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1 Introduction

The Rapid Cycling Medical Synchrotron (RCMS) was originally designed for therapeutic irradiation of tumors with protons [1]. In contrast, this preliminary paper explores a design variant of the RCMS – the iRCMS – that is optimized for delivering ions with $Z/A \approx 0.5$ for therapy, biology, or physics.

Species	Z	A	Z/A	Mass [u]	Mass/A [u]	Injection K.E. [MeV/u]	Extraction (max) K.E. [MeV/u]	Repetition rate [Hz]	Particles per pulse
Therapy									
Protons	1	1	1.000	1.0078		(7)	(250)	(30)	(1.7×10^9)
Carbon	6	12	0.500	12.0000	1.0000	20	450	30	2.7×10^7
Research									
Helium	2	4	0.500	4.0026	1.0007	20	450	30	1.6×10^8
Oxygen	8	16	0.500	15.9949	0.9997	20	450	30	3.3×10^6
Neon	10	20	0.500	19.9924	0.9996	20	450	30	3.3×10^6
Krypton	36	84	0.428	83.9115	0.9989	17.1	385	o(1Hz)	3.3×10^6
Xenon	54	131	0.412	130.9051	0.9993	16.5	371	o(1Hz)	3.3×10^6

Table 1: Fundamental parameters of the iRCMS, an ion variant of the RCMS, designed to accelerate ions with $Z/A \approx 0.5$. Proton parameters from the RCMS are included for comparison purposes only, as their acceleration is best performed in a separate dedicated ring.

For the sake of simplicity, this paper assumes that the total mass of an ion is just

$$M_{ion} = A\,u \tag{1}$$

Table 1 indicates that Equation 1 is accurate within an error of only about ±0.1% for species from Helium through Xenon [2]. After making this assumption, all ion species with the same Z/A value behave identically from the perspective of fully stripped single particle dynamics. For example, Table 1 shows that the maximum kinetic energy at extraction is the same for Helium, Oxygen and Neon (but is somewhat lower for Krypton and Xenon). Thus, it is natural to design the iRCMS for $Z/A = 0.5$ operation, typically with carbon ions.

Table 2 compares the primary parameters of the carbon iRCMS with those of the proton RCMS. The iRCMS circumference of ~ 55 m is about twice that of the RCMS. This is an approximate value, assuming only slightly longer straight sections, but scaling the arc magnets to new lengths for a higher rigidity with the same maximum bending field. Table 3 compares the basic kinematic parameters at injection and at the top of the energy ramp, for RCMS and iRCMS.

Accelerator		**RCMS**	**iRCMS**
Charge to mass number ratio, Z/A		1.0	0.5
Kinetic energy (max)	[MeV/u]	250	450
Rigidity (max)	[Tm]	2.432	6.826
Arc magnet dipole field (max)	[T]	1.436	1.432
Arc magnet bending radius, ρ	[m]	1.694	4.767
Arc magnet magnetic length	[m]	0.760	~ 2.14
Quadrupole magnetic length	[m]	0.14	~ 0.39
Arc half-cell length	[m]	1.1	~ 3.09
Number of half cells per arc		7	7
Circumference, C	[m]	30.65	~ 55

Table 2: Preliminary primary physical parameters of the RCMS and the iRCMS.

		RCMS		**iRCMS**	
		injection	**extraction**	**injection**	**extraction**
Kinetic energy, K	[MeV/u]	7	250	20	450
Momentum, p	[MeV/uc]	114.8	729.1	194.8	1023.2
Lorentz γ		1.0075	1.2664	1.0213	1.4796
Lorentz β		0.122	0.614	0.203	0.737
Rigidity, $B\rho$	[Tm]	0.383	2.432	1.299	6.826
Dipole field, B	[T]	0.226	1.436	0.272	1.432
Revolution frequency, F_{rev}	[MHz]	1.188	6.002	1.108	4.018
Revolution period, T_{rev}	[μs]	0.842	0.166	0.903	0.249

Table 3: Kinematic parameters at injection and at the maximum extraction energy at the top of the acceleration ramp, for RCMS (protons) and iRCMS (carbon ions).

