5th ICFA Mini-Workshop on Space Charge – Oak Ridge 2022
24/10/2022

Resonance Compensation for High Brightness Beams in the CERN PSB

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PSB-OP team

Overview

- Motivation
- Identification of resonances
  - Loss maps
- Resonance compensation
  - Resonance-by-resonance
  - Global settings
- Impact on High Brightness Beams
  - Emittance & profile shape
- Summary & Outlook

Motivation – LIU Upgrade

PSB is the first synchrotron of the CERN injector chain for protons:

- Defines the **maximum brightness** for the full complex operating with $\Delta Q_{x,y} \approx -0.5, -0.6$

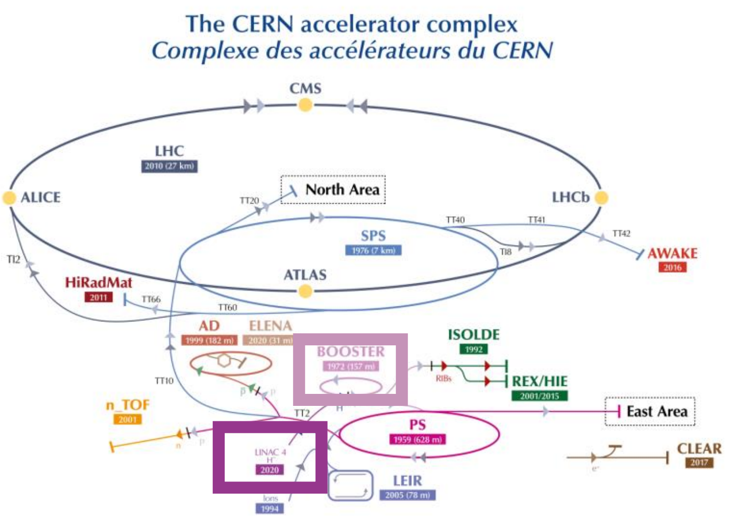
Aim of the **LIU project**

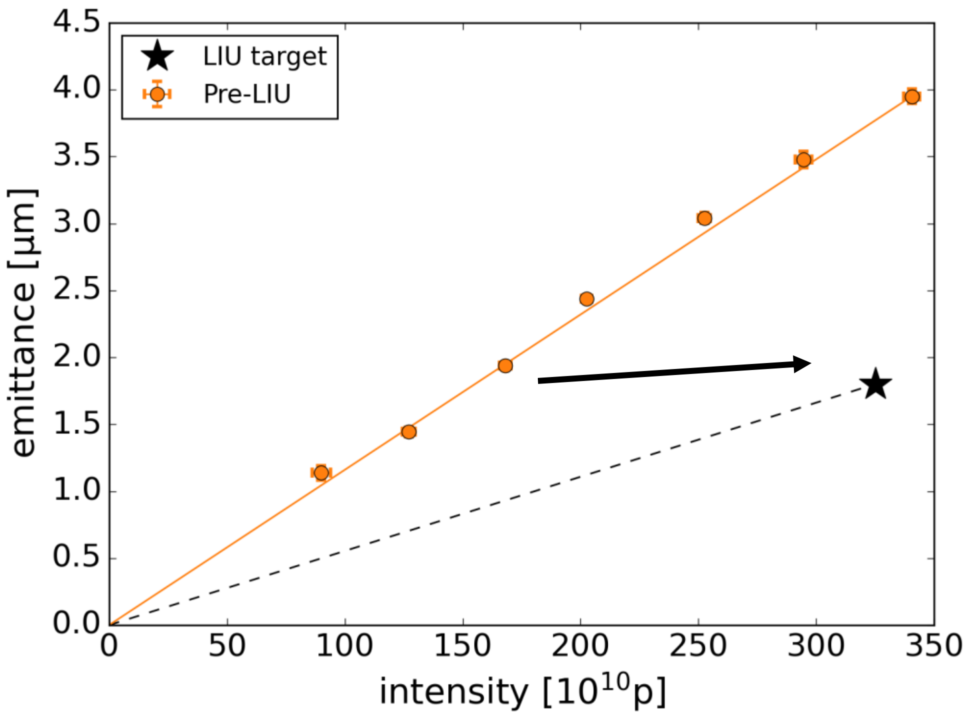
➢ **Double the brightness**

➢ **Maintain similar space charge tune shifts**

○ Increased injection energy 50 MeV → 160 MeV with the new **LINAC4**

○ Increased extraction energy from 1.4 GeV to 2 GeV





Motivation – Maximize brightness

Space charge remains the main brightness limitation in the PSB – the **working p** **preserve the bright**

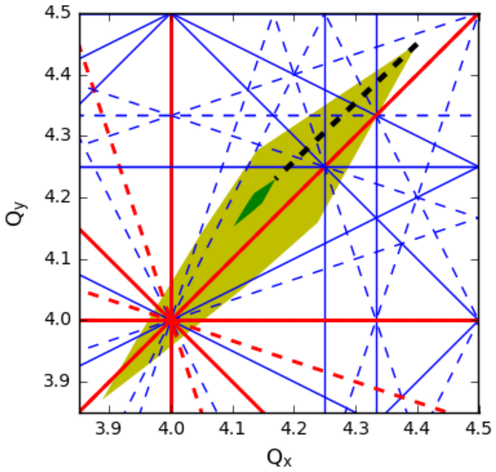
- ***High Injection Tu***

  minimizing
  energy tha
  significant

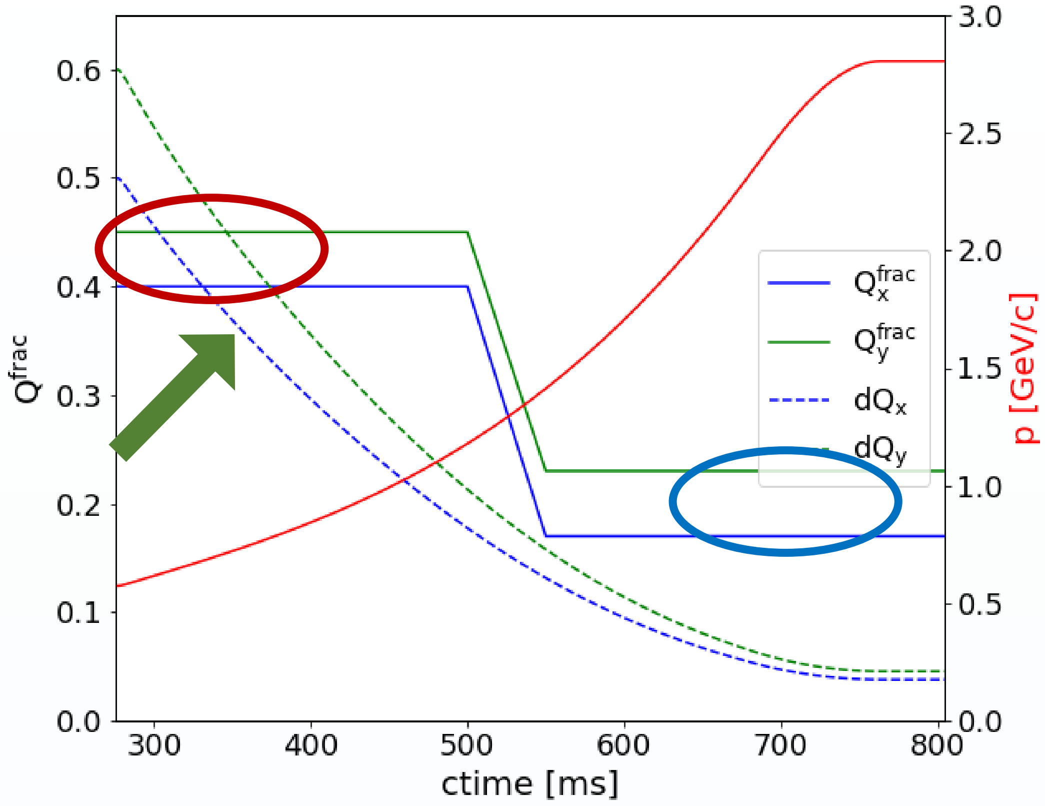
- ***Ramp to resonan***

  minimizing
  that can ca
  Losses
  Emittance
  Transverse

- **At low energy** many resonances are overlapped due to space charge
- During **the tune ramp,** the resonances are being crossed
- **At high energy** no impact from resonances & space charge is expected



