LHC Injectors Upgrade

Space charge driven beam loss for cooled beams and mitigation measures in the CERN Low Energy Ion Ring

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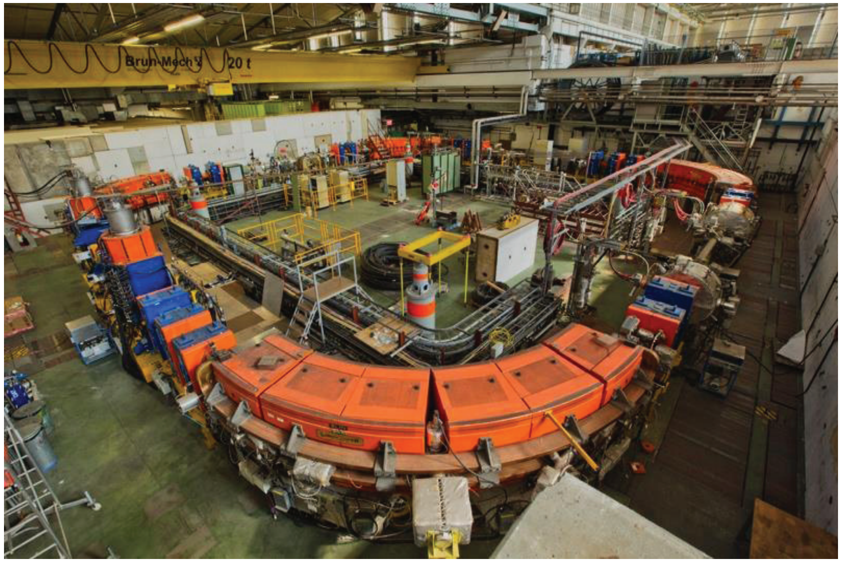
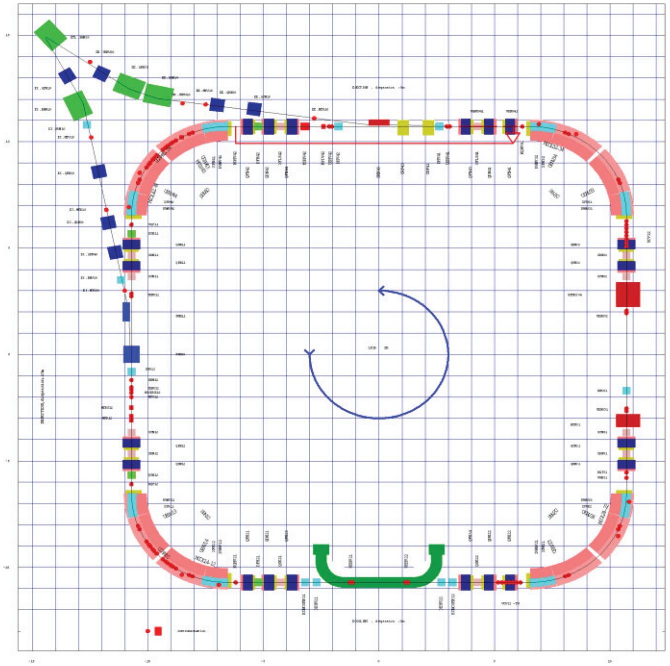
Introduction

- **Accumulator of the Pb-ion injector chain of the LHC**
- **High phase space densities achieved by:**
  - Multi-turn injections using 6D phase space painting → efficiency critically depends on the working point
  - Electron cooling

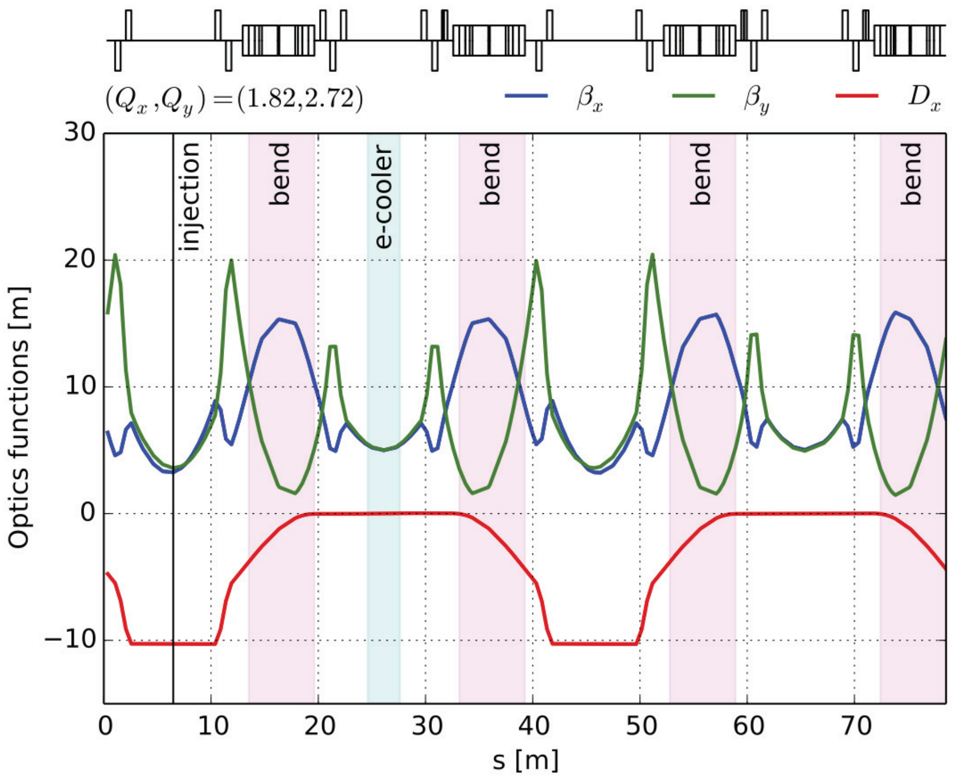




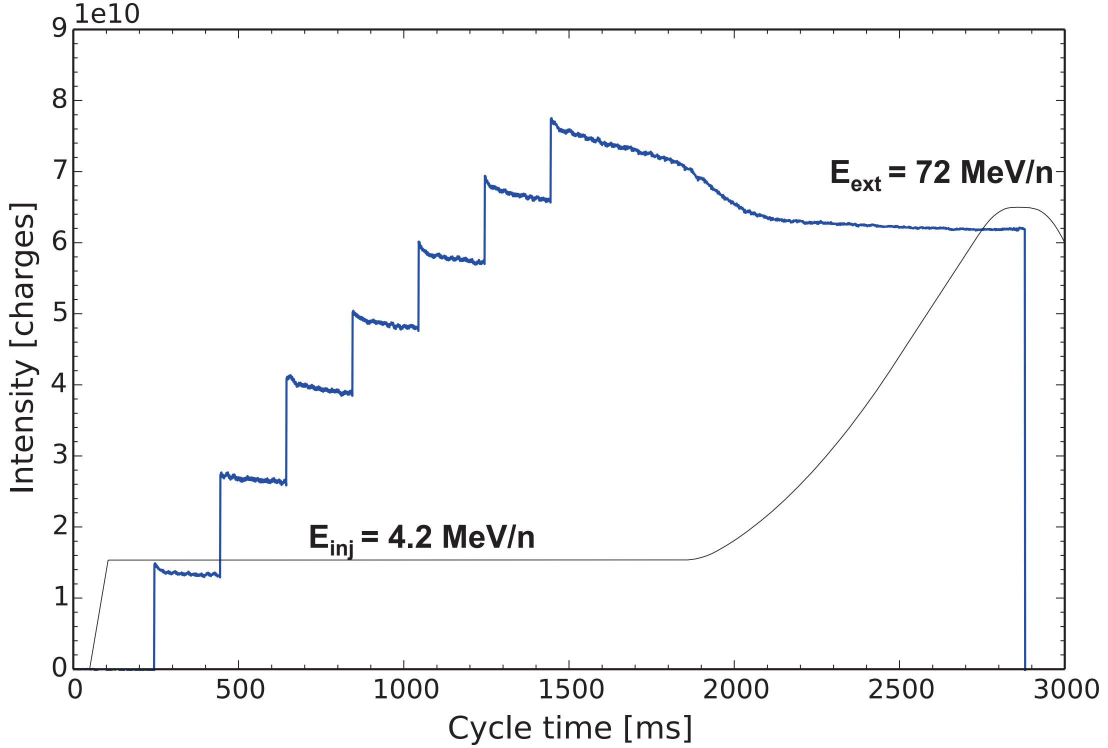
- **Performance limited by losses after RF capture**
  - Underlying mechanism was not understood
- **Started to study LEIR limitations within the LHC Injectors Upgrade (LIU) Project**
  - Goal: maximize intensity for future HL-LHC (burn-off dominated)

LEIR optics

- **Quasi-twofold lattice symmetry**
  - Perturbation from electron cooler
- **Optics functions constrained by injection and cooling processes**
  - Horizontal dispersion of 10 m in the injection region for longitudinal painting
  - Optimum cooling conditions in the past found to require $\beta_x \approx \beta_y \approx 5$ m
- **Vertical beam size especially critical at entrance and exit of the four 90° dipoles**



