Polarized Electrons Source for BINP C-Tau Factory

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Outline

• Introduction to BINP C-tau factory project.

• Longitudinal polarization scheme for C-tau.

• BINP experience with constructing PES for AmPS-complex.

• Worldwide overview of PES for High Energy Physics.

• Novel approach to beam-line optics with dispersion-free bends.

• Final remarks and conclusion.
Main features of the Novosibirsk Tau-Charm factory

- Symmetric energies of the electron and positron beams.
- Wide energy range.
- Crab-Waist collision scheme.
- High luminosity.
- Longitudinal polarization of the electron beam at IP.
- Polarized positrons? Possibly, under consideration.
- SC wigglers will provide constant damping time and constant emittances in full energy range.

Production of: $p\bar{p}$, $n\bar{n}$, $\tau^+\tau^-$, $J/\Psi$, $\Psi'$, $\Psi''$, $D\bar{D}$, $\Lambda_c\bar{\Lambda}_c$, ...

CP-violation studies

\[ E^+ = E^- = 1.0 - 2.5 \text{ GeV} \]

\[ L \approx 1 \cdot 10^{35} \text{ cm}^{-2} \text{s}^{-1} \]

\[ P = 70 - 80 \% \]

\[ \tau_{rad}(E) = 30 \text{ ms} \]
Polarization scheme with 3 snakes 
\( (\text{arc}=120^0, \text{2 damping wigglers in the arc’s middle}) \)

Number of snakes may vary from a single (at 1 GeV) to 3 or 5 at J/Psi and above to keep radiative depolarization rate low enough
Transparent spin rotator made of two solenoids

To decouple x,y-motions should be $T_x = -T_y$ (Litvinenko, Zholentz, 1980)

$$\begin{pmatrix} -\cos \varphi & -2r \sin \varphi \\ (2r)^{-1} \sin \varphi & -\cos \varphi \end{pmatrix}$$ - for the spin transparency! (Koop et al., SPIN2006)

Two solenoids rotate spin by the angle $\varphi$.

$\varphi = 180^0$ for full Siberian Snake.

Then $\int B ds \ (T \cdot m) = \pi \frac{B \rho}{1 + a} = 10.467 \cdot E \ (GeV)$

All quads between solenoids are not skewed!
Depolarization time in presence of snakes

\[ \tau_p^{-1} = \frac{5\sqrt{3}}{8} \lambda_e r_e c \gamma^5 \left( K^3 \left( 1 - \frac{2}{9} (\vec{n} \vec{v})^2 + \frac{11}{18} \vec{d}^2 \right) \right) \]

Here \( K = \rho^{-1} \), \( |\vec{v}| = 1 \)

Spin transparency cancels the betatron contribution to \( d \):

\[ \vec{d} = d_\gamma + d_\beta \], then:

\[ \vec{d}^2(0) = \frac{\pi^2}{4} \sin^2 \frac{\pi \nu}{n_{\text{snk}}} \]

\[ \langle \vec{d}^2 \rangle = \vec{d}^2(0) + \frac{\pi^2}{3} \frac{\nu^2}{n_{\text{snk}}^2} \]

Placing damping wigglers in minimum of \( |d| \) weakens depolarizing effects of SR

\[ \vec{d} = \gamma \frac{\partial \vec{n}}{\partial \gamma} \]

is the spin–orbit coupling vector

\[ \vec{d}^2(\theta) \]

\[ E = 1 \text{ GeV} \]

\[ \vec{d}^2(\theta) \]

\[ n_{\text{snk}} = 1 \]

\[ \vec{\theta} = \int K(\theta)d\theta \]
Polarization degree energy dependence

Assuming 90% polarization from PES

1 snake

3 snakes

5 snakes
4 Damping wigglers are switched on for operation below 2.5 GeV, making damping time and emittance independent of energy.  

Wigglers are installed in places where stable spin direction is longitudinal. There spin-orbit coupling is minimal. 

As a result, the equilibrium spin direction becomes longitudinal in the middle points between snakes. 

