TRIUMF **Document-129912**

Design Note TRI-DN-16-27
ARIEL Pre-separator Dipole Magnet

Document Type: **Design Note**

Release: **01** **Release Date:** **2016-09-14**

Author(s): **S. Saminathan & N. Muller**

	Name:	
Author(s):	**S. Saminathan**	**APPROVAL RECORD**
	N. Muller	
Reviewed By:	**R. Baartman**	
	M. Marchetto	
	F. Ames	
	P. Bricault	
Approved By:	**R. Laxdal**	

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History of Changes

Release Number	Date	Description of Changes	Author(s)
DRAFT	2016-06-21	For review	S. Saminathan & N. Muller
#01	2016-09-14	Initial release with updates on beam size specification	S. Saminathan & N. Muller

Keywords:

Pre-separator, Preseparator, Mass separator, RIB transport, ARIEL Pre-separator, Dipole magnet

Distribution List:

F. Ames
R. Baartman
P. Bricault
G. Clark
E. Guetre
B. Laxdal
D. Louie
M. Marchetto
A. Messenberg
N. Muller
B. Paley
A. Perera
S. Saminathan

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1 Introduction

The pre-separator beamline will be used to transport the extracted beam from the ARIEL target ion source to the mass separator room. Also it is used to pre-select the required ions. This allows us to minimize the radioactive contamination outside the target hall, i.e. before transporting the beam into the mass separator room. This beamline consists of a magnetic and an electrostatic bender for momentum and energy separation, respectively. The calculated beam envelope for the ARIEL pre-separator is shown in Fig. 1. ARIEL facility consist of two target ion sources called as Ariel Proton Target West (APTW) and Ariel Electron Target East (AETE) [1]. Each target ion source will be provided with its own pre-separator and both are optically identical. The detailed design of the pre-separator optics design is presented in Ref. [2]. In this document we have described the magnet bender (MB) requirements to meet the pre-separator optics design. It should be noted that the TRIUMF's radiation safety standard and the remote handling capability requirements are not included.

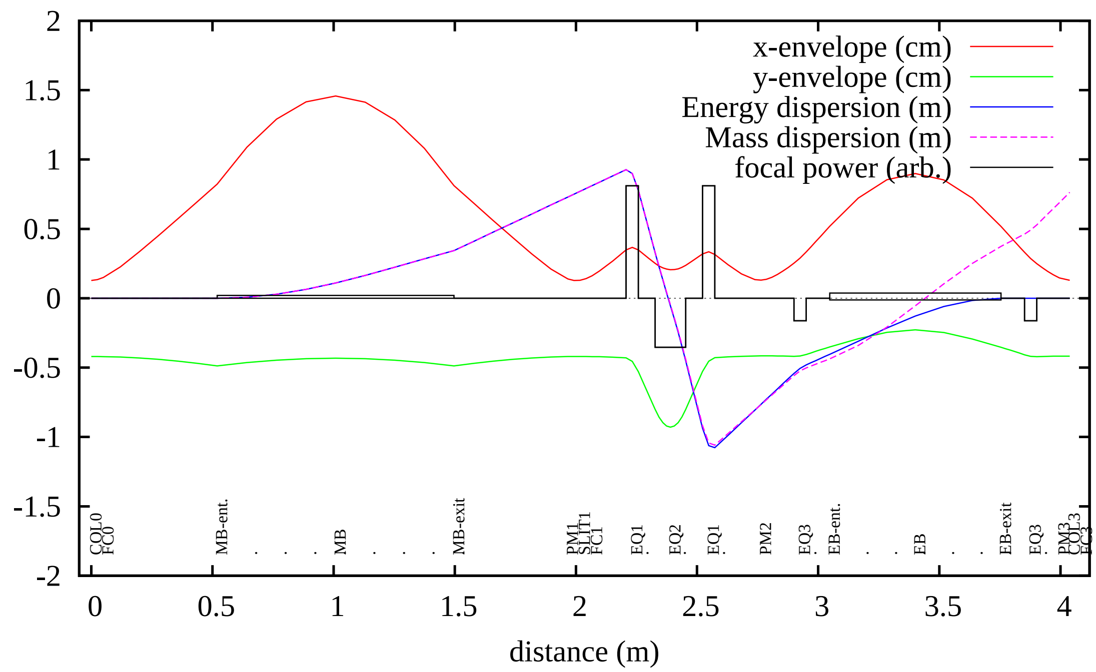

Figure 1: Calculated beam envelope (2 rms) with energy and mass dispersion for 60 keV ion beam through the pre-separator with $\varepsilon = 20\ \mu m$.

