ILC UNDULATOR BASED POSITRON SOURCE, TESTS AND SIMULATIONS

Alexander Mikhailichenko
Cornell University, LEPP, Ithaca, NY 14853

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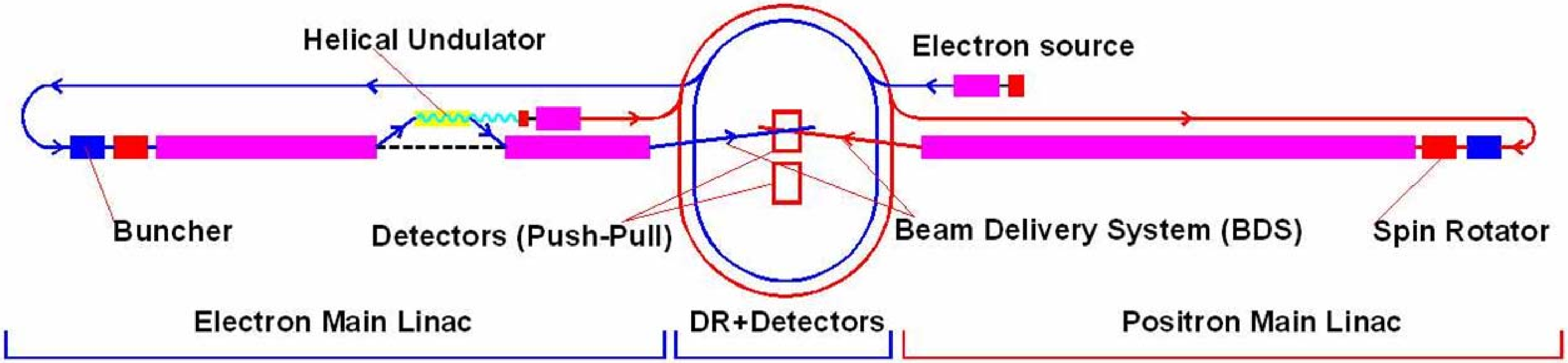
POSITRON SOURCE FOR ILC

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

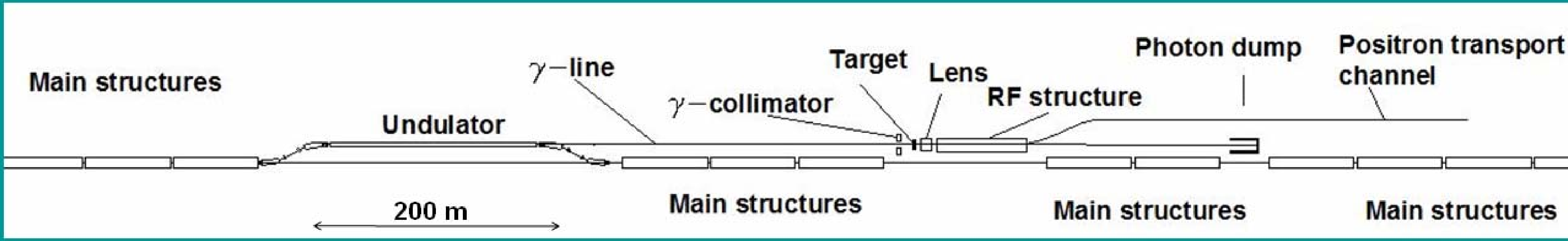


Main advantage of this scheme is that it allows **POLARIZED** >60% positron production

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

Positron source is a complex system which includes a lot of different components and each of these components could be a subject of a separate talk

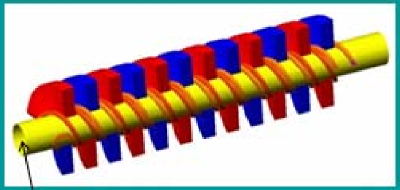
MORE DETAILED VIEW TO THE POSITRON SOURCE

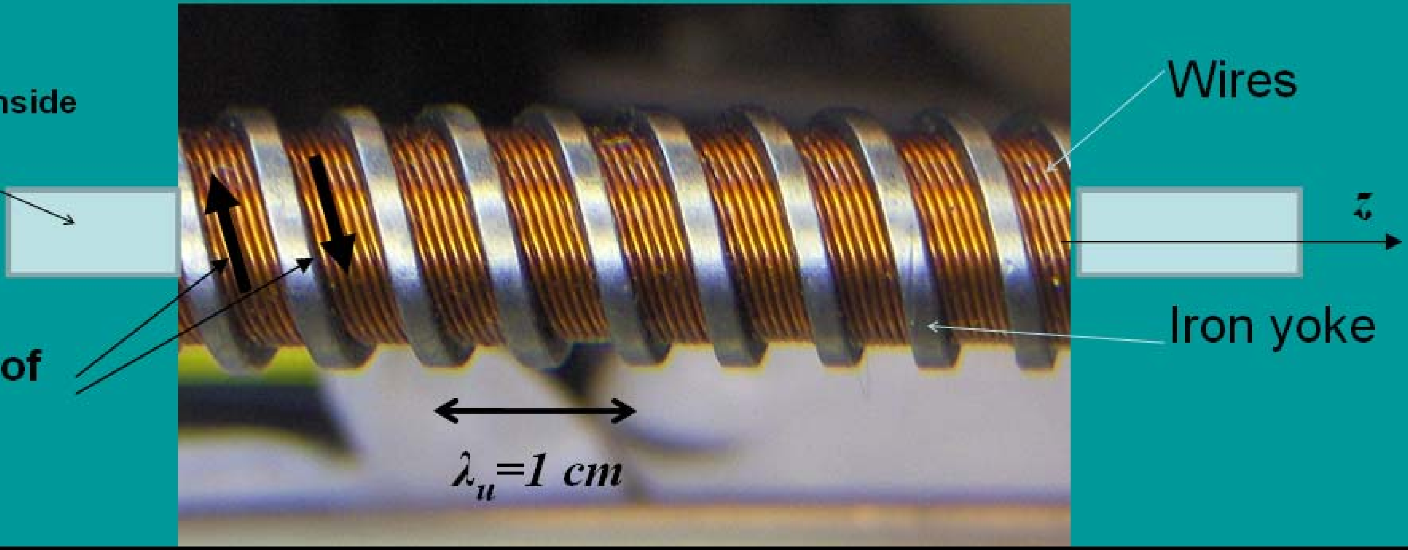


Helical undulator is a device for generation magnetic field of a type

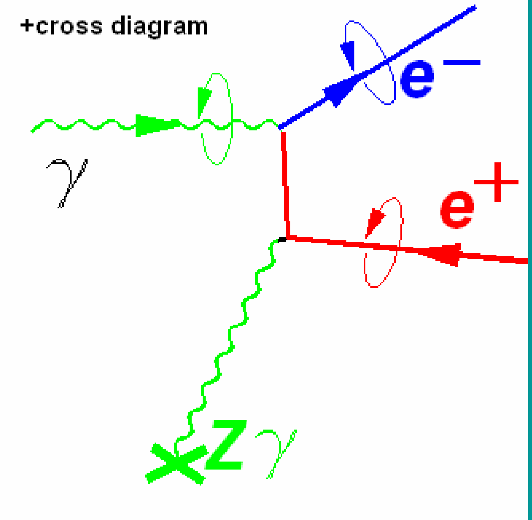
$$\vec{H}_\perp(z) = \vec{e}_x H_{xm} Cos\frac{2\pi z}{\lambda_u} + \vec{e}_y H_{ym} Sin\frac{2\pi z}{\lambda_u}$$

Radius of particle's helix $a \cong eH_\perp \Delta_u^2 / mc^2\gamma$



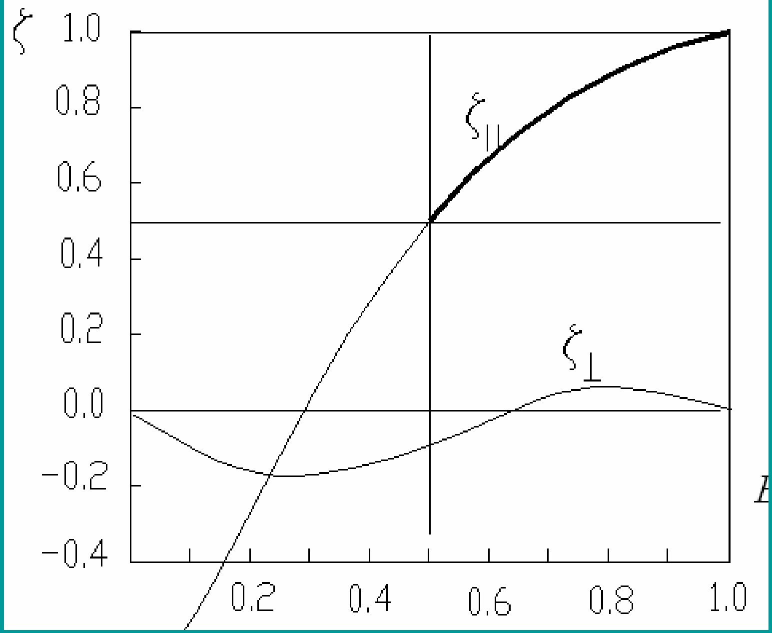


(POLARIZED) POSITRON PRODUCTION



Only gamma quanta can create positron (with electron)

Longitudinal polarization as function of particle's fractional energy $E^+/(E_\gamma-2mc^2)$



H.Olsen, L.Maximon, 1959

Photon polarization

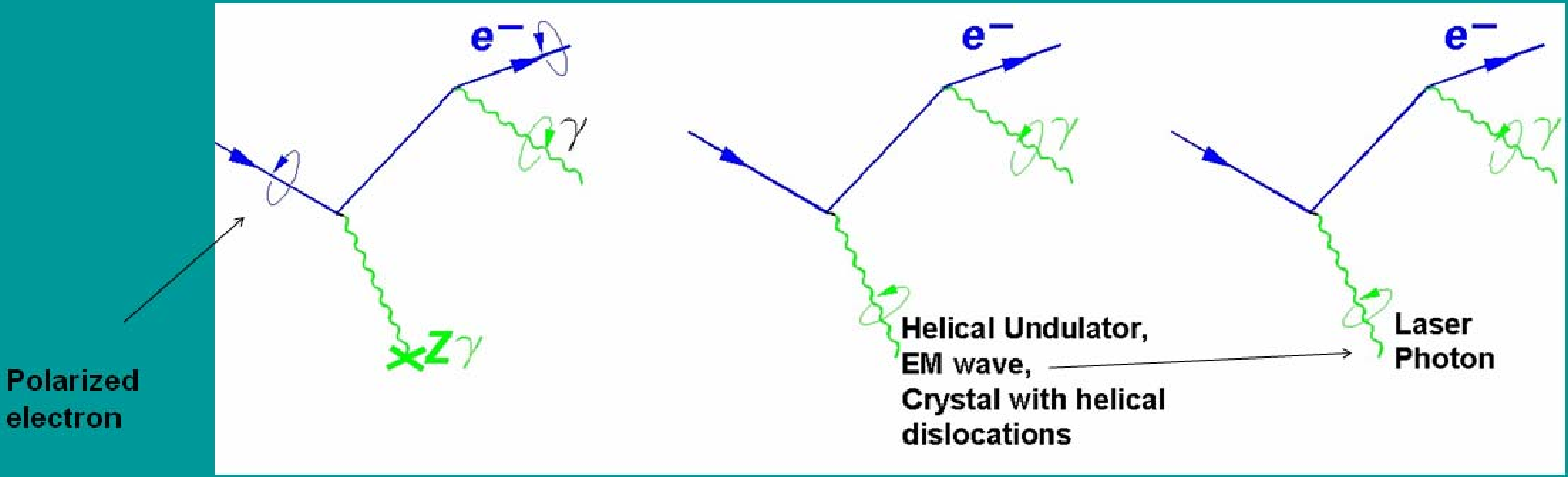
$$\vec{\varsigma} = \xi_2 \cdot \left[f(E_+,E_-) \cdot \vec{n}_\parallel + g(E_+,E_-) \cdot \vec{n}_\perp \right] = \vec{\varsigma}_\parallel + \vec{\varsigma}_\perp$$

Polarization is a result of selection positrons by theirs energy

1996

(1+2) ways to create (circularly polarized) photons in practical amounts

Well known processes reviewed for practical utilization in positron source



Polarized electron

Helical Undulator, EM wave, Crystal with helical dislocations

Laser Photon

E.Bessonov, A.Mikhailichenko,1996

V.Balakin, A. Mikhailichenko, 1979

E.Bessonov, 1992

Efficiencies of these processes are the same

WHY UNDULATOR

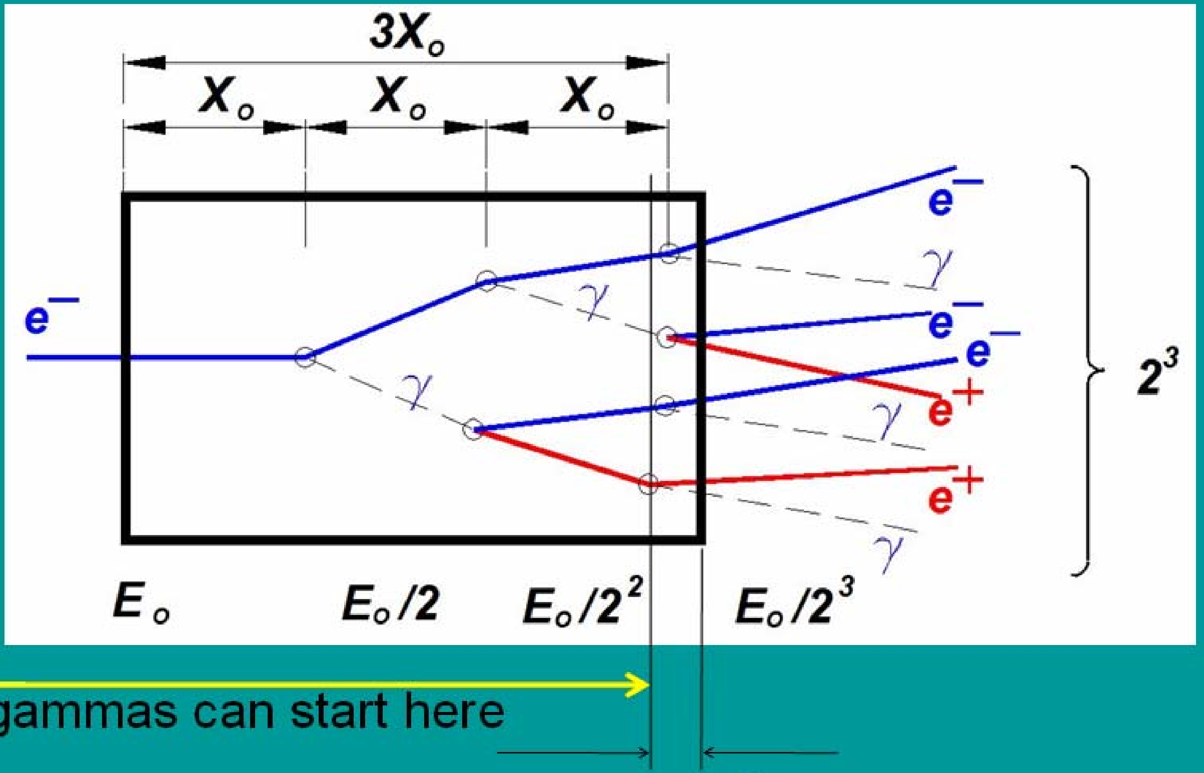
CONVENTIONAL POSITRON SOURCE–CASCADE PROCESS

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

Radiation length

H.Bethe, W.Heitler, 1934

l_{X0}=3.5mm for W; l_{X0}=3.5cm for Ti; l_{X0}=35cm for Li

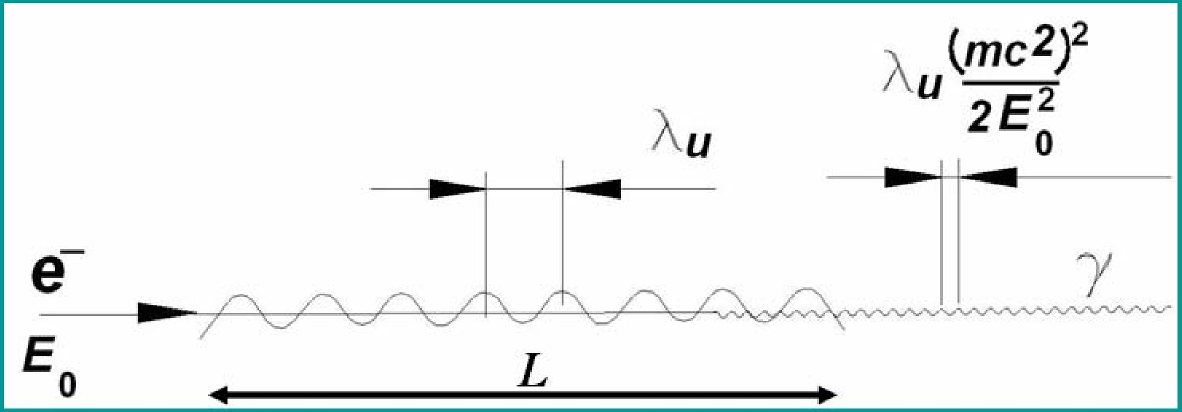


Source of gammas can start here

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

UNDULATOR SOURCE OF GAMMAS

Undulator corresponds to 90° illumination of energetic electron by laser



The number of quants

$$N_\gamma \cong L\sigma_\gamma n_\gamma$$

$$N_\gamma \cong L\tfrac{8\pi}{3}r_0^2\,\frac{H^2}{8\pi\eta c/\Delta_u} \propto 4\pi\alpha\,\frac{L}{\lambda_u}K^2$$

H **-- magnetic field value**

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

Deflection parameter

Energy of quanta, *n*-harmonic number

Angle to observer

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

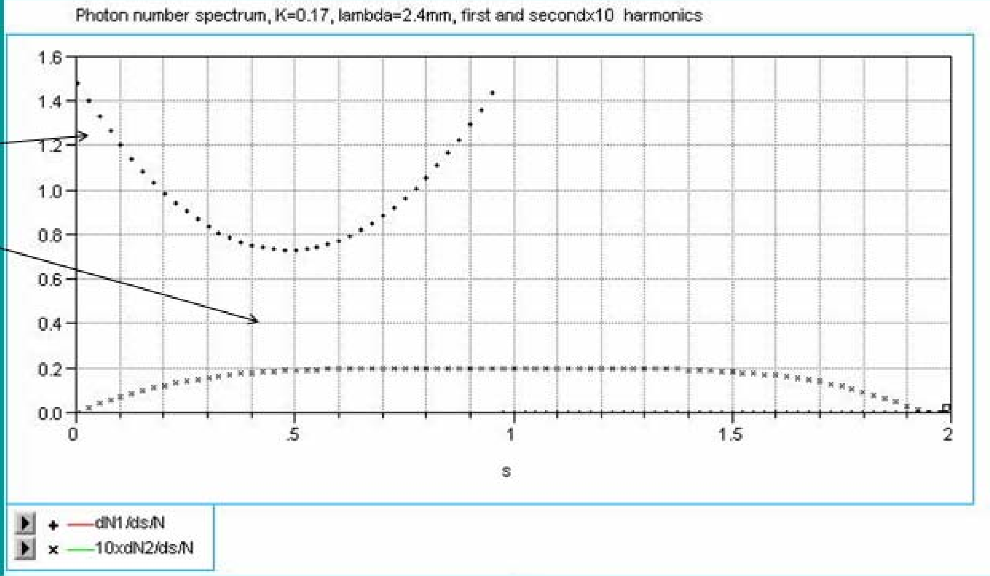
Engendering problems bring period to ~1 cm for given aperture ~8 mm

That is why undulator installed at ~150 GeV line, where E_γ~20 MeV

Analytical calculations of conversion

Spectral density of radiation

$$\frac{dN_\gamma}{dE_\gamma} = \sum_n \frac{dN_{\gamma n}}{dE_\gamma} = \frac{\alpha K^2 L}{\eta c 2\gamma^2} \sum_{n=1}^{\infty} F_n(K, \frac{E_{\gamma n}}{E_{\gamma \max}})$$



The number of positrons generated by a single photon in the target becomes

$$\frac{dN_+}{dE_+ d\tau} \cong 0.4 \frac{\alpha K^2 L}{\gamma^2 \eta c} \frac{7}{9} (1 - E / E_{\gamma 1})(1 - e^{-7\tau/9})$$

For E_0=150 *GeV*, L=150 *m*,
K^2=0.1, τ=0.5 (rad units)

$$\frac{1}{N_{tot}} \frac{dN_+}{dE_+} \cong 0.2\,[1/MeV]$$

Analytical formula taking into account finite length of undulator and finite diameter of target

E.Bessonov, A.Mikhailichenko, 1992

$$\Delta N_{+1} \cong 2 \cdot 10^{-2} \chi^2 \frac{L}{\lambda u} \delta \frac{K^2}{1+K^2} \frac{z_f}{z_i} \eta$$

For χ = ½ , L=200m , λ_u=1cm δ=0.5, K=0.35, η=0.3

$$\Delta N_{+1} \cong \mathbf{3}$$

χ is a fraction of target radius with respect to the size of the gamma spot at the target distance

η --geometrical efficiency of capture

$Z_{f,l}$ - are the coordinates of undulator end and beginning;

ACTIVITIES FOR CONVERSION SYSTEM IN LABS

√ **CODES FOR POSITRON CONVERSION (UNDULATOR → LINAC → further on)**

Cornell (special codes for conversion, eddy curr., target dynamics), ArgonneNL, SLAC

√ **UNDULATOR DESIGN**

Cornell, Daresbury/DESY/Rutherford Appleton Lab/Durham U.

√ **TARGET DESIGN**

Livermore, Cockroft/Liverpool/Daresbury, SLAC, ANL (eddy currents), Cornell, DESY/Zeuthen (target hall activation). BINP Novosibirsk (Liquid Pb)

COLLECTION OPTICS DESIGN/CALCULATIONS

SLAC, Livermore, ANL, Cornell

Requires more efforts

√ **COLLIMATORS**

Cornell, University of Liverpool, DESY/Zeuthen

√ **PERTURBATION OF EMITTANCE AND POLARIZATION**

Cornell, ASTeC Daresbury Lab, DESY/Zeuthen

√ **UNDULATOR CHICANE**

SLAC, ANL, Cornell

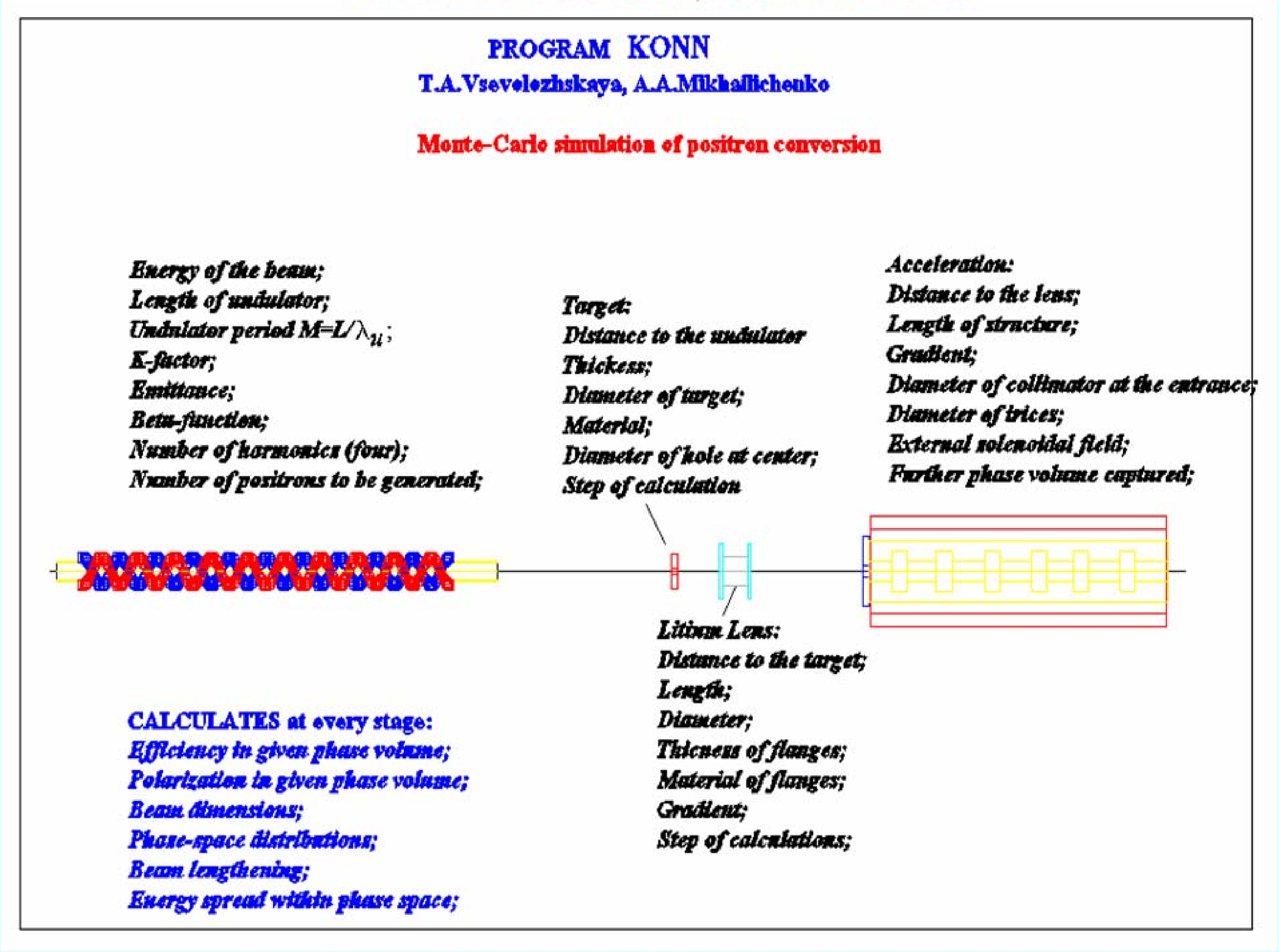
√ **UPDATES**

Cornell (Combining scheme for few targets)

Cornell codes for positron conversion

Undulator → target → focusing → post acceleration

Written in 1986-1987; restored in 2007



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; Solenoidal lens will be added soon

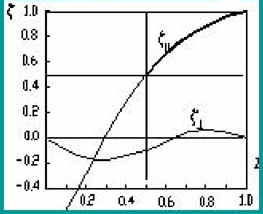
Also used CONVER (~EGS4; A.D.Bukin, BINP), OBRA

Polarization effects implemented in KONN

```
!    POLARIZATION CURVE APPROXIMATION
!
     EP4=EP-0.4
     EP6=EP-0.6
     PP=0.305+2.15*EP4
     IF(EP.LT.0.4)PP=PP-0.05*EP4-2.5*EP4**3
     IF(EP.GT.0.6)PP=PP-0.55*EP6-2.65*EP6**2+0.7*EP6**3    ! PP=PP-0.55*EP6-2.6*EP6**2
     IF(PP.GT.1.)PP=1.
!
```

EP=POSITRON ENERGY/ Egamma-$2mc^2$

Sentinel



Depolarization occurs due to spin flip in act of radiation of quanta having energy $0 < \eta\omega_\gamma \le E_1$ where E_1 stands for initial energy of positron. Depolarization after one single act

$$D = 1 - \left| \frac{d\boldsymbol{\sigma}_{\gamma e}(\zeta_1, \zeta_1) - d\boldsymbol{\sigma}_{\gamma e}(\zeta_1, -\zeta_1)}{d\boldsymbol{\sigma}_{\gamma e}} \right|$$

Where $d\sigma_{\gamma e}(\zeta_1, \zeta_1)$ stands for bremstrahlung cross section without spin flip, $d\sigma_{\gamma e}(\zeta_1, -\zeta_1)$ –the cross section with spin flip and $d\sigma_{\gamma e}$ is total cross section.

$$D = \frac{\eta^2 \omega_\gamma^2 \cdot [1 - \frac{1}{3}\zeta_{1\parallel}^2\ ]}{E_1^2 + E_2^2 - \frac{2}{3}E_1 E_2}$$

Energy after radiation

$$L_{dep} \cong \frac{1}{n\int D(\overset{\rho}{p}_1, \zeta_1)d\sigma} \longrightarrow L_{dep} \cong \frac{2X_0}{1 - \frac{1}{3}\zeta_\parallel^2} \cong 3X_0$$

Rad. length

Depolarization ~5%

Particles described by 2D array (matrix). One parameter numerates particles, the other one numerates properties associated with each particle: energy, polarization, angles to axes

Code has ~1400 rows;

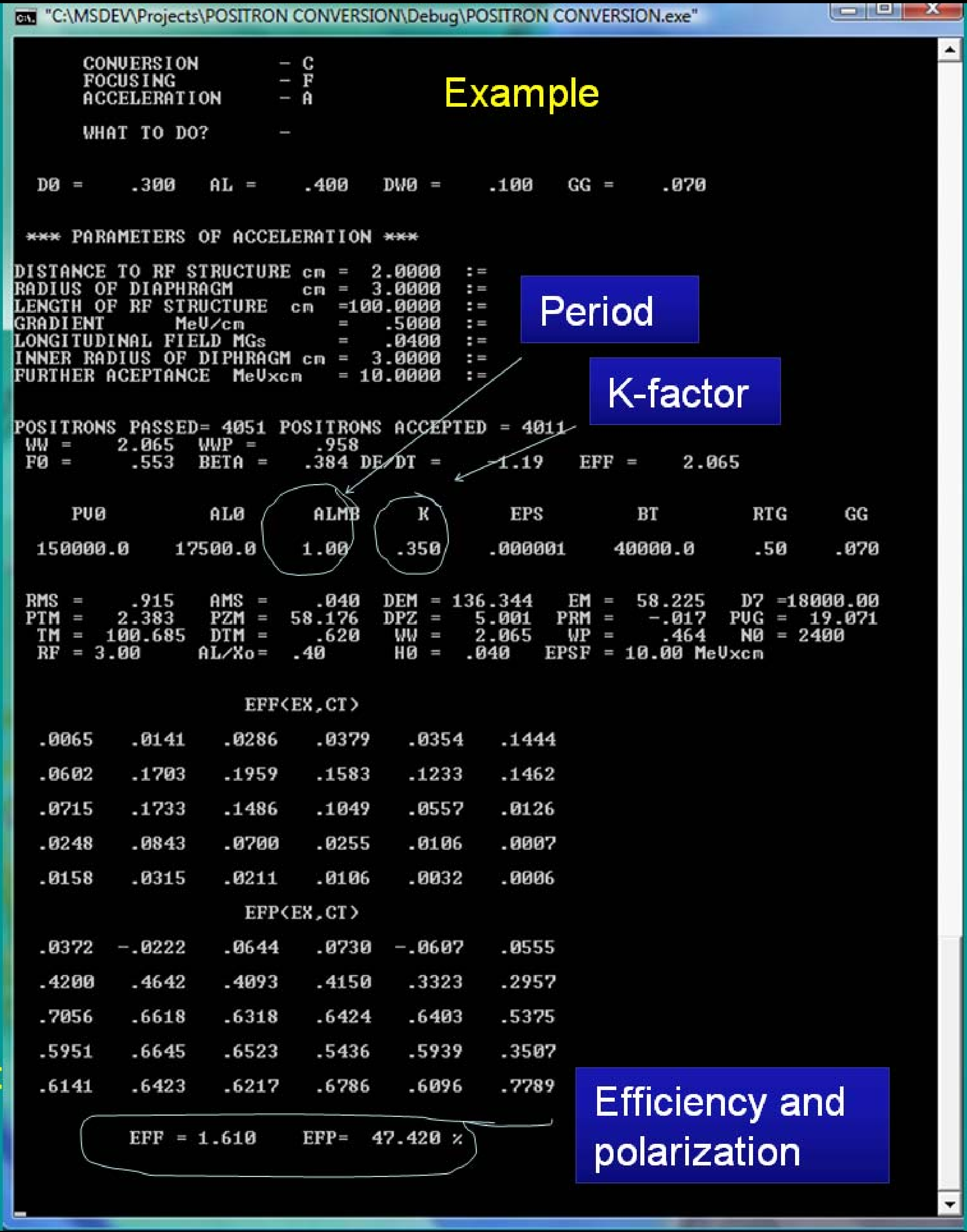
Will be added solenoidal lens;

