CETD Experience with High Efficiency S-band Klystrons

CLIC Workshop 2019
Jan. 23, 2019
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Contents

1. Company Overview

History

Founded: 1915

Developed the First X-ray tube to be produced in Japan.

Established: 2003

Renamed: Nov. 2018

Canon Electron Tubes & Devices Co., Ltd.

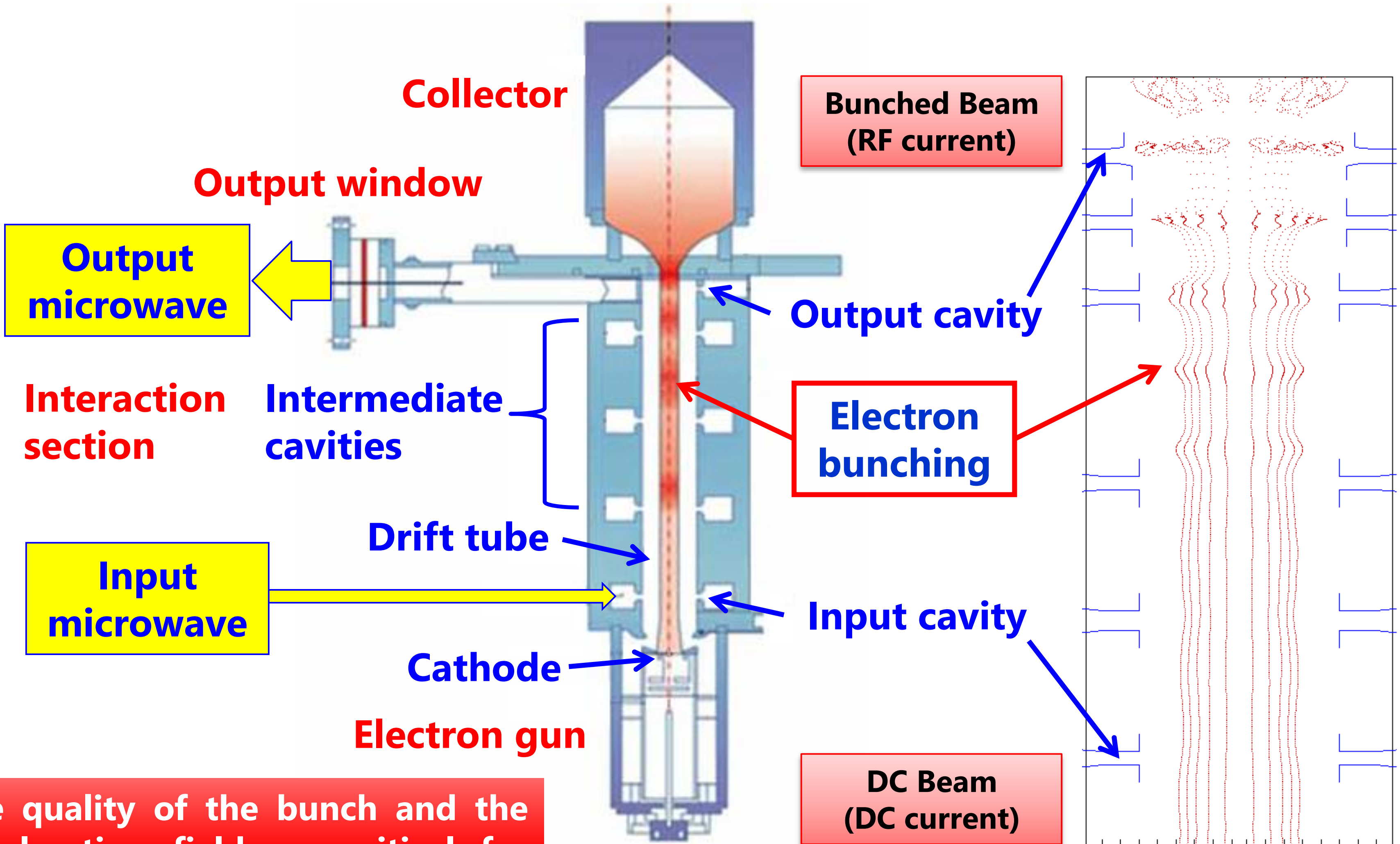
Headquarters

1385 Shimoishigami Otawara, Tochigi Japan

Products

Microwave Tubes
Power Grid Tubes
Radiation Detectors
X-ray Tubes
Image Intensifier
X-ray Flat Panel Detectors

