# A WIDEBAND INTERCEPTING PROBE FOR THE TRIUMF CYCLOTRON

V.Verzilov, D.Cameron, D.Gray, S.Kellogg, B.Minato and W.Rawnsley
Triumf, 4004 Wesbrook Mall, Vancouver, B.C., Canada

### *Abstract*

An intercepting probe for the TRIUMF cyclotron capable of measuring phase and time structure of the circulating beam was designed, manufactured, installed into the tank and tested in 2005. The signals extracted from the probe are then processed by a pair of diplexers, where low frequency and high frequency components are separated. The low frequency signal is directed to our standard electronics for processing and provides both dc current and a time of flight signal with a rise time of <0.1 µs. At the high frequency output a signal-to-noise ratio of about 4 at 250 nA average current and 0.1 % duty cycle was measured in the presence of rf noise from the cyclotron resonators. Beam time structure as short as 1 ns was resolved. Additional efforts will be required to further suppress the noise.

## INTRODUCTION

High frequency diagnostics can provide phase and time structure information about the beam. Two pairs of capacitive pick-ups have been available at the TRIUMF cyclotron for the purpose of beam phase measurement. They are located outside of the cyclotron resonators area but the rf leakage is still strong to make difficult accurate measurements with these probes.

For tuning purposes the cyclotron is typically operated at very low duty cycles (down to 0.1%). Though the peak current remains the same as for the normal operation, the average current is reduced to a level that allows intercepting probes to be used. All the existing intercepting beam probes of the cyclotron tank have a frequency bandwidth of a few MHz, which is not sufficient to measure timing properties of an individual bunch. For a phase measurement the bandwidth of at least up to ~50 MHz is required and it needs to be further extended in excess of 1 GHz in order to resolve the bunch time structure.

At the TRIUMF cyclotron one of the existing probes, was upgraded to the required bandwidth.

## PROBE DESIGN

### *Concept*

Two objectives determined the eventual design of the probe:

- achieve a useful bandwidth above 1 GHz
- suppress the induced signal due to the rf leakage from the cyclotron resonators

Stripline monitors have been known to provide a bandwidth from dc up to a few GHz in the beam current measurements on linacs [1-2]. We decided to base our design on this concept realizing at the same time that simple copying would not work in our case. The original idea of a narrow strip above an "infinite ground plate" can be hardly adopted for the circular accelerator where the $H^-$ beam spirals out from the central region towards the outside and therefore interacts only with the edge of the probe. In this case the so-called parallel plate transmission line can do a much better job. The impedance of the transmission line is approximately given by [3]

$$z=\frac{\eta}{\sqrt{\varepsilon}}\left(\frac{w}{h}+\frac{1}{\pi}\ln 4+\frac{\varepsilon+1}{2\pi\varepsilon}\ln\left(\frac{\pi e\left(w/h+0.94\right)}{2}\right)+\frac{\varepsilon-1}{2\pi e^2}\ln\left(\frac{e\pi^2}{16}\right)\right)^{-1}$$

where $\eta=377\Omega$, $w$ and $h$ are the plate width and inter-plate distance, respectively and $\varepsilon$ is the relative dielectric constant of the material in the space between the plates. In our case the dielectric is vacuum ($\varepsilon$ = 1) and thus the impedance can only be tuned by choosing an appropriate ratio of $w/h$.

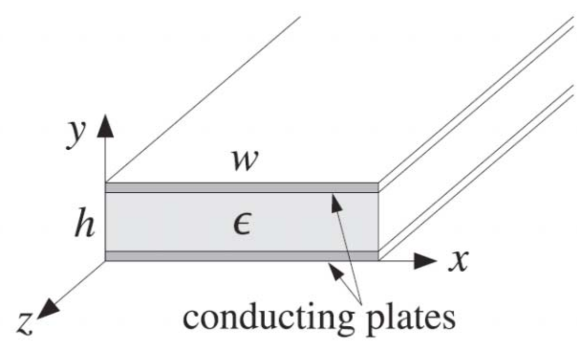


Figure 1: Parallel plate transmission line.

When a piece of this transmission line is placed such that the $H^-$ beam crosses it along a normal to the surface, orbital electrons are stopped in the front (signal) plate. The rear plate serves as a reference (ground) plate. There was another strong argument supporting the choice of the parallel plate transmission line for the probe. Identical signal and reference electrodes isolated from the cyclotron ground would help to suppress the background due to the rf leakage that induces in both electrodes nearly equal strength signals.

