Spear3 RF System

- RF Requirement
- Overall System
- High Power Components
- Operation and Control

SPEAR 3 History

1996	Low emittance lattices explored
1996	SPEAR 3 proposed
11/97	SPEAR 3 design study team formed
11/97	Director's Review
07/98	DOE Lehman Review
FY99	DOE BES and NIH discuss joint funding
11/98	Active cavity and WG arcing
01/99	Additional funding for NEW RF (476.3 MHz)
04/99	Active RFHVPS failure.
01/00	Cavities ordered (Received 05/03)
03/00	Klystron ordered (Received 08/01, Repaired 05/03)
05/01	2.5 MW PS ordered (Received 01/02)
11/01	Circulator ordered (Received 11/01)
02/02	WG parts ordered (Receive 04/02)
03/02	LLRF work in progress
04/03	Installation (6 months)
12/03	Commissioning (3 months)
03/04	User Beam (3.0 GeV, 100 mA, 18 nm-rad)

Electron Beam Energy Loss due to Synchrotron Radiation

Energy loss at bend magnets

$$U_{0\text{-bend}}\ (\text{keV/turn}) = 88.5*(E_b/\text{GeV})^4/(\rho/\text{m})$$

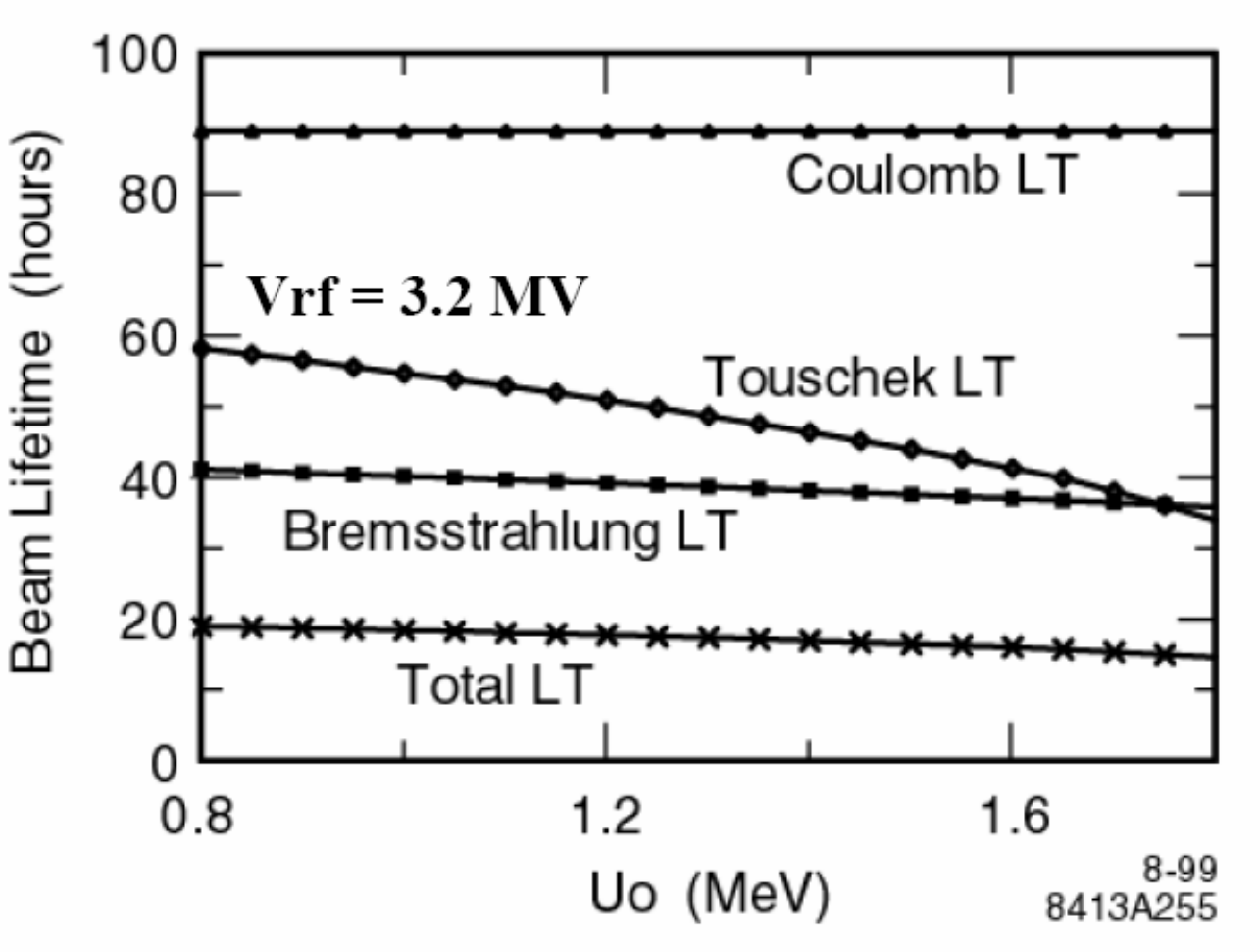
Energy loss at insertion device

$$U_{0\text{-ID}}\ (\text{keV/turn}) = 0.633*(E_b/\text{GeV})^2*\langle(B/\text{T})^2\rangle*(L/\text{m})^2$$

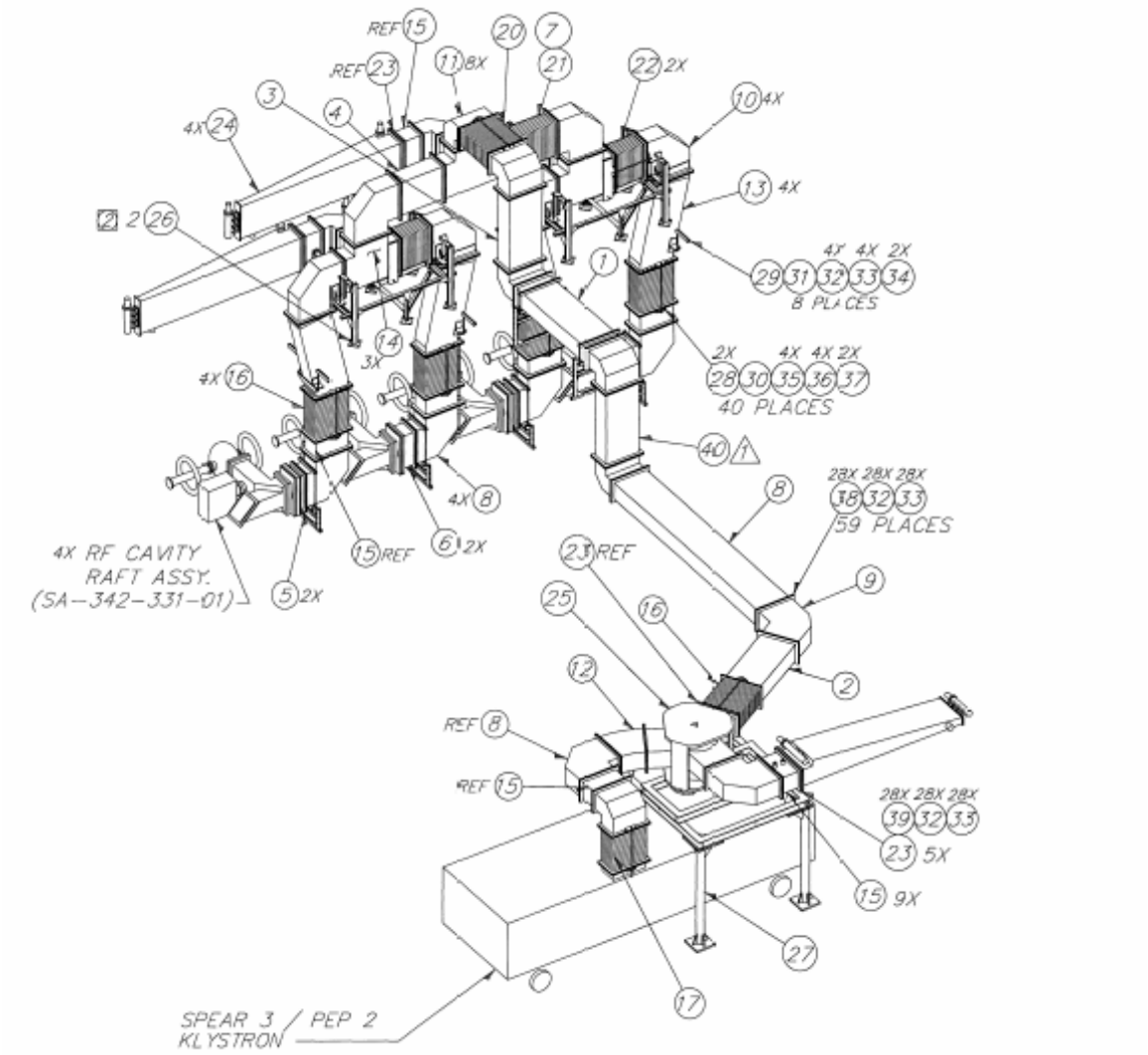
where <B> is the rms magnetic field of the pole
and L is the insertion device length

With beam energy E_b=3.0GeV, bend radius ρ=7.86m,
total beam power loss is 1.16MV*500mA=510 kW
in 2003, and 1.33MV*500mA=665 kW in 2012
as the insertion devices are added on.

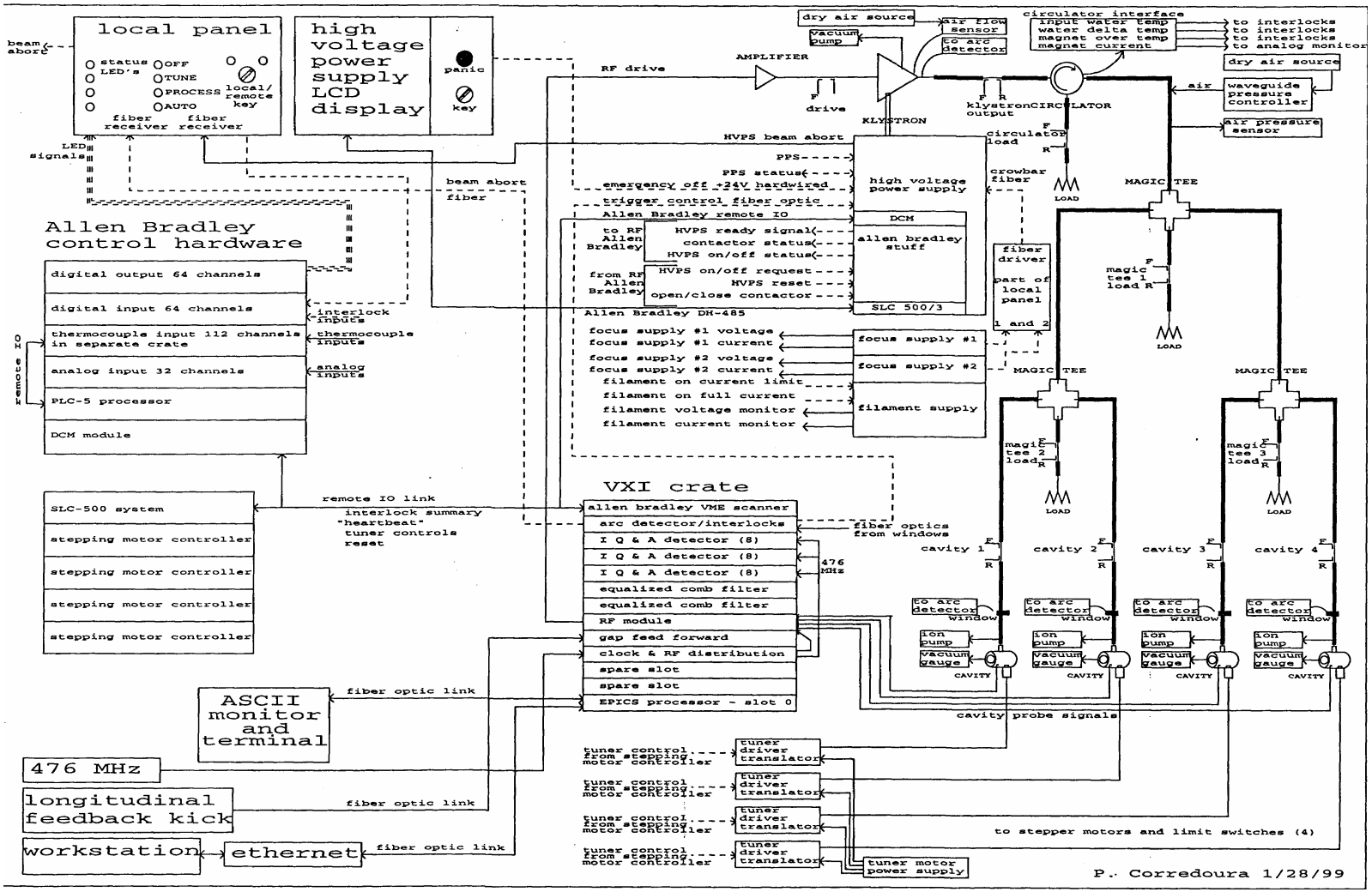
Spear 3 Beam Lifetime



Spear 3 RF Installation



SPEAR 3 Overall System



Klystron (Repaired Marconi)

- Maximum RF Power : P_{rf} = 1.2 MW
- Beam Power : $P_b = V_b * I_b$= 82 kV * 23.5 A = 1.93 MW
- Microperveance $\mu P = I_b/V_b^{1.5} * 10^6 = 1.00$
- Efficiency $\eta = P_{rf}/P_b$ = 62%
- Gain A = $10*\mathrm{Log}_{10}(P_{rf}/P_{drive})$ = 45 dB
- Drive amplifier power P_{drive} = 40 W
- Cathode heater power P_h = 110Vac*5.2A = 570 W
- Focusing magnet power P_m = 70.2V*47.5A = 3.33kW
- No bucking coil power
- LCW flow for 1.5MW : 275 gpm, 150 psi, 32 ±1 ^oC
- 2 VacIon pumps, 8 L/s each

