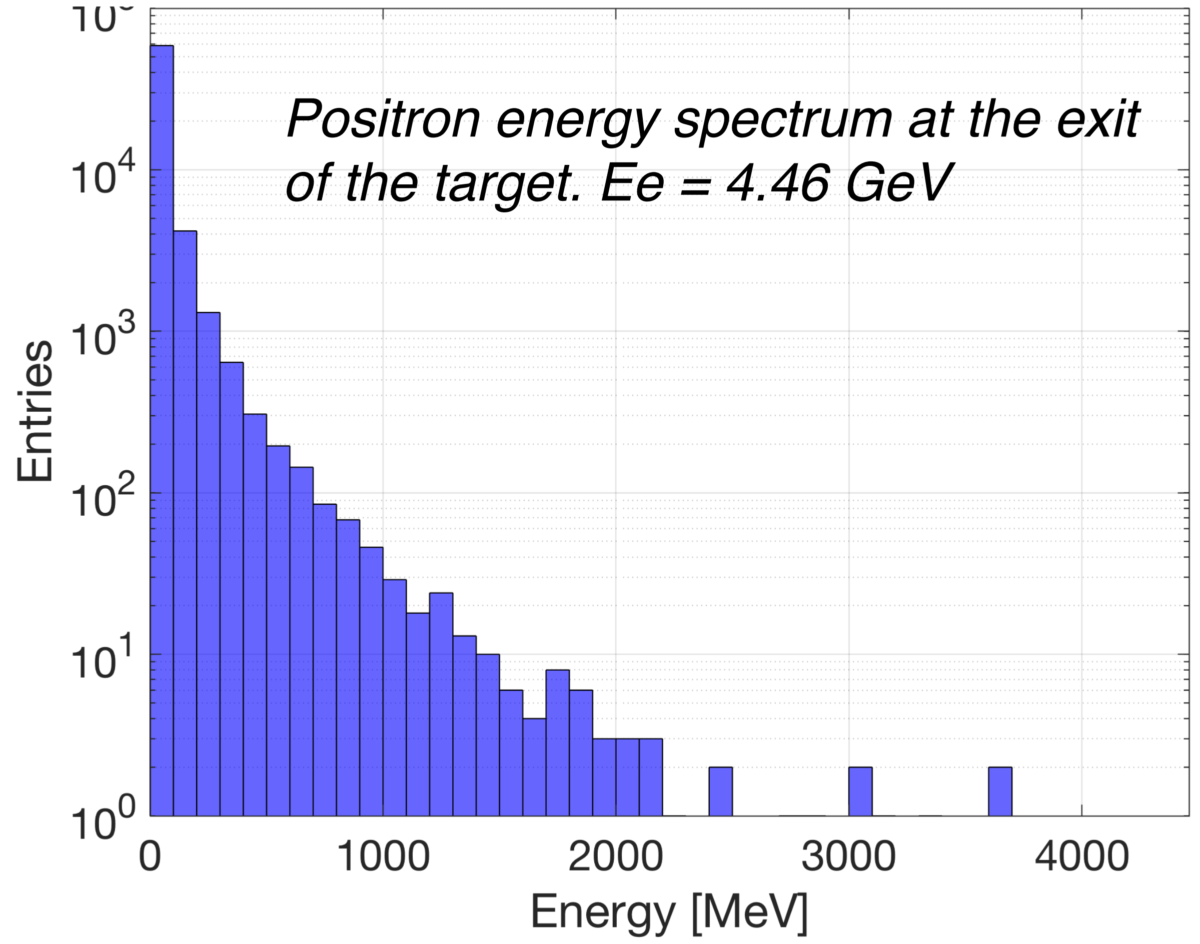
e+ source fixes the constraints for the peak and average current, the emittance, the damping time, the repetition frequency => **Luminosity!**

What are the main challenges

- **<u>High intensity</u>**=> 1) number of e+/e- pairs: higher primary beam energy and intensity, rather thick targets-converter or photon radiators (channeling, undulators) + 2) capture system (B field and RF sections)
- **<u>Emittances</u>** => weak multiple scattering => towards thin targets and small beam sizes on the targets + capture system
- **<u>Polarization</u>** => need the circularly polarized photon beam (Compton scattering, helical undulator, polarized bremsstrahlung)
- **<u>Reliability and radiation environment</u>** => prevent target failure (heat & stress) as a function of primary beam size and power. Minimize, whenever possible, the radiation load on the environment. Ensure remote handling/target removal system.

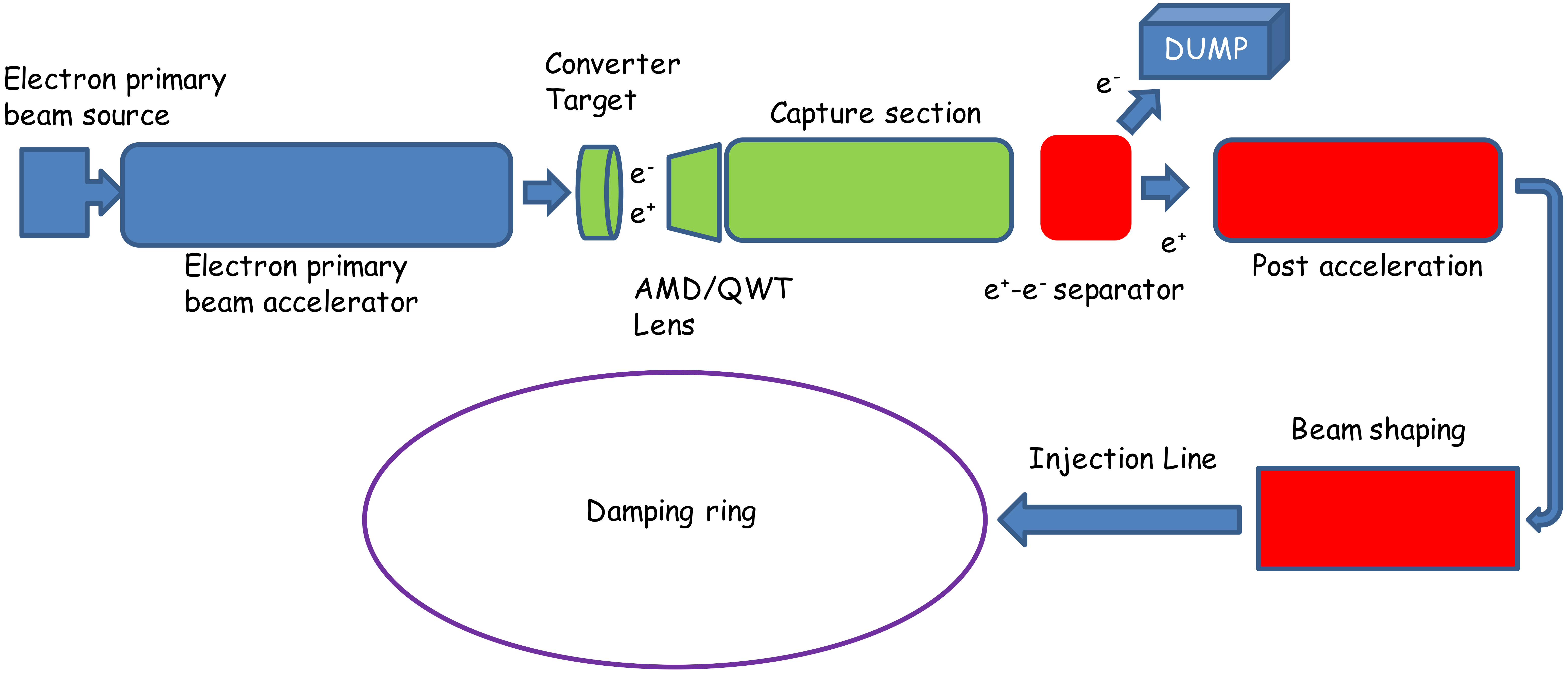
Positron emittance at the exit of the target, the AMD and the capture section at 200 MeV





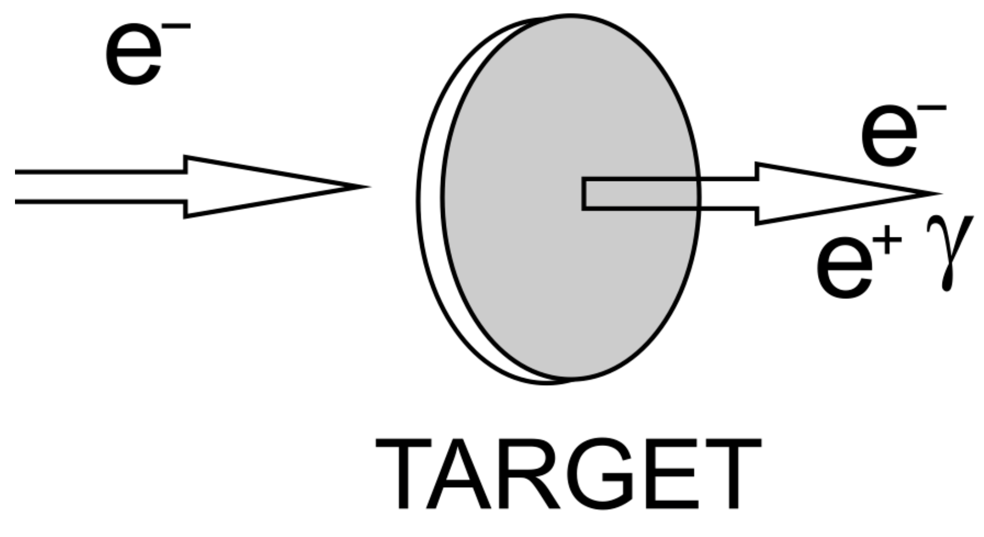
Accepted e+ flux is a function of target + capture system + primary beam characteristics!

Positrons sources: classical scheme



High production e+ divergence => appropriate capture, focusing and post acceleration sections need to be integrated immediately after the target.

Goal: matching the e+ beam (with very large transverse divergence) to the acceptance of the pre-injector linac.



Conventional positron target: bremsstrahlung and pair conversion

- Classical e+ source
- It was employed to produce e+ beam at the existing machines (ACO, DCI, SLC, LEP, KEKB…)

Positron source performances

Demonstrated (a world record for the existing accelerators): SLC e+ source: ~0.08e14 e+/s

Facility	**PEP-II**	**KEKB**	**DAFNE**	**BEPC**	**LIL**	**CESR**	**VEPP-5**
Research center	**SLAC**	**KEK**	**LNF**	**IHEP**	**CERN**	**Cornell**	**BINP**
Repetition frequency, Hz	120	50	50	12.5	100	60	50
Primary beam energy, GeV	33	3.7	0.19	0.14	0.2	0.15	0.27
Number of electrons per bunch	5×10^{10}	6×10^{10}	1.2×10^{10}	5.4×10^{9}	3×10^{9}	3×10^{10}	2×10^{10}
Target	W-25Re	W	W-25Re	W	W	W	Ta
Matching device	AMD	QWT	AMD	AMD	QWT	QWT	AMD
Matching device field, T	6	2	5	2.6	0.83	0.9	10
Field in solenoid, T	0.5	0.4	0.5	0.35	0.36	0.24	0.5
Capture section RF frequency, MHz	S-band	S-band	S-band	S-band	S-band	S-band	S-band
Positron yield, 1/GeV	0.054	0.023	0.053	0.014	0.0295	0.013	0.1
Positron output, 1/s	8×10^{12}	2×10^{11}	2×10^{10}	2.5×10^{8}	2.2×10^{10}	6.6×10^{10}	10^{11}

Future Collider project challenges

	SLC	CLIC (380 GeV)	ILC (250 GeV)	LHeC (pulsed)	LHeC (ERL)	LEMMA	FCC-ee
e- beam energy(GeV)	45.6	380	250	140	60	45	45.6
Norm. hor. emitt. (mm.mrad)	30	0.92	5	100	50	18	24.1
Norm. vert. emitt. (mm.mrad)	2	0.02	0.035	100	50	18	89
Bunches/macropulse	1	352	1312	10^5			2
Repetition Rate	120	50	5	10	CW		200 (Inj)
Bunches/second	120	17600	6560	10^6	20×10^6		16640
e+/second (10^{14})	0.08	1.1	1.3	18	440	100	8.5×10^4 (0.06@Inj)
Polarization	No	No/Yes	Yes	Yes	Yes	No	No

- *Linear Collider projects:* high request for polarization, requested intensity should be produced in "one shot".
- *Circular Collider projects:* polarization is under discussion, requirements are relaxed due to stacking and top-up injection.
- *Muon colliders (LEMMA):* ~ 1e16 e+/s to be defined based on the adopted baseline.

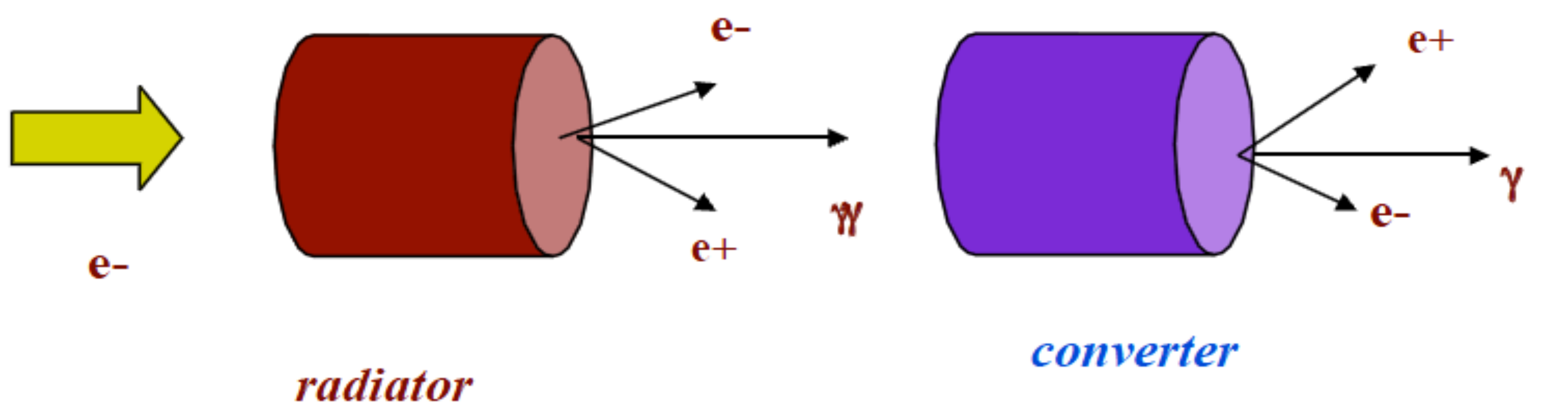
Positrons sources: ‘novel’ schemes

<u>Better solution:</u> Two-stage process to generate the positron beam

<u>First stage:</u> γ-ray generation
<u>Second stage:</u> e-/e+ and γ-ray beams are separated and the latter is sent to the target-converter

<u>The γ-rays can be generated by the following methods:</u>

- **Radiation from helical undulator**
- **Channeling radiation**
- **Compton scattering**



Two targets are used: a *radiator* to produce the photons and a *converter* for the materialization of the photons in e+e- pairs

Charged particles are swept off => the deposited power and PEDD are strongly reduced

Positron sources using channeling

Originally proposed by LAL group + Xavier Artru (IPNL)
(R. Chehab et al., in Proc. of the 1989 IEEE Particle Accelerator Conf., 1989, pp. 283–285)

- **Hybrid scheme** is based on a relatively new kind of e+ source using the intense radiation emitted by high energy (some GeV) electrons channeled along a crystal axis => ***channeling radiation***.

  Radiator is an *oriented crystal* and e-/e+ pairs are generated in the *amorphous converter*.

Planar vs. Axial channeling:

- Axial potentials are generally 5 to 10 times stronger than planar potentials.
- As radiated energy is proportional to the square of the channeling field => *axial channeling* is preferred for γ-radiation in a *positron source*.

