MULTIGAP AND POLYHARMONIC BUNCHING SYSTEMS AT FLNR CYCLOTRONS

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Abstract

Since 1997, different variants of bunching systems have been used at the axial injections of FLNR cyclotrons to increase ions capture into acceleration efficiency. Combination of two single gap Sine and Line bunchers are used at the axial injections of U400 and DC110 cyclotrons. Since 2015, a single gap double RF harmonic buncher has been installed into the upper part of the U400M injection in addition to the lower sine buncher, the experimental results is being presented. For the HV axial injection of the new DC280 cyclotron, two variants of polyharmonic bunchers will be used: a multigap buncher and a single gap one.

INTRODUCTION

At present time, axial injection systems with ECR ion sources are integral components of heavy ion cyclotrons at the Flerov Laboratory of Nuclear Reaction of the Joint Institute for Nuclear Research (FLNR, JINR). The axial injections allowed us to use bunchers for matching the longitudinal ion beam emittance with the cyclotron phase acceptance, as for linacs. The typical voltage of ion extraction from our ECR sources is $U_{inj}=15\div20$ kV. The typical phase acceptance (CPA) of our cyclotrons is $20^{\circ}\div30^{\circ}$. The typical capture into acceleration efficiency (CIAE) without beam bunching is $5\div8\%$.

The best type of bunchers from the point of view CIAE increasing is the buncher with saw-tooth voltage in the gap (linear buncher) [1]. The calculated CIAE with the bunchers is 80÷90%, but their using is restricted by technical difficulties. The simplier type of bunchers is the buncher with sinusoidal voltage in the gap (sine buncher). The simulated CIAE for the sine buncher is about 50% [2].

Unlike linacs, the design of the sine buncher for the FLNR cyclotrons cannot been made in form of a single gap $\lambda/4$ resonant cavity because our cyclotrons use relatively low accelerating frequencies: 5.4-22 MHz ($\lambda/4$ = 3.5÷14 m). Therefore, we have utilised bunchers with two grids that are fed with a special resonant system. The resonant system consists of two extended coaxial resonators (or cables), matching inductors and variable capacitors for resonance turning. The system allows us to form sinusoidal voltages at both buncher grids in anti-phases to prevent additional acceleration of ions in central phases and for decreasing influence RF fringing fields on CIAE before and after the buncher gap. The buncher can be installed into the vertical part of an axial injection at various distances from a cyclotron median plane (CMP). We received the best CIAE at the U400 cyclotron when the buncher was situated at 0.8 m above the CMP. The voltage amplitude at the gap was about 700 V (optimized by maximal CIAE). The CIAE was 15÷29% depending on ion current (the parameter decreases with ion current increasing) [3].

Experimental values of CIAE with our bunchers are typically lower than calculated ones. The reasons of it can be influence of space-charge effects. The effects become significant in vicinity of the CMP where the bunch pulse current is in one order higher than the DC ion current at the ECR exit. In addition, there are other factors such as: path difference of ions into longitudinal magnetic field of the axial channel and into the helical inflector; losses of ions at the buncher grids and at residual gas.

For further improvement of the FLNR cyclotrons CIAE we have made multigap and polyharmonic bunching systems.

One more way of the CIAE improvement is to increase energy of injected ions, we are planning to apply the method for our new DC280 cyclotron [4].

MULTIGAP BUNCHING SYSTEMS

Multigap Buncher for the U400

As a variant of a multigap system we have unilized two single gap bunchers. The bunchers have been situated at different distances from the U400 CMP. We use combination of linear buncher and existing sine buncher (Fig. 1). The linear buncher has been situated at 4.4 m from the CMP [5]. The system has been developed for RF frequency range of $5.4\div12$ M Γ I and U_{inj}= $13\div15$ kV ($\beta\lambda$ =80 mm). The voltage amplitudes at grids were about 180 V (linear) and 650 V (sine). The U400 CIAE without bunchers is over 5%. The system allowed us to reach $23\div38\%$ of CIAE, depending on ion current [6]. The contribution of the linear buncher to the CIAE was about 1.4.

