

BEAM LOSS BY LORENTZ STRIPPING AND VACUUM DISSOCIATION IN A 100 MEV COMPACT H⁻ CYCLOTRON*

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Abstract

There is increasing interest in using compact H⁻ cyclotrons at higher energies as high current drivers for RIB facilities, isotope production and recently for facilities testing safe reactor energy production. If the energy of these cyclotrons is increased above 100 MeV, the electric dissociation of the ions may become significant, unless the magnetic field is reduced. The dissociation produced by residual gas is another critical problem. We will describe how Lorentz stripping and vacuum dissociation were calculated for the 100 MeV CYCIAE-100 cyclotron being built in Beijing [1]. With peak magnetic fields of 1.35 T the electromagnetic stripping in the CYCIAE-100 would be less than 0.3% at high energy. With an average vacuum of 5E-8 Torr the vacuum losses would be below 0.6%. We will also show the activation fields calculated, during cyclotron operation and after an 8 hour pre-maintenance shut down, using the above dissociation rates.

INTRODUCTION

Although high efficiency H⁻ stripping extraction has become increasingly popular, the losses produced by Lorentz and gas stripping can be a problem. The Lorentz stripping is most often calculated with simple formulas assuming a uniform magnetic field [2, 3]. More detailed calculations are warranted for high energy cyclotrons where this stripping is a major problem. Predicted gas stripping losses due to collisions between H⁻ ions and residual gas molecules in the tank are also needed to determine vacuum tolerances. The best method for determining both losses is to integrate the stripping equations along cyclotron orbits.

LORENTZ STRIPPING AND MAGNET DESIGN FOR CYCIAE-100

Basic Equations for Lorentz Stripping

The binding energy of the H⁻ ion's second electron is only .75 eV. At higher energy, the cyclotron magnetic field produces a strong electric field in the rest mass frame of the H⁻ ion which can strip this electron from the ion. Let f be the fraction of the beam stripped in a distance L . Then:

$$f = 1 - e^{-\left(\frac{L}{\beta c \tau}\right)} \quad (1)$$

where c is the speed of light, β and γ are the usual relativistic parameters, and τ is the life time of the H⁻ in its rest-frame given by:

$$\tau(E) = \frac{A_1(\epsilon_0)}{E} e^{\frac{A_2(\epsilon_0)}{E}} \quad (2)$$

Here $A_1=2.47 \times 10^{-6}$ Vs/ m, $A_2=4.49 \times 10^9$ V/ m [4], E is the electric field in the rest frame of the ion. It is given by:

$$E = \gamma \beta c B \quad (3)$$

Code Development

Figure 1 shows the losses over a distance of 1 m calculated for different beam energies as a function of the magnetic field. This graph can be used to initially estimate the maximum allowable magnetic field at various energies. More detailed calculations are needed should initial estimates indicate significant losses. Lowering the peak fields to reduce beam loss can increase the size and weight of the magnet and, more importantly, the cost of the cyclotron.

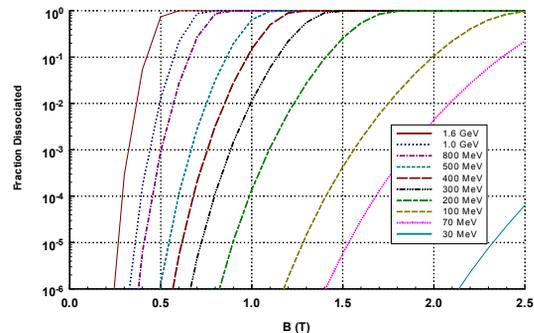


Figure 1: Fractional Lorentz stripping over a 1 m path for various energies as a function of B.

The differential equations for stripping were incorporated into GOBLIN [5], tracking accelerated orbits through the CYCIAE-100 magnetic field, as calculated with a 3D finite element program [6,7]. The losses along

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the beam's trajectory were determined by integrating these equations along with the equations of motion.

H⁻ Ion Dissociation

The CYCIAE-100's hill field will be less than 1.4 T. The maximum relativistic electric field is 2.0×10^8 V/m corresponding to a fractional loss of 7.7×10^{-5} /m. For comparison, the maximum magnetic field in the 500 MeV TRIUMF cyclotron is 0.6 T resulting in a maximum relativistic electric field of 2.1×10^8 V/m corresponding, to a fractional loss of 1.2×10^{-4} /m.