2 Preliminary Design Comments

A comparison of beam and accelerator parameters through the acceleration ramp is plotted in Figures 1 and 2, with numerical values listed in Table 6.

The iRCMS Radio Frequency (RF) range is only slightly lower than for the RCMS, because the competing effects of increased circumference and increased speed almost balance. With $Z/A = 1/2$, iRCMS requires approximately twice the RF voltage of the RCMS. The original RCMS lattice includes a space reserved for a second RF cavity [1], so additional straight section space is not required to support this higher RF voltage. It seems that the same RF technology used for the RCMS can also be used for the iRCMS.

The same maximum bending field of 1.43 T is assumed for the iRCMS main arc magnets, in order to maintain simplicity of design, lower costs, and to leverage the existing RCMS design. The dynamic range of the field is somewhat lower for iRCMS because the momentum range is smaller than for RCMS. The field ramp rate dB/dt is correspondingly smaller for the same 30 Hz repetition rate, as are eddy current effects. Thus, at first glance, magnet issues seem similar for RCMS and iRCMS. Nonetheless, a detailed analysis of eddy current effects requires a detailed magnet, vacuum chamber and lattice design.

Detailed lattice design and optimization is also required to maintain aperture constraints and to match to dispersion-free straights. Simply scaling the lengths of the main magnets and arcs with the rigidity is reasonable in this preliminary context, in order to evaluate iRCMS feasibility, but arc beam size constraints will require (presumably modest) changes in their design parameters. These changes are not expected to modify the fundamental observation that an iRCMS with listed parameters appears feasible with RCMS magnet and RF technology.

3 Injector Considerations

The iRCMS injector has different challenges than the RCMS injector. It must provide the fully stripped ions listed in Table 1 at 20 MeV, and should be able to change between ion species quickly, with little contamination from other ion species with similar Z/A.

Electron Beam Ion Trap (EBIT) and Electron Beam Ion Source (EBIS) technologies are the most promising for an iRCMS injector. When used to produce extracted ions both source types are operated using the principles of the Electron Beam Ion Source described in [5].

In practice, the EBIT source usually operates with higher current densities and higher electron beam energies, allowing it to produces bare ions (i.e. all electrons stripped away) up to Uranium [6]. EBIT sources are traditionally short, with interaction regions 2.5-4.0 cm long, a design which is sufficient for experiments and observations with trapped ions. The EBIT operates with relatively low currents, up to 250 mA for low energy beams. For light ions one can expect $\sim 10^7$ ions/pulse and confinement periods of less than 30 ms. However, for the production of highly charged heavy ions such as Xe^{54+}, the 73 keV e-beam current is limited to 70 mA, and only about 500 Xe^{54+} ions/pulse are extracted after a 500 ms confinement period[6].

EBIS sources are designed to provide beams for accelerators and external experiments, and hence typically have an ionization region about 1 m long. These sources typically operate with electron beam with $I_e < 0.5$ A, $E_e < 30$ keV and electron beam densities ranging from 100-2000 A/cm^2. High current EBIS technology under development at BNL uses a 20–30 keV, 10 A, 575 A/cm^2 electron beam to produce extracted ion beams up to 2.5×10^{11} charges per 10–40 microsecond pulse. This EBIS is designed to provide partially-stripped high-brightness ion beams up to U^{45+}, with a 1 second switching time between species, 5 Hz rep rate, and 17 keV/u extraction energy [4].

The production of bare light ions up to Ne is relatively easy for both conventional EBIT and EBIS sources. The conventional EBIS "Dione" at Saclay routinely produced 6.7×10^8 ions/pulse of C^{6+} and 10^8 ions/pulse of Ne^{10+} in less than 30 ms, operating with a 1 m trap, and electron beam current of up to 0.5 A, and current density of about 1000 A/cm^2 [7]. Some source development may be necessary if it is required to produce bare ions of the heavier research ions in quantities greater than 10^6 ions/pulse in less than 30 ms.

