Optimization of Beam Accumulation in NICA Booster Synchrotron

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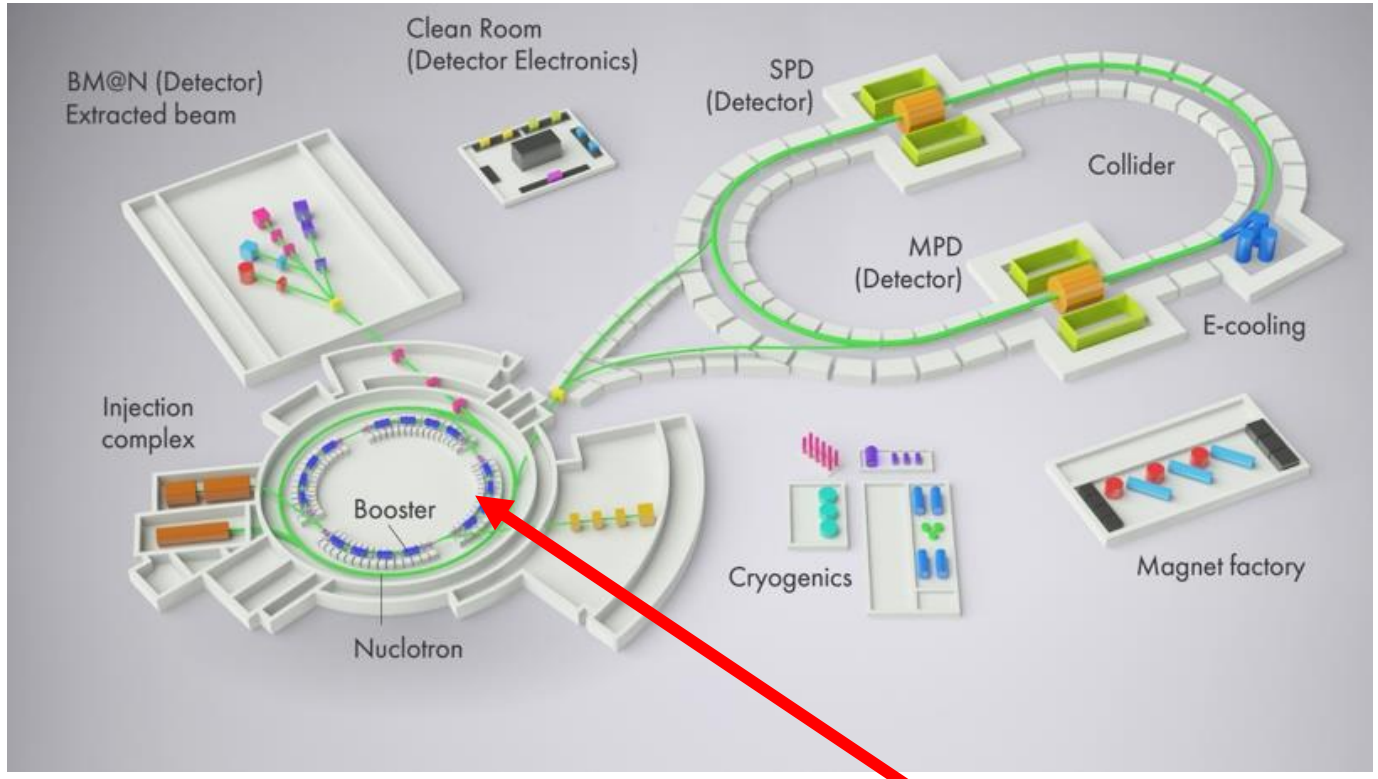
NICA Booster

- **Intensity** of beam is **crucial** for colliders at each stage;
- NICA Booster is the first stage accelerator after linac;
- Tasks of NICA Booster [1]:
  - Accumulate ions (up to 10x);
  - Accelerate intense beam to 578 MeV/nucleon;
  - … and transport them to Nuclotron accelerator



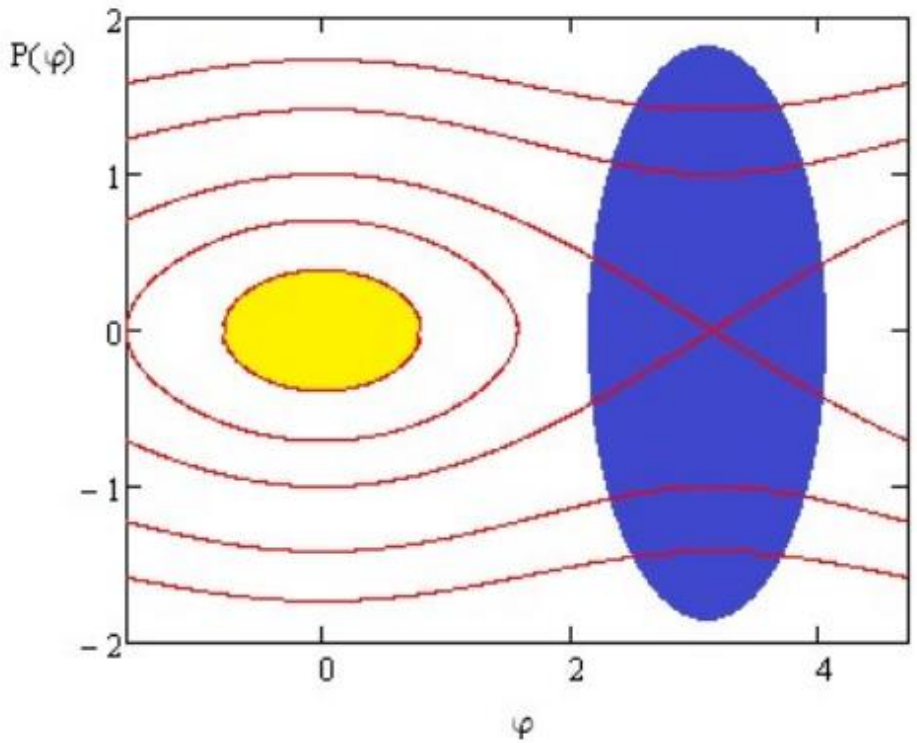
- Electron cooling reduces phase volume of beam
- Crucial issue: limit of intensity due to large ion beam space charge

[1] NICA Booster: a new-generation superconducting synchrotron. DOI: 10.3367/UFNe.2021.12.039138

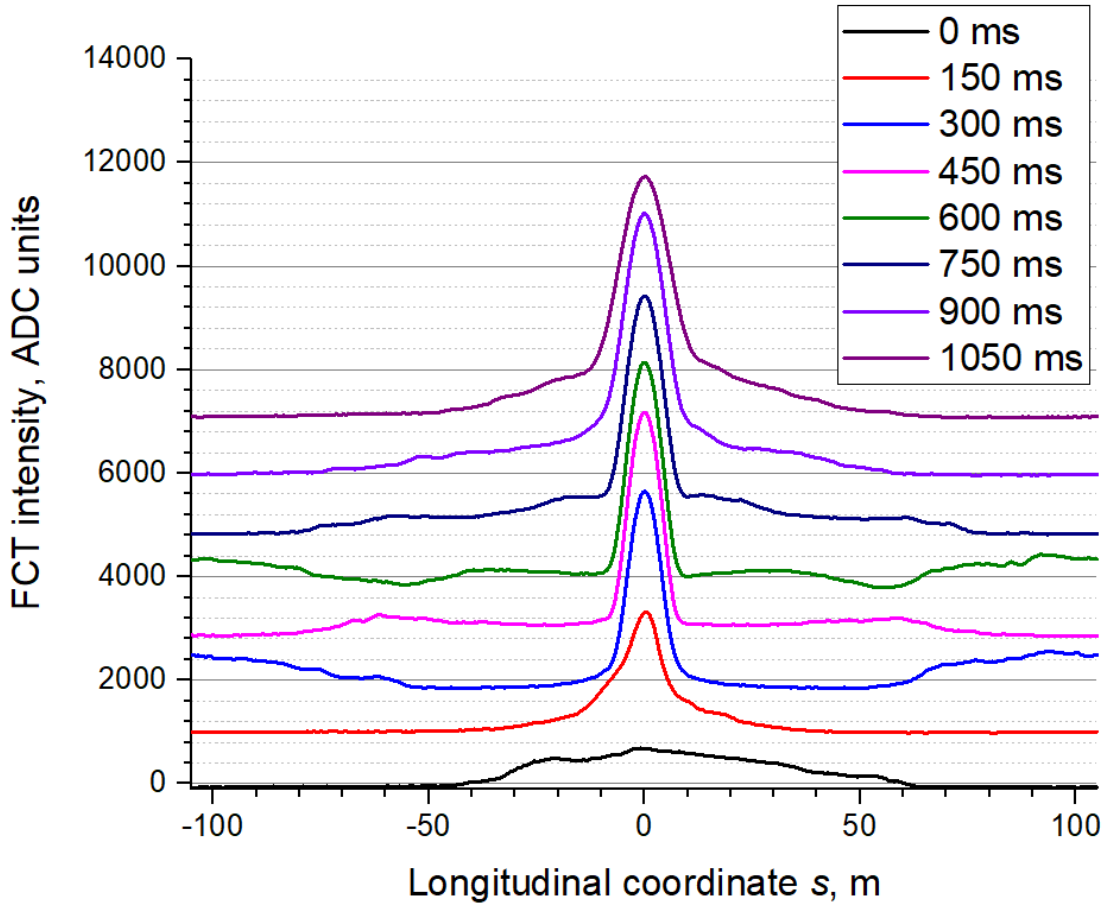
Plans and expectations

- Collider Run 1: achieved accumulation of $\mathbf{9.2 \cdot 10^7}$ $^{124}Xe^{26+}$ ions, extracted to Nuclotron $\mathbf{7 \cdot 10^7}$ ions;
- Space charge tune shift excites high-order even resonances, leading to losses;
- Task for Collider Run 2: luminosity of $\mathbf{10^{25}}$ $cm^{-2}s^{-1}$;
- We must provide maximum possible intensity in rings before Collider with minimum losses;
- Expected intensity in Booster is $\mathbf{2 \ldots 3 \cdot 10^8}$ $^{124}Xe^{26+}$ ions;
- How should we tune Booster to maximize accumulation and decrease losses during acceleration?
  - Tune electron cooling current;
  - Adjust working point;
  - Minimize space charge induced tune shift

