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A RING TO TEST STRIPPING ENFORCEMENT*

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1 INTRODUCTION

A design of a charge state enforcer ring is shown, which could be used in an ISL facility when ions are stripped, providing 75–90% transmission of the desired charge state. An ISL facility is likely to require stripping at or near 0.2 and 1.5 MeV/u. The ring described here can be used at both energies. This ring could be tested at LBL, using existing equipment for providing ions at both energies.

2 DESIGN OF THE RING

The ring comprises 8 dipoles to bend ions through a total of 360 degrees, 20 quadrupoles for transverse focusing, and 8 sextupoles to compensate for higher-order effects. The arrangement is shown in Figure 1. The criteria used in the design of these transverse ring elements were described in an earlier paper (1). These require that betatron tunes be integral or half-integral, and that chromaticity be zero. This ring has a horizontal tune of 2.5 and a vertical tune of 0.5. The circumference on the equilibrium orbit is 16.27 m. There are four longer straight sections: one is used for the stripper, one for a buncher cavity, the remaining two are used for extraction of the mean charge state. Two of these (stripper and buncher) are non-dispersive, the other two have dispersion which can be adjusted by quadrupole settings, which would usually be set for separation of adjacent charge states of 10–20 mm.

The injection channel goes through one of the dipole gaps. Ions are stripped immediately after injection, which decreases the rigidity and allows them to return again to the stripper. The magnetic field of the dipoles is set so that the mean charge state $\bar{q}$ remains on the quadrupole axis. In the straight section following the stripper straight section, these ions enter a narrow channel, and are deflected vertically (the deflecting device can be either electric or magnetic). This causes them to be displaced across the septum of a magnet

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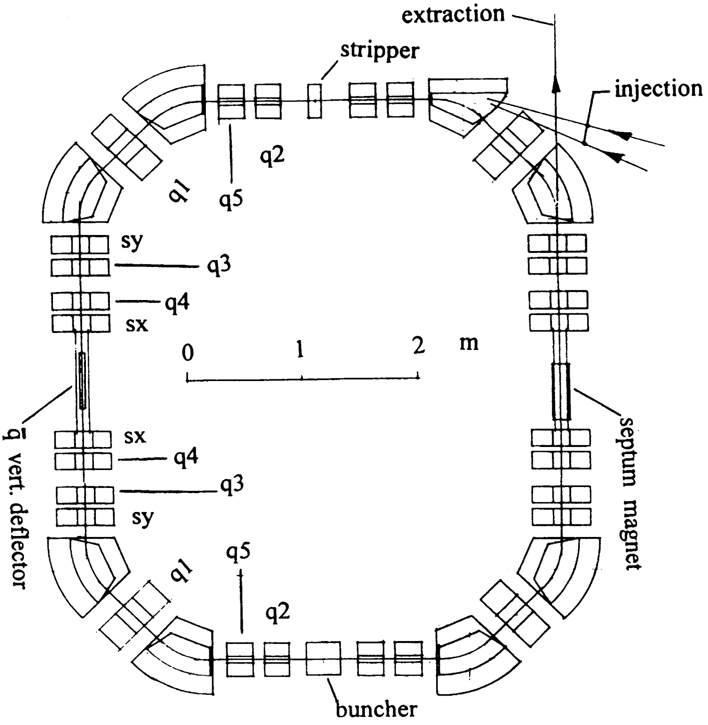


FIGURE 1: Schematic of the stripper enforcer ring. After entering from the injection channel, ions are recirculated through the stripping foil, with the mean charge state being extracted on each turn. Energy lost in the stripper is made up in a rf cavity (labeled buncher).

located on the opposite side of the ring, and to be deflected vertically into the extraction channel.

