ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

ECOLE DOCTORALE
DOCTORAL SCHOOL

PROGRAMME DOCTORAL EN PHYSIQUE
DOCTORAL PROGRAM IN PHYSICS

Magnetic Model of the CERN PS Accelerator

Mariusz Juchno

Objectives

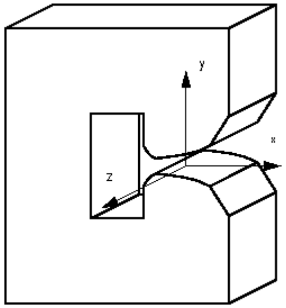
- To develop a model of the magnetic field inside the PS magnets, capable of accurately recreating the magnetic field along the beam trajectory.
- Implement and validate the magnetic model inside existing optical model of the PS accelerator.

Methodology

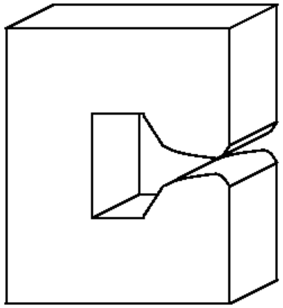
- Investigation of the field development inside the PS magnet
  - Broad numerical analysis in 2D and 3D
  - Magnetic measurements
- Derivation of quasi-static formulas of the field components.
- Implementation of the magnetic model in existing optical model the PS accelerator.
  - Simulation of the optical parameters with MAD-X model.
  - Beam-based measurements (tune and chromaticity).
  - Verification and calibration of the magnetic model.
  - Optical model enhancements.

Proton Synchrotron main magnetic unit

Open block



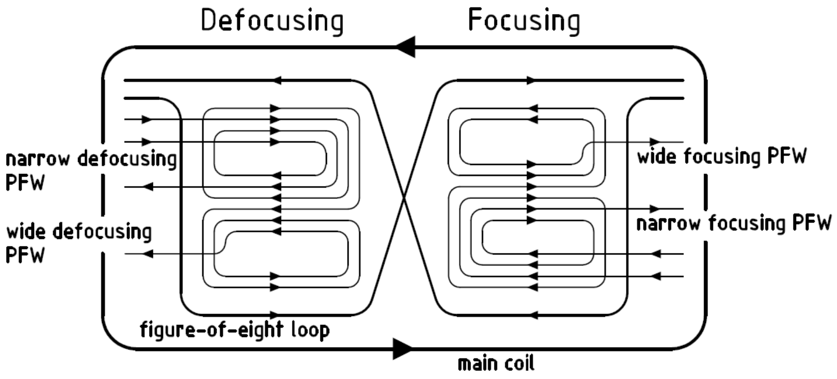
Closed block



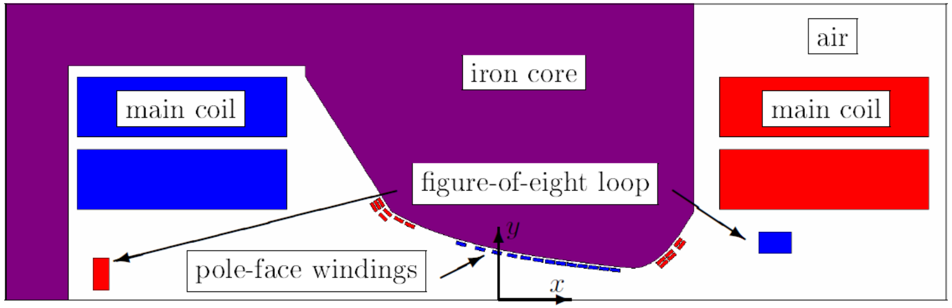
- Combined-function magnet with hyperbolic pole shape
  - Dipole field – guiding
  - Quadrupole field – focusing
  - Higher component are also present due to saturation
- Focusing and defocusing half (alternating-gradient focusing)
  - 5 C-shaped block in each half
  - Wedge shaped air gaps between blocks
- Complex geometry of coils system
- In total 100+1 main units of four different types.

Coils of the PS magnet

- Main coil
  - Dipole and quadrupole field mostly
- Figure-of-eight loop
  - Adjusts quadrupole field but also contributes to dipole field
- Pole-face windings (PFW)
  - Separately for focusing and defocusing half
  - Each winding has narrow and wide circuit
  - Corrects higher components of the field



- PFW Powering upgrade
  - Five currents (I_{f8}, I_{pfwFN}, I_{pfwFW}, I_{pfwDN}, I_{pfwDW}) insted of three (I_{f8}, I_{pfwF}, I_{pfwD})
  - Control of the four beam parameters Q_h, Q_v, ξ_h, ξ_v
  - One current remains free for controlling an additional physical parameter
  - Possibility of exploring new working points
  - **Debalancing PFW narrow and wide circuits leads to strong nonlinearities !!!**



Investigating contributions of separate circuits

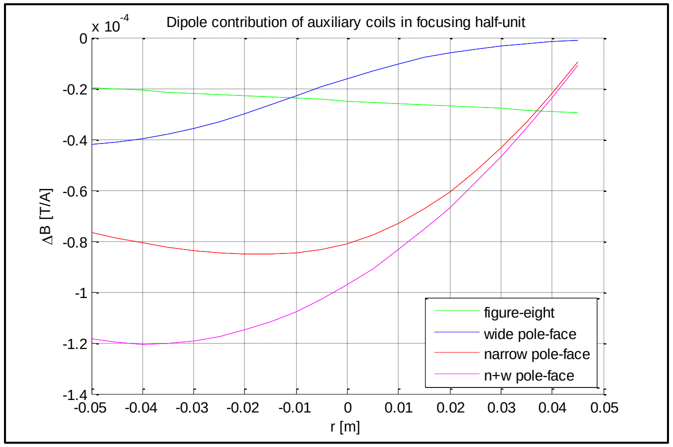
- 2D quasi-static numerical analysis (OPERA) of the magnetic field inside the PS magnet.
- Range of operations:
  - Injection $p_{inj} = 2.12$ GeV/c
  - Extraction $p_{extr} = 26$ GeV/c
- Current range:
  - Main coil $I_{mc} = 400\text{-}5500$ A ($\Delta I_{mc} = 250$ & 500 A)
  - Figure-of-eight loop $I_{f8} = \pm 1200$ A ($\Delta I_{f8} = 600$ A)
  - Pole-face windings $I_{pfw} = \pm 200$ A ($\Delta I_{pfw} = 100$ A)

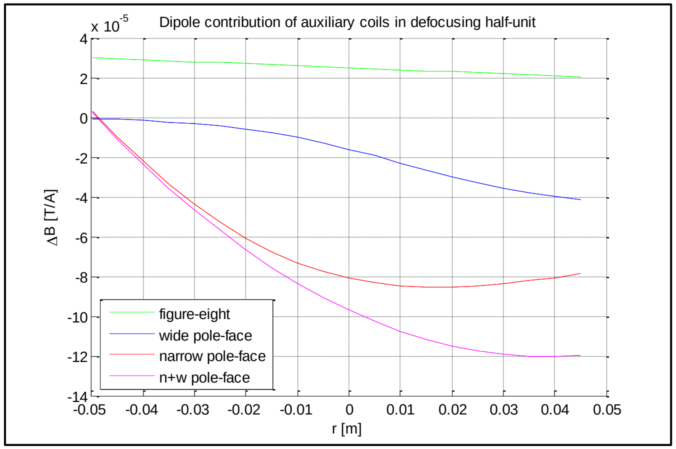
Contribution of auxiliary circuits

Focusing

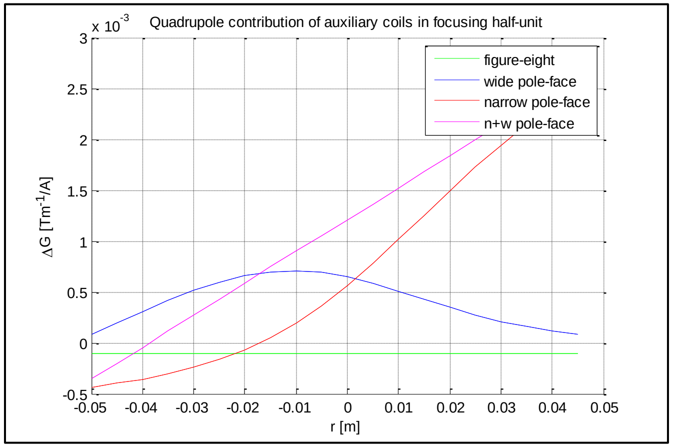
Defocusing

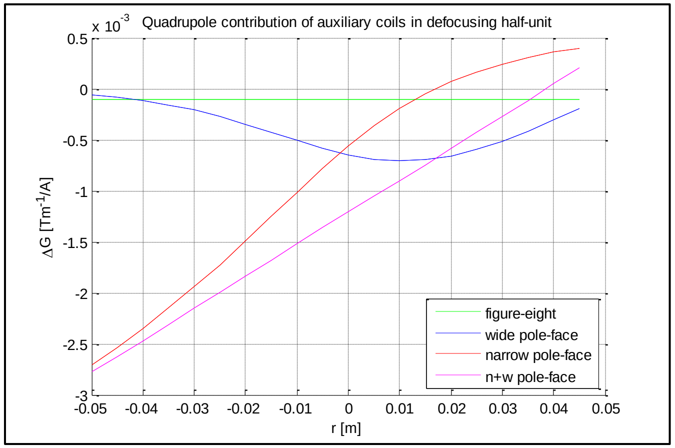
Dipole Contribution ΔB [T/A]





