SINGLE STAGE CYCLOTRON FOR AN ADS

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Abstract

In order to cope with the challenge of an ADS demonstrator, the accelerator is required to deliver a beam driving power in the range of 5 to 10 MWatt. Therefore it is mandatory to propose an accelerator design able to address highly demanding criteria which are a challenge for high power accelerator designers.

Taking into account the outstanding performances of the PSI ring cyclotrons, it is clear that cyclotrons are competitive challengers to high power linacs. The preliminary design studies of two options of a Single Stage Cyclotron Driver show that this concept could bring attractive solutions in term of reliability, cost effectiveness and power efficiency.

Some critical aspects of these designs which make use of the reverse valley magnetic field concept will be discussed in this paper.

THE PIONEERS OF HIGH POWER CYCLOTRONS

The requirements for ADS open different technical solutions for the driver accelerator. This reminds « the Meson factory race » in the 1970's where two rather different cyclotron designs were proposed in the same energy domain (500 to 600 MeV) to produce mesons.

These two large cyclotrons, the Swiss SIN [1] (today PSI) and the Canadian TRIUMF [2] were designed for 100 μA beam intensities which were very challenging in the 70's.

These two cyclotron facilities are based on rather different concepts.

THE PSI H+ TWO STAGES CYCLOTRON

The PSI has proved the soundness of large separated magnet spiral sectors (8) concept with 4 powerful large single gap RF λ/2 cavities delivering up to 600 KV peak voltage at the running-in. This design imposed a two stages cyclotron with a 72 MeV injector cyclotron (Figure 1). The cyclotrons operate with a high extraction efficiency based on the "single turn operation mode".

Since 1974 an outstanding intensity improvement program has been carried out. In 1984 the Philips compact isochronous injector has been replaced by a four separated sectors injector with an external 870 KeV injection line. In order to reduce the number of turns in the booster ring cyclotron, new copper resonators have been installed in 2008, resulting in a higher energy gain per turn. Since the very beginning the extracted beam intensity has been raised by a factor 20 and today the PSI cyclotron chain is delivering a 2.2 mA-590 MeV beam [3] with a 5.10^{-4} beam losses on the septum of the booster deflector.

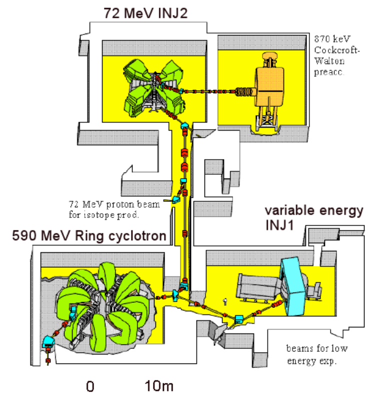

Figure 1: The layout of the two stages PSI cyclotron chain. INJ2 is the four separated sectors cyclotron superseding the old INJ1 compact cyclotron.

THE TRIUMF H- SINGLE STAGE CYCLOTRON

The TRIUMF design is the pioneer of a "single stage" acceleration up to 525 MeV exploiting the negative H- ion acceleration with two simultaneous extracted beams at 100 % extraction efficiency.

The relativistic electromagnetic stripping effect of the H- ions (the second electron is weekly bounded, 0.754 eV) requires a low magnetic field. Therefore the size of the machine is large (extraction radius 6.9 m, total iron weight of the magnet 2500 tons), the maximum B-field in the sector median plane being close to 6.1 kGauss. Besides a strong spiral is needed to achieve the vertical focusing (maximum spiral angle close to 70 deg.). As shown on the Figure 2, the acceleration is achieved by an unusual RF system made of λ/4 large resonators resulting in a single « Dee-gap » providing a 400 KeV peak energy gain per turn. The resonators are fed by a 1.8 MWatt RF Amplifier chain. The injection is external and axial from a 300 KeV injection line. The stripping extraction works in the "overlapping turns" extraction mode.

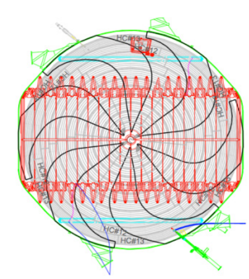

Figure 2: The TRIUMF 6 sectors single stage cyclotron with the RF resonators in red.

