# POSITRON SOURCES FOR e+e- COLLIDERS: APPLICATION TO ILC AND CLIC

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# POSITRON SOURCES FOR e-e+ COLLIDERS: APPLICATION TO ILC AND CLIC

- **INTRODUCTION**
- **The requirements for intense positron beams with low emittance dedicated to e+e- colliders put stringent conditions on the production and transport of the positrons. The positron beam qualities are related to the methods of production and to the capture and transport systems. Moreover, the necessity to damp the positron beam in appropriated damping rings induces limitations on the 6-D emittance, prior to injection in the rings.**
- **A presentation of the physical processes associated with positron production will be followed by a description of the main capture and transport systems and by the emittance preservation methods. As high intensity positron sources working on long term experiments are necessary, their reliability will be discussed. Important informations have been provided with dedicated positron experiments: some of them will be described. The positron sources of the two linear colliders under study, ILC and CLIC will be presented with some R&D activities. Last but not least, some recommendations in the choice of the solutions will be given in the summary & discussions.**

# POSITRON SOURCES FOR e-e+ COLIDERS: APPLICATION TO ILC AND CLIC

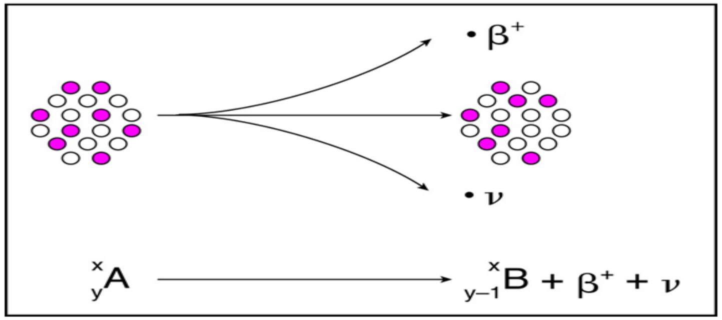
- **PLAN**
- **1-Physical processes associated with positron production**
- *** Nuclear $\beta^+$ decay**
- *** Electromagnetic showers**
- **2-Capture and acceleration of the positrons**
- *** The matching systems**
- *** The acceleration**
- *** Beam phase space optimization**
- *** Polarization selection**
- **3-Reliability**
- **4- Some dedicated experiments**
- **5- Application to ILC and CLIC**
- **6- Summary and discussion**

# POSITRON SOURCES FOR e+e- COLLIDERS: APPLICATION TO ILC AND CLIC

- **FIRST PART: THE PHYSICAL PROCESSES**

# POSITRON SOURCES FOR e-e+ COLLIDERS: APPLICATION TO ILC AND CLIC

- **THE PHYSICAL PROCESSES**
- **1- NUCLEAR β+ DECAY**
- **The $\beta^+$ radioactivity concerns atoms with an excess of protons. The transformation is represented hereafter:**
- $${}_{y}^{x}A \Rightarrow {}_{y-1}^{x}B + \beta^+ + \nu$$
- **Where a proton is exchanged with a neutron giving a positron and a neutrino. The new atom has a higher ratio[Number n/Number p]**
- **For instance:** ${}_{11}^{22}Na \Rightarrow {}_{10}^{22}Ne + \beta^+ + \gamma + \nu$



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- **POSITRONS WITH $\beta^+$ DECAY**
- **The positrons produced by radioisotope decay are polarized but being emitted isotropically and with a broad energy distribution.**
- **Electron-positron accelerators are requiring high intensities of positrons; for instance about $10^{12}$ $e^+$/s and even more and in a small solid angle. The intensity provided by radioactive sources may be 4 to 5 orders of magnitude lower. If we mention the BNL reactor using**
- **$^{64}$Cu, it exhibited in a total solid angle of 4π sterad , about $10^{12}$e+/s and with an energy spread of 200 keV. So, we have much less in a solid angle corresponding to a cone of 10 degrees, what it is currently accepted in positron machines.**
- **On next slide we present a table with some isotopes.**

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- **RADIOACTIVE β⁺ DECAY: tables**

