MCBI for FAIR

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FAIR project at GSI

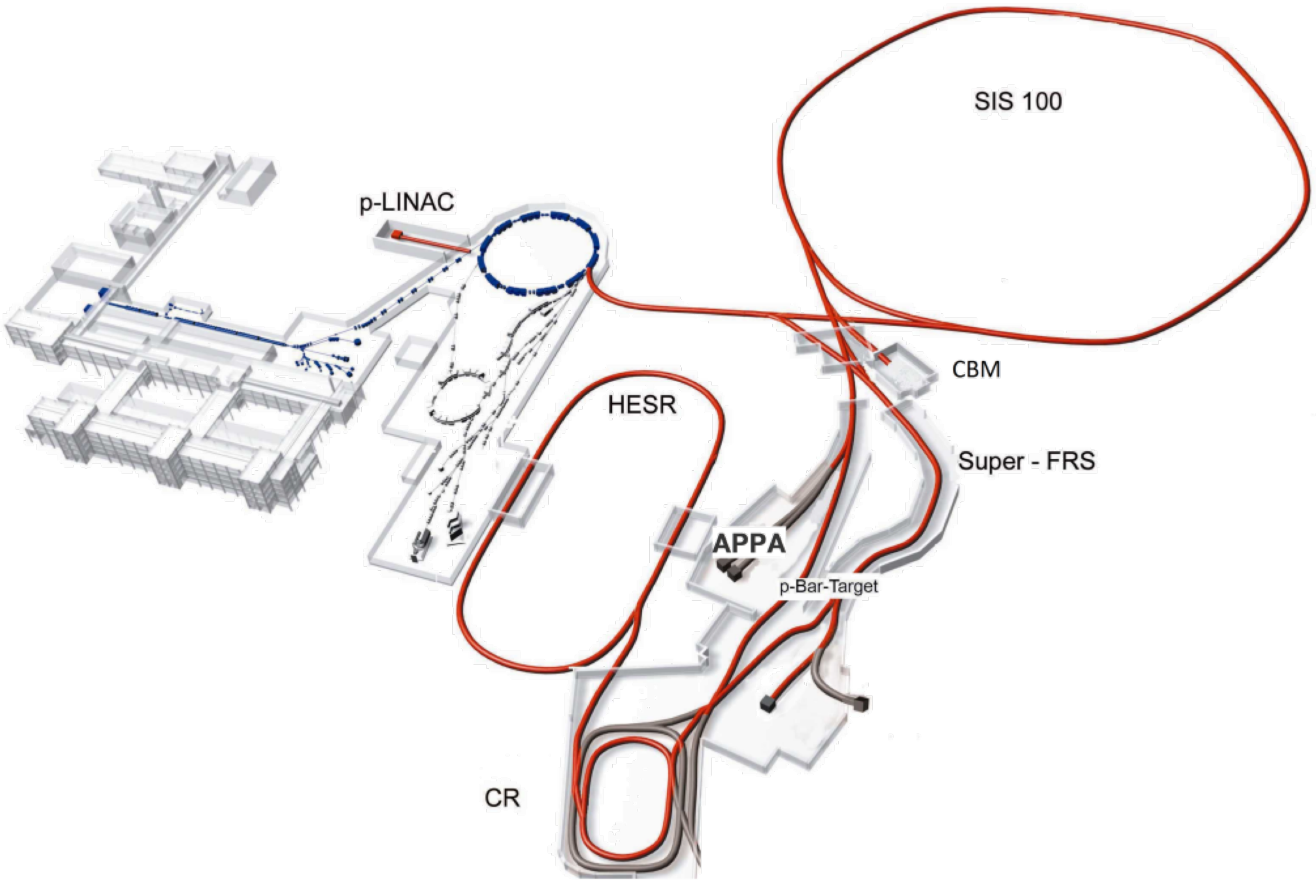
- Contract signed for site preparation area North. Excavation, retaining walls, ground water lowering etc.
- Contracts signed for building shell construction area North. Start of SIS100 tunnel construction: June 2018.
- Contract signed for site logistics.
- Contract signed for cranes and elevators.

July 4th 2017 Official Ground Breaking Ceremony

FAIR project at GSI

Four scientific pillars of FAIR:

- APPA
- CBM
- NUSTAR
- PANDA



FAIR project at GSI

- APPA Cave
  - Hedgehob, BIOMAT
  - SPARC fixed-target
- Super-FRS Target
  - LEB NUSTAR
  - HEB NUSTAR
  - ILIMA NUSTAR
  - EXL NUSTAR
- CBM Cave
  - CBM & HADES
- Strip-Foil
  - SPARC storage-ring
- Pbar Target
  - PANDA

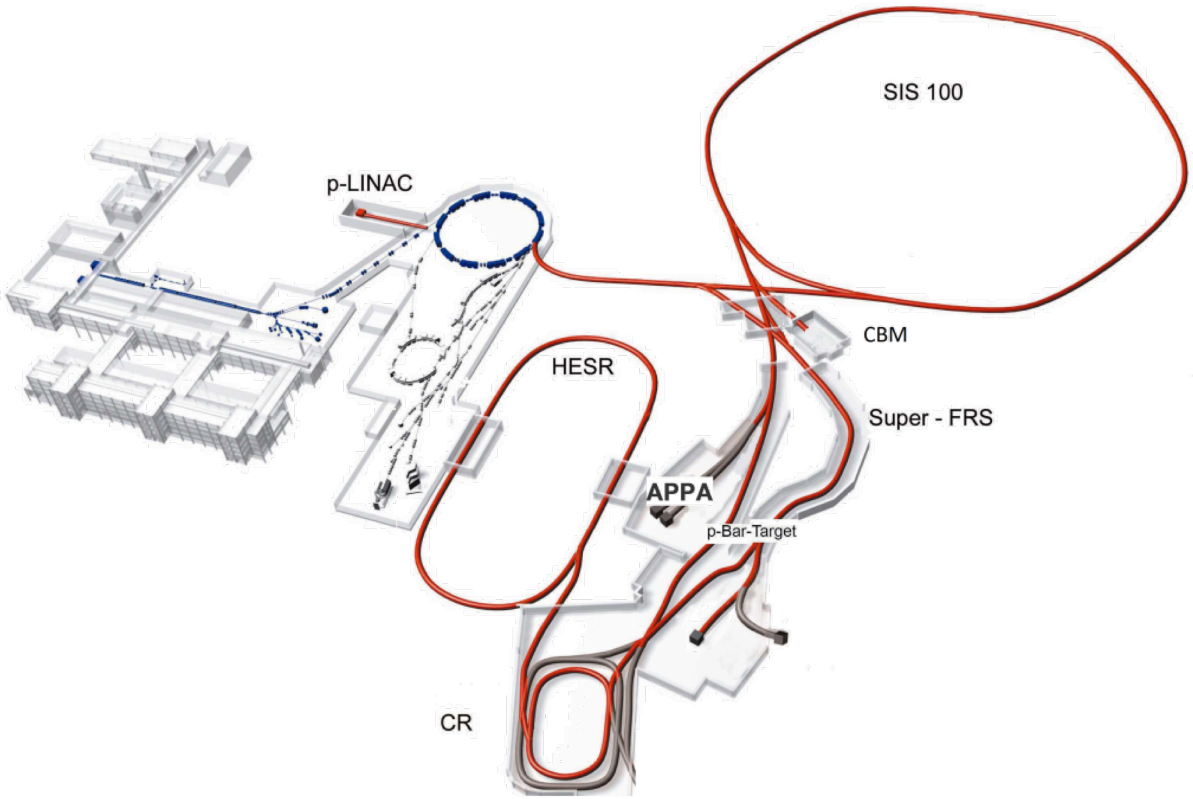
Slow Extraction
Fast Extraction

FAIR project at GSI

SIS100

- C: 5 x SIS18 = 1 083.6 m
- Ions H−U.
- U^{28+} 0.2→1.5 GeV/u
- p^{+} 4→29 GeV
- High-intensity, low-loss operation
- Coherent instabilities (head-tail, see the poster) is an important issue
- Space charge ΔQ_{sc} up to 0.3

- Under construction, commissioning 2025.



