Polarized Electrons Source for BINP C-Tau Factory

I.A.Koop,
BINP, 630090 Novosibirsk, Russia

IAS HKUST Conference on HEP
January 23-26, 2017
Hong Kong

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: $p\bar{p}, n\bar{n}, \tau^+\tau^-,$

$J/\Psi, \Psi', \Psi'', D\bar{D}, \Lambda_c\bar{\Lambda}_c, \ldots$

CP-violation studies

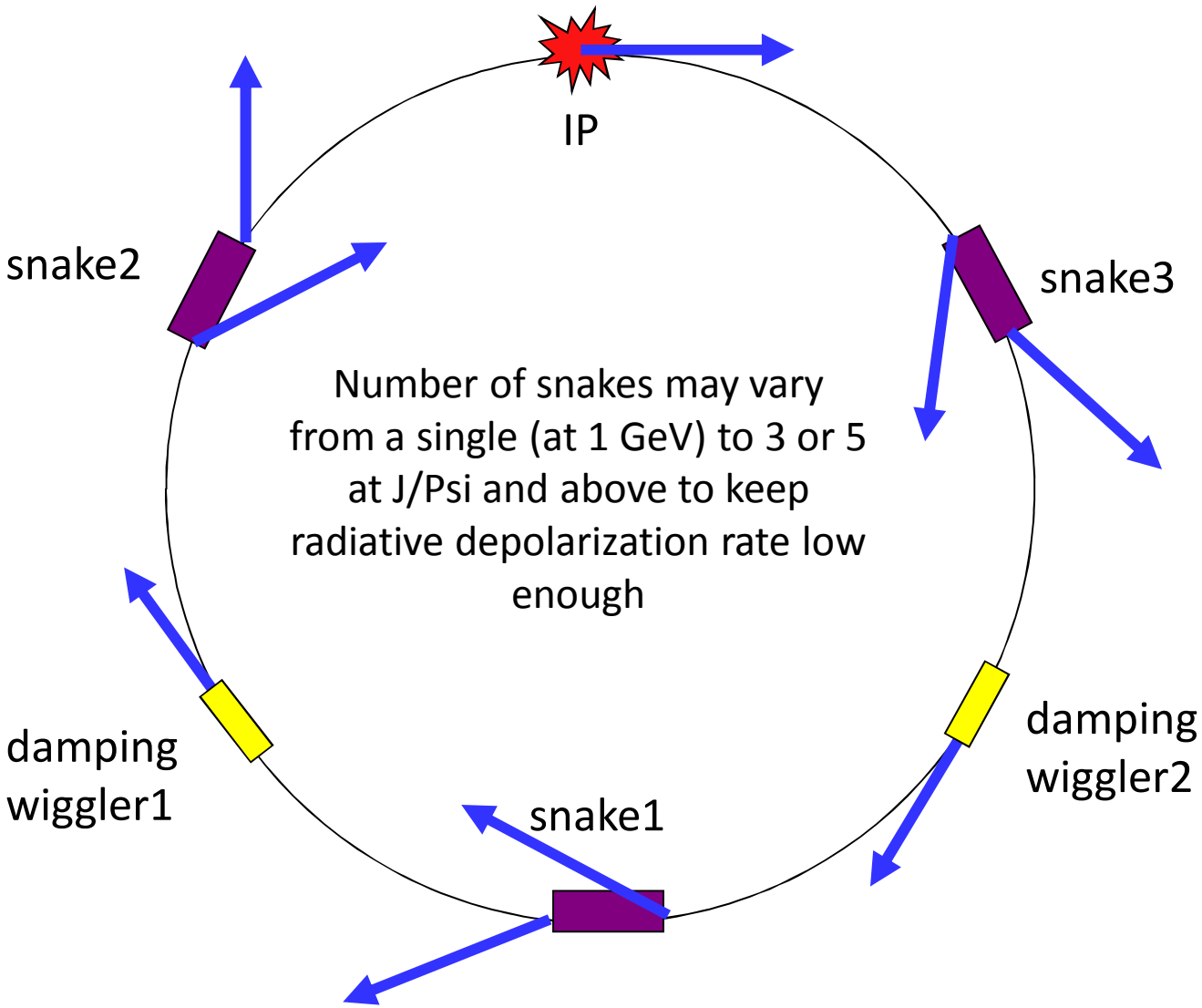
$$E^+ = E^- = 1.0 - 2.5\ GeV$$

$$L \approx 1 \cdot 10^{35}\ cm^{-2}s^{-1}$$

$$P = 70 - 80\ \%$$

$$\tau_{rad}(E) = 30\ ms$$

Polarization scheme with 3 snakes (arc=120^0 , 2 damping wigglers in the arc's middle)



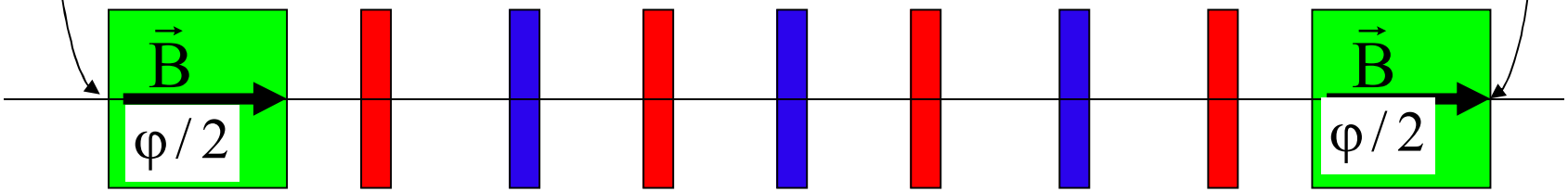
Transparent spin rotator made of two solenoids

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

$$T_x = \begin{pmatrix} -\cos\varphi & -2r\sin\varphi \\ (2r)^{-1}\sin\varphi & -\cos\varphi \end{pmatrix}$$

- for the spin transparency!

(Koop et al., SPIN2006)



$r = pc/eB$

Two solenoids rotate spin by the angle φ.

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

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

All quads between solenoids are not skewed!

Depolarization time in presence of snakes

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

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

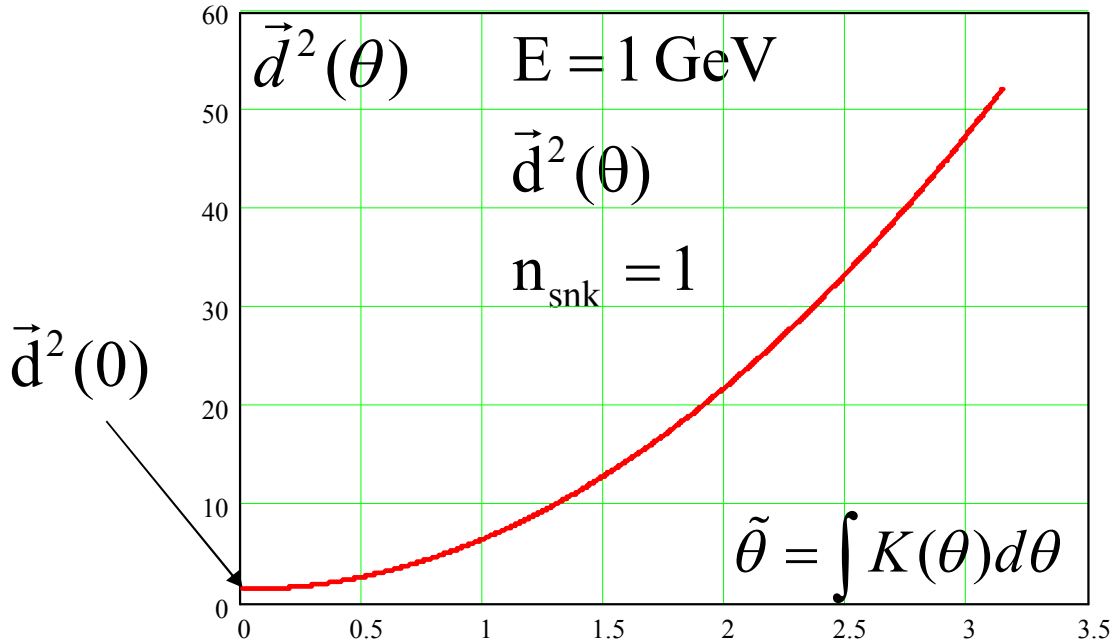
$\vec{d} = \gamma \frac{\partial \vec{n}}{\partial \gamma}$ is the spin – orbit coupling vector

