LITHIUM LENS FOR ILC POSITRON SOURCE

Alexander Mikhailichenko, Cornell University, LEPP, Ithaca, NY 14853

Abstract. Here we summarize the properties of Lithium Lens (LL) as a key element of collection optics in positron source of ILC. Usage of this lens allows for a drastic increase of collection efficiency compared to a traditional Adiabatic Matching Device (AMD) system. Other positive features of collection optics with LL are: an increase of e^+ polarization and significant cost reduction for the positron source in general.

INTRODUCTION

ILC principal scheme is shown in Figure 1. Helical undulator installed in a chicane at ~150 *GeV*. Here electron beam is used for generation of circularly polarized gammas. Further on these gammas are transformed into positrons inside thin target, ~$0.5X_0$. Meanwhile electron beam is going to IP without any significant disturbance.

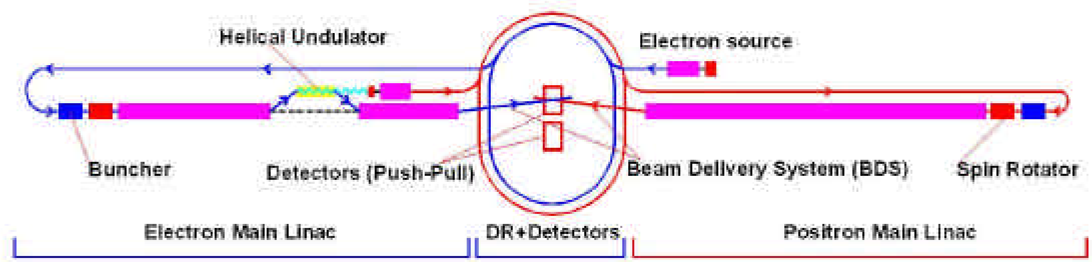

Figure 1: General layout of ILC. Helical undulator installed in a chicane at ~150*GeV* frontier.

Undulator positron source as a separate unit is shown in Fig.2 below.

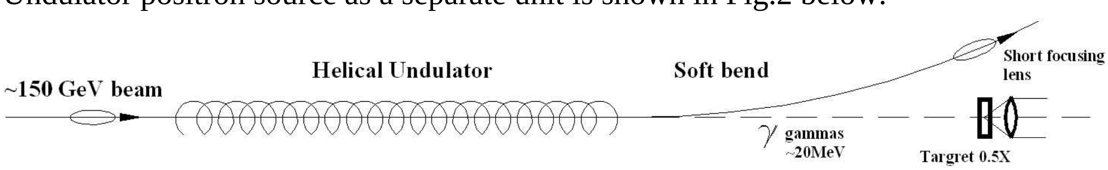

Figure 2: Concept of positron source. For ILC type machine the mostly appropriate is SC helical undulator having period 1.0-1.2cm.

Collection optics is an electro-optical system located right after the target, where the primary photons converted into electron-positron pairs. Main functionality is linked to a short-focused lens, having focal point inside the target, see Fig.3 below.

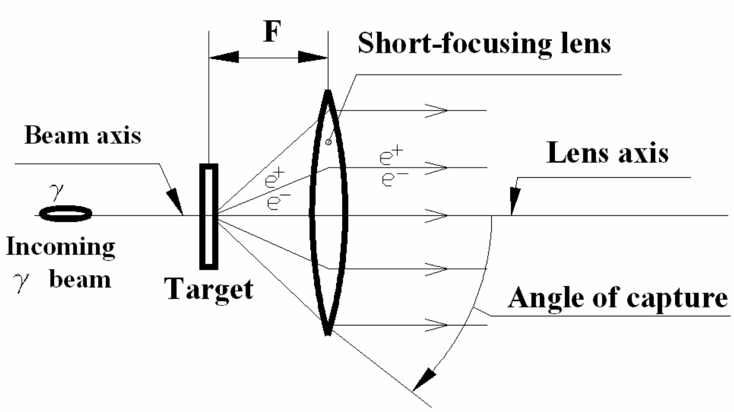

Figure3: Geometry of capturing. Target located at the distance F – the focal distance of the lens. Shortening the focal distance allows for a smaller beam size at the exit or the enlargement of the angle of capture.

For ILC the baseline for a target is a spinning Titanium disk (rod)[1]. This is done to avoid destruction of the target under significant power deposition in the material of the target under exposure to the primary gamma beam. Some other possibilities for conversion of the target include a liquid metal target using W, Pb/Bi or Hg [2]. Another example of target has first layer at the entrance made from Tungsten and the second (outer layer) made from Titanium. The full thickness of the target in this case becomes ~3mm.

Conversion efficiency is defined below as a ratio of the number of positrons created to the number of gammas

$$h = N_{positrons} / N_{gammas}$$

Typically, the conversion efficiency defined above depends on the photon energy, the type of material and thickness of the target.

After the positrons come out of target, they need to be captured. *Capturing efficiency* (Geometrical capturing efficiency) defined here as the ratio of captured positrons to the all amount of positrons created (in all angles and full energy interval; this amount of positrons is the same as used in previous relation.).

Table 1. Properties of some materials used in targeting

	Ti	Be	Li	W	Hg	Pb	Bi
Atomic weight, ***A***	47.9	9.012	6.939	183.8	200.6	207.2	208.98
Atomic number, ***Z***	22	4	3	74	80	82	83
Rad length X_0, [g/cm^2]	16.5	64.13	81.06	6.76	6.5	6.37	6.22
Length of X_0 l_{X_0}, cm	3.58	34.7	152.1	0.35	0.48	0.56	0.63
Density r, [g/cm^3]	4.50	1.846	0.533	19.254	13.59	11.34	9.79
Boil temperature, ^{o}C	3287	2970	1347	5660	356.58	1740	1560
Melt, ^{o}C	1660	1278	180.54	3410	-38.87	327.5	271.3

There are few types of focusing systems used for positron collection: so called Adiabatic Matching Device (AMD), Compact Solenoidal System (CSS), Lithium Lens (LL), and Horn Focuser System (HFS)[1]. The last two represent devices making so called Quarter Wave Transformations (QWT), which means that the beam rays coming out of the source with a wide angular spread, after passage through QWT are transformed into a parallel flow. Of course, such a transformation is chromatic sensitive.

The typical capturing efficiency calculated with so-called adiabatic matching device (AMD) is ~15-20% (see for example [3]), as one can see, that capturing angle, counted from straight –forward direction is something about 0.05-0.1 rad only (see Fig.4).

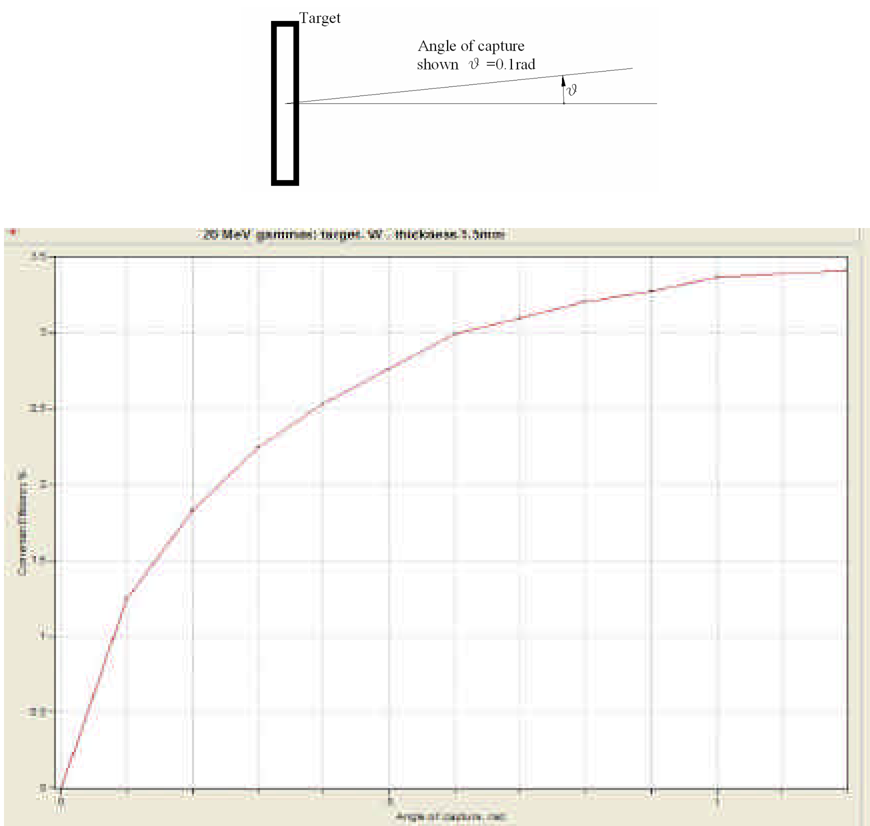

Figure 4: Capturing efficiency, %, as a function of capturing angle (within this angle the particles are captured by collection optics, see Fig.1) for 20 MeV gammas irradiating 1.5 mm thick-W target. Angle shown at the top is 0.1 rad. Energy of positrons captured ~15 ± 5 *MeV*.

