CLIC Project Meeting #43

Wednesday Dec 7, 2022, 1:30 PM → 7:30 PM Europe/Zurich

60/6-015 - Room Georges Charpak (Room F) (CERN)

High Efficiency klystrons update

Igor Syratchev for HE klystrons project team:

Zaib Un Nisa

Anis Baig

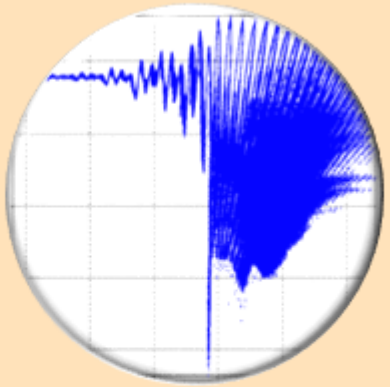
Nuria Catalan

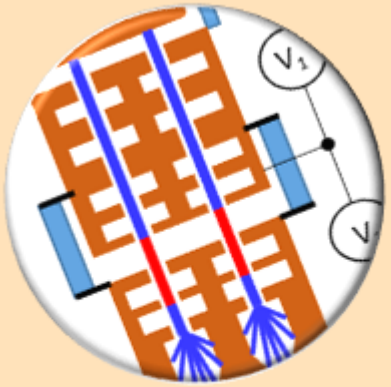
Jinchi Cai

Graeme Burt

Thales, CPI and Canon EDT

High efficiency klystrons projects at CERN





-Task 1: HE Design and simulation

- Development and maintenance of the fast and accurate 2D klystron codes.
- Klystron simulation code KlyC version 5 was released in May 2021. About 50 users worldwide.
- New KlyC version 6 will include CGUN tracking module for the beam optics simulation (gun, solenoid and collector). Will be released in January 2021.

Task 2:HE LHC 400 MHz klystron

- Validate the HE klystron technology (~70%) while upgrading and retro-fitting current LHC klystrons
- The klystron design is accepted by Thales. **Expected delivery of the prototype to CERN is in March 2023.**
- Prepare the acceptance tests at CERN

-Task 3: HE-TS MBK L-band klystron

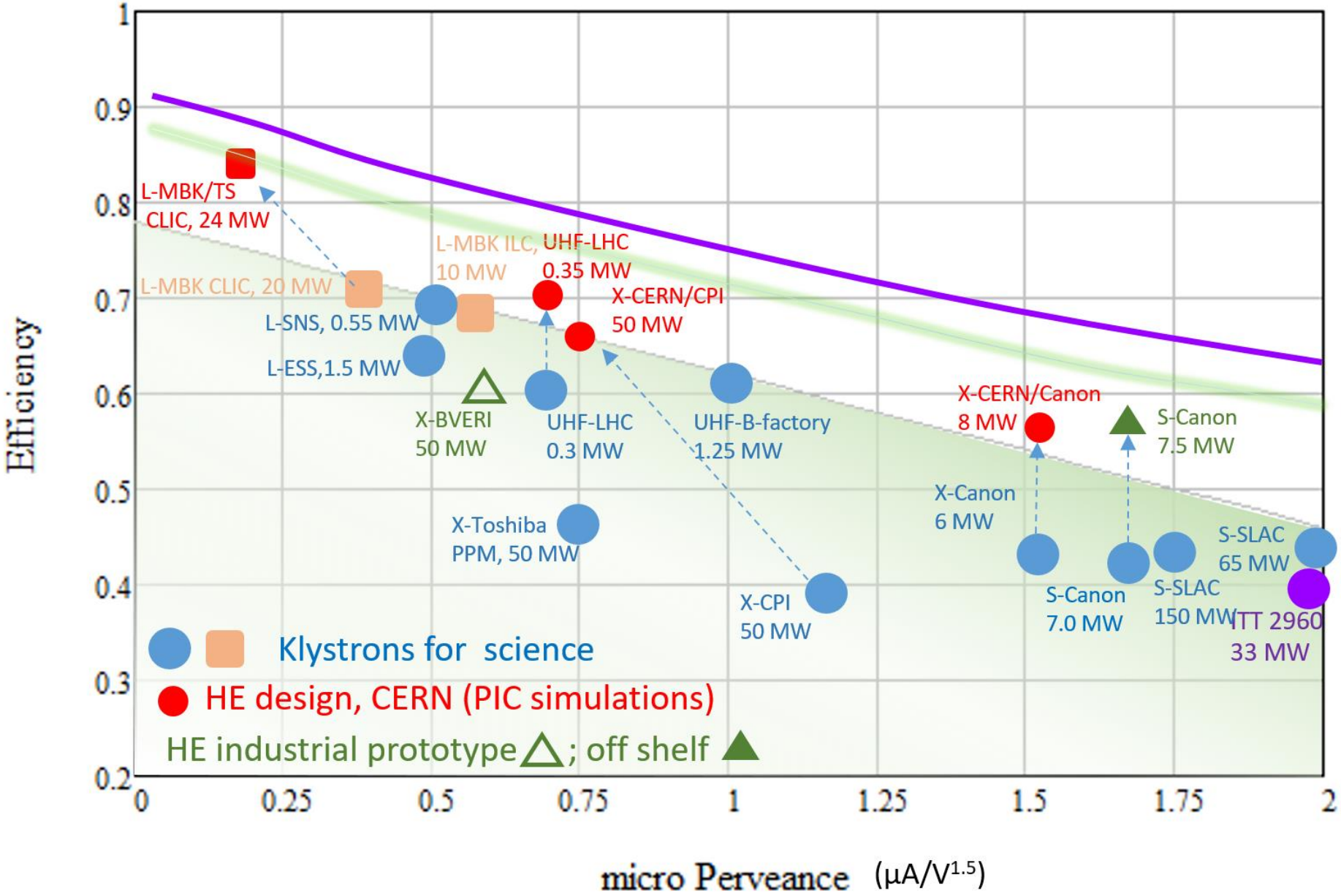
- **Demonstrate two-stage multibeam technology with 80%+ RF production efficiency**
- Complete design of TS MBK for CW FCC_{ee} : 400 MHz, 1.2 MW
- built demonstrator -> WP5 of the FCC SRF R&D Program
- Promote this new technology towards CLIC, ILC, CEPC, by means of design , collaboration with industry and fabricating a prototype

Task 4: HE X-band klystrons (8MW and 50MW) with high rep-rate

- Built klystrons and demonstrate ~60% efficiency. Collaboration with industry: Canon CETD (Japan) and CPI (USA).
- Reinforce synergies with CLIC, FLASH, Compact Light, Compton sources…

• great showcase for CERN's technology. Contribution to the worldwide society.

Efficiency performance of the selected commercial klystrons and the new HE klystrons.

