LHC Injectors Upgrade

LHC Injectors Upgrade

Analysis of TbT PS SEM grid measurements

V. Forte, G.P. Di Giovanni, M. Fraser, A. Guerrero Ollacarizqueta, A. Huschauer, F. Roncarolo, E. Senes, F. Tecker

Acknowledgements: F. Antoniou, C. Carli, A. Oeftiger, P. Skowronski

MSWG meeting

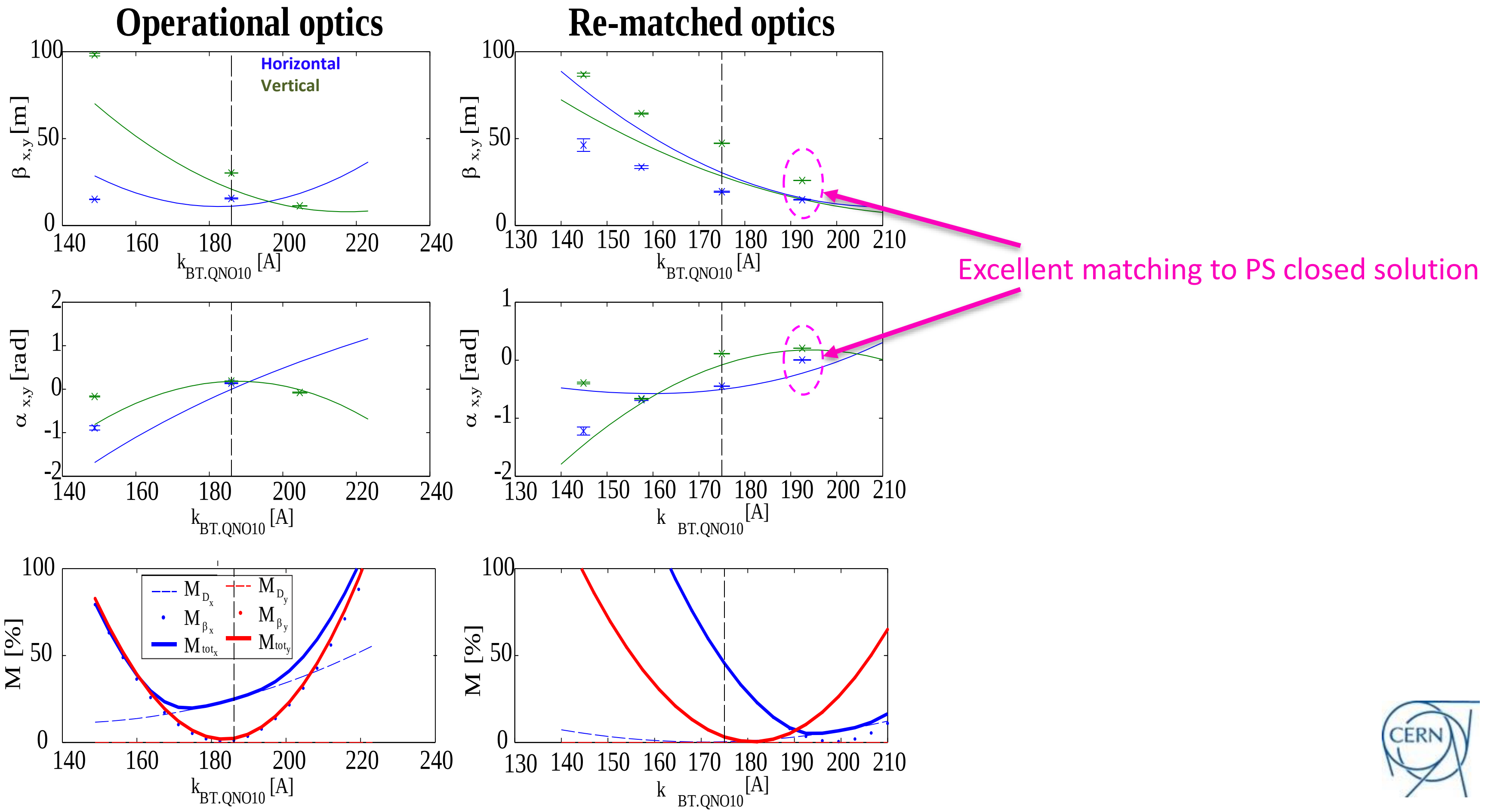
29 November 2018

Talk overview

- **Two optics used on BCMS (0.9 eVs) cycles (TFB ON, low chroma, coupling corrected)**
  - data taken in two MD sessions (not fully analysed yet) – 30th October and 7th November 2018
  - Operational optics
  - PPM-rematched optics
- **First order moments analysis**
  - Injection oscillations and $\Delta p/p$ dependence (energy matching) at BPMs and SEM grids
  - Dispersion at BPMs and SEM grids
- **TbT beam size at SMG52**
  - Horizontal measurements
  - Vertical measurements
- **SEM grid scattering blow-up**
- **Conclusions and next steps**

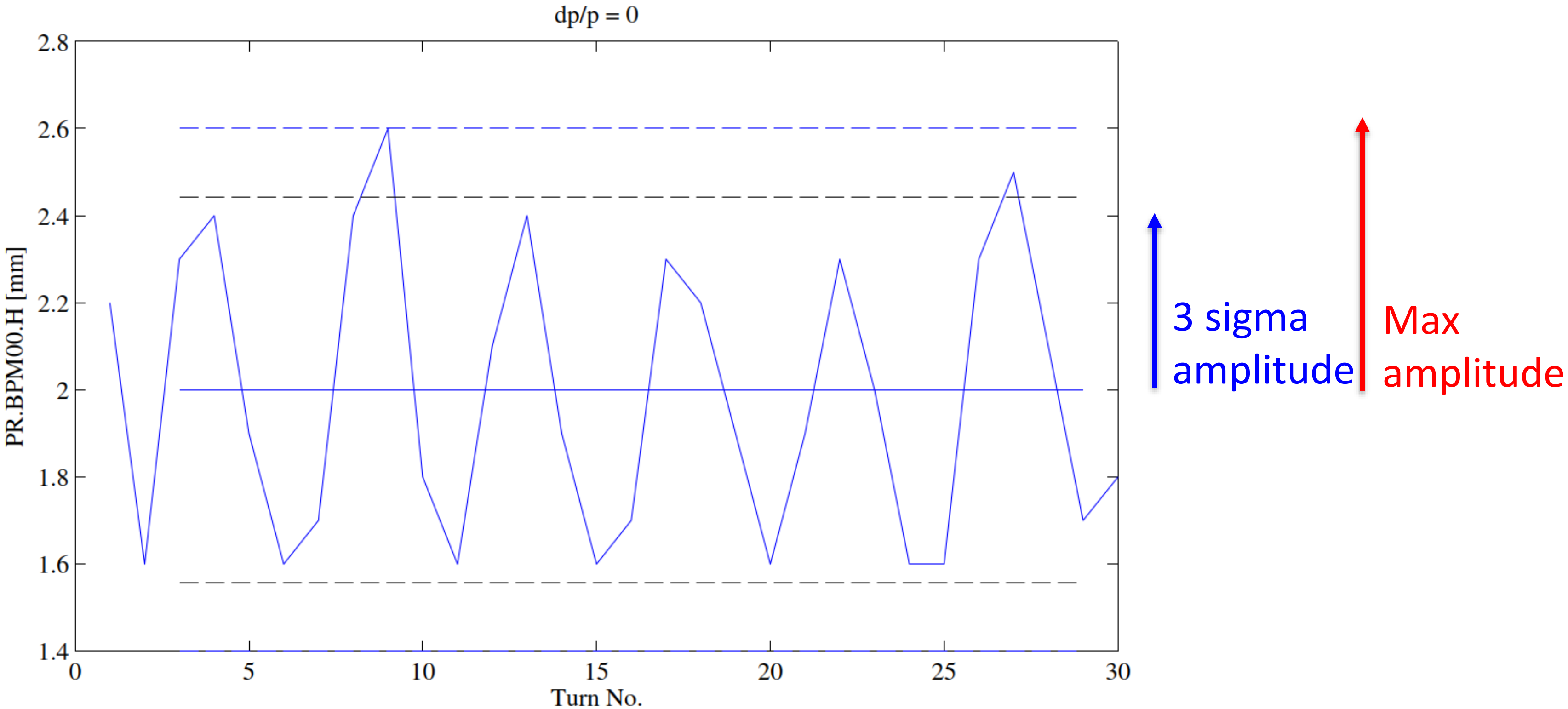
Operational and (PPM) re-matched optics

- **PPM optics minimises betatron and dispersive measurements and is suitable for parallel operation, as it moves only BT quads**
  - V. Forte *et al.*, "Overview Of The CERN PSB-to-PS Transfer Line Optics Matching Studies In View Of The LHC Injectors Upgrade Project", WEP2P006, HB2018
    - Work on transfer line understanding is improving ➔ analysis of quadrupolar gradient error (to be presented)



Injection offset and Δp/p dependance

- **Injection oscillations from first order moments by changing PSB extr frequency**
  - Mean (± 1 SD) oscillation for the BPMs in the PS ring
- **Orbit with RF OFF look flat**
  - ➔ energy reasonably matched
- **3-sigma modulation looks more reliable for noise rejection on the modulation amplitude**

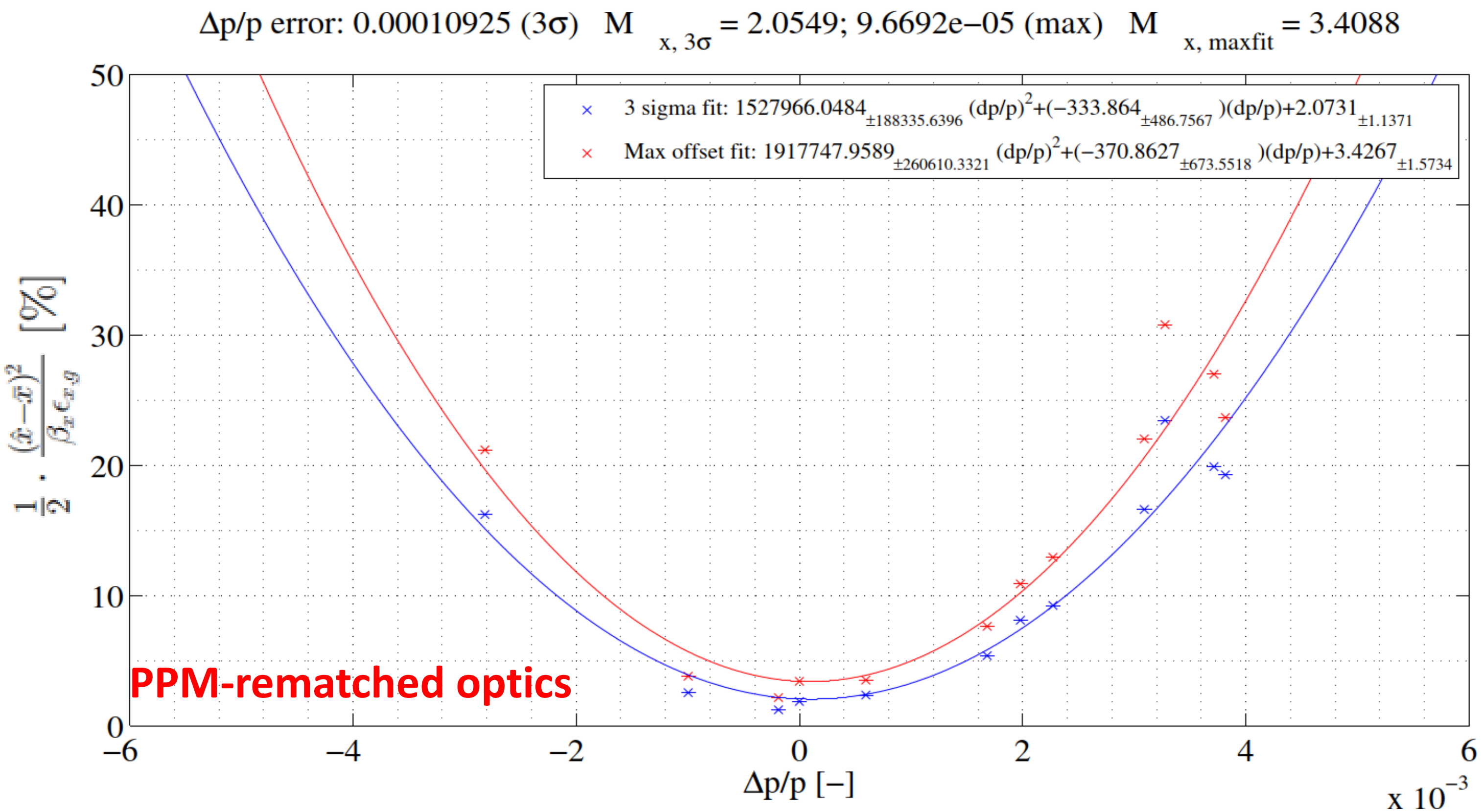


Injection offset and Δp/p dependance

- **Injection oscillations from first order moments by changing PSB extr frequency**
  - Mean (± 1 SD) oscillation for the BPMs in the PS ring (single BPM in this case)
- **Orbit with RF OFF look flat**

  ➔ energy reasonably matched
- **Parabolas do not have minimum at y=0**

  ➔ **residual emittance growth source from injection oscillation in the order of few percent (2% in this case)**

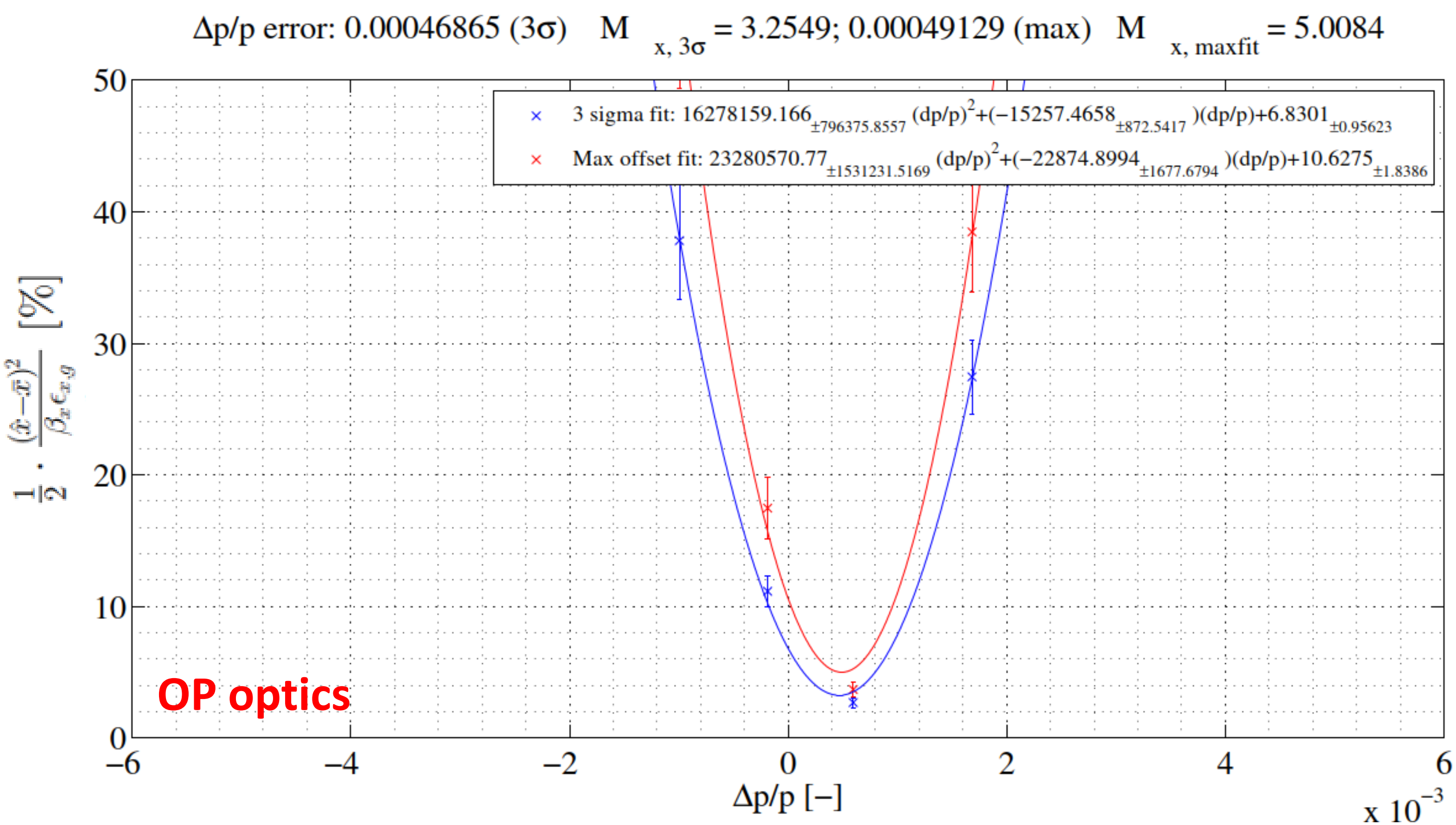


Injection offset and Δp/p dependance

Injection oscillations from first order moments by changing PSB extr frequency

- Mean (± 1 SD) oscillation for the BPMs in the PS ring (all BPMs in this case)

