OPTICS DEVELOPMENT FOR POSITRON POLARIZATION ANALYSES

We summarize here present situation with calculations of analyzing optics. Some fragments of this text were distributed earlier (Analyzing magnet-November 5, 2003; general description of optics with solenoidal lenses including 3D shaded drawings–November 10, 2003. The last was included in Status Report on E-166, represented on November 15, 2003 EPAC meeting, last slide).

The optics described below, which includes solenoidal lens(es), allows drastic increase for collection of positrons with appropriate energy and, in principle, size reduction for the calorimeter.

Although our DESY colleagues are planning to implement some other design for analyzing magnet, we keep here description of analyzing magnet too, believing that design represented here is much more compact.

Materials represented allow more realistic sight on the hardware, necessary for proper evaluation of the jobs required.

GENERAL VIEW

General view on the scene like it is appears in proposal for E-166 is represented in the sketch below.

The part of this optics with parallel translation is shown in figure below as more or less realistic setup. Compact analyzing magnet is shown too, although collaborators from DESY will make a different design. This will not affect residual optics of our interest at all.

Fig.1: E-166 analyzing optics.

Fig.2: Basic view on the optics hardware.
Short focusing solenoidal lenses and analyzing magnet have the only difference in core: in lenses the core is removed. In bending magnets, fringe vertical focusing is arranged. Together with focusing properties in radial direction these magnets provide focusing in both transverse directions. If short focusing lens is not present, the beam optics requires this distance to be \( \sim \)twice the distance between target and bending magnet. With short focusing lens this distance can be arbitrary. In principle, additional solenoidal lens(es) can be installed between magnets too. The distance shown in Figure is reserved initially for these purposes. So the distance between magnets is free parameter and defined only by background suppression needs.

Optics creates the image of hot spot of primary target onto the second positron target-converter. The last one might be a separate W disk or just material of the core itself. Radiation length in Iron is about 1.75 cm, so the first layers of the magnetized core will convert positrons into gammas.

The magnets are feed in series. Lenses can be feed in series too. Suggested current is about the same as in analyzing magnet, \( \sim 130 \) A.

Magnets shown are 90 deg ones, although beam optics is easier for smaller angle. Dimensions are given in mm. Geometrical bending radius of central line in magnets is running at \( \sim 102 \) mm, although effective bending radius, taking into account the fringe fields, runs at \( \sim 125 \) mm. Namely this bending radius defines the value of magnetic field in the bending gap \( \geq 2.65 \) kG. The gap itself was initially 40 mm, so the total number of Ampere-turns goes to be \( \leq 10 \) kA, i.e. \( \sim 5 \) kA-turns per coil. Further, with flat pole magnet aperture was increased to 50mm with the same value of ampere-turns.

The orientation of the axes shown below used in 3D calculation of magnetic fields and transmission properties.
FOCUSING SOLENOIDAL LENS(ES)

This lens located right after the target, see Fig. 2. Basically its function is similar to the one served by flux concentrator, used in all laboratories dealing with positron production. Focusing properties of this DC lens is much more modest, however, DC was chosen for simplicity. Similar lens can be installed after second magnet for proper focusing of positrons on the second target. Trajectories are shown below. Beam represented by 5 or 9 trajectories (for better distinguishing) starting from the point located ~16 mm from the iron. These trajectories are the central one, running without angle through the center and 4 or 8 satellite ones with maximal angle ±0.3 radians with respect to the longitudinal axis (to the first trajectory). Trajectories calculated by code UMKA [1], which uses the 3D fields obtained from MERMAID [2].

Fig. 5: Solenoidal lens. Water-cooled conductors in this yoke generate the field with longitudinal component at the axis up to 15 kG.
Fig. 6: Typical longitudinal field (kG) distribution at the axis (measured in cm).

The only longitudinal component (x-coordinate) has its value. 3D model. Printout from MERMAID. Focal distance for this lens is $F = 4(HR)^2 \int H^2 dl$. The last integral calculated by code (right column, kG×cm).

