THE ANKA INJECTOR

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Abstract

The ANKA injector is a 500 MeV electron injector for the 2.5 GeV ANKA synchrotron, Forschungszentrum Karlsruhe, Germany. The injector, presently under construction at Danfysik A/S, includes a 53 MeV race track microtron pre-injector, a 500 MeV booster synchrotron, and transfer lines. The injector will deliver an electron beam with an electron current of more than 7.5 mA and an emittance of 0.15 mm mrad. The multi-turn injection process of the pre-injector beam in the booster synchrotron is investigated and the position of the extraction kicker is discussed.

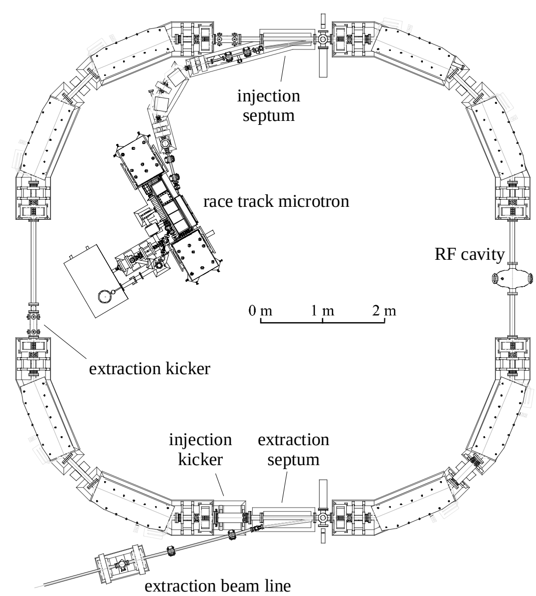

Figure 1: The injector complex.

1 INTRODUCTION

The ANKA injector is a 500 MeV electron injector for the 2.5 GeV ANKA synchrotron which presently is under construction at Forschungszentrum Karlsruhe, Germany [1,2]. The injector complex shown in Fig. 1 consists of a 53 MeV race track microtron pre-injector, a 500 MeV booster synchrotron, a transfer line between the microtron and the booster synchrotron, and a transfer line from the booster synchrotron to the ANKA synchrotron. The microtron delivers an electron pulse with a duration of 0.5-1 μs and a current of more than 10 mA, which is injected into the booster synchrotron by means of a multi-turn injection scheme. The injection process leads to a stored electron current of more than 15 mA in the booster synchrotron, which is accelerated to 500 MeV and subsequently extracted during a single revolution. The extracted electron pulse has a duration of ~56 ns, a current of more than 7.5 mA and an emittance of 0.15 mm mrad. The whole injection cycle is repeated with a rate of 1 Hz. The injector, presently being built at Danfysik A/S, will be commissioned in autumn 1999.

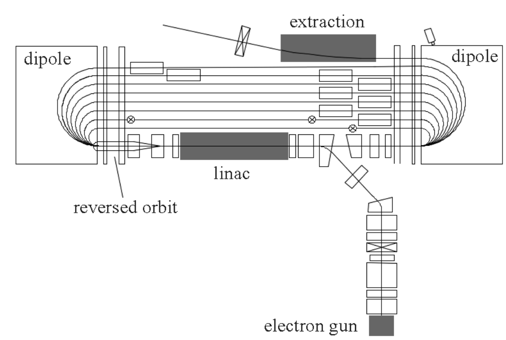

Figure 2: Schematic layout of the race track microtron.

2 THE PRE-INJECTOR

A race track microtron has been chosen as pre-injector due to its small energy spread, compactness, ease of operation and low price; all characteristics which are superior to those of a linear accelerator. The schematic layout of the microtron is shown in Fig. 2, while its main parameters are listed in table 1. The electron gun is a standard spherical Pierce type with a BaO cathode which provides ~500 mA of electrons in a 0.5-1μs long pulse. After the electron gun, the electron beam is deflected onto the axis of the linac which is of the Los Alamos side coupled standing wave type, allowing acceleration in both directions. The resonant energy gain of the linac is 5.3 MeV, implying that the speed of the electrons after the first passage of the linac differs from the speed of light by 0.5%. Hence, in order to avoid a phase lag in the first orbit, the beam is reversed in the left dipole and sent back on the axis of the linac with the aid of two small dipole magnets (see Fig. 2). After two passages of the linac, the velocity of the electrons is sufficiently close to the speed of light that the synchronous condition is fulfilled without any significant phase lag. In addition, the reversed orbit has the advantage that the first real orbit is sufficiently far away from the common axis to clear the linac. After ten passages of the linac, the electron beam is extracted with a 15° bending magnet.

Table 1: Main parameters of the race track microtron.

