
# PSB horizontal instabilities: beam observables and model predictions

**Chiara Antuono, Foteini Asvesta, Carlo Zannini**

**Acknowledgements : S. Albright, M. Barnes, G.P. Di Giovanni, L.M. Feliciano, E.K. Platia, G. Rumolo, and the PSB operation team**

**IPP-MD days 2025** **02/05/2025**

# Outline

- **Introduction**
- **Observation after LIU**
  - A new horizontal instability
- **Horizontal instability studies**
  - Test with kicker terminations
  - Expectations from the model
  - Additional verification of the model
- **Conclusions and outlook**

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- **Introduction**
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  - A new horizontal instability
- **2023-24 horizontal instability studies**
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# Horizontal instabilities at the PSB

- A **horizontal head-tail instability** has been observed for more than 40 years in the PSB at about ~**160 MeV, 330 MeV, 1.3 GeV** **[1]**

- Although the instability was **fully controlled** in everyday operation **by the TFB**, its source and mechanism remained unknown

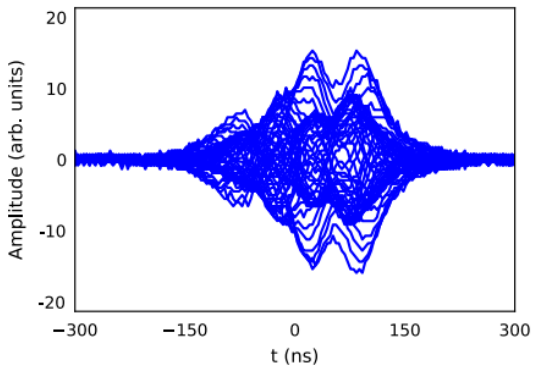
- **Simulations and theoretical analysis** predicted as a source the **unmatched impedance cables of the extraction kicker** **[1]**

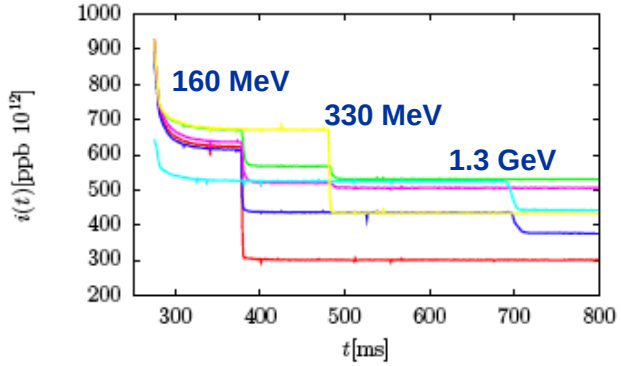
  - In 2018 before LS2, **experimental test** confirmed the involvement of the extraction kicker cable

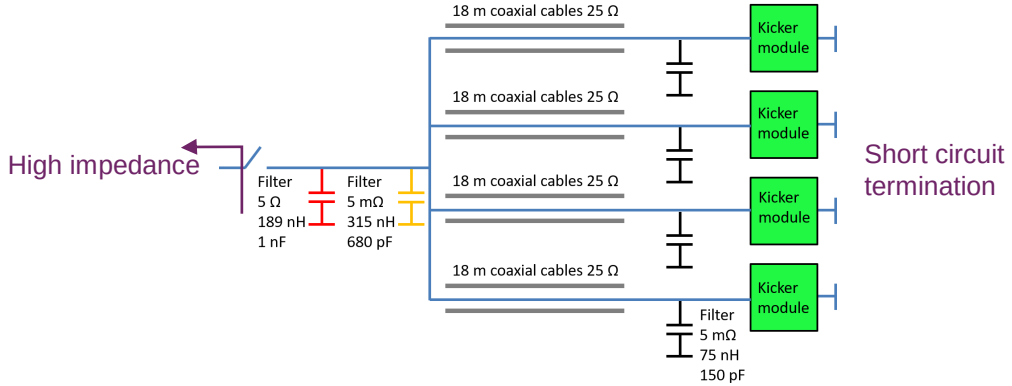
**Before LIU**

- All three experimentally observed instabilities were **predicted and explained** either by the **first or the second kicker resonance**

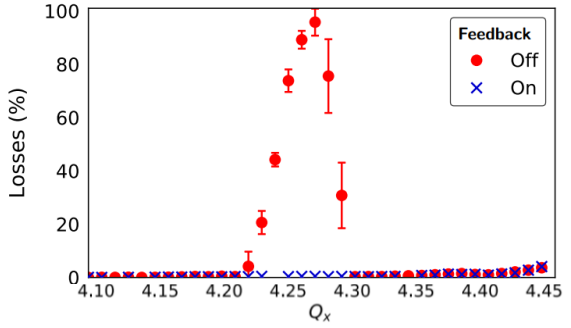
  - **Good agreement between model and beam-observables**



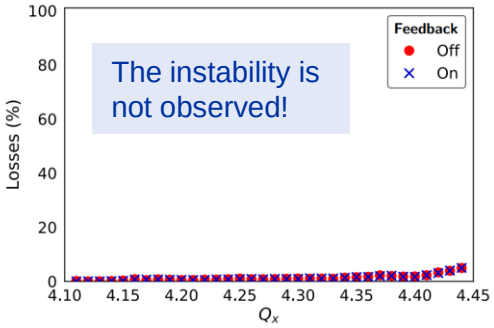




Unmatched impedance cable




Matched impedance cable




[1] E.K. Platia et al., Source of horizontal instability at the CERN Proton Synchrotron Booster, 2019, PRAB

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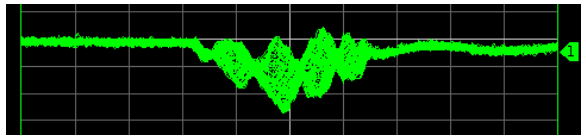
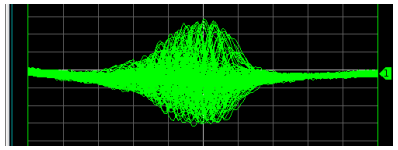
# A new horizontal instability after LIU

Unknown horizontal instability observed in 2021 for the first time **with high energy beam and** with **TFB on**, for intensities above $500 \cdot 10^{10}$ ppb **[2]**

**Mitigation strategy** identified using linear coupling and QSKHO quadrupoles **[2]**

- Accelerated more than 1000e10 protons!



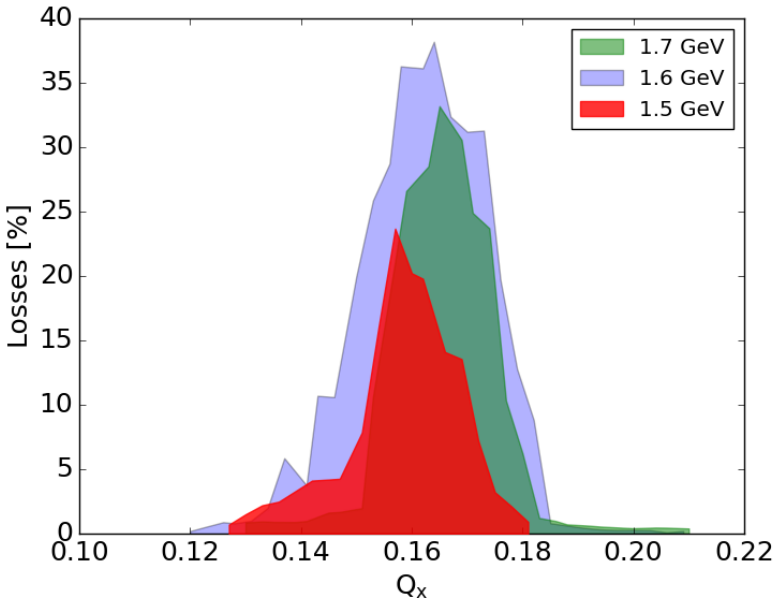


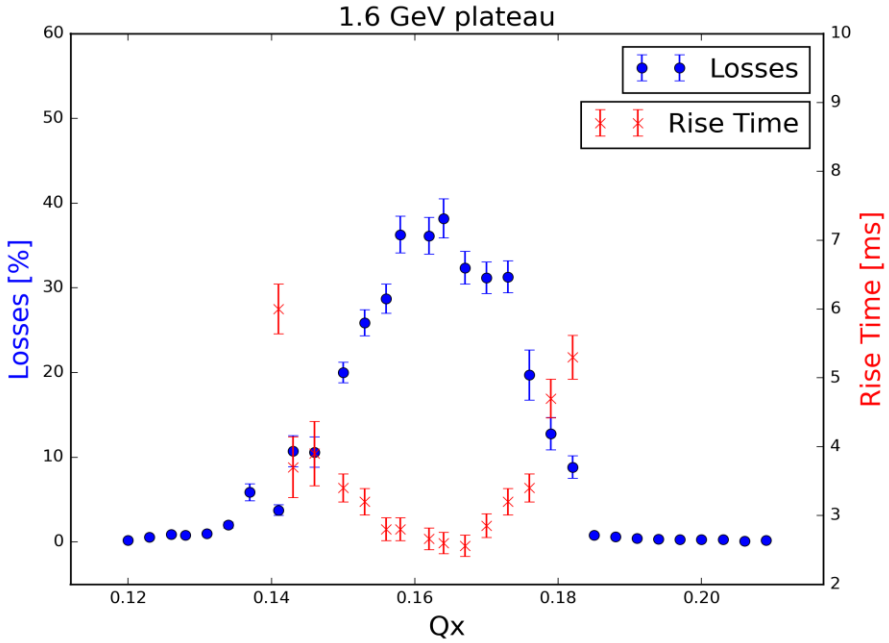
Many studies carried out since 2021 (more in backup)**:**

- Intensity thresholds $(N_{th})$ depends on **chromaticity [3]** and **longitudinal emittance [4]**
- Instability behaviour changes with horizontal tune and energy

**Energy-tune dependance**

- higher energy → higher critical $Q_x$




Following some beam observables **the suspect on the extraction kicker terminations** arose again


[2] F. Asvesta et al., High intensity studies in the CERN proton synchrotron booster, IPAC'22
[3] C. Zannini, *PSB reference measurements, CEI section meeting*
[4] C. Antuono et al, Status of the PSB impedance model and instability studies, IPP MD days 2023

