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Simulations of Coupler Kicks and Failure Modes

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Abstract

This memo contains studies on coupler kicks in the ILC cavities and the effect of failing quadrupoles and corrector dipoles in the main linac on the beam delivery system. Simulations were done using the Merlin library.

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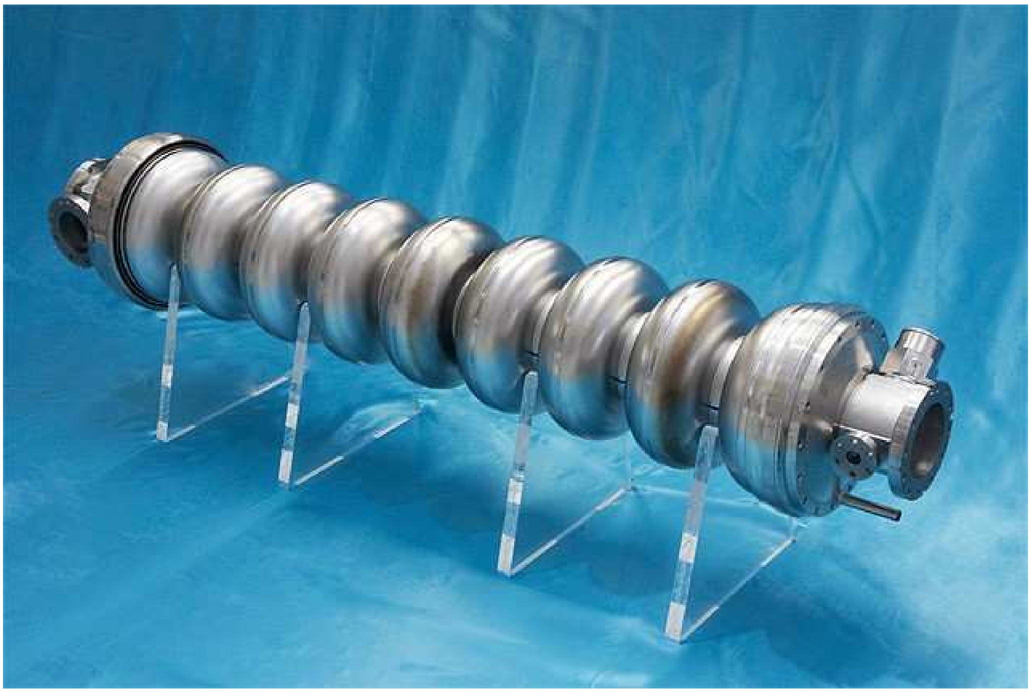

Figure 1: TESLA Cavity

1 Introduction

1.1 ILC

The ILC is a electron-positron collider which is designed to achieve high precision, energy and luminosity. The leptons offer a relatively clean environment (no QCD background). The high energies of $E_{CM} = \sqrt{s} = 500$ GeV can no longer be reached with a storage ring due to the growing energy losses by synchrotron radiation.
The alternative is a linear design where the bending of the trajectory is reduced to a minimum. The main linac is the more than 10 km long part of the machine which accelerates the particles from 15 GeV to 250 GeV. The than following Beam Delivery System (BDS) guides the correct bunches to the Interaction Point and does the collimation and final focusing. If bunches leave the design trajectory or the machine is not operating as planned, then the bunches are dumped before the BDS to prevent damage of the detector.

1.2 RF-Cavity

The ILC cavity is based on the TESLA design (Fig. 1). The 1 m long superconducting cavity consists of nine cells which are symmetric around the z-axis. Each cavity accelerates an electron by 31.5 MeV if the particle traverses the resonator in phase. The radio frequency (1.3 GHz) is introduced by a coupler that transfers the electromagnetic field from the klystron - a RF-amplifier.