Fig. 7: 3D field distribution in central region.
Fig. 8: Trajectories in a solenoidal lens. Overfocusing is present here. Solenoidal lens #1.

Trajectories starting at the left in Fig. 8 with angle $\pm 0.3$ radians with respect to the longitudinal axis. Isometric view is shown at the right. Azimuthally particles started evenly, so full angle shown is 0.6 radians. Azimuthtal twist is clearly visible. Longitudinal field is $\sim 15$ kG.

Fig. 9: Under focusing. Longitudinal magnetic field is $\sim 13$ kG. Variant #1 for solenoidal lens.

**BENDING MAGNETS**

Few magnets were investigated. All of them are bending positrons to a 90° in radial plane. Magnet #1 is flat pole sector one. Magnet #2 has flat poles but edges have angle 22° with respect to the central trajectory. Magnet #3 in addition to the magnet #2 has a gradient $\sim 0.13$ kG/cm.

**Magnet #1**

Magnet has aperture 40 mm and bending radius $\sim 125$ mm. Vacuum chamber has thickness of 0.5 mm, so effective vacuum aperture runs to be 39 mm. Amount of ampere-turns in single coil is 5 kA-turns. For coil reserved the height 30 mm. Copper conductor $4 \times 4$ mm$^2$ with round hole of 2.5mm in diameter serves as a conductor. AS the current is fixed at 140 A, the number of turns goes to be 70. As in vertical direction the number of turns goes to be 7, the number of turns in radial direction (thickness of the coil) goes to be 10, which occupy $\sim 50$ mm.

For improvement the flatness of the field the poles of magnet have shims and profiled chamfer at the edge.

Modeling of magnetic field in the magnet done with 3D code MERMAID. Input plane is represented in fig below. Extrusions done in z-direction (normally to the plane of picture). Material of yoke is annealed steel 1010.
Fig.10: Input plane of magnet #1 as it appears in MERMAID test run.

Input plane for the magnet #1. Here shims and chamfer profile are visible. The 3D shape obtained by extrusion of profiles in z-direction.

Fig.11: Dimensions are given in mm. Magnet #1.

3D map of magnetic field is represented in figure. For improvement the flatness of the field
So basic result from considerations done is that the bending magnet can be treated in beam-optics calculations as usual dipole rectangular magnet. Shims and chamfers can be adjusted so that it can be treated like this.

Example of trajectories starting in medial plane at lower x-coordinate in magnet #1. At the left— all particles have energy 10 MeV and angular spread ±0.5 rad. Field at maximum is ~2.35 kG. At the right —energy is 8 MeV and the same angular spread. One can easily see focusing provided by the magnet. For focusing of 10 MeV-particles, the field needs to be increased. There is no fringe focusing here. Contour lines circle the points with the same value of magnetic field (isomagnetics lines).

So if second magnet has image plane on the focusing plane of the first one, the hot spot will be transferred to the second target, at least in radial direction. In vertical direction magnets do not provide any focusing, so they act as a free space, what is not acceptable.
Magnets #2 and #3

We investigated also the possibility for vertical focusing by fringe fields. For this purpose edges of the poles must have angle not a $90^\circ$ with respect to the incoming trajectory.

![Fig. 14: Dimensions of magnet #2 and #3.](image)
The difference between these two ones in poles slope; #2 has no slope (poles are parallel) in #3 there is increased gap $\sim 2\text{cm}$ at the radial distance $\sim 85\text{ mm}$.

![Fig. 15: Trajectories in magnet #2. Now starting point located at the left, like it is in real model.](image)

![Fig.16: Trajectories for magnet #2, left, and magnet #3, right, in comparison. Vertical starting positions are $z=0$, $z=1$ and $z=1.25\text{ cm}$ for both magnets. Stronger vertical focusing for particles having larger angle is clearly visible here.](image)
FULL MODELING OF MOTION

For analyses of motion through all system geometry was inserted into numerical box, see below.