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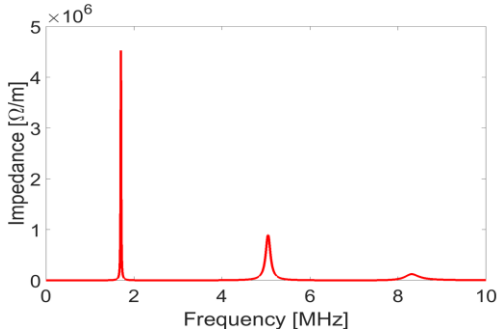
# Expectations from the model

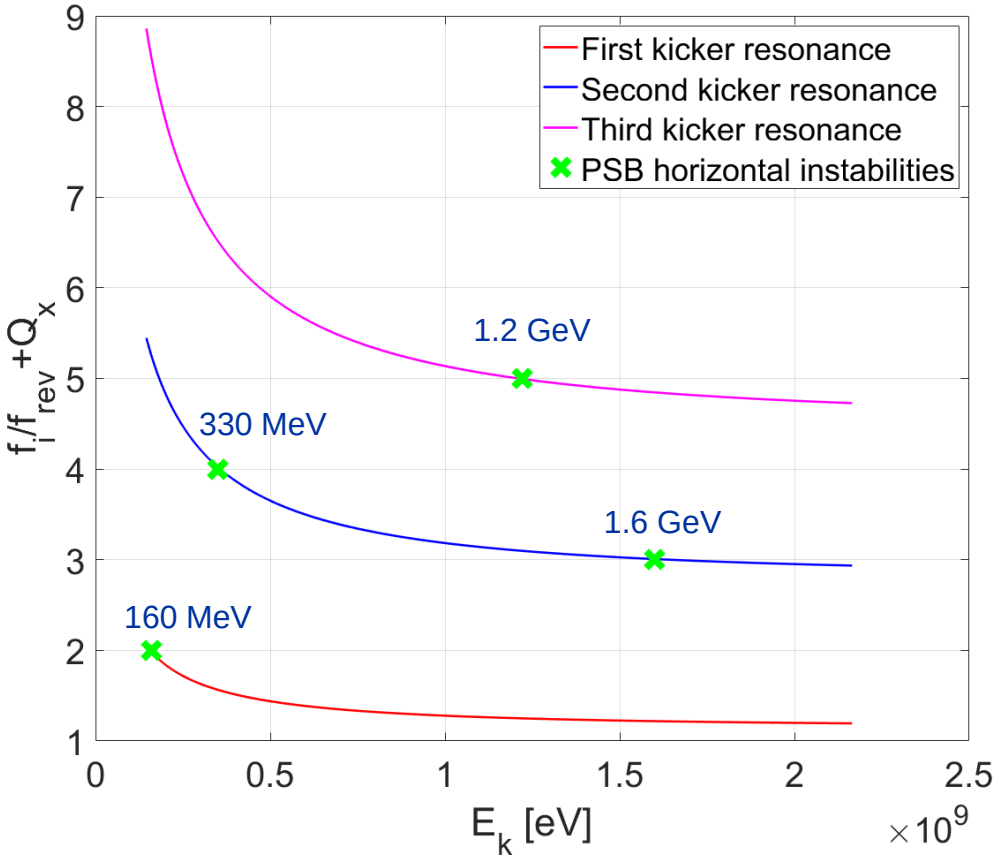
**Latest impedance model** based on more **precise extraction kicker circuit info** (including filters)**[5]**




With the **latest impedance model** of the PSB and with the operational tune $\mathbf{Q_x \sim 0.17}$

- We can plot the **Sacherer stability criteria** as a function of the energy

$$\frac{f_i}{f_{rev}} + Q_x = n$$




**Summary**:

- all the **observed instabilities** are explained:
  - ~ **160 MeV** by the **first kicker resonance**
  - ~ **1.2 GeV** by the **third kicker resonance**
  - ~ **330 MeV** and ~ **1.6 GeV** by the **second kicker resonance**


[5] C. Zannini et al., LOW IMPEDANCE DESIGN WITH EXAMPLE OF KICKERS (INCLUDING CABLES) AND POTENTIAL OF METAMATERIALS, Zermatt 2019 MCBI proceeding

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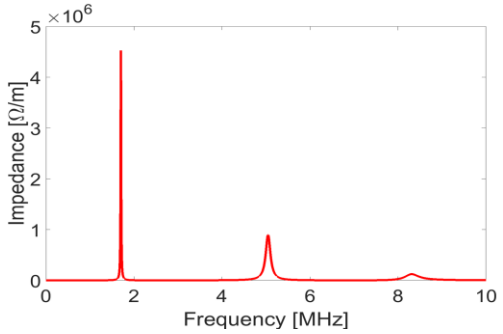


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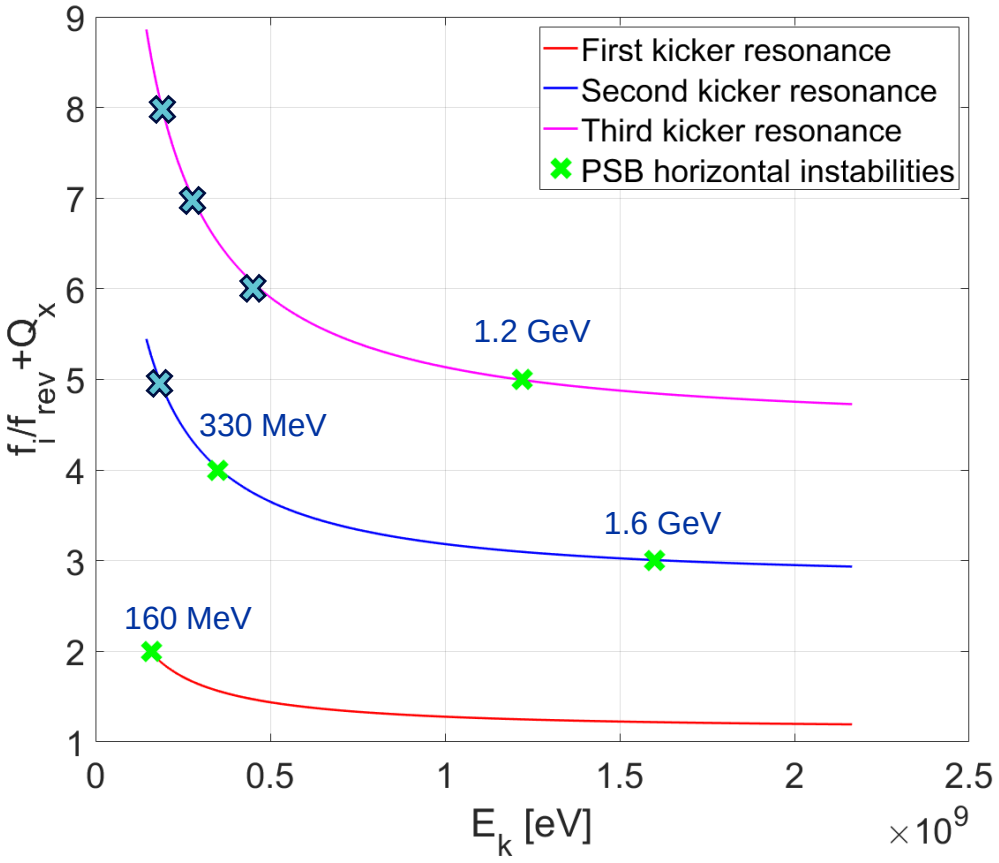


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  - ~ **160 MeV** by the **first kicker resonance**
  - ~ **1.2 GeV** by the **third kicker resonance**
  - ~ **330 MeV** and ~ **1.6 GeV** by the **second kicker resonance**
- Others instability are also predicted and could be checked in the future


[5] C. Zannini et al., LOW IMPEDANCE DESIGN WITH EXAMPLE OF KICKERS (INCLUDING CABLES) AND POTENTIAL OF METAMATERIALS, Zermatt 2019 MCBI proceeding

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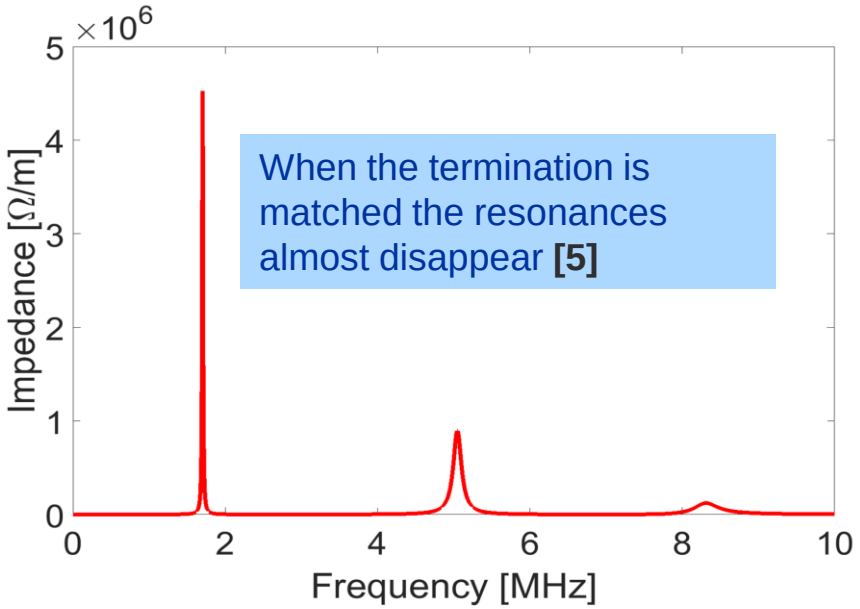
# Experimental verification

A **dedicated test** at the end of the 2023 Run with **two kicker terminations** was performed

