PHASE I OPERATIONS

K500 CYCLOTRON OPERATING EXPERIENCE

D.R. Poe and H.A. Thulin

The year 1987 was a successful year for operation of the K500. The total number of hours in the Research and Development category was 3090, compared to 2927 in 1986, in spite of the fact that the cyclotron was shut down for a total of 2276 hours (26% of total time) during 1987 to free manpower for the construction of the K800 cyclotron and for installation of the compact ECR source. Operation at 50 MeV/nucleon and above has now become routine for the higher ions; design energis for the K500 have been met for ions up to A=40 and exceeded for heavier ions. In addition, with the addition of the compact ECR source, high intensity (2.50 ena) ^{6,7}Li beams have become available at energies up to 40 MeV/nucleon. The reliability of operation, defined as the percentage of total scheduled operating time for which the operations were continuing, or (Research + Development + Overhead)/(Total - Off - Maintenance) was 70%, slightly lower than 1986. This decrease can be attributed to the definitive future of the Imsai computer which controlled the power supply for the K500 magnet. It had been planned to replace the K500 control system with a device analogous to that for the K800 magnet, but the Imsai failure and the unavailability of replacement parts required that this be done on a crash basis.

Table I -- Time Distribution (1987)

Use Category	Hours	Fraction of operating period
	Operation	
Research	2742	42.3 %
Development	348.25	5.4 %
Overhead	1277.75	19.7 %
	4368.00	67.4 %
Maintenance	237.5	3.7 %
Breakdown	1877.5	29.0 %
Total	6483.0	100 %
Off (Shutdown periods)	2276.0	

Table II
K500 Beams run in 1987
Hours of extracted beam

MeV/U	MASS	ION	Q	# HRS	% TOT
10	36	Ar	7	65.5	2.08
11.5	36	Ar	7	90.75	2.88
8	40	Ar	6	111.25	3.53
10	40	Ar	7	23	0.73
12	40	Ar	7	32.5	1.03
15	40	Ar	8	124.25	3.94
20	40	Ar	9	72.75	2.31
30	40	Ar	1	238.5	7.57
10	12	C	2	30.75	0.98
15	12	C	3	29.25	0.93
20	12	C	3	52.25	1.66
35	12	C	4	91.25	2.90
45	12	C	5	22.75	0.72
50	12	C	5	130.5	4.14
2.5	13	C	1	7	0.22
10	13	C	2	44.25	1.40
53	2	D	1	42.5	1.35
60	2	D	1	1.5	0.048
65	2	D	1	1.5	0.048
24.1	4	He	1	13.25	0.42
25	4	He	1	17.75	0.56
40.2	4	He	2	2	0.063
44	4	He	2	2.75	0.087
50	4	He	2	2	0.063
53	4	He	2	17	0.54
60	4	He	2	1.75	0.056
2.5	86	Kr	8	47.5	1.51
15	86	Kr	1	76	2.41
11	6	Li	1	64.5	2.05
25	6	Li	2	107.25	3.41
35	6	Li	2	120.5	3.83
40	6	Li	2	66	2.10
20	7	Li	2	181.25	5.75
27.5	7	Li	2	157.75	5.00
2.5	26	Mg	2	6.5	0.21
5.25	20	Ne	3	71	2.25
15	20	Ne	4	53.25	1.69
4.9	22	Ne	3	66	2.10
30	22	Ne	7	7.5	0.24
35	22	Ne	7	226.25	7.18
8	14	N	2	16.75	0.53
35	14	N	5	135.75	4.31
40	14	N	5	23	0.73
40	14	N	6	21.25	0.67
50	14	N	6	249	7.91
40.2	15	N	5	10	0.32
40	16	O	6	40	1.27
50	16	O	7	96.75	3.07
35	18	O	6	37.5	1.19
				3149.75	