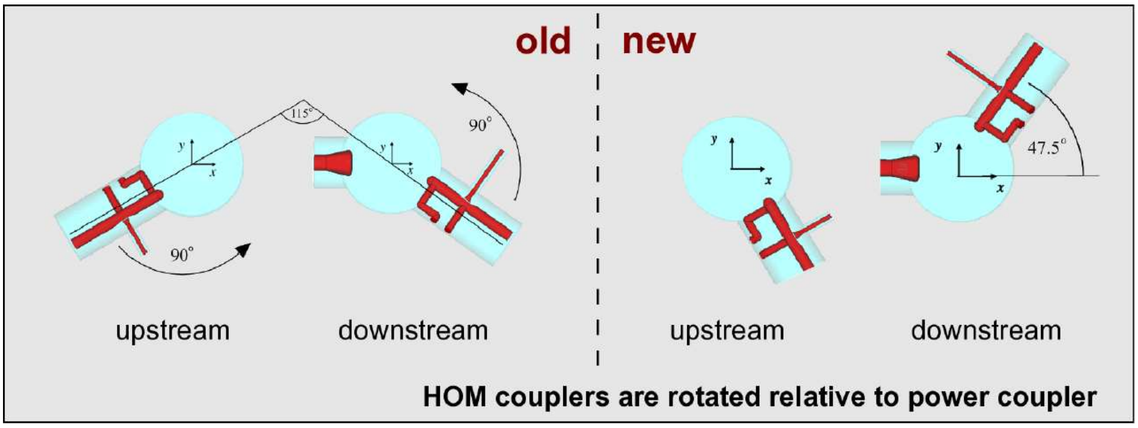

Figure 2: Old and new HOM coupler positions with respect to RF coupler

One higher order mode (HOM) coupler is situated upstream, one downstream of the nine cells. These three couplers break the symmetry around the z-axis and lead to a modification of the transverse dynamics. The HOM damp all frequencies apart from the 1.3 GHz ground mode of the cavity. In this study, two designs/positions for the HOMs are compared. The "old" coupler design is the one of TESLA, XFEL and suggested in the RDR for the ILC. According to old calculations, the wake fields in this configuration leads to quite strong transverse kicks. Therefore, a "new" design was considered: the HOM coupler are rotated around the z-axis by 90° with respect to the RF coupler. This minimises the wake field kick but increases the RF-kick. Fig. 2 shows the "old" and "new" design. New calculations predict a reduced size of the wake field kick even in the old coupler layout (depending on number of linked cavities). Therefore, the new design does not seem to be necessary or even counterproductive.

1.3 Emittance

Emittance is a variable characterising the quality of a particle beam. It is the occupied volume in phase space. In order to have a well-defined initial state and a high luminosity, this volume should be as small as possible. Within a conservative system, the emittance is constant. Therefore, one uses non-conservative effects like synchrotron radiation in the damping rings to cool down the transverse motion of the particles. The projected emittance in one dimension is proportional the product of the width of a bunch in x and $x' = \frac{dx}{dz}$ e.g. proportional to the product of the semi-major axes of the ellipse in the x-x'-plane. It can be calculated as the covariance of x and x':

$$\varepsilon^2 = \det\langle\Sigma\rangle, \quad \Sigma = (\mathbf{x} - \langle\mathbf{x}\rangle)(\mathbf{x} - \langle\mathbf{x}\rangle)^\top, \quad \mathbf{x} = \begin{pmatrix} x \\ x' \end{pmatrix} \tag{1}$$

If there is dispersion (η, η') i.e. a linear relation between energy and $\mathbf{x}$, a part of this spread can be corrected at the end with a dipole magnet. In such a case the really important variable is the dispersion-corrected emittance which can be calculated by the replacement

$$y \to y - \eta\delta,\ y' \to y' - \eta'\delta. \tag{2}$$

Here δ is the energy deviation of a particle.

1.4 Description of Beam Dynamics

The lattice of quadrupoles is arranged to form a FODO structure to obtain a net focusing effect. The constant gradient in these magnets leads to a displacement-dependent field strength and deflection. Therefore, the transverse motion follows a modified Harmonic Oscillator Equation, the Hill Equation:

$$x'' + \kappa(z)x = 0 \tag{3}$$

The solution includes a z-dependent β-function which is governed by the local strength of the magnets. This is for example used in the BDS to broaden the beam in the collimators or to focus the bunches at the Interaction Point.