Spin transparency cancels the betatron contribution to d: $\vec{d} = \vec{d}_\gamma + \cancel{\vec{d}_\beta}$, then:

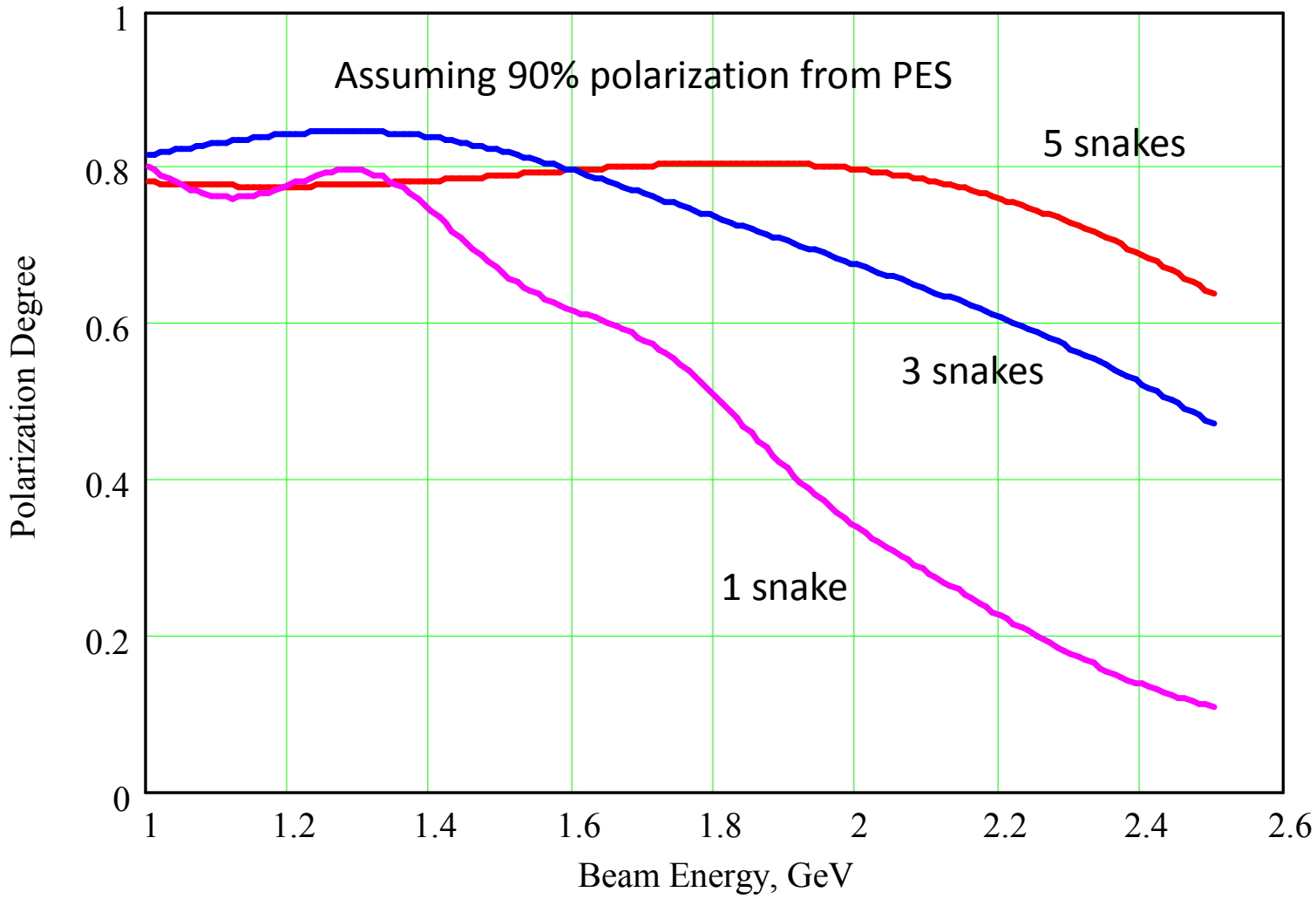
$$\vec{d}^2(0) = \frac{\pi^2}{4}\sin^2\frac{\pi\nu}{n_{snk}}$$

$$\left\langle \vec{d}^2 \right\rangle = \vec{d}^2(0) + \frac{\pi^2}{3}\frac{\nu^2}{n_{snk}^2}$$

