Impedance Issues in the CERN SPS

T.Linnecar,
CERN, Geneva, Switzerland

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- Hadron beams in the SPS
  - past and present results
  - future requirements
- Problems expected
- Identifying the source
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- Other solutions and conclusions

Past and present results

- Total intensity
  - 10^{13} in 1977 ➔ 4.84×10^{13} in 1997
- Single bunch intensity
  - 2×10^{8} in 1977 ➔ 1.6×10^{11} in 1980 's

To do this:

Constant fight against instabilities.

Examples:

- Damping of 2 HOM passbands in main TW cavities in 1st two years operation,
  - longitudinal 628MHz, transverse 460MHz
- Single bunch crossing transition: $\leq 2 \times 10^{10}$/ bunch
  - negative mass and head-tail instabilities
  - ppbar → inject (26 GeV) above transition ($\gamma_{tr} = 23.4$)
- Single-turn, long delay, RF feedback for main passband TW cavities → $\geq 3 \times 10^{13}$
- Short-delay RF feedback and single-turn around 352 MHz SC cavities. GΩ → 100k Ω / cavity @ f_s

Future Requirements

Two main projects with high intensity needs:

- **SPS as injector for LHC** (underway)
- **Neutrino beam to Gran Sasso** (under study)

other ? disappearance
appearance
732Km τ neutrino

Beam parameters:

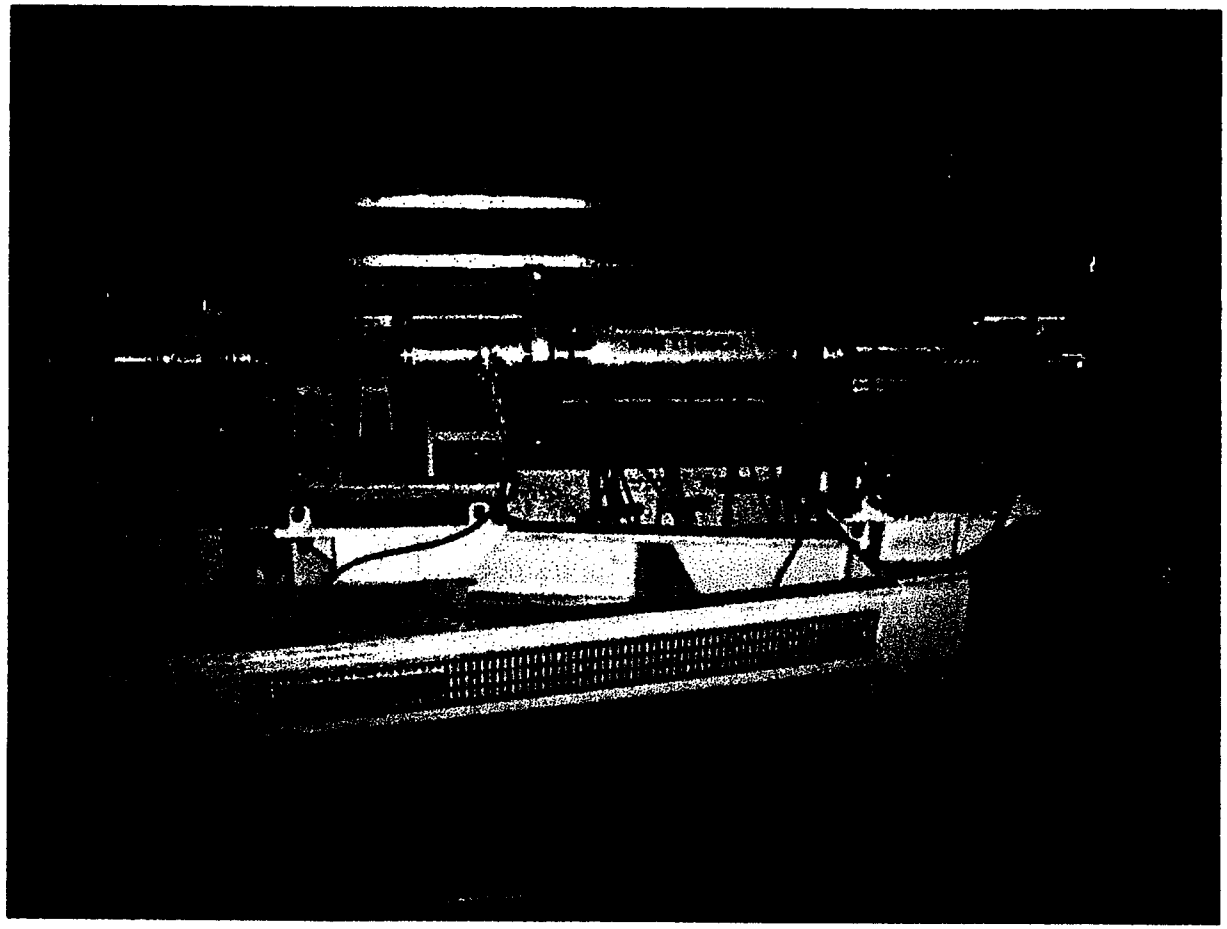
Operating Mode	Energy inj., top (GeV)	Total N (x 10^{12})	Bunch N (x 10^{10})	Batch I (A)	ε_l inj., top (eVs)	$\varepsilon_{H,V}$ top (μm)
Ppbar Collider (past)	26,315	0.2	20		0.6, 0.8	2.8, 2.8
Fixed target (present)	14, 450	48.4	1	0.33	0.2, 2	10,7
SPS for LHC (project)	26, 450	24	11-17	0.7-1.1	0.35, 0.6–1	3.5, 3.5 (3.0 at inj.)
Gran Sasso (under study)	14, 400	>70	2	0.5	0.2, < 2	10,10

Comments on beam parameters:

- **SPS for LHC**
  - single bunch intensity ~ ppbar
  - total intensity ~ 1/2 fixed target
  - batch intensities ~ 2 x fixed target
  - long emittance < 1/2 fixed target (but 1eVs would need new RF system in the LHC
  - transverse blow-up allowed < 15%
- **Gran Sasso**
  - total intensity ~ 2 x fixed target
  - emittance less important but must avoid micro losses during acceleration and extraction.

Problems expected

- **Single bunch - longitudinal**
  - fixed target: 1976, vac. chamber discontinuities in → μwave instability. Bunch into bucket transfer → install new 200 MHz RF in PS, injector.
  - Ppbar: 1980+, μwave limited N_b at injection. Longer, bigger bunches → install 100 MHz RF in SPS.
  - SPS for LHC: → Present knowledge of impedances suggests 4ns, 0.35 eVs bunch with 1.1(1.7)x 10^{11} protons may be unstable due to μwave.
- **Single bunch - transverse**
  - SPS for LHC: Lowest mode head-tail instability, higher modes OK? (Landau damping from frequency spread.)



Typical short straight section.

In the SPS: 6 LSS, (inj., ext. RF, etc.), 216 SSS, (correctors, BPM, etc.)

