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LHC Injectors Upgrade

LHC Injectors Upgrade Workshop

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Transverse effects with twice brighter beams in the PS

Matthew Fraser

S. Albright, F. Antoniou, H. Bartosik, H. Damerau, V. Forte, A. Huschauer, A. Lasheen, H. Rafique, E. Senes

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- What will change after LIU?
  - Overview of hardware upgrades, target beam parameters, upgraded injection scheme and recent MD's (low chromaticity and high intensity)
- Sources of emittance growth during transfer and on injection plateau:
  - Catalogue of (known) contributors and their weighting, with latest MD results
  - Brightness measurements and BT-BTP transfer line re-matching
  - The challenge of systematic errors, deconvolution and present uncertainties
- Conclusion and outlook:
  - Looking to the future at 2 GeV and operation with large longitudinal emittance

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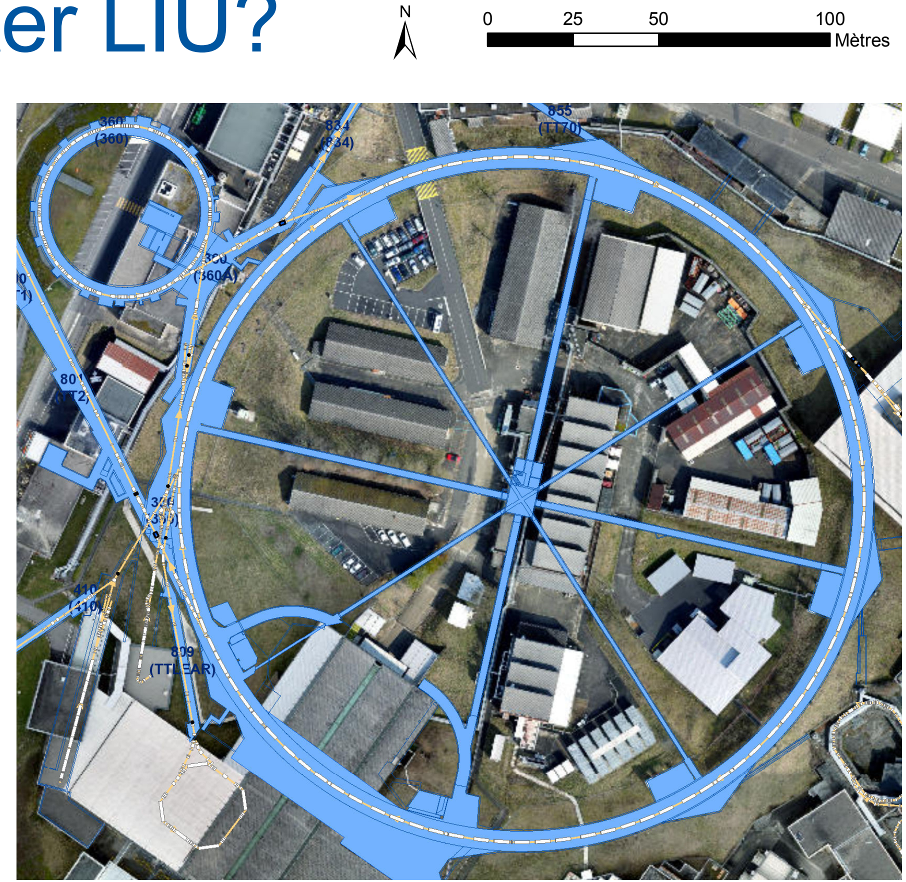
  - Blow-up from existing dispersion mismatch will be exacerbated: upgrade of the BT-BTP transfer line needed
  - Large momentum spread coupled with dispersion is a challenge for accurate betatronic emittance measurements (especially for bright beams!)

What will change after LIU?

Equipment	Comment
KFA14L1*	Spare magnet (no significant upgrade, minor improvements)
KFA10*	Spare magnets (with upgraded ferrite)
KFA20	System re-cabled like KFA10 (spare magnet to be built)

*Spares are presently planned for installation in LS2



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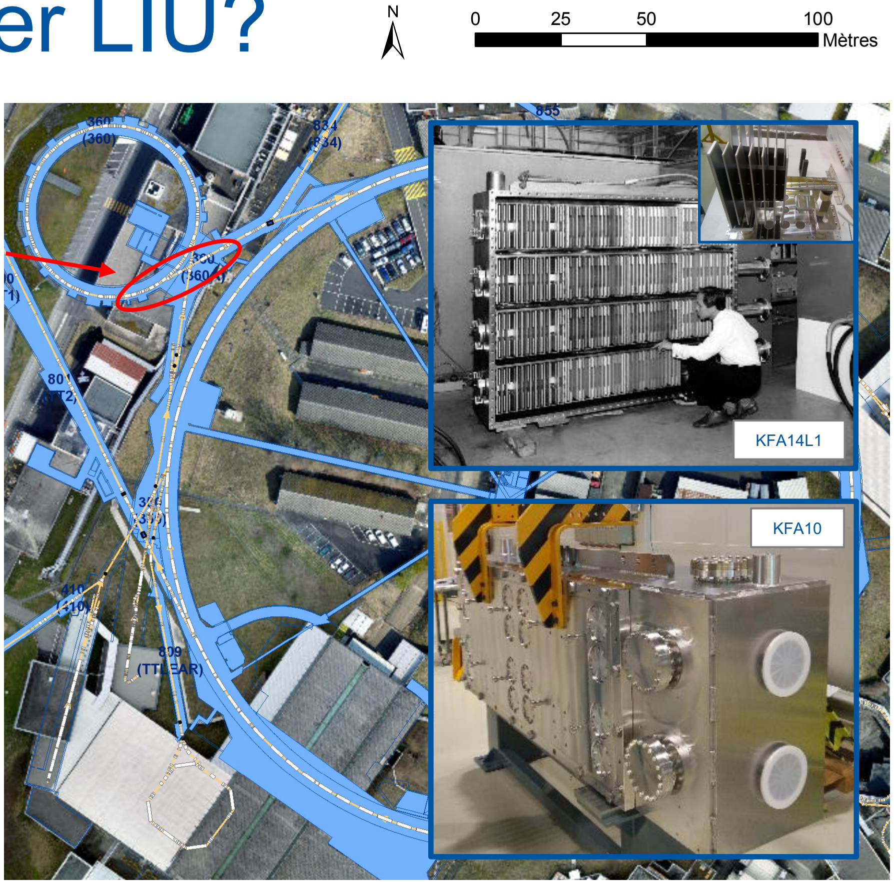

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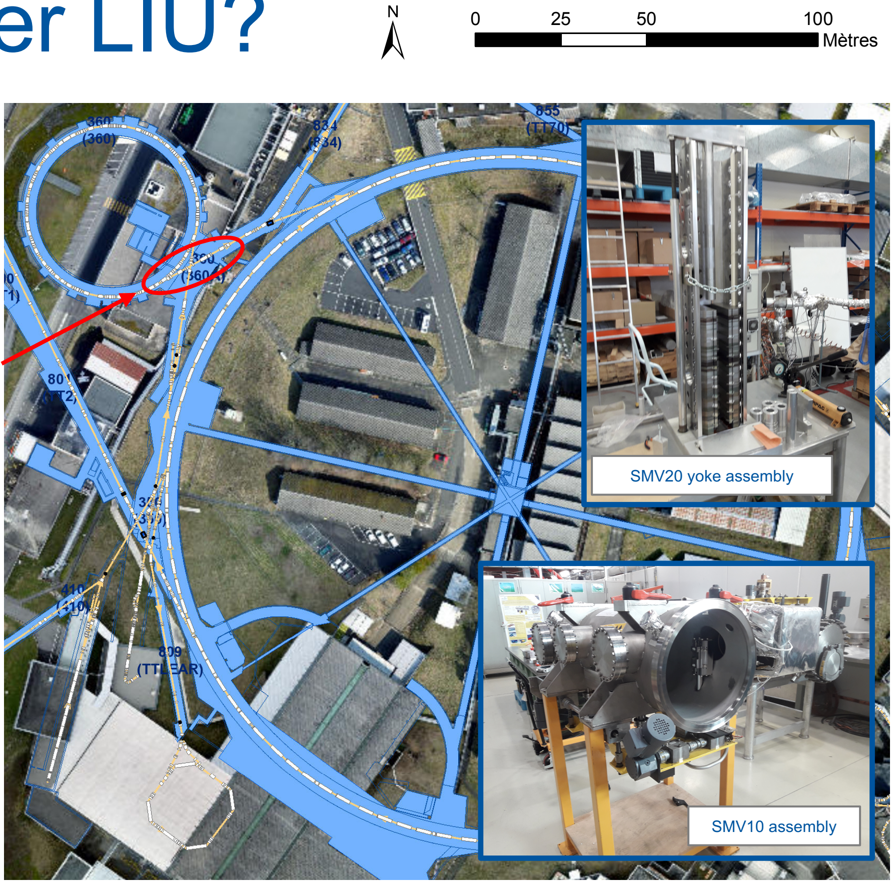

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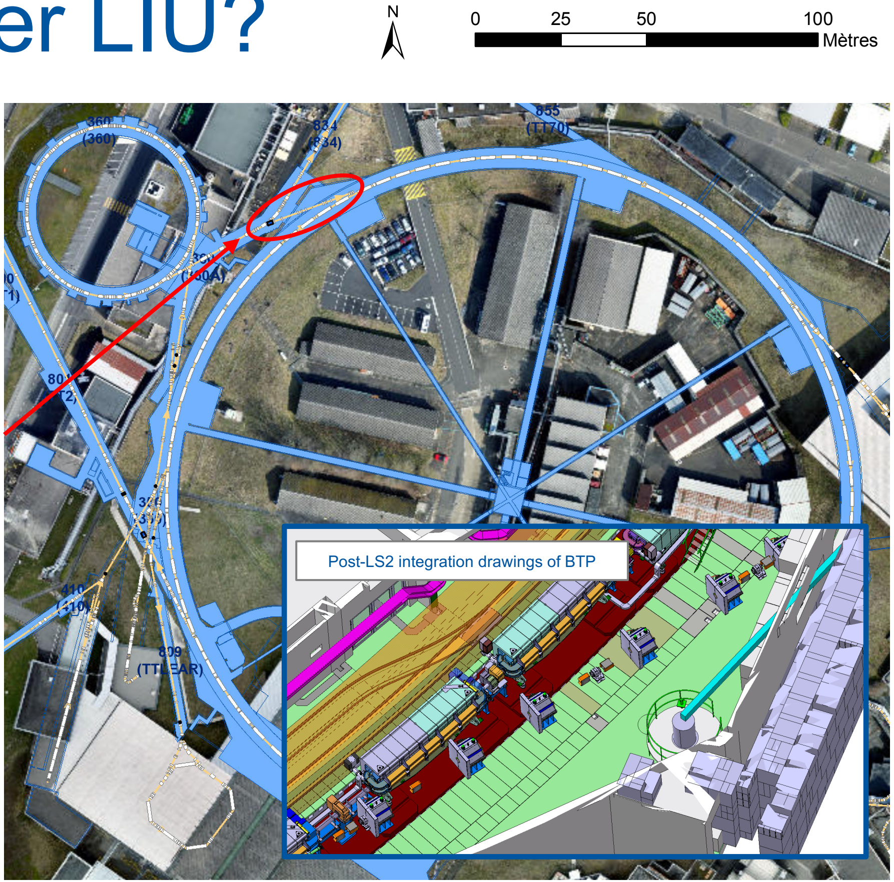

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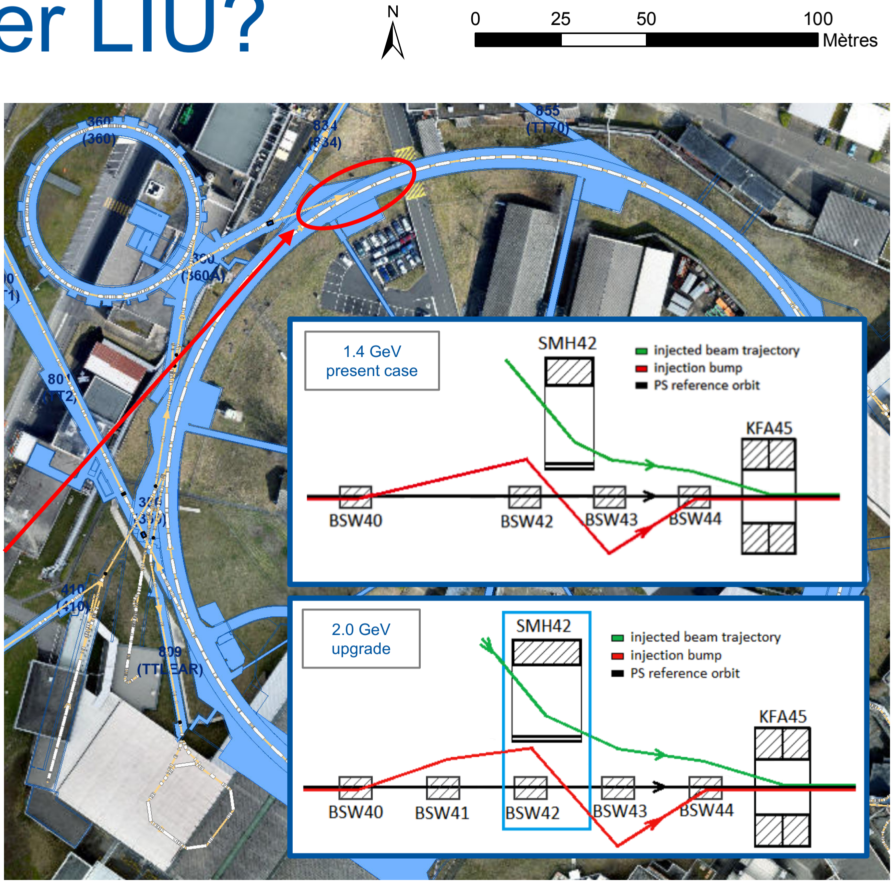