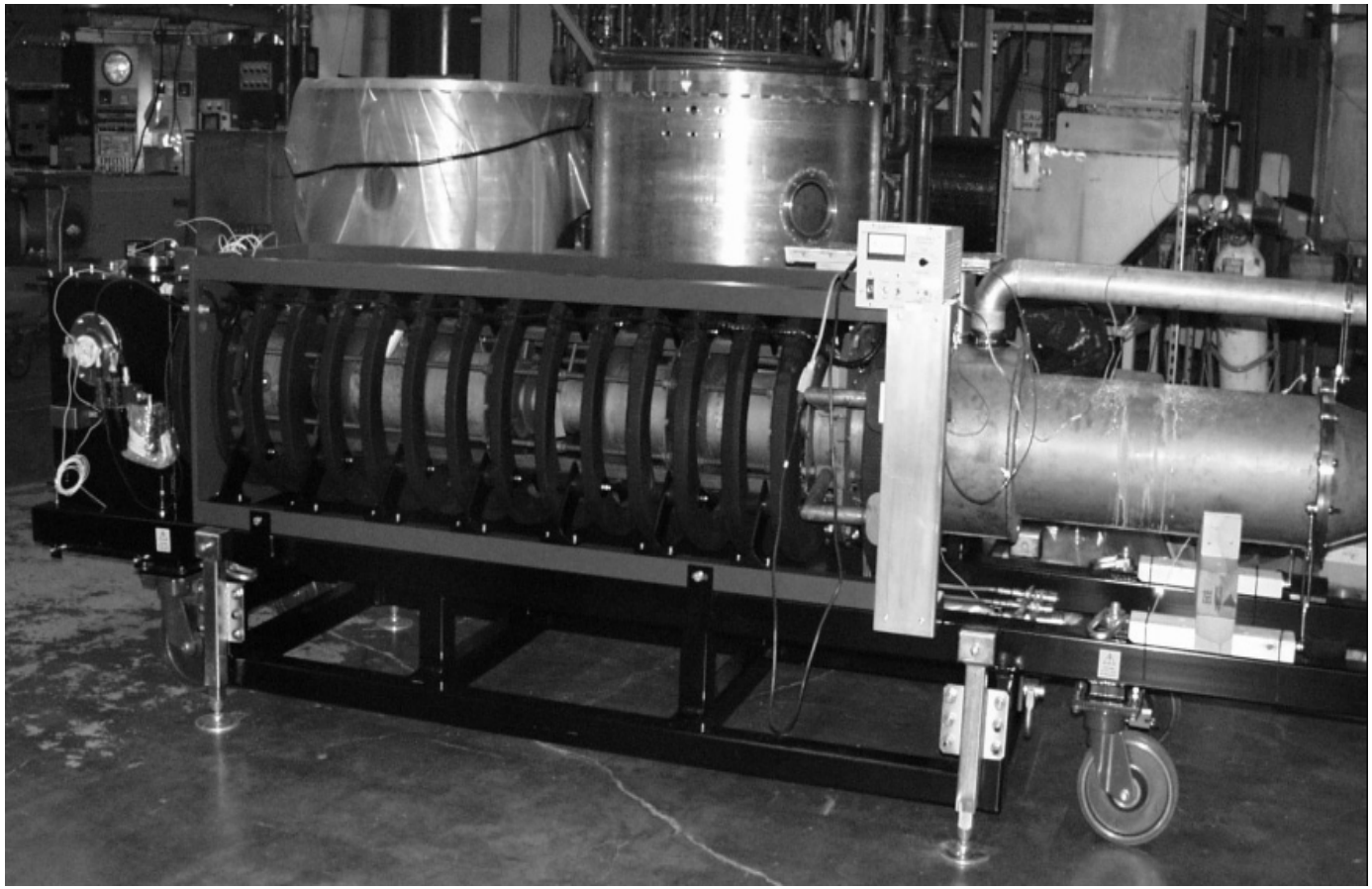
SPEAR 3 Klystron

- Spear3 klystron from Marconi
- That klystron was loaned to PEP2
- The klystron failed, and rebuilt by PCI
- SLAC Klystron Dept to produce 4 klystrons
- Those SLAC klystrons have higher power capability

Philips/EEV/Marconi Klystron Experience at SLAC

No.	Klystron	Date failed	Fil. Hrs	Failure type	Remedy
1	Philips #5	09/25/00	14,102	Heater short	Rebuilt at CPI
2	Philips #5	03/29/01	13,895	Anode dislocation	
3	Philips #5	05/22/01	5,740	Anode dislocation	Rebuilt at SLAC
4	Marconi #3	07/17/01	1,350	Vacuum leak (up to 10 mA pump current)	Rebuilt at CPI
5	Marconi #2	07/26/01	4,730	Vacuum leak (up to 60 mA pump current)	Rebuilt at CPI

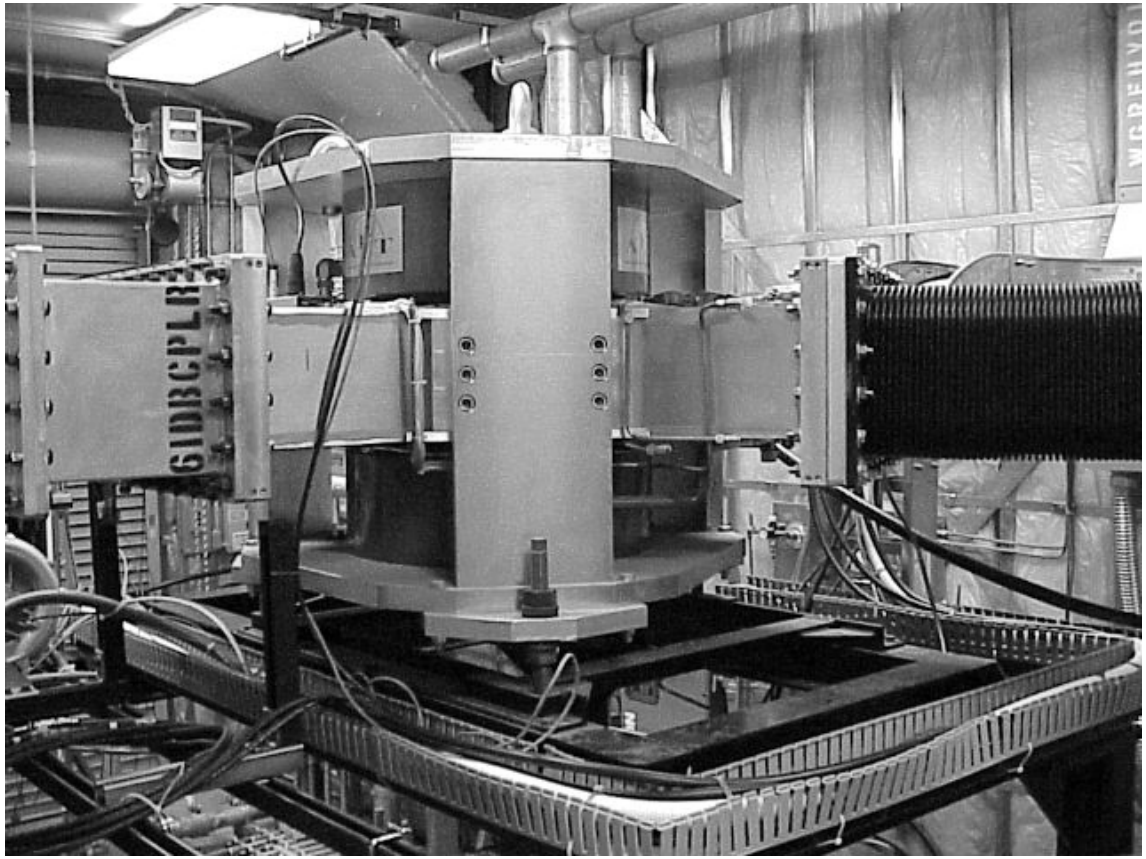
Marconi Klystron



ATF Circulator Specification

- Type: Y-Junction 3-port Circulator
- Frequency : 476 ± 10 MHz
- Forward Power : 1.2 MW cw
- Reverse Power : 1.2 MW cw
- Insertion Loss : < 0.1 dB (VSWR : <1.1, power reflection <0.25%)
- Isolation : > 26 dB (>14 dB in ± 10 MHz)
- Cooling LCW : >26 gpm (150 psig, 25~40^{o}C, nominal 35 ± 1^{o}C)
- Mounting Orientation : any

AFT Circulator



Water Load Specification

- Coolant : HCW (0.75% Corr-Shield by volume to LCW)
- Coolant supply : 150 psig, 10~70 ^{o}C
- Coolant return : 15 psig, <80^{o}C
- Coolant duct : Teflon tubing
- Frequency : 476 ±10 MHz
- Power : <1.2 MW average (<2.0 MW peak for 100 μs)
- VSWR : <1.05 (reflected power < 0.06%)
- RF Leakage : < 0.1 mW/cm^{2}
- Length : 9.5 feet overall
- Air pressure : <0.5 psig (0.25 psig nominal)

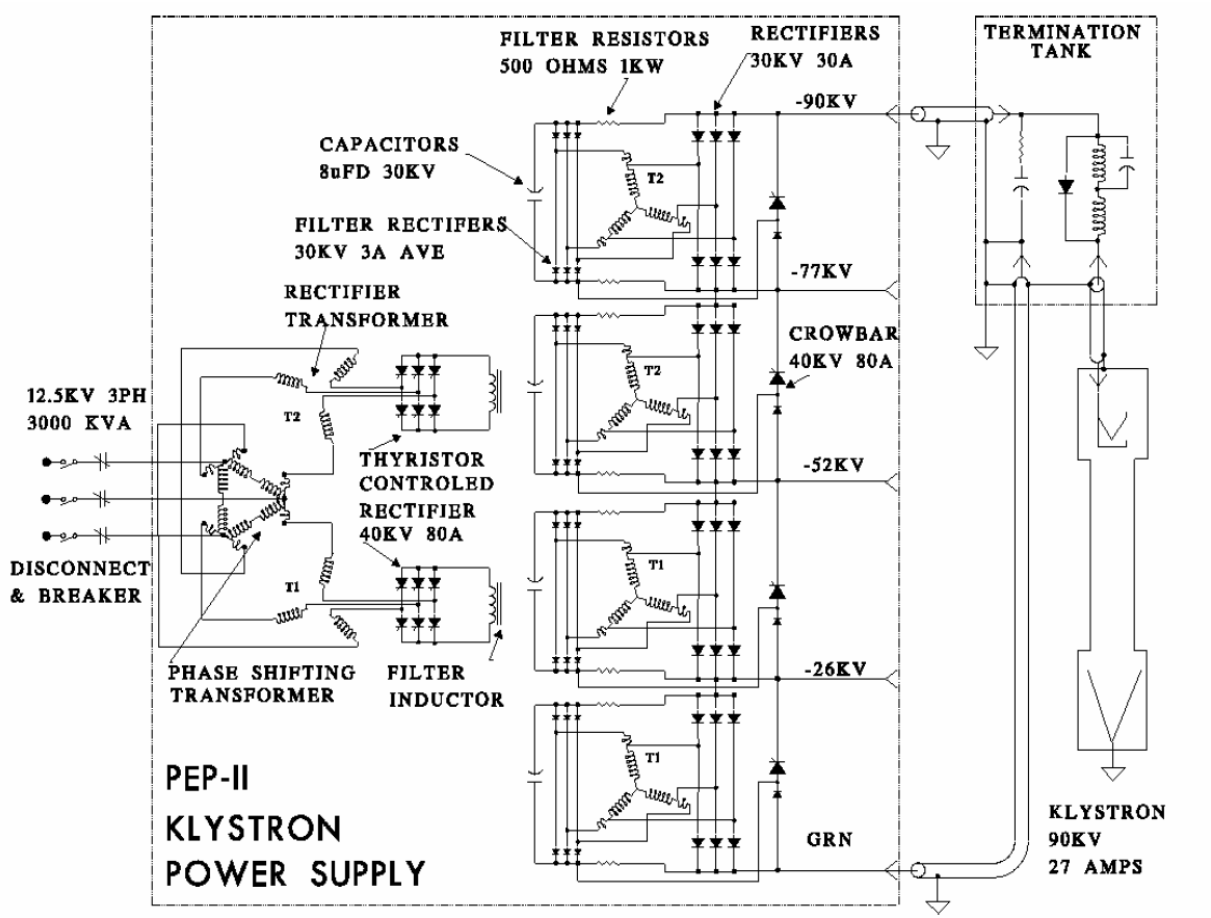
Water Load

HCW Station behind Booster

RFHV Power Supply Specification

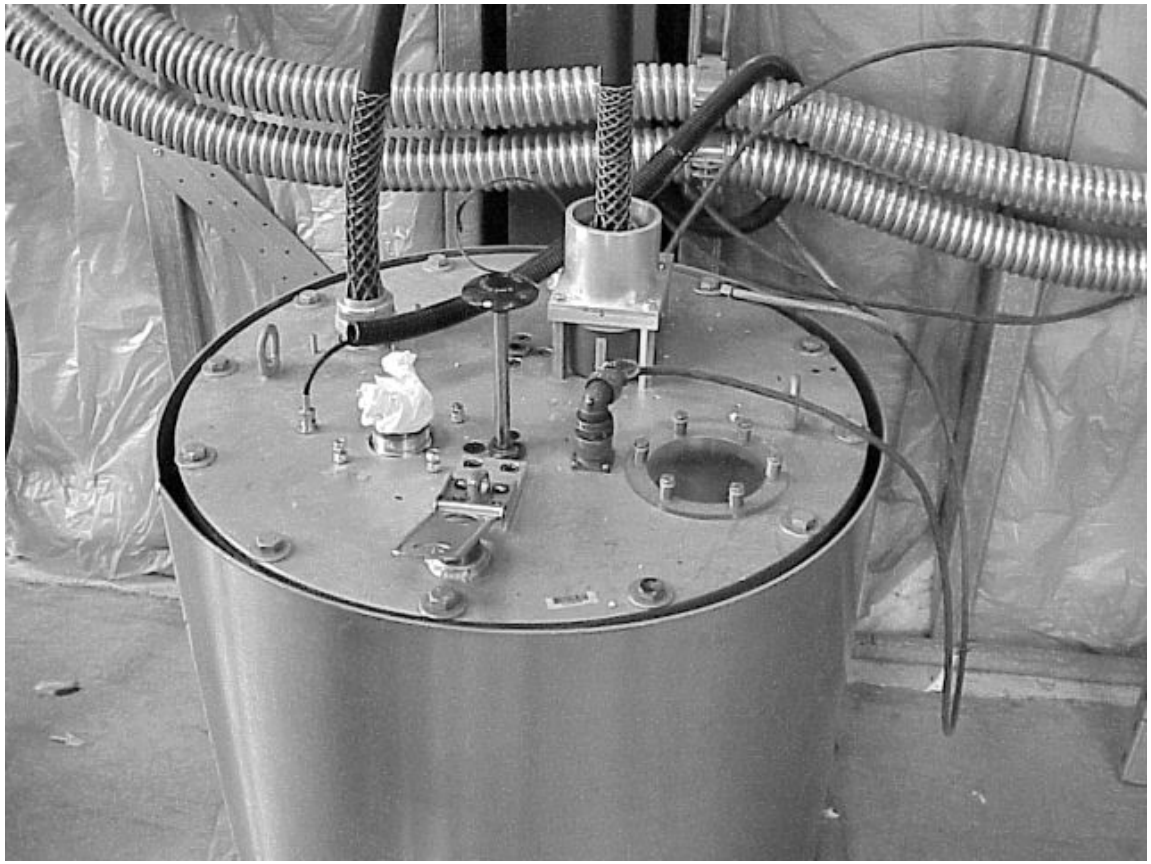
- Output DC power : 90 kV* 27A=2.43 MW
  Corresponds to microperveance of 1.00
  and 2.43 * 0.62 = 1.50 MW RF power
- Input AC power : 12.47 kV line-to-line, 127 A per phase
  Power supply efficiency = 2430/(1.73*127*12.47) = 0.89
  Lower efficiency at lower output voltage/power
- New filtering capacitors by General Atomics
- Light triggered crowbar SCR's
- Less than 0.5 Joules to the klystron in case of arcing
  at 80 kV per swinging ball test of crowbar

