PERFORMANCE OF THE 70 MeV INJECTOR TO THE ISIS SYNCHROTRON

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Abstract

The Injector to the synchrotron of the ISIS pulsed neutron source is a 70 MeV Alvarez linear accelerator which produces a 20 mA pulsed beam of H^- ions, at a pulse repetition rate of 50 Hz and pulse lengths of up to 300 µs. The accelerator has been in regular operation since 1985 during which time it has been under continuous development. The main features of the accelerator are described, together with data on its performance, and an account is also given of some of the problems experienced in its operation.

General Description Of The ISIS Injector

A description of the accelerator was last given in 1979(1) when it was in the process of being converted from a low duty cycle proton accelerator to a high duty cycle H^- ion accelerator. The historical background to the accelerator, given in the earlier paper, explains some of the unusual features of the present machine. For example, two of the accelerating cavities were built in the late 1950's and the remaining components, together with the building, were designed for minimum cost rather than for optimum operational performance or convenience. In short, the linac is far from representing the state of the art in the field, although it has been developed to give a satisfactory and competitive performance.

The accelerator is designed for a 20 mA pulsed beam current at 70 MeV, with pulse lengths up to 500 µs at a prf of 50 Hz. In practice, pulse lengths of greater than 300 µs have never been run at full prf. The H^- ions are produced by a Penning ion source(2), mounted on the high voltage terminal of a 665 keV, 444 mm long, accelerating column. High voltage is supplied by a commercial Cockcroft-Walton generator, to which are added a 0.01 µF storage capacitor and a 'bouncer' pulse voltage stabiliser. The 665 keV beam transport line is 4.7 m long and contains 3 quadrupole triplets, twin steering magnets and a single fundamental harmonic buncher cavity, together with an emittance measuring apparatus, beam current transformers and a beam stop. The buncher is a two gap coaxial resonator, fed from a pick-up loop in the first linac accelerator cavity, and is located 0.8 m from the linac. Beam transmission from accelerating column to linac output is normally just over 60%.

The linac has four accelerating cavities (tanks), the first of 10 MeV and each of the others 20 MeV. Tanks 1 & 4 are basically engineering copies of the appropriate lengths of the Fermilab linac, constructed from copper clad steel, while tanks 2 & 3 were taken from a former RAL 50 MeV linac and have fabricated sheet copper cavities mounted inside separate steel vacuum vessels. Evacuation of the tanks is by turbo-pumps. Tank 4 alone is fitted with post-couplers. The main parameters are given in Table I over page.

The quadrupole magnets in tank 1 are capable of operating in the FDFD focusing mode, but not at 50 Hz due to a limitation in power dissipation. Even with the lower strength FFDD mode, considerable ingenuity has been necessary in the design of the pulsed power supplies to keep the overall pulse length as short as possible whilst generating a good flat top pulse. Magnets in the remaining tanks are dc powered.

RF power to the tanks is provided by four identical amplifier chains consisting of:

(a) Two transistor stages amplifying from 10 mW input to 200 W maximum output;
(b) RCA 7651 tetrode stage of 4 kW maximum output;
(c) RCA tetrode stage of about 250 kW maximum output;
(d) Thomson TH 116 triode stage of about 2.5 MW maximum output.

Table I - Accelerating Cavity Parameters

Cavity Number	1	2	3	4
Construction	Cu clad steel	Vac vessel & Cu liner	Vac vessel & Cu liner	Cu clad steel
Length, m	7.15	11.96	11.24	12.11
Energy out, MeV	9.91	30.44	49.71	70.44
No of cells	56	41	27	24
DT aperture, mm	20-25	38.1	38.1	30
Acc rate, MeV/m	0.84-1.55	1.72	1.71	1.77-1.66
Q - theory	76,100	70,900	56,800	66,000
- measured	60,900	58,600	39,700	55,100
Power for ϕ_S=30°, MW - theoretical Q	0.44	1.31	1.40	1.51
- meas. Q + 20 mA beam	0.74	2.00	2.39	2.22
Focusing magnets - period	FFDD	FFDD	FFDD	FFDD
- excitation	Pulsed	DC	DC	DC
- gradient, T/m	40.0-15.0	7.5-6.1	4.6	5.3
- length, inches	1.0-2.75	4.5-6.0	9.0	7.5

