BEAM ORBIT AND POWER CONVERTER STABILITY AT THE CR

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Abstract

This paper introduces the sources of the beam orbit instability and as a consequence power converter requirements for the Collector Ring (CR) operated at the magnetic rigidity of Bρ=13 Tm. It presents a summary of the different factors causing beam orbit instability, which leads to an uncertainty of the precision mass measurements. The requirements to the power converters have been addressed, with reference to have good properties of the mass measurements in the CR operated in the isochronous mode.

INTRODUCTION

The CR is a dedicated storage ring designed to operate in three different optical modes [1]. One of this optics is adjusted specially to provide the best performance of the stochastic pre-cooling of antiprotons at the energy of 3 GeV. The second optics is used for pre-cooling of secondary particles, rare isotopes at a fixed kinetic energy of 740 MeV/u. The third optics is so called "isochronous mode", which gives the possibility to perform mass measurements of short-lived secondary rare isotope beams coming from the Super-FRS [2]. Mainly due to the fact that high mass resolving power is required in the isochronous mode one has a strong demand on the stability of power converters. There are two main causes for a reduction of the accuracy of mass measurements or the beam orbit stability at the CR. First, due to a ripple of the magnetic field in the bending magnets the precession of mass measurements varies from one moment to another. It also reduces the accuracy of a mass calibration. Second, displacement of the different magnetic elements and an instability of an environment temperature cause optical alignment distortions and the energy (mass) drift.

One has to provide the stability of power supplies in the frequency region from one Hz to tens of kHz. Such a system should suppress the ripple to the order of 10^{-6}. Also it is important to avoid the slow drift of the magnetic field. The CR magnet power supplies are designed to operate stably up to the maximum beam rigidity of 13 Tm.

FACTORS CAUSING BEAM ORBIT INSTABILITY

The accuracy of mass measurements depends on the frequency measurements, which is defined by the path length L passed by particles turn by turn in a ring [3]

$$\frac{\Delta(m/q)}{m/q} = -\frac{1}{\alpha_p}\frac{\Delta f}{f} = \frac{1}{\alpha_p}\frac{\Delta L}{L} \quad . \tag{1}$$

α_p is the momentum compaction factor of the ring. Obviously, the influence of a particular element on the path length is defined by deflecting angle and optical properties of the storage ring. Let us define the value of that influence. The change of the deflecting angle of the magnet $\Delta\theta_i$ with a fixed energy causes a closed orbit distortion and changes the path length of the orbit. From the simple analytical description the path length variation in a ring can be written in the general form as [3]

$$\Delta L = \Delta\theta_i D_i \ , \tag{2}$$

where the D_i is the dispersion function. The revolution frequency f is the constant in the ring and thus a circumference L too. Using formula (1) the relation between the path length change and the uncertainty of the mass measurement can be written:

$$\frac{\Delta(m/q)}{m/q} = \delta_m = \frac{1}{\alpha_p}\frac{\Delta\theta_i D_i}{L} \quad . \tag{3}$$

The relative change of the deflecting angle $\Delta\theta_i/\theta$ is proportional to the relative change of the magnetic field $\Delta B/B$ (which is directly related to the current instability of the power supplies ($\Delta I/I$)). All 24 CR bending magnets with the bending angle θ will cause an uncertainty δ_m in the mass definition:

$$\delta_m = \frac{2\pi}{\alpha_p}\frac{\Delta I}{I}\frac{\langle D_h\rangle}{L} \, . \tag{4}$$

For the CR the average dispersion function $<D_h>$ in the isochronous mode operation is 7 m, the bending angle of the dipole magnet is 0.261 rad, α_p=0.29. Using formula (4) one can estimate that a current instability of the order 10^{-6} relates to a relative mass uncertainty of 6.9×10^{-7}. The formula (4) can be used only in the cases when the revolution frequency f is less then $2f_{rip}N_{turn}$ (f_{rip} is a ripple frequency, N_{turn} is the number of turns to be performed for a mass measurement). If $f > 2f_{rip}N_{turn}$ then one has to use

$$\delta_m = \frac{2\pi}{\alpha_p}\frac{\Delta I}{I}\frac{\langle D_i\rangle}{L}\frac{2f_{rip}N_{turn}}{f} \tag{5}$$

