High efficiency in pulsed X-band

2nd Workshop on efficient RF Sources

Delivered by Paz Alonso-Arias

N. Catalán-Lasheras, A. Chauchet, S. González-Antón, C. Marrelli, I. Syratchev, Z. Un-Nisa, M. Webber, M. D. Jones, M. Boronat, T. Anno

23 September 2024

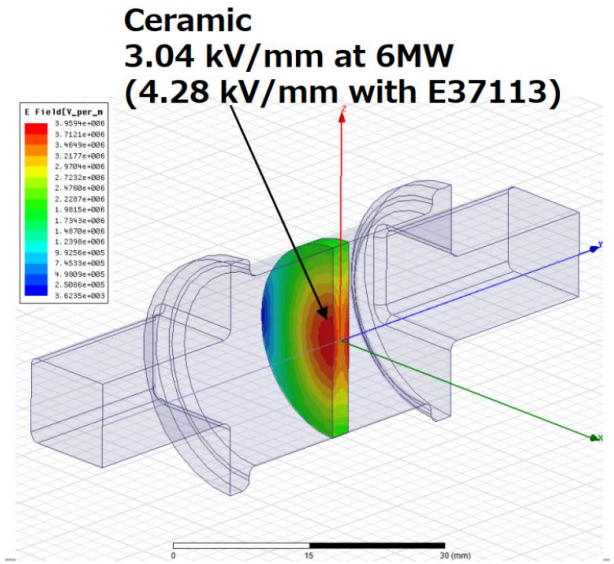
Introduction

High efficiency klystrons project at CERN

HE X-band klystron demonstrating >50% efficiency

Collaboration with industry

Design fo the HE X-band klystron



Canon ETD 37113

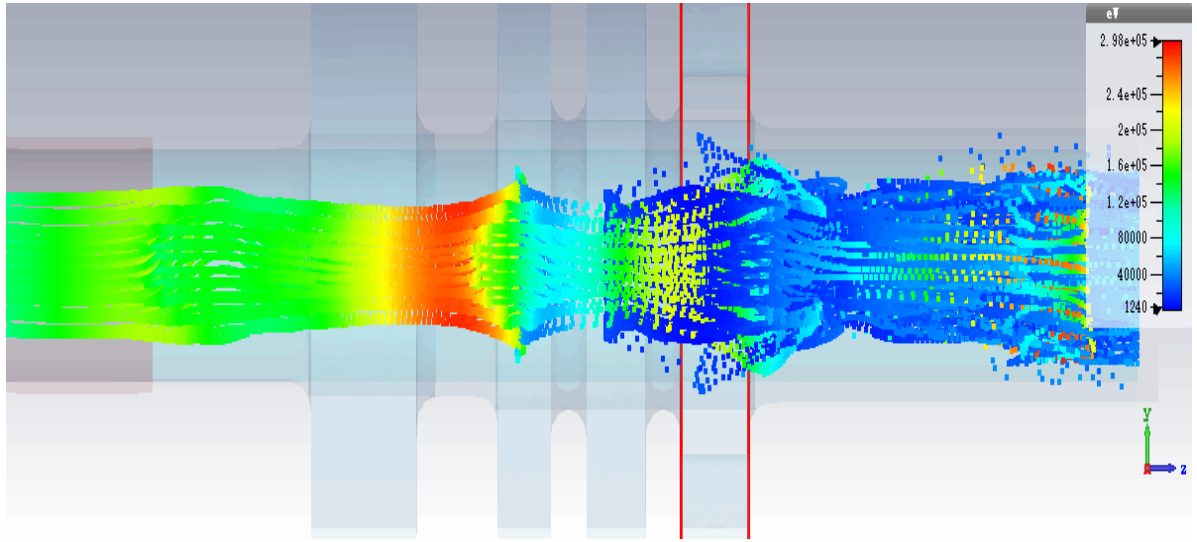
- 12 GHz, 6MW, 400 Hz
- Used in High Gradient X-band facilities (Xbox3) at CERN for several years (~10 years)

New window designed by CERN

- Efield 30% less strength on surface

Retrofit design with a COM circuit+ 2nd harmonic cavities

- ~60%



Design fo the HE X-band klystron: a summary

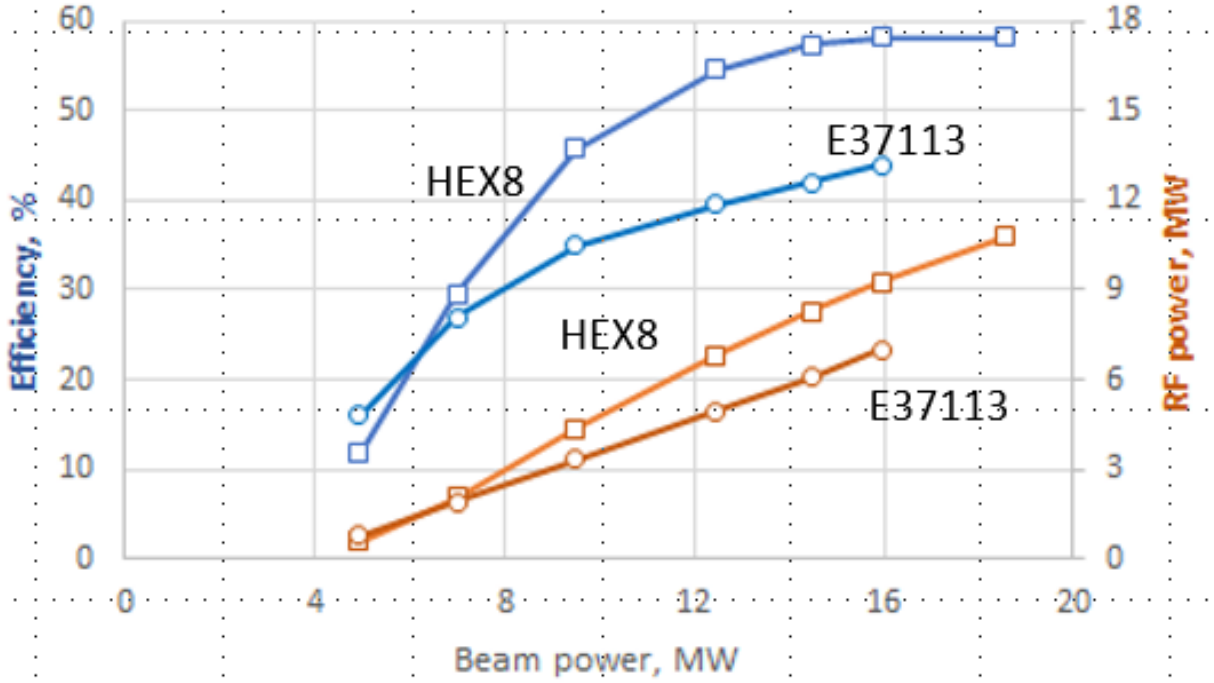
New window designed by CERN

- Efield 30% less strength on surface

Retrofit design with a COM circuit

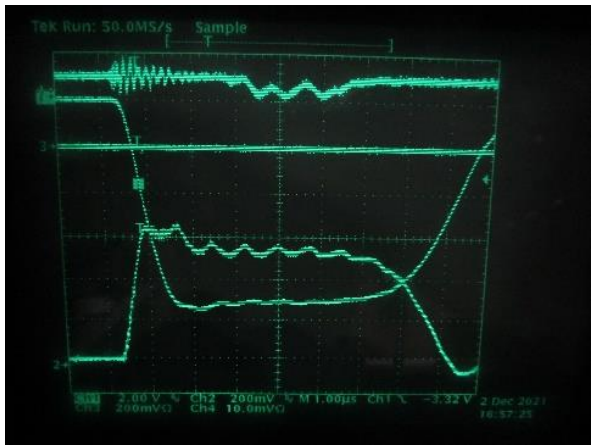
2nd harmonic cavities

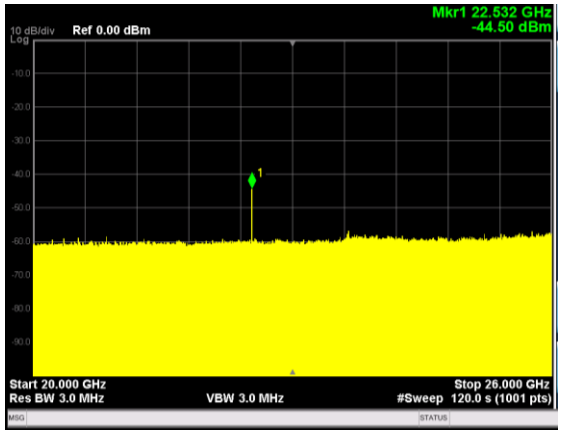
Same solenoid



Observed instabilities after manufacturing of the first prototype

- Found instabilities (self-oscillations) at 21-23GHz
- Mitigation measurements were developed
  - Replacement of 2nd harmonic triplet for doublet to avoid monotron oscillation
  - Damping of coupled modes with stainless steel
  - Different gap lengths for cavities