The output stage is pulsed from a hard valve modulator which uses two CW1600 tetrodes in parallel and a 50 μF capacitor bank charged to a maximum of 40 kV. The timing of triggers to the thyristor controlled charging circuit is optimised by a microprocessor controlled adaptive loop, to equalise the current taken by each phase of the 3-phase supply while yielding the desired capacitor bank charged voltage. An additional rf system for the debuncher cavity employs a commercial 40 kW amplifier following stages (a) & (b) above.

RF power is fed to the linac cavity on a 300 mm diameter, aluminium, coaxial line, which is of an RAL design permitting a degree of misalignment between flanged sections. The line has four 90° elbows, a further stub-supported 90° bend, incorporates a trombone line-stretcher and uses cross-linked polystyrene disk supports. The cavity is fed by a remotely adjustable feed-loop located on the air side of a 25 mm thick, 300 mm diameter, cross-linked polystyrene vacuum window.

The 70 MeV beam-transport line, leading to the synchrotron injection system, is 50 m long and contains three horizontal and two vertical bending magnets, 22 quadrupole magnets and appropriate steering magnets. A single gap debuncher cavity of 410 keV peak design voltage is located 36 m from the linac. For beam diagnostic use, the line contains 5 beam current transformers, 14 combined horizontal and vertical wire beam profile monitors, a beam chopper and 8 ionisation chamber beam loss monitors. A further 9 chambers are distributed along tanks 2 to 4 of the linac.

The first two horizontal bending magnets of bending angles +63° and -64.5°, together with associated quadrupole magnets, form an achromatic pair, and the third magnet of 24.69° provides the desired beam dispersion at the point of injection to the synchrotron. Two vertical bends of +/- 6.3° bring the beam to the correct height after passing over the sychrotron ring, to permit injection from the inner radius. In spite of some of the large bending angles, former High Energy Physics beam-line magnets with parallel edged poles have been used for all bends.

A number of developments and performance characteristics of the ISIS linac will now be discussed.

Ion Source Development

The main limitation on beam intensity has been the ion source although, as a result of steady improvement in the source performance, any further increase in beam current would begin to require a corresponding improvement in the present performance of the linac rf systems. Most of the ion source improvements have been described elsewhere(2) but a brief update of the source operational performance will be given. Fig 1 shows a scatter plot of 665 keV beam current readings over the operational life of ISIS and Fig 2 illustrates the operational life of individual ion sources during 1992. It is understood(3) that our Penning source, based on the Dudnikov design, should be capable of delivering pulsed currents of up to 100 mA and we intend to seek this by continued exploration of changes to the source dimensional parameters. Progress in this field has been limited by a lack of resources to maintain an ion source laboratory test rig, so that all trial developments have to made on the installed ISIS source.

Development of a multicusp volume H^- source was initiated at RAL some time ago, when it was thought that the Penning source would fail to meet the ISIS design requirements, but there have been no results of any interest to report so far. Results at other laboratories suggest that development of this source is not yet at a stage where it might be suitable for use on ISIS.