2. Principles of Klystrons

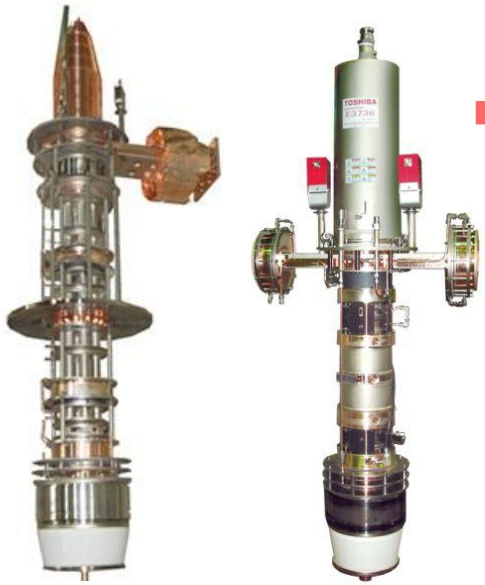


The quality of the bunch and the decelerating field are critical for the power efficiency of klystrons.

3. Efficiency Enhancement of Klystrons

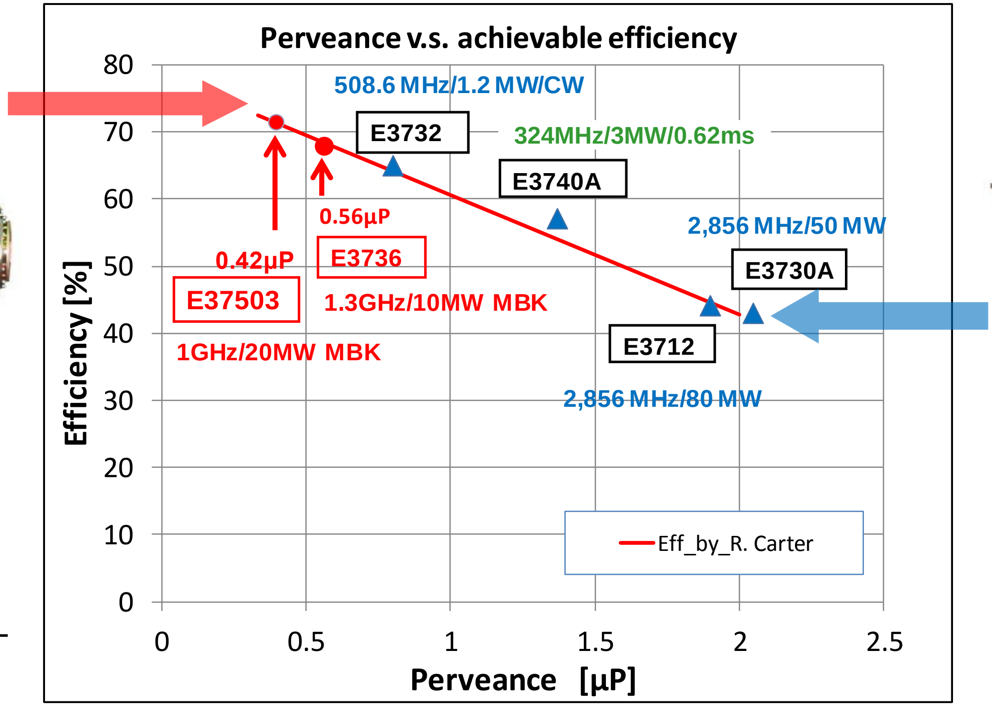
Low Perveance

Perveance=I/V$^{3/2}$



E37503 E3736

Multi-beam Klystrons (MBK)



E3712 E3730A

The efficiency of low-perveance klystron is more than 70%.
The MBK is a known solution to achieve high efficiency and high power.

