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An Assessment of the Feasibility for High Current Operation of Compact High Field Superconducting Cyclotrons.

Antaya, T.A.

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Plasma Science and Fusion Center
Massachusetts Institute of Technology
Cambridge MA 02139 USA

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T.A. Antaya

Massachusetts Institute of Technology

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Executive Summary

This report addresses the fundamental feasibility of a new class of high magnetic field Compact Superconducting Cyclotrons (CSCs) to produce intense (mA current) proton beams in a single accelerator stage. This high current feasibility is somewhat independent of the final energy of the proton beam since we have stipulated acceleration shall be in a single accelerator stage, which for cyclotrons means generally capturing nearly zero velocity ions into stable orbits at the cyclotron center. The importance of this question is that if it is feasible, then is it possible to develop portable configurations that would be well suited to a fielded radiography or active interrogation source for strategic nuclear materials detection. There are no such sources available presently. Much is known about the high intensity operation of cyclotrons- these issues were first addressed in the 1950s, and the fundamental feasibility of accelerated beam of order 10 mA and beyond have been established for cyclotrons. However existing uses of high current cyclotrons have not called for this set of characteristics: high field, low power, small footprint, portability and high current. Recent operating experience with an existing superconducting cyclotron, combined with data from fundamental studies of intensity limits, and data from advanced conventional cyclotrons, is used here to establish the necessary conditions that must be achieved for multi-milliampere operation of CSCs.

1. Introduction

The development of high intensity proton accelerators began with the consideration of the design and development of Meson Physics Facilities in the 1960s, as science with secondary pion beams required an intense high energy proton primary beam. Both linear accelerators and cyclotrons were given consideration for such facilities and both linear accelerator and cyclotron based meson physics facilities were built [1-3]. Until the new Spallation Neutron Source SNS [4] reaches its design intensity at an energy of 1 GeV, two of these original meson physics facilities, improved significantly over time since their first operation, will continue to hold the records for beam intensity and beam power at high energy for proton acceleration, as shown in Table 1.

Machine	Type	Energy (MeV)	Intensity (mA)	Power (MW)	Stages
PSI	Separated Sector Cyclotron (2000 tons; B_{ave}~0.5T, 1974)	590	2.2 (goal is 3.0)	1.3	3: 0.87 MeV; 72 MeV; 590 MeV
LANSE	Resistive LINAC (400m; 1972)	800	1.2	1	3: 0.75 MeV; 200 MeV; 800 MeV
SNS	Resistive & Superconducting LINAC (1000m, 2003)	1000	0.7 (goal is 1.4)	0.7	6: IS; 2.5 MeV; (DTL-CCL-SCL); 1000 MeV; A-Ring

Table 1. A comparison of the highest power high energy proton accelerator complexes is made.

LANSE (LANL), SNS (ORNL) and the Ring Cyclotron (PSI) are multi-stage accelerators that are not compact. In fact, some of the characteristics of these accelerators that enable high intensity are a direct consequence of the large fabrication scale.

For compactness and transportability in existing accelerators we have to look at low energy proton accelerators. Here again both linear accelerators and cyclotrons are represented, as shown in Table 2. The two linear accelerators shown in Table 2, LEDA [5], and GTA [6], are RFQs, which have a radiofrequency quadrupole vane structure that permits efficient ion acceleration from low velocity with sufficient transverse beam focusing and a continuous process of longitudinal beam bunching. The cyclotron in Table 2, Cyclone SEC of IBA, is a resistive magnet based isochronous cyclotron with an internal ion source, an elliptical pole gap, and the protons are self-extracted[7,8]. Fundamental to the successful operation of all of these advanced low energy proton accelerators is that they are well understood and have a quantitative beam dynamics basis of understanding. Also fundamental is that they operate with very high space charge forces because of the low starting velocity of proton beam. The two RFQs are in fact successful experimental demonstrations that the space charge effects which dominate the beam dynamics in the low energy part of proposed high energy accelerators could be mitigated. The Cyclone SEC operates routinely for 3 week production runs at intensities above 1 mA. The 15 mA internal current given in Table 2 was achieved during a beam tuning test and shows what is possible from ions emitted at thermal velocities from the plasma meniscus of a modern internal ion source, and captured into accelerated orbits in a precision cyclotron central region [9]. The Cyclone SEC uses quantitative beam simulations coupled with 3D magnetic field modeling to overcome the peak magnetic rigidity of the pole field and achieve self-extracted beams. Protons reaching the edge of the elliptical fall into a channel with reduce magnet rigidity and ions are conducted 'automatically' out of the cyclotron without use of any active extraction elements or adjustable magnetic or electric fields.