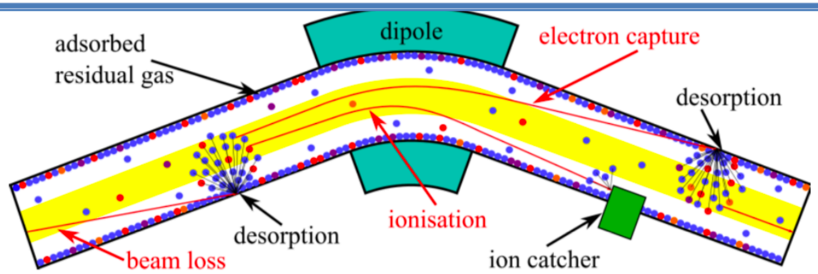
FAIR project at GSI

Existing and planned Heavy Ion Accelerators operated with Low Charge States worldwide			
AGS Booster	BNL, USA	5×10^9	Au^{31+}
LEIR	CERN	1×10^9	Pb^{54+}
NICA Booster	JINR; Russia	4×10^9	Au^{32+}
SIS18	**GSI/FAIR, Germany**	1.5×10^{11}	U^{28+}
SIS100	**FAIR, Germany**	5×10^{11}	U^{28+}
B Ring	**HIAF, China**	1×10^{11}	U^{34+}

P.Spiller, IPAC2018

Heavy-ion synchrotrons

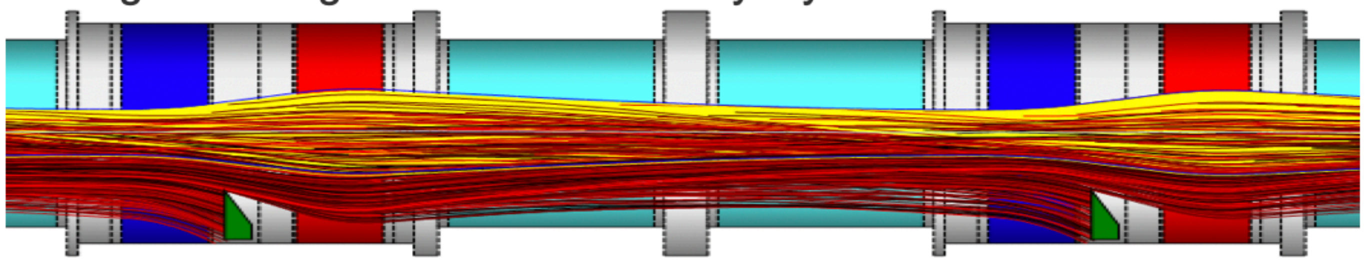
The Dominating Intensity Limitation for Heavy Ion Beams in Synchrotrons is the Interaction with the Residual Gas and thereby generated Charge State Changes. Due to Desorption Processes at High Beam Intensities the Static Residual Gas Pressure becomes the so called Dynamic Vacuum. Ionization in the Dynamic Vacuum is the dominating beam loss mechanism which appears much below the space charge limit.



Ionisation loss drives pressure bumps which itself accelerates the ionisation process.
> Dynamic vacuum instability

P.Spiller, IPAC2018

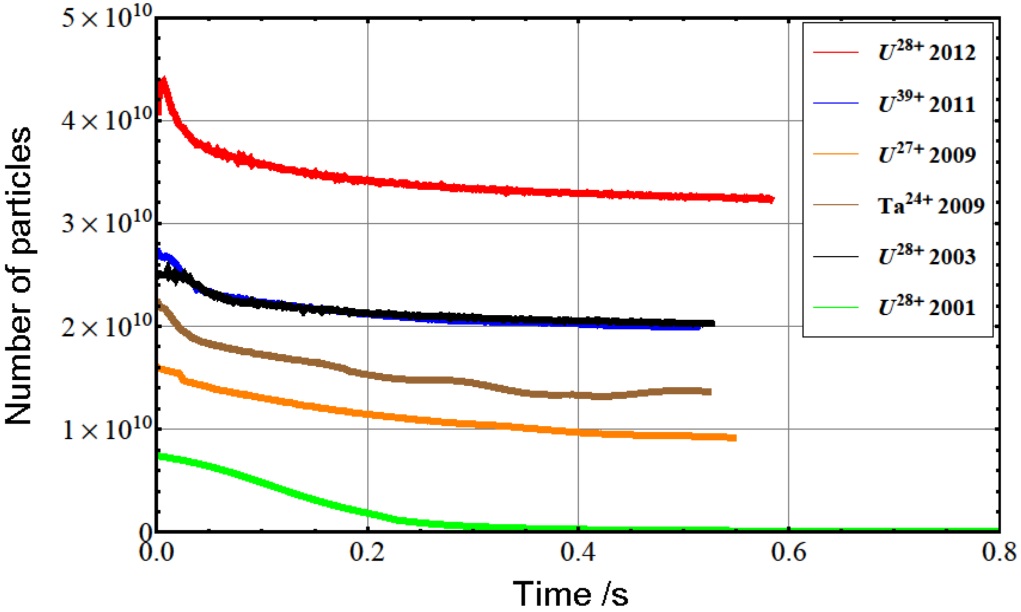
- SIS100 ion catcher system optimized for $U^{28+} \rightarrow U^{29+}$
  - >99% catching efficiency
  - all charge exchange loss is controlled by cryocatcher



SIS18 synchrotron

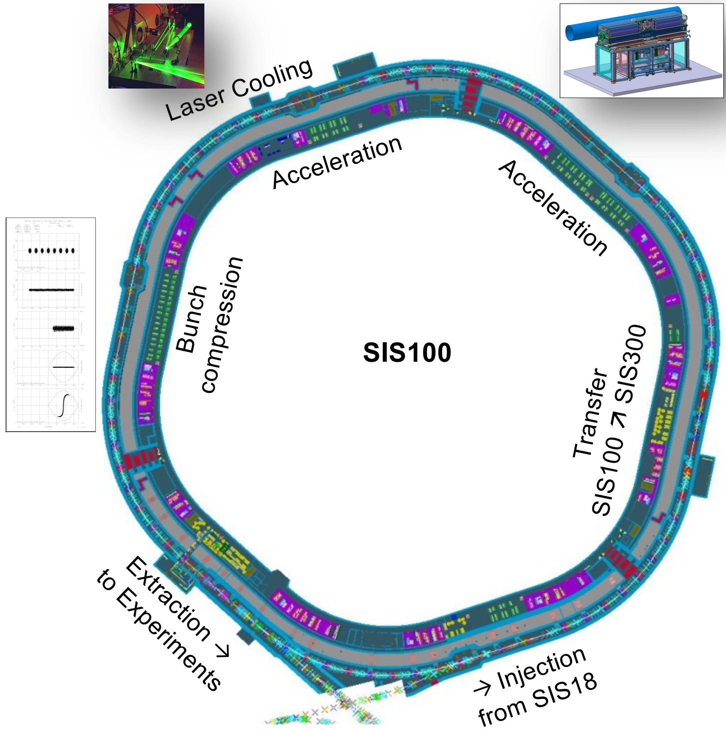
World Intensity Record for Low Charge State Heavy Ions