Fig. 17: Example of numeric map of the scene as it appears in MERMAID calculations with magnet #1. Dimensions are given in millimeters.

Fig. 18: Trajectories without solenoidal lens. At the left -isometric view, at the right- projection of trajectories onto the $x$-axis. During vertical excursion in the right picture, particles are mowing towards the viewer (to $-y$ direction) Vertical angle transported is 15mrad. In radial direction particles have focus behind $x=50$ cm, somewhere behind analyzing magnet.
With introduction of solenoidal lens system transports more particles, started with angles in vertical direction.

![Fig.19: Solenoidal lens is on. Top and isometric view on trajectories, respectively. Opening angle in this example is ±150 mrad for $x$ and $y$ directions. All particles within this angle pass through all chamber having vertical gap ± 20 mm (40mm total). Longitudinal field ~12kG. Energy of particles 11 MeV. Flat poles; field value between poles 3.08 kG generated by 5kA-turns per coil (two coils per magnet). Solenoidal lens is slightly weak for this energy, or bending field is a bit strong. So, the increase of geometrical capture here is ~10 times, compared with the case without solenoidal lens.

Below there are represented trajectories for optics with increased gap between magnet poles. Here it is ± 25 mm. Spread of angles is ± 200 mrad. Poles are not shimmed and flat. Trajectory in vertical direction remains within ± 18 mm however. Maximum of longitudinal field value, see Fig.6, is 11.725 kG for this particular example.](image1)

![Fig.20: Angular spread ± 200 mrad, energy $E = 9$ MeV, left and $E = 7$ MeV, right. Initial conditions are the same. Solenoidal lens #2.](image2)

With decreasing energy particles becomes over-focusing and for 7MeV as it is shown above, no particles passing through.

This selects particles with highest energy and, hence, highest polarization.
ANALYSING MAGNET

Basic idea here is to make the coil as compact as possible with closest location to the core. This is due to the fact, that $\bar{H}$ defined by circulation around the feeding current $\int \bar{H} d\vec{l} = 0.4\pi NI$ ($H$-in Gauss, $l$-in cm, current in Amperes). This value does not depend on the presence of iron. When $H$ is established, $B$ value can be calculated by $B-H$ curve of material of yoke. One other peculiarity is the following one: If there is no external longitudinal field at the top/bottom of central cylinder, there is a transition region, where magnetic field changes its direction. For reduction of this transition region there are two possibilities: first one is to make internal cylinder’s diameter as small as possible, the second one is to allow longitudinal magnetic field outside of cylinder. The last means, that cylinder is immersed into longitudinal magnetic field.

![Figure 21: Isometric view on analyzing magnet.](image)

At the end of magnetized core the flux is running is back plate, changing its orientation from longitudinal to the transverse one. The thickness of the plate defined by the simple rule, defined by the flux conservation

$$\frac{\pi D^2}{4} \cong \pi D \times h,$$

where $D$ stands for diameter of the core, and $h$ is the height of the plate. This yields $h \cong D/4$ i.e. half of radius. So the region of the core $\sim D/4$ is lost for analyses. Situation can be improved if outside the core longitudinal $B_x$ is present, so normal component is transferred from outside to inside region. This requires configuration, when magnetized iron is sitting deep inside, so some fraction of the flux jumping out of iron (lowering in the plate in the Fig. Below must be deep).
In this situation positron target can be located either far from the edge of analyzing magnet or in strong stray field. The last can be considered not bad approach as, the stray field is a focusing one. First option (with far target location) brings problems with collecting gammas into detector. The losses of region with longitudinal field are about 1 cm. The profile of magnetization obtained from calculations is accurate enough. In mostly cases the measurements of magnetization can be done only in one point (if necessary).

Transition region from longitudinal to transverse direction is ~halff of the radius of magnetized cylinder.
Fig. 24: Digital map, kG

Fig. 25: Enlarged digital map for the region around entrance
Fig. 26: B-distribution along the axis. Numbers behind the filed $B$ symbol mean the radial distance in mm.