1.5 MERLIN

MERLIN is a c++ library for accelerator simulations. For the simulations done for this study, the code was linked and compiled and ran typically for one day to compute one scenario. The backbone of the program is the tracking algorithm which calculates the (linear) effects on each particle by all the components of the accelerator.

For these simulations, a one-to-one (1-2-1) steering algorithm is used. It registers the displacement of the beam in each BPM for each individual change in the corrector coils. The inversion of the response matrix allows to steer the bunch through the middle of the BPMs.

2 Transverse Dynamics - Kicks

2.1 FODO-Structure and Betatron Oscillation

A series of alternating quadrupoles in the right distance and with the right strength can stabilise a beam by its net focusing effect.

A quadrupole which is focusing in one - say x-direction - defocuses in y-direction. But the deflection depends on the offset of the particle from the field-free, central axis. So, a focusing quadrupole at a position where the bunch is broad (in that direction) and a following defocusing quadrupole at the position with minimal bunch width do collimate the beam.

This FODO-structure keeps all the particles within a corridor, though they always have a certain divergence of their tracks or a different position in space. The transverse oscillation of single particles (or if there is a offset) of a whole set of particles (bunch) is called betatron oscillation.

2.2 RF- and Wake Field Kicks

The RF electromagnetic field from the klystron enters the cavity via its coupler and excites standing waves in the nine cells. In the vicinity of the RF- and HOM couplers, the rotational symmetry is broken and causes transverse EM-fields - even on the z-axis. This leads to a kick (a certain transverse voltage) which the electrons feel by passing through each cavity - the so called RF-kick. Each unit of 24 (or 26 depending on design) cavities, one klystron and one quadrupole has a correction dipole. This corrector coil allows to compensate the unavoidable misalignment of the quadrupoles as well as the RF-kick.

Electrons and positrons are charged particles. So, they are surrounded by an electric field, and, as they move, they cause a magnetic field as well. When these charges travel in a cavity, they excite electromagnetic fields whose form is governed by the shape of the cavity walls. Since the bunches fly nearly with the speed of light, the electric field becomes compressed in the longitudinal direction and it excites oscillations in their wake. So, the wake field of a charge influences the particles behind it (especially in the same bunch). The effect of the wake field within a rotationally symmetric cavity is included in MERLIN via a distance-dependent potential. This is calculated for each particle within each cavity of the linac. But, the wake field does also interact with the couplers - the three asymmetric parts of the cavities. This causes additional transverse kicks.

In the performed simulations, the RF kick is significantly stronger in the new coupler design (which tries to reduce the transverse wake field). So, there is a trade-off between RF-/wake field kick on the one hand and the old/new couplers (see Table 1):

Kicks	Old Coupler	New Coupler
Wake Field	strong	Coupler Asymmetry partially cancelled
RF	partially cancelled	strong
Wake Field: new calculations	9 times smaller than before	

Table 1: Trade-Off

In the following part, the growth of the emittance is studied depending on two types of klystron errors.

2.3 Klystron Jitter: Voltage and Phase

Some transverse kicks are unavoidable but they can be compensated by the corrector coils as long as these effects are predictable or measurable before the actual steering. But a real machine has errors which happen in real time: one example are fluctuations of the klystron. All these kicks are energy-dependent and there is a spread of $\Delta p/p \approx 0.001$ at the end of the linac. This causes the growth of the emittance.

The study was performed for a Gaussian error of 0.1% (as in RDR) on the accelerating voltage. The same deviation from the design value is applied to each set of 24 cavities

since they are all fed by the same klystron via waveguides. Here, only the RF-kicks are taken into account. A "perfect" machine without misalignment is considered.
As long as the voltage error is not too large (to cause a wrong phase relation, etc.), the error on the final energy is small due to error propagation (suppressed by $\sqrt{N_{\mathrm{klystrons}}} = 17.7$).
Even 10 times larger voltage errors of 1% does not exceed the emittance limits. Only with the new coupler design, the growth due to RF-kicks is significant (see Table 2). The simulation consists of 50 seeds per scenario with 10,000 particles per bunch. The values in Table 2 are the average and sigma of these seeds.