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

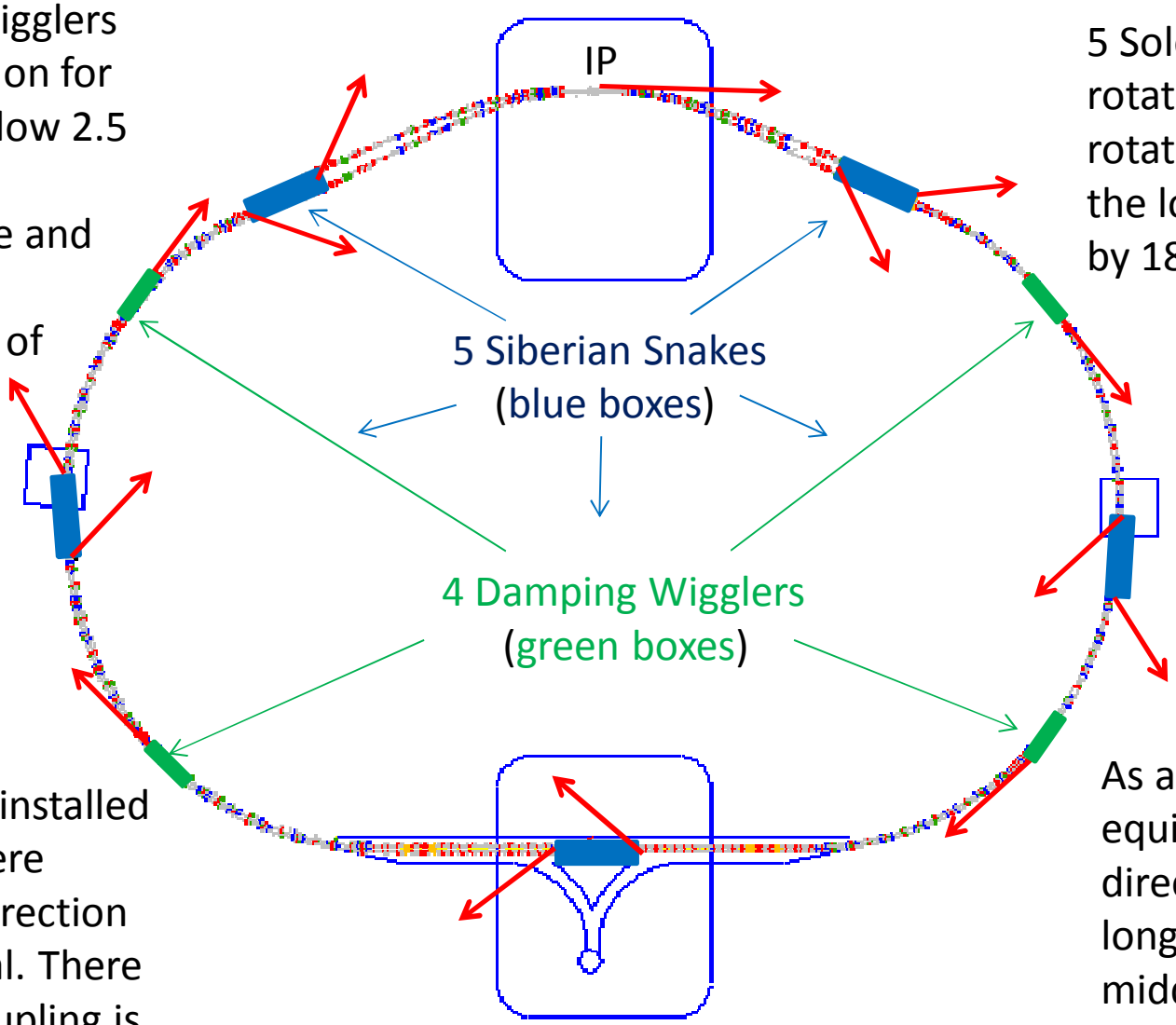


Polarization degree energy dependence



BINP C-tau factory layout with 5 snakes

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



5 Solenoid type spin rotators (Snakes) rotate spin around the longitudinal axis by 180^0 (as shown).

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

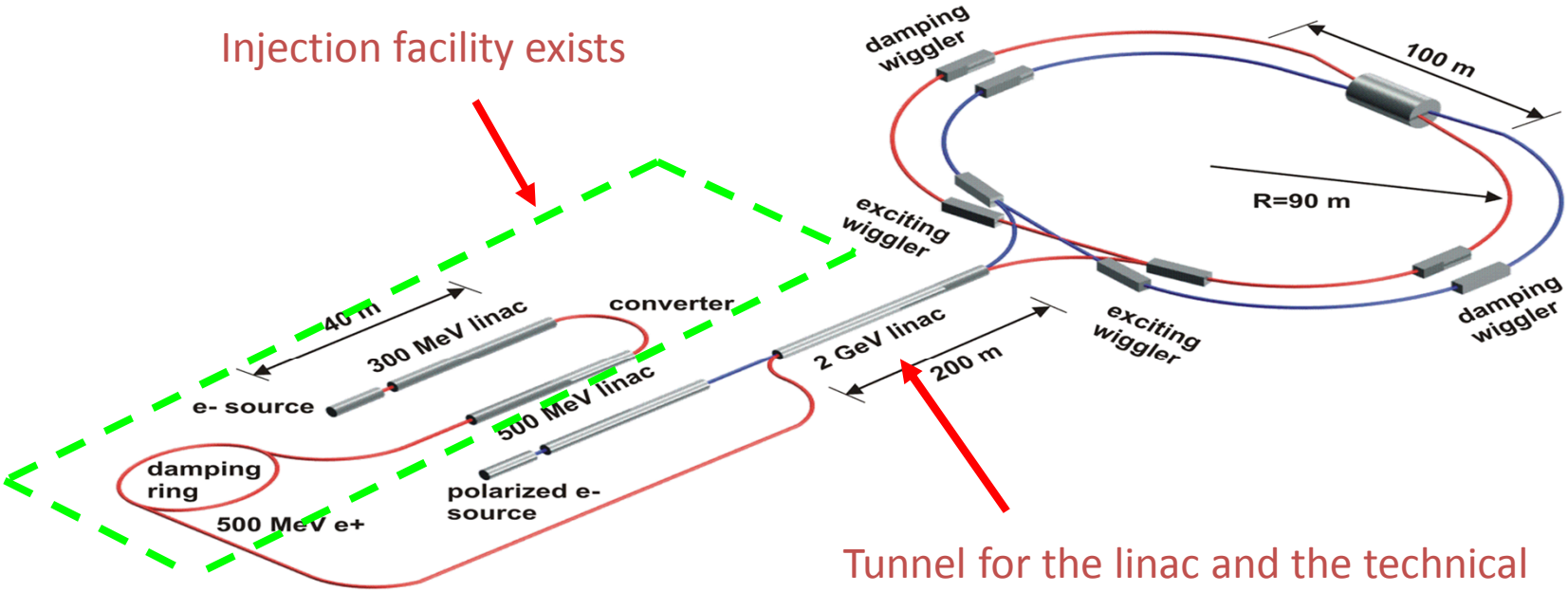
As a result, the equilibrium spin direction becomes longitudinal in the middle points between snakes.

The Novosibirsk C-tau factory parameters

Energy	1.0 – 2.5	GeV
Circumference	765	m
Crossing angle	60	mr
Emittances, $\varepsilon_x / \varepsilon_y$	8 / 0.04	nm
Number of bunches	390	
Number of particles/bunch	$7 \cdot 10^{10}$	
Total current	1.7	A
Beta function, β_x / β_y	4 / 0.08	cm
Sigma, σ_x / σ_y	18 / 0.18	mkm
Luminosity	$0.6 - 1.0 \cdot 10^{35}$	$cm^{-2}s^{-1}$