The buncher cavity serves two purposes: it makes up for energy lost in the stripper, and it acts to minimize energy spread in the emerging $\bar{q}$ beam. The frequency (a harmonic of the revolution frequency), the voltage and phase of the rf must be chosen appropriately in order to accomplish this. They are set so that energy lost in the stripper is restored, and so that ions arriving late are speeded up and ions arriving early lose energy. This produces what is known as a phase-stable rf bucket. The rf voltage determines the size of the bucket and this must be made large enough to encompass all of the ions. Ions with positive Δq will get a greater and those with negative Δq less energy gain for a given voltage than the $\bar{q}$ ions. This leads to a dependence on the rate of rise of the rf (hence the frequency) in order to minimize the energy spread of the extracted beam.

The momentum acceptance of the ring is large, on the order of $\pm 25\%$ in $\Delta q/q$, so only a small loss is experienced to the vacuum chamber walls on each turn. After some 12 revolutions for light ions, 14 for the heaviest, essentially all of the injected ions that survive have been extracted.

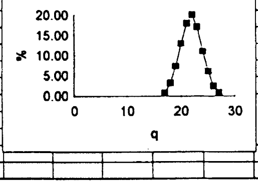
3 EXPECTED PERFORMANCE

To test the expected performance, calculations were done to see, to first order, if the use of this ring would seriously degrade transverse or longitudinal beam emittance. From the results so far, the calculations suggest that the degradation will be acceptable.

Calculations were performed with 5 ions-Ne, Ar, Kr, Xe, U- at two energies- 0.2 and 1.5 MeV/u. Use of a carbon stripping foil was assumed, in preference to a vapor or gas stripper because the carbon foil yields higher charge states (important particularly for the light ions) and a more precise definition for the stripped beam, important for ring performance. Equilibrium stripping fractions were taken from Reference 2. For each ion a table of stripping intensities was made – that for Kr at 1.5 MeV/u is shown as Table 1. The first column contains the stripped charge states q, the third column the expected intensity in each charge state (expressed as a percent of the original beam) after one stripping. This is also plotted in the accompanying graph. A small percentage (in this case 0.5%) falls outside the ring acceptance. On each turn, 20% is extracted as $q = 22$. After the second stripping,of the 79.5% reaching the stripping foil, 15.9% were extracted on turn 2 (column 4), 12.64% on turn 3, and so on. The table is terminated after 14 turns, though the 4% remaining can still contribute to the extraction efficiency. The amount each turn adds to $\bar{q} = 22$ is used in subsequent analysis of the contribution of each turn to the transverse and longitudinal emittance spread. Adding up the row for $\bar{q} = 22$ shows that we can expect over 93% of the original beam to be extracted. The ring operates continuously, with all turns existing simultaneously. Adding up the row showing recirculating intensities, we see that the total recirculating intensity, plus the original beam, amounts to 472% of the original beam intensity. This is an important consideration in evaluating the expected life of the stripper.

TABLE 1: Equilibrium stripping fractions for Kr at 1.5 MeV/u, resulting from repeated passes through a carbon stripping foil. Energy lost in the stripper is restored with a buncher rf cavity.