- W crystal: the potential depth U_0 is of 1 kV at normal temperature. The angle of incidence of the e- on the atomic rows should be smaller than the Lindhard critical angle: $\theta < \Psi_c = [2U/E]^{1/2}$
- The frequency of the radiated photon is given approximately by $\omega = 2\gamma^2 \Delta E_T$

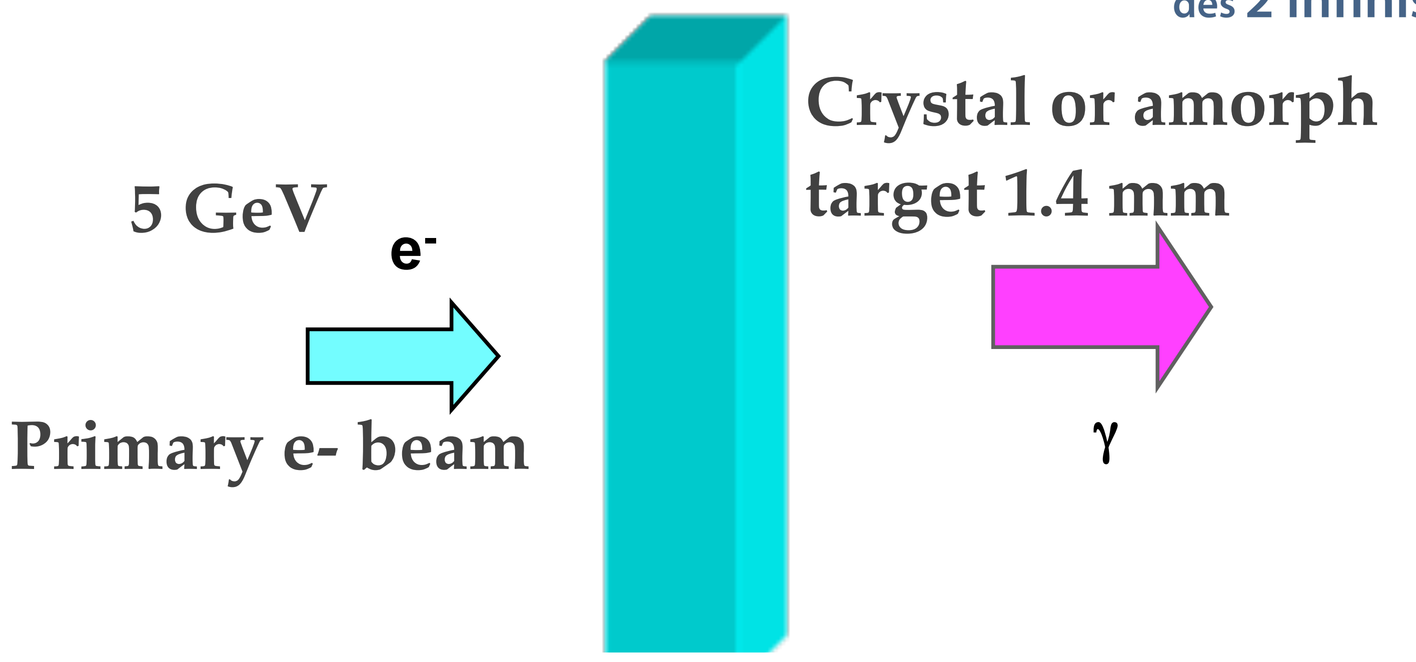
@ 1GeV for W

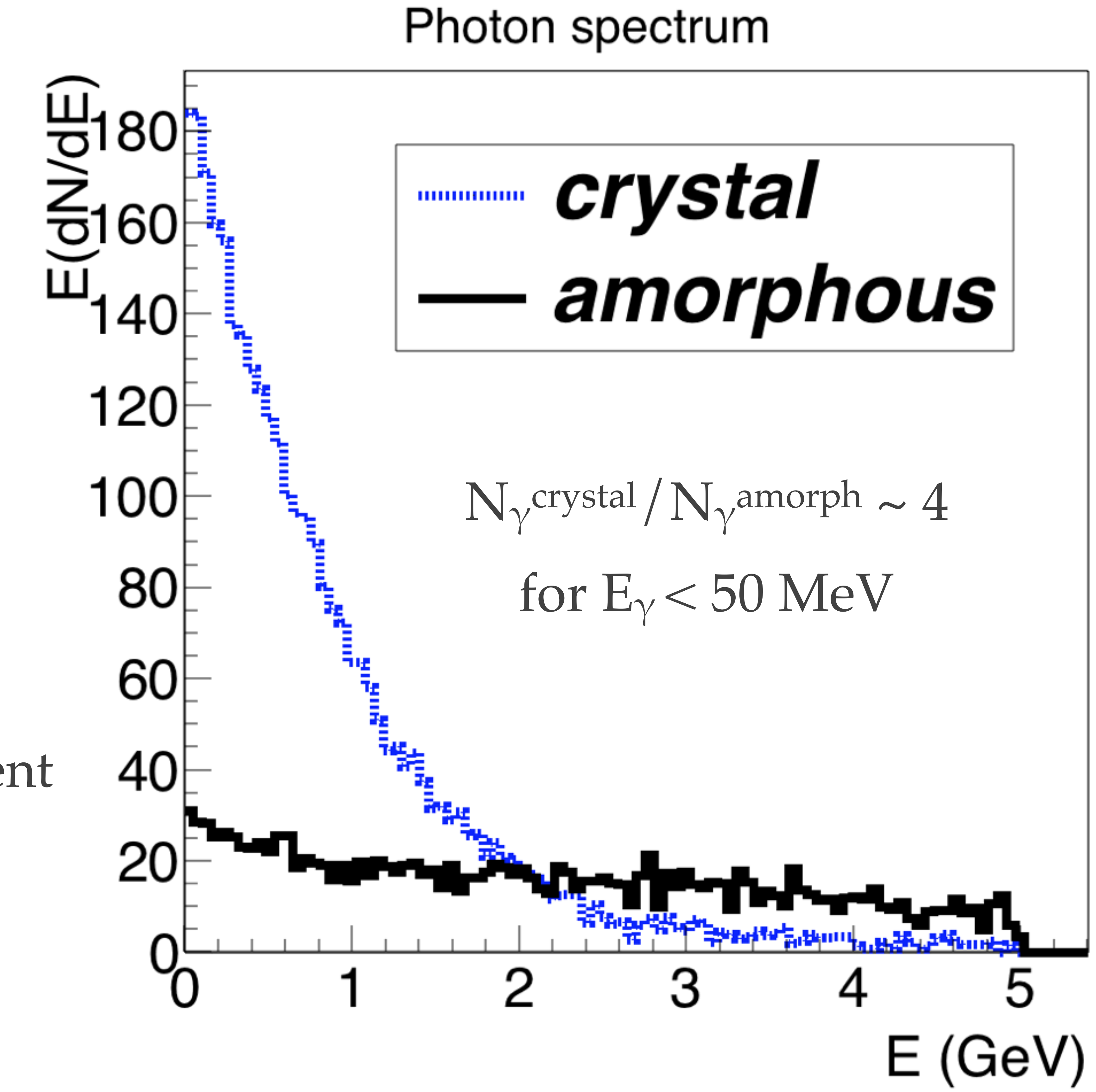
- $\Psi_c = 1.4$ mrad
- ΔE_T is of some eV => $\omega \sim 40$ MeV

Channeling vs. Bremsstrahlung

- For targets of the same thickness there is an enhancement of *the soft photons* production in the crystal oriented on its <111> axis compared to the amorphous.
- *Soft photons* will generate the *soft positrons* => easier to capture by matching devices.
- There is a threshold in energy, for which the energy radiated by channeling becomes more important than that of bremsstrahlung.
- It depends on crystal and incident energy: for W, E > 700 MeV. For other crystals (Si, Ge, C(d)) the threshold is higher.

V N Baier, Katkov, V M Strakhovenko, 1986 Phys. Stat. Solidi B 133, 583



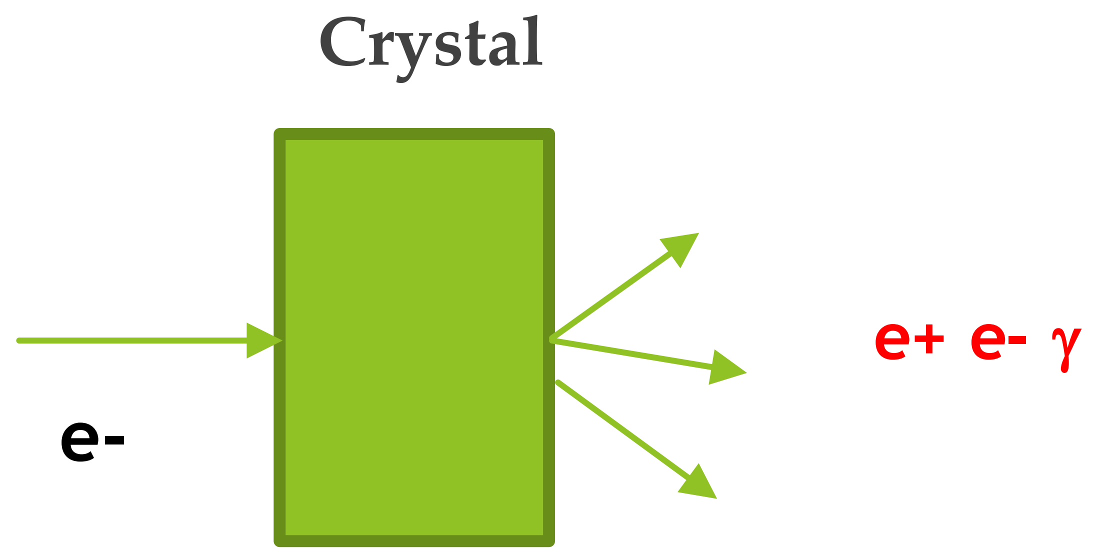


<u>**Proof-of-principle experiment in Orsay (1992-1993):**</u> observing radiation enhancement in a tungsten crystal oriented along the ⟨111⟩ axis submitted to a 2 GeV electron beam.

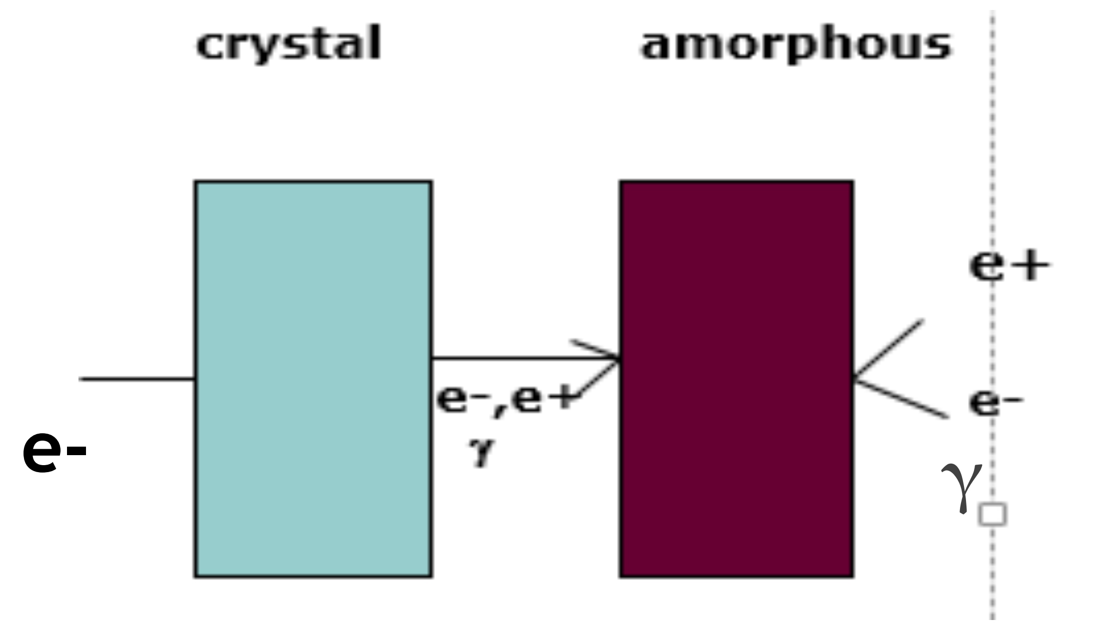
X. Artru et al., *NIM Section B*, 119.1 (1996): 246-252.

Positron Sources using channeling

- **Thick crystals:** radiation and conversion in the same target

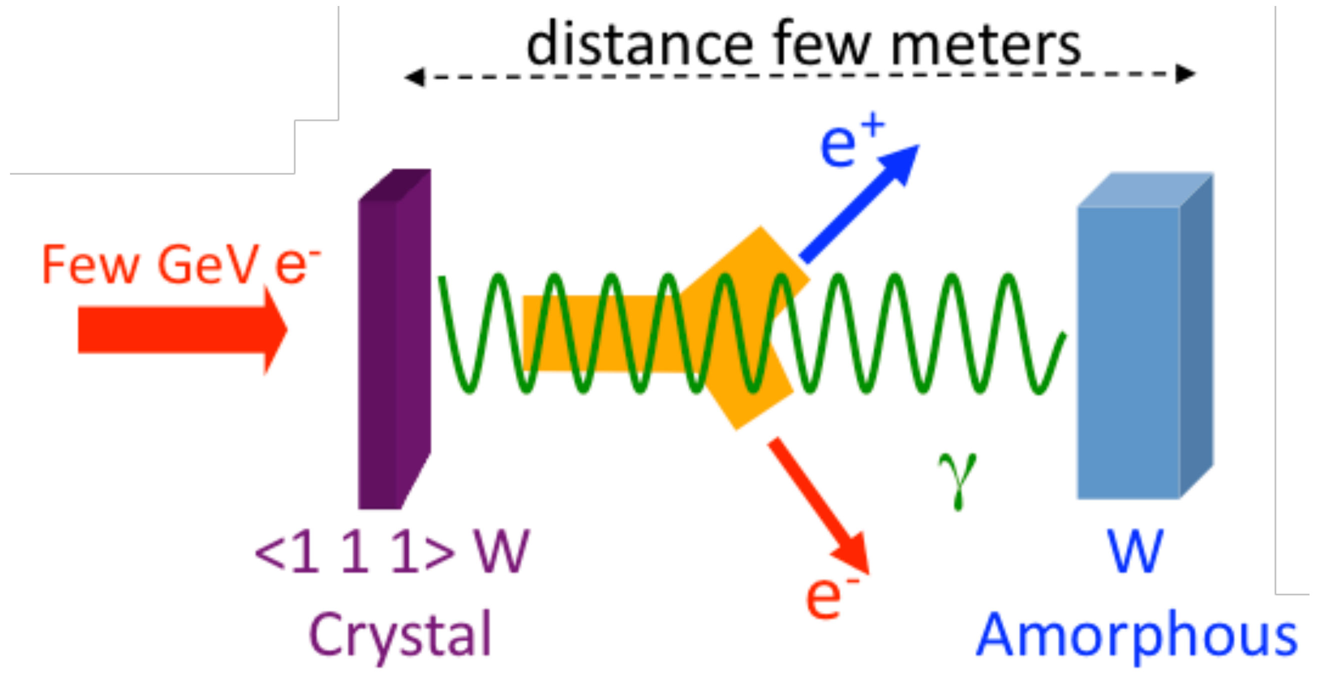


- **Hybrid scheme:** thin crystal radiator & thick amorphous converter



- **Optimized hybrid scheme:** decrease of the deposited energy

by sweeping off the e+/e- (from crystal)



Three approaches have been studied experimentally

Positron Sources using channeling

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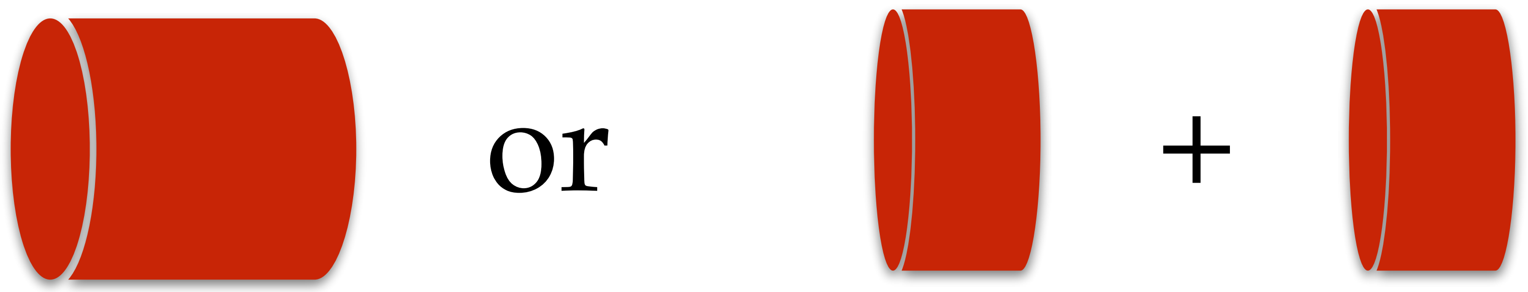
Crystal converter vs. Hybrid source

☞ Several experiments have been carried out at CERN and KEK with different configuration.