**Advanced Accelerator Concepts, Madison, 1986**

**Table 1**
Suitable positron-emitting isotopes (from E. Ottewitte, Ref. [10])

| Isotope | τ | β+/dis | β+ | Production Reaction |
|---|---|---|---|---|
| $Na^{22}$ | 2.6y | 0.89 | 0.54 | $Mg^{24}$ (d, α) |
| $Al^{26}$ | $7.4x10^5$y | 0.85 | 1.17 | $Mg^{24}$ (d, γ) |
| $Co^{55}$ | 18.2h | 0.60 | 1.50,1.03,0.53,0.26 | $Fe^{12}$(p,2n) |
| $V^{48}$ | 16.2d | 0.56 | 0.69 | $Ti^{48}$(p,n) |
| $Ni^{57}$ | 36h | 0.50 | 0.85,0.72,0.35 | $Ni^{58}$ (p,pn) |
| $Sr^{83}$ | 33h | 0.50 | 1.15 | $Sr^{84}$ (p,pn) |
| $Y^{86}$ | 14.6h | 0.50 | 1.80,1.19 | $Sr^{86}$ (p,n) |
| $Br^{76}$ | 17.2h | 0.44 | 3.57,1.7,1.1,0.8,0.6 | $Se^{76}$ (p,n) |
| $Nb^{90}$ | 14.6h | 0.40 | 1.51,0.66 | $Zr^{90}$ (p,n) |
| $Mn^{52}$ | 5.7d | 0.35 | 0.58 | $Cr^{52}$ (p,n) |
| $Ge^{69}$ | 40h | 0.33 | 1.22,0.61,0.22 | $Ga^{69}$ (p,n) |
| $As^{71}$ | 62h | 0.30 | 0.81 | $Ge^{72}$ (p,2n) |
| $As^{72}$ | 26h | 0.30 | 3.34,2.50,1.84,0.67,0.27 | $Ge^{72}$ (p,n) |
| $I^{124}$ | 4.5d | 0.30 | 2.20,1.50,0.70 | $Te^{124}$ (p,n) |
| $As^{74}$ | 17.5d | 0.29 | 1.53,0.92 | $Ge^{74}$ (p,n) |
| $Zr^{89}$ | 79h | 0.25 | 0.91 | $Y^{89}$ (p,n) |
| $Co^{56}$ | 77d | 0.20 | 0.44,1.50 | $Fe^{56}$(p,n) |
| $Cu^{64}$ | 12.8h | 0.19 | 0.65 | $Cu^{63}$ (n,γ) |
| $Rb^{84}$ | 33d | 0.17 | 1.63,0.82 | $Sr^{86}$ (d, α) |
| $Co^{58}$ | 71d | 0.15 | 0.47 | $Ni^{58}$ (n p) |

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- $\beta^+$ DECAY BY FUSION PROCESS: it has been proposed (Stein, 1974) to send high energy protons on a boron target in order to get positrons. Another possibility is given by fusion process:
- Proton production: $d + {}^{3}He \Rightarrow {}^{4}He$ (3.7 MeV) + p (14.7 MeV) + 18.4 MeV in Fusion process
- If plasma seeded with B atoms: $p + {}^{11}B \Rightarrow {}^{11}C + n$
- ${}^{11}C \Rightarrow {}^{11}B + \beta^+ + \nu$
- Half-life is quite short: 20 minutes about
- Other elements can be used in the fusion process with impinging p:
- # ${}^{13}C$, ${}^{17}O$, ${}^{19}F$, ${}^{26}Mg$….

# POSITRON SOURCES FOR e+e- COLLIDERS: APPLICATION TO ILC AND CLIC

- THE PHYSICAL PROCESSES
- 2- ELECTROMAGNETIC SHOWERS
- Charged particles impinging on targets loose energy by radiation and collision on the atoms . The energy lost by radiation – Bremsstrahlung - is distributed among photons which interact mainly with the nucleus Coulomb field and undergo materialization with e+e- pair creation.
- The energy lost by collision is used in atom excitation and secondary emission leading to ionization; this energy is dissipated in the target and leads to heating.

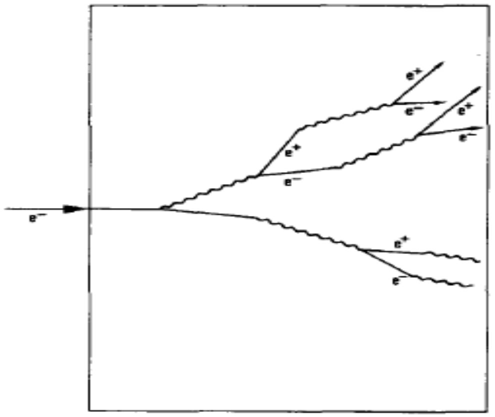

Fig. 1 Electron generated cascade shower

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- **ELECTROMAGNETIC SHOWERS**
- **The created photons may also interact with the electrons by elastic collision (Compton effect); cross-section decreases as photon energy increases. At energies above 10 MeV, for lead, it becomes very weak.**
- **Other processes as multiple scattering which affects the positron angular distribution and, hence, the positron emittance must be taken into account.**
- **As the created pairs contribute to ionization in the target, energy is deposited and heating is of concern.**
- **All of these processes are taken into account in shower codes as GEANT or EGS. For the sake of simplicity in the introduction to the shower development, we shall emphasize on bremsstrahlung and pair creation.**

