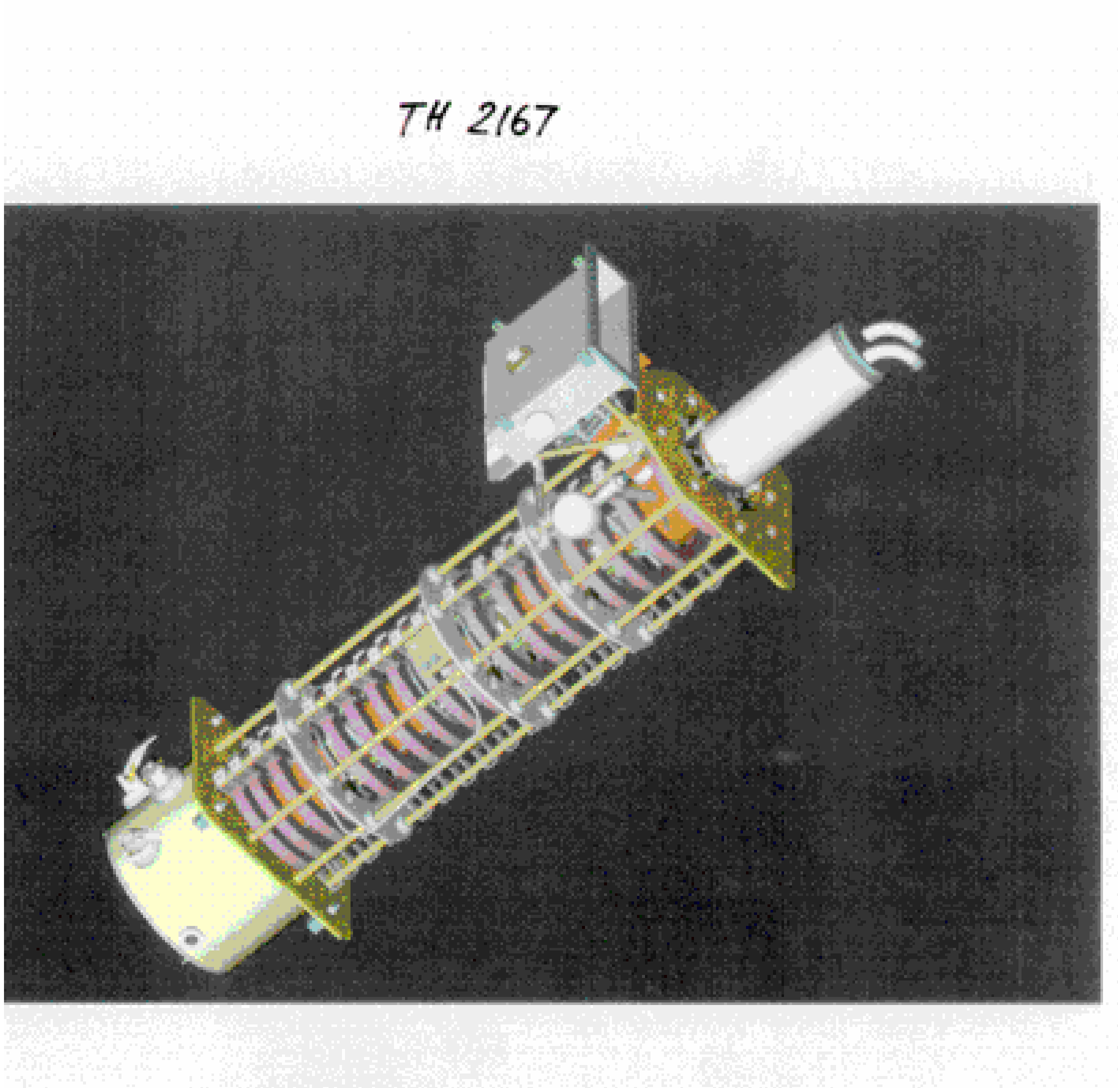
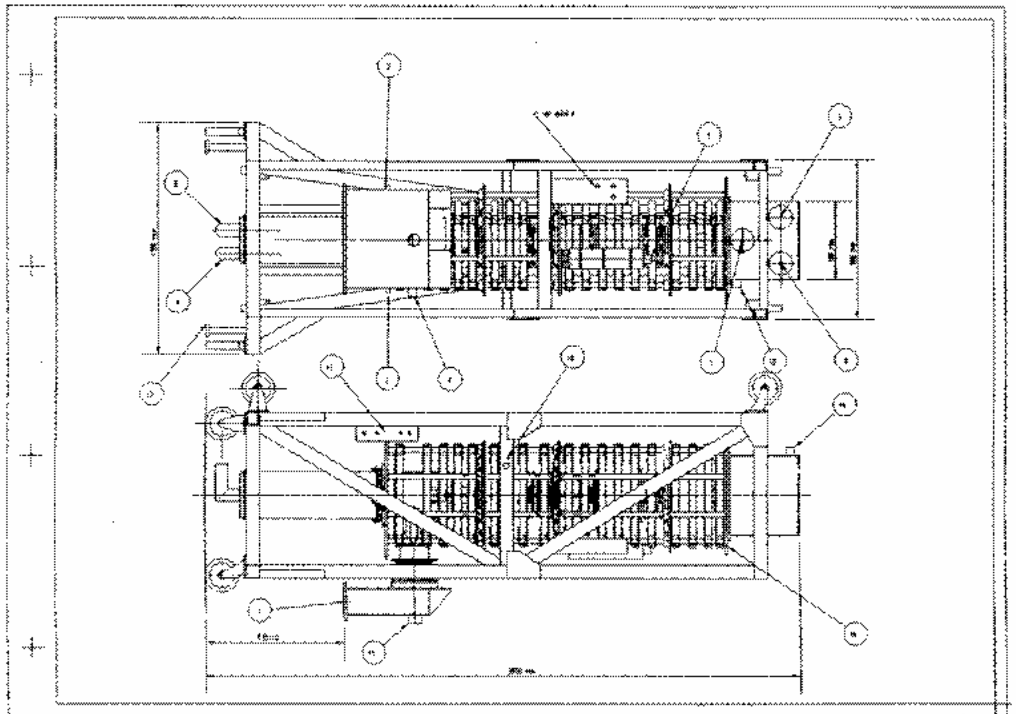
# LHC Klystrons – Review & Basic Characteristics



