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CERN

Magnetic Model of the CERN PS Accelerator

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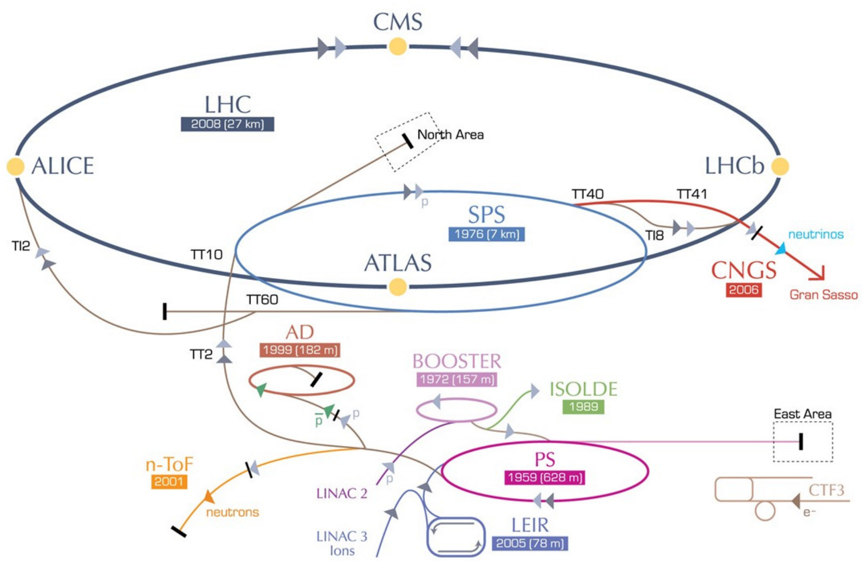
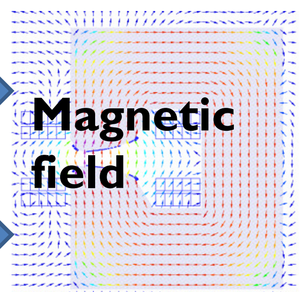
Introduction

CERN's accelerator complex



- **Measurements**
- **Magnetic model**



- **Exploring full potential of LHC physics**
  - Increasing the performance – luminosity
  - Upgrades of the injection chain
- **Proton Synchrotron (PS)**
  - Working point adjustments
    - Reducing beam losses
    - Increasing beam intensity
  - Control system
    - Field prediction for power supply control
  - Injection and extraction upgrades
    - PSB and SPS upgrades
    - Multi-turn Extraction

Motivation

- In 50 years of the PS operation all attempts to establish a field model, necessary for machine developments, have failed so far.
- After the cancellation of the PS2 project, it is now clear the PS will have to provide a reliable and high performance beams, for various working points, for the next 25 years.
- Setting a field model becomes now a necessity.

Objectives

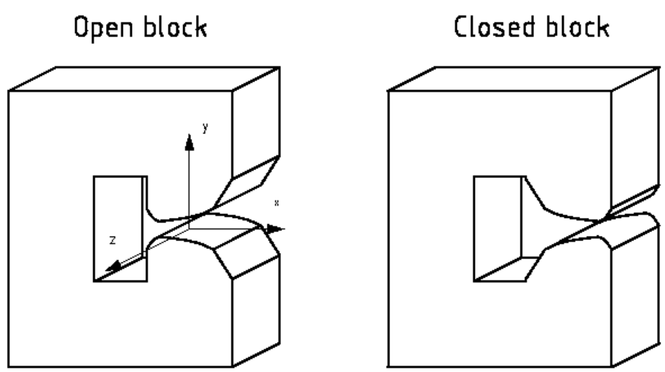
- To develop a model of the magnetic field inside the PS magnets, capable of accurately recreating the magnetic field along the beam trajectory.

- Implement and validate the magnetic model inside existing optical model of the PS accelerator.

