STATUS OF THE SUPERCONDUCTING COMPACT STORAGE RING COSY

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Abstract After initial injection studies with a normal conducting setup, commissioning with the superconducting magnets began in spring 1988. The first stored electron beam in a superconducting ring could be achieved with this machine in November 1988, a milestone in the development of superconducting compact storage rings. In the meantime much work has been done to increase the beam energy and to understand the actual limitations imposed by the superconducting magnets. A first test exposure of an x-ray mask has been made, which demonstrates the feasability of the whole concept.

Introduction

The COSY-ring has been developed as a prototype compact SR-source for x-ray lithography [1]. There are two inherent problems related with compact sources, i) the necessity of injecting high intensity at low energy, dictated by economy, and ii) the need of superconducting dipole magnets with small bending radii, motivated by compactness and the development potential towards future rings with smaller critical wavelengths for other applications.

In the first part of the project we have studied the injection process with normal conducting bending magnets and a 50 MeV racetrack microtron. Low energy injection of high currents is hampered by different physical effects such as low radiation damping rates, ion accumulation and lifetime limitations by Coulomb-scattering and the Touschek-effect. The injection studies have shown that ion accumulation is the prime handicap for higher intensities. However, with adequate methods to limit the deliterous effects of the ions (ion clearing, transverse beam excitation) it is possible to accumulate currents up to 100 mA [2]. No current limiting instability mechanisms have been observed, so even higher intensities can be expected under the vacuum conditions, which can be reached using superconducting dipoles with a cold bore.

These injection experiments have demonstrated that injection and accumulation of high currents at low energies is feasible, which is mandatory for any economic concept of a compact synchrotron radiation source. In this paper we report on the beam measurements and operational experience made during the commissioning of the superconducting COSY ring.

Achievements

The superconducting magnets, designed and manufactured by Siemens/Interatom [3] were installed in COSY after detailed tests. Field measurements revealed strong field distortions caused by ferromagnetic behavior of the stainless steel material, which has been used for the mechanical structure to support the coils. Although commissioning was hampered severely by these problems, the first stored electron beam in a superconducting ring could be obtained with COSY in November 1988 (see Fig. 1), a milestone in the development of compact storage rings.

Much effort has been made to reduce orbit deformations at injection and during energy ramping, which are caused by the local field distortions of the dipoles. Maximum intensities of 60 mA have been accumulated at 50 MeV with a 10 Hz repetition rate of the injection cycle and beam energies up to 550 MeV could be reached with a current of 1 mA.

The cold bore of the dipoles has been found to be very helpful to reach a vacuum level of typically $p = 2 \cdot 10^{-10}$ at zero current and reduced ion densities at low energy. Beam currents up to 40 mA can be stored at 50 MeV with a lifetime of about 2 min without any attempt to suppress ion accumulation. With the normal conducting COSY set-up ($p \cong 1 \cdot 10^{-9}$ mbar) the current was limited below 20 mA with a lifetime of about 20 sec under the same operating conditions [4], which demonstrates the importance of a good vacuum to limit the ion effects.

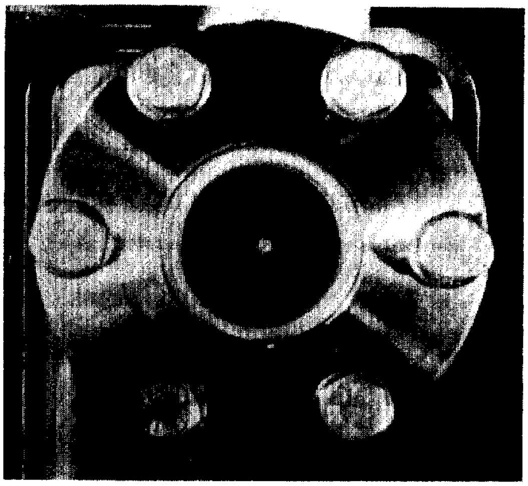

Fig. 1: *Synchrotron light from the first electron beam stored in the superconducting COSY ring.*

After the installation of a beamline with a 1 µm Si-membrane as a vacuum window, first test exposures have been made recently. As shown in Fig. 2, line structures with a thickness of 0.4 µm have been reproduced successfully with the proximity printing method, using a positive-tone resist (RAY-PF/Hoechst). This is also a demonstration that superconducting compact synchrotron radiation sources can be integrated into the specific environment of semiconductor processing lines.

