Aspects of Beam Stability on ISIS

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Features of ISIS Synchrotron

1. Ceramic vacuum chambers with profiled rf shields

2. Localised momentum beam loss collection

3. Large 120 by 40 mm^2 Al_2O_3 stripping foils

4. Separated, anti-correlated H-V injection painting

5. Fast programming of the betatron tunes

6. Linear lattice with no sextupoles or octupoles

7. Ionisation beam loss monitors for display and protection

8. R, C loading for 6 rf cavities

9. Feed-forward compensation for rf beam loading

10. Procedures for hands-on-maintenance and active handling

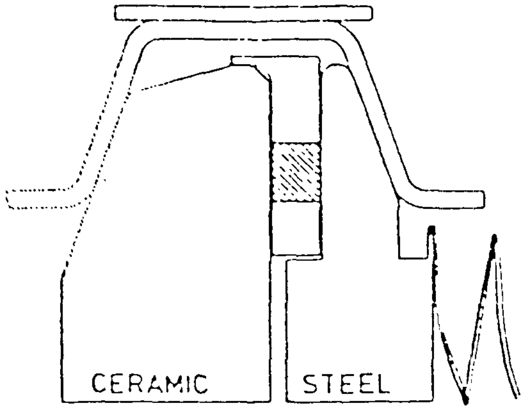


FIG 1·10
DEMOUNTABLE JOINT (FULL SIZE) SHOWING FLANGES, T-SEAL, AND V-BAND

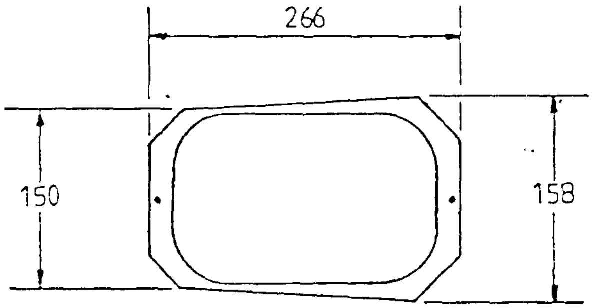


FIG 1·11
CROSS SECTION OF DIPOLE CHAMBER

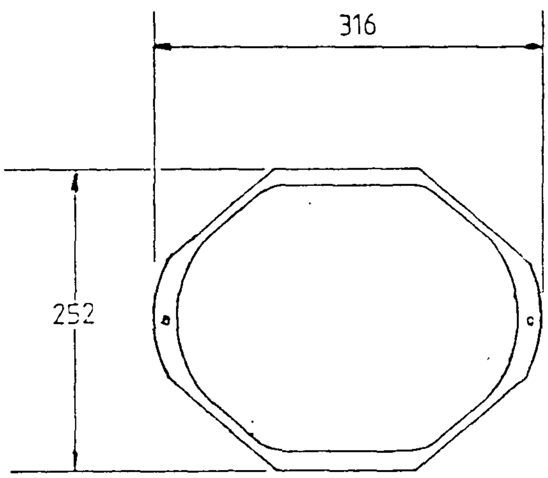
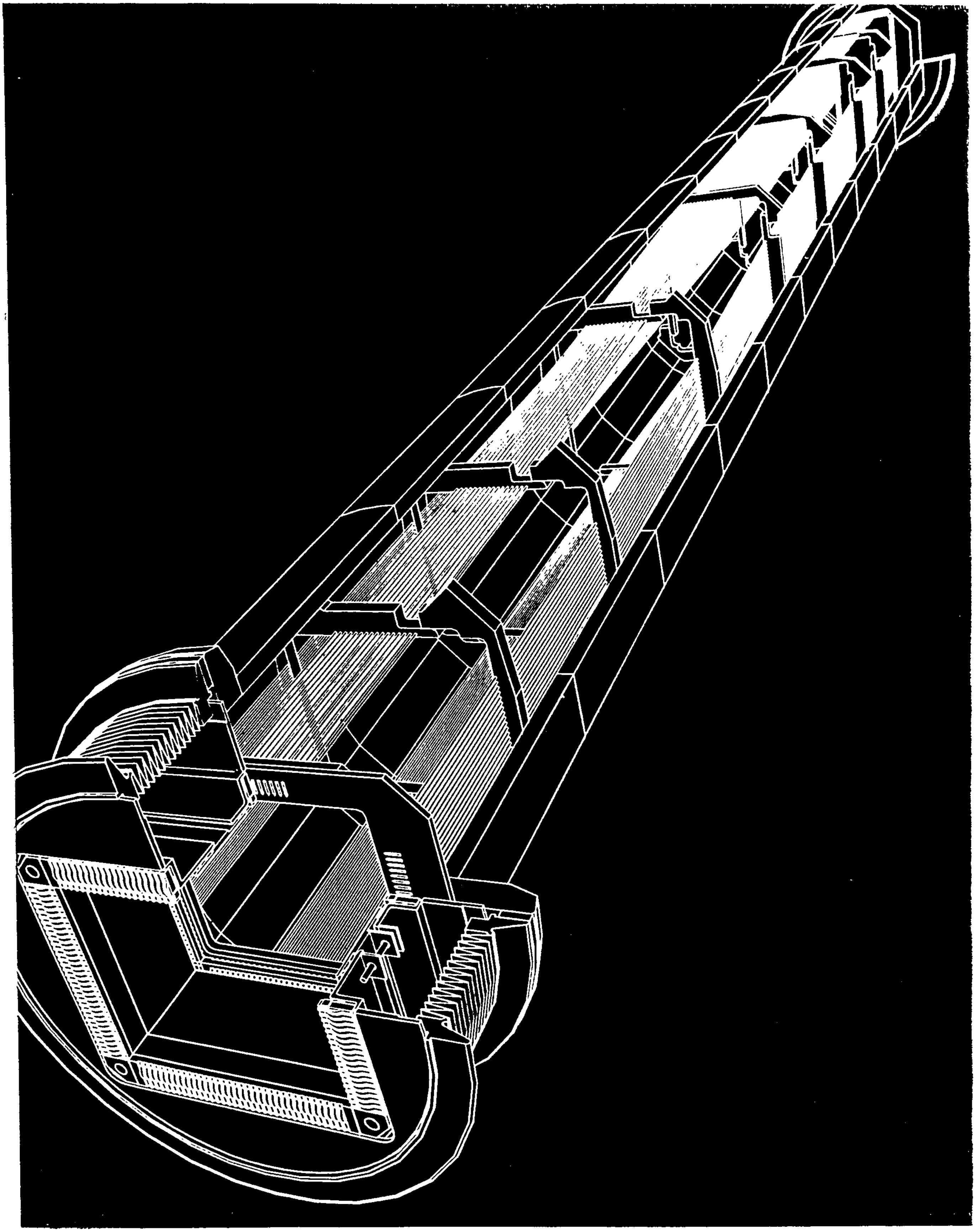
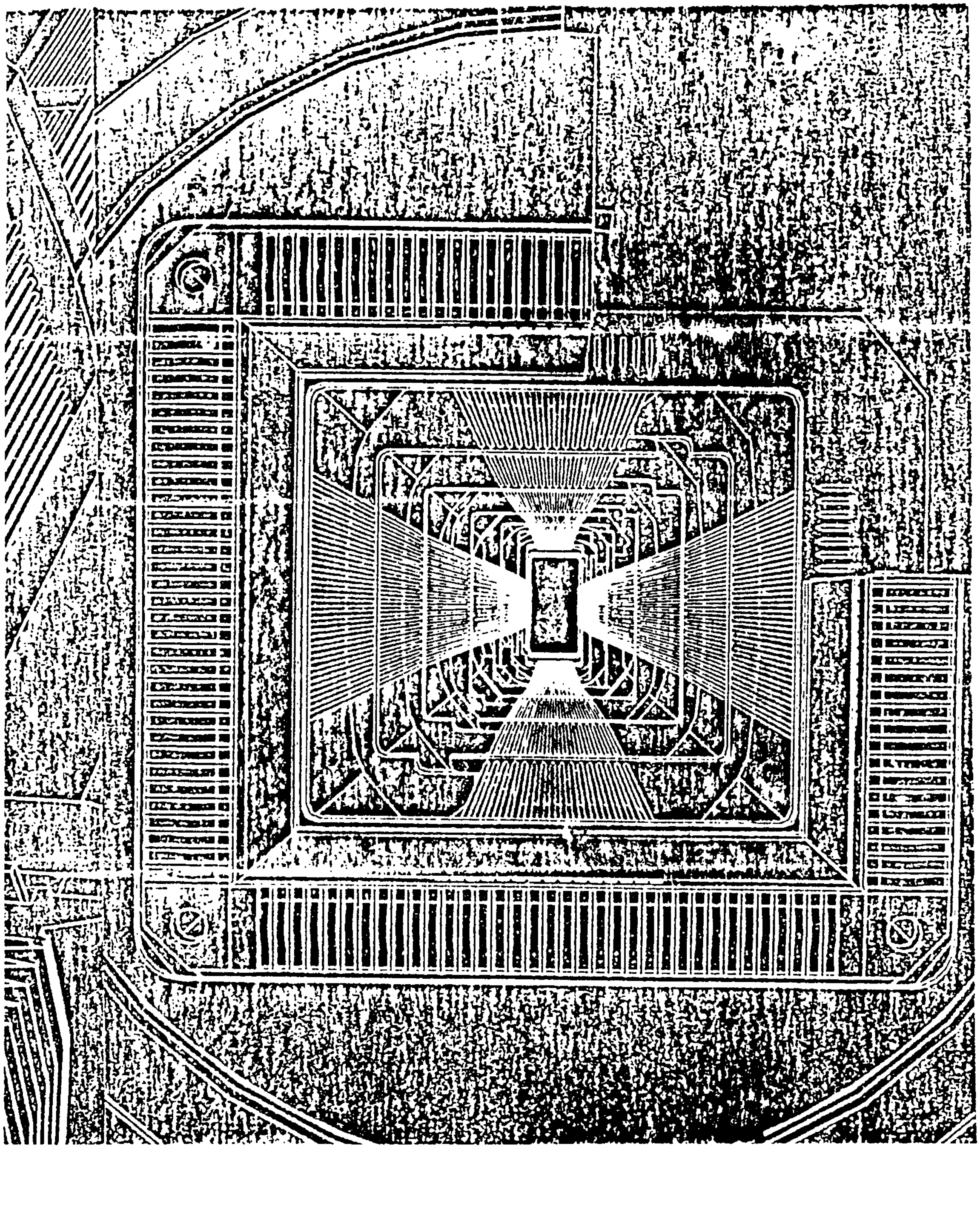


