STUDY OF BEAM CAPTURE IN COMPACT SYNCHROCYCLOTRON

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Abstract

Capture efficiency and main aspects of the beam dynamics during first turns and in a period of one synchrotron oscillation were studied in synchrocyclotron with driving magnetic field of ~5 Tesla. Corresponding simulations of the beam motion were done by means of numerical integration of the full equations of motion in the electro-magnetic field of accelerator. Main physical parameters for input data were taken similar to them for IBA S2C2.

TOOLS AND INITIAL DATA

To study the mentioned above processes so called 3-D (transverse and longitudinal) tracking code was used. Code is basing on numerical integration of full equations of motion in cylindrical coordinate system using t (time) as independent variable. This is the main difference from the tools used in [1].

Input parameters for these calculations are approximately reconstructs electromagnetic field of IBA S2C2 and were synthesized from data [1]-[3].

The dependence of RF-frequency on time which is needed for the particles tracking was calculated by means additionally developed procedure. Constructed curve ensures stable RF-phase of the synchronous particle. Driving magnetic field and corresponding $f_{RF}(t)$-curve for constant φ_s=60°RF inside the acceleration cycle where synchronous particle exists are presented in Fig. 1. RF-field was calculated by means of approximation [4] assuming two accelerating gaps (180°-dee) and constant with radius voltage U=10kV.

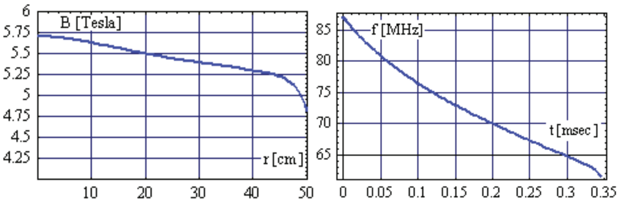

Figure 1: Driving magnetic field (left) and $f_{RF}(t)$ inside the acceleration cycle.

Kinetic energy of accelerating particle in our approximation is given by:

$$W = 2qU\cos\varphi_s \cdot N$$

where q is particle charge, N - number of passed turns (two accelerating gaps per turn are assumed here). So, the time needed to get total energy $E = \sqrt{(qB(r)\cdot r\cdot c)^2 + E_0^2}$ and take radius r in the driving magnetic field (see Fig. 1) defined by the equation

$$t = \int_0^{t_0} \frac{1}{f} dt = \int_1^N \frac{E_0 + 2qU\cos\varphi_s \cdot N}{qB(r)\cdot c^2} dN$$

where E_0 is the rest energy of the particle. This equation defines a connection between points in curves in Fig. 1.

For simulation of the beam acceleration from ion source output slit a bunch of 10000 particles was generated. Distribution of particles on transverse phase planes *(r, P_r)* and *(z, P_z)* is of Gaussian shape (see. Fig. 2) and matched with the parameters of the synchrotron central region optics which is taken similar to IBA S2C2 (see Fig. 3) [3]. Starting beam emittances are ε_r≈50π·mm·mrad and ε_z≈200π·mm·mrad.

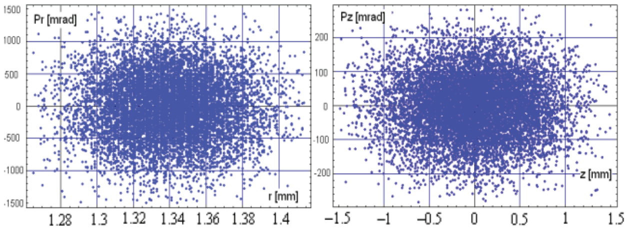

Figure 2: Distributions of particles on phase planes *(r, P_r)* and *(z, P_z)*.