3. Efficiency Enhancement of Klystrons

Example of MBK

E37503 Klystron for CLIC Project

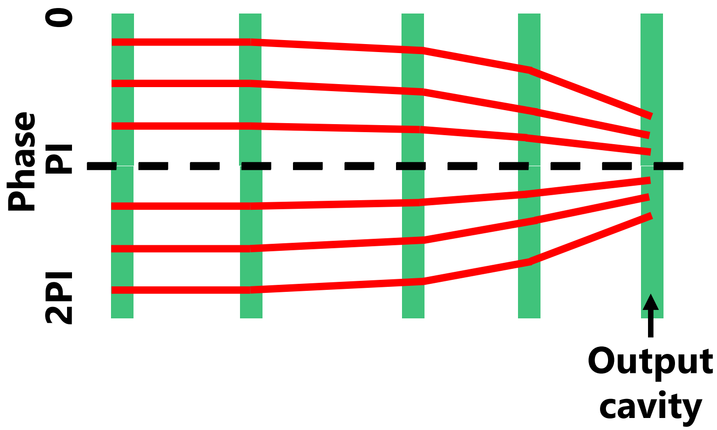
- **Six-low perveance beams**
- **Perveance of 0.42 μ A/V$^{3/2}$ for lower cathode voltage with higher efficiency**
- **Six coaxial cavities in interaction section**

Parameter	Design	Test result
Frequency [MHz]	999.516	
Peak power [MW]	20	20.5
Pulse length [ms]	150	150
Repetition rate [pps]	50	(25)
Beam voltage [kV]	166	159.5
Beam current [A]	170	180
Efficiency [%]	71	71.5
Power gain [dB]	50	53.9

3. Efficiency Enhancement of Klystrons

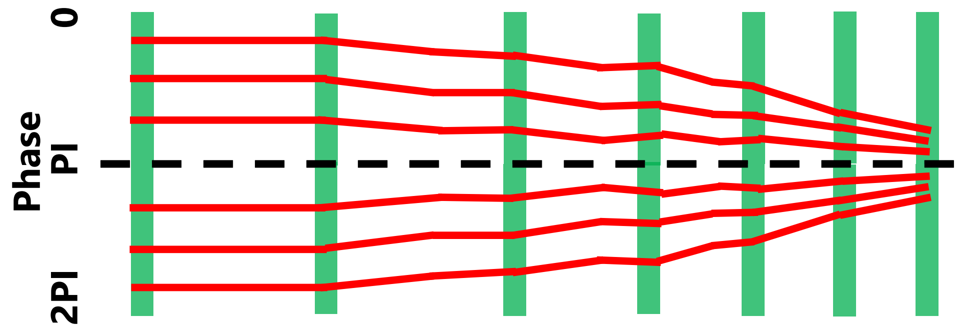
New Bunching Method

Classical Bunching



Core Oscillation Method (COM)

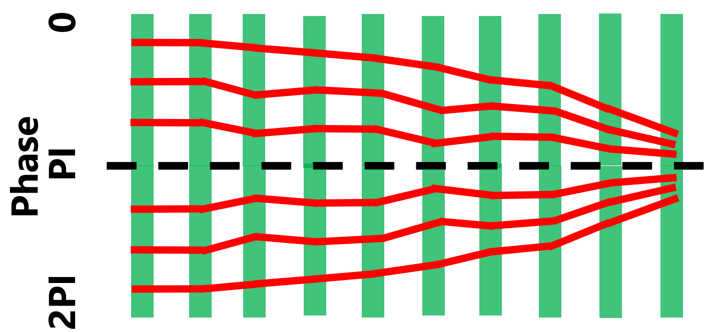
A. Y. Baikov, et al.



Core oscillation by long interaction section.

Bunching Alignment Collection (BAC)