RFHV Power Supply Schematic

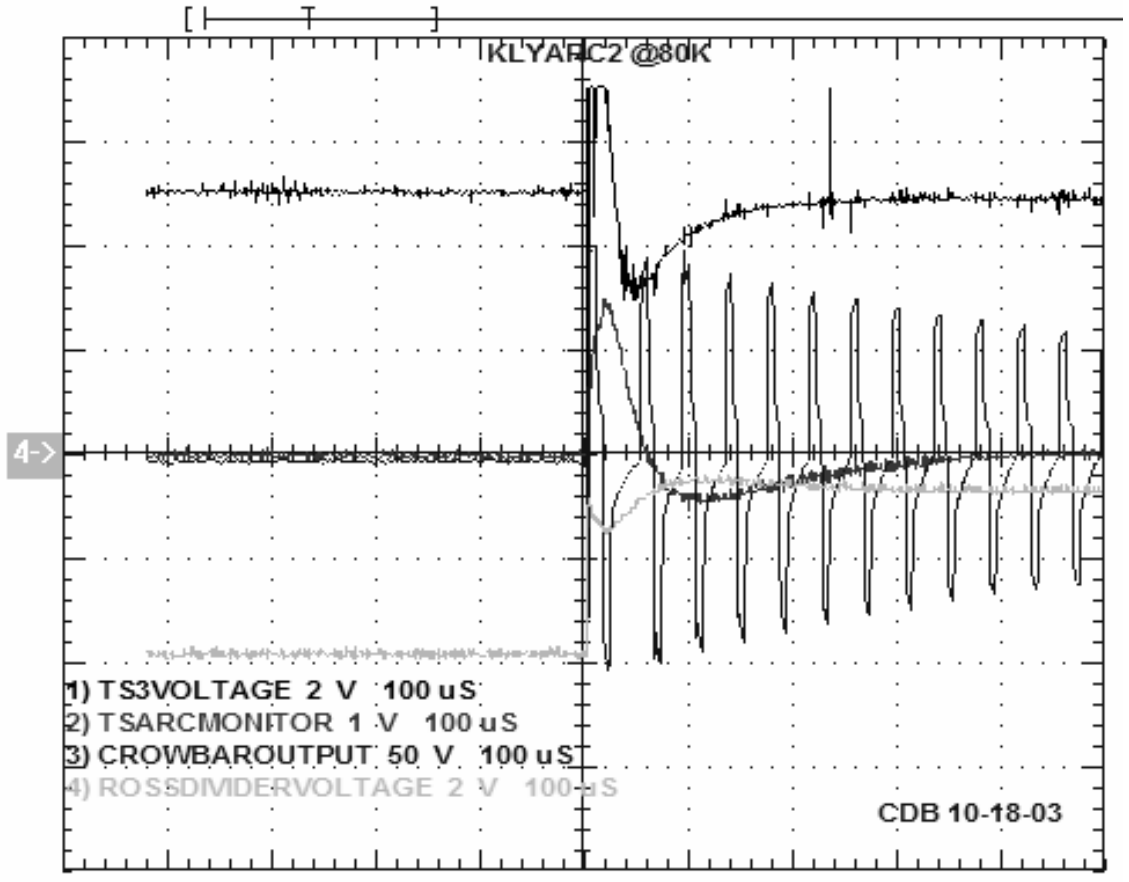


Spear3 RFHV Power Supply

Spear3 RFHV Power Supply Grounding Tank



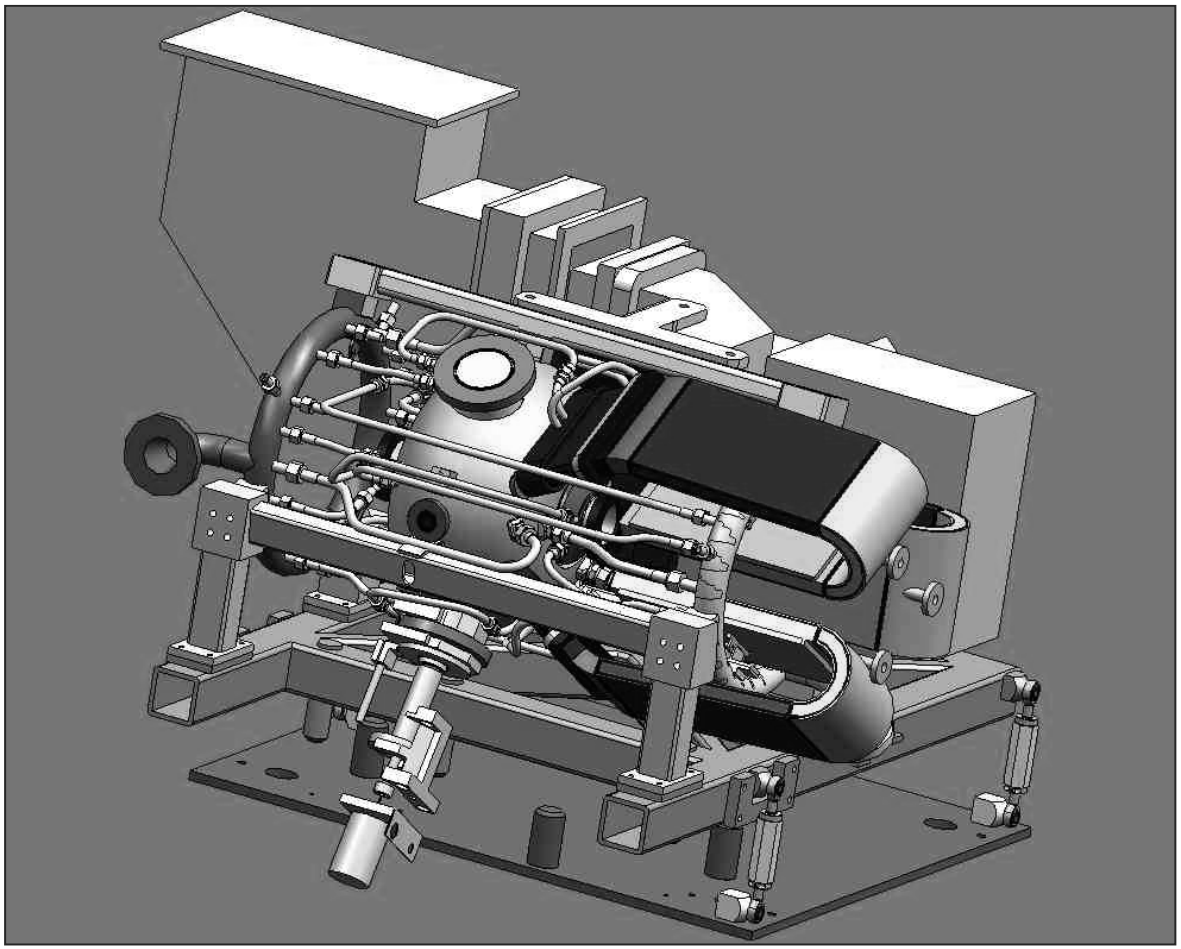
RFHV PS Swinging Ball Test



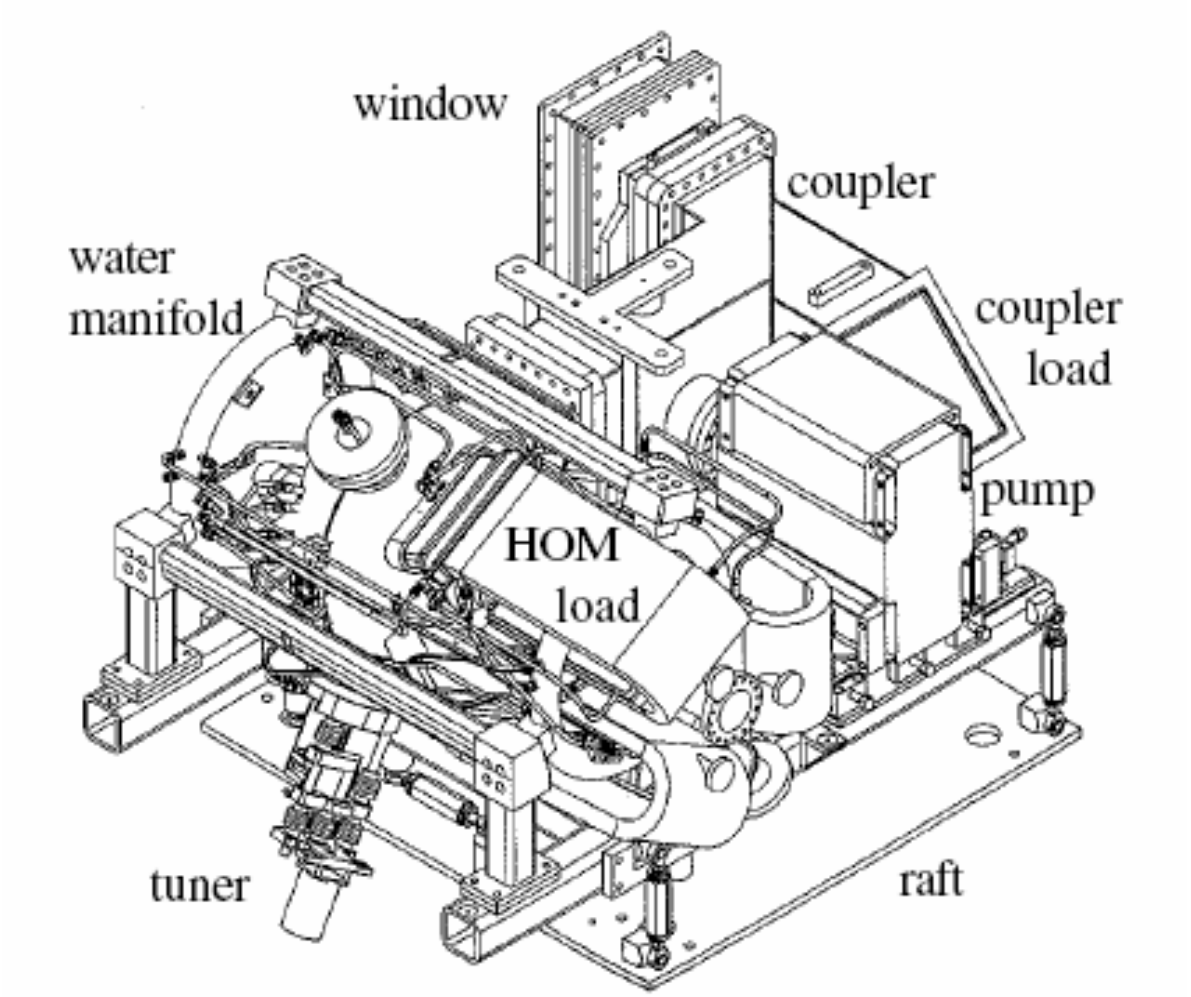
Spear3 RF Cavity Characteristics

- Frequency 476.3 MHz (different from PEP2 476.0 MHz)
- Shunt Impedance $R_a = V_g^2/P_{rf}$ = 7.62 MΩ (95 kW for 0.85 MV)
- Acceleration field ~ 3.9 MV/m
- Coupling $\beta = 1+P_b/P_c$ = 3.8 (high reflection at lower current)
- Window power <410 kW, Wall power < 80 W/cm^2
- 3 high power HOM loads at each of 4 cavities
- One HOM filter per cavity at the waveguide coupler
  Similar filters were used at Spear2
- One movable tuner per cavity
- Coupler window temperature is monitored by IR sensor
- Q ~ 30,000 at operating temperature (Fill time is Q/ω ~10 μs)
- If RF is turned off on orbit interlock trip, beam is lost in ~300 μs

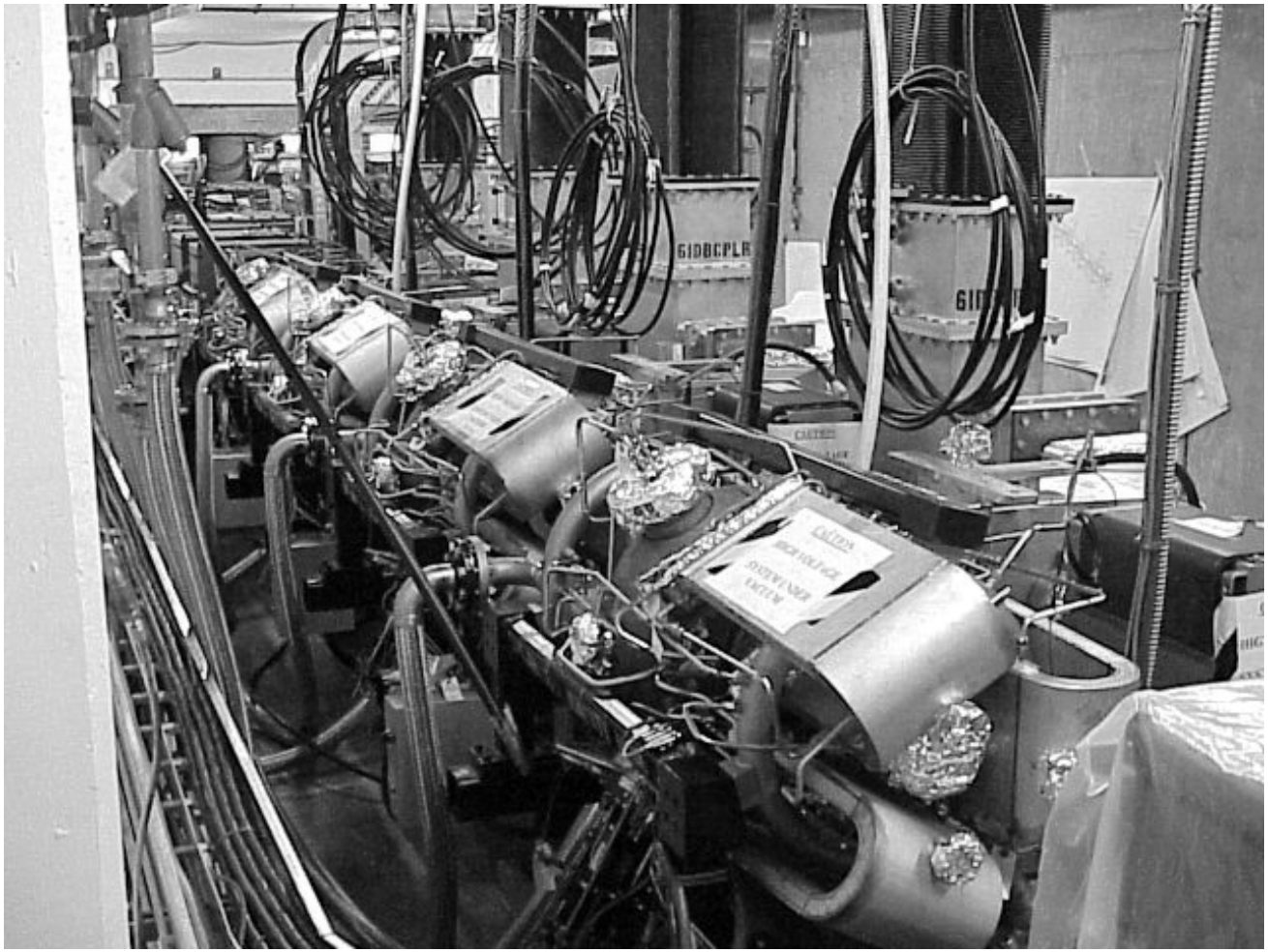
Spear3 RF Cavity Assembly



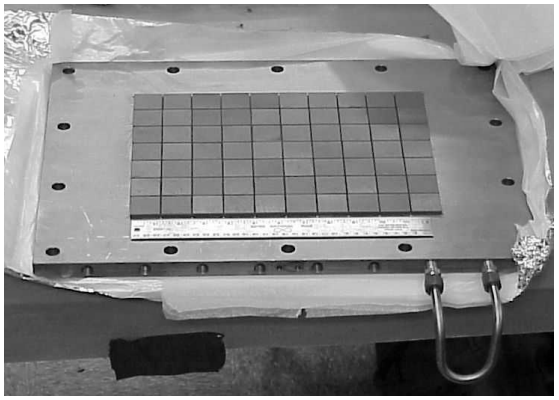
Spear3 RF Cavity Assembly



Cavities in the West Straight



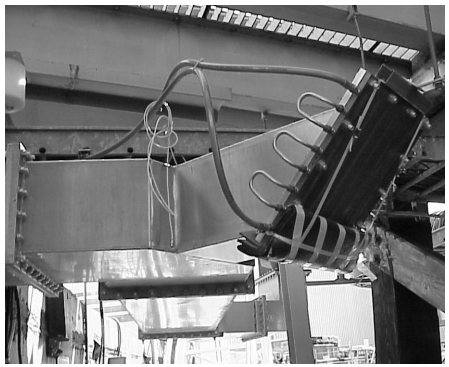
Cavities in the West Straight



Matrix of 1.0 inch square ferrite tiles. They are soft- soldered onto a copper plate.