2 Beam parameters

Maximum beam rigidity $(B\rho)_{\text{max}}$	0.55761 T m
Minimum beam rigidity $(B\rho)_{\text{min}}$	0.01439 T m
Horizontal size of the beam [2 rms] (x)	1.3 mm
Horizontal size of the beam divergence [2 rms] (x')	15.6 mrad
Vertical size of the beam [2 rms] (y)	4.2 mm
Vertical size of the beam divergence [2 rms] (y')	4.8 mrad
Correlation parameter in horizontal plane (r12)	0.0
Correlation parameter in vertical plane (r34)	0.0
Emittance [4 rms] (ε)	20.0 μm

Table 1: Beam parameters at the object slit.

3 Basic magnet requirements

Magnet type	Rotated pole face
Bending angle (θ)	112°
Effective pole face rotation angle (entrance and exit)	27.5°
Bending radius (ρ)	500 mm
Full air gap (Non-bend plane)	60.0 mm
Maximum field strength (B_{max})	≥ 1.1152 T
$B(I)$ linearity over the whole range	within $\pm 2\%$ [3]
Field homogeneity $(\Delta \int B\text{d}l)/(\int B\text{d}l)$ (see Fig. 4)	$\leq 6 \times 10^{-4}$

Table 2: Summary of the basic magnet requirements (see Fig. 2 and 3).

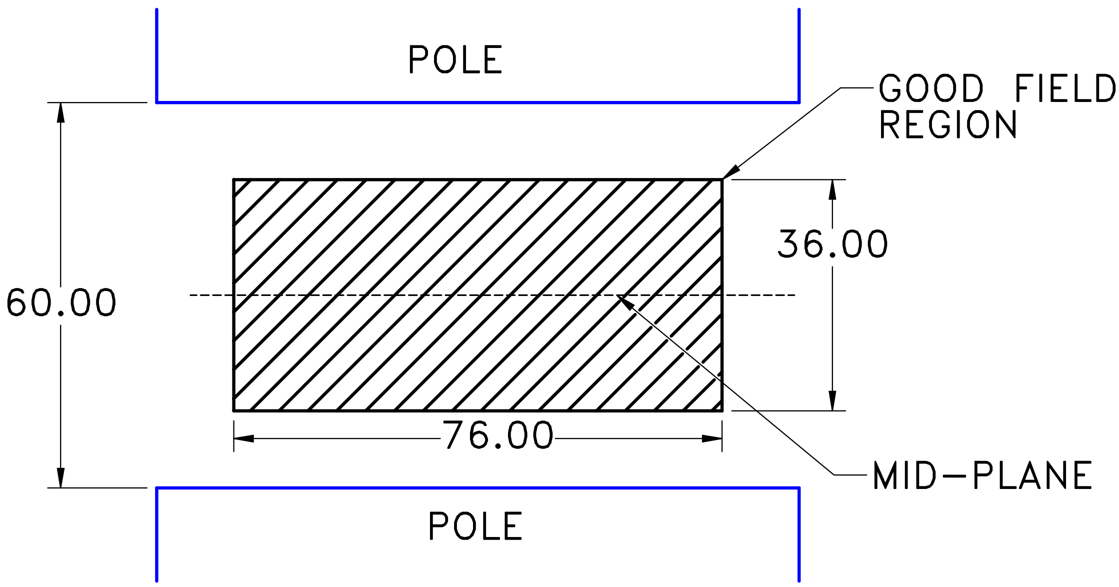

Figure 2: Vertical cross-section at the center of magnet. Dimensions are in mm.

