A non-intercepting cyclotron beam monitor

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ABSTRACT

The bunched nature of the cyclotron beam permits its measurements under both pulsed and steady conditions without interception of the particles. A simple monitor which consists of a toroidal current transformer and an amplifier tuned to the cyclotron orbital frequency operates satisfactorily down to currents of less than 5×10^{-7} A.

Much higher sensitivity, below 10^{-8} A, was provided by a system using frequency conversion and a synchronous detector, with the reference signal derived from the cyclotron oscillator. Output of the monitor provides a d.c. signal for the beam intensity indicator and also a video output which permits display of the beam envelope.

Calibration of the monitor is accomplished by means of a step-recovery diode pulse generator and a calibrated attenuator.

Probes described in the paper can be used also for energy measurements by a correlation method which is briefly described.

The cyclotron beam is bunched with a repetition frequency equal to the orbital frequency of acceleration. In the Nuffield Cyclotron, which has a repetition frequency of about 10·5 MHz the principal shape of each bunch is shown in Fig. 1. The very sharp rise is a source of higher harmonics, and only about 30% of the total spectral power is concentrated in the fundamental (Fig. 2).

In the signal from the beam current there is a certain amount of noise, not including components harmonically related to the supply frequencies (50 100 and 300 Hz). The beam noise originates mainly in the ion source, whose plasma exhibits quasi-random oscillations with frequency centred around 0·5 MHz. This arc noise produces continuous sidebands at every harmonic present in the beam current spectrum.

An interesting feature is the presence of subharmonic frequencies (½ f and in some cases ⅓ f). Their origin is unclear and is probably linked with internal oscillations during acceleration.

Beam intensity monitors based on selective amplification of the rf component of the beam current were described by Korshunov and Meleshko[1] and by Bergere *et al.*,[2] but very little was reported about their performance.

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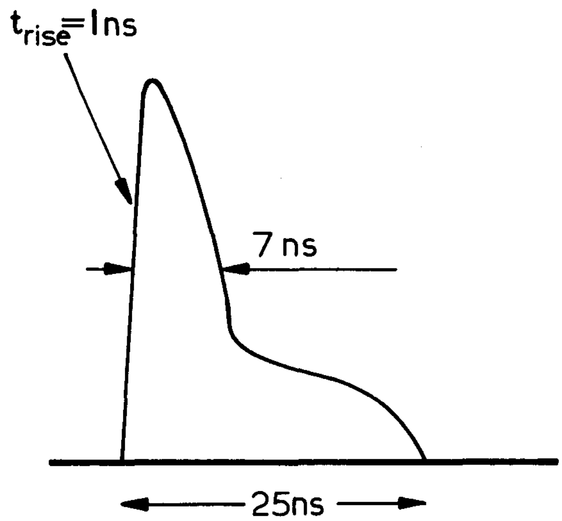

Fig. 1. A typical shape of the individual beam bunch (protons, 10 MeV)

It can be easily recognised that cyclotron laboratories are very noisy from the radio interference point of view. The particular difficulty encountered by us was that some of the interfering radiations have a frequency equal to that which we were trying to detect with our probe.

The inductive probe monitor occupies the shortest length of the beam transport line of all non-intercepting probes. It was made of a ferrite ring with μ_o = 1000 and of 70 mm internal diam. A three-turn coil was placed as a signal winding on the ring and another single turn was provided for calibration. The windings were encapsulated in epoxy resin and the whole probe machined to fit, vacuum tight, into the beam transport line. The total thickness of the probe is 25 mm. It was soon found that the beam transport line was imperfectly earthed despite many efforts and carried some rf voltage vs ground. Therefore, double electrostatic screens were needed to eliminate the unwanted signal.

In the first design we used a three-stage transistor preamplifier with a differential input, placed very close to the probe (Fig. 3). This was followed by a valve main amplifier, consisting of three rf stages, diode detector, d.c. amplifier and one stage of video amplification. The centre frequency was 10·5 MHz and the damping of coupled interstage rf transformers, plus some offset in frequencies of all tuned circuits, resulted in a bandwidth of 200 kHz. This was enough because frequency variations during machine runs are rarely higher than 50 kHz, and day-to-day frequency repeatability is also about 50 kHz.

