

RELIABILITY OF HYBRID POSITRON TARGETS FOR LINEAR AND CIRCULAR COLLIDERS

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- **OUTLINE**
- * INTRODUCTION
- * THE HYBRID SOURCE: SHORT RECALL AND PROPOSITIONS FOR COLLIDERS
- * PROBLEMS ASSOCIATED WITH THE RELIABILITY
- # Radiation resistance of the crystal
- # Heating effects on crystal and converter
- # The PEDD
- # The goniometer
- # Activation of the targets
- SUMMARY AND CONCLUSIONS

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► INTRODUCTION

- The main concerns for the new positron sources dedicated to linear colliders are, besides a high positron intensity, a low emittance and a reduced power deposition in the converters. The **hybrid source** exhibits interesting features for that. The large amount of photons radiated in axially oriented crystals is very promising for the expected yield. Moreover, the separation of the radiator and the converter with a sweeping magnet in between to sweep off the charged particles from the crystal allows a decrease of the power deposited in the converter and of the energy deposition density as well. In this presentation, we analyze the main problems related to the reliability of such device on the long-term.

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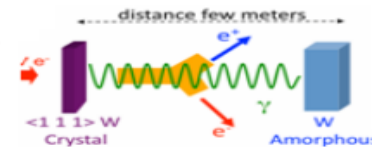
► THE HYBRID SOURCE: SHORT RECALL

- HYBRID SOURCES

- HYBRID SOURCES

combined

hybrid



Test at KEK

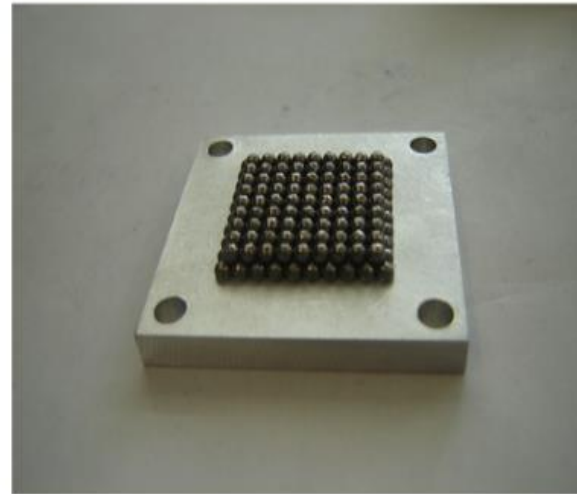
WHY USING AN HYBRID SOURCE:

* Use of a **thin** crystal leads to less energy deposition in the crystal → less heating → preservation of the high available potential well depth → more efficient channeling. Less deposited power on the converter (sweeping magnet)

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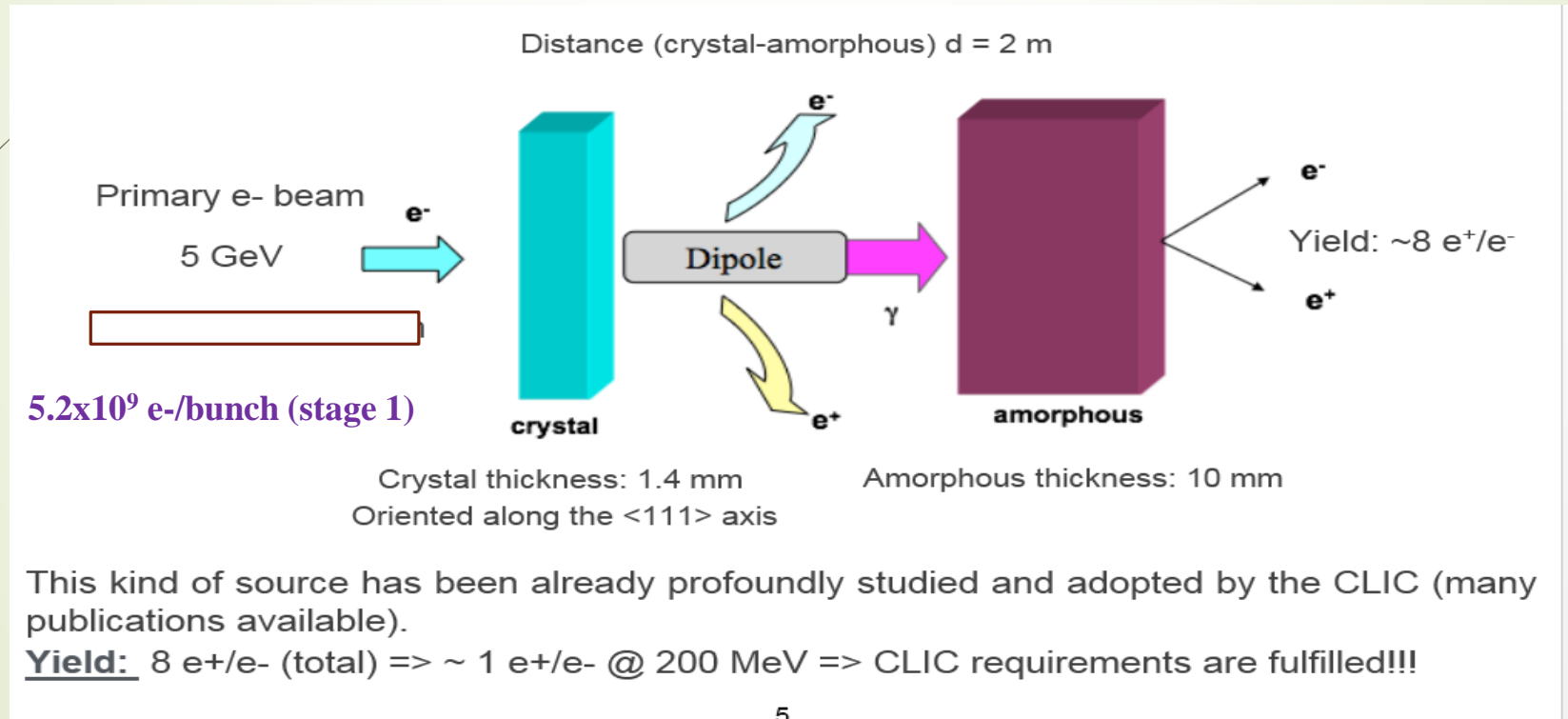
► HYBRID SOURCES WITH A GRANULAR CONVERTER

