June 17 2011 CBN 11-2

USAGE OF LIQUID METALS IN POSITRON PRODUCTION SYSTEM OF ILC

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May 23, 2011

Abstract

The positron production system of ILC uses the hard undulator radiation (~20MeV) caring power up to 200 kW for irradiation of ~0.5X_0–thick target. We describe the target made of liquid Bismuth-Lead alloy in comparison with the spinning W or Ti target. For the focusing of positrons we suggested a compact lens where the Liquid Lithium used as a conductor and a coolant. Liquid Lithium (or Bi/Pb) alloy used as a coolant of Graphite in a gamma beam absorber. Some crucial elements of the system such as pumps, windows, nozzles, and dynamics of liquid Lithium flow in a lens are described also. Highly efficient positron collection system with liquid Lithium lens allows relaxed parameters of the undulator and target.

PLAN

1. HOW TO OBTAIN POSITRONS
- Conventional positron source.
- Undulator-based polarized-positron source
- Positron source for ILC

2. UNDULATOR

3. TARGET
- W, Ti wheel target
- Liquid Lead/Bismuth target
- Cooling schemes

4. LITHIUM LENS
- Design
- Lithium flow
- Pumps, etc

5. COLLIMATORS AND THE PHOTON DUMP

6. PRIMARY ACCELERATING STRUCTURE

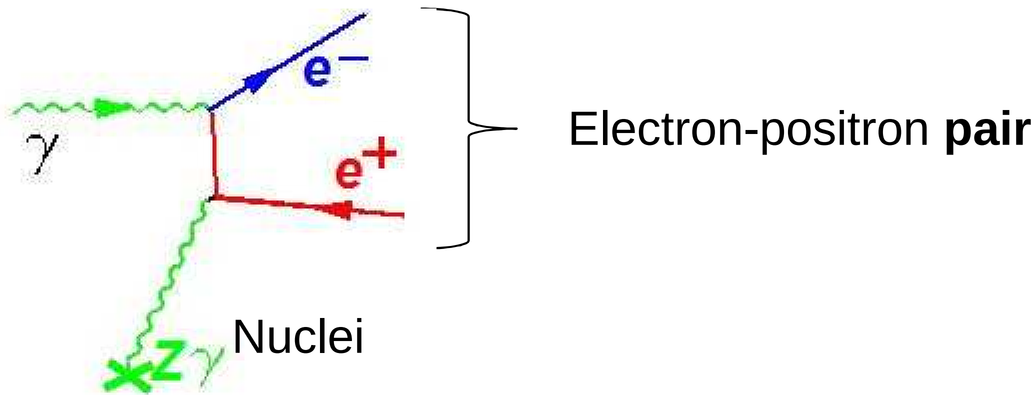
7. EXPERIMENT E-166 AT SLAC

8. PERSPECTIVES

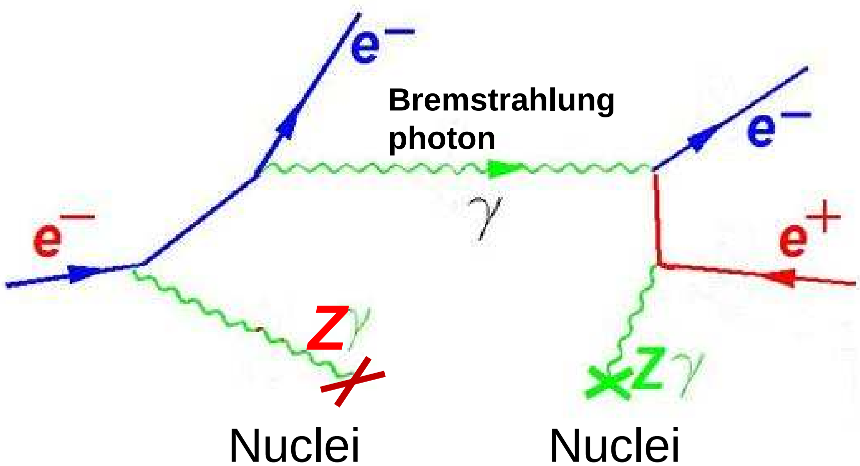
9. SUMMARY

1. HOW TO OBTAIN POSITRONS

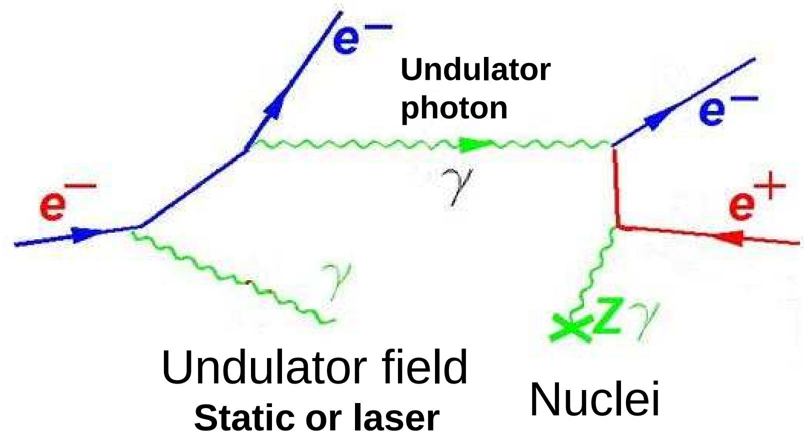
The only way to create a positron



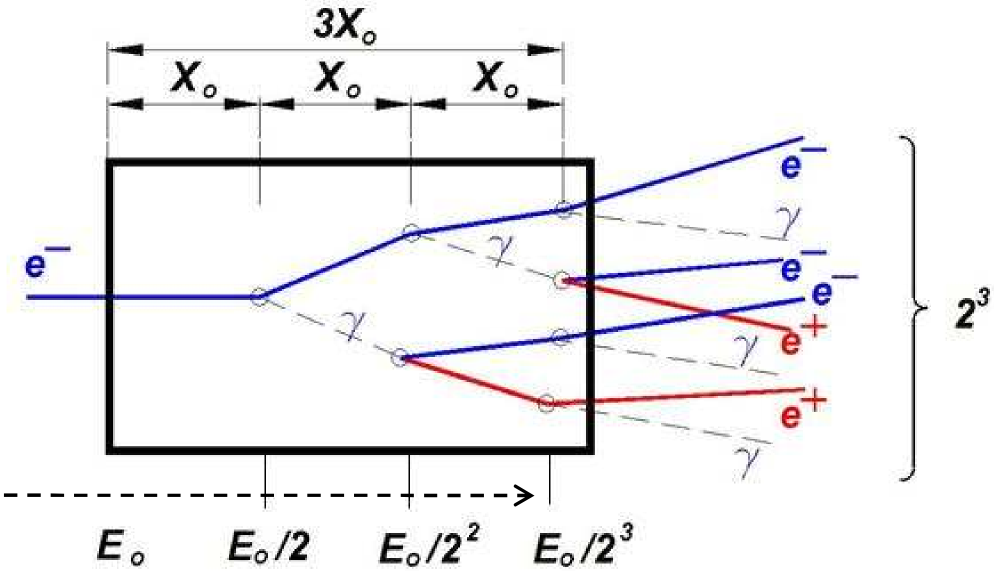
Conventional source



Undulator source



CONVENTIONAL POSITRON SOURCE-CASCADE PROCESS



With the source of gammas Process could be started here

***t*-thickness in X_0 units**

$$X_0^{-1} \cong 4r_0^2\alpha\frac{N_0}{A}Z(Z+1)\ln(\frac{183}{Z^{1/3}})[cm^2/gramm]$$ ←Radiation length

Number of positrons ~ $N_{pos} \cong N_\gamma \cong N_e \cong N_{tot}/3 = 2^t/3$.

The shower propagates until the energy of particles reaches $E_{crit} \cong 610/(Z+1.24)$

So the shower reaches its maximum at the depth $t_{\max} \cong \ln(E_0/E_{crit})/\ln 2$

with the number of the particles there about $N_{\max} \cong E_0/E_{crit}$

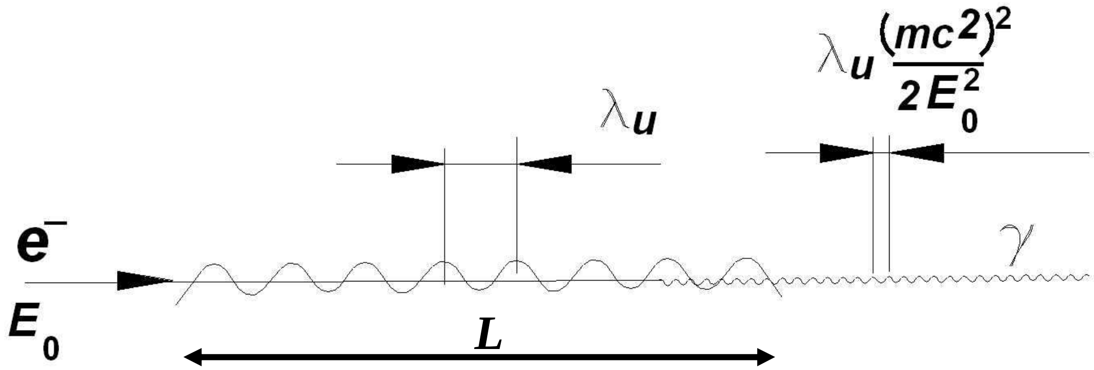
Transverse size of the cascade in maximum is of the order of Molière radius, $R_M \cong X_0 E_s/E_{crit}$

$E_s = \sqrt{4\pi/\alpha}\cdot mc^2 \cong 21.2MeV$ –is a scale energy.

Effective thickness of target is $l \cong \dfrac{<xx'>}{<x'^2>}$ **~1mm only**

GAMMA SOURCE WITH UNDULATOR OR LASER

Undulator corresponds to 90^o illumination of energetic electron by laser



$$N_\gamma \cong L\sigma_\gamma n_\gamma \qquad \sigma_\gamma \cong (8\pi/3)r_0^2 \qquad n_\gamma \cong \frac{H^2}{8\pi\hbar c/\lambda\!\!\!^{-}_u}$$

Photon density

***H* is magnetic field value**

The number of quants radiated by each electron

$$N_\gamma \cong Lr_0^2 \frac{H^2}{\hbar c/\lambda\!\!\!^{-}} \propto 4\pi\alpha \frac{L}{\lambda_u} K^2 \sim 8.7\text{x}10^2 K^2 \sim 150 \quad \text{for } K\text{\textasciitilde}0.4$$

$$K = eH\lambda_u / 2\pi mc^2 \cong 0.934 \cdot H[T] \cdot \lambda_u[cm]$$ **Deflection parameter**

Energy of quanta, *n* – harmonic number

Angle to observer

$$E_{\gamma n} \cong \frac{n \cdot 2.48 \cdot (\gamma / 10^5)^2}{\lambda_u [cm](1 + K^2 + \gamma^2 \vartheta^2)} [MeV]$$

That is why undulator installed at ~150 GeV line, where $E_{\gamma max}$ ~20 MeV

For the reference:

Total energy carried out by these photons~

$$E = N_\gamma E_\gamma \cong 150\text{x}20 MeV$$

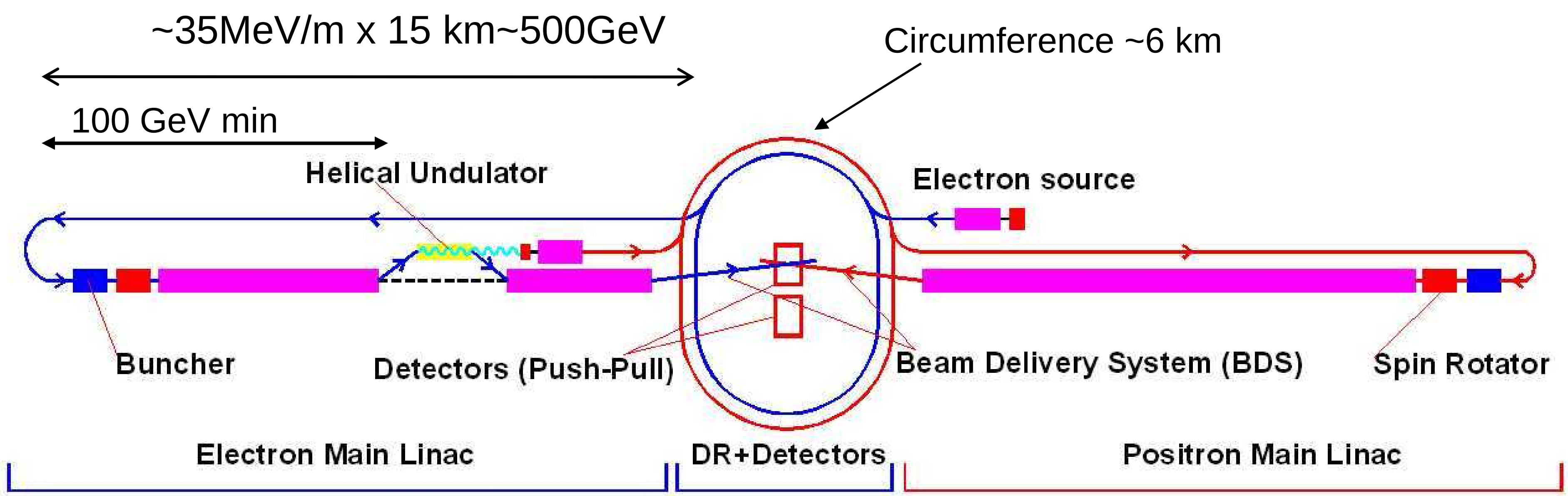
By all $2\text{x}10^{10}$ particles in a 2800 bunchs in 5 Hz (K=0.4)

$E_{tot}=150x20x10^6x2x10^{10}\,x1.6x10^{-19}x5x2800=3x2.8x1.6x5x2800=135kJ/sec$

Only ~12% of photons interact with the target.
One can use the second target and combine the positrons in a damping ring.
Rest amount should be dumped.

POSITRON SOURCE FOR ILC

The undulator scheme of positron production has been chosen as a baseline for ILC accommodated from TESLA design, originated for VLEPP (Novosibirsk, 1979)

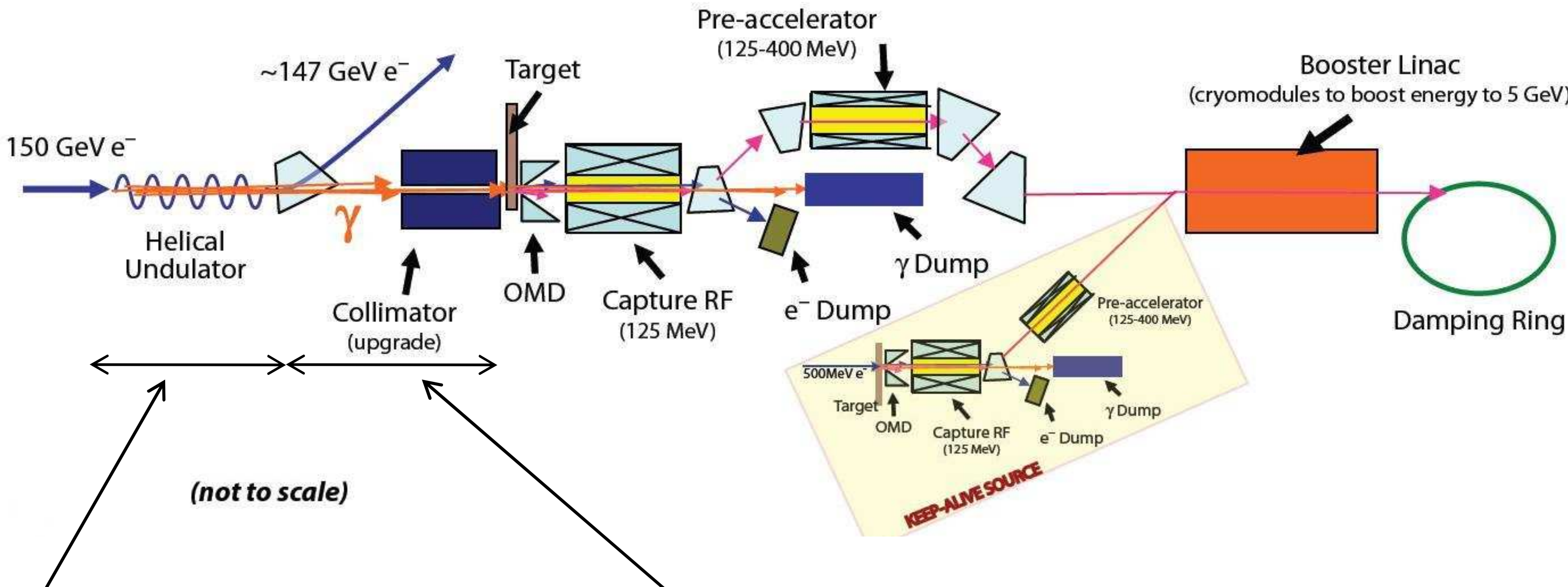


Main advantage of this scheme is that it allows **POLARIZED** (>60%) positron production

In principle, the positrons could be generated by positrons, so the linacs become independent

Conversion system of ILC as it appears in ILC Reference Design Report,

ILC-REPORT-2007-001, Vol.3, p.III-41

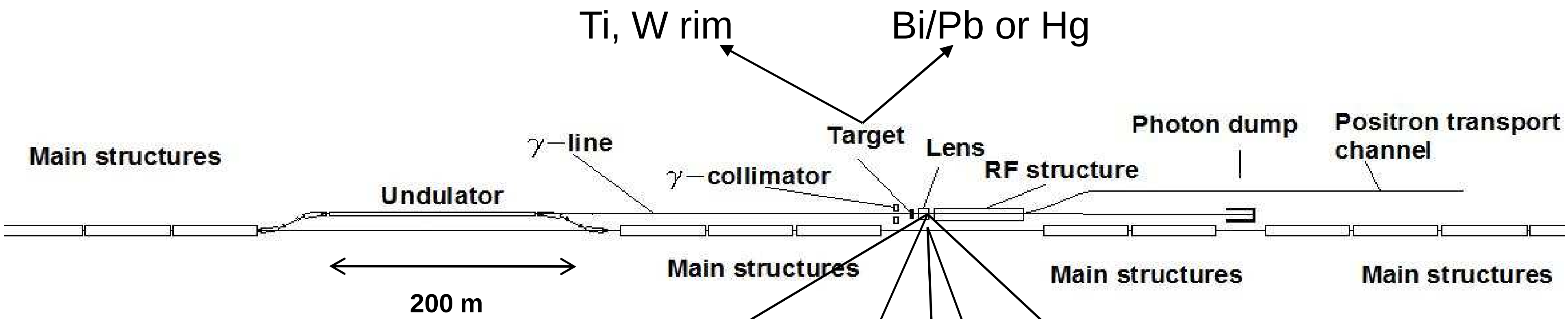


Helical undulator is ~150 m long.

The distance between the end of undulator and the target is ~150-300 m

OMD stands for Optical Matching Device

MORE DETAILED VIEW ON THE UNDULATOR POSITRON SOURCE



Adiabatic matching device

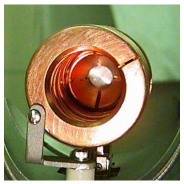
Original suggestion;
Target immersed in strong field;

Identified the problems with induced fields in moving Ti metal

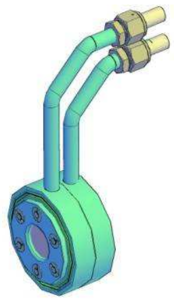
Flux concentrator

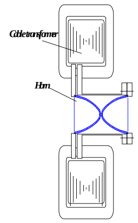
Under development at Livermore

Combined Flux Concentrator and solenoid



Lithium lens

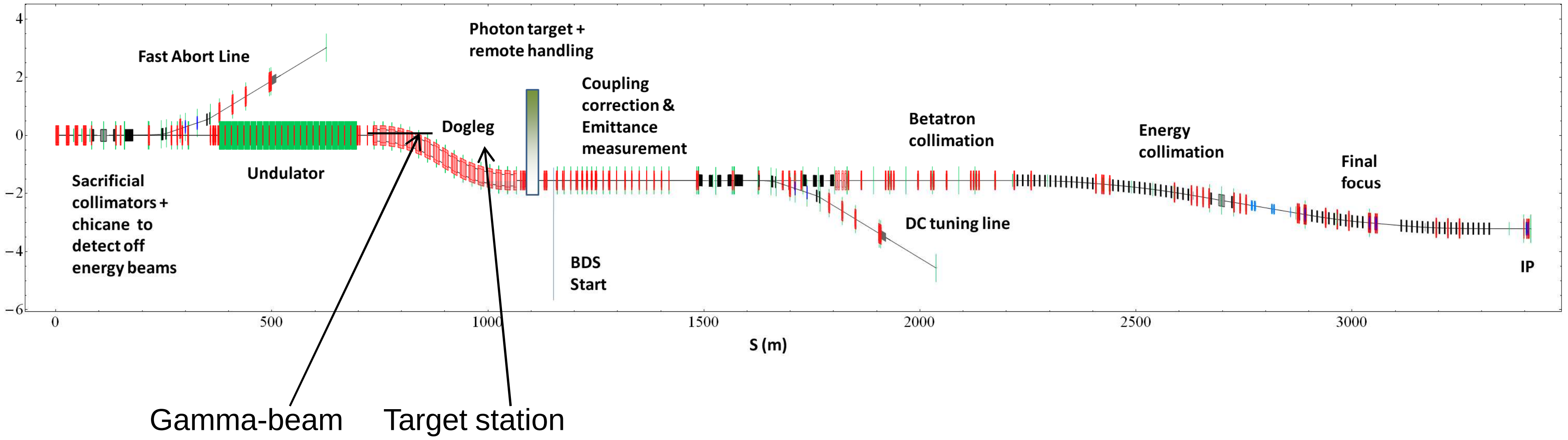




X lens-miniature horn; Ø=2cm, length ~2cm

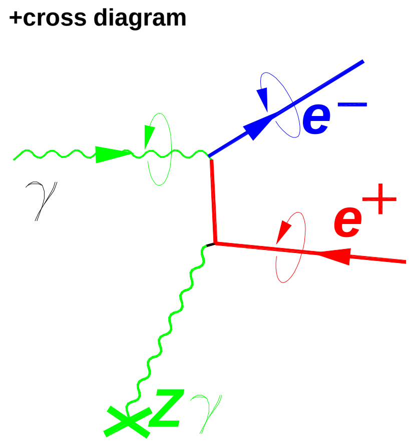
ONE AMONG LATEST LAYOUTS

Undulator located at the end of the linac

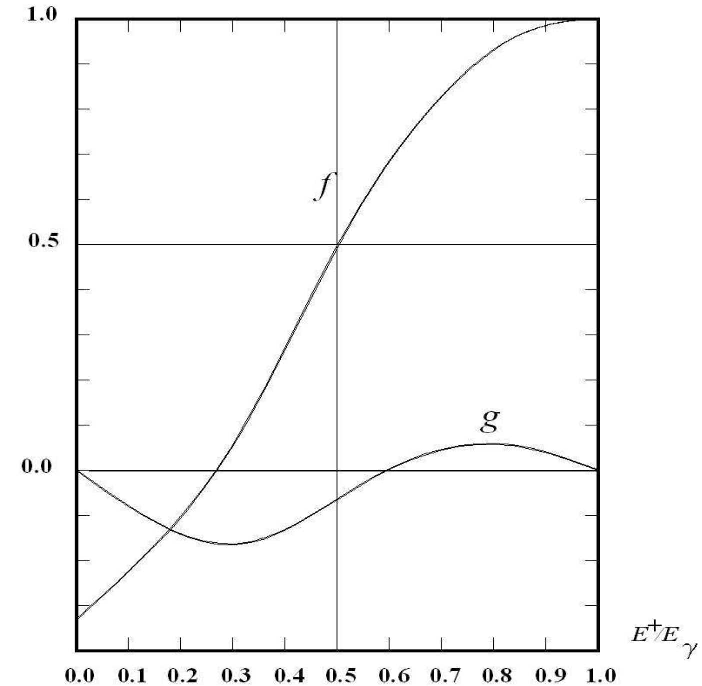


J.Jones, d.Angal-Kalinin, WEPP031,STFC (Science and Technology Facilities Council) Daresbury Laboratory, Proc of IPAC’10, Kyoto, Japann, 2010

PRODUCTION OF *POLARIZED* POSITRONS



H.Olsen, L.Maximon, 1959



f, g as functions of particle's fractional energy $E^+/(E_\gamma - 2mc^2)$

Photon polarization

$$\vec{\varsigma} = \xi_2 \cdot \left[f(E_+, E_-) \cdot \vec{n}_\parallel + g(E_+, E_-) \cdot \vec{n}_\perp \right] = \vec{\varsigma}_\parallel + \vec{\varsigma}_\perp$$

Positron polarization

Polarization is a result of selection of positrons by theirs energy

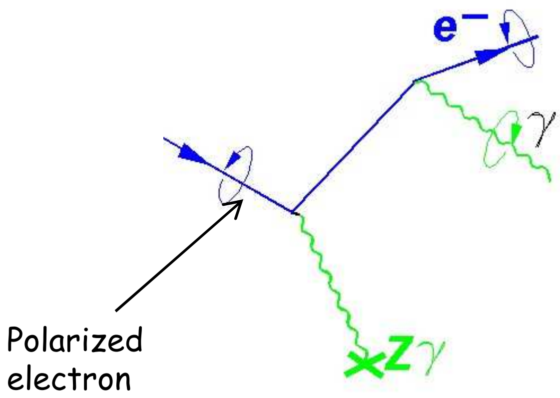
Fragment from publication of Balakin-Mikhailichenko, Budker INP 79-85, Sept. 13, 1979.

Circularly polarized photons are produced in helical fields of minimal period. Much more interesting is to obtain such fields with the help of the usual helical static fields and the electromagnetic waves. It may well be that the method of gamma production in helical crystals can be useful in future.

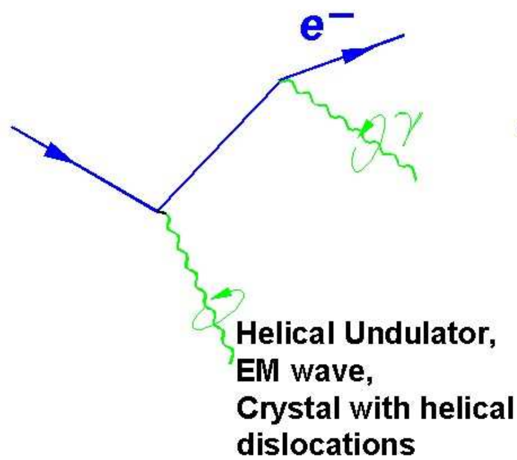
Scattering on the Laser radiation is the same process as the scattering on the electromagnetic wave.

PRODUCTION OF CIRCULARLY POLARIZED PHOTONS

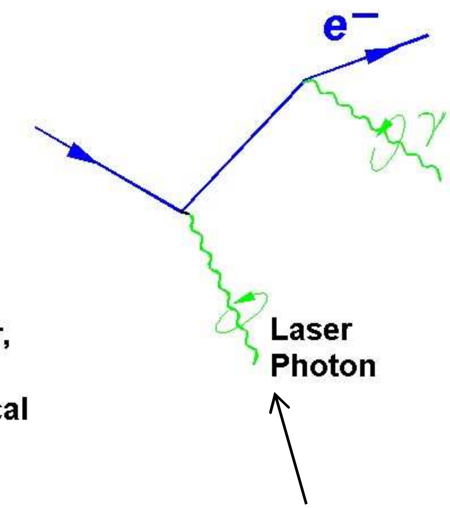
Well known processes reviewed for practical utilization in a positron source



E.Bessonov, A.Mikhailichenko, EPAC96



V.Balakin, A. Mikhailichenko, 1979



E.Bessonov, Hamburg 1992

KEK team-1995

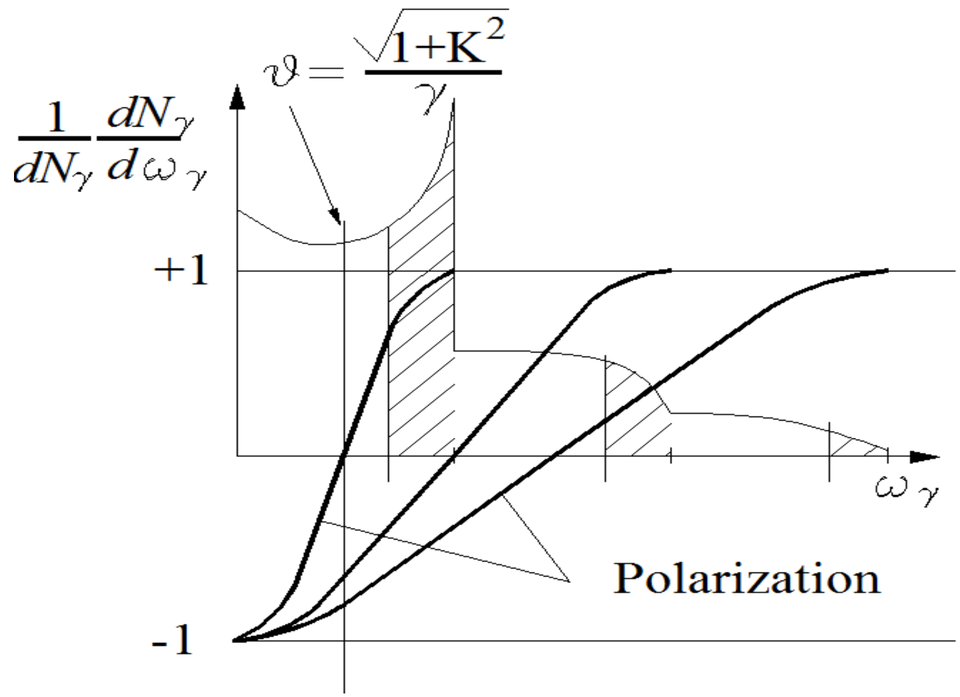
UNDULATOR SHOULD BE HELICAL

Spectral distribution and polarization schematics for Undulator Radiation

All higher harmonics have zero intensity in straight forward direction

Angle of radiation and the energy of the photon are not independent

Polarization curve needs to be convolved with the photon density

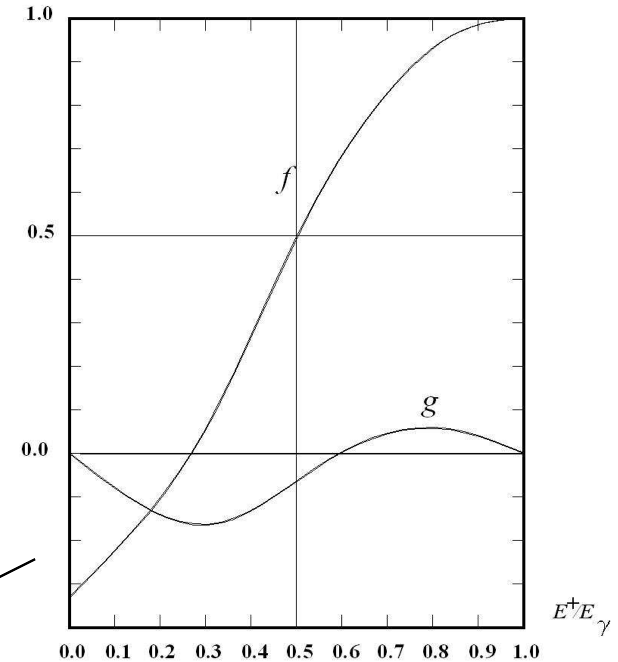


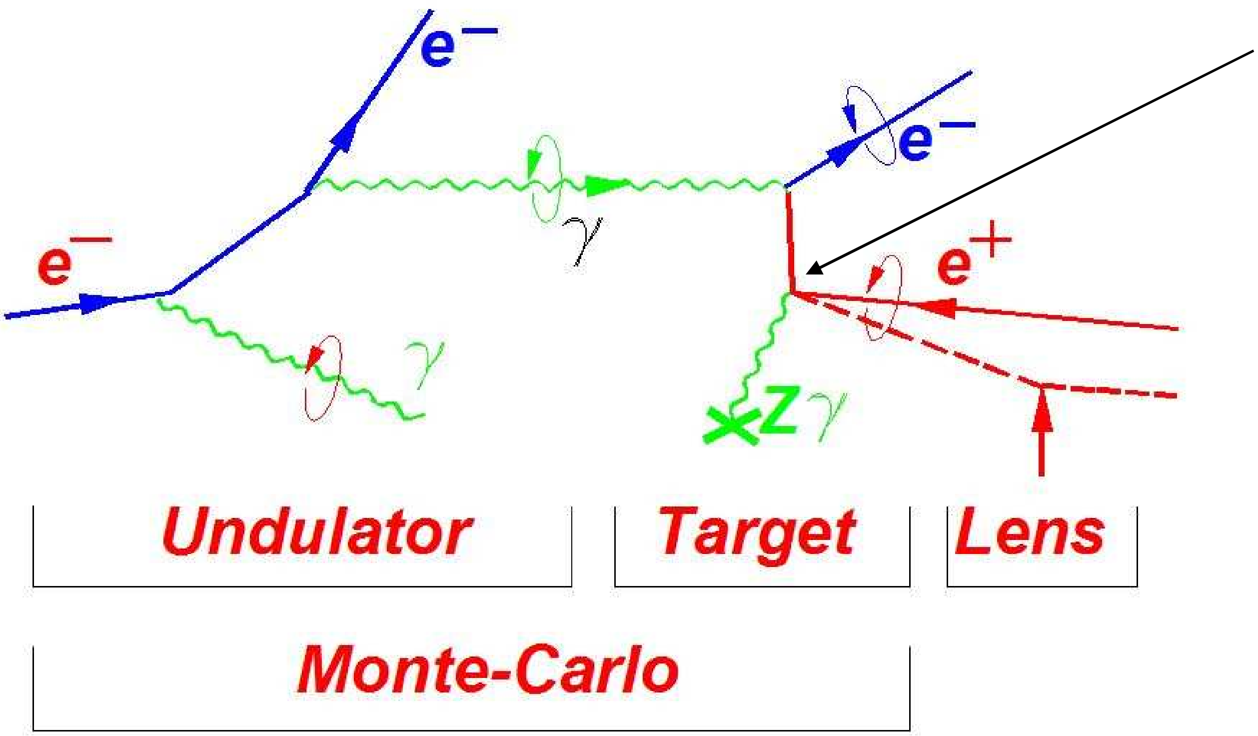
Hatched areas correspond to the passage of radiation through the collimator

Collimator helps to enhance integrated photon polarization

Start to end simulation Code KONN

Initiated in 1986; continued in 2007- 2011





PROGRAM KONN

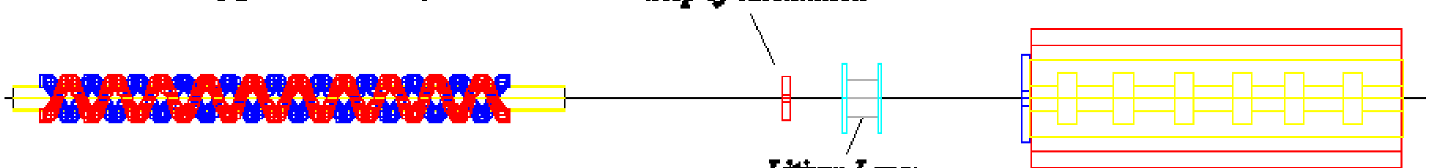
T.A.Vsevolozhskaya, A.A.Mikhailichenko

Monte-Carlo simulation of positron conversion

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

Target:
Distance to the undulator
Thickess;
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 irices;
External solenoidal field;
Further phase volume captured;



Litium Lens:
Distance to the target;
Length;
Diameter;
Thicness 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, now is ~3000 lines

Resulting efficiency and polarization calculated with KONN

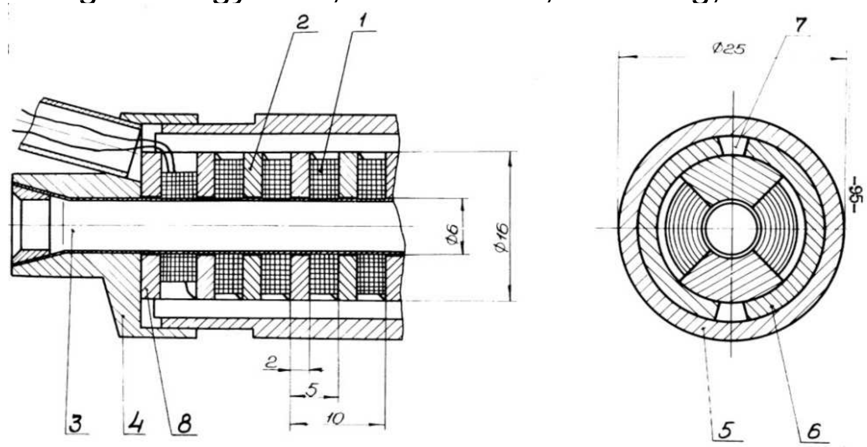
*readius of target is an equivalent of the radius of collimator

Beam energy, *GeV*	150	250	350	500
Length of undulator, *m*	170	200	200	200
K factor	0.44	0.44	0.35	0.28
Period of undulator, *cm*	1.0	1.0	1.0	1.0
Distance to the target, *m*	150	150	150	>150
Radius of target*, *cm*	0.049	0.03	0.02	0.02
Emittance, *cm·rad*	1e-9	1e-9	1e-9	1e-9
Bunch length, *cm*	0.05	0.05	0.05	0.05
Beta-function, *m*	400	400	400	400
Thickness of target $/X_0$	0.57	0.6	0.65	0.65
Distance to the length, *cm*	0.5	0.5	0.5	0.5
Radius of the lens, *cm*	0.7	0.7	0.7	0.7
Length of the lens, *cm*	0.5	0.5	0.5	0.5
Gradient, *MG/cm*	0.065	0.065	0.08	0.1
Wavelength of RF, *cm*	23.06	23.06	23.06	23.06
Phase shift of crest, *rad*	-0.29	-0.29	-0.29	-0.29
Distance to RF str., *cm*	2.0	2.0	2.0	2.0
Radius of RF collimator, *cm*	2.0	2.0	2.0	2.0
Length of RF str., *cm*	500	500	500	500
Gradient, *MeV/cm*	0.1	0.1	0.1	0.1
Longitudinal field, *MG*	0.015	0.015	0.015	0.015
Inner rad. of irises, *cm*	3.0	3.0	3.0	3.0
Acceptance, *MeV·cm*	5.0	5.0	5.0	5.0
Energy filter, E > -*MeV*	54	74	92	114
Energy filter, E< -*MeV*	110	222	222	222
Efficiency, e^+/e^-	1.5	1.8	1.5	1.5
Polarization, %	70	80	75	70

2. UNDULATOR

Historical remark: First SC undulator with period 10 mm was tested in 1986;

T.A.Vsevolozhskaya et al., “ Helical Undulator for the Conversion System of the VLEPP Project”, SLAC-TRANS-0225, 13th Int. Conf. on High-Energy Acc., Novosibirsk, 7-11 Aug, 1986.



1-windings, 2-iron yoke, 3-StSteel thin-wall tube, 4-end cup, 5-helium vessel, 6-Iron yoke, 7-groove for Helium.