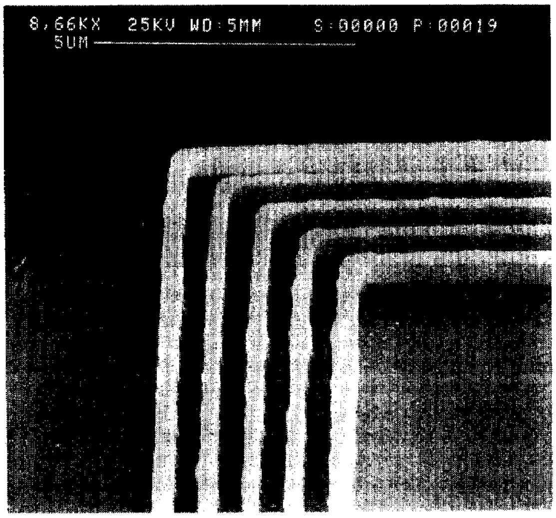

Fig. 2: *Line pattern with 0.4 µm structure dimensions produced by X-ray lithography using COSY.*

Table 1: Principal COSY Design Parameters

Critical wavelength	λ_c	= 12	Å
Injection energy	E_{inj}	= 50	MeV
Final energy	E_f	= 592	MeV
Circumference	L	= 9.6	m
Number of lattice cells	N	= 2	
Rf-frequency	f_{rf}	= 500	MHz
Synchrotron damping time (592 MeV)	τ_s	= 0.76	msec
Tunes	$\nu_{x,y}$	= 1.139 / 1.189	
Chromaticities	$\xi_{x,y}$	= -2.5 / -6.3	
Emittance (592 MeV)	ε_0	= $2.6 \cdot 10^{-6}$	mrad
Nominal field in sc magnet	B_0	= 4.47	T
Bending radius	ρ	= 0.44	m
Field index	n	= 0.525	
Magnet current (592 MeV)	I_M	= 1575	A

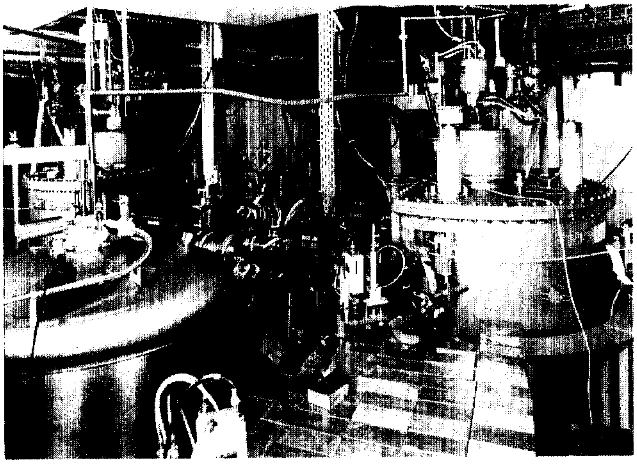

Fig. 3: View on the superconducting COSY ring

Problems

Commissioning of COSY suffered significantly from the limited field quality of the dipole magnets. The field distribution of the superconducting dipoles has been measured at very low excitation (magnets at room temperature), showing field distortions caused in part by geometrical tolerances of the coil configuration and, to a greater extend, by magnetization effects in the stainless steel structure supporting the coils.