### *Electromagnetic and Thermal Simulations*

The design and optimization of the whole probe where performed using HFSS 9. At the initial step the optimum spacing between the plates was determined on the basis of compromise between minimizing the leakage current due to knock-on electrons and keeping the plate width within practical limits. Eventually, a 3 mm distance between signal and reference electrodes was chosen.

At the second step, the probe model was further developed from a series of iterations with the aim to optimize the wideband coupling of the parallel plate transmission line to the coaxial cable which presented a major problem. The optimization was complicated by mechanical constraints necessitated that the coaxial cables are attached to the transmission line at 90º. This is the factor mostly limited the bandwidth of the probe.

The optimum impedance match between the cable and the transmission line was done in two steps. Firstly, in the last part of ~ 10 mm (plate tips), the width was reduced by introducing a dielectric layer between the plates. At the given thickness of the dielectric, the plate width decreases by a factor of 2 in the case of boron nitride. Secondly, the tips were specially shaped to improve the impedance match at the 90º bend. During simulations different model parameters were varied to minimize return losses. The final VSWR remained below 1.15 up to 2 GHz and was considered acceptable given the geometrical dimensions of the probe and the 90º bend. It is believed that further improvements are only possible when both constrains are removed.

The HFSS model was imported in ANSYS Workbench and simulations of a static temperature map for tantalum plate thicknesses of 0.075 and 0.3mm was calculated. At beam energies around 500MeV orbital electrons become a principal source of heat generation. Simulations show that steady state temperatures on the head with a 1uA beam are very reasonable in case of thick and thin plates Generated heat is completely removed from the head connected to the massive copper frame. The thickness of 0.3mm was chosen for the reason of mechanical rigidity only.

### *Practical Implementation*

In manufacturing of the head we closely followed the HFSS simulation model. The core of the monitor, the 50 Ω transmission line, was built with two strips cut from a tantalum foil of 0.3 mm in thickness. The strips were attached to a pair of "c" shaped copper frames for rigidity and better heat removal.. Secondary electron capture barriers were soldered to the frames on both sides.

Copper frames where assembled on a boron nitride ceramic support. Short pieces of 50 Ω kapton coax (Caburn) with mounted on one side rf connectors were soldered to the copper frame tips. The ceramic assembly was mounted on an aluminium frame and protected from the sides by a pair of stainless steel plates, see Fig. 2.

Figure 2: Photograph of the wideband head.

The head was first studied in the lab with a network analyser, then mounted on the drive and connected to coaxial cables. Two types of coaxial cables were used to transport the signals inside the tank. A 2.5 m long kapton cable with a loss of 2 dB/m at 1 GHz was installed in the low frequency arm. A 4.2 mm diameter and 2.5 m in length silicon dioxide assembly with a loss of 0.09 dB/m at 1 GHz from Times Microwave was installed in the high frequency arm. The signals are brought out of the tank by means of Ceramaseal SMA feedthroughs.

The signals extracted from the probe are then processed by a pair of diplexers, where low frequency and high frequency components are separated. The low frequency signal is directed to our standard electronics for processing and provides both dc current and a time of flight signal with a rise time of <0.1 µs. Electronics for processing the high frequency signals is still under development

The probe was mounted on a 3 m long existing drive and is capable of travelling over 20” in the direction making 27 degree with respect to the cyclotron radius. For proper operation the beam has to cross the head normal to the surface. For this the head is tilted by 27 degrees with respect to the direction of motion.

## MEASUREMENTS

### *Lab Measurements*

Before assembling on the drive, the head was studied in the lab using the network analyzer. The measured VSWR was found to be quite different from that calculated with HFSS. We did not observe the nearly flat predicted response in the range of frequencies below 2 GHz. Instead we measured a broad peak at 1.7 GHz (the red curve in the Fig. 3). The high frequency peak shifted from 3 GHz to 3.5 GHz with its amplitude a factor of two higher than had been calculated. The discrepancy was found to be mostly due to a tiny modification introduced at the mechanical design stage.

With the aim of diminishing the probability of breaking the ceramic support, slot cuts for the coaxial cable were displaced by ~1.5 mm from their positions in the EM model. As the result, the coaxial cables were soldered not to the center of the tips but closer to their ends. After this displacement was taken into account in the EM model a new simulation run was performed. The agreement was greatly improved with the exception of the peak amplitude that was attributed to the quality of coupling between the transmission line and coaxial cables which, at this frequency, becomes very demanding.

