Positron source development for the future Linear Collider

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on behalf of the Positron Source collaboration
LAL / IPNL / CERN / KEK / IHEP

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4èmes Journées Collisionneur Linéaire

23 March 2016, Chimie ParisTech

Outline

1. Introduction: positron sources are critical components of the future LC.
2. Polarized positron sources (ILC baseline).
3. Unpolarized positron sources (ILC backup, CLIC baseline).
4. Summary and perspectives.

Thanks to all the collaborator working on e+ sources for providing the information for this presentation.

Introduction: e+ Sources

Background

- High intensity low emittance positron beams are required in HEP, especially by the future Linear Collider (LC) project.
- It has been comprehensively analysed that having both beams polarized will increase precision of the measurements and provides versatile methods to search for New Physics.
- Polarized electron beams are more easily to obtain with e.g. AsGa photocathodes (~90% of polarization).
- Production of **polarized positron** beams **remains a challenge**.
- Strong efforts are put on the development of the high intensity unpolarized/polarized positron source for the future LC.

Why e+ sources are critical components of the future LC

- High luminosity at the future LC => needs high average and peak e- and e+ flux.
- e+ are produced within large 6D phase space value (e+/e- pairs produced in a target-converter).
- Moreover, thermal effects in the target limits the e+ source intensity.
- e+ produced are transferred to the DR with their phase space characteristics (injection at high 6D emittance).

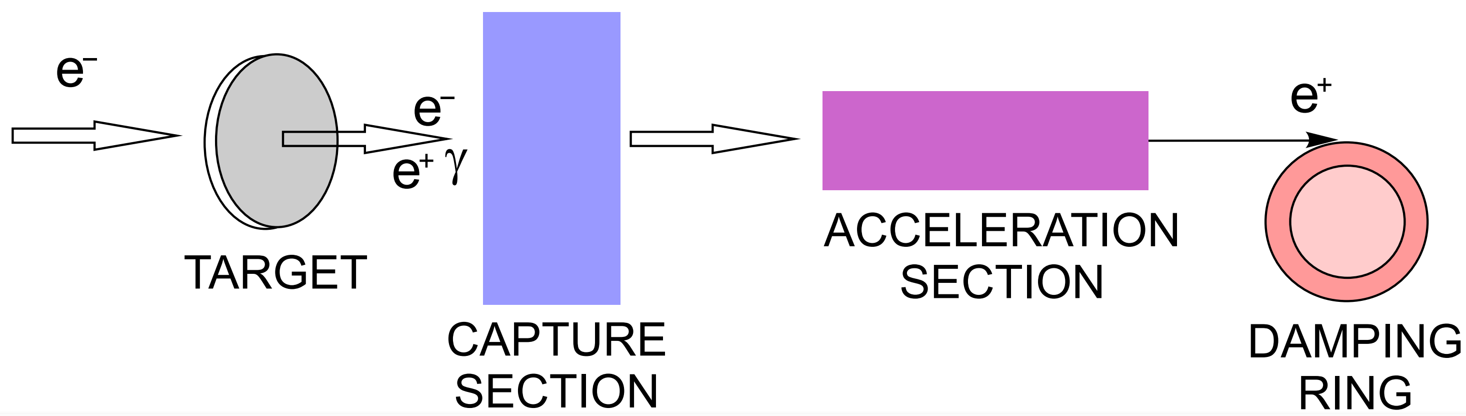
So, e+ source fixes the constraints for:

- e+ cooling time in DR => repetition frequency and so =>
- maximum and average bunch current
- maximum and average train current and so =>

=> **Luminosity**.

Positron Sources

Conventional positron source: bremsstrahlung and pair conversion



Energy deposition in target => Heating
Inhomogeneous energy deposition =>
Peak Energy Deposition Density (PEDD)
=> mechanical stresses => target failure!

☞ Very difficult to realize for the future linear colliders due to the target thermal and mechanical stresses issues.

- SLC e+ source: ~ 3.5e10 e+/bunch & 1 bunch/train & 120 Hz => 0.042e14 e+/s
- CLIC e+ source: ~ 4e9 e+/bunch & 312 bunch/train & 50 Hz => 0.6e14 e+/s
- ILC e+ source: ~ 2e10 e+/bunch & 1312 bunch/train & 5 Hz => 1.3e14 e+/s

Positron sources

Better solution: Two-stage process to generate the positron beam.

First stage: γ-ray generation.

Second stage: e-/e+ and γ-ray beams are separated and the latter is sent to the target-converter.

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

The γ-rays can be generated by the following methods:

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

- γ-rays produced by channeling effect in the oriented crystals can be used for the **unpolarised positron source**.

- **Polarized positrons** can be obtained by using polarized γ rays produced in helical undulator or in Compton scattering.

Polarized e+ Sources

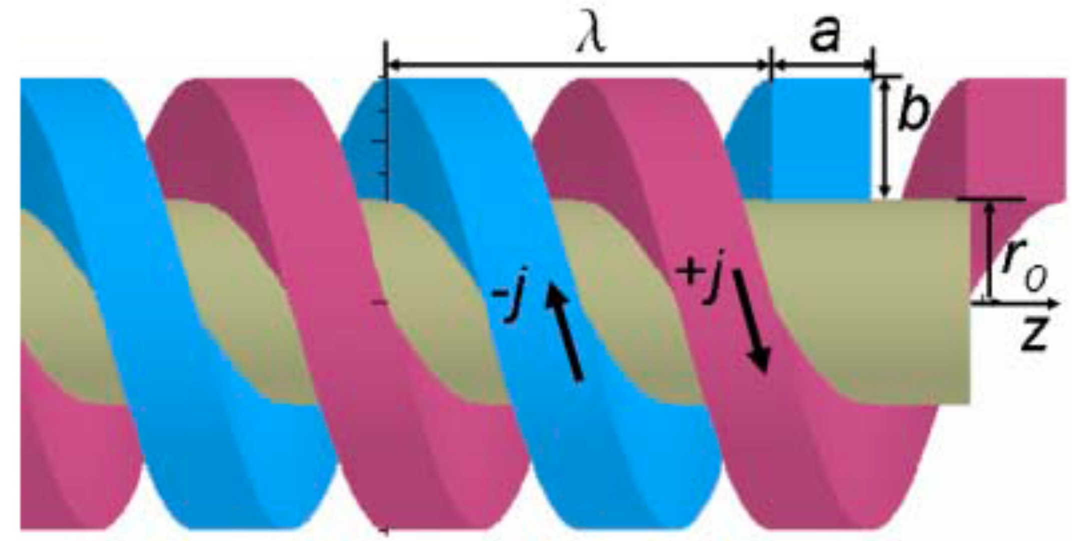
Undulator Based Polarized e+ Source

- Helical undulator: a pair of conductors which are wound in a form of double helix.

- e- traversing the undulator undergo helical oscillations (with the same period as the undulator) and emit photons.

- Key parameters: e- beam energy, magnetic field and undulator period.

- For fixed magnetic field and undulator period, the number of γ-rays generated ~ undulatory length.



$$K = 0.934 B_0[T]\lambda_u[cm]$$

$$E_{c1} = \frac{2\gamma^2 hc/\lambda_u}{1 + K^2 + 2\gamma\lambda_C/\lambda_u}$$

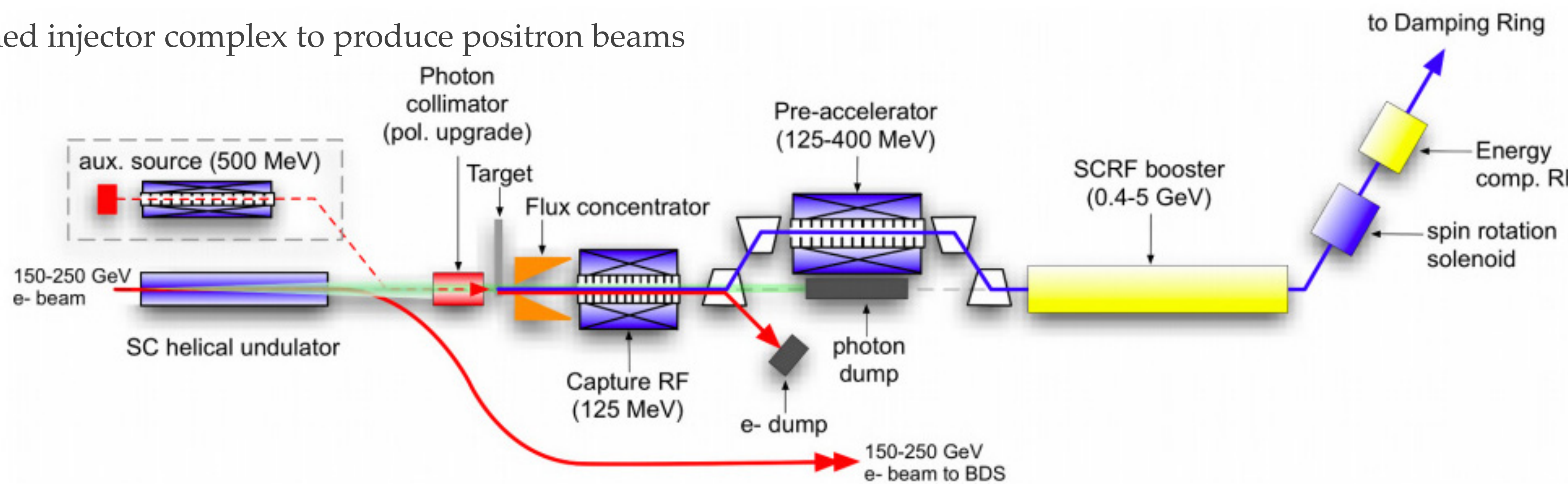
$$E_\gamma(n,\theta) = \frac{nE_{1c}}{1 + (\gamma\theta)^2/(1+K^2)}$$

- The circularly polarized photons are emitted in $1/\gamma$. Correlation between the photon energy-polarization-emission angle => enhancement of the polarization by photon beam collimation.

e+ Source: ILC Baseline

Efforts are shared between USA, UK, CERN, Germany and Japan. A proof-of-principle experiment E-166 in FFTB at SLAC.