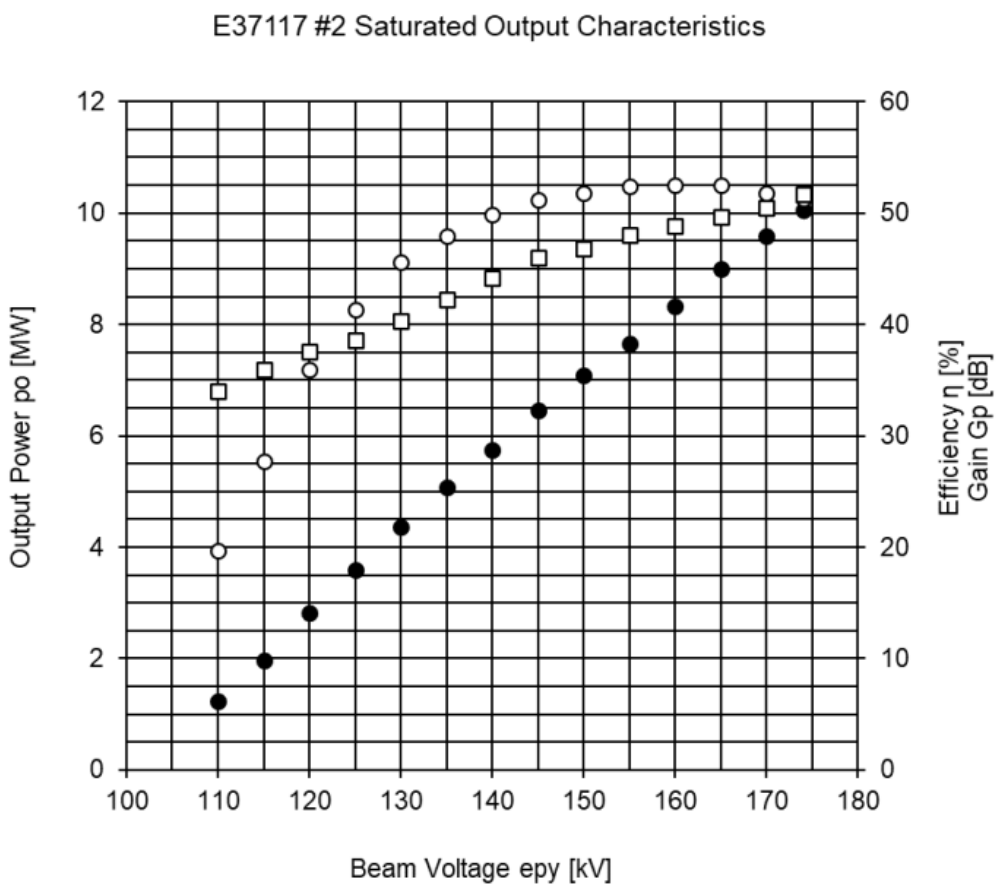
More info at: Igor Syratchev, Zaib Un Nisa, Jinchi Cai, Graeme Burt, Toshiro Anno, *DC Beam Stability issues in the first commercial prototype of a High Efficiency 8MW X-Band Klystron*, CLIC-Note-1176, 2022.

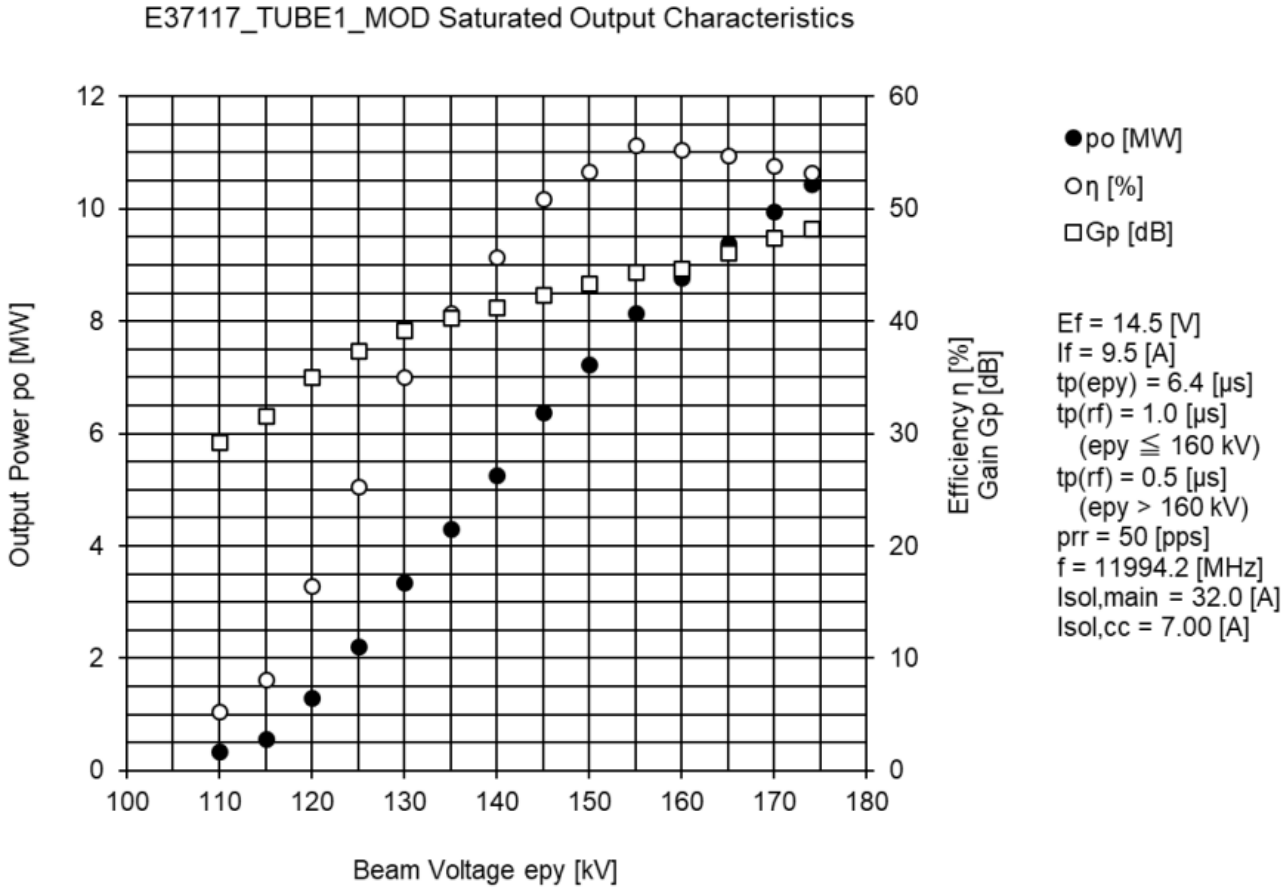
The E37117 tube: high efficiency for X-band medium pulsed power

	E37113 at factory	Retrofit design E37117 at factory
Voltage, kV	154	154
Current, A	93	94
Frequency, GHz	11.994	11.994
Peak power, MW	6.2	8.12
Sat. gain, dB	49	46
Efficiency, %	42	**57**
Life time, hours	30 000	30 000
Solenoidal magnetic field, T	0.35	0.42
RF circuit length, m	**0.127**	**0.127**

Reported measurements by Canon

Confirmation of >50% for both prototypes





Test campaign at CERN

The E37117 tubes have been assembled in **Xbox3 test facilities**
The test stand have been modified to test klystrons
Improved interlock system to protect klystron
Two independent measurements: RF power and calorimetry

RF power measurements

- Careful calibration of the components and line to PXI
- Measurement directly from HPDC with power meter / spectrum analyser
- Logging via PXI for further processing

