BEAM STABILITY ISSUES IN IOTA

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ABSTRACT

Electron and proton beam stability issues for the IOTA ring are considered. No need for a special impedance reduction is concluded.

ELECTRONS

Stability analysis is performed for a single bunch of $\sigma_z = 2\text{cm}$ rms length with $N = 1\cdot 10^9$ electrons at 150 MeV. The impedance is estimated as given by 10 full gaps in the vacuum chamber of radius $b = 2.5\text{cm}$ [1,2]. The single gap impedance can be estimated as a broadband resonator with the shunt impedance $R_s \simeq Z_0/(\pi b)$ and the quality factor $Q \simeq 1$. The total estimated weighted impedance $Z\beta$ is presented in Fig. 1, assuming the average beta-function $\beta = 3\text{m}$.

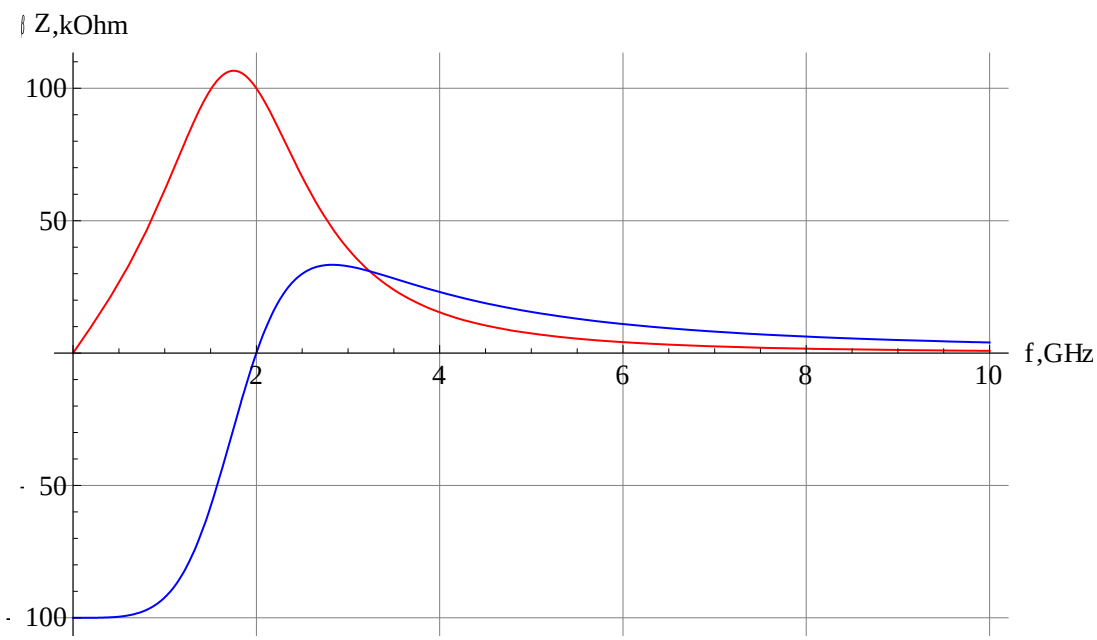

Fig. 1: Transverse impedance model of IOTA, real (red) and imaginary (blue) parts.

Growth rates and coherent tune shifts can be estimated within the hollow-beam (air-bag) approximation, see Eq. (6.188) of Ref. [3]. For the first three head-tail modes, the results are presented in Fig. 2. According to this figure, the tune shifts are limited as $\text{Im}(dQ_x) \le 5\cdot 10^{-6}$; $|\text{Re}(dQ_x)| \le 5\cdot 10^{-6}$.

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To stabilize that beam, the required rms tune spread is estimated as $\Delta Q \simeq 2 \cdot 10^{-6}$. Since the mode tunes could be both positively and negatively shifted, both positive and negative incoherent tune shifts have to be provided by the machine nonlinearity. In other words, the tune shifts from the own degree of freedom and from another one must be of the opposite signs, while each of them has to exceed by absolute value the specified limit, $2 \cdot 10^{-6}$, which is at least an order of magnitude below the foreseen nonlinearity [2]. The required tune spread scales linearly with the bunch intensity.

