CERN

Approaching the high-intensity frontier using the Multi-Turn Extraction at the CERN Proton Synchrotron

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20 June 2018

Outline

- **Introduction**
- **The CT and MTE schemes**
- **Optimization of the MTE process**
- **MTE performance at high-intensity**
- **Conclusions and outlook**

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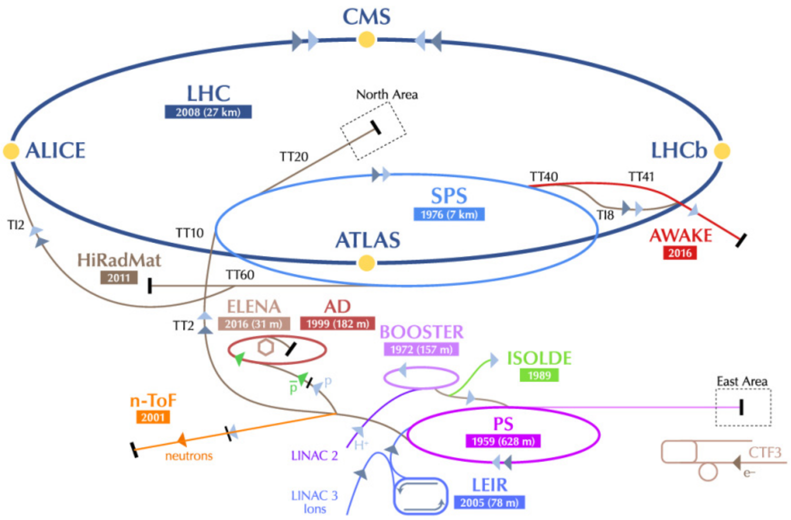
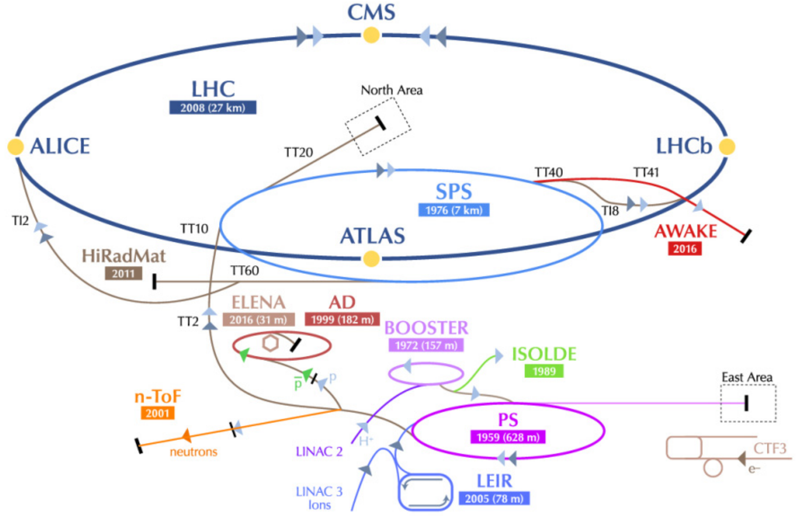
Introduction



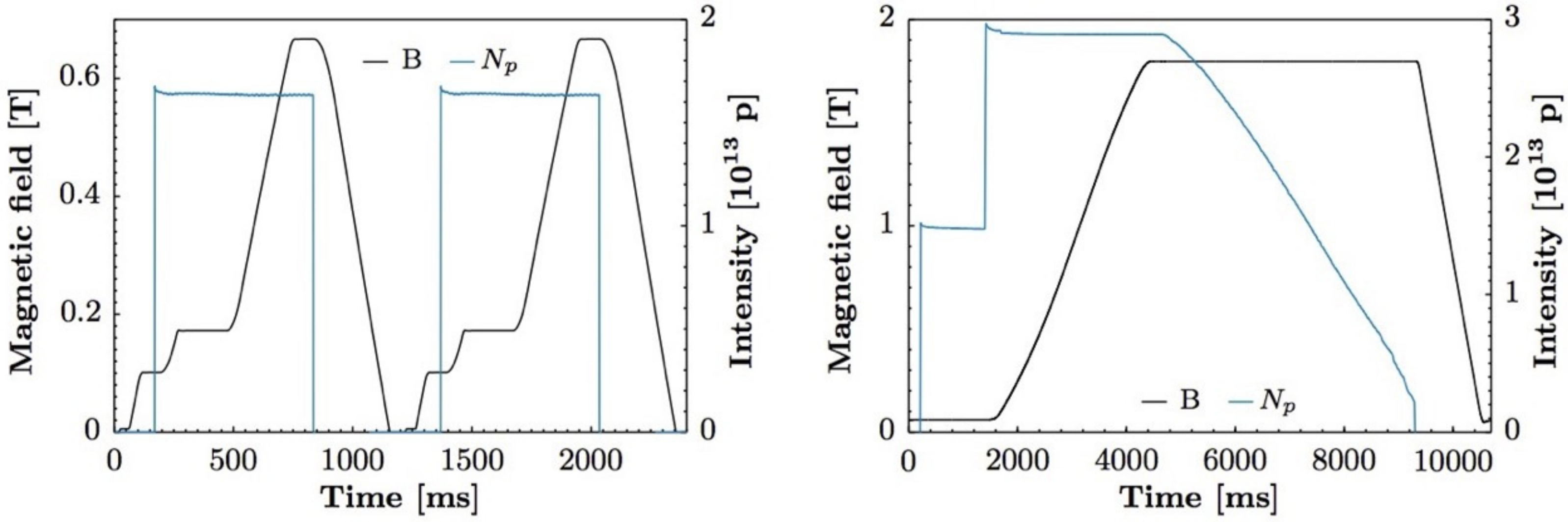
Introduction

- **CERN accelerator complex creates proton and heavy ion beams for physics research at the LHC**
  - LIU and HL-LHC projects well underway to boost the performance of the accelerators
- **Variety of fixed target facilities to complement physics research at the LHC**
  - Experimental facilities mostly requiring **high-intensity** beams in contrast to **high-brightness** beams for the LHC
- **High-intensity beams for SPS fixed target physics have to fulfil very special requirements**
  - Uniform filling of the ring required to reduce beam loading and provide almost continuous spill to experimental facilities



Introduction

- **Optimization of duty cycle by filling the SPS with two consecutive PS extractions**
  - PS extraction taking place at 14 GeV/c
  - Extracting two **five-PS-turns long pulse**
  - Allows to fill 10/11 of the SPS (leaving a kicker gap)



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- Optimization of the MTE process
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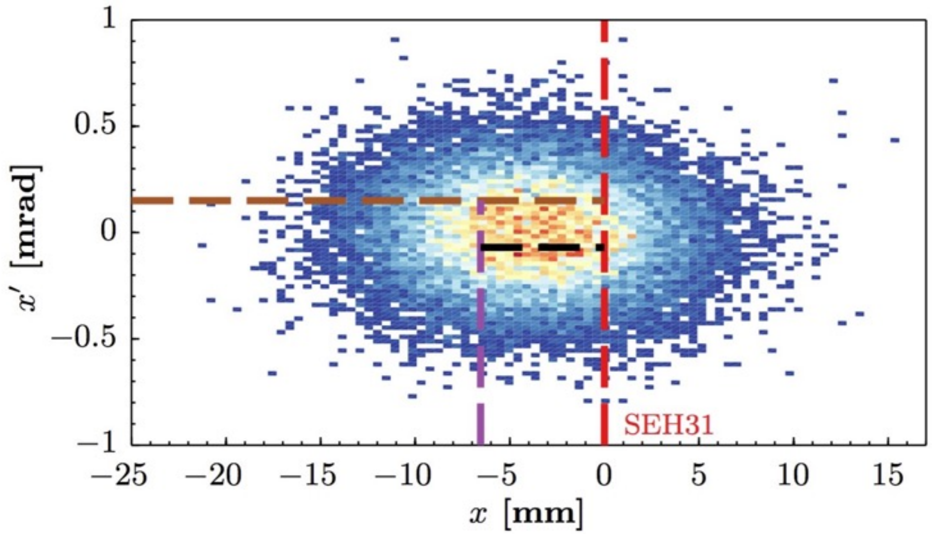
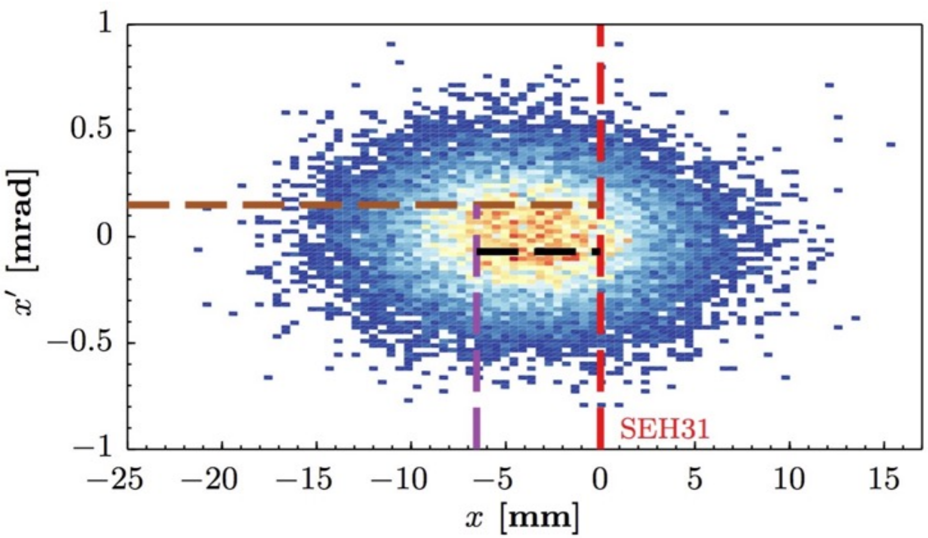
Continuous Transfer scheme



Continuous Transfer scheme

- **Developed in the 1970s to provide five-turn spill**
  - Beam **horizontally shaved** at an electrostatic septum and extracted at a downstream magnetic septum
  - $Q_x = 6.25$ set to shave-off four beamlets and extract the core in the last turn
  - Obvious draw-back of beam loss due to direct particle impact
  - **CT operation incompatible with future high-intensity beams** due to large radioactive activation of the PS ring



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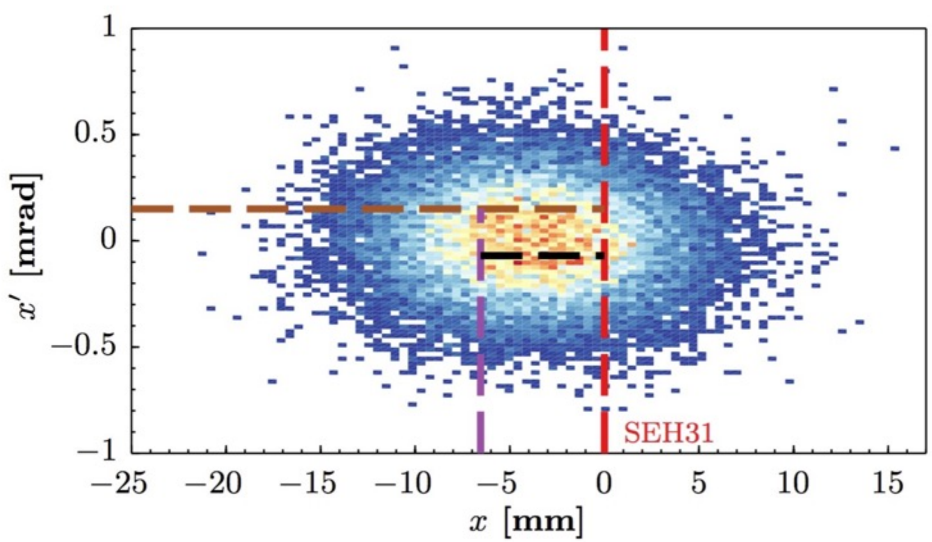

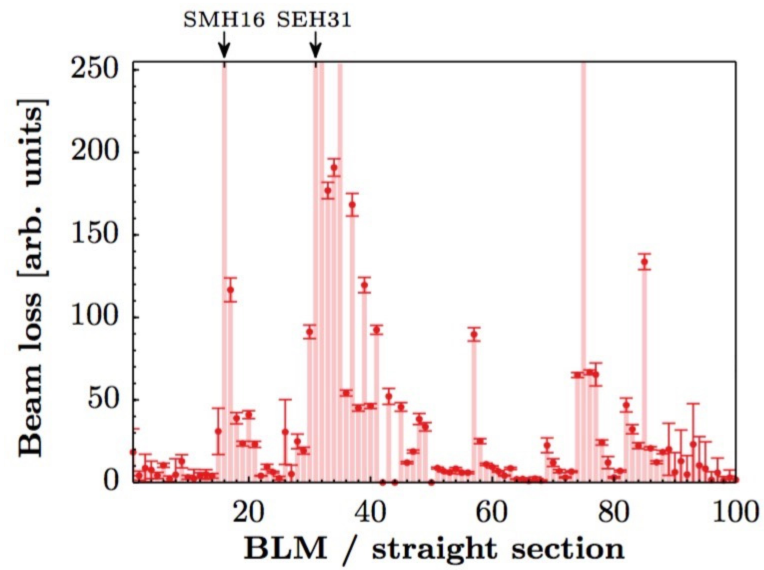

Multi-Turn Extraction scheme

Multi-Turn Extraction scheme

- **MTE proposed to overcome CT drawbacks**
- **Resonant extraction process based on beam splitting in the horizontal phase space**
  - **Non-linear elements** (sextupoles and octupoles) applied to excite fourth order resonance $4Q_x = 25$
  - Controlled **adiabatic crossing** of this resonance to **split the beam** into four islands and one core