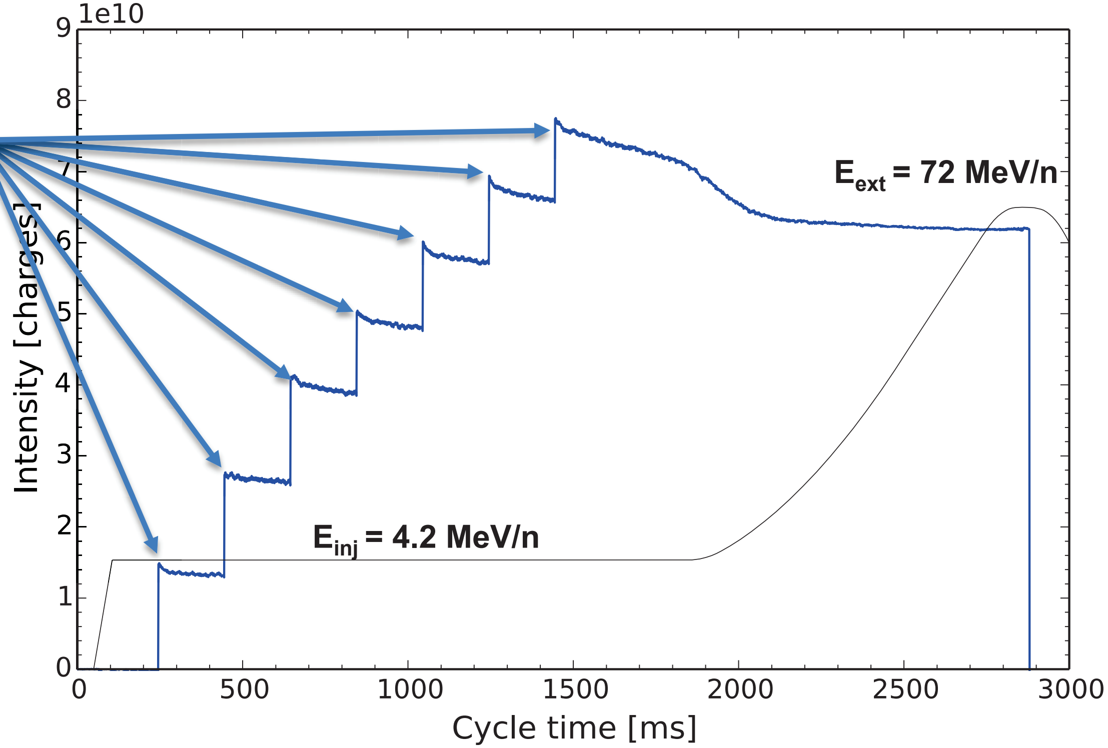
LEIR cycle



1e10
9
8
7
6
5
4
3
2
1
0
Intensity [charges]
0
500
1000
1500
2000
2500
3000
Cycle time [ms]
E_{ext} = 72 MeV/n
E_{inj} = 4.2 MeV/n

LEIR cycle

Multi-turn injections:
6D painting with typical efficiency of 50-70%



LEIR cycle

Electron cooling:
Coasting beam

Multi-turn injections:
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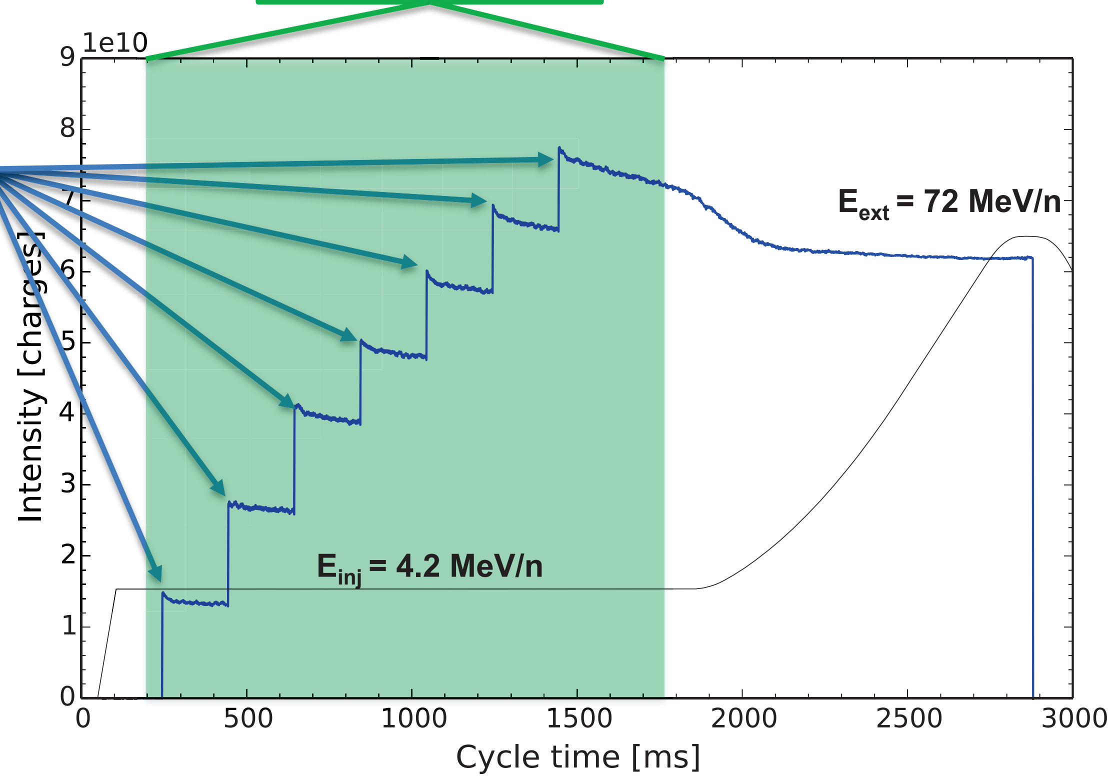
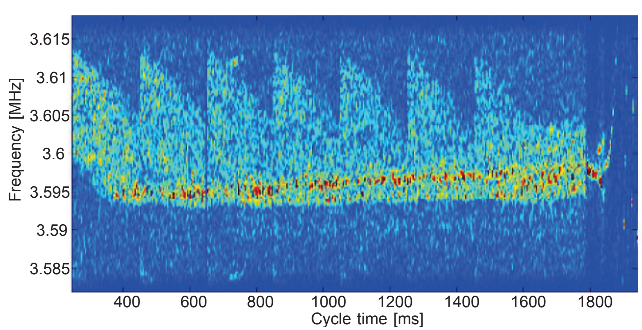


Longitudinal Schottky spectrum: cooling, dragging and stacking



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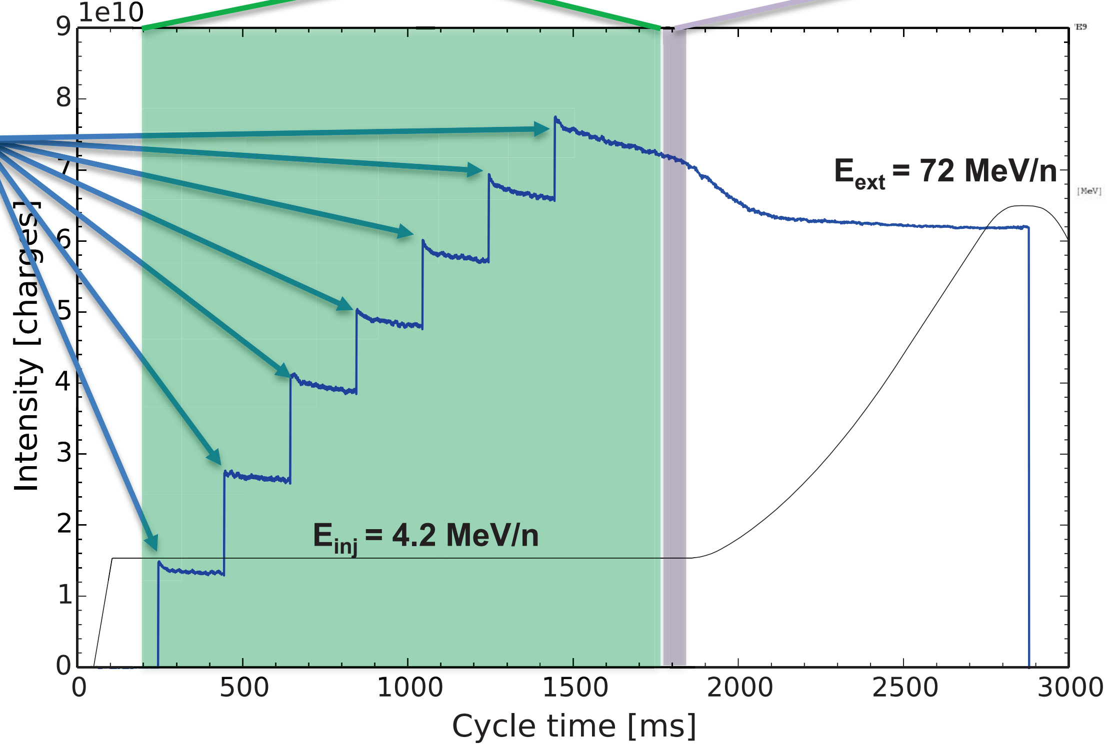
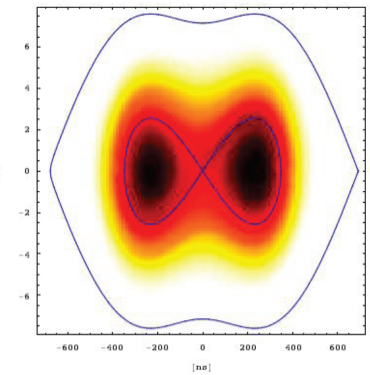
Coasting beam

RF capture: *h*=2 and double harmonic





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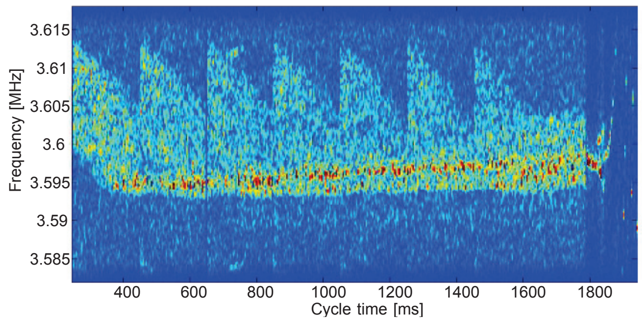