Will be added more graphics;

Possibility for the file exchange with graphical and statistical Codes (JMP);

Possibility for the file exchange with PARMELA;

Few seconds for any new variant



"C:\MSDEV\Projects\POSITRON CONVERSION\Debug\POSITRON CONVERSION.exe"

Example

```
     CONVERSION          - C
     FOCUSING            - F
     ACCELERATION        - A

     WHAT TO DO?         -


  D0 =     .300   AL =     .400   DW0 =     .100   GG =     .070


 *** PARAMETERS OF ACCELERATION ***

DISTANCE TO RF STRUCTURE cm =  2.0000  :=
RADIUS OF DIAPHRAGM      cm =  3.0000  :=
LENGTH OF RF STRUCTURE  cm  =100.0000  :=
GRADIENT      MeV/cm        =    .5000  :=
LONGITUDINAL FIELD MGs      =    .0400  :=
INNER RADIUS OF DIPHRAGM cm =  3.0000  :=
FURTHER ACEPTANCE  MeVxcm   = 10.0000  :=

POSITRONS PASSED= 4051 POSITRONS ACCEPTED = 4011
 WW =    2.065  WWP =      .958
 F0 =     .553  BETA =   .384 DE/DT =    -1.19   EFF =    2.065


    PV0         AL0        ALMB      K         EPS        BT         RTG      GG

  150000.0    17500.0      1.00     .350     .000001    40000.0      .50     .070


 RMS =     .915   AMS =     .040  DEM = 136.344   EM =  58.225   D7 =18000.00
 PTM =    2.383   PZM =   58.176  DPZ =    5.001  PRM =    -.017  PVG =  19.071
  TM =  100.685   DTM =     .620   WW =    2.065   WP =     .464   N0 = 2400
  RF = 3.00      AL/Xo=  .40       H0 =   .040   EPSF = 10.00 MeVxcm


                   EFF<EX,CT>

  .0065    .0141    .0286    .0379    .0354    .1444

  .0602    .1703    .1959    .1583    .1233    .1462

  .0715    .1733    .1486    .1049    .0557    .0126

  .0248    .0843    .0700    .0255    .0106    .0007

  .0158    .0315    .0211    .0106    .0032    .0006
                   EFP<EX,CT>

  .0372   -.0222    .0644    .0730   -.0607    .0555

  .4200    .4642    .4093    .4150    .3323    .2957

  .7056    .6618    .6318    .6424    .6403    .5375

  .5951    .6645    .6523    .5436    .5939    .3507

  .6141    .6423    .6217    .6786    .6096    .7789


        EFF = 1.610     EFP=  47.420 %
```

Period

K-factor

Efficiency and polarization

Codes used in other Labs are FLUKA, EGS4 and Geant4 SLAC, ANL

Results depend on the collection system model used

Cornell model uses Lithium lens for the focusing as a primary unit

Calculation of conversion is fast growing activity

Good example gives Argonne National Laboratory–

began calculations with Li lens also (W.Gai, W.Liu, K.-J.Kim, 2007)

Modeling and test of undulators is other important component of conversion system development

Cornell LEPP and Daresbury/Liverpool U. are the only developers of undulators for the conversion system

ILC Beam parameters important for undulator choice

ge$_x$=8 10^{-6} m rad -high edge ; ge$_y$=8 10^{-8} m rad –high edge
b$_x$ ~200 m in undulator

Angular spread in radiation	$\alpha \cong \sqrt{1+K^2}/\gamma$	3 ·10^{-6} (*K*=1)
Angular spread in beam, vert.	$y' \cong \pm\sqrt{\gamma\varepsilon_y / \beta_y\gamma}$	±3.5 ·10^{-8}
Angular spread in beam, hor.	$x' \cong \pm\sqrt{\gamma\varepsilon_x / \beta_x\gamma}$	±3.5 ·10^{-7}
Radius of beam helix	$a \cong \Delta_u K/\gamma$	5 ·10^{-7} cm (*K*=1)
Beam size, vertical	$y \cong 2\times\sqrt{\gamma\varepsilon_y\beta_y/\gamma}$	1.4·10^{-3} cm
Beam size horizontal	$x \cong 2\times\sqrt{\gamma\varepsilon_x\beta_x/\gamma}$	1.4·10^{-2} cm

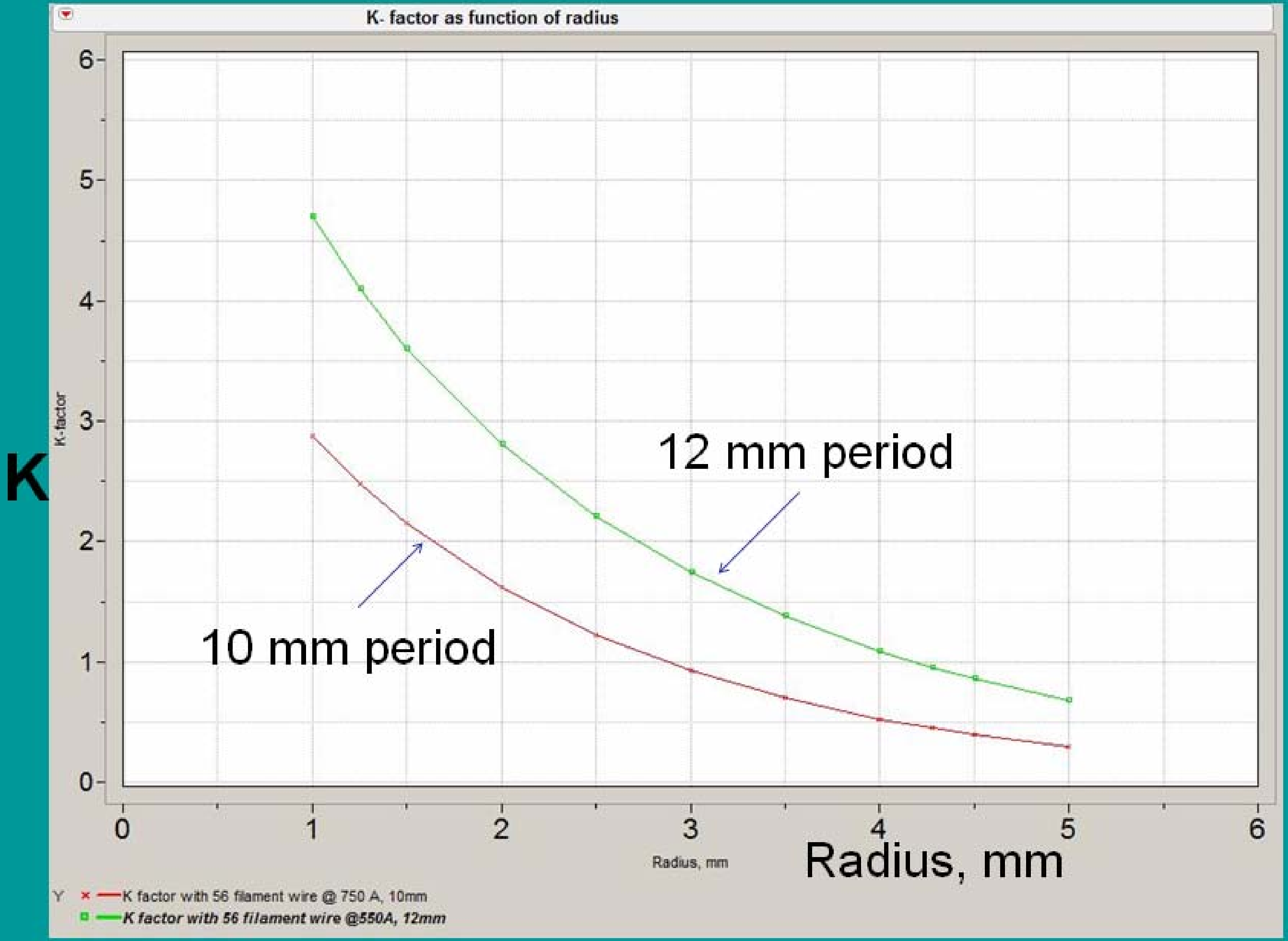
50 sigma ~7 mm ; At the beginning of operation one can expect emittance degradation

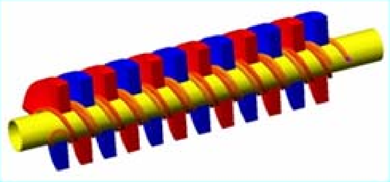
Desire to make tuning of ILC robust and less sensitive to misalignments; Wakes~1/Ø^3

At Cornell the undulators having Ø=8 mm tested so far; Ø=6.35 (¼") under fabrication.

Daresbury deals with aperture Ø=5.23mm

K factor as function of radius of undulator chamber





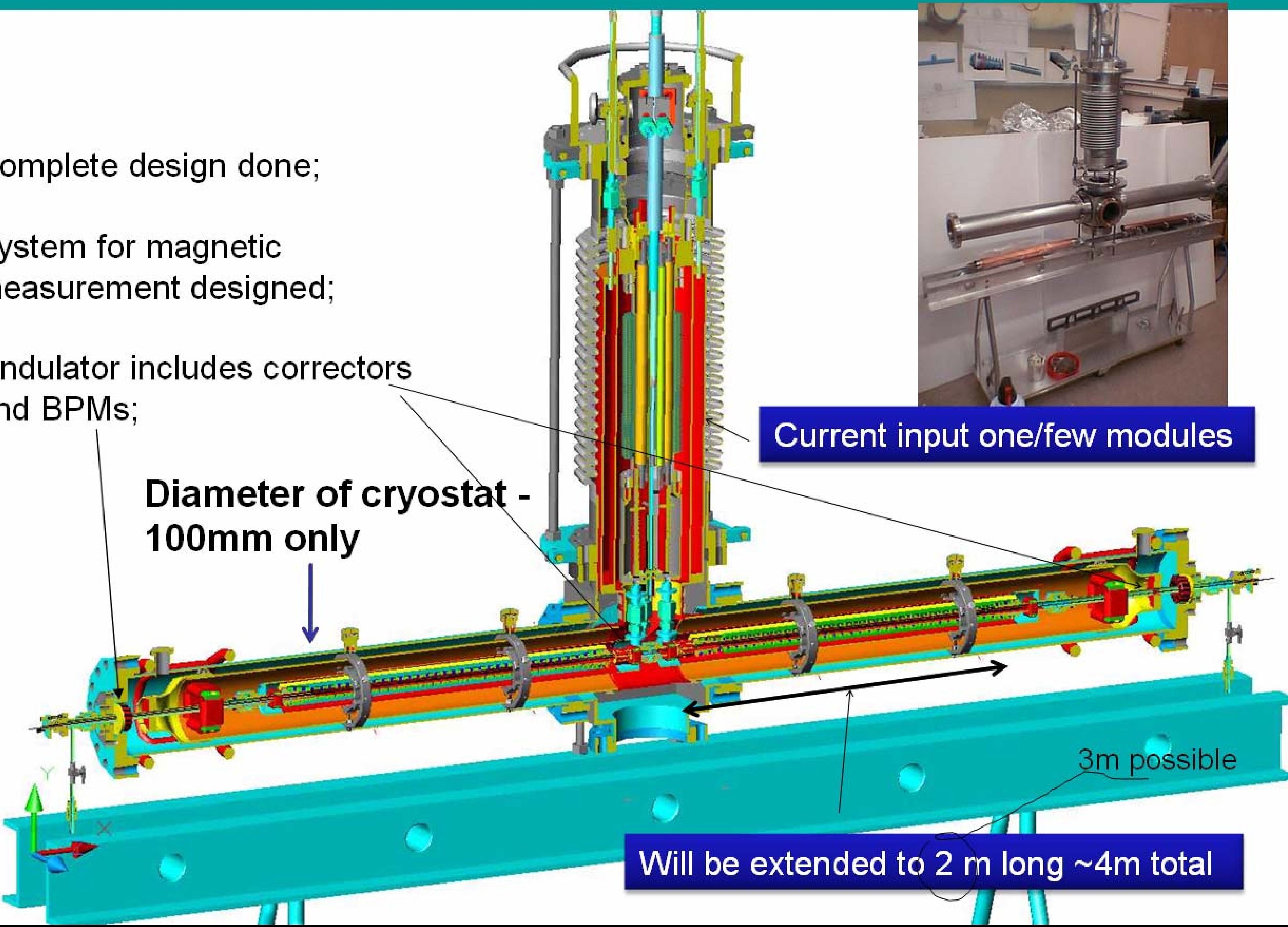
We think, that aperture must be kept as big as possible

UNDULATOR DESIGN (Cornell)

Complete design done;

System for magnetic measurement designed;

Undulator includes correctors and BPMs;



Diameter of cryostat - 100mm only

Current input one/few modules

Will be extended to 2 m long ~4m total

3m possible

Technology developed for fabrication of continuous yoke of necessary length (2-3m)

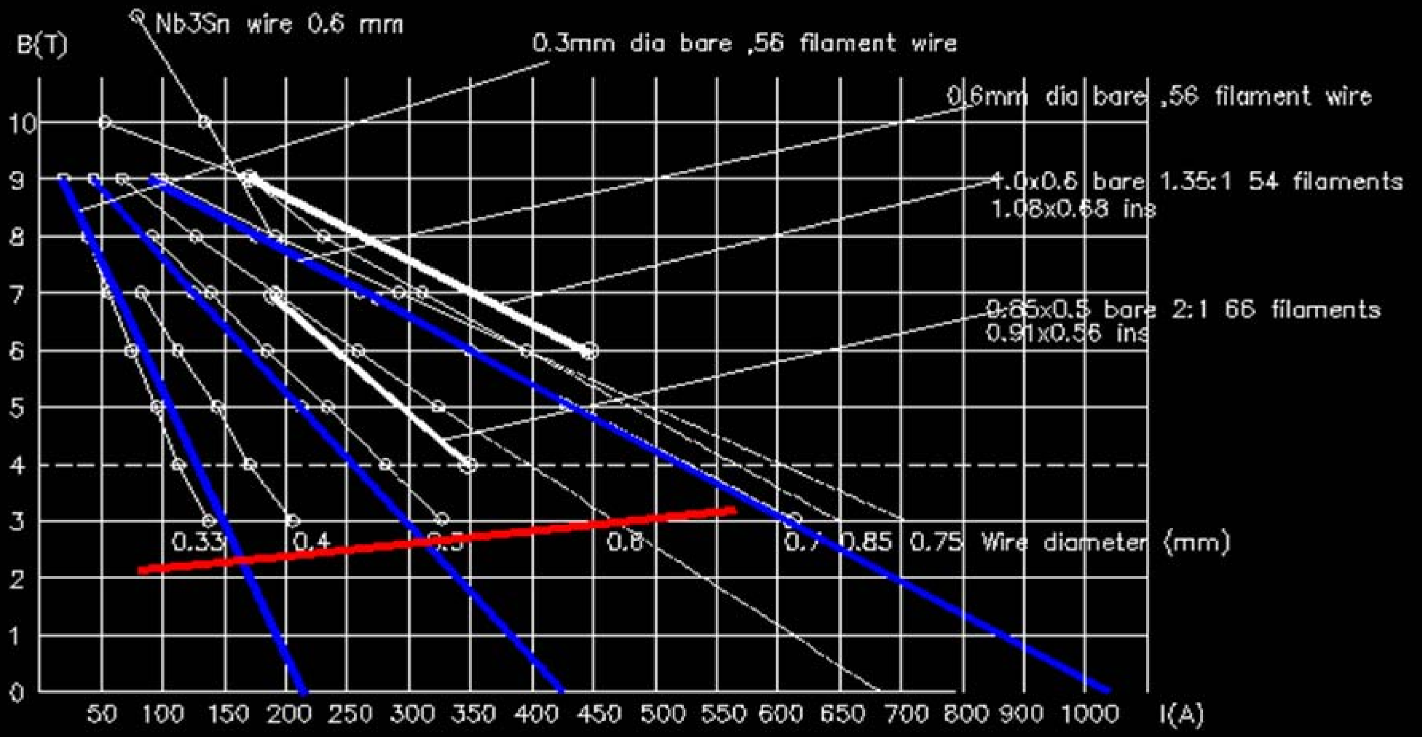
Wire having diameter 0.33mm chosen as a baseline one for now

For 10mm period the coil has 8(z)x11(r) wires; bonded in 4strands

For 12mm period the coil has 12(z)x12(r) wires bonded in 6 strands

Two meter long yoke under visual inspection by William Trusk

Wires for undulator



CRITICAL CURRENT VERSUS FIELD FOR DIFFERENT WIRE SIZES @ 4.2K
FOR 54&56 FILAMENT SUPERCONDUCTOR (NbTi IN Cu MATRIX)

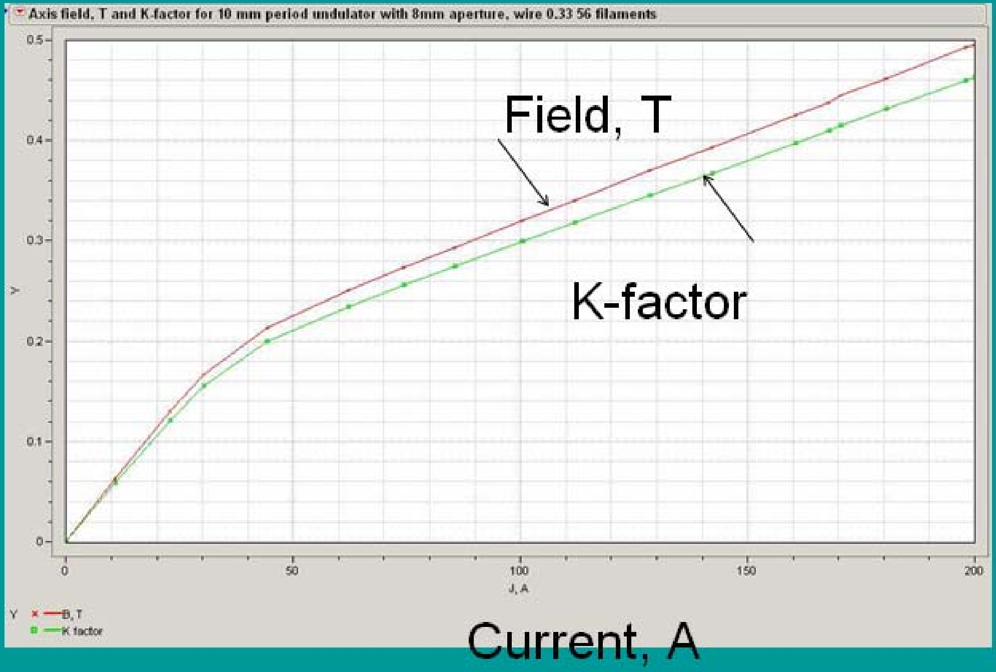
sc_wire_graphs.dwg

All new wire is a 56 filaments with SC to Cu ratio 1:0.9
We switched to 0.3 mm bare from 0.6 bare
Wounding with bonded tape of four and six wires in parallel

Operation at lower pressure of He

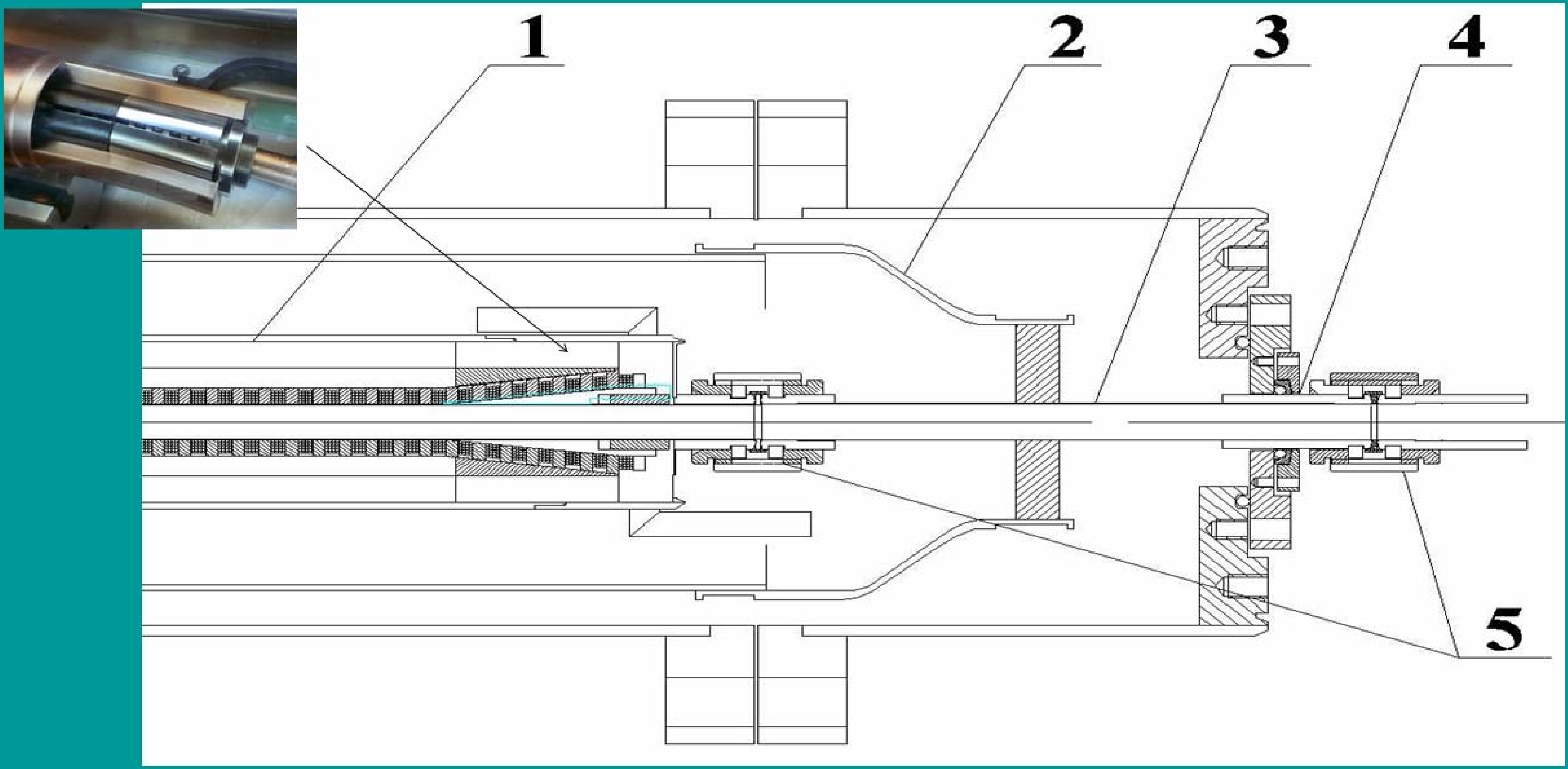
Dewar sealed and used for low pressure experiments; two oil pumps deliver vacuum down to -24”Hg with Helium level covering the undulator

Temperature as function of pressure



Measured excitation curve for undulator with 8mm aperture

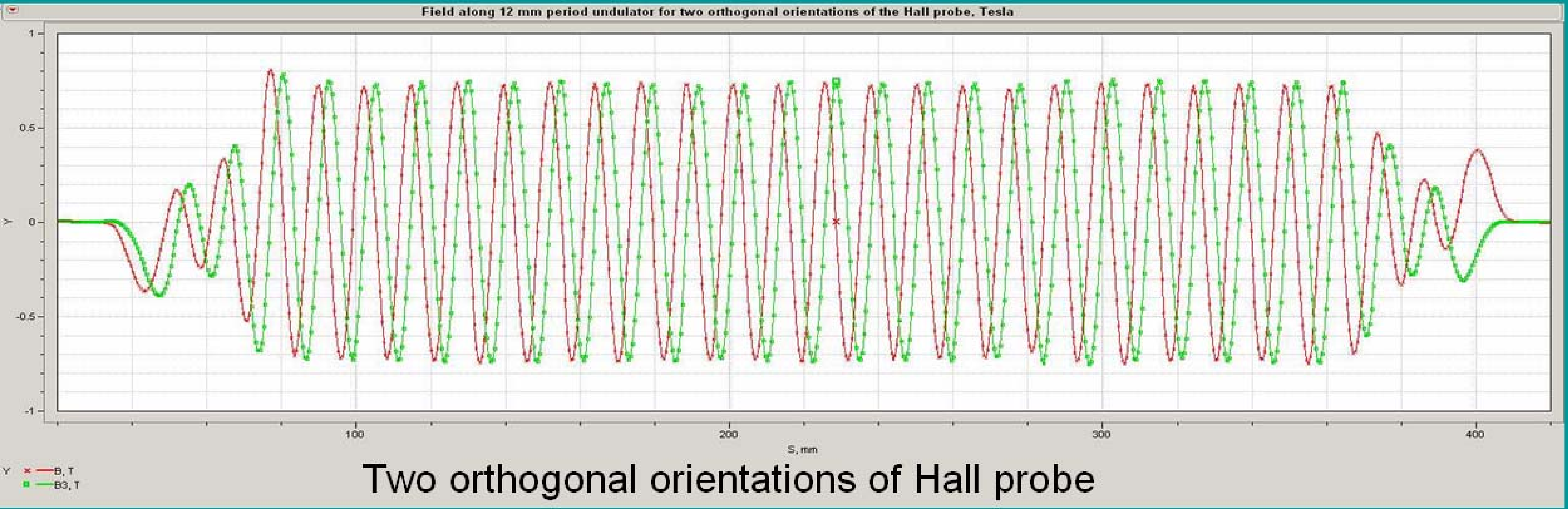
Much attention was paid to smoothness of chamber



Schematics of transition region between cold mass and the room temperature flange in Cornell undulator. 1—cold mass, 70 oK shield, 3—StSteel thin wall tube, 4—Wilson type sealant, 5—Conflat® joints.

OFC vacuum chamber, RF smoothness

Typical field distribution

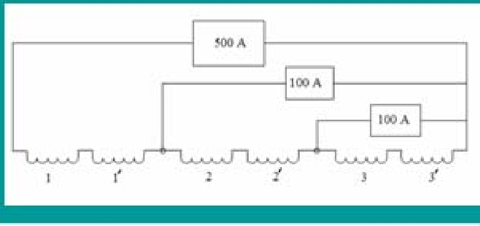


Two orthogonal orientations of Hall probe

Simplified tapering

Undulators tested at Cornell

Aperture available for the beam is 8 mm in Ø clear



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≈0.92 (calculated)	K≈1 (calculated)

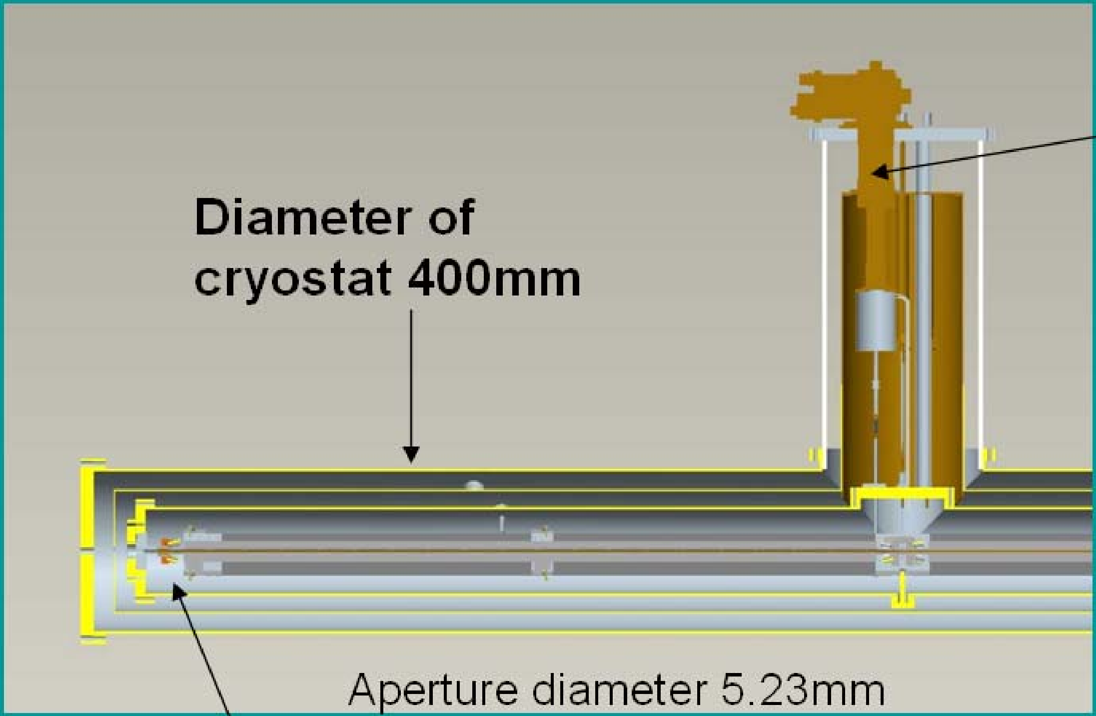
*) Wire – Ø0.6 mm bare; **) Wire – Ø0.4 mm bare; ***) Wire – Ø0.3 mm bare

For aperture Ø6.35mm we expect for period 10mm K=0.7; for period 12mm K=1.2

Two sections of 45 cm long each will be installed in cryostat and measured in 2007;
The plan is to test it with the beam at Cornell ERL test module setup.