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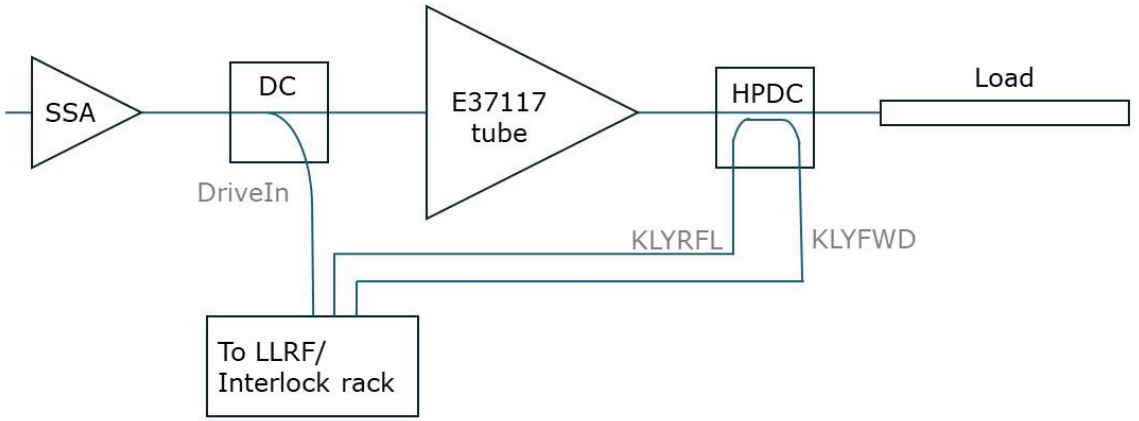
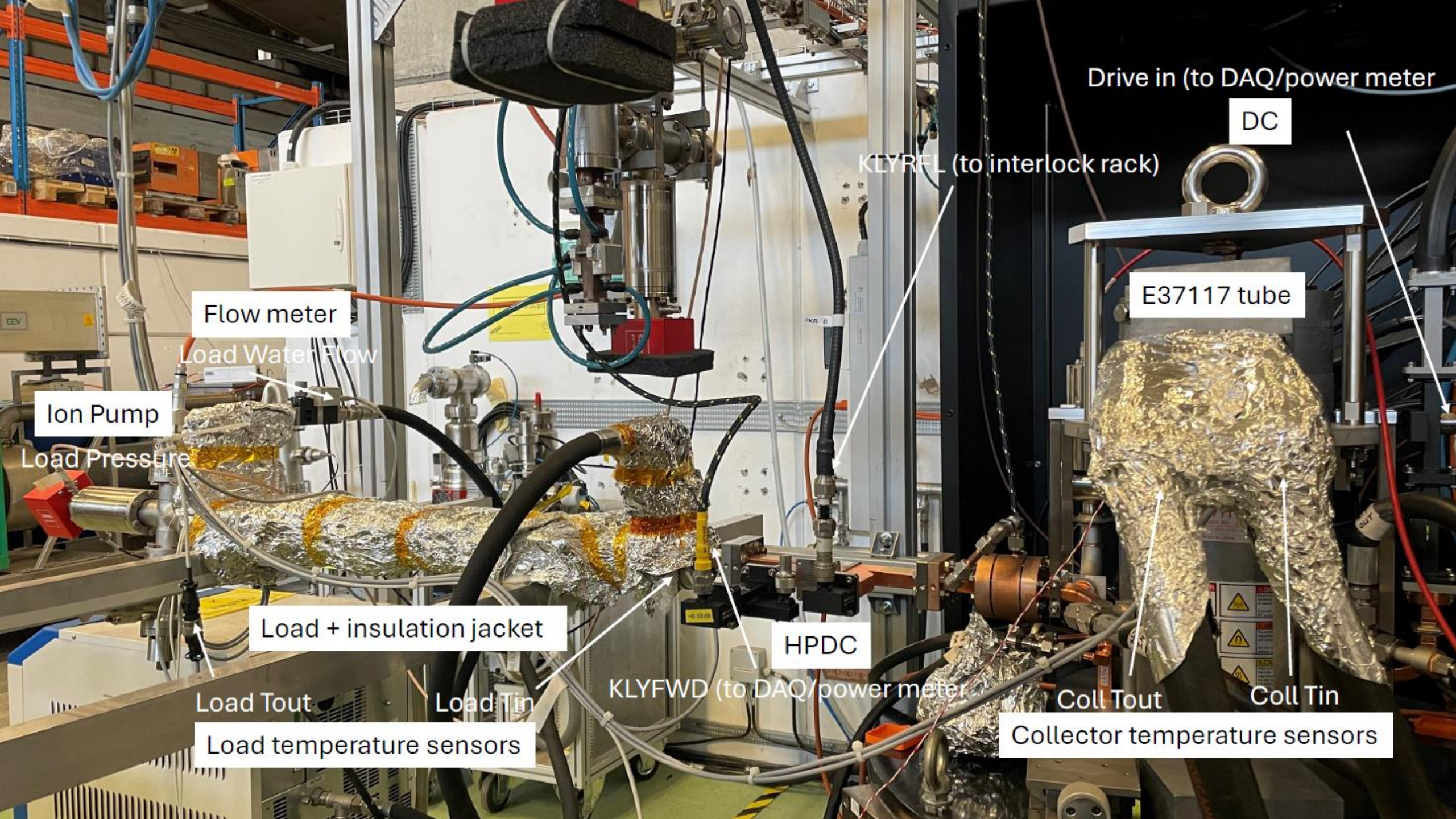



Drive in (to DAQ/power meter
DC
KLYREL (to interlock rack)
E37117 tube
Flow meter
Load Water Flow
Ion Pump
Load Pressure
Load + insulation jacket
HPDC
KLYFWD (to DAQ/power meter
Load Tout
Load Tin
Load temperature sensors
Coll Tout
Coll Tin
Collector temperature sensors

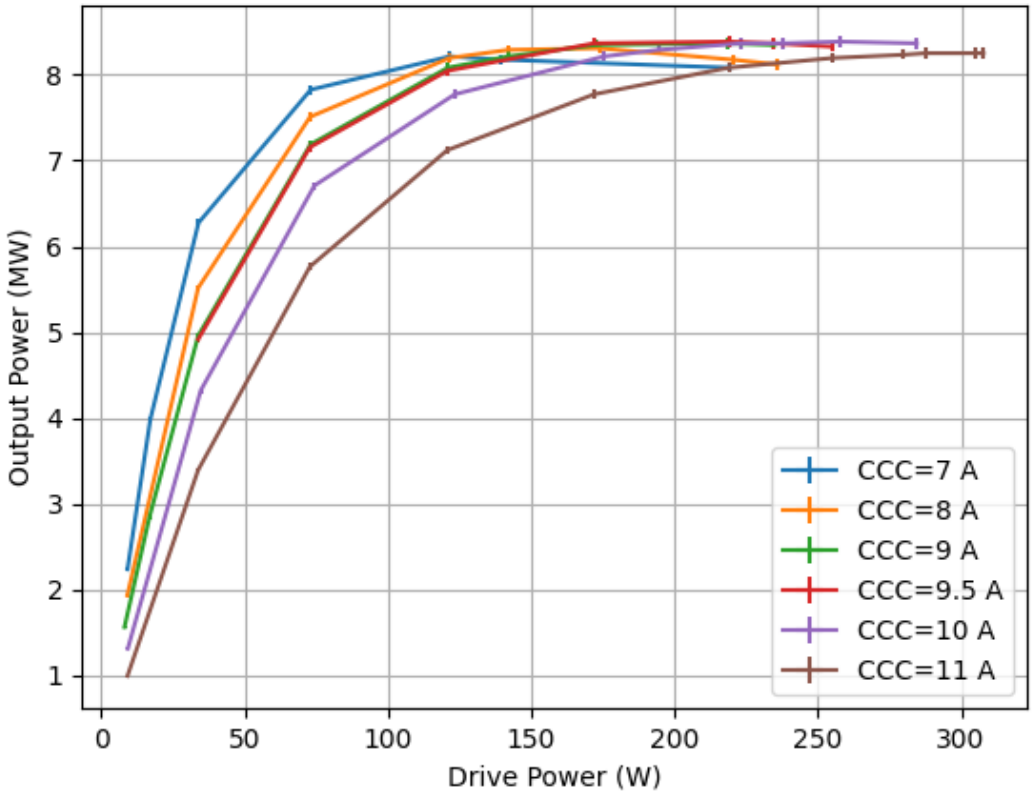
E37117 22M001 test results

Meas. of transfer characteristics

- Beam Size
- DC Power
- Frequency of operation

Sweep over counter coil solenoid current (CCSC) from 7A to 11A to find best operational point

- A small improvement expected for a slightly higher MCSC (confirmed by Canon)