Combined injector complex to produce positron beams



- **SC helical undulator:** 147m active length (max 231 m), 11.5 mm period, K ~0.92 (B ~0.86 T) with beam aperture 5.85 mm.
- **e+ target:** 400 m downstream the undulator, 0.4X0 (1.4 cm) thickness, Ti6Al4V rim rotated with 100 m/s tangential speed.
- **Flux concentrator:** 12 cm length, Bmax = 3-5 T, Bend = 0.5 T.
- **NC capture RF:** 1.3 GHz, ~10 m length up to 125 MeV.
- **e+ polarization:** default ~30%, polarization upgrade up to 60% with photon collimators.

ILC Baseline: Undulator

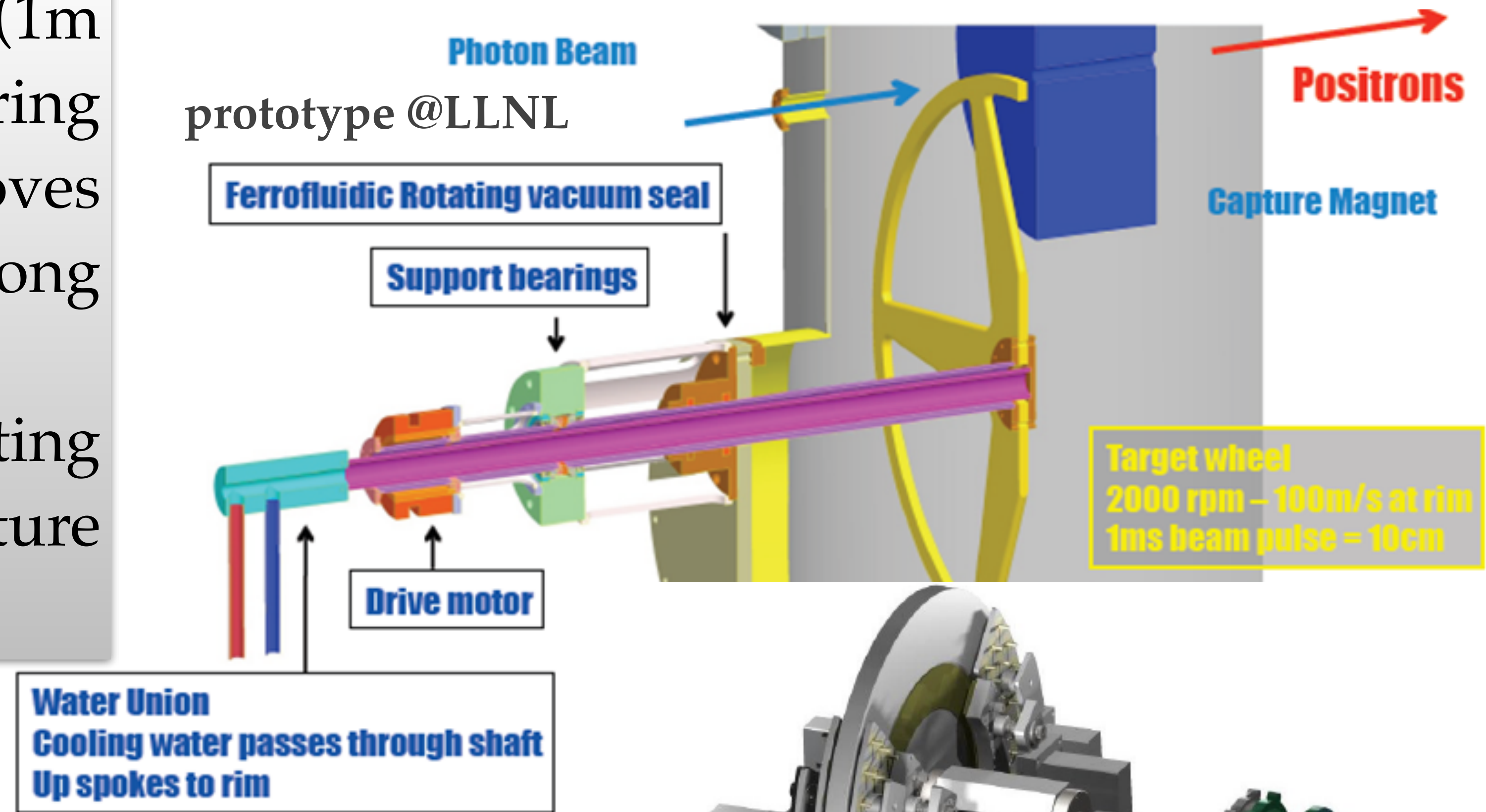
Undulator prototyping (STFC/RAL/Daresbury): two identical long undulators, 1.75 m each in length are successfully fabricated by RAL team. They have been magnetically tested and proven easily to achieve the field strength required.

The RAL team has since incorporated both of these undulators into a single 4 m-long cryogenic module (which operates at -269 C) of the design required by ILC.

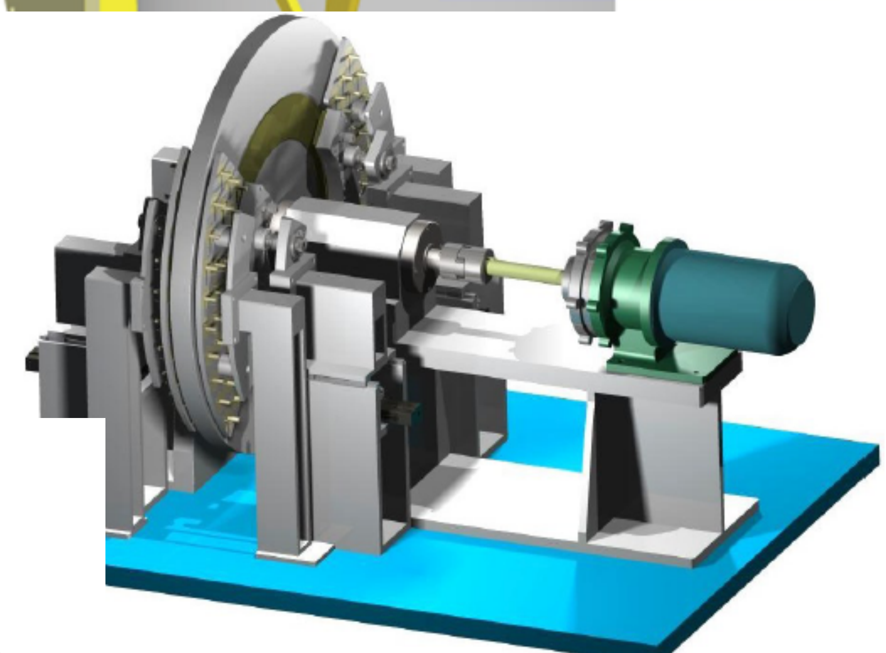
ILC baseline: e+ target issues

e+ target: wheel made of Ti6Al4V (1m diameter and 0.4X0 (1.4 cm) thick. During operation the outer edge of the rim moves at 100 m/s (2000 rpm) to smear out long ms pulses.
Design and prototyping of the Rotating Target FerroFluidic Seal and the capture magnet are ongoing.

prototype @LLNL

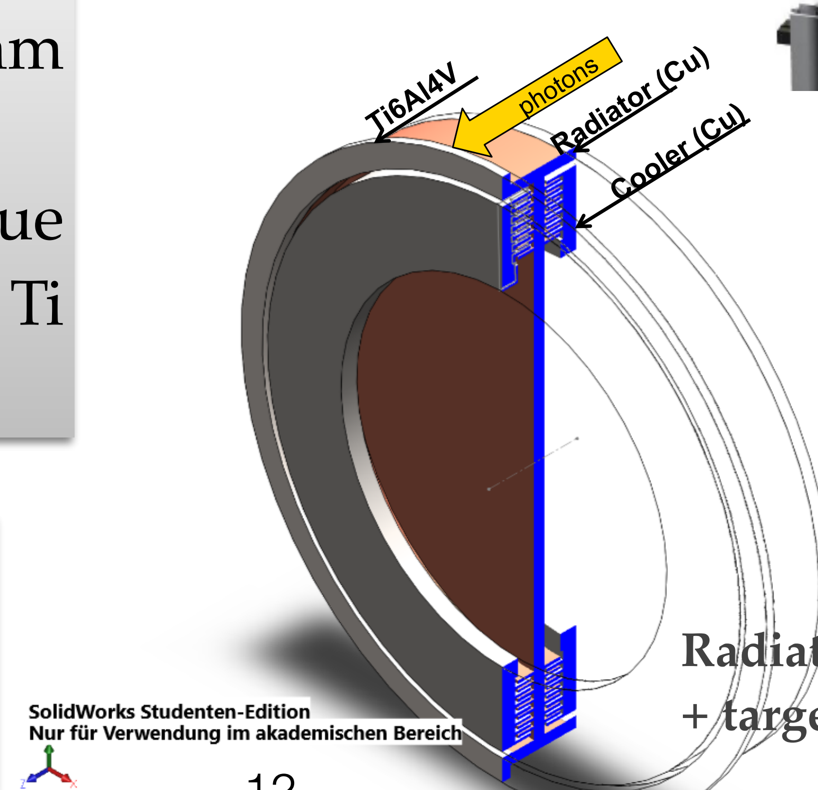


Energy deposition @ 500 GeV (nom. lumi): 2 kW <=> ΔT_{max}/pulse~130 K, photon beam spot size on target ~1mm => PEDD 67.5 J/g.
Max. thermal stress in target => fatigue limit and ultimate tensile strength in Ti material.



Active Sliding Contact Cooling of e+ target (IHEP/ANL)

Polarization upgrade to 50-60% => increase in energy deposition and PEDD due to beam collimation.



