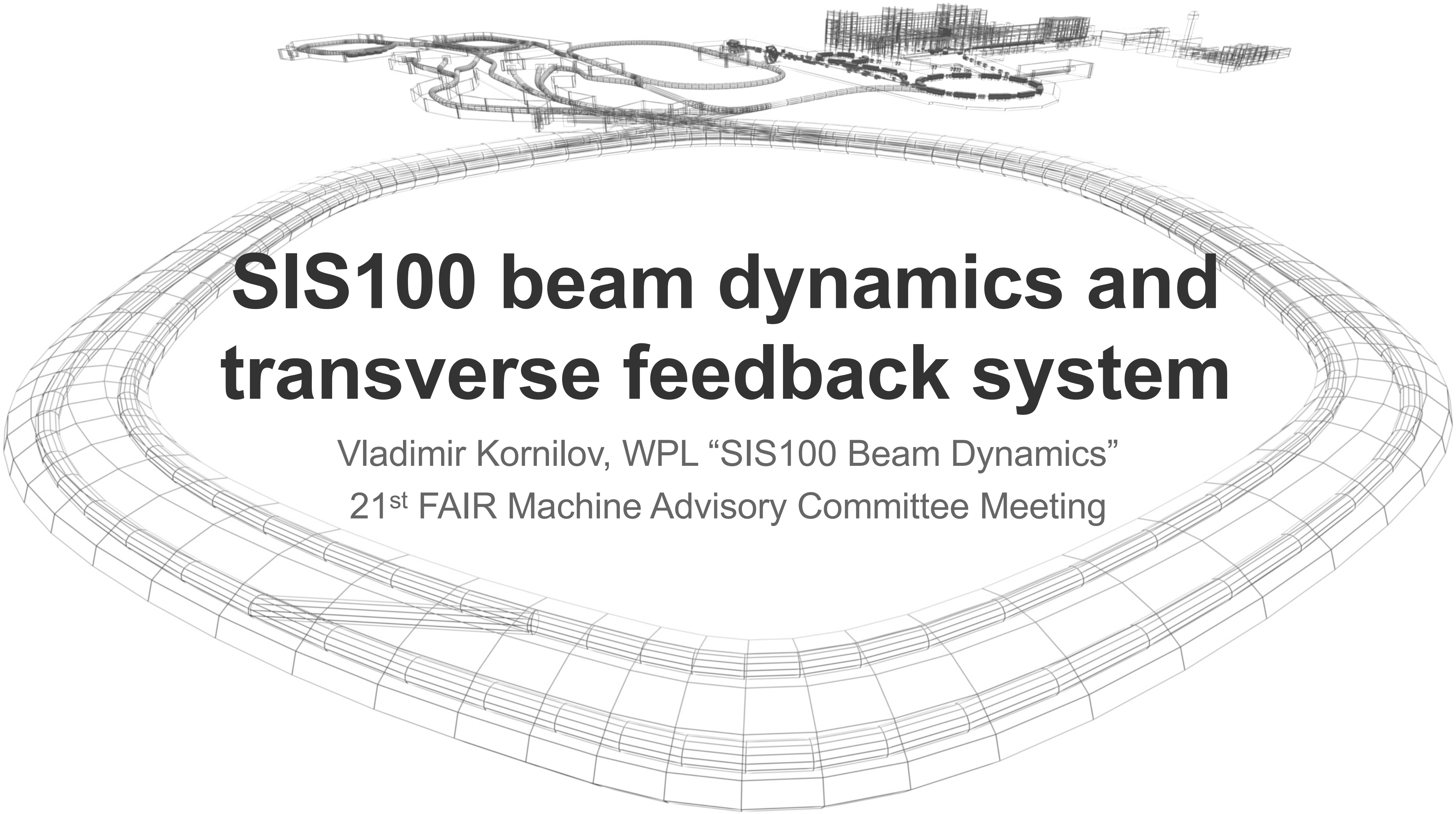


SIS100 beam dynamics and transverse feedback system

Vladimir Kornilov, WPL "SIS100 Beam Dynamics"

21st FAIR Machine Advisory Committee Meeting

Work package description
2.8.1 SIS100 Beam Dynamics

- The focus: high-intensity low-loss operation
- Beam survival and beam quality preservation with magnet field errors, space-charge and impedances
- Instabilities & Mitigation
- https://wiki.gsi.de/foswiki/bin/view/SIS100BD/WebHome

Recommendations from the 20th FAIR MAC

- **R19.8** Investigate the possibility of a resistive-wall instability damper.

- **R20.10** Include both longitudinal and transverse coherent instability analysis in the SIS100 high intensity beam dynamics model.

- **R20.11** Consider separating low-frequency and high-frequency transverse feedback kickers (e.g. an electrostatic and an electromagnetic device) or make sure that there is a sufficient room in the ring to install it in the future

SIS100 Beam Parameters

SIS100 will provide beams for the FAIR scientific pillars APPA, CBM, NUSTAR and PANDA: a large variety of beam parameters (ions H−U, extraction energy 0.4-29 GeV/u, and so forth).

Here we consider 3 reference cycles:

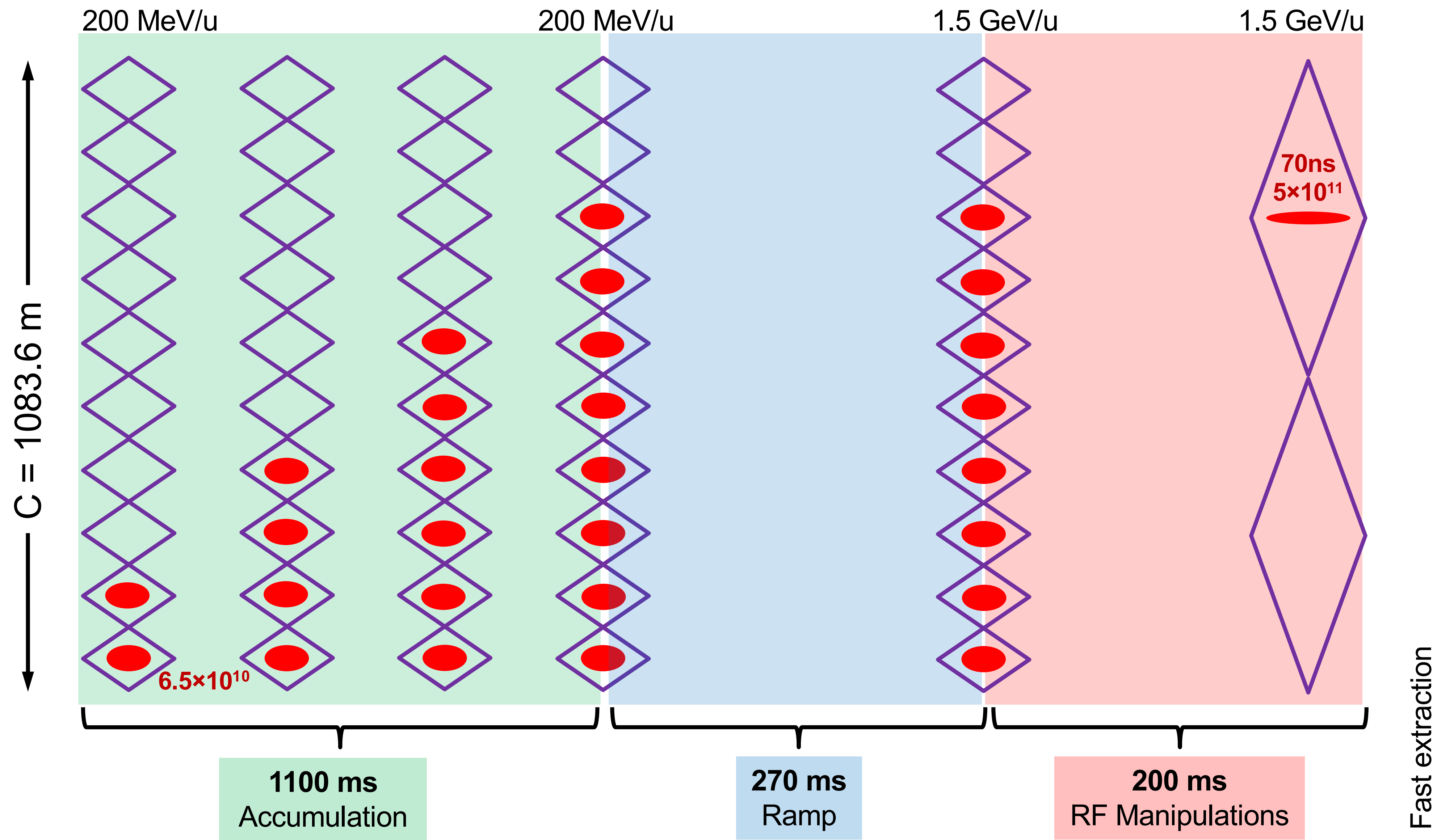
- U^{28+} beams with fast extraction (NUSTAR storage rings, APPA plasma physics)
- U^{28+} beams with slow extraction (RIB production)
- p^{+} beams with fast extraction (antiproton production)

Baseline scenarios. There are options, alternatives.