Usage of collection optics has a peculiarity here as the target in baseline made as a spinning rim, perturbs the focusing magnetic field as a result of eddy currents induced in a moving metal [2]. So the magnetic field must be absent (or significantly reduced) in a target region. Indeed, AMD optics requires the presence of magnetic field in the target. This method proposed many years ago at SLAC and served successfully for

[1] Also called X-lens; used in BINP, Novosibirsk for positron collection at VEPP-2 complex.

SLC, reaching one-to-one conversion at ~30GeV primary electron beam. One other solution for collection optics with a partial flux concentrator one can find in [5].

Positrons generated efficiently with its energy close to the so called critical one, when ionization losses equates with radiation ones, which is around 600/Z~ 10 MeV, so the entire thickness of target, few radiation lengths, is used for the generation of photons. As positrons are created by photons having a wide spectrum, the positrons are distributed over energy widely as well. In contrast with ordinary electron/positron conversion, the usage of an undulator allows for a remarkably narrow spectrum.

For a small-aperture solenoidal lens the field drops at the distance ~diameter of aperture, so the usage of a small-aperture solenoid as a lens also becomes possible here. The pulsed solenoidal magnet is considered as baseline for the positron capturing system, though currently it delivers a lower efficiency than AMD [3].

On the other hand if optics captures the particles in an angle up to 0.5 rad, then geometrical efficiency becomes ~80%. So finding more effective capturing principles and devices becomes a very important business for an ILC type machine.

An increase in the efficiency of capturing helps in lowering of the maximal temperature of the hot spot in a target. It also helps in the reduction of field in undulator as a sequence.

Li lens emerges as a device satisfying these requirements [4].

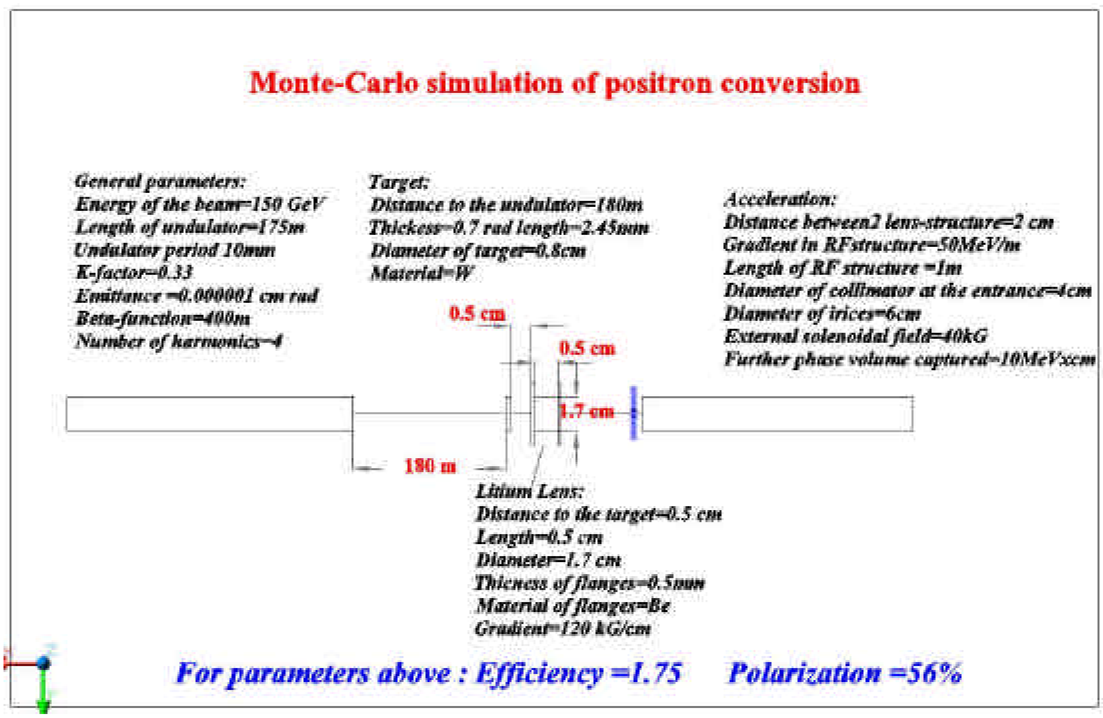

Figure 5: Set of parameters used in Monte-Carlo modeling.

A bit more detailed view on the target and Lithium lens is shown in Fig. 6 below.

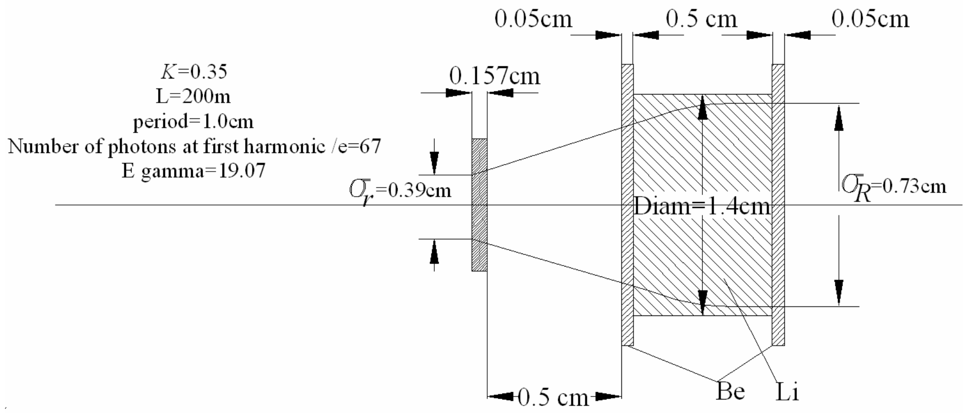

Figure 6: Geometry of W target and Lithium lens used in calculations.

Efficiency as a function of feeding current is represented in Fig.7. For this particular graph the parameters are kept fixed except for the current in lens. Parameters are: K=0.4, period of undulator l_u=1cm, length of undulator L=200m, distance to the target (calculated from the end of undulator) d=180m, thickness of the W target is $0.55X_0$ (~1.925mm) ; other parameters are pretty close to the ones shown in Fig.5.

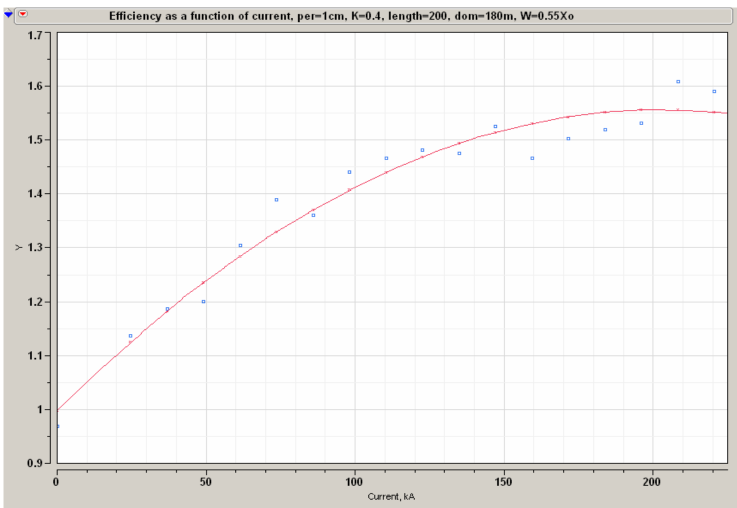

Figure 7: Efficiency as a function of feeding current. Calculated with Monte-Carlo code KONN.