Following an idea of [P.Sievers](#) for the target of a neutrino factory (protons on target $\rightarrow \pi^+\pi^- \rightarrow \mu^+\mu^- \rightarrow \nu$), we considered a granular target made of small W spheres (2 mm diameter) instead of the compact W target. Four granular targets were built at LAL (2, 4, 6 and 8 staggered layers) and sent to KEK. Simulations have shown the ability of such targets to serve as converters providing equivalent yields and better performances for the deposited powers and Peak Energy Deposition Density (PEDD). For example the yield for a 8 mm compact converter is close to that of a 8 layers granular.



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CLIC: baseline source



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► ILC Linear collider: results of simulations

- Granular target: 6 layers
- Total positron yield of
- about ~14 e⁺/e⁻
- Deposited energy of ~400 MeV/e⁻
- Energy deposition density
- of about ~1.4 GeV/cm³ /e⁻

W crystal <111>, 1 mm thick
Incident energy: 10 GeV

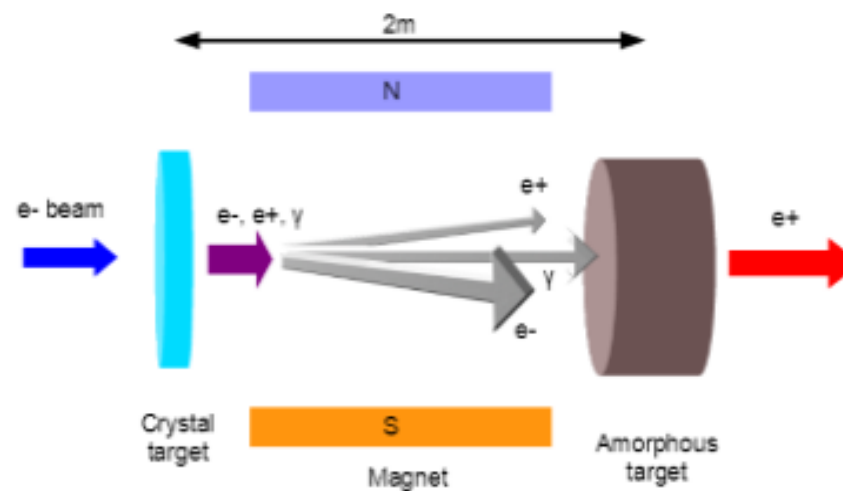


Figure 5.1: Hybrid scheme using crystal and granular target for ILC.

The pulse time structure of ILC has been modified before the target in order to decrease the power deposited by pulse. → 1ms → 13 macropulses @ 300 Hz

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FCC-ee Positron Source (CLIC design)

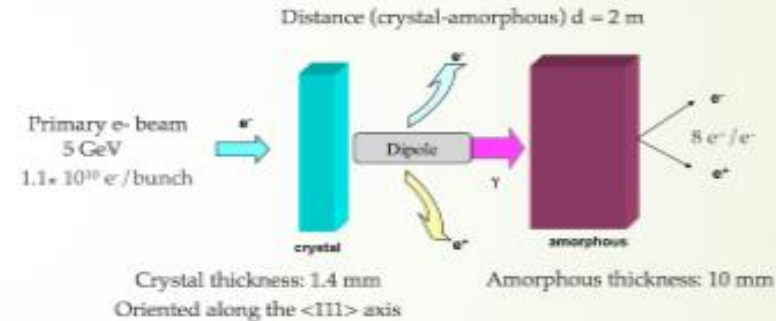
Hybrid scheme

Target Parameters Crystal		
Material	Tungsten	W
Thickness (radiation length)	0.4	λ_0
Thickness (length)	1.40	mm
Energy deposited	-1	kW

Target Parameters Amorphous		
Material	Tungsten	W
Thickness (Radiation length)	3	λ_0
Thickness (length)	10	mm
PEDD	30	J/g
Distance to the crystal	2	m

- 10 kW
< 35 J/g

- **Flux Concentrator (FC):** peak field is 6 T, DC solenoid field is 0.5 T, length = 20 cm, aperture 40 mm.
- **Accelerating structures:** L-band 2GHz, 25 MV/m, aperture 30 mm.