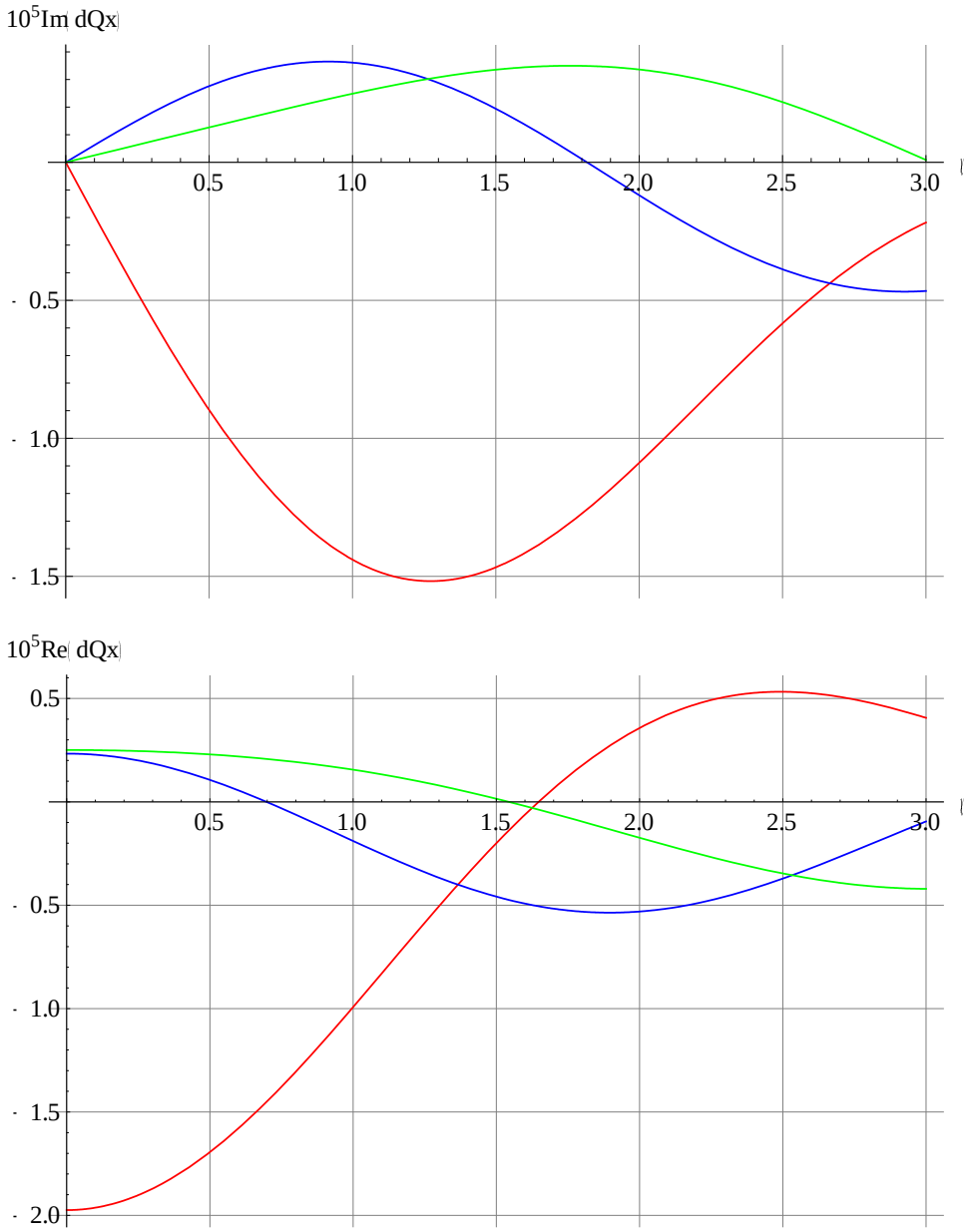

Fig. 2: Imaginary (top) and real (bottom) parts of the coherent tune shift for the first three head-tail modes versus the head-tail phase.

PROTONS

Stability analysis is performed for a coasting beam of 1.4μs length with $N = 2.5 \cdot 10^{10}$ protons at 2.5MeV, corresponding to the relativistic factor $\beta = 0.073$. For transversely Gaussian distribution with unnormalized rms emittance $\varepsilon = 2\mu\text{m}$ this leads to the space charge tune shift $\Delta Q_{sc} = 0.3$ at the beam axis. The resistive wall impedance $Z(\omega)$ is given by a well-known formula

$$Z = -i \frac{Z_0 \beta C}{\pi \kappa b^3}; \;\; \kappa^2 \equiv -4\pi i \omega \sigma / c^2 \; .$$

The weighted impedances $Z\beta_x$, $Z\beta_y$ are presented in Fig. 1, assuming the average beta-functions $\beta_x = 3\text{m}$, $\beta_y = 2\text{m}$, the ring of a circumference $C = 35$ m, the aperture radius $b = 2.5$ cm, and the conductivity $\sigma = 1.3 \cdot 10^{16} \text{s}^{-1}$ (stainless steel). The skin depth at the revolution frequency is small enough, $\delta = 0.6\text{mm}$, so the thick wall approximation used for the impedance computation is justified. Since the beam is non-relativistic, the real part of the geometrical impedance is zero, while its imaginary part is negligible in comparison with the space charge contribution.