Accelerating Column Breakdown

Spark breakdown of the accelerating column occurs at a typical rate of about once per hour due to charging of the insulators by electrons stripped from the H^- beam(4). Such beam trips are damaging as they contribute to the total number of thermal quenches experienced by the ISIS neutron target, and these are thought to shorten the target life. Recently, it has been found possible to prevent the Cockcroft-Walton generator tripping on over-current, following a column spark, by increasing the value of the resistor between the 0.01μF storage capacitor and the column high voltage terminal from 10 kΩ to 1 MΩ. The CW voltage then recovers within 2 or 3 pulses and it is unnecessary to trip the linac beam. Since the effective capacity at the column high-voltage terminal is then much reduced, it is necessary to compensate for the much larger droop in the column voltage during the beam pulse and this is achieved by a bouncer circuit connected to the earthy terminal of the storage capacitor. During the beam pulse the voltage at the input end of the 1 MΩ resistor is increased by a pre-set value, to produce a current in the 1 MΩ resistor exactly balancing the beam current flowing down the column. A prototype bouncer circuit has been successfully used for some months and a final version of it should be in use by the time this paper is published.

Beam Parameters

Transverse emittance of the beam is measured at 665 keV using a single traversable slit 1 m upstream from an array of detector wires. These wires are at 10 mm spacing but the array is traversed in 10 steps of 1 mm during a measurement. Typical measured emittance plots for a 40 mA beam current are shown in Fig 3. The dots shown plotted are measurement points at which the detected signal is greater than a defined background noise level, and the irregular contour lines are equal intensity contours plotted at 0.05, 0.1, 0.3, 0.5, 0.7 and 0.9 of peak intensity.

Values normally quoted for beam emittance are often ambiguous when it is not made clear whether the contour enclosing the quoted area is regular or highly irregular in shape. Since in most accelerator applications the beam has to be accepted by equipment which has a beam acceptance shape close to an ellipse, beam emittance should properly be quoted for an elliptical area which encloses a given beam current or fraction of the beam, as has been suggested by Keller et al(5). Independently of their work a computer program has been written which, for a set of emittance measurement data, finds the parameters of the smallest area ellipse enclosing a specified fraction of the beam current. The ellipses shown plotted in Fig 3 have been calculated in this way for 40, 80 and 98% of the total beam current.

Plotting the emittance of the bounding ellipse against ln(1/(1-f)), where f is the fractional current enclosed by the ellipse, gives the result shown in Fig 4. The results lie approximately on a straight line which, as discussed by Allison(6), should be the case for a Gaussian phase space density distribution. A value for the rms emittance can be calculated from the slope of this line or directly from the original measurement data. Using Allison's notation, (where $\varepsilon_{4rms} = 4\varepsilon_{rms}$), and taking the momentum normalised values, emittances for the beam of Fig 3 are:

	H - plane	V - plane	
ε(norm) for 90% beam current in elliptical contour	1.46	2.24	πμmrad
ε_{4rms}(norm) from slope in Fig 4	1.20	1.82	πμmrad
ε_{4rms}(norm) from original measurement data	1.49	1.75	πμmrad

The 665 keV beam emittance figure for the horizontal plane, which is the plane normal to the long dimension of the ion source extraction slit, always shows a very significant degree of aberration but it is not clear where this originates. Possibilities are in the ion source extraction gap, in the 90° gradient bending magnet following extraction, in the electrostatic focusing at the entrance to the accelerating column or from non-linear space charge forces. A trial change to a more Pierce-like extraction geometry failed to produce any improvement.

Measurement of the 70 MeV beam emittance is made close to the linac output, using 3 beam profile monitors in a drift space, with the beam brought to a waist near to the drift space centre to provide good resolution in computing the emittance by beam tomography. A similar measurement can be made close to the injection point into the synchrotron, but accuracy here is poor due to momentum dispersion and unfavourable focal conditions. The shape of the 70 MeV measured beam emittance is generally good so ellipse fitting is not essential. Typical emittance figures for 99% of a 20 mA, 70 MeV beam are 25 πμmr in each plane, or 9.9 πμmr momentum normalised.