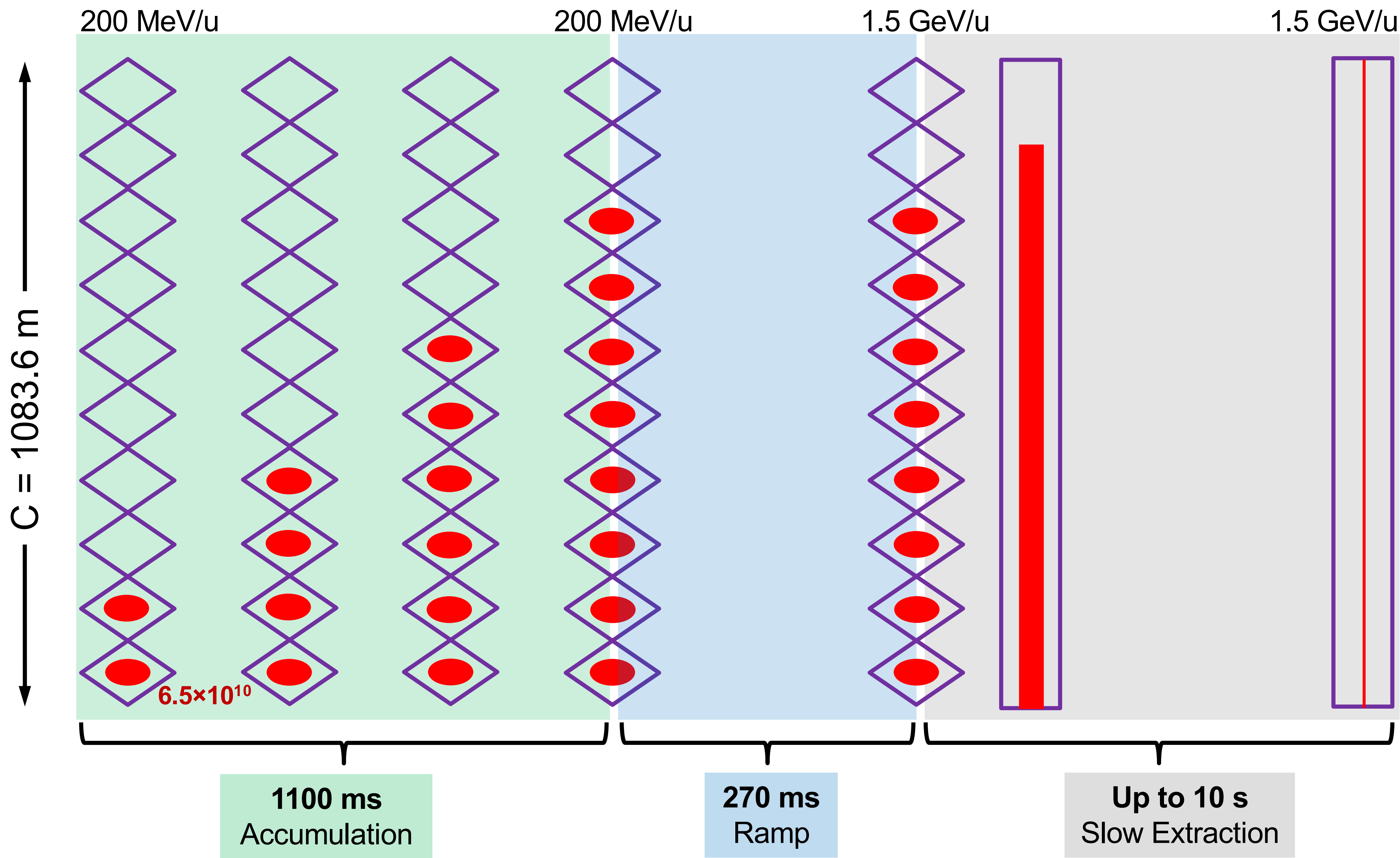
- Transverse and longitudinal are decoupled.
- For the longitudinal analysis, RF cycles must be considered in detail.

- SYS Report „SIS100 Cycles“, H. Liebermann, D. Ondreka, Version 5.2, 6.11.2018
- Brochure “Reference Beam Parameters of the International Facility for Antiproton and Ion Research FAIR“
- MAC13 April 2015, Beam Parameters along the Accelerator Chain, O.Boine-Frankenheim.

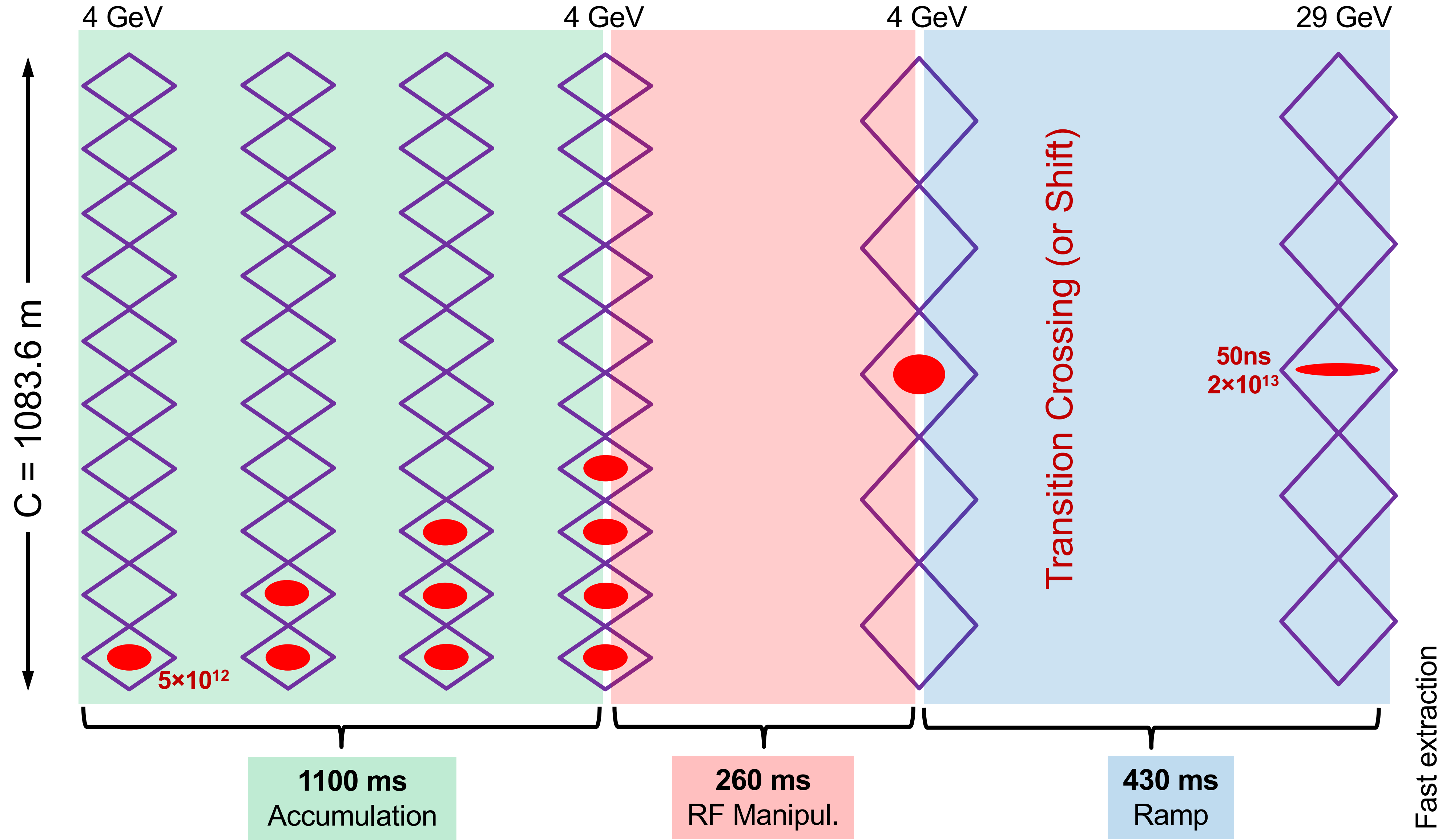
Reference Cycle: U^{28+} fast extraction