Machine	Type	Energy (MeV)	Intensity (mA)	Power (MW)
LEDA (LANL)	RFQ (front end demo for the proposed APT)	6.7	100	0.7
GTA (LANL)	RFQ (cryogenic cooling, demo for full GTA accelerator)	3.2	32	0.1
Cyclone SEC (IBA, Belgium)	Cyclotron (commercial isochronous cyclotron for Pd-103 production)	14	15 test- internal 2.5 external	0.2

Table 2. A comparison of high current low energy proton accelerators is shown.

Clearly, the ultimate high intensity performance in small accelerators has been achieved with RFQs [10]. To develop 6.7 MeV protons LEDA is 4m long. A further increase in RFQ energy would require either longer length, a higher gradient, or perhaps more efficiently, a change in the acceleration structure on the high energy side of the machine. Modern cyclotrons as well can operate at mA intensity levels, in a simple configuration with beam self-extraction, but the Cyclone SEC is a low field resistive coil cyclotron, which makes it large, so that is also not easily transportable. It does, however, serve as an existence proof that well designed cyclotrons can accelerate and extract milli-amphere currents of protons in a single accelerator stage.

Fundamental Limits on the High Intensity Operation of Cyclotrons

The fundamental limits on the acceleration of ions at high intensity in cyclotrons concern the stability of the accelerated beam, phase space dilution during acceleration, and the ability to extract the full energy beam from the cyclotron without losses. This set of issues was addressed quite early in the development of isochronous cyclotrons [11]. In a single stage isochronous cyclotron, low velocity ions are captured into stable orbits on every RF cycle. Each captured beam bunch has a transverse (radial, axial) width, a finite longitudinal extent along the azimuthal acceleration path, an energy spread (or distribution of particle momenta), and a total electric charge. Since is possible to capture into stable orbits and accelerate ions on every RF cycle, the isochronous cyclotron is a *continuous wav*e (CW) accelerator. In cyclotrons, proton beams may be obtained by accelerating stripped hydrogen nuclei (H^+), excited hydrogen atoms that have a captured electron (H^-), or even molecular hydrogen ions (H_2^+). Since H^- ion acceleration must be done at low magnetic field (<1T) to avoid Lorentz stripping of the extra electron, it cannot be used in a CSC, which achieves compactness by operating at isochronous fields in excess of 5T. H_2^+ acceleration, having only specialized benefits related to it making possible proton acceleration in an optimized heavy ion cyclotron that is designed to accelerate Z/A=0.1-0.5 ions species but not Z/A=1, will not be considered here. In an H^+ ion cyclotron, the accelerated beam bunch has a net positive charge, and this positive charge results in internal repulsive electrostatic forces acting upon individual protons in the bunch, which we call the space charge force. This force is negligible in accelerators of all types in the extreme relativistic regime ($\beta>0.99$), so it is applicable in cyclotrons that operate at $\beta=0.01\text{-}0.7$, and is most important in cyclotrons either on the first accelerated orbits where the ion velocity is low, or in the accumulated effects of many orbits required for full acceleration.

To assess space charge effects in cyclotrons, we separate this force into longitudinal (s) and transverse (x,z) Frenet-Seret components. When we look at the transverse space charge force in cyclotrons, even to mA current levels, there can be a tune shift (ν_z decreases), but this shift can be compensated by the flutter field design, so we generally find that the transverse space charge force on individuals accelerated beam bunches does not provide a limit on either acceleration or extraction at levels of a few mA [12].