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EXAMPLES OF HIGH POWER CYCLOTRON DESIGNS

Inspired by the successful and promising high intensities of the PSI cyclotron chain, multi-stages high power cyclotron designs have been proposed. A good review of these designs is given in the L.Calabretta and François Méot [4] paper, which is briefly summarized hereafter:

The Energy Amplifier Driver

For driving the Energy Amplifier proposed by Prof. C. Rubbia [5] in 1995, a 3 stages cyclotron (Figure 3) has been investigated in details [6]. The goal was to deliver a 12 MWatt proton beam (12 mA - 1 GeV). The extraction method which was chosen was the PSI “separated turns” mode. Hence low number of turns in each stage was mandatory resulting in high energy gain per turn in the two last stages:

Two compact injector cyclotrons able to deliver 6.25 mA-15 MeV beam in a 30 deg RF phase width. One injector extracting H- beam by a classical electromagnetic septum channel and the second injector extracting H- beam by stripping to provide H+. These two 15 MeV beams are funneled up to the injection line in an intermediate stage four Separate Sector Cyclotron (ISSC) accelerating the beam up to 120 MeV. A final stage ring cyclotron made of 12 magnet sectors and 6 RF cavities boosts the energy up to 1 GeV.

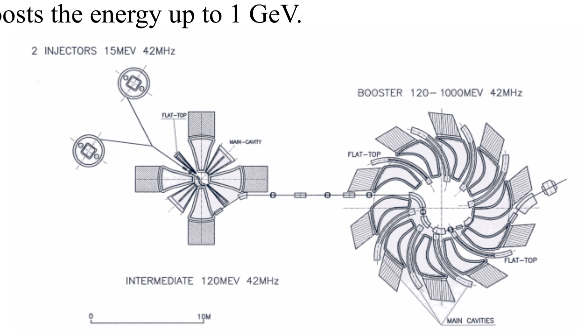

Figure 3: The 3 stages cyclotron of the Energy Amplifier.

The PSI Dream Machine

A layout of a multi-stages 10mA proton beam at 1 GeV was also investigated by T. Stammbach [7] at PSI. The final booster is shown in Figure 4.

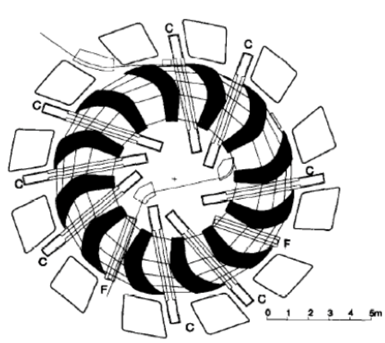

Figure 4: The 10 MWatt “Dream Machine”, a 12 separated sectors – 8 RF cavities.

The 800 MeV/u DAEδALUS Cyclotron Chain

The proposed design to drive the DAEδALUS [8] experiment is a two stages cyclotron complex based on H2+ acceleration which has important advantages:

- a compact injector cyclotron which accelerates H2+ beams up to 60 MeV/amu. The extraction is made by turn separation via two usual electrostatic deflectors.
- the Superconducting Ring Cyclotron (SRC) boosts the beam energy up to 800 MeV/amu. The extraction of the beam as protons is made by stripping of the H2+. The SRC is made of 6 sectors excited by RIKEN-type [9] superconducting coils. Acceleration is given by 4 large monogap PSI-type resonators. The high magnetic rigidity of H2+ requires a maximum 4.72 T magnetic field in the sectors. As shown in Figure 5, the extracted trajectory is a long path due to the internal inwards motion of the stripped H+ beams.

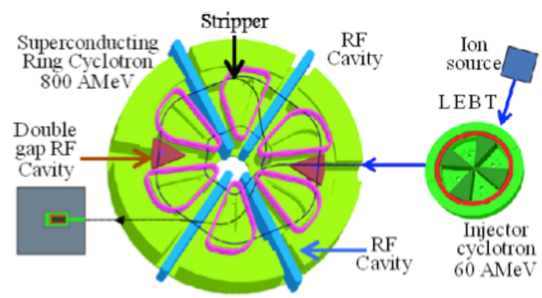

Figure 5: Layout of the two stages DAEδALUS cyclotron chain. The SRC H2+ 800 MeV/amu cyclotron is equipped with 6 RF cavities (4 large PSI type monogap cavities and 2 double gap cavities).