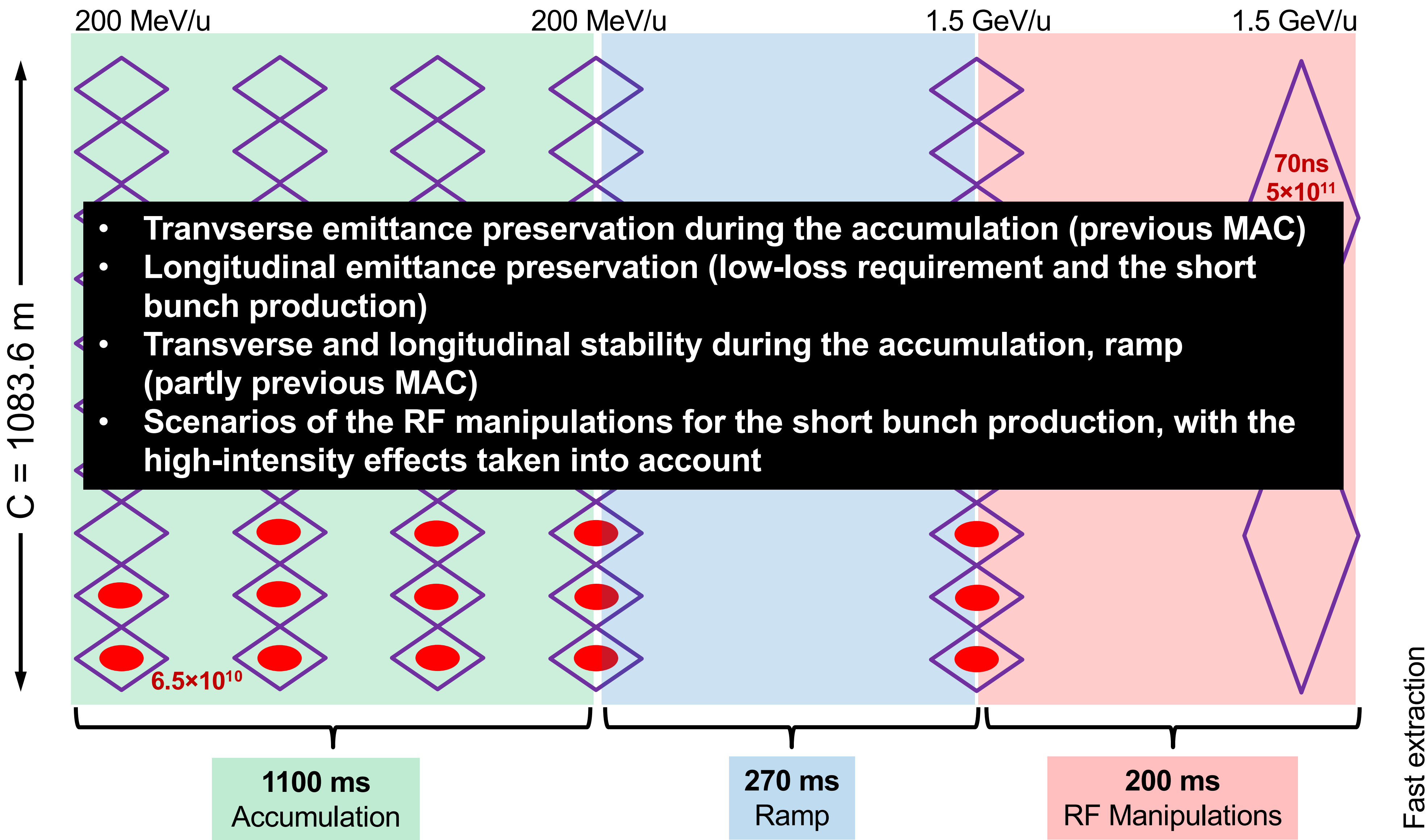
Reference Cycle: U^{28+} slow extraction



Reference Cycle: protons



Reference Cycle: U^{28+} fast extraction

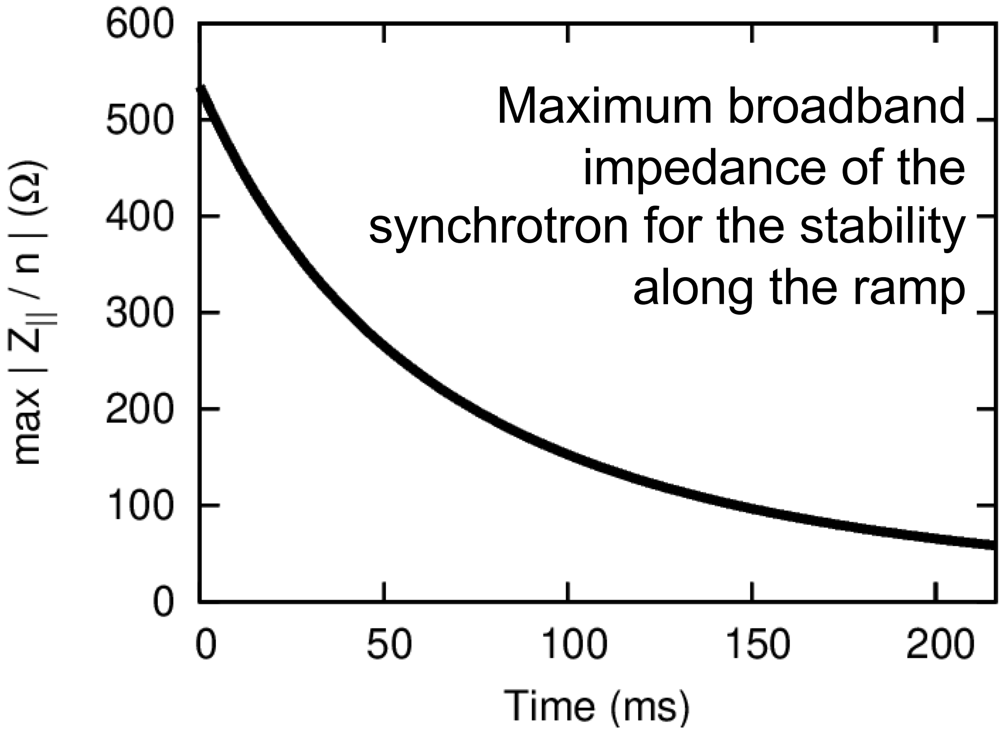


- **Tranvserse emittance preservation during the accumulation (previous MAC)**
- **Longitudinal emittance preservation (low-loss requirement and the short bunch production)**
- **Transverse and longitudinal stability during the accumulation, ramp (partly previous MAC)**
- **Scenarios of the RF manipulations for the short bunch production, with the high-intensity effects taken into account**

U^{28+} Cycles: longitudinal stability

Boussard criterion for the loss of Landau damping

$$\left|\frac{Z_{\parallel}}{n}\right|_{\max} = \frac{2\pi|\eta|\gamma m\beta^2 c^2}{q I_{\text{peak}}}\delta^2_{\text{rms}}$$

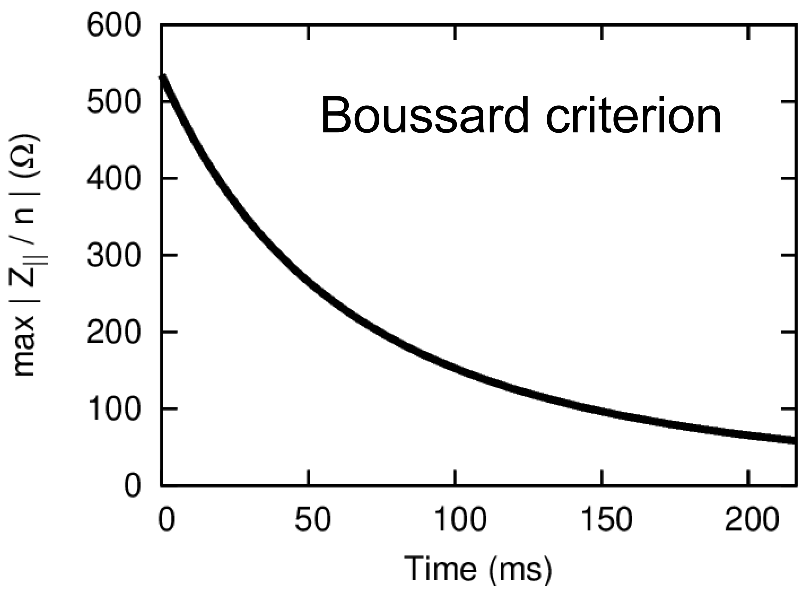


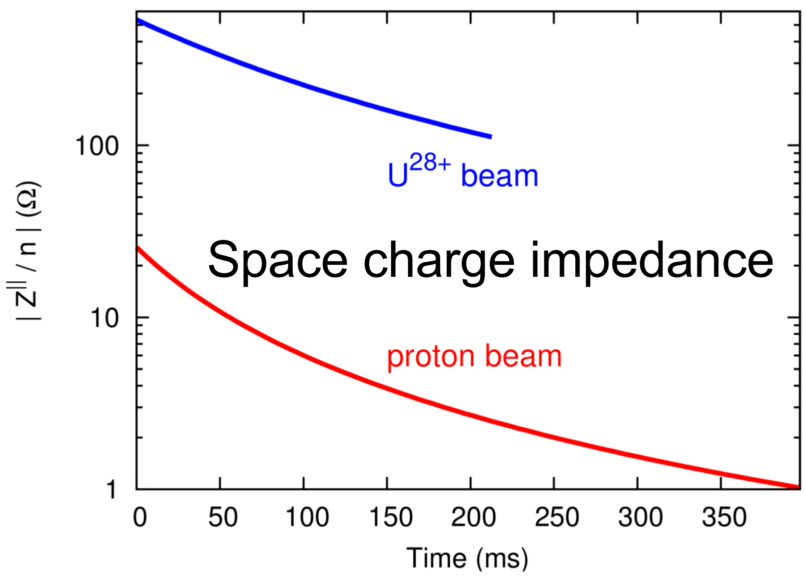
Example: at the CERN PS (a comparable ring), Z/n=i20Ω has been measured.
Estimation for SIS100: between 10-20 Ω.