Quadrupole Contribution ΔG [Tm^{-1}/A]

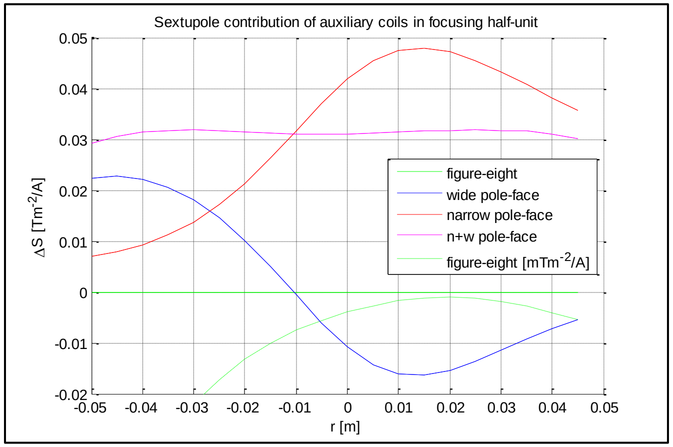


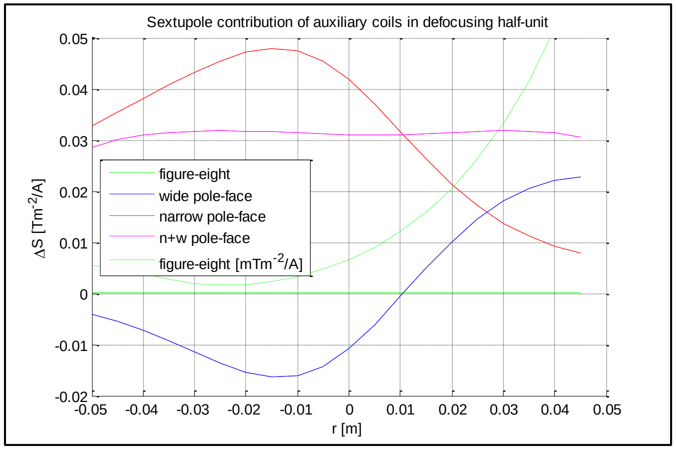


Contribution of auxiliary circuits

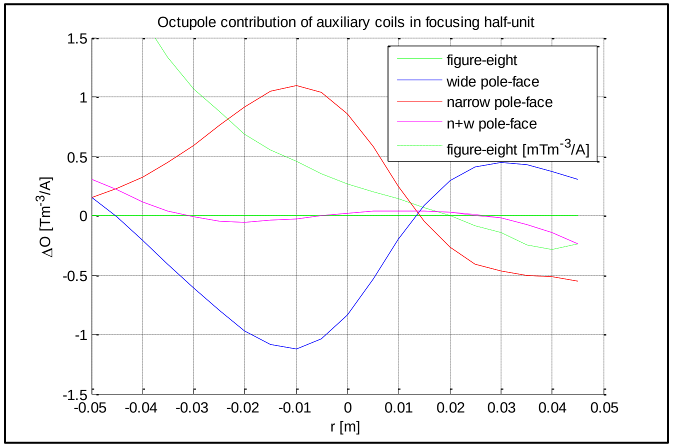
Focusing **Defocusing**

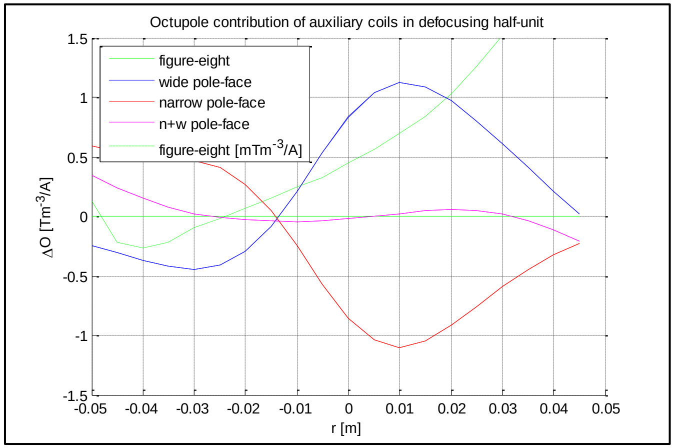
Sextupole Contribution
ΔS [Tm^{-2}/A]





Octupole Contribution
ΔO [Tm^{-3}/A]





Formulas of the field model

- Field multipoles in the Taylor coefficients [T/m^{n-1}]

$$B_n(x) = \left. {}^{d^{n-1}B_y(x)} \big/ {}_{dx^{n-1}} \right|_{x=x_0}$$

- Main and auxiliary field multipoles

$$B_{n,mc} = N_{mc} I_{mc}\ T_f\ \mathrm{H}_{n,mc}\left(N_{mc} I_{mc}\right)$$

$$B_{n,aux} = N_{aux} I_{aux}\ T_f\ \mathrm{H}_{n,aux}\left(F_{n,aux}\right)$$

Linear field transfer function

$$T_f = {}^{\mu_0} \big/ {}_{g}$$

Equivalent magnetomotive force

$$F_{n,aux} = N_{mc} I_{mc} + \sum\nolimits_{aux} f_{n,aux} N_{aux} I_{aux}$$

- Total multipole component

$$B_{n,tot} = B_{n,mc} + \sum\nolimits_{aux} B_{n,aux}$$

Formulas of the field model

- Circuit efficiency function $[1/m^{n-1}]$

$$H_n(NI)=H_{n\,0}\left[1+\sum_i \frac{\sigma_{n\,i}}{2}\left(1+\tanh s_{n\,i}\,\frac{NI-NI_{sn\,i}}{NI_{nom}}\right)\right]$$

- Main circuit efficiency

$$H_{n,mc}=\eta_n-(n-1)\,{g'}\!/_{g}\;\eta_{n-1}$$

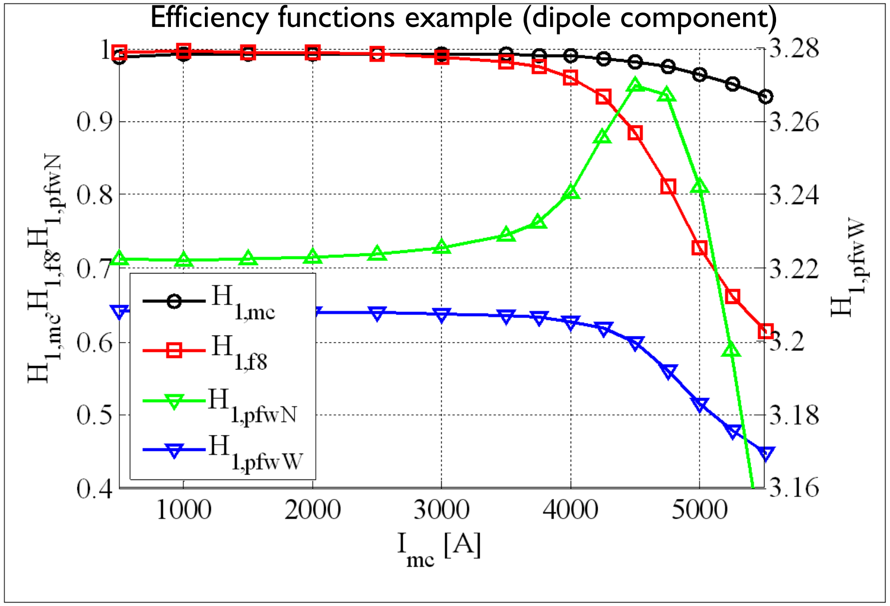
$$\eta_n(x)=\left.{d^{n-1}\eta_{mc}(x)}\Big/{dx^{n-1}}\right|_{x=x_0}$$

