BNL-211904-2019-TECH

C-A/AP/622

FY2019 parameters for Gold ions in Booster, AGS, and RHIC

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July 2019

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U.S. Department of Energy

USDOE Office of Science (SC), Nuclear Physics (NP) (SC-26)

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July 15, 2019

Sections 1 through **6** of this report give parameters for **low-energy** gold ions circulating in RHIC at injection and in AGS at extraction.

Section 7 gives parameters for Au79+ ions circulating in RHIC at the standard injection magnetic rigidity of **81.11378003 Tm**.

Section 8 gives parameters for **medium-energy** Au79+ ions circulating in RHIC at 31.2 GeV per nucleon.

The standard parameters for gold ions circulating in Booster, AGS, and RHIC are documented in [1]. For convenience they are listed here in **Sections 9** through **11**.

Gold ions normally come from EBIS but can be provided by Tandem if EBIS is down for maintenance or repairs. **Section 12** gives parameters for Tandem Au31+ ions circulating in Booster. In order to achieve a single bunch of Tandem ions at Booster extraction, a 6 to 3 to 1 bunch merge is required. This has been developed by Keith Zeno and is documented in [2, 3].

Different bunch merges and fill patterns in AGS are used depending on the desired bunch intensity in RHIC and the desired number of bunches to be injected into RHIC per AGS cycle. These are illustrated in **Sections 13** through **17**. The standard bunch merges done in Booster and AGS are documented in [1].

Bucket and bunch parameters for clean injection of low-energy gold ions into RHIC are documented in [4].

Parameters of past medium and low energy gold ion setups are documented in [5].

1 Electron RF frequency

The Au79+ ions circulating in RHIC at low energy are to be cooled with a beam of bunched electrons. The RF frequency f_E used for acceleration of the bunches needs to be synchronized with the revolution frequency f of the gold ions. This is accomplished by imposing the constraint [6]

$$nf = f_E \tag{1}$$

where

$$f_E = 704.005148 \text{ MHz} \tag{2}$$

and n is a positive integer.

The parameters listed in **Sections 3** through **6** are obtained by taking

$$n = 9279,\ 9194,\ 9123,\ 9077,\ 9044 \tag{3}$$

for energies 1, 2, 3, 4, 5, respectively.

2 Gold ion mass

The values of the fundamental constants listed on page one of C-A/AP/Note 574 [1] give

$$mc^2 = 183.433\,337\,044 \text{ GeV} \tag{4}$$

for the mass-energy equivalent of the Au79+ ion.

More recent values of the fundamental constants, listed on page eleven of C-A/AP/Note 608 [7], give

$$mc^2 = 183.433\,343\,902 \text{ GeV}. \tag{5}$$

The fractional difference between these two values amounts to

$$\frac{183.433\,343\,902 - 183.433\,337\,044}{183.433\,337\,044} = 3.74 \times 10^{-8} \tag{6}$$

which, for the computation of various parameters that appear in this note, is entirely negligible.

3 RHIC injection energies 1, 2, 3

	Energy 1	Energy 2	Energy 3	Unit
Q	79	79	79	
mc^2	183.433343902	183.433343902	183.433343902	GeV
W/A	2.91554792413	3.66145111778	4.82988847577	GeV
cp/A	3.73228478257	4.49720196646	5.68527631587	GeV
E/A	**3.84668164952**	**4.59258484317**	**5.76102220117**	GeV
$B\rho$	31.0451102170	37.4076842606	47.2900756836	Tm
β	0.970260895656	0.979231112769	0.986852006006	
γ	4.13118067214	4.93225056501	6.18710507853	
η	-0.05669	-0.03920	-0.02421	
n	**9279**	**9194**	**9123**	
f	75.8707994396	76.5722371112	77.1681626658	KHz
h	120	120	120	
hf	9.10449593275	9.18866845334	9.26017951989	MHz
δC	0	0	0	mm