RF frequency	2.9986 GHz
Resonant energy gain	5.3 MeV
Final electron energy	53 MeV
Pulse current	>10 mA
Pulse length	0.5-1μs
Repetition rate	1-10 Hz
Energy spread	<0.3 %
Emittance (hor./ver.)	~0.2 mm mrad

Table 2: Main parameters of the booster synchrotron.

Final energy	500 MeV
Circumference	26.4 m
Dipole field	1.00 T
RF frequency	500 MHz
Pressure	$<10^{-7}$ mbar
Horizontal tune (design value)	1.50-1.95 (1.776)
Vertical tune (design value)	1.33-1.15 (1.173)
Horizontal chromaticity	-0.29
Vertical chromaticity	-2.69
Horizontal acceptance	55 mm mrad
Vertical acceptance	17 mm mrad
Momentum acceptance	1.1%
Momentum compaction factor	0.27
Horizontal emittance	0.15 mm mrad
Repetition frequency	1 Hz
Circulating current	>15 mA
Extracted current	>7.5 mA
Pulse length of extracted beam	~56 ns

3 THE BOOSTER SYNCHROTRON

The four-fold symmetric lattice of the Booster synchrotron is shown in Fig. 1, and its main parameters are listed in table 2. The lattice has eight 45° rectangular dipole magnets, defining in total four short and four long straight sections. A family of horizontally focusing quadrupoles are located symmetrically in the long straight sections, while vertical focusing is provided by the edge focusing at the end-faces of the dipole magnets; a scheme only feasible for dipole magnets, having a rather small bending radius. The length of the long straight sections have been selected with the aim of confining the horizontal and vertical betatron tunes Q_x and Q_y between the systematic resonances $3Q_x+2Q_y=8$ and $Q_x+2Q_y=4$. In addition, this choice ensures clearance between the transfer lines and the nearby quadrupoles. No sextupole magnets have been included in the lattice because the hail-tail instability is of little significance for circulating currents below 40 mA, roughly a factor of three higher than the specified value. Hence, the dynamical acceptances are much larger than the physical acceptances listed in table 2. Finally, the acceleration is performed by a 500 MHz RF cavity inserted in the center of one of the long straight sections.

For Q_x=1.776 and Q_y=1.173 (design values), the lattice functions are shown in Fig. 3. Having separate power supplies for dipole and quadrupole families, the horizontal and vertical tunes can vary in the ranges 1.5-1.95 and 1.33-1.15, respectively. The smallest emittance of 0.15 mm mrad is obtained for the design parameters.

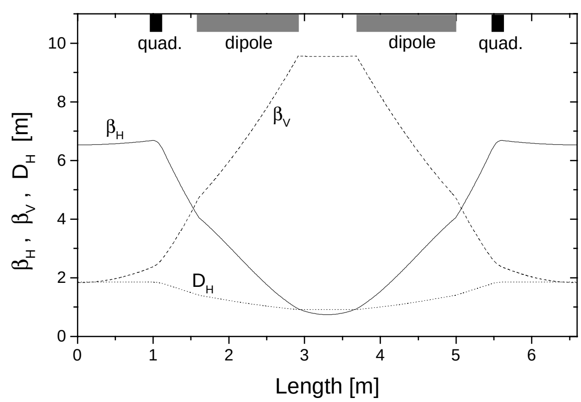

Figure 3: Betatron and dispersion functions in one super period of the booster synchrotron lattice (1/4 of the circumference) for Q_x=1.776 and Q_y=1.173.

4 INJECTION AND EXTRACTION

In order to store as many electrons as possible in the booster synchrotron, the microtron beam is injected over several revolution periods of the booster synchrotron, a so-called multi-turn injection. The multi-turn injection process is performed with only one injection kicker magnet located diametrically opposite to the septum magnet, which is installed in one of the long straight sections (see Fig. 1). The magnetic field of the septum magnet is shielded by a 1.5 mm thick septum blade, located 21 mm from the design orbit. The injection process takes place on the falling edge of the half cosine-shaped current pulse, which excites the injection kicker.

An analysis of the multi-turn injection process reveals that the injection is most efficient if the horizontal and vertical betatron functions of the transfer line are well matched to those of the booster synchrotron lattice. In this case, the beam size (1 sigma) after injection is

$$E(s) = \sqrt{\varepsilon_{x,m}\beta_x(s)} + \left|\frac{\Delta p}{p}D_x(s) + A\sqrt{\beta_x(s)}\cos(\psi_x(s) - \psi_x(s_i) + \lambda)\right| \quad (1)$$

where

$$A = \frac{1}{\sqrt{\beta_x(s_i)\cos(\lambda)}}\frac{\Delta p}{p}\left(D_{x,bl} - D_x(s_i)\right) \ , \qquad (2)$$

$$\tan(\lambda) = -\beta_x(s_i)\frac{\frac{d}{ds}D_{x,bl} - \frac{d}{ds}D_x(s_i)}{D_{x,bl} - D_x(s_i)} \ , \qquad (3)$$