- Circuit saturation

$$\eta_{mc}=\frac{R_{gap}}{R_{core}+R_{gap}}$$

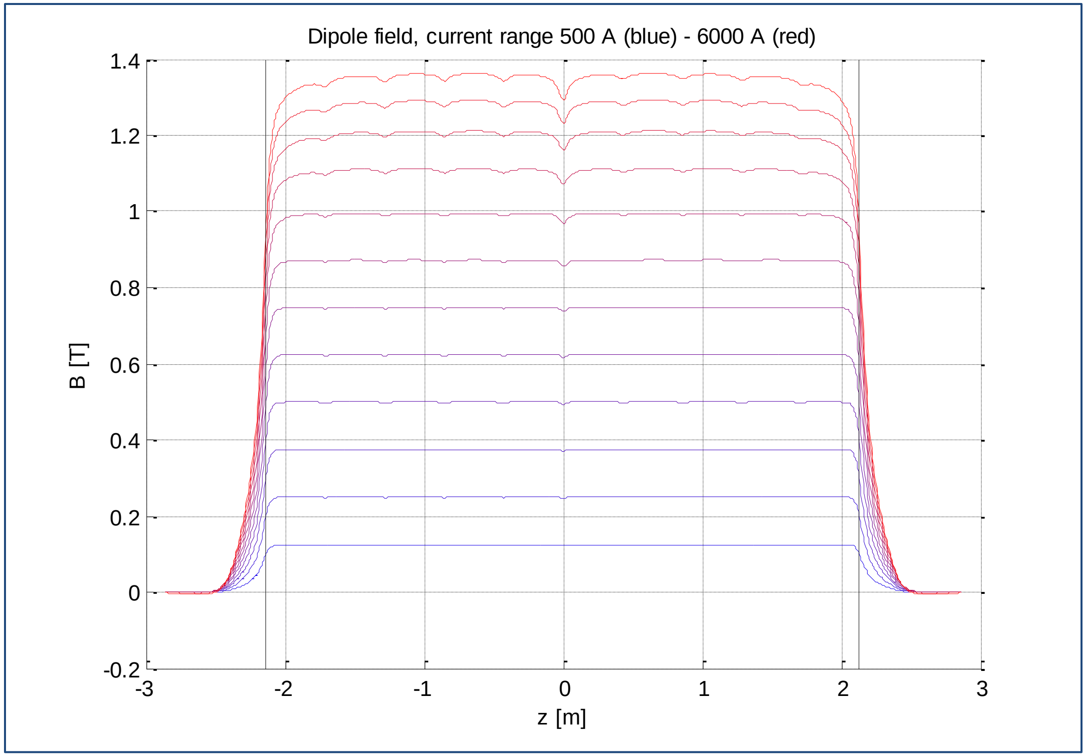
$$R_{gap}=g/A_{gap}\mu_0$$

$$R_{core}=l/A_{core}\mu_{Fe}\mu_0$$

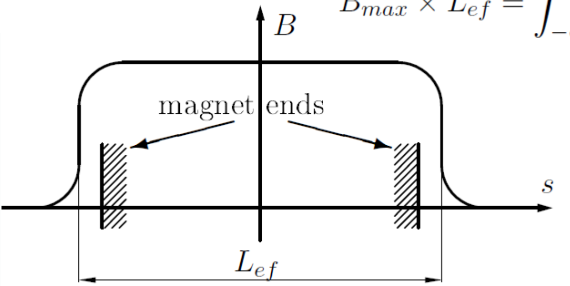


Effective magnetic length corrections

- 3D numerical analysis

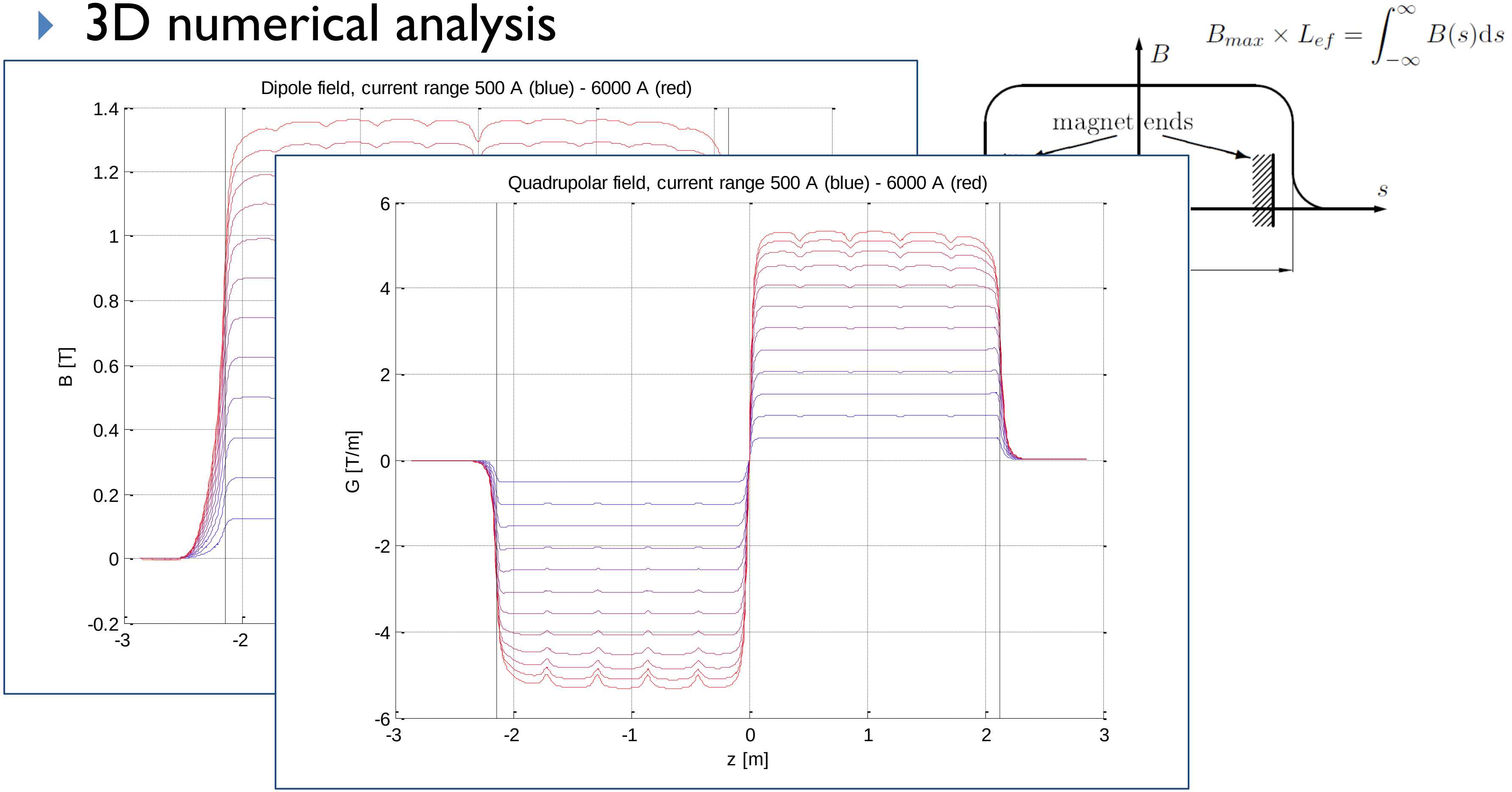


$$B_{max} \times L_{ef} = \int_{-\infty}^{\infty} B(s)\mathrm{d}s$$



Effective magnetic length corrections

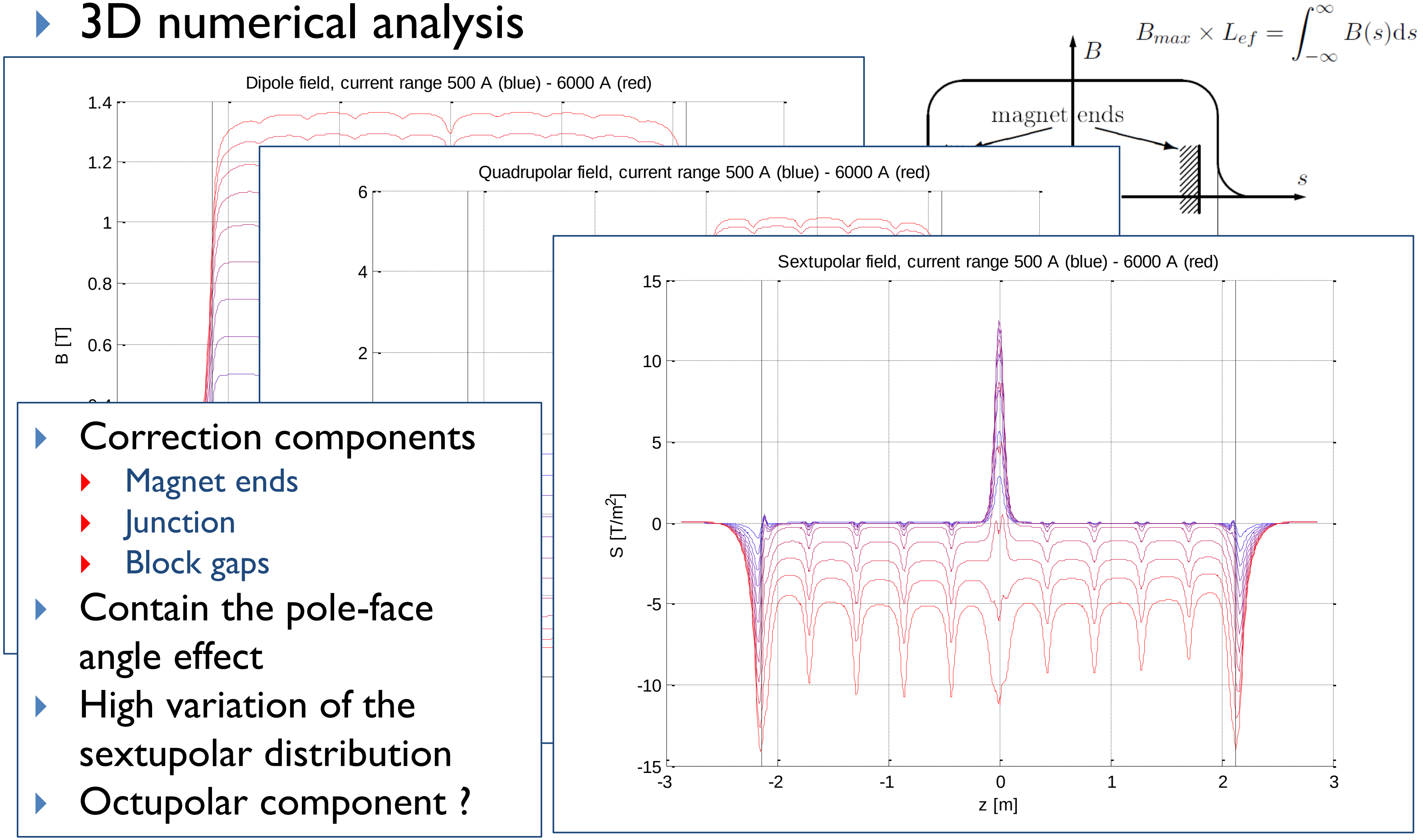
- 3D numerical analysis



$$B_{max} \times L_{ef} = \int_{-\infty}^{\infty} B(s)\mathrm{d}s$$

Effective magnetic length corrections

- 3D numerical analysis

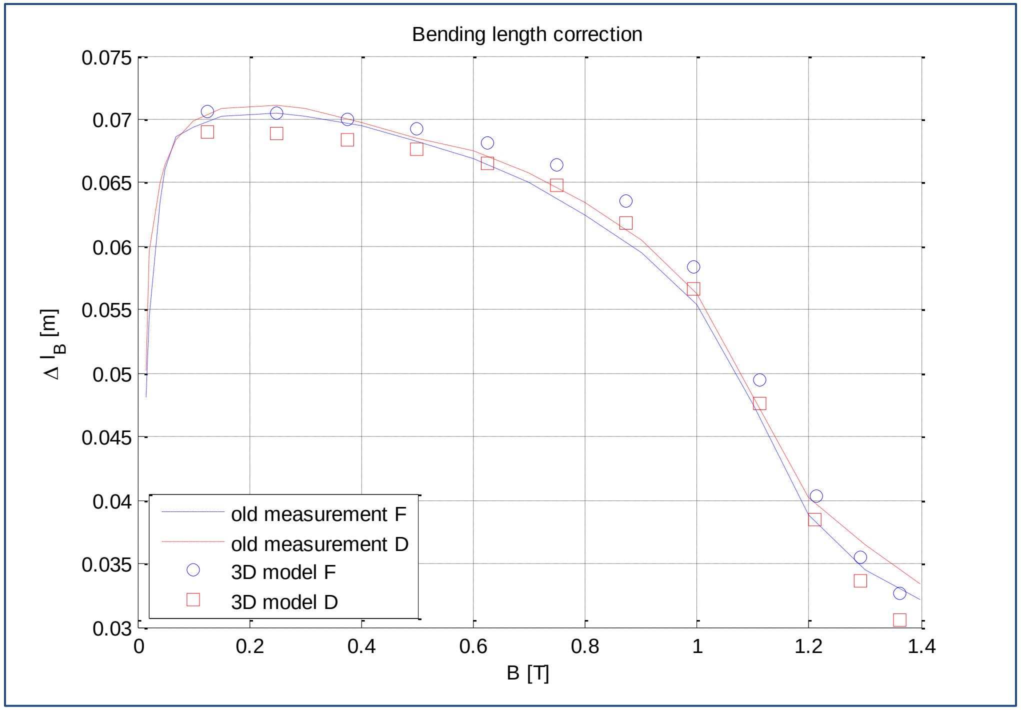