Experiment WA103 at CERN



8 mm crystal **4 mm crystal** **4 mm amorph. target**

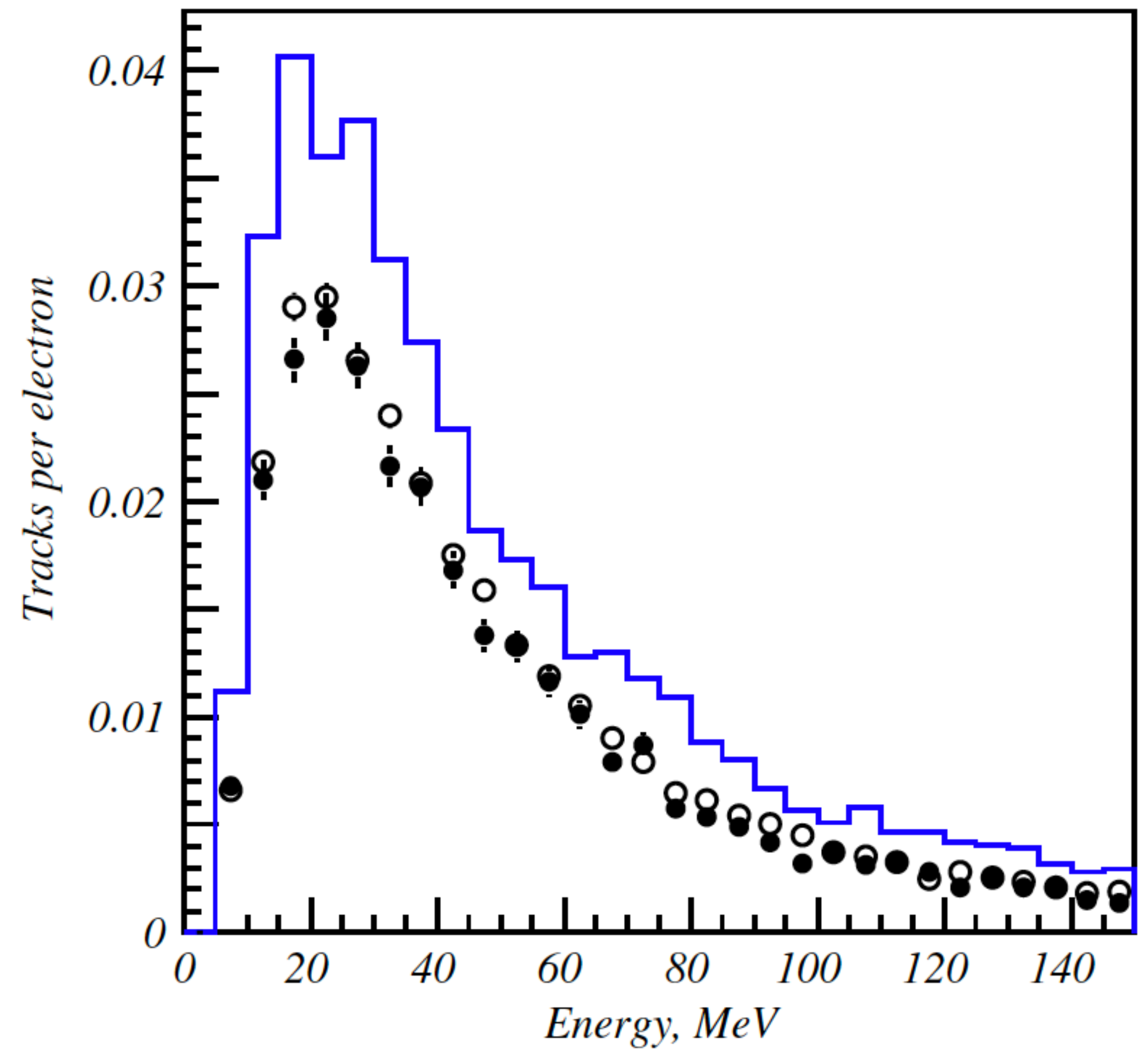


Fig. 12. The positrons energy spectra for the 1 kG magnetic field normalised per 1 incident electron. The spectra are not corrected by the reconstruction efficiency and the detector acceptance. The dark points represent the 8 mm crystal target. The open points, the "4 mm crystal target + 4 mm amorphous target". The histogram is the 8 mm crystal simulation. The electron energy is 10 GeV.

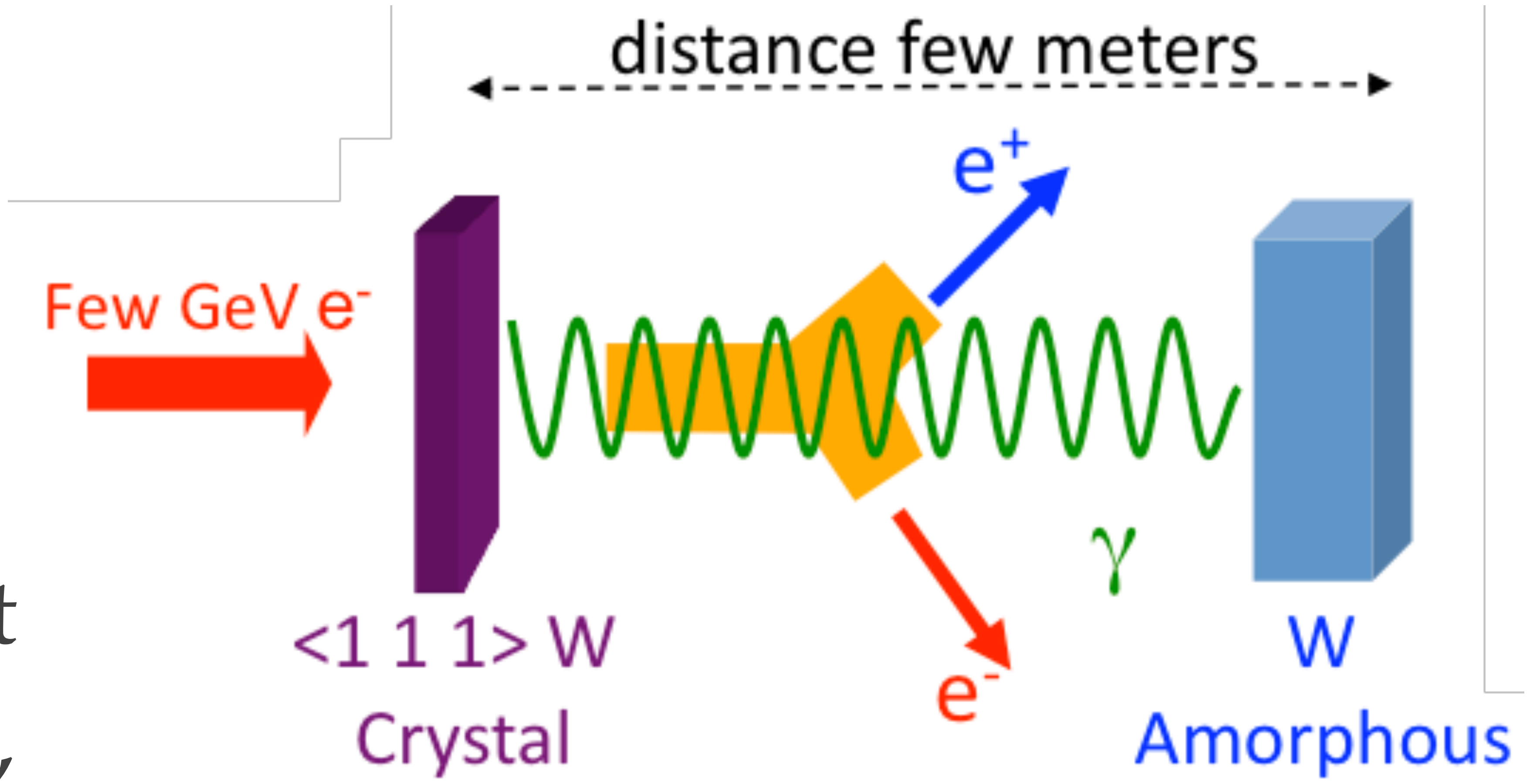
X. Artru et al., NIMB 240 (2005) 762

- Both types of targets have been tested at CERN.
- The positron yield was the same for 8 mm crystal and [4 mm crystal + 4 mm amorphous converter]. There is an optimum thickness < 4 mm.
- Further calculations indicated $d_{opt} < 2$ mm. For future hybrid sources based on W crystals, at the same incident energy (< 10 GeV) we shall consider 1-2 mm thick crystals (cf. ILC and CLIC).

Positron Sources using channeling

Advantages of the optimized hybrid scheme

- Thin crystal => higher enhancement, more γ produced per e- => less energy deposition => less heating => higher potentials
- Thick amorphous converter: high conversion $\gamma \rightarrow$ e-/e+
- Distance between radiator and converter: use dipole magnet to sweep off e+/e- after the crystal => less energy deposition, weaker density: avoids high values of PEDD

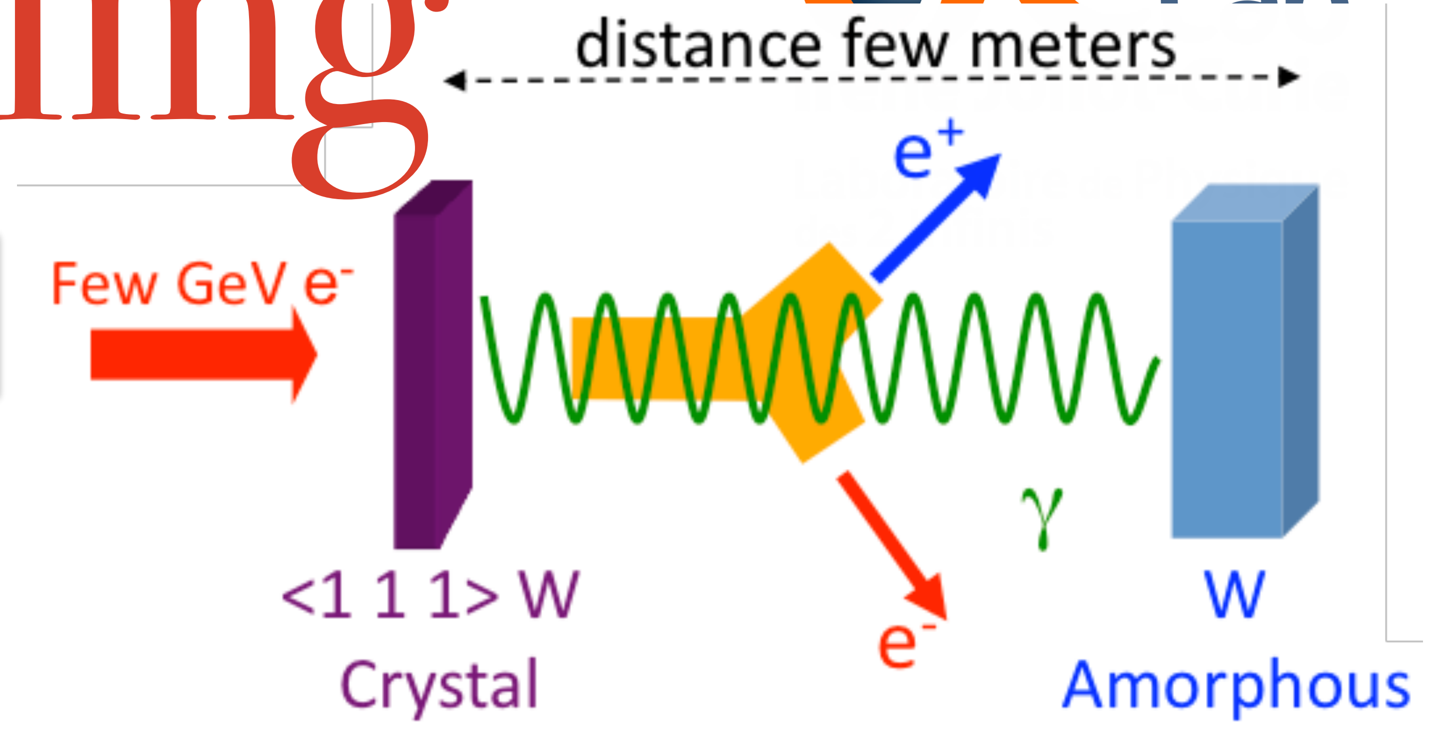


X. Artru et al. NIM B 266 (2008) 3868-3875

This scheme is proposed to be used for the Future Linear Colliders.

A baseline design for the CLIC positron source.

Positron Sources using channeling



Optimization of the radiation characteristics for the positron production

- **Crystal properties**
  - ***Crystal quality:*** crystals with good mosaicity (typically 400-500 μrad FWHM)
  - ***Crystal kind and orientation:*** high Z materials and axial channeling. Tungsten W => high atomic potential (1 keV) at <111> orientation.
  - ***Thickness of the crystal:*** optimum thickness is between 1-2 mm for $E \leq 10$ GeV
- **Thickness of the amorphous target (high Z material):** compromise between the requested yield and the amount of deposited energy => what is essential is **the accepted positron yield**
- **Distance between the radiator and converter:** 1) installation of a sweeping magnet 2) increase the size of the photon beam => contribute to lower the deposited energy density
- **Incident e- beam:** some GeV (to get $U_{ch} >> U_{bremss}$), U is the energy radiated. Incident electron beam with weak divergence $\theta < \Psi_c$.

Reliability of the crystal for e+ production

Effect of crystal temperature on the positron yield

☞ With temperature, crystal strings undergo thermal vibrations => reduction of the available potential for channeled particles.

X.Artru et al. Part. Accel., Vol.59 (1998) 19-41

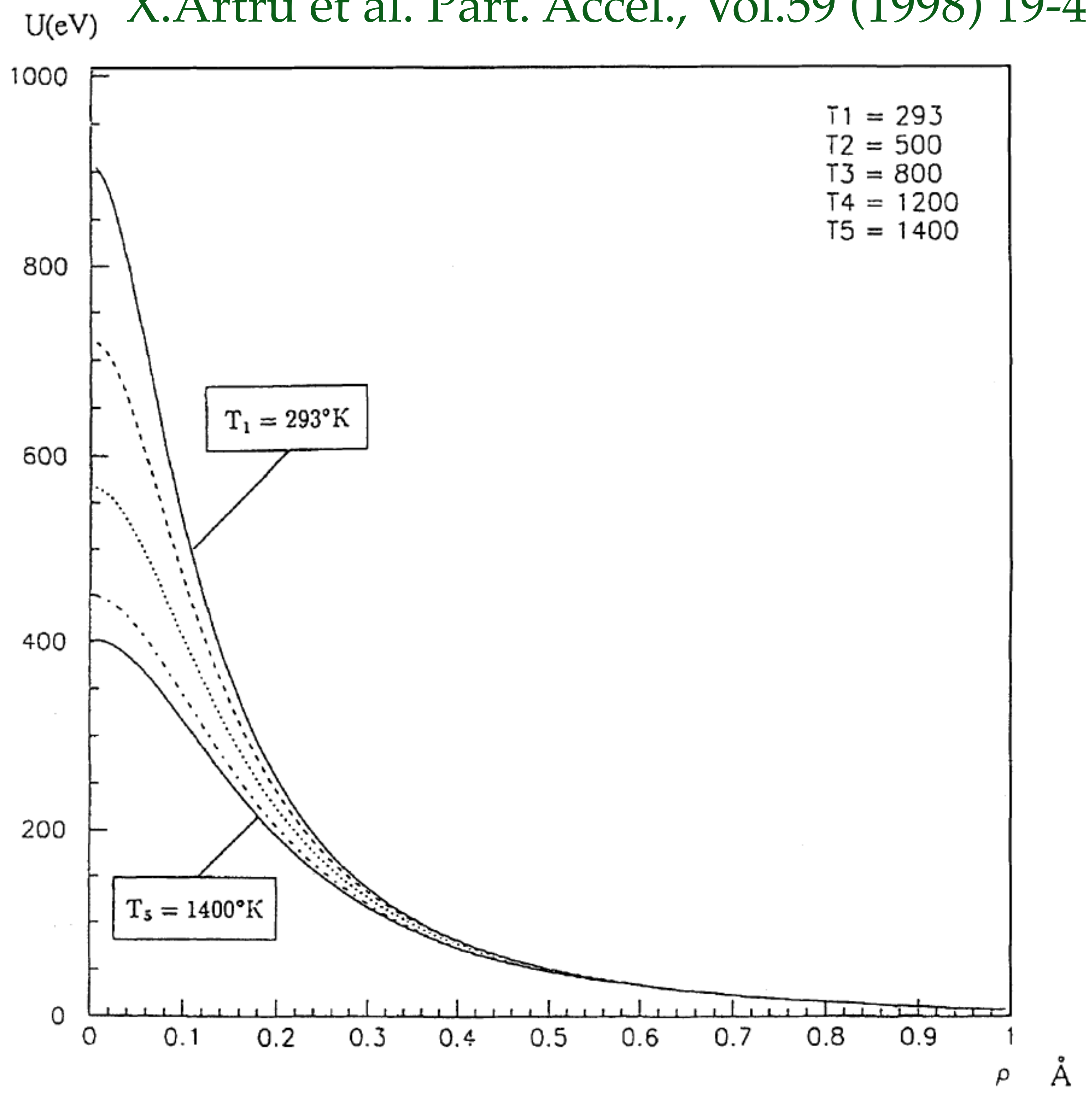


FIGURE 9 Continuum potentials for the ⟨111⟩ axis of the tungsten crystal. The temperatures are expressed in K.