Table III

K500 Experiments in 1987

EXPT.#	SPOKES-PERSON	MONTH	BEAMS USED	
Disc.	Mallory	Jan.	(14)N:	35/u
86042	Porile	Jan.	(12C:	15/u,45/u
86013	Gonthier	Jan.	(16)O:	50/u
86007	Cramer	Jan.-Feb.	(12)C:	35/u, 50/u
86010	Morrissey	Feb.	(40)Ar:	8,10,12/u
86026	McHarris	Feb.	(22)Ne:	15/u
Disc.	Zeller	Feb.	(2)D:	60/u
86027	Shaheen	Mar.	(40)Ar:	20,30/u
Disc.	Mallory	Mar.	(12)C:	35/u
"	"	"	(14)N:	40.3/u
"	"	"	(15)N:	35/u
85042	Mikolas	Mar.-Apr.	(22)Ne:	35/u
86028	Becchetti	Apr.	(20)Ne:	15/u
"	"	"	(12)C:	15/u
86032	Kashy	Apr.	(7)Li:	20/u
86034	Wilson	May	(40)Ar:	10,20,30/u
"	"	"	(4)He:	25/u
"	"	"	(2)D:	25/u
86001	Benenson	May	(7)Li:	27.5/u
86041	Cebra	June	(14)N:	8,35,50/u
85040	Anantaraman	June	(6)Li:	35/u
87014	Ogilvie	June	(6)Li:	25/u
87022	Gai	June	(22)Ne:	35/u
86026	McHarris	July	(20)Ne:	5.3/u
87003	Garg	July	(14)N:	50/u
Disc.	Sherrill	July	(12)C:	10/u
87005	Winfield	July	(12)C:	50/u
86036	Sherrill	Aug.	(36)Ar:	10/u
"	"	"	(86)Kr:	2.5/u
87002	Gil	Aug.	(36)Ar:	11/u
87013	Ogilvie	Aug.	(6)Li:	40/u
Disc.	Gelbke	Sep.	(6)Li:	40/u
87019	Y. Chen	Oct.	(12)C:	20/u
"	"	"	(40)Ar:	15/u
"	"	"	(86)Kr:	15/u
"	"	"	(14)N:	40/u
87024	Mikolas	Oct.	(16)O:	40/u
87009	Becchetti	Oct.	(7)Li:	20/u
Disc.	Nadesen	Oct.	(6)Li:	35/u
86020	Mikolas	Oct.-Nov.	(6)Li:	11/u
87016	Sherrill	Nov.	(26)Mg:	2.5/u
"	"	"	(13)C:	10/u
Disc.	Lynch	Nov.	(40)Ar:	30/u

Disc. = Director's Discretionary Time

Table II shows all of the beams which were extracted in 1987. Argon beams as a group were responsible for more hours of operation than any other species, whereas 50 Mev/u Nitrogen was run longer than any other beam; 249 hours.

Table III shows the experiments run in 1987, including the beams run for them.

Dee Stem Cooling

Last year's Annual Report reported the cooling of the dee stem corona rings by water supplied through polyethylene tubes inside the resonators. This change has allowed dee voltages above 80 kV, with 95 kV in short test runs. Voltage is limited by dee sparking and transmitter power. There were no instances of corona ring failure during 1987. This is especially significant in that many of the high energy beams run routinely in 1987, especially 50 Mev/u Carbon, Nitrogen and Oxygen, would previously have led to corona ring failure before the cooling tubes were installed.

Second Harmonic Acceleration

Operation of the cyclotron on second harmonic, in which the RF frequency is two times the particle frequency, became routine in 1987. All beams with energy between 2.5 and 10 Mev/u were run on second harmonic as a routine operational procedure.

K500 VACUUM STATUS

P. Miller, G. Humenik, D. Poe, M. Mallory, and A. McCartney

We are reporting the status of the K500 vacuum system, comparing some information from previous years and concentrating on the most recent information and on vacuum-related improvements seen in the operation of the K500 cyclotron in 1987.

A. High Vacuum Pumps

Turbomolecular pumps and cryopumps are attached in the valleys of the K500 cyclotron magnet, named "A", "B" and "C", following the convention for the naming of the rf stations and dees. Each dee (lower half) accomodates one cryopump[1]. Three turbomolecular pumps are needed for regenerating the cryopumps and pumping helium and neon gases. They are located on top of the cyclotron on 8 inch diameter stainless steel extension tubes 10 feet from the surface of the yoke. Their effective pumping speed is limited by conductance of the 3-inch diameter hole 40 inches long through the magnet pole. The pumping speed for air is 53 l/s each.

Since November 1983 cryopump "A" has not been used, because of excessive cryogen demands, except for a few weeks in Feb. 1985,[2] and the cryopanel has been removed. The measured pumping speed for nitrogen gas is 3600 l/s in this mode (2 cryopumps).

B. Pressure measurements

First use of cryopanels in the K500 was around the beginning of March 1982. Before April 1982 there was an ion gauge at the median plane, mounted on the probe channel. This gauge was removed when the probe was installed in the cyclotron. From then until approximately 1 June 1982, when the present "C-valley" ion gauge was installed on the upper pole, the only ion gauge recorded was the one mounted at the turbo pump "A". Data from these gauges are listed in Table I.