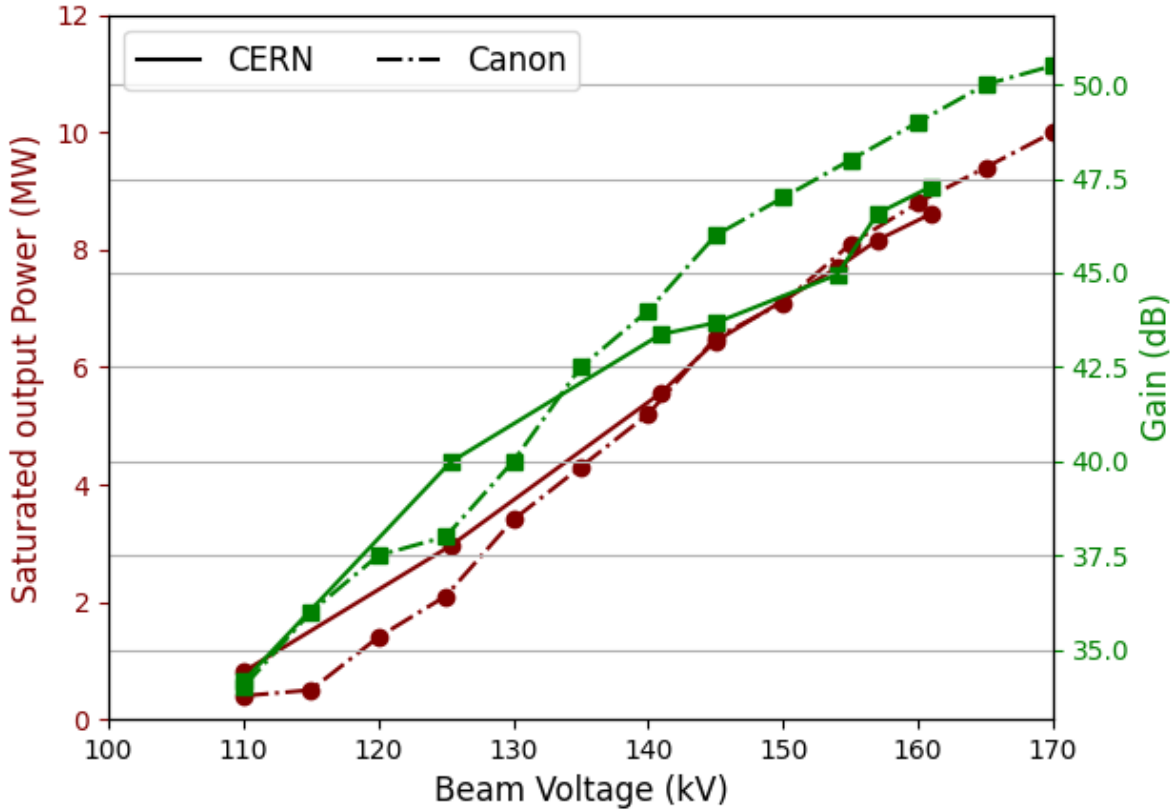


E37117 22M001 test results

Transfer characteristics at nominal frequency and different beam voltages

Up to 9.2± 0.05 MW @ 167 kV

Meas. At CERN are coherent with Canon report, but what about efficiency? ($\eta = \frac{P_{RF}}{P_b}$)

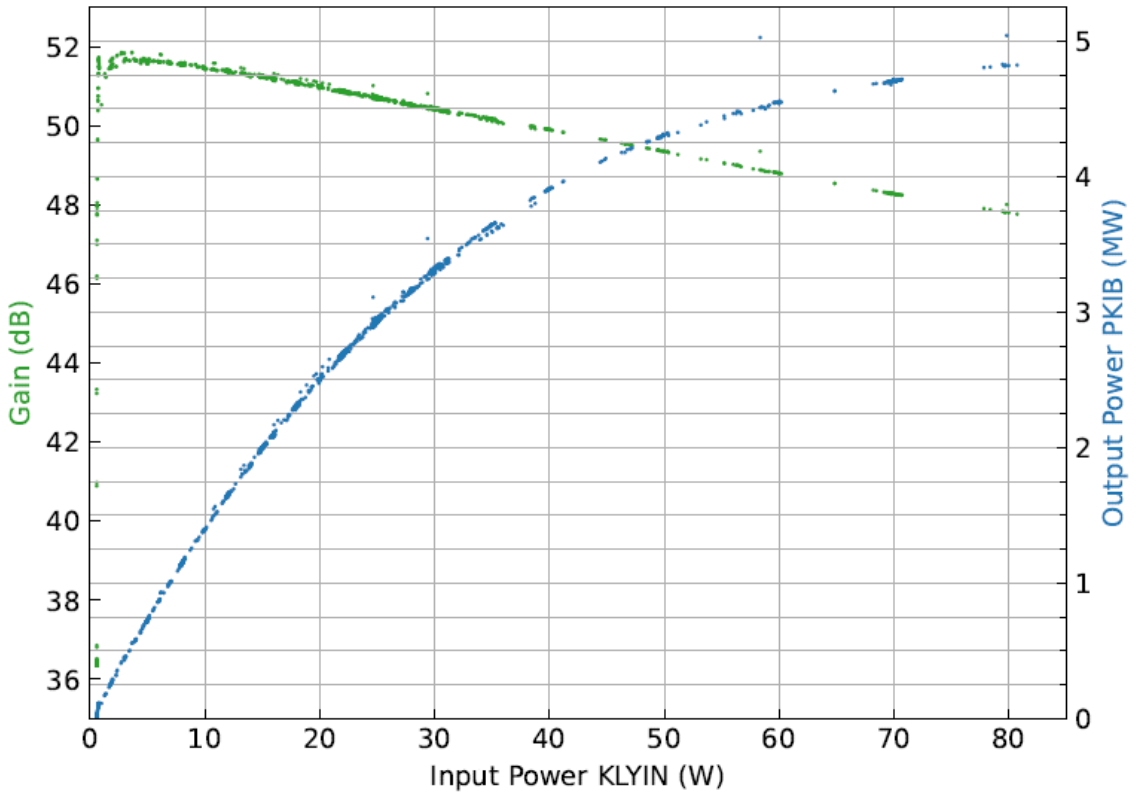


E37117 22G002 test results

Nominal operation

- 154kV beam voltage]
- Central frequency 11.994GHz
- Pulse length 1.5us

< 5MW output power instead of 8MW as expected!