Table 1: Fraction of H⁻ Dissociated in CYCIAE-100

Energy gain per turn	Distance Travelled	Fraction dissociated
170 keV	4400 m	4.0×10^{-3}
200 keV	3700 m	3.4×10^{-3}
250 keV	3000 m	2.7×10^{-3}
300 keV	2500 m	2.3×10^{-3}

Table 1 shows the losses between injection and extraction for various energy gains per turn. These vary between 4.0×10^{-3} at 170 keV per turn to 2.3×10^{-3} at 300 keV per turn. Figure 2 shows how the loss increases with energy. Here energy gains per turn were assumed to be constant with radius, although we expect the rf gap accelerating voltage to increase with radius. Therefore calculated losses are conservative.

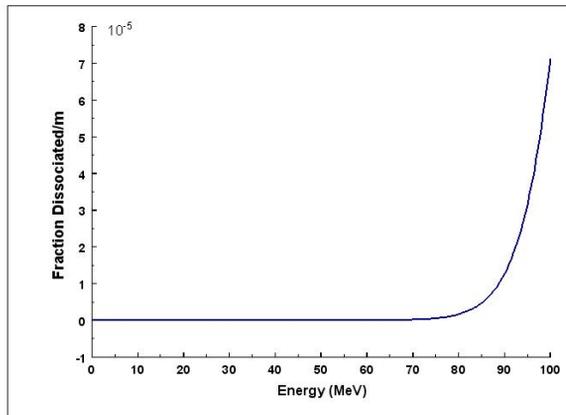


Figure 2: Dissociation of H⁻ as a function of energy in the CYCIAE-100.

With $\sim 500 \mu\text{A}$ circulating current, a peak hill field of 1.4 T, a pole radius of 1.85m, and a dee voltage of 50-60 kV the total Lorentz loss will be $\sim 1.7 \mu\text{A}$. Anticipating a current upgrade, the CYCIAE-100 is being designed with a peak hill field of 1.34 T and a pole radius of 2.0 m so

that the loss will be less than $2 \mu\text{A}$ with a current of $\sim 1 \text{ mA}$. The magnet will weigh ~ 435 Tons.

GAS STRIPPING

Some H⁻ ions will be stripped during acceleration when they collide with residual gas molecules in the tank. The nitrogen equivalent stripping pressure method (N2ESP) [8] was used to calculate these losses. The nitrogen pressure P_{E_s} , required to produce the same stripping losses as the partial pressures of H₂, H₂O, N₂ and O₂ in the tank, was calculated. Assuming circular orbits, constant energy gain per turn, and a N₂ stripping cross-section inversely proportional to β^2 , we find [8,9] the fractional loss f_g occurring between energies E_0 and E to be:

$$f_g = 1 - e^{-K(\beta(E)\gamma(E) - \beta(E_0)\gamma(E_0))} \tag{4}$$

Where:

$$K = \frac{2\pi R_\infty m_0 c^2 A P_E \sigma_0}{R_u T \Delta E} \tag{5}$$

Here β and γ are the relativistic factors, $R_\infty = c/\omega$ where ω is the ion's angular rotation frequency, $m_0 c^2$ is the H⁻ rest mass, A is Avogadro's number, R_u is the universal gas constant, T is the absolute temperature of the gas. ΔE is the energy gain per turn, and σ_0 is a constant so that the N₂ stripping cross section is $\sigma = \sigma_0/\beta^2$.

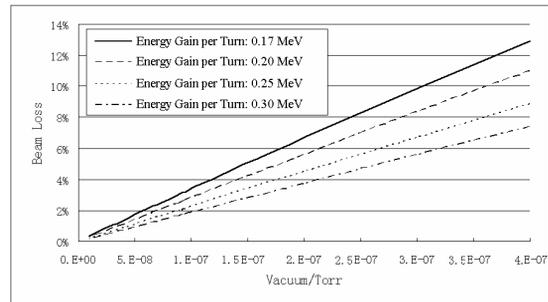


Figure 3: H⁻ beam loss versus N₂ equivalent pressure.

