LITHIUM LENS (I)

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Abstract. Technical/Engineering aspects of Lithium Lens (LL) considered**.** LL dimensions and parameters adopted for undulator based positron source for International Linear Collider. Sealing technique for windows represented in this publication also. This publication is a part of preparation work for numerical modeling of LL.

OVERVIEW

Usage of Lithium Lens (LL) for positron collection was suggested years ago [1]-[4]. Lithium lens with solid Lithium is in exploitation for decades now. Usage of LL for antiproton collection is also a well developed topic [5]-[11].

Naturally, usage of LL for positron collection in a scheme with undulator [13], developed in Novosibirsk, included LL from the very beginning [14]-[15].

From the other hand usage of LL for positron collection still not a widely accepted idea, so Novosibirsk lens remains the only one in operation. In resent times we applied some efforts to implement LL into ILC positron source [16]-[21]. Development of positron source for ILC as it is now in baseline design described in [22]. Latest results on practical test undulator-based positron source demonstrated positron polarization ~ 80% and electron polarization ~90% respectively obtained with Tungsten target [23].

Also interesting looks a possibility for implementation of LL for muon collider [24]-[25]. System with Liquid Lithium is under consideration for Fusion Materials Irradiation studies [26].

Current publication is the first one in series dedicated to demonstration of benefits from potential usage of LL in International Linear Collider.

Support for this investigation obtained from ILC GDE Regional Directorship of America.

LITHIUM LENS CONCEPT

The concept of Lithium Lens is rather simple. Particles are focused by fields generated by the current running through the body of Lithium cylinder, so the particles are going through the Lithium co-directionally with the current flow. Despite the concept is rather simple a lot of challenges need to be addressed to this issue.

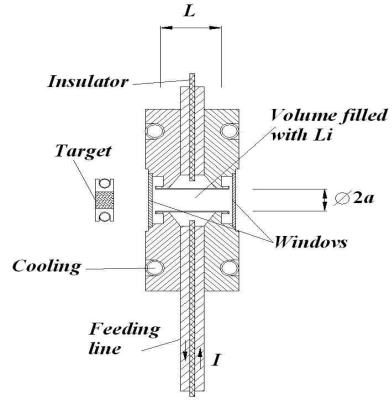


Figure 1: Lithium lens concept. Current *I* running thought the body of Lithium cylinder. Effective length *L* and diameter 2*a* are general parameters of the lens.

If the total current running through the Lithium rod is I Amperes, diameter of rod is $2a$ cm, its effective length is L (see Fig. 1), and then the focal distance and gradient come to

$$F \cong \frac{5 \cdot a^2 (HR)}{IL} \quad , \quad G \cong \frac{0.2I}{\pi a^2}$$

where (HR) $=pc/300$ stands for magnetic rigidity. Average power dissipated just by electric current running through Lithium rod comes to

$$\overline{P} = I^2 R f \tau = I^2 \frac{\rho L}{\pi a^2} f \tau \, ,$$

where $\rho \approx 1.44 \cdot 10^{-5} Ohm \cdot cm$ is specific resistance of Lithium, f is a repetition rate, τ is effective pulse duty. One can see, that current density $\sim I/a^2$ is a decisive parameter for the lens. Just for estimation, for current I=150 kA, a=0.5cm, L=0.5cm, f=5Hz, τ =2$msec$ resistance of the rod comes to

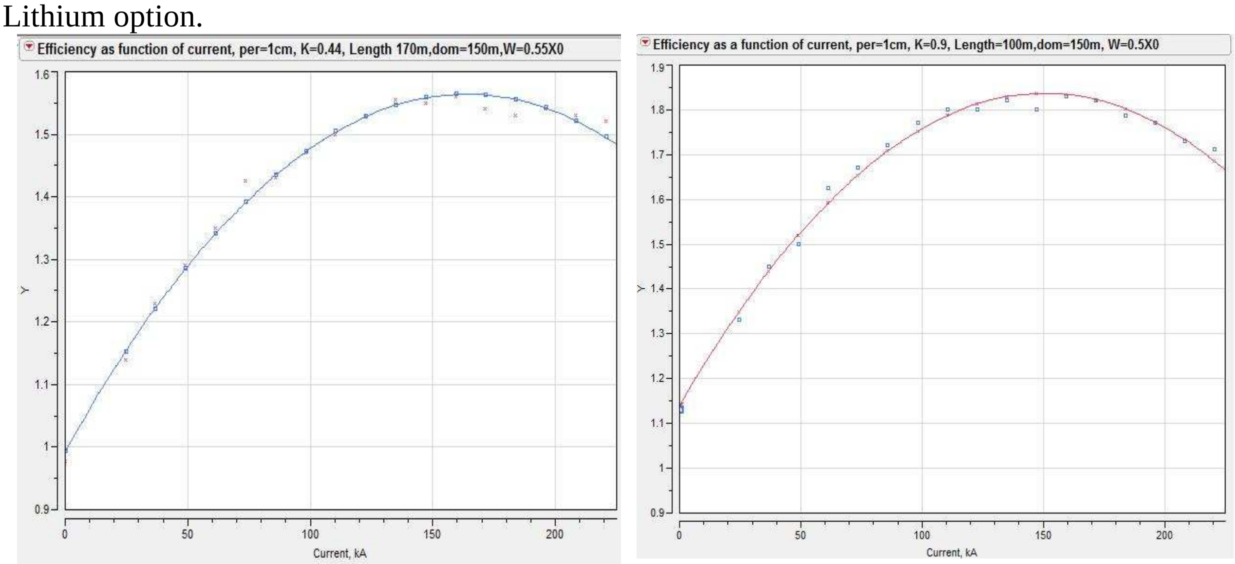
$$R = \rho L / \pi a^2 \cong 0.9 \cdot 10^{-5} \Omega \, ,$$

voltage drop along the rod comes to $\Delta V = IR \cong 1.35V$, pulsed power comes to

$$P = I^2 R = I \cdot V \cong 182kW$$

and, finally, the average power becomes to be as high as $\overline{P} = Pf\tau \cong 1.82kW$.

We will be interested in lens operating with liquid Lithium, so that means that the temperature is above 180.54 ^{o}C. So some tubing needs to be added in Fig.1 to fulfill the LL concept with liquid Lithium option.



(a) (b)

Figure 2: Efficiency of positron production normalized to the primary electron as function of feeding current in lens. (a): K=0.44, 170m long undulator; (b): K=0.9, 100m long undulator.

Efficiency of positrons captured in normalized emittance 6MeV-cm calculated with numerical code KONN (Monte-Carlo start to end simulator of undulator based positron source) is shown in Fig.2. One can see that LL can potentially add ~50% of positrons per each target station.