- Taking into account the U(T), simulations have been undertaken with a W crystal 8 mm thick (<111> axis) and E_{e-} = 10 GeV.
- **<u>Result:</u>** variation of ~ 600 degrees in the crystal decreased the positron yield by 15 %.

<u>To avoid the potential decrease with increasing temperature:</u>

- It is better to use thin crystals to limit the amount of deposited energy
- the crystal must be cooled (system of many crystals on the translation stage of a goniometer with additional cooling).

Reliability of the crystal for e+ production

Radiation damage of the crystal

R.Chehab et al. in Proc. of EPAC 1998

Radiation damage experiment at SLAC (1996)

In order to study the radiation damages on the W crystal, a thin crystal (0.3 mm thick) has been installed upstream of the SLC e+ target and irradiated during 6 months.

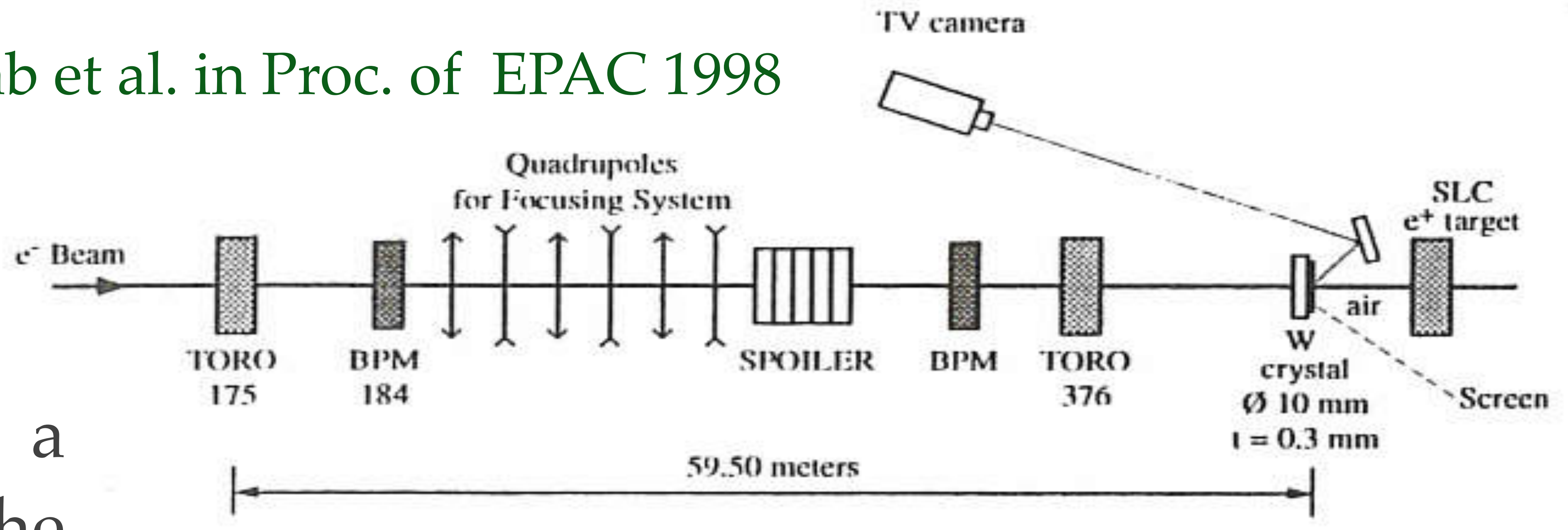


Figure 3: The SLC experimental set-up

- **<u>The SLC beam:</u>** E = 29.5 GeV, average intensity: 2.5×10^{10} e-/pulse, Frequency: 10 and 30 Hz, Integrated intensity (6 months): 1.2×10^{19} e-, Spot area on the crystal: 6.2 mm^2, Total fluence: 2×10^{20} e-/cm^2
- **<u>Results:</u>** No damage was observed (same rocking curve after and before irradiation). No modification in the mosaic spread of the crystal was observed. The damage threshold should be higher (for e-).

☞ *This fluence corresponds to the level of appearance of damages on a Si crystal hitted by 28 GeV and 450 GeV protons (BNL & Fermilab)*

☞ Reliability of the amorphous target-converter!

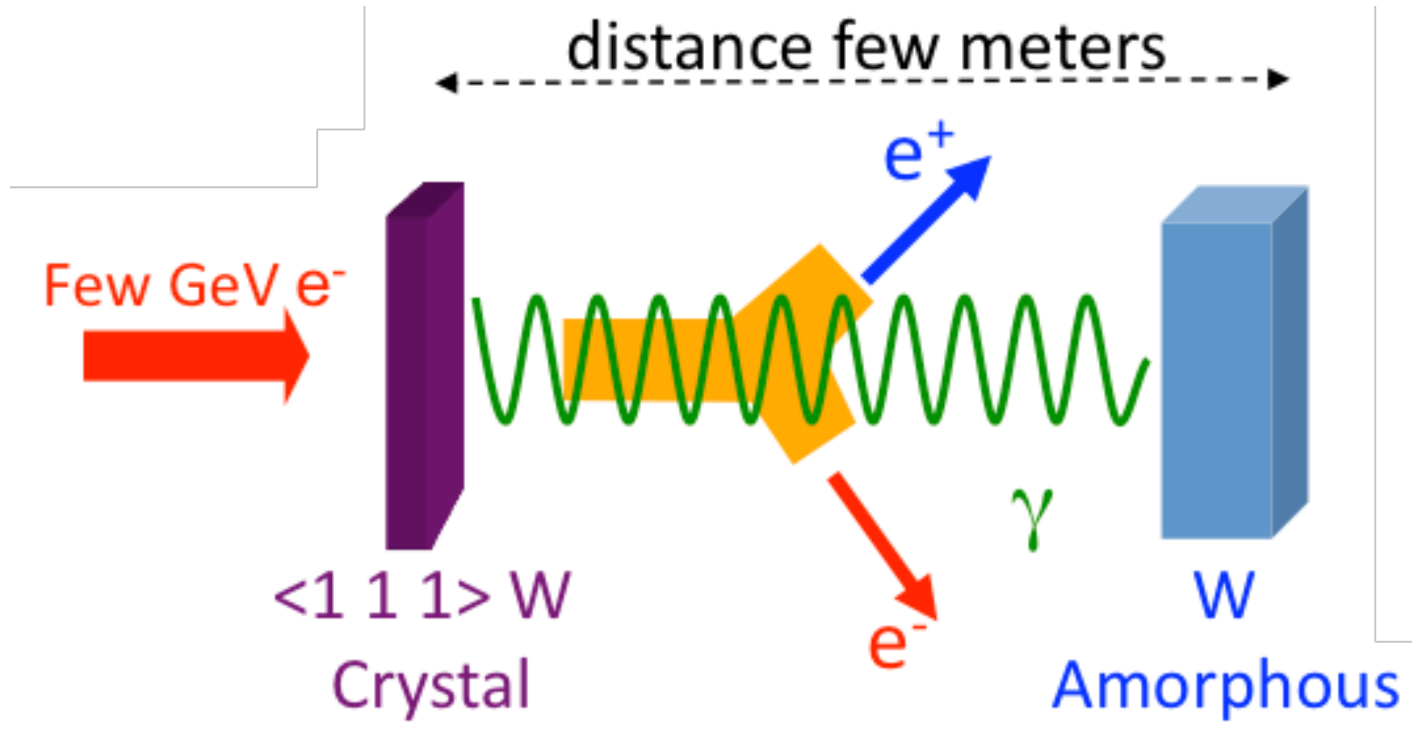
Hybrid e+ source: applications

KEKB/SuperKEKB => Crystal e+ source @KEKB during 1 year.
Experimental R&D program on hybrid scheme

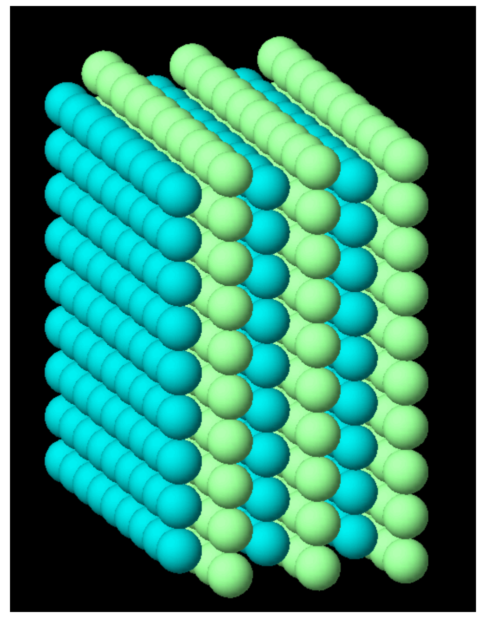
CLIC => Hybrid scheme

FCC-ee => Hybrid or conventional scheme

LEMMA => Hybrid scheme is under consideration



Recent idea: to replace the compact target-converter by a **granular** one made of **small spheres** => *new option for the amorphous converter*



Granular target can provide **better heat dissipation** associated with the ratio Surface/Volume of the spheres and the **better resistance to the shocks** (studies are ongoing).

Crystal e+ source for KEKB

☞ W crystal target has been successfully employed at the e+ source of the KEKB for 1 year (2006)

- The crystal thickness was 10.5 mm, primary e- beam 4 GeV
- The enhancement strongly depends on the crystal thickness (the thicker the crystal, the lower enhancement wrt amorphous target having the same thickness).
- **Results:**
  - **At KEKB, the e+ yield increased by ~25%** compared to that for a conventional tungsten plate with a thickness of 14 mm.
  - **The steady-state heat load** on the crystal target **decreased by ~20%**.
  - After a two-month operation, **no degradation of the e+ production efficiency was observed**.

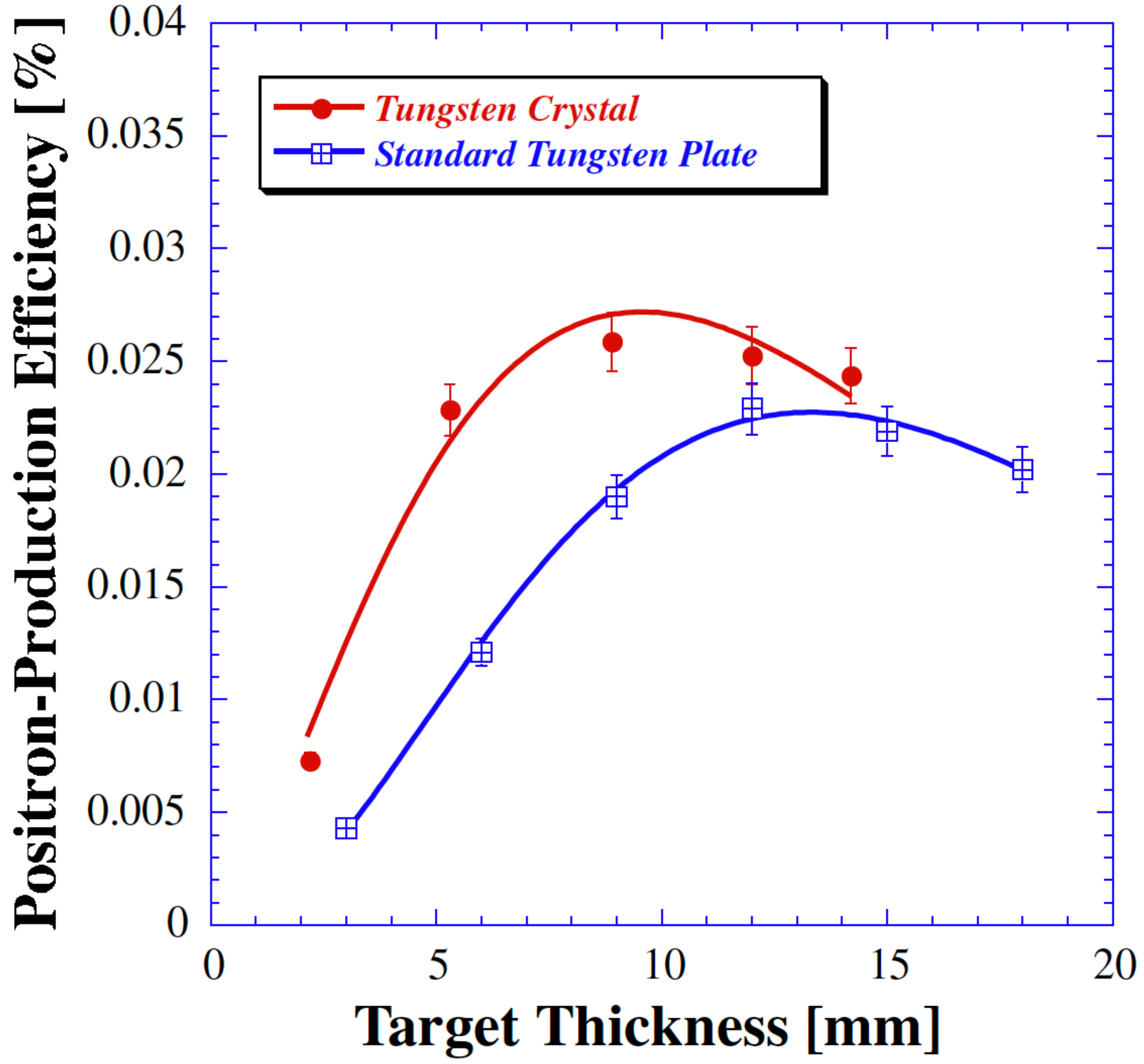


FIG. 2. (Color) Positron-production efficiencies measured for the tungsten crystal as a function of the crystal thickness (see [13] in detail). The incident electron energy and positron momentum were 4 GeV and 20 MeV/c, respectively. The solid curves through the data are gamma-function fits of the data.