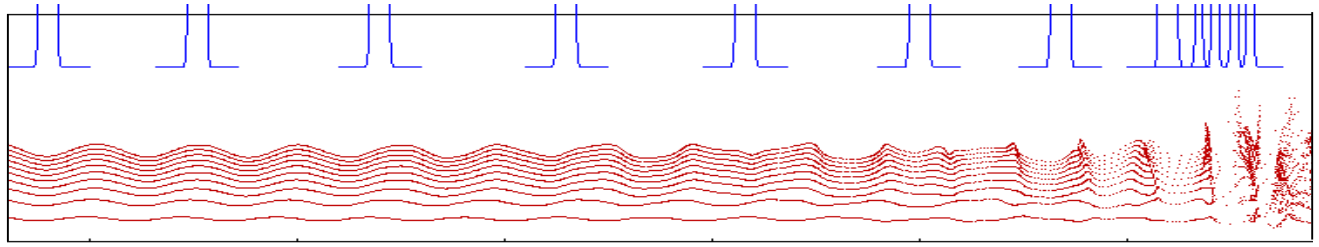


10 MW class HE X-band klystron.

CERN-Canon ETD collaboration

Klystron RF Circuit

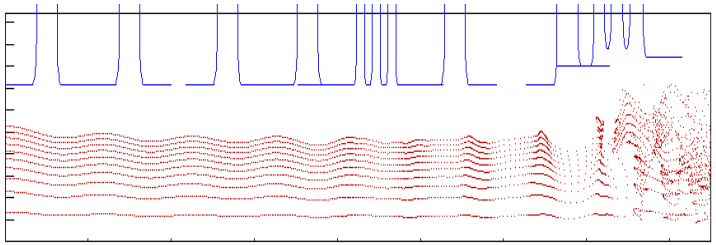
Design 1
- Long COM circuit
- New solenoid



Eff. = 58.6%

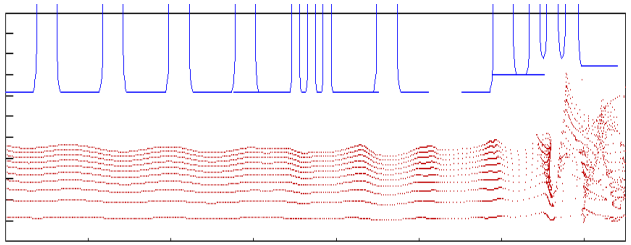
2019

Design 2
- Short COM circuit
- 2nd harmonic
- New solenoid



Eff. = 56.4%

Design 3
- Short circuit (same as existing 6-MW tube)
- 2nd harmonic
- Existing solenoid

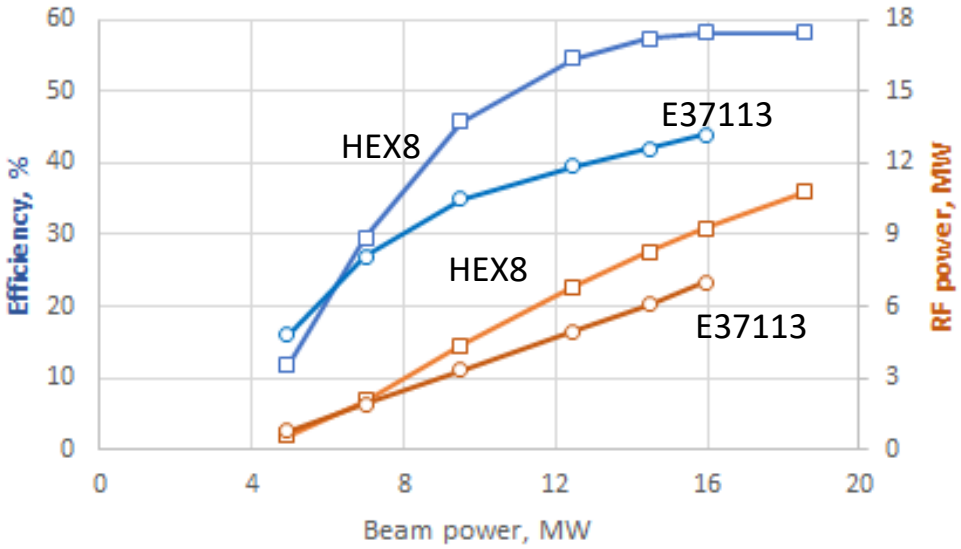


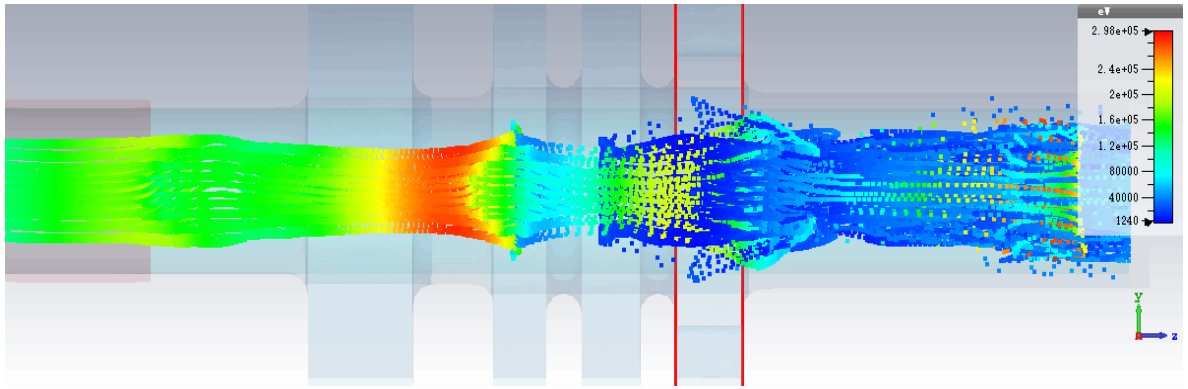
Eff = 56.4%

We decided to fabricate this tube.

2020

Retro-fit High Efficiency 8 MW, 12 GHz klystron





- The same modulator
- Re-used solenoid
- Re-used cathode

Retrofit design

8-10 MW	E37113 at factory	HEX COM_M (CERN/Canon)
Voltage, kV	154	154
Current, A	94	94
Frequency, GHz	11.994	11.994
Peak power, MW	6.2	8.1
Sat. gain, dB	49	48
Efficiency, %	42	56.4
Life time, hours	30 000	30 000
Solenoidal magnetic field, T	0.35	0.42
RF circuit length, m	**0.127**	**0.127**

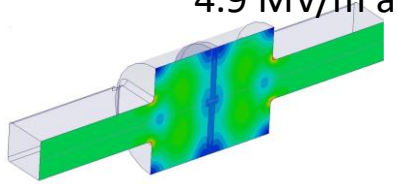
New RF window with increased peak RF power capacity

Compact RF window with TW in ceramic was designed at CERN to decrease the electric field strength on ceramic. **At Canon, it is now commercialized as a separate RF device.**