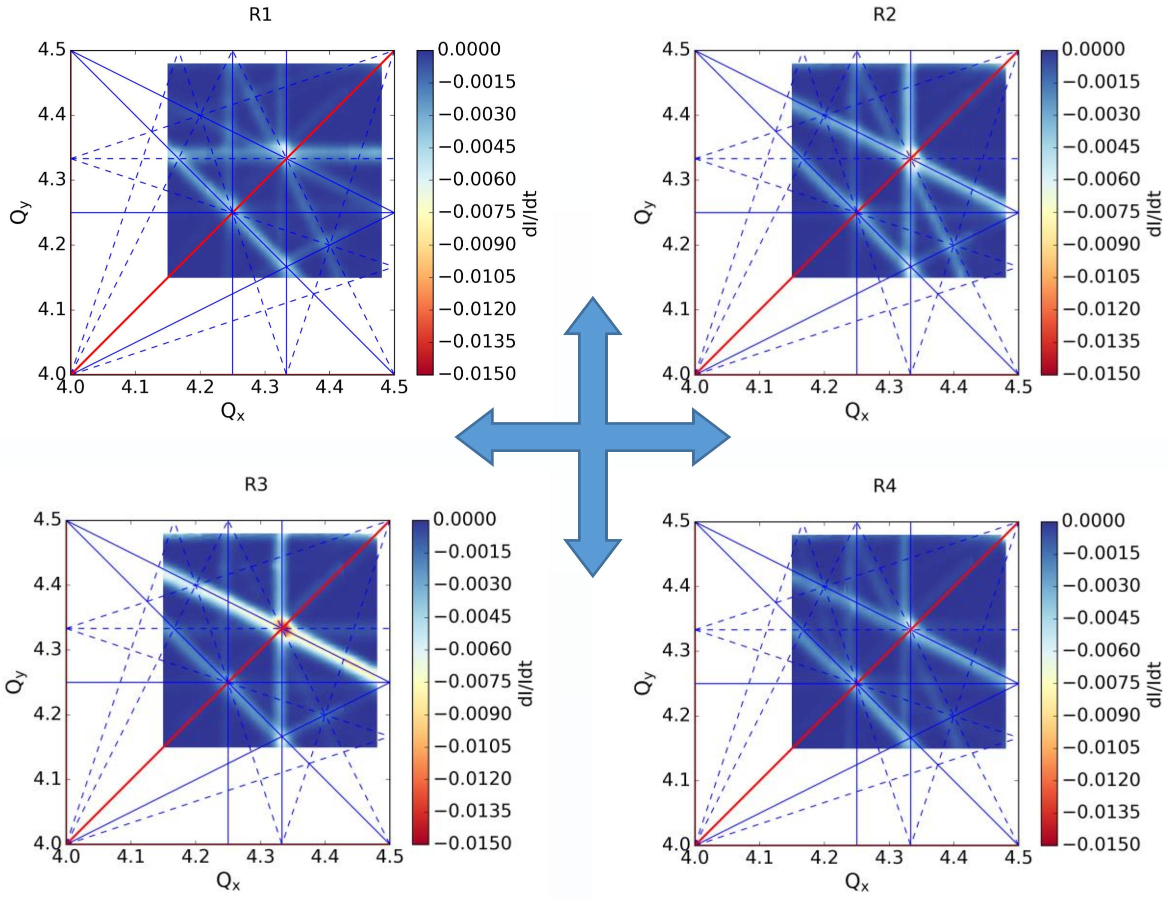
Resonance identification & compensation studies needed!



Resonance Identification

One tune ($\boldsymbol{Q_x}$ ***or*** $\boldsymbol{Q_y}$) is being varied during C350-700ms from $[\mathbf{4.15-4.48}]$ (and **vice versa**) while the other is kept constant.
The resonances can be seen through the loss rate calculated from the intensity curve.
The study is done on a **flat cycle** with a **low brightness** beam ($\Delta Q_x \approx \Delta Q_y \approx -0.035$)

→ **All sextupole** & **octupole** resonances can be seen in **all rings**
→ **Normal sextupole** resonances are stronger in **R2, R3 & R4**
→ **Skew sextupole** resonances are stronger in **R1**
→ **Octupole** resonances are strong in **all rings**

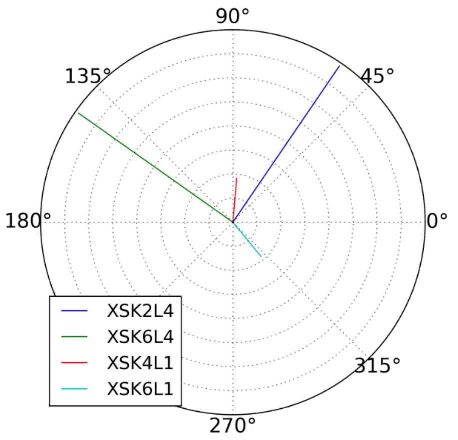


Resonance Compensation – Individually

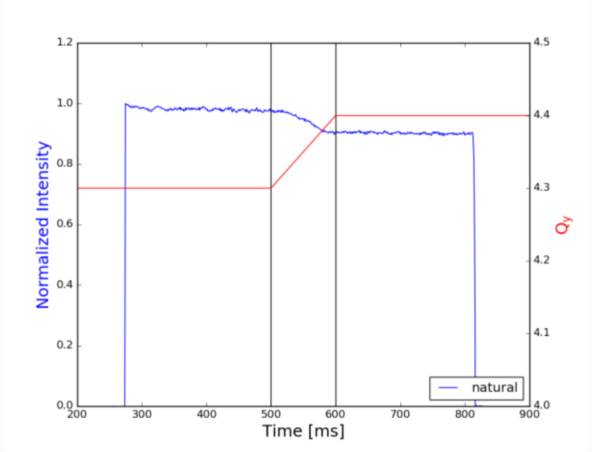
For each resonance:
1. Resonances dynamically crossed
2. Identified **suitable correctors**
3. **Vary currents** while monitoring losses
4. **Verify** configuration

2. RDT/MADX-PTC

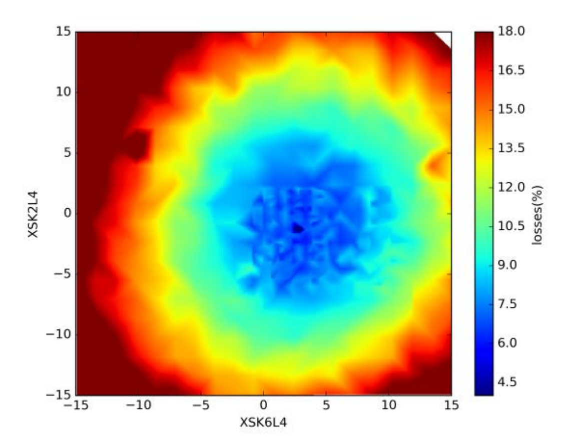
For every observed resonance, identify (RDT, MADX-PTC) complementary corrector pairs



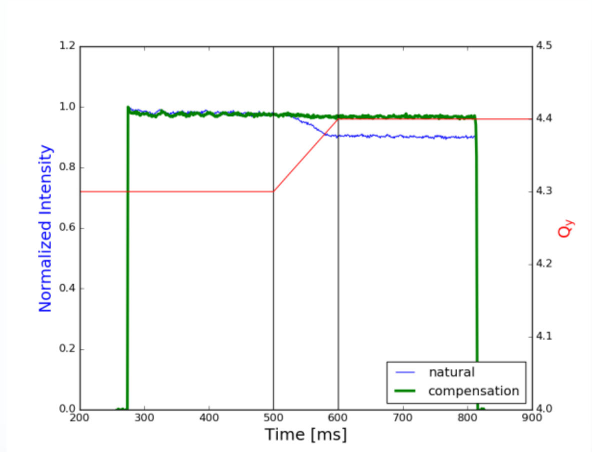
1. Cross dynamically



3. Vary currents

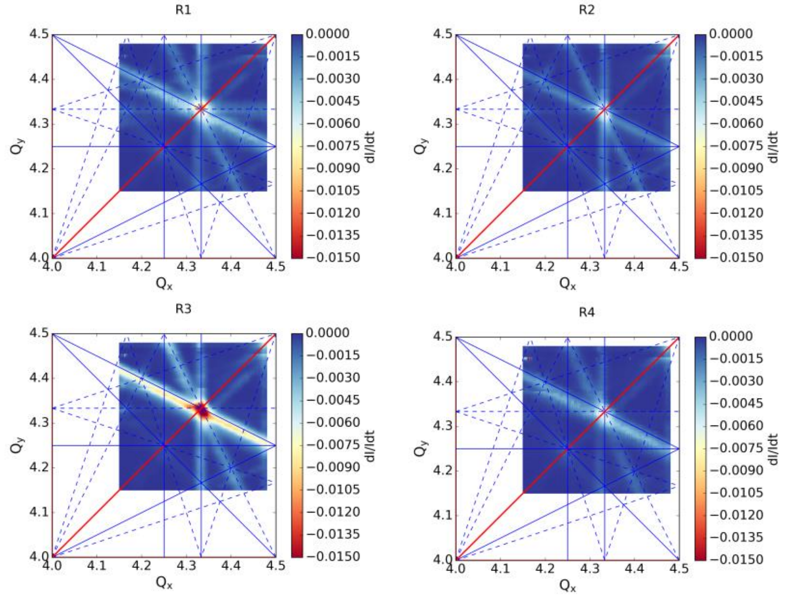


4. Validation



Resonance Compensation – Globally

4th order normal resonances:
The compensation values estimated experimentally seem identical for all resonances



3rd order skew resonances
not enough correctors…

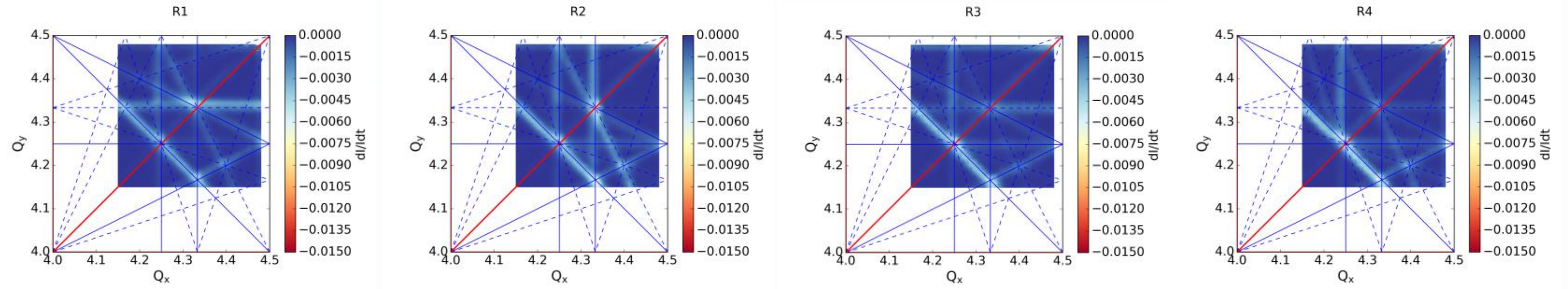
3rd order normal resonances:
Using **PTC and the MADX model** where the resonances are crossing each other:

- Calculate the RDTs of the resonances based on the **compensation values**
- Calculate the RDTs of **each available magnet** for all resonances of interest