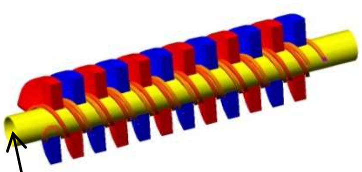
Length of undulator ~30cm, K_{max}~0.4 (required K=0.35), period 10*mm*

Undulator designed at Cornell

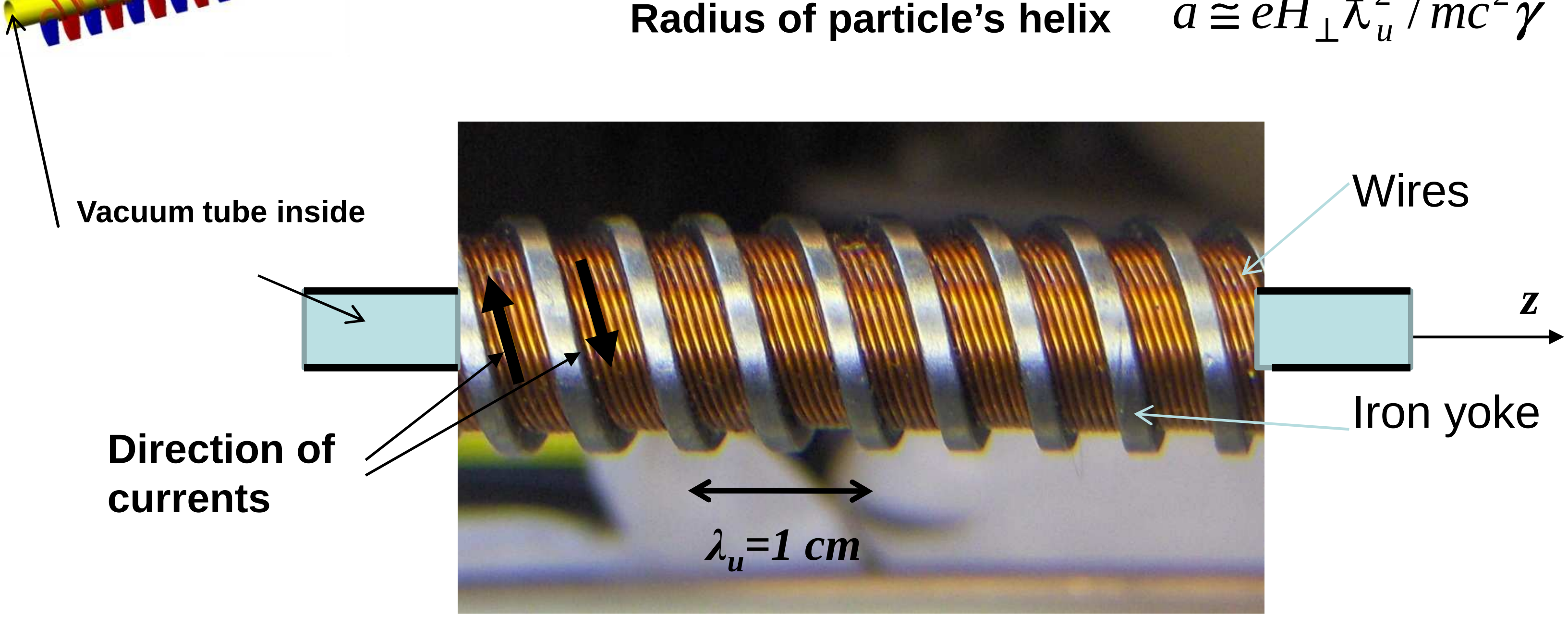
12 –mm period undulator core. Aperture available for the beam is 8 mm clear. Measured *K*~0.83 (Iron yoke removed)

Helical undulator is a device for generation magnetic field of a type

$$\vec{H}_\perp(z) = \vec{e}_x H_{xm} Cos\frac{2\pi z}{\lambda_u} + \vec{e}_y H_{ym} Sin\frac{2\pi z}{\lambda_u}$$



Radius of particle's helix $a \cong eH_\perp \bar{\lambda}_u^2 / mc^2\gamma$



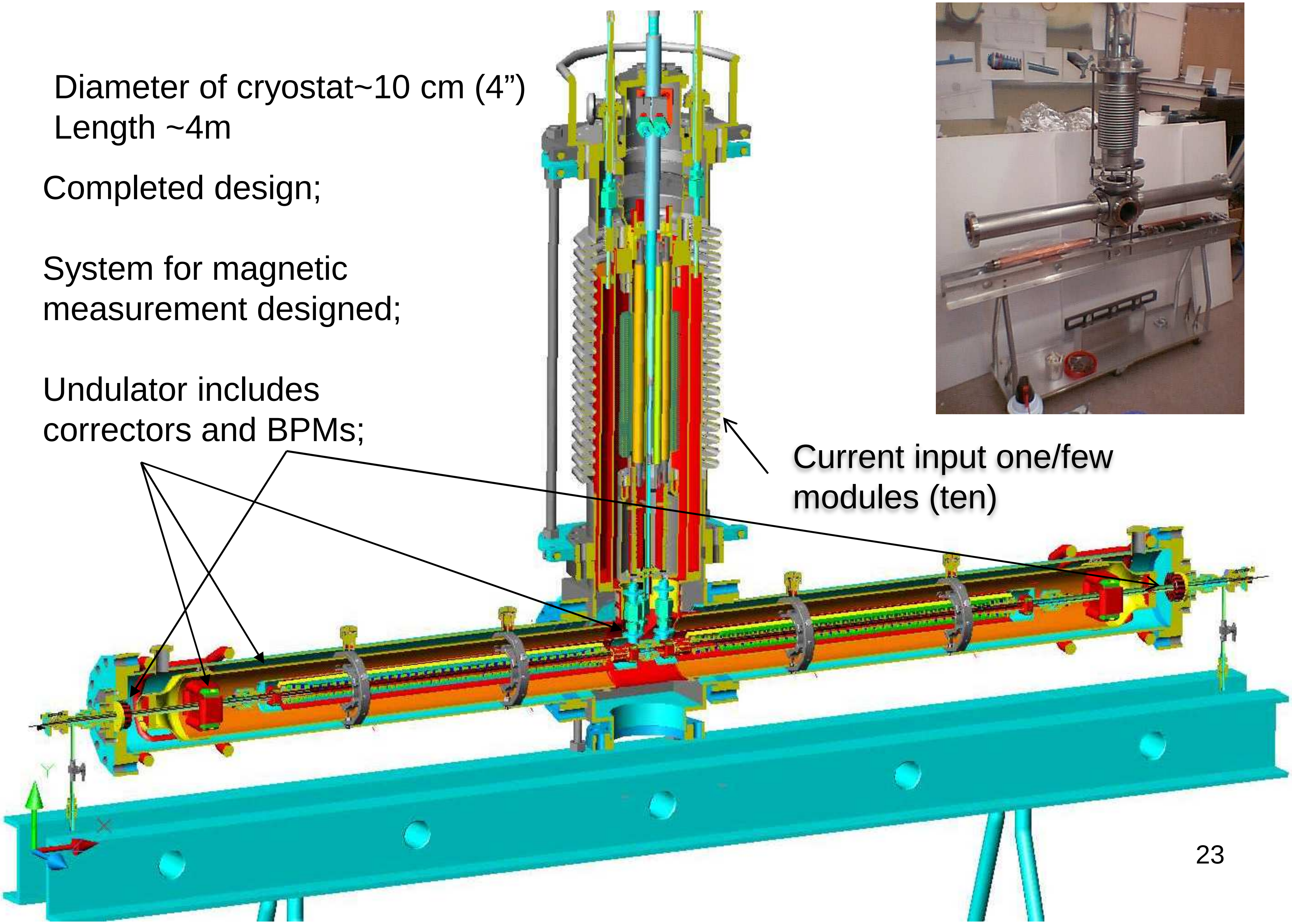
UNDULATOR DESIGN (CORNELL)

Diameter of cryostat~10 cm (4”)
Length ~4m

Completed design;

System for magnetic measurement designed;

Undulator includes correctors and BPMs;



Current input one/few modules (ten)

UNDULATOR DESIGN (UK)

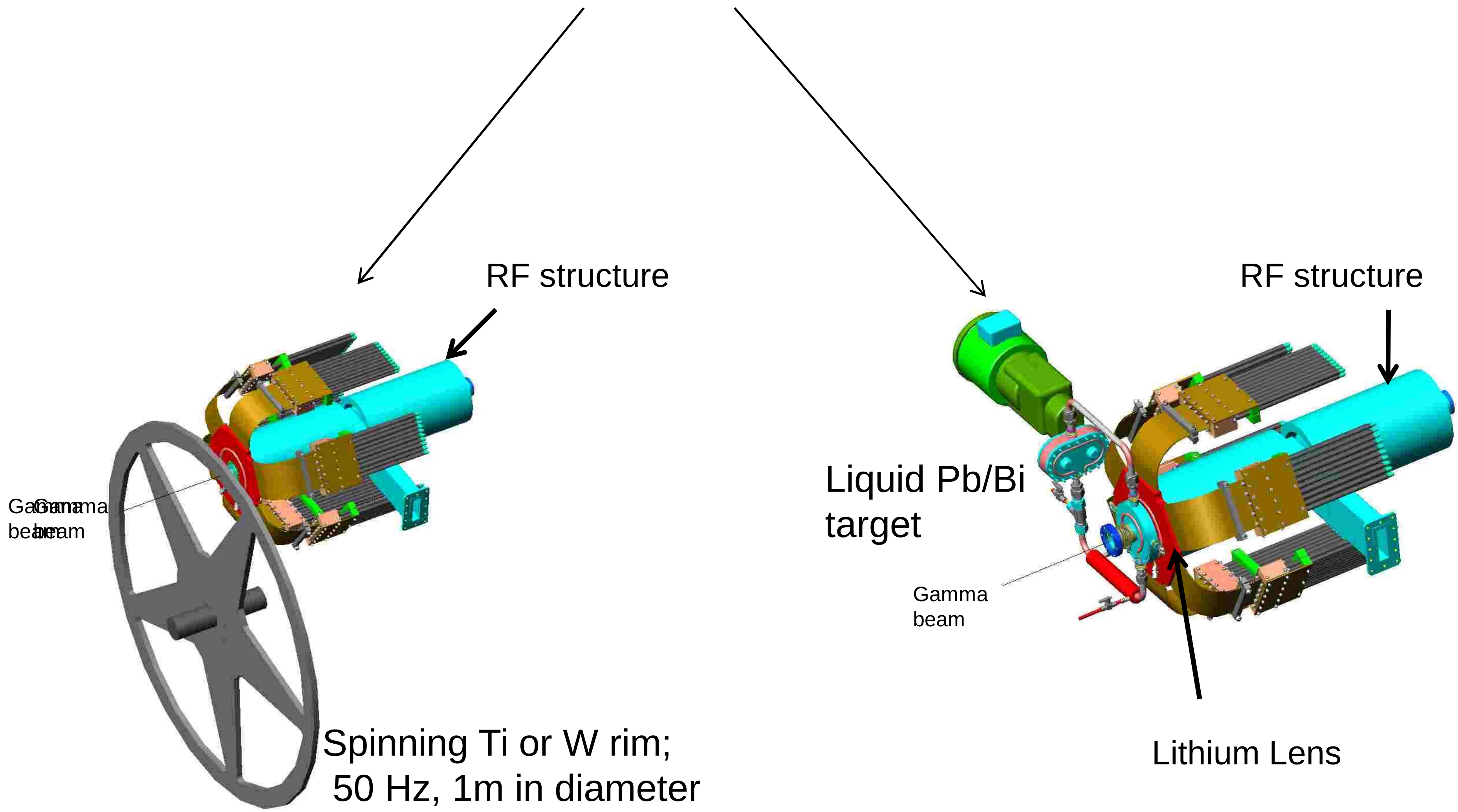
Undulator period	11.5 mm
Field on axis	0.86 T
Peak field homogeneity	<1%
Winding bore	>6 mm
Undulator length	147m; 4 m-long sections
Nominal current	215 A
Winding concentricity	20 µm
Winding tolerances	100 µm
Straightness	100 µm
NbTi wire Cu:SC ratio	0.9
Winding block	9 layers x 7 wire ribbon

Ian Bailey, presentation at LCWS10 and ILC 10, Beijing, March 29, 2010

3. TARGET

A.Mikhailichenko, “ Liquid Metal Target for ILC”, EPAC06, MOPLS108, Edinburg, Schotland 2006, Proc., pp. 816-818.

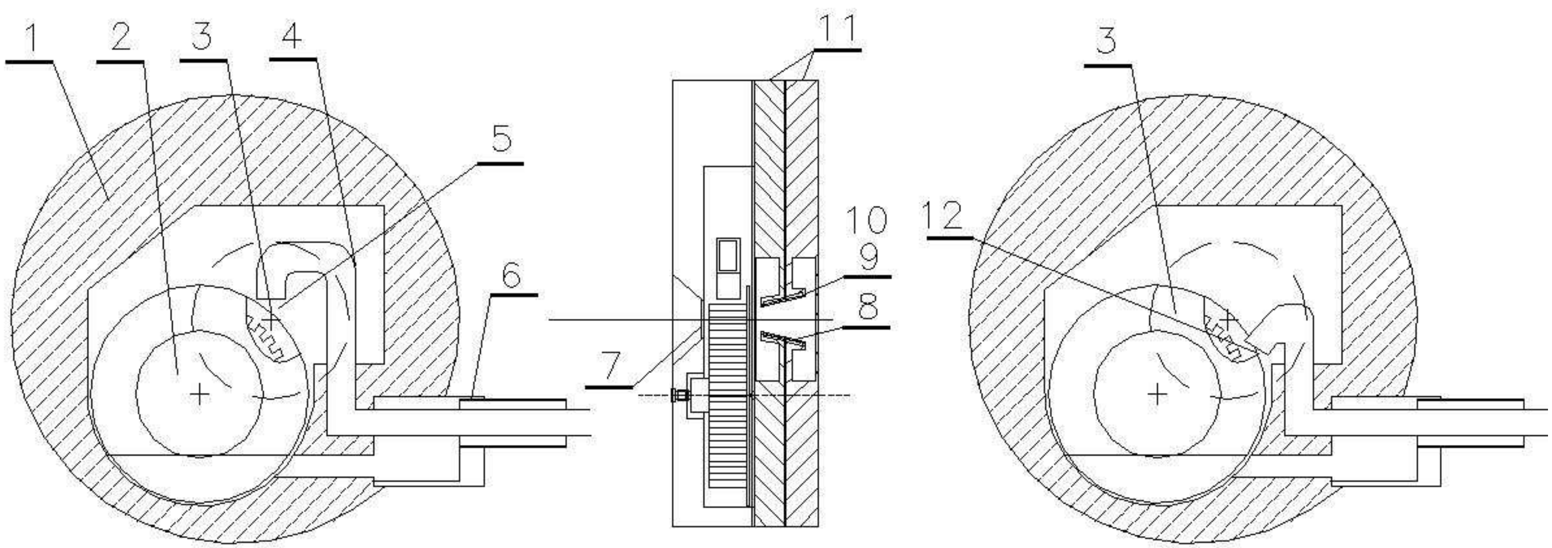
Two approaches in the target design



Liquid Mercury target suggested for VLEPP,

1986 A.Mikhailichenko, PHD Thesis

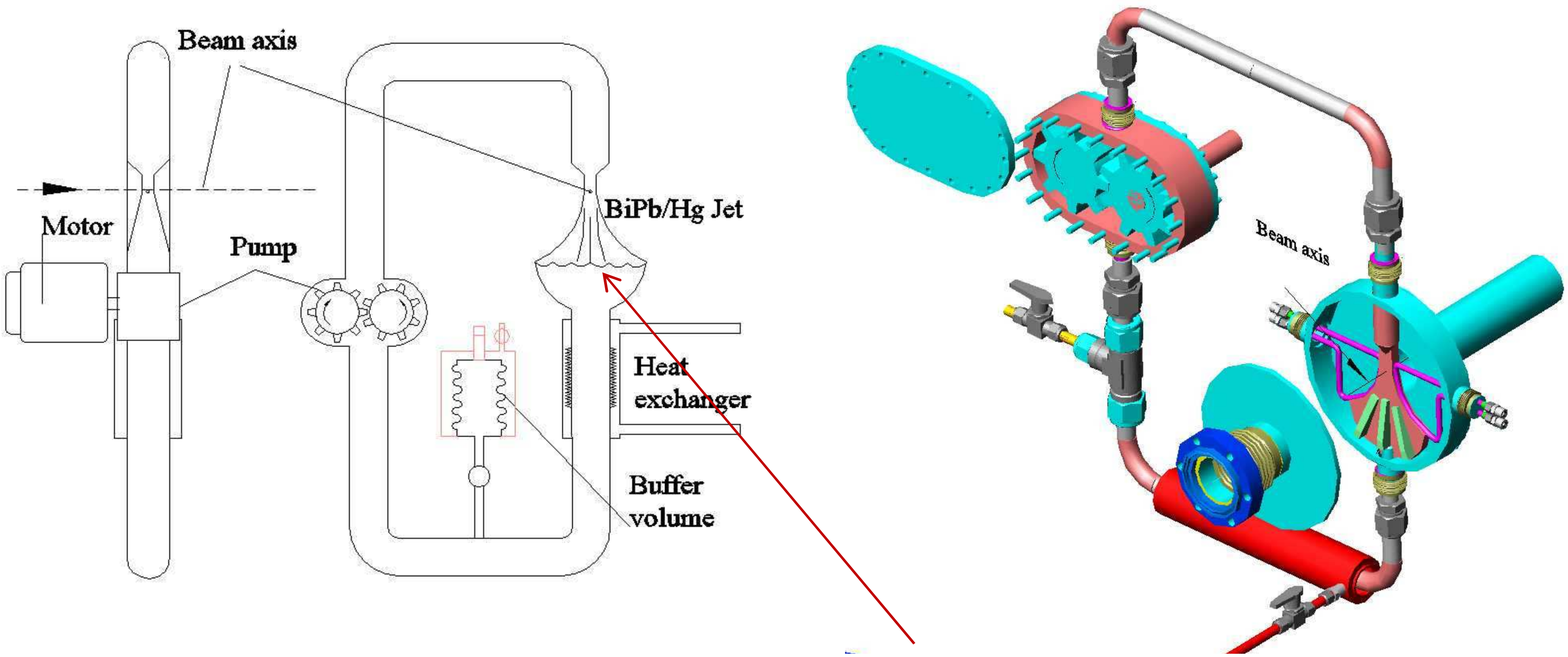
Variant 1 Variant 2



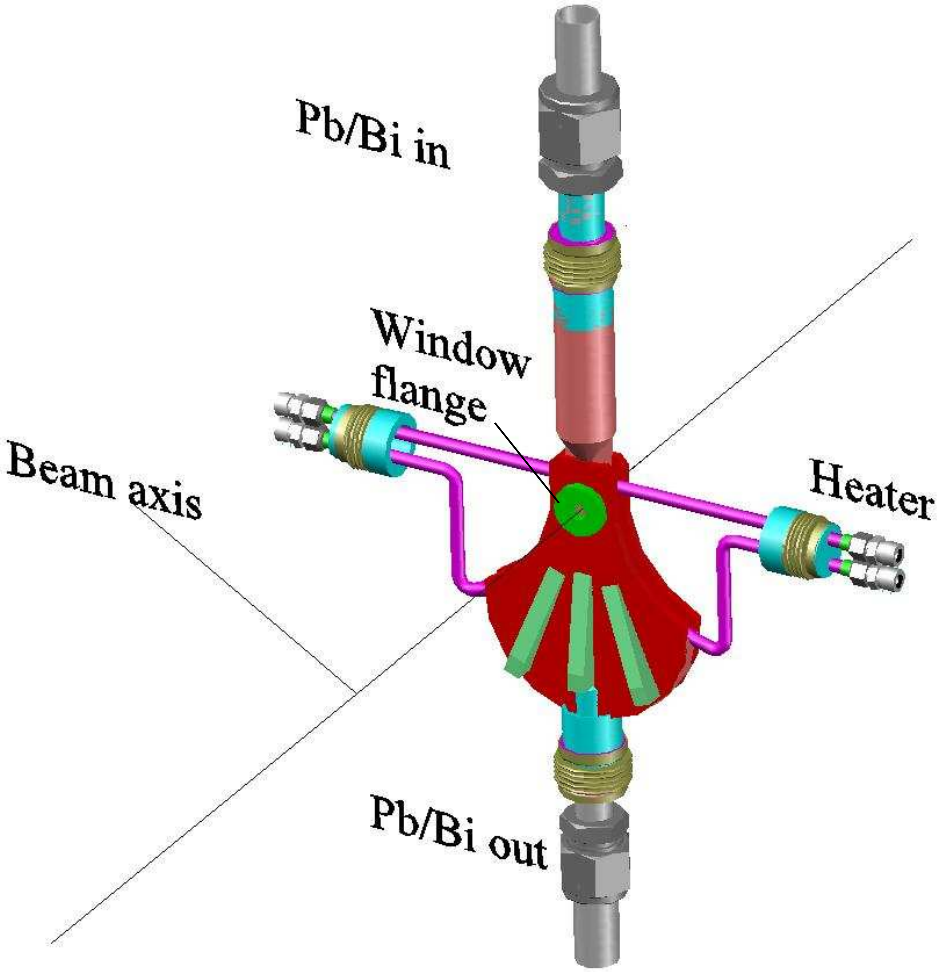
Variant 1. 1-Titanium case, 2 is the teethed wheel, 3 is the target focusing point, 4 is the nozzle, 5 is the Mercury jet, 6 is the feeding tubes, 7 is secure Titanium foil, 8 is the conicaly shaped lens, 9 is the volume with liquid Lithium, 10 is Beryllium made flange, 11 are the current leads made from Titanium. Variant 2. 3 is the target focusing point, 12 is the nozzle.

Bunch population N_e=10^{12}

Liquid metal target concept



Jet hits the liquid metal surface



The jet chamber could be made from Ti (Melt @1668^{o}C) or Niobium (melt @ 2464^{o}C)

Windows cooled by the metal jet itself.

Material for windows: ^{4}Be; ^{22}Ti;

Boron Nitride- BN (^{5}B^{7}N, sublimates @2700^{o}C)

Boron Carbide (B4C) , melts @2350

Jet cross section is (width x thickness)= 1cmx0.24cm

Jet velocity~10m/s provides for 1 ms the distance ~1 cm

Hg can be used as well

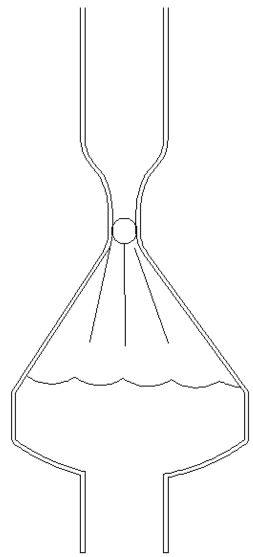
Back window could be omitted; this requires differential pumping and cooled traps.

Careful design required in this case.

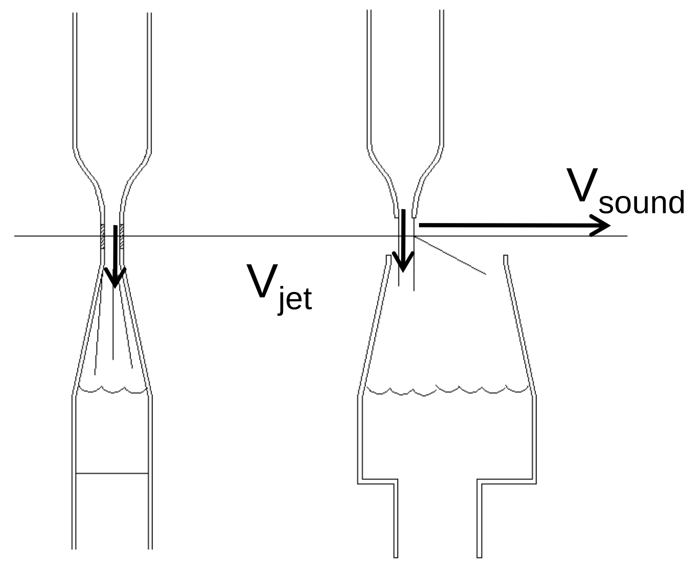
Temperature jump in *out*-window -150^{o}C max after 1 ms train; front window not heated at all.

Windowless jet requires protective shield or distance

Front view



Side view.



Droplets from the target have a speed of sound

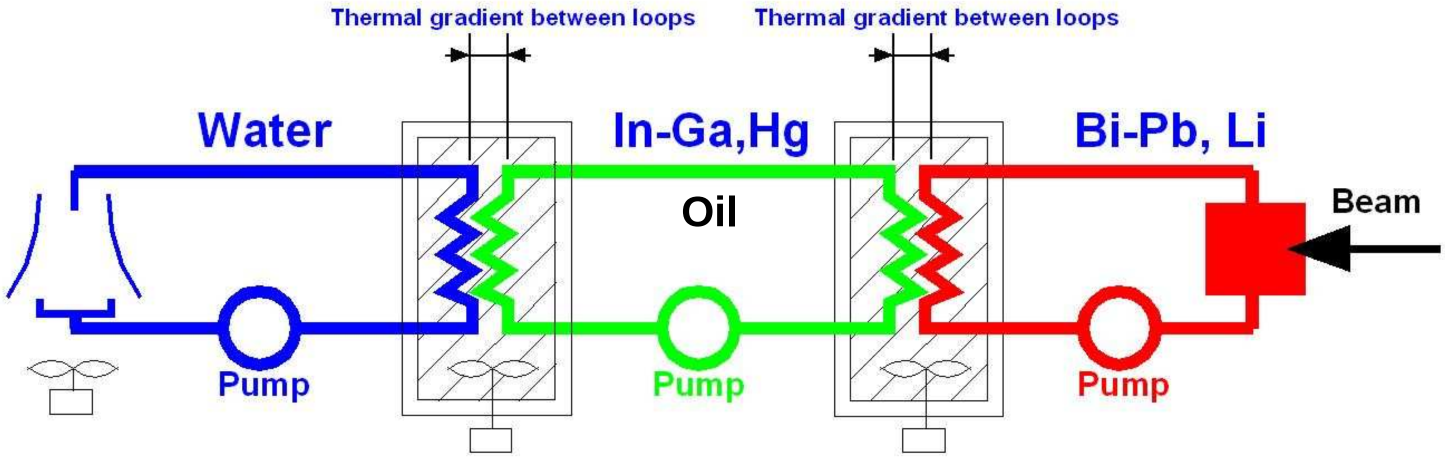
ℓ_p,

Liquids used for the targeting and cooling

	H_2O	**Lithium**	**Pb-Bi** (55wt%/45wt%)	**Hg**	**Ga**
ρ g/cm^3	1.0	0.534	8.94	13.56	5.9
C_v J/g/^{o}C	4.1813	3.58	0.197	0.1395	0.37
T_{melt}, ^{o}C	0	180.54	125.9	-38.83	29.76
T_{boil}, ^{o}C	100	1342	1670	357	2204
l_{Xo}, cm	36.08	152.1	0.709	0.48	2.11
Latent heat, kJ/g	2.26	21.2	0.86(Pb)	0.294	3.6
Nucl.int.length, cm	83.3	133.6	17.6(Pb)	14.58	23.92
Ionization, MeV/cm	1.992	0.875	12.7(Pb)	15.31	8.1

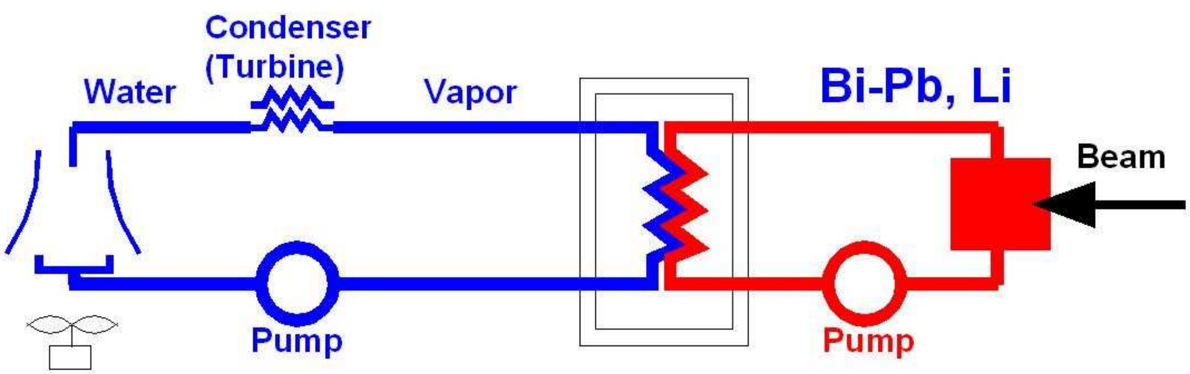
Gallium has better performance with Indium.
Gallium metal price is approaching 1000$/kg, so the system containing 3L of Gallium will have a weight of Ga ~17.7kg and will cost ~18k$, which is acceptable.
Addition of Indium with its ~750$/kg will reduce the price, proportionally to percentage of Indium in the alloy. Savings are not drastic, however.
Lithium metal price ~$64/kg is low at this scale.
Mercury metal trades at 700$/34.5 kg; 34.5 kg represents so called flask=76 lb.
Na-K coolants in use for nuclear reactors, however extreme chemical activity makes usage of this coolant problematic in civil installations.

COOLING SYSTEMS



$$Q = -k \cdot Area \cdot \frac{\Delta T}{l}$$

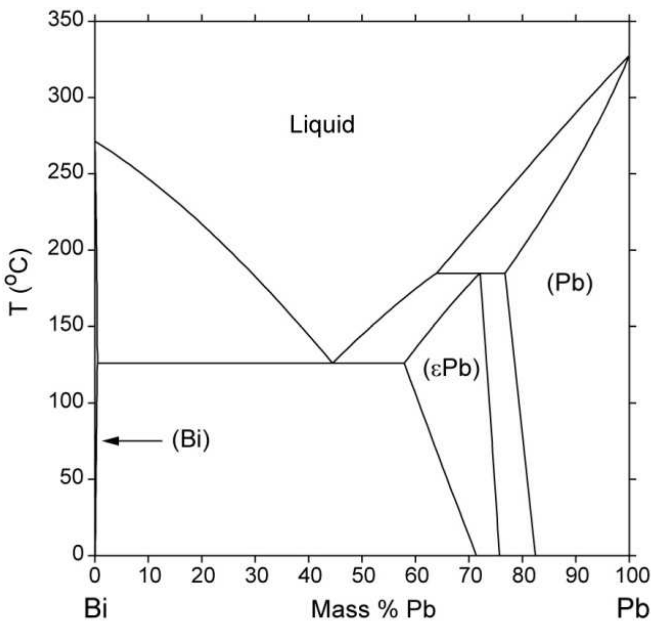
Maximal value of *ΔT* defined by the coolant



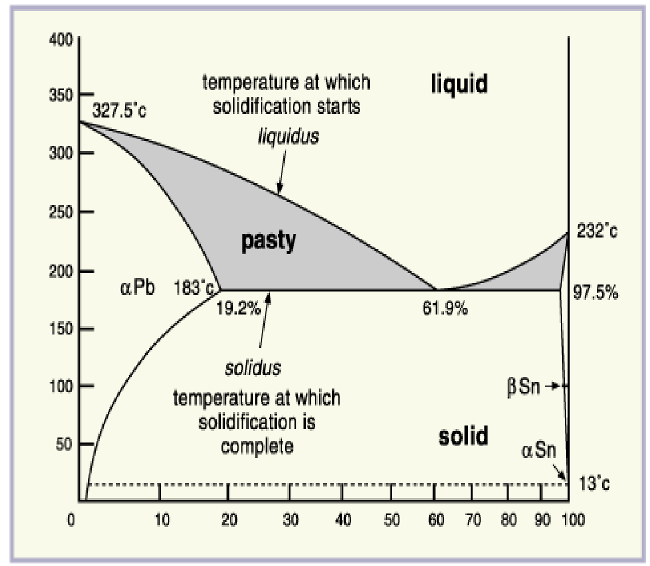
3-contour cooling system, at the top. 2-contour vapor cooling system at the bottom.

Bi-Pb alloy composed with 55.51Mass% of Bi and 44.49 Mass% of Pb has liquid phase at 125.9°C. Phase diagram of this alloy is rather branchy with different modifications of Pb sub-phases.

Bi Pb diagram



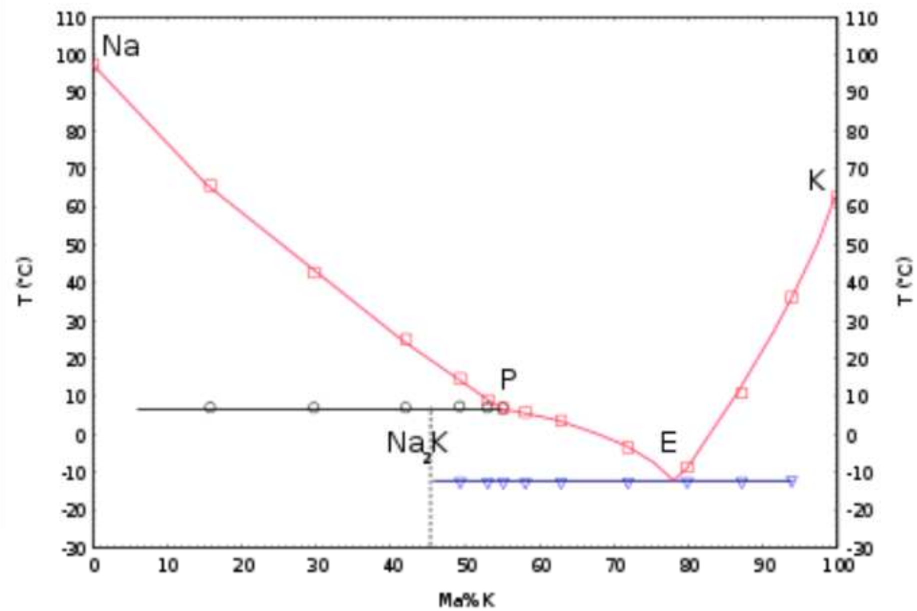
Pb- Sn diagram



Nuclear reactor cooling (Wikipedia) [edit]

Molten sodium is used as a coolant in some types of fast neutron reactors. It has a low neutron absorption cross section, which is required to achieve a high enough neutron flux, and has excellent thermal conductivity. Its high boiling point allows the reactor to operate at ambient pressure. However, using sodium poses certain challenges. The molten metal will readily burn in air and react violently with water, liberating explosive hydrogen. During reactor operation, a small amount of sodium-24 is formed as a result of neutron activation, making the coolant radioactive.

Sodium leaks and fires were a significant operational problem in the first large sodium-cooled fast reactors, causing extended shutdowns at the Monju Nuclear Power Plant and Beloyarsk Nuclear Power Plant.



Sodium-potassium phase diagram, i. e. melting point of sodium as a function of potassium content in it (in atomic percent)

Where reactors need to be frequently shut down, as is the case with some research reactors, the alloy of sodium and potassium called NaK is used. It melts at −11 °C, so cooling pipes will not freeze at room temperature. Extra precautions against coolant leaks need to be taken in case of NaK, because molten potassium will spontaneously catch fire when exposed to air. The phase diagram with potassium shows that the mixtures with potassium are liquid at room temperature in a wide concentration range. A compound Na_2K melts at 7 °C. The eutectic mixture with a potassium content of 77 % gives a melting point at −12.6 °C.[22]

B.F.Gromov et al., "Use of Lead-Bismuth Coolant in Nuclear Reactors and Accelerator-Driven Systems", Nuclear Engineering and Design 173, (1997) 207-217.

LOSSES FOR DIFFERENT MATERIAL OF TARGET

If energy Q deposited in mass m, then the temperature rise is

$$\Delta T = \frac{Q}{mc_V},$$

where c_V stands for the heat capacity. In its turn, for the $1cm^2$ cross section

$$Q \cong l[cm]\times 1[cm^2]\times 2[MeV/g/cm^2]\times \rho[g/cm^3].$$

For the gamma target, the length l is a fraction of radiation length, $l \cong \frac{1}{2}X_0/\rho$,

$$Q \cong X_0 \times 1[MeV]$$

From the other hand $m = \rho\times 1[cm^2]\times\frac{X_0}{2\rho} = \frac{1}{2}X_0\times 1[g],$

so the temperature gain goes to be

$$\Delta T \cong \frac{2}{c_V[J/g/^oK]}[^oK] \quad \left(\cong \frac{2A}{25[Mol/g/^oK]\cong const:(D-P\ law)}\right)$$

For Ti c_V=0.5 $J/g/^oK$; for W c_V=0.134 $J/g/^oK$; for Pb c_V=0.13 $J/g/^oK$,
So ratio of temperatures comes to

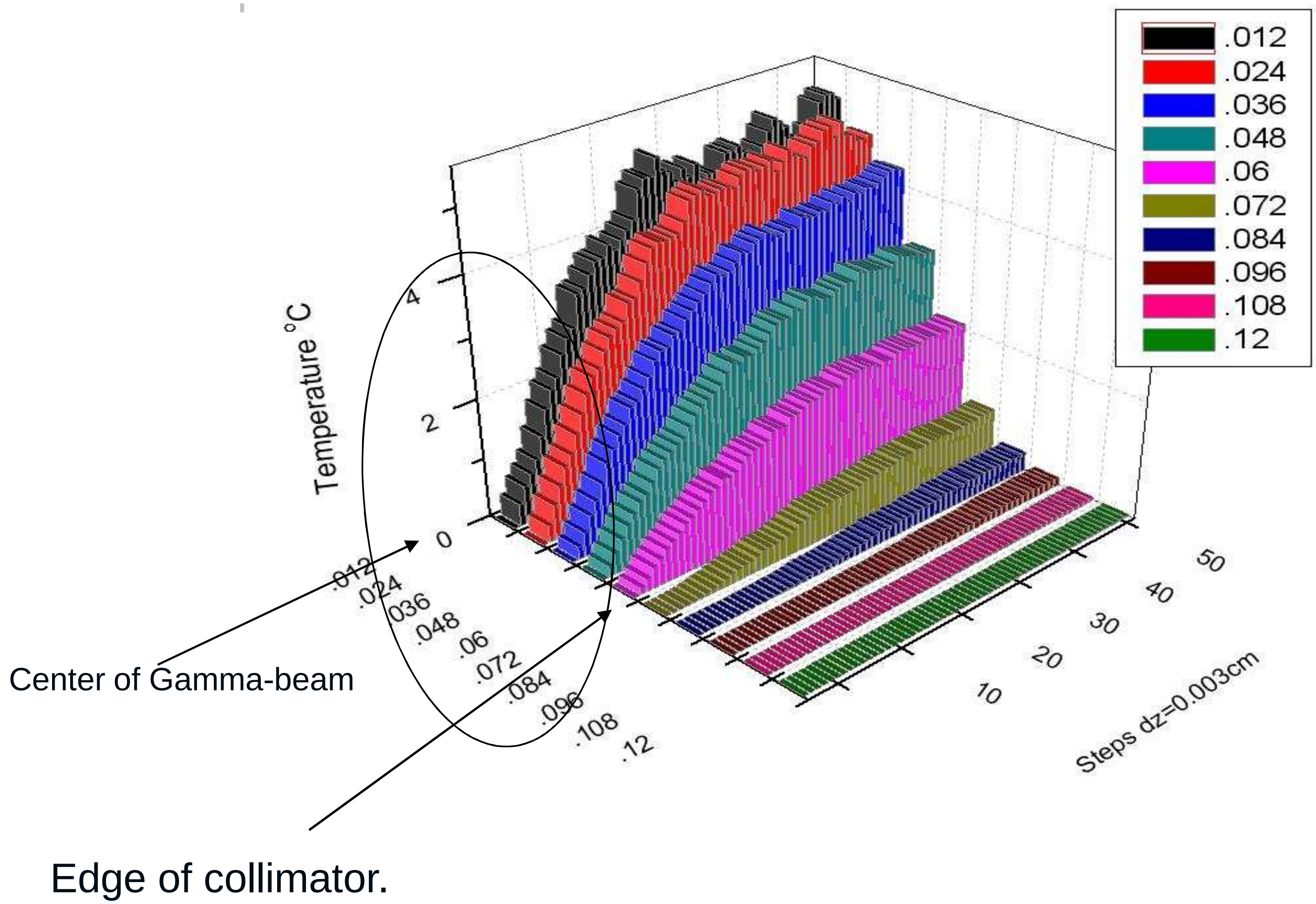
$$\Delta T_{Ti} : \Delta T_W : \Delta T_{Pb} \cong 1:3.7:3.8; \qquad (A_{Ti}:A_W:A_{Pb}\cong 47:183:207)$$

The ratio difference in temperature gain is not so drastic; however it is important if the temperature approaching the melting threshold.

Usage of heavier targets desirable from the point of lowering of focal depth (~10 times) needed to be serviced by capturing optics, however. Also, the positron production efficiency is higher for heavier materials. All together this gives ~50% higher yield for W compared with Ti.