The TAMU 800 MeV Superconducting Strong Focusing Cyclotron

This 800 MeV-15 MW design proposed by the Texas A&M University [10] is a two stages superconducting cyclotron.

It is a stack of coupled-cyclotrons providing 3 beams of 5 MW each in parallel (cf. Figure 6). It uses superconducting RF resonators with a high quality factor, about 10^{10} at 4.2°K. It uses strong focusing by quadrupole channels to obtain high betatron tune numbers. The 100 MeV injector is a stack of three coupled-four sectors cyclotrons. The booster ring is made of :

- 12 Flux coupled stack of dipole magnet sectors with low magnetic field (0.6 T). Therefore the overall diameter of the machine is large, about 20 m.
- 10 superconducting 100 MHz RF cavities providing a 20 MeV energy gain per turn resulting in 35 turns to reach the extraction energy. A 5 cm dynamic aperture is obtained on the extraction radius.

The large energy gain per turn allows the possibility to insert Strong Focusing transport channels made of Panofsky Quadrupoles providing a strong gradient of the order of 4 T/m.

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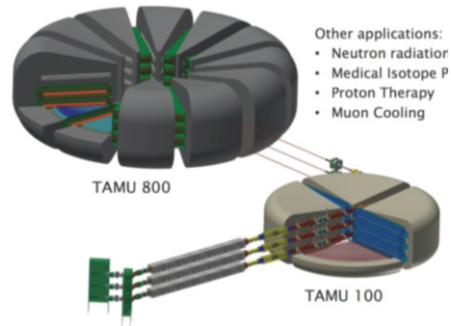

Figure 6: The two stages, strong focusing 800 MeV 3 stack cyclotron.

THE LESSONS FROM THE PIONEERS

Over the last 20 years, the regular and impressive progress toward high intensity acceleration has delivered important lessons:

Simulations

Figure 7 shows the excellent agreement between simulations, which take into account beam halo using the OPAL code, and the current measurements with the radial probe of the PSI final booster. This performance [11] demonstrates that the cyclotron community has the ability to simulate the acceleration of high power beams.

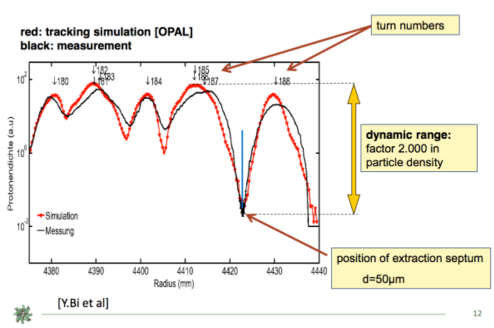

Figure 7: Comparison between simulated and measured relative beam intensity in the turn separation extraction process in the PSI Ring Cyclotron showing the losses on the extraction septum.

Showstoppers

As seen from Figure 8, the main weak point of PSI down time in 2009 was the extraction, i.e., the electrostatic devices with the septa (27%).

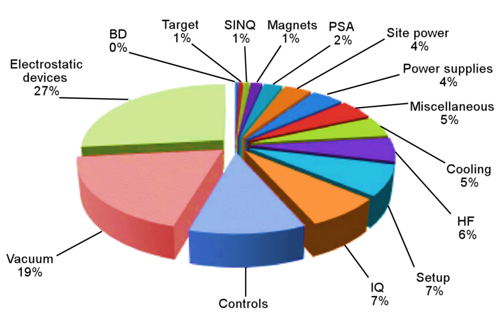

Figure 8: The main causes of PSI downtime in 2009.

To overcome this difficult extraction problem, a possible way is to avoid interactions between the circulating high power beam and the material of the extraction device by:

- either the single turn extraction which requires a multi-stage cyclotron complex
- or the overlapping turns which requires a "septum free" extraction device.

Extraction Issue

Single Turn Extraction In this process, on the extraction radius R where the radial betatron tune number is νr ,at the maximal kinetic energy T= E0(γ-1), the radial separation d between the accelerated turns resulting from the Energy gain per turn E_g is given by the following expression :

$$d = R\frac{\gamma}{\gamma+1}\frac{E_g}{T}\frac{1}{\nu_r^2}$$

In cyclotrons, longitudinal space charge forces dominate. An insight in the intensity limit was given by the W.Joho [12] practical formula:

$$I_{max} = 1.4_{mA} T_{MeV} \beta_{max} \Delta\phi/2\pi\ (100\ \text{turns}/N)^3$$

where T is the final kinetic energy, β_{max}=v/c of the particle, Δϕ the phase width of the beam which makes N turns in the cyclotron.