I. A. Guzilov

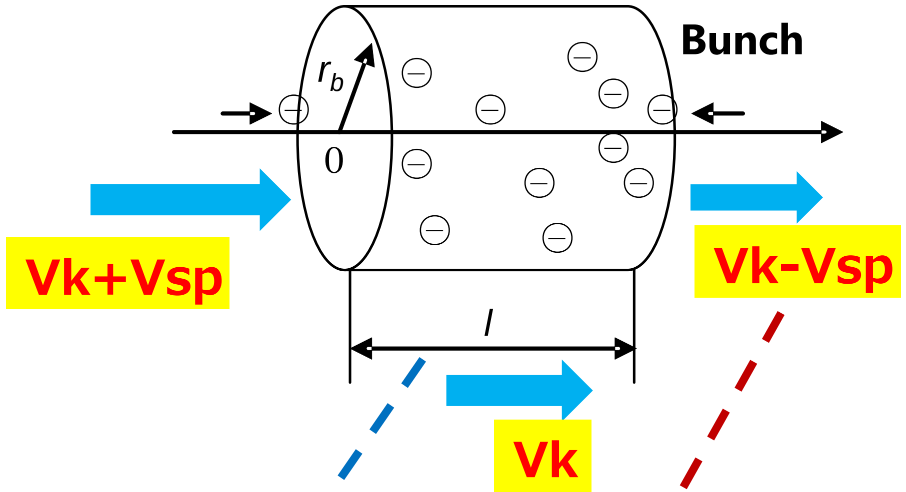


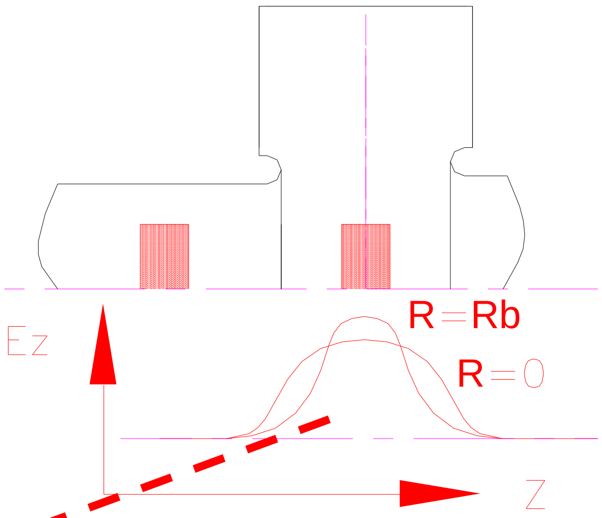
Core oscillation in reduced length.

New bunching methods were proposed to increase the power efficiency of klystrons.

3. Efficiency Enhancement of Klystrons

Rough Estimation by Simplified Model





$$\eta \approx B(l) \cdot \left(1 - \frac{\Delta V_{beam}}{V_k}\right) \cdot G(r_d, r_b) \;, 0 < \Delta V_{beam} \leq V_{sp}$$

$B(l)$: Deceleration factor due to finite length of bunch.
ΔV_{beam} : Maximum potential spread in electron bunch.
V_k : Beam voltage.
$G(r_d, r_b)$: Deceleration factor due to distribution of electric field in output cavity.