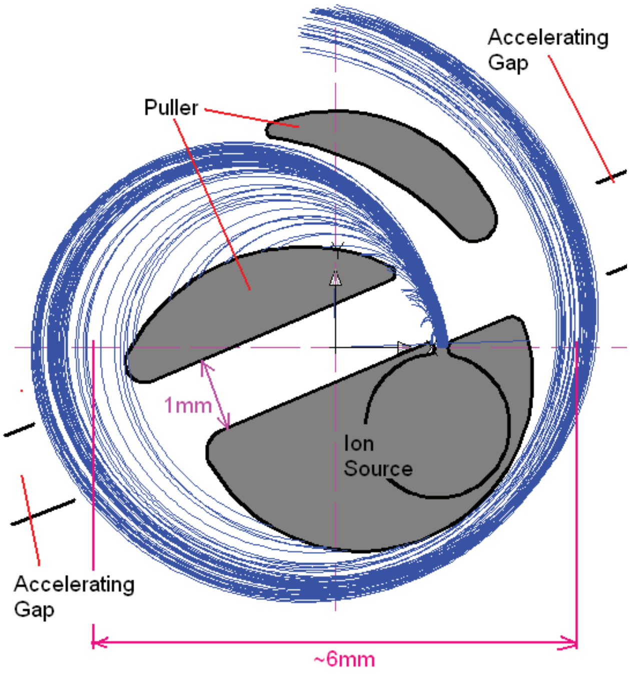

Figure 3: Central region elements and particles trajectories on the 1st turn.

These particles are uniformly distributed on starting phases due to RF-voltage in a range of [-90; +90]°RF. Energy of starting particles is 10eV. Initial time length of the bunch of 50μs was finally decreased down to 20μs when size and position of capture window were preliminary defined.

CAPTURE EFFICIENCY STUDY

Several RF frequency curves were used (see Fig. 4) to find the optimal one from beam capture efficiency point of view.

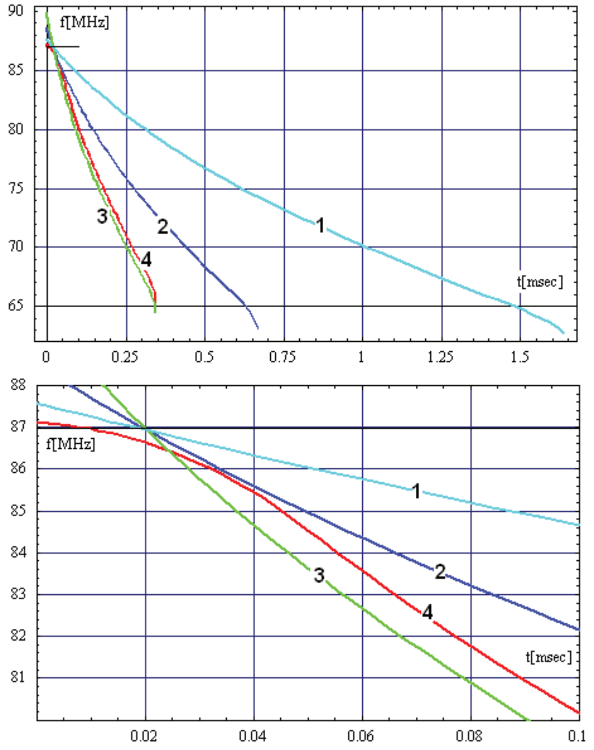

Figure 4: RF curves used for beam capture study in whole acceleration cycle (top) and in the very beginning part of RF-cycle.

These curves are not based on any RF-system design. Curves 1-3 ensure constant RF-phase of the synchronous particle: 84, 75 and 60°RF, correspondingly. RF-phase for synchronous particle changes during acceleration for the curve 4.

For curves 1-3 start time for the middle of the bunch time-width equals ~20μs; for curve 4 ~10μs. Distributions of captured in acceleration particles on plane (*time, RF-phase*) are shown in Fig. 5 for these four RF-curves.