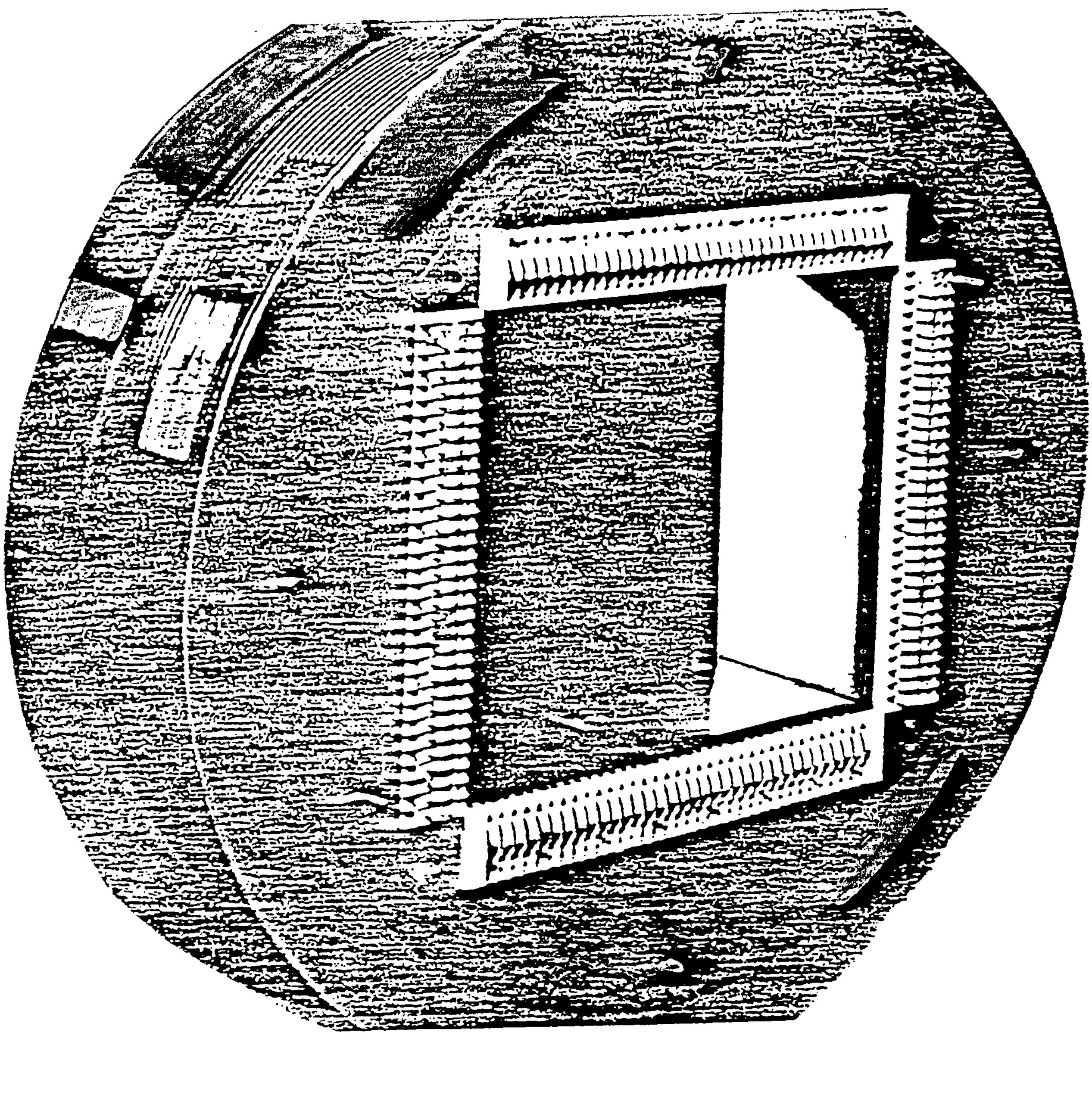
FIG 1·12
CROSS SECTION OF DOUBLET QUADRUPOLE CHAMBER



