Accelerating Heavy Ions in Fermilab

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Recently several laboratories¹ initiated discussions on the design and construction of high energy heavy-ion colliders to study the formation and the characteristics of quark/gluon plasma. The beam energies considered are >30 GeV/nucleon and the costs of the machines considered are all in the hundreds of megabuck class. We consider here a poor-man's scheme of entering into a first phase of such studies.

The Fermilab Tevatron can be modified to accelerate heavy ions which can be used to strike fixed targets³. Assuming that the Tevatron can accelerate protons to 1 TeV, it can, then, accelerate U_{238}^{92+} (say) to 386 GeV/nucleon. When striking a stationary U ion this is equivalent to colliding beams of beam energy 12.6 GeV/nucleon. Although this is less than 30 GeV/nucleon it is high enough to be of interest and should give a strong indication on whether a step toward higher energy should be taken.

For the present discussion it is adequate and, indeed, more illuminating to approximate the mass of an ion with mass number A by Ax (proton mass). We will also understand by the momentum and the energy of an ion the momentum per nucleon and the energy per nucleon. We shall never need to talk about the momentum and the energy of the whole ion.

When a proton synchrotron is used to accelerate heavy ions the operating ranges of the rf frequency and the guide field strength will correspond to different momentum ranges of the ion. The rf will operate for ions over the same momentum range (same β range) as for protons but the guide field will

operate over a momentum range of the ion equal to $\frac{Z}{A}$ times that of the proton (same rigidity $B\rho$ range) (Z = charge number, A = mass number). Without modifying at least one of these systems the momentum range over which the ion can be accelerated is rather severely limited. The principal objective of this investigation is, thus, to find the most expedient and economical scheme, namely to decide what systems to modify and what systems to add. The operable momentum ranges of the various Fermilab synchrotrons for proton and for uranium ion are

	<u>particle</u>	<u>Operable momentum range (GeV/c)</u>	
Tevatron	p	151	1001
	U ⁹²⁺ { 238 {	151	1001
		58.3	387
400 GeV Main Ring	p	8.89	401
	U ⁹²⁺ { 238 {	8.89	401
		3.44	155
Booster	p	0.644	8.89
	U ⁴⁰⁺ { 238 {	0.644	8.89
		0.108	1.49

In this table U⁴⁰⁺ is assumed for the Booster because below ~1.5 GeV/c the efficiency of stripping to U⁹²⁺ is rather poor. From this table we conclude the following.

1. Assuming that the "400 GeV proton capability of the Main Ring is retained (questionable with overpass), the top of the Main Ring range (155 GeV/c) does overlap the bottom of the Tevatron range (151 GeV/c).

2. If no modification is made to the Main-Ring rf system one needs to add a synchrotron to bridge the gap between the Booster and the Main Ring. This synchrotron can be designated as

$$\begin{array}{c} \text{U}^{92+} \\ 238 \end{array} \quad 1.49 \text{ GeV/c} \text{ --- } 8.89 \text{ GeV/c}$$

and is equivalent to a 23 GeV/c proton synchrotron. Such a synchrotron will cost more than M\$60.

3. It is more economical to modify the Main Ring rf system to extend the lower limit of the frequency range down to ~45 MHz corresponding to a momentum of 1.49 GeV/c. Such an rf system may cost about M\$10. The guide field of the Main Ring needs no modification to operate down to 172 G for U^{92+} at 1.49 GeV/c. With this modification one can inject the 1.49 GeV/c beam from the Booster (after stripping to 92+) directly into the Main Ring.

4. It is difficult to conceive of extending the lower limit of the Booster rf down farther. Thus we need a 0.644 GeV/c U^{40+} injector into the Booster. A linac would be prohibitively expensive. It is equivalent to a 3 GeV proton linac which may cost around M\$200. Thus, we are forced to consider a linac/synchrotron combination. In this case, it would make more sense and the logistics would be much simpler to accelerate the ions in this synchrotron all the way to 1.49 GeV/c (or slightly higher) and inject directly into the Main Ring instead of accelerating to 0.644 GeV/c, extracting and injecting into the Booster and there, accelerating further to 1.49 GeV/c. The 1.49 GeV/c synchrotron will cost more and require a larger rf frequency modulation than the 0.644 GeV/c synchrotron but the simplicity

and the reduced interference derived from bypassing the Booster is well worth the cost. In any case, it is doubtful that the Booster vacuum can be sufficiently improved for accelerating non-fully-stripped ions. This has the added advantage that one can now choose a higher final momentum, say, 1.7 GeV/c at which the stripping efficiency to 92+ is approaching 100%. An appropriate energy for the linac is 10 MeV or a momentum of 0.137 GeV/c.