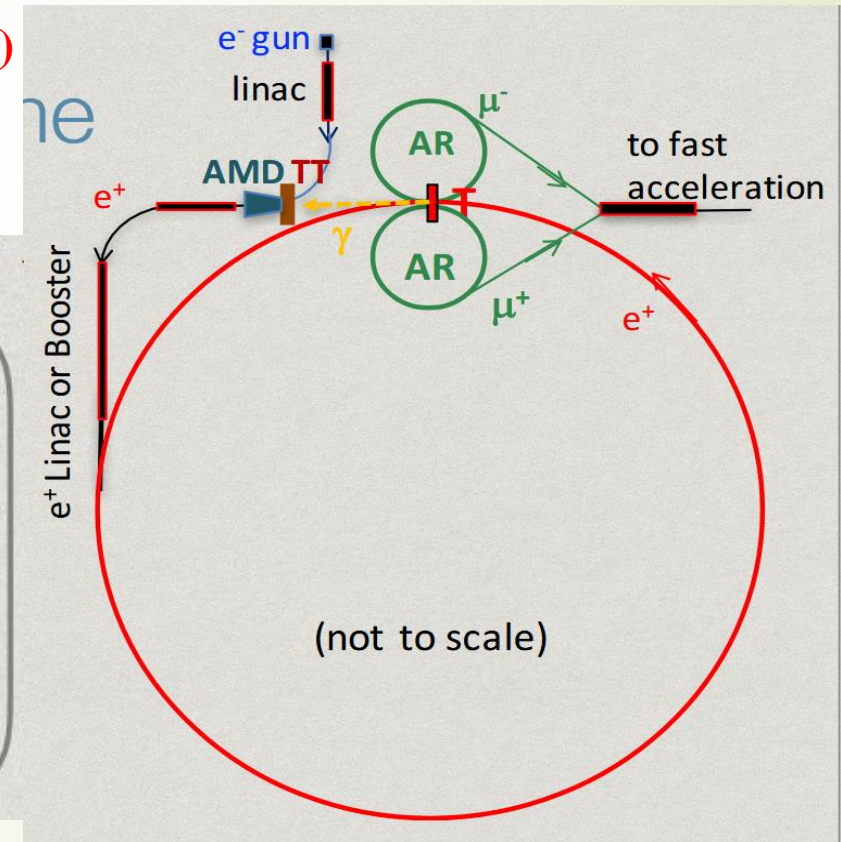
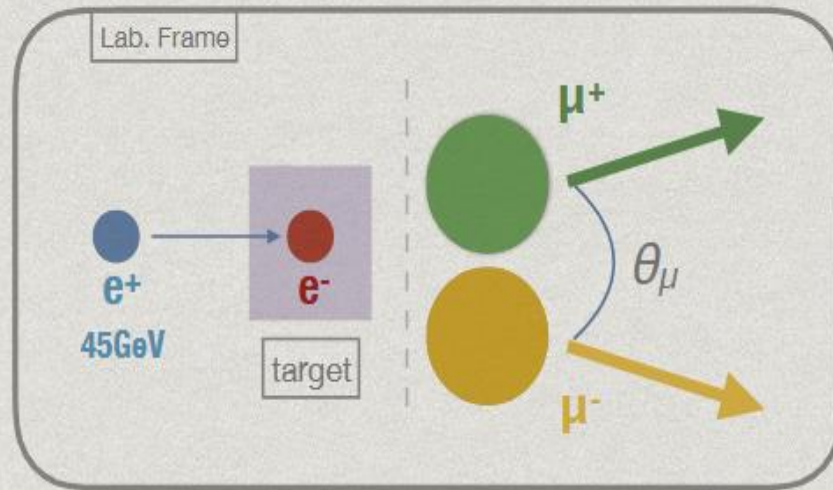
	@ 200 MeV	@ 2.86 GeV
e^+ yield, N_{e^+}/N_{e^-}	0.9	0.7
Emittance, $\mu\text{m rad}$	21	1.4

⇒ CLIC e^+ source design seems compatible with the FCC-ee requirements => optimisation with FCC-ee beam parameters.