Table I -- Beam chamber pressure [microtorr] recorded on selected days, measured by various ionization gauges.

Date	Old MP ion g. (probe)	A turbo ion g.	B turbo ion g.	C-valley ion g.	A-valley ion g.
2 Mar '82	7.4	9.1			
3 Mar '82	9.9	1.1			
15 Apr '82		2.25			
20 Apr '82		0.126			
25 May '82		0.132			
1 Jun '82		0.21		2.3	
18 Jun '82		2.0		8.0	
27 Jul '82		0.71		5.4	
3 Sep '82		1.1		4.5	
6 Feb '85		1.35	2.0	8.0	
8 Jul '86		2.3	0.74	4.7	
26 Sep '86		1.4	0.41	2.4	
9 Jan '87		2.1	0.65	5.8	22.
20 Mar '87		1.2	0.80	2.2	9.5
27 Mar '87		0.23	1.9	1.08	5.9
10 Jul '87		--	0.21	0.98	2.5
16 Feb '88		0.33	0.28	1.5	5.0

The "C-valley" ionization gauge is mounted on the upper pole cap on a 2 inch diameter copper tube 8 feet long to place it far enough from the magnet to allow simple magnetic shielding to be used. This gauge was formerly called "median plane ion gauge." The hole through the magnet pole is 1 inch in diameter, 40 inches long. In December 1986 another ionization gauge was installed in the same way on valley "A". There are, in addition, ion gauges mounted at the turbo pump inlets. A residual gas analyzer (UTI Instruments, model AMX-100-MUX) is also attached to the system between turbo pump C and the beam chamber.

The support tube for the "C-valley" ion gauge represents both a source of gas (from surface outgassing) and a limited conductance path to the beam chamber. These factors determine a minimum measurable pressure. The ionization gauge becomes insensitive to the beam chamber pressure below this limit, estimated to be in the 0.1 to 1 microtorr range. The "A-valley" ion gauge should have the same limiting pressure.

Referring to Table I, much of the time variation of pressure observed can be attributed to leaks, whose presence can be confirmed by conventional helium tracer methods and by observing the mass spectrum of the residual gas in the beam chamber. We have eliminated many water leaks, the most troublesome being cracks in welds on the copper dee stems. At present the pressure is determined by the equilibrium between air leaks and the pumping speed of the 2 cryopumps. The main leak is at an indium seal for the support insulator for one dee stem (B-lower). The beam chamber pressure is satifactory, although we anticipate some beam attenuation when we accelerate very heavy ions, such as bismuth, as is planned in the future.[3] This effect can be seen in some of the probe data plotted in Fig. 1.

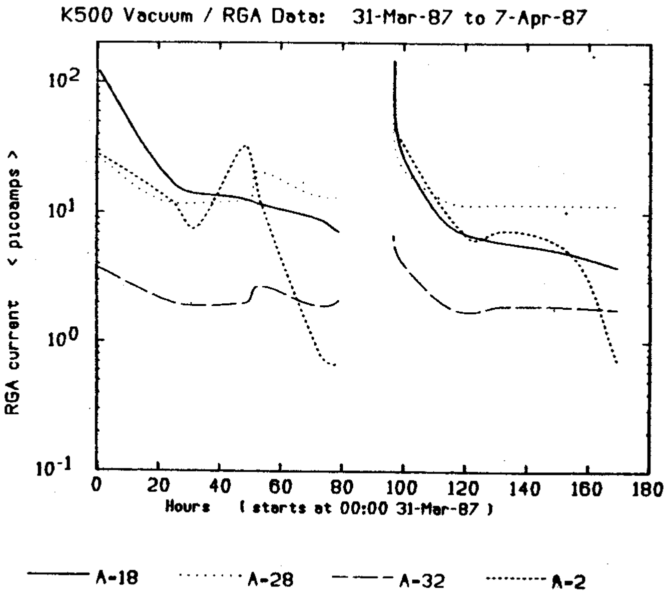

Fig. 1: Residual gas composition during typical pumpdown of the beam chamber and subsequent operation of the cyclotron.

The internal PIG ion source (in use from 1982-1985) was not running when the data in Table I were taken. Typical C-valley pressure with source operating was 20 microtorr. The present ECR ion source has no effect on the beam chamber vacuum, and the introduction of this source was one major step in improving the accelerator vacuum.