Layout of the BINP C-tau factory injection complex

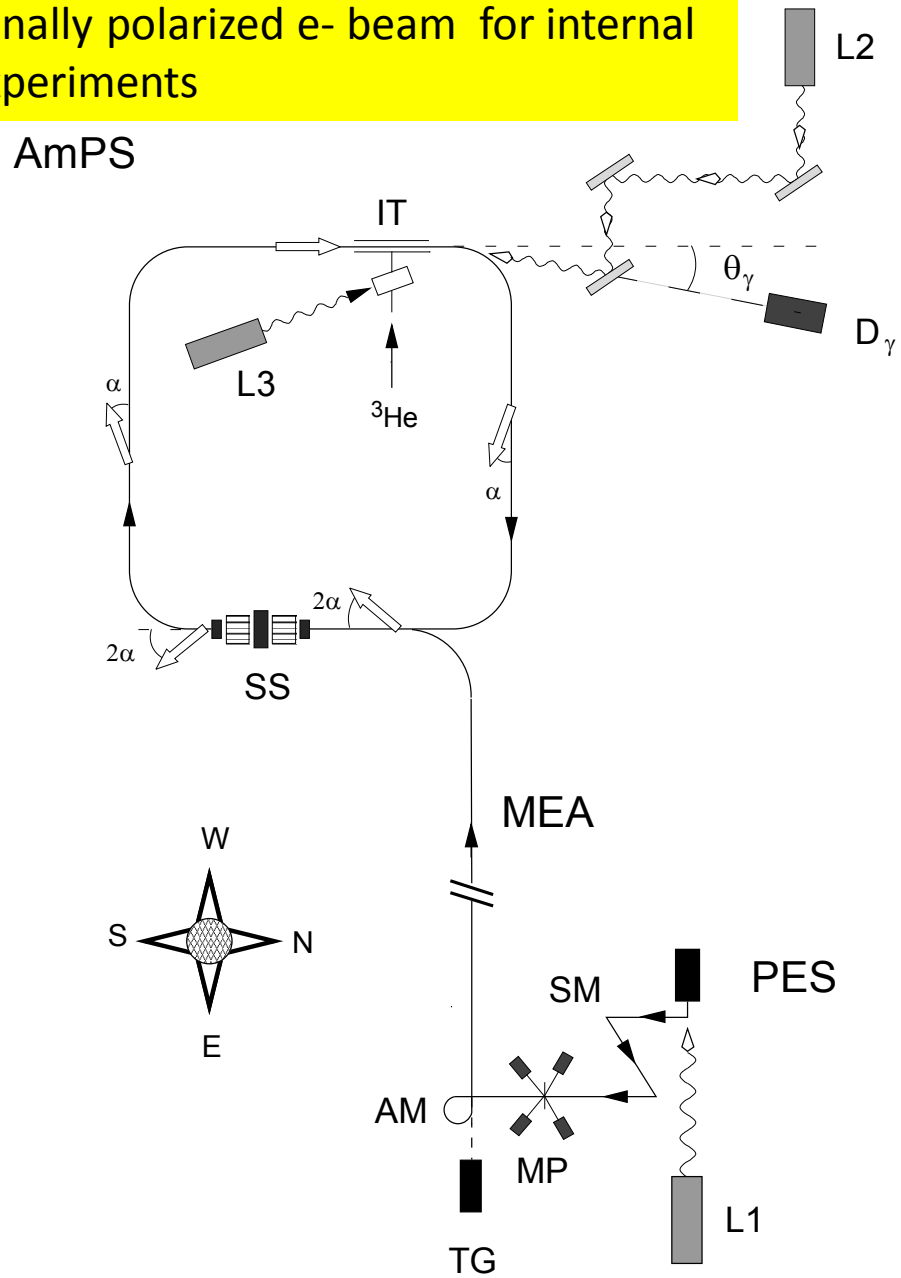
Injection facility exists



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



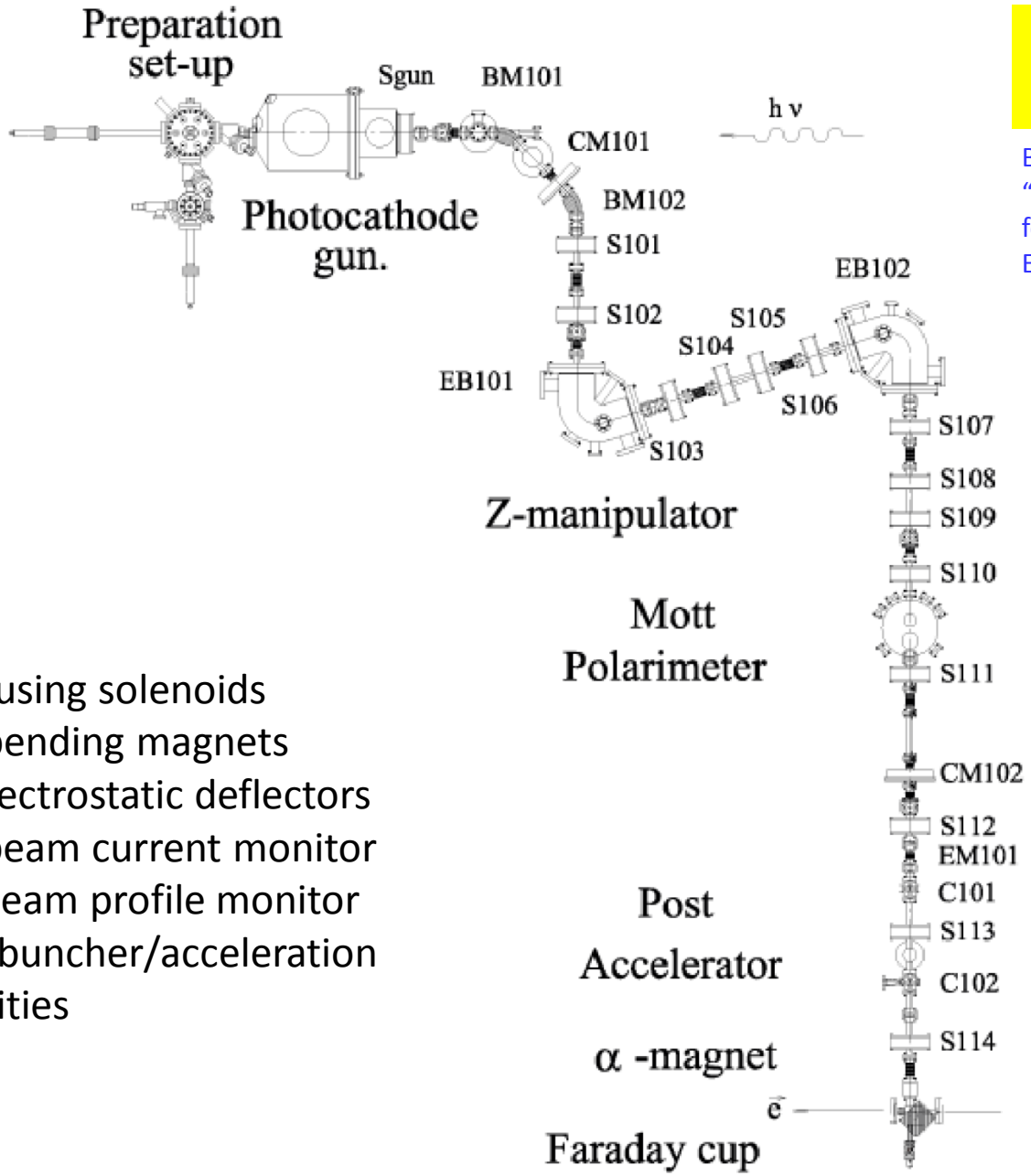
P.W.M.Ferro-Luzzi et al.,
"Longitudinally polarized electrons at AmPS",
SPIN 98, Protvino, Russia.

B.L.Militsyn
"A pulsed Polarized Electron Source for Nuclear Physics Experiments", Ph.D. thesis, 1998.

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

Polarized Electron Source at AmPS stretcher ring

B.L.Militsyn et al.
"The pulsed polarized electron source for nuclear physics experiments at AmPS", EPAC98,1415-1417, Stockholm 1998



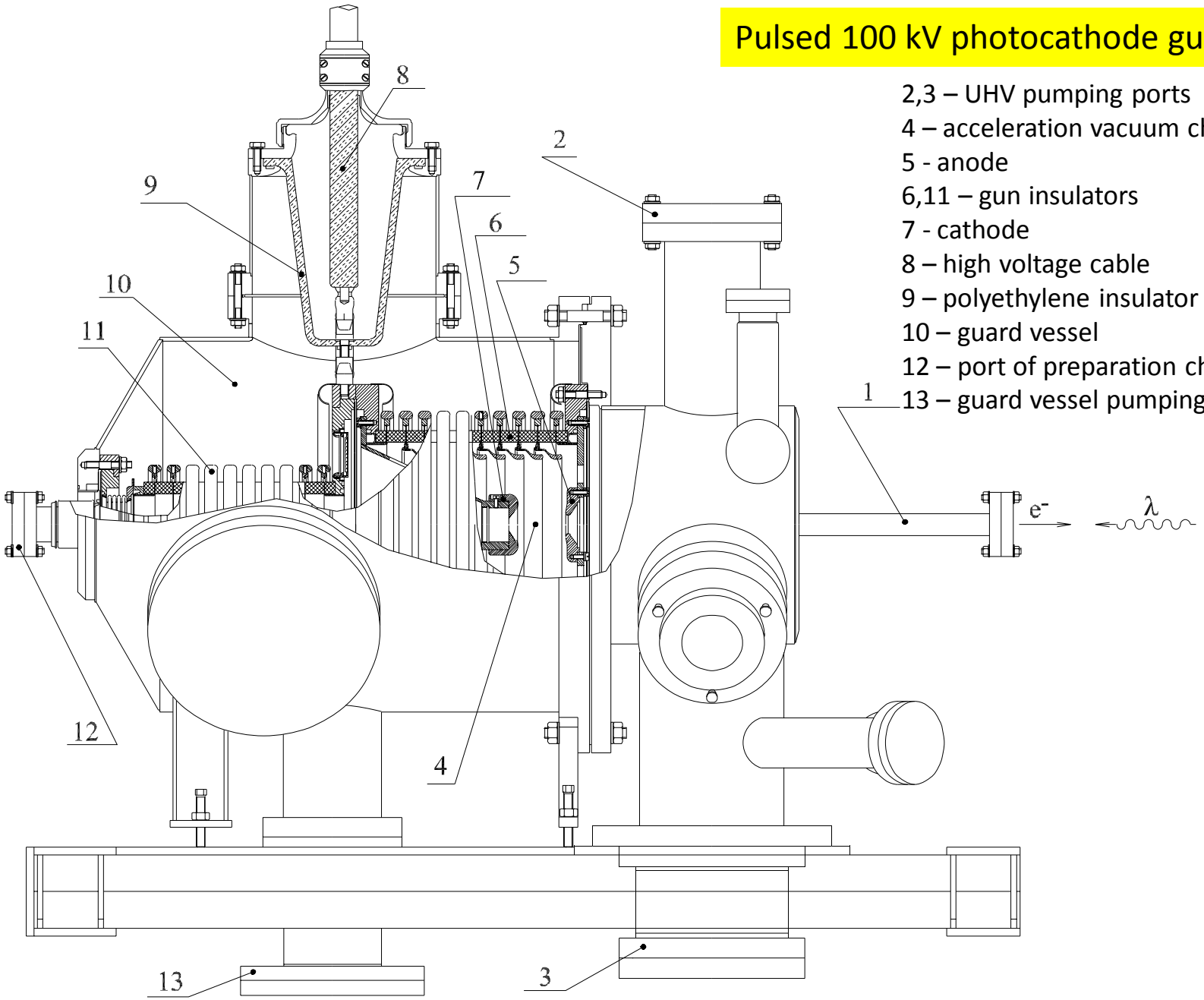
S – focusing solenoids
BM – bending magnets
EB – electrostatic deflectors
CM – beam current monitor
EM – beam profile monitor
C – RF buncher/acceleration cavities

Pulsed Polarized Electron Source for AmPS.