# POSITRON SOURCES FOR e+e- COLLIDERS: APPLICATION TO ILC AND CLIC

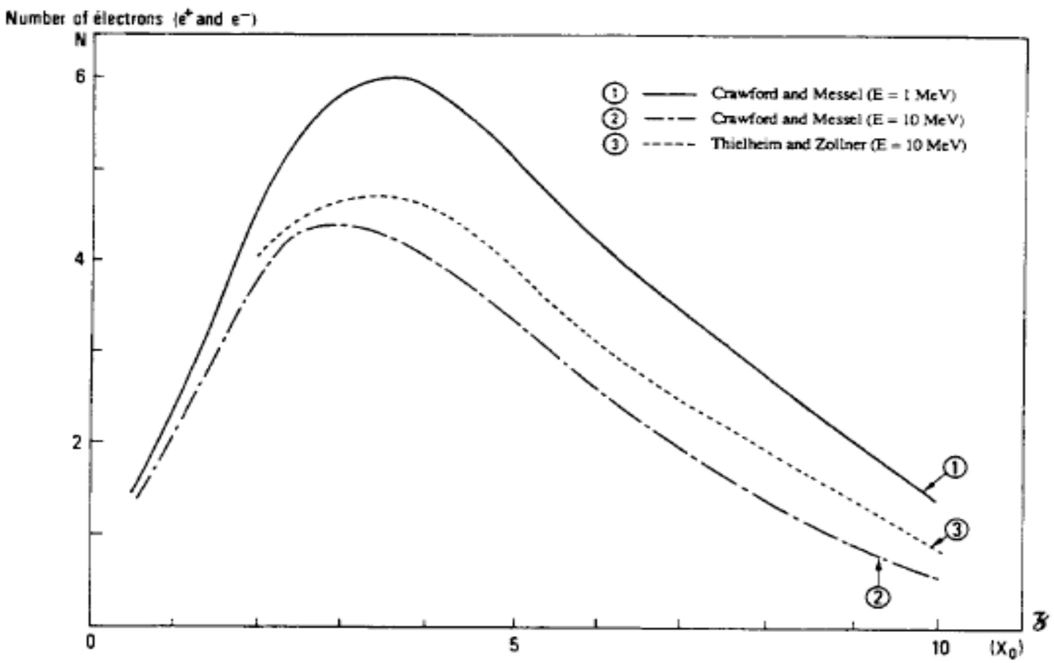
- **Electromagnetic shower: a simple approach**
- **The positron yield is determined by the pair production cross-section (Heitler):**
- $$\sigma_{pair} \sim \alpha Z^2 r_o^2 [28/9] \ln(183/Z^{1/3})$$
- **Where $\alpha$ is the fine structure constant (1/137), Z, the atomic number, $r_o$ the classical electron radius. The mean free path for pair production is:**
- $$l_{pair} = 1/[N\sigma_{pair}]$$
- **Where N is the number of atoms per unit volume**
- **The decrease of intensity of a beam of primary photons creating pairs is, then:**
- $$dn/n = -dx/l_{pair}$$
- **Giving the exponential decrease: $n= n_o e^{-x/lpair}$ ; comparison with the radiation length $l_{rad}$ given by $1/[4Z^2 N \alpha r_o^2 \ln(183/Z^{1/3})]$ leads to the relation: $l_{rad}=(7/9)l_{pair}$. Then,**
- $$n= n_o e^{-(7x/9lrad)}$$
- **Providing the asymptotic value for pair production: ~(7/9)l, where the target thickness l is expressed in $l_{rad}$ units.**

# POSITRON SOURCES FOR e+e- COLLIDERS: APPLICATION TO ILC AND CLIC

- **METHODS FOR SHOWER ANALYSIS**
- **Analytical approach (see B.Rossi)**
- **Considering the so-called Approximation B where bremsstrahlung and pair production are taken into account and where the ionization losses are taken at a constant rate, we can get for the position of the shower maximum:**
- $$T^{-}_{max} = 1.01[\ln(Eo/\varepsilon_o) - 1]$$
- **Where Eo is the incident electron energy and $\varepsilon_o$ the material critical energy (when radiation losses and ionization losses are equal). For W, $\varepsilon_o$= 8 MeV**
- **The number of created pairs at shower maximum is given by:**
- $$\Pi^{-}_{max} = \{0.31/[\ln(Eo/\varepsilon_o) - 0.37]^{1/2}\} Eo/\varepsilon_o$$
- **These quantities corresponding to impinging electrons on the target are essential for the description of the transition curve which represents the number of created pairs along the target thickness.**

# POSITRON SOURCES FOR e+e- COLLIDERS: APPLICATION TO ILC AND CLIC

- **ELECTROMAGNETIC SHOWER: TRANSITION CURVE**
- **Transition curves for 1 GeV incident electron in lead: 2 cut-off energies are considered: 1 and 10 MeV.**



