LATTICE DESIGN OF HISTRAP: HEAVY ION STORAGE RING FOR ATOMIC PHYSICS

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Abstract

HISTRAP, a Heavy-Ion Storage Ring for Atomic Physics, is a proposed 46.8-m-circumference synchrotron-cooling-storage ring optimized to accelerate, cool, decelerate, and store beams of highly charged very-heavy ions at energies appropriate for advanced atomic physics research. This four-fold symmetrical ring has a maximum bending power of 2 Tm. It has achromatic bends and uses quadrupole triplets for focusing.

1. Introduction

HISTRAP, a Heavy-Ion Storage Ring for Atomic Physics, is a proposed 2.0-Tm synchrotron-storage-cooler ring to be located at Oak Ridge National Laboratory. HISTRAP will be injected with ions from either the existing Holifield Heavy Ion Research Facility 25-MV tandem accelerator[1] or from a dedicated electron cyclotron resonance (ECR) source and 250 keV/nucleon radio frequency quadrupole (RFQ) linac.

The following desired capabilities for atomic physics research controlled the ring design: the need to accumulate, store, accelerate and decelerate highly charged very-heavy ions; the need for electron beam cooling to provide beams with extremely good angular and energy resolution for precision spectroscopic studies; the need to study interactions between the circulating ion beam and internal fixed targets; the need to study interactions between extracted ion beams and external fixed targets; the need to study electron-ion interactions with circulating beams; the need to study photon-ion interactions with circulating beams; and the desire to store beams with multiple charge states separated by up to ± 4%. This charge state requirement is equivalent to a momentum acceptance of ± 4%.

These needs resulted in the proposed HISTRAP facility shown in Fig. 1. The ring has a circumference of 46.8 m and is designed for beams with magnetic rigidities between 0.1 and 2.0 Tm. The apertures were chosen for an acceptance of at least 40π mm mrad in both the horizontal and vertical planes. The lattice consists of four 90° achromatic bends connected by dispersionless straight sections. The four straight sections are each 4 m long. One straight section is required for the injection septum and the rf acceleration/deceleration cavity. Another straight section contains the electron beam cooling system. With matched electron-ion velocities, the electrons will cool the ion beam, improving the ion beam quality. With unmatched electron-ion velocities, electron-ion interactions can be studied in a circulating beam mode. Another straight section will eventually contain apparatus for a resonant slow-extraction system to feed external beam lines. The last straight section has been kept completely free of accelerator hardware to allow space for apparatus to do in-ring experiments with stored ions.

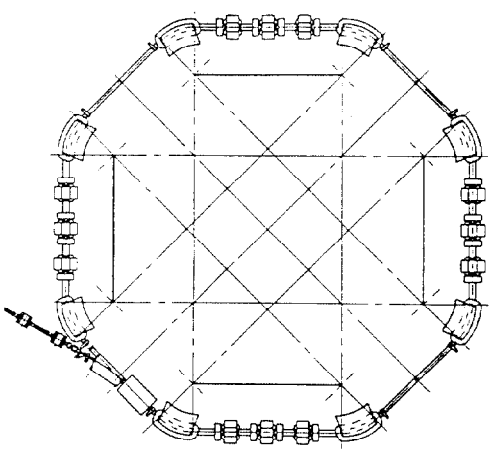

Fig. 1: The synchrotron-cooler-storage ring consists of four 4-m-long straight sections connected by 90° achromatic bends. Each achromat consists of two 45° dipoles separated by a quadrupole triplet.

2. Lattice

Several separated-function lattices with four straight sections were studied in some detail. Because it is desirable to have injection, acceleration, extraction, cooling, and most internal experiments in dispersionless regions, all four 90° bends were chosen as achromats giving only dispersionless straight sections. The resulting lattice shown in Fig. 1 is fourfold symmetric and each achromat has reflection symmetry about its center. The achromats consist of two 45° dipoles separated by FDF quadrupole triplets. This lattice appears to minimize the number of quadrupoles, gives a small vertical β function in the dipoles, and gives a small dispersion function in the quadrupoles. The dispersion function must be small if more than one charge state is to circulate in the ring with reasonable quadrupole apertures. More complicated lattices seem to give no overall advantage.

