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The Heavy Ion Beam Source

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THE

HEAVY-ION BEAM SOURCE

FOR

R H I C

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SUMMARY

In this note we describe a scheme to obtain a high performance relativistic heavy ion collider (RHIC) of a size which fits the present CBA tunnel at BNL.
The project is made of two parts: the Source of heavy ions and the Collider itself. We like to keep these two parts well separated since different kind of work analysis is to be done for each of them; but yet it is obvious that the performance of one of them depends crucially on the performance of the other.

THE SOURCE

This, in turn, is made of the following parts:

1. The negative-ion source
2. The Tandem vandeGraaff
3. The Booster Ring
4. The AGS.

The proposed new addition to the BNL facilities is the Booster Ring. There are also included transfer lines that go from the Tandem to the Booster, and from the Booster to the AGS. We will not cover the design of these transport lines.

1. The Negative-Ion Source

The elements that have been proposed are given in Table 1. These elements are adequate to cover most of the experimental program with the Collider since their atomic mass varies like n^3 with n an integer. They have also been chosen because they can be easily produced as negative-ions to be fed into the source for the Tandem.
Typical currents that can be generated at the source for these elements is around 200 micro-amp-particle, except for deuterium for which we can expect as much as one milli-amp-particle. Of course protons are generated by a different and higher intensity source: the 200 MeV Linac.

2. The Tandem vandeGraaff

The proposed mode of operation of the Tandem is the two-stages. In the first stage, the negative ions (Q=-1) are accelerated from ground to a +15 MV potential. At this point the kinetic energy of

Table 1. Proposed Elements for RHIC

Element	(n)	Atomic No. Z	Mass No. A	Rest Energy GeV/A	A/Z
Proton	(1)	1	1	0.9383	1.0
Deuterium	(1)	1	2	0.9375	2.0
Carbon	(2)	6	12	0.9310	2.0
Sulphur	(3)	16	32	0.9302	2.0
Copper	(4)	29	63	0.9299	2.2
Iodine	(5)	53	127	0.9302	2.4
Gold	(6)	79	197	0.9308	2.5

the negative ions is 15 MeV, large enough they can hit a first stripping target located in the high-voltage terminal. The most probable charge state Q_T which results depends on the element as shown in Table 2. Finally the ions are accelerated by the third stage, increasing their energy by (+15MV)Q_T . In Table 2 we give also the most probable charge state Q_F of the ions after one more (and last) stripping target located at the end of the Tandem. Of course there is no need for the second target in the case of the deuterium beam, since it was completely stripped at the first target.

The expected stripping efficiencies S_T and S_F are also given in Table 2. The Tandem output currents are calculated by taking into account the stripping efficiencies and an overall Tandem transmission efficiency of 75% .

The following cycle is proposed: the pulse length is at most 150 micro-sec long, and the repetition period is 1.2 sec to match the Booster Ring and the AGS cycles.

There are good experimental evidences that suggest the beam quality (intensity, emittance and energy spread) remains constant over the length of the pulse. More experimental work is planned to coorroborate this fact for any element chosen. In the meantime we assume for the purpose of our design that this is true.

At the end of the Tandem, after the last stage of stripping, the total beam emittance does not exceed 2 π mm-mrad, and the relative kinetic energy spread is around 10^{-4} , mostly due to power supply regulation errors. Again we assume that this applies for any element chosen.

The beam, to be captured by the single rf bucket in the Booster, has to be pre-bunched. We assume that the bunching factor over all the pulse length is 0.5, and that the bunch length (~100 m) equals half of the Booster circumference. Therefore the distance, center-to-center, between bunches will be twice that. We assume also that the bunching is 100% efficient, and will cause an increase of the beam energy spread by a factor 2 or 3.

3. The Booster Ring

The circumference of this ring is just one quarter of the AGS circumference. The most important parameters are listed in Table 3.

We assume that the betatron acceptance is 50 π.mm-mrad in both planes. It could be larger in the horizontal plane, but very likely the extra amount is not useful because of linear and non linear coupling between the two mode of oscillations.