Bare ion production of a particular species depends on a threshold bombarding electron beam energy E_e, the current density j_e, and the confinement time T. An increased quantity of ion charge can be produced and trapped with increased electron beam space charge, which is proportional to the current I_e and the trap length L for a given energy. Donets has presented the relationship between E_e and the ionization factor $j_e\ T$ [5]. The graph can be used to construct Table 4.

There is a strong inverse correlation between beam intensity and charge state with EBIS and EBIT. Higher intensities and repetition rates are only achievable with lower charge states from the injector. The column with the

Ion species	Last electron ionization potential [V]	Electron beam energy [eV]	Ionization factor [C/cm^2]	Conf period T[ms] for j_e [A/cm^2]		
				j_e =1000	j_e =5000	j_e =55000
C^{6+}	$\sim$ 490	980	$\sim$10	10	2	0.2
O^{8+}	$\sim$ 870	1740	$\sim$10	10	2	0.2
Ne^{10+}	$\sim$ 1360	2720	$\sim$32	32	6	0.6
Fe^{26+}	$\sim$ 9280	18560	$\sim$320	320	64	6
Kr^{36+}	$\sim$ 17950	35900	$\sim$5600	5600	1120	101
Xe^{54+}	$\sim$ 41300	82600	$\sim$32000	32000	6400	582

Table 4: Ion species and properties for an iRCMS EBIS preinjector for bare ion production, including confinement period for various electron beam current densities j_e.

Species	I_e		% compensation by bare ion charge state	Ionization potential [kV]	e$^-$ beam energy [keV]	Ions/pulse		Conf period T	
	EBIT [mA]	EBIS [mA]				EBIT	EBIS	EBIT [ms]	EBIS [ms]
He^{2+}	200	1000	20		20	6.0×10^7	1.0×10^{10}		
C^{6+}	200	1000	20	0.49	20	2.0×10^7	1.7×10^9	2.5	2
O^{8+}	200	1000	20	0.87	20	1.5×10^7	1.3×10^9	2.5	2
Ne^{10+}	200	1000	20	1.36	20	1.2×10^7	1.1×10^9	8.0	6
Fe^{26+}	150	1000	5	9.28	30	9.4×10^5	1.0×10^8		64
Kr^{36+}	100	1000	2	17.95	40	2.7×10^5	2.0×10^7	2800	1120
Xe^{54+}	70	1000	1	41.30	73	2.0×10^4	7.0×10^6	22800	6400

Table 5: Comparison of ion and preinjector parameters between example EBIT and EBIS preinjectors for iRCMS. The EBIT ions/pulse column assumes electron beam fluxes of $j_e = 4000 - 1400$ A/cm^2. The EBIS ions/pulse column assumes electron beam fluxes of $j_e = 5000$ A/cm^2.

heading 55,000 A/cm^2 in Table 4 is from a High Current EBIT source proposed by Marrs [8]. Such a source would be similar to the BNL EBIS in that it would operate with a 5 A electron beam and would have an extended length of 25 cm. Another option would be to accept less frequent pulses for heavy ions and adapt the BNL EBIS to use a high energy 5000 A/cm^2 electron beam. Reducing the BNL EBIS electron beam from 10 A to 1 A should make it easier to raise the beam energy from 30 kV to 80 kV while still providing sufficient quantities of ions in the 0.7 m trap length. In Table 5 the number of ions/pulse of each species is estimated for a conventional EBIT [6] and a BNL EBIS adapted for high voltage, 5000 A/cm^2 operation. The quantities are believed to be conservative for all entries. The EBIS Xe^{54+} result is significantly larger than the EBIT experimentally obtained value because of a factor of 3.5 improvement in current density due to the electron beam current.

For heavy ions the current density of the electron beam determines how long it takes to convert all the ions into the fully stripped state. In general, unless there is strong cooling, some ions will be lost with increased confinement time. If more bare ions are available than required, the confinement time can be reduced such that ions are extracted before all of them have reached the fully stripped state. For example, by extracting the ions after only 10% of the time necessary to produce all bare ions, one could expect to have produced about 2% bare ions. This enables one to increase the pulse frequency at the expense of quantity of the bare ions extracted per pulse. One can see from the required EBIT confinement times that extracting Xe^{54+} after only 500 ms gives a relatively low abundance. The charge analyzed spectrum shows the most probable charge state to be Xe^{50+} [6].