Longitudinal accumulation



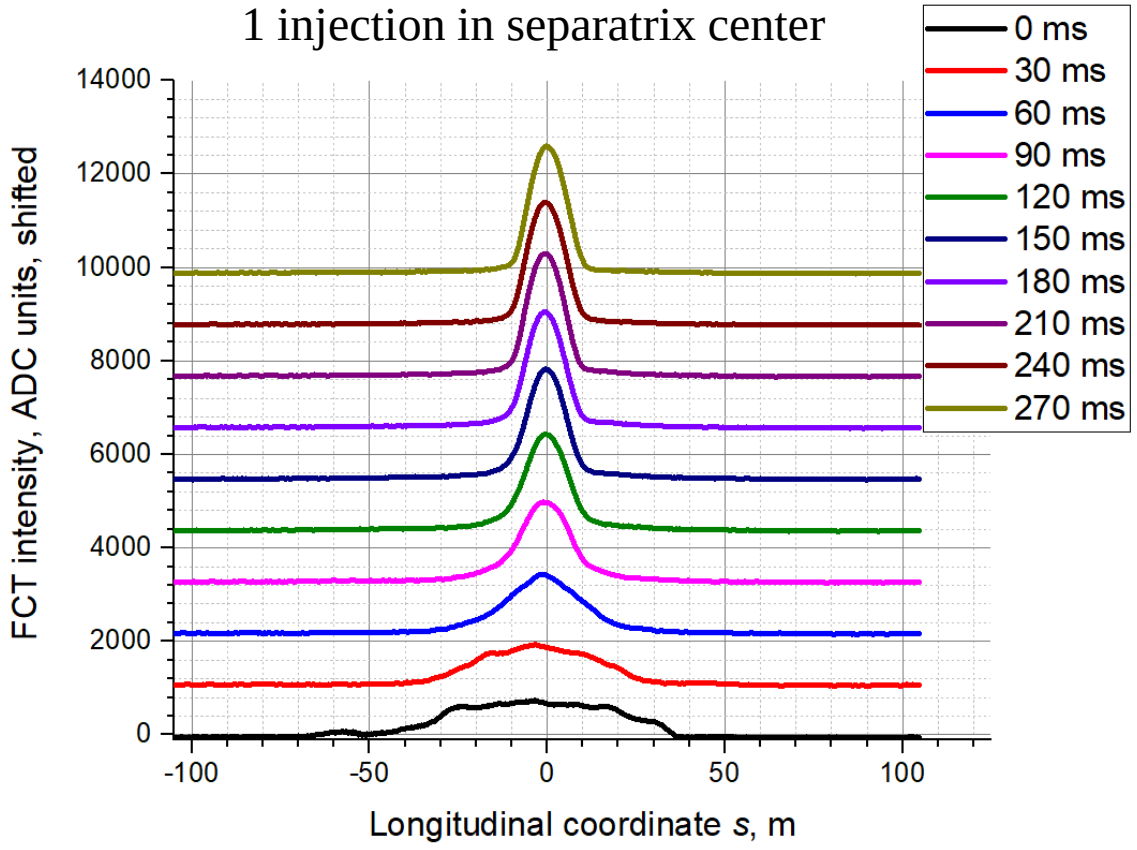
Scheme of beam accumulation in longitudinal phase space



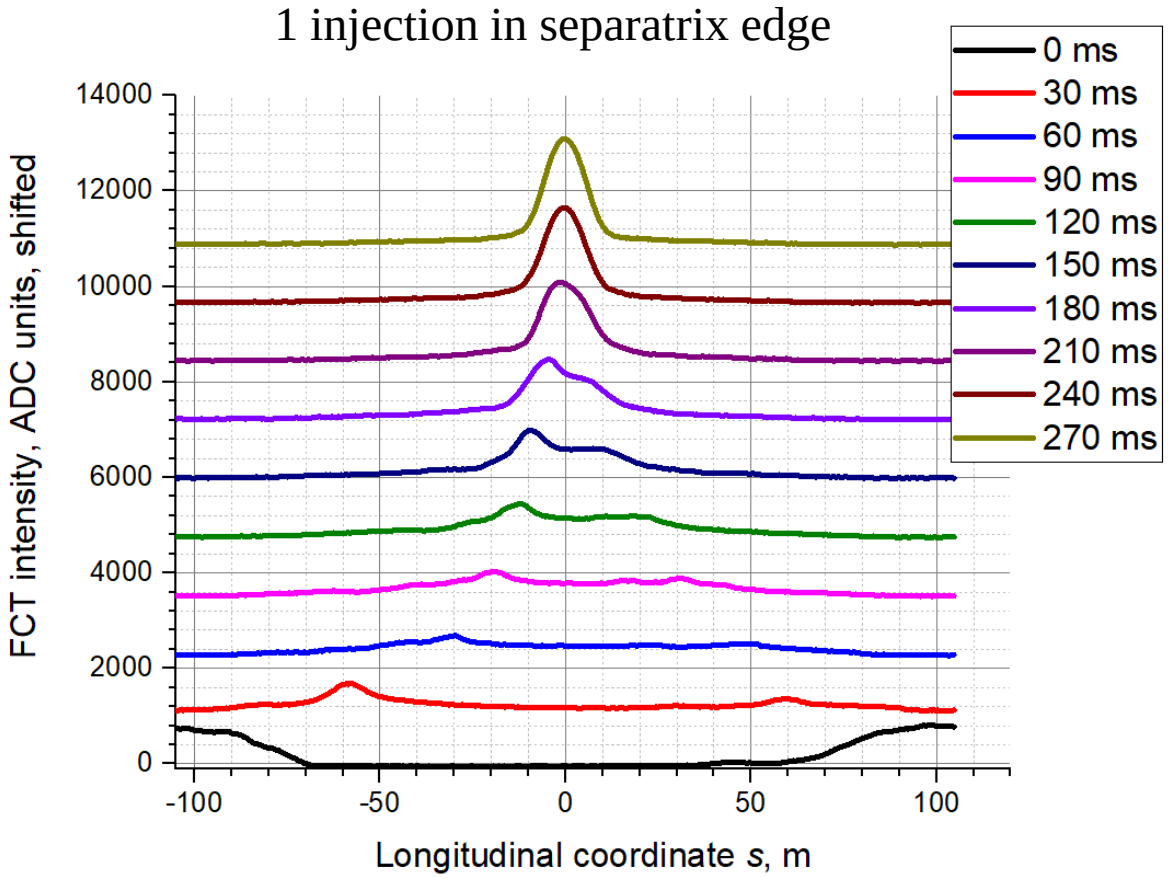
Accumulation of three subsequent injections
FCT = fast current transformer

- At linac exit: $\mathbf{2..2.3 \cdot 10^7}$ ions;
- Ion source KRION-6T: 10 injections per cycle;
- Optimistically we accumulate $\mathbf{2.2 \cdot 10^8}$ $^{124}Xe^{26+}$ ions;
- 1st injection is in separatrix center, next are in edge.