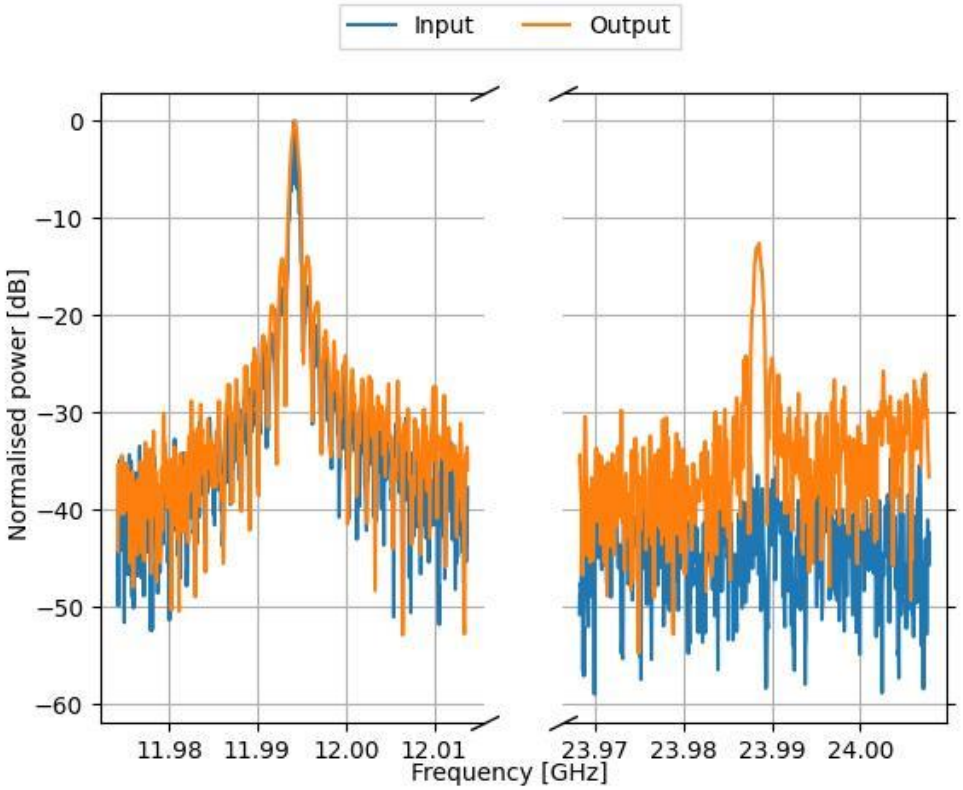
Klystron 22G002 under suspicion

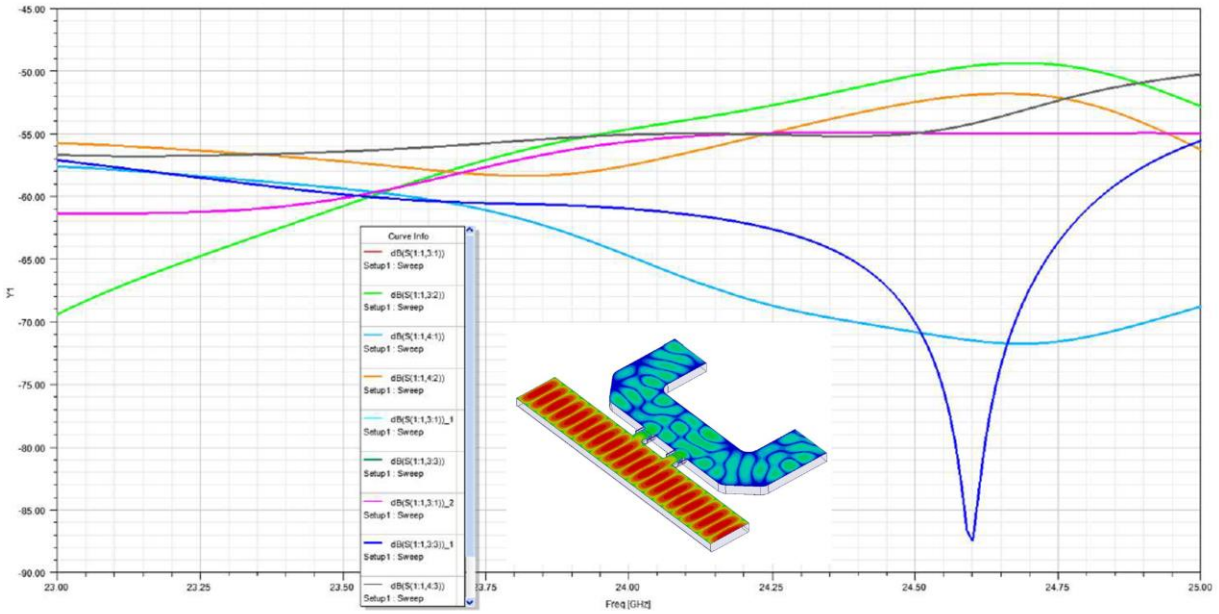
Why is the output power so low?

- Instabilities in the pulse
- Degradation due to second harmonic
- Bad matching of the load
- Others?

Klystron 22G002 under suspicion

Spectral content of output



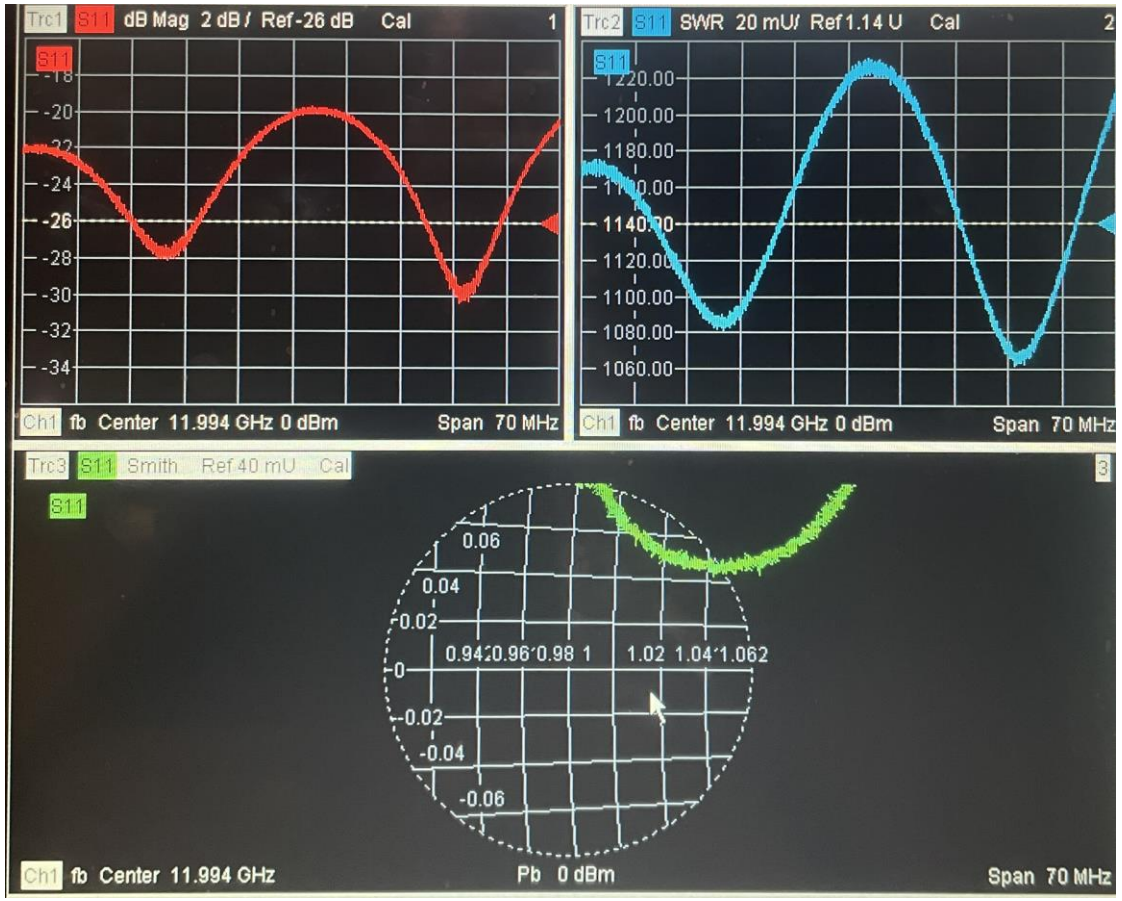


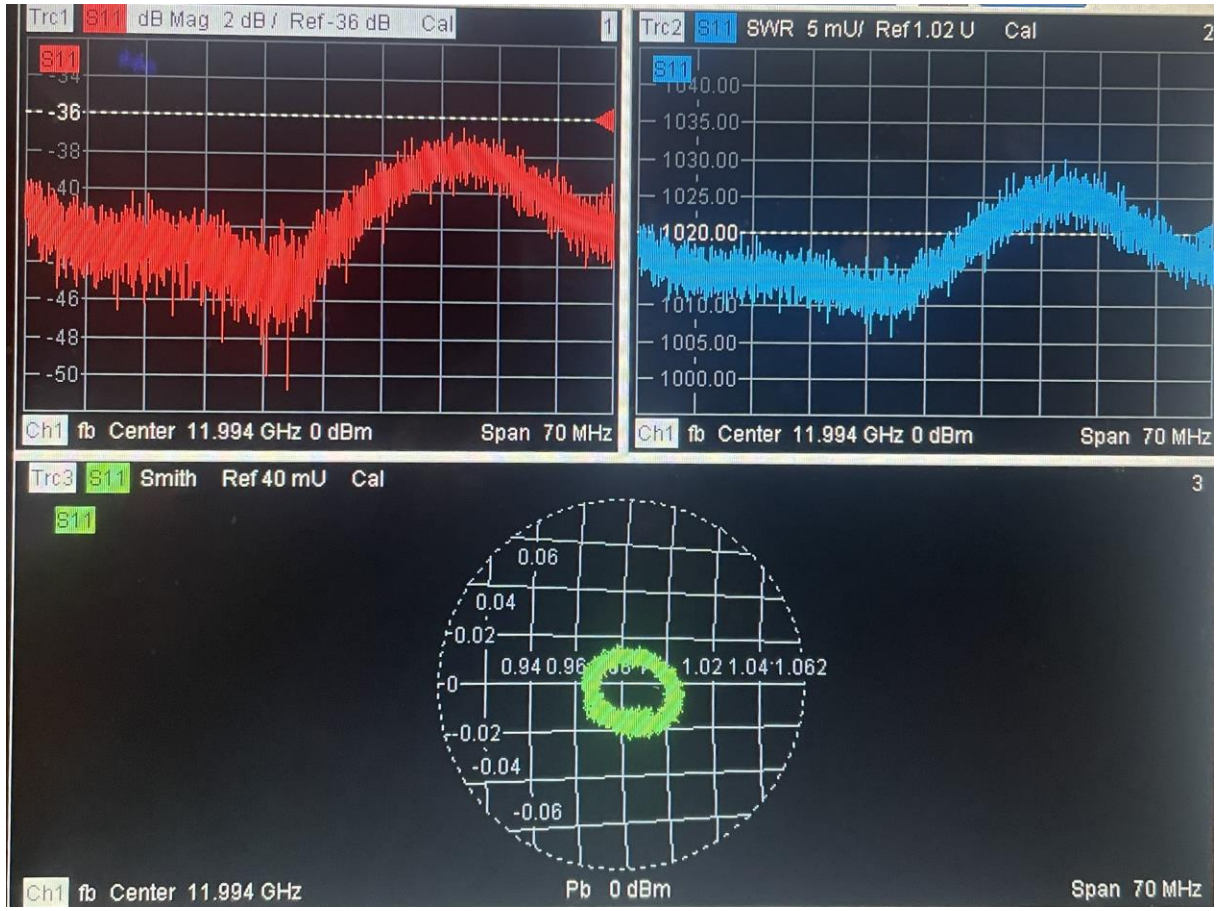
~10dB difference between fundamental frequency and first harmonic (24GHz) at port 3 of HPDC