The longitudinal space charge force is more important, particularly on early orbits during the acceleration in isochronous cyclotrons. To see this, consider an ion beam crossing an acceleration gap during accelerating in a cyclotron, as shown in Figure 1. The ion with a phase angle ϕ_s crossing the dee gap gains energy $\Delta T_s=qV_0\sin\phi_s$. This is the typical situation in a cyclotron and corresponds to the ion (s) crossing the dee centerline after the voltage has gone through zero, or alternative, crossing the gap after the peak voltage. If the number of acceleration gaps per revolution is ζ, then the energy gain in 1 turn would be $T_1=\zeta qV_0\sin\phi_s$. A cyclotron with 1 dee has $\zeta=2$. Isochronous cyclotrons are not phase stable and as a consequence the energy gain per turn and the total energy gain are ‘programmed’ by the design of the isochronous magnetic field, to control the accelerated ion phase ϕ_s essentially on a turn by turn basis. If N is the total number of beam revolutions in the cyclotron, and $\phi(t)$ on average differs little from the programmed quasi-constant phase ϕ_s, then the total energy gain is $T\approx NT_1=N\zeta qV_0\sin\phi_s$.

In a cyclotron, because of the finite phase width of the beam, an ion near the ‘head’ of the bunch arrives earlier at the next acceleration gap, gaining an energy $\Delta T_{head} > \Delta T_s$, while ions at the tail of the bunch cross after the synchronous phase ion and gain an energy $\Delta T_{tail} < \Delta T_s$. As a consequence, the bunch acquires an energy spread $\delta T=qV_0(\sin\phi_1-\sin\phi_2) \approx \delta T=qV_0\delta\phi$ for small angles, which is generally true. The phase width and energy spread $\{\delta\phi,\delta T\}$ constitute the longitudinal phase space of the beam.

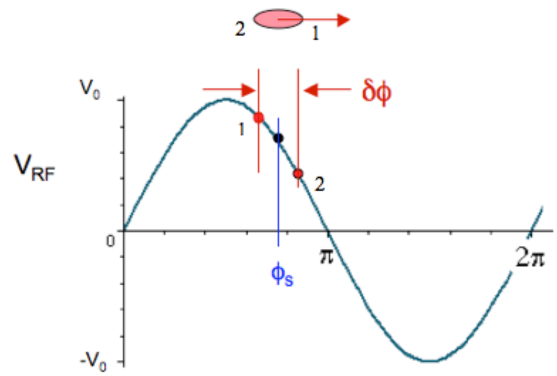

Figure 1. The relationship between dee gap crossing times and accelerating voltage is shown for a beam bunch accelerating in a cyclotron.

Hence the intrinsic phase width of the beam δϕ in time results in an energy spread δT during acceleration. This energy spread δT in turn results in a growth in the radial width of the beam (δx in F-S coordinates), because the ions at the head, after gaining more energy, move radial outward in a cyclotron with respect to the center and tail of the bunch. Hence $\delta x \propto \delta\phi$. The longitudinal space charge force acting on the bunch over many turns in a cyclotron acts to increase the phase envelope δϕ, and this then drives a larger radial spread, the so called longitudinal- radial coupling, as has been reported by many authors [13-15], as shown in Figure 2.