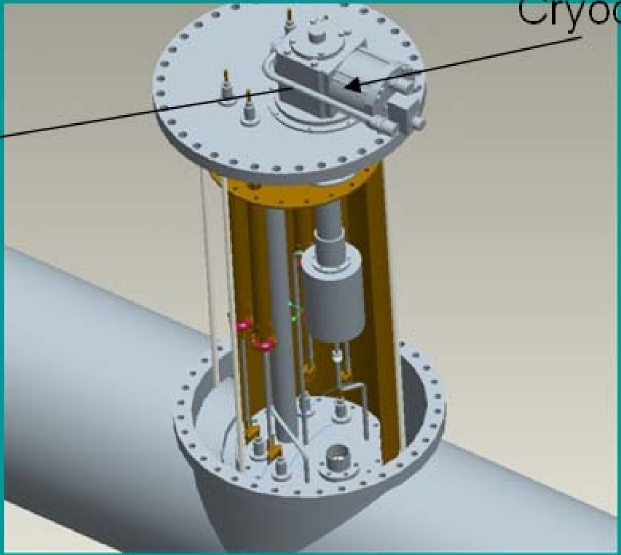
4m long prototype will be assembled in general to the end of 2007, Field distribution will be measured earlier in 2008

UNDULATOR DESIGN (Daresbury)-This Conference



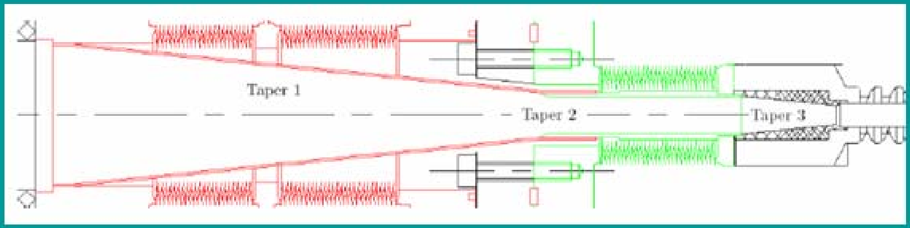
Diameter of cryostat 400mm

Aperture diameter 5.23mm

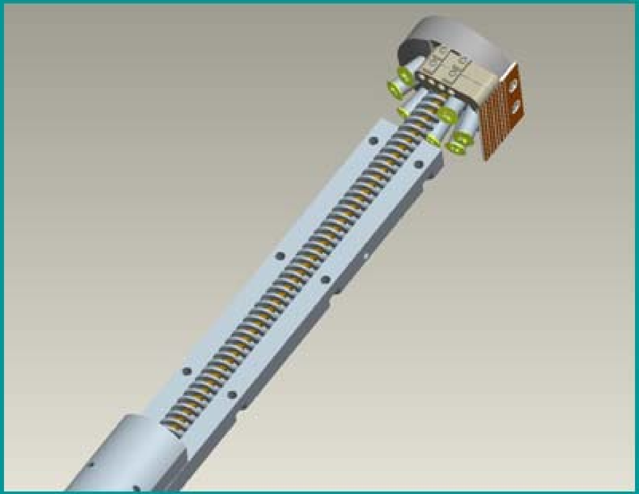


Cryocooler

Cryocooler for test only (vibration)



Tapering of vacuum chamber



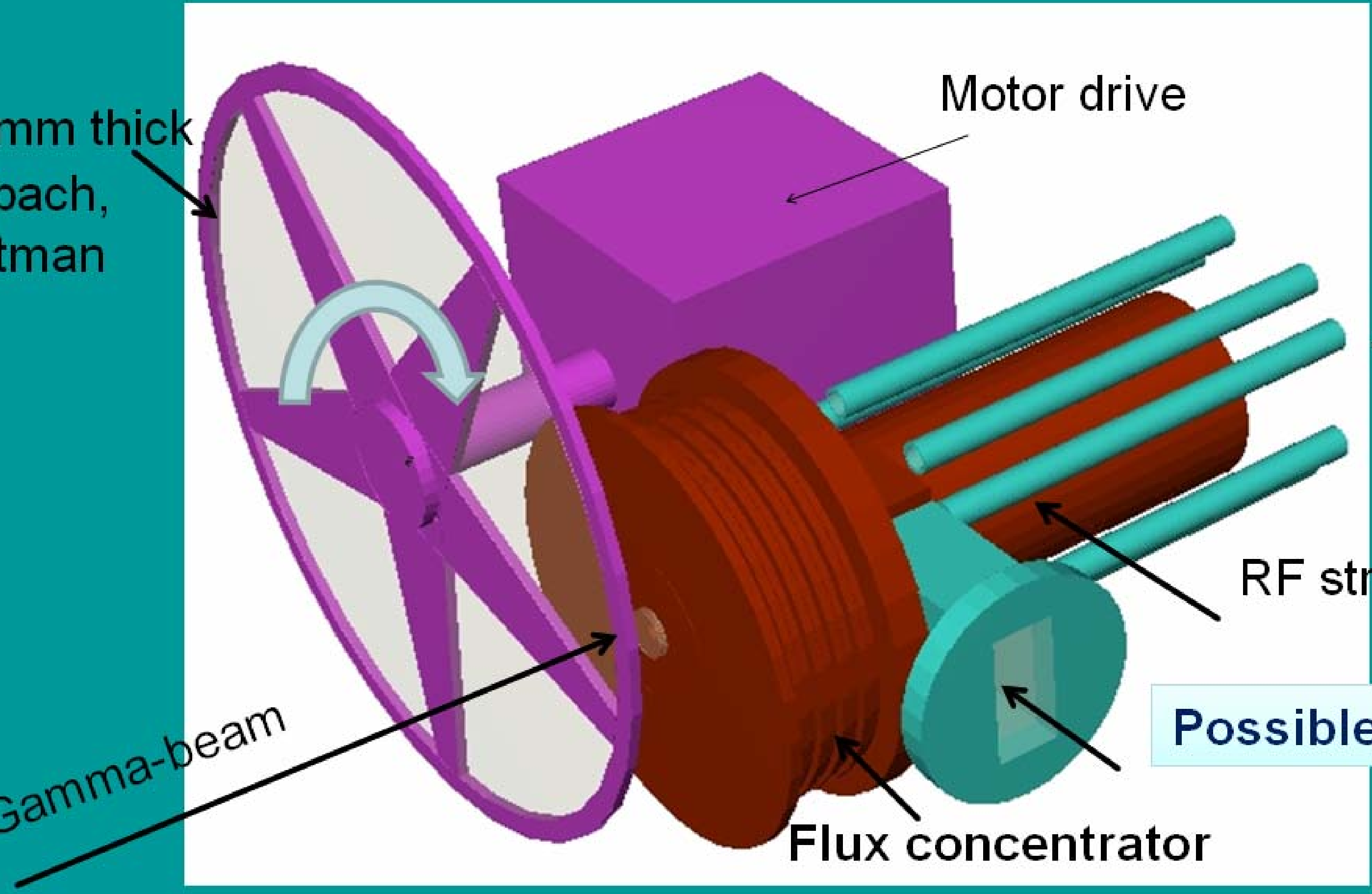
Wounded with nine SC wires bounded as a tape

K=0.92 measured for period 11.5 mm

TARGET DESIGN

Ti rotating wheel target is under development at Livermore, SLAC, Daresbury.

Ti ~14mm thick
J.Rossbach,
K.Floettman



J.Bailey, U. of Liverpool

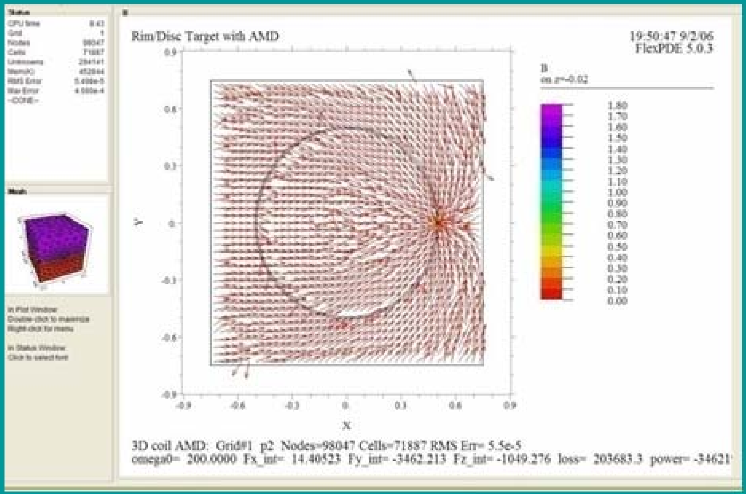
T. Piggott, LLNL

Possible kick by RF input

At Cornell we calculated the power dissipated in metal wheel spinning in magnetic field and found that it is big. Calculation confirmed at ANL and LLNL

Looking for some other solutions (updates) such as Liquid metal target with Pb/Bi or Hg
Spinning compact W+Ti disk

Focusing with spatially localized magnetic systems (Lithium lens)



```
CPU time     8:43
Grid         1
Nodes        98047
Cells        71887
Unknowns     294141
Mem(K)       452844
RMS Error    5.498e-5
Max Error    4.680e-4
-DONE-
```

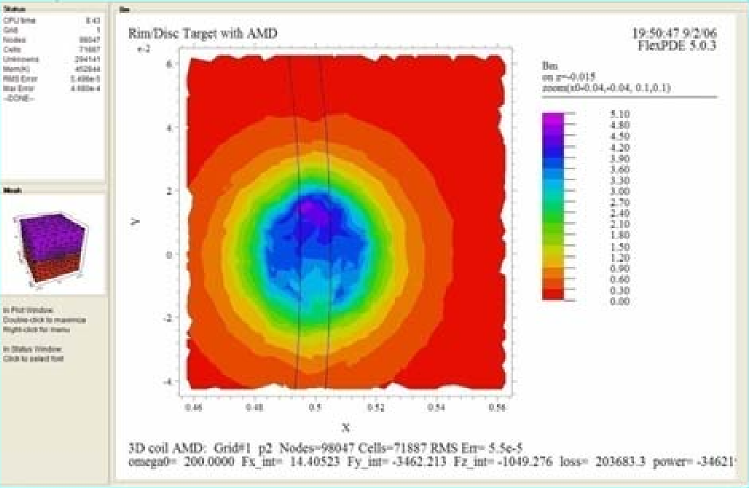
Rim/Disc Target with AMD

19:50:47 9/2/06
FlexPDE 5.0.3

B
on z=-0.02

```
3D coil AMD:  Grid#1  p2  Nodes=98047 Cells=71887 RMS Err= 5.5e-5
omega0=  200.0000  Fx_int=  14.40523  Fy_int= -3462.213  Fz_int= -1049.276  loss=  203683.3  power= -34621
```

Top view to the vector field



```
CPU time     8:43
Grid         1
Nodes        98047
Cells        71887
Unknowns     294141
Mem(K)       452844
RMS Error    5.498e-5
Max Error    4.680e-4
-DONE-
```

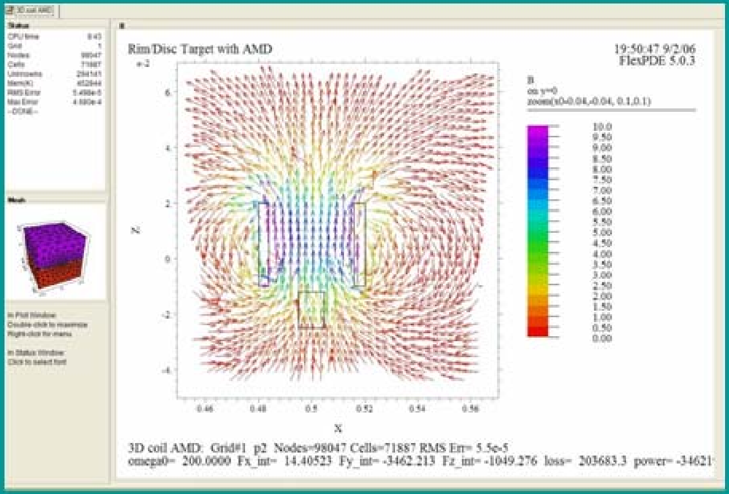
Rim/Disc Target with AMD

19:50:47 9/2/06
FlexPDE 5.0.3

Bm
on z=-0.015
zoom(x0-0.04,-0.04, 0.1,0.1)

```
3D coil AMD:  Grid#1  p2  Nodes=98047 Cells=71887 RMS Err= 5.5e-5
omega0=  200.0000  Fx_int=  14.40523  Fy_int= -3462.213  Fz_int= -1049.276  loss=  203683.3  power= -34621
```

Contour plot of field amplitude.
Drag is seen here even for narrow rim



```
CPU time     8:43
Grid         1
Nodes        98047
Cells        71887
Unknowns     294141
Mem(K)       452844
RMS Error    5.498e-5
Max Error    4.680e-4
-DONE-
```

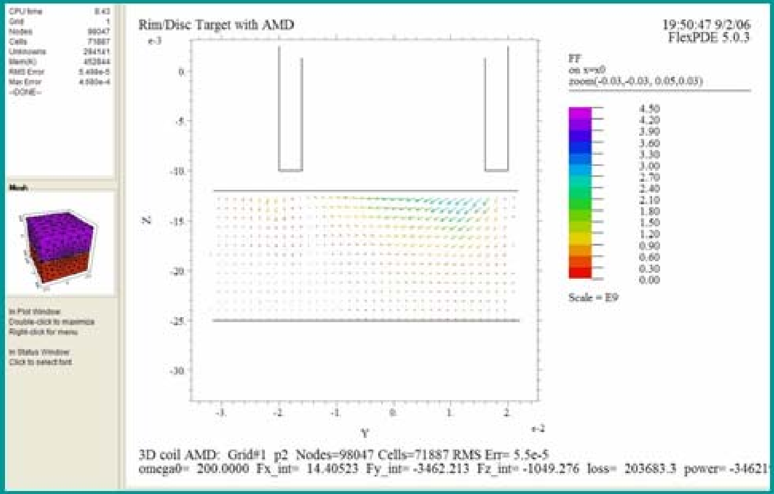
Rim/Disc Target with AMD

19:50:47 9/2/06
FlexPDE 5.0.3

B
on y=0
zoom(x0-0.04,-0.04, 0.1,0.1)

```
3D coil AMD:  Grid#1  p2  Nodes=98047 Cells=71887 RMS Err= 5.5e-5
omega0=  200.0000  Fx_int=  14.40523  Fy_int= -3462.213  Fz_int= -1049.276  loss=  203683.3  power= -34621
```

Fields in cross section
through the center of coil



```
CPU time     8:43
Grid         1
Nodes        98047
Cells        71887
Unknowns     294141
Mem(K)       452844
RMS Error    5.498e-5
Max Error    4.680e-4
-DONE-
```

Rim/Disc Target with AMD

19:50:47 9/2/06
FlexPDE 5.0.3

FF
on x=x0
zoom(-0.03,-0.03, 0.05,0.03)

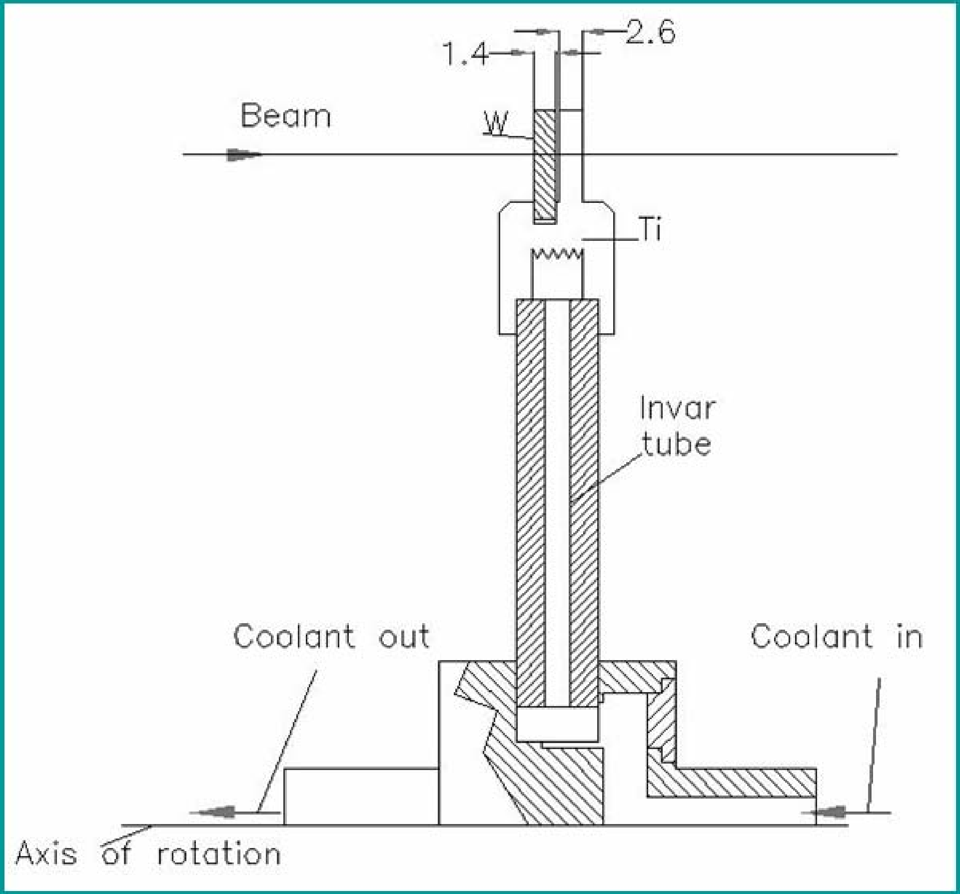
Scale = E9

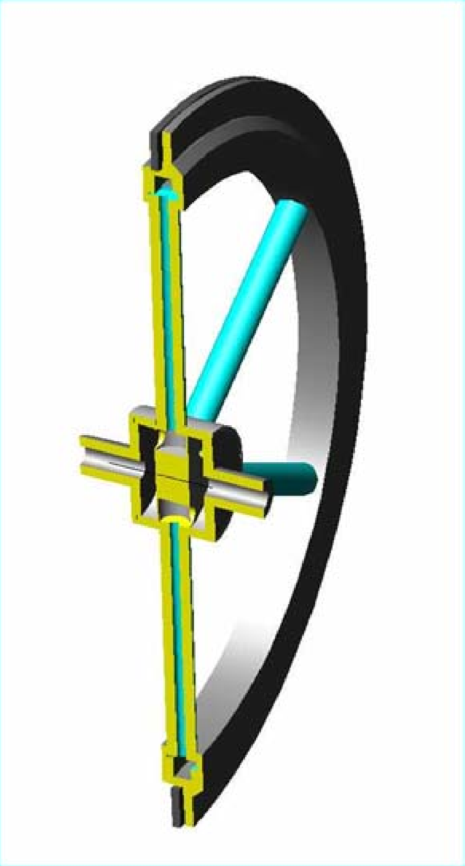
```
3D coil AMD:  Grid#1  p2  Nodes=98047 Cells=71887 RMS Err= 5.5e-5
omega0=  200.0000  Fx_int=  14.40523  Fy_int= -3462.213  Fz_int= -1049.276  loss=  203683.3  power= -34621
```

Forces in cross section YZ
plane through the center of coil

Sandwich type target concept in attempt to make target thinner

First layer (at the entrance is W, the last fraction might be Ti



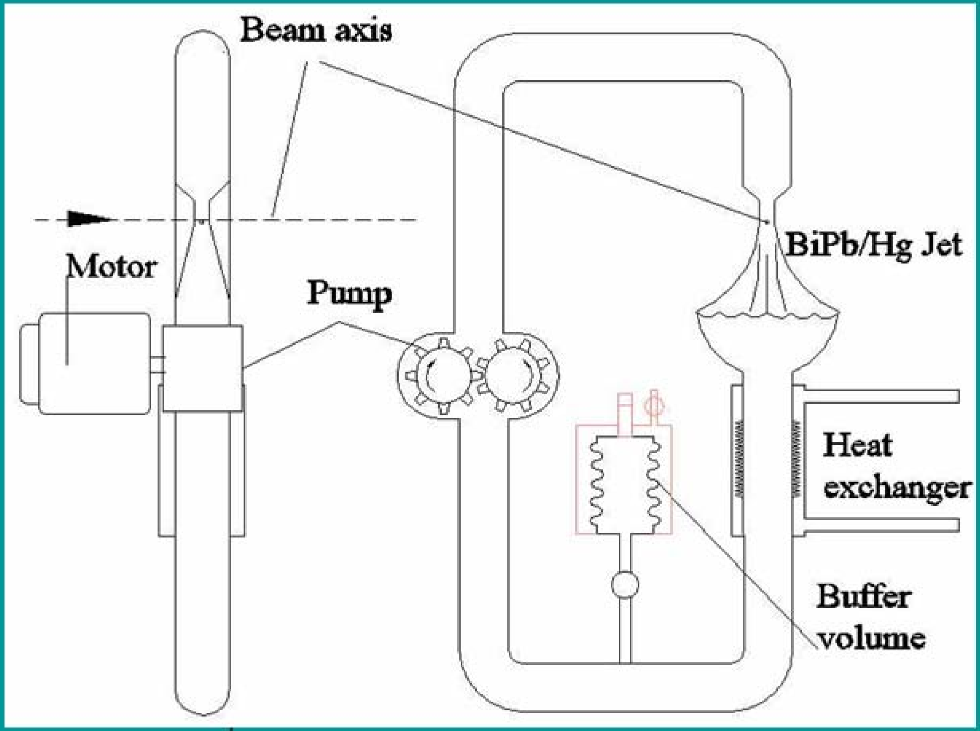


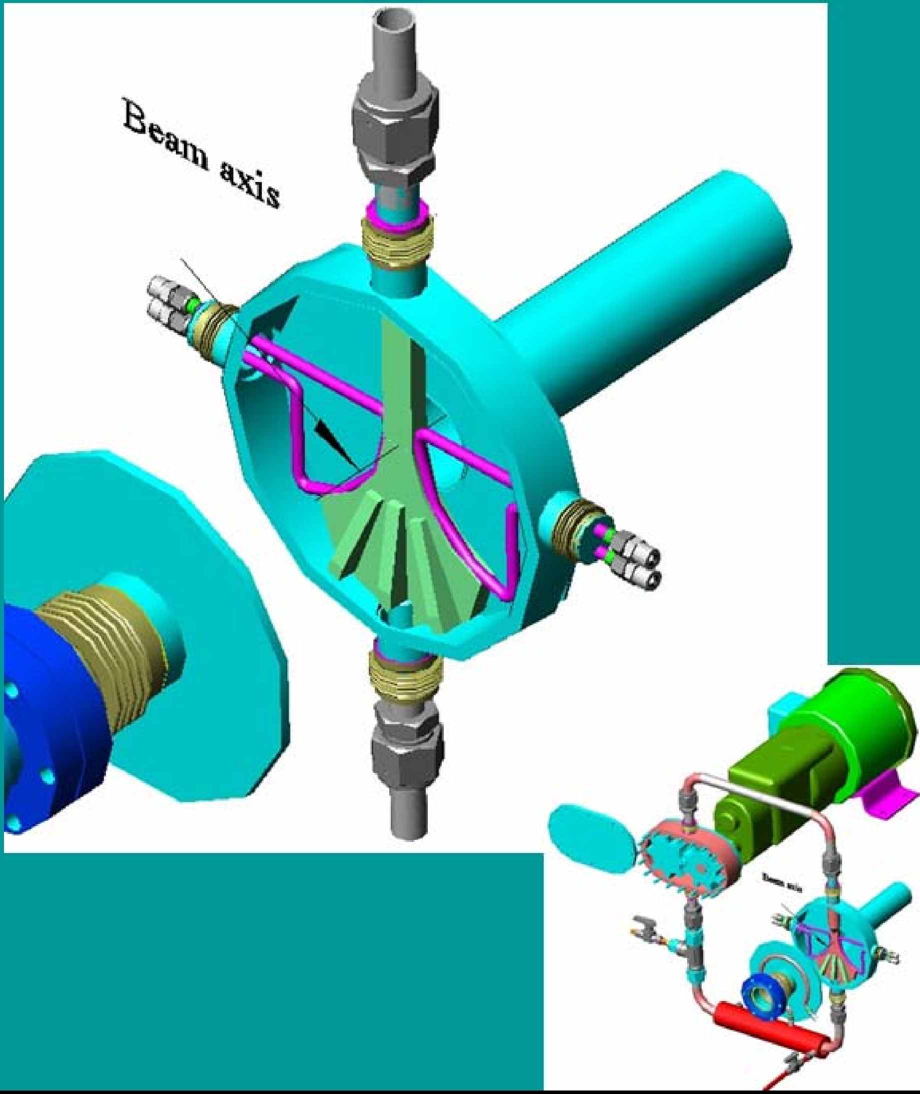
More compact design is possible

LIQUID METAL TARGET

High Z metals could be used here such as Bi-Pb, Mercury.

BiPb has melting temperature 154 deg C.   Hg has boiling temperature 354 deg C





Gear pump.   Hg Jet velocity~10m/s

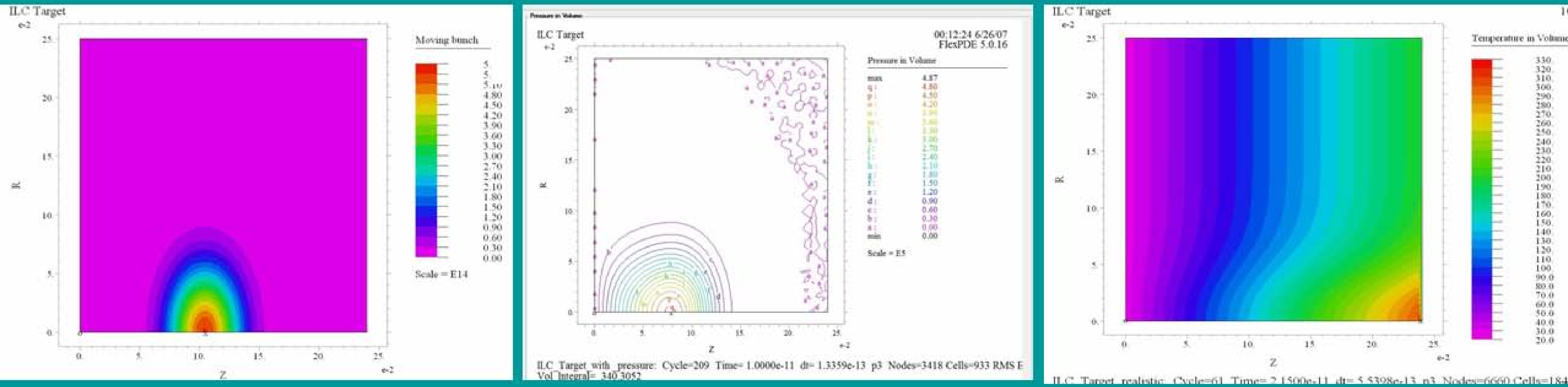
Calculations show absolute feasibility of this approach

FlePDE model (Cornell) calculates temperature and pressure according equations

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

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

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

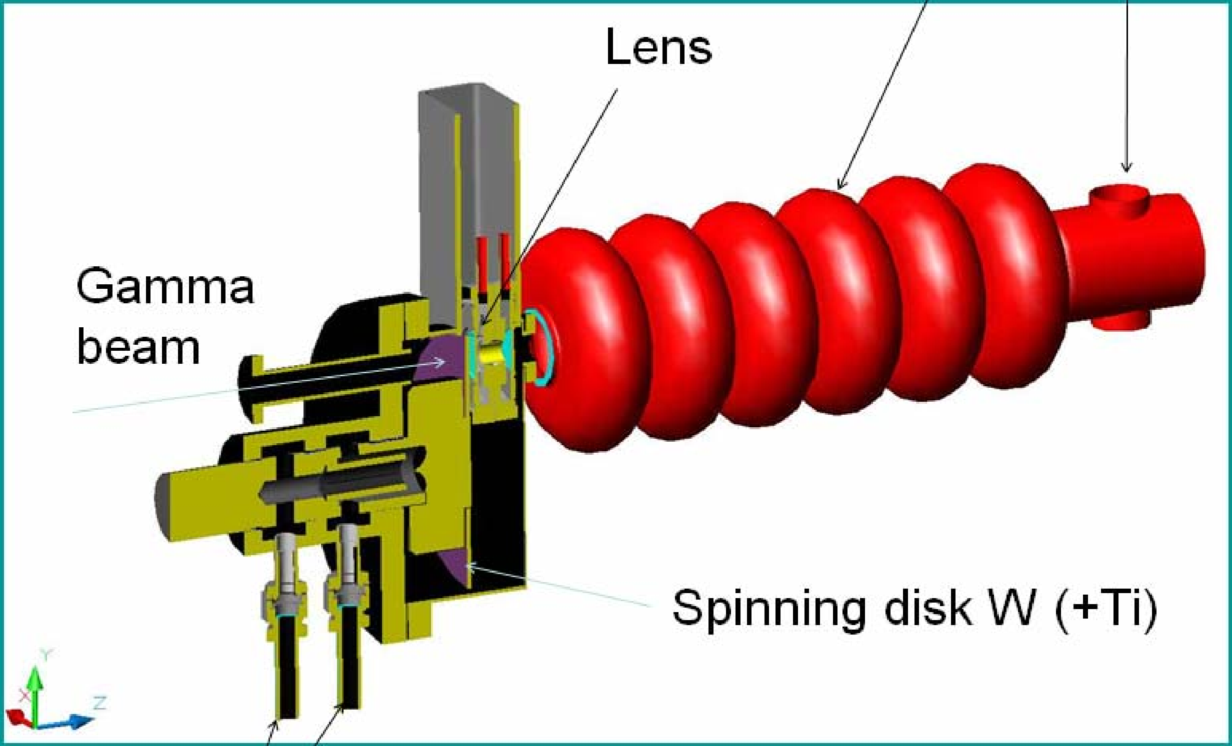


ILC_Target_with_pressure: Cycle=209 Time= 1.0000e-11 dt= 1.3359e-13 p3 Nodes=3418 Cells=933 RMS E
Vol_Integral= 340.3052

ILC_Target_realistic: Cycle=61 Time= 2.1500e-11 dt= 5.5398e-13 p3 Nodes=6660 Cells=184

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

Conversion unit on a basis of spinning W+Ti and short focusing lens



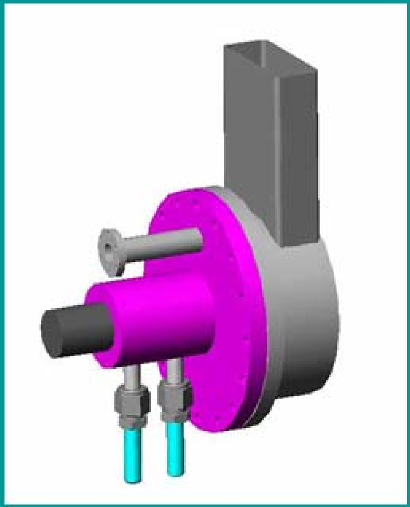
RF structure; input-far from the target side