Y. Okubo (CETD), IPAC18

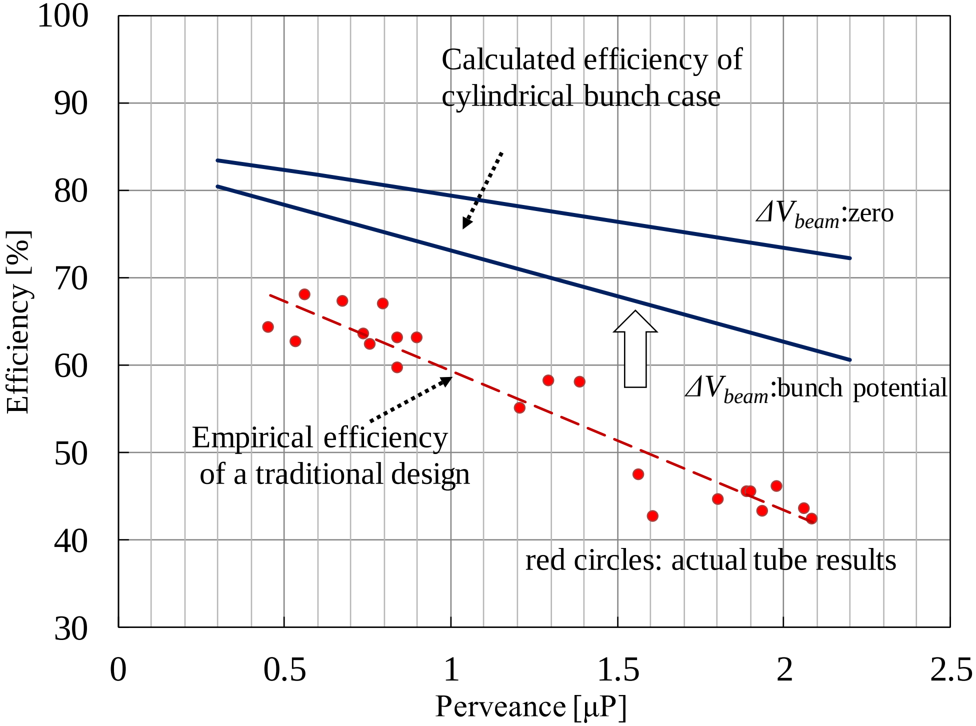
3. Efficiency Enhancement of Klystrons

Rough Estimation by Simplified Model

Assuming cylindrical bunch,

$$B(l) = \frac{1}{\pi} \cdot \frac{\lambda_e}{l} \sin\left(\pi \cdot \frac{l}{\lambda_e}\right), \qquad G(r_d, r_b) \sim \frac{1}{2} \cdot \left(\frac{1}{I_0(\theta_{r_d})} + 2\right), \qquad \text{where } \theta_{r_d} = \frac{2\pi r_d}{\gamma \lambda_e}$$

$$V_{sp} = 15 \cdot \frac{Perv. \cdot V_k^{\frac{3}{2}} \cdot \lambda_e}{\beta \cdot l} \cdot \left\{ \frac{l}{r_b} \cdot \sqrt{1 + \left(\frac{l}{r_b}\right)^2} - \left(\frac{l}{r_b}\right)^2 + \ln\left| \frac{l}{r_b} + \sqrt{1 + \left(\frac{l}{r_b}\right)^2} \right| \right\}$$



λ_e: beam wavelength
β: beam drift velocity
γ: relativistic beam energy

The efficiency of high-perveance tubes will be increased by 10 to 15%.

Y. Okubo (CETD), IPAC18

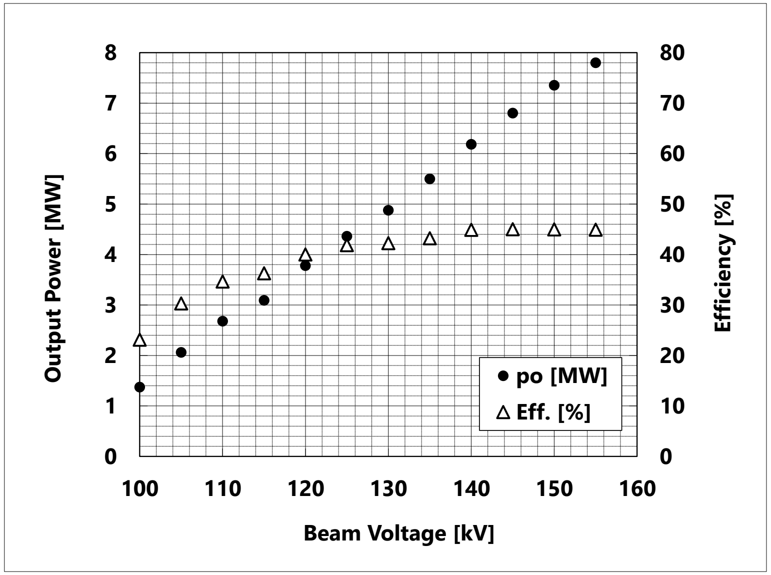
4. Development of High Efficiency S-band Klystron

Base Model: E3772A (2856MHz, 7.5MW)

