Development of the debuncher for the injector part of the accelerator complex NICA

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Abstract. The developed and currently manufactured debuncher for the injector part of the accelerator facility NICA is designed to reduce the energy spread by a factor of up to ten in the ion bunches with $Z/A=(0.33-1)$ at the output of the LU-20 linac. The debuncher includes a Split-Ring cavity, a vacuum system, a solid-state RF amplifier and an RF controller. The main design parameters are described.

1. Introduction

The Nuclotron based Ion Collider fAcility and Multi Purpose Detector (NICA/MPD) [1] aim to create an accelerator facility for research in the field of particle physics in the previously inaccessible area of parameters and experimental conditions. Among other things the injector of light ions in the NICA facility includes an accelerator LU-20 and a debuncher.

In the frame of NICA project, the light ions injector equipment is assumed to be replaced by the new one in the future. The debuncher described in the present paper will be a prototype for the new one. The debuncher is intended to reduce by a factor of up to ten the width of the energy spectrum of the accelerated ion beam after the linear accelerator LU-20 and 6 m drift space.

The ion energy at the LU-20 output is 5 MeV/nucleon. The debuncher is to be optimized for $Z/A=0.5$ and operate in the range $Z/A=0.3-1.0$ at $Z=1$ and the relative ion speed $\beta=0.1028261$.

The relative energy spread of the ion bunch is supposed to be $dE/E=\pm 2.5 \times 10^{-4}$ at the debuncher output. The total phase length of the ion bunch is of 30-35° at the debuncher input.

The main technical parameters of the debuncher

The debuncher consists of a cavity and vacuum, alignment and RF systems.

All the debuncher equipment will be localized close to the debuncher cavity. Location conditions of the electronic equipment provide the radiation dose rate as small as $\leq 2 \mu$Sv/h.

The RF master generator signal will be sent from the control system of the LU-20 accelerator.

The main parameters of the debuncher are presented in Table 1.
Table 1. The main parameters of the debuncher.

| Parameter                                              | Designation | Unit | Value  |
|--------------------------------------------------------|-------------|------|--------|
| Adjustment range of the cavity accelerating voltage   | $UT$        | kV   | 0-200  |
| Operating frequency                                    | $f$         | MHz  | 145.25 |
| Tuning range of the cavity                            | $\Delta f$ | kHz  | ±250   |
| Coupling coefficient of the feeding line and the cavity| $\beta$     | kHz  | 1.0    |
| Instability of the input power of the cavity           | $\delta P$  | %    | ≤3     |
| Instability of the accelerating voltage flat-top       | $\delta U$  | %    | ≤2     |
| Operating pressure                                     | $p$         | mbar | ≤3·10^{-8} |
| Adjustment range of the accelerating voltage phase    | $\Delta \phi$ | degree | 360 |
| Power of the RF master generator signal                | $P_m$       | dBm  | 20-30  |
| Rise/full length of the pulse                          | $\tau_R$    | µsec | 200    |
| Flat-top length of the pulse                           | $\tau$      | µsec | 100-300|
| Pulse repetition rate                                  | $F$         | Hz   | ≤0.5   |

2. Cavity types for the debuncher

Several different types of the cavity, which can be used in the debuncher potentially, have been considered and simulated. They are shown in Figure 1.

\[ \text{Figure 1. The cavity types considered for the debuncher (}n\text{ is the number of accelerating gaps).} \]

Electrodynamic parameters, multipacting and manufacturing technology have been investigated. The results are summarized in Table 2.

The cavity with 2 gaps is the simplest variant, but there are multipacting conditions in this cavity. The cavities with 4 and 5 gaps are unreasonably difficult for manufacturing.

As a result, the cavity with 3 gaps (the so called Split-Ring cavity [2]) has been chosen. Its main advantage is the absence of the multipacting condition. It has rather acceptable electrodynamic parameters such as shunt impedance $R_{\text{sh.eff}}$, Q-factor $Q_0$, power loss $P$, max electric field $E_{\text{max}}$ comparing with the Kilpatrick criterion $E_k$.

3. Split-Ring cavity

3.1. Field distribution

Calculated distribution of electric and magnetic fields on the cavity surface as well as electric field in the cavity volume and on its axis are shown in Figure 2.
Table 2. Calculated parameters of the cavities.