A later design of the probe amplifier is shown in Fig. 4. The advent of complex integrated circuits made it possible to reduce the total number of components. The whole amplifier is attached to the probe, providing outputs for the monitoring of the average d.c. levels and the beam envelope. For 200 kHz bandwidth the noise level corresponds to 0·1 μA of beam current. It is noise that puts a limit on the sensitivity of a well shielded probe. The noise is contributed both by the beam itself and by the input stage of amplification. It was possible to reduce it by using a synchronous detector. The block-diagram is shown in Fig. 5. The synchronous detector assembly was made by Brookdeal

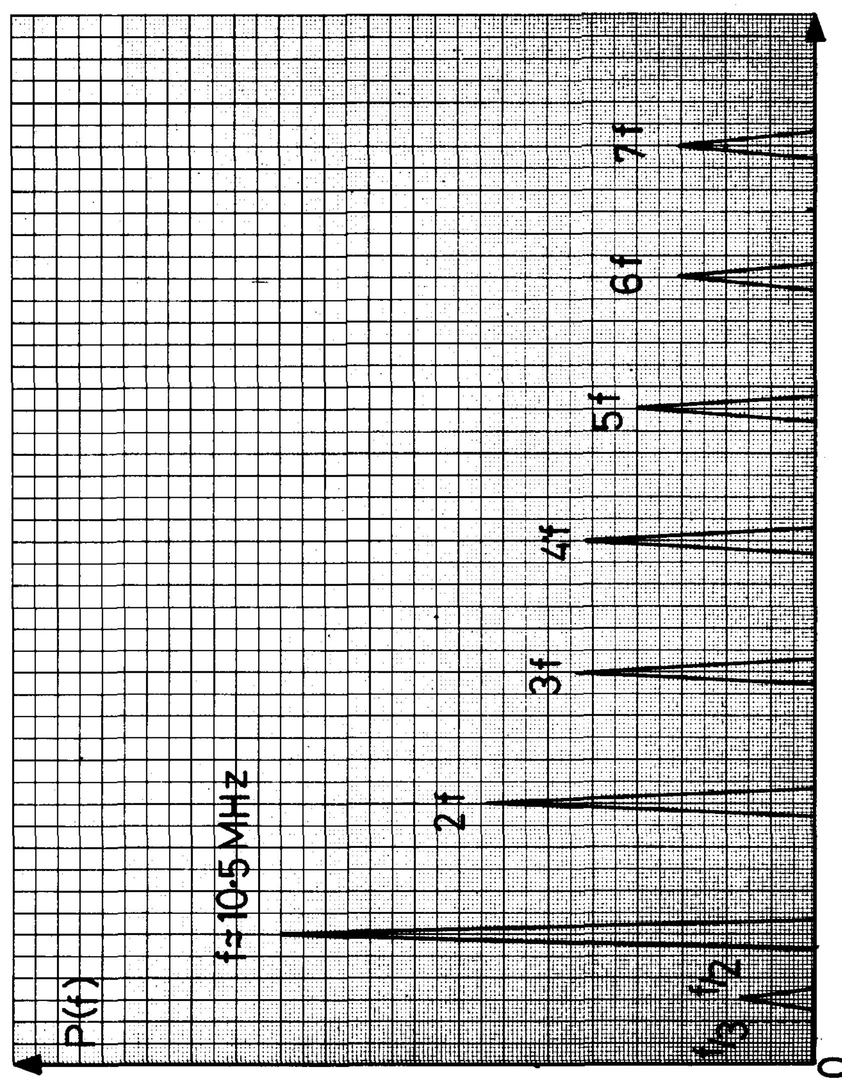

Fig. 2. Power spectrum of cyclotron beam current (protons, 10 MeV)