4 Corresponding AGS extraction parameters

	Energy 1	Energy 2	Energy 3	Unit
Q	77	77	77	
mc^2	183.434181300	183.434181300	183.434181300	GeV
W/A	2.91556123404	3.66146783289	4.82991052486	GeV
cp/A	3.73230182100	4.49722249689	5.68530226992	GeV
E/A	**3.84669921018**	**4.59260580903**	**5.76104850101**	GeV
$B\rho$	31.8516221228	38.3794876307	48.5186108306	Tm
β	0.970260895657	0.979231112770	0.986852006006	
γ	4.13118067219	4.93225056511	6.18710507853	
η	-0.04475	-0.02727	-0.01228	
h	12	12	12	
hf	4.32463556806	4.36461751534	4.39858527195	MHz
T/h	231.233356953	229.115150752	227.345825572	ns
R	128.457981391	128.457981391	128.457981391	m

5 RHIC injection energies 4, 5

	Energy 4	Energy 7.3000	Energy 5	Unit
Q	79	79	79	
mc^2	183.433343902	183.433343902	183.433343902	GeV
W/A	6.37837144646	6.36886627461	8.86482729097	GeV
cp/A	7.24995557522	7.24037222699	9.75160716085	GeV
E/A	**7.30950517185**	**7.30000000000**	**9.79596101636**	GeV
$B\rho$	60.3050632557	60.2253490540	81.1137779506	Tm
β	0.991853128875	0.991831811917	0.995472230296	
γ	7.85011322489	7.83990505437	10.5204663404	
η	-0.01432	-0.01436	-0.007126	
n	**9077**	N/A	**9044**	
f	77.5592319048	77.5575649979	77.8422321981	KHz
h	120	120	120	
hf	9.30710782858	9.30690779975	9.34106786378	MHz
δC	0	0	0	mm

6 Corresponding AGS extraction parameters

	Energy 4	Energy 7.3000	Energy 5	Unit
Q	77	77	77	
mc^2	183.434181300	183.434181300	183.434181300	GeV
W/A	6.37840056414	6.36889534942	8.86486775910	GeV
cp/A	7.24998867180	7.24040528035	9.75165167725	GeV
E/A	**7.30953854028**	**7.30003332557**	**9.79600573525**	GeV
$B\rho$	61.8717109827	61.7899259134	83.2210092307	Tm
β	0.991853128874	0.991831811917	0.995472230295	
γ	7.85011322442	7.83990505446	10.5204663393	
η	-0.002387	-0.002429	0.004806	
h	12	12	12	
hf	4.42087621857	4.42078120488	4.43700723529	MHz
T/h	226.199502216	226.204363812	225.377139809	ns
R	128.457981391	128.457981391	128.457981391	m

7 Standard RHIC injection [1] versus energy 5

	Standard	Energy 5	Unit
Q	79	79	
mc^2	183.433343902	183.433343902	GeV
W/A	8.86482753983	8.86482729097	GeV
cp/A	9.75160741084	9.75160716085	GeV
E/A	9.79596126523	9.79596101636	GeV
$B\rho$	**81.1137800300**	**81.1137779506**	Tm
β	0.995472230526	0.995472230296	
γ	10.5204666076	10.5204663404	
η	-0.007126	-0.007126	
n	N/A	**9044**	
f	77.8422322162	77.8422321981	KHz
h	360	120	
hf	28.0232035978	9.34106786378	MHz
δC	0	0	mm

8 Gold in RHIC at 31.2 GeV per nucleon

Parameter	Injection	Transition	Store	Unit
Q	79	79	79	
mc^2	183.433343902	183.433343902	183.433343902	GeV
W/A	8.86482753983	20.3825172488	30.2688662746	GeV
cp/A	9.75160741084	21.2933019477	31.1861025135	GeV
E/A	9.79596126523	21.3136509742	**31.2**	GeV
$B\rho$	**81.11378003**	177.117488177	259.405711561	Tm
β	0.995472230526	0.999045258528	0.999554567742	
γ	10.5204666076	**22.8900**	33.5075394105	
η	-0.007126	0.0	0.00102	
f	77.8422322162	78.1216297391	78.1614558286	kHz
h	360	360	360	
hf	28.0232035978	28.1237867061	28.1381240983	MHz
δC	0	0	0	mm