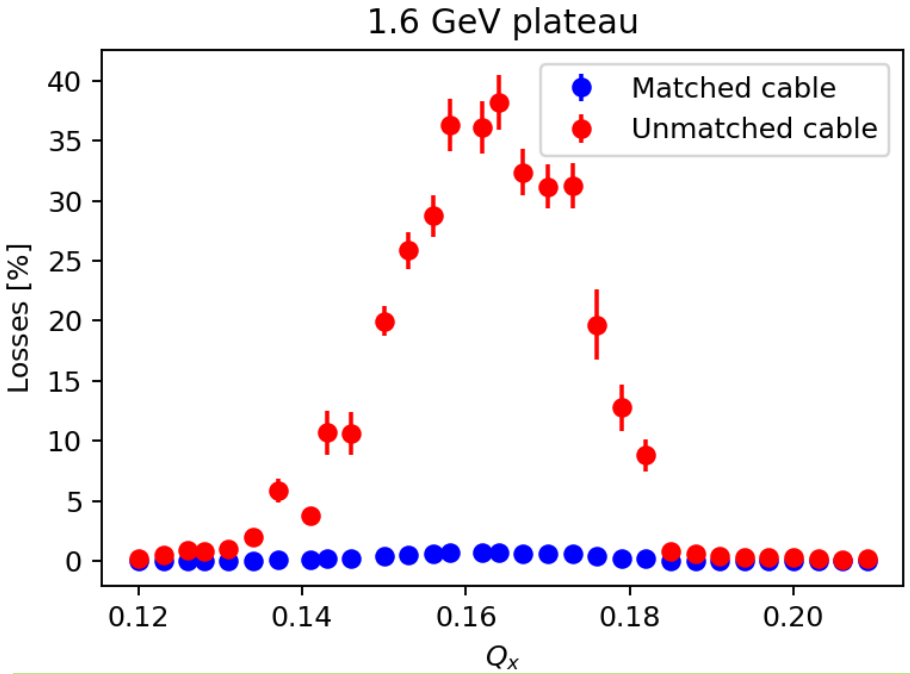



When the termination is matched the resonances almost disappear **[5]**

Operational termination -> **unmatched** kicker cable

Modified termination -> **matched** kicker cable

Last test on 31/10/23




- The **cause** of the instability is clearly identified
  - **losses disappear when the kicker termination is matched**

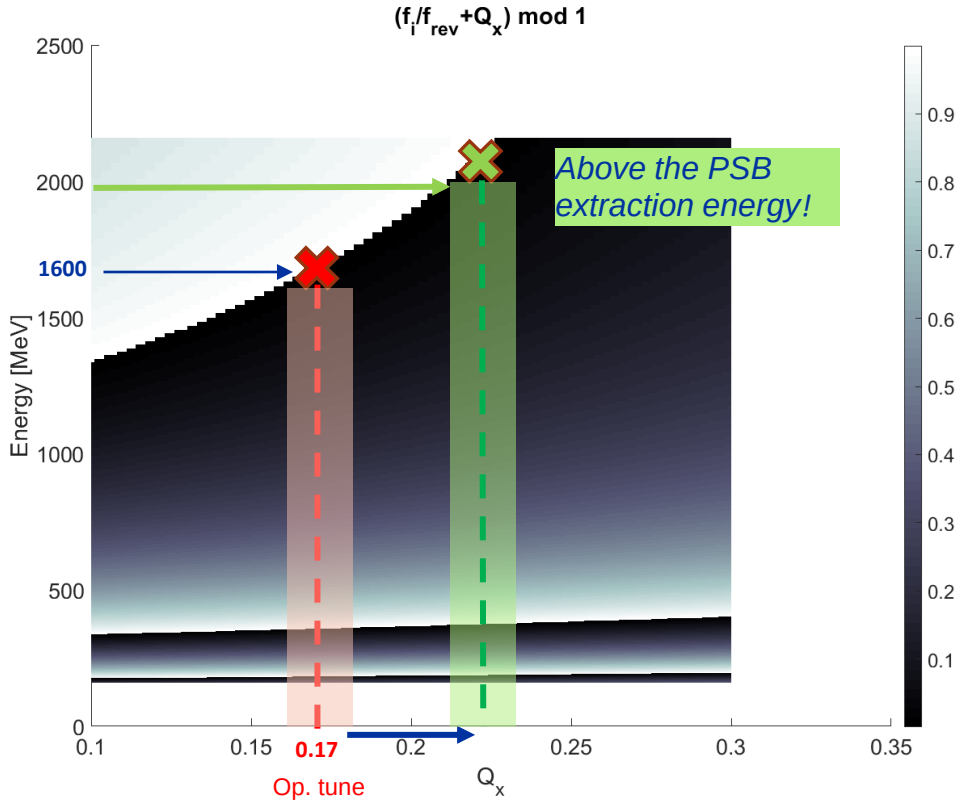
[5] C. Zannini et al., LOW IMPEDANCE DESIGN WITH EXAMPLE OF KICKERS (INCLUDING CABLES) AND POTENTIAL OF METAMATERIALS, Zermatt 2019 MCBI proceeding

# Cure of the instability

- Studies **with the latest impedance model and**
  - **Sacherer stability criteria :** $\frac{f_i}{f_{rev}} + Q_x = n$

Instability occur→ sharp change from black to white

**Second kicker resonance**




**Increase of $Q_x$** : instability pushed beyond 2 GeV

**Operational solution**

- Change of working point ($Q_x$)

**Successfully tested in 2024 operation**
**Instability not observed without TFB and linear coupling**

- Lower emittance and almost perfect transmission
- Improved beam quality and overall performance

| | 2023 | 2024 |
|---|---|---|
| Intensity [ppb] | $825 \cdot 10^{10}$ | $837 \cdot 10^{10}$ |
| Transmission | 0.983 | 0.996 |
| Horizontal emittance [mm mrad] | 7.806 | 7.04 |
| Vertical emittance [mm mrad] | 9.02 | 6.057 |

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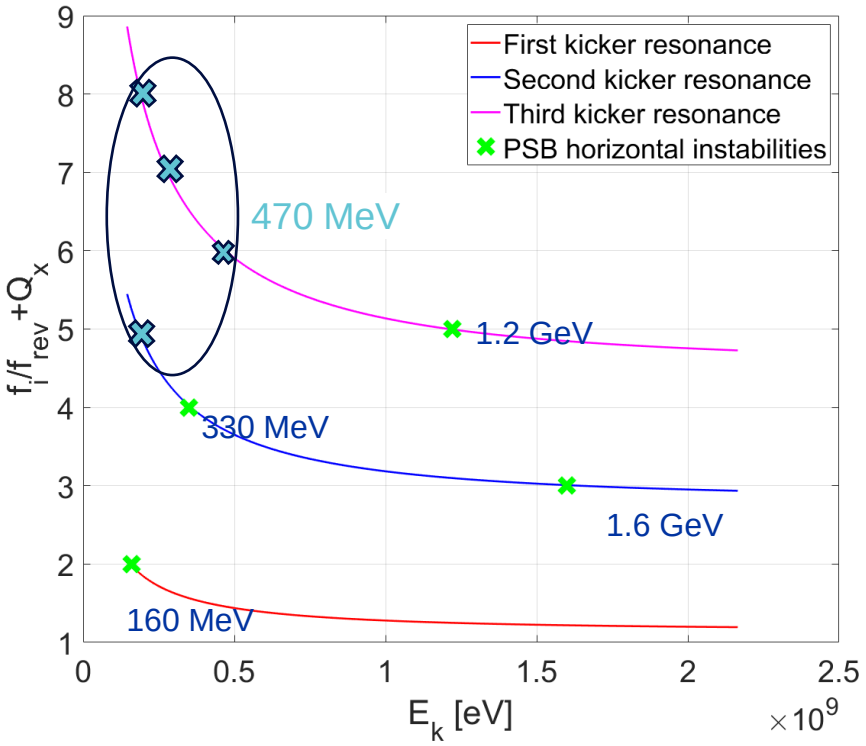
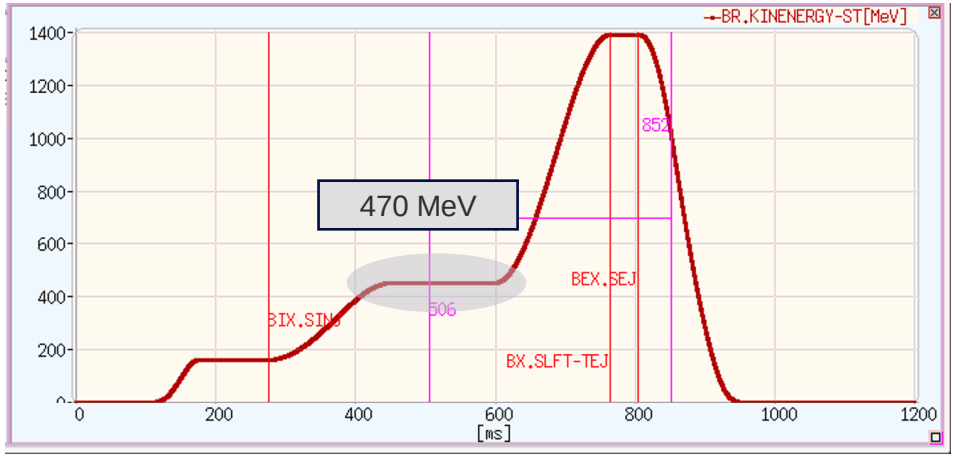
# Additional verification of the PSB model

