A VERY WIDE BANDWIDTH FARADAY CUP SUITABLE FOR MEASURING GIGAHERTZ STRUCTURE ON ION BEAMS WITH VELOCITIES DOWN to $\beta < 0.01$*

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Abstract

A stripline Faraday Cup of exceptional bandwidth (DC to 6.1 gigahertz) has been developed. An electrostatic shield in the ground-plane geometry prevents electric-field coupling of incoming ions so that the time distribution of low-velocity ($\beta \gtrsim$ .01c) particles can be measured. The cup is very rugged compared to other detectors used for ion-bunch timing measurements. We have measured bunch widths of 400 picoseconds on 3.9 MeV $^{84}Kr^{+15}$ beams (200 nanoampere average). Bunch widths down to 100 picoseconds should be observable with a sampling oscilloscope. Beam bunch shapes have been monitored at current levels of 1.0 nanoampere to 10 microampere average.

Introduction

The ATLAS Positive-Ion Injector(1) upgrade has significantly increased beam current and the ion-mass regime available for research. The next upgrade will complete this cycle with the added capability of accelerating uranium beams. These advances have focussed attention on the issue of suitable RF timing and energy measurement diagnostics, especially for low-velocity ($\beta \approx$ .01c) particles. A diagnostic was desired that could function over a large range of beam currents, be rugged, and economical. In addition, we wished to avoid detectors that would be marginal for certain ion-mass ranges, exhibit a limited lifetime, or have intrinsically unstable calibration parameters. The Wide Bandwidth Faraday Cup satisfies our criteria for RF timing measurements and will also function as a time-of-flight detector for energy determination.

Bandwidth Considerations

Accurate bunching information is dependant on sufficient frequency response from the overall measuring system. That is, the combined response of Faraday cup, amplifiers, oscilloscope, and interconnecting cables must be sufficient for the narrowest beam bunch anticipated. A good estimate of the bandwidth requirement is given by

$$f = \frac{0.35}{T_r} \qquad (1)$$

where: f = upper(-3DB) frequency response and
T_r = risetime of bunch measured from the 10% to 90% points.

For example, 1.0 ns wide (FWHM) bunches require a system response of approximately 875 MHz for accurate timing measurements. The low end frequency response should be sufficient to avoid differentiation of bunching signals.

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Transmission Line Faraday Cups

The bandwidth indicated can be achieved by utilizing either coaxial or stripline construction techniques.

Equation 2 estimates the fundamental cut-off frequency of a 50Ω coaxial Faraday cup of 0.5 in.^{2} target area.

$$\lambda_c = \pi(R+r)\sqrt{\epsilon_r} \qquad (2)$$

here: λ_c = Cut-off Wavelength
R = Inner radius of outer conductor - 0.0467 M
r = Radius of inner conductor - 0.0202 M
ϵ_r = Dielectric constant relative to air - 1.0

The cut-off wavelength for this example is 0.105 meters or 2.86 GHz. This limit can be improved. However, bandwidths beyond a few gigahertz would be difficult to achieve with large diameter coaxial Faraday cups.

Striplines

Striplines have much the same frequency limitations as coaxial lines, however, their flat geometry allows greater flexibility in accommodating Faraday cups of acceptable target area. This advantage permits the use of thin dielectrics which are necessary for high-frequency operation. The fundamental cut-off frequency for a stripline is given by

$$f_c = \frac{1}{2H\sqrt{\mu\epsilon}} \qquad (3)$$

where: f_c = Cut-off frequency (Hz)
H = Dielectric Thickness (m)
μ = Permeability of Dielectric (H/m)
ϵ = Permittivity of Dielectric (F/m)

The extremely uniform dimensions of a printed circuit board yields precision striplines at low cost. High-frequency performance is enhanced because of this uniformity and without the expense of precision machining operations. We have had no trouble manufacturing 6 → 10.0 GHz bandwidth striplines without resorting to mode suppression techniques.