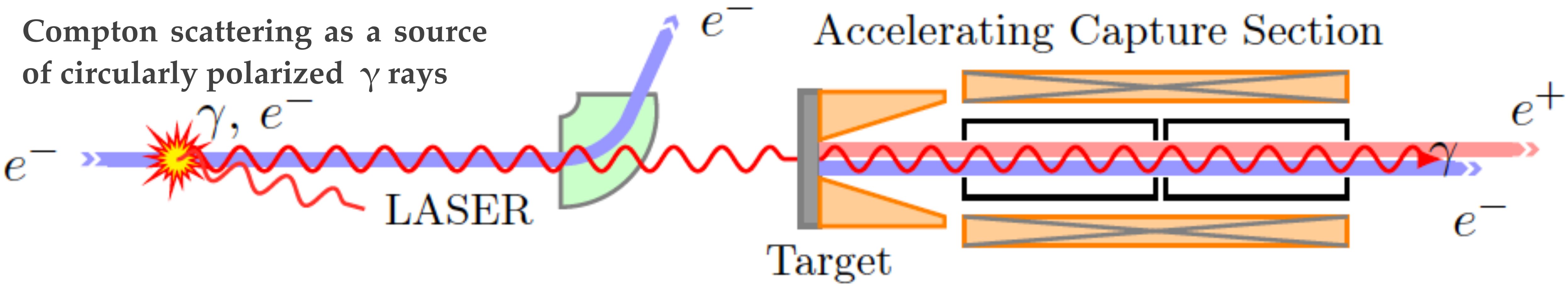
Radiative thermal cooling of e + target (DESY/CERN)

ILC baseline: critical points

- **Undulator:** 150 m long SC helical undulator with a ~6 mm inner diameter vacuum chamber (prototyping STFC/RAL/Daresbury).
- **Photon collimator:** absorbs ~ 50% of photon beam power (DESY).
- **Target-converter:** target wheel (Lancaster/Cockcroft/STFC/LLNL), rotating vacuum seal (LLNL), target cooling system (radiative thermal cooling DESY/CERN and active sliding contact cooling IHEP/ANL), remote handling/target removal engineering design (IHEP).
- **Thermal shock problem:** energy deposition causes shockwaves in the material => target can be broken if induced thermal stress exceeds the ultimate tensile strength of the target material (SLC e+ target failure).
- **e+ capture system:** flux concentrator (LLNL).

Polarized e+ source: Compton scheme

Alternative solution. Efforts are shared between USA, France and Japan. A proof-of-principle experiment at KEK by T. Omori et al. demonstrated production of 2e4 e+ per bunch with the polarization of ~ 73%.

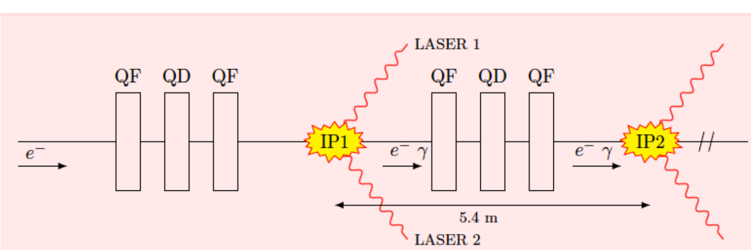


- **Compton scattering** is used to **boost low energy** laser photons to high energy by colliding them with high energy electrons.
- $E_{\gamma max}$~$4\gamma^2 E_L$, scattered gamma ray flux is emitted in 1/γ, polarization by photon beam collimation (e. g. with E ~ 2 GeV and E_L ~ 1 eV => $E_{\gamma max}$ ~ 60 MeV).
- **The Compton cross section** is relatively **low** => **low number of e+** per bunch crossing.
- To improve the efficiency => high gain optical cavities (Fabry-Perot) coupled to high average power laser amplifiers to increase laser power available at the IP.

Compton scheme: proposals

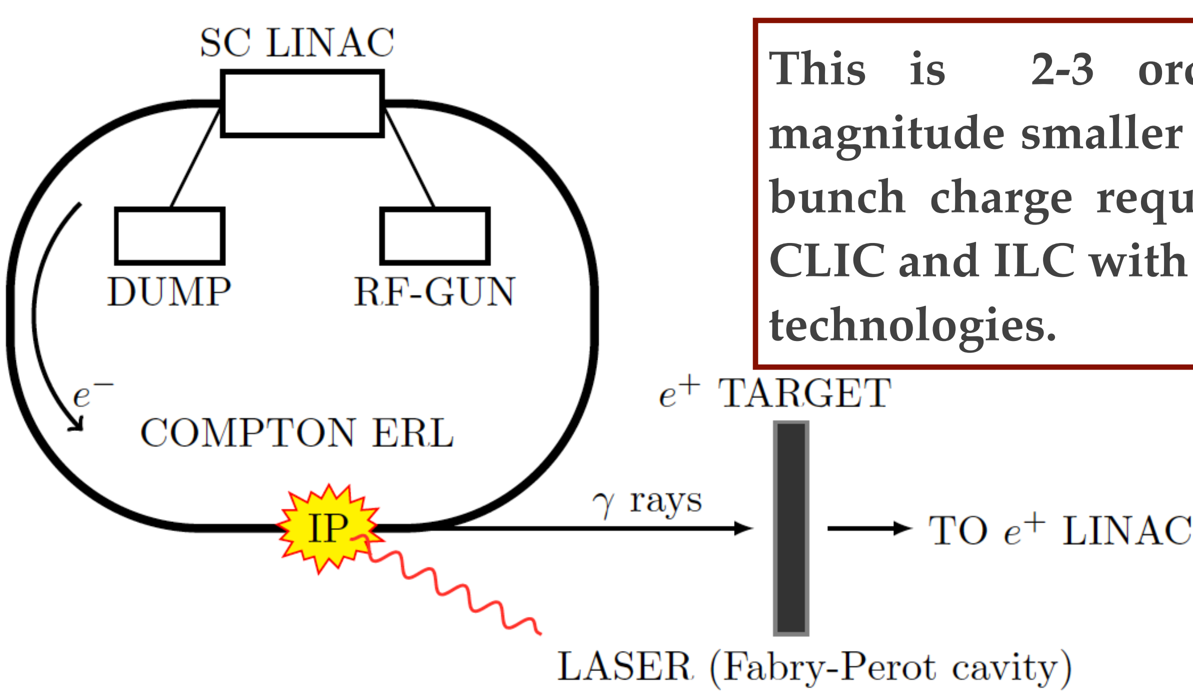
According to the e- drive beam generation scheme used for Compton scattering there are three different options:

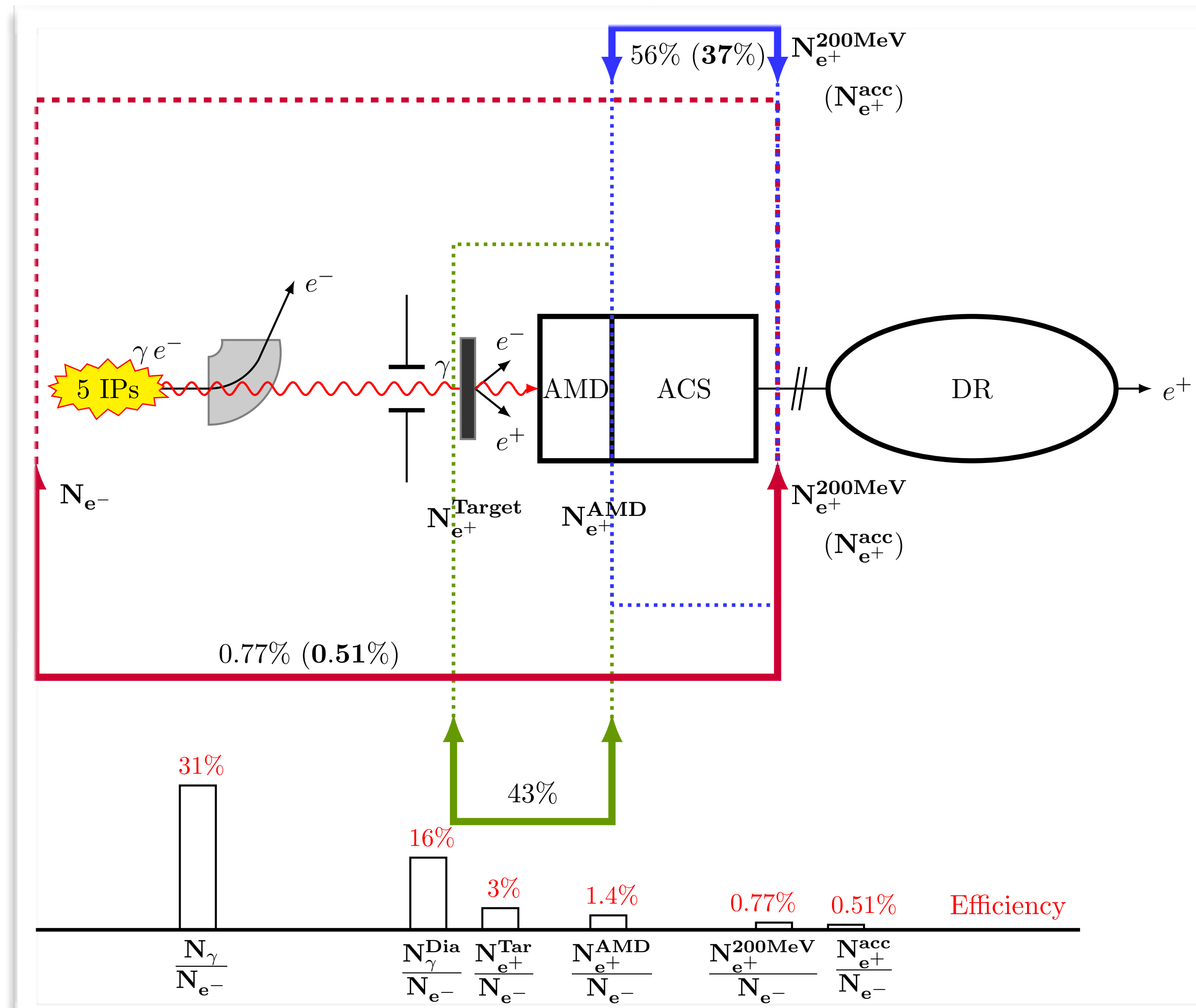
- **The linac** production scheme (low Frep, high charge, high power laser).
- **The storage ring** production scheme/Compton Ring (high Frep, high charge but long bunches).
- **The Energy Recovery Linac** (ERL) production scheme (high Frep, lower charge but shorter bunches).