The time dependence of the partial pressures of the constituents of the residual gas is displayed qualitatively in Fig. 2 for an 8-day period when the beam chamber was vented and pumped down again twice. The residual gas analyzer (RGA) measures the ion current from a Faraday cup intercepting the ions with mass number A emerging from the quadrupole mass analyzer. The ion current is plotted vs. time for A=2 (H_2), A=18 (H_2O), A=28 (N_2&CO) and A=32 (O_2). The beam chamber was vented to atmospheric pressure (dry nitrogen) for 3 hours until T=-7 hr. and again from T=86 to T=89 hr. At T=0 the C-valley pressure was 4 microtorr; at

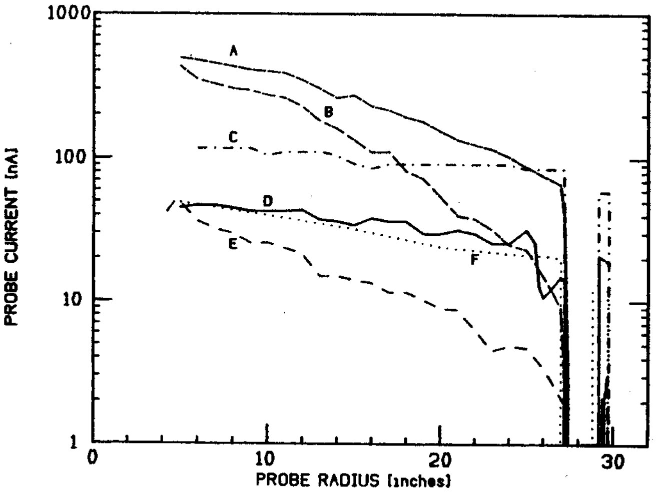

Fig. 2: Beam current vs. radius from the beam probe. Attenuation caused by charge-changing collisions with residual gas molecules decreases as the charge state is increased (process is stripping-dominated). Beam and vacuum conditions are:

Label	E/A [MeV/u]	Ion	C-valley pressure [microtorr]
A	10	$^{40}Ar^{7+}$	3.7
B	10	"	7.4
C	30	$^{40}Ar^{11+}$	1.1
D	20	$^{40}Ar^{9+}$	1.2
E	2.5	$^{86}Kr^{8+}$	3.6
F	10	$^{7}Li^{1+}$	2.5

T=80 hr. it was 1 microtorr. The pressure variation was similar on the second pumpdown. The ion currents have not been calibrated or corrected to take account of sensitivity variations with different molecular species.

The ultimate pressure seems to be determined primarily by the size of air leaks, although this pressure is not far above the partial pressure of water vapor (about a factor of 5 in Fig. 1), which is known to desorb from surfaces for hundreds of hours. We infer that an ultimate pressure of 0.2 microtorr could be achieved by elimination of all air leaks.

Figure 3 is similar to Fig. 1, but contains only data for A=18 (water) and shows the effect of turning off the cryopumps, thereby allowing them to reach room temperature. Two of the turbo pumps (A & C) were providing all of the pumping for the beam chamber. The C-valley ion gauge pressure was 100 microtorr at T=16 hr., 52 microtorr at T=52 hr. The A-valley pressure remained a factor of 1.5 times higher than C. After T=52 the C-valley pressure increased to 178 microtorr due to a leak associated with repair work and decreased gradually to 120 microtorr over the next 80 hr. The ion current is about 20 times higher after 80 hr. than it was with normal cryopumping (Fig. 1).

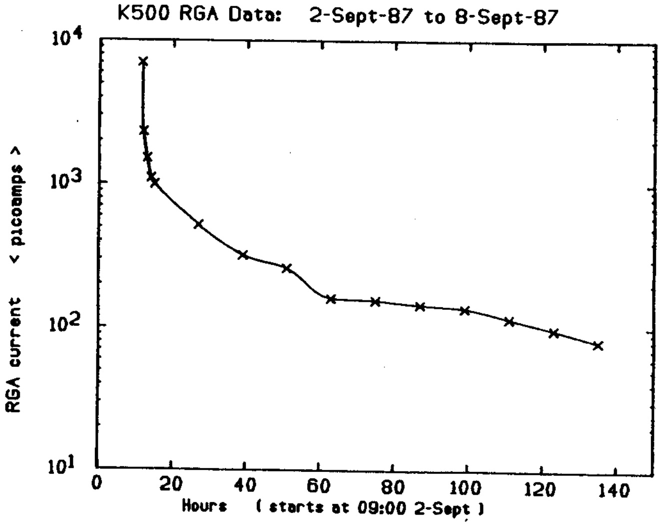

Fig. 3: Residual water vapor vs. time after cryopumps were turned off. Conditions: cyclotron off, pumping with 2 turbo pumps (A and C) 2-8 Sept. 1987.