9 Gold in Booster (standard setup) [1]

Parameter	Injection	Merge porch	Extraction	Unit
Q	32	32	32	
mc^2	183.456851494	183.456851494	183.456851494	GeV
W/A	1.9762739452	72.089750	107.75879	MeV
cp/A	60.701960016	373.44950	460.77475	MeV
E/A	0.9332293272	1.0033428	1.0390118	GeV
$B\rho$	1.24651715338	7.6688003	9.46202773202	Tm
β	0.065045062608	0.37220529	0.44347401	
$\gamma - 1$	0.002122166406	0.07741156	0.11571376	
η	-0.953	-0.8186	-0.7605	
ϵ_H (95%)	12.1π	12.1π	12.1π	mm mrad
ϵ_V (95%)	5.68π	5.68π	5.68π	mm mrad
h	4	1	1	
hf	**386.560**	**553.000**	**658.910**	KHz
R	$201.780/(2\pi)$	$201.780/(2\pi)$	128.4526/4	m

Here ϵ_H and ϵ_V are the normalized horizontal and vertical transverse emittances. These follow from the assumption that during injection the horizontal and vertical acceptances in Booster are completely filled. The horizontal and vertical acceptances are 185π and 87π mm mrad (un-normalized) respectively.

Parm	Injection	Ext	Ext	Ext	Unit
V_g	5.730	25.2	25.2	25.2	kV
A_S	16.076	318.54	318.54	318.54	eV s
dB/dt	0	**70**	**35**	**0**	G/ms
ϕ_s	0	50.999	22.866	0	deg
F_s	1.1557	0.8139	0.9849	1.0260	kHz
$A_{\rm bk}$	16.076	36.294	140.88	318.54	eV s
A_b	1.82	13.987	13.987	13.987	eV s
Δt	635.1	264.6	235.1	229.8	ns
ΔE	1.836	34.11	38.00	38.84	MeV

Parameter	Injection	Extraction	Unit
No. Bunches	4	1	
Bucket Width	2586.92053	1517.65795	ns
Ions/Bunch	1.25/4	1.04	10^9
Bunch Area	0.037/4	0.071	eV s/A

10 Gold in AGS (standard setup) [1]

Parameter	Injection	Porch	Extraction	Unit
Q	77	77	77	
mc^2	183.434174442	183.434174442	183.434174442	GeV
W/A	0.10529199	0.16448553	8.86486804031	GeV
cp/A	0.45515837	0.57738456	9.75165192809	GeV
E/A	1.0364299	1.09562347	9.79600598164	GeV
$B\rho$	3.88434088	4.9274243	83.2210113714	Tm
β	0.43915981	0.52699177	0.995472230863	
γ	1.1130788	1.1766500	10.5204669972	
η	-0.793	-0.708	0.00481	
$\beta\gamma$	0.48881949	0.62008488	10.472833	
$\beta\gamma^2$	0.54409463	0.72962288	110.17909	
h	24	4	12	
hf	**3.915000**	**0.783**	**4.43700723782**	MHz
R	128.4526	128.4526	128.457981391	m

Parameter	Inj	Porch	Porch	Ext	Unit
h	24	12	4	12	
V_g	119.8	100	15.0	185.2	kV
A_S	35.84	100.8	202.8	4979	eV s
dB/dt	0	0	0	0	G/ms
ϕ_s	0	0	0	180	degrees
F_s	4.346	2.581	0.577	0.0967	kHz
A_{bk}	35.84	100.8	202.8	4979	eV s
A_b	17.73	39.4	118.2	147.75	eV s
Δt	140	203	775	28.0	ns
ΔE	83.6	127	102	3365	MeV

Parameter	Inj	Porch	Porch	Ext	Unit
h	24	12	4	12	
Bucket Width	255.428	425.713	1277.139	225.377	ns
No. of Bunches	12	6	2	2	
Ions/Bunch	0.53	1.06	3.18	3.0	10^9
Bunch Area	0.09	0.20	0.60	0.75	eV s/A

11 Gold in RHIC (standard setup) [1]

Parameter	Injection	Transition	Store	Unit
Q	79	79	79	
mc^2	183.433337044	183.433337044	183.433337044	GeV
W/A	8.86482757134	20.3825164868	99.0688663094	GeV
cp/A	9.75160741084	21.2933011516	99.9956648563	GeV
E/A	9.79596126192	21.3136501774	**100.000**	GeV
$B\rho$	**81.11378003**	177.117481555	831.763013151	Tm
β	0.995472230863	0.999045258528	0.999956648563	
γ	10.5204669974	**22.8900**	107.395963664	
η	-0.00713	0.0	0.00182	
f	77.8422322425	78.1216297391	78.1928970559	kHz
h	360	360	2520	
hf	28.0232036073	28.1237867061	197.046100581	MHz
δC	0	0	0	mm