Cooling channels were drilled out from a solid copper plate.

HOM load plate, water-cooled

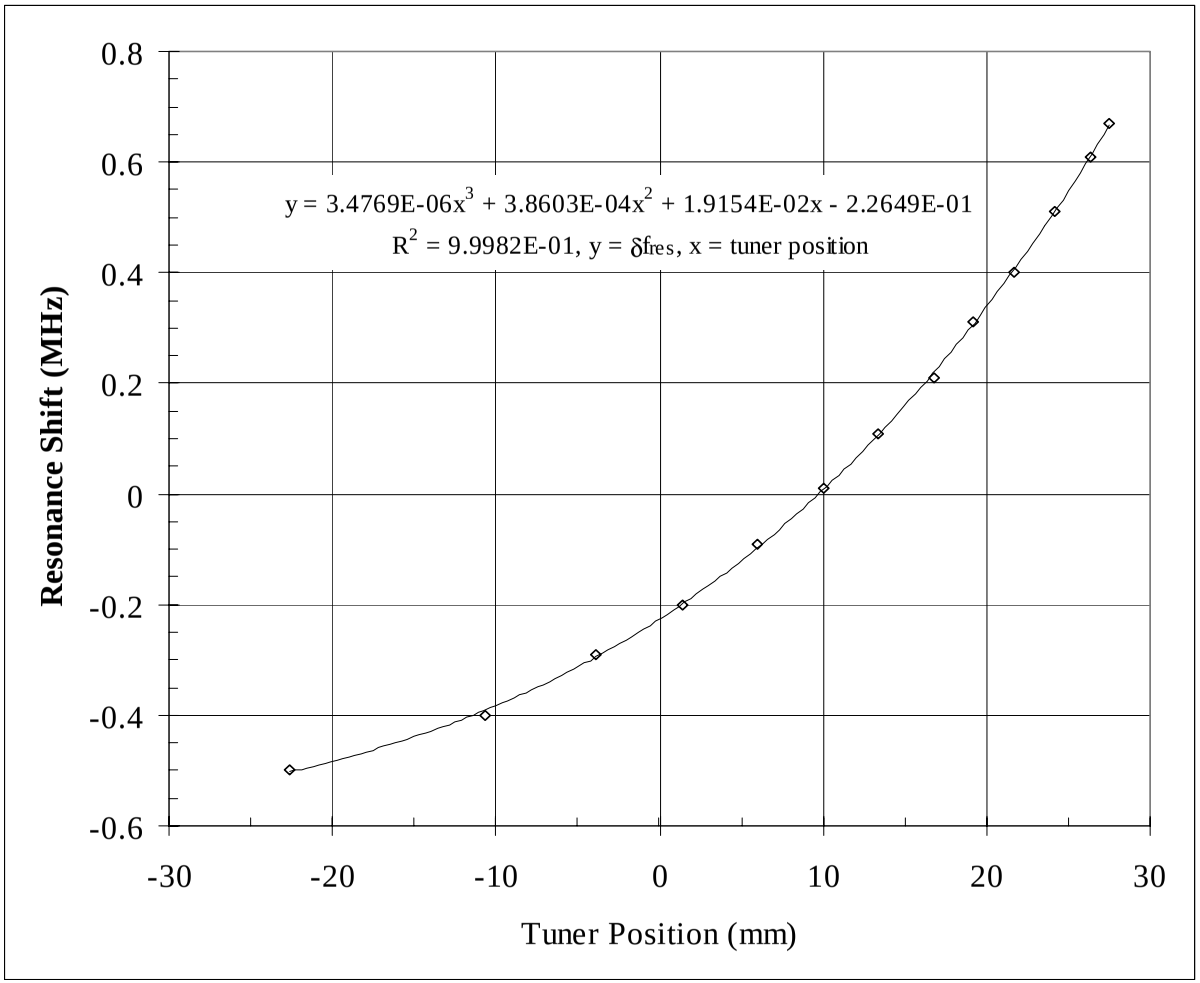


HOM load at E- and H-mitre

LCW flow is 6 gallons per minute. No appreciable ΔT is detected, but the flow is interlocked.

Movable Tuner below the Cavity

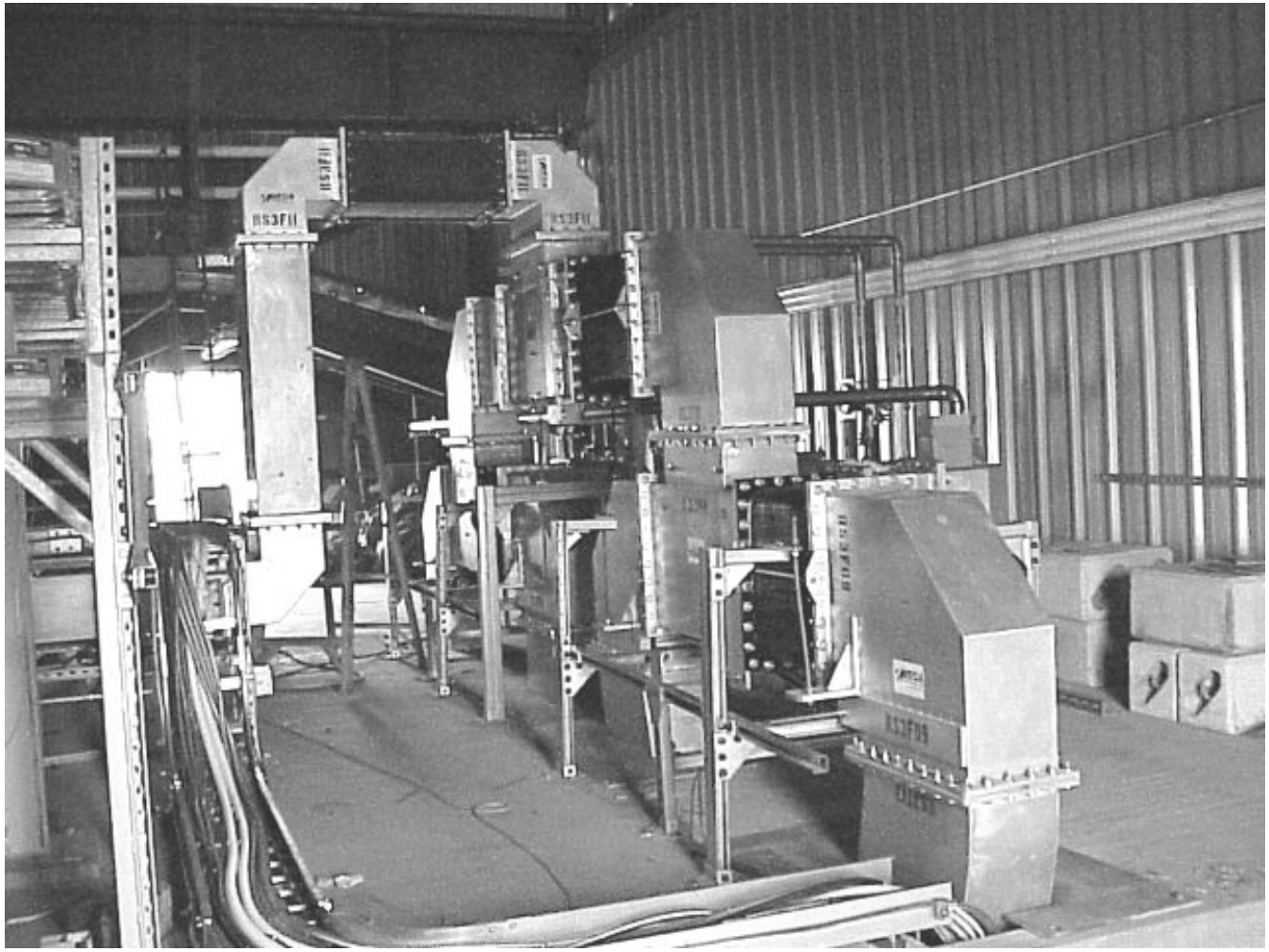
Movable Tuner Tuning Range



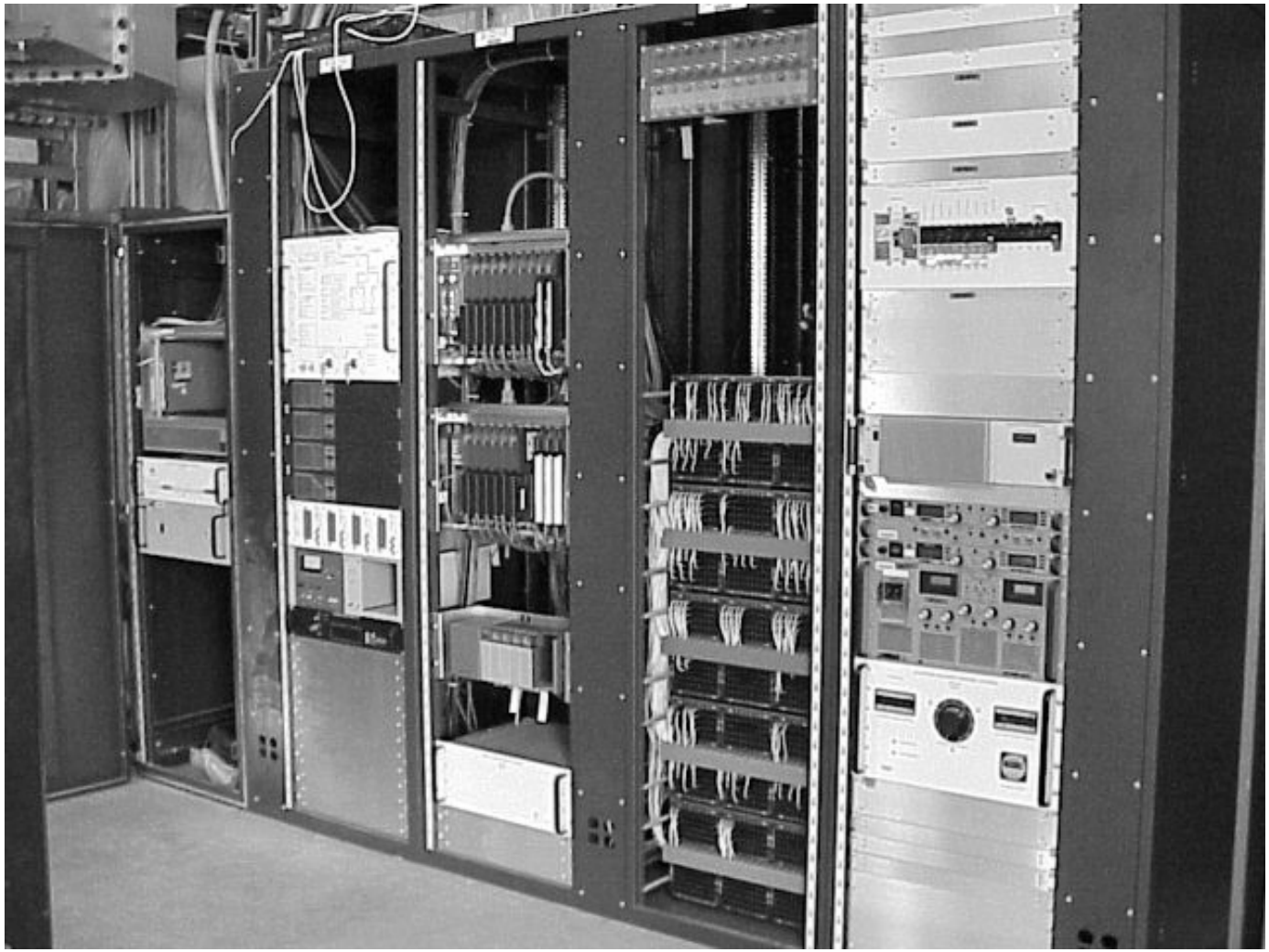
Waveguide Network & Phasing

- Magic Tees : Divide RF power evenly.
- Magic tee loads are to compensate for any mismatch
  and absorbs reflected power (two arms are 90 degree apart)
- Bellow lengths are adjusted to match the RF phase in cavities
- Guided wavelength $\lambda_g = \lambda_0/[1-(\lambda_0 /2a)^2]^{1/2}$, $\lambda_g = c/f$
- Waveguide sections are positively pressurized with dry air
  to ensure that there is no mechanical gap (no RF leakage)
  and no moisture enters into the system
- Window at the klystron is cooled by forced air

