THE STATUS OF POSITRON SOURCE DEVELOPMENT AT CORNELL

Alexander Mikhailichenko
Cornell University, LEPP, Ithaca, NY 14853

LCWS2007, May 30-June 4, 2007 Hamburg, DESY
ACTIVITIES

✓ CODE FOR POSITRON CONVERSION (UNDULATOR → LINAC → further on)
   Choice of undulator parameters → main issue
   Choice of target dimensions
   Choice of collection optics parameters

✓ UNDULATOR DESIGN (main activity)
   Undulators with period 10 and 12 mm having 8 mm aperture (tested)
   Designed undulators with aperture "¼" (7mm magnetic core)

TARGET DESIGN (in addition to Livermore, SLAC, Daresbury)
   Rotating Tungsten target (including new sandwich type)
   Liquid metal target: Bi-Pb or Hg

COLLECTION OPTICS DESIGN
   Lithium lens
   Solenoid

✓ COLLIMATORS
   Collimator for gammas
   Collimators for full power beam

✓ PERTURBATION OF EMITTANCE AND POLARIZATION
   Perturbation of emittance in regular part
   Polarization handling

✓ UNDULATOR CHICANE
   Minimal possible parallel shift

✓ COMBINING SCHEME
   Two-target scheme

These positions not closed finally
CODE FOR POSITRON CONVERSION

Undulator → target → focusing → post acceleration
Written in 1986-1987; restored in 2007

PROGRAM KONN
T.A.Vsevolozhskaya, A.A.Mikhailchenko
Monte-Carlo simulation of positron conversion

Equivalent of collimator

Energy of the beam;
Length of undulator;
Undulator period $M-L/\lambda_M$;
K-factor;
Emittance;
Beta-function;
Number of harmonics (four);
Number of positrons to be generated;

Target:
Distance to the undulator;
Thickness;
Diameter of target;
Material;
Diameter of hole at center;
Step of calculation;

Acceleration:
Distance to the lens;
Length of structure;
Gradient;
Diameter of collimator at the entrance;
Diameter of truces;
External solenoidal field;
Further phase volume captured;

Lithium Lens:
Distance to the target;
Length;
Diameter;
Thickness of flanges;
Material of flanges;
Gradient;
Step of calculations;

CALCULATES at every stage:
Efficiency in given phase volume;
Polarization in given phase volume;
Beam dimensions;
Phase-space distributions;
Beam lengthening;
Energy spread within phase space;

Interactive code; Solenoidal lens will be added soon
Particles described by 2D array (matrix). One parameter numerates particles, the other one numerates properties associated with each particle: energy, polarization, angles to axes.

Code has ~1400 rows;
Will be added solenoidal lens;
Will be added more graphics;

Possibility for the file exchange with graphical and statistical Codes (JMP);
Possibility for the file exchange with PARMELA;

Few seconds for any new variant.
Monte-Carlo simulation of positron conversion example

General parameters:
- Energy of the beam = 150 GeV
- Length of undulator = 175 m
- Undulator period = 10 mm
- K-factor = 0.35
- Emittance = 0.000001 cm rad
- Beta-function = 400 m
- Number of harmonics = 4

Target:
- Distance to the undulator = 180 m
- Thickness = 0.5 m
- Length = 1.7 m
- Diameter of target = 0.8 cm
- Material = W

Acceleration:
- Distance between 2 lens-structure = 2 cm
- Gradient in RF structure = 50 MeV/m
- Length of RF structure = 1 m
- Diameter of collimator at the entrance = 4 cm
- Diameter of irises = 6 cm
- External solenoidal field = 40 kG
- Further phase volume captured = 10 MeV x cm

For parameters above:
- Efficiency = 1.54
- Polarization = 50%

So K-factor can be small, K < 0.4, what brings a lot of relief to all elements of system.
Modeling of E-166 experiment
Phase space right after the target

Dependence of polarization seen in experiment
Complete design done;

System for magnetic measurement designed;

Undulator includes correctors and BPMs;

Current input one/few modules (ten)

Will be extended to 2 m long ~4 m total

3 m possible
Other possible solution for correctors at the ends of extended sections.

Diameter of cryostat = 4” (101.6mm)

Cryostat expandable; shown with the terminals for Hall probe insertion; Field distribution will be measured in this cryostat; will be tested with beam.
Technology developed for fabrication of continuous yoke of necessary length (2-3m)

Wire having diameter 0.33mm chosen as a baseline one for now

For 10mm period the coil has 8(z)x11(r) wires; bonded in 4-strands

For 12mm period the coil has 12(z)x12(r) wires bonded in 6 strands

Two meter long yoke under visual inspection by William Trusk
Wires for undulator

All new wire is a 56 filaments with SC to Cu ratio 1:0.9
We switched to 0.3 mm bare from 0.6 bare
Wounding with bonded tape of four and six wires in parallel
Dewar sealed and used for low pressure experiments; two oil pumps deliver vacuum down to -24"Hg with Helium level covering the undulator.
For Dewar pumped down -24”Hg (-609.6mmHg), the temperature = 3 °K