Injection in center and edge



Cooling of beam injected in separatrix center

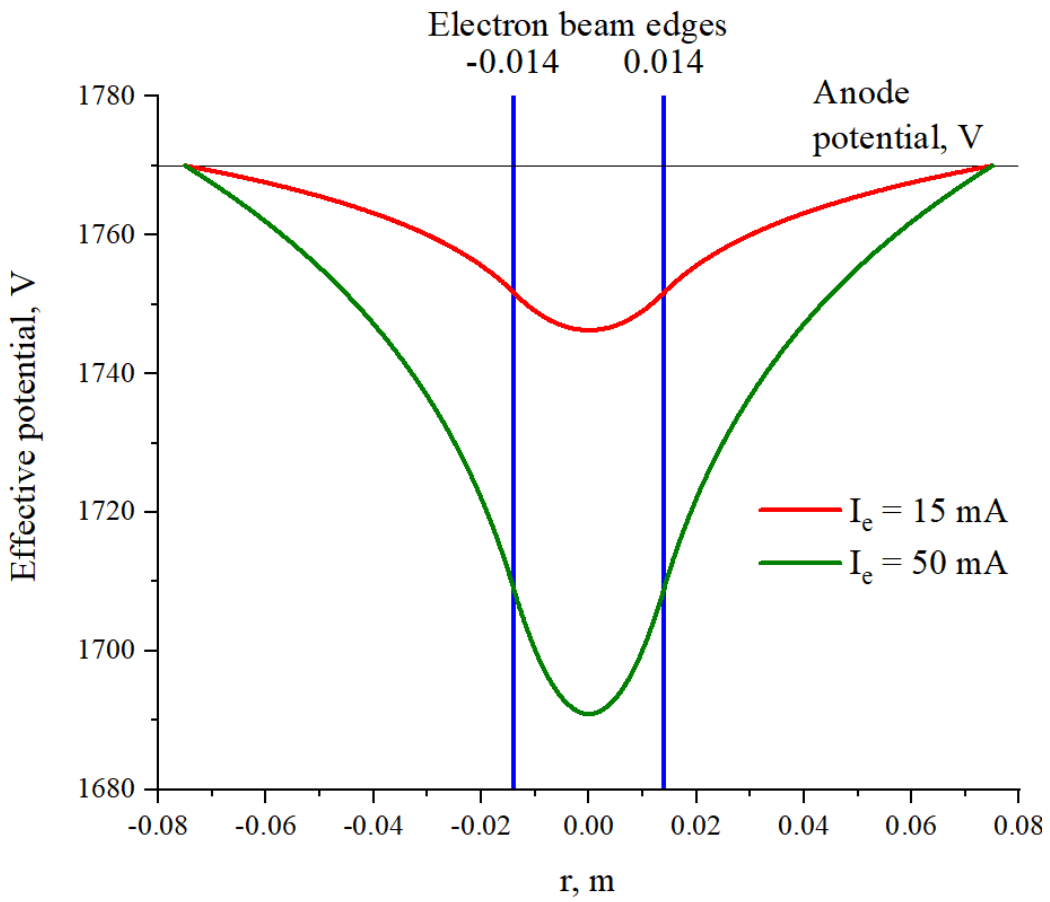


Cooling of beam injected in separatrix edge

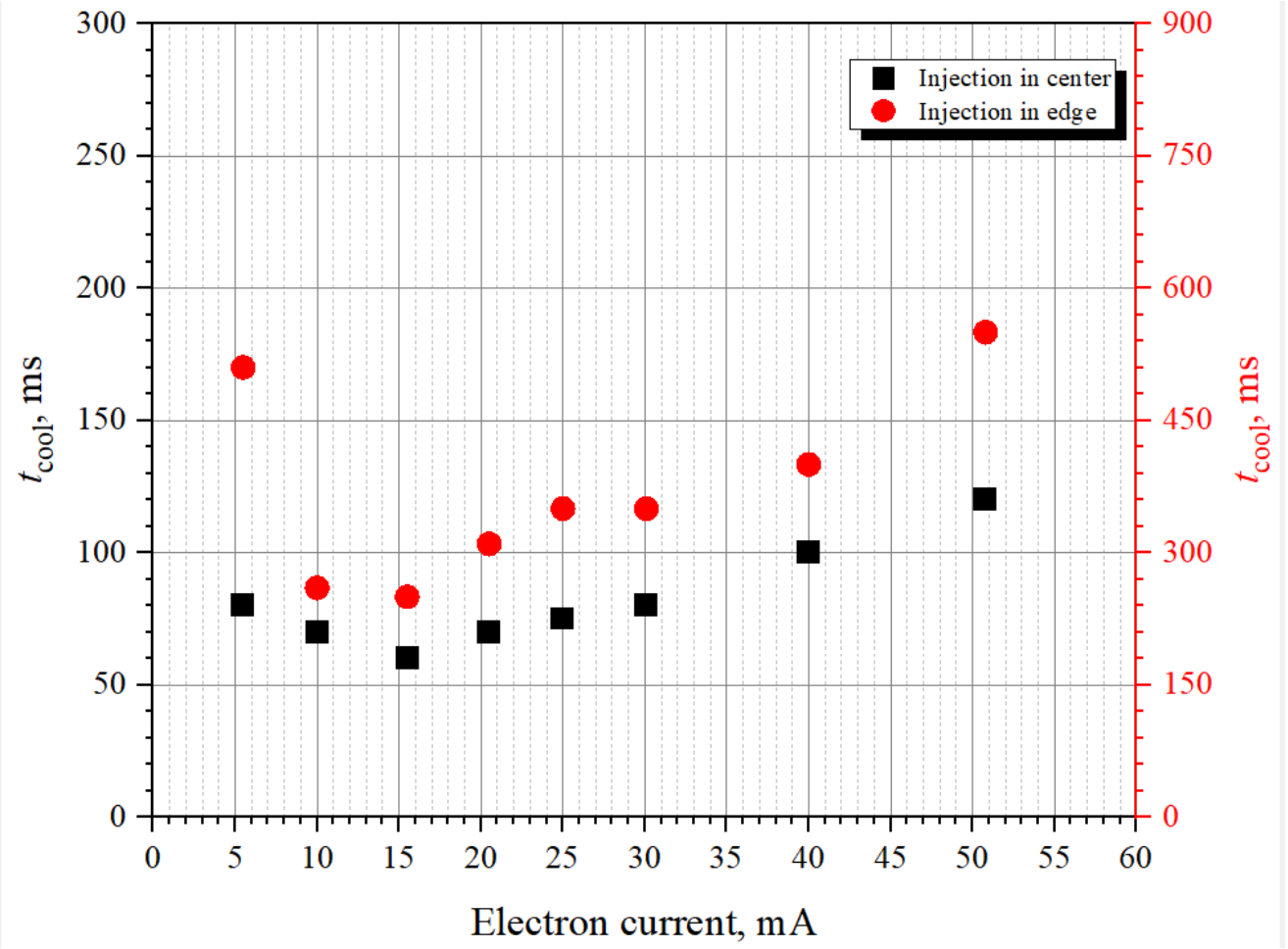
Characteristic time ~ 70-100 ms

Characteristic time ~ 250 ms
Beam is fully grouped by ~ 400 ms

Tuning of electron cooling current



Blue lines are electron beam edges
Potential sagging affects electrons energy



Cooling time dependence on electron beam current for ion beam injected in separatrix center and edge.

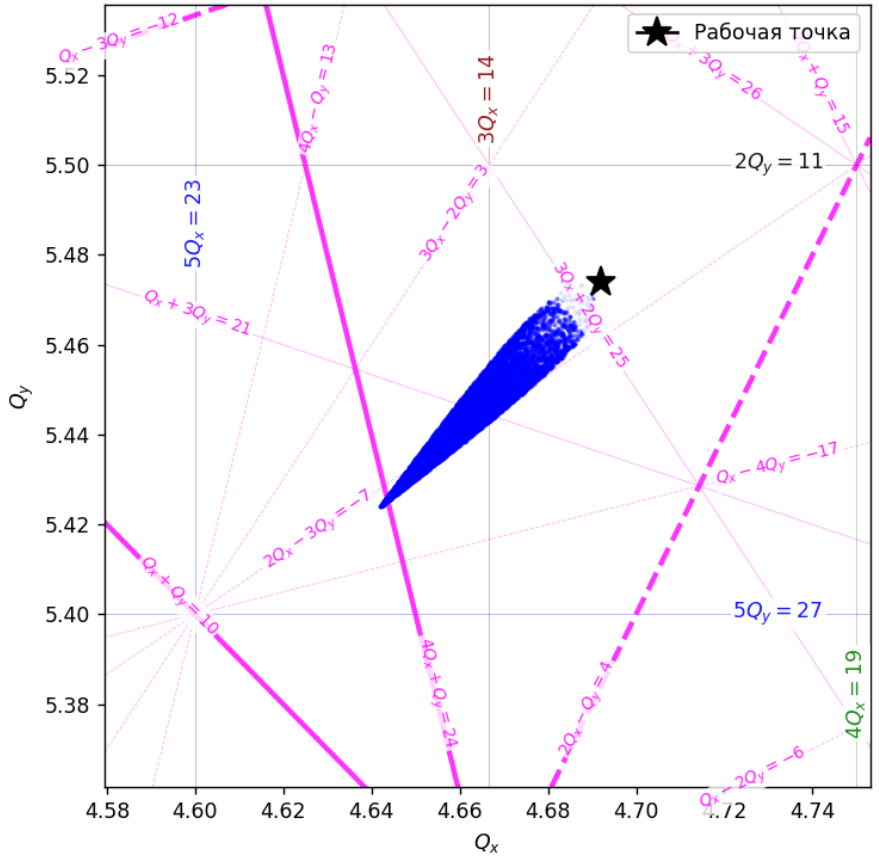
Accumulation in Oct. 2025

10x injections. Qx=4.692 Qy=5.474.

Achieved by proper orbit correction, chromaticity correction. At this working point, there is low dispersion near cooling system (D_x = 0.15 m). No acceleration was done. 250 ms between injections.



Maximum accumulation of 9.2×10^7 ions



Accumulation in Jan. 2026

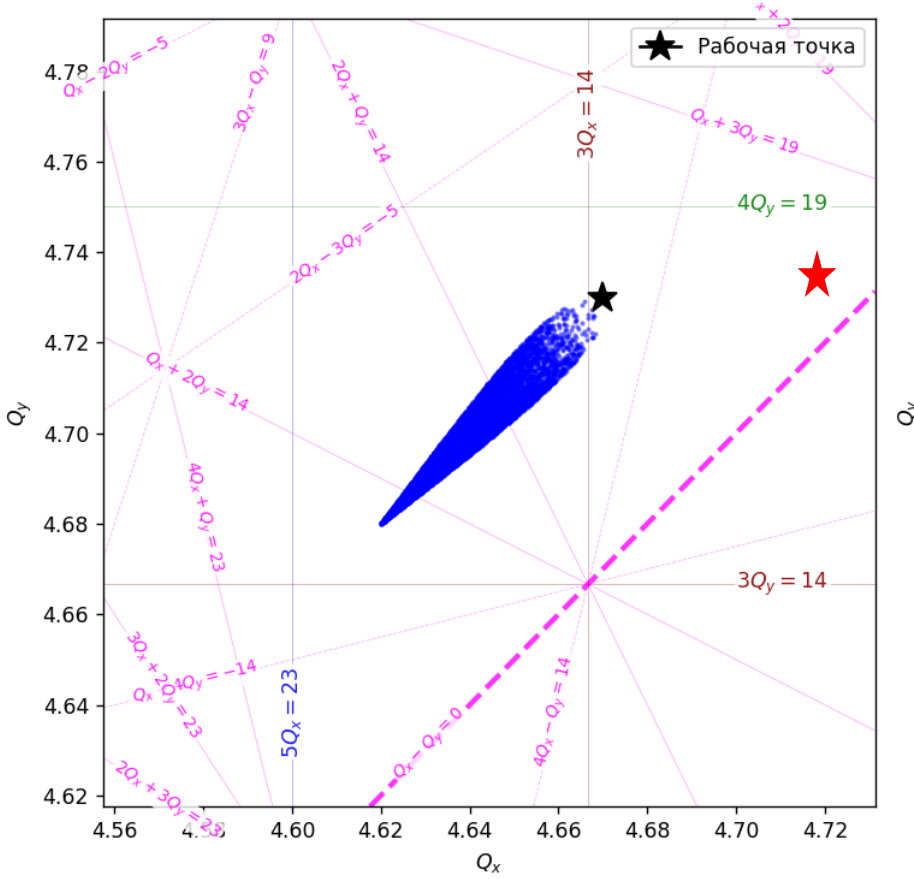
3x injections. Qx=4.67 Qy=4.73

Accumulated beam was accelerated without losses up to 200 MeV/nucleon and transported to Nuclotron.
Dispersion near cooling system D_x = 0.22 m. 250 ms between injections.