$\varepsilon_{x,m}$ is the horizontal emittance of the microtron beam, $\beta_x(s)$ is the horizontal betatron function of the booster lattice, $\Delta p/p$ is the relative momentum spread of the microtron beam, D_x is the horizontal dispersion of the booster, $D_{x,bl}$ is the horizontal dispersion at the end of the injection transfer line, $\psi_x(s)$ the horizontal betatron phase of the booster lattice, and s_i is the position of the injection septum. The last term in Eq. (1), oscillating synchronously with the betatron motion, originates from a non-matched dispersion at injection. Utilizing Eq. (1), the horizontal position of the beam edge (facing the injection septum) at the injection septum can be determined for all roundtrips after injection. If the maximum displacement d_{max} of the edge from the design orbit is less than the distance d_{sep} to the injection septum blade (21 mm), the injection was successful. Thus, the following two quality factors of the injection process are defined:

$$Q_1 \equiv \int_{d_{\max}<d_{sep}} dt_i \quad \text{and} \quad Q_2 \equiv \int_{d_{\max}<d_{sep}} dt_i\left(d_{sep} - d_{\max}\right) \qquad (4)$$

where t_i is the time of injection relative to the center of the injection kicker pulse. Hence, Q_1 is simply the time over which the injection is successful, whereas Q_2 weights both the duration of the injection and how far the injected beam is from the injection septum. Obviously, large values of Q_1 and Q_2 reflect a good injection. Q_1 and Q_2 are maximized by varying the amplitude $\Delta x'_{max}$ of the injection kicker pulse, the full width τ of the injection kicker pulse, and the initial angle x_i' of the injected beam relative to the design orbit. It is found that the injection is most efficient (large Q_1 and Q_2) if $D_{x,bl}$ is close to zero, corresponding to a non-matched dispersion at the injection. For example, the maximum Q_1 and Q_2 values for $D_{x,bl}$=0.2 m and several values of the horizontal tune Q_x is seen in Fig. 4. According to the figure, the injection is successful in a rather large Q_x interval for more than 0.5 µs, corresponding to a high injection efficiency for more than six revolution periods of the booster. However, the injection is best in the interval Q_x=1.75-1.85 because the injection efficiency is smaller close to the $2Q_x$=3, $3Q_x$=5, and Q_x=2 resonances. Typically, values of the free parameters are $\Delta x'_{max}$=5 mrad, τ=1.5 µs, and x_i'=-1 mrad.

The electron beam is extracted from the booster synchrotron in a one-turn process, involving one extraction kicker and an extraction septum magnet. The required strength of the kicker is reduced by almost an order of magnitude by displacing the closed orbit to a horizontal position ~2 mm from to extraction septum during the last ~40 ms before extraction; the displacement is produced by separate windings on the four dipole magnets closest to the extraction septum. In addition, the kick strength is reduced by locating the kicker in the position where the horizontal betatron function has a maximum (see Fig. 1 and 3) and the phase advance from the kicker to the extraction septum minus $\pi/2$ is close to a multiple of π. In order to obtain a high extraction efficiency, the extraction kicker has been designed with a rise time of ~30 ns, a time much shorter than the revolution period of 88 ns. Investigating the beam size and path after multi-turn injection, the distance between the extraction septum and the design orbit is chosen to 25 mm.

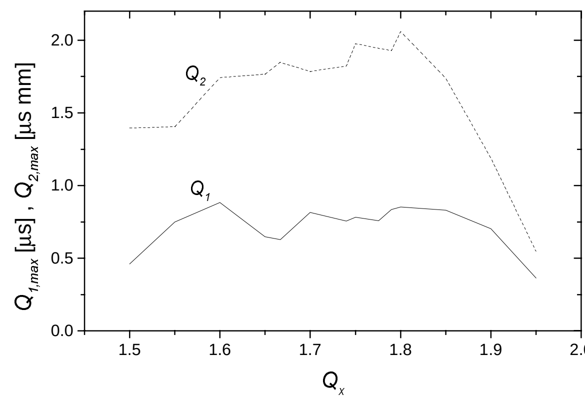

Figure 4: The maximum Q_1 and Q_2 values for several values of the horizontal tune Q_x. Realistic parameters: $D_{x,bl}$=0.2 m, $\varepsilon_{x,m}$=0.1 mm mrad, $\Delta p/p$=0.2%, and the effective septum blade thickness is 3.5 mm.

CONCLUSION

The ANKA injector has very good beam properties, considering its size and its simplicity. The circulating current in the booster synchrotron is, however, limited by the head-tail instability. Nevertheless, upgrading the injector with sextupoles will make it possible to operate the injector as an accumulator in which a high circulating current can be stored. The investigation of the multi-turn injection process of the microtron beam shows that a highly efficient injection over more than six revolutions is feasible.

REFERENCES

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