One can see that for K=0.9 efficiency ~1.5 could be reached for LL current ~50 kA, while for K=0.44 current should be ~100kA. Amount of energy radiated by primary beam in case K=0.9 for the same efficiency is bigger, that for K=0.44 in ratio

$$\frac{Energy\ radiated\ \ for\ K = 0.90}{Energy\ radiated\ \ for\ K = 0.44} = \left(\frac{0.9}{0.44}\right)^2 \frac{100}{170} \cong 2.46 \text{ times.}$$

One positive factor here is that for K=0.9 the lens must be ~2 times weaker, although extra current could be considered as a reserve. This ratio could be reduced to ~2 times with decreasing the undulator length below 100m, but that will require higher current. So LL must be designed for current ~150kA which will be good for any case.

LL DESIGN

Current running through the lithium rod could be 80-130kA with ~1 msec flat top, while its duty measured at the pedestal could be ~5msec. From Fig.2 it follows, that lens gives ~50% increase of secondary positron flux.

LL case made from Niobium or from hot rolled 316 Stainless steel Reduced Activation Ferric (RAF) steel. This allows avoiding penetration of Lithium through the body of material, as Lithium actively reacting with Oxygen trapped in voids or dissolved in material.

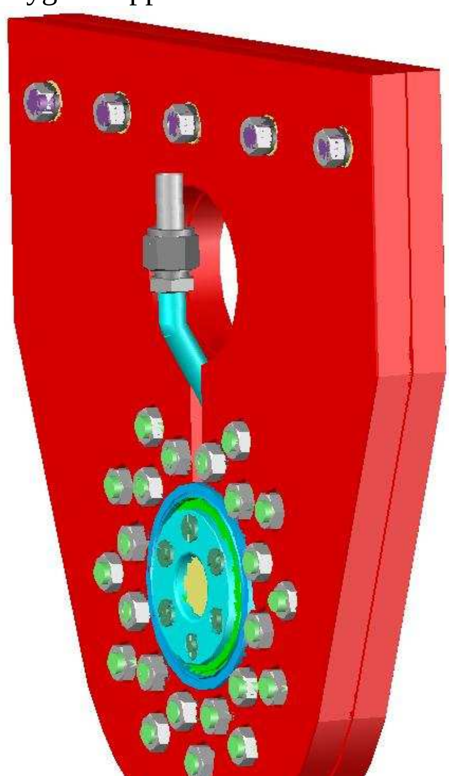


Figure 3: General view on Lithium Lens with current leads attached. One tube of liquid Lithium duct is visible in this figure also. Thickness of the package shown is ~2.54 cm.

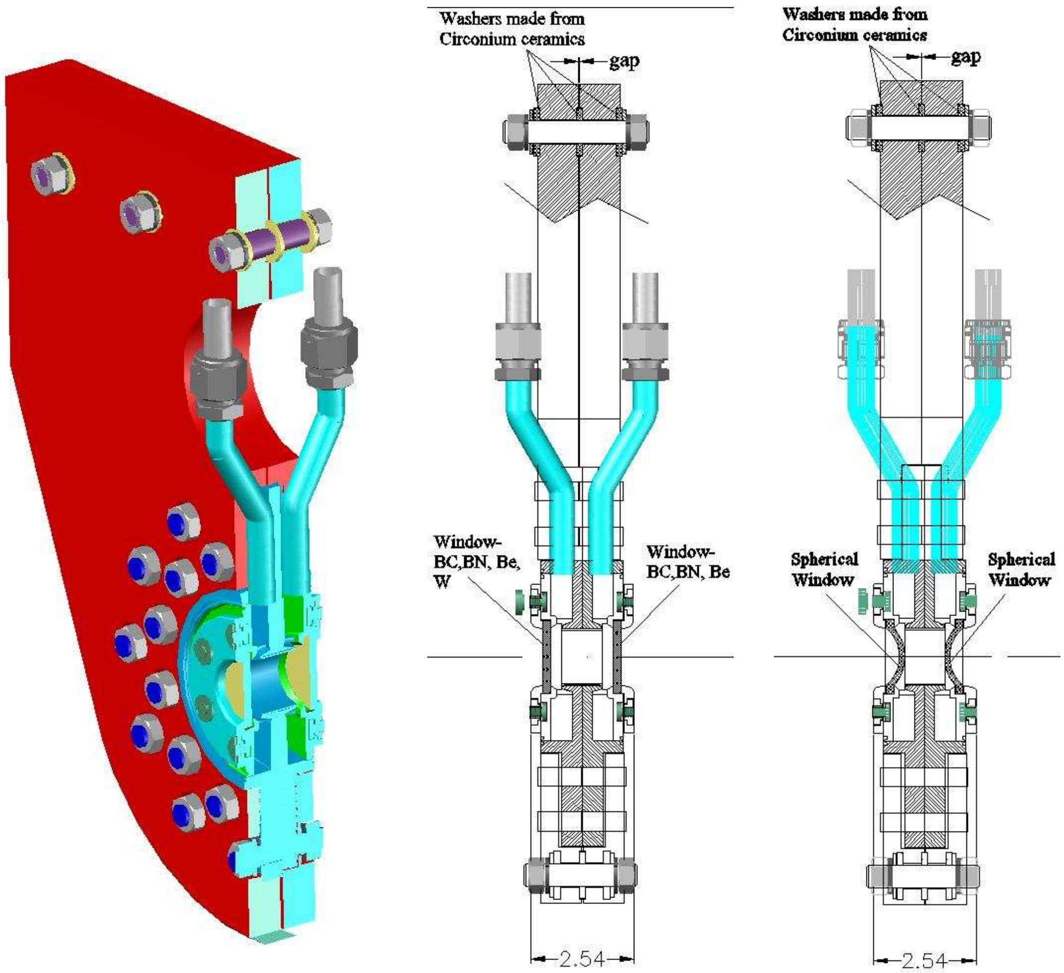


Figure 4: 3D cut across the liquid LL through axis, at the left (lens shown empty). 2D cross sections of LL, at the right. Two shapes of windows geometry are shown at the right. Dimension is given in cm.

Possible upgrades.

Usage of first (entrance) window made from Tungsten allows working without rim (or any other) target at all. One peculiarity of conversion system with gammas is that entrance side of target not heated under exposure to the gamma flux as the number of charged particles (positrons and electrons) linearly increased along target. Liquid Lithium will serve is this case for cooling W window as well. This might bring, potentially, big relief and design simplification for overall conversion unit.

Utilization of two positron target stations with combining positrons in longitudinal phase space will allow doubling of positron production rate [15]. In principle, two positron targets, even without any focusing at all, will allow to have the rate 1:2 (i.e. each initial electron or positron could create two positrons within acceptance of damping ring).

Windows.

Windows made either from Beryllium (Be), Boron Carbide (BC), Boron Nitride (BN) or W. Chemical formula of Boron Carbide (BC) is B_4C.