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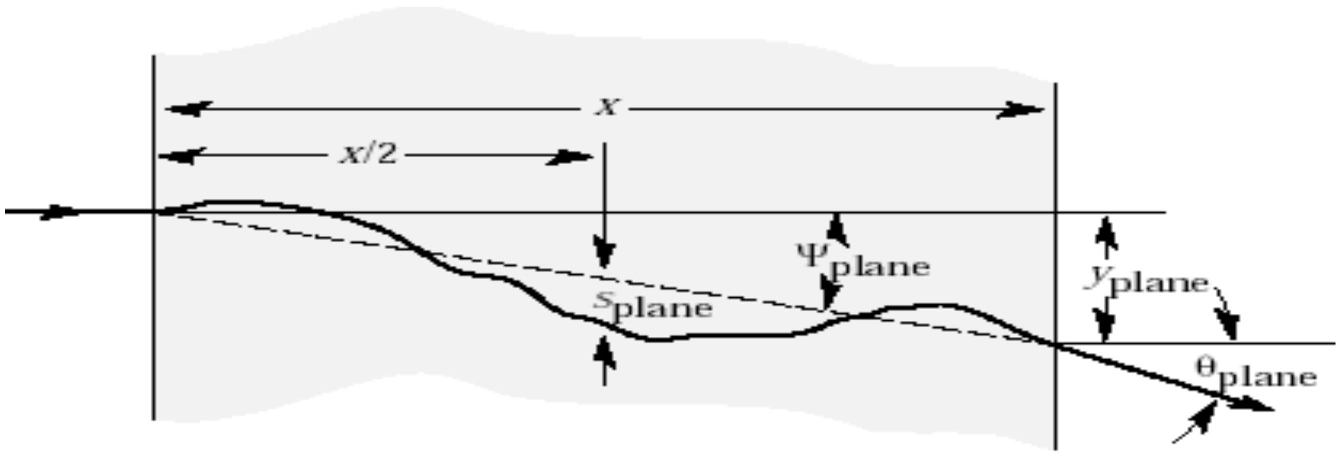
**MULTIPLE SCATTERING:** **the distribution of scattering angles after a distance x through a material of radiation length Xo is approximately gaussian:**

$$dP(\theta_p)/d\theta_p = \{1/\theta_o(2\pi)^{1/2}\}\exp[-\theta_p^2/2\theta_o^2]$$

**With $\theta_o$, rms angle of scattering given by: $\theta_o=(14/pc)[x/Xo]^{1/2}$**

**Lateral view of particle trajectory**



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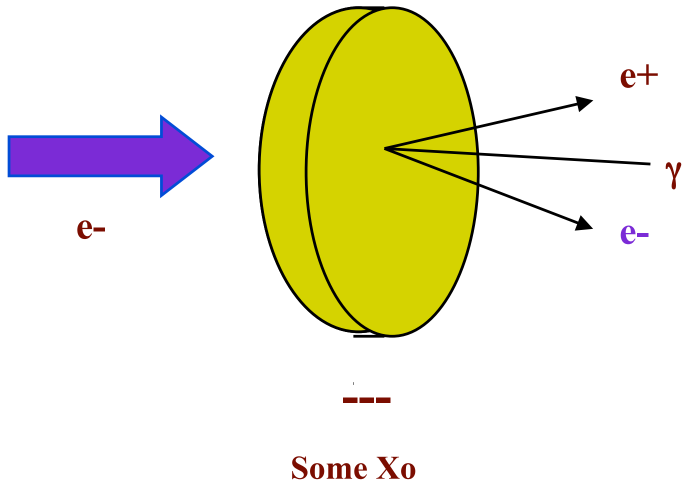
- **ELECTROMAGNETIC SHOWERS: M-C SIMULATION**
- **The analytical approach presented above does not give a precise estimation of the positron beam characteristics. High Z materials are often used for the target in order to improve the pair creation. Multiple scattering becomes important and the particle trajectory in the target is, then, complicated. Longitudinal development and lateral spread of the particle trajectory cannot be separated. Moreover, the energy deposition in the target being inhomogeneous induces severe thermal gradients which may lead to target destruction. So, a precise Monte Carlo simulation taking into account the different processes in the target is mandatory.**
- **Two codes are often used to describe the electromagnetic showers: EGS and GEANT ; we have used both in our calculations and comparative tests showed less than 10 % discrepancies between the respective results.**
- **What can be obtained from the simulations: e+ yield, e+ phase space, deposited energy in the target.**

# POSITRON SOURCES FOR e+e- COLLIDERS: APPLICATION TO ILC AND CLIC

- **1-2-1 Electromagnetic shower in one target**
- **The impinging particle on the target is an electron; in order to get an intense positron beam, an intense electron beam is sent on a thick target of high Z number (W, for instance). Positron beam emittance related to important multiple scattering and thermal problems are, then, of concern. We present here three models of targets which are or will be used:**
- **(a) the classical target: a thick amorphous disk. Typically, W piece, a few Xo thick**
- 