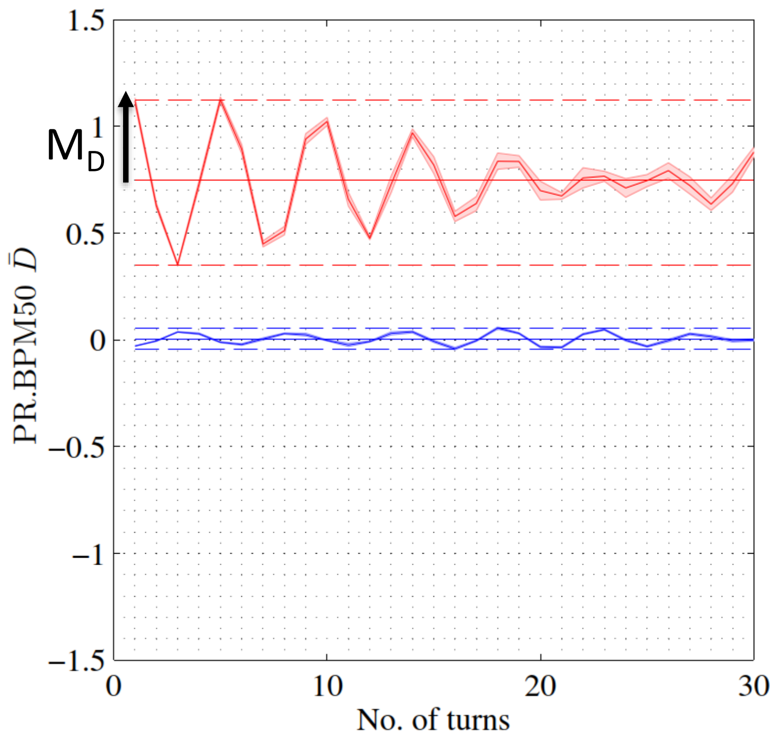
- **Residual momentum mismatch Δp/p seems between 1e-4 (PPM-rematched ,~1% em. growth) and 4e-4 (OP, ~9% em. growth)**

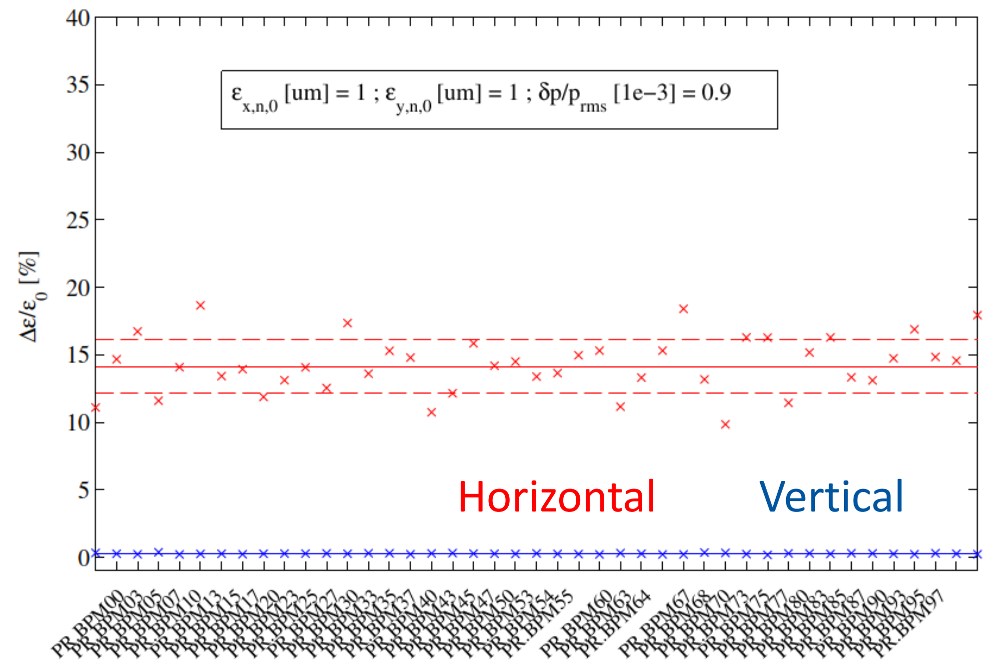


Dispersion at BPMs

OP optics

- Dispersion from BPMs gives constant normalised dispersive mismatch:
  - M_{Dx}= 0.39 $\sqrt{m}$ ➔ emittance growth ~14 (±$2_{1\sigma}$)%
  - M_{Dy}= 0.05 $\sqrt{m}$ ➔ emittance growth ~0%

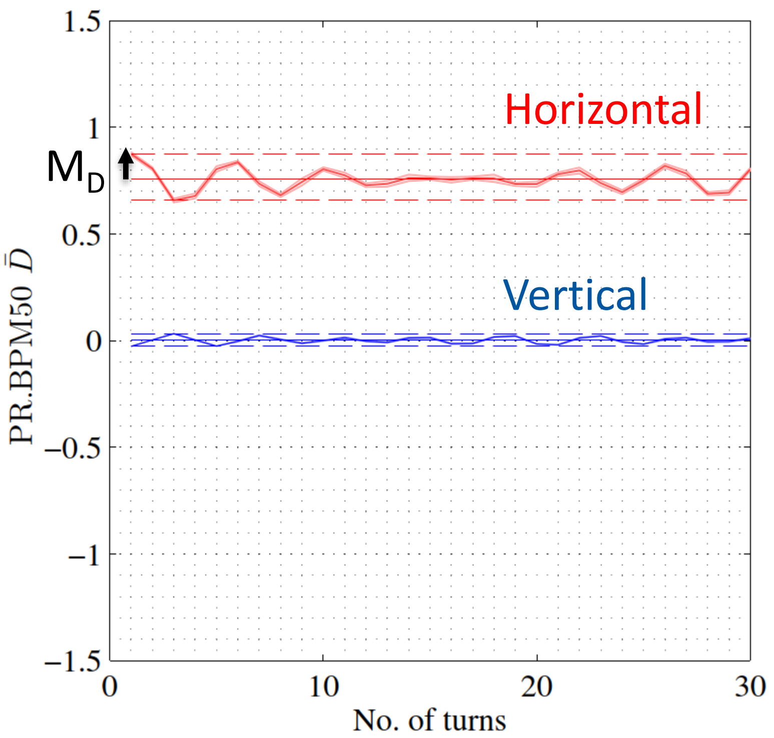


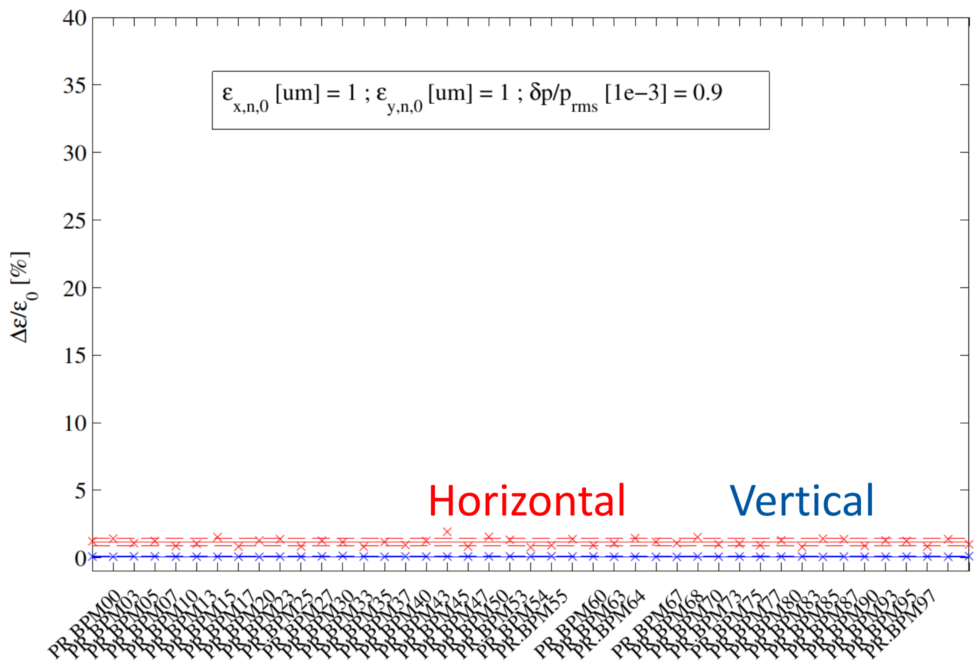


Dispersion at BPMs

PPM-rematched optics

- Dispersion from BPMs gives very constant normalised dispersive mismatch:
  - M_{Dx}= 0.12 $\sqrt{m}$ ➔ emittance growth ~1%
  - M_{Dy}= 0.03 $\sqrt{m}$ ➔ emittance growth ~0%
- Some coupling is visible in the horizontal plane



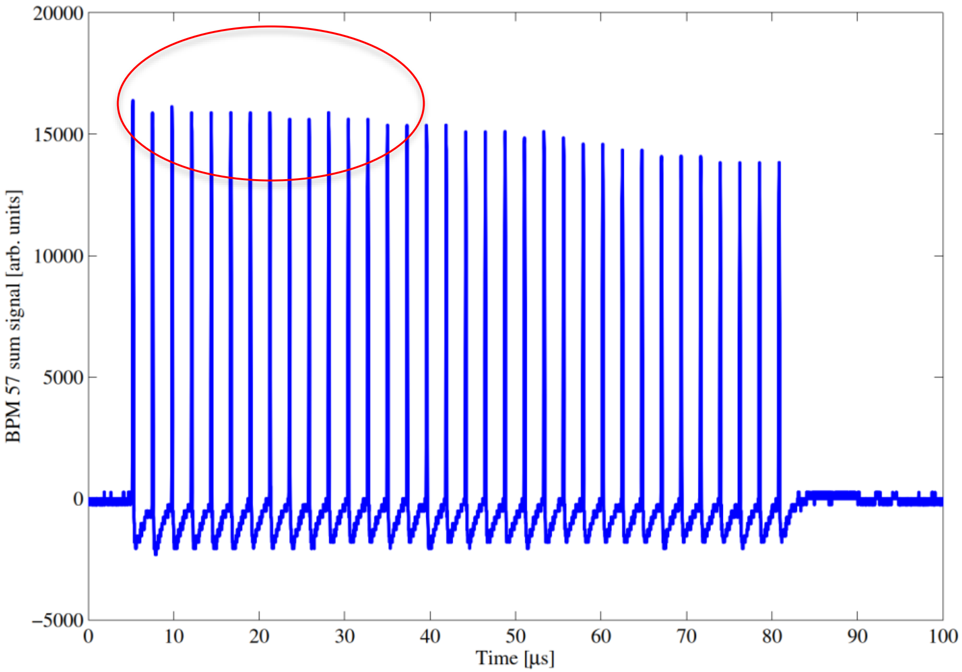


Intensity evolution along measurements

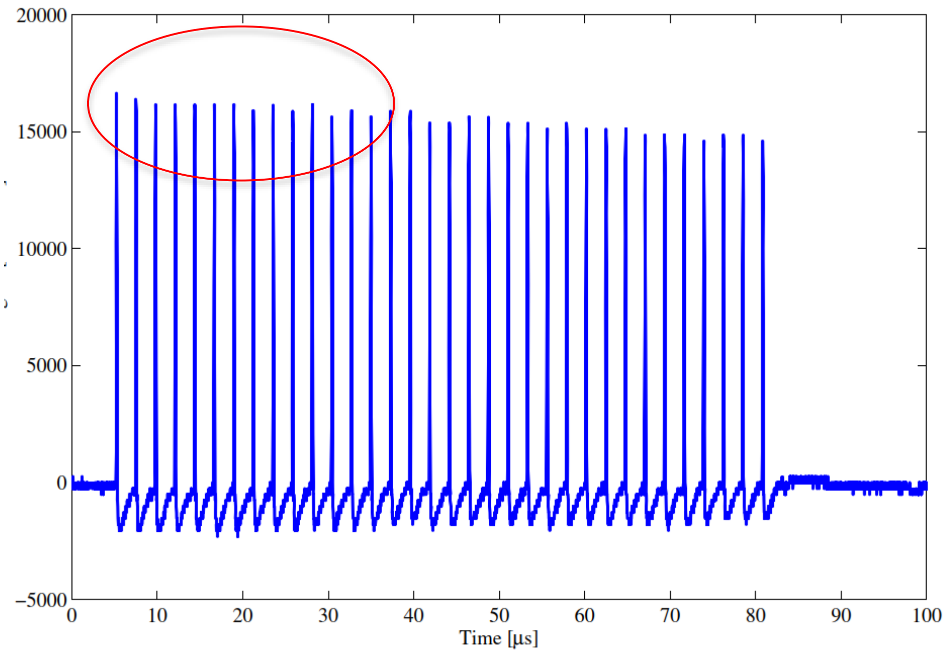
We consider the first 14 turns

- Losses present with RF OFF and ON for longer periods
- No reduction of bunch length observed (first and last turn) ➔ to be refined with tomo data from latest measurements
- To avoid start of filamentation