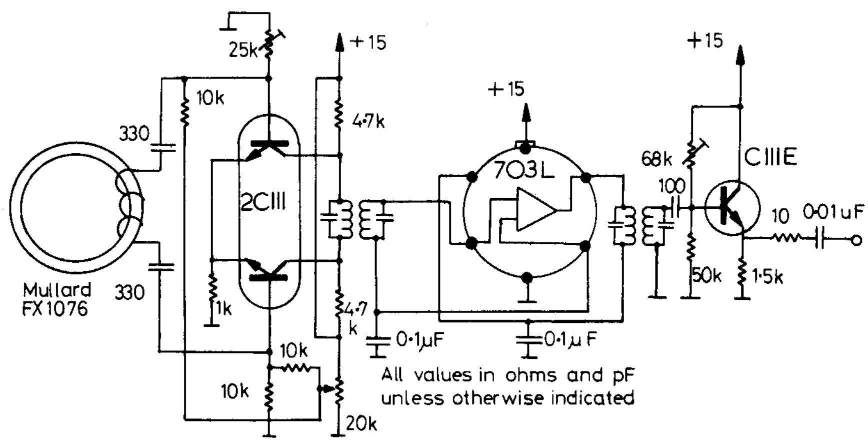

Fig. 3. Transistor preamplifier for the beam pick-up probe

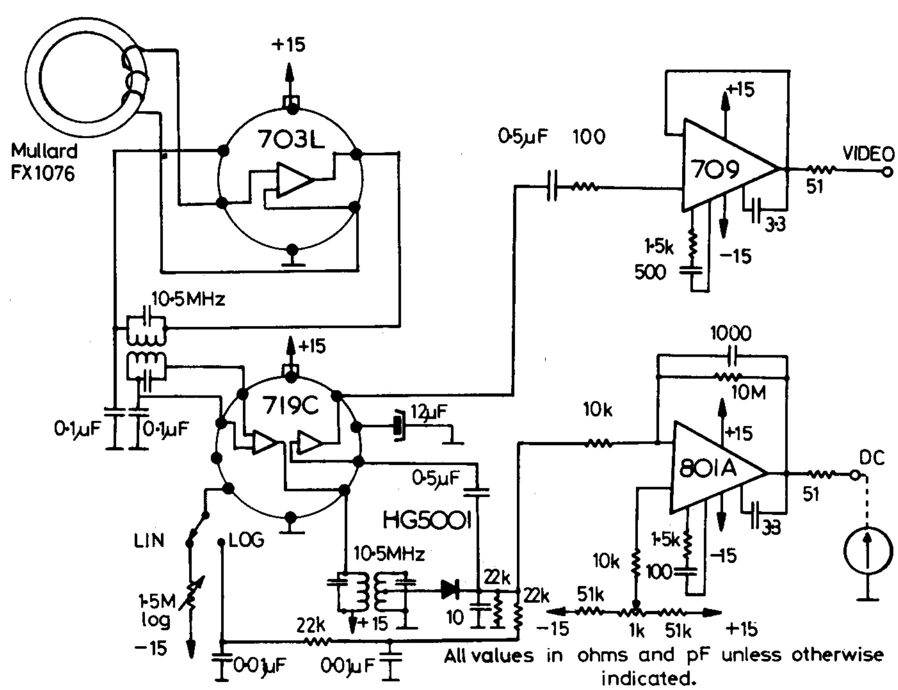

Fig. 4. Integrated beam probe amplifier

Electronics Ltd. (Models FL355 and MS 320). Because the upper frequency limit of the system was 0·5 MHz it was necessary to heterodyne down both the signal and the reference voltage. A crystal controlled oscillator and balanced mixers lowered the frequencies in question to about 0·3 MHz. Balanced mixers based on Hewlett-Packard design (Model 10514A) and of our own construction, built around the integrated circuit 101 TAB (Mullard), performed equally well. The noise level in this arrangement was equivalent to no more than 0·01 μA of the particle beam (Fig. 6).

The video output, displayed in the control room on an oscilloscope, gives useful information on the modulation and slow (5 μs rise time) pulsing of the beam. Fig. 7 shows the beam probe with attached preamplifier (ferrite ring separately) and the unit containing heterodyning and local oscillator circuits.

Using the fast outputs obtainable from two probes separated by approx. 9·56 m, an attempt was made to measure the energy of the beam by a modified time-of-flight method.

