# BNL 200 MeV Linac

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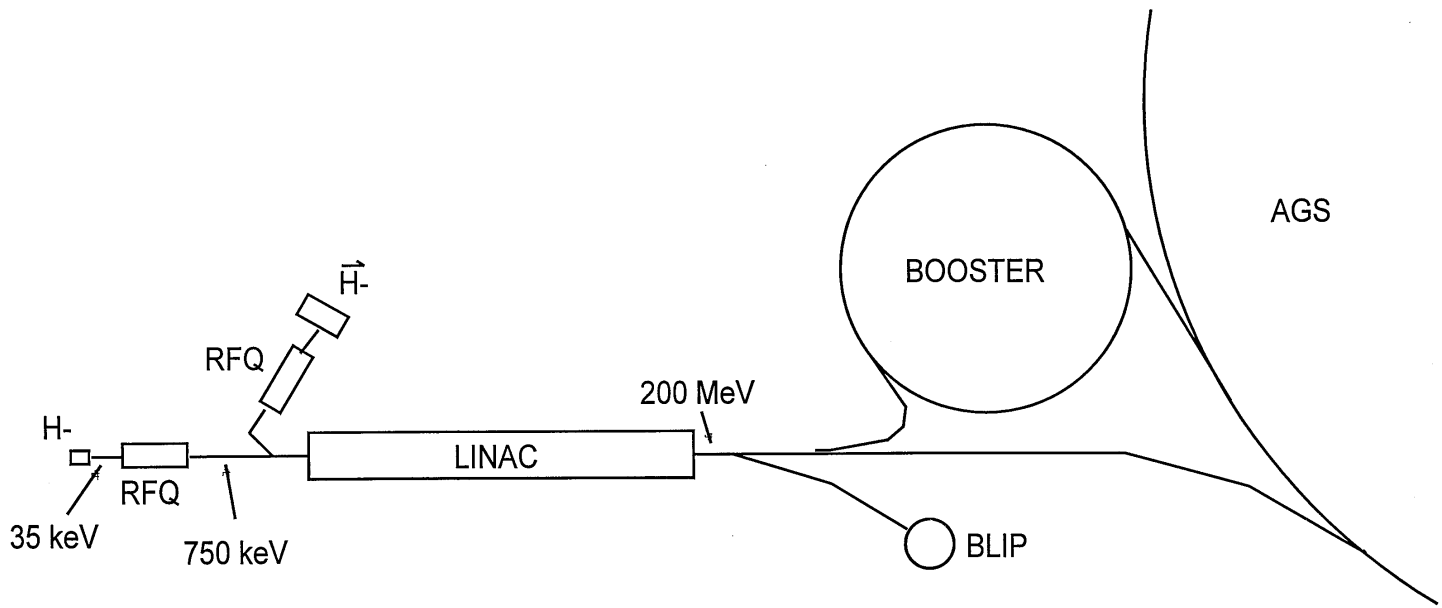
# Acknowledgements


- Contributors: J
  V. Lodstro, B. Brosco

# General Parameters

- H-
- Energy = 200 MeV
- Current 35 mA
- 500 μs, 7.5 Hz
- Up to 150 μA avg. for BLIP
- Polarized proton 300 μA, 65% Polarization

# Linac Layout



# Linac History

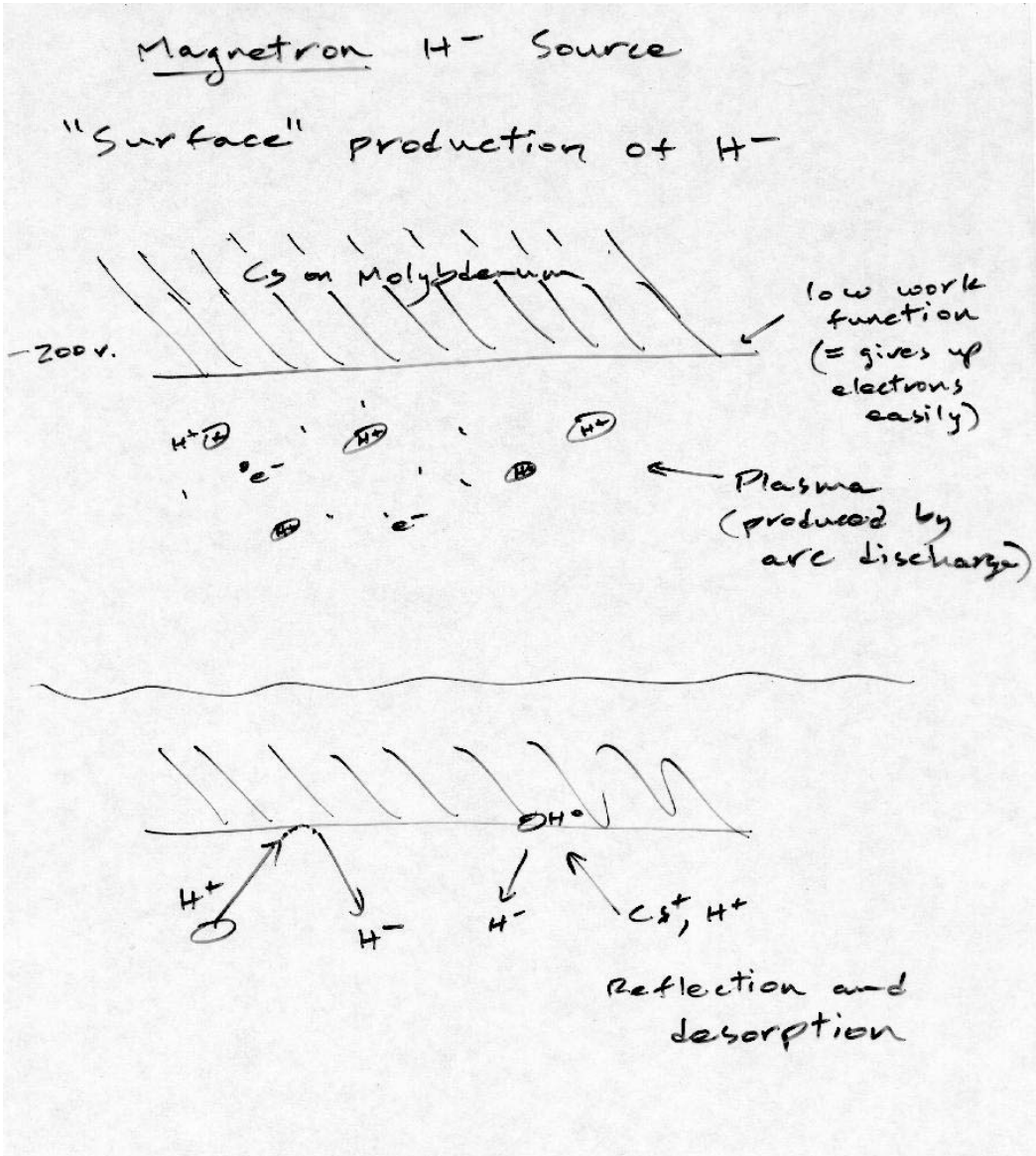
- Construction started -April, 1967
- First Beam - November, 1970
- Total Facility Cost 22.5 M$

| Year | Rep-Rate Hz | Beam Width µs | Current mA | Avg. Current µA |
|---|---|---|---|---|
| 1970 | 10 | 200 | 100 | 200 |
| 1972 | 10 | 100 | 55 | 44 |
| 1973-75 | 10 | 100 | 60 | 60 |
| 1976- | | Switch to 5 Hz Operation | | |
| 1979 | 5 | 220 | 50-70 | 55-77 |
| 1982 | | Switch to H- acceleration | | |
| 1984 | 5 | 200 | 25 | 25 |
| 1984 | | Add Polarized H- Operation | | |
| 1986 | 5 | 470 | 25-30 | 59-71 |
| 1989 | | Switch To RFW Pre-Injector | | |
| 1990 | 5 | 500 | 25 | 63 |
| 1996 | 7.5 | 330(500) | 38 | 95(155) |
| 2000 | | Add OPPIS for polarized Proton | | |

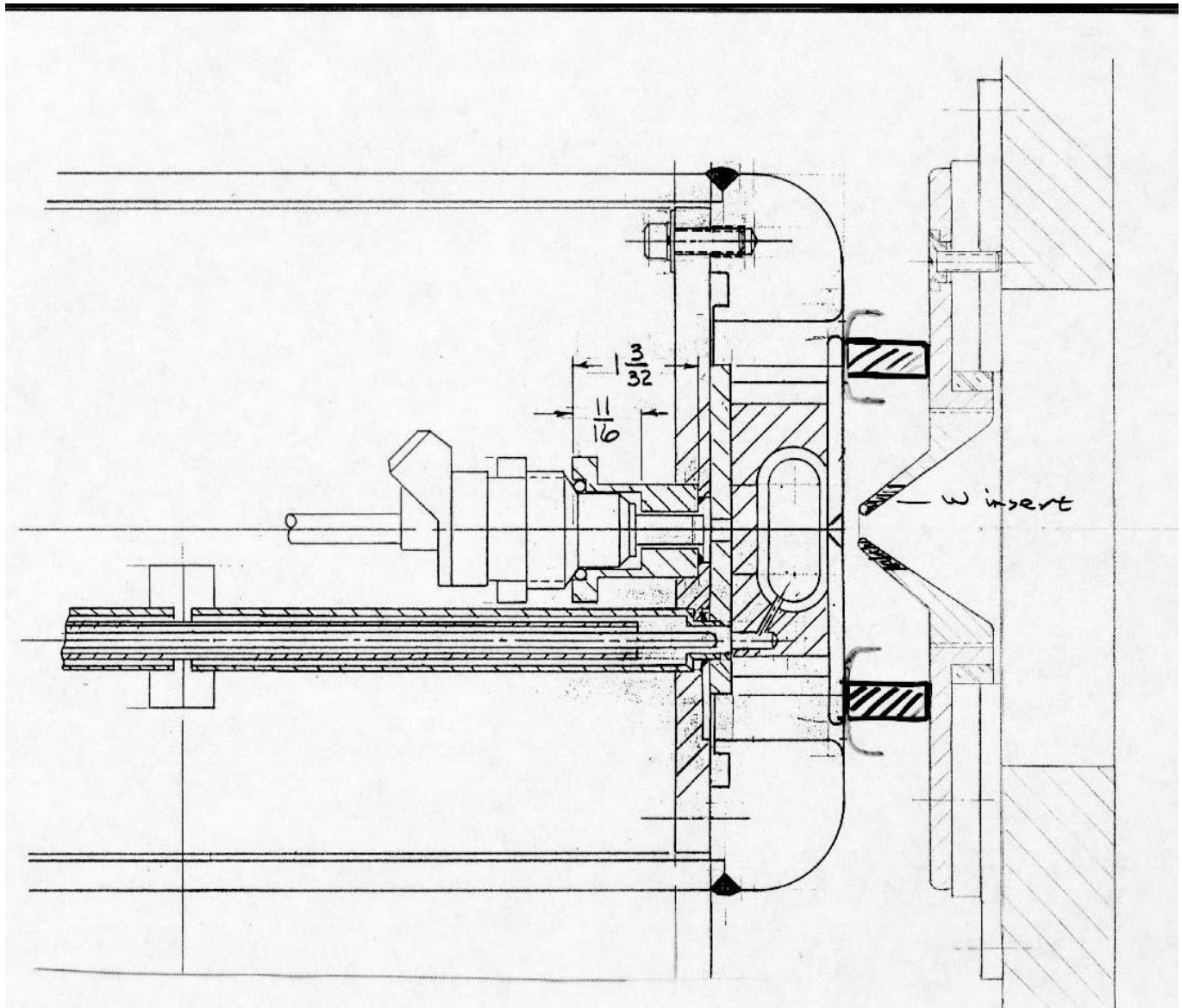
# Ion-Source

- Magnetron H- (same as FNAL except circular aperture instead of slit)
- 80-120 mA, 35 keV extraction (e/H- :0.5 – 1.)
- 700 μs,10 Hz
- Emittance = 0.375 π mm mrad (rms, nor)
- Runs for 3-6 months continuous, very stable, 8 Hours to replace and restart
- Used for last 18 years