Electrostatic Shielding

Electric fields from moving ions extend in all directions and will couple to an unshielded Faraday cup. As a result, current will be induced in the Faraday cup prior to the ion's arrival. This effect

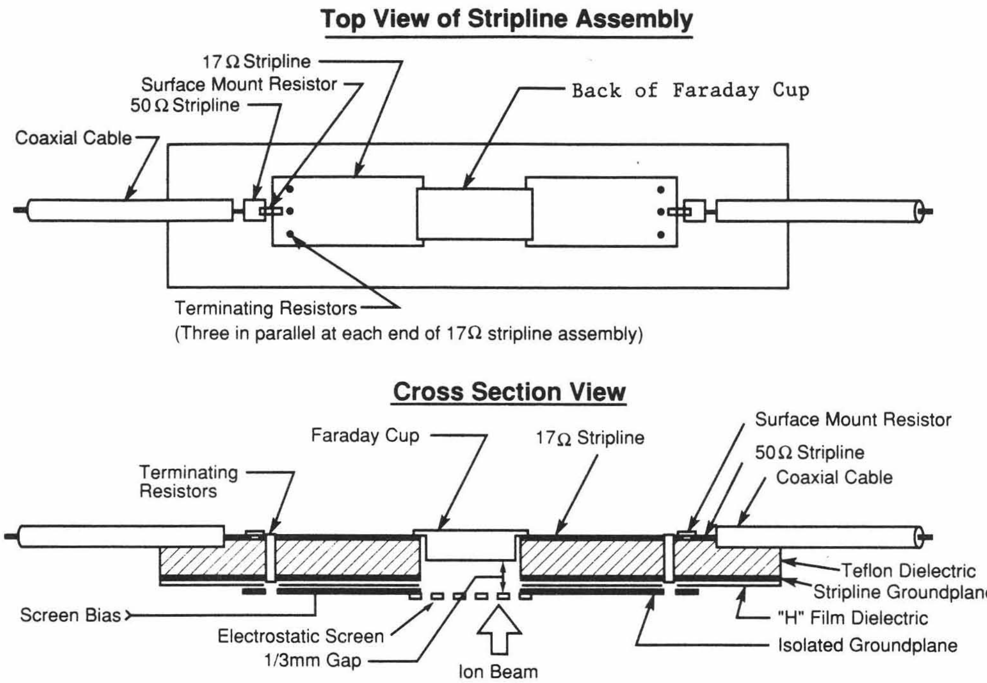


Figure 1

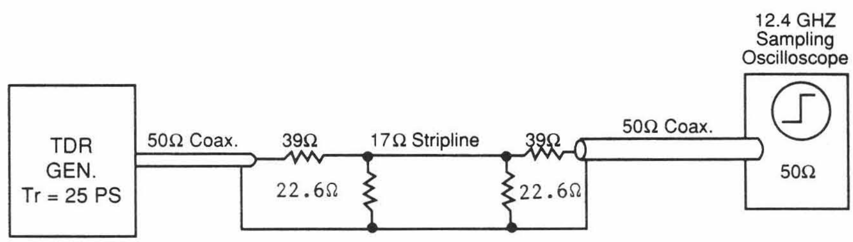
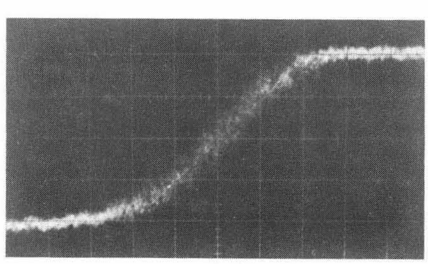


Figure 2

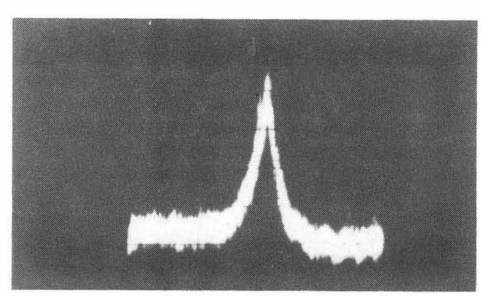
Faraday Cup Output Response
Input pulse rise time = 52 picoseconds
Output pulse rise time = 64 picoseconds



Output pulse at 20 picoseconds/cm

Figure 3

Bunching Analysis
Inside Alpha Cryostat



3.9 MeV Kr_{84}^{+15} 400 picoseconds (FWHM)

Figure 4

reduces the high-frequency performance to an extent that depends on the ion's velocity.

Effective electrostatic shielding is accomplished by the placement of a metallic screen in close proximity of the Faraday cup's surface. The screen is capacitively coupled to the stripline assembly and functions as part of the RF ground plane. We used a commercially photo-etched Molybdenum screen 0.005 in. thick, with a grid pattern comprised of 0.005 in. wires at 0.026 in. intervals. This geometry provides 80% particle transmission and effective electrostatic shielding. The spacing between the screen and Faraday cup face must be chosen for acceptably low precursor field induction with the lowest velocity ions, as determined by

$$D = TV \quad (4)$$

where: D = Screen to Faraday Cup spacing
T = Precursor field time limit
V = Ion velocity

We chose a precursor field time limit of 1.1×10^{-10} sec as acceptable for $\beta = 0.01$ velocity ions. Equation 4, with these parameters, was used to determine the screen spacing at 0.013 in. (1/3 mm).