5 Solenoid type spin rotators (Snakes) rotate spin around the longitudinal axis by 180° (as shown).
# The Novosibirsk C-tau factory parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy</td>
<td>1.0 – 2.5</td>
<td>GeV</td>
</tr>
<tr>
<td>Circumference</td>
<td>765</td>
<td>m</td>
</tr>
<tr>
<td>Crossing angle</td>
<td>60</td>
<td>mr</td>
</tr>
<tr>
<td>Emittances, $\varepsilon_x/\varepsilon_y$</td>
<td>8 / 0.04</td>
<td>nm</td>
</tr>
<tr>
<td>Number of bunches</td>
<td>390</td>
<td></td>
</tr>
<tr>
<td>Number of particles/bunch</td>
<td>$7 \cdot 10^{10}$</td>
<td></td>
</tr>
<tr>
<td>Total current</td>
<td>1.7</td>
<td>A</td>
</tr>
<tr>
<td>Beta function, $\beta_x/\beta_y$</td>
<td>4 / 0.08</td>
<td>cm</td>
</tr>
<tr>
<td>Sigma, $\sigma_x/\sigma_y$</td>
<td>18 / 0.18</td>
<td>mkm</td>
</tr>
<tr>
<td>Luminosity</td>
<td>$0.6 - 1.0 \cdot 10^{35}$</td>
<td>cm$^{-2}$s$^{-1}$</td>
</tr>
</tbody>
</table>
Layout of the BINP C-tau factory injection complex

Injection facility exists

Tunnel for the linac and the technical straight section of the factory is ready
Amsterdam Pulse Stretcher complex with longitudinally polarized e- beam for internal target experiments

BINP in collaboration with NIKHEF and ISP (SB RAS) has built PES and SC solenoids for Siberian Snake at AmPS


AmPS – Amsterdam Pulse Stretcher
PES – Polarized Electron Source
SM – Spin Manipulator
MP – Mott Polarimeter
L1 – Laser (Ti-Sapphire) for PES
AM – Alpha Magnet
TG – Thermionic Gun
MEA – up to 720 MeV linac
SS – Siberian Snake
IT – Internal Target (polarized!)
L2 – Compton Polarimeter
L3 – Laser for polarized $^3$He target
S – focusing solenoids
BM – bending magnets
EB – electrostatic deflectors
CM – beam current monitor
EM – beam profile monitor
C – RF buncher/acceleration cavities

Polarized Electron Source at AmPS stretcher ring

B.L. Militsyn et al.
**Pulsed Polarized Electron Source for AmPS.**

*Built in 1995 by BINP in collaboration with NIKHEF (Amsterdam) and ISP (Novosibirsk).*

- **AmPS energy range**: 440 – 720 MeV
- **Beam polarization**: 80 %
- **Polarization lifetime**: 3000 – 4500 s
- **Cathode voltage (pulsed)**: -100 kV
- **Photocathode type**: Strained InGaAsP
- **Laser type**: Ti – Sapphire
- **Light wavelength**: 700 – 850 nm
- **Laser power in a pulse**: 200 W
- **Pulse duration**: 2.1 μs
- **Repetition rate**: 1 Hz
- **Maximum current from a gun**: 150 mA
- **Operational current**: 15 – 20 mA
- **Photocathode recession time**: (depends on laser power) 190 – 560 hours
Pulsed 100 kV photocathode gun for AmPS

2,3 – UHV pumping ports
4 – acceleration vacuum chamber
5 - anode
6,11 – gun insulators
7 - cathode
8 – high voltage cable
9 – polyethylene insulator
10 – guard vessel
12 – port of preparation chamber
13 – guard vessel pumping port
-100 kV pulsed power supply of AmPS PES

- Dramatic increase of a cathode’s lifetime: up to 560 hours! Before in DC mode it was only 4-5 hours.
- Good enough pulse flat top uniformity
- Reliable and safe
CEBAF load-locked dc high voltage GaAs photogun with an inverted-geometry ceramic insulator

This robust design (option b) with small modifications could serve as a solution for C-Tau PES!
200 keV Polarized Electron Gun for ILC
(Nagoya University, M. Yamamoto et al.)

- Ultra high vacuum < $10^{-9}$ Pa
- High field gradient > MV/m

Photocathode puck ($\phi$23mm)

- Photocathode preparation with Load-Lock (cleaning, NEA activation)
**Electrode Design & Fabrication (Nagoya U.)**

**Mo cathode**
- Material: pure Mo (>99.96%)
- Size: \( \Phi 162 \text{mm} \)
- Space Charge Limit: 30A
- Maximum field gradient: 
  - 7.8 MV/m \( @ \) electrode

**Ti anode**
- Material: pure Ti (JIS-grade 2)

**Gap:** 22mm
Reducing field emission dark current

Electrode shape

anode

\[ R \text{ 24} \]

\[ \text{flat top} \phi 2 \]

gap

\[ R \text{ 15} \]

\[ \phi 48 \text{: mm} \]