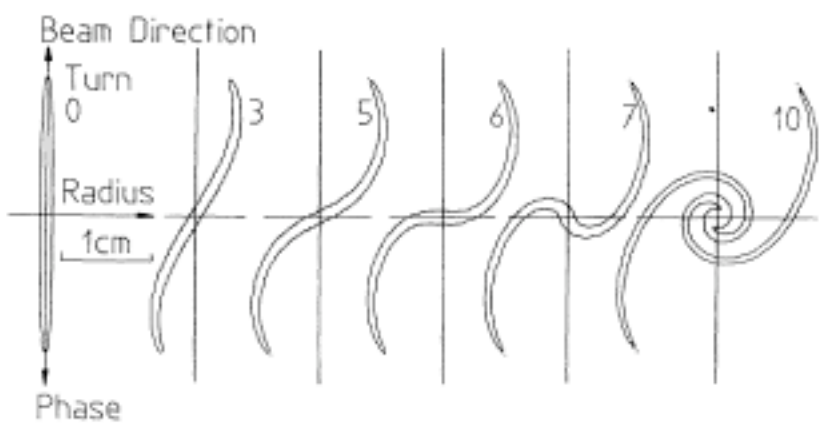

Figure 2. A beam in a cyclotron with high longitudinal space charge twists into a spiral structure, resulting in a growth in the radial beam width (horizontal coordinate in the plot). From Ref [13].

After several orbits outward from the machine center, with the longitudinal space charge driving this vortex motion, the beam structure is set: a central core with halo has developed. While driven by the radial-longitudinal coupling in cyclotron, the formation of central core and large divergence tail is a common feature of beams with high space charge in periodic magnetic transport systems and accelerators, including linear acclerators [16-20].

This halo, which sets the envelope of the beam, has important consequences for beam extraction from a cyclotron at high intensity, because the radial aperture of the extraction channel in a cyclotron is generally less than the axial aperture. Beam is lost in proportion to this size mismatch when the radial beam width is greater than the extraction channel's radial aperture, and this can be the most important contribution to the losses which set the overall extraction efficiency. In the usual way, we take $R=C/2\pi$ to be the equilibrium orbit radius, which is not a circle in an isochronous cyclotron, where C is the orbit circumference [$C = \oint ds$ over one closed orbit]. Then we can write the average orbit spacing in a cyclotron as

$$\frac{dR}{dN} \cong \kappa R \frac{T_1}{T} \tag{1}$$

where κ is constant of order 0.5 that depends upon machine parameters in isochronous cyclotrons. In Equation (1) we see that the orbit spacing decreases as the energy T increases. (This is fundamantal: cyclotron orbits are Fermat Spirals with $r \propto \theta^{1/2}$ where $\theta \equiv 2\pi N$.) The width δx of an orbit is set by the normalized radial emittance $\varepsilon_{xx'}$, dR/dN and the energy spread ΔT:

$$\delta x = \sqrt{\frac{4R}{\beta\gamma\nu_x}\frac{\varepsilon_{xx'}}{\pi} + \left(\frac{dR}{dN}\frac{\Delta T}{T_1}\right)^2} \sim R\sqrt{\frac{4}{\beta\gamma\nu_x}\frac{\varepsilon_{xx'}}{\pi} + \left(\kappa\frac{\Delta T}{T_1}\right)^2} \tag{2}$$

The normalized emittance is derived from the initial beam formation process at the ion source and has an evolution that can be successfully modeling during acceleration in cyclotrons. High intensity proton cyclotrons mostly still use internal PIG ion sources, where the initial emittance is set by the exit slit width, and the gas pressure in the discharge, both of which are larger when higher intensity is required. The energy spread during acceleration in cyclotrons has multiple origins, including the evolution of the integral phase ϕ_s , the isochronism (how good the field design is), the stability of the RF voltage, and the phase width of the beam. As we indicated earlier, for high extraction efficiency, we need a narrow beam width δx. In the limit of a small beam emittance, Equation (2) reduces to $\delta x \propto \Delta T/T_1$. Thus a high energy gain per turn (T_1) can be used to achieve high extraction efficiency, and this is the historical approach to the development of high intensity cyclotrons, such as the Ring Cyclotron of PSI shown in Table 1. The PSI complex consists of a multi-cusp proton ion source, a Cockcroft-Walton pre-injector at 0.8 MeV, a separated sector injector cyclotron operating at 72 MeV, and the ring cyclotron that boosts the final energy of 590 MeV. Separated orbits are achieved in both of the cyclotrons and space charge affects are generally more important in the injector cyclotron. The Ring cyclotron has a measured emittance of 2 mm·mrad and an extraction efficiency of 99.97% and is now operating at 2.2 mA, with developments planned to raise the final intensity to 3 mA. At 2.2 mA of extracted current, the PSI Ring Cyclotron produces the highest average power proton beams of any accelerator. While not discussed here, we observe that the accelerator operation in this complex does have issues with space charge forces in the stage to stage transitions, and collimators are used in the center of the ring cyclotron to the clean up the injected beam emittance, removing the halo described above [21].