Parameter	Injection	Store	Unit
h	360	2520	
V_g	393.1	3000	kV
A_S	174.4	164.4	eV s
dB/dt	0	0	G/ms
ϕ_s	0	180	degrees
F_s	0.200	0.232	kHz
A_{bk}	174.4	164.4	eV s
A_b	137.9	137.9	eV s
A_b	0.70	0.70	eV s/A
Δt	26.8	4.00	ns
ΔE	3549	24052	MeV

12 Tandem Au31+ in Booster

At injection as documented in C-A/AP/Note 397 [8]:

1. $B\rho = 0.8813444$ Tm
2. $B = 635.633798754$ Gauss
   (629.5 Gauss measured)
3. Inflector $V = 28.312$ KV
4. $f = 66.2678758864$ kHz
5. $6f = 397.607255319$ kHz
6. $W/A = 0.927701900621$ MeV per nucleon

Note that the inflector voltage given above is higher than that given in [8]. This is because the distance between the cathode and septum of the inflector was increased from 17 to 21 mm prior to RHIC Run 12.

At extraction as documented in [8]:

1. $B\rho = 9.4307359$ Tm
2. $B = 6.80714671809$ kG
3. $f = 640.486082311$ kHz
4. $6f = 3.84291649387$ MHz
5. $W/A = 100.816293106$ MeV per nucleon

At extraction with same $B\rho$ as setup for Au32+ ions from EBIS:

1. $B\rho = 9.46202808578$ Tm
2. $B = 6.82973355563$ kG
3. $f = 642.214767962$ kHz
4. $W/A = 101.453513566$ MeV per nucleon

13 AGS injection timing

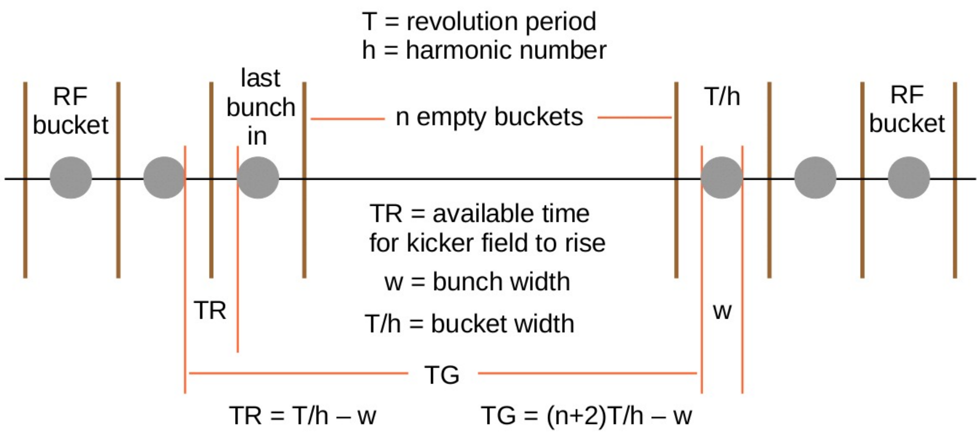

Figure 1: Timing for the injection of gold bunches into AGS RF buckets. Here T is the revolution period on the AGS injection porch and T/h is the width of the RF harmonic h bucket. The **time available** for the injection kicker magnetic field to rise is $T_R = T/h - w$, where w is the **width** of the bunch in the bucket. For injection of the last bunch, the kicker pulse must fit inside the **time gap** $T_G = (n + 2)T/h - w$, where n is the number of empty buckets following the last bunch.