For the present performances of the PSI machine as shown in Figure 7 with 188 turns in the ring and Δϕ= 8°, we find 2.18 mA which is very close to the measured 2.2 mA.

The remarkable properties of the approximate I_{max} formula are that:

I_{max} does not depend on the final radius or beam shape.

I_{max} is inversely proportional to N^3, hence requiring powerful accelerating cavities to provide high peak voltages.

The drawback of this extraction is the need of an intermediate energy injector to reduce the number of turns in the booster ring. The matching of the different injection/extraction channels is highly demanding and could be a source of reduced reliability for an industrial design.

Overlapping Turns Extraction The stripping extraction which removes electrons (from H- or H2+) uses this method. The efficiency is high but there are still drawbacks. The binding energy of H- is weak (0.75 eV) and the acceleration at high energy requires a low magnetic field resulting in a large size machine (TRIUMF-type). Nevertheless the binding energy of H2+ (2.8 eV) allows acceleration in a high magnetic field which reduces the drawback of having twice the magnetic rigidity, resulting in an acceptable radius increase compare to a proton machine (cf. DAEδALUS).

Moreover, this process uses a thin stripping Carbon foil which has a limited lifetime due to heating by electrons, fatigue effects, radiation damages and production of neutral hydrogen (with a low probability).

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An alternative attractive possibility is the “septum free” extraction in a reverse field valley, which requires a bump increasing the negative field of the valley, produced by iron bars outside the median plane. This method avoids any interaction with the circulating beam, and obviously, in this process, turns could overlap.

SINGLE STAGE CYCLOTRON DRIVERS (S2CD™)

Two options of a single stage cyclotron were investigated [13].

- option A: acceleration of protons up to 600 MeV (10 mA) and extraction by a “septum-free” channel
- option B: based on the acceleration of H2+ ions up to 1600 MeV kinetic energy delivering 800 MeV (10 mA) protons by stripping

Common Features

Three features common to the two options are discussed.

Feature1 A 6 sectors magnet excited by a single large superconducting coil whose particular shape is producing a reverse magnetic field in the valleys in order to get a strong field flutter, hence a strong vertical focusing ν_z^2. This reverse valley field concept was explored by M.K.Craddock [14].

The symmetry of the sectors makes easy the shimming of the magnet on the axis of the sectors (Figure 9).

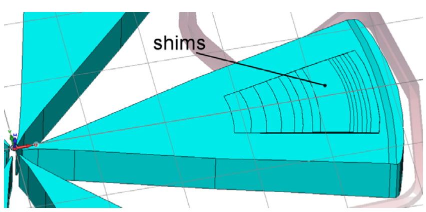

Figure 9: Sector shimming.

Figure 10 illustrates the magnetic field in the median plane. The Figure 11 shows the reverse field at large radii in the axis of the valleys. The large magnetic field flutter provided by the reverse valley field avoids spiraling the sector edges to get a strong vertical focusing. This allows to install classical double gap RF delta cavities in the valleys. The figure shows the equilibrium orbits of the option A in the first quadrant.

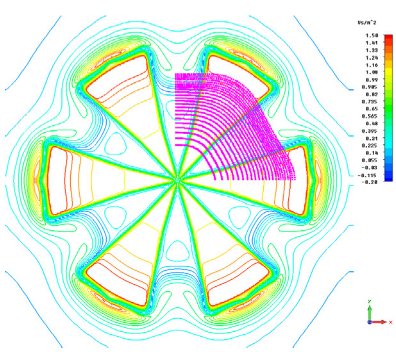

Figure 10: The 6 sectors B-field of the option A.

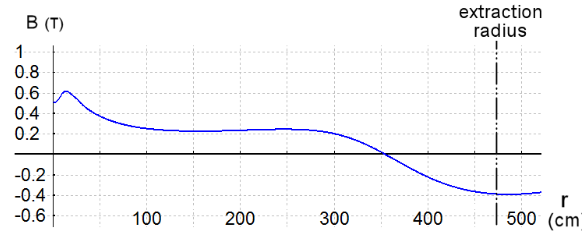

Figure 11: Radial plot of the magnetic field in the valley.