In the mid-1990s, for Accelerator Transmutation of [radioactive] Waste and Thorium fission cycle energy amplifiers, a number of studies were undertaken for MW power level accelerators [22]. Two of these studies were of cyclotron based driver accelerators. An extension of the PSI approach outlined above to 10 mA at 1 GeV, was studied, concluding that there were no fundamental feasibility issues limiting such a development [23].

Another study at that time was of a single stage superconducting cyclotron, and using performance data from the K1200 heavy ion superconducting cyclotron, it was concluded that 10 mA at 1 GeV was possible with either an improved deflector design or by reducing the septum beam losses a factor of seven over observed levels in the existing K1200 superconducting cyclotron [24].

The CSCs built to date have dominantly been variable energy, heavy ion accelerators for nuclear science. They have operated in single stage mode or as boosters. They use bright external ion sources rather than internal PIG sources, and are able to operate at high energy in a single accelerator stage. The K500 at MSU is illustrative of the general features of these superconducting cyclotrons [25]. The K500 can operate at high intensity, but owing to the differences in focusing optimization versus the final energy, a design decision as to the purpose of this cyclotron, heavy ions are to be accelerated and the K500 cannot accelerate proton beams (H^+) directly, though is can accelerate H_2^+. When optimizing a variable energy superconducting isochronous cyclotron, one has to choose between heavy ions at moderate energies or protons at high energy [26]. The larger K1200 cyclotron [27], mentioned above, is of equivalent design, and is similarly constrained, so a direct comparison between these heavy ion CSCs and the PSI ring cyclotron complex or other accelerators for the production of intense proton beams are not possible. In addition, since the K500 is designed for variable final energy, from a few MeV/nucleon to 60 MeV/nucleon, and accelerates all species from H_2 to U, it has a complex beam extraction system that includes two electrostatic deflectors and multiple adjustable magnetic elements, to allow for a variable extraction path that is optimized for a selected ion and desired final energy. This complex path has a smaller radial and axial acceptance, and lower extraction efficiency, than that of the ring cyclotron at PSI, as a result. The small extraction acceptance is a consequence of design choices made in the variable energy/species operation that makes the transverse dimensions of the high voltage electrostatic deflectors quite compact (it sits on the edge of a pole tip where the axial pole gap is smallest.). Operationally, most of the beam is loss on the leading edge of the grounded septum electrode of first electrostatic deflector. The first electrostatic deflector's job is to initiate the separation of the extracted beam to from the internal beam. In the K500, operationally, the beam losses on this compact deflector are limited to 1 kW power levels to reduce needed maintenance [28]. Finally, the existing heavy ion CSCs are designs from the 1980s, and employ first harmonic resonant extraction design concepts developed in the 1960s-1970s. More recently, cyclotrons with passive extraction channels (no electrostatic deflectors) have been developed for fixed energy protons beams, permitting much higher current operation [29,30].

Conditions for High Intensity/High Extraction Efficiency Operation of Single Stage CSCs

Recent data for high intensity heavy ion operation of the K500 can be used to establish the requirement for high extraction efficiency of a CSC. Internal, refractory cathode based 'PIG' arc discharge ion sources. Routinely used for proton ion beams in cyclotrons, PIG ion sources have short lifetimes for heavy ion species, due to cathode erosion [31]. So the K500 and other similar heavy ion cyclotrons instead use beams from an external ion source, typically an ECR ion source, injected from outside along the cyclotron symmetry axis, and then inflected into the median plane at the center of the machine, where the ions are captured into accelerated orbits [32]. ECR ion sources are simple, reproducible, microwave plasma ion sources that operate at low overall power levels and low gas consumption, and introduce no gas load in the center of the cyclotron. While developed initially for highly charged heavy ion beams, ECR sources are also bright sources for proton ion beams. For example, the LEDA accelerator of Table 2 uses an ECR ion source operating at 2.45 GHz to product 110 mA proton beams at 75 keV for injection into the LEDA RFQ [33]. For these reasons we must employ a compact ECR for proton beam CSCs optimized for high current AI applications.