Again, in the case of SIS100, the important role of space charge (next slide)

U^{28+} Cycles: longitudinal stability

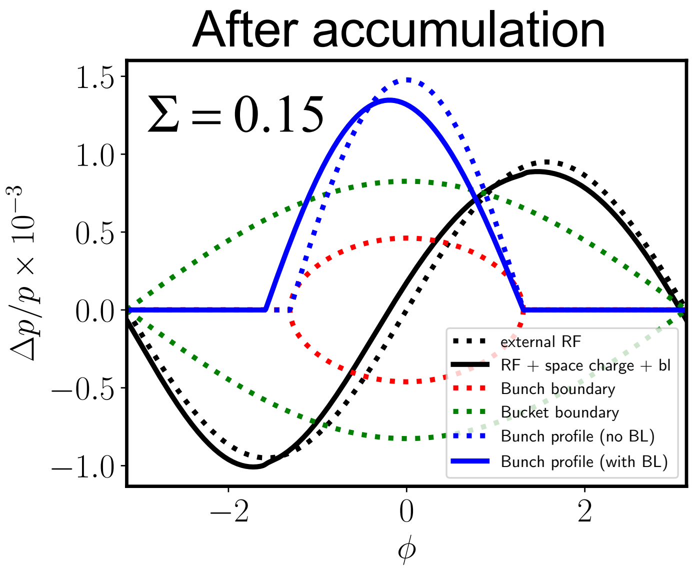
Differently to the broadband impedance, the shift due to space charge does not cause the instability
(O. Boine-Frankenheim, PRSTB 3, 104202, 2000)

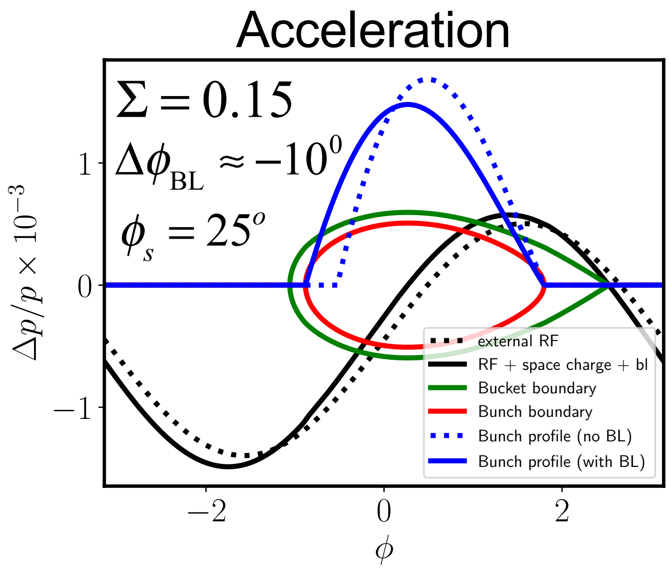




Conclusion for the Microwave Instability during the accumulation and the ramp: the bunches are stable for the expected impedances.

U^{28+} Bunches





Space charge parameter:

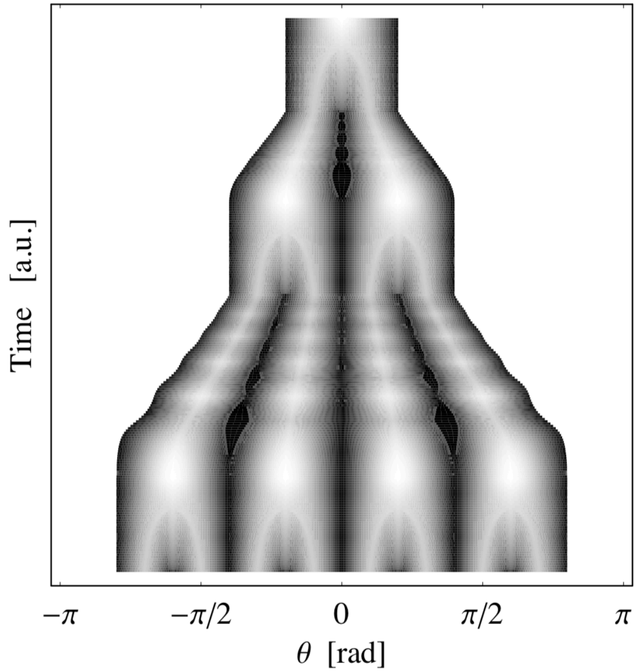
$$\Sigma = \frac{1}{\frac{V_0}{V_{sc}} - 1}$$

Bunch profile shift and deformation due to cavity impedance.

Matched (stable) elliptical bunch distributions with space charge and cavity impedances.

Remark: Tolerable dilution factor 2 for full cycle. Tracking simulations still under progress

U^{28+} short bunch production



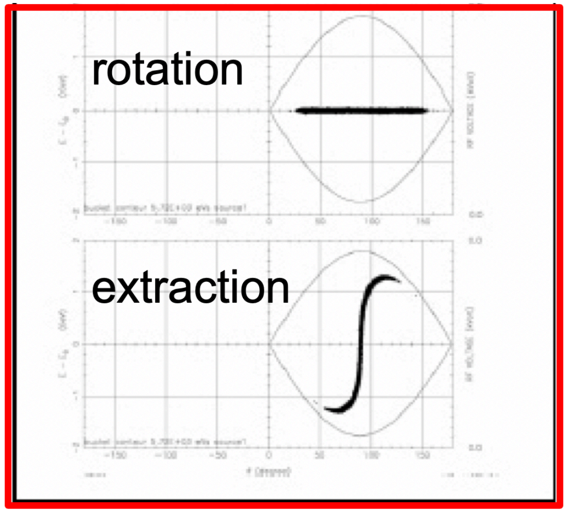
Simulations for the emittance preservation and RF scenarios with the high-intensity effects (Beam Loading and Space Charge) are under progress (M.Kirk, SYS)

There is an alternative scenario: long barrier, bunch rotation. It will be further studied with the high-intensity effects.

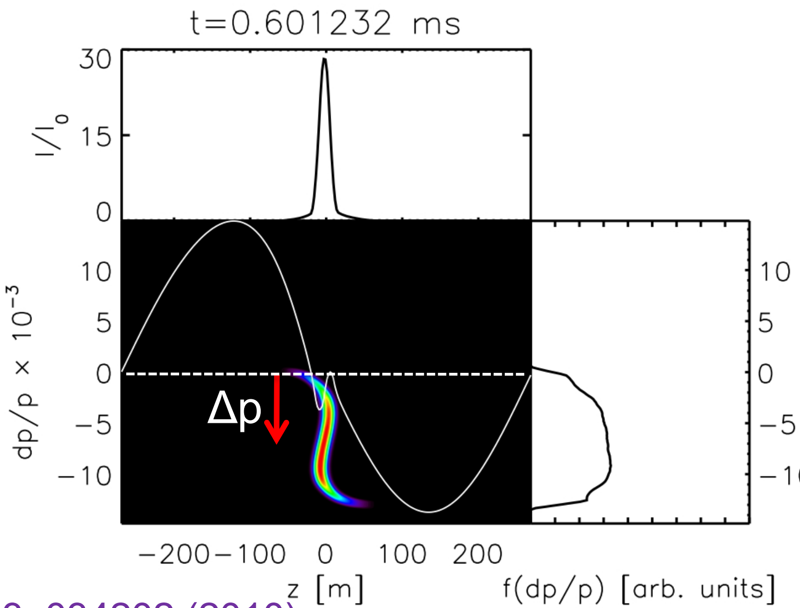
	Bunch pattern	Harmonic numbers
1. Bunch merging	$8 \otimes b \oplus 2 \otimes e \rightarrow 4 \otimes b \oplus 1 \otimes e$	$10 \rightarrow 5$
1. Batch compression	$4 \otimes b \oplus 1 \otimes e \rightarrow 4 \otimes b \oplus 6 \otimes e$	$5 \rightarrow 6 \rightarrow 7 \rightarrow 8 \rightarrow 9 \rightarrow 10$
2. Bunch merging	$4 \otimes b \oplus 6 \otimes e \rightarrow 2 \otimes b \oplus 3 \otimes e$	$10 \rightarrow 5$
2. Batch compression	$2 \otimes b \oplus 3 \otimes e \rightarrow 2 \otimes b \oplus 8 \otimes e$	$5 \rightarrow 6 \rightarrow 7 \rightarrow 8 \rightarrow 9 \rightarrow 10$
3. Bunch merging	$2 \otimes b \oplus 8 \otimes e \rightarrow 1 \otimes b \oplus 5 \otimes e$	$10 \rightarrow 5$
Fast Bunch rotation		2

H.Damerau, PhD Thesis TU Darmstadt

Reference Cycle: U^{28+} fast extraction



Effect of cavity impedance on the bunch rotation:



magnetic alloy (MA) loaded rf cavities with total: 360 kV (400 kHz)

Large transverse space charge

$$\Delta Q_y^{sc} \approx -0.5$$

(during the last turns)

O. Boine-Frankenheim PRSTB 13, 034202 (2010)

Fast bunch rotation for 70 ns bunch production

U^{28+} Bunches

Reminder from the previous MAC:

Single-bunch head-tail modes due to the Resistive-Wall Impedance.