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➤ POSITRONS FOR MUONS (LEMMA)

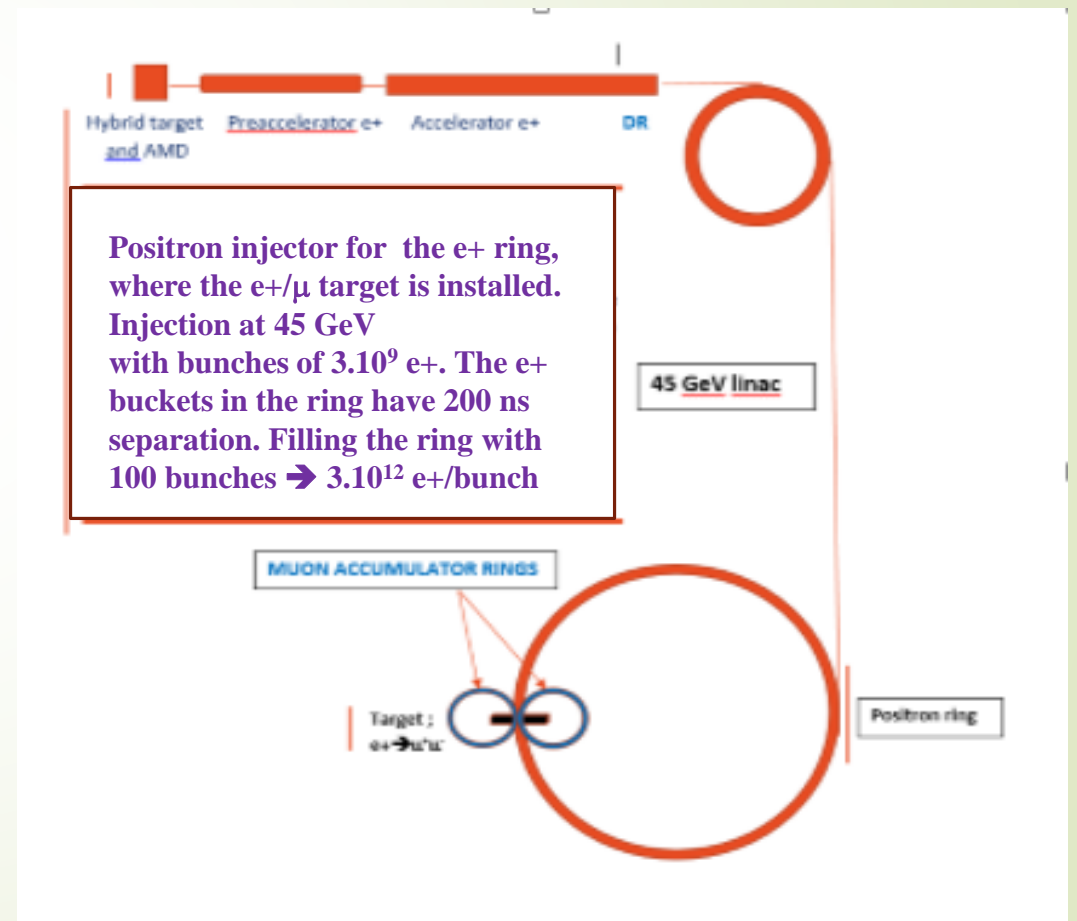
* direct muon production via e^+e^-



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POSITRONS FOR LEMMA The e^+ source is similar to that of CLIC baseline with LEMMA parameters. A 5 GeV e^- beam is impinging on a 1.4 mm W crystal; the amorphous W converter is 10 mm thick. The incident beam is made of macropulses containing 100 bunches of $4 \cdot 10^9 e^-$ with 200 ns separation; repetition rate is 100 Hz.

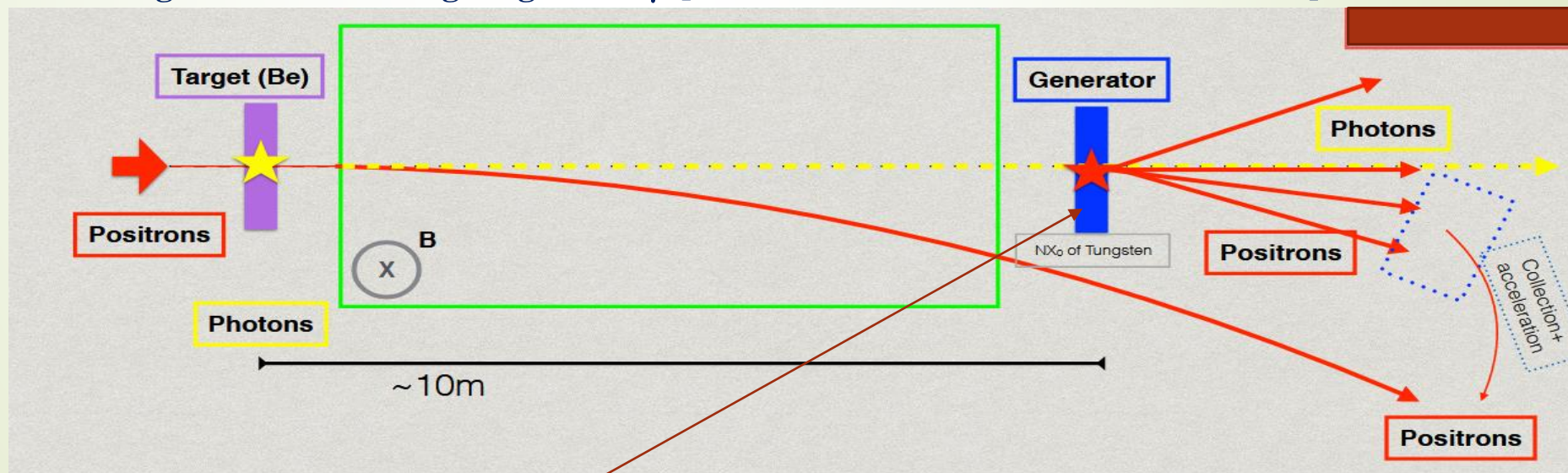
The wished number of incident positrons on μ target is $1.5 \times 10^{18} e^+/\text{second}$ with a small transverse dimension beam $\rightarrow \mu$ target reliability?



