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# RF cycles in RHIC

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RHIC/RF-4

# RHIC Project
BROOKHAVEN NATIONAL LABORATORY

**RHIC/RF Technical Note No. 4**

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# RF CYCLES IN RHIC

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This is basically an introduction of RHIC RF system and RF cycles intended to illustrate what an RF cycle might be, how the bunch changes and the $V_{rf}$ program.

First, I'll use a few slides to tell you about the RF systems and their parameters. Then, I'll try to show how to devise an RF cycle, which has 4 major region, i.e. injection, acceleration, transfer and storage. Simply put, to specify an RF cycle is just to specify the RF voltage program. Each region has a different requirement.

**Slide 1**

**RF Cycles in RHIC**

1. **RF systems**
2. **RF cycles**
   - **Injection**
   - **Acceleration**
   - **Transfer**
   - **Storage**

RHIC is a collider for ions ranging from proton all the way to fully stripped gold ions. All ions except protons will go through transition in RHIC. In terms of whether a beam goes through transition or not, we can divide the physics program into 3 main categories SLIDE 2. Gold ions and protons represent two extreme cases, so are their RF cycles. Other cycles fall in between.

**Slide 2**

Three protocol cases:

- $Au \leftrightarrow Au$,
  both beams go through transition.
- $p \leftrightarrow p$,
  no beams go through transition.
- $Au \leftrightarrow p$,
  only one beam goes through transition.

The utimate task for the RF systems is to put the bunches in storage buckets for physics experiments. The task can be divided into a few stages: capture injected bunches, accelerate them to goal energy level, and then put the bunches in the storage buckets with as little beam loss as possible.

RHIC RF systems are designed to have two types of cavities: accelerating and storage. Storage cavities are used to accept bunches from accelerating cavities. The accelerating cavities capture bunches from AGS and accelerate them to desired energies (in collaboration with dipole field programs.), if the bunches aren't short enough for safely transferring in the storage system, the accelerating cavities have to manage to shorten the bunches (SLIDE 3, top).

See (SLIDE 3, bottom) for the the configuration of cavities in the rings.

Slide 3

| |
|---|
| Objective:<br>• To capture beams from AGS and accelerate them to desired energies.<br>• To create short bunches and store them for a long time.<br>• To make the beams collide.<br><br>Two RF systems:<br>• Accelerating cavities: to capture, accelerate and shorten the bunches.<br>• Storage cavities: to store shortened bunches.<br><br>In each ring:<br>• 2 accelerating cavities.<br>• 2 storage cavities.<br><br>Two rings share: 4 (6?) storage cavities around one IR region. |

Let's present some cavities parameters. The circumference ratio of RHIC ring and its injector AGS is $\frac{19}{4}$, the harmonic number of AGS is 12. The "minimum harmonic number" is then $\frac{19}{4} \times 12 = 57$, which is also the "minimum number" of bunches RHIC can accelerate. To be able to upgrade to double the number of bunches. The harmonic number of accelerating cavities has to be in groups of $57 \times 2 = 114$. 342 is chosen. The bucket lengths are large enough to accept proton and ion bunches. Each cavity can provide 200 $kV$, a total of 400 $kV$. The acceleration voltage is chosen as 300 $kV$.

The storage cavities are purchased from CERN, which has a designed frequency of 200 $MHz$. The harmonic number (in groups of 114) has to be chosen to reflect this constaint. $h_{storage} = 114 \times 22$ gives arise of 196.1 $MHz$. Each cavity can provide a maximum 1 $MV$, a total of 6 $MV$. Such high voltage is required to contain intrabeam scattering problem.

**Slide 4**

Accelerating cavity: (2 per ring.)

- $h = \frac{19}{4} \times 12 \times 2 \times 3 = 57 \times 2 \times 3 = 342.$
- 26.7 $MHz$.
- 200 $kV$. (total 400$kV$)

Storage cavity: (2 per ring + common cavities.)