$$B_{max} \times L_{ef} = \int_{-\infty}^{\infty} B(s)\mathrm{d}s$$

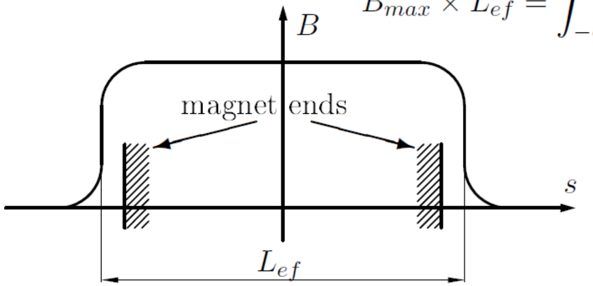
- Correction components
  - Magnet ends
  - Junction
  - Block gaps
- Contain the pole-face angle effect
- High variation of the sextupolar distribution
- Octupolar component ?

Effective magnetic length corrections

- Bare machine corrections



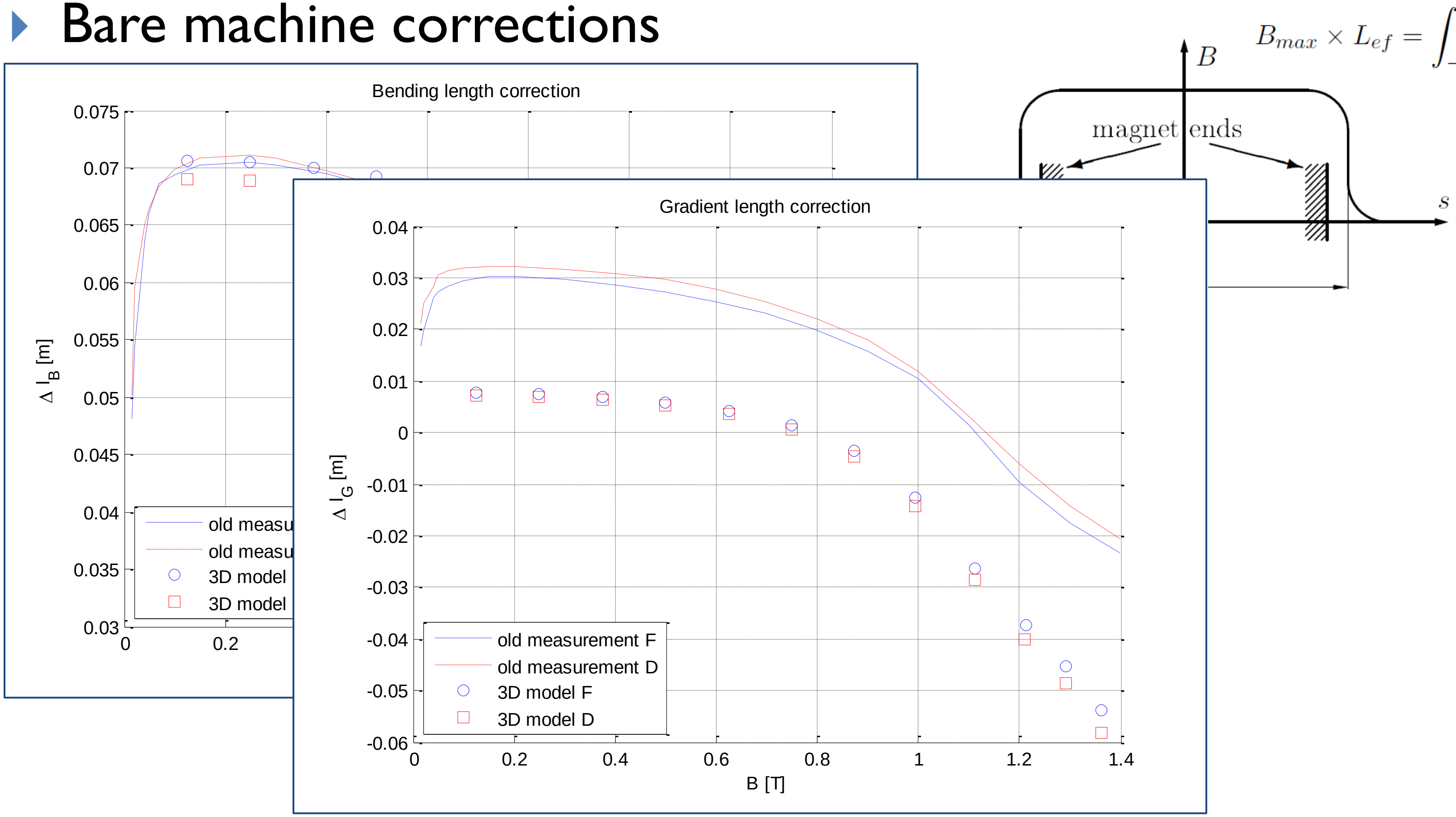
$$B_{max} \times L_{ef} = \int_{-\infty}^{\infty} B(s)\mathrm{d}s$$



Effective magnetic length corrections

- Bare machine corrections

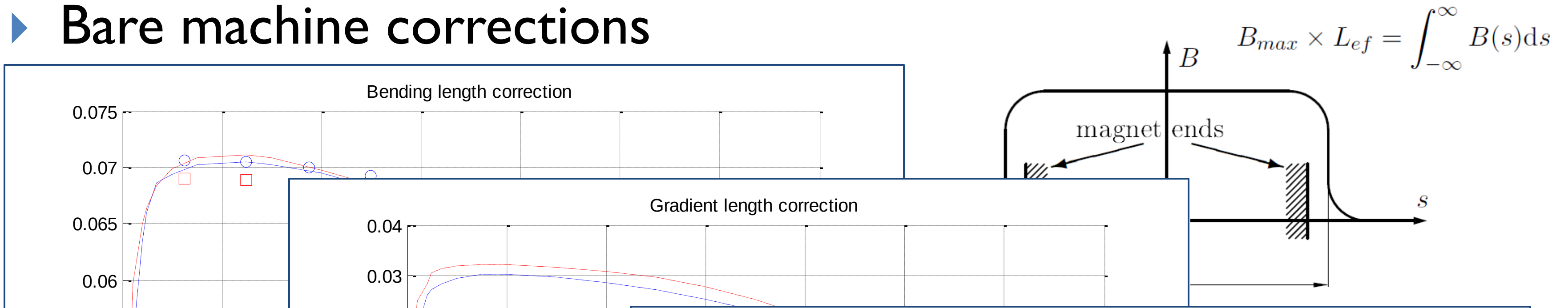
$$B_{max} \times L_{ef} = \int_{-\infty}^{\infty} B(s)\mathrm{d}s$$