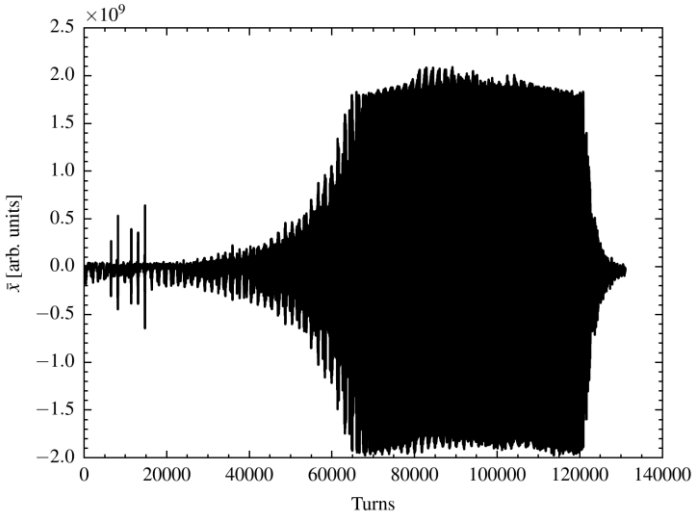


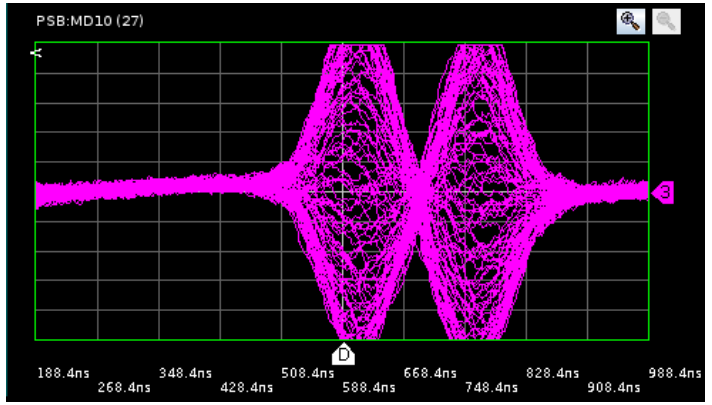

Accurate measurement of these instabilities is challenging

A specific MD cycle was implemented to measure the instability at 470 MeV




The 470 MeV was detected, further validating the PSB impedance model



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# Conclusions and outlook

- **Horizontal instability** observed at the PSB for the **first time after LIU** with:
  - high energy beam (~1.6 GeV)
  - TFB on
  - for intensities above 500e10 ppb

- Predictions with **the latest impedance model** suggested the involvement of the **unmatched impedance termination of the extraction kicker**
  - **Experimentally confirmed** in 2023 in a dedicated MD
  - Proposed a **mitigation strategy successfully tested** during the PSB operation

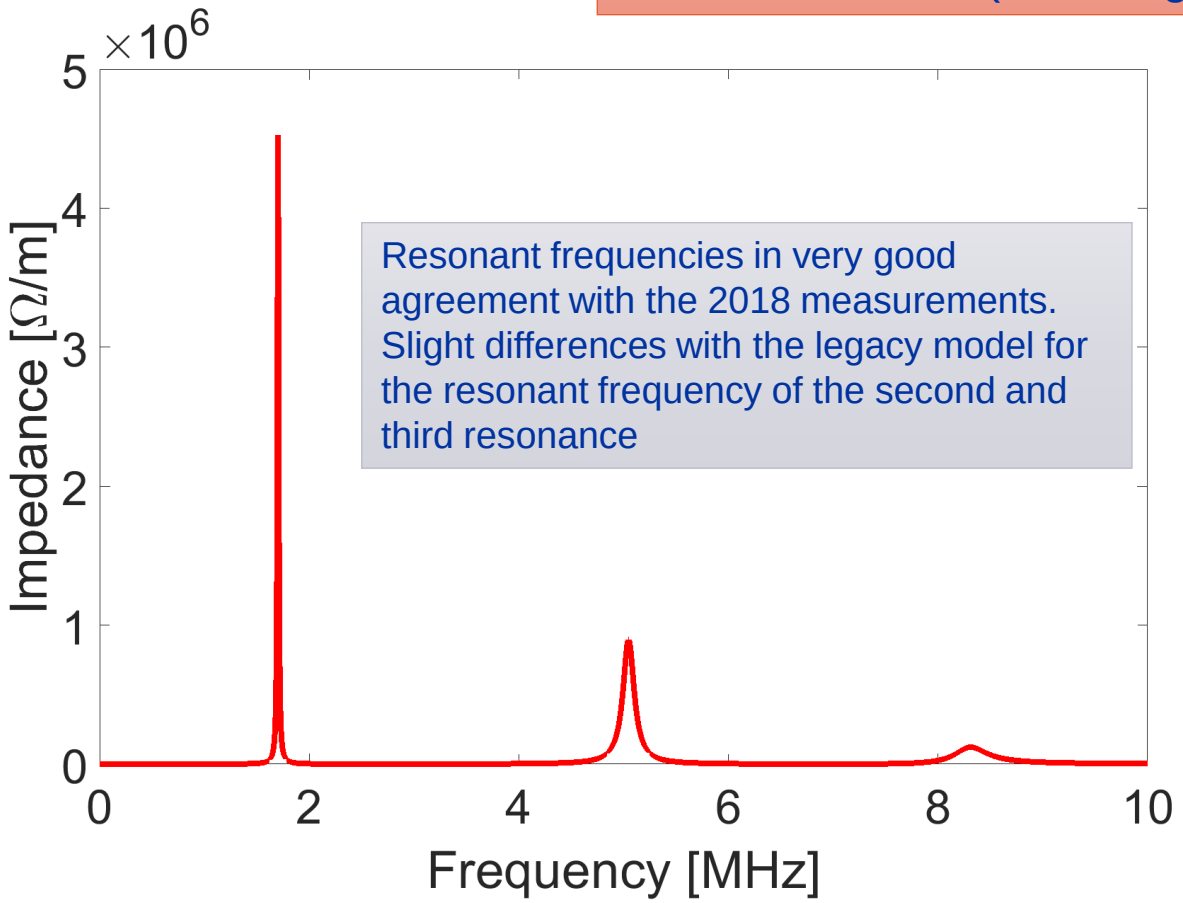
- **The latest impedance model can explain all the observed instabilities**
  - **Additional instabilities** are also predicted
    - MDs in 2024 confirmed the presence of the instability at about 470 MeV
    - Further investigation of predicted instabilities could be nice but not straightforward

# Thank you!

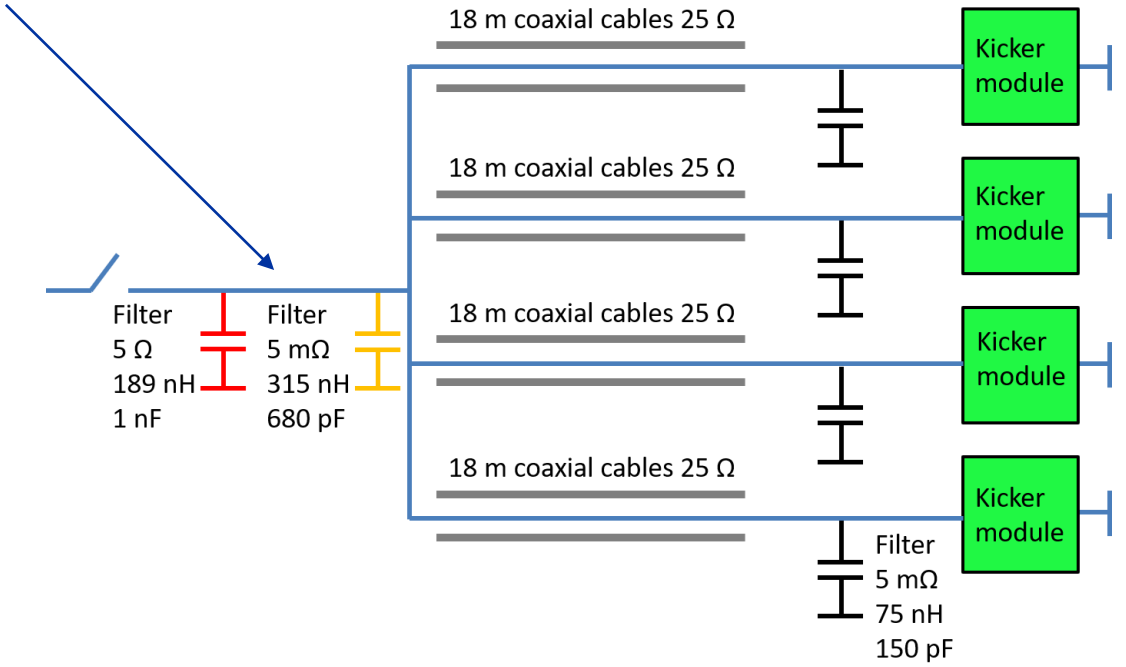
# Backup

# Impedance model of the extraction kicker

Latest impedance model based on more precise kicker circuit info (including filters) [3]




Resonant frequencies in very good agreement with the 2018 measurements. Slight differences with the legacy model for the resonant frequency of the second and third resonance




[3] C. Zannini et al., LOW IMPEDANCE DESIGN WITH EXAMPLE OF KICKERS (INCLUDING CABLES) AND POTENTIAL OF METAMATERIALS, Zermatt 2019 MCBI proceeding

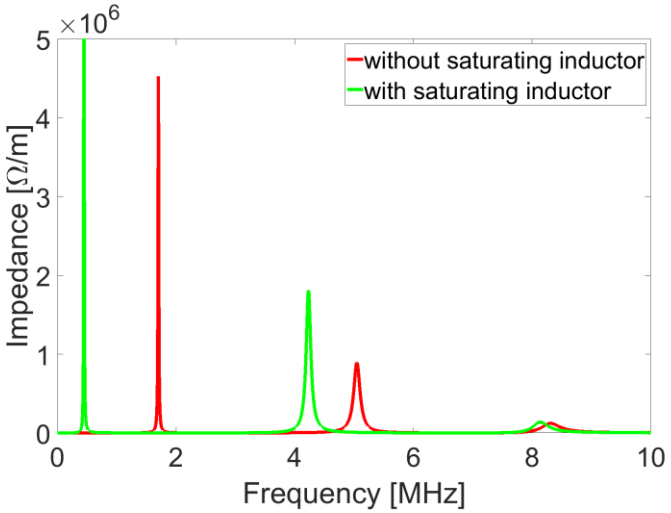
# Expectations from the model: could we cure the instability?