Window could be attached to the flange by brazing; this is well developed technique, see for example [27], [28], but we are suggesting much more simple procedure.

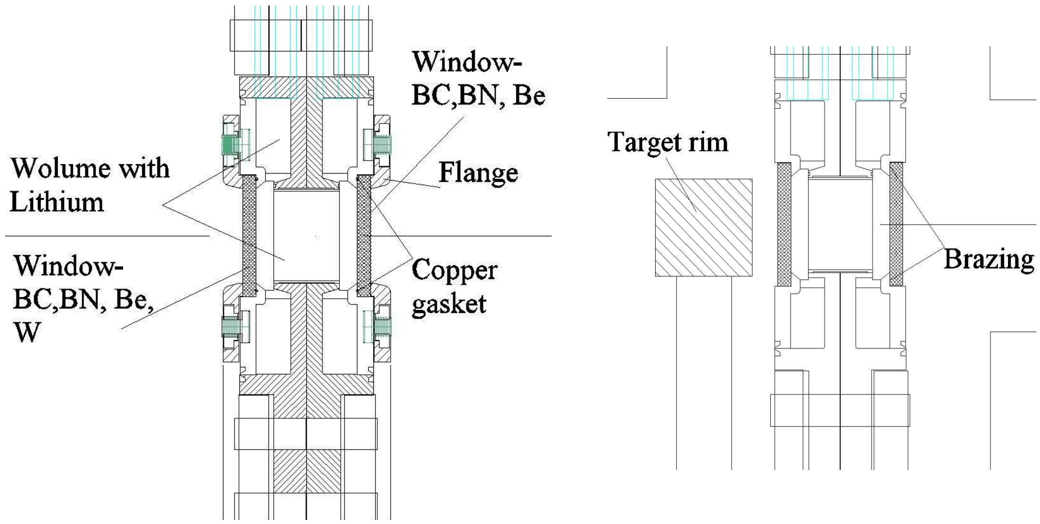


Figure 5: The concept of window attachment. Attachment made with the flange shown at the left. Attachment of window made by brazing is shown at the right. See Fig.10 for full setup.

For sealing we are suggesting usage of annealed Nickel, Oxygen-free Copper or Iron gaskets. Additional flange, which is shown in Fig.5, compresses window disk to the gasket ring. Usage of flange increases the thickness of package on ~5 mm total, which could be tolerated.

Efficiency and polarization of captured positron beam calculated with KONN for different thickness of Be window is shown in Fig 6. One can see, that efficiency drops ~60% while the thickness of Be flanges come to 8 mm at each side. However polarization here increases, so some manipulation of parameters of system allow play back efficiency on expence of polarization, so with 8 mm-thick Be flanges efficiency could be tuned back to 1.5 and polarization ~0.6 (60%) still guarantied.

So we concluded that the thickness of window is not as issue here. Thickness should be determined by mechanical requirements only.

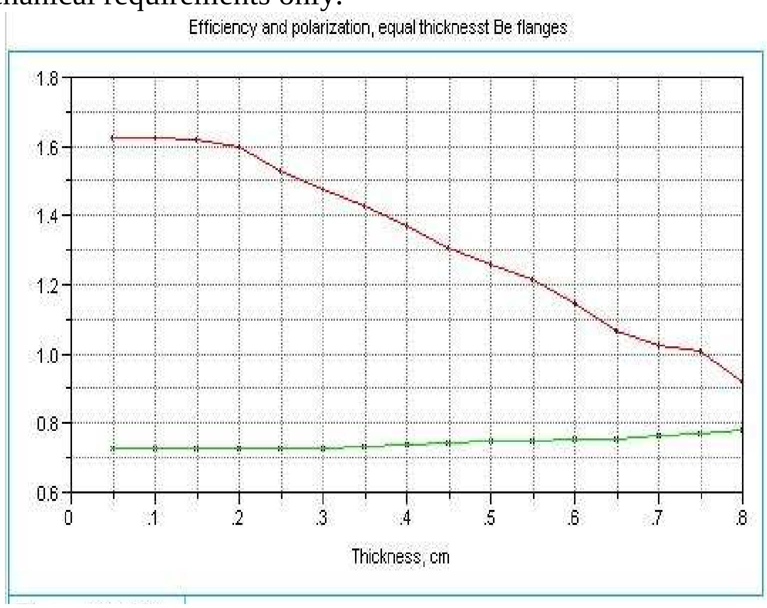


Figure 6: Efficiency (upper graph) and polarization (lower graph) as functions of Be flanges thickness.

Some rise of polarization could be explained by scattering of low energy positrons, having lower polarization at the moment of creation.

Dependence on lens diameter represented in Figures 7-9. During change of radius all other parameters, including gradient in the lens (which was G=65 *kG/cm*) kept fixed. So graph in Fig.7 demonstrates quadratic dependence, naturally.

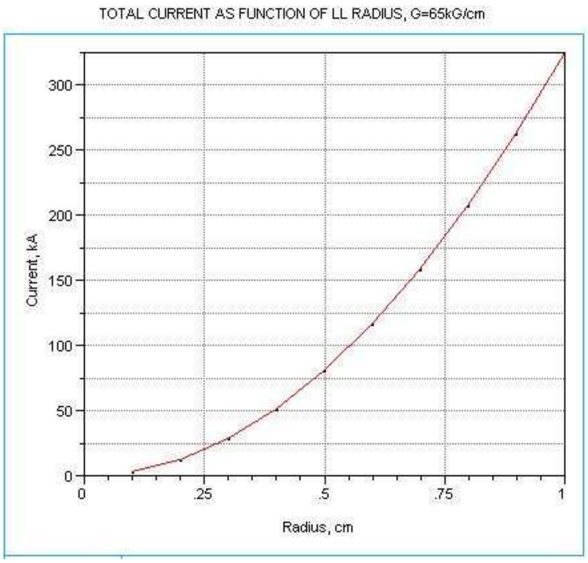


Figure 7: Total current running in Lithium rod.

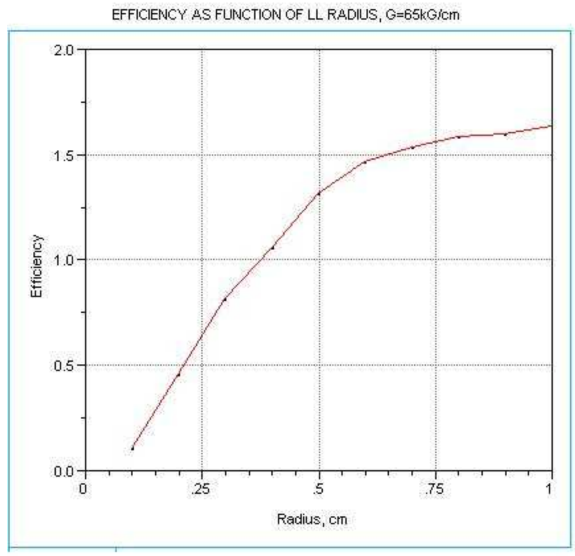


Figure 8: Efficiency as function of radius.