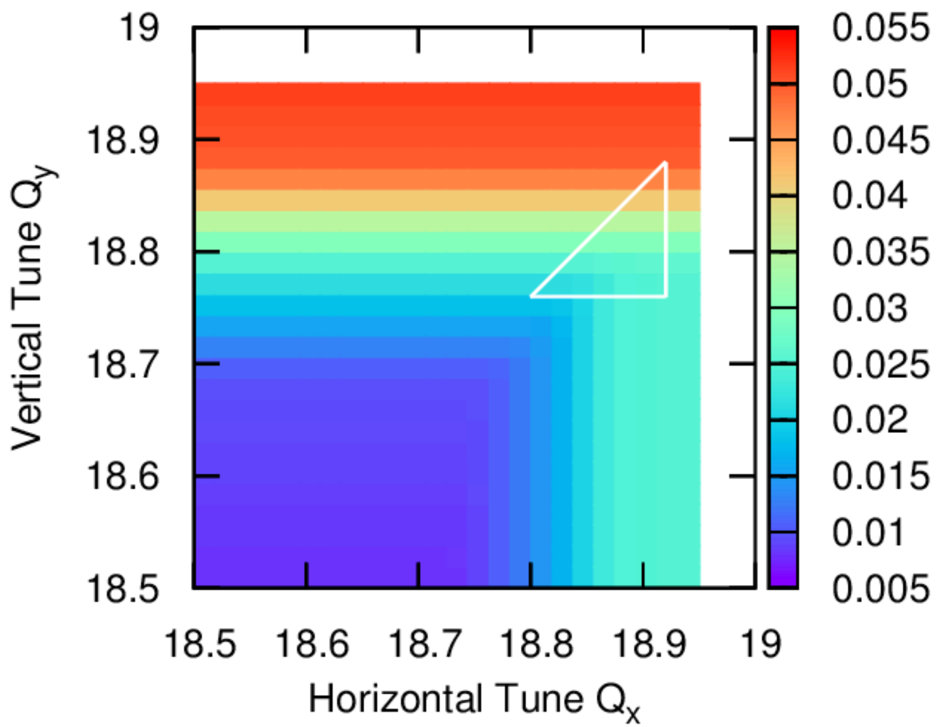
It was discussed that:

- the safety margin of stability due to octupole is small
- octupoles can degrade the single-particle stability

It was concluded, that a TFS is desirable to secure the beam stability. Physics-based specs for a TFS have been formulated.

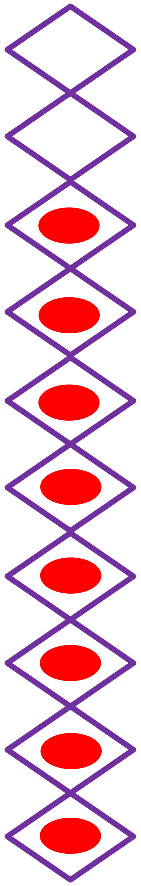
Now, other aspects of the U-cycle are considered

Color: Growth Rate ΔQ, 10^{-3} of the most unstable mode. ΔQ=0.04 corresponds to the growth time 25ms.



White triangle: schematic for the good area from the beam-loss simulations

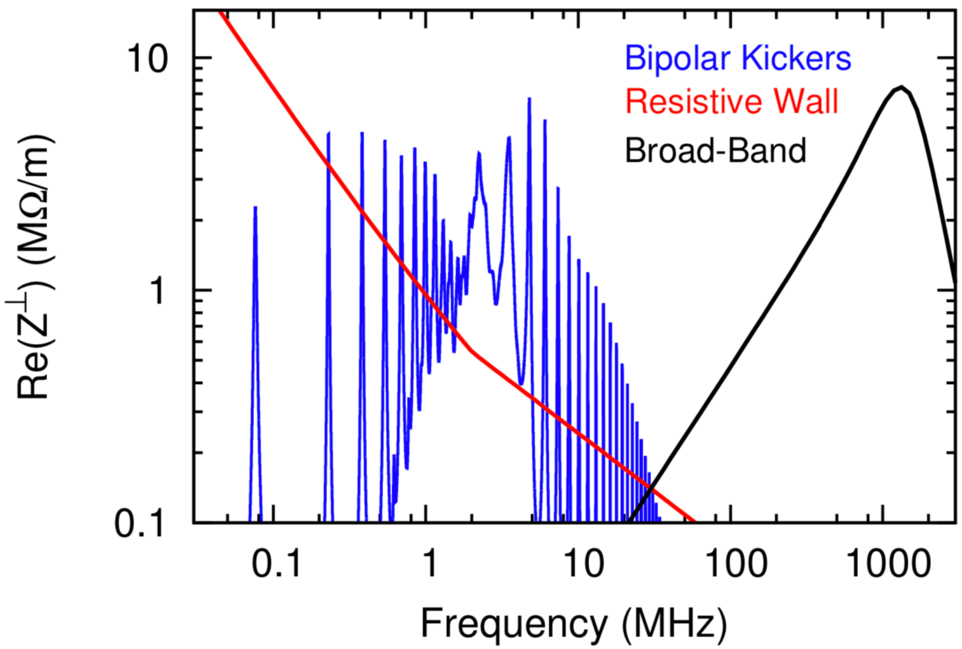
U^{28+} Bunches



1. The coupled-bunch instability.
- the gap of two empty buckets weakens the instability.
- Low-order head-tail modes (higher growth rates) are not stabilized by negative chromaticity.

This should be studied quantitively.

2. Peaks of the kicker impedance. During the ramp, the modes cross the peaks and can cause strong instabilities.



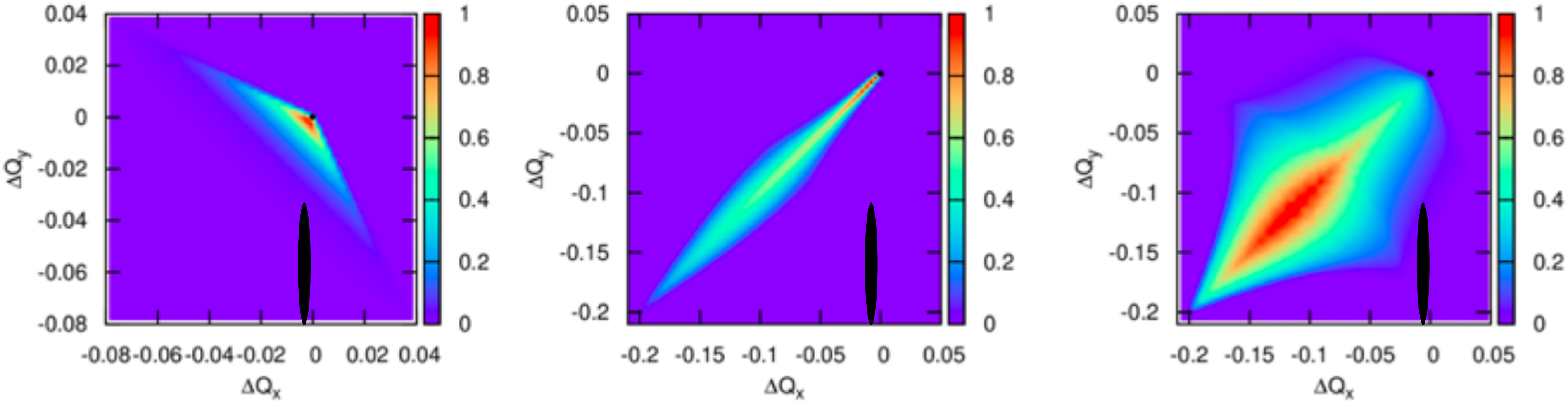
3. Stabilization from the octupoles with space charge taken into account

U^{28+} Bunches

Ongoing study indicates loss of Landau damping due to space charge also for head-tail modes in bunches.