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

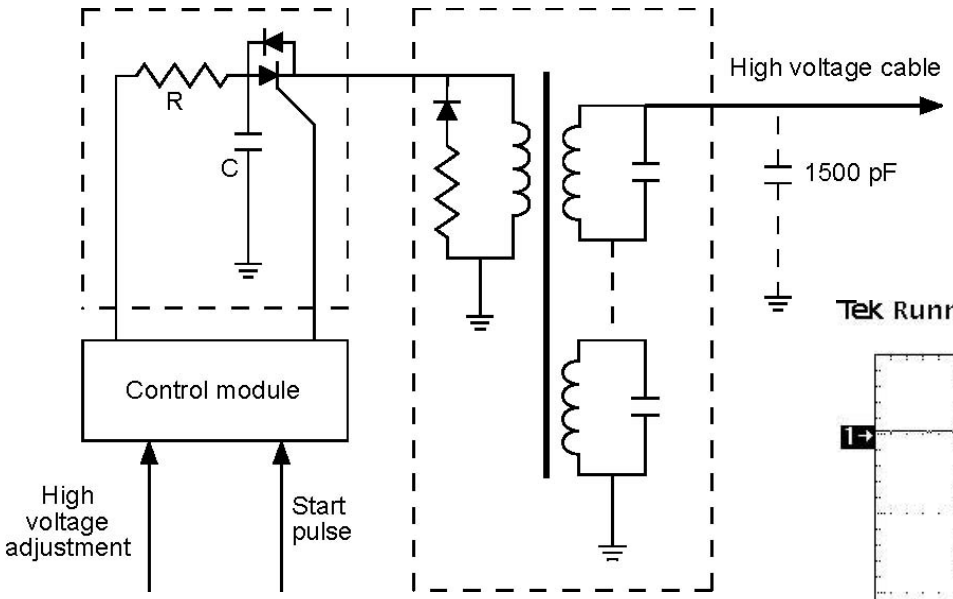
- AmPS energy range 440 – 720 MeV
- Beam polarization 80 %
- Polarization lifetime 3000 – 4500 s
- Cathode voltage (pulsed) -100 kV
- Photocathode type Strained InGaAsP
- Laser type Ti – Sapphire
- Light wavelength 700 – 850 nm
- Laser power in a pulse 200 W
- Pulse duration 2.1 μs
- Repetition rate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