- $h = 57 \times 2 \times 22 = 2508.$
- 196.1 $MHz$.
- 1 $MV$. (total 6 $MV$)

A few words about the full bunch length and RMS bunch length. The full bunch length is directly proportional to the RMS bunch length, the proportionality is distribution dependent. We find it's more convenient to use full bunch length instead of RMS bunch length. However, if one needs to know the RMS bunch length, one can easily assume a particular distribution and find that proportional factor.

**Slide 5**

Full bunch length:

- $L_{bun}(m)$.
- $\tau_{bun}(ns)$.

RMS bunch length:

(line density distribution dependent)

- $\sigma_{bun} = L_{bun}/b \ (\tau_{bun}/b)$.
- Gaussian distribution: $b = 2\sqrt{6} \approx 4.9$.
- Cosine square distribution:
  $b = 2(\frac{1}{3} - \frac{2}{\pi^2})^{-\frac{1}{2}} \approx 5.5$.

We only speak of full bunch length!

Here's a question: How short a bunch is needed to fit into a storage bucket? Since the storage buckets have a length of 5.1 $ns$, in principle the bunch length has to be less than that so as not to lose particles. In practice, a safety margin is needed. The problem of long bunches is that the particles may end up in adjacent buckets.

**Slide 6**

How short a bunch is needed to fit into a storage bucket?

The storage system (196.1 $MHz$) provides a bucket:

- $\tau_{bkt} \approx 5.1\ ns.$
- $L_{bkt} \approx 1.53\ m.$

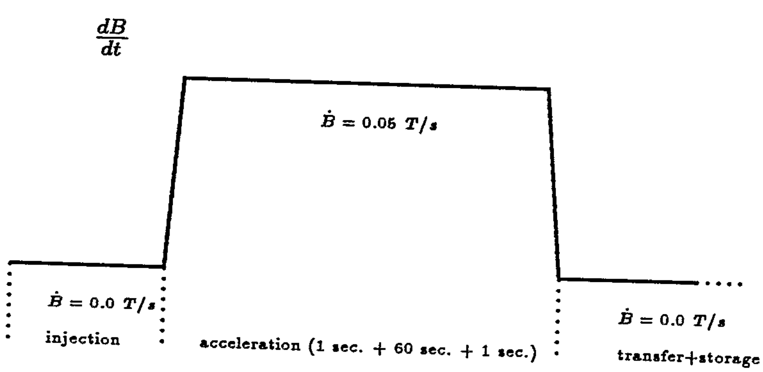
For a safety margin of 80%, the bunch length has to be less than

$\tau_{bun} \approx 4\ ns$ (288° in the bucket.).

An RF cycle is intrinsically related with the dipole field cycle. The superconducting magnet provides a very simple cycle. The objective is to accelerate the beam fast.

**Slide 7**

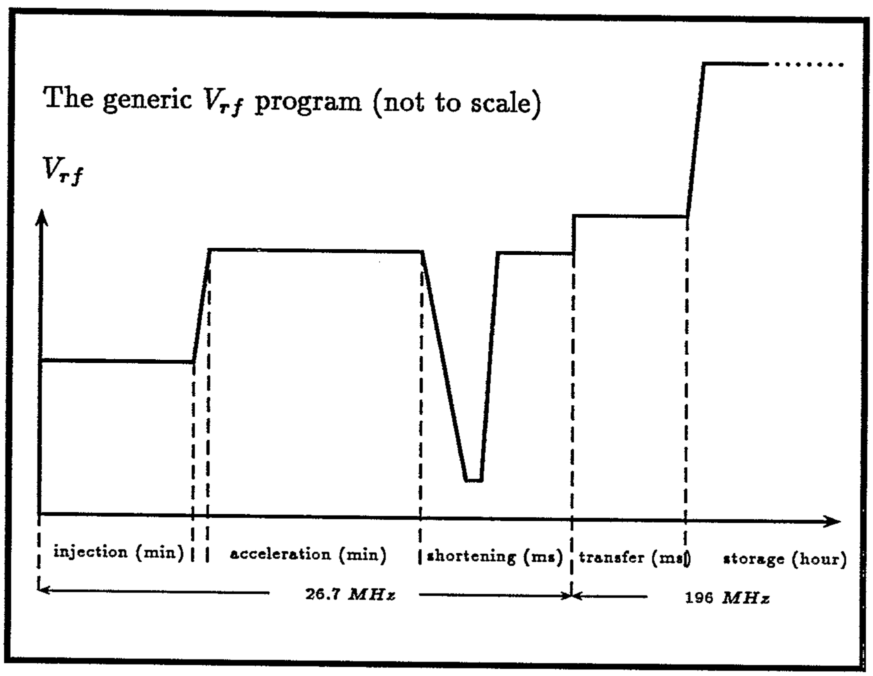
The magnetic cycle is rather simple.




