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ISOCHRONOUS MODE OF THE EXPERIMENTAL STORAGE RING (ESR) AT GSI

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Abstract

The isochronous optics of the ESR is a unique ion-optical setting in which the particles within a finite momentum acceptance circulate at constant frequency. It is used for direct mass measurements of short-lived exotic nuclei by a Time-of-Flight method. Besides the mass spectrometry, the isochronous ESR has been used as an instrument for the search of short lived isomers stored in the ring, which was performed in 2021 for the first time. Introduction to the isochronous mode of the ESR, recent machine experiments with the new LSA control system will be presented here. Possible improvements of the isochronous optics at the ESR and perspectives of the isochronous mode at CR, FAIR will be outlined.

INTRODUCTION

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 at the facility GSI [1]. They impinge on a thick (1-8) g/cm^2 production targets and then secondary beams of several hundred MeV/u are produced via fission or fragmentation and separated in flight either by the FRagment Separator (FRS) [2] or in the straight transfer line from the SIS18, injected and stored in the Experimental Storage Ring (ESR) [3] (see Fig. 1).

The ESR is a unique instrument for the physics experiments with highly charged ions. The ESR is operated for accumulation, storage, cooling and deceleration of heavy ion beams in the energy range from 4–400 MeV/u. The decelerated beams can be used for in ring experiments or can be fast extracted either to the low energy CRYRING [4] (with extraction energy of 10 MeV/u) or to the Heavy Ion TRAP facility (HITRAP) [5] with the extraction energy of 4 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. Each dipole magnet is equipped with 17 special correction coils (102 in total) which smooth the radial magnetic field in the good field region of ±110 mm of the dipole.

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). The relative change of revolution time T (or revolution frequency f)

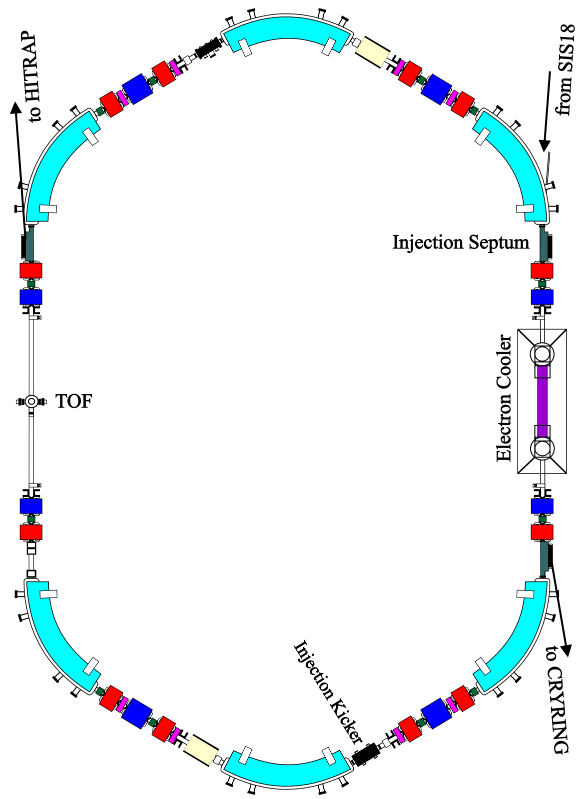

Figure 1: Layout of the Experimental Storage Ring (ESR). Dipoles, focusing, defocusing quadrupoles and sextupoles are marked by light blue, red, blue and pink colors correspondingly. Positions of the electron-cooler and the TOF detector are indicated in the straight sections.

due to different mass-to-charge ratio m/q and velocity v of the stored ions circulating in the ring can be written:

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

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) [6] the velocity spread is reduced by 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.

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To measure masses of extremely short-lived exotic nuclei, which are not accessible with the SMS, a special isochronous ion-optical setting of the ESR was developed [7, 8]. In the Isochronous Mass Spectrometry (IMS) [9] γ of the injected ions is chosen to be equal γ_t. Thus, the second term in the right hand 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 [10]. 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 are then detected by a channel plate detector. After several ten 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 ten µs can be measured.

ISOCHRONOUS MODE RECOMMISSIONING

In 2021 the isochronous setting of the ESR was recommissioned with the new LSA (LHC Software Architecture) [11] control system for the coming experiment of the search rare two-photon decay of highly charged ions in the isochronous ring. A carbon beam $^{12}C^{6+}$ at energy of 370 MeV/u was injected in the ESR via the direct transfer line from the SIS18. Due to the half-aperture of a kicker magnet, the beam can only be injected on the outer closed orbit which is about of $\Delta p/p \approx +0.2\%$ from the central one.

A dependency of the revolution frequency of the stored beam from its velocity (or momentum) is a most important property of the isochronous ring and called the isochronicity curve (or cooler curve). To measure it, the energy of a stored beam is changed by applying the electron cooler voltage and the corresponding revolution frequency shift is recorded. To match the isochronous condition in first order, experimentally, one has to either change the extraction energy of SIS18 (change the γ) or to change slightly the isochronous optics of the ESR (match the γ_t). One of the defocusing quadrupole magnets in the arc is very sensitive to the γ_t and indifferent in a small range to the other ring properties. Changing the strength of this quadrupole in a range of few percents and measure the isochronicity curve we could find the best isochronous condition. This procedure was repeated in the physics experiment, the results are illustrated in Fig. 2. After first-order isochronicity correction, higher order nonlinearities become visible. In order to investigate an effect of the dipole correction coils KP on the isochronicity we have switched most powerful of them one at time off and measured the corresponding curves. The result is illustrated in Fig. 3. The understanding of their nonlinear behavior will help to build a more accurate ion-optical model of the isochronous ESR. An analysis of individual contribution of the dipole correction coils to the isochronicity curve is in progress. Based on it, a new correction scheme was calculated using 4 families of sextupole magnets in contrast to the previous empirical experimental setting using 2 families made in 2000. The new scheme was applied in the experiment (see Fig. 4 below).

