

A Novel RF-ExB Spin Manipulator at COSY

Juli 07, 2014 | Sebastian Mey for the JEDI Collaboration | Forschungszentrum Jülich

Content

Spin Motion in an RF Wien-Filter

The RF-ExB Dipole

Field Distribution and Compensation

Measurements

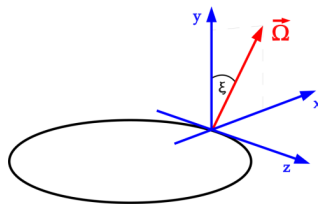
Conclusion

The Thomas-BMT Equation

$$\frac{d\vec{S}}{dt} = \frac{e}{\gamma m} \vec{S} \times \vec{\Omega}$$

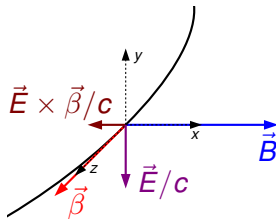
$$\vec{\Omega} = (1 + \gamma G)\vec{B}_{\perp} + (1 + G)\vec{B}_{\parallel} + \left(\frac{\gamma}{\gamma + 1} + \gamma G \right) \frac{\vec{E} \times \vec{\beta}}{c}$$

- spin precession of revolving, relativistic particles in the main dipoles' guiding field
- manipulation of the precession axis $\vec{\Omega}$ with RF fields oscillating resonantly on the spins' precession frequency



Thomas-BMT Equation in Case of a Wien-Filter

- consider device with pure radial magnetic and vertical electric field
- net Lorentz force can be adjusted to zero: $\vec{F} = e(\vec{E} + c\vec{\beta} \times \vec{B}) \stackrel{!}{=} \vec{0}$



$$\vec{\Omega} = (1 + \gamma G) \vec{B}_{\perp} + \cancel{(1 + G) \vec{B}_{\parallel}}^0 + \left(\frac{\gamma}{\gamma + 1} + \gamma G \right) \frac{\vec{E} \times \vec{\beta}}{c}$$

$$\frac{\vec{E} \times \vec{\beta}}{c} = -(\vec{\beta} \times \vec{B}) \times \vec{\beta} = \vec{\beta} \cdot \underbrace{(\vec{\beta} \cdot \vec{B})}_{=0} - \vec{B} \cdot (\vec{\beta} \cdot \vec{\beta}) = -\beta^2 \vec{B}$$

$$\Rightarrow \vec{\Omega} = \left(1 - \frac{\beta^2 \gamma}{\gamma + 1} + (1 - \beta^2) \gamma G \right) \vec{B} = \frac{1 + G}{\gamma} \vec{B}$$



Spin-Resonance Strength of a RF Wien-Filter *

- $B_x(t) = \hat{B}_x \cos(\omega_{\text{RF}}t + \phi)$
- particles sample localized RF field once each turn, define modulation tune $\nu_m = \frac{\omega_{\text{RF}}}{\omega_{\text{rev}}}$
 - $\Rightarrow b(\theta) = \int \hat{B}_x dl \cos(\nu_m \theta + \phi) \sum_{n=-\infty}^{\infty} \delta(\theta - 2\pi n)$
 - $\Rightarrow \int \hat{B}_x dl \cos(2\pi n \nu_m + \phi)$ is the spin kick in turn n
- resonance strength given by amplitude of Fourier integral over driving fields along orbit:

$$\begin{aligned}\epsilon_{\perp} &= \frac{1+G}{2\pi\gamma} \oint \frac{b_{\perp}(\theta)}{B\rho} e^{ik\theta} d\theta \\ &= \frac{1+G}{2\pi\gamma} \frac{\int \hat{B}_{\perp} dl}{B\rho} \sum_{n=-\infty}^{\infty} \cos(2\pi n \nu_m + \phi) e^{i2\pi kn} \\ &= \frac{1+G}{2 \cdot 2\pi\gamma} \frac{\int \hat{B}_{\perp} dl}{B\rho} (e^{i\phi} \sum_n e^{i2\pi(k+\nu_m)n} + e^{-i\phi} \sum_n e^{i2\pi(k-\nu_m)n})\end{aligned}$$