From 1981 until the late 1990s, the K500 cyclotron operated as a stand-alone heavy ion accelerator, first with internal ion sources, and after 1985 with external ECR ion sources. The K500 now serves as an injector for the K1200 cyclotron, where it accelerates intense low charge state heavy ions, which are stripped at injection in the K1200 and reaccelerated to higher final energies [34]. As a high intensity, low charge injector, the conditions for initial beam acceleration with high space charge forces are present. A set of tabulated transmission data for numerous heavy ion species have been assembled for the K500 cyclotron, starting from the charge state analyzed ECR ion source beams, transported in a low energy beam transport system in a tunnel under the cyclotron, through an upward axial injection into the K500, then accelerated to full energy followed by beam extraction [35]. Ion species range from ^{16}O to ^{238}U, at final energies of 8-12 MeV/nucleon. As a example, a K500 ECR source is capable of producing 0.6-0.7 mA of Kr^{14+} ions, with a 90% beam emittance of 50-70 mm·mrad. The DC ECR beams are bunched during axial injection into the cyclotron to enhance the captured ion efficiency. Ions captured into accelerated orbits in the K500 center are accelerated to full energy at a final radius of 25 inches. The beam current at full energy is measured just ahead of the first electrostatic deflector entrance. The beam current is also measured just after the cyclotron exit. Typical extraction efficiencies, defined as the ratio of these two current measurements (out/in), typically are 75-85%. The actual phase width of ions captured into accelerated orbits is not measured, but a beam simulation for the case of 81% extraction efficiency suggests a phase width $\Delta\phi_{min}$=4° is likely. These simulations also suggest that a 20% loss can be explained as due primarily to the thickness of the grounded beam septum plate of the first electrostatic deflector, which comes close to the edge of the full energy beam. The overall transmission efficiency in general is sensitive to the central region centering coil. In fact a deliberate mis-centering of the beam at low turn number is helpful, which suggests a type of field error induced phase compression is important in the K500 tuning for high extraction efficiency. This phase compression by means of a field perturbation was first observed in a separated sector cyclotron at GANIL [36], and if indeed this is being exploited in the K500 tuning for high extraction efficiency, it suggests that the initial captured beam phase width in the center is much larger than the estimated $\Delta\phi_{min}$=4° required for high extraction efficiency. An operating mode with approximately 99% extraction efficiency, or losses not higher than the precision of the current measurements, has been developed and it is estimated that the starting ion emittance at the ECR source for such a beam is approximately 2 mm·mrad.

An Assessment of the Feasibility for High Current Operation of Compact High Field Superconducting Cyclotrons

The highest power beam extracted from an accelerator is presently from a cyclotron. A modern commercial SPECT isotope production cyclotron, using a conventional internal ion source, produces 14 MeV proton beams at 2-2.5 mA, with passive non-resonant self-extraction at 90% levels. The existing heavy ion CSCs at 5T, using external ion sources for intermediate charge heavy ions, operate on the edge of mA currents, with the highest extraction efficiencies for narrow phase width beams. Multiple studies for intense proton beam drivers have found to be feasible the 10 mA operation of a high energy cyclotron, by managing the longitudinal-radial coupling driven that principally by the longitudinal space charge force.

What then are the necessary conditions and required developments for a single stage 10 mA CSC for Active Interrogation?