# LHC Klystron TH 2167

SBU Tubes et Dispositifs Hyperfréquences

## RCD TH 2167



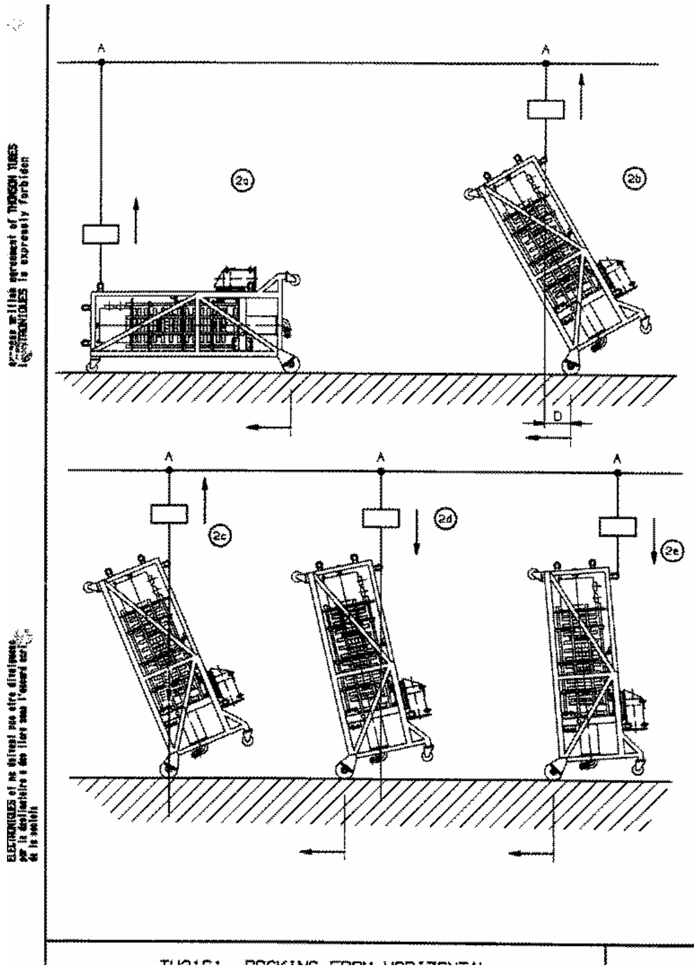
THALES ELECTRON DEVICES

THALES

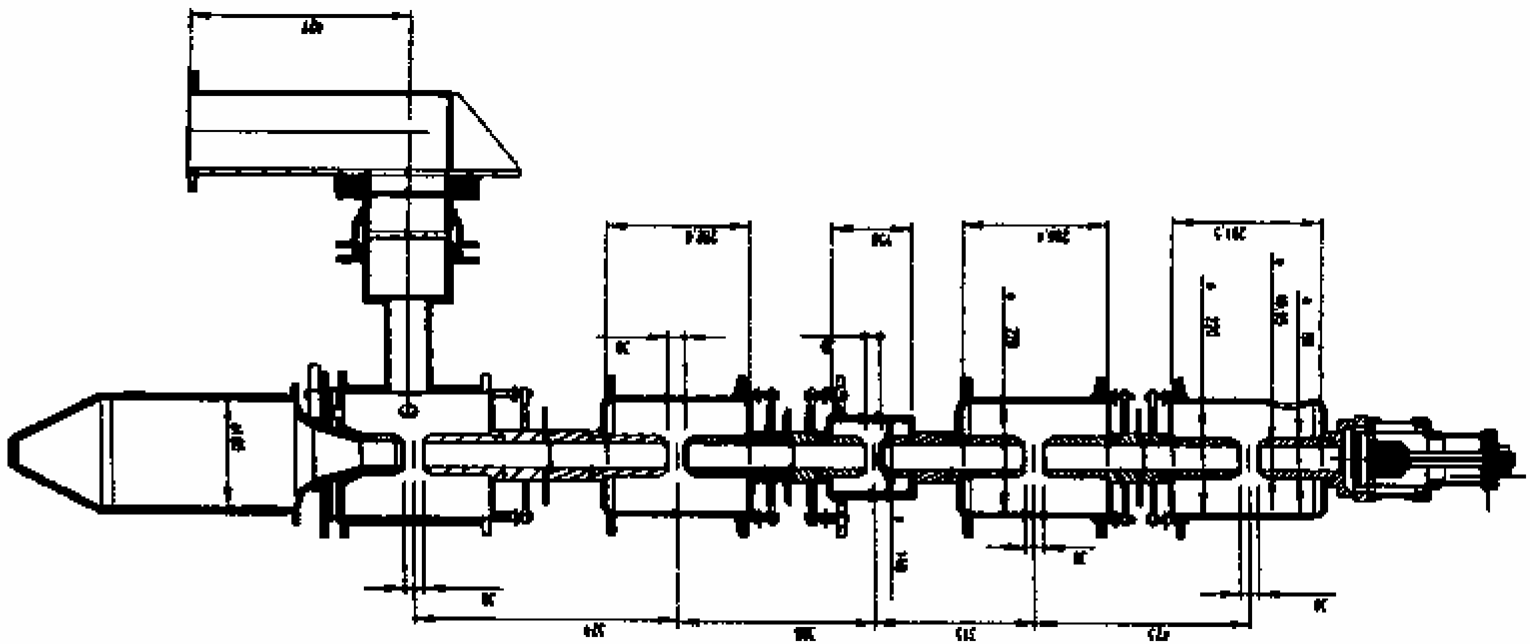
# LHC Klystrons

- 20 Ordered:  16 plus 4 spares
- Some Features
  - Modulating Anode to vary beam current
  - Air cooled gun (not oil as LEP klystrons)
  - Filament and cathode at High Voltage
  - Operating HV levels 46, 50 & 54 kV
  - Ion pump –> 8l/sec
  - Crossbar transition to waveguide
- Characteristics
  - Operating frequency 400 MHz
  - Power rating 300 kW
  - VSWR < 1.2
  - Group delay < 250 nS
  - Mod Anode current < 2.5 mA
  - Gain 37 dB
  - $2^{nd}$ & $3^{rd}$ harmonic output power better than 30 dB down on fundamental

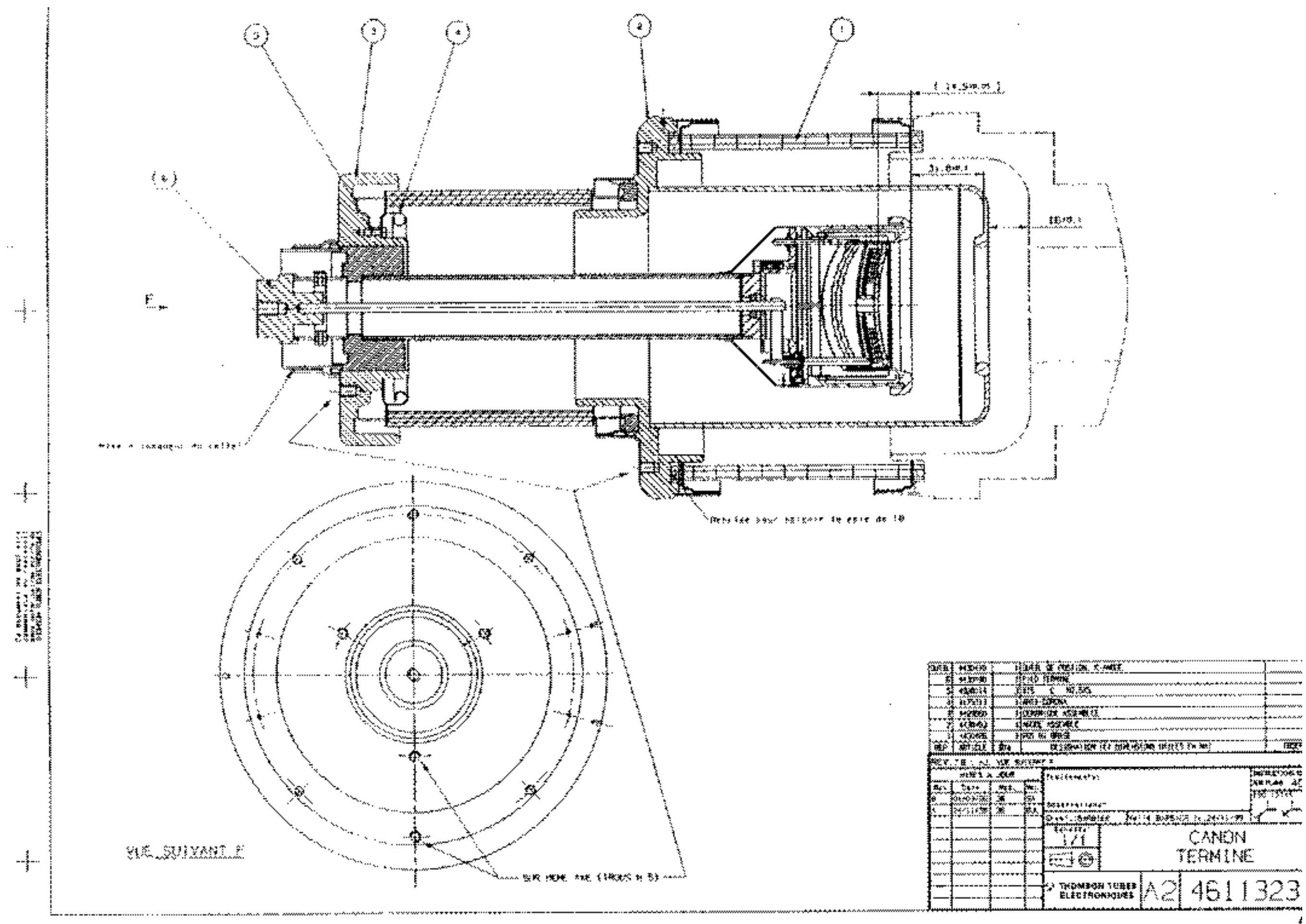
# Horizontal to Vertical Positioning



# Structure



# Gun



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1/1
THOMSON TUBES ELECTRONIQUES
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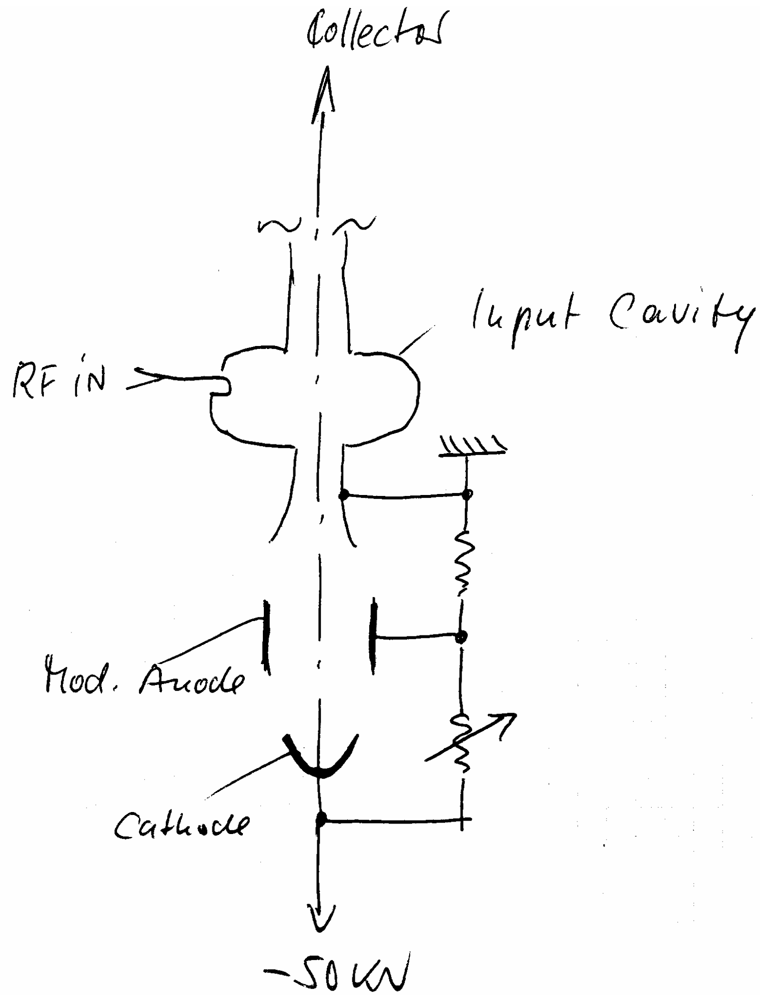
# Mod Anode Connection