[* S. Y. Lee, 10.1103/PhysRevSTAB.9.074001 (2006)]



Resonance Condition

- spin tune given by γG
- ⇒ resonance at $\gamma G = |k \pm \nu_m| \Leftrightarrow f_{\text{RF}} = f_{\text{rev}}|k + \gamma G|; k \in \mathbb{Z}$
- d at 970 MeV/c: $\beta = 0.459; \gamma = 1.126; G = -0.142\,987;$
- ⇒ $f_{\text{rev}} = 750\text{ kHz}; \gamma G = -0.16098:$

k	0	1	-1	2	-2
f_{RF} / kHz	120	629	871	1380	1621

Content

Spin Motion in an RF Wien Filter

The RF-ExB Dipole

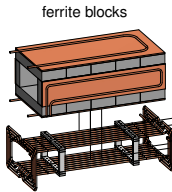
Field Distribution and Compensation

Measurements

Conclusion

The RF-ExB Dipole

RF-B Dipole



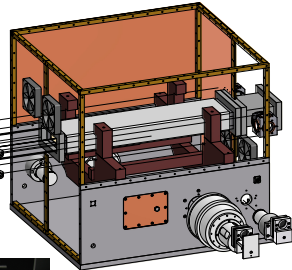
coil: 8 windings, length 560 mm

RF-E Dipole

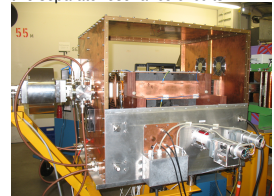
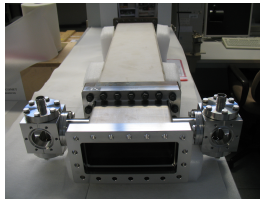
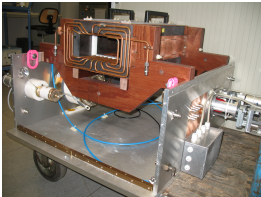
two electrodes in vacuum chamber

distance 54 mm, length 580 mm

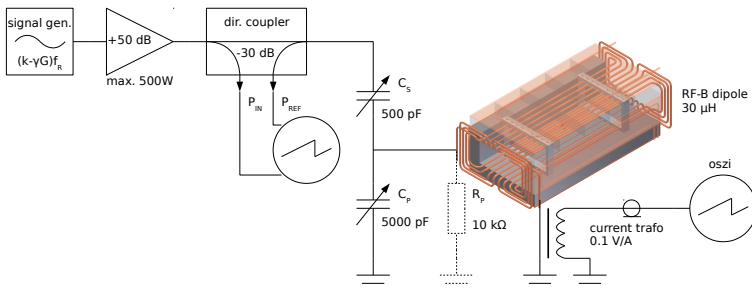
shielding Box



ceramic beam chamber
two separate resonance circuits

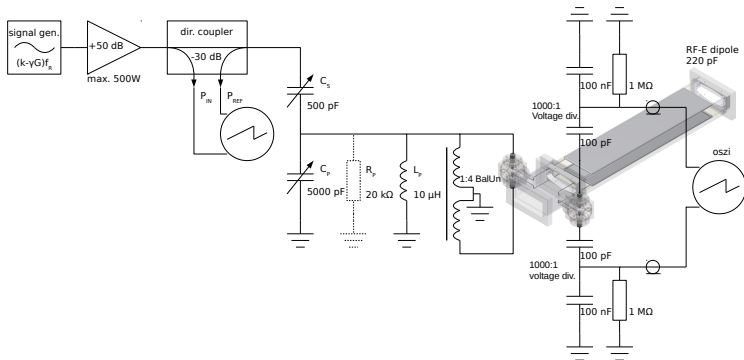


RF-B Circuit



- amplitude limited by losses $\Rightarrow \hat{I}_{\max} \approx 5 \text{ A}$
- tuning to 50Ω with bidirectional coupler
- frequency range 630 kHz - 1170 kHz
- current in coil directly available via current transformer