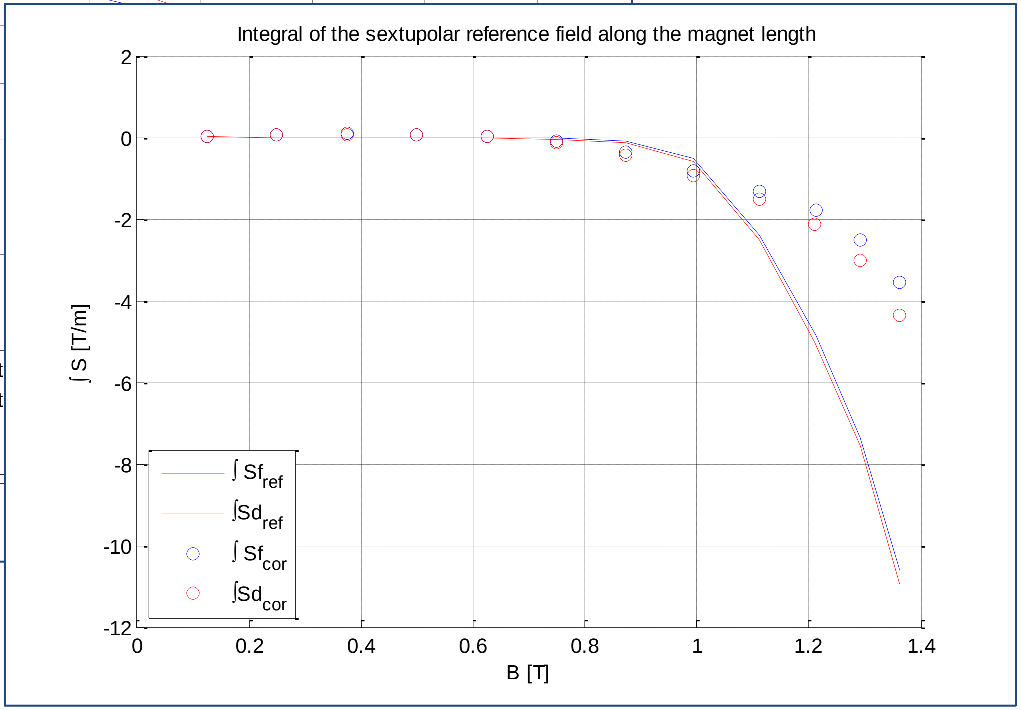


Effective magnetic length corrections

- Bare machine corrections

$$B_{max} \times L_{ef} = \int_{-\infty}^{\infty} B(s)\mathrm{d}s$$

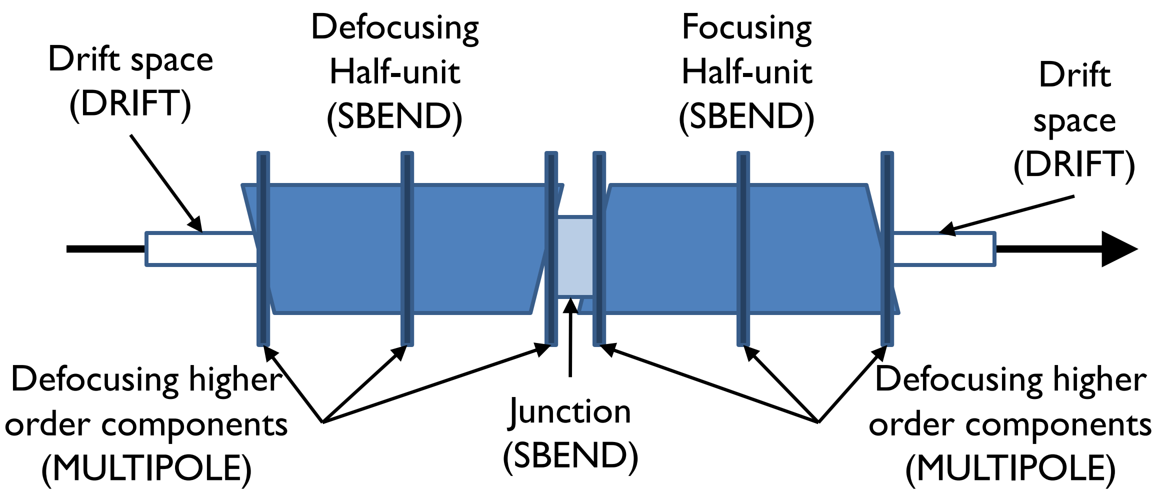




- Validation with beam-based measurements
- Quadrupolar correction discrepancy (JUNCTION)
- Strong sextupolar correction
- Radial position dependency!
- Auxiliary coils!
- Octupolar component?

Magnet representation in the optical model

- Official optics
  - Static elements length
  - SBEND
    - Bare machine 14 GeV/c quadrupolar component
    - No pole-face angle
  - MULTIPOLE
    - Beam-based fit
  - JUNCTION=DRIFT
- Model optics
  - Dynamic elements length – effective length correction
  - SBEND
    - Up to K2 from the model
    - Integrated pole-face angle effect
  - MULTIPOLES
    - K3 (and higher?)
  - No JUNCTION element
  - Beam-based matched effective lengths corrections?



Drift space (DRIFT)

Defocusing Half-unit (SBEND)

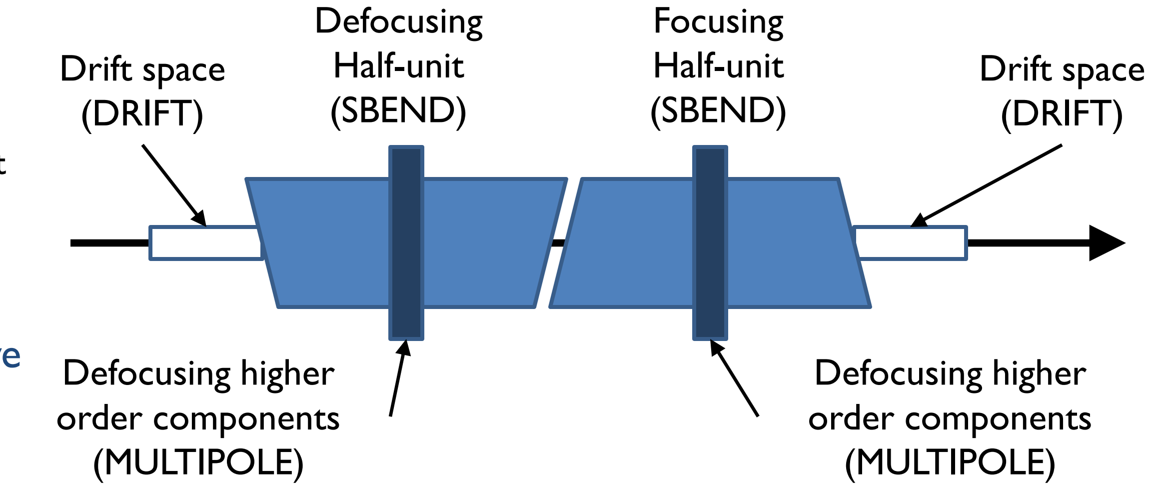
Focusing Half-unit (SBEND)

Drift space (DRIFT)

Defocusing higher order components (MULTIPOLE)

Junction (SBEND)

Defocusing higher order components (MULTIPOLE)



Drift space (DRIFT)

Defocusing Half-unit (SBEND)

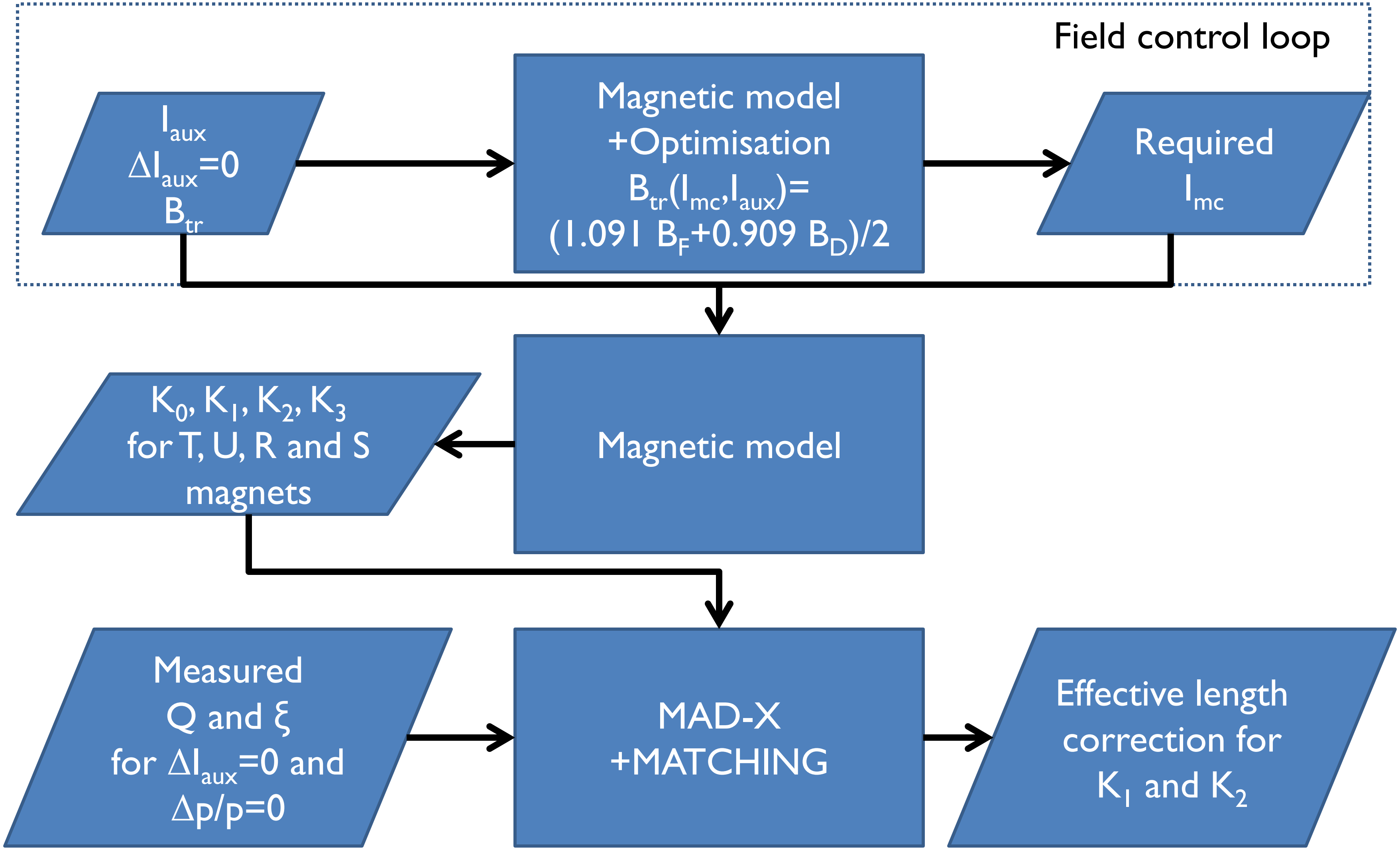
Focusing Half-unit (SBEND)