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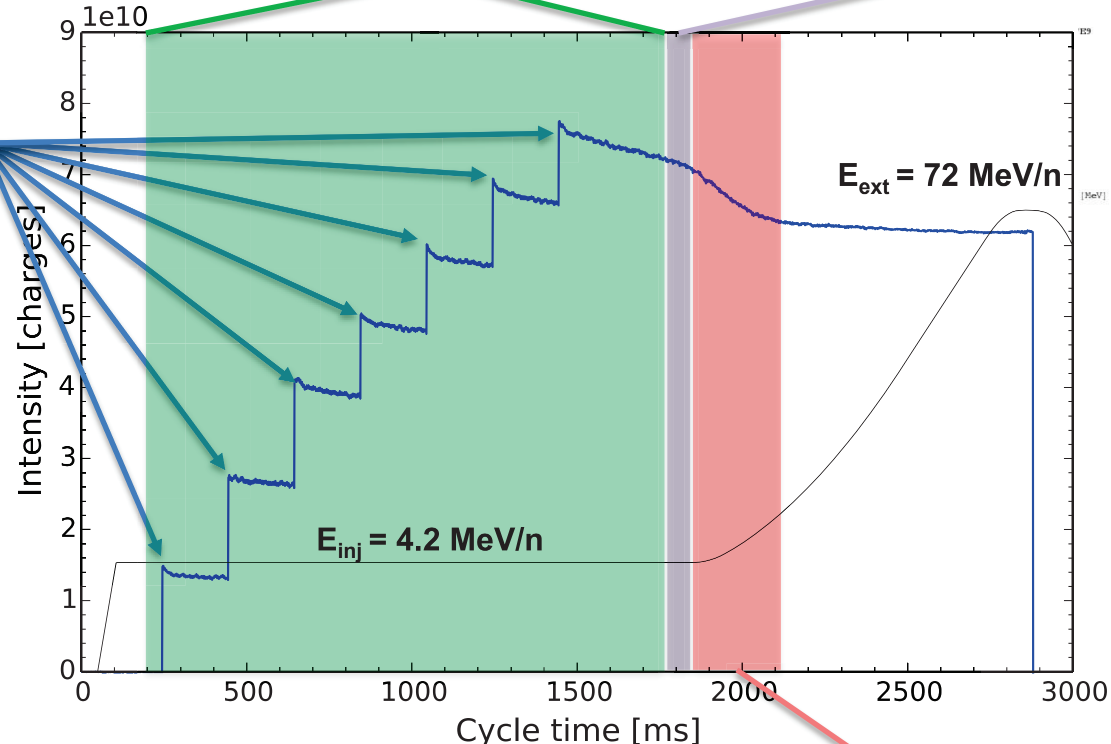
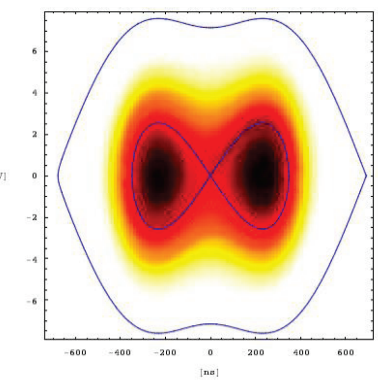
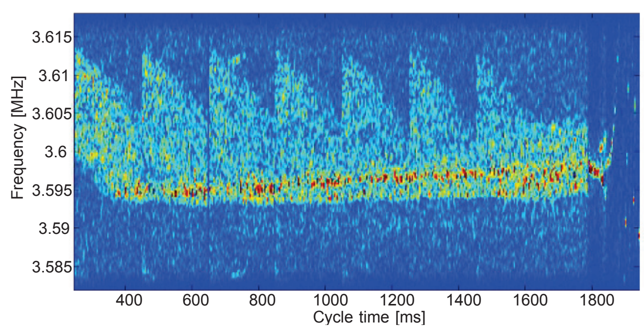


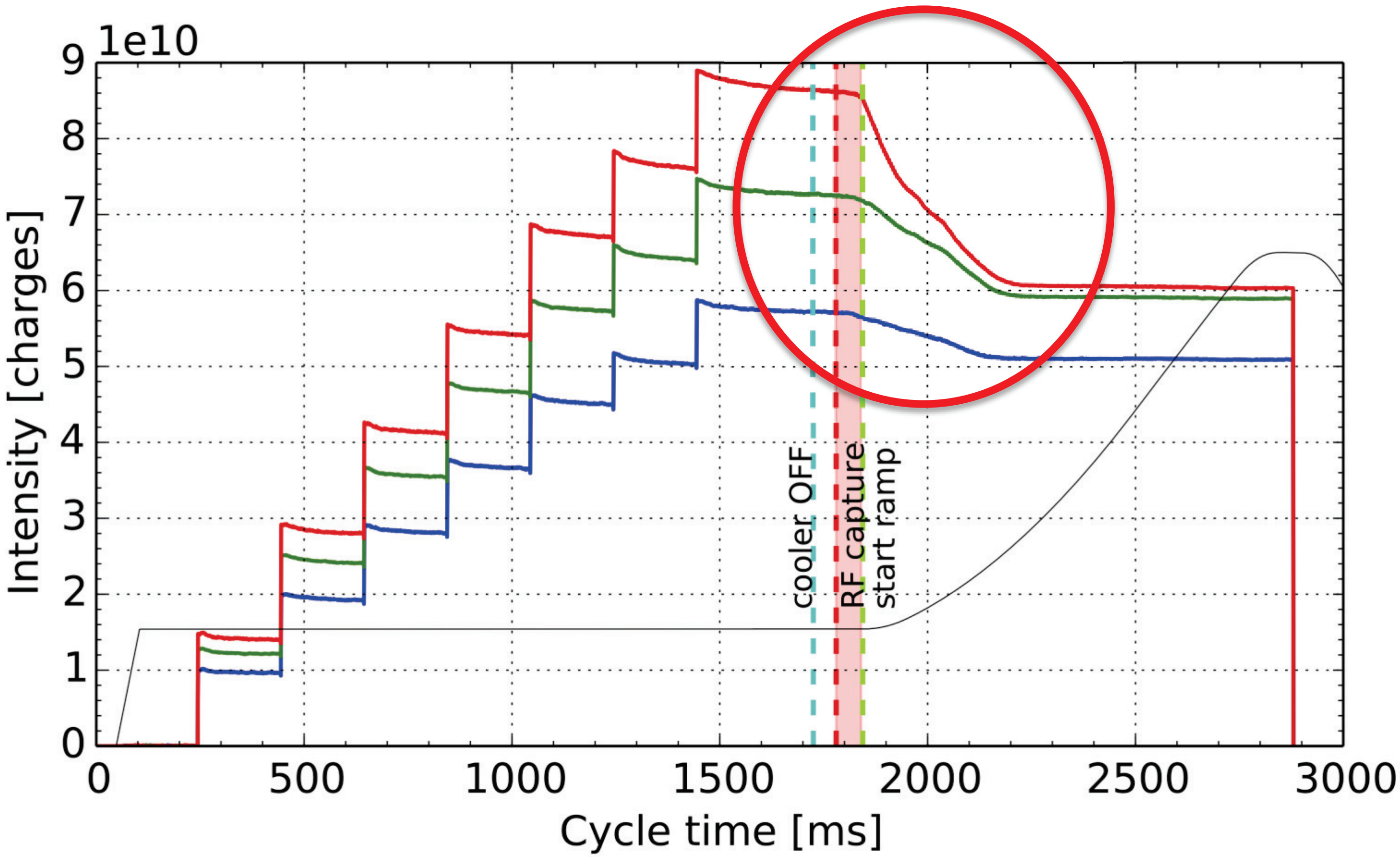


Regime of beam loss

Longitudinal Schottky spectrum: cooling, dragging and stacking

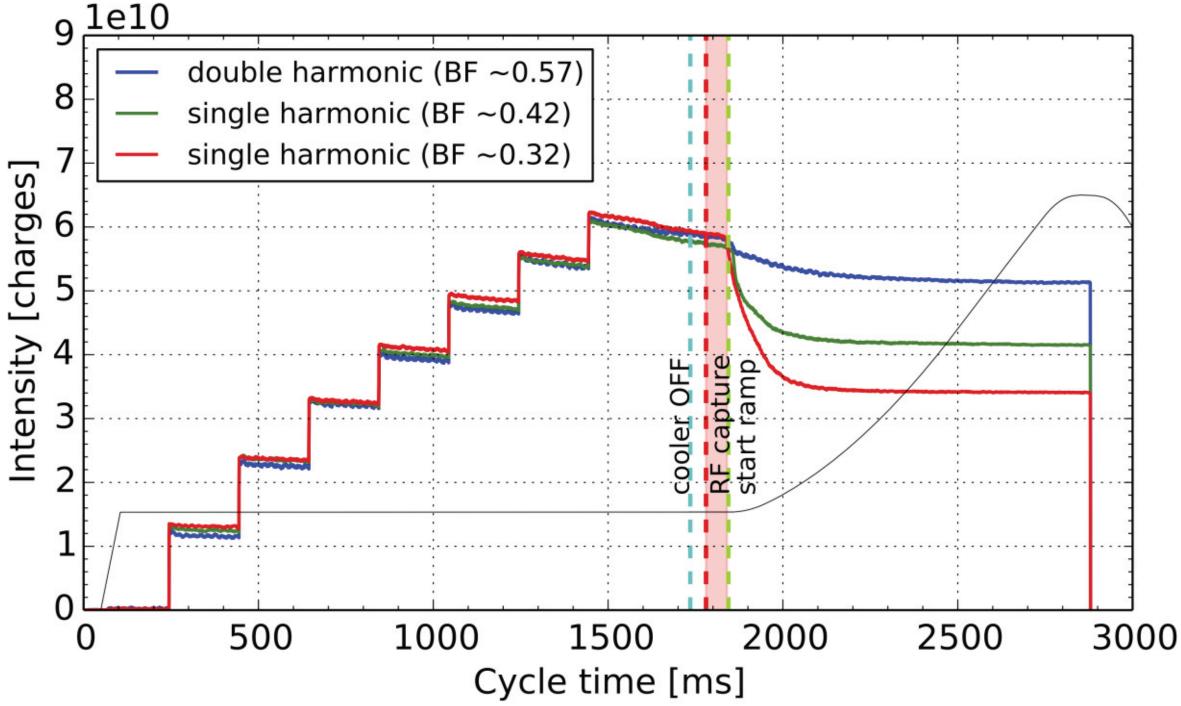


Loss pattern after RF capture



- **It appeared as if intensity achievable at extraction saturated**
  - Study program since end of 2015 to characterize and mitigate theses losses

Losses depend on line density



- **Iso-adiabatic capture in single/double RF with and without longitudinal blow-up**