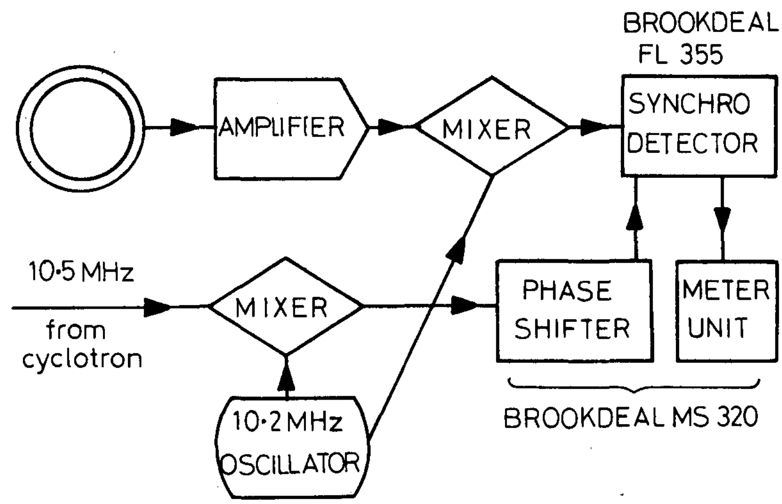

Fig. 5. Use of the lock-in amplifier for filtering the beam probe signals

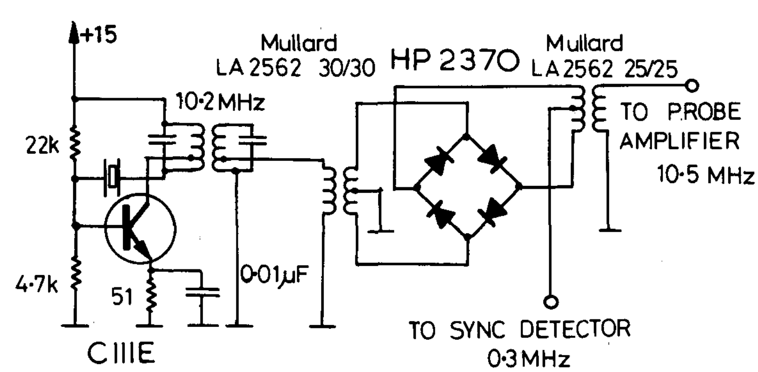

Fig. 6. Crystal-controlled oscillator and balanced mixer

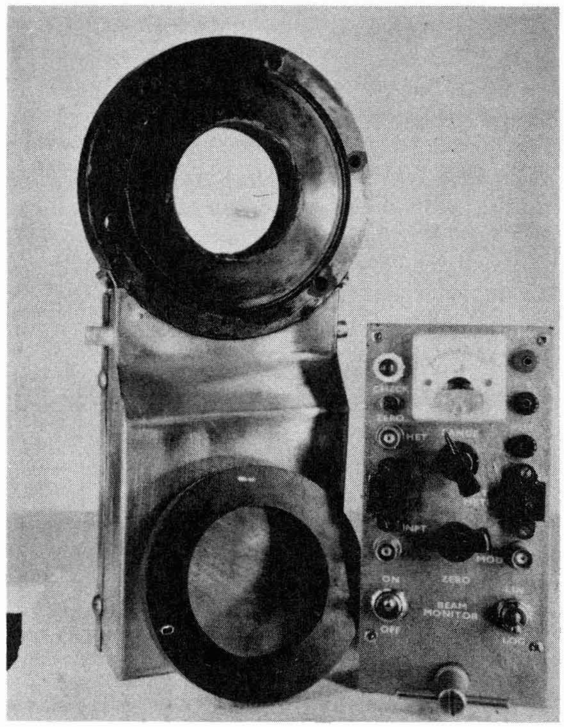

Fig. 7. Beam probe with preamplifier box, ferrite ring, and heterodyne unit

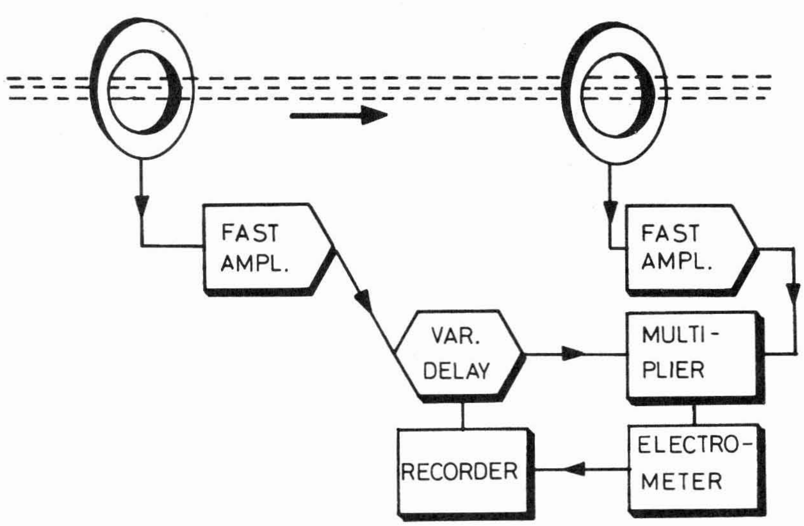

Fig. 8. Correlation method of measuring the particle energy

For 10 MeV proton the time-of-flight was about 219 ns and for 2·35 MeV deutrons it was 635 ns. A correlation method was tried instead of the standard coincidence technique because of the erratic operation of coincidence circuits with very noisy fast signals from probes (Fig. 8). The amplifiers had a rise time of about 3 ns but the response of the multiplier was just about 40 ns. The multiplier employed the principle of a PIN-diode modulator.

Despite this inadequacy a cross-correlation curve was obtained with a clear maximum corresponding to the time-of-flight. After the delays in connecting cables were measured by the time domain reflectometry method it was possible to determine the energy of the beam.

We hope that using this approach it will be possible to improve the energy resolution to about 1% and at the same time to deduce from the shape of cross-correlation curves the energy spread of the beam.[3] It may even be possible to obtain a continuous display of these quantities together with more obvious beam intensities and envelopes.

For the calibration of pick-up probes the single turn winding is fed with a signal derived from the cyclotron frequency and 'sharpened' by a step-recovery diode module (analogous to Hewlett-Packard Model 33007A). The calibration is not absolute and requires an initial comparison with an independent measurement of the beam current.

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