Figure 12 shows the resulting focusing betatron frequencies.

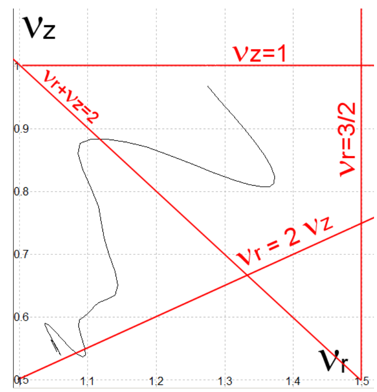

Figure 12: Focusing frequencies νr and νz.

Feature 2 Acceleration is provided by 6 delta cavities in the valleys. Double-gap RF cavities have been selected because they allow acceleration at low energy and are compatible with axial injection in a single stage cyclotron design. This cavity consists of a classical half-wave resonator with a delta-shaped resonant line (with a central dee and a stem) as shown on the Figure 13. It has been defined with the help of the electromagnetic code CST from Microwave Studio.

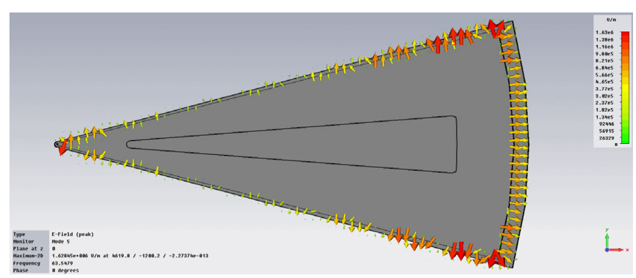

Figure 13: The delta double gap cavity.

A radial increasing peak voltage law, from 160 KVolts at injection up to 450 KVolt at extraction, is obtained. Moreover the large size of the stems allows to install the pumping system. No thorough investigation of the RF transmitters has been carried out up to now.

The following table gives the characteristics of the RF accelerating cavities.

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Table 1: Main Characteristics of the Single Stage Cyclotron RF Cavities

	Option A: H+	Option B: H2+
Type of cavity	λ/2, double-gap, tapered walls	
Frequency	49 MHz	36.3 MHz
Peak Voltage / injection	160 kV	160 kV
Peak Voltage / extraction	450 kV	450 kV
Losses / cavity	400 kW	350 kW
Beam Power / cavity	1000 kW	1300 kW
Total power / cavity	1400 kW	1650 kW
Total Electric Power/ cavity (DC/RF η=70%)	2000 kW	2360 kW

Feature 3 The beam is injected axially in the central region. A particular feature of the magnet is the large space (low magnetic field) in the central region which allows a multi-beam acceleration, i.e., up to 3 beams, provided by 3 low energy axial injection lines fed by 3 ion source platforms (cf. Figure 14).

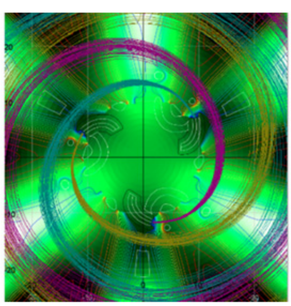

Figure 14: Central region with 3 simultaneous injected beams.

The 2 Extraction Possibilities

The particular geometry of the reverse valley field concept makes the extraction very attractive by using the overlapping turns extraction in two different ways:

Option A: The extraction of protons is "septum free", i.e., an anti-septum channel is needed, therefore highly reducing the burden of septum losses, hence the constraints of single turn extraction (Figure 15).

Option B: The extraction of protons by stripping of H2+ in the reverse valley field is a very short outwards oriented path for two reasons: the jump of the center of curvature outside the cyclotron and the twice smaller radius of curvature of the protons (Figure 16).

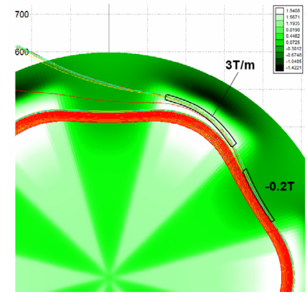

Figure 15: H+ extraction with a negative (-0.2T) field bump in the valley and a 3T/m gradient corrector in the downstream sector. Only the last 50 MeV acceleration is shown.