The horizontal and vertical tunes of the ring were chosen to be near 7/3, which avoids structure resonances and facilitates extraction by slow excitation of a sextupole resonance. In particular, $\nu_x = 2.3088$ and $\nu_y = 2.2744$ were used in the lattice calculations. These values of tune and the requirement of having non-dispersed straights comprise three lattice conditions. With the length of the straight sections fixed at 4 m and the length of the dipole magnets fixed, there are only four lattice parameters which can be varied to meet the three lattice conditions. These parameters are the strength of the F quadrupoles, the strength of the D quadrupoles, the distance between the F and D quadrupoles, and the distance between the F quadrupole and the dipole. These conditions and parameters leave only one free parameter which was varied to minimize the vertical β function in the dipoles and quadrupoles. The horizontal β function was relatively insensitive to this variation. The resulting β functions and the dispersion function are shown in Fig. 2 for the lattice. The resulting lattice parameters are listed in Table 1.

A maximum dispersion function of 1.5 m occurs in the F quadrupoles. This dispersion corresponds to a displacement of ± 6 cm for co-circulating charge states separated by ± 4%. The maximum vertical β function occurs in the dipoles and is 5.7 m. In the

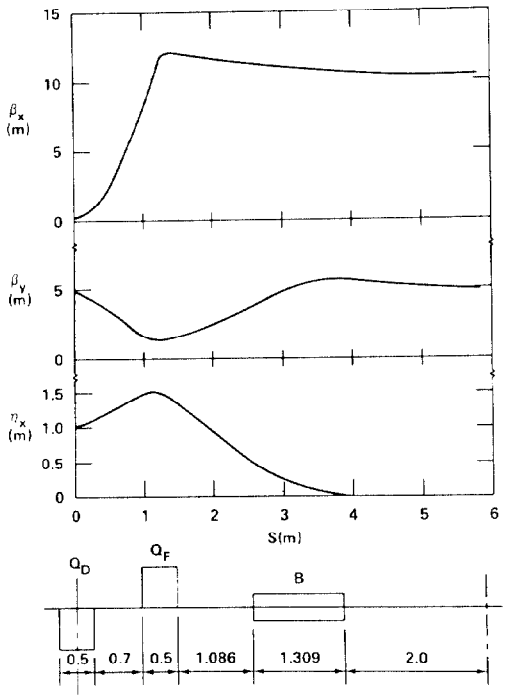

Fig. 2: Horizontal, β_x, and vertical, β_y, betatron functions and dispersion function, η_x, for one-eighth of the ring circumference. The ring has four-fold rotational symmetry and each quadrant has reflection-symmetry about the center of the defocussing quadrupoles.

Table 1. Parameters of the Synchrotron Lattice Obtained from SYNCH Calculations

Magnetic rigidity	$B\rho$ = 2.0 Tm	
Circumference	C = 46.7577 m	
Long straight (4)	s = 4.0 m	
Dipole (8)	ρ = 1.6666 m	
	θ = 45°	
	ℓ_D = 1.309 m	
Quadrupole (12)	ℓ_Q = 0.5 m	
Q_F (8)	G_F = 3.6977 T/m	
Q_D (4)	G_D = -4.1769 T/m	
Tune	ν_x = 2.3088	ν_y = 2.2744
Chromaticity	ξ_x = -6.1846	ξ_y = -1.5242
Beta function		
Dipole	$\beta_{x,max}$ = 11.4 m	$\beta_{y,max}$ = 5.7 m
Quadrupole	$\beta_{x,max}$ = 12.2 m	$\beta_{y,max}$ = 5.0 m
Straight	β_x = 10.5 m	β_y = 4.9 m
Dispersion function		
Dipole	$\eta_{x,max}$ = 0.49 m	
Quadrupole	$\eta_{x,max}$ = 1.51 m	
Straight	η_x = 0 m	

straight sections the horizontal and vertical β functions are about 10 m and 5 m, respectively. The need to cool using an electron beam provides some limits to the acceptable straight-section β values. A lower limit to acceptable β values is given by an upper limit to the cooling time, because a small β gives a large angular divergence which takes longer to cool. An upper limit to the desired ultimate emittance gives an upper limit to acceptable β values because the minimum angular divergence, θ, of the ion beam from cooling is fixed by the minimum angular divergence of the electron beam. Since the emittance $\varepsilon = \theta^2\beta$ and θ is fixed, a small emittance can only be obtained if the cooling section has a small β function. About $\beta \sim 10$ m gives an optimal cooling rate for ions with an energy of 50 MeV/nucleon, an emittance of 40π mm mrad, and an electron thermal temperature of 0.1 eV.