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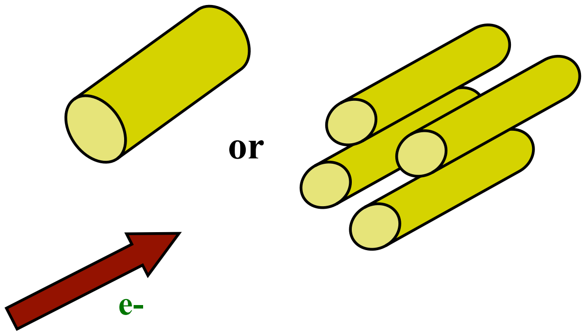
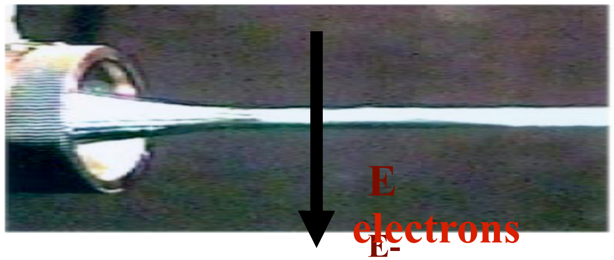
- **1-2-1 Electromagnetic shower in one target:**
- **(b) The wire target; in order to limit the important multiple scattering in large transverse size and thick targets and to allow low energy positrons to leave the target without being absorbed before the downstream edge of the target, wire targets have been proposed (R.Miller et al, 1990). In these targets, positrons are allowed to emerge from the sides. For SLC beam (33 Gev incident) one mm diameter and 10 Xo long W wires showed promising results (3xyield) [calculations by R.Miller et al]**
- **Similar conclusions were derived from a recent study (N.Shul'ga, 2006)**




**Appropriate focusing device is foreseen. The better collection is due to lower transverse momenta.**

# POSITRON SOURCES FOR e+e- COLLIDERS: APPLICATION TO ILC AND CLIC

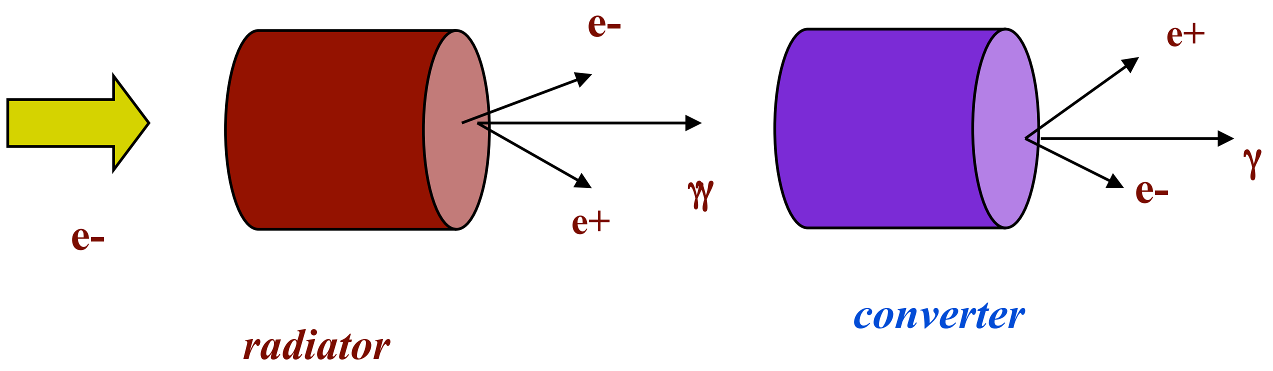
- **1-2-1 Electromagnetic shower in one target**
- **( c) The liquid target; the more recent proposition came from the late G.Silvestrov from Budker Institute. A free plain jet of liquid metal [ gallium-indium alloy and lead] flowing out of a narrow nozzle is one of the proposed solutions.  Mercury (Hg) has also been proposed previously. The main advantages of this kind of target are:**
- **# Heat removal**
- **# Avoid target destruction with high energy densities**
- **# Reduction of beam energy deposition due to side exit of the secondaries**




- **Other possibilities consist in: concave liquid metal flow, mercury in aluminum containers,…**

# POSITRON SOURCES FOR e+e- COLLIDERS: APPLICATION FOR ILC AND CLIC

- **1-2-2 SEPARATE TARGETS FOR γ PRODUCTION AND PAIR CREATION**




**Two targets are used: a *radiator* to produce the photons and a *converter* for the materialization of the photons in e+e- pairs**
**The radiator may be a source of photons as a magnetic undulator, a Compton backscattering device, a monocrystal providing channeling radiation,…The Converter is a piece of amorphous material (W, for example).**

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- **MOTIVATIONS FOR SEPARATE TARGETS**
- **# Obtaining polarized positrons using polarized photons produced in helical undulators or in Compton process**
- **# Avoid target destruction using a powerful γ source (undulator, Compton) associated to a thin converter**
- **# Avoid excessive thermal heating using a crystal in channeling conditions delivering an intense photon beam associated to a thin converter**
- **# Improve significantly the positron yield using coherent pair production in oriented monocrystals with a photon beam at glancing incidence from the crystal rows; in that case, the converter is a crystal**