4 Conclusions

1. An ion variant of the RCMS, the iRCMS, accelerates ions from Helium to Neon over a kinetic energy range from 20 to 450 MeV/u, and heavier ions such as Krypton and Xenon from about 17 to about 380 MeV/u.
2. A simple scaling of main arc magnet lengths produces a machine circumference of approximately 55 m, about twice that of the RCMS. Higher accuracy requires more realistic lattice design development.
3. Magnet and RF technologies suitable for the RCMS are also appropriate for iRCMS. No particular challenges are foreseen.
4. Ion generation appears to be the most challenging technical issue. EBIT and EBIS ion sources promise to deliver fully stripped high current light ion (Carbon) therapy beams, in combination with an RFQ and a DTL.
5. The generation of high intensity heavy ion beams (in a high charge-state) requires further development. Repetition rates for heavy ions will likely be a few Hz or less. This is probably adequate for research beams, but probably not for therapy beams.

5 Acknowledgments

We are very grateful for productive discussions with Michael Herman about sample user specifications for the iRCMS.

References

[1] *Conceptual Design of the RCMS*, C. Gardner and S. Peggs (editors), unpublished, March 27, 2003.

[2] *The 2003 atomic mass evaluation*, G. Audi, A.H. Wapstra and C. Thibault, Nuclear Physics A **729** (2003) pp. 337–676.

[3] *Extraction of highly charged ions from the electron beam ion trap at LBNL for applications in surface analysis and materials science*, T. Schenkel et al., Rev. Sci. Instr. **73** 2, February 2002, pp. 663–6.

[4] *Progress on Test EBIS and the Design of an EBIS-Based RHIC Preinjector*, J.G. Alessi et al., 2005 Particle Accelerator Conference, pp. 363–5 (Knoxville, 2005).

[5] E.D. Donets in "The Physics and Technology of Ion Sources", edited by I.G.Brown, (Wiley,New York 1989), chap. 12.

[6] J.W. McDonald et. al. RSI 73 (1) 2002 pp.30-35.

[7] J. Faure et. al. AIP conf proc. no.188, pp. 102-112.

[8] R.E. Marrs et. al. UCRL-JC-132602 (1998).