- Two possible solutions to suppress the **1.6 GeV** instability: further and dedicated studies are needed

## 2. Long-term hardware solution

- Insertion of a saturating inductor

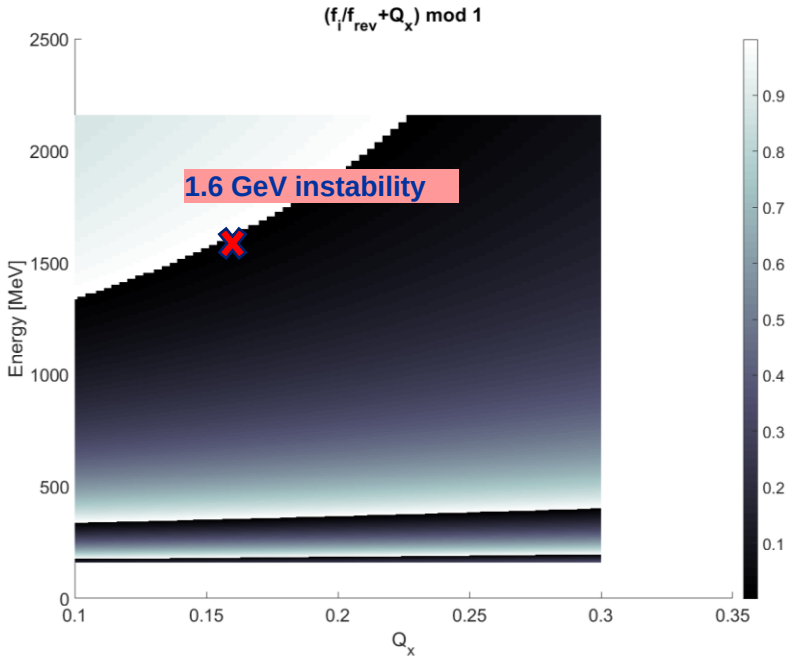
Case study investigated for the suppression of the 160 MeV instability



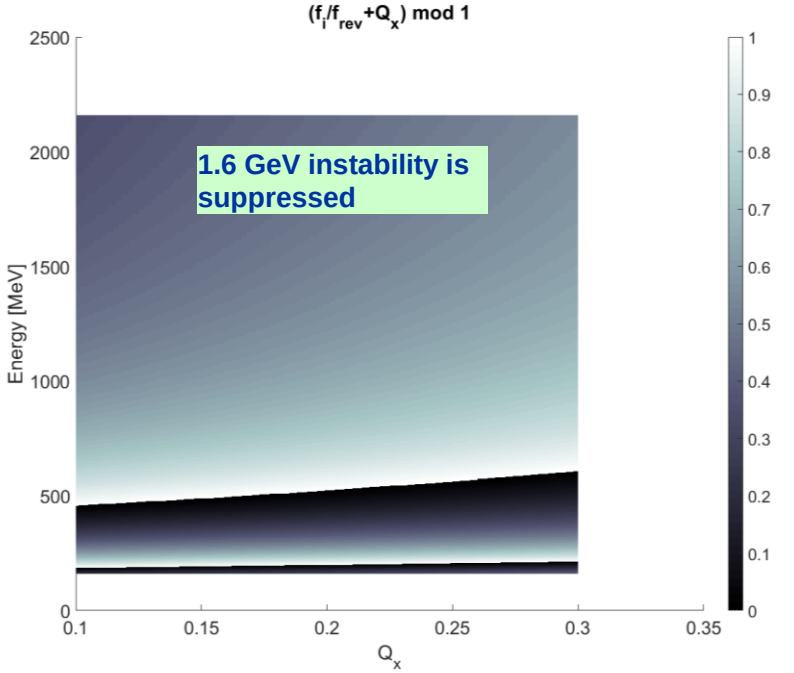

**saturating inductor** in the kicker circuit (between the kicker and the transmission lines) as proposed by M. Barnes

Expectation considering the second kicker resonance

**without** saturating inductor




**with** saturating inductor



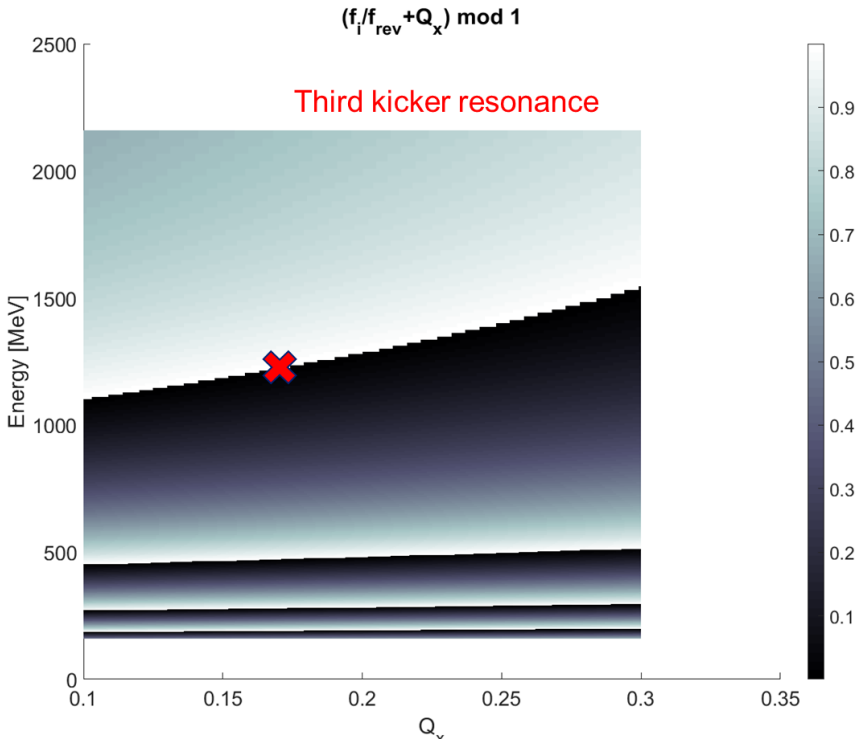
# Possible future limitations

**PSB horizontal kicker instability**

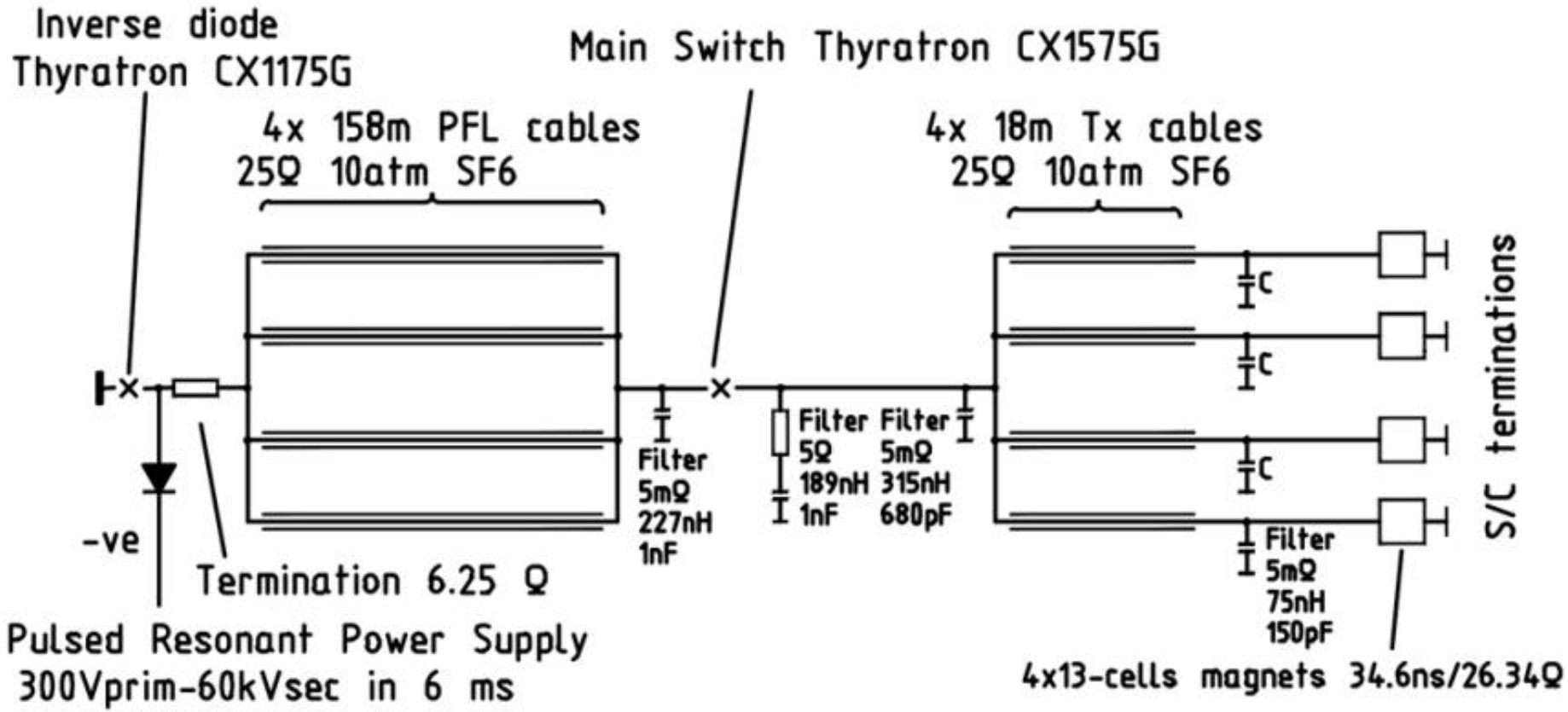
-Not limited 2024 Run

-However, with the aim of **increasing intensity** (and the energy , e.g. ISOLDE) both the instabilities at **1.6 GeV and 1.3 GeV** might be a limitation

- Activity already observed during measurements for the 1.3 GeV instability increasing the intensity up to **1.28e13 p/b with the TFB on**.
- The **change of tune for the 1.3 GeV** to mitigate the instability (as for 1.6 GeV) cannot be done easily since the **curve of energy with tune is quite flat**
  - tune has to change a lot to push the instability!