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- **1-2-2-1 A MAGNETIC UNDULATOR AS A RADIATOR**
- **A planar undulator may be used to avoid putting a thick solid target in an intense beam (cf. TESLA project)**

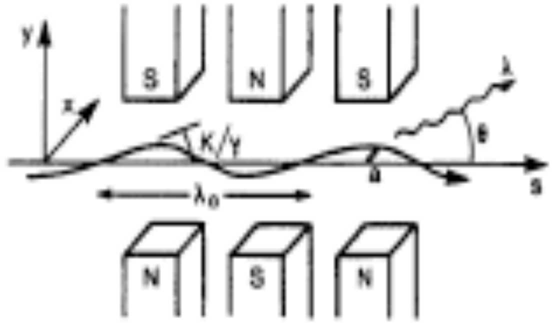


Fig. 2 Schematic of planar undulator and coordinate system

- **An helical undulator providing circularly polarized photons to produce polarized positrons in a thin amorphous target [ILC baseline project]**

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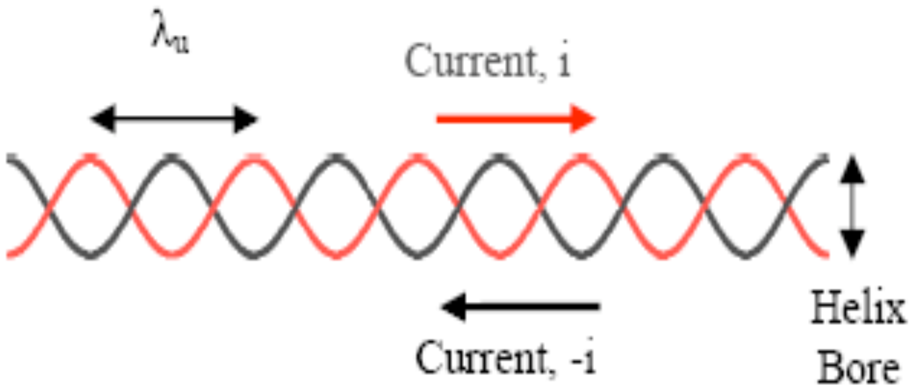
- THE HELICAL UNDULATOR




**A SC helical undulator is made of two SC wires wound around a tube with currents flowing in opposite directions. The undulator period and the electron orbit period are the same: $\lambda_u$. Synchrotron radiation, circularly polarized is emitted in a conical angle $\theta \sim 1/\gamma$ around the e- direction of motion.**

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- **THE HELICAL UNDULATOR**
- *** Radiation wavelength: the radiation emitted in an helical undulator of period $\lambda_u$ and field B by electrons of relative energy $\gamma$, is given by:**
- $$\lambda = (\lambda_u/2\gamma^2)(1 + K^2) \quad \text{(first harmonic, on axis)}$$
- **where $K = eB\lambda_u/(2\pi mc)$ is the undulator deflection parameter.**
- **In order to get $\gamma$'s with enough energy (~30 MeV) to produce e-e+ pairs in a target , we need electrons having more than 150 GeV as we are dealing with periods $\lambda_u$ of ~1 cm. The bore aperture is ~4-5 mm.**
- *** Number of photons : the number of photons is proportional to the number N of periods. For ILC it is needed about $10^4$ periods (100 m)**
- *** Technology: superconducting wires as well as permanent magnet designs are foreseen.**