RF-E Circuit



- $\hat{U}_{\max} \approx 5 \text{ kV}$ limited by high-voltage feedthroughs
- frequency range 630 kHz - 1060 kHz
- electrode voltage directly available via capacitive voltage divider

Content

Spin Motion in an RF Wien-Filter

The RF-ExB Dipole

Field Distribution and Compensation

Measurements

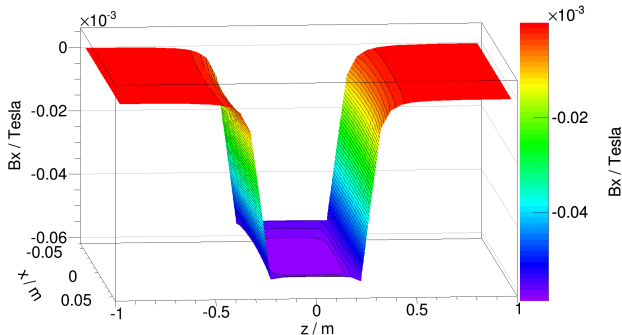
Conclusion

Magnetic Flux Density

$$\hat{I} = 1 \text{ A}$$

$$\hat{B}_x = 0.058 \text{ mT}$$

$$\int \hat{B}_x dz = -0.035 \text{ T mm}$$



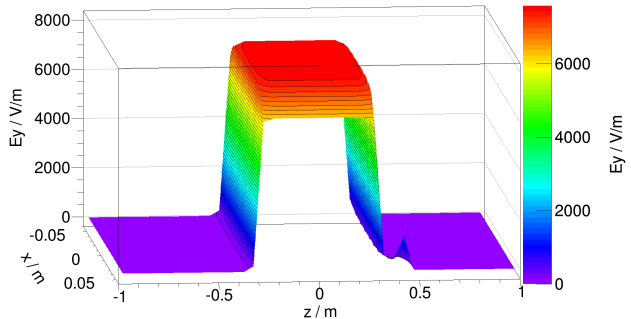
- distribution of radial component of magnetic flux density
- fields shown in central beam plane at $y = 0$

Electric Field

$$\hat{U} = 395 \text{ V}$$

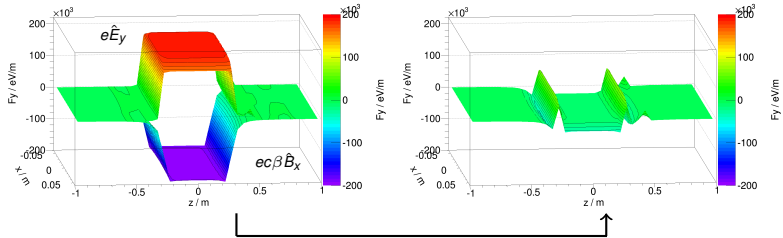
$$\hat{E}_y = 7594 \text{ V/m}$$

$$\int \hat{E}_y dz = 4818 \text{ V}$$



- distribution of vertical component of electric field

Lorentz Force



$$F_y = e(\hat{E}_y + c\beta\hat{B}_x)$$

- $\beta \equiv \beta_z = 0.459$; $\hat{I} = 1 \text{ A}$; $\hat{U} = 395 \text{ V}$
- optimization for integral compensation along beam path

