# THE $H^-$ HIGH INTENSITY BEAM EXTRACTION SYSTEM FOR TRIUMF

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## Summary

The TRIUMF cyclotron is being upgraded for extraction of a 100 μA $H^-$ beam at an energy of 450 MeV for injection into a post-accelerator. The system includes RF cavities operating at the 20th harmonic of the ion orbit frequency to boost the energy gain per turn to 1 MeV, an RF radial deflector at one-half of the RF fundamental frequency for turn dilution, electrostatic deflectors with a prestripper, and iron-free magnetic channels. The principal requirements for these additional devices are outlined, as well as the space and radiation constraints they must satisfy. The layout of the extraction system with respect to the beam trajectories and the mechanical and electrical design concepts of the devices are presented and discussed.

## Introduction

TRIUMF is proposing the construction of a 30 GeV 100 μA proton accelerator system (KAON factory) which uses the existing cyclotron as an injector.[1] The proposal hinges on the availability, from the existing cyclotron, of an extracted 100 μA $H^-$ beam, at ~450 MeV, to be injected through multi-turn injection into the accumulator ring preceding the booster synchrotron. So far, $H^-$ current up to 200 μA has been accelerated successfully in the cyclotron to 500 MeV, with extraction through stripping. Direct cw extraction of 100 μA $H^-$ beam implies the use of electrostatic and magnetic channels as normally done in other cyclotrons. However, due to the high energy and the high intensity of the TRIUMF beam, and to the small separation between successive turns at extraction (1.5 mm), special techniques have to be devised to protect the extraction septa from thermal or radiation damage and to achieve high extraction efficiency. A challenging aspect is also the necessity to supply positive voltages up to 60 kV to the outer electrode in the extraction channel. Positive voltages are more difficult to control in a magnetic environment.

To increase the separation between successive turns at extraction two methods are being evaluated. A system of three booster cavities resonant at the fourth harmonic of the radio frequency at 100 kV, inserted in the outer region of the cyclotron vacuum tank, should increase the energy gain per turn from 320 keV to 920 keV, and spacing between successive turns to at least 4 mm. These cavities, covering the region between 430 MeV and 500 MeV where fractional (8%) electromagnetic stripping occurs, have the additional advantage of reducing the beam losses in the present mode of operation. A second method is based on inducing a coherent radial oscillation in the vicinity of the $\nu_r$=3/2 resonance at 428 MeV through a radial beam perturbation generated by an RF deflector at 11.5 MHz, or half the fundamental accelerating frequency. The separation between successive turns can be increased through this method to 6 or 7 mm corresponding to a dilution of beam density at extraction by a factor four to five. Assuming that the effective thickness of the curved extraction septum can be kept below 1 mm, this method would be compatible with 90% extraction efficiency even if a separated turn structure[2,3] cannot be achieved at the extraction radius.

To protect the first electrostatic septum and to avoid radiation or thermal damage to the tank periphery the beam which would otherwise hit the septum is extracted by a 1 mm wide stripper placed upstream of the septum, and channelled to a beam dump or to a special experimental station outside.

## Layout of Extraction Elements

Possible layouts for the above two extraction methods are shown in Figs. 1a and 1b, along with schematic extraction trajectories. The new elements have, whenever possible, been inserted in regions free from existing devices, although modifications to cryopanels, probes and service access ports are envisaged. In both layouts the prestripper is located on a ~450 MeV orbit, at an azimuth compatible with extracting the stripped beam down beam line 4A. The prestripper is followed 50 cm downstream by a positive electrostatic channel 1 m long, ~13 mm wide, operating at 50 kV/cm. In the layout of Fig. 1a, a second positive electrostatic channel is placed immediately after the first one. The two deflectors give the beam a radial momentum component $\Delta p/p$ of about 10 mrad and since $\nu_r$≈3/2 the corresponding deviation from the internal orbits will peak ~60° downstream and peak again every 240° thereafter. At 1 1/2 turns (60° + 2 × 240°) after the first electrostatic deflector, the deviation of the extracted trajectory from the internal orbits is calculated to be 10 cm, large enough for the insertion of a system of two magnetic channels which will conveniently extract the beam through port 2 towards the areas proposed for future expansion. The position of the RF deflector has been optimized for high beam dilution at the prestripper location.