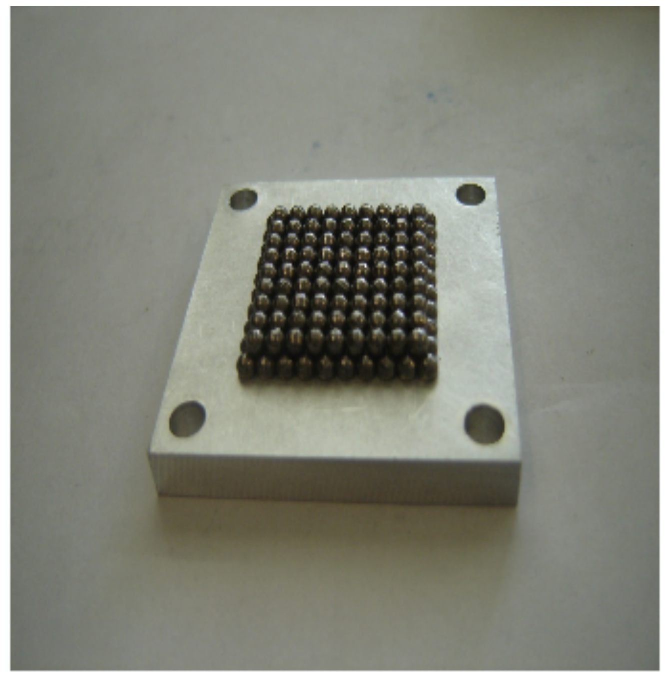
T. Suwada et al. PRST-AB 10 (2007) 073501

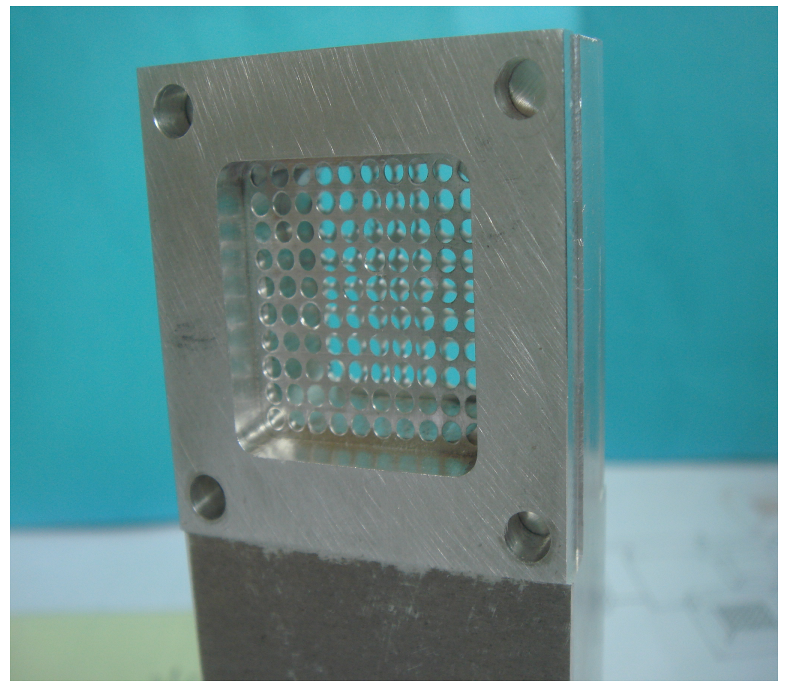
Experimental activity on hybrid source

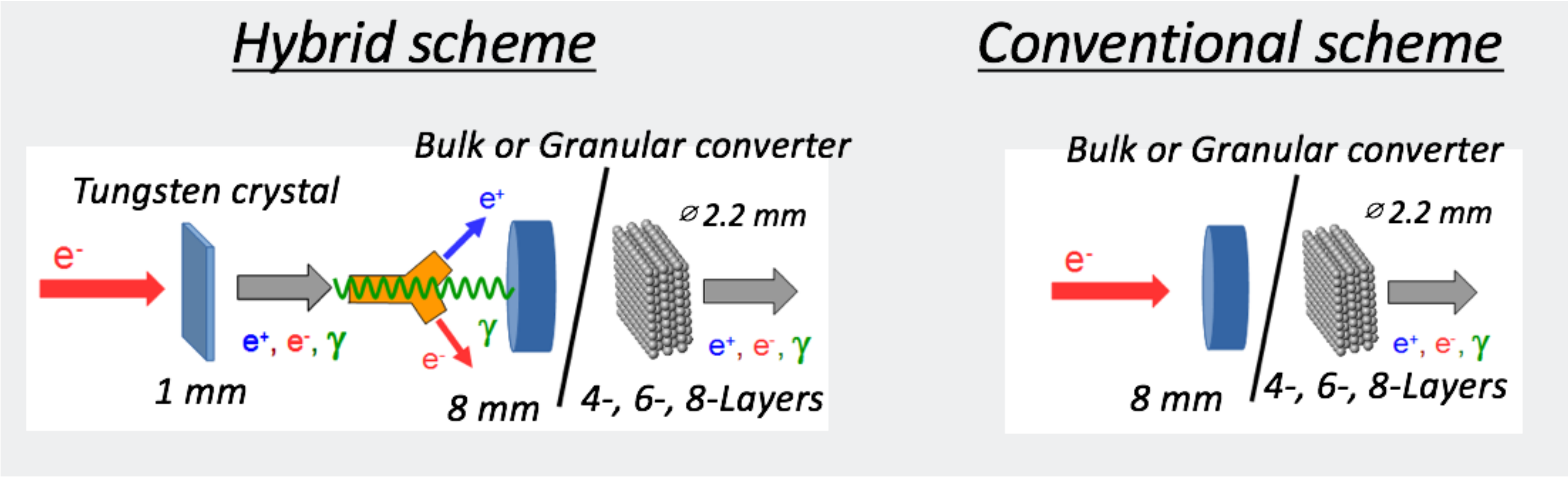
The experimental activities have restarted in KEK (SuperKEKB injector linac) in 2015/2016. **Goals**: *e+ yield and target temperature measurements* to compare different targets (Bulk & Granular) => e+ source performances.

Experimental conditions:

- Energy = 7-8 GeV, single bunch (Frep =1 to 50 Hz), Charge = 1-2 nC
- Emittance (norm)~ 150(H)/63(V) mm mrad, beam divergence < 0.1 mrad
- Crystal W: 1mm thick, <111> orientation
- Granular targets: 4, 6 and 8 layers. Bulk target (reference): 8 mm thick
- Temperature rise on the converter : thermocouples



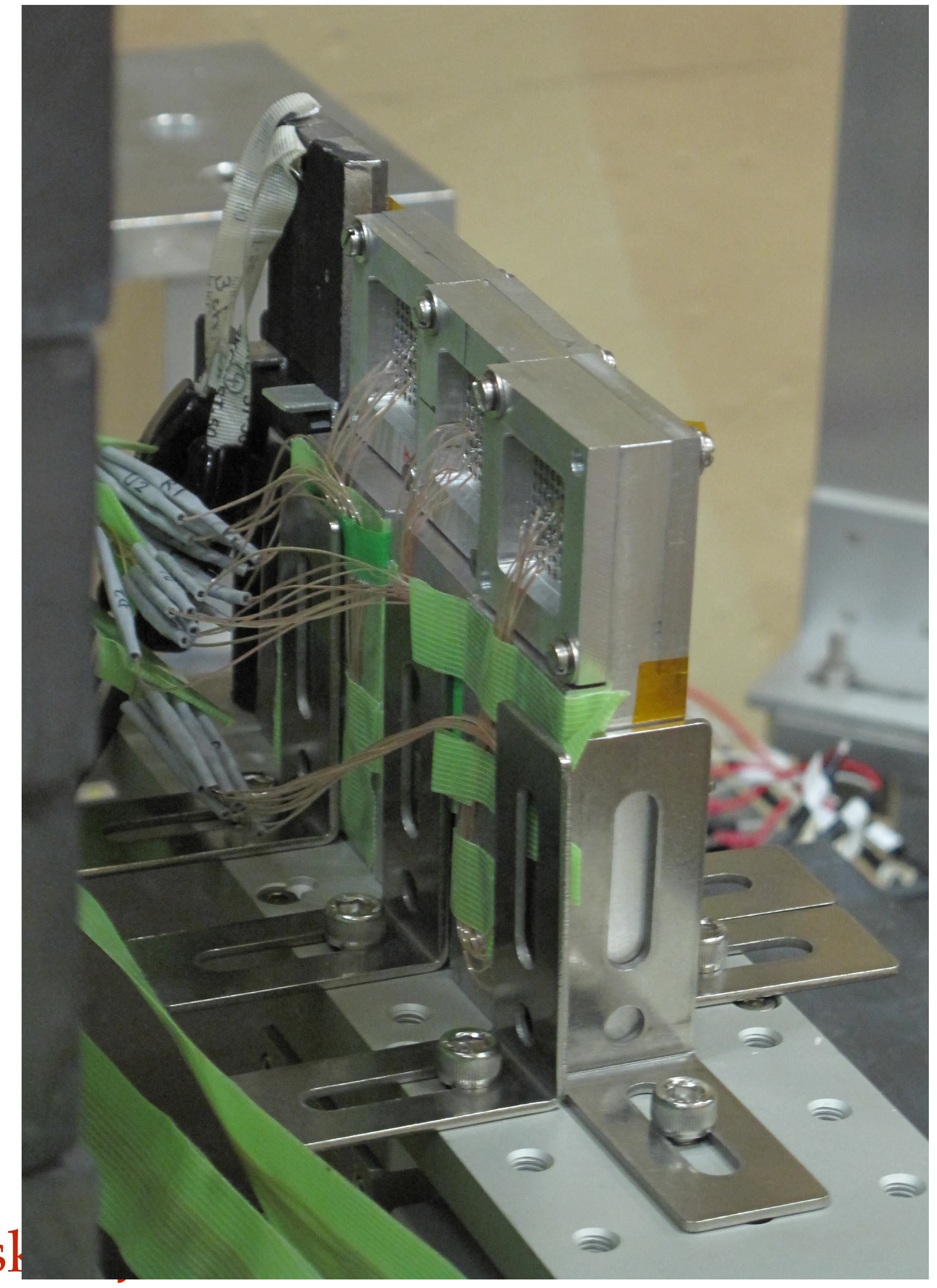




Experimental activity on hybrid source

Photons and e+ detection:

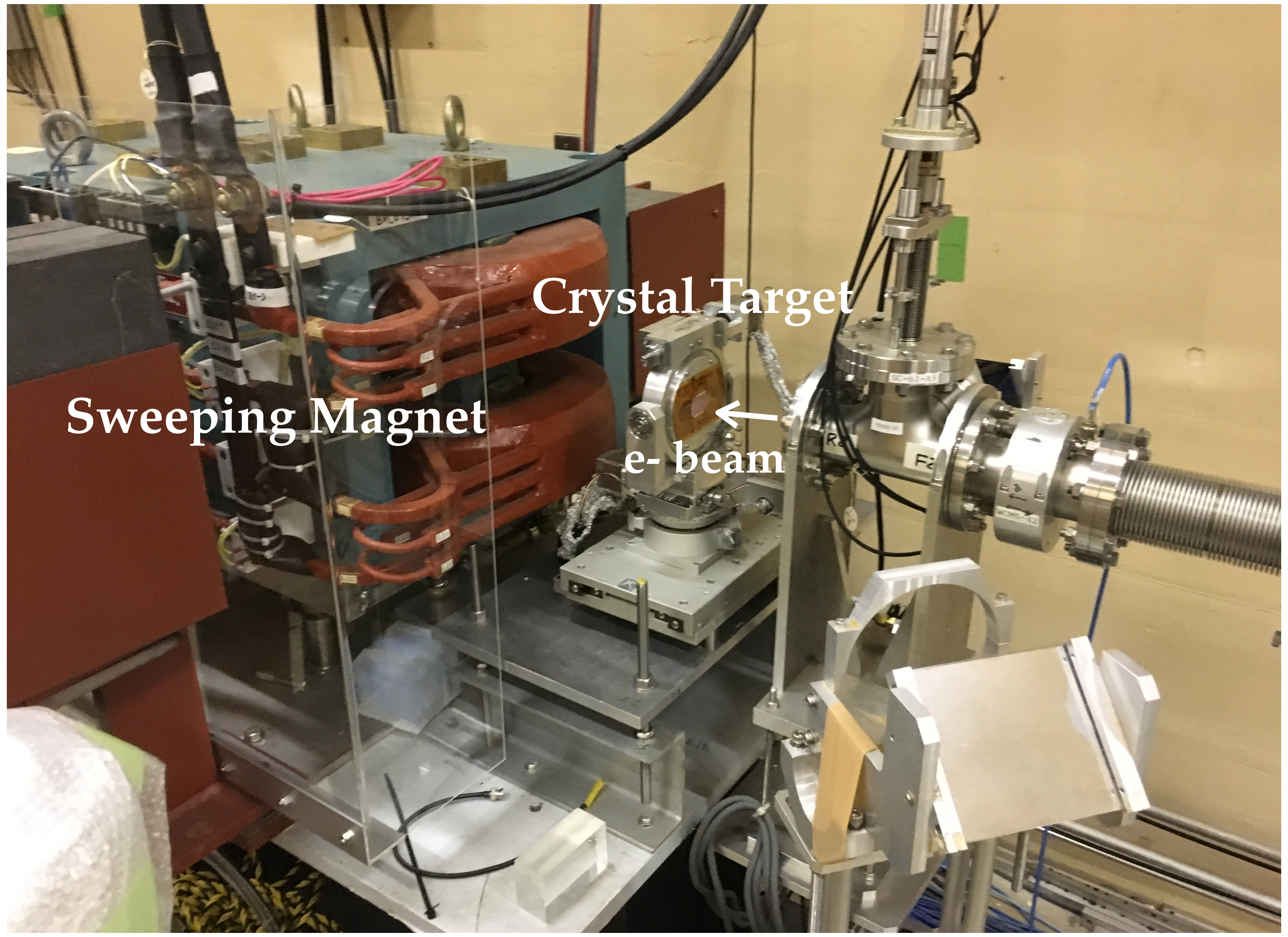
- **Photon detection:** CVD diamond detector 500 μm thick, 4x4 mm^2. Weak interaction efficiency (~0.3 %) but enough γ rays (>10^{11} per shot)
- **Positron detection:** produced e+ are analysed by a spectrometer (60^o bending magnet) at 5-20 MeV/c and then detected by 5 mm lucite Cherenkov detector

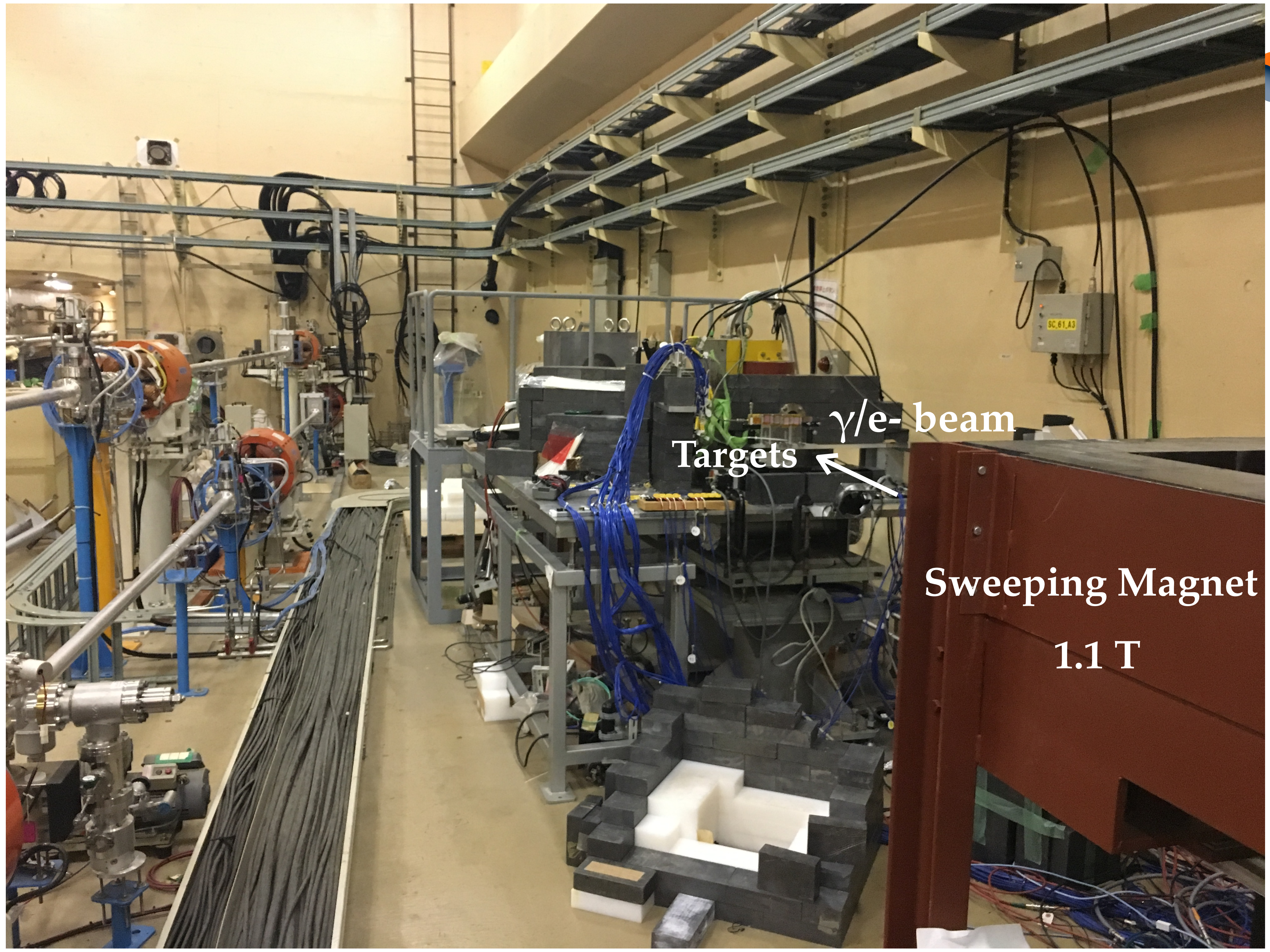


The e+ detection system is simulated by using the GEANT4. Typical momentum acceptance is 2.6% (FWHM) at the positron momentum 20 MeV/c. ***Collaboration with V. Rodin (KNU-Ukraine, Cockcroft Institute-UK).***