Momentum spread in the 70 MeV beam is measured using a simple magnet spectrometer. Excitation of the 24.69° horizontal bending magnet in the 70 MeV beam-line is increased to deflect the beam into a separate line at 50°. The upstream beam is defined by a slit and, with appropriate quadrupole focusing magnet settings, an image of the slit is formed at the position of a beam profile monitor in the 50° line. Beam momentum spread depends on the settings of the debuncher cavity, typical figures being:

	dp/p (Debuncher off)		dp/p (Minimum with debuncher on)	
	90% beam	100% beam	90% beam	100% beam
Measured beam	3.9×10^{-3}	6.0×10^{-3}	1.9×10^{-3}	3.2×10^{-3}
Computed beam (for axial dynamics & no space charge)	3.4×10^{-3}	5.5×10^{-3}	0.33×10^{-3}	0.44×10^{-3}

It is probable that the measured minimum value with debuncher on is significantly larger than the computed value due to limited resolution of the spectrometer. When the beam is set up for best ISIS synchrotron operation, with the debuncher field level and phase both freely optimised, it is generally found that the measured beam momentum spread ends up close to the value for the debuncher off.

Cavity Field Control

Stability of the linac beam, particularly in energy, has proved to be a very important factor in achieving reliable operation of the ISIS synchrotron, and this has required the development of adequate control over the amplitude and phase of the cavity fields.

Amplitude stabilisation is achieved using a feedback system in which a detected cavity field signal is compared with a reference level and the error signal used to modulate the drive to the rf system at the 10 mW level. During the cavity field rise-time, when the large error signal would heavily saturate the feed-back amplifier, the amplifier is automatically gated off and the rf drive is preset to a separately controlled level. Typical rf cavity pulses are shown in Fig 5 for the acceleration of a 22 mA, 200 μs beam. The cavity feed-line forward wave signal shows the extra power being turned on for beam loading. The field level overshoot at the start of the flat-top and also after the beam switches off are of no operational importance. The only significant disturbance is a transient 1.5% dip in field level at the beginning of the beam pulse. It is known that this could be corrected by an appropriate feed-forward control signal, but operationally this is found to be unnecessary.

Cavity phase is similarly pulse stabilised with a closed loop gain of about 30. An important source of disturbance to the phase in tanks 2 & 3 is the effect of multipactor loading in these cavities at the operating field level which, with no feedback control, can produce a 10^{0} phase change during the rf pulse. The main problem has been in achieving long term phase stability, allowing the linac parameters to be re-established quickly and repeatably following a shut-down and eliminating the need for periodic adjustments. This has been effected largely by installing semi-rigid, semi-air spaced cabling for all phase reference lines.

One further improvement has been the introduction of a technique(7), similar to the Δt method used at LAMPF, for setting-up the design settings of field level and phase in each cavity. This has eliminated a large amplitude coherent phase oscillation in the linac and has probably contributed to the improvement achieved in the ISIS operating intensity.

Beam Losses

In a high mean beam current linac, such as the ISIS injector, it is essential to keep beam losses to a minimum. In addition to prompt radiation and activation problems, the mean power in the beam exceeds 15 kW and can quickly cause serious damage if the beam goes astray. Beam loss protection is provided by the 17 beam loss monitors distributed along the Injector beam path. A beam trip can be initiated if the signal from any one monitor, integrated over a pulse, exceeds a pre-set value. For the 70 MeV beam the trip level is set for a beam loss of 0.05μC per pulse, equivalent to a local continuous loss of 1.2% full beam current. In practice the trip occurs if such a loss is detected on four of any eight consecutive pulses. This logic, carried out by a dedicated microprocessor, prevents any unnecessary beam trips due to single isolated bad pulses.

The signals from these monitors are also permanently displayed and used by the crew when tuning for minimum beam loss, since losses are too small to be resolved by the beam current transformers. Signals due to pulsed X-ray emission from the cavities are normally larger than those due to beam loss and so are arranged to be subtracted automatically from both the displayed and trip level signals.