Measured excitation curve for undulator with 8mm aperture, wire-0.33 mm, 56 filaments
Random point; spread of amplitudes~5%
No need for $K$ factor to be high
This is useful for higher polarization

Ratio of Power radiated at first harmonics to the all power in all angles

Angular distribution of intensity of radiation for different $K$
ILC Beam parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Formula</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Angular spread in radiation</td>
<td>$a \approx \sqrt{1+K^2/\gamma}$</td>
<td>$3 \cdot 10^{-6}$ (K=1)</td>
</tr>
<tr>
<td>Angular spread in beam, vert.</td>
<td>$y' \approx \pm \sqrt{\gamma \varepsilon_x / \beta \gamma}$</td>
<td>$3.5 \cdot 10^{-8}$</td>
</tr>
<tr>
<td>Angular spread in beam, rad.</td>
<td>$y' \approx \pm \sqrt{\gamma \varepsilon_x / \beta \gamma}$</td>
<td>$3.5 \cdot 10^{-7}$</td>
</tr>
<tr>
<td>Radius of helix</td>
<td>$a \approx \kappa K / \gamma$</td>
<td>$5 \cdot 10^{-7} \text{ cm}$ (K=1)</td>
</tr>
<tr>
<td>Beam size, vertical</td>
<td>$\sqrt{\langle y^2 \rangle} \approx 2 \times \sqrt{\gamma \varepsilon_y \beta / \gamma}$</td>
<td>$1.4 \cdot 10^{-3} \text{ cm}$</td>
</tr>
<tr>
<td>Beam size, radial</td>
<td>$\sqrt{\langle x^2 \rangle} \approx 2 \times \sqrt{\gamma \varepsilon_x \beta / \gamma}$</td>
<td>$1.4 \cdot 10^{-2} \text{ cm}$</td>
</tr>
</tbody>
</table>

50 sigma ~7 mm ; At the beginning of operation one can expect emittance degradation

That is why we have chosen as big aperture as possible -- Ø8 mm clear.

This 8 mm diameter allows K~0.4-0.5
K factor as function of radius of undulator chamber

NbTi wire 56 filaments demonstrate best properties
Sectioning coil in radial direction allows further enhancement
Details of design. 1–Iron yoke, 2–Copper collar, 3, 4–trimming iron nuts. Inner diameter of Copper vacuum chamber is 8mm clear.

Period kept even

We developed simplified tapering allowing smooth end without diameter expansion
Sectioned coils for undulators

10 mm undulator operated with two PS 500+50 A; 4x6 wires (0.6mm in diam. bare)
Undulator 12 mm feed with one PS;
In a future there will be <3 PS for coils sectioned in radial direction
Identification of losses in joints

Tested SC transformer scheme to identify time decay (losses in joints)

For undulator with 36 turns decay time found to be ~400 sec (5 joints)

This defines the resistance to be $<1 \times 10^{-15} \Omega$

This scheme used in 1986 to feed SC undulator

Scheme allows to work with captured flux

SC transformer with keys
Distribution box for switches

SC transformer installation— at the left
Typical field distribution

Field along 52 mm period plotted for two orthogonal orientations of the Hall probe. Tests.

Simplified tapering
Undulators tested so far

Aperture available for the beam is 8 mm in Ø clear

OFC vacuum chamber, RF smoothness

<table>
<thead>
<tr>
<th>SC wire</th>
<th>54 filaments</th>
<th>56 filaments</th>
<th>56 filaments</th>
<th>56 filaments</th>
</tr>
</thead>
<tbody>
<tr>
<td># layers</td>
<td>5*</td>
<td>6*</td>
<td>11***</td>
<td>9** (12*** ) +sectioning</td>
</tr>
<tr>
<td>(\lambda = 10 \text{ mm @ } 300 \text{°K} )</td>
<td>K=0.36 tested</td>
<td>K=0.42 tested</td>
<td>K=0.467 tested</td>
<td>K≈0.5 (calculated)</td>
</tr>
<tr>
<td>(\lambda = 12 \text{ mm @ } 300 \text{°K} )</td>
<td>K=0.72 tested</td>
<td>K=0.83 tested</td>
<td></td>
<td>K≈1 (calculated)</td>
</tr>
</tbody>
</table>

*) Wire – Ø0.6 mm bare
**) Wire – Ø0.4 mm bare
****) Wire – Ø0.3 mm bare

For aperture diam. ¼” we expect for period 10 mm K=0.7; for period 12 mm K=1.2

Two sections of 45 cm long each will be measured in cryostat to the end of this year; The plan is to test it with the beam at Cornell ERL test module setup.

4m long prototype will be assembled in general to the end of 2007, Field distribution will be measured earlier in 2008
TARGET DESIGN

Ti rotating wheel target is under development at Livermore, SLAC, Daresbury.