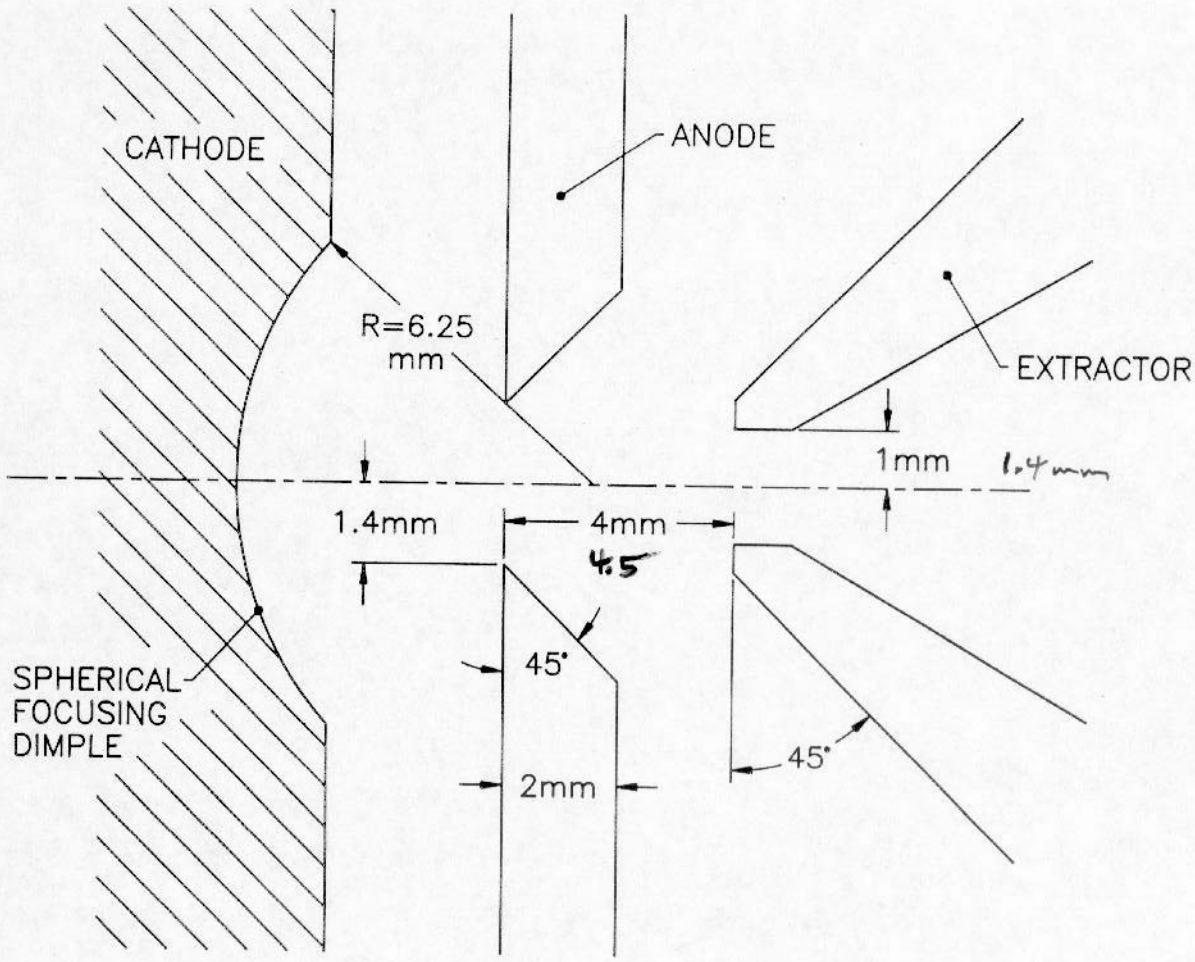
# Ion Source Working



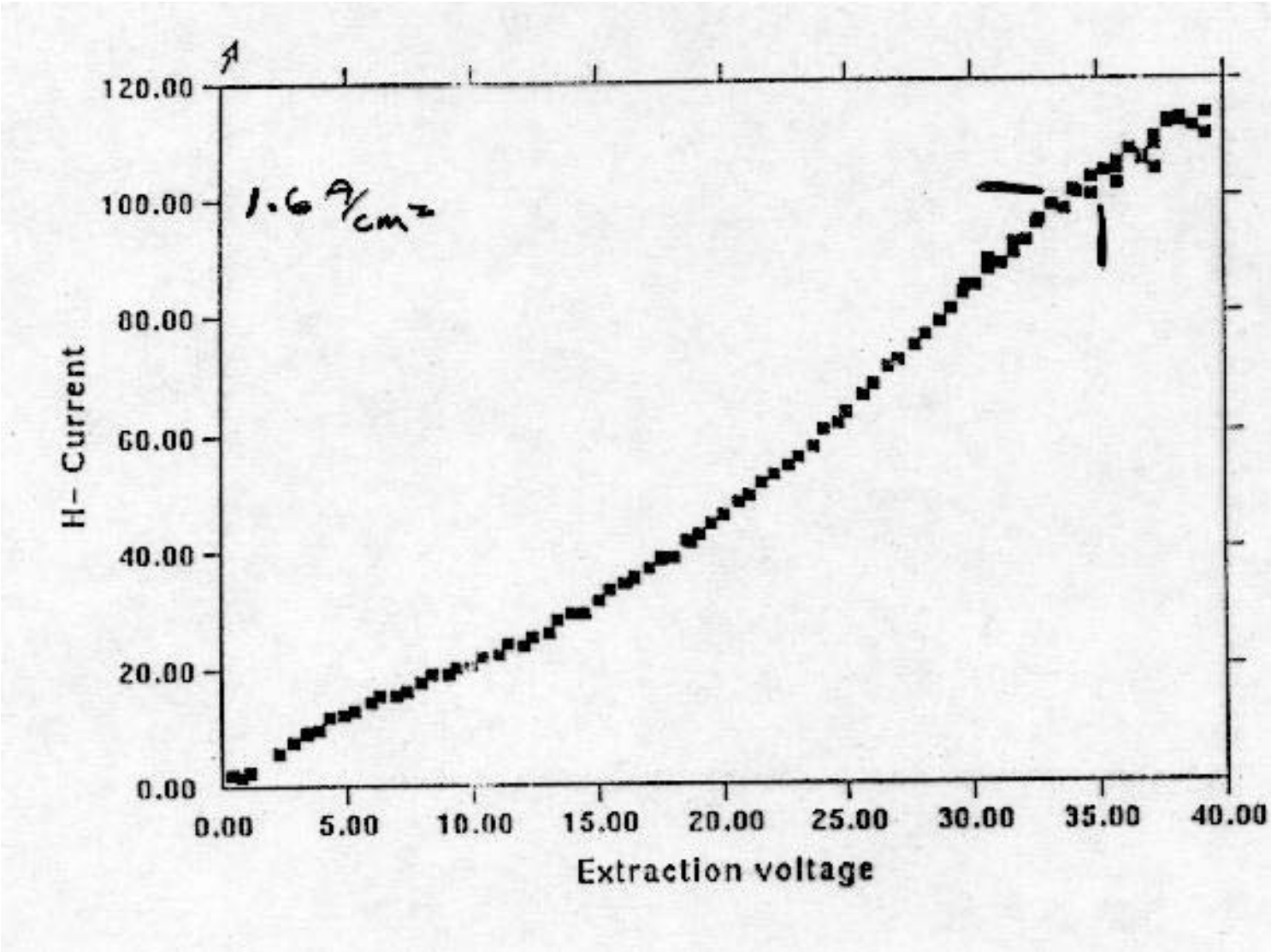
# Ion Source



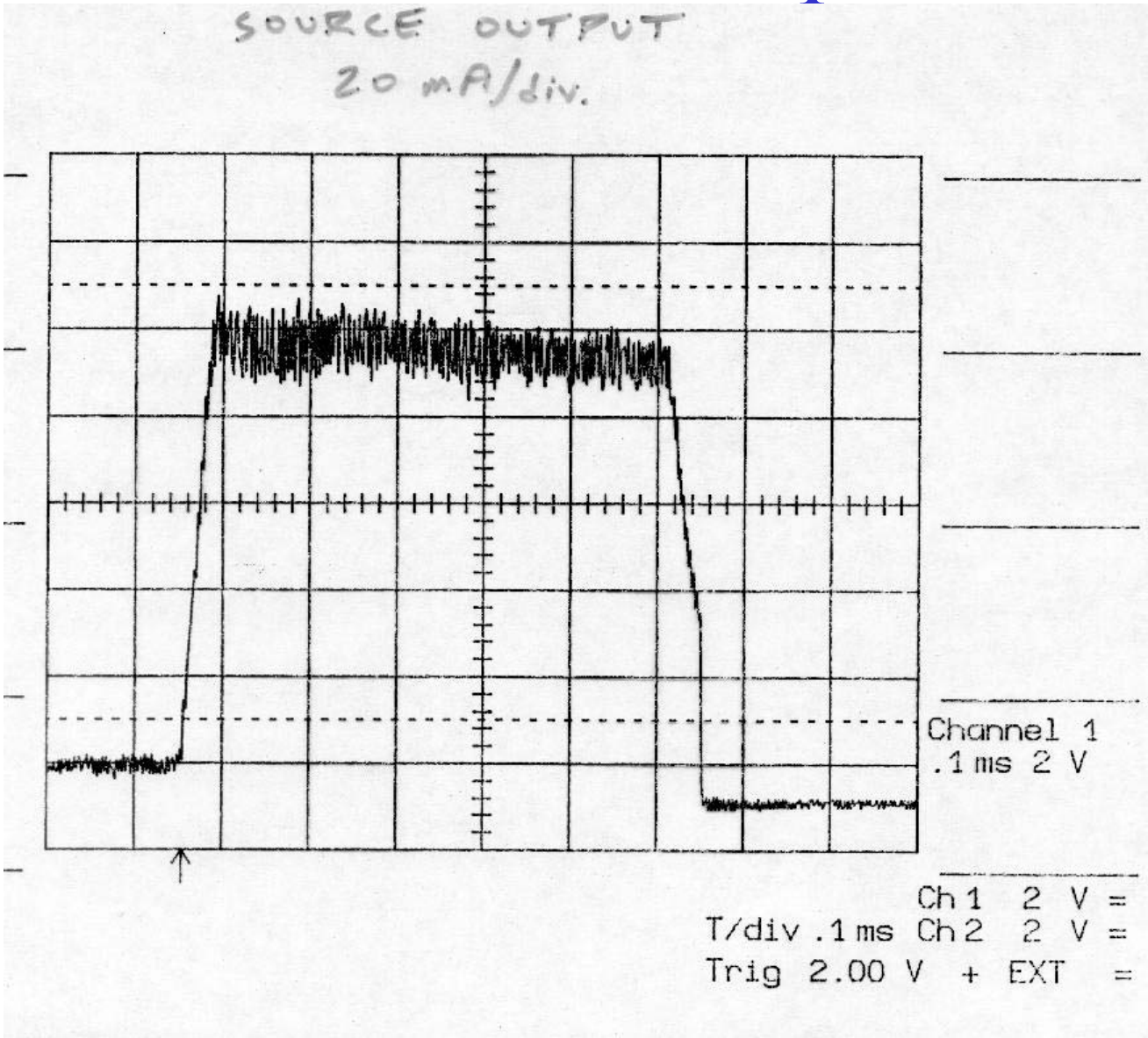
# Ion Source Extraction



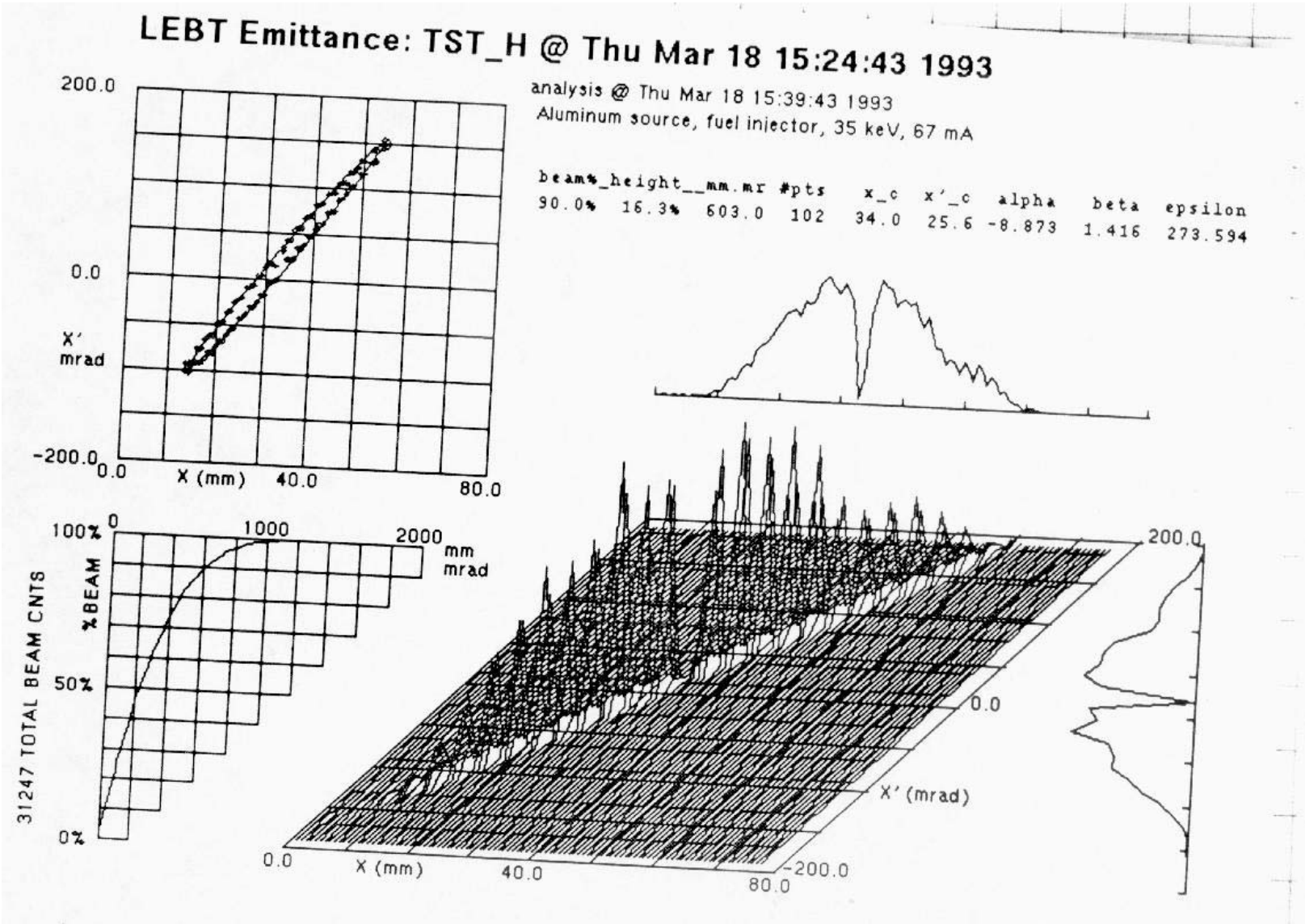
# Current vs Extraction Voltage



# Ion Source Output

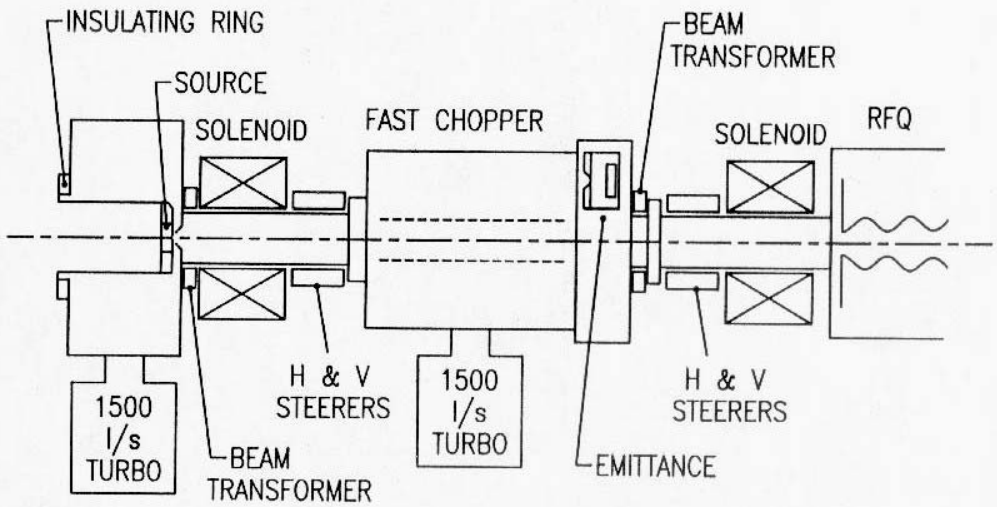


# Ion Source Emittance



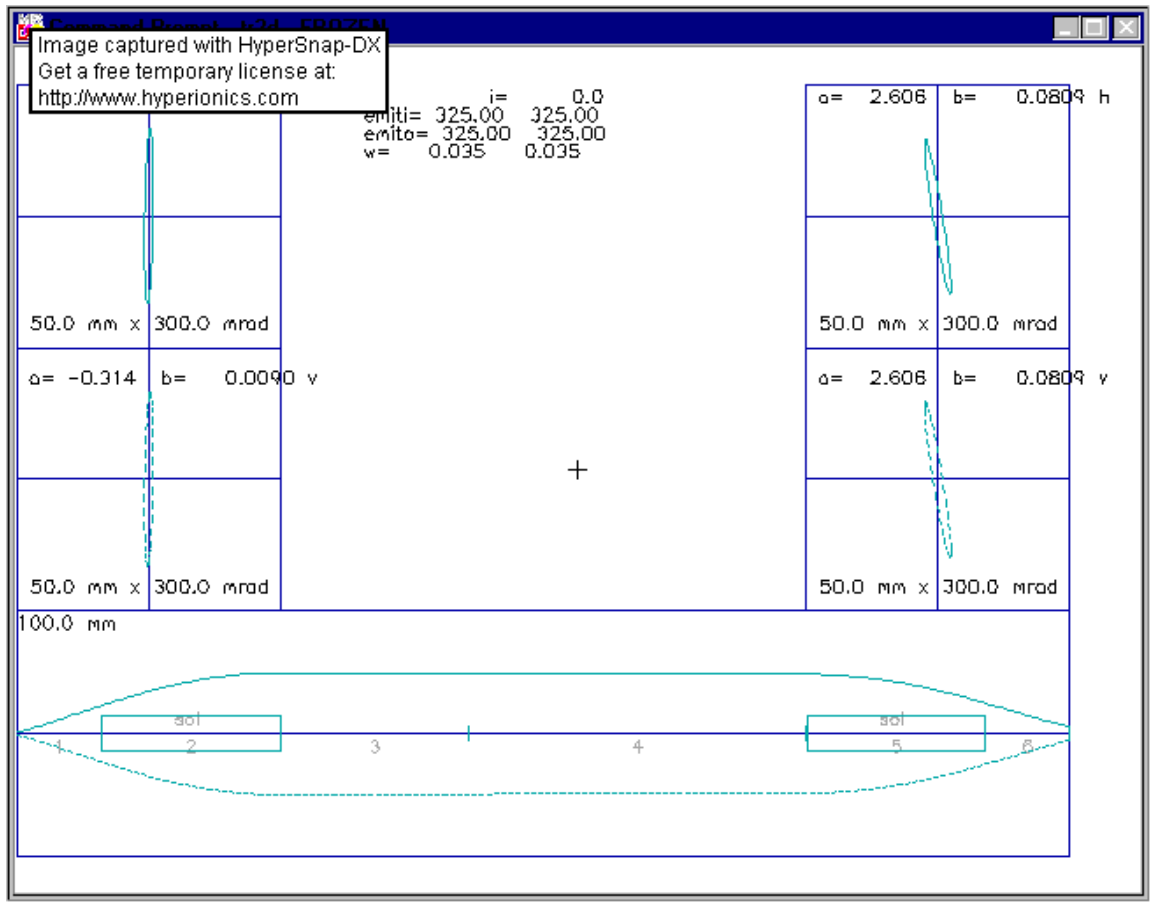
# Photo of Source

# LEBT Layout


INSULATING RING
SOURCE
SOLENOID
FAST CHOPPER
BEAM TRANSFORMER
SOLENOID
RFQ
1500 l/s TURBO
H & V STEERERS
BEAM TRANSFORMER
1500 l/s TURBO
EMITTANCE
H & V STEERERS

# LEBT

- 1.4 meters long, 2 solenoids, pulsed (2.5 kG)



# Photo of OPPIS LEBT

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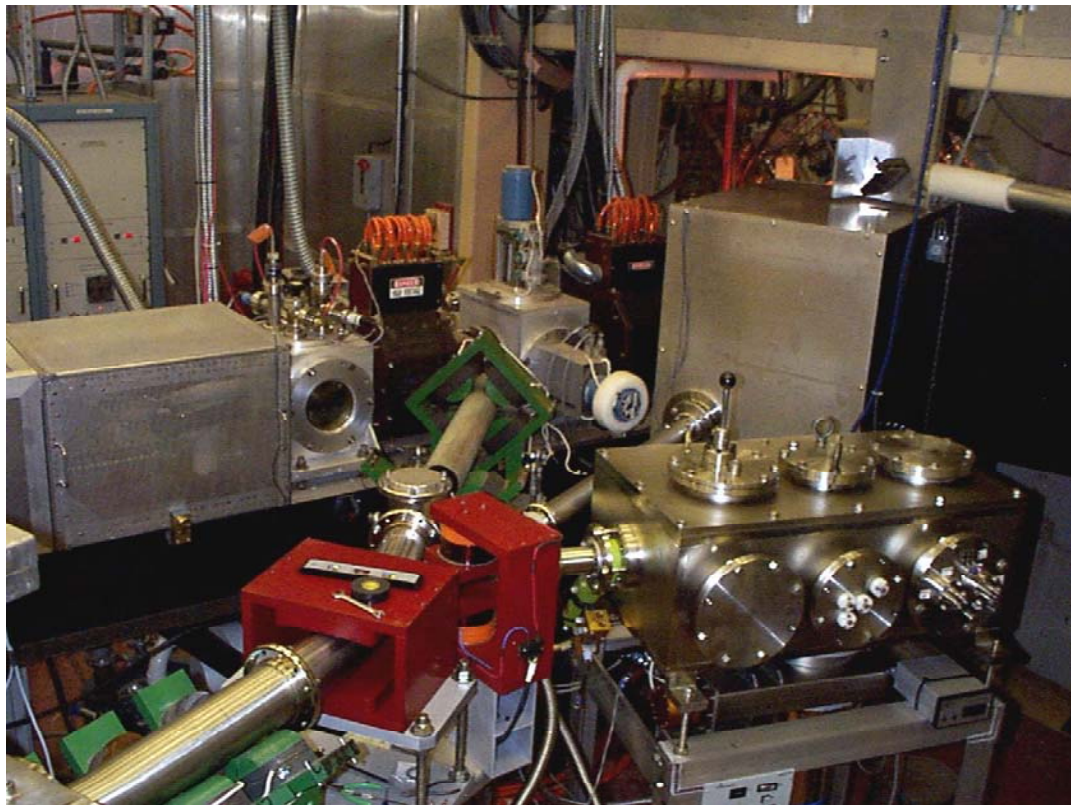
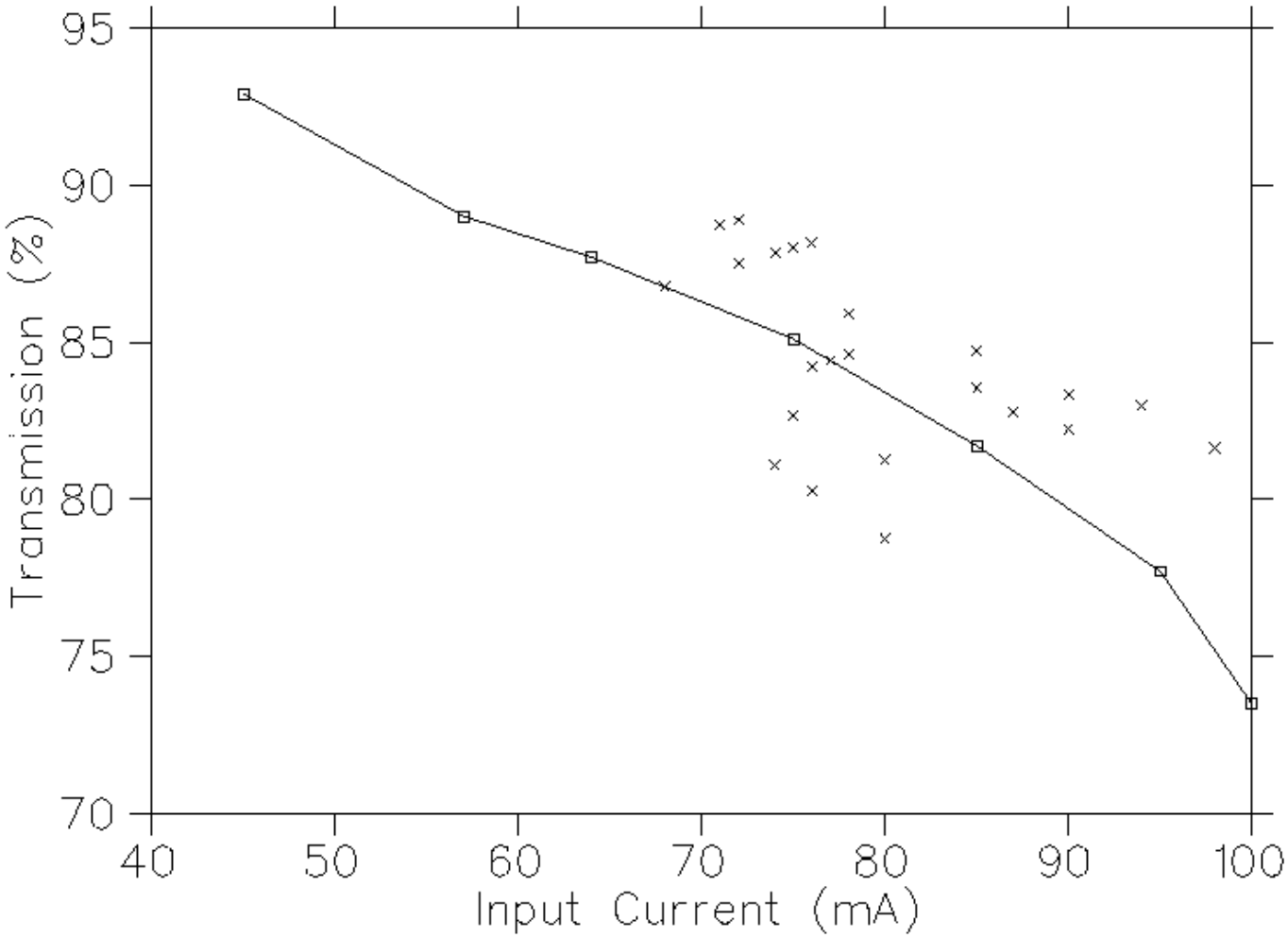
# Photo of OPPIS LEBT



# RFQ

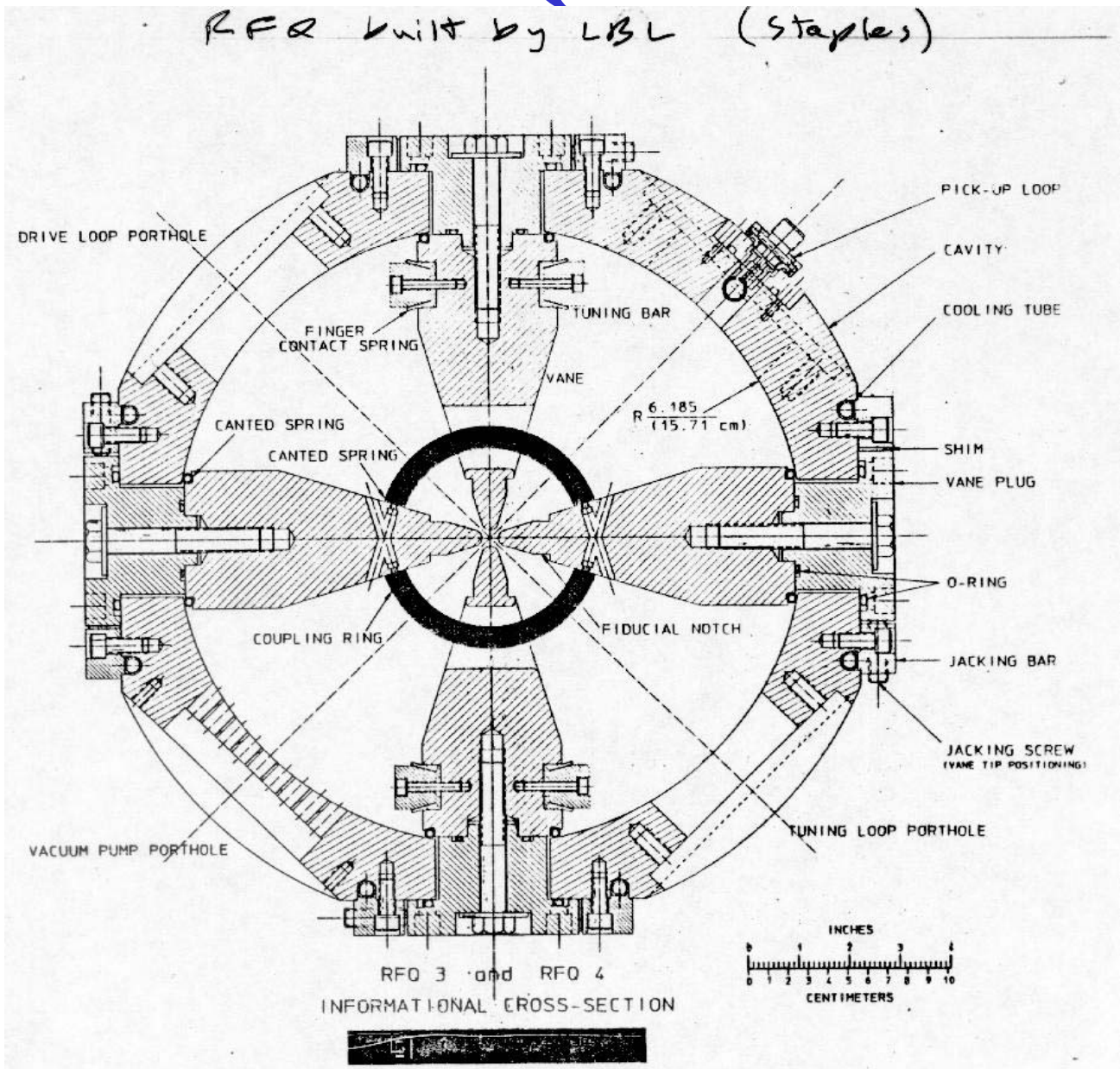
- Built by LBL;  (1989)
- 35 keV --> 750 keV
- 1.6 meters,146 cells, P=121+35 kW, 1.48Kp, Vane Voltage 67.2 kV,Q=6644
- Transmission (80-90%)
- Input and output emittance (0.375 -0.400)
- Runs extremely reliably - **no downtime in 10 years**

# RFQ Transmission

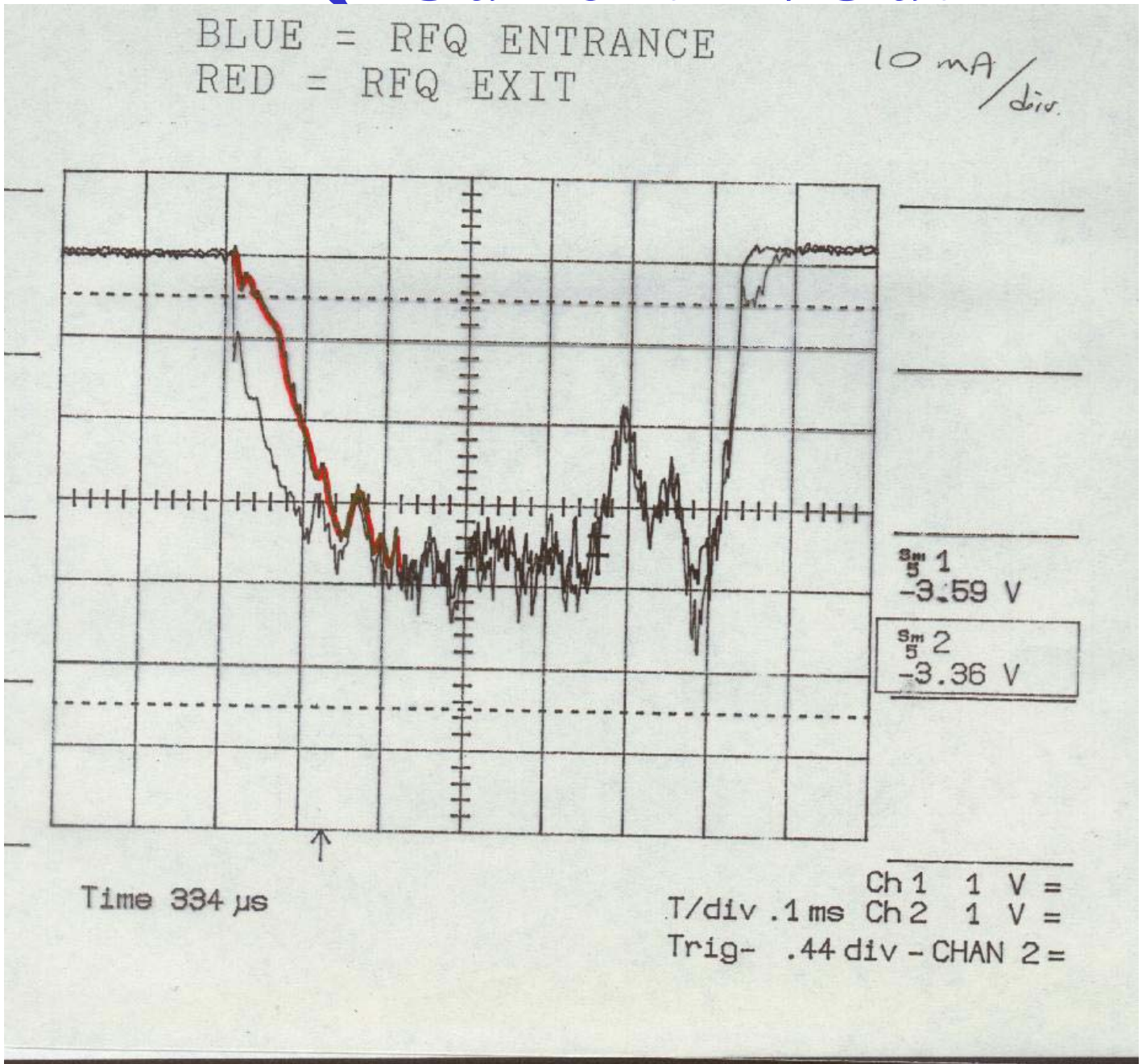


# Photo of RFQ

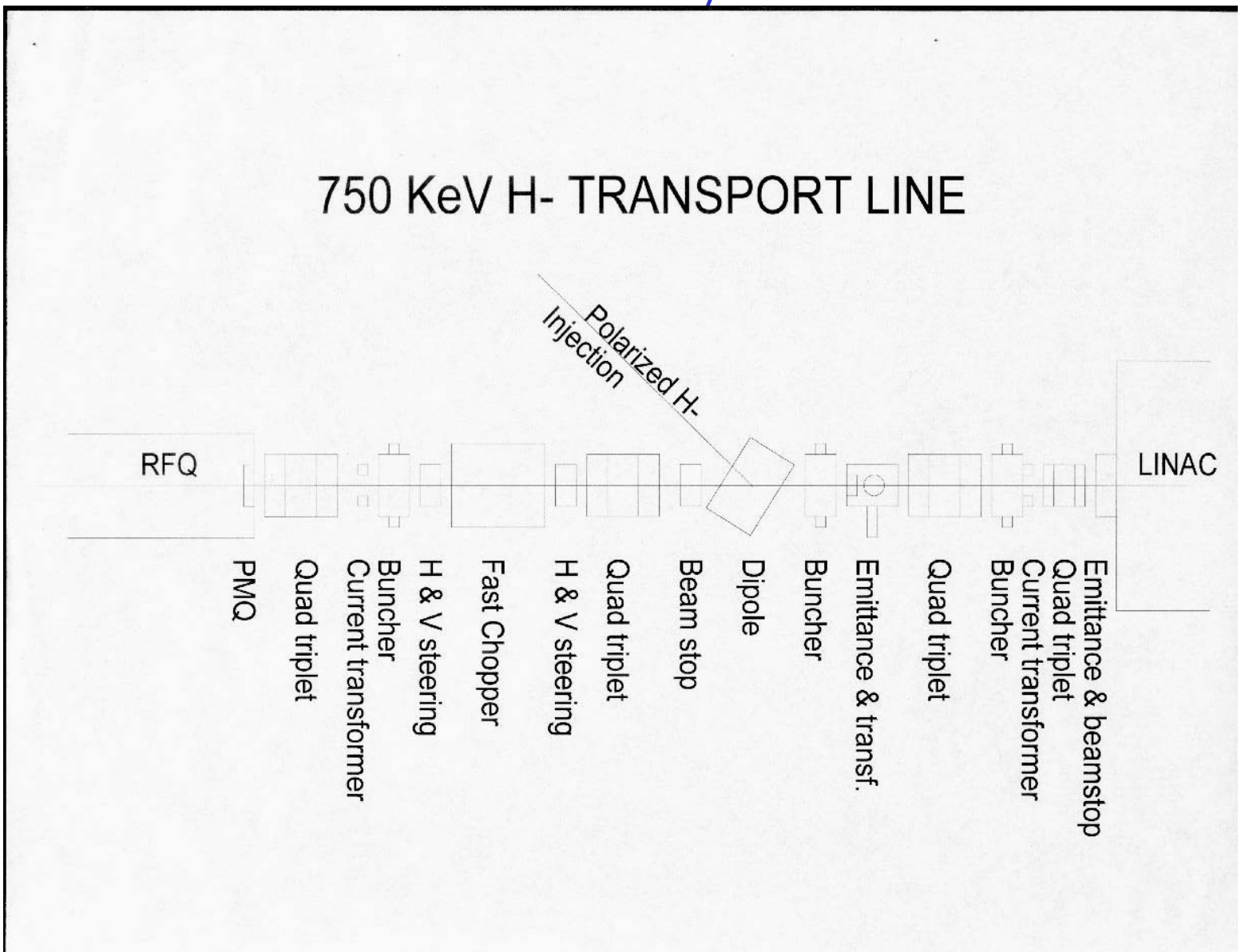
# RFQ


RFQ built by LBL (Staples)
PICK-UP LOOP
CAVITY
COOLING TUBE
DRIVE LOOP PORTHOLE
TUNING BAR
FINGER CONTACT SPRING
VANE
R 6.185 (15.71 cm)
CANTED SPRING
CANTED SPRING
SHIM
VANE PLUG
O-RING
COUPLING RING
FIDUCIAL NOTCH
JACKING BAR
JACKING SCREW (VANE TIP POSITIONING)
TUNING LOOP PORTHOLE
VACUUM PUMP PORTHOLE
INCHES
CENTIMETERS
RFQ 3 and RFQ 4
INFORMATIONAL CROSS-SECTION