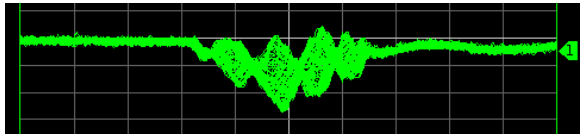
# Kicker circuit

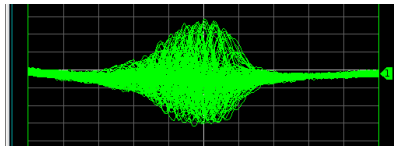


# A new horizontal instability

- Horizontal instability observed in 2021 for the **first time with high energy beam** with **TFB on**, for intensities above 500e10 ppb

  - Many studies carried out since 2021 *:
    - Instability behaviour remained unchanged over the years
    - Intensity threshold depends on chromaticity



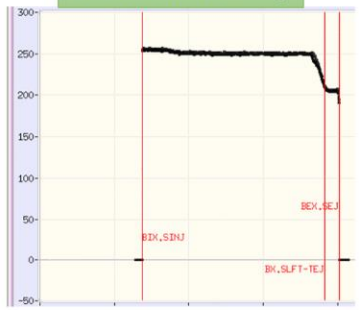


C. Zannini, CEI section meeting, 12/08/2021

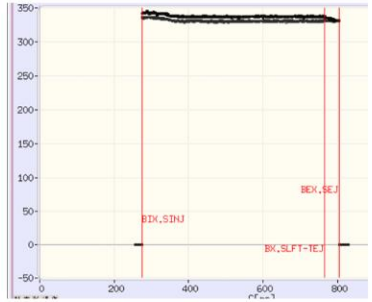
## nTOF Instability: measurements as function of chromaticity

- Instability threshold measured as function of chromaticity
  - Higher chromaticity than natural bring to a slight increase of the threshold (from 250e10 ppb to 300-350e10 ppb in ring 2)
  - Smaller chromaticity to a significant reduction of the threshold (from 250 ppb to 150 ppb in ring 2)

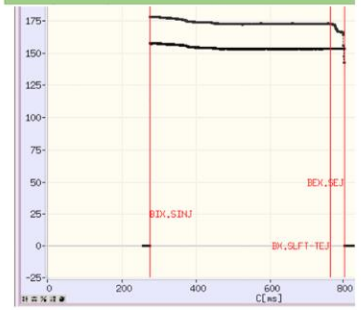
Natural chromaticity



Higher chromaticity than natural



Lower chromaticity than natural



Intensity threshold with TFB off

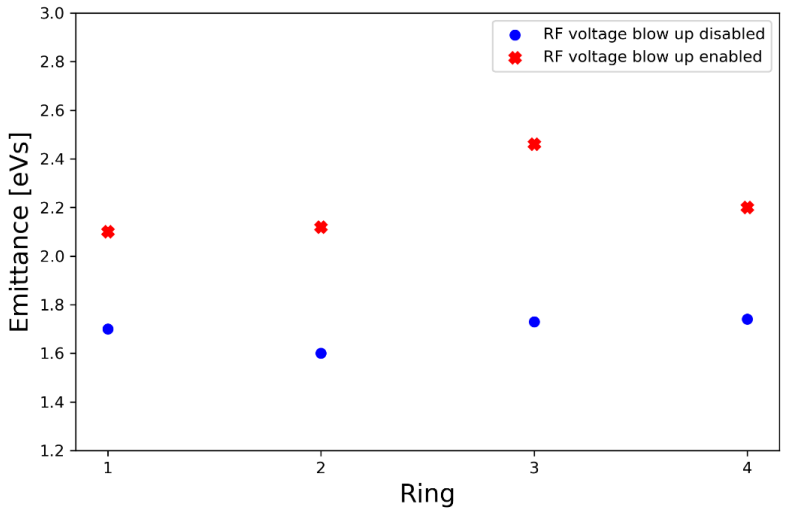
| Ring TFB off | 2021 |
|---|---|
| R1 | ~250e10 ~C740 ms |
| R2 | ~250e10 ~C700 ms |
| R3 | ~350e10 ~C720 ms |
| R4 | ~350e10 ~C720 ms |

- **Mitigation strategy** identified: currently cured using linear coupling and QSKHO quadrupoles
  - Accelerated more than 1000e10 protons!

# Observation in 2022 : Nth dependence with emittance

| Ring TFB off | 2021 | 2022 |
|---|---|---|
| R1 | ~250e10 ~C740 ms | ~300e10 ~C680 ms |
| R2 | ~250e10 ~C700 ms | ~350e10 ~C680 ms |
| R3 | ~350e10 ~C720 ms | ~530e10 ~C680 ms |
| R4 | ~350e10 ~C720 ms | ~390e10 ~C670 ms |

RF blow-up enabled in 2022




| 2022 $\bar{\epsilon} = 2.2$ | 2022 $\bar{\epsilon} = 1.7$ |
|---|---|
| ~300e10 ~C680 ms | ~210e10 ~C680 ms |
| ~350e10 ~C680 ms | ~255e10 ~C675 ms |
| ~530e10 ~C680 ms | ~380e10 ~C680 ms |
| ~390e10 ~C670 ms | ~320e10 ~C680 ms |

Similar Nth

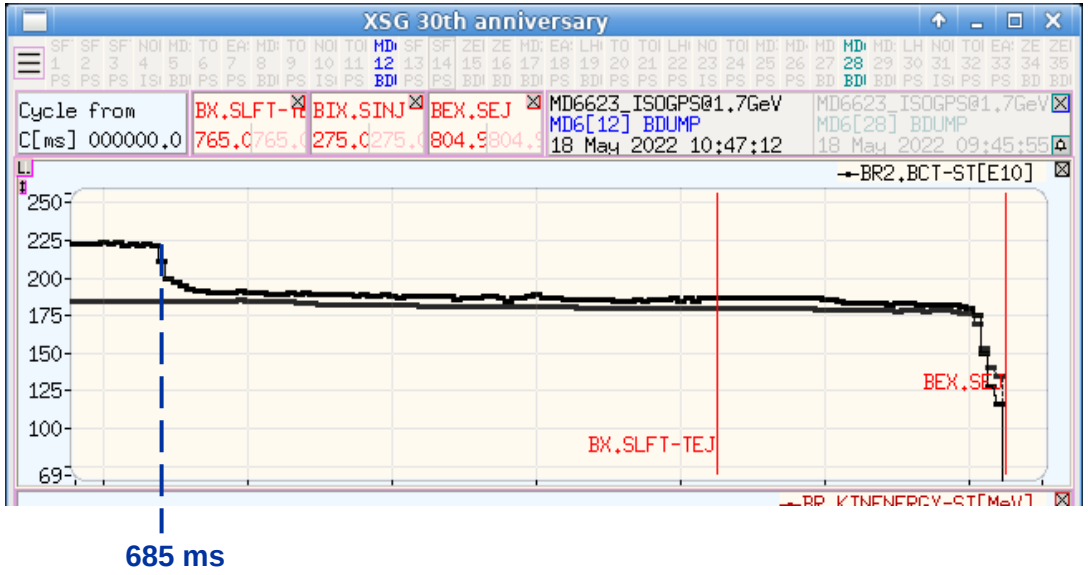
- Initial difference between 2021 and 2022!
  - **the different longitudinal emittance**
  - **Higher emittance → higher thresholds**
- **Unchanged behaviour with time of the instability**:
  - Similar intensity threshold
  - Same behaviour with chromaticity

# Observation in 2022 : test changing tune and intensity

- We **changed the tune** to see how the Nth changes

| Ring TFB off | 1.7 GeV cycle |
|---|---|
| R1 | ~175e10<br>~ C695 ms |
| R2 | ~160e10<br>~ C690 ms |
| R3 | ~400e10<br>~ C670 ms |
| R4 | ~210e10<br>~ C675 ms |

- We turned off the TFB from C600 ms
- We increased the intensity step by step
- Instability around C685 ms



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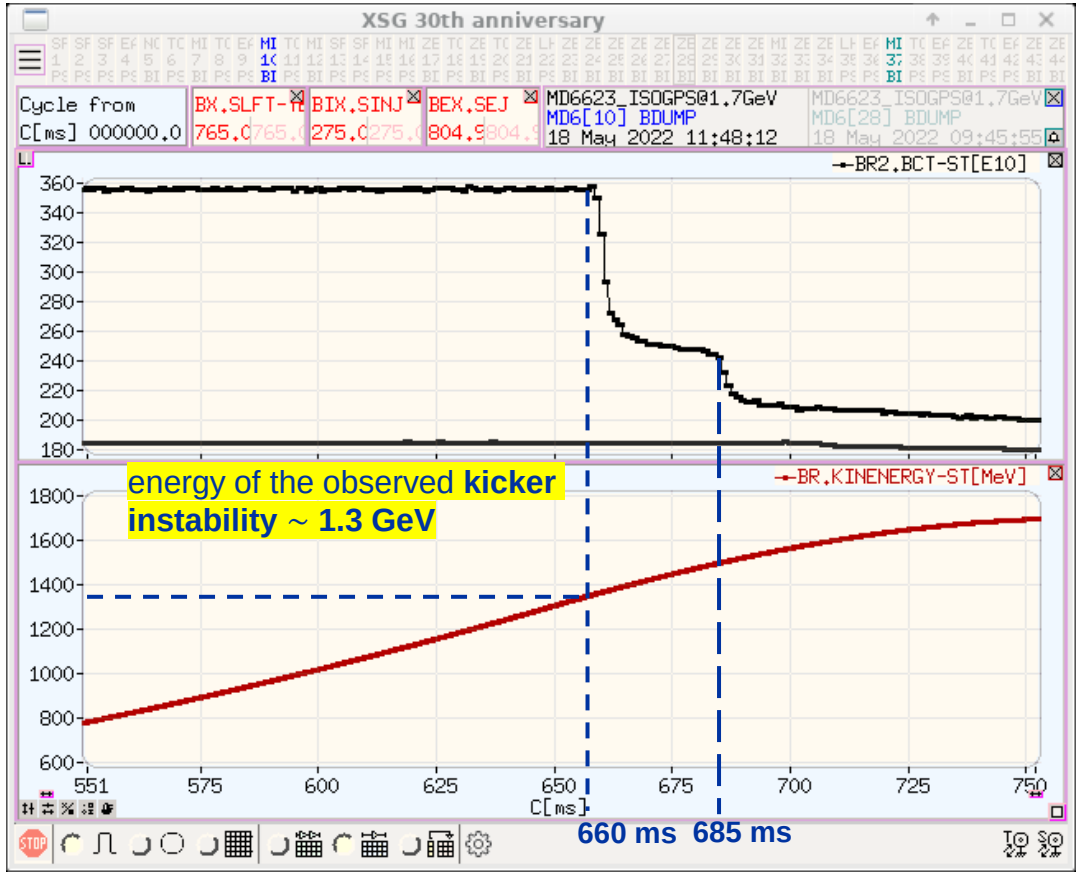
- **Further increasing the intensity** the instability **around 1.3 GeV** is observed