Drift space (DRIFT)

Defocusing higher order components (MULTIPOLE)

Defocusing higher order components (MULTIPOLE)

Flowchart: corrections for the basic case



Field control loop

I_{aux}
$\Delta I_{aux}=0$
B_{tr}

Magnetic model
+Optimisation
$B_{tr}(I_{mc},I_{aux})=$
$(1.091\ B_F+0.909\ B_D)/2$

Required
I_{mc}

Magnetic model

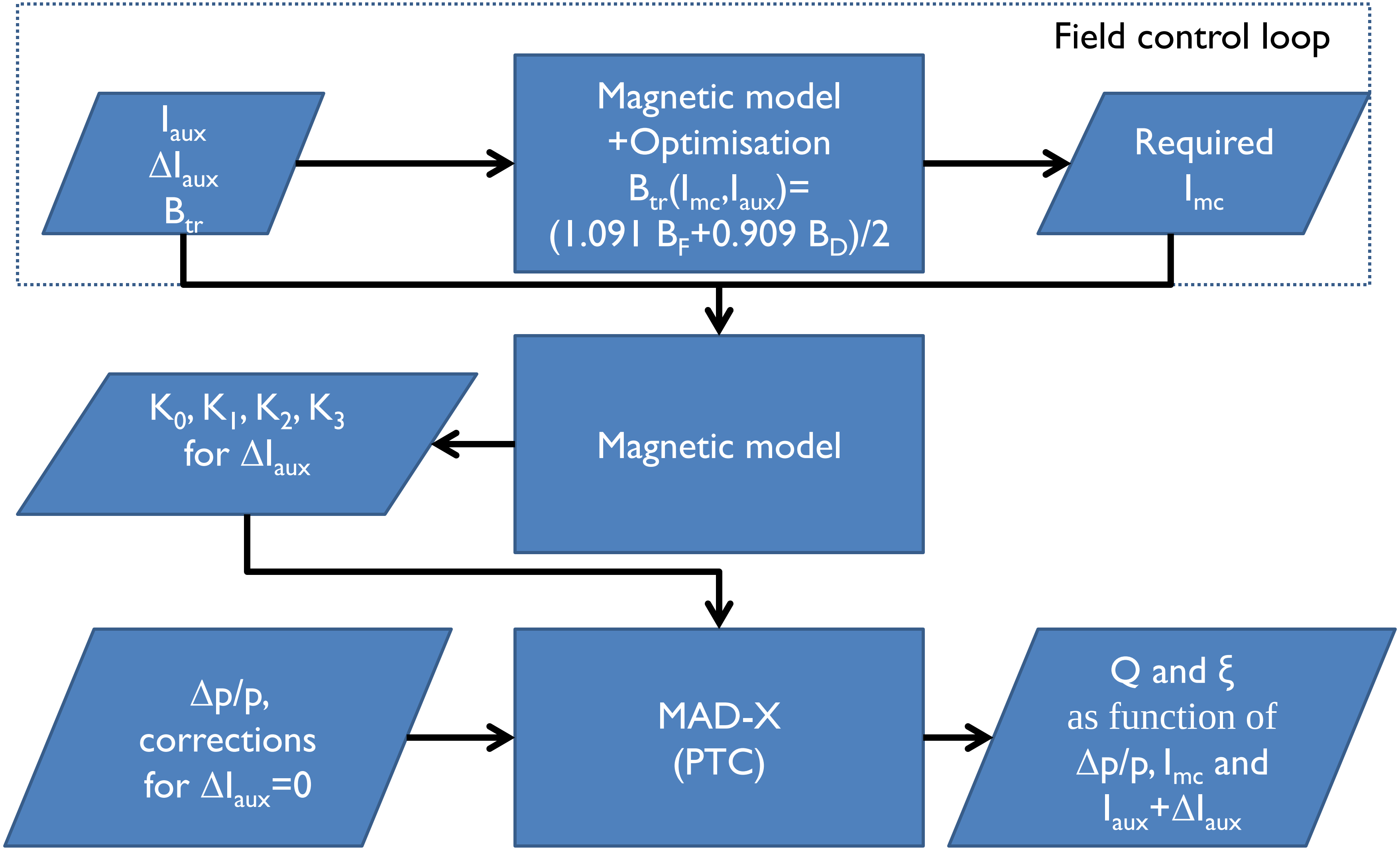
K_0, K_1, K_2, K_3
for T, U, R and S magnets

Measured
Q and ξ
for $\Delta I_{aux}=0$ and
$\Delta p/p=0$

MAD-X
+MATCHING

Effective length correction for
K_1 and K_2

Flowchart: chromaticity analysis for ΔI_{aux}



Field control loop

I_{aux}
ΔI_{aux}
B_{tr}

Magnetic model
+Optimisation
$B_{tr}(I_{mc},I_{aux})=$
$(1.091\ B_F+0.909\ B_D)/2$

Required
I_{mc}

Magnetic model

K_0, K_1, K_2, K_3
for ΔI_{aux}

$\Delta p/p$,
corrections
for $\Delta I_{aux}=0$

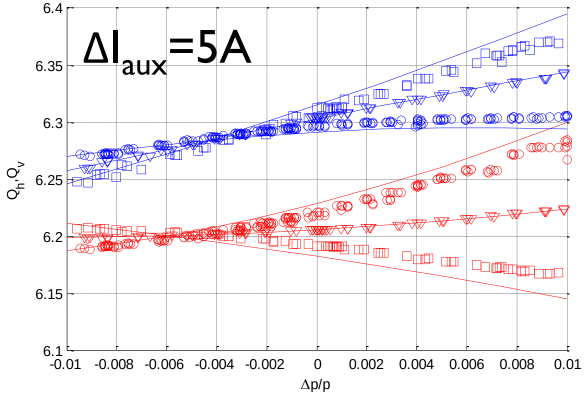
MAD-X
(PTC)

Q and ξ
as function of
$\Delta p/p$, I_{mc} and
$I_{aux}+\Delta I_{aux}$

Nonlinear chromaticity (14 GeV)

- ▽ measured Q_h (basic)
- ▽ measured Q_v (basic)
- ○ measured Q_h (+ΔI)
- ○ measured Q_v (+ΔI)
- □ measured Q_h (-ΔI)
- □ measured Q_v (-ΔI)
- — calculated Q_h
- — calculated Q_v

Narrow focusing PFW variation



Narrow defocusing PFW variation

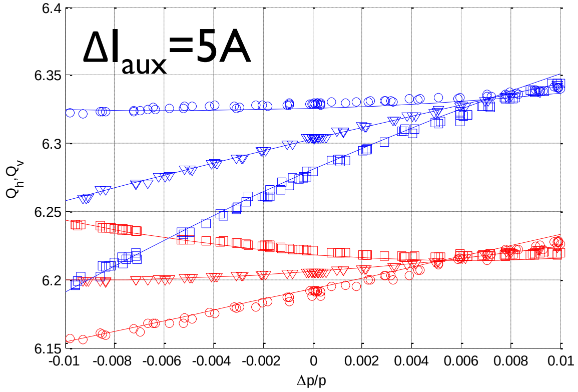
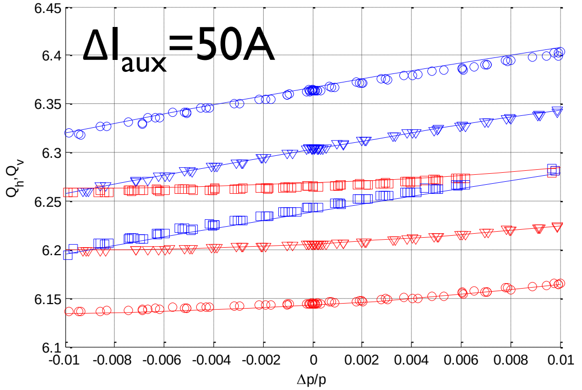
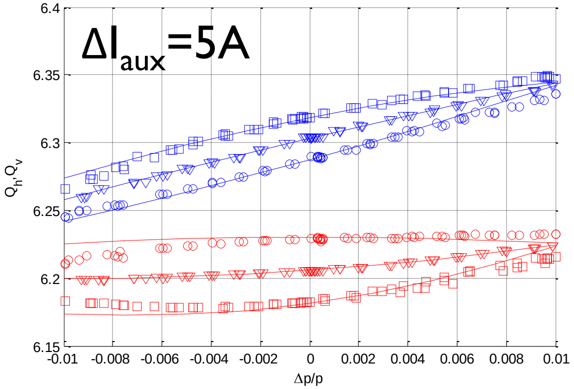