Table 2: Gas Stripping Losses as a Function of Vacuum in the CYCIAE-100

Beam Loss	N2ESP(Torr)	Vacuum level (Torr)
10%	$3.3\text{E-}7$	$8.0\text{E-}7$
5%	$1.5\text{E-}7$	$4.1\text{E-}7$
3%	$1.0\text{E-}7$	$2.7\text{E-}7$
1%	$3.5\text{E-}8$	$9.0\text{E-}8$
0.6%	$2.0\text{E-}8$	$5.2\text{E-}8$

Figure 3 shows the losses between injection and extraction calculated as a function of P_E for different energy gains per turn (constant with radius). Losses are conservative since the energy gain per turn is designed to increase with radius.

Table 2 shows gas stripping losses as a function of vacuum for an r.f. frequency of 44.37 MHz and .2 MeV energy gain per turn. To keep losses below .6%, the vacuum level will have to be less than 5.2 E-8 Torr.

RESIDUAL RADIOACTIVE FIELDS

The Monte-Carlo program FLUKA [10] was used to estimate the radiation produced by collisions between the stripped beam and cyclotron components. Massive components are the vacuum tank made from aluminum alloy LF2 and the magnet made from iron. Calculated strengths of prompt fields during cyclotron operation were used to design shielding and select radiation resistant components in and around the cyclotron. The

residual activation remaining after the cyclotron is turned off was also calculated to estimate dose rates to personnel and the cooling time required before maintenance. Figure 4 shows the distribution of beam losses produced by Lorentz and gas stripping, mainly on the inner side of the vertical tank wall at the median plane.

Prompt radiation fields are mainly from neutrons and photons. Because the dose equivalent rate of neutrons is about 10 times that of photons, neutrons are the most important component of the prompt radiation. The field is about .5 Sv/h at a radius of 300 cm without the yoke and 11.6 mSv/h with the yoke.

The induced activation in accelerator components will be the main source of occupational radiation exposure. Another source is loose contamination. The major radioactive species in the vacuum tank after a cooling time of 8 hours are shown in Table 3.

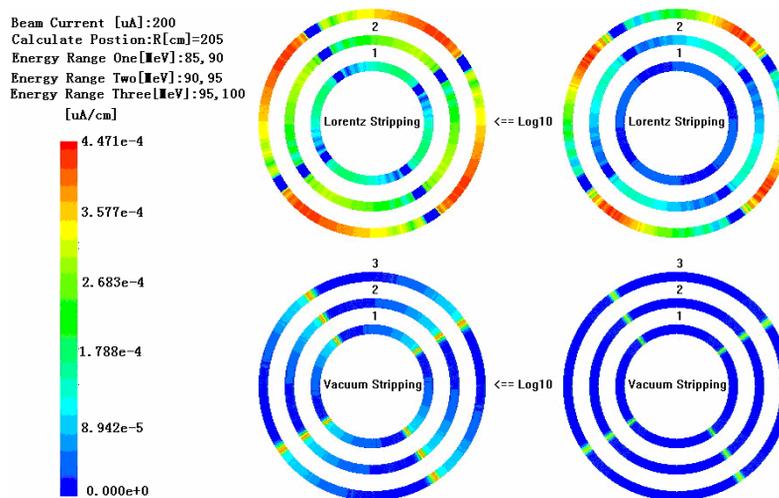


Figure 4: The distribution of beam loss on the inner side of vacuum tank.

Table 3: Major Radioactive Species in the Vacuum Tank after a Cooling Time of 8 Hours

Element	Specific Activity Bq/cm ³	T _{1/2}	Γ (mSv/h)/MBq @1.0 meter
Be7	2.21E+08	53.3d	9.29E-06
F18	2.74E+08	1.8h	1.85E-04
Na22	1.78E+08	2.6y	3.59E-04

CONCLUSION

In high energy compact H- cyclotrons it is extremely important to study the beam loss caused by Lorentz stripping and vacuum dissociation. In line with that consideration, we developed software to calculate the losses for CYCIAE-100 in detail. Based on these results, the radiation fields were estimated. Simulated results were given for a running and for a cooled down cyclotron.

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