cathode

Nagoya & KEK

Gap 0.5mm results

F.Furuta et al., NIM-A 538 (2005) 33-44

Test sample

I.Koop, HKUST IAS, Hong Kong
## Best photocathodes

From L.Gerchikov presentation at PESP 2008 workshop

<table>
<thead>
<tr>
<th>Sample</th>
<th>Composition</th>
<th>P&lt;sub&gt;max&lt;/sub&gt;</th>
<th>QE(ω&lt;sub&gt;max&lt;/sub&gt;)</th>
<th>Team</th>
</tr>
</thead>
<tbody>
<tr>
<td>SLSP16</td>
<td>GaAs(3.2nm)/GaAs&lt;sub&gt;0.68&lt;/sub&gt;P&lt;sub&gt;0.34&lt;/sub&gt; (3.2nm)</td>
<td>92%</td>
<td>0.5%</td>
<td>Nagoya University, 2005</td>
</tr>
<tr>
<td>SL5-777</td>
<td>GaAs(1.5nm)/In&lt;sub&gt;0.2&lt;/sub&gt;Al&lt;sub&gt;0.23&lt;/sub&gt;Ga&lt;sub&gt;0.57&lt;/sub&gt;As(3.6nm)</td>
<td>91%</td>
<td>0.14%</td>
<td>SPbSPU, 2005</td>
</tr>
<tr>
<td>SL7-307</td>
<td>Al&lt;sub&gt;0.4&lt;/sub&gt;Ga&lt;sub&gt;0.6&lt;/sub&gt;As(2.1nm)/In&lt;sub&gt;0.19&lt;/sub&gt;Al&lt;sub&gt;0.2&lt;/sub&gt;Ga&lt;sub&gt;0.57&lt;/sub&gt;As(5.4nm)</td>
<td>92%</td>
<td>0.85%</td>
<td>SPbSPU, 2007</td>
</tr>
</tbody>
</table>

I.Koop, HKUST IAS, Hong Kong
SL Al$_{0.19}$ In$_{0.2}$ Ga$_{0.61}$As(5.4nm)/Al$_{0.4}$Ga$_{0.6}$As(2.1nm)
(PESP 2008, L.G. Gerchikov et al., SPTU & FTI, St.Petersburg, Russia)

$P_{\text{max}} = 92\%$, $\text{QE} = 0.85\%$
## Main parameters of PES for C-tau

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam polarization</td>
<td>90 %</td>
</tr>
<tr>
<td>Photocathode Quantum Efficiency</td>
<td>0.5%</td>
</tr>
<tr>
<td>Cathode voltage (pulsed mode)</td>
<td>100 kV</td>
</tr>
<tr>
<td>Photocathode type</td>
<td>AlInGaAs/AlGaAs Super Lattice with strained QW (Yu.Mamaev et al., St. Petersburg SPU)</td>
</tr>
<tr>
<td>Laser type</td>
<td>Ti – Sapphire</td>
</tr>
<tr>
<td>Light wavelength</td>
<td>700 – 850 nm</td>
</tr>
<tr>
<td>Laser energy in a pulse</td>
<td>10 mkJ</td>
</tr>
<tr>
<td>Pulse duration</td>
<td>2 ns</td>
</tr>
<tr>
<td>Repetition rate</td>
<td>50 Hz</td>
</tr>
<tr>
<td>Number of electrons/pulse</td>
<td>$2 \times 10^{10}$</td>
</tr>
</tbody>
</table>
New approach to beam transport through the Z-shaped spin manipulator: dispersion free bends!

Beam from PES is not monochromatic due to space charge or due to the voltage ripples. The idea of a new spin rotator is to bent beam by crossed E and B fields chosen in such ratio that such bend becomes achromatic, at least in linear approximation on $\delta=\Delta p/p$.


Spin precession frequency:

$$\Omega = -\frac{e}{\gamma mc} \left[ \left( a + \frac{1}{\gamma} \right) B + \left( a + \frac{1}{\gamma} \right) E \right]$$

$$\Omega_v = -\frac{e}{\gamma mc} \left[ B + \frac{E}{\beta} \right] = -\frac{eB}{\gamma mc} \cdot \frac{1}{\gamma^2 + 1}$$

Spin tune: $\nu = \Omega/\Omega_v - 1 = \gamma(1+2a)$

In general: $\frac{1}{\rho} = -\frac{e}{\gamma \beta mc^2} \left( B + \frac{E}{\beta} \right)$, $\gamma = \frac{1}{\sqrt{1 - \beta^2}}$

We want: $\frac{d}{d\beta} \left( \frac{1}{\rho} \right)_{\beta=\beta_0} = 0 \rightarrow E = -\frac{\beta_0}{2 - \beta_0^2} B$

Then: $\frac{1}{\rho} \rightarrow -\frac{eB}{\gamma_0^2 \beta_0 mc^2} \cdot \frac{\gamma_0^2 - 1}{\gamma_0^2 + 1}$ - achromatic in linear approximation! Here we remind that the velocity dependence of $\rho^{-1}(\beta)$ is given by:

$$\rho^{-1}(\beta) = -\frac{eB \sqrt{1 - \beta^2}}{\beta mc^2} \left( 1 - \frac{\beta_0}{\beta(2 - \beta_0^2)} \right)$$
Focusing properties of the dispersion free bend and the second order dispersion