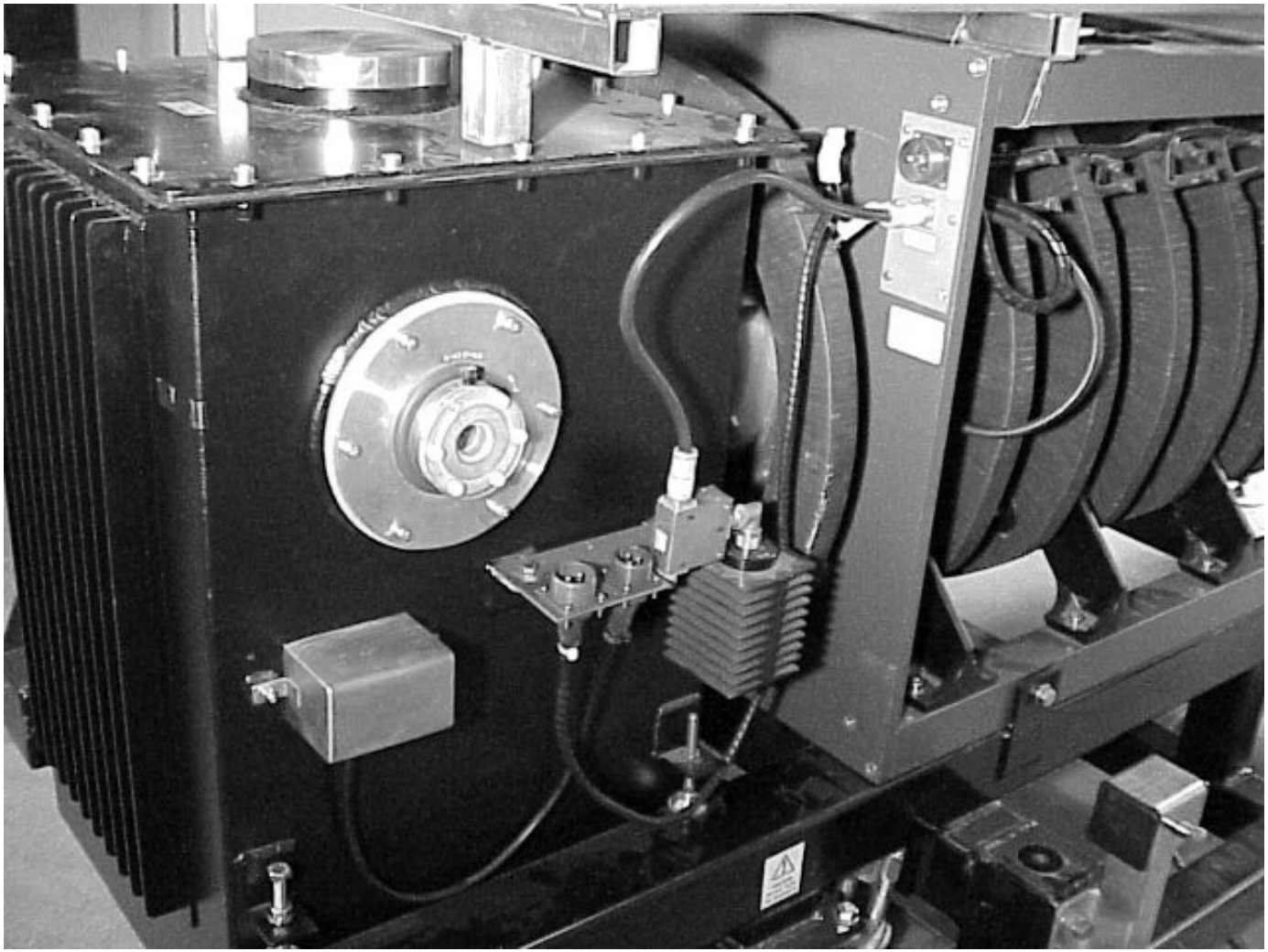
Magic-T and Bellow Network



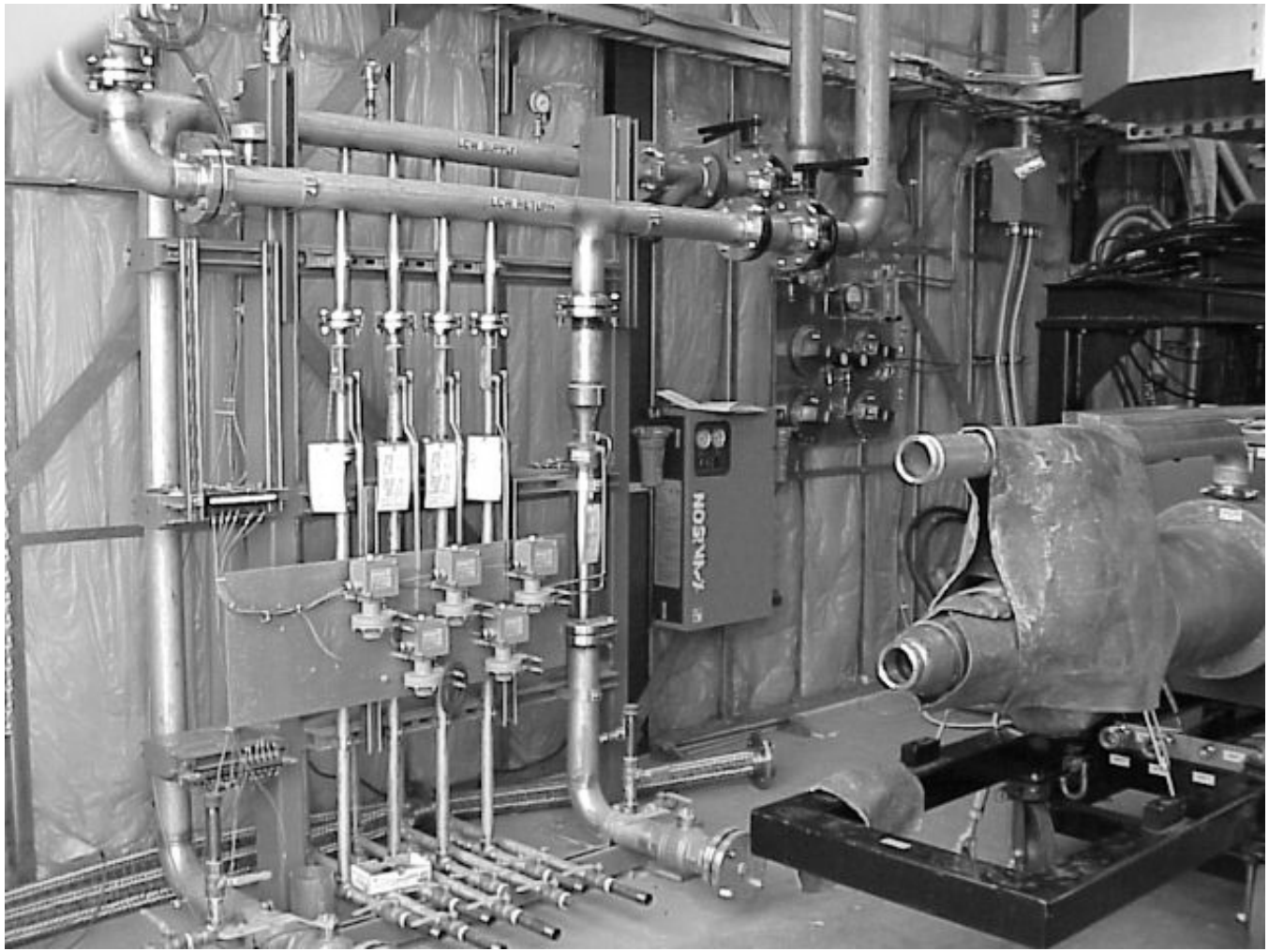
LLRF in Room 101, Bldg 132



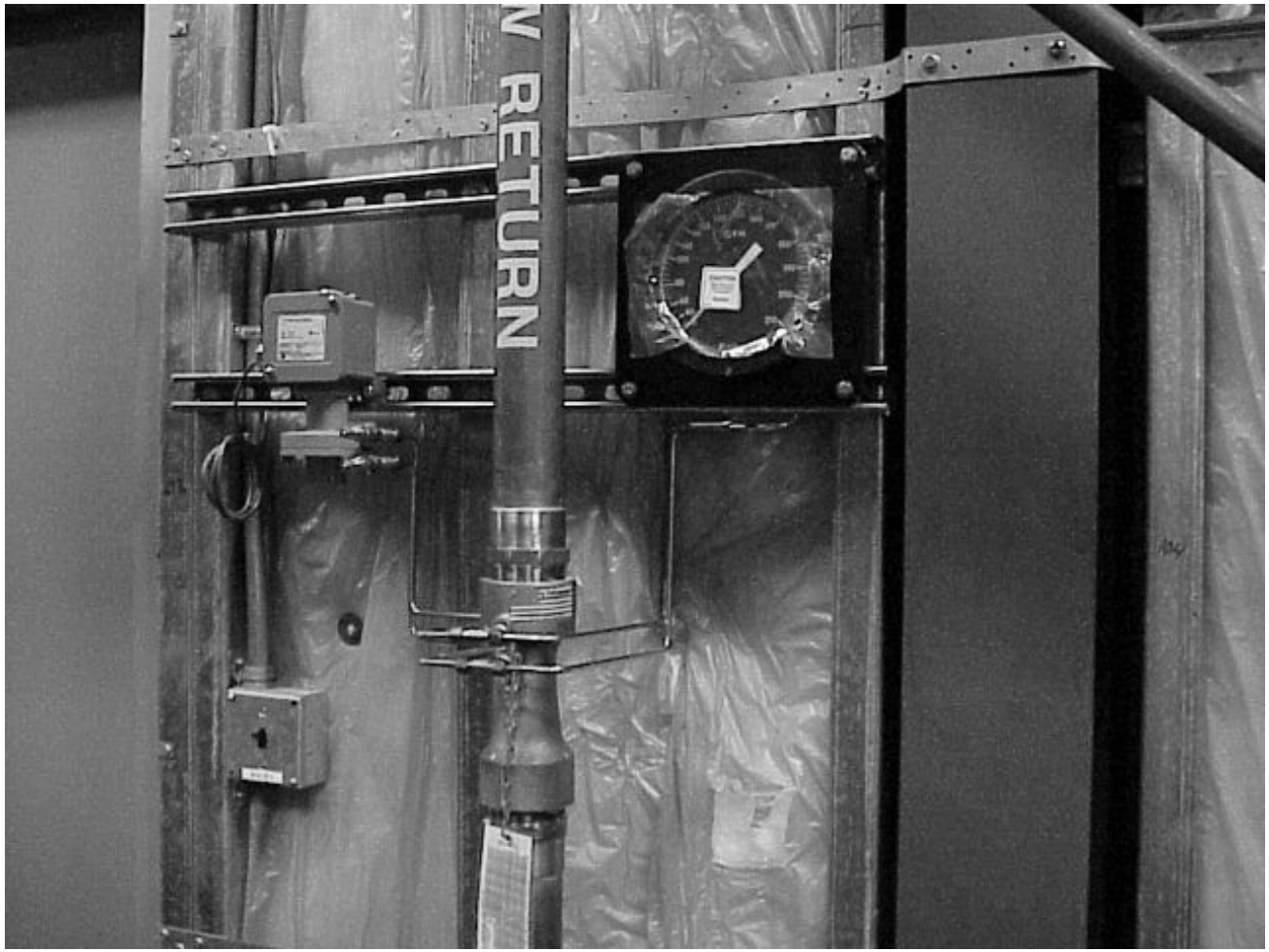
Connections to Klystron



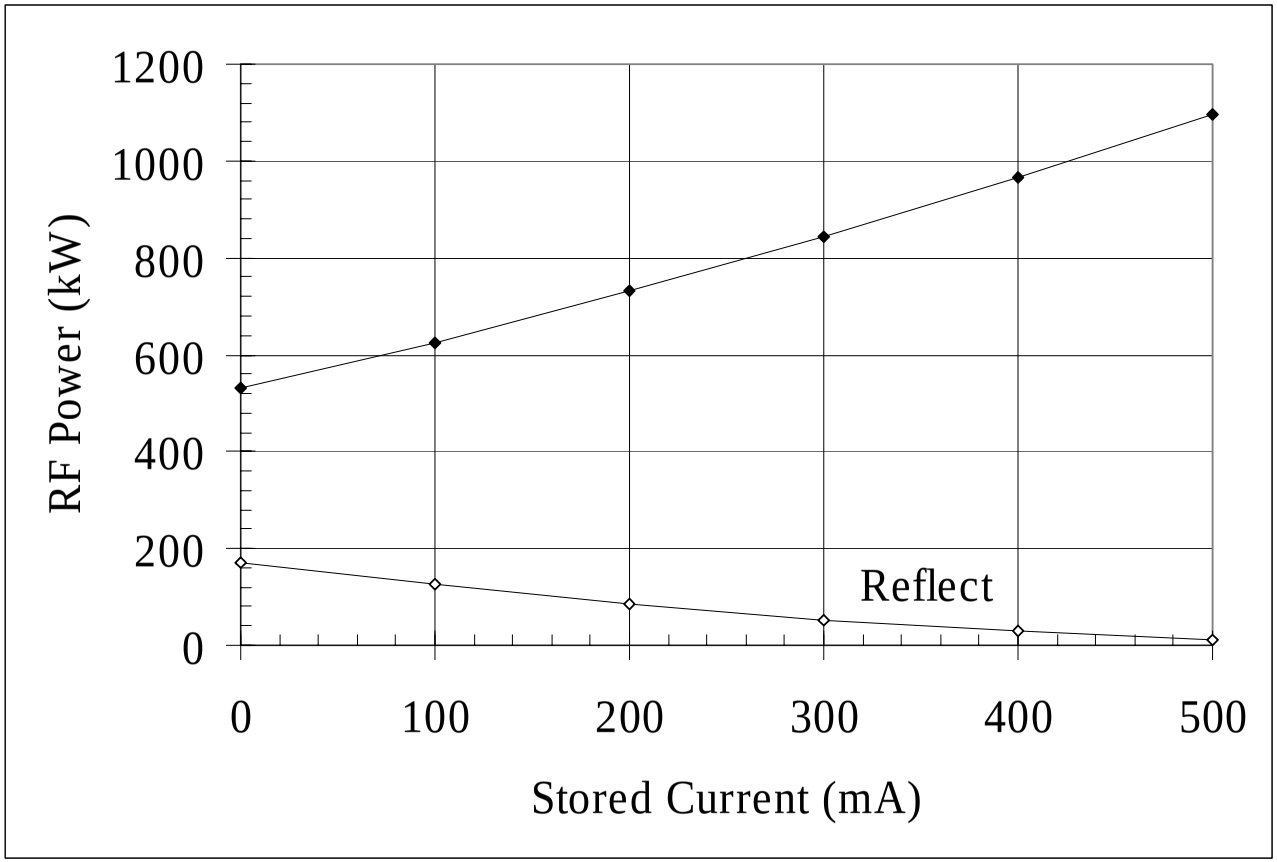
Connections to Klystron

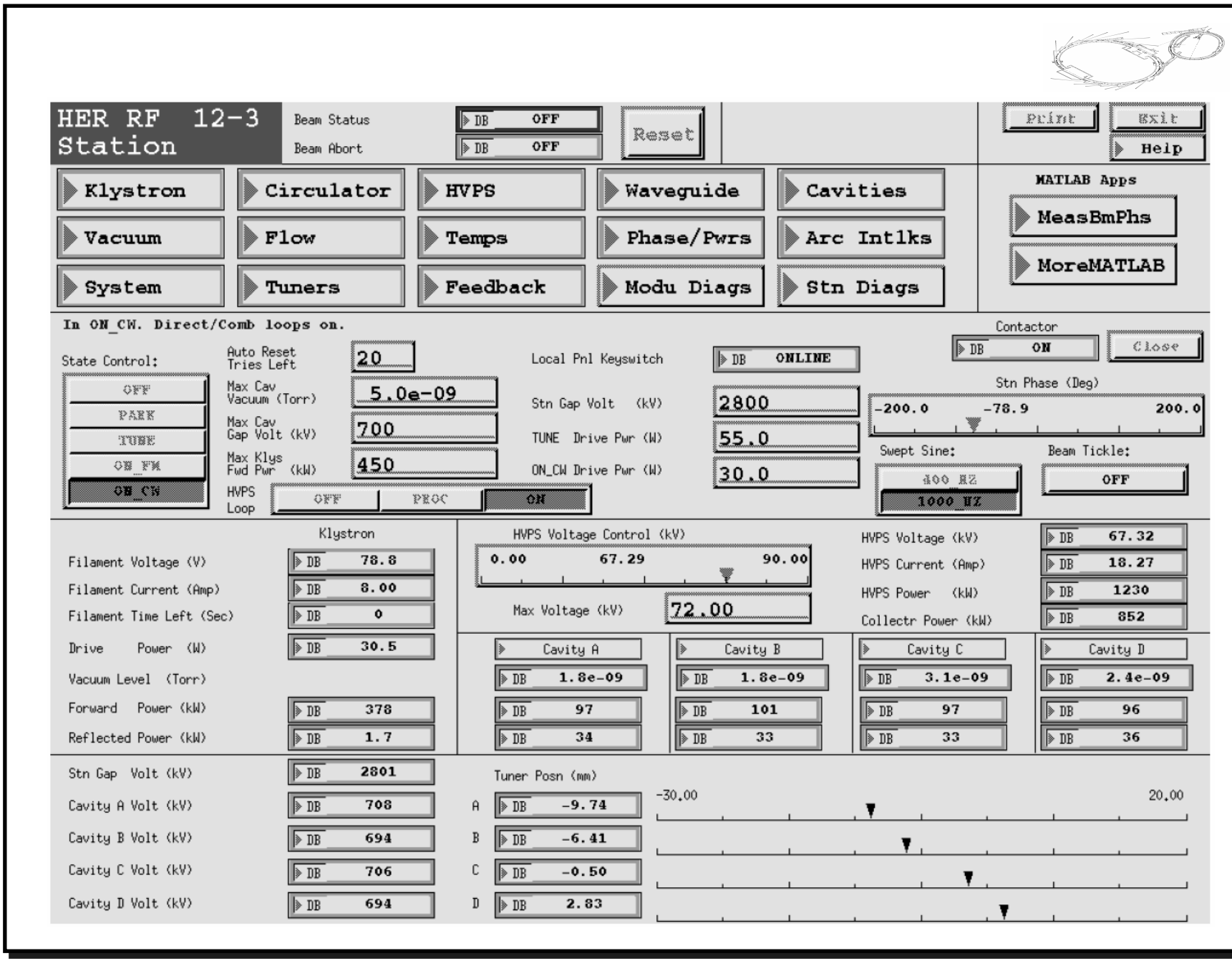


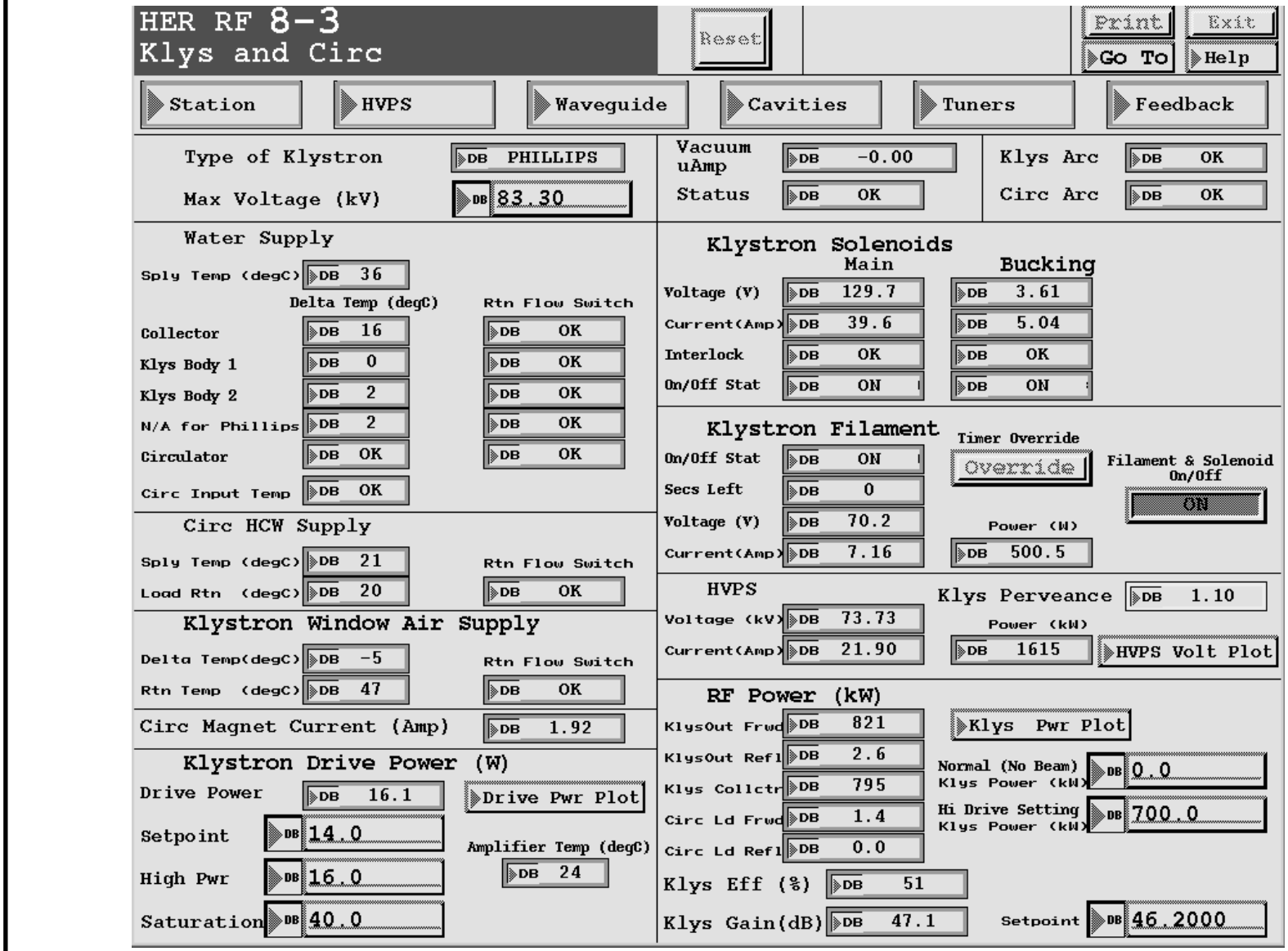
Flow monitor and interlock

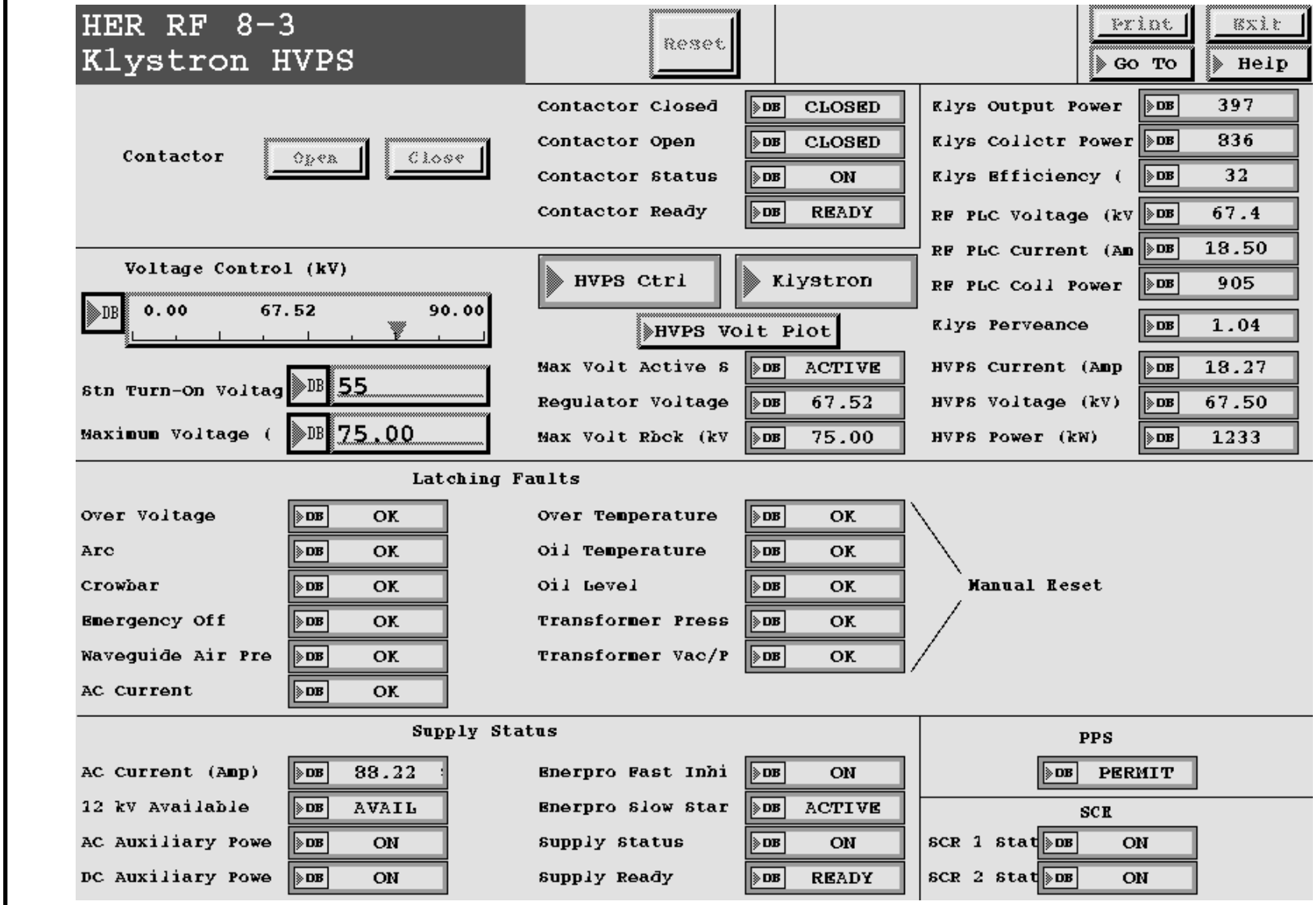


Power Balance with Beam Loading




HER RF 12-3 Station
Beam Status
Beam Abort
DB OFF
DB OFF
Reset
Print
Exit
Help
Klystron
Circulator
HVPS
Waveguide
Cavities
Vacuum
Flow
Temps
Phase/Pwrs
Arc Intlks
System
Tuners
Feedback
Modu Diags
Stn Diags
MATLAB Apps
MeasBmPhs
MoreMATLAB
In ON_CW. Direct/Comb loops on.
State Control:
OFF
PARK
TUNE
ON_FM
ON_CW
Auto Reset Tries Left
20
Max Cav Vacuum (Torr)
5.0e-09
Max Cav Gap Volt (kV)
700
Max Klys Fwd Pwr (kW)
450
HVPS Loop
OFF
PROC
ON
Local Pnl Keyswitch
DB ONLINE
Stn Gap Volt (kV)
2800
TUNE Drive Pwr (W)
55.0
ON_CW Drive Pwr (W)
30.0
Contactor
DB ON
Close
Stn Phase (Deg)
-200.0
-78.9
200.0
Swept Sine:
400 HZ
1000 HZ
Beam Tickle:
OFF
Klystron
Filament Voltage (V)
DB 78.8
Filament Current (Amp)
DB 8.00
Filament Time Left (Sec)
DB 0
Drive Power (W)
DB 30.5
Vacuum Level (Torr)
Forward Power (kW)
DB 378
Reflected Power (kW)
DB 1.7
HVPS Voltage Control (kV)
0.00
67.29
90.00
Max Voltage (kV)
72.00
HVPS Voltage (kV)
DB 67.32
HVPS Current (Amp)
DB 18.27
HVPS Power (kW)
DB 1230
Collectr Power (kW)
DB 852
Cavity A
DB 1.8e-09
DB 97
DB 34
Cavity B
DB 1.8e-09
DB 101
DB 33
Cavity C
DB 3.1e-09
DB 97
DB 33
Cavity D
DB 2.4e-09
DB 96
DB 36
Stn Gap Volt (kV)
DB 2801
Cavity A Volt (kV)
DB 708
Cavity B Volt (kV)
DB 694
Cavity C Volt (kV)
DB 706
Cavity D Volt (kV)
DB 694
Tuner Posn (mm)
A DB -9.74
B DB -6.41
C DB -0.50
D DB 2.83
-30.00
20.00


HER RF 8-3
Klys and Circ
Reset
Print
Exit
Go To
Help
Station
HVPS
Waveguide
Cavities
Tuners
Feedback
Type of Klystron
PHILLIPS
Max Voltage (kV)
83.30
Vacuum uAmp
-0.00
Status
OK
Klys Arc
OK
Circ Arc
OK
Water Supply
Sply Temp (degC)
36
Delta Temp (degC)
Rtn Flow Switch
Collector
16
OK
Klys Body 1
0
OK
Klys Body 2
2
OK
