Non-linear chromaticity measurements in SPS

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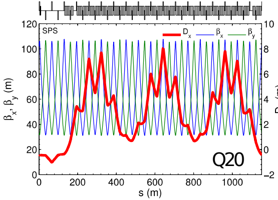
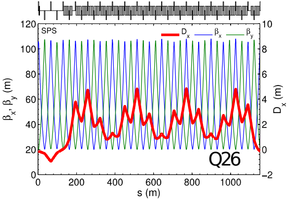
Carrying on the SPS non-linear optics characterization [1]

- **Non-linear optics model is basic ingredient for studying incoherent (and coherent!) effects in view of LIU (LHC Injector Upgrade Project)**
- **Magnetic model of SPS main magnets not available**
- **Development of effective non-linear optics model based on beam measurements**
  - At 26 GeV/c injection energy
  - Two optics (Q20 and Q26) allow for different sampling of multipole errors due to different dispersion and optics functions





[1] Improved Methods for the Measurement and Simulation of the CERN SPS Non-linear Optics, IPAC 2016, THPMR036.

Multipole components in MADX model

allowed multipole errors of dipoles

first allowed multipole error of quadrupoles

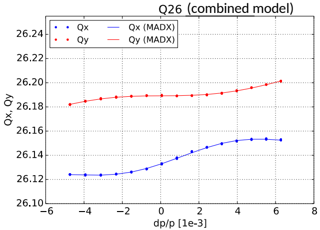
error order	6-pole		10-pole		14-pole		12-pole		6-pole		8-pole	
chromaticity order	$Q'_{x,y}$		$Q'''_{x,y}$		$Q'''''_{x,y}$		$Q''''_{x,y}$		$Q'_{x,y}$		$Q''_{x,y}$	
variable name	b3a	b3b	b5a	b5b	b7a	b7b	b6f	b6d	b3f	b3d	b4f	b4d
element	MBA	MBB	MBA	MBB	MBA	MBB	QF	QD	LSF	LSD	LOF	LOD
magnet type	dipoles						quadrupoles		sextupoles		octupoles	

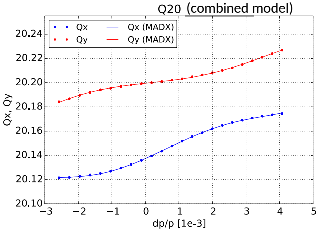
Remanent fields of main component in sextupoles and octupoels

- **Systematic mulitpole errors on SPS main magnets**
  - Placed at main magnets according to allowed error harmonics
  - These errors are mainly due to remanent fields from ramping to top energy
- **The model is fitted to the data by**
  - calculate the response matrix for all multipole errors on the nonlinear chromaticity in MADX-PTC
  - apply an SVD algorithm
  - SVD can be applied to one measurement set individually, or to multiple sets at the same time (a good non-linear model should be able to predict the chromaticity for all optics)

Combined optics modelling

- **Consistent MADX model can be achieved with**
  - same 3rd, 5th and 7th order components in main dipoles and 6th order component in quadrupoles in both optics
  - same 3rd order component due to **remanent fields in sextupoles** in both optics
  - 4th order components due to **remanent fields in octupoles** (different for the two optics, justified due to different octupole settings on preceding cycle during the measurements)





Whats new?

Including Q22 and widening the momentum scan:

What prevents a wider momentum scan?

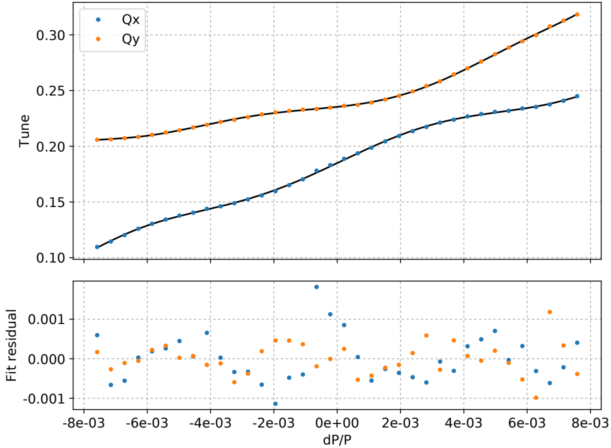
- Energy spread + chromaticity → **Beam losses**
- High chromaticity → **Fast decoherence**

By lowering the beam intensity we can:

- Reduce RF voltage → Reduce energy spread → **Reduce losses**
- Reduce chromaticity → **Reduce decoherence**

Bunch intensity has been lowered to $\sim 2 \cdot 10^{10}$
and RF total voltage to 300KV