Global solutions estimated

$$\begin{bmatrix} Re[RDT^{sext1}_{3Qx}] & Re[RDT^{sext2}_{3Qx}] & Re[RDT^{sext3}_{3Qx}] & Re[RDT^{sext4}_{3Qx}] \\ Im[RDT^{sext1}_{3Qx}] & Im[RDT^{sext2}_{3Qx}] & Im[RDT^{sext3}_{3Qx}] & Im[RDT^{sext4}_{3Qx}] \\ Re[RDT^{sext1}_{Qx+2Qy}] & Re[RDT^{sext2}_{Qx+2Qy}] & Re[RDT^{sext3}_{Qx+2Qy}] & Re[RDT^{sext4}_{Qx+2Qy}] \\ Im[RDT^{sext1}_{Qx+2Qy}] & Im[RDT^{sext2}_{Qx+2Qy}] & Im[RDT^{sext3}_{Qx+2Qy}] & Im[RDT^{sext4}_{Qx+2Qy}] \end{bmatrix} \times \begin{bmatrix} F_{ksext1} \\ F_{ksext2} \\ F_{ksext3} \\ F_{ksext4} \end{bmatrix} = \begin{bmatrix} Re[RDT^{meas}_{3Qx}] \\ Im[RDT^{meas}_{3Qx}] \\ Re[RDT^{meas}_{Qx+2Qy}] \\ Im[RDT^{meas}_{Qx+2Qy}] \end{bmatrix}$$

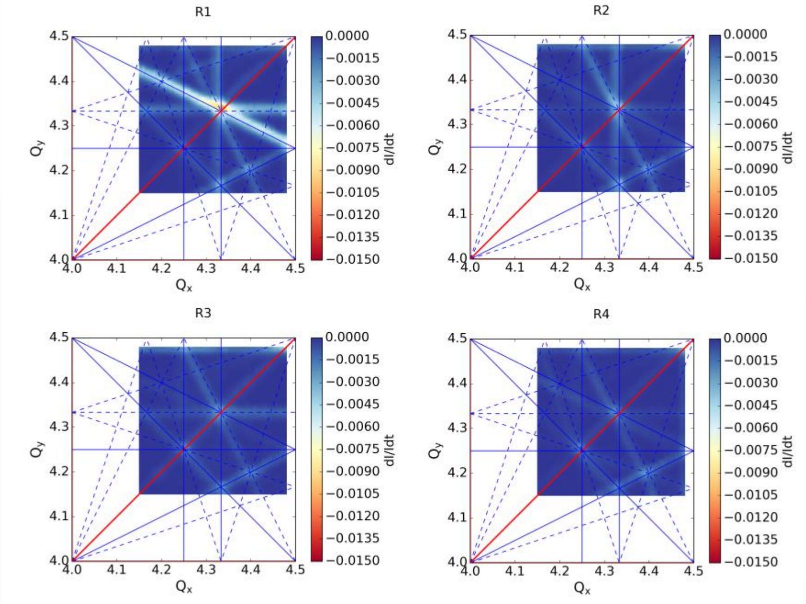
- **Significant suppression of both resonances** in all rings but R2 (current limitation)



Resonance Compensation – Globally

Testing the **global configurations**

- ✓ Significant **suppression**
- ○ **current limitations** &/or **limited # of correctors**
- ○ Not possible to refine solutions for **partially compensated** resonances
- ○ Significant **cross-talk** of corrections & resonances – misalignment & FeedDown

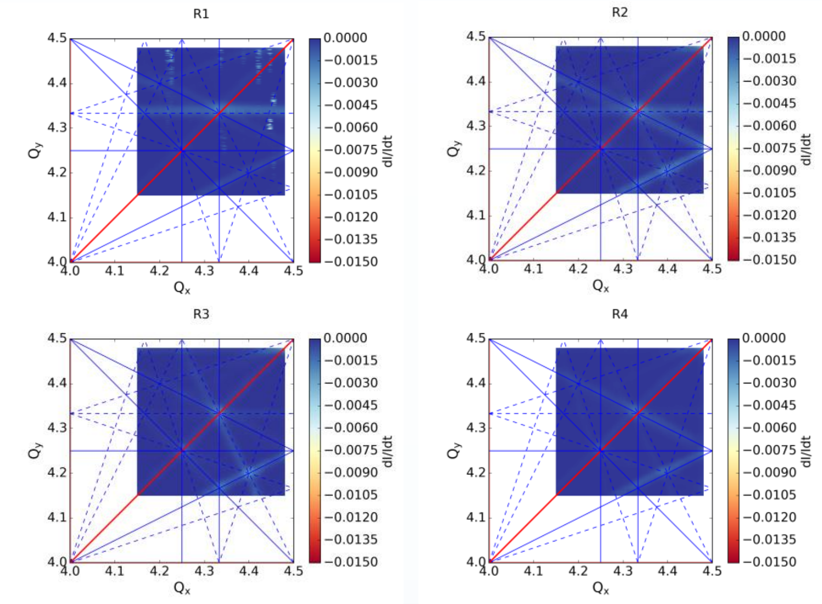


→ **Optimization Framework GeOFF**

- **Fast convergence** for individual resonances
- **Flexible** to add extra corrector magnets either for investigations of individual resonances or global settings

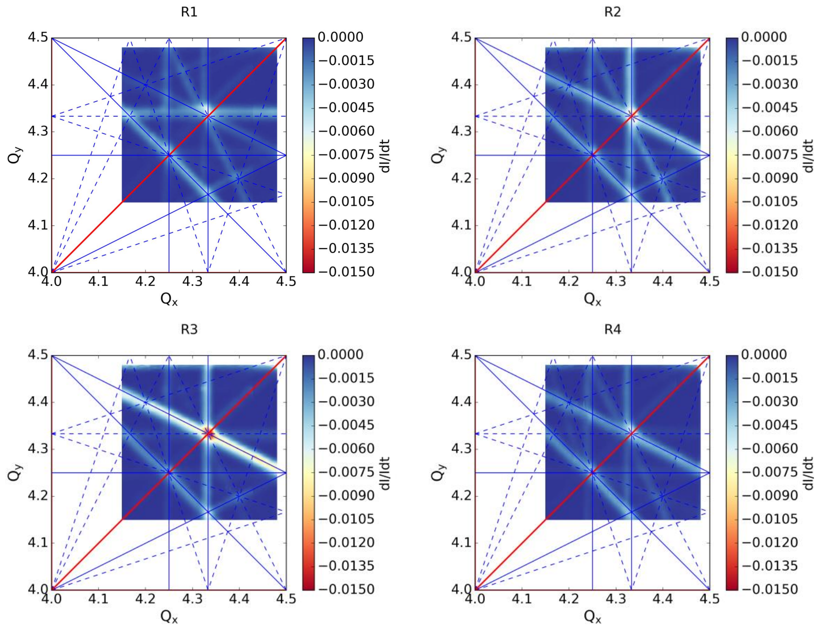
✓ **Better compensation** of partially corrected resonances using more correctors

✓ **Global settings** for all rings (including cross-talks)

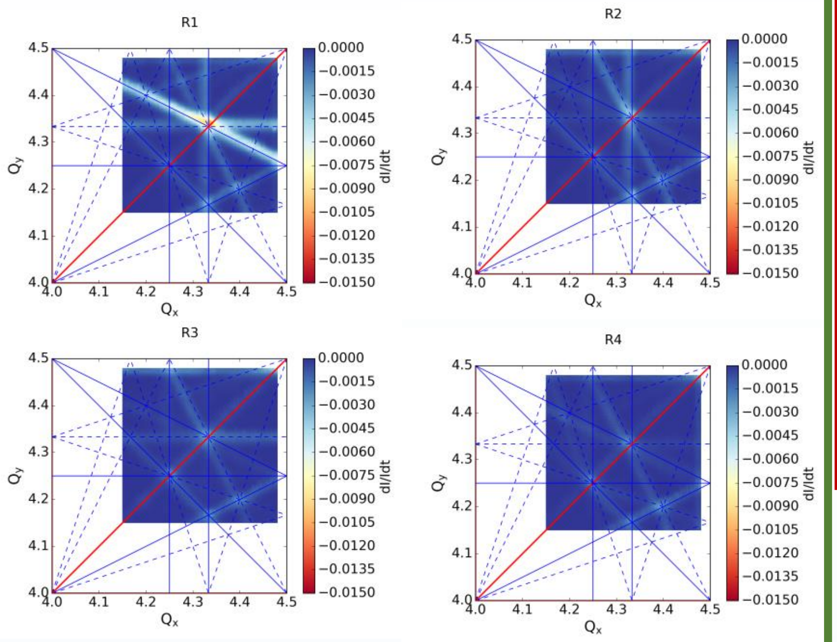


Resonance Compensation - Summary

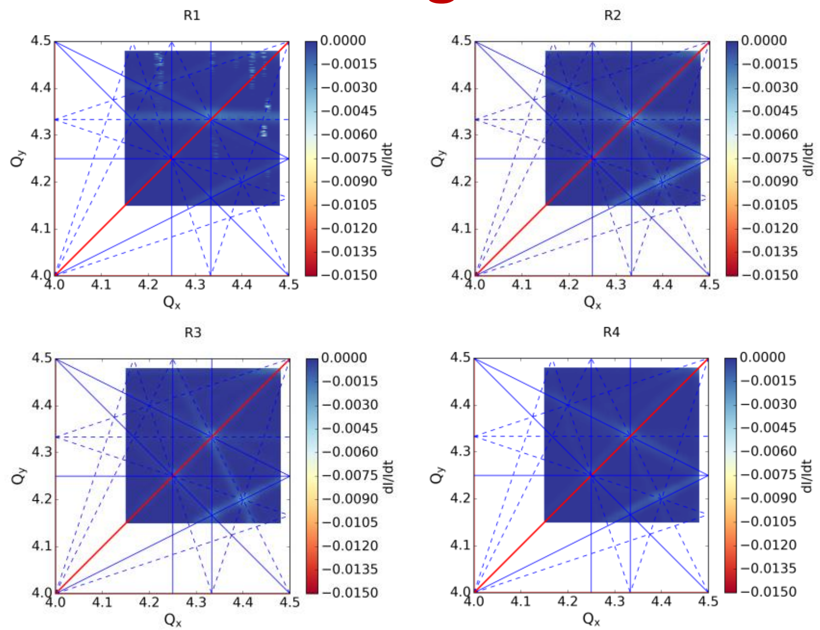
Natural excitation



Analytical estimations



Final configuration



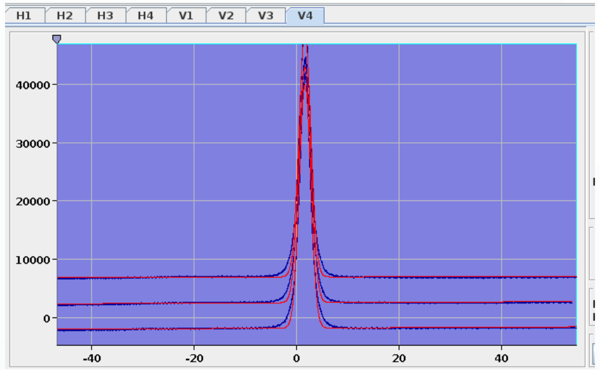
✓ **All resonances suppressed in the operational regime**