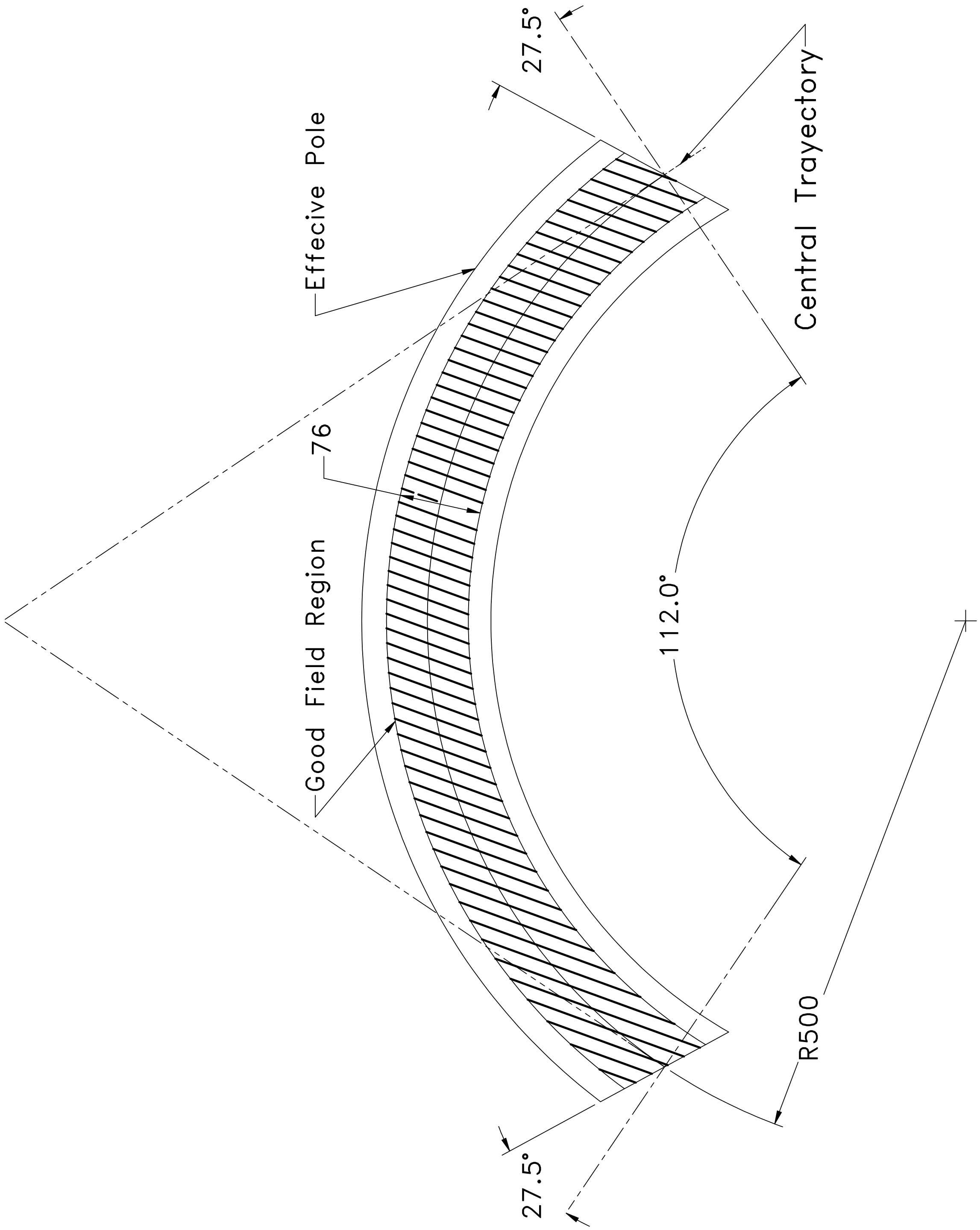

Figure 3: Plan view of the magnet's effective pole in the horizontal plane. Dimensions are in mm and degree.