| Number of gaps | $n$ | 2   | 3   | 4   | 5   | 5   |
|----------------|-----|-----|-----|-----|-----|-----|
| Diameter×length | $D\times L$ | mm  | 250×520 | 412×288 | 414×415 | 404×494 | 530×492 |
| Effective voltage | $UT$ | kV  | 200 | 200 | 200 | 200 | 200 |
| Shunt impedance | $R_{sh\text{, eff}}=(UT)^2/P$ | MOhm | 8.42 | 11.68 | 25.5 | 25.5 | 41.6 |
| Q-factor | $Q_0$ | 10000 | 9430 | 11700 | 15046 |
| Power loss | $P$ | kW | 4.7 | 3.4 | 1.6 | 1.6 | 1.0 |
| Max electric field | $E_{max}$ | MV/m | 10.3 | 8.0 | 5.3 |
| Relative max electric field | $E_{max}/E_k$ | 0.80 | 0.62 | 0.41 |
| Multipacting presence | | yes | no | yes | no | yes |
| Frequency of the nearest non-operating mode | $f_m$ | MHz | 420.8 | 121.1 | 240.0 | 116.5 |

Figure 2. Distribution of electric (a) and magnetic (b) fields on the cavity surface, electric field in the cavity volume (c) and on the cavity axis (d).

3.2. Thermal effects in the cavity
For operations with $UT=200$ kV, $\tau=400$ µsec, $F=1$ Hz the estimated average power loss $P<50$ W/m$^2$ is rather low, resulting in a temperature rise of 0.5°C at the drift tubes with respect to the cavity walls.

3.3. Multipacting effects in the cavity
First of all, test calculations were performed for the GSI four-gap debuncher at 108 MHz [3, 4]. The results showed that the GSI debuncher is not free of multipacting. The combination of its frequency, voltage and dimensions creates conditions for the development of the medium intensity multipacting. The experimental studies of this debuncher showed that prolonged conditioning (at least a week) allowed one to get working conditions and the debuncher is currently operating successfully. The results of the performed calculations are confirmed by experimental results.

The two-gap 145 MHz cavity is not free of multipacting too, and its intensity is similar to that of the GSI debuncher.

The three-gap 145 MHz Split-Ring cavity is practically free of multipacting. The results of multipacting investigation in the cavity are shown in Figure 3: electron trajectories, increase in the number of particles as a function of the voltage $UT$ and the number of electrons in time at different voltages $UT$. 
The four- and five-gap 145 MHz cavities of similar type have the multipacting conditions similar to those of the GSI debuncher.

The five-gap 145 MHz Split-Ring cavity is practically free of the multipacting development.

4. Beam dynamics
The debuncher is intended to reduce the energy spread of the accelerated ion beam after the linear accelerator LU-20 and 6 m drift space. The ion energy spectrum at the LU-20 output depends on the operation regime. The beam dynamics simulations were performed for rectangular phase space with a specified small phase length and real energy spread at the LU-20 output. Thus, any real phase space at the LU-20 output can be modelled as a sum of several rectangular phase spaces.

Figure 4 shows simulated distributions in the beam-line LU-20 – drift space – debuncher at Z/A=0.5.

To decrease the energy spread to $dE/E = \pm 2.5 \cdot 10^{-4}$, the optimal voltage $UT$ in the cavity should be $UT = 58$ kV; 121 kV and 190 kV for $Z/A$ = 1.0; 0.5 and 0.3 respectively.

5. Engineering design
The design of the debuncher is shown in Figure 5. It includes a copper plated stainless steel cavity body, a copper vibrator with drift tubes, an input coupler with N-type connector, a pin-antenna with N-type connector, a frequency tuner with stepper-motor, input and output aperture connection pipes, two connection pipes for vacuum sensors IKR-060 and TPR-018, a connection pipe for the turbo pump HiPace 700, alignment and RF systems. All the vacuum connectors are of the ConFlat type.
6. RF system

The RF system is intended to provide RF feeding of the debuncher with a peak power up to 7 kW. It includes an RF amplifier, and RF controller with a control system and a stepper-motor controller.

The master RF signal goes from the LU-20 control system, which carries out its phase control, to RF controller input.

The RF controller provides monitoring of both the RF signals from the cavity and forward and the reflected RF signals from the directional coupler located at the RF amplifier output.

Adjustment of the RF master signal power can be made from the control terminal of the LU-20 control system and ETHERNET via controlled attenuator. The accelerating voltage stabilization (i.e. RF power stabilization of the RF master signal) is realized using feed-back circuit and RF signal from the cavity.

The RF controller allows us to adjust the resonant frequency of the cavity in such a way as to make it equal to the operation frequency. This adjustment is realized via the following circuit: control terminal of LU-20 control system – ETHERNET – RF controller with the stepper-motor controller – tuner of the cavity.

The RF amplifier is made on the base of four MRFX1K80H LDMOS transistors with a max output power of 1800 W each. Input RF power comes from the RF controller. Amplified power of four transistors is summarized in the RF combiner and then passed to the cavity via coaxial directional coupler to monitor forward and reflected RF power.

The control system provides a possibility of connection to the LU-20 control system via ETHERNET and coaxial cables to monitor the signals as well as to adjust the accelerating voltage.

References

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