We are looking for some other guarantied solutions

Ti needle target

Liquid metal target with Pb/Bi or Hg

Spinning compact W disk

Sandwich type target with W+Ti \rightarrow \text{New} \quad \text{Together}
FlePDE model calculates temperature and pressure according equations

\[ \nabla(k \nabla T) + \dot{Q} = \rho c_v T \]

\[ \ddot{P} - \nabla(c_0^2 \nabla P) = \frac{\Gamma}{V_0} \dot{Q} \]

\[ \dot{Q} = \sum_j \frac{2c Q_{bunch}}{\sqrt{\pi} \sigma_z \sigma_y} \frac{Z}{r_x} \exp\left( -\frac{(z+z_0-c(t-j \cdot T))^2}{\sigma_z^2} \right) \exp\left( -\frac{r^2}{\sigma_r^2} \right) \]

The thermal pressure \( p_T \) can be expressed

\[ p_T = \Gamma(V) \frac{c_v T}{V} = \Gamma(V) \frac{\varepsilon_T}{V} \]

where \( \Gamma(V) = V c_v (\frac{\partial P}{\partial T}) \) characterizing the ratio of the thermal pressure to the specific thermal energy \( \frac{\varepsilon_T}{V} \) called Grüneisen coefficient.

Instant position of the bunch moving in the target, at the left. Isotherms right after the bunch passage, at the right.
A.D. Bukin, A.A. Mikhailichenko, "Optimized Target Strategy for Polarized Electrons and Positrons Production for Linear Collider".
Needle type target made from Ti

We are using numerically available codes to evaluate efficiency. Cylindrical target example
Sandwich type target concept (earlier design)
First layer (at the entrance is W, the last fraction might be Ti)

By this one can expect more compact design
Liquid metal target

High Z metals could be used here such as Bi-Pb, Mercury. InGa alloy also can be used here if filled with W powder.

BiPb has melting temperature 154 deg C. Hg has boiling temperature 354 deg C

Gear pump. Hg Jet velocity~10m/s

Calculations show absolute feasibility of this approach
Conversion unit with liquid metal target and Lithium lens (described below)
Conversion unit on a basis of spinning W(+Ti) and Lithium lens

RF structure; input-far from the target side

Spinning disk W (+Ti)

Size ~30cm in diameter
**COLLECTION OPTICS DESIGN**

Efficiency = \( N_{e^+} / N_{\text{gammas}} \)

- **Angle shown** \( \approx 0.3 \text{ rad} \)
- **Target** – Tungsten (W)
- **Thickness** – 1.5 mm
- **20 MeV photons**
- **Particles from 10 to 19 MeV only**

Efficiency as function of capturing angle; within this angle the particles are captured by collection optics
Many different systems possible here. Shown is Cornell positron capturing system.

Efficiency of positron accumulation in CESR with system turned on/off changes 5 times;

This design introduced in 2000; it doubled positron accumulation in CESR, coming to 100 mA/min anytime (R=100m)

This serves as a prototype for ILC capturing system with solenoid (see below)
Lithium lens basics

If steady current $I$ runs through the round conductor having radius $a$, its azimuthal magnetic field inside the rod could be described as

$$H_\phi(r) = \frac{0.4 \pi r I}{2 \pi a^2}$$

where magnetic field is measured in Gauss, $a$ -- in cm, $I$ -- in Amperes. Current density comes to $j_s = I / \pi a^2$ The particle, passed through the rod, will get the transverse kick

$$\alpha \equiv \frac{H(x) \cdot L}{(HR)} = \frac{0.21 L x}{a^2 \cdot (HR)}$$

So the focal distance could be defined as the following

$$F = \frac{a^2 \cdot (HR)}{0.2 IL}$$

This picture drawn for the focusing of electron beam to the target.
If the focal distance is given, the current required could be found as 

\[ I \equiv \frac{\alpha^2 \cdot \langle HR \rangle }{0.2FL} \]

For the primary electron beam of say, 20 MeV \( \langle HR \rangle \equiv 66kGcm \) Suggesting \( F=0.5 \text{ cm} \), \( L=2 \text{ cm} \), \( a=0.5 \text{ cm} \)

\[ I \equiv \frac{0.5^2 \cdot 66}{0.2 \cdot 0.5 \cdot 2} = 83.25kA \]

Scattering of the beam in a Lithium rod target could be estimated as 
\[ \sqrt{\langle \theta^2 \rangle} \approx \frac{13.6 \text{ MeV}}{pc} \sqrt{\frac{\langle t_{\gamma} \rangle}{X_u}} \]

where \( X_u \) is an effective radiation length of Lithium, \( X_u = 83.3 \text{ g/cm}^2 \) \( (\text{or } 156 \text{ cm}) \),
\( t_{\gamma} \) is the thickness of the rod in \( \text{g/cm}^2 \), \( \sqrt{\langle \theta^2 \rangle} \approx \frac{13.6}{20} \sqrt{\frac{2}{156}} \approx 0.077 \text{ rad} \)

Resistance of the 1 cm long 1 cm in diameter Lithium rod could be estimated as
\[ R = \rho L / \pi a^2 \approx 1.44 \cdot 10^{-3} \cdot 2 / \pi / 0.5^4 \approx 3.7 \cdot 10^{-3} \text{ Ohm} \]

the instant power dissipation in the rod as big as
\[ P = I^2 \cdot R \approx 83.25^2 \cdot 10^4 \cdot 3.7 \cdot 10^{-3} = 2.5 \cdot 10^3 \text{ W} \]