Multigap Buncher for the DC110

The similar system has been installed at the D110 cyclotron injection [7]. The system was developed for RF frequency of $7.65^{\pm0.16}$ MFu and U_{inj} =20 kV ($\beta\lambda$ =98 mm). The bunchers have been situated at 0.8 m (sine) and 2.45 m (linear) above the CMP. The calculated phase distribution after bunched beam drifting for 2.45 m and corresponding distribution of the particle density in the bunch of $_{132}Xe^{20+}$ ions at the DC110 CMP are shown in Fig. 2. The calculations have been carried out with the use of the large particle method without account for the space charge effects and other effects mentioned above. The voltage amplitudes was 700 V for linear buncher (with ideal saw tooth voltage) and 300 V for sine one. The calculated CIAE was about 61% for the CPA value of 30°.

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Figure 1: Layout of two bunchers system at the U400. Where: the linear buncher forms bunches with phase extent of 180° before the sine one. The sine buncher forms bunches before the CMP with phase extent of 20° .



Figure 2. Left: Calculated dependence of the ion phases (after drifting for 2.45 m) at the buncher output Fi out on the phases at the buncher input Fi in for A/Z = 6.6. Right: Calculated distribution of the particle density in a bunch at the DC110 CMP.

To create saw-tooth voltage in the gap of the linear buncher, the special modulator has been developed. The maximal peak to peak voltage was up to 700 V which was created with using transistor modulator. The modulator allows us to form bipolar saw-tooth voltage ± 350 V at the buncher grids. The maximal pick-to-pick voltage in the gap is ± 700 V. The experimental signal of the grid voltage has distortions caused by operation of transistors (Fig. 3).



Figure 3. The experimental shape of saw-tooth voltage at the linear buncher grid.

The experimental CIAE for the system was $34\div38\%$ for ion currents in the region from 20 to 100 μ A. The corresponding experimental gap voltage amplitudes were about 700 V (linear) and over 430 V (sine). The CIAE without bunchers was about 9%. The linear buncher contribution to the CIAE was about 1.4.

POLYHARMONIC BUNCHING SYSTEMS

Creation of linear bunchers for cyclotrons is accompanied by some technical difficulties. For example, installation of the buncher near the CMP is restricted by possibility to translate saw-tooth voltage from a generator to a buncher at the distance of few meters without signal distortions. Another problem is creation of voltage amplitudes higher than 1 kV because of necessity to use lamp schematics instead of transistor one in presence of cyclotron fringing magnetic field. Therefore, we have started to develop polyharmonic bunchers. The type of bunchers was successfully used for linacs at fixed RF frequencies, but for cyclotrons it has to be tunable in RF frequency range. The problem is hardly solved for single gap polyharmonic bunchers and can be simplified a bit for multigap ones.



Figure 4. Left: Calculated dependence of the ion phases (after drifting for 3.8 m) at the buncher output Fi out on the phases at the buncher input Fi in for A/Z = 7, f=7.68 MHz. Right: Calculated distribution of the particle density in a bunch at the DC280 CMP.

Polyharmonic Multigap Buncher for the DC280

The DC280 cyclotron will be equipped with HV injection [4]. The injection voltage will be up to 80 kV ($\beta\lambda$ =157 mm). If we will use a linear buncher, the maximal voltage amplitude in the gap will be about 5 kV. The estimated power of the saw-tooth voltage generator is more than 10 kW. Therefore using of a polyharmonic buncher with a resonant feeding system looks like more attractive. To simplify the system turning to DC280 frequencies (7.3÷10.4 MHz) we will use only three RF harmonics.

The buncher consists of a drift tube with a length of $\beta\lambda/2$, which allows us to decrease the RF voltage amplitude of first harmonic in two times to 1.2 kV (the harmonic corresponds to the cyclotron accelerating frequency). The second harmonic with maximal amplitude of 1 kV will be applied to the wolfram grid located before the drift tube. The third one with maximal amplitude of 0.6 kV will be applied to the grid located after the drift tube. Grounded grids are mounted between the drift tube and the harmonic grids in order to exclude the mutual influence of the harmonics. The total power of resonant feeding system (three separated tunable resonators) is estimated not more than 250 W.