In another experiment the cryopanels were shut off and were pumped by all three turbo pumps for 101 hr. before the data shown in Table II were measured over the following 3 hours. Various combinations of the turbo pumps were valved off from the beam chamber and readings of the ion gauges and the RGA were made. The effects of individual turbopumps can be seen clearly in these data. Ten measurements were made. The pressure data are plotted as a ratio to the value in the second measurement P/P_{ref}, where P_{ref} is P(2). The ratio is plotted as a function of measurement index. Note that the reference condition is all 3 pumps pumping on the beam chamber. Fig. 4 and Fig. 5 present the ion gauge readings; Fig. 6 uses RGA ion currents as P.

The ion gauge for C-turbo was turned on just before the measurements were started. The plot in Fig. 5 shows a decreasing pressure trend, which is from the slight outgassing of the gauge tube that occurred during the experiment. The results of the experiment confirm our model of the contributions of individual turbopumps.

C. Leaks

The repair of leaks in the dee stems has taken considerable effort. The instances where a dee stem was removed from the cyclotron are listed in Table III. Most of these events were required to fix leaks in the vacuum. In a few cases a stem was removed to fix problems unrelated to the vacuum (water, rf contacts). Most of the leak problems fall in two

Table II--Ionization gauge pressures and RGA ion currents in pumping experiment with turbomolecular pumps alone 28 Nov 1987.

Meas.	Pumps	A-val.	C-val.	A-turbo	B-turbo	C-turbo	A=18	A=28	A=32
		microtorr					pA		
1	B,C	45	31.5	0.40	4.8	--	118	410	80
2	A,B,C	32.5	23	2.67	3.55	4.6	117	288	55
3	A,B,C	32	22.7	2.80	3.50	3.59	117	293	55
4	A,C	44.2	32.1	3.95	0.34	4.55	124	412	78
5	A,B,C	34	23	2.86	3.40	3.28	120	286	56
6	A,B	44	33	3.95	4.82	0.39	4.5	0.93	0.13
7	A	80	61	7.2	0.52	0.37	4.3	0.93	0.19
8	B	84	62	0.33	8.6	0.34	3.9	0.90	0.17
9	C	86	61.5	0.29	0.56	7.6	137	720	138
10	A,B,C	34.2	24.3	2.8	3.6	3.2	143	300	60

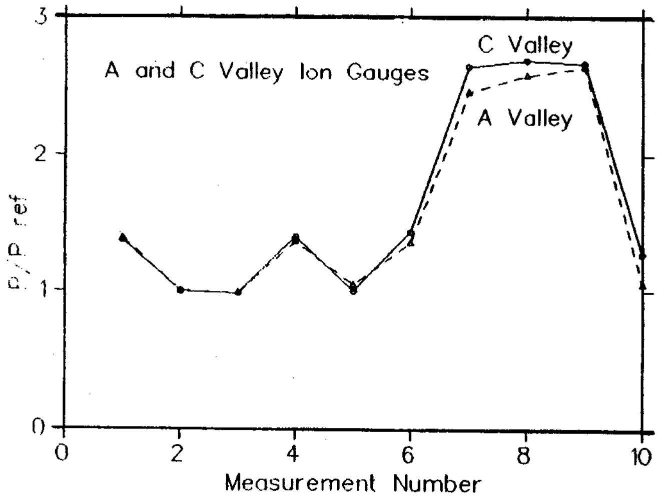

Fig. 4: Beam chamber pressure in turbopumping experiment (see text and Table II).

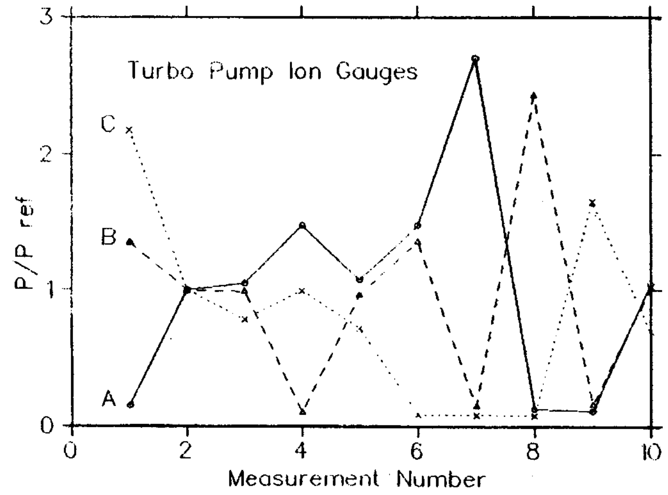

Fig. 5: Turbo pump inlet pressure (see text and Table II).

categories: cracked welds in the copper dee stem, and leaks of the indium wire seals on the support insulators. We often detect small leaks in the indium seals that appear after some months of operation and which remain small enough that the operation of the cyclotron is not impaired. We do not generally repair such leaks unless there is some other reason to remove the dee stem from the cyclotron.