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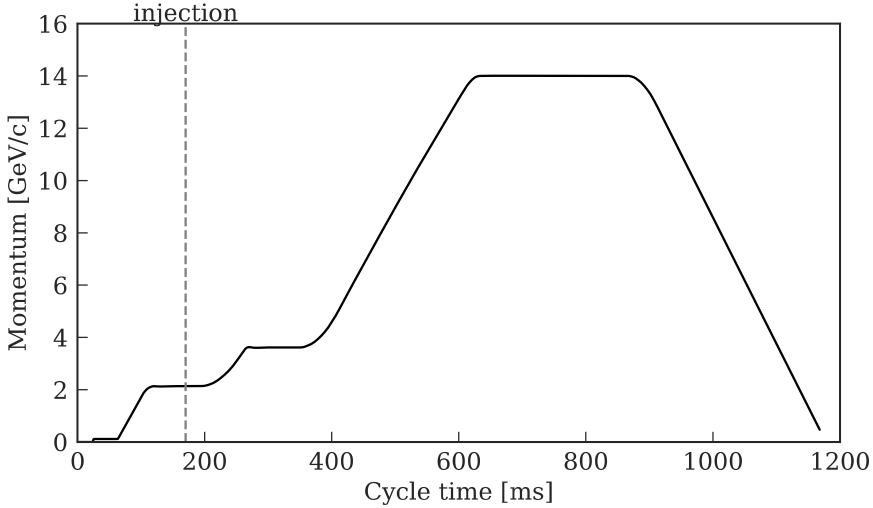

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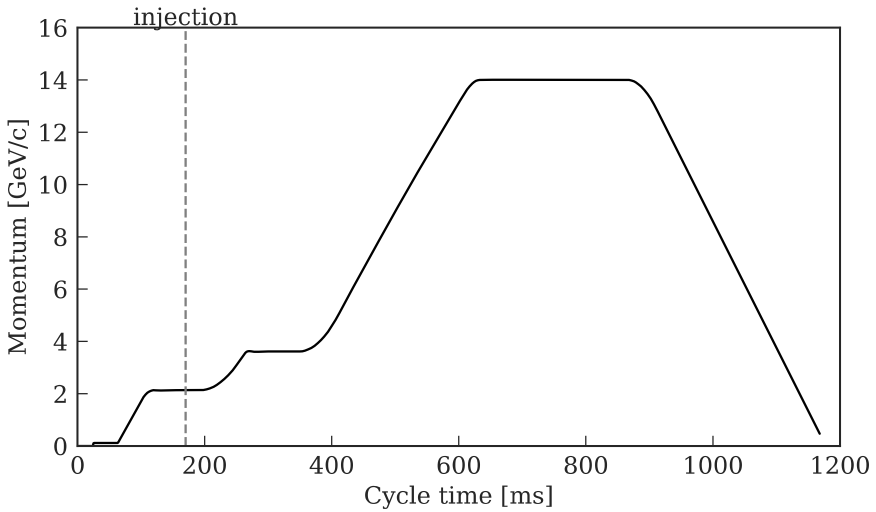

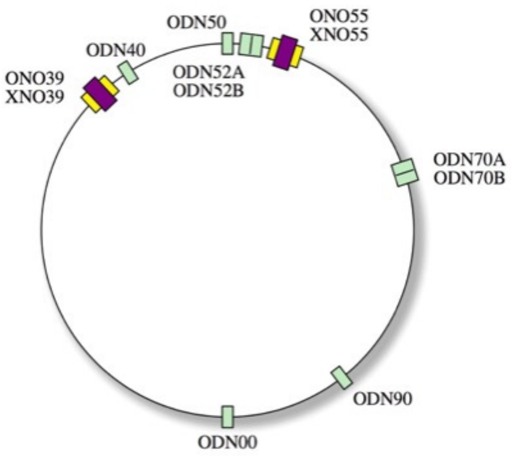

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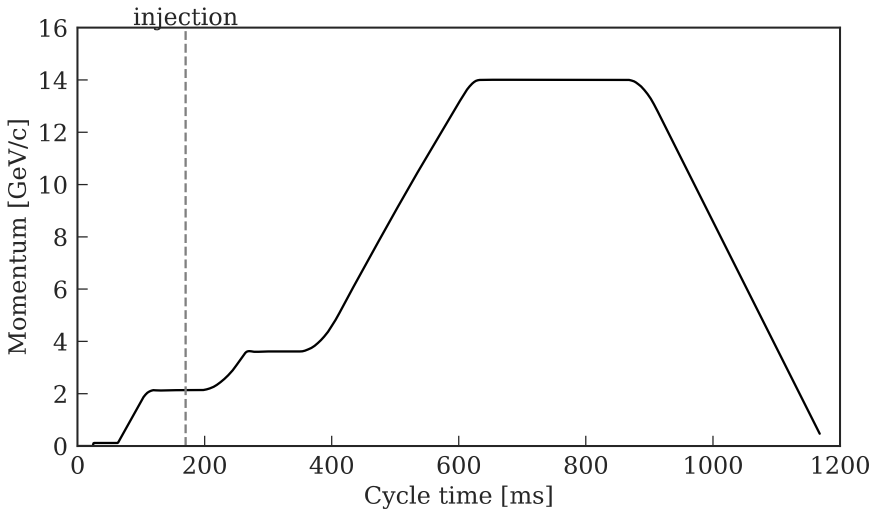

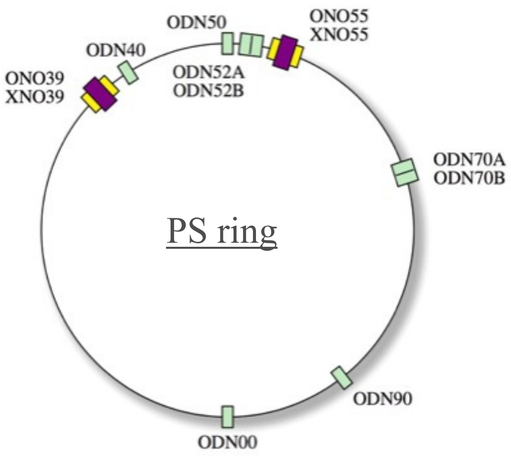

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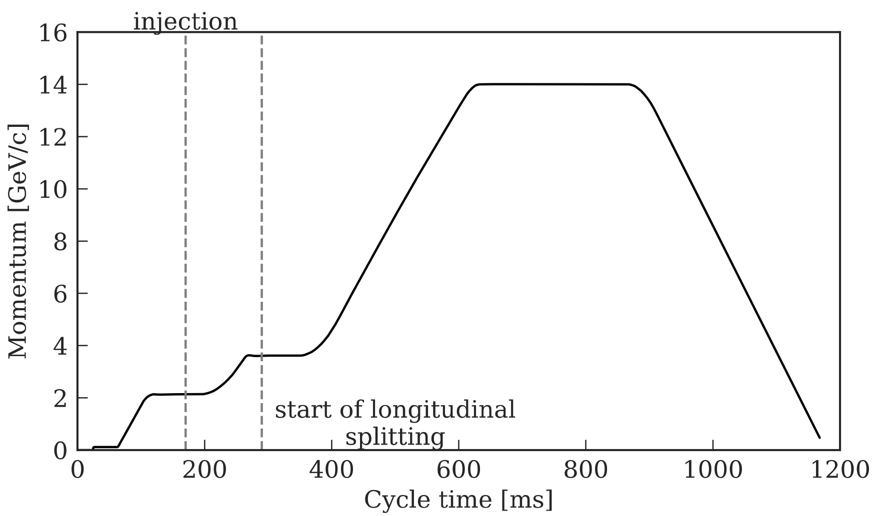

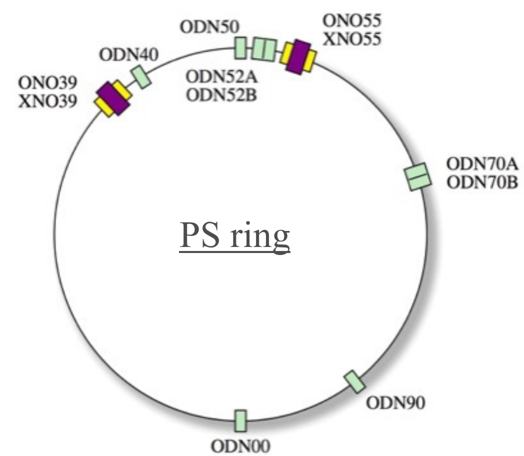

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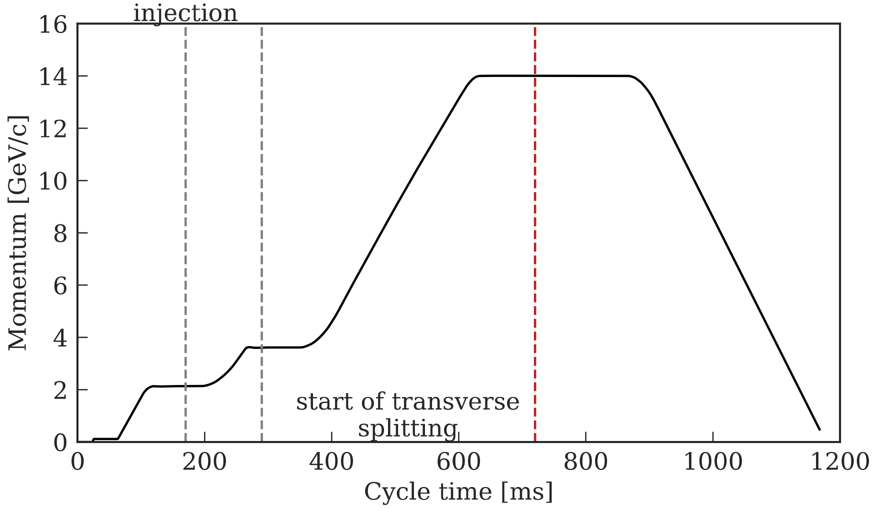

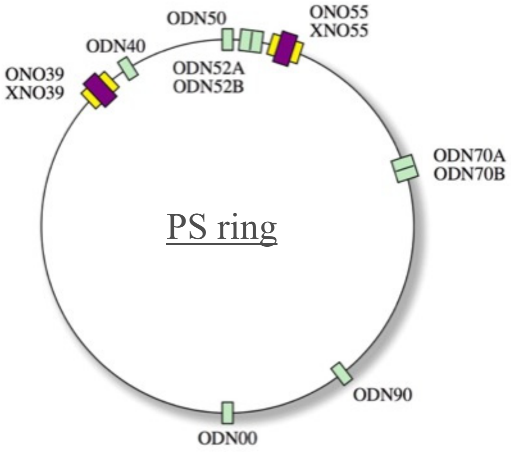

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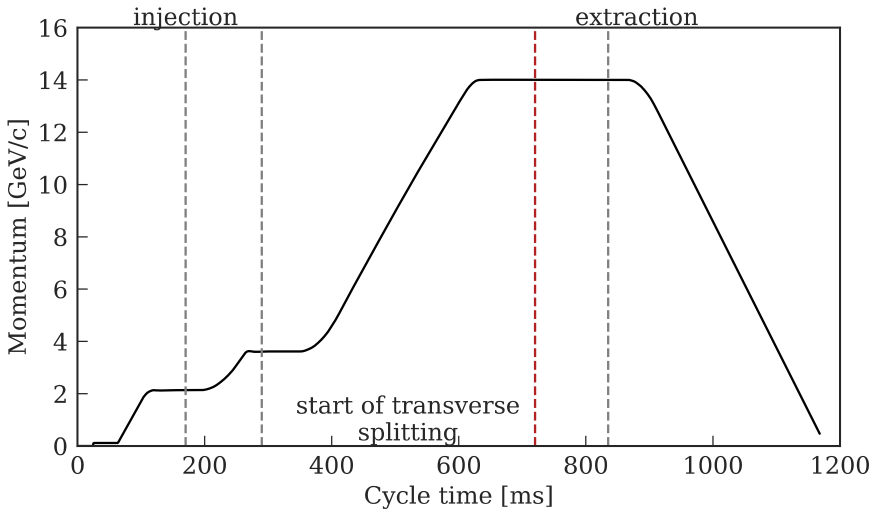