Efficiency calculated for the invariant transverse emittance 9*MeV*x*cm*, although dependence on emittance is slow down to ~6 *MeV*x*cm*. Dependence of polarization on LL radius is weak, Fig.9.

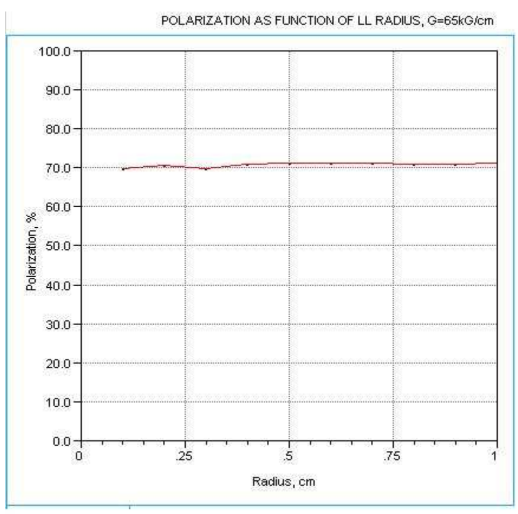


Figure 9: Polarization while radius is changing.

So the radius of the lens could be chosen ~0.65 cm, which will require current in the Lithium rod I~137*kA*.

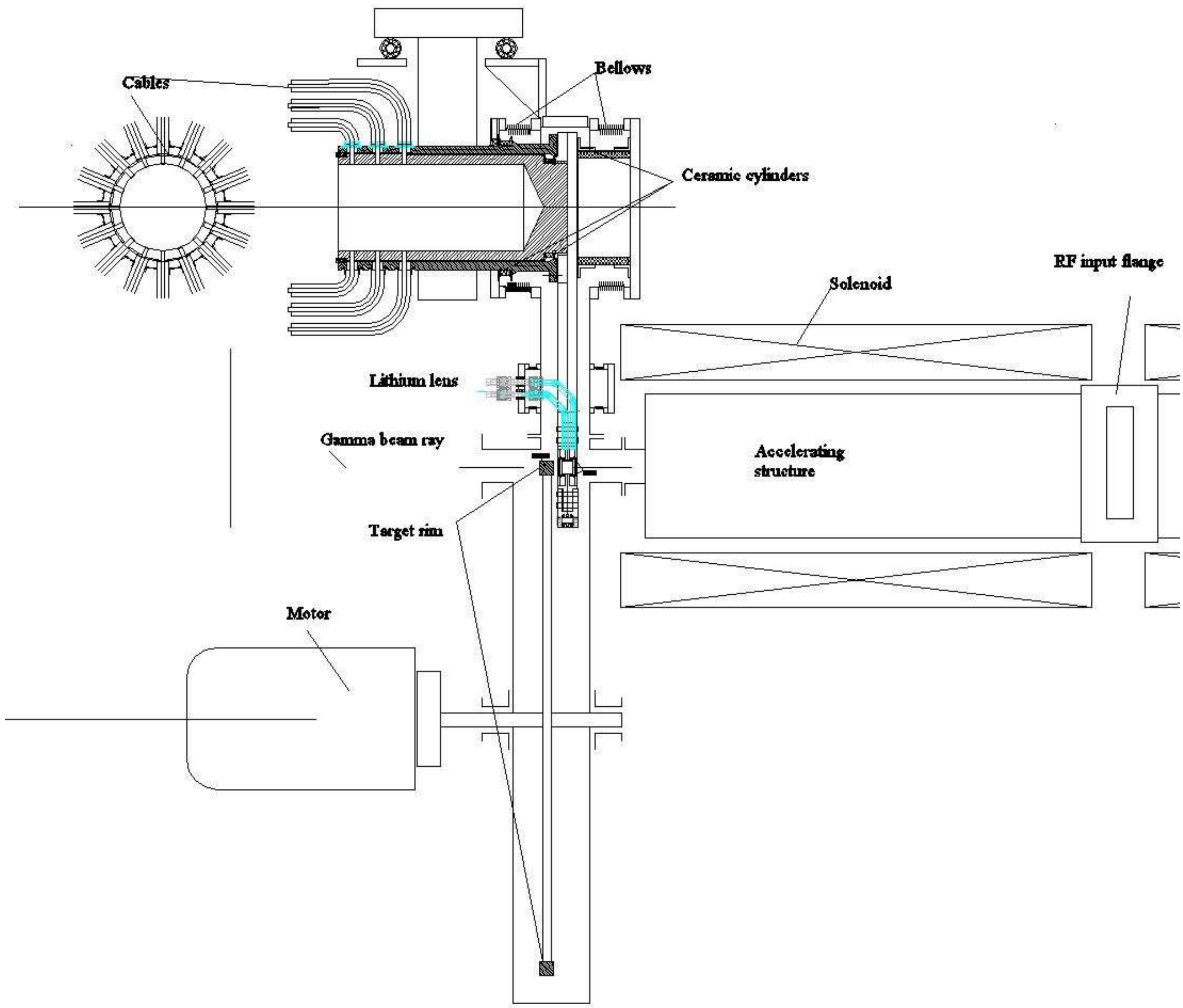


Figure 10: Concept of installation fixture. Bellows allow lens movement in 3D within ±6mm along the beam and ±2mm in each of transverse directions with compensation of atmospheric pressure.

For compensation of force arising from atmospheric pressure, the second bellow is added from opposite side of the case. This last flange is connected mechanically to the inner fixture through ceramic cylinder so the forces applied to the inner fixture in opposite directions (see Fig.10). The same trick applied to the inlet/outlet of Lithium duct (smaller bellows in Fig. 10, Fig.11).

Vacuumed transition combined with transforming from strip line to a coaxial type of current duct.