End Emittance $\gamma\varepsilon$	no Voltage Error	0.1% Error	1% Error
Old Coupler	20.3 ± 0.2	20.3 ± 0.2	20.42 ± 0.3
New Coupler	25.1 ± 0.2	25.1 ± 0.6	28.3 ± 5.2

Table 2: Results for emittance at the end of the main linac due to RF-Kicks

The influence of phase errors was studied as well. A larger Gaussian relative error of 1%, but did not affect the emittance. The 1% has the same effect on energy spread (due to $|\sin(-5.3°)| \approx 0.1$).
The Fig. 3 shows representative graphs for the emittance along the main linac. The old coupler design seems to be the better solution due to the rescaled wake field and the trade-off with the RF-kicks. The four graphs show the results of different scenarios:

1. old coupler, large wake field (old calculation), no RF-kick
2. new coupler, dispersion corrected emittance, no wake field, but RF-kick
3. old coupler, small wake field (new calculation), no RF-kick
4. new coupler, cancelling wake field, no RF-kick

The bunches in that simulation had a size of 100,000 particles. 5 runs were performed to characterise typical behaviour.

3 Failure Modes

Errare humanum est. But not only human. Any machine can fail, too. If one considers one of the largest and most complicated machines ever planned? Well, then you should also plan the errors and failures.

Failures even of a single component can impose a threat to the detector or the machine since the bunches are so small in spatial dimension, highly populated (2×10^{10}) and highly energetic (up to 250 GeV per particle). The Beam Delivery System (BDS) includes measures to collimate the beam. Therefore, a series of small apertures (windows with a size of mm) strip off the halo around a bunch. They consist of spoilers and absorbers out of copper or titanium.

Since they are quite close to the beam, they can be easily hit if something goes wrong. The problem is that a focused bunch can deposit so much heat within a small region that the maximal tensile strength is exceeded and the material is damaged.

In this section, one studies the effect of partly failing quadrupoles or their correction coils.

3.1 Quadrupoles

In the ILC, superconducting quadrupoles are planned. Within the main linac, the quadrupole strength (which is normalised with respect to the energy) is constant. Therefore, the magnetic field strength/gradient increases along the accelerator.

Even if a magnet fails completely, the field does not vanish instantaneously. Expecting a time constant of 1 ms for a superconducting coil, the field should not be reduced by more than 0.04% within the 370 ns spacing between two bunches of the same train. To allow an even stronger field decay, we focused on the case of 99% remaining field strength.

It is important to notice, that the failures need something else to be problematic: misalignment. In a perfectly aligned machine, the particles follow a centered trajectory which passes the quadrupoles in their field-free region. This means that a quadrupole failure would have no direct effect (Fig. 4). The 1%-failure of quadrupole # 233 leaves the very small oscillations in y-direction unharmed ($\leq \pm 0.02\ \mu$m). A typical value for the amplitude of mean position in y in a machine with misalignment is $\leq 10\ \mu$m in the main linac. During this study, the following Gaussian-distributed misalignment was applied to the cavities and quadrupoles (see Table 3). This study does not cover the misalignment of cryomodules as a whole.

	Transverse: x & y	Rotational
Cavities	300 μm	none
Quadrupoles (main linac)	300 μm	none
Quadrupoles (BDS)	200 μm	none

Table 3: Sigma of Misalignment

3.1.1 Field reduced by 1%

We let fail one component per scenario (quadrupole # 150, 200, 250, 300) and looped over 100 seeds with randomised misalignment. No large loss with more than 10% of the particles in any of the collimators is registered during the 4×100 simulations.

3.1.2 Field reduced by 5%

Within 4×100 simulations, there were only 4 events with more than 10% of the particles beeing lost in either RCOLSP4 or RCOLSPEX. They look like a grazing shot (Fig. 5). But one can see the increased oscillation of the mean bunch position (Fig. 6) downstream of the failing quadrupole.

3.1.3 Field reduced by 10%

5 quadrupoles (0, 55, 156, 245, 311), 97 seeds: 50 losses with more than 10% of the initial particles. In several cases, even more than 90% of the particles hit the spoilers and collimators. This means that around of 1% of the misalignment scenarios lead to potentially hazardous bunch losses. 22 (of these 50) runs are especially dangerous since their cross-section is small: $\sigma_x \cdot \sigma_y < 10^{-9}$ m^2. A strongly focused beam can deposit enough heat to cause thermal fracture. An overview is given in Table 4.