Formula (3) can be rewritten in such a way, which gives us a relation to estimate the possible mass error measurements depending on the closed orbit distortion. Using random orbit distortion Δx_{rms} and averaging over a random betatron phases of the closed orbit we obtain:

$$\delta_{rms} = \langle\Delta x\rangle_{rms}\frac{2\sqrt{2}\sin(\pi Q_h)}{\alpha_p L}\frac{\langle D_h\rangle}{\langle\beta_h\rangle} \, , \tag{6}$$

where Q_h is the horizontal betatron tune, $<\beta_h>$ is the average betatron amplitude function. In the CR Q_h=4.42 and $<\beta_x>$=25 m. The closed orbit disturbance of 0.2 mm relates to the mass shift of 1.66×10^{-6}.

The changing of the ring circumference L can have a seasonal depending character. The relative circumference variation of 10^{-5} gives a change of the mass calibration of 3.4×10^{-5}. The estimations show that maximum daily mass shift with respect to temperature delays of seasonal change is about 6×10^{-6}. There are also possible displacements of the elements because of fast (daily) temperature change.

NUMERICAL CALCULATIONS

The formulae (4) and (5) give the required power stability in the case that there are no any factors reducing the mass resolving power. In ref.[4] it was shown that the optical properties of a ring and the initial beam emittance give an essential contribution in the reduction of the mass resolving power. A path length spread within the beam due to the finite beam emittances ε_{xy} is derived by [4]

$$\frac{\Delta L}{L}=\frac{1}{4}\left(\varepsilon_x\langle\gamma_x\rangle+\varepsilon_y\langle\gamma_y\rangle+\frac{\varepsilon_x}{\rho^2}\langle\beta_x\rangle\right), \qquad (7)$$

where $<\gamma_{xy}>$ are the average Twiss parameters, ρ – the bending radius of a dipole magnet. On can see that the mass resolving power has a limit, which is defined by the ring optics functions $\gamma_{x,y}$, $\beta_{x,y}$ and the beam emittance $\varepsilon_{x,y}$. According to the formulae (1) and (7) for the CR (where $<\gamma_{xy}>$ =0.55) to have an uncertainty of the mass measurements of less than 10^{-5} the beam emittance should be less then 10π mm·mrad.

To study the influence of a power converter instability on the mass resolving power in combination with magnet field errors we perform numerical Monte-Carlo simulations. As a start condition we consider 100 particles within a beam emittance of 10π mm·mrad. To calculate the frequency spectrum we track all particles in the ring over 100 and 1000 turns with field errors given in ref.[5]. The simulations show that the field errors of the magnets have little influence on the increase of frequency spread if a nonlinear correction is applied. In Fig.1 the frequency spectra are shown for three cases: 1 – no field errors (ΔB/B=0); 2 - integrated field errors $\Delta B/B=1\text{x}10^{-4}$, and 3: $\Delta B/B=3\text{x}10^{-4}$. One can see that an increase of the field errors by a factor of 3 increases slightly the width of the spectra. The contribution of the field errors to the uncertainty of the mass definition is about $7\text{x}10^{-7}$.

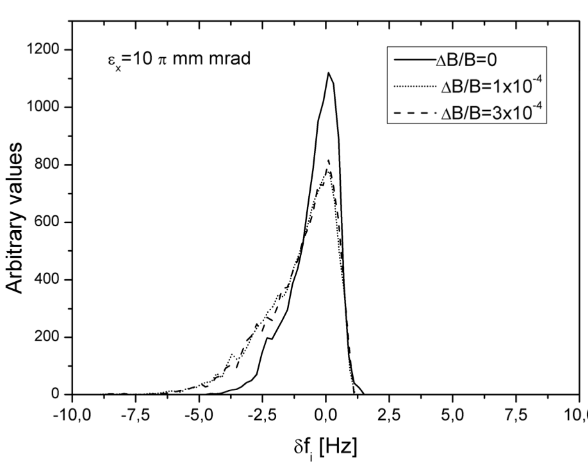

Figure 1: The frequency spectra for 100 particles tracked over 100 turns within the beam emittance of 10π mm·mrad. There is no ripple of the power supplies.