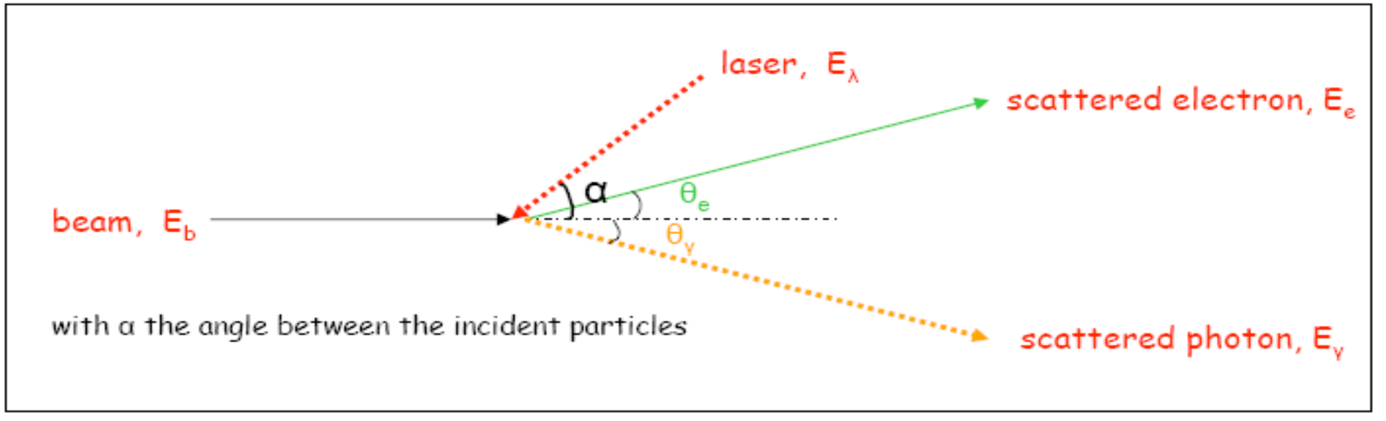
# POSITRON SOURCE FOR e+e- COLLIDERS: APPLICATION TO ILC AND CLIC

## COMPTON BACKSCATTERING

The backscattered photon has an energy >> $(h\nu)_{laser}$ : with $E_b \sim 1$ GeV, $E_\gamma \sim 20$ MeV
These $\gamma$ can create e+e- pairs in a target. If $(h\nu)$ circularly polarized, $\gamma$ also.

Process : $e_b + \gamma_L \rightarrow e' + \gamma'$

The scattered $\gamma$: $\lambda = \lambda_{laser}/2\gamma^2(1 + \cos\theta_\gamma)$



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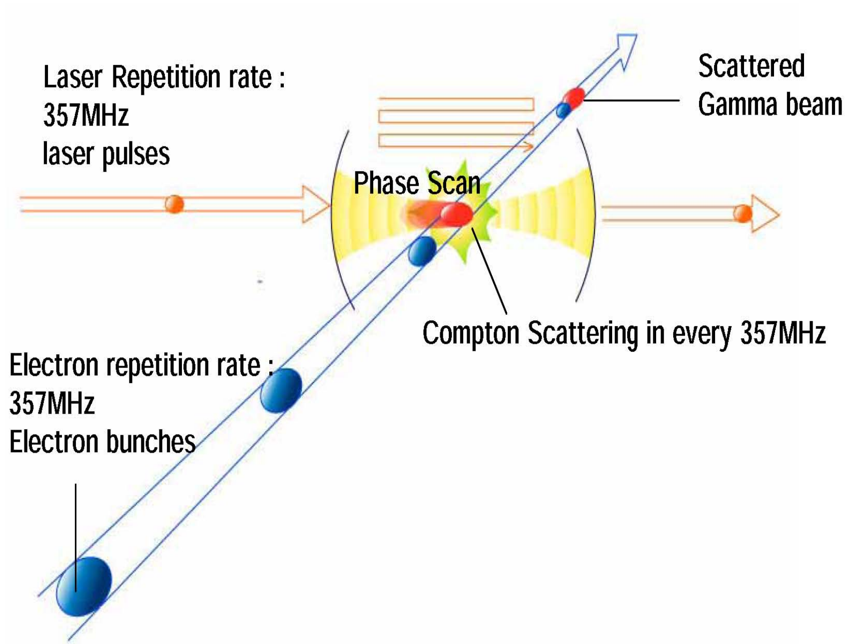
- **COMPTON BACKSCATTERING: USE OF OPTICAL CAVITY**
- **In order to improve the available laser power at the Compton interaction point, an optical cavity (FP) is used.**

**The figure [M.Kuriki] shows how with a F-P Cavity and a high repetition rate, it is possible to enhance the number of e-beam-laser collisions**



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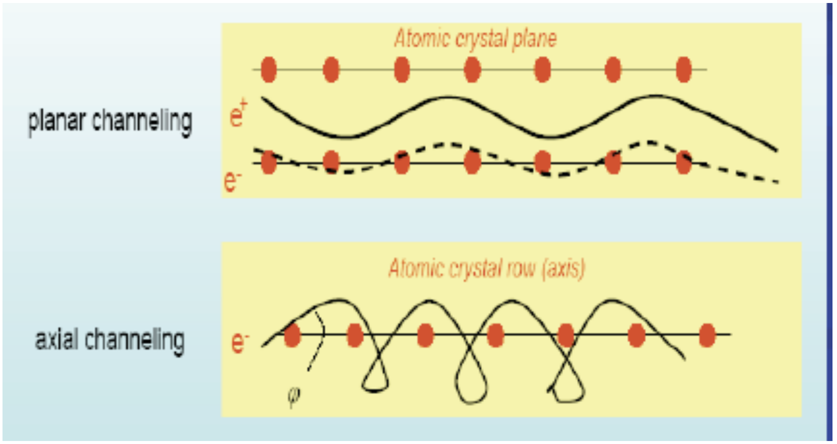
- **PHOTONS FROM CHANNELING IN ORIENTED CRYSTALS**
- **The average potentials in the neighbourhood of crystal atoms when an incident electron penetrates the crystal at glancing incidence to the rows/planes makes the electron "trapped" in the potentials and it radiates quite intensively (Kumakhov). The radiation becomes much more intense than ordinary bremsstrahlung at energies > 1 GeV, for W. Channeled electrons are then a powerful source of photons.**
- 