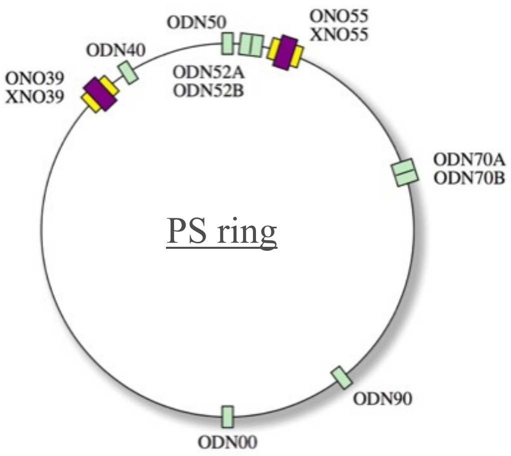

Multi-Turn Extraction scheme

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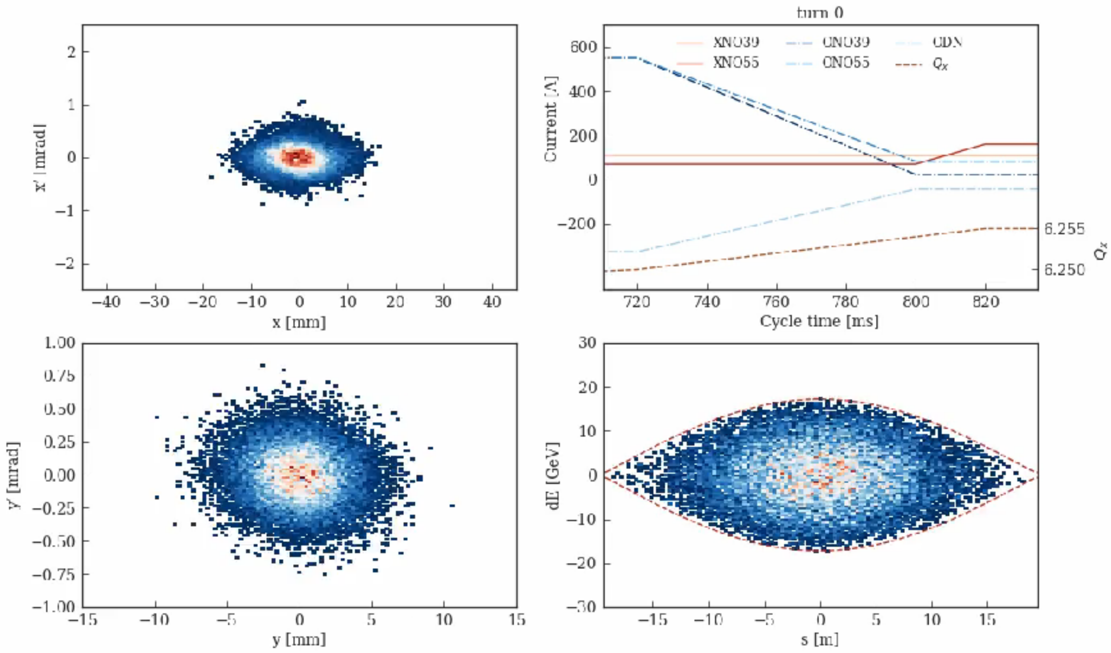

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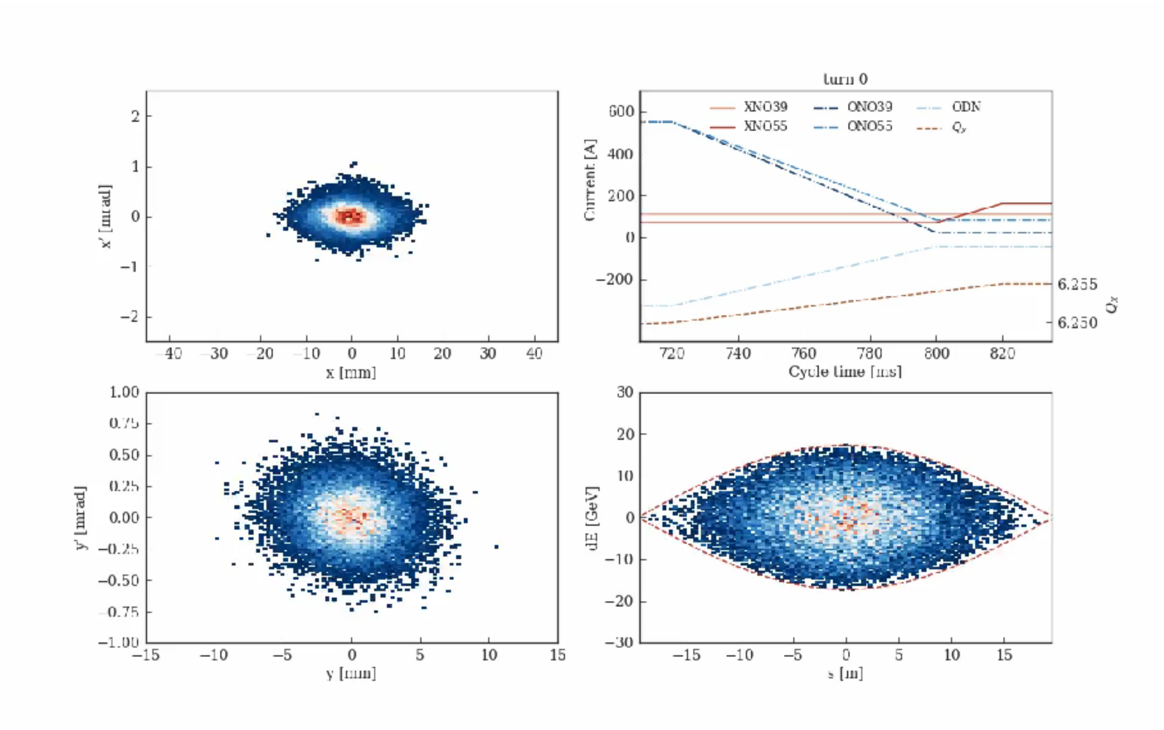

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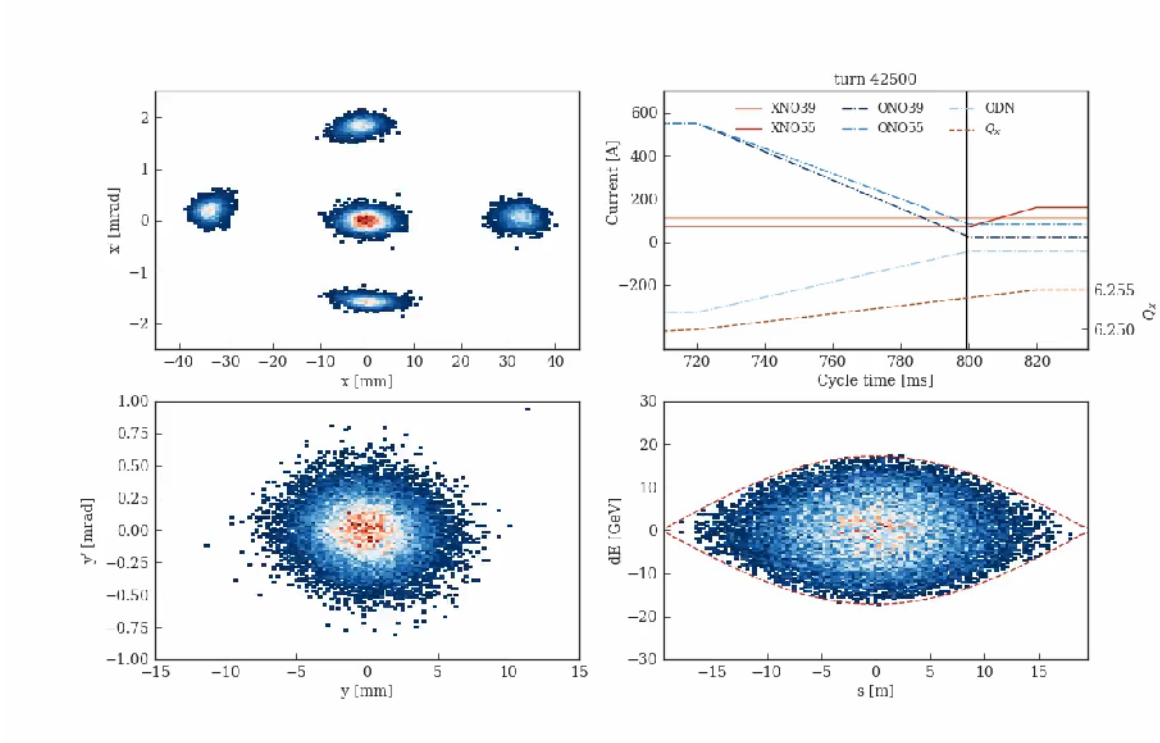
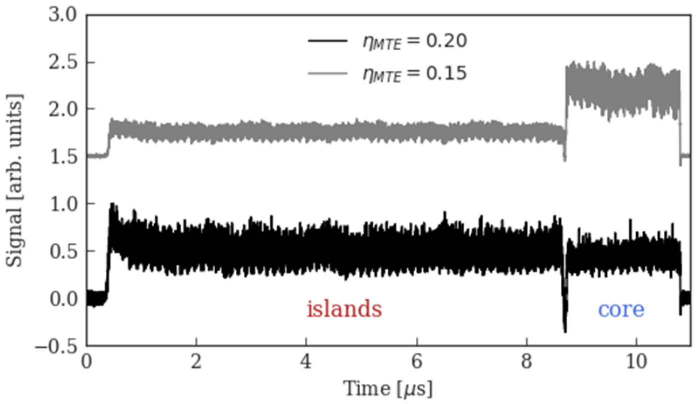


Multi-Turn Extraction scheme

$$\eta_{\mathrm{MTE}} = \frac{\langle I_{\mathrm{Island}} \rangle}{I_{\mathrm{Total}}}$$



Multi-Turn Extraction scheme

- **Figure of merit describing the MTE process**
  - Obtained from beam intensity measurement in the transfer line between PS and SPS

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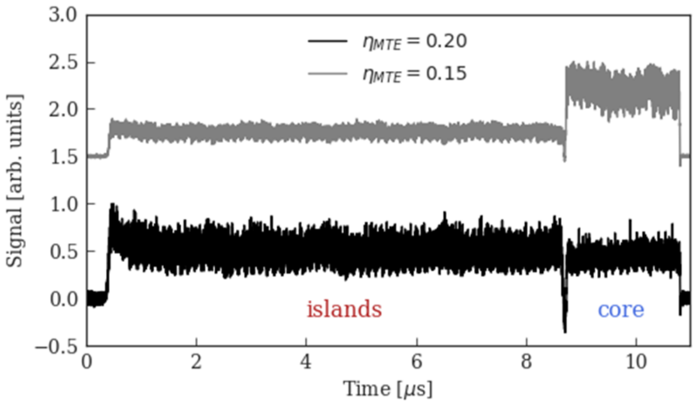
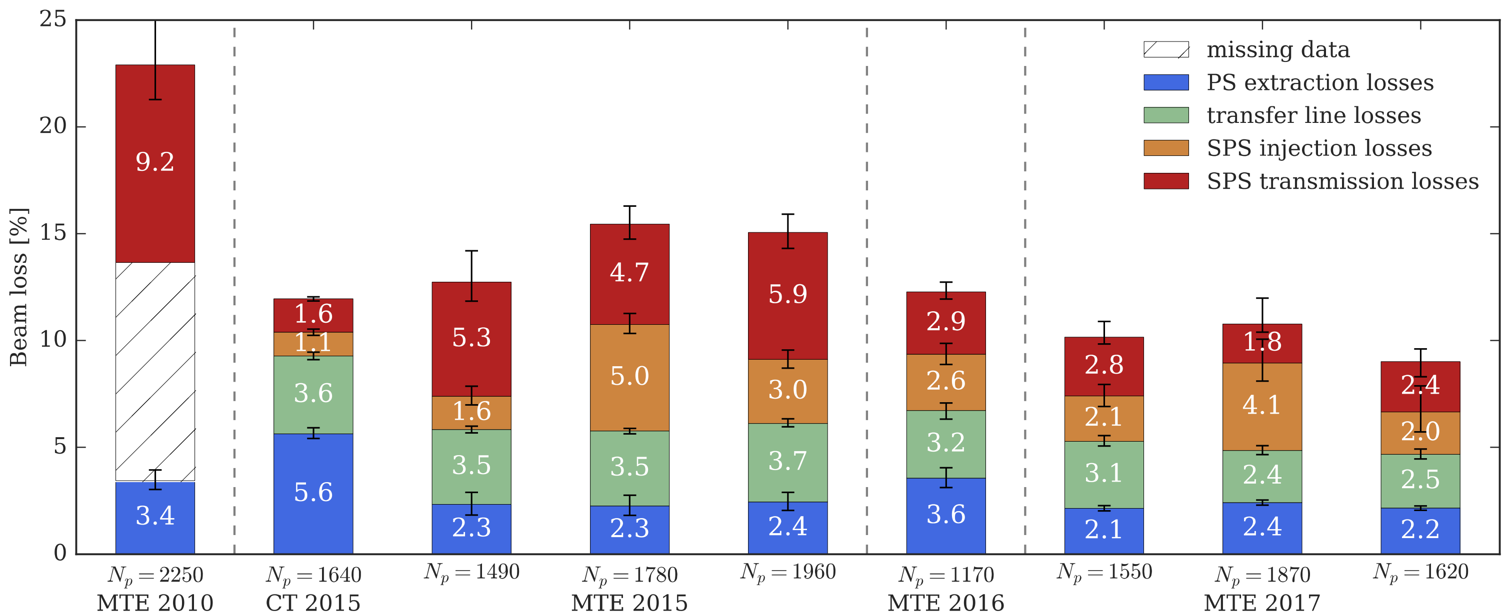