Measurements with RF OFF and Optics C

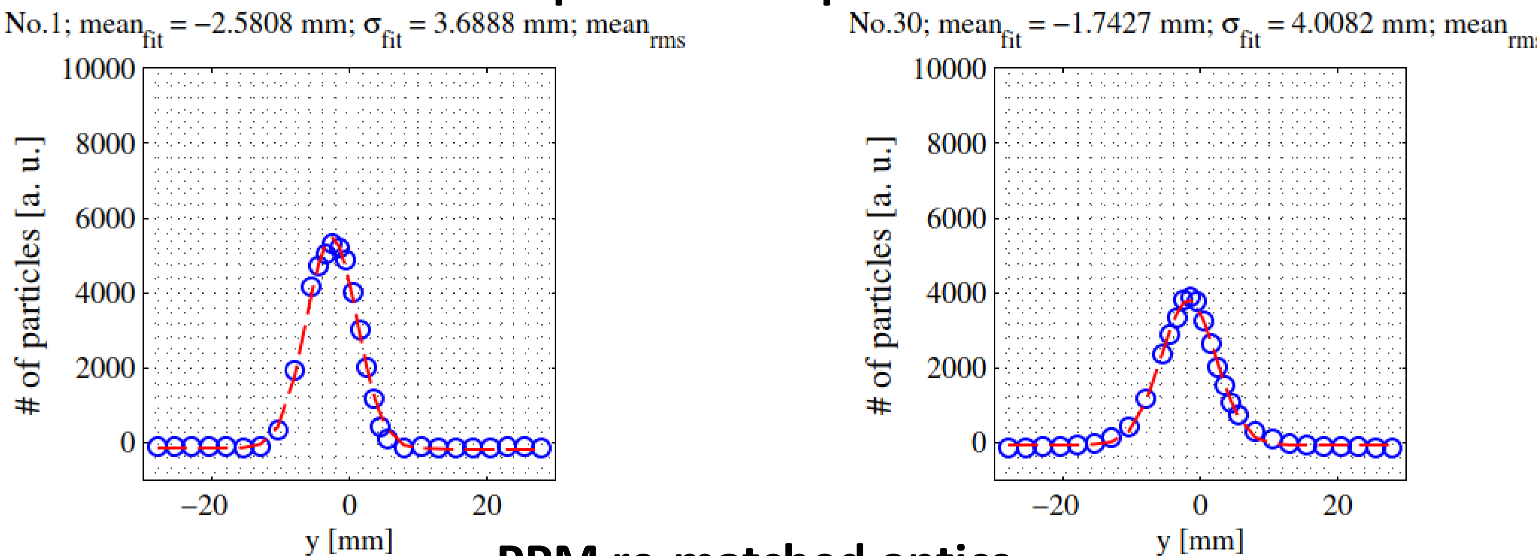


Measurements with RF OFF and Optics C

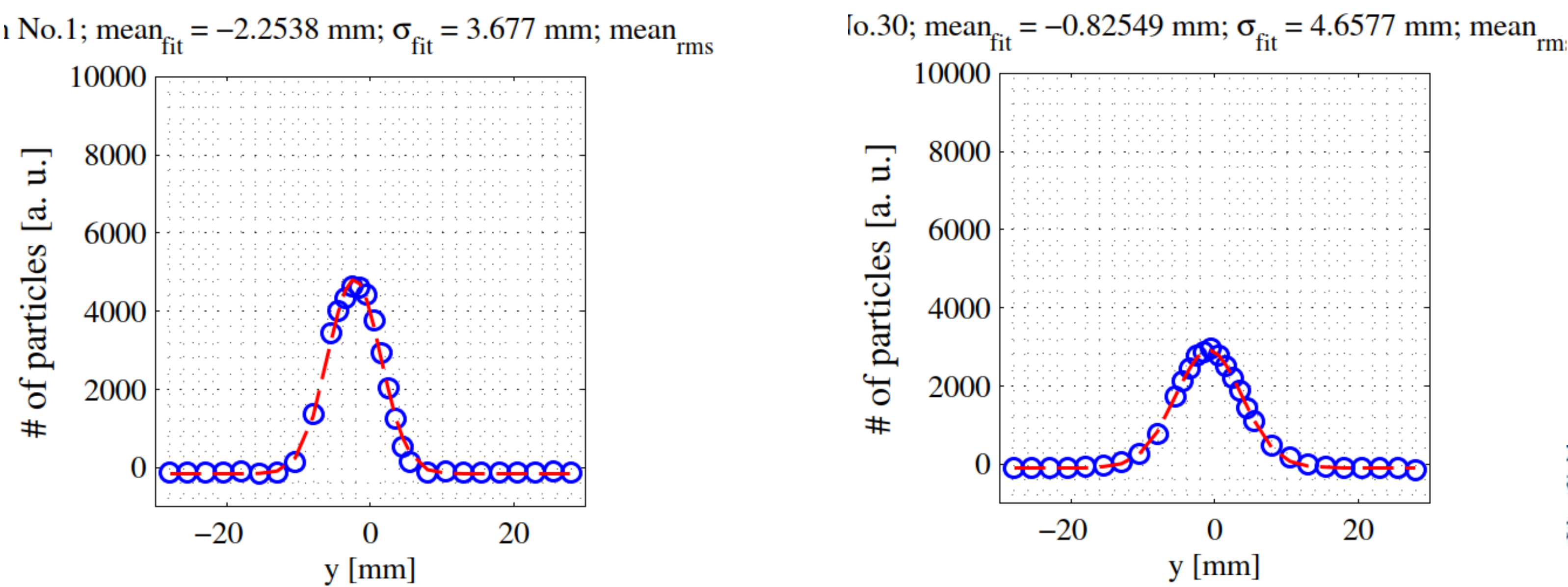


TbT horizontal profiles at SMG52

Operational optics

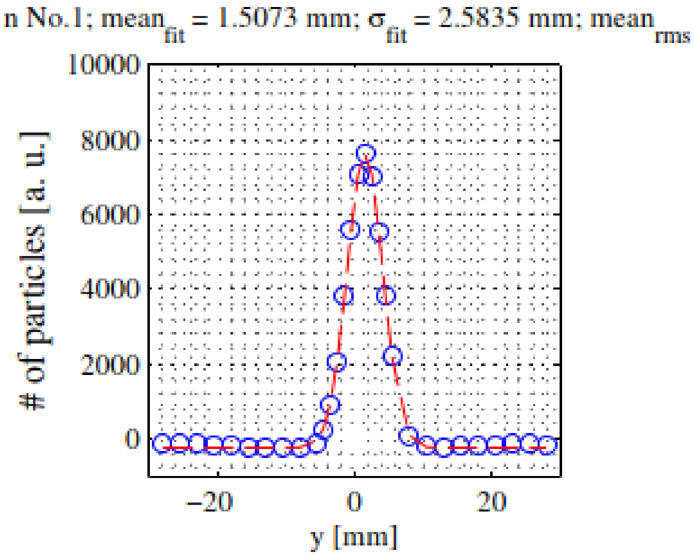


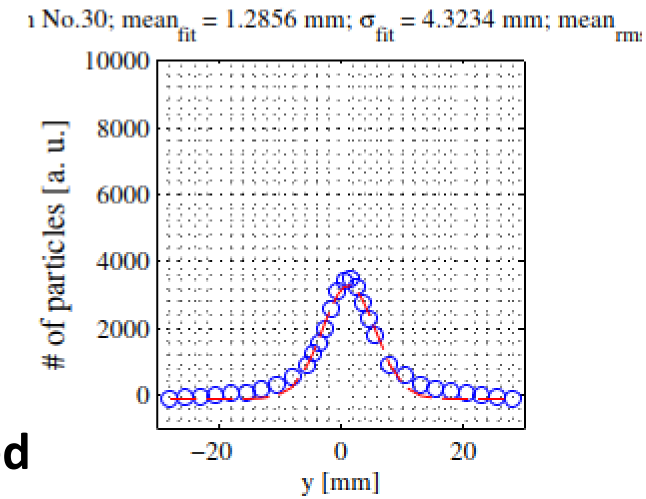
PPM re-matched optics



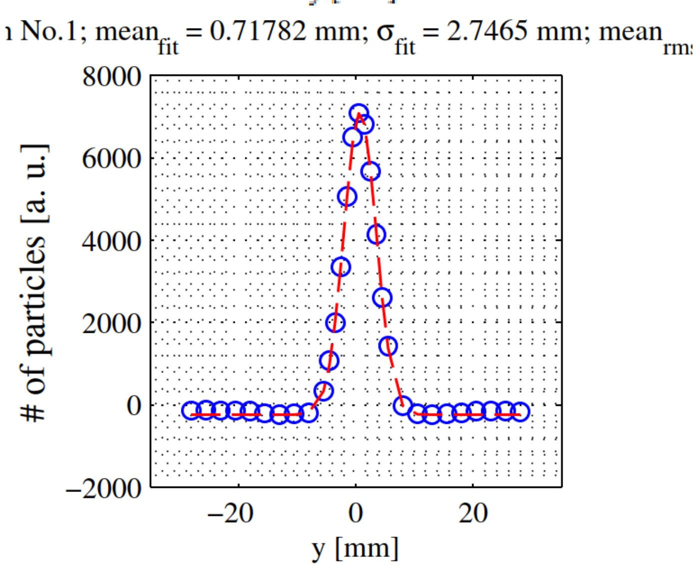
TbT vertical profiles at SMG52

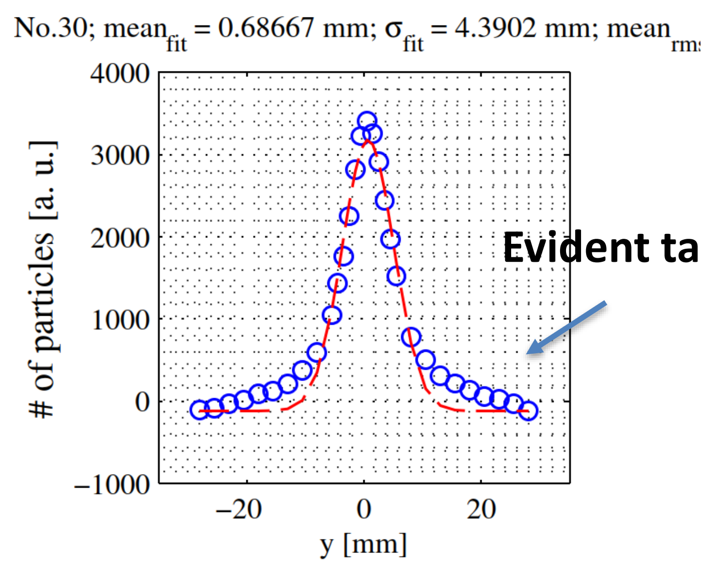
Operational optics





Re-matched



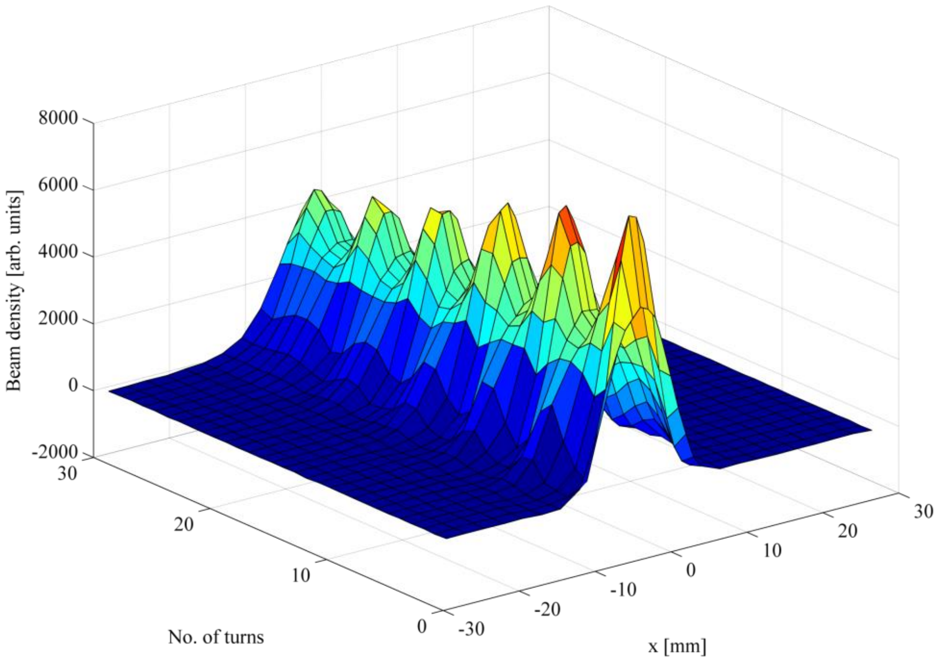


Evident tails

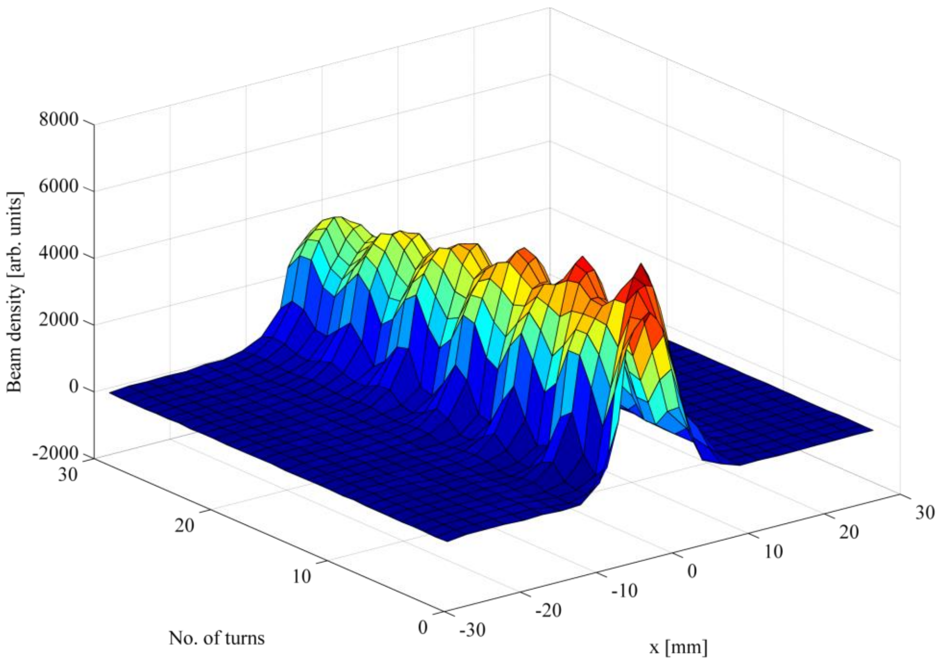
TbT vertical profiles at SMG52

- Example of evolution in time of beam profiles in both optics
  - **Beating of peaks (→ beam sizes in lossless regime)** is synonymous of **mismatch**:
    - (Already) visually larger beating for OP optics

OP optics

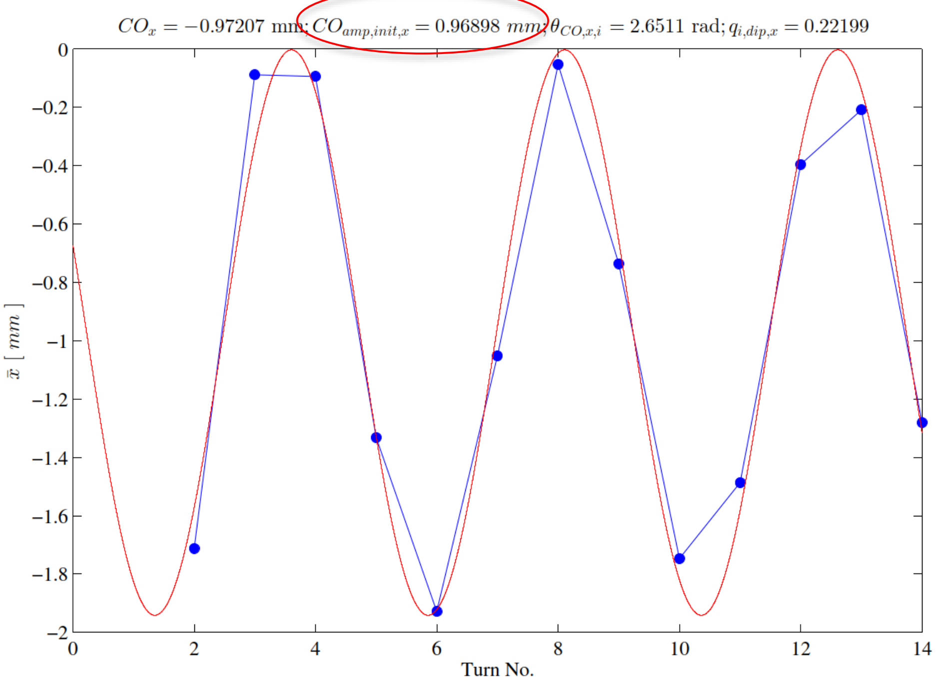


PPM-rematched optics

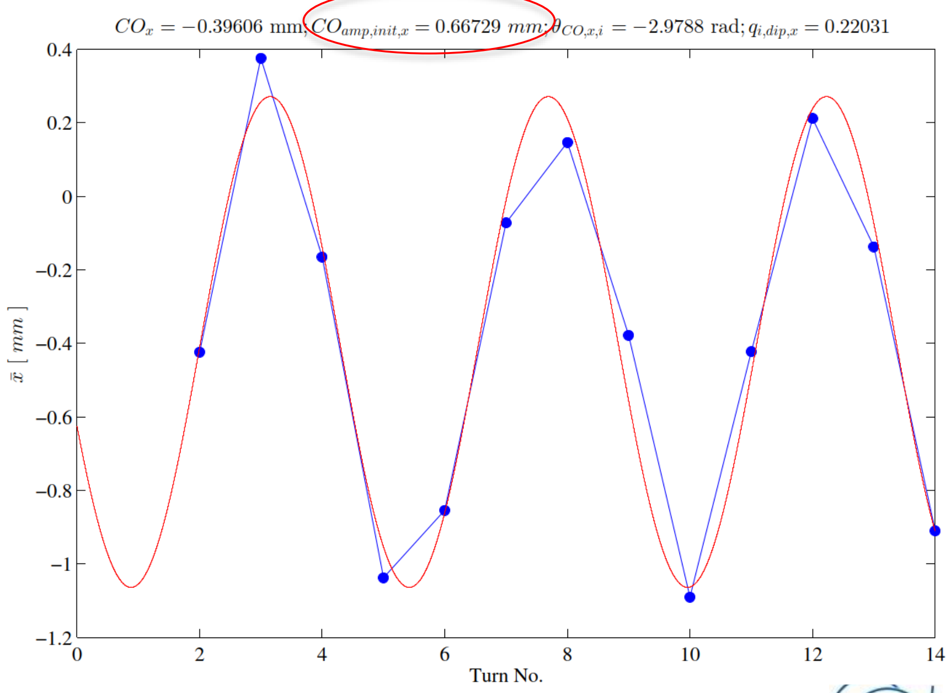


Injection oscillations

- **Important to correct to minimum modulations peak level**
  - On the TbT SEM-grid it is possible to derive injection oscillations and tune
    - Mean value of Gaussian fit
    - **0.5 mm (peak), which is an optimal OP value, would be already + 2% emittance growth in the horizontal plane for a BCMS-like beam**
    - **1 mm (peak) would be +8% emittance growth !!!**



Operational optics



PPM-rematched optics

Fit functions for turn-by-turn data

- **Method as in M. Benedikt, C. Carli *et al.*, *[here]()***

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH
ORGANISATION EUROPEENNE POUR LA RECHERCHE NUCLEAIRE

CERN - PS DIVISION

PS/ AE/ Note 2001-003 (MD)

STUDY OF A NEW PSB-PS TRANSFER LINE OPTICS WITH
IMPROVED DISPERSION MATCHING BY MEANS OF
TURN-BY-TURN BEAM PROFILE ACQUISITIONS

M. Benedikt, Ch. Carli, Ch. Dutriat, M. Giovannozzi, A. Jansson,
M. Martini, U. Raich and K. Schindl

Horizontal (x) and vertical (y) dispersion fitting functions

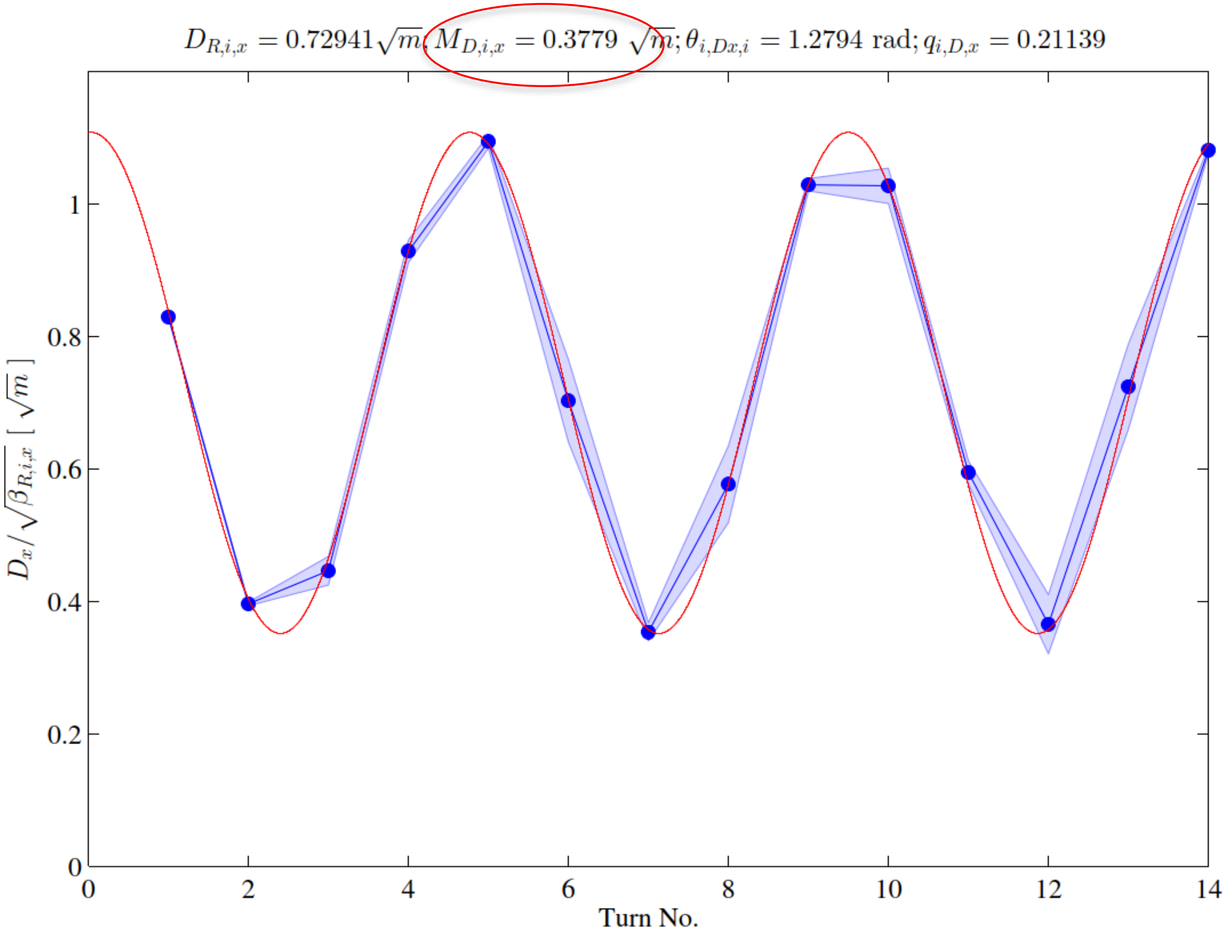
$$\frac{D_{n_{x,y}}}{\sqrt{\beta^{*}_{R,i,x,y}}} = \mathbf{d}_{\mathbf{R}_{\mathbf{i},\mathbf{x},\mathbf{y}}} + \mathbf{M}_{\mathbf{D}_{\mathbf{i},\mathbf{x},\mathbf{y}}} \cos[2\pi \mathbf{q}_{\mathbf{i},\mathbf{D},\mathbf{x},\mathbf{y}}(n-1) + \boldsymbol{\theta}_{\mathbf{i},\mathbf{D}_{\mathbf{x},\mathbf{y}}}]$$