Similarly in the layout of Fig. 1b the booster cavities have been designed and positioned to maximize beam dilution at the 450 MeV extraction radius and at the same time allow the beam to be accelerated to 500 MeV. A different solution is shown for the electrostatic channels. The second channel with reversed polarity is placed about 70° downstream of the first one. The inward momentum kick at this azimuth increases the deviation of the extracted trajectory from the internal orbits to 6.5 cm at the location of the magnetic channels. This is still acceptable and the solution may be preferred if a combination of a lower positive voltage on the first extractor and a higher negative voltage on the second one is found more reliable. The beam dynamics aspects of the two extraction methods being proposed are presented separately at this conference.[4]

## Engineering of Extraction Equipment

### RF Boosters

Beam dynamics studies indicate that for maintaining the beam quality a slow increase in the booster field gradient with radius is essential.[4] The booster (Fig. 2) consists of a capacitively loaded λ/4 long section of a coaxial transmission line of rectangular cross section split along the beam plane to allow for beam passage, and operating at the fourth harmonic of the RF (92 MHz). The peak voltage of 120 kV is generated with ≈30 kW of RF power, and an additional ≈6 kW will be required due to beam loading for each of the three cavities. The cavities are slightly trapezoidal in shape, the outside dimensions are ≈1.5 × 1.4 × 0.4 m high. They will be radially adjustable under operating conditions for precise positioning allowing beam optimization.

Each booster would be split into two separate units, mounted to the cyclotron chamber floor and lid,

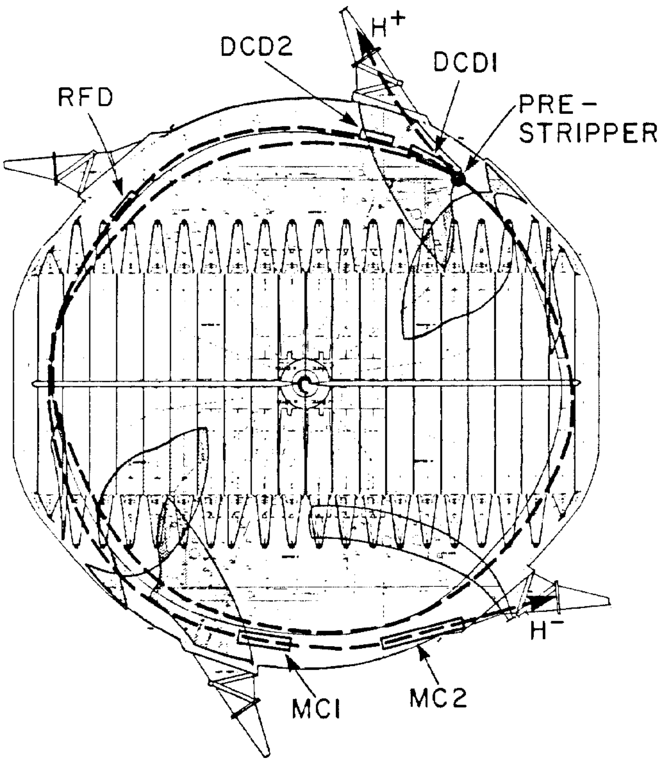


Fig. 1(a). Resonant extraction scheme. DCD: electrostatic channel, RFD: RF deflector, MC: magnetic channel.

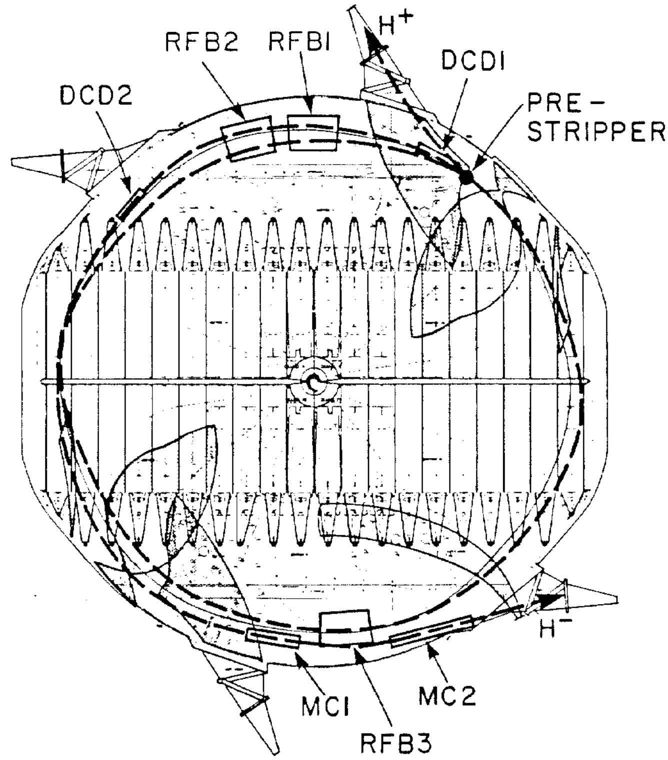


Fig. 1(b). Scheme using increased energy gain per turn. DCD: electrostatic channel, MC: magnetic channel, RFB: RF booster.

respectively. The beam plane is clear of all hardware except for two vertical guide pins translating the motion from the lower half (master) to the top floating half (slave) when booster position is adjusted under vacuum. As a consequence the number of penetrations through the vacuum envelope is increased to accommodate the flexible cooling manifolds for both halves.