The beam is injected into the Booster and stacked in the betatron phase space by wrapping the machine circumference with the beam pulse for some number n of consecutive turns which corresponds to a total number of particles N_B . It is assumed that the beam will fill up quickly the available acceptance in both planes, with the help eventually of other available steering means, until the space

Table 2. Tandem Operation Parameters*

Element	Q_T	S_T	Kinetic Energy MeV/A	β_F	Q_F	S_F	Current μ-amp-part
Deuterium	+1	70 %	15.0	.1768	+1	100 %	525.
Carbon	+5	61	7.5	.1262	+6	90	82.
Sulphur	+9	34	4.7	.1002	+14	40	20.
Copper	+11	27	2.9	.0782	+22	27	11.
Iodine	+13	20	1.65	.0595	+31	20	6.
Gold	+13	19	1.0	.0463	+36	17	5.

* Two-Stage Mode _ 75 % transmission efficiency.

Table 3. Booster Ring Parameters

Circumference		201.84 m
Periodicity		12
Period Structure:		
	QF/2 O B O QD/2 QD/2 O B O QF/2	
	QF/2 S QD/2 QD/2 O B O QF/2	
Drifts:	O	0.6516 m
	S	3.703 m
Phase Advance /Cell		100.5°
Betatron Tunes, H and V		~6.7
Transition Energy, γ_T		6.5
$\beta_{max} / \beta_{min}$		16. / 2. m
η_{max}		1.7 m
Dipole (B):	Length	2.4 m
	Max. Field	12 KG
	Bending Radius	13.751 m
	Aperture, H×V (full)	3.25 × 10. in^2
Quads (QF/2, QD/2):	Half-length	0.25 m
	Bore Radius	4 in
	max. Pole Tip Field	12.7 KG

charge limit is reached. This corresponds to a maximum number $N_{s.c.}$ of particles that can be injected according to the formula

$$\frac{N_{s.c.}}{\varepsilon_N} = (\beta\gamma^2)\,\frac{4\pi\, B_f\, \Delta\nu}{3\, r_o\, F}\,\frac{A}{Q_F^2} \qquad (1)$$

where B_f is the bunching factor, defined as the ratio of the average current to the peak current, $\Delta\nu$ is the maximum allowable tune depression, A the mass number, Q_F the charge state, $r_o = 1.535*10^{-18}$ m, and F a form factor that for $\beta \ll 1$ is very close to 1. At the left-hand side of equation (1) , ε_N is the normalized emittance; the actual emittance is given by

$$\varepsilon = \varepsilon_N / (\beta\gamma) \qquad (2)$$

Here the emittances as usual are always given in π mm-mrad units. It is important that the phase space density N_B / ε_N is as large as possible, since the luminosity in the collider depends on this quantity, provided that no other effects will cause even a stronger limitation than the space charge at injection in the Booster. The other parameter the luminosity depends upon is of course N_B itself. It is therefore essential to get the largest density N_B / ε_N and the largest number N_B of particles. Another important side effect is also that by increasing N_B one also increases the number of particles that can be transferred to the Collider per AGS pulse and reduces the Collider filling time.

There is some uncertainty to what value to assign to B_f and $\Delta\nu$. We propose here a bunching factor of 0.5 and $\Delta\nu$ = 0.1. The bunching factor of 0.5 corresponds to the rf capture process at injection and to the early stage of acceleration in the Booster. As the beam velocity increases during acceleration the bunching factor can be lowered correspondingly.

The different species are injected into the Booster with no further stripping, that is with the charge state Q_F as shown in Table 2. Table 4 gives the maximum number $N_{s.c.}$ of particles that can be injected with the corresponding normalized emittance ε_N . We also give in the same Table the revolution period T_{rev} and the number N_B of particles with n=8 turns injected assuming the beam current values given in Table 2. The largest number of turns that can be efficiently injected in one plane is taken here to be 8, and this corresponds to a dilution factor as large as 6.25.