$$\int \hat{F}_y dz = 0 \text{ eV/m}$$

Content

Spin Motion in an RF Wien Filter

The RF-ExB Dipole

Field Distribution and Compensation

Measurements

Conclusion

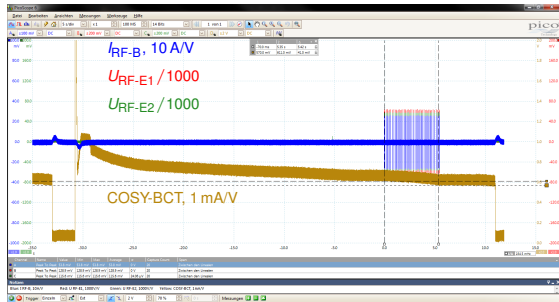
First Measurement of Field Compensation

$$f_{\text{RF-ExB}} = f_{\beta_Y} = 1186 \text{ kHz}$$

$$\hat{I} = 0.27 \text{ A}$$

$$\hat{U}_1 = 129 \text{ V}$$

$$\hat{U}_2 = 116 \text{ V}$$



- measurement exactly on betatron frequency for max. sensitivity
- diagnosis with COSY beam current transformer
- pulsed mode of operation, 38 pulses, each 10 ms long
- compensation observed, minimum of 7 % beam-loss achieved
- fringe fields and transient time behaviour have to be further studied



Measurement Proposal

- resonance Strength of Wien-Filter:

$$|\epsilon_{B_{\perp}} dl| = \frac{1+G}{4\pi\gamma} \frac{\int \hat{B}_x dl}{B\rho}$$

- compare with measured one from Foissart-Stora scan:

- vector polarization of spin-1 particle: $P_V = \frac{N_1 - N_{-1}}{N_1 + N_0 + N_{-1}}$
- crossing resonance rotates spin axis, resulting polarization:

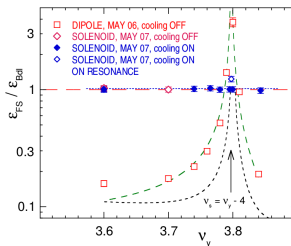
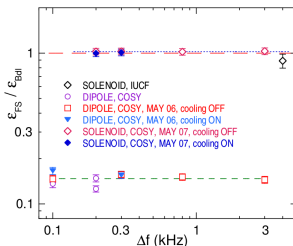
$$P_V^f = P_V^i \cos \vartheta$$

- $\frac{P_V^f}{P_V^i} = 2 \exp \left(- \frac{(\pi \epsilon_{FS} f_c)^2}{\frac{\Delta f}{\Delta t}} \right) - 1$

- measurements of ratio $\frac{\epsilon_{FS}}{\epsilon_{BdL}}$ should yield 1 if the RF Wien-Filter is perfectly matched since it doesn't introduce coherent beam oscillations

Measurement Proposal (cont.)

- measurements by Spin@COSY collaboration:
 - RF-solenoid: $|\epsilon_{B_{\parallel}} dl| = \frac{1+G}{4\pi} \frac{\int \hat{B}_{\parallel} dl}{B\rho}$
 - RF-dipole: $|\epsilon_{B_{\perp}} dl| = \frac{1+\gamma G}{4\pi} \frac{\int \hat{B}_{\perp} dl}{B\rho}$
(doesn't take into account induced coherent betatron oscillations)



Content

Spin Motion in an RF Wien Filter

The RF-ExB Dipole

Field Distribution and Compensation

Measurements

Conclusion



Conclusion

Hardware development

- RF dipole for spin manipulation with minimal beam disturbance has been successfully commissioned
- RF-B amplitude: $\int \hat{B}_x ds = 0.175 \text{ T mm}$ @ $\hat{I}_{\max} = 5 \text{ A}$
- RF-E amplitude: $\int \hat{E}_y ds = 24 \text{ kV}$ @ $\hat{U}_{\max} = 1975 \text{ V}$
- ± 1 spin harmonics at 629 kHz and 871 kHz available for studies

Measurements

- resonance strength measurements planned for August/ September 2014 in JEDI-beam-time with polarized d-beam



Thanks for Your Kind Attention!