N/A for Phillips
2
OK
Circulator
OK
OK
Circ Input Temp
OK
Circ HCW Supply
Sply Temp (degC)
21
Rtn Flow Switch
Load Rtn (degC)
20
OK
Klystron Window Air Supply
Delta Temp(degC)
-5
Rtn Flow Switch
Rtn Temp (degC)
47
OK
Circ Magnet Current (Amp)
1.92
Klystron Drive Power (W)
Drive Power
16.1
Drive Pwr Plot
Setpoint
14.0
Amplifier Temp (degC)
High Pwr
16.0
24
Saturation
40.0
Klystron Solenoids
Main
Bucking
Voltage (V)
129.7
3.61
Current(Amp)
39.6
5.04
Interlock
OK
OK
On/Off Stat
ON
ON
Klystron Filament
Timer Override
On/Off Stat
ON
Override
Filament & Solenoid On/Off
ON
Secs Left
0
Voltage (V)
70.2
Power (W)
Current(Amp)
7.16
500.5
HVPS
Klys Perveance
1.10
Voltage (kV)
73.73
Power (kW)
Current(Amp)
21.90
1615
HVPS Volt Plot
RF Power (kW)
KlysOut Frwd
821
Klys Pwr Plot
KlysOut Refl
2.6
Normal (No Beam) Klys Power (kW)
0.0
Klys Collctr
795
Hi Drive Setting Klys Power (kW)
700.0
Circ Ld Frwd
1.4
Circ Ld Refl
0.0
Klys Eff (%)
51
Klys Gain(dB)
47.1
Setpoint
46.2000


HER RF 8-3
Klystron HVPS
Reset
Print
Exit
Go To
Help
Contactor
Open
Close
Contactor Closed
CLOSED
Contactor Open
CLOSED
Contactor Status
ON
Contactor Ready
READY
Klys Output Power
397
Klys Collctr Power
836
Klys Efficiency (
32
RF PLC Voltage (kV
67.4
RF PLC Current (Am
18.50
RF PLC Coll Power
905
Klys Perveance
1.04
Voltage Control (kV)
0.00
67.52
90.00
HVPS Ctrl
Klystron
HVPS Volt Plot
Stn Turn-On Voltag
55
Maximum Voltage (
75.00
Max Volt Active S
ACTIVE
Regulator Voltage
67.52
Max Volt Rbck (kV
75.00
HVPS Current (Amp
18.27
HVPS Voltage (kV)
67.50
HVPS Power (kW)
1233
Latching Faults
Over Voltage
OK
Arc
OK
Crowbar
OK
Emergency Off
OK
Waveguide Air Pre
OK
AC Current
OK
Over Temperature
OK
Oil Temperature
OK
Oil Level
OK
Transformer Press
OK
Transformer Vac/P
OK
Manual Reset
Supply Status
AC Current (Amp)
88.22
12 kV Available
AVAIL
AC Auxiliary Powe
ON
DC Auxiliary Powe
ON
Enerpro Fast Inhi
ON
Enerpro Slow Star
ACTIVE
Supply Status
ON
Supply Ready
READY
PPS
PERMIT
SCR
SCR 1 Stat
ON
SCR 2 Stat
ON

HER RF 8-3
Feedback

Print | Exit | Go To | Help

Station | Direct Lp | Ripple Lp | Drive Pwr | Gap Volt | Modu Diags

In ON_CW. Direct/Comb loops on.