# Specified Parameters (1)

***4.4.1 Electrical parameters***

| | |
|---|---|
| Rated output power | 300 $kW_{cw}$ |
| Operating frequency ($f_o$) | 400.8 MHz |
| -1dB Bandwidth (Operation 1dB below Saturated Output at each Working Point, see Table 3. | ≥ ± 1 MHz |
| Gun Perveance ($pg = I_b \cdot U_{MA}^{-1.5}$) @ $U_b$=50 kV and $I_b$=8A | $1.5 \cdot 10\text{-}6\ (A \cdot V^{-1.5})$ -0%+10% |
| Load VSWR @ any RF Phase | ≤ 1.2 |
| Beam voltage ($U_b$) @ Rated Output Power | ≤ 54 kV |
| Beam Current ($I_b$) @ Rated Output Power | ≤ 9 A |
| Cathode-to-Mod. Anode Voltage ($U_{MA}$) @ Rated Output Power | ≤ 35 kV (see 4.4.3 1)) |
| Modulation Anode Current ($I_{MA}$) @ Rated Output Power | ≤ ± 2.5 mA |
| Saturated Gain @ all Working Points | ≥ 37 dB |
| Group Delay within frequency range $f_o$ ± 0.25 MHz and operation @ 1 dB below saturated Output (All Working Points) | ≤ 250 ns |
| DC-to-RF Conversion Efficiencies @ Saturated Output Power and Load VSWR ≤ 1.1 | See Table 3 |
| RF Test Power (to be generated for at least 1 hour during acceptance tests) | 330 $kW_{cw}$ |
| Beam Voltage @ RF Test Power | ≤ 58 kV |
| Beam Current @ RF Test Power | ≤ 10 A |
| Harmonic Content in Output Signal (measured @ rated output power and an output termination consisting of a waveguide load with a return loss of ≤ -26 dB at all possible propagating modes in the frequency range 400 to 1200MHz | |
| @ 2nd Harmonic | ≤ -30 dB |
| @ 3rd Harmonic | ≤ -30 dB |
| Signal Ratio of fundamental to other discrete frequencies within bandwidth and ≤ 80 to 100% of saturated Output Power (all working points) | ≥ 60dB |
| RF Phase Variation over Beam Current @ constant Beam Voltage and RF Drive Signal | ≤ 15°/A |
| RF Phase over Beam Voltage Variation @ constant Beam Current and RF Drive Signal (1 dB below saturated Output) | ≤ 10°/% |

# Specified Parameters (2)

| | |
|---|---|
| | conductivity ≤ 5µS/cm |
| Nominal Water Temperature | 25 ± 2°C |
| Cooling Water Connectors: | |
| Collector | SANDVIK, Type 48.3 × 2.6, 316L |
| Body | WALTHER Quick Connector Type DN12 |
| Cooling Water Flows: | |
| Collector | ≤ 500 l/min |
| Body | ≤ 12 l/min |
| Cooling Water Pressure Drops: | |
| Collector | ≤ 3 bars |
| Body | ≤ 3 bars |
| Test Pressure of Water Circuits | 10 bars |
| Cooling of Output Window, HV Tank and Focusing Coils (connections, pressures and flows to be specified by manufacturer) | Air cooled |
| Air Flow and Pressure Drop: | |
| HV Insulation Box | ≤ 1500 l/min, ≤ 20 mbars |
| Output Window | ≤ 1000 l/min, ≤ 60 mbars |

Table 2

| Working Point | $U_b$ (kV) | $I_b$ (A) | Beamperv. ($\mu AV^{-1.5}$) | $P_{DC}$ (kW) | Saturation efficiency | $P_{out\ sat.}$ (kW cw) |
|---|---|---|---|---|---|---|
| I | 46 | 7 | 0.71 | 322 | ≥ 0.62 | ≥ 200 |
| II | 50 | 8 | 0.72 | 400 | ≥ 0.63 | ≥ 250 |
| III | 54 | 9 | 0.72 | 486 | ≥ 0.62 | ≥ 300 |

Table 3

# Specified Parameters (3)

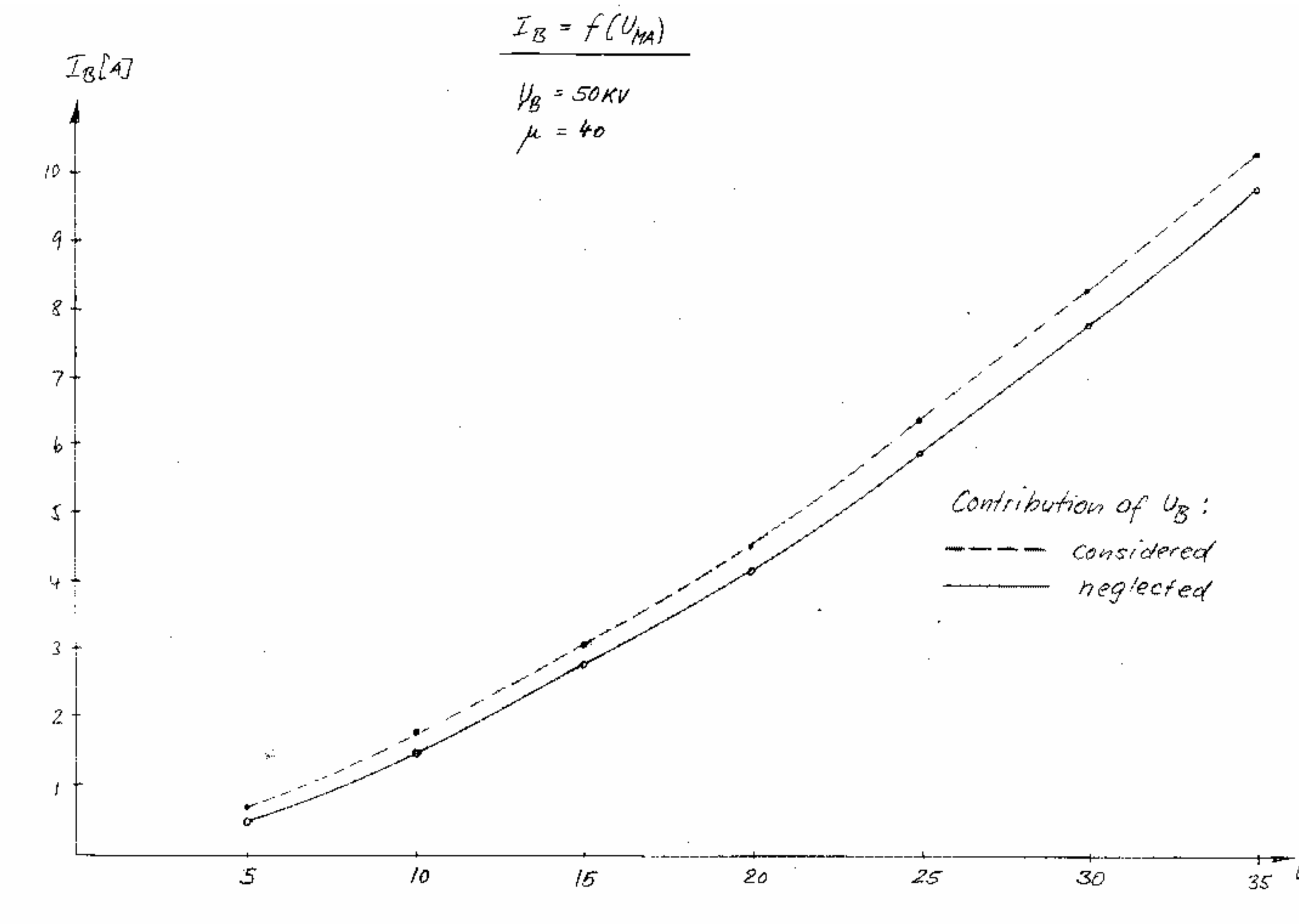
| | |
|---|---|
| RF Output Power over Beam Voltage Variation @ constant Beam Current and RF Drive Signal (1 dB below saturated Output) | ≤ 0.1 dB/% |
| Body Dissipation (under all possible operating conditions) | ≤ 10 kW (see 4.4.3 1)) |
| Continuous Collector Dissipation Capability (with or without RF Drive) | ≥ 500 kW |
| Cathode Heater: | |
| Voltage | ≤ 30 Vac |
| Current | ≤ 30 Aac (see 4.4.3 2)) |
| Ion Pump Voltage | ≥ 5 kV (See 4.4.3 3)) |
| RF Radiation from any Surface @ Test Power | ≤ 0.1 mW/cm$^2$ |
| Magnetic Field 1 m from Klystron Axis | ≤ 0.5 mT |
| DC Test Voltages (cold cathode): | |
| Cathode/Modulation Anode to Ground | ≥ 70 kV for 15 min |
| Cathode to Modulation Anode | ≥ 60 kV for 15 min |