SIS100: up to double of the no-space-charge octupole strength is needed

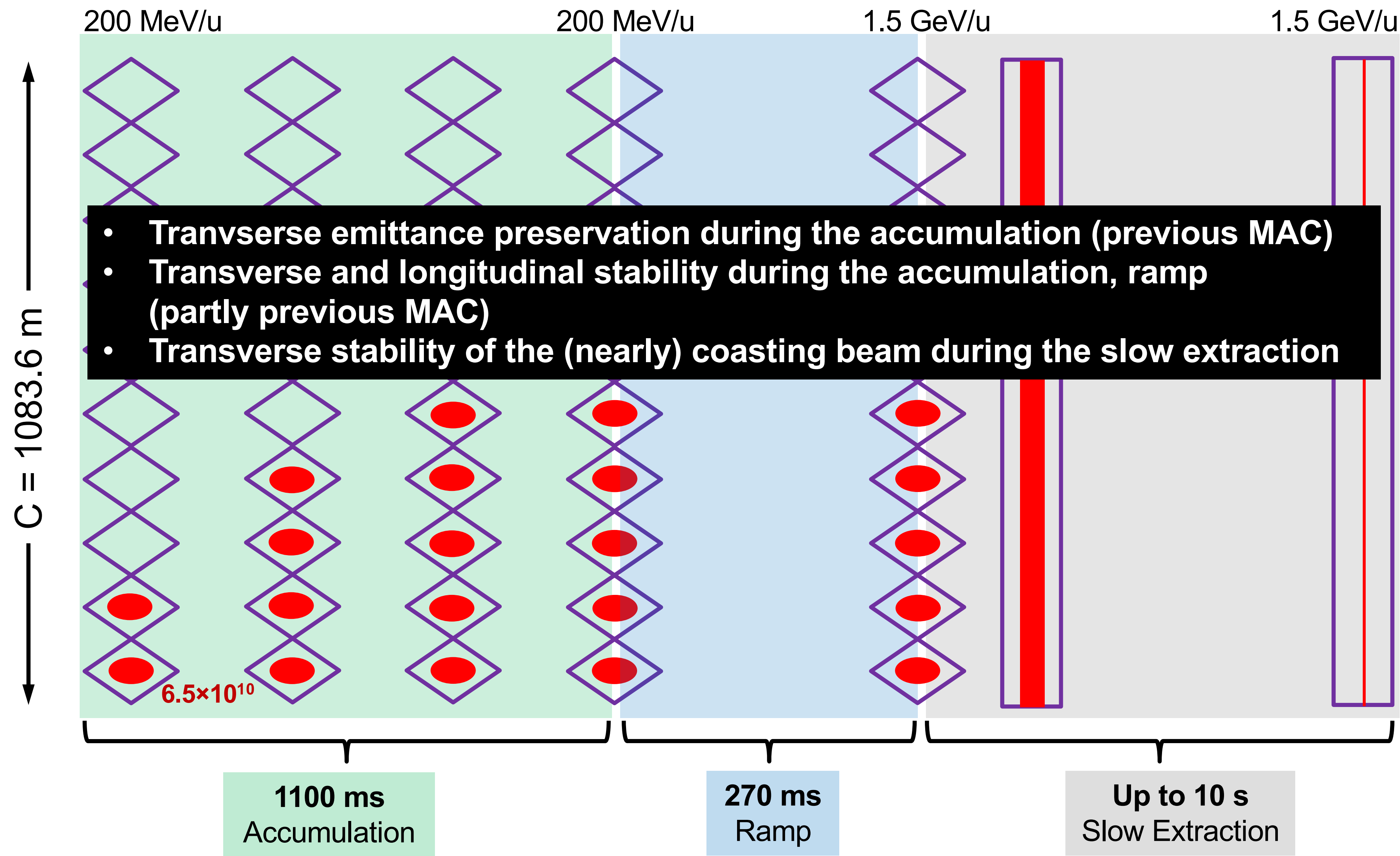
Octupole tune spread | Space-charge tune spread | Combined



Black: schematic for the frequency of the coherent mode

The full-cycle considerations strengthen the need for a TFS

Reference Cycle: U^{28+} slow extraction



- Tranvserse emittance preservation during the accumulation (previous MAC)
- Transverse and longitudinal stability during the accumulation, ramp (partly previous MAC)
- Transverse stability of the (nearly) coasting beam during the slow extraction

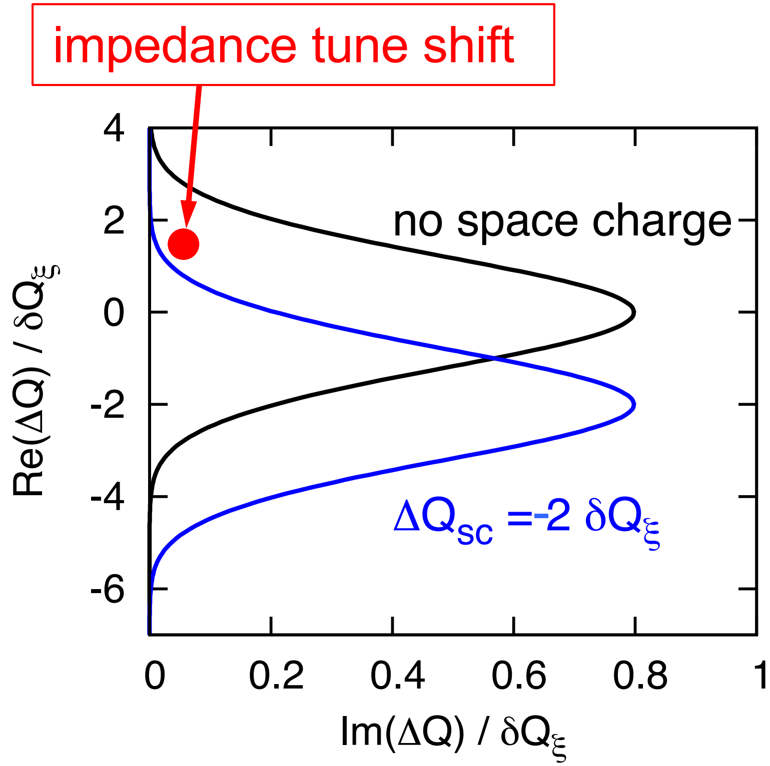
Reference Cycle: U^{28+} slow extraction

- For slow extraction, the beam is de-bunched (weak bunching or barrier)
- The natural chromaticity is needed for stability:

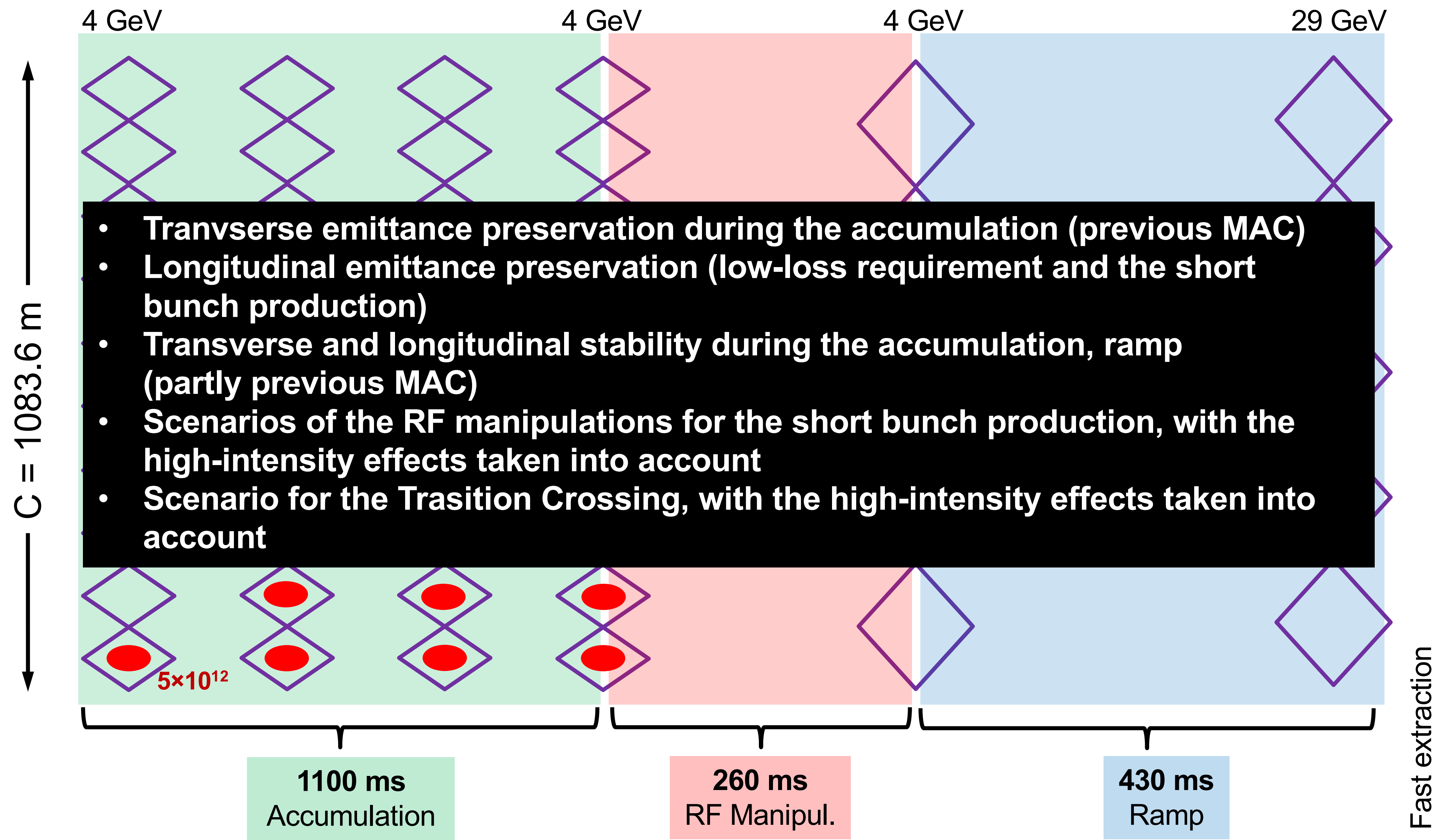
$$\delta Q_\xi = \left|\eta(n - Q_0) + Q_0\xi\right|\delta_p$$

- The transverse blowup for the slow extraction weakens space-charge, and allows for the chromaticity reduction (needed for slow extraction)
- Octupoles may be used for additional damping, but it can have drawbacks
- TFS can stabilize the beam and provide flexibility