Lens

Gamma beam

Spinning disk W (+Ti)

Coolant



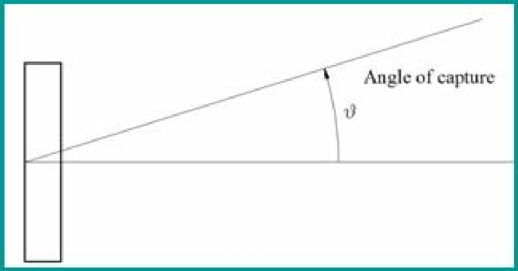
Size ~30cm in diameter

COLLECTION OPTICS DESIGN

Efficiency= N_{e+} /N_{gammas}, %

Angle of capture, rad

Angle shown~0.3 rad



Target – Tungsten (W)

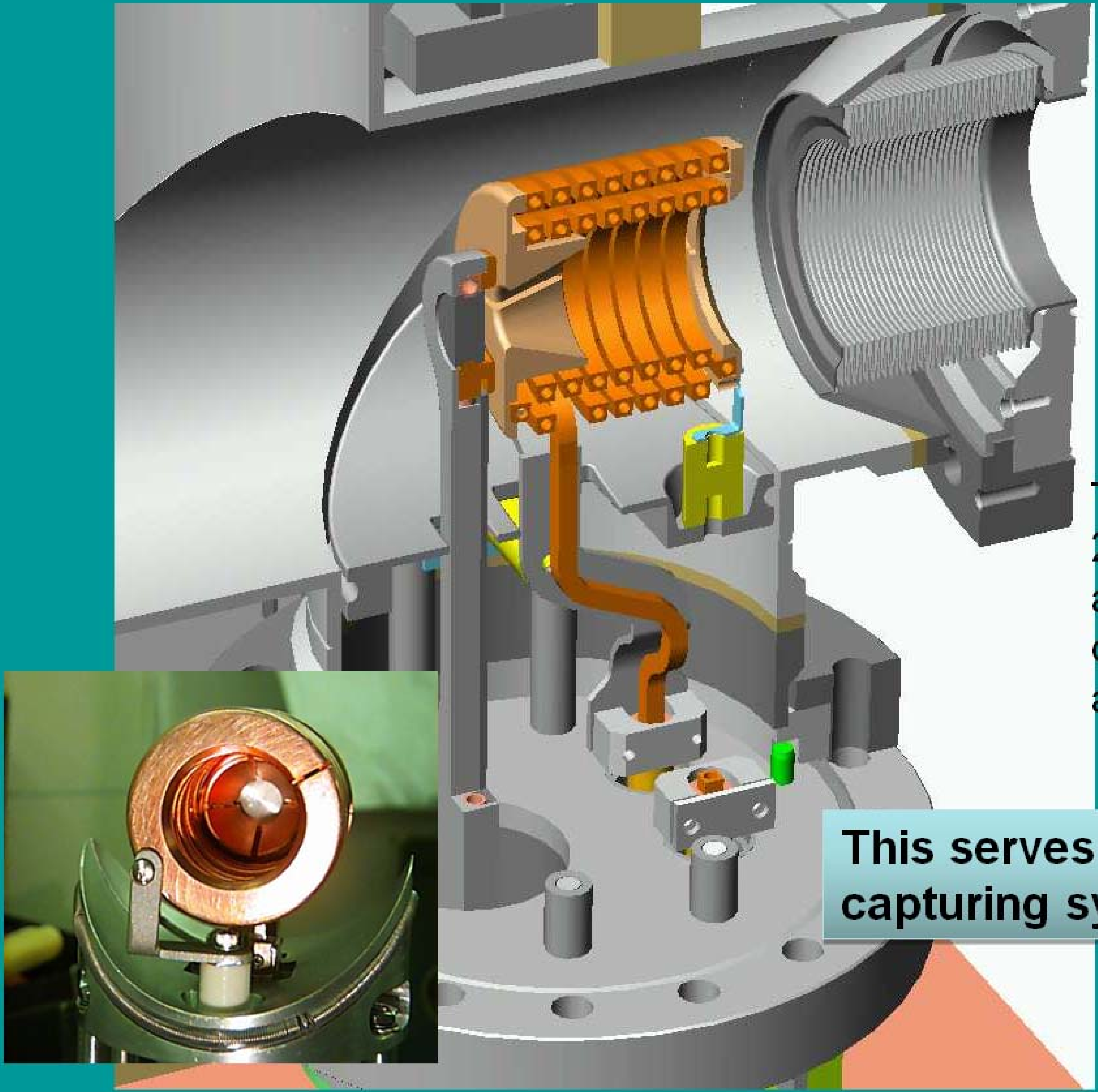
Thickness – 1.5 mm

20 MeV photons

Particles from 10 to 19 MeV only

Efficiency as function of capturing angle; within this angle the particles are captured by collection optics

Many different systems possible here. Shown is Cornell positron capturing system



Efficiency of positron accumulation in CESR with system turned on/off changes 5 times;

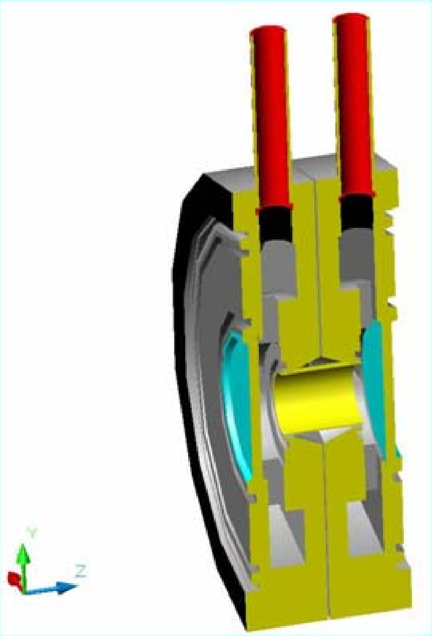
This design introduced in 2000; it doubled positron accumulation in CESR, coming to 100 mA/min anytime (R=100m)

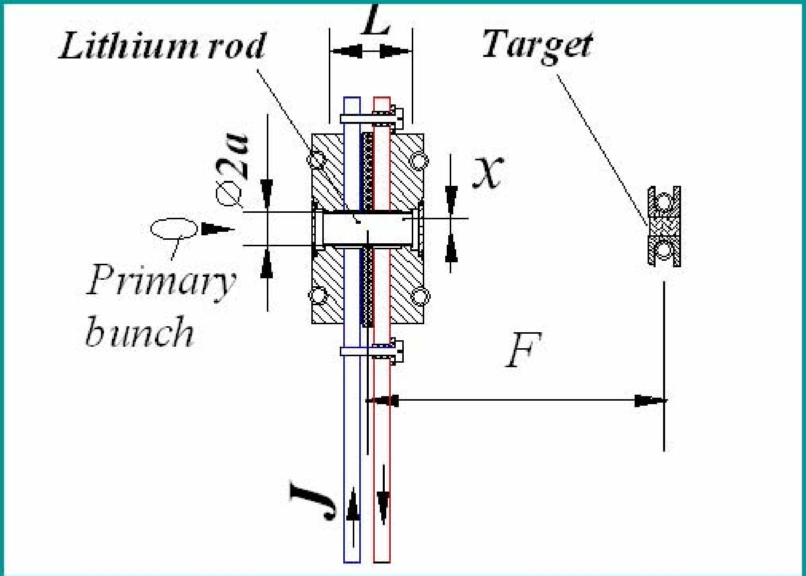
This serves as a prototype for ILC capturing system with solenoid

LITHIUM LENS BASICS

Current *I* runs through Li rod along axis

Beam is going in axial direction trough Li



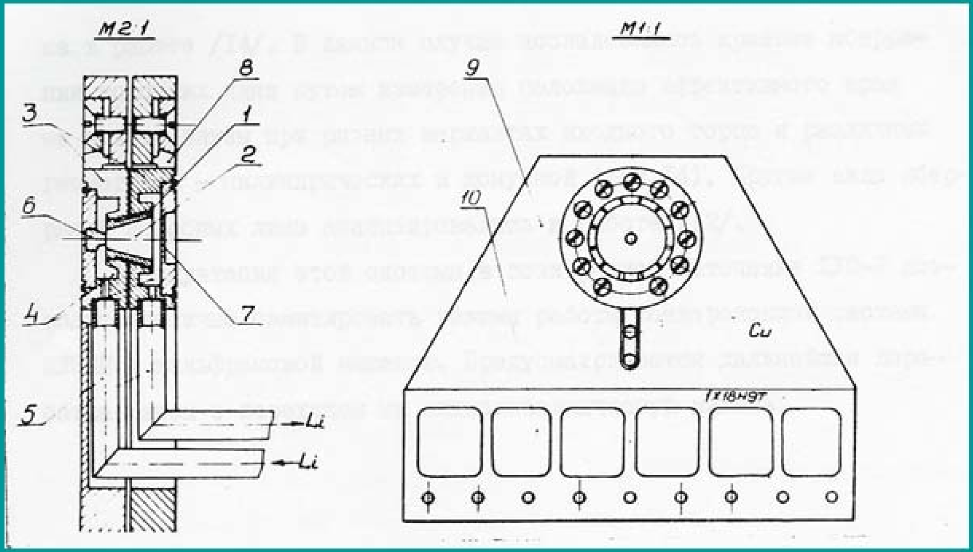


Focal distance $F \cong \frac{a^2 \cdot (HR)}{0.2JL}$ ~1 cm for 100 kA level

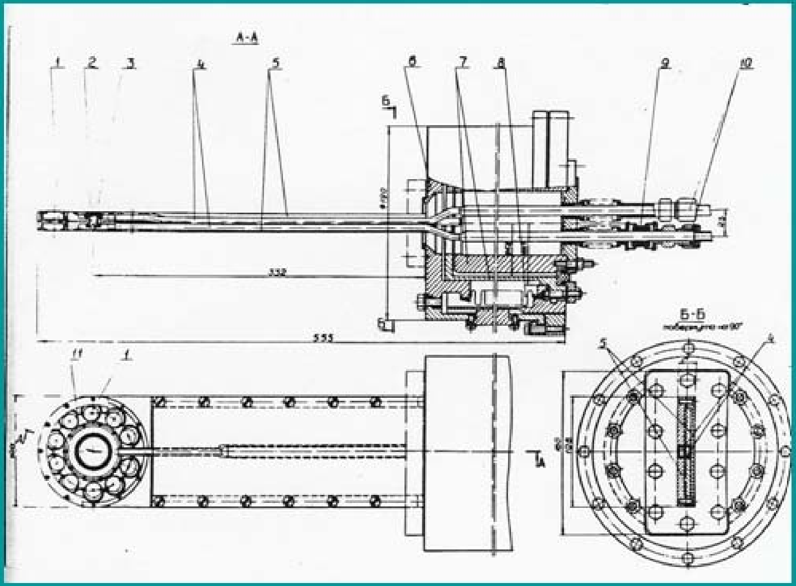
Energy deposition in Be window below destruction level

Li lens was planned for VLEPP

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

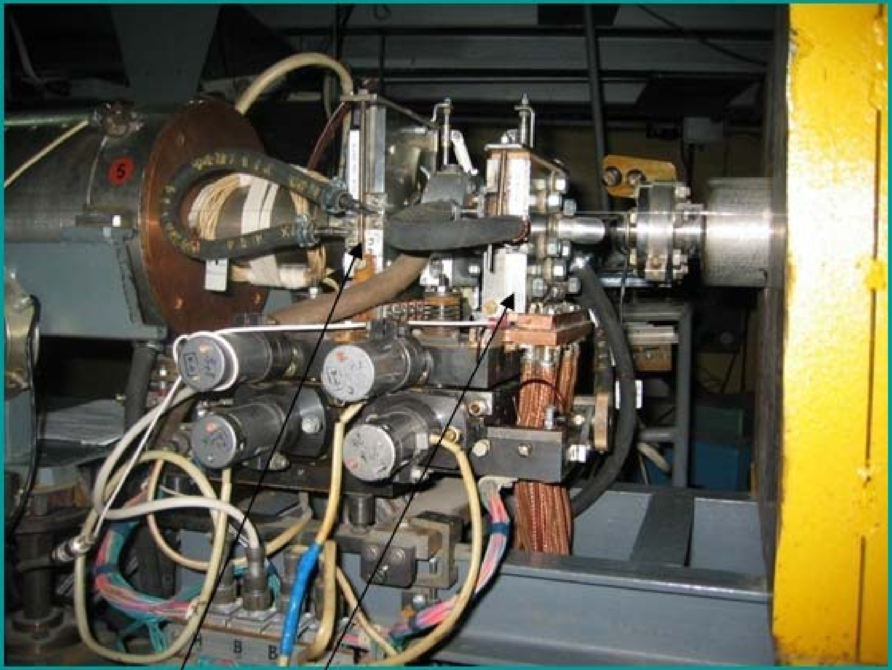


1-ex-centric contact pushers;2-conic lens body; 3-W target; 4-Ti tubing for LI supply; 5-flat current leads; 6-vacuum chamber; 7-coaxial fraction of current leads; 8-bellows; 9-ceramic insulators; 10-conical gasket; 11-set of ex-centric pushers.

VLEPP planned to have 10^{12} particle per bunch

Doublet of Lithium lenses in Novosibirsk BINP

Photo- courtesy of Yu Shatunov (May 2007)



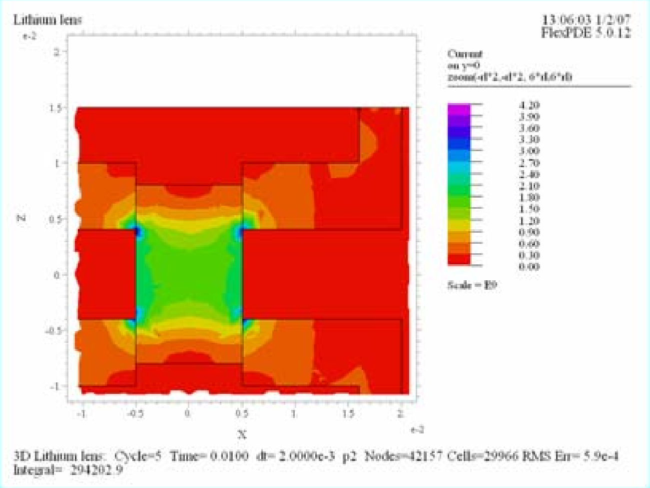
First lens is used for focusing of primary 250 MeV electron beam onto the W target,

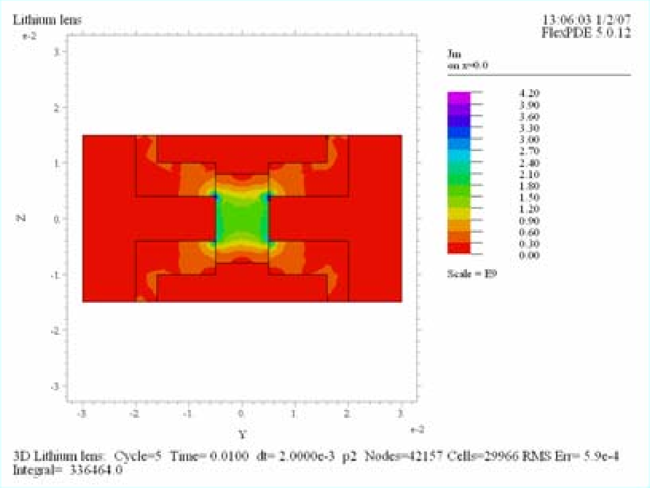
Second lens installed after the target and collects positrons at ~150MeV

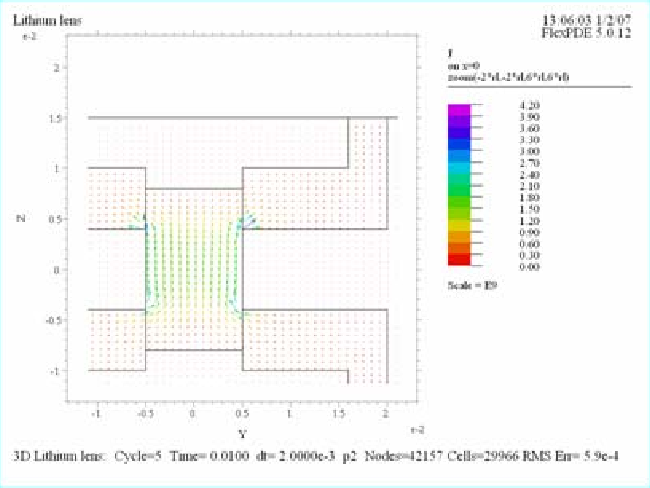
Number of primary electrons per pulse $\sim 2 \cdot 10^{+11}$; ~0.7Hz operation (defined by the beam cooling in Damping Ring)

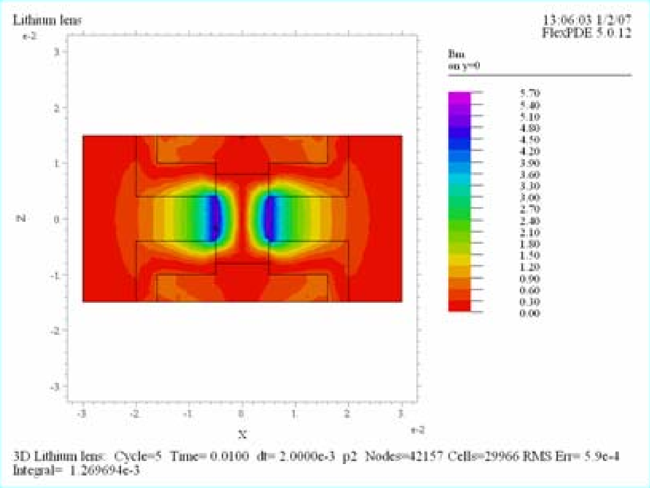
Lenses shown served ~30 Years without serious problem (!)

Recent calculation of Lithium lens done with FlexPDE© code at Cornell









Time dependent 3D calculations

Li lens resume

Lithium lens is well developed technique
It is much simpler for positrons, than for antiprotons

Utilization of Lithium lens allows Tungsten survival under condition required by ILC with $N_e \sim 2x10^{10}$ with moderate K~0.3-0.4 and do not require big-size spinning rim (or disc). Thin W target allows better functioning of collection optics (less depth of focusing).

Usage of Li lens allows drastic increase in accumulation rate, low K-factor.

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

Liquid targets such as Pb/Bi or Hg allow further increase of positron yield.

SOLENOIDAL LENS

One can equalize the focal length of the Lithium lens and the solenoidal one

$$\frac{1}{f} \cong \frac{GL}{(HR)} = \frac{\int H_{\parallel}^{2}(s)ds}{4(HR)^{2}}$$

where (*HR*) =*pc*/300 stands for magnetic rigidity.

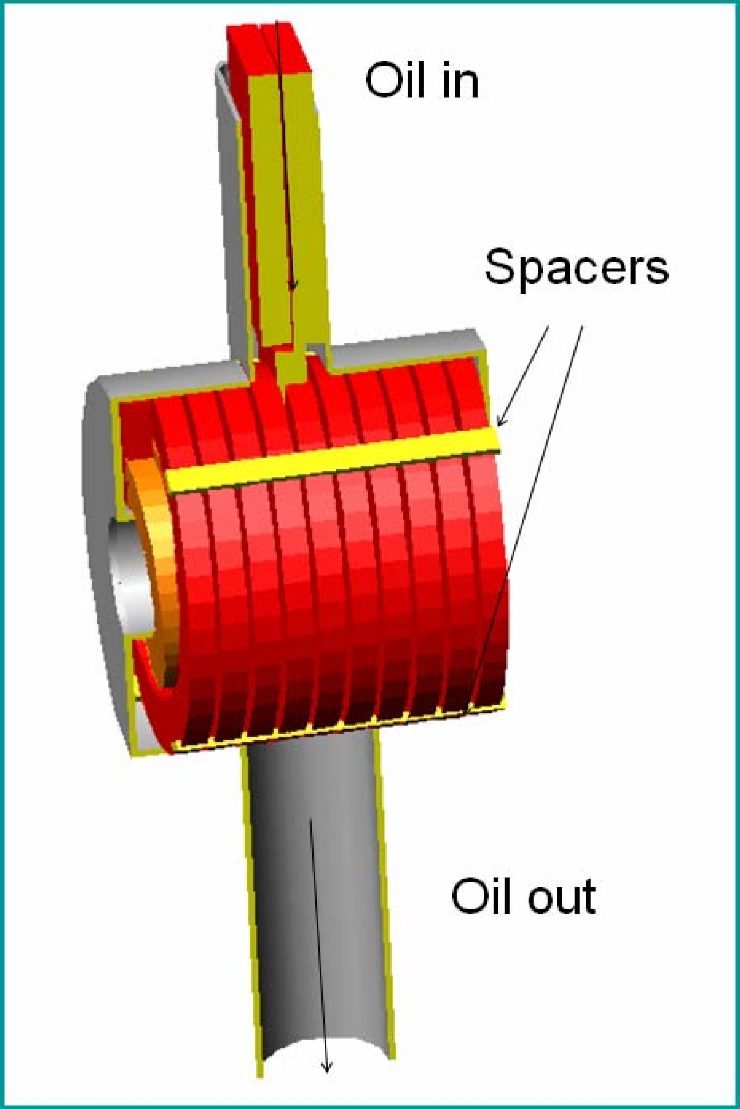
Maximal field comes to $H_{\parallel \max} \cong$ 63kG (for 30MeV particles)

For generation of such field the amount of Ampere-turns required goes to be

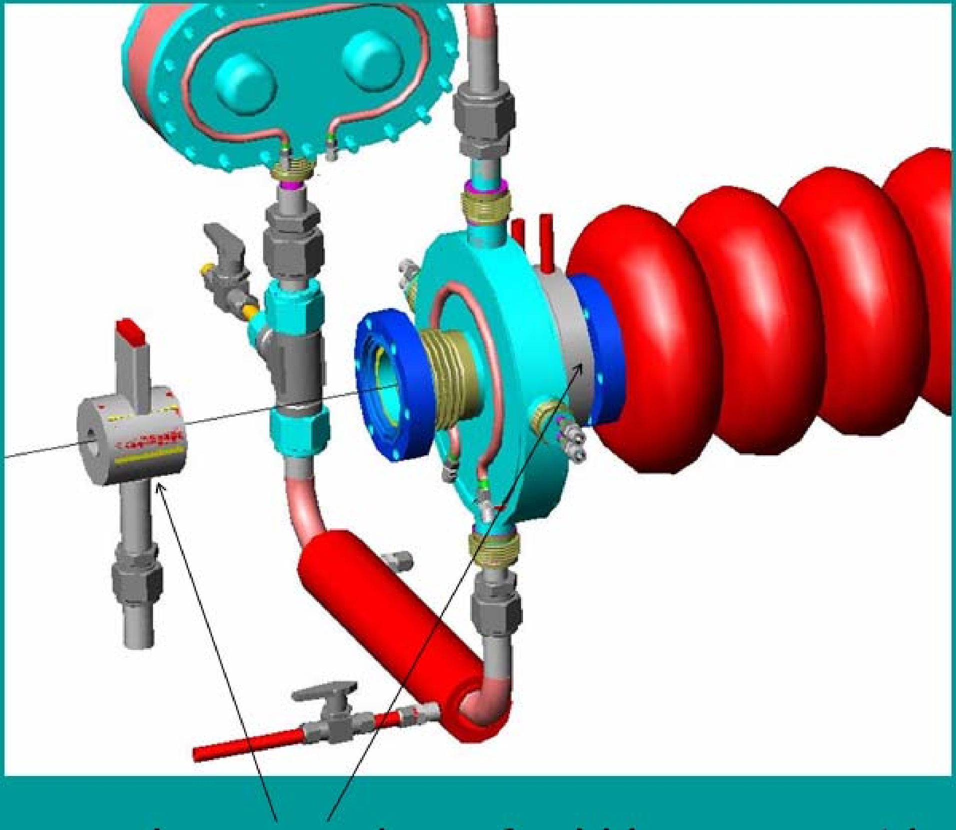
$$nJ \cong \frac{H_{\parallel \max}\Lambda}{0.4\pi \cdot n} \longrightarrow$$ 262 kAxturns (30 MeV)

No flux concentrator possible for 1 msec; skin~3-4mm

Solenoidal lens could be designed with dimensions ~ a bit larger than the Lithium lens



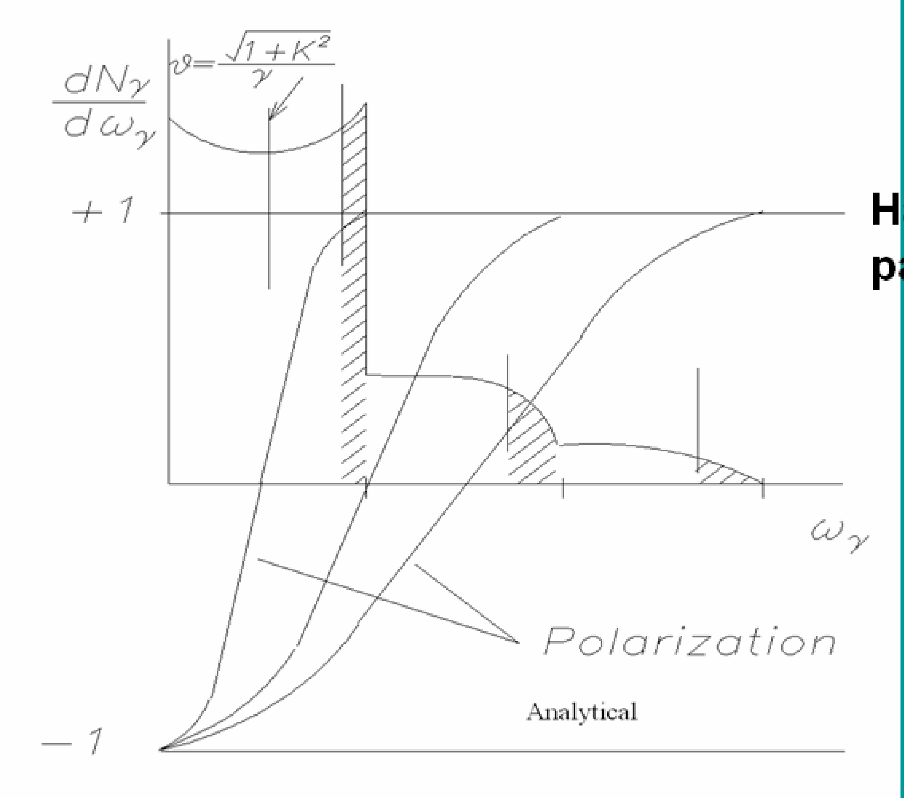
For the number of turns =20, current in one turn goes to I_1~15 kA during~10msec duty time; Two harmonics for feeding current.
Conductor cross-section~ 5x10mm^2;
Coolant-oil



Lenses in comparison; for Li lens current leads are not shown

COLLIMATORS

Collimator for gammas –installed in front of target



Hatched are transmitted part of spectrum

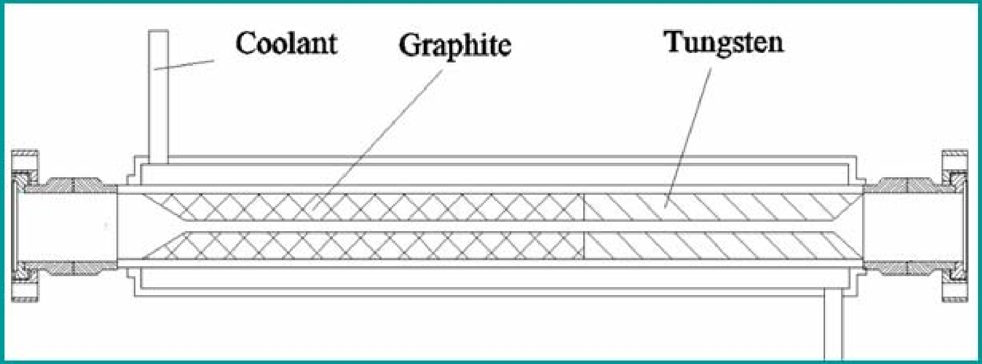
Collimator for full power primary electron beam –installed in front of undulator

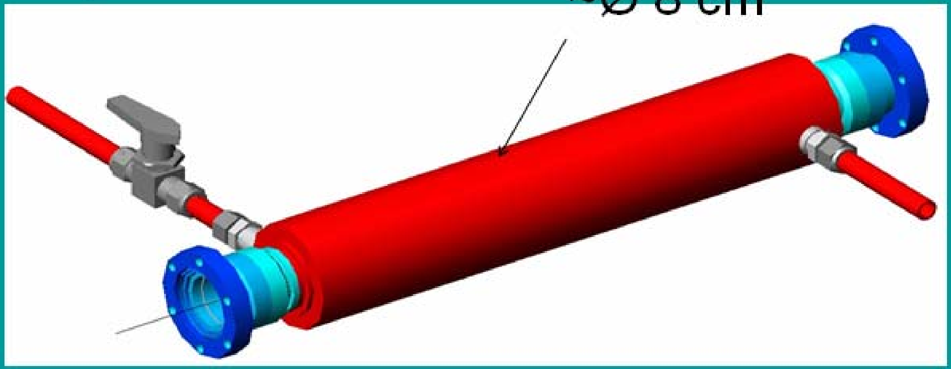
A.Mikhailichenko, "*Collimators for ILC*", EPAC 2006, Scotland, 26-30 Jun 2006. Proceedings, pp.807-809.