		1.5 MeV/u Kr beam thru Carbon stripper						Brho = 0.6736 T-m									
q	Injected		% distributed to each channel														
17		0.80	0.64	0.51	0.40	0.32	0.25	0.20	0.16	0.13	0.10	0.08	0.06	0.05	0.04	3.75	
18		3.20	2.54	2.02	1.61	1.28	1.02	0.81	0.64	0.51	0.41	0.32	0.26	0.20	0.16	14.98	
19		7.30	5.80	4.61	3.67	2.92	2.32	1.84	1.47	1.16	0.93	0.74	0.59	0.47	0.37	34.18	
20		13.00	10.34	8.22	6.53	5.19	4.13	3.28	2.61	2.07	1.65	1.31	1.04	0.83	0.66	60.86	
21		18.00	14.31	11.38	9.04	7.19	5.72	4.54	3.61	2.87	2.28	1.82	1.44	1.15	0.91	84.27	
22	100.00	20.00	15.90	12.64	10.05	7.99	6.35	5.05	4.01	3.19	2.54	2.02	1.60	1.27	1.01	93.63	<% extracted for
23		17.00	13.52	10.74	8.54	6.79	5.40	4.29	3.41	2.71	2.16	1.71	1.36	1.08	0.86	79.59	100% injected
24		11.00	8.75	6.95	5.53	4.39	3.49	2.78	2.21	1.76	1.40	1.11	0.88	0.70	0.56	51.50	
25		6.00	4.77	3.79	3.01	2.40	1.91	1.51	1.20	0.96	0.76	0.61	0.48	0.38	0.30	28.09	
26		2.40	1.91	1.52	1.21	0.96	0.76	0.61	0.48	0.38	0.30	0.24	0.19	0.15	0.12	11.24	
27		0.80	0.64	0.51	0.40	0.32	0.25	0.20	0.16	0.13	0.10	0.08	0.06	0.05	0.04	3.75	
	n= 0	1	2	3	4	5	6	7	8	9	10	11	12	13	14		
%	recirc.=	79.50	63.20	50.25	39.95	31.76	25.25	20.07	15.96	12.69	10.08	8.02	6.37	5.07	4.03	372.18	< recirculating
																100.00	< injected
																472.18	< intensity on
	total %	99.50															stripper



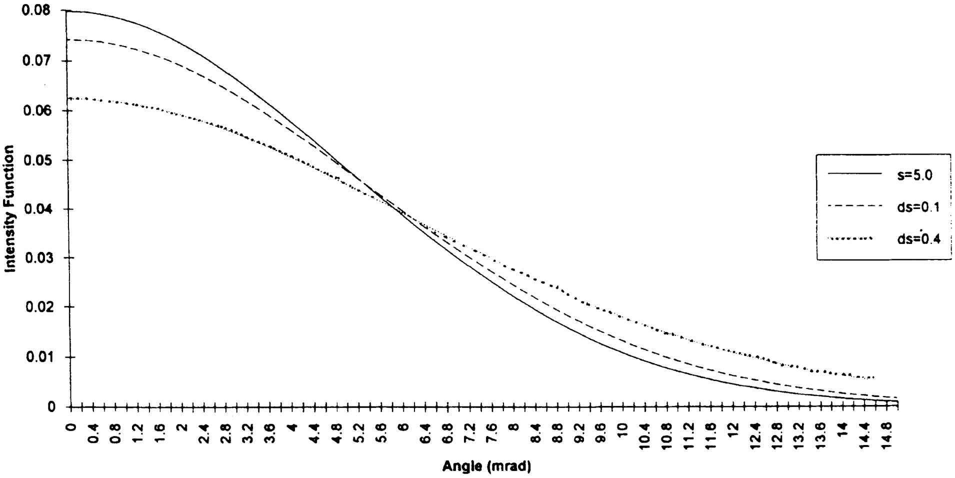


FIGURE 2: Growth of the transverse emittance, which is proportional to the angular divergence, due to scattering in stripping. Initial divergence FWHM (s) is taken as 5 mrad. Two cases of the resulting spread in the extracted beam are considered, one with half-angle (ds) of 0.1 mrad on each turn, one with ds=0.4 mrad.

To estimate transverse emittance growth in repeated stripping, a calculation was done in which an angular distribution, initially gaussian, was subjected to repeated transformations simulating a passage through a foil. Emittance growth will be proportional to angular growth because ring properties are such that the spot size on the stripping foil is constant. The intensity distribution before stripping was divided into many narrow slices, and then each slice was converted to a gaussian with the FWHM caused by stripping. Recombining all of these distributions gives an overall (non-gaussian) distribution for the result of the stripping event. This process was repeated a number of times corresponding to the expected number of turns in the ring. For each turn, the integrated intensity was adjusted to correspond to the expected intensity contribution to the extracted beam of that turn. The result of two such calculations are shown in Figure 2.