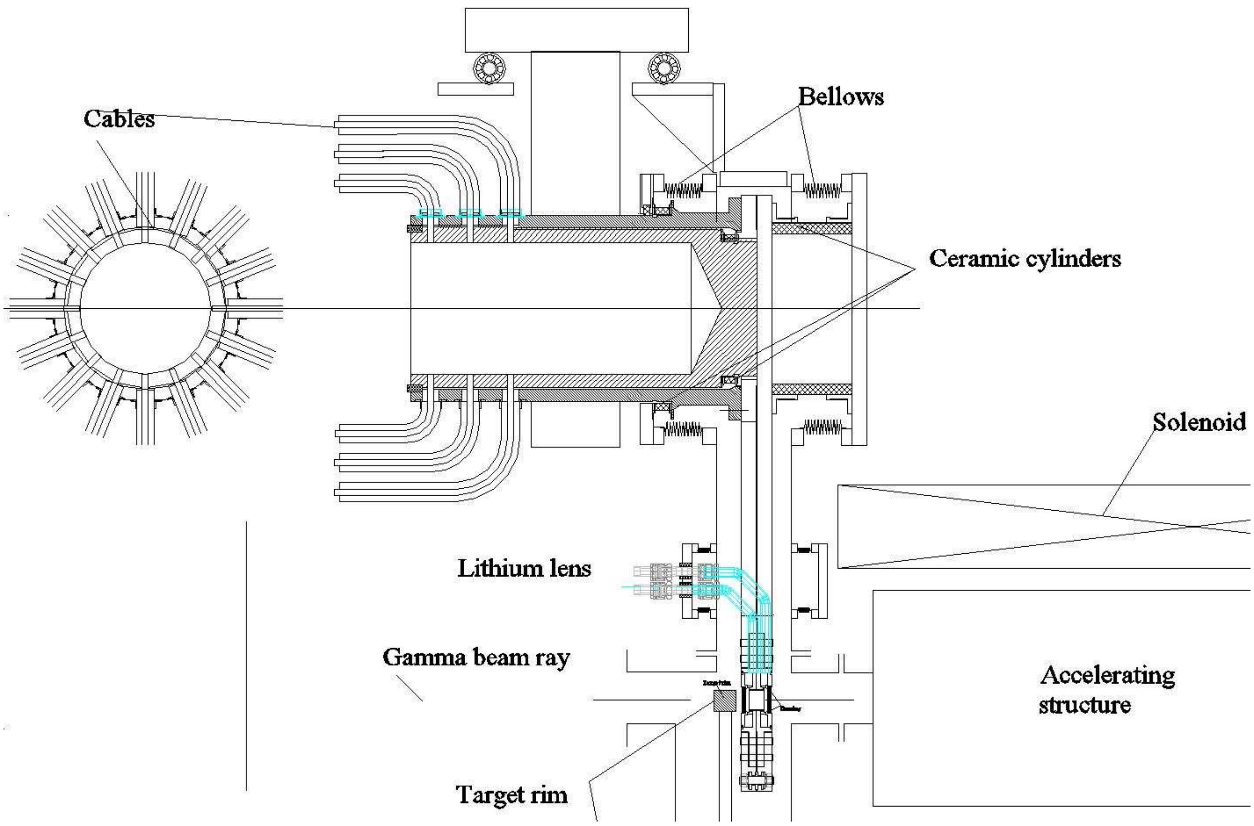


Figure 11: Scaled fragment from Fig.10. Transition from strip line to coaxial made for easy transition from vacuum to atmosphere. Variant with radial location of feeding current leads (cables) is shown here.

Electrical/vacuum insulation made with help of ceramic thick-wall cylinders. Additional ceramic cylinder (the very right in Fig.11) serves for transduction of atmospheric pressure to the opposing side

Total number of cables caring up to 120 kA total is 16x3=48 in one design (Fig.11) and 14x4=56 in another (Fig.12), so each cable caring <2.5kA in ~4 msec time duty.

Solenoid participates in focusing of positrons after Lithium lens.

We are considering the current duct between pulser and lens made as a strip line instead of many cables. The choice will be made later.

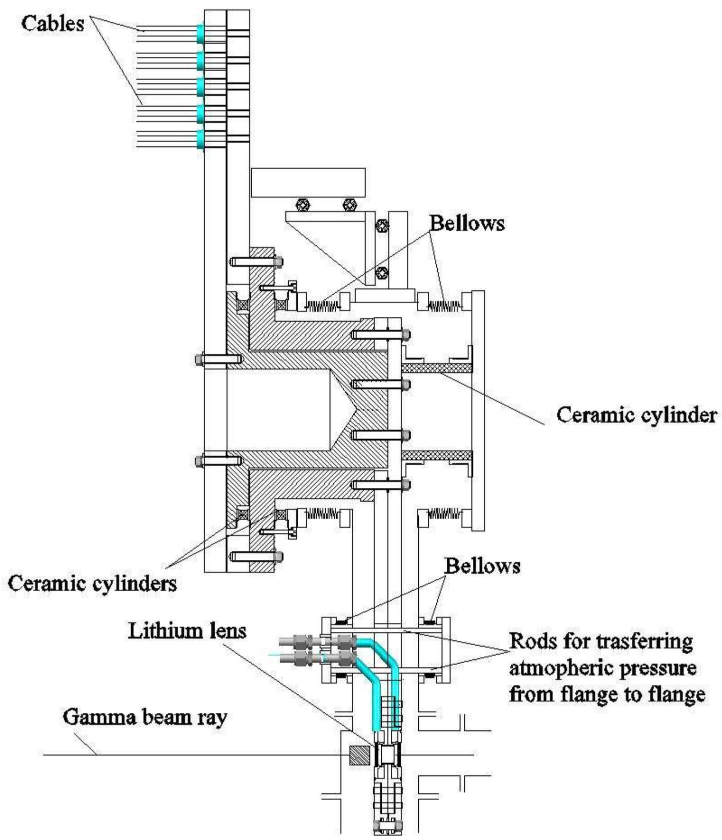


Figure 12: Another variant of transition to current duct and transition from vacuum to atmosphere for 150 kA line.

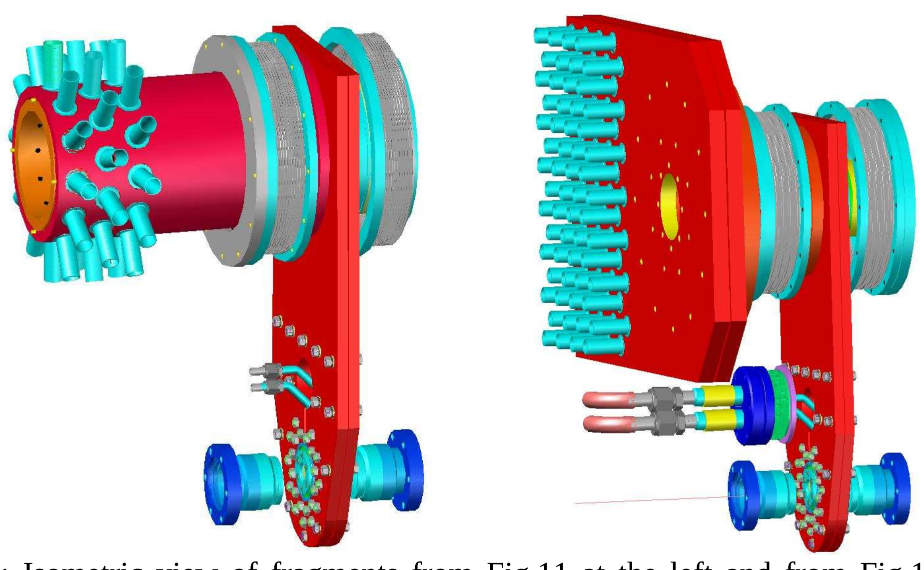


Figure 13: Isometric view of fragments from Fig.11 at the left and from Fig.12 at the right (current duct rotated 90^o). LL shown equipped with current ducts and bellows, see Fig.11. Case for the rim target and cables are not shown. Lithium tubing here runs at one side.