Methodology

- Investigation of the magnetic field inside the PS magnet
  - Broad numerical analysis in 2D and 3D (static, transient, demagnetization).
  - Magnetic measurements (real-time using B-train system, dedicated with spare magnets).
  - Establish separate contributions of different circuits.
  - Derive quasi-static formulas of the field components taking into account dynamic and hysteresis effects.
- Implementation of the magnetic model in the existing optical model of 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.
- Investigation of the possibility of implementing the model in the control system of the accelerator

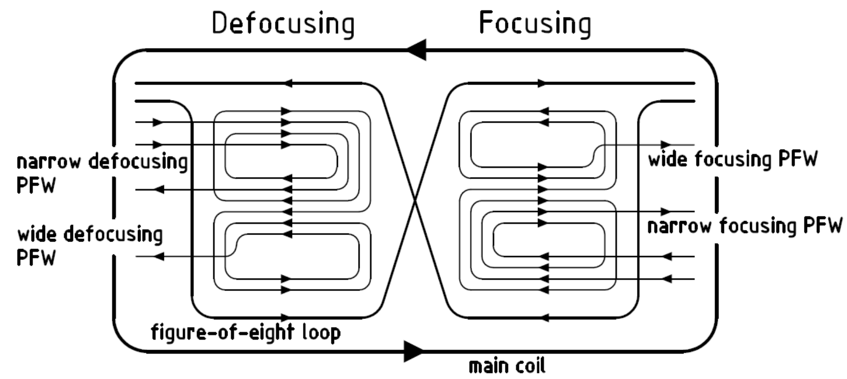
Proton Synchrotron main magnetic unit

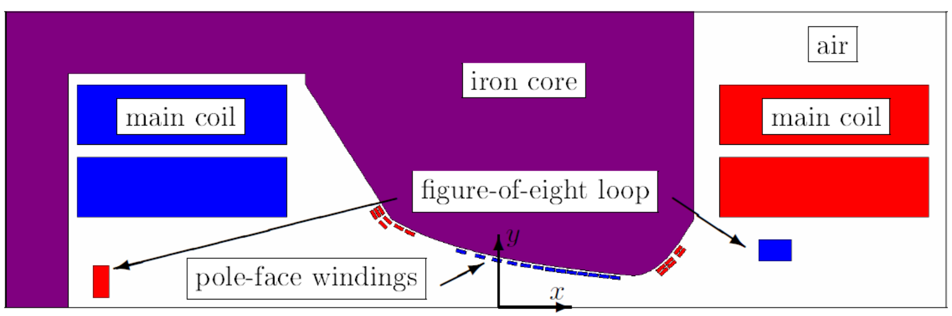


- Combined-function magnet with hyperbolic pole shape
  - Dipole field – guiding
  - Quadrupole field – focusing
  - Higher component are also present due to saturation
- Focusing and defocusing half (alternating-gradient focusing)
  - 5 C-shaped block in each half
  - Wedge shaped air gaps between blocks
- 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}) instead of four (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

Work done so far

- The contributions of separate circuits have been identified by numerical modelling and analysis.
- This led to the formulation of a « Transfer matrix ».
- The association and correction of the « Transfer matrix » with physical formulas based on the magnetic circuits is being explored
- Several machine measurements were performed to validate the formulas and parameters identified so far.