## RF Deflector

The electrodes length along the orbit is 50 cm to achieve the required effect with 20 kV peak. The radial oscillation is generated at the open end of the electrode, however many turns must elapse before the modulation of turn separation is achieved. Hence there must be a gap in the beam plane extending to at least the radius of 517 MeV orbit if the present cyclotron operation is not to be affected.

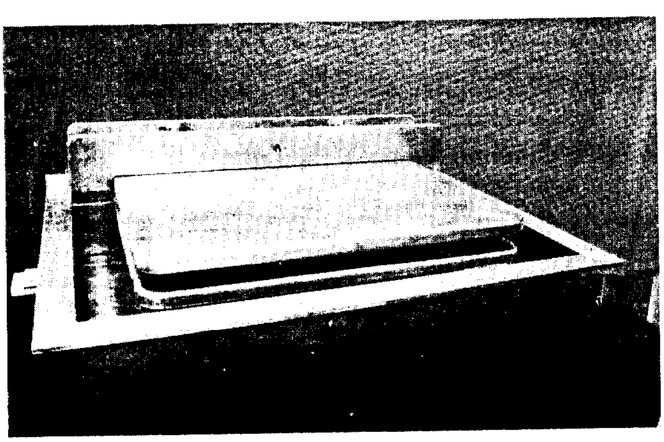

Fig. 2. 115 MHz RF booster with top ground electrode removed.

An open C-type structure was selected (Fig. 3). To suppress the RF leakage the electrodes are completely enclosed except for beam entrance and exit. The unit, very simple and lightweight, is connected to a cylindrical coaxial inductive stub designed to operate as a $\lambda/4$ resonator. The power required is about 4 kW to get 27 kV peak on the deflecting electrode. Coarse and fine tuning were obtained with variable capacitors. The maximum voltage on the coaxial line is only about 25 kV peak, so the stub could be brought out of the vacuum chamber through a ceramic insulator.

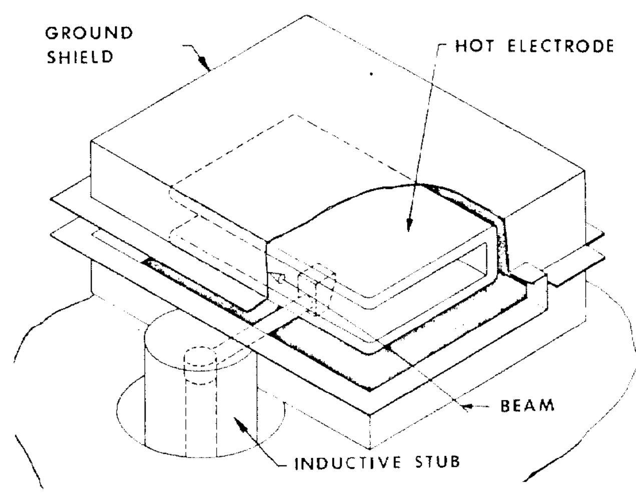


Fig. 3. Outline of RF deflector.

## Electrostatic Deflectors

The nominal design calls for a 1 m long septum and a positive antiseptum generating a radial field of 50 kV/cm, and located in a magnetic field of up to

0.5 T. Both electrodes are curved to clear the orbiting and extracted $H^-$ beams, and further an opening for the pre-stripped beam of $H^+$ has to be incorporated in the design of the support structure.

The septum is made of 140 Mo vertical foils 5 mm wide and 0.076 mm thick separated by 2 mm gaps. They are located by two matching stainless steel templates 10 cm apart which are contoured to the 450 MeV beam orbit, and centred on the beam plane. Each foil is preloaded to 34±2 N by retaining each end with BeCu leaf springs. In case of failure the leaf springs remove the foil from the beam plane. The first and last 7 foils are insulated and may be instrumented.