Let's look at the generic RF cycle SLIDE 8. The plot is not in scale, see the time scale on the bottom.

The voltage is held at a constant matching voltage in the injection region, then adiabatically raised to acceleration level (300 $kV$). At the end of acceleration, if the bunch length is greater than that of the bucket, a bunch rotation is carried out, first adiabatically decrease the voltage to debunch the beam, then quickly turn on the voltage to a large value (usually the same acceleration volts). After the bunch rotates a quarter of synchrotron period, the voltage drops down to zero quickly and the storage cavities are switched on to accept the bunches at their matching voltages. Then, the voltage is raised adiabatically to 6 $MV$ to counter intrabeam scattering phenomenon.

**Slide 8**



Three questions to be answered (SLIDE 9).

**Slide 9**

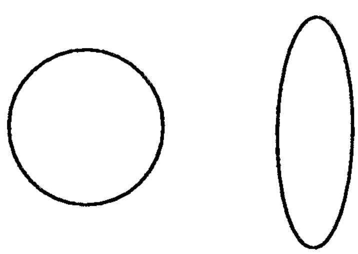
Questions:

1. How to shorten the bunches (less than $4ns$)?
   - bunch compression
   - bunch rotation
2. How fast to adiabatically ramp up and down the voltage?
3. What's the matching voltage at injection and transfer?

Bunch compression is done by adiabatically raise the voltage ( SLIDE 10, left). For short bunches comparing with the buckets, as they are usually at the end of acceleration, the required voltage is to the power of 4 of reduction factor. For example, to compress a 5 $ns$ bunch into 4 $ns$ bunch, the final voltage is over 700 $kV$, away over the designed specification. This is a very expensive method.

**Slide 10**

Bunch compression: Adiabatically increase $V_{rf}$.



$V_0$ $\tau_0$      $V_2$ $\tau_2$

$$V_2 \approx (\frac{\tau_0}{\tau_2})^4 V_0$$

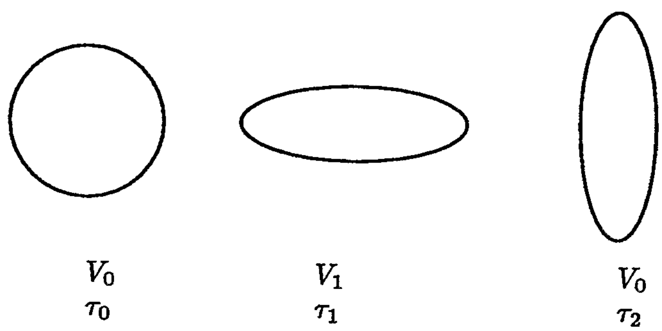
$$V_2 \approx (\frac{5}{4})^4 \times 300 = 730\ kV$$

Expensive!

Bunch rotation is another technique to make short bunches (SLIDE 11). It has two steps, first to adiabatically decrease the voltage to make a longer bunch, then suddenly turn on to a higher voltage. The elongated bunch starts to rotate, you wait for a quart of the synchrotron period to produce a shorter bunch. There is still a 4th power relation, but unlike the compression method, it involves in reducing the voltage. A potential drawback of this method is that the voltage $V_1$ may be prohibitively low.