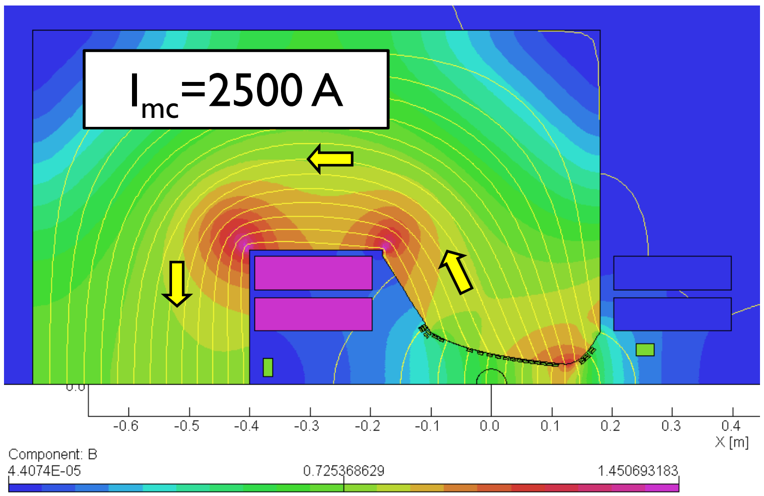
First results

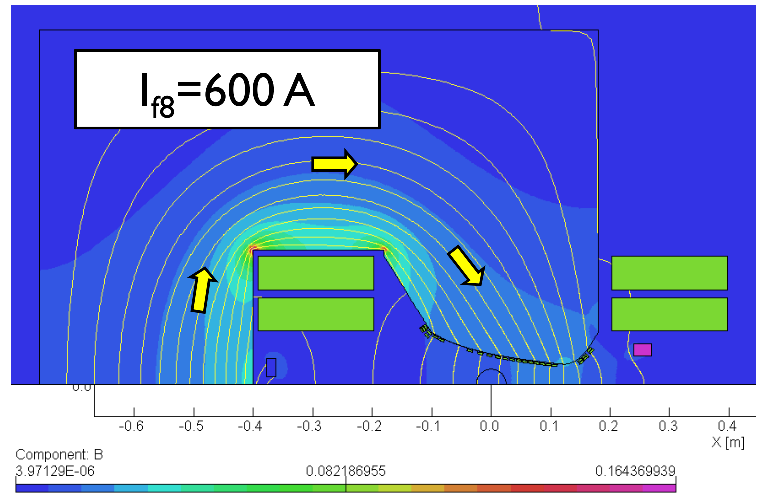
- The numerical approach seams to be capable of recreating measured data. The requested accuracy may be probably achieved once dynamic and hysteresis effects are implemented.
- The simplified model set so far could reproduce measurements done in the past on relative variations of the machine tune.

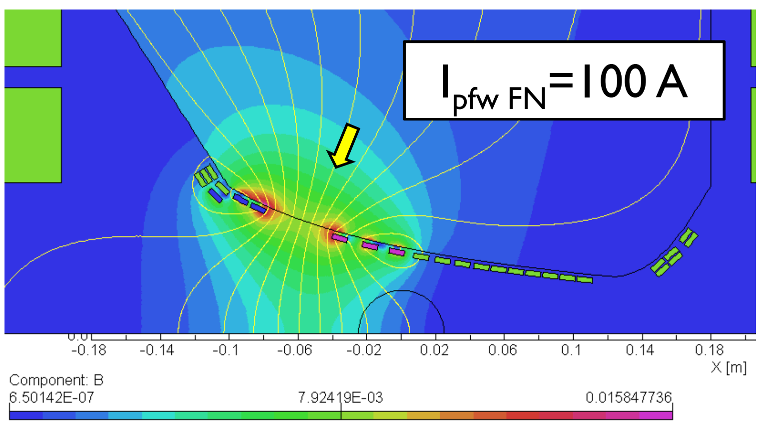
Investigating contributions of separate circuits

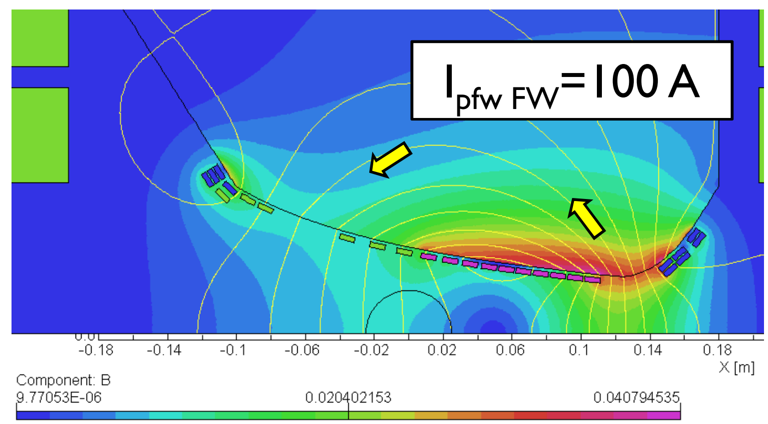
- 2D quasi-static numerical analysis of the magnetic field inside the PS magnet.
- Range of operations:
  - Injection $p_{inj} = 2.12$ GeV/c
  - Extraction $p_{extr} = 26$ GeV/c
- Current range:
  - Main coil $I_{mc} = 400\text{-}5500$ A
  - Figure-of-eight loop $I_{f8} = \pm 1200$ A
  - Pole-face windings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