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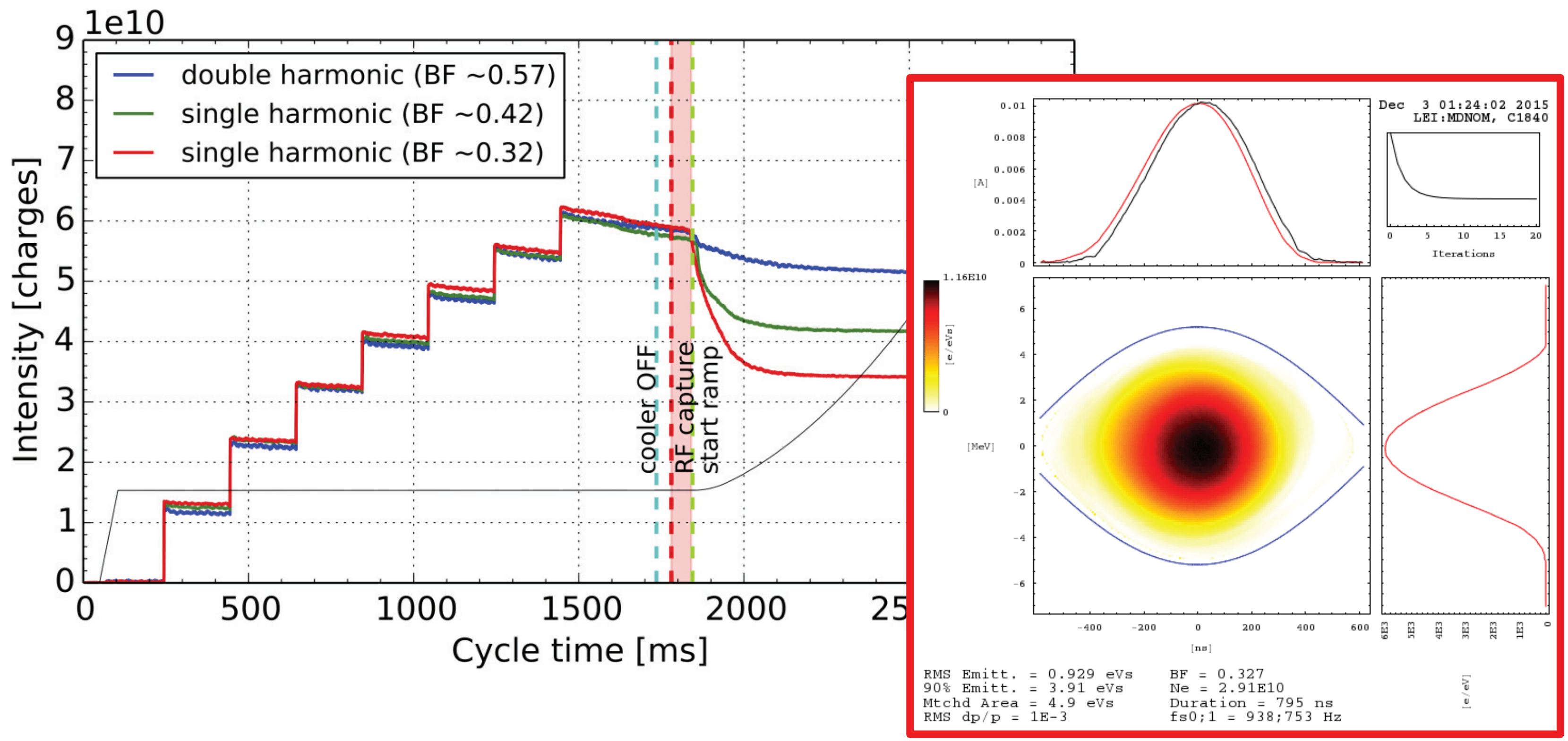

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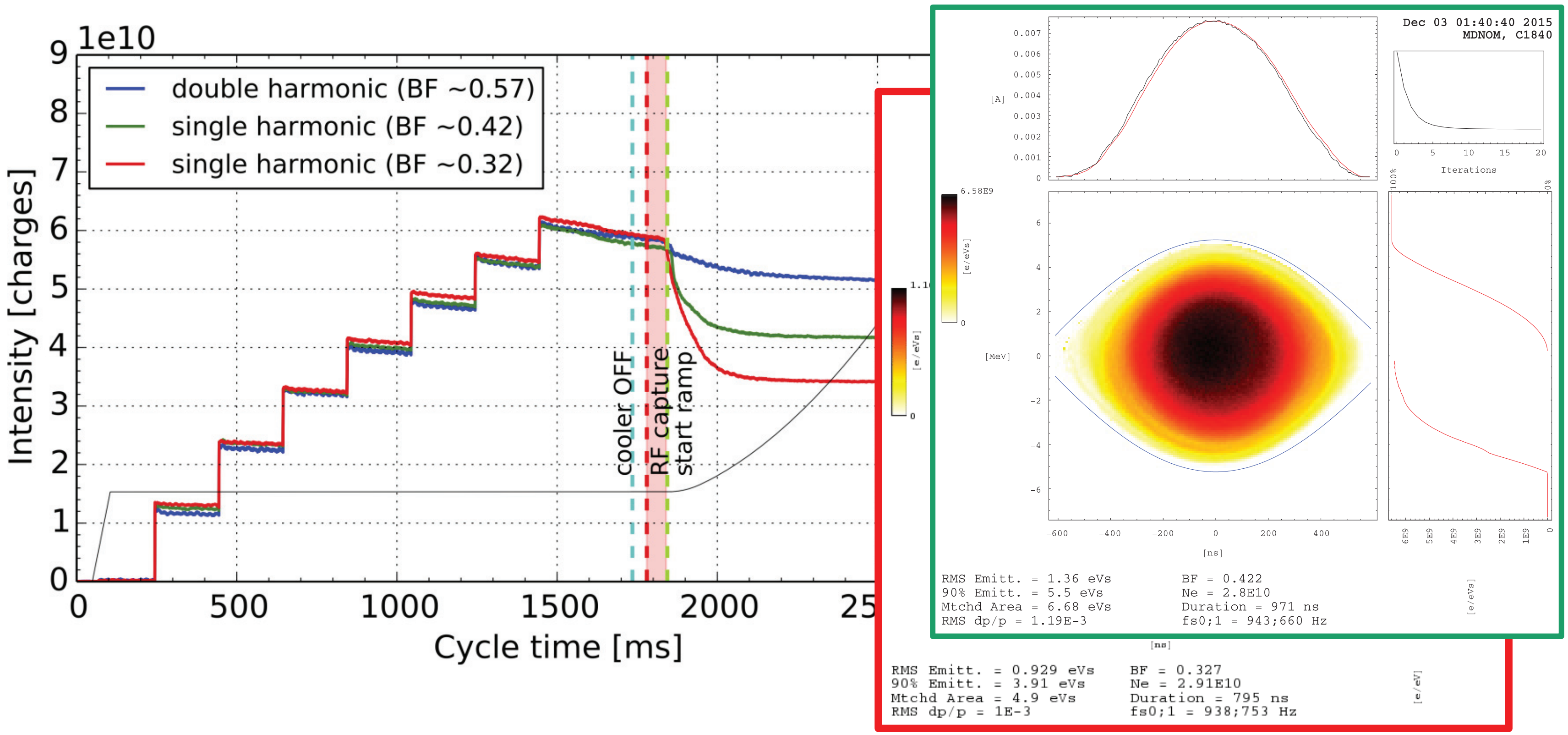

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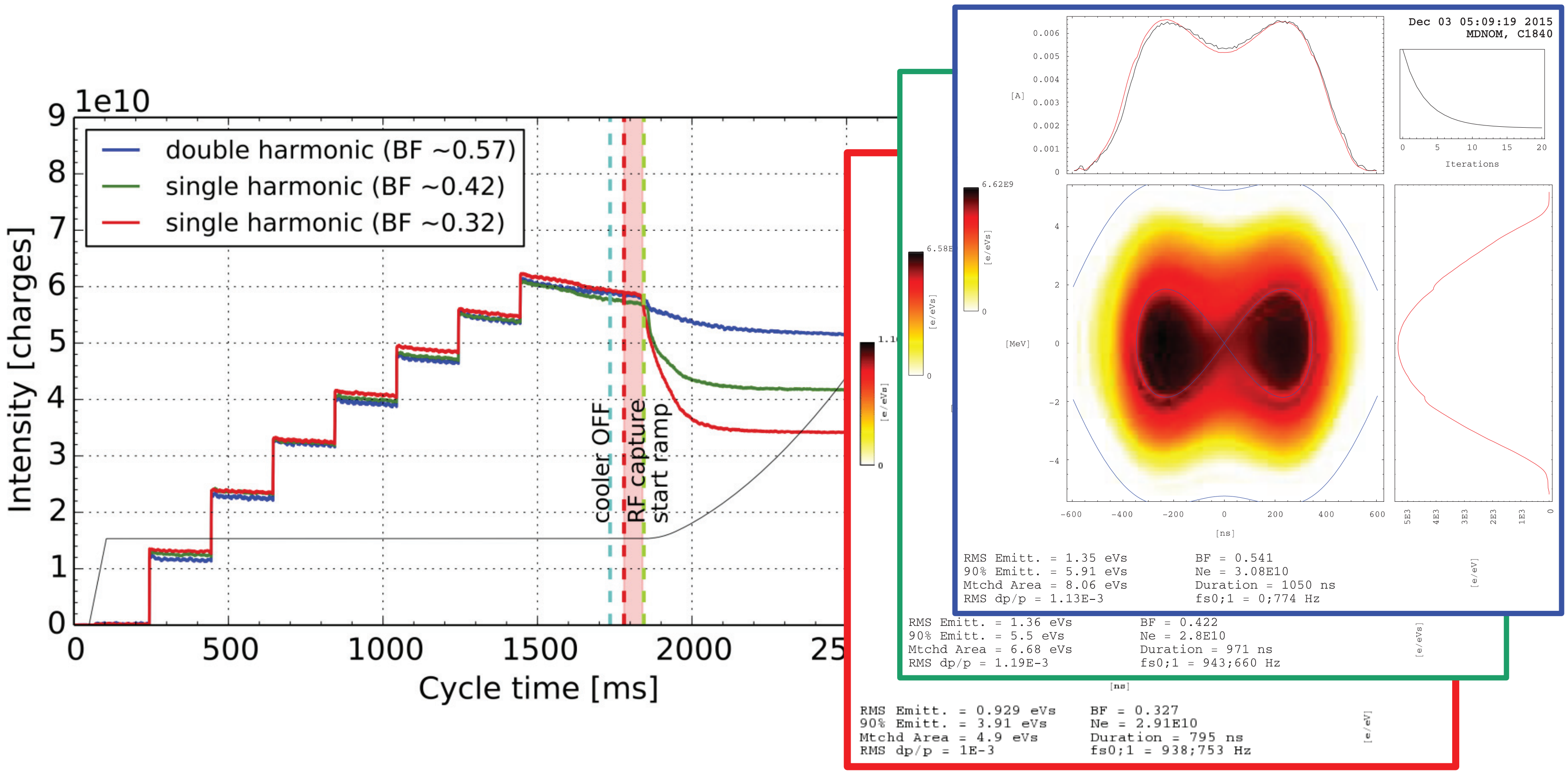