**Slide 11**

Bunch rotation: How low does $V_1$ have to go?




$$V_1 \approx \left(\frac{\tau_2}{\tau_0}\right)^4 V_0$$

In many an occasion, adiabatic manipulation of the cavities are required. Adiabaticity means to change slowly so as not to disturb. But how slow is slow enough?

The time scale for the motion of particles is the synchrotron period $T_\nu$. If the change is done over many synchrotron period, the change is essentially adiabatic.

Mathematically, it's postulated that the fractional change of the bucket area is proportional to the change of time in the unit of synchrotron period. The proportionality constant is the determinant of adiabaticity. The smaller the constant $\alpha$, the more adiabaticity.

**Slide 12**

Adiabatically ramping up and down $V_{rf}$

$\frac{dA_{bkt}}{A_{bkt}} = \alpha \frac{dt}{T_\nu}$ (Liliequist and Symon)

$T_\nu$: synchrotron period.

- $\alpha \ll 1$ Adiabatic.
- $\alpha \gg 1$ Fast turn on.

At $t_1$: $V_1, T_{\nu 1}$. At $t_2$: $V_2, T_{\nu 2}$. $\delta t = t_2 - t_1$.

$V(t) = \frac{V_1}{(1-\frac{\alpha(t-t1)}{T_{\nu 1}})^2}$

$\delta t = \frac{T_{\nu 1}}{\alpha}(1 - \sqrt{\frac{V_1}{V_2}})$

If $V_2 \gg V_1$, then $\delta t = \frac{T_{\nu 1}}{\alpha}$.

Take $\alpha = 0.1 \sim 0.2$, $\delta t = (5 \sim 10) T_{\nu 1}$

The final question is to match a bunch in two buckets. It's necessary to match bunches when they are transfered between two RF systems to avoid beam loss and emittance blowup. Suppose we have a bunch matched to the bucket ($f_{rf1}$), we want to transfer it into another bucket ($f_{rf2}$). The question is: can we match the bunch in the second bucket perfectly? If not, how close we can make it to match?

The emittance is a measure of the bunch length and the energy spread within the bunch ( SLIDE 13)

**Slide 13**

How to match a bunch between two RF **buckets** ($f_{rf1} < f_{rf2}$) with minimum longitudinal emittance ($\epsilon \propto \tau_{bun} \times dE$) blowup?

The main handle is $V_{rf2}$.

- Too low $V_{rf2}$ may not create large enough bucket to accept the bunch, or the bunch will tumble in the bucket.
- Too high $V_{rf2}$ will stretch the bunch to increase energy spread in the bunch.

To find out if a bunch is matched or not in the second bucket is to compare the equations of motion. If they are matched, you can find a relation to accomplish it. For a short bunch in both buckets, it's no problem. The condition is simple, and bunch length independent as expected.

**Slide 14**

From the Hamiltonian

$\mathcal{H}(\phi, W) = \frac{1}{2}AW^2 + B[\cos(\phi) - \cos(\phi_s) + (\phi - \phi_s)\sin(\phi_s)]$

$W = \frac{\Delta E}{\omega_{rf}}, A = \frac{\eta\omega_{rf}^2}{E_s\beta_s^2}, B = \frac{eV_{rf}}{2\pi h}, \eta = \frac{1}{\gamma_{tr}^2} - \frac{1}{\gamma^2}$

It can be proven:

only if the bunch is in the linear regions of both the buckets, the bunch can be matched perfectly, whose condition is

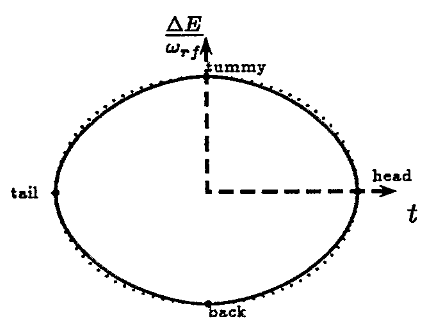
$$\left(\frac{eV_{rf}f_{rf}^2}{h|\eta|}\right)_1 = \left(\frac{eV_{rf}f_{rf}^2}{h|\eta|}\right)_2$$

Then, what is usually done to match a bunch?