14 AGS injection kicker pulse

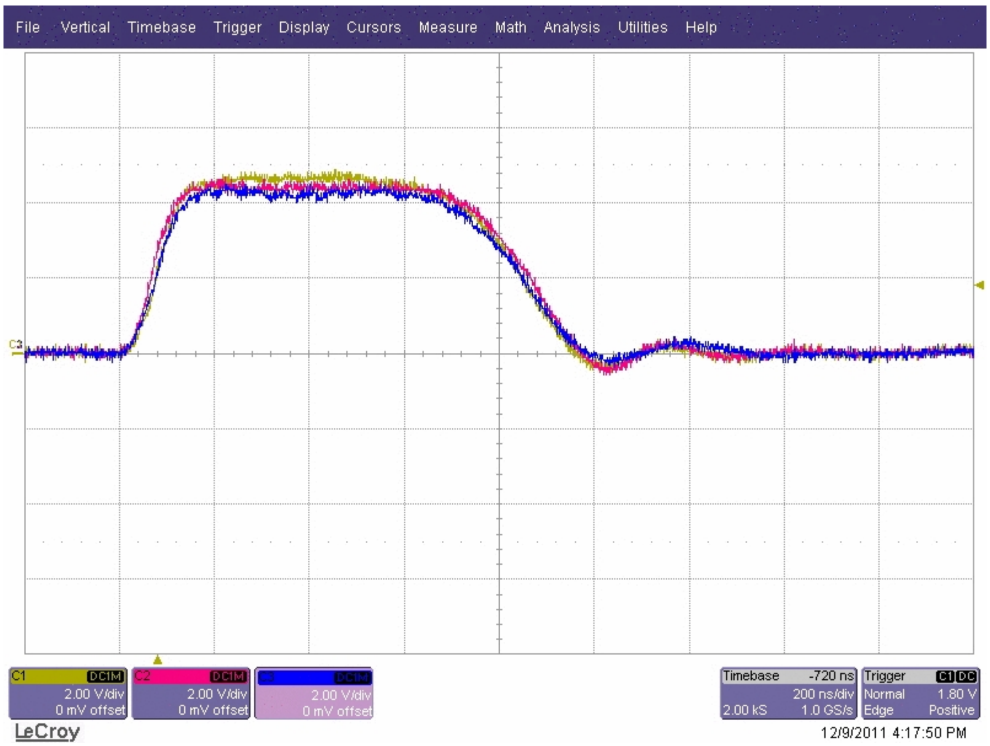

Figure 2: AGS injection kicker waveforms in the short pulse mode. The three traces are from the three modules of the kicker. They were taken by Yugang Tan on 9 Dec 2011. The time per division is 200 ns. The rise time of the pulse is approximately 100 ns. The width of the pulse is approximately 1000 ns.

15 Fill pattern and kicker timing for 6 to 1 merge

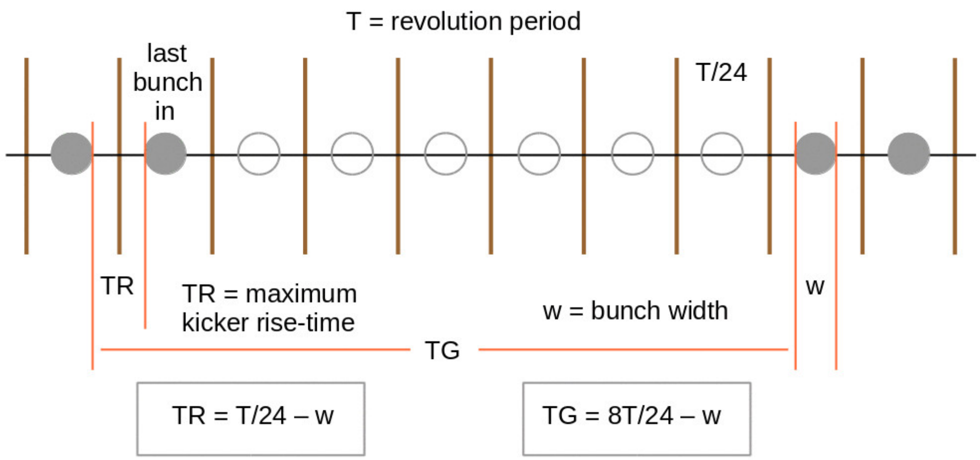

Figure 3: AGS fill pattern and injection kicker timing for 6 to 1 merge. Here T is the revolution period on the AGS injection porch and $T/24 = 255$ ns is width of the RF harmonic 24 bucket. The kicker rise time is 100 ns. This means that the bunch width, w, must be less than $T/24 - 100 = 155$ ns. The fill pattern is 6 adjacent filled harmonic 24 buckets followed by 6 adjacent empty buckets, followed by another 6 adjacent filled buckets. This allows each group of 6 adjacent bunches to be merged into a single bunch as documented in [1]. One ends up with a merged bunch sitting in every other harmonic 4 bucket. Each merged bunch is then squeezed into a harmonic 12 bucket for subsequent acceleration as documented in [9, 10]. The **time gap available** for the kicker pulse is $8T/24 - w = 2040 - w$ ns, which is more than enough to accommodate the full width of the pulse.