THE TEMPERATURE ALONG THE **W** TARGET FOR DIFFERENT RADIUSES

per 10^{13} initial electrons; spinning target; KONN



Each particle radiates 2.76 GeV in undulator

Rim **W** target;

R=50 cm

f=50 Hz

K=0.92

Eff=1.6

Effp=32%

Lund=35m

λ_u=1.15cm

Dis=300 m

G=45kG/cm

I=110kA

Rcoll=0.5cm

DISTRIBUTION OF TEMPERATURE IN TARGET T(R,Z) DEG PER 10^13 INITIAL ELECTRONS

DELTA R = .100 cm, DELTA Z = .003 cm

Collimator

R→

.008	.005	.002	.001	.000	.000	.000	.000	.000	.000
.300	.113	.030	.004	.000	.000	.000	.000	.000	.000
.581	.219	.051	.008	.000	.000	.000	.000	.000	.000
.840	.317	.068	.011	.001	.000	.000	.000	.000	.000
1.106	.416	.083	.010	.001	.000	.000	.000	.000	.000
1.408	.504	.097	.011	.001	.000	.000	.000	.000	.000
1.654	.579	.113	.013	.001	.000	.000	.000	.000	.000
1.858	.662	.122	.013	.001	.000	.000	.000	.000	.000
2.060	.749	.135	.014	.001	.000	.000	.000	.000	.000
2.276	.816	.143	.013	.002	.000	.000	.000	.000	.000
2.432	.886	.156	.014	.002	.000	.000	.000	.000	.000
2.616	.946	.158	.015	.002	.000	.000	.000	.000	.000
2.797	.997	.165	.015	.001	.000	.000	.000	.000	.000
2.874	1.051	.175	.016	.001	.000	.000	.000	.000	.000
3.001	1.118	.181	.016	.001	.000	.000	.000	.000	.000
3.053	1.167	.188	.018	.001	.000	.000	.000	.000	.000
3.240	1.220	.203	.019	.001	.000	.000	.000	.000	.000
3.322	1.276	.202	.018	.002	.000	.000	.000	.000	.000
3.428	1.303	.213	.019	.001	.000	.000	.000	.000	.000
3.532	1.385	.221	.018	.002	.000	.000	.000	.000	.000
3.581	1.416	.225	.018	.001	.000	.000	.000	.000	.000
3.649	1.431	.227	.019	.001	.000	.000	.000	.000	.000
3.732	1.483	.232	.018	.002	.000	.000	.000	.000	.000
3.807	1.479	.239	.019	.001	.000	.000	.000	.000	.000
3.788	1.511	.249	.022	.002	.000	.000	.000	.000	.000
3.845	1.534	.246	.021	.002	.000	.000	.000	.000	.000
3.901	1.562	.248	.020	.002	.000	.000	.000	.000	.000
3.984	1.590	.253	.021	.001	.000	.000	.000	.000	.000
3.966	1.643	.254	.020	.001	.000	.000	.000	.000	.000
4.029	1.636	.257	.019	.002	.000	.000	.000	.000	.000
4.089	1.699	.260	.019	.001	.000	.000	.000	.000	.000
4.131	1.712	.266	.021	.001	.000	.000	.000	.000	.000
4.220	1.738	.257	.021	.001	.000	.000	.000	.000	.000
4.261	1.731	.268	.021	.001	.000	.000	.000	.000	.000
4.267	1.743	.268	.021	.001	.000	.000	.000	.000	.000
4.219	1.748	.270	.020	.001	.000	.000	.000	.000	.000
4.278	1.750	.270	.024	.001	.000	.000	.000	.000	.000
4.308	1.769	.274	.022	.001	.000	.000	.000	.000	.000
4.334	1.773	.279	.021	.001	.000	.000	.000	.000	.000
4.315	1.808	.274	.024	.001	.000	.000	.000	.000	.000
4.342	1.824	.275	.025	.001	.000	.000	.000	.000	.000
4.307	1.830	.282	.024	.001	.000	.000	.000	.000	.000
4.440	1.850	.277	.025	.001	.000	.000	.000	.000	.000
4.406	1.847	.281	.024	.001	.000	.000	.000	.000	.000
4.435	1.864	.275	.024	.001	.000	.000	.000	.000	.000
4.421	1.865	.270	.024	.001	.000	.000	.000	.000	.000
4.424	1.893	.277	.023	.001	.000	.000	.000	.000	.000
4.394	1.912	.284	.022	.001	.000	.000	.000	.000	.000
4.452	1.929	.276	.023	.001	.000	.000	.000	.000	.000

Now the target is not spinning

DISTRIBUTION OF TEMPERATURE IN TARGET T(R,Z) DEG PER 10^13 INITIAL ELECTRONS

DELTA R = .100 cm, DELTA Z = .003 cm

Collimator

R→

.178	.111	.052	.012	.001	.001	.000	.000	.000	.000
6.306	2.380	.628	.076	.004	.001	.000	.000	.000	.000
12.211	4.606	1.062	.160	.009	.002	.000	.000	.000	.000
17.650	6.666	1.420	.233	.020	.001	.002	.000	.000	.000
23.229	8.744	1.735	.215	.022	.001	.001	.000	.000	.000
29.563	10.592	2.031	.237	.023	.000	.000	.000	.000	.000
34.737	12.165	2.363	.272	.025	.001	.000	.000	.000	.000
39.023	13.906	2.565	.268	.026	.001	.000	.000	.000	.000
43.268	15.722	2.833	.297	.025	.000	.000	.000	.000	.000
47.793	17.145	3.002	.270	.032	.000	.000	.000	.000	.000
51.077	18.602	3.274	.302	.033	.000	.000	.000	.000	.000
54.937	19.866	3.320	.311	.042	.000	.000	.000	.000	.000
58.733	20.944	3.455	.312	.028	.000	.000	.000	.000	.000
60.357	22.063	3.681	.329	.025	.000	.000	.000	.000	.000
63.027	23.468	3.808	.333	.029	.000	.000	.000	.000	.000
64.106	24.499	3.939	.378	.030	.000	.000	.000	.000	.000
68.045	25.610	4.259	.396	.025	.001	.000	.000	.000	.000
69.764	26.800	4.235	.379	.032	.000	.000	.000	.000	.000
71.979	27.366	4.476	.399	.026	.000	.000	.000	.000	.000
74.173	29.083	4.638	.378	.038	.000	.000	.000	.000	.000
75.208	29.744	4.727	.378	.022	.001	.000	.000	.000	.000
76.633	30.043	4.762	.397	.030	.000	.000	.000	.000	.000
78.364	31.152	4.869	.378	.032	.000	.000	.000	.000	.000
79.947	31.063	5.025	.399	.031	.000	.000	.000	.000	.000
79.545	31.740	5.219	.456	.038	.000	.000	.000	.000	.000
80.736	32.216	5.176	.448	.032	.000	.000	.000	.000	.000
81.911	32.812	5.205	.423	.033	.001	.000	.001	.000	.000
83.666	33.400	5.312	.440	.029	.000	.000	.000	.000	.000
83.296	34.506	5.341	.428	.030	.001	.000	.000	.000	.000
84.613	34.365	5.394	.392	.041	.000	.000	.000	.000	.000
85.876	35.674	5.450	.400	.030	.001	.000	.000	.000	.000
86.751	35.954	5.579	.432	.027	.000	.000	.000	.000	.000
88.622	36.495	5.402	.434	.025	.000	.000	.000	.000	.000
89.485	36.344	5.629	.440	.026	.001	.000	.000	.000	.000
89.609	36.608	5.621	.433	.022	.000	.000	.000	.000	.000
88.595	36.706	5.672	.429	.030	.001	.000	.000	.000	.000
89.832	36.755	5.675	.494	.026	.000	.000	.000	.000	.000
90.468	37.159	5.757	.472	.029	.001	.000	.000	.000	.000
91.011	37.239	5.867	.449	.026	.000	.000	.000	.000	.000
90.623	37.963	5.753	.507	.022	.000	.000	.000	.000	.000
91.176	38.300	5.777	.515	.026	.001	.000	.000	.000	.000
90.441	38.423	5.921	.494	.026	.000	.000	.000	.000	.000
93.246	38.856	5.822	.534	.028	.000	.000	.000	.000	.000
92.526	38.793	5.903	.513	.026	.000	.000	.000	.000	.000
93.128	39.141	5.767	.496	.018	.001	.000	.000	.000	.000
92.849	39.155	5.677	.498	.025	.000	.000	.000	.000	.000
92.913	39.756	5.822	.493	.018	.000	.000	.000	.000	.000
92.267	40.144	5.969	.467	.017	.001	.000	.000	.000	.000
93.494	40.505	5.786	.490	.020	.000	.000	.001	.000	.000

K=0.44; Eff=1.58; Effp=67%; Rcoll=0.06; Lamb=1cm;Lund=170m; 150 GeV

Each particle radiates 1.07 GeV in undulator

DISTRIBUTION OF TEMPERATURE IN TARGET T(R,Z) DEG PER 10^13 INITIAL ELECTRONS

DELTA R = .012 cm, DELTA Z = .003 cm

R-> [redacted]

.000	.002	.005	.005	.002	.001	.000	.000	.001	.000
.365	.276	.205	.168	.110	.003	.000	.002	.000	.000
.630	.589	.400	.335	.208	.009	.000	.000	.000	.000
.804	.866	.643	.526	.347	.015	.000	.000	.000	.000
.996	1.144	.844	.708	.439	.023	.000	.000	.000	.000
1.350	1.308	1.092	.853	.550	.041	.000	.000	.000	.000
1.756	1.601	1.381	1.003	.631	.059	.000	.000	.000	.000
2.041	1.888	1.566	1.090	.720	.083	.001	.000	.000	.000
2.200	2.169	1.756	1.234	.826	.100	.002	.000	.000	.000
2.539	2.410	1.884	1.418	.882	.131	.004	.000	.000	.000
2.765	2.504	2.116	1.522	.970	.164	.006	.000	.000	.000
2.889	2.745	2.174	1.598	1.046	.184	.011	.000	.000	.000
3.405	2.935	2.336	1.676	1.141	.215	.014	.001	.000	.000
3.445	3.031	2.486	1.734	1.180	.221	.019	.003	.000	.000
3.630	3.099	2.709	1.879	1.282	.255	.024	.003	.000	.000
3.804	3.366	2.830	2.012	1.255	.304	.036	.001	.001	.000
3.820	3.389	2.844	2.121	1.300	.313	.042	.002	.001	.000
3.997	3.618	2.998	2.189	1.402	.311	.060	.005	.001	.000
3.872	3.878	3.013	2.248	1.475	.331	.075	.008	.001	.001
4.001	4.074	3.173	2.340	1.531	.363	.068	.012	.000	.000
4.115	4.137	3.271	2.485	1.543	.398	.076	.016	.001	.000
4.245	4.110	3.366	2.621	1.583	.453	.078	.024	.003	.000
4.678	4.128	3.461	2.563	1.694	.481	.086	.023	.005	.000
4.814	4.149	3.584	2.633	1.698	.524	.097	.018	.007	.000
4.803	4.301	3.690	2.614	1.685	.543	.117	.026	.006	.000
5.067	4.599	3.619	2.682	1.803	.547	.138	.026	.007	.001
4.838	4.644	3.660	2.743	1.800	.569	.141	.039	.005	.003
4.777	4.696	3.764	2.846	1.845	.586	.164	.045	.008	.003
4.601	4.571	3.884	2.951	1.909	.586	.174	.046	.010	.004
4.773	4.570	3.850	2.987	1.909	.587	.209	.050	.012	.004
4.615	4.601	3.955	2.980	1.953	.589	.199	.048	.017	.006
4.778	4.607	3.991	3.097	1.988	.620	.206	.060	.023	.005
4.536	4.546	4.049	3.020	1.992	.649	.197	.071	.022	.008
4.564	4.695	3.976	3.130	1.944	.660	.216	.072	.021	.010
4.549	4.763	3.918	3.164	2.030	.673	.210	.075	.025	.009
4.406	4.773	3.948	3.052	2.070	.699	.220	.089	.027	.008
4.793	4.688	3.979	3.063	2.068	.706	.237	.082	.026	.009
4.798	4.726	3.949	3.037	2.084	.711	.239	.086	.033	.008
4.836	4.790	4.093	3.101	2.086	.749	.245	.096	.038	.011
4.715	4.577	4.049	3.134	2.072	.750	.252	.093	.037	.009
4.563	4.692	4.043	3.169	2.004	.749	.286	.097	.034	.013
4.610	4.854	4.076	3.145	2.051	.787	.286	.107	.037	.017
4.703	4.731	4.053	3.276	2.035	.765	.277	.117	.044	.011
4.918	4.692	4.151	3.213	2.095	.777	.282	.130	.043	.012
5.080	4.635	4.091	3.223	2.105	.809	.307	.135	.043	.015
4.997	4.797	4.176	3.189	2.117	.798	.326	.140	.041	.017
4.898	4.821	4.066	3.165	2.101	.792	.296	.133	.046	.021
4.679	4.969	4.171	3.156	2.094	.762	.319	.132	.053	.021
4.523	5.009	4.138	3.187	2.137	.782	.319	.123	.063	.020
4.538	4.797	4.185	3.277	2.138	.764	.316	.131	.064	.024
4.531	5.012	4.166	3.228	2.116	.781	.319	.142	.062	.022
4.705	4.771	4.190	3.206	2.133	.786	.308	.146	.058	.023
5.104	4.749	4.259	3.182	2.099	.788	.312	.134	.059	.024
5.189	4.636	4.317	3.128	2.129	.817	.313	.134	.063	.023
5.185	4.620	4.330	3.140	2.153	.825	.303	.138	.057	.028
5.079	4.663	4.286	3.128	2.091	.823	.322	.134	.061	.029

Moving target

DISTRIBUTION OF TEMPERATURE IN TARGET T(R,Z) DEG PER 10^13 INITIAL ELECTRONS

DELTA R = .012 cm, DELTA Z = .003 cm

R-> [redacted]

.000	.366	.891	.766	.294	.231	.000	.000	.110	.000
61.159	46.252	34.342	28.174	18.390	.567	.000	.275	.000	.000
105.617	98.783	67.078	56.238	34.923	1.450	.000	.000	.000	.000
134.738	145.274	107.852	88.149	58.141	2.573	.025	.000	.000	.050
166.932	191.743	141.460	118.791	73.655	3.934	.000	.000	.000	.000
226.272	219.360	183.026	143.001	92.135	6.916	.000	.070	.000	.000
294.366	268.408	231.499	168.095	105.857	9.946	.000	.000	.000	.000
342.125	316.534	262.530	182.721	120.720	13.948	.231	.000	.000	.000
368.868	363.671	294.349	206.862	138.410	16.831	.295	.000	.000	.000
425.653	404.083	315.942	237.827	147.805	22.008	.662	.000	.046	.000
463.673	419.850	354.846	255.157	162.570	27.548	1.023	.000	.000	.000
484.464	460.318	364.562	267.948	175.372	30.790	1.784	.000	.000	.000
570.879	492.064	391.750	280.971	191.264	36.087	2.275	.246	.000	.000
577.650	508.118	416.767	290.663	197.778	37.072	3.208	.565	.000	.000
608.652	519.617	454.206	314.976	214.973	42.696	4.064	.570	.000	.000
637.811	564.410	474.500	337.353	210.375	50.997	6.041	.131	.123	.000
640.545	568.291	476.761	355.608	218.024	52.550	7.114	.349	.242	.000
670.182	606.625	502.650	367.037	235.150	52.199	10.080	.839	.119	.000
649.275	650.198	505.209	376.906	247.331	55.479	12.514	1.405	.182	.105
670.760	683.094	532.002	392.349	256.708	60.871	11.425	2.056	.054	.000
689.872	693.557	548.392	416.580	258.708	66.692	12.724	2.675	.251	.000
711.817	689.077	564.338	439.400	265.416	75.893	13.020	4.029	.506	.000
784.330	692.138	580.342	429.650	284.009	80.706	14.401	3.933	.756	.000
807.120	695.661	600.961	441.406	284.761	87.820	16.322	3.081	1.119	.000
805.369	721.066	618.735	438.359	282.589	91.042	19.697	4.382	1.046	.000
849.548	771.024	606.704	449.717	302.273	91.773	23.204	4.288	1.116	.221
811.220	778.575	613.700	459.937	301.816	95.389	23.658	6.522	.875	.459
800.987	787.428	631.179	477.260	309.269	98.307	27.423	7.545	1.324	.502
771.494	766.389	651.142	494.839	320.040	98.310	29.215	7.787	1.658	.727
800.309	766.280	645.544	500.830	320.038	98.435	35.071	8.403	2.057	.715
773.733	771.435	663.186	499.719	327.486	98.805	33.397	8.063	2.785	.939
801.143	772.357	669.241	519.308	333.390	103.875	34.529	10.058	3.871	.858
760.605	762.134	678.826	506.274	333.931	108.824	33.058	11.834	3.699	1.287
765.209	787.192	666.652	524.772	325.880	110.589	36.224	12.129	3.596	1.695
762.684	798.661	656.898	530.469	340.428	112.829	35.192	12.593	4.199	1.521
738.784	800.192	661.873	511.769	347.102	117.257	36.807	14.967	4.447	1.385
803.648	786.068	667.198	513.551	346.693	118.341	39.750	13.728	4.368	1.527
804.455	792.443	662.102	509.171	349.473	119.208	40.148	14.402	5.610	1.337
810.827	803.191	686.244	520.007	349.774	125.541	41.145	16.020	6.394	1.836
790.541	767.371	678.829	525.540	347.476	125.695	42.285	15.628	6.230	1.579
765.124	786.768	677.815	531.287	335.965	125.630	48.003	16.346	5.715	2.203
772.885	813.800	683.430	527.345	343.876	132.009	47.986	17.887	6.214	2.796
788.617	793.229	679.595	549.286	341.152	128.322	46.447	19.619	7.306	1.768
824.523	786.624	695.988	538.730	351.329	130.290	47.276	21.816	7.198	1.981
851.787	777.160	685.842	540.311	352.949	135.594	51.520	22.700	7.206	2.435
837.876	804.250	700.175	534.671	354.944	133.738	54.654	23.493	6.908	2.825
821.201	808.332	681.701	530.736	352.325	132.775	49.629	22.237	7.706	3.438
784.468	833.114	699.302	529.240	351.133	127.829	53.541	22.193	8.837	3.468
758.353	839.836	693.726	534.303	358.301	131.182	53.518	20.638	10.598	3.311
760.916	804.293	701.618	549.469	358.503	128.069	53.013	21.894	10.654	4.053
759.666	840.416	698.492	541.247	354.832	130.926	53.415	23.809	10.373	3.694
788.896	799.929	702.600	537.479	357.705	131.744	51.558	24.539	9.651	3.926
855.792	796.170	714.141	533.448	351.962	132.154	52.366	22.490	9.896	3.961
869.960	777.358	723.870	524.532	356.965	137.057	52.398	22.537	10.522	3.891
869.400	774.687	725.933	526.515	361.019	138.362	50.765	23.213	9.591	4.755
851.572	781.763	718.550	524.466	350.632	137.991	53.952	22.394	10.235	4.802

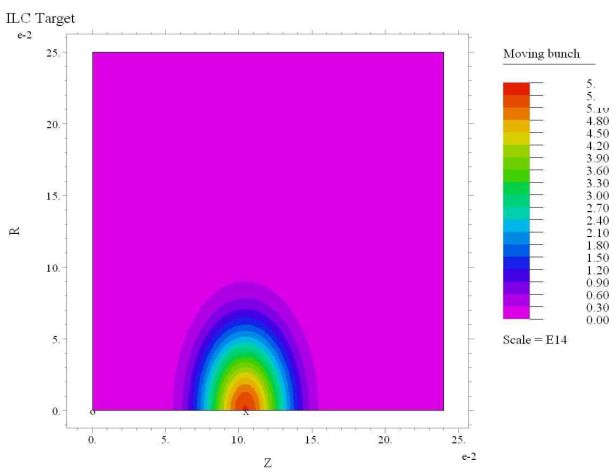
Stationary target

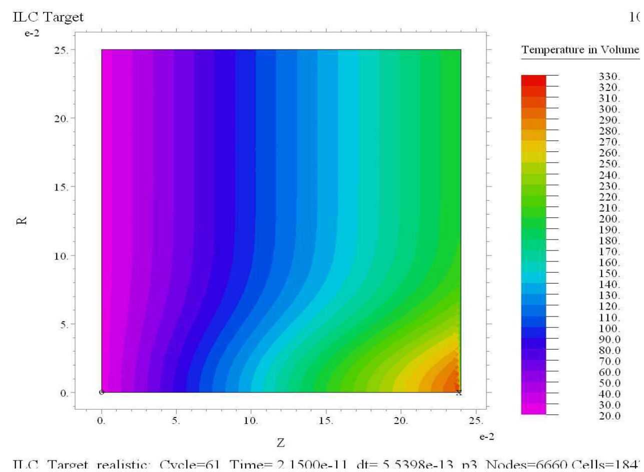
We used FlePDE code also for calculation of temperature and pressure with equations;

Temperature $$\nabla(k\nabla T)+\dot{Q}=\rho c_V \dot{T}$$ $$\ddot{P}-\nabla(c_0^2\nabla P)=\frac{\Gamma}{V_0}\ddot{Q}$$ Pressure

$$\dot{Q}=\sum_i \frac{2cQ_{bunch}}{\pi\sqrt{\pi}\sigma_z\sigma_{\perp\gamma}^2 l_T}\frac{z}{l_T}\exp\left(-\frac{(z+z_0-c(t-i\cdot t_0))^2}{\sigma_z^2}\right)\cdot\exp\left(-\frac{r^2}{\sigma_{\perp\gamma}^2}\right)$$

$\Gamma(V)=V/c_V(\partial P/\partial T_V)$ characterizing the ratio of the thermal pressure to the specific thermal energy called Grüneisen coefficient.



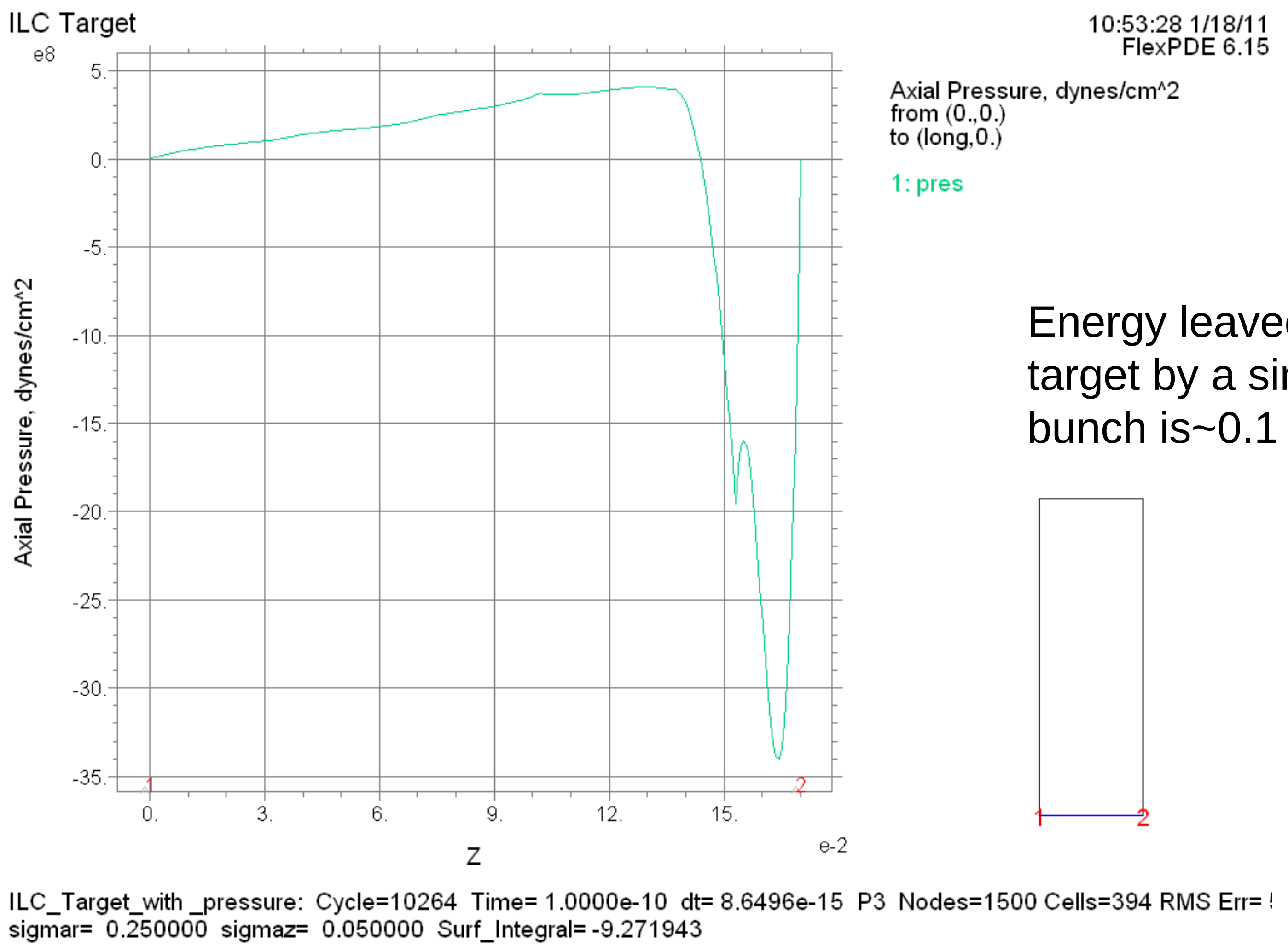


Instant position of the bunch moving in the target, at the left. Isotherms right after the bunch passage, at the right.

The negative pressure phenomenon confirmed here: after the bunch passed at the exit side the substantial negative pressure developed.

This effect is a general one and might be important for the targets made from **Carbon.**

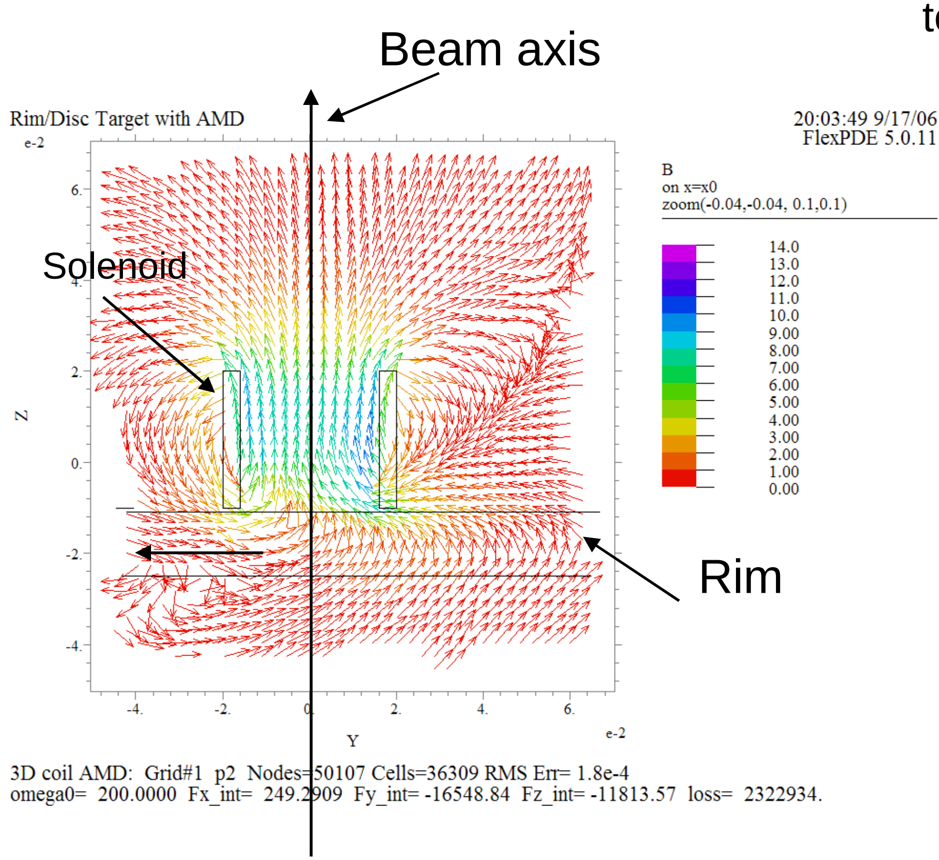
Dyne/cm^2=10^{-6} bar



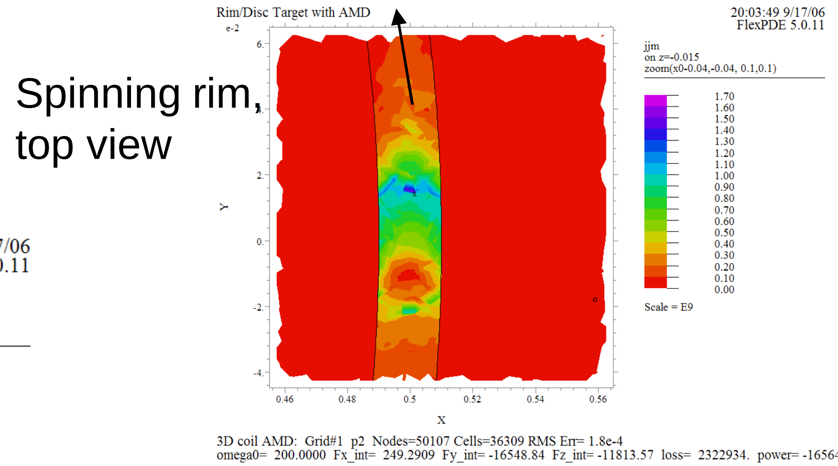
Energy leaved in the target by a single bunch is~0.1 Joule

Pressure along the target; beam passed from the left to the right 0.1 *ns* ago

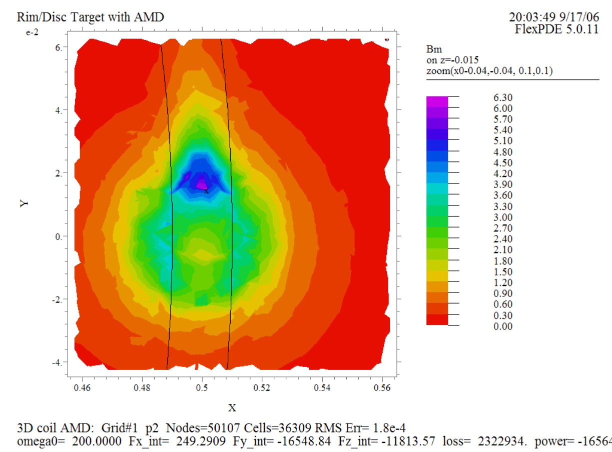
IT WAS FOUND, THAT MOVING METAL PERTURBS MAGNETIC FIELD OF OMD



Spinning rim, side view



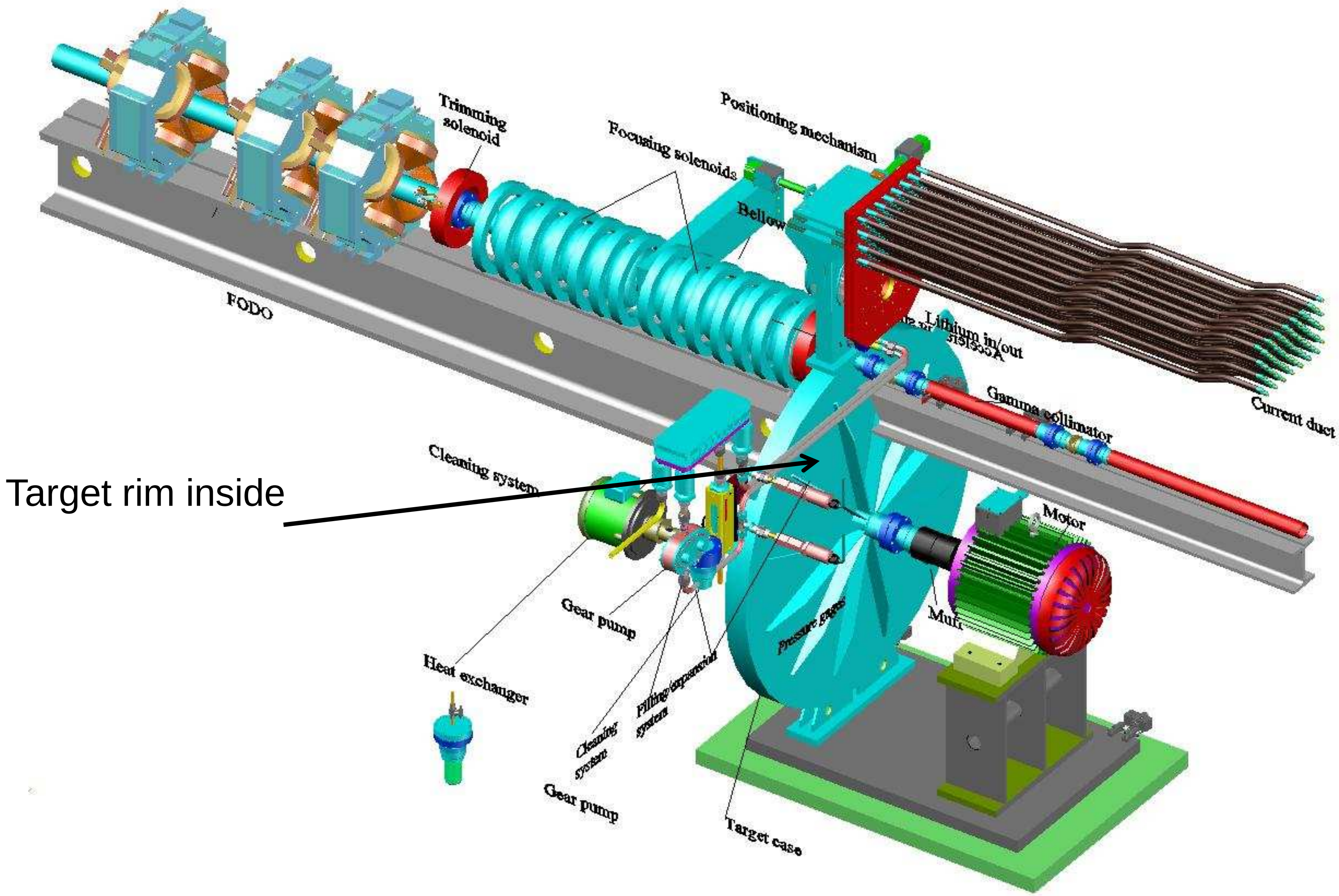
Modulus of field in a rim



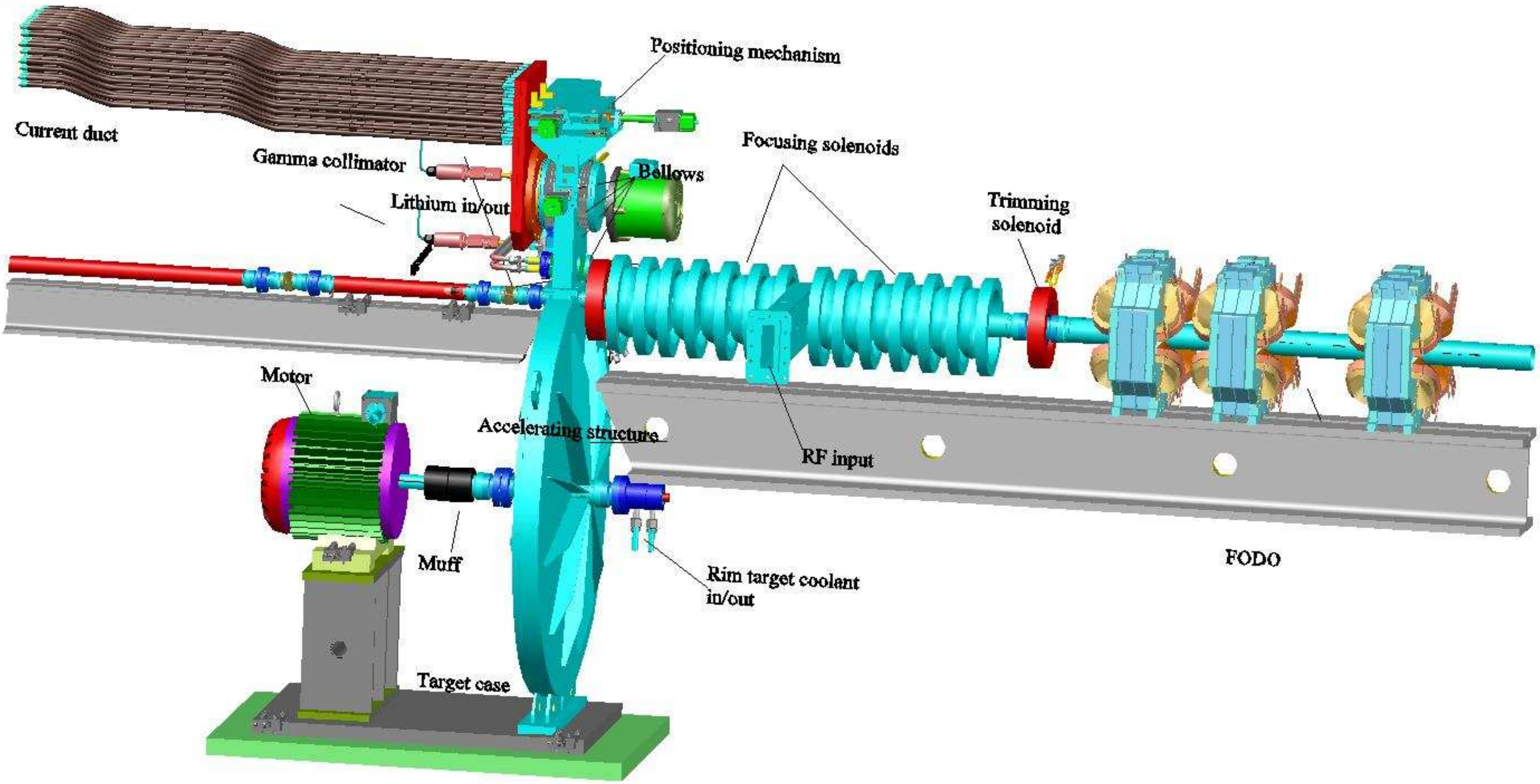
Modulus of field between the coil and the rim

Lithium lens has no stray fields

Target station. Spinning rim, Lithium lens.



View from the other side



4. LITHIUM LENS

A.Mikhailichenko,” Lithium Lens (I)”, CBN -09-4, Aug 2009, 17pp.
http://www.lepp.cornell.edu/public/CBN/2009/CBN09-4/CBN%2009-04.pdf
A.Mikhailichenko,” Lithium Lens (II)”, CBN -10-3, Aug 2010, 37pp
http://www.lepp.cornell.edu/public/CBN/2010/CBN10-3/CBN%2010-03.pdf

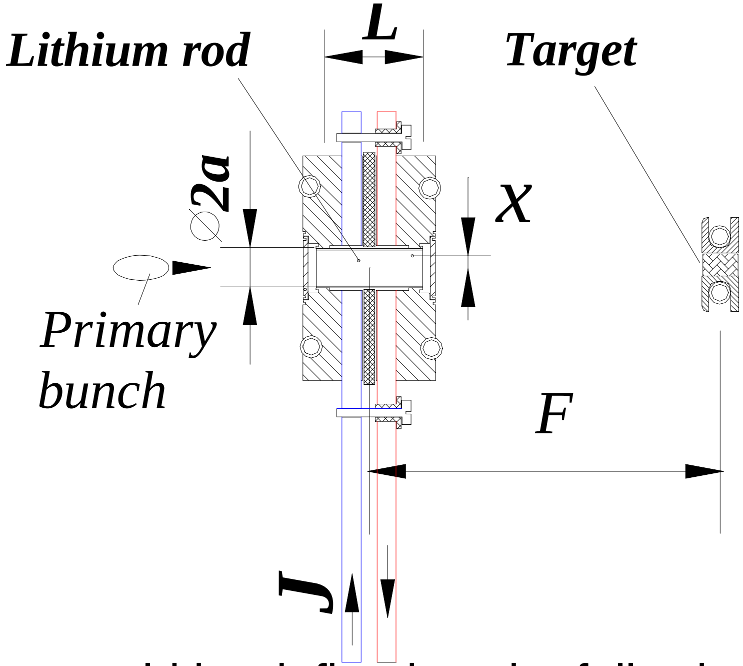
LITHIUM LENS BASICS

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

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

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

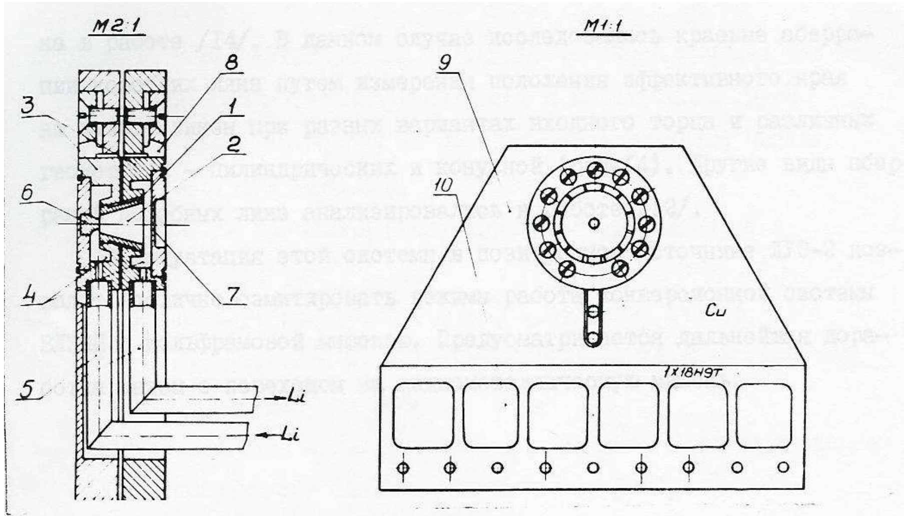
$$\alpha \cong \frac{H(x)\cdot L}{(HR)} \cong \frac{0.2 I L x}{a^2\cdot(HR)}$$



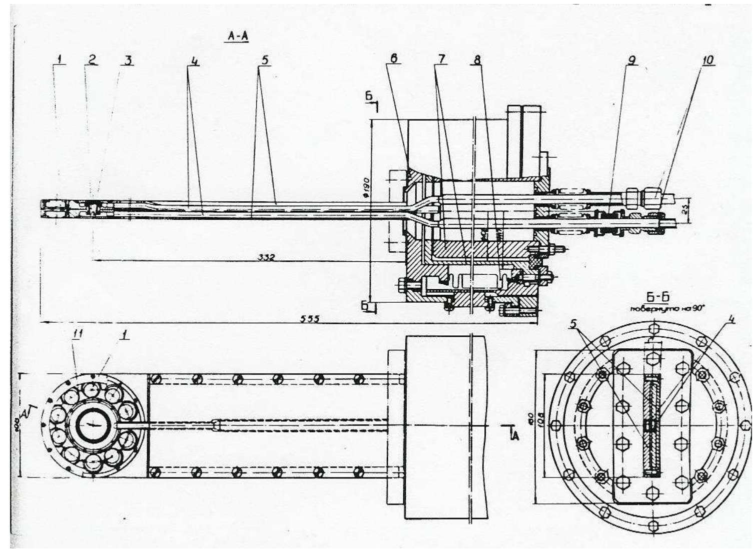
This picture drawn for the focusing of electron beam to the target

So the focal distance could be defined as the following $F \cong \dfrac{a^2\cdot(HR)}{0.2IL} \sim 1cm$

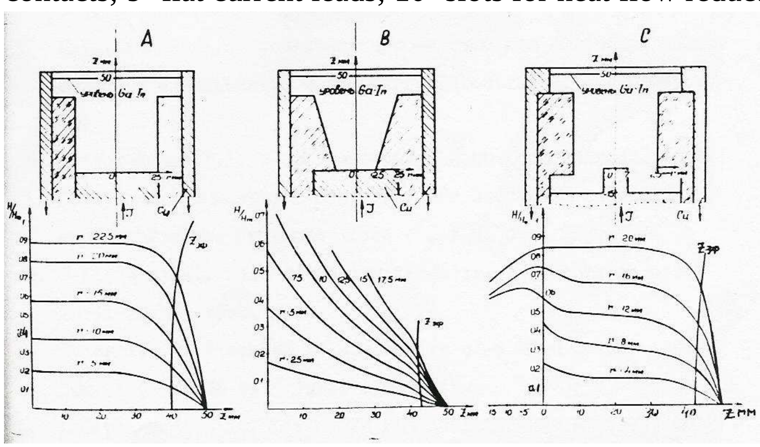
T.A.Vsevolojskaja, A.A.Mikhailichenko, **G.I.Silvestrov,** A.D.Cherniakin,
“To the Conversion System for Generation of Polarized Beams in VLEPP”, BINP Internal Report, 1986



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.