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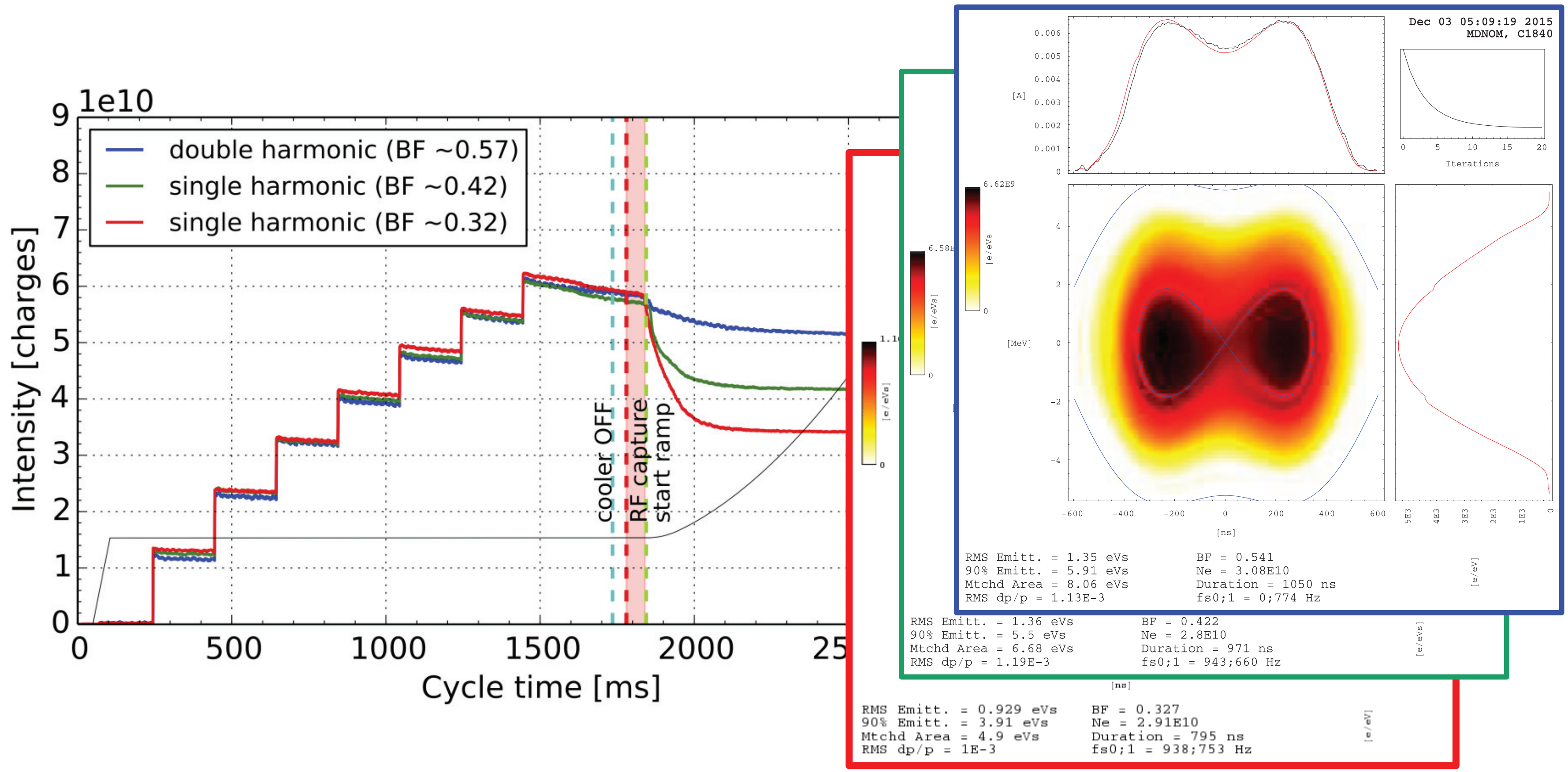
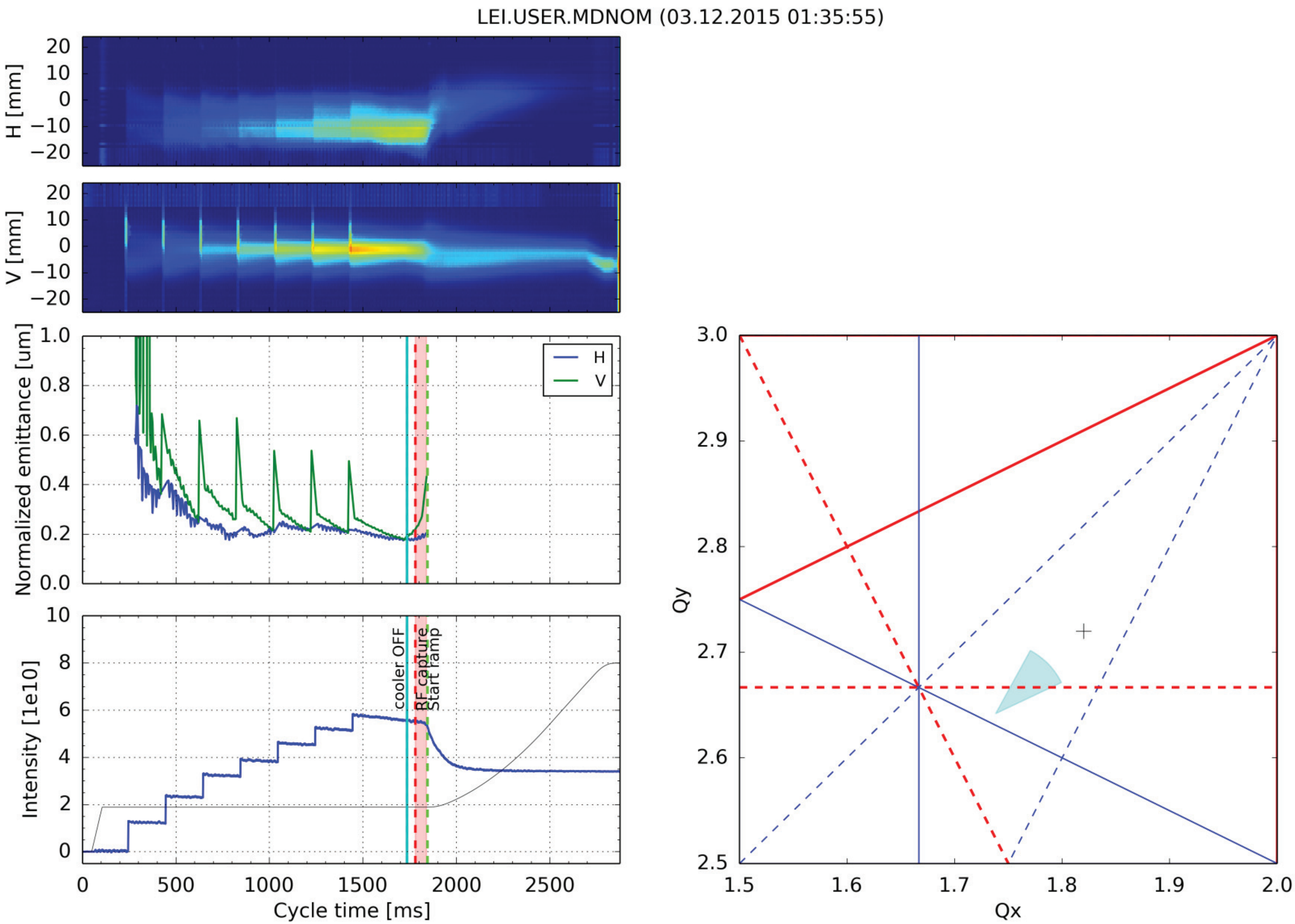
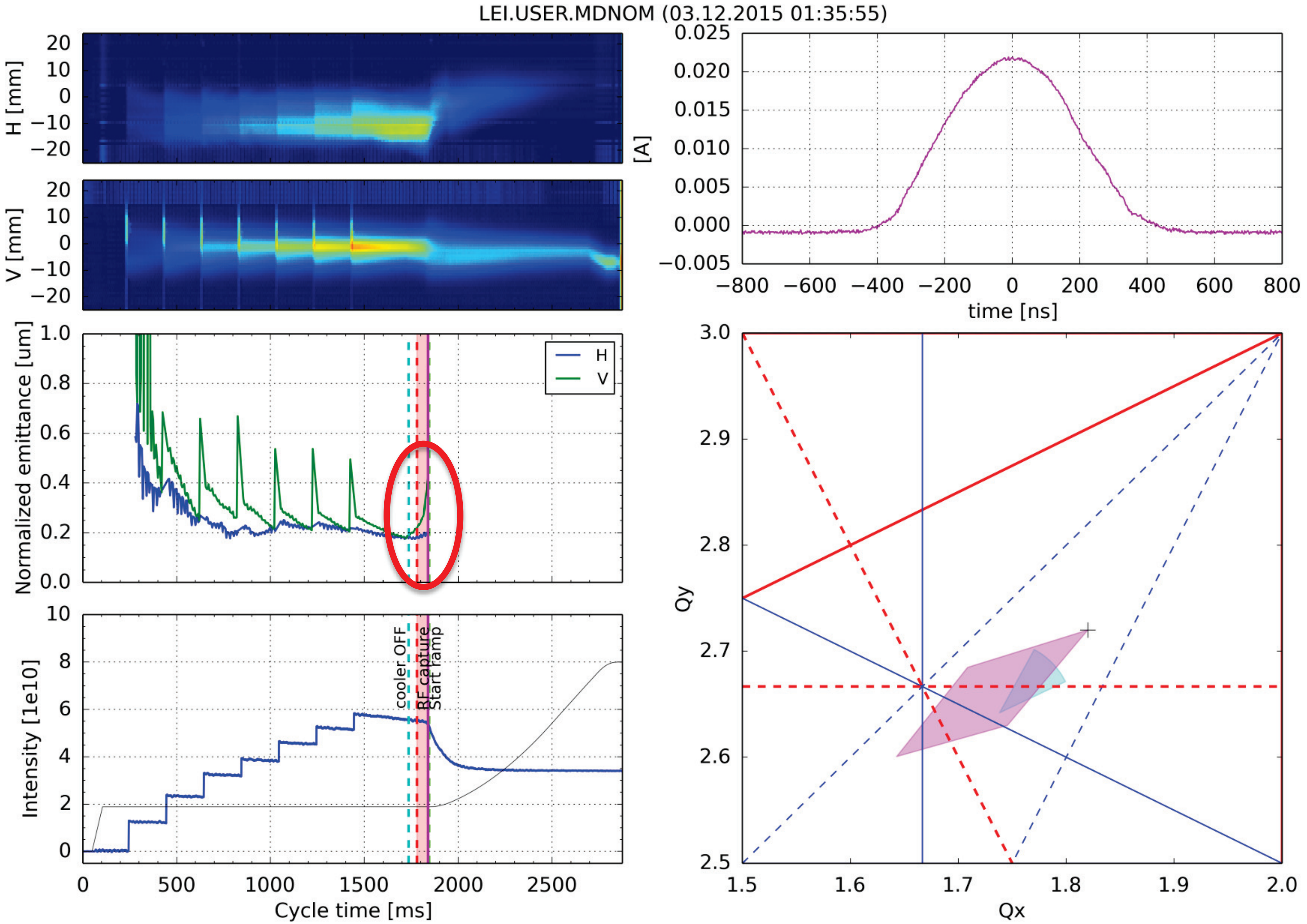