Station State: DB ON_CW

	Direct Loop	Comb Loop
Loop Control	ON	ON
Loop Gain (dB)	13.2000	14.8000
Gain Offset (dB)	0.0000	0.0000
Conv Factor	183.0000	147.0053
DAC Counts	DB 836	DB 808
Loop Phase (Deg)	-12.7	2.5
Phase Offset (Deg)	DB 14.8	DB -24.7
Total Phase (Deg)	DB 2.0	DB -22.2
For Ramping ON: Gain Delta (dB)	1.0	5.0
Init Gain Offset (dB)	-10	-15

Tuner Loop: ON | Load Angle Offset: ON | Tuners

HVPS Loop: OFF | PROC | ON

HVPS Loop Status: DB GOOD

TUNE - DAC Control - ON_CW: ON | ON

DAC Control Status: DB GOOD

Direct Feedback Loop Options

Freq Offs Tracking: ON | Integral Compensation: ON | Lead Compensation: ON

Ripple Loop: ON | Gain Tracking: ON

Woofer State: Kick

Taxi Link OK

Gap FF Loop: ON | LFB Woofer: ON | Single TAXI sync: Send

Stn Gap Voltage (kV)	DB 2199	Stn Volt Plot
Gap Volt Setpoint (kV)	2200	
HVPS Voltage (kV)	DB 72.42	HVPS Volt Plot
Klys Out Fwd Pwr (kW)	DB 749	Klys Pwr Plot
Drive Power (W)	DB 16.3	Drive Pwr Plot
Drive Pwr Setpoint (W)	14.0	
High Pwr Drive Pwr (W)	16.0	
Saturatd Drive Pwr (W)	40.0	

Klys Gain (dB): DB 46.6

Gain Setpoint(dB): 46.2000

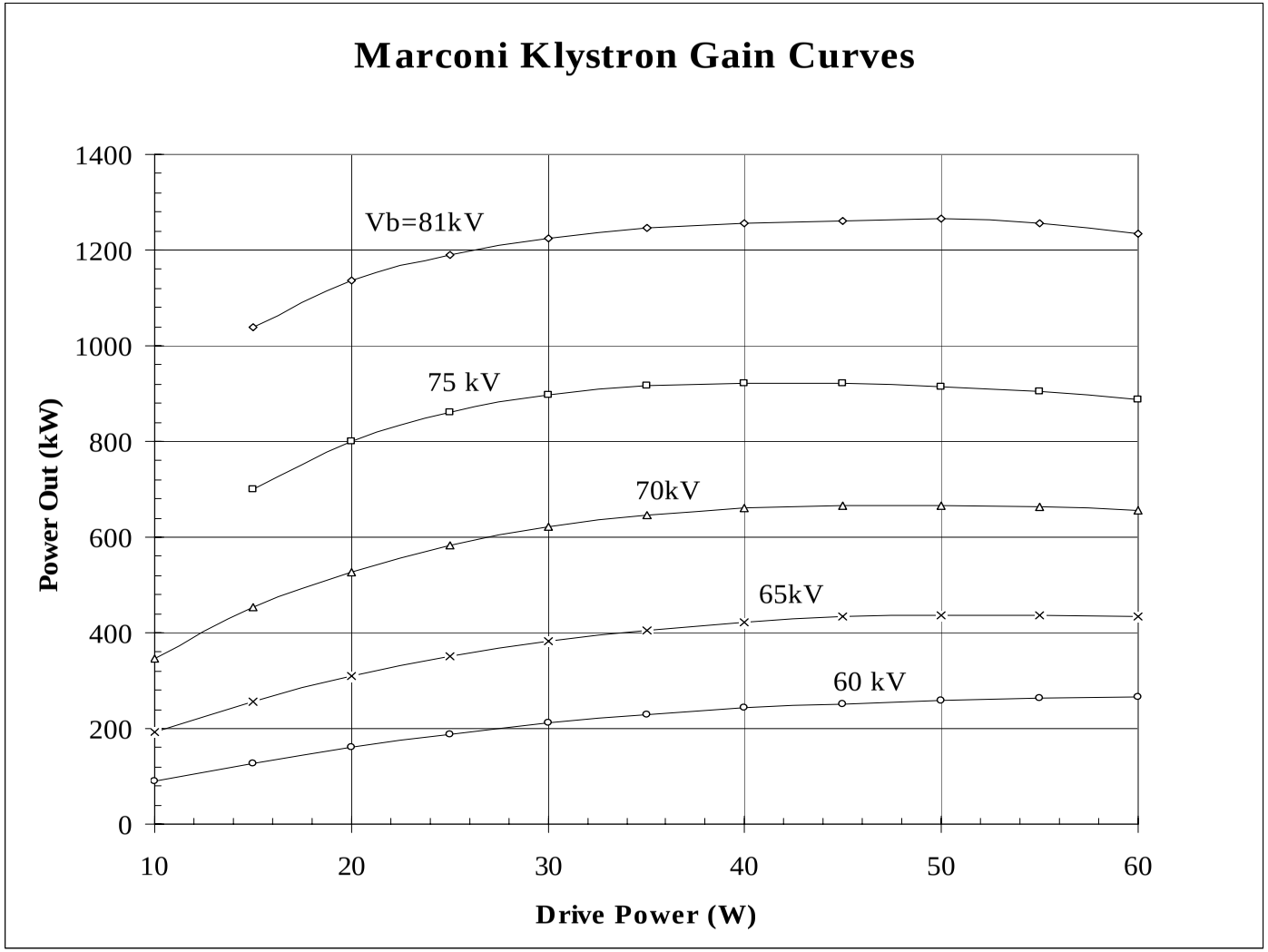
Station Phase (Deg)

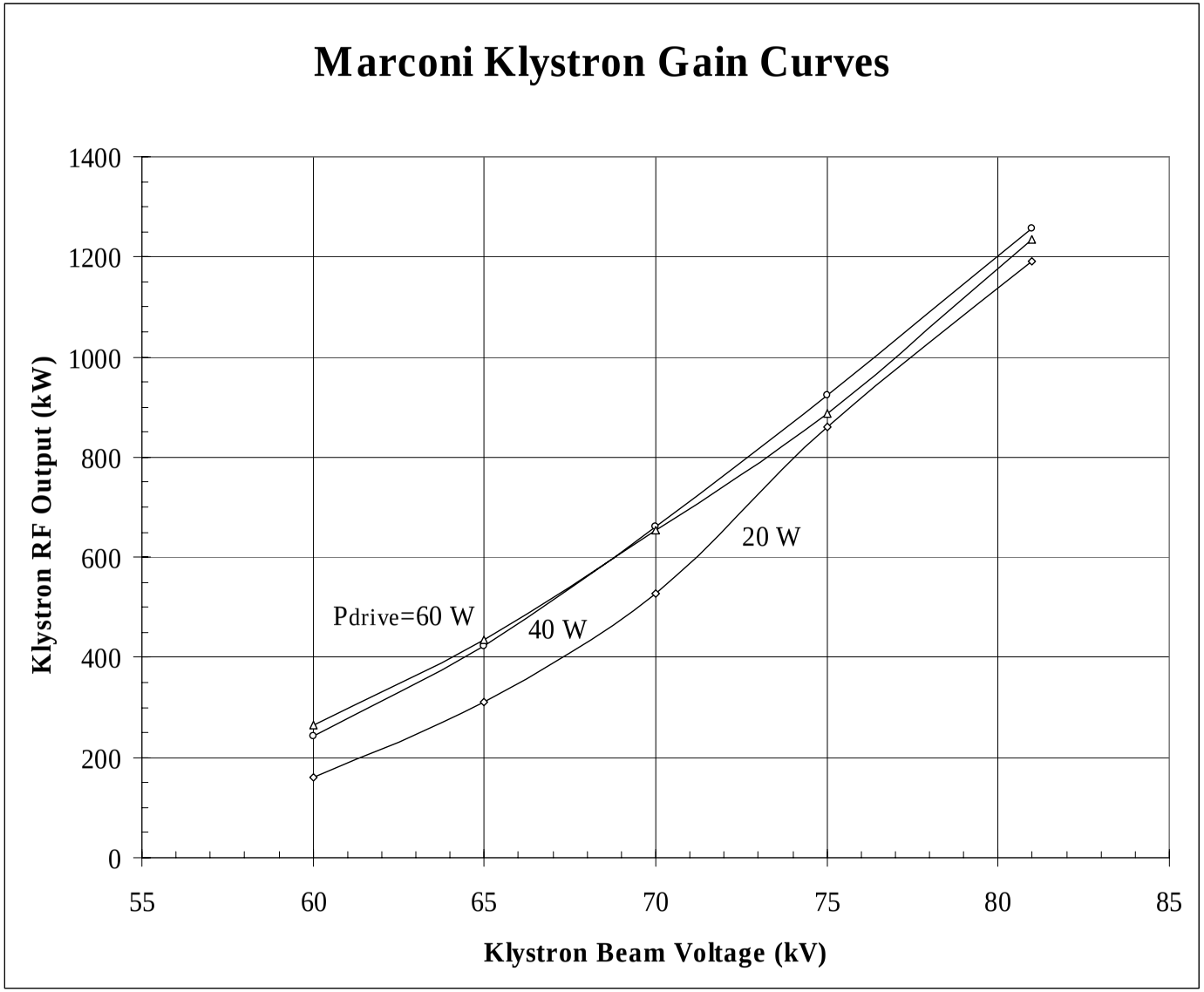
Offset	104.81	Ramp Delta	0.1
Base	-133.01	Monitor Delta	0.1
Total	DB -13.4	Cav Freq Offset	DB 14.8

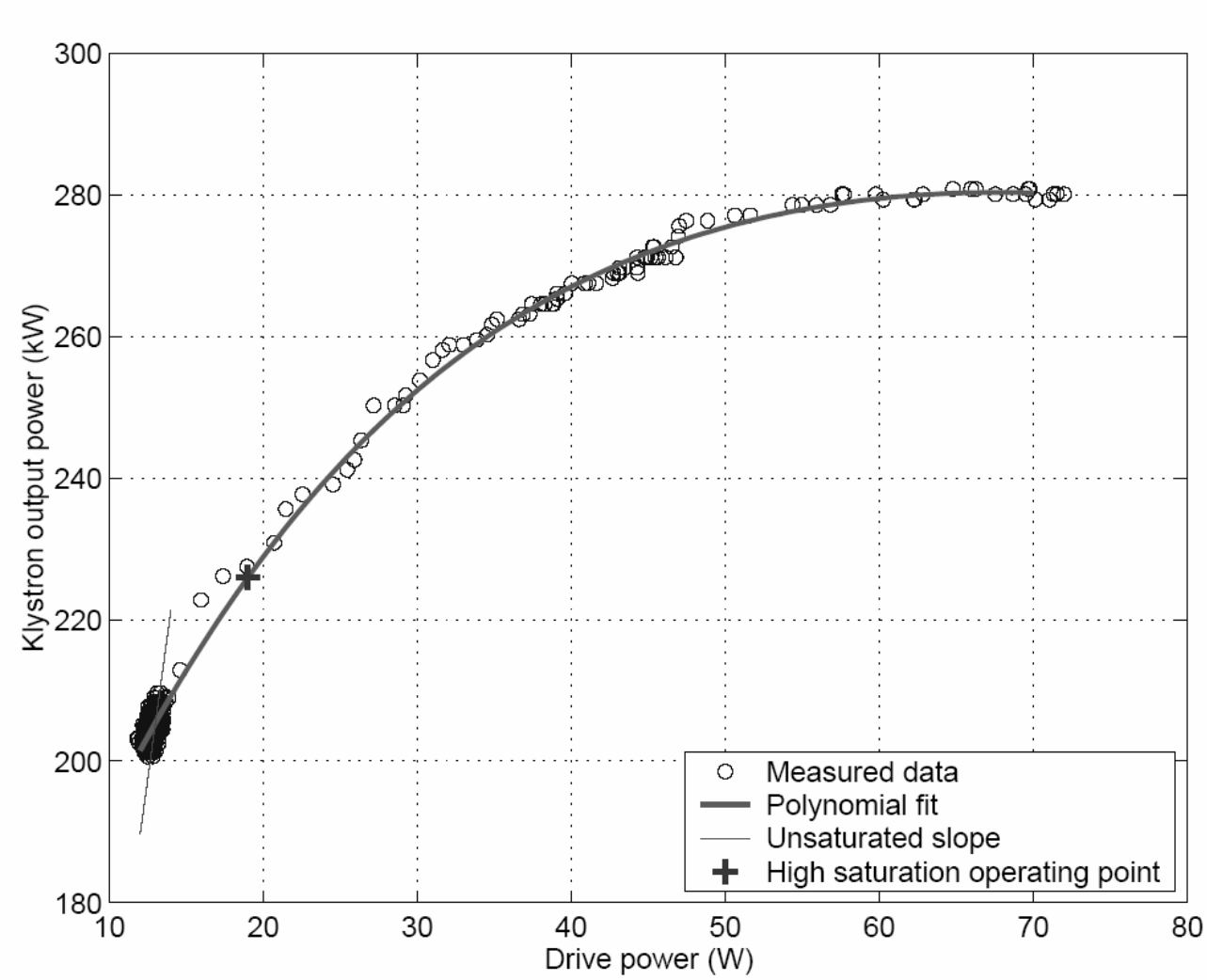
MATLAB Applications

Meas Rippl | MeasDirCls | MoreMATLAB

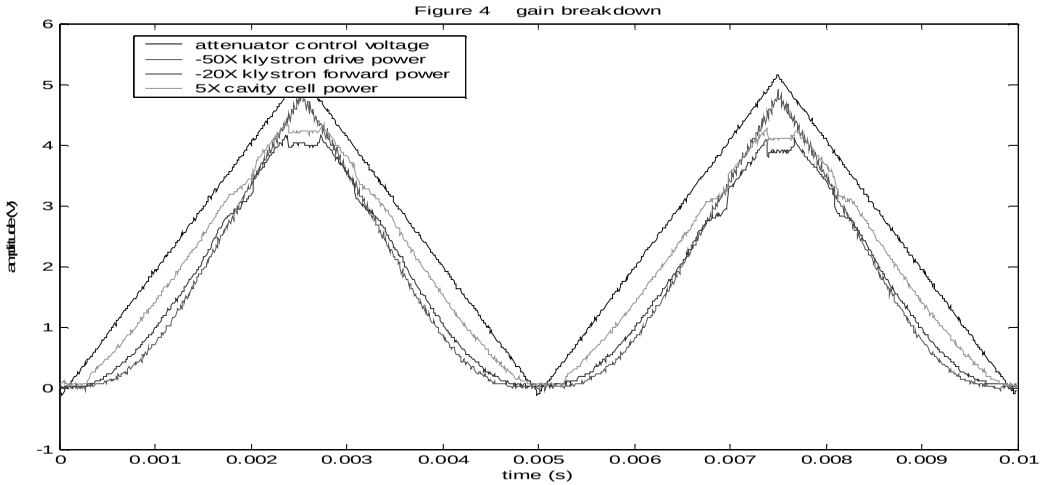
Plot Total | MeasBmPhs

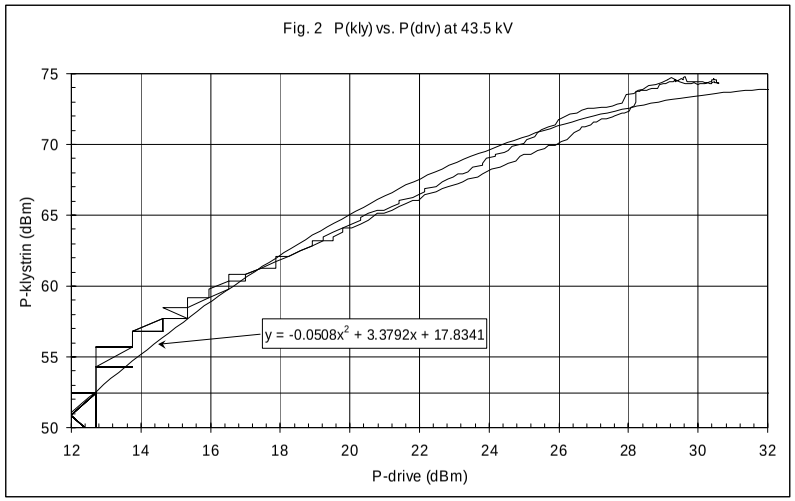

Marconi Klystron Gain Curves
Power Out (kW)
1400
1200
1000
800
600
400
200
0
10
20
30
40
50
60
Drive Power (W)
Vb=81kV
75 kV
70kV
65kV
60 kV