The frequency of leaks in the rf couplers (insulator failures) decreased from about 10/year to about 1/year when the ECR ion source

Table III--Dee stem repair history (dee stem removed from cyclotron). The entry "Weld water leak" means that a crack in a weld on the dee stem allowed cooling water to enter the vacuum and was repaired by welding over the crack.

Stem	Date	Reason for removing stem from cyclotron
A-upper	3/86	Weld water leak
B-upper	3/85	Weld water leak
	4/85	Weld water leak
	5/86	Weld water leak, repl. water seal
C-upper	7/83	Weld water leak
	10/83	Weld water leak
	10/84	Indium seal leak
	10/85	Weld water leak
A-lower	10/83	Replace insulator
	11/83	Repair frozen water lines
	12/83	Replace water seals
	6/85	Indium seal leak
	2/86	Repair rf joint
	3/87	Weld water leak, indium seal leak
	5/87	Weld water leak, repl. water seal
	9/87	Align water slots
B-lower	9/83	Install cryopump
	11/83	Repair frozen water lines
	3/85	Indium seal leak
C-lower	9/83	Install cryopump
	11/83	Repair frozen water lines
	6/84	Replace insulator
	1/85	Replace insulator
	3/86	Repair rf joint

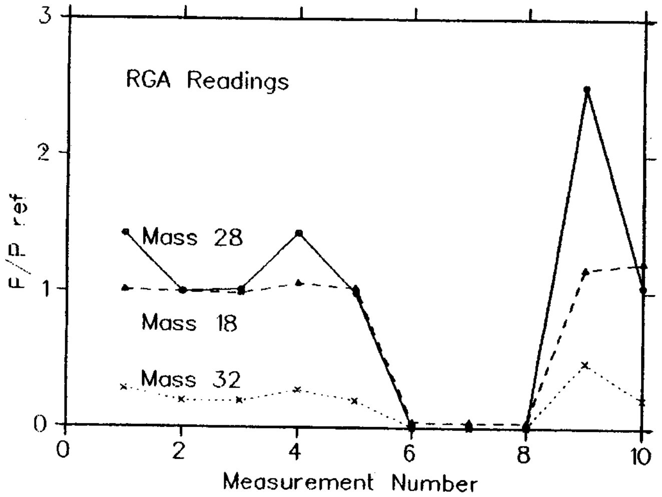

Fig. 6: Residual gas measured by RGA near C turbopump during turbopumping experiment (see text and Table II). P_{ref} for mass 32 is 288 pA, the same as for mass 28.

replaced the internal source at the beginning of 1986. An improved insulator geometry and an rf interlock based on the ratio of forward to reflected power also contributed to the observed improvement.[4]

The top and bottom magnet poles are sealed to the cryostat by a double ring: indium wire inside and a rubber O-ring just outside the indium. This joint does not have any appreciable spring compliance to maintain contact to the indium during deflections of the magnet in response to changing magnetic loads. When the magnet is turned off the pole lifts slightly off the deformed indium wire, and the O-ring is the only effective seal. The O-ring was assembled originally from rubber cord stock using adhesive to join the ends. When this glue joint failed we obtained manufactured O-rings of the correct diameter and replaced the one on the upper pole. Unfortunately the seal on the lower pole is not accesssible without a major disassembly or modification of the cyclotron. A conceptual design was made for a system for lowering the lower pole similar to that on the K800 in case it should be necessary to replace this O-ring in the future.

Conclusion

During the past year a good improvement in the K500 vacuum has been obtained. The attenuation of beams of ions as heavy as ^{86}Kr is now small at the normal pressure of 1 microtorr. The K500 is operating smoothly, and we believe that the vacuum improvements have had a role in this success.