- **Iso-adiabatic capture in single/double RF with and without longitudinal blow-up**
  - Clear dependence of losses on line charge density

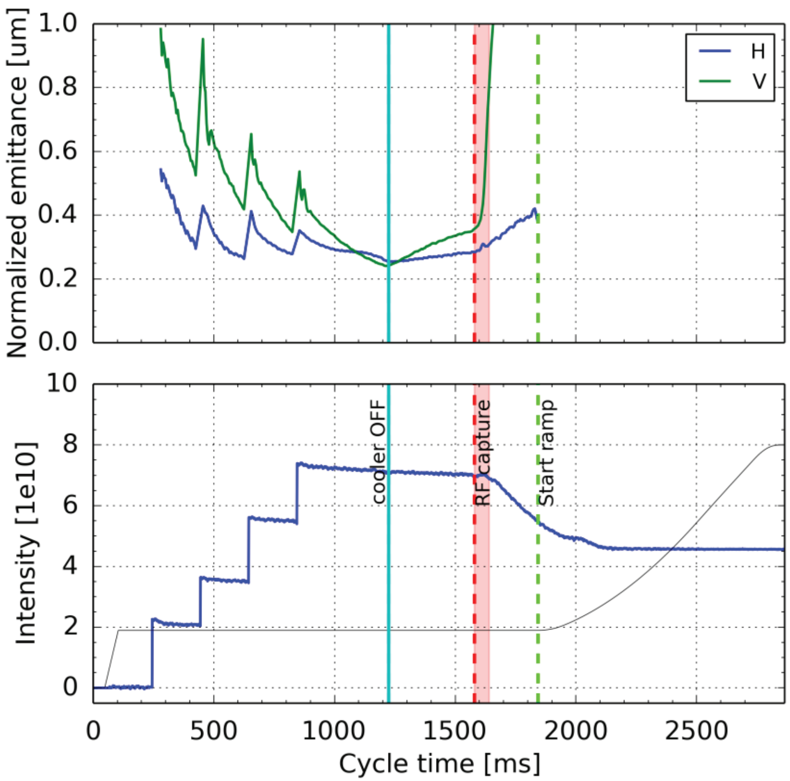
Space charge detuning

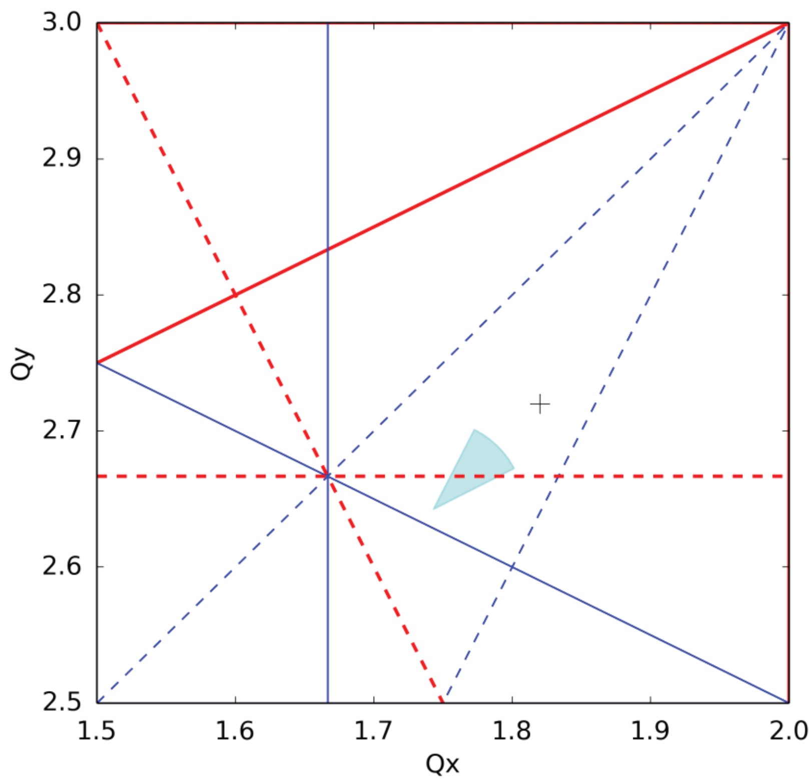


Space charge detuning



Losses after capture on injection plateau





- **Studies of losses at long injection plateau with advanced RF capture**
  - Same loss characteristics → not related to the ramp (e.g. particles outside RF bucket)
  - Emittance increase drastically changes at RF capture (especially in the vertical plane)

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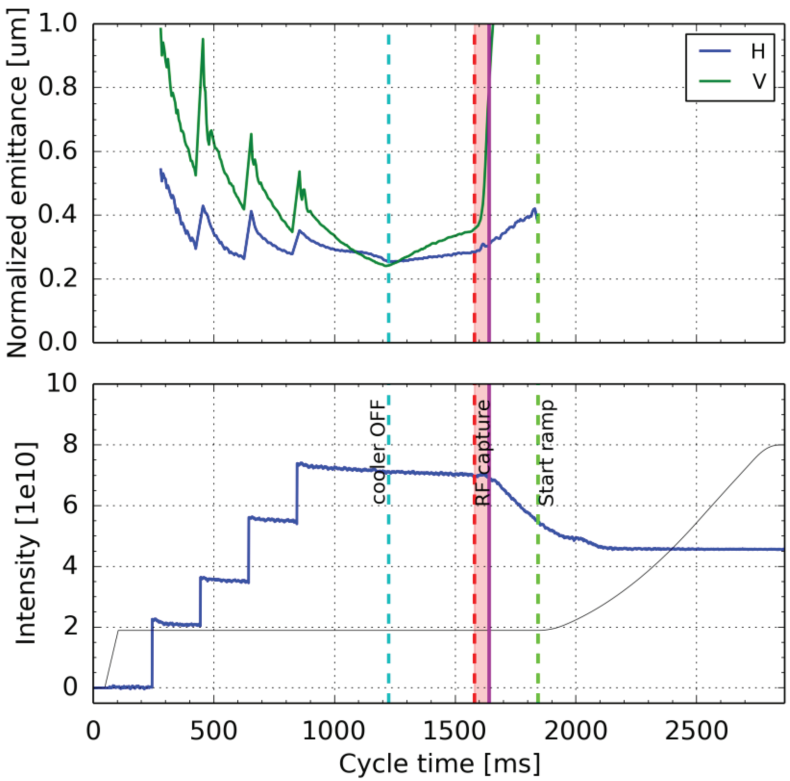