Operational optics, RF OFF (6.21, 6.24) from beam position at SMG52

- **Dispersion is obtained by changing extraction frequency of the PSB and deriving Δp/p through slip factor from MadX PSB. Then every blue marker point is the slope of the linear correlation between position and Δp/p**

Related analytical $\Delta\varepsilon/\varepsilon_0$ = 13% (OP optics)

- **considering $\varepsilon_{0,norm}$=1 um and dp/p_{rms}=0.9e-3**

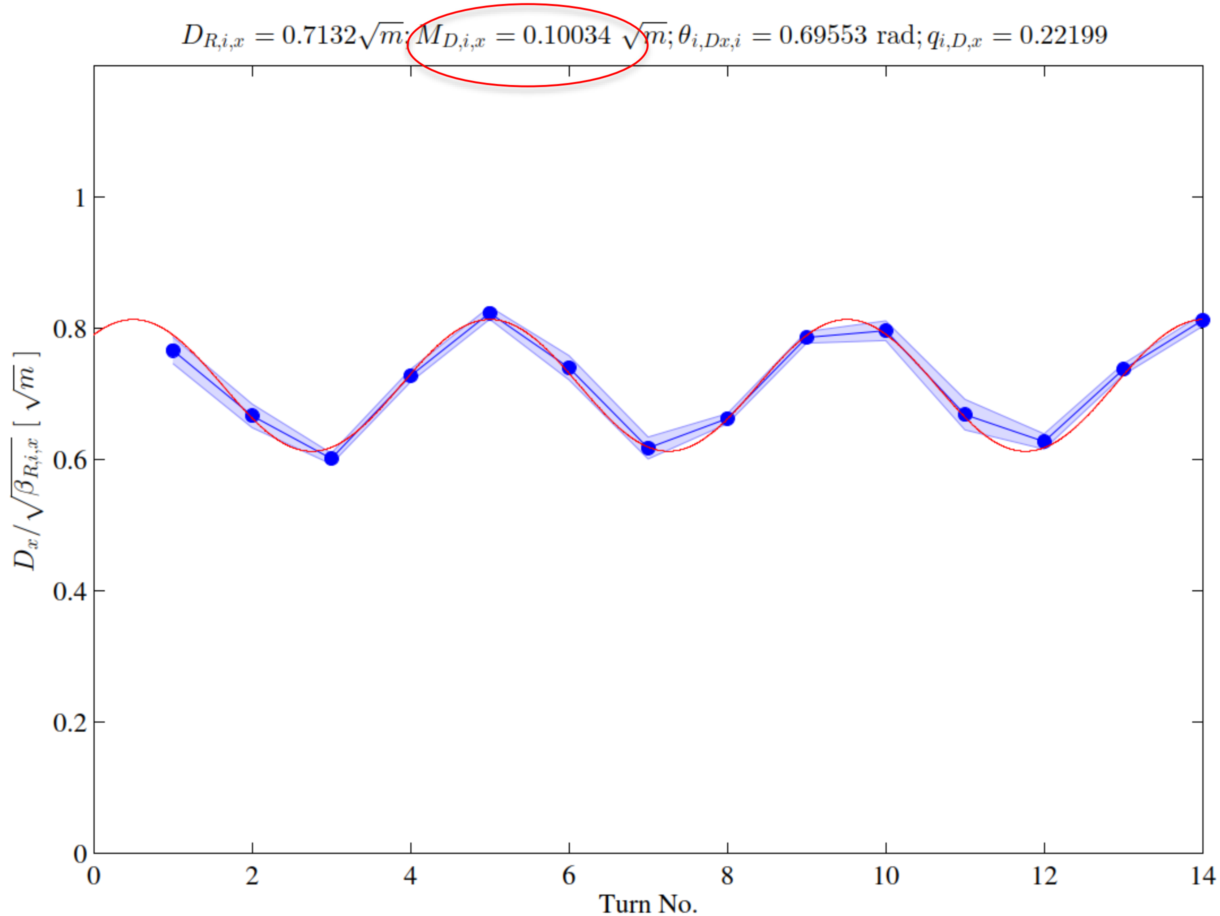


PPM-rematched optics, RF OFF (6.21, 6.24) from beam position at SMG52

- **Dispersion is obtained by changing extraction frequency of the PSB and deriving Δp/p through slip factor from MadX PSB. Then every blue marker point is the linear correlation between position and Δp/p**

Related analytical $\Delta\varepsilon/\varepsilon_0$ = 1% (PPM-rematched optics)

- **considering $\varepsilon_{0,norm}$=1 um and dp/p_{rms}=0.9e-3**



Constraints for total beam size fit parameters

- **Method as in M. Benedikt, C. Carli *et al.*, *here***

$$\frac{\sigma^2_{x,y}}{\beta_{R_{x,y}}} = \frac{\epsilon_{x,y,g}}{\pi}\frac{1}{2}\left\{\left(M_{g,x,y} + \frac{1}{M_{g,x,y}}\right) + \left(M_{g,x,y} - \frac{1}{M_{g,x,y}}\right)\cos[4\pi q_{x,y}(n-1) + 2\theta_{i,\beta_{x,y}}]\right\} +$$
$$+ \frac{\delta p}{p}^2_{rms}\{d_{R,x,y} + M_{D_{x,y}}\cos[2\pi q_{x,y}(n-1) + \theta_{i,D_{x,y}}]\}^2 +$$
$$+\beta_{R_{x,y}}(\Delta x, y)'^2\left[\frac{n-\frac{1}{2}}{2} - \frac{\sin[2\pi q_{x,y}(2n-1)]}{4\sin(2\pi q_{x,y})}\right]$$

Boundaries of fit parameters are derived from systematic errors assumptions

$0 \leq \epsilon_{x,y,g,0} \leq \infty$

* *where* $\beta^*_{R,x,y,i}$=12.05 (21.71) m (from Injection 7 optics)

$1 \leq M_{g,x,y} < \infty$

$M_{rms} = 0.5(M_{g,t} + \frac{1}{M_{g,t}})$

$0 \leq q_{x,y} \leq q_{i,D,x,y}$

$-\infty \leq \theta_{i,D_{x,y}} < \infty$

$-\infty \leq \theta_{i,\beta_{x,y}} < \infty$

$0.93 \cdot \frac{\delta p}{p}^*_{i,rms} \leq \frac{\delta p}{p}_{rms} \leq 1.07 \cdot \frac{\delta p}{p}^*_{i,rms}$

* *where* $\cdot \frac{\delta p}{p}_{i,rms} = 0.902 \times 10^{-3}$ (from R3 recent brightness measurements, see Appendix)

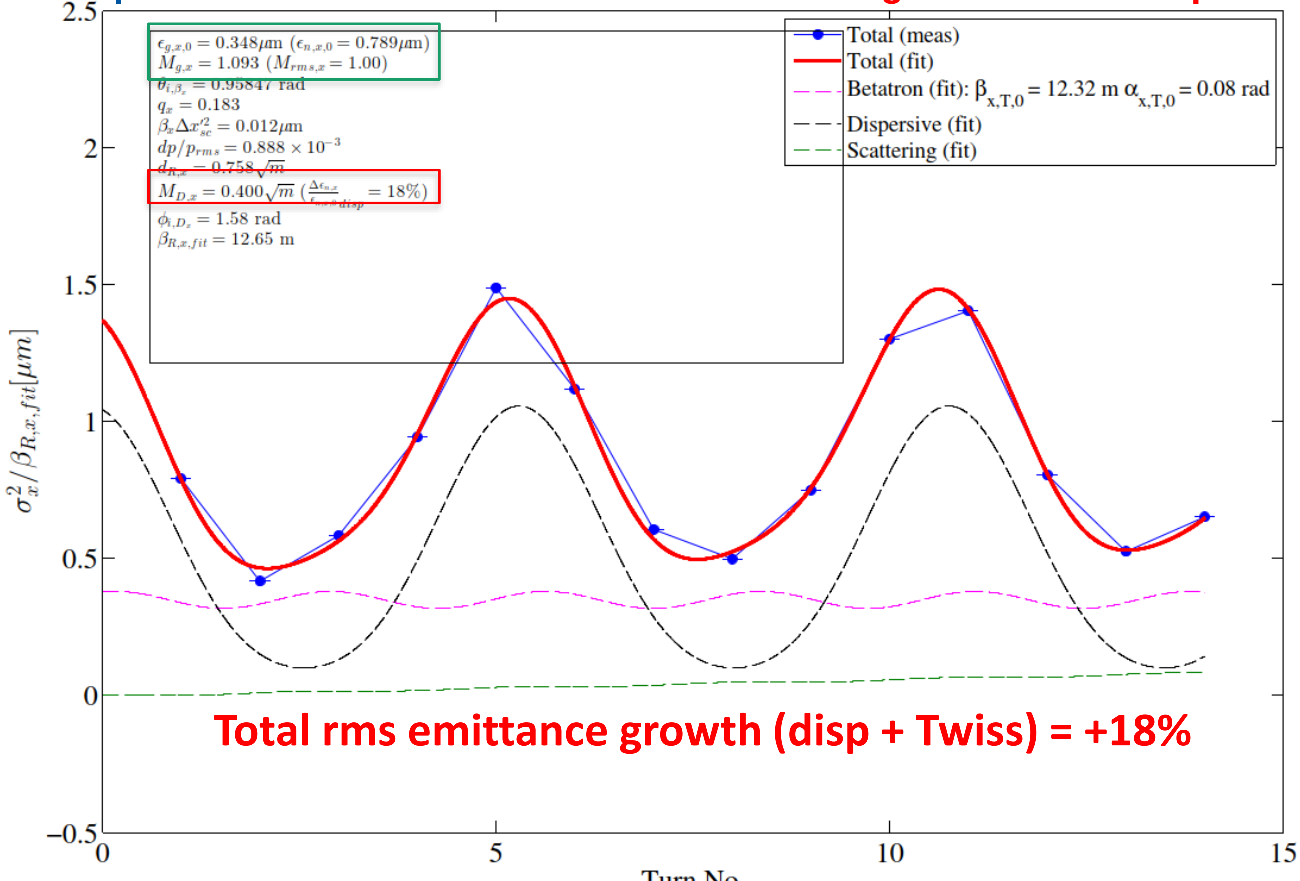
$0.95 \cdot M_{D_{i,x,y}} \leq M_{D_{x,y}} \leq 1.05 \cdot M_{D_{i,x,y}}$

$0.95 \cdot d_{R_{i,x,y}} \leq d_{R_{x,y}} \leq 1.05 \cdot d_{R_{i,x,y}}$

$0.95 \cdot \beta^*_{R,i,x,y} \leq \beta_{R_{x,y}} \leq 1.05 \cdot \beta^*_{R,i,x,y}$

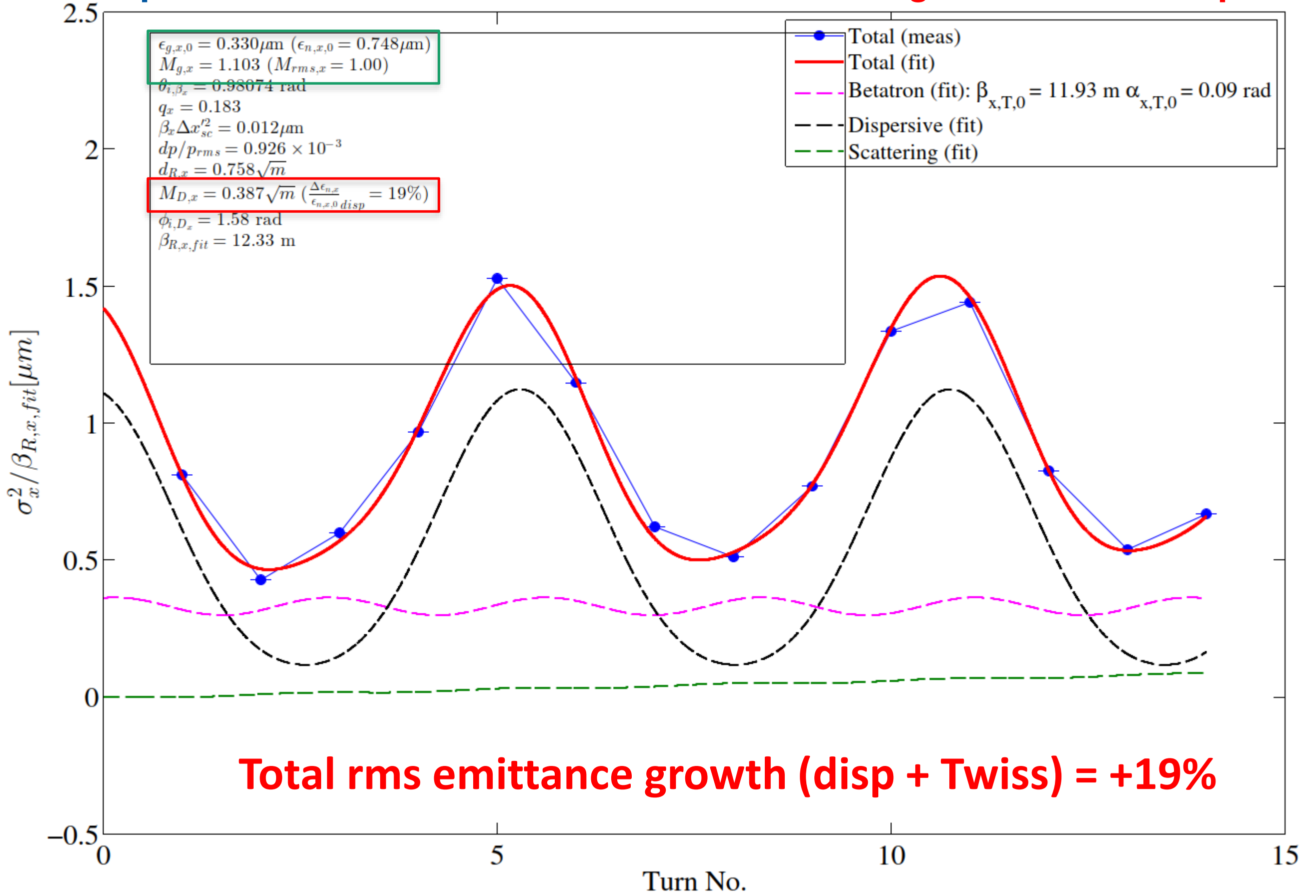
Operational optics, RF OFF (6.21, 6.24) : beam size

- **All parameters are free apart dp/p_{rms} which was imposed = 0.888 e-3 to be equal to WS measurements**
  - $\varepsilon_{x,n,0}$=0.789 um (intensity for this shot was ~68e10 ppb) ➔ **Bx ~ 62 e10 p/um**
- **Betatron mismatch is extremely small M_g =1.09 ➔ M_{rms} ~ 1.0 ➔ $\varepsilon_{after\ filamentation}=M_{rms}\varepsilon_0$**
- **Beam size is dispersion-dominated ➔ Estimated emittance growth due to dispersion is +18%**



Operational optics, RF OFF (6.21, 6.24) : beam size

- **With free dp/p_{rms} ➔ $\varepsilon_{x,n,0}$=0.748 um <u>(because fitted dp/p_{rms}= 0.926 e-3 !!!)</u>**
  - Intensity for this shot was 64e10 ppb ➔ **<u>Bx ~ 85.56 e10 p/um</u>**
- **Betatron mismatch is extremely small M_g =1.1 ➔ M_{rms} ~ 1.00 ➔ $\varepsilon_{after\ filamentation}=M_{rms}\varepsilon_0$**
- **Beam size is dispersion-dominated ➔ Estimated emittance growth due to dispersion is +19%**

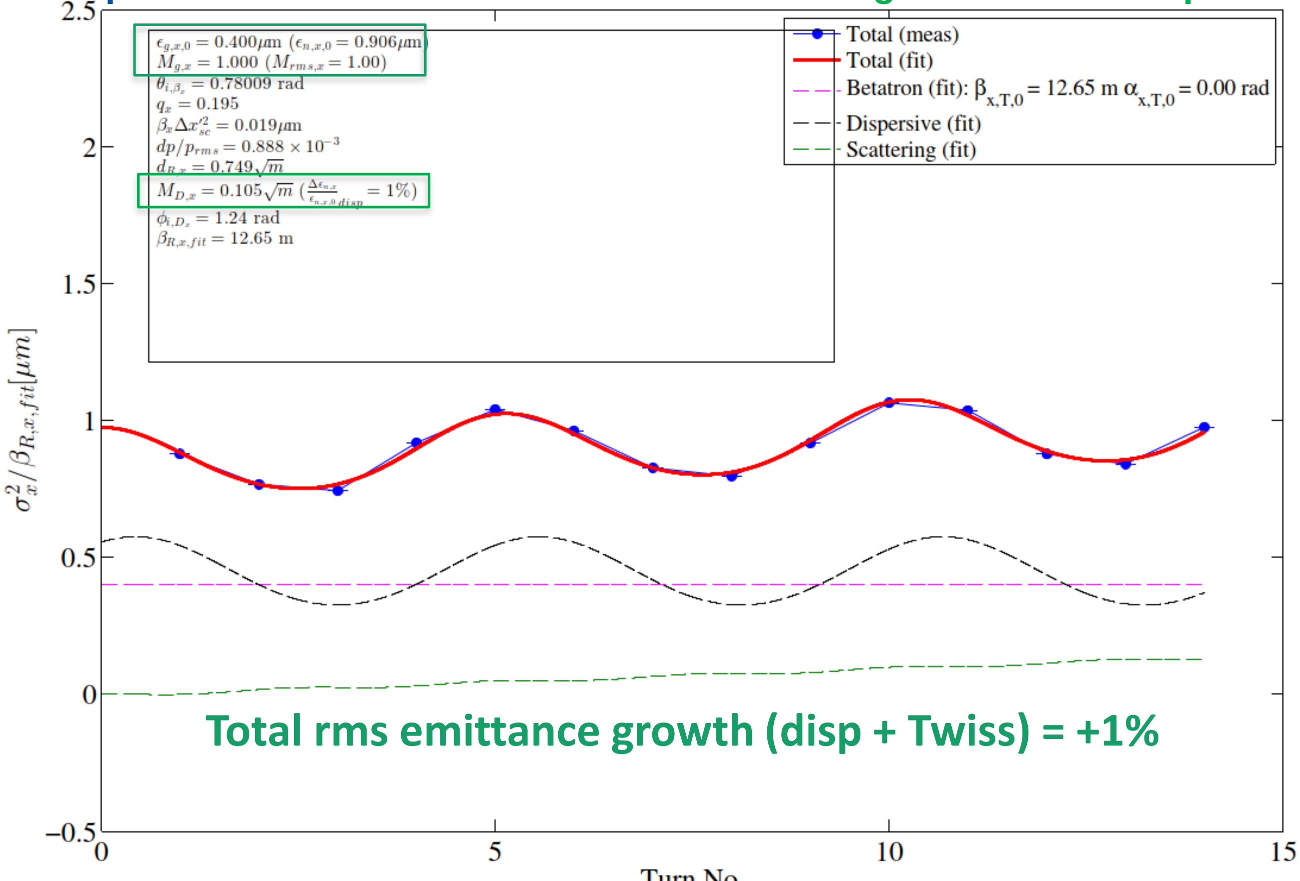


PPM-rematched optics, RF OFF (6.21, 6.24) : beam size

- **All parameters are free apart dp/p_{rms} which was imposed = 0.888 e-3 to be equal to WS measurements**
  - $\varepsilon_{x,n,0}$=0.906 um (intensity was 62.8e10 ppb) ➔ **Bx ~ 69e10 p/um**

