Choosing RF system for low energy RHIC operation

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I. Introduction.

While becoming an important part of RHIC physics program, the low energy RHIC operations present substantial challenges. There is a significant body of both theoretical and experimental studies addressing these problems and possible remedies [1-16].

While main physics challenge in reaching high luminosity rests with the space charge induced tune spread, there are other technical limitations strongly affecting the luminosity, life-time and overall RHIC performance in low energy collisions.

II. Role of RF system

One of the technical challenges is the limited acceptance of existing RF system, specifically, the size of the RF bucket area. For very low energy RHIC operations (see [8,12,16]) longitudinal emittance of injected ion bunch frequently exceeds the bucket area. If bucket is full, it opens ways for particles to escape RF buckets via intra-beam scattering (IBS) process and Touschek effect.

In short, for normal collider operation at low energy it is important to have an RF bucket acceptance exceeding the longitudinal emittance of the ion bunch. A margin ~ 2 is also desirable to keep ions from de-bunching.

In addition, it is strongly desirable – especially at lowest energies - to elongate ion bunches for reducing space charge tune spread, ΔQ_{sc}, which is proportional to peak current of ion beam. E.g., for a given number of particles per bunch, ΔQ_{sc} is inversely proportional to the ion bunch length. For a given RF bucket acceptance and longitudinal emittance of the beam, the later can be increased by reducing RF harmonic.

The equations for synchrotron oscillations are well known

$$\delta = \frac{E - E_0}{E_0}; \quad \varphi = 2\pi h_{RF} f_o \tau;$$
$$\frac{d\delta}{dn} = -\frac{eZ \cdot V_{RF}}{A \cdot E_n} \sin\varphi; \quad \frac{d\varphi}{dn} = 2\pi h_{RF} \eta \cdot \delta \tag{1}$$

where E_o is the energy per nucleon of the ion with charge Ze and atomic number A, h_{rf} is RF harmonic number of RF system with voltage V_{RF}, $f_o = C / \mathrm{v}_i$ is the revolution frequency of ions, C is the circumference of the ring , and

$$\eta = \frac{1}{\gamma_o^2} - \frac{1}{\gamma_t^2} \tag{2}$$

is the slip factor with $\gamma_o = E_o / mc^2$ being relativistic factor of ions and γ_t that at the transition energy (in RHIC $\gamma_t \sim 23$). The Hamiltonian of the system is:

$$H = 2\pi h_{RF}\eta\frac{\delta^2}{2} + \frac{eZ\cdot V_{rf}}{A\cdot E_o}(\cos\varphi + 1).$$

The acceptance of the RF bucket is the phase space area inside the RF separatrix (see Fig.1) is given by a simple formula:

$$\varepsilon_{acc} = \frac{4C}{\pi \nu_i}\cdot\sqrt{\frac{2eZ\cdot E_o}{\pi\eta A}\cdot\frac{V_{rf}}{h_{rf}^3}}\,. \tag{3}$$