Collimator for gammas (Cornell)

Pyrolytic Graphite used here. The purpose of it is to increase the beam size before entering the W part. Ø of aperture ~3 mm

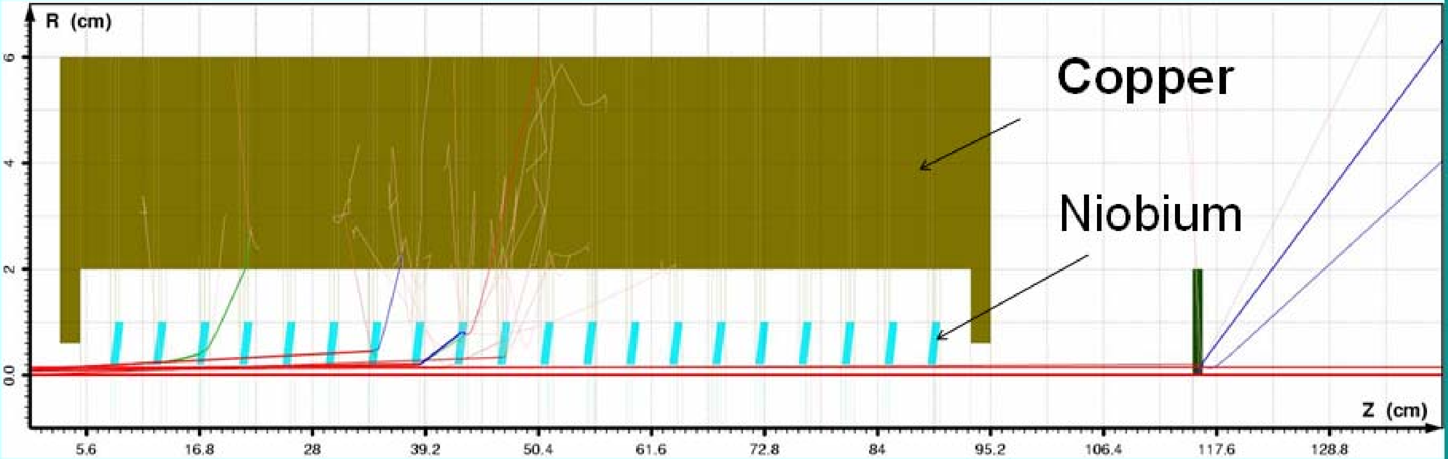
Transverse dimensions defined by Moliere radius





~Ø 8 cm

Collimator for gammas (DESY, U. of Liverpool)

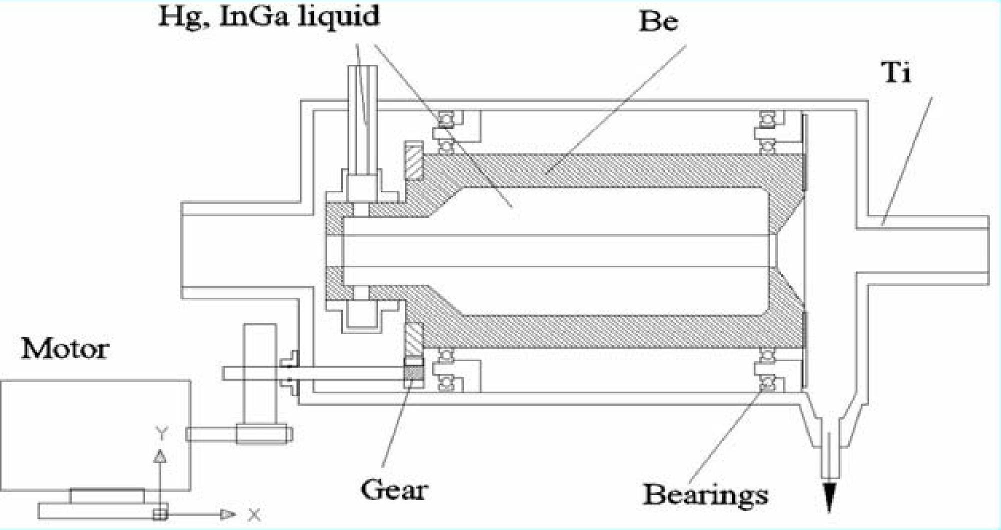


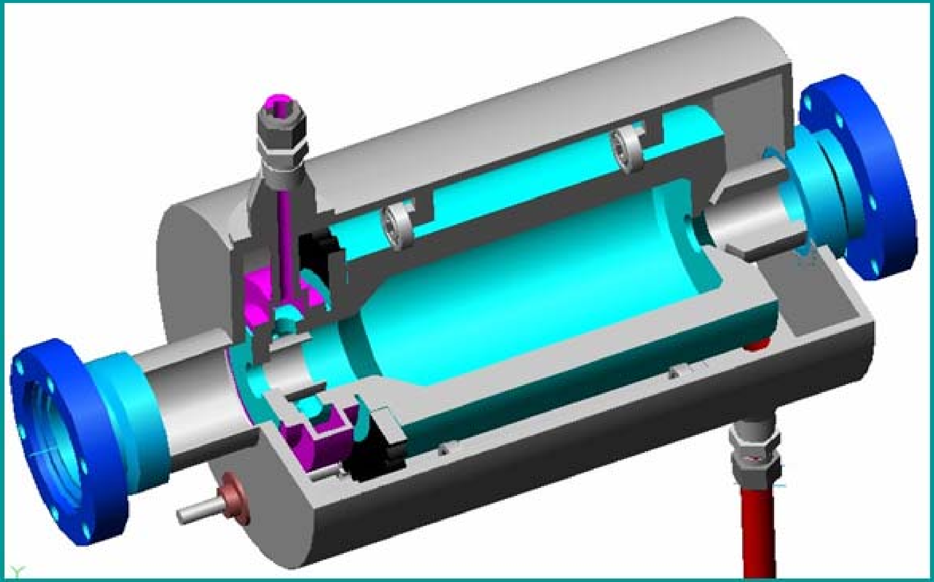
N. Golubeva , V. Balandin; Lei Zang

Power collimator able to accept direct hit of main beam (Cornell)

Installed in front of undulator

Spinning Liquid metal formed a cylinder as result of centrifugal force





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

Differential pumping from both sides

PERTURBATION OF EMITTANCE AND POLARIZATION

Perturbation of emittance

Perturbation of emittance is small as the beam propagates as a straight line

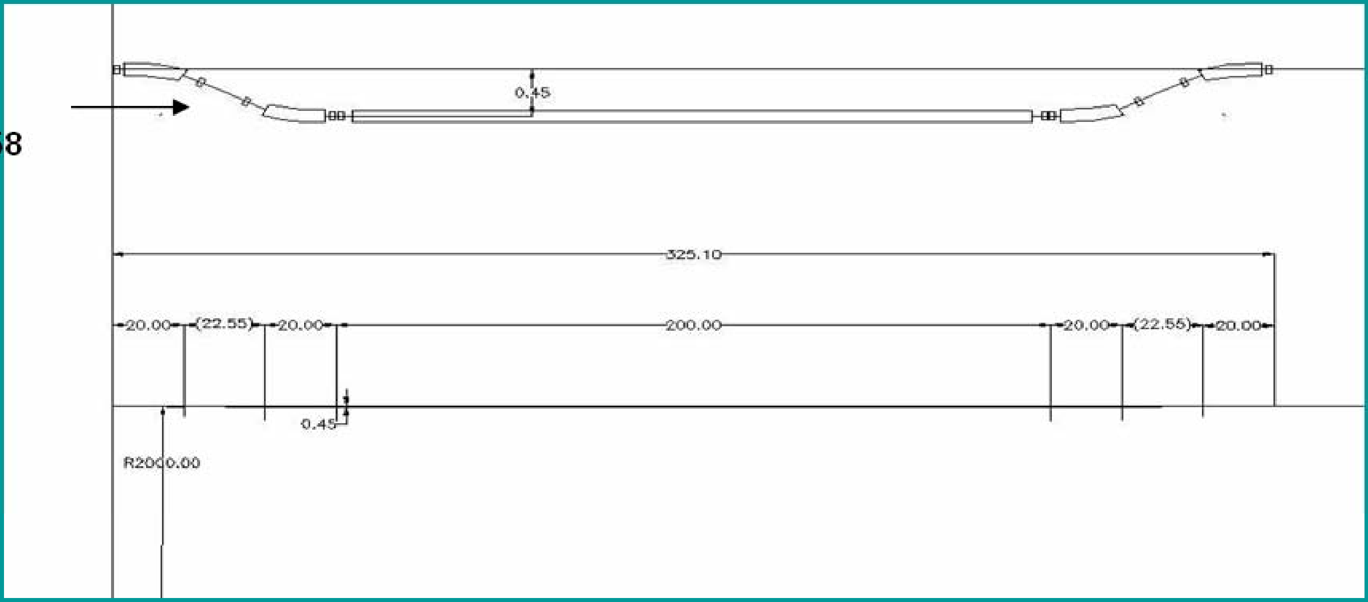
Perturbation of polarization

Perturbation polarization due to multiple scattering	**- absent**
Spin flip in target	**~5%**
Spin flip in undulator	**- hardly mentionable**
Depolarization at IP	**~5%**
Cinematic depolarization in undulator	**-absent**

Polarization drop could be reduced by increasing the length of undulator, making target thinner (two targets) and beams more flat at IP.

UNDULATOR CHICANE

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

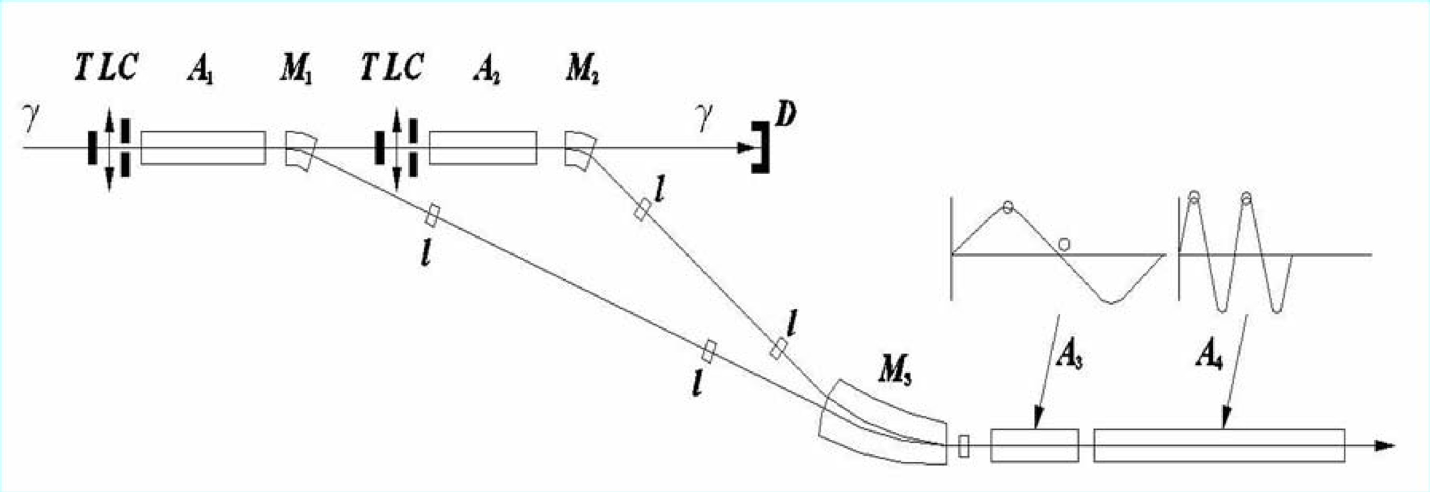


Very high density of SR in any bending magnet, as emittance is extremely small

Systematic analyses of problem done in

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.

COMBINING SCHEME (Cornell)



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.

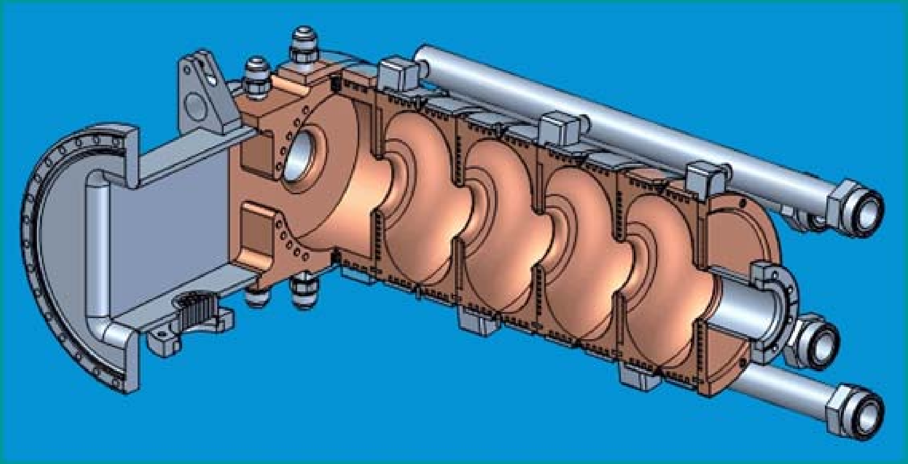
Combining in longitudinal phase space could be arranged easily in the same RF separatrix in damping ring.

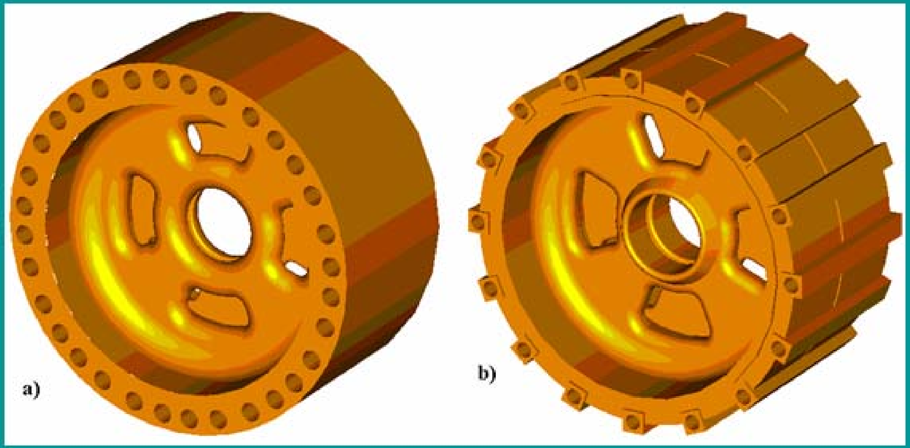
Additional feed back system required for fast dump of coherent motion.

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

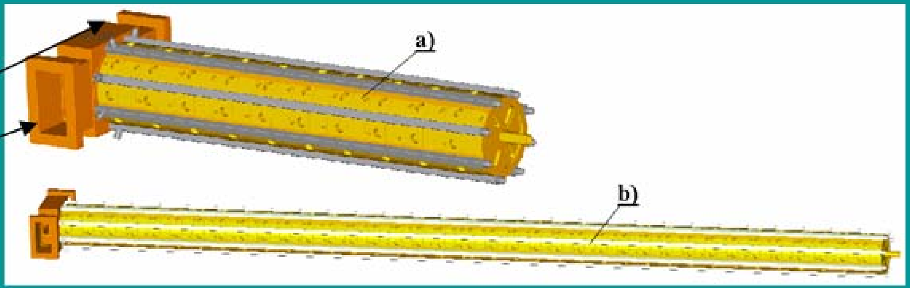
RF STRUCTURES – SLAC and JNR (Dubna)

Structures located right after the target are working in strong solenoidal field (up to 5T)





Accelerating structure, developed at SLAC



Symmetrical input at far from target end

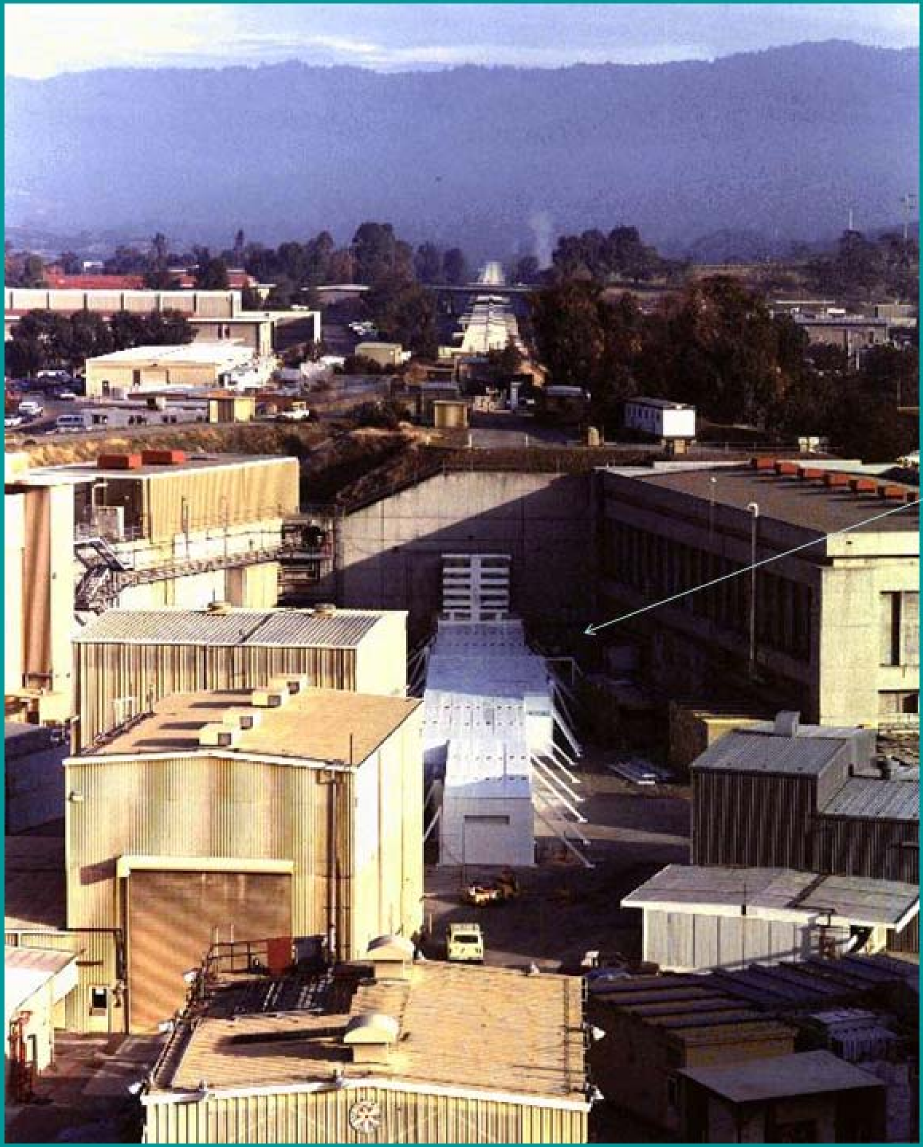
Accelerating structure developed at Dubna (under test in DESY), JINR a) –for high (19 MeV/m) gradient, b) –for moderate (8.5 MeV/m) gradient .

E166 at Final Focus Test Beam area at SLAC

Scale down period of undulator so 50 GeV beam can generate ~9 MeV gammas.

First suggested in 1992

11 Institutions, 33 members

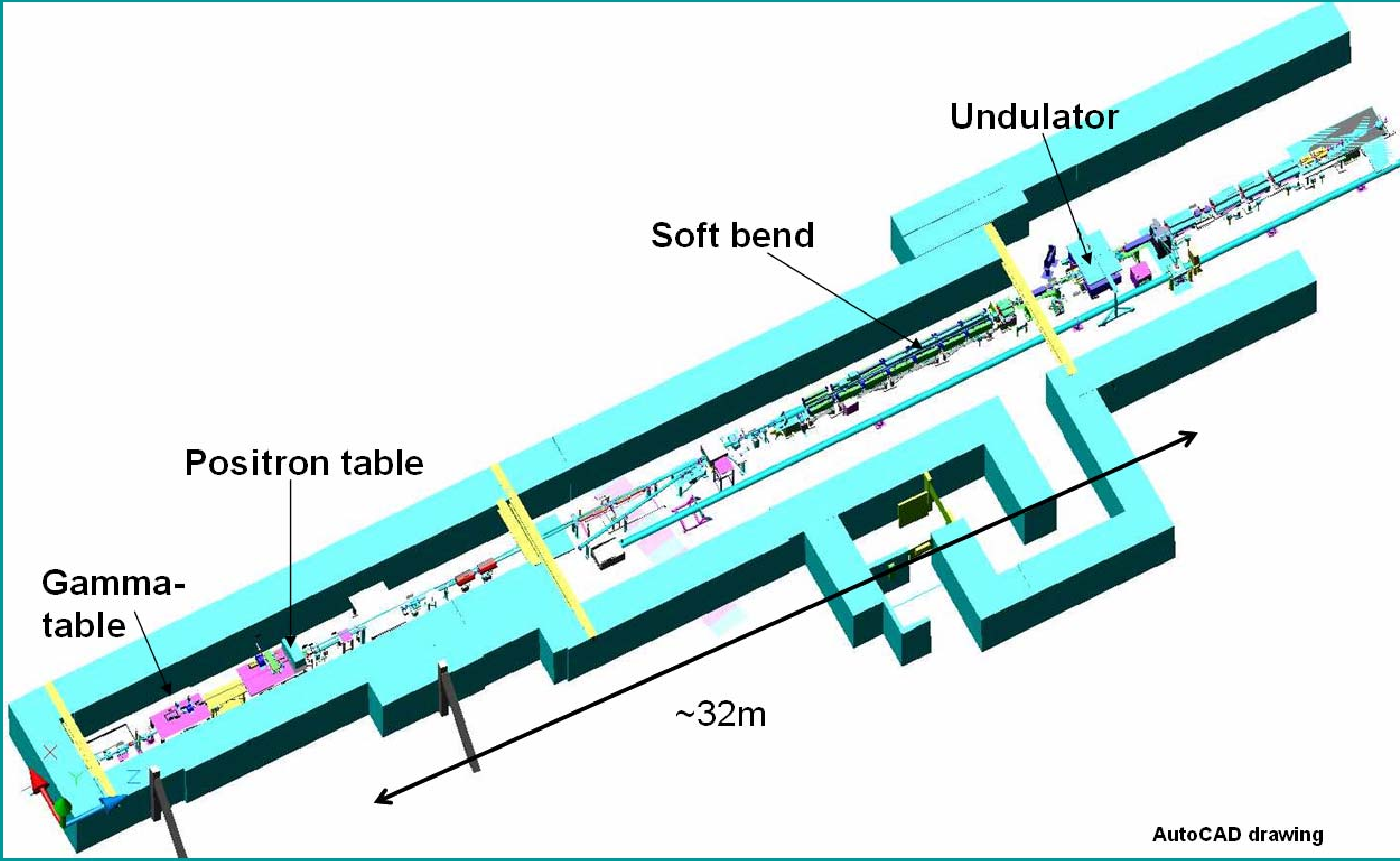


50 GeV, 2×10^{10} e-/pulse, up to 30 Hz

FFTB area

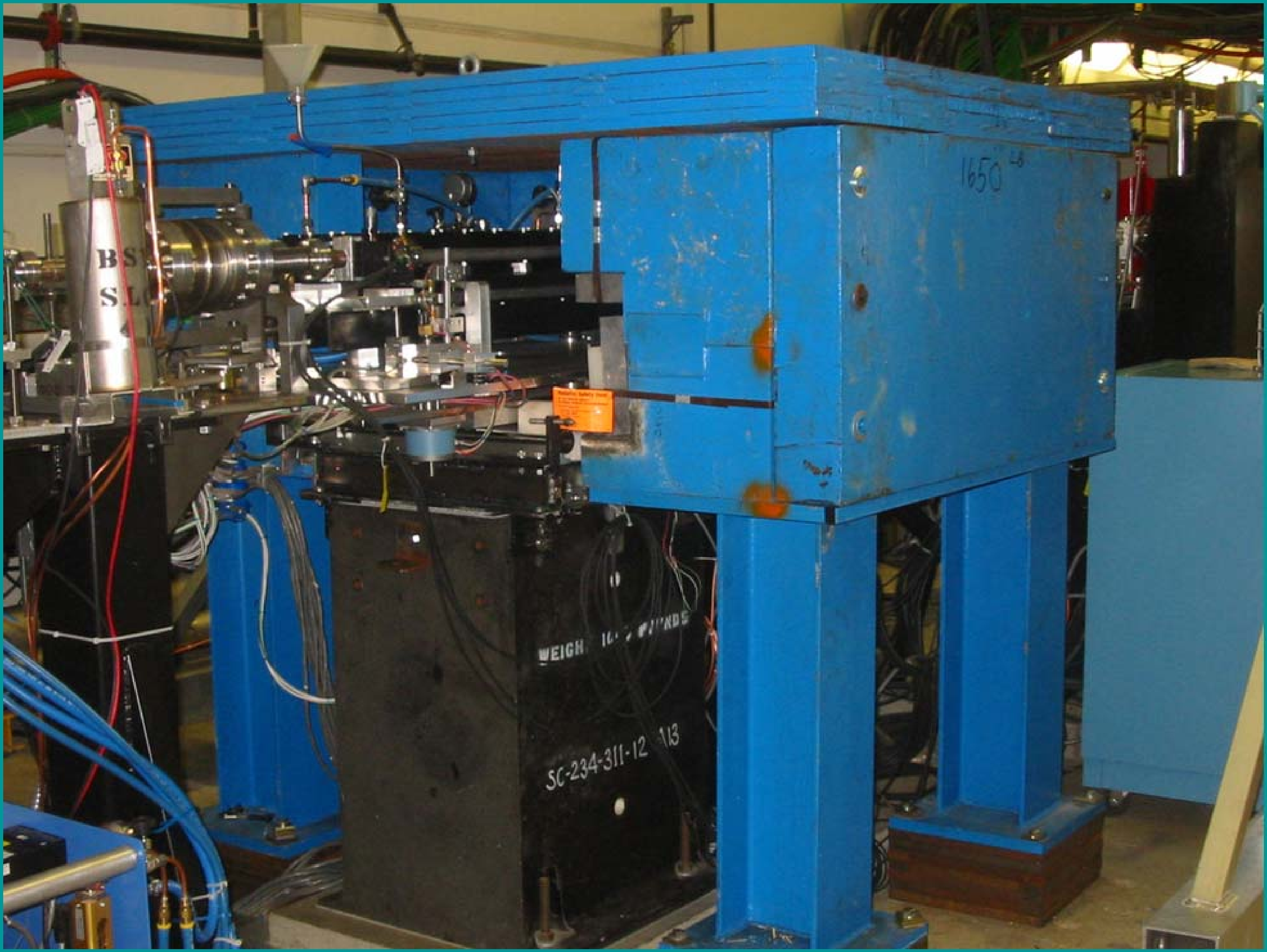
Measurement of positron polarization by coverting positrons into gamms again and use Compton helicity-dependet transmission attenuation

3D scope of E-166



AutoCAD drawing

Undulator area (SLAC FFTB)

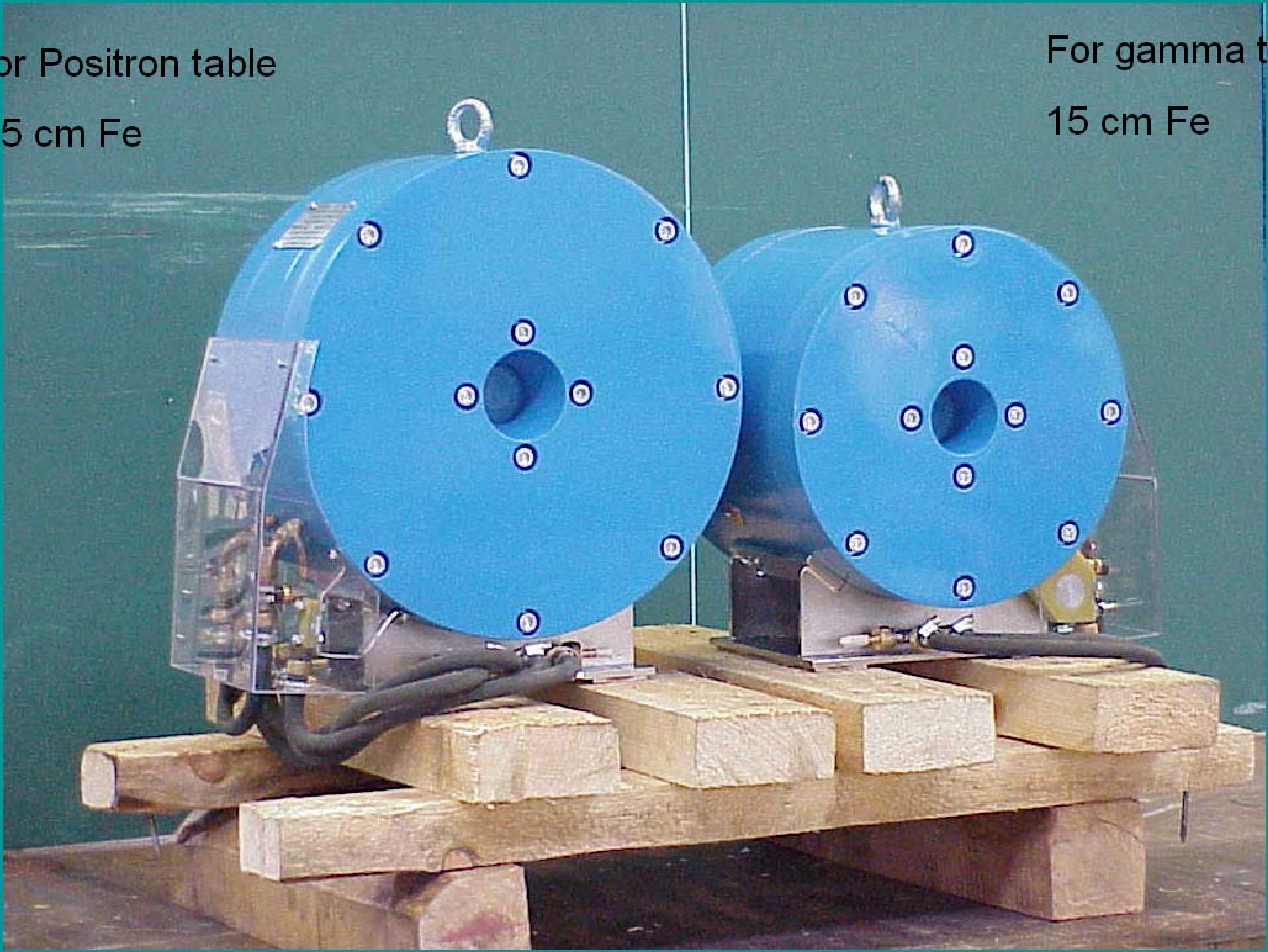


Helical undulator (Cornell)

2.3 kA; 12μsec; conductor 0.6x0.6 mm^2

1 m long; period 2.54 mm; K=0.2; Ø of aperture 0.88 mm

Analyzing magnets (DESY)