So a current ~150 kA for the lens parameters (length l=4.5mm, diameter Ø=1.4cm) is about optimal.

LITHIUM LENS ENERGETIC

The concept of a Lithium lens is represented in Fig.8. If a steady current I runs through the round conductor having a radius a, its azimuthtal magnetic field inside the rod could be described as

$$H_\varphi(r) = \frac{0.2Ir}{a^2} \text{ [practical system]}, \quad H_\varphi(r) = \frac{Ir}{2\pi a^2} \text{ [SI system]}, \tag{1}$$

where in practical units the magnetic field is measured in *Gs*, 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 radial kick

$$\alpha \cong \frac{H_\varphi(r) \cdot L}{(HR)} \cong \frac{0.2ILr}{a^2 \cdot (HR)}, \tag{2}$$

where (HR) –is a magnet rigidity, pc=300(HR). The kick (2) could be expressed also as $\alpha \cong r/F$, where F is the focal length, Fig 3. The last one is about the distance to the target. So the focal distance could be defined as the following

$$F \cong \frac{a^2 \cdot (HR)}{0.2IL} \quad . \tag{3}$$

One can see from (3) that focal distance is the first order function in contrast to the solenoidal lens, for which $F = \frac{4(HR)^2}{\int H_\parallel^2(s)ds}$, where $H_\parallel(s)$ stands for the longitudinal field distribution along the axis. Also, as it could be seen from (3), the focal distance is reversely dependent on current density in first order.

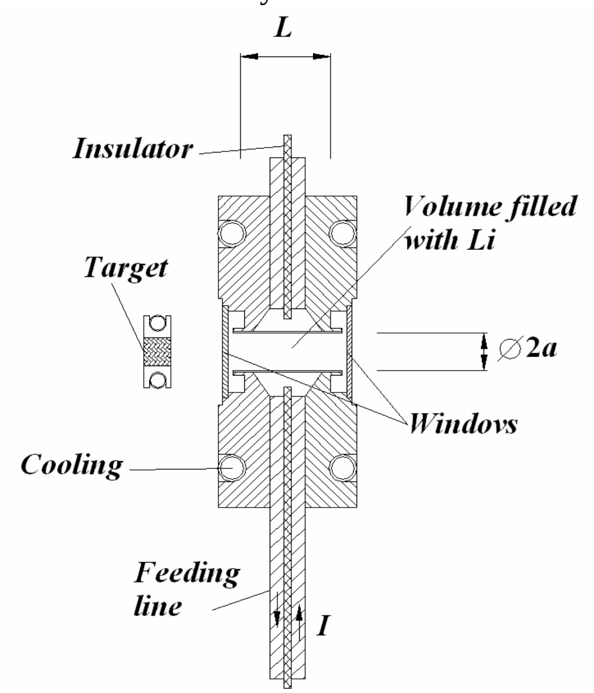

Figure 8: The Lithium Lens concept. The windows made on Be, Ti or BN.

If the focal distance is given, the current required could be found as

$$I \cong \frac{a^2 \cdot (HR)}{0.2FL}. \tag{4}$$

For the primary electron beam of say, 20 *MeV*, $(HR) @ 66$ *kG-cm*. Suggesting $F @ 1cm$, $a @ 0.5cm$, $L @ 0.5\ cm$, (4) yields $I @ \frac{0.5^2 \times 66.6}{0.2 \times 1 \times 0.5} = 166.5kA$.

It is evident that such big current can run in a pulsed regime only. In this case the penetration of the current inside the rod becomes an important issue here.

The magnetic field at the surface of the conductor always remains constant, however.

$$H_J(a) = \frac{0.2I}{a} .$$

So formally the problem of penetration of a magnetic field inside the rod could be solved as a diffusion of magnetic field in cylindrical conductor, when the field at the surface of conductor is given. From Maxwell equations one can obtain the equations for diffusion of magnetic field and current. They are

$$\frac{\partial^2 H_J(r,t)}{\partial^2 r} + \frac{1}{r}\frac{\partial H_J}{\partial r} - \frac{H_J}{r} = smm_0 \frac{\partial H_J}{\partial t} \tag{6}$$

$$\frac{\partial^2 j_s}{\partial^2 r} + \frac{1}{r}\frac{\partial j_s}{\partial r} = smm_0 \frac{\partial j_s}{\partial t} \tag{7}$$

where the current density $j_s(r,t) = \frac{1}{r}\frac{\partial (rH_J(r,t))}{\partial r}$. $\int_0^a j_s(r,t) 2prdr = I(t)$.

Equation (7) could be solved for any form of input current by Laplace method,

$$j_s(t) = \frac{1}{2pi}\int_D j_s(p) e^{pt} dp . \tag{8}$$

Substitute (8) into (7) one can obtain

$$\frac{\partial^2 j_s(r,p)}{\partial^2 r} + \frac{1}{r}\frac{\partial j_s(r.p)}{\partial r} - smm_0 p j_s(r,p) = 0 . \tag{9}$$

One can recognize here the Bessel equation for index zero. Basically all these mathematics are the same as for the calculation of skin-effect. Solution for (9) could be represented as

$$j_s(r,p) = A \cdot J_0(smm_0 p \cdot r) + B \cdot Y_0(smm_0 p \cdot r) .$$

Asymptotic value of current density is $j_s(r, p \to 0) = I / pa^2$. One can obtain an exact solution for any form of feeding current. On practice the feeding current is a half-sinusoidal wave, arranged as a result of the discharge of battery trough transformer.

For the current density could be homogenous with accuracy ~1%, good recommendation is that the half sine wave duty must be

$$T_{half\,\sin} \cong \frac{mm_0 s}{8} pa^2 ,$$

meanwhile the classic formula for skin depth gives $T_{d=a} \cong \mu\mu_0 \sigma \pi a^2$. So the time for acceptable field quality is about 10% of time, calculated for skin-depth penetration, so this is a relaxed requirement.

Resistance of the 0.5 *cm* long 1*cm* in diameter Lithium rod could be estimated as

$$R = \frac{1}{\sigma} \times L / \pi a^2 \approx 1.44 \times 10^{-5} \times 0.5 / \pi \; / 0.5^2 \approx 0.9 \times 10^{-5}\, Ohm, \tag{10}$$

Where $1/\sigma \approx 1.44\ 10^{-5}$ *Ohm-cm* taken as a specific resistance of Lithium.

The last number together with (4) gives the instant power dissipation in the rod as big as

$$P = I^2 \times R \approx 166.5^2 \times 10^6 \times 0.9 \times 10^{-5} \approx 250\, kW.$$

If the pulse lasts for τ seconds with repetition rate *f*, *Hz*, then the average power dissipation will be $< P >= I^2 \times R \times f\tau$. For *f*=5*Hz*, $\tau \approx 4ms$, the last goes to

$$< P >= 2.5 \times 10^5 \times 5 \times 4 \times 10^{-3} \approx 5\ kW.$$

The resistive voltage drop along the rod could be found as low as

$$U \approx I \times R \approx 166.5 \times 10^3 \times 0.9 \times 10^{-5} \approx 1.5V.$$

So this voltage drop is small. Inductance of feeding line unit length having *l* could be estimated as

$$L_l \cong \mu_0 dl / \Delta,$$

Where $\mu_0 = 4\pi \cdot 10^{-7} H/m$ –is a magnetic permeability of vacuum, $d-$is gap between strips and $\Delta-$is their width. Substitute for estimation $d/\Delta \cong 1/50$, $l \cong 50cm \equiv 0.5m$, one can obtain

$$L_l \cong 1.25 \cdot 10^{-8} H.$$

Impedance, associated with this inductance goes to

$$Z \approx i\omega L_l \approx i1.96 \times 10^{-5} Ohm,$$

Where we suggested frequency $\omega \approx 2\pi / 4ms \approx 1.57 \times 10^3 rad/s$. The voltage associated will go to $|U_l| \approx I \times Z \approx 166.5 \times 10^3 \times 1.96 \times 10^{-5} = 3.25V$. Inductance of the rod could be estimated as

$$L_r \cong \mu_0 L \cdot \{\ln(2\Delta / a - 3/4) \cong 5.3 \cdot 10^{-9} H$$

Impedance, associated with this inductance goes to

$$Z \approx i\omega L_r \approx i1.57 \times 10^3 \times 5.3 \times 10^{-9} \approx i8.3 \times 10^{-6} Ohm,$$

and the voltage associated will go to $|U_l| \approx$ 0.138V. So the total voltage drop in secondary loop becomes U_2=3.25+0.138+1.5=4.9V~5V.