Conventional long pillbox window

4.3 MV/m at 6 MW

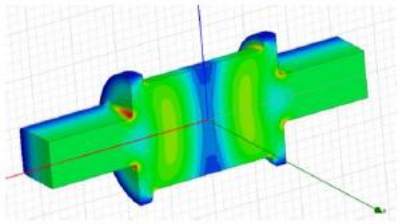
4.9 MV/m at 8 MW



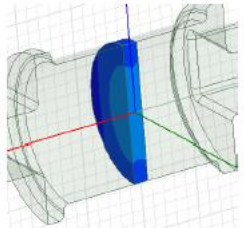
Designed for 6-MW klystron

E field strength on ceramic surface decreased by 30%

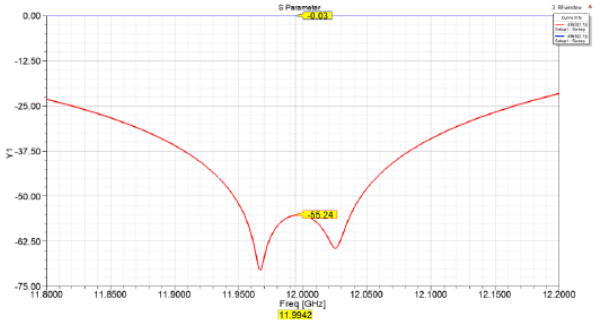
E-field



E-field on Ceramic



Bandwidth



RF Parameters at f_0 = 11.9942 GHz

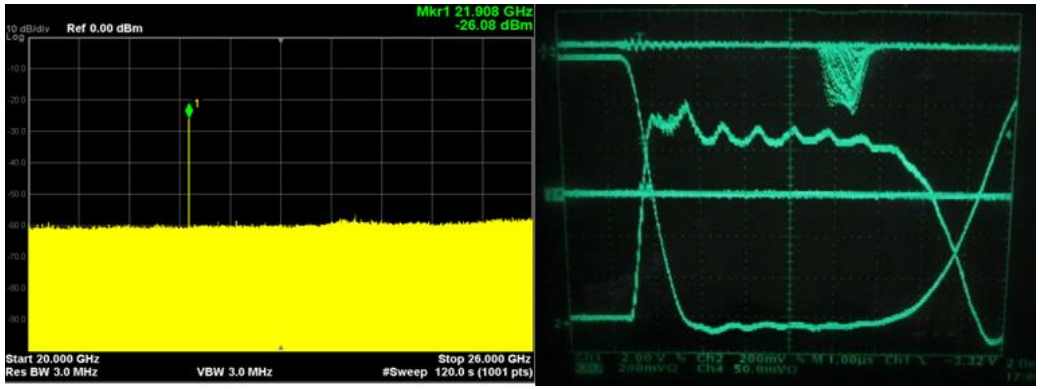
Compact window with TW in ceramic

3.5 MV/m at 8 MW

3.9 MV/m at 10 MW

	Value	Units
f_0	11.9942	GHz
P_{IN}	10	MW
Material	Al_2O_3	
Relative Permittivity	9.8	
Dielectric Loss Tangent	0.002	
s_{11}	-55	dB
s_{21}	-0.03	dB
$E_{Max\ Ceramic}$	3.9	MV/m

The first prototype was built and tested at Canon in December 2021.
Unexpectedly, in the first tests with DC beam at different voltages, a number of instabilities (self-oscillations) at 21-23GHz were found!

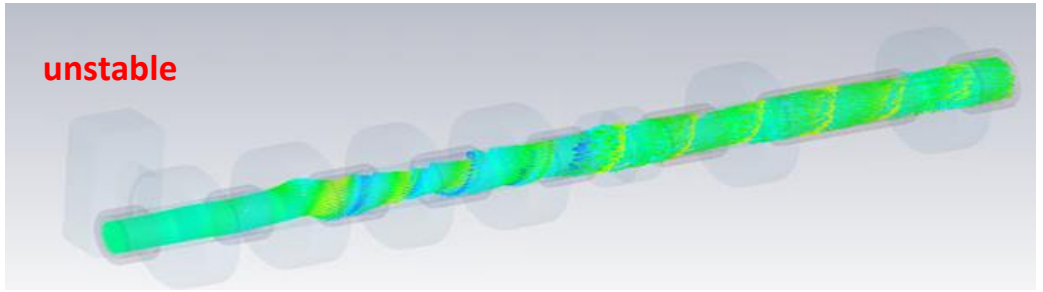


CLIC – Note – 1176

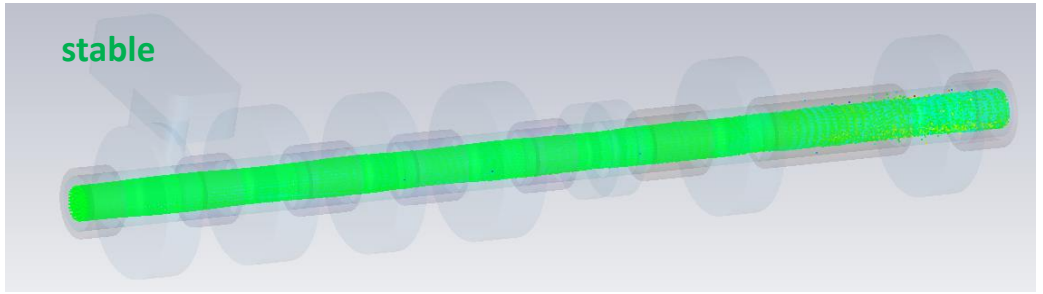
DC BEAM STABILITY ISSUES IN THE FIRST COMMERCIAL PROTOTYPE OF A HIGH EFFICIENCY 8MW X-BAND KLYSTRON.

Igor Syratchev[1)], Zaib Un Nisa[1)], Jinchi Cai[2)], Graeme Burt[3)], Toshiro Anno[4)]
1) European Organization for Nuclear Research, Geneva, Switzerland
2) Chengdu University, China
3) Lancaster University, Lancaster, UK
4) Canon Electron Tubes & Devices Co., Ltd. (CETD), Japan

The first commercial prototype of the new High Efficiency (HE) 8MW klystron was built and tested at CETD in the fall of 2021. Unexpectedly, in the first tests with DC beam at different beam voltages, a number of instabilities (self-oscillations) at 21-23GHz were found. As a result, at CERN, we have launched and completed a dedicated investigation program to analyse these instabilities and developed special mitigation measures for minimization of their impact on the klystron fabrication processes. In this paper, we will report the outcome of these studies.



All the instabilities were analyzed/understood and mitigated by correcting the cavities impedances and other special measures [**https://cds.cern.ch/record/2812566?ln=en**].



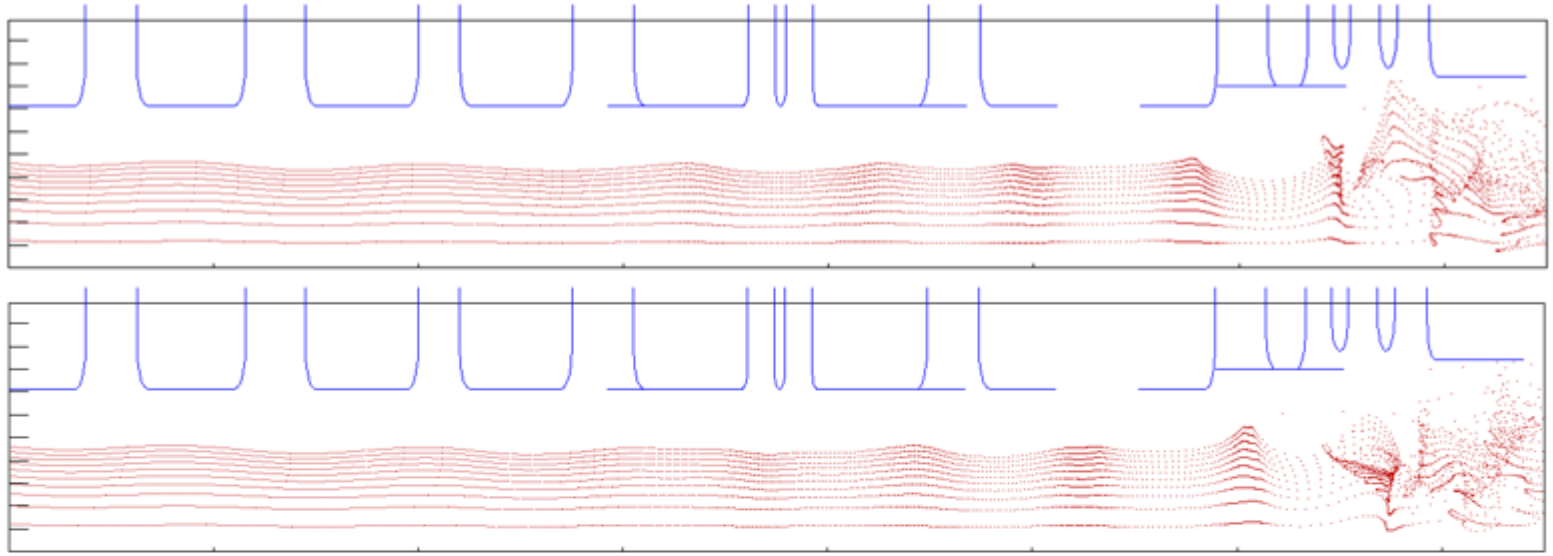


Figure 19. Snapshot of electrons trajectories at a saturated input power for the nominal operating point at 154kV, 94A and 0.4T (top); and at 174kV, 113A and 0.42T (bottom).