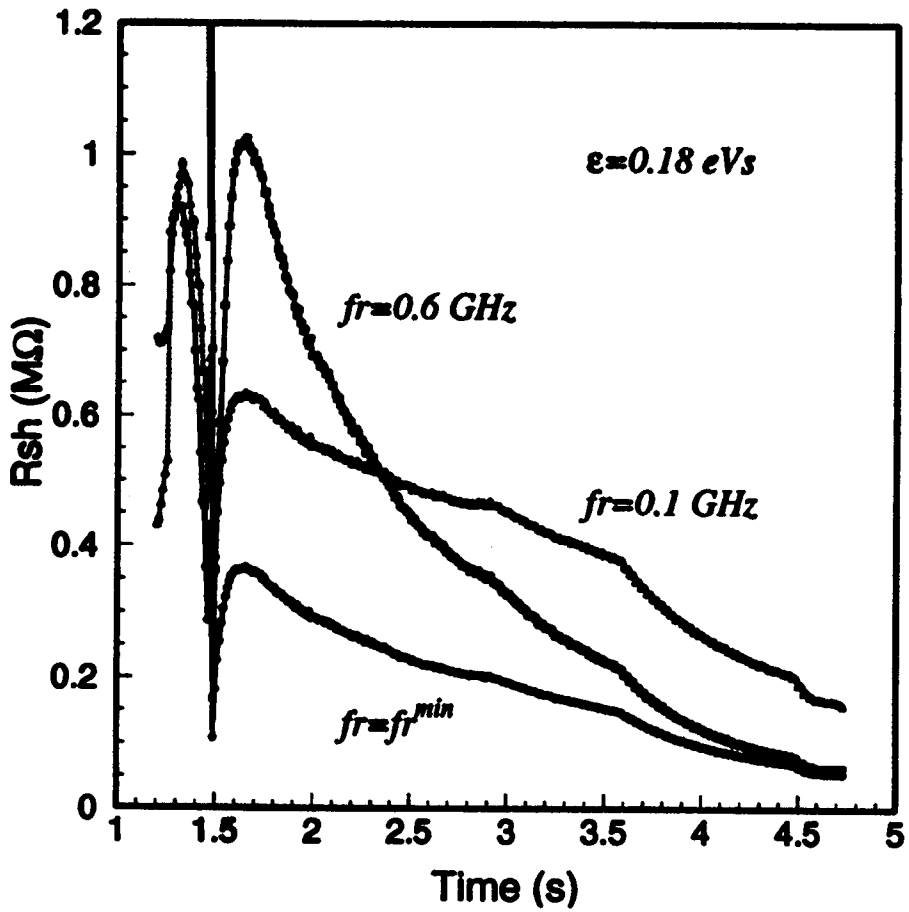
5 main vacuum chamber types (but many others as well)

$$R_{sh} < \frac{|\eta| E}{e I_0} \left(\frac{\Delta p}{p}\right)^2 \frac{\Delta \omega_s}{\omega_s} \frac{F}{f_0 \tau} x\, G(x)$$

- **Multi-bunch - longitudinal**

$x\, G(x) = x \min\{ J_m^2(\ldots) \}$

  - Studies on normal fixed target and batch type beams
  - Emittances at 445 GeV for 4 x 10^{13} ~ 2 eVs (with LHC transfer voltage - lower with programmed voltage)
  - Bunch intensity dominant parameter for emittance blow-up. Some influence from gap ➔ wakefield over several bunches
  - Spectrum of unstable modes - sometimes lines but generally broad spectrum filling space between bunch spacing frequency lines.
  - Beam unstable already for N > 4 x 10^{12} . More unstable as energy increases.
  - **Coupled bunch instabilities!**



Coupled bunch instability threshold during normal operation in fixed target cycle for a beam intensity 4.2 x 10^{13} and different resonant frequencies f_r

For any f_r the threshold decreases as energy increases.

Threshold curves for different f_r can cross.

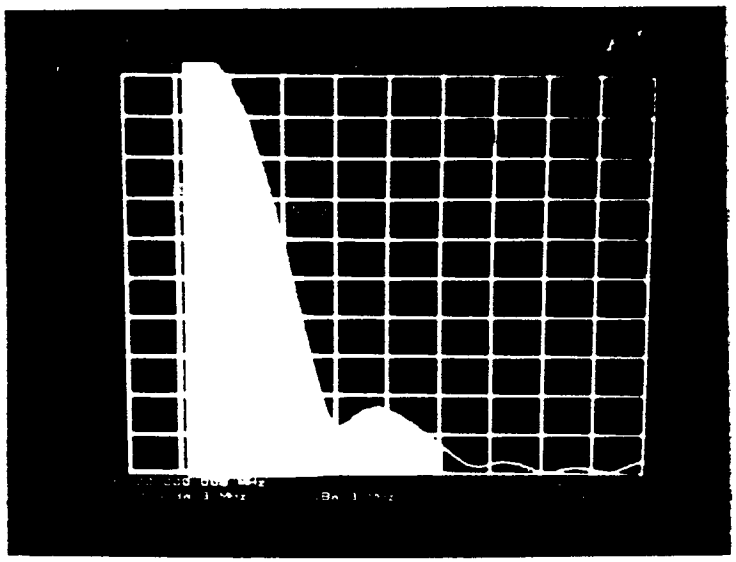
E.Shaposhnikova

- **Multi-bunch transverse**
  - Modes with high mode numbers - several HOMs in different RF cavities damped, others?
  - Resistive wall instability of concern. Batch studies show that risetimes of modes and the most dangerous mode number is modified by batch structure of beam.

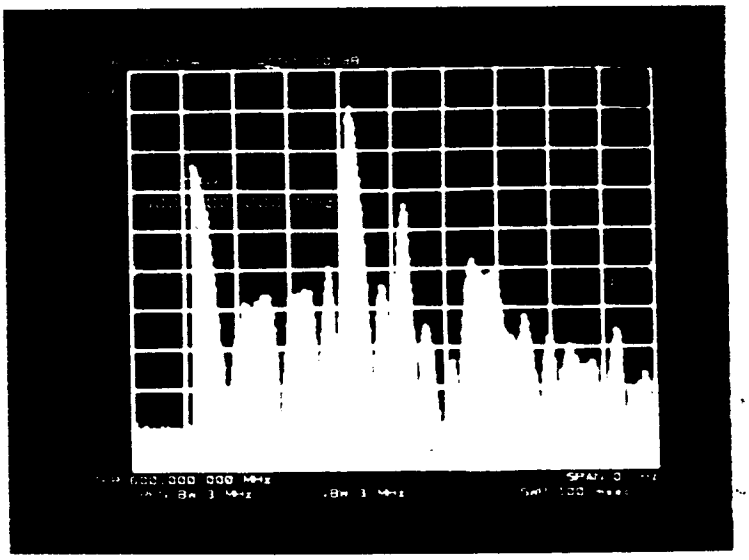
What are the sources of all these instabilities?