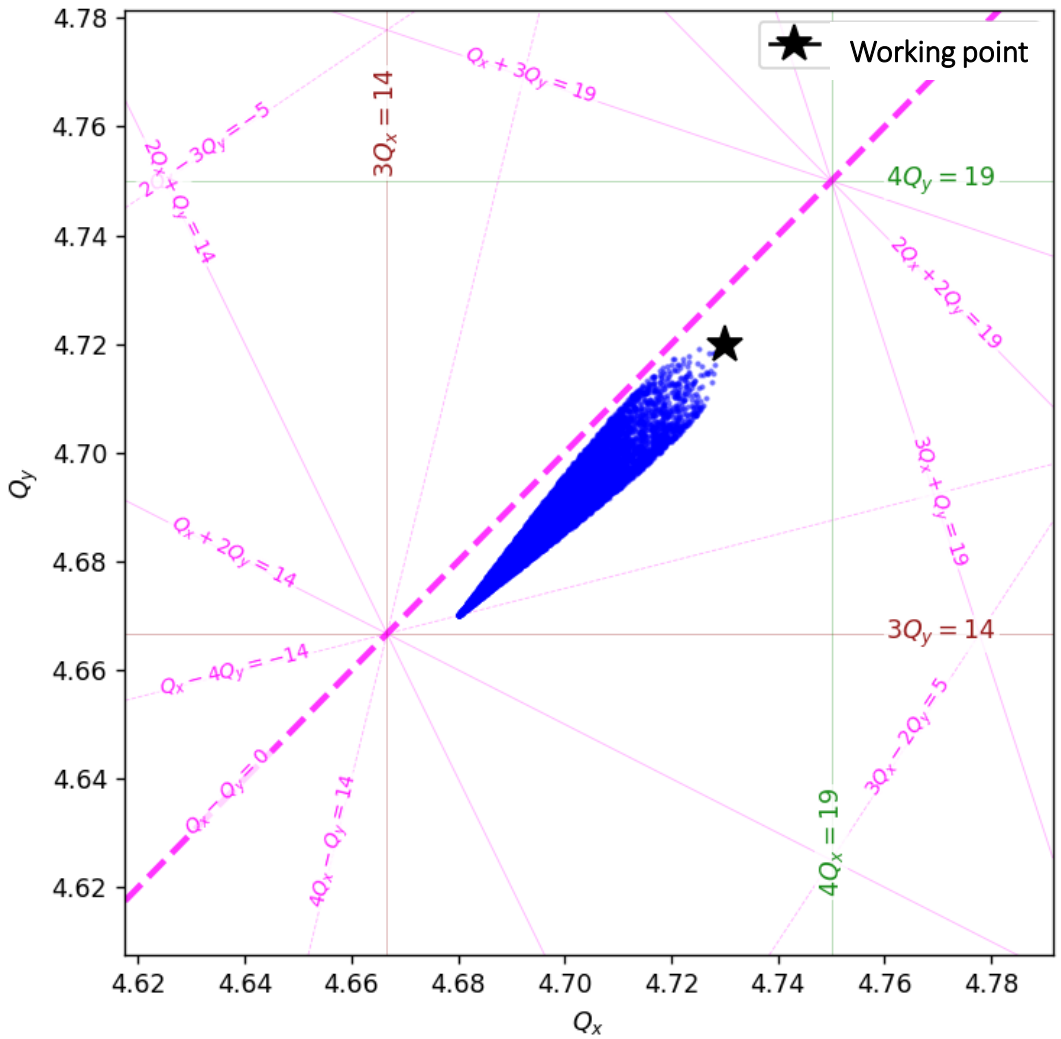
We want Qx=4.72, Qy=4.74 or Qx=4.74, Qy=4.72, but coupling induced by solenoid prevents us from it.



Maximum accumulation of 7×10^7 ions

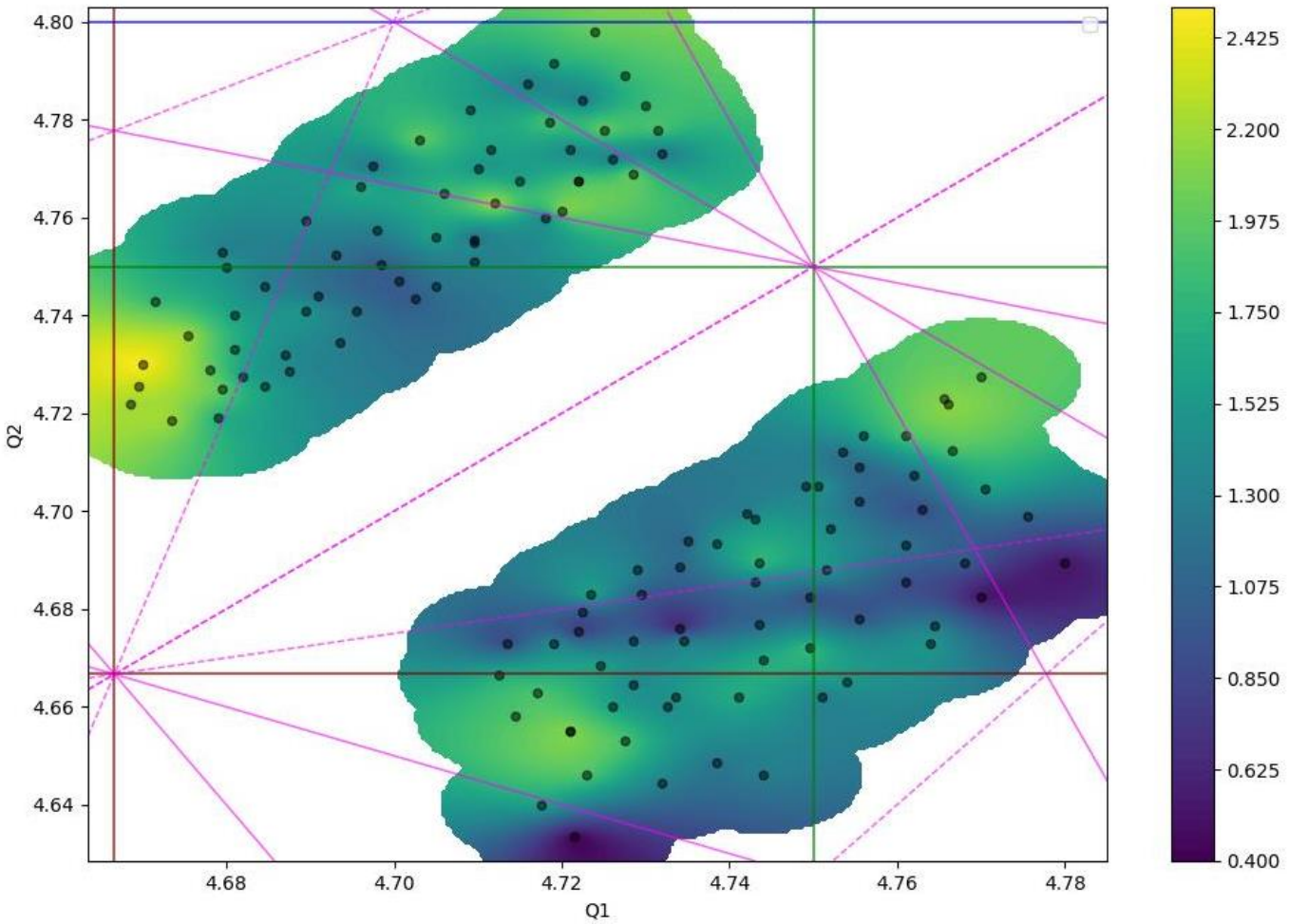


Накопление: выбор рабочей точки



Desired working point 4.74/4.72 with coupling correction…

Measured betatron frequencies



… and the results of working point scan (solenoid field is 0.07 Tesla)