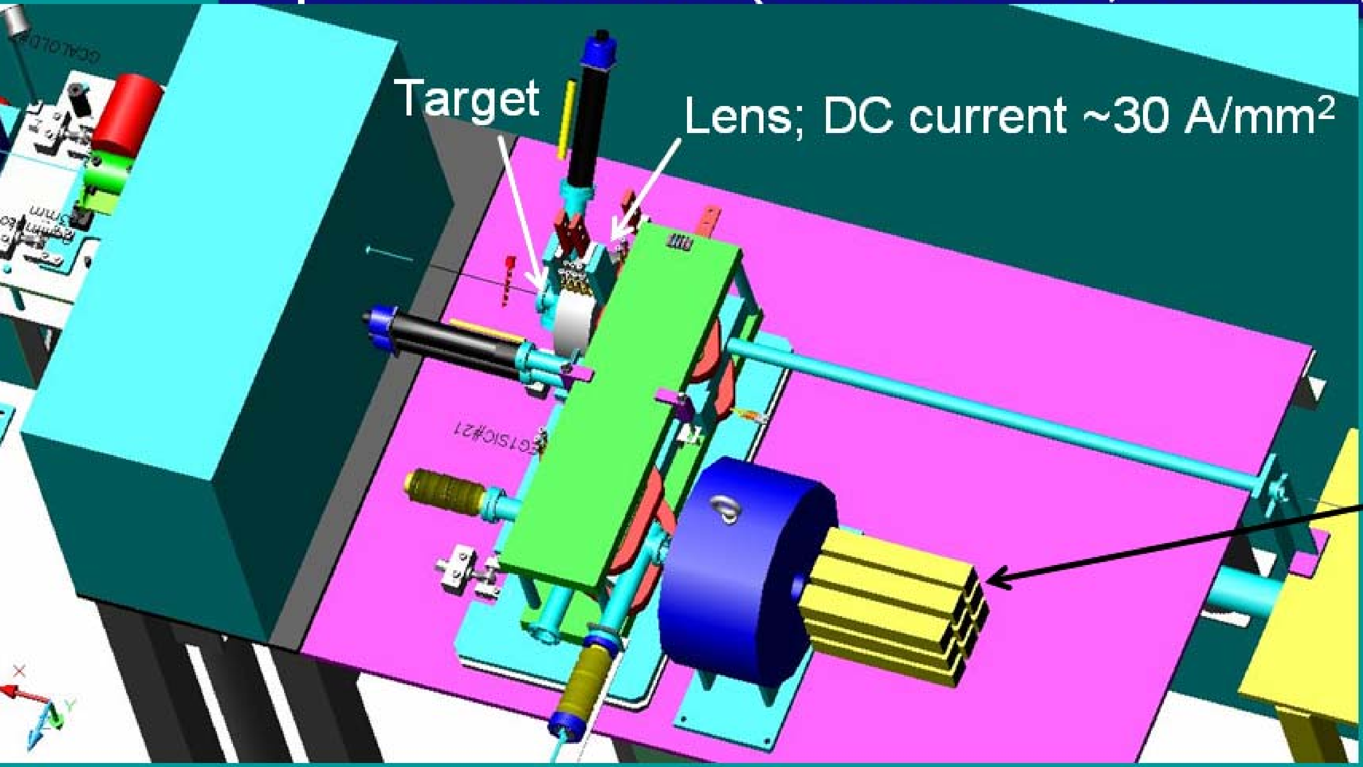
For Positron table

7.5 cm Fe

For gamma table

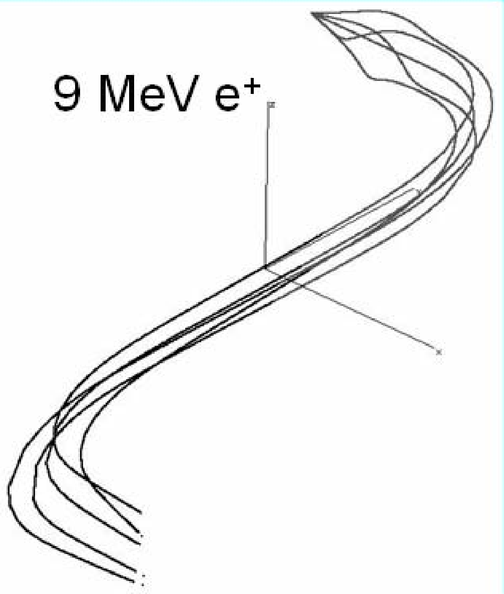
15 cm Fe

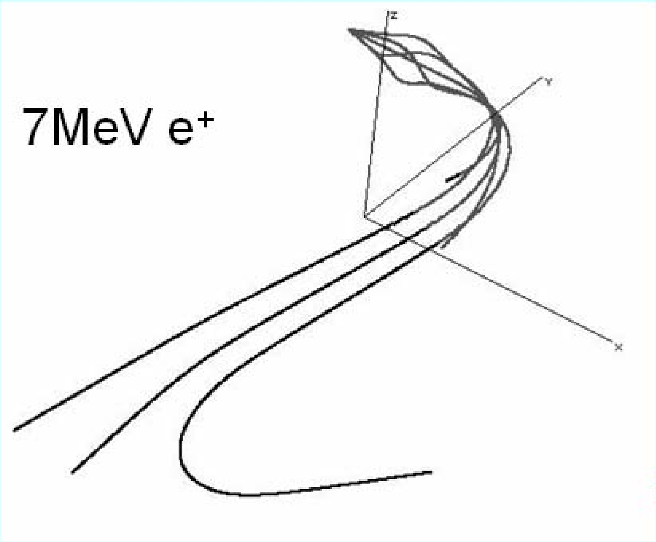
Spectrometer (Princeton, SLAC, Cornell)



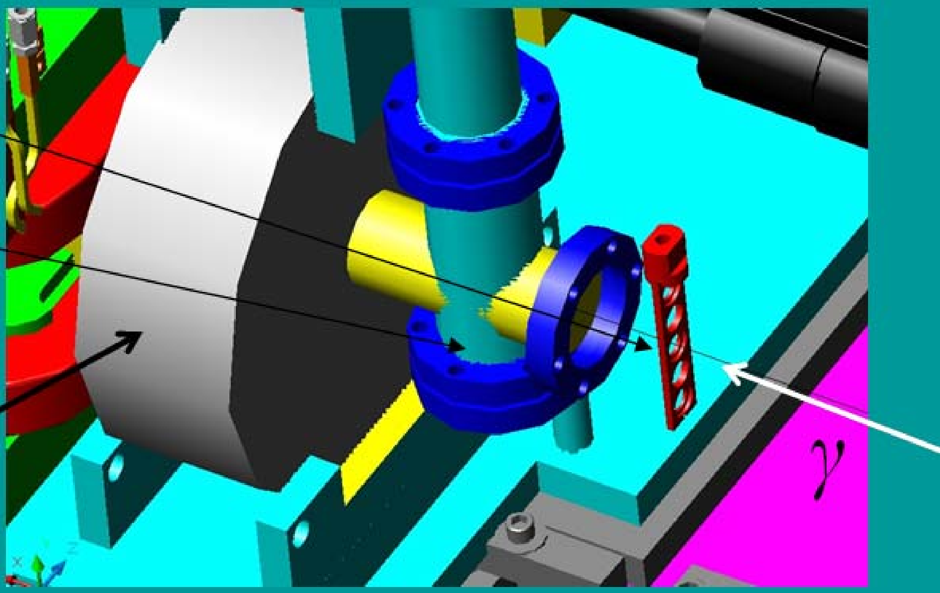
DESY, Humboldt University

Trajectories calculated in 3D field





Target scan



Target holder has 5 slots

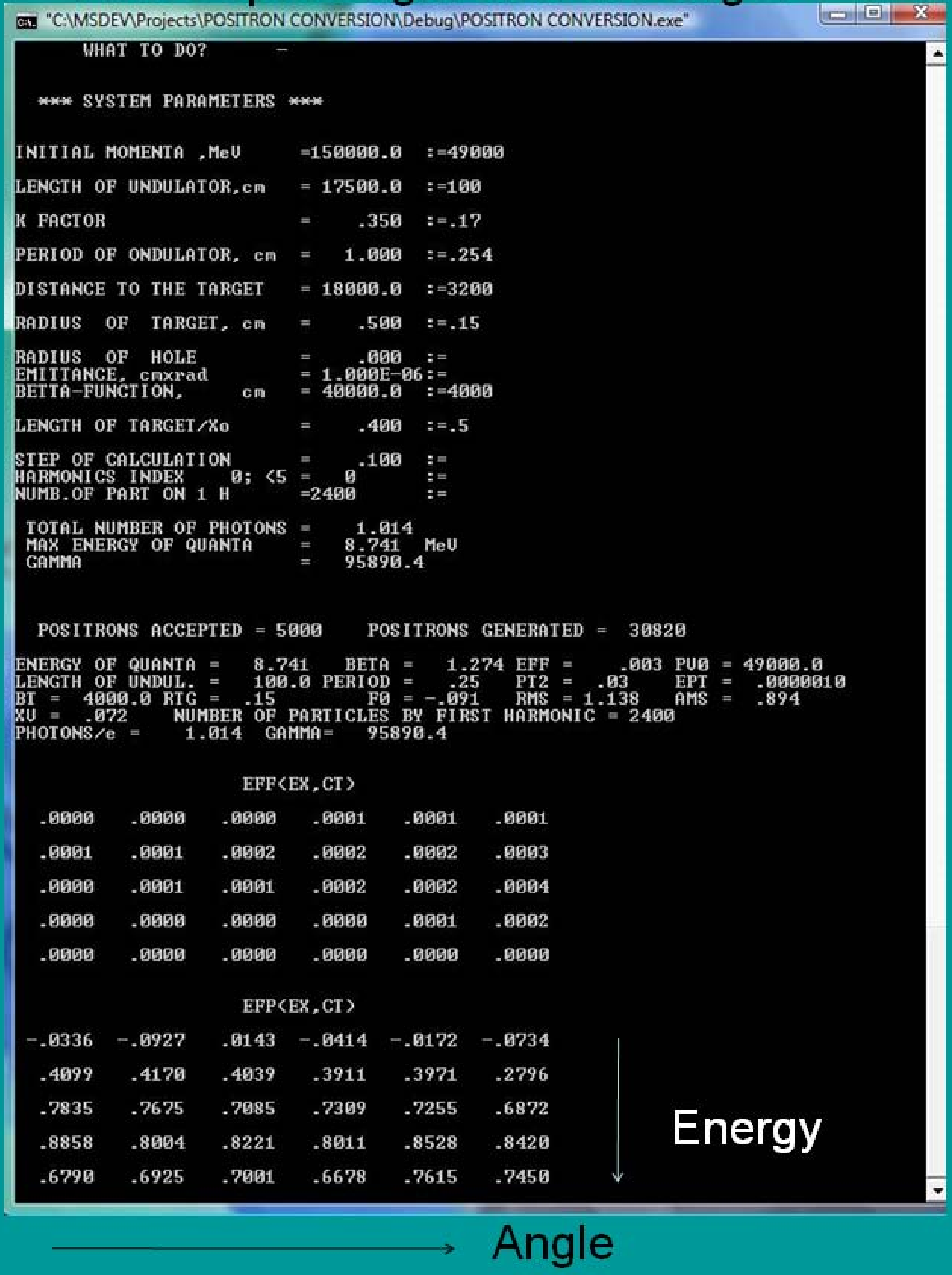
Located inside the chamber and can be moved remotely

DC solenoidal focusing lens; multi-turn, sectioned; water cooled conductor

W target gives ~45% higher yield, than Ti one with the same thickness, ~$0.4X_0$

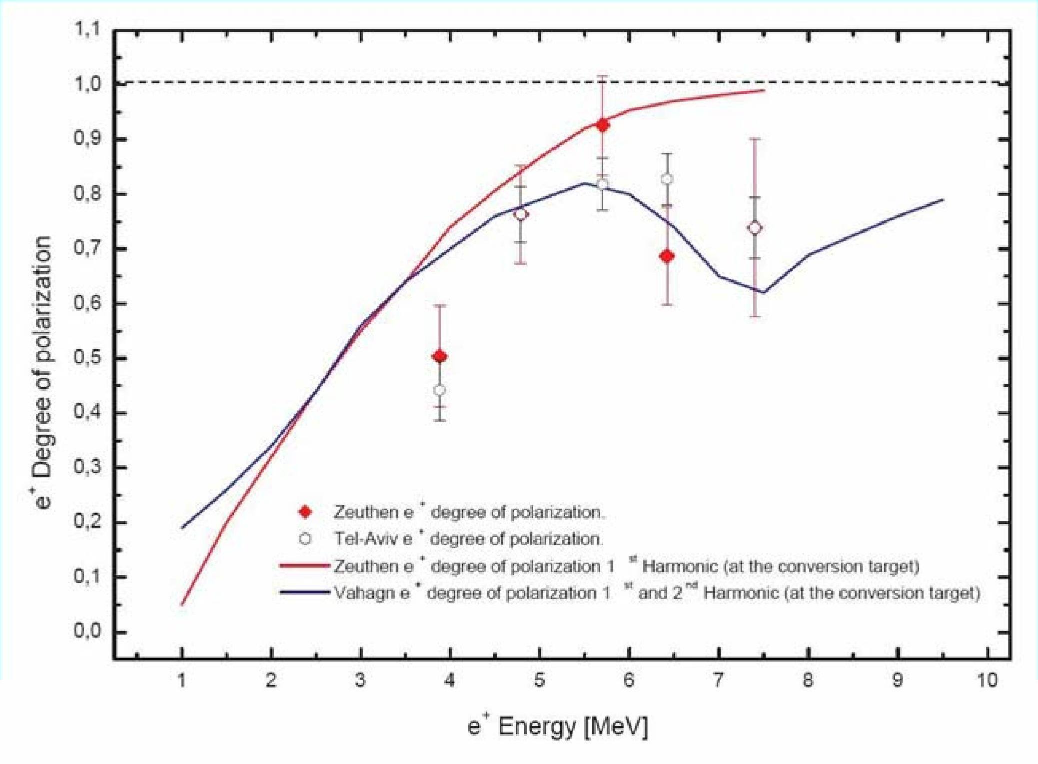
Modeling of E-166 experiment with KONN

Phase space right after the target



```
     WHAT TO DO?      -

  *** SYSTEM PARAMETERS ***

INITIAL MOMENTA ,MeV      =150000.0  :=49000

LENGTH OF UNDULATOR,cm    = 17500.0  :=100

K FACTOR                  =    .350  :=.17

PERIOD OF ONDULATOR, cm   =   1.000  :=.254

DISTANCE TO THE TARGET    = 18000.0  :=3200

RADIUS  OF  TARGET, cm    =    .500  :=.15

RADIUS  OF  HOLE          =    .000  :=
EMITTANCE, cmxrad         = 1.000E-06:=
BETTA-FUNCTION,     cm    = 40000.0  :=4000

LENGTH OF TARGET/Xo       =    .400  :=.5

STEP OF CALCULATION       =    .100  :=
HARMONICS INDEX    0; <5 =   0       :=
NUMB.OF PART ON 1 H       =2400      :=

 TOTAL NUMBER OF PHOTONS =    1.014
 MAX ENERGY OF QUANTA     =   8.741  MeV
 GAMMA                    =   95890.4


  POSITRONS ACCEPTED = 5000    POSITRONS GENERATED =  30820

ENERGY OF QUANTA =   8.741   BETA =   1.274 EFF =     .003 PV0 = 49000.0
LENGTH OF UNDUL. =   100.0 PERIOD =    .25   PT2 =  .03    EPT =  .0000010
BT =  4000.0 RTG =  .15          F0 = -.091   RMS = 1.138   AMS =  .894
XV =  .072    NUMBER OF PARTICLES BY FIRST HARMONIC = 2400
PHOTONS/e =    1.014  GAMMA=   95890.4


                   EFF<EX,CT>

  .0000   .0000   .0000   .0001   .0001   .0001

  .0001   .0001   .0002   .0002   .0002   .0003

  .0000   .0001   .0001   .0002   .0002   .0004

  .0000   .0000   .0000   .0000   .0001   .0002

  .0000   .0000   .0000   .0000   .0000   .0000


                   EFP<EX,CT>

 -.0336  -.0927   .0143  -.0414  -.0172  -.0734

  .4099   .4170   .4039   .3911   .3971   .2796

  .7835   .7675   .7085   .7309   .7255   .6872

  .8858   .8004   .8221   .8011   .8528   .8420

  .6790   .6925   .7001   .6678   .7615   .7450
```

Dependence of polarization seen in experiment



Preliminary

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

Results under submission for publication

CONCLUSIONS

Start to end Monte-Carlo simulation code for conversion running at Cornell confirmed low K factor possible with focusing by Li lens; K<0.4 –big relief for conversion system

Standard packages FLUKA, Geant, EGS4 used for conversion calculations in ANL, SLAC

Dynamic models of pulsed target heating developed (Cornell)

Eddy currents calculations done (Cornell, ANL, LLNL) show problems with spinning target in magnetic field

Cornell team tested 10 and 12 mm period undulators, aperture **8 mm**. Reached K=0.467 for 10 mm period. Reached K=0.83 for 12 mm period
Will be build undulators with 6.35mm aperture, K~0.7 for 10mm; and K~1.2 for 12mm;
Pumping of Helium was tested at Cornell, gain >10%;
Arranged fabrication of yokes up to 3 m long in industry;

Daresbury team tested undulator with period 11.5 mm, K=0.93, aperture 5.35 mm

4-m long Undulator module fabrication and its test is a priority job→ end 2007; Cornell and Daresbury

Undulator design satisfies ILC demands, polarization at initial stage will be 30%; possible 60%

Target requires **more efforts** for final choice;
Collection optics requires **more efforts** for other than Lithium lens (Li lens-OK);

For 2x500 GeV, conversion system requires **more efforts** (one solution is to move the system as a whole to a new 150 GeV point)

E-166 diffused any doubts about undulator-based positron production for ILC

Back-up slides

E-166 experiment at SLAC

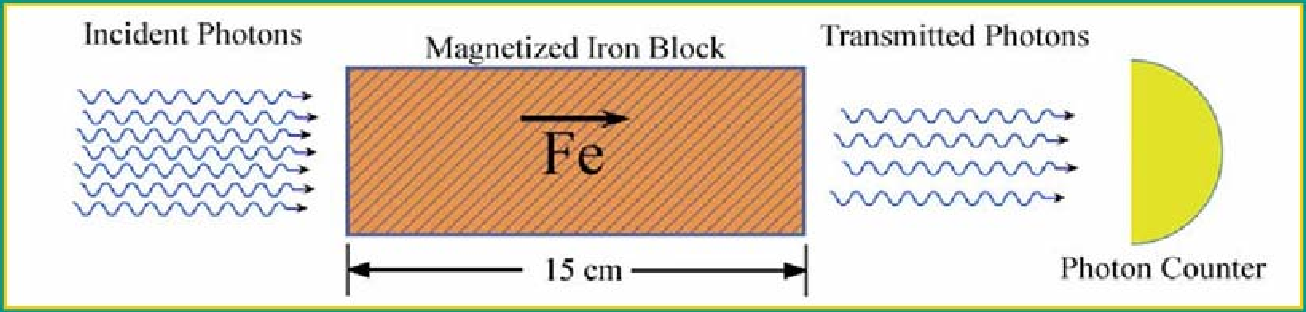
Experimental test of polarized positron production With gammas generated by high energy beam in undulator

Just remind

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

Goes to few mm period for 50 GeV beam

Transmission Polarimetry



- Compton scattering depends on polarization
- Attenuation: $T(L) = e^{-nL(\sigma_{phot}+\sigma_{pair}+\sigma_{comp\,0})}\, e^{\pm nLP_\gamma P_e \sigma_{pol}}$
- Asymmetry: $\delta(L) = \dfrac{T^+ - T^-}{T^+ + T^-} \approx nLP_e P_\gamma \sigma_{Pol}$
- By knowing P_e => P_γ can be calculated:

A-analyzing power

$$P_\gamma = \frac{\delta}{nL\sigma_{pol} P_e} = \frac{\delta}{A_\gamma P_e}$$

$$\delta = 0.0266$$

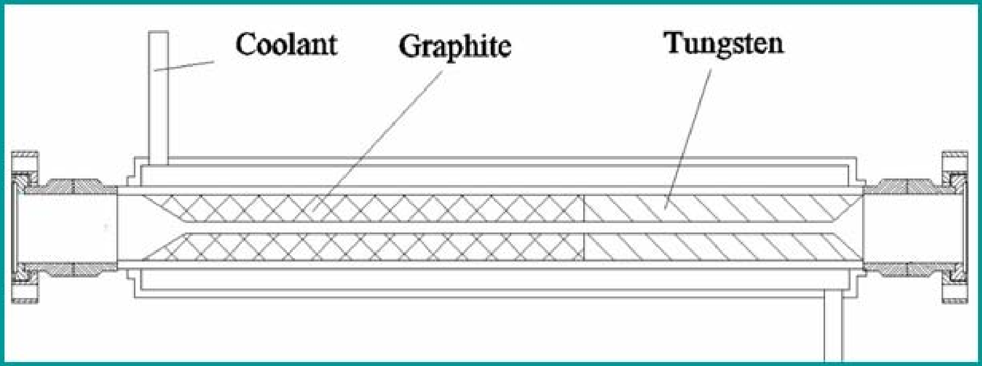
$$P_e = 0.07$$

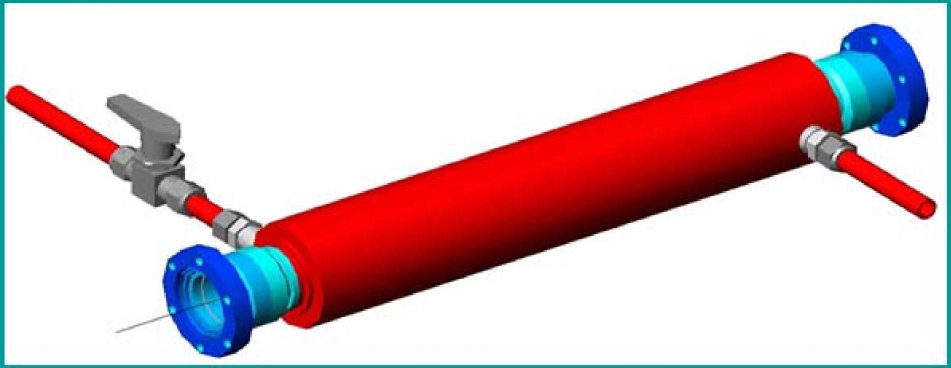
$$\langle A_\gamma^E \rangle = 0.62$$

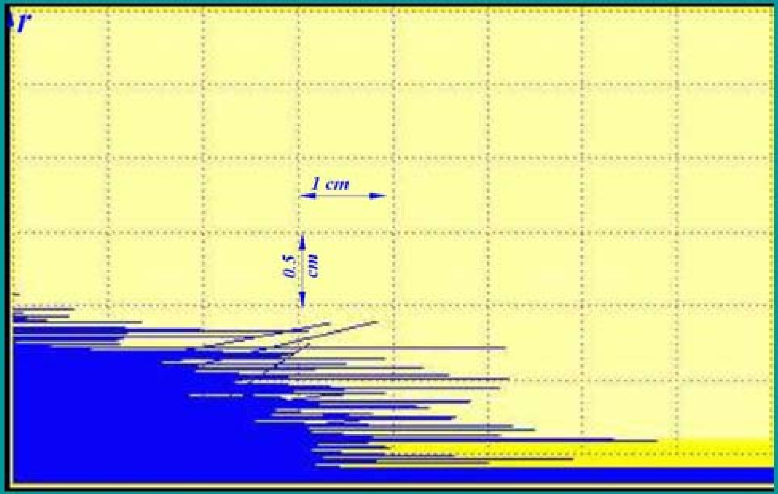
Collimator for gammas (Cornell)

Pyrolytic Graphite (PG) is used here. The purpose of it is to increase the beam size before entering to the W part. Ø of aperture ~3 mm

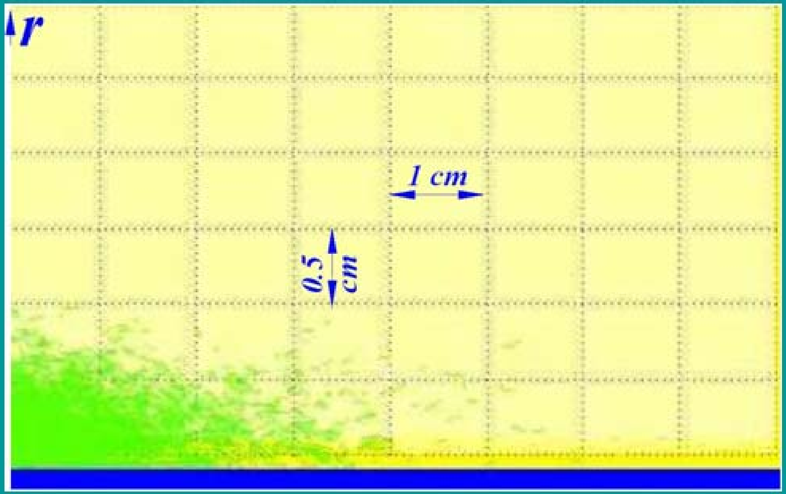
Transverse dimensions defined by Moliere radius





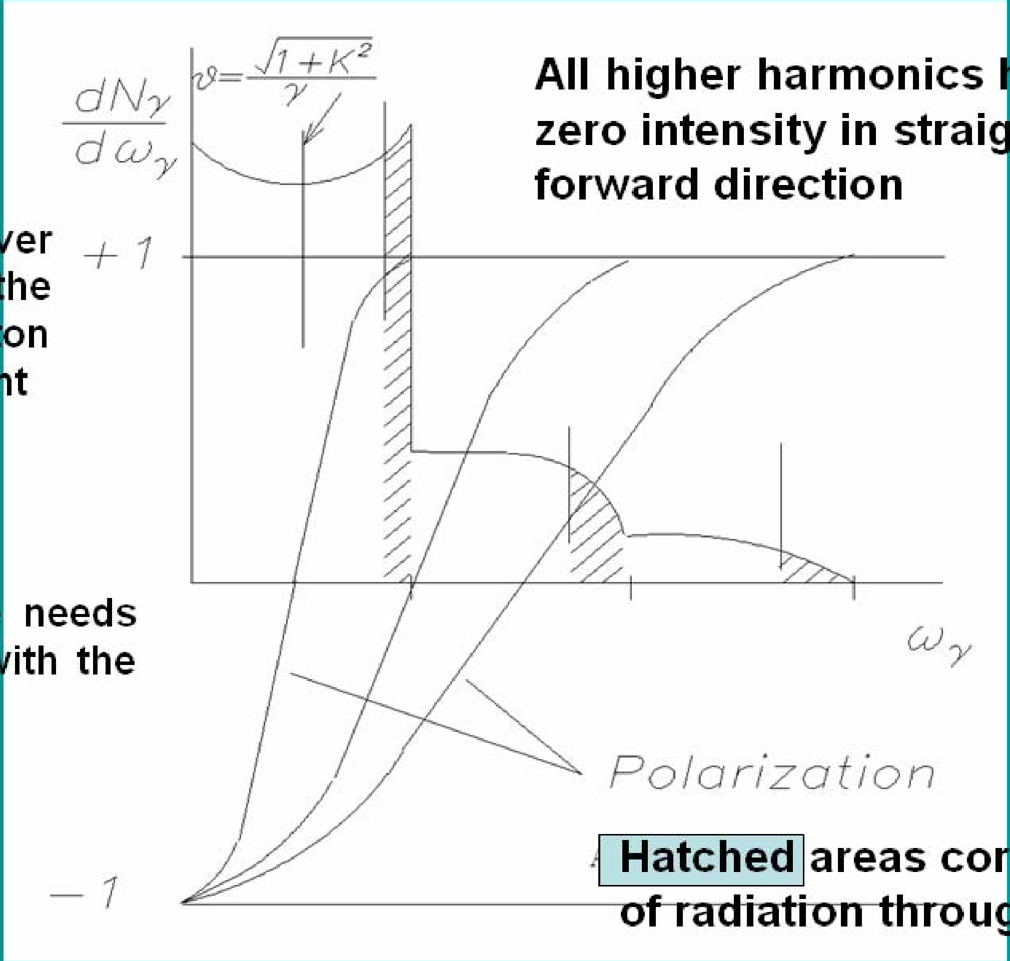


Gamma-beam. s_g= 0.5cm, diameter of the hole (blue strip at the bottom) *d*=2 mm. Energy of gamma-beam coming from the left is 20 *MeV*.