CST simulations of HPDC by I. Syratchev show -55 dB from HOM1 (port1 to 3), or -48 dB from HOM3

Klystron 22G002 under suspicion

Bad matching of the load





Calorimetry measurements will help

Easy indirect measurement of RF and DC power

$$P_{avg} = c\,\dot{m}\,\Delta T,$$

with $c = 4186\,\frac{J}{kg℃}$ for water at 30℃ , $\dot{m}$ the water flow (l/s), and ΔT the temperature difference.

And

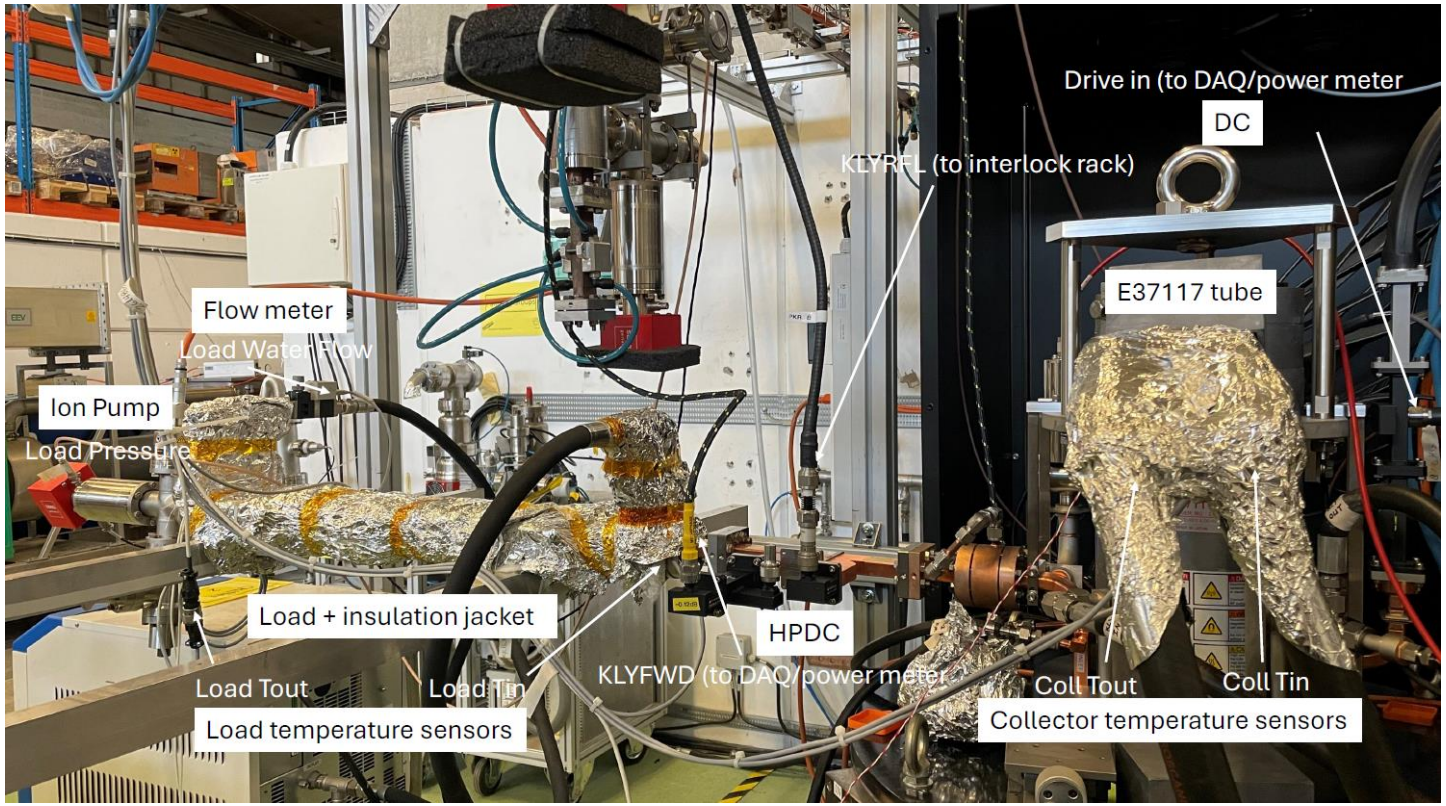
$$P_{peak} = \frac{P_{avg}}{dutycycle},$$

with $dutycycle = t_p$* PRR (*)

Calorimetry does not lie

Setup includes:

- PT1000 temperature sensors
- Flow meters
- Insulating jackets



Calorimetry in diode mode

Easy indirect measurement of RF and DC power

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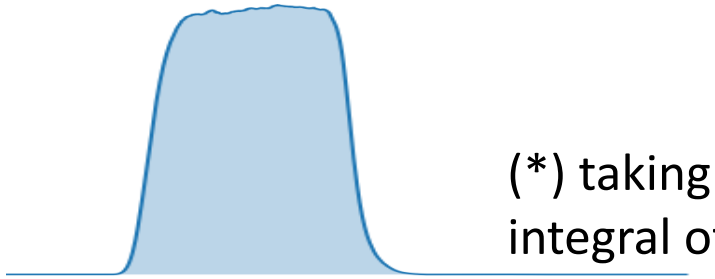
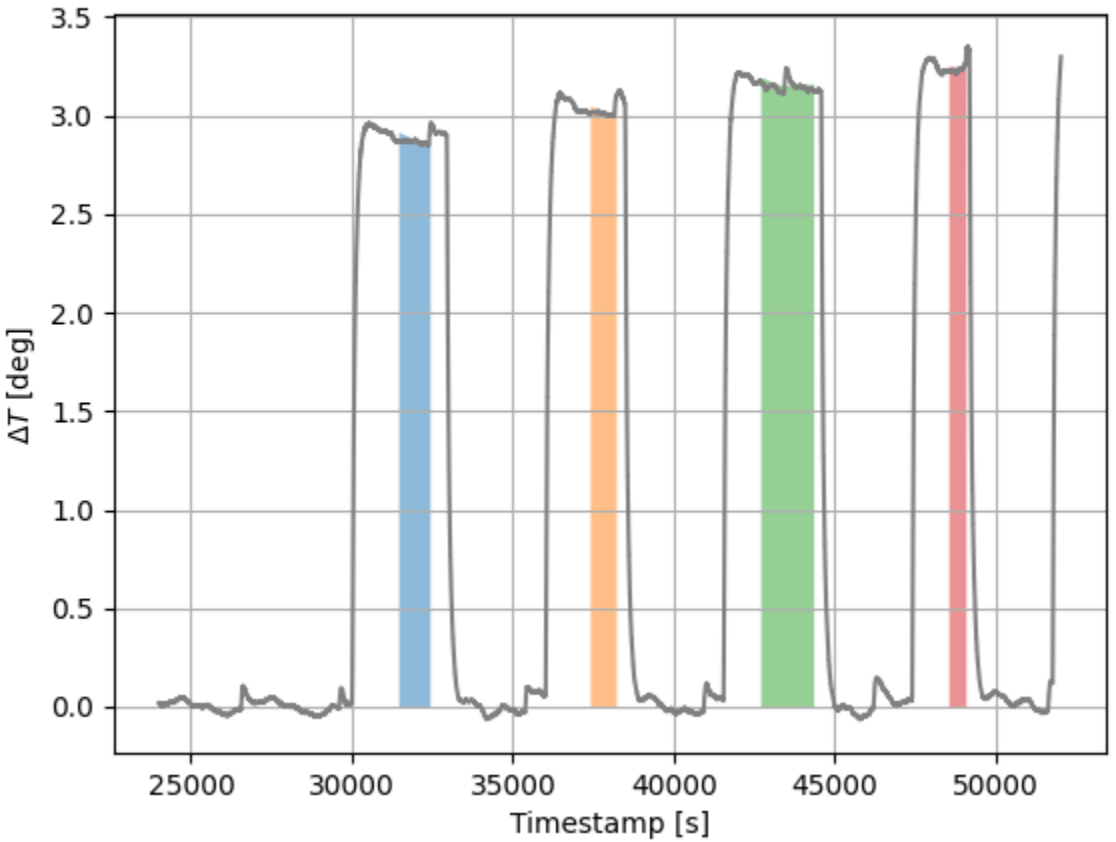
Calorimetry does not lie