References

1. P. Miller et. al. Annual Report 1982-83, p.128
2. R. Blue et. al. Annual Report 1983-84, p. 210
3. M.L. Mallory Annual Report 1986, p.111
4. J. Vincent et. al. Annual Report 1983-84, p. 203 and P. Miller et. al. Annual Report 1985, p. 119

K500 RF LIMIT STUDIES

M.L. Mallory, J. Vincent and T. Jones

Introduction

The K500 cyclotron was designed to accelerate heavy ions. After the 1986 Tokyo cyclotron conference, where questions were raised about proton acceleration on superconducting cyclotrons, a feasibility study of proton acceleration on the K500 was assigned to F. Marti and K. Subotic. They determined that the orbit dynamics does allow proton acceleration. In January, 1987 we proposed a study be made of the K500 rf limits to determine if an rf solution for proton acceleration was possible. In the following sections the results of this study are reported.

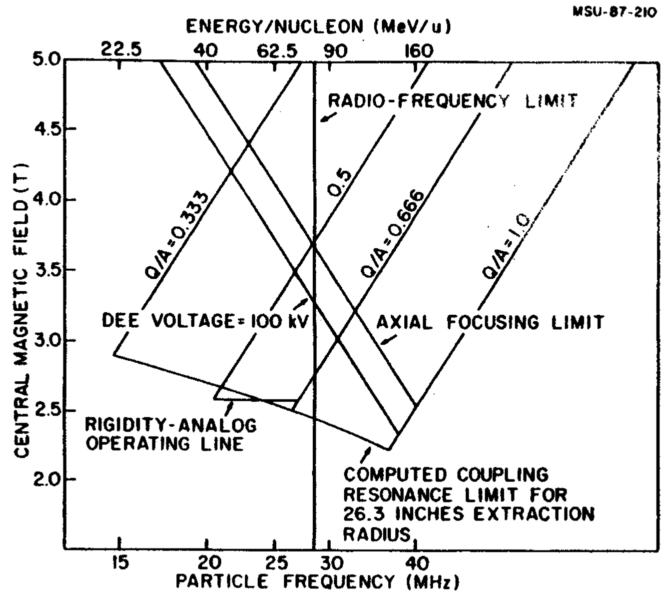

Fig. 1: The operating diagram of the K500 cyclotron for large Q/A is shown. Present limits are the axial focussing limit, the coupling limit, and the upper frequency limit of 28.2 MHz. To accelerate protons (Q/A = 1) will require a change in the upper frequency limit.

K500 R.F. Limits

The acceleration of protons and other large Q/A ions require high frequencies for the K500. This is illustrated in Fig. 1, where the operating diagram of the K500 cyclotron for light ions is shown. The high frequency limit of the rf system had not been measured previously in a systematic manner. Figure 2 is a simple schematic of the major rf components. Each component was tested for its upper rf range, where it is assumed no modification would be introduced. The synthesizer is capable of frequencies up to 200 MHz. The driver amplifier is limited to 32 MHz and the power amplifier is limited to 42 MHz. The rf cavity was found to resonate at 28.2 MHz for the lowest short position. Therefore the rf cavity is the limiting component for obtaining higher frequencies.

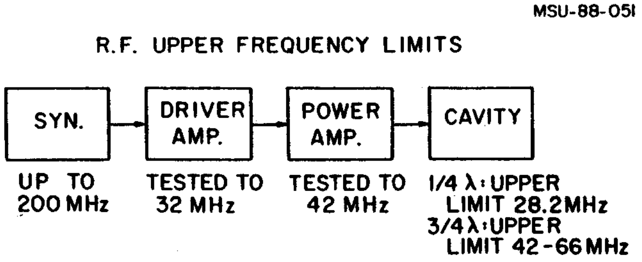

Fig. 2: A schematic diagram of the major rf units listing their measured upper frequency limits. The rf cavity is the lower limit for higher frequency.

Higher Frequency Option for the K500 Cavity

The most direct method of achieving higher frequencies for the cavity is to redesign the rf short. The ultimate short mechanical limit outside the accelerator vacuum chamber is at the rf vacuum insulator. Figure 3 is a calculation of the voltage and current at the vacuum insulator corona ring. A frequency of 32.87 MHz is obtained at this short position. The lower portion of Fig. 3 is a 2 dimensional representation of the resonator used in the calculation with distances measured from the cyclotron medium plane. A mechanical sketch of a