At cryogenic temperatures, however, the material related part of the field errors is strongly enhanced. For example, the deviation of the integrated dipole component is about 20 times larger at the field level of 0.38 T for injection than expected by extrapolation from the room temperature field measurements. This is caused by the poor thermal stability of the stainless steel material of the magnets, leading to a structural phase transition from a paramagnetic austenite to the ferromagnetic martensite phase [5] with a corresponding increase in permeability. Due to saturation effects, the field errors depend in a nonlinear way on the exciting current, and because of the irreversible nature of the phase transition, magnetization is accumulated after each warm-up of the magnets with the result of a poor long term reproducibility of the field.

Part of the integral field errors could be compensated using the correction windings of the dipoles and by modifications of the optics. The more difficult problems to handle are a global reduction in good field aperture, symmetry violation of the field in respect to the horizontal plane and closed orbit distortions. With the help of controlled transverse alignment variations of the quadrupoles, additional steering magnets for correction at lower energies, and a variable rf-frequency during ramping to compensate circumference variations of the deformed orbit, we tried to minimize orbit distortions and center the beam empirically in the available good field aperture.

The β-functions in the quadrupoles have been measured at different energies (Fig. 4), revealing large deviations from the design optics at low energy, in contrast to measurements which have been made with the normal conducting dipoles in the beginning of the project. The behaviour of the horizontal β-functions can be related qualitatively with a too small gradient in the dipoles, which approaches the nominal value when the stainless steel structure is saturated at high energies.

In vertical direction the behaviour of the β-function is more complicated and cannot be explained by perturbations of the linear optics alone, which indicates the existence of strong nonlinear multipoles in the dipole magnets. At high energy the deviations become smaller but do not vanish as in the horizontal case.

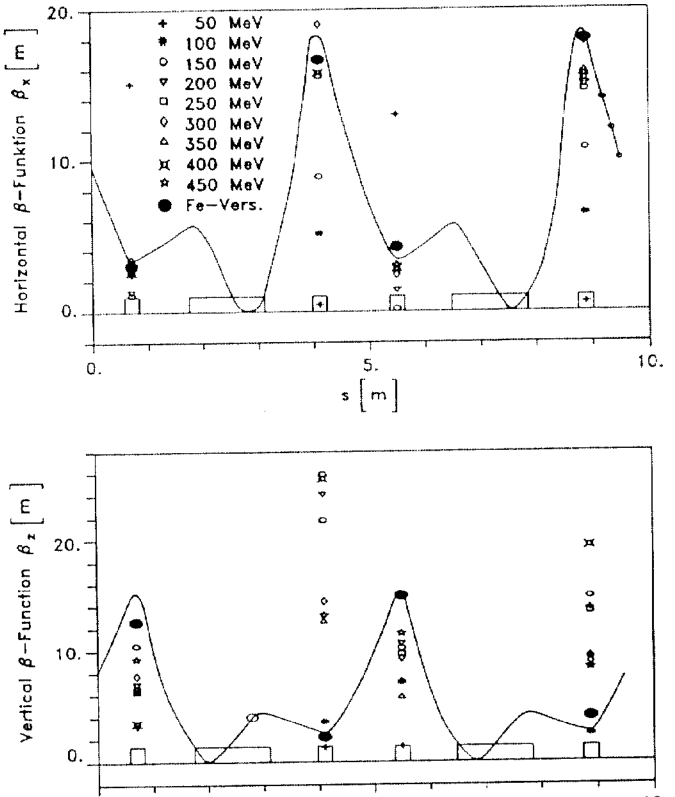

Fig. 4: Nominal β-functions and measured β-values in the quads. For comparison, the β-values obtained with normal conducting dipoles at 50 MeV are also given (Fe-version)

Beam dimension measurements have been made at a source point with zero dispersion. The horizontal beam size decreases with increasing energy at lower energies with a minimum around 100 MeV and increases linearly for higher energies as shown in Fig. 5. This behavior can be explained quantitatively taking into account emittance broadening by multiple scattering between the electrons in a bunch.