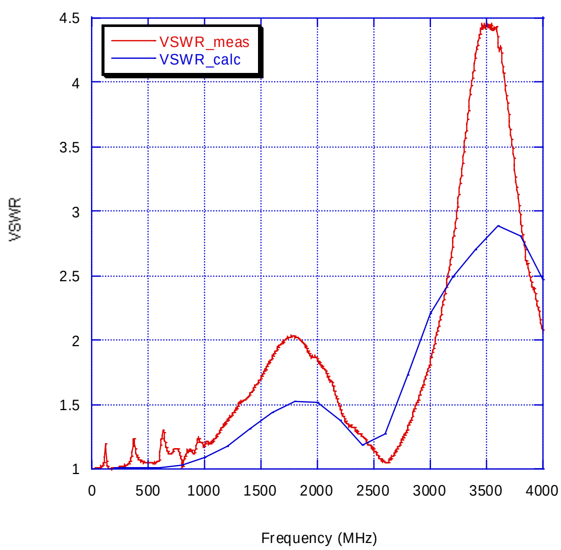


Figure 3: The VSWR of the probe assembly. Measurements (red) and simulations (blue) taking into account a 1.5 mm displacement of the coaxial cables with the respect to the center of the tips.

## *Beam Measurements*

Since the installation of the probe in the cyclotron tank, a few hours of beam development shifts were dedicated to test the functionality of the probe. Measurements were done with the cyclotron operating at a 0.1% duty cycle and an average beam current of up to 250 nA. Typical signals from the probe are shown in the Fig. 4. The useful beam induced signal is represented by the negative pulses with a fixed phase with respect to the accelerating rf field in the resonators. The observed signal-to-noise ratio is about 4.

The beam time structure is less than 2 ns wide, demonstrating the wideband characteristics of the probe. In other measurements bunch widths as short as 1 ns were measured.

In addition the frequency spectrum of the probe signal was measured with a 1.8 GHz HP8591A spectrum analyzer. The spectrum extends up to 1.2 GHz. It is believed that the observed bandwidth is strongly affected by the attenuation in the cables from the probe to the electronic rack, which at 1.2 GHz amounts 10 dB.

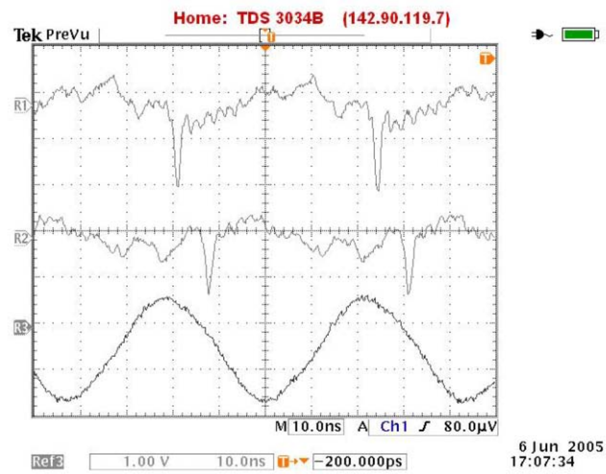


Figure 4: Waveforms of the signal from both ends of the wideband probe measured with the 350 MHz scope along with the 1st harmonic of the rf sine wave. The vertical scale is 20 mV/div (1 V/div for the sine wave) and the horizontal scale is 10 ns/div.

## CONCLUSIONS

An intercepting probe with a bandwidth in excess of 1 GHz was designed for the TRIIUMF cyclotron. The model of the probe head in the form of a 50 Ω parallel plate transmission line was developed and simulated with HFSS 9 to operate up to 2 GHz. Thermal simulations show that probe can withstand at least 500 nA of average current. The probe was manufactured and tested during the year 2005. The probe demonstrated a bandwidth of at least 1.2 GHz with a signal-to-noise ratio of about 4 at 250 nA average current and 0.1% duty cycle. Beam time structure as short as 1 ns was resolved.

## REFERENCES

[1] J.M. Bogaty, R.C. Pardo, and B.E. Clifft, "A Very Wide Bandwidth Faraday Cup Suitable for Measuring Gigahertz Structure on Ion Beams with Velocities Down to β < 0.01", Linac Conference, Los Alamos National Laboratory (1990).

[2] M. Bellato, A.Danielli, and M.Poggi, NIM **A382** (1996) 118.

[3] B.C.Wadell, Transmission line design handbook, Artech House, Boston, London , 1991.