An unusual feature of the ISIS Injector is the presence of beam collimation inside one of the cavities. At the time that ISIS was designed it was specified that the 70 MeV beam should not exceed a normalised emittance of 10π μmr. Some attempt was made to design the 70 MeV beam-line to incorporate suitable collimators, but the technical requirements could not be met within the beam path length available, and collimation at the input to the linac would not have been suitable because of emittance growth during the early stages of rf acceleration. As a compromise the collimation is installed in the apertures of the early drift-tubes of tank 2, where emittance growth is largely complete and yet where the beam energy is low enough for activation problems to be small. The collimation takes the form of a series of graphite tubes, of slowly decreasing aperture, which are split and made a slight interference fit in the drift-tubes in the hope of achieving some degree of thermal contact. The degree of beam interception is not known, but the 70 MeV beam emittance is within its specification and the collimators have not given any problems.

Activation of the injector has never seriously interfered with hands-on repair and maintenance of the linac or the 70 MeV beam-line. 18 hours after a recent operations cycle, the maximum measured radiation level along the linac was 100 μSv/hr on contact with the beam pipe between tanks 3 & 4. On the 70 MeV beam-line, 35 hours after operation, measurements of 2000 μSv/hr on contact were made at two points, but these fell to 50 μSv/hr at 0.5 m.

Injector Reliability

Figures for the operation of ISIS during the 1992 operations year were as follows:

Scheduled user time	4182 hrs
Beam-on-target time	3564 hrs (85.2%)
Lost time	618 hrs
Equipment down-time	797 hrs (Allowing for concurrent equipment faults)
Total beam-on-target	533 mA.hrs

The Injector was responsible for 46% of the above equipment down-time and the loss of 8.8% of the ISIS scheduled user time. A breakdown of the figures amongst the different areas of the Injector, and between events of less than and greater than one hour's duration, are given in the following Table.

Events of duration:	All		< 1 hr		> 1 hr
Ion source	62.2 hrs		23.2 hrs		39.0 hrs
Source supplies	10.2		4.3		5.9
Cockcroft-Walton	0.7		0.7		0.0
Accelerating Column	7.0		7.0		0.0
Bouncer	2.5		0.3		2.2
Buncher cavity	0.9		0.9		0.0
Linac cavities	75.7		2.8		72.9
Modulators	25.1		10.7		14.4
RF systems	129.3		17.2		112.1
Magnet power supplies	4.7		3.7		1.0
Beam-line magnets	5.4		0.0		5.4
Debuncher	6.8		6.8		0.0
Cooling water	2.7		2.7		0.0
Beam-line vacuum	36.8		0.1		36.7
TOTAL	370.0 hrs	=	80.4 hrs	+	289.6 hrs

A large fraction (68%) of the Injector equipment down-time arose from a limited number of major events which are detailed below.

Ion Source: The 1992 ISIS scheduled operating time was divided into 7 operating cycles each of 3 to 4 weeks duration. During each cycle one change of ion source was normally required, accounting for 34 hrs down-time.

Linac Cavity RF Window: Tank No 3 suffered three consecutive failures of the cross-linked polystyrene rf vacuum window, at one week intervals, following a 4 year period without failure or change of window in this tank. Experience had shown that the only solution to this problem was to reduce the level of electron discharges by opening up the cavity to clean off all organic based coatings from the cavity and drift-tube surfaces. This process involved removal of the linac tunnel shielding roof, the cavity vacuum vessel lid and the upper half of the rf cavity. The work, including rf reconditioning the cavity, took about a week. This lost time does not appear in the statistics because it was accommodated by programme re-scheduling, but the window failures accounted for 73 hrs of down-time.

RF System Valve Changes: The 4 main rf systems including modulators contain a total of 20 thermionic valves. As yet it has not been possible to anticipate the end of life of any of these and hence valves are invariably replaced during operational periods, accounting for 62 hrs down-time in 1992. We have no test rig for the TH116 valve which has to be conditioned in use on the accelerator.