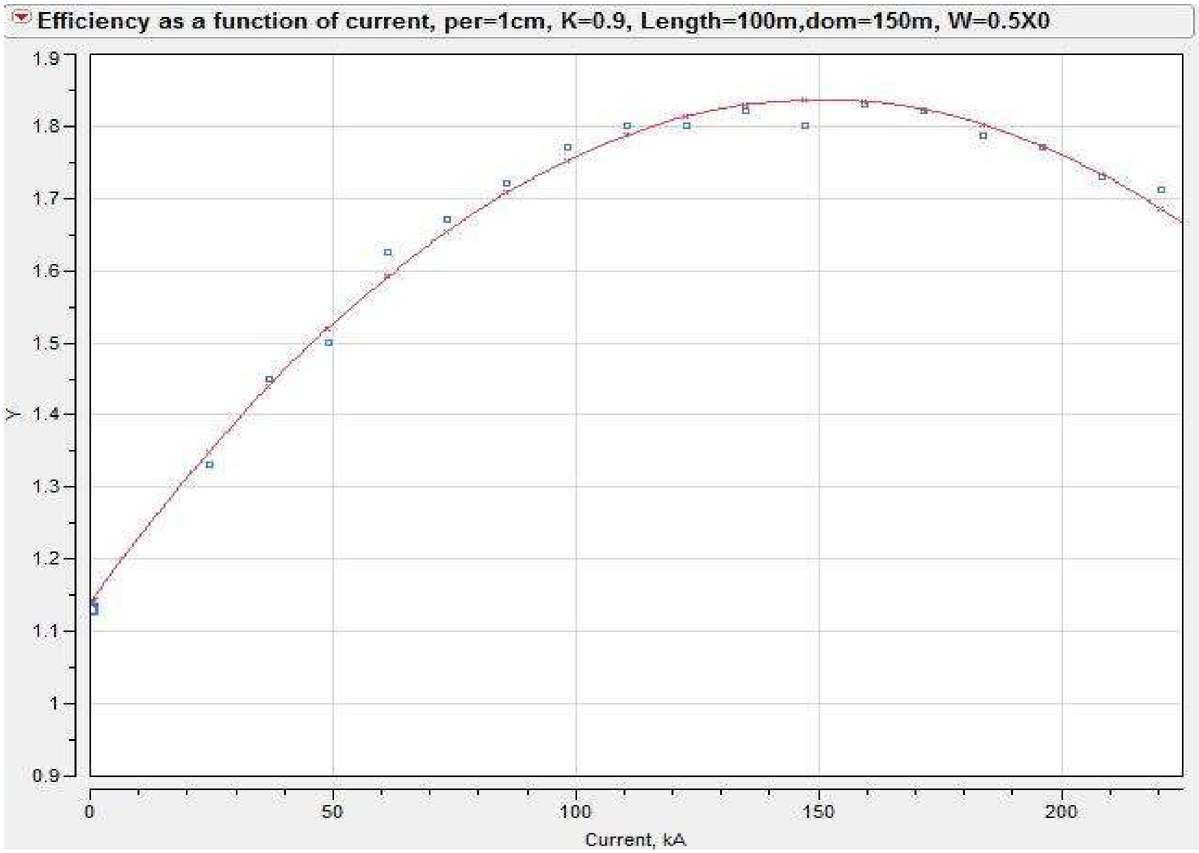


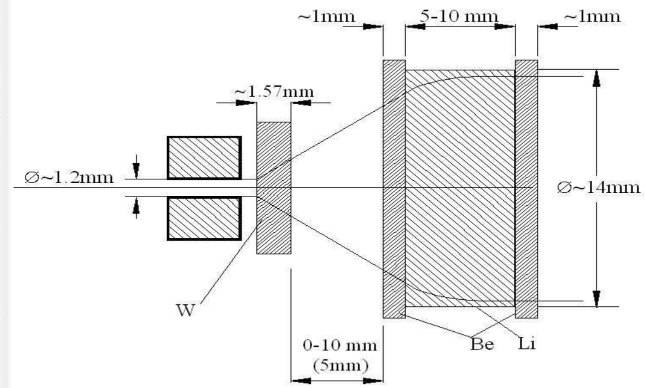
1-ex-centric contact pushers;2-conic lens body; 3-W target; 4-Ti tubing for LI supply; 5-flat current leads; 6-vacuum chamber; 7-coaxial fraction of current leads; 8-bellows; 9-ceramic insulators; 10-conical gasket; 11-set of ex-centric pushers.



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

First of all, how important is the lens for the collection business?



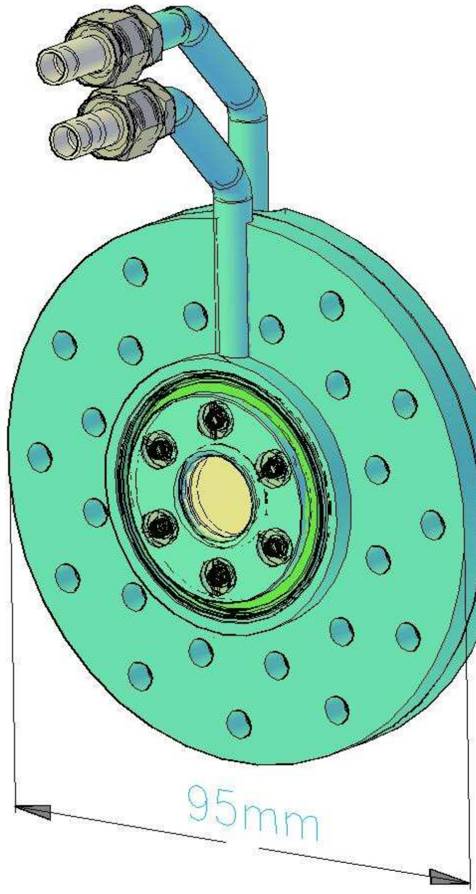


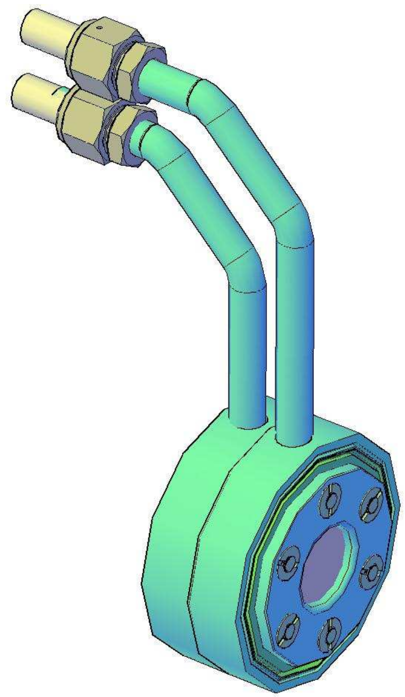
Typical dimensions

Efficiency of positron production normalized to the primary electron as function of feeding current in a lens. *K*=0.9, 100m long undulator, lens is 0.5 cm-long, ε`6MeV-cm.

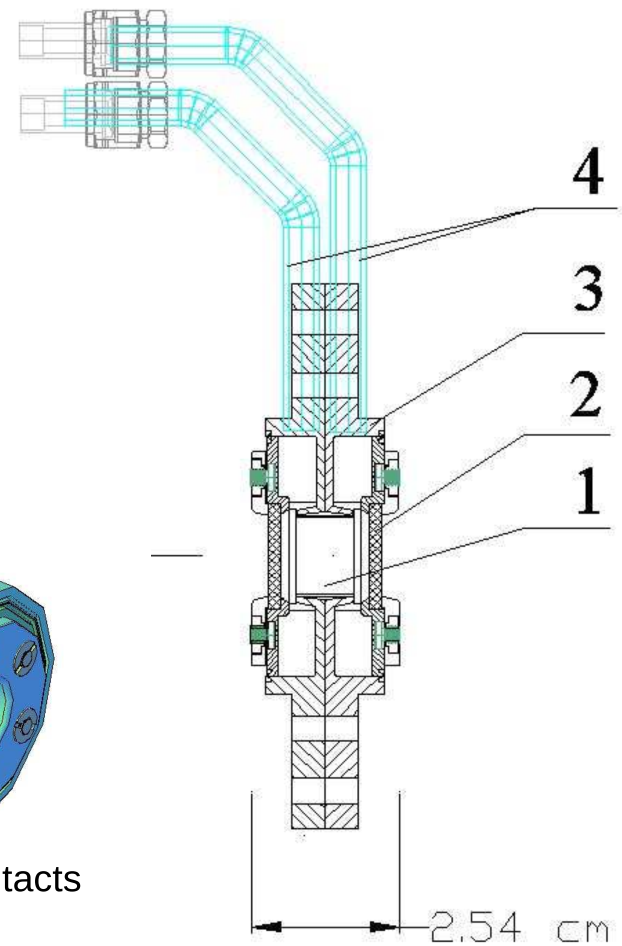
One can see that LL potentially adds ~70% of positrons. But even without lens the efficiency is more than one already.

Lens with liquid Lithium for ILC design



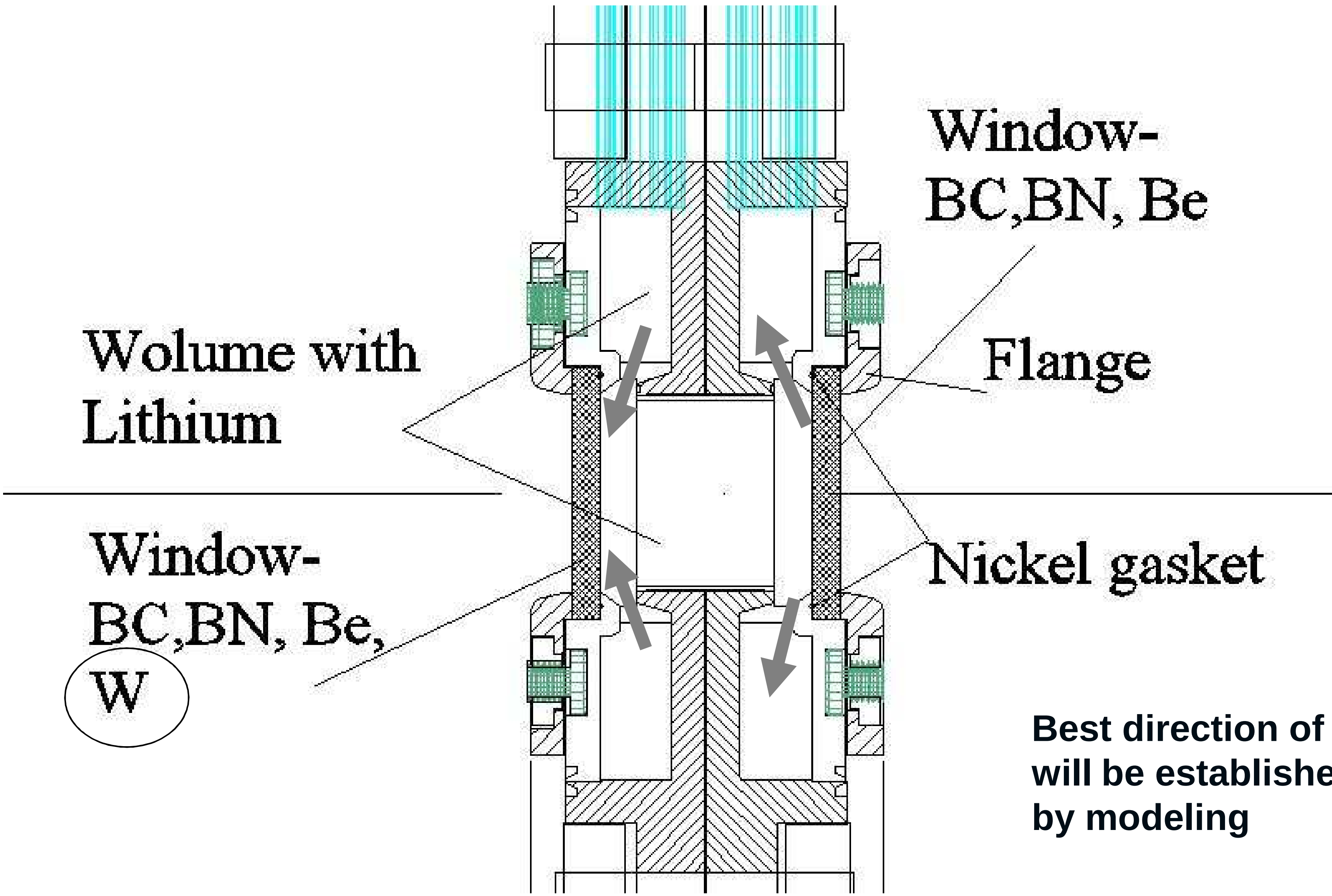


Classic collets contacts



Lithium Lens for ILC positron source; extended flanges serve for electrical contact. 1–volume with Lithium, 2–window (Be/BC/BN), 3–electrical contacts with caverns for Li, 4–tubing for Lithium in/out. At the center- the latest design.

Windows attachment technique



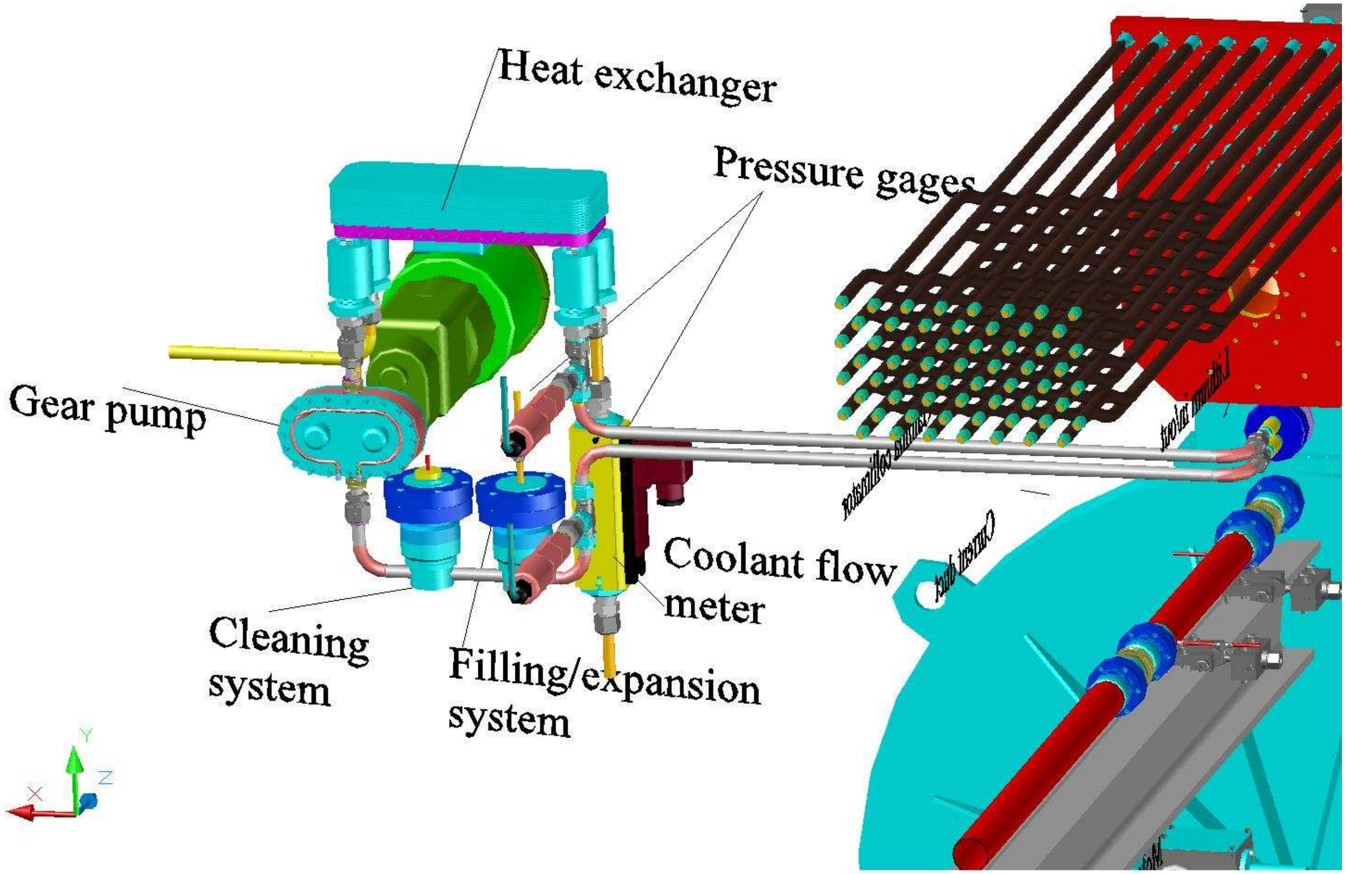
Best direction of flow will be established by modeling

Table 1: properties of 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*	1.44×10^{-5}	1.9×10^{-5}	$>10^{14}$	7.14×10^{-3}	5.5×10^{-6}
Length of X_o, lX_o	*cm*	152.1	34.739	27.026	19.88	0.35
Boil temperature	°C	1347	2469	Sublim. at melt	3500	5660
Melt temperature	°C	180.54	1287	2973	2350	3410
Compressibility	cm^2/kg	8.7×10^{-6}	9.27×10^{-7}			2.93×10^{-7}
Grüneisen coeff.	-					2.4
Speed of sound (long)	*m/sec*	6000	12890	16400	14920	5460
Specific heat	*J/g°K*	3.6	1.82	1.47	0.95	0.134
Heat conductivity	*W/cm/°C*	0.848	2	7.4	0.3-0.4	1.67
Thermal expansion	1/°C	4.6×10^{-6}	11×10^{-6}	2.7×10^{-6}	5×10^{-6}	4.3×10^{-6}

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

Lithium loop



Gear pump with Zirconium ceramic gears and case is desirable for elimination of back current flow along the cooling loop

Temperature in lens

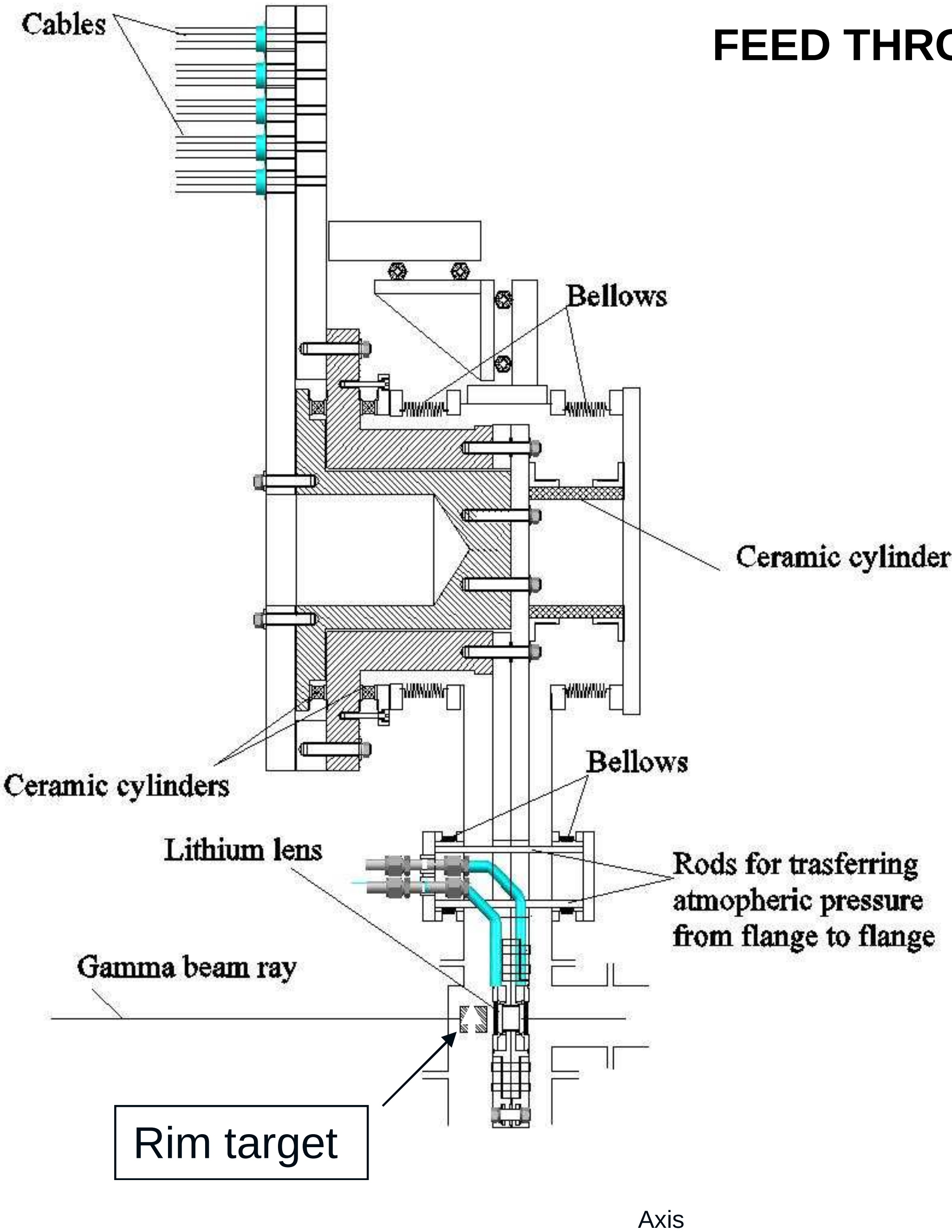
K=0.92; λ=1.15; Eff=1.6; Effp=32%; Undulator length=35m; Distance to target=300m

DISTRIBUTION OF TEMPERATURE IN LENS T(R,Z) DEG PER 10^13 INITIAL ELECTRONS

DELTA R = .070 cm, DELTA Z = .050 cm, PHOTONS GENERATED = 76991

Be entr.	39.396	23.757	16.011	11.015	6.154	3.953	2.325	1.351	.861	.275
	38.128	22.818	15.563	10.848	6.569	4.287	2.792	1.669	1.254	.433
Li	15.000	9.208	6.263	4.499	2.633	1.745	1.173	.689	.425	.162
	14.017	8.512	6.076	4.383	2.648	1.802	1.217	.795	.492	.197
	13.356	7.904	5.805	4.219	2.664	1.849	1.276	.875	.568	.198
	12.685	7.414	5.488	4.143	2.651	1.842	1.333	.948	.609	.205
	12.128	6.922	5.273	4.042	2.591	1.882	1.314	.968	.652	.221
	11.566	6.518	5.049	3.814	2.604	1.856	1.315	.959	.663	.221
	11.103	6.203	4.873	3.616	2.603	1.802	1.297	.904	.709	.213
	10.406	6.081	4.592	3.504	2.588	1.751	1.305	.913	.663	.226
	9.889	5.853	4.370	3.399	2.467	1.774	1.240	.915	.659	.224
	9.733	5.852	4.353	3.523	2.629	1.944	1.376	1.030	.738	.238
Be exit	19.89	12.03	9.07	6.89	4.98	3.58	2.46	1.72	1.25	.40
	20.17	12.17	9.15	6.93	5.04	3.76	2.65	1.84	1.42	.48

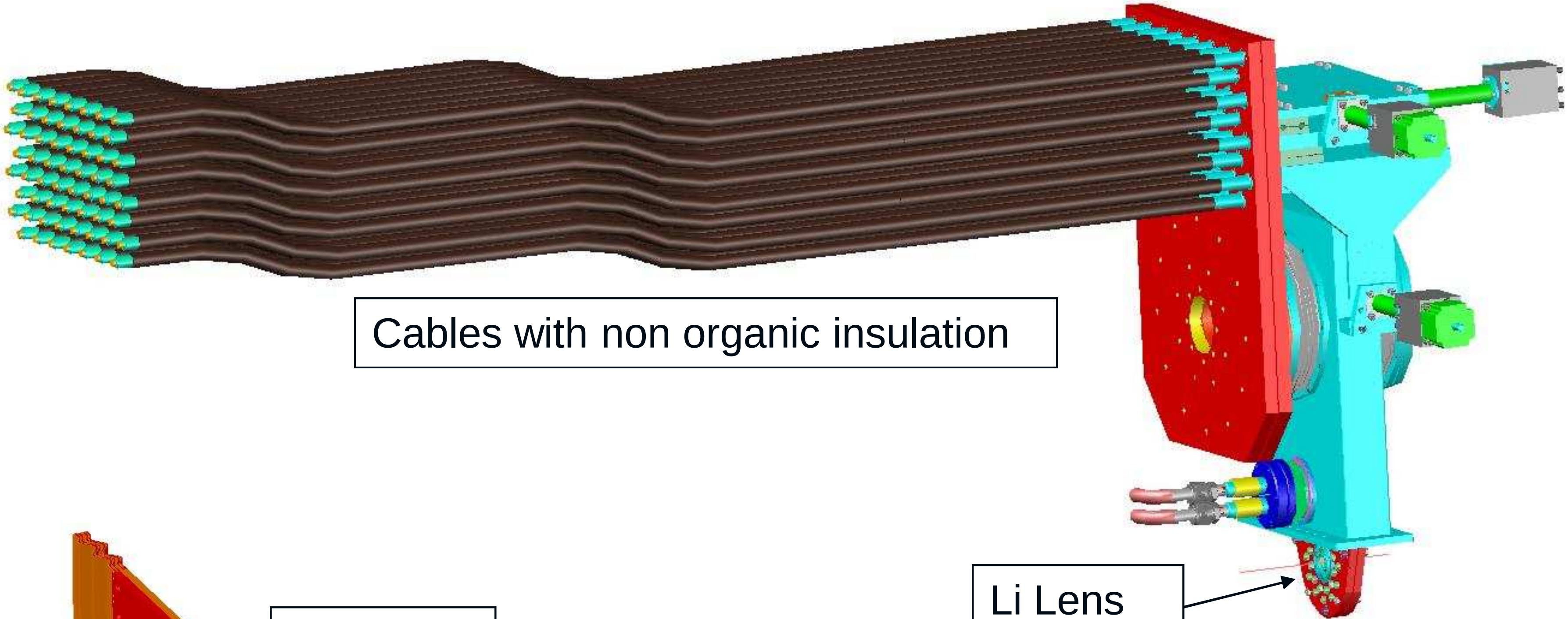
FEED THROUGH IN DETAIL

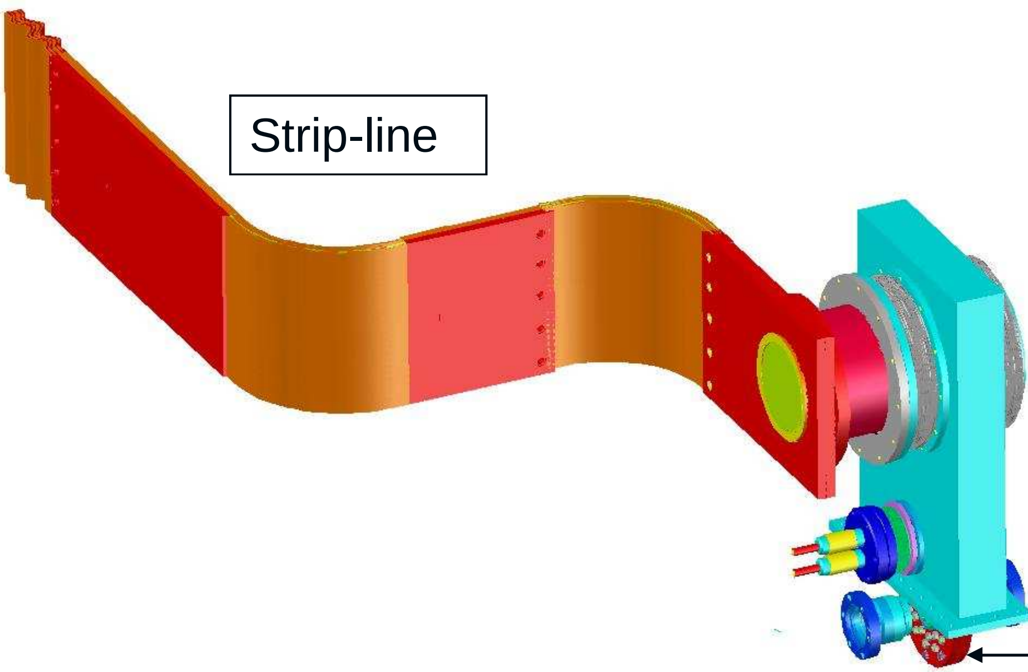


System with two bellows excludes net force from atmospheric pressure;

Positioning system serves for adjustment the distance between target and lens –what is required by optimization of yield/heating for the entrance window

Variants of current duct





Current duct must be able to transfer ~ 150 kA in ~4 ms pulse with repetition rate up to 10 Hz

EQUATIONS FOR MODELING WITH FlexPDE

Electromagnetics

$$\vec{E} = -\frac{\partial \vec{A}}{\partial t} - grad(U) \qquad \vec{B} = rot(\vec{A}) \qquad \vec{j} = \sigma \cdot (\vec{E} + \vec{v} \times \vec{B}) \qquad div(\vec{j}) = 0$$

$$div(grad(A_x)) + \mu \cdot j_x = 0 \qquad div(grad(A_y)) + \mu \cdot j_y = 0 \qquad div(grad(A_z)) + \mu \cdot j_z = 0 \qquad \Delta Q_{tot} = \int_0^{\Delta T} dt \int_V (\vec{j} \cdot \vec{E}) dV = \int_0^{\Delta T} dt \int_V \frac{j^2}{\sigma} dV$$

Hydrodynamics

momentum flux density tensor

Deviatoric stress tensor

$$\frac{\partial}{\partial t} \rho v_i = -\frac{\partial \Pi_{ik}}{\partial x_k} \qquad \Pi_{ik} = P \cdot \delta_{ik} + \rho \cdot v_i v_j - \sigma'_{ik} - \mu_0 (H_i H_k - \tfrac{1}{2} H^2 \delta_{ik}) \qquad \sigma'_{ij} = \eta \left(\frac{\partial v_i}{\partial x_j} + \frac{\partial v_j}{\partial x_i} - \tfrac{2}{3} \delta_{ij} \frac{\partial v_k}{\partial x_k} \right) + \zeta \cdot \delta_{ij} \frac{\partial v_k}{\partial x_k}$$

In vector form

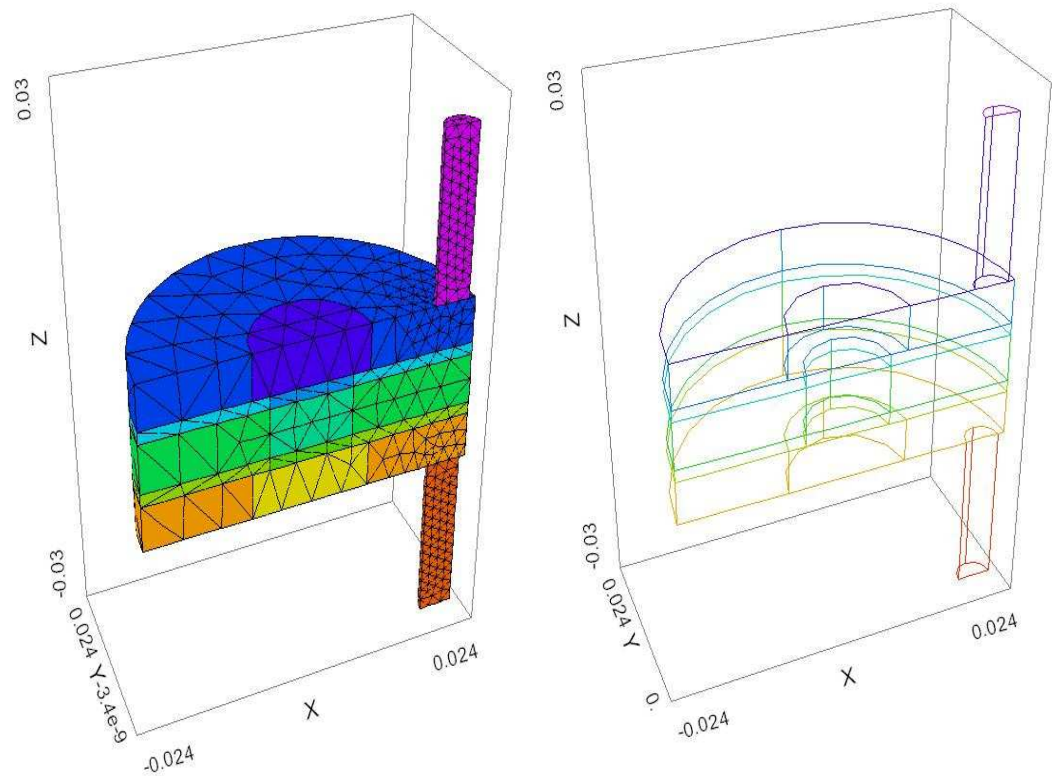
$$\rho \cdot (\frac{\partial \vec{v}}{\partial t} + (\vec{v} \cdot \vec{\nabla})\vec{v} + grad(P) - \eta \cdot \nabla^2 \vec{v} = (\vec{j} \times \vec{B})$$

For pressure

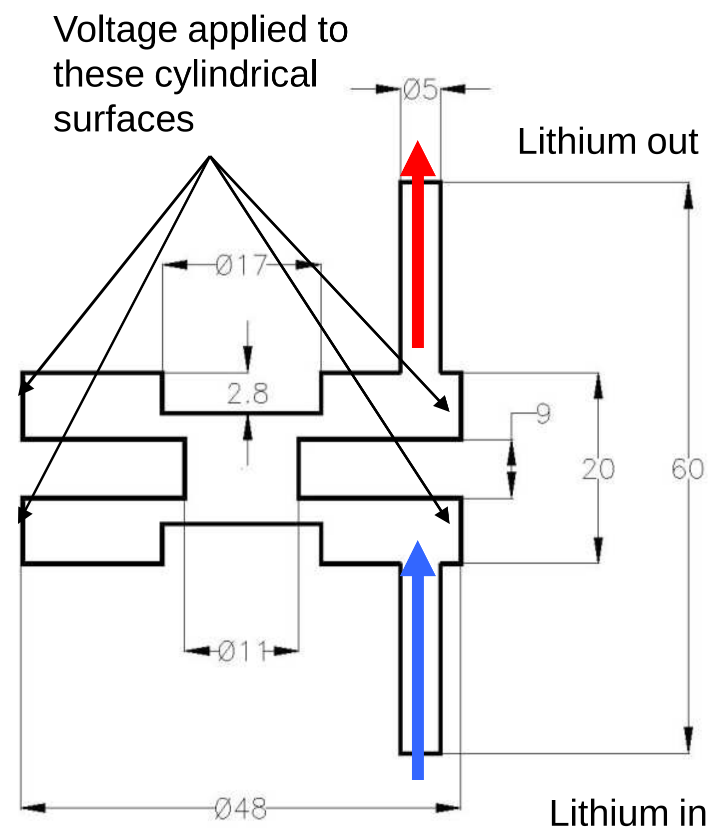
$$div(grad(P)) \left\{ -\frac{1}{c_B^2} \frac{\partial^2 P}{\partial t^2} \right\} = div(\vec{j} \times \vec{B}) - \rho \cdot div \left(\frac{\partial \vec{v}}{\partial t} + (\vec{v} \cdot \vec{\nabla})\vec{v} \right) + C\eta \cdot div(\vec{v}) \left\{ -\Gamma \cdot \ddot{Q}(\vec{r}, t) \right\}$$

Temperature

$$\rho \cdot C_p \left(\frac{\partial T}{\partial t} + \vec{v} \cdot grad(T) \right) - div(k \cdot grad(T)) + P \cdot div(\vec{v}) = (\vec{j} \cdot \vec{E}) + \sigma'_{ik} \frac{\partial v_i}{\partial x_k} + \dot{Q}(\vec{r}, t)$$

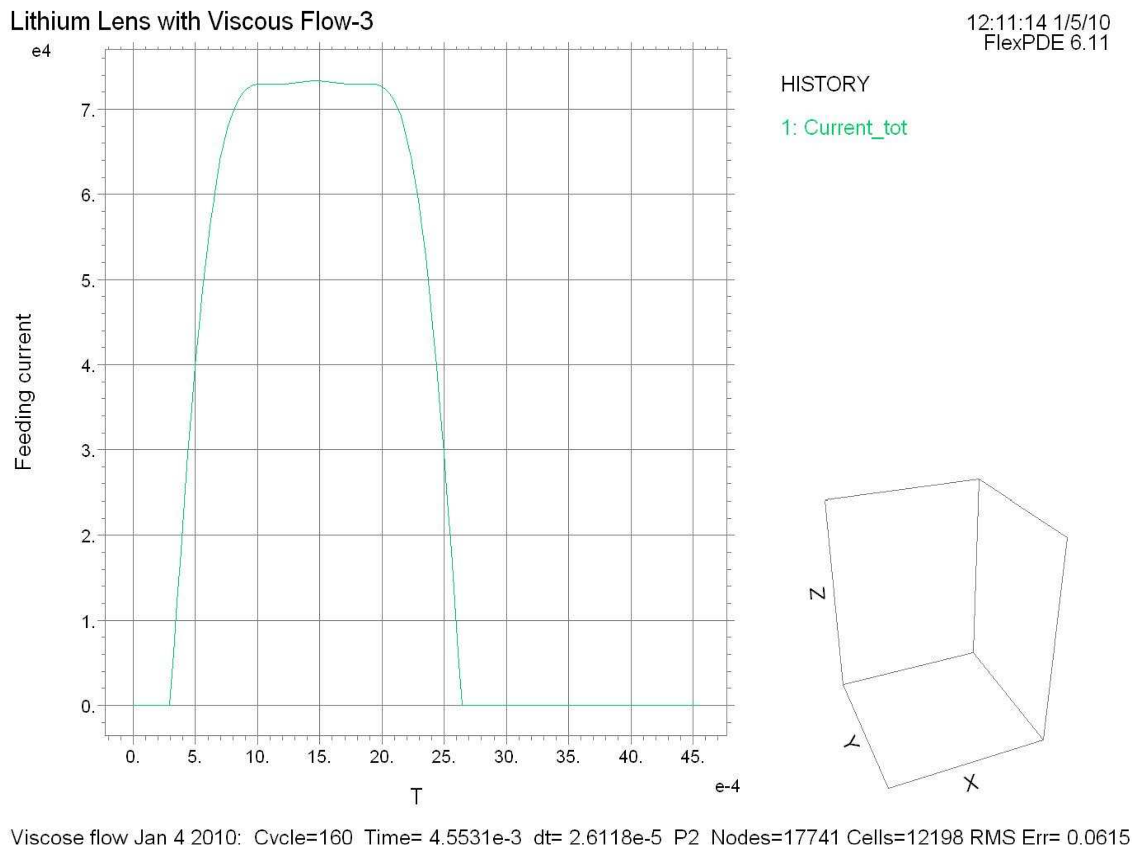


Model as it appears in FlexPDE



Dimensions, *mm*

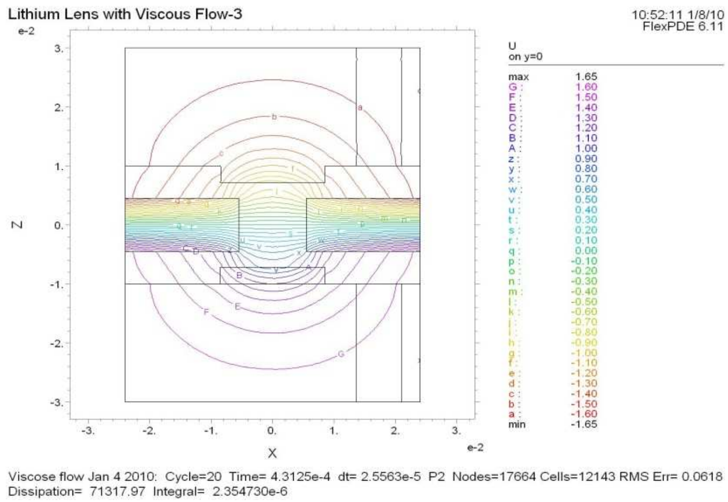
Feeding voltage composed with three odd harmonics 1,3,5