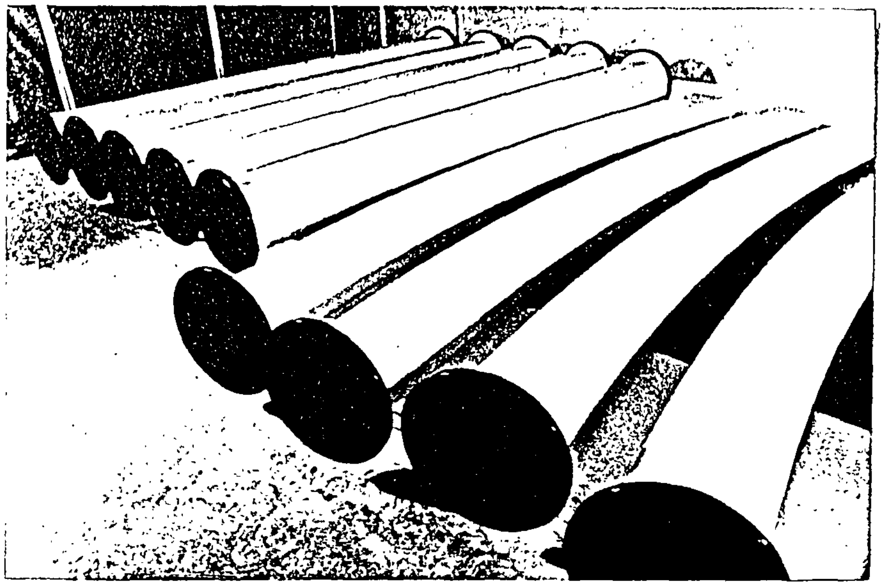
QUADRUPOLE CHAMBER SHIELD



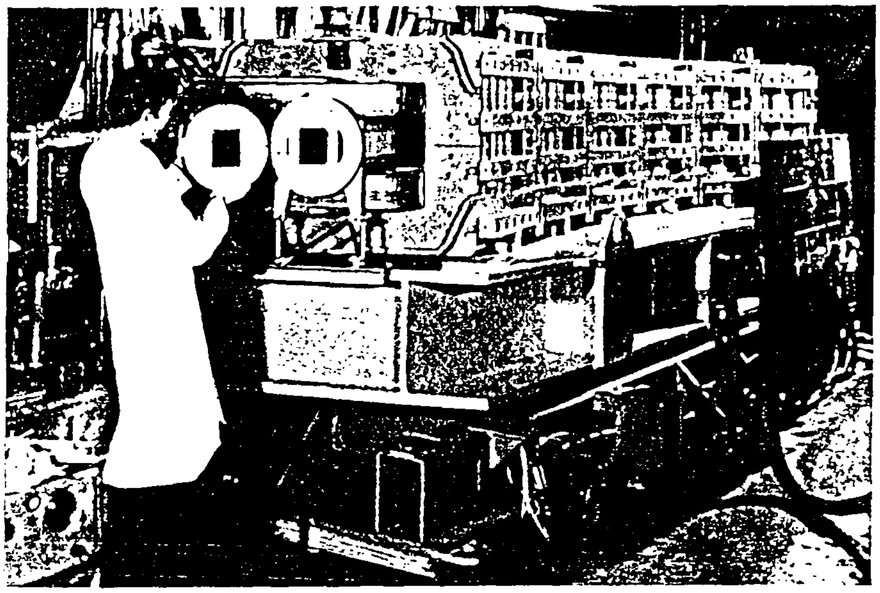
Profiled Quadrupole Wire RF Shield



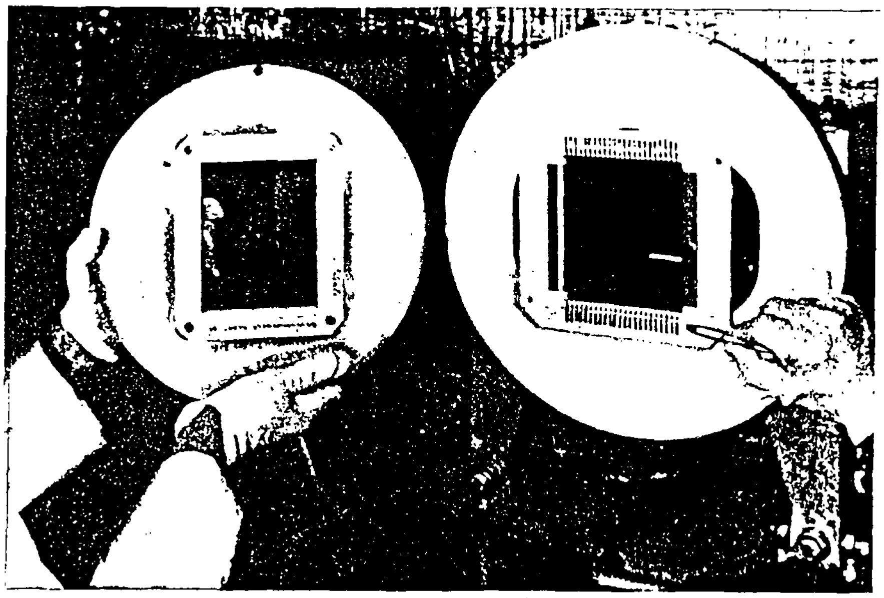
Shielded ISIS Bellows Section



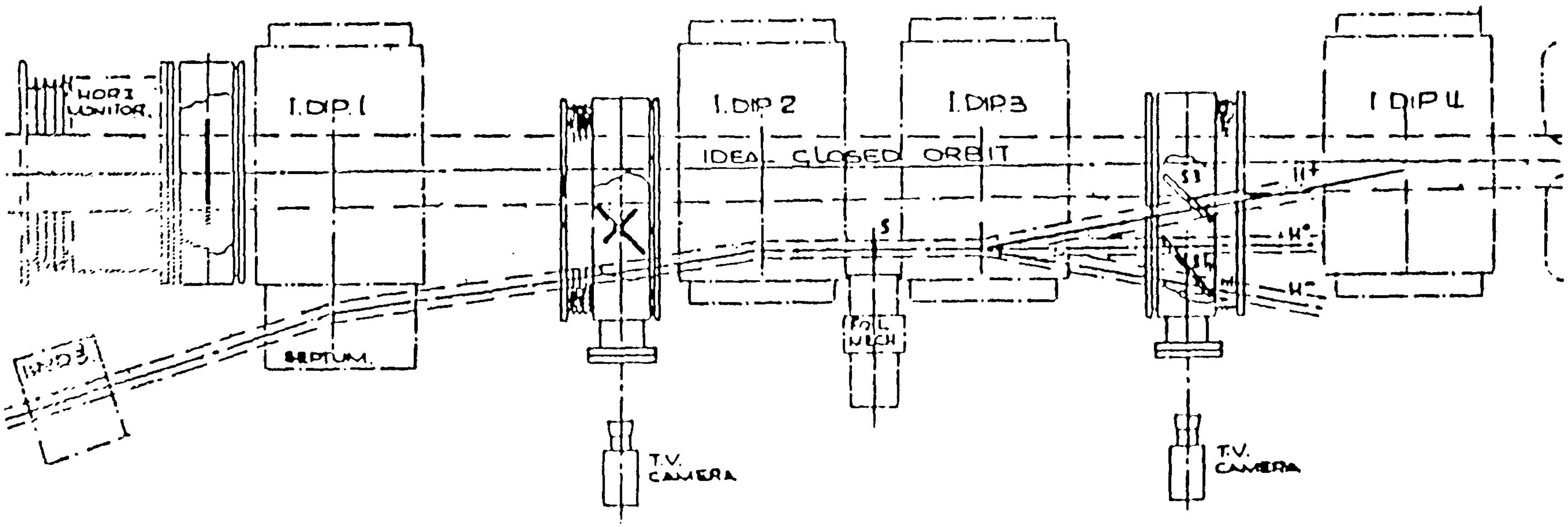
Photograph 4   Ceramic Vacuum Chambers



Photograph 5   Ceramic Chamber in Bending Magnet



Photograph 6   RF Shield in Ceramic Chamber



Separated Anti Correlated H-V Injection Painting

ISIS Beam Stability Topics

1. Longitudinal coasting beam resistive wall - not observed

2. Longitudinal bunched beam - not observed in normal operation

3. Transverse coasting beam resistive wall - cured by lowering Q_v

4. Transverse bunched beam head-tail - cured by ramping Q_v

5. Electron-proton - not observed throughout 70 to 800 MeV

Coasting Beam Longitudinal Motion

Operation above Keil-Schnell Instability Threshold

Profiled vacuum chamber wall, following beam

Z/n (70 MeV)	$\sim 700\ \Omega$
Z/n (without profiling)	$1000\ \Omega$
$\Delta p/p$	$\sim \pm\ 2\ 10^{-3}$