According to simulations the scheme with 5 IPs and two crossing lasers per IP provide ~5e7 e+/nC J

This is 2-3 orders of magnitude smaller than e+ bunch charge required by CLIC and ILC with present technologies.





Compton scheme: present issues

In order to reach the performance needed:

1. R&D on high power laser systems and the optical cavities (targeting 1J/pulse of stored laser power).
2. e- beam stability in the Compton Rings and technological R&D to design an extremely challenging ERL accelerators with a current in Amperes domain (low Frep of a few tens of MHz with high charge per bunch).
3. Possibility of the continuous stacking to increase the charge per bunch in the DR.

History of the Compton source R&D at ATF-KEK

- 2007: 2 mirror optical cavity (~2.5 kW)
- 2010: LAL 4 mirror cavity (up to 50 kW)
- 2011: KEK-Hiroshima cavity (2.6 kW)

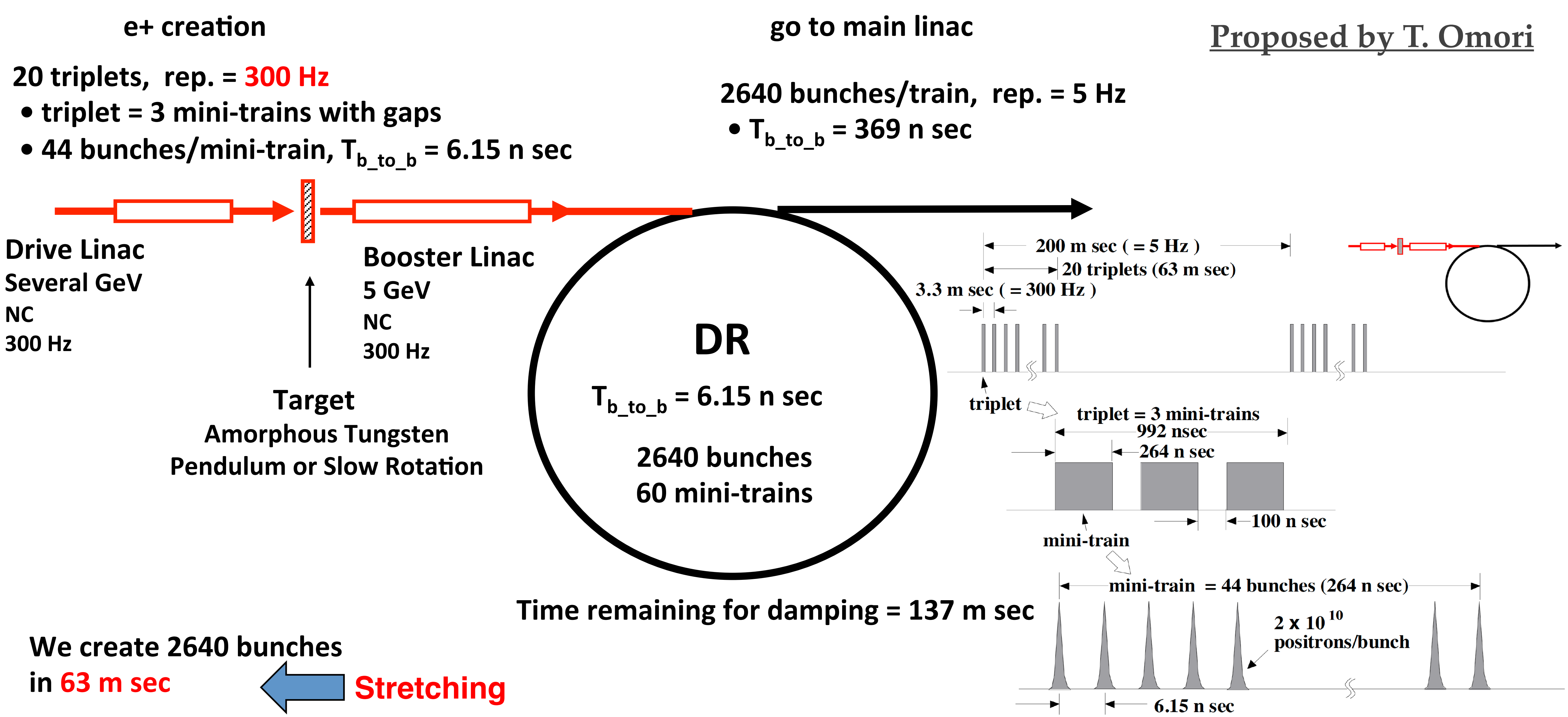
Unpolarized e+ sources

Unpolarized e+ Source: Conventional Scheme

Efforts are shared between ANL, IHEP, Hiroshima U, U of Tokyo, KEK, DESY, U of Hamburg, CERN. **Following design is the backup for proposed ILC e+ source.**

- The proposed ILC e+ source contains risks => backup solution.
- So-called 300 Hz conventional source: e+ generation in 63 ms (cf. undulator : in 1 ms)

Proposed by T. Omori



Unpolarized e+ Source: Conventional Scheme

<u>Conventional e+ source but still needs some more R&D.</u>

High current, high rep rate drive linac ~6 GeV and booster linac ~5 GeV.

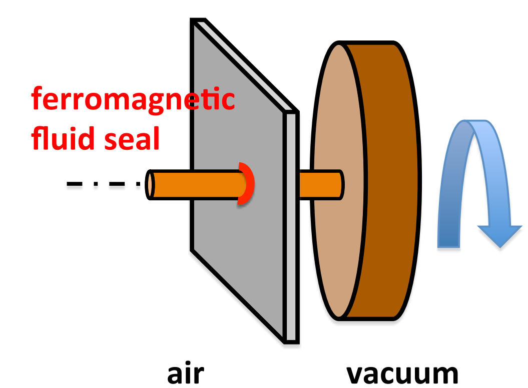
Moving target (slow rotation ~5 m/s required vs. 1/20 of undulator scheme)

Flux concentrator (pulse length ~1 µs (cf. ~1 ms in undulator scheme) => almost existing FC technology.

Shock waves and thermal dynamics: in principle OK because triplet to triplet separation 3.3 ms in time but studies are ongoing.

Parameters for target and captures		Parameters for the 300 Hz scheme	
Drive beam energy	6 GeV	#Drive e-/bunch	2×10^{10}
Beam size	4.0 mm (rms)	#Bunches/triplet	132 (in 996 ns)
Target material	Tungsten	#Bunches/train	2640 (in 63 ms)
Target thickness	14 mm	Repetition of the trains	5 Hz
Max. AMD field	7 T	Results numbers in () are for the 300 Hz scheme	
Taper parameter	60.1/mm	$e+$yield	$1.6/e^-$
AMD length	214 mm	PEDD in the target	$1.04\ \mathrm{GeV/cm^3}/e^-$ (22.7 J/g)
Const. field	0.5 T	Energy deposit in the target	823 MeV/e^- (35 kW)
Max. RF field	25 MV/m	Energy deposit in the AMD	780 MeV/e^- (33 kW)
RF frequency	1.3 GHz	Energy deposit in the RF section	470 MeV/e^- (20 kW)

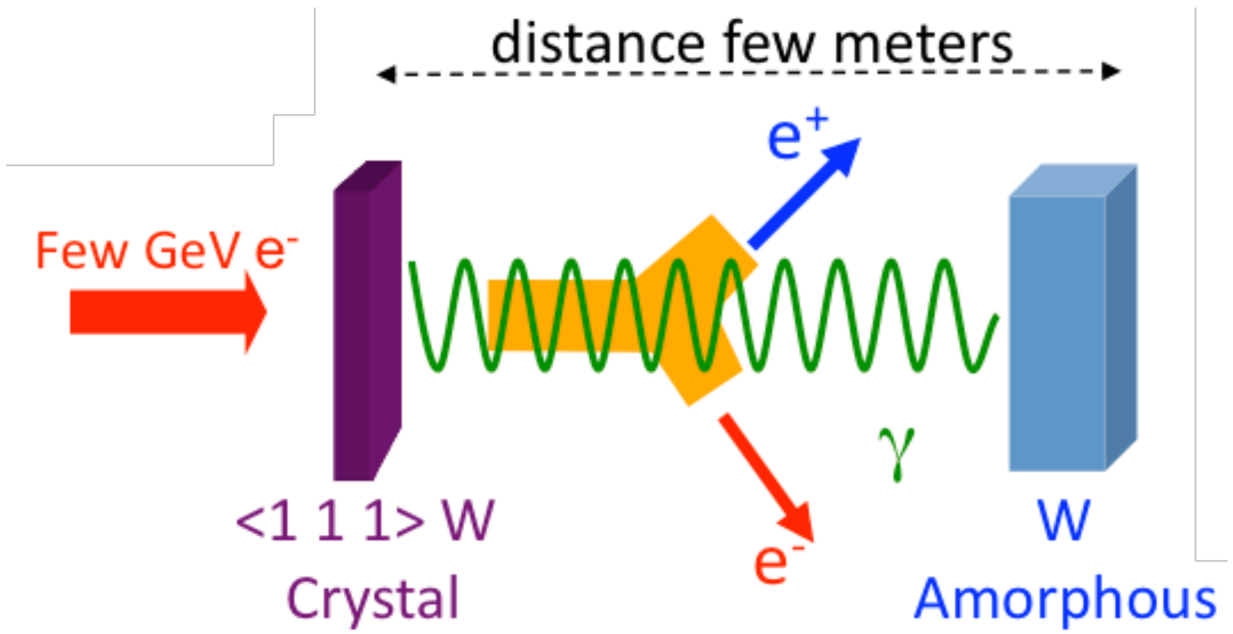
A full target prototype d = 500 mm (no water channels and not W material) in two years for continuous running test.