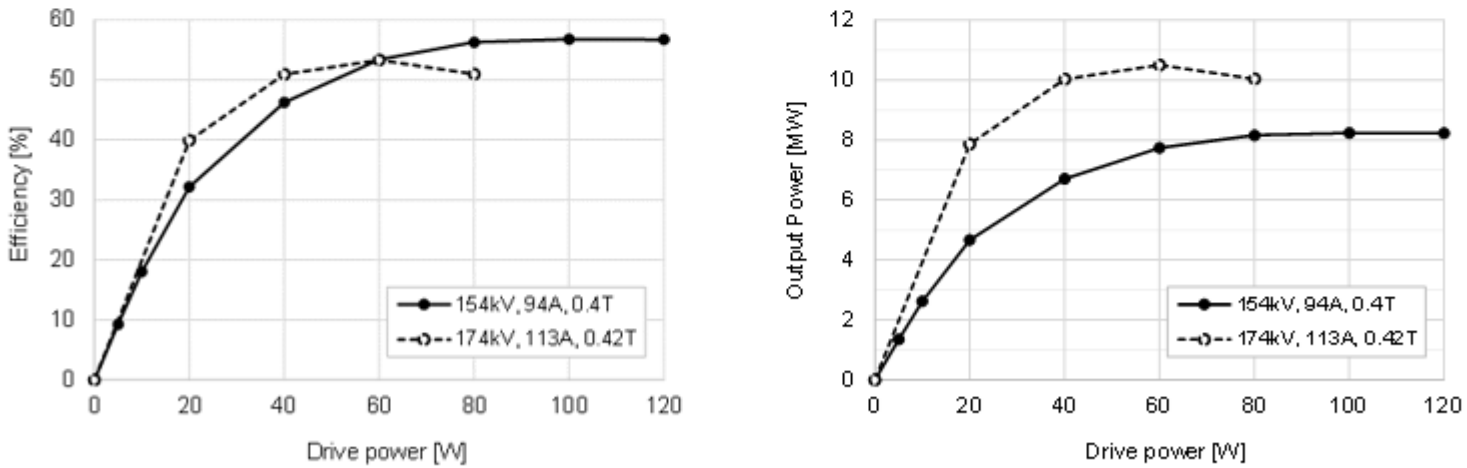
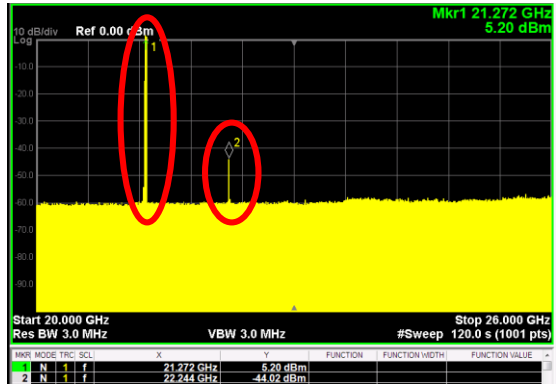


Figure 20. The klystron's power transfer curves at 154kV (0.4T) and at 174kV (0.42T).

The new and stable (up to 170kV; 10 MW) klystron RF circuit design.

The tube#2 was built and tested at Canon in July 2022. As it was predicted in simulations, above 170kV (>10MW RF power), oscillations were successfully eliminated by increasing main coil current or counter coil current of focusing magnet.