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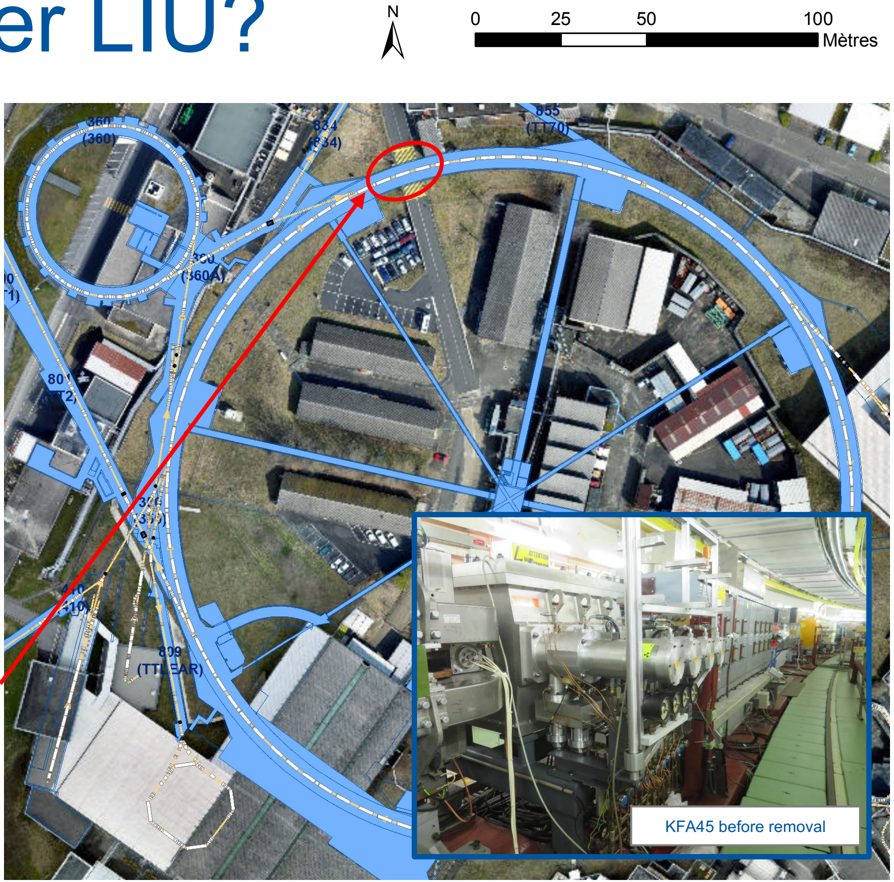

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TFB	Upgraded power amplifiers from 3 to 5 kW for operation at 2 GeV

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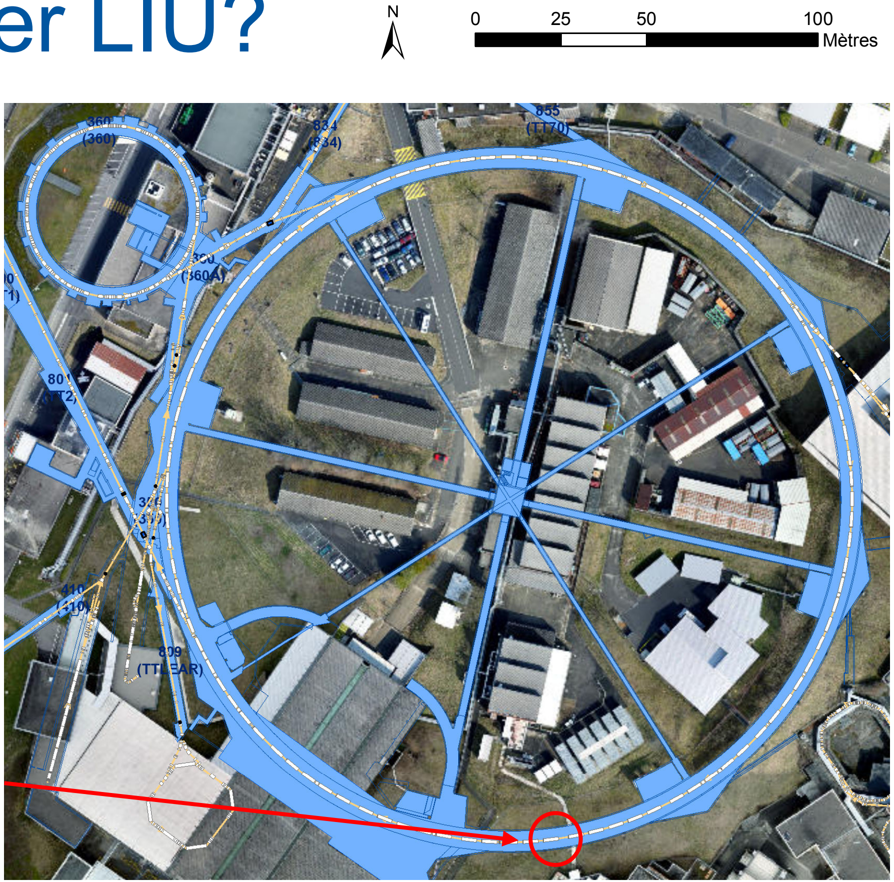

Beam parameters

Scenario	Type	N [10^{11} p/b]	$\varepsilon_{x,y}$ [μm]	E [GeV]	ε_z [eVs]	B_l [ns]	Δp/p [10^{-3}]	$\Delta Q_{x,y}$
Today*	BCMS – OP “0.9 eVs”	~7.5	1.0	1.4	0.85	145	0.9	(0.24, 0.34)
	BCMS – large ε_z “1.5 eVs”	~7.5	1.1	1.4	1.45	155	1.4	(0.14, 0.25)
LIU target**	BCMS	16.25	1.43	2.0	1.48	135	1.1	(0.20, 0.31)
	Standard	32.50	1.80	2.0	3.00	205	1.5	(0.18, 0.30)

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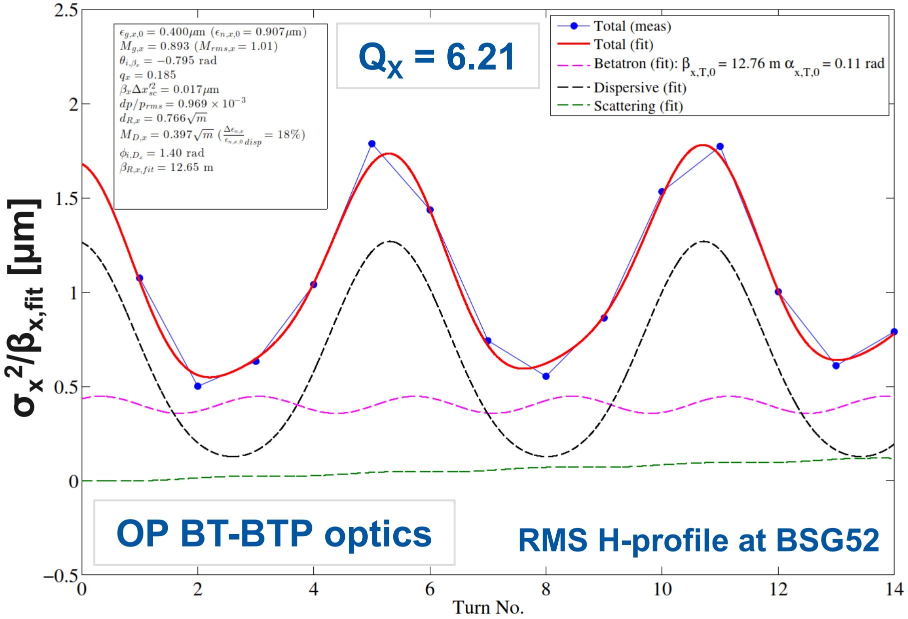
Known issue with H dispersion mismatch

- Dispersion function is mismatched on transfer to PS causing blow-up:
  - Long-standing BT-BTP design issue
  - MD's last year quantified mismatch empirically with PS BPM's, fast turn-by-turn SEM electronics delivered in 2018
  - Dispersion reproduced with MADX and re-matched optics on R3 used for MD's



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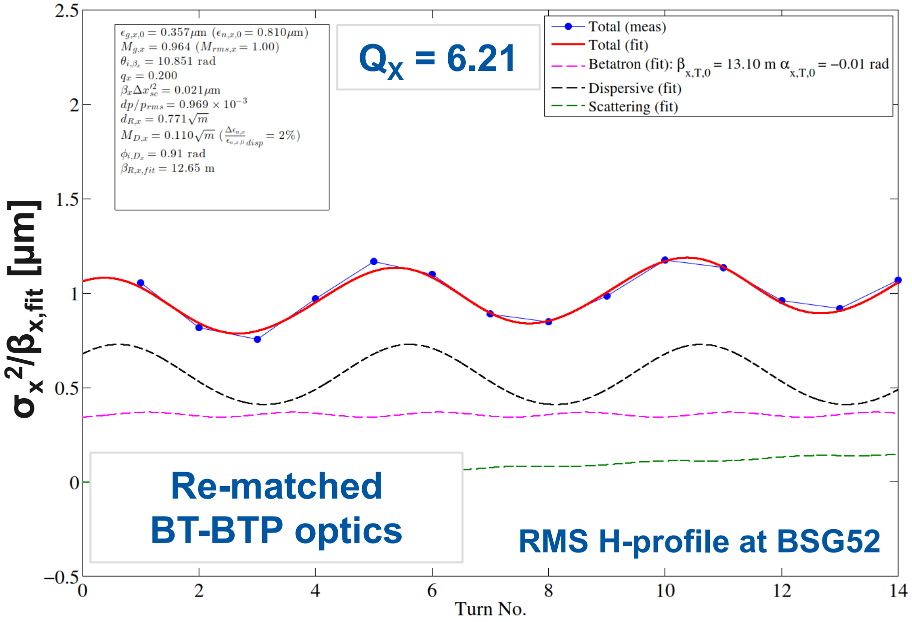

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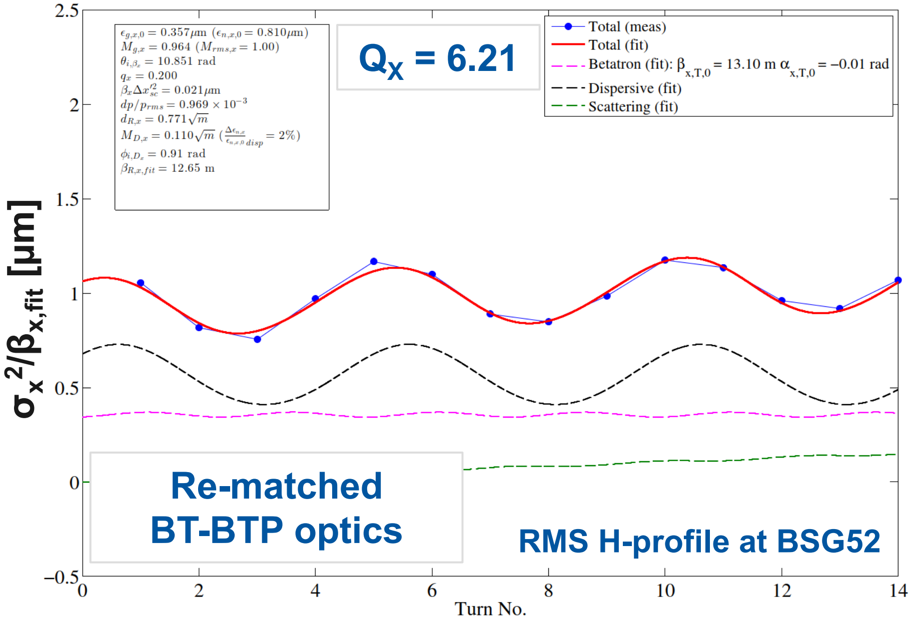
- Mitigation under LIU project is the upgrade of BT-BTP transfer line



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BCMS cycle with low chromaticity