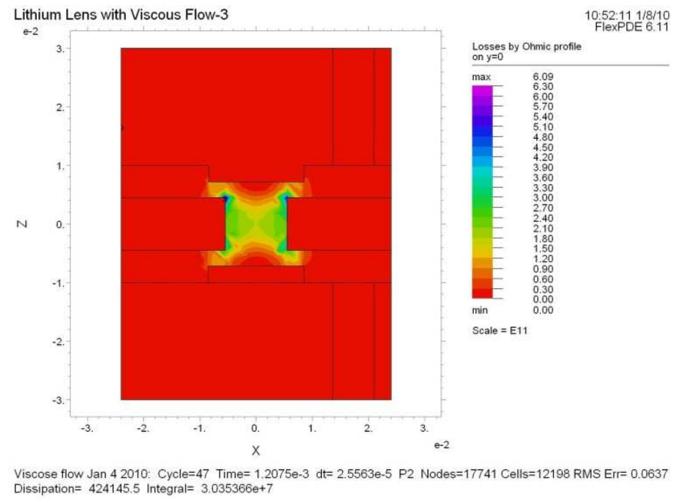
Voltage applied

$$U(t) = U_0 \cdot [-4.5 \cdot Sin(\frac{\pi \cdot (t - \tau/10)}{\tau}) - 0.9 \cdot Sin(\frac{3\pi \cdot (t - \tau/10)}{\tau}) - 0.17 \cdot Sin(\frac{5\pi \cdot (t - \tau/10)}{\tau})]$$

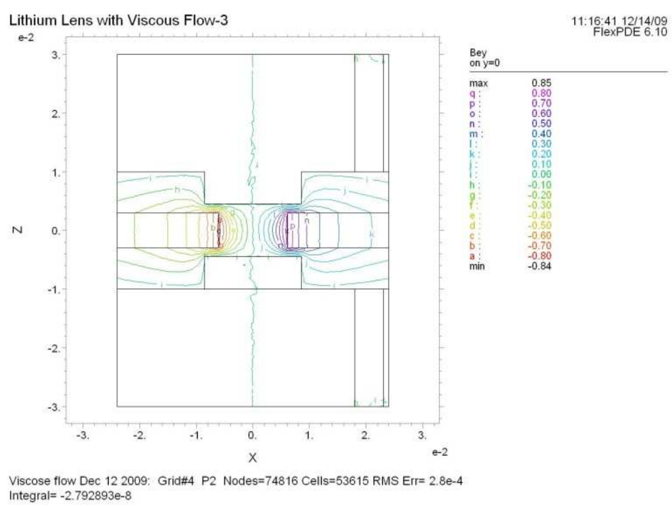
Calculation done with FlexPDE© code (frames from the cinema)



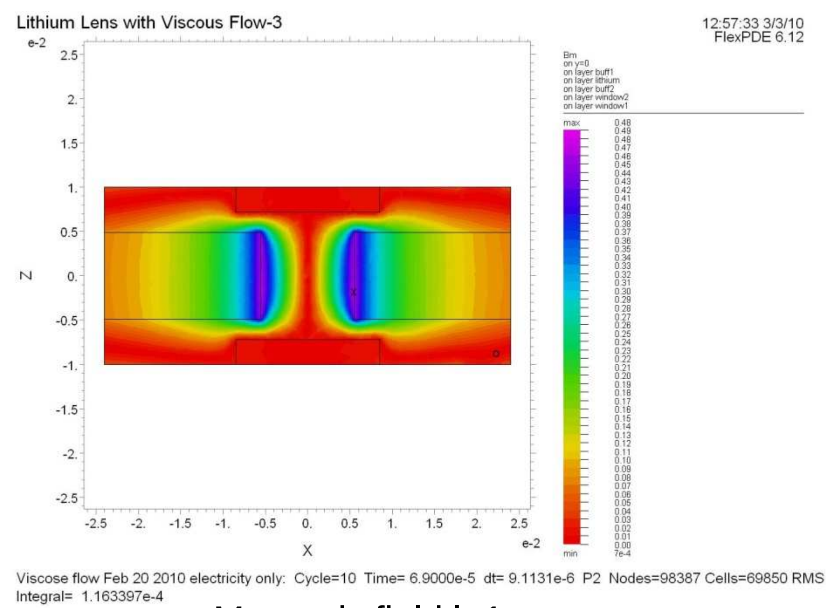
Potential



Ohmic losses

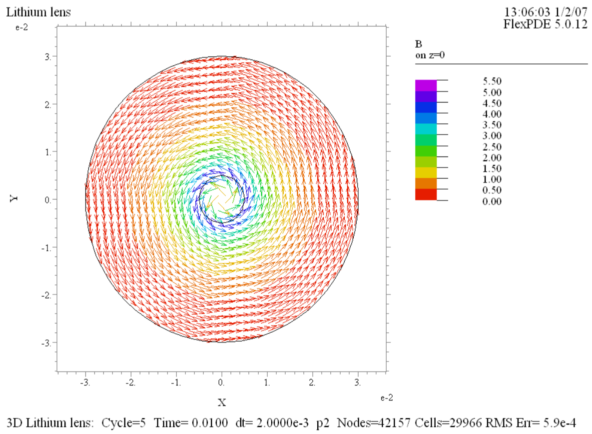


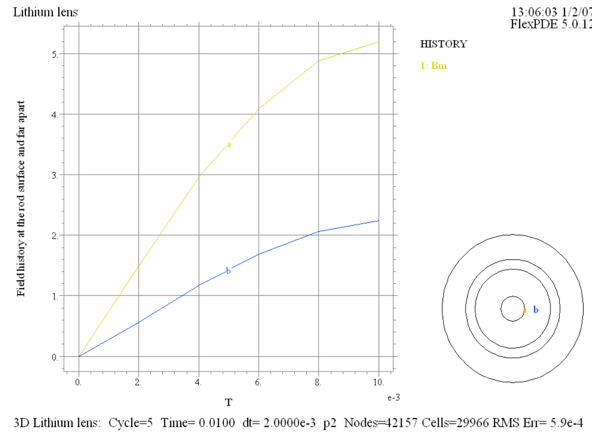
Magnetic field; *l*=0.5cm

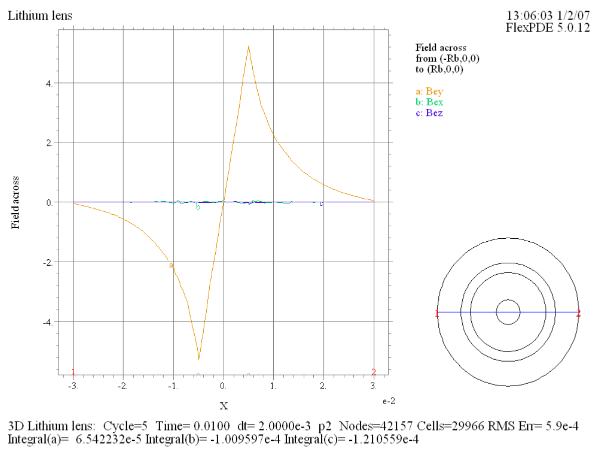


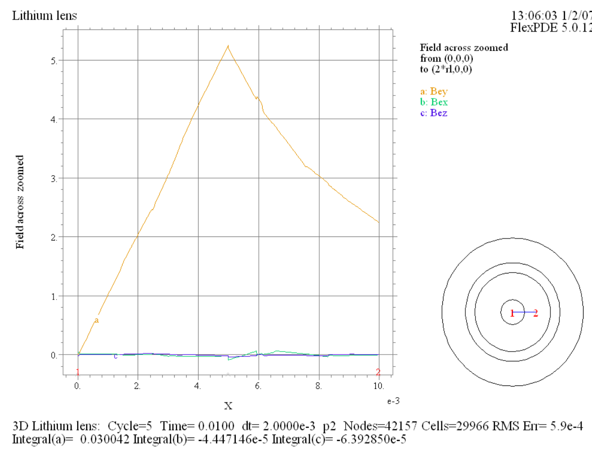
Magnetic field l=1cm

Spatial field distribution over time

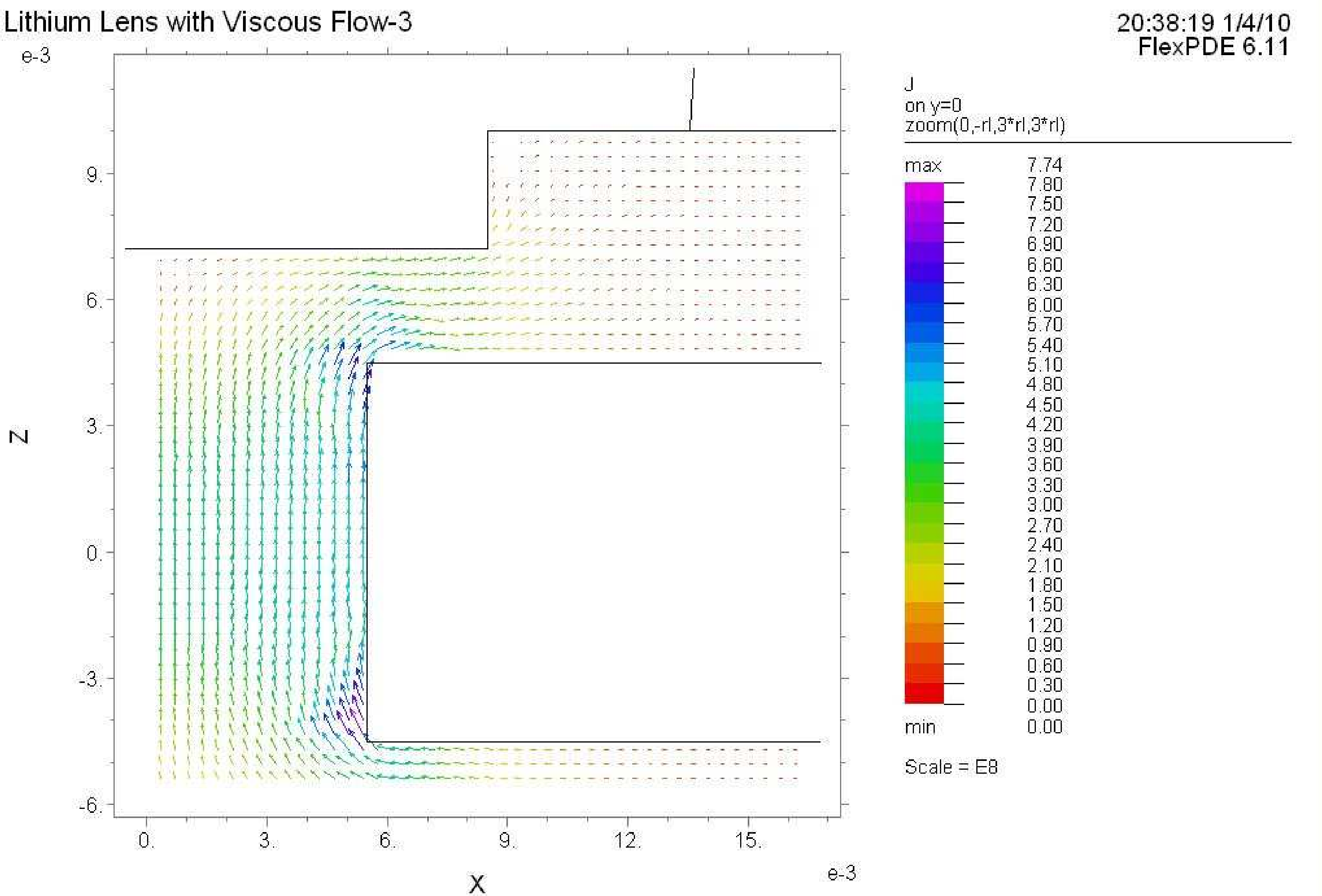






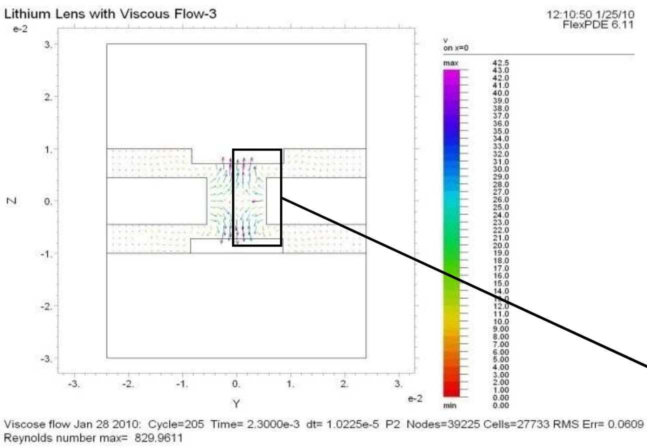


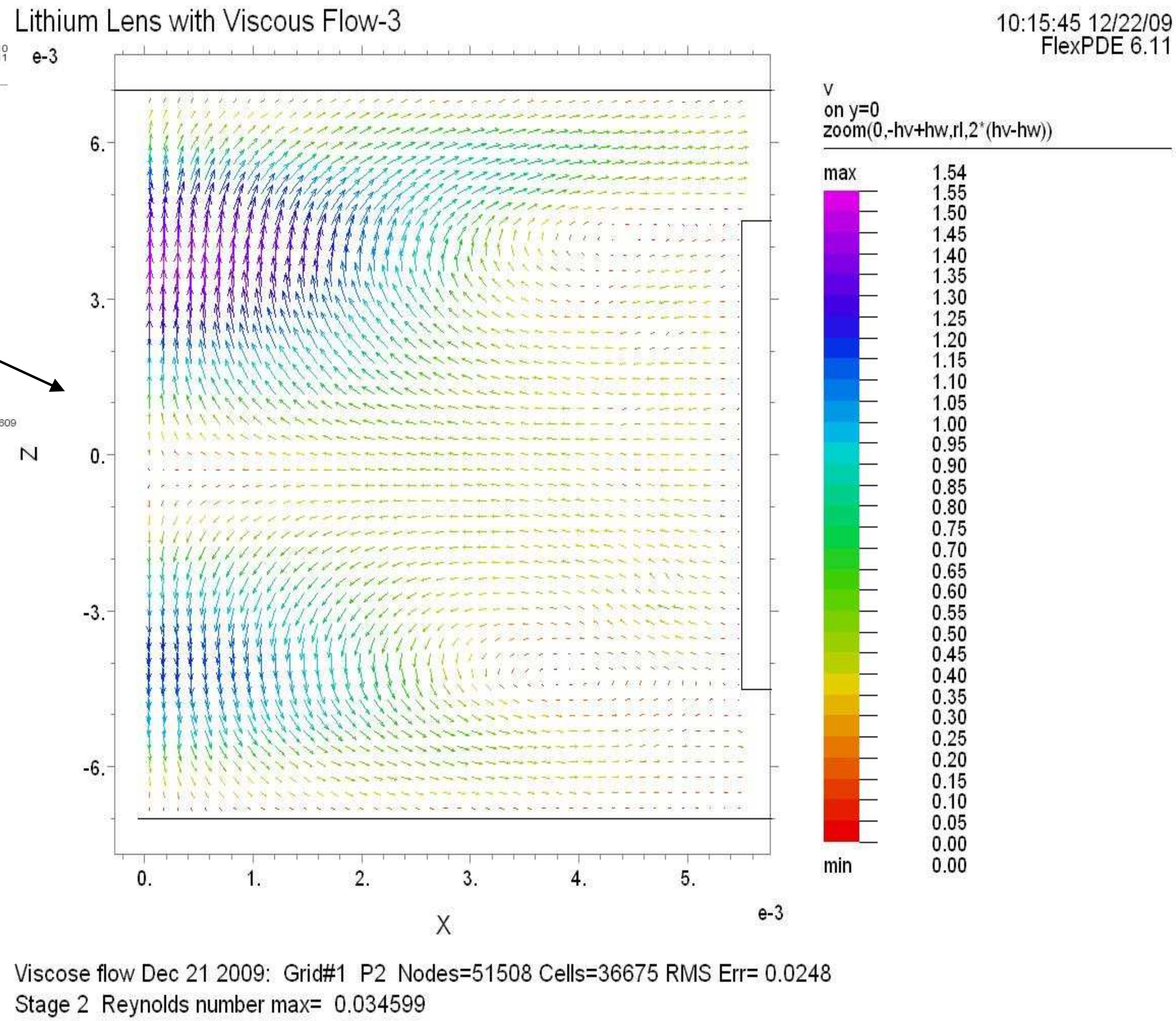
Current flow



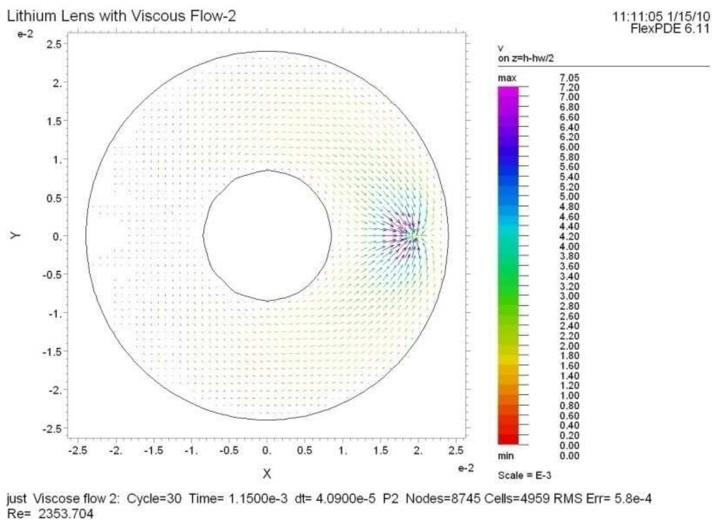
Viscose flow Jan 4 2010: Cycle=88 Time= 2.4381e-3 dt= 2.6118e-5 P2 Nodes=17741 Cells=12198 RMS Err= 0.0609
Power of dissipation, Watts= 126634.3

Identified vortex lithium flow

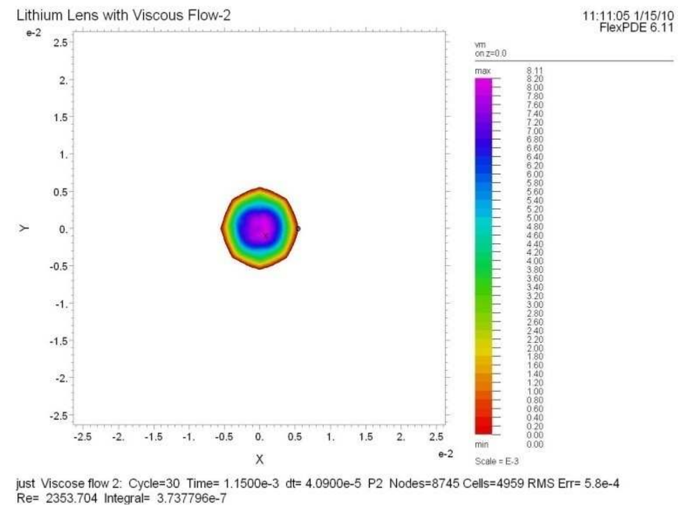




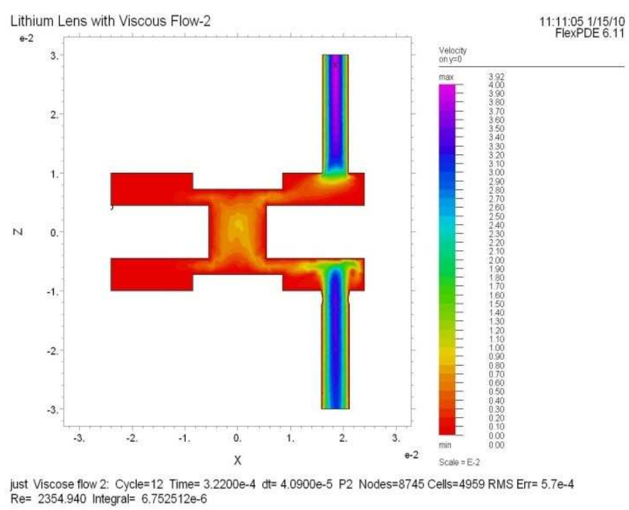
$$grad(P) \cong (\vec{j} \times \vec{B})$$



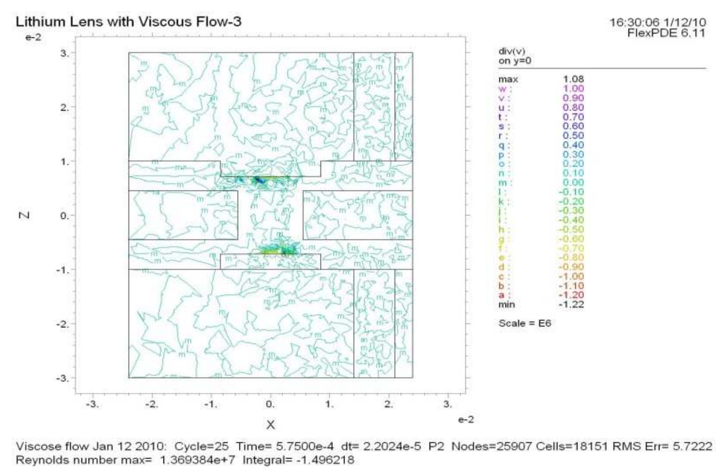
Velocity profile just below outlet tube.



Velocity profile in the middle of model (across the plane with central point {x=0, y=0, z=0}.

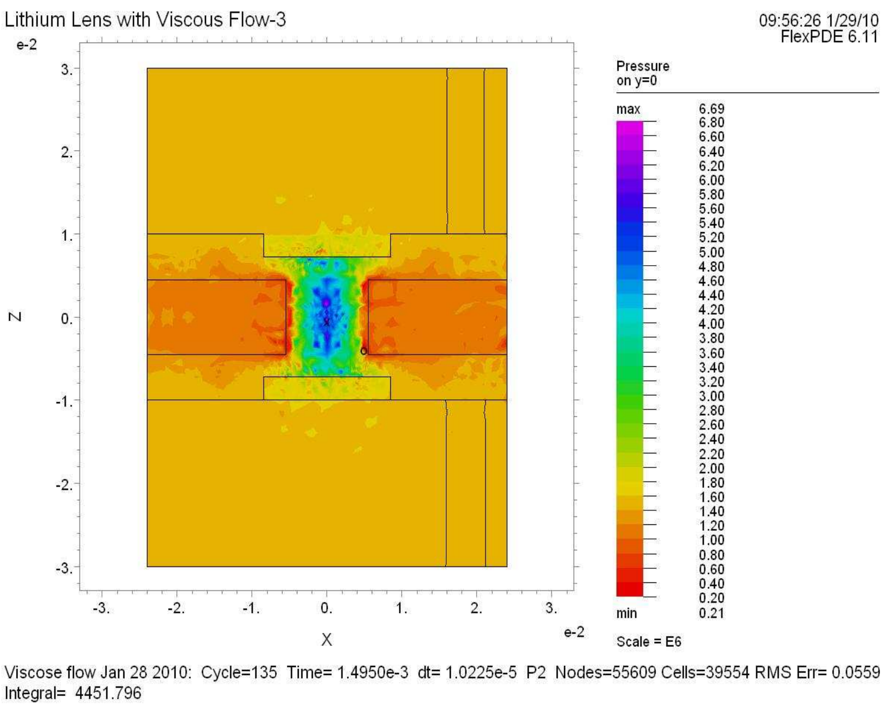


Laminar flow of Lithium

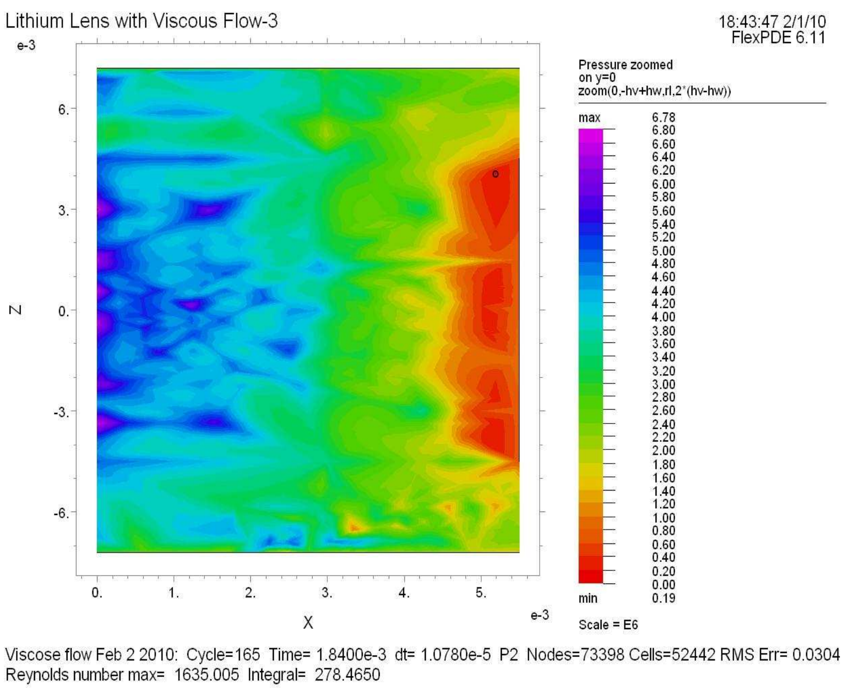


Contour plot of *div(**v**)* ; it is zero practically everywhere with numeric accuracy.

PRESSURE DYNAMICS



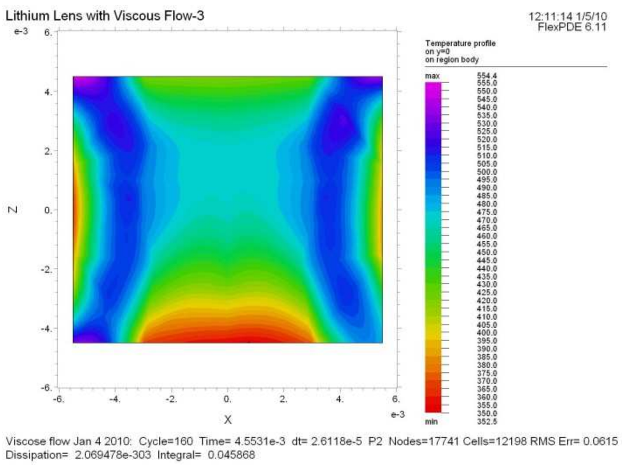
Pressure in a volume while current is running



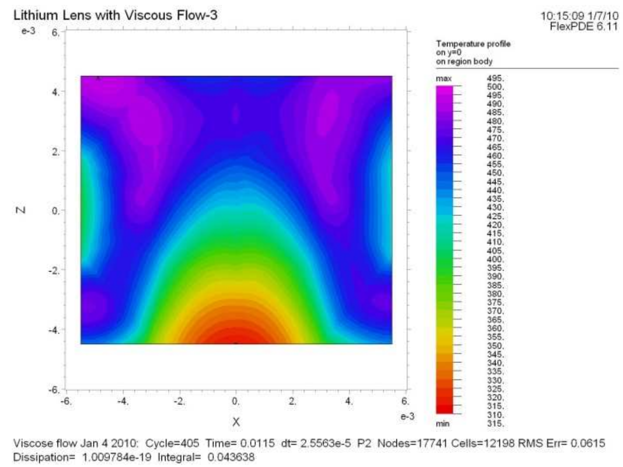
Pressure from previous Figure zoomed at central region, term ***J***x***B*** in on.

Time is~1.84 *msec* from beginning of process

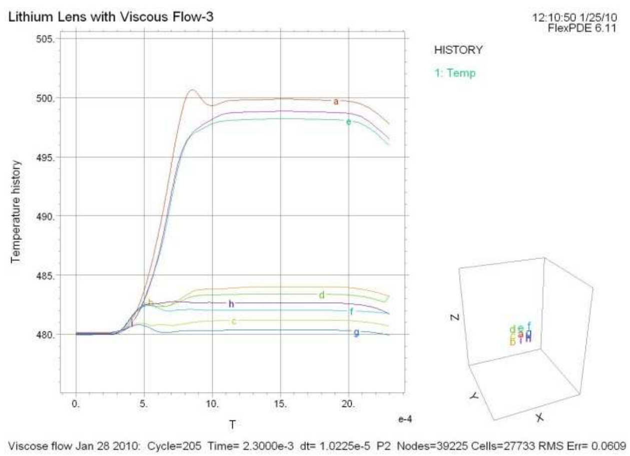
Temperature dynamics



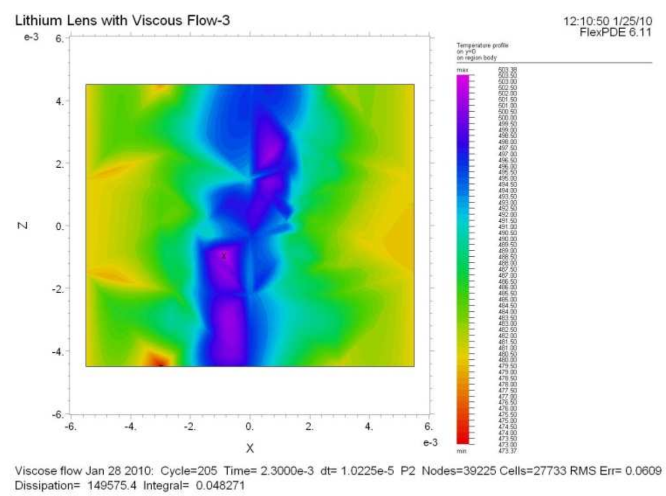
Temperature profile painted, 4.5 *msec* passed since start



Temperature profile painted, 11.5 *msec* passed since start; just in/out temperature fixed

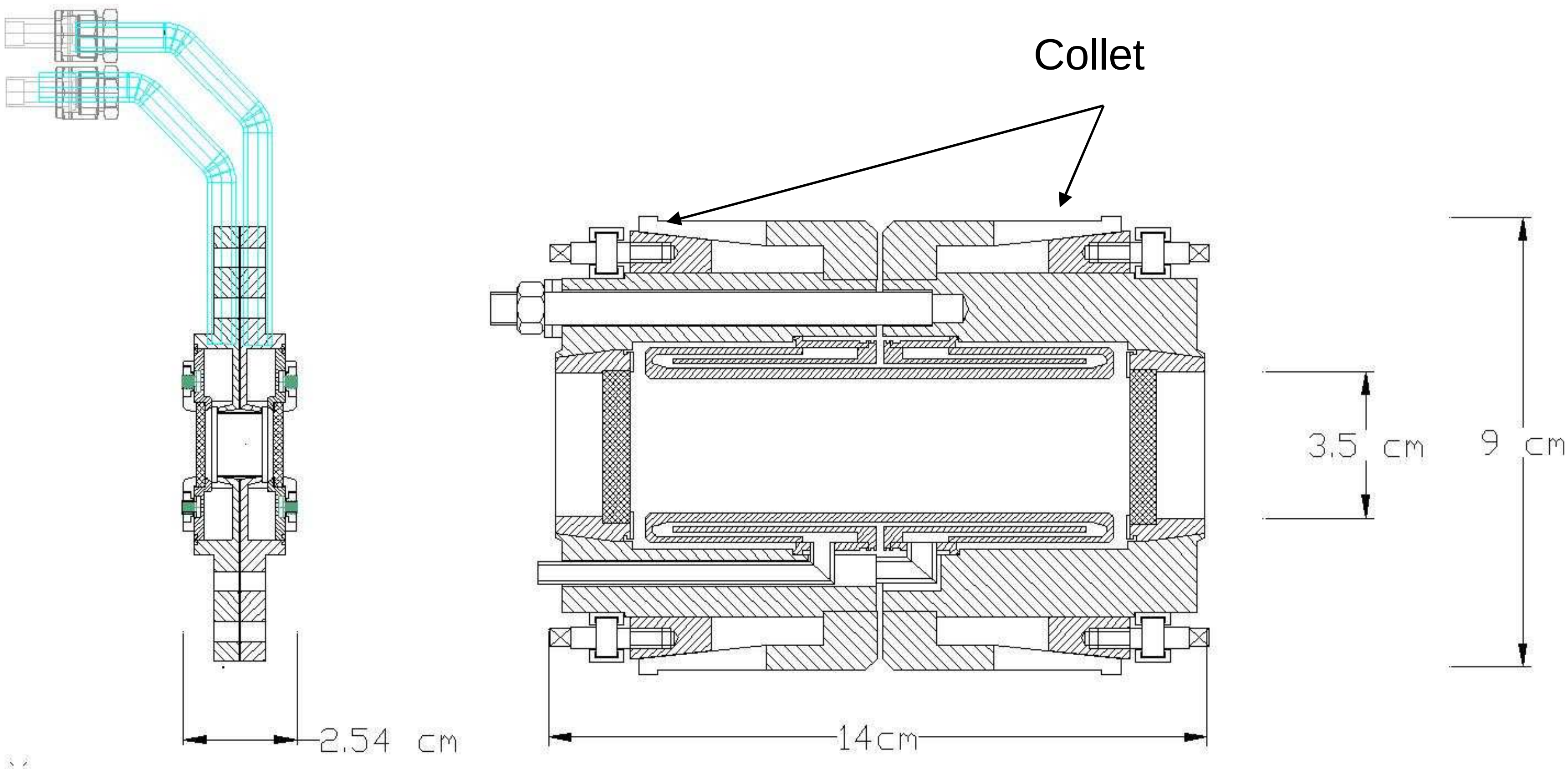


Temperature history at the same points, when the walls temperature kept constant at 480^{o}K



Temperature profile painted, 2.3 *msec* passed since start; just in/out temperature fixed

Li lens for ILC and Li lens for collection of antiprotons

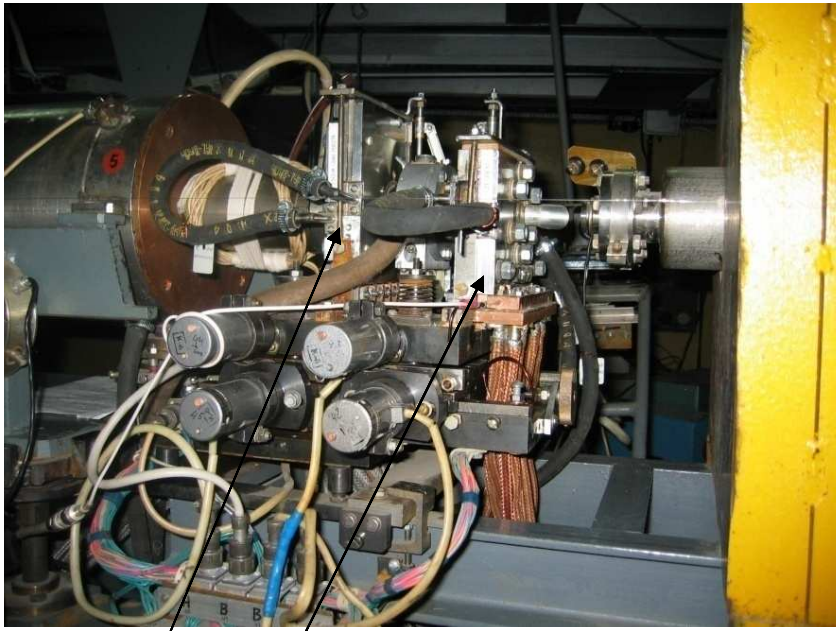


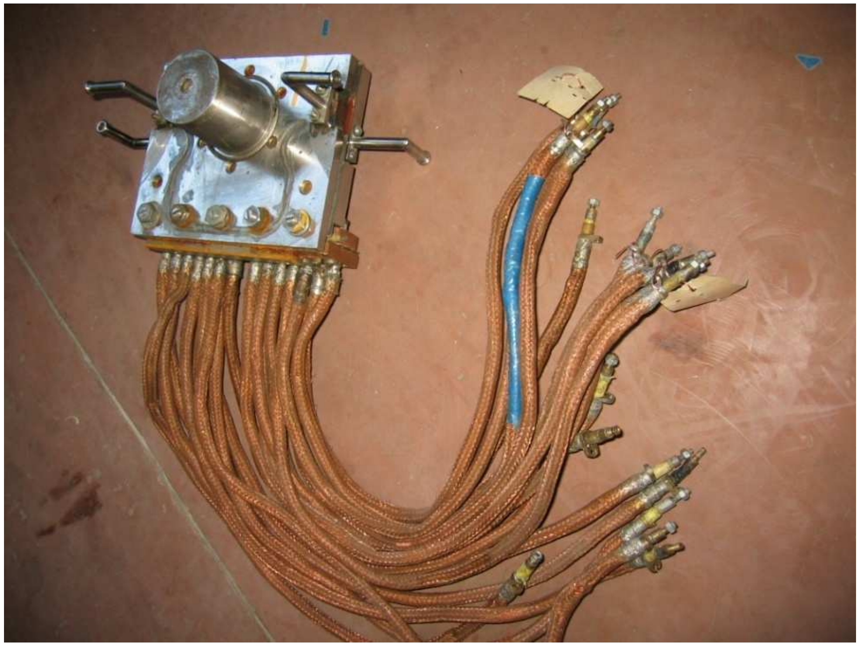
Lithium lenses represented with the same scale factor.

	Positrons	**Antiprotons**	**Neutrino factory**
Diameter, *cm*	1.4	2-3.6	1.8- 6
Length, *cm*	1	10	15
Current, *kA*	<75	~850	500
Pulse duty, *msec*	~4	0.1	~1
Repetition rate, *Hz*	5	0.7	0.7
Resistance $\mu\Omega$	32	50	27
Gradient, *kG/cm*	<65	55	45
Surface field, *kG*	43	100	80-40
Pulsed Power, *kW*	~360	36000	6750
Average Power, *kW*	**~7.5**	3.6	4.7
Temperature gain/pulse, ^{o}K	**85**	80	80
Pressure at axis, *atm*	~19	400	256-64

Doublet of Solid 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,

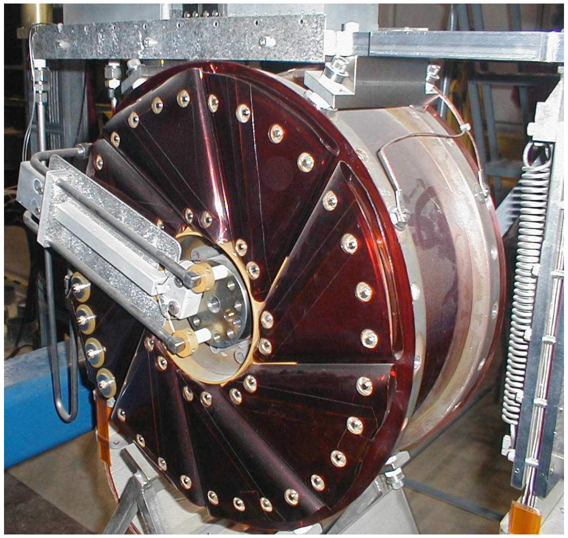
Second lens installed after the target and collects positrons at ~150MeV

Number of primary electrons per pulse ~$2 \cdot 10^{+11}$; ~0.7Hz operation (defined by the beam cooling rate in a Damping Ring)

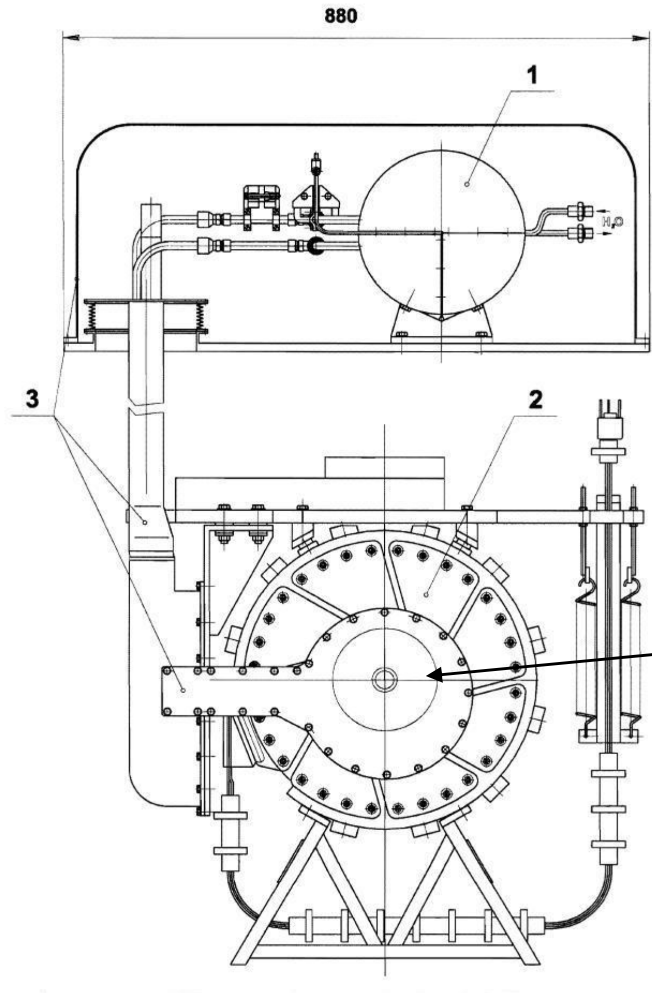
Lenses shown served ~30 Years without serious problem (!)