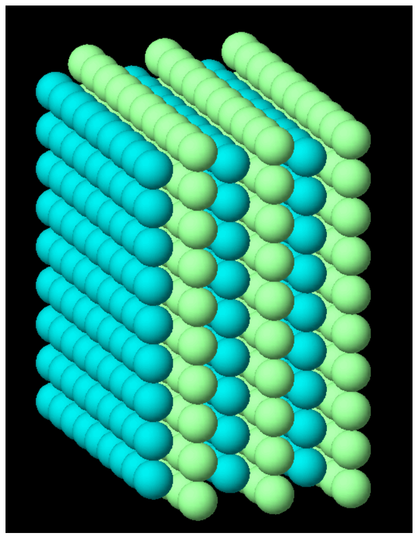
Unpolarized e+ Source: Hybrid Scheme

Efforts are shared between LAL, IPNL, CERN, IHEP and KEK. Originally proposed by R. Chehab V. Strakhovenko and A. Variola. **A baseline design for the CLIC positron source.**

- 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**.
- Channeling radiation in axially oriented crystals is a powerful source of photons => useful to produce the high intensity e+ beams.
- There were several experiments to study the hybrid e+ source (proof-of-principle experiment in Orsay, experiment WA 103 @ CERN and experiment @ KEK).



Recent idea: to replace the compact target-converter by a **granular** one made of **small spheres**.



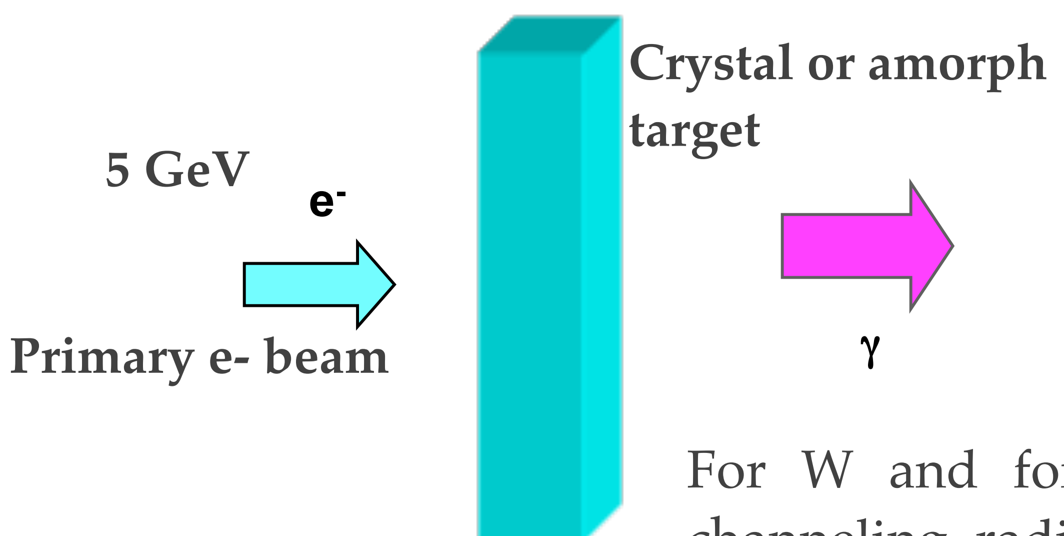
Granular target-converter

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).

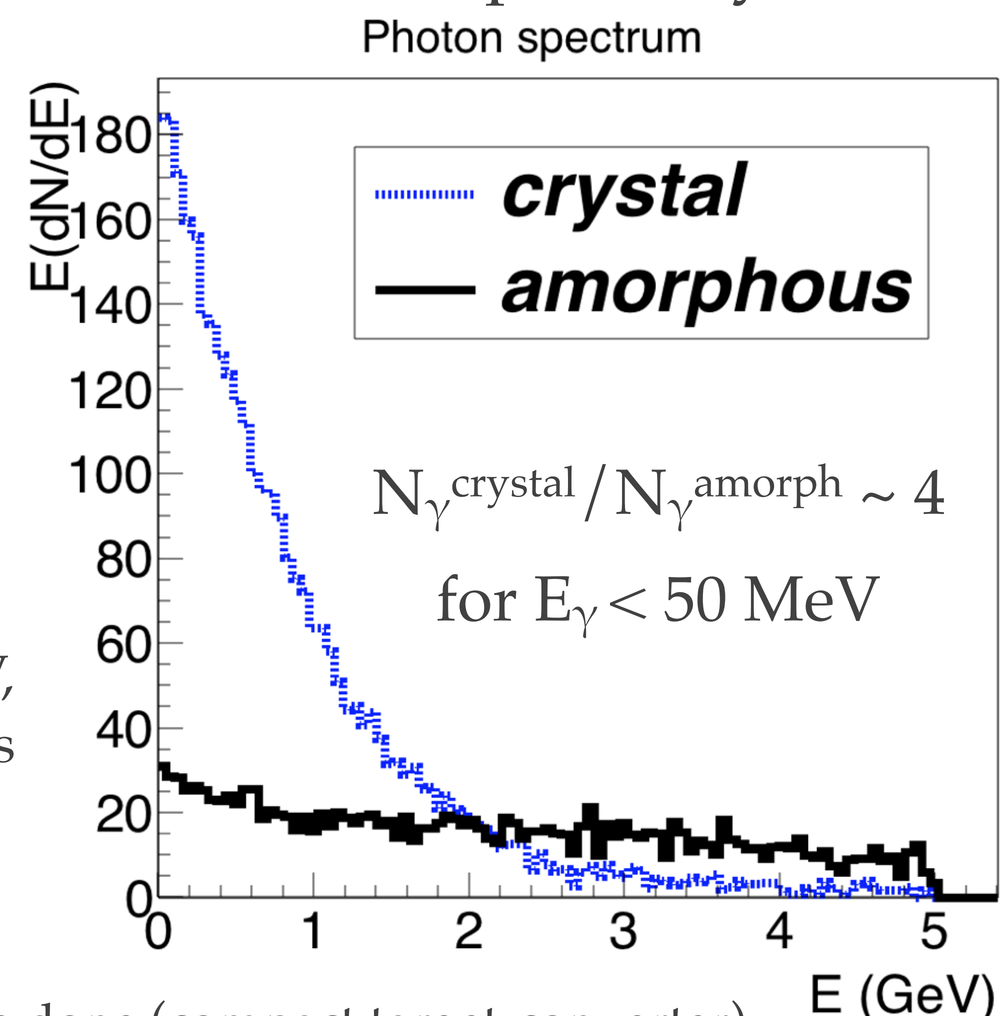
e+ Source Using Channeling

- For targets of the same thickness (1.4 mm) there is an enhancement of the soft photons production in the crystal compared to the amorphous => mainly due to channeling.

- The soft photons create the soft positrons => easier capture by matching devices.



For W and for E > 1 GeV, channeling radiation becomes larger than bremsstrahlung.



☞ A design and optimization of the CLIC e+ source parameters are done (compact target-converter).

☞ An alternative solution based on the hybrid scheme is proposed for the unpolarised e+ source of the ILC (modifying the beam time structure following T. Omori suggestions, 300 Hz solution).

e+ Source: CLIC Baseline

Target Parameters Crystal		
Material	**Tungsten**	**W**
Thickness (radiation length)	**0.4**	**χ_0**
Thickness (length)	**1.40**	**mm**
Energy deposited	**~1**	**kW**

Target Parameters Amorphous		
Material	**Tungsten**	**W**
Thickness (Radiation length)	**3**	**χ_0**
Thickness (length)	**10**	**mm**
PEDD	**30**	**J/g**
Distance to the crystal	**2**	**m**