Quadrupoles	> 10% of a bunch	strongly focused	out of ... runs
1%	none	none	400
5%	4	none	400
10%	50	22	485

Table 4: Less than 1% of the bunches are critical, even for 10% failure.

3.1.4 Total Failure

If more than 8 quadrupoles fail at same time, then even the bunch gets lost within the main linac [1].

3.2 Corrector Coils

The Corrector Coils are electromagnetic dipoles placed at roughly the same position as the quadrupoles, which allow to compensate transverse offsets (misalignment) of the quadrupole and RF-kicks.

The simulations show a smaller probability to lose larger fractions of a bunch in the collimators for the same relative reduction as for the quadrupoles (out of 4×100 runs, Fig. 5):

Corrector Coils	> 10% of a bunch	strongly focused	out of ... runs
1%	none	none	400
5%	none	none	400
10%	32	12	400

Table 5: Less than 1% of the bunches are critical, even for 10% failure.

4 Discussion and Conclusion

4.1 Coupler Kicks/Emittance

With the new calculation and their smaller result for the transverse voltage in the old coupler design, the effective emittance grows very slowly and reaches the RDR goal. Due to the larger RF-kicks, the new couplers are not favorable.

4.2 Failure Modes

For a failure of 4 quadrupoles (# 150, 200, 250, 300 of 312 in the lattice file) or 4 corrector coils, one per scenario each with 1%, no major loss was registered within the 100 simulations. It is important to assure that the system reacts immediately when some components fail. Even if the spoilers and collimaters withstand single bunches, a whole train of more than 2000 bunches has to be dumped properly or it will harm the machine.

5 Outlook

5.1 Support from other Projects

The results of these studies are based on the a lot of input one has to rely on. There are the drafts and descriptions in the Reference Design Report which are often technically challenging and not always state of the art. One ingredient is the strength of the coupler kicks, based on numerical simulations of the EM-field in the cavities. The predictions have changed considerably and need confirmation.

Both, the already operating FLASH (former Tesla Test Facility) and the X-ray Free Electron Laser XFEL, share the TESLA-cavities with the ILC design. The experience made at these accelerators will help to optimise the Terascale lepton collider.

5.2 Further Research

With the progress of the ILC design, the study has to be updated. One important feature is the undulator in the electron linac. It is one possibility to produce circularly polarised photons which can be converted into longitudinally polarised electron-*positron*-pairs. Then, possible changes of the lattice have to be considered.

Depending on the technology used for the quadrupoles and corrector coils, the time constants differ. This determines how much the field strength is altered during the time span the machine needs to react (dump the hazardous beam) to a failure.

References

[1] P Eliasson *et al.* EUROTEV-2006-040.

[2] E Wilson, *An Introduction to Particle Accelerators*, Oxford University Press, 2001.