The numerical simulations show a strong dependence of the frequency spectra on a current variation of the power converters. If a ripple is presented, the spectra are deformed depending on the frequency of the ripple. In Fig.2 the frequency spectra at different values of relative current instability $\delta_i = \Delta I/I$ is shown. In the numerical simulations the instability δ_i corresponds to 2σ of a Gauss distribution. For example if $\delta_i=10^{-5}$ the width of the frequency spread on the WFHM is about 5 Hz, which relates to an accuracy of the mass definition $1.4\text{x}10^{-5}$. We see that a ripple of order $\delta_i=10^{-4}$ doubles the uncertainty of the mass measurements. The spectra shown in fig.2 are calculated for the high ripple frequency of 30 kHz. The revolution frequency of the particle in the CR is 1.2 MHz.

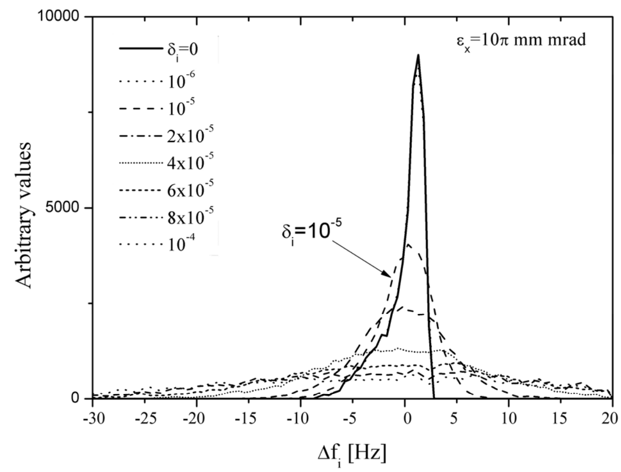

Figure 2: The calculated frequency spectra for different relative current instabilities $\delta_i=\Delta I/I$. The ripple frequency is 30 kHz. The beam emittance is 10π mm·mrad.

An accurate determination of the mass depends on how well one knows the standard used for the calibration defined by reference masses and how well one can determine the centroids in a frequency spectrum. Low frequency ripple of the power supplies will deform the spectrum by shifting the centroid of the spectrum peak as shown in Fig.3. Fig. 4 shows the required power converter stability depending on the ripple frequency. The demand on power converter becomes stronger with increasing the number of turns for isochronous mass measurements.

If we will perform a mass measurement over 100 turns the relative current variation of 10^{-5} with a frequency of 50 Hz will change the position of the centroid by 3.7 Hz in the frequency spectrum, that gives a relative mass shift of 10^{-5}. Systematic numerical analysis of the frequency spectra depending on the current variation of the dipole magnets brings us to the conclusion that power converters instability should be less than $5\text{x}10^{-7}$ in order to be able to perform the mass measurements with an accuracy better than $7\text{x}10^{-7}$ if the beam emittance is 10π mm mrad.

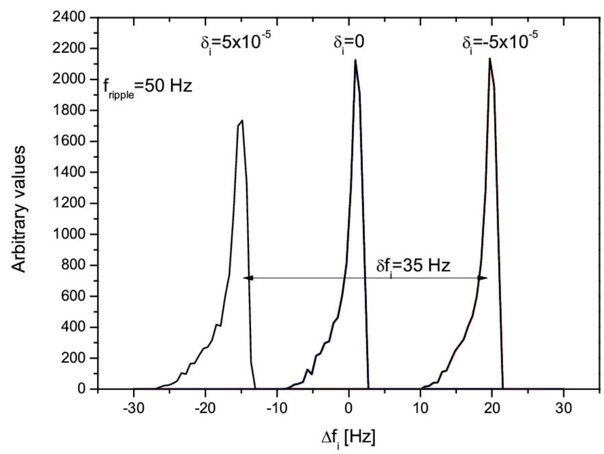

Figure 3: The frequency spectrum shifts due to low frequency ripple (50Hz) with an amplitude of δ_i=10^{-4}. The beam emittance is 10π mm·mrad.

