# Design considerations of a spectrometer dipole magnet for the Photo Injector Test facility at DESY in Zeuthen (PITZ)[*]

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## *Abstract*

The test and optimization of electron guns at the Photoinjector Test Facility at DESY in Zeuthen (PITZ) demands dedicated diagnostics. The physical specifications of a spectrometer magnet for measurements at a beam momentum range from 15 to 40 MeV/c will be discussed. It will be used for measurements of the momentum distribution, slice emittance and the longitudinal phase space using two different methods. The first method combines the dipole magnet with a RF - transverse deflecting cavity, the second combines it with a Cherenkov radiator whose light is measured by a streak camera. Especially the first method is aiming for a good resolution in order to determine slice momentum spread. The design has to meet the demands of all these techniques for a measurement with high resolution and for bunch trains containing 7200 pulses of 1 nC charge at a repetition rate of 10 Hz. Since there is not enough space for a separate beam dump after the dispersive section the beam has to be transported to the dump of the main beamline.

## INTRODUCTION

The main goal of PITZ is to test and to optimize L-Band RF photo injectors for Free-Electron Lasers (FELs) like FLASH and XFEL at DESY in Hamburg and to study the emittance conservation by using a matched booster cavity. The demands on such a photo injector are a small transverse emittances, a charge of about 1 nC, short bunches (of about 20 ps) and the possibility of long bunch trains of 0.8 ms length. Besides the accelerating cavities, the electron beam line (shown in figure 1) consists essentially of diagnostics elements. The physical design considerations of the second spectrometer magnet for measurements after the booster cavity will be discussed in this paper. The second high energetic dispersive arm will be used to measure the following beam parameters:

- the momentum distribution
- slice emittance [1] and
- the longitudinal phase space using:
  - a Cherenkov radiator and a streak camera [2] or
  - the RF-deflector [3].

On the one hand, the measurement of the longitudinal phase space requires to resolve a very small momentum spread of 1 keV/c, but on the other hand the measurement of slice emittance has to be done at a booster phase (off-crest) resulting in a large momentum spread. For the complete analysis and understanding of the system, the ability of the spectrometer to operate in a large range of gun and booster parameters is important. Therefore it is a demanding task to fulfill all the conditions at the same time.

A major design request is to allow the measurement of bunch trains with up to 7200 pulses and a repetition rate of 10 Hz for a long period. This requires a huge beam dump of $(2 \cdot 2 \cdot 2)$ m$^3$ after the dispersive section, but there is not enough space for a separate dump, so that the beam has to be transported to the dump of the main beamline. For long pulse trains also special diagnostics is needed because a screen would be destroyed.

Since the RF-deflector acts in vertical plane the dipole has to deflect the beam in horizontal direction. The deflecting angle can not be larger than $90^o$ due to the spatial restrictions, so a $180^o$-bend like in the case of the first spectrometer magnet after the booster cavity [1] is excluded.

## EQUIPMENT

In order to fulfill the measurement tasks, the following devices have to be included in or before the dispersive section:

- a screen station containing YAG and OTR-screen for the measurement of momentum distribution, slice emittance and longitudinal phase space (with RF-deflector) as well as a Cherenkov radiator for longitudinal phase space measurements (with streak camera);
- a quadrupole magnet and a slit placed about 1 m (focal length of the quadrupole) before the screens for slice emittance measurements;
- a beam position monitor (BPM) with a large aperture, due to the beam dispersion, for the measurement of mean momentum of different bunches in a long pulse train;
- a kicker in vertical direction before the spectrometer in order to analyze a single pulse out of a long pulse train and a corresponding off-axis screen.