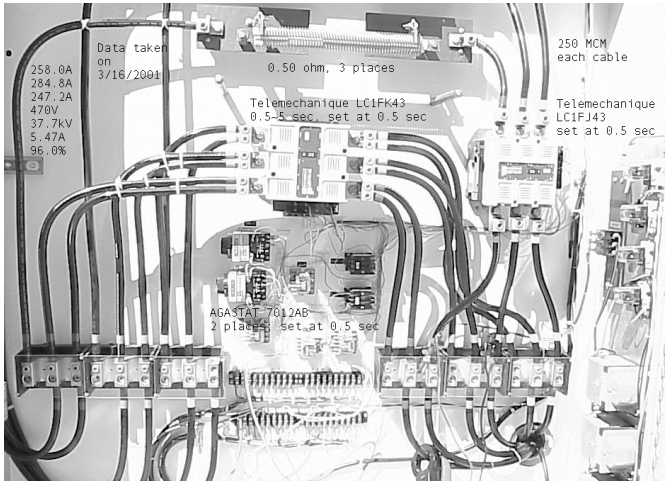

Marconi Klystron Gain Curves
Klystron RF Output (kW)
1400
1200
1000
800
600
400
200
0
55
60
65
70
75
80
85
Klystron Beam Voltage (kV)
Pdrive=60 W
40 W
20 W


300
280
260
240
220
200
180
10
20
30
40
50
60
70
80
Klystron output power (kW)
Drive power (W)
Measured data
Polynomial fit
Unsaturated slope
High saturation operating point

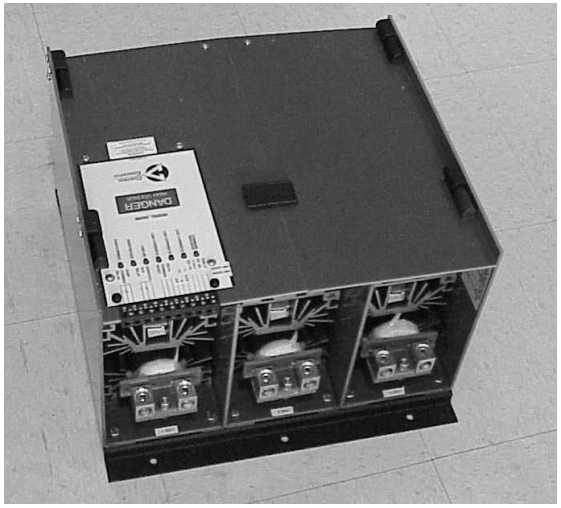
Booster klystron saturation





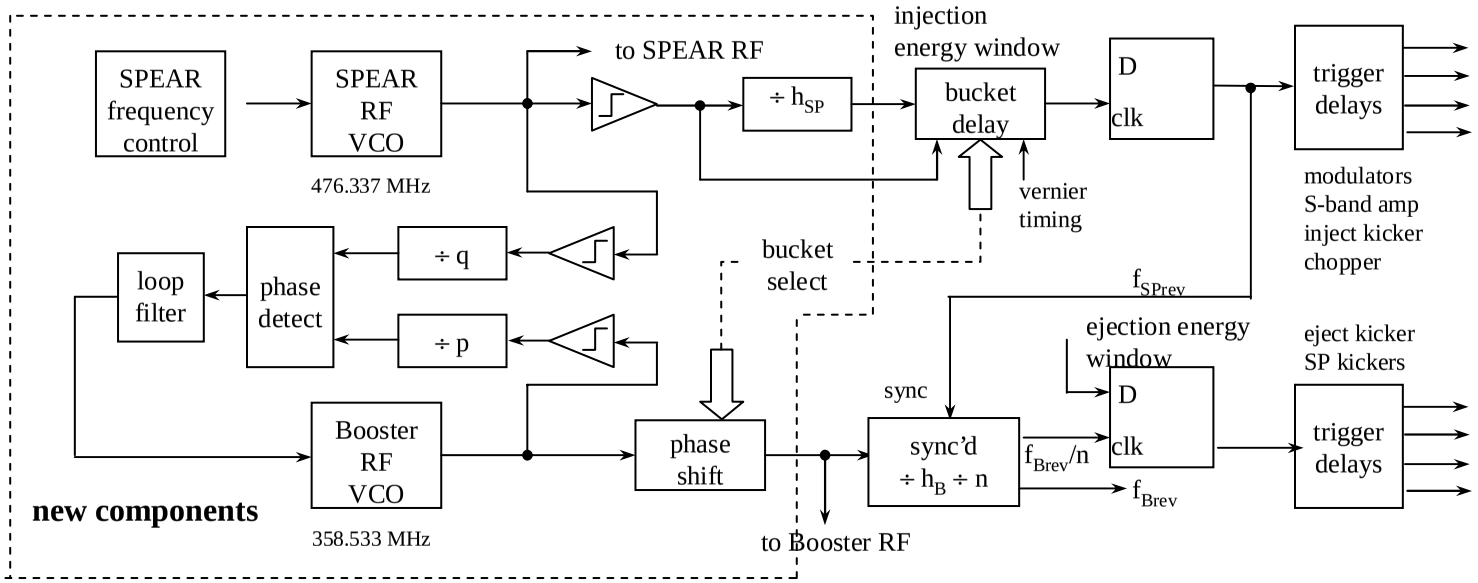


Existing Booster RF Soft-Start, Mechanical

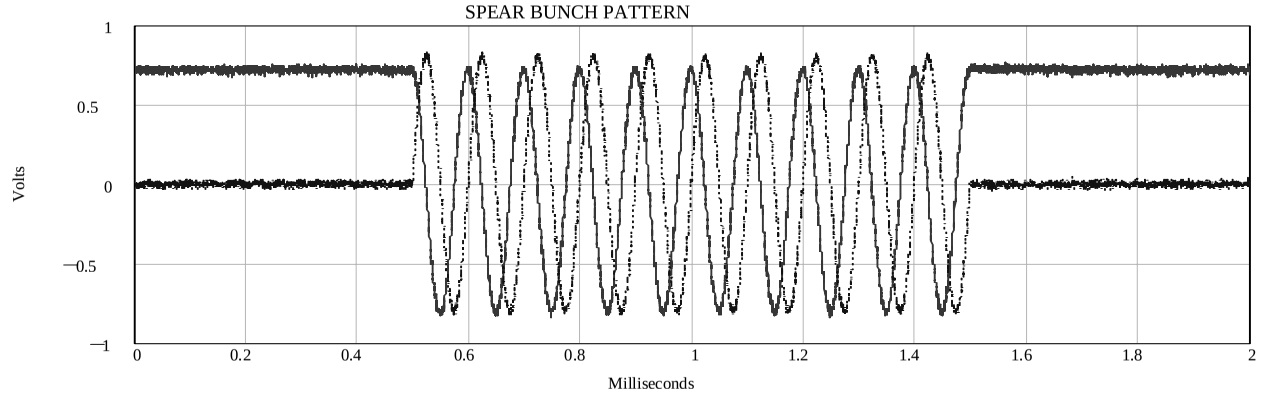


SCR Assembly with Built-In Soft Start

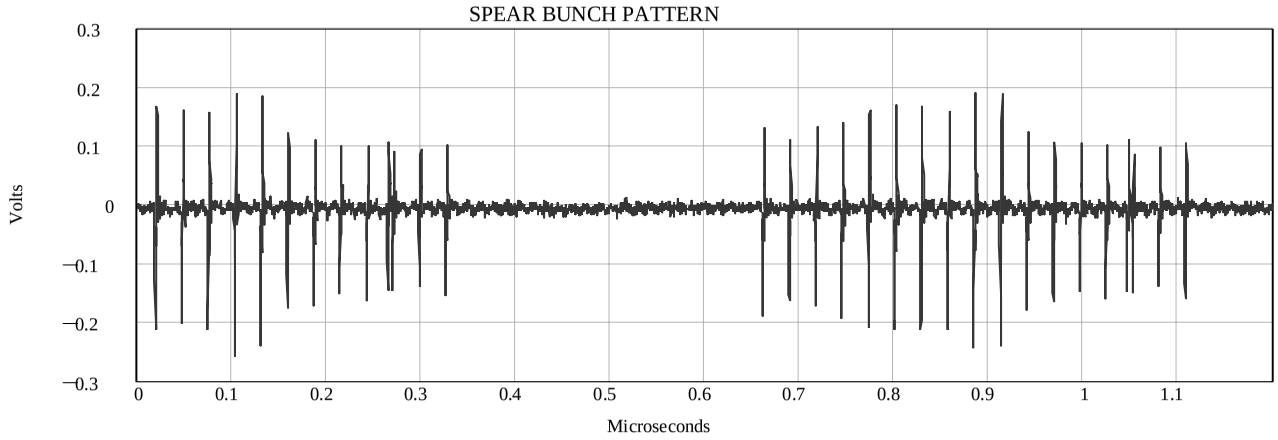
Timing System



- Single-bunch filling
- Phase-lock Booster RF (358.505 MHz)
  to SPEAR RF (476.300 MHz)
- $C_{Boo}/C_{SPEAR} = 4 / 7$
- $f_{Boo}/f_{SPEAR} = 70 / 93$



Driving I&Q Modulator



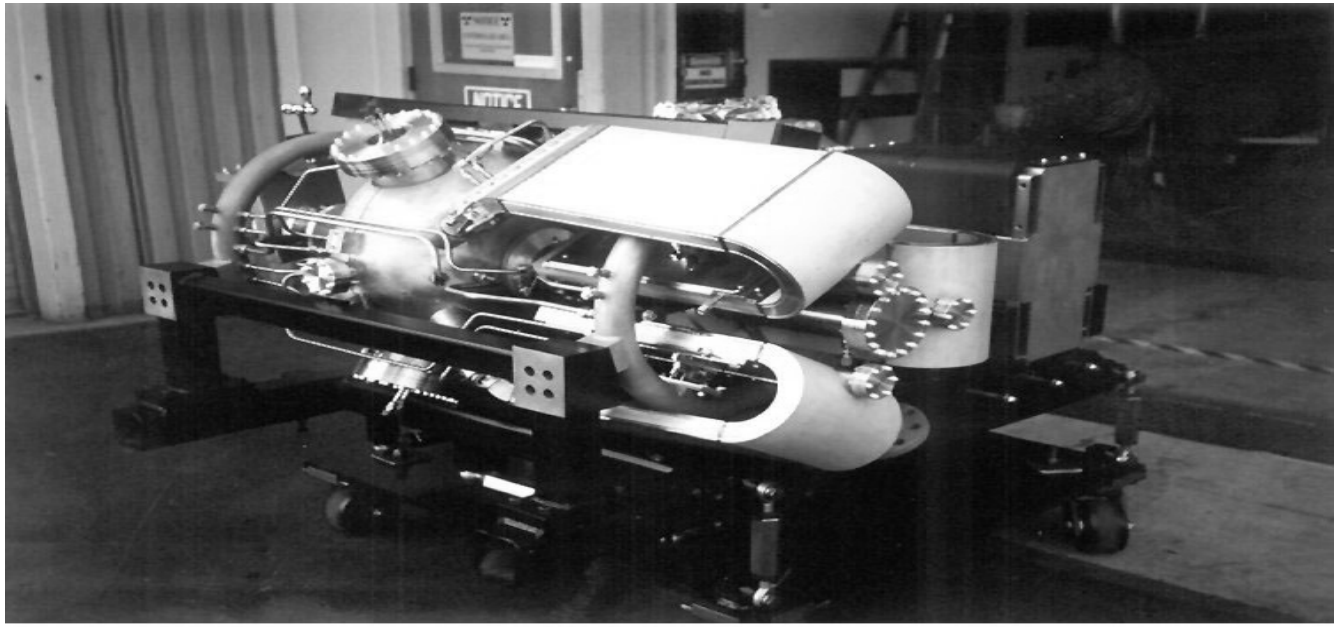
Test Fill Pattern in Spear2

SPEAR 3 Cavity Production

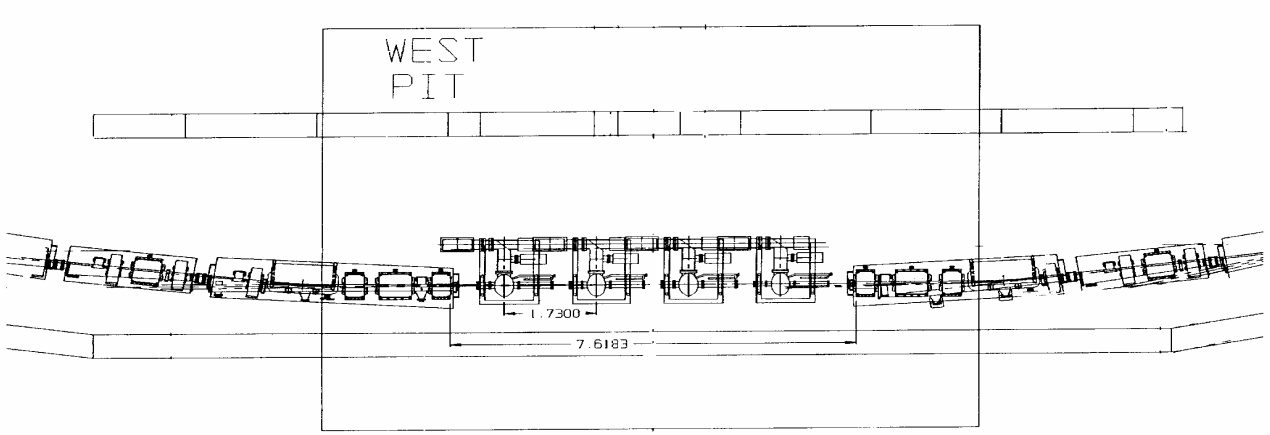
Cavity body milling at Accel

Electroforming at Accel

SPEAR 3 (PEP-II) RF Cavities



BR_040 RF Cavity 8-19-97



PEP-II RF Cavity Assemblies

CAV_13 PEP- II RF Cavity 8-19-97