Ion beam space charge induced tune shift

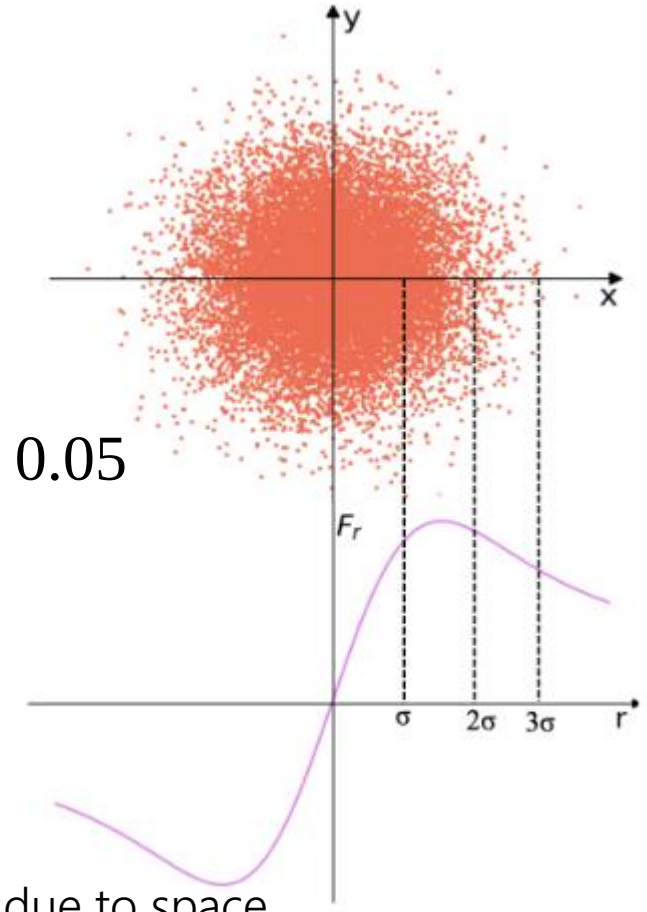
For bunched beam with Gaussian distribution:

$$\Delta Q_x = -\frac{N r_0}{\pi \beta^2 \gamma^3 B_f} \frac{2}{4\varepsilon_x^{1\sigma}\left(1+\frac{\sqrt{\varepsilon_y^{1\sigma}\langle\beta_y\rangle}}{\sqrt{\varepsilon_x^{1\sigma}\langle\beta_x\rangle}}\right)} \qquad r_0 = \frac{1}{4\pi\varepsilon_0}\frac{Z^2 e^2}{A m_0 c^2} \qquad B_f = \frac{I_{avg}}{I_{peak}}$$

Maximum allowed tune shift, without crossing resonances: $|\Delta Q_{x,y}| \leq 0.05$

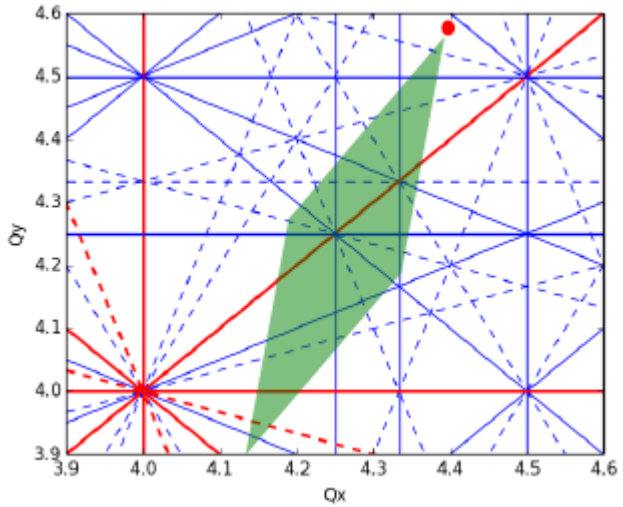
Thus we accumulate N_{max} particles:

$$N_{max} = |\Delta Q_x| \frac{\pi \beta^2 \gamma^3 B_f}{r_0} \cdot \frac{4\varepsilon_x^{1\sigma}\left(1+\sqrt{\varepsilon_y^{1\sigma}\langle\beta_y\rangle}/\sqrt{\varepsilon_x^{1\sigma}\langle\beta_x\rangle}\right)}{2}$$



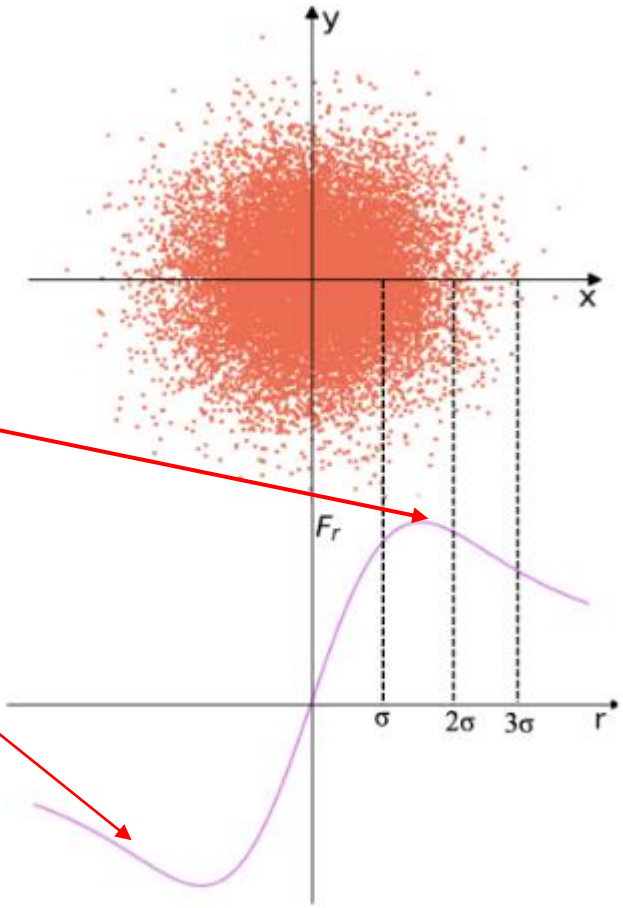
Force acting on ions due to space charge field

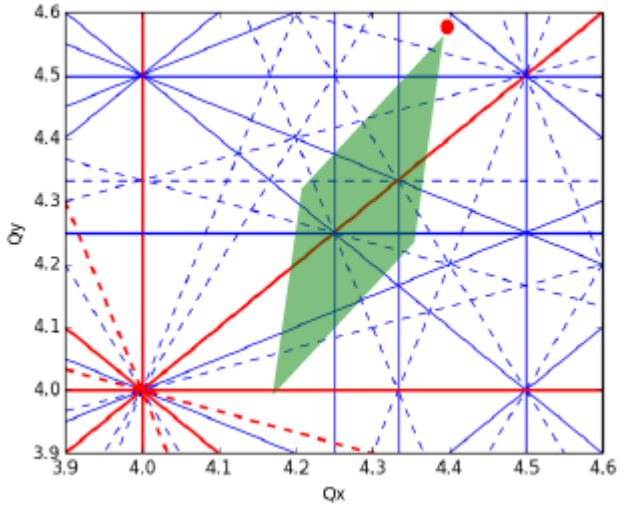
Particle loss mechanism

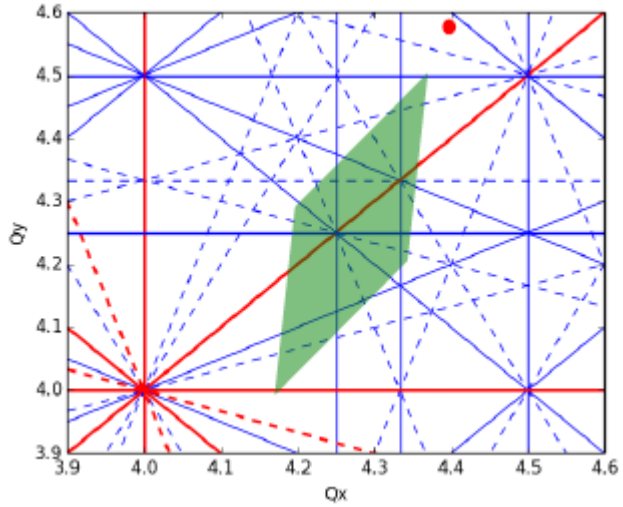


… on low order resonances

… on high-order resonances due to non-linearity of force on beam tails





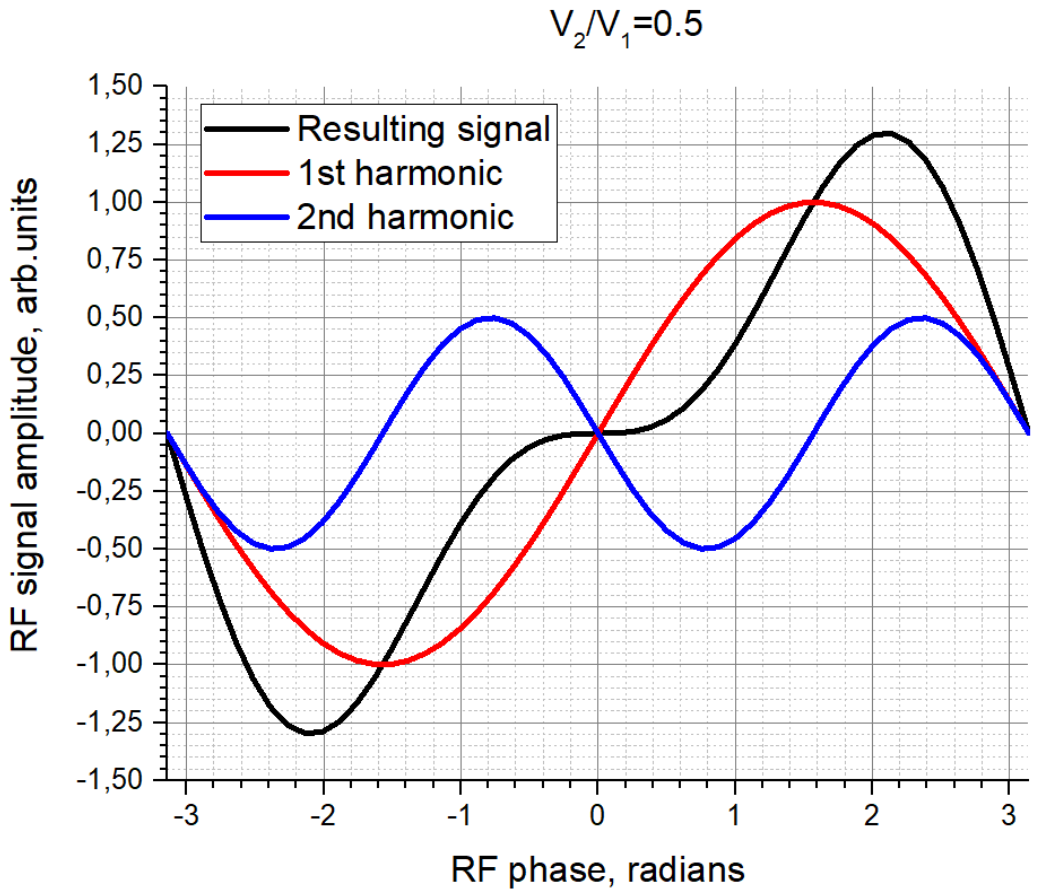


How can we achieve better accumulation?