4 Aperture size

The so called 'good field region' is determined by a central region around the theoretical beam trajectory, where the field quality has to be within certain tolerances. In our case the good field region is defined as the sum of beam width, margin for orbit displacement (2 mm), margin for a installation/alignment (typically 6 mm). The field homogenity in the good field region should be better than 6×10^{-4} over the width of ± 38 mm.

4.0.1 Half size of the pole width

Maximum 4rms beam size in the bend plane (horizontal plane (x)) is calculated by using the code TRANSOPTR, which is ∼30 mm. The minimum pole width is given by

$$\text{Half width of the good field region in the horizontal plane} = 30 + 8 = 38 \text{ [mm]} \tag{1}$$

4.0.2 Half size of the pole gap

Maximum 4rms beam size in the non-bend plane (vertical plane (y)) is calculated by using the code TRANSOPTR, which is ∼10 mm. The minimum pole gap is given by

$$\text{Half width of the good field region in the vertical plane} = 10 + 8 = 18 \text{ [mm]} \tag{2}$$

5 Beam rigidity

Maximum beam rigidity is defined as

$$(B\rho)_{\max} = \frac{p}{e} = 0.5576 \text{ [T m]} \tag{3}$$

6 Magnetic field strength

From the maximum beam rigidity and the required bending radius of the magnet the calculated magnetic field strength ($B_{\max}$) for a dipole magnet

$$B_{\max} = \frac{B\rho}{\rho} = 1.1152 \text{ [T]} \tag{4}$$

with ρ being the magnet bending radius in [m].

7 Field clamps

The dipole magnet shall be build with field clamps at the entrance and exit edges. The clamps shall be parallel to the pole edges. The fiedl clamps shall be designed such that the magnetic field in the clamp is less than 1.2 T and such that the field 150 mm from the clamp is less than 5 G.

8 Integral field

From the rigidity and bending angle (θ), the required field integral is:

$$\int_{-\infty}^{+\infty} B\mathrm{d}l = (B\rho)_{\max} \times \theta \simeq 1.089997 \text{ [T m]} \tag{5}$$

The increment dl is taken along the ion trajectory.

9 Field homogeneity

The parabolic distribution of the vertical field in a dipole magnet causes an error in the x-direction momentum, represented as

$$\Delta x' = \frac{\Delta \int B_y \mathrm{d}l}{B\rho} \tag{6}$$

where

$$B_y(y=0) = B_{y0}[1 + k2\frac{x^2}{g^2}] \tag{7}$$

g characterizes a width of the parabolic distribution, while k_2 denotes the field inhomogeneity over this region.

We thus have

$$\Delta x' = \frac{B_{yo}L}{B\rho} k_2 \frac{x^2}{g^2} = \theta k_2 \frac{x^2}{g^2} \tag{8}$$

where θ is the nominal bend angle and L is the effective length of the dipole.

The TRANSOPTR calculation shows that the intrinsic 2nd order aberrations from a magnetic bender causes an emittance growth about 2%. We ask for the same amount of emittance growth due to the parabolic field component, so we require [4]

$$\Delta x' = \frac{Lx^2}{2\rho^3} \tag{9}$$

From equation 8 and 9, we obtain

$$k2 = \frac{g^2}{2\rho^2} \tag{10}$$

Substituting a good field region of $g = \pm 38$ mm in the bend plane and the bending radius $\rho = 500$ mm into above equation 10, we get the field inhomogeneity k_2 over this region needs to be $< 3 \times 10^{-3}$. We require field inhomogeneity less than factor of 5 smaller, i.e. $\left[\frac{\Delta \int B\mathrm{d}l}{\int B\mathrm{d}l}\right] \leq 6 \times 10^{-4}$.

10 Power supply

10.1 General requirement

- According to Canadian standards (comply to CSA).
- Comply to TRIUMF control standards.
- Requirement for the ripple of the power supply, $\Delta I/I \leq 1 \times 10^{-4}$ (see Sec. 10.2)
- Polarity switch is not necessary.

