X-band High Efficiency Klystron Development

Workshop on Efficient RF Sources
5 July 2022
Toshiro Anno

Contents

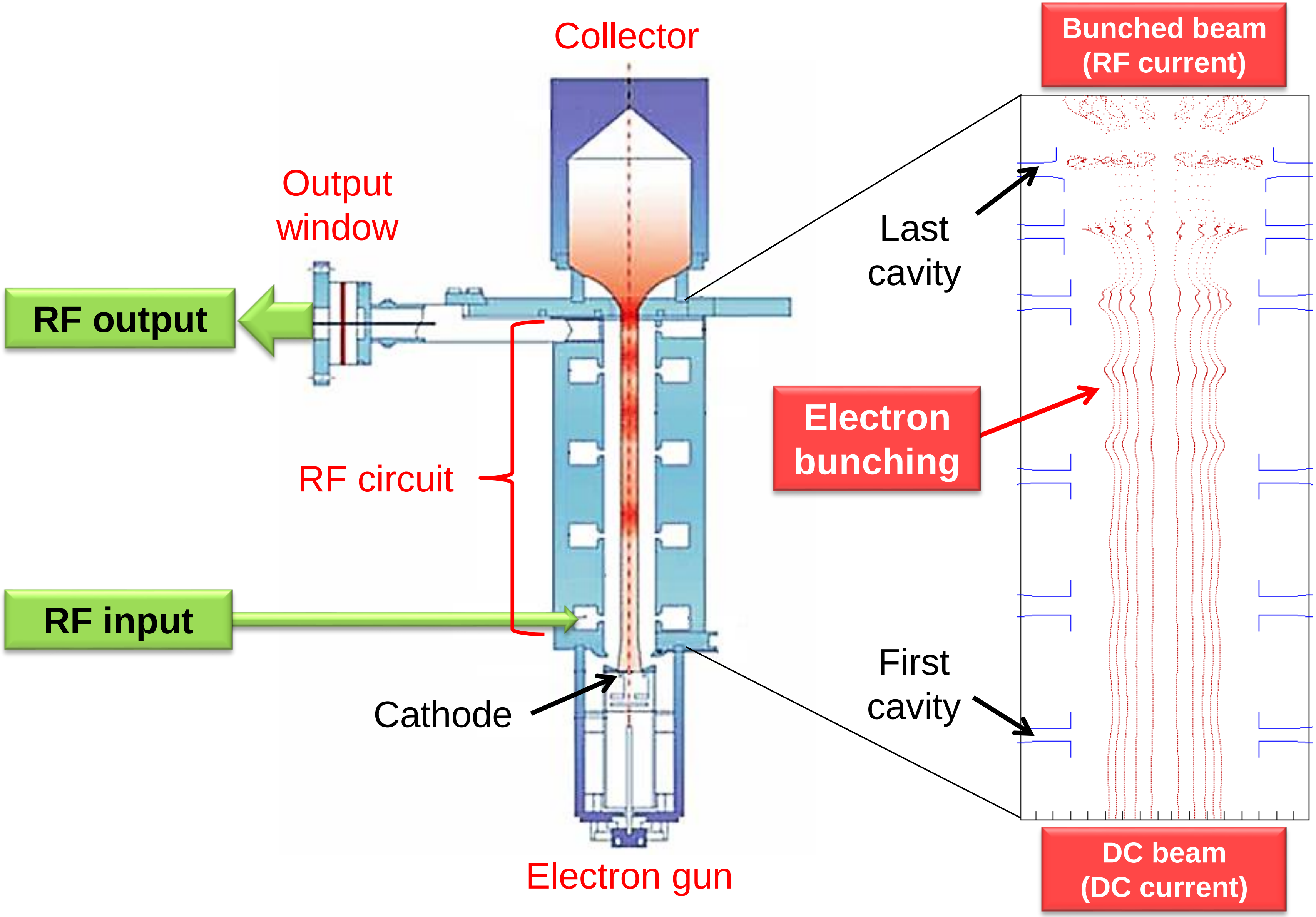
1. Company Overview

Company profile

Company Name	Canon Electron Tubes & Devices Co., Ltd. **(CETD)**
Founded	1915 (A part of Toshiba Corp.)
Established	October 1st, 2003 (Renamed: Nov. 1st, 2018)
Headquarters	1385, Shimoishigami, Otawara-shi, Tochigi 324-8550 , Japan
Business	Development, manufacture and sales of electron tubes and applied products
Main Products	Klystrons, Gyrotrons, Power Grid Tubes, X-ray Tubes, FPDs (Flat Panel Detectors), X-ray Image Intensifiers

Pictures of main products

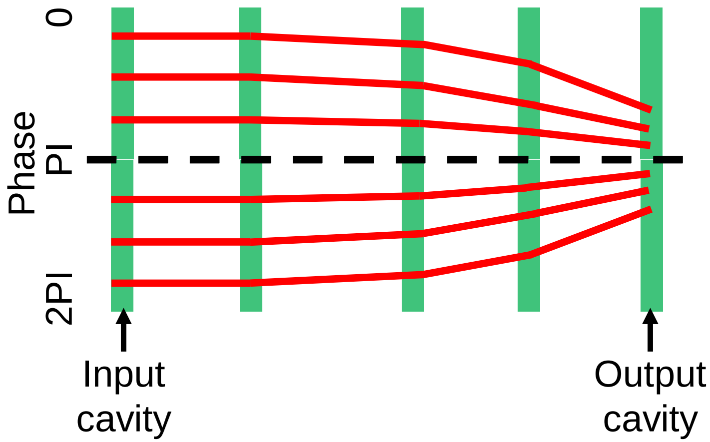
2. Principles of Klystrons



2. Principles of Klystrons

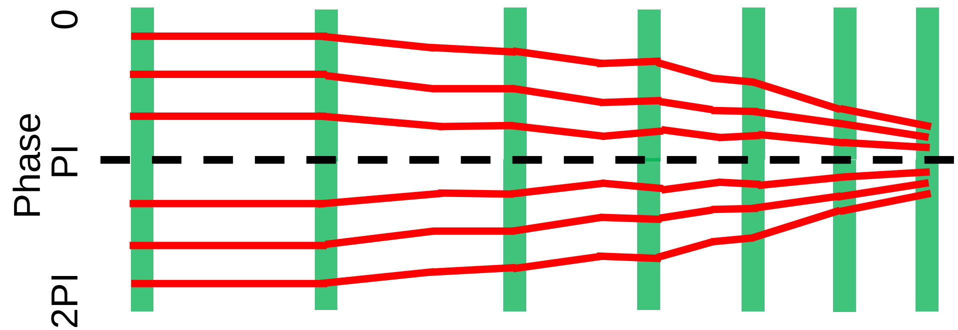
Bunching Methods for High Efficiency

Classical Bunching



Core Oscillation Method (COM)

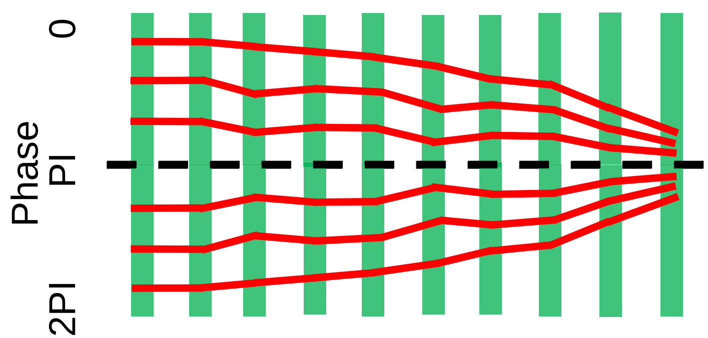
A. Y. Baikov, et al.



Core oscillation by long interaction section.

Bunching Alignment Collection (BAC)

I. A. Guzilov



Core oscillation in reduced length.

These bunching methods can increase efficiency of klystrons even with high perveance (>1μP).

3. High Efficiency 8-MW Klystron

High efficiency klystron development in collaboration with CERN started in 2018 to increase efficiency of existing klystron used in Xbox-3.

- Upgrade tube design without modifications of modulators.
- Target output power more than 8 MW (~60% efficiency).
- Designed by KlyC developed at CERN and confirmed by CST-3D simulations at CERN.
- Confirmed by FCI simulation at CETD.