The entire scheme is now as follows:

Linac² (new, M\$ 30) (~100 m long)

	<u>Section I</u>		<u>Section II</u>
Ion	U^{5+}	stripping	U^{40+}
Energy	0 - 1.2 MeV		1.2 MeV - 10 MeV
Momentum	0 - 47.5 MeV/c		4.75 MeV/c - 137 MeV/c

Booster (new, M\$40) (~same size as 8 GeV p Booster)

Ion	U^{40+}	strip to 92+
Momentum	0.137 GeV/c - 1.70 GeV/c	
Energy	10 MeV - 1 GeV	
rf frequency	7.673 MHz - 46.493 MHz	

Main Ring (new rf system, M\$10)

Ion	U^{92+}
Momentum	1.70 GeV/c - 150 GeV/c
Energy	1 GeV - 149 GeV
rf frequency	46.493 MHz - 53.104 MHz

Tevatron (no modification)

Ion	U^{92+}
Momentum	150 GeV/c - 387 GeV/c
Energy	149 GeV - 386 GeV
rf frequency	53.104 MHz - 53.105 MHz

The total cost is ~M\$80. The construction and commissioning of the whole injector (Linac and Booster) and of the new Main Ring rf system can be carried out totally independent of the operation of the Tevatron complex. Downtime is required only to install the rf cavities in the Main Ring and to connect the beam pipe between the new Booster and the Main Ring. The injection and extraction systems in both the Main Ring and the Tevatron can be used without modification. If the work is properly organized, the interruption should not have to be more than ~1 month.

With a 230 μA (particle) beam from the Linac one can inject $\sim 2 \times 10^{11}$ ions per Tevatron pulse. There will be losses during stripping, adiabatic capture, beam transfers between synchrotrons, etc.; but the overall efficiency should be better than $\frac{1}{2}$, i.e. one should be able to get more than 1×10^{11} U^{92+} /pulse out of the Tevatron.

References

¹Notably BNL and ORNL

²The design of a 230 μA (particle), 10 MeV/nucleon U^{40+} linac was made by LANL for ORNL. The important parameters are given in Table 1.

³The study for one specific scheme was made by A.G. Ruggiero, "Heavy-Ion Beams for Fermilab", October 1983

Table 1 LOS ALAMOS NATIONAL LABORATORY -- ACCELERATOR TECHNOLOGY DIVISION

CONCEPTUAL HEAVY ION LINAC FOR OAK RIDGE

<div> <div> <div>PIG Source & Injector</div> <div>RFQ 25 MHz</div> <div>π-π Wideröe 25 MHz - FOFODODO</div> <div>Stripper</div> <div>Alvarez 100 MHz - FODO</div> </div> <div> $I_e = 12$ mA $I_p = 2.4$ mA $\epsilon_n = 0.09\pi$ cm·mrad $V = 476$ kV </div> <div> $^{238}\text{U}^{+5}$ $\Delta\phi = \pm 34^\circ$ $\Delta(W/A) = \pm 0.0027$ MeV/A </div> <div> $\text{U}^{+5} \rightarrow \text{U}^{+40}$ </div> </div>				
W/A (MeV/A)	0.010	0.200	1.2	10.0
β	0.0046	0.021	0.051	0.15
f (MHz)	25	25		100
L (m)	35	42		25
P (MW)	1.7	2.5		4.2
q/A min	0.021	0.021		0.168
^{238}U	I_p (mA)	2.4	2.3	$2.3 \rightarrow .23$
	I_e (mA)	12.0	11.4	$11.4 \rightarrow 9.1$
Structure Cost (\$K)	7875	9376		3810
No. RF Power Modules	3	4		6
RF Power Cost \$K	1687	2250		3375
Total Costs \$K	9562	11626		7185

Debunched $\Delta(W/A) = \pm 0.00051$ MeV/A
 (conserved during acceleration)
 for linac

$$\frac{\Delta W}{W} = \pm 0.51 \times 10^{-4}$$

$$\frac{\Delta p}{p} = \frac{1}{2} \frac{\Delta W}{W} = \pm 0.255 \times 10^{-4}$$