Stripline Faraday Cup Design

Figure 1 shows a cross section view of the stripline Faraday cup assembly. The printed circuit board is cut away to receive the machined copper Faraday cup. Striplines adjacent to the cutout are etched to match the Faraday cup impedance and carry signal currents to end terminations. Spacing of the electrostatic shield has been set at 0.013 in. which, in conjunction with the cups width, determines characteristic impedance. Equation 5 was used to estimate characteristic impedances of both the Faraday cup and printed circuit striplines.

$$Z_o = 377 \left[\frac{H}{W}\right] \left(\frac{1}{\epsilon_r}\right)^{1/2} \quad (5)$$

where: Z_o = Characteristic impedance
W = Strip width
ϵr = Dielectric constant

These calculations are only approximate because edge effects are not accounted for. Time Domain Reflectometry (TDR) Techniques were used to evaluate all sections of the stripline Faraday cup. The complete assembly is checked using TDR response analysis. Impedance matching to a few percent was relatively easy to achieve. The TDR generator we used has an output risetime of 25 picoseconds, which in conjunction with a 12.4 GHz sampling oscillo- scope, yields impedance profiles out to 9.0 GHz bandwidth. Figure 1 shows a top view of the stripline segments which provide attachment points for surface mount resistors, and connection to 50Ω coaxial cables. Figure 2 shows an electrical equivalent of the stripline Faraday cup. The coaxial cables are used to inject test pulses for TDR and risetime measurements. As the drawing shows, either end can be driven and the resulting signals monitored with the other coaxial cable. One of the coaxial cables is replaced with a terminating resistor when testing is finished. The remaining cable is used to transmit beam signals for evaluation. Frequency response is checked by two methods. TDR pulses are injected into one of the 50Ω coaxial cables and the resulting output viewed on a sampling oscilloscope. This provides a record of risetime and pulse response characteristics. We also used a RF sweep generator to drive the cup from 10 MHz to 8.0 GHz, the resulting output confirmed the bandwidth implied by risetime measurements. Figure 3 shows the pulse response characteristics when a 52 picosecond risetime pulse is injected into one end of the stripline Faraday cup. This unit exhibited a bandwidth of over 9.0 GHz with no apparent ringing.

Faraday Cup Bias and Operation

As shown in Fig. 1, the electrostatic screen is isolated for DC voltages. This permits the application of bias on the screen, to suppress electrons, when accurate peak beam-current measurements are desired. If a positive bias is applied, the overall beam current sensitivity is enhanced by a a factor of 3.9. This is an advantage when measuring low beam-current bunching and has no apparent effect on bunch-width measurements according to our testing. We apply a standard bias of plus or minus 180 VDC, with the polarity primarily dependant on beam intensity.

For most beams, we simply use a broad bandwidth 60 DB amplifier to boost the Faraday cup signals and display them on a 12.4 GHz sampling oscilloscope. The signal to noise ratio of the overall system is sufficiently high to allow direct visual interpretation of the oscilloscope signals with no other processing. When weak beams are measured we use digital processing techniques to enhance signal-to-noise ratios and store the results in a Nicolet Digital oscilloscope. This process allows beams as weak as 1.0 nanoampere (electrical) to be analyzed.

Faraday Cup Uses

The Wide Bandwidth Faraday Cup has been in use at ATLAS for one year now. Several versions of this design are permanently installed and routinely used. A low beta ($\beta = 0.01c$), close screen, version is installed in our Positive Ion Injector line where RF bunching is monitored for beam bunch initialization. A miniaturized version is installed in the first Positive Ion Injector cryostat and operates at liquid helium temperatures. This cup has 10.1 GHz bandwidth and is used to set up bunching into the first accelerating cavity. Here, the bunches are a few hundred picoseconds wide as shown in Fig. 4. A high-velocity version of the Faraday cup has been developed and is installed at the end of ATLAS where ion velocities are up to 20% the speed of light. This design has five times more sensitivity than the low beta version due to a wider cup-to-screen spacing and 50Ω impedance. This Faraday cup has been used to monitor stripping foil energy loss of a 1.0 nanoampere silicon beam and will be used to monitor beam timing for timing sensitive experiments.

References

1) P. K. Den Hartog, et al., Nucl. Instrum. Methods in Phys. Res. B40/41, 900 (1989).