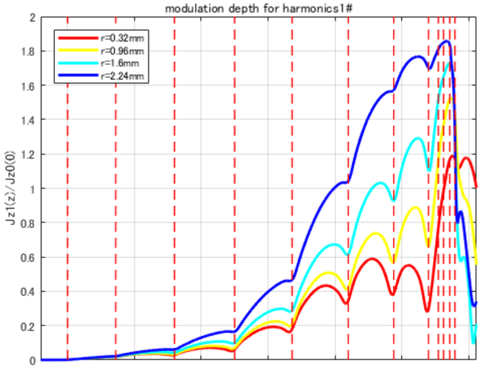
Parameter	E37113
Frequency	11.994 GHz
Peak output power	6 MW
Pulse length	5 μs
Repetition rate	400 pps
Beam voltage	154 kV
Perveance	1.55 μP
Efficiency	43%

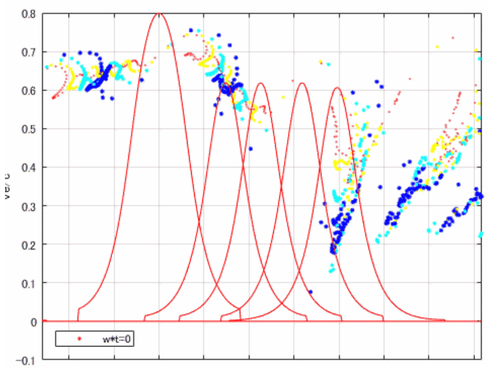
N. Catalan, CLIC 2019

Xbox-3 at CERN

3. High Efficiency 8-MW Klystron

Tube with COM bunching circuit and 4-cells output coupler was designed at CERN by KlyC and confirmed by CST and FCI.

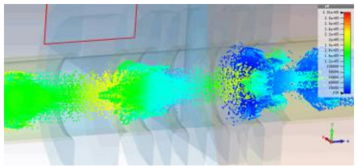


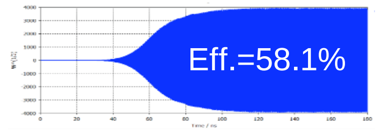


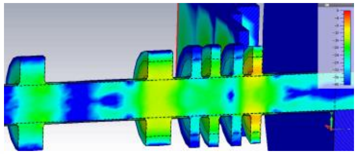
No reflected electrons.
84 MV/m max.

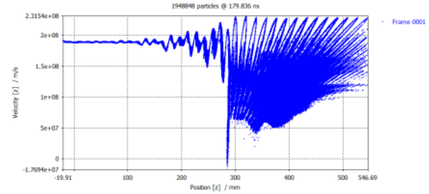
CST

Output coupler



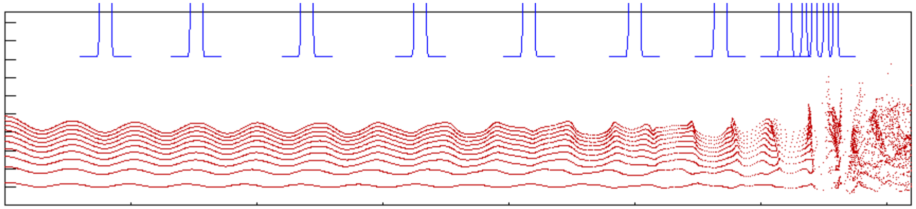


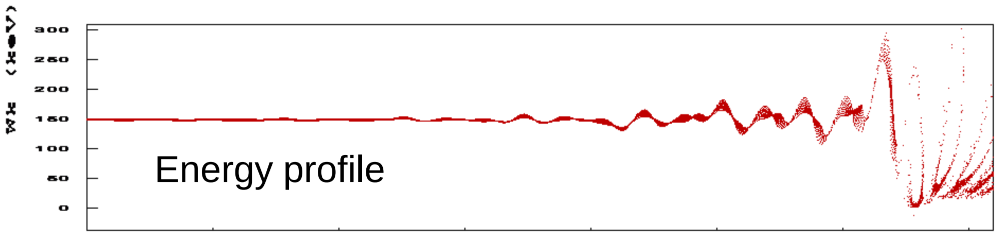




KlyC and CST simulation by J. Cai and I. Syratchev

FCI

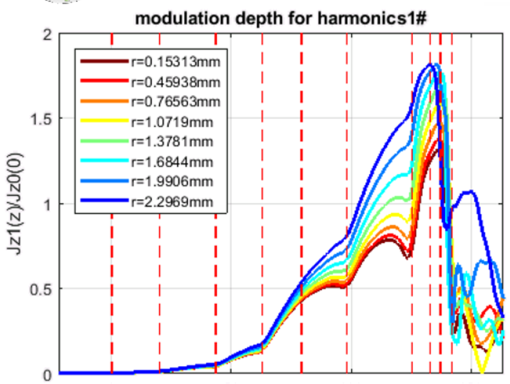


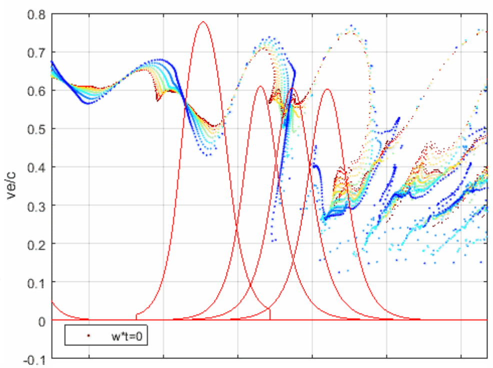


Parameter	KlyC	CST	FCI
Beam voltage [kV]	154	154	154
Beam current [A]	90	90	90
Drive power [W]	100	100	100
Output power [MW]	8.25	8.05	8.12
Power efficiency [%]	59.5	58.1	58.6

3. High Efficiency 8-MW Klystron

Design of much shorter tube with 2nd harmonic triplet (3-cells cavity) operating in pi mode in bunching cavities and 3-cells output coupler was studied. Length decreased to almost half.

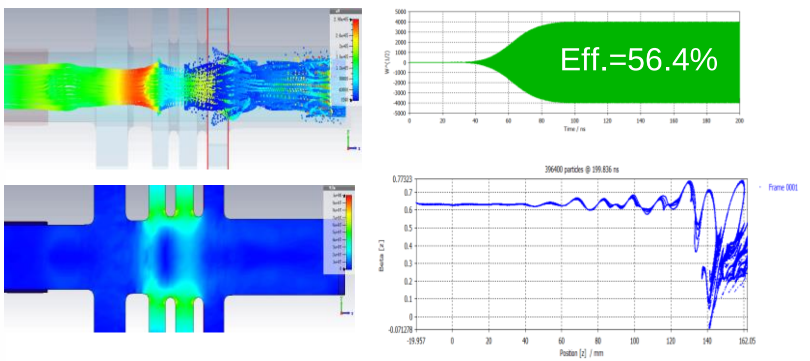




No reflected electrons.
87 MV/m max.

CST

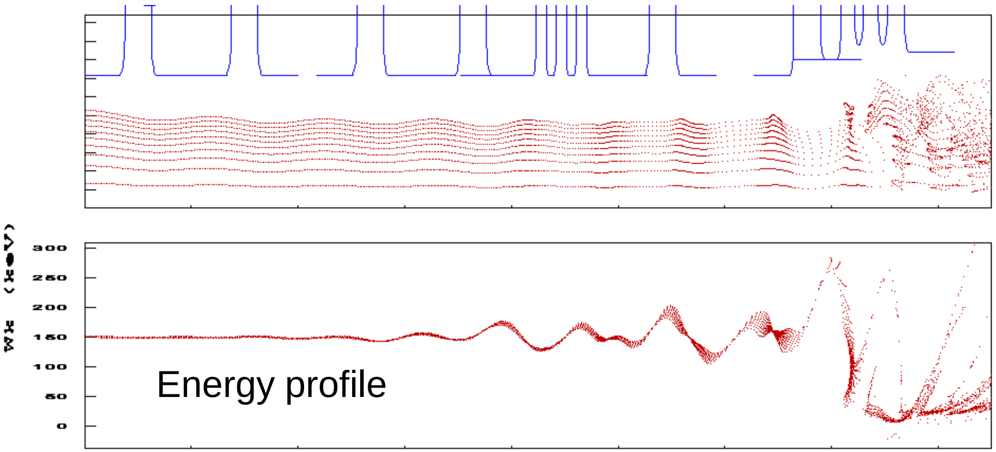
Output coupler



KlyC and CST simulation by J. Cai and I. Syratchev

FCI

2nd harmonic triplet (pi mode)