Positron component of cascade

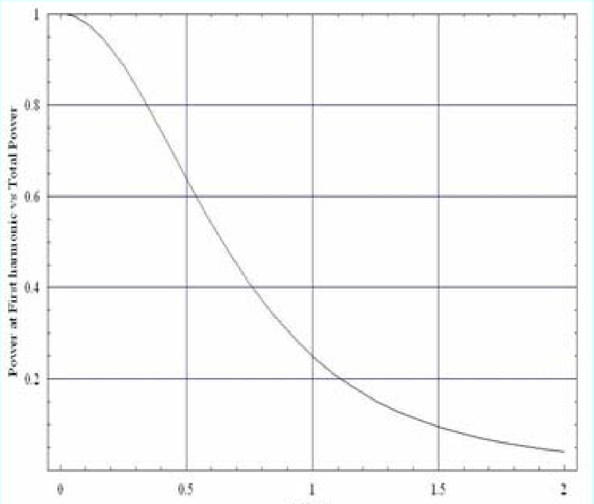
Spectral distribution and polarization schematics



All higher harmonics have zero intensity in straight forward direction

Angle to observer (radiation) and the energy of the photon are not independent

Polarization curve needs to be convolved with the photon density



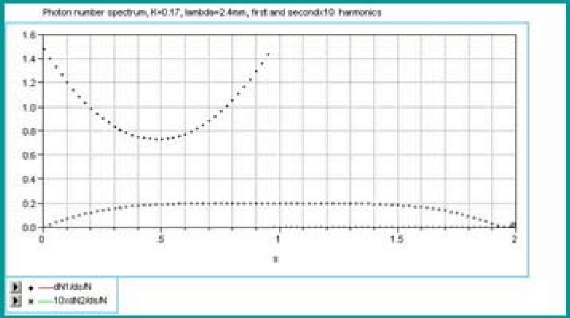
Ratio of Power radiated at first harmonic to the all power; at K=0.7 it is 50%

Hatched areas correspond to a passage of radiation through a diaphragm

Diaphragm helps to enhance integrated photon polarization

Analytical calculations of conversion

Spectral density of radiation $$\frac{dN_\gamma}{dE_\gamma}=\sum_n \frac{dN_{\gamma n}}{dE_\gamma}=\frac{\alpha K^2 L}{\eta c 2\gamma^2}\sum_{n=1}^{\infty}F_n(K,s)$$



where $s=E_{\gamma n}/E_{\gamma n\max}$ $E_{\gamma\max}$ **is the energy of photon radiated straightforward**

$$F_n(K,s)=J_n'^2(n\kappa)+\frac{1+K^2}{4K^2}\frac{(2s-1)^2}{s(1-s)}J_n^2(n\kappa)\qquad \kappa=2K\sqrt{s(1-s)/(1+K^2)}$$

The number of positrons generated by a single photon in the target becomes

$$\frac{dN_+}{dE_+d\tau}\cong 0.4\frac{\alpha K^2 L}{\gamma^2\eta c}\frac{7}{9}(1-E/E_{\gamma 1})(1-e^{-7\tau/9})$$

H. Bethe, W.Heitler, 1934

For *E*$_0$=150 *GeV, L*=150 *m*, *K*^{2}=0.1, τ=0.5 (rad units)

$$\frac{1}{N_{tot}}\frac{dN_+}{dE_+}\cong 0.2\,[1/MeV]$$

η --geometrical efficiency of capture

Analytical formula taking into account finite length of undulator and finite diameter of target

E.Bessonov, A.Mikhailichenko, 1992

$$\Delta N_{+1}\cong 2\cdot 10^{-2}\chi^2\frac{L}{\lambda u}\delta\frac{K^2}{1+K^2}\frac{z_f}{z_i}\eta$$

$Z_{f,l}$ - are the coordinates of undulator end and beginning calculated from the target position;

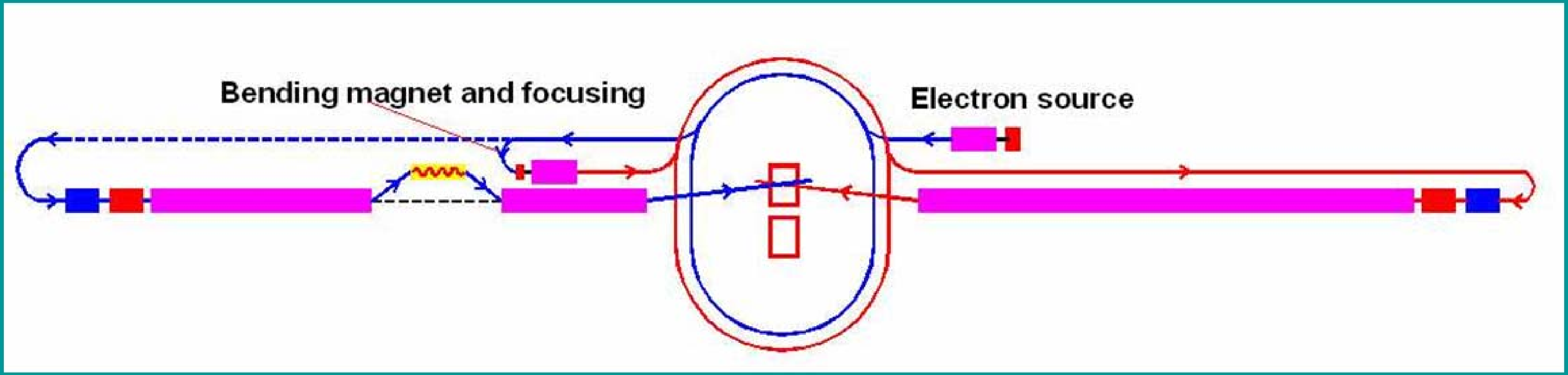
χ is a fraction of what is the target radius in respect to the size of the gamma spot at the target distance

For χ = ½ , L=200m , λ_u=1cm δ=0.5, K=0.35, η=0.3

$\Delta N_{+1}\cong$ **3**

Scheme is rather flexible

Filling positron ring from electron source



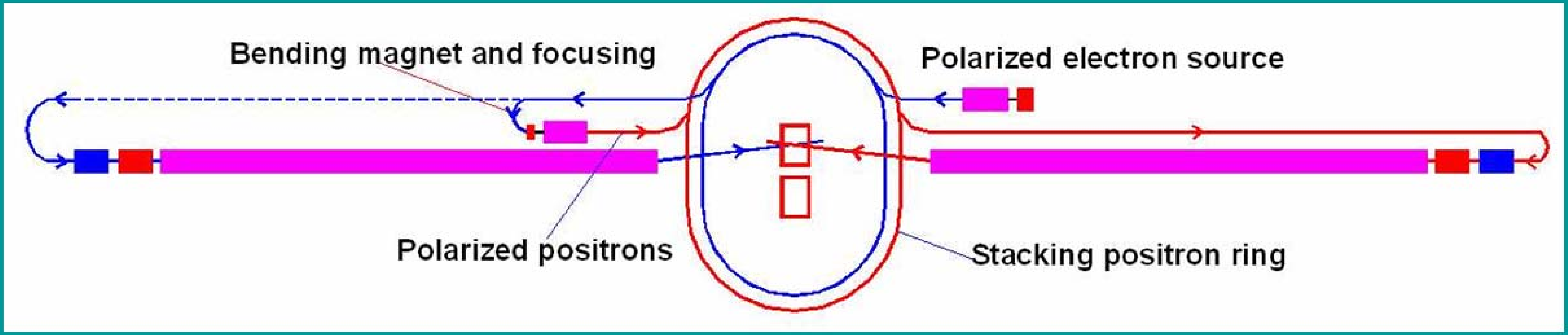
Comment: One practical application of a diagram with polarized electron

POLARIZED POSITRON PRODUCTION WITH STACKING IN DR

If stacking in DR is allowed, then there is one additional way to generate polarized positrons.

Calculations show that efficiency ~1.5% is possible for the first process with polarization ~75%

Realization of this method



The efficiency is the same as for back-scattering of laser radiation

Undulator-based scheme remains more advantageous, however

Estimation

H.Bethe, W.Heitler, 1934

Total cross-section per one atom

$$\sigma_{tot} \cong \int_0^1 \frac{A}{N_0 X_0} G(x)dx \cong \frac{7}{9}\frac{A}{N_0 X_0}$$

$$G(x) = x^2 + (1-x)^2 + \frac{2}{3}x(1-x) - x(1-x)/(9\ln(183Z^{-1/3})$$

The number of the positrons at the exit of the target

$$N_+ \cong N_\gamma \sigma_{tot} N \cong \frac{7}{9} N_\gamma \tau$$

τ-thickness in X_0 units (~0.5)

Let η describes the geometrical efficiency of capture, then for η=0.3

$$N_+ / N_\gamma \approx \frac{7}{9}\cdot\tau\cdot\eta = \frac{7}{9}\cdot 0.5\cdot 0.3 \approx 0.11(11\%)$$

This factor must be reduced by 1/3 –cross section difference from 7/9 , coming to

$$N_+ / N_\gamma \approx 3.5\%$$

So the number of photons per electron required ~30 for each positron at the exit

Using the formula for the number of photons

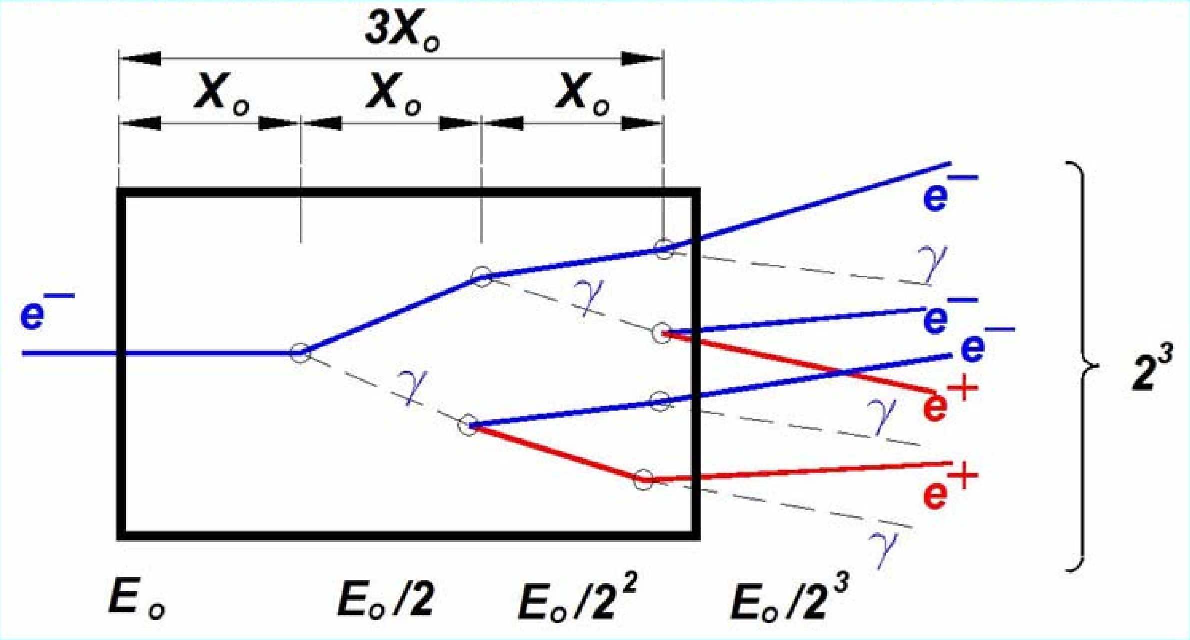
$$30 = 4\pi\alpha \frac{L}{\lambda_u} K^2 \quad \rightarrow \quad K^2 = 30\lambda_u / 4\pi\alpha L$$

Substitute here L=200m, λ_u=*1cm,* one can obtain $K \approx 0.13$

In reality K~0.3-0.4 required for spare

Gamma beam passes thought target with~13% attenuation; few targets can be used (Cornell)

CONVENTIONAL POSITRON SOURCE-CASCADE PROCESS



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 the energy of particles reaches the critical one, $E_{crit} \cong 610/(Z+1.24)$

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**

E166 collaboration

Helical Undulator based polarized positron source for the ILC

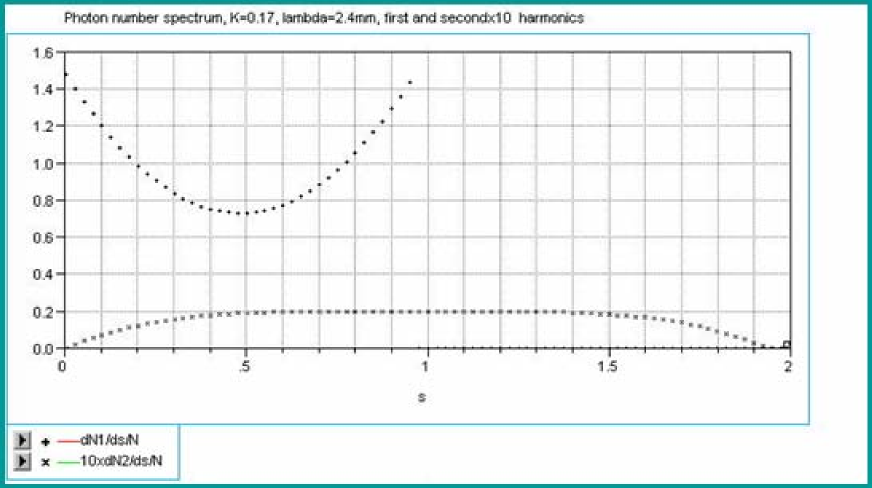
Undulator radiation in E-166

$$\frac{dN_\gamma}{dL} = \frac{30.6}{\lambda[mm]}\cdot\frac{K^2}{1+K^2}\,\frac{phot}{m\,e^-} = 0.37\,\frac{phot}{m\,e^-}; K = 0.17$$

$$E_C = 24.8[MeV]\frac{\left(E_e/50[GeV]\right)^2}{\lambda\,[mm]\left(1+K^2+\gamma^2\theta^2\right)} \sim 9.6\ MeV$$

Energy spectrum

Polarization



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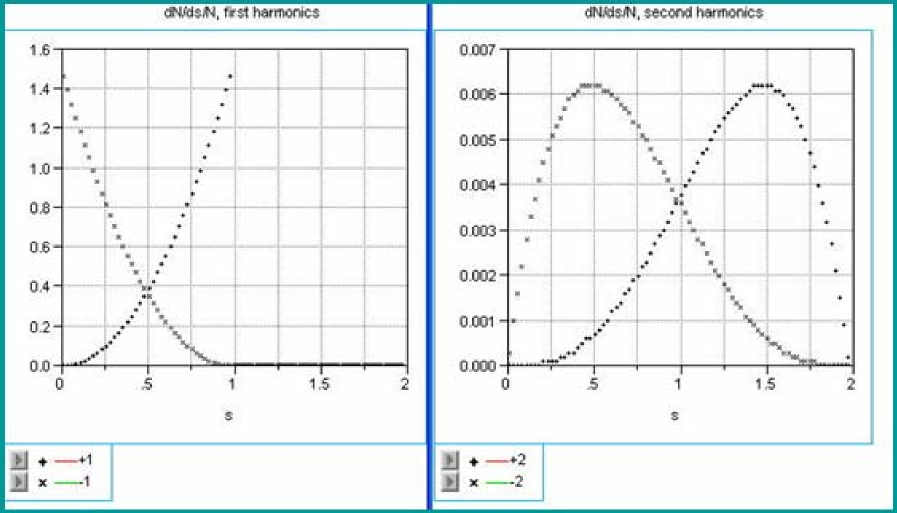
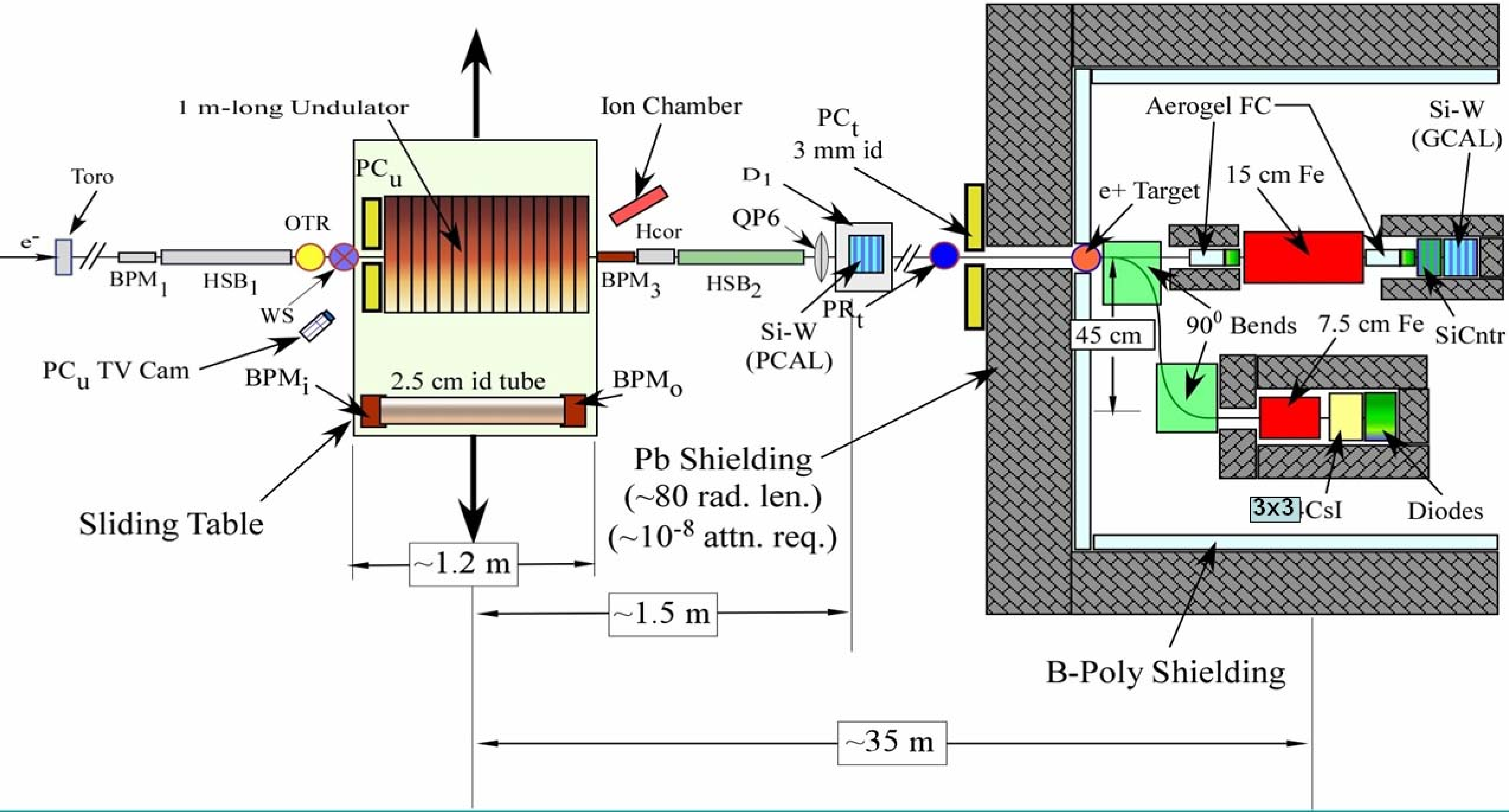


K=0.17

E-166 : Plan View, r2
(50 GeV)



Energy deposition in Be flanges is going by secondary particles (positrons and electrons) is $\delta E \sim 2\ MeVcm^2/g$, Secondary beam diameter $d \approx 1cm$.
Area illuminated is going to be $S = 1/4\ \pi d^2 \approx 0.4\ cm^2$.
Volume density of Be is $\rho \approx 1.8\ g/cm^3$, for thickness 0.5 *mm*
Energy deposited in a material of flange going to be

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

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

$$E_{tot} \cong \Delta E \times N \times n_b \times e \qquad \text{Joules},$$

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

$$E_{tot} \cong \quad 1.8\ J.$$

Factor reflecting spare particles, ~1.5-2 , factor two- reflecting equal amount of electrons and positrons and, finally, factor reflecting efficiency of capturing (~30%).
So the final number comes to→ ≈21*J*.
Temperature gain by heat capacity of Be $C_v \approx 1.82\ J/g/degC$ comes to

$$\Delta T \cong \frac{E_{tot}}{mC_v} \cong \frac{E_{tot}}{\rho SlC_v} \cong \frac{21}{1.8 \times 1.82 \times 0.05 \times 0.2} \cong \quad 660 \text{ deg.}$$

One needs to add the initial temperature which is above melting point of Lithium, coming to maximal temperature ~850-900 deg. Meanwhile the melting temperature of Be is 1278 deg, so it withstands.

If the focal distance is given, the current required could be found as $I \cong \frac{a^2 \cdot (HR)}{0.2FL}$

For the primary electron beam of say, 20 *MeV* $(HR) \cong 66kGcm$. Suggesting F=0.5 cm, L=2cm, a=0.5cm

$$I \cong \frac{0.5^2 \cdot 66}{0.2 \cdot 0.5 \cdot 2} = 83.25kA$$

Scattering of the beam in a Lithium rod target could be estimated as $\sqrt{<\theta^2>} \cong \frac{13.6MeV}{pc}\sqrt{\frac{t_{Xo}}{X_{Li}}}$

where X_{eff} –is an effective radiation length of Lithium, $X_{Li} = 83.3g/cm^2$ (or 156 *cm*),

t_{Xo} –is the thickness of the rod in *g/cm*². $\sqrt{<\theta^2>} \cong \frac{13.6}{20}\sqrt{\frac{2}{156}} \cong 0.077$ rad

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

$$R = \rho L / \pi a^2 \cong 1.44 \cdot 10^{-5} \cdot 2 / \pi / 0.5^2 \cong 3.7 \cdot 10^{-5}$$ *Ohm.*

the instant power dissipation in the rod as big as $P = I^2 \cdot R \cong 83.25^2 \cdot 10^6 \cdot 3.7 \cdot 10^{-5} = 2.5 \cdot 10^5$ *W.*

If the pulse lasts for τ seconds with repetition rate *f* , *Hz*, then the average power dissipation will be

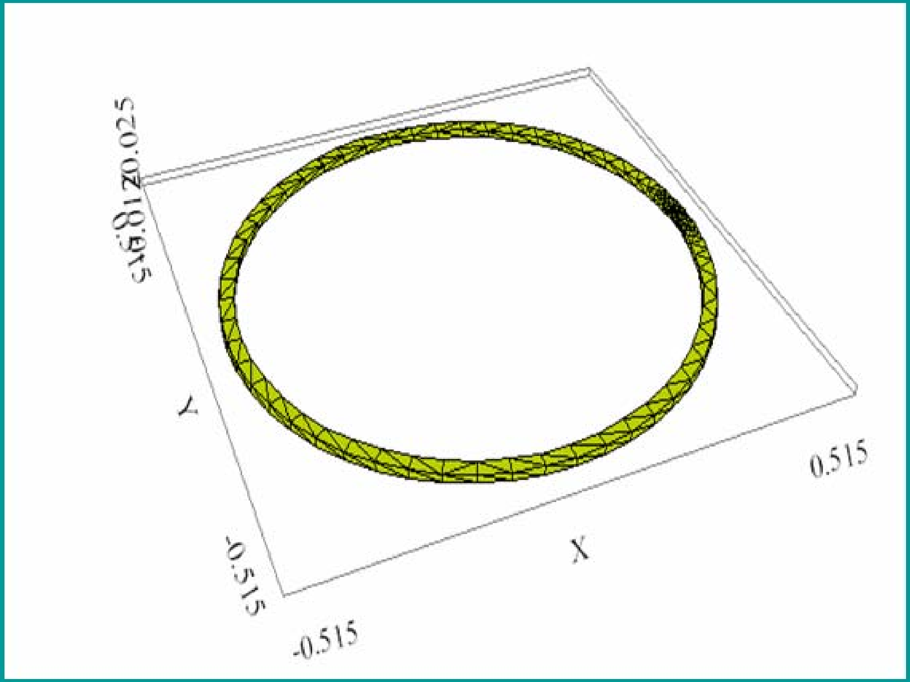
$$< P >= J^2 \cdot R \cdot f\tau$$

. For *f*=5*Hz*, $\tau \cong 2ms$ the last goes to $< P >= 2.5 \cdot 10^5 \cdot 5 \cdot 2 \cdot 10^{-3} \cong$ 2.5 *kW*

This is much, much easier, than for focusing of (anti) protons.

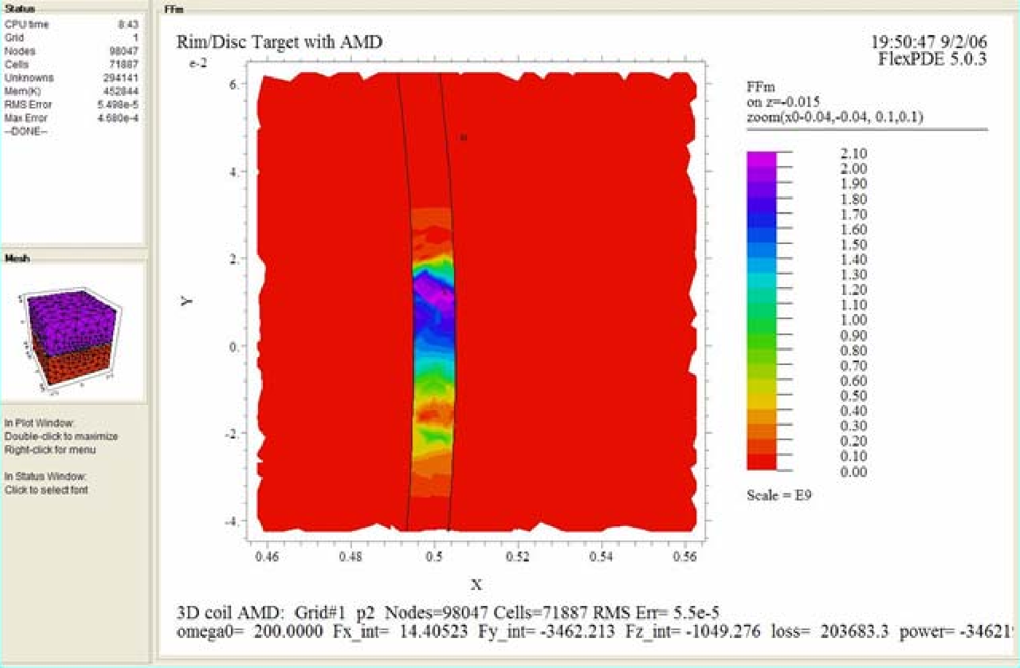
The problem is to spin the metal target is the presence of magnetic field

Geometry of rim



Thickness of rim ~0.4 rad length

Full width varied from 0.25 cm to full disc



CPU time	8:43
Grid	1
Nodes	98047
Cells	71887
Unknowns	294141
Mem(K)	452844
RMS Error	5.498e-5
Max Error	4.680e-4

--DONE--

In Plot Window:
Double-click to maximize
Right-click for menu

In Status Window:
Click to select font

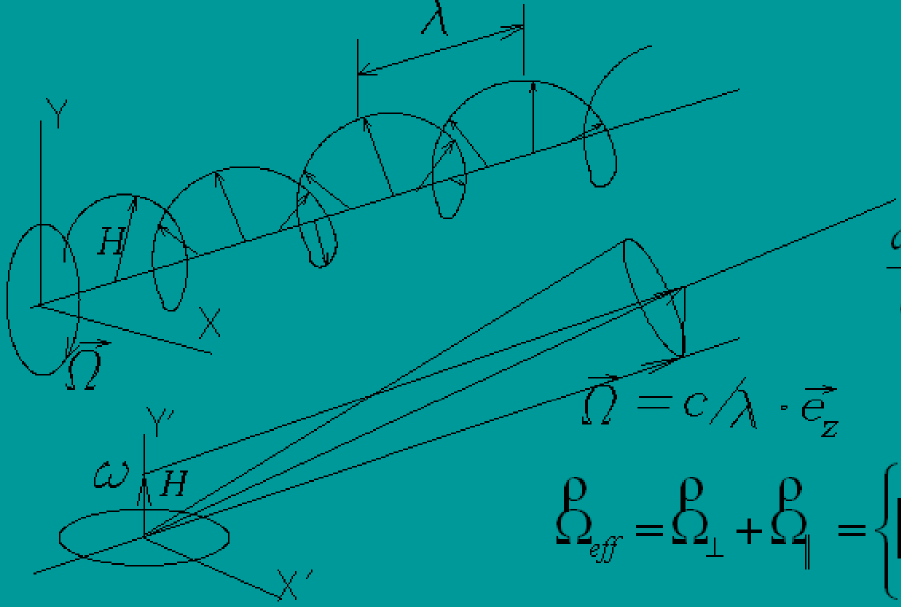
```
3D coil AMD:  Grid#1  p2  Nodes=98047 Cells=71887 RMS Err= 5.5e-5
omega0=  200.0000  Fx_int=  14.40523  Fy_int= -3462.213  Fz_int= -1049.276  loss=  203683.3  power= -34621
```

Contour plot of forces induced by eddy currents in rim. Drag is seeing clearly

Kinematic depolarization in undulator

Process can be considered in a system of reference rotating with frequency $\vec{\Omega} = \frac{c}{\Delta_u}$

Yu.Shatunov, V.Ptitsyn, E.Perevedentsev,1993



$$\frac{d\vec{\zeta}}{dt} = \vec{\zeta} \times (\vec{\Omega}_s - \vec{\Omega}) \equiv \vec{\zeta} \times \vec{\Omega}_{eff}$$ where

$$\vec{\Omega}_{eff} = \vec{\Omega}_\perp + \vec{\Omega}_\parallel = \left\{[1+\gamma G]\cdot\frac{eH_\perp\Delta_u}{mc\cdot\gamma}\cdot\frac{c}{\Delta_u}; 0; \frac{c}{\Delta_u}\right\} \equiv \left\{[1+\gamma G]\frac{K}{\gamma}\cdot\frac{c}{\Delta_u}\vec{e}_\perp; 0; \frac{c}{\Delta_u}\vec{e}_\parallel\right\}$$

$G=(g-2)/2$ can be represented as $G = 1/\gamma_0$ where γ_0 corresponds to 440.65 MeV

so $\vec{\Omega}_{eff} = \vec{\Omega}_\perp + \vec{\Omega}_\parallel = \left\{\left[1+\frac{\gamma}{\gamma_0}\right]\cdot\frac{eH_\perp\Delta_u}{mc\cdot\gamma}\cdot\frac{c}{\Delta_u}; 0; \frac{c}{\Delta_u}\right\} \cong \left\{\frac{K}{\gamma_0}\cdot\frac{c}{\Delta_u}\vec{e}_\perp; 0; \frac{c}{\Delta_u}\vec{e}_\parallel\right\}$

Does not depend on Energy→
depolarization $\approx (K/\gamma_0)^2$

During passage through undulator spin rotates around *y'* $\varphi = \Omega_\perp t = \frac{K}{\gamma_0}\cdot\frac{c}{\Delta_u}\cdot\frac{L}{c} = \frac{KL}{\gamma_0\Delta_u} \cong$ 50 rad

This needs to be taken into account while preparing polarization at IP

Depolarization at IP

- Depolarization arises as the spin changes its direction in coherent magnetic field of incoming beam. Again, here the deviation does not depend on energy, however it depends on location of particle in the bunch: central particles are not perturbed at all. Absolute value of angular rotation has opposite sign for particles symmetrically located around collision axes.
- This topic was investigated immediately after the scheme for polarized positron production was invented. This effect is not associated with polarized positron production exclusively because this effect tolerates to the polarization of electrons at IP as well. Later many authors also considered this topic in detail. General conclusion here is that depolarization remains at the level ~5%

E.A. Kushnirenko, A. A. Likhoded, M.V. Shevlyagin, *“Depolarization Effects for Collisions of Polarized beams”*, IHEP 93-131, SW 9430, Protvino 1993.