Assuming $B \sim 1/ r^{n_B}$, $E \sim 1/ r^{(n_E+1)}$

$$\nu_x^2 = (1-n_B)(\gamma^2 + 1) + n_E \gamma^2$$

$$\nu_z^2 = n_B(\gamma^2 + 1) - n_E \gamma^2$$

$$\nu_x^2 + \nu_z^2 = \gamma^2 + 1$$

$$\nu_x = \nu_z \text{ for } n_E = 0, n_B = 0.5$$

Hamiltonian description of orbital motion in crossed E and B fields is derived by S.R.Mane, NIMA 687 (2012) 40-50

In higher orders the curvature $\rho^{-1}$ of the dispersion free bend is:

$$\left. \frac{r_0}{\rho} \right|_{r=r_0} = 1 - \left( \frac{3}{2} - \frac{1}{2\gamma^2} \right) \delta^2 + \left( \frac{7}{2} - \frac{2}{\gamma^2} + \frac{1}{2\gamma^4} \right) \delta^3 \quad \text{with } \delta = \frac{\Delta p}{p}$$
Preliminary Z-shape spin manipulator parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>PES Beam Energy:</td>
<td>E=100 keV</td>
</tr>
<tr>
<td>Lorentz factors:</td>
<td>$\beta=0.54822$, $\gamma=1.195695$</td>
</tr>
<tr>
<td>Spin tune:</td>
<td>$\nu=1.198468$</td>
</tr>
<tr>
<td>Velocity/spin rotation angles:</td>
<td>$\phi=75.1^0 / 90^0$</td>
</tr>
<tr>
<td>Bending radius:</td>
<td>$\rho=25$ cm</td>
</tr>
<tr>
<td>Vertical magnetic field:</td>
<td>B=108.6 Gs</td>
</tr>
<tr>
<td>Radial electric field:</td>
<td>E= -10.5 kV/cm</td>
</tr>
<tr>
<td>Magnetic field index:</td>
<td>$n_B=0.5$</td>
</tr>
<tr>
<td>Electric field index:</td>
<td>$n_E=0$</td>
</tr>
<tr>
<td>Betatron tunes:</td>
<td>$\nu_x = \nu_z = 1.1022$</td>
</tr>
</tbody>
</table>

Z-manipulator is comprised from two achromatic bends, which rotate spin by $90^0$ each, and a set of solenoids in between and after. Choosing appropriate spin rotations by these solenoids one can receive any wanted direction of the polarization after passing through Z-manipulator.
Preliminary Z-shape spin manipulator layout

- Both two dispersion free bends rotate beam by $75^0$, while spin vector by $90^0$.
- Then the first pair of solenoids rotate spins around the longitudinal axis by any needed angle, keeping beam focusing almost constant.
- The second bend rotates spins again by $90^0$ around the vertical axis.
- At the exit of Z-manipulator two solenoids can rotate spins around the longitudinal axis.
- Adjusting the strength and polarities of solenoids in each pair one can vary the spin rotation angle between $-90^0$ and $+90^0$, thus providing achievement of any arbitrary spin direction at the end of such spin rotator.
- Polarity of the second dispersion free bend could be chosen opposite to that shown on the picture.
Bunching and pre-acceleration before injection into main linac

• The laser pulse width is planned to be within 1-2 ns.

• The bunching and pre-acceleration of a beam before injection into main linac can be done either at the main linac frequency or at its subharmonic. In the Amsterdam polarization project setup it was done directly at 2856 MHz.

• The bucket width of C-Tau factory is 6 ns. So, there is no need to squeeze the polarized e-beam into a single linac-frequency bucket. The train of 3-5 bunches fits the task, occupying less than 1.6 ns.

• Alpha-magnet is planned to be used for the injection of polarized beam into main 2.5 GeV linac. Its opposite to drifts sign of the slip-factor helps very much to improve the bunching efficiency.
Conclusion

- BINP has a good experience in constructing of PES. First was made in 90-th in collaboration with the NIKHEF and ISP.

- Since that time the Super-Lattice cathodes were developed with up to 92% polarization level and 0.85% of quantum efficiency (SPTU & FTI, St.Petersburg – tested at SLAC, Nagoya University). We intend to use these cathodes for the C-Tau project.

- New idea to use crossed E and B fields to bent beam in Z-shape spin-manipulator, creating the dispersion free bends, will improve the polarized beam quality. Instead of DC high-voltage power supply now the pulsed one can be used. This greatly reduces the dark-current problem and makes the cathode life-time much longer.

- PES for C-Tau need to be developed early in advance...
Thank you for your attention!