Investigating contributions of separate circuits









Transfer matrix formulation

- Decomposed magnetic field in the linear range (I_{mc} < 3000A)

$$B_n\left(I_{mc}, I_{f8}, I_{pfwN}, I_{pfwW}\right) = p_{n\,mc} \times I_{mc} + p_{n\,f8} \times I_{f8} + p_{n\,pfwN} \times I_{pfwN} + p_{n\,pfwW} \times I_{pfwW}$$

$n = 1, 2, 3$ corresponds to dipole, quadrupole and sextupole component

- Transfer matrix with constant contribution coefficients

	Closed (focusing) block			Open (defocusing) block		
	Dipole	**Quadrupole**	**Sextupole**	**Dipole**	**Quadrupole**	**Sextupole**
P_{mc}	2.4958E-04	1.0261E-03	-1.1741E-05	2.4959E-04	-1.0266E-03	-1.1253E-05
P_{f8}	-2.4980E-05	-1.0258E-04	-4.9043E-06	2.4980E-05	-1.0251E-04	8.0704E-06
P_{pfwN}	-1.6098E-05	6.4759E-04	-1.0835E-02	-1.6098E-05	-6.4759E-04	-1.0836E-02
P_{pfwW}	-8.1006E-05	5.6230E-04	4.1829E-02	-8.1007E-05	-5.6223E-04	4.1828E-02

Transfer matrix formulation

- Behaviour of the magnetic field is not linear
  - Hyperbolic pole tip
  - Non-linear magnetic properties
- $p_n = p_n(I_{mc})$ to increase accuracy
- Difference between numerically calculated and modelled field using different parameters fitting

	Closed (focusing) block			Open (defocusing) block		
	Dipole [T]	**Quadrupole [T/m]**	**Sextupole [T/m^2]**	**Dipole [T]**	**Quadrupole [T/m]**	**Sextupole [T/m^2]**
Constant	6.42e-04	3.23e-03	8.88e-03	6.20e-04	2.32e-03	1.46e-02
Linear	3.83e-04	2.01e-03	7.80e-03	3.84e-04	2.09e-03	8.64e-03
Poly2	9.85e-05	5.39e-04	2.40e-03	9.98e-05	5.16e-04	2.09e-03

- At higher field level strong non-linear behaviour due to iron saturation
  - Additional square and cross terms might be introduce
  - *arctangent* function to fit matrix parameters

Establishing physical formulas

- Generic formula of the field model

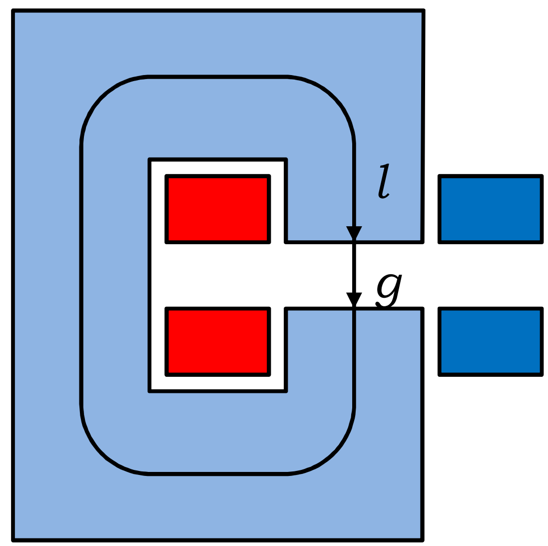
$$B_n = B_n\left(I, \frac{dI}{dt}, t, I(-t) \right)$$

- Steady field and saturation contribution
- Remanent field (hysteresis)
- Dynamic effects (eddy currents)