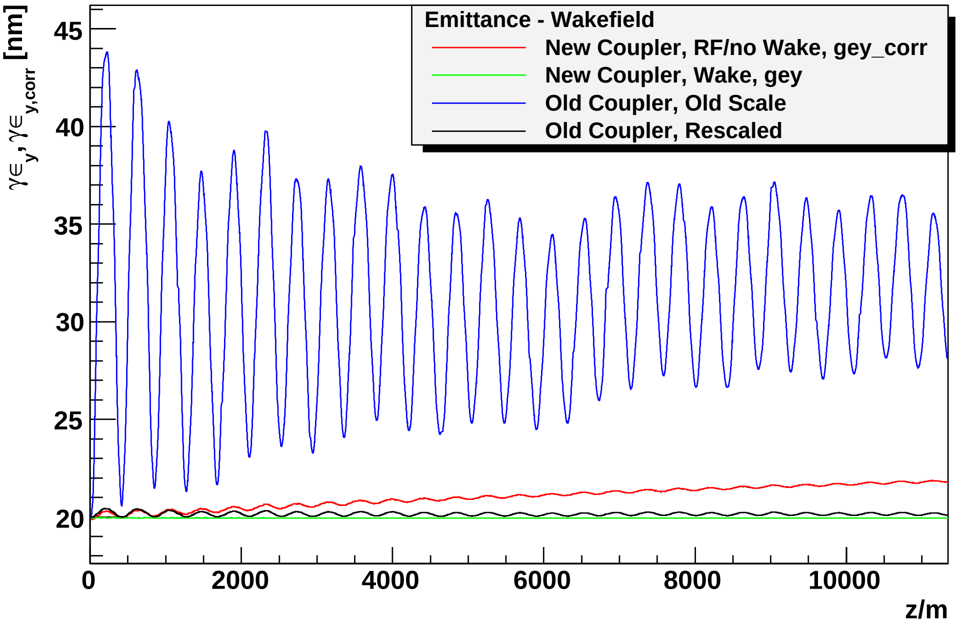

Figure 3: Emittance in y-direction for different coupler designs and transverse kicks.

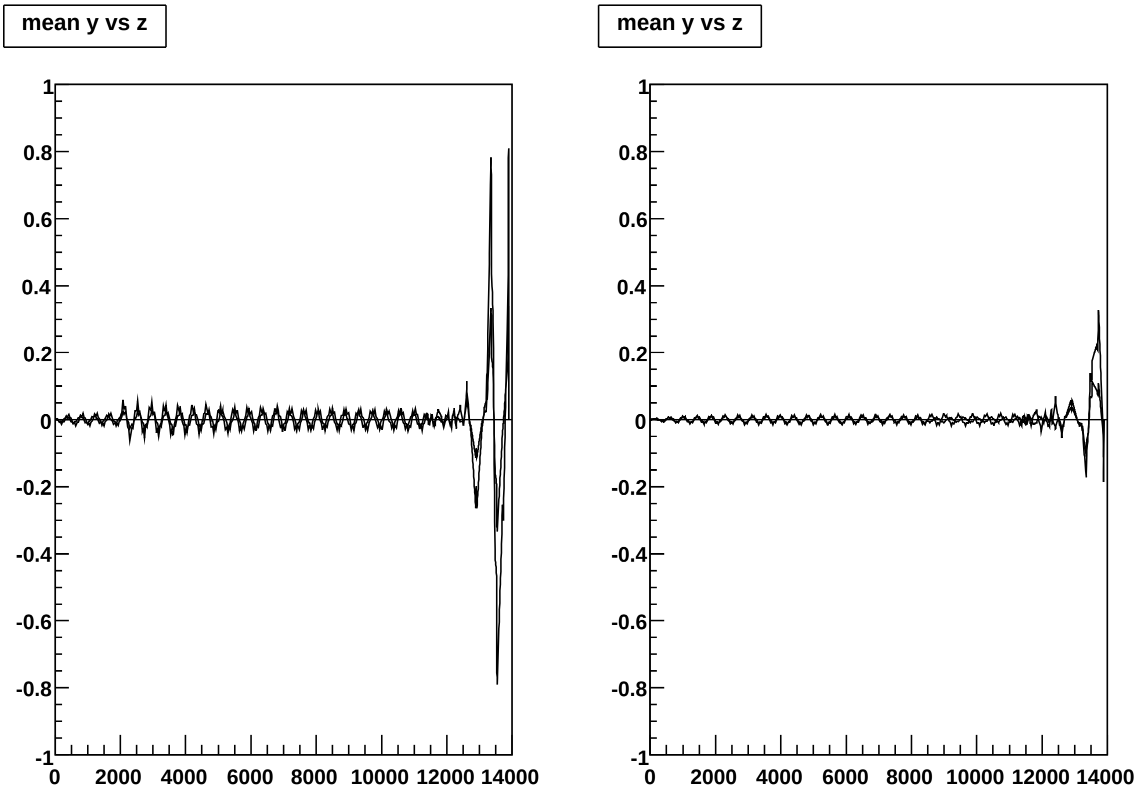

Figure 4: The left plot shows two trajectories (mean y in μm vs z in m) for quadrupole failure in # 55, the right plot shows the trajectories for a failure in quadrupole # 233. The trajectory is only minimally changed in a perfectly aligned machine.