The parameters required could be delivered by the usage of a transformer with a transforming coefficient, say *k*=1:20. So the power supply must deliver about $U_1 \cong 0.1\ kV$ and $J_1 \cong 8.325\ kA$. These estimations did not take into account stray

fields. So the last numbers will be higher. A bit more detailed description of the power supply is described below.
Current running through the road interacts with its magnetic field. Force volume density acting at some point is $\vec{f} = \vec{j} \times \vec{B}$ so the pressure gradient inside lens body $\vec{\nabla} P = \vec{f} = \vec{j} \times \vec{B}$ becomes

$$\vec{\nabla} P = \frac{dP}{dr} = \frac{I}{\pi a^2} B_J(r) \qquad (11)$$

Substitute here the field value from (1) $B_J(r) = \mu_0 H_J(r) = \mu_0 I r/(2\pi a^2)$ one can obtain the equation for the pressure as

$$\frac{dP}{dr} = \frac{\mu_0 I^2}{2\pi^2 a^4} r \equiv \frac{\mu_0 j_s^2}{2} r \qquad (12)$$

As the pressure at the surface of Lithium cylinder has zero value, the integral of (12) becomes

$$P = \frac{\mu_0 j_s^2}{2}(a^2 - r^2) = \frac{\mu_0 j_s^2 a^2}{2}(1 - \frac{r^2}{a^2}) = P_0 \cdot (1 - \frac{r^2}{a^2}), \qquad (13)$$

so the axial pressure becomes

$$P_0 = P(r=0) = \frac{\mu_0 j_s^2}{2} a^2 = \frac{\mu_0 I^2}{2\pi^2 a^2} = \mu_0 \frac{H_{max}^2}{2} \text{ [SI]}, \quad P_0 = \frac{H_{max}^2}{2} \text{[practical]} \qquad (14)$$

where $H_{max} = I/(2\pi a)$ is the maximal field at the surface of the lens. In our case, for *a*=0.5*cm*, *I*=160 *kA*, $H_{max} \cong 0.2I/a \cong 0.2 \cdot 160[kA]/0.5[cm] \cong 64kG$, i.e. 6.4*Tesla.* As $1T \Leftrightarrow \cong 4atm$, then pressure at the axis comes to

$$P_0 = \frac{H_{max}^2}{2} \cong 4 \cdot 6.4^2 \cong 163 atm \cong 16.5 MPa.$$

As it could be seen from (13) that the pressure drops quadratically to zero at the surface as a function of r/a, $P = P_0(1 - r^2/a^2)$.We would like to remind here that Young modulus for Lithium is around 4.9 *GPa* (for W ~400 *GPa*), so there will be no problem here. Real pressure profile in the body of lens, especially in the region near the flanges calculated with numerical code FlexPde with real distribution of current $\vec{\nabla} P = \vec{j}(\vec{r},t) \times \vec{B}(\vec{r},t)$.

As the heat evacuated by the flow of liquid lithium is in a closed loop, there is no problem with overheating during average power deposition. Energy deposited in the body of lens *during the pulse* comes to

$$Q = Pt = I^2 \cdot Rt \cong 250 \cdot 10^3 [W] \cdot 4 \cdot 10^{-3} [s] \cong 10^3 Joules. \qquad (15)$$

For the flow rate v_{Li}~10m/s, the distance passed by the time t comes to $v_{Li} \cdot t \cong 1000[cm/s] \cdot 4 \cdot 10^{-3}[s] \cong 4cm$, i.e Lithium could be renewed during the pulse about eight times, so the temperature gain will be ~8 times lower as with stationary Lithium without cooling. So the temperature gain comes to (heat capacity of Li C_v=3.58$J/g/^oK$)

$$\Delta T = \frac{Q}{mC_v} = \frac{Q}{\rho \pi a^2 v_{Li} t \cdot C_v} \cong \frac{10^3}{0.533 \cdot \pi \cdot 0.25 \cdot 4 \cdot 3.5} = 170^o K$$

SCATTERING IN LITHIUM

Material of conductor (Li) must scatter particles much less, than the angular spread of focused particles. This is always true for the collected particles after the target. Scattering of the beam in a Lithium rod target could be estimated as

$$\sqrt{<q^2>} \cong \frac{13.6MeV}{pc}\sqrt{\frac{t_{Xo}}{X_{Li}}}$$

where X_{eff} –is an effective radiation length of the Lithium, $X_{Li} = 83.3 g/cm^2$ (or 156 *cm*), t_{Xo} –is the thickness of the rod in *g/cm*^{2}. So for parameters used above, $\sqrt{<q^2>} \approx \frac{13.6}{20}\sqrt{\frac{1}{156}} \approx 0.04 rad$, i.e. ~13 times smaller, than the angular spread in the beam.

LITHIUM LENS ENGINEERING

A lot of engineering work for Lithium lens usage in VLEPP Linear Collider was done in BINP, Novosibirsk [7] (see references in there). Other well known Laboratories where LL are used for antiproton focusing are FermiLab and CERN. Lenses used here are much more powerful than is required for positron focusing. So the dimensions of LL for positron production are typically *ten times smaller*, than ones used in antiproton business.

Lithium sealed in Ti cylindrical container. Flanges made either from Beryllium, Titanium or Boron Nitride (BN).

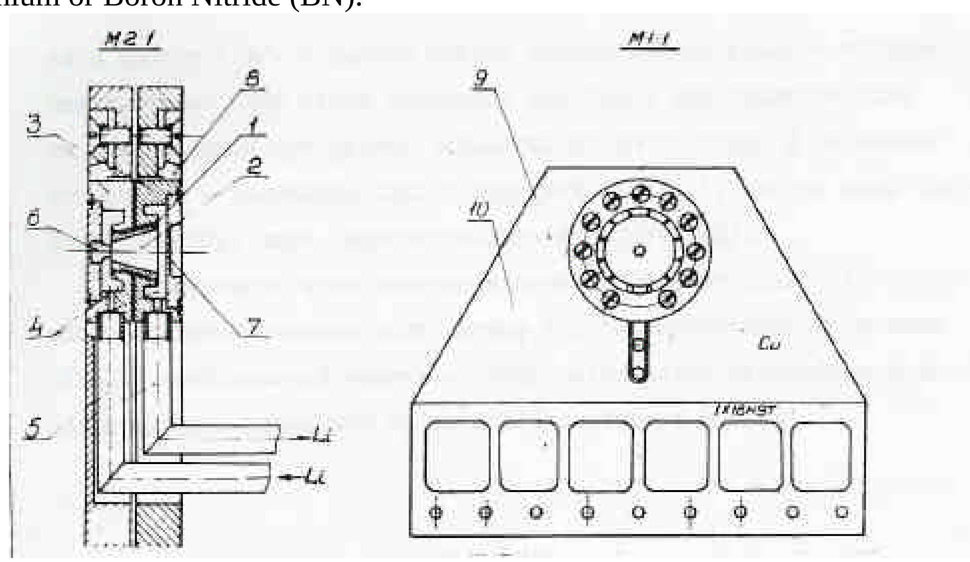

Figure 9 [7]**:** 1-conic lens body; 2- working volume; 3- lens case; 4- buffer volumes; 5- feeding tubes for liquid Li; 6- target; 7- exit flange; 8-conic contacts; 9- flat current leads; 10- slots for heat flow reduction. In this design the W target implemented in entrance flange.