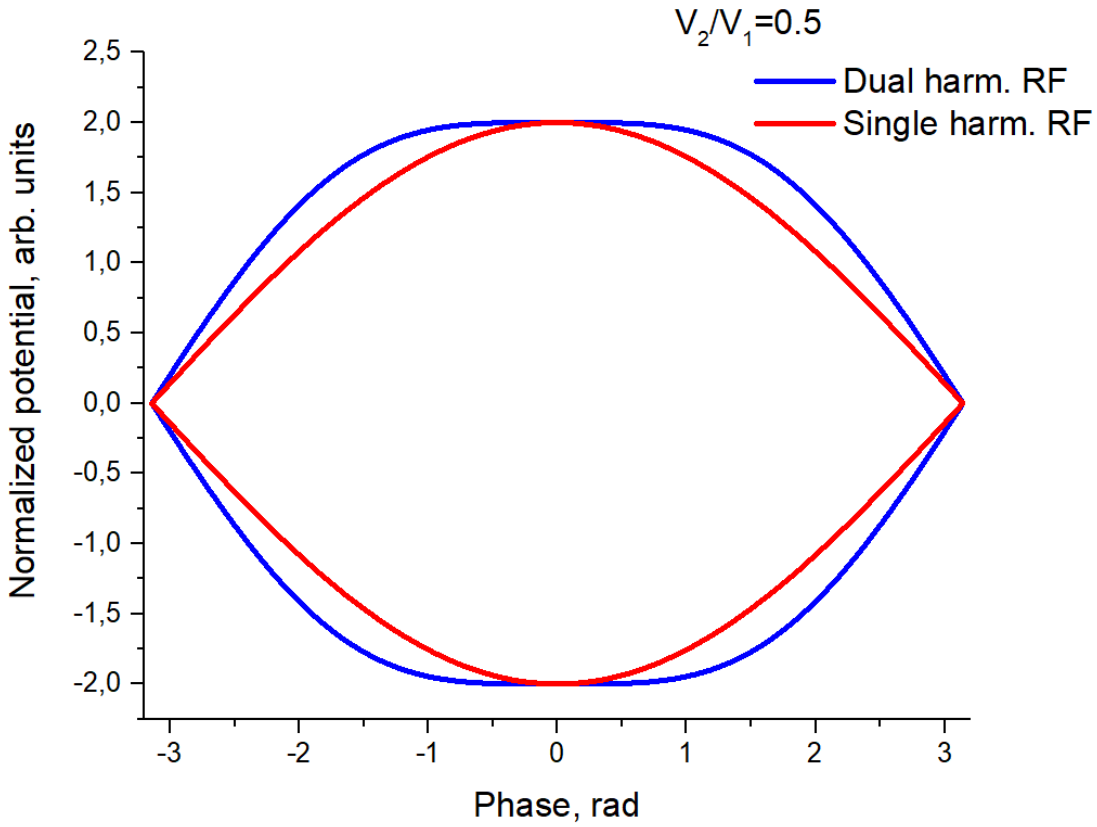
- Without change of accelerator design $\beta, \gamma, r_0, \langle\beta\rangle$ are constants;
- Normalized transverse emittance $\varepsilon_x^{1\sigma} \cdot \beta\gamma$ should not exceed 0.3 mm·mrad;
- Maximum transverse emittance must satisfy $3\sigma_{x,y} \leq r_e$, where r_e is electron beam radius, so 99% of ion beam is under cooling;
- Multipole correctors can be used to reduce strength of high-order even resonances.
- $|\Delta Q|$ is chosen as required maximum tune shift and considered to be constant.
- Thus, we are allowed to vary beam bunching factor: $\boldsymbol{B_f = I_{avg}/I_{peak}}$.

$$N_{max} = |\Delta Q_x| \frac{\pi\beta^2\gamma^3 B_f}{r_0} \cdot \frac{4\varepsilon_x^{1\sigma}\left(1+\sqrt{\varepsilon_y^{1\sigma}\langle\beta_y\rangle}/\sqrt{\varepsilon_x^{1\sigma}\langle\beta_x\rangle}\right)}{2}$$

Beam bunching and acceleration with two harmonics



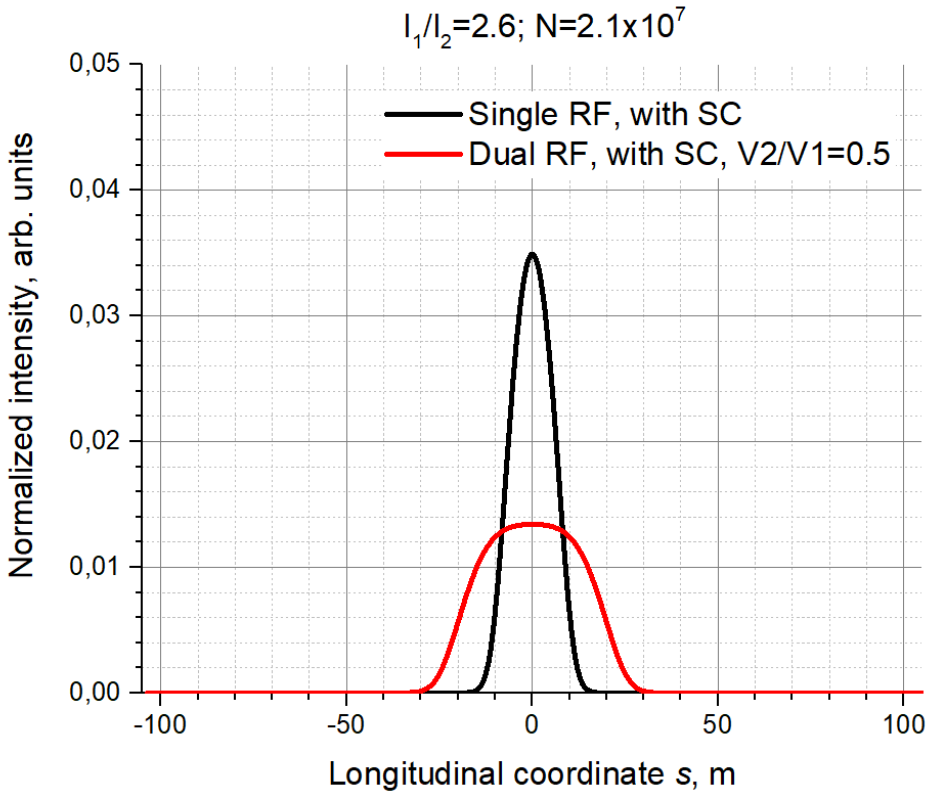
Double-harmonic RF system signal formation



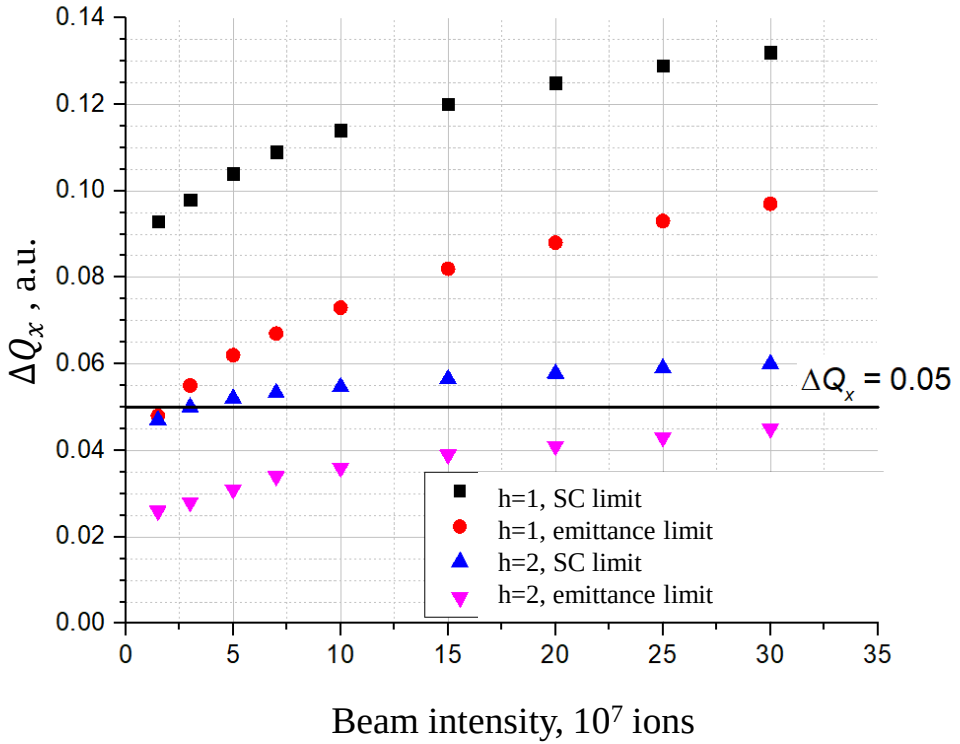
Comparison of single and double RF separatrices. Note that double RF produces broader separatrix

Betatron tune shift for beam accumulation

- SC limit: beam is cooled to equilibrium between injections (**large phase density is bad!**);
- Emittance limit: beam is not cooled to equilibrium, its transverse size must fit into electron beam ($3\sigma_{x,y} \leq r_e$).



