INVESTIGATION OF THE ANKA INJECTOR

L. Præstegaard[1], H. Bach[1], D. Einfeld[2], N. Hertel[3], L. Kruse[1], S. P. Møller[3],
B. R. Nielsen[1], J. S. Nielsen[3], F. Pérez[2], and M. Pont[2]
[1]Danfysik A/S, DK-4040 Jyllinge, Denmark
[2]Forschungszentrum Karlsruhe, D-76021 Karlsruhe, Germany
[3]Institute for Storage Ring Facilities, University of Aarhus, DK-8000 Aarhus C, Denmark

Abstract

The 500-MeV ANKA injector consisting of a 53-MeV racetrack microtron pre-injector, a 500-MeV 26.4-m circumference booster synchrotron, and two transfer lines have been constructed and commissioned by the company Danfysik with assistance from the University of Aarhus. The article presents the conclusions of a thorough characterization of both the racetrack microtron and the booster synchrotron. In particular, the properties of the electron beam are characterized in detail throughout the entire 1-second cycle of the injector. The results are employed to examine where and why beam losses do occur, suggesting how to improve the performance of the injector in the future.

1 INTRODUCTION

The ANKA injector is a 500-MeV electron injector for the 2.5-GeV ANKA synchrotron radiation source which recently was taken into operation at Forschungszentrum Karlsruhe, Germany [1]. The complete injector, which has been manufactured and commissioned by the company Danfysik A/S with assistance from the University of Aarhus, includes a 53-MeV racetrack microtron pre-injector, a 500-MeV booster synchrotron, a transfer line between the microtron and booster synchrotron, and a transfer line from the booster synchrotron to the ANKA synchrotron. The paper presents highlights of a detailed investigation of the beam properties and performance of the ANKA injector [2] while the design and the commissioning results of the injector have been published previously [3,4,5].

2 THE RACETRACK MICROTRON

The momentum distribution of the racetrack microtron beam is inferred from the distribution of revolution frequencies shortly after the beam is injected into the booster synchrotron, using the relation

$$\frac{\Delta p}{p} = -\frac{1}{\alpha_p}\frac{\Delta f_{rev}}{f_{rev}}$$

where Δp is a momentum deviation, Δf_{rev} a revolution frequency deviation, f_{rev} is the center revolution frequency, and α_p is the momentum compaction factor of the booster synchrotron. The revolution frequency spectrum is obtained by a spectral analysis of a beam pickup signal shortly after injection in order to avoid the effect of synchrotron radiation damping. A statistical analysis of the distribution yields a relative momentum spread of 0.0011±0.0001 (one standard deviation) for the nominal setting of the racetrack microtron. In figure 1, the measurement of the momentum spread is repeated for several values of the forward rf power. It is observed that the momentum spread decreases when the forward power is reduced below the nominal value of 2.46 MW in good qualitative agreement with theoretical simulations of the longitudinal dynamics. The figure also shows that the smaller momentum spread is accompanied by a decrease of the output beam current.

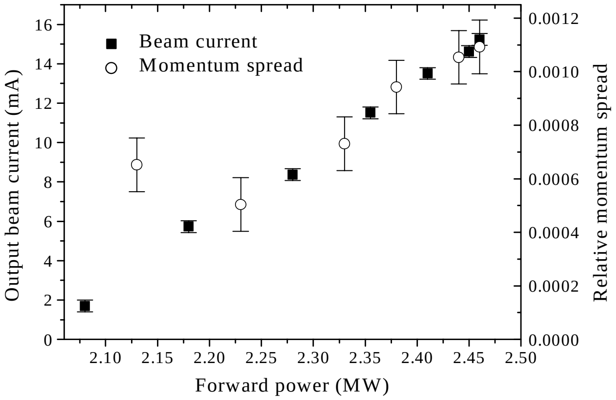

Figure 1: Beam current and relative momentum spread of the output beam of the ANKA recetrack microtron.

The transverse emittances of the output beam of the racetrack microtron beam is determined by recording the beam profile with a beam viewer versus the excitation of an upstream quadrupole magnet, the so-called *variable quadrupole method* [6]. The excitation scan is performed for two different beam momenta (different excitations of the 180° dipole magnets), facilitating a correction of the finite dispersions at the beam viewer. In addition, the transverse emittances are established from the transverse beam profile of the electron beam, inferred from the synchrotron radiation emitted in one of the 180° dipole magnets. The resulting horizontal and vertical emittances are 0.21±0.08 µm and 0.21±0.05 µm, respectively.

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Table 1: Design and achieved beam parameters of the output beam of the ANKA racetrack microtron.