- Steady field amplitude

$$B_{gap} = NI \frac{R_{gap}}{R_{core} + R_{gap}} \frac{\mu_0}{g}$$

$$R_{core} = \frac{l}{\mu_{iron} A_{core}}$$



Establishing physical formulas

- Complete formula for steady field inside the pole gap
  - Additional formulas for auxiliary circuits
  - Coupling through the iron permeability
  - Dependency on horizontal coordinate
    - Pole gap length
    - Mean flux path
    - Iron permeability
  - Formulas for quadrupolar and sextupolar components

$$G_y = \frac{\partial B_y(x)}{\partial x} \qquad S_y = \frac{\partial^2 B_y(x)}{\partial x^2}$$

Performing machine measurements

- Total field measurement using B-train installation

$$B(t) = B_0 + \int_0^t \dot{B}\,dt$$

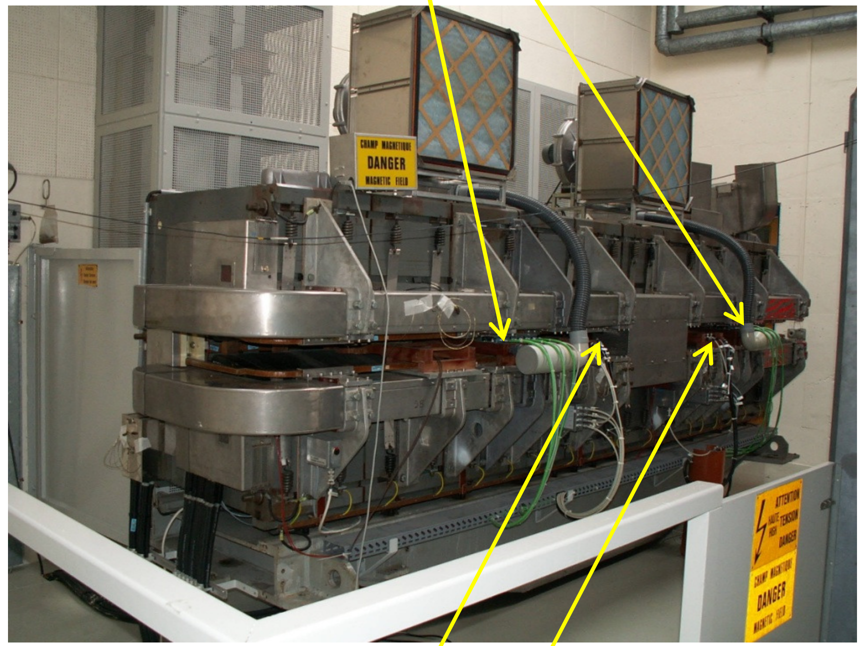
- Field marker – ”picking-strip”
  - Saturation of a ferromagnetic strip
  - B_0 = 49.8 G
- Flux coils
  - Induced voltage $\dot{B} = k \times V_{coil}$
- Field control using B_{train} signal

$$B_{train} = \frac{0.909 \times B_D + 1.091 \times B_F}{2}$$

- In scope of this research, possible extension for quadrupole and sextupole measurement

- Reference magnet

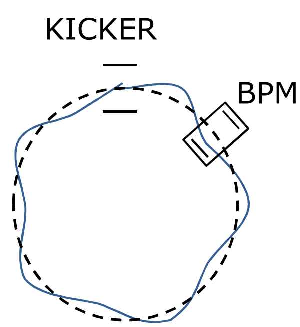
3 × peaking strip (F block)
3 × peaking strip (D block)



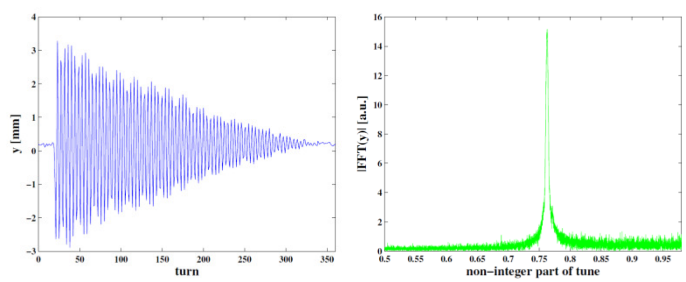
3 × coils (F block)
3 × coils (D block)