- Important step was made last year deploying the TFB on operational LHC and MD beams:
  - PFW used to correct chromaticity at low energy
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  - Emittance well-preserved along injection plateau
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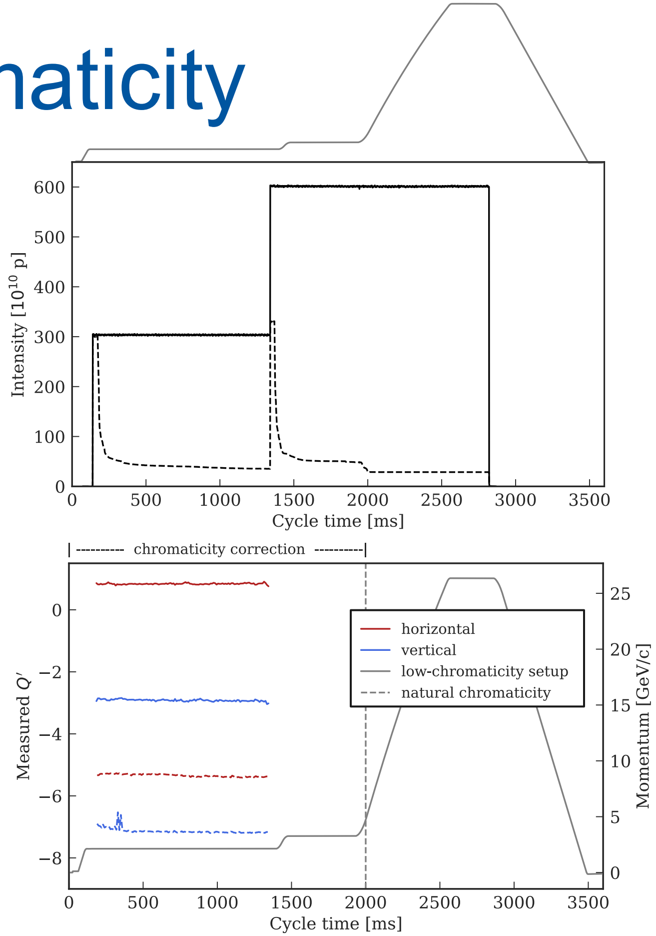

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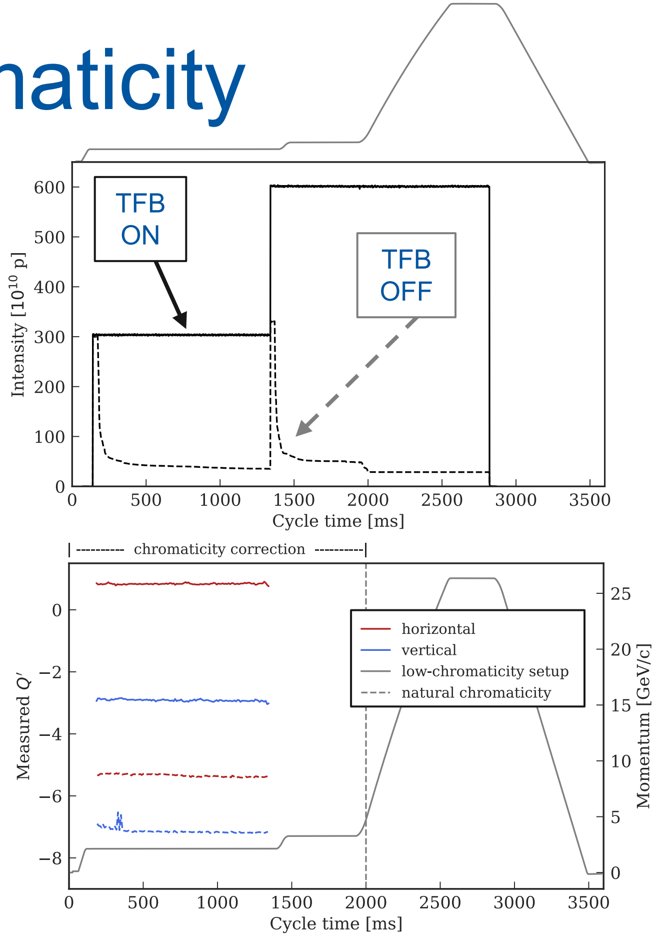

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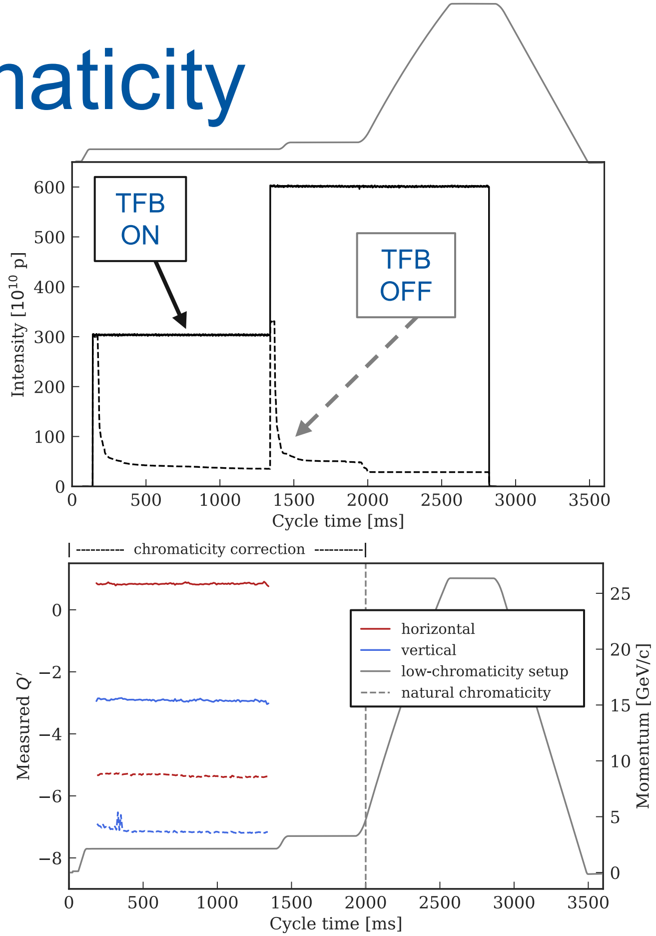
- Next steps:
  - Upgraded TFB system in LS2
  - Further approach zero chromaticity (and vertical)
  - Implementation also on standard production beams



High intensity MD’s

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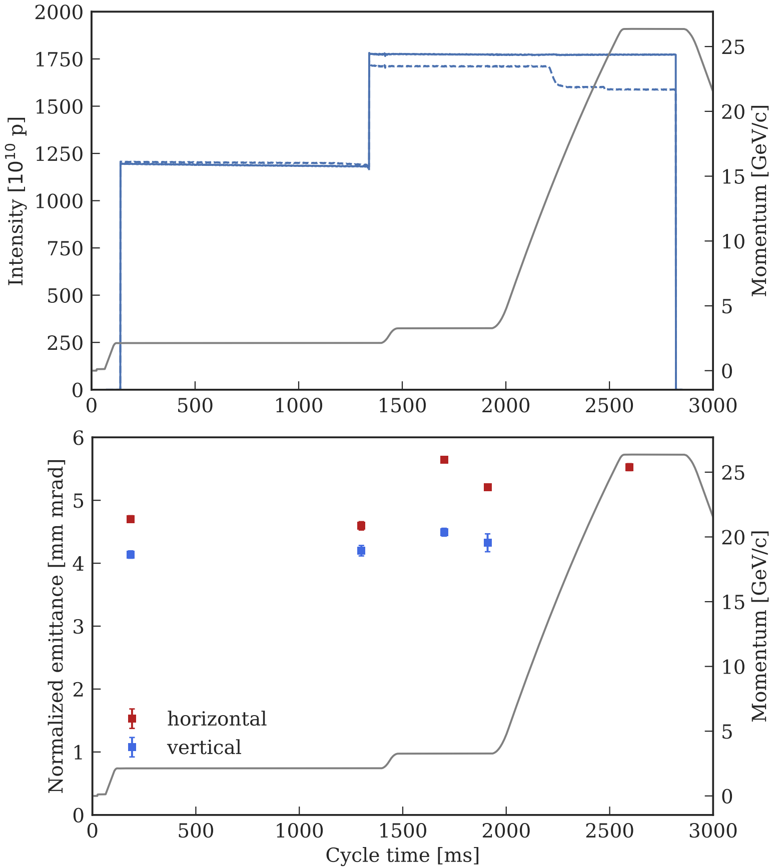
  - Intensity of 2.6 x 10^{11} ppb at PS extraction seems within reach using presently available RF upgrades



High intensity MD's

- Successful set-up and optimisation of HI beams:
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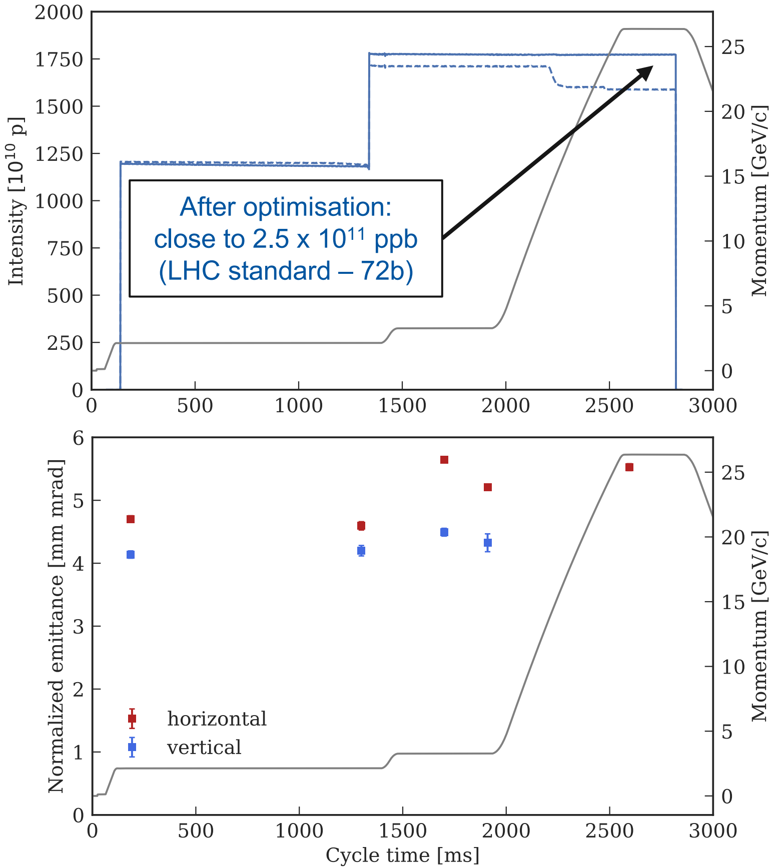
  - Transverse tune optimization along the flat bottom:
    - Adjustment of the TFB gain settings according to increased intensity
    - Vertical chromaticity increased by $\Delta Q'_y \approx 1$ during the ramp



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Expected emittance growth sources **today (1)***

*For input emittance of 1 mm mrad (rms, norm) at 1.4 GeV and 75e10 p

Source	Expected $\Delta\varepsilon/\varepsilon$ BCMS OP [%]	Expected $\Delta\varepsilon/\varepsilon$ BCMS 1.5 eVs [%]	Comment
Dispersion mismatch	15 (in H) 1 (in V)	36 (in H) 3 (in V)	Estimates taken empirically from turn-by-turn SEM and BPM data in the first turns after injection
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Injection mis-steering	Negligible with TFB ON (<%)		For 0.5 mm (max.) oscillation with TFB OFF: one computes ~ 2%
Injection bump	Negligible (<%)		No blow-up observed (measurements on second instance) [ref:1] Studies have specified BSW synchronization to avoid blow-up [ref:2]
Injection energy error	Negligible after correction (< %)		Potentially a strong source of blow-up, $\Delta p/p$ ~ few 10^{-4} is important and needs operational attention!