Figure-of-eight variation



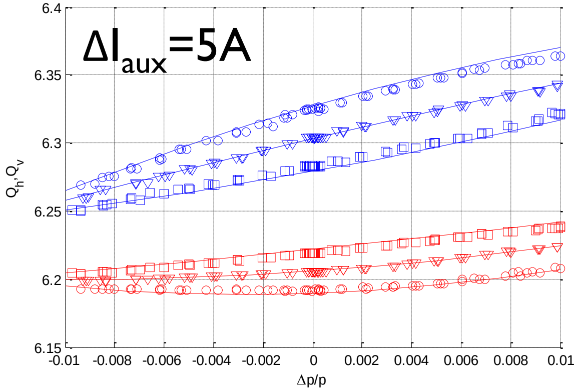
I_{f8}=543.3A

Wide focusing PFW variation



I_f=43.5A

Wide defocusing PFW variation



I_d=-52.56A

Measurement data: matrix measurement campaing

14 GeV Transfer Matrices

- Reproduced with the model

	ΔI_{fn}	ΔI_{fw}	ΔI_{dn}	ΔI_{dw}	ΔI_{f8}
ΔQ_h	0.00457	0.00486	-0.00250	-0.00321	-0.00125
ΔQ_v	-0.00235	-0.00312	0.00447	0.00481	0.00128
$\Delta \xi_h$	0.14514	-0.04095	0.08578	-0.01965	0.00076
$\Delta \xi_v$	-0.09837	0.02351	-0.11875	0.03079	0.00023

- Predicted in 1974

	ΔI_{fn}	ΔI_{fw}	ΔI_{dn}	ΔI_{dw}	ΔI_{f8}
ΔQ_h	0.00462	0.00473	-0.00252	-0.00313	-0.00184
ΔQ_v	-0.00247	-0.00317	0.00458	0.00477	0.00191
$\Delta \xi_h$	0.12792	-0.02221	0.07440	-0.01440	0.00000
$\Delta \xi_v$	-0.08729	0.01300	-0.10619	0.02190	0.00000

- Reproduced with the model for **dp/p= -0.002**

	ΔI_{fn}	ΔI_{fw}	ΔI_{dn}	ΔI_{dw}	ΔI_{f8}
ΔQ_h	0.00288	0.00525	-0.00360	-0.00292	-0.00126
ΔQ_v	-0.00119	-0.00333	0.00602	0.00436	0.00127
$\Delta \xi_h$	0.12698	-0.02163	0.09310	-0.02615	0.00072
$\Delta \xi_v$	-0.08603	0.01115	-0.12886	0.04016	0.00025

- Measured matrix

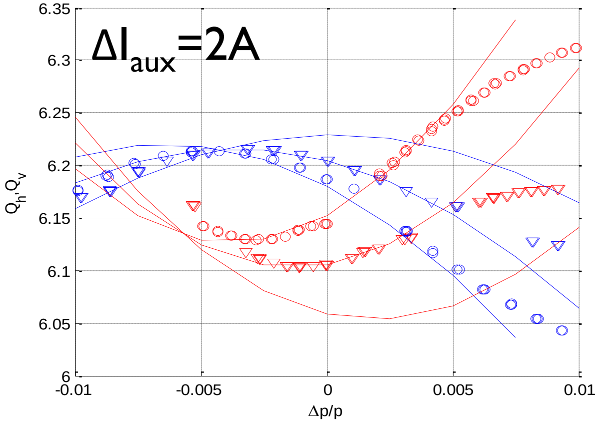
	ΔI_{fn}	ΔI_{fw}	ΔI_{dn}	ΔI_{dw}	ΔI_{f8}
ΔQ_h	0.00283	0.00455	-0.00314	-0.00268	-0.00121
ΔQ_v	-0.00128	-0.00322	0.00512	0.00410	0.00121
$\Delta \xi_h$	0.11215	-0.01152	0.07699	-0.01671	0.00079
$\Delta \xi_v$	-0.07358	0.00768	-0.10599	0.02229	-0.00033

- **In the model MRP=0 for dp/p=0 BUT in reality MRP$\neq$0 for dp/p=0**

Nonlinear chromaticity (2 GeV)

- ▽ measured Q_h (basic)
- ▽ measured Q_v (basic)
- ○ measured Q_h (+ΔI)
- ○ measured Q_v (+ΔI)
- □ measured Q_h (-ΔI)
- □ measured Q_v (-ΔI)
- — calculated Q_h
- — calculated Q_v

Narrow focusing PFW variation



Narrow defocusing PFW variation

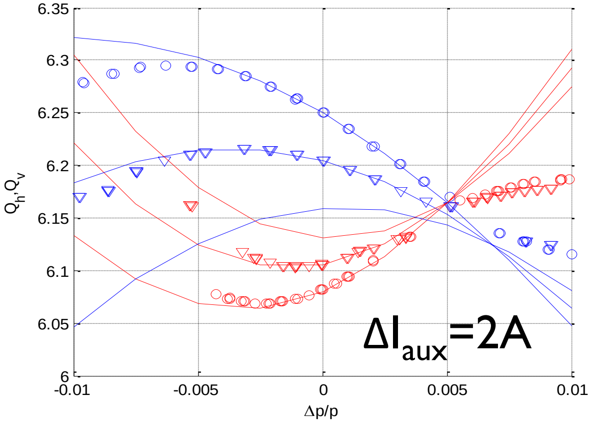
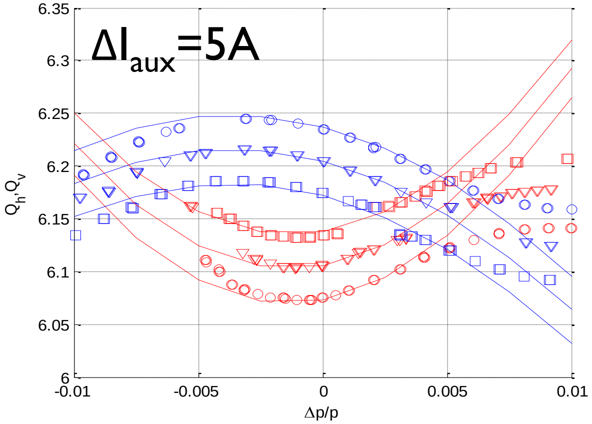
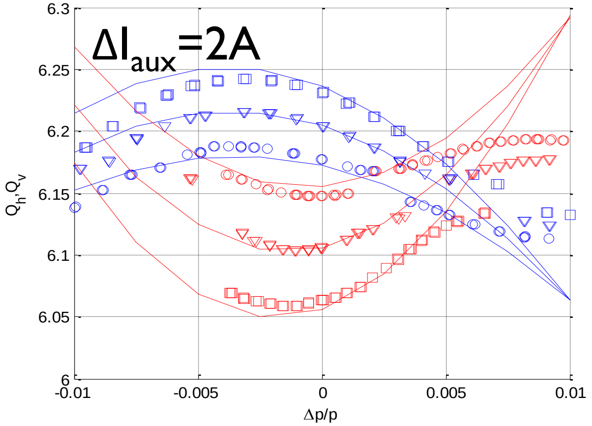


Figure-of-eight variation



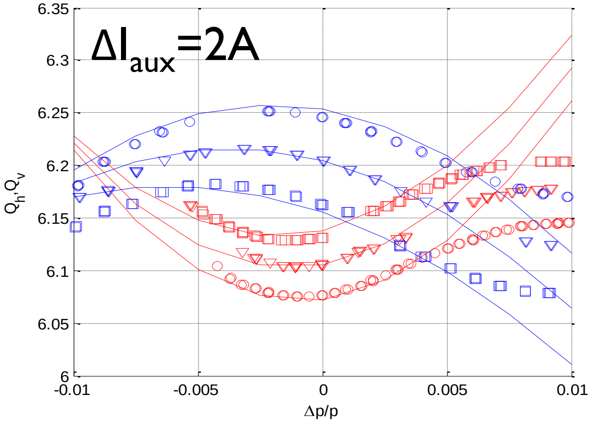
I_{f8}=-0.018 A

Wide focusing PFW variation



I_{fn}=-0.015A I_{fw}=-14.545A

Wide defocusing PFW variation



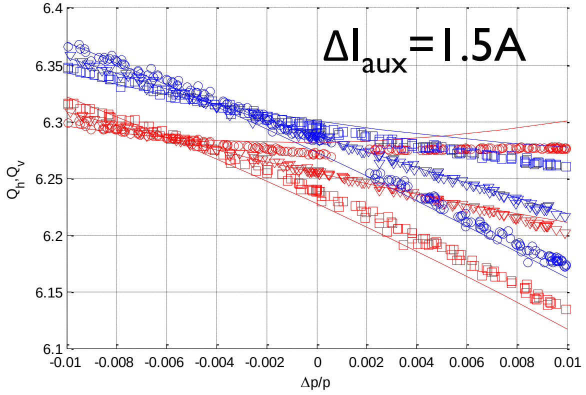
I_{dn}=-4.669A I_{dw}=-8.235A

Measurement data: A. Huschauer

Nonlinear chromaticity (3.5 GeV)