If the pulse lasts for \( \tau \) seconds with repetition rate \( f \), Hz, then the average power dissipation will be
\[ \langle P \rangle = I^2 \cdot R \cdot f \tau \]

For \( f=5 \text{ Hz} \), \( \tau=2 \text{ ms} \), the last goes to
\[ \langle P \rangle = 2.5 \cdot 10^3 \cdot 5 \cdot 2 \cdot 10^{-3} \approx 2.5 \text{ kW} \]

This is much, much easier, than for focusing of (anti) protons.
To the Conversion System for Generation of Polarized Beams in VLEPP, BINP, 1986

1-ex-centric contact pushers, 2-conic lens body, 3-W target, 4-Ti tubing for LI supply, 5-flat current leads, 6-vacuum chamber, 7-coaxial fraction of current leads, 8-bellows, 9-ceramic insulators, 10-conical gasket, 11-set of ex-centric pushers.

Field measured in liquid Gallium model.
A-cylindrical lens with homogenous current leads supply at the end.
B-conical lens with the same current feed.
C-lens with cylindrical target at the entrance flange.
Two possibilities were considered at the time: 1-Mercury jet    2-W disc spin by Gallium
Just reminding, that for VLEPP project the beam with $10^{12}$ electrons/positrons was used.

Variant 1-Mercury jet, Variant 2-spinning W disc, 1-case, 2-disc, 3-beam axis, 4-
feeding tube for Hg, 5-Hg jet, 6-tubes, 7-Protective Ti disc, 8-Lithium lens container,
9-Lithium volume, 10- entrance flange of the lens, 11-current leads, 12-Ga jet
nozzle.
Energy deposition in Be flanges is going by secondary particles (positrons and electrons) is $\delta E \sim 2 \text{ MeV cm}^2/g$. Secondary beam diameter $d \approx 1 \text{ cm}$. Area illuminated is going to be $S = \frac{1}{4} \pi d^2 \approx 0.4 \text{ cm}^2$. Volume density of Be is $\rho \approx 1.8 \text{ g/cm}^3$, for thickness $0.5 \text{ mm}$. Energy deposited in a material of flange going to be

$$\Delta E = \Delta E \cdot \rho \cdot t \cdot l / \text{cm} \approx 2 \cdot 1.8 \cdot 0.05 \approx 0.2 \text{ MeV per particle}$$

So the total energy deposited by train of $n_b$ bunches with population $N$ each, comes to

$$E_{\text{tot}} = \Delta E \times N \times n_b \times e \quad \text{Joules,}$$

where $e$ stands for the charge of electron. The last expression goes to be

$$E_{\text{tot}} \equiv 1.8 \text{ J.}$$

Factor reflecting spare particles, $\sim 1.5-2$, factor two- reflecting equal amount of electrons and positrons and, finally, factor reflecting efficiency of capturing ($\sim 30\%$). So the final number comes to $\approx 21 \text{ J.}$

Temperature gain by heat capacity of Be $C_v = 1.82 \text{ J/g/degC}$ comes to

$$\Delta T = \frac{E_{\text{tot}}}{mC_v} \equiv \frac{E_{\text{tot}}}{\rho \cdot S \cdot C_v} \equiv \frac{21}{1.8 \times 1.82 \times 0.05 \times 0.2} \equiv 660 \text{ deg.}$$

One needs to add the initial temperature which is above melting point of Lithium, coming to maximal temperature $\sim 850-900 \text{ deg.}$ Meanwhile the melting temperature of Be is 1278 deg, so it withstands.
Recent calculation of Lithium lens done with FlexPDE® code
Spatial field distribution over time (cinema)
Power dissipated per pulse goes to 0.6 kJ for the current ~135 kA and time duration half sin wave with period 40 msec.

Energy stored -21.6 J so reactive component is low.

(Dissipation for time from zero to 10 msec is 0.3 kJ)

Feeding with 5th harmonic allows making current flat.

The transformer with Lithium Lens (example), 1-fixture, 2-flat coaxial line, 3-transformer yoke, 4-cable windings. Lens with a current duct could be removable from the beam path.
Doublet of Lithium lenses in Novosibirsk BINP

Photo- courtesy of Yu Shatunov

First lens is used for focusing of primary 250 MeV electron beam onto the W target.
Second lens installed after the target and collects positrons at ~150MeV
Number of particles in pulse ~2E+11; ~0.7Hz operation (defined by the beam cooling in Damping Ring)
Lenses shown served ~30 Years without serious problem (!)
Li lens resume

Utilization of Lithium lens allows Tungsten survival under condition required by ILC with \(N_e \sim 2 \times 10^{10}\) with moderate \(K \sim 0.3-0.4\) and do not require big-size spinning rim (or disc). Thin W target allows better functioning of collection optics (less depth of focusing).

Liquid targets as Pb/Bi or even Hg allows further increase of positron yield.

Lithium lens (and x-lens) is well developed technique.

Usage of Li lens allows drastic increase in accumulation rate, low K-factor.

Field is strictly limited by the surface of the lens from the target side.