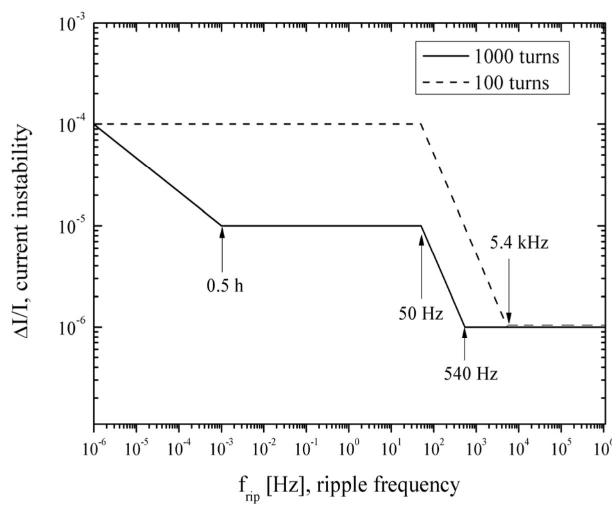

Figure 4: The required current stability of the bending magnets depending on the ripple frequency. 100 and 1000 are the numbers of turns for the isochronous mass measurement.

CR POWER CONVERTER

Since the CR ring is designed both for antiprotons and heavy ions with opposite charge, the magnet power converters must be able to reverse the current polarity. This can be achieved by a true bipolar design for the converters of the corrector magnets, whereas the other converters are unipolar and have mechanical reversing switches to change the current polarity. In order to change the operation conditions of the CR from rare isotopes to antiprotons and vice versa as fast as possible all CR currents are required to be ramped up to the nominal current or down to zero within 30 s. No particular requirements have to be fulfilled for the current accuracy during the ramp. The basic parameters of the CR power converters are listed in Table 1.

The dipole magnets are connected as a series string and will only require a single high power current converter. The 12 quadrupole and 6 sextupole families are individually powered, to provide optimum versatility in adjusting the lattice functions.

Table 1: CR magnet power converter ratings. (QW – wide quadrupole, QN – narrow quadrupole, SW – sextupole)

Family	Magnet Number per family	Volts (V)	Curr. (A)	Power per magnet (kW)	δ_i ΔI/I
Dipole	24	88	1400	125	10^{-6}
QW01,QW12	2	23	3215	71	10^{-4}
QW02-QW12	4	23	3215	71	10^{-4}
QN03 (4)	4	5.6	3800	21	10^{-4}
SW1-SW6	4	28	385	11	10^{-3}

The current ratings shown in Table 1, were optimised to ensure a balance between simplification and feasibility of the magnet design, against minimising the losses in the cable and power converter efficiencies. Each magnet family has the same design current, but may have a different design voltage. This allows common power converter units to be specified, minimising spares and simplifying replace ability.

It is envisaged that fully equipped power converter racks that include ac distribution, controls and thermal management will be delivered. Their performance specification figures are shown in Table 2; these are gauged on that required by other new accelerators.

Table 2: Power converter performance specifications

Performance	**Dipole**	**Quadrupole**	**Sextupole**
Type	bipolar	bipolar	bipolar
Stability	± 1 ppm	± 50 ppm	± 50 ppm
Reproducibility (0.5 hrs)	± 5 ppm	± 50 ppm	± 100 ppm
Accuracy (1 year)	± 50 ppm	± 50 ppm	± 200 ppm
Ripple > 50 Hz (0.5kHz -1.2MHz)	± 14 mA (1.4 mA)	0.3 A (0.1 A)	0.3 A (0.1 A)
Operating range	70-100%	3-100 %	10 – 100 %

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