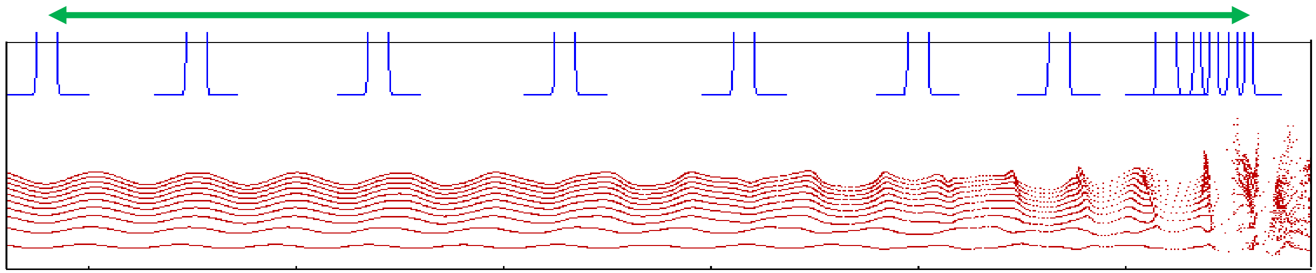


Parameter	KlyC	CST	FCI
Beam voltage [kV]	154	154	154
Beam current [A]	94	94	94
Drive power [W]	80	80	80
Output power [MW]	8.31	8.16	8.16
Power efficiency [%]	57.4	56.4	56.4

3. High Efficiency 8-MW Klystron

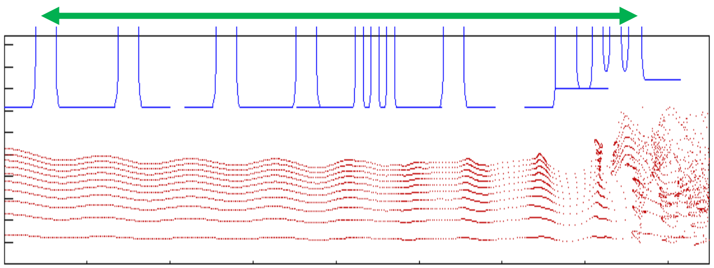
The second design still required new solenoid. We further studied performance of tube that can fit into existing solenoid, and it worked in simulations.

Design 1
- Long circuit
- New solenoid



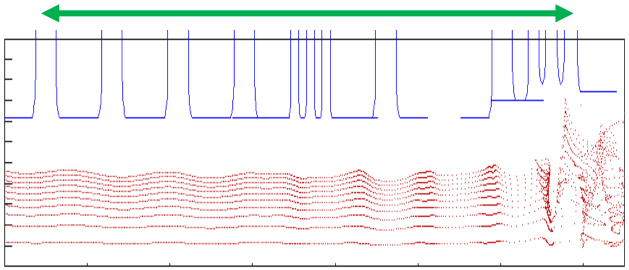
Eff. = 58.6%

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



Eff. = 56.4%

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



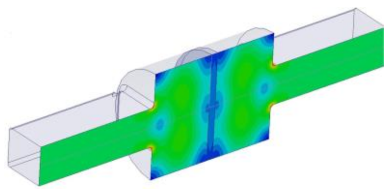
Eff = 56.4%

We decided to fabricate this tube.

3. High Efficiency 8-MW Klystron

Compact RF window with TW in ceramic was designed at CERN to decrease the electric field strength on ceramic.

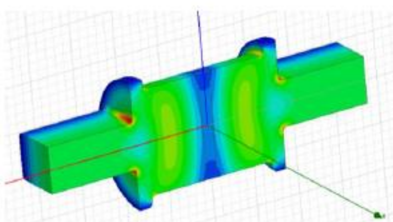
Conventional long pillbox window
4.3 MV/m at 6 MW
4.9 MV/m at 8 MW



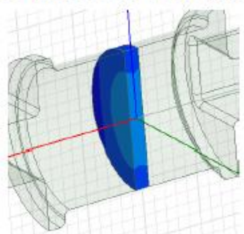
Designed for 6-MW klystron

E field strength on ceramic decreased by 30%

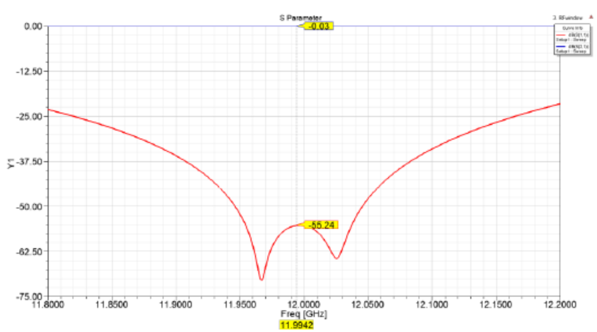
E-field



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

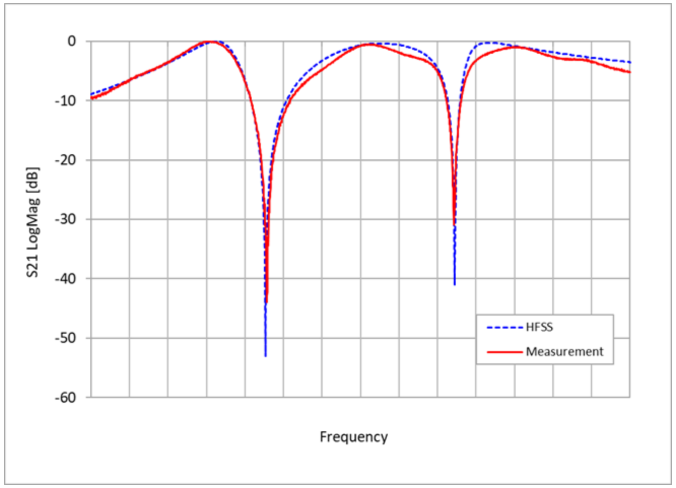
	Value	Units
f_0	11.9942	GHz
P_{IN}	10	MW
Material	Al_2O_3	
Relative Permittivity	9.8	
Dielectric Loss Tangent	0.002	
s_{11}	-55	dB
s_{21}	-0.03	dB
$E_{Max\ Ceramic}$	3.9	MV/m

C. Serpico and I. Syratchev

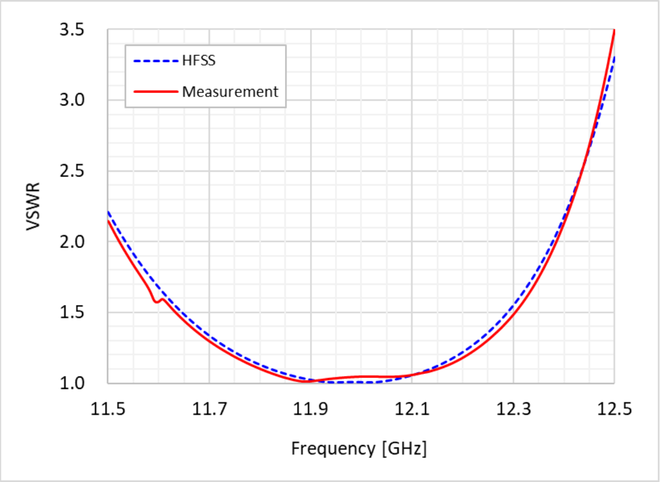
3. High Efficiency 8-MW Klystron

First prototype was fabricated and tested in late 2021 at CETD's factory. Measurement results of 3-cells output coupler and output window are shown.

Blue: HFSS simulation
Red: Measurement



S21 of 3-cells output coupler
(Max S21 was shifted to 0 dB for comparison)

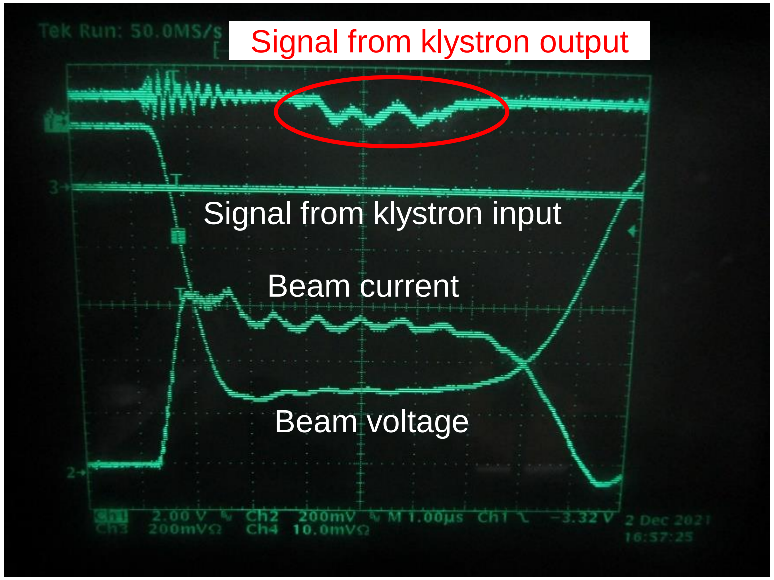


VSWR of RF output window

First prototype

3. High Efficiency 8-MW Klystron

Conditioning of klystron usually starts in diode mode (DC). During diode mode operation, some oscillations were observed unexpectedly at below the design voltage of 154 kV.