Plan is to repeat optimization of the cone angle in Li rod.
Solenoidal lens instead of LI lens

One can equalize the focal length of the Lithium lens and the solenoidal one

\[
\frac{1}{f} \equiv \frac{GL}{(HR)} = \frac{\int H^2(s)ds}{4(HR)^2}
\]

\[
\int H^2 ds = H^2_{\text{max}} \cdot L \cdot \eta = 4(HR)GL
\]

where \((HR) = pc/300\) stands for magnetic rigidity.

Typically longitudinal continuity \(L \eta \approx 1.5 \div 2 D\), where \(D\) stands for diameter of solenoidal lens. The Lithium lens has the length \(L = 0.5 \text{cm}\). Diameter of solenoidal lens is something about 5 cm, then for \(HR\) = 100 kGcm (for 30 MeV particles), one can obtain

\[
H^2_{\text{max}}(s) = \frac{4 \cdot 150 \cdot 100}{15} = 4000 \text{ kG}^2
\]

So the maximal field comes to \(H_{\text{max}} = 63\text{kG}\) (for 30 MeV particles)

For generation of such field the amount of Ampere-turns required goes to be

\[
\eta J \equiv \frac{H_{\text{max}} \Lambda}{0.4\pi \cdot \eta} \quad \rightarrow \quad 262 \text{kAturns} \text{ (again, for 30 MeV particles)}
\]

No flux concentrator possible for 1 msec; skin~3-4 mm
Solenoidal lens could be designed with dimensions ~ a bit larger than the Lithium lens

For the number of turns \( n = 20 \), current in one turn goes to \( I \sim 15 \text{ kA} \) during \( \sim 10 \text{msec} \) duty time; Two harmonics for feeding current.

Conductor cross-section \( \sim 5 \times 10 \text{mm}^2 \); Coolant-oil.

Lenses in comparison; for Li lens current leads are not shown.
Other focusing possibilities to be mentioned

Other short -focusing elements-such as horn, can be used here as well. Design also was done, horn lens, so called x-lens was at service for positron capture for may years at BINP (G. Budker, G. Silvestrov)

So the device has ideal dependence for linear focusing. The focal distance of this lens goes to \( F = \frac{HR}{0.4λk} \).

As the particles here going through material of the horn, it manufactured usually from Aluminum ( \( \rho = 24.3 \, \text{g/cm}^3 \) [\( \approx 9 \, \text{cm} \text{m} \)]) or Beryllium ( \( \rho = 66 \, \text{g/cm}^3 \) [\( \approx 35.8 \, \text{cm} \text{m} \)])
Fig. 2a Special profile of the "linear" lens.

Fig. 2b Sectional view of the "linear" lens:
1 - lens body
2 - coaxial conductor
3 - insulation
4 - damping device for demountable contact
5 - flat conductor for connection to the transformer.
COLLIMATORS

✓ Collimator for gammas
✓ Collimators for full power primary beam

Collimator for gammas

Pyrolytic Graphite (PG) is used here. The purpose of it is to increase the beam diameter, before entering to the W part. Vacuum outgassing is negligible for this material. Heat conductivity ~300 W/m-oK is comparable with metals. Beryllium is also possible here, depending on task.

Transverse dimensions defined by Moliere radius

Gamma-beam. $\sigma_\gamma = 0.5\text{cm}$, diameter of the hole (blue strip at the bottom) $d=2\text{ mm}$. Energy of gamma-beam coming from the left is 20 MeV.

Positron component of cascade
High power collimator

This a liquid metal one. Liquid formed a cylinder as result of rotation and centrifugal force.

High average power collimator. Beam is coming from the right.
Kinematical perturbations due to multiple scattering in a target

Let us consider the possible effect of kinematical depolarization associated with rotation of spin vector while particle experience multiple scattering in media of target before leaving. Typically polarized positron carries out \((0.5 - 1)\)k energy of gamma quanta. As positrons/electrons created have longitudinal polarization, it is good to have assurance that during scattering in material of target polarization is not lost. Each act of scattering is Coulomb scattering in field of nuclei. So RMT equation describing the spin \(\zeta\) motion in electrical field of nuclei looks like:

\[
\frac{d\zeta}{dt} = \frac{1}{mc^2\gamma} \left[ G_\gamma + \frac{\gamma}{\gamma + 1} \right] \zeta \times \left( \vec{E} \times \vec{v} \right).
\]

(A16)

where \(\vec{E} = \frac{Ze}{r^3}\) stands for repulsive (for positrons) electrical field of nuclei, factor \(G = \frac{\gamma - 1}{2} \approx 1.1596 \times 10^{-3} = \frac{\alpha}{2\pi}\). Deviation of momentum is simply \(\frac{d\vec{p}}{dt} = e\vec{E}\).