Table 1

*4.4.2 General parameters*

| | |
|---|---|
| Transport and operating positions | horizontal and vertical |
| Maximum overall dimensions of complete assembly | see 4.4.3 4) |
| Support for horizontal and vertical klystron position | see 4.4.3 5) |
| Tipping Device | see 4.4.3 6) |
| Maximum X-radiation at any klystron surface | 5 µSv/h |
| | see 4.4.3 7) |
| HV connectors for cathode, heater and modulation anode | see 4.4.3 8) |
| RF Input Connector | Type N, 50Ω, female |
| RF output connector | Half-height WR 2300 flange see 4.4.3 9) |
| Ion Pump Connector | LEMO, Type ERA.3S.415.FPA |
| Focusing Coil Connector | SOCAPEX, Type SL/EM 22B |
| Cooling Water | Demineralized Water, |

# Mod Anode Characteristic



# Some Explanations: 1

Perveance

1) Diode: $p = \frac{I_b}{U_b^{3/2}}$

$p$ = constant, depends only on geometry of gun

2) Triode:

a) gun perv. $p_g = \frac{I_b}{\left(U_{MA} + \frac{U_b}{\mu}\right)^{3/2}}$

LEP Klystrons: $\mu \approx 35 \cdots 40$

LEP/LHC klystrons: $p_g \approx 1.5 \cdot 10^{-6} \, [A/V^{3/2}]$ (@ rated output)

b) beam perv.

Joachim's Addendum:

$p_b = p_g \left(\frac{U_{MA}}{U_b} + \frac{1}{\mu}\right)^{3/2}$

$p_b = \frac{I_b}{U_b^{3/2}} \, [A \cdot V^{-3/2}]$

↓

variable $= f(U_{MA})$

LEP/LHC klystrons:

$p_b \approx 0.7 \cdot 10^{-6} \, [A \cdot V^{-3/2}]$ (@ rated output)

# Some Explanations: 2

Efficiency (empirical)

$$\eta \approx 0.78 - 0.16 \cdot \mu p$$

e.g. @ $\mu p = 0.7 \longrightarrow \eta \approx 66\%$

Output Power $P_{RF} = f(U_b)$

$$P_{RF} = \eta \cdot U_b \cdot I_b$$

$$P_{RF} = \eta \cdot p_b \cdot U_b^{5/2}$$

$\Delta U_b \ll U_b$ : $\Delta U_{RF} \sim \Delta U_b^{5/4}$

⇒ 1% ripple on $U_b$ → 1.2% ripple on $U_{RF}$

$$\frac{\Delta U_{RF}}{\Delta U_b} = 1.2\ \%/\% \quad (0.1\,dB)$$

Output Phase ( $\phi = f(U_b)$ )

$$\gamma = 1 + \frac{U_b(kV)}{512}, \quad \gamma = \frac{1}{\sqrt{1-\left(\frac{v}{c}\right)^2}}$$

$U_b = 50\,kV$: $v = 0.4123 \cdot c$

Interaction length: 1.648 m → t = 13 ns

⇒ 1% ripple on $U_b \longrightarrow \Delta\phi_{RF} = 8.4°$

$$\frac{\Delta \phi_{RF}}{\Delta U_b} = 8.4\ °/\%$$

$U_b$ : 25 kV …. 50 kV $\longrightarrow \Delta\phi_{RF} = 706°$

# Some Explanations: 3

**Test Power:** $P_{test}$ : 330 kW

$P_f$ : 300 kW
$P_r$ : 360 " } Joachim
(seen by circulator)

$$P_e = \frac{1}{4}\left(\sqrt{P_f} + \sqrt{P_r}\right)^2 = 330\ \text{kW}$$

# Measurements on LEP Klystrons (1)

- 6 -

Points 4-5

Fréquence RF: 352.21 MHz

Puissance d'entrée = 59 W

$U_{MA}$ = 67 kV

| $U_k$ kV | Phase /° | P. sortie (coupleur) kW | I cath. A | $I_{MA}$ mA |
|---|---|---|---|---|
| 87 | 0 | 1050 | 17.9 | 0.2 |
| 86 | +9 | 1036 | 17.9 | 0.2 |
| 85 | +20 | 1022 | 17.9 | 0.2 |
| 84 | +30 | 994 | 17.9 | 0.2 |
| 83 | +38 | 965 | 17.9 | 0.2 |
| 82 | +48 | 936 | 17.9 | 0.3 |
| 81 | +50 | 922 | 17.9 | 0.3 |
| | | | | |
| | | | | |
| | | | | |

$$\frac{U_{max} - U_{min}}{U_{moy}} = 7.1 \%$$

8.4 °/% (max: 15° %)

-0.08 dB/% (max: 0.2 dB %)

Remarques: (Thomson TH 2089)

# Measurements on LEP Klystrons (2)

- 6 -

Points 4-5

Fréquence RF: 352.21 MHz

Puissance d'entrée = 90 W

$U_{MA}$ = 47 kV 60

| $U_k$ kV | Phase /° | P. sortie (coupleur) kW | I cath. A | $I_{MA}$ mA |
|---|---|---|---|---|
| 90 | 0 | 1004 | 16.7 | 0.5 |
| 89 | -7 | 994 | " | 0.5 |
| 88 | -15 | 984 | " | 0.5 |
| 87 | -21 | 966 | " | 0.5 |
| 86 | -30 | 949 | " | 0.4 |
| 85 | -38 | 933 | " | 0.2 |
| 84 | -44 | 912 | " | 0.2 |
| | | | | |
| | | | | |
| | | | | |

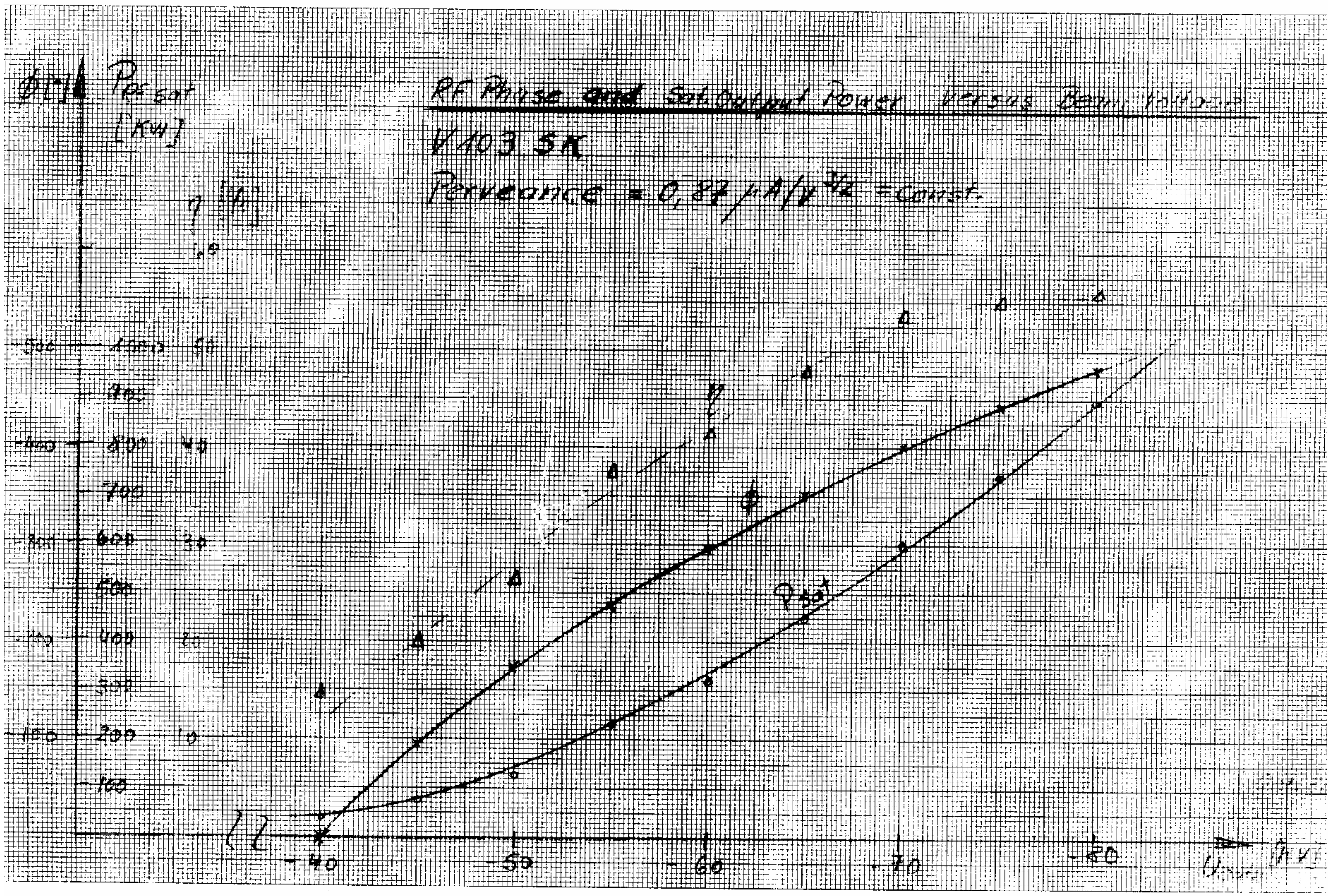
$\frac{U_{max} - U_{min}}{U_{moy}}$ = 6.9 %