- **Betatron mismatch is extremely small M_g =1.0 ➔ M_{rms} ~ 1.0 ➔ $\varepsilon_{after\ filamentation}=M_{rms}\varepsilon_0$**

- **Beam size is dispersion-dominated ➔ Estimated emittance growth due to dispersion is +1%**

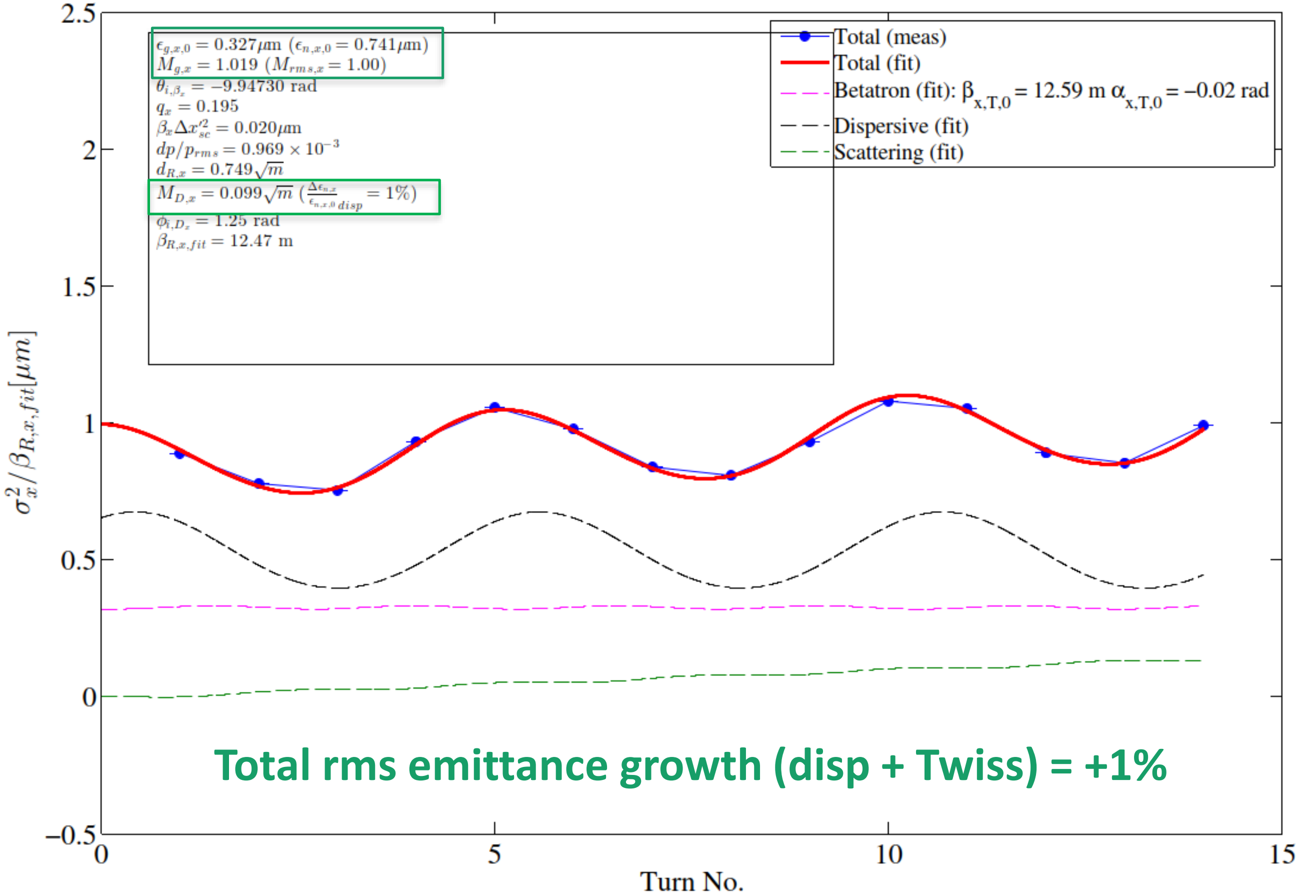


PPM-rematched optics, RF OFF (6.21, 6.24) : beam size

- **With free dp/p_{rms} ➔ $\varepsilon_{x,n,0}$=0.8 um , but for fitted dp/p_{rms}= 0.969 e-3 !!!**
  - $\varepsilon_{x,n,0}$=0.741 um (intensity was 62.8e10 ppb) ➔ **Bx ~ 84.75e10 p/um**

- **Betatron mismatch is extremely small M_g =1.019 ➔ M_{rms} ~ 1.00**

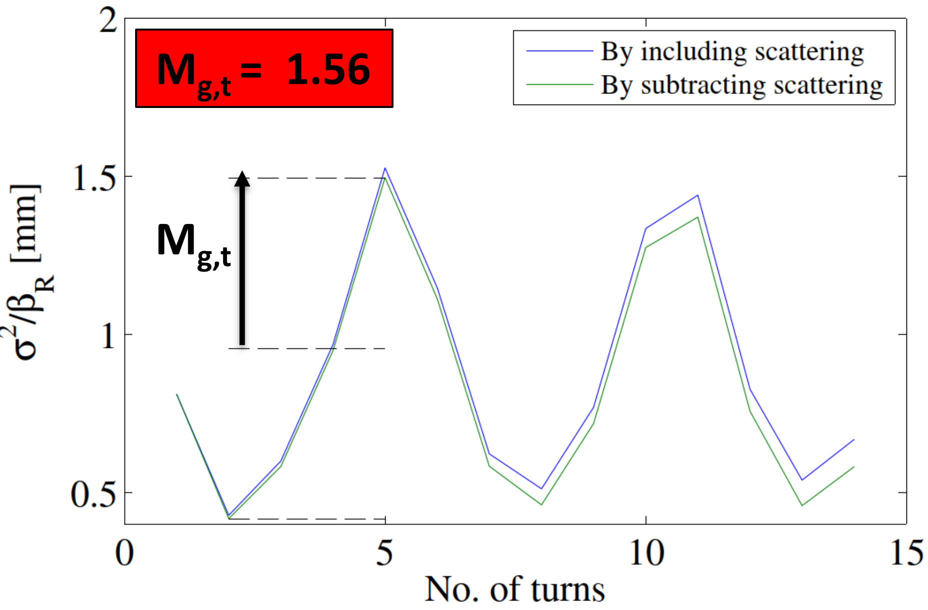
- **Beam size is dispersion-dominated ➔ Estimated emittance growth due to dispersion is +1%**



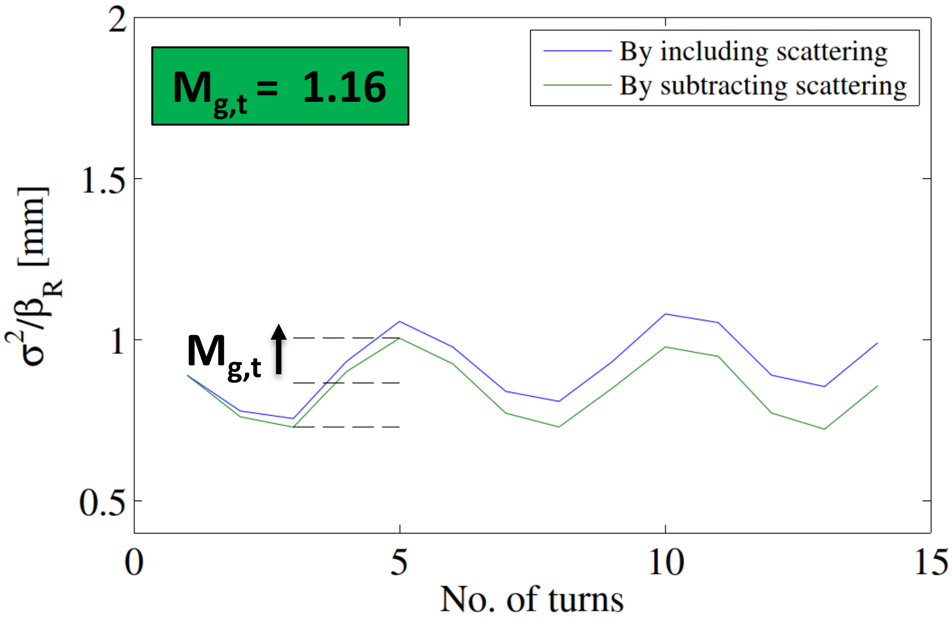
M_g from total beam size (squared) – RF OFF

- **Approximation (to be followed up analytically) of global mismatch ($M_{g,t}$) on modulation of total beam size (betatron + dispersion) in first 5 turns**
  - by subtracting scattering from fit
- **Almost factor 4 reduction in σ^2 beating**

Operational optics

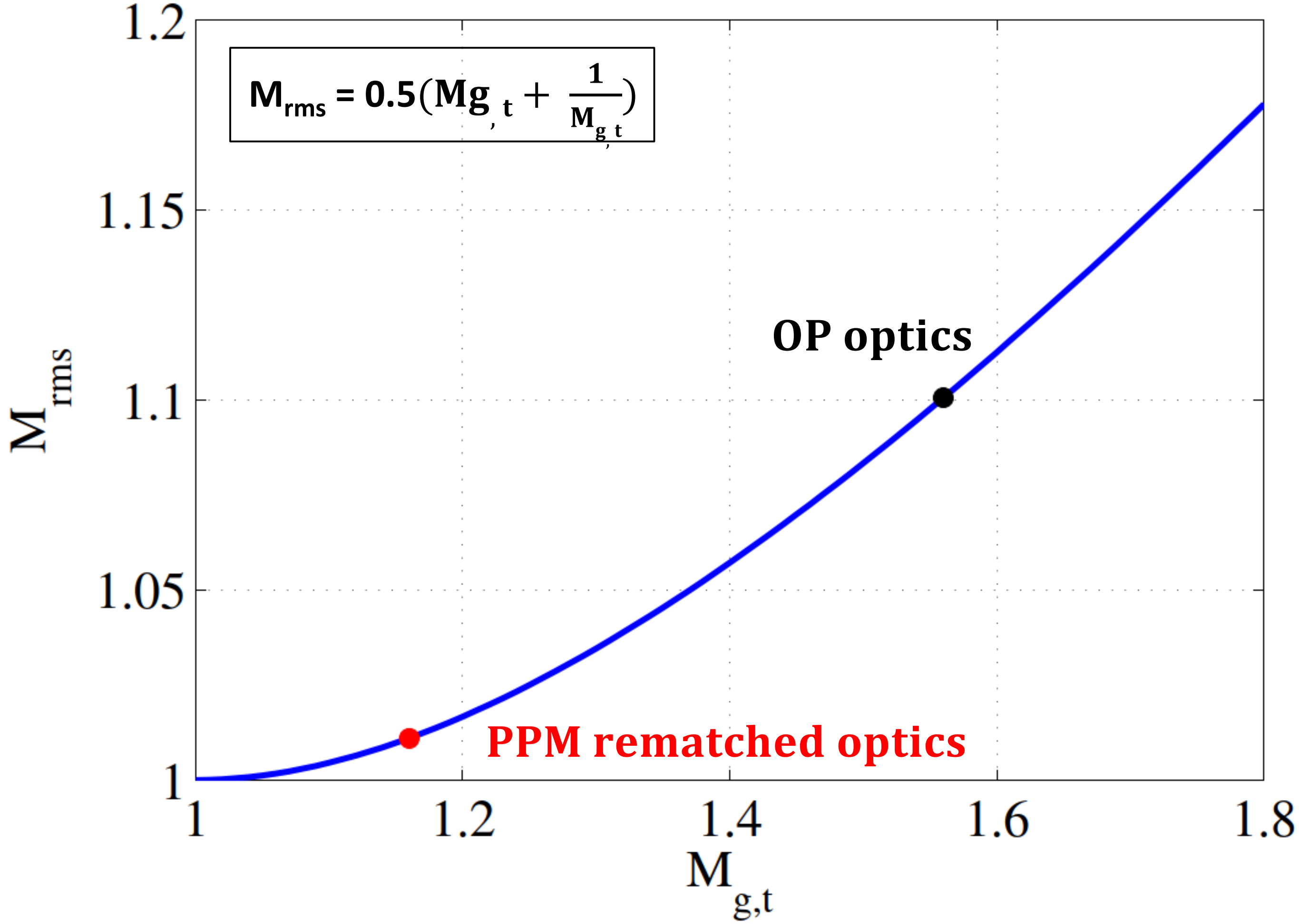


PPM-rematched optics



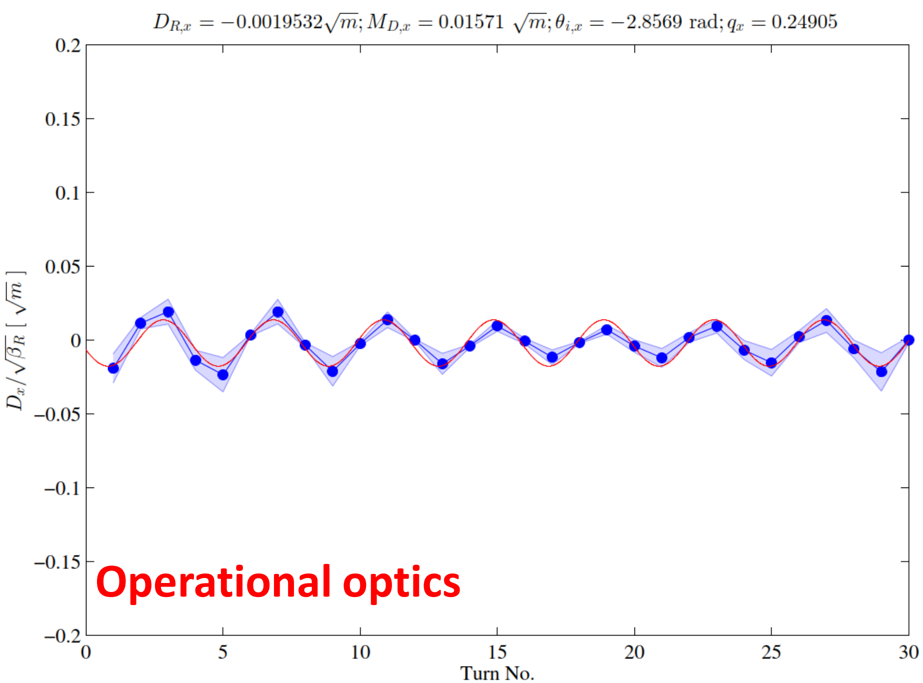
M_{rms} from $M_{g,t}$ (approximation from total beam size squared)

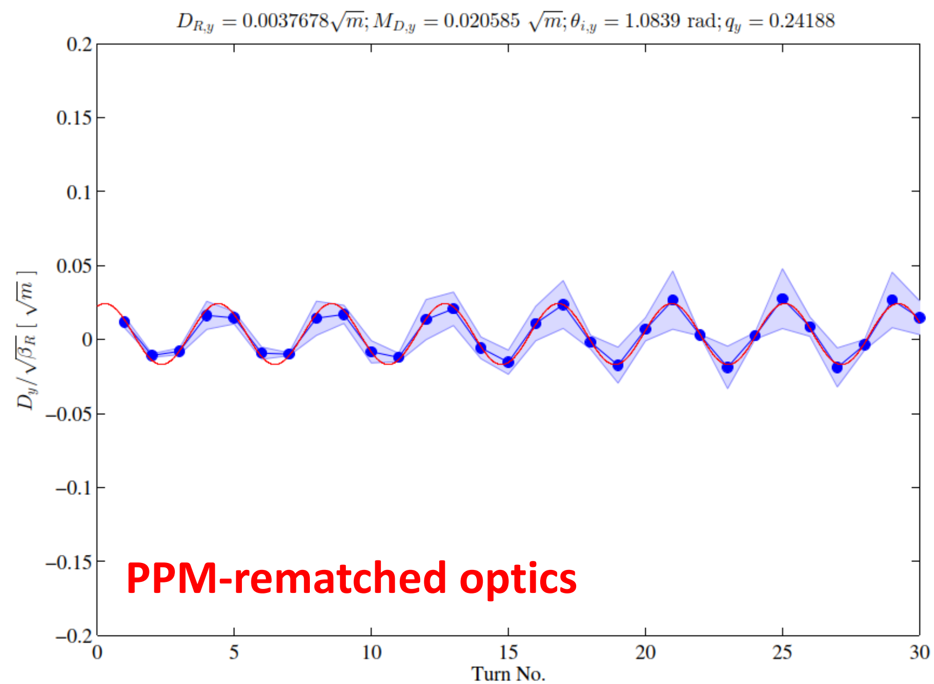
- RMS emittance growth $\mathbf{M_{rms}}$ for different $\mathbf{M_{g,t}}$ (from total beam size squared)
  - $\varepsilon_{after\ filamentation} = M_{rms}\varepsilon_0$