Temperature measurements:

- Standard K-type thermocouples (with area < 1 mm^2) attached to the backside of the targets (glued by an epoxy thermal conductive paste)
- The output has been calibrated (0 -100^{o}C) and sent by a 40 m long extension cables to the experimental room





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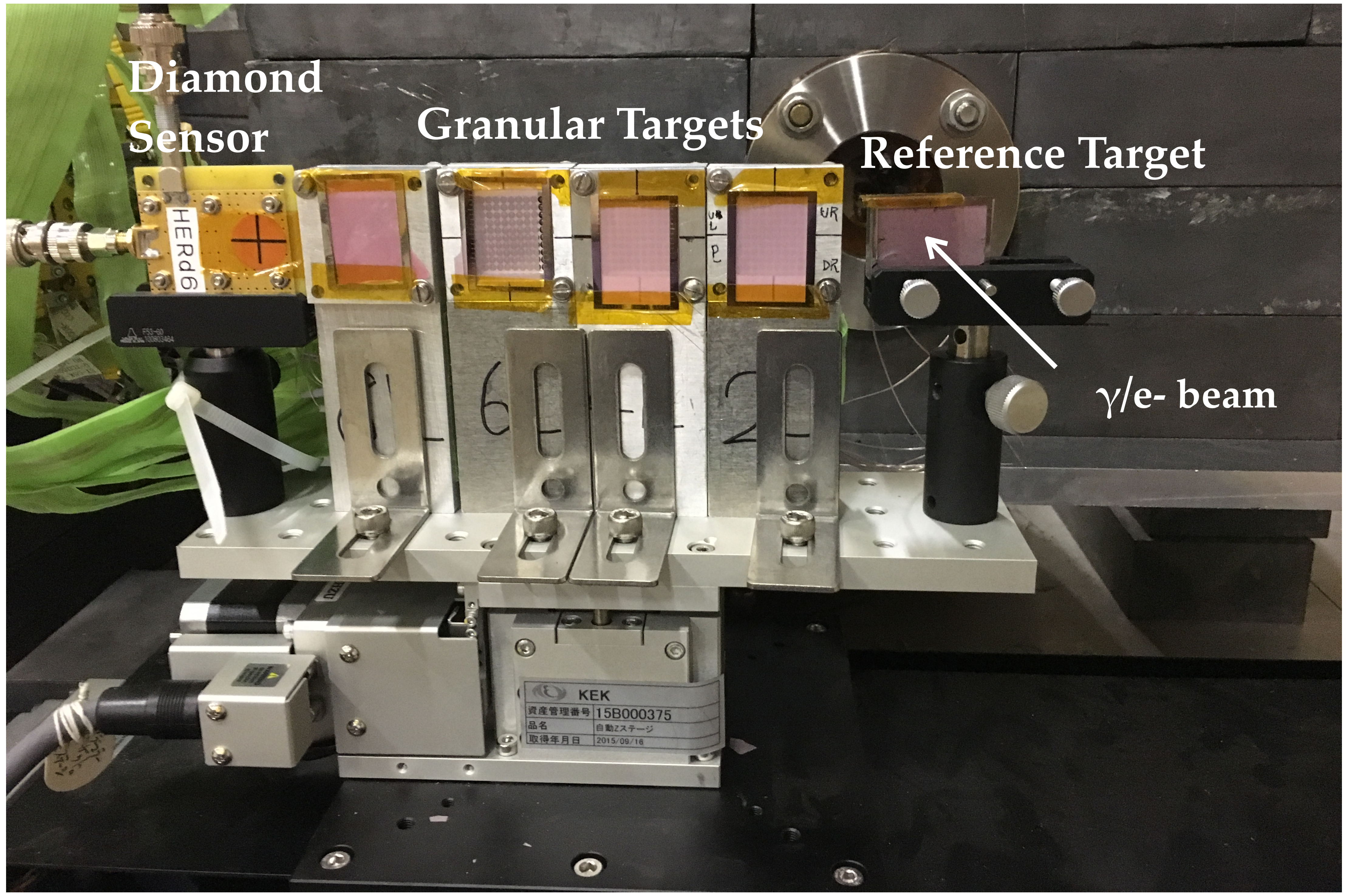
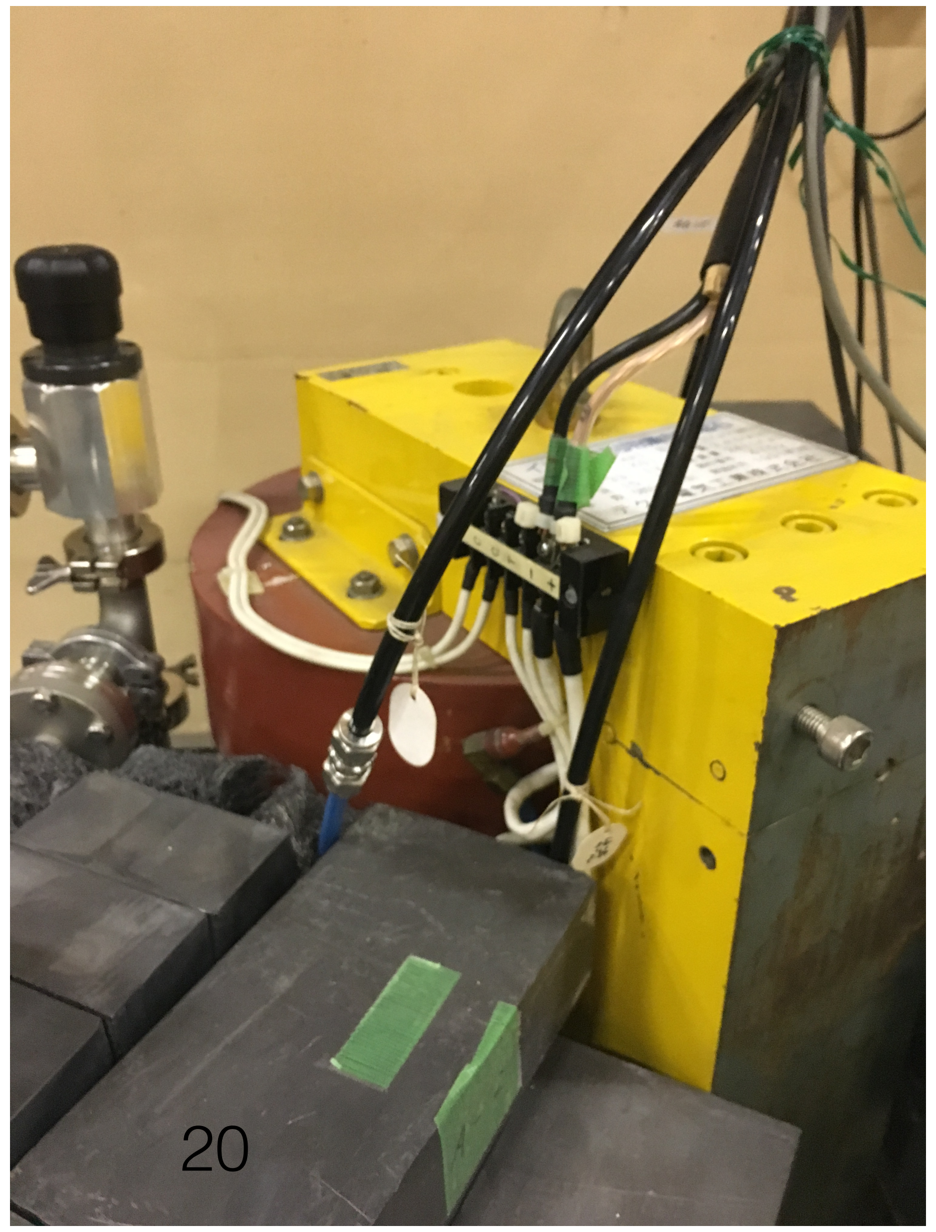
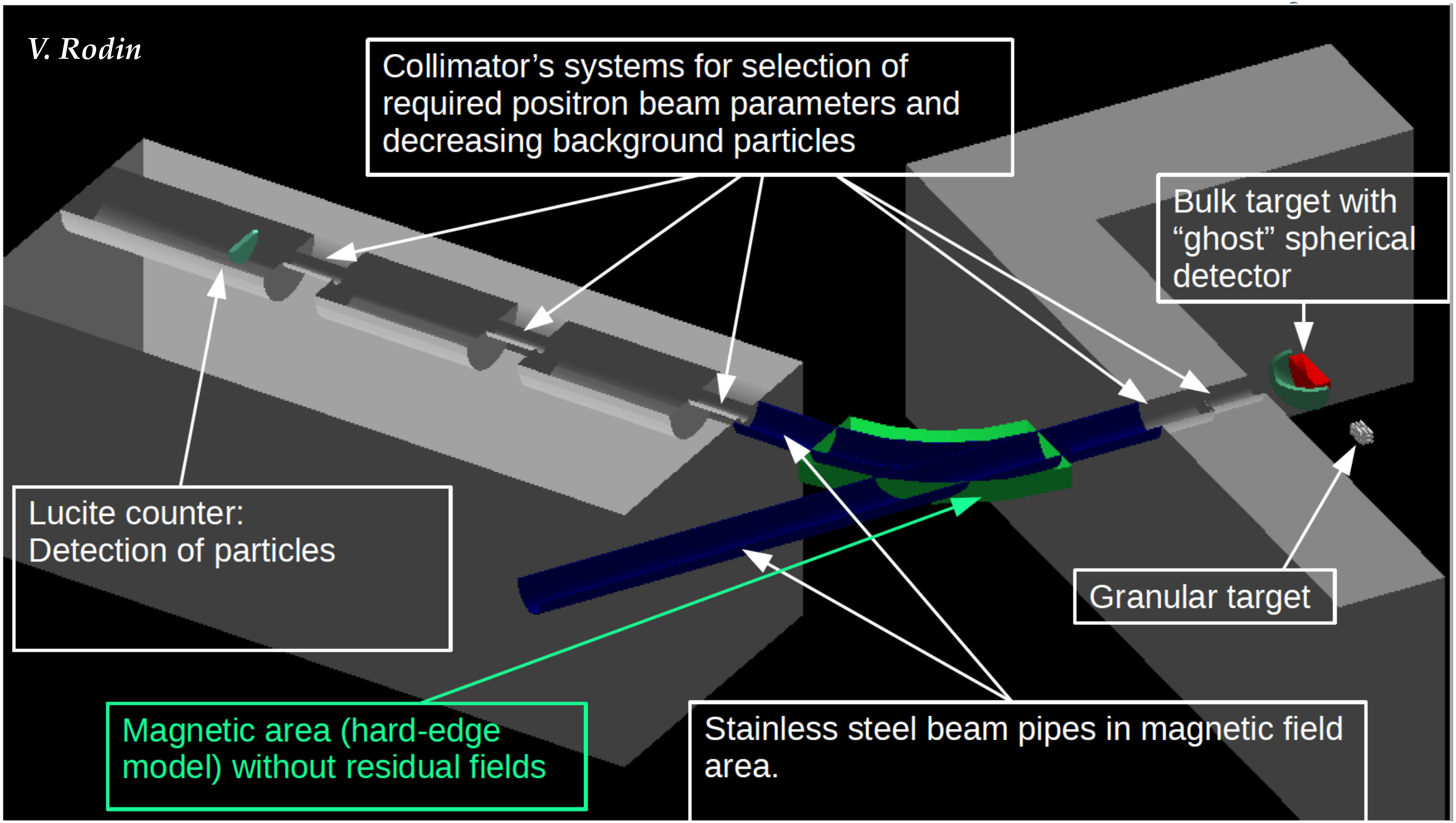
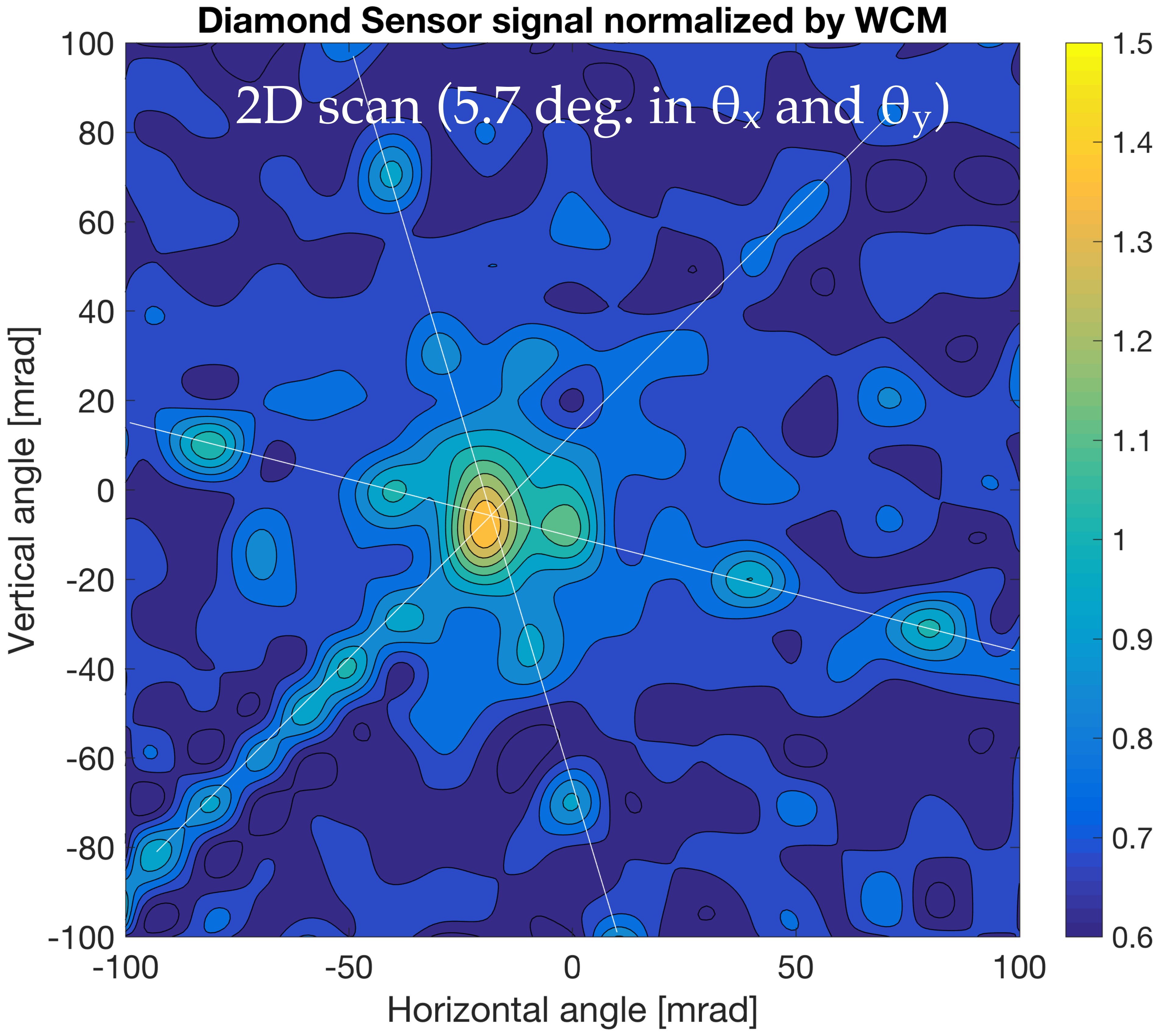