In case of additional questions contact s.mey@fz-juelich.de

Content

Spin Motion in an RF Wien Filter

The RF-ExB Dipole

Field Distribution and Compensation

Measurements

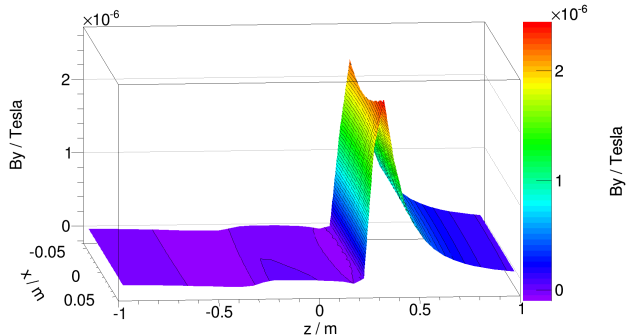
Conclusion

B_y

$$\hat{I} = 1 \text{ A}$$

$$\hat{B}_y \approx 10^{-3} \hat{B}_x$$

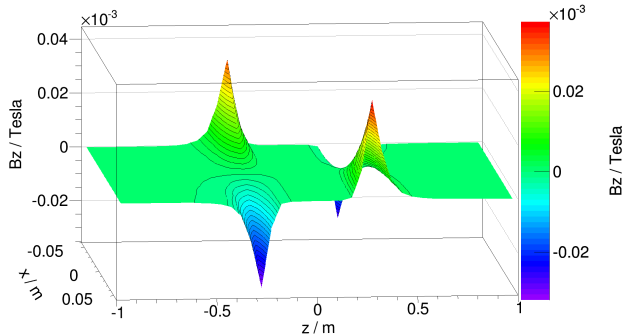
in central field region



- vertical component dominated by fields from leads to the coil

B_z

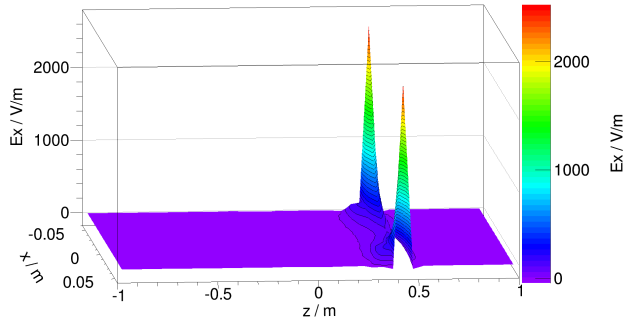
$$\hat{I} = 1 \text{ A}$$



- longitudinal component dominated by fields from the coil going around the beam chamber

E_x

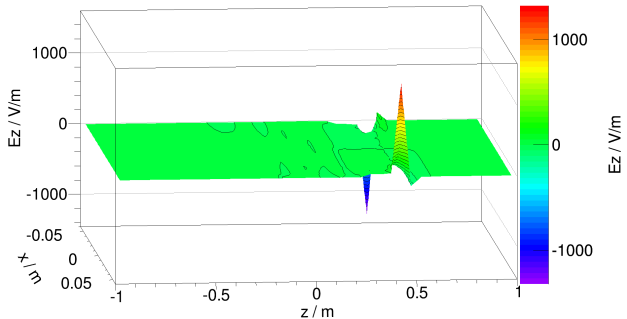
$\hat{U} = 395 \text{ V}$
 $\hat{E}_x \approx 10^{-3} \hat{E}_y$
 in central field region



- distribution of radial component of electric field dominated by fields from leads to the electrodes