Loss of Landau damping due to space charge



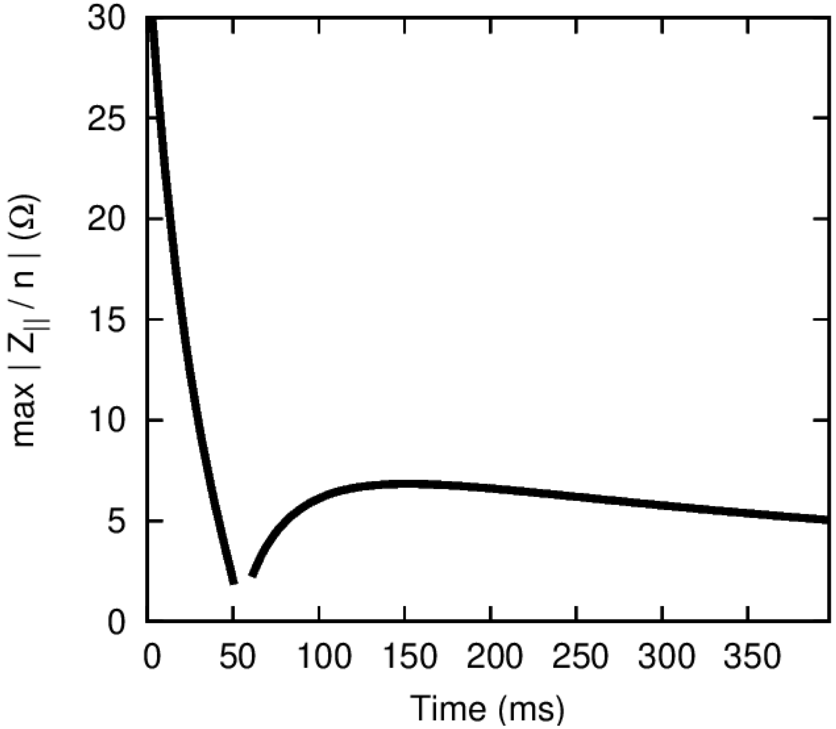
Reference Cycle: protons



- **Tranvserse emittance preservation during the accumulation (previous MAC)**
- **Longitudinal emittance preservation (low-loss requirement and the short bunch production)**
- **Transverse and longitudinal stability during the accumulation, ramp (partly previous MAC)**
- **Scenarios of the RF manipulations for the short bunch production, with the high-intensity effects taken into account**
- **Scenario for the Trasition Crossing, with the high-intensity effects taken into account**

Stability of proton bunches

Boussard criterion $$\left|\frac{Z_{\parallel}}{n}\right|_{\max} = \frac{2\pi|\eta|\gamma m\beta^2 c^2}{qI_{\text{peak}}}\delta^2_{\text{rms}}$$



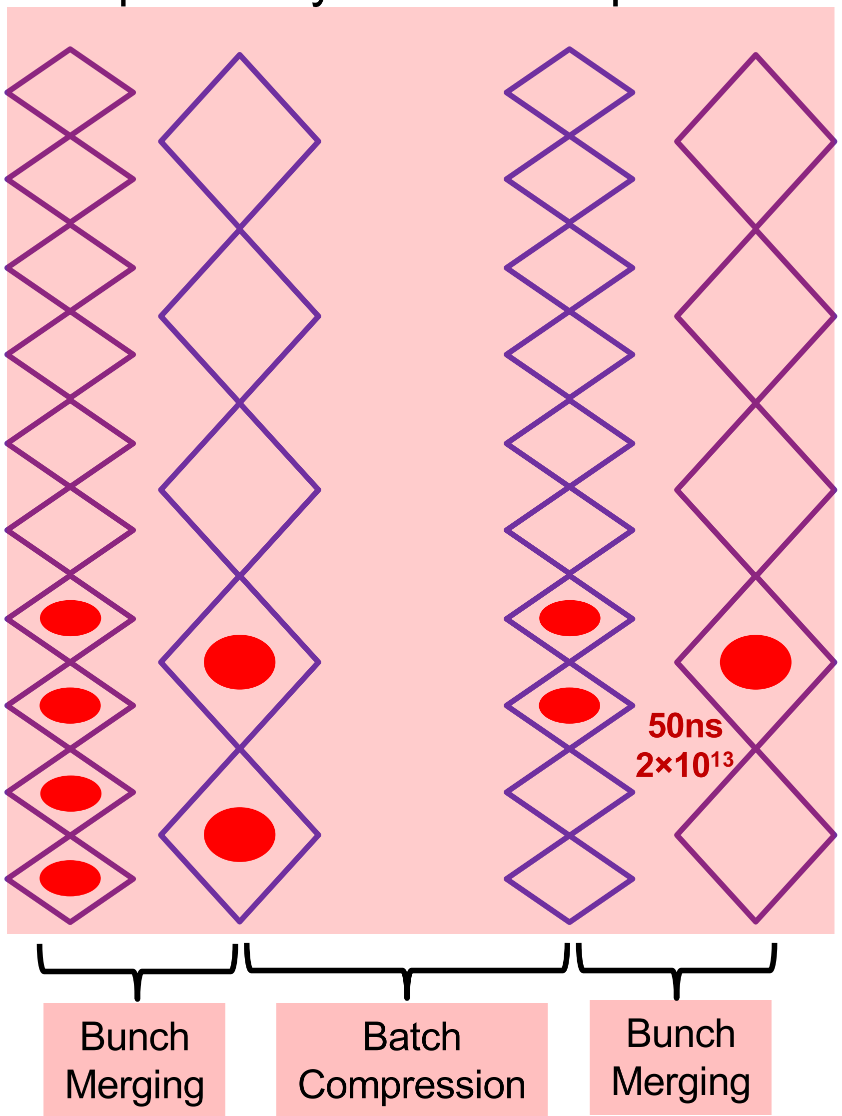
Alternatives:

- One-bunch ramp, matched, shrinking to 50 ns.
- One-bunch ramp, unmatched, larger emittance, with the bunch rotation for 50 ns.
- Two-bunch ramp, RF manipulations at the top.
- Other lattice settings (γ_t=45.5, transition „shift")
- …

The Microwave Instability during the ramp, especially after the transition, seems to be an issue. Various RF scenario are under consideration.

Proton cycle: RF manipulations

One possibility for RF manipulations:



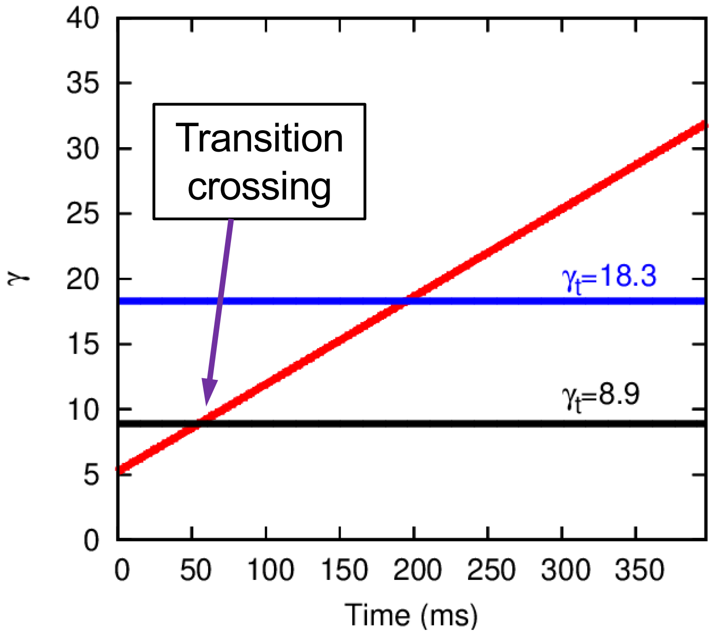
The optimized RF cycle should satisfy:

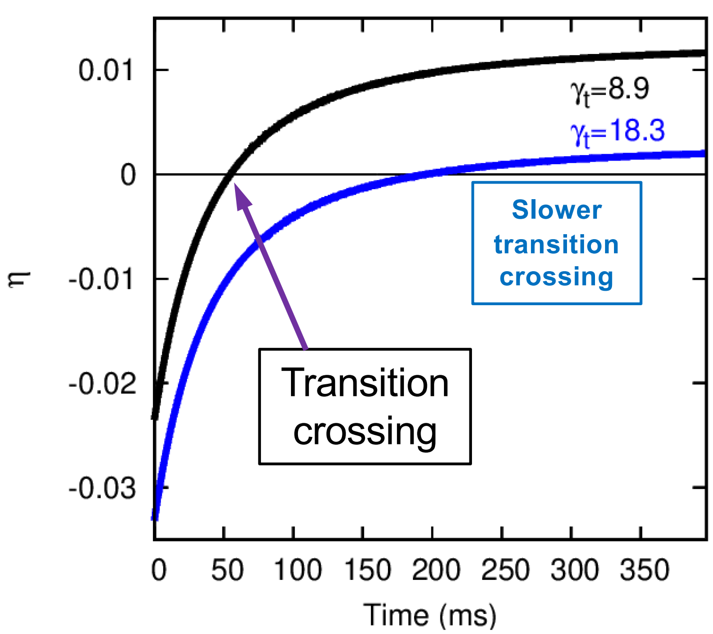
- Production of a high-intensity 50 ns bunch
- Momentum acceptance $\delta_p = \pm 0.005$
- Take into account Beam Loading, Space Charge
- Bunch stability (previous slide)

Simulations for the longitudinal emittance preservation and RF scenarios with the high-intensity effects are under progress (Y.Yuan, TU Darmstadt).