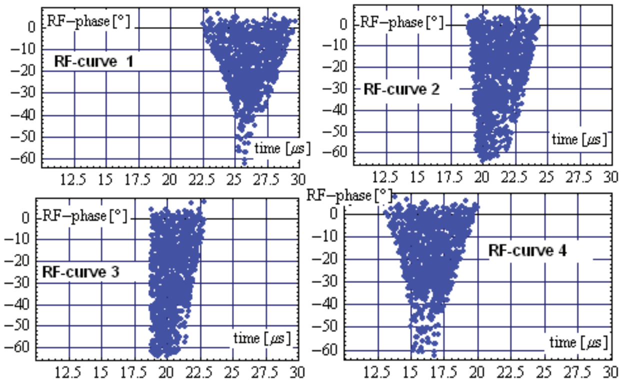

Figure 5: Initial distributions of captured in acceleration particles on plane (*time, RF-phase*).

Some parameters of the considered RF-curves at initial time moment are presented in the Table 1.

Table 1: Parameters of RF-curves at Synchronous Particle Starting Moment

RF-curve	***t_0 (μs)***	***$df/dt\|_{t0}$ (MHz/ms)***	***φ_s (deg)***
1	20	-31	84
2	20	-72	75
3	20	-126	60
4	10	-25	85

These four cases have different rates of RF-frequency change $df/dt|_{t0}$ at injection in the centre (at $t=t_0$) and due to this different synchronous particle phase φ_s.

Optimal for injection is case with RF-curve 2: for this case integral number of particles captured into stable acceleration is the maximal one.

Calculations show that particles with RF-phases in the range of [-60; +10]° are successfully accepted in synchrotron regime of stable acceleration. The width of the time-window for these particles is 5-7μs.

Quantitative analysis of losses at injection and during a period of one synchrotron oscillation was carried out to estimate capture as a function of injection time relative to moment when the RF-frequency equals to the revolution frequency of the particles in the centre.

To do this, narrow time distributed bunch (time-duration ~2μs) with RF-phases range [-90; +90]° was accelerated on 500 turns (one synchrotron oscillation) with losses analysis. The initial position of this bunch then changed in time in a range of [0; 12]μs. Obtained results for RF-curve 2 are shown in Fig. 6.

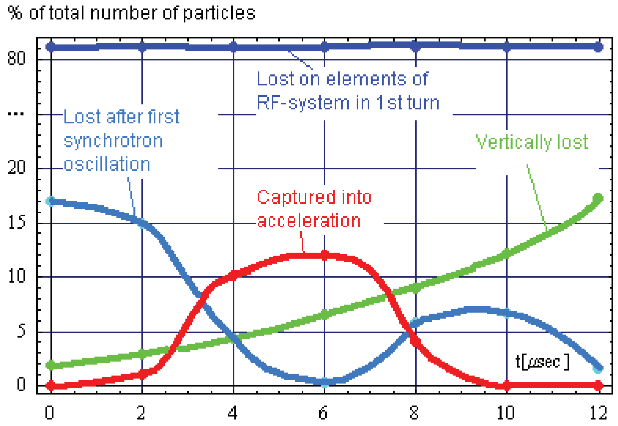

Figure 6: Capture efficiency and amount of losses as function of injection time.

Figure 6 also shows the interplay between captured into acceleration particles and those returned to the synchrocyclotron center after one synchrotron oscillation.

Basing on obtained results the capture efficiency of the accelerator was estimated taking into account amount of total captured particles and total duration of the RF-frequency modulation cycle. The collected data gives $k=8\cdot10^{-4}$. So, to get an extracted beam current of tenth of nA ion source must ensure the intensity of tenth of μA of continuous current in the centre.

CONCLUSIONS

The developed particles tracking software allows to study the capture efficiency in the synchrocyclotrons for different magnetic field maps and RF-frequency modulation data. Additional procedure was developed to construct the RF-curve which is ensuring constant equilibrium RF-phase for the synchronous particle during whole acceleration cycle.

Capture efficiency for the synchrocyclotron with driving magnetic field of ~5 Tesla was studied. Obtained results give $k=8\cdot10^{-4}$. The developed software can be used for optimization of the central region geometry of such a type accelerators.

REFERENCES

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