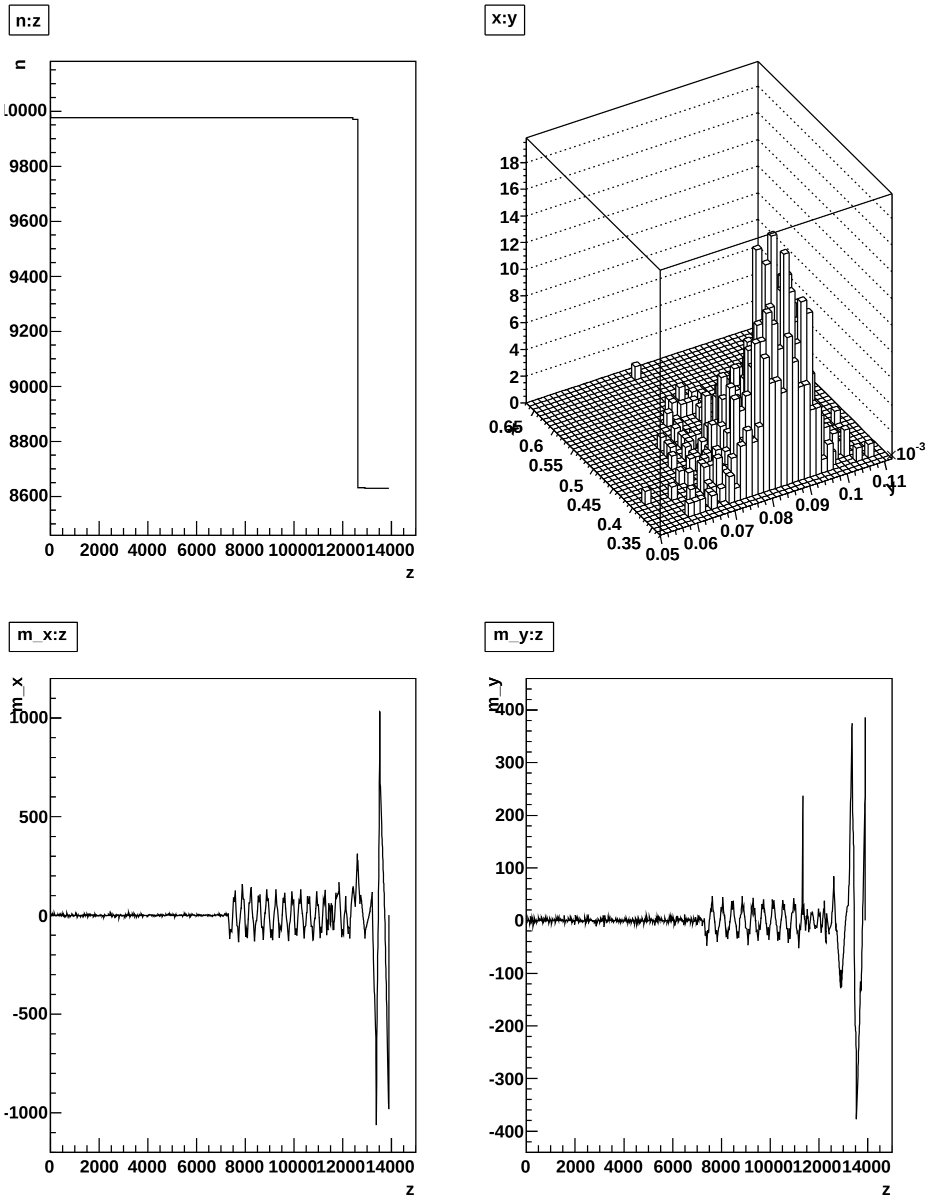

Figure 5: The upper left plot shows the number of particles vs z (in m) in case of a 5 % lower magnetic field in quadrupole # 200 for one of the worst cases of random misalignment of the quadrupoles and cavities. The loss of about 1400 particles (at the collimator SP4) is clearly visible. The x-y distribution (in μm) of the lost beam particles at SP4 is shown in the upper right plot. The lower plots show the mean x and y position (in μm) of the beam for this configuration.