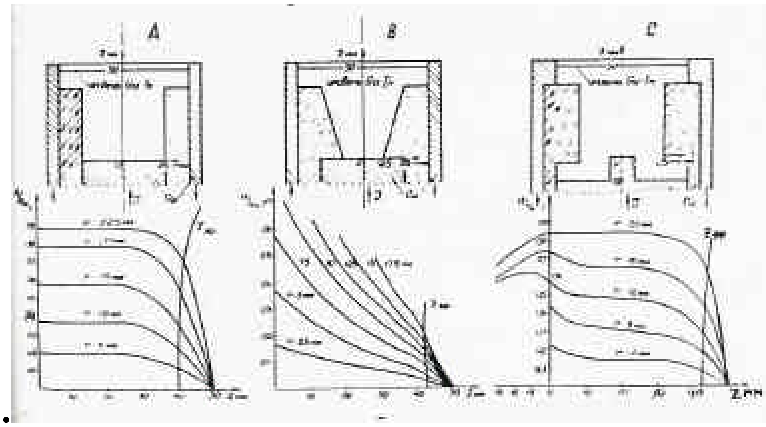

Figure 10 [7]**:** Field measured in liquid Gallium model. A-cylindrical lens with homogenous current leads supply at the end B- conical lens with the same current feed C –lens with cylindrical target at the entrance flange

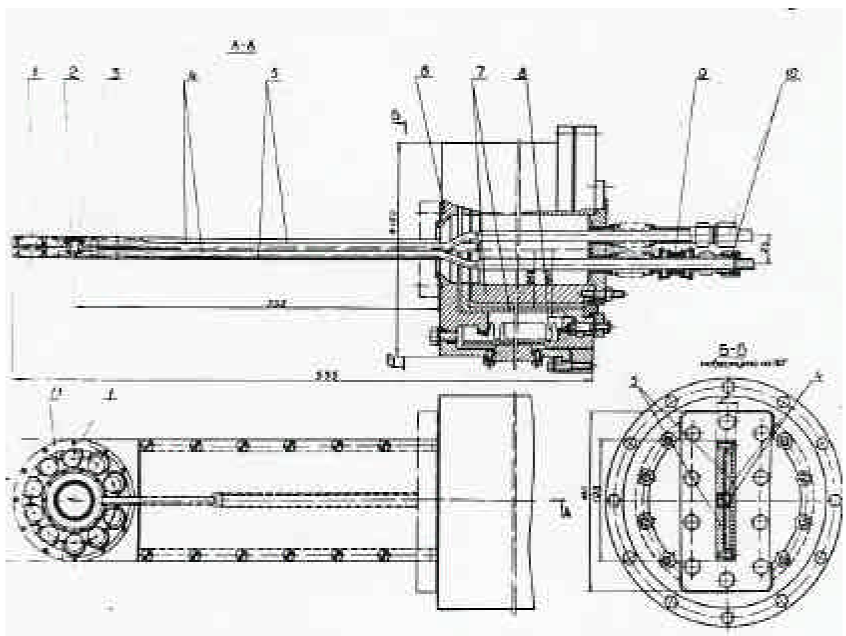

Figure 11 [7]**:** 1-ex-centric contact pushers; 2-conic lens body; 3-W target; 4-Ti tubing for LI supply; 5-flat current leads; 6-vacuum chamber; 7-coaxial fraction of current leads; 8-bellows; 9-ceramic insulators; 10-conical gasket; 11-set of ex-centric pushers.

Numerical calculations with start-to-end code [2] shows, that collection by Lithium lens allows at least 1:1.5 conversion of initial electron (positron) beam into the secondary one in phase volume $\varepsilon_{x,y} \cong p_{\perp} c \times \Delta l \cong 2 MeV \times cm$. The gradient of such lens required G~65 *kG/cm*. Active body of lens has radius r=0.7*cm*, length L=0.5 *cm* with Be flanges of l=0.5 *mm* thick. To reach this gradient the feeding current required ~150kA. For modeling of such lens we used 3D FlexPDE code. Cross section of such lens is represented in Fig.12. Flow of Lithium is arranged in symmetrical way. Flanges have a slight spherical shape for better withstanding of pressure.

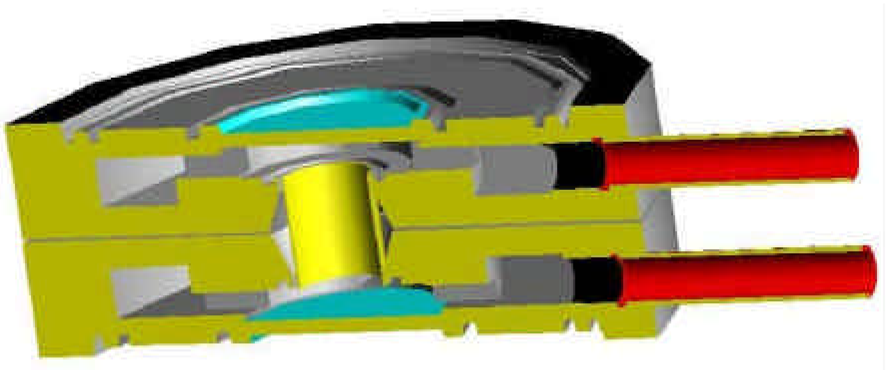

Figure12: Lithium lens cut-off. Enlargement is ~2 times on this picture.

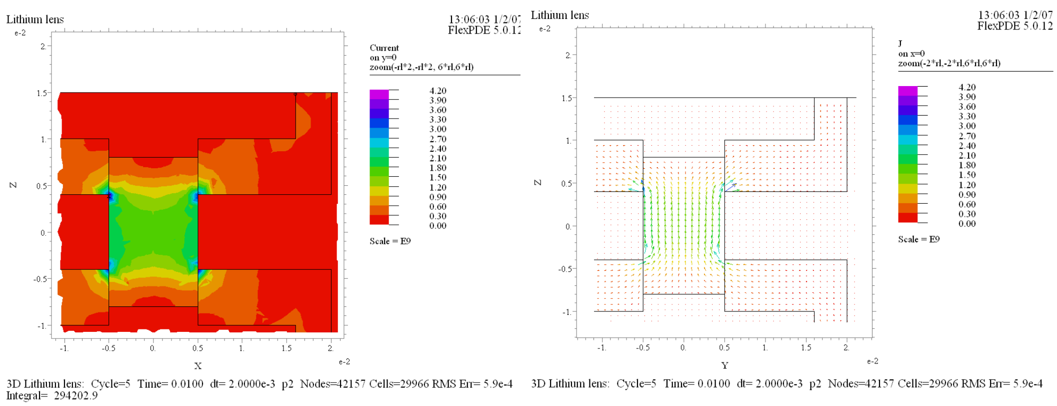

Figure13: Cross section of lens with liquid Li and distribution of current in it calculated with FlexPDE©.

Cooling is going by circulating liquid Li. Melting temperature 180.54 deg C is low enough for these purposes. The possibility to use the first flange as a target, if it is made from W alloy will be re-evaluated.

Pumps for liquid metals are well developed. This might be usual gear pump or the one using ponderomotive force, while the current induced by the magnet of the pump is flowing through the liquid Lithium jet.