6.4 °/% (max: 15°/%)

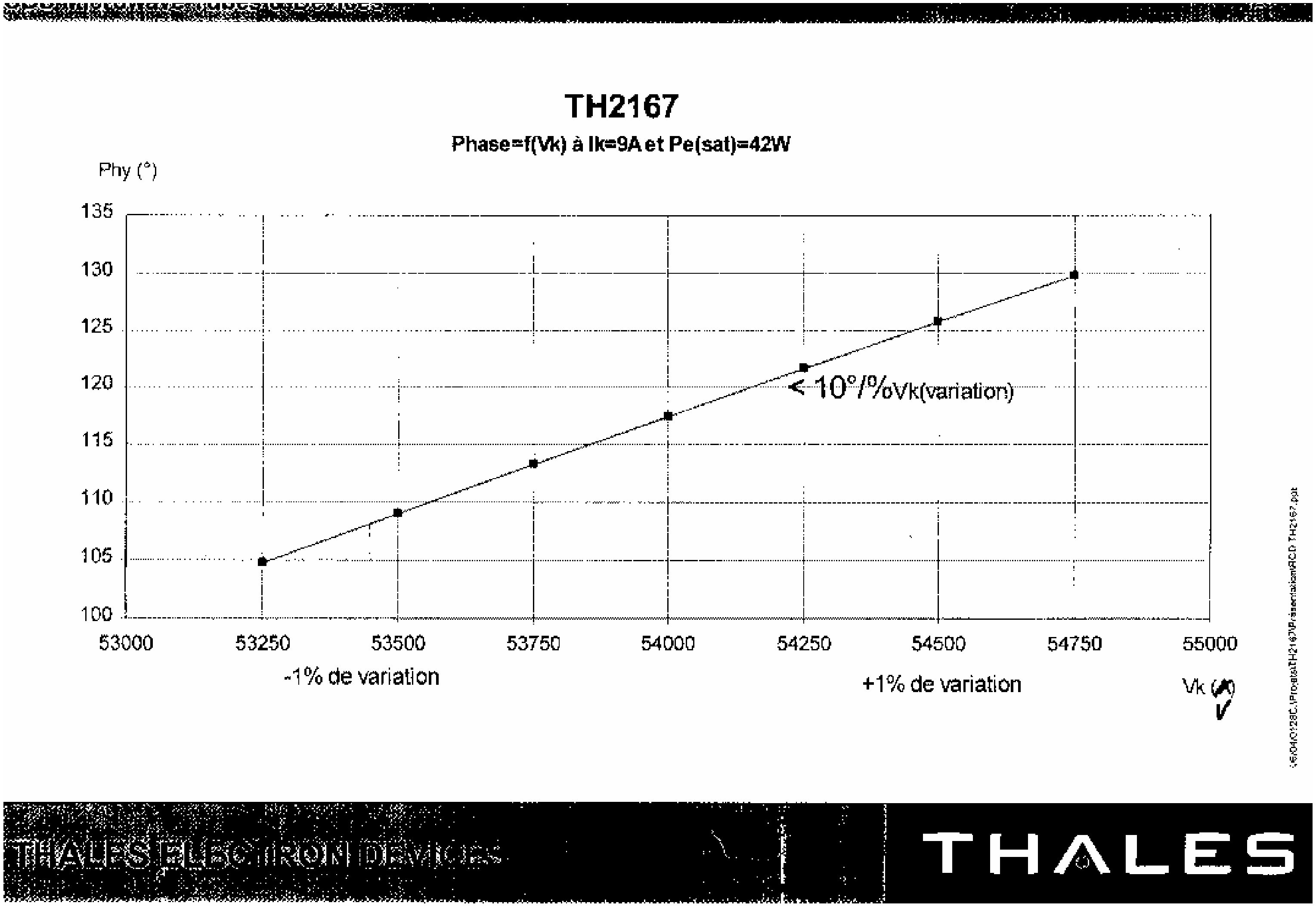
-0.08 dB/% (max: 0.2 dB %)

Remarques: (Philips YK1350)

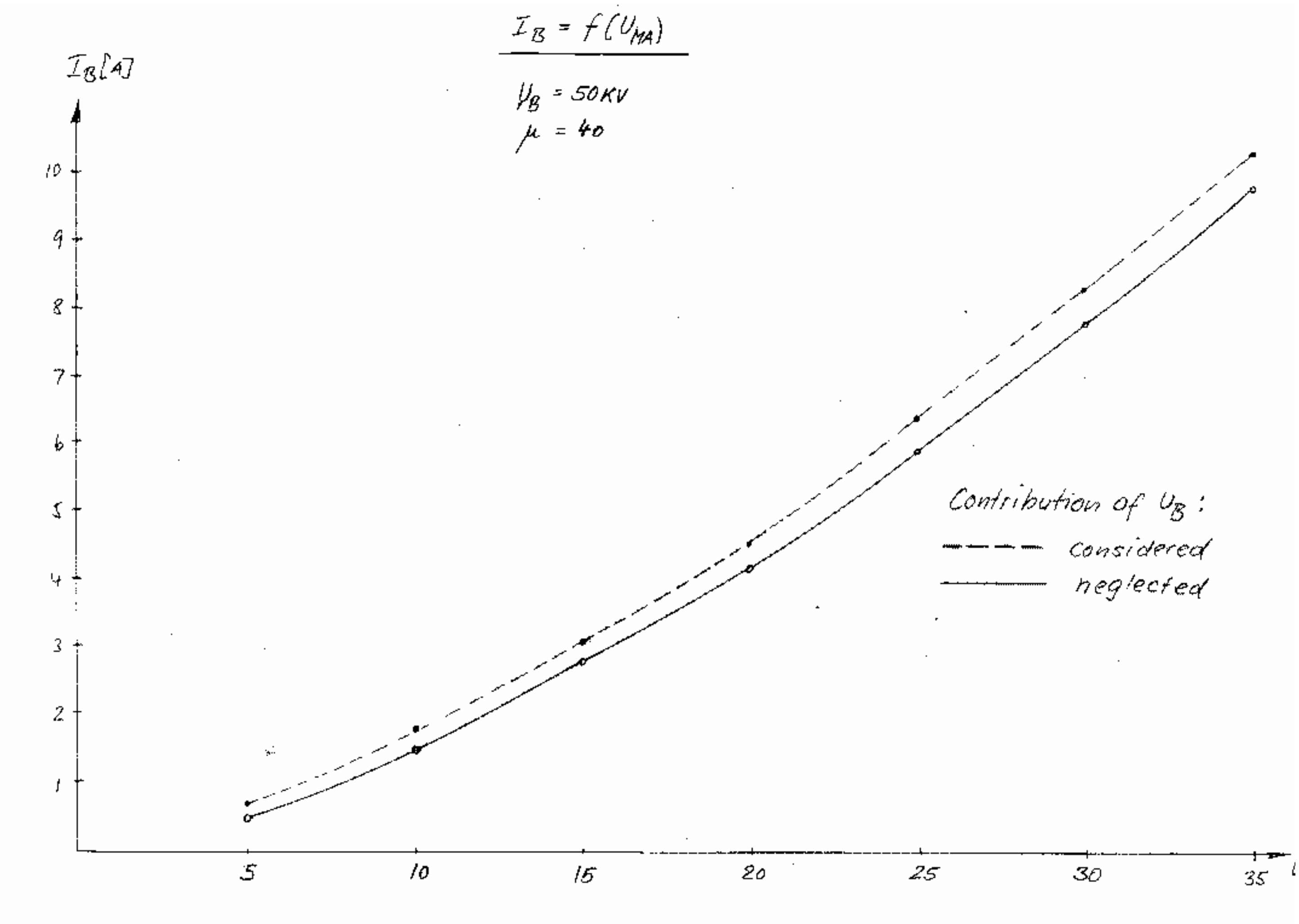
# RF output Power & Phase vs. DC Voltage – LEP Klystron