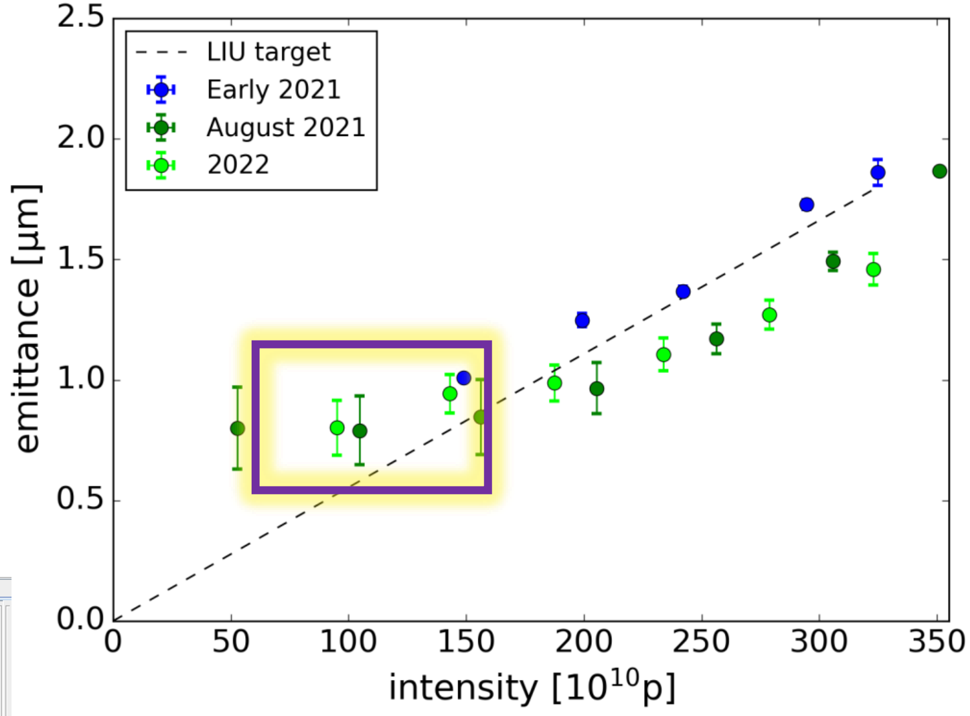
All studies at low energy *– global configuration cannot be scaled (corrector current limitations)*

High Brightness beams

- **LIU target** for the LHC brightness already **achieved** using the **individual resonance compensation** settings
  - *Changing correctors while crossing resonances*
- **LIU target exceeded** when including
  - **global resonance compensation**
  - **β-beating correction**
  - **applying the design working point evolution**
- **Large transverse tails** are observed causing losses at LHC injection – especially for "**BCMS**" regime

*note **emittance plateau** for the BCMS regime up to ~150e10 (injected emittance & foil scattering)*





High Brightness beams – Transverse tails

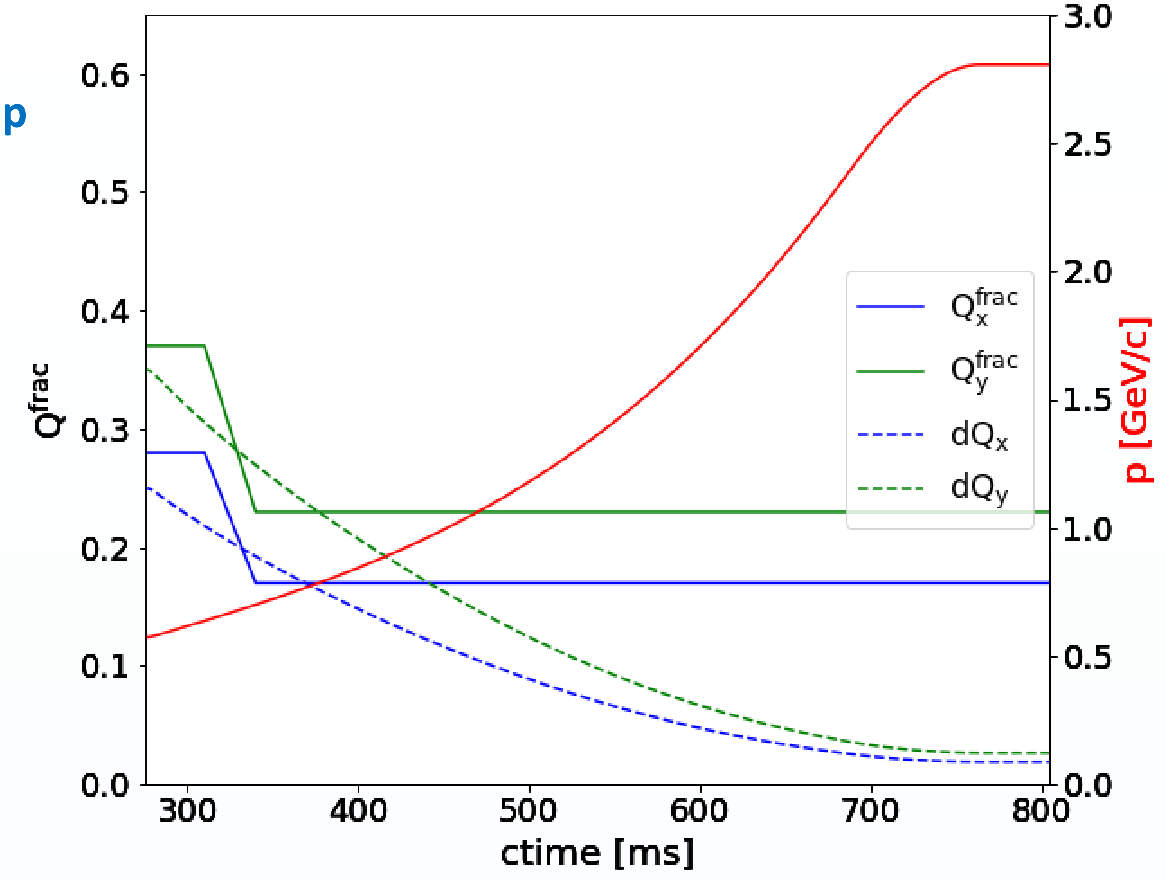
- ***High Injection Tunes** (4.4/4.45)***:
  minimizing interaction with integer resonances for low energy that causes: **significant emittance blow-up**
- ***Ramp to resonance free space** (4.17/4.23)*:
  minimizing interaction with higher order resonances that can cause: **Losses**
  Emittance blow-up
  Transverse tails

Nom

*note **emittance plateau** for the BCMS regime up to ~150e10*

***Smaller** space charge tune shift*

- ***lower injection tunes** (4.37/4.28)* **OptB**
- ***faster ramp down***
  - *ramping down **even faster - minor blow-up*** **OptT**