Lenses designed at BINP Novosibirsk for FERMILAB

Lens with liquid Lithium



Lens with solid LI



1-liquid lithium pump; 2-toroidal transformer; 3-lithium cirquit protection.

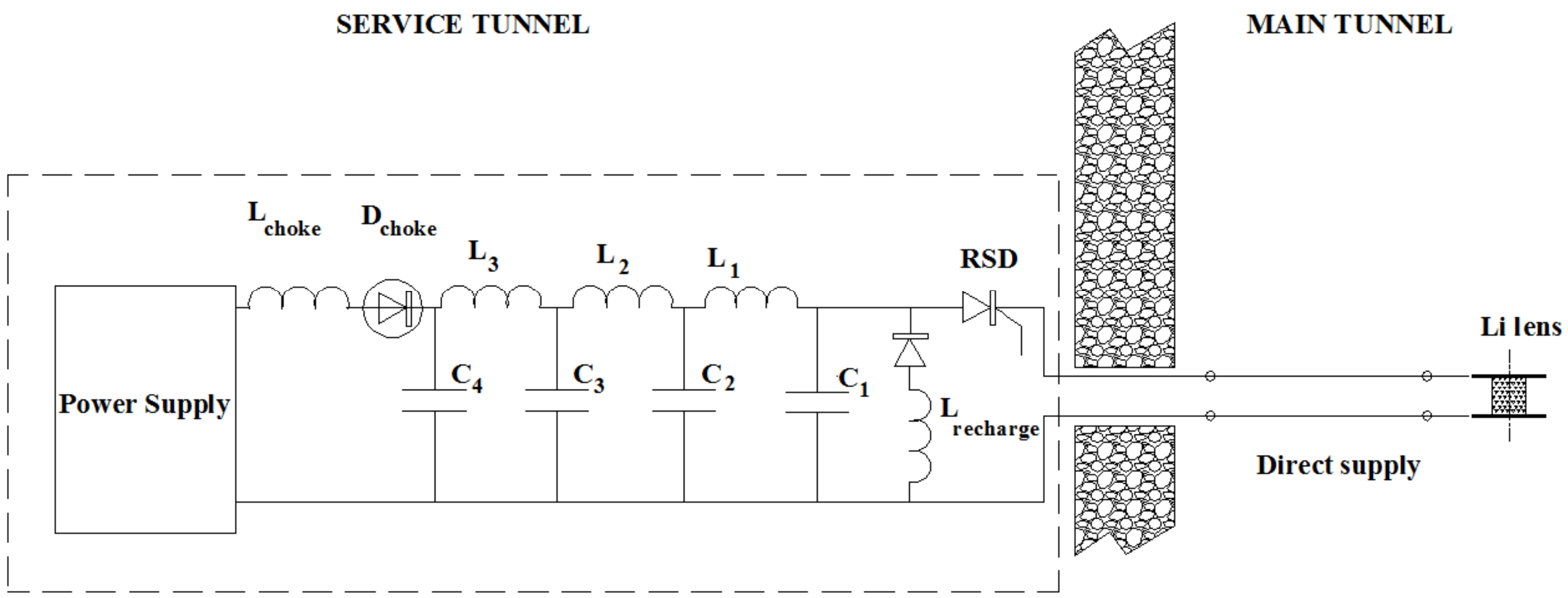
B.Bayanov et al., “Liquid Lithium Lens for FermiLab Antiproton Source”, Novosibirsk BINP, 98-23, 1998.

NEW TYPE OF COMMUTATORS FOR HIGH CURRENT

Fig.2. Reverse – switched dinistors for peak current from 200 kA to 500 kA and blocking voltage of 2400 V, encapsullated in hermetic metal – ceramic housing and without housing (RSD sizes of 64, 76, and 100 mm)

S.A. Belyaev, V.G.Bezuglov, V.V.Chibirikin, G.D.CHumakov, I.V.Galakhov, S.G.Garanin, S.V.Grigorovich, M.I.Kinzibaev, A.A.Khapugin, E.A.Kopelovich, F.A.Flar, O.V.Frolov, S.L.Logutenko, V.A.Martynenko, V.M.Murugov, V.A.Osin, I.N.Pegoev, V.I.Zolotovski, ”*New Generation of High-Power Semiconductor Closing Switches for Puled Power Applications*”, 28 ICPIG, July 15-20, 2007, Prague, Czech Republic, Topic#17, pp.1525-1528.

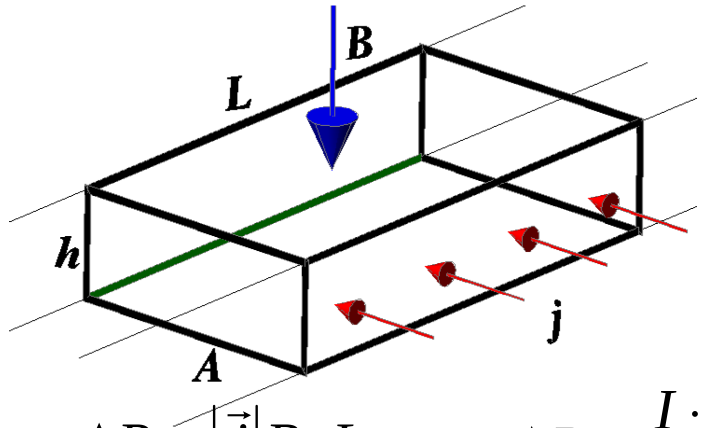
POWER SUPPLY SCHEMATICS



WITH RDS, THE POWER SUPPLY IS PRETTY GUARANTEED

PUMPS

MGD pump

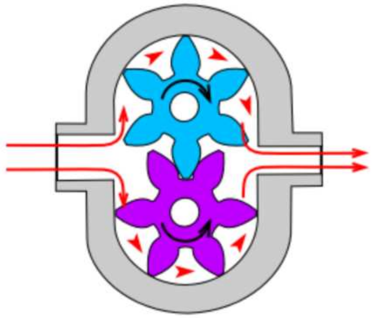


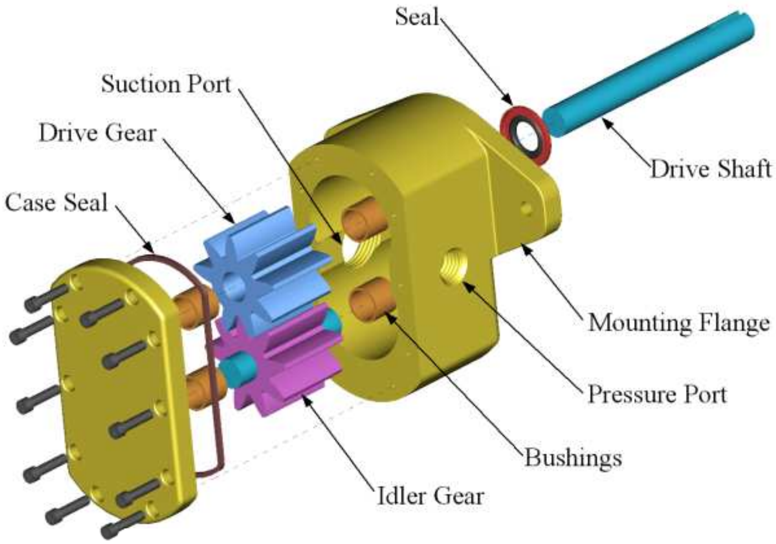
$$\vec{\nabla} P = \vec{j} \times \vec{B} \cong \left|\vec{j}\right| \cdot B \qquad \Delta P = \left|\vec{j}\right| B \cdot L \qquad \Delta P = \frac{I \cdot B \cdot L}{L \cdot h} = \frac{I \cdot B}{h}$$

For example, if I=400 A, h=4mm, B=1T, then ΔP=10^5Pa ~1atm

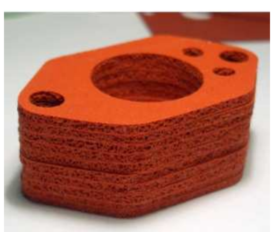
The flow meter works with the same components as the pump. $\vec{E} = \vec{v} \times \vec{B}$
So the E.M.F. will be vxBxA.
For example, if v=1m/s, B=1 T, A=10cm=0.1m, then *E.M.F.=0.1V*, i.e. the macroscopic value, which could be measured pretty accurately.

Gear pump (From Wikipedia)





Made from 316 StSteel, Ti, Ceramics, etc.



HT gaskets.
Auburn Co. (at the left) and McNeil Co. (at the right).

Materials: Aluflex (-54^{o}C-+500^{o}C), Blue-Gard (+370^{o}C) Fiberfrax(+700^{o}C-+1260^{o}C) Viton (+220^{o}C)

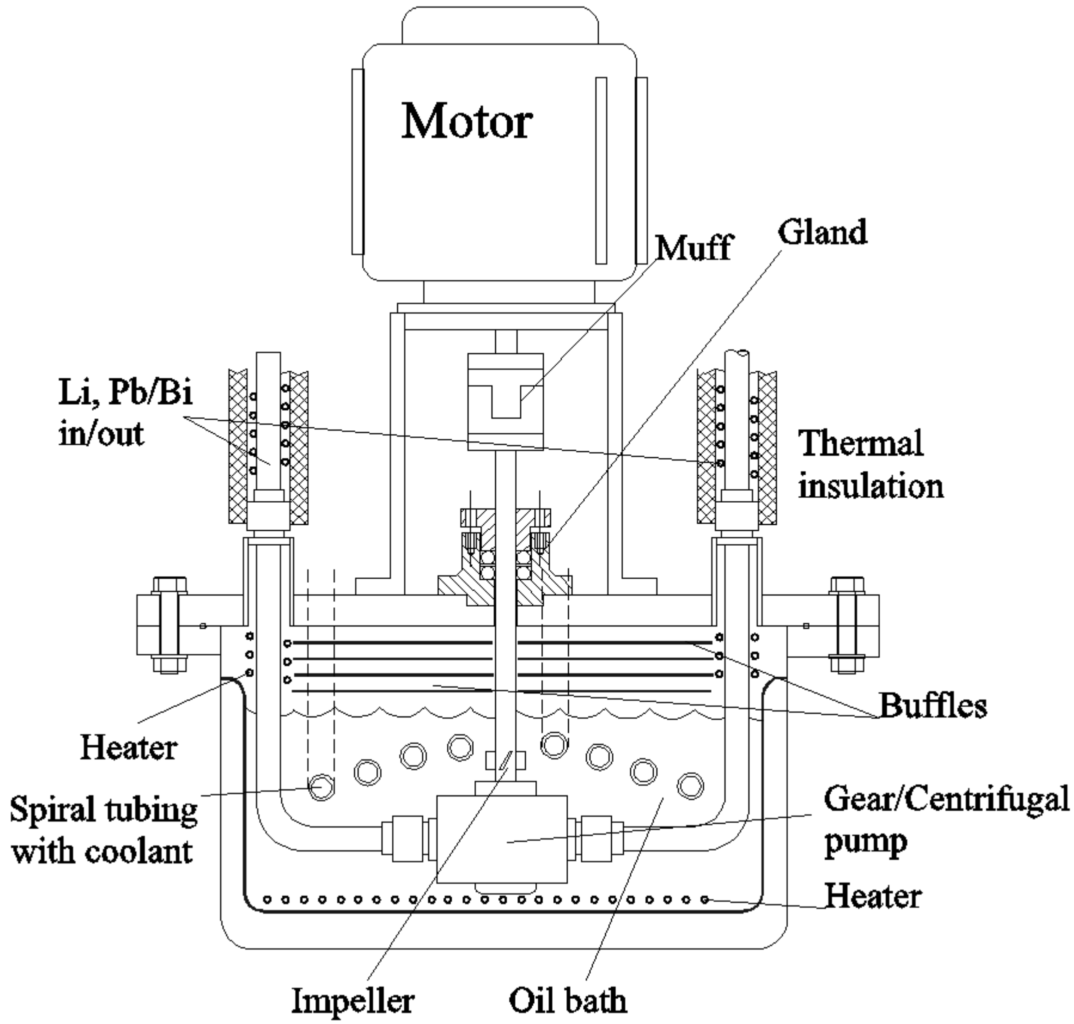
One example

SCHERZINGER
PUMP TECHNOLOGY

Scherzinger

Transfer pumps for high temperature applications
Extreme temperatures and low viscosities, particularly with thermal oils,
are no problem for these transfer pumps.
Fluid transfer remains reliable
even at temperatures up to 300℃ and low viscosities.

- Flow rates: 1 m^3/h or 2.5 m^3/h
- Differential pressure: Max. 10 bars



Pump setup. This pump is working for Bi/Pb, Li, Ga, Hg

Piston-type pump

B.Bayanov et al., “Liquid Lithium Lens for FermiLab Antiproton Source”, Novosibirsk BINP, 98-23, 1998.

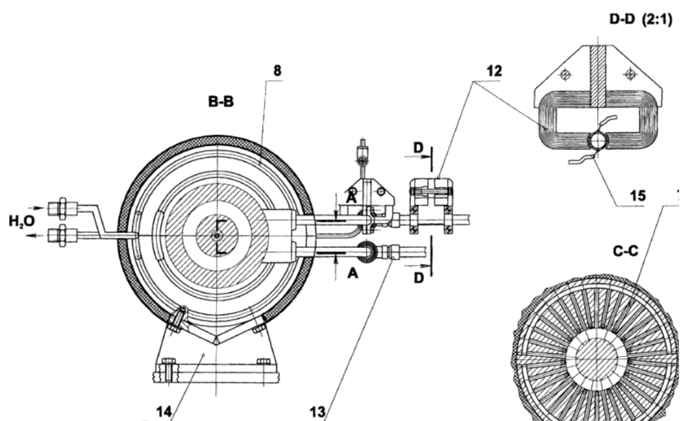


Fig. 9b .Liquid lithium pump and heat exchanger.

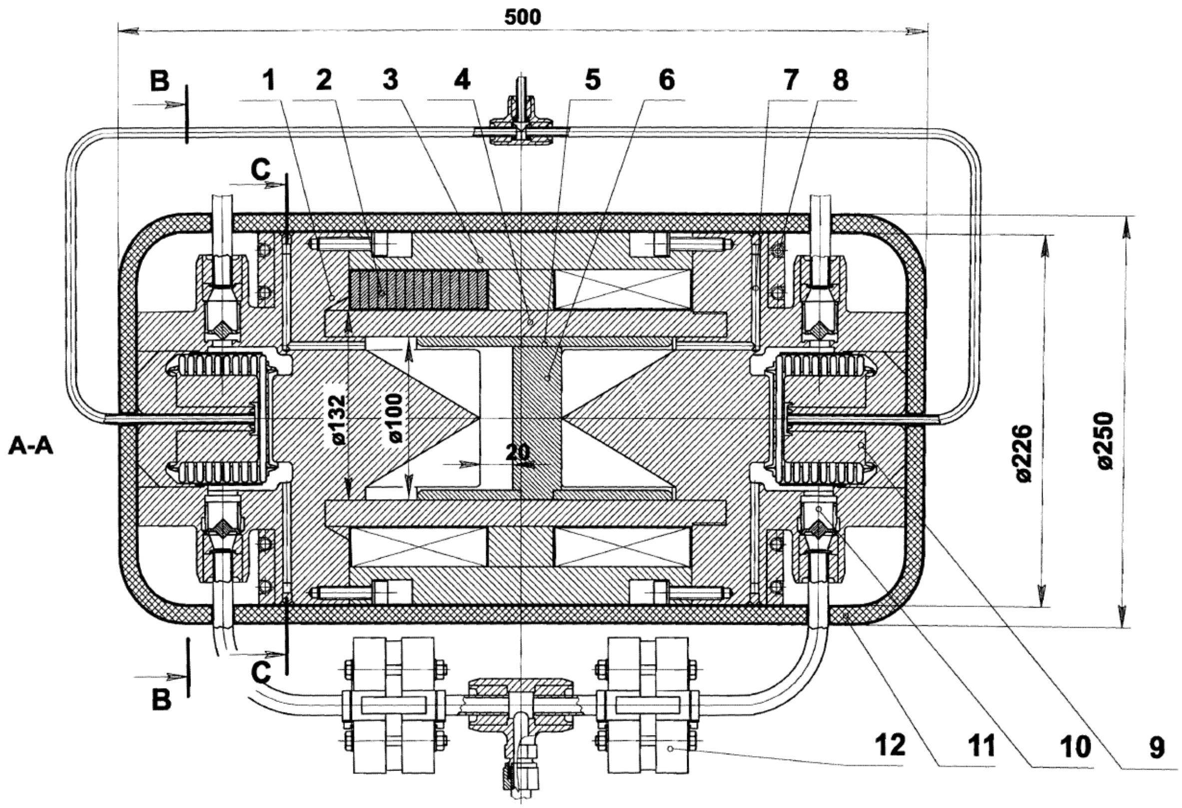


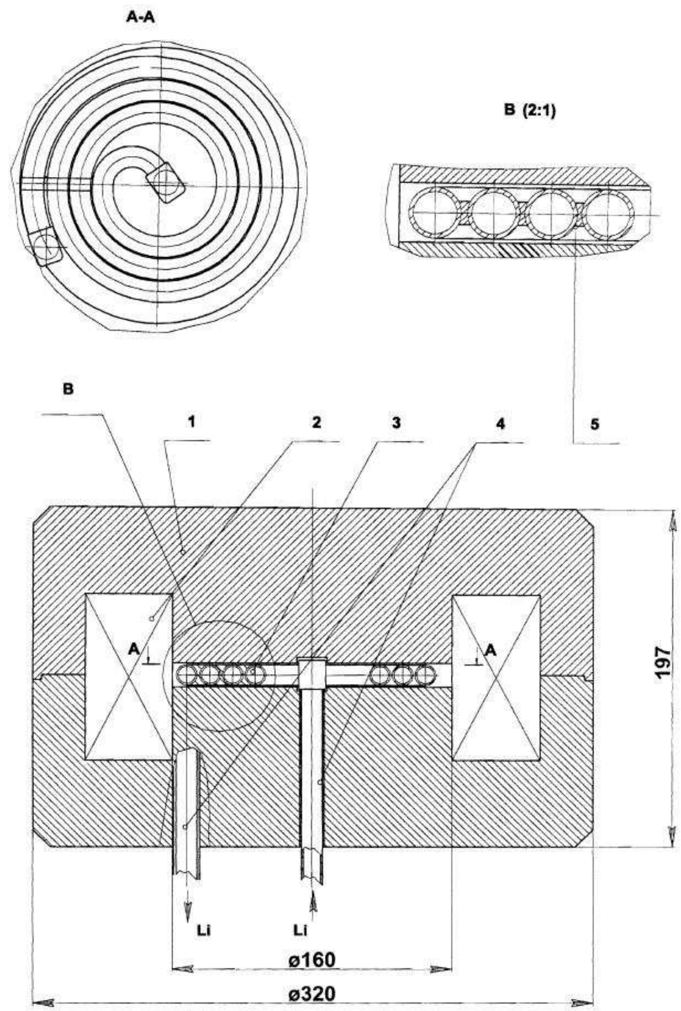
Fig.9a . Liquid lithium pump and heat exchanger.

1-face disks; 2-exciting coil; 3-return yoke; 4-inside ferromagnetic wall of cylinder; 5-plunger; 6-ferromagnetic insert of plunger; 7-cooling channels of heat exchanger; 8-cooling water; 9-system to apply and control of liquid lithium static pressure; 10- switching valves; 11 - thermo-insulation; 12 -system to measure liquid flow rate; 13-jont of liquid lithium pipes; 14-pump support; 15 -contacts for potential measurements.

Spiral type

B.Bayanov et al., “Liquid Lithium Lens for FermiLab Antiproton Source”, Novosibirsk BINP, 98-23, 1998.

1-DC magnet yoke;
2-exciting coils;
3-spiral tybe;
4-liquid Lithium inputs;
5-soldered shortened inserts.



Liquid lithium pump of spiral type.

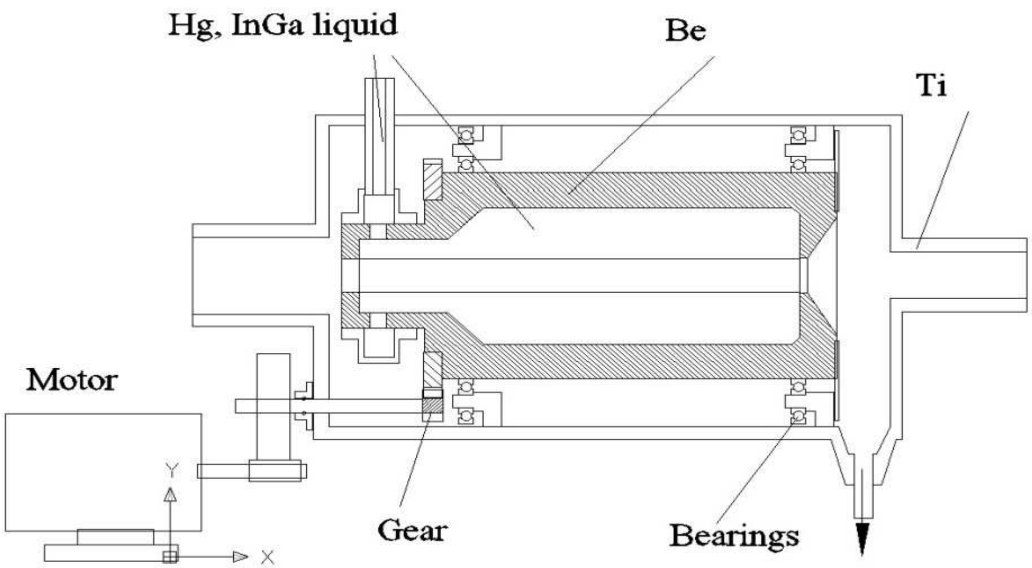
5. COLLIMATORS AND THE PHOTON DUMP

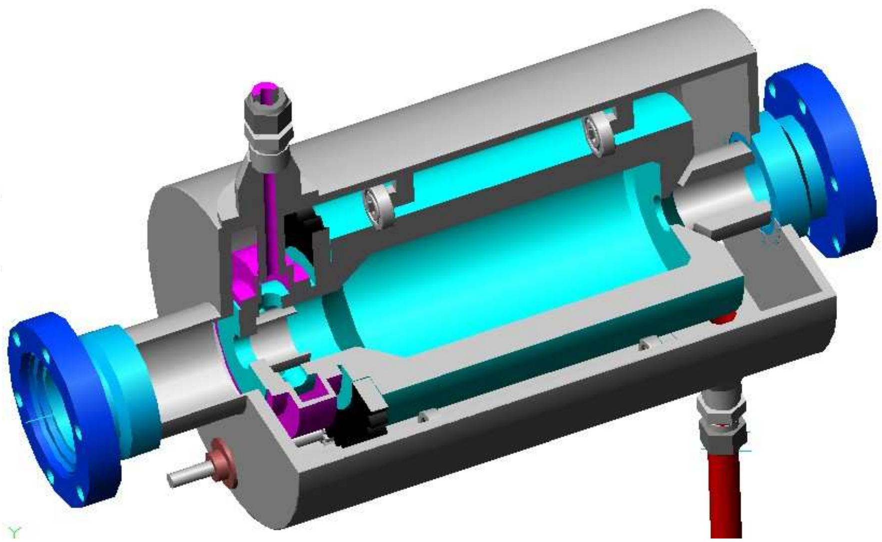
A.Mikhailichenko,” Physical Foundations for Design of High Energy Beam Absorbers”, CBN09-9, Oct. 23, 2008, Cornell, LEPP, http://www.lns.cornell.edu/public/CBN/2008/CBN08-8/CBN08-8.pdf

High Power Collimator for the Main Beam

Installed in front of the undulator

Spinning Liquid metal formed a cylinder as result of centrifugal force



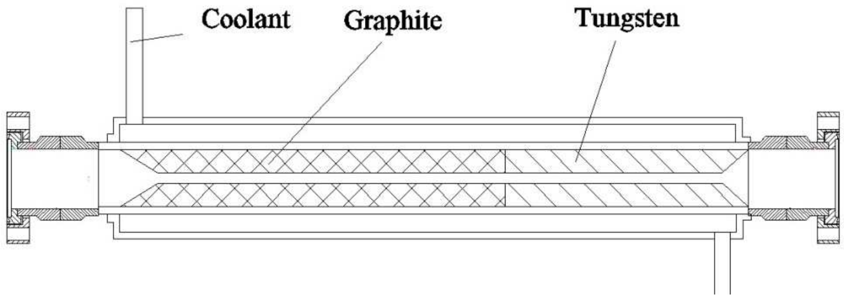


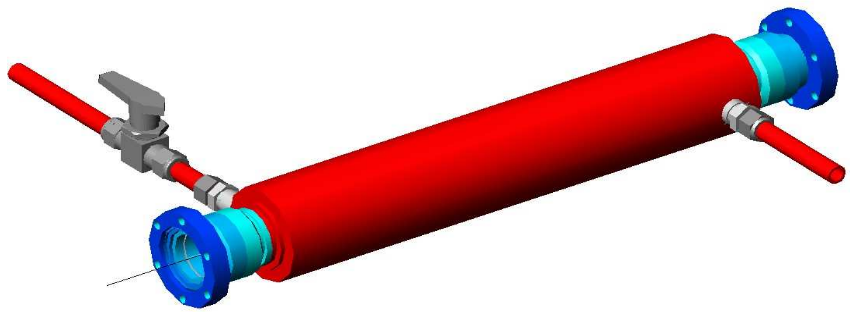
High average power collimator. Beam is coming from the right.

T.A.Vsevolojskaja, A.A.Mikhailichenko, G.I.Silvestrov, A.D.Cherniakin,
“To the Conversion System for Generation of Polarized Beams in VLEPP”, BINP Internal Report, 1986

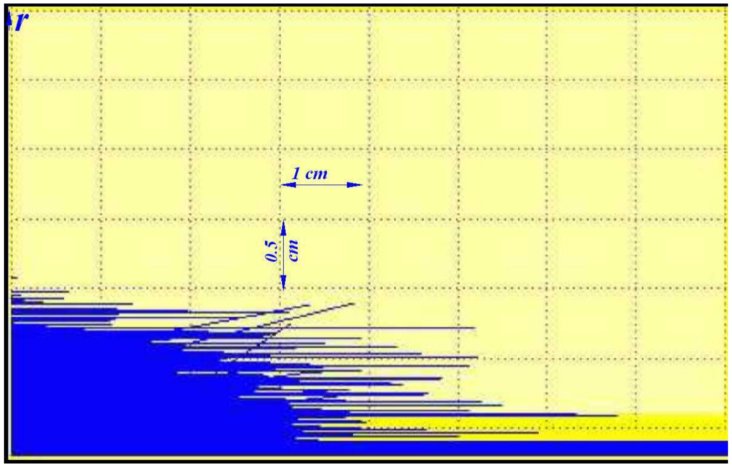
Collimator for gammas

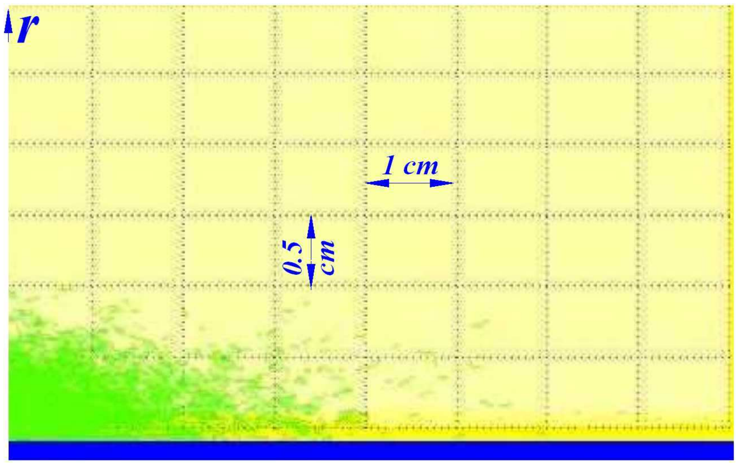
Pyrolytic Graphite (PG) is used here. The purpose of it is to increase the beam diameter, before entering to the W part. Vacuum outgassing is negligible for this material. Heat conductivity ~300 W/m-ºK is comparable with meals. *Beryllium* is also possible here, depending on task.





Transverse dimensions defined by Moliere radius

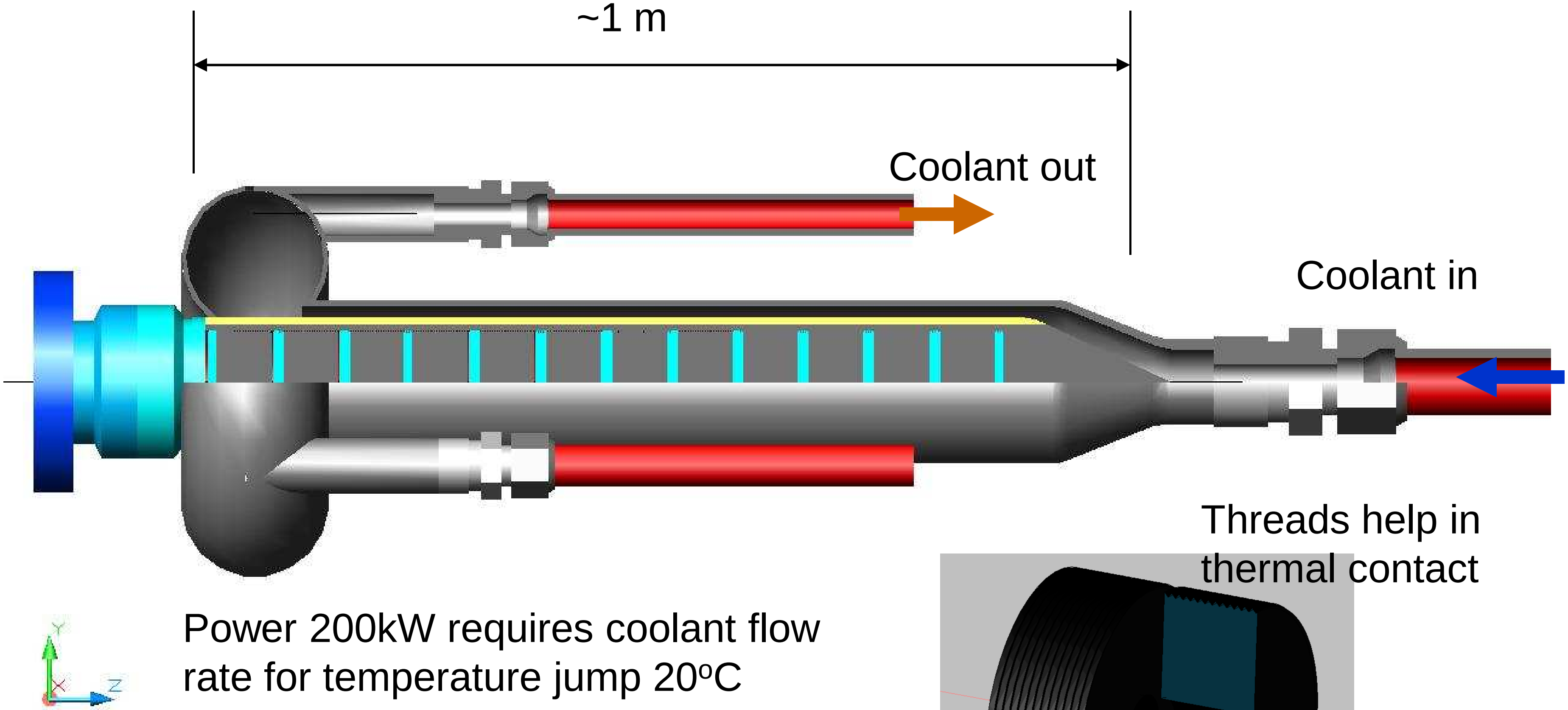




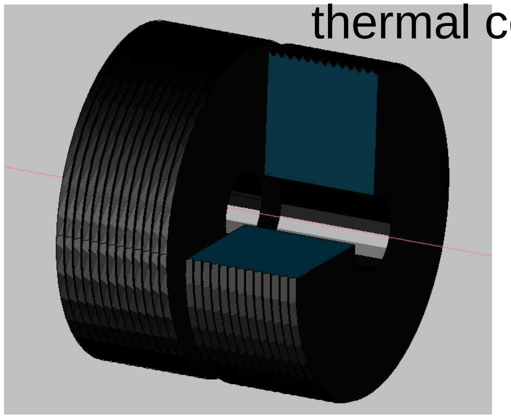
Gamma-beam. σ_γ= 0.5cm, diameter of the hole (blue strip at the bottom) *d*=2 mm. Energy of gamma-beam coming from the left is 20 *MeV*.

Positron component of cascade

Gamma dump with PG and Ti baffles



Threads help in thermal contact

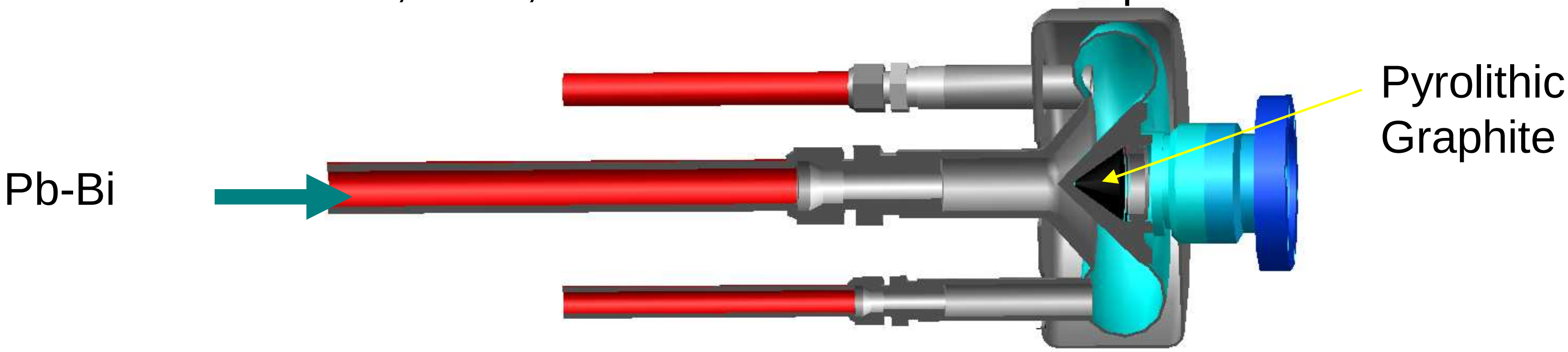


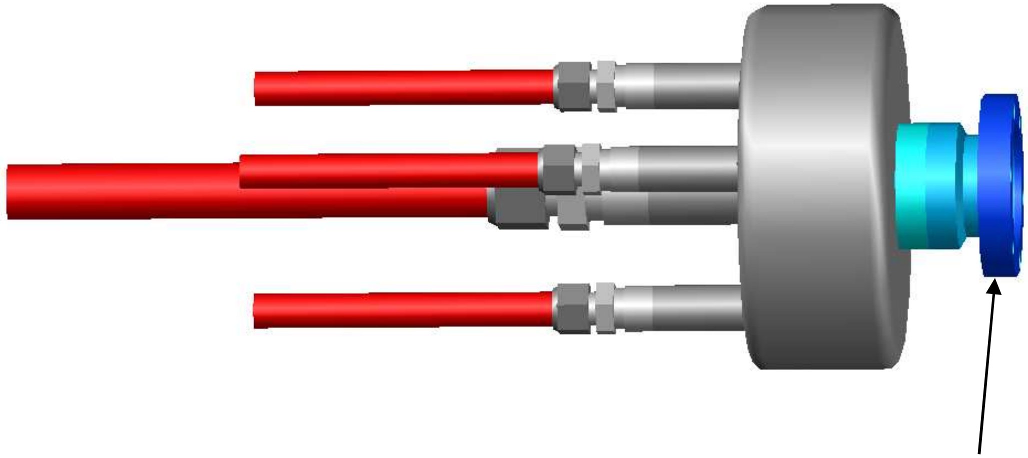
Power 200kW requires coolant flow rate for temperature jump 20^{o}C

$$\dot{m} \cong \frac{E_{tot}}{\Delta T C_p} \cong \frac{2 \cdot 10^5}{20 \cdot 4.18 \cdot 10^3} \cong 2.4 L/\sec$$

Example of the beam dump proposed at Cornell for ERL

15 MeV beam, 0.1 A; Coolant-Pb-Bi in the first loop





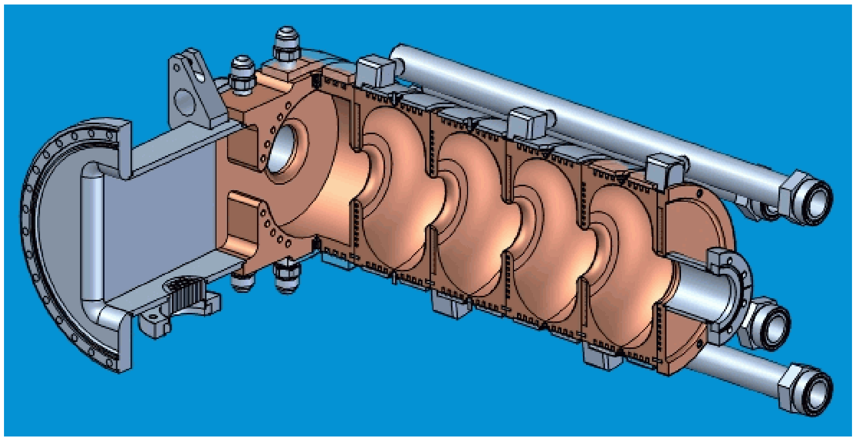
Cone keeps its shape while expanding. Diameter of the flange -4in

A.Mikhailichenko, ‘Physical Foundations for Design of High energy Beam Absorbers”, CBN 08-8, Ithaca, CLASSE, Oct 23, 2008.