Between 8 - 20% error between measured and expecte
P_{avg}
2 options:

-Meas. very sensitive to temperature calibration
-It is real, we don't have expected beam power (lower beam voltage, higher perveance)



(*) taking into account integral of real waveform



Challenges of efficiency measurement

RF conversion efficiency calculated as

$$\eta = \frac{P_{RF}}{P_b}$$

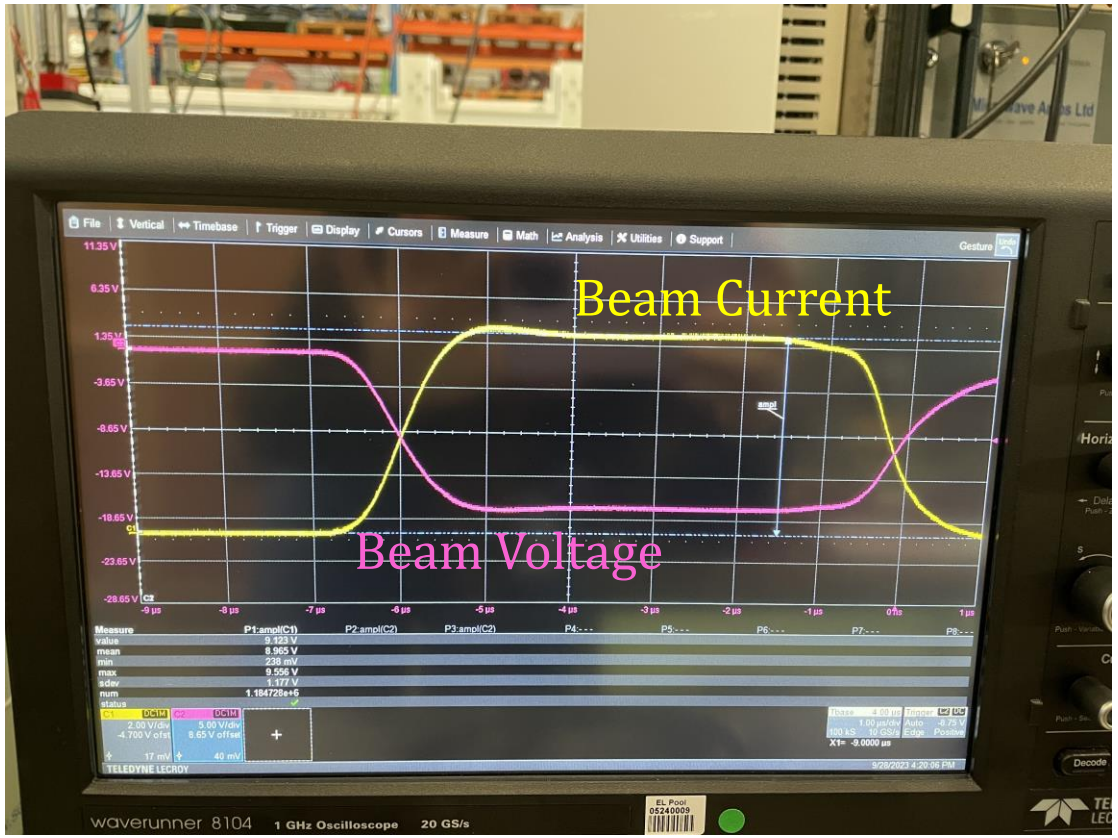
We can't continue trusting CT measurement and uPE measured by Canon

Uncertainty in voltage measurement due to installed CVD

- Stangenes model with 5% accuracy
- Calibrated ~10 years ago…

Thermal stability and isolation

- Calorimetry in collector dependant on water station regulation



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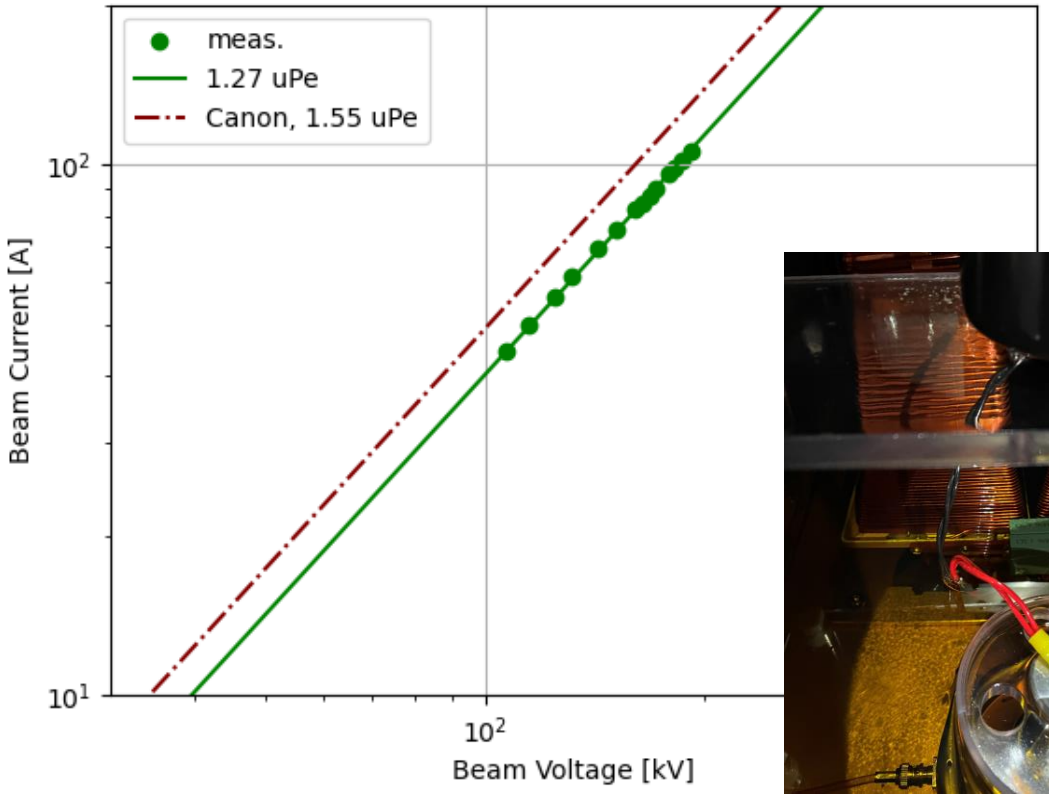


Conclusions

TAKE-AWAY MESSAGE

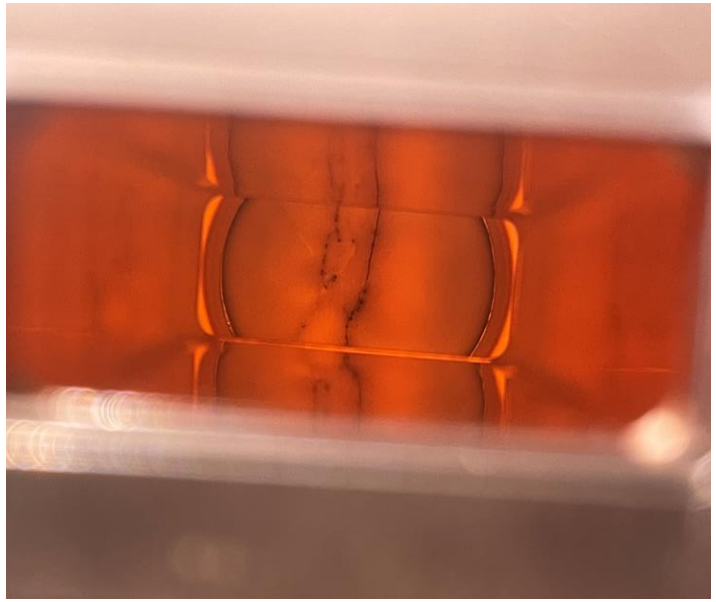
Demonstrated improved efficiency of refurbished tubes from 42 to 56%

The followed methodology at CERN does not provide the reliability and accuracy we need for efficiency measurements (lack of experience!)