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► POSITRONS FOR LEMMA: AUXILIARY SOURCE TO COMPENSATE LOSSES IN e^+ RING

The circulating positron beam in the e^+ ring is losing about 3% in the interaction with the internal μ target. In order to mitigate these losses, the photons created in the μ target are impinging on a thick (4-5 X_0) W target to produce e^+e^- pairs. These positrons would need to be captured, accelerated and injected in the ring. Simulations are giving $\sim 6 e^+/\gamma$. [see M.Boscolo et al. arXiv:1803.06696v2]



R.Chehab/Hybrid/POSIPOL-18

Conventional target

Slide from F.Collamati, LEMMA proposal, dec 2017

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► RELIABILITY- RADIATION RESISTANCE FOR THE CRYSTAL

A- RADIATION RESISTANCE

Radiation resistance is one of the key problems for the reliability of the crystal sources. The main source of damage being the Coulomb scattering of the incident electrons on the nuclei of the crystal string. When the recoil energy of the string nucleus is above some threshold ($E_d \sim 25$ eV),* the nucleus can be displaced from its site. Also, if the recoil energy is larger than $2 E_d$ the nucleus can provoke a cascade of displacements among the neighbouring nuclei.



Ref: [X.Artru et al. NIMA 344 \(1994\)443](#)

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► RADIATION RESISTANCE OF THE CRYSTAL

RADIATION DAMAGE EXPERIMENT AT SLAC

A 0.3 mm W crystal has been installed upstream of the SLC positron converter. It was irradiated during a period of 6 months. Incident electron intensity as beam position and dimensions on the crystal were continuously controlled.

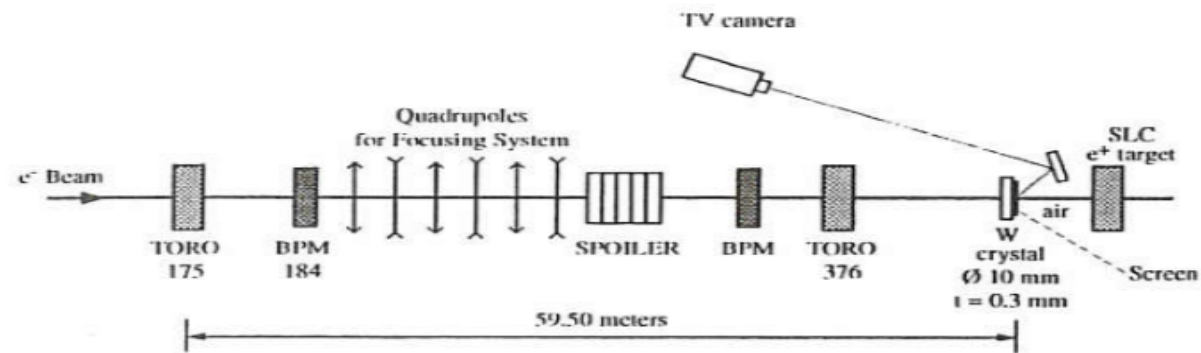


Figure 3: The SLC experimental set-up

Ref: [R.Chehab et al. Proceedings of EPAC 1998 Conference , Stockholm, june 1998](#)

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► RADIATION RESISTANCE OF CRYSTALS

RESULTS OF THE CRYSTAL IRRADIATION AT SLAC

The SLC beam: $E = 29.5$ GeV

average intensity: 2.5×10^{10} /pulse

Frequency: 10 and 30 Hz

Integrated intensity (6 months): 1.2×10^{19} e-

Spot area on the crystal: 6.2 mm²

Total fluence: 2×10^{20} e-/cm²

Analysis:

X-ray and γ analysis have been operated by diffractometry methods at the Max-Planck Institute of Stuttgart, **before** and **after** irradiation. **No modification in the mosaic spread of the crystal was observed.** The result of the measurement done after irradiation is shown. The damage threshold should be higher (for e-).