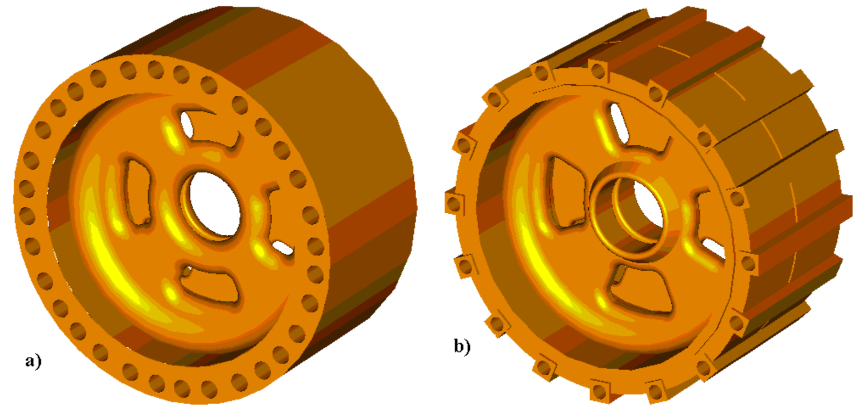
6. PRIMARY ACCELERATING STRUCTURE

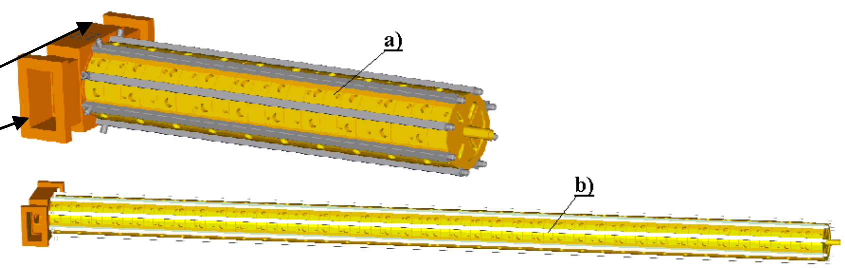
RF STRUCTURES – SLAC and JNR (Dubna)

Structures located right after the target are working in strong solenoidal field (up to 3T)



Accelerating structure, developed at SLAC

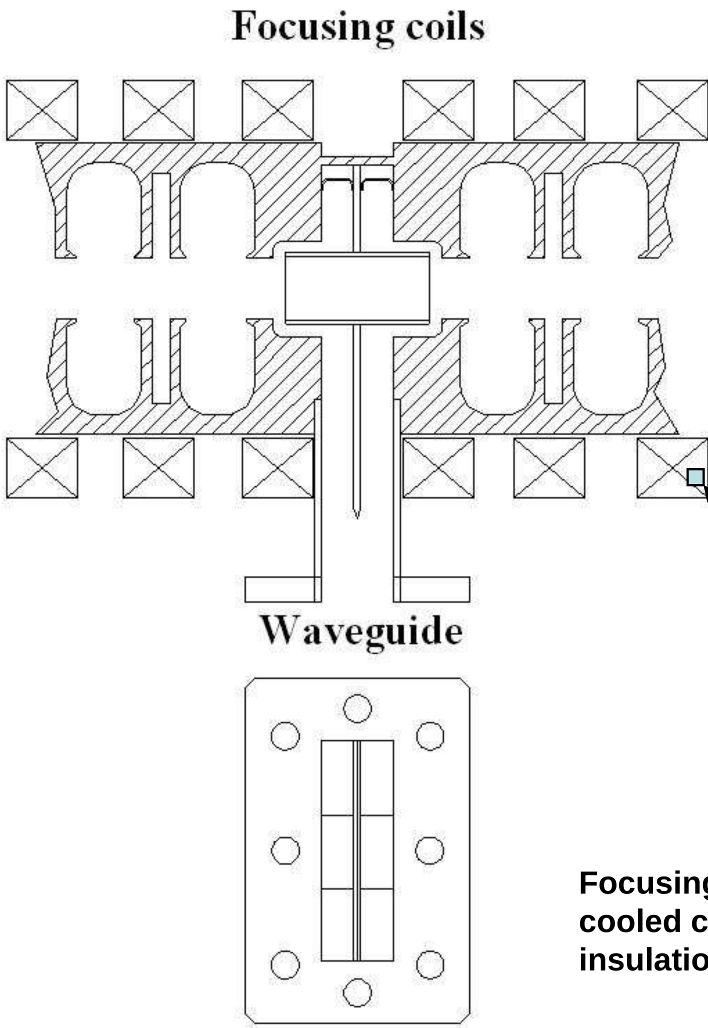




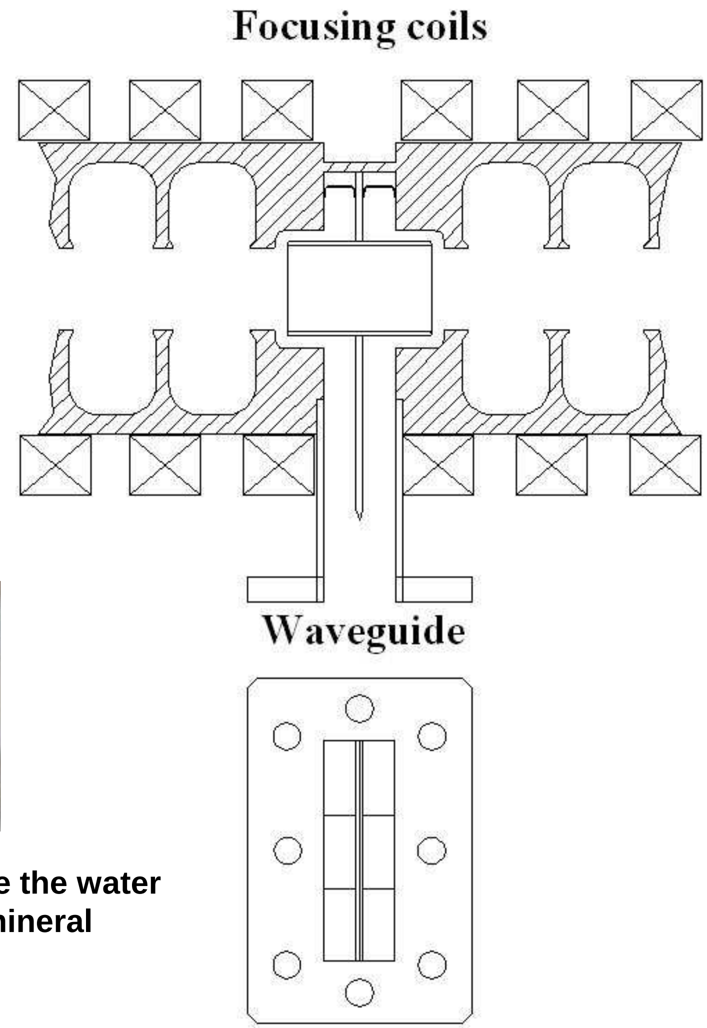
Symmetrical input at far from target end

Accelerating structure developed at Dubna (under test in DESY), JINR a) –for high (19 MeV/m) gradient, b) –for moderate (8.5 MeV/m) gradient .

L.V. Kravchuk, V.A. Moiseev, A.N. Naboka, V.V. Paramonov, A.K. Skasyrskaja

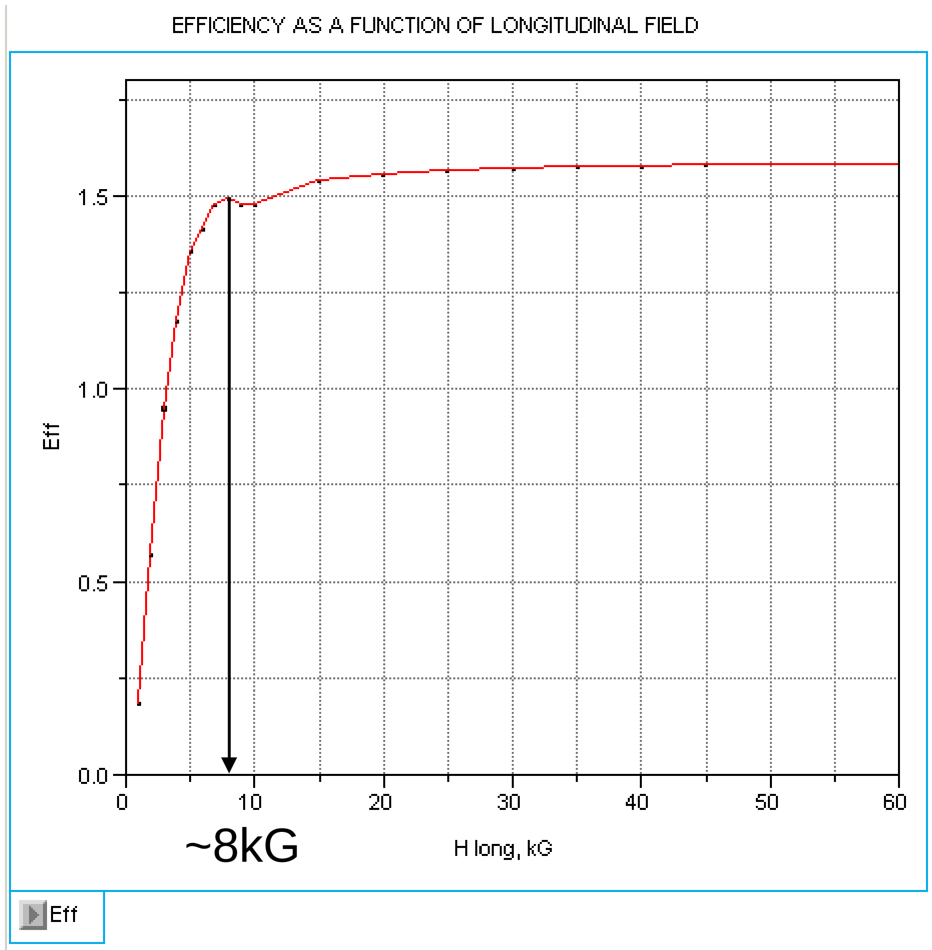


Focusing coils could use the water cooled conductor with mineral insulation



Possible solutions for pulsed solenoids-longitudinal slit of structure or usage of Cu-StSteel bimetallic structure.

If all other parameters are kept fixed, then efficiency of conversion as a function of longitudinal magnetic field looks like:



Pretty moderate field indeed

7. EXPERIMENT E-166 AT SLAC

E-166:

Experimental test of polarized positron production with gammas generated by high energy beam in helical undulator

17 Institutions, 33 members

Just remind

$$E_{\gamma n} \cong \frac{n \cdot 2.48 \cdot (\gamma / 10^5)^2}{\lambda_u [cm](1 + K^2 + \gamma^2 \vartheta^2)} [MeV]$$

Goes to few mm period for 50 GeV beam

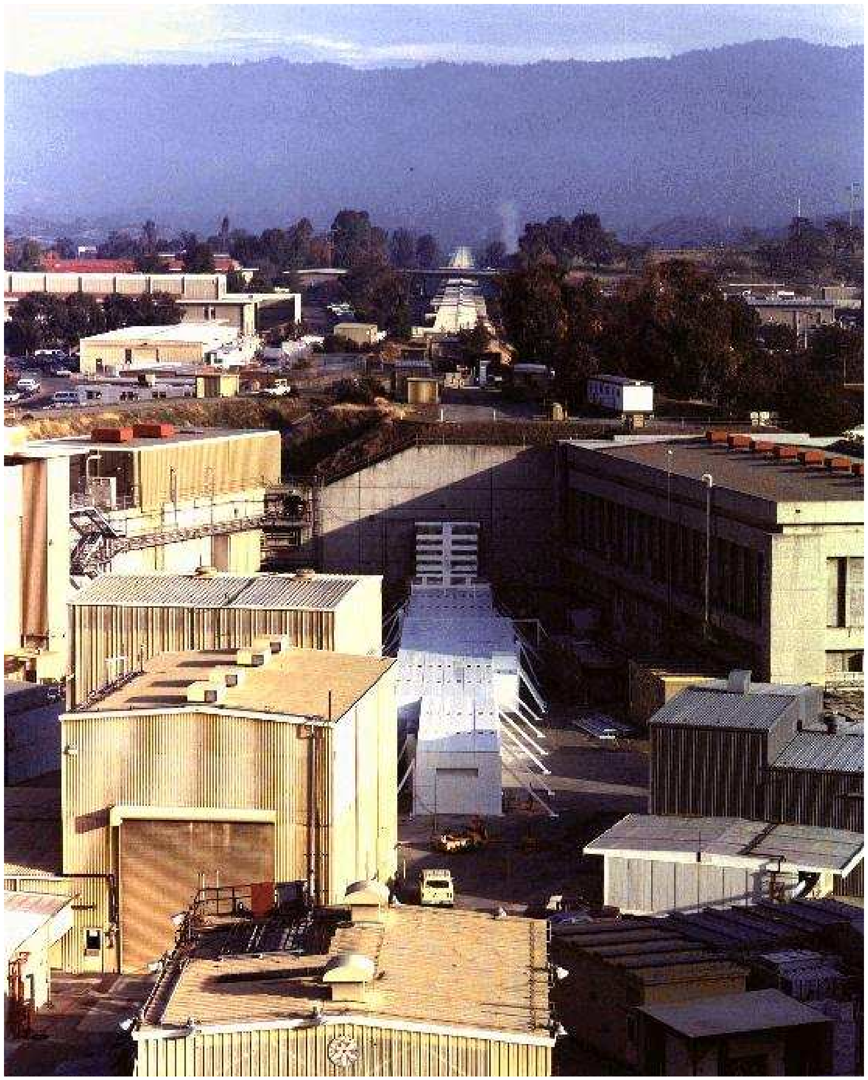
First suggested in 1992

50 GeV e⁻ E - 166 10 MeV γ

International Polarized Positron Collaboration

Final Focus Test Beam (FFTB)→E166

First magnets delivered from Novosibirsk in 1991



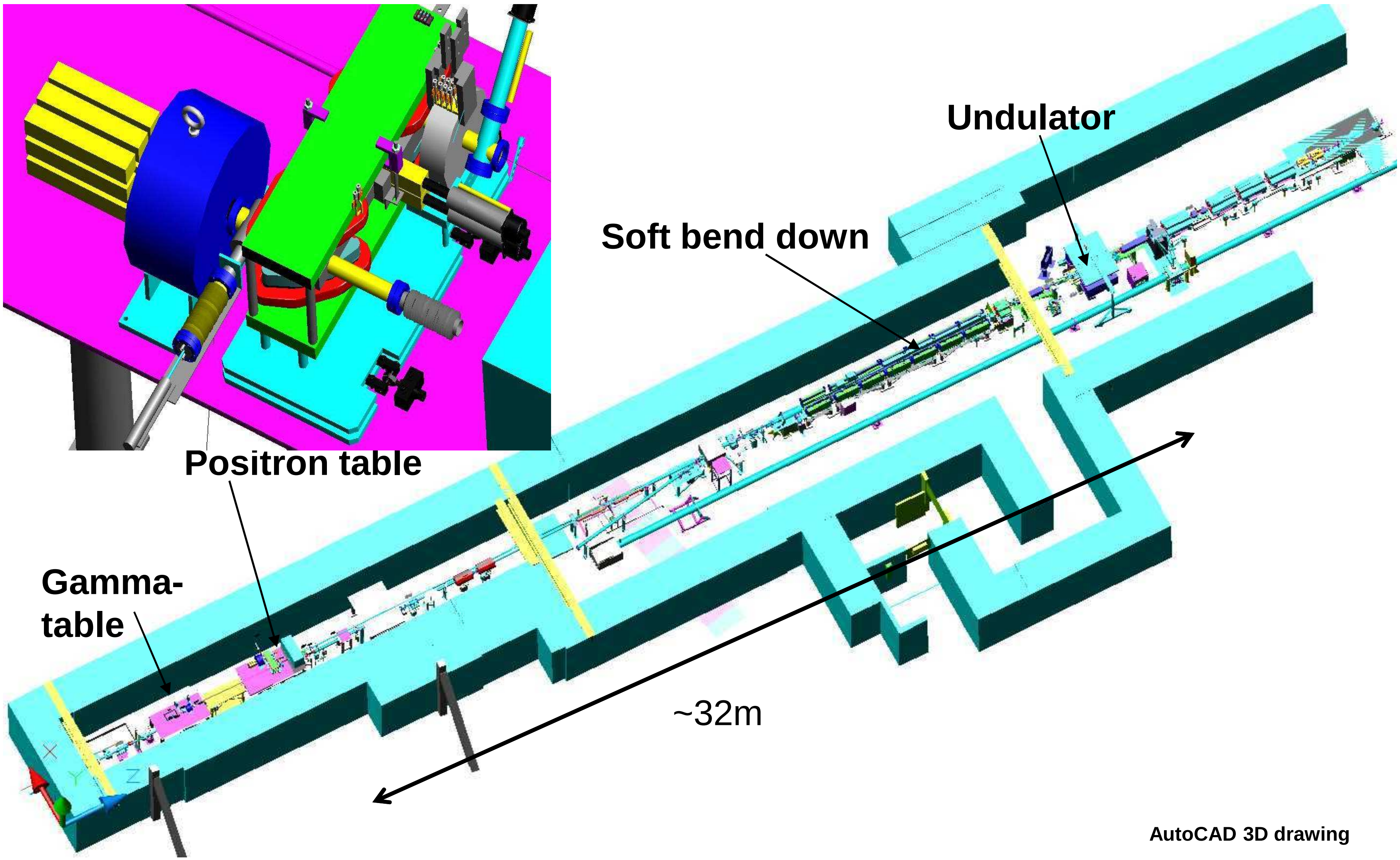
Demonstration of polarized e+ production

FFTB at SLAC with 50 GeV, $2x10^{10}$ e-/pulse, up to 30 Hz

1 m long helical undulator

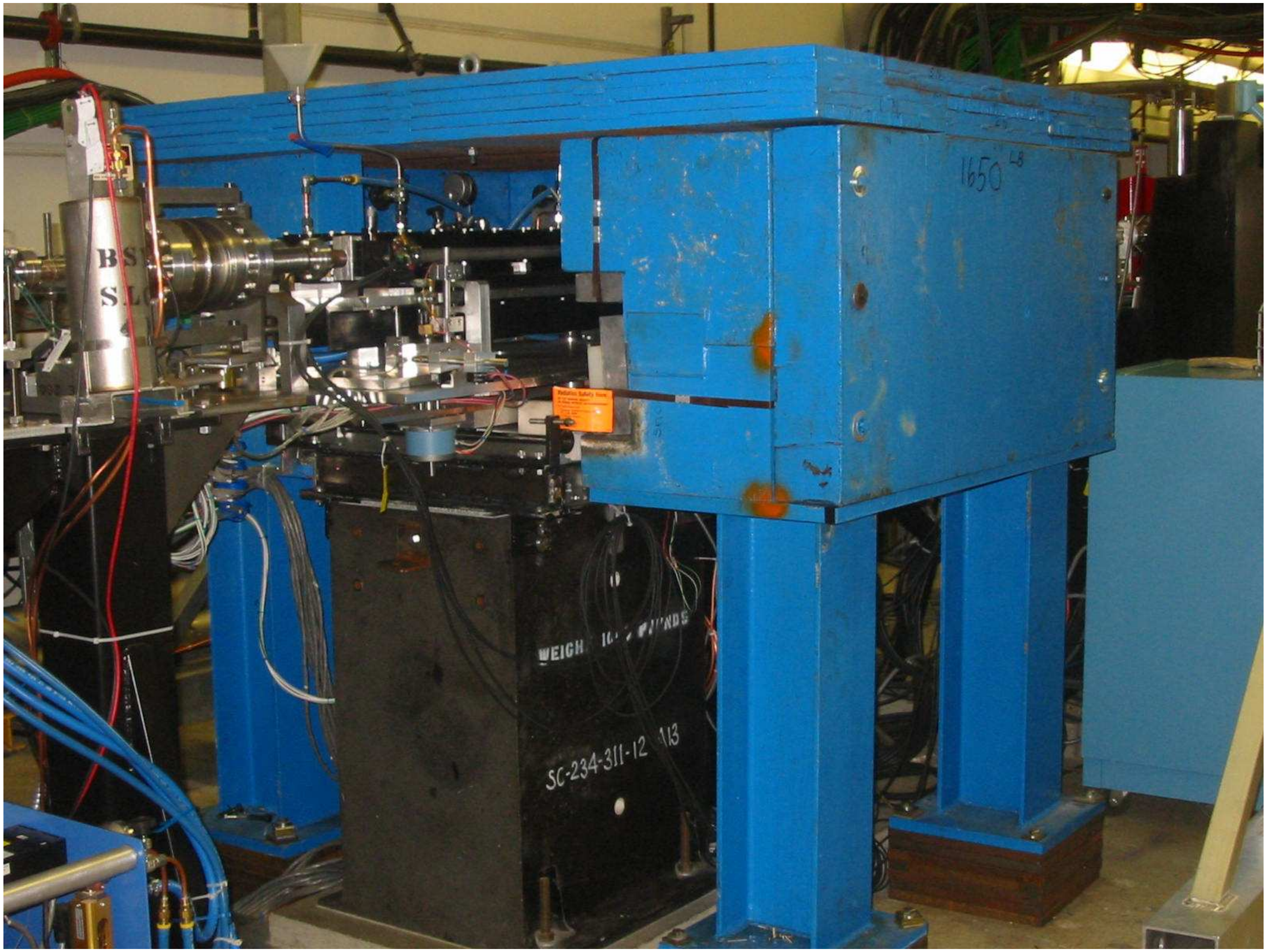
Measurement of positron polarization by Coverting Positrons into gamms again and use Compton helicity-dependet transmission attanuation

3D scope of E-166



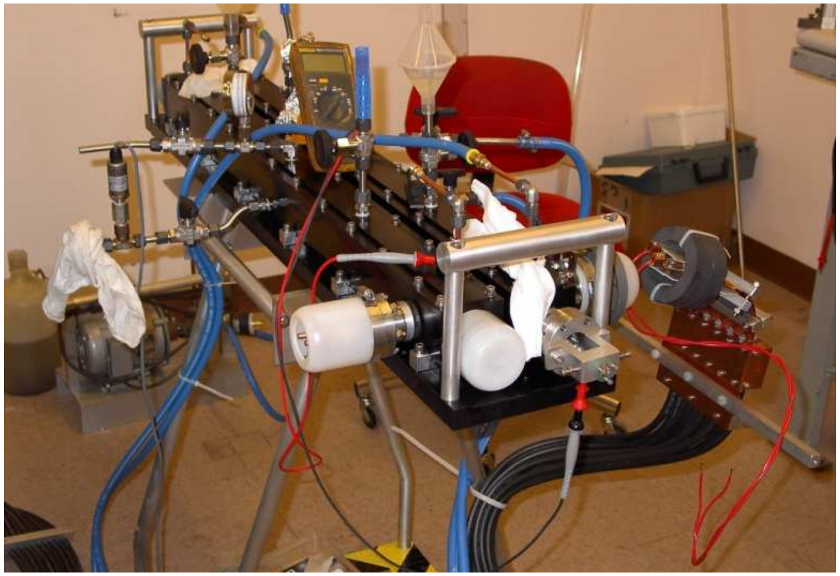
AutoCAD 3D drawing

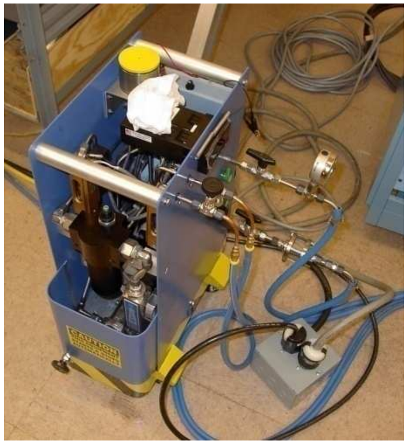
Undulator covered by local shielding

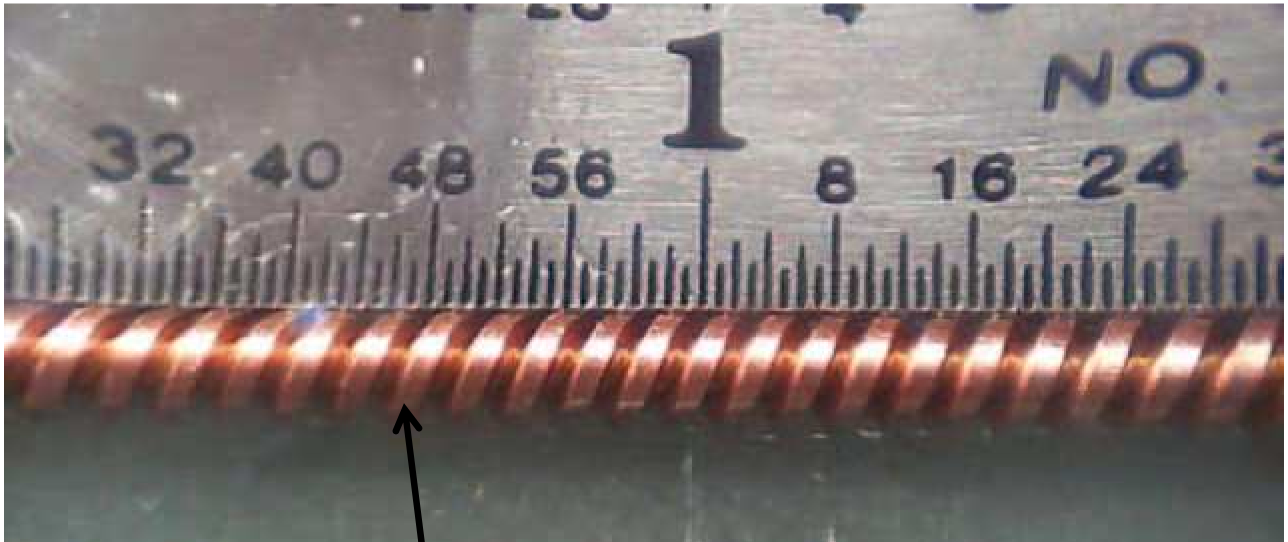


Helical undulator (Cornell)

Coolant-Oil, Ferrofluid



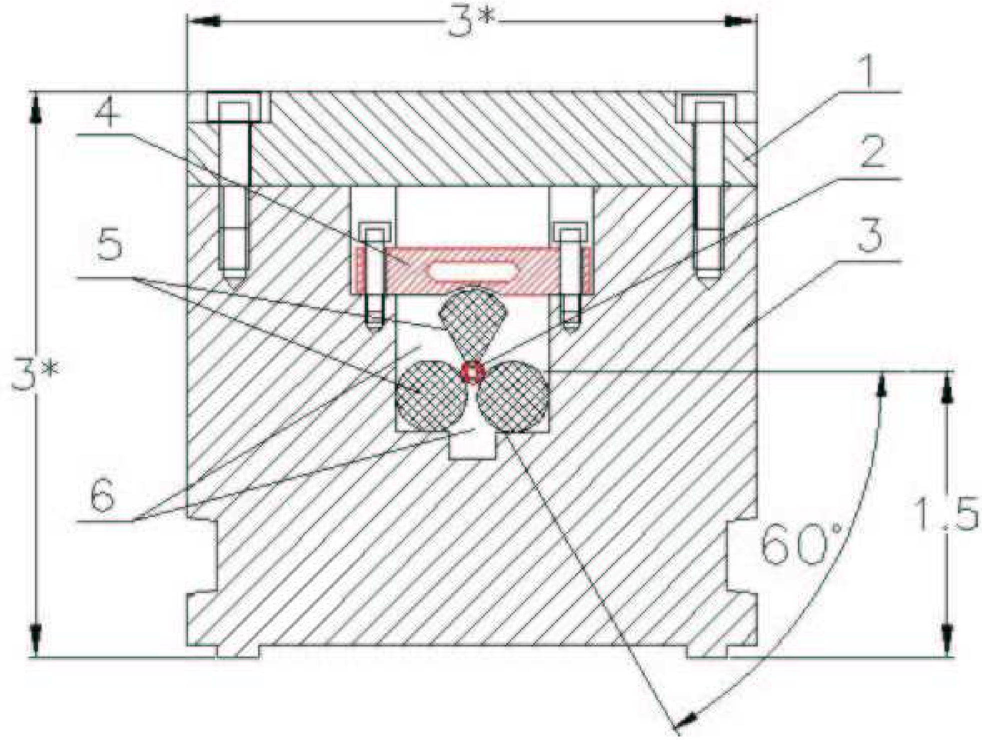




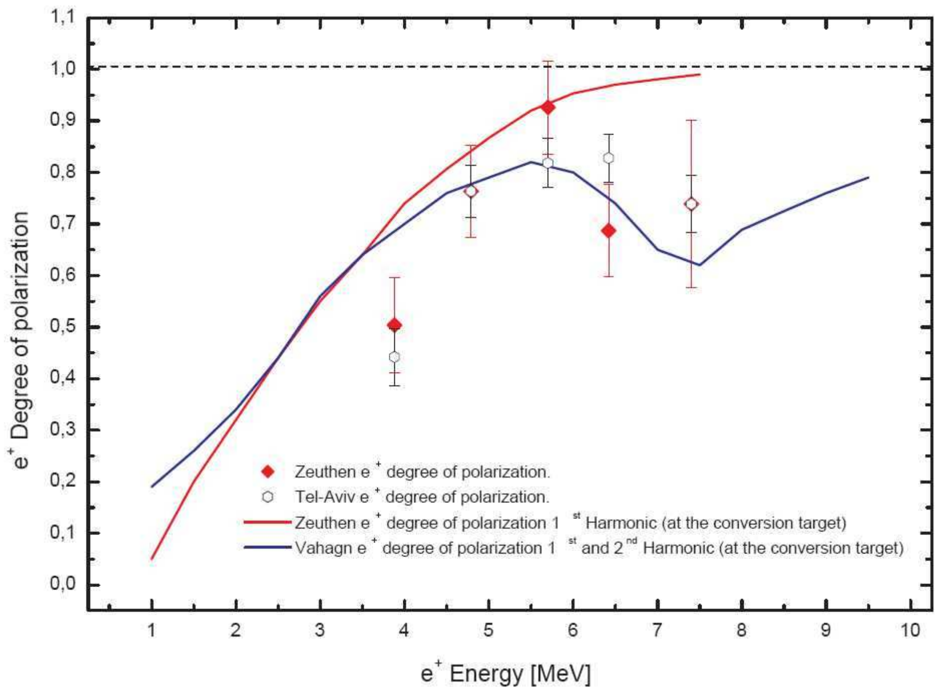
Scaled view on the undulator windings. Wire with rectangular cross-section has dimensions 0.6 × 0.6mm^2, period -2.54 mm.

Pulsed urrent up to 2.3 kA in a wire.

Smallest scale division is 1/64 of an inch.



Cross-section of undulator. Two G10 rods are placed in corners of long groove. Third rod with help of spring loading bars 4 compresses the windings to the other two. 1 -is a cover, 2 -is bi-helix. 3 -is a undulator mount, 5 -are G10 rods, 6 -is filled with coolant. Parts 1, 3 are made from Aluminum. Dimensions are given in inches. Undulator cover 1 is sealed with Indium gasket.

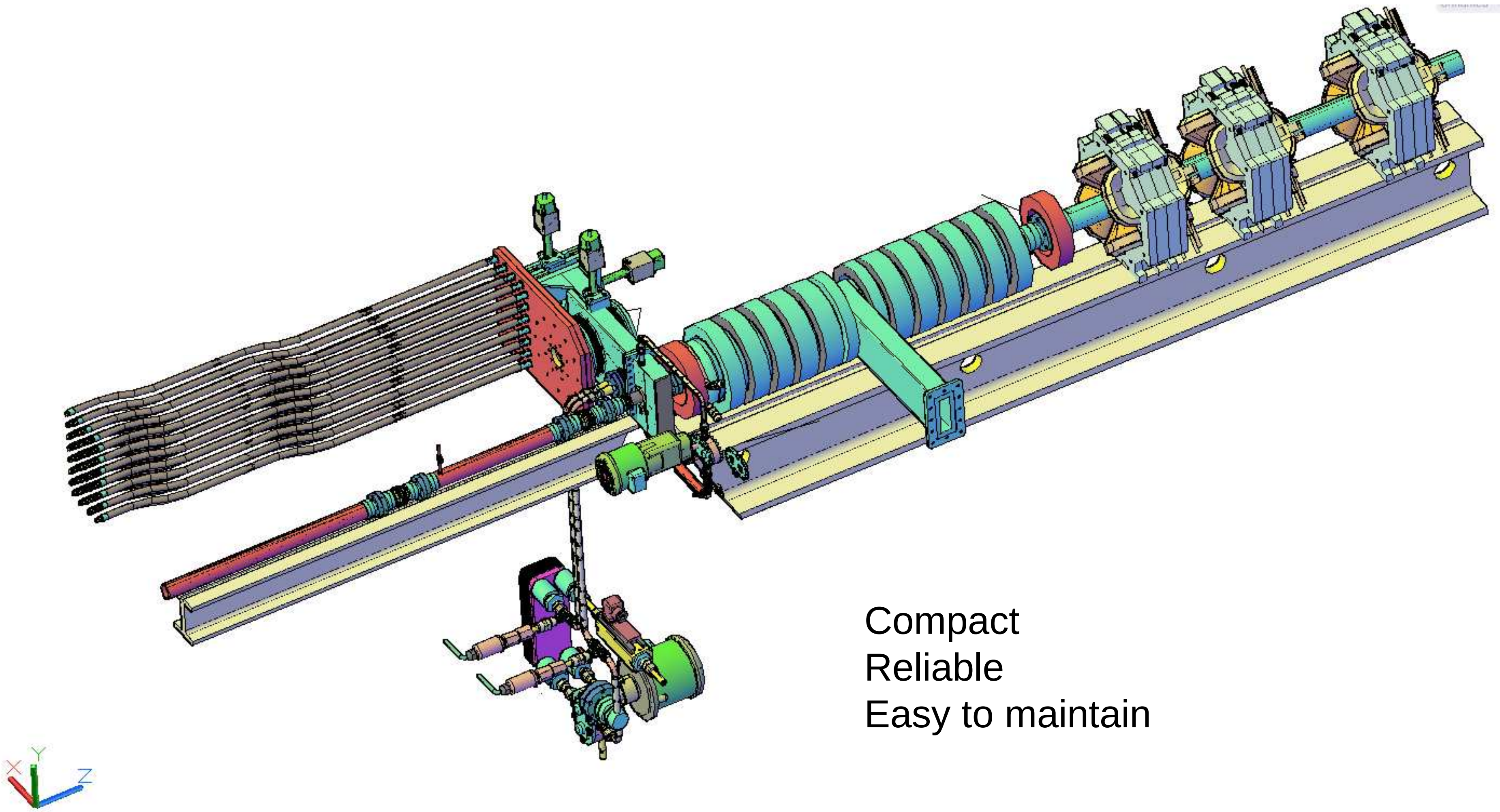


Degree of longitudinal polarization for positrons and electrons as measured by the E166 experiment.

Results published in PRL,NIM

8.PERSPECTIVES

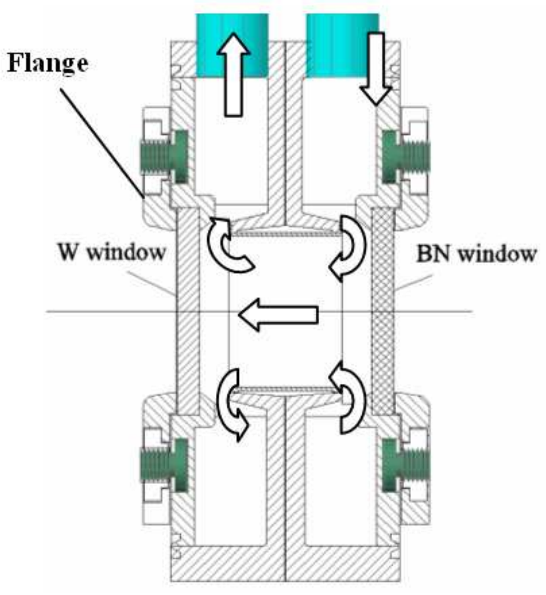
Conversion system with liquid Pb/Bi target and liquid Lithium lens



Compact
Reliable
Easy to maintain

COMBINED TARGET-COLLECTION SYSTEM FOR THE POSITRON PRODUCTION IN ILC,

A.Mikhailichenko, PAC11, THP076, NY 2011



Beam energy, GeV	100	150	250
Length of undulator, m	220	170	170
K factor	0.66	0.36	0.28
Period of undulator, cm	1	1	1
Distance to the target, m	200	350	600
Thick. of target/X_o	0.55	0.57	0.6
Radius of lens, cm	0.6	0.6	0.6
Gradient, kG/cm	60	60	65
Length of the lens, cm	0.7	0.7	0.7
Current, kA	108	108	117
Radius of collimator, cm	0.2	0.5	0.15
Rad, of irises in RF, cm	3	3	3
Rad of coll. before RF, cm	2	2	2
Acceptance, MeVxcm	9	9	9
Energy filter E> , MeV	51	54	63
Energy filter E< , MeV	110	110	180
ΔT per train 10^13 e-, ºC	172	139	270
ΔT in lens from beam, ºC	18	35	80
ΔT in lens from current, ºC	90	90	100
Efficiency, e+/e-	1.52	1.57	1.52
Polarization, %	54	57	64

9. SUMMARY

- **Liquid metals have wide area for application in ILC positron source**

- Start to end Monte-Carlo simulation code for conversion -KONN confirmed that low *K* factor is possible with focusing by Li lens; $K<0.4$ –big relief for the conversion system

- Utilization of Lithium lens allows Tungsten survival under condition required by ILC with N_e~$2x10^{10}$ with moderate *K*~0.3-0.4 . Thin W target allows better functioning of collection optics (less depth of focusing).

- Lithium lens is well developed technique and the lens with parameters required for ILC is guarantied.

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

- Liquid metal target allows compact design and stability under dynamical load; could comete with spinning rim target.

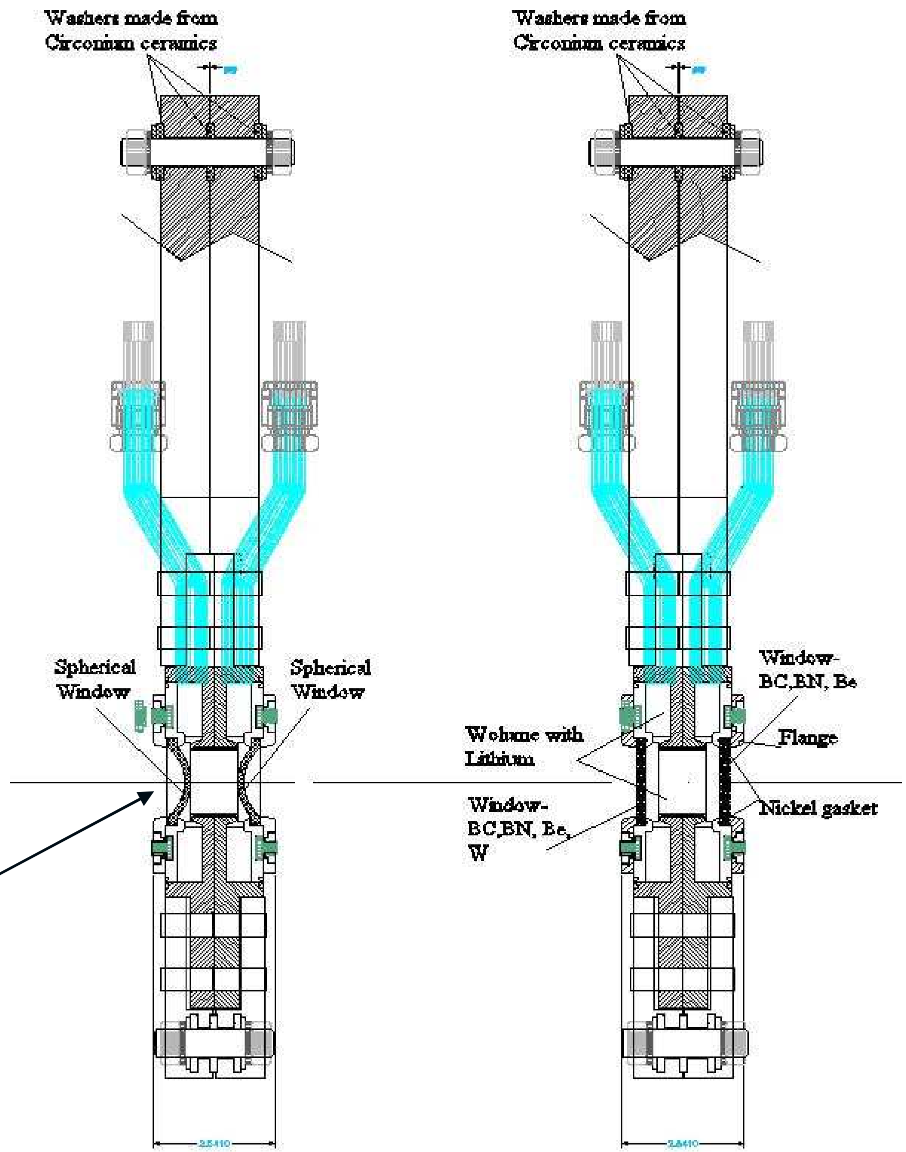
- Combined Lithium lens with W flange can work for ILC; for CLIC all parameters are relaxed.