- ▽ measured Q_h (basic)
- ▽ measured Q_v (basic)
- ○ measured Q_h (+ΔI)
- ○ measured Q_v (+ΔI)
- □ measured Q_h (-ΔI)
- □ measured Q_v (-ΔI)
- — calculated Q_h
- — calculated Q_v

Narrow focusing PFW variation



Narrow defocusing PFW variation

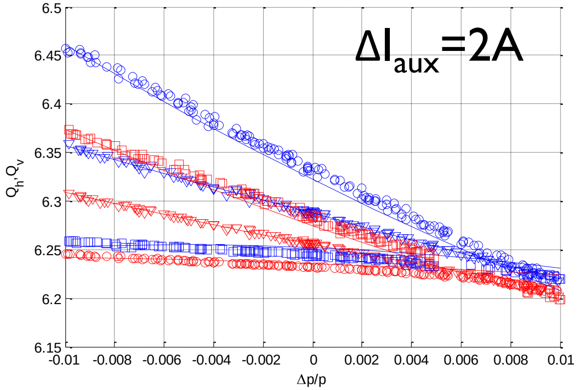
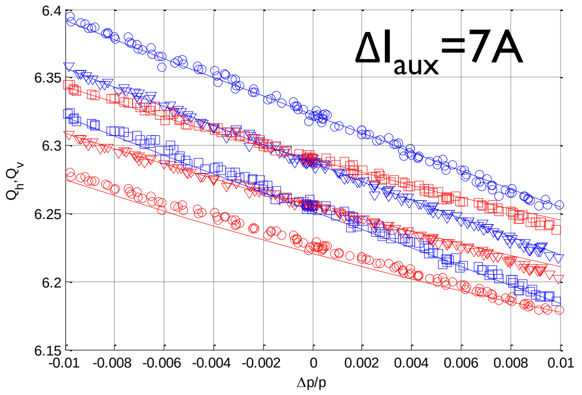
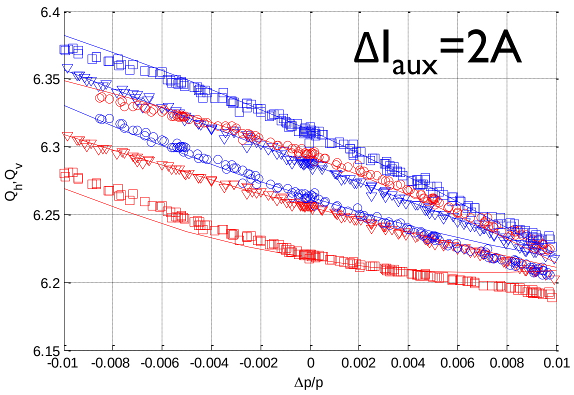


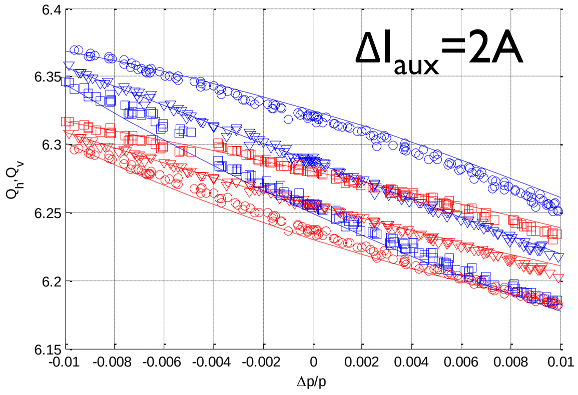
Figure-of-eight variation



Wide focusing PFW variation



Wide defocusing PFW variation



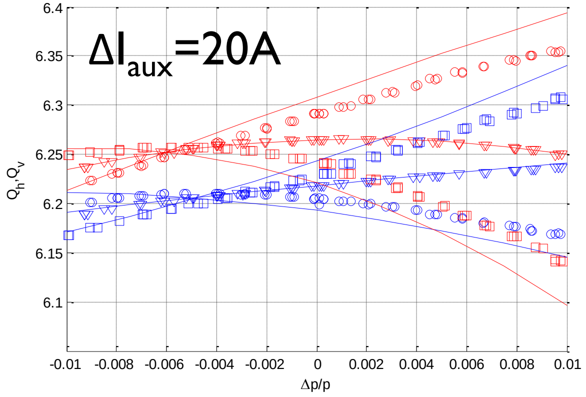
I_{aux}=0A

Measurement data: matrix measurement campaing

Nonlinear chromaticity (26 GeV)

▽ measured Q_h (basic)
▽ measured Q_v (basic)
○ measured Q_h (+ΔI)
○ measured Q_v (+ΔI)
□ measured Q_h (-ΔI)
□ measured Q_v (-ΔI)
— calculated Q_h
— calculated Q_v

Narrow focusing PFW variation



Narrow defocusing PFW variation

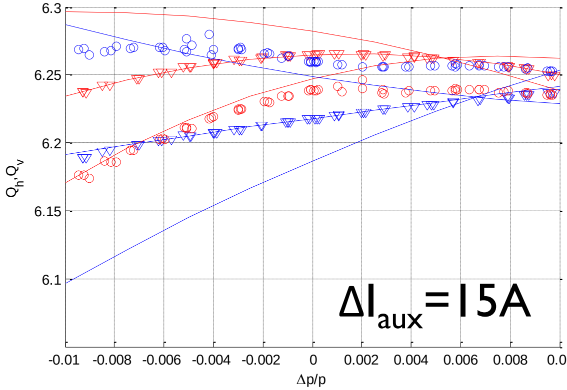
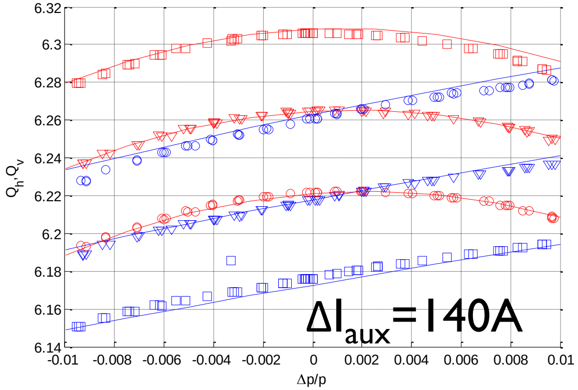
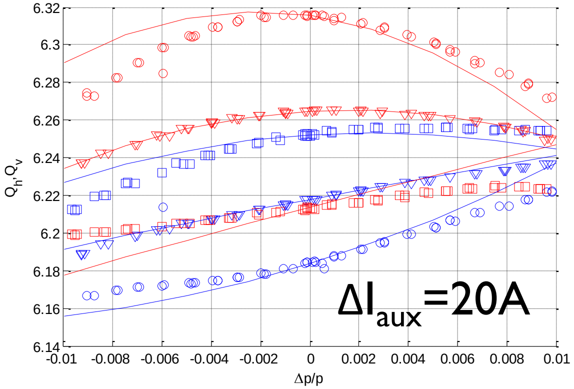


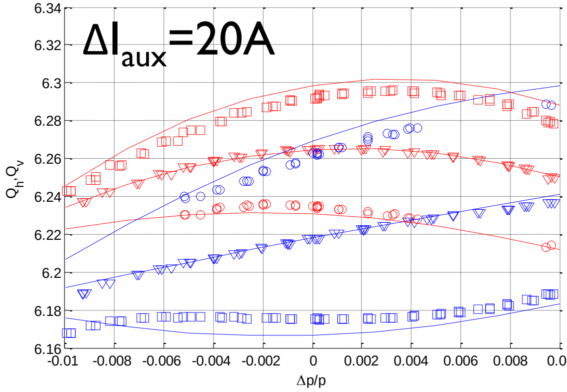
Figure-of-eight variation



Wide focusing PFW variation



Wide defocusing PFW variation



I_{f8}=1370.8A

I_f=205.1A

I_d=80.4A

Measurement data: matrix measurement campaing

What next?

- Further validation with the beam-based measurements
- Real-time magnetic measurements with a prototype coil
- Effective length corrections
  - Understanding discrepancies
  - Investigating radial position dependency
  - Implementing auxiliary coils dependency
- Detailed nonlinear chromaticity analysis
- Consolidation with the up to date (official) optics model

Possible error sources

- Random errors
  - Manufacturing tolerances
    - ☐ Numerical estimation by introducing random displacements within manufacturing tolerances (Monte-Carlo)
    - Coils position
    - Pole shape
    - Blocks alignement
- Systematic errors
  - Magnetic field related displacement
    - Poles atractiontion
      - ☐ (Th. Zickler, Deformation Measurements on the PS Main Magnets)
    - Lorentz forces (coils, eddy currents)
  - Main coil terminals