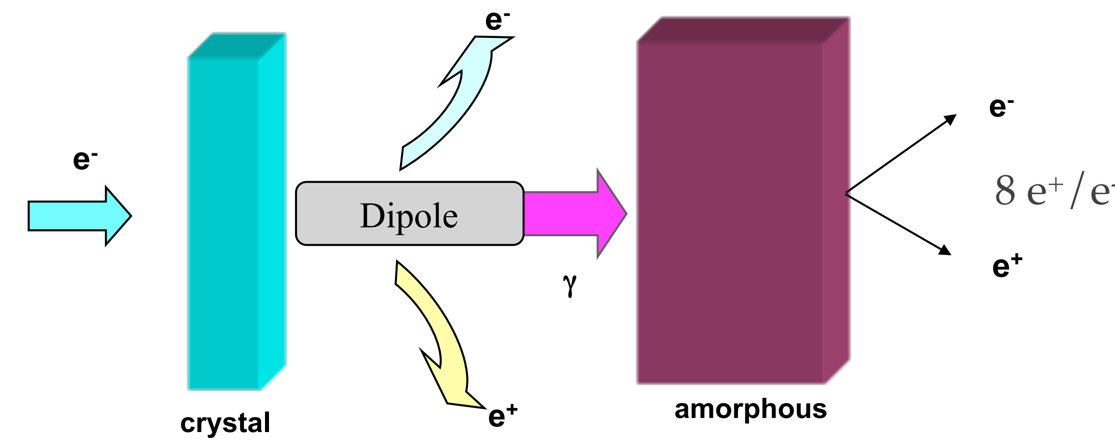
< 35 J/g

Distance (crystal-amorphous) d = 2 m

Primary e- beam

5 GeV

1.1×10^{10} e-/bunch



Crystal thickness: 1.4 mm

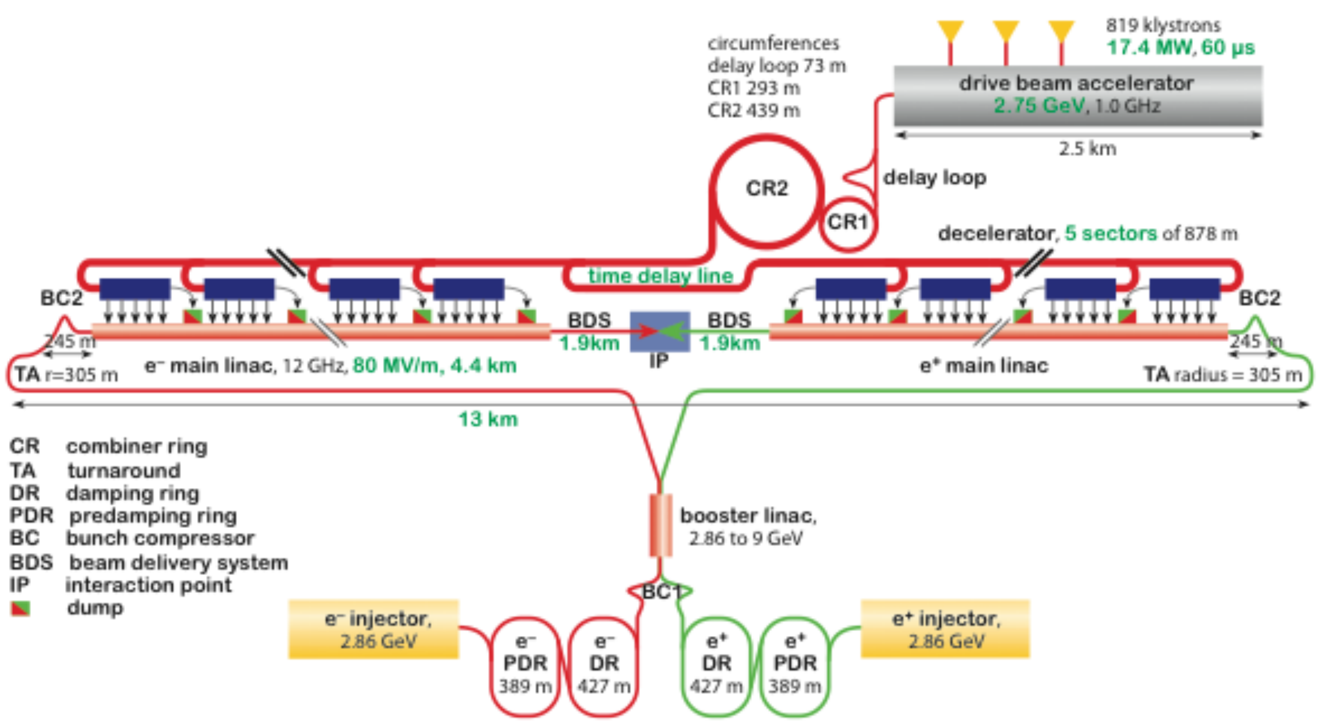
Oriented along the <111> axis

Amorphous thickness: 10 mm

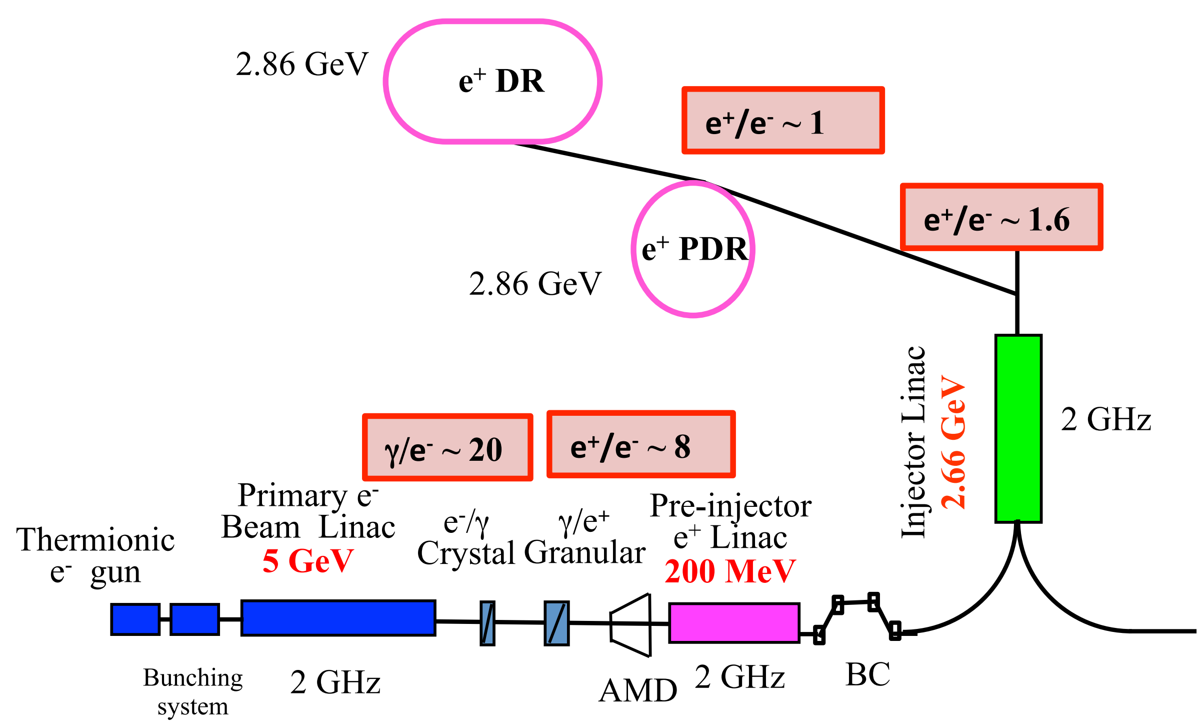
__Target-converter:__ easier to cool (under study at CERN), PEDD is well below the critical limit imposed by SLC target.