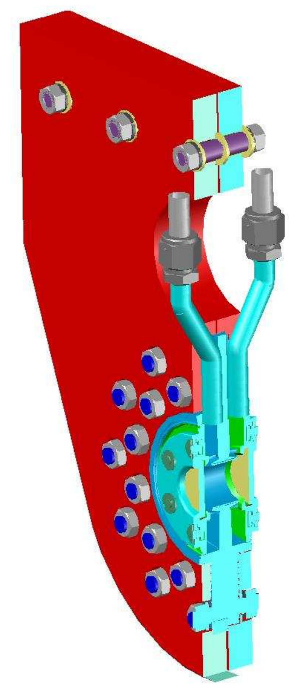
- E-166 confirmed the polarization ~80% achievable with undulator-based positron production scheme for ILC

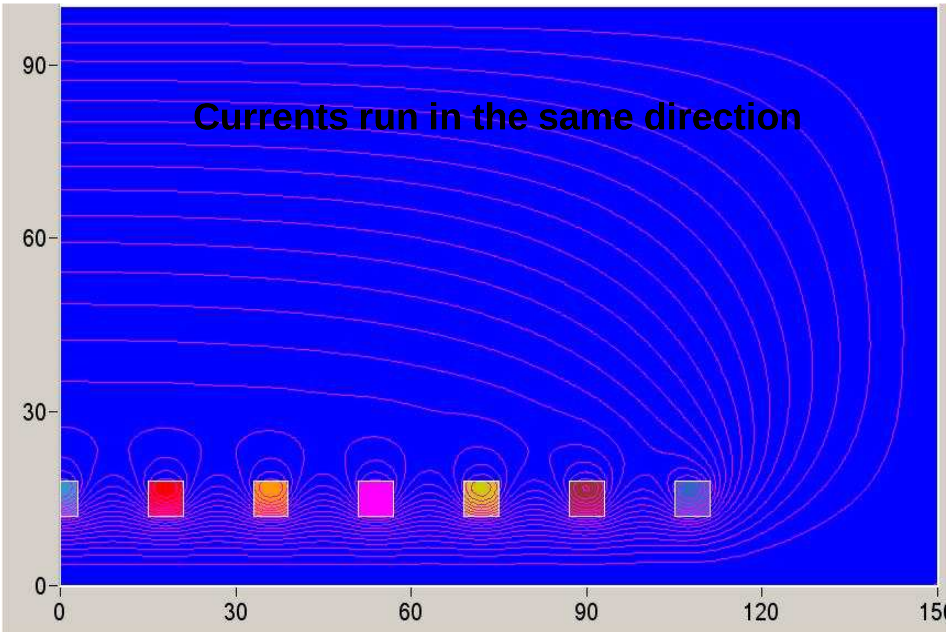
END

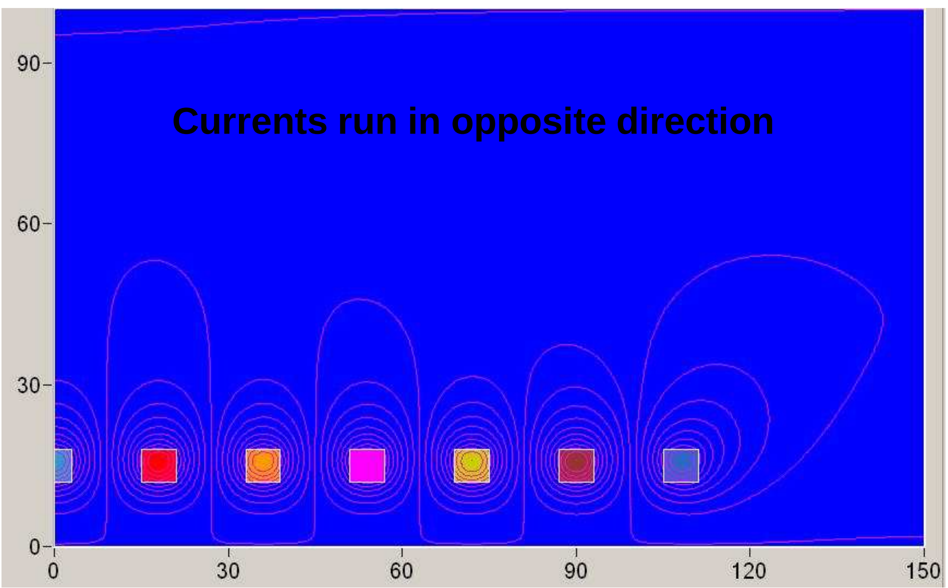
Backup slides

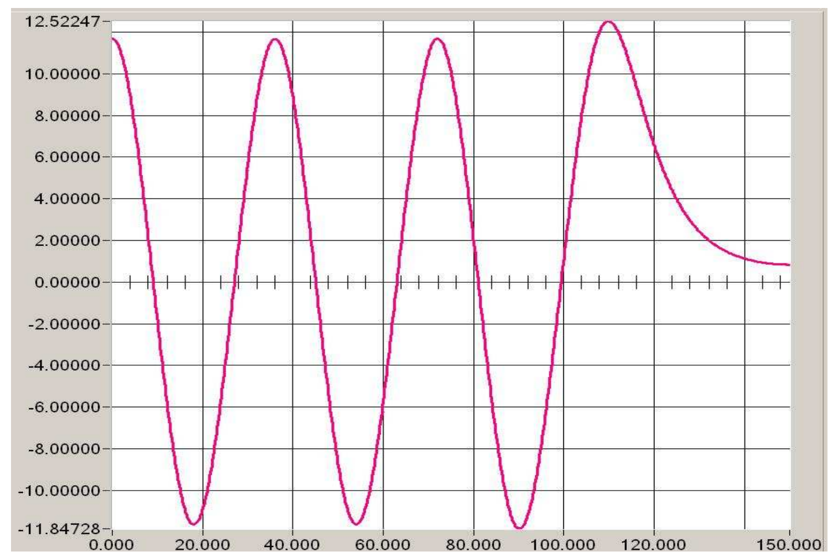
Can be used for compensation of spherical aberrations











Current density ~130A/mm^2; coil cross section is 6x6cm^2 Field in kG

Laser bunch as an undulator

The number of the quantas radiated by an electron by scattering on photons - real from the laser or virtual from the undulator:

$$N_\gamma \cong 4\pi\alpha \frac{L}{\lambda_u}\frac{K^2}{1+K^2} = 4\pi\frac{e^2}{\hbar c}\frac{L}{\lambda_u}\left(\frac{eH\lambda_u}{2\pi mc^2}\right)^2 \approx \left(\frac{e^2}{mc^2}\right)^2 \frac{L\lambda_u}{2\pi\hbar c} H^2 \cong r_0^2 L \frac{H^2}{\hbar\Omega} \cong \sigma_\gamma n_\gamma L$$

$$K = eH\lambda_u / 2\pi mc^2 \cong 0.934 \cdot H[T] \cdot \lambda_u[cm] \quad K = \beta_\perp \gamma \quad \sigma_\gamma \cong \pi r_0^2 \quad n_\gamma \cong \frac{H^2}{\hbar\Omega} \quad \Omega = \frac{2\pi c}{\lambda_u}$$

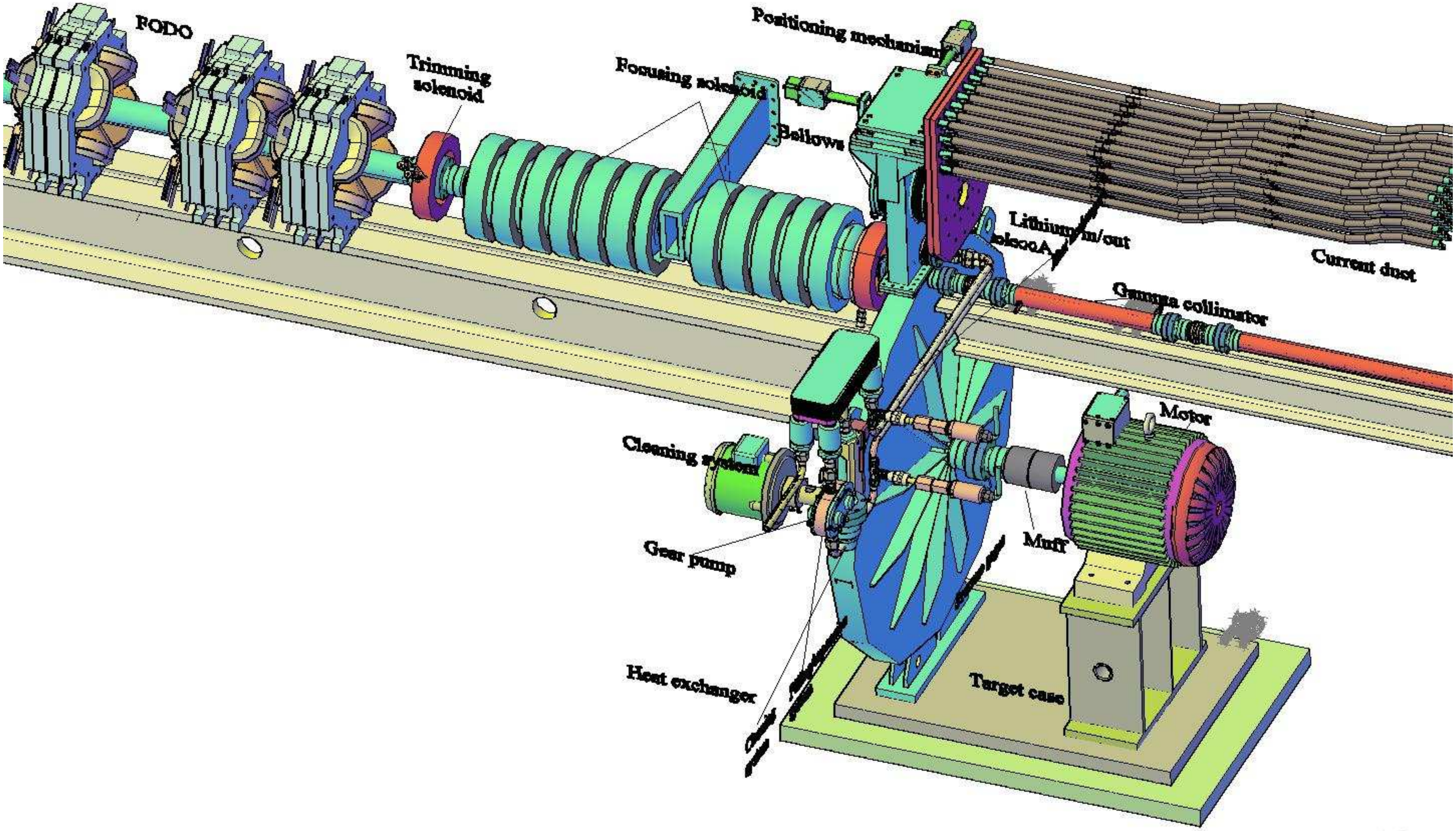
Formation length in undulator $l_f \cong \lambda_u$ L- length of undulator

$$N_\gamma \cong L/\sigma_\gamma n_\gamma = L/l_\gamma$$

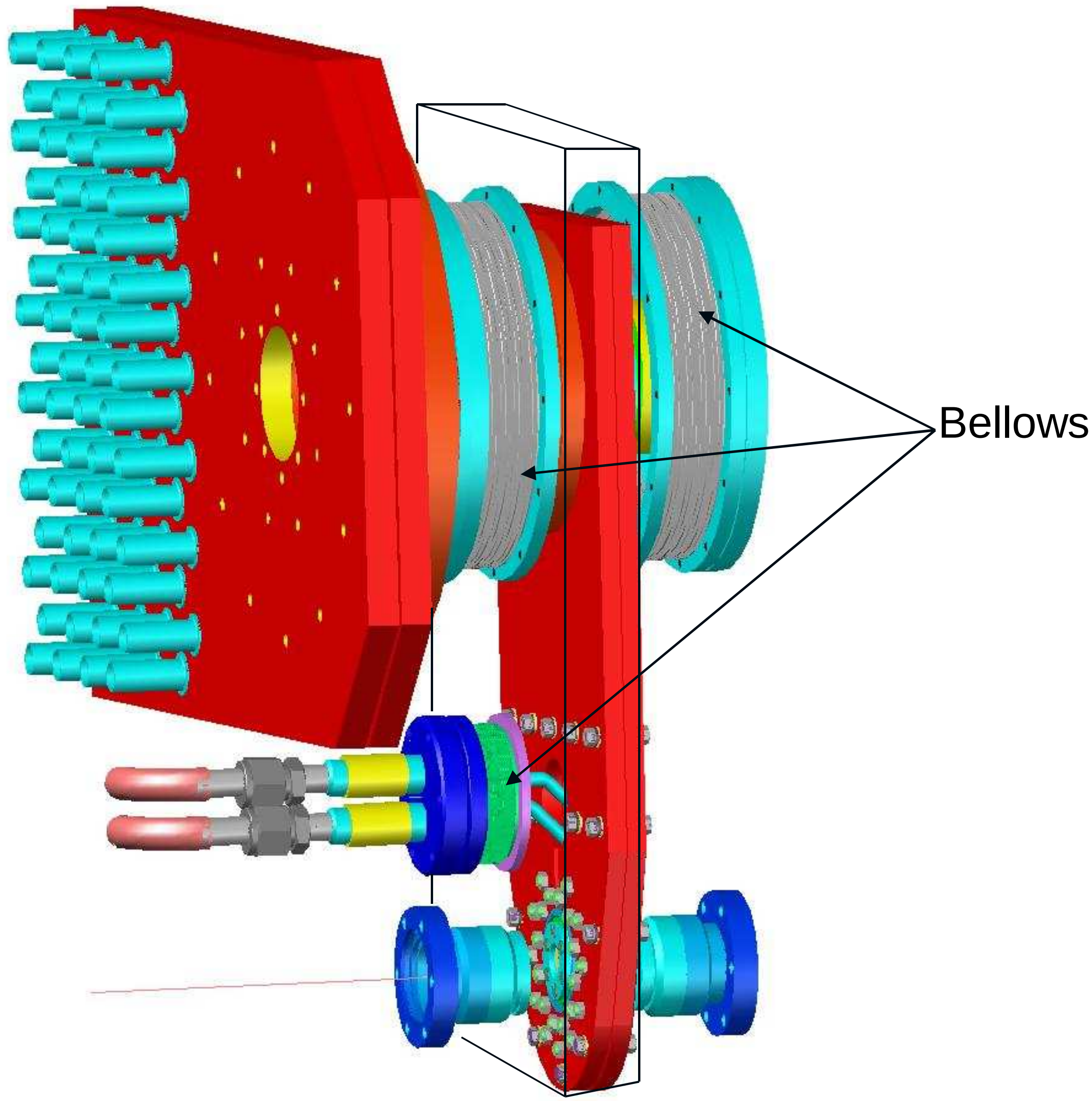
$l_\gamma \cong 1/\sigma_\gamma n_\gamma$ – Length of interaction

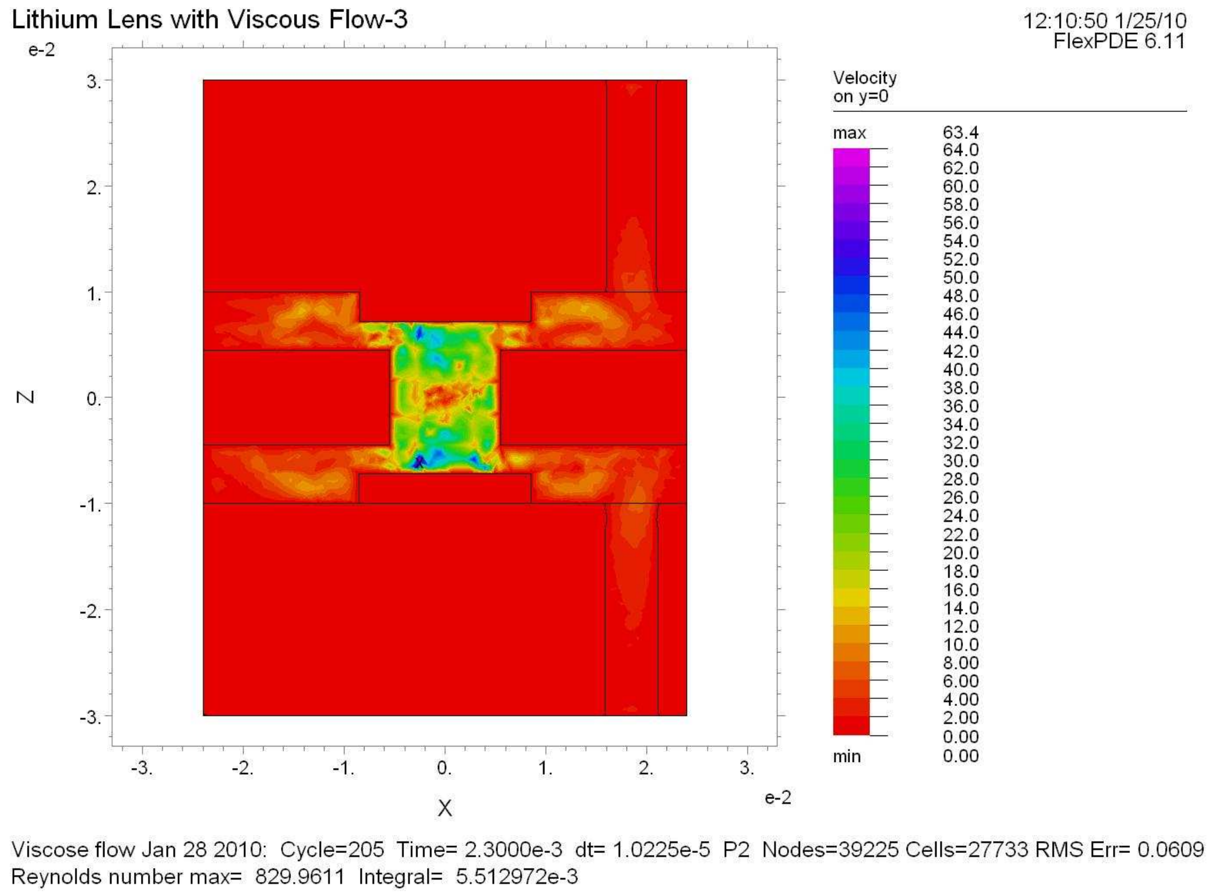
Written in this form it is clear that the photon back scattering (especially with 90^o crossing angle) is an equivalent of radiation in an undulator (as soon as the photon energy is much less, than the energy of particle).

The ILC conversion system with rotating target and the liquid Lithium lens.



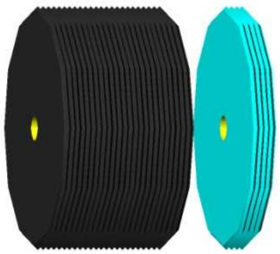
Scaled view on vacuumed feed through and lens; vacuum case not shown





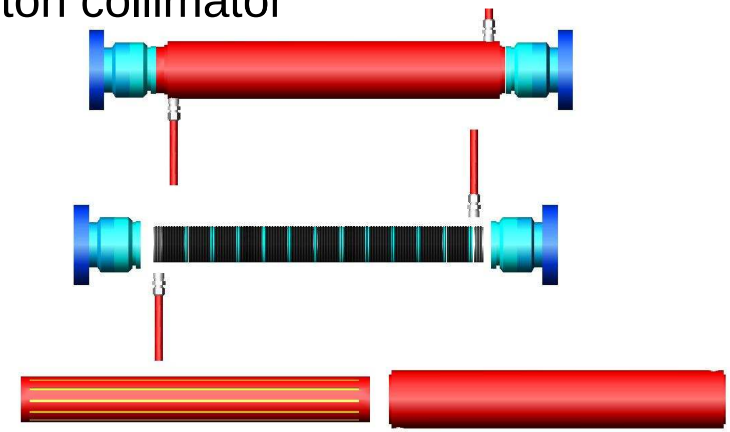
Velocity contour painted. One can see slight asymmetry induced by systematic flow. Turbulence pretty manifested.

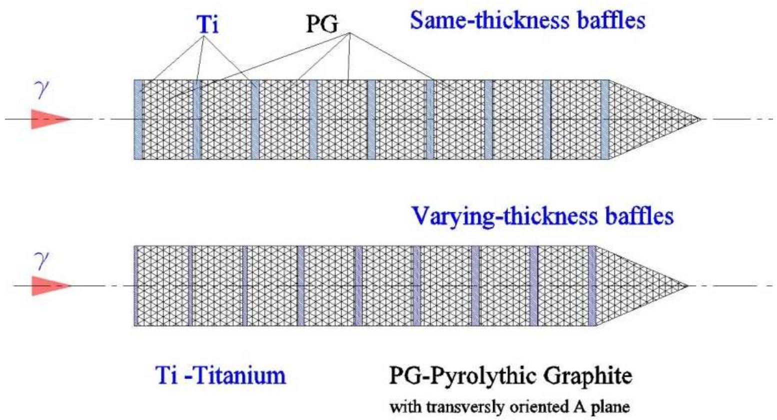
Gamma collimator and gamma absorber (cont.)



PG and Ti spoilers

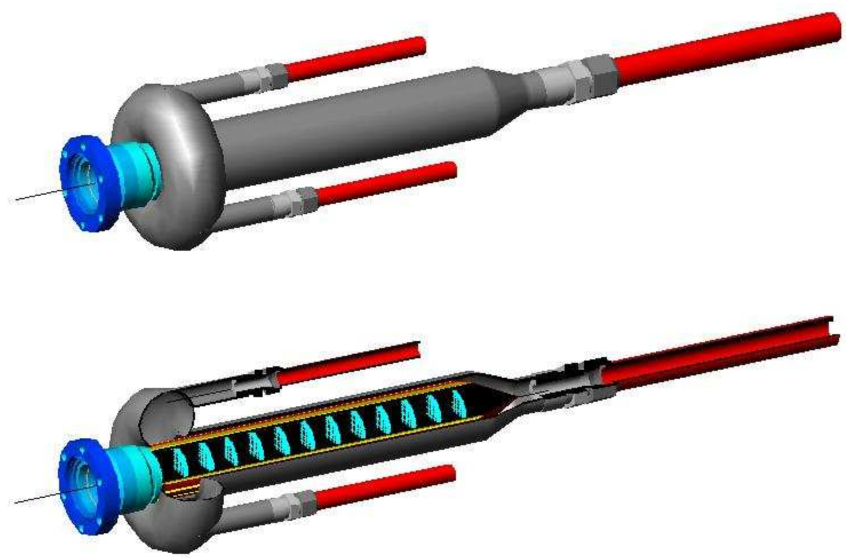
Photon collimator

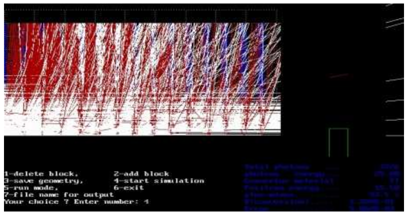




Spoilers with different thickness

Photon beam absorber

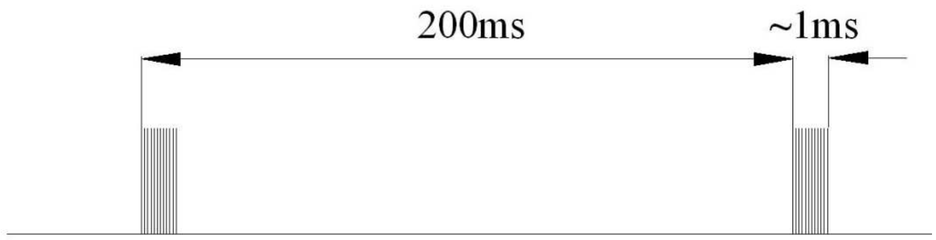




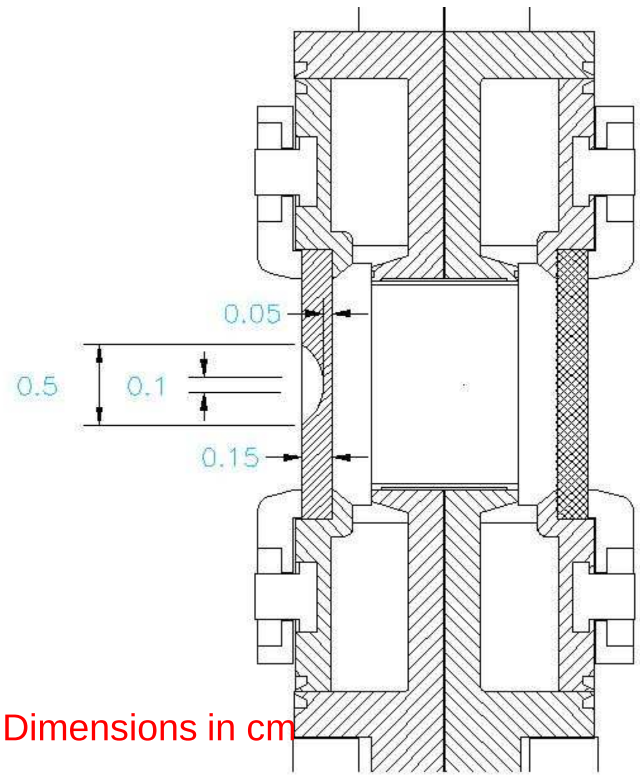
Modeling

For ERL Ti spoilers not required

Beam pattern



Flange with recession has faster relaxation time



Dimensions in cm

Equation for thermal diffusion in window

$$\nabla(k\nabla T)+\dot{Q}=\rho c_V \dot{T}$$

defines time of relaxation from its characteristic

For Be: k=2 $W/cm/^oK$, ρ=1.84g/cm^3 , c_V=1.82 $J/g/^oK$

$$\frac{dx^2}{k}=\frac{dt}{\rho c_V}\rightarrow\quad \delta^2=\frac{k}{\rho c_V}\tau\rightarrow\ \tau=\frac{\rho c_V}{k}\delta^2$$

If δ=0.05cm

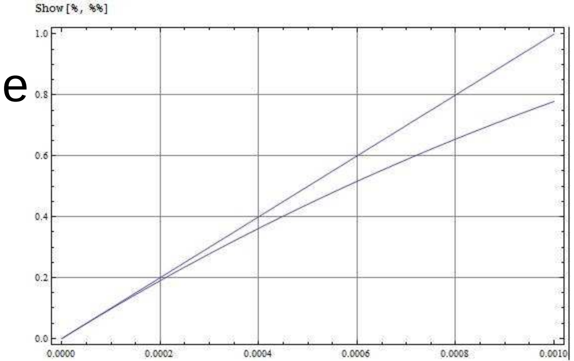
$$\tau=\frac{1.84\cdot 1.82}{2}2.5\cdot 10^{-3}\cong 4.2ms$$

This gives ~20% temperature drop within train for Be

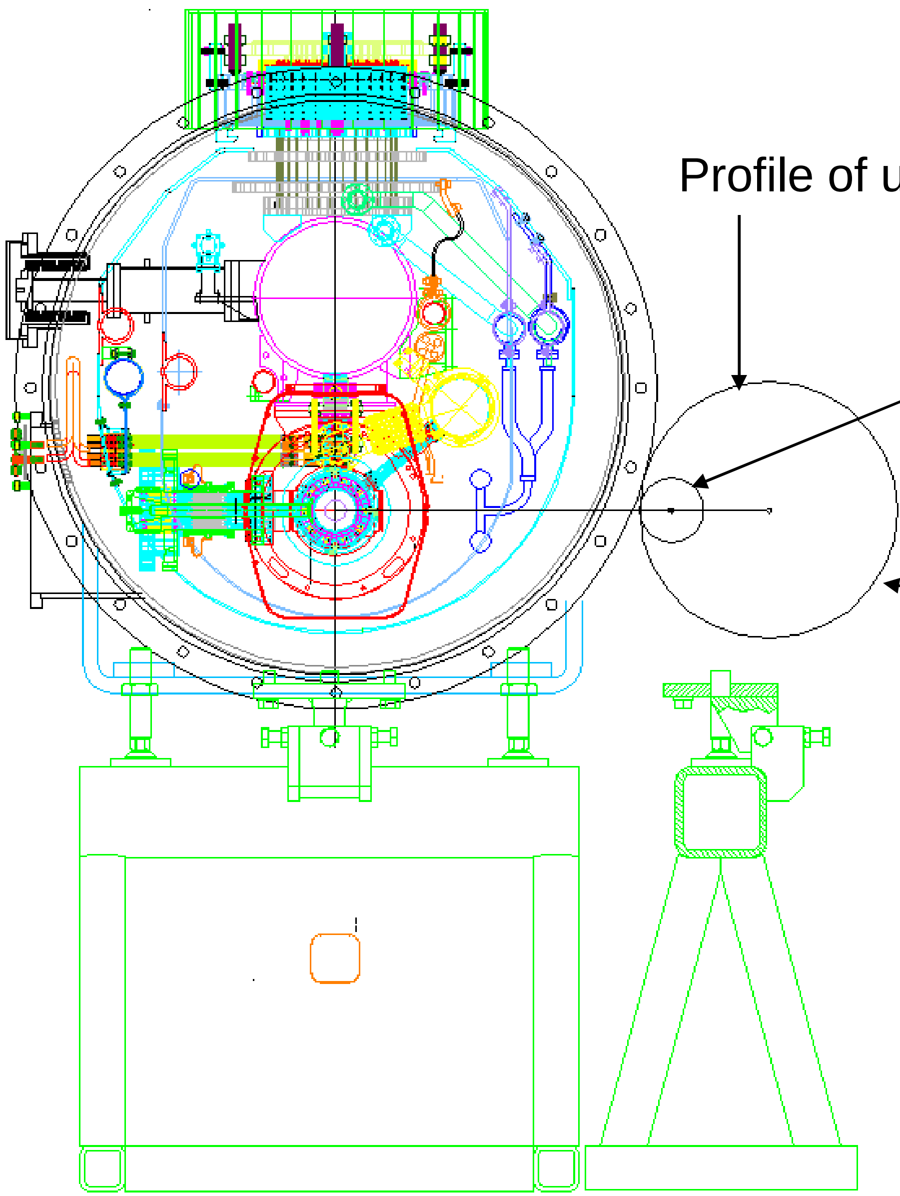
For Li thermal skin-layer for 1 *msec* time goes to

$$\delta=\sqrt{\frac{k}{\rho c_V}\tau}=\sqrt{\frac{0.848}{0.533\text{x}3.6}0.001}=0.021cm$$

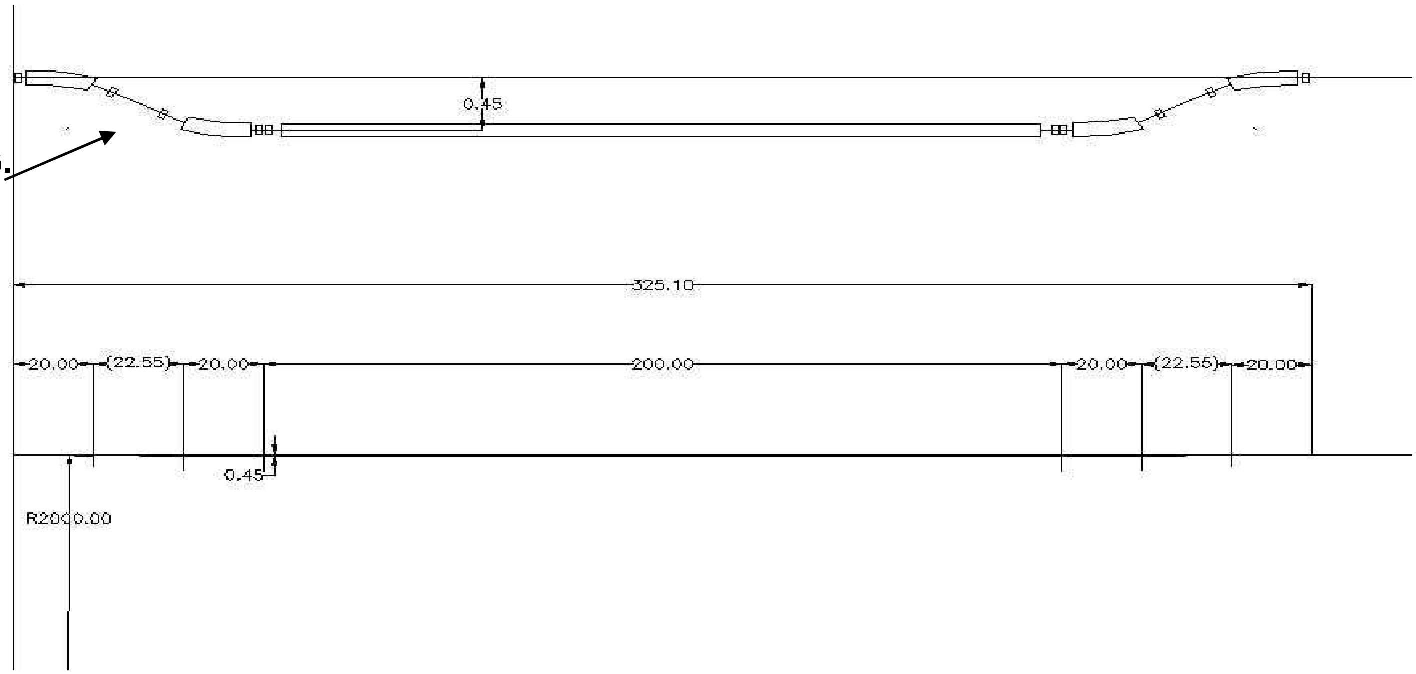
```
τ = 0.001
m = 4.
Plot[t/τ * e^(-t/τ 1/m), {t, 0, τ}, Frame → True, GridLines → Automatic]
Plot[t/τ, {t, 0, τ}, Frame → True, GridLines → Automatic]
Show[%, %%]
```



WHAT IS THE MINIMAL SPACING?



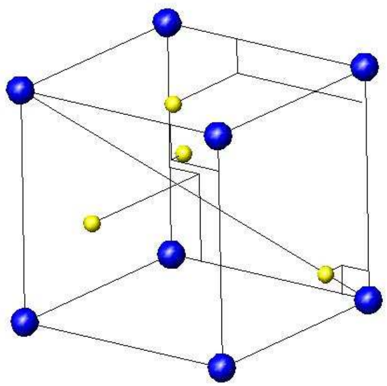
V.V. Vladimirsky, D.G. Koshkarev,1958



Very high density of SR in any bending magnet, as emittance is extremely small

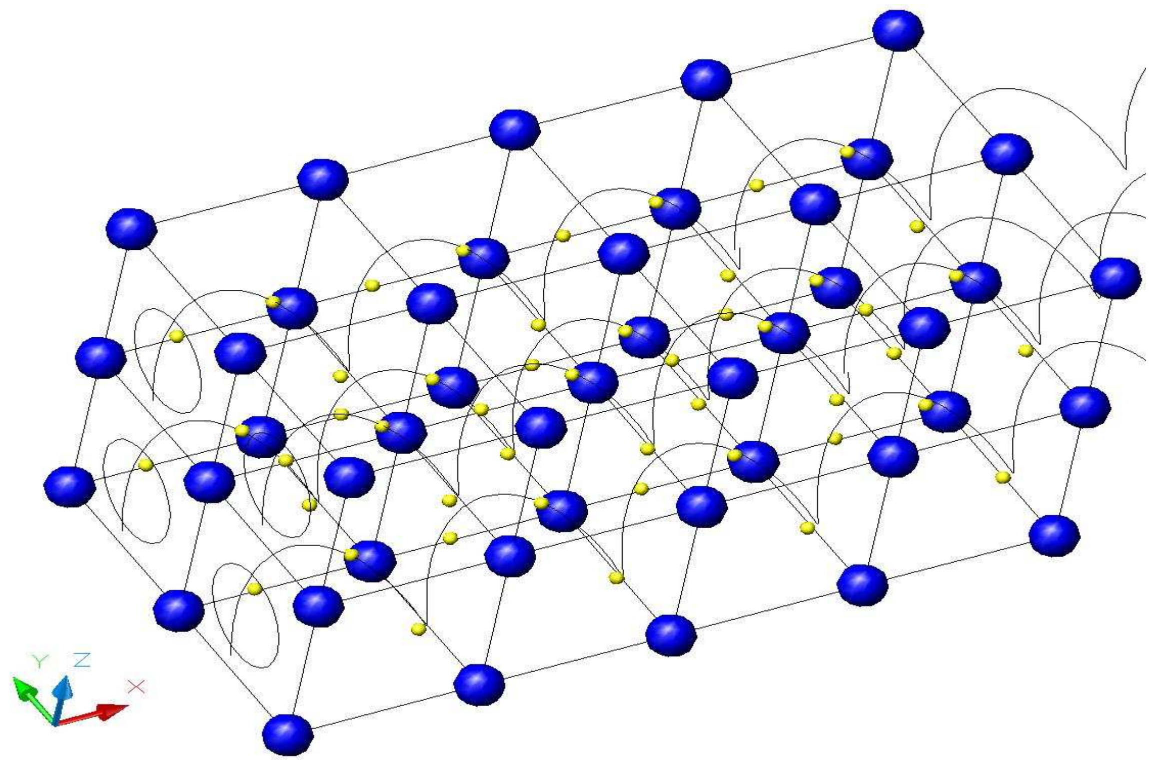
T.A.Vsevolojskaya, A.A.Mikhailichenko, G.I Silvestrov, A.N. Cherniakin, "*To the Project of Conversion System for Obtaining Polarized Beams at VLEPP Complex*", internal report BINP, Novosibirsk, 1986.

Helical (chiral) crystals



Crystal structure MnSi and FeGe

P.Bak, M.H.Jensen, J.Phys.C: Solid St.Physics, 13,(1980) L881-5

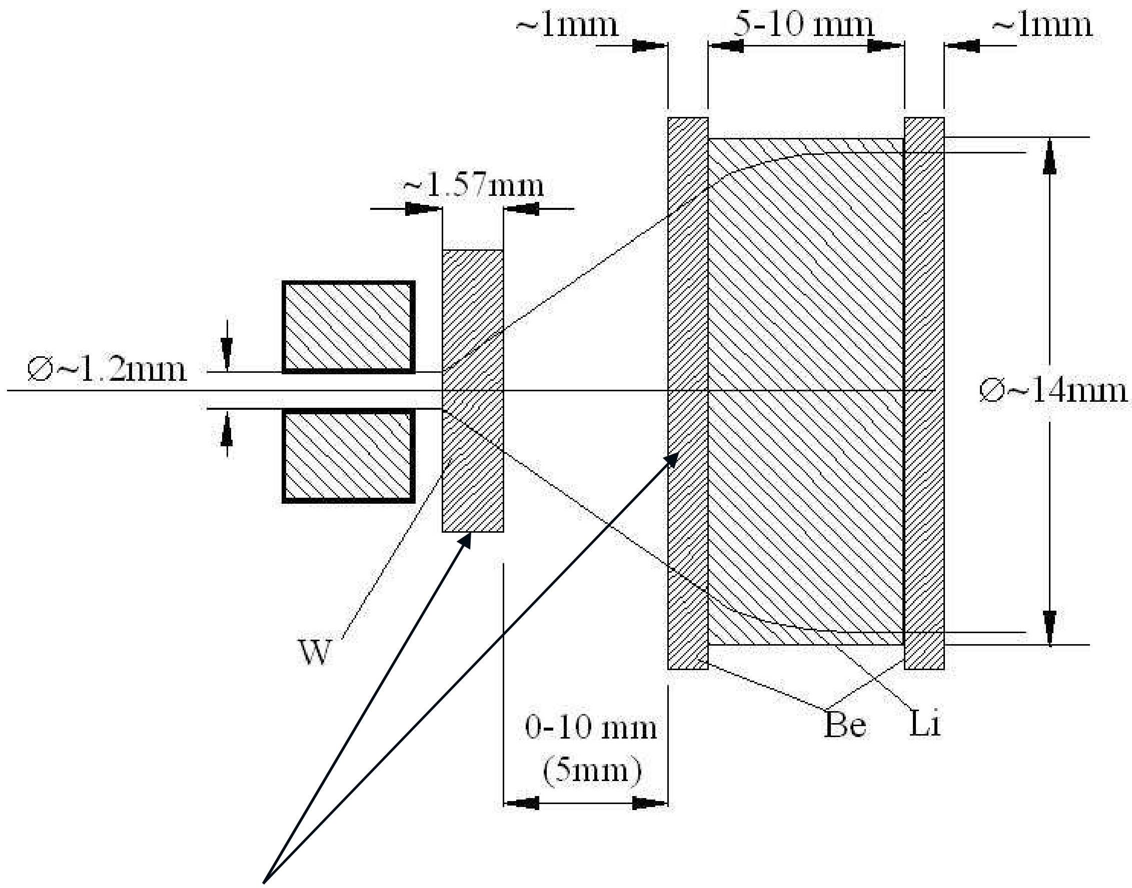


Helical structure demonstrates also $CsCuCl_3$, $Ba_2CuGe_2O_7$, MnS_2

KONN –Monte-Carlo code for positron production starting from undulator

KONN can calculate now the energy deposition and temperature rise in target and in Li lens at any point.

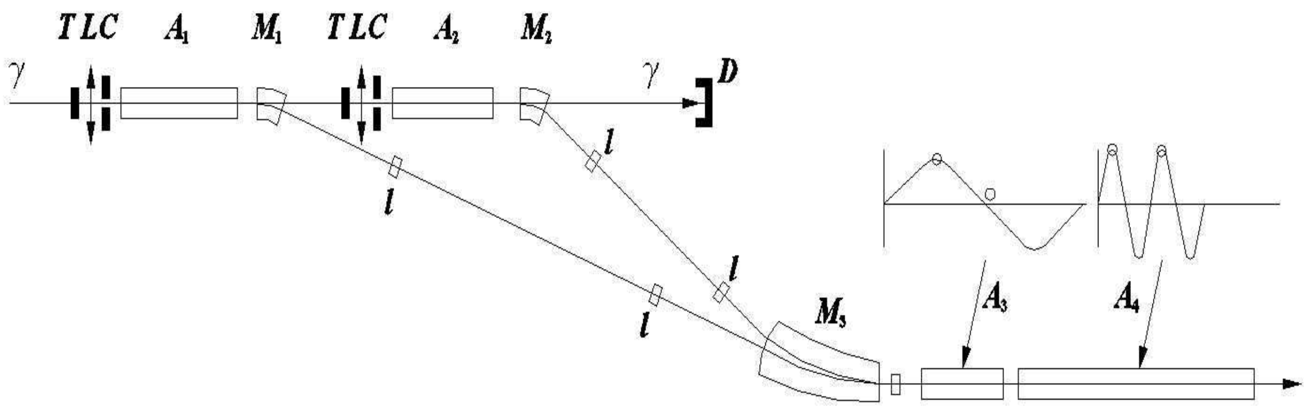
Distance between target and the lens serves for enlargement the spot size on the entrance window



←Typical parameters

Target could be combined with entrance flange

COMBINING SCHEME



Energy provided by acceleration structures *A*1 and *A*2 are slightly different, *A*1>*A*2.

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 required for fast dump of coherent motion.

Combining scheme allows ~double positron yield and cut in half the length of undulator→increase of polarization

TESTED UNDULATORS

For aperture available for the beam 8 mm in Ø clear OFC vacuum chamber, RF smoothness

SC wire	54 filaments	56 filaments	56 filaments	56 filaments
# layers	5	6	11	9 (12) +sectioning
λ=10 mm @*300 ºK*	K=0.36 tested	K=0.42 tested	K=0.467 tested	K≈0.5 (calculated)
λ=12 mm@*300 ºK*	K=0.72 tested	K=0.83 tested		K≈1 (calculated)

For aperture available for the beam 6.35 mm (1/4”) in Ø clear OFC vacuum chamber, RF smoothness

# layers	11			12+sectioning
λ=13.5 mm@*300 ºK*	K=1.48 tested			K≈1.6 calculated
λ=10.0 mm@*300 ºK*	K≈0.7calculated			K≈0.72 calculated