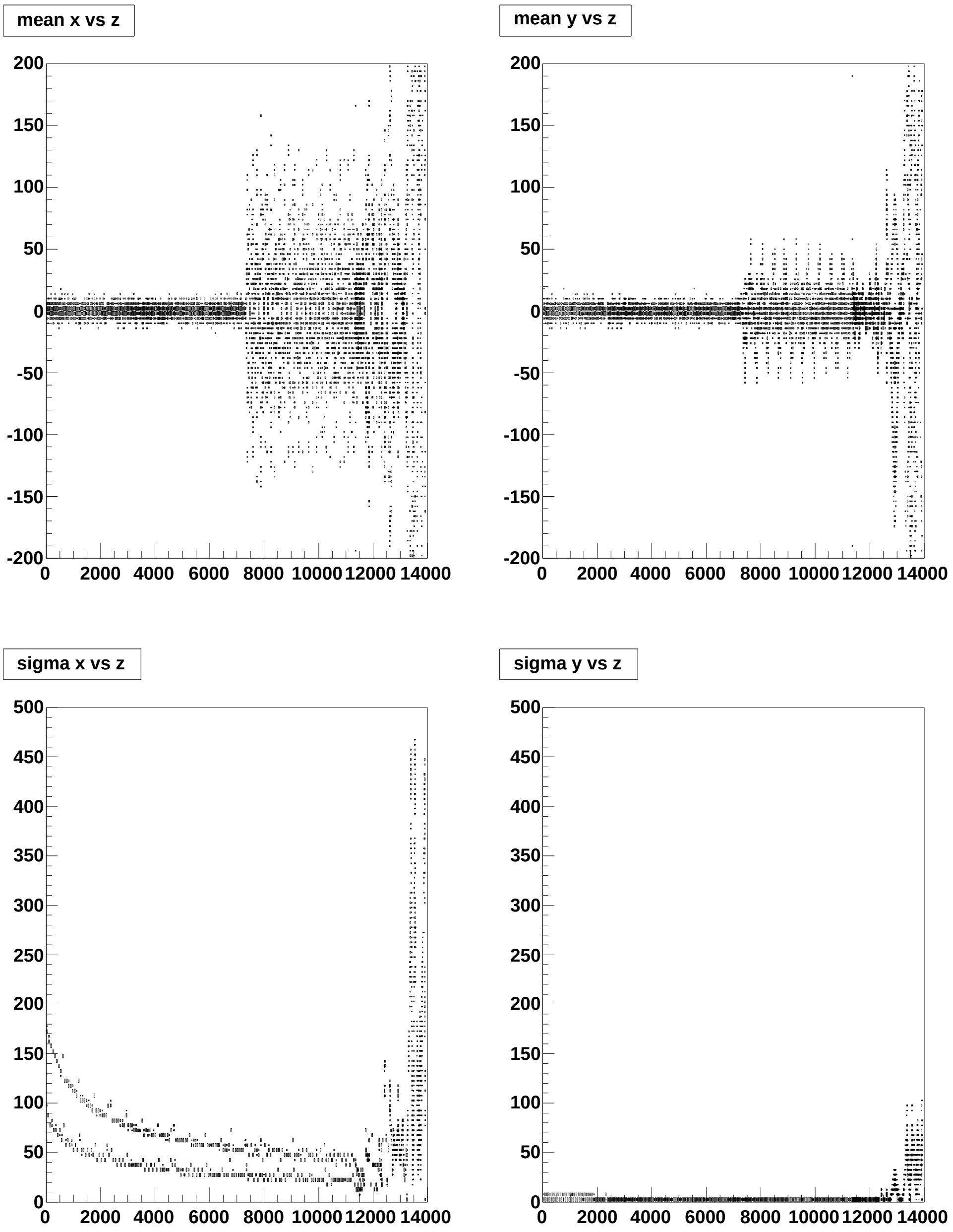

Figure 6: The upper plots show the mean x and y distribution (in μm) vs z (in m) for 100 different misalignment configurations. The lower plots show the sigma of the x and y positions of the beam vs z. A larger transverse oscillation is visible in x and y direction behind quadrupole # 200 with 5% smaller magnetic field.