The initial FWHM (s) was taken as 5 mrad. The result with scattering angle FWHM (ds) is shown for ds= 0.1 and 0.4 mrad. Both, as expected, lower the peak intensity and broaden the tail of the distribution. These results suggest that scattering FWHM on the order of 0.1 mrad will have a small effect on emittance growth; the effect of 0.4 mrad scattering will be significantly greater. Scattering in thin carbon foils will depend upon ion species and energy. Calculations show that in scattering of ^{132}Xe by a 3.0 μgm carbon foil, half-angles should be on the order of 0.1 mrad at 1.0 MeV/u but will be on the order of 1 mrad at 0.1 MeV/u (3). Some experimental data would be helpful in permitting us to be more precise in the estimates of scattering for this ring.

To study longitudinal emittance growth, a calculation was done in which ions are passed through the stripper (energy loss per stripping is taken as 3 keV/u), then through the buncher gap, then again through the stripper, etc. for the specified number of turns. After the first stripping there are *n* ion beams, where *n* is the number of stripped states. Each ion beam is

TABLE 2: Stripper Ring optimum performance for T=0.2 MeV/u ions. Revolution frequency is 0.378803 MHz.

ion	A	$\bar{q}$	Δq max	$\Delta q/\bar{q}$ max	h	peak kV	$^{\sigma}$dT/T %	$^{\sigma}$rev rev deg	$^{\sigma}$prod (rev deg)* (% dT/T)	Energy increase %	extr. %	stripper intensity %
Ne	20	5	1	0.20	20	120	5.23	2.1	11.02	1.05	75	196
Ar	40	8	2	0.25	10	120	0.46	3.5	1.63	–3.25	77	279
Kr	84	11	3	0.27	10	90	2.42	2.4	5.78	–0.60	86	346
Xe	132	17	4	0.24	10	140	2.52	1.9	4.89	–0.85	72	438
U	238	21	5	0.24	10	160	1.96	2.0	3.98	–1.15	85	506

assigned an intensity corresponding to its stripping fraction. At the second stripping, each ion beam generates an additional *n* ion beams, with appropriate *q* and intensity. During each turn, the mean charge state $\bar{q}$ is assumed extracted. Finally, the superposition of all extracted beams yields a distribution which can be measured in terms of phase spread and energy spread.

In the calculations, for each ion species and incident energy, the three buncher variables- phase, harmonic number, and peak rf voltage- were found which gave the smallest growth of longitudinal emittance in the extracted beam. These results are shown in Table 2, for 0.2 MeV/u incident energy, and in Table 3, for 1.5 MeV/u incident energy. The extracted mean energy was slightly lower, in most cases. Energy spread FWHM is given as a percent of mean energy; phase spread FWHM is given in terms of revolution frequency (not the rf frequency).

The spreads in energy and phase represent an increase over initial energy and phase spreads, presumably these spreads will combine quadratically. In the case of Ar at 0.2 MeV/u, the low value of $\Delta T/T$ suggests that some additional improvement might be found for the other ions.

TABLE 3: Stripper Ring optimum performance for T=1.5 MeV/u ions. Revolution frequency is 1.043126 MHz.

ion	A	$\bar{q}$	Δq max	$\Delta q/\bar{q}$ max	h	peak kV	$^{\sigma}$dT/T %	$^{\sigma}$rev rev deg	$^{\sigma}$prod (rev deg)* (% dT/T)	Energy increase %	extr. %	stripper intensity %
Ne	20	8	2	0.25	10	70	0.83	0.092	0.0076	–0.09	99	206
Ar	40	13	3	0.23	30	70	0.79	0.110	0.0087	–0.11	98	290
Kr	84	22	5	0.23	30	90	0.84	0.121	0.0101	–0.11	94	472
Xe	132	30	5	0.17	40	90	0.72	0.112	0.0081	–0.11	95	426
U	238	43	5	0.12	40	120	0.48	0.088	0.0042	–0.09	91	509