E_z

$$\hat{U} = 395 \text{ V}$$



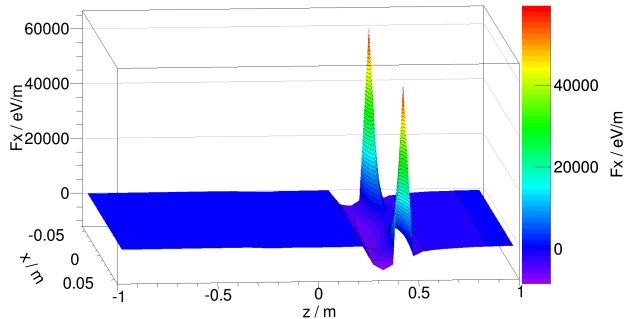
- distribution of longitudinal component of electric field dominated by fields from leads to the coil

F_x

$$\beta \equiv \beta_z = 0.459$$

$$\hat{I} = 1 \text{ A}$$

$$\hat{U} = 395 \text{ V}$$

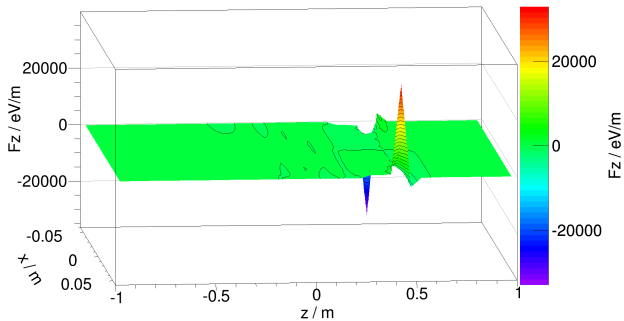


- $F_x = e(\hat{E}_x + c\beta\hat{B}_y)$

F_z

$$\hat{I} = 1 \text{ A}$$

$$\hat{U} = 395 \text{ V}$$

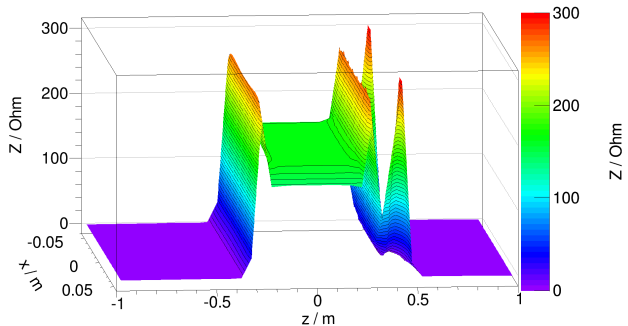


Wave Impedance

$$\hat{I} = 1 \text{ A}$$

$$\hat{U} = 395 \text{ V}$$

$$Z_{\text{theory}} = 173 \Omega$$



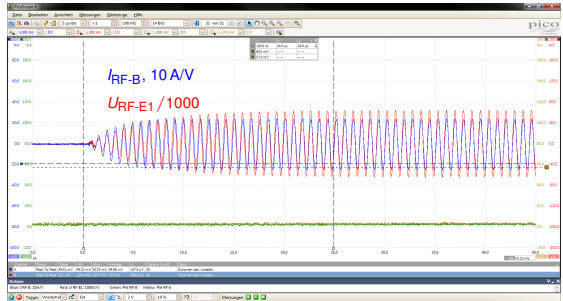
$$\blacksquare \quad Z = \frac{\hat{E}_x}{\hat{H}_y} = -\frac{\hat{E}_y}{\hat{H}_x} = \beta_z Z_0$$

Transient Time Behaviour

$$\Delta t = 45 \mu\text{s}$$

$$\hat{I} = 0.27 \text{ A}$$

$$\hat{U}_1 = 129 \text{ V}$$

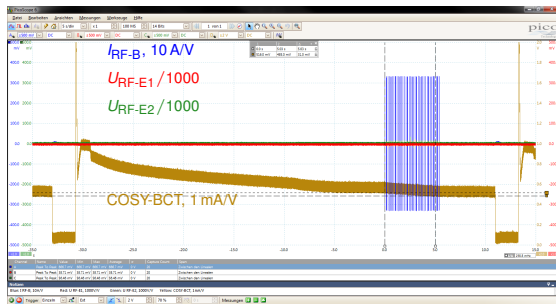


- Wien-Filter condition not fulfilled during first $\approx 15 \mu\text{s}$ of each pulse
- complete transient time lasts $\approx 100 \text{ ms}$
- ⇒ rework of resonance circuit required
- ⇒ ultimate precision needs feed forward control during activation cycle