__Yield:__ 8 e+/e- (total) => ~ 1 e+/e- @ 200 MeV => CLIC requirements are fulfilled!!!

Separate injector complexes to produce electron and positron beams

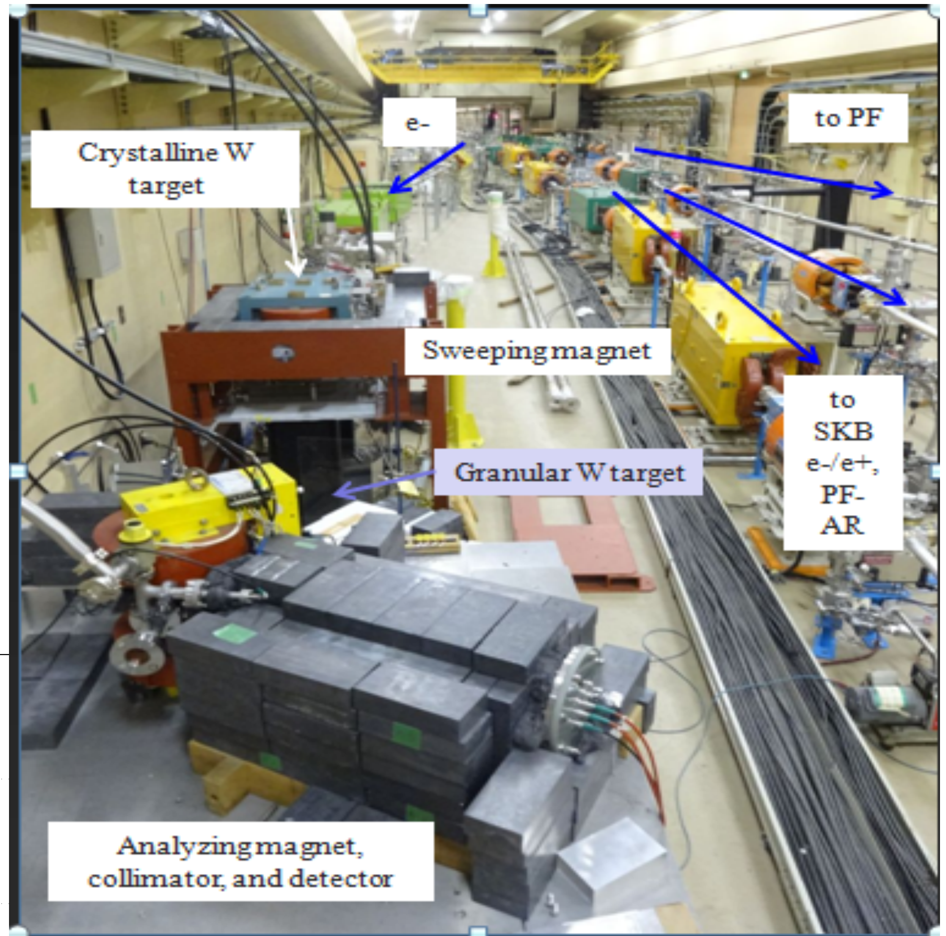


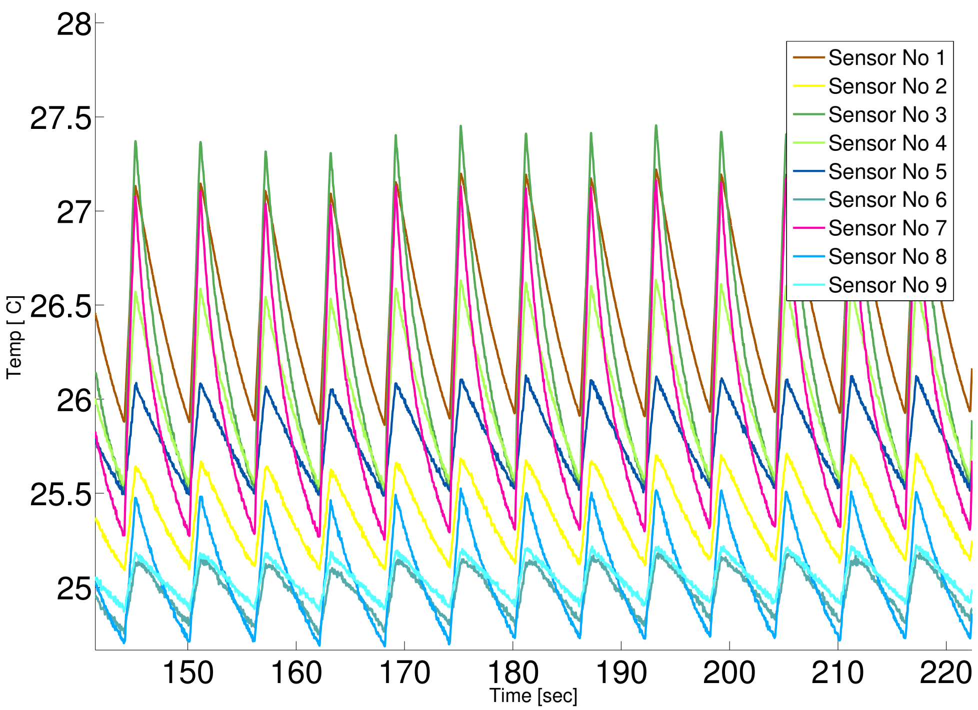
__unpolarized__ e+

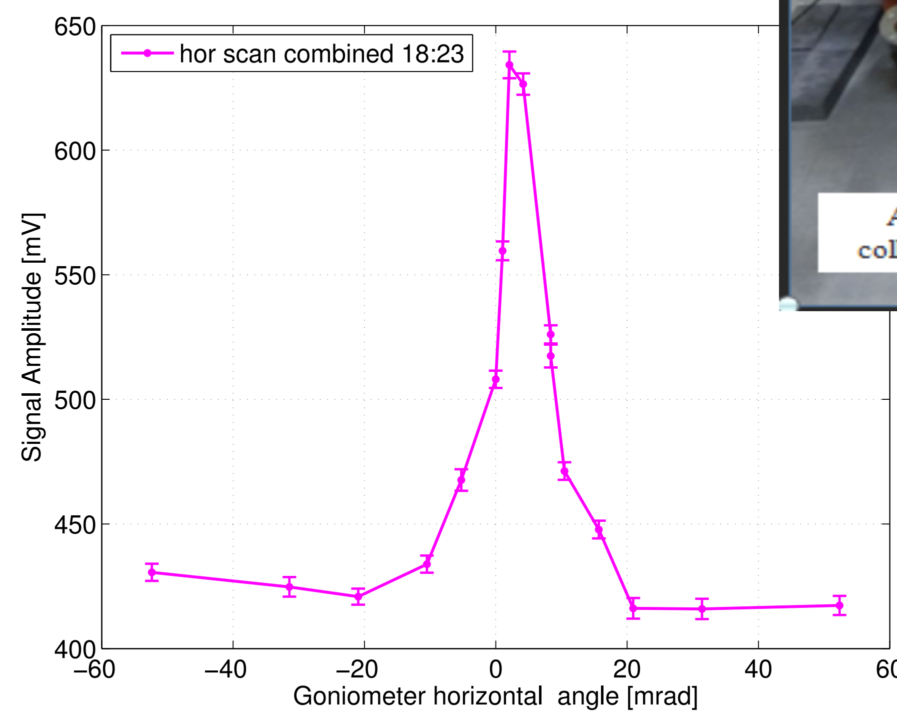


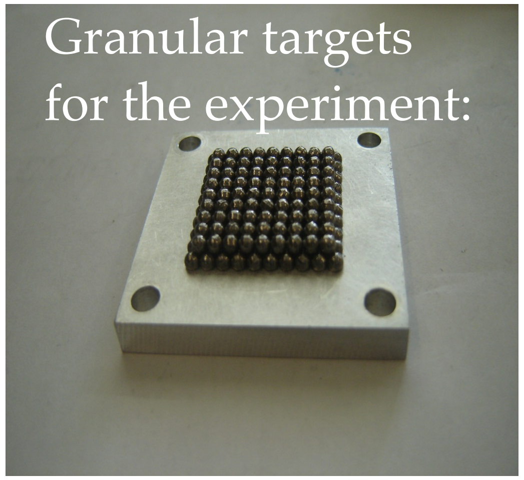
Hybrid Scheme: Recent Investigations

- Beam test took place last autumn at the KEKB injector linac to study the granular converter. Next one => this autumn (LAL and KEK).
- KEKB beam for the test: E = 8 GeV, 1 mm rms, 1nC, 50 Hz.
- **Goals: e+ yield and temperature measurements to compare different target-converters => e+ source performances.**









Simulations of the temperature distribution of the granular converter and thermal shocks are ongoing (LAL/IHEP/CERN).

Data taken should improve our understanding on thermal load and heat dissipation in the target.

Summary and Perspectives

- The main concern for e+ source is not only the e+ yield but also the high amount of deposited energy in the target due to the high intensities required by the LC.
- Extensive R&D, studies and tests are ongoing => extended collaborations between many laboratories all around the worlds.
- **ILC baseline is the undulator based e+ source:** heat load is a serious problem => it requires a challenging rotation target (100 m/s).
- **ILC backup solution:** 300 Hz truly conventional e+ source => due to stretching less problems with heat load. However, the shock waves can be an issue.
- **CLIC baseline is a hybrid e+ source.** New design with a granular converter. Experimental tests are mandatory. The KEKB results are a major step towards understanding of the thermal load in the targets.
- **Today, all studies are mainly focused on engineering design, manufacture and testing of the prototypes for the high intensity e+ sources.**

The 11th International workshop **POSIPOL** will be held in **Orsay** and hosted by **LAL**.

This workshop is mainly focused on the e+ sources and is addressed to the community working on the e+e- collider projects and on development of sources for industrial and medical applications.

Backup

Nominal parameters of ILC e+ source

Parameter	Symbol	Value	Units
Positrons per bunch at IP	n_b	2×10^{10}	number
Bunches per pulse	N_b	1312	number
Pulse Repetition Rate	f_{rep}	5	Hz
Positron Energy (DR injection)	E_0	5	GeV
DR Dynamic Aperture	$\gamma(A_x + A_y)$	<0.07	m rad
DR Energy Acceptance	Δ	0.75	%
DR Longitudinal Acceptance	A_l	3.4 x 37.5	cm-MeV
Electron Drive Beam Energy[a]	E_e	150/175/250	GeV
Undulator Period	λ	1.15	cm
Undulator Strength[b]	K	0.92/0.75/0.45	-
Undulator Type	-	Helical	-
Undulator Length	L_u	147	m
Photon Energy (1^{st} harm cutoff)	E_{c10}	10.1/16.2/42.8	MeV
Photon Beam Power	P_γ	63.1/54.7/41.7	kW
Target Material	-	Ti-6%Al-4%V	-
Target Thickness	L_t	0.4 / 1.4	r.l. / cm
Target Absorption	-	7	%
Incident Spot Size on Target	σ_i	1.4/1.2/0.8	mm, rms
Positron Polarisation	P	31/30/29	%

[a]For centre-of-mass energy below 300 GeV, the machine operates in 10 Hz mode where a 5 Hz 150 GeV beam with parameters as shown in the table is a dedicated drive beam positron source.

[b]K is lowered for beam energies above 150 GeV to bring the polarisation back to 30 % without adding a photon collimator before the target.

Nominal parameters of ILC e- source

Parameter	Symbol	Value	Units
Electrons per bunch (at gun exit)	N	$3x10^{10}$	Number
Electrons per bunch (at DR injection)	N	$2x10^{10}$	Number
Number of bunches	n_b	1312	Number
Bunch repetition rate	f_b	1.8	MHz
Bunch train repetition rate	f_{rep}	5	Hz
FW Bunch length at source	Δt	1	ns
Peak current in bunch at source	I_{avg}	3.2	A
Energy stability	σ_E/E	<5	% rms
Polarization	P_e	80 (min)	%
Photocathode Quantum Efficiency	QE	0.5	%
Drive laser wavelength	λ	790±20 (tunable)	nm
Single bunch laser energy	u_b	5	μJ

Energy deposition/accumulation on Target

Parameter			Centre-of-mass energy E_{cm} (GeV)				
			200	230	250	350	500
Positron pulse production rate		**Hz**	**5**	**5**	**5**	**5**	**5**
Electron beam energy (e+ prod.)		**GeV**	**150**	**150**	**150**	**178**	**252**
Number of electron bunches	n_b		**1312**	**1312**	**1312**	**1312**	**1312**
Electron bunch population	N_+	$\times 10^{10}$	**2**	**2**	**2**	**2**	**2**
Required undulator field	B	**T**	**0.86**	**0.86**	**0.86**	**0.698**	**0.42**
undulator period length	λu	**cm**	**1.15**	**1.15**	**1.15**	**1.15**	**1.15**
undulator *K*	K		**0.92**	**0.92**	**0.92**	**0.75**	**0.45**
Average photon power on target		**kW**	**91**	**100**	**107**	**55**	**42**
Incident photon energy per bunch		**J**	**9.6**	**9.6**	**9.6**	**8.1**	**6.0**
Energy deposition per bunch (e+ prod.)		**J**	**0.72**	**0.72**	**0.72**	**0.59**	**0.31**
Relative energy deposition		**%**	**7%**	**7%**	**7%**	**7.20%**	**5%**
Photon rms spot size on target		**mm**	**1.4**	**1.4**	**1.4**	**1.2**	**0.8**
Peak energy density in target		J/cm^3	**232.5**	**232.5**	**232.5**	**295.3**	**304.3**
		J/g	**51.7**	**51.7**	**51.7**	**65.6**	**67.5**

CLIC injector beam parameters

Parameter	Unit	CLIC polarized electrons	CLIC positrons	CLIC booster
E	GeV	2.86	2.86	9
N	10^9	4.3/7.8	4.3/7.8	3.75/6.8
n_b	-	312/354	312/354	312/354
Δt_b	ns	1	1	0.5
t_{pulse}	ns	312/354	312/354	156/354
$\varepsilon_{x,y}$	μm	< 100	7071, 7577	$600,10 \cdot 10^{-3}$
σ_z	mm	< 4	3.3	$44 \cdot 10^{-3}$
σ_E	%	< 1	1.63	1.7
Charge stability shot-to-shot	%	0.1	0.1	0.1
Charge stability flatness on flat top	%	0.1	0.1	0.1
f_{rep}	Hz	50	50	50
P	kW	29	29	85