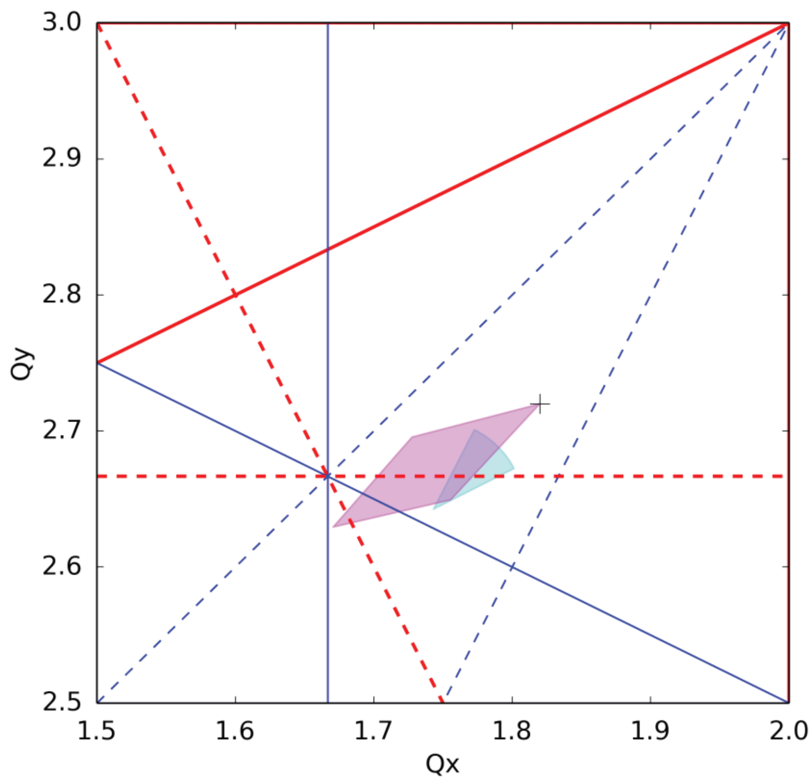

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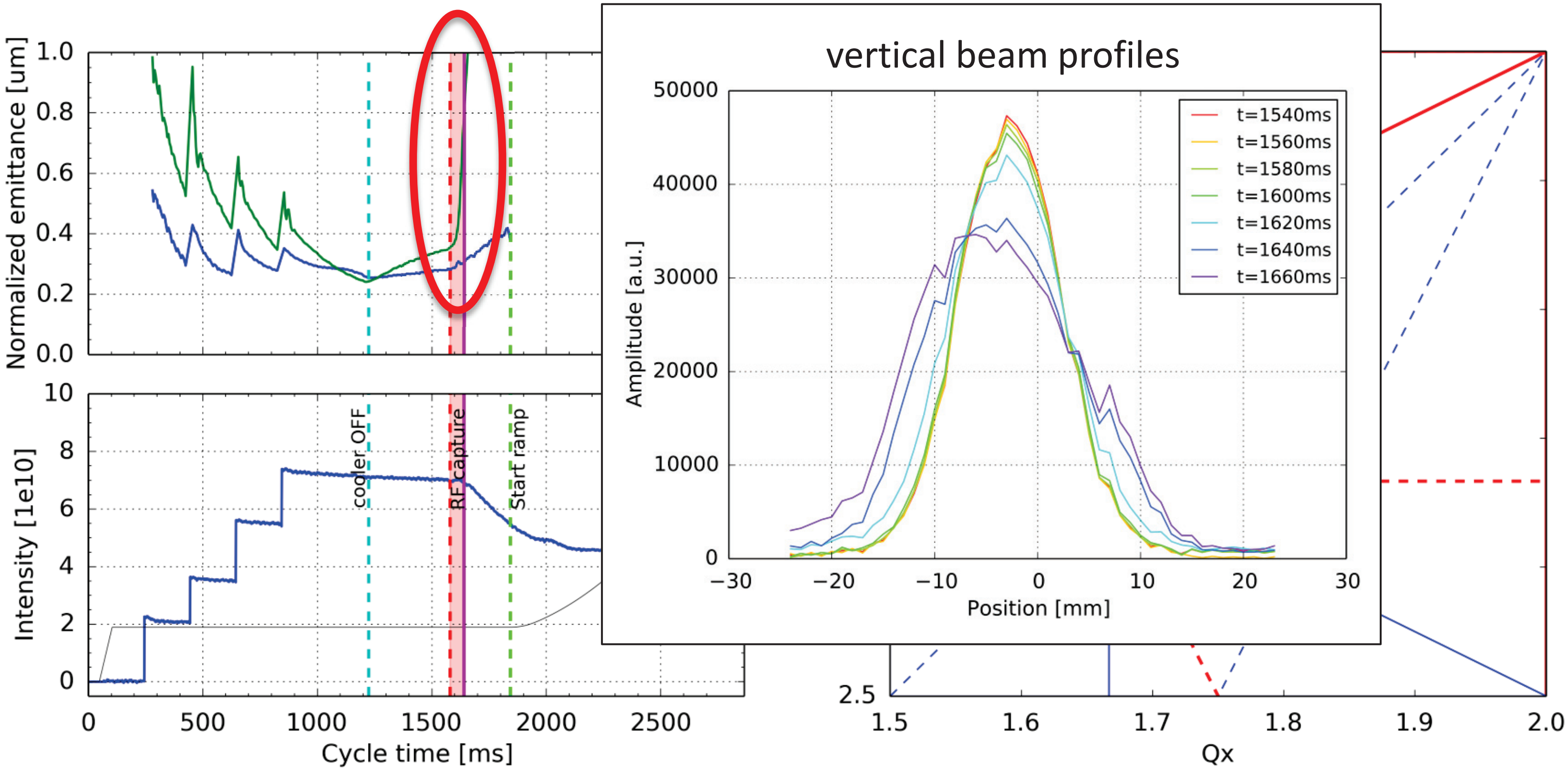

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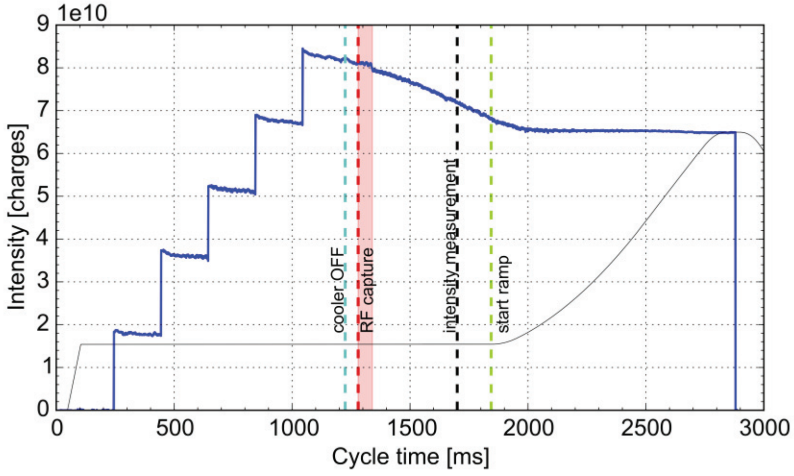
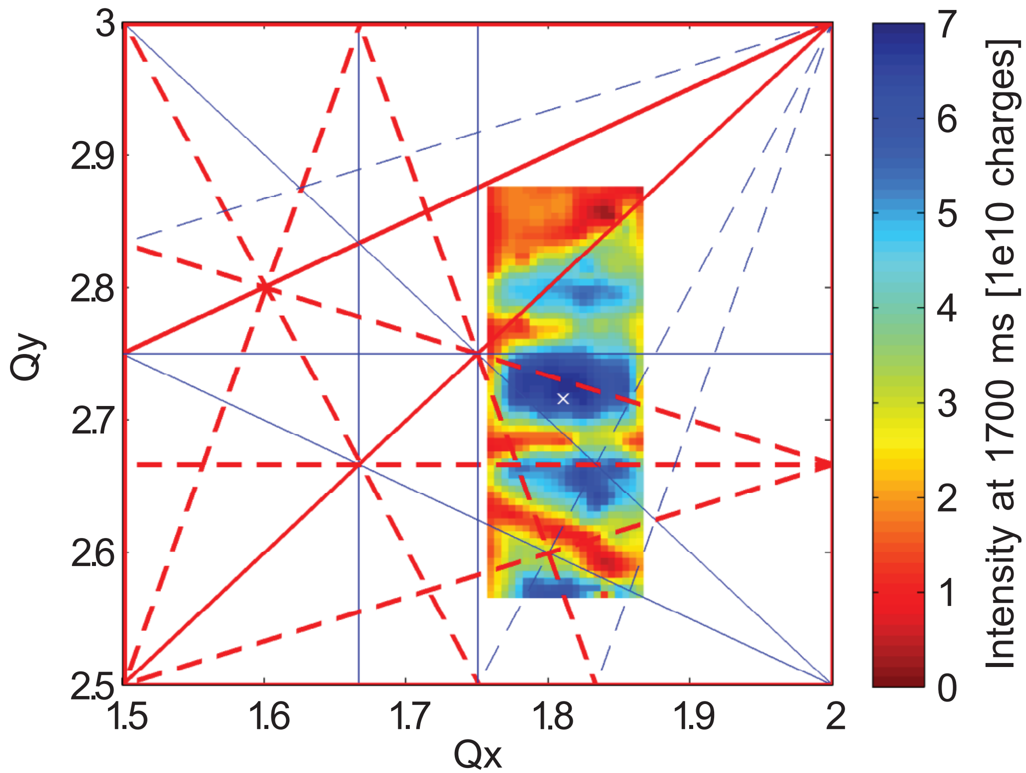
Tune scan





- **Measurement technique:**
  - Working point moved with cooler ON
  - Beam loss at 1700 ms investigated (after RF capture)

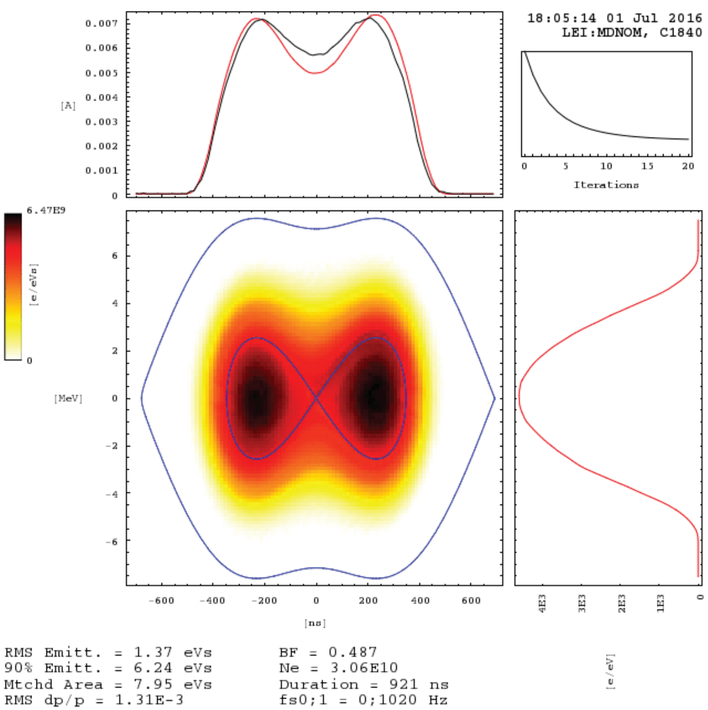
- **Strong losses close to sextupole resonances**
  - Skew: 3Qy = 8
  - Normal: Qx + 2Qy = 7

- **Octupole resonances appear to be excited as well**

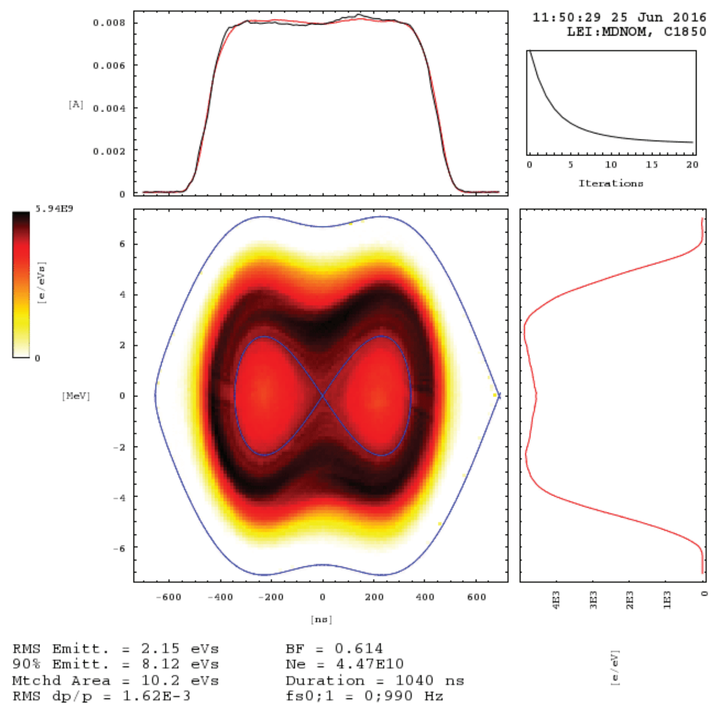
Mitigation measures (I)

- **Maximize bunching factor to reduce transverse space charge detuning**
  - Iso-adiabatic capture of coasting beam in double harmonic RF (bunch lengthening)
  - Offset the capture frequency away from central beam energy results in **flat line density profile**