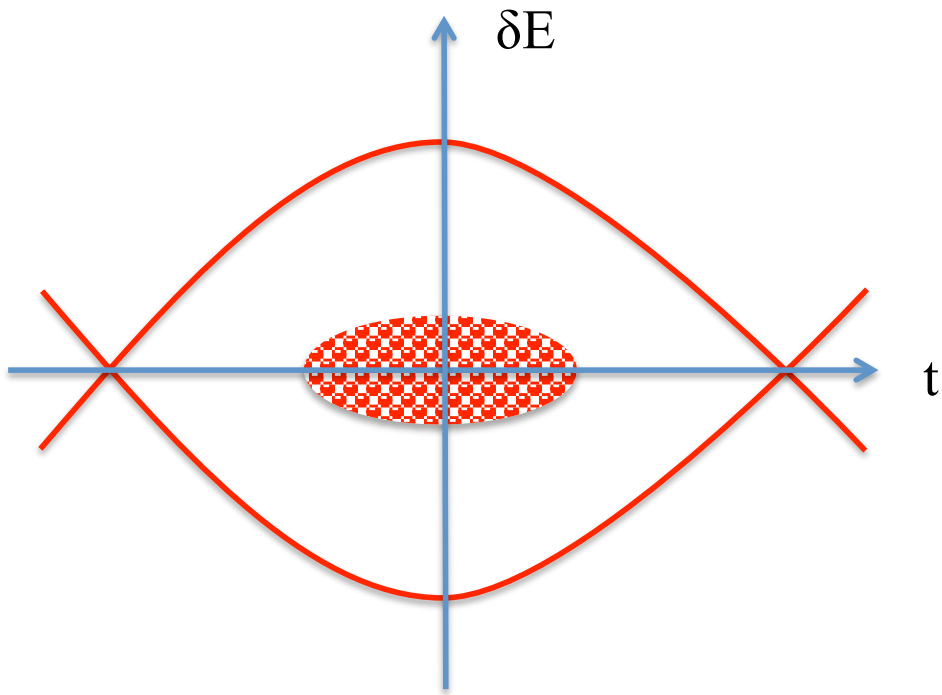

Fig. 1. RF separatrix with acceptance exceeding the longitudinal emittance of the ion bunch.

Two main scalings following from formula (3) are:

a) the energy acceptance is proportional to 3/2 power of beam energy: $\varepsilon_{acc} \propto \gamma_0^{3/2}$;
b) the voltage required to keep constant acceptance is proportional to cube of the harmonic number (i.e. doubling RF frequency requires 8-fold increase in voltage!)

According to [17], RHIC injection complex could be capable to deliver $5.6\cdot 10^8$ Au ions per bunch with longitudinal emittance of 0.14 eV·sec. If higher intensities for bunch are needed, the merging and re-bucketing in the injector chain would increase the emittance at least to the total of the merged bunches. In some cases resulting longitudinal emittance can be at large as 1 eV sec [18].

As can be seen from Table I, existing RF system do not provide sufficient RF acceptance at low energies.

Table I. RF bucket acceptance (i.e eV sec) of existing and planned RHIC RF[1] systems

E_o, Gev/u	*γ*	*200 MHz 4 MV*	*56 MHz 2 MV*	*28 MHz 450 KV*	*9 MHz 10 KV*
2.55	*2.7*	**0.017**	**0.072**	**0.097**	**0.075**
3.85	*4.1*	**0.032**	**0.147**	0.197	0.152
5.75	*6.1*	**0.061**	0.283	0.379	0.294
10	*10.6*	0.155	0.718	0.963	0.746

Clearly, the lowest frequency (9 MHz) cavity needs only 10 kV of voltage to comfortably compete with energy acceptance of MV and sub-MV voltages in higher frequency RF systems. As indicated in [8], there are significant additional advantages of using 9 MHz system, especially at higher voltage ~ 100 kV. While providing a necessary RF bucket acceptance, such RF system will operate longer ion bunches and reduce the strength of space charge. According to our RF experts [19], the peculiarities of our 9 MHz cavities make difficult attainment of such RF voltage. It will require a large number of such cavities, which most likely would not fit into remaining space in IP4.

At the same time, there are very low frequency compact ferrite-loaded RF cavities used in AGS, which comfortably provide voltage from 8 to 12 kV [20]. Hence, I suggest using a dedicated lower frequency of 4.5 MHz RF system with maximum voltage of 10 kV for low energy operation of RHIC. Table 2 gives the beam parameters with the use of this system:

Table II. Bunch parameters with 10^9 Au ions and 4.5 MHz RF system[2].

Energy, Gev/u	***2.55***	***3.85***	***5.75***	***10***
γ	***2.7***	***4.1***	***6.1***	***10.6***
V_{rf}, kV	10	5	2	2
RF bucket, eV sec	**0.236**	**0.319**	**0.379**	**0.950**
RMS bunch length, nsec	21.5	18.0	16.3	10.2
Q_s	0.0016	0.0006	0.0002	0.0001
ΔQ_{sc}	**0.057**	**0.028**	0.013	0.007

What transpires from the Table 2 is that low frequency RF is an excellent remedy for solving many of low energy operation problems. The RF bucket acceptances are larger,

[1] Maximum RF voltage for the systems are rounded

[2] Bunch intensity: 10^9 ions per bunch. For bunch lengths, I assume an ion bunch with 95% longitudinal emittance of 0.1 eV sec. The bunch length scales as a forth root of the emittance. For space charge tune spread I assume RMS normalized beam emittance of 2.5 mm mrad (95% emittance of 15 mm mrad).

the bunch lengths are longer, the synchrotron tunes are lower, and what is the most important, the space charge induced spread is under better control.