BEAM ENERGY DEPOSITION

Taking into account that the energy deposition in material is going by secondary particles (positrons and electrons) at the level $dE \sim 2\ MeVcm^2/g$, one can evaluate for the secondary beam diameter $d \approx 1.4$cm, the area illuminated is going to be $S = \frac{1}{4}\pi d^2 \approx 1.54\ cm^2$. Volume density of Be is $\rho \approx 1.8\ g/cm^3$, so the energy deposited in a material of flange going to be

$$\Delta E \approx dE \times \rho \times t/1cm \approx 2 \times 1.8 \times 0.05 \approx 0.2\ MeV \text{ per particle}$$

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

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

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

$$E_{tot} @ 0.2 \times 10^6 ´ 2 \times 10^{10} ´ 2800 ´ 1.6 \times 10^{-19} @ 0.2 ´ 2 ´ 2.8 ´ 1.6 \sim 1.8\ J.$$

This amount must be multiplied by the factor reflecting spare particles, ~1.5-2 , also multiplied by factor two- reflecting equal amount of electrons and positrons and, finally, multiplied by factor reflecting efficiency of capturing (~30%). So the final number comes to

$$E_{tot} \rightarrow E_{tot} @ 1.8 ´ 2 ´ 2 ´ 3 \tilde{} 7.2 ´ 3 \tilde{} 21J.$$

Temperature gain by heat capacity of Be C_v @ 1.82 $J/g/^oC$ comes to

$$\Delta T \cong \frac{E_{tot}}{mC_v} \cong \frac{E_{tot}}{rSlC_v} \cong \frac{21}{1.8 \times 1.54 \times 0.05 \times 1.82} \cong 83 \text{ deg.}$$

Total temperature gain adds a resistive temperature gain by Litium ~170deg (see above), so the total temperature gain comes to 250^{o}C. One needs to add the initial temperature which is above melting point of Lithium, coming to maximal temperature ~300*deg*. brining total temperature jump~500^{o}C. Meanwhile the melting temperature of Be is 1278 deg, so it withstands (for Boron Nitride the melting temperature is ~2967^{o}C).

We intentionally kept the component of heating arising from electrons. Although the lens *defocuses* the electrons and spreads those to significantly larger area so they do not give input at the outer flange; this input remains in input flange however. The low energy component of positrons indeed becomes over focused; and might increase the particle density at the center. Some amount of heat will be carried out through the contact with Li. For the one millisecond duty of the pulse, the liquid moving with ~1m/sec will pass ~1mm. To the next train which arrives in 1/5 sec i.e. in 200 *ms*, the Lithium will be refilled the volume of lens few times. Boron Nitride is another candidate for the output window.

POWER SUPPLY

PS schematics represented in Fig.14 below. Feeding with 5th harmonic allows making current flat.

The pulser installed in closed cabinet in service tunnel. Size of this cabinet could be estimated as $2 ´ 1 ´ 1\ m^3$. Transformer installed in close vicinity of lens. Multilayer strip-line current duct is running through the hall connecting service and main tunnels. Carefully designed transformer and ducts could provide negligible vibrations.

The parameters required could be delivered by usage of transformer with transforming coefficient, say k=1:20. So the power supply must deliver about $U_1 \cong 0.1\ kV$ and $J_1 \cong 8.325\ kA$. These estimations did not take into account stray fields. So the last numbers will be higher.

Transformer made as a cable one. This type of transformer is known as having low stray fields. The art of engineering of low stray transformers is well known up to *MA* level of currents.

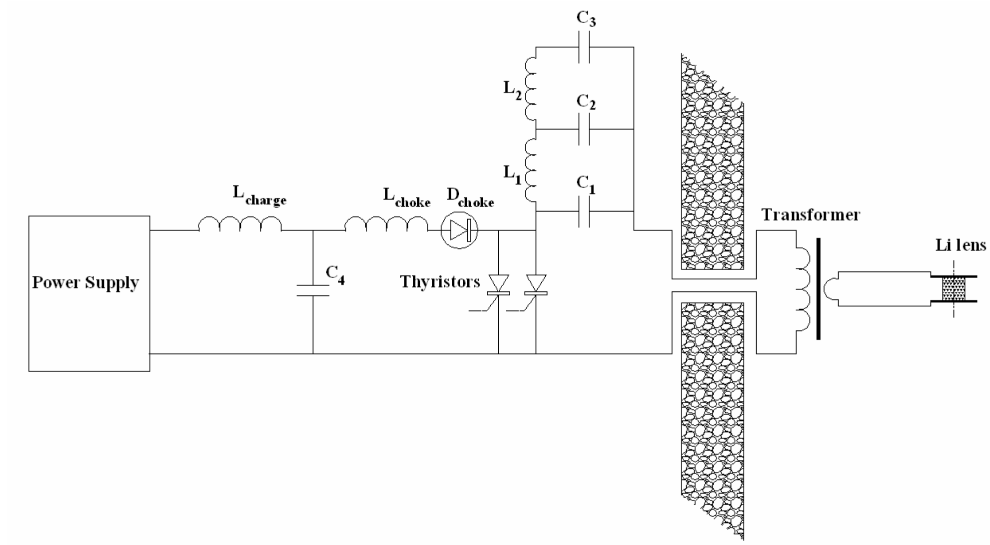

Figure 14: PS schematics.

For calculation of area S of transformer's laminated iron, we can use formula for induced voltage

$$U_2 \approx 10^{-8} \Delta B \cdot S / t \ ,$$

where ΔB stands for the change of inductance in the core of transformer and t is an effective duty time of pulse (in our case $t \approx 4ms$ suggested). With confidence one can put $\Delta B \approx 20\ kG$. So the area goes to be

$$S \approx 10^8 \frac{U_2 t}{\Delta B} = 10^8 \frac{5 \cdot 4 \cdot 10^{-3}}{20 \cdot 10^3} \approx 100 cm^2 .$$

So toroid with cross section $10cm \times 10cm$ and big radius ~10 cm looks adequate. Permalloy or cold crystallized steel tape can be used here.

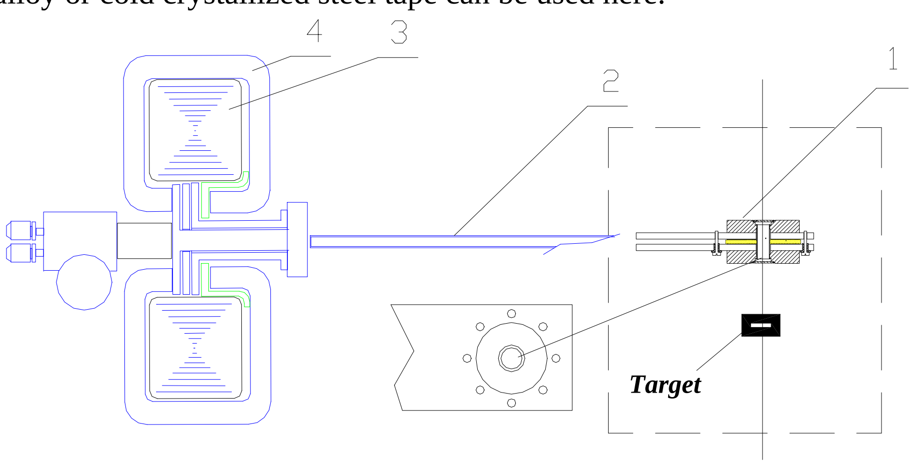

Figure 15: The transformer with Lithium Lens schematics. 1-fixture, 2-flat coaxial line, 3-transformer yoke, 4-cable widings. Lens with a current duct could be made removable from the beam path.

Optimization of power supply is supposed to reduce the pulse lens duration, remembering, that the beam only exists for ~1m, so square pulse shape could provide significant reduction in power deposition in material of Lithium.

For CLIC-type machine with a significantly shorter pulse the heat deposition reduction and the size of transformer reduction could reach the order of magnitude.

LENS INSTALLATION

Right after the target the acceleration structure is installed. It immersed in solenoid, generating longitudinal field ~3-4T. The best candidate for such a solenoid is the one wound with Aluminum conductor (see Figs 16-17. Aluminum accumulates much less radioactivity. The same is valid for the first section of *accelerator structure*. Technology for Al structure fabrication exists.

RF power input arranged far from the target entrance for better symmetry of field in initial sections, so the power input does not disturb the beam, where its energy is low.