Identifying the sources

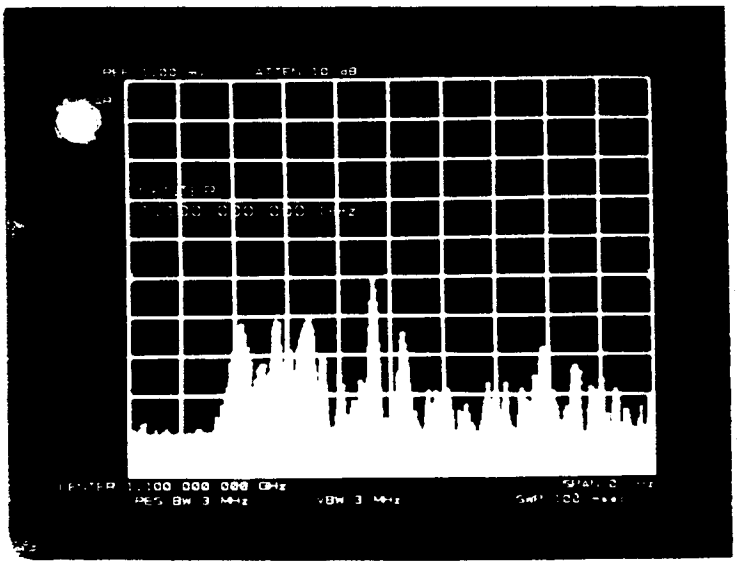
- **Impedances leading to single bunch instabilities**
- Broad-band impedance model
  - Threshold intensities
    - τ_b variation of captured bunch as f(N)
    - observation of high frequency signals
  - Low frequency inductive part
    - bunch lengthening
    - change in debunching time
- For the SPS the broad-band model is far from reality
  → prediction by scaling difficult for future operation
  → better model contains a number of resonant peaks.