Once again, instead of usage cables we are considering feeding the lens through strip-line of appropriate dimensions equipped with flexible insertions.

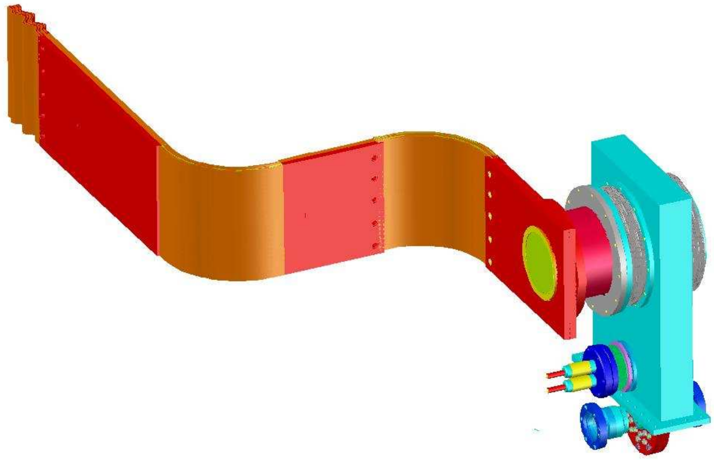


Figure 14: Current duct as a strip-line pair. Flexible elements are visible here.

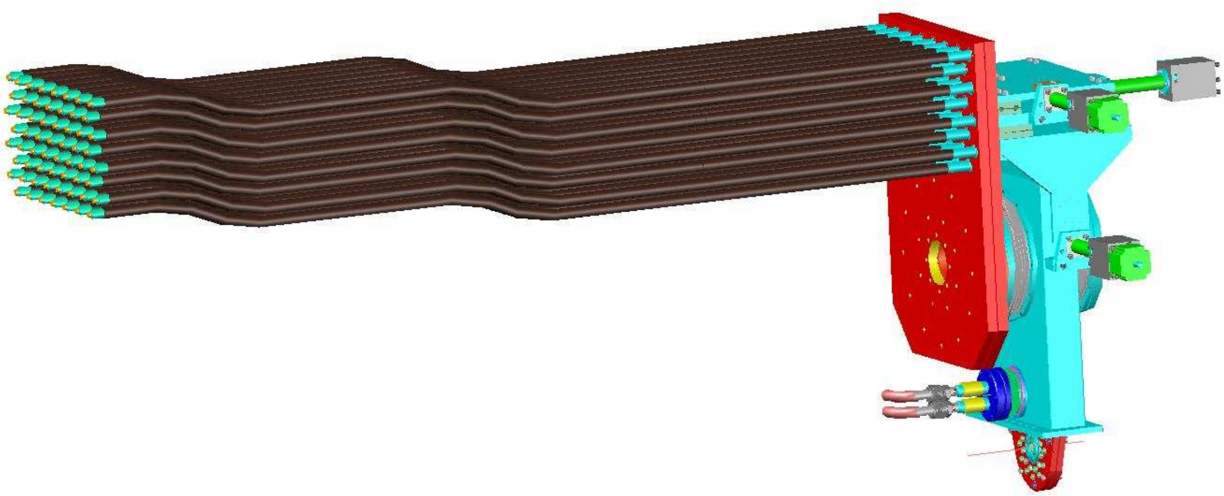


Figure 15: Another variant of attachment of current duct (From Fig.9). Coaxial cables running to the pulser are shown here also.

Mechanisms with stepping motors allow motion not only in longitudinal direction (along the beam line), but in transverse directions also due to flexibility of bellows against transverse deflections.

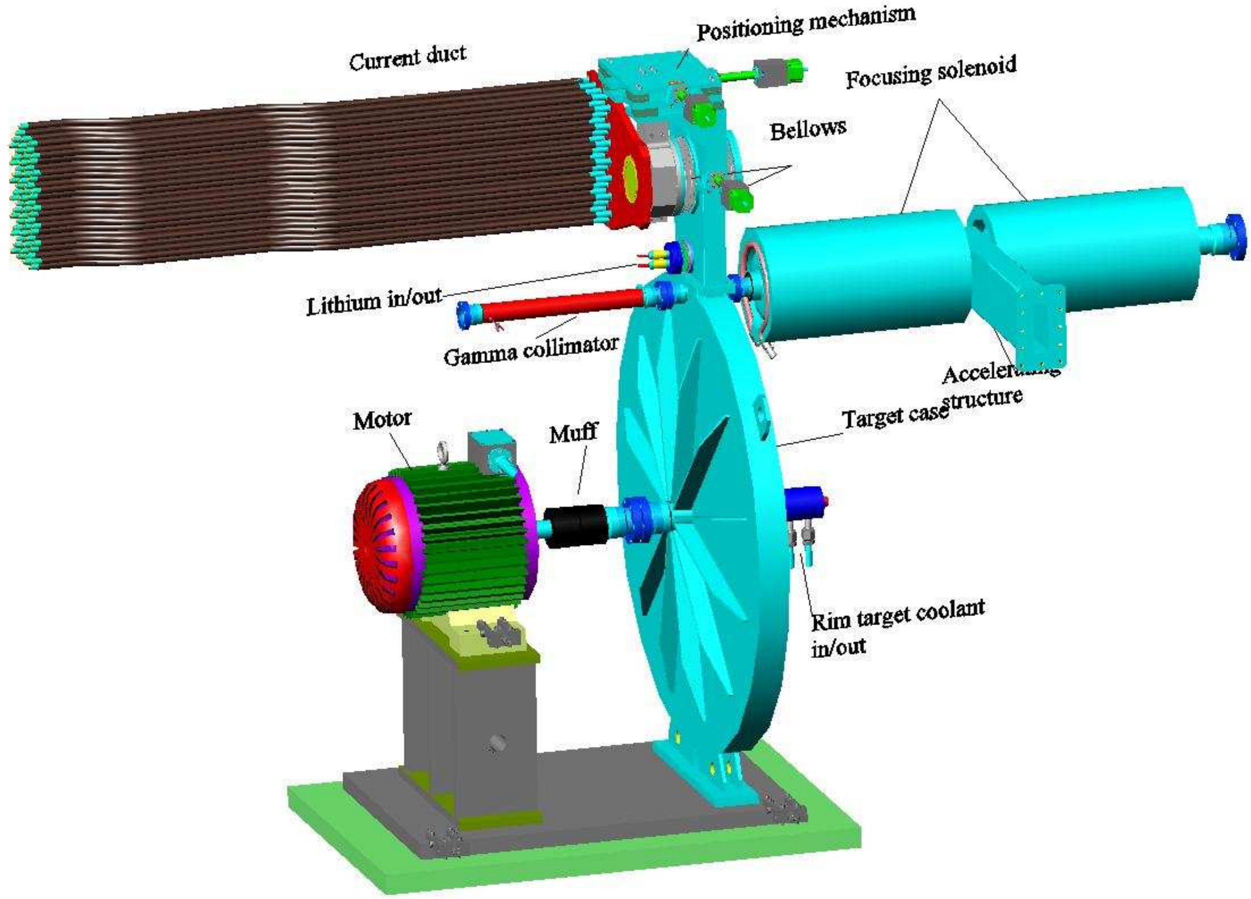


Figure 16: Isometric view on target installation. Diameter of target rim is ~1 meter. It is shown here the current duct with cables.