The calculated phase distribution after bunched beam drifting for 3.8 m and corresponding distribution of the particle density in a bunch at the DC110 CMP are shown in Fig. 4. The calculated CIAE was about 80 % for the CPA value of 40°. The loses of ions at the buncher grids was estimated as $8 \div 10\%$. The calculated phase spread after the

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helical inflector is $\pm 15^{\circ}$, which can be a reason of the CIAE decreasing too. We plan to reach more than 50% of the CIAE with the buncher.

Single Gap Polyharmonic Bunchers

To minimise ion losses at the buncher grids we are planning to use a single gap polyharmonic buncher. In this case, we need to sum few harmonics at a gap as it was made in [8], for example. The method of turning of a special resonant system has been proposed in [9]. To test of the system workability we have created a model of a single gap buncher with two harmonics.



Figure 5. Principal scheme of resonant system of the double harmonic buncher. Where: HB is the buncher, $L1 \div L4$ are coaxial cables (L=1 m); C1,C3 are variable capacitors for the 1-st harmonic ($12 \div 495 \text{ pF}$); C1'is the compensation capacitor (60 pF); C2 are variable capacitors for the 2-nd harmonics ($12 \div 495 \text{ pF}$); C5,C6 are coupling capacitors (22 pF and 64 pF); S1,S2 are RF generators for 1-st and 2-nd harmonics; D1,D2 are motor drives.



Figure 6. Typical voltage (U) and current (I) distribution along the resonant system (Lr=L1+L2+L3+L4, Fig. 5) for the first (1) and the second (2) harmonics.

The buncher has been installed into the axial injection of the U400M cyclotron at 4.4 m above the U400M CMP. The U400M RF frequency range is 11.5÷24 MFI, U_{inj}=18 kV ($\beta\lambda$ =45 mm). The buncher has been utilized in combination with the sine buncher, situated at 0.75 M above the CMP. The CIAE with the sine buncher was 13÷15%, that is lower than one for the U400. The reason of it can be lower $\beta\lambda$ that leads to bunch squeezing to a shorter length in presence of the same debunching factors. In 2015, the system has been tested with the RF frequencies of 14.68 MHz (1-st harmonic, U1=140 V) and 29.36 MHz (2-nd harmonic, U2=70 V). The regime has been used for acceleration of $_{48}$ Ca⁺⁶ and $_{40}$ Ar⁺⁵ ions. The CIAE without bunchers was about 5%.

The experimental CIAE after addition the upper double harmonic buncher was about 19% at the ion current is about 70 μ A. The contribution of the double harmonic buncher to the CIAE was over 1.35, that is comparable with contribution of the linear buncher for the U400. The buncher resonant system (Fig. 5) allows us to carry out the buncher turning in the U400M RF frequency range. The 2-

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nd harmonics signal applied to the point where the 1-st harmonics has the maximal voltage (Fig. 6). For the U400M, the scheme has been modernized to form voltages at both grids in anti-phases. The similar principle will be used for a single gap polyharmonic buncher at the D280.

CONCLUSION

The multigap and polyharmonic bunching systems are efficiently utilized at the FLNR cyclotrons. The experimental CIAE value is in $1.5\div 2$ times lower than the calculated one for ion injection voltage up to 20 kV. The experimental CIAE depends on $\beta\lambda$ value (Table 1). Increasing the ion injection energy and using polyharmonic bunchers can improve the CIAE.

Table 1: Parameters of the FLNR Bunchers				
Cyclotron	βλ mm	Туре	CIAE %	Notes
U400M	45	Multigap polyharm.	19	Testing
U400	80	Multigap	23÷38	Linear+Sine
DC110	98	Multigap	34÷38	Linear+Sine
DC280	157	Multigap polyharm.	>50	Expected

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