10.2 Requirement for the ripple of the power supply

The ripple in a dipole power supply causes a shift of beam axis downstream, represented as

$$\Delta x = \beta_x \frac{\Delta B_y L}{B\rho} \tag{11}$$

where β_x is smoothed β function; about 0.933 m in our case, L is the effective length of dipole, and $B\rho$ is the magnetic rigidity of beam.

We require such a shift to be much less than the beam radius, around 0.001 m (2 rms) at the slit location

$$\beta_x \frac{\Delta B_y L}{B\rho} \leq \sqrt{\beta_x \epsilon} \tag{12}$$

We thus have

$$\frac{\Delta B_y}{B} \leq \frac{\sqrt{\beta_x \epsilon}}{\beta_x} \frac{\rho}{L} = \frac{\sqrt{\beta_x \epsilon}}{\beta_x \theta} \tag{13}$$

where θ is the nominal bend angle of the dipole. Substituting $\sqrt{\beta_x \epsilon} = 0.001$ m, $\beta_x = 0.933$ m and $\theta = 112°$ into above equation 13, we get $\Delta B_y/B_y = 5 \times 10^{-4}$. We require $\Delta B_y/B_y$ less than factor of 5 smaller, i.e. $\Delta B_y/B_y \approx \Delta I/I \leq 1 \times 10^{-4}$. This is the constraint for the ripple of the power supply at the normal operating regime.

11 Vacuum chamber

- Non magnetic material and Ultra High Vaccum (UHV) compatible (i.e., $\leq 1 \times 10^{-8}$ Torr) [1].
- Clearance for the beam path in the vertical plane should be $\geq$ 34 mm [full gap]. This gives a vertical acceptance about 250 μm at the center of the magnet.
- Clearance for the beam path in the horizontal plane should be at least $\pm$38 mm (except at the entrance and exit flanges). This gives a horizontal acceptance about 140 μm at the center of the magnet.
- Comply to TRIUMF radiation safety standards and remote handling capability in the target station.

12 Hall probe requirements

- Absolute accuracy should be better than $\pm$2.0 G and the relative accuracy should be better than $\pm$0.05 % at 1.2 T.
- A preferred location for the hall probe placement is on the bottom/top pole face.
- Power supply unit of the hall probe ahould be according to Canadian standards (comply to CSA).
- Comply to TRIUMF control standards.

13 Field Measurement

13.1 Field strength at the magnet center

- It must be checked that the field at the magnet center can reach 1.1152 T, and run continuously for three hours.
- We require a calibration (B vs. I) curve, giving vertical component of the B field at the center of the magnet for at least twenty different currents while the magnet is ramped up to the maximum current, then at least twenty more points when the magnet is ramped down to zero current. Immediately after, we require the same measurement to be repeated with the opposite polarity [3].
- We also require a residual B field measurement at the center of magnet with zero current ($I = 0$ A) just after operating the magnet at 1.1152 T.

13.2 Field map and integrals

We require a field map in the mid-plane and calculation of field integrals for the specified region as shown in Fig. 4. Proposed measurement procedure [5]:

- Check that the field integral, in the mid-plane, along the central integral path (geometrical trajectory) passing by the center of the magnet exceeds the expected value of 1.089997 T m (see Fig. 4).

- In the mid-plane only, measure (map) the vertical field at every 8 mm along the central path and also the vertical field at every 8 mm along the direction perpendicular to the central path. The required measurement region is shown in the figure 4. We want this measurement for two B_{max} field settings, one measurement for the field at the center is equal to 1.1152 T and the second measurement the field at the center is equal to 0.4072 T.

  The field integral along the central path and around the central path may be calculated from the measured field map. We require the field integral for a total of 11 paths. For the spacing between the paths refer table 3. Relative field integral error (RFE) (see Eq. 15) must be less than 6×10^{-4} over the width (g) ± 38 mm.

  The expected (hard edge (he)) integral field along the each trajectory is given by

$$\left[\int B\mathrm{dl} \right]_{\mathrm{he}} = L_i \times B_{\mathrm{max}} \tag{14}$$

  where L_i is the effective length of each integral path, i.e. $L_i = f(g)$ (see table 3 and Fig. 5). The effective length calculation is described in the Appendix.