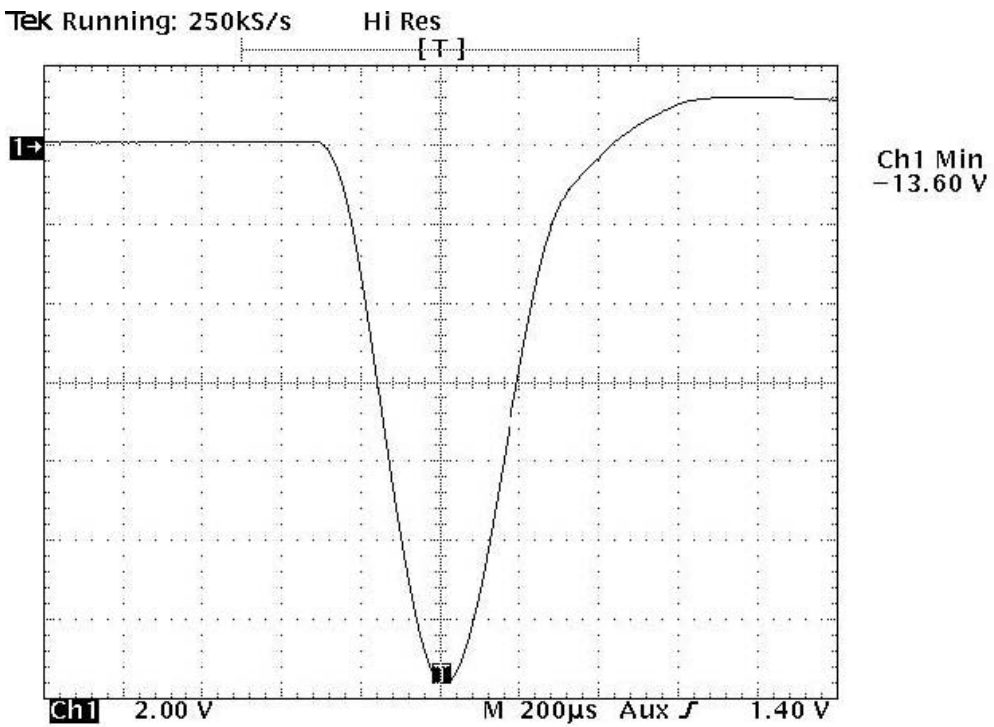
Pulsed 100 kV photocathode gun for AmPS



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

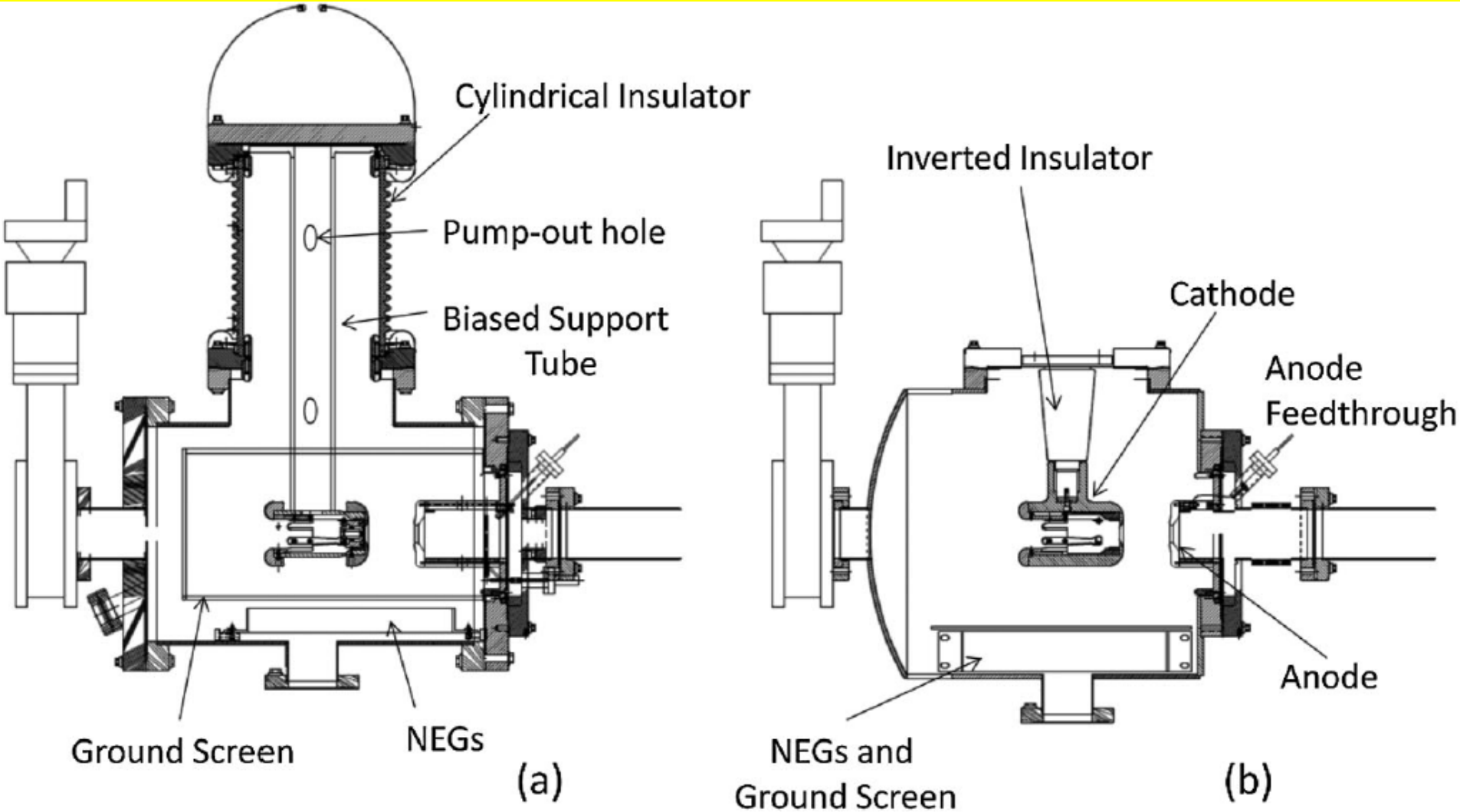
-100 kV pulsed power supply of AmPS PES





- 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

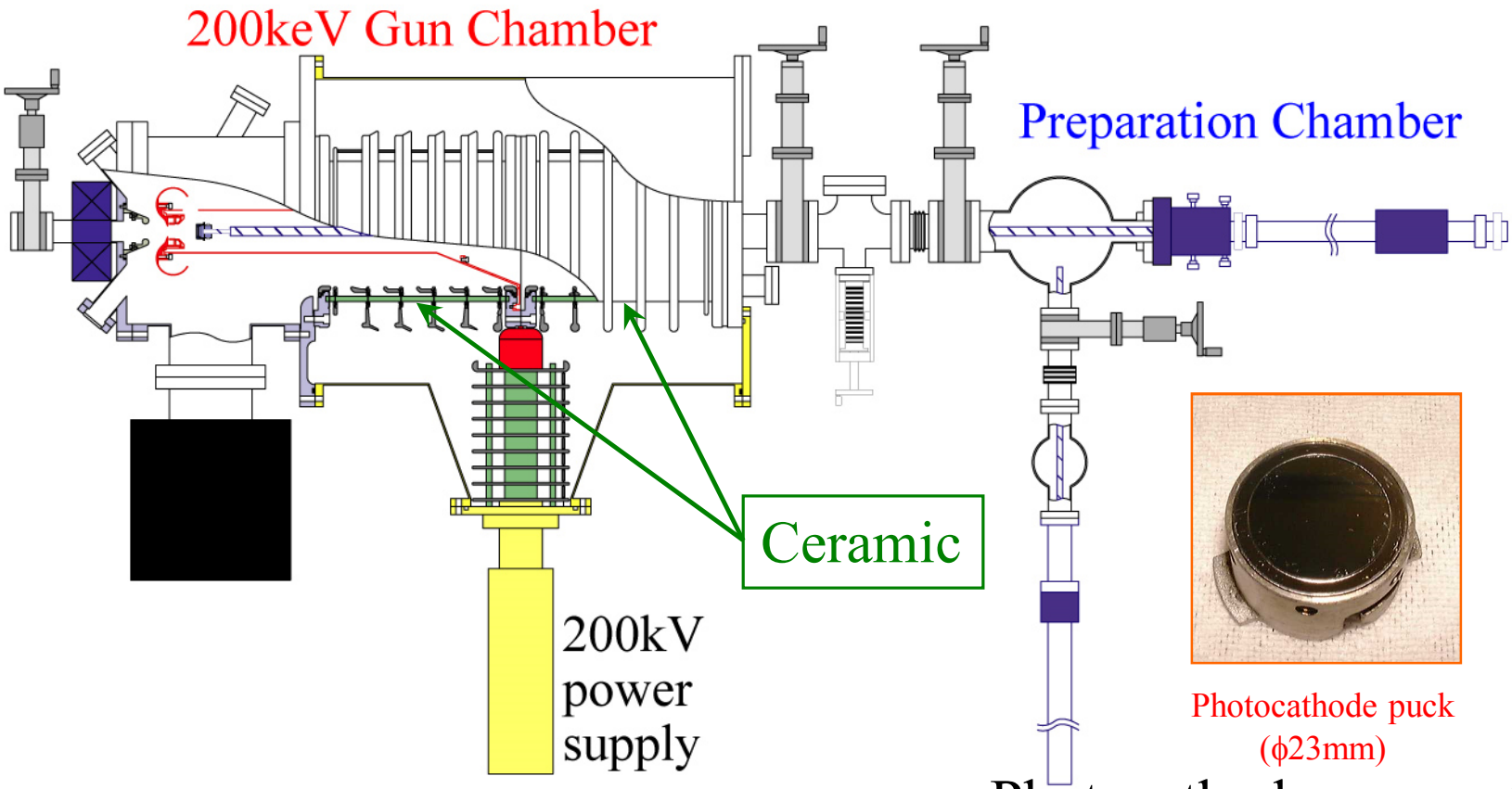
CEBAF load-locked dc high voltage GaAs photogun with an inverted-geometry ceramic insulator



This robust design (option b) with small modifications could serve as a solution for C-Tau PES!

200 keV Polarized Electron Gun for ILC

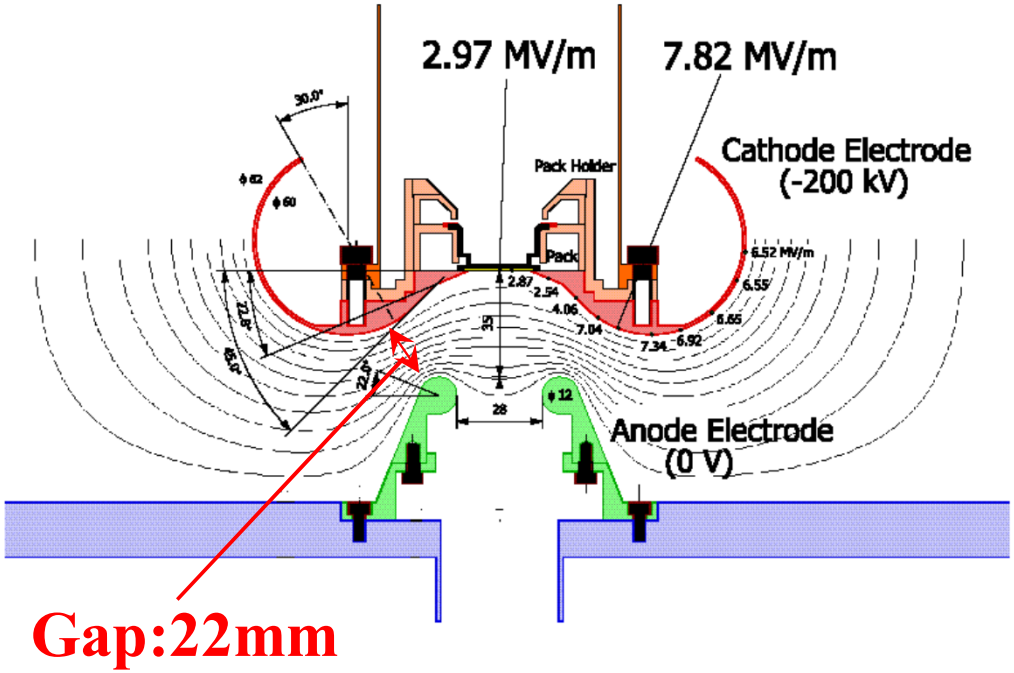
(Nagoya University, M.Yamamoto et al.)



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

- Photocathode preparation with Load-Lock (cleaning, NEA activation)

Electrode Design & Fabrication (Nagoya U.)