# RFQ Current In/Out



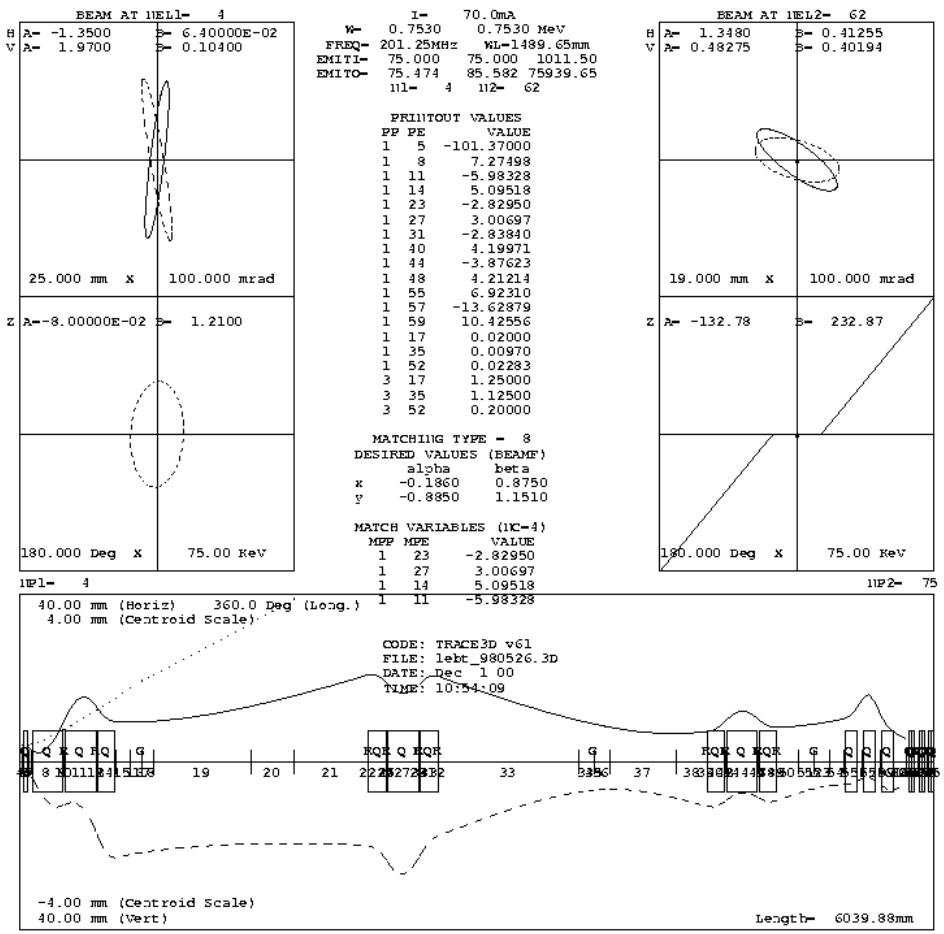
# MEBT Layout


750 KeV H- TRANSPORT LINE
Polarized H-
Injection
RFQ
LINAC
PMQ
Quad triplet
Current transformer
Buncher
H & V steering
Fast Chopper
H & V steering
Quad triplet
Beam stop
Dipole
Buncher
Emittance & transf.
Quad triplet
Buncher
Current transformer
Quad triplet
Emittance & beamstop

# MEBT

- Performance - measured
  - transmission (80-85%)
  - emittance -0.56π mm mrad, (rms, Nor)
- Bunching - longitudinal matching questions

# MEBT (750 keV) Trace

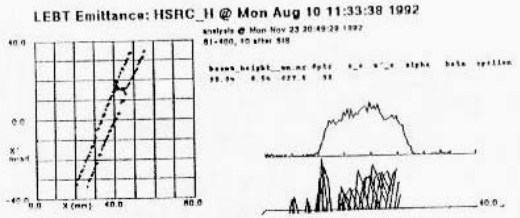


# 35 keV Chopper

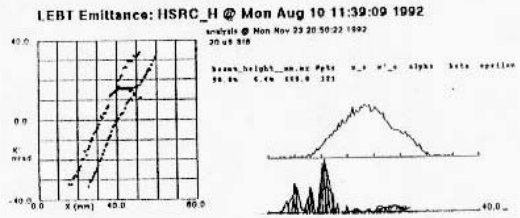
- 38 cm long, 8 cm gap, 15 plates
- ±800 Volts: 110 mrad kick, rise time 10 ns, beam rejected at entrance to RFQ
- Space Charge effects: Need much higher Voltage than expected to get good rejection,
- Chopper off: lose 1/3 beam current due to emittance distortion from back ground ions.

# Neutralization in LEBT

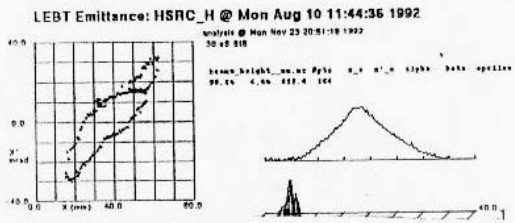
10 μs



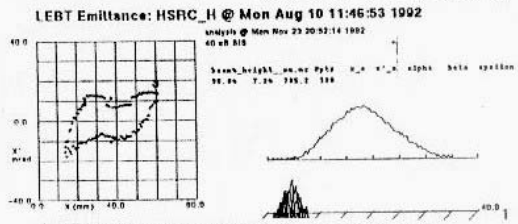

20 μs



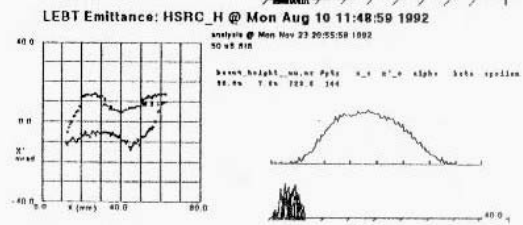

30 μs

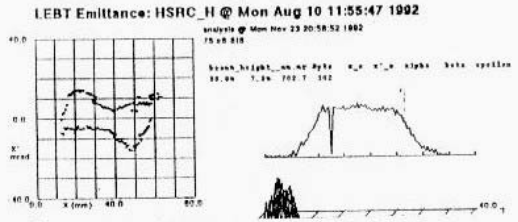



40 μs

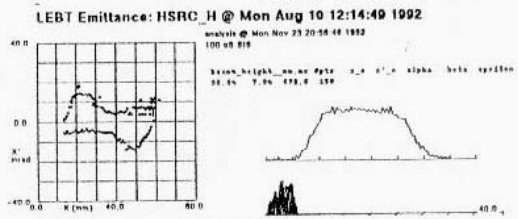



50 μs

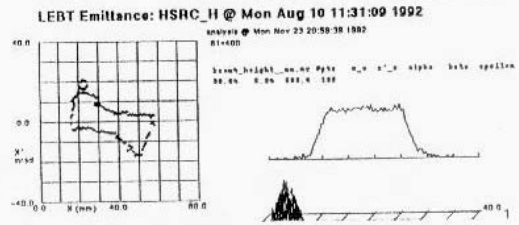


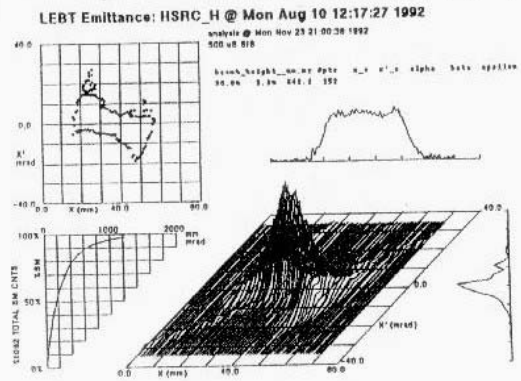

75 μs




100 μs



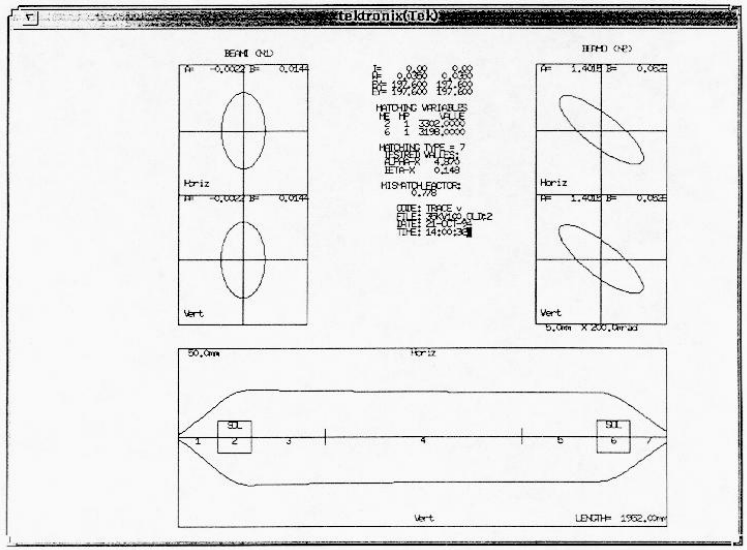

300 μs

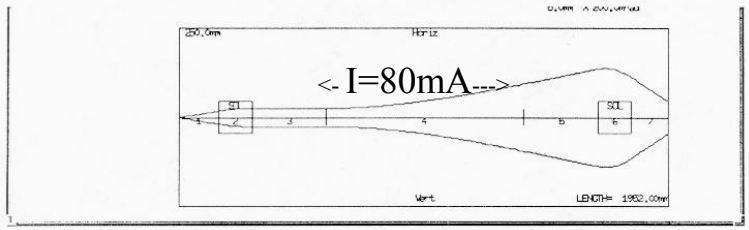



500 μs

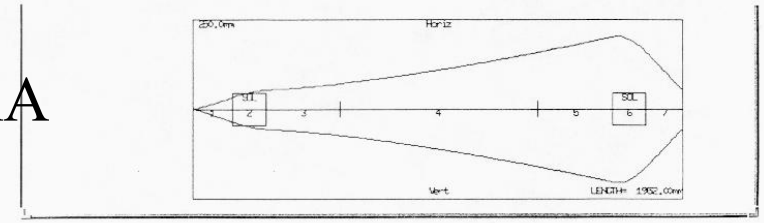
# Neutralization in LEBT (Trace)

I=0




I=80 mA



# Neutralization in MEBT

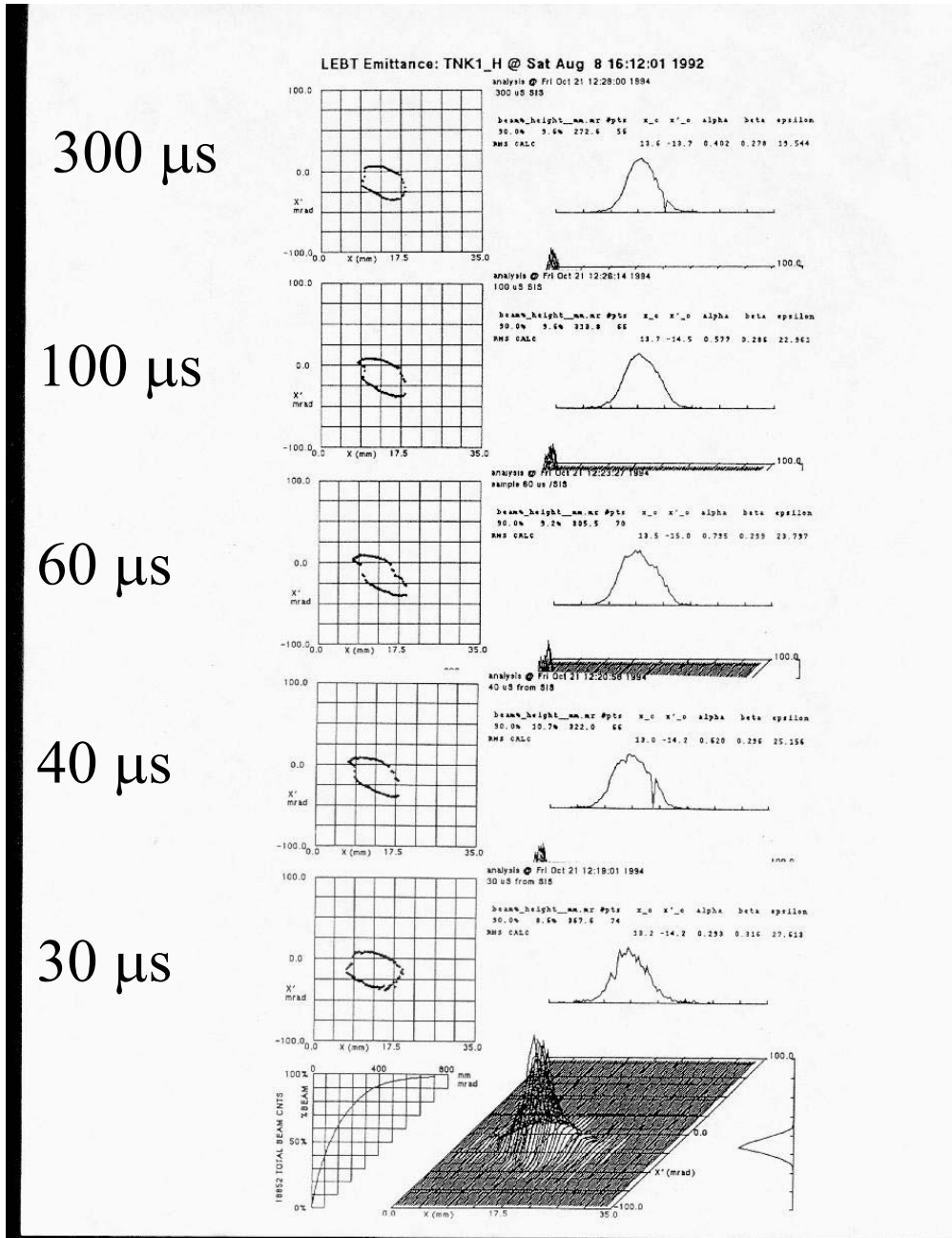
300 μs

100 μs

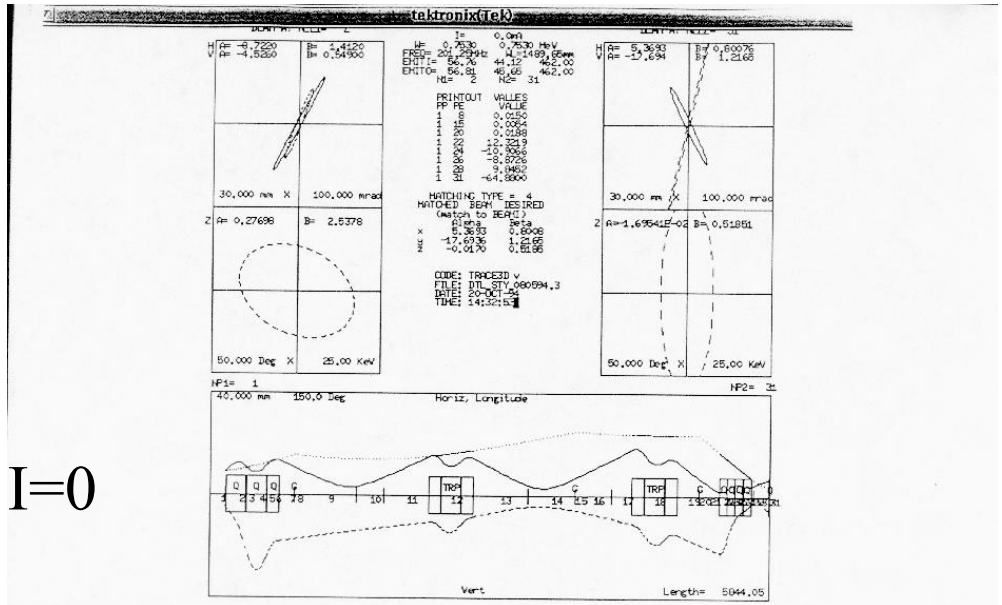
60 μs

40 μs

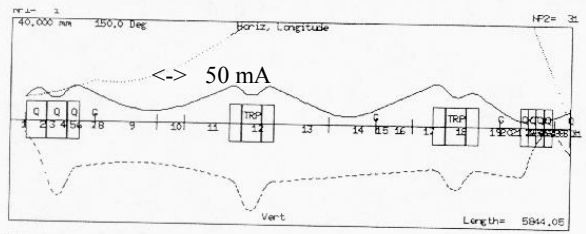
30 μs



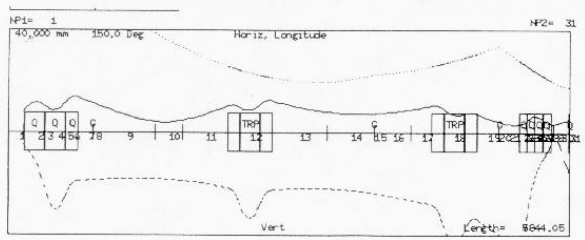
# Neutralization in MEBT (Trace)




I=0




I=50 mA



# 750 keV Chopper

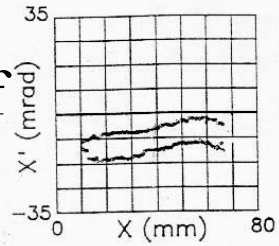
- 1 meter long
- 15 plates, traveling wave
- 4 cm plate separation
- ± 1000 V => 34 mrad Kick (beam deflected into slits at 3 meters down stream)

# Chopper On/Off

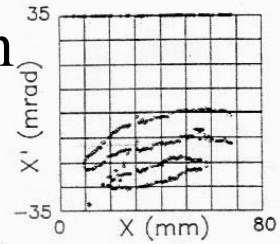
35 keV Chopper

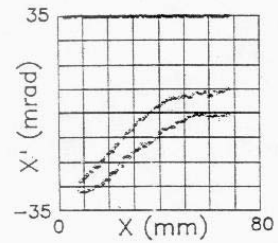
750 keV Chopper

off

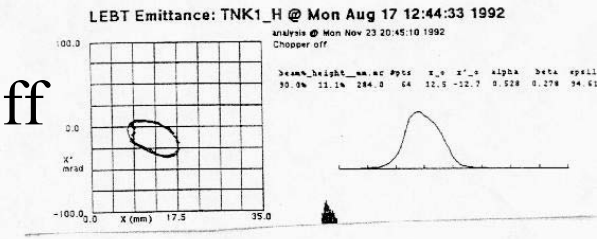



on

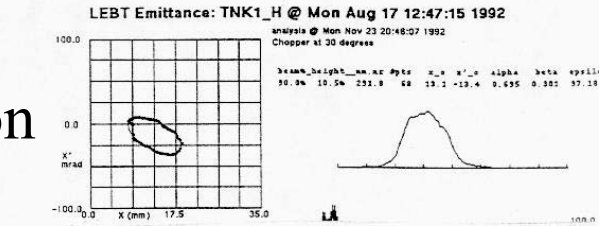


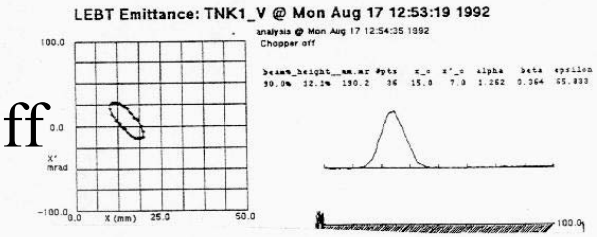

off



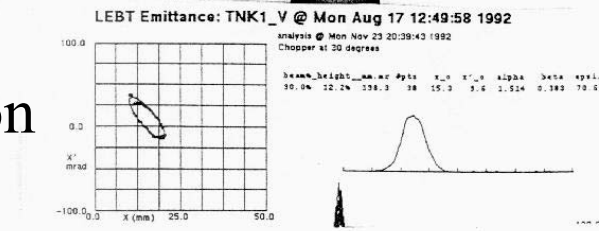

on




off




on



# Bunchers

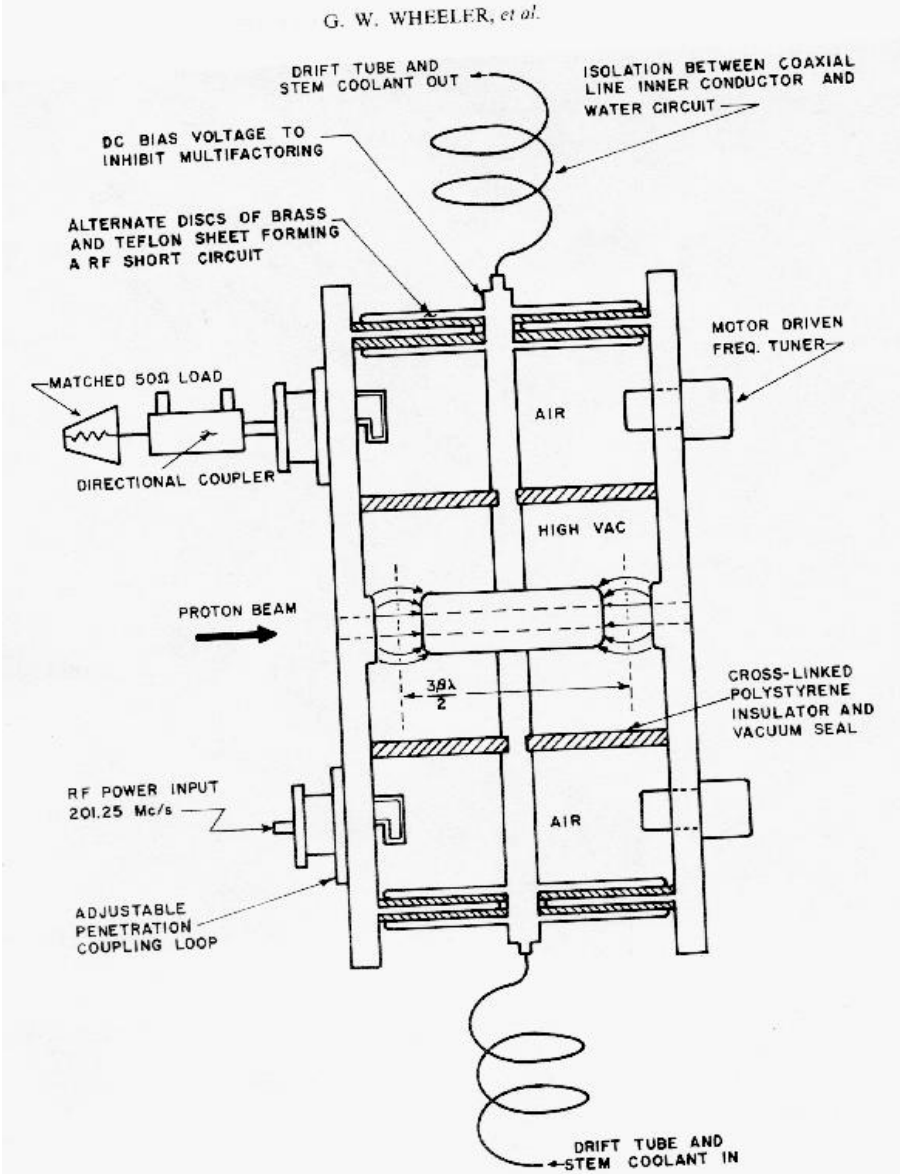



FIGURE III.1.d.2 Layout of Buncher Cavity.