At extraction one has 2 bunches, each of which sits in its own harmonic 12 bucket and is separated from its neighbor by 5 empty buckets. This gives ample room for both the rise time and full width of the extraction kicker pulse, which are 292 and 672 ns respectively [11]. The harmonic 12 bucket widths $T/12$ at extraction are listed in Sections 4 and 6, and range from 225 to 231 ns.

16 Fill pattern and kicker timing for 3 to 1 merge

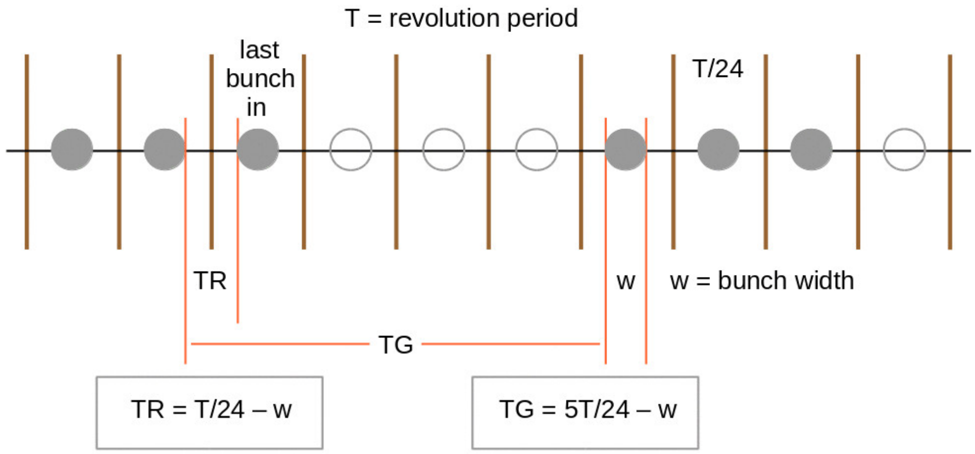

Figure 4: AGS fill pattern and injection kicker timing for 3 to 1 merge. Here T is the revolution period on the AGS injection porch and $T/24 = 255$ ns is width of the RF harmonic 24 bucket. The kicker rise time is 100 ns. This means that the bunch width, w, must be less than $T/24 - 100 = 155$ ns. The fill pattern is 3 adjacent filled harmonic 24 buckets followed by 3 adjacent empty buckets, followed by another 3 adjacent filled buckets and so on until there are 4 groups of three bunches. This allows each group of three bunches to be merged into a single bunch. The merge requires harmonics 24, 16, and 8 on the injection porch. One ends up with a merged bunch sitting in every other harmonic 8 bucket. Each merged bunch is then captured in a harmonic 12 bucket for subsequent acceleration. All of this was set up by Iris Zhang and is documented in [12]. The **time gap available** for the kicker pulse is $5T/24 - w = 1275 - w$ ns, which is enough to accommodate the full width of the pulse.

At extraction one has 4 bunches, each of which sits in its own harmonic 12 bucket and is separated from its neighbors by 2 empty buckets. As before, this gives ample room for both the rise time and full width of the extraction kicker pulse, which are 292 and 672 ns respectively [11]. The harmonic 12 bucket widths $T/12$ at extraction range from 225 to 231 ns.