Length: 1.0 m
Weight: 40 kg

E3772A Klystron for Medical Linac

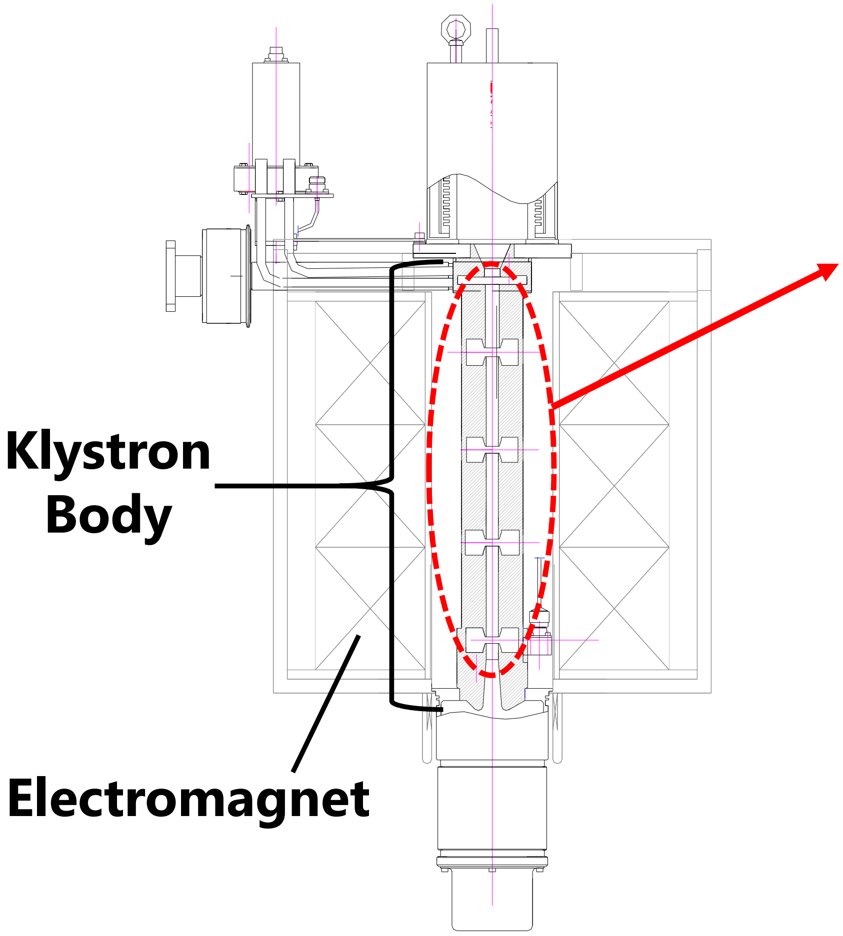
Parameter	Value
Frequency [MHz]	2856
Peak power [MW]	7.5
Pulse length [µs]	4.5
Repetition rate [pps]	200
Beam voltage [kV]	155
Beam current [A]	109
Micro perveance [µA/V$^{3/2}$]	1.79
Efficiency [%]	45
Power gain [dB]	51
Solenoid coil power [kW]	3.7



We applied the new bunching method to the high-perveance klystron.

4. Development of High Efficiency S-band Klystron

Design Concept



1. Increase number of cavity in interaction section.

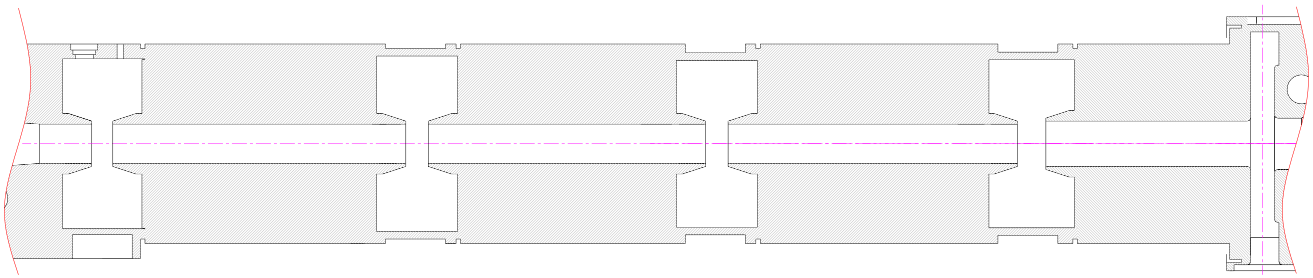
2. Keep body length same as original to use same electromagnet.