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KFA14 ripple	< 1 (in H only)	< 2 (in H only)	Synchronisation with beam will be an important commissioning [ref:3]	TFB should be effective to compensate ripple (< 30 MHz), effectiveness of damping to be computed
KFA10/20 ripple	2 – 3 (in V only)	2 – 3 (in V only)	Depends on ring and PS injection energy [ref:4]	
KFA45 ripple + post-pulse	0 – 3.5 (in H only)	0 – 3.5 (in H only)	Depends on ring and PS injection energy [ref:5]	KFA45 field measurements now available: to be analysed

Expected emittance growth sources **today (2)***

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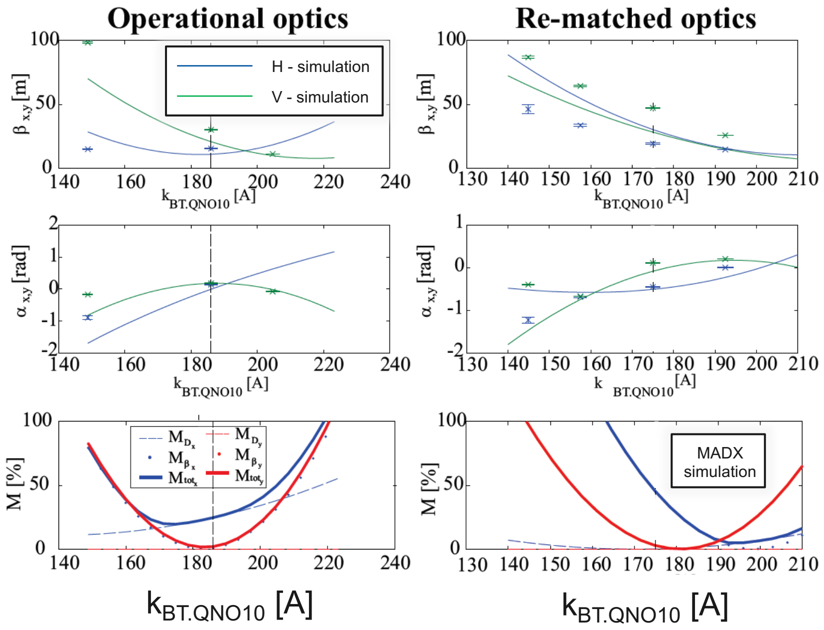
Source	Expected $\Delta\varepsilon/\varepsilon$ BCMS OP [%]	Expected $\Delta\varepsilon/\varepsilon$ BCMS 1.5 eVs [%]	Comment
PS optics mismatch induced by space-charge	Negligible (< %)		PS closed solution with considering KV (rms) tune spread
Space-charge blow-up in TL	To be assessed		To be checked (in simulation)
Space-charge blow-up in PS	Negligible (< %)	To be assessed	Studies of sensitive of blow-up to WP at injection show a range of Q_X,Q_y ~ 0.02 where no blow-up is observed from 2 to 15 ms after injection

BT-BTP optics for brightness studies

- Re-matched optics was provided to study sensitivity of blow-up at injection to dispersion mismatch [ref6]:
  - Ring 3 only: for PPM operation and parallel MD's
  - MADX model compared to betatronic mismatch measured on the PS injection BSG's:



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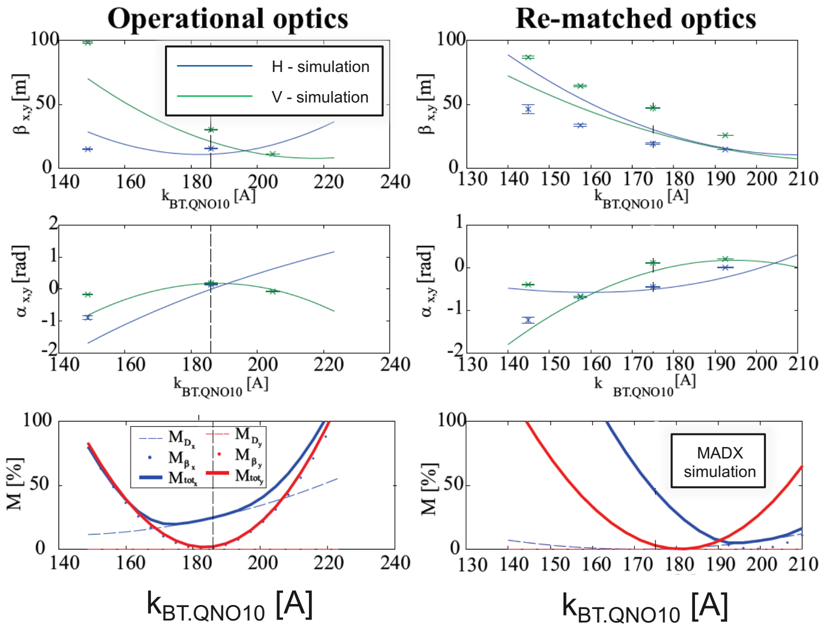

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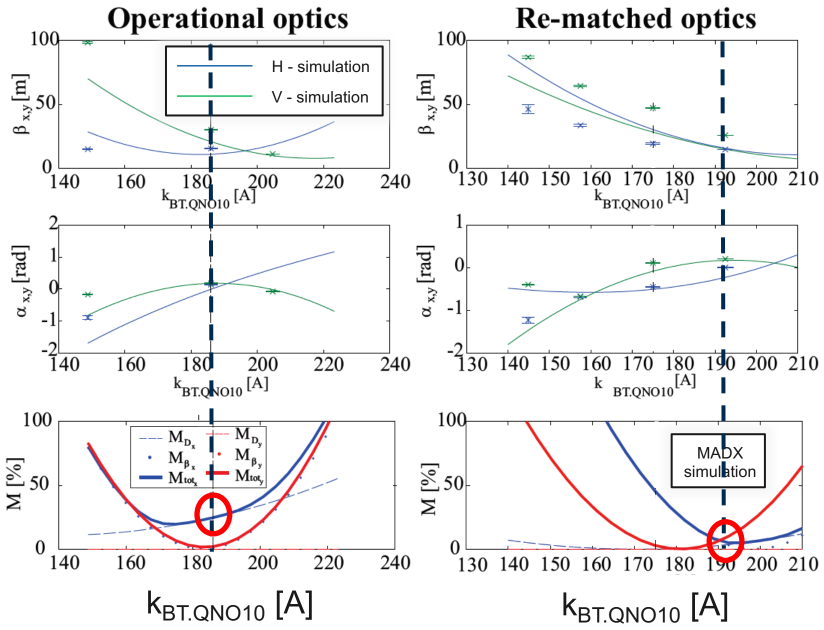
  - **MADX model good enough to significantly reduce mismatch**



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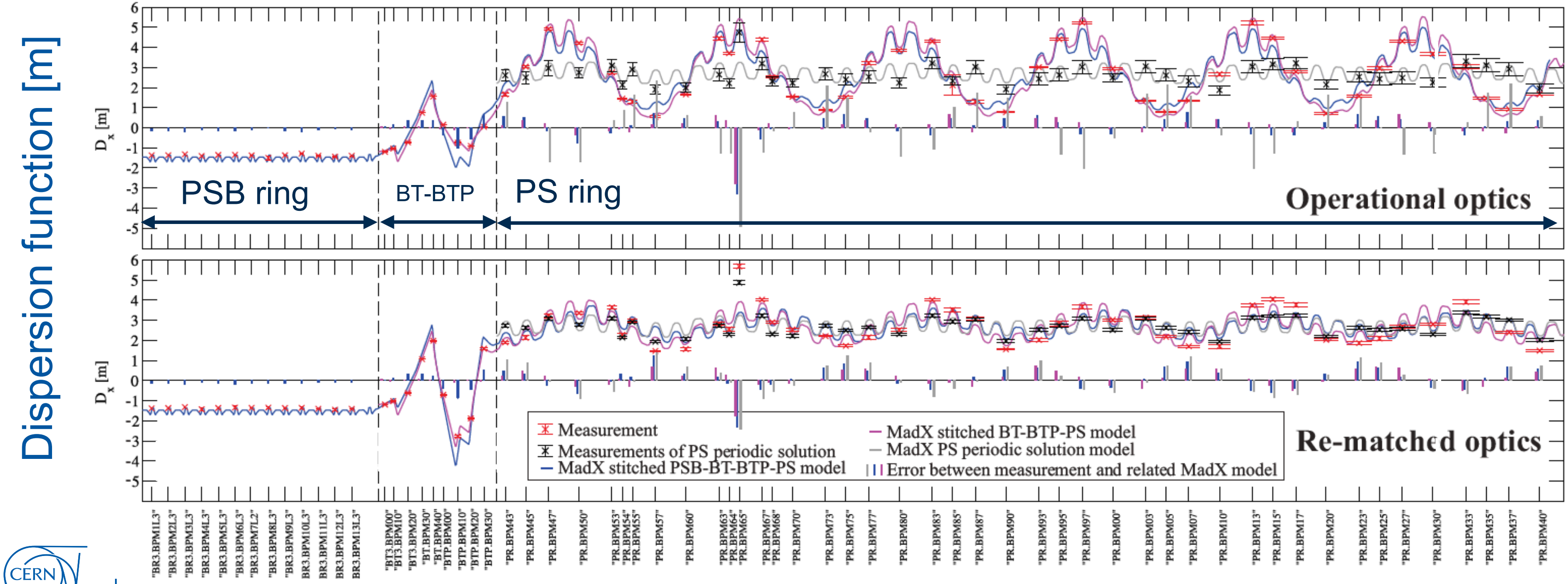

Dispersion mismatch at injection

$\varepsilon_n = (\beta\gamma)_{\mathrm{rel}}\, \varepsilon_g$
is not forgotten!

- Blow-up independent of initial emittance, proportional to $\left(\frac{\Delta p}{p}\right)^2$
  - i.e. a constant offset as *f(*intensity*)* on brightness curves:

$$\Delta\varepsilon = \frac{1}{2} M_D^2 \left(\frac{\Delta p}{p}\right)^2 \text{ where } M_D^2 = \left(\frac{\Delta D^2 + (\beta\Delta D' + \alpha\Delta D)^2}{\beta}\right)$$

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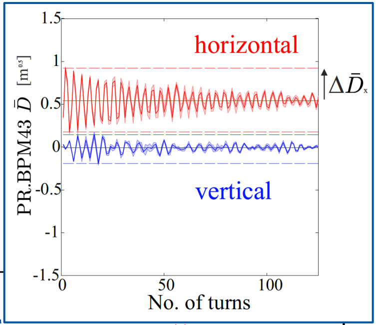
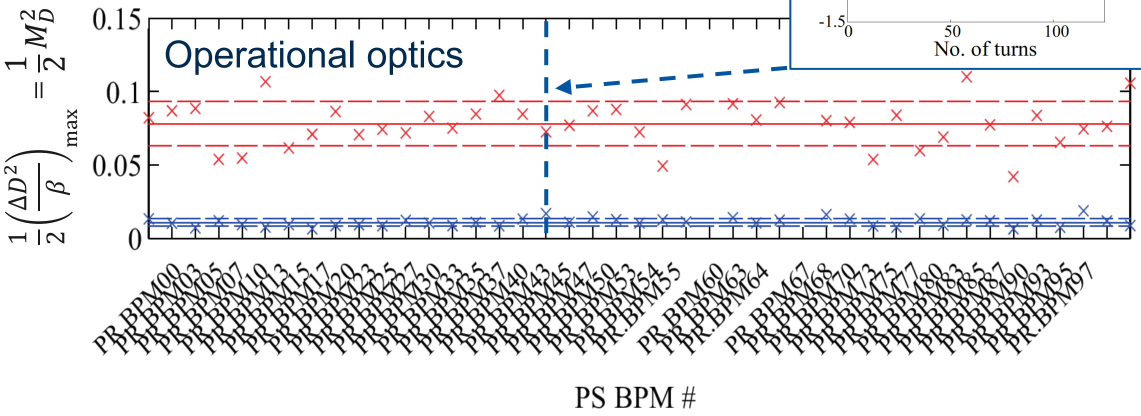


Technique	**M_D [$m^{1/2}$]**
	Operational
T-by-turn BPM response (D mismatch from Δf steering)	0.40 ± 0.04



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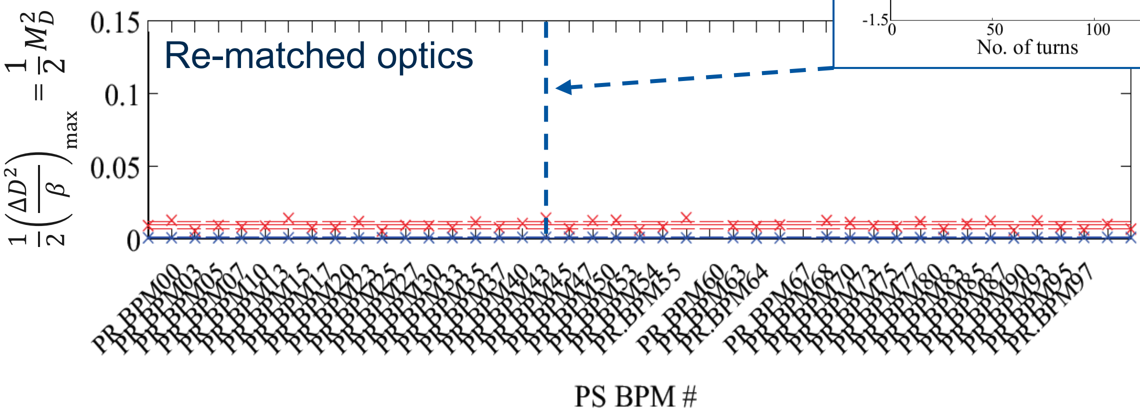

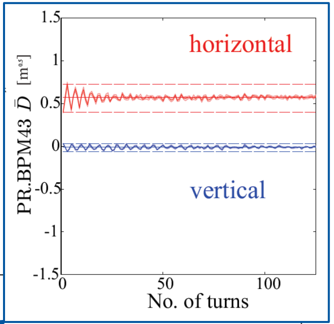

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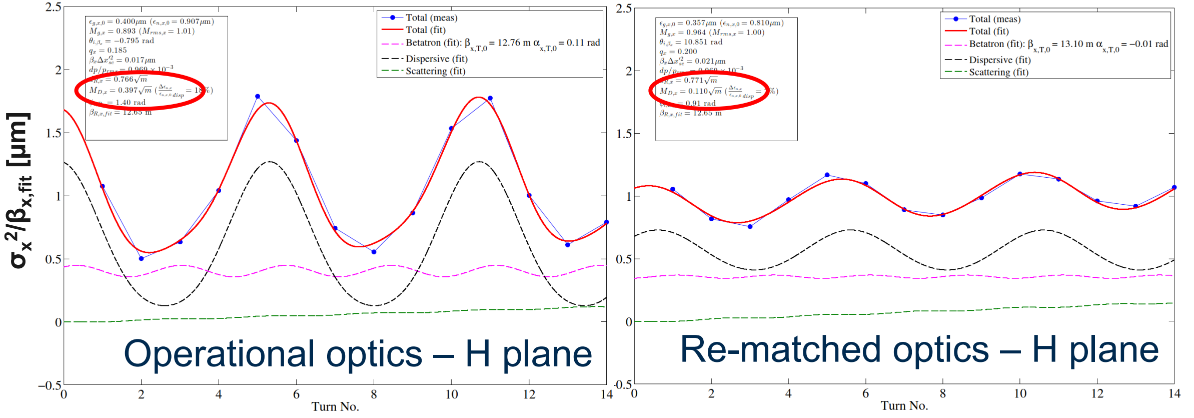
$$\Delta\varepsilon = \frac{1}{2} M_D^2 \left(\frac{\Delta p}{p}\right)^2 \text{ where } M_D^2 = \left(\frac{\Delta D^2 + (\beta\Delta D' + \alpha\Delta D)^2}{\beta}\right)$$

Technique	M_D [$m^{1/2}$]	
	Operational	Re-matched
T-by-turn BPM response (D mismatch from Δf steering)	0.40 ± 0.04	0.14 ± 0.02
T-by-turn SEM envelope beating (fitted D mismatch)*	0.397	0.110

*error analysis to be completed



Dispersion mismatch at injection

$\varepsilon_n = (\beta\gamma)_{rel}\, \varepsilon_g$ is not forgotten!