As listed in Table 1, the natural chromaticities of the lattice are given by $\xi_x = -6.18$ and $\xi_y = -1.52$. In order to have co-circulating charge states of the same species in the storage mode, it may prove necessary to cancel this chromaticity by using families of sextupole and higher order correction magnets. Since all the quadrupoles are in dispersive regions, this cancellation could be achieved locally by placing a sextupole magnet next to each quadrupole magnet. These sextupoles are shown in Fig. 1.

To explore the lattice tune range we have also studied the properties of a twofold symmetrical version of this lattice. The lattice has the same geometrical arrangement shown in Fig. 1, however, the quadrupole strengths have a twofold symmetry. The four straight sections remain nondispersive by having two families of achromats. The resulting four quadrupole strength parameters allow, with acceptable lattice functions, tune changes from 2.2 to 2.5 with the condition that $\nu_x \approx \nu_y$. Other two and fourfold symmetrical solutions are also possible with non zero dispersion in the straight sections.

3. Tracking Studies

The physics program proposed for the HISTRAP facility requires the simultaneous storage of ions with differing charge states. To accomplish this will require that particles which differ in rigidity by 4% or more must be stable simultaneously in the ring. To verify the feasibility of this, we have performed tracking studies for particles which differ in momenta. The LIE3 option of the code MAD (version 5.01) has been used for these studies. We first used the TRANSPORT option in MAD for the tracking studies, but found that the results were seriously (and unphysically) effected by the lack of symplectic symmetry inherent in that option. The calculations were made with two families of sextupole magnets chosen to correct the linear chromaticity of the ring to zero. No account has yet been taken for magnetic field and alignment errors. The momentum defect of injected particles was varied from -5% to +5% and particles were injected at positions equally displaced from the central orbit in the horizontal and vertical transverse directions at the following values; $\sigma_x = \sigma_y$ = 0.1, 0.2, 0.3, 0.4, 0.5, 1, 2, and 4, where $\sigma = 1$ represents a transverse displacement of 20.4 millimeters. At all these conditions, the particles were found to be stable for 2000 orbits. Several cases were run for 10000 orbits with no observable change in their behavior. Fig. 3

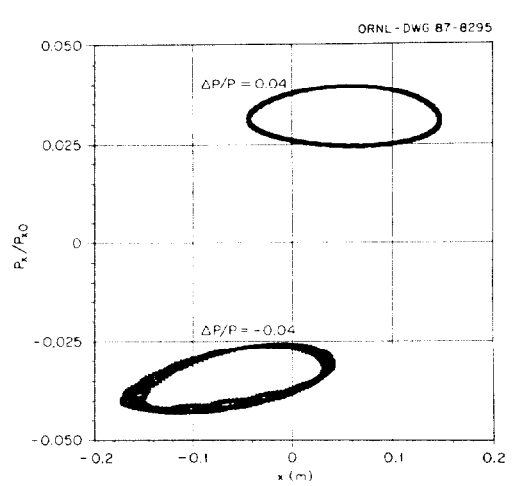

Fig. 3: Horizontal phase space trajectories of particle with $\Delta p/p = \pm 4\%$.

shows the phase space trajectories of particles with $\Delta p/p = \pm 4\%$. Figure 4 shows the tune variation due to momentum deviation with and without these sextupole magnets. These results encourage us to believe that it will be possible to store several charge states in the ring simultaneously.

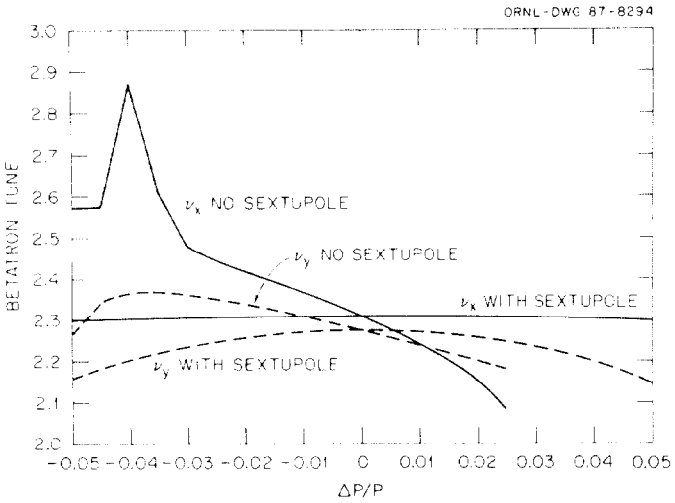

Fig. 4: Variation of the horizontal tune, ν_x, and vertical tune, ν_y, due to momentum deviation with and without chromoticity correction sextupole magnets.