Measurement at Spin Resonance Frequency

$$f_{\text{RF-ExB}} = 871 \text{ kHz}$$

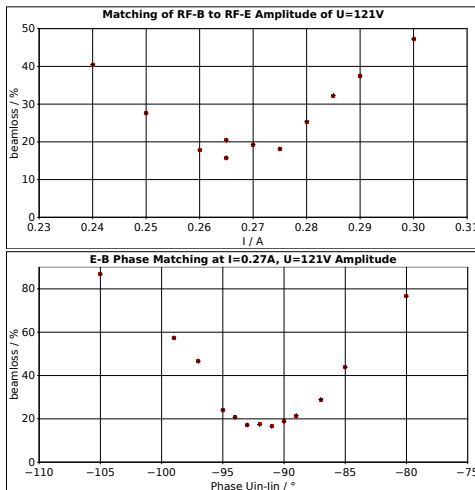
$$\hat{I} = 3.38 \text{ A}$$



- $f_{-1} = f_{\text{rev}} | - 1 + \gamma G |$
- relatively low current in RF-B-part already induces beamloss
- fields at $\hat{I} = 3.38 \text{ A}$: $\hat{B}_x = 0.2 \text{ mT}$; $\int \hat{B}_x dz = 0.12 \text{ T mm}$
- required power $\approx 120 \text{ W}$

First Systematic Measurements

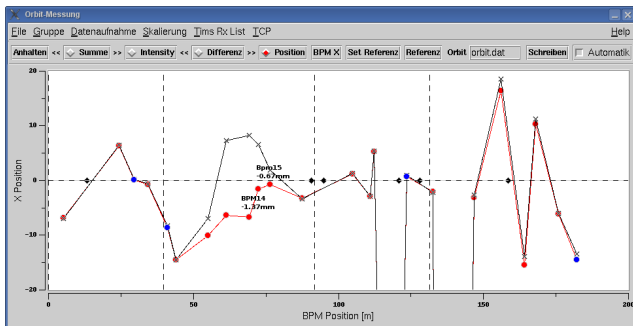
- set up well cooled beam
- orbit correction in the RF-dipole
- tune measurement
- fix one setting for the amplitude of RF-E-part
- vary amplitude and phase offset of RF-B-part to reach minimum beam loss



Orbit Corrections

$$\Delta x = 0.7 \text{ mm}$$

$$\Delta x' = 0.06 \text{ mrad}$$

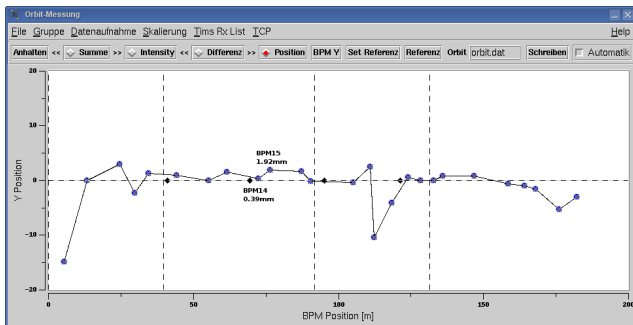


- corrected orbit with closed bump at RF-Dipole
- BPM 14 and 15 at Dipole before and after RF-ExB
- distance $\Delta z = 4.2 \text{ m}$

Orbit Corrections

$$\Delta y = 1.53 \text{ mm}$$

$$\Delta y' = 0.13 \text{ mrad}$$



- corrected orbit with closed bump at RF-Dipole
- BPM 14 and 15 at Dipole before and after RF-ExB
- distance $\Delta z = 4.2 \text{ m}$