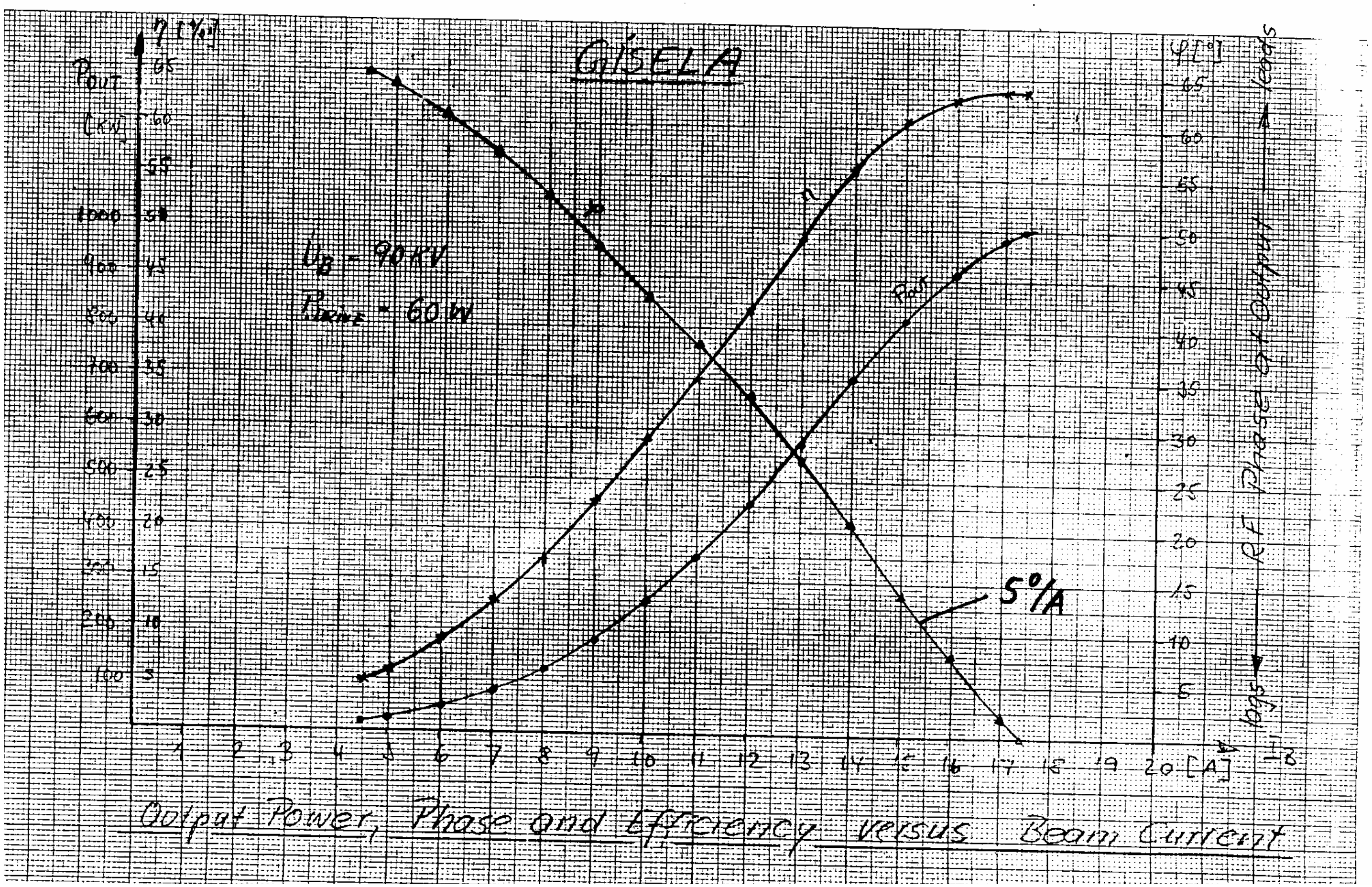
# RF Phase vs. DC Voltage – LHC Klystron