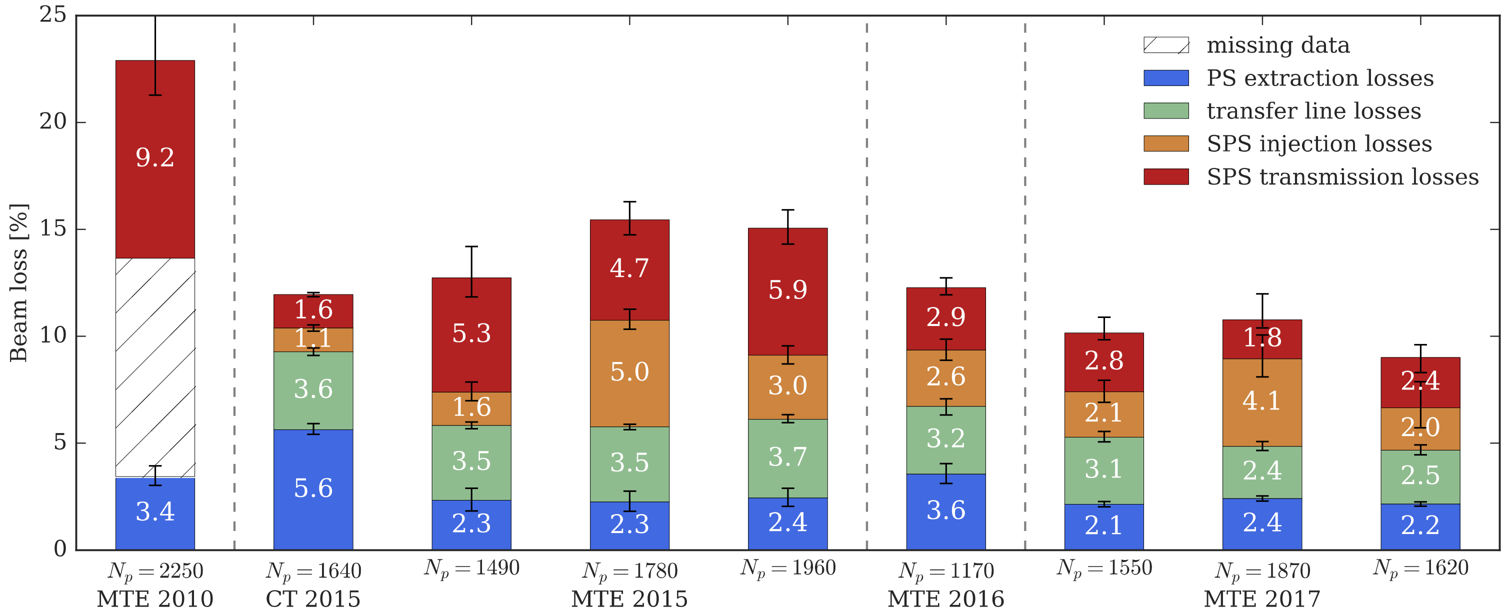
- **SPS fixed target beams operationally produced using MTE since 2015**
  - Typical extracted proton intensity 1.5 – 2.0 x 10^{13} per PS extraction
- **Future facilities such as the SHiP experiment require up to 2.5 x 10^{13} p**
  - Series of dedicated studies performed in 2017 to **asses MTE performance** at these intensities and understand potential limitations
  - Essential step to decide on the future of the CT hardware

MTE performance evolution since 2010



MTE performance evolution since 2010

- **Drastic loss reduction at PS extraction clearly visible**



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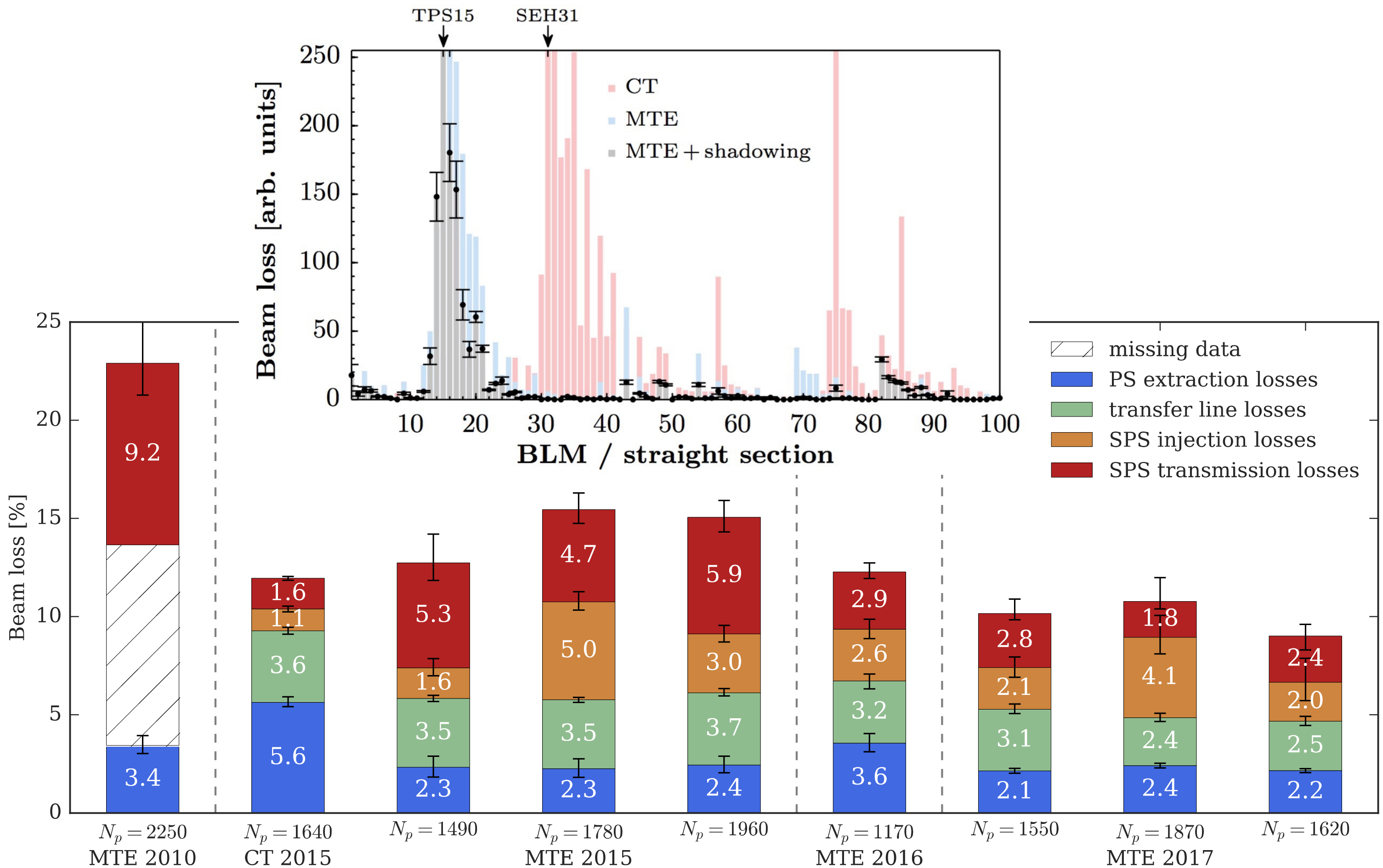

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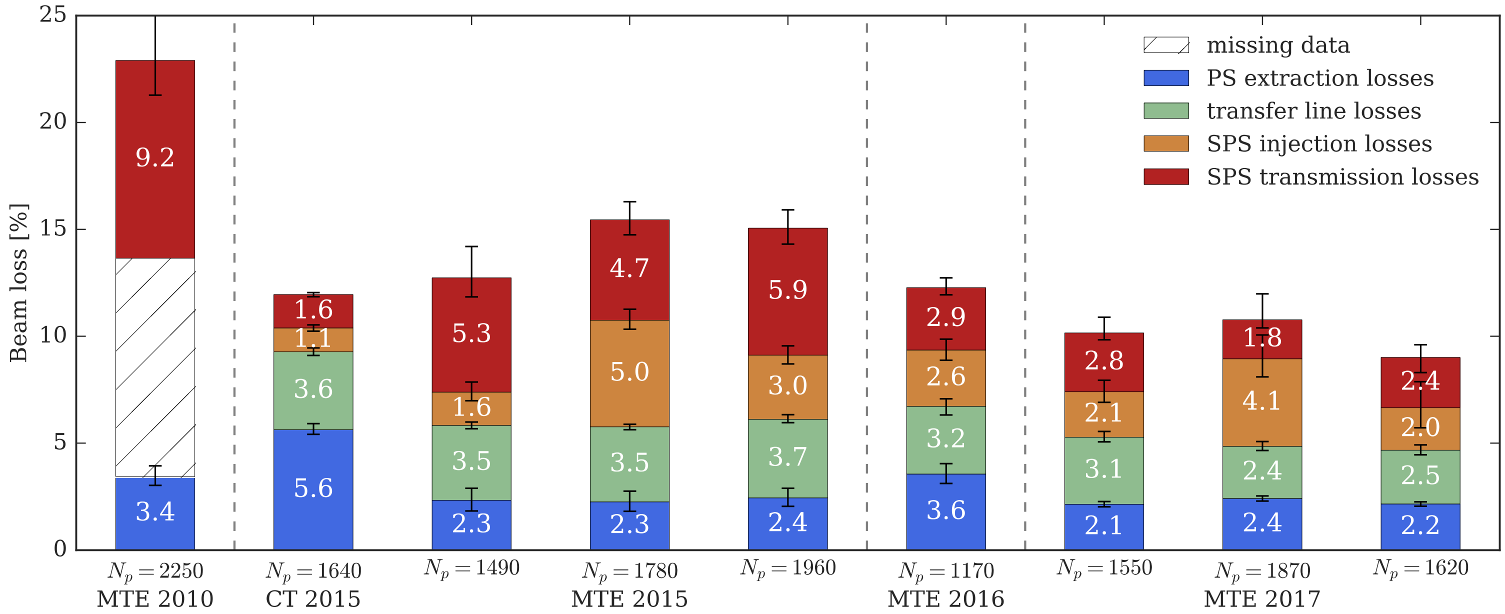
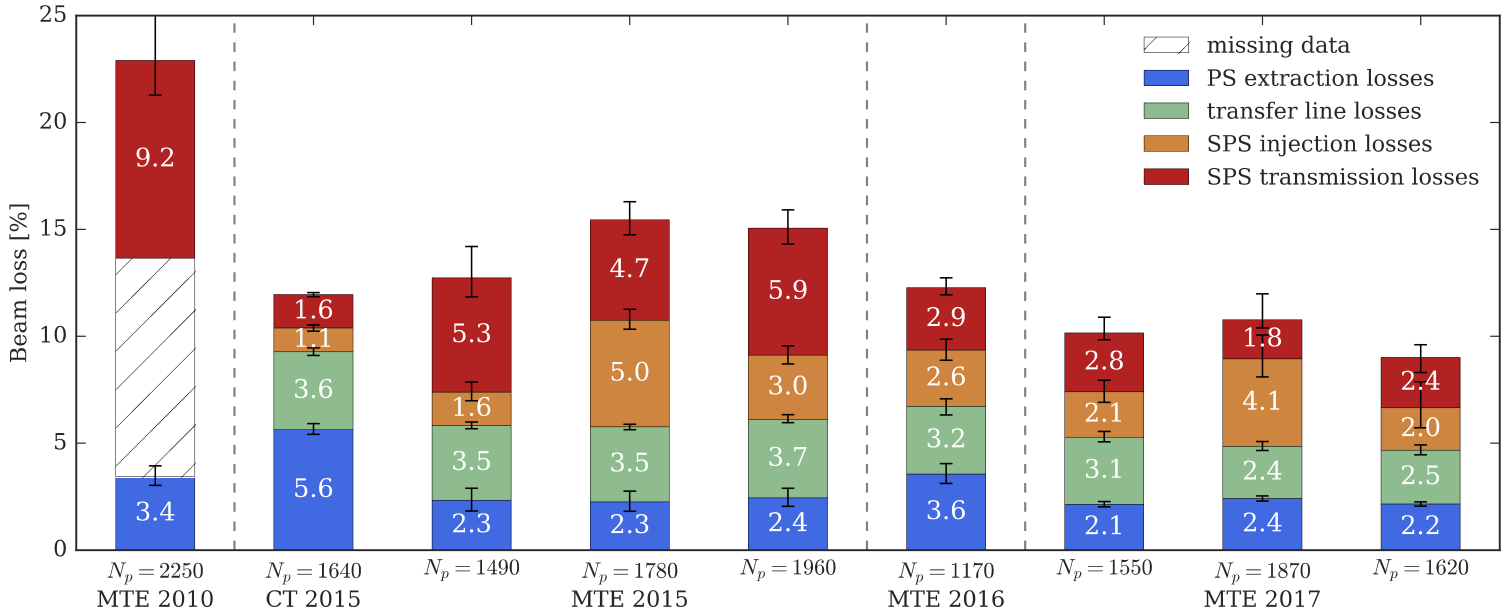


MTE performance evolution since 2010

- **Drastic loss reduction at PS extraction clearly visible**
- **MTE performance significantly improved over the years**
- **Total losses along the chain smaller than in the CT era**
  - The CT extraction has been optimized over more than three decades
- **Decreased SPS transmission due to higher vertical emittance of the MTE beams**



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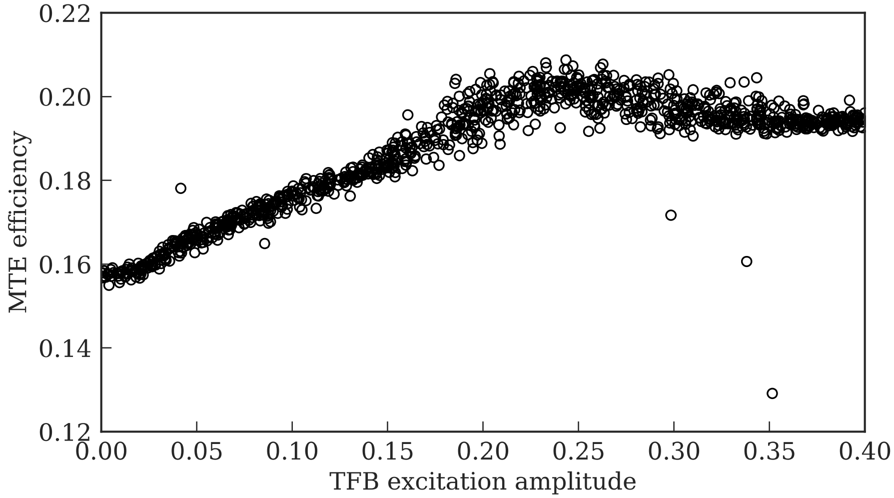
Transverse excitation and core emittance growth