Performing machine measurements

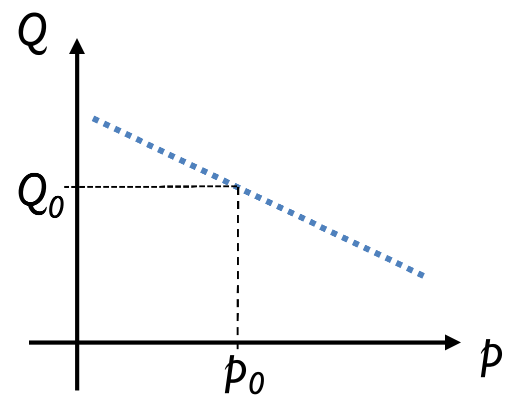
- Tune measurements
  - Exciting a coherent betatron oscillation with kicker
  - Measuring beam position with a pick-up



  - Non-integer part of the tune obtained with Fourier Transform



- Chromaticity measurements
  - Modulating beam momentum using RF frequency
  - Tracking tune



$$\frac{\Delta Q}{Q_0} = \xi \frac{\Delta p}{p_0}$$

First comparison with measurement data

- Powering configuration used in measurements from 1992

	I_{mc}	I_{f8}	I_{pfwF}	I_{pfwD}
Cycle E	669.2 A	0 A	0 A	0 A
Cycle A	2677.5 A	450.35 A	39.05 A	-45.08 A

- Cycle E comparison

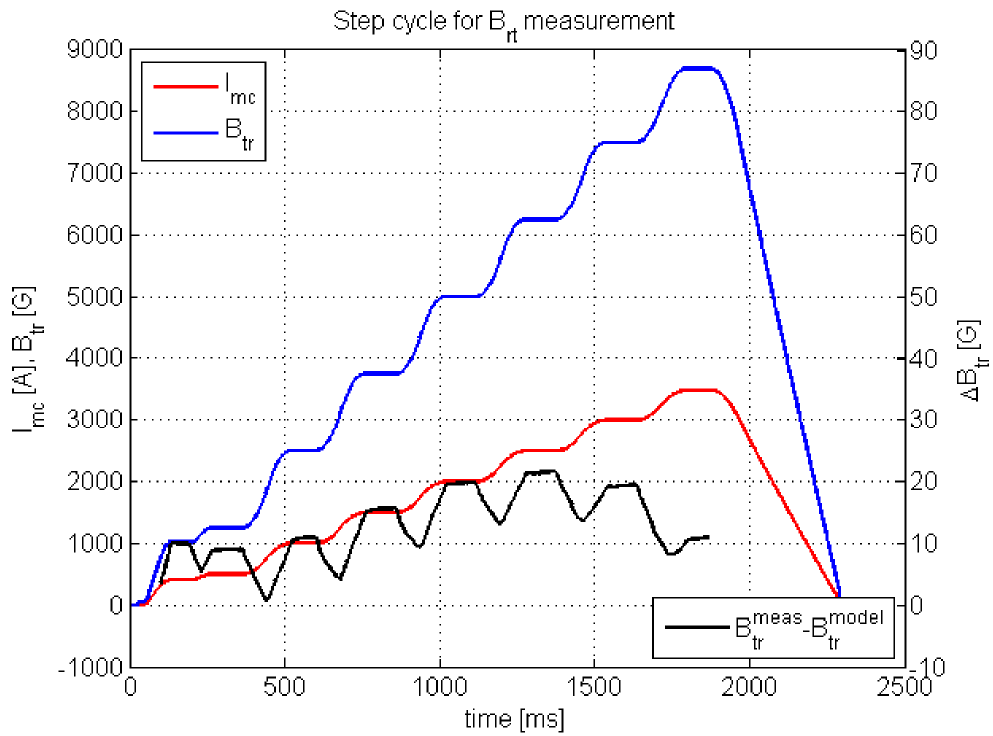
	Focusing half-unit			Defocusing half-unit		
	Dipole [T]	**Quadrupole [T/m]**	**Sextupole [T/m²]**	**Dipole [T]**	**Quadrupole [T/m]**	**Sextupole [T/m²]**
measured	0.16688	0.68500	0.25000	0.16712	-0.68600	0.15000
modelled	0.16659	0.68448	-0.00926	0.16662	-0.68574	-0.00144
difference	0.00029	0.00052	0.25926	0.00050	-0.00026	0.15144