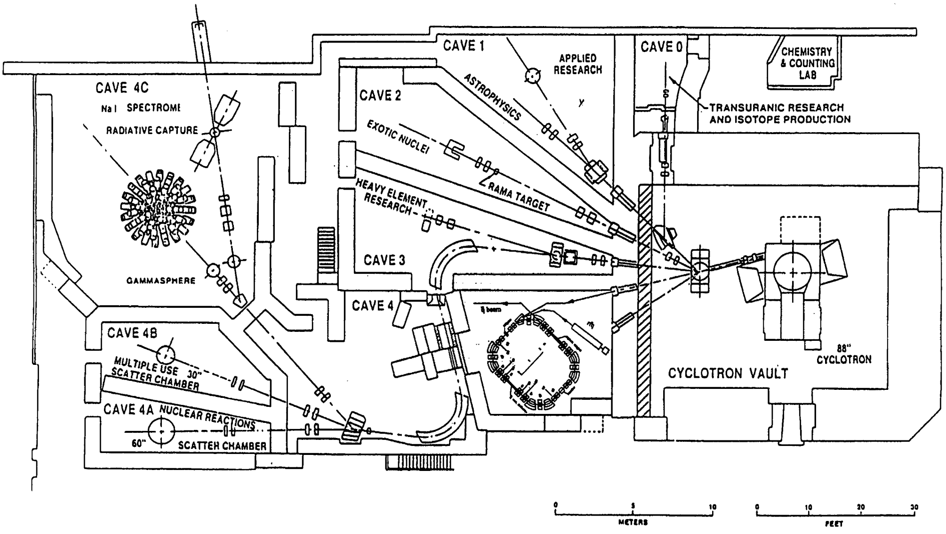


FIGURE 3: Schematic showing the proposed stripping enforcer ring installed at the 88-inch cyclotron.

Studies will continue, with more sophisticated calculations (such as higher order magnetic focusing effects, and coupling of longitudinal and transverse forces) to verify these results and to relate them to realistic beams and experiments forseen for the ISL facility.

4 PROPOSED TEST FACILITY

The 88" Cyclotron at LBL can be used as a source of ions to test ring performance. It can deliver a wide range of ion species at suitable energies. A plan showing the proposed installation in an existing cyclotron cave is shown as Figure 3. One of the existing cyclotron transport lines will be redirected to inject into the ring. Also installed in the cave will be an rfq, originally used as a Bevatron injector, which can be used as an alternate injector to the ring, for 0.2 MeV/u light ions. The rfq will be useful because the available cyclotron time is limited by commitments to other experiments.

The value of a such a test facility to a future ISL proposal will be great. The stripping enhancement ring is an untried concept, but any ISL facility which proposes to use such a ring to enhance intensity output will have to be sure of its success. The only way to know this is to perform tests with such a ring beforehand. The cost will be modest, and the ring components can be reused in an ISL facility, wherever it may be.

Questions to be studied include stripper foil lifetime, required thickness, resulting charge states, all as a function of ion species. The ease of tuning the magnetic elements and the operation of the buncher will need to be understood. The intensity of the extracted ion beam can be measured, and compared to the intensity of the input beam. The transverse emittance can be measured, and compared to input emittance. After passing through a bending magnet, the energy spread can be measured.

REFERENCES

1. F. Selph, Proc. of the ORNL Workshop on Prod. and Use of Intense Radioactive Beams at the IsoSpin Laboratory, CONF-92210121, 359-362 (Oct. 1992).
2. K. Shima *et al.*, Atomic Data and Nuclear Data Tables **51**, 173–241 (1992).
3. K.E.G. Loebner, Proc. of the ORNL Workshop on Prod. and Use of Intense Radioactive Beams at the IsoSpin Laboratory, CONF-92210121, 353–356 (Oct. 1992).