- **Horizontal dipolar excitation crucial to obtain proper intensity sharing between islands and core**
  - Provided by the transverse feedback (TFB) system in open loop
  - $\eta_{\mathrm{MTE}} \approx$ 0.15 - 0.16 in the absence of such an excitation
  - Nominal value $\eta_{\mathrm{MTE}} \approx$ 0.20 only achievable above a certain excitation amplitude



Transverse excitation and core emittance growth

- **Observation of significant core emittance growth in the SPS**
  - $\varepsilon^{n}_{x,core} \approx 13$ mm mrad observed compared to 5 mm mrad of the islands
  - Potential side effect of excitation with TFB

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- **Investigation of impact of TFB parameters on core emittance**
  - Excitation frequency found to importantly affect the core emittance
  - Relatively wide frequency range with small emittance growth while η_{MTE} is close to the nominal value
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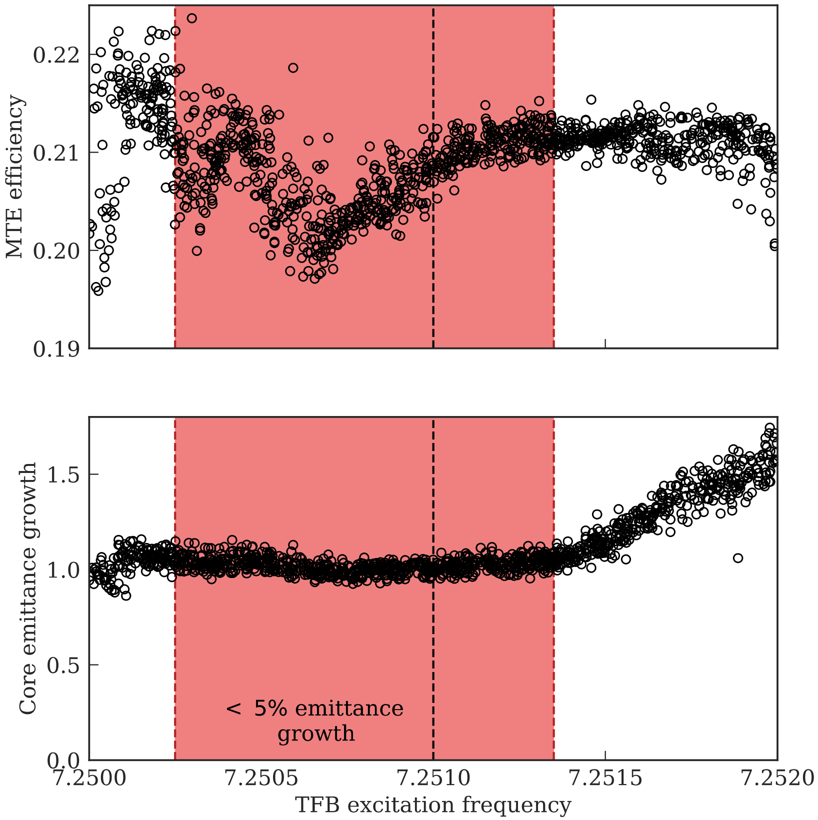
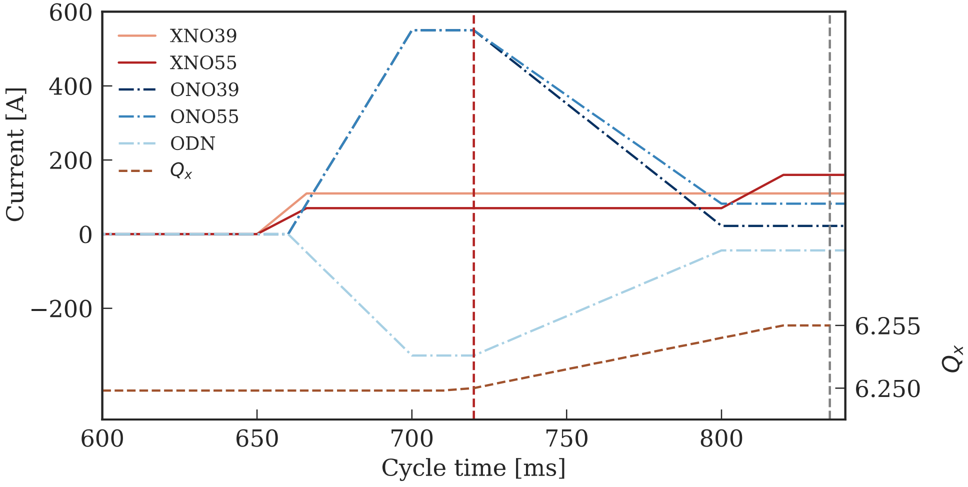


Optimization of the settings of the non-linear elements



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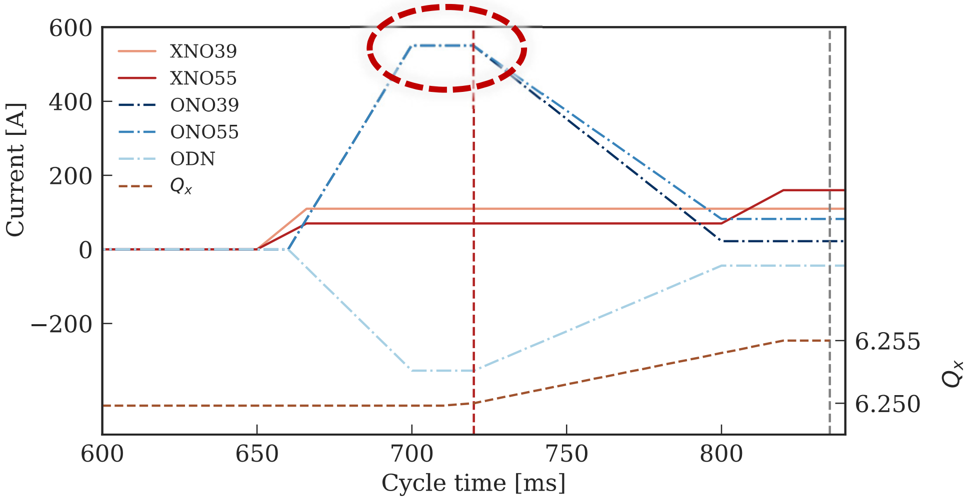

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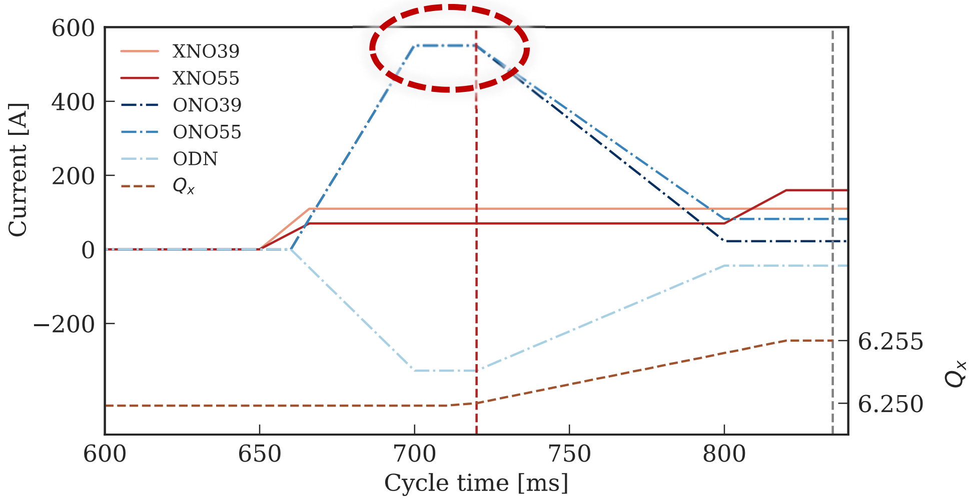
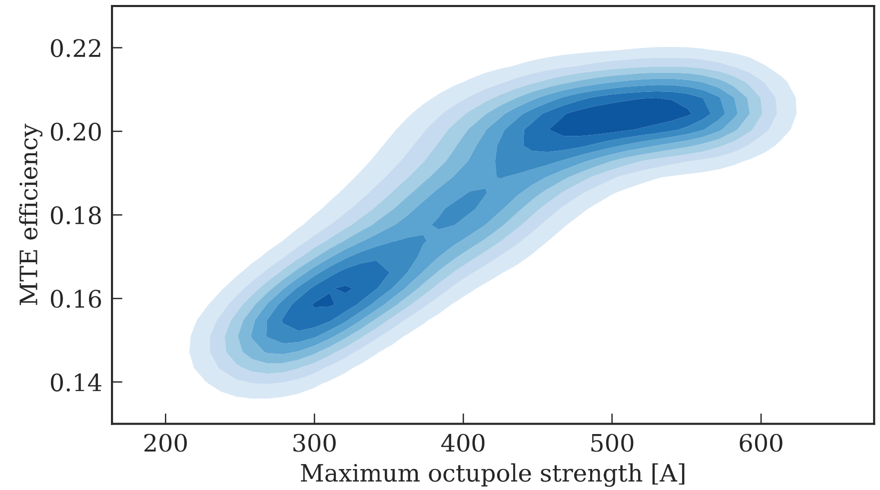
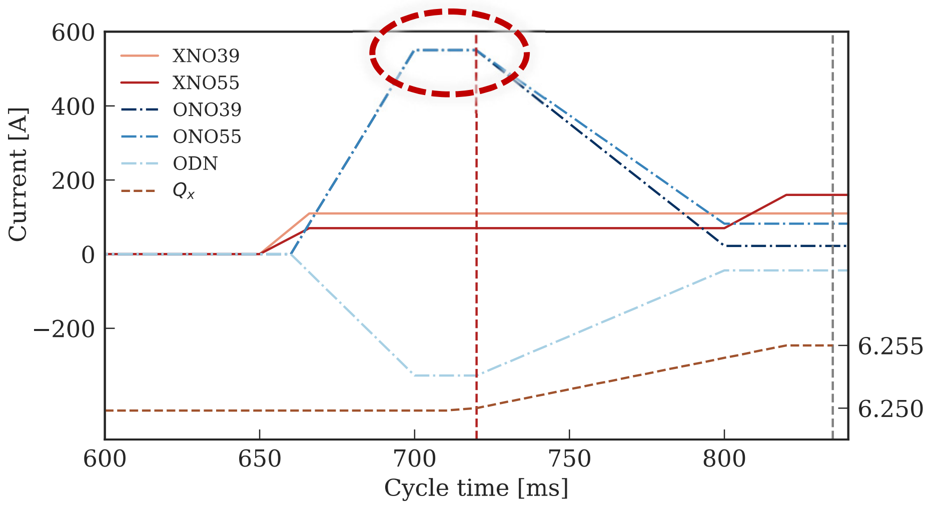
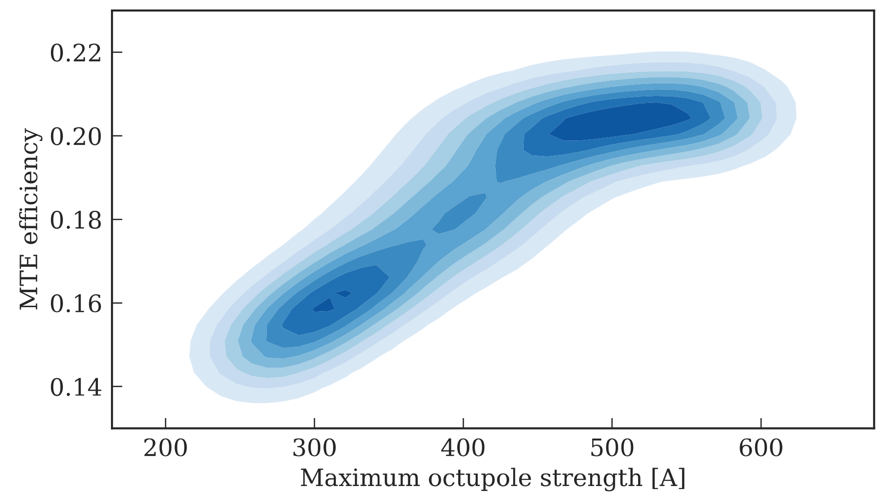




Optimization of the settings of the non-linear elements

- **Settings define evolution of the islands' size in time and the adiabaticity of the process**
    - Maximum strength of the octupoles ONO39 and ONO55 at resonance crossing
    - Significant improvement of MTE efficiency at highest possible strength