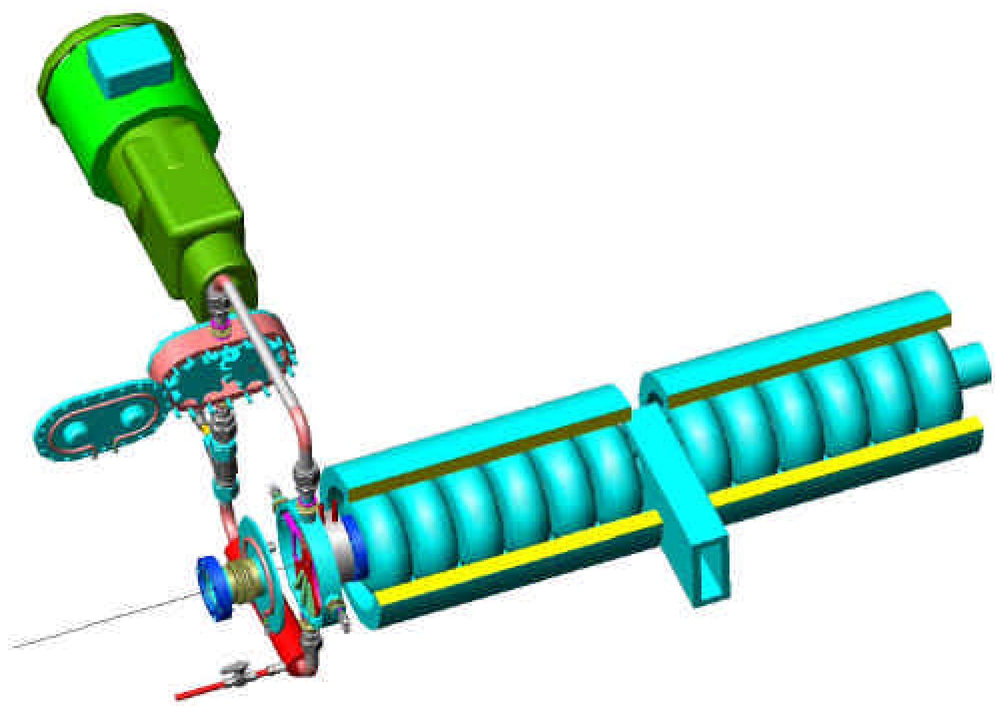

Figure 16: View to the liquid metal target, Lithium lens and accelerating section. Pump for liquid Lithium is similar to the one, used for liquid metal pump shown here. Shown also the focusing solenoid made with Al conductor.

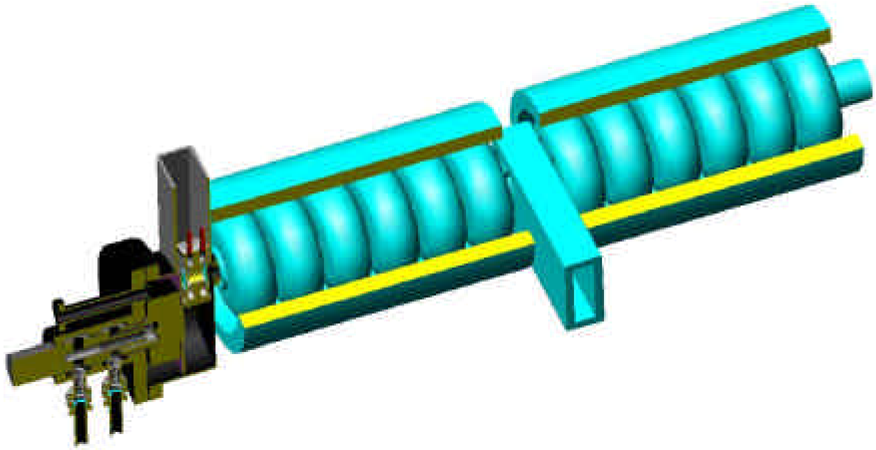

Figure 17: Lithium lens installed right after the spinning target disc.

Diameter of target disc~20 cm. Here again the Lithium lens located in vacuum and its position could be adjusted transversely.

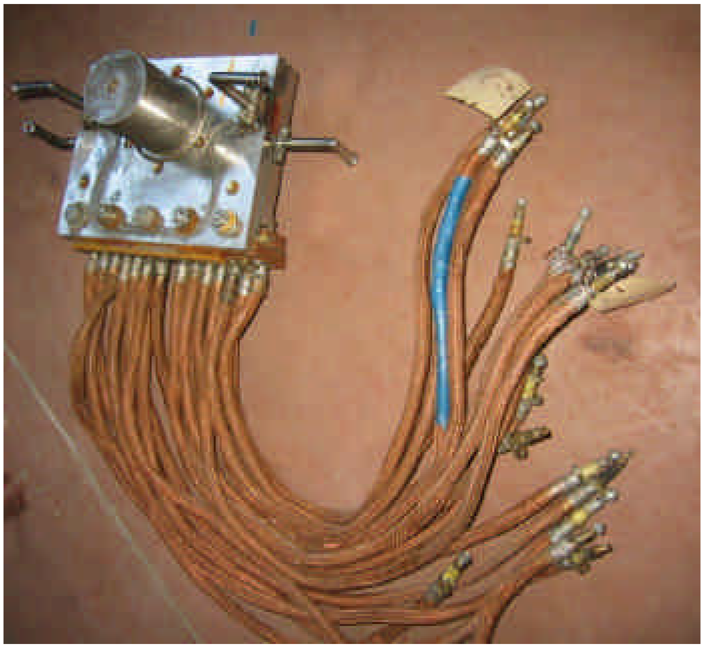

Figure 18: Lithium lens with feeding cables connecting lens with secondatry windings of a transformer. (Courtesy of Yu. Shatunov, BINP).

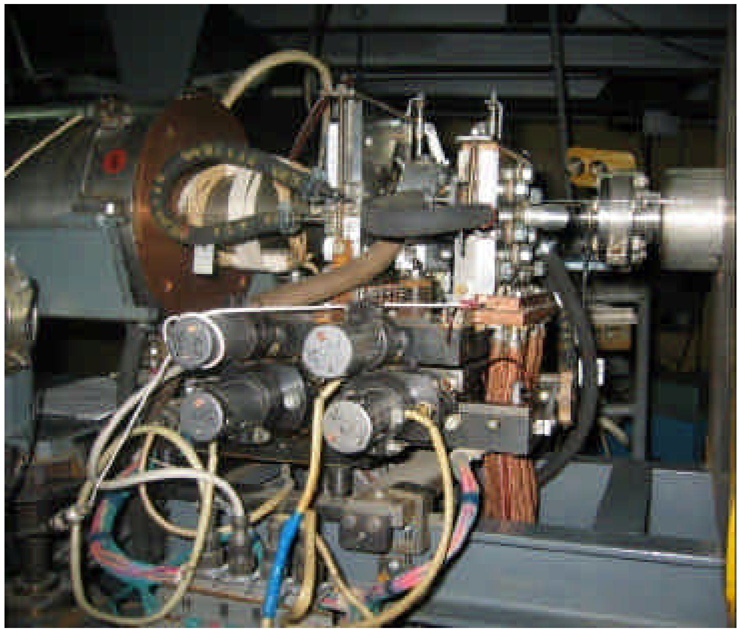

Figure 19: Doublet of Lithium lenses. (Courtesy of Yu. Shatunov, BINP).

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 primary electrons per pulse is up to $\sim 2 \cdot 10^{+11}$; ~0.7Hz operation (defined by the beam size damping rate in a Storage Ring booster- BEP). Lenses shown in Figs.18, 19 served ~30 Years without any serious problem (!).

CIVIL CONSTRUCTION

For the conversion system with Lithium lens the extension in tunnel diameter does not required. Schematic of positron conversion system is shown in Fig.20. Minimal offset of undulator and main beam line defined by cryomodule dimensions as it is shown in Fig.21. *Total length occupied by undulator and magnets for off set chicane counted to be ~300 m total.*

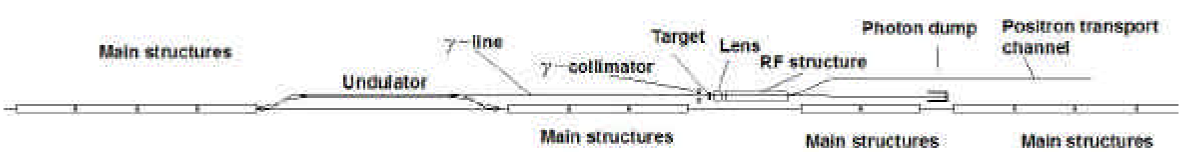

Figure 20: In tunnel near target two main accelerating structures removed allowing allocation target, collection optics and first sections of positron accelerator.