# Linac

- Basically the same as FNAL's, built in 1970
- Performance - transmission, emittance, beam loss, radiation levels/activation
  - Stable from year-to-year with respect to operating values
  - No careful delta-t, etc. - could be better
  - Probably misalignments
- Vacuum for linac - Ion pumps/cryos

# Linac Current & Emittance

| Location | Simulation | Measurement |
|---|---|---|
| | **Peak Current (mA)** | |
| L3 | 62.9 | 62.9 |
| L4 | 62.2 | 57.8 |
| L5 | 54.6 | 53.2 |
| T1 | 37.1 | 37.7 |
| T9 | 36.4 | 35.9 |
| | **Emittance (rms,nor) pi mm mr** | |
| RFQ | 0.375 | |
| Buncher | 0.473 | 0.57 |
| 200 MeV | 1.85 | 1.92 |
| H SEM | +-0.29 MeV | +-8e-4 (del p/P) |
| Bucnh Rotation in AGS | +-0.5 MeV | +- 1.4e-3 (del p/PP |

# BNL Linac

- 200 MeV
- 9 Accelerating Cavities
- 475 Meter Long
- 286 Cells (295 Quads)
  6 -84 cm/cell
  1.3 -40 cm/gap
- Average Field 2.5 MV/m , 5-10 MV/m in gaps
  Tank1 56 cells, 10 MeV, 180 keV/gap
  Tank9 19 cells, 20 MeV, 1MeV/gap

# Linac Parameters

TABLE II.1.h.1

Summary drift tube table

200 MEV linac final drift tube table

A.B.

$\phi_s = -32°$

| | Cavity numbers | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 1 In | 1 Out | 2 In | 2 Out | 3 In | 3 Out | 4 In | 4 Out | 5 In | 5 Out |
| Proton energy (MEV) | 0.75 | 10.42 | 37.54 | | 66.18 | | 92.55 | | 116.54 | |
| Proton velocity, $\beta$ | 0.04 | 0.148 | 0.275 | | 0.357 | | 0.414 | | 0.457 | |
| Energy gain (MEV) | 9.67 | | 27.12 | | 28.64 | | 26.37 | | 23.99 | |
| Cavity length (m) | 7.44 | | 19.02 | | 16.53 | | 16.68 | | 15.58 | |
| Cavity diameter (cm) | 94 | | 90 | | 88 | | 88 | | 84 | |
| Drift tube diameter (cm) | 18 | | 16 | | 16 | | 16 | | 16 | |
| Bore hole diameter (cm) | 2.0 | 2.5* | 3.0 | | 3.0 | | 3.0 | | 4.0 | |
| D.T. corner radius (cm) | 2.0 | | 4.0 | | 4.0 | | 4.0 | | 5.0 | |
| Bore hole corner radius (cm) | 0.5 | | 1.0 | | 1.0 | | 1.0 | | 1.0 | |
| Cell length (cm) | 6.04 | 21.8 | 22.2 | 40.8 | 41.1 | 53.0 | 53.3 | 61.5 | 61.8 | 67.9 |
| Gap length (cm) | 1.3 | 6.7 | 4.4 | 12.7 | 12.2 | 19.3 | 19.5 | 25.1 | 22.6 | 26.9 |
| g/L | 0.21 | 0.31 | 0.20 | 0.31 | 0.30 | 0.36 | 0.37 | 0.41 | 0.37 | 0.40 |
| Axial transit time factor | 0.64 | 0.81 | 0.86 | 0.81 | 0.82 | 0.75 | 0.75 | 0.69 | 0.73 | 0.69 |
| Shunt impedance (MΩ/m) | 27.0 | 47.97 | 53.5 | 44.8 | 44.6 | 35.2 | 35.0 | 28.5 | 29.6 | 25.0 |
| Drift space following cavity (m) | 0.22 | | 0.6 | | 0.75 | | 1.0 | | 1.0 | |
| Accumulated length (m) | 7.66 | | 27.28 | | 44.56 | | 62.24 | | 78.82 | |
| Number of unit cells | 56 | | 60 | | 35 | | 29 | | 24 | |
| Number of full drift tubes | 55 | | 59 | | 34 | | 28 | | 23 | |
| Average axial field E0 (MV/m) | 1.60–2.31 | | 2.0 | | 2.60 | | 2.60 | | 2.56 | |
| Average gap field Eg (MV/m) | 7.62 | 7.45 | 10.0 | 6.45 | 8.7 | 7.2 | 7.03 | 6.3 | 6.9 | 6.4 |
| Peak surface field E max (MV/m) | 8.9 | 10.2 | 12.6 | 9.7 | 13.1 | 12.9 | 12.9 | 13.2 | 14.0 | 14.1 |
| Cavity excitation power (MW) | 0.51 | | 1.40 | | 2.36 | | 2.57 | | 2.75 | |
| Total power/cavity for 100 mA (MW) | 1.48 | | 4.12 | | 5.22 | | 5.21 | | 5.15 | |
| Total power/cavity for 200 mA (MW) | 2.45 | | 6.84 | | 8.08 | | 7.85 | | 7.55 | |
| Factor $x$, (Stem losses, etc.) | 1.30 | | 1.30 | | 1.35 | | 1.40 | | 1.45 | |

| | Cavity numbers | | | | | | | | | | Total Final |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | 6 In | 6 Out | 7 In | 7 Out | 8 In | 8 Out | 9 In | 9 Out | | | |
| Proton energy (MEV) | 138.98 | | 160.53 | | 181.01 | | 200.30 | | 200.30 | | |
| Proton velocity, $\beta$ | 0.491 | | 0.520 | | 0.545 | | 0.566 | | 0.5665 | | |
| Energy gain (MEV) | 22.44 | | 21.55 | | 20.48 | | 19.29 | | 199.55 | | |
| Cavity length (m) | 15.54 | | 15.83 | | 15.88 | | 15.73 | | 138.23 | | |
| Cavity diameter (cm) | 84 | | 84 | | 84 | | 84 | | | | |
| Drift tube diameter (cm) | 16 | | 16 | | 16 | | 16 | | | | |
| Bore hole diameter (cm) | 4.0 | | 4.0 | | 4.0 | | 4.0 | | | | |
| D.T. corner radius (cm) | 5.0 | | 5.0 | | 5.0 | | 5.0 | | | | |
| Bore hole corner radius (cm) | 1.0 | | 1.0 | | 1.0 | | 1.0 | | | | |
| Cell length (cm) | 68.2 | 73.1 | 73.3 | 77.4 | 77.6 | 81.1 | 81.3 | 84.3 | | | |
| Gap length (cm) | 27.1 | 30.8 | 30.9 | 34.2 | 34.3 | 37.1 | 37.3 | 39.7 | | | |
| g/L | 0.40 | 0.42 | 0.42 | 0.44 | 0.44 | 0.46 | 0.46 | 0.47 | | | |
| Axial transit time factor | 0.68 | 0.65 | 0.64 | 0.61 | 0.61 | 0.58 | 0.58 | 0.55 | | | |
| Shunt impedance (MΩ/m) | 24.8 | 21.7 | 21.5 | 19.0 | 18.9 | 16.8 | 16.7 | 14.9 | | | |
| Drift space following cavity (m) | 1.0 | | 1.0 | | 1.0 | | | | 6.57 | | |
| Accumulated length (m) | 95.36 | | 112.19 | | 129.07 | | 144.80 | | 475.07 ft. | | |
| Number of unit cells | 22 | | 21 | | 20 | | 19 | | 286 | | |
| Number of full drift tubes | 21 | | 20 | | 19 | | 18 | | 277 | | |
| Average axial field E0 (MV/m) | 2.56 | | 2.56 | | 2.56 | | 2.56 | | | | |
| Average gap field Eg (MV/m) | 6.4 | 6.1 | 6.1 | 5.8 | 5.8 | 5.6 | 5.6 | 5.4 | | | |
| Peak surface field E max (MV/m) | 14.1 | 14.2 | 14.2 | 14.3 | 14.3 | 14.5 | 14.5 | 14.8 | | | |
| Cavity excitation power (MW) | 2.91 | | 3.13 | | 3.19 | | 3.24 | | 22.06 | | |
| Total power/cavity for 100 mA (MW) | 5.16 | | 5.28 | | 5.24 | | 5.17 | | 42.03 | | |
| Total power/cavity for 200 mA (MW) | 7.41 | | 7.43 | | 7.29 | | 7.10 | | 62.00 | | |
| Factor $x$, (Stem losses, etc.) | 1.50 | | 1.55 | | 1.55 | | 1.55 | | | | |

* Bore hole diameter changes in cell #18 (at start of full D.T. #18).

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | ·2760 | ·3580 | ·4150 | ·4580 | ·4922 | ·5212 | ·5460 | | |
| $\beta_g = L/\lambda$ | ·0406 / ·2464 | ·1491 | ·2740 | ·3559 | ·4130 | ·4560 | ·4909 | ·5198 | ·5447 | ·5662 | |

C. W. WHEELER, *et al.*

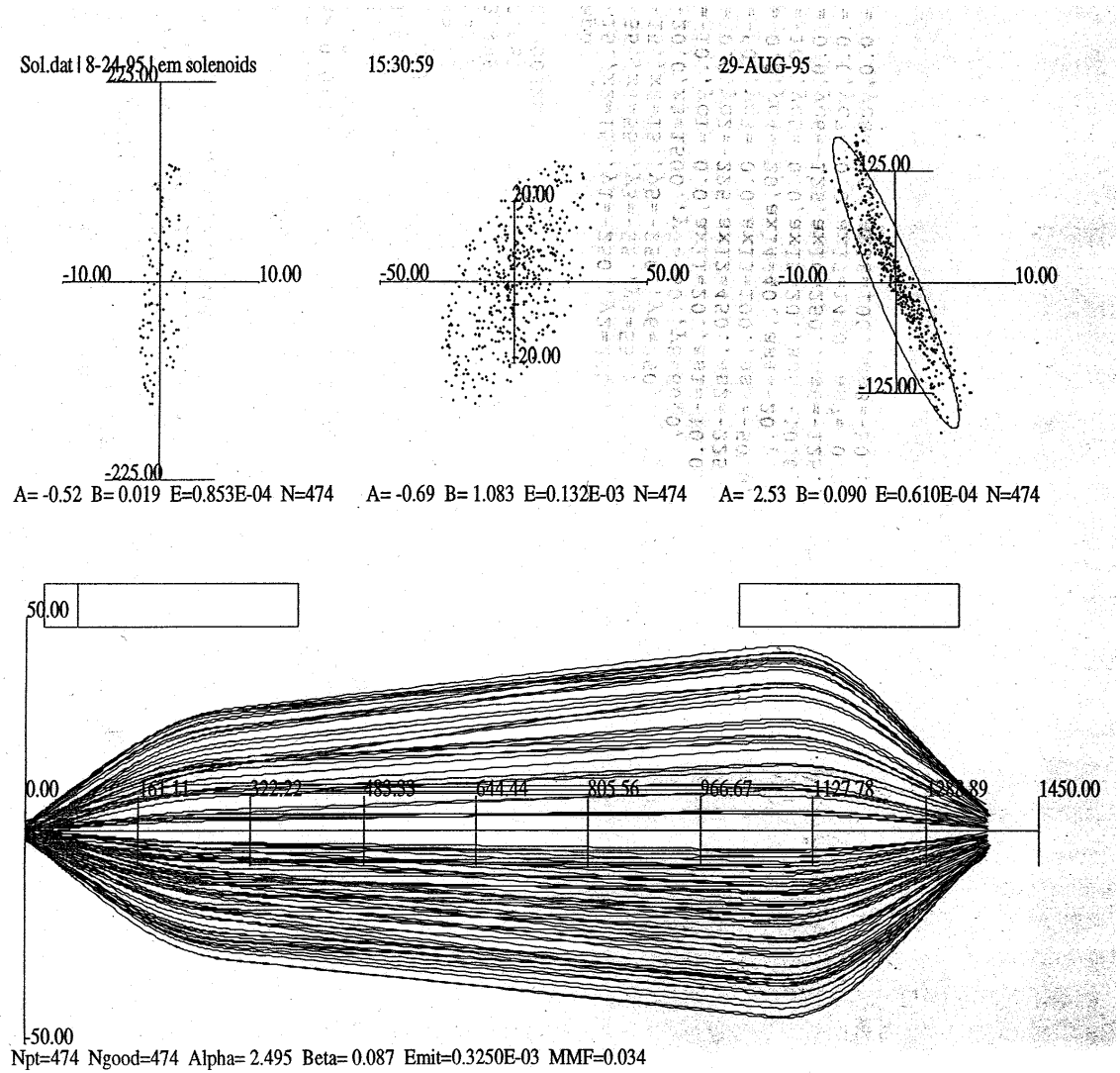
# Beam Dynamics

- Ratio of SC term to emit term in BNL linac
- Emitances
- Quad rotation
- MEBT
- Linac
- Blip

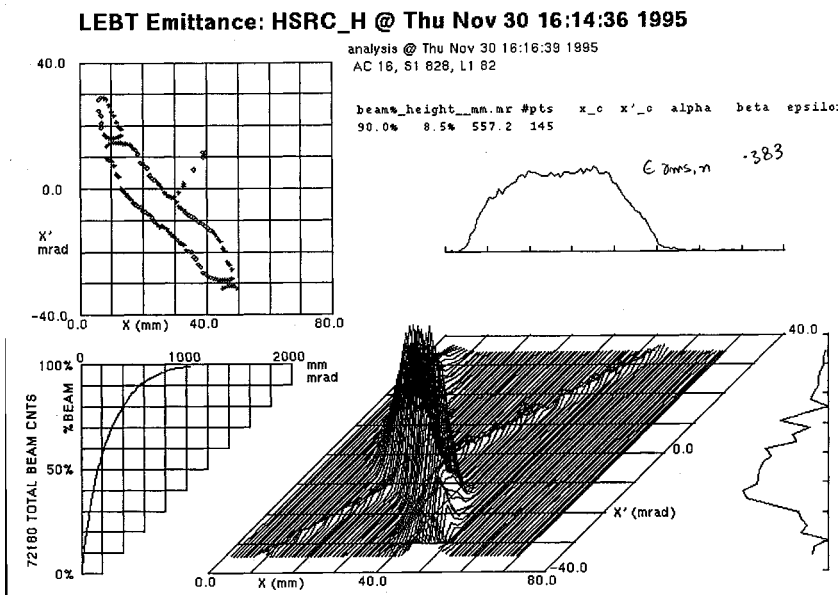
# Ration of Space Charge to Emittance Term in BNL Linac

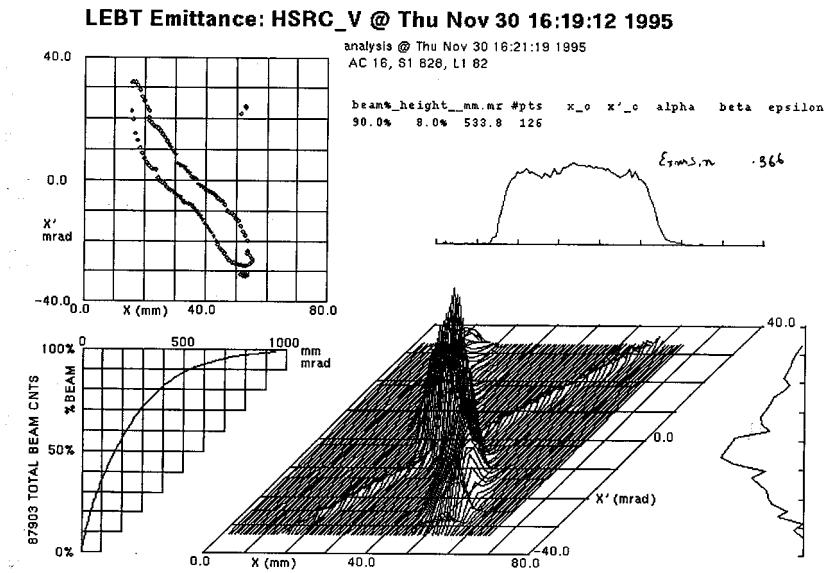
| Linac Sec | $\varepsilon$ rms,nor | R mm | Emit term | SC Term | Ratio | $\lambda_D$ mm |
|---|---|---|---|---|---|---|
| IS 35 keV | 0.400 | 25 | 2.11E-3 | 0.327 | 155 | 5E-4 |
| RFQ 750 keV | 0.425 | 25 | 1.16E-4 | 2.5E-3 | 22 | 5E-3 |
| DTL 10 MeV | 0.56 | 10 | 2.19E-4 | 0.4E-5 | 0.4 | 3E-2 |
| DTL 200 MeV | 2.88 | 3.5 | 4.65E-3 | 2.7E-6 | 5.7E-4 | 1.94 |
| Emit Term=$(4\varepsilon)^2/R^3$ | | | SC Term K/R ($K=qI/(2\pi\varepsilon_0 c^3\beta^3\gamma^3)$) | | | |

# Ray Trace Through LEBT

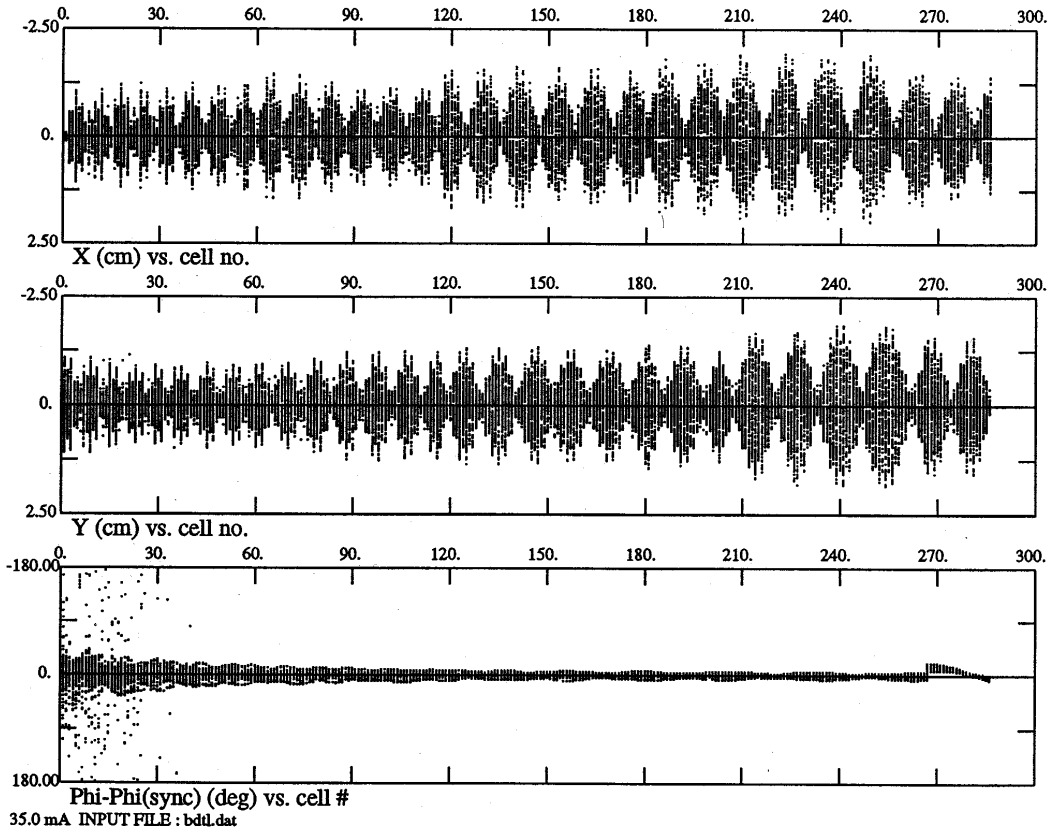


# LEBT Emittances

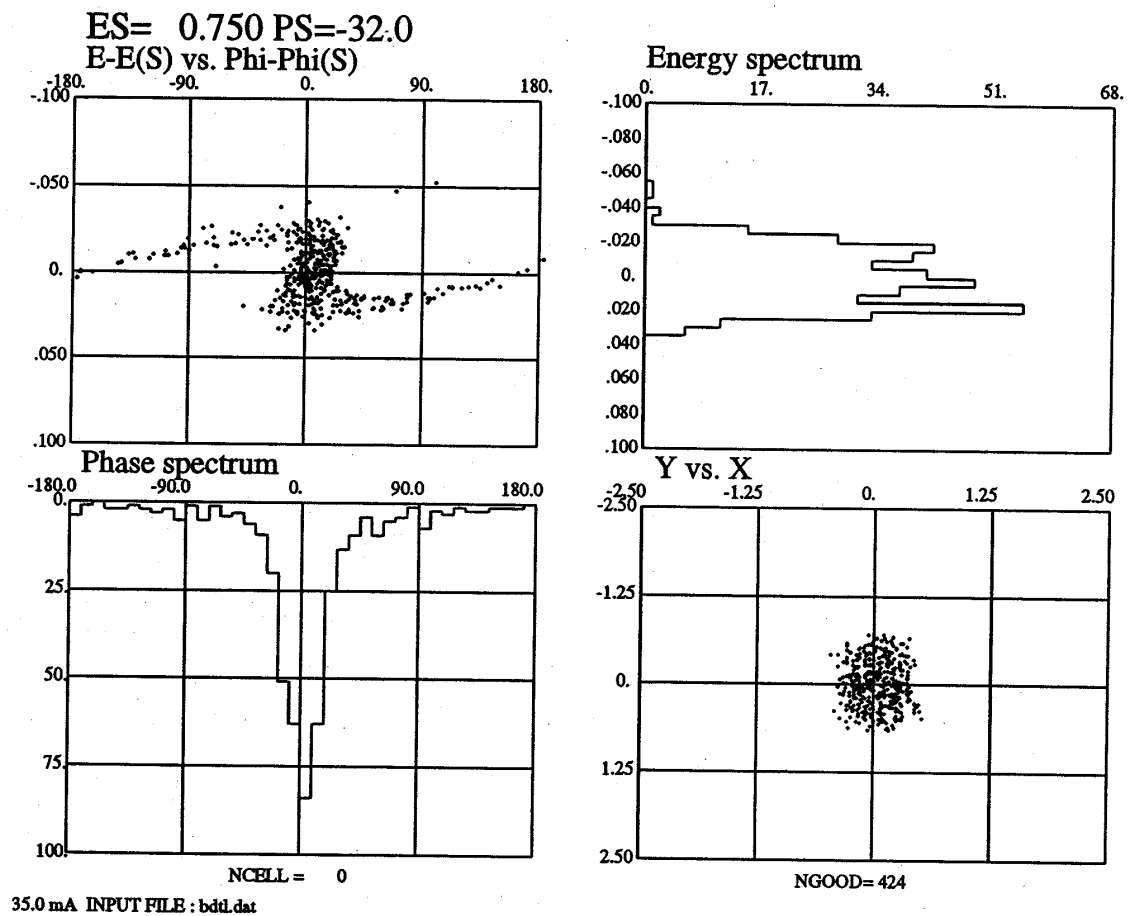


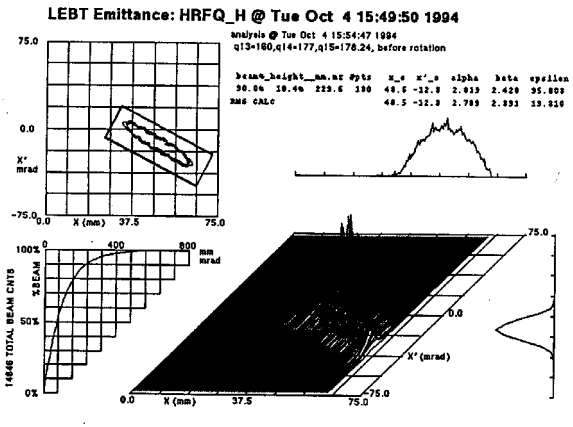
# PARMILA RUN

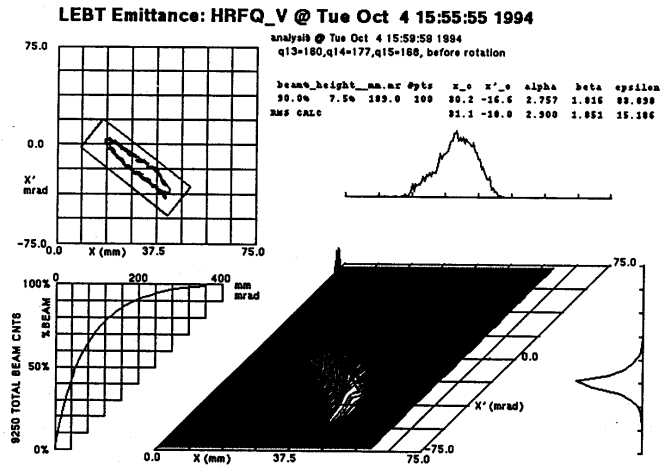

0. 30. 60. 90. 120. 150. 180. 210. 240. 270. 300.
-2.50
0.
2.50
X (cm) vs. cell no.
0. 30. 60. 90. 120. 150. 180. 210. 240. 270. 300.
-2.50
0.
2.50
Y (cm) vs. cell no.
0. 30. 60. 90. 120. 150. 180. 210. 240. 270. 300.
-180.00
0.
180.00
Phi-Phi(sync) (deg) vs. cell #
35.0 mA INPUT FILE : bdtl.dat