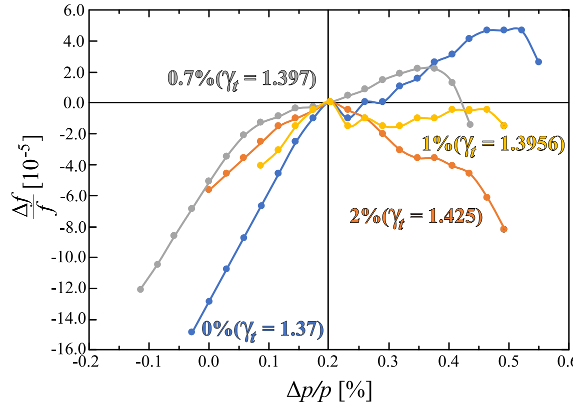

Figure 2: The isochronicity curves corresponding to the different strengths of one defocusing quadrupole family GE01QS3D of the ESR. The strength of 1% higher than default one shows a good agreement of γ_t = 1.3956 with a beam γ. The injection orbit Δp/p=+0.2% has been chosen as a starting point for the measurements. The sextupole setting was not applied.

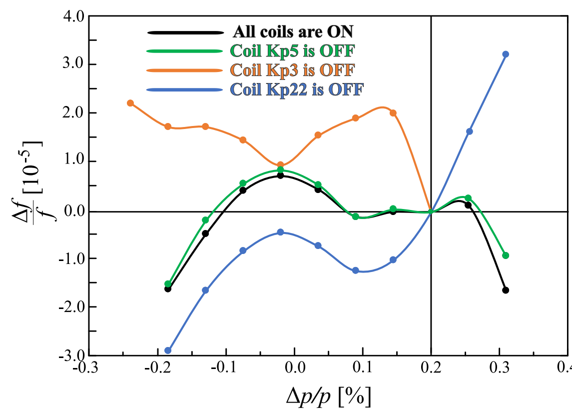

Figure 3: The effect of most powerful dipole correction coils on the isochronicity. The injection orbit Δp/p=+0.2% has been chosen as a starting point for the measurements. The sextupole setting was not applied.

ISOCHRONOUS ESR FOR THE NUCLEAR TWO-PHOTON DECAY

In 2021 the Schottky Mass Spectrometry (SMS) was applied in the Isochronous mode of the ESR for the first time to search for rare nuclear two-photon decay. It is an electromagnetic decay mode of an atomic nucleus whereby a nucleus in an excited state deexcites by emitting two gamma photons simultaneously, while the emission of a single gamma ray is strictly forbidden for low energy $0^+ \rightarrow 0^+$ transitions by angular momentum conservation. IMS enabled us to measure nuclear isomers with lifetimes as short as a few tens of ms since the electron cooling of the beam is not required. Instead of the conventionally employed TOF detector, the newly developed highly-sensitive non-destructive resonant

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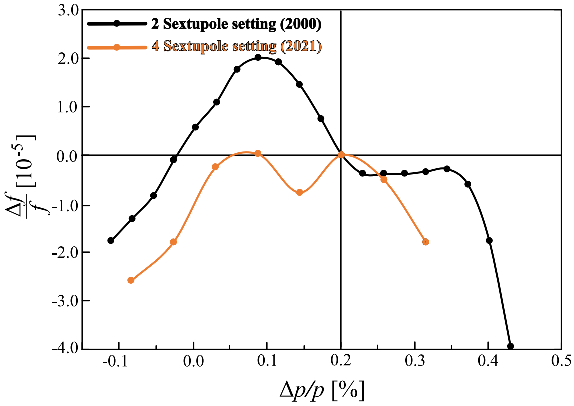

Figure 4: The isochronicity curves corresponding to the different settings using 2 sextupole families (black curve) and 4 of them (red curve). The injection orbit Δp/p=+0.2% has been chosen as a starting point for the measurements.

410 MHz Schottky detectors was utilized [12], which enabled us to monitor in time steps of about 10–20 ms the frequencies and intensities of all secondary ions stored in the ESR. This combined Schottky and Isochronous Mass Spectrometry made possible simultaneous mass and lifetime measurements of very short-lived rare nuclei. A similar technique has been recently employed also at the CSRe ring in Lanzhou [13].

In another experiment ^{78}Kr beam with an energy of 368.5 MeV/u (γ=1.3956) was fragmented in a thick 1 cm beryllium target. Nuclei of interest $^{72}Ge^{32+}$ and $^{70}Se^{34+}$ were selected within the transfer line, injected and stored in the ESR. A newly calculated sextupole setting applied to the ESR magnets (see Fig. 4), was decisive to place the beam onto a flat region of the isochronicity curve. Furthermore, through a careful adjustment of the transverse scrapers in a dispersive (−7 m) straight section of the ESR, nonlinear tails of the isochronicity curve were removed. According to very first, still preliminary results of the presently ongoing analysis, we were able to observe the low-lying 101 keV isomeric state in ^{70}Br, which would imply reaching a mass resolution of better than 10^{-6}.

This result is a major milestone achievement towards realization of the ILIMA experiment at the Collector Ring [14] of FAIR [15], where it has been proposed to employ such combined SIMS technique to address he most exotic nuclei provided from the Super-FRS [16]. A careful study of nonlinear effects of the ESR in the isochronous mode is essential to create a second-order correction scheme using potential of 8 independent sextupole magnets of the ESR. A commissioning of the achromatic isochronous mode described in [17] is necessary to proof the effect of emittance compensation by chromaticity correction in the isochronous ring [18] which will be then used in the future CR.

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