Optimization of the settings of the non-linear elements

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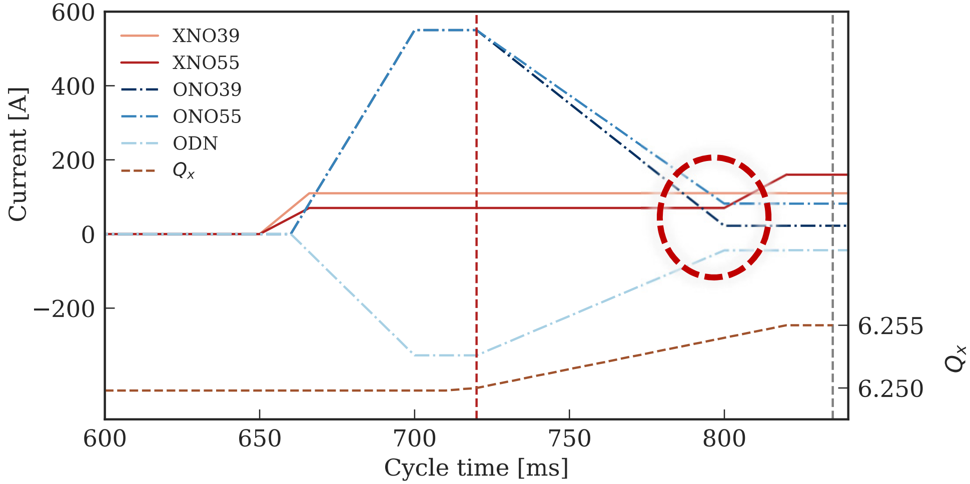
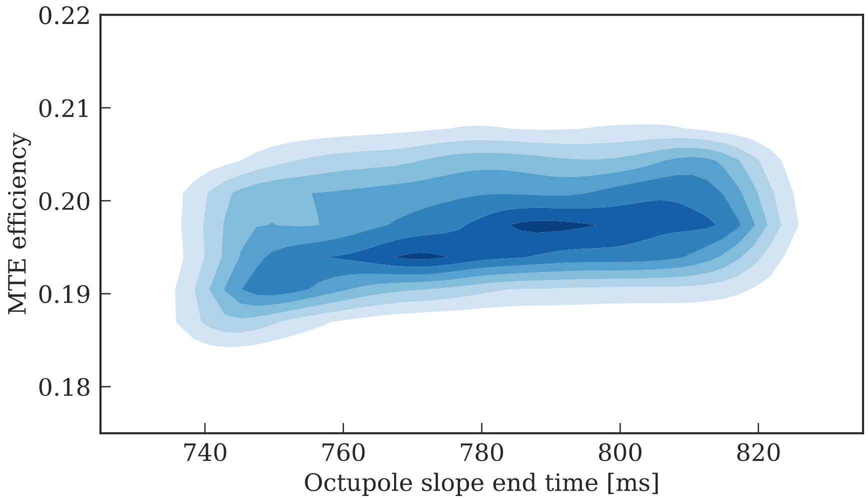
  - Only mild impact of variations of the descending slope





Optimization of the settings of the non-linear elements

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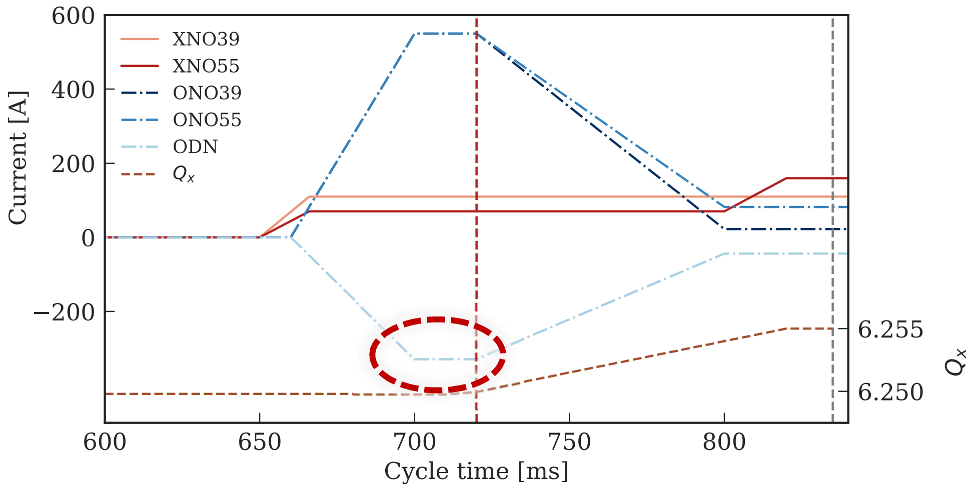
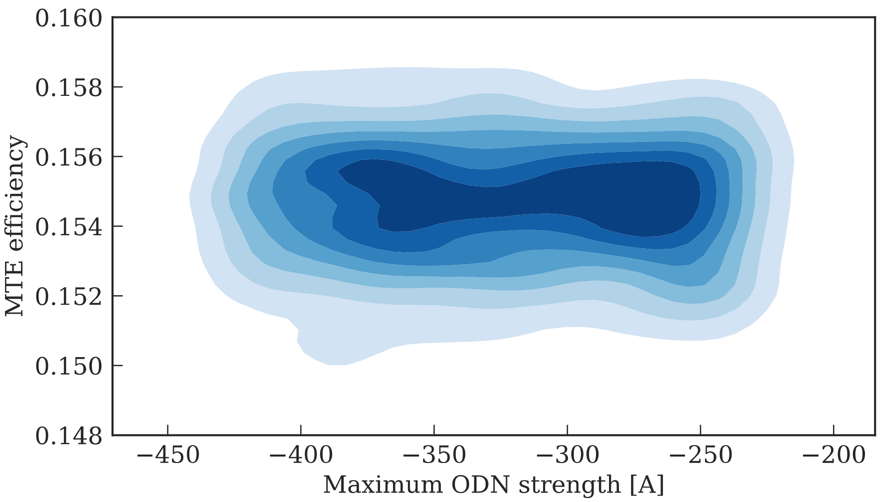
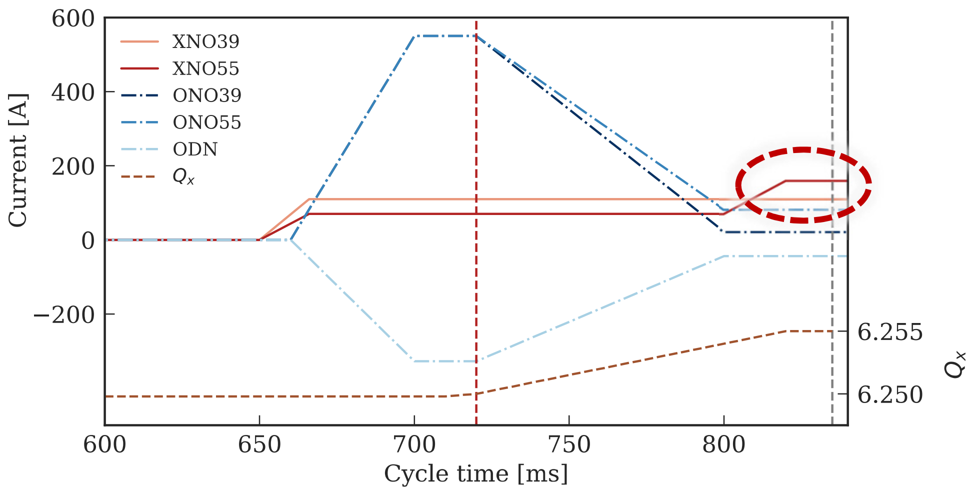
  - Basically no impact of the ODN circuit used to non-linearly decouple the transverse planes

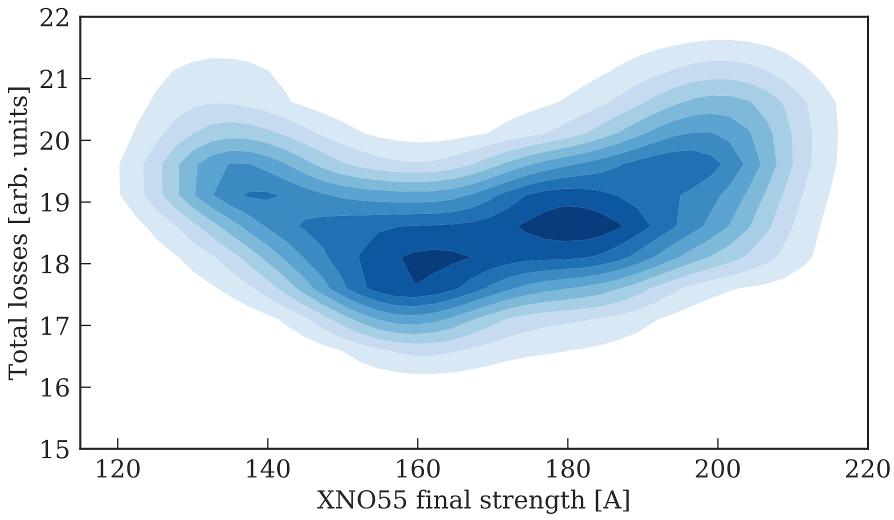




Optimization of the settings of the non-linear elements

- **Settings define evolution of the islands' size in time and the adiabaticity of the process**
  - Optimization of extraction losses by acting on the final rotation using XNO55





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MTE performance at high-intensity

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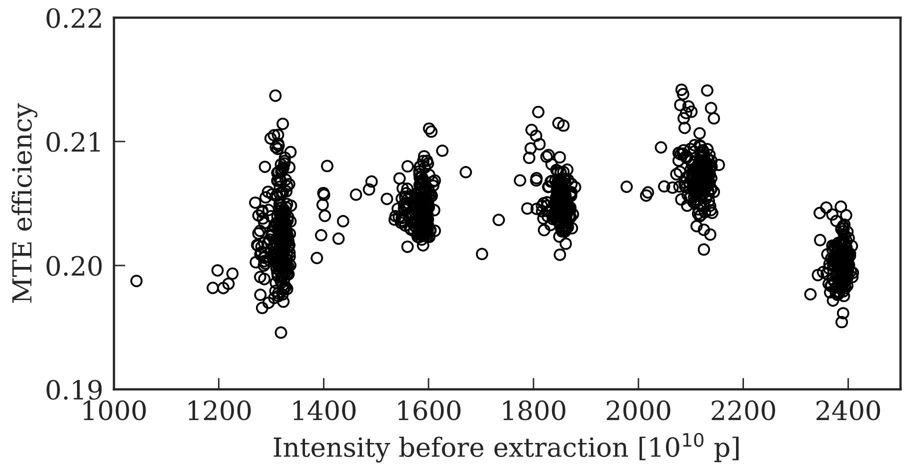
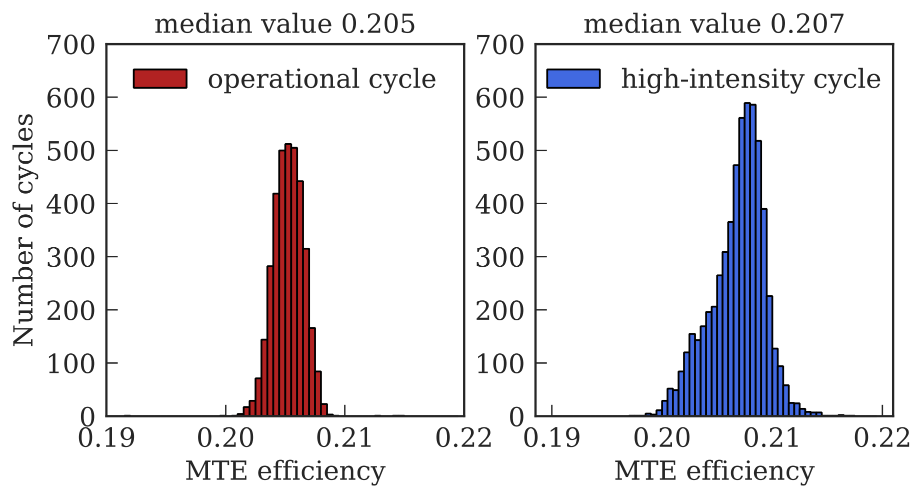


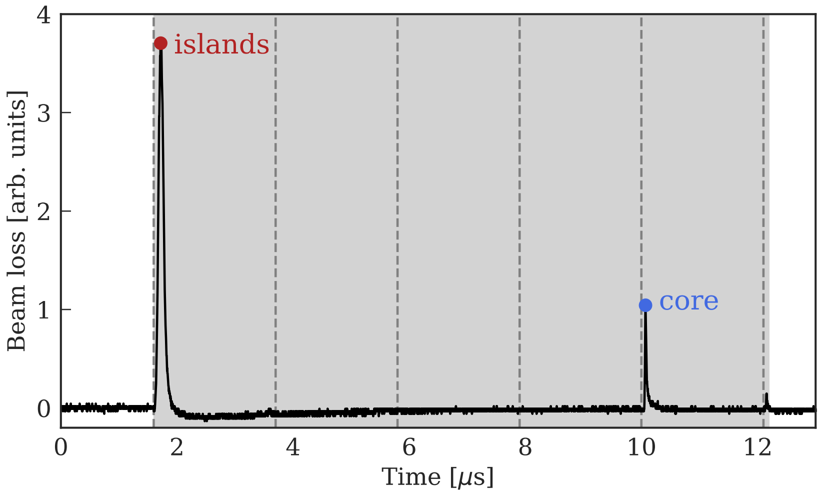
MTE efficiency at high-intensity

- **Investigation of scaling with intensity of three main quantities**
  - Splitting efficiency
  - Extraction losses
  - Longitudinal beam stability
- **Comparison between operational and high-intensity cycle**
  - Very **similar distribution of η_{MTE}** for the probed intensity range
  - Remark: median value always adjustable using the TFB



Extraction losses at high-intensity

- **Evaluated with fast beam loss monitors**
  - Providing intra-turn loss evolution
  - Extraction losses clearly distinguishable between islands and core
  - Different height of peaks caused by different extraction kicker rise times



Extraction losses at high-intensity

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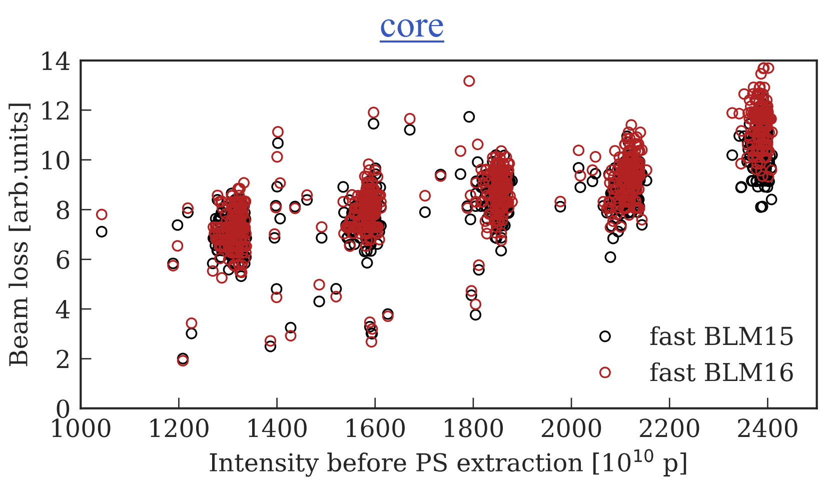
different extraction kicker rise times