RF System Amplifier Circuit: The 4616 valve has always been a source of problems from parasitic oscillations, circuit breakdown and frequent re-tuning during valve ageing. Down-time of 24 hrs resulted from a single incident requiring the replacement of a grid-circuit, in which the tuning mechanism had suffered mechanical failure after a life of nearly 20 years.

RF System Coaxial Lines: Down-time of 23 hrs resulted from two failures of the cross-linked polystyrene support insulator in the 12" coaxial rf feed-line to one cavity. This has been a recurring problem, but only for the insulator closest to the cavity coupling loop, and is probably associated with sparking across the line in the vicinity of the loop. Evidence of such sparking is often found on inspection of the lines even though not detected during operation, but it does not always result in a failure.

Beam-line Vacuum: Beam operation closely following a period in which the 70 MeV beam-line had been at atmospheric pressure gave rise to 37 hrs lost time during which the beam-line had to be vacuum conditioned. Above normal pressure in the line caused beam loss due to stripping which in turn created further outgassing. This limited the permitted beam current for a considerable period.

Summary

The Injector has been under constant development over its operational life but it is only fairly recently that it has been able reliably to meet its full design specification. Many of the difficulties have arisen from the fact that the original accelerator was never designed for high mean intensity operation. Development work will continue, in particular to improve its reliability and also to achieve a higher pulsed output beam current.

Acknowledgement

This paper describes the work of a large number of past and present members of the Linac Group, together with other ISIS accelerator staff, to whom the author makes grateful acknowledgement.

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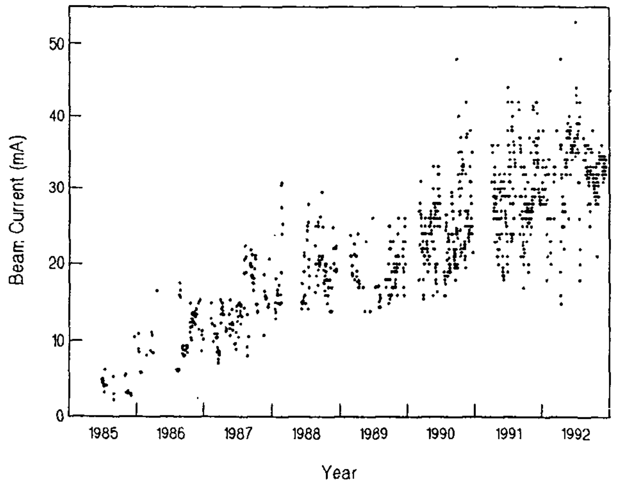

Fig 1 Pulsed current recorded from operational ion sources (at 665 keV).

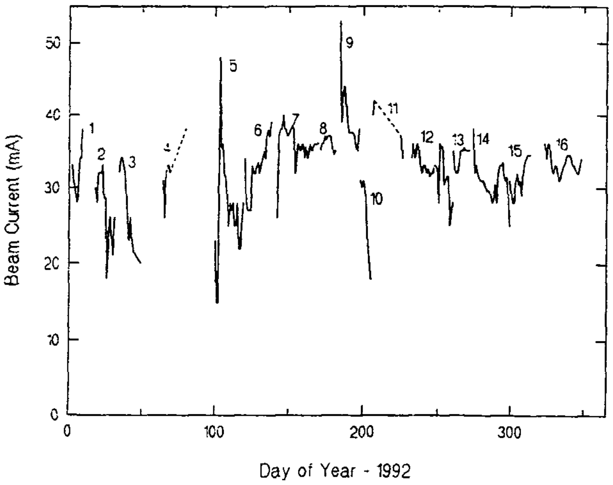

Fig 2 Record of current output from recent operational ion sources (at 665 keV).