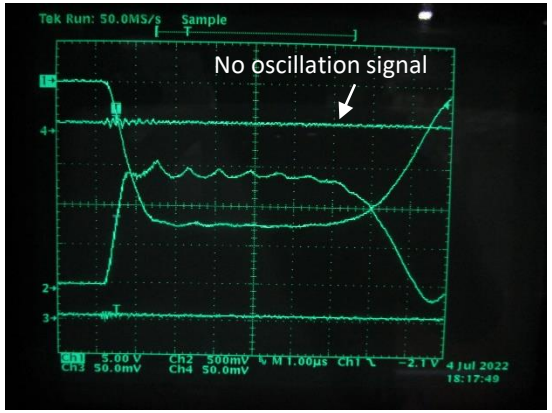
174kV

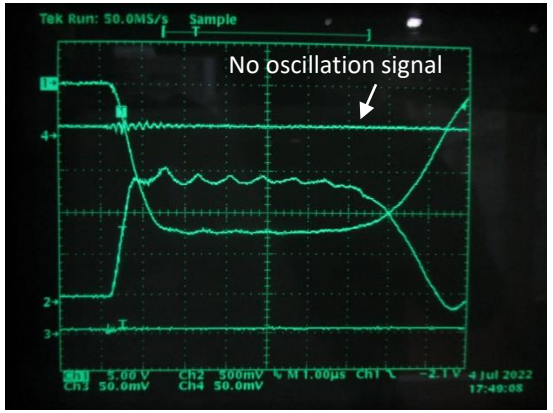


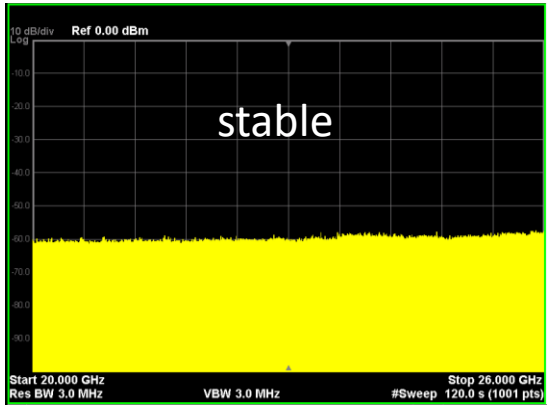
I_{main}=30A, $I_{counter}$=7A

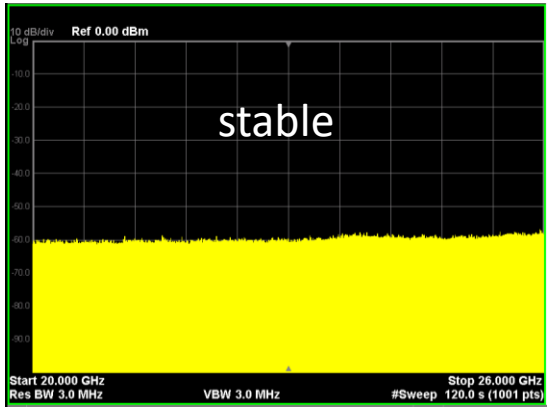
Original solenoid (0.4T) coils settings

174kV







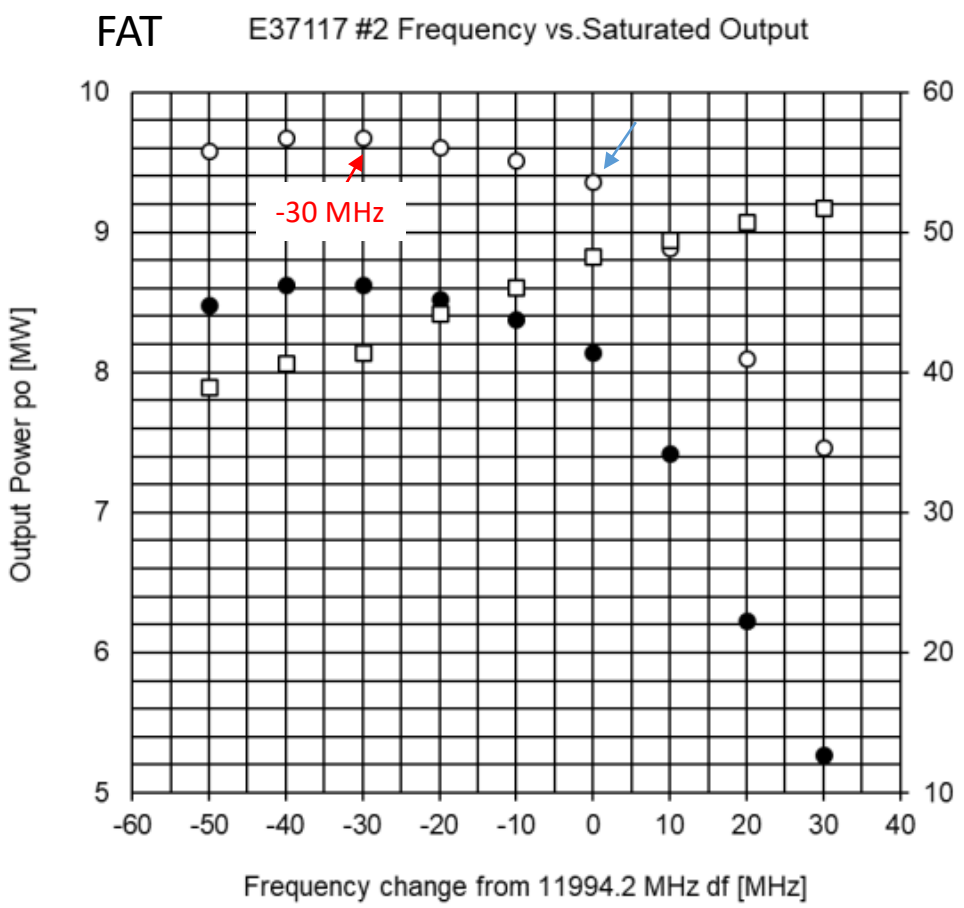


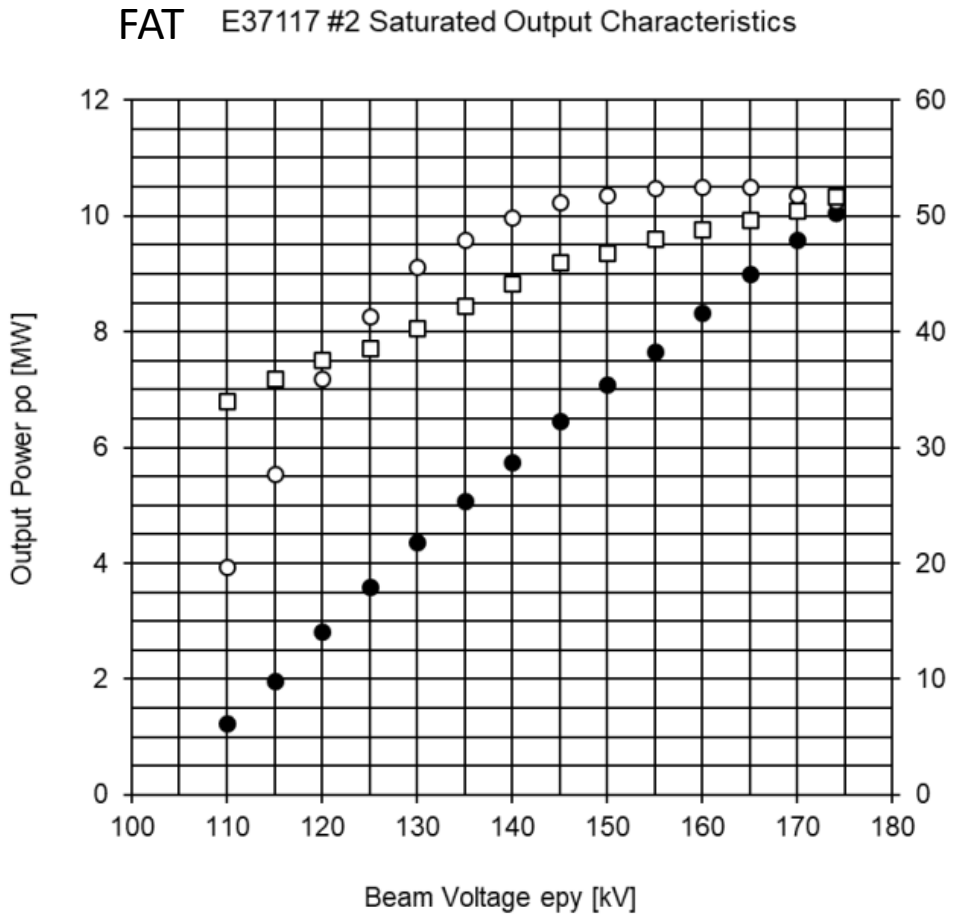
I_{main}=30→32A, $I_{counter}$=7A

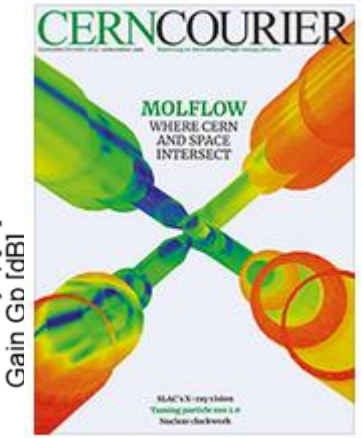
I_{main}=30A, $I_{counter}$=7→11A

Adopted solenoid (0.42T) coils settings

The second tube was a success and showed expected performance in terms of power production, yet at a **lower frequency!**



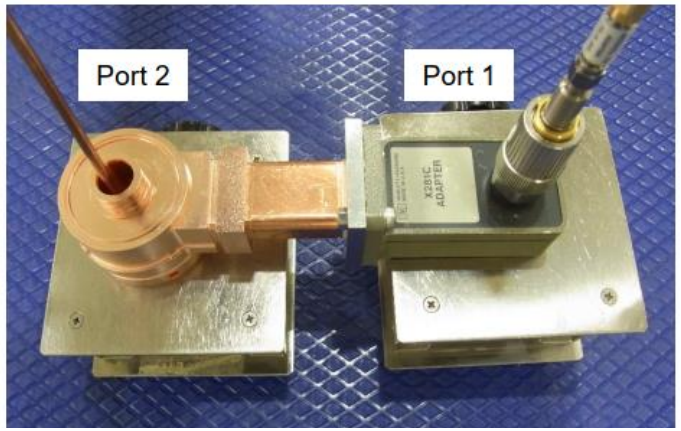


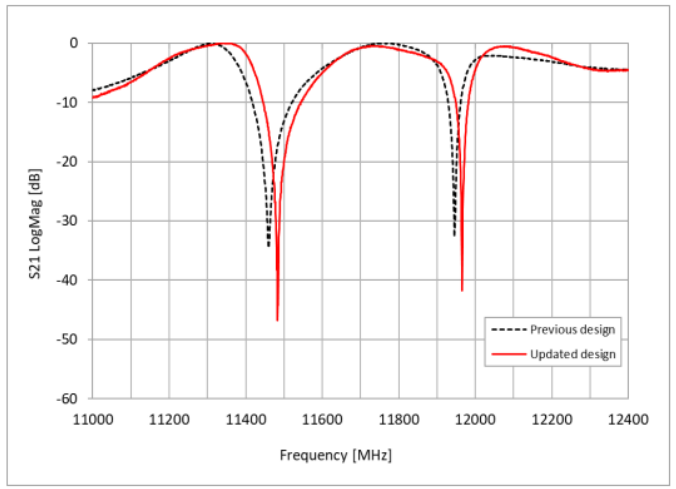


Tube arrived to CERN

However at 11.994GHz efficiency is still high: 53.3%. It will be installed in Xbox#3 early 2023.