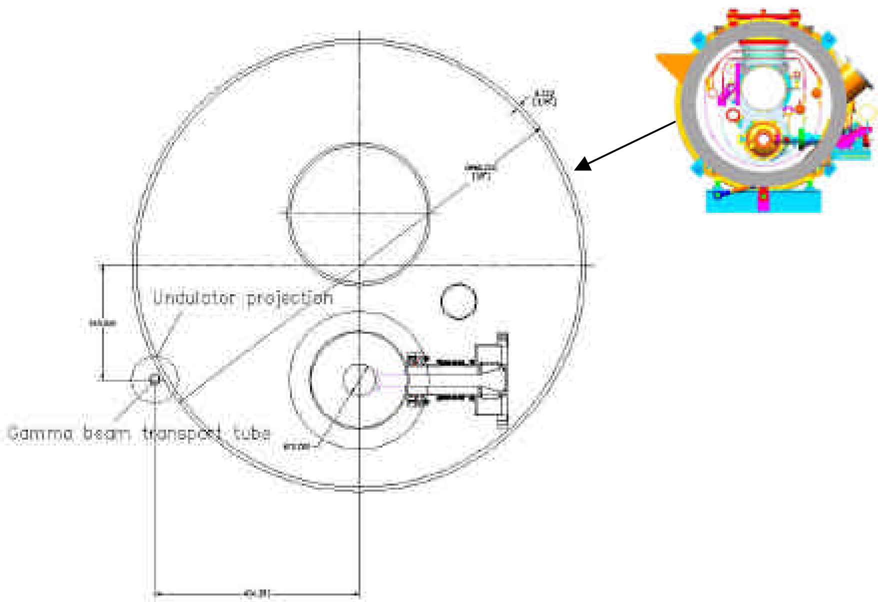

Figure 21: To the choice of minimal shift between axes. Diameter of undulator cryostat is 4in (~100 mm).

Chicane represented schematically in Fig.22 below. Achromatic bend arranged with the help of two bending magnets and two horizontally-focusing quadrupoles located in between.

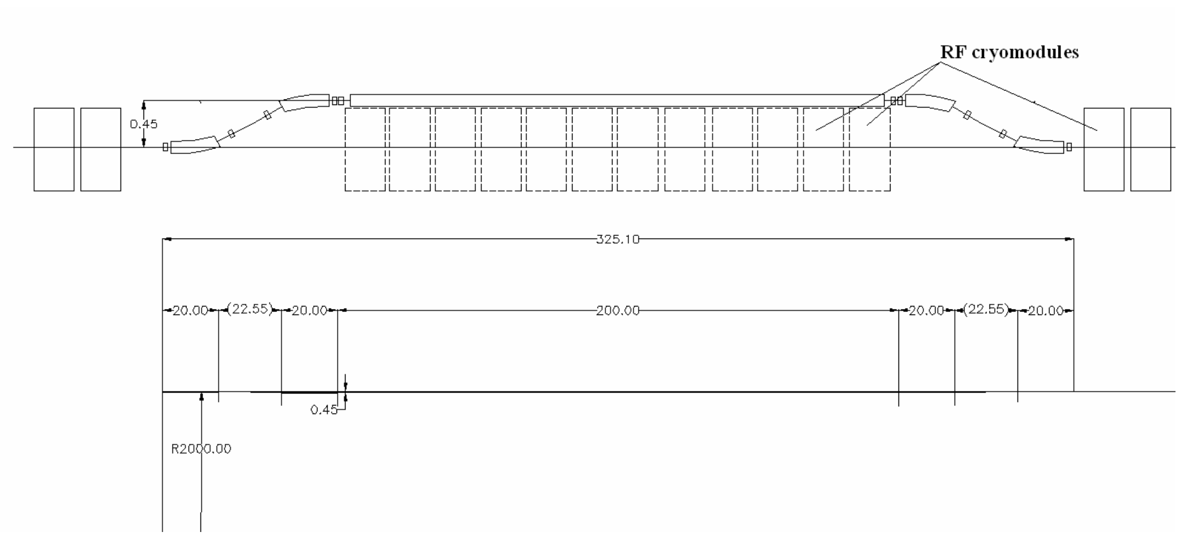

Figure 22: Chicane schematics. At the top-the general concept is represented (transverse dimension is enlarged). In principle, RF cryomodules could remain not removed at the line parallel to undulator. In the sketch the dimensions are represented in meters.

At all distances of chicane the RF structures are supposed to be removed. If they are not, then the distance offset requires an additional ~50 *mm* to accommodate the undulator cryostat (having ~100 *mm* in diameter). Bending radius in magnets is 2*km* chosen for reduction of SR from the bends. The distance ~45 *cm* chosen so that gamma-beam could bypass the cryomodules of the main accelerating structure, see Fig.21.

Here, suppose that at the distance ~180 *m* gamma beam is going in parallel with RF structures down to the location of positron conversion target station. At this region few RF structures (likely two) removed again allowing for the installation of the target, collection optics and pre-accelerator.

If removal of RF structures is allowable at all distances to the target station, then minimal offset allowance becomes ~half of undulator cryostat, i.e.~5 *cm* or ten times smaller, that in first case.

CONCLUSIONS

AMD as an element of collecting positron optics is so ineffective, that it forces to compensate for its bad collection ability by increasing the flux of primary photons. Under these circumstances one is forced to use spinning Ti rim, which reduces efficiency even further. It was shown earlier that eddy fields in moving target immersed in a magnetic field might sweep the positron beam. In its turn, excessive photon flux (15% used for positron production only) and scattered positrons/electrons lost during collection, generates severe radiation activity in nearby accelerating structure and elements of collection optics itself.

Utilization of Lithium lens allows Tungsten survival under conditions required by ILC with N_e~2x10^{10} with moderate K~0.3-0.4 and do not require a large size spinning rim (or disc). Thin W target allows better functionality of collection optics (less focusing depth as a result of thinner target). In turn this drastically reduces the radioactive background.

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

Meanwhile Lithium lens (and x-lens) is a well developed technique. Usage of Li lens allows for a drastic increase in accumulation rate, lowering *K*-factor. As the *K* factor could be made lower by at least 2.5-3 times, the photon flux goes down ~6-10 times. In turn this will reduce the energy spread in primary beam accordingly.

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

The usage of a conical shape of lens will allow for further reduction of feeding current and power deposition. Such calculations are under way with the help of FlexPDE code.

One comment we would like to make here is that usage of Li lens in other than ILC beam format, say the CLIC one, allows for further simplifications for the lens as the feeding current pulse becomes shorter. This allows for more relaxed conditions for the power supply also.

Summing up, the technology of focusing elements with Li lens is the promising technology and needs to be implemented in ILC positron source design. Parameters of the lens summarized in Table 2 below.

Table 2. Parameters of conversion system for the best polarization performance.

Parameter	Value
General parameters	
Energy of primary beam	~150 GeV
Undulator *K* factor	£ 0.4
Undulator period	10-12 mm
Undulator length	£ 200 m
Efficiency	$1.5\ e^{+}/e^{-}$
Polarization	³ 60%
Target	Tungsten 1.75 mm
Energy of quanta	~18 MeV
Distance to the target*	180 m
Lens	
Feeding current	£ 160 kA
Field at surface	65 kG
Gradient	£ 130kG/cm
Pulsed power	250kW
Average power	5kW
Pulsed duty	4msec
Lens diameter	1-1.7 cm
Length	0.5-1 cm
Axial pressure	~163atm
Temperature gain per pulse	£ 170^{o}C at 160kA

* Calculated from the end of undulator

Parameters of lens might be slightly different from what is indicated in Table 2 as a result of further optimization. So these parameters could be recommended for ILC. For CLIC-type machine with significantly shorter pulse the heat deposition reduction and the size of transformer reduction could reach the order of magnitude.

Calculations with KONN show, that for some reduces version with Li lens, the minimal length of undulator with *K*~1, having period 1 cm is going to be ~30 *m* only. Average level of polarization becomes ~36%. Conversion efficiency remains 1:1.5 however (i.e. for each primary electron 1.5 positrons created in average). These figures could serve as a reference for further usage.

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