Even at lowest suggest operation energy of 2.5 GeV/u full intensity beam with 10^9 Au ions per bunch would have $\Delta Q_{sc} \sim 0.057$. One should compare this with $\Delta Q_{sc} \sim 0.122$ for proposed upgraded 80 kV 9 MHz RF system with the same bucket acceptance [8]. The ΔQ_{sc} falls as square of the ion beam energy and stays bellow 0.02 for energies above 4.5 GeV/u! According to [9], space-charge induced tune spreads below 0.02 are reasonable for operating RHIC, and they should be kept below 0.03 to have lifetime above 20 minutes. It means that we need reducing intensities below nominal 10^9 ions per bunch for ion's energy blow 4 GeV/u.

For comparison with prior studies, with 4.5 MHz RF system limiting $\Delta Q_{sc} \leq 0.03$ should allow operating with full intensity at 3.85 GeV and would require reducing the intensity to $5.25 \cdot 10^8$ ions per bunch at 2.55 GeV.

Naturally, this configuration is also well suited for low energy electron cooling with all its promises of increased luminosity [6,8]. Lower value of space charge induced tune spread, ΔQ_{sc}, ensures a long natural life-time for the ion beam if the transverse aperture is not a limitation.

At energies above 4 GeV/u the dedicated 4.5 MHz RF system provides the room for a nominal value of the beam-beam tune spread typical for ion beam collision in RHIC. It also provides window for trade-offs: for example, increasing the space-charge induced tune spread by cooling beam transversely to increase the ratio between the available transverse aperture and the transverse beam size. Hence, an optimum luminosity lifetime can be established. If necessary, the intensity of the ion bunches can be also trimmed to optimize the recorded luminosity.

III. Accessible energies for low energy run

As clearly indicated in [5], the existing RHIC RF system has a limited frequency tuning range. The low energy scan required the change of RF harmonic in RHIC RF systems. Colliding beams in both STAR and PHENIX detectors and satisfying their triggering requirements limit the choice of energies to quite a few choices (see Table 1 in [5]).

A proposed dedicated 4.5 MHz RF system would utilize ferrite-loaded cavities, which are broadly tunable. Low energy scan require a modest ±3.5% (± 160 kHz) frequency tuning range. It will cover all energies of interest from 2.5 MeV/u up. Hence, the harmonic number can be fixed – for example at 60 – and RHIC will operate with 55 bunches colliding both at STAR and PHENIX.

It means that this dedicated RF system will support experiments required a detailed scan at any RHIC energy above 2.5 GeV/u.

IV. Discussions and conclusions

Finally, there is a question abound how detectors will deal with the collisions of long bunches at half of the regular 9 MHz collision frequency? The later is not a problem since RHIC produced various filling pattern on a number of occasions. Furthermore, we could keep number of RF buckets to be fixed at 60.

The remaining question is if pro-longed collisions could be a problem for detectors to collect the data. Both STAR and PHENIX coordinators [21] indicated that the detectors could accept such pattern with acceptance window of about 50 nsec per collision in STAR and 20 nsec per collision in PHENIX. I was told that it will not be trivial, but it is doable.