Wide momentum-scan tune-shift in Q22



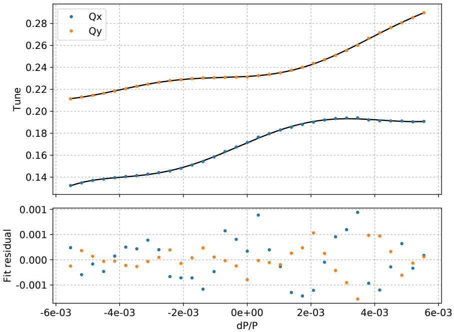
Horizontal (QPH: +0.50)
Q[0] : 1.85e-01 +/- 0.14 %
Q[1] : 1.35e+01 +/- 1.26 %
Q[2] : 2.21e+02 +/- 45.77 %
Q[3] : -1.66e+06 +/- 7.37 %
Q[4] : -1.87e+08 +/- 29.44 %
Q[5] : 6.12e+11 +/- 13.81 %
Q[6] : 4.29e+13 +/- 46.07 %
Q[7] : -1.46e+17 +/- 24.69 %

Vertical (QPV: -0.20)
Q[0] : 2.35e-01 +/- 0.07 %
Q[1] : 3.01e+00 +/- 3.82 %
Q[2] : 1.25e+03 +/- 5.51 %
Q[3] : 1.59e+06 +/- 5.21 %
Q[4] : -1.22e+08 +/- 30.79 %
Q[5] : -6.52e+11 +/- 8.81 %
Q[6] : 2.93e+13 +/- 45.88 %
Q[7] : 1.89e+17 +/- 13.01 %

- Black line is a polynomial fit (7^{th} order)
- Above the 7^{th} order errors (from the covariance matrix) explode
- Each point is the average of $\sim$5 acquisitions

Wide momentum-scan tune-shift in Q20/Q26

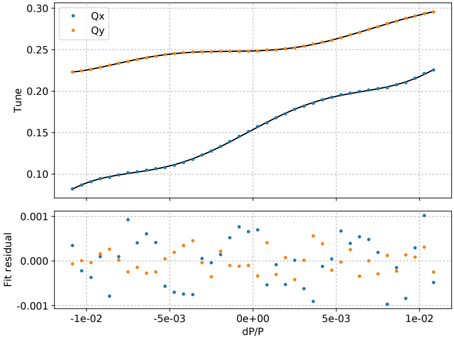
Q20



Horizontal (QPH: +0.45)
Q[0] : 1.71e-01 +/- 0.12 %
Q[1] : 1.23e+01 +/- 1.48 %
Q[2] : -9.13e+02 +/- 16.24 %
Q[3] : -3.28e+06 +/- 7.46 %
Q[4] : 2.84e+08 +/- 53.19 %
Q[5] : 1.58e+12 +/- 19.99 %
Q[6] : -1.75e+14 +/- 57.60 %
Q[7] : -4.64e+17 +/- 54.43 %

Vertical (QPV: -0.50)
Q[0] : 2.32e-01 +/- 0.05 %
Q[1] : 1.75e+00 +/- 6.19 %
Q[2] : 2.17e+03 +/- 4.09 %
Q[3] : 2.65e+06 +/- 5.52 %
Q[4] : -5.58e+08 +/- 16.14 %
Q[5] : -1.47e+12 +/- 12.88 %
Q[6] : 1.90e+14 +/- 31.82 %
Q[7] : 5.69e+17 +/- 26.49 %

Q26

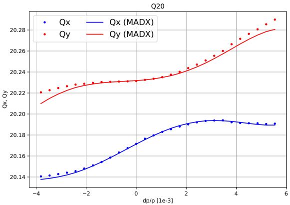


Horizontal (QPH: +0.30)
Q[0] : 1.54e-01 +/- 0.14 %
Q[1] : 1.07e+01 +/- 0.97 %
Q[2] : -2.31e+02 +/- 18.95 %
Q[3] : -6.92e+05 +/- 5.33 %
Q[4] : 4.53e+07 +/- 25.81 %
Q[5] : 1.11e+11 +/- 11.24 %
Q[6] : -5.43e+12 +/- 37.94 %
Q[7] : -1.04e+16 +/- 25.32 %

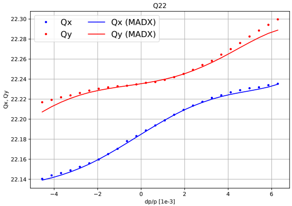
Vertical (QPV: -0.15)
Q[0] : 2.49e-01 +/- 0.04 %
Q[1] : 6.12e-01 +/- 7.67 %
Q[2] : 5.51e+02 +/- 3.57 %
Q[3] : 3.48e+05 +/- 4.77 %
Q[4] : -6.75e+07 +/- 7.78 %
Q[5] : -4.65e+10 +/- 12.11 %
Q[6] : 7.74e+12 +/- 11.96 %
Q[7] : 3.97e+15 +/- 29.72 %