- The instability behaviour is complex
- The intensity thresholds could change with the energy and the tune as well
- Again, the **suspect of an involvement of the kicker termination arose**

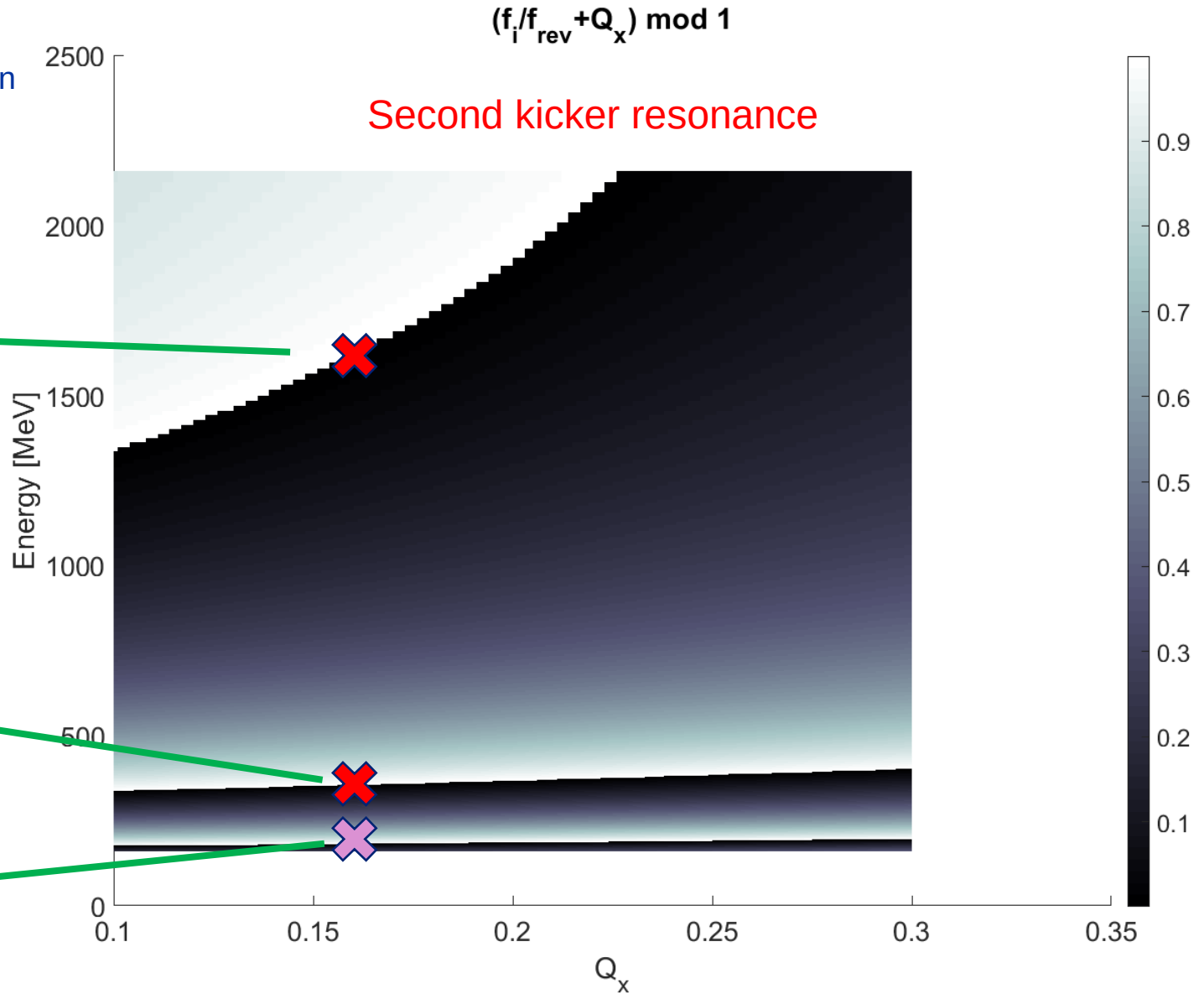
# Expectations from the model

- With the **latest impedance model** of the PSB :
  - We can plot the Sacherer stability criteria as a function of the tune
  - An instability could occur when there is a sharp change in the colour from black to white
    - Focus on the operation tune $\mathbf{Q_x}$ ~ 0.17

~ **1.6 GeV** instability observed without/with horizontal feedback

**~330 MeV** instability observed without horizontal feedback

**~180 MeV** expected instability from second kicker resonance

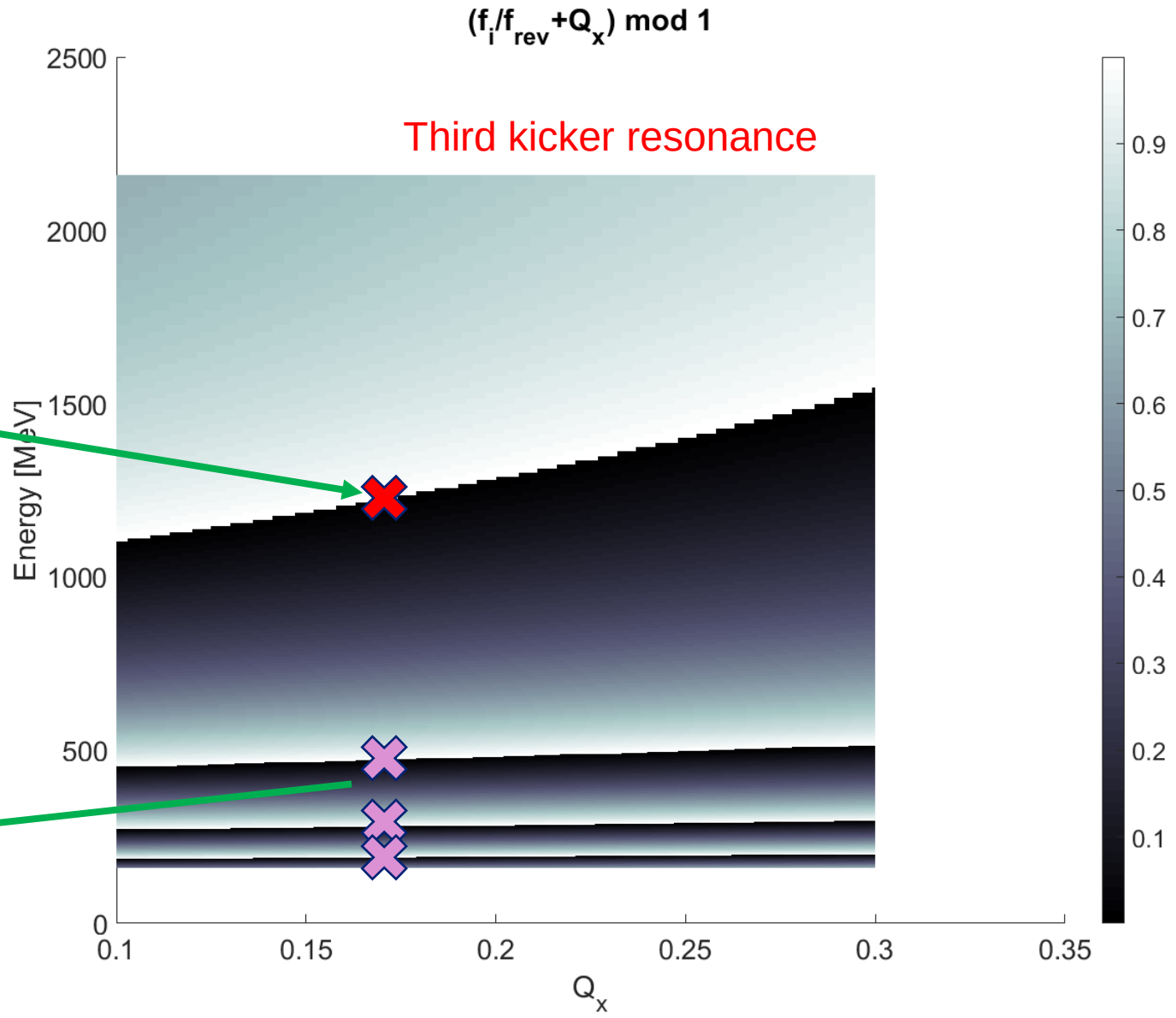


# Expectations from the model

- With the latest impedance model of the PSB :
  - We can plot the Sacherer stability criteria as a function of the tune
  - An instability could occur when there is a sharp change in the colour from black to white
    - Focus on the operation tune $\mathbf{Q_x}$ ~ 0.17