Example of diode signal

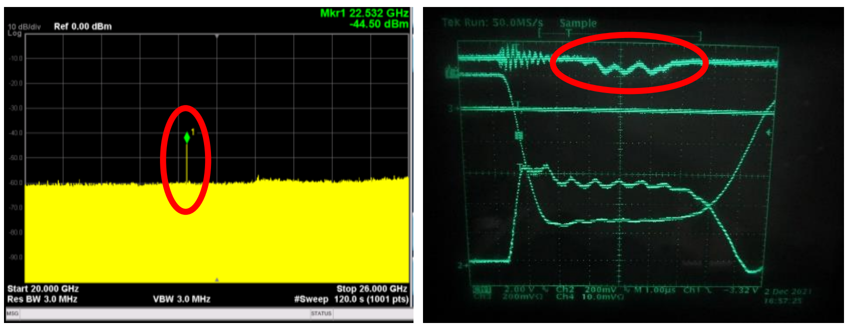
We started investigation using spectrum analyzer.

3. High Efficiency 8-MW Klystron

Oscillation investigation results

There seemed to be two types of oscillations. The klystron was tested below 135 kV to avoid the ion pump current burst caused by beam interception.

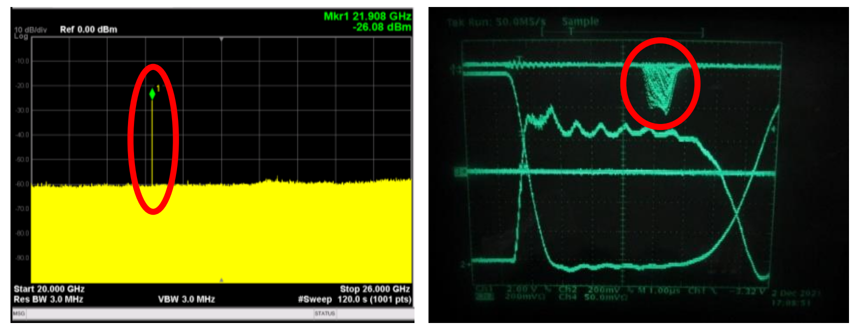
Voltage [kV]	Frequency [GHz]
85 - 125	22.5



Example of 22.5 GHz oscillation at 92 kV

TM01 pi/2 mode in 2nd harmonic triplet (22.5 GHz) was suspected.

Voltage [kV]	Frequency [GHz]
107 - 125	21.9 - 22.0



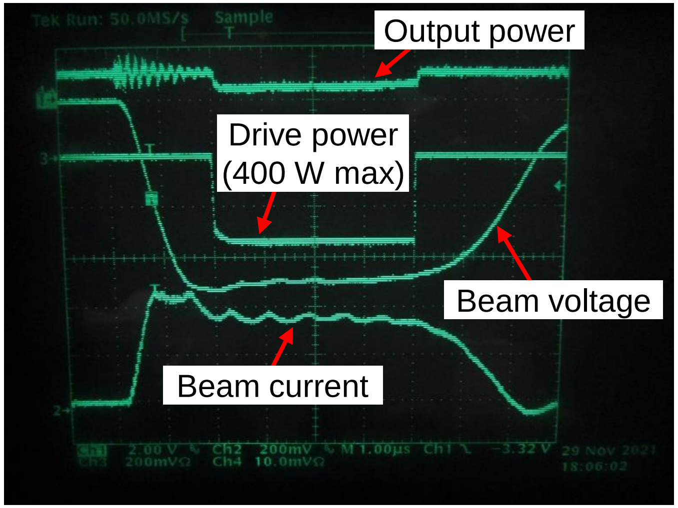
Example of 21.9 GHz oscillation at 125 kV

Through some quick eigen mode analysis, coupled TE modes in bunching cavities were suspected.

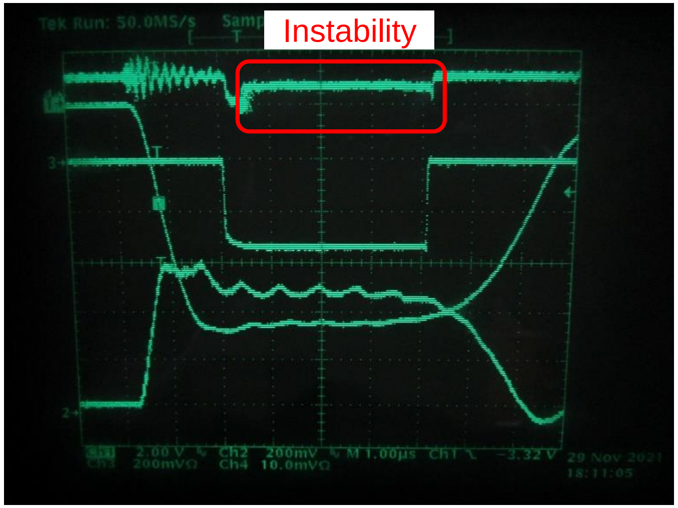
3. High Efficiency 8-MW Klystron

<u>RF test result</u>

Due to oscillations, beam voltage was limited to 70 kV for stable operation whereas design operating point was 154 kV. At such a very low voltage, peak RF output power was only several kW (consistent with simulation).

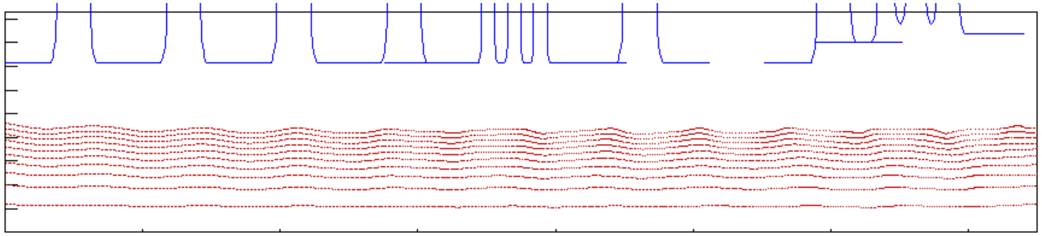


70 kV (Stable)



85 kV (Unstable)

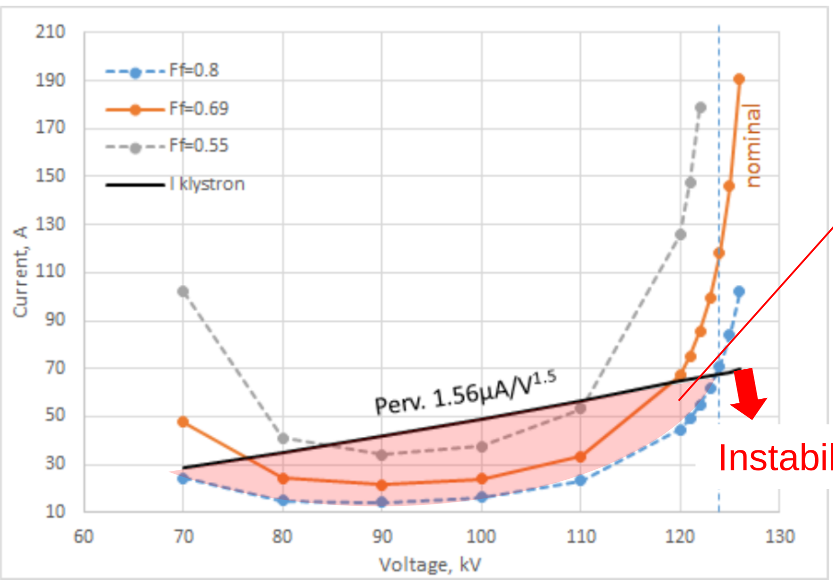
FCI simulation at 70 kV
(Pin = 400 W)



3. High Efficiency 8-MW Klystron

To reach higher voltages, oscillations must be mitigated. Analysis started at CERN. 22.5-GHz oscillation was identified as TM01 pi/2 mode of the 2nd harmonic triplet by KlyC and CST simulations.