4. Beam Energy and Intensity

The ring will be injected with ions from either the existing Holifield Heavy Ion Research Facility 25-MV tandem accelerator or from a dedicated ECR source and 250 KeV/nucleon RFQ. The highest-charge-state and hence highest energy beams will be obtained with tandem injection. Fig. 5 shows the maximum energy these ions can be accelerated to in HISTRAP. Light ions and Q/A = 1/2 will be accelerated to 48 MeV/nucleon, whereas the very-heavy ions will be accelerated to ~7 MeV/nucleon. The ECR source will provide beams with a lower charge state and lower current than can be obtained from the tandem accelerator. The corresponding maximum energies for these ions are also shown in Fig. 5. Results for two cases are listed: a high-current (1 μA) low-charge-state case and a low-current (1 nA) high-charge-state case. The corresponding intensities are shown in Fig. 6.

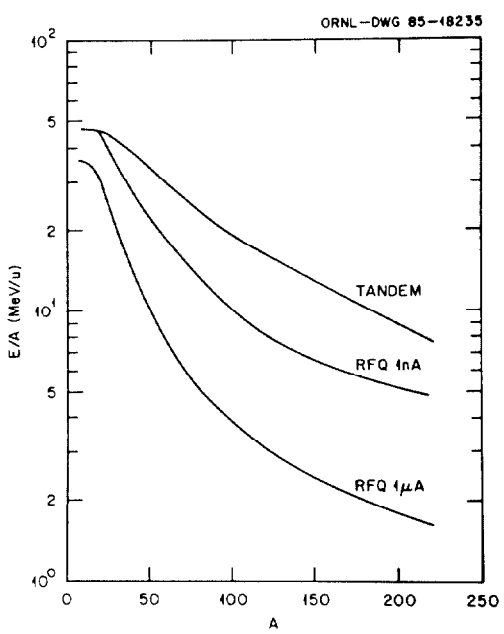

Fig. 5: Maximum ion energy from HISTRAP as a function of mass number with injection from either the tandem accelerator or injection from the ECR and RFQ preaccelerator. For injection from the RFQ two cases are shown: a high-charge-state low-current case (1 nA) and a low-charge-state high-current case (1 μA).

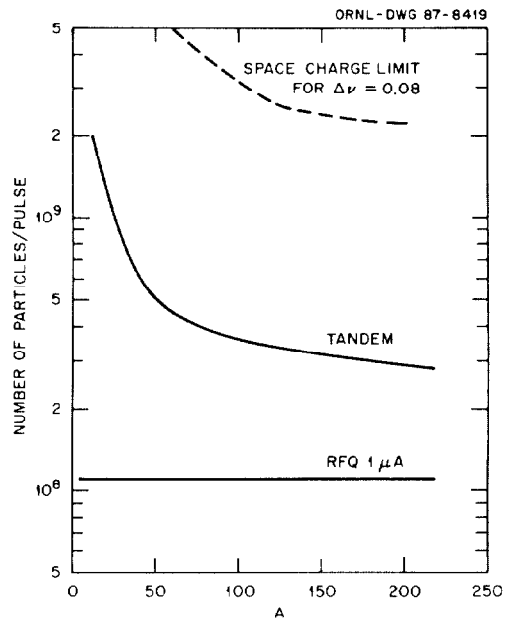

Fig. 6: Beam intensity as a function of mass number.

The horizontal acceptance of HISTRAP will be appreciably larger than 40π mm mrad with an operational mode in which ions are injected, accelerated to the maximum energy, and extracted. Assuming small, closed orbit errors and allowing for adiabatic damping, a beam with 200π mm mrad can be accepted at injection. This will result in a three fold intensity increase for maximum-energy ions over those shown in Fig. 6. More details of HISTRAP can be found in Ref. 2.

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