Collisions outside the window would be lost, but would not constitute a problem. As shown in Fig. 2, even for the worst-case scenario of 2.55 GeV/u (γ=2.7) collisions, STAR will accept 90% of events, while PHENIX will accept 58% of events. Situation dramatically improves at higher energies, and PHENIX will accept >90% of the events at energies above 5.5 GeV/u. (see Fig. 3)

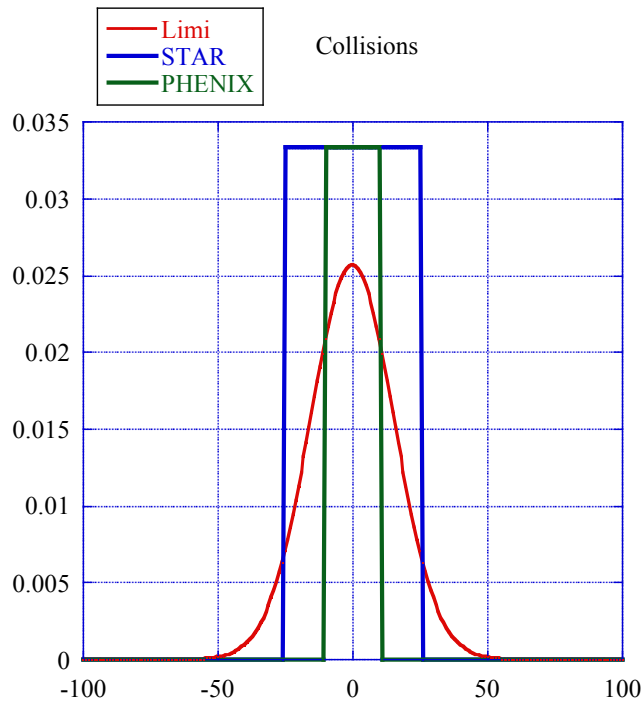

Fig. 2. Time structure of beam collision for 2.55 GeV/u Au beam with 4.5 MHz RF system. The window indicate the STAR and PHENIX acceptance.

I want to conclude that the dedicated low frequency RF system opens new opportunity for high luminosity operation of RHIC at low energies. It is fully compatible with low energy electron cooling and all luminosity gains promised by using it. Detailed studies of the luminosity gains with 4.5 MHz RF and electron cooling are underway [22].

Unique feature of this proposed RF system is that low energy scan no longer will be limited to a small number of rigidly fixed energy points. Instead, the proposed RF system will provide collision at any desirable energy above 2.5 GeV/u ($\sqrt{s} = 5GeV$).

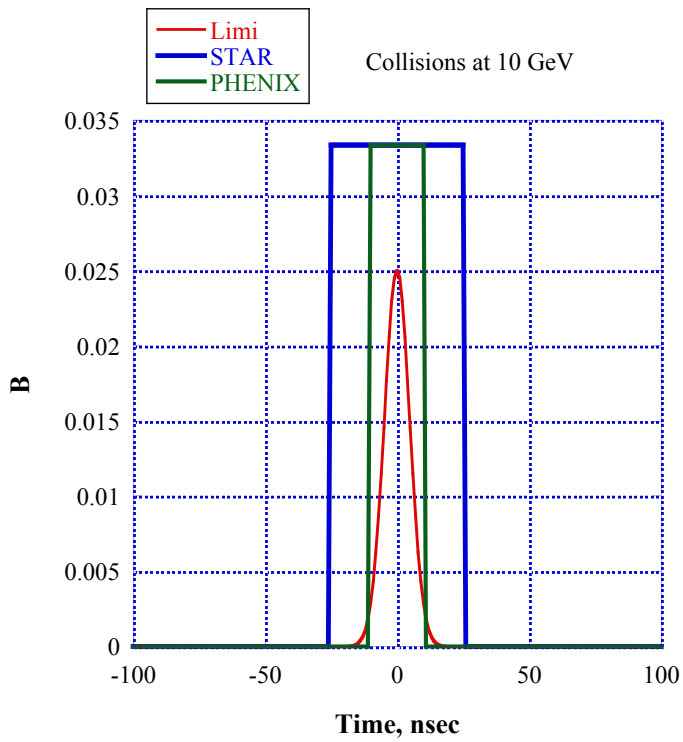

Fig. 3. Time structure of beam collision for 10 GeV/u Au beam with 4.5 MHz RF system. The windows indicate the STAR and PHENIX acceptance.

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