500 GeV

CLIC main parameters

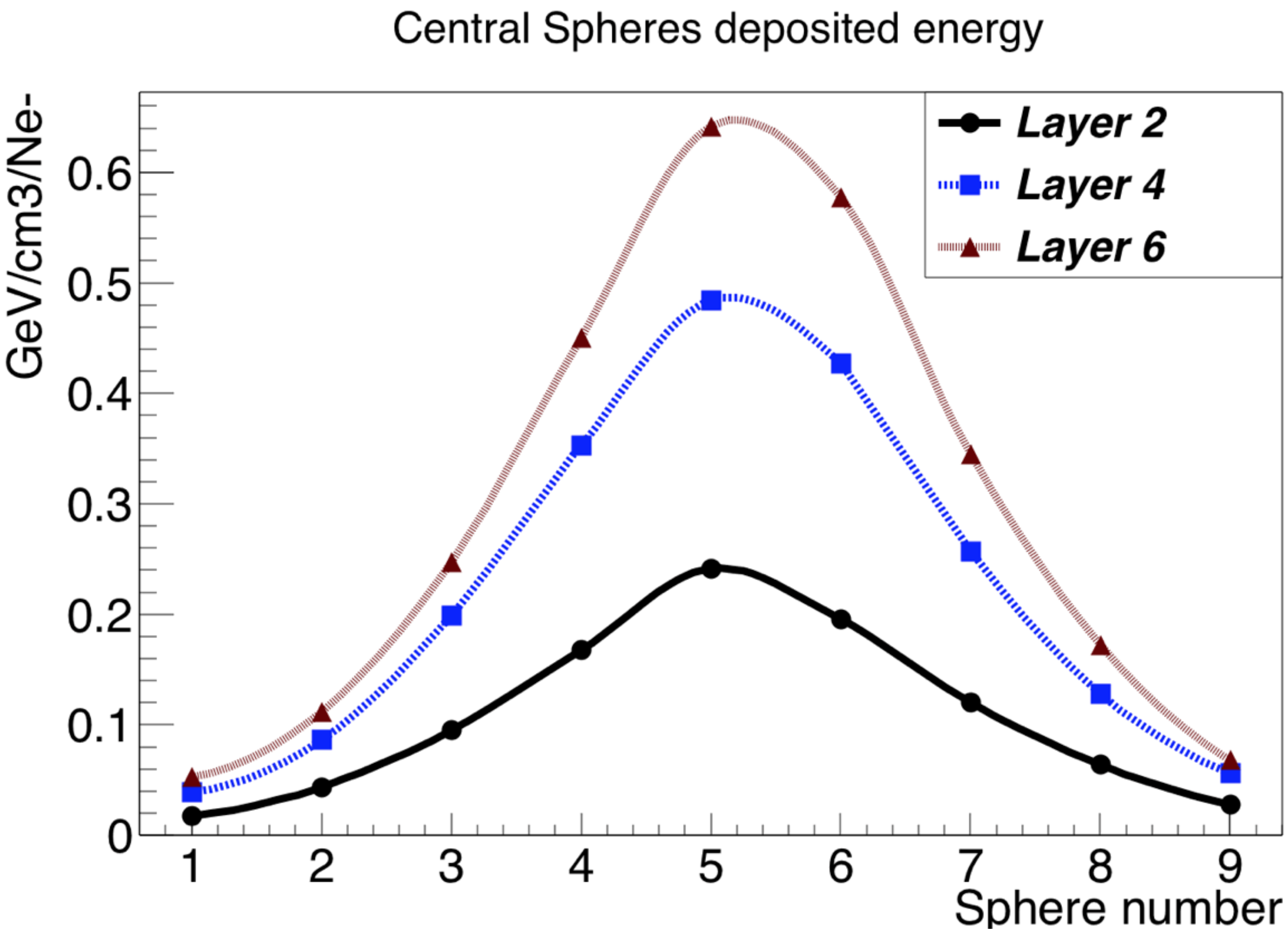
parameter	symbol		
centre of mass energy	E_{cm} [GeV]	500	3000
luminosity	$\mathcal{L}$ [10^{34} cm^{-2}s^{-1}]	2.3	5.9
luminosity in peak	$\mathcal{L}_{0.01}$ [10^{34} cm^{-2}s^{-1}]	1.4	2
gradient	G [MV/m]	80	100
site length	[km]	13	48.3
charge per bunch	N [10^9]	6.8	3.72
bunch length	σ_z [μm]	72	44
IP beam size	σ_x/σ_y [nm]	200/2.26	40/1
norm. emittance	ϵ_x/ϵ_y [nm]	2400/25	660/20
bunches per pulse	n_b	354	312
distance between bunches	Δ_b [ns]	0.5	0.5
repetition rate	f_r [Hz]	50	50
est. power cons.	P_{wall} [MW]	271	582

e+ source using channeling

<u>There were several experiments to study the hybrid e+ source.</u>

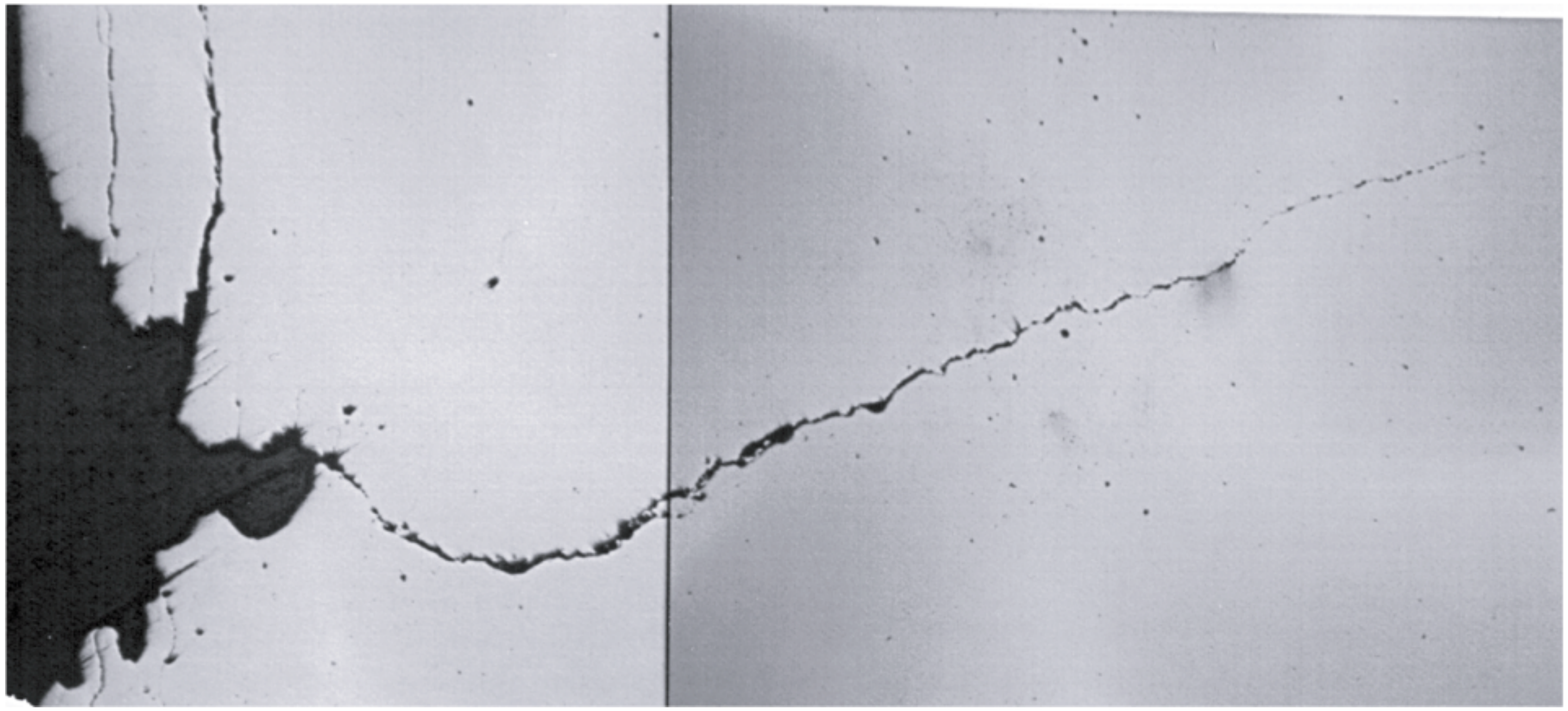
- Proof-of-principle experiment in Orsay (observing radiation enhancement in a tungsten crystal oriented along the ⟨111⟩ axis submitted to a 2 GeV electron beam). X. Artru et al., *NIM Section B*, 119.1 (1996): 246-252.
- Experiment at CERN (4 mm and 8 mm thick tungsten crystals and a compound target made of a 4 mm crystal followed by a 4 mm amorphous disk were used. The gain was about 3 for the 4 mm target and about 2 for the 8 mm and the compound targets.). X. Artru et al., NIM Section B, 201.1 (2003): 243-252.
- Experiment at KEK (tungsten crystal target has been successfully employed at the e+ source of the KEKB injector linac. The crystal thickness was 10.5 mm, primary e- beam 4 GeV. 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). T. Suwada et al., *Physical Review Special Topics-Accelerators and Beams* 10.7 (2007): 073501.

Test at the KEKB linac



- The lateral density distribution along a central axis has been calculated.
- The deposited energy density is calculated on adjacent spheres at the exit of the converter (maximum deposited energy density).

SLC e+ target



- The heating of the material results in thermal stresses that may be large enough to cause material failure.
- Failure of the target occurred after three years of operation with an elevated power deposition toward the end of the three years.
- If shock exceeds strain limit of material chunks can spall from the face=> the SLC target showed spall damage after radiation damage had weakened the target material.

ILC baseline design