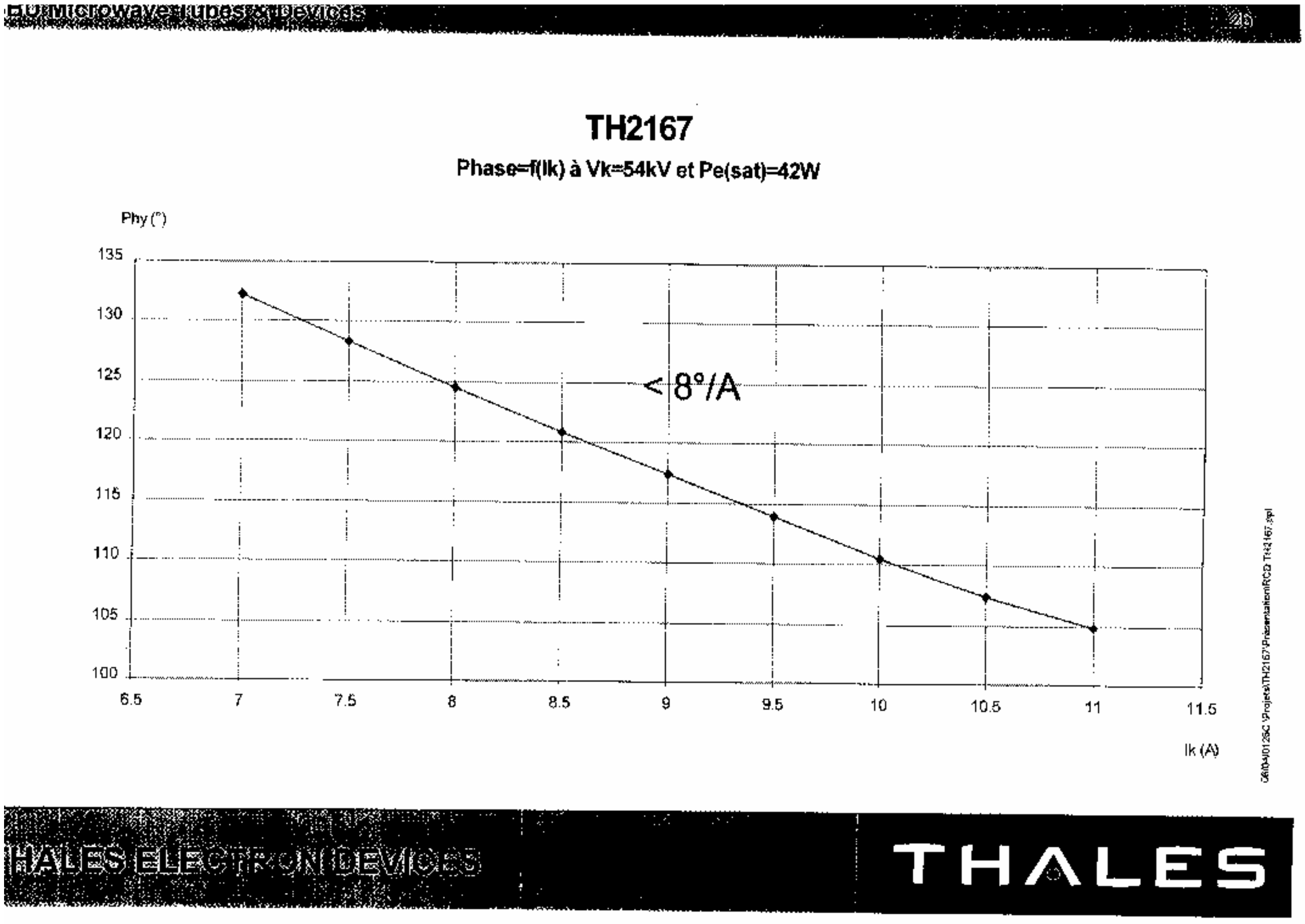
# Mod Anode Characteristic



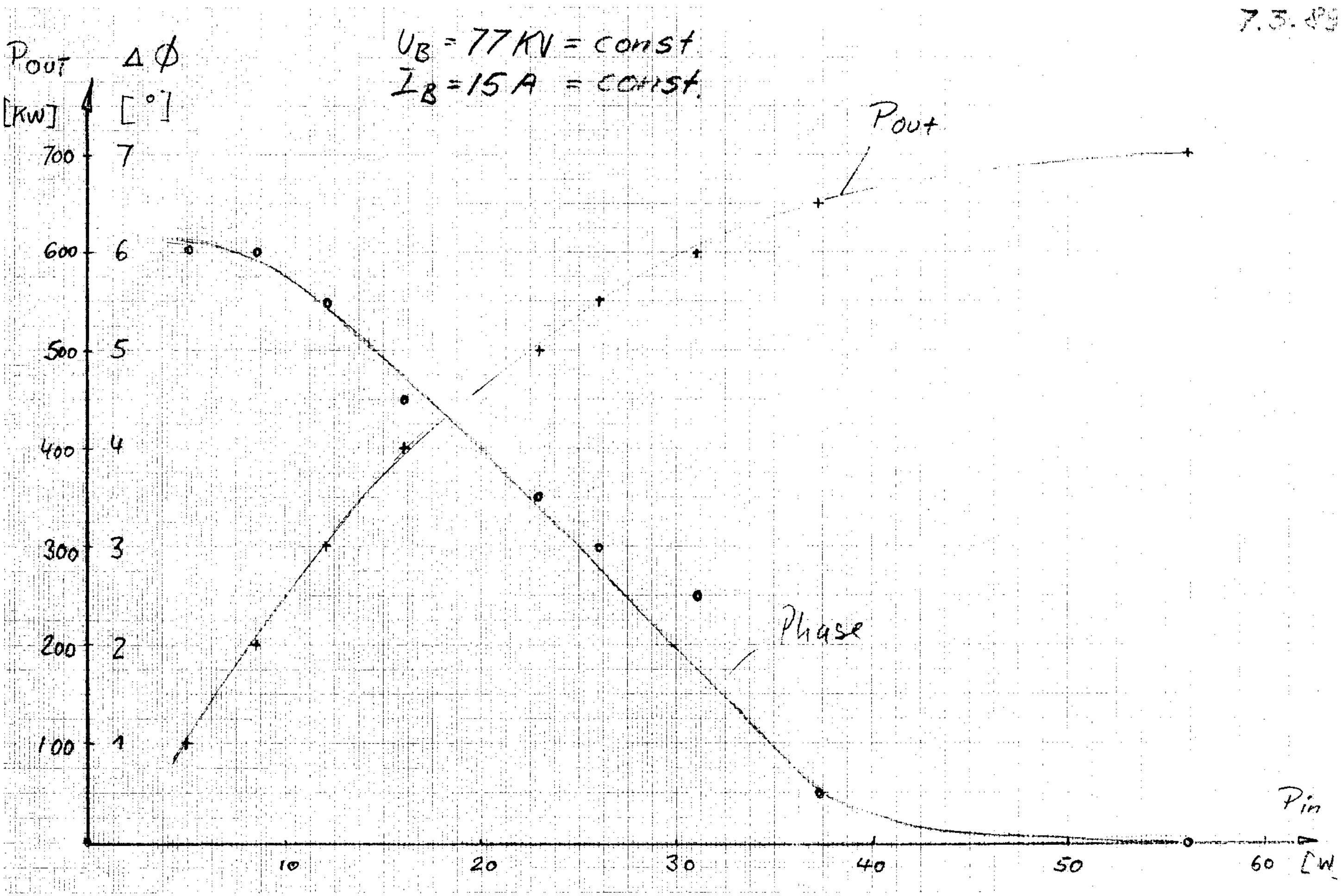
# RF output Power, Phase & Efficiency vs Beam Current – LEP Klystron



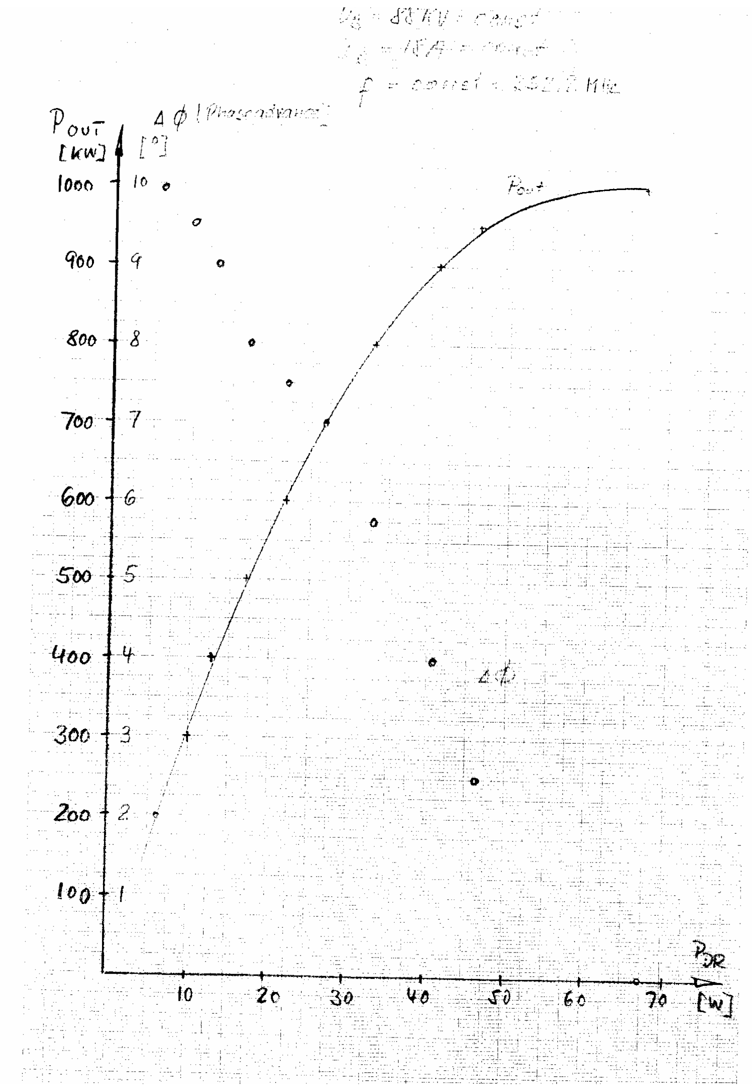
# RF Phase vs. Beam Current – LHC Klystron



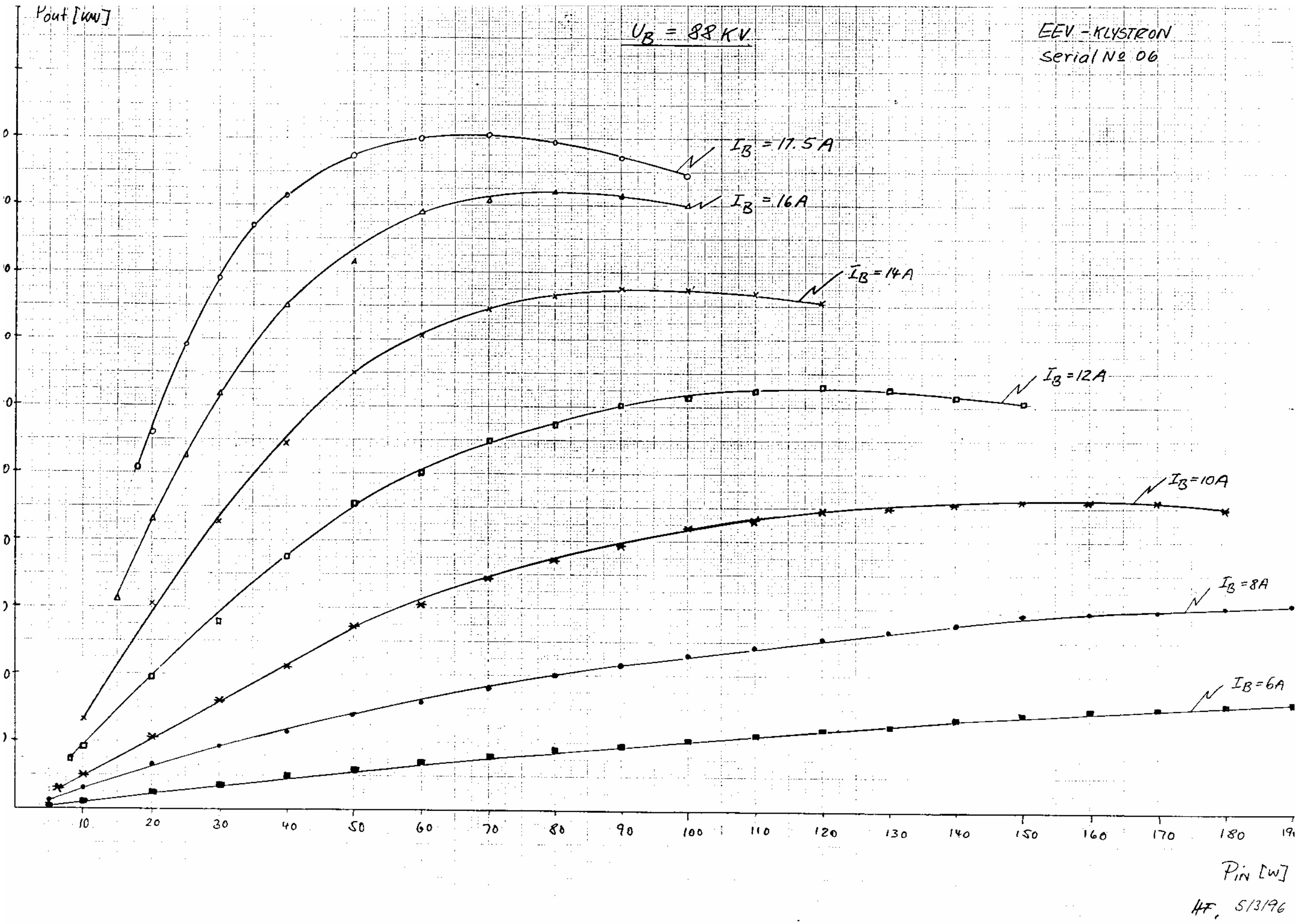
# RF Output Power & Phase Vs. Input Power – LEP Klystron