## SPECTROMETER DESIGN OPTIONS

The position of an electron behind the dipole magnet in dispersion direction can be described by:

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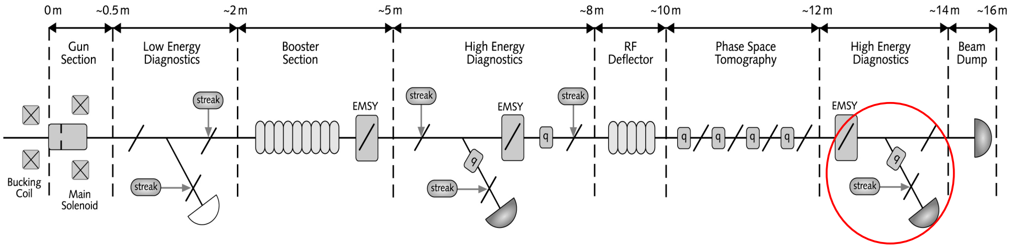

Figure 1: The PITZ2 setup consists of three spectrometer magnets for the analysis of longitudinal beam properties. The last one, the so-called second high-energetic dispersive arm (HEDA2), whose design is discussed in this paper, is marked.

$x_{DA} = R_{11} \cdot x_0 + R_{12} \cdot x_0' + R_{16} \cdot \frac{\Delta p}{<p>}$, where $R_{11}$, $R_{12}$ and $R_{16}$ are the matrix elements of the transport-matrix. In order to reach a high resolution momentum measurement the first two summands need to be small. There is a screen station about 1 m upstream the dipole and another one 1 m downstream. An electron with the horizontal position $x_0$ and the horizontal divergence $x_0'$ at the point P (see figure 2) will hit these screens $S_1$ or $S_2$ at the horizontal position $x_S = 1 \cdot x_0 + (L_b + L_{SS}) \cdot x_0'$. If $n \cdot (R_{11} \cdot x_0 + R_{12} \cdot x_0') = 1 \cdot x_0 + (L_b + L_{SS}) \cdot x_0'$, one can use a quadrupole of the tomography module to focus the beam on the screen $S_1$ or $S_2$ to improve the resolution like it was done in case of HEDA1 [1] or apply a deconvolution. So the ratio $\frac{R_{12}}{R_{11}}$ needs to be $\frac{R_{12}}{R_{11}} = L_{SS} = \pm\, 1\; m$ to minimize the influence of transverse beam size and divergence. In the case of using the screen before the dipole ($L_{SS} = -1\; m$) a slit for the measurement with short pulse trains could be provided. The deflecting radius of the dipole magnet should be considerably bigger than the gap of the pole shoes which is expected to be about 50 mm, in order provide a homogeneous field and to minimize fringe fields. The drift length in the dispersive arm $L_{DA}$ has to include the length of the quadrupole magnet and its focal length. All elements have to be placed within a distance of 1.93 m to the main beamline due to safety requirements. On the one hand a large dispersion ($R_{16}$) improves the momentum resolution, but on the other hand the beam size in the dispersive arm might become too large and the beam will hit the beam tube. The momentum spread times the dispersion ($R_{16}$) determines the (rms) beam size. Figure 3 shows the momentum spread (rms value) divided by the mean momentum of the particles in the beam. Therefore the dispersion should not be larger than $R_{16} \leq 600$ mm.

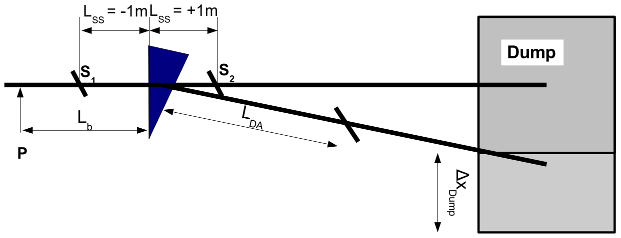

Figure 2: Bending magnet with small deflection angle.

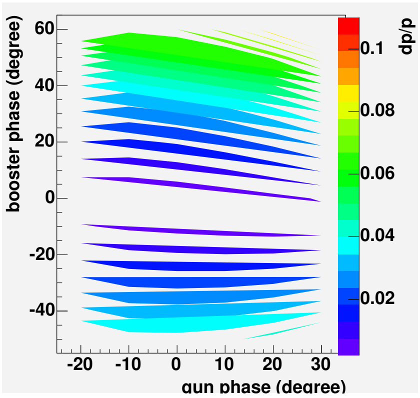

Figure 3: Relative rms momentum spread as a function of gun and booster phase.