Learning many important lessons!

- Importance of good interlock system

High hopes for calorimetry measurements



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FUTURE WORK

Development of new methodology and setup that ensure accurate measurements (accuracy in efficiency meas. <5%)

Calibration of the CVD

- Collaboration with Scandinova to develop a load simulating the klystron

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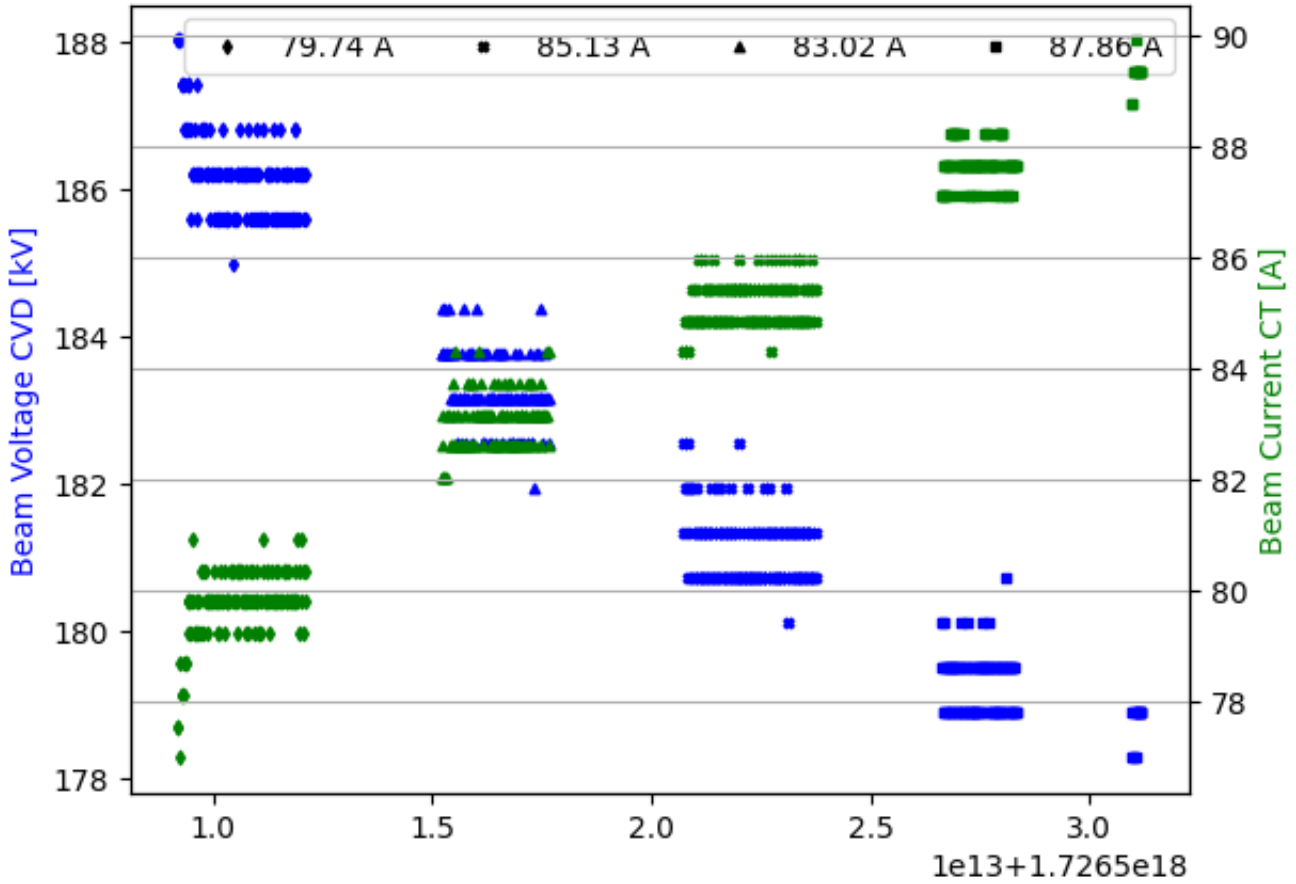
Challenges of efficiency measurement

Stability of klystron/modulator system

Provisional results for different operational points

+-0.2MW deviation



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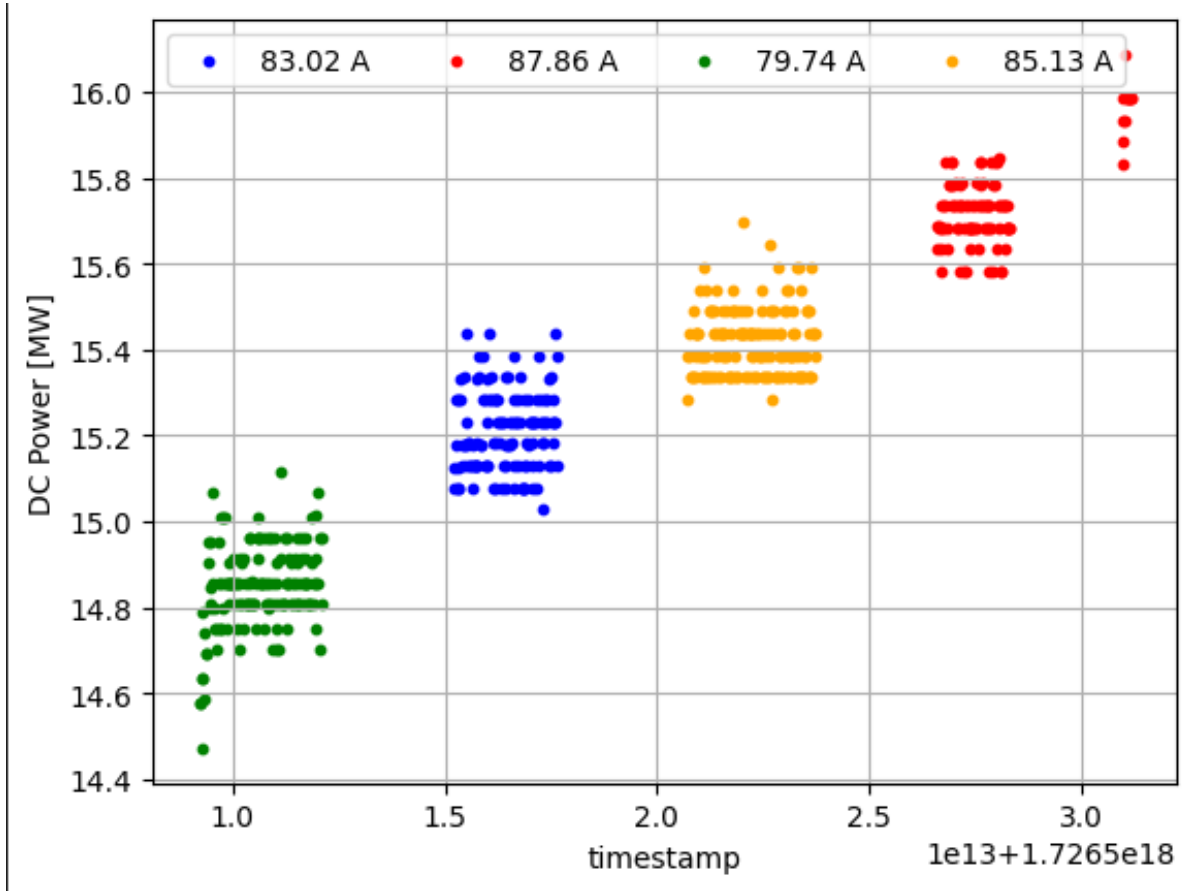

Calorimetry results

Not conclusive yet