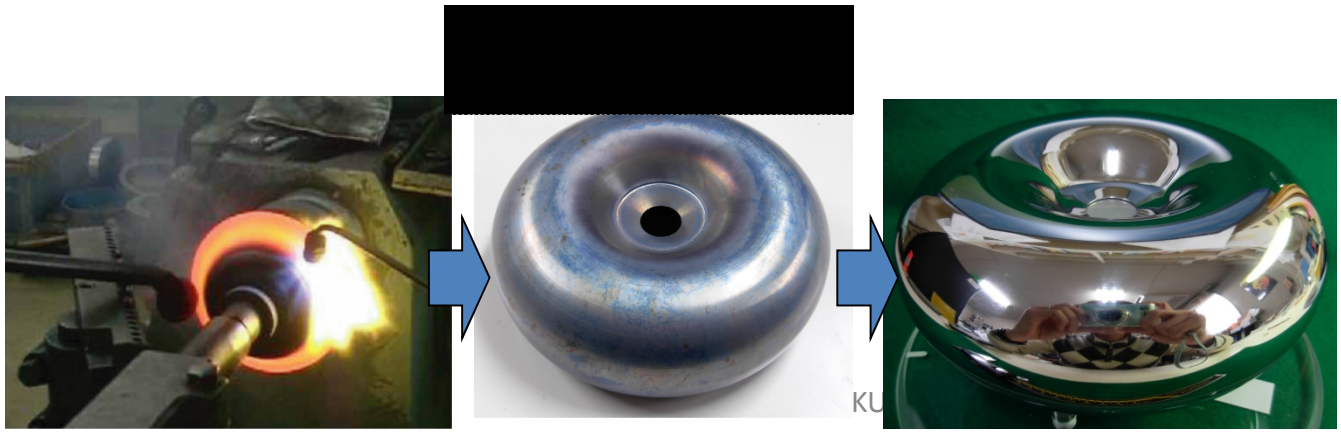
Mo cathode

Material : pure Mo (>99.96%)
Size : ϕ 162mm
Space Charge Limit: 30A
Maximum field gradient:
7.8 MV/m @electrode

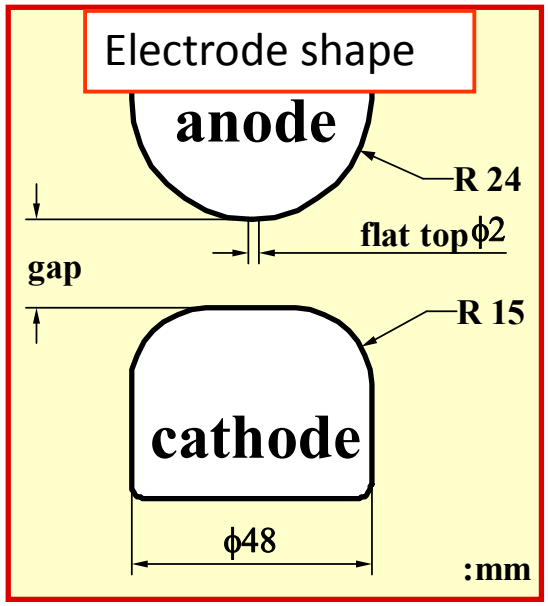
Ti anode

Material : pure Ti (JIS-grade 2)

[redacted]



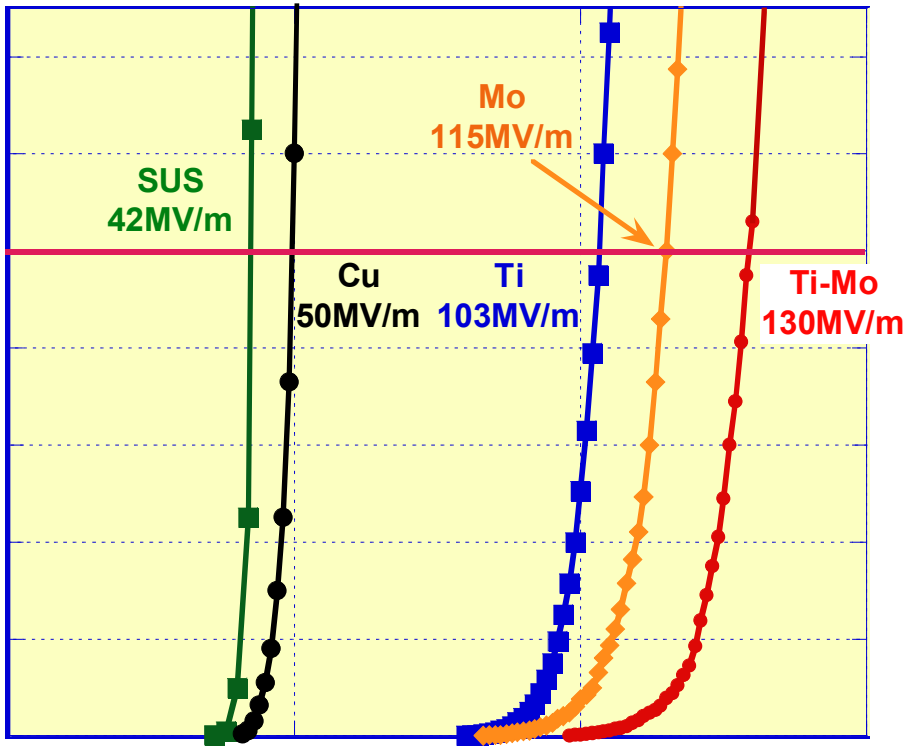
Reducing field emission dark current



Test sample

Nagoya & KEK

Gap 0.5mm results



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

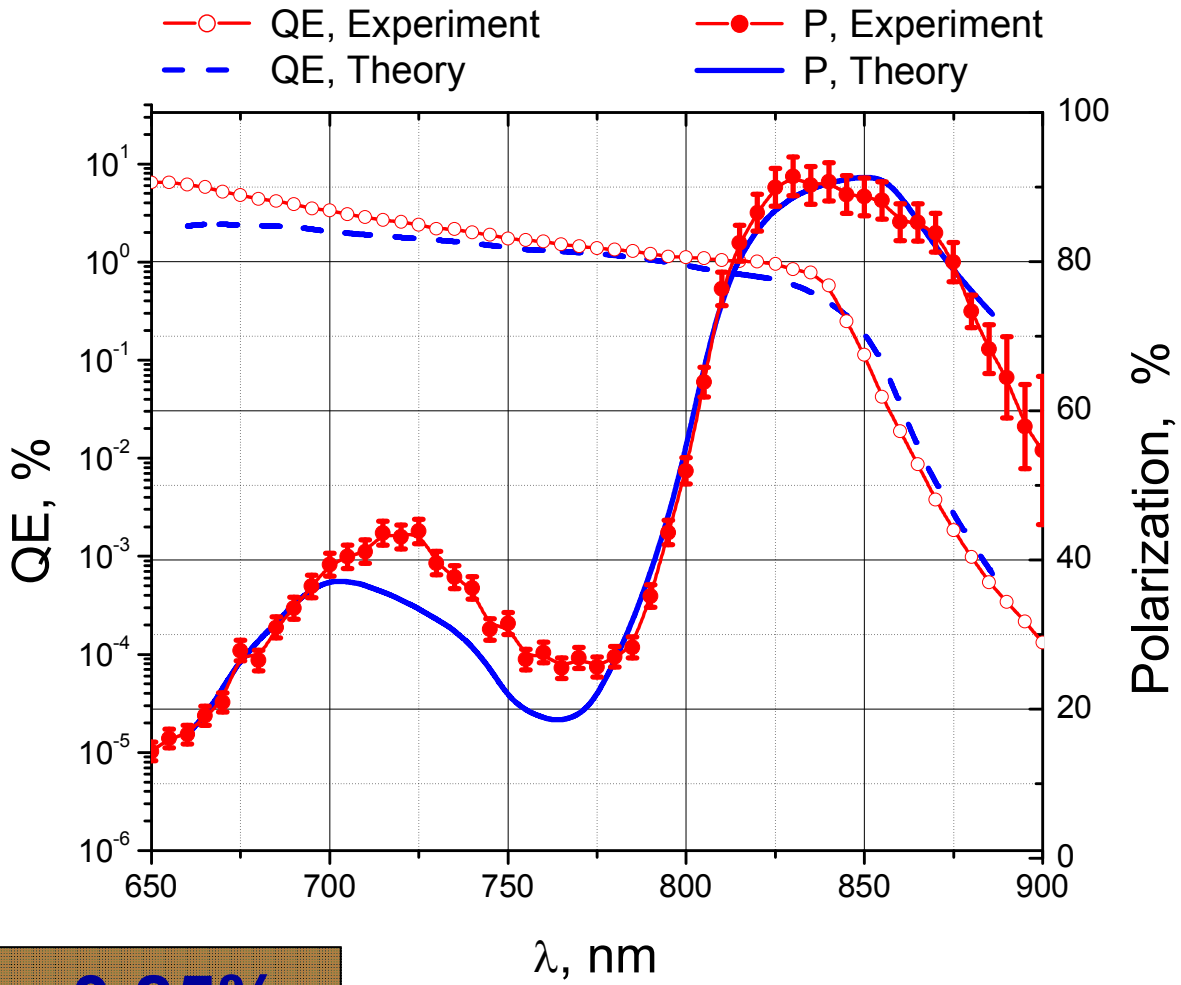
Best photocathodes

From L.Gerchikov presentation at PESP 2008 workshop

Sample	Composition	P_{max}	$QE(\omega_{max})$	Team
SLSP16	GaAs(3.2nm)/ $GaAs_{0.68}P_{0.34}$ (3.2nm)	92%	0.5%	Nagoya University, 2005
SL5-777	GaAs(1.5nm)/ $In_{0.2}Al_{0.23}Ga_{0.57}As$(3.6nm)	91%	0.14%	SPbSPU, 2005
SL7-307	$Al_{0.4}Ga_{0.6}As$(2.1nm)/ $In_{0.19}Al_{0.2}Ga_{0.57}As$(5.4nm)	92%	0.85%	SPbSPU, 2007