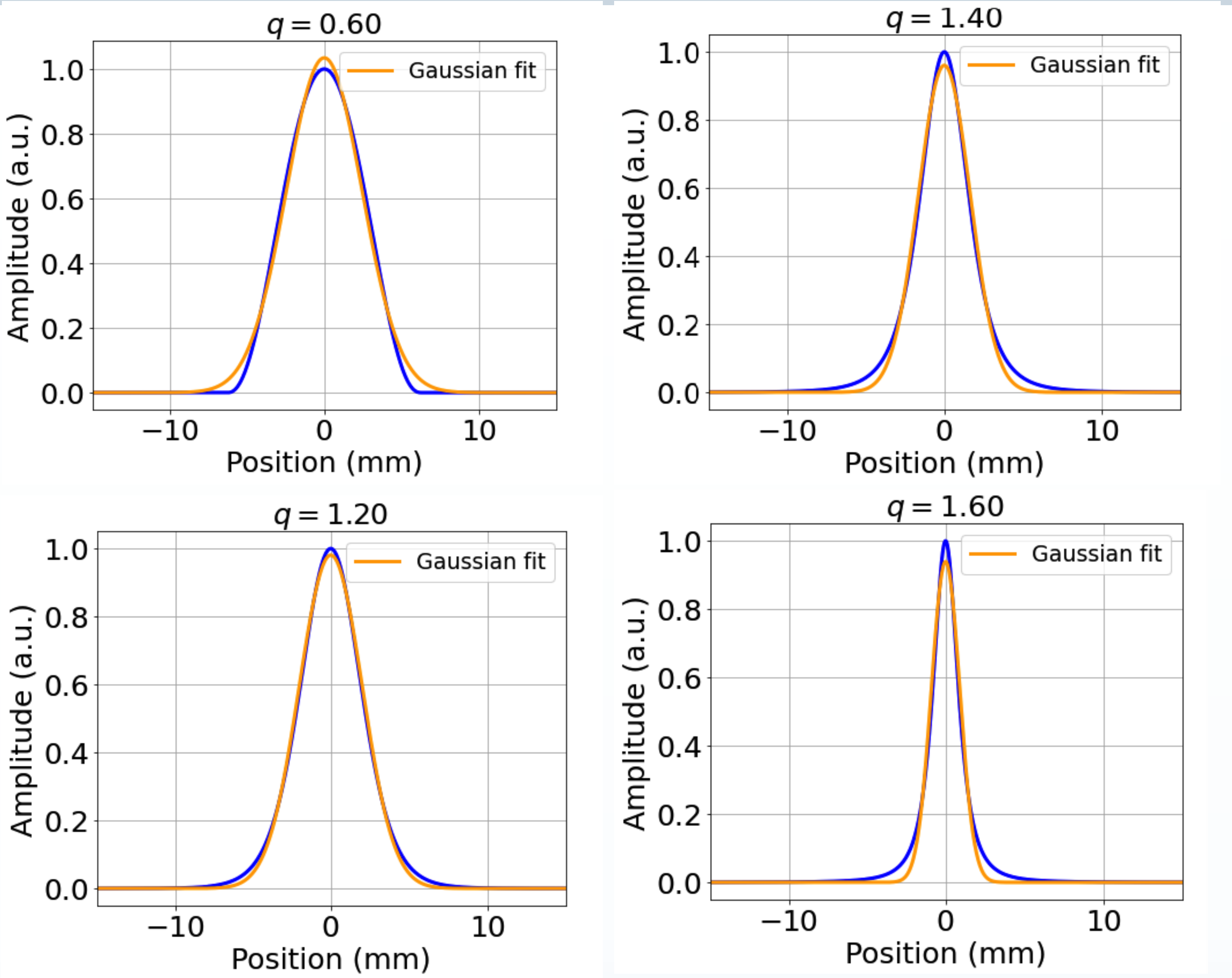


Transverse tails characterization – qGausian

- Generalized Gaussian function:
- q-factor characterizes the tail population:
  - $\boldsymbol{q = 1}$ **: Gaussian tails**
  - $\boldsymbol{q > 1}$**: overpopulated tails**
  - $\boldsymbol{q < 1}$**: underpopulated tails**
- β controls the height/width:

$$\sigma_{QG} = \begin{cases} [\beta(5-3q)]^{-\frac{1}{2}}, & q < 5/3 \\ \infty, & \frac{5}{3} \leq q < 2 \\ undefined, & 2 \leq q < 3 \end{cases}$$

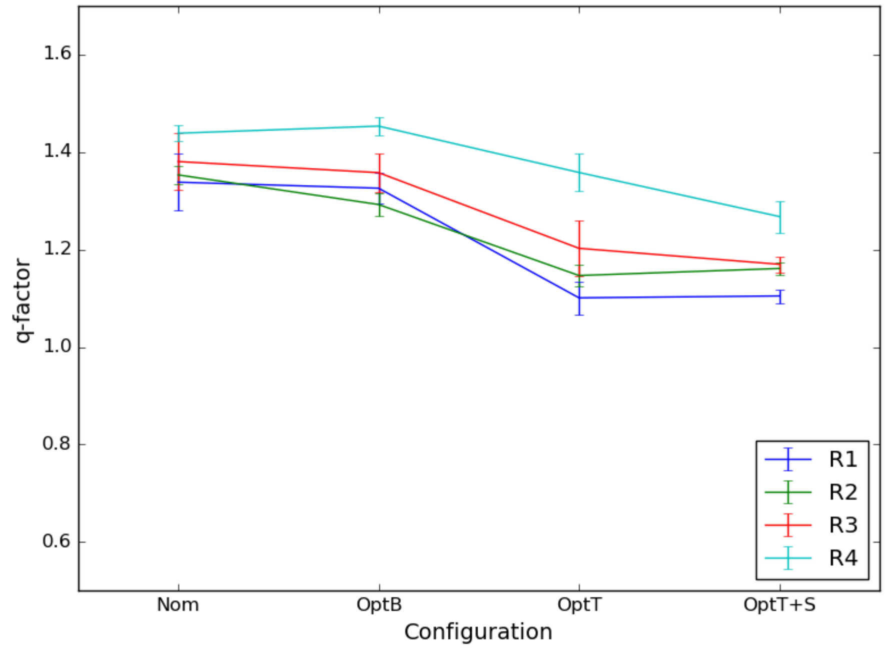
T. Prebibaj et al.: LN4/PSB MPC #66

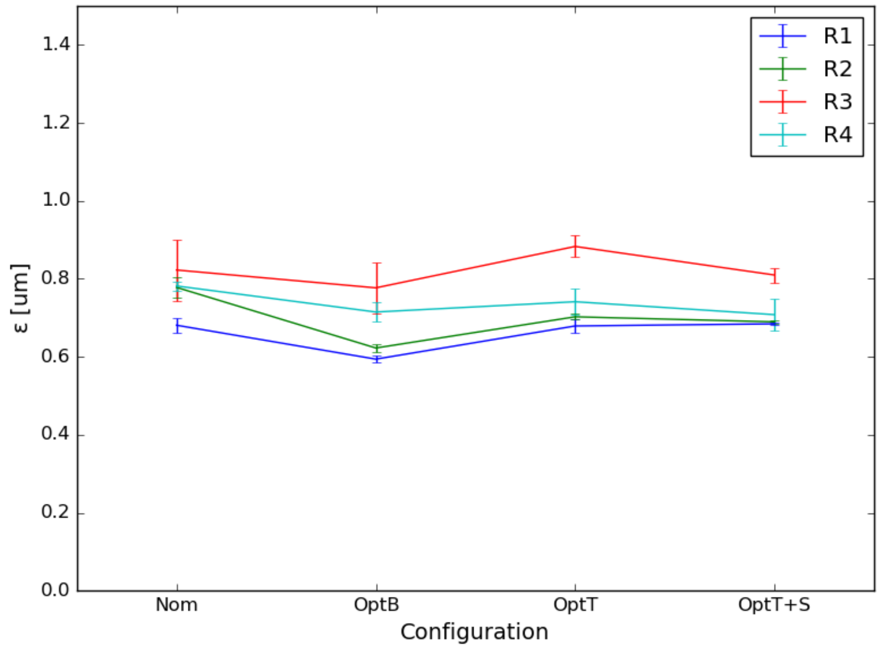


High Brightness beams – Transverse tails (*V*)

Checking the different configurations (***Nom***, ***OptB***, ***OptT***, & ***OptT + Shavers***) in the PSB:

- **Minor impact on emittances** (brightness) for the nominal BCMS intensity (~**85e10**)
- **Tail content reduces** in all rings – from ~1.4 to 1.2
- **Variation** of tail content per ring – *R4 seems to always behave worse than the others*
- **Shaving** doesn't give any substantial impact (for rings other than R4)



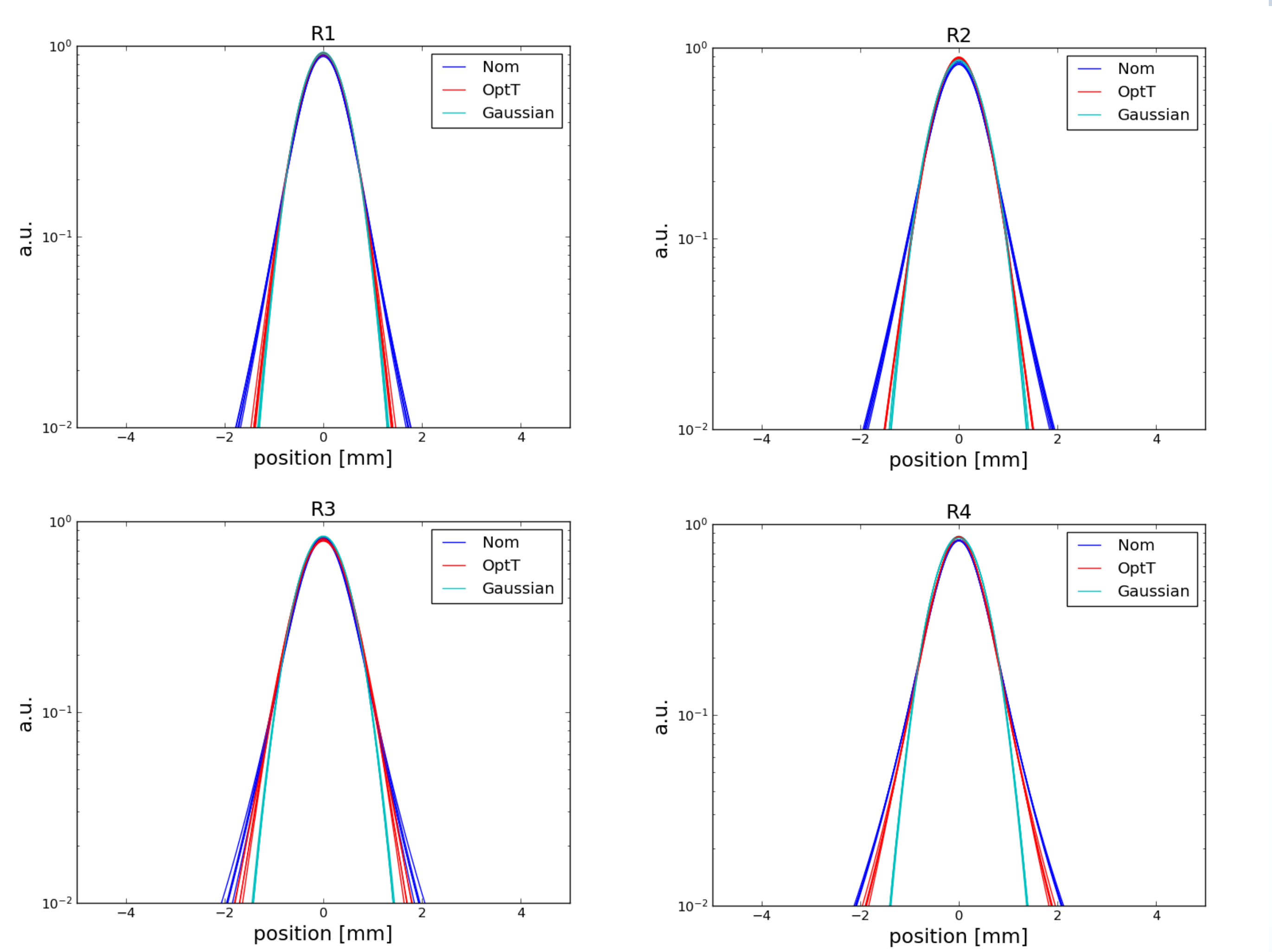


High Brightness beams – Transverse tails (*V*)

Comparison of the vertical profiles in all rings for the **Nominal (Nom)** and **Optimized Tails (OptT)** variants show **reduction of the transverse tails**

*Plotting in **logscale** to better characterize the tails **–** **Gaussian** for reference*

- **R1 & R2** seem to benefit the most showing the largest tail reduction
- **R3 & R4** show some improvements but less significant.