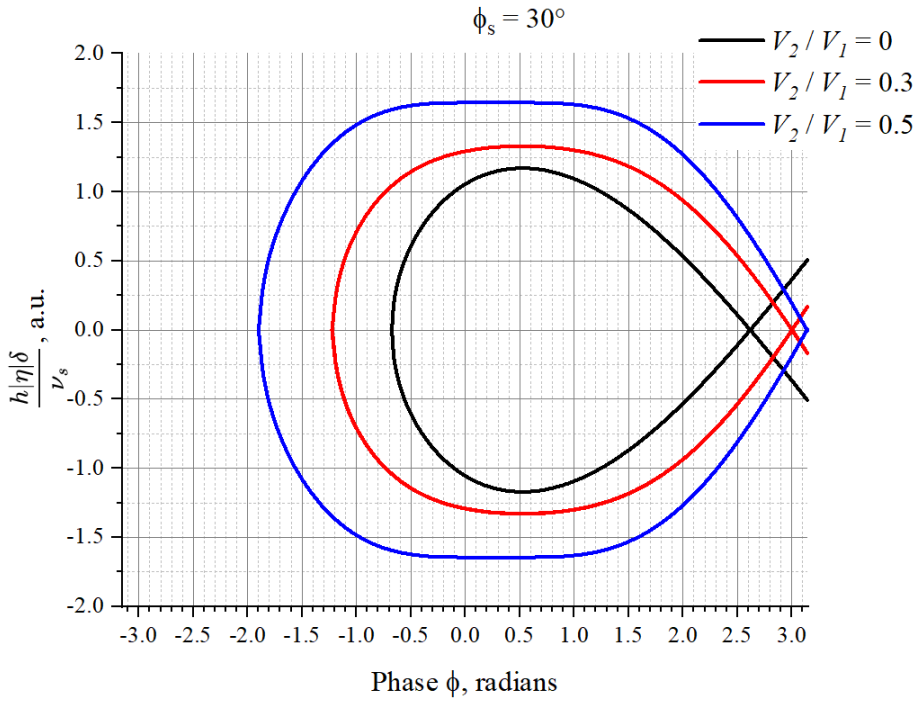
Comparison of self-consistent distributions for single and double RF



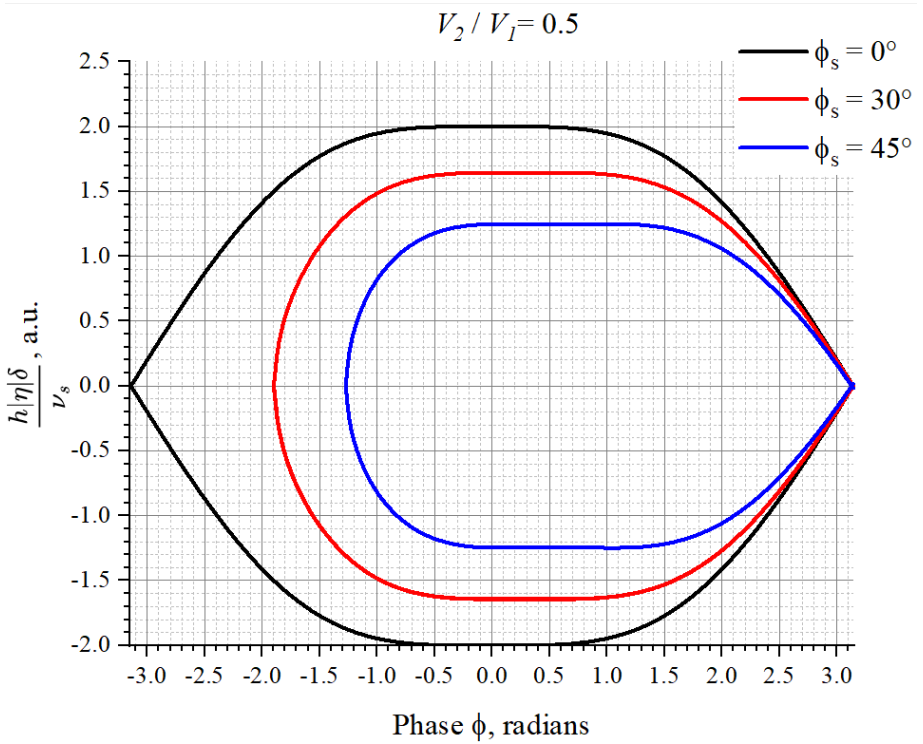
ΔQ_x for beams of different intensities and different RF shapes

Bunching and acceleration with two harmonics

- Adiabatic acceleration is necessary;
- Ratio of amplitudes V_2/V_1 should be steadily decreasing to prevent growth of $\Delta Q_{x.y}$.
- Flat and wide potential well is necessary for largest $B_f = I_{avg}/I_{peak}$



Separatrices for different harmonic amplitudes ratios



Separatrices for different synchronous phases

When do we turn 2nd harmonic off?

Tune shift should be decreasing during acceleration. $\Delta Q_x \propto \frac{1}{\beta^2 \gamma^3 B_f}$

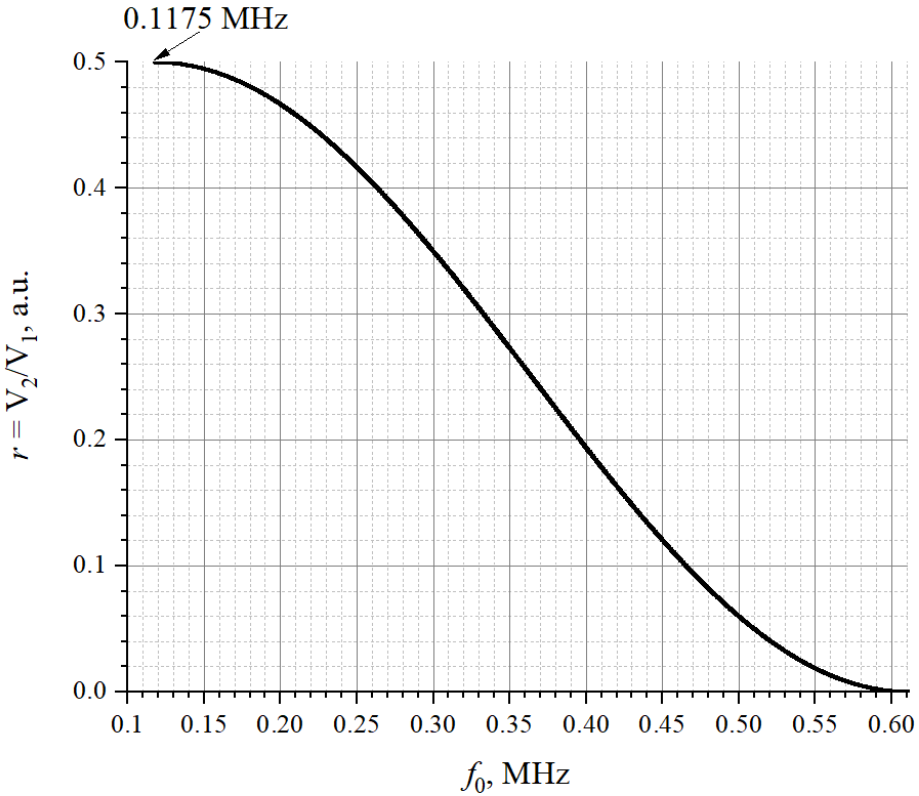
But bunching factor grows!

We introduce $r(f) = V_2 / V_1$

a dependence steady enough to prevent growth of B_f

$$r \cdot \frac{1}{2}\left[\cos\left(\pi \cdot \frac{f - f_0}{f_{fin} - f_0}\right) + 1\right]$$

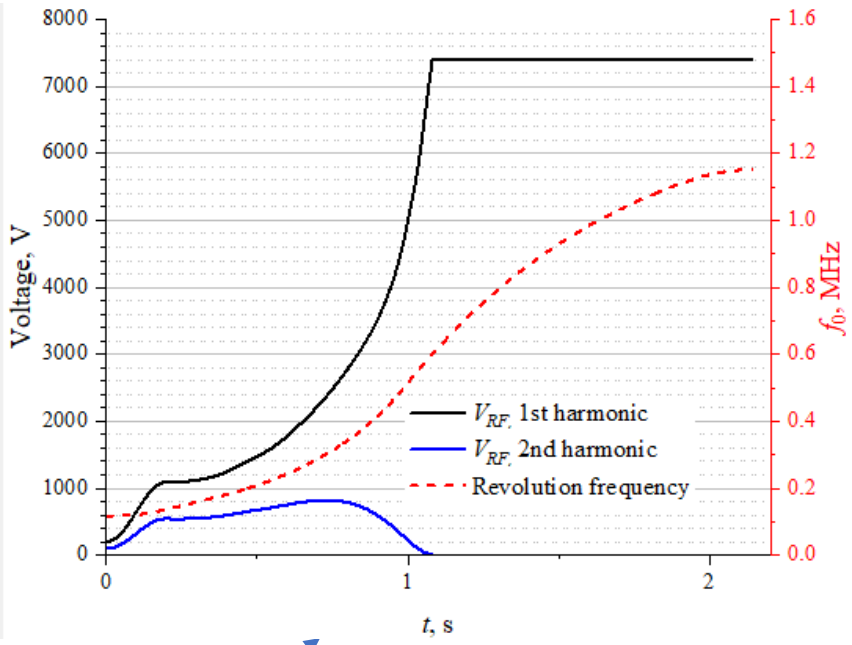
where f_0, f_{fin} are beam circulation frequencies at injection energy and at 100 MeV/nucleon correspondingly.