Magnet yoke and core made from annealed steel 1010. In this geometry, the total current, required for magnetization of core to $\sim23$kG is $\sim10$ kA. The coil made with 70 turns arranged in seven sub-coils (pancake-type) having five radial turns in two longitudinal layers, see Figure. Subdivisions done for easier winding and for easy change the iron length, using the same coils.

Each sub-coil wounded with copper conductor starting from smaller radius. All coils electrically connected in series. The water flow can be arranged in parallel, however. Conductor is a square one having side size of $4\times4$ mm$^2$ with round hole for water having diameter 2.5 mm. Edges are rounded with radius 0.3 mm. Total area of conductor’s cross-section is $\sim10.45$ mm$^2$. Average length of single turn is $\sim20$ cm, yielding total conductor length $\sim200$ cm, or 2 meter per sub-coil. Such small length allows easy winding from smaller radius by well-known technology.

Resistance of single sub-coil is going to be

$$R = 1.8 \times 10^{-6} \cdot 200 / 0.1045 \approx 3.6 \cdot 10^{-3} \Omega,$$
which brings total resistance of seven pancakes connected in series to
\[ R_{tot} = 7 \times R \cong 2.52 \times 10^{-2} \Omega. \]
As the current running in conductor is
\[ I_1 = \frac{10000}{70} \cong 143 A, \]
the power dissipated in all coils goes to be
\[ P = I_1^2 R_{tot} = 143^2 \times 2.52 \times 10^{-2} \cong 515 W. \]
If we suggest, that water gains 10 degrees C passing through the coil, the flow rate in individual coil must be
\[ Q[L/\text{sec}] = \frac{P[W]}{10 \cdot 4186 \cdot \frac{1}{7}} \cong 0.0017 = 1.7 \text{ cm}^3/\text{sec}. \]
Factor 1/7 reflects the situation, when the coils are cooled in parallel.
The pressure drop \( \Delta P \) in water channel, having length \( L \) can be defined from the following formula [3]
\[ Q[cm^3/\text{sec}] \cong 6.4 \times 10^3 \sqrt{\frac{\Delta P[\text{atm}]}{L[cm]}} [cm]^{5/2}. \]
This yields
\[ \Delta P[\text{atm}] \cong \frac{Q^2 \times L}{4.1 \times 10^7 \times d^5} \cong \frac{1.7^2 \times 200}{4.1 \times 10^7 \times 0.25^5} \cong 0.014 \text{ atm} \cong 0.2 \text{ psi} \]
This number shows that all coils can be cooled in series. In principle the coil can be wound as a whole, layer by layer. In this case for every length of iron core separate coil required.

The same consideration can be applied to the coil of bending magnet design.
VACUUM CHAMBER

Vacuum chamber made from aluminum parts by welding. Extra port(s) can be welded easily around center of symmetry for installation of scraper. This scraper will cut unnecessary particles.

Standard Al/StSteel transitions used for attachments of flanges and pumping ports. For allowing installation of solenoidal lenses, the conflate core of the flange screwed to the transition. This allows removing of the flange extension and insertion of solenoidal lens.

CONCLUSIONS

We found that fringe focusing along in magnets is not effective, as the angular spread is big. The last results in big difference among entering angles and, hence, big spread in focusing.

Introduction of focusing elements, such as solenoidal lens and gradient in magnets, allows increase of geometrical efficiency ~ 20 times, if compared with ballistic angular acceptance ~5/75 rad in vertical direction and natural 2-magnet acceptance in radial direction. Solenoidal lens is a DC one with relaxed properties. Second solenoidal lens desirable for better focusing on the target, but not vital.

We also suggesting Aluminum chamber in traditions of FTFB. Here Al will reduce scattering in the walls.

Materials represented allow more realistic sight on the hardware, necessary for proper estimation the jobs required.

REFERENCES