Summary & *Outlook*

- Studies for **resonance identification** revealed excited resonances **up to 4th order** in all PSB rings.
- Through compensation studies combining **analytical, experimental techniques** & the **optimizer:**
  - Compensation (full or partial) of all observed resonances
  - Schemes for the **simultaneous compensation** of multiple resonances
- **Target LHC brightness** achieved with satisfactory compensation of all observed resonances
- Working point & resonance compensation modifications for the LHC **beam reduced the transverse tails** in all rings (q-factors: *1.4 -> 1.2 still not Gaussian!*)
  - Ring-to-ring variations are observed

- *Include **measured errors** (through compensation values) **in simulations** to improve the model*
- *using the machine model*
  - ***Refine compensation schemes** &*
  - *Investigate **different configurations** for the compensation that can be **scaled with energy***
- ***Investigate ways for reducing the transverse tails with higher brightness – S. Albright talk***

Summary slide, 5th ICFA mini-workshop on Space Charge
Theme: Bridging the gap in space charge dynamics

In 1-2 sentences, summarize the content of this presentation
(If relevant, specify type of facility, species, tune shift):

- The CERN PSB defines the maximum brightness for the proton chain while operating on a maximum space charge tune shift of -0.5/-0.6

✓ Identification & compensation of multiple non-linear resonances both individually & globally to maximize brightness

✓ Proposal of alternative operational scenarios to balance brightness & transverse distribution quality

From your perspective, where is the gap regarding space charge effects?
(understanding/control/mitigation/prediction/?)

- Refining & understanding the modeling of the higher order nonlinearities to better predict (& overcome) limitations imposed from their interplay with the strong space charge effects

What is needed to bridge this gap?

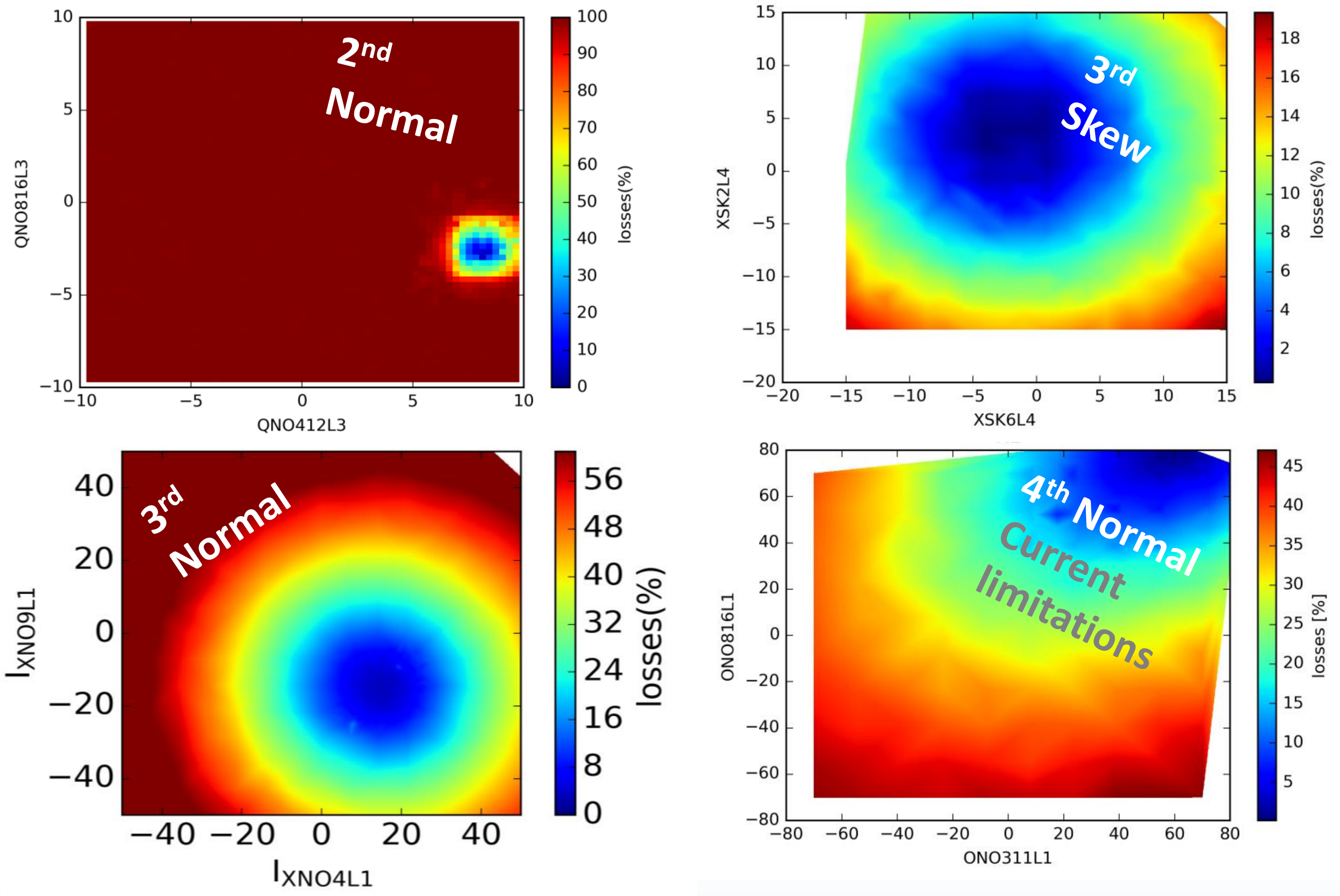
- Measurements of the nonlinear components, with independent methods to get the most accurate description (e.g., through induced losses & compensation, beam spectrum, magnetic measurements)
- Benchmarking experiments to validate simulation models and characterize the effects
- Resources for lengthy space charge simulations

Thank you for your attention!

Resonance Compensation – Individually

For each resonance:
1. Resonances dynamically crossed
2. Identified **suitable correctors**
3. **Vary currents** while monitoring losses
4. **Verify** configuration

- Partial compensation of 2Qy
- Full compensation of all 3rd order resonances
- Partial compensation of 4th order resonances due to current limitations



Resonance Compensation

✓ **Individual resonance compensation**

	Normal Sextupole						Skew Sextupole				Octupole	
	2Qy		**Qx + 2Qy**		**3Qx**		**2Qx + Qy**		**3Qy**		**4Qx / 2Qx+2Qy / 4Qy**	
	QNO 412L3	QNO 816L3	XNO 4L1	XNO 9L1	XNO 4L1	XNO 9L1	XSK 2L4	XSK 6L4	XSK 2L4	XSK 6L4	ONO 4L1	ONO 816L1
R1	9.16	-3.11	0	-10.56	8.57	-20	-4	-3.67	-8	2.15	-44.7	-49.9(12L1)
R2	10.5	-3.1	15	-12.85	25.7	-34.99	4.83	-1.33	0.43	-1.19	- 46.66	47.77
R3	7.83	-2.9	3.58	-39.99	10.9	-39.64	2.37	-3.95	-1.33	2.78	-39.5	-44.7(12L1)
R4	9.51	-2.23	15	-9.44	20	-17.14	-3	-4.67	-2.43	-1.86	-49.9	-49.9(12L1)