Proton cycle: the ramp

Slip-Factor $\eta = \frac{1}{\gamma_t^2} - \frac{1}{\gamma^2}$





$$T_c = \left(\frac{\beta_t^2 \gamma_t^4}{2\omega_0 h} \frac{|\tan \phi_s|}{\dot{\gamma}^2} \right)^{1/3}$$

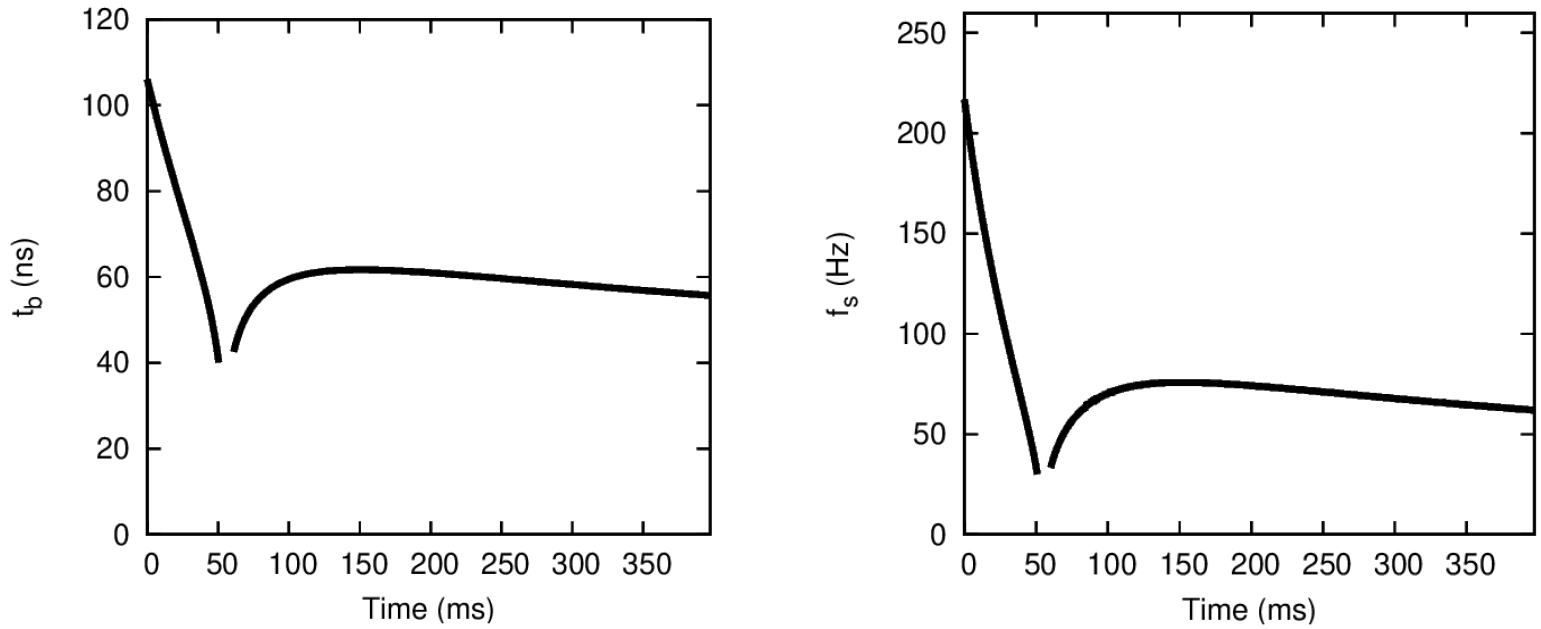
Nonadiabatic time T_c=4.5ms

The black lines: the nominal scenario with the possibility of a γ_t−jump

The blue lines: the heavy-ion type lattice for comparison (no γ_t−jump possible)

Proton cycle: transition crossing

The ramp of the proton bunch with the transition crossing:
the bunch length and the synchrotron frequency



Empty data on the plots: inside the nonadiabatic time (T_c=4.5ms) around the transition crossing

Proton cycle

Transverse stability:

- Head-tail Instability. Cures: high chromaticity at accumulation, chromaticity ramp at transition. Support from the octupoles and additional flexibility with TFS.
- Beam Break-Up Instability at transition. Cures: Chromaticity ramp and octupoles.

Bunches are stable. TFS is needed if a small chromaticity is required.

Issues due to the transition crossing:

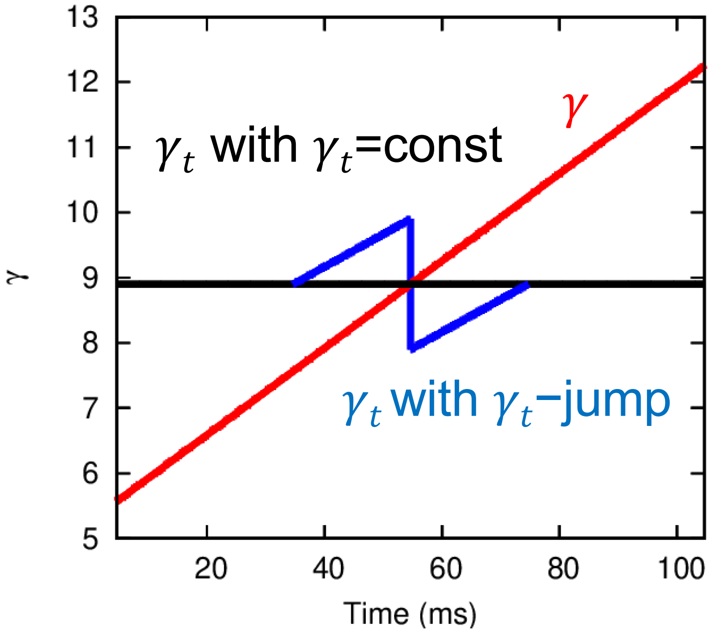
- Frozen and nonlinear synchrotron motion
- Chromatic nonlinearity (results in emittance blowup)
- Longitudinal space-charge mismatch (high-intensity effect, should be studied)

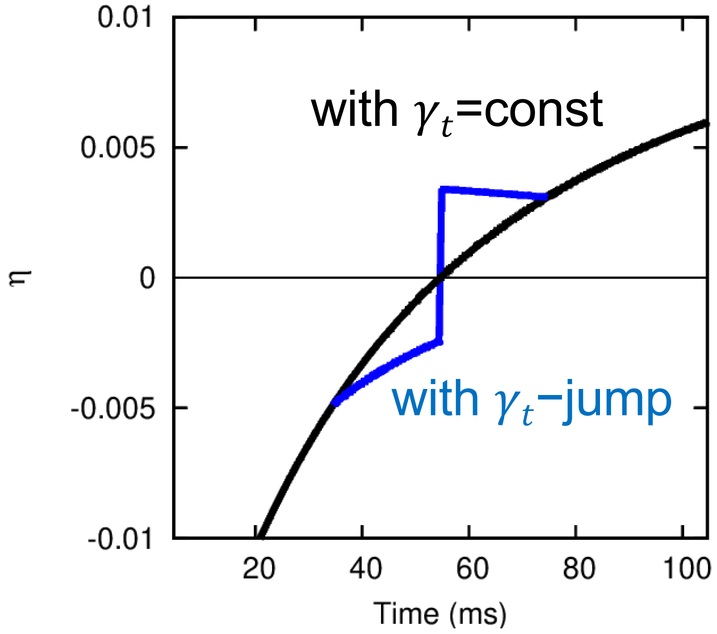
These issues will be cured (at least partly) by the γ_t−jump

Proton cycle: transition crossing

Using the special fast quadrupoles:
Rise Time = 20 ms
Jump Time = 0.5 ms
D.Ondreka, MAC10, November 2013.

Slip-Factor $\eta = \frac{1}{\gamma_t^2} - \frac{1}{\gamma^2}$





Without γ_t−jump: small η ($|\eta| < 2.5\times10^{-3}$) for 30 ms.
With γ_t−jump: small η for 0.5 ms.

Injection errors

Due to large transverse beam sizes and bunch lengths, the emittance blowups are expected to be <1%. Conclusion: no need for the function as injection error damper.

The frequency range of the TFS (25kHz−10MHz) can be covered by a single kicker.

Summary

Heavy-ion beams (reference U^{28+}):

- Longitudinal stability: stable during the accumulation & ramp for the expected impedances. Ongoing simulations for the RF manipulations.
- Detailed scenarios for the short bunch production are under progress.
- Transverse stability: the need for TFS is strengthened, octupoles are still important.

p^+ beam:

- Longitudinal stability: scenarios for a short bunch production are under progress.
- The γ_t−jump should support a safe transition crossing.
- Transverse stability: TFS will provide flexibility w.r.t. the chromaticity corrections

There is a strong need for a TFS.
TFS should be available at the operation start.

Ongoing simulations of RF cycles for high-intensity beams