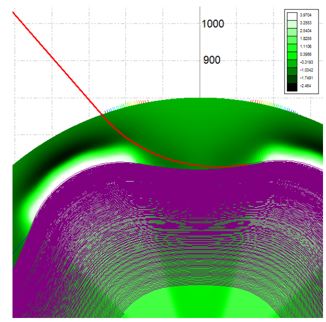

Figure 16: The short extraction path of stripping extraction of H2+ in the reversed valley field.

Critical Issues

In order to reach the high level of reliability of an industrial cyclotron-based ADS demonstrator, the following issues should be further investigated:

Superconducting Coil The complex shape for getting the reverse field in the valleys and the length (48m for the H+ option) of the coils are certainly a big technical challenge.

RF cavities Each large RF cavity will have to handle in the 1.4 to 1.65 MWatt total power. According to experts, one single RF window can handle up to 700-800 Kwatt. Obviously this means that three such windows are needed for each cavity. Because of the presence of magnetic stray fields, it is not possible to locate the power amplifier close to the cavities. Therefore the power has to be transmitted through long RF feeders to the coupling loops.

Extraction This is certainly the most important concern for minimizing the beam losses. According to the PSI experience in a multi-stages cyclotron the different extraction channels with their septa are the most frequent causes of troubles and reduce the MTBF. Therefore a single stage cyclotron concept eliminates these channels. Further detailed studies of the overlapping turns extraction are in progress for the two options.

H2+ acceleration (option B) For cyclotrons accelerating H2+, a high vacuum quality is required. For large machines the outgasing rate of the RF cavities and

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of the vacuum chamber should be carefully controlled. CERN technical experience in this field on the needed passivation processes is certainly relevant.

Moreover the dissociation of the vibrational states contained in the beam could be critical. Nevertheless this issue is certainly worth being more deeply investigated (e.g. choice of the ion source type) because of the possible high energies of the removed protons.

CONCLUSIONS

To enter the 5-10 MW beam power domain while keeping the beam losses within the accelerator in the 0.01 % to 0.05 % range requires to investigate new concepts for increasing the reliability while decreasing the costs.

Parallel Concept

The studies of three various cyclotron designs reveal a common feature, the parallel concept aiming at obtaining a multiplying factor for the accelerated intensity while lowering the space charge problems and reducing the beam trips:

- Daeδalus: Acceleration of H2+ ions allows a factor 2 on the extracted proton beam intensity owing to the stripping.
- TAMU: the Superconducting Strong Focusing multi-stage cyclotron is a stack of three separate proton beams allowing a factor 3 on the final intensity.
- S2CD: the single stage concept via the injection of three beams in a common median plane of acceleration reduces by a factor 3 the requirements of a single injection stage.

Single Stage Cyclotron

Avoiding an injector cyclotron reduces the number of components and could be an asset for extraction reliability. In addition to the compactness of such a single stage based facility (Figure 17), it should also certainly result in a cost effective solution for an ADS demonstrator.

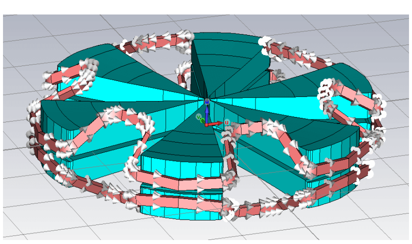

Figure 17: 3D view of the 6 sectors single stage AIMA Developpement cyclotron with reverse valley B-Field

High Global Yield of the Accelerator

The power needed to run the cyclotron driver should be optimized to reach a global yield close to 40 %. Therefore for feeding the large magnets, superconducting technology is required.

Table 2 provides a tentative rough preliminary estimates for the electric power needed to run a single stage 600 MeV-6 MWatt cyclotron.

Table 2: Total Electric Power of an H+ Single Stage Cyclotron (Option A)

Total RF Power	12 MW
Superconducting Magnet	1 MW
Injection (3 sources+3 axial lines with bunching, foc. lenses, inflectors)	1 MW
Extraction channel	1 MW
Total Electric Power	15 MW

Therefore for this 6 MW beam power the overall efficiency of the single stage H+ cyclotron is about 40%.

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