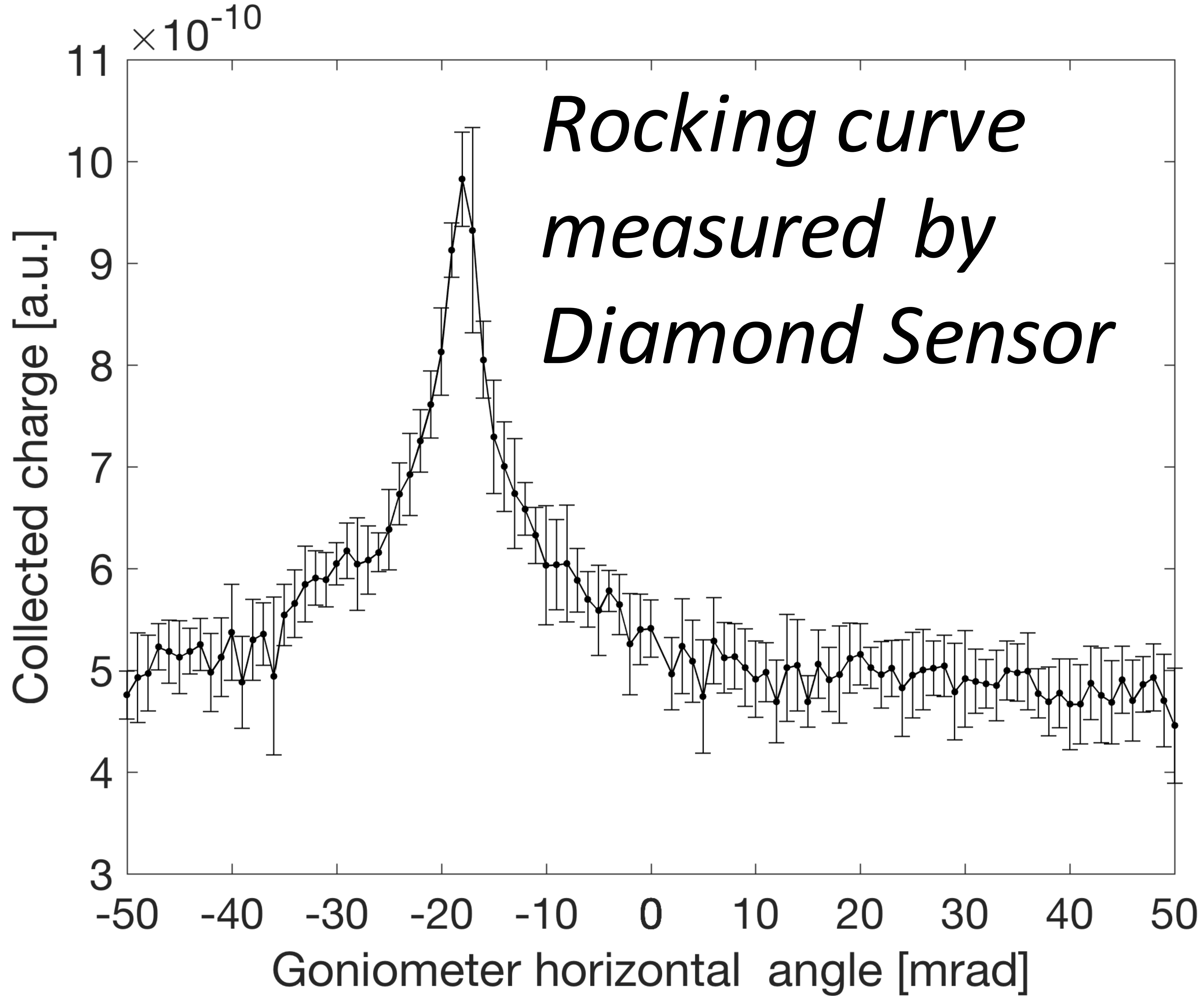

V. Rodin
Collimator's systems for selection of required positron beam parameters and decreasing background particles
Bulk target with "ghost" spherical detector
Lucite counter: Detection of particles
Granular target
Magnetic area (hard-edge model) without residual fields
Stainless steel beam pipes in magnetic field area.

Experimental activity on hybrid source



STEREOGRAPHIC PROJECTION

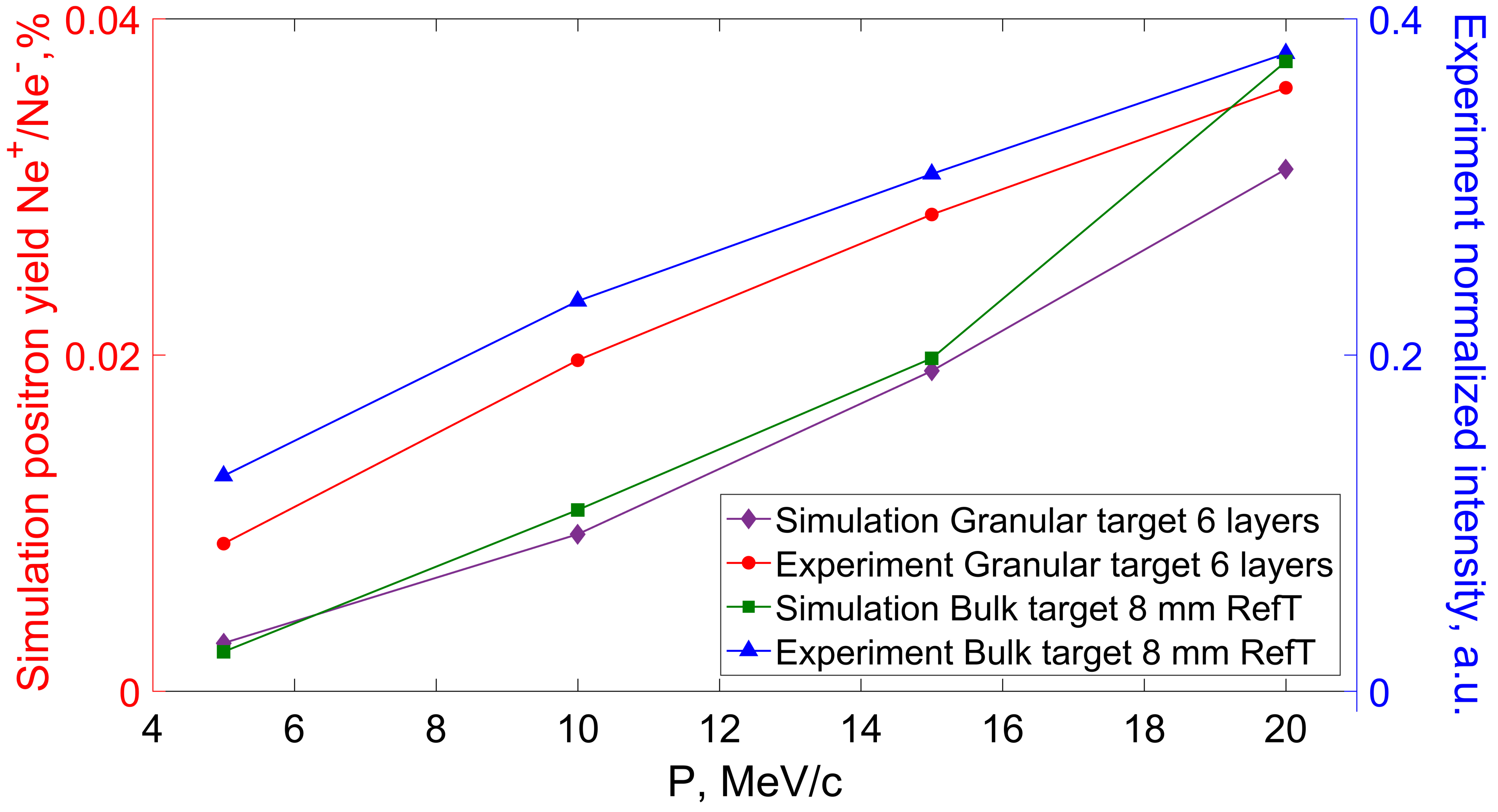
<110> axis is at 35.2 degrees from <111> and <100> axis is at 54.7 degrees from <111>



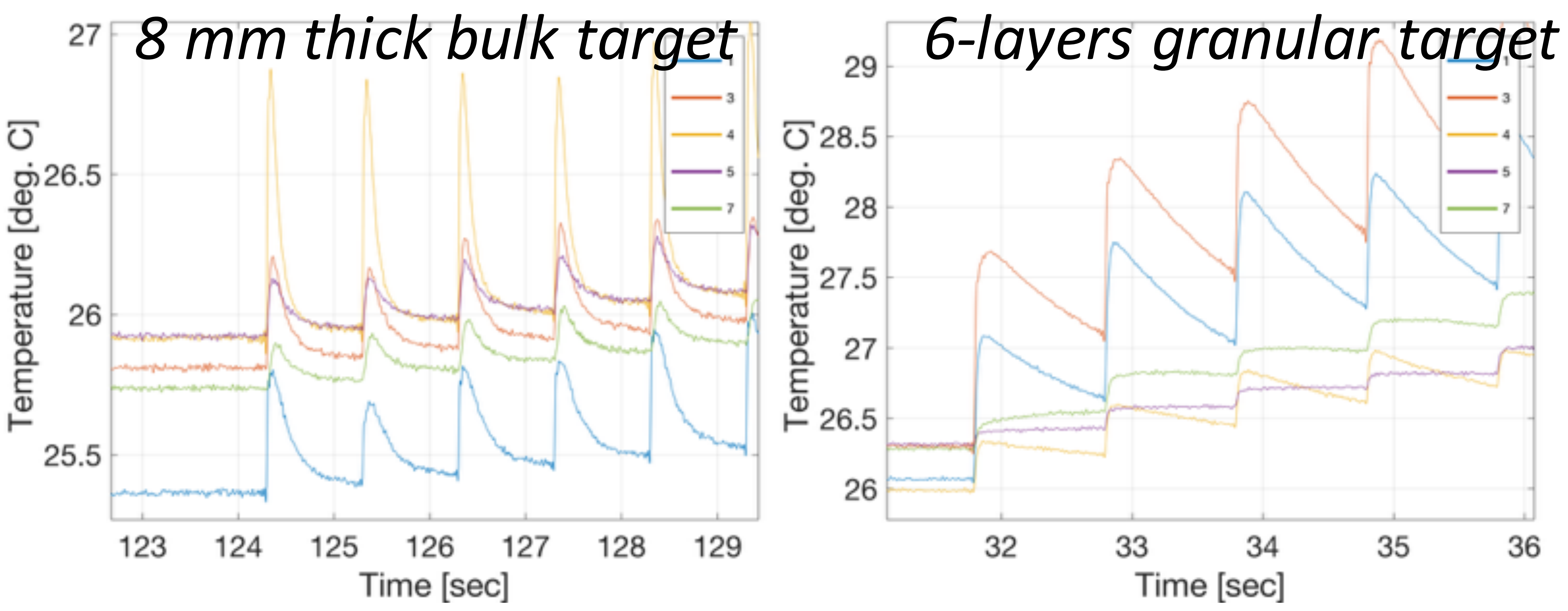
To align <111> crystal axis with respect to the electron beam, a 2D angular scan has been performed.

Data suggest an increase by a factor of two in the photon production => the simulations and further analysis of the background are under way to describe the experimental data.

Experimental activity on hybrid source



Bunch-by-bunch temperature rise



<u>Positron yield:</u> once the crystal axis was aligned with the e- beam, e+ yield was measured systematically for various conditions in hybrid and conventional schemes.

The studies are ongoing

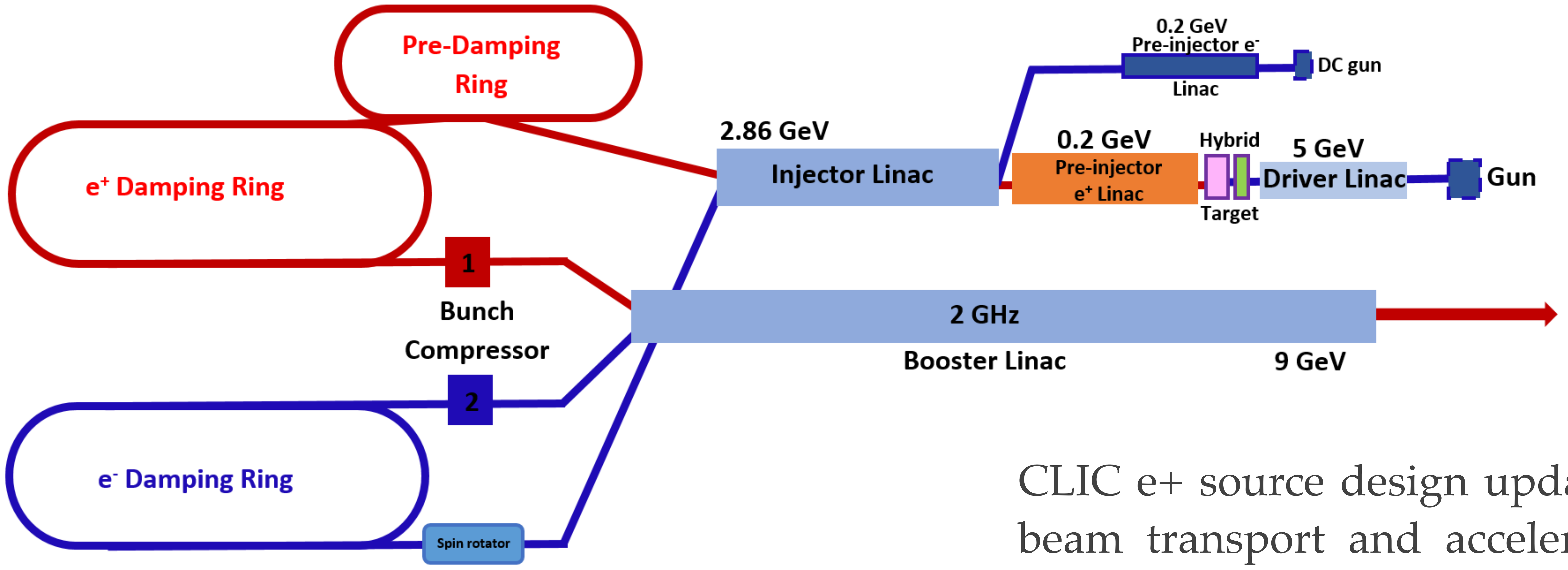
<u>Temperature measurements:</u> it was performed in order to estimate the heat load in the bulk and granular converters.

Bunch-by-bunch temperature rise => PEDD information.

Temperature at equilibrium => total energy deposition.

CLIC Positron Source

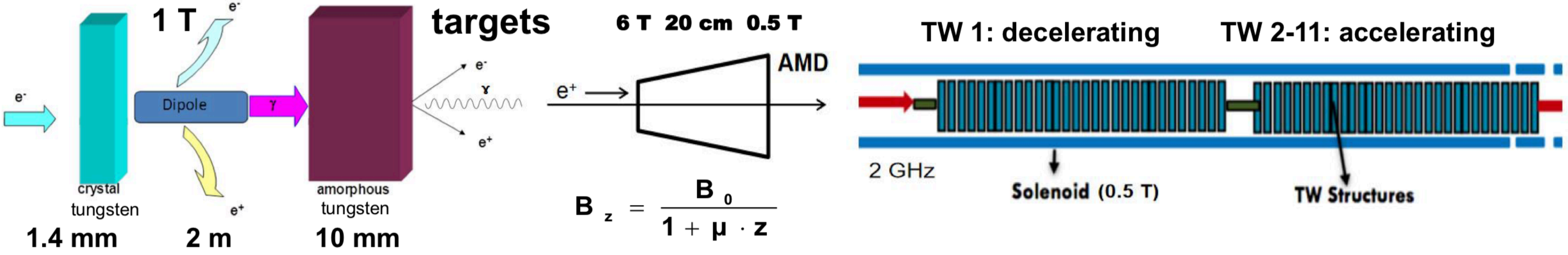
Separate injector complex to produce positron beam



- **Electron Driver:** 5 GeV beam, NC L-band TW 352 bunches/pulse, 1 nC
- **e+ target:** 1.5 mm crystal + 3.7X0 (1.3 cm) thickness, (avg power dep ~ 10 kW, PEDD ~25 J/g)
- **Capture:** Flux Concentrator Bmax = 3 T
- **e+ polarization:** No

CLIC e+ source design update (compared to CDR): target layout, new beam transport and acceleration design from the target to the pre-damping ring => final e+ yield ~1.7 e+/e-, PEDD = ~25 J/g.