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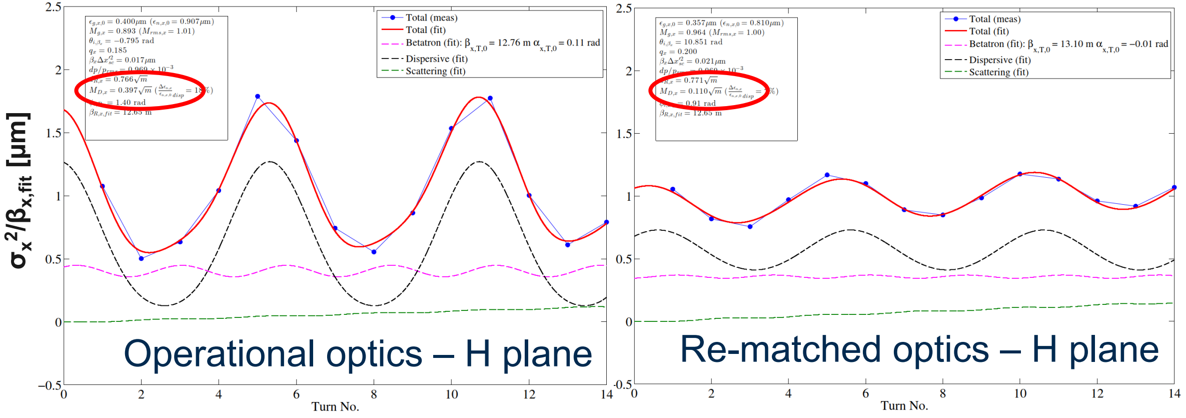
T-by-turn SEM envelope beating (fitted D mismatch)*	0.397	0.110
	*error analysis to be completed	
	$\Delta\varepsilon$ BCMS OP abs. [mm mrad]	
	0.15	0.011 – 1.8



Betatronic mismatch at injection

$\varepsilon_n = (\beta\gamma)_{\text{rel}}\, \varepsilon_g$
is not forgotten!

- Blow-up dependent on initial emittance, expected to be negligible:
  - i.e. a linear *f(*intensity*)* on brightness curves:

$$\Delta\varepsilon = \frac{\varepsilon_0}{2}\left(M_g + \frac{1}{M_g} - 2\right) \text{ where } M_g + \frac{1}{M_g} = \beta\gamma_0 + \gamma\beta_0 - 2\alpha\alpha_0$$

β- mismatched
β_0 - matched

Betatronic mismatch at injection

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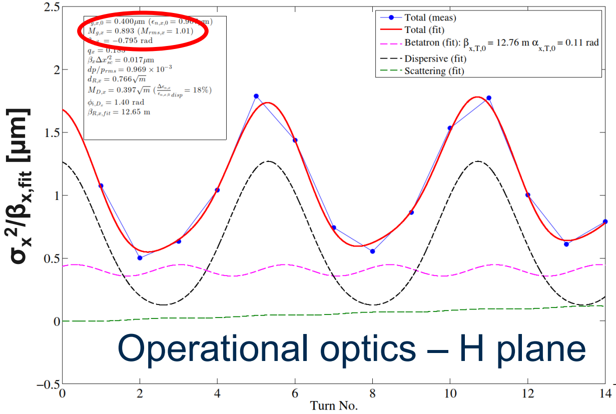
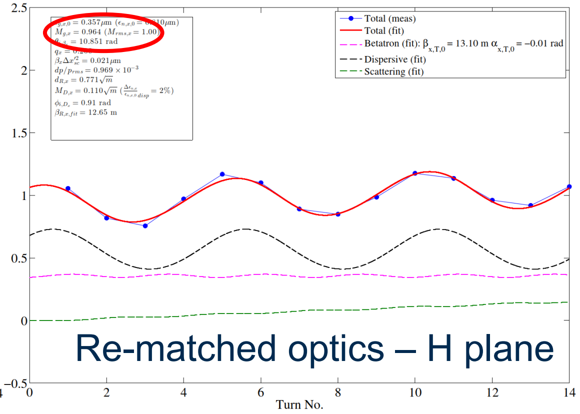
β- mismatched
β_0 - matched

  - Envelope would beat twice as fast ($2q_H$) if betatronic mismatch was dominant

Technique	M_g	
	Operational	Re-matched
T-by-turn SEM envelope beating (fitted mismatch)*	0.89	0.96

*error analysis to be completed





Betatronic mismatch at injection

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- Blow-up dependent on initial emittance, expected to be negligible:
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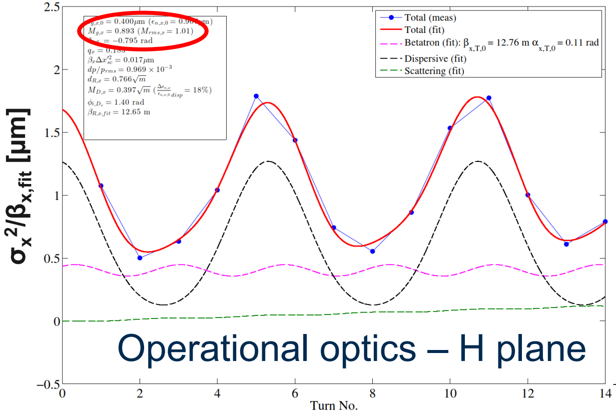
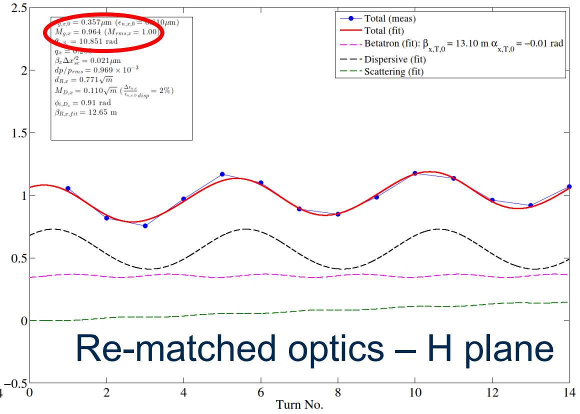
β- mismatched
β_0 - matched

  - Envelope would beat twice as fast ($2q_H$) if betatronic mismatch was dominant

Technique	M_g	
	Operational	Re-matched
T-by-turn SEM envelope beating (fitted mismatch)*	0.89	0.96
	$\Delta\varepsilon$ BCMS OP abs. [mm mrad]	
	0.007	negligible

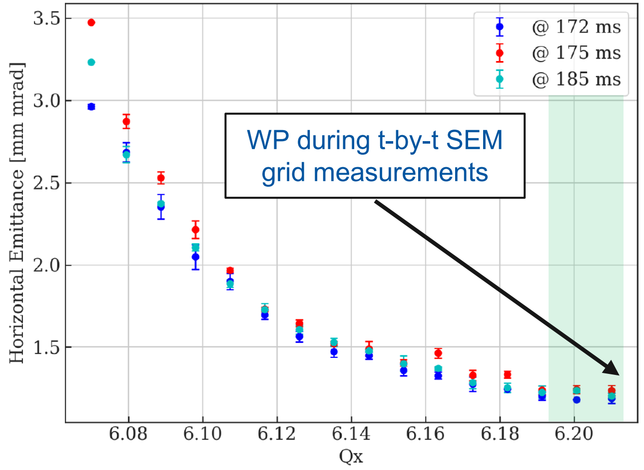
*error analysis to be completed

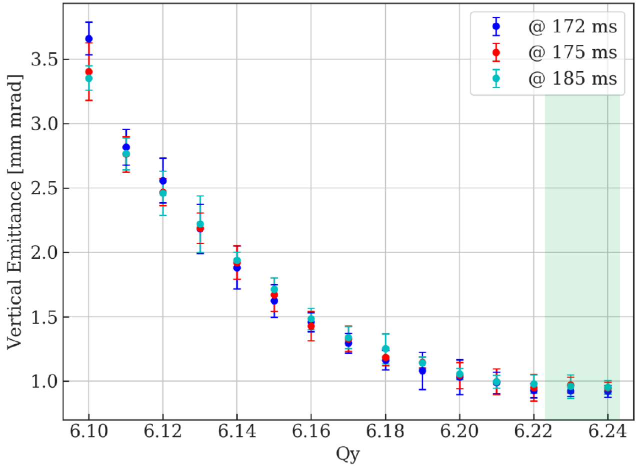




Space-charge in PS

- Sensitivity of blow-up after injection to WP:
  - BCMS OP on Ring 3: low Q' cycle, 72e10 p
  - WP shows little sensitivity over range of 0.02
  - "Fast" blow-up appears only close to integer
  - **No significant impact on blow-up from the space-charge induced tune spread at timescales > 2 ms**





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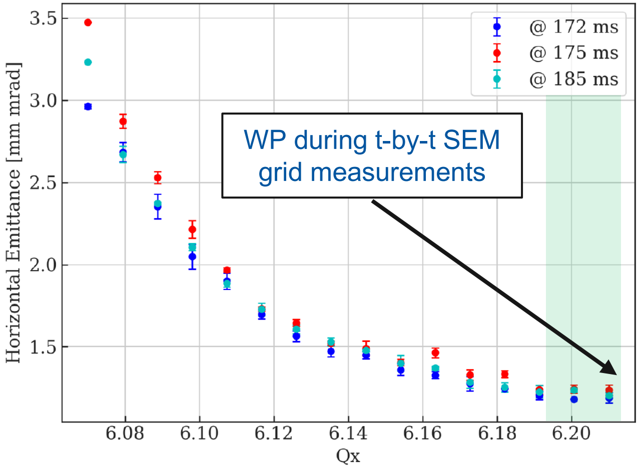
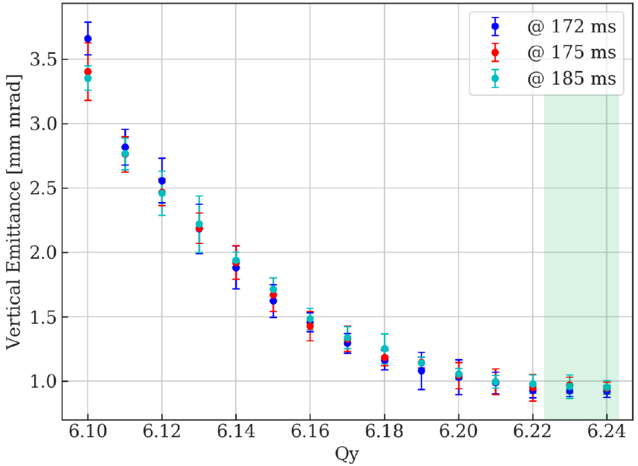
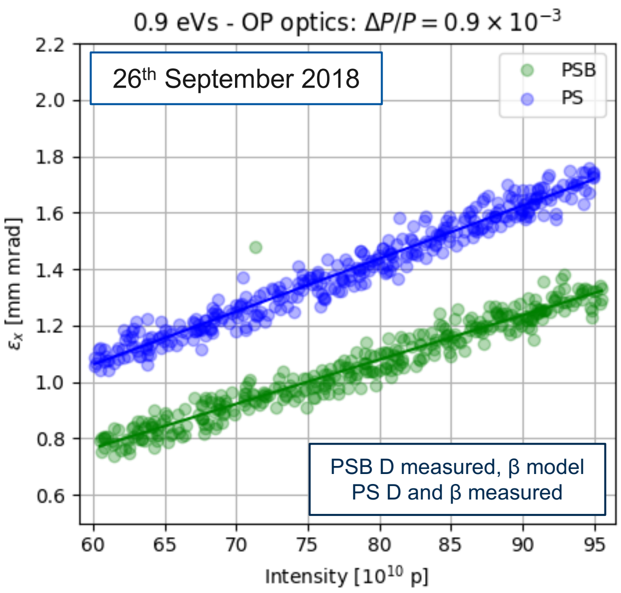
- Next steps:
  - Simulations with space-charge to be carried out and benchmarked with measurements