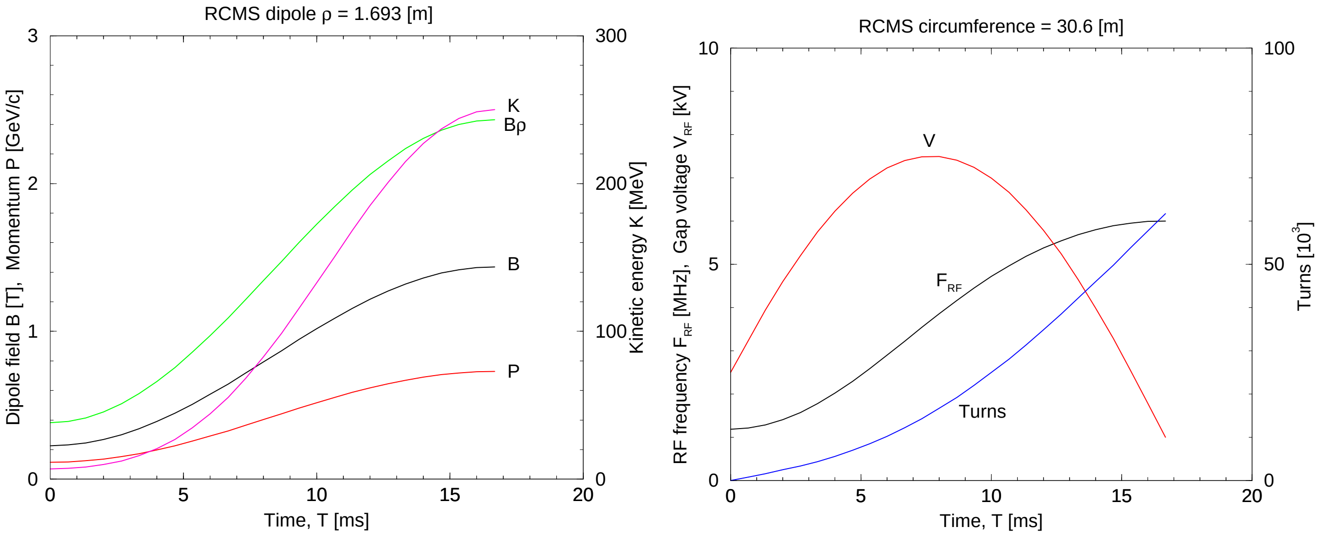

Figure 1: Key parameters in the RCMS acceleration cycle for protons. LEFT: dipole field B, rigidity $B\rho$, kinetic energy K, and momentum P, in the acceleration (rising) phase of a synchrotron cycle. RIGHT: RF frequency F_{RF}, RF gap voltage V_{RF}, and total number of turns, for the nominal proton RCMS acceleration ramp.

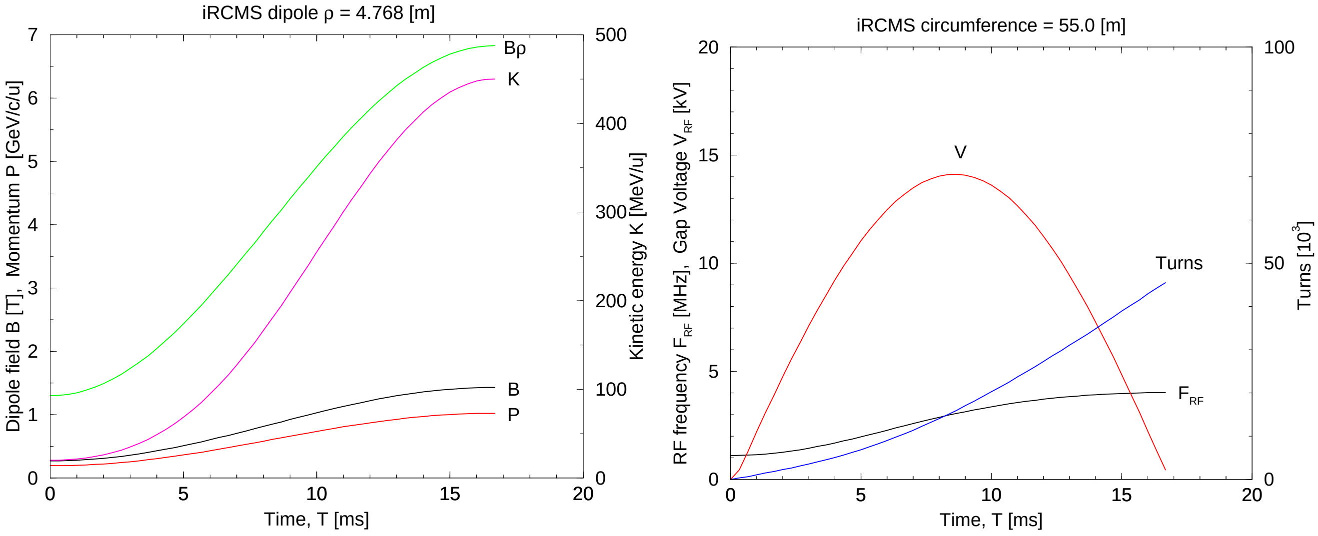

Figure 2: Key parameters in the iRCMS acceleration cycle for ions with Z/A=0.5. LEFT: dipole field B, rigidity $B\rho$, kinetic energy K, and momentum P, in the acceleration (rising) phase of a synchrotron cycle. RIGHT: RF frequency F_{RF}, RF gap voltage V_{RF}, and total number of turns, for the nominal Z/A=0.5 iRCMS acceleration ramp.