That fluence corresponded to the level of appearance of damages on a Si crystal hit by 28 GeV and 450 GeV protons (BNL & Fermilab)

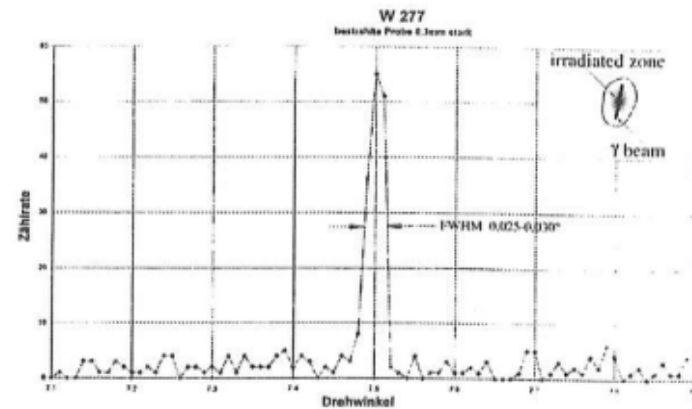


Figure 4: Mosaic distribution function of sample C2 obtained by γ -diffractometry. The γ beam is on the irradiated zone.

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► RELIABILITY- HEATING ON CRYSTAL AND CONVERTER

2.2.2 The Crystal in Warm Regime

Heating the crystal, with the energy deposited by the shower, makes the thermal vibration amplitude u_1 larger. As the radiation intensity spectrum, in channeling conditions, is a decreasing function of u_1 ,⁵ this intensity becomes lower when the crystal is heated.

We can observe the effects of the temperature on the continuum potentials of the $\langle 111 \rangle$ axis (Figure 9). These potentials have been estimated using the expression given by Baier *et al.*¹⁰

$$U(x) = V_0 \left[\ln \left(1 + \frac{1}{x+b} \right) - \ln \left(1 + \frac{1}{x_0+b} \right) \right], \quad (8)$$

where

- $V_0 = Ze^2/d = 430$ V, for the tungsten crystal oriented along its $\langle 111 \rangle$ axis,
- $x = \rho^2/a_s^2$; ρ being the distance to the axis and a_s , the screening radius,
- $b = 2u_1^2/a_s^2$; u_1 being the thermal vibration amplitude,
- $x_0 = S/\pi a_s^2$; S being the entire area associated with individual axis,
- u_1 is increasing with the temperature; its values is derived from Gemmel¹¹ and given in Table I.

Ref: [X.Artru et al. Particle Accelerators vol.59,\(1998\)19-41](#)

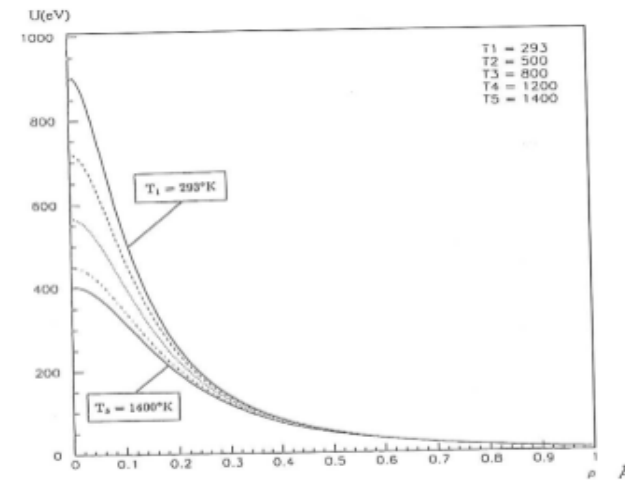


FIGURE 9 Continuum potentials for the $\langle 111 \rangle$ axis of the tungsten crystal. The temperatures are expressed in K.

T (K)	400	500	600	700	800	1000	1200	1400
UTHERM (u_1)	0.058	0.065	0.071	0.077	0.082	0.091	0.100	0.109

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CRYSTAL HEATED

Taking into account the variation of the potential with the temperature, simulations have been undertaken with a W crystal 8 mm thick (<111> axis) . It resulted that a variation of ~ 600 degrees in the crystal decreased the positron yield by an amount of 15 %. (Incident e- beam of 10 GeV and 5×10^{11} e-/pulse; 150 Hz)

In order to keep a moderate temperature in the crystal:

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

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► CRYSTAL COOLING

HEATING AND COOLING: THE CRYSTAL

With an incident e- beam of 10 GeV and a transverse size of 2.5 mm rms, the energy deposited and PEDD/ μ pulse are:

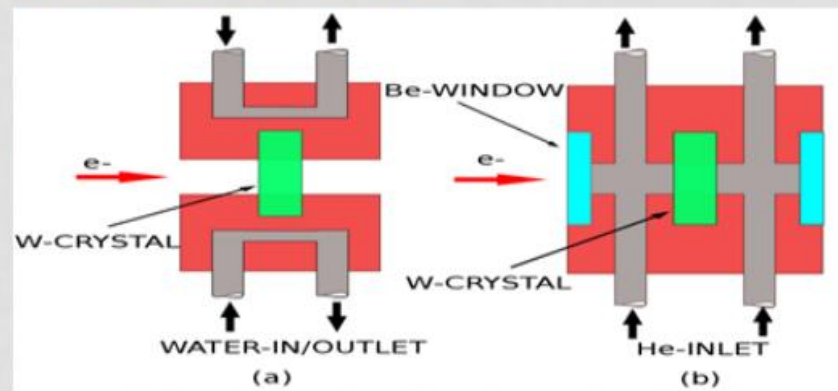
$$E_{\text{dep}} = 2.6 \text{ Joule}$$

$$\text{PEDD} \rightarrow 5.8 \text{ J/g}$$

The crystal needs cooling: \rightarrow solution: a 5-crystal holder in a goniometer.