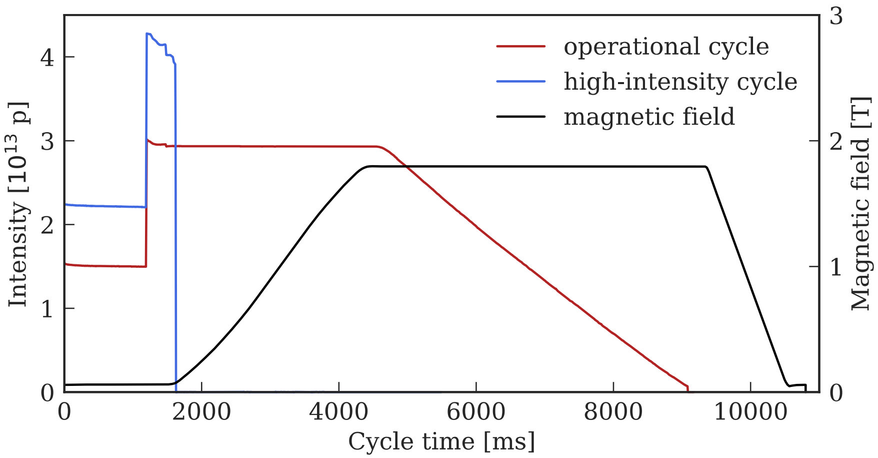
intensity

intensity rather than any unexpected phenomenon

0
1000 1200 1400 1600 1800 2000 2200 2400
Intensity before PS extraction [10^{10} p]

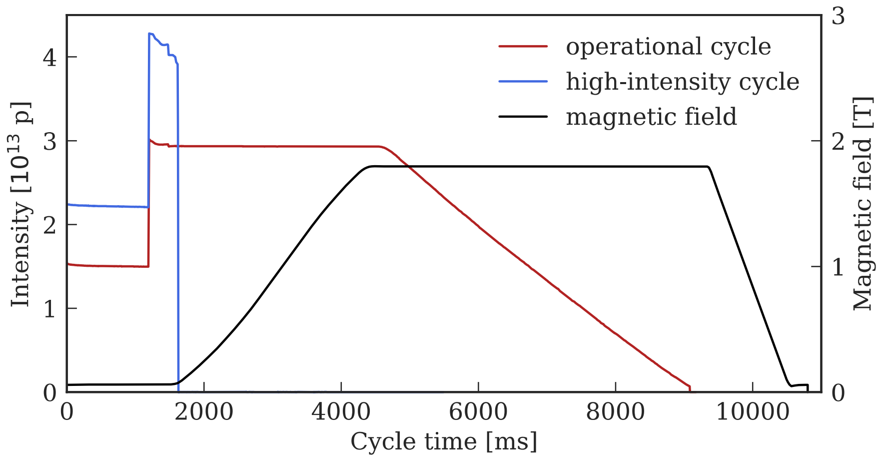


SPS performance tests



SPS performance tests

- **Transfer of the high-intensity beams to the SPS as final step following the optimization of MTE in the PS**
  - Main focus on injection of first batch as proof of principle
  - High-intensity beams dumped at 27 GeV
  - Increased losses compared to operational intensity observed at:
    - Injection: clearly attributed to increased vertical emittance
    - Start of acceleration and transition crossing: further careful adjustment of machine parameters required



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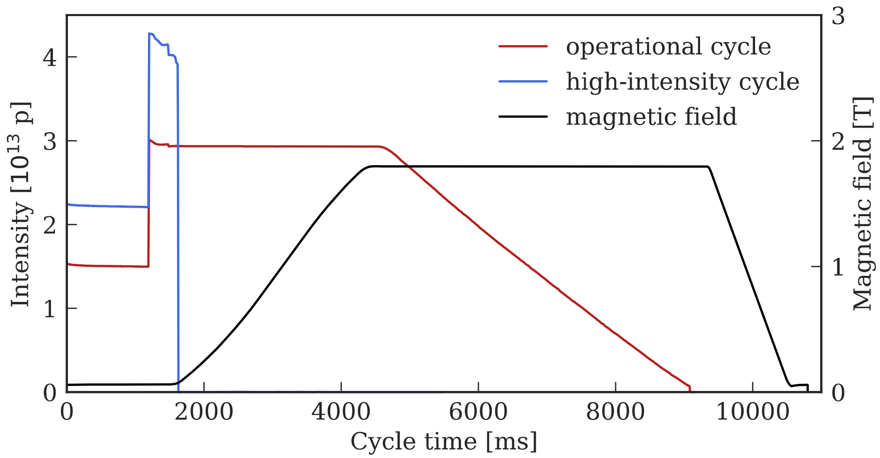
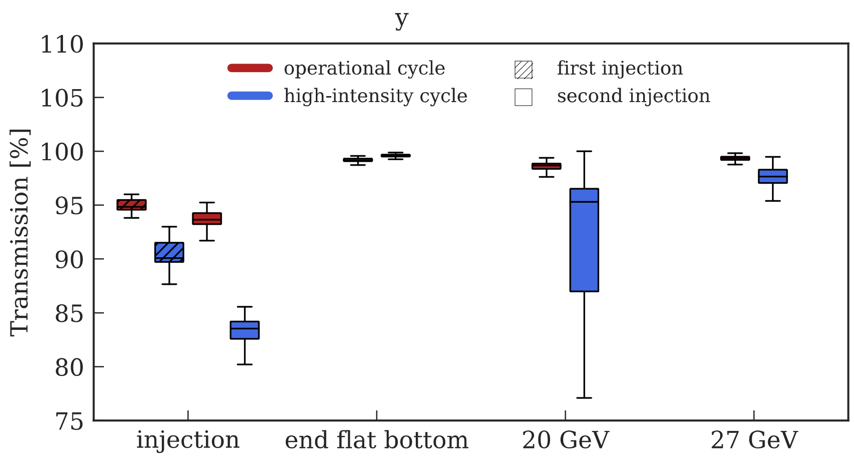
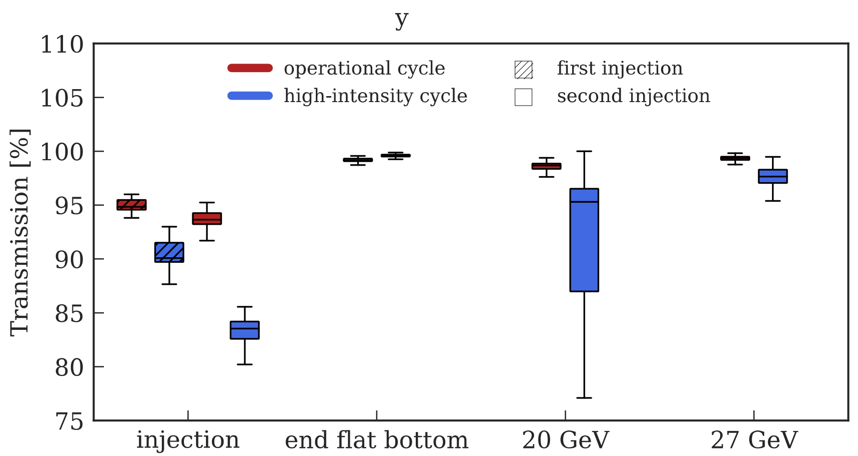
  - High-intensity beams dumped at 27 GeV
  - Increased losses compared to operationa
    - Injection: clearly attributed to increased ver
    - Start of acceleration and transition crossing required





SPS performance tests

- **Transfer of the high-intensity beams to the SPS as final step following the optimization of MTE in the PS**
  - Main focus on injection of first batch as pı
  - High-intensity beams dumped at 27 GeV
  - Increased losses compared to operationa
    - Injection: clearly attributed to increased ver
    - Start of acceleration and transition crossing required
- **Best achieved transmission after injection similar to operational beams**



- Introduction
- The CT and MTE schemes
- Optimization of the MTE process
- MTE performance at high-intensity
- **Conclusions and outlook**

Conclusions and Outlook

Conclusions and Outlook

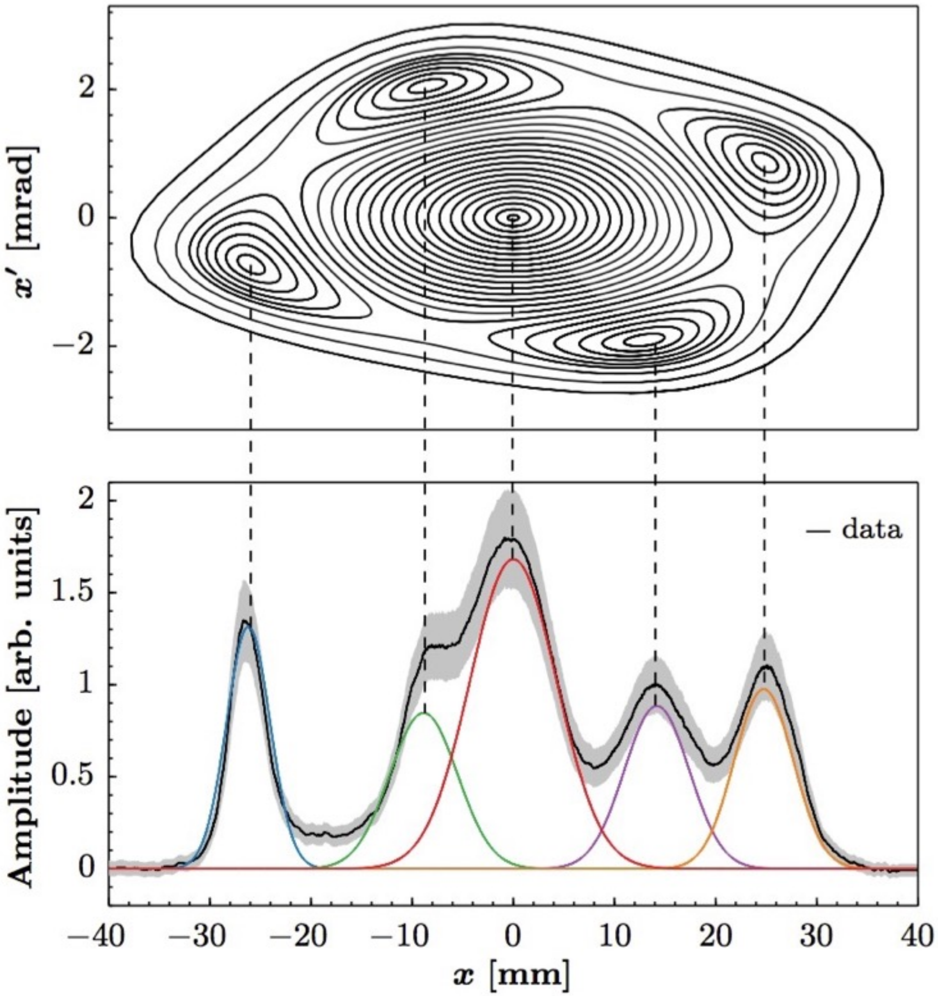
- **MTE performance has been constantly improved since its start of operation in 2015**
- **High-intensity MTE beam has been prepared and tested in PSB, PS and SPS**
  - PSB and PS performance comparable to that of the operational MTE beam
  - SPS performance dominated by vertical emittance delivered by the PSB
  - Reduced SPS transmission clearly related to vertical emittance and insufficient setup time
- **No major limitation for MTE beams at high-intensity observed along the accelerator chain**
  - MTE beams will profit from the upgrades foreseen by the LIU project: Linac4 to deliver smaller transverse emittances
- **Decision taken to dismantle the CT hardware during the Long Shutdown 2 based on the successful high-intensity tests**

Conclusions and Outlook

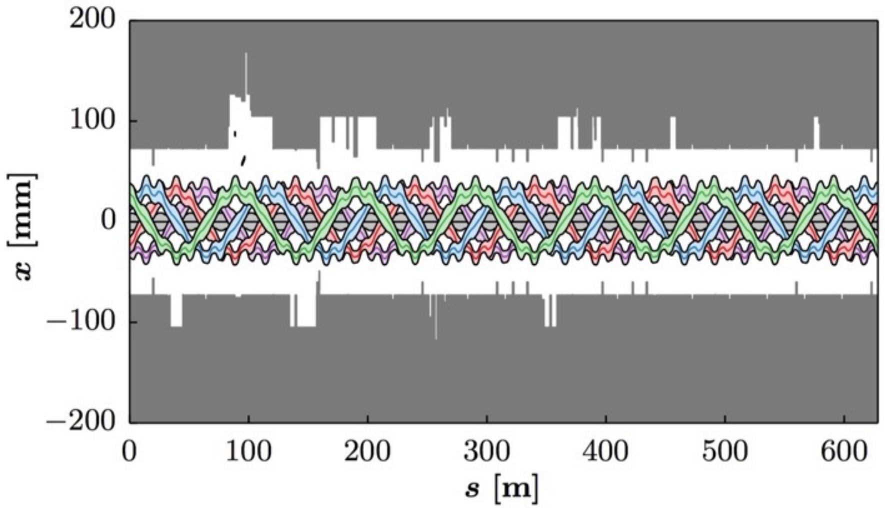
- **Further studies to improve the performance and understanding of the MTE process**
  - Both experimental and simulation studies being performed
- **Experimental studies**
  - Longitudinal barrier bucket to avoid beam loss during kicker rise times
  - Continuous improvement of the magnetic stability of the PS
    - Reduction of power converter ripples
    - Slow horizontal tune feedback (considering tune evolution over several cycles)
- **Simulation studies**
  - Impact of the horizontal dipolar excitation on the splitting process
  - Importance of direct space charge forces in the process

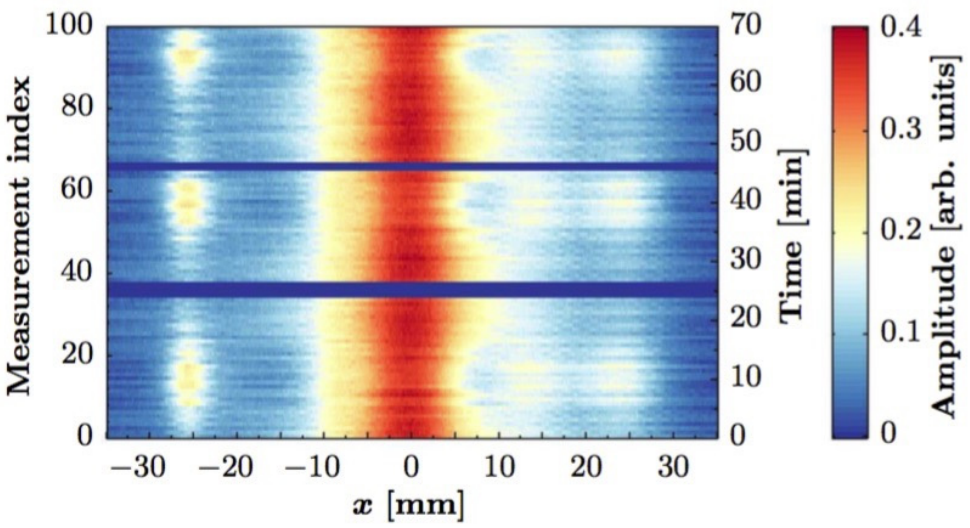
Thank you for your attention!