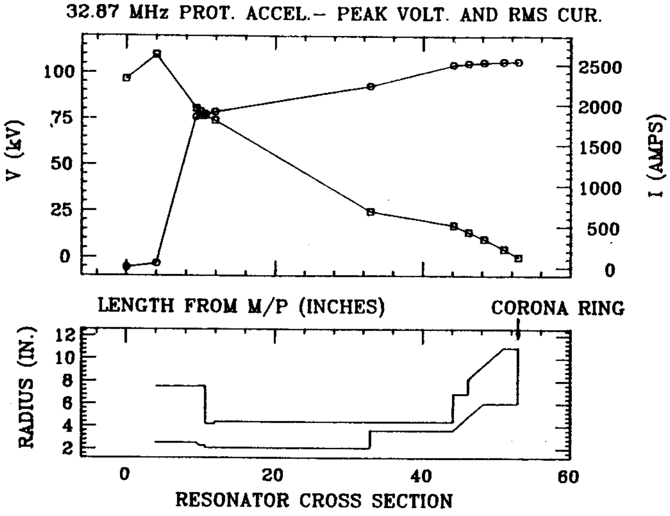

Fig. 3: A plot of the measured cavity voltages and currents for a short on the rf cavity located at the vacuum insulator corona ring. A frequency of 32.87 MHz is obtained and this would allow proton acceleration.

possible temporary short is shown in figure 4. This short and the frequency at this location would allow acceleration of protons.

Another option studied was the utilization of higher rf cavity modes. Figure 5 is the calculation of the frequency versus short position for several rf cavity modes, where the normally operated mode is λ/4. The 3/4 λ mode is found to resonate from 42 to 66 MHz. To drive this mode, would require operating the first two stages of the rf amplifier at 1/2 the cavity frequency. This is called frequency doubling and an experiment verifying this was performed. In the test, the cyclotron cavity and the final stage of the rf amplifier were operated at 19 MHz (λ/4) and the rest of the system at 9.5 MHz. A dee voltage of 50 KV was obtained. The acceleration of protons at 80 KV and a frequency of 66 MHz would require power levels greater than 300 KW per cavity, where the present rf power levels are now limited at 80 KW (just doubling the frequency of the final amplifers decreases its power tube plate efficiency by 1/2.) For the proton particle to be in resonance for the above rf doubling would require it to be accelerated in the 2nd harmonic mode. In summary, these studies have determined the present K500 rf limits. Proton internal beam acceleration does seem possible, but would require rf system modifications.

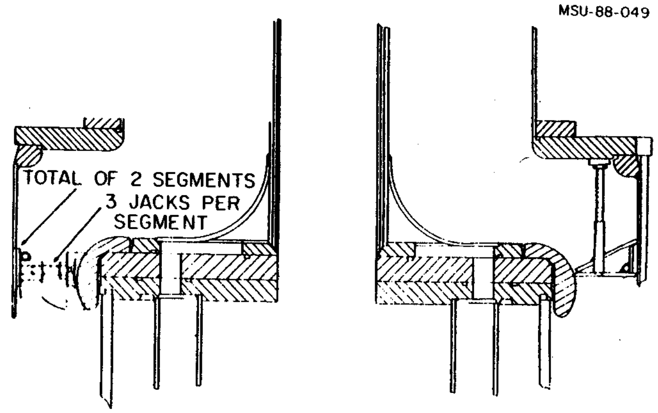

Fig. 4: A mechanical drawing of the rf resonator at the vacuum insulator. Several proposed temporary shorts at the corona ring are shown and these would allow frequencies for the K500 cyclotron which could be used for proton acceleration.

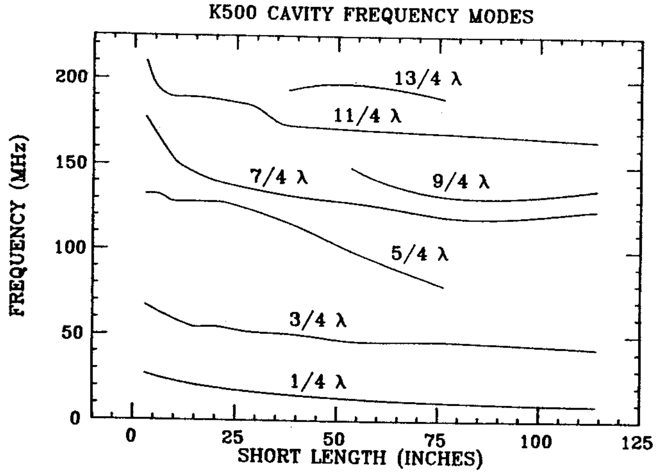

Fig. 5: A theoretical calculation of the various short positions for several cavity modes. The higher frequency modes would require greater power.