So the spin equation becomes

\[
\frac{d\zeta}{dt} = \frac{1}{mc^2\gamma} \left[ G_\gamma + \frac{\gamma}{\gamma + 1} \right] \zeta \times \left( \frac{\vec{e} \times \vec{v}}{dt} \right).
\]

(A17)

We neglected variation of energy of particle during the act of scattering, so \(\frac{d\vec{p}}{dt} = \frac{m\gamma \dot{v}}{dt}\) and vector \(\vec{p}\) just changes its direction. Introducing normalized velocity as usual \(\vec{\beta} = \frac{\vec{v}}{c}\); equation of spin motion finally comes to the following

\[
\frac{d\zeta}{dt} = \left[ G_\gamma + \frac{\gamma}{\gamma + 1} \right] \zeta \times \left( \vec{\beta} \times \vec{\beta} \right) = \left[ G_\gamma + \frac{\gamma}{\gamma + 1} \right] \zeta \times \frac{d\Phi}{dt}.
\]

(A18)

where \(\Phi\) stands for the scattering angle and the vector \(\frac{d\Phi}{dt}\) directed normally to the scattering plane. For intermediate energy of our interest \(\gamma \approx 40\), so the term in bracket \(-1\) and, finally

\[
\frac{d\zeta}{dt} = \zeta \times \frac{d\Phi}{dt}.
\]

(A19)

The last equation means that spin rotates to the same angle as the scattering one, i.e. spin follows the particle trajectory.

—

See A. Mikhailichenko, CBN 06-1, Cornell LEPP, 2006.
Polarization effects implemented in KONN

POLARIZATION CURVE APPROXIMATION

EP = POSITRON ENERGY / E_{\gamma} - 2mc^2

EP4 = EP \cdot 0.4
EP6 = EP \cdot 0.6
PP = 0.305 + 2.15 \cdot EP4
IF (EP \lt 0.4) PP = PP - 0.05 \cdot EP4 - 2.5 \cdot EP4**3
IF (EP \gt 0.6) PP = PP - 0.55 \cdot EP6 - 2.65 \cdot EP6**2 + 0.7 \cdot EP6**3
IF (PP \gt 1.0) PP = 1.0

Sentinel

Depolarization occurs due to spin flip in act of radiation of quanta having energy \( \hbar \omega \approx E_1 \) where \( E_1 \) stands for initial energy of positron. Depolarization after one single act

\[
D = 1 - \frac{d\sigma_{\text{p}}(\zeta_1, \zeta_1') - d\sigma_{\text{p}}(\zeta_1, \zeta_1)}{d\sigma_{\text{p}}}
\]

Where \( d\sigma_{\text{p}}(\zeta_1, \zeta_1') \) stands for bremsstrahlung cross section without spin flip, \( d\sigma_{\text{p}}(\zeta_1, \zeta_1) \) --the cross section with spin flip and \( d\sigma_{\text{p}} \) is total cross section.

\[
D = \frac{\hbar^2 \omega^2 [1 - \frac{1}{3} \zeta_1^2]}{E_1^2 + E_2^2 - \frac{2}{3} E_1 E_2}
\]

Energy after radiation

\[
L_{\text{dep}} = \frac{1}{n \int D(\vec{p}_1, \zeta_1') d\sigma}
\]

Rad. length

\[
L_{\text{dep}} = \frac{2X_0}{1 - \frac{1}{3} \zeta_1^2} \approx 2X_0
\]

Depolarization \( \sim 5\% \)
Spin flip in undulator

Positron or electron may flip its spin direction while radiating in magnetic field. Probability:

\[
\frac{1}{\tau} [\text{sec}^{-1}] = w_{\text{flip}} = \frac{5 \sqrt{3} r_0^2}{16} \frac{\omega_0^3}{\alpha \gamma^2} \gamma^5 \left(1 - \frac{2}{9} \zeta_||^2 - \frac{8 \sqrt{3}}{15} \frac{e}{|e|} \zeta_\perp \right)
\]

Probability of radiation:

\[
w_{\text{rad}} = \frac{I}{\hbar \omega_0 2 \gamma^2} = \frac{2}{3} \frac{e^4 \hbar^2 \gamma^2}{m^2 c^3} \frac{1}{\hbar \omega_0 2 \gamma^2} = \frac{1}{3} \frac{\alpha \gamma^2 \omega_0}{\omega_0}
\]

\[\lambda_c = r_0 / \alpha = e^3 / m c^3 / \alpha \approx 3.8616 \times 10^{-11}\]

The ratio

\[
\frac{w_{\text{flip}}}{w_{\text{rad}}} = \frac{15 \sqrt{3}}{16} \frac{\lambda_c^2}{\lambda_2^2} \gamma^5 \left(1 - \frac{2}{9} \zeta_||^2 - \frac{8 \sqrt{3}}{15} \frac{e}{|e|} \zeta_\perp \right) \quad (K \sim 1)
\]

Effect of spin flip still small (i.e. radiation is dominating).
Depolarization at IP

- Depolarization arises as the spin changes its direction in coherent magnetic field of incoming beam. Again, here the deviation does not depend on energy, however it depends on location of particle in the bunch: central particles are not perturbed at all. Absolute value of angular rotation has opposite sign for particles symmetrically located around collision axes.

- This topic was investigated immediately after the scheme for polarized positron production was invented. This effect is not associated with polarized positron production exclusively because this effect tolerates to the polarization of electrons at IP as well. Later many authors also considered this topic in detail. General conclusion here is that depolarization remains at the level ~5%.