Spin flip in undulator

Positron or electron may flip its spin direction while radiating in magnetic field. Probability:

$$\frac{1}{\tau}[\sec^{-1}] = w_{flip} = \frac{5\sqrt{3}}{16}\frac{r_0^2}{\alpha}\frac{\omega_0^3}{c^2}\gamma^5\left(1-\frac{2}{9}\zeta_\parallel^2-\frac{8\sqrt{3}}{15}\frac{e}{|e|}\zeta_\perp\right)$$

Probability of radiation:

$$w_{rad} \cong \frac{I}{\eta\omega_0 2\gamma^2} = \frac{2}{3}\frac{e^4H^2\gamma^2}{m^2c^3}\frac{1}{\eta\omega_0 2\gamma^2} = \frac{1}{3}\alpha\gamma^2\omega_0$$

$\Delta_c = r_0/\alpha = e^2/mc^2/\alpha \cong 3.8616\cdot 10^{-11}$

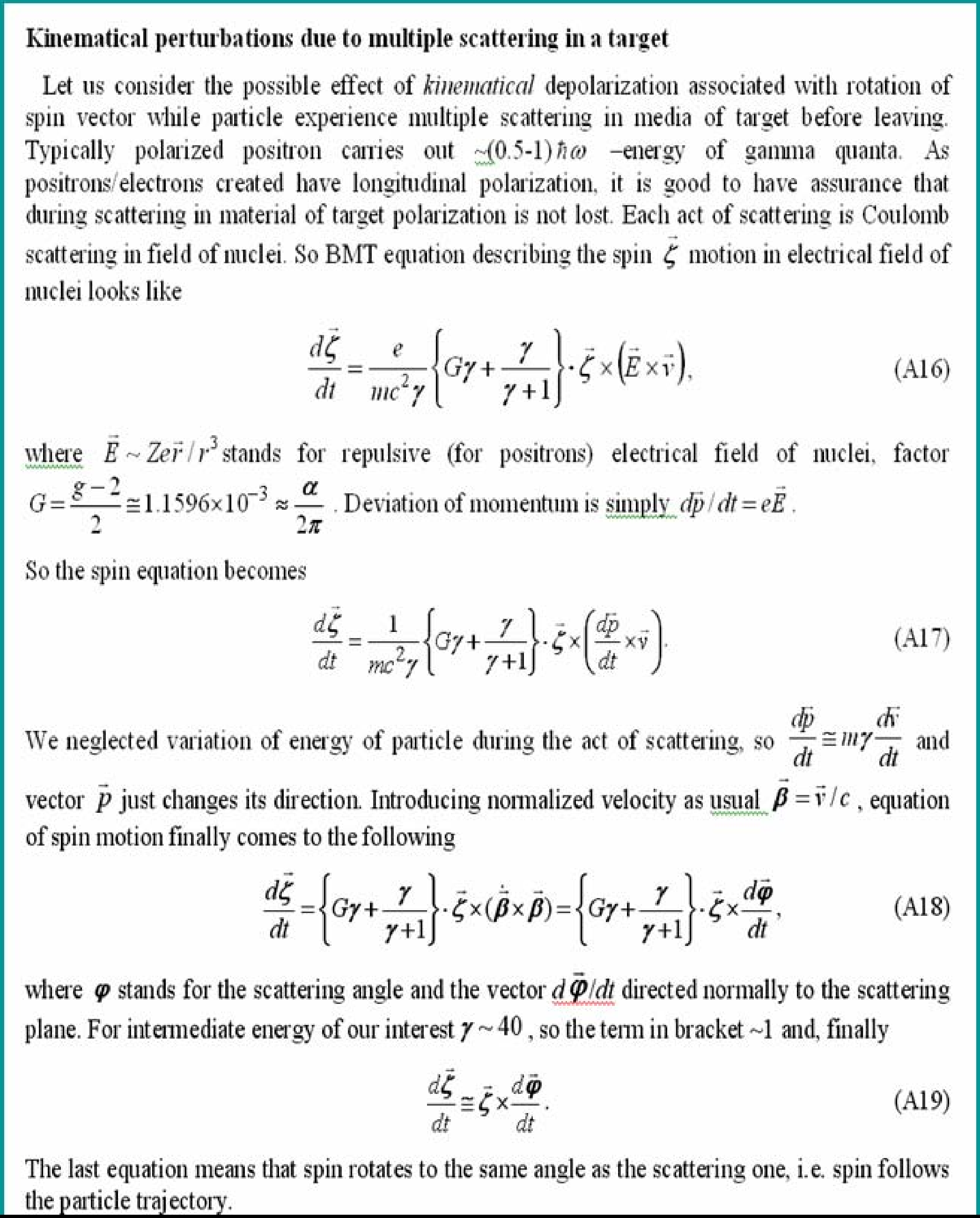
The ratio

$$\frac{w_{flip}}{w_{rad}} = \frac{15\sqrt{3}}{16}\boxed{\frac{\Delta_c^2}{\Delta_u^2}}\gamma^3\left(1-\frac{2}{9}\zeta_\parallel^2-\frac{8\sqrt{3}}{15}\frac{e}{|e|}\zeta_\perp\right) \qquad \text{(K\~{}1)}$$

Effect of spin flip still small (i.e. radiation is dominating).

PERTURBATION OF EMITTANCE AND POLARIZATION

- See A. Mikhailichenko, CBN 06-1, Cornell LEPP, 2006.



Kinematical perturbations due to multiple scattering in a target

Let us consider the possible effect of *kinematical* depolarization associated with rotation of spin vector while particle experience multiple scattering in media of target before leaving. Typically polarized positron carries out ~(0.5-1)$\hbar\omega$ –energy of gamma quanta. As positrons/electrons created have longitudinal polarization, it is good to have assurance that during scattering in material of target polarization is not lost. Each act of scattering is Coulomb scattering in field of nuclei. So BMT equation describing the spin $\vec{\zeta}$ motion in electrical field of nuclei looks like

$$\frac{d\vec{\zeta}}{dt}=\frac{e}{mc^2\gamma}\left\{G\gamma+\frac{\gamma}{\gamma+1}\right\}\cdot\vec{\zeta}\times\left(\vec{E}\times\vec{v}\right), \tag{A16}$$

where $\vec{E}\sim Ze\vec{r}/r^3$ stands for repulsive (for positrons) electrical field of nuclei, factor $G=\frac{g-2}{2}\cong 1.1596\times10^{-3}\approx\frac{\alpha}{2\pi}$. Deviation of momentum is simply $d\vec{p}/dt=e\vec{E}$.

So the spin equation becomes

$$\frac{d\vec{\zeta}}{dt}=\frac{1}{mc^2\gamma}\left\{G\gamma+\frac{\gamma}{\gamma+1}\right\}\cdot\vec{\zeta}\times\left(\frac{d\vec{p}}{dt}\times\vec{v}\right). \tag{A17}$$

We neglected variation of energy of particle during the act of scattering, so $\frac{d\vec{p}}{dt}\cong m\gamma\frac{d\vec{v}}{dt}$ and vector $\vec{p}$ just changes its direction. Introducing normalized velocity as usual $\vec{\beta}=\vec{v}/c$, equation of spin motion finally comes to the following

$$\frac{d\vec{\zeta}}{dt}=\left\{G\gamma+\frac{\gamma}{\gamma+1}\right\}\cdot\vec{\zeta}\times(\dot{\vec{\beta}}\times\vec{\beta})=\left\{G\gamma+\frac{\gamma}{\gamma+1}\right\}\cdot\vec{\zeta}\times\frac{d\vec{\boldsymbol{\varphi}}}{dt}, \tag{A18}$$

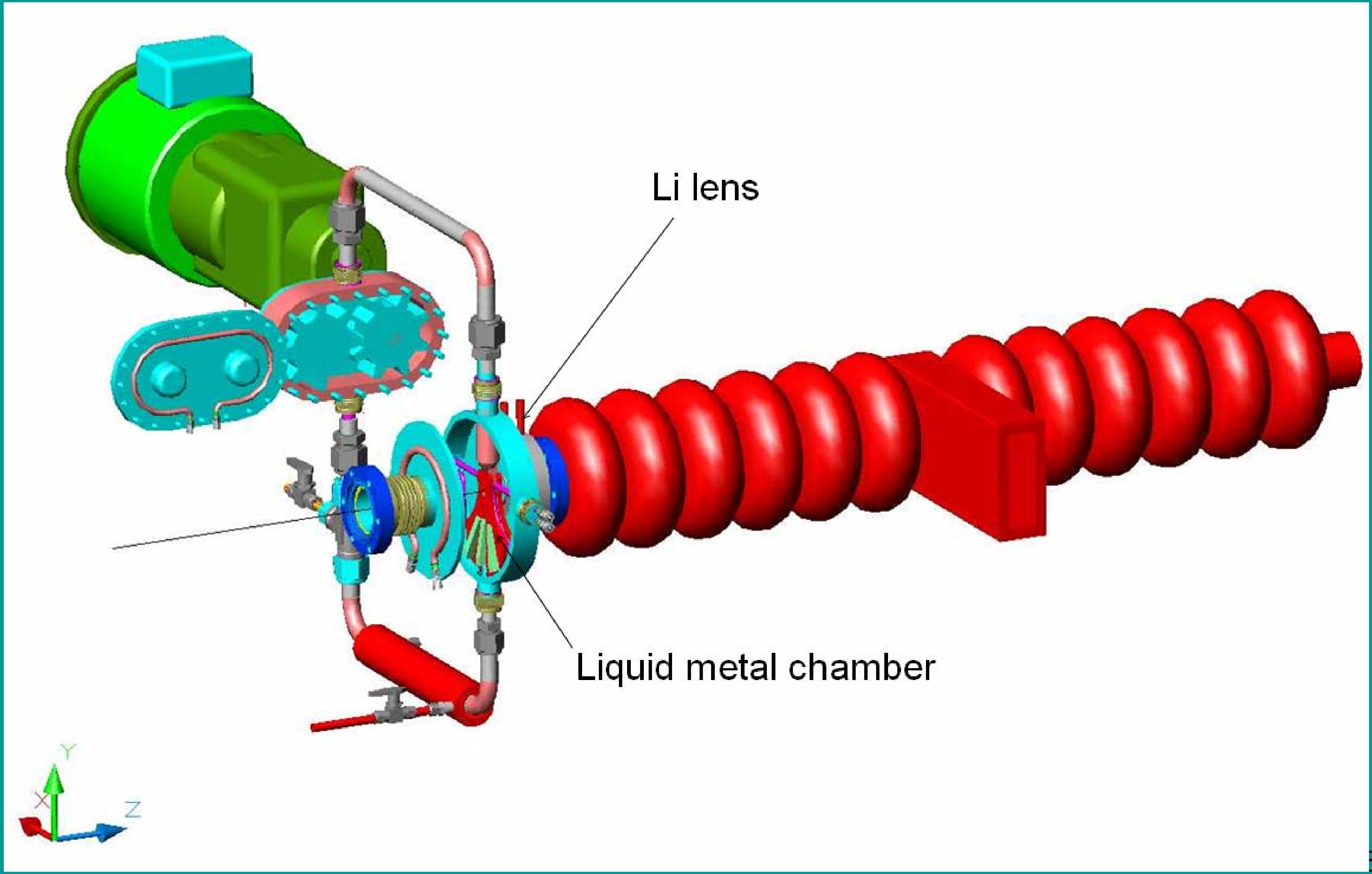
where $\boldsymbol{\varphi}$ stands for the scattering angle and the vector $d\vec{\boldsymbol{\varphi}}/dt$ directed normally to the scattering plane. For intermediate energy of our interest $\gamma\sim 40$, so the term in bracket ~1 and, finally

$$\frac{d\vec{\zeta}}{dt}\cong\vec{\zeta}\times\frac{d\vec{\boldsymbol{\varphi}}}{dt}. \tag{A19}$$

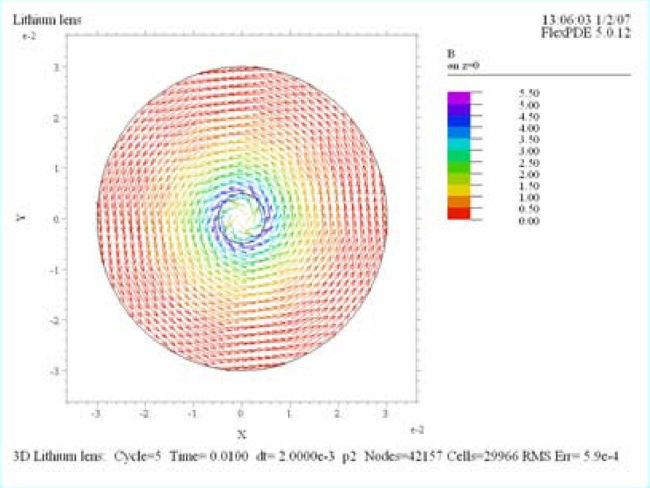
The last equation means that spin rotates to the same angle as the scattering one, i.e. spin follows the particle trajectory.

Fragment from CBN 06-1

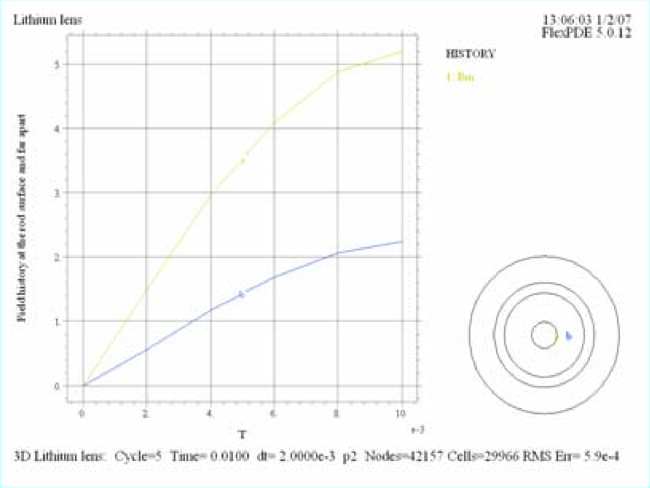
Conversion unit with liquid metal target and Lithium lens (described below)



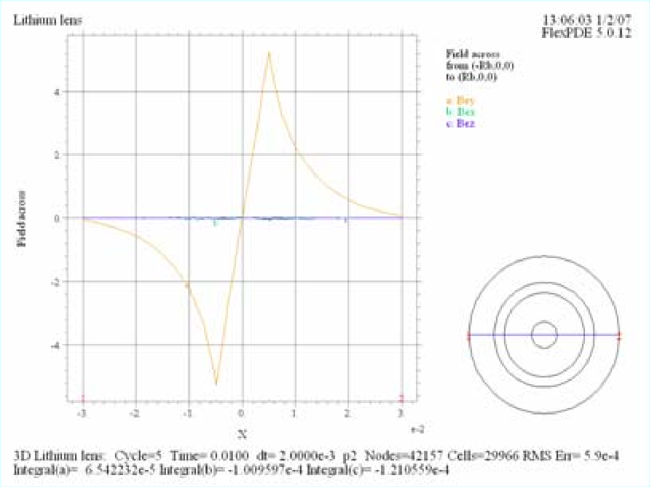
Spatial field distribution over time (cinema)



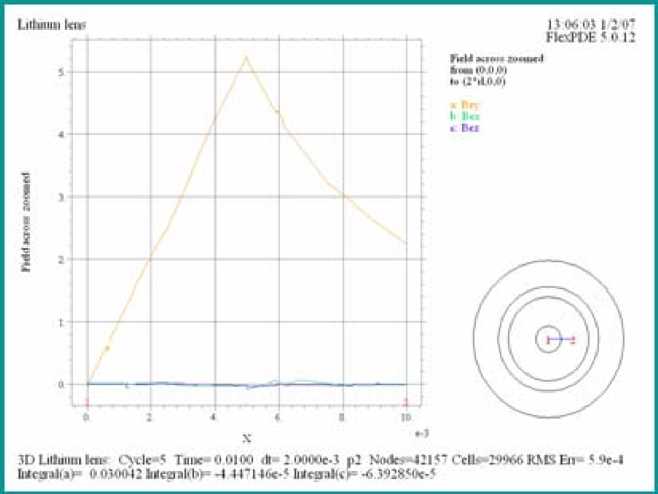
3D Lithium lens: Cycle=5 Time= 0.0100 dt= 2.0000e-3 p2 Nodes=42157 Cells=29966 RMS Err= 5.9e-4



3D Lithium lens: Cycle=5 Time= 0.0100 dt= 2.0000e-3 p2 Nodes=42157 Cells=29966 RMS Err= 5.9e-4

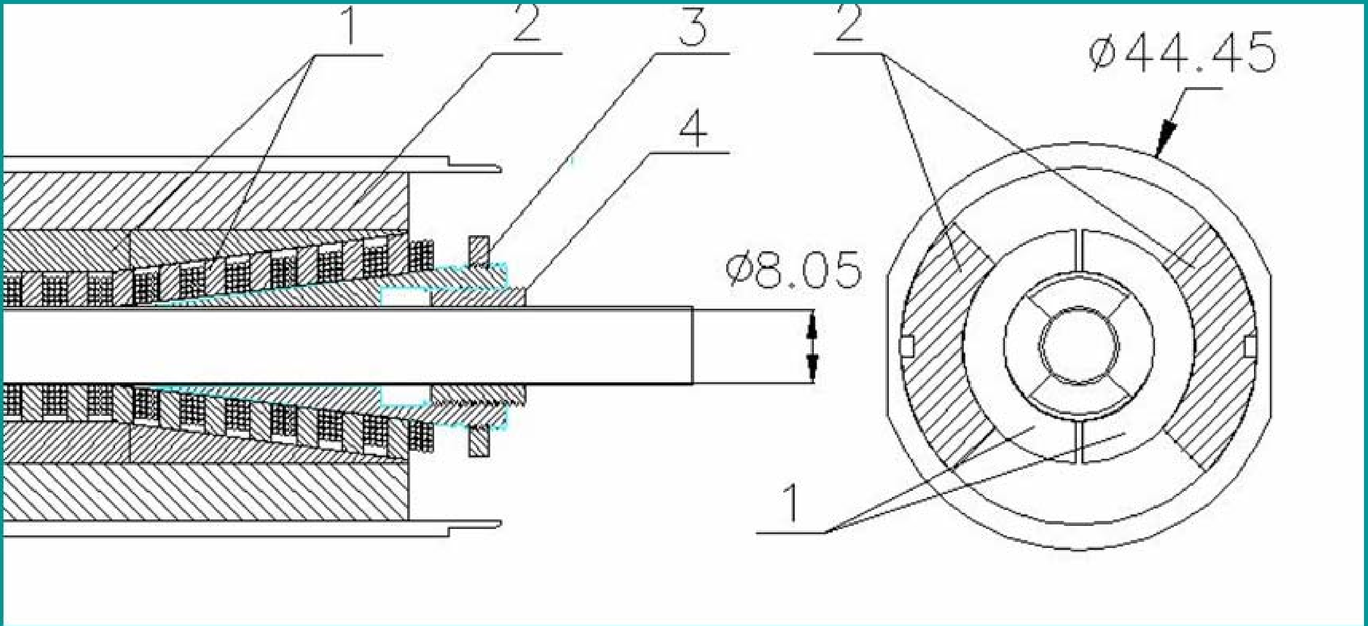


3D Lithium lens: Cycle=5 Time= 0.0100 dt= 2.0000e-3 p2 Nodes=42157 Cells=29966 RMS Err= 5.9e-4
Integral(a)= 6.542232e-5 Integral(b)= -1.009597e-4 Integral(c)= -1.210559e-4



3D Lithium lens: Cycle=5 Time= 0.0100 dt= 2.0000e-3 p2 Nodes=42157 Cells=29966 RMS Err= 5.9e-4
Integral(a)= 0.030042 Integral(b)= -4.447146e-5 Integral(c)= -6.392850e-5

End region design

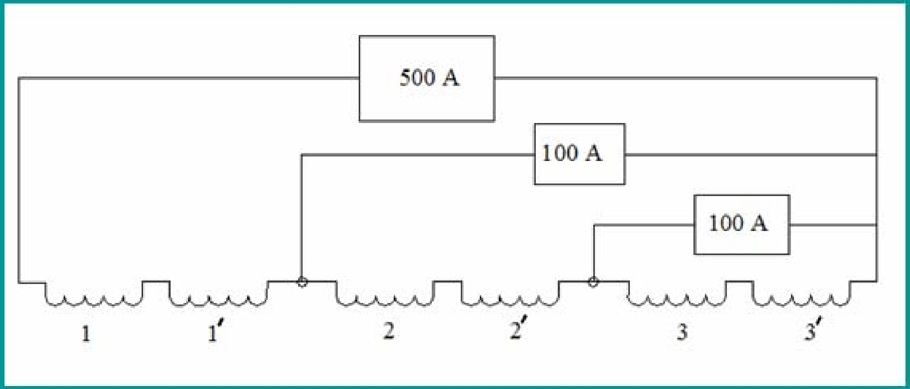


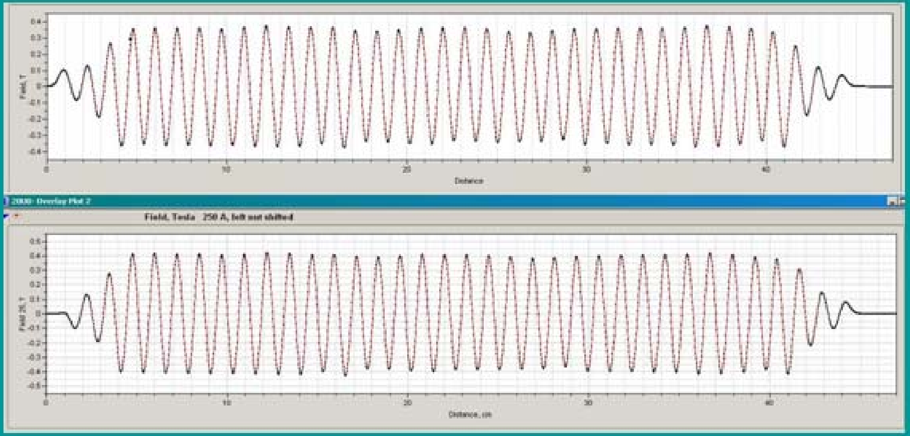
Details of design. 1–Iron yoke, 2–Copper collar, 3, 4–trimming Iron nuts. Inner diameter of **Copper** vacuum chamber is 8mm clear.

Period kept even

We developed simplified tapering allowing smooth end without diameter expansion

Sectioned coils for undulators





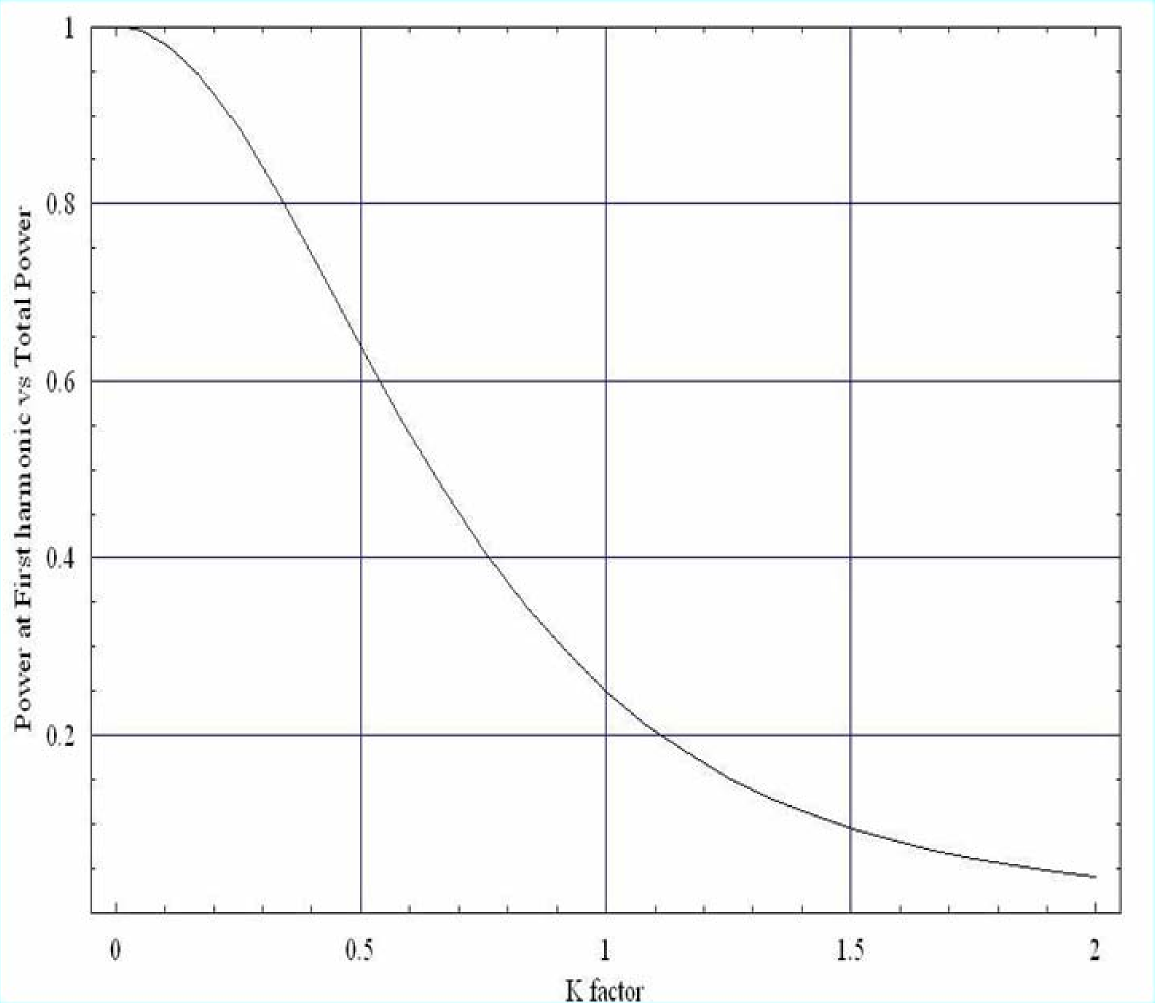
10 mm undulator operated with two PS 500+50 A; 4x6 wires (0.6mm in diam. bare)

Undulator 12 mm feed with one PS;

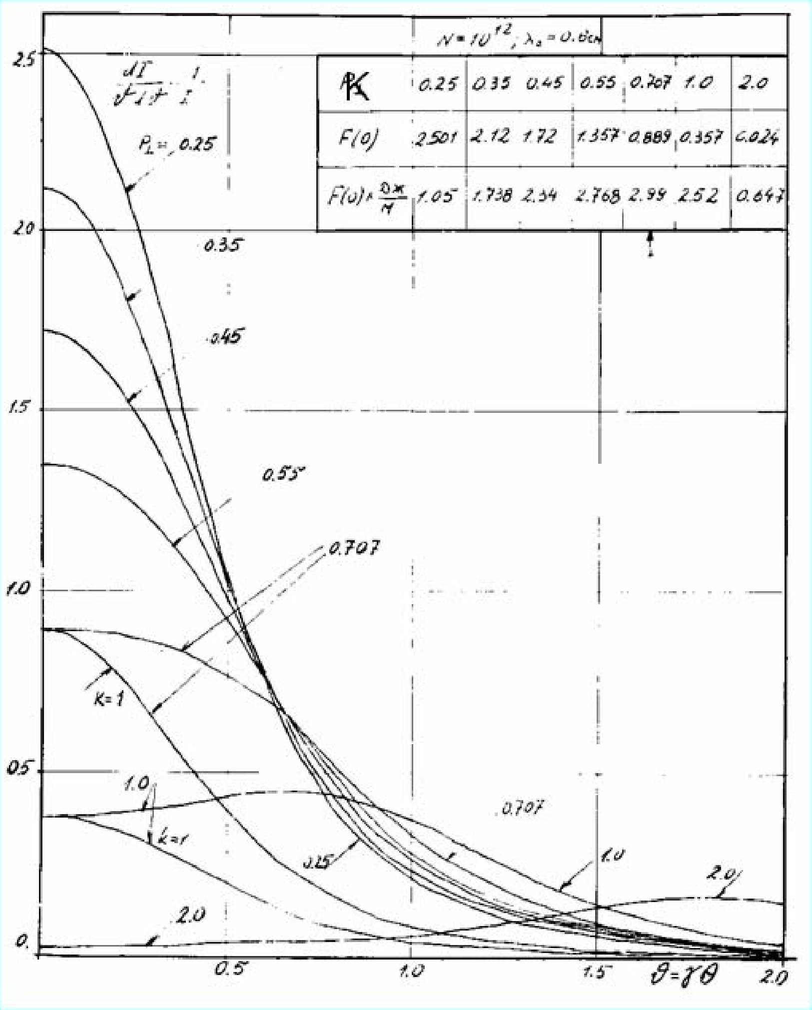
In a future there will be <3 PS for coils sectioned in radial direction

No need for K factor to be high

This is useful for higher polarization



Ratio of Power radiated at first harmonics to the all power in all angles



Angular distribution of intensity of radiation for different K

ACTIVITIES AT CORNELL

√ **CODE FOR POSITRON CONVERSION (UNDULATOR → LINAC → further on)**
- Choice of undulator parameters → main issue
- Choice of target dimensions
- Choice of collection optics parameters (Li lens)

√ **UNDULATOR DESIGN** (main activity)
- Undulators with period 10 and 12 mm having 8 mm aperture tested at Cornell
- Designed undulators with aperture ¼” (7mm magnetic core)

TARGET DESIGN (in addition to Livermore, SLAC, Daresbury
- Rotating Tungsten target (including new sandwich type)
- Liquid metal target: Bi-Pb or Hg
- Dynamics of heating

COLLECTION OPTICS DESIGN
- Lithium lens
- Solenoidal lens

√ **COLLIMATORS**
- Collimator for gammas
- Collimators for full power beam

√ **PERTURBATION OF EMITTANCE AND POLARIZATION**
- Perturbation of emittance in regular part
- Polarization handling

√ **UNDULATOR CHICANE**
- Minimal possible parallel shift

√ **COMBINING SCHEME**
- Two-target scheme

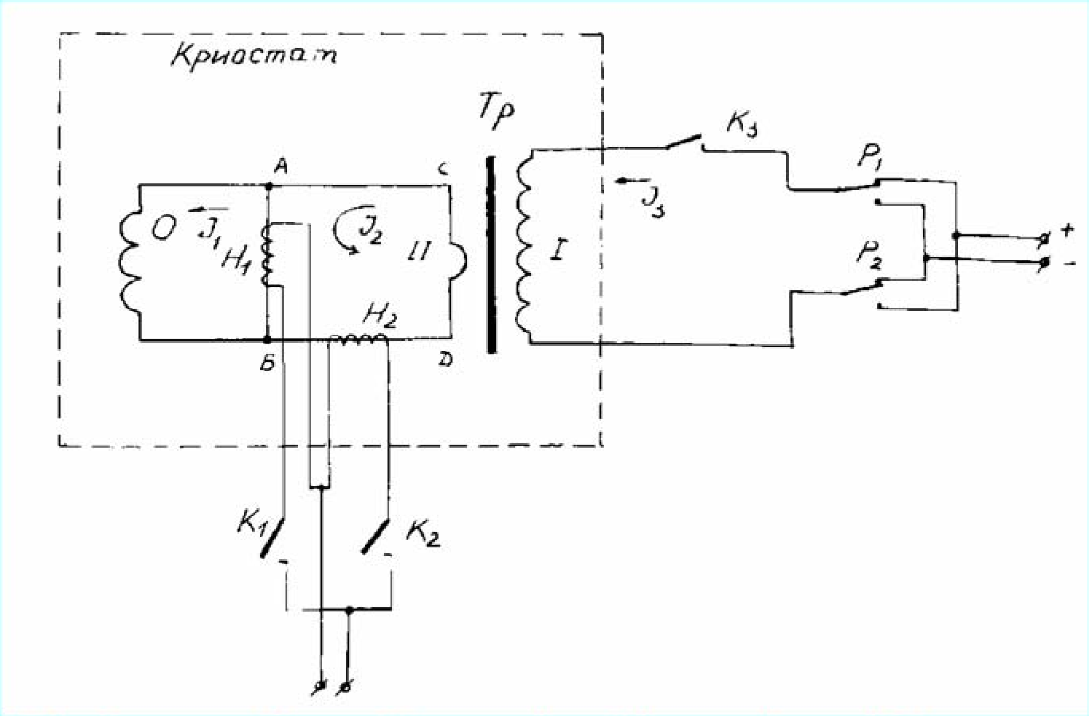
Identification of losses in joints

Tested SC transformer scheme to identify time decay (losses in joints)

For undulator with 36 turns decay time found to be ~400 sec (5joints)

This defines the resistance to be <1E-15Ω

This scheme used in 1986 to feed SC undulator



Scheme allows to work with captured flux

SC transformer with keys