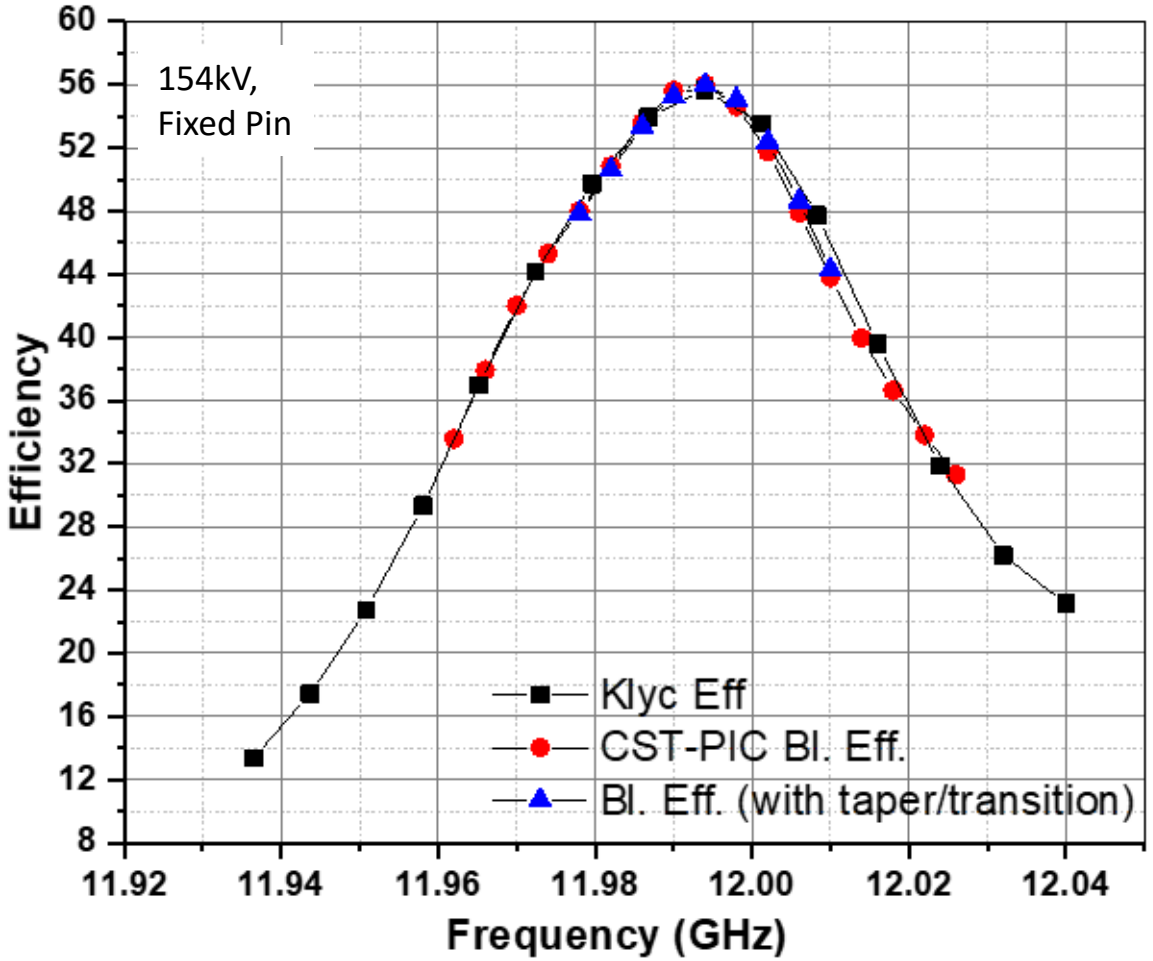
The problem with detuning was identified. It concerned the method used at Canon on how to adjust the frequency (dimension) of individual cell in the multi-cells coupler using HFSS simulations. The new dimension were calculated and verified in PIC simulation at CERN. Following, the new coupler was built for the refurbished klystron #1.