- 3.2×10^{10} U^{28+} accelerated and extracted successfully
- further upgrade program
- still a factor of 6 in intensity is missing



So far SIS18 has been operated without specific instability mitigation measures

The SIS100 synchrotron



- Fast ramping superferric ‘nuclotron’ magnets (4 T/s) **with “cool” and thin beam pipe.**
- Cycle rates of up to 1 Hz (**1 s accumulation after injection**)
- Slow extraction (over seconds) or fast extraction (single compressed bunches)

FAIR: Beam intensity limitations

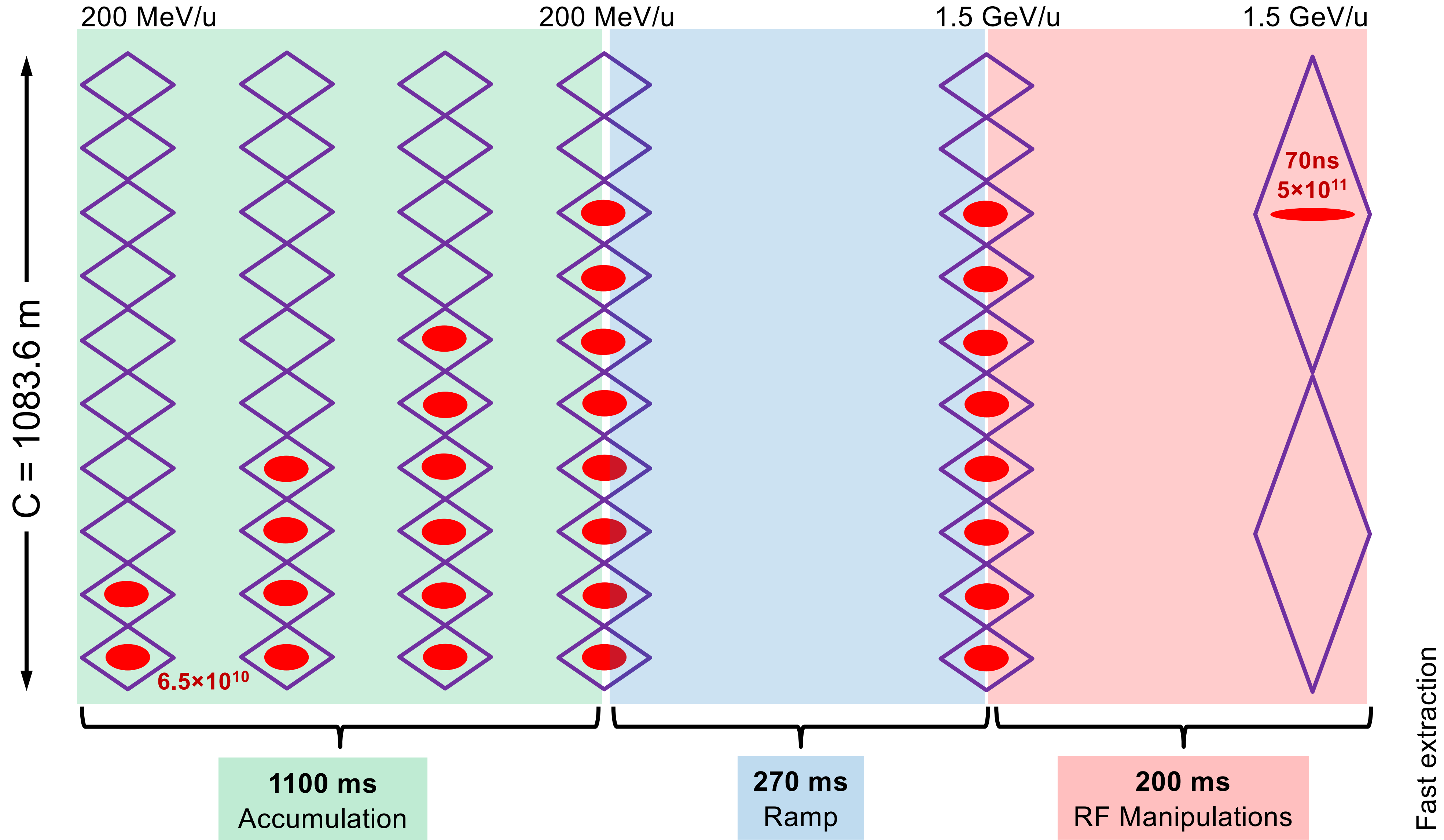
Beam intensity and quality limitations for protons (and light ions):
- Space charge at SIS18/100 injection energies !
- Transitions crossing in SIS100 (protons).
- Beam loss below activation level of accelerator components (< 1 W/m)
- Coherent beam instabilities and heat load.

Intensity limitations for intermediate charge state heavy-ions in SIS18/100:
- Beam lifetime: Large cross sections for electron stripping/capture
  -> residual gas pressure of the order of 10^{-12} mbar required for sufficient lifetime
- Uncontrolled beam loss below limit for dynamic pressure instabilities (desorption).
- Activation and damage of components.