Fitting the model to experimental data

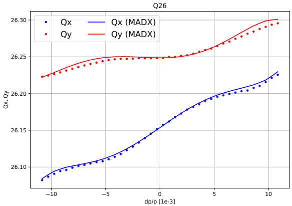
Q20



Q22



Q26

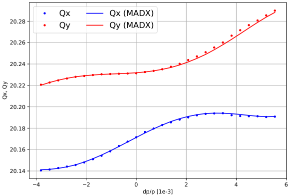


b3a: -3.4e-3	b4d: -3.0e-1	b5a: -6.6	b6a: 7.0e3	b7a: 5.8e4	ksremd: -2.0e-2
b3b: 3.6e-3	b4f: -1.5e-2	b5b: -1.5	b6b: -9.0e1	b7b: 1.8e5	ksremf: 1.3e-2

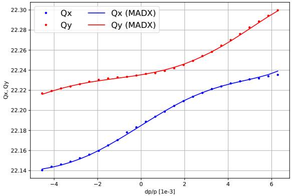
- Fitting only **terms common to all 3 optics**
- The fit does not reproduce well the observations
- more degrees of freedom are required

Allowing for an independent residual field in octupoles...

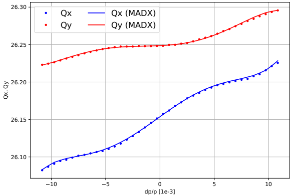
Q20



Q22



Q26

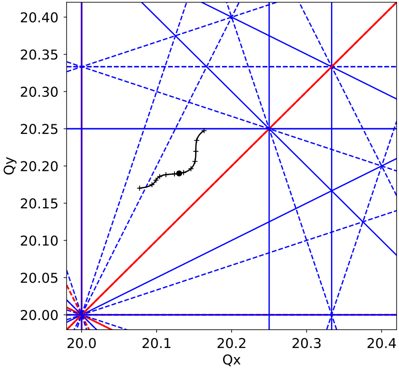


b3a: -2.1e-3	b5a: -8.8	b6a: 3.6e3	b7a: 7.4e4	ksremd: -1.6e-2
b3b: 2.2e-3	b5b: -6.4	b6b: 3.0e1	b7b: 6.4e4	ksremf: 1.0e-2

koremd Q20: -1.2	koremf Q20: 4.1e-2
koremd Q22: -1.1	koremf Q22: 5.2e-2
koremd Q26: -0.62	koremf Q26: -0.25

- Octupolar residual field is very similar in Q20/Q22 but not for Q26
- **Q20/Q22** have been measured the **isame day, Q26 the day after**

Tune foot-print from last week high intensity run (Q20)



- Similar chromaticity to the one used during measurements
- Energy spread: +/-5.5e-3 (dP/P used during measurements)

Helpfull to understand **losses from large dP/P** particles
(as in uncaptured beam)

Some remarks and final thoughts...

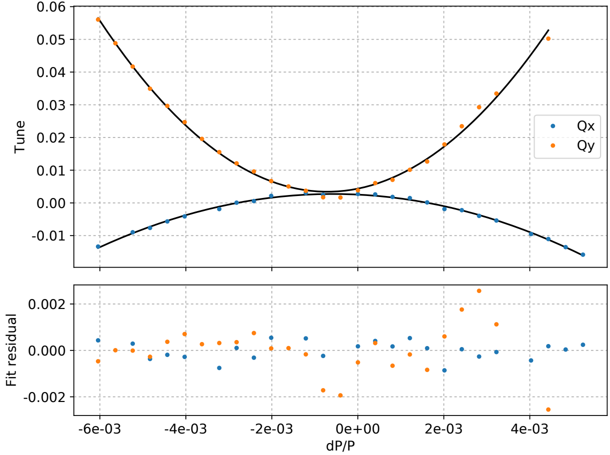
Wide dP/P scans for Q20/Q22/Q26:

- Lowering the bunch intensity did the trick

Effective model extended to 3 optics:

- Remanent sextupolar component confirmed
- Q20/Q22 show a consistent octupolar field, while Q26 no
    - Maybe due to remanent fields? This could be tested

The results here presented are to be considered as a first attempt, a refined analysis is ongoing...



Horizontal
Q[0] : 2.54e-03 +/- 5.12 %
Q[1] : -6.50e-01 +/- 4.05 %
Q[2] : -1.11e+03 +/- 1.55 %

Vertical
Q[0] : 4.36e-03 +/- 7.68 %
Q[1] : 2.65e+00 +/- 3.79 %
Q[2] : 3.74e+03 +/- 1.52 %