- Cycle A comparison

	Focusing half-unit			Defocusing half-unit		
	Dipole [T]	**Quadrupole [T/m]**	**Sextupole [T/m²]**	**Dipole [T]**	**Quadrupole [T/m]**	**Sextupole [T/m²]**
measured	0.65227	2.74050	1.20000	0.68388	-2.73200	-1.55000
modelled	0.65333	2.74896	1.17631	0.68395	-2.74027	-1.42816
difference	-0.00106	-0.00846	0.02369	-0.00007	0.00827	-0.12184

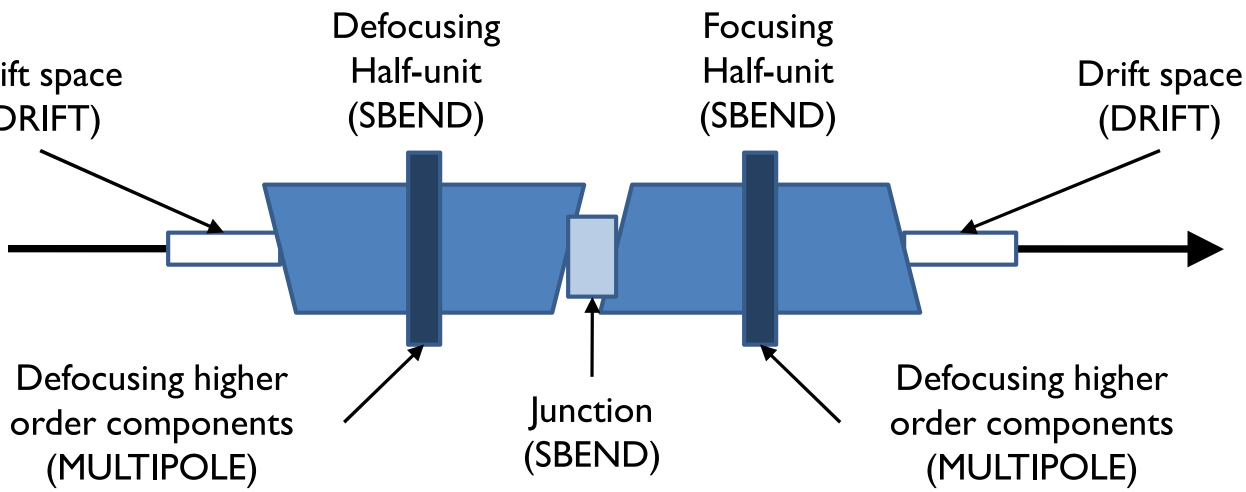
First comparison with measurement data

- Step cycle measurement and difference between measured and modelled field
  - Discrepacies up to 20 G
  - Dynamic and hysteresis effects are not yet included in the model
- Example of history dependent effect in SFTPRO cycle
  - Measured current difference correstponds to 5 G
  - Remanent field has to be investigated and implemented in the model



	Measured B_{tr} [G]	I_{mc} [A] Alone in SC	I_{mc} [A] Full SC	Estimated $\lvert\Delta B_{tr}\rvert$ [G]
Injection	1013.7	404.9	404.5	1
Flat-top	6666	2668.08	2666	5

Magnet representation in the optical model

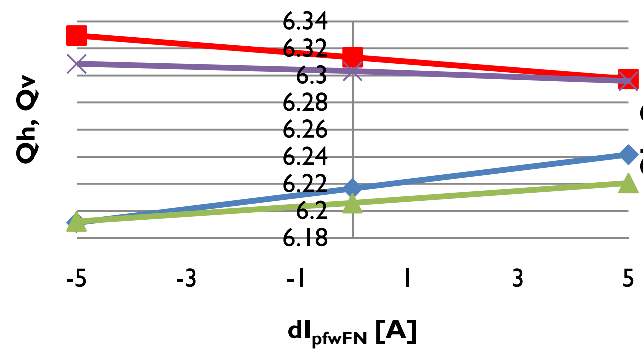


- Drift spaces under the main coil
- Focusing and defocusing sector magnet
  - Bending angle
  - Quadrupole and sextupole components – from magnetic model
  - Pole-face angles – no data available
  - Effective bending length – from old measurements
- Thin-lens multipoles
  - Octupole and higher components
  - Currently inactive
- Central junction
  - Quadrupole and sextupole component
  - Data unavailable