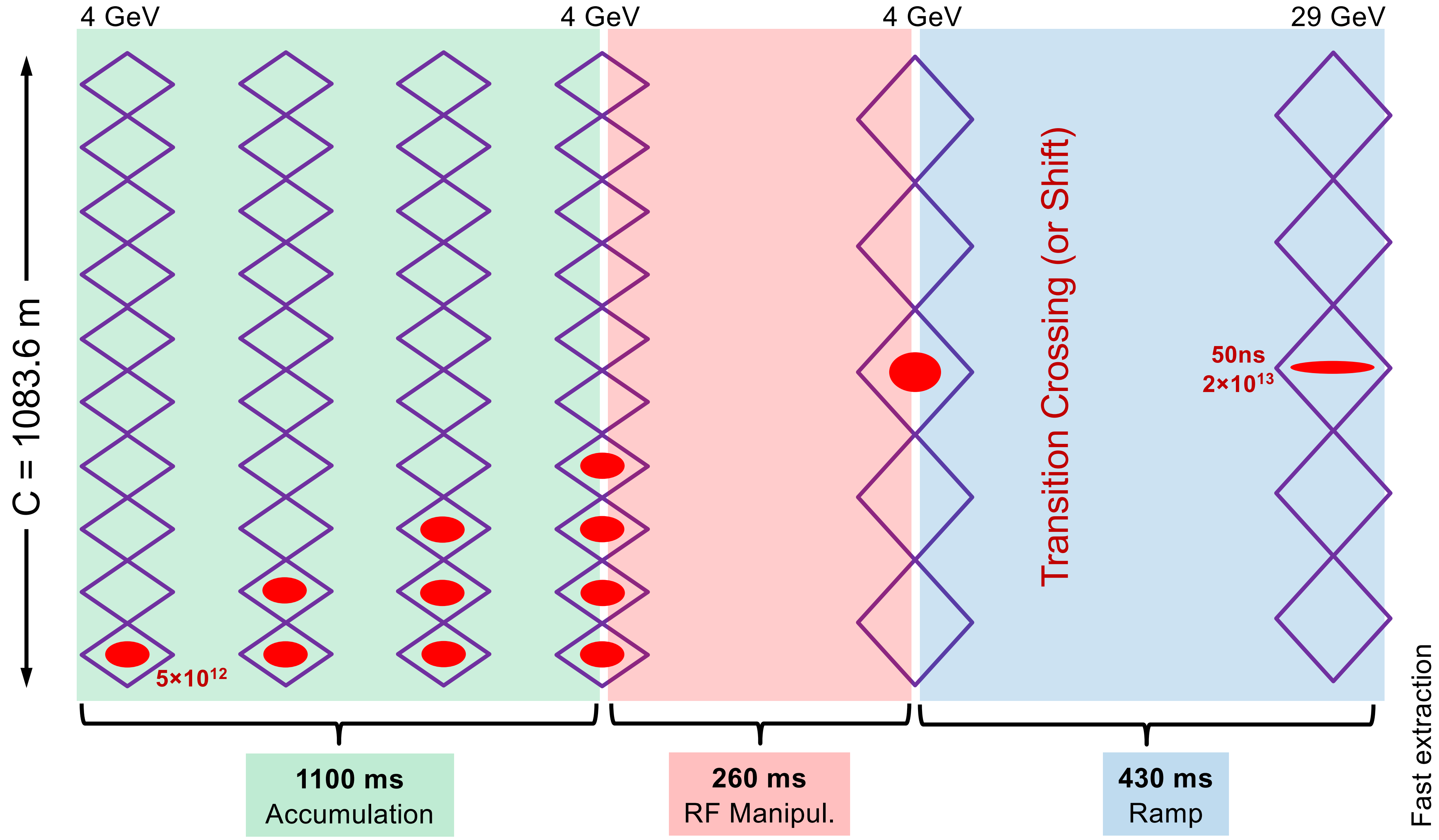
Heavy-ions:
- Current/emittances from injector
  - Ion sources
  - Stripping efficiency of heavy-ions at low energies.
- Efficiency of the multi-turn injection in SIS18

present assumption: ion intensities are not limited by coherent instabilities

SIS100 Reference Cycle: U^{28+} fast extraction

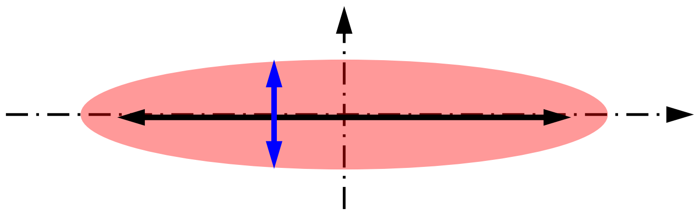


SIS100 Reference Cycle: protons

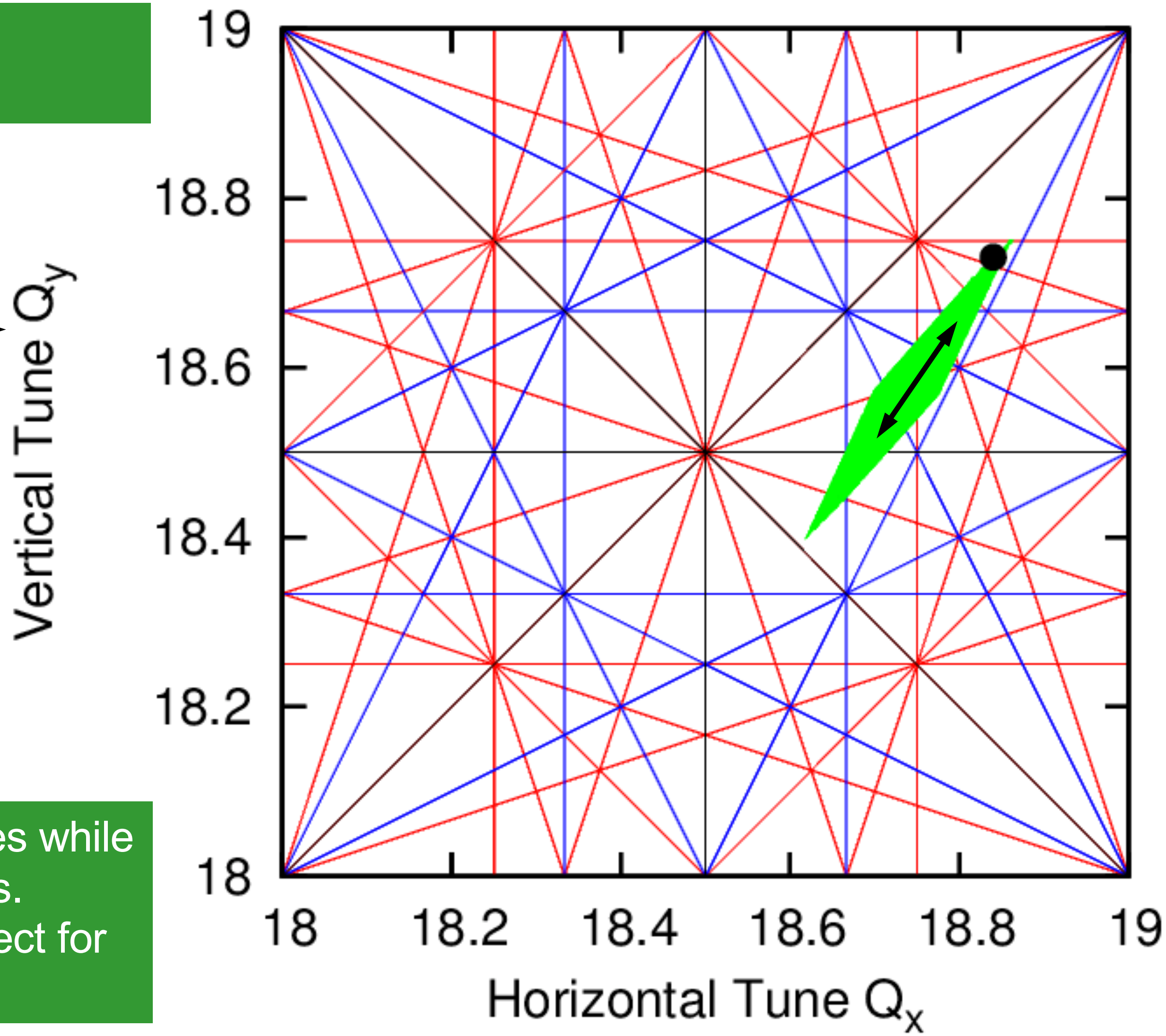


SIS100 RESONANCE DIAGRAM

Special situation for SIS100:
Tune spread due to space-charge



$f_{longitudinal} \approx 1.5$ kHz
($T \approx 600$ us)
$f_{transverse} \approx 5$ MHz
($T \approx 0.2$ us)