By inspecting Table 4 one can see that the beam intensity is limited by the Tandem currents for the lighter ions up to Copper. For Copper the Tandem current output is about the space charge limit at injection into the Booster. For Iodine and Gold very clearly there is a space charge limitation by a factor as large as

Table 4. Beam Intensity, Emittance at Injection into the Booster

Element	ε_N π. mm. mrad	T_{rev} μsecs	N_B * $\times 10^9$	$N_{s.c.}$ $\times 10^9$
Deuterium	8.8	3.81	100.	438.
Carbon	6.3	5.33	22.	37.
Sulphur	5.0	6.72	6.7	11.
Copper	3.9	8.60	4.7	5.5
Iodine	3.0	11.31	3.4	3.2
Gold	2.3	14.53	3.6	2.2

* With 8-turn injection

2. The particles numbers in the dashed squares are the proposed ones for the estimates in our scheme. For Gold only 4 or 5 turns are required to be injected.

The beam is captured at injection by an harmonic number h=1 rf system, so that only one bunch is made and all the particles given in Table 4 are in this bunch. The analysis of the rf capture and acceleration is not given in this note. The acceleration period is taken to be 0.6 sec for Gold and the overall repetition rate 0.8 Hz. Toward the end of the acceleration, the bunch is made short enough to match the length of the rf buckets in the AGS.

Assuming a top field of 12 kG, we have a maximum kinetic energy of 367 MeV/A for Gold which corresponds to $\beta\gamma = 0.971$.
To minimize the amount of rf frequency swing it is sufficient to accelerate the lighter ions to the same value which corresponds to the full acceleration for Gold. In this case the required frequency swing covers the range of β-values from 0.046 to 0.7. Observe that the ion beam will never have to cross the Booster transition energy during their acceleration.

A vacuum of 10^{-10} mmHg seems to be quite adequate for the survival of practically all the beam against electron capture or loss processes during the acceleration cycle.

After extraction from the Booster and on their way to the AGS the ions go through one more stripping target. The ions injected into the AGS are then completely stripped. We assume a 50% beam loss for Gold, 20% for Iodine and 5% for Copper and Sulphur. Carbon and Deuterium do not need any further stripping.

4. The AGS

The major parameters of the ring are given in Table 5. Since the injection energy is 367 MeV/A and the ions are completely stripped, there is no requirement for improvement in either the vacuum or the rf system. The accelerator, as it is, suits very well for the acceleration of the ions to the maximum energy.

The scenario that we propose is that one bunch at the time is transferred from the Booster to the AGS, accellerated to the top energy and then transferred to the Collider. The AGS cycle rate is taken to be 0.8 Hz and that 0.6 seconds are needed for the acceleration. The transfer line between the Booster and the AGS is not discussed here.

We assume that the final stripping does not cause to significant increase in the beam emittance, therefore, since at the transfer $\beta\gamma = 0.971$ the emittance values given in Table 4 are just about those the beam is injected with into the AGS. These emittances are

Table 5. AGS Parameters

Circumference	807.11 m
Periodicity	12
Betatron Tunes, H and V	~8.7
Transition Energy, γ_T	8.5
Betatron Acceptance	~30 π mm·mrad
Injection Energy (proton)	200 MeV
Ejection Energy (proton)	28. GeV
RF Frequency	2.50 - 4.457 MHz
Harmonic Number, h	12
Peak RF Voltage	300. KV
Magnetic Rigidity, $B\rho$ at extraction	96.5 KG·m

considerably smaller than the ring betatron acceptance.

There is some uncertainty to what value to assign to the beam longitudinal emittance. The figures that correspond to injection into the Booster are very small, but we expect some dilution during the capture process and the acceleration cycle. A realistic estimate is probably 0.2 eV/A-sec, and we will use this figure as input to the design of the Collider. On the other hand, the rf buckets in the AGS are the smallest at injection. If we assume a constant voltage of 300 kV, the bucket area is not less than 1.0 eV/A-sec.

At the end of the acceleration in the AGS, the bunch of ions is taylored so that it will fit inside one of the rf buckets in the Collider. For this purpose we take a final total bunch length of 14 nanosec.