Observation of the splitting in the PS

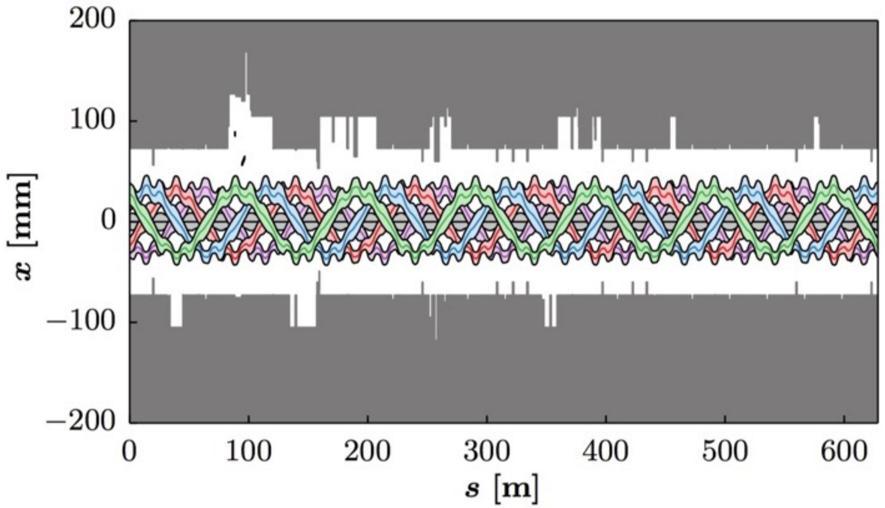


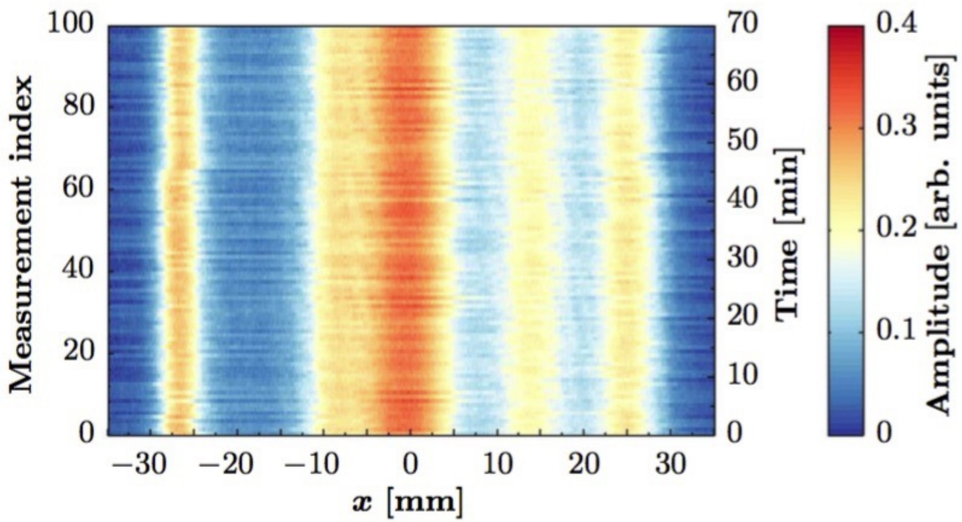
MTE challenges



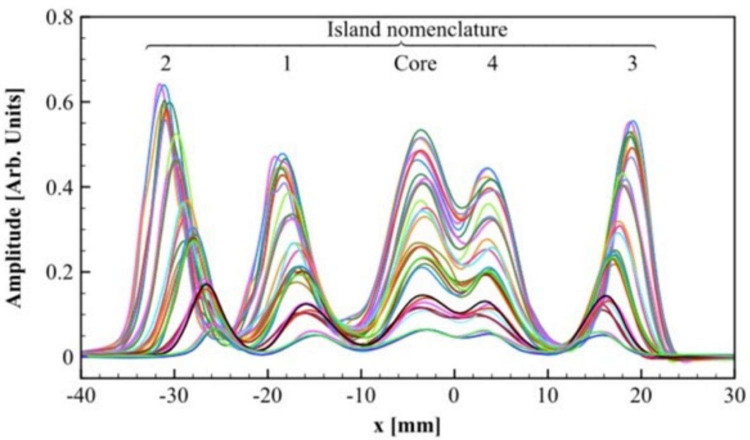


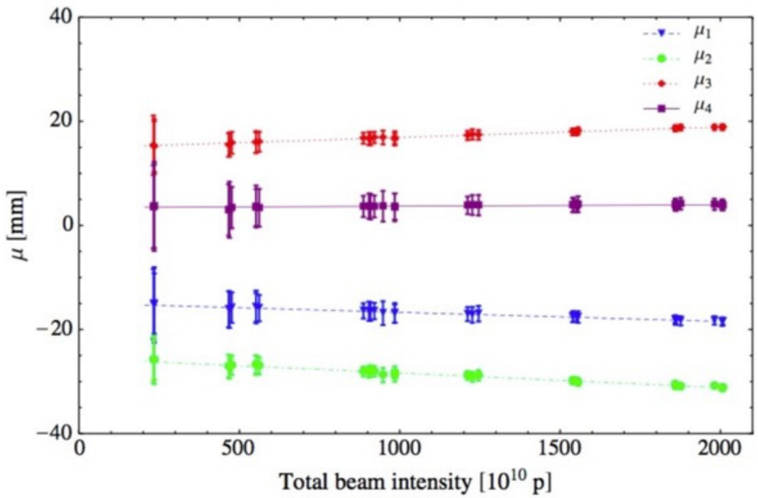
MTE challenges

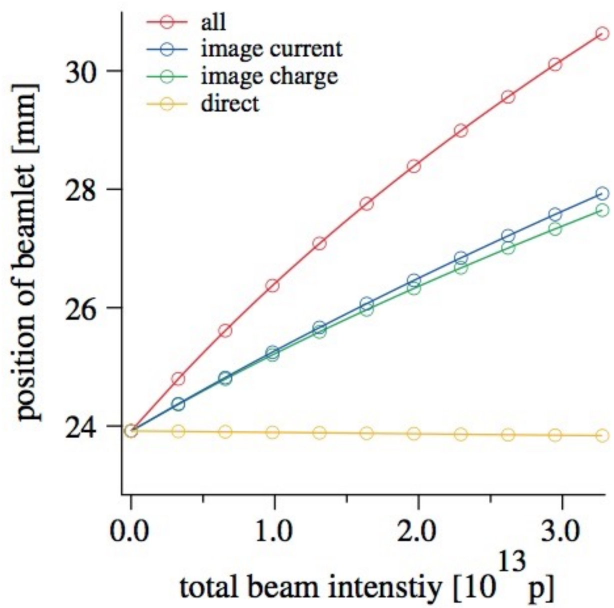




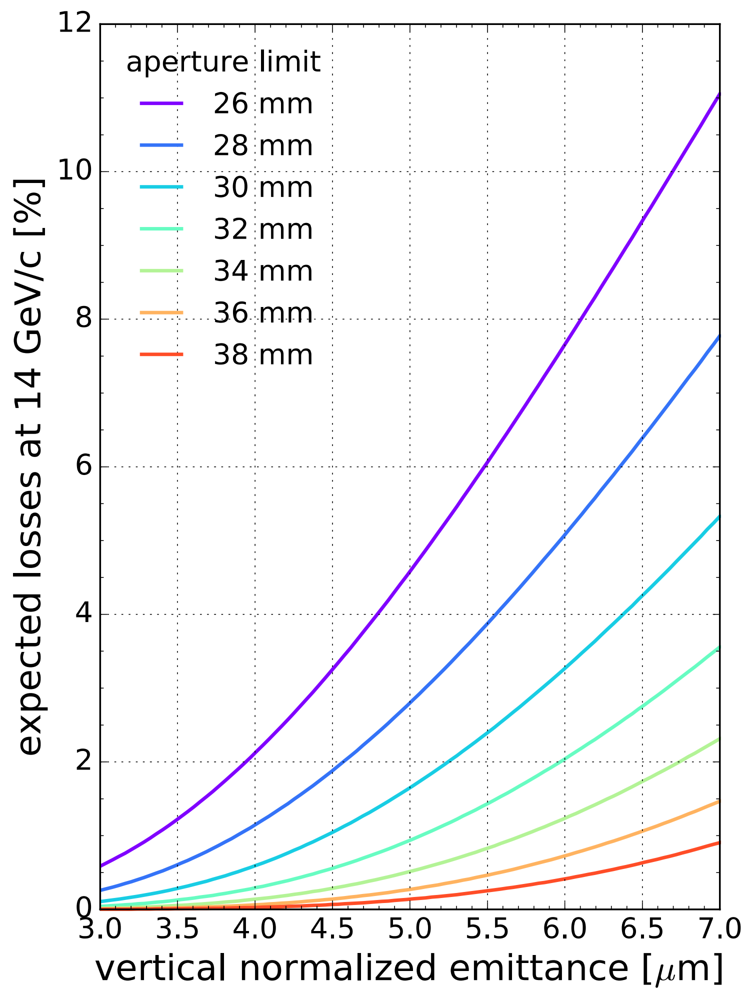
Impact of indirect space charge forces



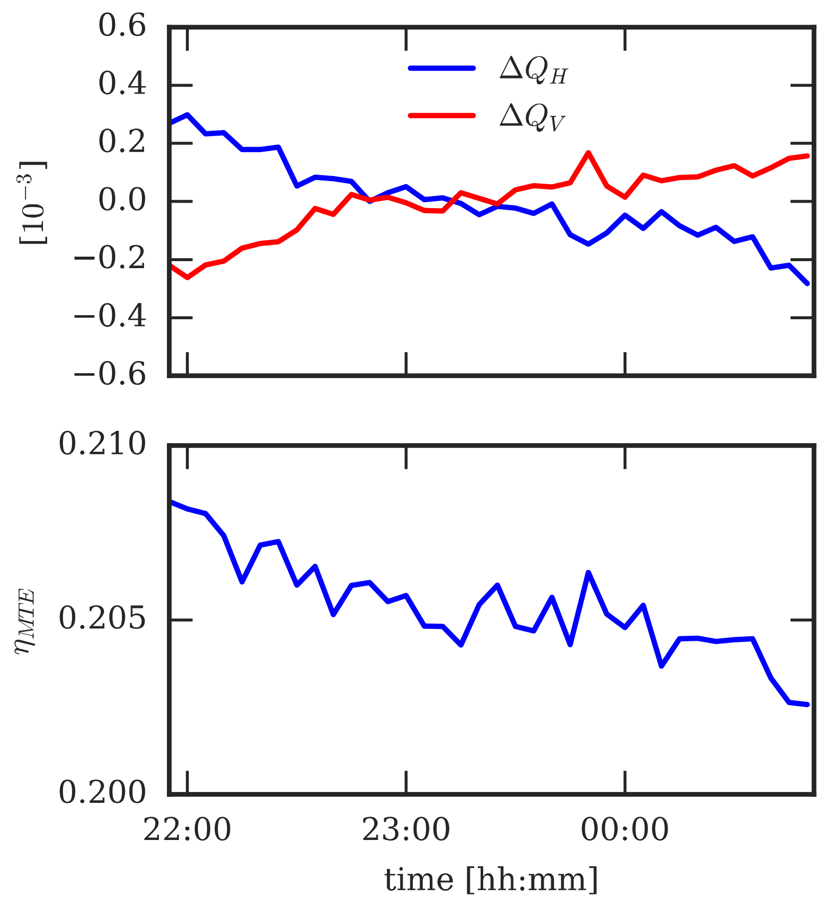




SPS acceptance



Need for a slow tune feedback



Impact of tune ripple on MTE splitting