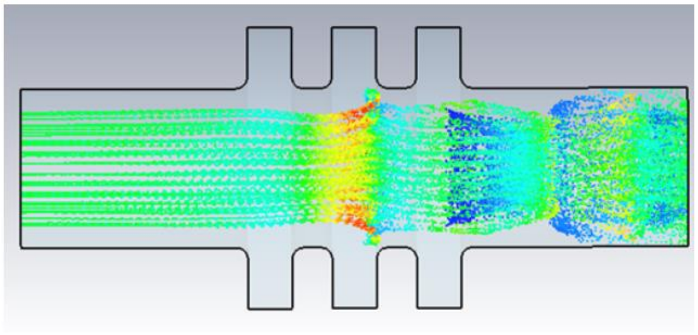
Ff=0.8: Larger beam radius
Ff=0.69: Nominal beam radius



Instability zone from 70 to 125 kV (Ff=0.8)
Consistent with test result

Instability zone

Monotron oscillation threshold currents in the 2nd harmonic triplet for different beam tunnel filling factors as functions of the klystron voltage.

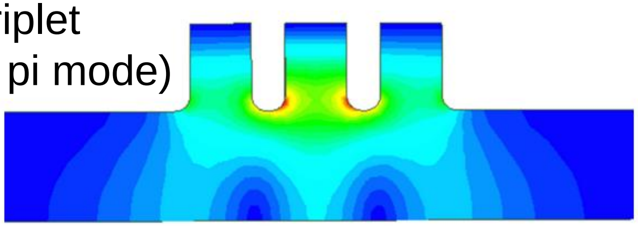


Particle trajectories simulated in CST 3D PIC solver at 92 kV beam voltage.

3. High Efficiency 8-MW Klystron

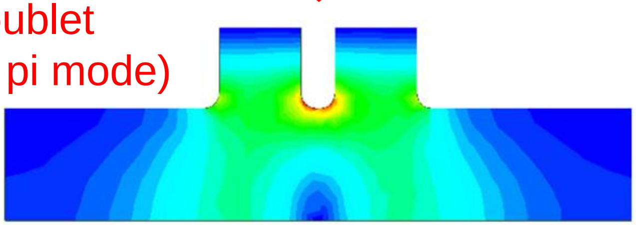
We have tried mitigation and found that by reducing iris thickness of triplet to 60% increased threshold of monotron oscillation to safe level. However, effective impedance of operating π mode decreased by about 30% and triplet lost its benefit. We decided to substitute it by doublet. Threshold current even for the larger beam radius (Ff=0.8) exceeded the klystron current with a good margin.

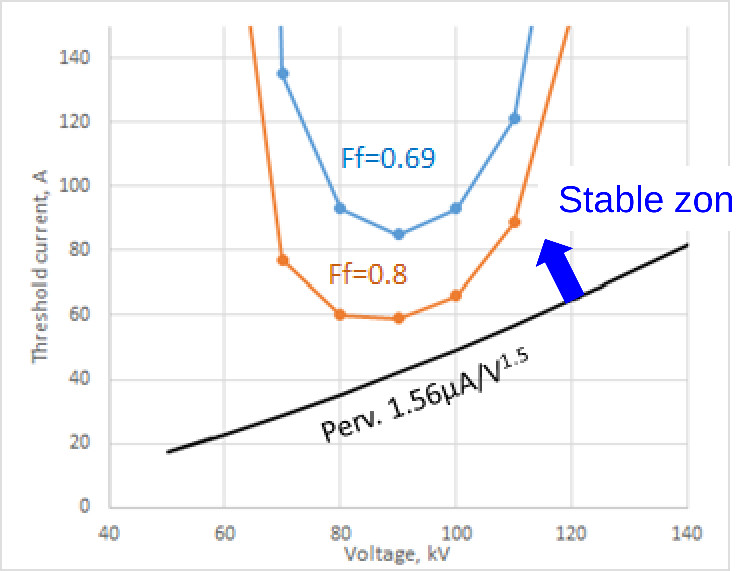
Triplet
(TM01 pi mode)



Substituted

Doublet
(TM01 pi mode)



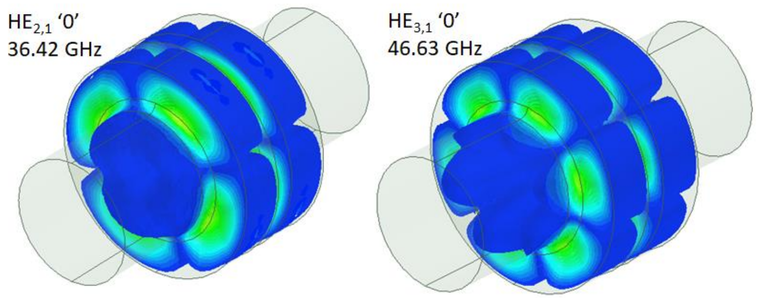


Monotron oscillation threshold currents in the 2nd harmonic doublet for different beam tunnel filling factors as functions of the klystron voltage.

3. High Efficiency 8-MW Klystron

Other potential instabilities in coupled 2nd harmonic cavities were associated with $HE_{N,1}$ hybrid modes (N=2,3). These modes were at high frequencies (36.4GHz and 46.6GHz), but still stayed trapped.

To investigate the mode stability, fast and accurate method to analyze arbitrary instabilities in linear beam devices were used.



Instability onset will be satisfied if $Q_0/Q_{beam} < -1$

Q_0 : Intrinsic quality factor of known mode

Q_{beam}: Beam loading quality factor

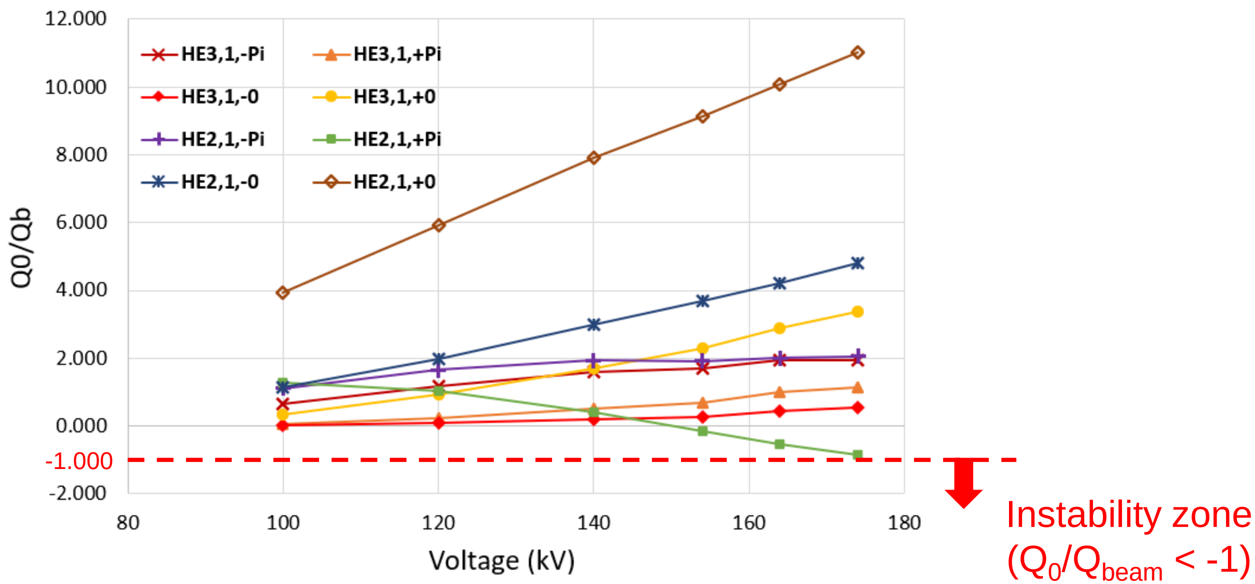
Beam will be decelerated and extract more RF power than RF power dissipated in cavity walls.

To calculate the Q_{beam}, it is sufficient to measure the beam power at a collision plane for two regimes, the first without the imported mode field-map (DC) and the second with the imported mode field-map (RF).

J.C. Cai, I. Syratchev and G. Burt, 'Numerical Analysis of Resonant Multipolar Instabilities in High Power Klystrons', IEEE Trans. on Electron Devices, vol.68, issue.7, pp. 3617 - 3621, June 2021.