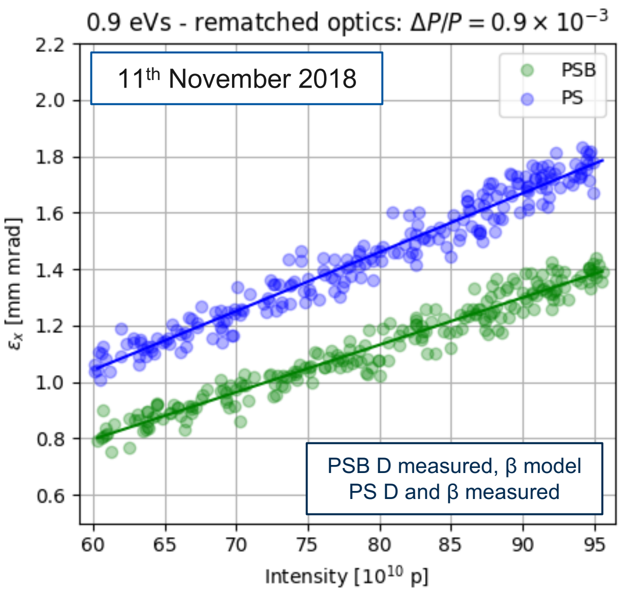




Measured H blow-up: BCMS 0.9 eVs

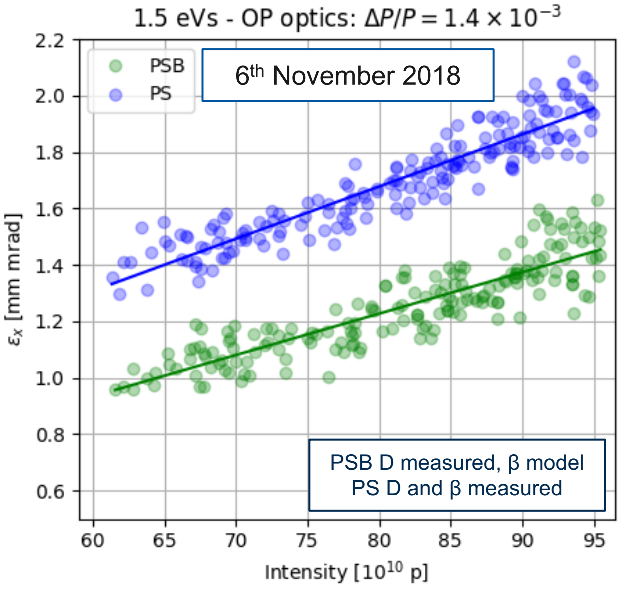
- Re-matching BT-BTP has only a small impact on filamented **horizontal emittance** measured 15 ms after injection using the wire-scanner:

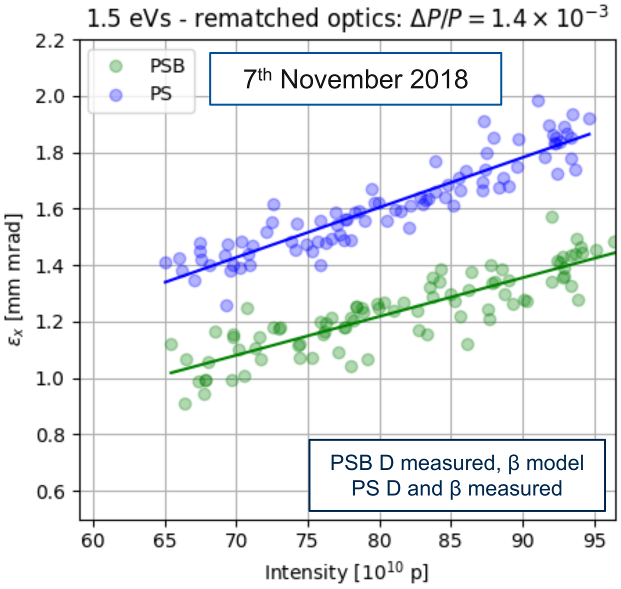




Measured H blow-up: BCMS 1.5 eVs

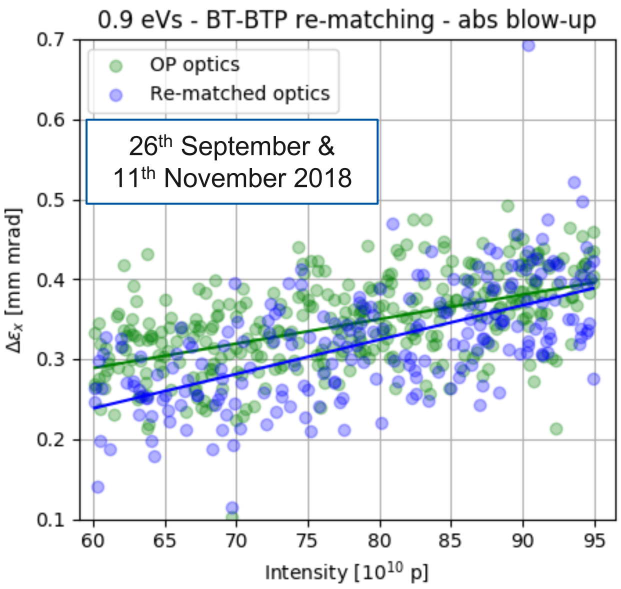
- Re-matching BT-BTP has only a small impact on filamented **horizontal emittance** measured 15 ms after injection using the wire-scanner:

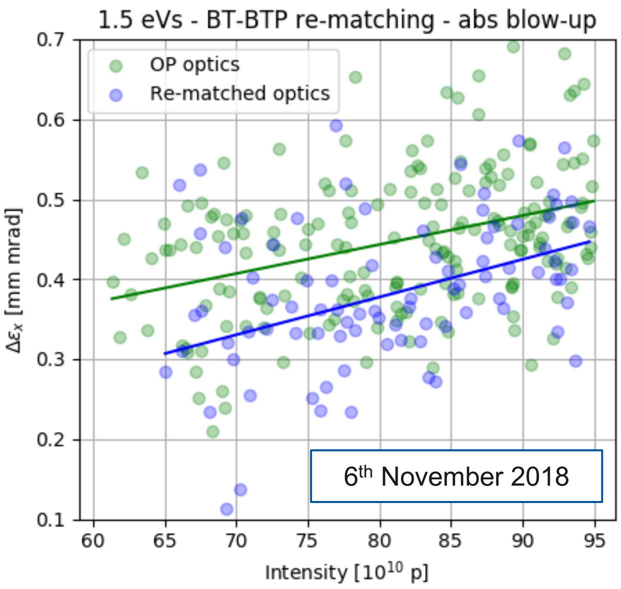




Measured H blow-up: re-matching BT-BTP

- Re-matching BT-BTP has only a small impact on filamented **horizontal emittance** measured 15 ms after injection using the wire-scanner:





Measured H blow-up: BCMS from R3

- Re-matching BT-BTP has only a small impact on filamented **horizontal emittance** measured 15 ms after injection using the wire-scanner:

Beam type	Relative momentum spread [1e-3]	OP optics $\Delta\varepsilon$ abs. [mm mrad] @ I = 75e10 p	
	Measured by TOMO	Expected	Measured
BCMS OP	0.9	0.15	0.33 ± 0.06
BCMS 1.5 eVs	1.4	0.36	0.43 ± 0.06
Ratio (1.5 eVs/OP)	$2.4 = (1.4/0.9)^2$	2.4	~ 1.3

*Dominant blow-up only from dispersion included in expected blow-up (other sources only few %)

Measured H blow-up: BCMS from R3

- Re-matching BT-BTP has only a small impact on filamented **horizontal emittance** measured 15 ms after injection using the wire-scanner:

Beam type	Relative momentum spread [1e-3]	OP optics $\Delta\varepsilon$ abs. [mm mrad] @ I = 75e10 p		Rematched optics $\Delta\varepsilon$ abs. [mm mrad] @ I = 75e10 p	
	Measured by TOMO	Expected	Measured	Expected	Measured
BCMS OP	0.9	0.15	0.33 ± 0.06	0.011	0.30 ± 0.09
BCMS 1.5 eVs	1.4	0.36	0.43 ± 0.06	0.027	0.35 ± 0.09
Ratio (1.5 eVs/OP)	2.4 = $(1.4/0.9)^2$	2.4	~ 1.3	2.4	~ 1.2

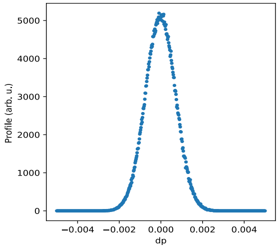
*Dominant blow-up only from dispersion included in expected blow-up (other sources only few %)

- A large, missing systematic contribution to the emittance growth is observed
- Difficult to explain entirely with the expected sources of blow-up

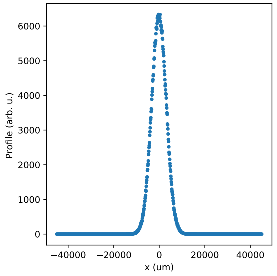
Impact of deconvolution algorithms

- Observed systematics in the measured data, see "Impact of deconvolution algorithms" in F. Antoniou's presentation, but also numerically:

Longitudinal
Gaussian (0.5 eVs)



Transverse
Gaussian (2.5 um)



Distributions	Quadrature (Gauss. fit) Emittance Error [%]	Deconvolution Emittance Error [%]
6D Gaussian $\varepsilon_T = 2.5$ um, $\varepsilon_L = 0.5$ eVs	+ 0.6	+ 0.25

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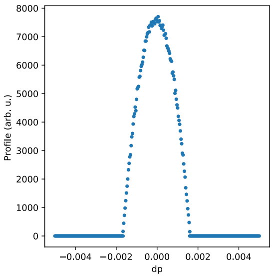
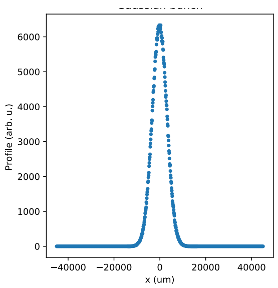
Parabolic (0.5 eVs)



Transverse
Gaussian (2.5 um)

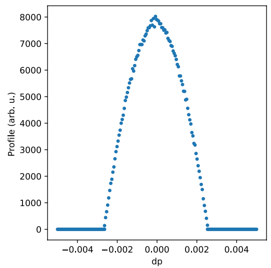


Distributions	Quadrature (Gauss. fit) Emittance Error [%]	Deconvolution Emittance Error [%]
6D Gaussian ε_T = 2.5 um, ε_L = 0.5 eVs	+ 0.6	+ 0.25
4D Gaussian + 2D Parabolic ε_T = 2.5 um, ε_L = 0.5 eVs	+ 4.4	+ 2.7

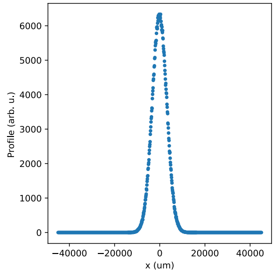
Impact of deconvolution algorithms

- Observed systematics in the measured data, see "Impact of deconvolution algorithms" in F. Antoniou's presentation, but also numerically:

Longitudinal
Parabolic (1.4 eVs)



Transverse
Gaussian (2.5 um)



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4D Gaussian + 2D Parabolic $\varepsilon_T = 2.5$ um, $\varepsilon_L = 1.4$ eVs	+ 14.9	+ 7.5

Contents

- What will change after LIU?
  - Overview of hardware upgrades, target beam parameters, upgraded injection scheme and recent MD's (low chromaticity and high intensity)
- Sources of emittance growth during transfer:
  - Catalogue of (known) contributors and their weighting, with latest MD results
  - Brightness measurements and BT-BTP transfer line re-matching
  - The challenge of systematic errors, deconvolution and present uncertainties
- Conclusion and outlook:
  - Looking to the future at 2 GeV and operation with large longitudinal emittance

Conclusion

- Turn-by-turn measurements after injection have confirmed and quantified the dispersion dominated mismatch
- Significant H (rms) blow-up in PS of ~ 0.33 mm mrad measured on BCMS OP 0.9 eVs compared to an expected blow-up of ~ 0.15 mm mrad:
  - No known physical source can explain the relatively large blow-up observed
- Re-matching BT-BTP TL made no significant impact on filamented emittance:
  - Same conclusion was reached after T-by-T SEM MD's in early 2000's [Ref7]
- Systematic errors play an important role in emittance measured from profiles:
  - Uncertainty in the optics parameters (e.g. β in PSB) and systematic errors in the momentum deconvolution algorithm (distribution dependent) are likely culprits
- No evidence yet that space-charge is driving the apparent blow-up

Outlook

- Too early to state firmly the expected blow-up during transfer at 2 GeV with the apparent role played by systematic errors:
  - Bright beams with large D make absolute emittance measurements challenging
- Lack of sensitivity to re-matching of the transfer line is concerning…
  - Further studies are planned in 2019 to check impact of systematic errors: from changing (filamented) distributions, including simulations with space-charge
  - Single coherent report to be published with full analysis of BGI and WS data
- Improved tools are needed to effectively de-convolute beam profiles
  - Will need to use lessons learnt in LS2 and apply them in operation in Run 3

Acknowledgement

- Thanks to the PSB and PS OP crews for putting up with us on very busy MD days and helping taking the data presented

- Thanks to BE-BI for the provision of the turn-by-turn SEM grid electronics and acquisition in 2018

References

- [Ref1] Studies by E. Senes, presented by M.A. Fraser at LIU Beam Performance Meeting, Emittance growth at PS injection for different longitudinal emittances, CERN, Geneva, 5 July 2018
- [Ref2] M. Serluca et al., Optics Studies and Space Charge Effects during the Injection Process at the CERN PS, Space charge meeting, CERN, Geneva, 6 April 2017
- [Ref3] M.A. Fraser, KFA14 flat-top ripple measurements, ABT-TCM meeting, CERN, Geneva, 1 October 2018
- [Ref4] V. Forte et al., *New beam-based and direct magnetic waveform measurements of the BTx.KFA10(20) vertical recombination kickers and induced emittance blow-up simulations at 1.4 and 2 GeV*, CERN-ACC-NOTE-2018-0032, 9 Apr 2018. - 30 p.
- [Ref5] V. Forte et al., *Magnetic Waveform Measurements of the PS Injection Kicker KFA45 and Future Emittance Growth Estimates,* CERN-ACC-NOTE-2018-0031, 9 Apr 2018. - 47 p
- [Ref6] V. Forte et al., Overview of the CERN PSB-to-PS Transfer Line Optics Matching Studies in View of the LHC Injectors Upgrade Project, WEP2PO006, HB 2018, Daejeon, Korea, 18 -22 June 2018
- [Ref7] M. Benedikt et al., Study of a new PSB-PS Transfer Line Optics with Improved Dispersion Matching by means of turn-by-turn beam profile acquisitions, PS/AE/Note 2001-003 (MD), CERN, Geneva.