T	B	$\dot{B}$	$\dot{B}/B$	β	γ	K	P	F_{rev}	Turns	V_{rf}
ms	T	T/s	Hz			MeV/u	MeV/c/u	MHz		kV
RCMS (protons)										
0.000	0.226	0.0	0.0	0.121	1.007	7.00	114.82	1.188	0	2.500
1.000	0.237	21.4	90.2	0.127	1.008	7.68	120.27	1.244	1198	3.595
2.000	0.269	42.0	156.3	0.144	1.011	9.86	136.39	1.407	2489	4.598
3.000	0.320	61.1	190.7	0.171	1.015	13.99	162.64	1.671	3977	5.484
4.000	0.390	78.1	200.1	0.207	1.022	20.68	198.07	2.020	5758	6.229
5.000	0.476	92.3	194.0	0.249	1.033	30.57	241.44	2.438	7913	6.816
6.000	0.574	103.2	179.9	0.296	1.047	44.15	291.20	2.899	10503	7.227
7.000	0.681	110.5	162.3	0.346	1.066	61.62	345.59	3.381	13562	7.454
8.000	0.793	113.8	143.5	0.394	1.088	82.76	402.69	3.858	17103	7.491
9.000	0.907	113.1	124.7	0.441	1.114	106.90	460.48	4.309	21114	7.336
10.000	1.018	108.5	106.5	0.483	1.142	132.96	516.89	4.720	25563	6.993
11.000	1.123	99.9	89.0	0.519	1.170	159.54	569.95	5.078	30407	6.471
12.000	1.217	87.9	72.2	0.550	1.197	185.11	617.77	5.379	35589	5.784
13.000	1.297	72.7	56.0	0.575	1.222	208.10	658.65	5.620	41053	4.949
14.000	1.361	54.9	40.4	0.593	1.242	227.07	691.14	5.801	46738	3.988
15.000	1.407	35.2	25.1	0.606	1.257	240.84	714.10	5.924	52584	2.924
16.000	1.431	14.3	10.0	0.612	1.265	248.52	726.71	5.990	58534	1.786
16.667	1.436	-0.0	-0.0	0.614	1.266	250.00	729.13	6.002	62530	1.000
iRCMS (carbon ions)										
0.000	0.272	0.0	0.0	0.203	1.021	20.00	194.7	1.108	0	0
1.000	0.283	20.5	72.4	0.211	1.023	21.52	202.1	1.148	1115	2.219
2.000	0.313	40.2	128.4	0.232	1.028	26.33	223.8	1.265	2297	4.761
3.000	0.363	58.5	161.4	0.266	1.037	35.16	259.2	1.452	3619	7.117
4.000	0.430	74.8	174.1	0.311	1.052	48.96	307.0	1.695	5148	9.230
5.000	0.511	88.4	172.8	0.363	1.073	68.68	365.5	1.979	6936	11.038
6.000	0.605	98.8	163.3	0.419	1.101	94.93	432.6	2.282	9015	12.476
7.000	0.708	105.8	149.5	0.475	1.136	127.73	505.9	2.587	11399	13.487
8.000	0.816	109.0	133.7	0.528	1.177	166.36	582.9	2.877	14085	14.027
9.000	0.925	108.4	117.2	0.576	1.223	209.39	660.9	3.139	17051	14.069
10.000	1.031	103.9	100.8	0.618	1.272	254.83	736.9	3.367	20269	13.607
11.000	1.131	95.7	84.6	0.653	1.320	300.31	808.5	3.558	23702	12.654
12.000	1.221	84.2	68.9	0.681	1.366	343.33	873.0	3.713	27315	11.244
13.000	1.299	69.6	53.6	0.703	1.407	381.50	928.1	3.833	31071	9.426
14.000	1.360	52.6	38.7	0.719	1.440	412.68	971.9	3.922	34936	7.266
15.000	1.403	33.8	24.1	0.730	1.464	435.13	1002.9	3.981	38879	4.841
16.000	1.427	13.7	9.6	0.736	1.477	447.59	1019.9	4.012	42872	2.238
16.667	1.432	-0.0	-0.0	0.737	1.480	450.00	1023.2	4.018	45548	0.450

Table 6: The main accelerator and beam parameters during the acceleration phase of the synchrotron cycle for the RCMS with Z/A=1 protons (top), and iRCMS with Z/A=0.5 carbon ions (bottom).