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_{max}= 92%, QE = 0.85%

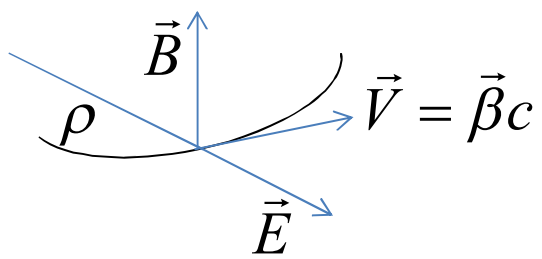
Main parameters of PES for C-tau

- Beam polarization 90 %
- Photocathode Quantum Efficiency 0.5%
- Cathode voltage (pulsed mode) 100 kV
- Photocathode type AlInGaAs/AlGaAs Super Lattice with strained QW (Yu.Mamaev et al., St. Petersburg SPU)
- Laser type Ti – Sapphire
- Light wavelength 700 – 850 nm
- Laser energy in a pulse 10 mkJ
- Pulse duration 2 ns
- Repetition rate 50 Hz
- Number of electrons/pulse $2*10^{10}$

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 δ=Δp/p.

See I. A. Koop, A. V. Otboyev, P. Yu. Shatunov and Yu. M. Shatunov, "Two Examples of In-Flight Spin Flippers", Physics of Particles and Nuclei, 2014, Vol. 45, No. 1, pp. 279–282.



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: $\frac{1}{\rho} = -\frac{e}{\gamma\beta mc^2}\left(B+\frac{E}{\beta}\right), \quad \gamma = \frac{1}{\sqrt{1-\beta^2}}0$

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

Then: $\frac{1}{\rho} \rightarrow -\frac{eB}{\gamma_0\beta_0 mc^2}\cdot\frac{\gamma_0^{\,2}-1}{\gamma_0^{\,2}+1}$ - 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 $B \sim 1/r^{n_B}$, $E \sim 1/r^{(n_E+1)}$

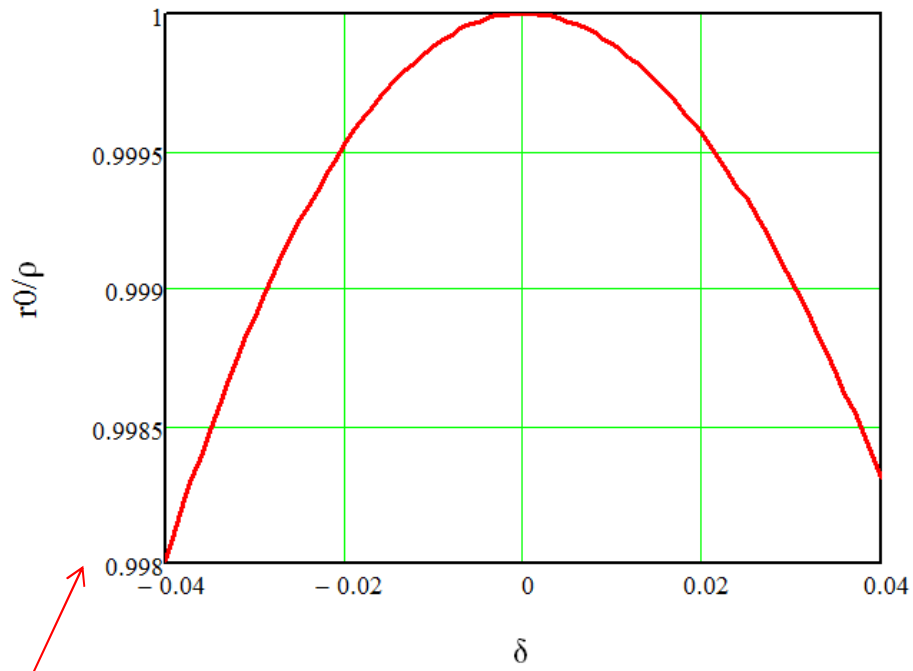
$$\nu_x^{\ 2} = (1-n_B)(\gamma^2+1) + n_E\gamma^2$$

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

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

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

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 ρ^{-1} of the dispersion free bend is:

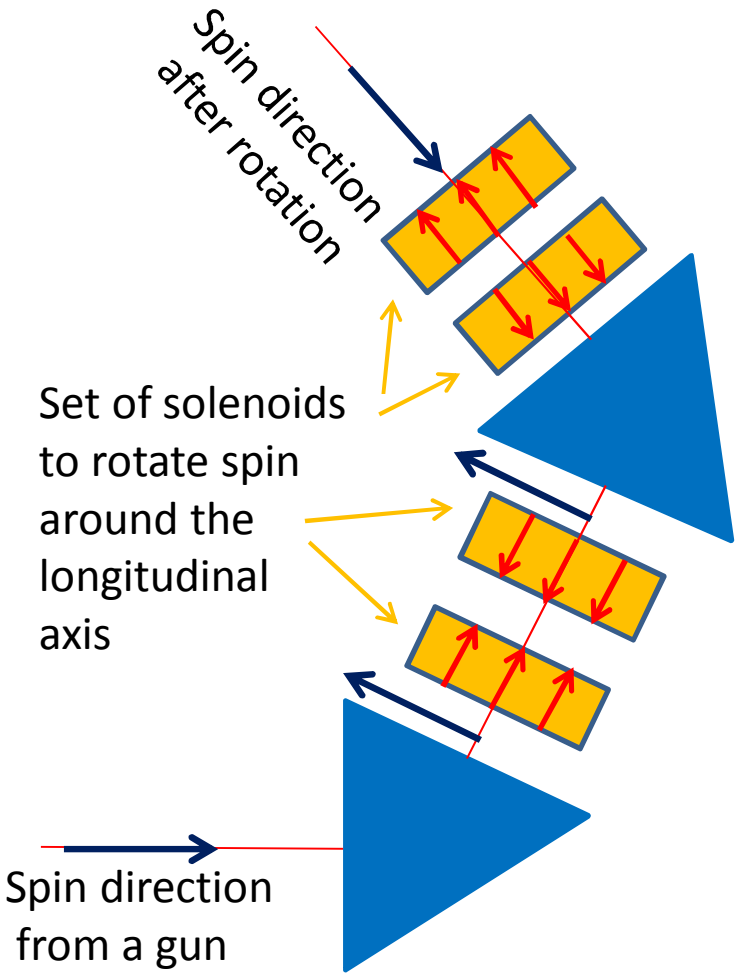
$$\left.\frac{r0}{\rho}\right|_{r=r0} = 1 - \left(\frac{3}{2} - \frac{1}{2\gamma^2}\right)\delta^2 + \left(\frac{7}{2} - \frac{2}{\gamma^2} + \frac{1}{2\gamma^4}\right)\delta^3 \quad \text{with } \delta = \frac{\Delta p}{p}$$

Preliminary Z-shape spin manipulator parameters

PES Beam Energy:	E=100 keV
Lorentz factors:	β=0.54822, γ=1.195695
Spin tune:	ν=1.198468
Velocity/spin rotation angles:	ϕ=75.1^0 / 90^0
Bending radius:	ρ=25 cm
Vertical magnetic field:	B=108.6 Gs
Radial electric field:	E= -10.5 kV/cm
Magnetic field index:	n_B=0.5
Electric field index:	n_E=0
Betatron tunes:	$\nu_x = \nu_z = 1.1022$

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!