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ACHROMATIC ISOCHRONOUS MODE OF THE ESR AT GSI

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Abstract

The isochronous optics of the ESR is a unique ion-optical setting in which the ring is operated as a Time-of-Flight Mass-Spectrometer and is used for direct mass measurements of short-lived exotic nuclei [1]. The present isochronous optics had been performed only making a negative dispersion in the straight sections of the ESR of about - 7 m. This negative dispersion makes the injection into the ESR very complicated and restricts the transmission of the ions in the ring. Moreover, the non-achromatism of the ESR brings a supplementary uncorrectable first-order transverse contribution to the revolution time. In order to make the ESR achromatic, to improve injection and the isochronicity a new achromatic isochronous optics has been calculated.

INTRODUCTION

The Experimental Storage Ring (ESR) [2] at GSI is the core instrument for unique physics experiments. The ESR is operated for accumulation, storage, cooling and deceleration of heavy ion beams in the energy range from 4-400 MeV/u. It is a symmetric ring with two arcs and two straight sections and a circumference of 108.36 meters. The ESR consists of 6 dipole magnets (deflection angle is 60°) and 10 quadrupole families (20 quadrupoles in total). For the second-order corrections 8 sextupole magnets are installed in the arcs. The ESR can be operated at a maximum magnetic rigidity of 10 Tm. For reducing transverse and longitudinal emittances of the stored ion beams, the ESR is equipped with the electron cooler which is installed in one of straight sections of the ring. In another straight section the internal gas-jet target and TOF detector are installed (see Fig. 1).

Relativistic fragments of several hundred MeV/u are produced via fragmentation or fission of primary beams coming from the high-energy heavy-ion synchrotron SIS18 [3], in a thick (1-8) g/cm^2 production targets at the entrance of the FRagment Separator (FRS) [4]. Secondary beams are separated in flight in the FRS within about 150 ns and are then injected and stored into the ESR (see Fig. 1). The relative change of revolution time T due to different mass-to-charge ratio m/q and velocity v of the stored ions circulating in the ring can be written:

$$\frac{\Delta T}{T} = \frac{1}{\gamma_t^2} \cdot \frac{\Delta(m/q)}{(m/q)} + \left(\frac{\gamma^2}{\gamma_t^2} - 1\right)\frac{\Delta v}{v}, \qquad (1)$$

where γ is the relativistic Lorentz factor and γ_t is the transition energy of the ring. If the second term in Eq. (1) becomes negligible, then the revolution time defines m/q.

To achieve this condition, two complimentary methods are developed and successfully used in the ESR. In the Schottky Mass Spectrometry (SMS) [5] the velocity spread is reduced in the electron cooler to about 10^{-7} depending on the intensity. Thus, the disturbing second term in Eq. (1) gets eliminated. The revolution frequencies are measured by Schottky pick-ups installed in the other straight section of the ESR. The disadvantage of this technique is that the electron cooling takes at least a few seconds thus limiting the accessible nuclides.

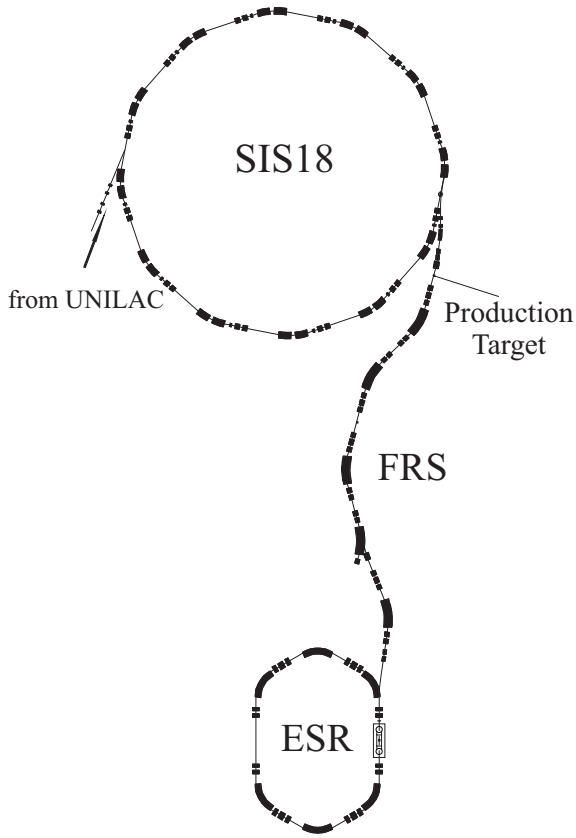

Figure 1: The layout of the high-energy radioactive beam facility at the present GSI. The stable primary beams are accelerated by the linear accelerator UNILAC to an energy of 11.4 MeV/u and then by the synchrotron SIS18 to energies 100-1000 MeV/u. They impinge on a production target at the FRS and then secondary beams are separated in flight and injected in the ESR.