  Relative field integral error is defined by

$$RFE = \left| \frac{\Delta \int B\mathrm{dl}}{\int B\mathrm{dl}} \right| = \left| \frac{\left[\int B\mathrm{dl} \right]_{\mathrm{meas}} - \left[\int B\mathrm{dl} \right]_{\mathrm{he}}}{\left[\int B\mathrm{dl} \right]_{\mathrm{he}}} \right| \tag{15}$$

  where the $\left[\int B\mathrm{dl} \right]_{\mathrm{meas}}$ is the measured field integral along the each integral path.

- TRIUMF may accept other measurement grids and other ways of calculating $\left[\int B\mathrm{dl} \right]_{\mathrm{meas}}$ and ($\left[\int B\mathrm{dl} \right]_{\mathrm{he}}$). Other methods must be proposed at bid time and include details of how the calculation will be made.

13.3 Data

- TRIUMF to get a copy of all the measured data, including field components and coordinates (indexed against the physical dimensions of the magnet) for each measurement point. Complete material specifications (B vs H curve) have to be given.

- We require a copy of magnet design drawings, Solidworks model and also magnet simulations (OPERA3D preferred).

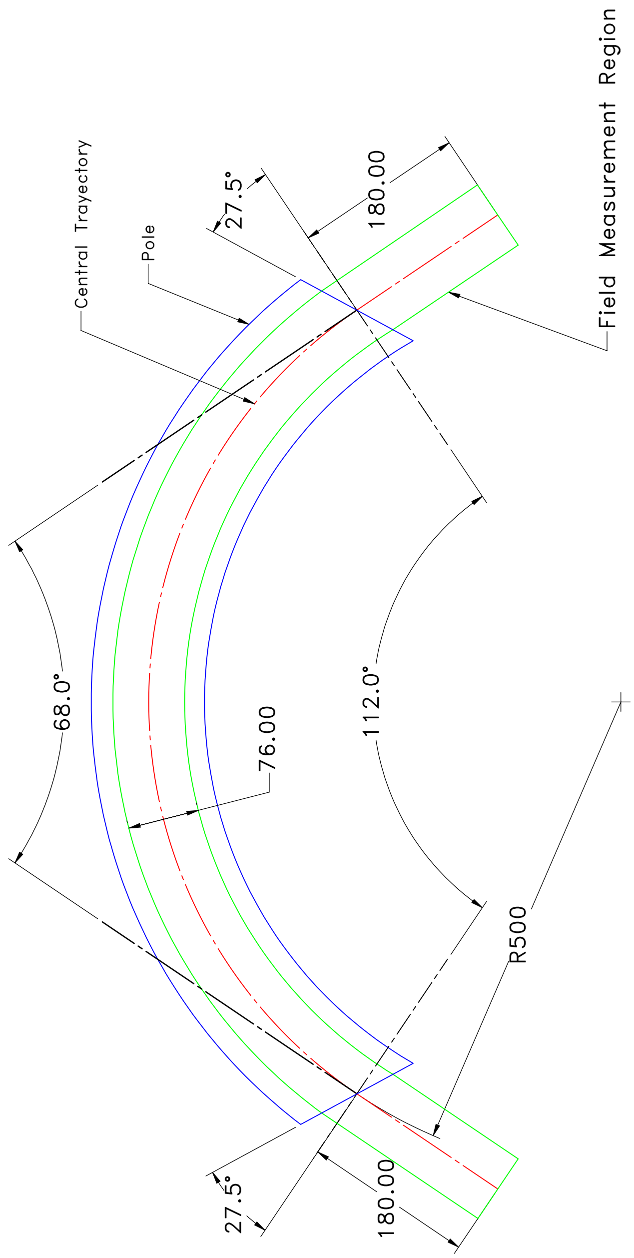

Figure 4: Schematic description of the central trajectories (red dashed line) and measurement region (green solid line) with a magnet pole (blue solid line) in the horizontal plane. Measurements in mm and degree.