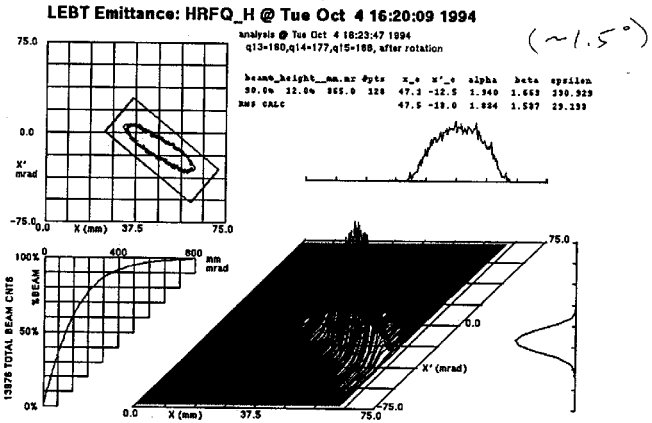
# Linac Input Phase Space

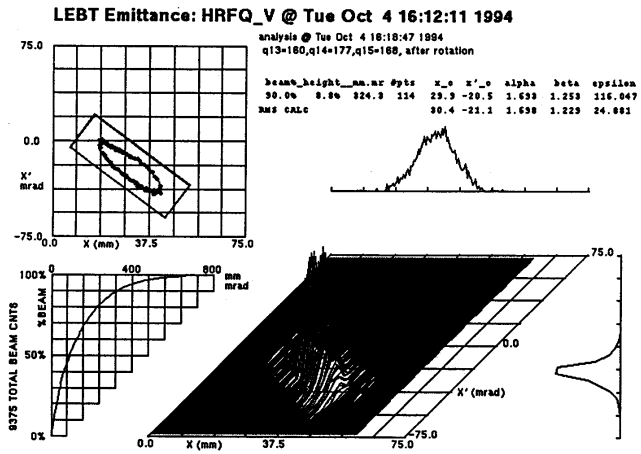


# Quad Rotation

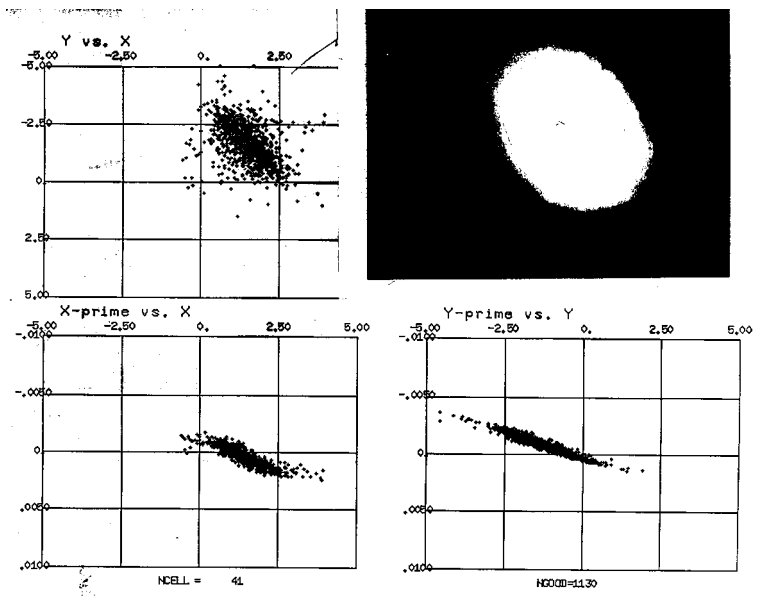


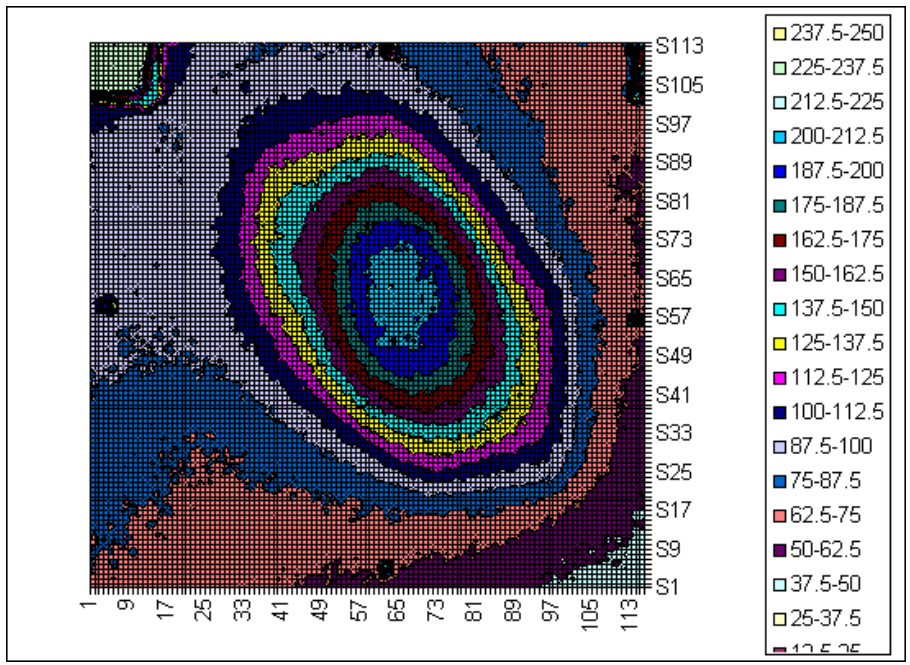



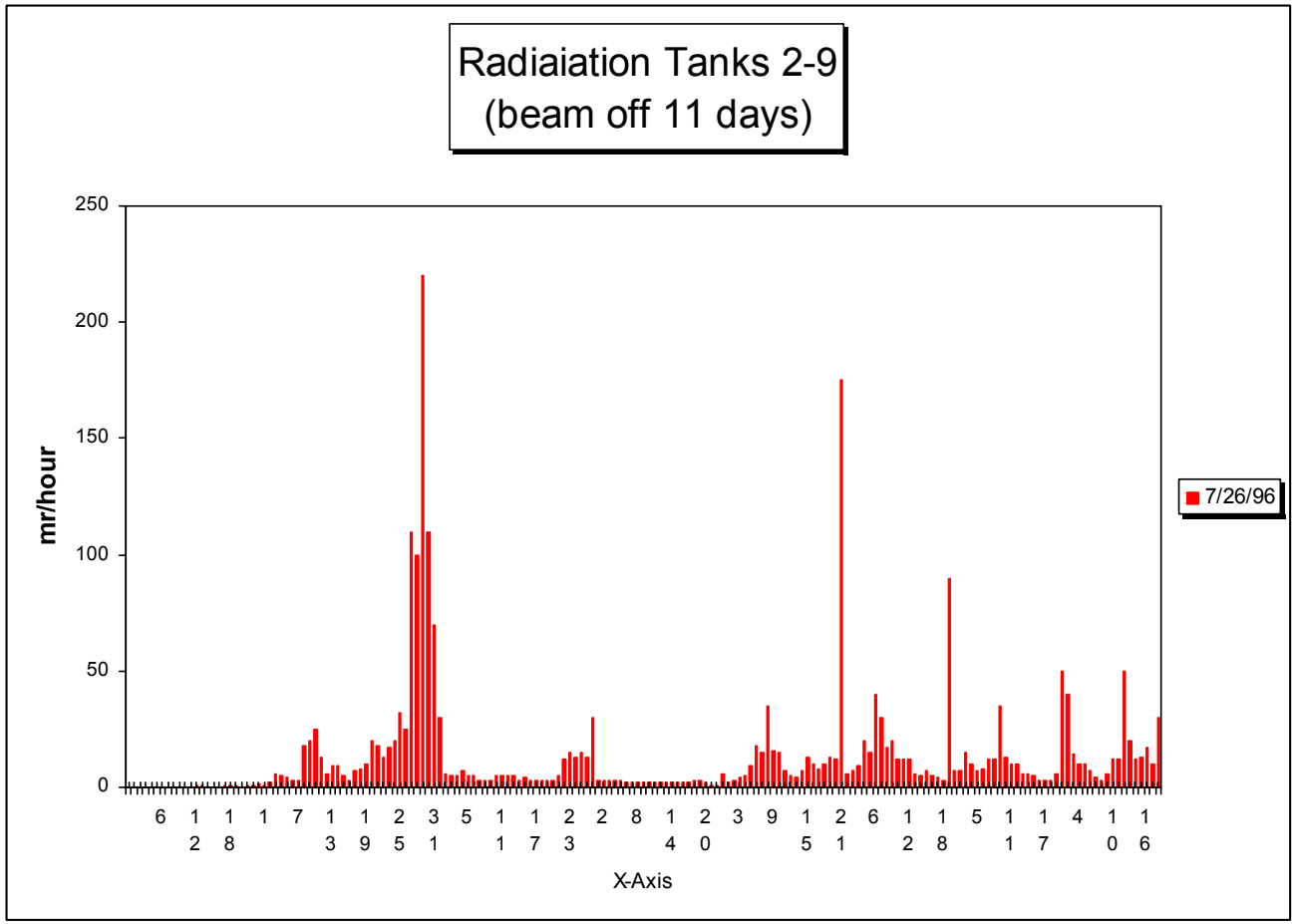



# Quad Rotation (Cont.)



# Radiation Along Linac



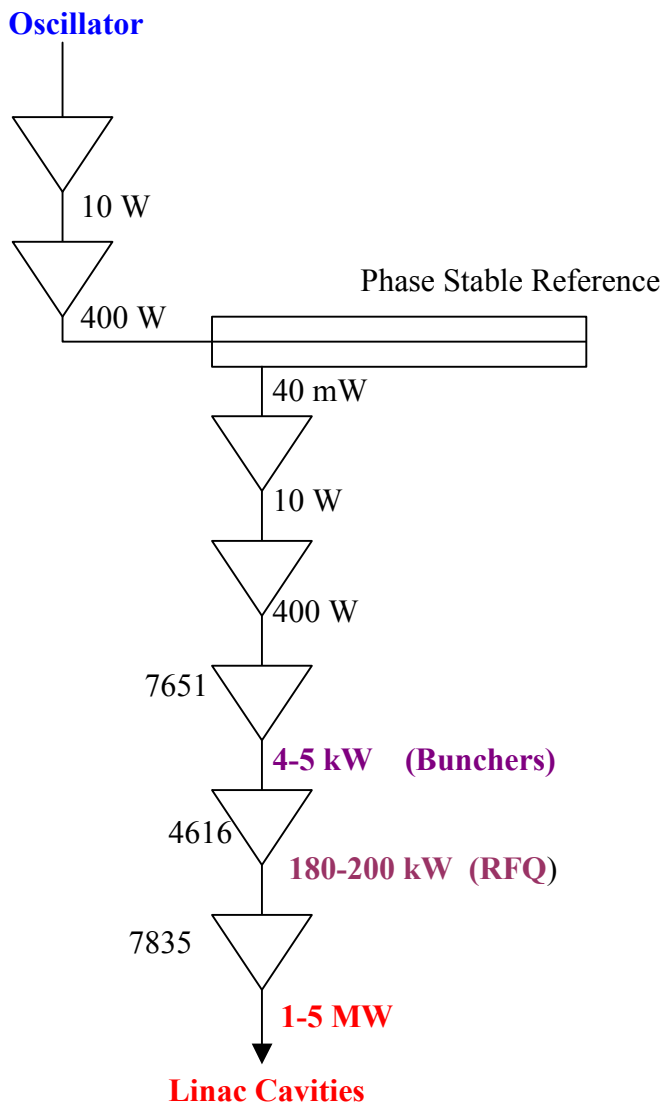
# Linac RF System

- Schematic
- Photos
- Comments on new transmission line
- Tube lifetime, costs, etc.

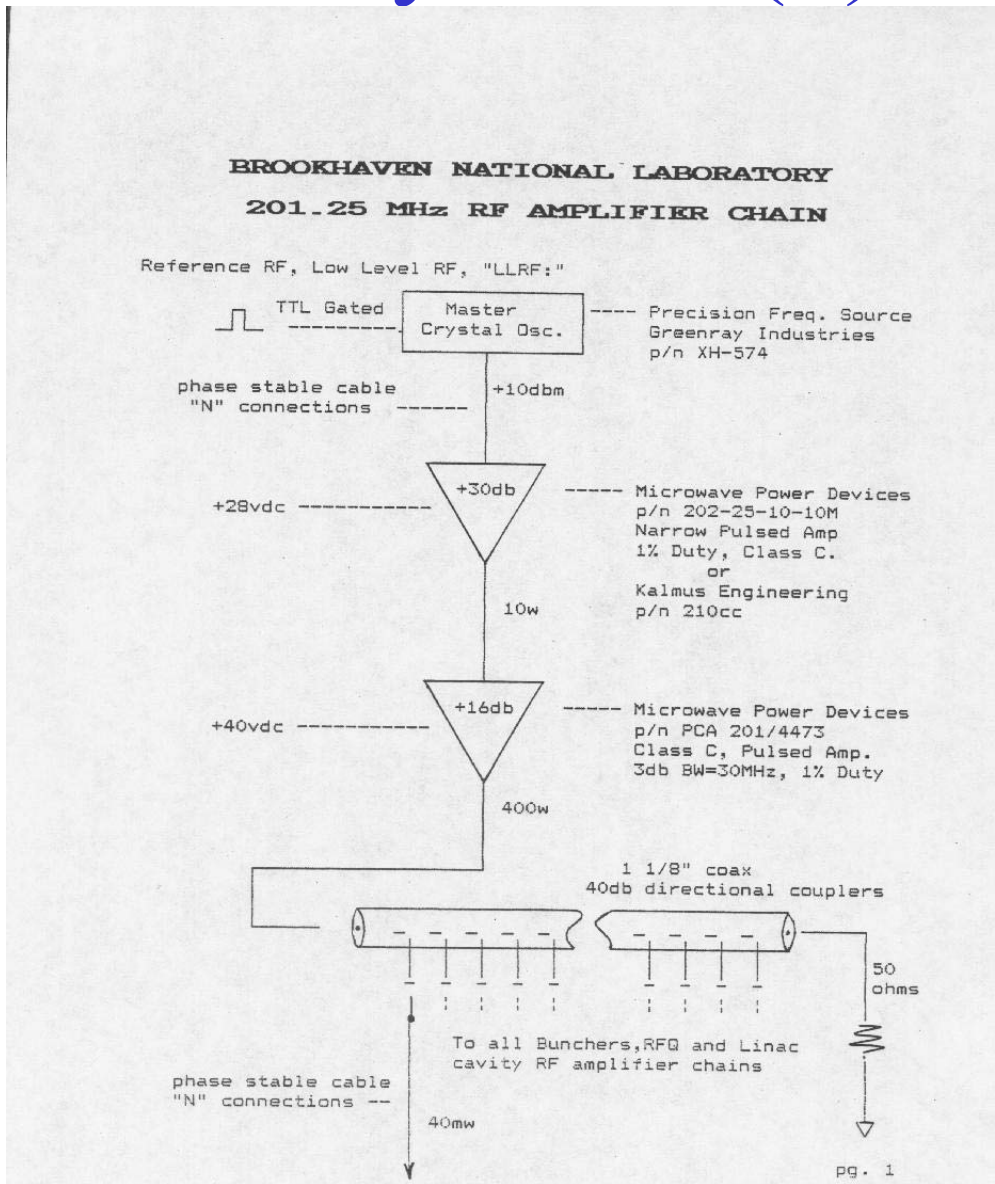
  12000 hrs, $20,000

  3 Tubes /years

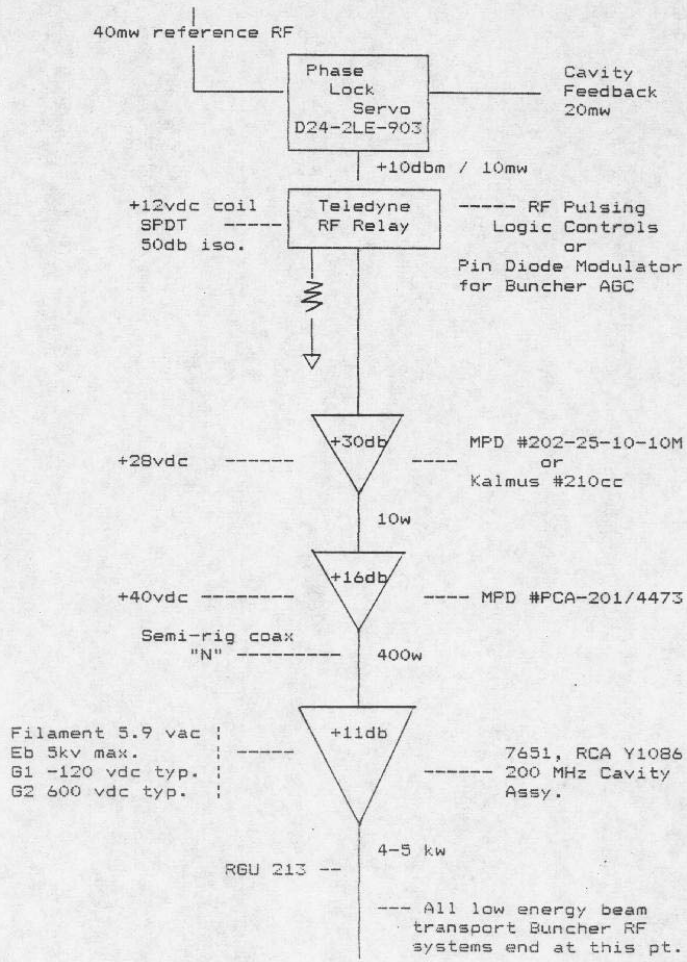
# RF Systems


Oscillator
10 W
400 W
Phase Stable Reference
40 mW
10 W
400 W
7651
4-5 kW (Bunchers)
4616
180-200 kW (RFQ)
7835
1-5 MW
Linac Cavities

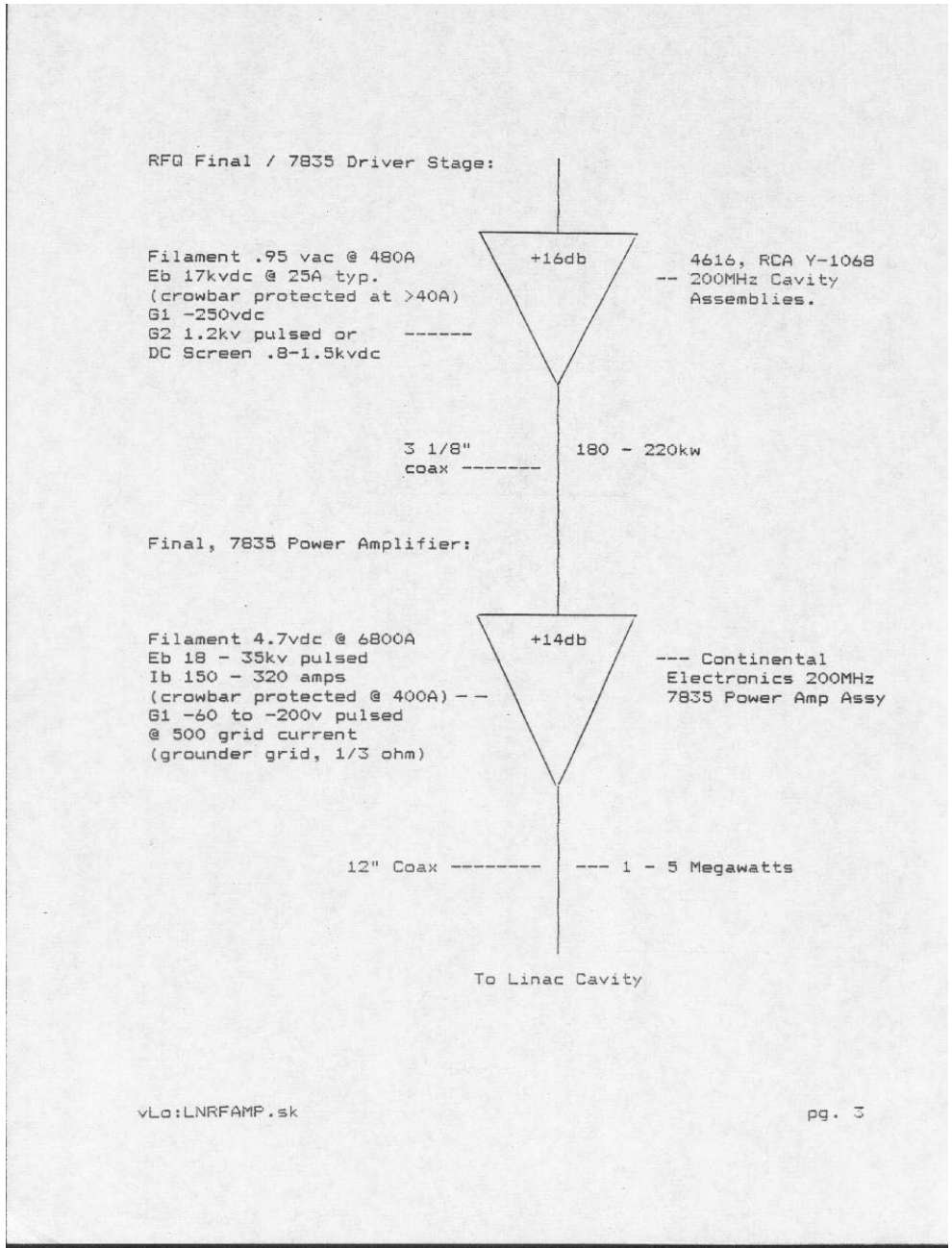
# RF Systems (1)


BROOKHAVEN NATIONAL LABORATORY
201.25 MHz RF AMPLIFIER CHAIN
Reference RF, Low Level RF, "LLRF:"
TTL Gated
Master Crystal Osc.
Precision Freq. Source
Greenray Industries
p/n XH-574
phase stable cable
"N" connections
+10dbm
+30db
+28vdc
Microwave Power Devices
p/n 202-25-10-10M
Narrow Pulsed Amp
1% Duty, Class C.
or
Kalmus Engineering
p/n 210cc
10w
+16db
+40vdc
Microwave Power Devices
p/n PCA 201/4473
Class C, Pulsed Amp.
3db BW=30MHz, 1% Duty
400w
1 1/8" coax
40db directional couplers
50
ohms
To all Bunchers,RFQ and Linac
cavity RF amplifier chains
phase stable cable
"N" connections
40mw
pg. 1

# RF Systems (2)


40mw reference RF
Phase Lock Servo D24-2LE-903
Cavity Feedback 20mw
+10dbm / 10mw
+12vdc coil SPDT 50db iso.
Teledyne RF Relay
RF Pulsing Logic Controls or Pin Diode Modulator for Buncher AGC
+30db
+28vdc
MPD #202-25-10-10M or Kalmus #210cc
10w
+16db
+40vdc
MPD #PCA-201/4473
Semi-rig coax "N"
400w
+11db
Filament 5.9 vac
Eb 5kv max.
G1 -120 vdc typ.
G2 600 vdc typ.
7651, RCA Y1086 200 MHz Cavity Assy.
4-5 kw
RGU 213
All low energy beam transport Buncher RF systems end at this pt.
pg.2

# RF Systems (3)


RFQ Final / 7835 Driver Stage:
Filament .95 vac @ 480A
Eb 17kvdc @ 25A typ.
(crowbar protected at >40A)
G1 -250vdc
G2 1.2kv pulsed or
DC Screen .8-1.5kvdc
+16db
4616, RCA Y-1068
-- 200MHz Cavity
Assemblies.
3 1/8"
coax
180 - 220kw
Final, 7835 Power Amplifier:
Filament 4.7vdc @ 6800A
Eb 18 - 35kv pulsed
Ib 150 - 320 amps
(crowbar protected @ 400A)
G1 -60 to -200v pulsed
@ 500 grid current
(grounder grid, 1/3 ohm)
+14db
--- Continental
Electronics 200MHz
7835 Power Amp Assy
12" Coax
--- 1 - 5 Megawatts
To Linac Cavity
vLo:LNRFAMP.sk
pg. 3