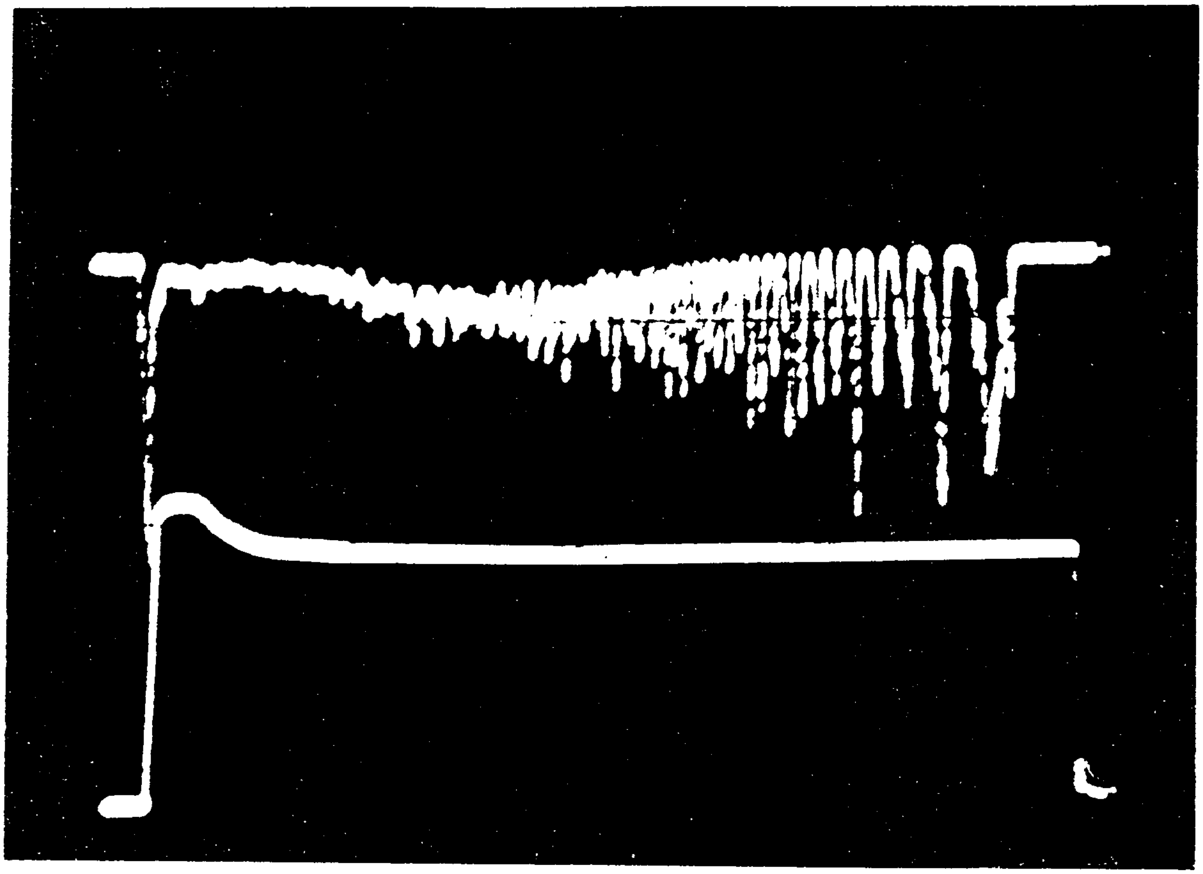
Observations of residue of linac bunch structure

Fast longitudinal monitor $\rightarrow$ spectrum analyzer

Analogue output for 202.5 MHz (or harmonics)

Rapid debunching of linac bunches $< 50\ \mu s$

Debunching of 202.5 MHz Residual Linac Bunch Structure



Upper trace: Spectrum Analyzer Analogue Output Signal

Initial peak: Debunching of residual linac bunch structure

Later peaks: 202.5 MHz harmonics of circulating bunches

(non-equilibrium distributions)

Interpretation of Coasting Beam Longitudinal Stability

Rapid debunching of residual linac bunch structure

Instability infers pairs of sideband frequencies :

$$A \cos(nw+p)t + B \cos(nw-p)t$$

Derivatives of frequencies for longitudinal space charge forces :

$$(B-A)\ nw \cos nwt \sin pt - (B+A)\ p \sin nwt \sin pt + ...$$

First term: zero for symmetrical bunches, when B = A

Second term: antidamping above γ_t, damping below γ_t

In agreement with observations of debunching

For $Z_\perp = R$, one sideband damps, one antidamps

No net effect, provided growth time > oscillation period

Control of Longitudinal Bunched Beam Motion

Cavity voltage and resonant frequency control loops

Beam radial and phase control loops

Quadrupole mode feedback (needed if tuning errors)