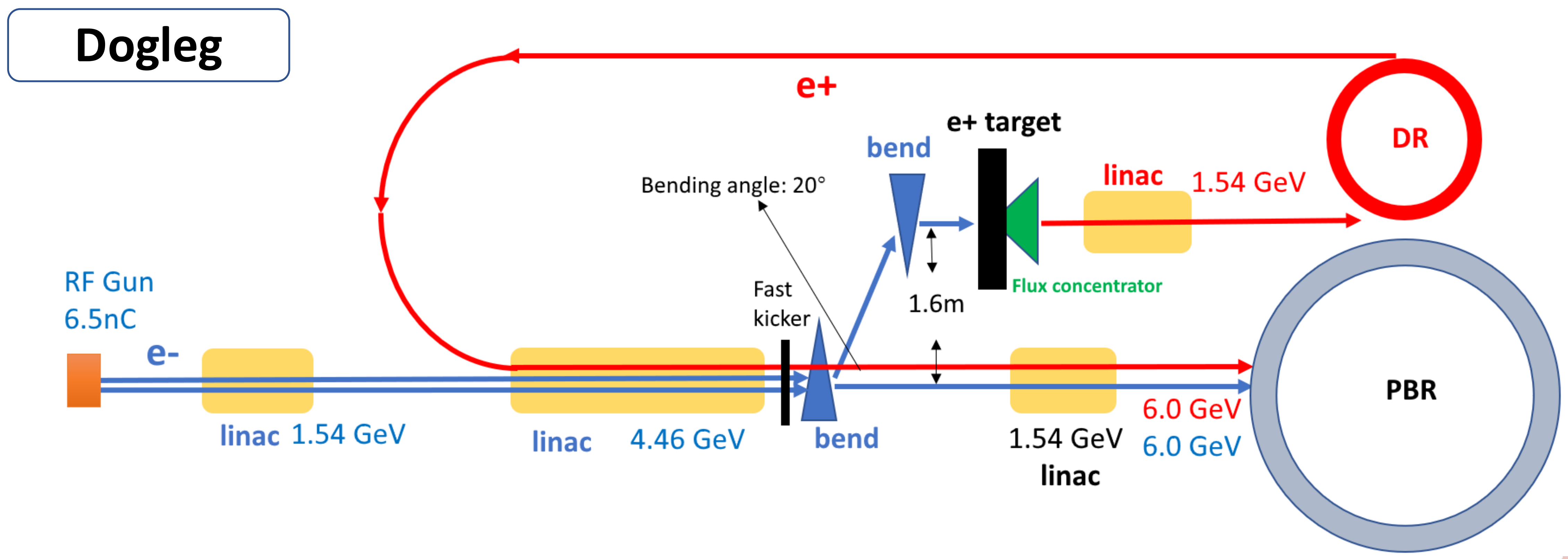
Hybrid scheme (CLIC CDR)

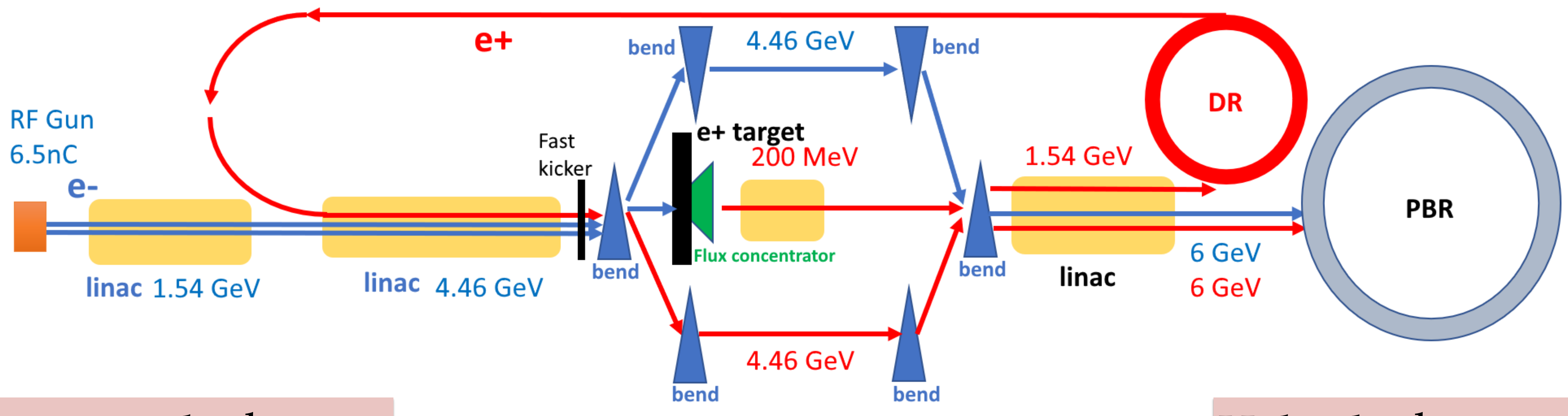


$$B_z = \frac{B_0}{1 + \mu \cdot z}$$

FCC-ee positron source

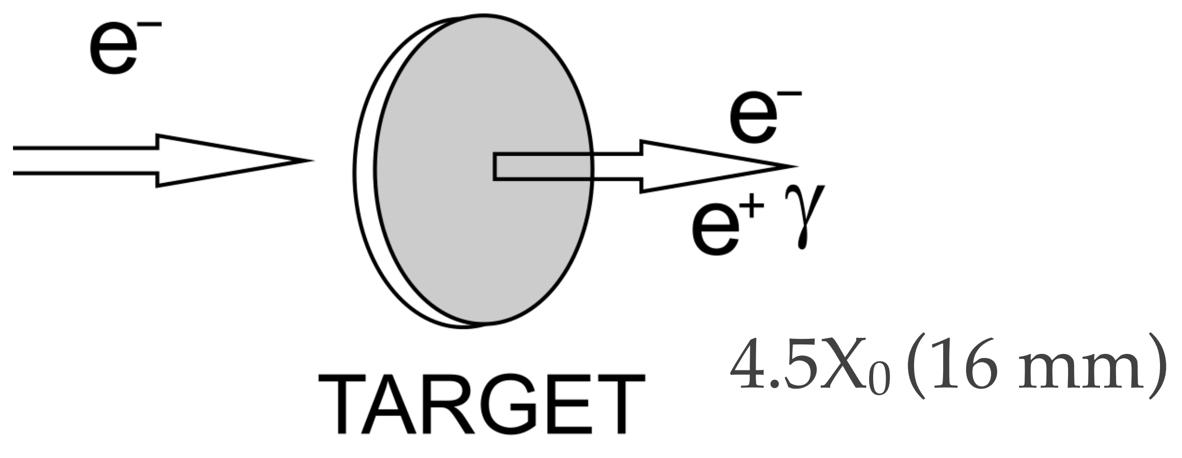
Preliminary



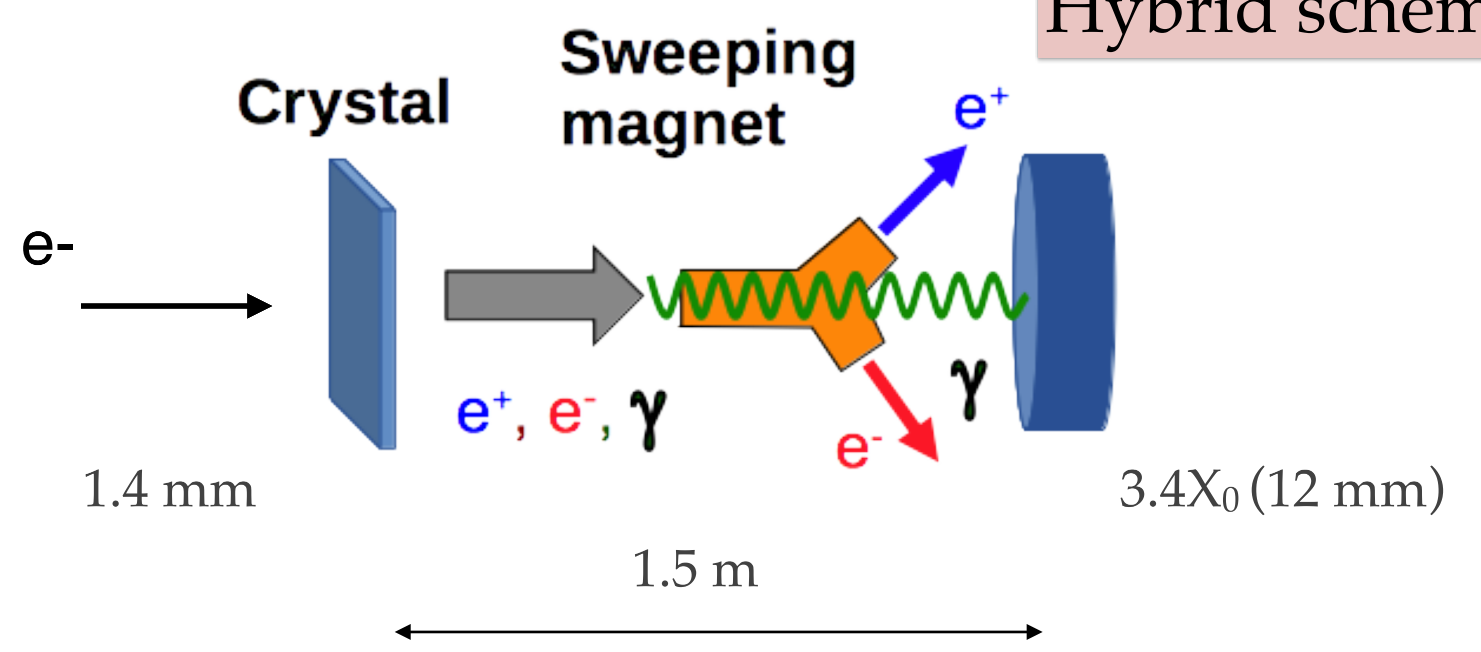


Primary e^- beam for e^+ production	
Beam energy	4.46 GeV
Bunch charge	4.2×10^{10}
Bunch length (rms)	**1** mm
Bunch transv. size (rms)	**0.5** mm
Bunch separation	60 ns
Nb of bunches per pulse	2
Repetition rate	100-**200** Hz
Beam power	12 kW

Conventional scheme



Hybrid scheme



The final choice of the e+ target will be made based on the estimated performances.

*Alternative option: 20 GeV linac as the FCC-ee injector => higher energy for e+ production

The complete filling for Z running (most demanding) =>
Requirement @ DR: ~2.1×10^{10} e+/bunch (4.3 nC)
~0.5 e+/e- without safety factor

LEMMA: positrons for muons

☞ Positron-driven scheme: Low EMittance Muon Accelerator (LEMMA)

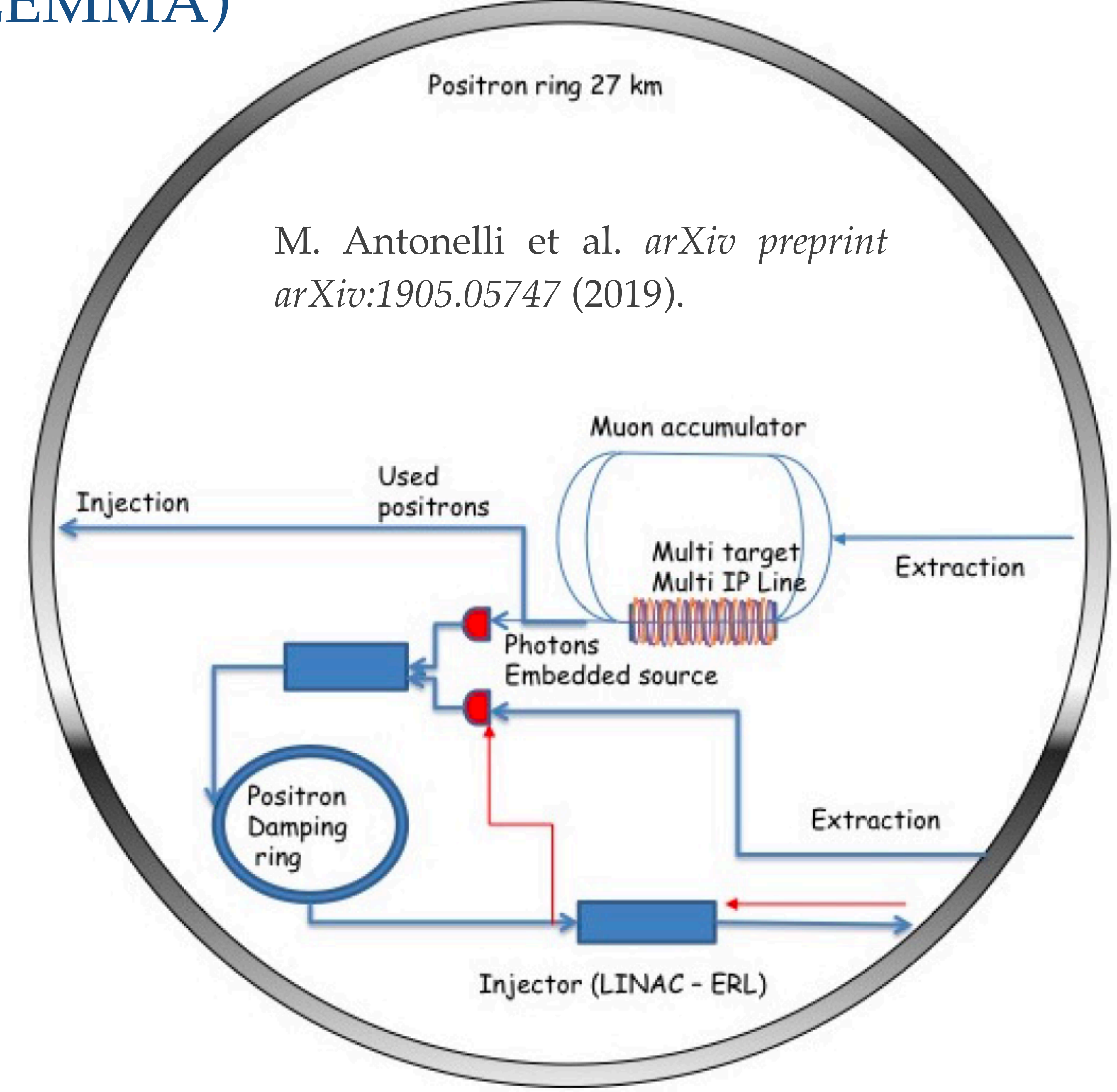
Goal: low emittance muon beams from direct pair production. $e^+e^- \rightarrow \mu^+\mu^-$ Max efficiency $\sim 10^{-5}$.

Muons produced at $\sqrt{s}$ around the $\mu^+\mu^-$ threshold ($\sqrt{s} \approx 0.212$GeV) in asymmetric collisions (corresponds to about 45 GeV e+ beam interacting with target).

Initial injection: the e+ source has to provide trains of **1000 bunches** with **5×10^{11} e+/bunch** to inject in the DR at 5 GeV.

But the e+ source needed to replace the e+ lost in the muon production process is a real challenge (very short time available ~ 50 ms).

=> Flux of 10^{15} - 10^{16} e+/s is needed (experience from ILC/CLIC + R&D program on new targets).



M. Antonelli et al. *arXiv preprint arXiv:1905.05747* (2019).