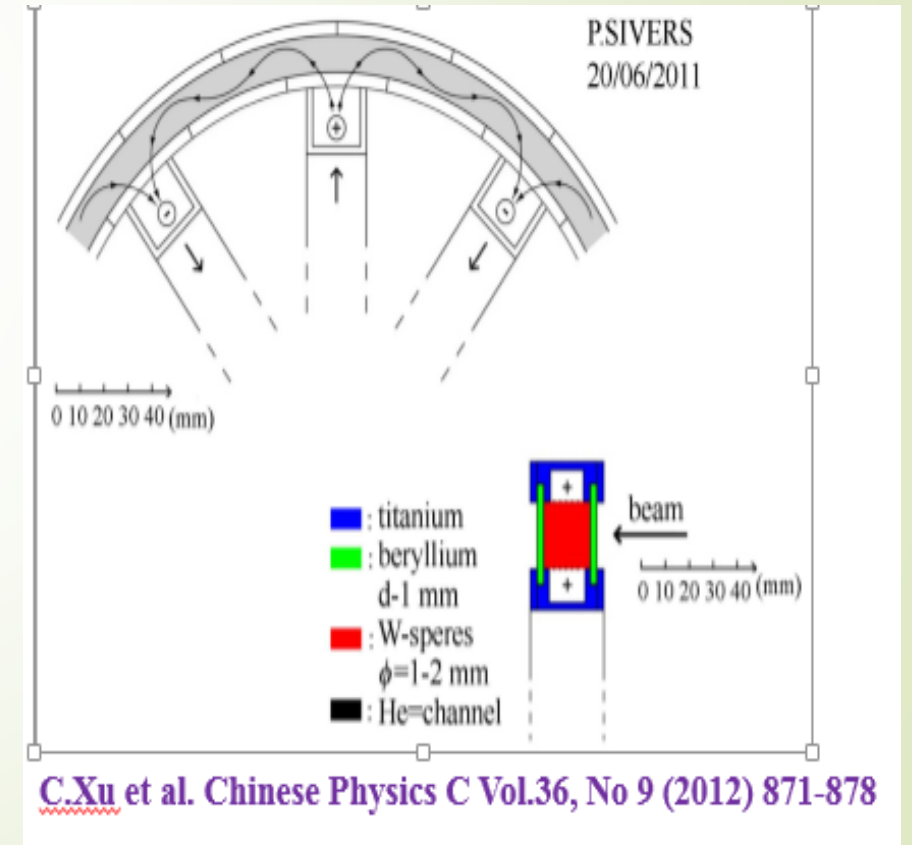
Cooling is realized with water or He jet.

Max. Temperature rise is:
 275°K \Rightarrow Water
 406°K \Rightarrow He



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- **HEATING OF THE CONVERTER**
- The large amount of deposited energy due to the high positron beam intensity required for the future linear colliders is leading to important heating and thermal shocks. The average heating as the energy deposition density can be mitigated using rotating converters as wheel (see figure) or pendulum. The **Peak Energy Deposition Density (PEDD)** may provoke thermal shocks leading to breaking → SLC
- As an example, the converter foreseen for the hybrid source of ILC is receiving a deposited power of 10 kW: this is two times less than for a conventional source using 4.8 GeV e⁻ and a 16 mm W target or 60% less with a 3 GeV e⁻ beam
- (see former project of purely conventional source @ POSIPOL 17)



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- **RELIABILITY: THE PEDD**
- Analysis of the SLC target helped to define a threshold for the damages. expressed for W as 35 J/g. The linear collider projects are taking into account such limitation.
- In such situation, is the **granular converter** bringing some benefit?
- The PEDD for the ILC case with $E=10$ GeV, $\sigma=2.5$ mm is of 23 J/g; close value is obtained in the purely conventional case ($E=4.8$ GeV; $t=16$ mm but with a 40 % wider e- beam).
- The PEDD in the **hybrid** case corresponds to 100 bunches, whereas the PEDD for purely conventional corresponds to 66 bunches.
- Simulations made by S.Jin (IHEP) have shown that using granular converter with 2 mm diameter W spheres presented maximum shock pressure of 40 Mpa whereas it was for a W compact converter of 400 Mpa, in the same working conditions.
- Obviously it is needed thin windows for the granular converter to allow use of a cooling gas jet which circulates between the spheres. In the case of a bulk converter, water cooling is foreseen. The behavior of the windows regarding the corresponding PEDD must also be checked. Simulations with thin Be windows gave good results.