Feed-forward compensation with one turn delay -0.4 to 2 ms

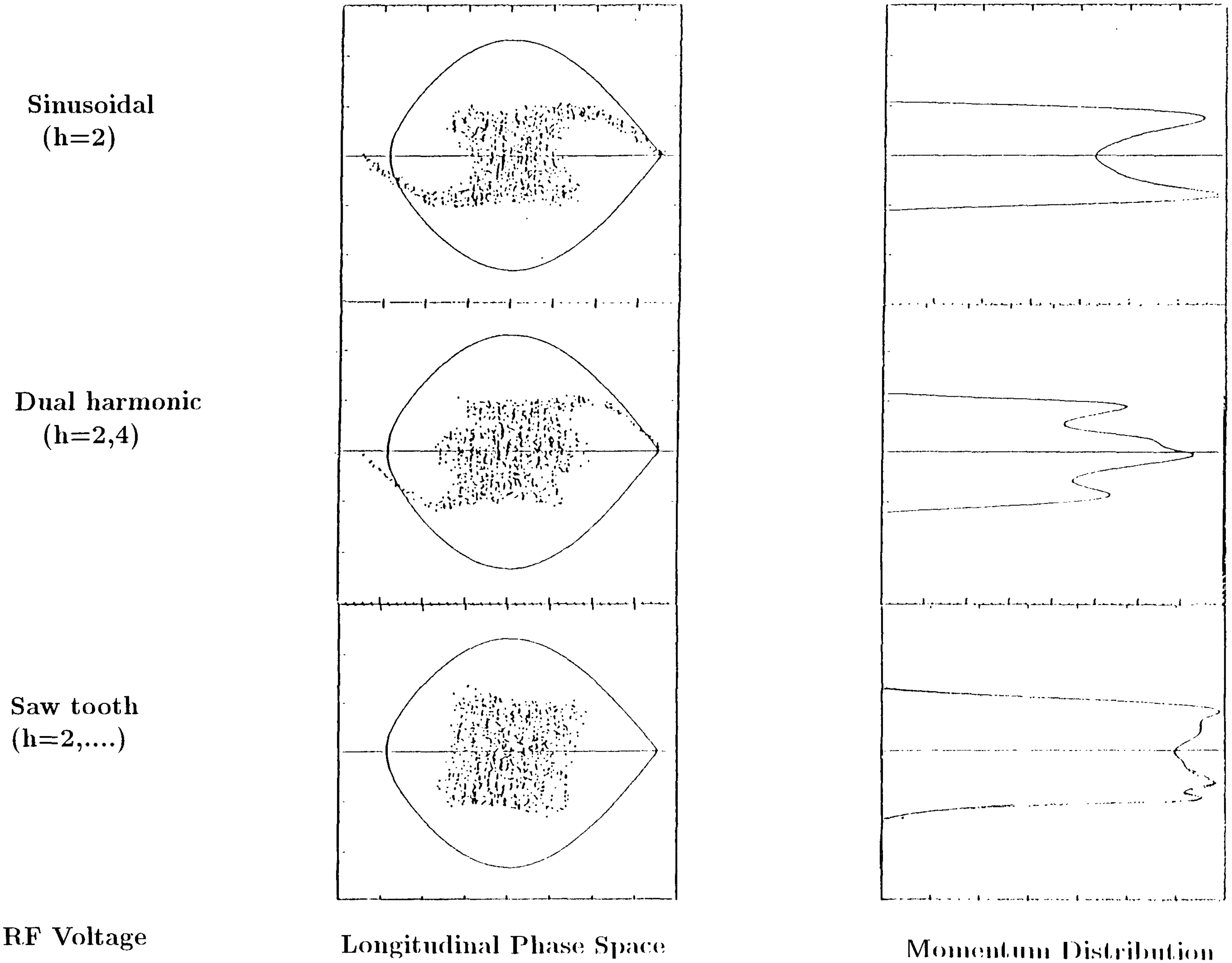
Cavity tuning for resonance with drive frequency for -0.4 to 2 ms

for reactive beam loading compensation 2 to 10 ms

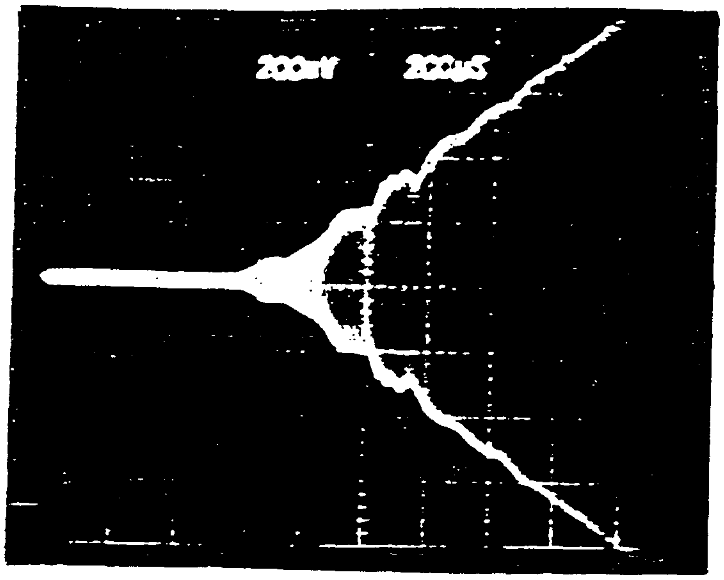
Voltage waveform	(kV)	0	3	60	144	100
	(ms)	-0.3	-0.2	1.0	5.0	10.0

Trapping loss ($2.5\ 10^{12}$ ppp) $\sim$ 6%

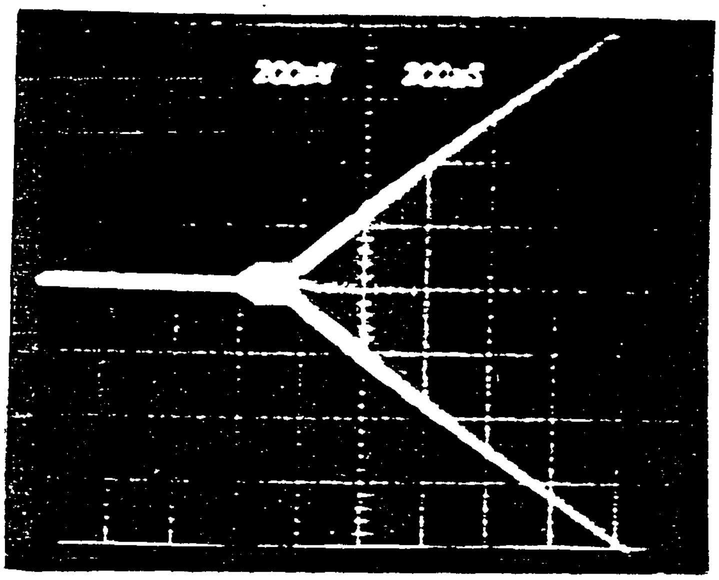
($2.5\ 10^{13}$ ppp) $\sim$ 11%


Sinusoidal
(h=2)
Dual harmonic
(h=2,4)
Saw tooth
(h=2,....)
RF Voltage
Longitudinal Phase Space
Momentum Distribution