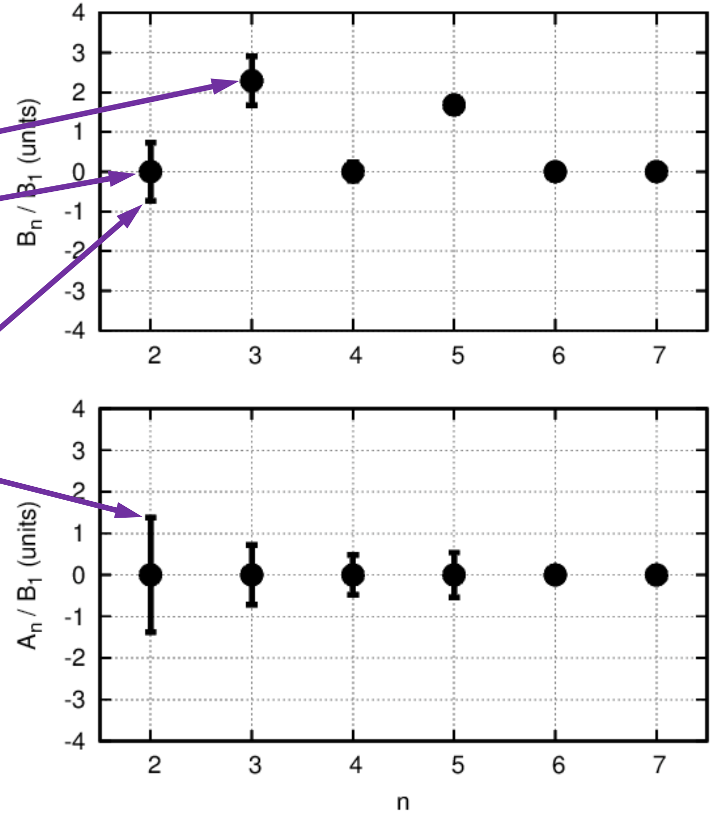
Particles cross different resonances while performing synchrotron oscillations.
Errors + Space-charge: a key aspect for SIS100 beam dynamics

SIS100 Dipole Magnet Model

The field measurements of the dipole series provide
the model of the dipole magnets for particle tracking simulations

Fixed values are the systematic components

The bars show the random components, i.e. the amplitude of the Gaussian distribution among magnets



Assumptions for the magnet model:

1. Only the allowed (B_3, B_5, B_7) systematic components are nonzero
2. The random errors = sample standard deviations

r_0=30mm
Plot: $\pm 2\sigma$ bars
1 unit = 10^{-4}

B_n normal ; A_n skew
B_2 , A_2 quadrupole
B_3 , A_3 sextupole
B_4 , A_4 octupole

The model used in simulations.
From the 50 (a half) of the series magnets

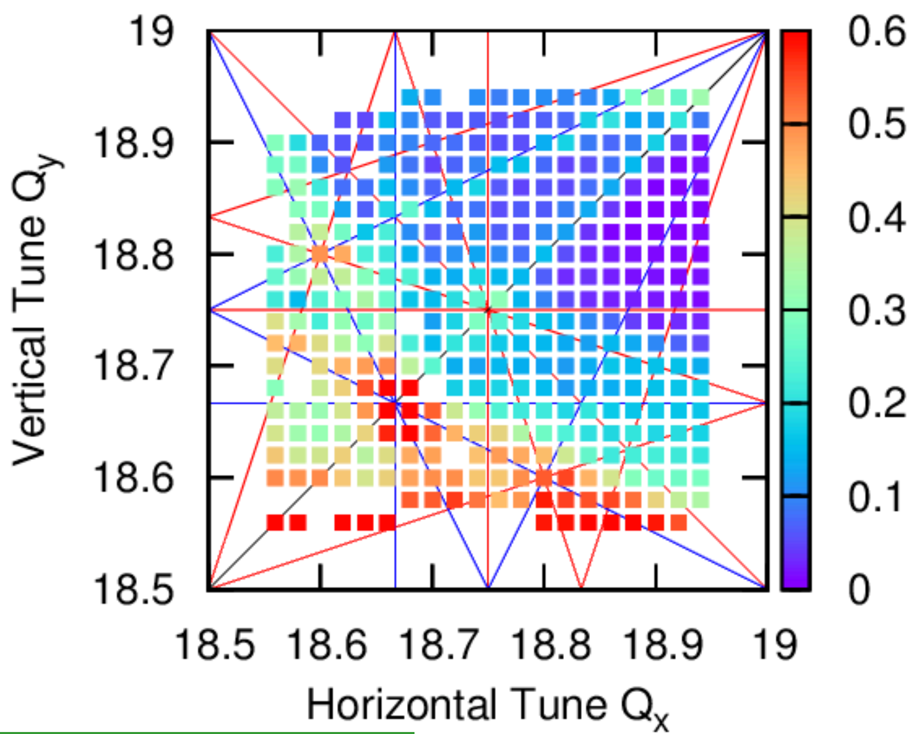
Beam Loss Simulations

Particle tracking simulations using the code Elegant

M.Borland, "*elegant: A Flexible SDDS-Compliant Code for Accelerator Simulation*" Advanced Photon Source LS-287, September 2000.

We have other code developments (MADX, SixTrackLib, Micromap, …)

- 6D particle dynamics in the complete SIS100 lattice with the errors
- Frozen space charge in 3D Gaussian bunch
- Every square: beam loss (color, 1 is 100%) after tracking a bunch for 20 000 turns.

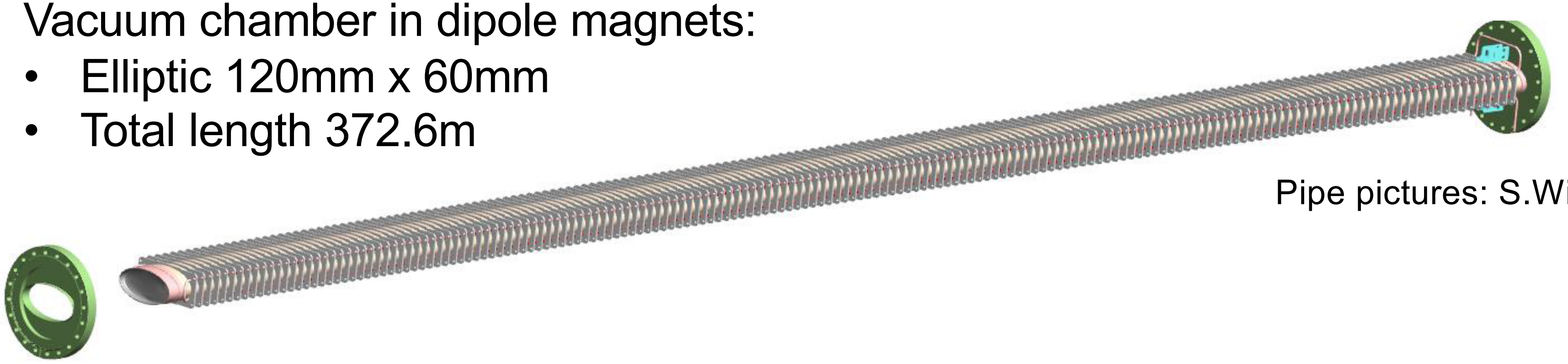


There is a good tune area.
Single particle stability first.