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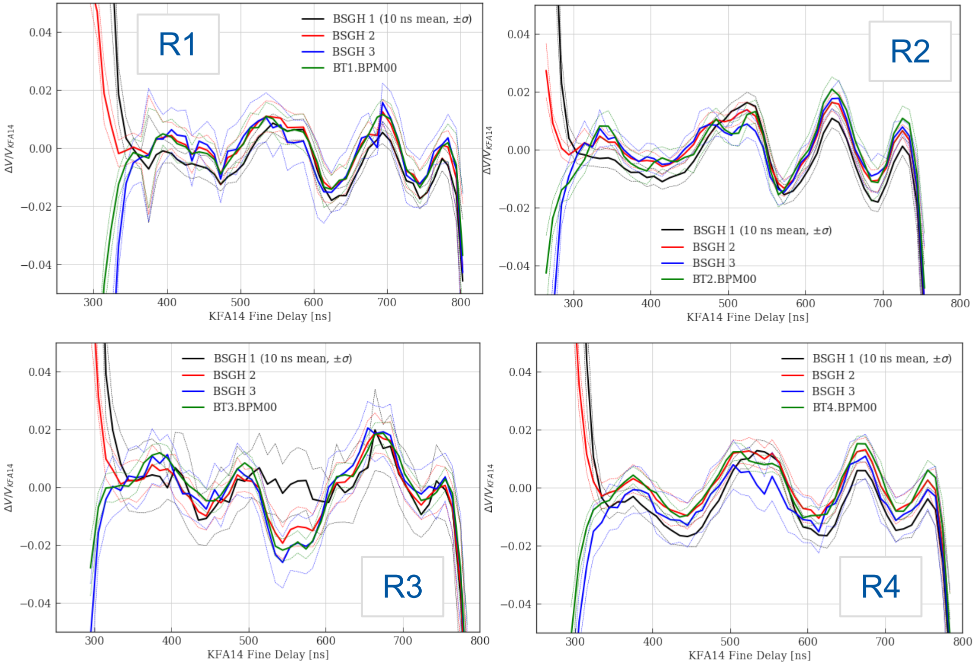
Extra slides

Blow up from KFA14

- PSB extraction kicker waveforms measured for all rings [ref3]:
  - Beam-based measurements using short (σ = 10 ns) INDIV bunch
  - Ripple < ±1.5%



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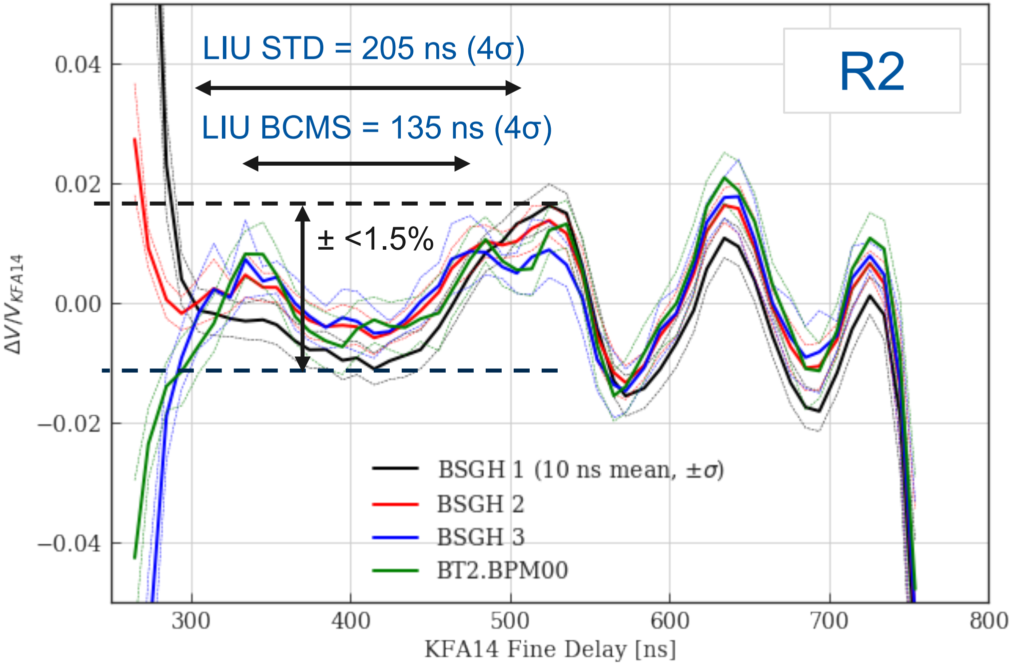

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  - Beam-based measurements using short (σ = 10 ns) INDIV bunch
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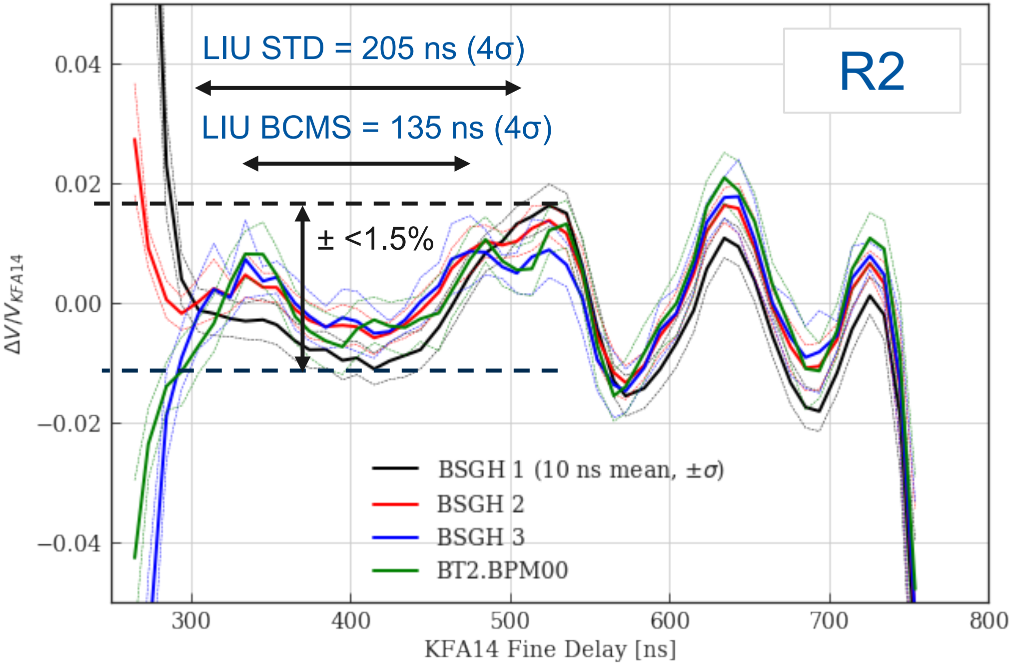
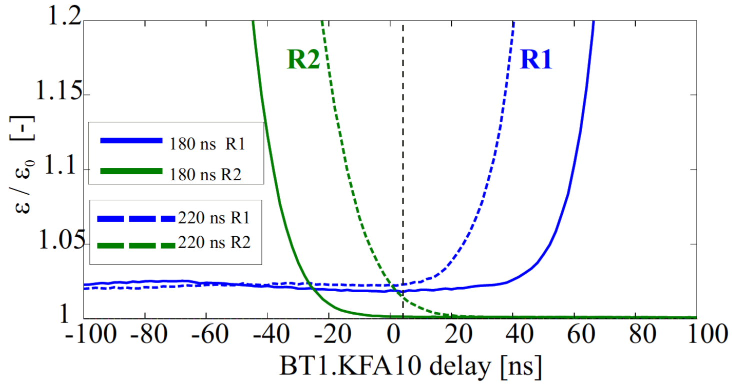
- Beam-kicker synchronisation is an important commissioning step



Blow up from KFA10 and KFA20

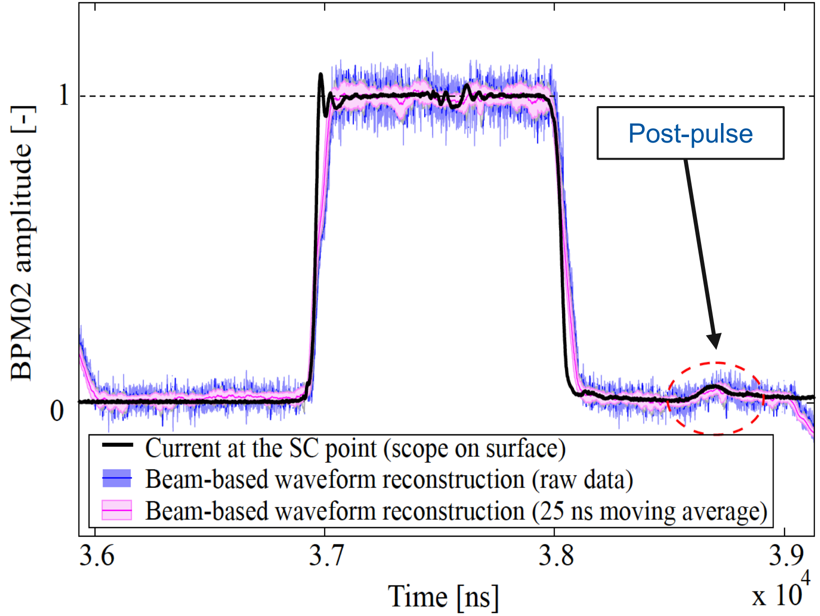
- Recombination kicker waveforms measured and emittance growth assessed [refX]:
  - Beam-based measurements carried out using long bunches
  - Rise-times limit length of bunches
  - **Vertical** blow-up depends on bunch length
  - Estimated blow-up depends on ring, worst-case < 3%
  - Worst-case LIU standard beam at 2 GeV (205 ns) from 2 – 3% shown in table:



KFA	Vertical blow-up [%]			
	R1	R2	R3	R4
BT1.KFA10	1.9	1.9	0	0
BT4.KFA10	0	0	1.9	1.9
BT2.KFA20	1.0	2.2	0.0	0.3
Total	**2.1**	**2.9**	**1.9**	**1.9**

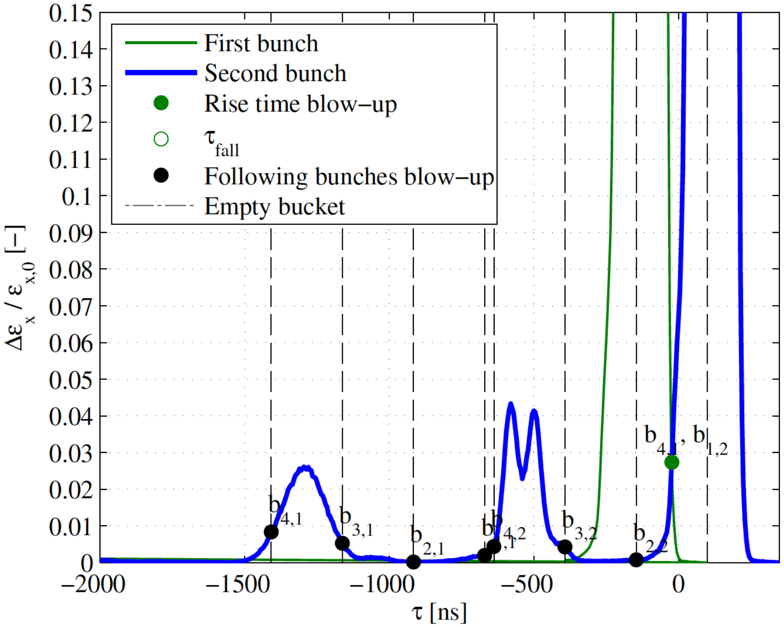
Blow up from KFA45

- Beam based measurements combined with PSpice model current to estimate emittance blow-up [ref5]:
  - Measurements resolution limited (~5%)



Blow up from KFA45

- Beam based measurements combined with PSpice model current to estimate emittance blow-up [ref5]:
  - Measurements resolution limited (~5%)
  - Blow-up at 3.5% for certain bunches
- Post-pulse ripple shown to be constant and does not scale with voltage
- Next steps:
  - Magnetic measurements made in tunnel at start of LS2 available, blow-up estimates to be reviewed



Measured H blow-up: $\Delta\varepsilon$ unaccounted for?