3. High Efficiency 8-MW Klystron

As a result of the Q_0/Q_{beam} calculations, HE modes in doublet were confirmed to be stable up to 174 kV even in larger beam radius condition (Ff=0.8).



Q_0/Q_{beam} as a functions of beam voltage for the spatial harmonics (0 and π) of TE21 and TE31 modes. Here, + or – signs indicates the different rotation directions of the modes

3. High Efficiency 8-MW Klystron

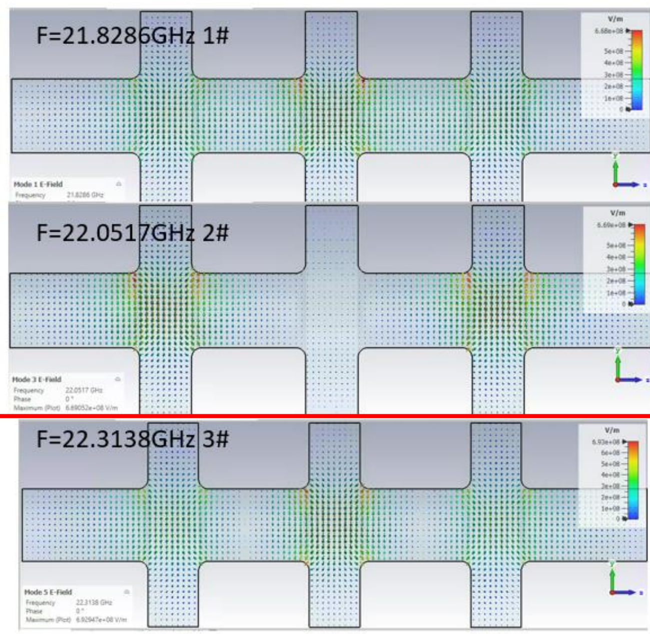
Oscillations at over 107 kV have been also analyzed. Because more than one oscillation was found, this suggest that we must deal with coupled TE11 modes.

Assembly of three bunching cavities (cavity #2 to #4) was simulated in CST eigenmode solver. Two detected modes were identified as TE11 0 and pi/2 coupled modes.

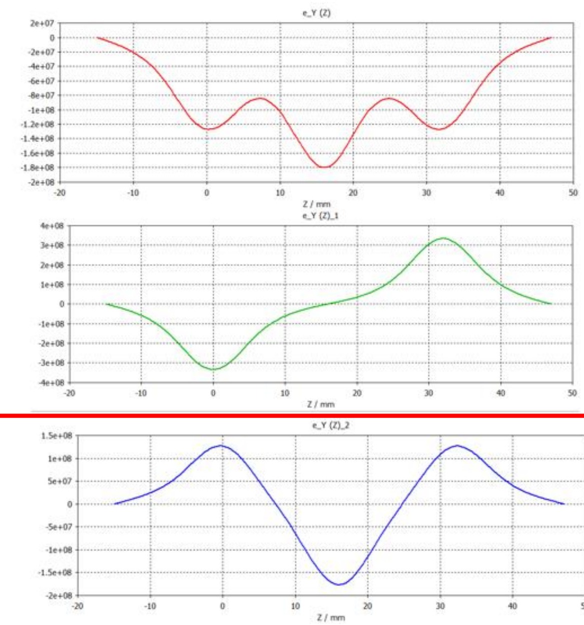
0 mode

pi/2 mode

pi mode



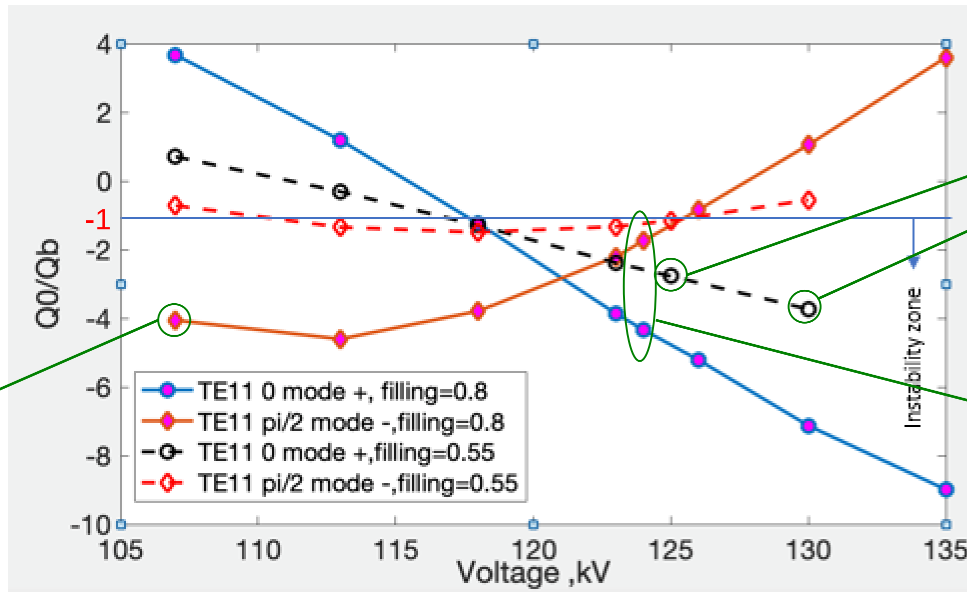
TE11 coupled modes in the three bunching cavities.

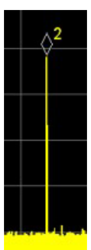


Transverse component of electric filed along Z-axis.

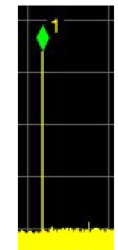
3. High Efficiency 8-MW Klystron

Q_0/Q_{beam} dependency on voltage of TE11 0 and pi/2 coupled modes were analyzed. Cases for two different beam radii (Ff=0.55 and 0.8) were addressed. Simulation results agree well with measured data.

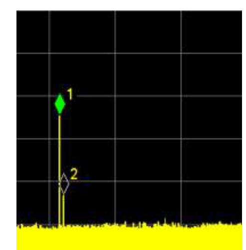




22.016 GHz
(107kV, Ff=0.8)



21.908 GHz
(125-130kV, Ff=0.55)



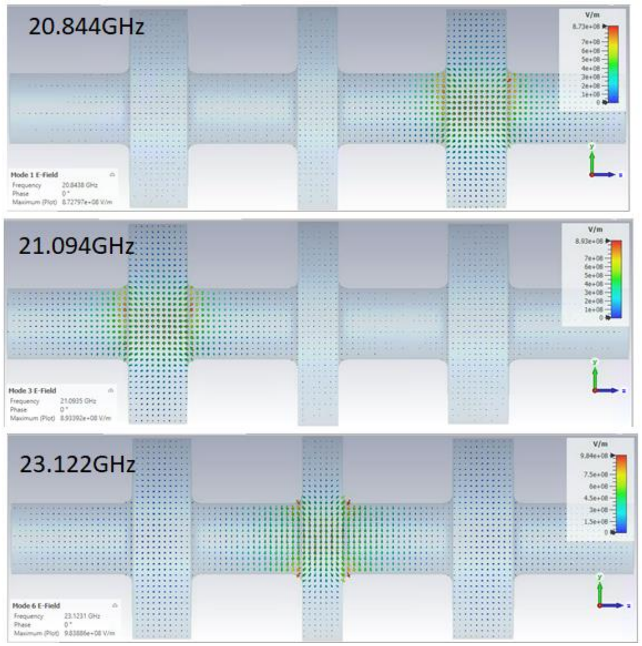
21.896 & 21.932 GHz
Competing modes
(124kV, Ff=0.8)

Q0/Q beam as a functions of beam voltage for the spatial harmonics (0 and π/2) of TE11 mode. Here, '+' and '-' signs indicate the different rotation directions of the modes.

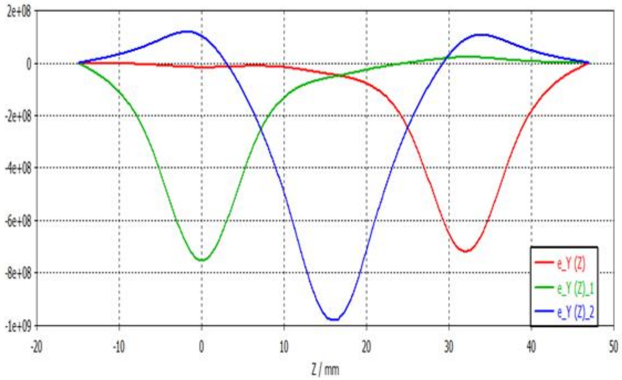
3. High Efficiency 8-MW Klystron

For mitigation of these modes, cavities gaps lengths varied within ± 20% interval with respect to original gap length, and detuning of TE11 modes of 1.8 GHz was obtained.