Similar to Pre-LS2

Different from Pre-LS2

New resonances

Correctors connected in 2021

All values in **Amps**

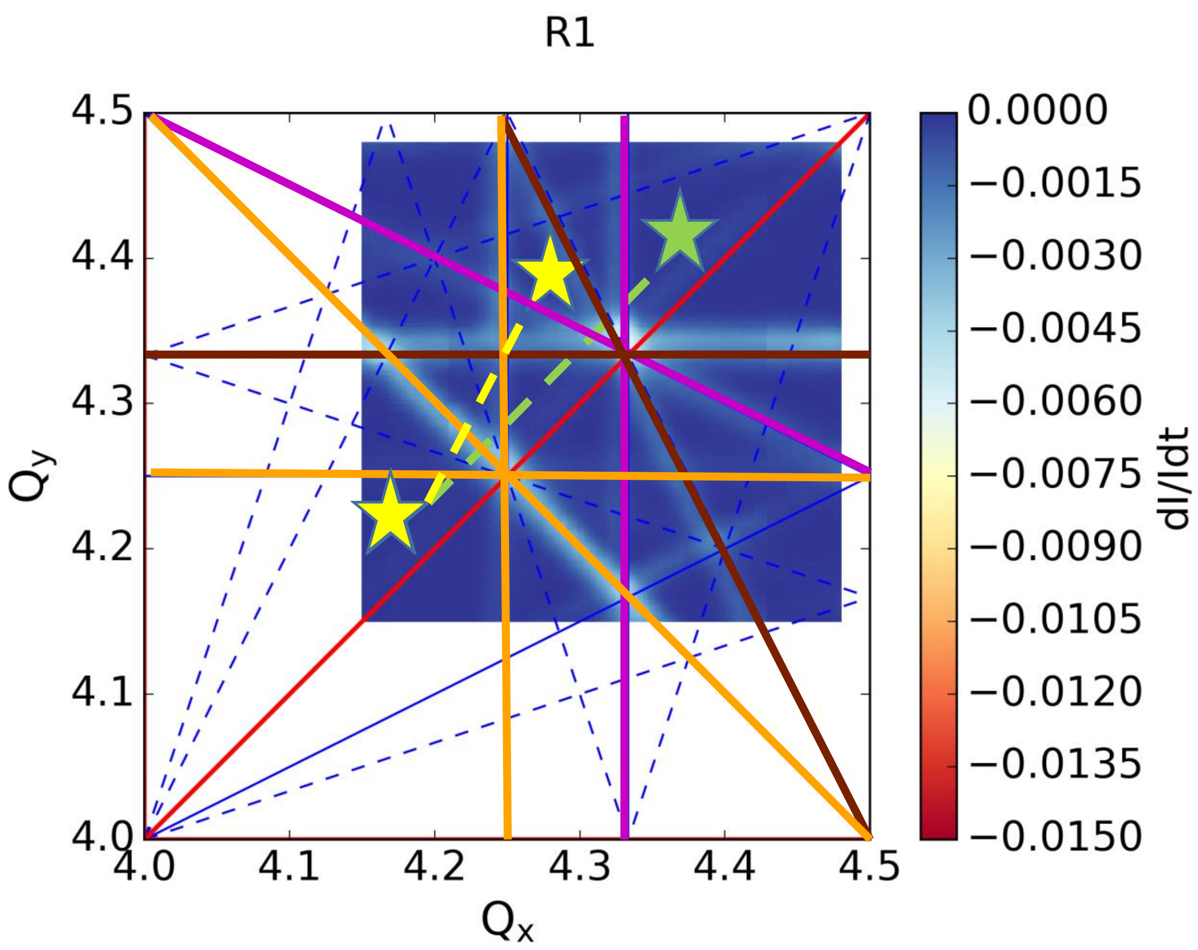
High Brightness beams – Transverse tails

Typical operation, excited resonances are crossed
- **Normal sextupoles**
- **Skew sextupoles**
- **Normal octupoles**

Improved situation *only* ***1 resonance of each sextupole type*** *is crossed:*
- **Less correctors**
- **Lower power**

➢ ***allows ramping corrections*** *to follow the ramp of the main magnets*

✓ ***Better control of resonances***



Resonances Along the Cycle

Resonance compensation settings are defined at injection energy

➢ *Should the settings scale with energy?*

3Qx & Qx+2Qy **perfectly compensated @160 MeV**

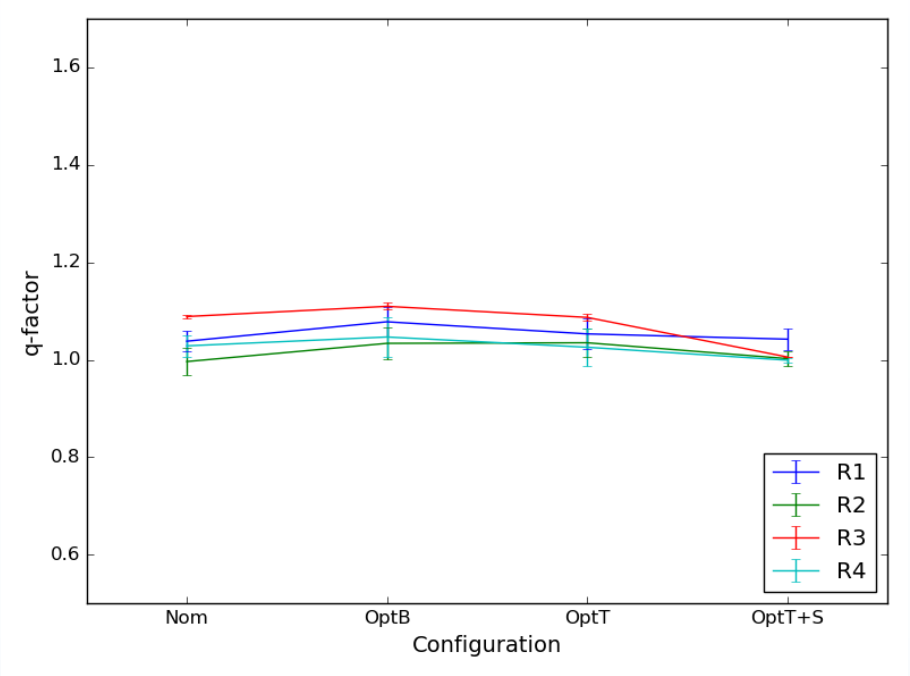
- ***Constant I @ 320 MeV***
  - **Partial** compensation of the resonance
- ***Constant K @ 320 MeV***
  - Not possible to test due to **current limitations**

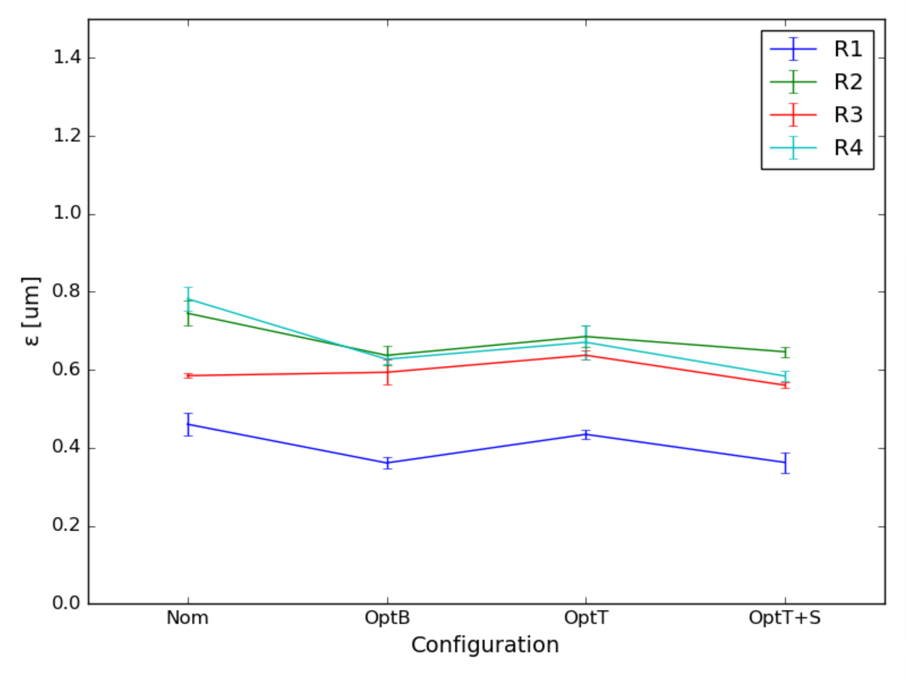
➢ *Investigate different options for scaling the compensation*

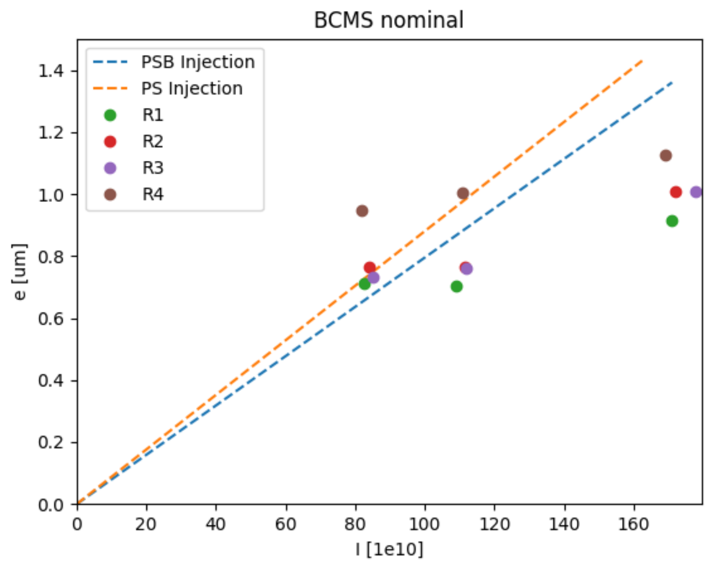
High Brightness beams – Transverse tails (*H*)

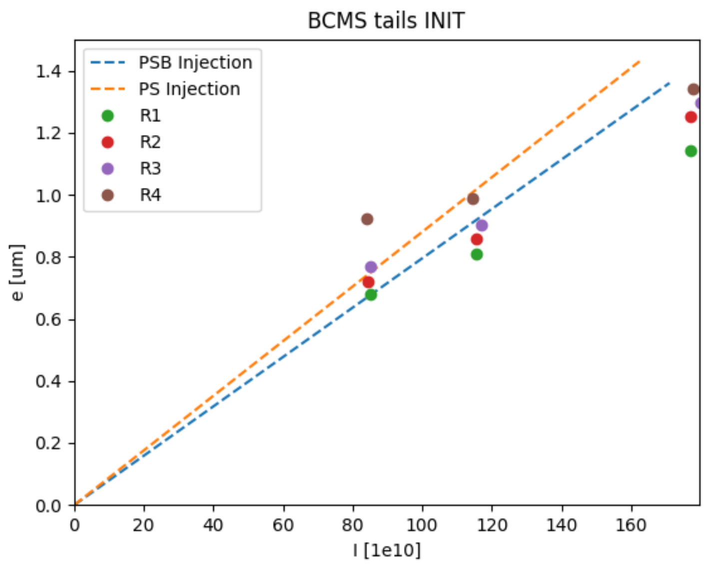
Checking the different configurations (***Nom***, ***OptB***, ***OptT***, & ***OptT + Shavers***) in the PSB:

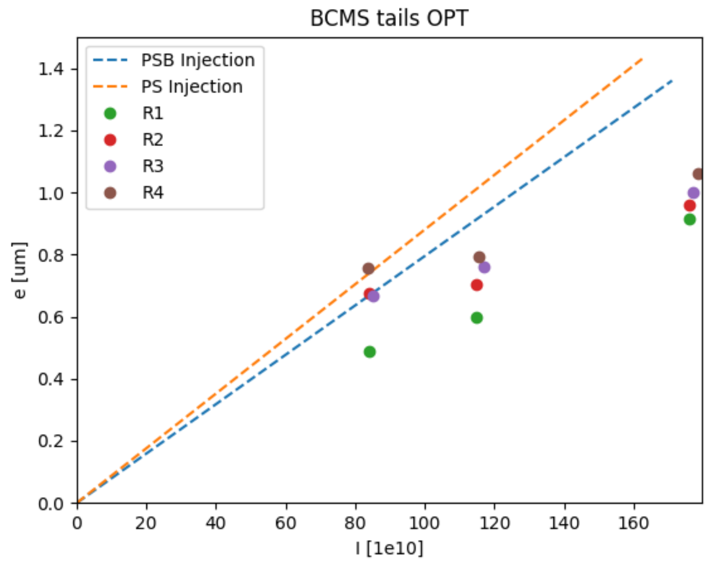
- **Minor impact on emittances** (brightness) for the nominal BCMS intensity (~**85e10**)
- **No variation** of tail content
  - Tails in the horizontal plane cannot be seen in the PSB due to **dispersion & dp/p**
  - Testing with **<dp/p** again **not possible to observe tails**

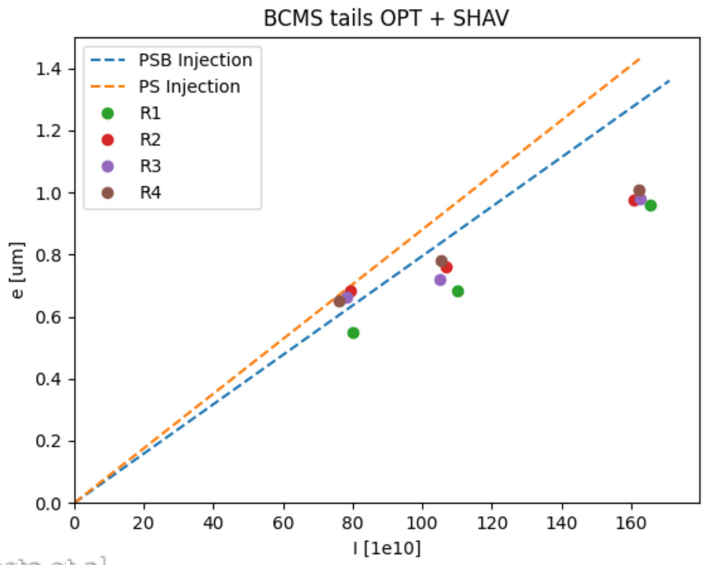




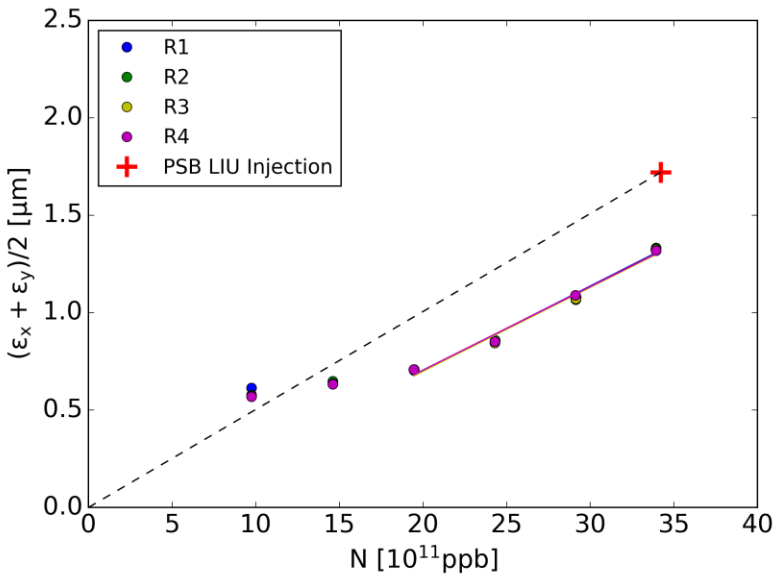

BCMS nominal
PSB Injection
PS Injection
R1
R2
R3
R4
e [um]
I [1e10]

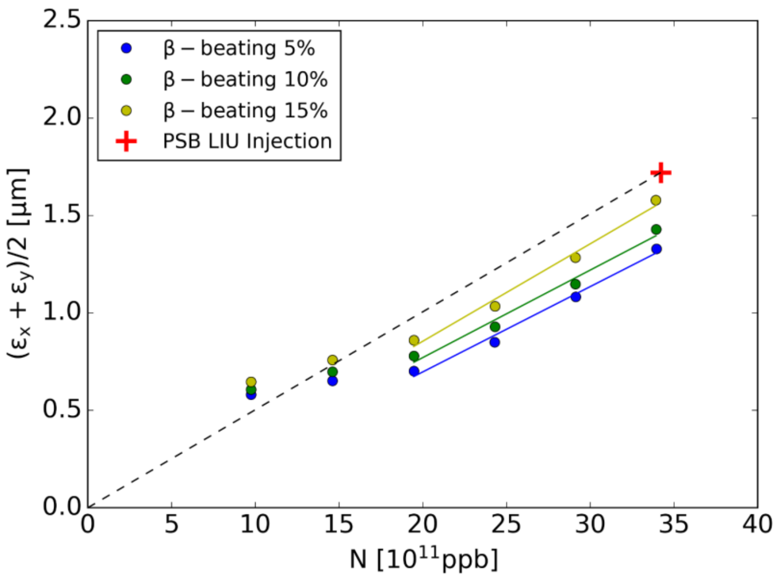

BCMS tails INIT
PSB Injection
PS Injection
R1
R2
R3
R4
e [um]
I [1e10]

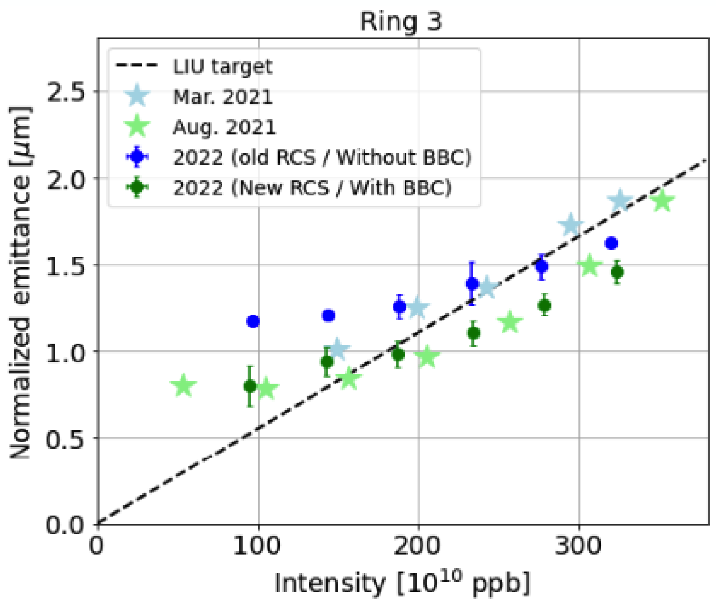

BCMS tails OPT
PSB Injection
PS Injection
R1
R2
R3
R4
e [um]
I [1e10]

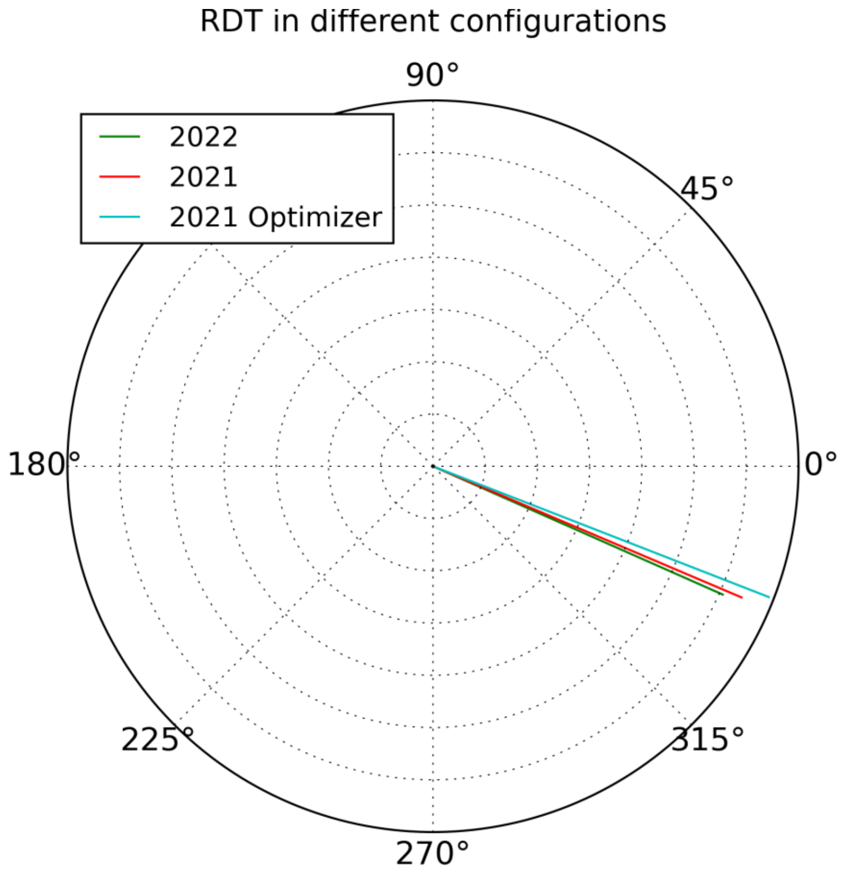

BCMS tails OPT + SHAV
PSB Injection
PS Injection
R1
R2
R3
R4
e [um]
I [1e10]

Brightness curve – “realistic” simulations








RDT in different configurations
90°
45°
0°
315°
270°
225°
180°
2022
2021
2021 Optimizer