- To elucidate the challenge we face with systematics, let's consider what effective emittance blow-up is missing to give the measured values
  - Assuming independent error sources, adding linearly:

$$\Delta\varepsilon_{\text{missing}} = \varepsilon_{\text{PS,meas}} - \left(\varepsilon_{\text{PSB,meas}} + \frac{1}{2} M_D^2 \left(\frac{\Delta p}{p}\right)^2\right)$$

Beam type	$\Delta\varepsilon_{\text{missing}}$ for OP optics [mm mrad]	$\Delta\varepsilon_{\text{missing}}$ for Re-matched optics [mm mrad]
BCMS OP	0.18 ± 0.06	0.29 ± 0.09
BCMS 1.5 eVs	0.07 ± 0.06	0.32 ± 0.09

  - A large, missing systematic contribution to the emittance growth is observed
  - Difficult to explain entirely with the expected sources of blow-up

Dispersion mismatch vs. DP/P

- Study of blow-up measured with wire-scanners using standard LHC25 beam as function of longitudinal emittance:
  - $\Delta\varepsilon \propto \left(\frac{\Delta p}{p}\right)^2$ for large Δp
  - Factor two larger mismatch observed
  - Deconvolution/systematics in both machines play a role

Technique	M_D [$m^{1/2}$]	
	I = 1.6e12 p	I = 2.0e12 p
Wire-scanner profile $\Delta\varepsilon$ (Deconvolution of dispersive component needed)	0.77 ± 0.003	0.74 ± 0.003
T-by-turn data (BPM/SEM)	0.40 ± 0.04	

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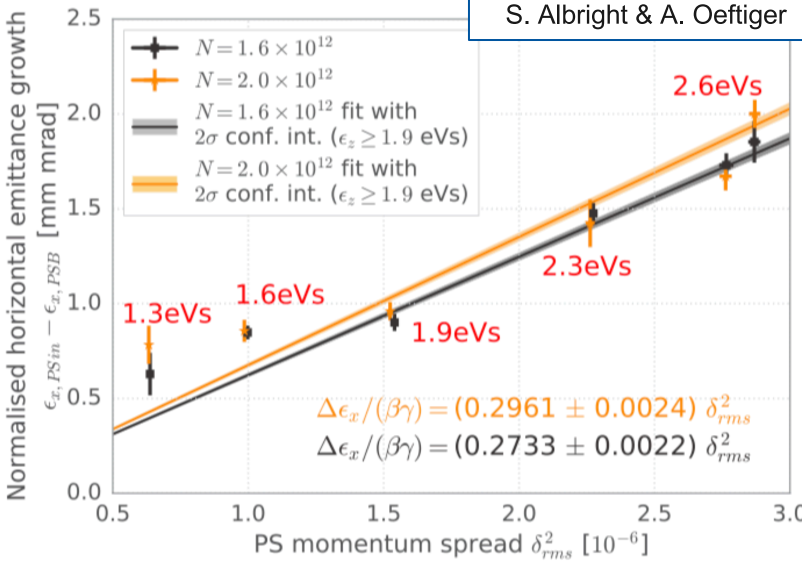
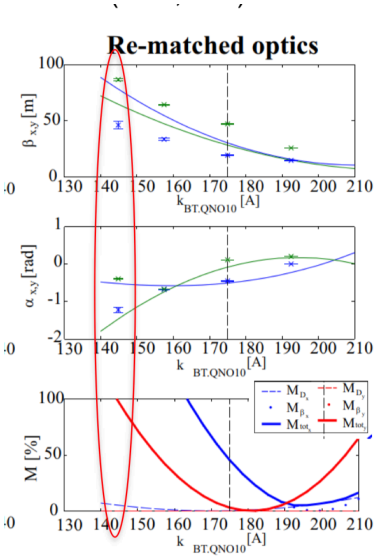


Introducing significant betatronic mismatch

- Deliberate mismatch to excite betatronic mismatch:



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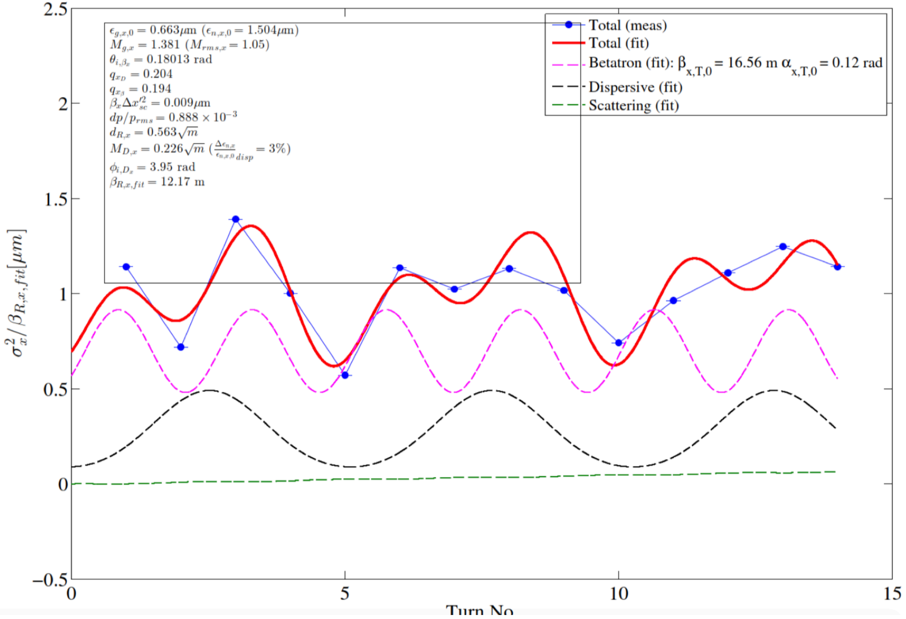
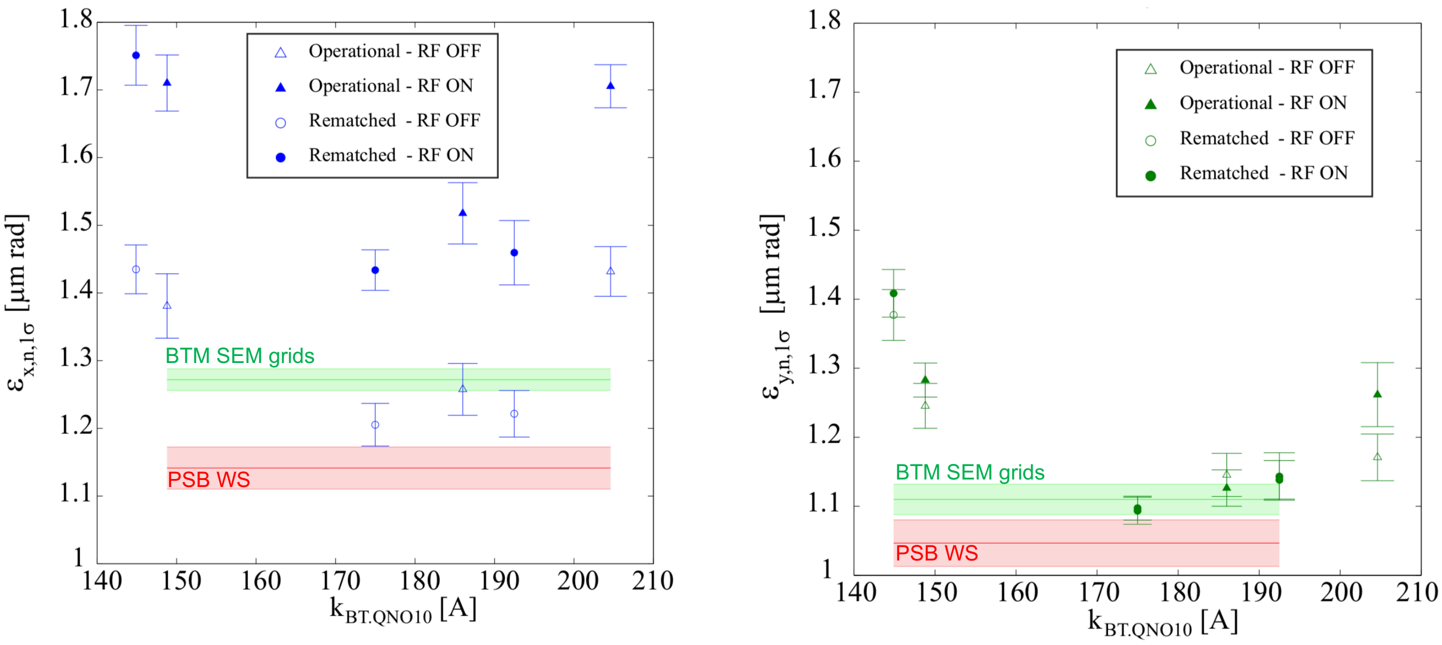


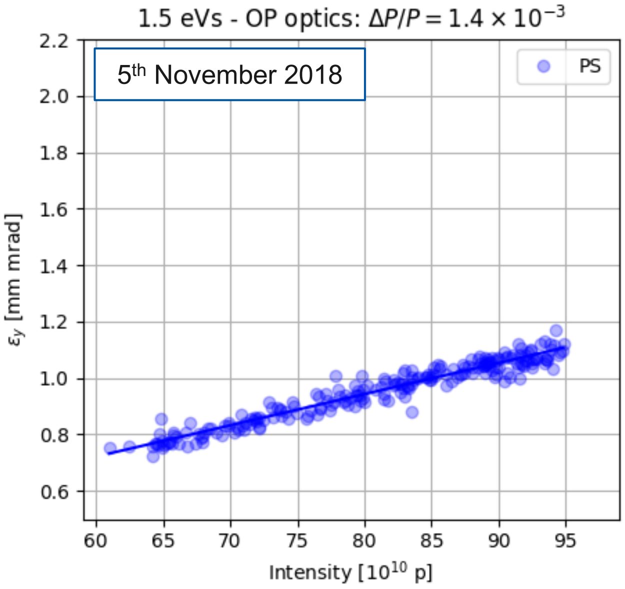
Sensitivity studies with mismatch of BT-QNO10

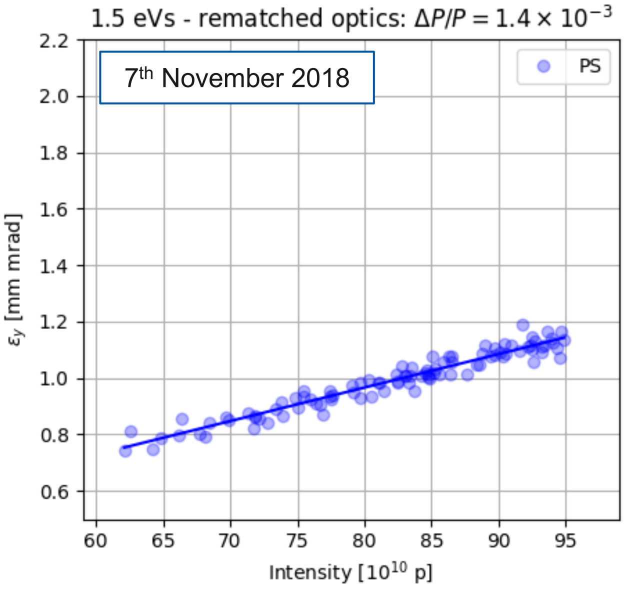
- Systematic emittance blow-up studies



Measured V blow-up: BCMS 1.5 eVs

- Re-matching BT-BTP has no impact on filamented **vertical emittance** measured 15 ms after injection using the wire-scanner:





Summary of blow-up studies

- Emittance blow-up measurements are sensitive to systematic errors and appear unreliable
  - Important to better understand role played by errors on optics functions, changing distributions with filamentation and deconvolution etc.

- Horizontal blow-up measured after filamentation is larger than expected from the observed envelope oscillations at injection:
  - In other words, re-matching TL (validated by T-by-T measurements) has very little impact
  - Same conclusion was reached after T-by-T SEM MD's in early 2000's
  - Difficult to attribute the unknown blow-up source to imperfections (e.g. steering, kicker ripple, injection energy error, etc.)
  - No blow-up seen in ~ ms after injection on WS measurements: indicates fast effects (< 2 ms, comparable to profile measurement integration time) or systematic error