Vertical dispersion vs. turns

- **RF OFF:**
  - **Negligible contribution: $M_{DR,y} = 0.02\ \sqrt{m}$****
    - **Fully consistent with dispersion from BPMs (see Appendix)**
    - **Related analytical $\Delta\varepsilon/\varepsilon_0 = 0\%$**

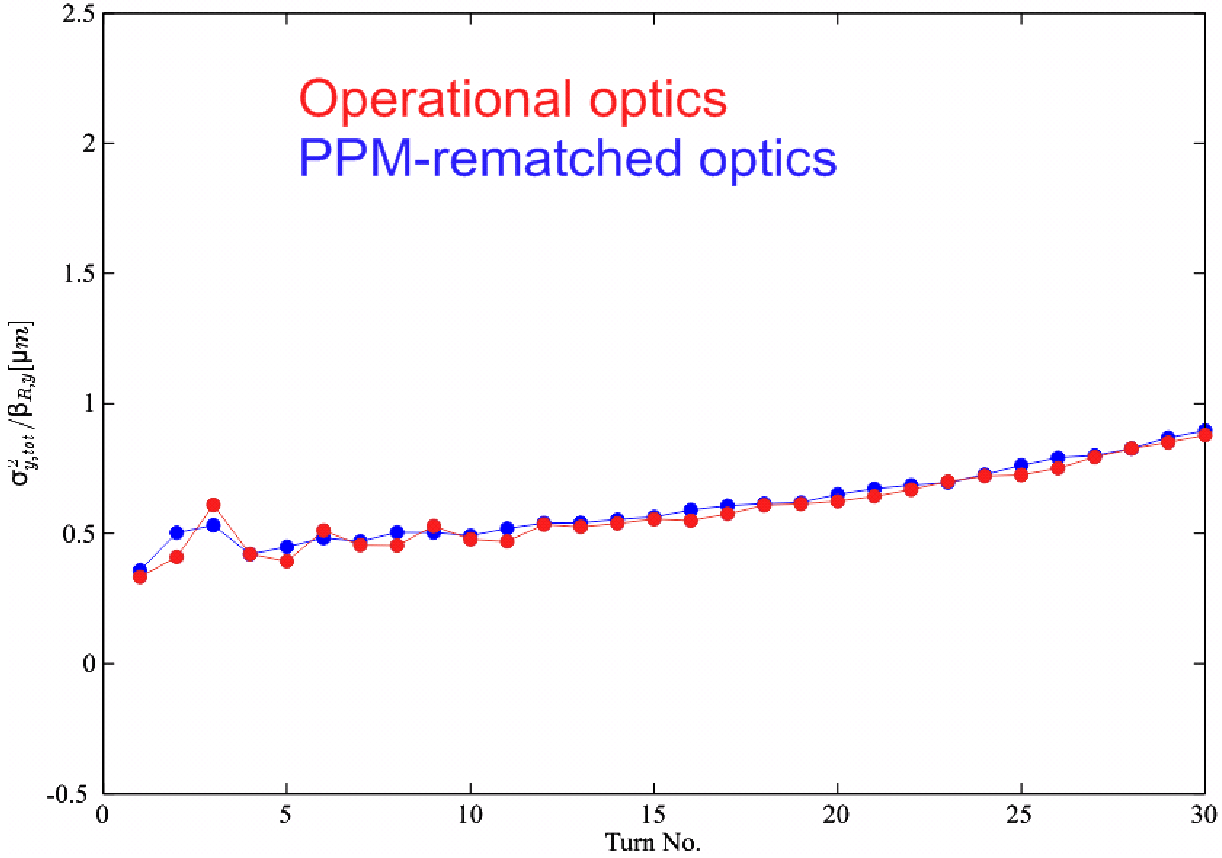




**$\beta_{R,y}$ = 21.71 m at SMG52 (From "Injection 7" optics)

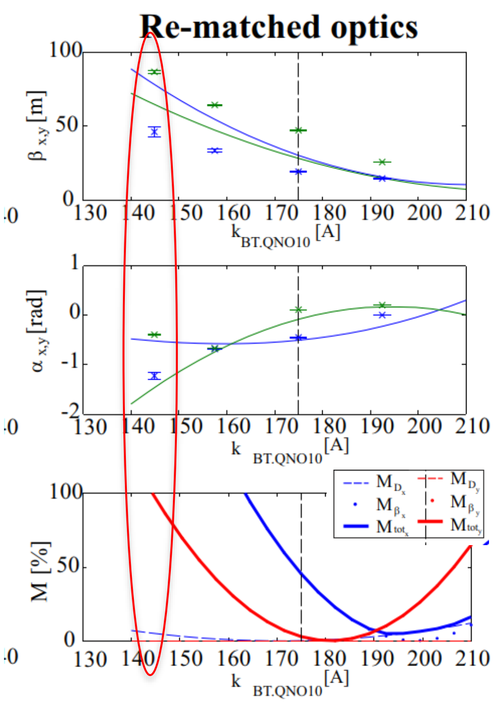
Vertical beam size vs. turns

- **RF OFF:**
  - **PPM-rematched optics qualitatively reduces beating**
  - **Modulation fits were not fully convincing due to leak of modulation**
    - **Analysis to be completed for measurements far from Qy=6.25**
  - **Scattering slope in the same order of horizontal plane**

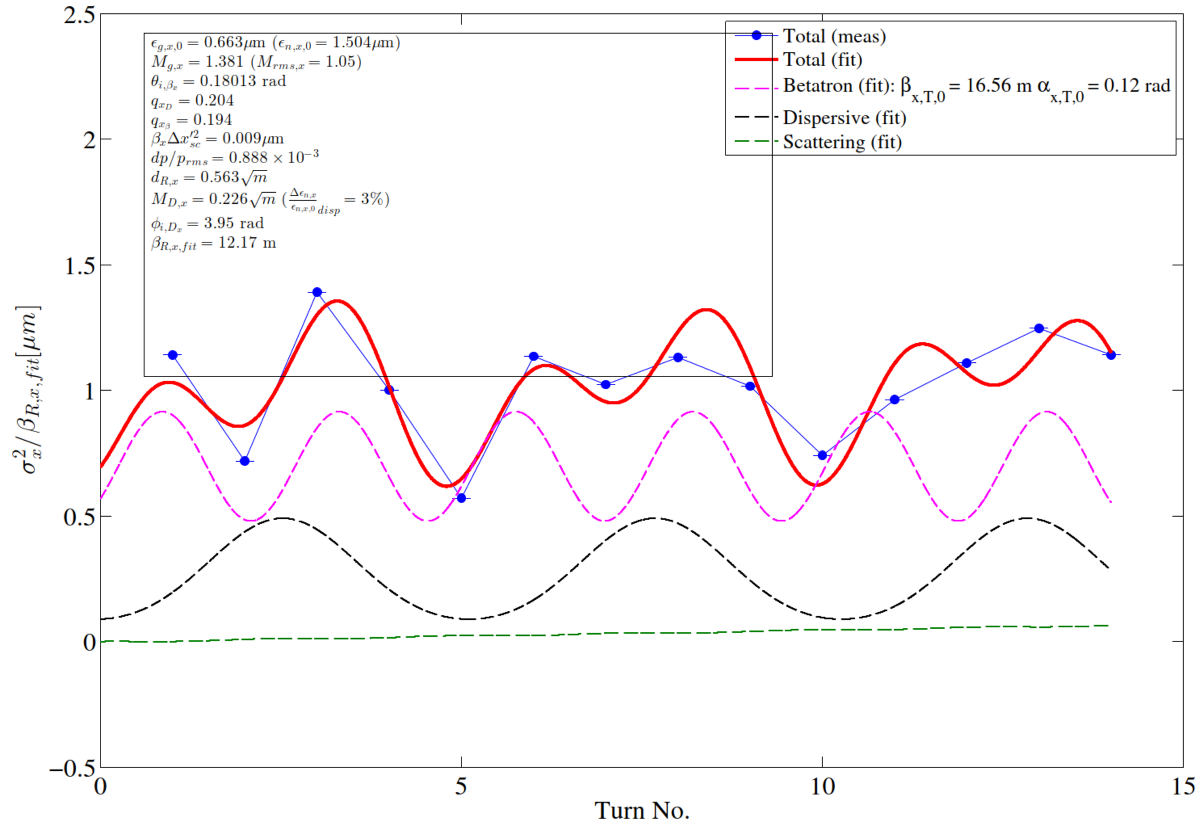


Preliminary: a mismatched case - PPM-rematched optics and BT.QNO10 at 150 A

- **Horizontal betatron amplitude increases but not as expected (M_g =1.38 instead of ~2.5)**
  - Fit more complicated and not optimal (large residuals)
    - ➔Tuning of fit to be followed up
  - Tune (6.21,6.33)



HB2018 –WEP2P006



SEM grid Coulomb scattering

Theoretical multiple scattering through small angles [1]:

- d_{wire} = 40 μm
- Radiation length X_0= 0.35 cm (Tungsten)
- Wire spacing 1 mm (in [-6,6] mm) and 2.5 mm (in [-28.5,-6] and [6, 28.5] mm)

$$\theta_0 = \frac{13.6\ \mathrm{MeV}}{\beta c p} \cdot z \cdot \sqrt{\frac{d_{\mathrm{wire}} \cdot \frac{\pi}{4}}{X_0}} \cdot \left[1 + 0.038 \cdot \ln\left(\frac{d_{\mathrm{wire}} \cdot \frac{\pi}{4}}{X_0}\right)\right] =$$

$$\frac{13.6}{2127 \cdot 0.9160} \cdot 1 \cdot \sqrt{\frac{40 \times 10^{-4} \cdot \frac{\pi}{4}}{0.35}} \left[1 + 0.038 \cdot \ln\left(\frac{40 \times 10^{-4} \cdot \frac{\pi}{4}}{0.35}\right)\right] = 0.5\ \mathrm{mrad}$$

$$\beta_x \theta_0^2 = 12.05 \cdot 0.5^2 \cdot \text{fill factor} = 0.03 \div 0.09\ \mu\mathrm{m}$$

$$\beta_y \theta_0^2 = 21.71 \cdot 0.5^2 \cdot \text{fill factor} = 0.05 \div 0.16\ \mu\mathrm{m}$$

where

$$\text{fill factor} = \frac{d_{\mathrm{wire}}}{\text{wire spacing}} \cdot \frac{\pi}{4} = \frac{40 \times 10^{-6}}{1(2.5) \times 10^{-3}} \cdot \frac{\pi}{4} = 0.01 \div 0.03$$

- **Order of magnitude is consistent with TbT fits ($\beta\theta^2$~0.02-0.03 um)**

[1] Formula (33.14) in C. *Patrignani et al. (Particle Data Group), Chin. Phys. C, 40, 100001 (2016)*

Conclusions

- **TbT SEMgrids profiles were obtained and analyzed**
  - Signal-to-noise of measured profile was very satisfying (**thanks BI !)**
  - Profiles were reasonably Gaussian
    - some tails arise in the vertical ones after 30 turns q_y=0.25?
  - Analysis to be completed and refined

- **First order methods (with BPMs) used to evaluate dispersion**
  - Operational and PPM-rematched optics reflected results already presented in the past (2017 MD with three screens, HB2018)
    - 1-2 % emittance growth in PPM re-matched optics and ~15% emittance growth in OP optics due to dispersive mismatch)

  - Minimum emittance growth due to injection oscillations difficult to bring below 2%
    - Due to correction of injection oscillation typically at 0.5 mm peak amplitude level

  - Correlation of injection oscillation with Δp/p could be used to approximate energy mismatch
    - Energy mismatch must be below ~1e-4 to give emittance growth in the order of 1% ➔ Always check before measurements!

Conclusions

- **Fitting method proposed by M. Benedikt and C. Carli in the past was applied to evaluate also betatron matching (uncertain to date)**
  - Dispersion value and mismatch consistent with BPM results
  - Operational and PPM-rematched optics validated ➔ **mismatch dominated by dispersion**

$\Delta\varepsilon/\varepsilon_0$	Inj osc	$Disp_x$	$Twiss_x$
Op optics	2%	15-18%	0%
PPM-rematched optics	2%	1÷2%	0%

@ PS inj. point	$M_{\beta x}$ [%]	$M_{\beta y}$ [%]	M_{Dx} [%]	M_{Dy} [%]	$M_{tot,x}$ [%]	$M_{tot,y}$ [%]
Operational optics	6	6	15	2	16	6
Rematched optics*	3	3	2	0	4	3

3-screens (HB2018)

  - Vertical matching was qualitatively improved
    - Need to change working point for a better fit of mismatch parameters
    - However in the vertical plane we do not see emittance growth typically…
  - M_{rms} could be approximated from total geometrical mismatch M_g
    - Values of $M_{rms,x}$ =~10% (OP optics) and $M_{rms,x}$=1÷2% (PPM-rematched optics)

- **Estimation of brightness strictly depend on systematics! Thus…**
  - **We wait for comparison in systematic brightness measurements from ABP performed on both optics** for BCMS 0.9 eVs and **especially for BCMS 1.5 eVs, where dp/p_{rms}~1.5e-3 (➔ emittance growth due to dispersion is ~3 times larger!) and transverse space charge is reduced**

Next steps

- **Complete analysis**
  - Vertical matching
  - Horizontal betatron mismatch ➔ why so lower than expected?
  - Analytical evaluation of global mismatch $\mathbf{M_{g,t}}$
  - Evaluation of beam size using different strategies (e.g. statistical rms)
  - Comparison of residual injection oscillations with BPMs ($\Delta p/p=0$)
- **Analysis of bunch lengthening through tomoscope data on-going**
  - Could correlate rms bunch length to rms momentum spread