The electropolished and stress-relieved Type 347 stainless steel antiseptum has three full-length cooling channels formed from a 44 mm o.d. thin wall tube. It is curved parallel to, and 13 mm behind, the septum. The electrical and cooling connections are combined, and are mounted by means of two hollow alumina insulators 144 mm long, located horizontally 10 cm below the medium plane. This is necessary to avoid activation of the insulators by spilled beam. One insulator is fixed, the other one restrained, permitting free movement caused by thermal expansion. The high voltage cable runs inside one of the cooling tubes ($N_2$ gas at 2 atm) and connects through the inside of the fixed insulator. The aluminum support structure consists of a wide I-beam with the vertical wall relieved where possible to permit passage for the prestripped $H^+$ beam, and to minimize activation induced by lost beam. The entire unit is enclosed in a Cu shielding box with only a 40 mm opening on the beam side, grounded to the tank lid and floor, to provide protection against the stray RF fields of the cyclotron dees.

## Magnetic Channels

The electrostatic deflectors generate a displacement of at least 6.5 cm. A further displacement of 70 cm is required to bring the beam to an exit port at the tank wall. This is achieved most economically by two magnetic channels (see Fig. 1). Since the maximum TRIUMF field is relatively low, 0.57 T, a channel strength of 0.9 Tm is adequate.

A conceptual design of an active magnetic channel, 0.2 T by 2 m long, has been produced with the aid of the program GFUN.[5,6] It is based on the use of 13.5 $mm^2$ hollow pyrotenax conductor. The channel is divided into two separate coils to reduce power and cooling requirements. The most stringent coil requires 1100 A, for a power density of 600 $A/cm^2$, 45 kW at 40 V, weighs 120 kg and is cooled by 26 ℓ/min of water. The second coil is similar in size but half the power. The maximum field gradient in the space occupied by accelerated beam is 70 mT/m, or 88 mT/m when averaged around an orbit. The absolute field change is 3 mT maximum.

A passive iron channel will be required in the exit horn, radius 8.9 m, where the vertical gap is only 7 cm. This would be 0.9 m from the circulating beam.

## Tests and Measurements

The first extraction method which will be tested in the cyclotron is the one schematized in Fig. 1a involving the RF deflector. The effect on the beam of the 11.5 MHz unit was recently measured in the cyclotron and coherent oscillations and dilution factors agreeing with numerical predictions were found.[4] Also an experimental deflector 50 cm long, and of a slightly different design, was built, instrumented and installed in the cyclotron outside of the beam orbits (Fig. 4). It was possible to hold a positive voltage of 80 kV with ~120 μA of dark current under normal cyclotron operating conditions. The formation of a separated extraction beam trajectory will be demonstrated as soon as one complete electrostatic channel, presently under design, can be installed in the cyclotron together with the RF deflector and the corresponding prestripper. The extraction efficiency will then be measured.

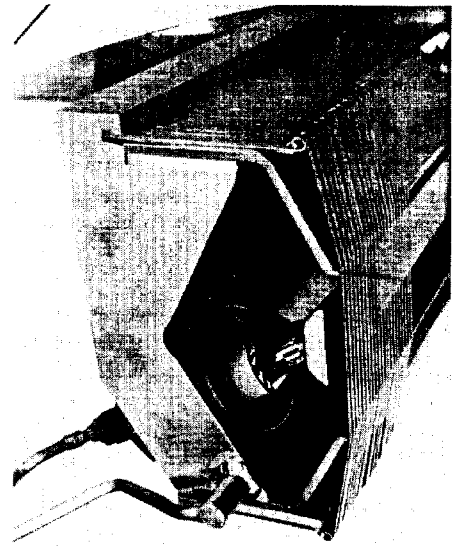

Fig. 4. Experimental electrostatic channel during assembly.

Following signal level measurements on a smaller unit operating at the fifth harmonic (115 MHz), one 92 MHz booster is being built, and it will be tested under power in 1986. The development of the $H^-$ extraction system in the cyclotron requires dedicated machine time, obtained mainly during shutdowns. In addition, some of the elements have to be installed at the periphery of the machine where residual radiation levels during shutdowns are of the order of 300 mrem/h. This requires that all elements be extensively tested for performance and reliability in the laboratory before installation. A special vacuum chamber and magnet will be used for tests on the electrostatic and magnetic channels, and the RF cavities.

The results obtained so far - including both calculations and experimental tests - persuade us that we can proceed with confidence to the extraction of a high intensity $H^-$ beam from TRIUMF.

## Acknowledgement

The authors wish to thank Mr. Richard Lee for continuing support in computing.

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