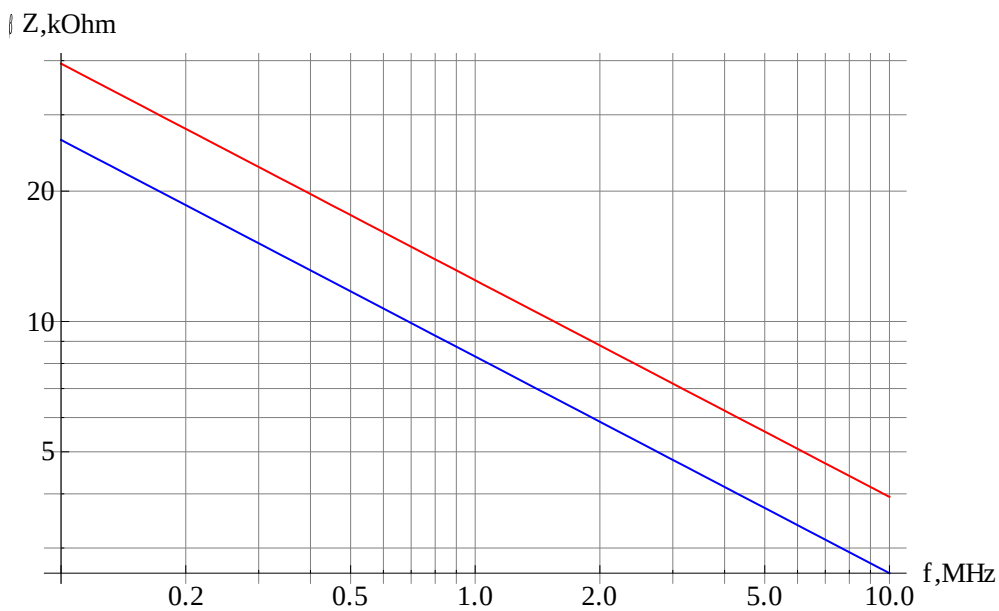

Fig. 1: Transverse impedances of IOTA (real parts): horizontal (red) and vertical (blue).

The coherent tune shift of a coasting beam can be computed as [3]

$$\Delta Q_x = -i \frac{N r_0 \beta_x}{C \beta} \frac{Z}{Z_0} \; ,$$

where $Z_0 = 4\pi / c = 377\text{Ohm}$, and r_0 is the classical proton radius. According to Ref. [4], the threshold value of the space charge tune shift $\Delta Q_{\text{sc,th}}$ is only logarithmically sensitive to the coherent tune shift:

$$\Delta Q_{\text{sc,th}} \approx 1.7\sigma_Q \ln\left(\frac{\Delta Q_{\text{sc,th}}}{\text{Im}\,\Delta Q_x}\right)$$

Here $\sigma_Q = \left[\xi - (n + Q_x)\right](\delta p / p)_{\text{rms}}$ is effective chromatic tune spread for the chromaticity ξ and harmonic number n. For $(\delta p / p)_{rms} = 0.0037$, a reasonably low chromaticity $\xi = 3$ and the most unstable harmonic $n + Q_x \approx 0$, this yields $\Delta Q_x \cong 10^{-6}$ and $\Delta Q_{\text{sc,th}} = 0.3$.

Another option to operate the protons is to bunch them. It is foreseen a possibility to grow RF voltage up to 1kV at harmonic number $h = 8$, leading to the synchrotron tune $Q_s = 0.02$ [2]. Assuming the same phase space density as for the described above coasting beam, this leads to rms bunch length 1.6m and rms momentum spread $\sigma_{dp/p} = 0.0057$. The threshold value of the space charge tune shift at the bunch centroid $\Delta Q_{\max}$ was estimated at Ref. [5] as

$$\Delta Q_{\max} \cong 2Q_s k^{4/3}\left(\frac{Q_s}{\text{Im}\,Q_x}\right)^{1/3},$$

where $k \cong \xi\sigma_{dp/p} / Q_s$ is a number of the most unstable head-tail mode and $\text{Im}\,Q_x$ is the growth rate of this mode. Due to a weak dependence of this value on the growth rate, it can be estimated as the same as for the coasting beam. Assuming $k = 1$, this yields $\Delta Q_{\max} \cong 1$. If needed, the bunched beam could be intentionally made unstable with lower synchrotron tune or positive chromaticity, where the most unstable mode is $k = 0$, so there is no intrinsic Landau damping.

SUMMARY

Both electron and proton beam in the IOTA ring can be stable with the designed vacuum chamber. However, if needed for special studies, the proton beam can intentionally destabilized by means of low or positive chromaticity.

REFERENCES

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