Two cases will be considered, to use a small deflection angle, but a large drift length or large deflection angle with a smaller drift.

## *One Magnet*

An easy possibility to transport the beam to the main beam dump is to expand the dump by about a meter in horizontal direction and to use a dipole magnet with a small deflection angle as shown in figure 2. Since the distance between the dipole magnet and the center of the beam dump is about 4.5 m, only a small deflection angle of about $15^o$ can be used. The main advantage of this scheme is the large drift length in the dispersive section in order to place all the diagnostic devices. For an angle of $15^o$ the dump has to be enlarged by about $\Delta x_{Dump}$=1.2 m in x-direction and the dispersion is about 0.25 to $0.29 \cdot L_{DA}$ for useful values of the deflection radius and pole face rotation. Therefore a drift length ($L_{DA}$) of about 2 m leads to an useful dispersion. Afterwards a quadrupole magnet can be used to optimize the beam size for the dump.

## *Two or Four Magnets*

To use a larger dispersion angle ($30^o$ - $90^o$) a second dipole magnet has to be used to transport the beam to the beam dump of the main beamline (shown in figure 4 at the top). The second dipole needs to have at least the same

Table 1: Different possible dipole magnet settings.

| $\alpha$ | r (mm) | $L_{DA}$ (mm) | $\beta_{in}$ | $\beta_{out}$ | $L_{SS}$ (mm) | $R_{11}$ | $R_{12}$ (mm) | $R_{16}$ (mm) | $\Delta < p >$ | $\Delta p_{rms}$ | $\Delta\epsilon_{long}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| $15^o$ | 500 | 2000 | -$14^o$ | -$13.16^o$ | -1000 | -1.94 | 1940 | 518.74 | $2.4 \cdot 10^{-5}$ | $6.5 \cdot 10^{-3}$ | 0.47 |
| $15^o$ | 500 | 2000 | $15^o$ | $15.81^o$ | 1000 | 2.21 | 2208 | 553.97 | $1.76 \cdot 10^{-5}$ | $1.79 \cdot 10^{-2}$ | 0.47 |
| $30^o$ | 500 | 1000 | -$13^o$ | -$13.13^o$ | -1000 | -1.00 | 999 | 535.74 | $8.9 \cdot 10^{-6}$ | $1.6 \cdot 10^{-3}$ | 0.47 |
| $30^o$ | 500 | 1000 | $18^o$ | $18.63^o$ | 1000 | -1.28 | 1285 | 612.14 | $8.2 \cdot 10^{-6}$ | $4.9 \cdot 10^{-3}$ | 0.49 |
| $30^o$ | 400 | 790.56 | $13.99^o$ | $16.27^o$ | 1000 | 1 | 1000 | 479 | $3.4 \cdot 10^{-6}$ | $5.1 \cdot 10^{-3}$ | 0.47 |
| $60^o$ | 300 | 318.35 | $0^o$ | $0^o$ | -1000 | -0.42 | 419 | 425.69 | $5.7 \cdot 10^{-6}$ | $4.5 \cdot 10^{-4}$ | 0.44 |
| $60^o$ | 550 | 908.54 | $0^o$ | $0^o$ | -1000 | -0.93 | 930.6 | 1061.8 | $4.9 \cdot 10^{-6}$ | $4.7 \cdot 10^{-4}$ | 0.45 |
| $60^o$ | 600 | 900 | $30^o$ | -$25.83^o$ | -1000 | -0.59 | 592.3 | 861.55 | $5.4 \cdot 10^{-6}$ | $2.5 \cdot 10^{-4}$ | 0.44 |
| $90^o$ | 500 | 250 | $45^o$ | $0^o$ | -1000 | 0.5 | 500 | 750 | $5.4 \cdot 10^{-6}$ | $2.5 \cdot 10^{-4}$ | 0.44 |
| $90^o$ | 300 | 700 | $45^o$ | $45^o$ | 1000 | 1 | 1000 | 1700 | $4.6 \cdot 10^{-6}$ | $4.2 \cdot 10^{-4}$ | 0.44 |
| $90^o$ | 700 | 300 | $45^o$ | $45^o$ | 1000 | 1 | 1000 | 1300 | $4.2 \cdot 10^{-6}$ | $7.1 \cdot 10^{-4}$ | 0.45 |