# RF Transfer-Line

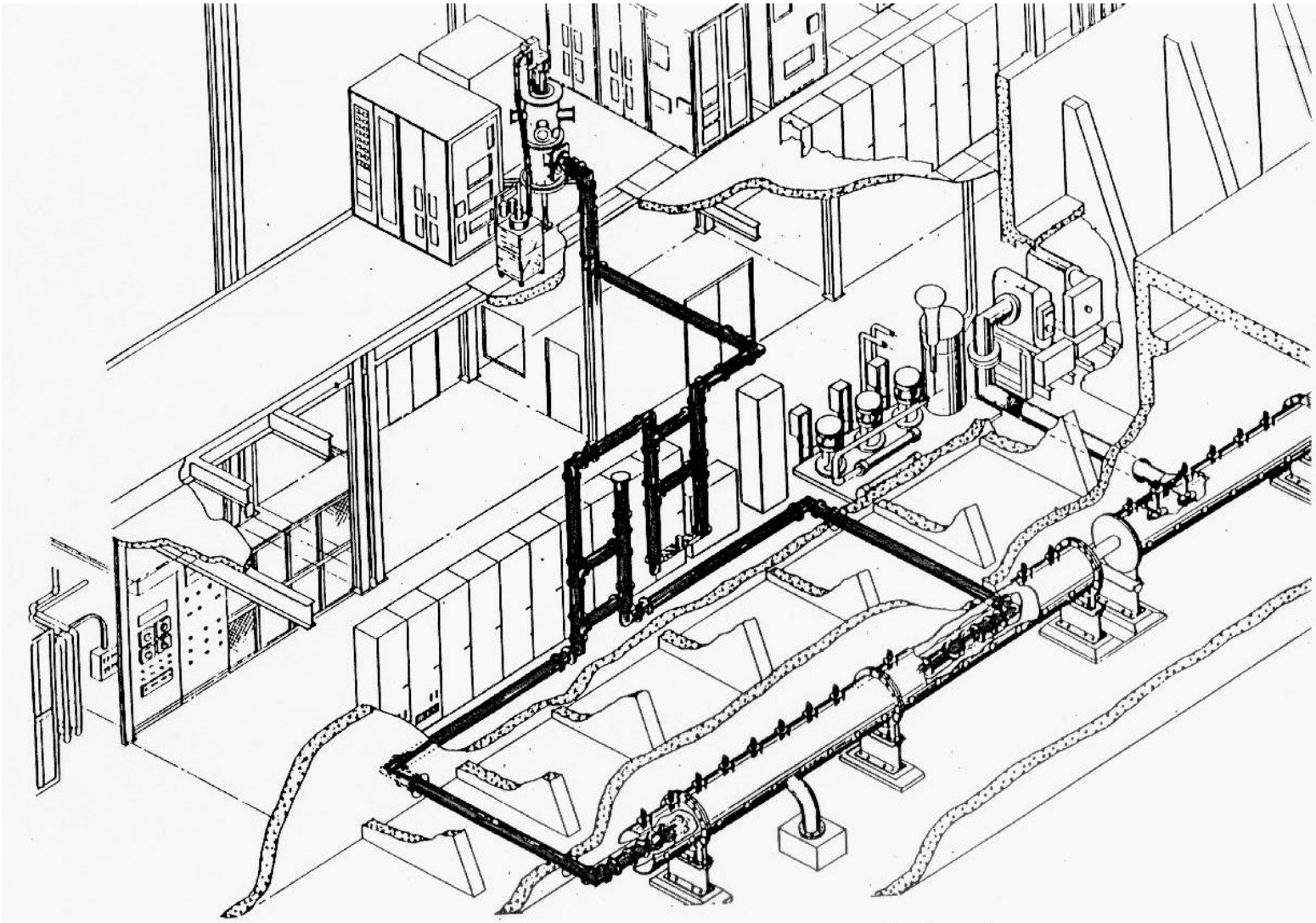
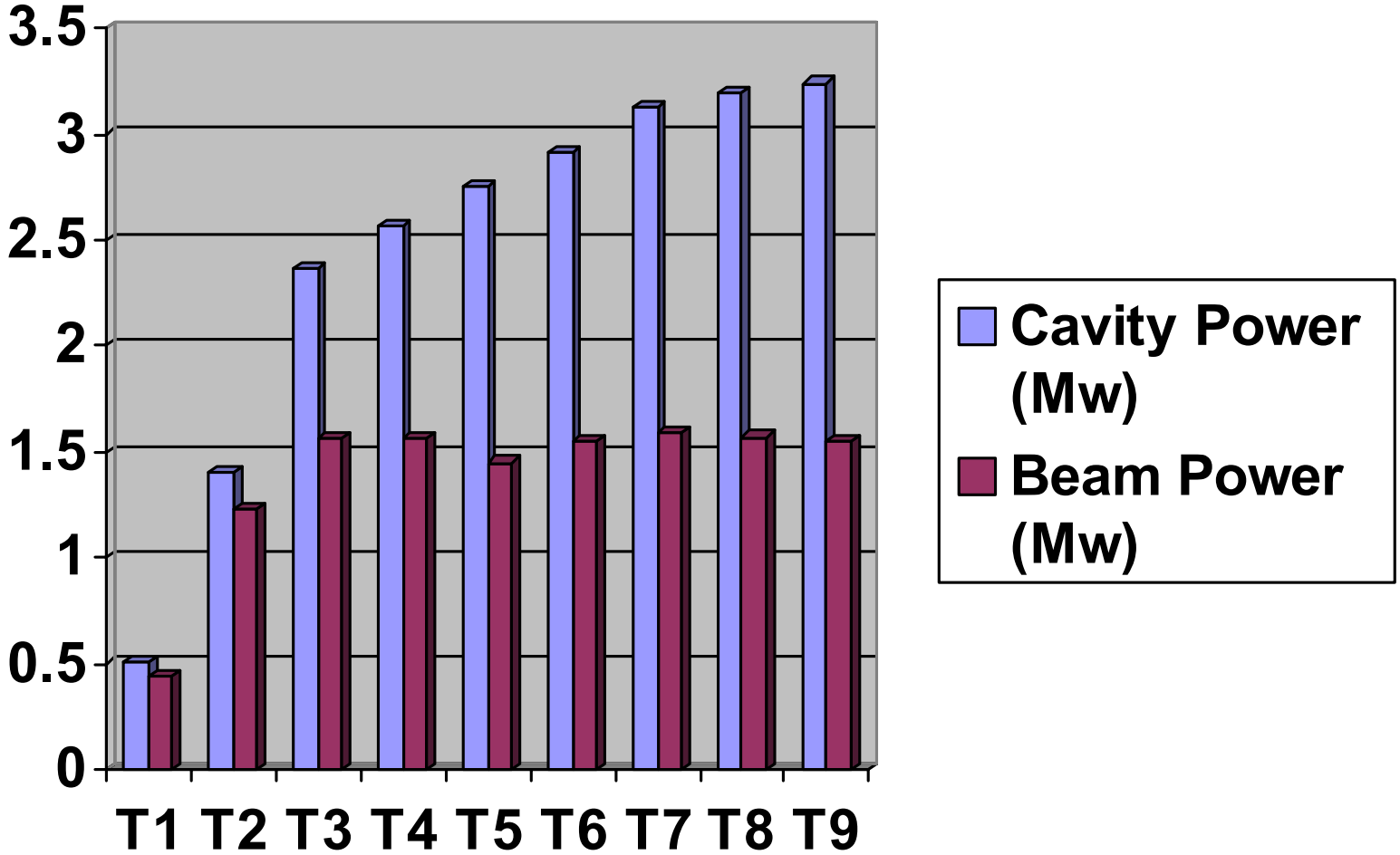


FIGURE III.3.b.2 RF transmission-line layout.

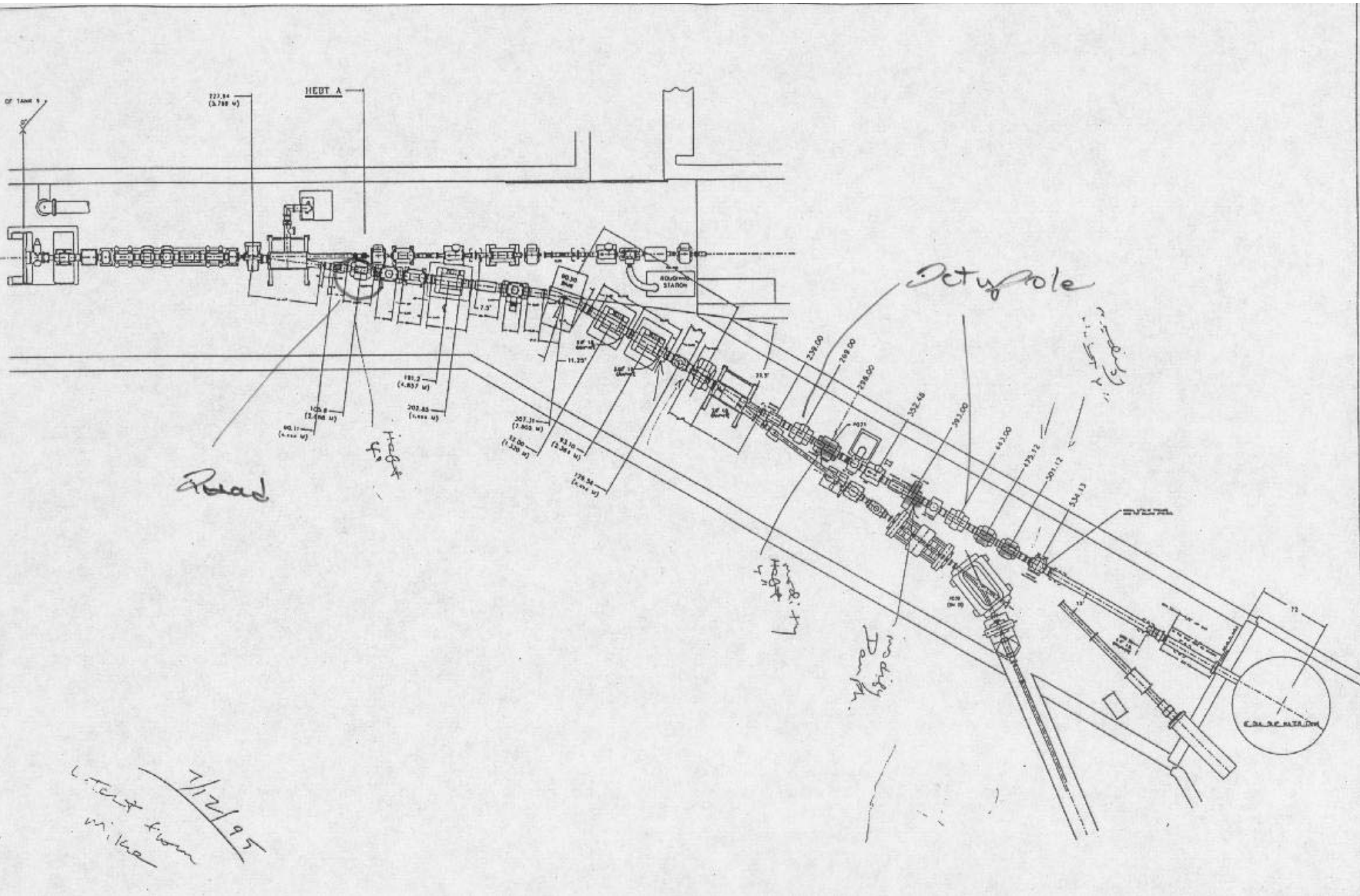
# Linac Power


3.5
3
2.5
2
1.5
1
0.5
0
T1 T2 T3 T4 T5 T6 T7 T8 T9
Cavity Power (Mw)
Beam Power (Mw)

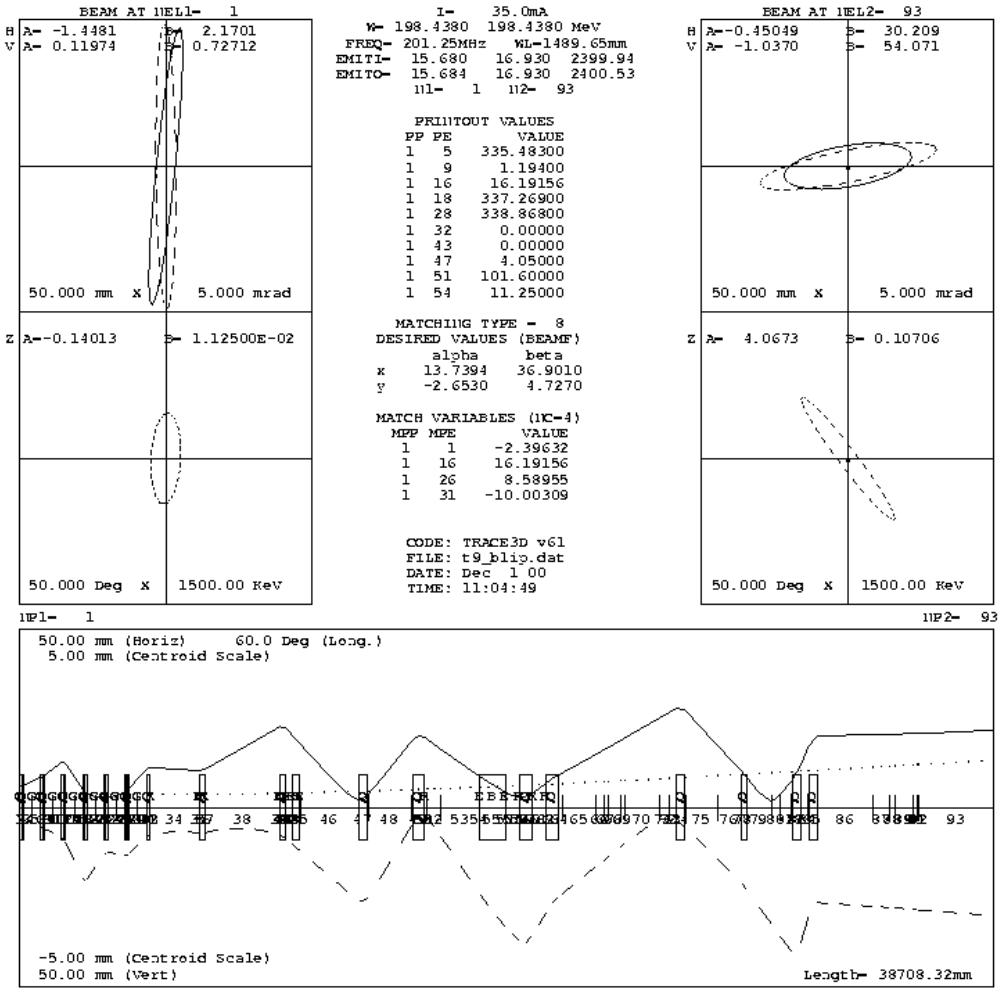
# HEBT

- Schematic
- Trace calc to BLIP
- Calc to Booster

# Layout of BLIP Beam Line



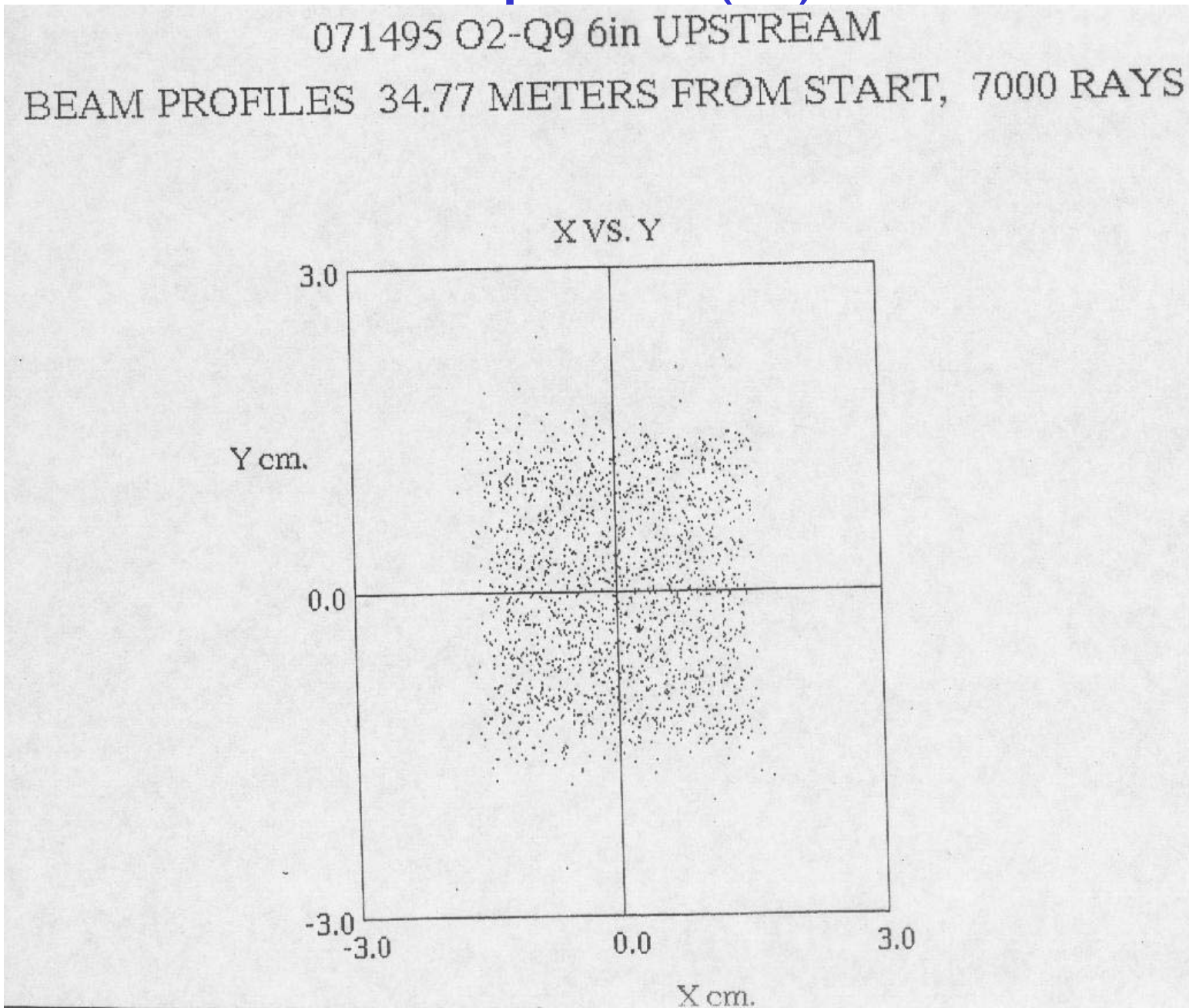
# BLIP Trace Output



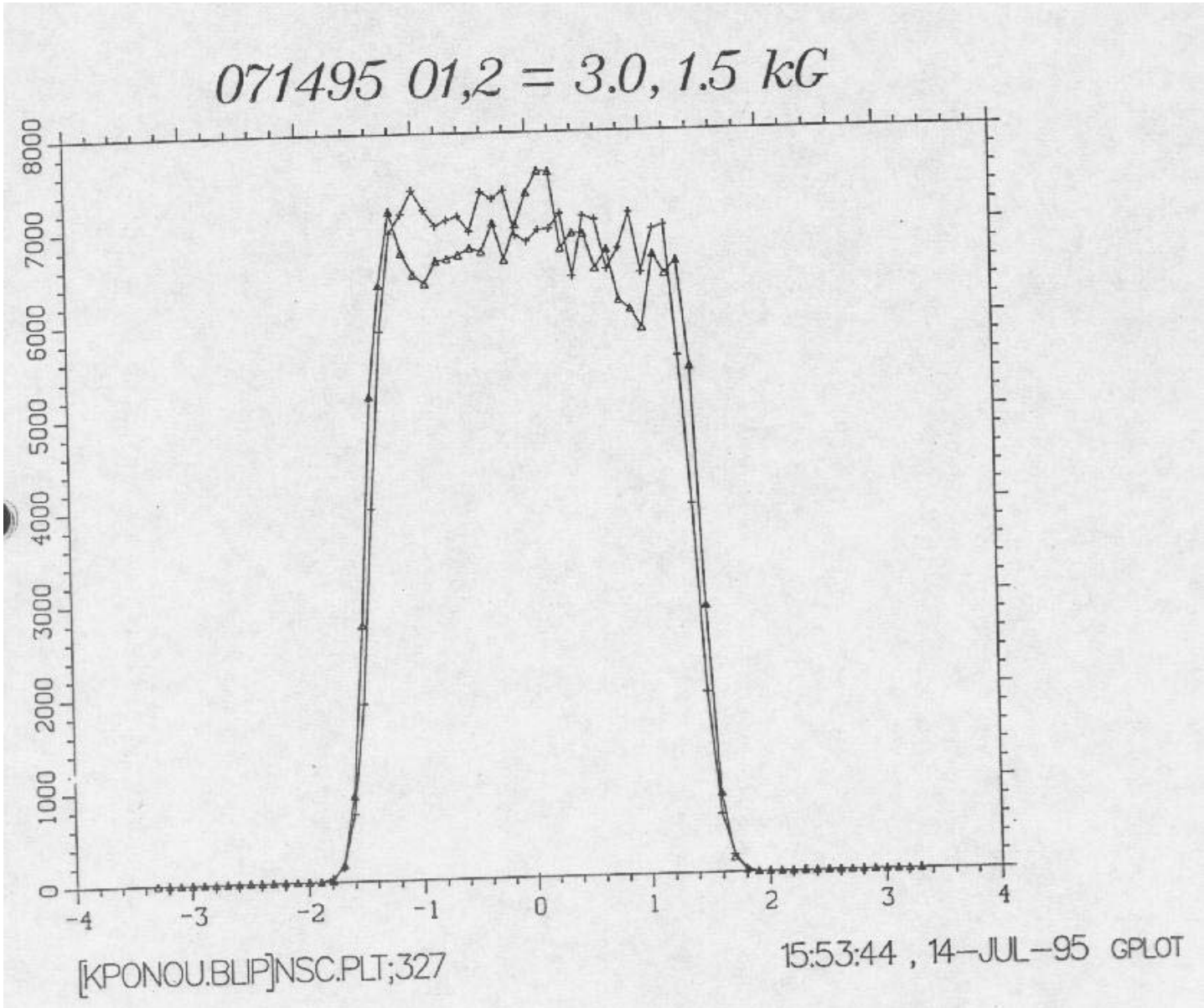
# BLIP

- Experience with octupoles?

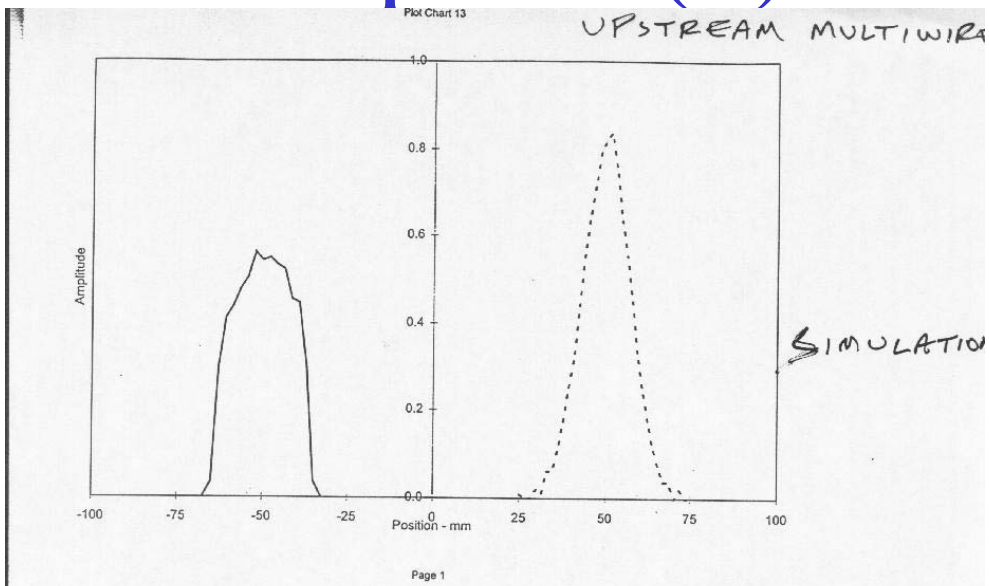
# Octupoles (1)

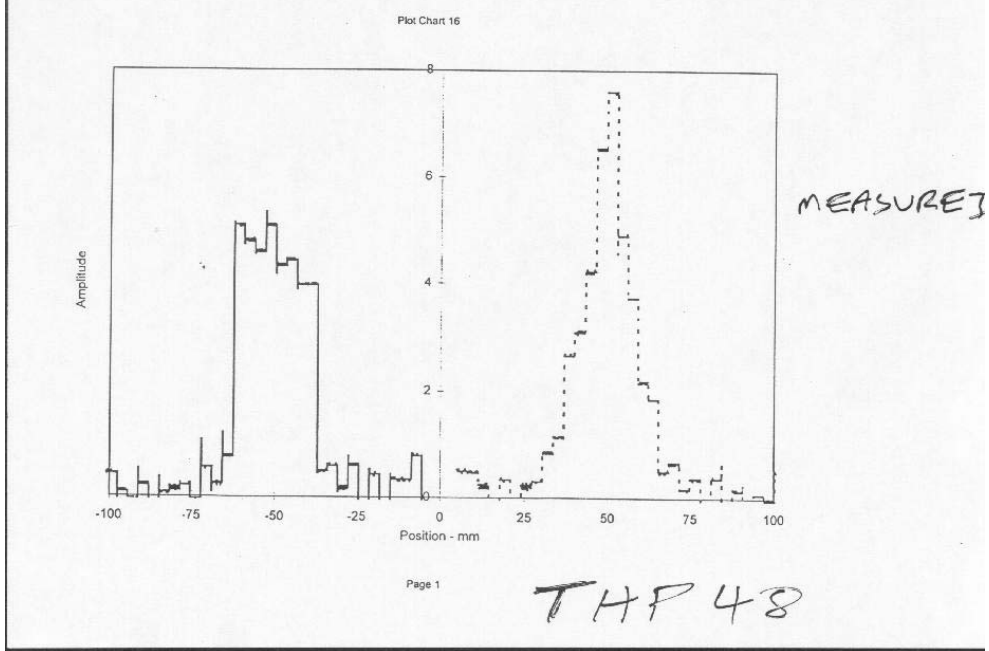

071495 O2-Q9 6in UPSTREAM
BEAM PROFILES 34.77 METERS FROM START, 7000 RAYS
X VS. Y
3.0
0.0
-3.0
Y cm.
-3.0
0.0
3.0
X cm.

# Octupoles (2)


071495 01,2 = 3.0, 1.5 kG
0
1000
2000
3000
4000
5000
6000
7000
8000
-4
-3
-2
-1
0
1
2
3
4
[KPONOU.BLIP]NSC.PLT;327
15:53:44 , 14-JUL-95 GPLOT