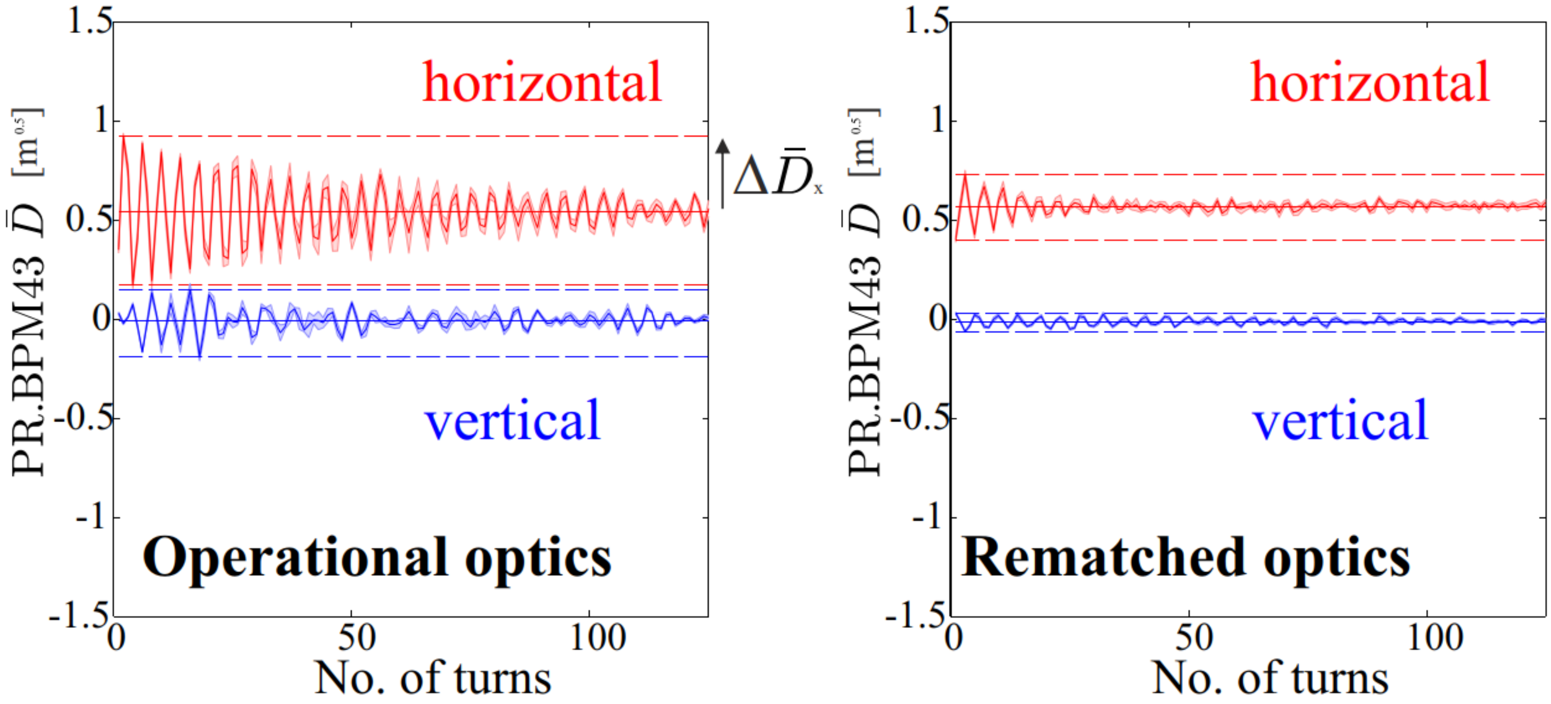
Thanks

Appendix

TbT dispersion from BPMs

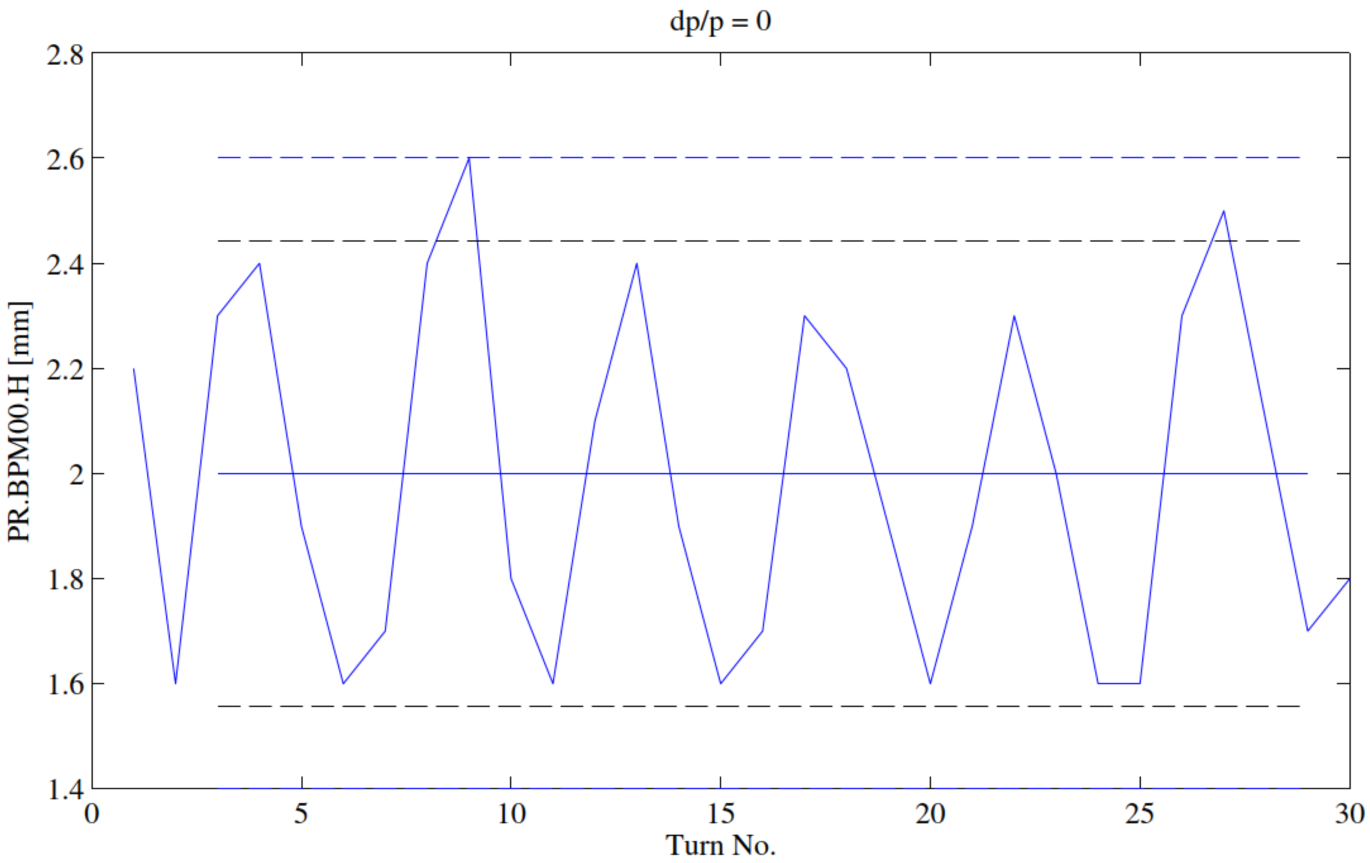
OVERVIEW OF THE CERN PSB-TO-PS TRANSFER LINE OPTICS MATCHING STUDIES IN VIEW OF THE LHC INJECTORS UPGRADE PROJECT

V. Forte*, S. Albright, W. Bartmann, G.P. Di Giovanni, M. A. Fraser, C. Hessler, A. Huschauer, A. Oeftiger - CERN (Geneva, Switzerland)



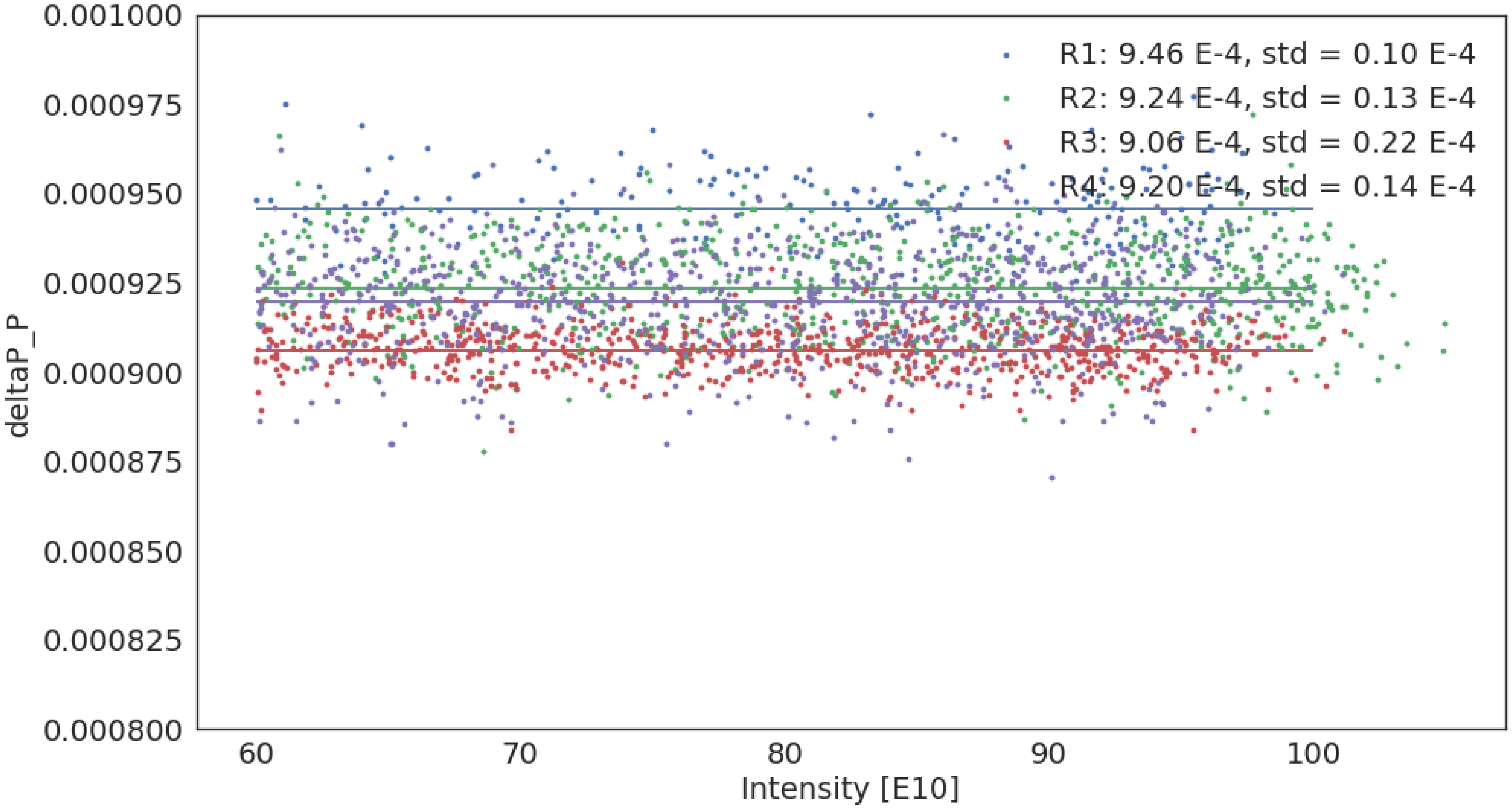
PPM-rematched optics (dispersion from first order moment)

- **PPM-rematched optics (RF OFF)**



PSB extracted dp-p_{rms}

- **dp/p_{rms} from tomoscope during BCMS OP brightness scans (courtesy F. Antoniou)**



PSB extracted dp-p$_{rms}$

- **Extracted from M. Fraser - LIU Beam Performance Meeting, 5th July 2018**

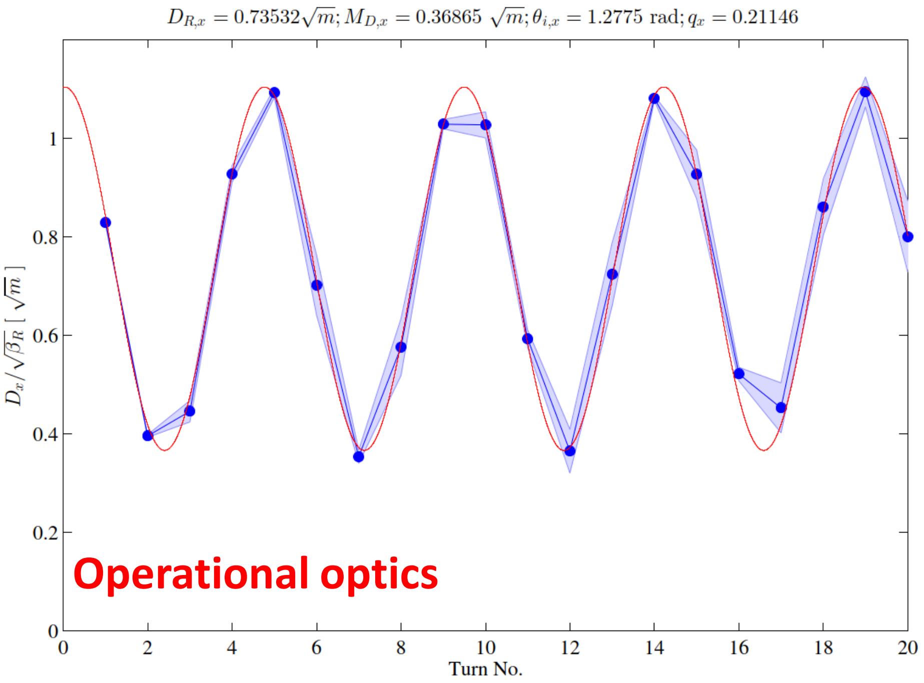
Emittance measurements: systematic errors

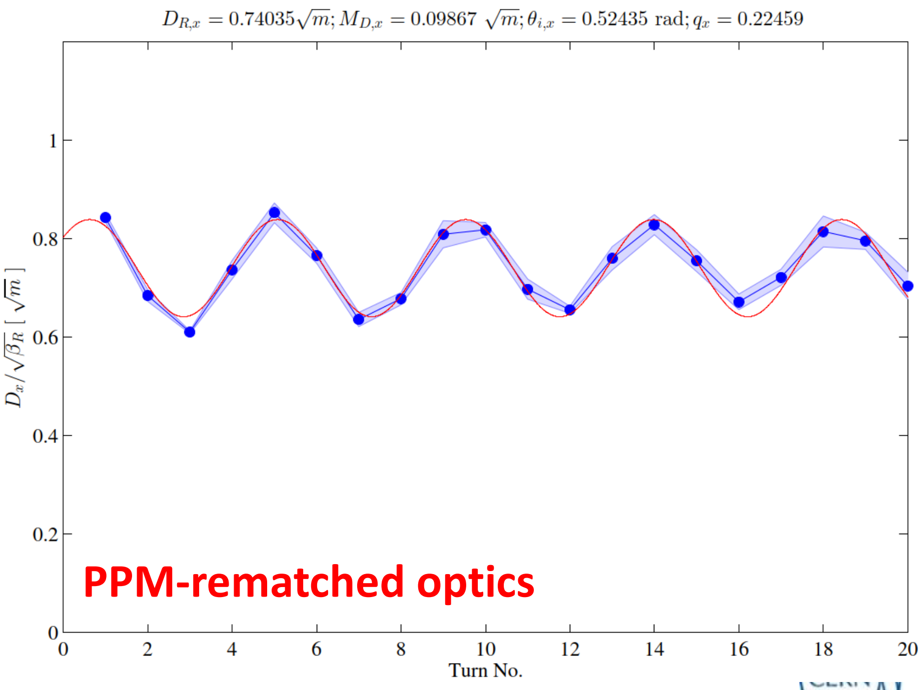
- **Summary of systematic error sources, selected topics discussed to be discussed in more detail:**
  - Absolute accuracy of emittance measurements with different devices, in different machines is hard to deduced
  - Up to 25% systematic error on the accuracy would not be unreasonable to quote

Error	Estimated Magnitude [%]	Error on Emittance [%]	Measurable / Correctable?	Comments
Optical functions (β, D)	< 5	< 5	Yes / Yes	On-going optics measurements, systematic error unclear on β and D. Dependence on SC composition?
Momentum spread	~ 7	Depends on: $\sqrt{\beta\varepsilon}$ vs. $D\frac{\Delta P}{P}$ $\sim$ few $-$ 25	Yes (indirect) / Yes	Discrepancy of ε_L ~ 15% matched area between PSB and PS tomoscope: RF voltage calibration?
Momentum deconvolution			No / Yes	Deconvolution has its limits: simple RMS deconvolution shown as robust in simulation
Beam movement at WS	~ 2	~ 5	Yes / Yes	Depends on steering. Radial loop works on same timescale as WS (ms)
Calibration of WS (IN vs. OUT)	?	To be evaluated	Yes / Yes	Systematic measurements in comparison to new prototype WS to be taken next week
Resolution SEM grids	$\sim 1 - 2$	To be evaluated	No / Yes	For BTM grids: resolution of PS SEM grids is far worse

Horizontal dispersion vs. turns

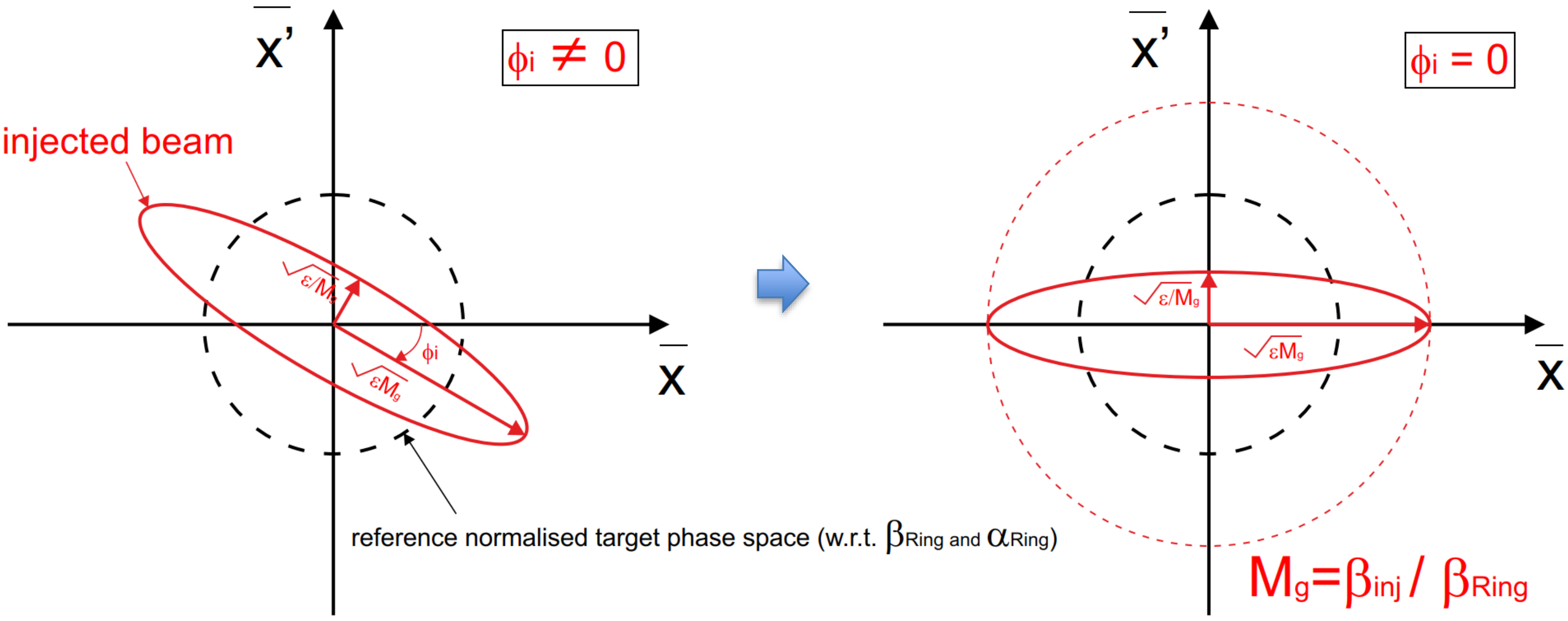
- RF OFF (check RF ON):
  - **Consistent** periodic dispersion from fit $D_{R,x}$ **= 0.73-0.74 $\sqrt{m}$** (~2.57 m)**
  - $M_{D,x}$ **improved** in re-matched optics: **from 0.37 to 0.1 $\sqrt{m}$****
    - **Fully consistent with dispersion from BPMs (see Appendix)**
    - **Related analytical $\Delta\varepsilon/\varepsilon_0$ = 14% (operational optics) ; 1% (PPM-rematched optics)**
      - **considering $\varepsilon_{0,norm}$=1.1 um and dp/p_{rms}=0.9e-3**





**$\beta_{R,x}$ = 12.05 m at SMG52 (From "Injection 7" optics)

Horizontal dispersion vs. turns



**$\beta_{R,x}$ = 12.05 m at SMG52 (From "Injection 7" optics)

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH
ORGANISATION EUROPEENNE POUR LA RECHERCHE NUCLEAIRE

CERN - PS DIVISION

PS/ AE/ Note 2001-003 (MD)

PDF here

STUDY OF A NEW PSB-PS TRANSFER LINE OPTICS WITH IMPROVED DISPERSION MATCHING BY MEANS OF TURN-BY-TURN BEAM PROFILE ACQUISITIONS