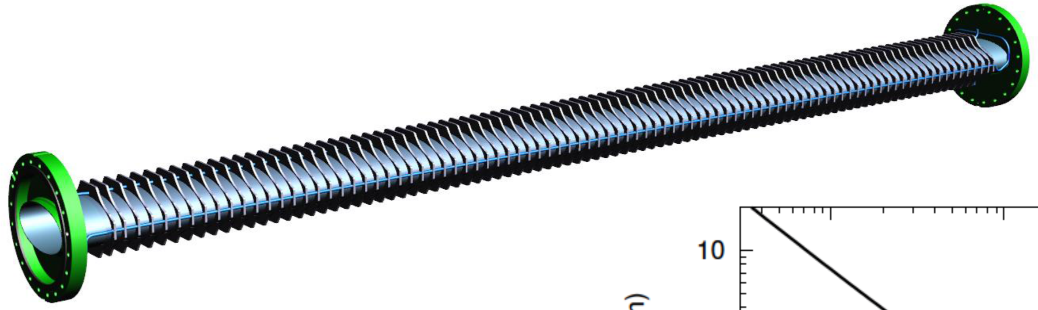
Resistive-Wall Impedance

Vacuum chamber in dipole magnets:

- Elliptic 120mm x 60mm
- Total length 372.6m

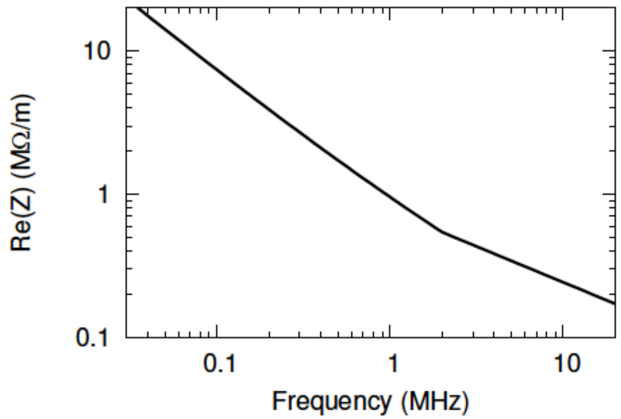


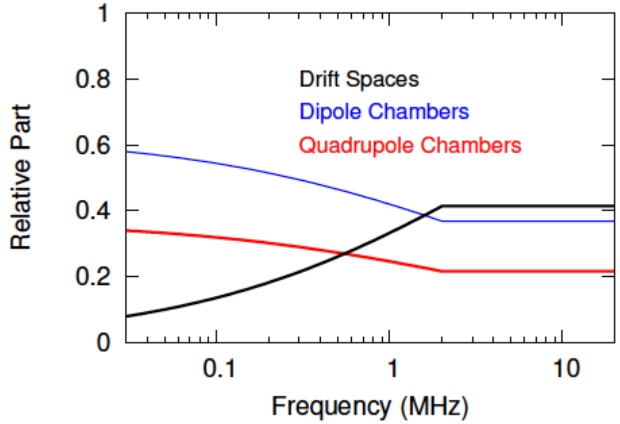
Pipe pictures: S.Wilfert, MAC19



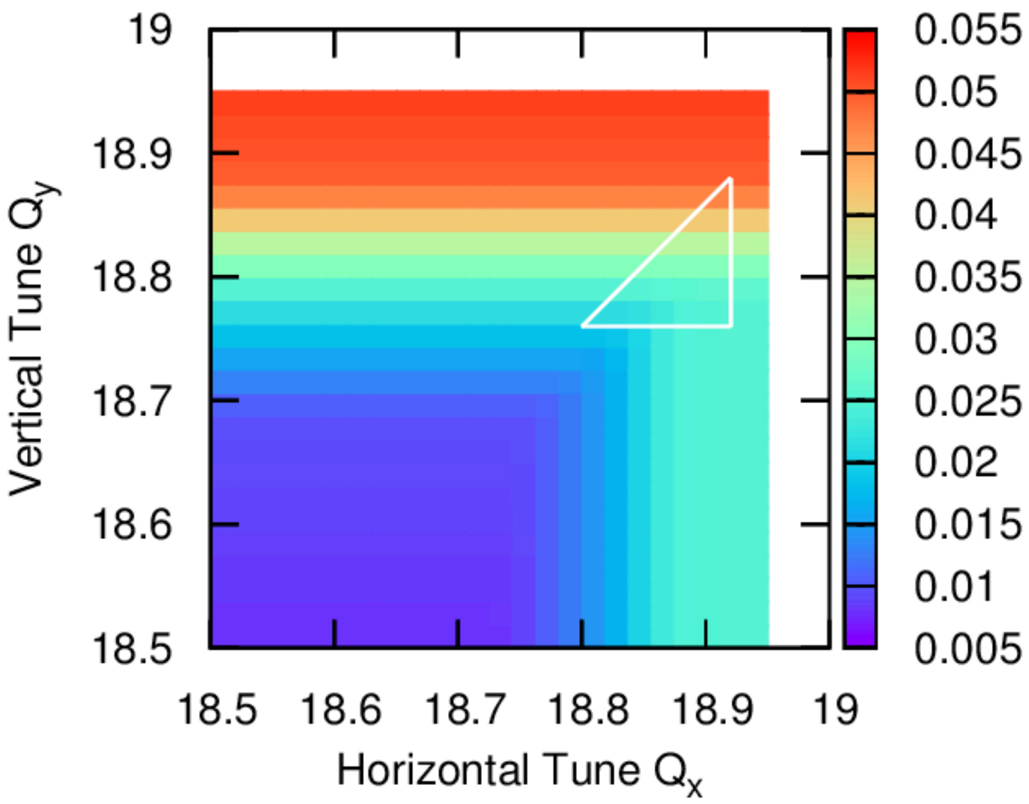
Vacuum chamber in quadrupoles:

- Elliptic 133.4mm x 65.2mm
- Total length 282.5 m





Single-Bunch Head-Tail Instability

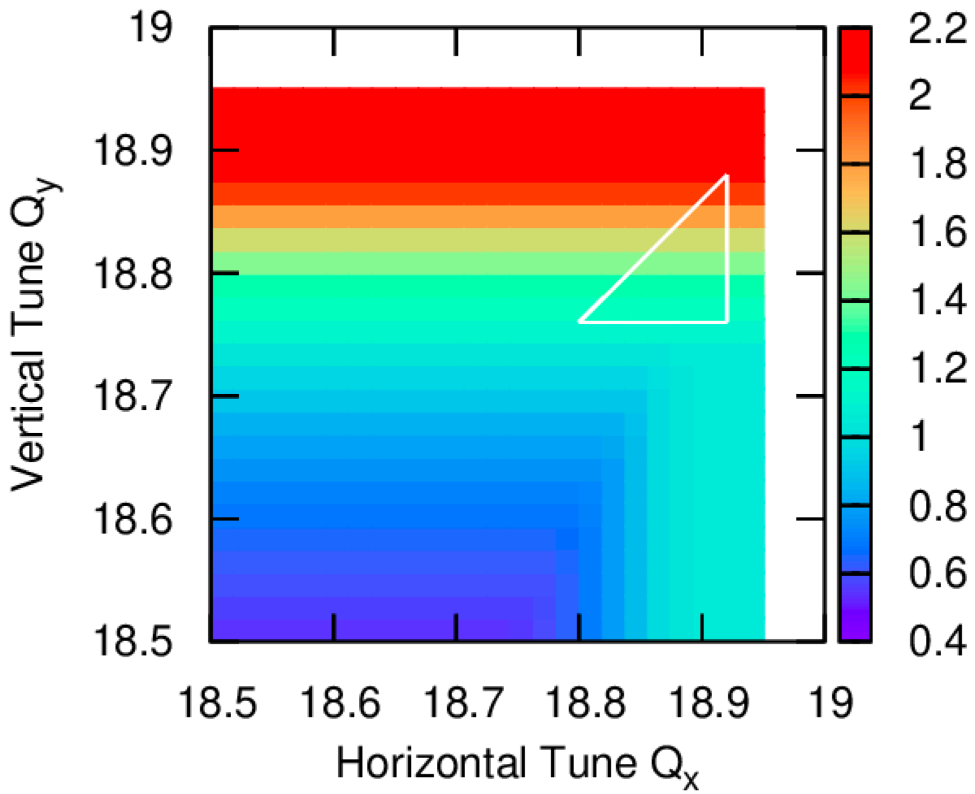


Color: Growth Rate ΔQ, 10^{-3} of the most unstable mode. Vert, horiz, k=1, k=2, k=3