Gamma collimator uses a Pyrolithic graphite at front end and Tungsten absorber at the exit end. Some general parameters of LL represented in Table 1. Dimensions are effective ones corresponding to rigid edge model.

Table 1. Parameters of Lithium lens

Parameter	Units	Value
Length	*cm*	0.6
Radius	*cm*	0.7
Current	*kA*	150 max
Flat top	*ms*	1
Windows	-	Be/Bc/BN
Distanse to the target	*cm*	0.5

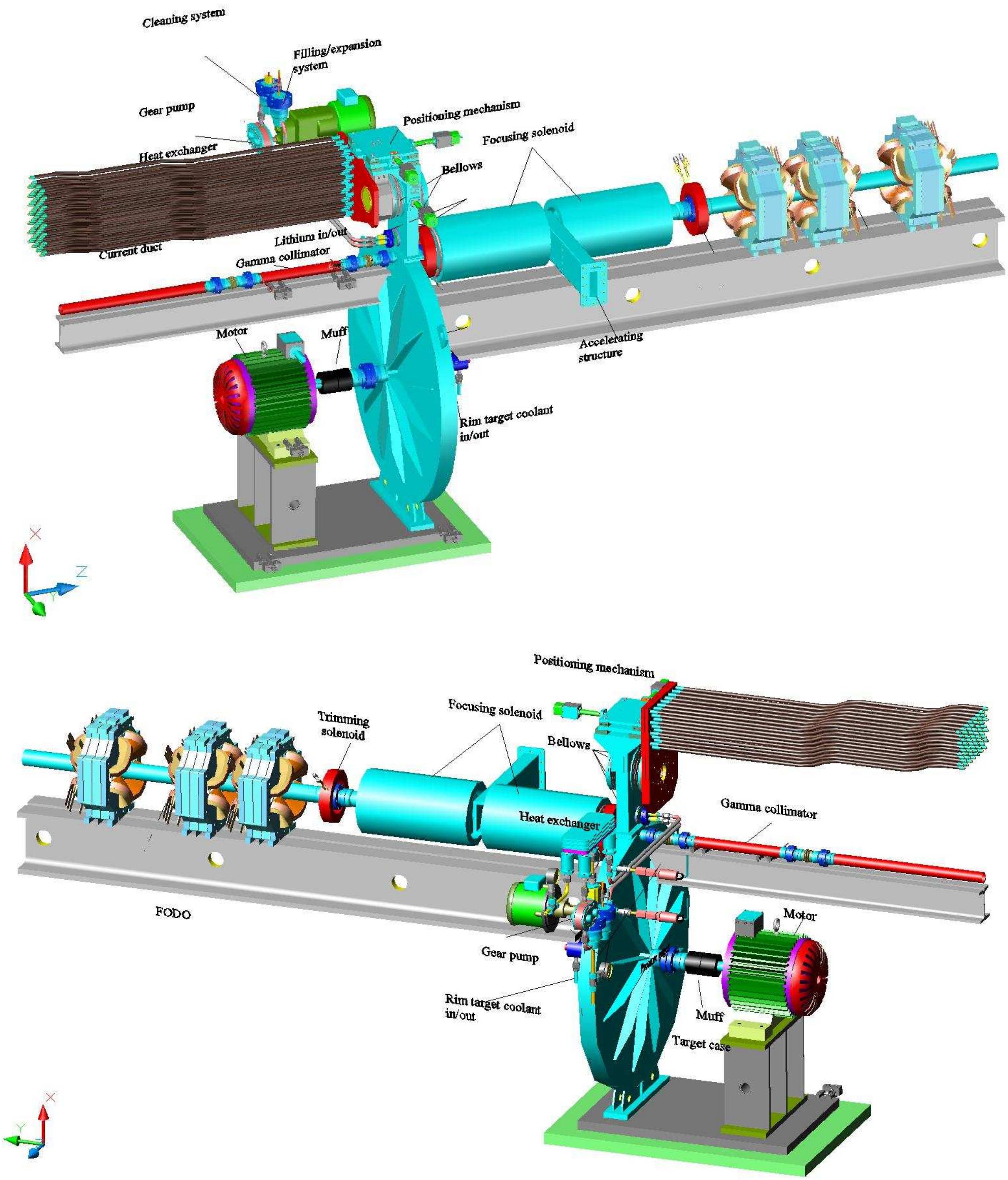


Figure 17: Conversion system layout. At lower figure the current duct shown with variant from Fig. 11, Fig.13.

Short trimming solenoids serve for matching beam envelope. One solenoid located right after the lens, the second one –after accelerating structure before FODO.

PULSER

For feeding lens a 150*kA* with 1 *msec* flat top required. Voltage required defined mostly by stray (parasitic) inductance of lens itself, transitions and, mostly by transferring line. Although usage of transformer might be beneficiary here, we considering for the moment direct feeding in a view of well developed semiconductor commutators existence.

Figure 18: Reverse Switched Dinistors (RSD) for peak current from 200 kA to 500 kA and blocking voltage of 2400 V, encapsulated in hermetic metal-ceramic housing and without housing (RSD sizes of 64, 76 and 100 mm) [29].