Beam Extraction is not required- Internal Secondary Target AI CSC

In some of the recent studies done for an AI CSC, the secondary production target has been internally located, to exploit collimation coming from the return path iron in the cyclotron electromagnetic circuit [37]. If an internal target is sufficient, then the approach taken in the IBA Cyclone SEC, in which already a 15 mA internal beam current has been observed, can be used. Ion sources of the PIG type, used in the Cyclone SEC, have emittances of order 100 mm·mrad [38], which would result in a low extraction efficiency in a CSC, using the experience of the K500 and assuming no improvement factor for an optimized fixed species/energy extraction design. If instead beam extraction were not required, then this large emittance would not be a constraint, since it does not affect accelerating the beam to full energy. A proton beam PIG ion source has operated at 9T [39]. Therefore we find that if the AI CSC uses an internal target, that no additional development is required for10 mA operation of a CSC.

Beam Extraction is required- External Secondary Target AI CSC

If the AI CSC uses an internal ion source, the 90% extraction efficiency of the Cyclone SEC would not be sufficient. Taking 1% as an arbitrary standard for extraction efficiency, either the acceptance of the extraction channel must be increased, or the ion beam emittance must be reduced. Internal PIG ion sources have been around for a long time, and expecting that multi-mA operation is possible with significantly reduced starting emittances from a PIG ion source without throwing away intensity is not likely. The CSC at high field (~7T) will be more compact than any existing cyclotron, so that using a PIG qualitatively goes in the wrong direction for increasing the extraction channel acceptance, since in general all components including the extraction elements are getting smaller. So the ion source must be brighter, and we find then that an extracted beam AI CSC at 10 mA cannot use an internal ion source.

The AI CSC with extracted beam must use a bright external ion source of the ECR type. K500 extraction efficiency studies suggest that this source must be capable of 10 mA at an emittance of order 2 mm·mrad, and that the accelerated beam should have a phase width $\Delta\phi$ or order 4° or less. The injection line from the ECR ion sources to the K500 is rather long, and some non-linear distortions during the low energy beam transport are typically observed. One would expect to maintain a lower starting emittance by the elimination of the low energy beam transport system. This can be accomplished by placing the ECR ion source on the axis of the CSC. We think that a factor of 5 improvement in injection acceptance would be expected at a minimum, so we tentatively take as a target an ECR ion source capable of 10 mA at an emittance of 10 mm·mrad. A small permanent magnet ECR of Saclay produces 24 mA of hydrogen ions at an extraction voltage of 40 keV, 85 mA at 80 kV, and more than 100 mA at 90 kV, with normalized emittances of order 0.2 mm·mrad [40]. Other proton ECR ion sources have similar performance [41,42]. Since $\beta \cong 0.01$ at these energies, this normalized emittance corresponds to about 20 mm·mrad unnormalized. Cutting the emittance in half, and observing that the proton fraction of the total H ion extracted current from such an ion source can be as high as 75%, 10 mA at 10 mm·mrad is possible. Hence the estimated ion source performance is already in hand.

The narrow phase width needed for high extraction efficiency from the K500 we take as essential, since the radial-longitudinal coupling due to space charge will be higher during acceleration at 10 MA than is at present. Since the phase width alternately is observed as a radial beam width, careful use of central region collimators to cut the high divergence tail of the initial beam, to narrow the phase width, may be done. In addition, the fixed energy and ion species of the AI CSC allows for a higher extraction acceptance design than in the existing variable energy CSCs. The 9T CSC for radiotherapy has a passive, self-extraction type geometry [43], and performance data from the first operation of that cyclotron will be available soon.

Given all of this, certainly multiple mA extracted current operation of an AI CSC for external targets is now feasible. A development program that includes beam simulations and experimental measurements should be performed to further refine and insure that the necessary beam parameters can be demonstrated prior to machine construction. This development program primarily should address these effects in the low velocity, space charge dominated central region of a CSC, and to address all of the relevant beam physics, should include the axial injection from an external source and measurements of the properties of the initial accelerated beam formation process.