deflection angle as the first one in order to deflect the beam parallel to the main beamline or larger to bring it to the center of the main dump. The main disadvantage is that the drift length in the dispersive arm is more limited the larger the deflecting angle becomes. It is needed to couple the current of both dipole magnets to simplify the operation.

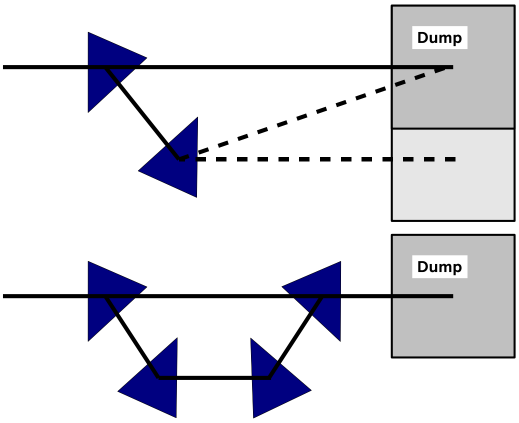

Figure 4: $60^o$ bending magnet (top) or bunch compressor (bottom).

There is the idea to construct a complete bunch compressor which might be useful in a later setup. The main advantage is that the bunch is brought back to the main beamline before the dump.

## COMPARISON OF DIPOLE MAGNETS

Table 1 shows a comparison of different possible deflecting angles and adequate setting for a high resolved momentum measurement.

In the table, $\alpha$ is the deflecting angle, $r$ is the deflecting radius, $L_{DA}$ is the drift length in the dispersive arm, $\beta_{in}$ and $\beta_{out}$ are the pole face rotations at the entrance and exit of the dipole magnet. $R_{11}$, $R_{12}$ and $R_{16}$ determine the momentum resolution of the measurement. $\Delta < p >$ describes the discrepancy of the determination of the mean momentum due to the dipole magnet, $\Delta p_{rms}$ is the discrepancy of the determination of the momentum spread and $\Delta\epsilon_{long}$ is the discrepancy of the determination of the longitudinal emittance (using the streak camera) due to the dipole magnet. $\Delta\epsilon_{long}$ does not include effects of the Cherenkov radiator or the optics. These rather small discrepancies can be reached only for a proper focussing on one of the concerning screens $S_1$ or $S_2$, otherwise the resolution gets much worse.

Non of the setups fulfills all requirements at the same time. Therefore only a compromise has to be found. The setups with the large deflection angles show a rather large dispersion, which limits the range of the possible booster phase and leads to a small drift length in the dispersive arm. This makes measurement of slice emittance difficult. In the case of small deflection angles the resolution gets worse. The determination of mean momentum is very good for all the cases, but there is a strong difference in the resolution of momentum spread.

## SUMMARY

Different magnet settings were compared and their advantages and disadvantages were discussed. In general small deflecting angle leads to a worse resolution and for large deflection angle the drift space after the quadrupole magnet is not sufficient to ensure good slice emittance measurements.

## REFERENCES

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[2] J. Rönsch et al., “Longitudinal Phase Space Studies at PITZ”, FEL’05, SLAC, Stanford, USA, 2005.

[3] S. Korepanov et al., “Design Consideration of the RF Deflector to Optimize the Photo Injector for PITZ”, FEL’06, Berlin, September 2006.