Let's pick out the representive points of a bunch: head, tummy, tail and back (SLIDE 15). The dotted line is matched to the first bucket. The solid line is matched to the second bucket provided a relation at the bottom of SLIDE 15 is true.

Matching from one ring to another, you can tune both $V_{rf}$ and $\eta$. This is the case from AGS to RHIC. Matching within a single ring, you can only tune $V_{rf}$ as transfering between accelerating cavities and storage cavities.

**Slide 15**




To find a $V_{rf2}$ such that

head → tummy → tail → back → head

$$\left(\frac{eV_{rf}(1-\cos(\omega_{rf}\tau/2))}{h|\eta|}\right)_1 = \left(\frac{eV_{rf}(1-\cos(\omega_{rf}\tau/2))}{h|\eta|}\right)_2$$

Some parameters at ejection from AGS and parameters at injection in RHIC. The emittance is specified by other studies, which is beyond the scope of this talk to elaborate.

**Slide 16**

Beam parameters from AGS:

| | $\epsilon$ $(eVs/u)$ | $V_{rf}$ $(kV)$ | $\gamma$ | $\tau_{bun}$ $(ns)$ |
|---|---|---|---|---|
| Au | 0.3 | 320 | 12.6 | 16.46 |
| p | 0.3 | 320 | 31.2 | 11.78 |

At injection in RHIC:

| | $\epsilon$ $(eVs/u)$ | $V_{rf}$ $(kV)$ | $\gamma$ | $\tau_{bun}$ $(ns)$ |
|---|---|---|---|---|
| Au | 0.3 | 173 | 12.6 | 16.46 |
| p | 0.3 | 16 | 31.2 | 11.78 |

The matching voltage for proton in RHIC is rather low. It's mainly due to the fact that it's close to the transition in RHIC. Low matching voltage is no good. First, any fluctuation will generate large emittance growth. Second, the induced voltage from storage system will disturbe the bunch and blow up the emittance. It's desirable to raise the matching voltage ( SLIDE 17).

**Slide 17**

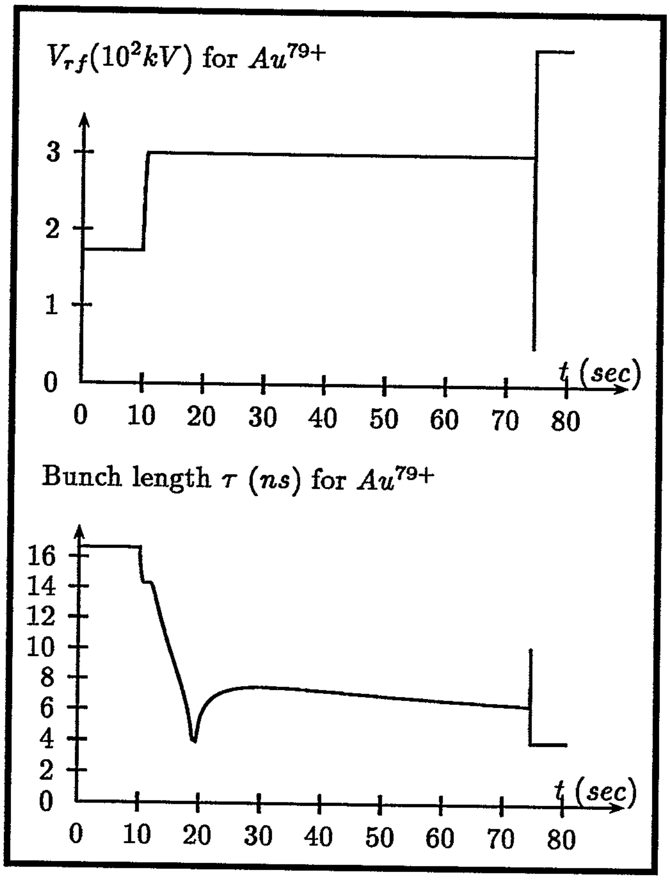
The matching voltage for proton $V_{matching}$ is too low at 16 $kV$.