To measure masses of extreme short-lived exotic nuclei, which are not accessible with the SMS, a special isochronous ion-optical setting of the ESR was developed [6, 7]. In the isochronous mode γ of the injected ions becomes equal γ_t. Thus, the second term in the right side of Eq. (1) also gets equal to zero and particles become isochronous. The revolution time of the circulating ions is measured with a TOF detector [8]. This detector is equipped with a thin carbon foil (20 µg/cm^2) where the secondary electrons are released at each turn of the circulating ion. These electrons

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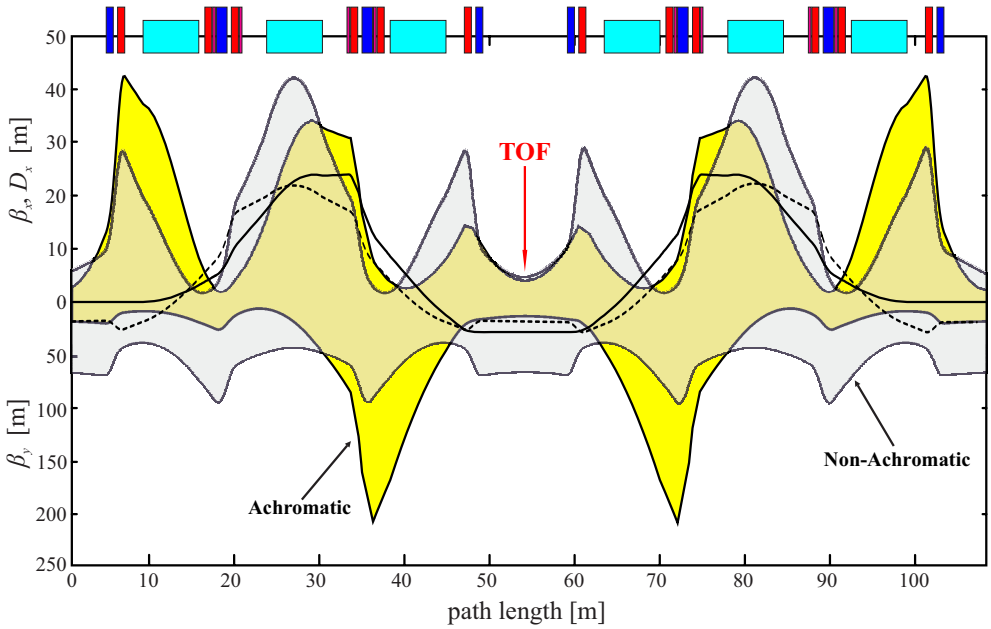

Figure 2: The calculated β-functions of the achromatic (yellow) and non-achromatic (transparent grey) optics of the ESR. The corresponding dispersion functions are indicated by black solid (achromatic) and dashed (non-achromatic) curves. The TOF detector position is marked by red arrow. Magnets positions are indicated on the top of the picture.

are then detected by a channel plate detector. After several tens turns the revolution time can be determined with a good accuracy. The clear advantage is that cooling is not needed and nuclei with half-lives down to a few tens μs can be measured.

ISOCHRONOUS OPTICS

The γ_t of the standard ESR operation mode is about 2.4, while γ of nuclei of interest is about 1.4. In order to reach the isochronous condition $\gamma = \gamma_t$, the dispersion of the ESR has to significantly be increased. The isochronous setting has been originally calculated using the five ESR quadrupole families [7]. The main peculiarity of this optics is the large negative dispersion in the straight sections (D≈-7 m) whereas the FRS is an achromatic system at the last focal plane before the injection into the ESR. This leads to a large dispersion mismatch. Additionally, there is a mismatch in the transverse phase space. These effects induce incorrect betatron and dispersion motions in the ring, and, therefore, strongly reduce the transmission of the ions into the ESR. In order to make the ESR achromatic, to facilitate the FRS-ESR matching and to improve the isochronicity of the ESR, the new achromatic optics has been calculated it was using 10 quadrupole families. The calculation has been performed with the ion-optical code GICOSY [9].