	Design	Achieved
Pulse current	10 mA	16 mA
Pulse length	0.5-1μs	0-1.6 μs
Rel. mom. spread	<0.003	0.0011±0.0001
Hor. emittance	0.2 μm	0.21±0.08 μm
Ver. emittance	0.2 μm	0.21±0.05 μm

The main measured beam properties of the ANKA racetrack microtron and the associated design values are shown in table 1, demonstrating that the ANKA racetrack microtron performs according to specifications or better. The measured momentum spread and transverse emittances of the output beam are smaller than those of other selected racetrack microtrons, and significantly smaller than those of selected modern linear accelerators. For the present application, this is a considerable advantage as the injection efficiency of the multi-turn injection process in the booster synchrotron strongly favors a small momentum spread and small transverse emittances of the racetrack microtron beam.

A theoretical analysis of the longitudinal dynamics of the ANKA racetrack microtron reveals a positive feedback mechanism between the beam and the fields of the accelerating structure, limiting the total beam current of all beam recirculations below 329 mA. For an output beam current of the racetrack microtron of 14 mA, the total beam current of all beam recirculations is 283 mA, suggesting that an output beam current significantly above 14 mA can not be expected for the ANKA racetrack microtron. However, a pre-buncher at the fundamental frequency after the electron gun would provide a significantly higher output beam current because a considerable higher percentage of the electrons are injected into the longitudinal acceptance of the rf system for the same beam loading of the linac.

3 BEAM PROPERTIES OF BOOSTER SYNCHROTRON

Assuming a uniform filling pattern in the booster synchrotron, the beam current has the following form in frequency domain [7]:

$$I_b(\omega) = Q\omega_{rf}\,\delta(\omega) + 2Q\omega_{rf}\,\exp\left(-\tfrac{1}{2}(\omega\sigma_s)^2\right)\times \sum_{n=1}^{\infty}\delta(\omega - n\omega_{rf})\;,$$

where the synchrotron sidebands have been omitted, ω is the angular frequency, Q the total charge of a single bunch, ω_{rf} is the angular rf frequency, and σ_s is the bunch length (one standard deviation). Hence, the bunch length can be determined from the relative amplitude of all rf harmonics up to 5 GHz which can be measured by a spectrum analyzer knowing the impedance of the beam pickup and the transmission coefficient of the associated cable. Subsequently, the bunch length can be converted to a momentum spread, utilizing the relation between the bunch length and the momentum spread in the linear region of the longitudinal phase space. The resulting momentum spread throughout the whole ramp of the beam energy is shown in figure 2, revealing a good agreement with the theoretical equilibrium value between synchrotron light damping and excitation. The measured relative momentum spread at full energy is $(3.6\pm0.4)\cdot10^{-4}$.

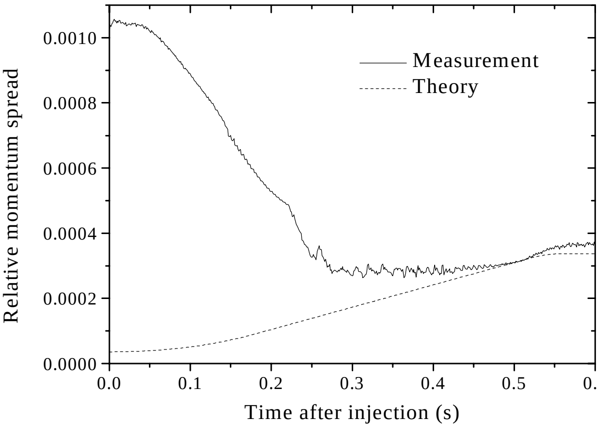

Figure 2: Relative momentum spread of the circulating beam in the ANKA booster synchrotron.

The transverse emittances of the circulating beam of the booster synchrotron are determined from the transverse beam profile in the center of the dipole magnets which is inferred from an analysis of the emitted synchrotron radiation. In order to obtain information about the contribution of diffraction to the measured beam profile, the beam profile is recorded for various positions of the camera detecting the synchrotron radiation. This method facilitates a very good resolution of the transverse beam profile. The resulting transverse emittances are plotted in figure 3 during the entire

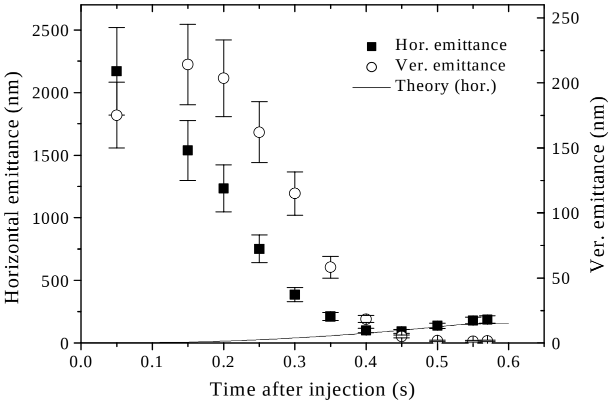

Figure 3: Hor. and ver. emittance of the circulating beam during ramping.

ramping of the beam energy, showing a good agreement with the theoretical equilibrium value between synchrotron light damping and excitation.