Two ways to increase the matching voltage: $V_{ags}$, $\gamma_{tr}^{rhic}$

- If the bunch is shortened in AGS by factor of 2, we increase $V_{ags}$ by an effective factor of $2^4$.
- $\gamma_{tr}^{rhic} = 19$ to increase $V_{matching}$ by a factor of 2. $\gamma_{tr}^{rhic} = 9$ to increase $V_{matching}$ by a factor of $2^4$.

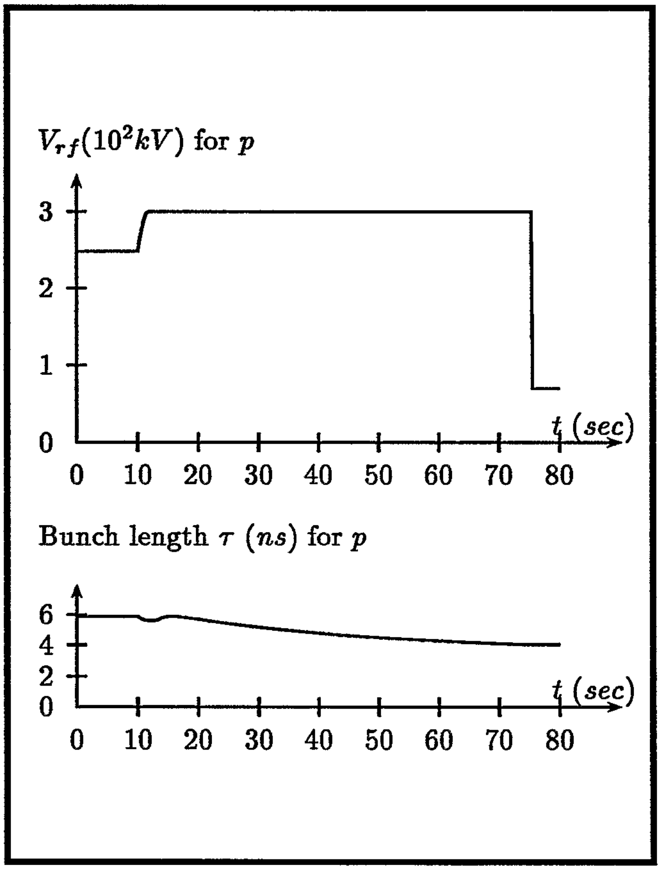
Gold cycle is shown in SLIDE 18. At the end of acceleration, a bunch rotation is done to fit in storage bucket.

**Slide 18**



Proton cycle is shown in SLIDE 19. The bunch is short enough to fit right in the storage bucket.

**Slide 19**



In general after transition, the bunch gets shorter and shorter as its energy get larger. If RHIC is to be operated at lower energies. A bunch rotation generally needs performing. Two extreme cases are presented here.

**Slide 20**

For constant $\dot{B}$ and $V_{rf}$ and after transition, the bunch length reaches its maximum at $\gamma_3 = \sqrt{3}\gamma_{tr} = 40.88$.

| | $\epsilon$ $(eVs/u)$ | $V_{rf}$ $(kV)$ | $\tau_{3bun}$ | $\tau_{bun}$ $(top)$ |
|---|---|---|---|---|
| Au | 0.3 | 300 | 7.42 | 6.34 |
| p | 0.3 | 300 | 5.87 | 4.04 |

$V_1$ $(kV)$ in bunch rotation process, and $V_{st}$ initial storage voltage.

| | $V_1(kV)$ $(\gamma_3)$ | $V_1(kV)$ $(\gamma_{top})$ | | $V_{st}(kV)$ $(\gamma_3)$ | $V_{st}(kV)$ $(\gamma_{top})$ |
|---|---|---|---|---|---|
| Au | 25 | 48 | | 827 | 441 |
| p | 65 | 300 | | 324 | 70 |