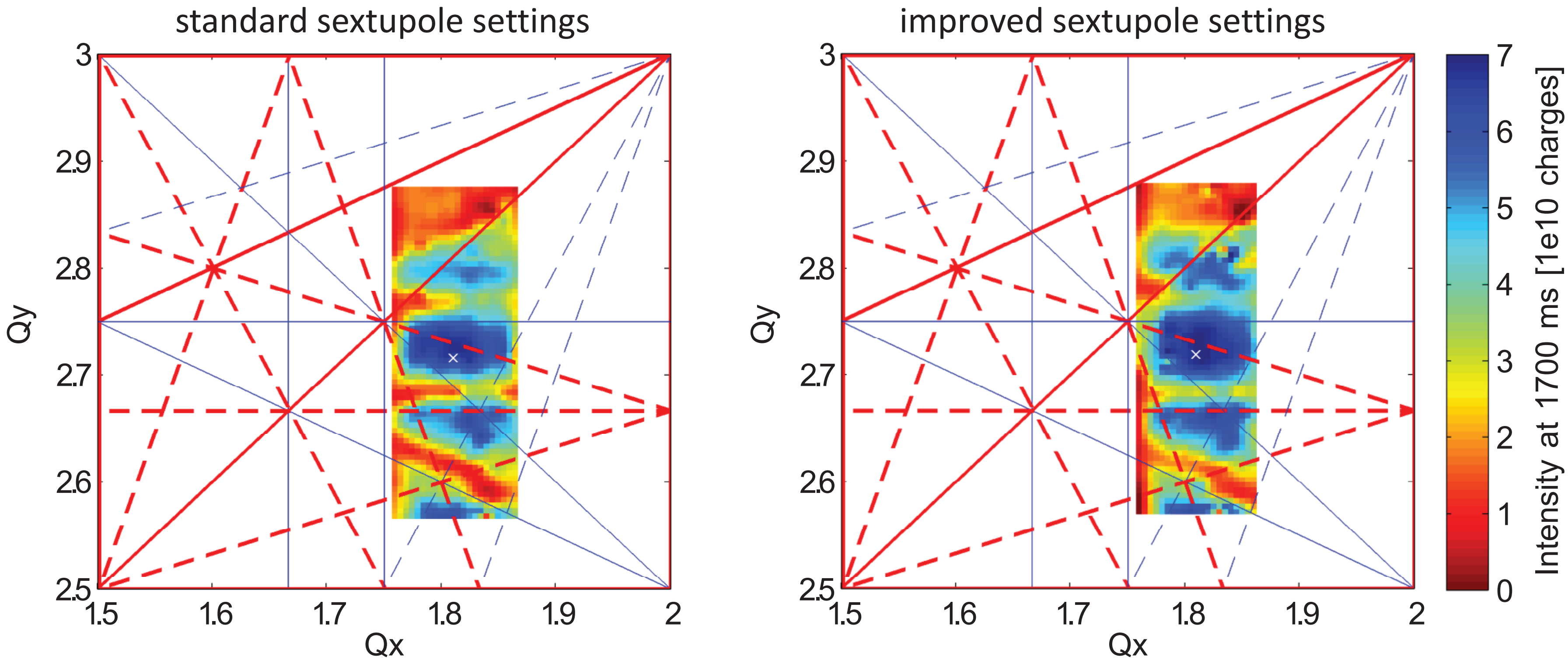
capture frequency centered



capture frequency offset

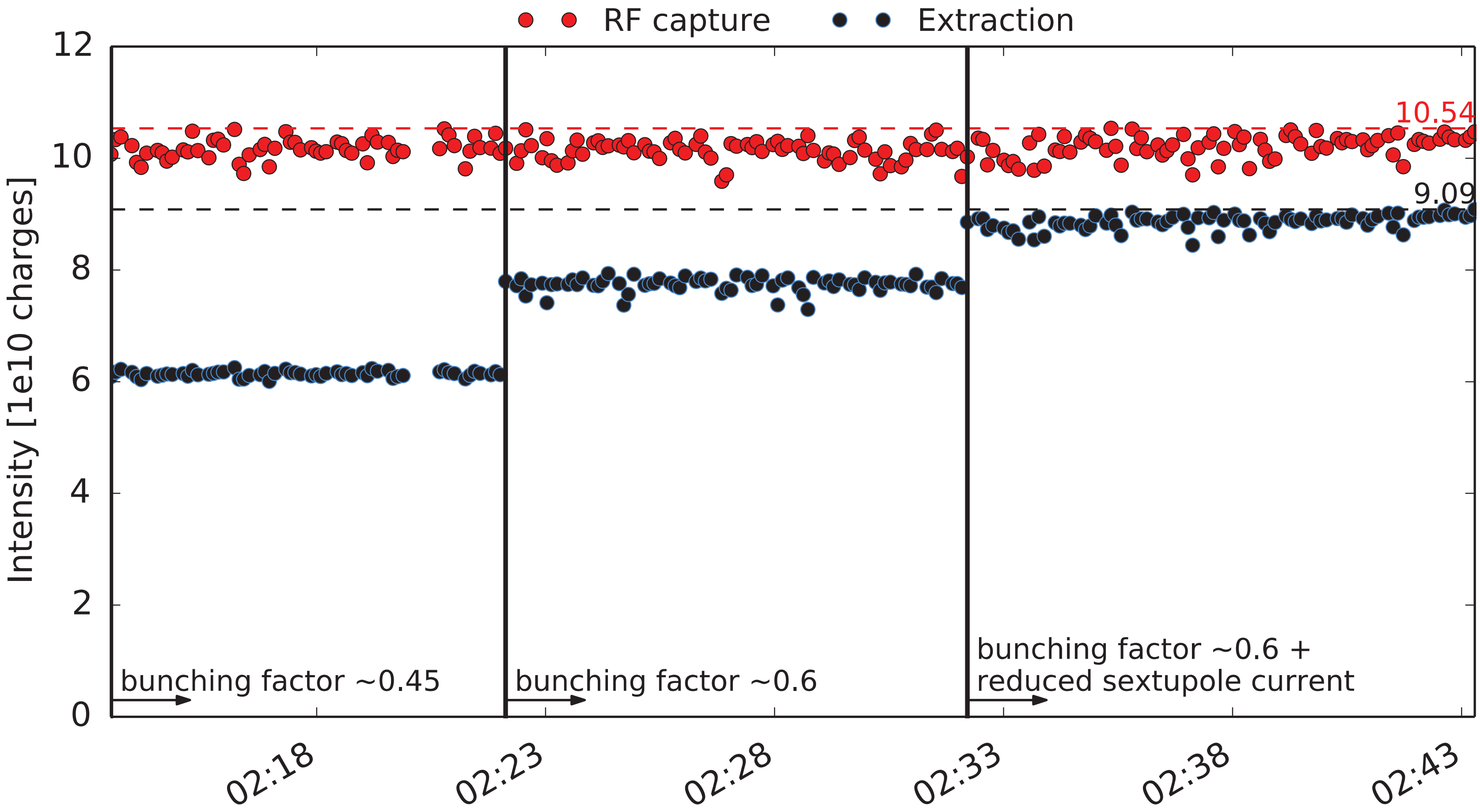


Mitigation measures (II)



- **Reduction of sextupole excitation**
  - Reduced current in the chromatic sextupoles at the end of injection plateau
  - Clear beneficial impact on resonance excitation and beam loss
- **Optimization of vertical orbit correction (aperture restriction in dipoles)**

Mitigation measures implemented



Future prospects and further mitigations

- **Maximization of accumulated intensity by reducing injection spacing to 100 ms**
  - Efficiency of electron cooling with increased electron current to be verified
- **Understand the origin of the skew sextupolar resonance**
  - Measurement of resonance driving terms
  - Resonance compensation
  - Further characterization of the loss mechanism
- **Optimization of the longitudinal distribution**
  - Maximizing the longitudinal emittance in combination with increased RF voltage using second cavity

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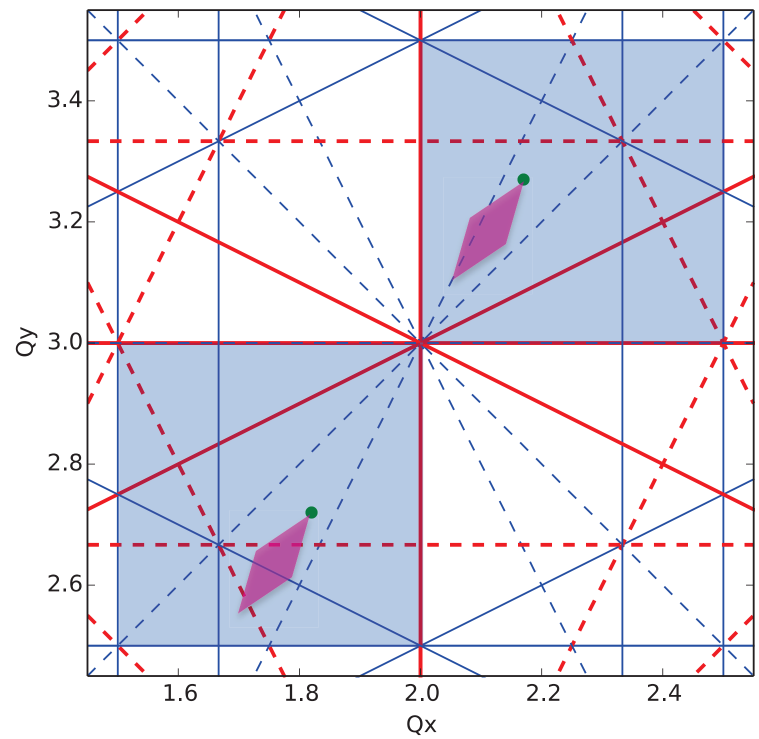
- **Operation at a different working point**
  - Needs development of completely new machine optics
  - Critical point: optimization of injection efficiency
- **Optics change before RF capture**
  - Aim: gain vertical aperture in the bending magnets



Summary and conclusions

- **Experimental characterization of the LEIR intensity limitation**
  - Beam loss during and after RF capture
  - Identified interplay of betatron resonances and large direct space charge detuning as driving mechanism
  - Excessive vertical emittance growth after RF capture
- **Clear loss reduction after implementation of mitigation measures**
  - Maximized bunching factor
  - Reduced excitation of chromatic sextupoles
- **Future steps**
  - Maximize accumulated intensity with 10 Hz injection rate
  - Develop new machine optics to avoid low order resonances
  - Detailed studies of resonances (including driving term measurements) and possibly compensation
  - Simulation studies (magnetic model, space charge, impedance, …)

LHC Injectors Upgrade

Thank you for your attention!