17 Fill pattern and kicker timing for 2 to 1 merge

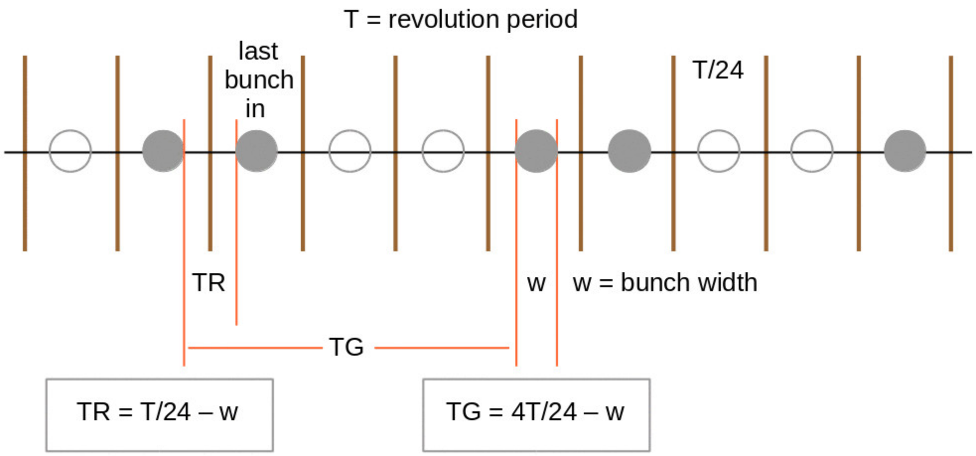

Figure 5: AGS fill pattern and injection kicker timing for 2 to 1 merge. Here, as before, the bunch width w must be less than $T/24 - 100 = 155$ ns. The fill pattern is 2 adjacent filled harmonic 24 buckets followed by 2 adjacent empty buckets, followed by another 2 adjacent filled buckets and so on until there are 6 groups of two bunches. This allows each group of two bunches to be merged into a single bunch. One ends up with a merged bunch sitting in every other harmonic 12 bucket. The **time gap available** for the kicker pulse is $4T/24 - w = 1020 - w$ ns. In this case the available gap is not quite wide enough to accommodate the full width of the pulse. The result is that a small part of the first injected bunch (or possibly a small part of the next-to-last injected bunch) scrapes against machine apertures.

At extraction one has 6 bunches, each of which sits in its own harmonic 12 bucket and is separated from its neighbors by 1 empty bucket. One again finds that there is sufficient room for both the rise time and full width of the extraction kicker pulse [11].

As noted by Kevin Mernick, the small loss at injection could be avoided by injecting the last two bunches early by 2 buckets, thereby leaving a gap of 4 empty harmonic 24 buckets for the injection kicker pulse. However, at extraction, 2 of the 6 bunches would then be sitting in adjacent harmonic 12 buckets which would give a time of just $T/12 - w$ for the extraction kicker field to rise. This is less than the 292 ns rise time of the kicker pulse documented in [11].

References

[1] C.J. Gardner, "FY2016 Parameters for Gold Ions in Booster, AGS, and RHIC," C-A/AP/Note 574, October 2016.

[2] K.L. Zeno, Booster-AGS-EBIS-2019 elog, 11 February 2019.

[3] K.L. Zeno, "Run 16 Tandem gold performance in the injectors and possible improvement with AGS type 6:3:1 bunch merge in the Booster," C-A/AP/Note 576, October 2016.

[4] C.J. Gardner, "Bucket and bunch parameters for clean injection of low energy gold ions into RHIC," C-A/AP/Note 607, July 2018.

[5] C.J. Gardner, "FY2014 Parameters for Gold Ions in Booster, AGS, and RHIC," C-A/AP/Note 525, July 2014.

[6] As given by Kevin Mernick.

[7] C.J. Gardner, "Notes on the setup of Ruthenium and Zirconium ions in Booster and AGS for RHIC Run 18," C-A/AP/Note 608, July 2018

[8] C.J. Gardner, "FY10 Parameters for the Injection, Acceleration, and Extraction of Gold Ions in Booster, AGS, and RHIC," C-A/AP/Note 397, August 2010.

[9] C.J. Gardner, "Simulation of 6 to 3 to 1 merge and squeeze of Au77+ bunches in AGS," C-A/AP/Note 563, May 2016.

[10] C.J. Gardner, "Double and triple-harmonic RF buckets and their use for bunch squeezing in AGS," C-A/AP/Note 569, August 2016.

[11] Iris Zhang, Booster-AGS-EBIS-2019 elog, 20 March 2019. The rise time and full width of the AGS extraction kicker pulse are 292 ns and 672 ns respectively. The relative trigger times of the 4 kicker modules have been adjusted so that the length of the flat top portion of the resulting pulse is 119 ns. This is much longer than the flat top portion of the pulse from a single module and is needed to accommodate the longer bunch lengths at low energy.

[12] Iris Zhang, Booster-AGS-EBIS-2019 elog, 14 June 2019.