The betatron and dispersion functions of both isochronous settings are illustrated in Fig. 2. It can be seen, that the dispersion function of the achromatic mode is smaller on average, which allows to increase the momentum acceptance of the ESR from ±0.25% to ±0.35%. Additionally, a smaller dispersion (D≈-5 m) at the position of the time-of-flight (TOF) detector shall increase its efficiency. The calculated horizontal acceptance stays the same of 20 mm mrad, whereas vertical transverse acceptance is decreased from 20 to 7 mm mrad, due to large vertical betatron function at the defocusing quadrupoles (see Fig. 2).

NUMERICAL SIMULATIONS

Two isochronous optics have been considered in terms of the revolution time. First of all, for each setting a negative influence of the second-order isochronicity has been corrected with one sextupole setting. Then, the second-order effect of the transverse emittance to the revolution time has been compensated, correcting natural chromaticity with 2 additional families of sextupole magnets [10]. After all, a dedicated Monte-Carlo simulation has been performed with the program MOCADI [11].

In the simulations we have used a beam of 10^5 one sort particles with transverse emittance of 5 mm mrad in both planes circulating 100 turns in the ESR. The dependence of the revolution time spread on the momentum deviation in the ring has been simulated and the corresponding results are illustrated in Fig. 3.

From this figure one can see, that after one sextupole correction, contribution to the revolution time from the transverse motion becomes visible for both non-achromatic and achromatic isochronous settings (grey and yellow distribution, correspondingly). After 3 sextupole correction, the transverse contribution is perfectly compensated for the achromatic optics (red distribution on the right picture of Fig. 3). In contrast to the achromatic optics, the broader width of the time distribution of the non-achromatic mode is not compensated by the sextupole correction (black distribution on the left picture of Fig. 3).

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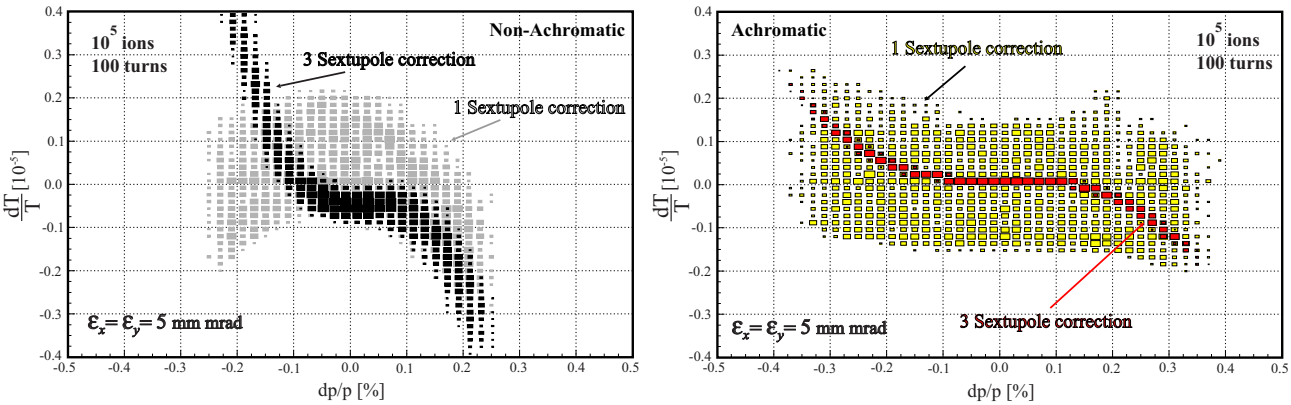

Figure 3: The revolution time spread as a function of the momentum deviation for the non-achromatic (left picture) and achromatic (right picture) isochronous optics.

This is a consequence of nonzero dispersion, which brings an additional uncorrectable first-order effect on the revolution time proportional to the horizontal emittance [12]. Due to motion in one plane there is no first-order contribution from the vertical motion.

This effect makes the isochronous conditions not sufficient for the precise mass measurements (necessary mass resolution of 10^{-6}) in the future large acceptance isochronous rings CR [13] and SRing [14]. It can be only avoided by a trimming of the horizontal emittance, which is undesirable due to the transmission loss. Still the non-achromatic optics is successfully used in the ESR [1], since experimentally, we never injected beam with the emittance more than 5 mm mrad in both directions, due to FRS-ESR mismatch.

The tails of the distributions correspond to the third-order longitudinal motion and can either be cut by the momentum acceptance restriction with $B\rho$-tagging [15] in the FRS or be compensated with octupole magnets [12], which are not available in the ESR.

Therefore, as one can see from Fig. 3, the achromatic isochronous setting of the ESR has clear advantages in comparison with the non-achromatic optics. The new setting will be checked in the future ESR beam time and the sextupole correction scheme will be experimentally verified and will be then used in the future Collector Ring (CR) [16] at FAIR [17].

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