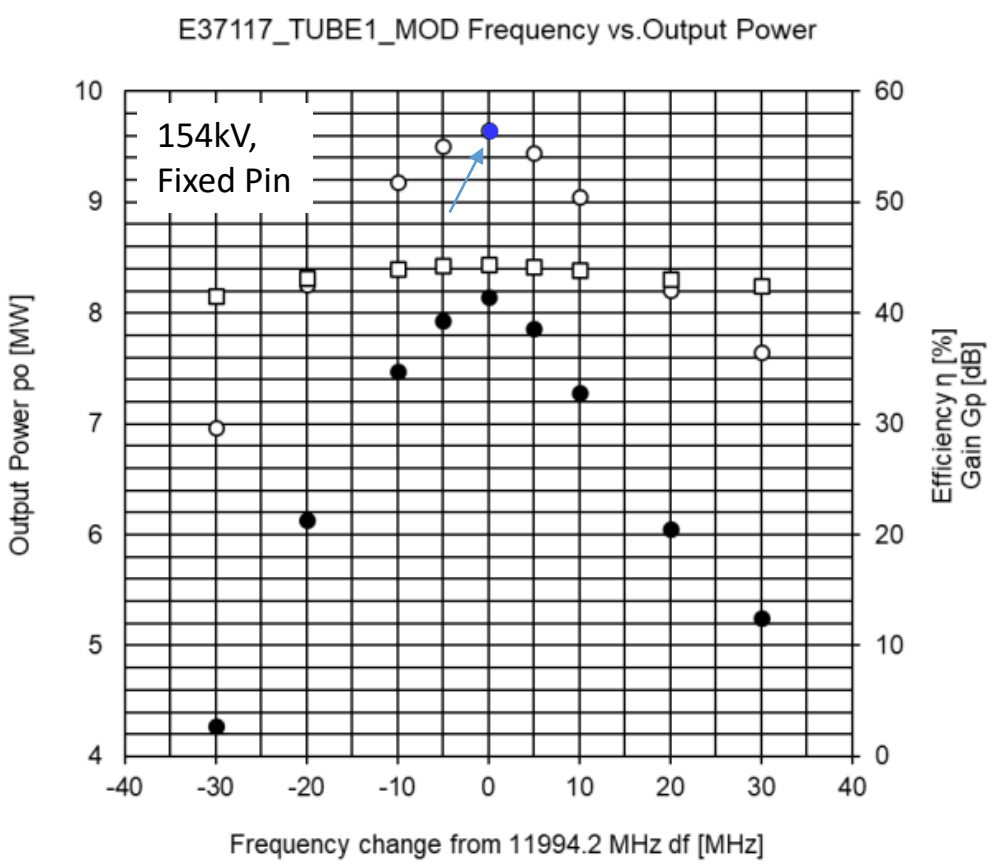


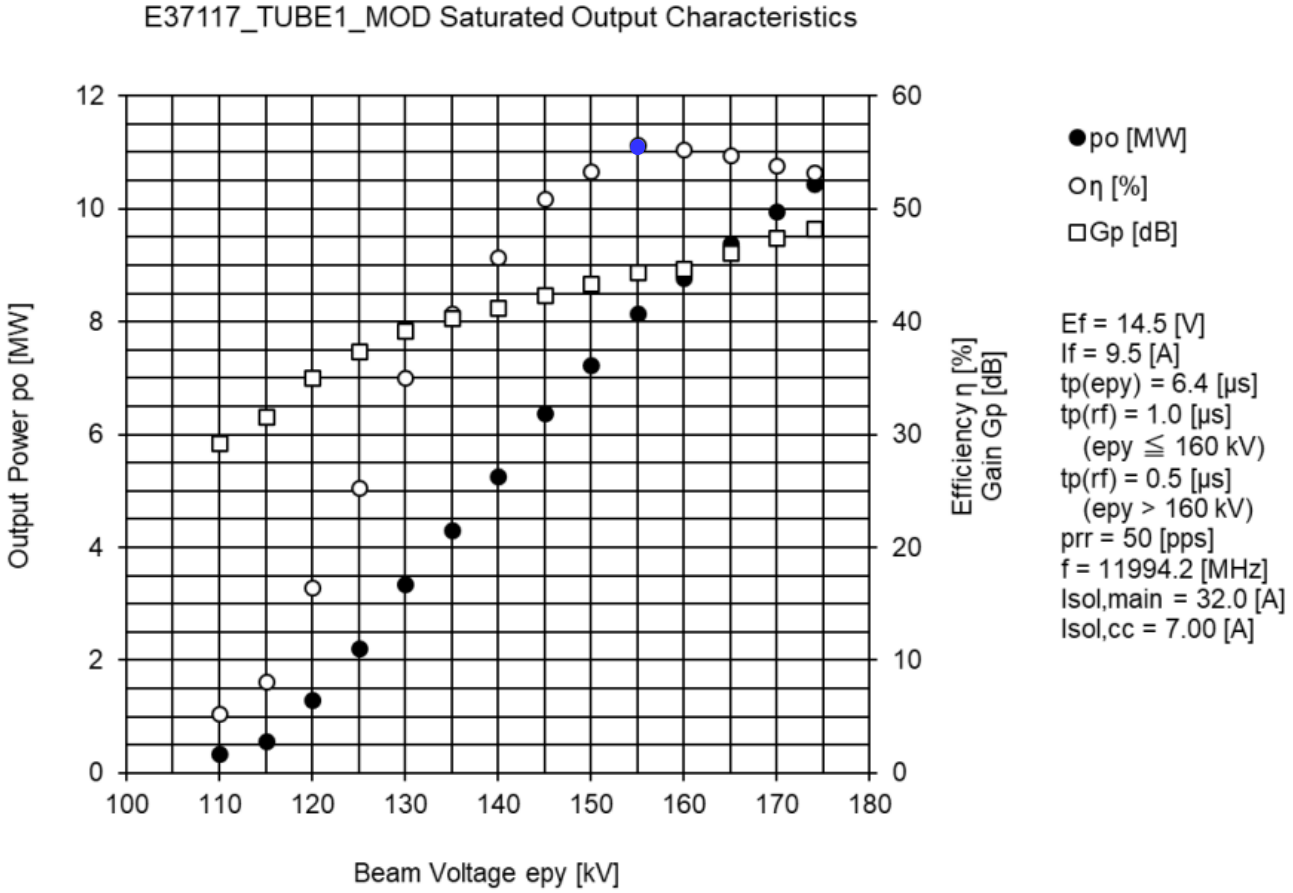
Measurement
(Black: Previous design, Red: Updated design)

Predicted klystron performance in simulations
with different codes used at CERN



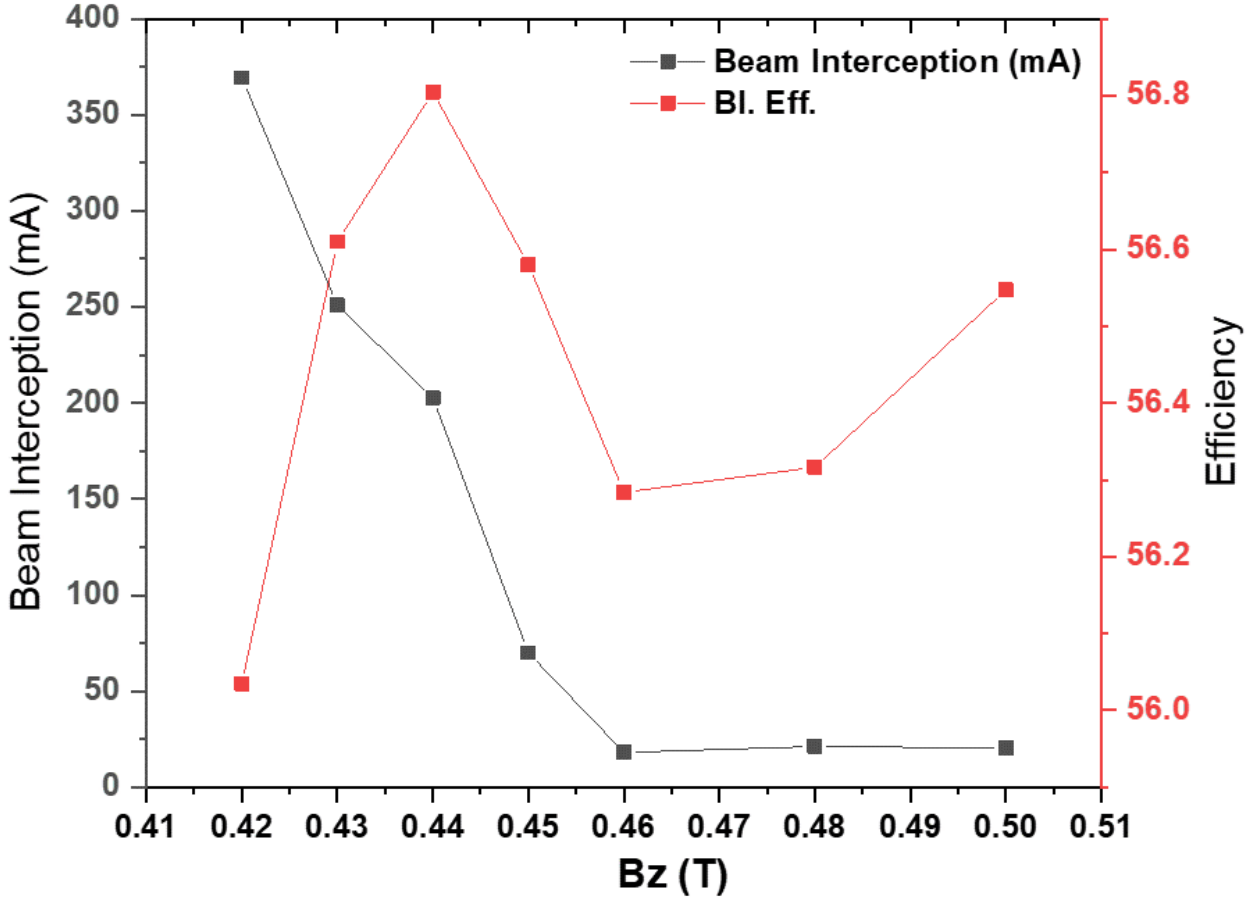
The klystron#3 (refurbished klystron#1) was tested at Canon in December 2022.