**Planar: 1-D**

**Axial: 2-D**

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- **AXIAL CHANNELING OF RELATIVISTIC ELECTRONS**
- **Axial potentials are generally 5 to 10 times stronger than planar potentials. Moreover, the radiated energy is proportional to the square of the channeling field; that explains why axial channeling is preferred for γ-radiation in a positron source. In the case of W, one of the most used crystal for this purpose, the potential depth is of 1 kV at normal temperature. Provided the angle of incidence of the e- on the atomic rows is smaller than the Lindhard critical angle,**
- $\Psi_c = [2U/E]^{1/2}$ ,
- **where U is the potential depth and E, the electron energy, the e- will develop a rosette motion and as in a magnetic wiggler, will radiate. The frequency of the radiated photon is approximately,**
- $\omega = 2\gamma^2 \Delta E_T$
- **Where γ is the Lorentz factor and $\Delta E_T$ is the transverse energy loss between channeled states. Typically, $\Delta E_T$ is of some eV and for 1 GeV e- beam, we can obtain 40 MeV photons, which represents an interesting energy to produce e+e- pairs**

# POSITRON SOURCES FOR e+e- COLLIDERS: APPLICATION TO ILC AND CLIC

- **OTHER CRYSTAL EFFECTS FOR POSITRON PRODUCTION**
- **COHERENT BREMSSTRAHLUNG**
- **At angles larger than the Lindhard critical angle, the electrons crossing planes or chains of atoms at regular steps, emit radiation with interference effects. These photons have larger energy than those due to channeling (the period of oscillation is ~a/θ, where a is the interatomic distance and θ, the incidence angle; it is, typically, 10 times smaller than for channeling).**

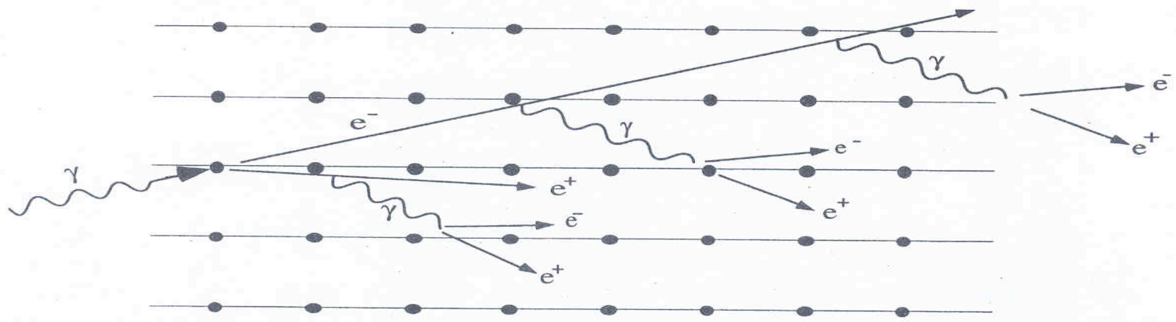


*Figure 13 : Pair production associated to coherent bremsstrahlung.*

# POSITRON SOURCES FOR e+e- COLLIDERS: APPLICATION FOR ILC AND CLIC

- OTHER CRYSTAL EFFECTS FOR POSITRON SOURCE
- PAIR CREATION IN STRONG FIELD
- At very small angles of incidence of high energy photons on the atomic strings, enhanced pair creation is observed. Experiment at CERN with a Ge crystal and a 150 GeV photon beam, showed an order of magnitude enhancement w.r.t. Bethe-Heitler mechanism. This enhancement is due to coherent pair production and pair production in strong fields. Some threshold exists, depending on crystal temperature: it is of 22 GeV at normal temperature and of 13 GeV at 100° Kelvin, for W and of 50 GeV for Ge (100°K).
- See, A.Belkacem et al Phys.Rev.Lett
- E.Uggerhoj et al.

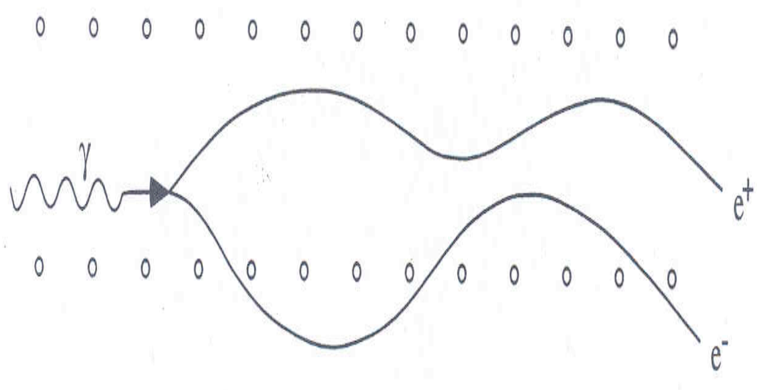


Figure 14 : Pair creation in strong field.

Threshold: $\omega_b = m^3 u_1 d/(Z\alpha)$

$u_1$; thermal vibration

d; interatomic distance

For W, $u_1$=0.05 Å