At this point, once the ion bunch has been ejected from the AGS, the Source of ions ends its function.

THE COLLIDER

In this section we describe only the input parameters for the design of the Collider.

The two transfer lines that connect the AGS to the two magnetic rings are part of the Collider system, but they will not be described here. The two rings and the transfer lines will be accomodated in the CBA tunnels that already exist on site. Thus the size of the Collider is given and matches the size of the CBA tunnel.

Each ion bunch accelerated in the AGS is extracted and transferred to one of the two Collider Rings. The bunch is captured by a stationary rf bucket standing by. It is essential that the shape of the bunch prior extraction from the AGS is taylored to match the shape of the buckets in the Collider. Major parameters of the Collider Rings are given in Table 6.

Beam parameters at injection are given in Table 7. It is assumed that, because of all the required manipolations, the betatron emittances and the longitudinal phase space area are somewhat diluted to the final values shown in Table 7 and taken to be the same for all species, with the exception of protons.

The bunch area, S, and the beam emittance, $\mathcal{E}$, are defined for 95% of the beam population

$$S = 6\pi\, \sigma_\tau\, \sigma_E \qquad (3)$$

where σ_τ is the rms bunch length in unit of time and σ_E the rms energy spread:

$$\mathcal{E} = 6\pi \frac{\sigma_{H,V}^2}{\beta_{H,V}} \qquad (4)$$

where $\sigma_{H,V}$ is the rms beam width or height and $\beta_{H,V}$ the horizontal or vertical amplitude lattice functions. The relation between the actual emittance and the normalized emittance is given by eq. (2).

The number of the ions per each bunch transferred to the Collider is also given in Table 7. It was derived from Table 4 after adjusting for the losses between the Booster and the AGS. Assuming a maximum rigidity of 839.5 T-m we give, also in Table 7, the maximum kinetic energy that can be reached in the Collider Rings.

The two rings are filled in the box-car fashion. The total number of bunches accepted is 57 per ring; an equivalent number of AGS pulses is required which gives a filling time of a little more than one minute per ring. The situation is different for the proton beam since 12 bunches can be accelerated at the same time in the AGS; thus only five AGS pulses would be required and the filling time is less than ten seconds.

The bunch separation is 67 meters and this corresponds to a rise time of 200 nano-sec for the injection kickers.

The two magnetic ring have a horizontal lay-out, side by side, with a separation of 24 cm between the two beam axis. The periodicity is threefold.

Table 6. General Parameters for the Collider

Circumference	3833.8 m
Revolution Frequency ($\beta = 1$)	78.1972 KHz
Filling Mode	Box-Car
No. of Bunches / Ring	57
Filling Time / Ring	~ 1 minute
Periodicity	3 (6)
Magnetic Rigidity, $B\rho$:	
at injection	9.65 T-m
at top energy	839.5 T-m

Table 7. General Beam Parameters for the Collider

Element	Proton	Deuterium	Carbon	Sulphur	Copper	Iodine	Gold
Injection:							
Kinetic Energy, GeV/A	28.	13.6	13.6	13.6	12.4	11.2	10.7
β	.99947	.99947	.99793	.99794	.99757	.99704	.99680
Norm. Emitt., π mm·mrad	25.	10.	10.	10.	10.	10.	10.
Bunch Area, eV/A-sec	0.3	0.2	0.2	0.2	0.2	0.2	0.2
Bunch Length, nsec	±7.	±7.	±7.	±7.	±7.	±7.	±7.
Energy Spread, $\pm 10^{-4}$	4.7	6.2	6.2	6.2	6.8	7.5	7.8
No. ions / Bunch, $\times 10^{9}$	1000.	100.	22.	6.4	4.5	2.6	1.1
Top Energy:							
Kinetic Energy, GeV/A	250.7	124.9	124.9	124.9	114.9	104.1	100.0
$\beta\gamma$	268.2	134.2	135.2	135.3	124.6	112.9	108.4