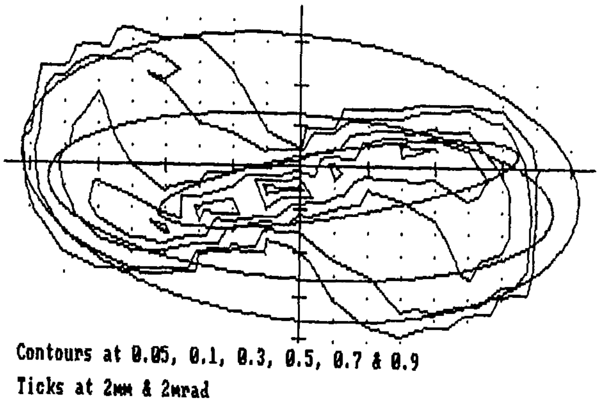

Fig 3a Emittance plot of 40 mA, 665 keV beam - H plane. (See text for detailed description)

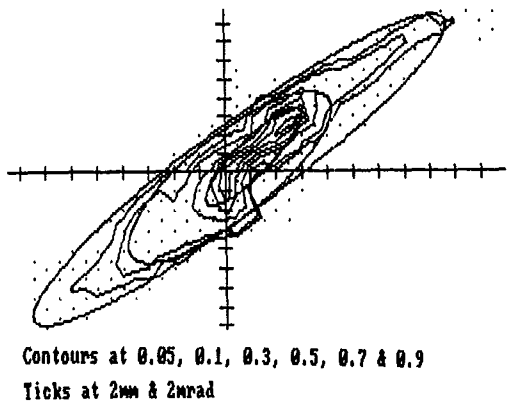

Fig 3b - V plane.

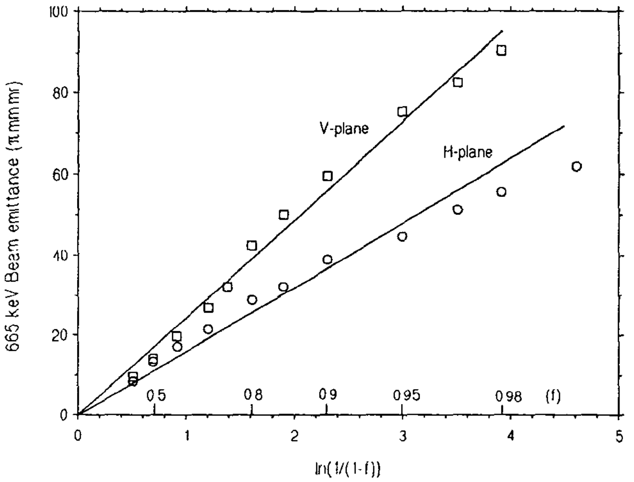

Fig 4 Emittance area of fitted ellipse as function of fractional beam enclosed (f), for beam of Fig 3.

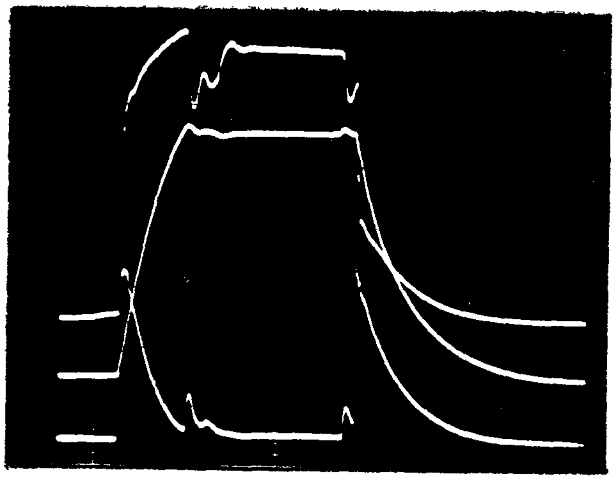

Fig 5 Cavity RF system oscilloscope pulses.

Top: Forward wave in cavity feed-line.
Middle: Cavity field level.
Bottom: Reflected wave in cavity feedline.