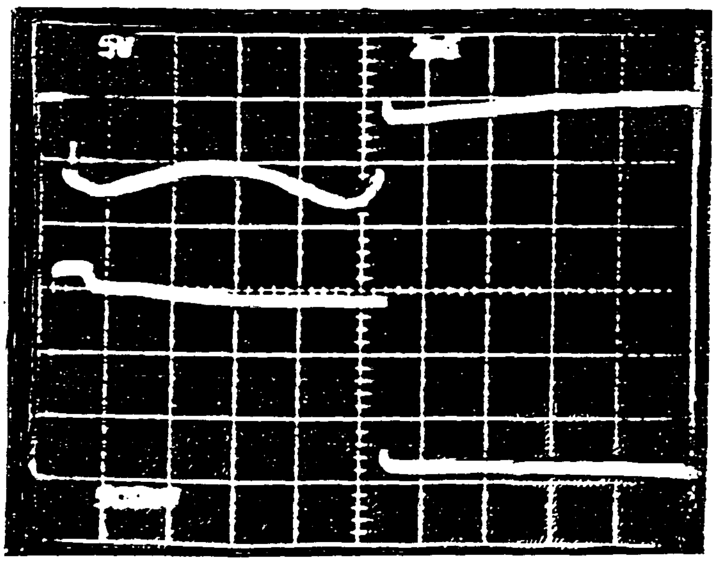
No Feed -forward



Beam Feed-forward



Beam Intensity



Vertical Coasting Beam Resistive Wall Instability

Storage ring mode maximum intensity (10^{13})	4.0
Linac 70 MeV injected beam (mA, μs)	16, 410
Stripping and injection losses (%)	2.5
Vertical tune instability threshold	>3.73
Mode frequency at $Q_v = 3.8$ (kHz)	130
Coasting beam mode ($m - Q_v$)	4-Q_v
Profiled vacuum chamber wall	S/S
Frequency for shield thickness of 1 skin depth (kHz)	140
Approximate growth time of instability (ms)	2.1

Aspects of (4-Q_v) Coasting Beam Instability

At 4 10^{13}, (4-Q_v) instability appears for $Q_v \geq 3.73$

RF shield wire diameter equals skin depth for (4 - 3.78) w_0

Profiling of shield reduces $Z_\perp = j \frac{RZ_0}{\beta^2\gamma^2} \left(\frac{1}{a^2} - \frac{1}{b^2}\right)$

Operation above stability threshold for wide range of modes

Beam more stable than expected, only (4-Q_v) observed

Chromatic tune spread (natural ξ)	$\pm$	0.01
Incoherent ΔQ spread for 4 10^{13}	$\sim$	0.2
Coherent ΔQ shift for 4 10^{3}	$\sim$	-0.05

Absence of (4-Q_v) Instability for Normal Operation

Unchopped injected beam ($\sim$ 150 turns)

Sinewave fall of guide field (near B min)