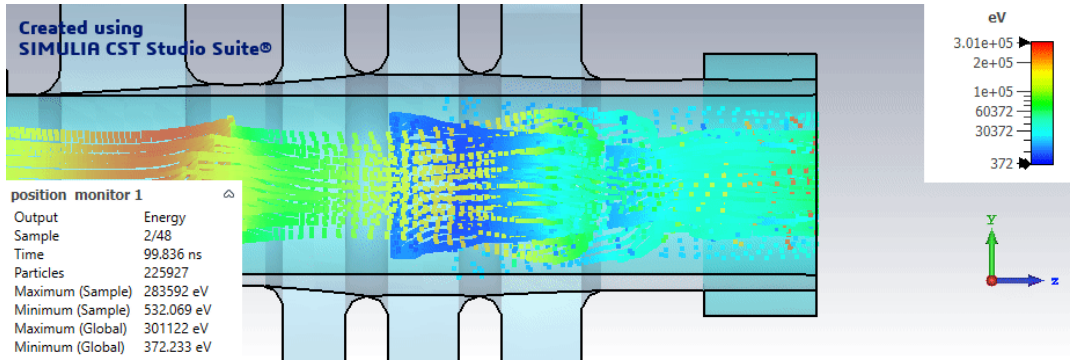


- At operating frequency klystron showed 56.2% (cf. simulated 56.4% in original design). That corresponds to 35% RF peak power increase compared to the original Canon tube at the same operating voltage.
- Tube can reach 10.5MW with existing Xbox#3 ScandiNova modulator (with 174kV max recommended).
- In a range of RF power levels from 6MW to 10.5 MW the klystron is 50%+ efficient and can be used for different application in this range by adjusting modulator type.

…and still this was not the end…



We found in PIC simulations (it was not expected), that by another and small increase of solenoidal field from 0.42T to 0.44T, the efficiency gains another 0.8% and also it provides even less beam interception.



Q. Igor (CERN): … may I suggest one measurement if you can do it. Following our simulations, we saw that efficiency can be increased by almost 1%, if magnetic solenoidal field will be increased up to 0.44T (33.5A) from 0.42T (32A)?

A. Toshiro-san (Canon): …We have additionally tested the performance at solenoid current of I main=33.5A (and I cc=7A). The output power increased a bit as you say:
154 kV, 93.6 A, **Pout=8.2MW, Eff=56.9%.**

IFAST IIF PITCH

Permanent Magnet Solenoid for High Efficiency Klystrons

PM4HEK

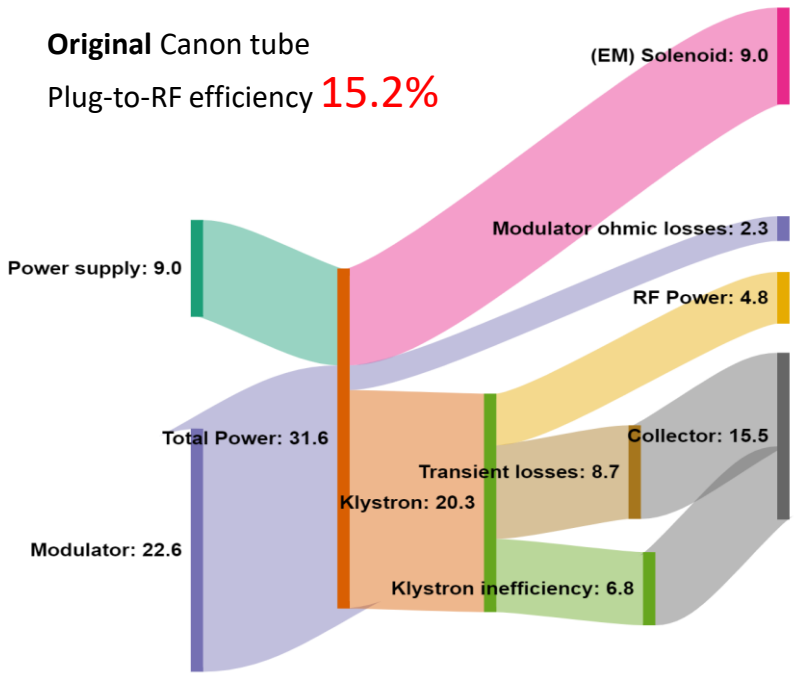
CERN & ELYTT (Spain)

Submitted by:
Nuria Catalan Lasheras
Senior physicist SY/RF

APPROVED

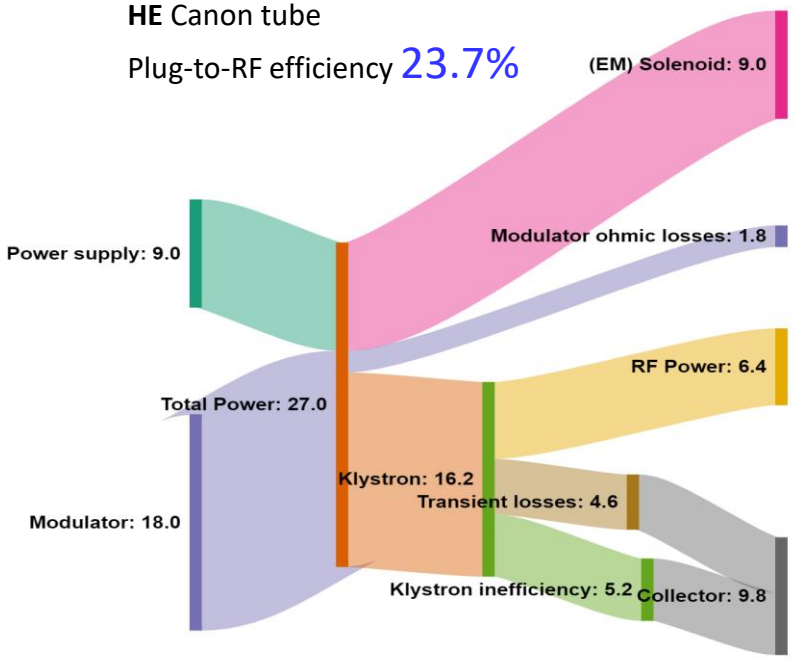
Original Canon tube

Plug-to-RF efficiency 15.2%



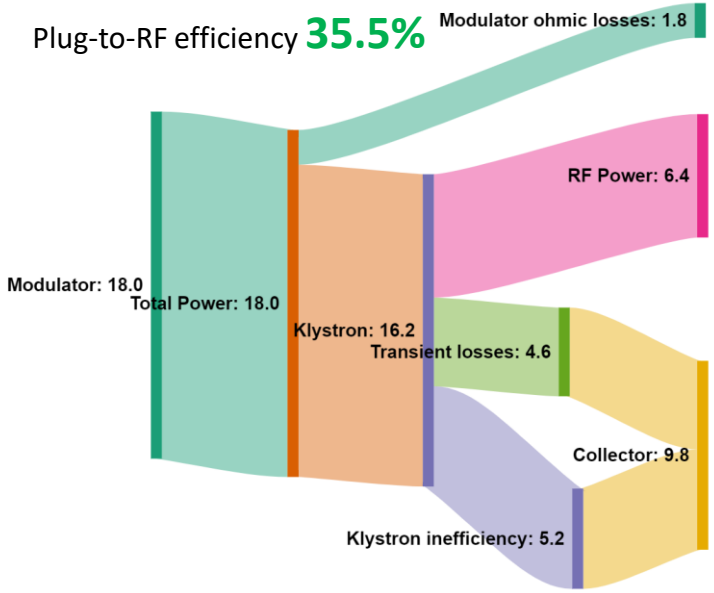
HE Canon tube

Plug-to-RF efficiency 23.7%



HE Canon tube + **PM solenoid**

Plug-to-RF efficiency **35.5%**



Efficiency performance of the selected commercial klystrons and the new HE klystrons. December 2022.