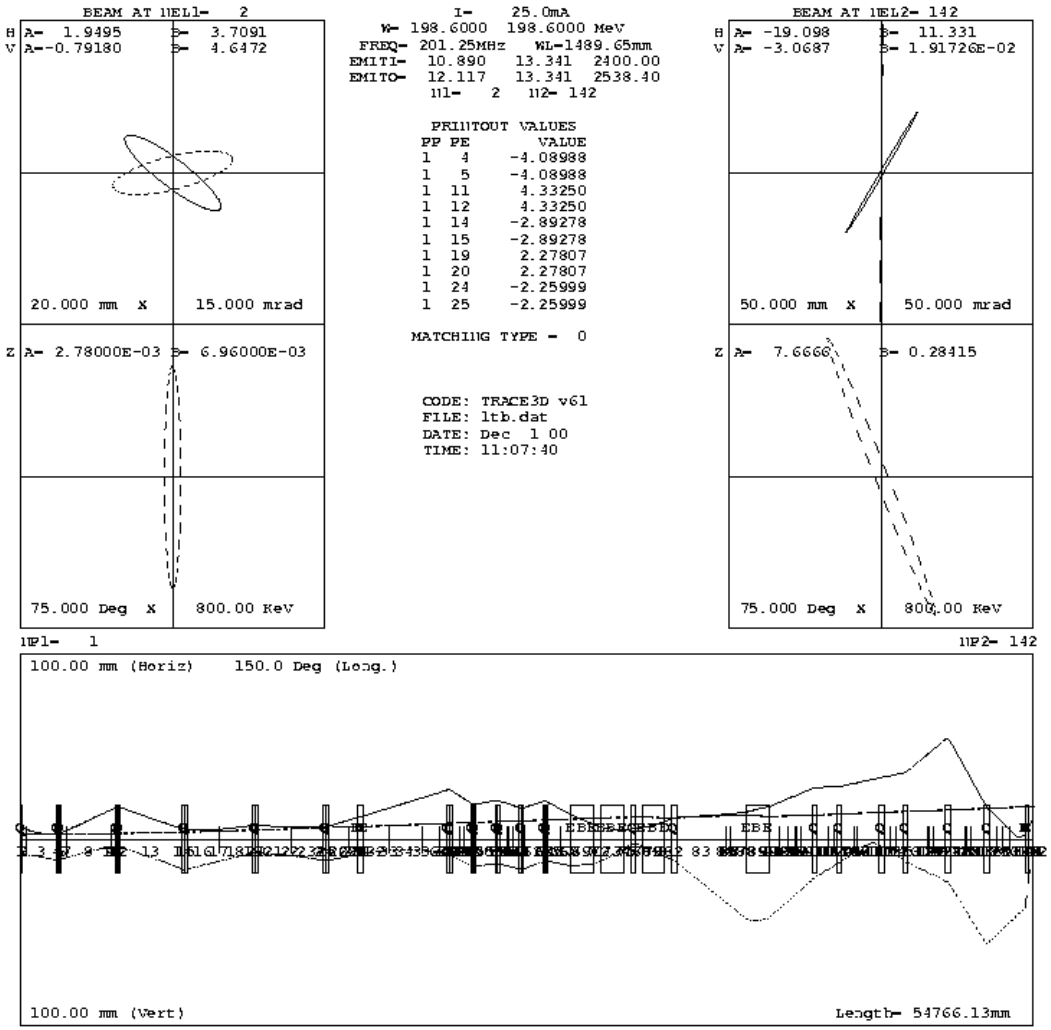
# Octupoles (3)


Plot Chart 13
UPSTREAM MULTIWIRE
Amplitude
1.0
0.8
0.6
0.4
0.2
0.0
-100
-75
-50
-25
0
25
50
75
100
Position - mm
SIMULATION
Page 1


Plot Chart 16
Amplitude
8
6
4
2
0
-100
-75
-50
-25
0
25
50
75
100
Position - mm
MEASURED
Page 1
THP48

# Photos of HEBT area

# LTB Trace Output



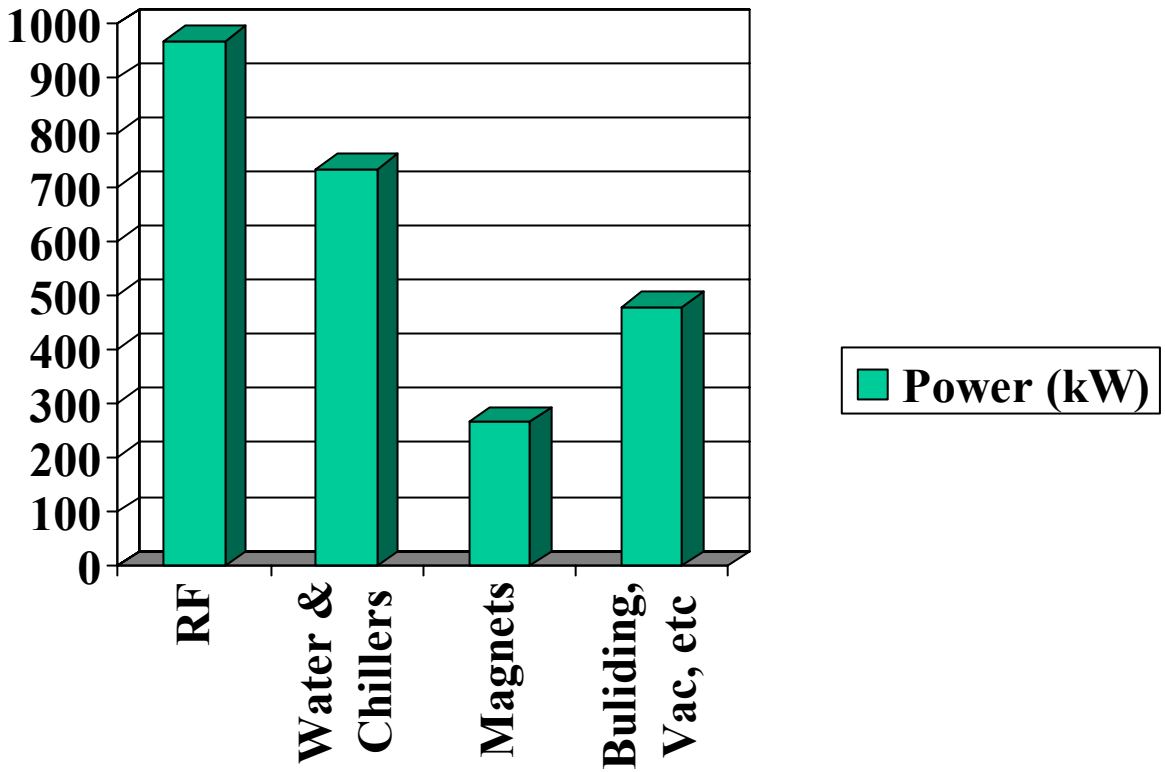
# Diagnostics in the Linac

- Transformers
  - where located
  - how fast response
- Emittance measurements
- Harps, SEMS
- Fast pickups
  - not used much
- Stripline position monitors

# Diagnostics in the Linac

| Device | LEBT | MEBT | Tanks | HEBT | LTB | BLIP |
|---|---|---|---|---|---|---|
| Trans. | 1 | 3 | 9 | 3 | 3 | 3 |
| Pol. Trans. | | | 1 | | 2 | |
| FC | 1 | 1 | | | | |
| Fast FC | | 1 | | | | |
| Emitance | | 2 | | | | |
| Sems | | | 8 | 3 | 3 | 1 |
| Harps | | | | 1 | 3 | 2 |
| BPM | | | 6 | 3 | 4 | |

# Power to Run Linac -2.5 MW (7.5 Hz ,140 μA)

- 

# Linac Power

Vin/Brian/Spinner measurements, 7/15/96, as linac turned off.
(note: Vin reported 50 kW type fluctuations in the measurements, as va

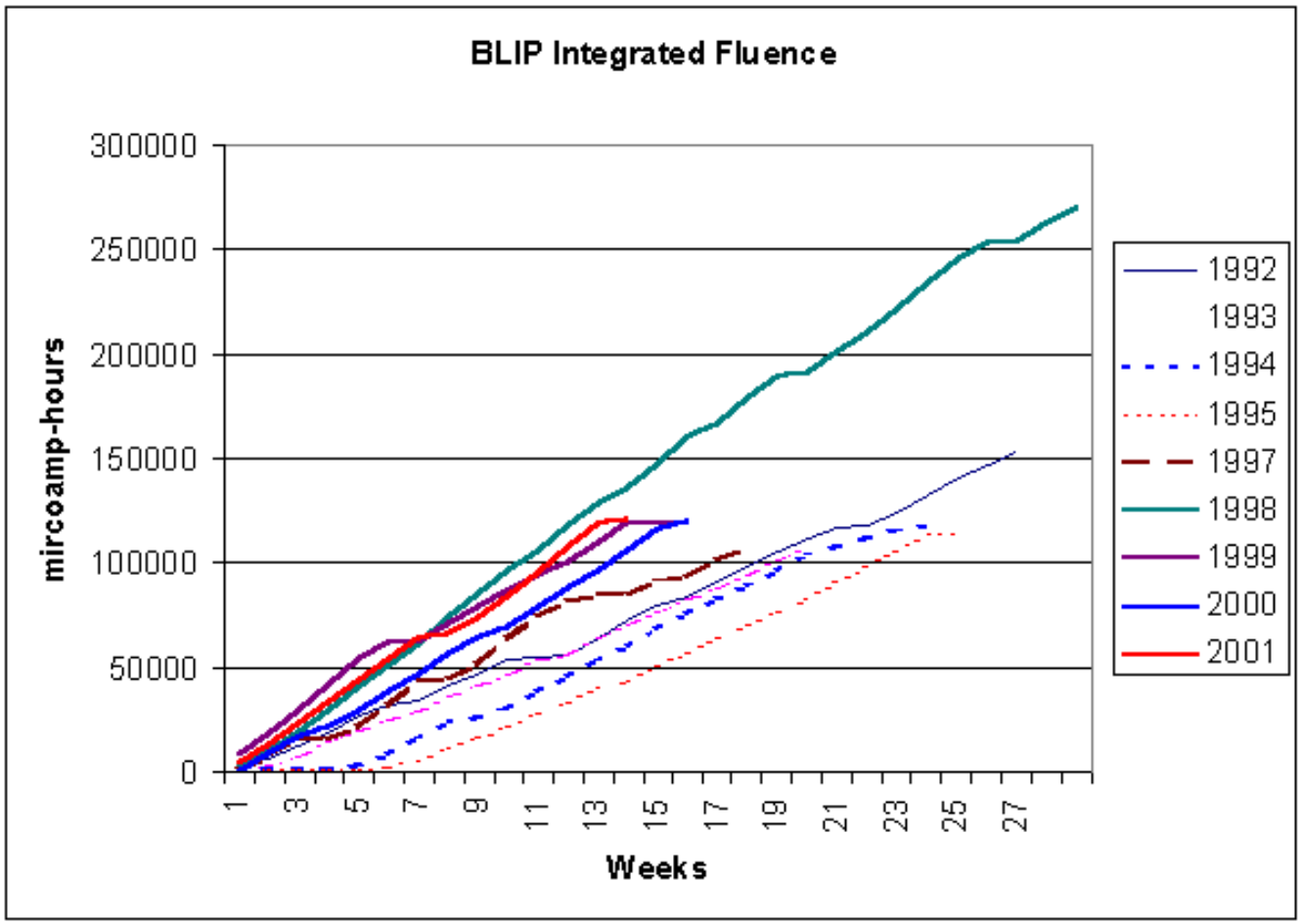
| | kW | Differential | |
|---|---|---|---|
| Linac full on (7.5 Hz, 140 uA) | 2438 | | |
| BLIP transport off | 2206 | 232 | |
| RF and quad pulsing off | 1943 | 263 | (Quads < 20 kW) |
| RF HV PS off | 1925 | 18 | |
| LEBT bunchers off | 1920 | 5 | |
| HEBT off | 1934 | -14 | |
| 7835 filaments to 6000 A | 1705 | 229 | |
| 4616's off | 1651 | 54 | |
| 7835 plate modulators off | 1544 | 107 | |
| 7835 filament off (from 6000 A) | 1226 | 318 | |
| LEBT sol/chop/extr off | 1223 | 3 | |
| LEBT pulsed quads/RFQ off | 1212 | 11 | |
| Tank cooling water off | 1072 | 140 | |
| Transport water off | 1045 | 27 | |
| RF cooling water off | 794 | 251 | |
| Source | 793 | 1 | |
| BLIP cooling water | 788 | 5 | |
| Chillers off | 478 | 310 | |

Remaining = building, lights, vacuum, etc.

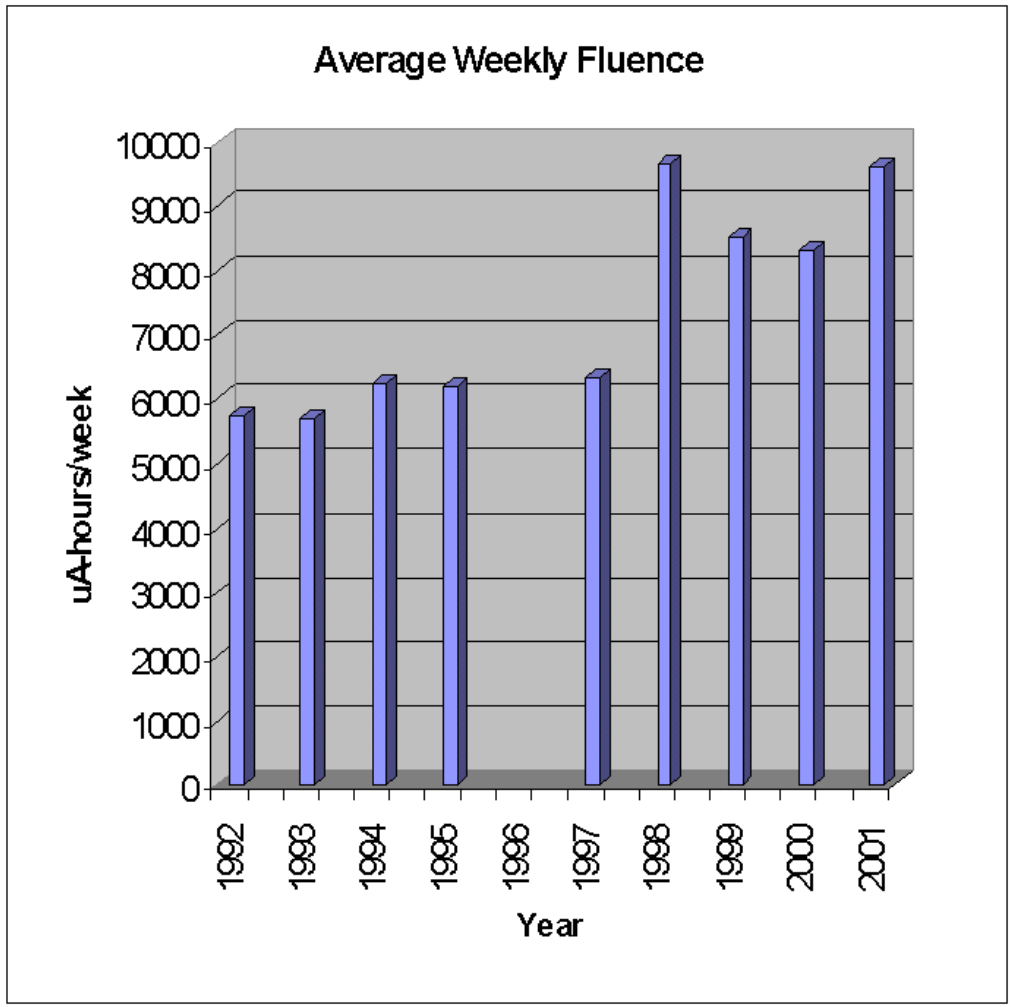
RF systems:

| | |
|---|---|
| RF pulsing off | 243 |
| RF HV PS off | 18 |
| 7835 filaments to 6000 A | 229 |
| 4616's off | 54 |
| 7835 plate modulators off | 107 |
| 7835 filament off (from 6000 A) | 318 |
| TOTAL RF | 969 |
| Pwr/sys | 107.66667 |