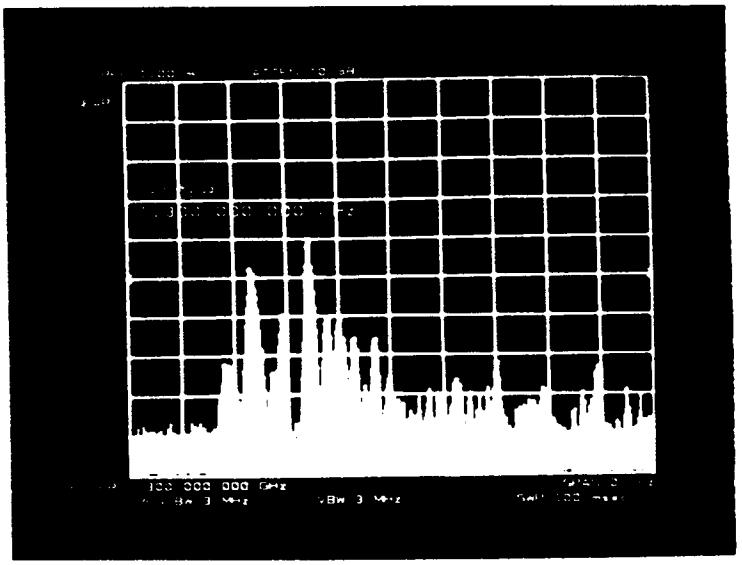
100 MHz



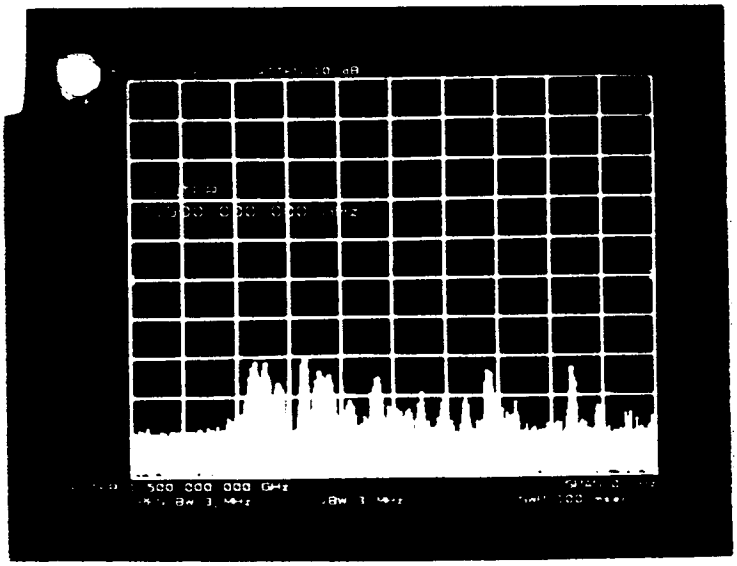
600 MHz



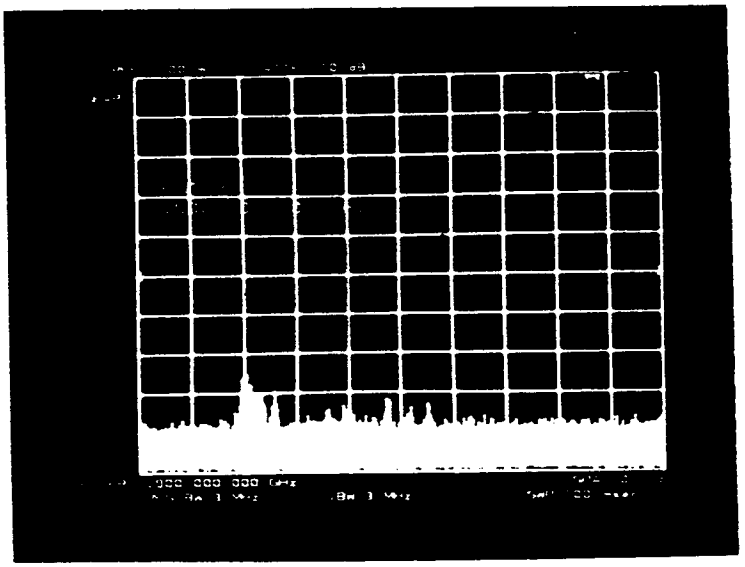
1.1 GHz



1.3 GHz



1.5 GHz



1.9 GHz

RF off

$\tau = 5ns$

Signals from spectrum analyzer

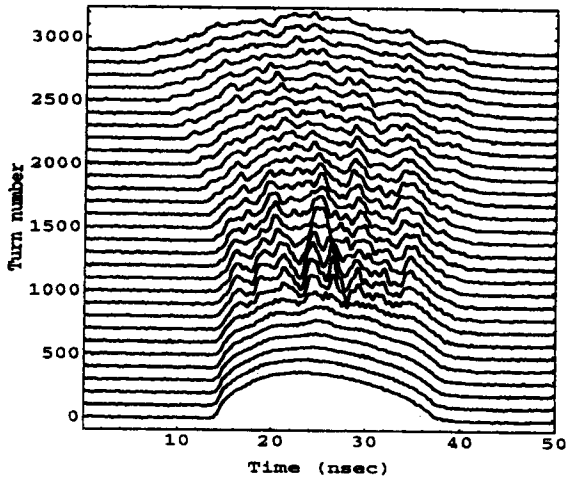
$\Delta f = 3MH$

Measuring the spectrum of unstable modes

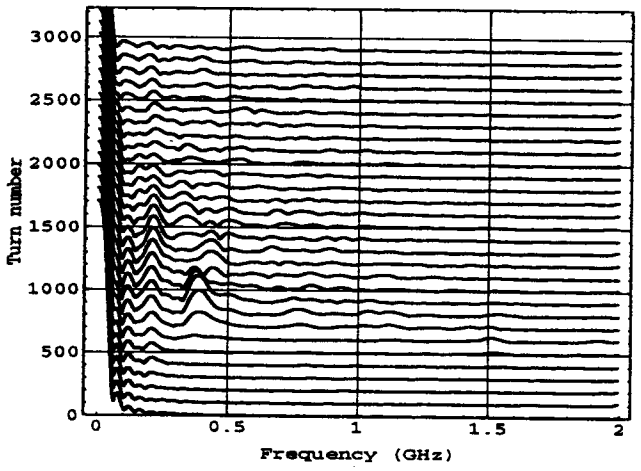
- Inject single, high intensity bunches above threshold into the machine with RF off
- Different resonant impedances →modulation of line density at resonant frequencies
- Observe spectrum during slow debunching. → η and $\Delta p/p$
- Record maximum amplitude observed as a function of frequency. At each point average of many (10) bunches.
- Unstable bunch spectrum centred at f_r, bandwidth $\Delta f_{spect} \sim 1/\tau_b$, hence <u>long bunches</u> → fine structure .
- Exact saturation formula unknown. Simulation shows that for $\Delta f_r < 1/\tau_b$, max. amplitude is f(R_{sh}/Q and N)
- Analyse data
  - spectrum analyser, res. 3 MHz, scan 100 MHz to 4 GHz
  - digital scope and then FFT. Sampling gives data to 2 GHz

Fourier analysis of longitudinal bunch profiles

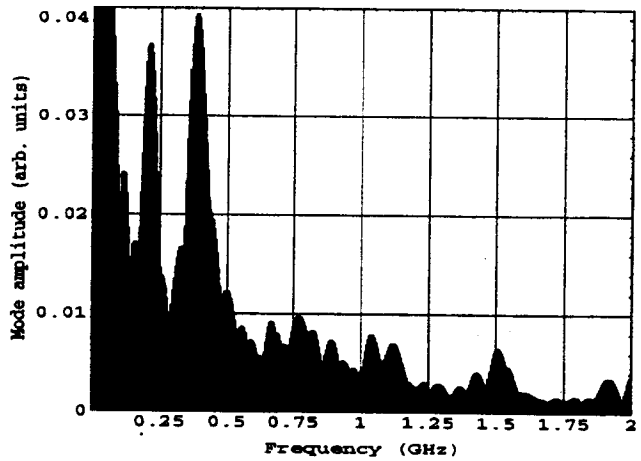
Mountain range in time domain



Mountain range in frequency domain

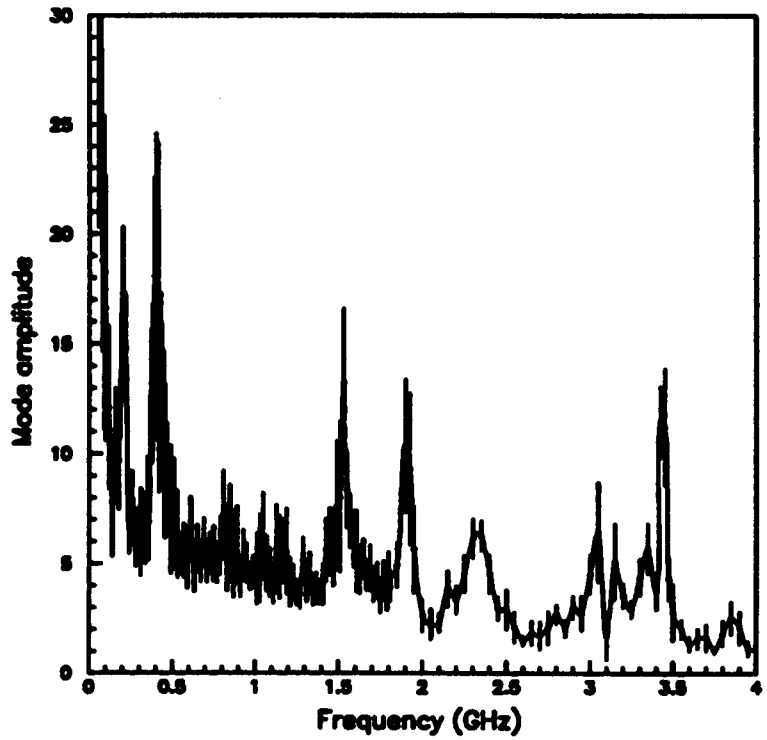


Projection of frequency spectrum



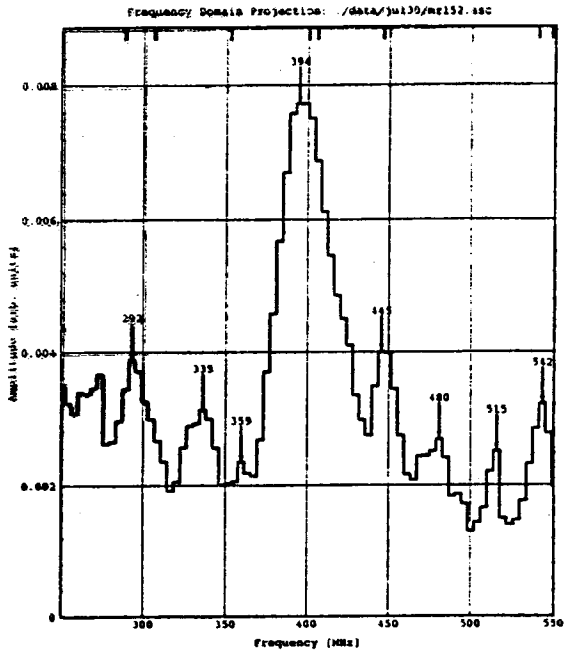
$$\mathrm{Im}(\Omega) = \omega_r \left(\frac{N e^2 \omega_0 |\eta| \frac{R_{sh}}{Q}}{16\pi E_0} \right)^{\frac{1}{2}}$$