Injected beam intensity (ppp) $\sim 2.9\ 10^{13}$

RF on during or just after injection interval

No (4-Q_v) instability observed

Trim quadrupoles ramped for constant injection tunes

Vertical tune higher than for storage ring operation

RF and associated chromatic effects may inhibit (n-Q_v) modes

Vertical Head-Tail Instability at ISIS

Interval (ms)	0 - 2	2 - 4	4 - 10
	stable	unstable	stable

Head-tail chromatic phase shift at 3 ms, $\Delta\psi = 2.8\ \pi$

Expected/observed head-tail mode (m) : 2 (never seen) / 1

Cured by ramping Q_v over 2 to 4 ms, $\Delta Q = -0.12$

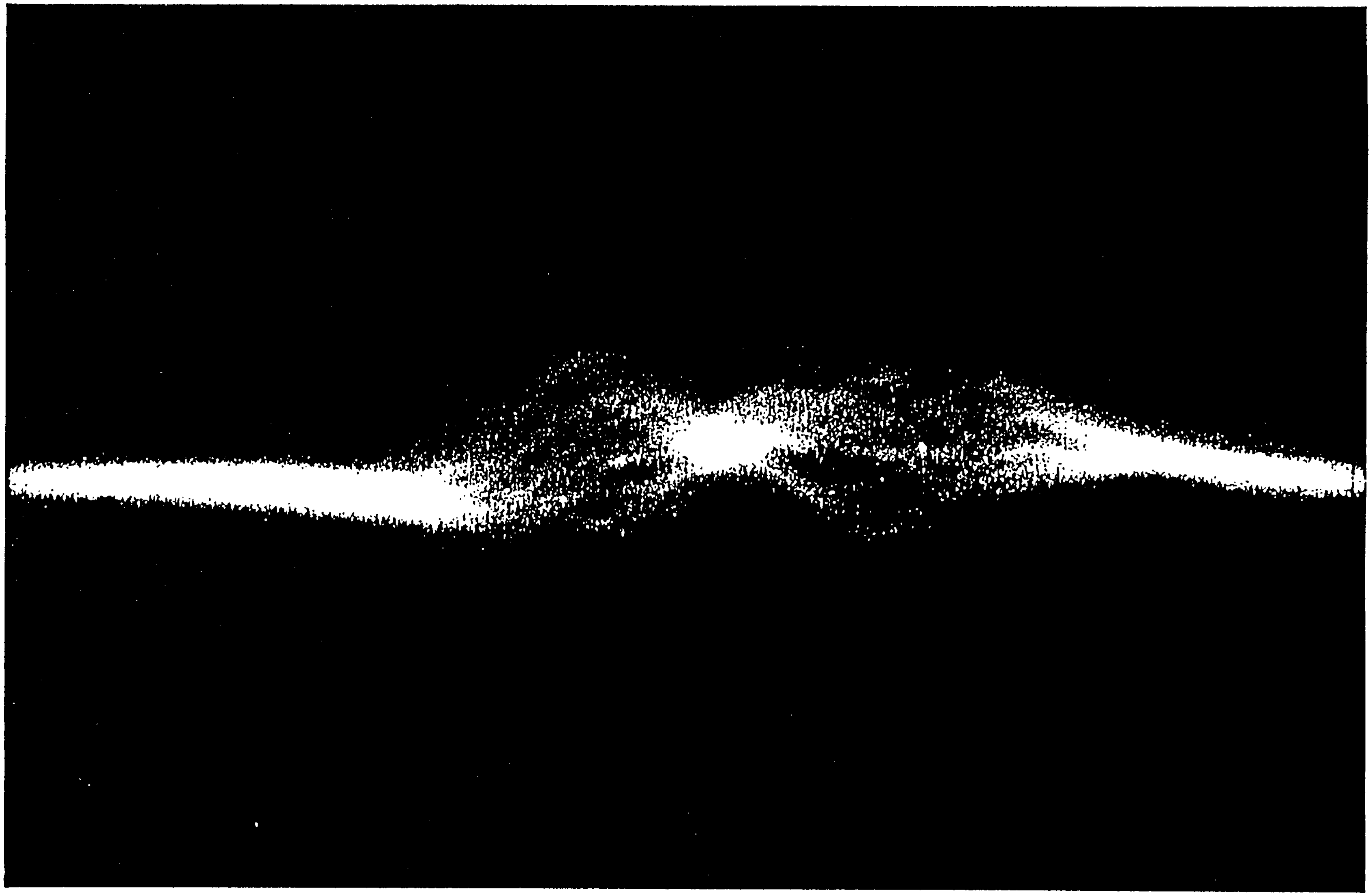
Natural negative value of chromaticity, $\xi = -1.2$

Wall resistances unequal at separated sidebands, $(n \mp Q_v)\ w_0$

Unusual form for the head-tail instability

Largest forces at some low n sidebands , $(n + Q_v)$

$|\xi|$ has to be reduced for largest forces at $(4 - Q_v)$



Vertical resistive-wall head-tail instability,
mode $m = 1$

FEATURES OF ISIS m=1 HEAD TAIL INSTABILITY

Head - tail phase shift $\Delta\psi = 2.8\ \pi$

Expected mode (never seen) $m = 2$

Cancellation for coherent betatron mode at bunch centre :

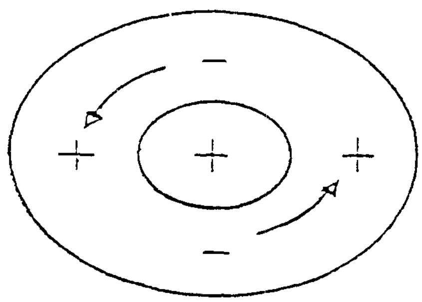
(a) Between $+\Delta$ p and $-\Delta$ p particles ; traditional theory.

(b) Between small and large phase oscillation particles -

Large ϕ : antidamped at head and tail, damped at ℄.

Small ϕ : antidamped directly.

Explains how all particles may be anti-damped.

Head  Tail

Electron-Proton Instability Comparison with PSR

	PSR	ISIS
Bunched beam threshold (10^{13})	3.5	? (>2.7)
Unbunched beam threshold (10^{13})	0.8	? (>4.0)
Energy range (MeV)	800	70-800
Unbunched transverse resistive wall	No	Yes, Q_v=3.8
Vacuum chamber	S/S	S/S, ceramic, wires
Unbunched N/C (10^{11} m^{-1})	0.9	2.5-1.6
Unbunched N/Cε (10^{17} m^{-2})	0.13	0.05-0.13
Bunched N/BC (10^{11} m^{-1})	11.4	5.3-8.2
Bunched N/BCε (10^{17} m^{-2})	1.63	0.11-0.5

Features of ISIS and PSR Rings (Coasting Beam)

	PSR	ISIS
Ring circumference (m)	90.2	163.4
Injection energy (MeV)	800	70
Trans acceptances ($\pi\mu$rm)	200,140	520,420
Trans rms emittances ($\pi\mu$rm)	7,13	50.0
Max protons per pulse (10^{13})	0.8	4.0
Vacuum chambers	un-profiled	profiled
Bellows sections	un-shielded	shielded *
Stripped electron collection	no	yes
Frequency of rf system	linac sub-harmonic	adjustable
Voltage for rf system	marginal	sufficient
Extraction kickers	transm line (50Ω)	lumped (7 Ω) ground plane *
Instability	e-p	resistive wall ($Q_v \rightarrow 3.8$)

Electron Trapping in Proton Potential Well

V	=	g λ (unbunched beam)	
λ	=	charge/unit length	
λ(ISIS)/λ(PSR)	=	5 * 90.2 / 163.4	= 2.76
g(ISIS)/g(PSR)	=	$\sim$ 1.7 / 3.4	= 0.5 (average)
g(ISIS)/g(PSR)	=	$\sim$ 1.7 / 5.1	= 0.333 (peak)
V(ISIS)/V(PSR)	=	$\sim$ 0.92	

Larger potential well for trapped electrons in PSR

Effect in unshielded bellows may be larger than estimate