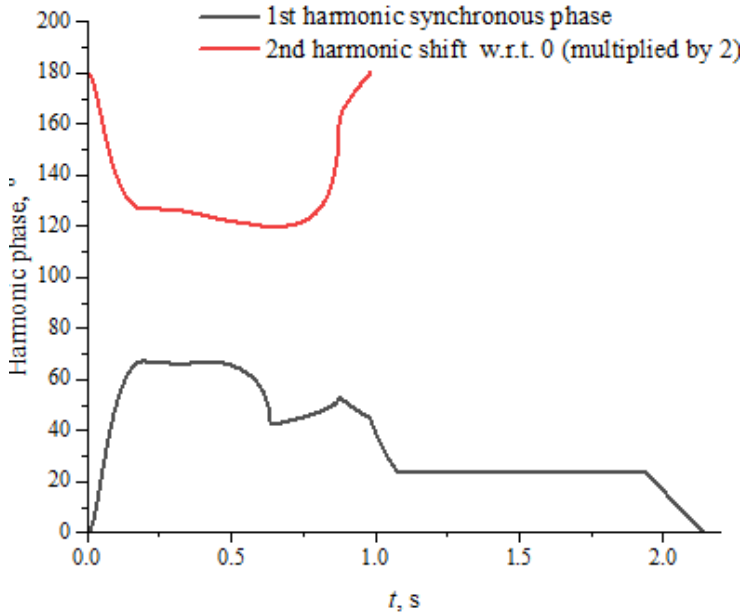
That's how the ratio V_2/V_1 is changed during acceleration

Acceleration law table

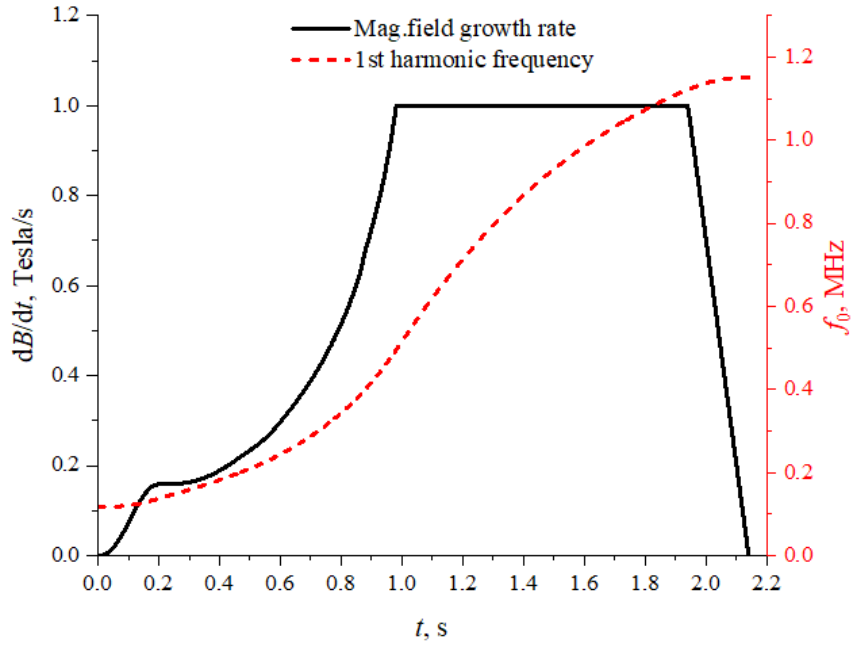
- Based on the algorithm that matches acceleration voltage with magnetic field growth rate, adapted for two RF harmonics



RF harmonics amplitudes



Phases of harmonics



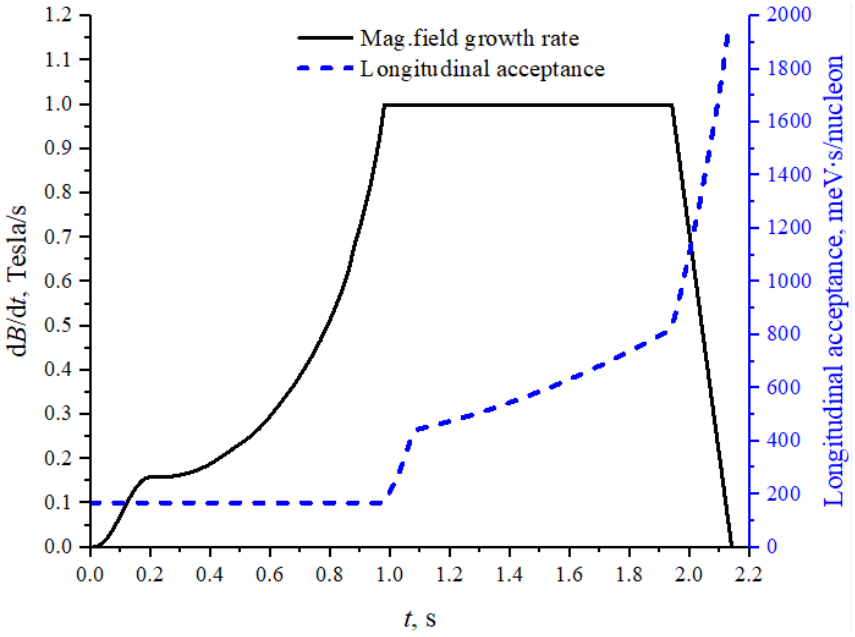
1st harmonic frequency

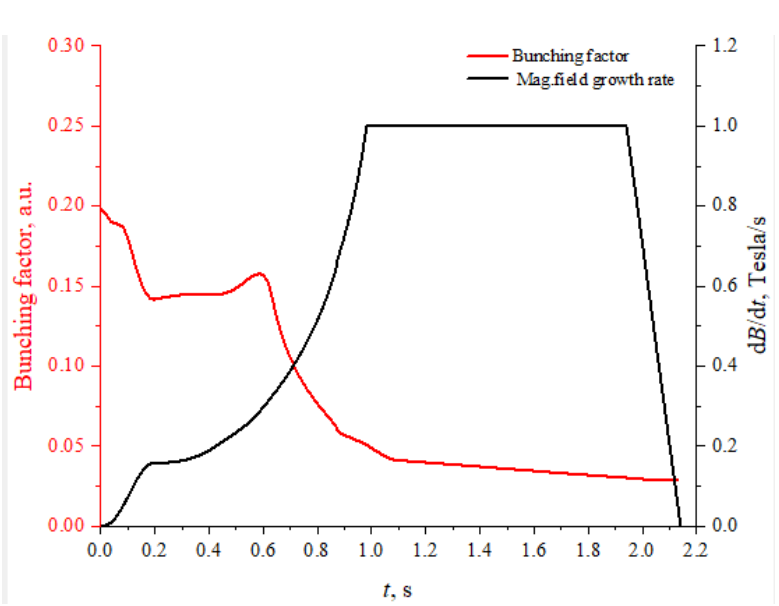
Tune shifts during acceleration for $3 \cdot 10^8$ ions

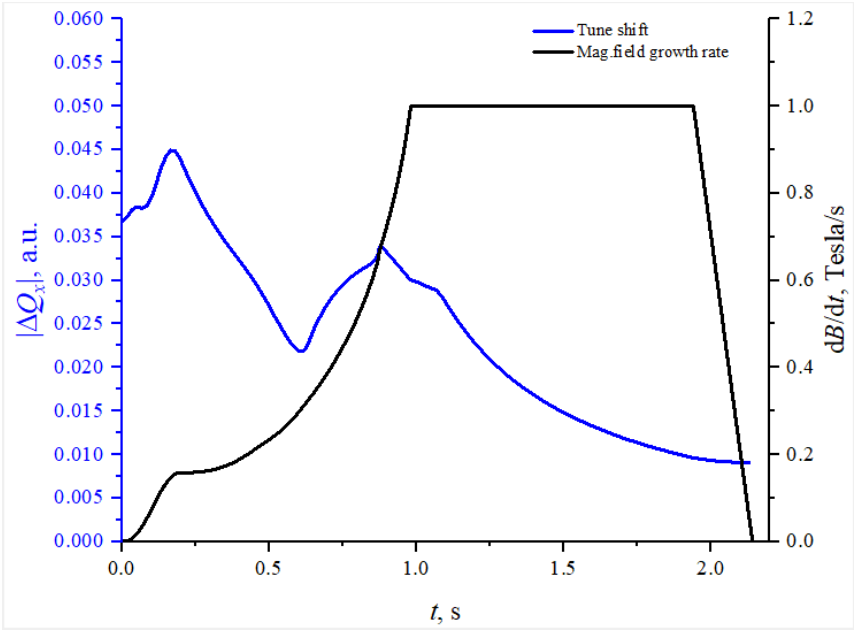
Peak current rises during acceleration;

It is safe to turn 2nd harmonic off only at energies about 100 MeV/nucleon

We do not exceed tune shift of 0.05 anytime during acceleration







RF harmonics amplitudes

Bunching factor

Tune shift

Conclusions

- Acceleration tuning is iterative process;
- Working point selection, orbit correction, coupling correction, cooling tuning.
- Electron cooling may work with longer times, as it may be profitable;
- For example, detuning of transverse cooling or “hollow beam”;
- Use of 2nd harmonic increases bunching factor 2-3x times, thus increasing limit of maximum accumulation;
- We plan to check in ongoing run the accumulation and acceleration with 2 harmonics with orbit, chromaticity and coupling correction.
- The acceleration must preserve 2nd harmonic as long as it is profitable.
- Larger beam extraction energy leads to small geometric emittance and decreases loss in beam transportation channel.

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