M. Benedikt, Ch. Carli, Ch. Dutriat, M. Giovannozzi, A. Jansson, M. Martini, U. Raich and K. Schindl

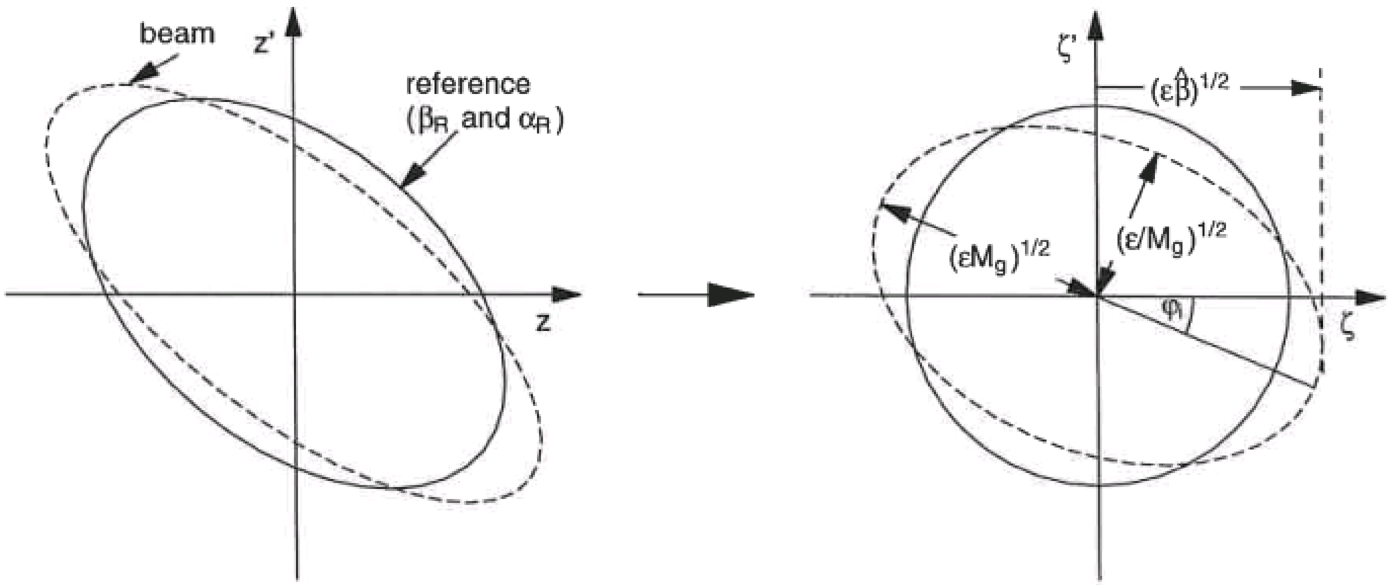


Figure 7: *Transformation into normalized phase space. Particles lying on an ellipse corresponding to the reference Twiss parameters β_R and α_R with emittance ϵ are transformed onto a circle with radius $\sqrt{\epsilon}$.*

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH
ORGANISATION EUROPEENNE POUR LA RECHERCHE NUCLEAIRE

CERN - PS DIVISION

PS/ AE/ Note 2001-003 (MD)

PDF here

STUDY OF A NEW PSB-PS TRANSFER LINE OPTICS WITH IMPROVED DISPERSION MATCHING BY MEANS OF TURN-BY-TURN BEAM PROFILE ACQUISITIONS

M. Benedikt, Ch. Carli, Ch. Dutriat, M. Giovannozzi, A. Jansson, M. Martini, U. Raich and K. Schindl

ellipse in the normalized phase space, described by normalized Twiss parameters $\hat{\beta}$ and $\hat{\alpha}$. In the present application the reference lattice parameters will refer to the PS lattice, whereas the latter ones describe the injected beam. To determine the normalized lattice parameters one describes first the phase ellipse in real phase space by parametrizing it with the phase μ :

$$\begin{aligned} z &= \sqrt{\epsilon\beta}\cos(\mu) \\ z' &= \sqrt{\epsilon/\beta}\,(\sin(\mu) - \alpha\cos(\mu)) \end{aligned}$$

and then transforms to normalized phase space to obtain :

$$\begin{aligned} \zeta &= \sqrt{\frac{\beta}{\beta_R}\epsilon}\cos(\mu) \\ \zeta' &= \sqrt{\frac{\beta_R}{\beta}\epsilon}\left(\sin(\mu) - \left(\alpha - \frac{\beta}{\beta_R}\alpha_R\right)\cos(\mu)\right) \end{aligned} \quad .$$

From above expressions, the normalized lattice parameters :

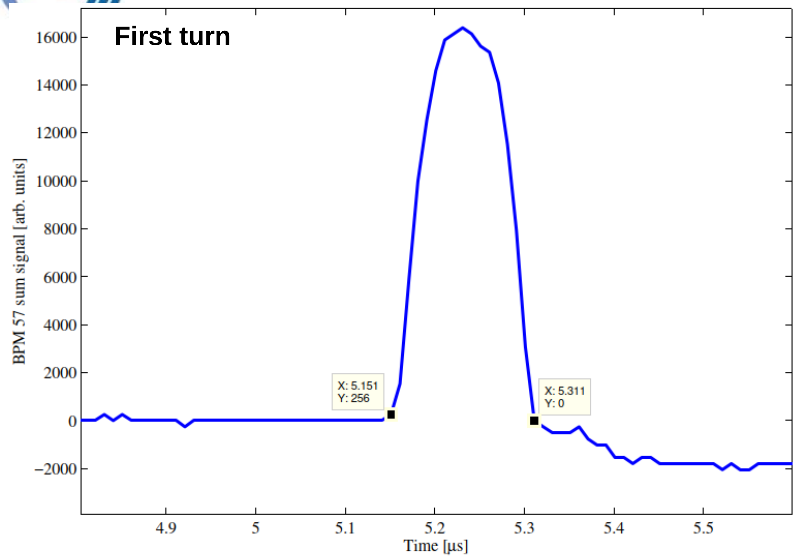
$$\begin{aligned} \hat{\beta} &= \frac{\beta}{\beta_R} \\ \hat{\alpha} &= \alpha - \frac{\beta}{\beta_R}\alpha_R \end{aligned} \qquad (1)$$

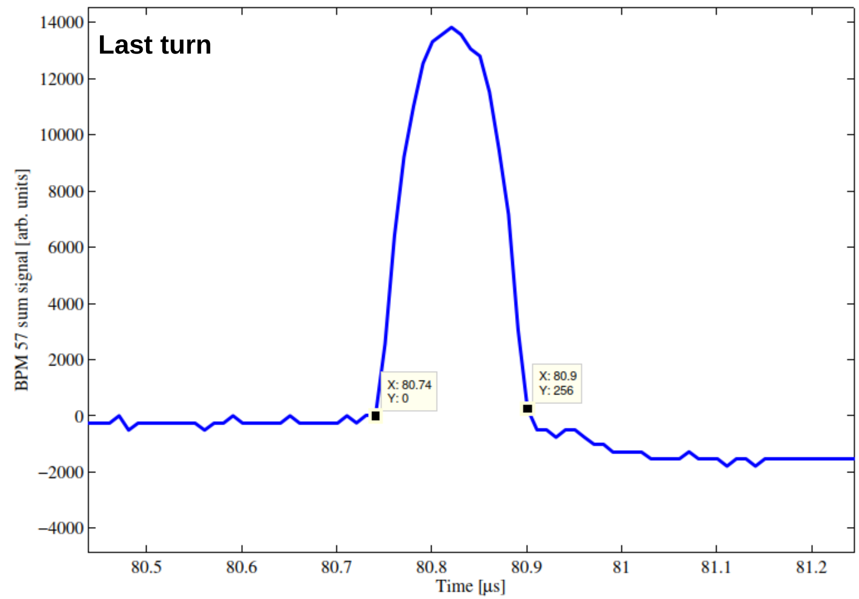
are deduced. A convenient way to parametrize the mismatched beam is to introduce the geometric mismatch factor M_g and the angle ϕ_i shown in Fig. 7. The normalized lattice parameters are given by :

$$\hat{\beta} = \frac{1}{2}\left(M_g + \frac{1}{M_g}\right) + \frac{1}{2}\left(M_g - \frac{1}{M_g}\right)\cos(2\phi_i)$$

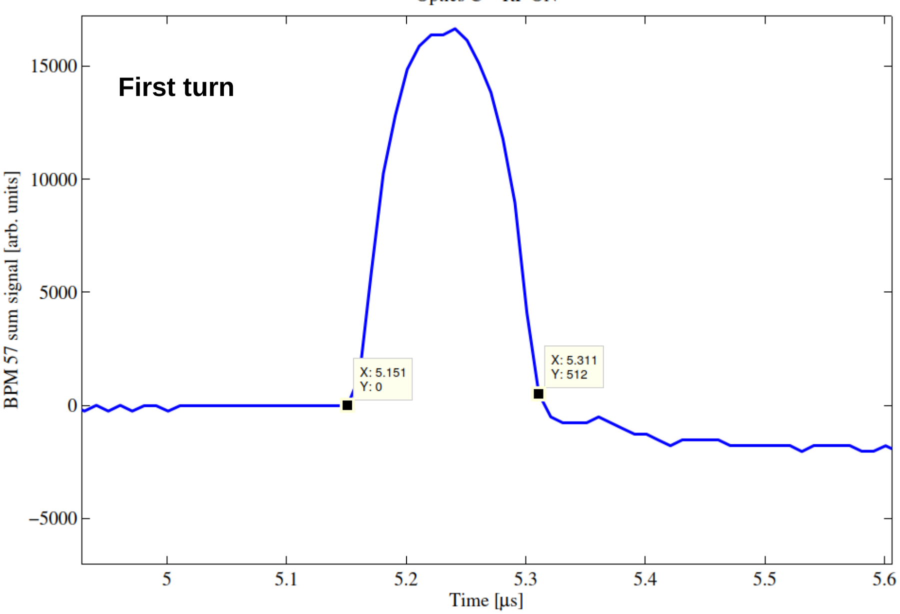
CERN

Optics C – RF OFF

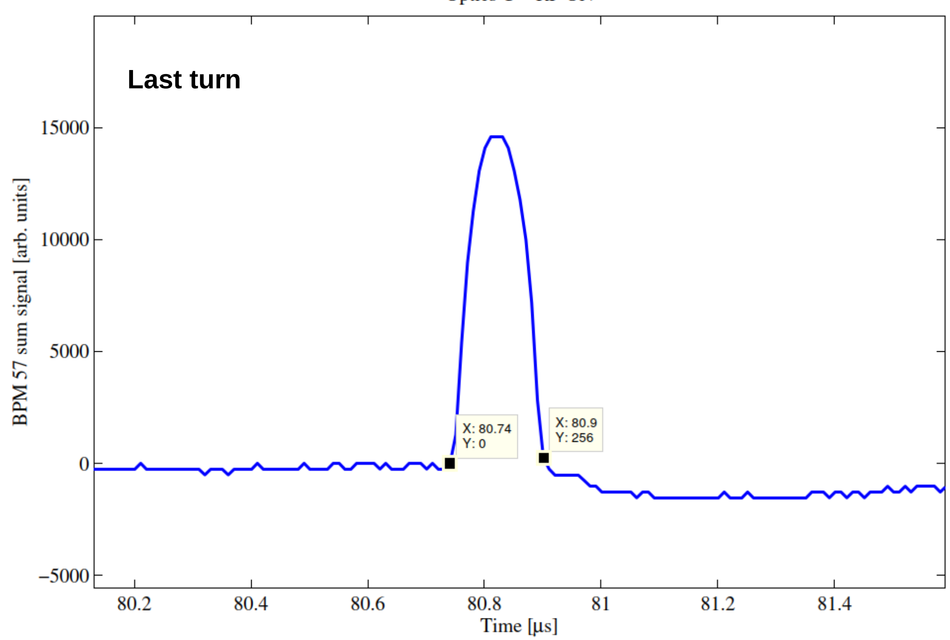




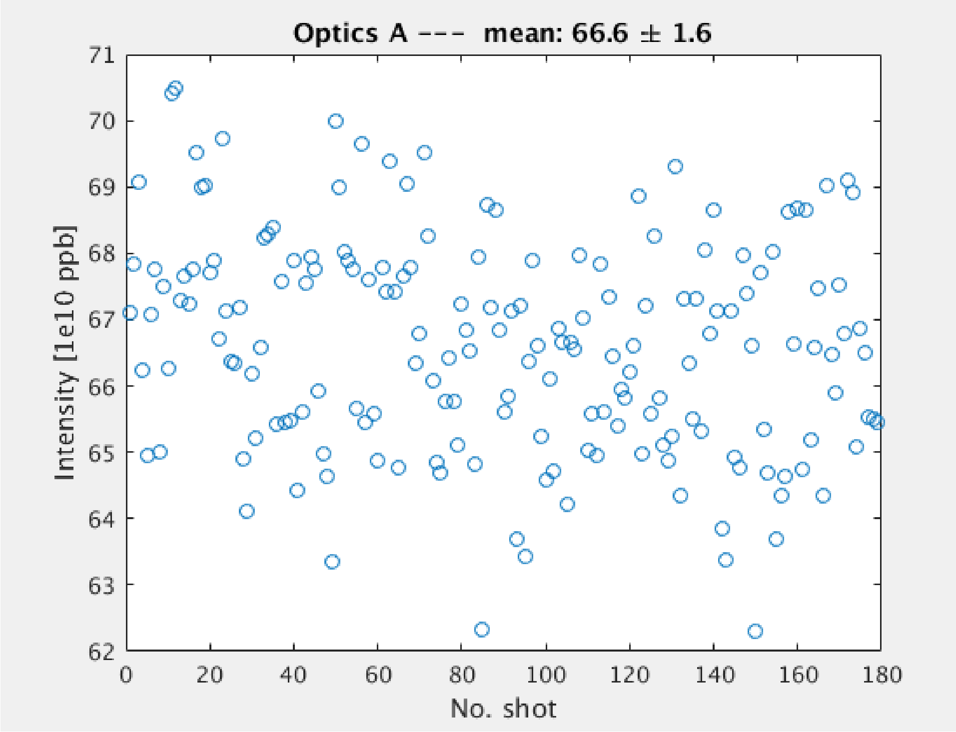
Optics C – RF ON

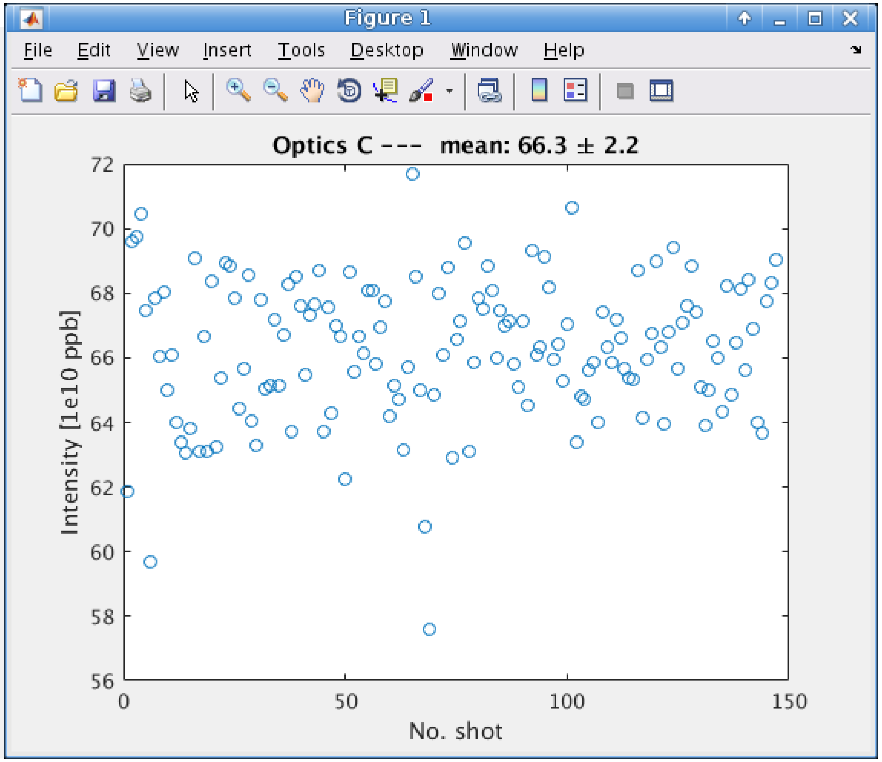


Optics C – RF ON

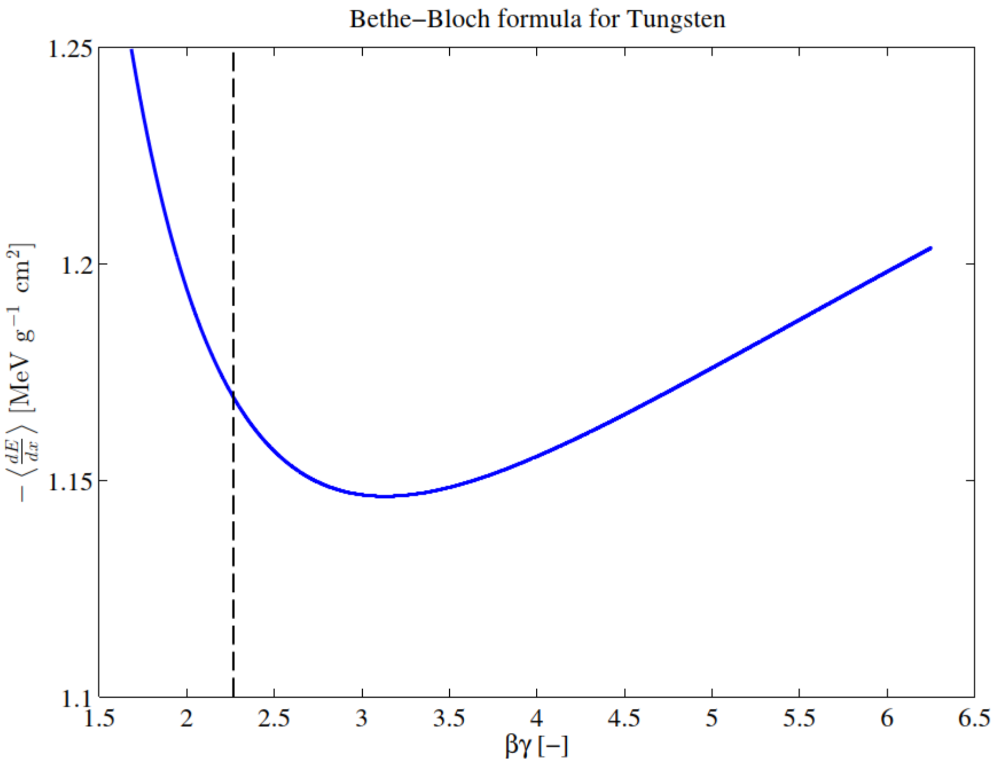


Intensities





Energy loss: Bethe-Bloch formula



- Density $\rho =$ **19.3 g/cm^3**
- Wire diameter **d_{wire}= 40 μm = 40e-4 cm**

Energy loss per turn per particle:

1.17 [MeV·g^{-1}·cm^2] x 40e-4 [cm] x 19.3 [g·cm^{-3}] = 0.09 MeV / turn

Wirescanner measurements for PPM-rematched optics