Modes almost look like modes of individual cavities, however still some residual coupling remains.



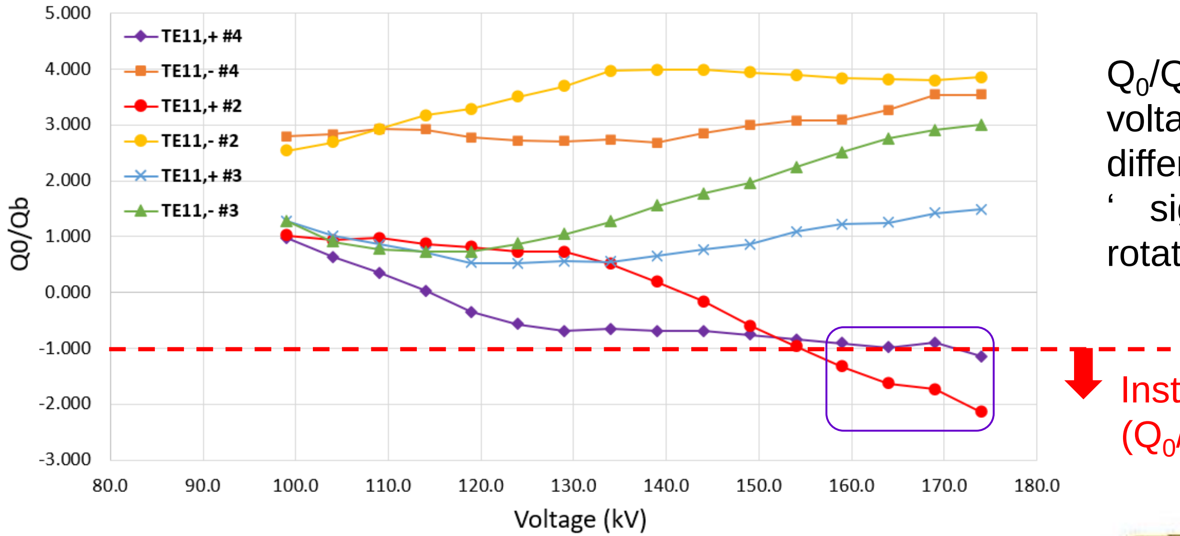
TE11 coupled modes in the new set of three bunching cavities.



Transverse component of electric filed along Z-axis.

3. High Efficiency 8-MW Klystron

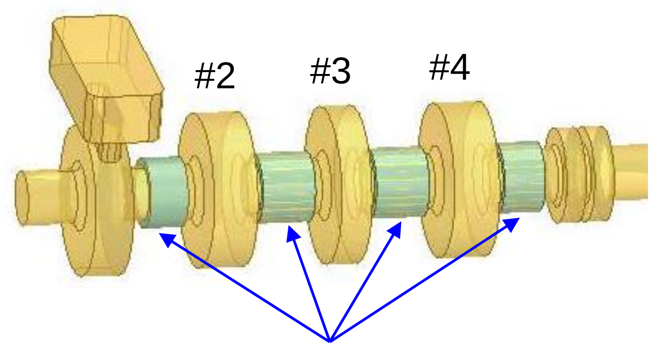
TE instabilities with new cavities were analyzed for voltage range from 100 to 174 kV with filling factor of 0.8 and magnetic field of 0.4T.



Q_0/Q_{beam} as functions of beam voltage for TE11 modes in different cavities. Here, '+' and '-' signs indicate the different rotation directions of the modes.

Modes located in cavity #2 and cavity #4 are almost at threshold of instability.

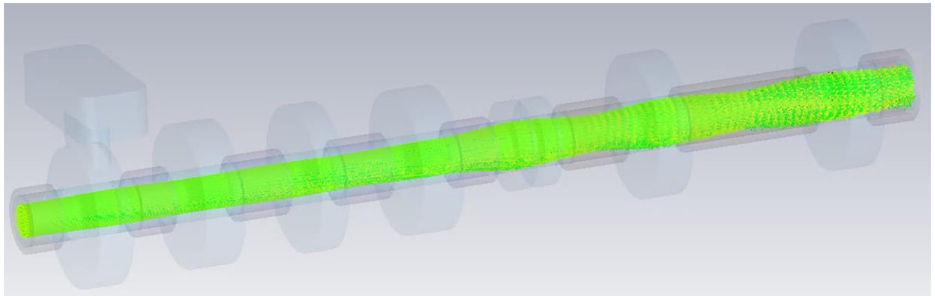
We decided to use stainless steel in first four drifts to keep safe margin for TE mode instabilities.



Stainless steel in first 4 drifts

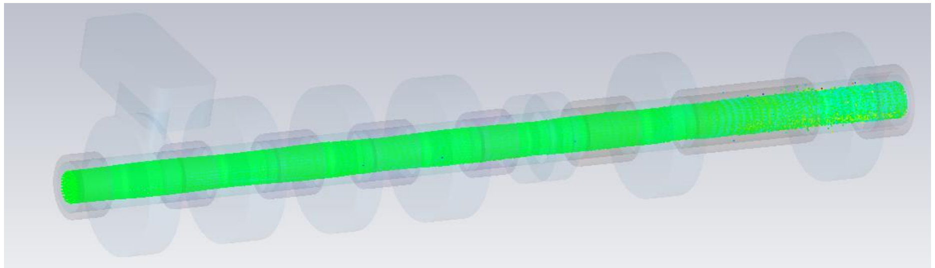
3. High Efficiency 8-MW Klystron

DC beam stability was confirmed in CST-PIC simulation at design operating point of 154 kV and magnetic field of 0.4T, with nominal beam radius.



DC, V=154 kV, Ff=0.69, Bz=0.4 T, Simulation time = 4000 ns

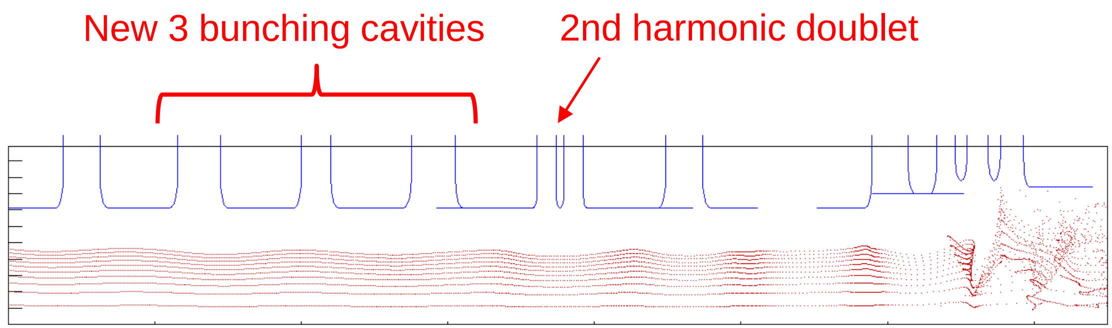
At 174 kV, 0.42 T and nominal beam radius condition, stable DC beam was confirmed in CST-PIC simulation.



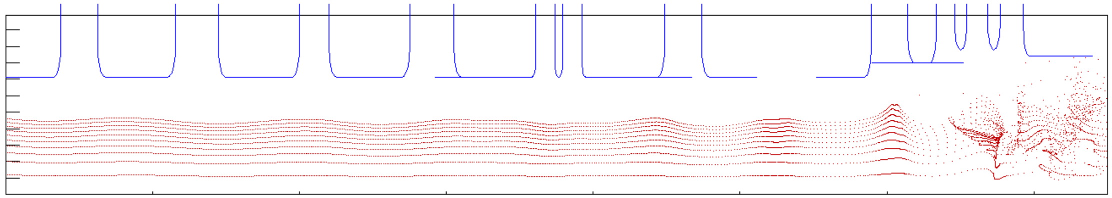
DC, V=174 kV, Ff=0.69, Bz=0.42 T, Simulation time = 4000 ns

3. High Efficiency 8-MW Klystron

RF performance was simulated by KlyC and FCI. 8-MW and 10-MW RF power were expected at 154 kV and 174 kV, respectively.