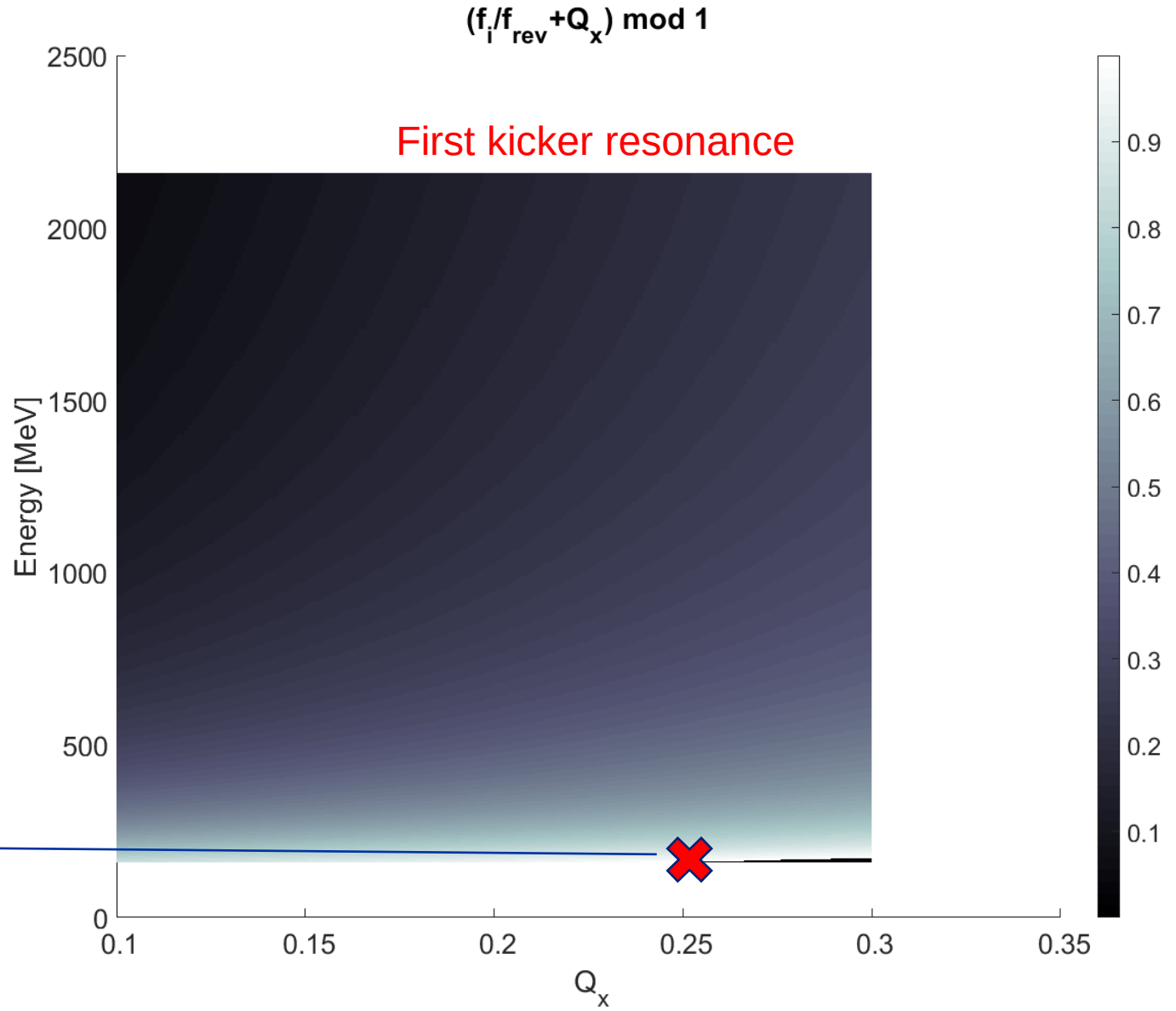
- **1.2 GeV** predicted by the third kicker resonance
  - Similar to beam observations (see slide 10) at about 1.3 GeV
  - The instability introduced by the third resonances should be weaker and indeed the 1.3 GeV instability appears at higher intensities

Additional instabilities expected from the third kicker resonance



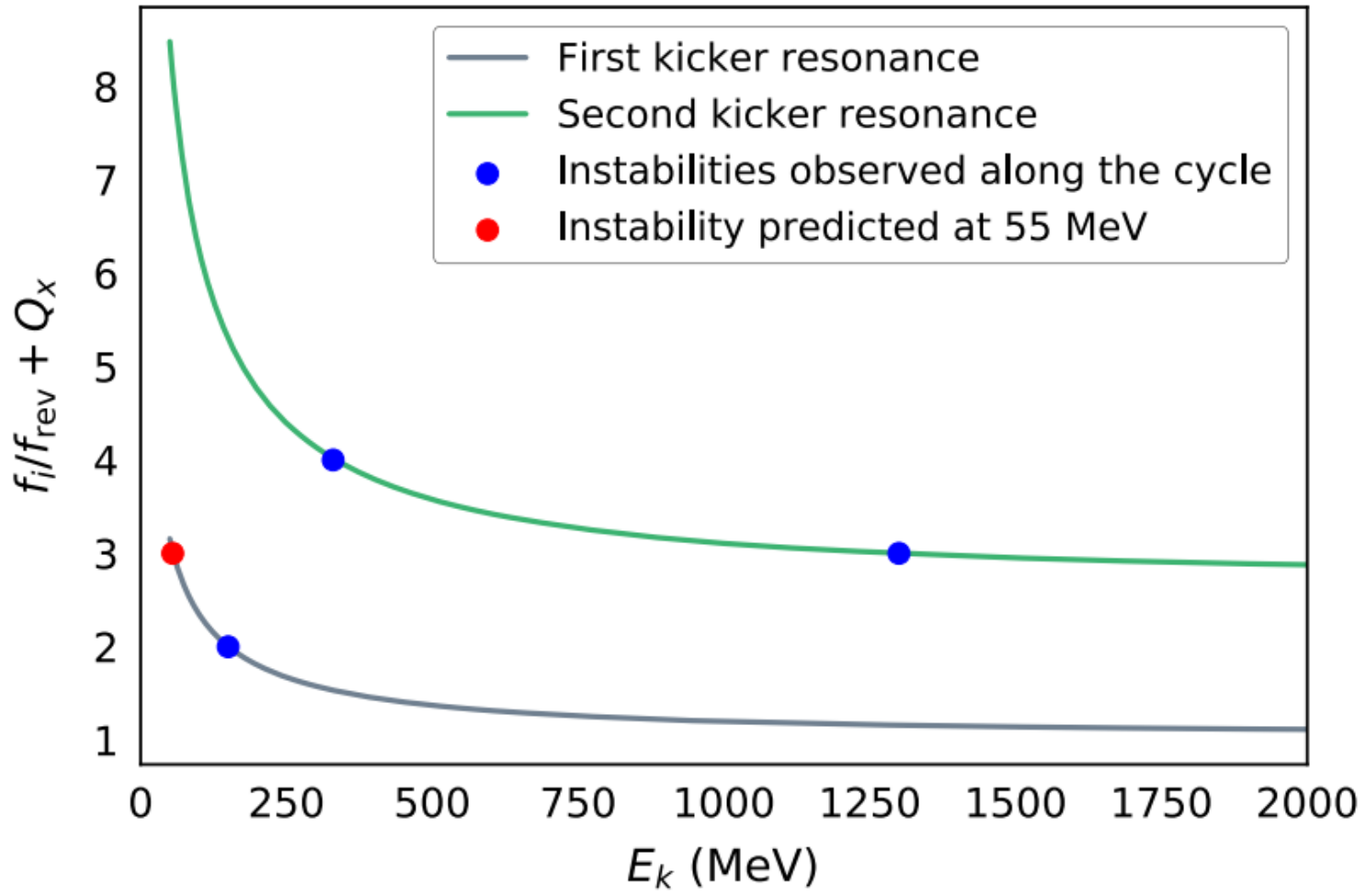
# Expectations from the model

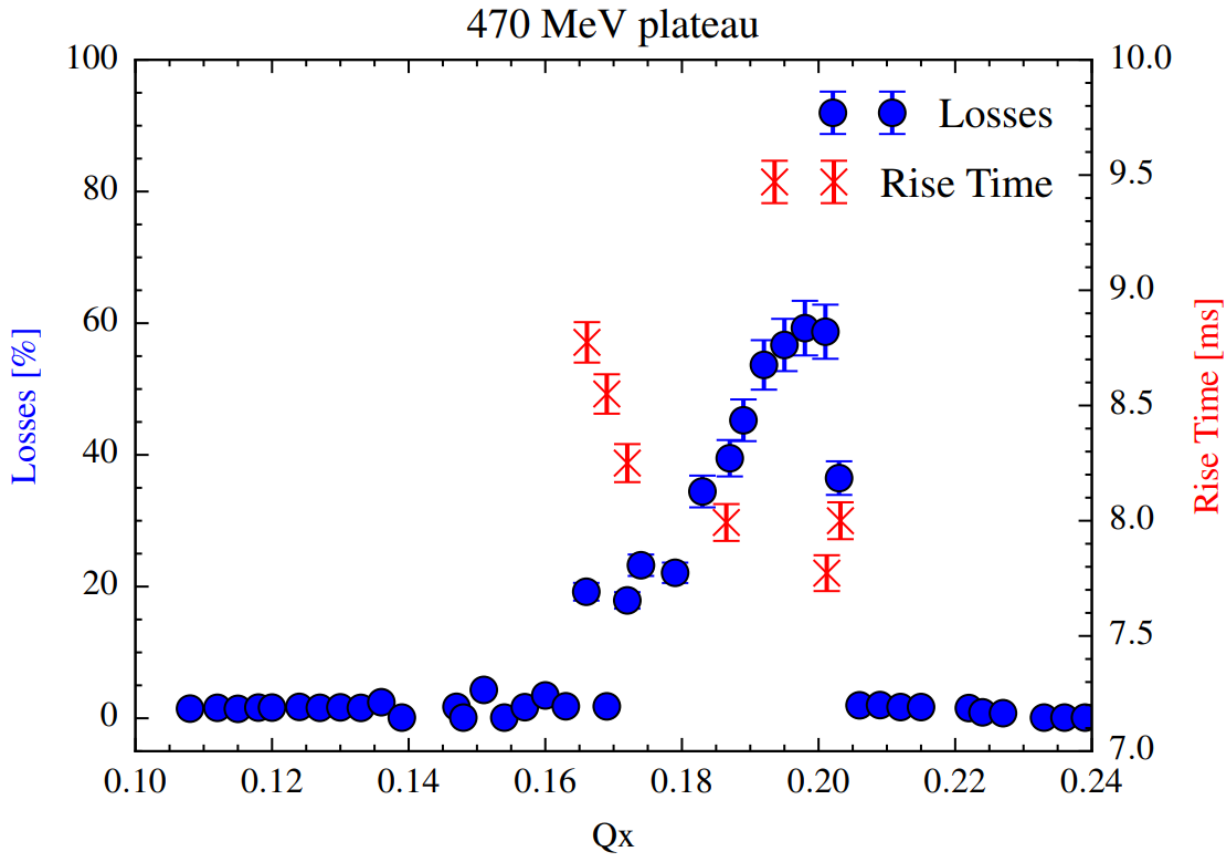
- With the latest impedance model of the PSB :
  - We can plot the Sacherer stability criteria as a function of the tune
  - An instability could occur when there is a sharp change in the colour from black to white
    - Focus on the operation tune $\mathbf{Q_x}$ ~ 0.17




Instability observed at **injection energy** (**160 MeV**) without horizontal feedback

# Prediction with old impedance model




470 MeV plateau
Losses
Rise Time
Losses [%]
Rise Time [ms]
Qx
100
80
60
40
20
0
10.0
9.5
9.0
8.5
8.0
7.5
7.0
0.10
0.12
0.14
0.16
0.18
0.20
0.22
0.24