The transverse emittances of the output beam of the ANKA injector are determined by means of the extended version of the variable quadrupole method discussed above utilizing three quadrupole magnets in the transfer line from the booster synchrotron to the ANKA storage ring. As above, each quadrupole magnet is scanned for two different beam momenta in order to correct for a finite dispersion at the downstream beam viewer. This also enables a determination of the momentum spread of the beam. The resulting emittances and momentum spread are presented in table 2.

Table 2: Measured and achieved beam parameters of the ANKA injector booster synchrotron.

	Design	Achieved
Beam current (53 MeV)	>15 mA	35 mA
Beam current (500 MeV)	>7.5 mA	12 mA
Hor. emit. (500 MeV)	150 nm	165±22 nm
Ver. emit. (500 MeV)		2.3±0.8 nm
Rel. mom. spr. (500 MeV)	$3.4\cdot10^{-4}$	$(3.6\pm0.4)\cdot10^{-4}$
Extr. beam current	>7.5 mA	9.5 mA
Pulse length (extr. beam)	56 ns	52 ns
Hor. emit. (extr. beam)	<200 nm	153±12 nm
Ver. emit. (extr. beam)		11±2 nm
Rel. mom. spr. (extr. beam)	<0.001	$(3.0\pm0.6)\cdot10^{-4}$

4 PERFORMANCE OF THE BOOSTER SYNCHROTRON

The most important measured beam properties of the ANKA booster synchrotron and the associated design values are summarized in table 2, demonstrating a performance which exceeds the design values. A comparison with other booster synchrotrons reveals that the charge accelerated to full energy per second is comparable to or better than that of more expensive booster synchrotrons. The impressive performance of the ANKA booster synchrotron is to a large extent a consequence of the excellent beam properties of the ANKA racetrack microtron. Nevertheless, a substantial beam loss takes place the first ~100 ms after injection due to a relatively low capture efficiency of the injected beam. A detailed examination of the longitudinal dynamics of the ANKA booster synchrotron suggests that the beam loss can be decreased by a careful adjustment of the detuning of the rf cavity and by disabling the amplitude loop of the rf cavity during the injection process, both reducing the harmful effect of transient beam loading. In order to achieve a capture efficiency close to 100 percent, however, a subharmonic pre-buncher operating at the rf frequency of the booster synchrotron should be installed in the injection transfer line of the racetrack microtron, facilitating an injection of all electrons of the racetrack microtron beam in the center of the longitudinal bucket of the booster synchrotron.

A detailed analysis of the extraction process reveals that the beam is extracted 7/4 revolutions after the activation of the extraction kicker magnet (two-turn extraction process) as opposed to the expected 3/4 revolution (one-turn extraction process). The reason is a combination of a too small bump of the beam towards the extraction septum prior to the extraction process and an additive effect of two successive deflections by the extraction kicker magnet. Fortunately, even for the two-turn extraction process, the extraction efficiency is about 90 percent and the measurements of the horizontal emittance and the momentum spread of the extracted beam agree with the those of the circulating beam, demonstrating that the two-turn extraction process does not deteriorate the beam quality significantly. Nevertheless, the one-turn extraction process is more advantageous because it produces a slightly longer extracted electron pulse and reduces the sensitivity of the electron pulse towards a variation of the kicker magnet field. Owing to the large excitation reserve of both the bumper windings and the kicker magnet supply, the one-turn extraction process should be feasible, unless the leak field of the extraction septum magnet impedes the beam from being displaced close enough to the extraction septum. At least, the one-turn extraction process can be accomplished if the shielding of the septum magnet is improved by a highly permeable iron vacuum chamber or the horizontal tune is decreased to 1.7 for which the closed orbit displacement by the leak field is a factor 3.5 smaller.

Implementing the proposed improvements, the output charge of the ANKA injector is expected to increase by about a factor of two. This would make an ANKA-type injector even more attractive for future synchrotron radiation sources.

5 REFERENCES

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