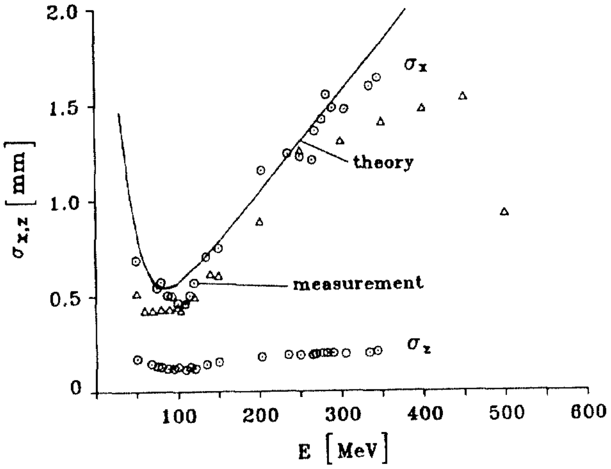

Fig. 5: *Beam dimension measurements ($I_b \cong 1$ mA) for two different tunes and comparison with a multiple scattering model calculation (the data point at 500 MeV has been obtained by shifting the tune towards stronger coupling).*

Lifetime measurements at different energies are shown in Fig. 6 for a beam current of about 1 mA. Up to energies of 350 MeV the lifetime increases monotonically, following qualitatively the behavior of the expected Coulomb scattering lifetime for a mean gas pressure of $5 \cdot 10^{-10}$ mbar. A model calculation of the Touschek lifetime, taking multiple scattering and bunch lengthening into account, is too pessimistic. For energies above 350 MeV, the lifetime decreases strongly. Several working points have been tried for energy ramping. It turned out that the beam lifetime is lowered, if the horizontal beam size became larger than about 1.6 mm in the dipoles. By shifting the tune towards a coupling resonance to decrease the horizontal beam size, energies up to 550 MeV can be reached. For higher energies the horizontal good field aperture of the dipoles is too small to store the beam without untolerable particle losses.

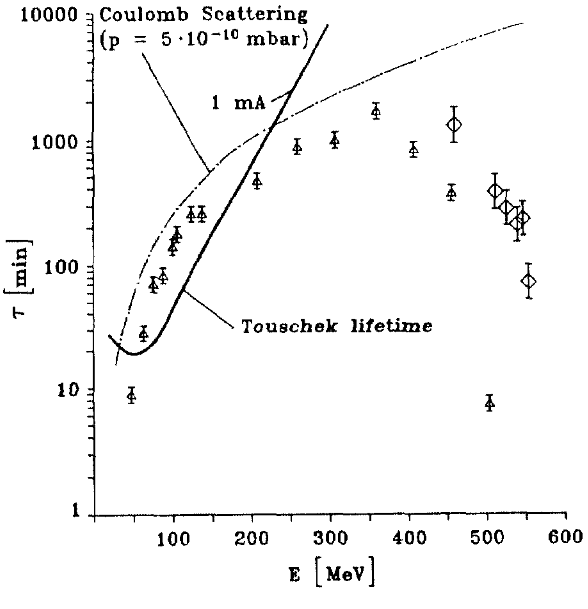

Fig. 6: *Beam lifetimes measured for two different tunes. For comparison the expected Coulomb lifetime ($p = 5 \cdot 10^{-10}$ mbar) and the Touschek lifetime are also given.*

These measurements indicate that the geometrical deformation of the magnet coils due to the field forces can be excluded as a major source of field errors, which strengthens the confidence in the engineering tools used for the mechanical design of the magnets.

Resumé

The commissioning results obtained confirm the basic accelerator physical concept of COSY as well as the technical feasibility of superconducting compact rings. In particular they demonstrate that

i) injection of electrons at 50 MeV and accumulation of beam currents of at least 100 mA is possible, and
ii) the material problems limiting the field quality of the present superconducting magnets are well understood and not inherent, so that
iii) fabrication of superconducting 180°-bending magnets with a field level of 4.5 T lies within today's technology.

In addition, the experience gained with the first superconducting rings is very helpful to design machines with energies above 1 GeV for micromechanical and medical applications. All these developmental efforts help to make synchrotron radiation available for a growing variety of applications outside the classical domain of basic research.

References

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