14 Appendix [6]

$$\beta = \frac{1}{2}(\pi - \theta) \tag{16}$$

$$c_i = \frac{R + g}{cos(\beta)} \tag{17}$$

$$M = tan(\alpha + \beta) \tag{18}$$

$$e = \frac{Rcos(\beta) - Rsin(\beta)}{M} \tag{19}$$

$$x_i = \frac{Me + c_i tan(\frac{\pi}{2} - \beta)}{M + tan(\frac{\pi}{2} - \beta)} \tag{20}$$

$$y_i = tan(\frac{\pi}{2} - \beta)(c_i - x) \tag{21}$$

$$R_i = \sqrt{x_i^2 + y_i^2} \tag{22}$$

$$L_i = 2R_i \left(\frac{\pi}{2} - atan2(x_i, y_i)\right) \tag{23}$$

where, R is the nominal bending radius (500 mm)
θ is the nominal bending angle (112°)
α is the edge angle (27.5°), and $i = f(g)$

g [mm]	L_i [mm]
-40	941.77
-32	948.73
-24	955.78
-16	962.91
-8	970.11
0	977.38
8	984.73
16	992.13
24	999.60
32	1007.12
40	1014.70

Table 3: Measurement points for field map in the mid-plane (see Fig. 5).

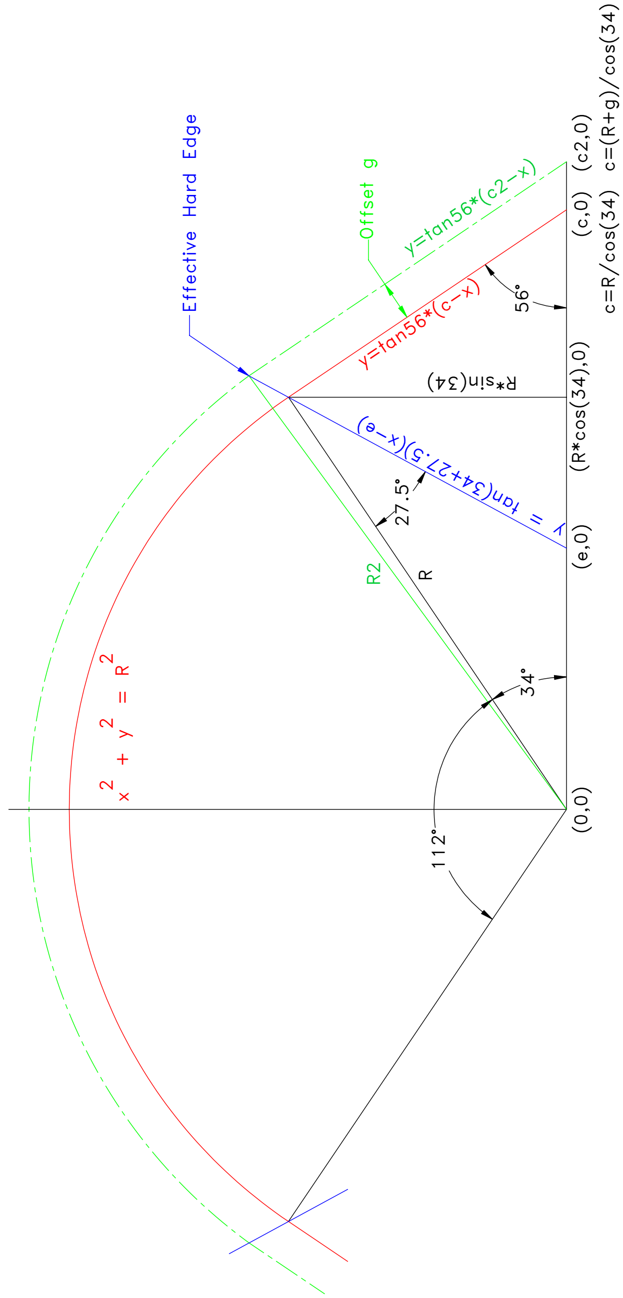

Figure 5: Plan view for calculating the effective legth.

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