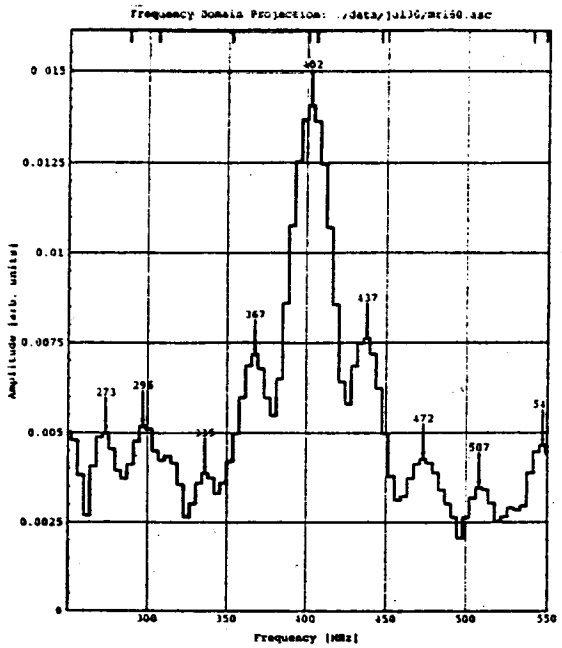
2×10^{10}



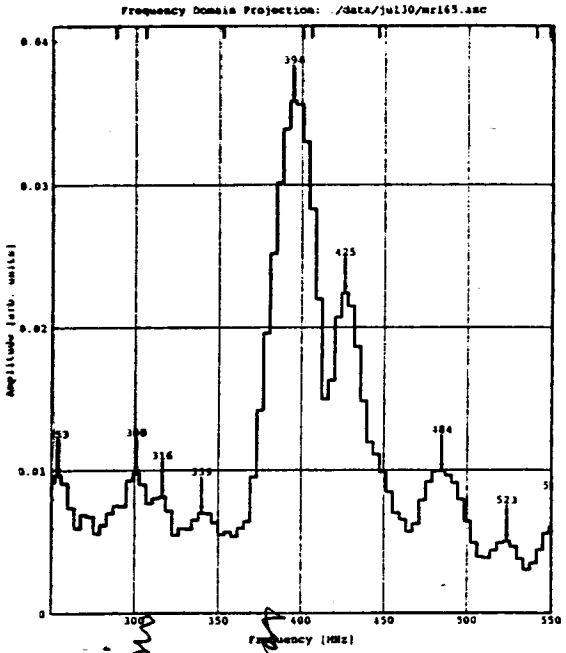
Measured spectrum of unstable modes.

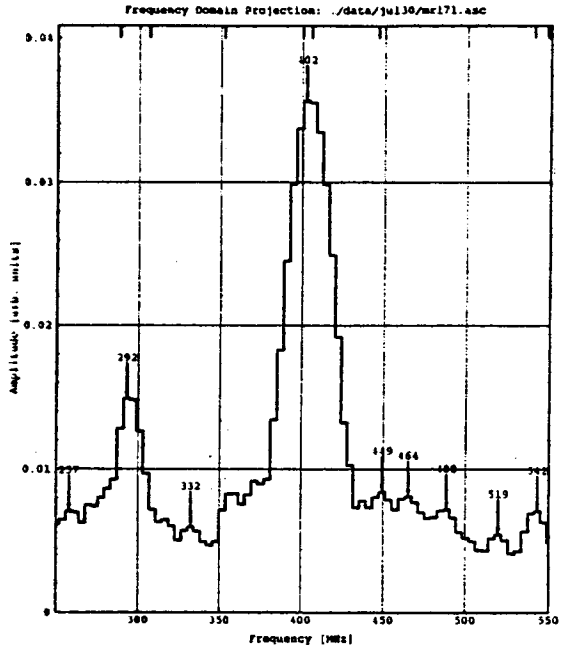
Experimental parameters: E = 26 GeV, $\eta = 5.26 \times 10^{-4}$, $\varepsilon_l = 0.25$ eVs, $\tau_{deb} = 80$ ms, saturation time ~ 50 ms, $\tau_b = 25$ ns