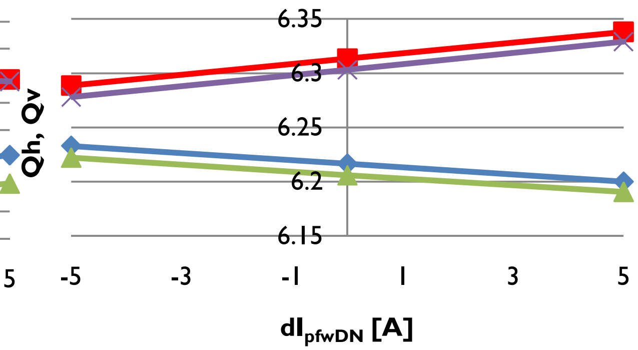
Tune calculation with MADX and field model

- **Working point:**
  - p = 14 GeV/c
  - B_{tr} = 6666.6 G
  - I_{f8} = 543.3 A
  - I_{pfwF} = 43.5 A
  - I_{pfwD} = -52.6 A

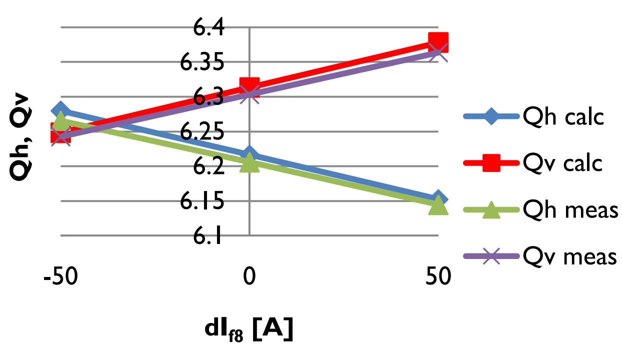
Tune vs PFW FN current variation



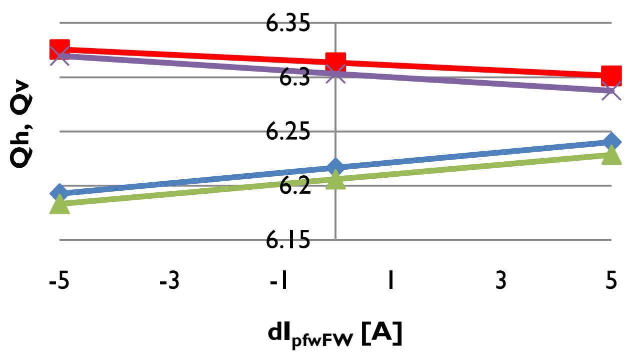
Tune vs PFW DN current variation



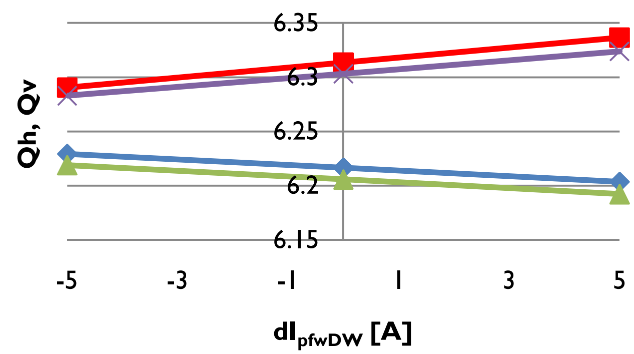
Tune vs Fo8 current variation



Tune vs PFW FW current variation



Tune vs PFW DW current variation



- Possibility to interpolate measurements for other working points and improve procedures controlling the beam parameters

Aspects of the optical model that need further work

- Effective bending and focusing length
- Pole-face angles (edge focusing)
- Field inside junction area
  - 3D modelling and magnetic measurements

- Degradation of optical parameters at stabilised field
  - Transient analysis
  - Real-time magnetic measurements
  - Beam based measurements

Scheme of work