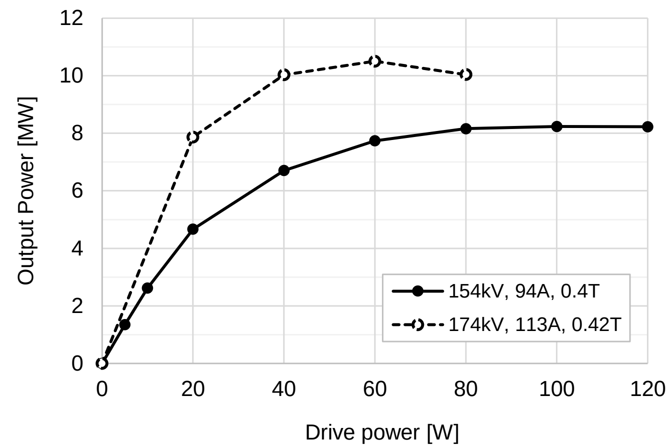


154kV, 94A, Bz=0.4T, Pin=100W, Pout=8.2MW, Eff.=56.8%



174kV, 113A, Bz=0.42T, Pin=60W, Pout=10.5MW, Eff=53.3%

Beam trajectories by FCI simulations.



Power transfer curves at 154 kV and 174 kV by FCI simulations.

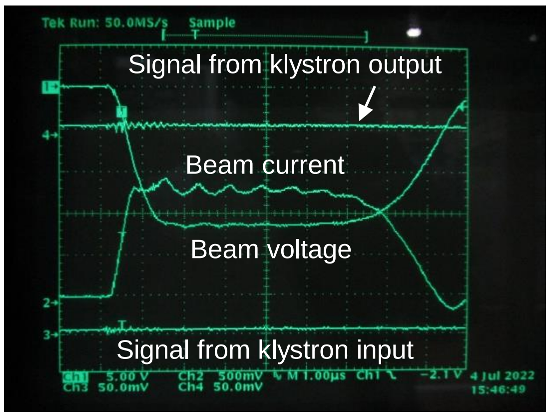
3. High Efficiency 8-MW Klystron

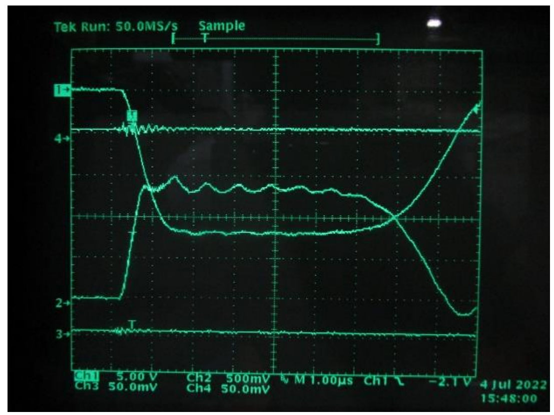
<u>Status of 2nd prototype</u>

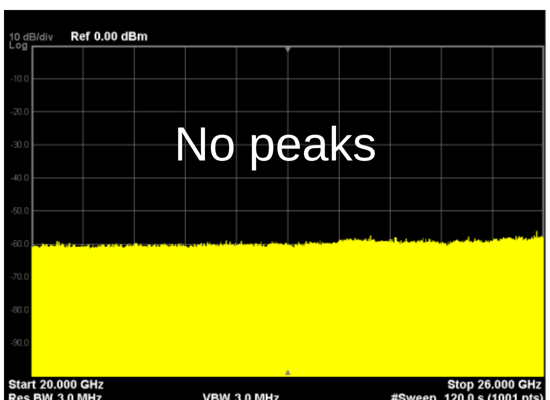
- Four stainless-steel drifts were successfully incorporated.
- Tube with updated RF circuit has been built.
- Conditioning has started recently.
- DC stability was tested. Results are shown in next slides.

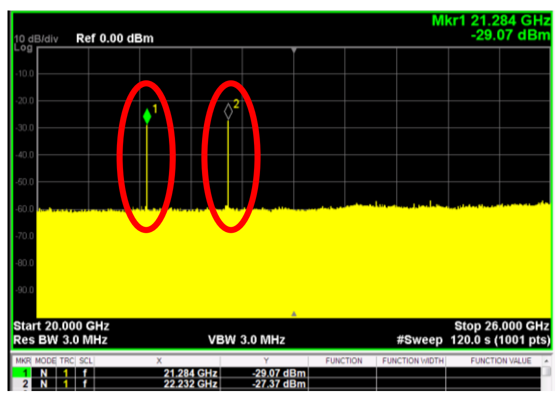
3. High Efficiency 8-MW Klystron

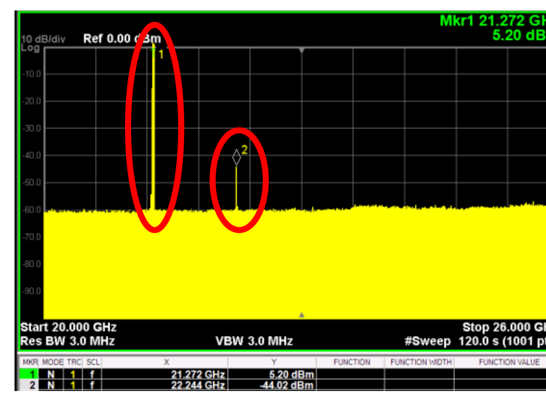
Tube was tested at relatively large beam radius condition (I_{main}=30 A, $I_{counter}$=7 A). Stability was improved and there were no oscillations below 170 kV. However, at higher voltages, some oscillations were observed (21.3 and 22.2 GHz).







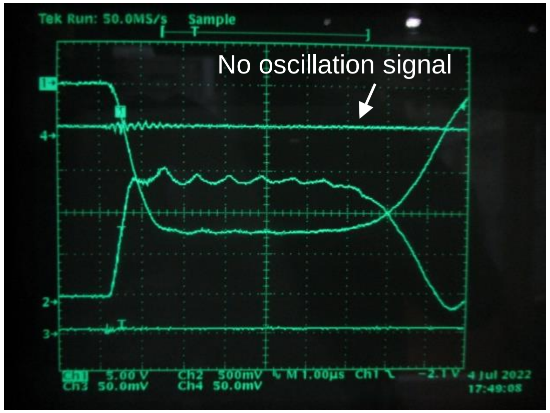


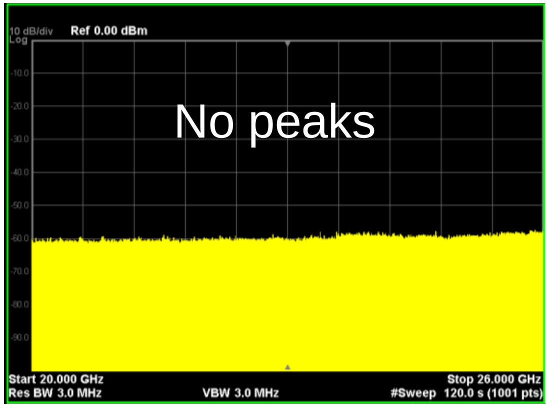


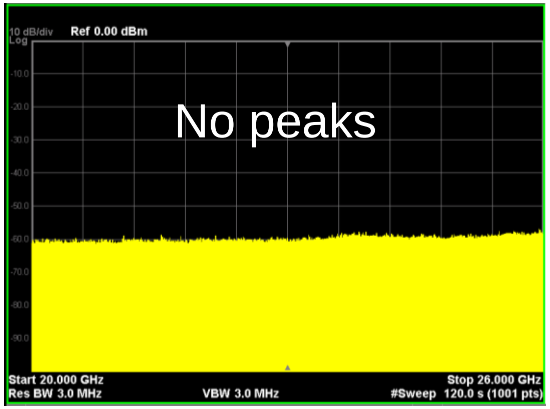
165 kV | 170 kV | 174 kV

3. High Efficiency 8-MW Klystron

Oscillations were successfully eliminated when beam radius was decreased by increasing main coil current or counter coil current of focusing magnet. Results at 174 kV is shown.







I_{main}=30→32A, $I_{counter}$=7A

I_{main}=30A, $I_{counter}$=7→11A

4. Summary

- High efficiency 8-MW X-band klystron was designed in collaboration with CERN to upgrade existing 6-MW klystron in Xbox-3.
- Oscillations were observed in the first prototype and mitigation measures were developed.
- DC stability of second tube was improved and operation at 174 kV was possible.
- RF performance will be tested after RF conditioning.

DC stability issues and mitigation measures are detailed in CLIC-Note-1176.
https://cds.cern.ch/record/2812566

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.

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