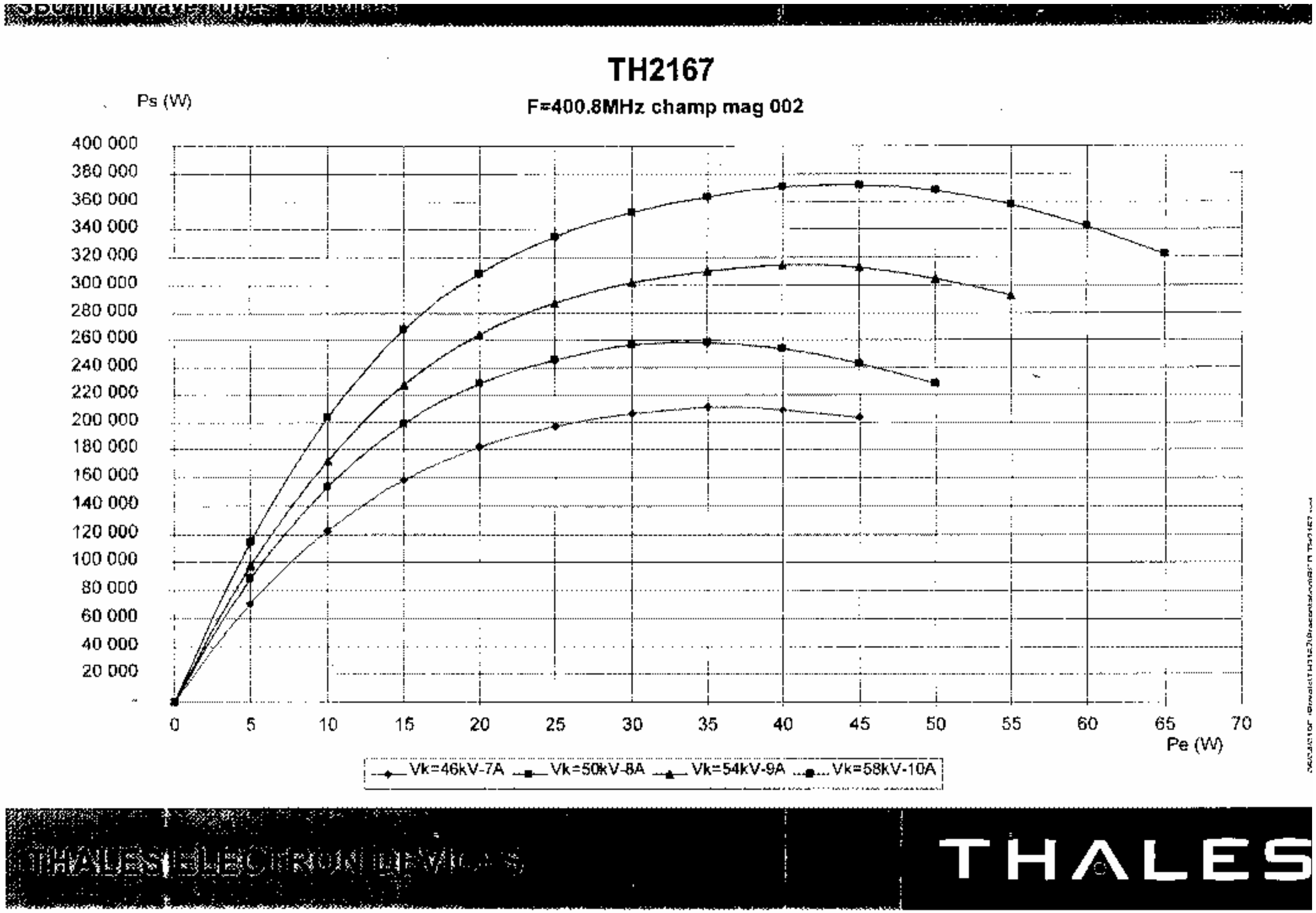
# RF Output Power & Phase vs. Input Power – LEP Klystron



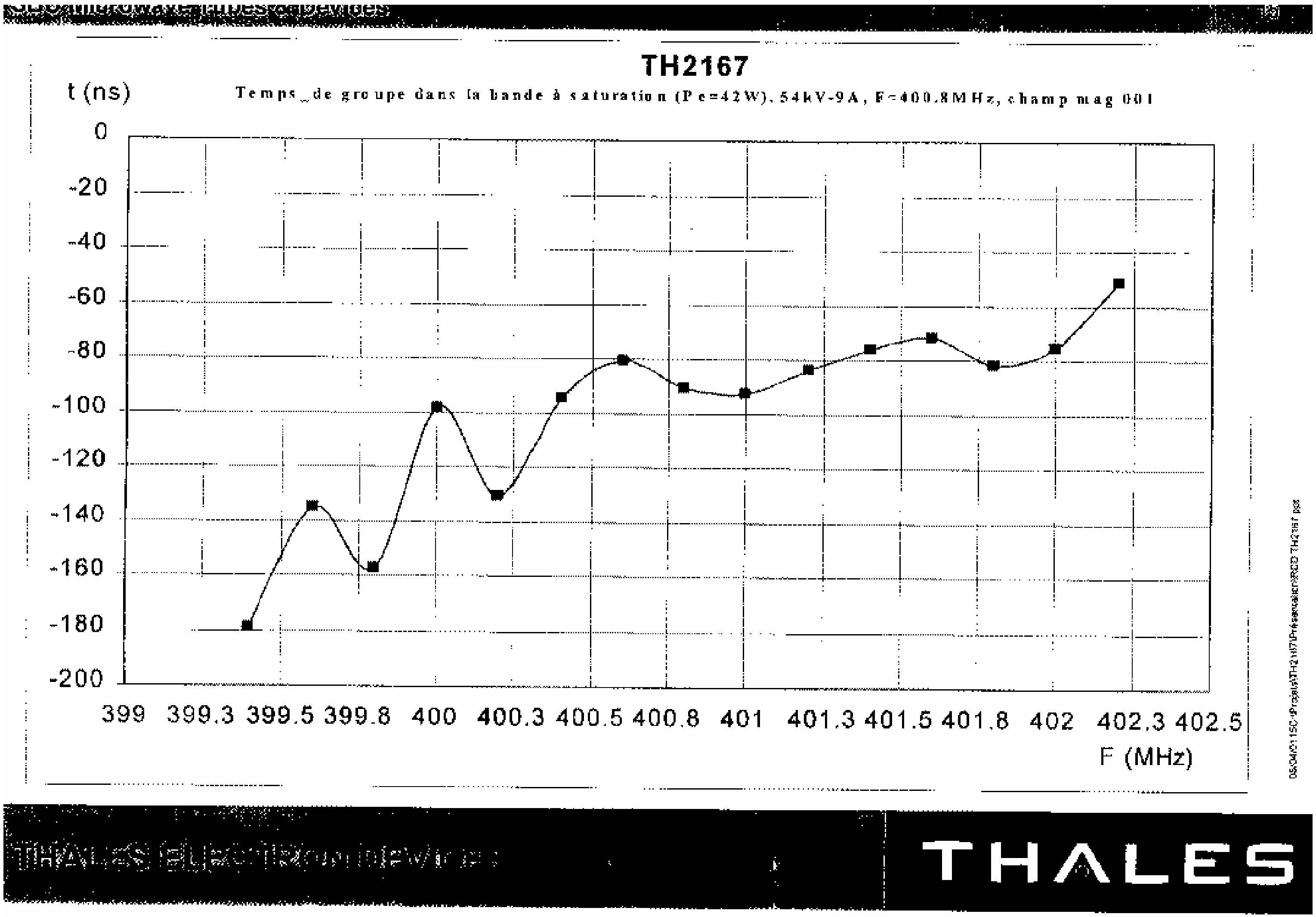
# RF Output Power & Phase vs. Input Power, Various $I_b$ – LEP Klystron



# RF Output Power vs. Input Power, Various DC Voltage/$I_b$ – LHC Klystron



# Group Delay vs. Frequency – LHC Klystron



## Group Delay vs. Frequency – Drive Amplifier