Kinematic depolarization in undulator

Process can be considered in a system of reference rotating with frequency

$$\tilde{\Omega} = \frac{c}{\lambda_u}$$

$${\frac{d\tilde{\zeta}}{dt}} = \tilde{\zeta} \times (\tilde{\Omega} - \tilde{\Omega}_s) = \tilde{\zeta} \times \tilde{\Omega}_{\text{eff}}$$

where

$$\tilde{\Omega}_{\text{eff}} = \tilde{\Omega}_1 + \tilde{\Omega}_2 = \left[ 1 + \gamma G \right] \frac{eH \lambda_u}{mc \gamma \lambda_u} ; 0 ; \frac{c}{\lambda_u}$$

$$G = (\gamma - 2)/2$$ can be represented as $$G = 1/\gamma_0$$ where $$\gamma_0$$ corresponds to 440.65 MeV

so

$$\tilde{\Omega}_{\text{eff}} = \tilde{\Omega}_1 + \tilde{\Omega}_2 = \left[ 1 + \gamma \frac{\gamma_0}{\gamma} \right] \frac{eH \lambda_u}{mc \gamma \lambda_u} ; 0 ; \frac{c}{\lambda_u}$$

$$\cong \left[ 1 + \gamma \frac{\gamma_0}{\gamma} \right] \frac{eH \lambda_u}{mc \gamma \lambda_u} ; 0 ; \frac{c}{\lambda_u}$$

During passage through undulator spin rotates around $$y'$$

$$\varphi = \tilde{\Omega}_1 t = \frac{K}{\gamma_0 \lambda_u} \frac{c}{\gamma_0} \frac{L}{\lambda_u} \cong 50 \text{ rad}$$

This needs to be taken into account while preparing polarization at IP.

Does not depend on Energy $$\rightarrow$$ depolarization $$\cong (K/L \gamma_0)^2$$
Polarization effects implemented in KONN

Polarization Curve Approximation

$\text{EP} = \text{POSITRON ENERGY/ Egamma-2mc}^2$

$\text{EP4} = \text{EP}_4 + 0.4$
$\text{EP6} = \text{EP}_6 - 0.6$
$\text{PP} = 0.305 + 2.15 \times \text{EP4}$

$\text{IF} (\text{EP} < 0.4) \text{PP} = \text{PP} - 0.05 \times \text{EP4} - 2.5 \times \text{EP4}^2$

$\text{IF} (\text{EP} > 0.6) \text{PP} = \text{PP} - 0.55 \times \text{EP6} - 2.65 \times \text{EP6}^2 + 0.7 \times \text{EP6}^3$

$\text{IF} (\text{PP}) \text{PP} = 1$

Sentinel

Depolarization occurs due to spin flip in act of radiation of quanta having energy $0 < h \omega < E_1$ where $E_1$ stands for initial energy of positron. Depolarization after one single act

$$D = 1 - \left| \frac{d\sigma_p(\zeta_1, \zeta_1) - d\sigma_p(\zeta_1, -\zeta_1)}{d\sigma_p} \right|$$

Where $d\sigma_p(\zeta_1, \zeta_1)$ stands for bremsstrahlung cross section without spin flip, $d\sigma_p(\zeta_1, -\zeta_1)$ —the cross section with spin flip and $d\sigma_p$ is total cross section.

$$D = \frac{\hbar^2 \omega^2 \frac{1}{2} \zeta_1^2}{E_1^2 + E_2^2 - \frac{2}{3} E_1 E_2}$$

Energy after radiation

$$L_{dep} = \frac{1}{n \int D(\vec{p}_1, \zeta_1) d\sigma} \quad \rightarrow \quad L_{dep} = \frac{2X_0}{1 - \frac{1}{3} \zeta_1^2} = 2X_0$$

Rad. length

Depolarization $\sim 5\%$
Depolarization at IP

- Depolarization arises as the spin changes its direction in coherent magnetic field of incoming beam. Again, here the deviation does not depend on energy, however it depends on location of particle in the bunch: central particles are not perturbed at all. Absolute value of angular rotation has opposite sign for particles symmetrically located around collision axes.

- This topic was investigated immediately after the scheme for polarized positron production was invented. This effect is not associated with polarized positron production exclusively because this effect tolerates to the polarization of electrons at IP as well. Later many authors also considered this topic in detail. General conclusion here is that depolarization remains at the level ~5%.

Kinematic depolarization in undulator

Process can be considered in a system of reference rotating with frequency \( \tilde{\omega} = \frac{c}{\lambda_u} \)

\[
\frac{d \tilde{\xi}}{dt} = \tilde{\xi} \times (\tilde{\omega}_z - \tilde{\omega}) = \tilde{\xi} \times \tilde{\omega}_{\text{eff}}
\]

where

\[
\tilde{\omega}_{\text{eff}} = \tilde{\omega}_1 + \tilde{\omega}_1 = \left[ 1 + \frac{1}{\gamma_0} \right] \left\{ \frac{eH}{mc} \frac{c}{\lambda_u} , \frac{c}{\lambda_u} \right\}
\]

\( G = (g-2)/2 \) can be represented as \( G = 1/\gamma_0 \) where \( \gamma_0 \) corresponds to 440.65 MeV