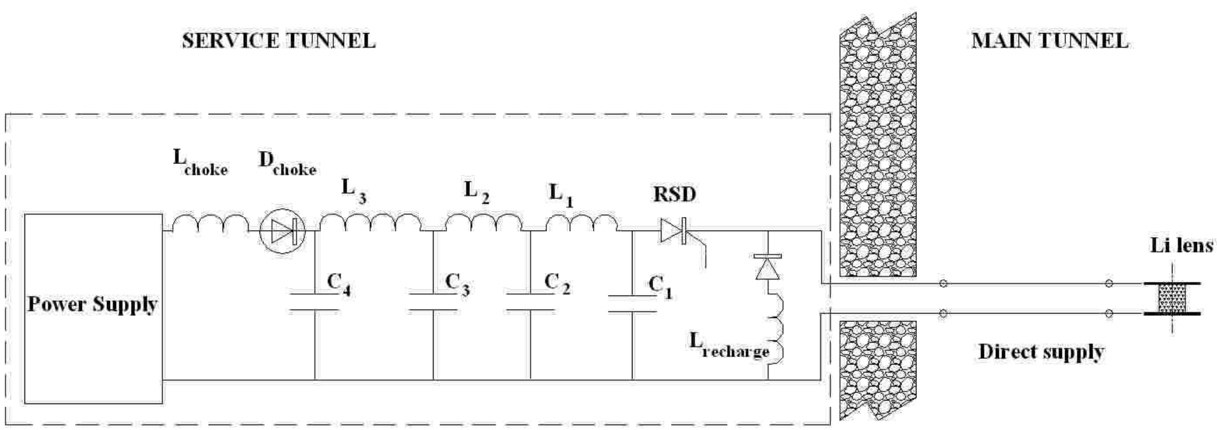


Figure 19: Concept of LL pulser.

Pulser electrically insulated from the ground. LL has no contacts with ground also. This will help avoiding influence of high current pulse on surrounding electronics.

There is well developed technique for effective charge of capacitors with constant power for reduction of losses. In [30] the power supply able to feed Lithium lens with current up to 1.5 MA and repetition rate up to several *Hz* described.

PUMPING OF LIQUID LITHIUM

As the temperature of liquid Lithium is ~190 ^oC only practically all technical solution used for pumping of hot water could be easily accommodated here. Pumping is going with gear pump.

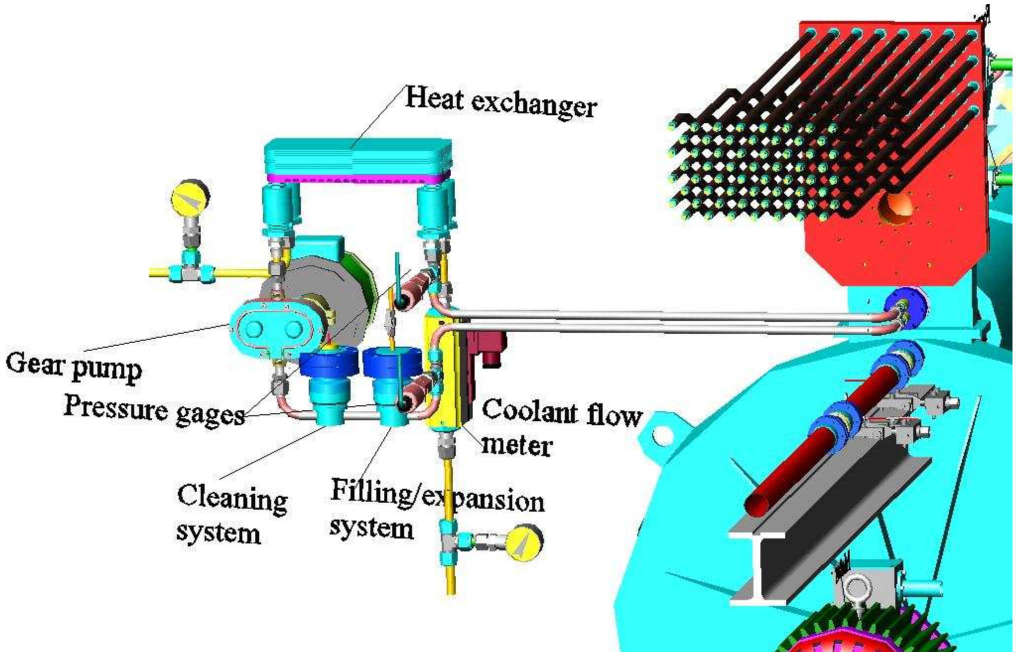


Figure 20: Concept of LL pumping/cooling system. Thermal insulation is not shown here.

Filling system consists of bellow filled with Lithium and squeezed by hydraulic pressure.
All system and ducts wrapped by thermo-insulated sleeves. Cleaning system eliminates oxides.
Properties of some materials accumulated in Table 1.

Table 1: properties of Lithium, Li[1], Be, BC, BN, W

	Units	Li	Be	BN	B_4C	W
Atomic number, ***Z***	-	3	4	5/7	5/6	74
Yong modulus	*GPa*	4.9	287	350-400	450	400
Density, ρ	[g/cm^3]	0.533	1.846	3.487	2.52	19.254
Specific resistance	*Ohm-cm*	$1.44\ x10^{-5}$	$1.9\ x10^{-5}$	$>10^{14}$	$7.14\ x10^{-3}$	$5.5\ x10^{-6}$
Length of ***X***0, ***l***Xo	*cm*	152.1	34.739	27.026	19.88	0.35
Boil temperature	^oC	1347	1287	Sublim. at melt	3500	5660
Melt temperature	^oC	180.54	2469	2973	2350	3410
Compressibility	cm^2/kg	$8.7\ x10^{-6}$	$9.27\ x10^{-7}$			$2.93\ x10^{-7}$
Grüneisen coeff.	-					2.4
Speed of sound (long)	*m/sec*	6000	12890	16400	14920	5460
Specific heat	J/g^oK	3.6	1.82	1.47	0.95	0.134
Heat conductivity	$W/cm/^oC$	0.848	2	7.4	0.3-0.4	1.67
Thermal expansion	$1/^oC$	$4.6x10^{-6}$	$11x10^{-6}$	$2.7x10^{-6}$	$5x10^{-6}$	$4.3x10^{-6}$

[1] Total mass of Lithium in ~70*kg* human body is ~7*mg*.

SUMMARY

Angular spread of secondary positrons in undulator-based method is small. Even so, usage of lens allows increase of positron yield ~50% per target.

Conceptual design of LL indicates that technical solution is well supported. Dimensions of LL are chosen as a baseline. Technical solution for the window sealing chosen and allows easy exchange windows if necessary. Basically sealing is going with the help of compressing flange and annealed Nickel (or OFC, Armco) gasket.

Dependence of positron yield as function of window thickness is pretty monotonic. Be windows of up to 5 mm thick is possible. Usage of BC, BN windows allow have them thinner.

Dimension set developed could be used in numerical modeling of energy deposition, cavitations and shock waves generation by primary gammas and secondary particles.

Current in LL one can expect not more, than 150 kA; for K=0.9 this comes to 50kA.

Polarization 0.7 (70%) is possible with this equipment, both for K=0.44 and K=0.92 .

Utilization of front window made from Tungsten potentially allows exclusion of target unit at al. In this case the lens and target becomes a compact unit. This variant becomes possible with reduced K~0.44. Undulator with K=0.44 could be made with aperture diameter 8 mm, the one with K=0.9 will require aperture less than 6 mm

As the gamma beam attenuation is <16%, second target station is feasible.

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