0.04 corresponds to the growth time 25ms. Conservative model for the vacuum pipe impedance

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

Coupled-Bunch Head-Tail Instability



Color: Growth Rate ΔQ, 10^{-3} of the most unstable mode.
Vert, horiz, k=0

For 10 U^{28+} bunches at injection

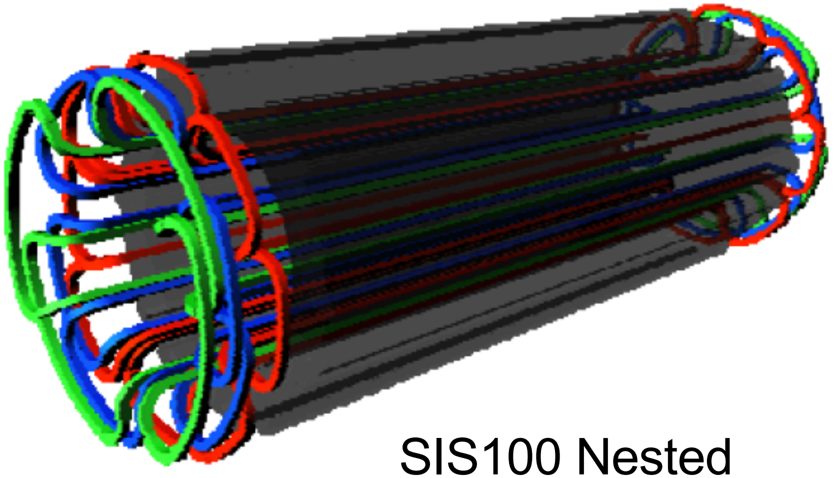
$\Delta Q = 2 \times 10^{-3}$ corresponds to the growth time 0.5ms.
Conservative calculation!

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

Coupled-Bunch Head-Tail Instability

Octupoles Magnets in SIS100

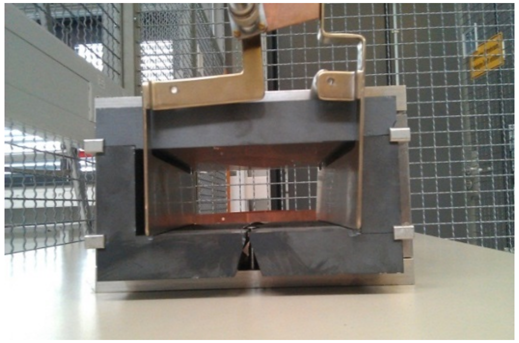
- Max octupole $\Delta Q_\sigma = 13\times 10^{-3}$, should be enough to stabilize $\Delta Q_Z = 9\times 10^{-3}$
- Effect of space charge: $\times 2$ of the octupole power is needed (see the talk V.Kornilov on Thursday)
- Conservative calculations indicate enough stability for SB, CD instabilities
- Safety margin is needed for other impedance sources, chromaticity corrections.
- Octupoles reduce the Dynamic Aperture: possible restrictions.

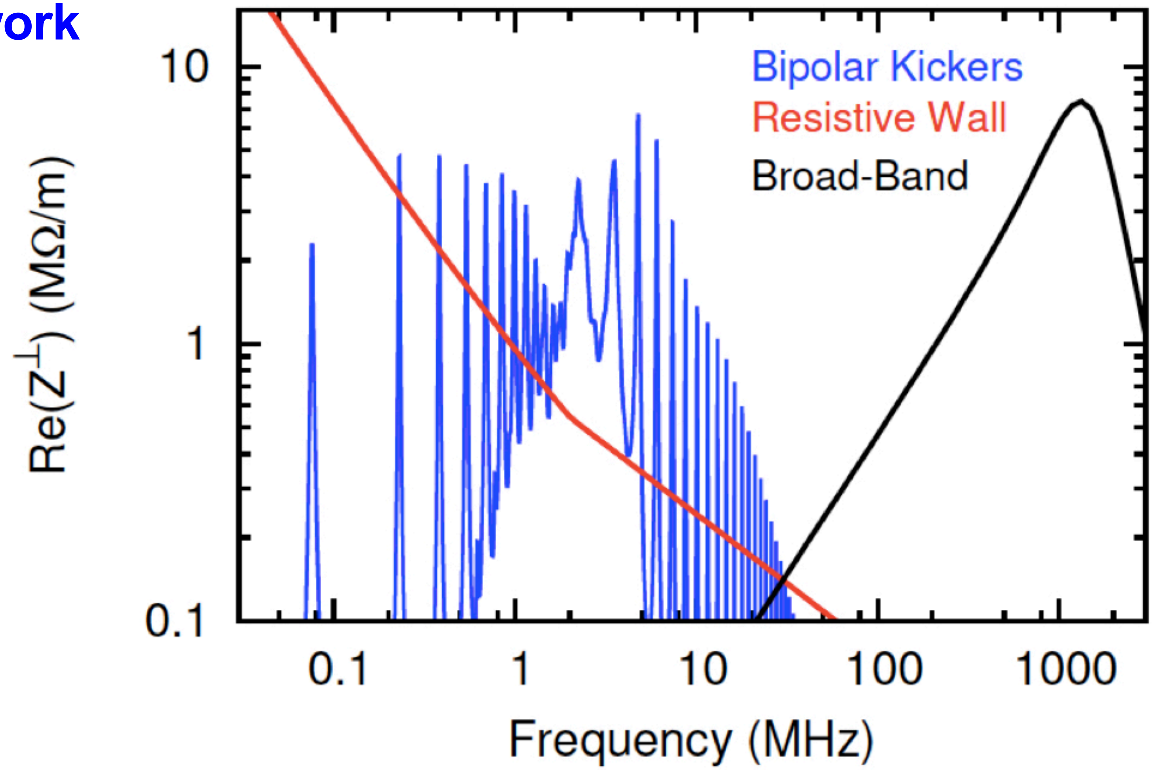


SIS100 Nested Corrector Magnets (12)

SIS100 transverse impedances

Kicker + Pulse Forming Network





Broad-Band Impedance:
PS-based (scaled) model:
$R_{\perp} = 7M\Omega/m \; f_r = 1.5GHz$

SIS100 heavy-ion cycles

Transverse stability:

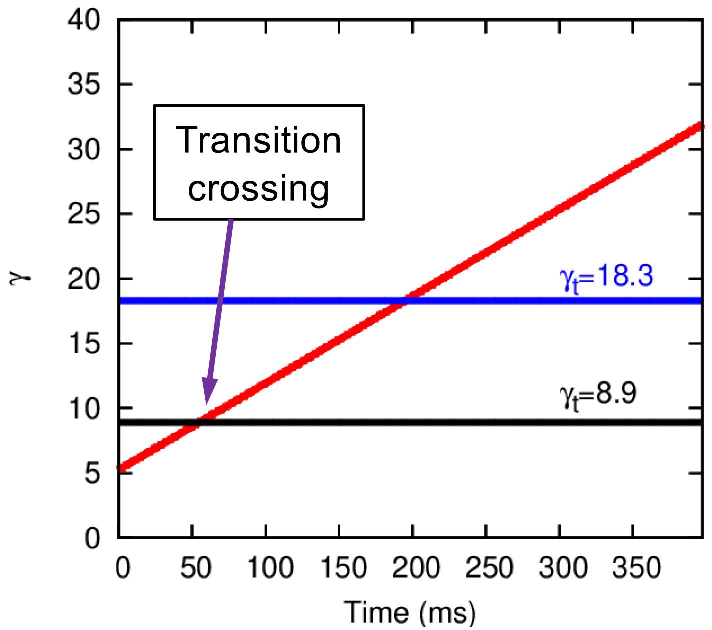
- Single-bunch and Coupled-bunch Head-tail Instability. Cures: octupoles (role of space charge) Support and additional flexibility with TFS.
- Double RF bucket as a mitigation at the injection
- Possibly, stabilizing transverse emittance blowup
- TMCI are suppressed by space charge
- e-cloud: not an issue due to the bunch gaps
- Coasting beam (barrier or weak bunching): chroma control, support of TFS, possibly octupoles
- Strong kicker impedances: safety margin by a TFS needed

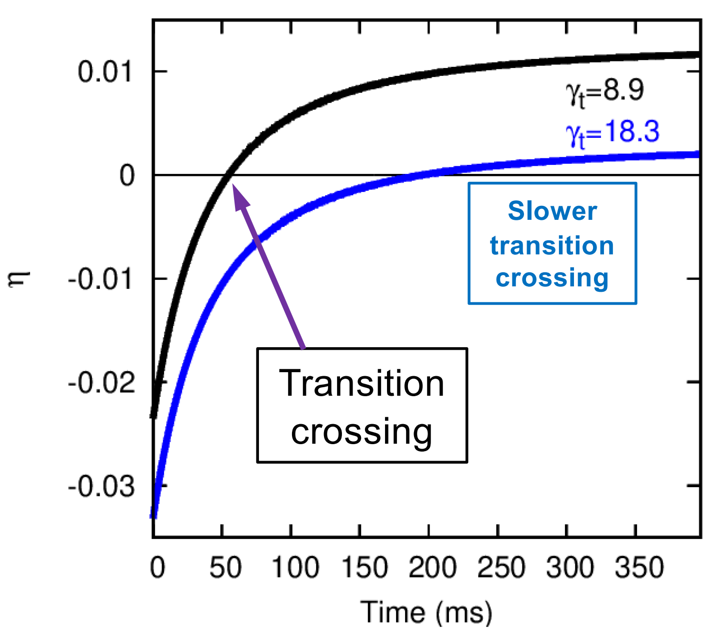
Longitudinal stability:

- Bunches are stable.
- Longitudinal Feedback system at the start version.

SIS100 proton cycle

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

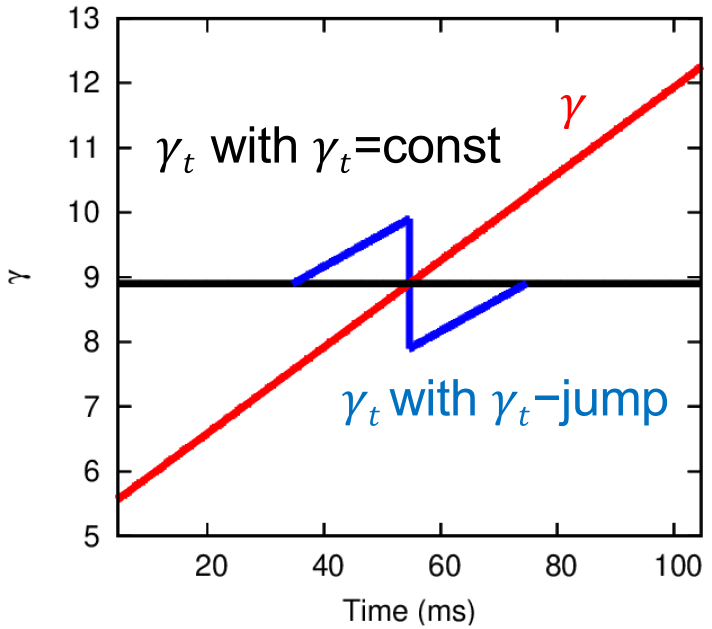
The black lines: the nominal scenario with the possibility of a γ_t−jump

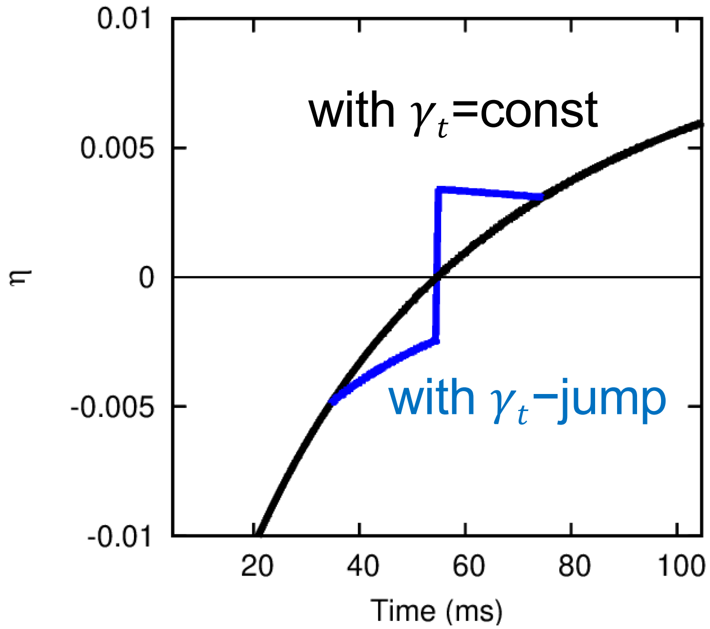
The blue lines: the heavy-ion type lattice for comparison (no γ_t−jump possible)

SIS100 proton cycle

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.

SIS100 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

Mitigation in SIS100

The full-cycle considerations for SIS100 strengthen the need for a TFS.

The 21st Machine Advisory Committee (May 2019) recommended to include a TFS (transverse feedback system) into the start version of SIS100

Mitigation in SIS100

TFS for SIS100: physics-based specs

- Present assumption: the function as an injection error damper is not needed
- Bandwidth: 25kHz → 30MHz
- Multi-sampling along the bunch (even k=0 has intra-bunch oscillations)
- Sampling rate 16 ns.
- Instability damping time: 100 turns, $\Delta\theta$ = 16 μrad
- Adjustable gain, lattice parameters, …, for different cycles
- 1 or 2 dedicated warm BPM.

We are enthusiastic to learn from the TFS experience at CERN PS, RAL ISIS, Fermilab Booster