Summary and Conclusions

The best transmission data for a compact superconducting cyclotron has come recently from the K500 at MSU, as described above. The first element in the beam extraction path is an electrostatic deflector. The deflector entrance is on one of the sector hills where the magnet gap is minimum, so it is compact, and the ion path through this deflector is long. Its mechanical shape is fixed and generally does not match the orbit precisely of any particular extracted beam, so ions are lost here. It has an operation power limit set at 1 kW of beam lost in transit of this deflector. The K500 can do 99% extraction efficiency, so if we did nothing but shift from rare highly charged heavy ion beams to protons, we would expect to do 100 kW level beams- or a 10th of a milli-amphere at 1 GeV, with no further work.

From many beam studies, we know that the starting transverse emittance of K500 high transmission efficiency beams is about 2 mm-mrad, the phase width is about 4 RF degrees, and the energy spread is about 0.1%. Since the K500 accelerates many ions and many energies, the isochronous field is only as good as it has to be for any ion, so the phase width and energy spread are larger in general than in a fixed energy cyclotron. We can take credit for protons at fixed energy: simplified RF (less energy spread), better isochronism (smaller phase width), fewer extraction elements (higher extraction acceptance)- maybe we lower the extraction losses to 0.2%, or at 1kW of losses, 0.5MW of beam is allowed.

At higher energy we'd use a higher sector number- at least 4, perhaps 6, but we don't need dees in all of the valleys, because we do not follow the small $\delta x \propto \Delta T/T_1$ via maximum feasible T_1 prescription of PSI, for high intensity beams in their accelerator chain, so we can put the deflector in a empty valley (no dee) where it can be axially larger, so that either the overall acceptance is larger, or a factor of 2 higher beam losses are tolerated (2 kW without worrying about damages), and this gets us to 1 MW of beam power.

We would also use a brightness proton ECR ion source - 10x increase in intensity for the same starting transverse emittance (x100 in brightness) compared with heavy ion ECRs at present, and significantly simplify the axial injection line as well. If we do that without altering the longitudinal phase space, we get to 10 MW (10 mA at 1 GeV). But we need to demonstrate this prediction experimentally, as the assumptions presented here require calibration/verification. Since all of this happens in the analytic 'solenoidal' field at the cyclotron center, these measurements can be performed in a properly defined, high field ion source/central region test stand.

Without the measurements in hand, one can cut the phase space in the center, so one is comfortable projecting a factor of three (3 mA extracted, 3 MW at 1 GeV, or 2.5mA at 1.2 GeV), but where exactly it gets hard between 3 and 10 mA is to be determined!

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Nomenclature

v … ion velocity
p … ion momentum
q= Ze … ion charge
M_0=Am_0 … ion rest mass
$\Re$=p/Ze … ion magnetic rigidity

E … Total Energy
E_0= Am_0c^2 … Rest Energy
T … Kinetic Energy
β= v/c … ratio of ion velocity to the speed of light
γ=E/E_0 … relativistic factor
M=γM_0 … relativistic mass

ω_0 … ion cyclotron resonance frequency
ω_{rf} … RF frequency
h=ω_{rf} /ω_0 … acceleration harmonic
ϕ … ion phase with respect to the RF acceleration
ϕ_0 … ion central phase with respect to RF acceleration

n … field index weak focusing cyclotrons
k=-n … field index isochronous cyclotron
ν_x, ν_y, ν_s … radial (x), vertical (y) and longitudinal (s) betatron oscillation tunes
$\varepsilon_{xx'}$, $\varepsilon_{yy'}$, $\varepsilon_{ss'}$ … transverse (x,y) and longitudinal (s) beam emittances

$\vec{E}$,$\vec{B}$ … Electric Field, Magnetic Induction

Fundamental Constants

e = 1.602 177 33 x10^{-19} Coulombs

m_e = 9.109 389 7 x10^{-31} kg = 0.501 999 06 MeV

m_p = 1.672 623 x10^{-27} kg = 938.272 31 MeV = 1.007 276 470 u

m_0 ≡ 1 u = 1.660 538 782 x10^{-27} kg = 931.494 027 MeV

m_p/m_e = 1836.152

c = 299 792 458 m/s

μ_0 = 4π x10^{-7} N/A^2

ε_0 = 1/μ_0c^2 = 8.854 187 82 x 10^{-12} A^2 s^4/m^3kg