So

\[
\tilde{\omega}_{\text{eff}} = \tilde{\omega}_1 + \tilde{\omega}_1 = \left[ 1 + \frac{1}{\gamma_0} \right] \left\{ \frac{eH}{mc} \frac{c}{\lambda_u} , \frac{c}{\lambda_u} \right\} \approx \left\{ \frac{K}{\gamma_0} \frac{c}{\lambda_u} , \frac{c}{\lambda_u} \right\}
\]

During passage through undulator spin rotates around \( y' \) \( \varphi = \tilde{\omega}_1 t = \frac{K}{\gamma_0} \frac{c}{\lambda_u} \frac{L}{c} = \frac{KL}{\gamma_0 \lambda_u} \approx 50 \text{ rad} \)

This needs to be taken into account while preparing polarization at IP

\( \text{Does not depend on Energy} \rightarrow \text{depolarization} \approx (KL/\gamma_0)^2 \)
CONCLUSIONS ABOUT POLARIZATION

Perturbation of spin is within 10% total (from creation).

This number could be reduced by increasing the length of undulator, making target thinner (two targets) and beams more flat at IP.

After the first target only 13% of photons are lost. So it is possible to install second target and collect positrons from this second target.

Combining in longitudinal phase space could be arranged easily in the same RF separatrix in damping ring.

Additional feed back system will be required for fast dump of coherent motion.

Energy provided by acceleration structures A1 and A2 are slightly different, A1>A2.

This combining can help in reduction of power deposition in target if each target made thinner, than optimal.

Combining scheme allows double positron yield and cut in half the length of undulator.
CONCLUSIONS

Restored start to end code for Monte-Carlo simulation of conversion; Confirmed low K factor possible here; K<0.4 with period 10 mm

For 500 GeV, a conversion system requires more efforts; one solution is to move the system as a whole to a new 150 GeV point.

Tested 10 and 12 mm period undulators, aperture 8 mm, ~40 cm each; Reached K=0.467 for 10 mm period with for 56 filament wire diameter 0.33mm; Longitudinal field profile measured; Reached K=0.83 for 12 mm period undulator wire 0.63mm;

Pumping of Helium was tested, gain >10%;
Radial sectioning will be implemented in the following models

Our calculations show that these parameters satisfy ILC

4-m long Undulator module fabrication and its test is a priority job→ end 2007;
Helical iron yokes of 3 m long obtained from industry;
Wire 0.33 used for latest model; strands x4(used) and by x6 (obtained).

Designed undulator with 6.35mm aperture, K~0.7 for 10mm; and K~1.2 for 12mm

Target, collection optics and spin handling are in scope of our interest.
Back-up slides
Polarized $e^\pm$ production

The way to create circularly polarized positron, left. Cross-diagram is not shown. At the right-the graph of longitudinal polarization as function of particle's fractional energy.

The way to create circularly polarized photon

Polarized electron

V. Balakin, A. Mikhailichenko, 1979

E. Bessonov, A. Mikhailichenko, 1992

Polarization of positrons is a result of positron selection by energy

\[ \hat{\xi} = \xi_2 \left[ f(E_\gamma, E_{\perp}) \cdot \mathbf{\hat{n}}_1 + g(E_\gamma, E_{\perp}) \cdot \mathbf{\hat{n}}_\perp \right] = \hat{\xi}_1 + \hat{\xi}_\perp \]
<table>
<thead>
<tr>
<th>Item</th>
<th>9/07-8/08</th>
<th>9/08-8/09</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Other Professionals</td>
<td>31.0</td>
<td>32.55</td>
<td>63.55</td>
</tr>
<tr>
<td>Graduate Students</td>
<td>21.8</td>
<td>23.762</td>
<td>45.562</td>
</tr>
<tr>
<td>Undergraduate Students</td>
<td>5.0</td>
<td>5.250</td>
<td>10.25</td>
</tr>
<tr>
<td>Total salaries and Wages</td>
<td>57.8</td>
<td>61.562</td>
<td>119.362</td>
</tr>
<tr>
<td>Fringe Benefits</td>
<td>10.23</td>
<td>10.742</td>
<td>20.972</td>
</tr>
<tr>
<td>Total Salaries, Wages and Fringe Benefits</td>
<td>68.03</td>
<td>72.304</td>
<td>140.334</td>
</tr>
<tr>
<td>Equipment</td>
<td>25</td>
<td>49</td>
<td>74</td>
</tr>
<tr>
<td>Travel and transportation</td>
<td>7.5</td>
<td>7.5</td>
<td>15</td>
</tr>
<tr>
<td>Materials and Supplies</td>
<td>30</td>
<td>45</td>
<td>75</td>
</tr>
<tr>
<td>Other direct costs</td>
<td>19.528</td>
<td>21.286</td>
<td>40.814</td>
</tr>
<tr>
<td>Subcontract</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Total direct costs</td>
<td>153.33</td>
<td>195.089</td>
<td>348.417</td>
</tr>
<tr>
<td>Indirect costs</td>
<td>62.263</td>
<td>73.634</td>
<td>135.897</td>
</tr>
<tr>
<td>Total direct and indirect costs</td>
<td>212.321</td>
<td>268.723</td>
<td>481.044</td>
</tr>
</tbody>
</table>