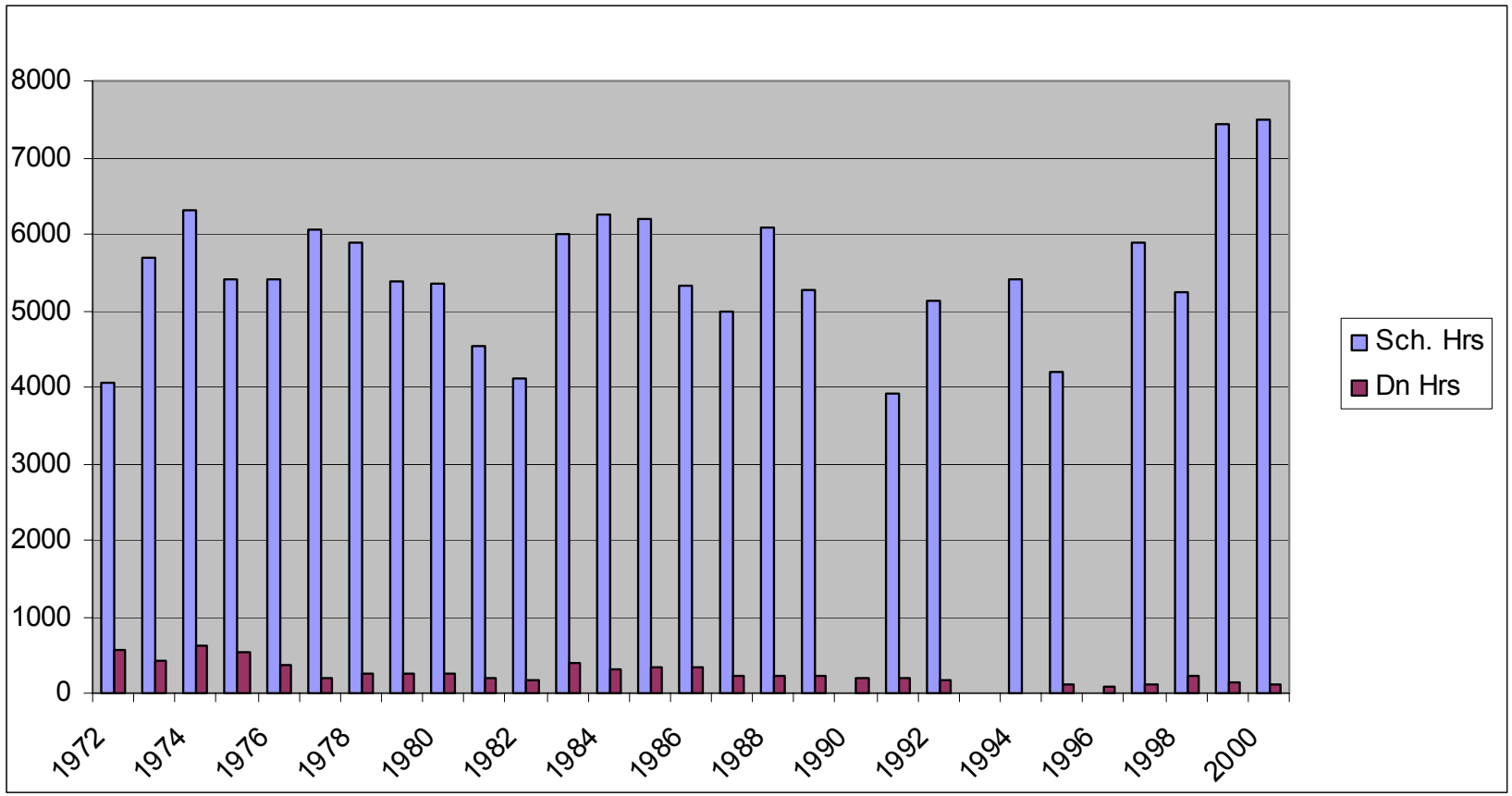
# Accumulative Fluence



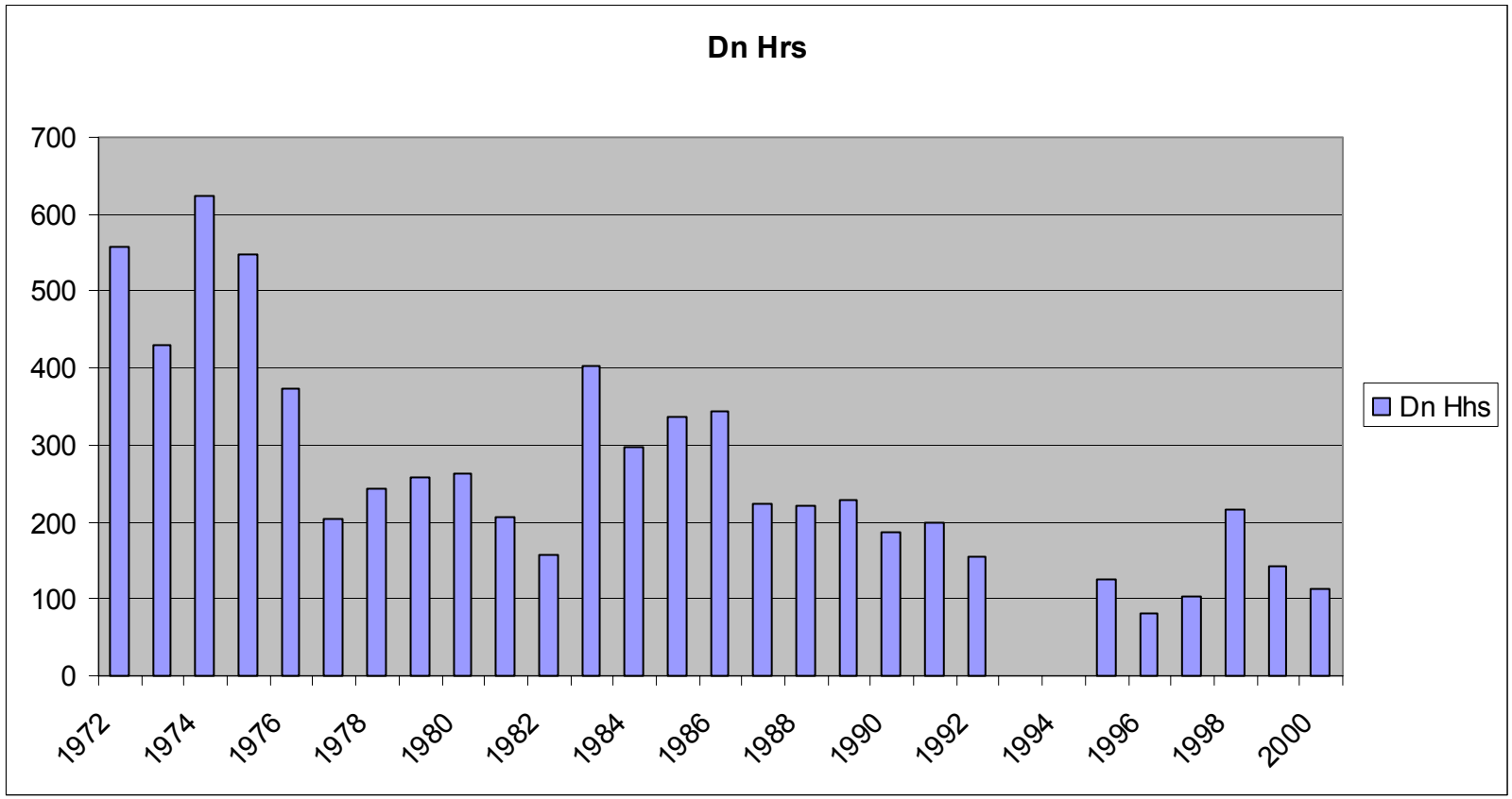
# Average Weekly Fluence



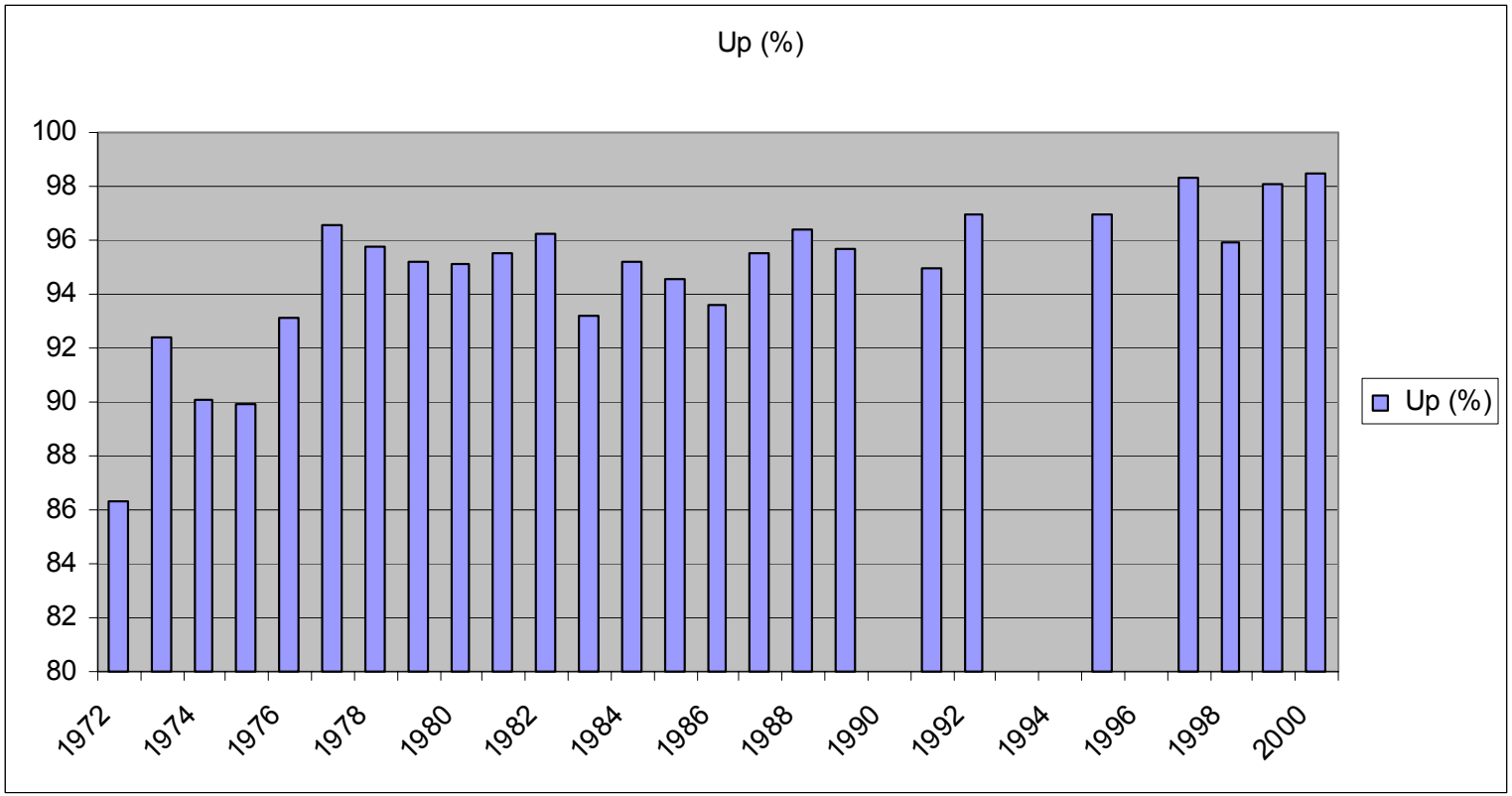
# Linac Operation



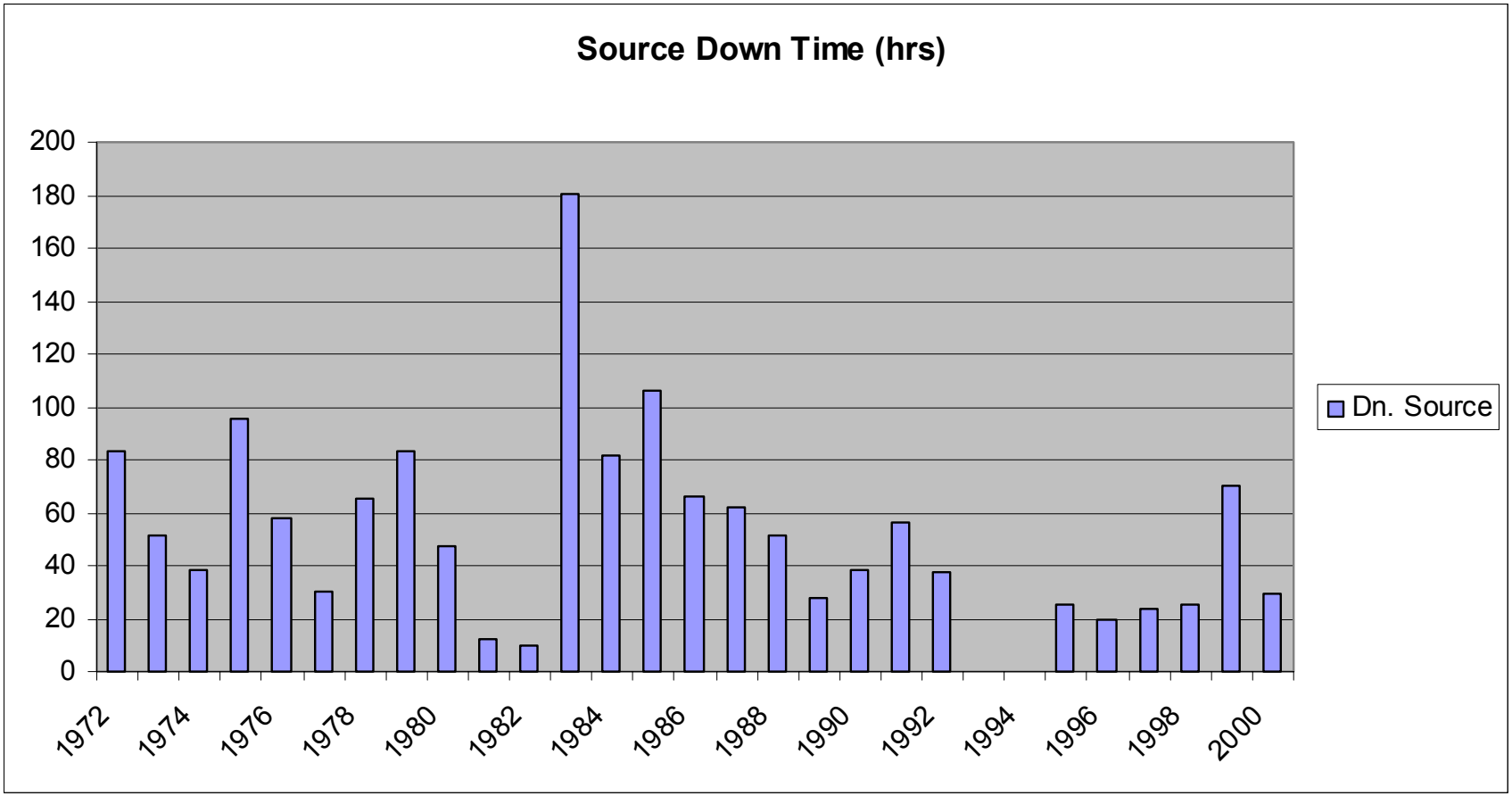
# Linac Operations (cont.)



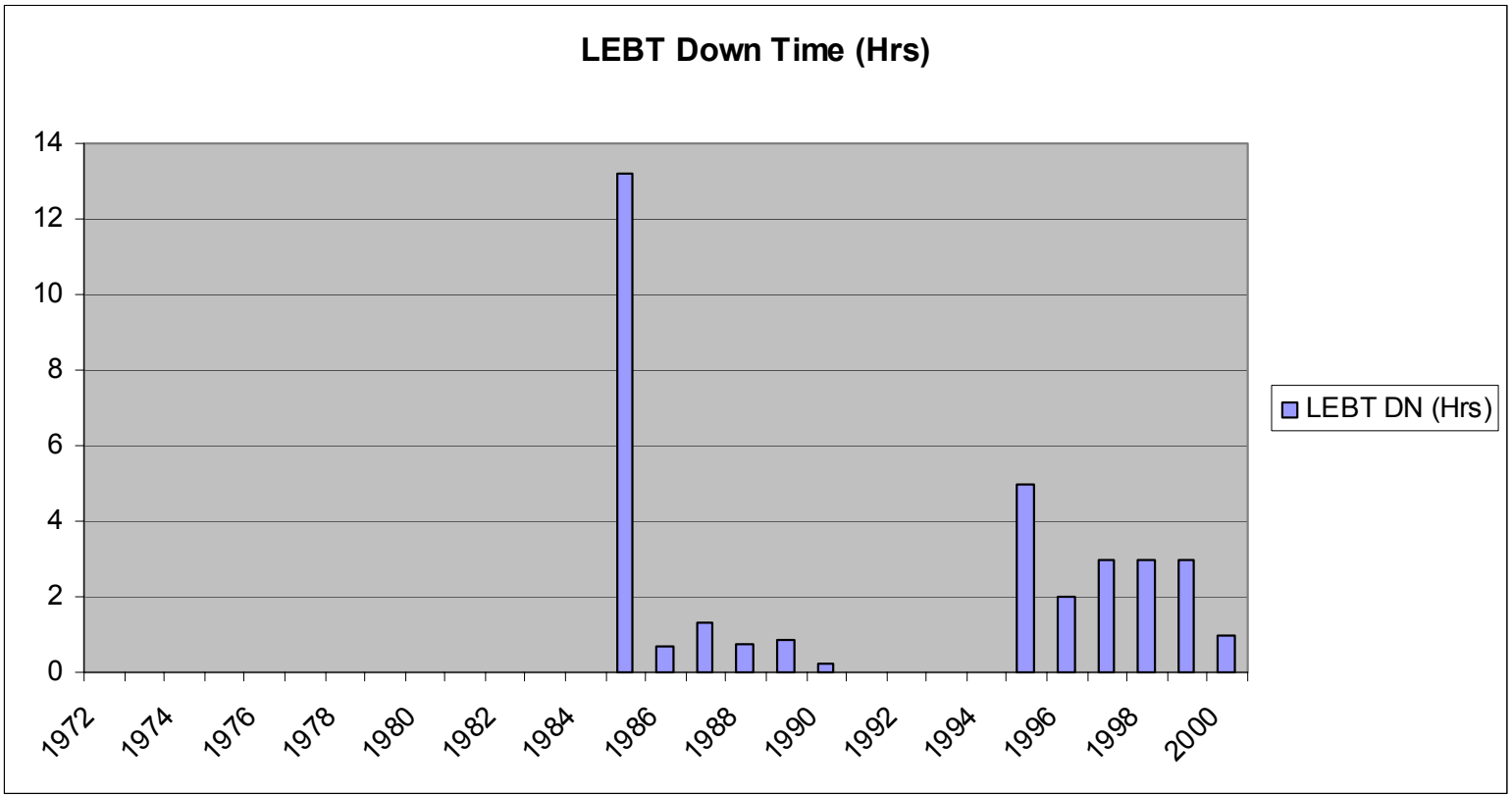
# Linac Operations (cont.)



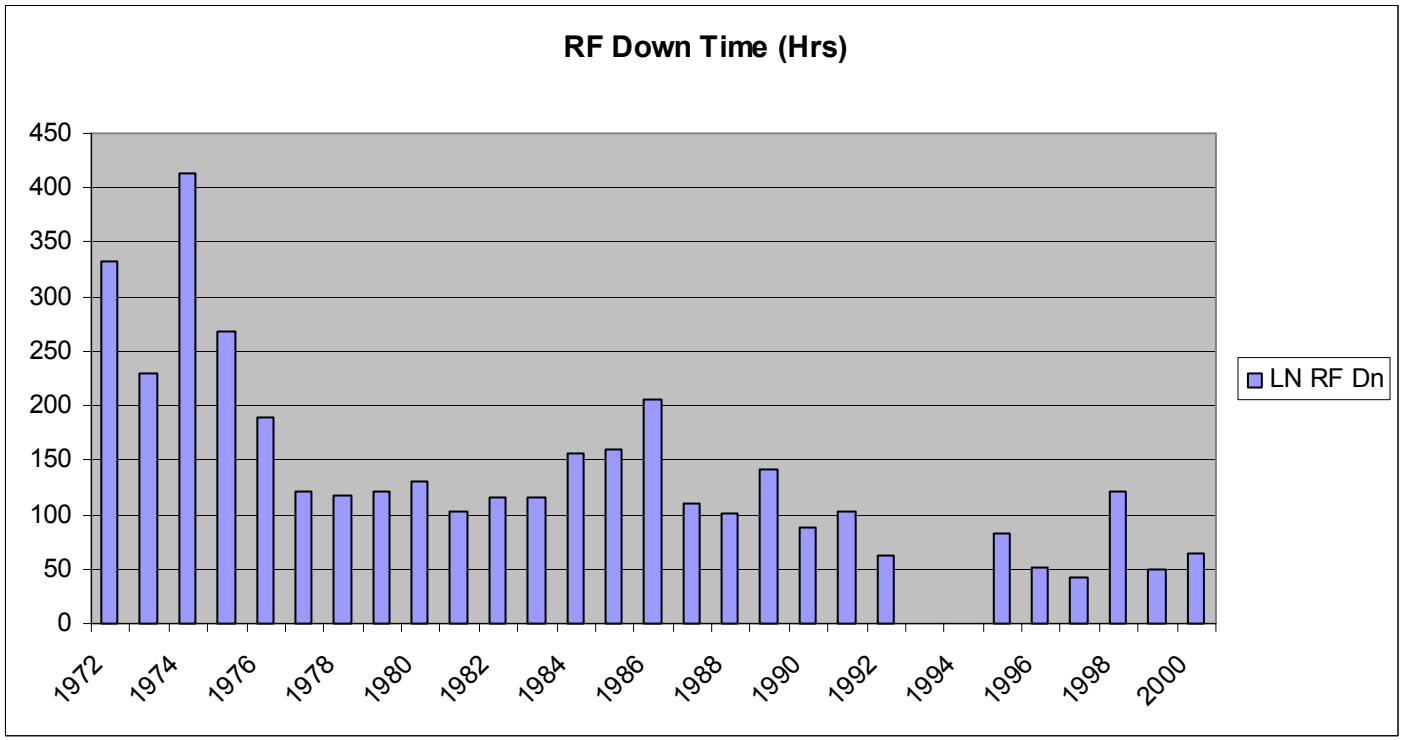
# Linac Operation (cont.)



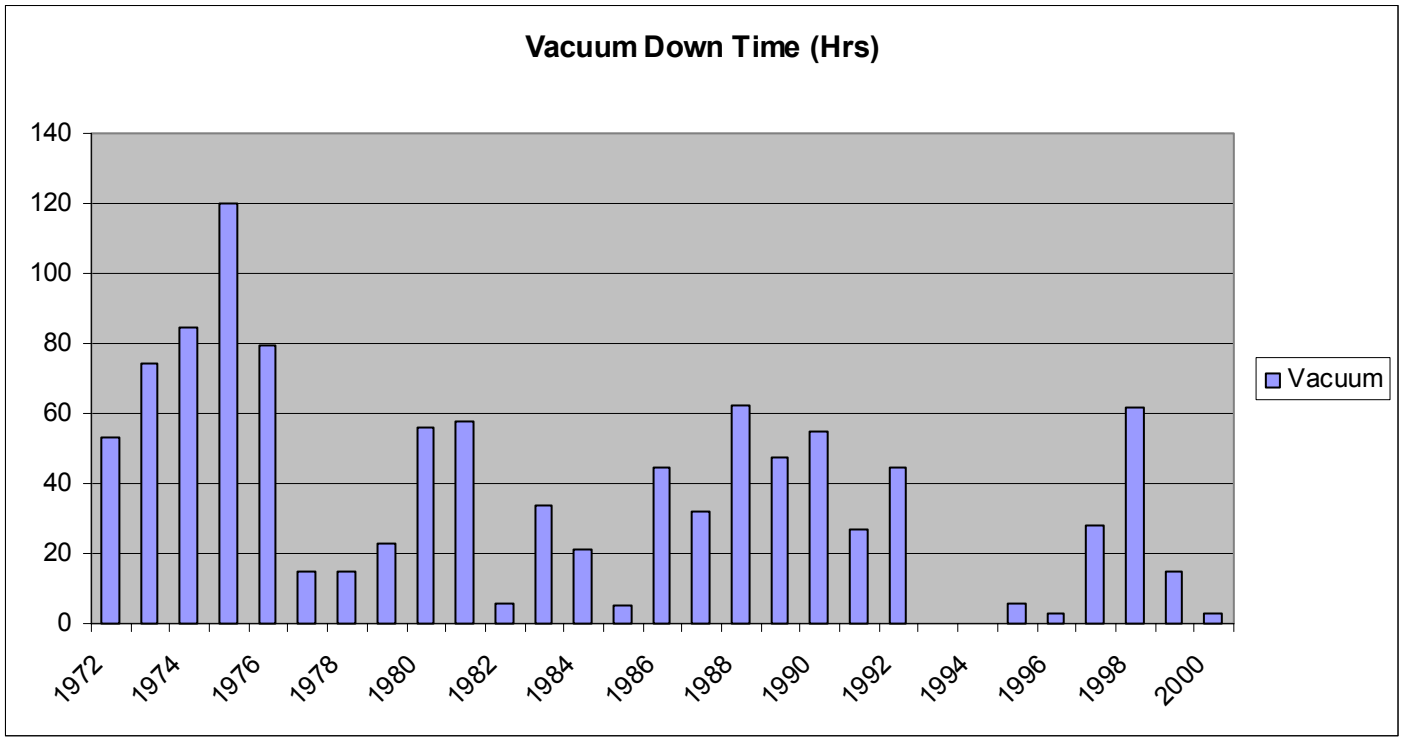
# Linac Operation (cont.)



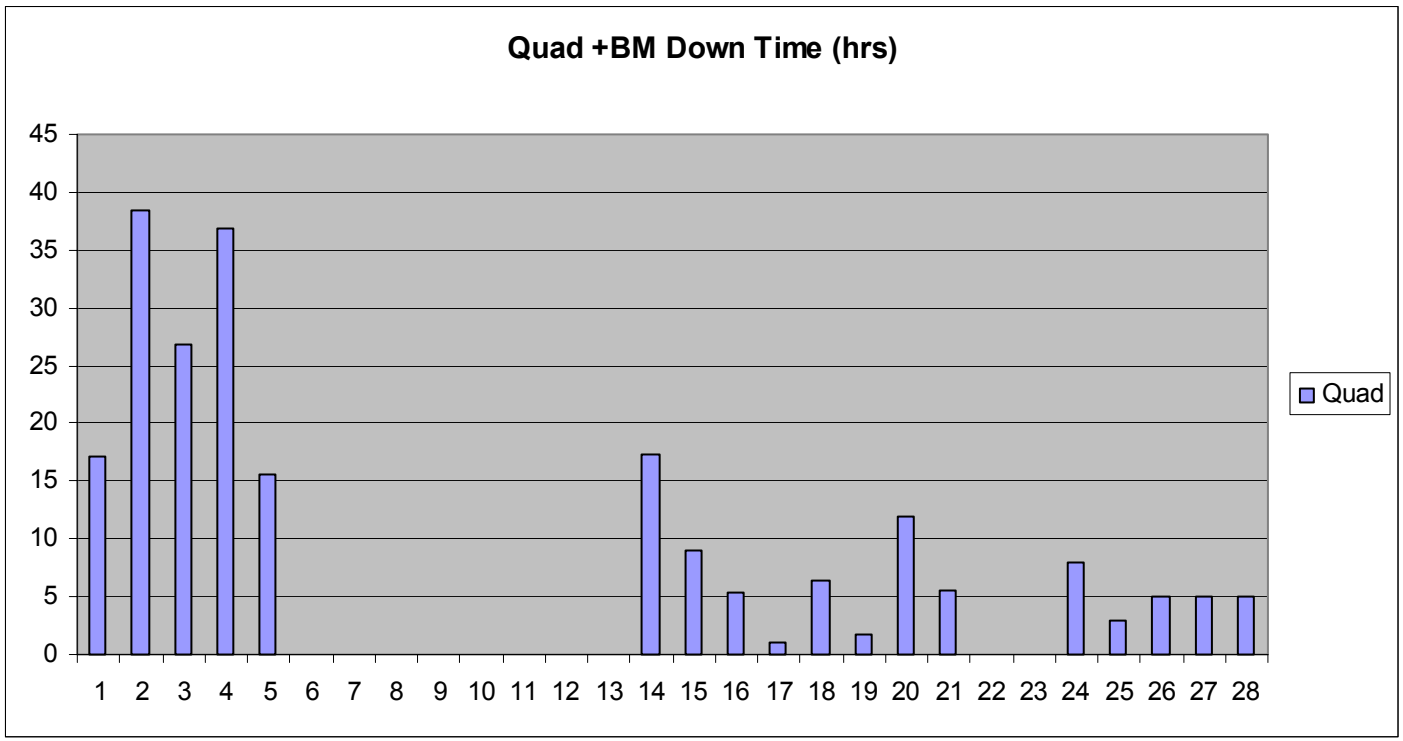
# Linac Operation (cont.)



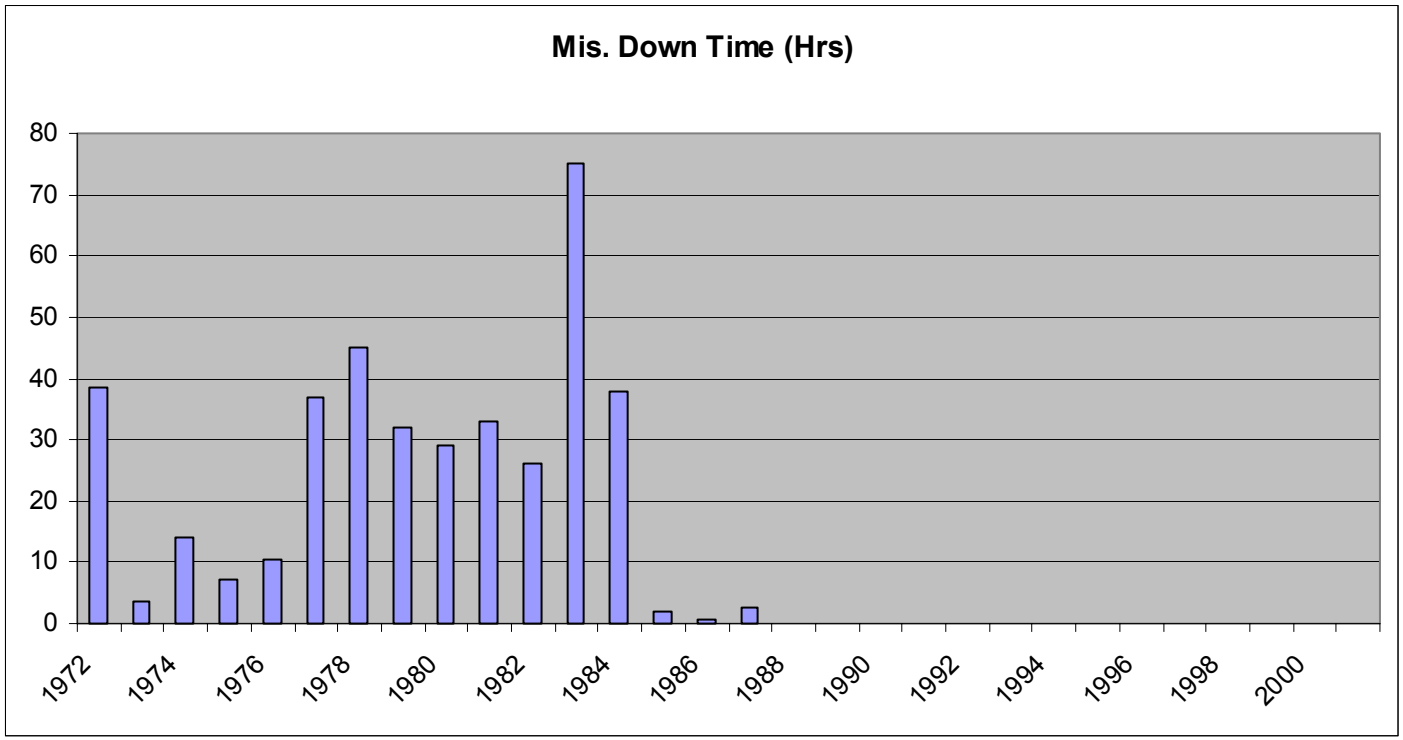
# Linac Operation (cont.)



# Linac Operation (cont.)



# Linac Operation (cont.)



# High Intensity Aspects

- RF tube (4616) failures => lower rep rate 5Hz
- Vacuum failures=>Achromat, Bigger dia beam pipe, Aluminum pipe & conflat flange
- Window failures=> Change to Be window from aluminum

# Operating staff info

- 2 Physicist (Part Time)
- 1 Mechanical Engg. (Part Time)
- 1 Electrical Engg. (Part Time)
- 6 Tech/Supervisor
- C-AD support: Controls, Vacuum, ESH, Operators
- Run unattended nights & weekends (MCR or call-ins)