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- **RELIABILITY- THE GONIOMETER**
- **GONIOMETER** : working conditions for goniometers under vacuum conditions
- **Proof of Principle experiment @ Orsay (1992-1993)**
- # The general beam conditions during the channeling experiment done with a 1 mm W crystal oriented on its <111> axis were: 1.1 GeV <E- < 2 GeV; e- beam: $2 \cdot 10^8$ to $6 \cdot 10^9$ e-/pulse with 30 ns pulses at 25 Hz.
- Later on, the goniometer was also used for OTR (Optical Transition Radiation) experiments in 1996-1997; the conditions were E- = 2 GeV; e- beam pulses of 30 ns with $1 \cdot 10^9$ to $2 \cdot 10^{10}$ e-/pulse 25 Hz. In 2000, this goniometer has been installed at CERN for the WA 103 experiment.
- **Experiment WA103 @ CERN (2000-2001)**
- The experiment was done during two summer periods in 2000 and 2001. The incident secondary electron beam from the transfer lines of the SPS had a rather low intensity of 10^4 e-/burst of 3.2/5.2 sec with 14.4/16.8 period
- *The " Microcontrole" goniometer used in Orsay and CERN was, after the end of the experiment in good working conditions.*

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- **RELIABILITY: THE GONIOMETER (2)**
- Experiments with electron beams in other places
- In MAMI and Jlab Coherent bremsstrahlung experiments with GeV electron beams and C(d) crystals mounted on a goniometer to generate polarized photons have been operated with a great stability of the goniometer. In MAMI, the goniometer is working since 10 years.
- *Communication of A.Mazzolari and L.Bandiera (Ferrara)*
-
- Experiments with bent crystals (UA9,..)
- Goniometers are being used on UA9 experiment on SPS with the 400 GeV proton beam and also for an experiment on LHC. The set-up was stable during the whole experiment. Informations from the goniometer showed very good repeatability. Previously the NA48 experiment on SPS site used also a goniometer during a long time.
- *Communication of A.Mazzolari and L.Bandiera (Ferrara)*
- **=>> Good reliability is observed for the goniometers in use since many years**

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- **RELIABILITY- ACTIVATION OF THE TARGET**
- The activation is related to photon/electron interaction with the nuclei causing emission of nucleons (protons, neutrons, etc..) when the impinging particle has an energy over the nucleus binding energy. The threshold is of some MeV for heavy materials as W. In such materials the main interaction is of (γ, n) type. The photon absorption by the nucleus leads to its excitation followed by a de-excitation leading to emission of secondaries as neutrons. The main process is related to the GDR (Giant Dipole resonance) which exhibits a maximum $E(\gamma)$ around 14 MeV for W. **The neutrons may be a radiation hazard themselves or provoking induced activity. Their number N_n is rising with the nuclear size [$\sim NZ/A$, where $N=A-Z$].**
- The description of this process can be quantitatively operated with codes as FLUKA or GEANT. As underlined by Frascati physicists after tests on the Beam Test Facility, the experimental results are in better agreement with FLUKA (L.Quintieri et al. *Quantification of the validity of simulations based on GEANT4 and FLUKA for photo-nuclear interactions in the high energy range*, in The European Physical Journal Conferences 153, 06023, (2017).

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- **RELIABILITY: ACTIVATION OF THE TARGET (2)**
- For electron triggered targets, the bremsstrahlung photons initiate the (γ, n) process; Concerning the hybrid targets, the process is generated by the photons created in the crystal. The neutron yield is expressed in $n.s^{-1}.kW^{-1}$. The power of incident beam being expressed in kW. As an example, in the case of a 6 GeV e- beam incident on a thick heavy target (Pb), the neutrons with $E_n < 25$ MeV are about 3 times more numerous than for $E_n > 25$ MeV

Simulations for the hybrid source as for the source surroundings must be undertaken.

We may notice that tungsten (collimators) and stainless steel (shielding) are highly susceptible of activation w.r.t. copper (cavities)

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► Summary & Conclusions

- The hybrid positron source represents a solution for many collider projects. It has been chosen as the baseline solution for CLIC. Its reliability is is, therefore, an important question.
- **Radiation resistance** of the crystal has been studied and tested (SLAC). No damage being noticed up to a fluence of $2 \cdot 10^{18}$ e-/mm²; If the damage threshold ($\gg 2 \cdot 10^{18}$ e-/mm²) can be estimated to be between 10^{19} and 10^{20} e-/mm²) we can foresee thousands of working hours for an incident e- beam with $\sigma = 2.5$ mm). Anyway, the remedy is annealing of the crystal.
- **Heating**: cooling the crystal keeps its high field; appropriate cooling of bulk or granular converters have been considered and may ensure a stable working condition.
- **PEDD**: the hybrid source allows the decreasing of the energy deposited density; moreover, if the converter is granular, thermal shock waves are much less harmful, even harmless.

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- **SUMMARY & CONCLUSIONS (2)**
- **GONIOMETER:** Use of a goniometer to align the crystal axes on the beam direction is not a problem at all; the experience gathered in many experiments allow us to rule out any objection of this kind.
- **ACTIVATION OF THE TARGET/SURROUNDINGS:** this is a problem not to neglect for both kinds of targets conventional/hybrid. The example of SLC target where it was impossible to approach at less than 5 meters, remind us about this problem. Extensive simulations with existing codes (GEANT4, FLUKA) must help for a quantitative and precise evaluation of the problem.