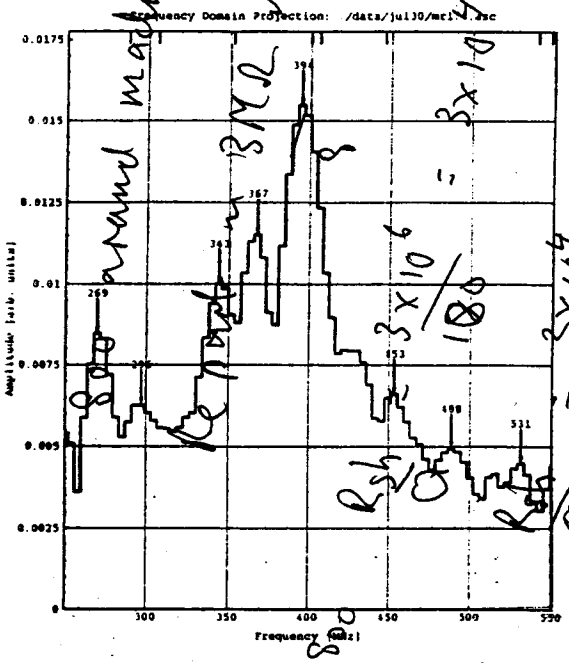


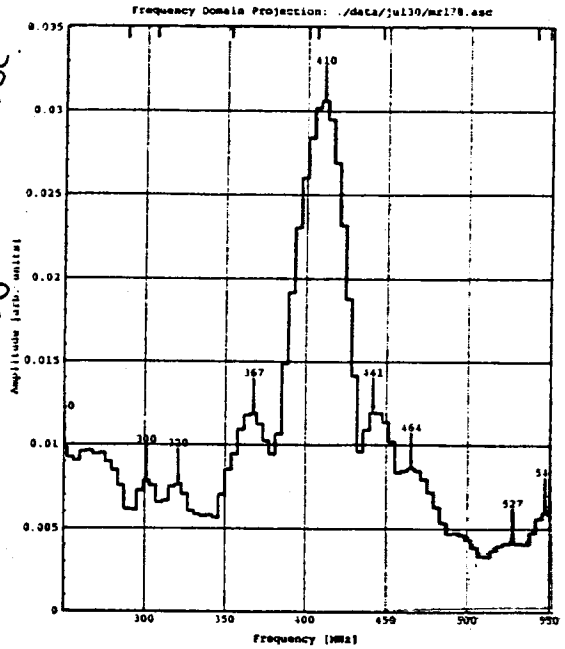


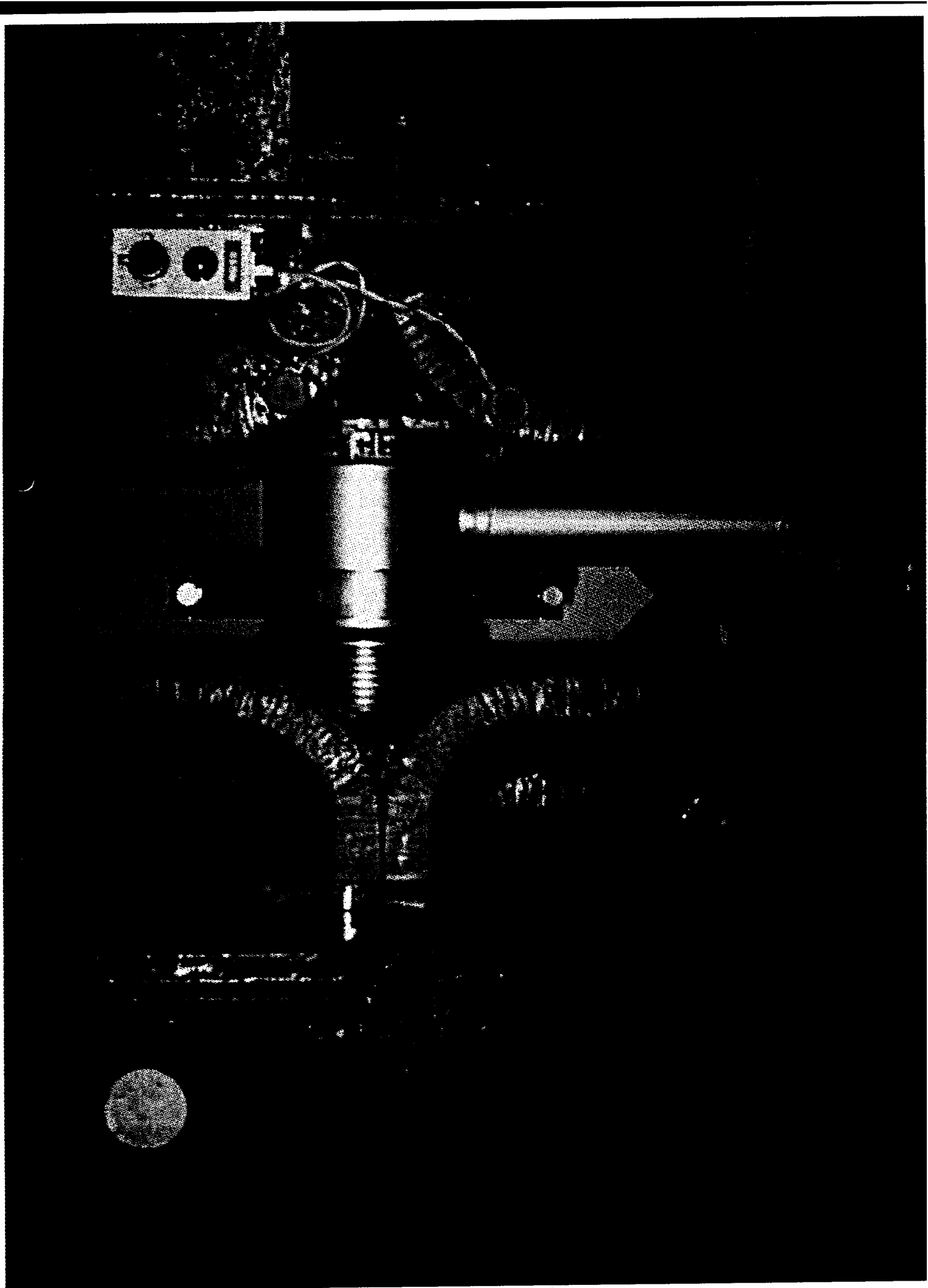
$N \sim 2 \times 10^{10}$

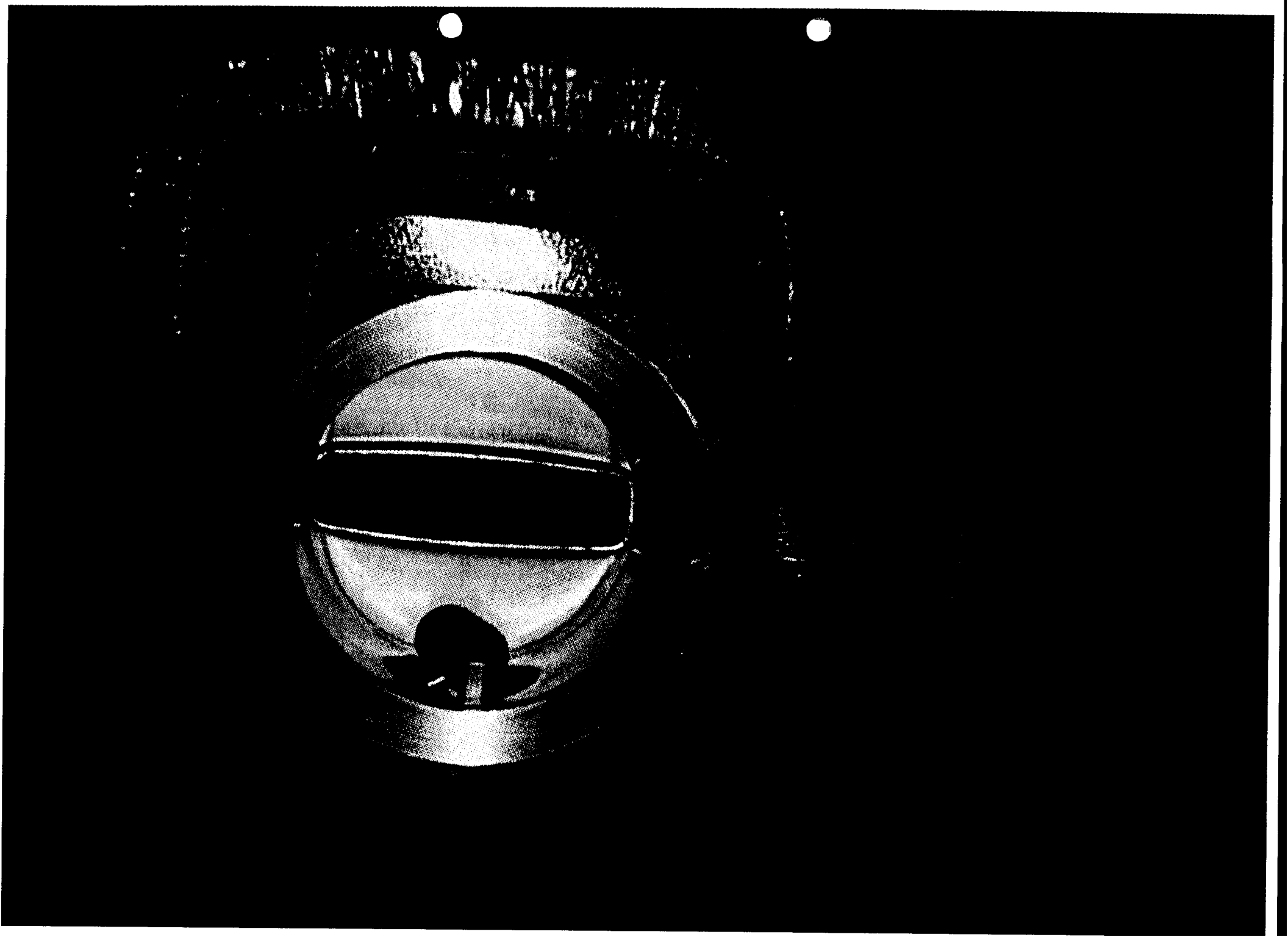












From spectrum of unstable modes:

- Dominant sources identified:
  - 200 MHz, 800 MHz RF fundamental
  - 400 MHz magnetic septa (MSE)
  - > 1.4 GHz, vacuum ports

- Using sources identified, with their R_{sh}/Q and Q found from calculations or measurement → simulations of bunch lengthening give close agreement with experimental results

- It seems model is good even if we are still missing 10% impedance

- **Impedances leading to multi-bunch instabilities**

- Less progress, so far, than with single bunch instability sources.
- Experimental indications of
  - Longitudinal source in range 900 MHz to 1200 MHz, maybe next passband of 200 MHz TW cavities
  - Also pumping ports may be possible longitudinal source at high energies.
- Instability spectrum is broad-band, not easy to interpret. Methods to analyse spectra are being investigated. (E. Shaposhnikova - this workshop.)

- In the transverse plane resistive wall impedance - source well known.

- High frequency modes in the cavities up to ~1 GHz measured and damped

- Pumping port transverse modes also calculated - no problem expected

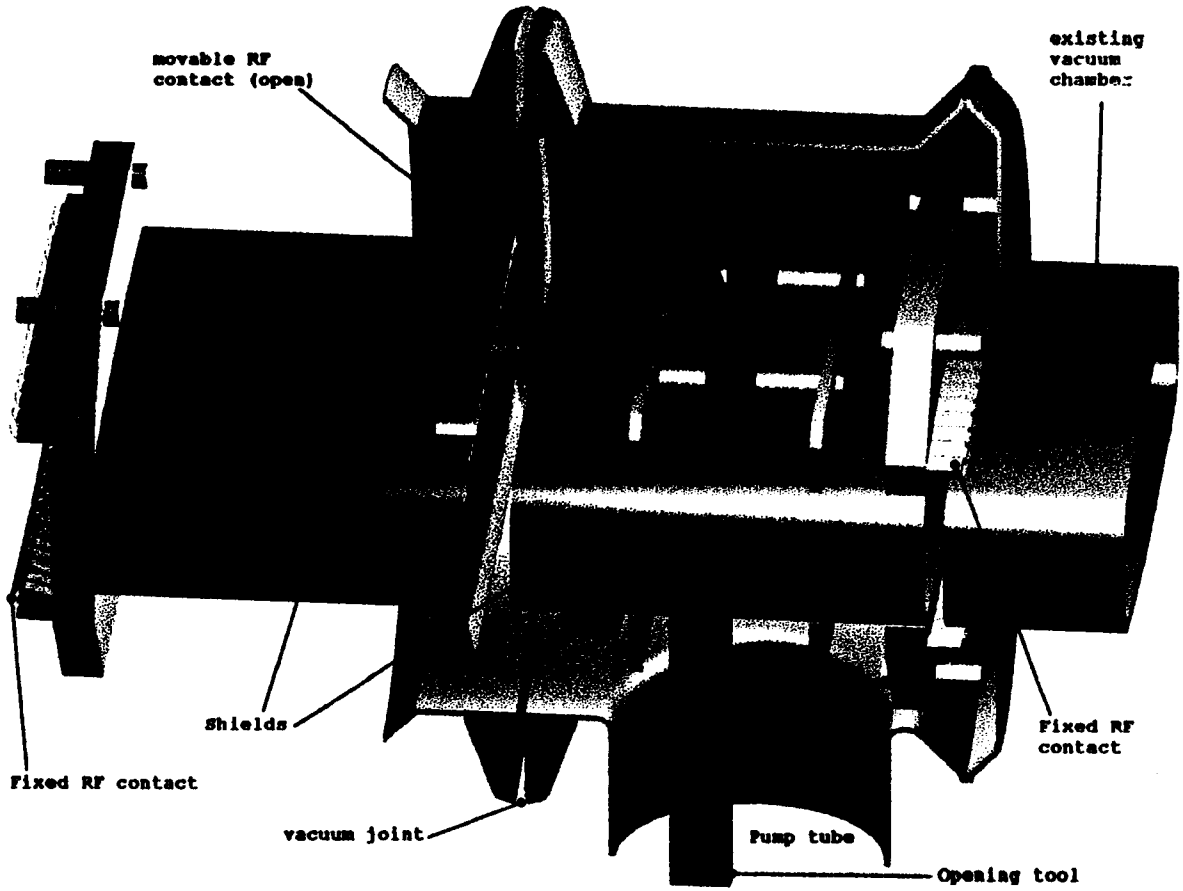
Summary of known impedance sources in the CERN SPS

Source	Freq. Range GHz	Comment
HOM in RF cavities	0.1 – 1.109 0.286 – 1.14 0.912 – 2.78	25 long. Modes damped 25 trans. Modes damped 13 modes seen, undamped
Pumping ports	1.39 – 4.23	Max. long R_{sh}/Q at 1.55, 1.91, 2.14, 2.96 GHz
400 MHz band, MSE septa	0.343 - 0.49	16 septa installed now, 8 coming later

What are we doing about it?

- Elements with high R_{sh}/Q
  - Screening of pumping ports
  - Screening of septa
- Elements with high R_{sh}
  - Damping
  - Removal of unused elements

A. Spinks at NX



Pumping port screening, cut-away view

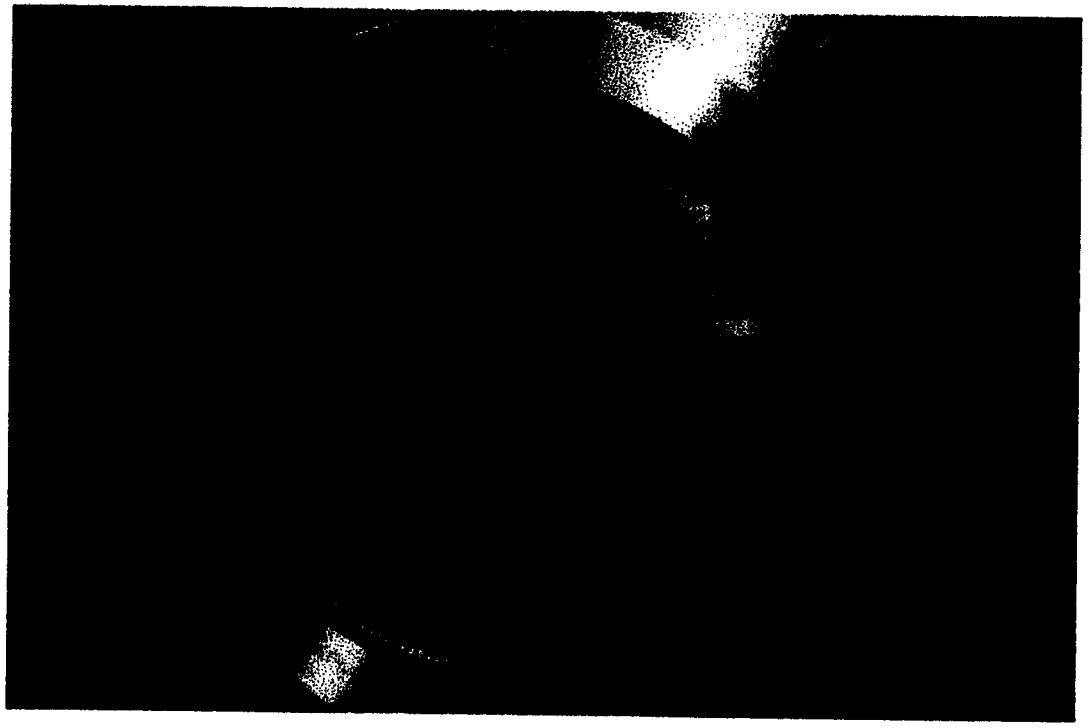
Critical points in design:

- Easy to install and align. One out of two dipole magnets (300) in the machine have to be removed - remainder in SSS
- Moveable RF contacts in centre to allow separation and removal of magnet in future. Tool to operate mechanism. Flexibility to take up angle and position errors.
- Pump-down time and residual pressure should not change significantly. Pumping holes near side good for longitudinal modes, attention transverse!
- Shielding at GHz frequencies must be good. RF contacts in the centre and at the ends - uneven weld.

Prototypes being manufactured. Installation over two long shutdowns.

10 dB reduction

A. Riggio et al.



RF screen, covering half of $\phi = 28$ cm circumference fitted along 2.67 m chamber.

Steel sheet with $\phi = 6$ mm holes

Damping resistors, floating, installed at each end.

<u>RF shield in the magnetic septum vacuum tank</u>.
Prototype installed in ring last year - no temp. effects. 8 septa screened last shutdown - remainder next shut down

Elements with high R_{sh}

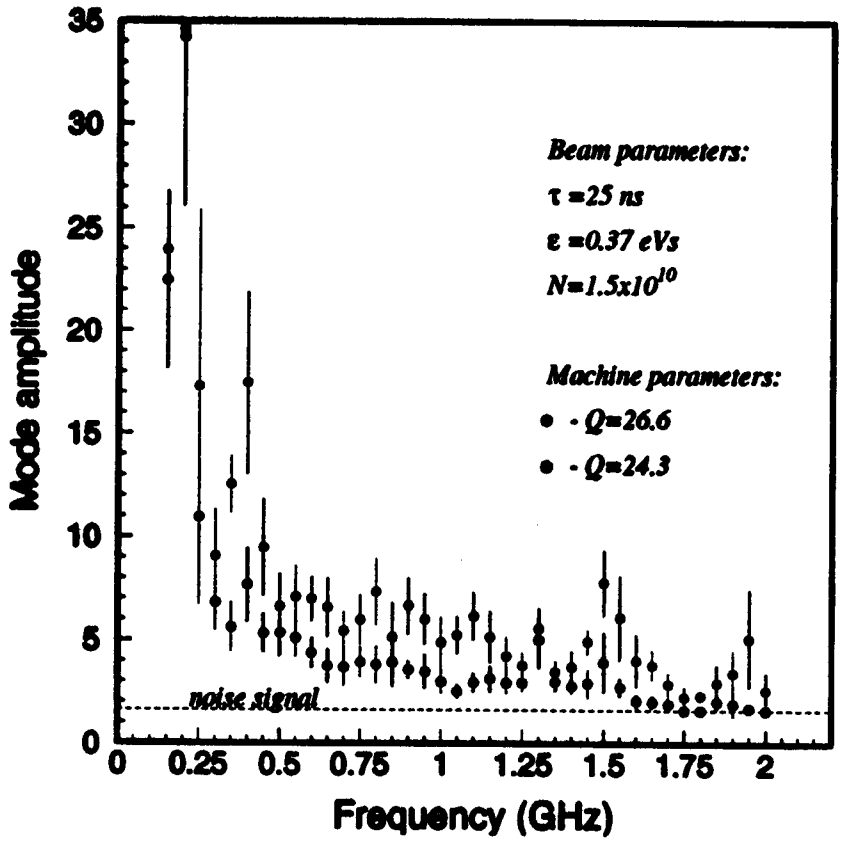
- RF cavities primary suspects
  - HOMs up to ~ 1 GHz already passively damped
  - If confirmation that next passband is a problem is obtained, then we will study ways of damping.
- Pumping ports may be a factor - screening will help
- When LEP stops, we will remove:
  - 100 MHz and 200 MHz SW RF, 352 MHz SC RF. This means 28 cavities, leaving 9.
  - Other lepton dedicated elements removed. (Wiggler, some instrumentation etc.)
  - This cleaning will also help with transverse modes.

But it is not sure we have found everything, our search for sources will continue.

200 MHz LHC system allows longer bunches. (or low obs ers)
Good at injection — higher capture voltage, less beam-loading problems.

Other means of controlling instabilities

- **Single bunch microwave.**
  - Change γ_{tr} from 23.4 to 19.5. With injection at 26 GeV the change in η gives a change in threshold by a factor 2.6.
  - Can be done by dedicated set of quadrupoles or significantly lowering the machine tune.
  - We have tested it by operating the machine at q = 24.3, near multiple of machine superperiodicity of 6. (Resonance in dispersion). Then we use method described to measure spectrum of unstable modes.



Effect on beam reduced by a factor ~2 at all frequencies except 200 MHz and 1.3 GHz.

Spectrum of unstable modes for two values of γ_{tr}

- **Coupled - bunch instabilities.**
  - Improved RF feedback around main RF cavities
  - Feedforward on the main RF cavities
  - Longitudinal feedback using recuperated 200 MHz SW cavities.
    - Delicate point under study - coupling between amplifier and cavity for 25 ns bunch spacing.
  - Landau damping using the existing 800 MHz cavities
    - Analysis has* shown bunch shortening mode preferable to bunch lengthening mode. (Confirms experimental results at HERA and SPS). Mainly due to reduced requirement on phase accuracy between two RF systems during acceleration.

* E. Shaposhnikova

– New damper design extending bandwidth to > 20 MHz. This should damp all modes for the SPS for LHC beam, bunch spacing frequency 40 MHz, but not for the Gran Sasso beam, bunch spacing frequency 200 MHz. For the latter we rely on octupoles for Landau damping.

Conclusions

- Future uses of SPS at high intensities have created the need for an exciting programme of machine studies and development projects.

- Although standard techniques such as Landau damping and feedback are being explored, a vigorous programme to reduce the machine impedance is underway.

Acknowledgement: This is a summary of the work of many people in the SL division and some from the PS division. A large team is working on the screening problems.