3. Use narrow drift tube for 2nd harmonic cavities.

4. Development of High Efficiency S-band Klystron

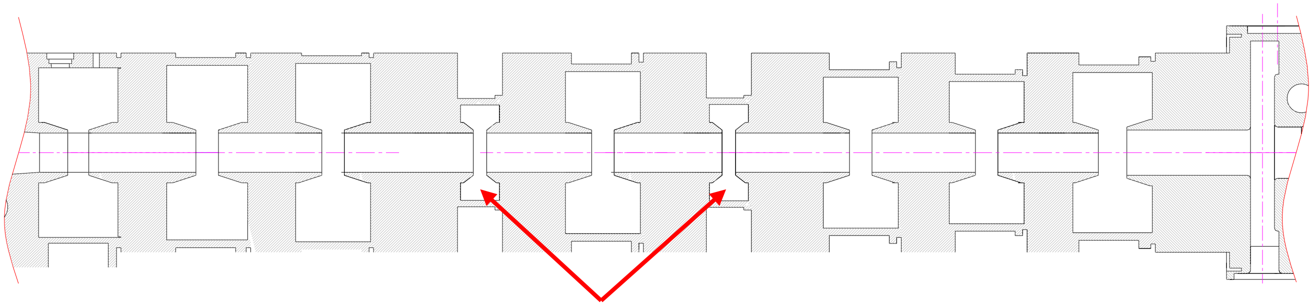
Comparison of interaction section

Conventional design (E3772A)



5 cavities

High efficiency design



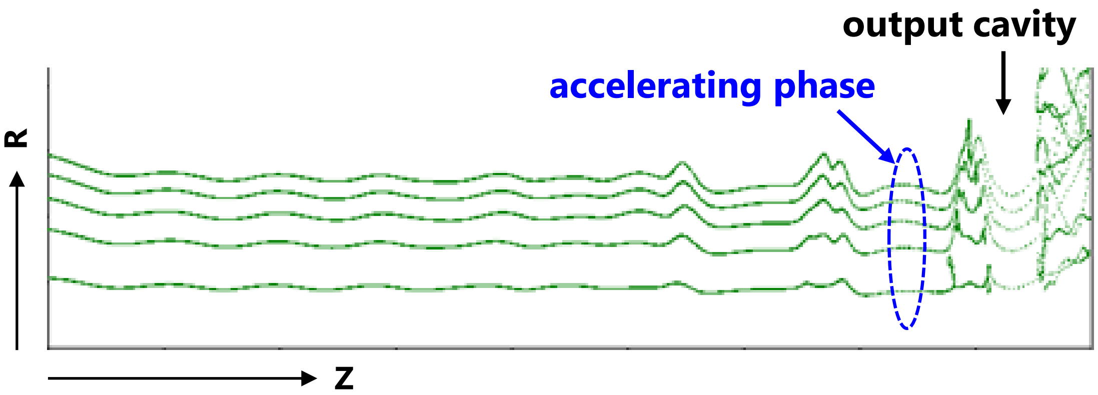
10 cavities

2nd harmonic cavities

4. Development of High Efficiency S-band Klystron

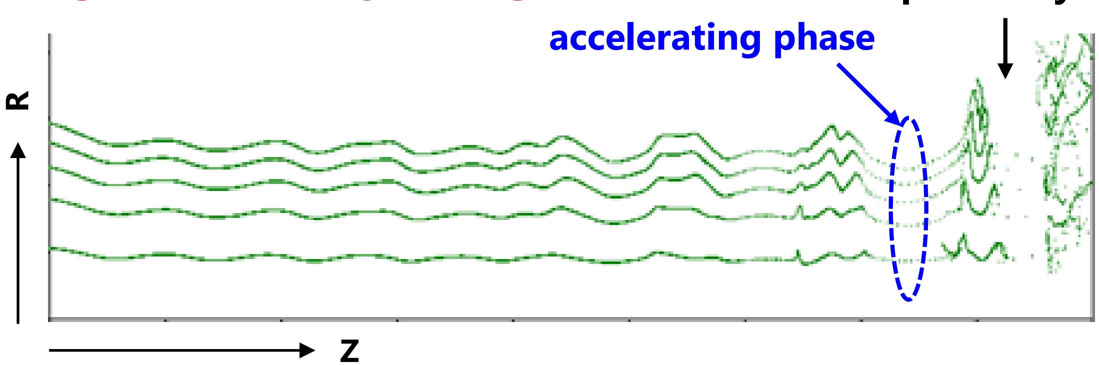
FCI Simulation

Conventional design (E3772A)



High efficiency design

output cavity



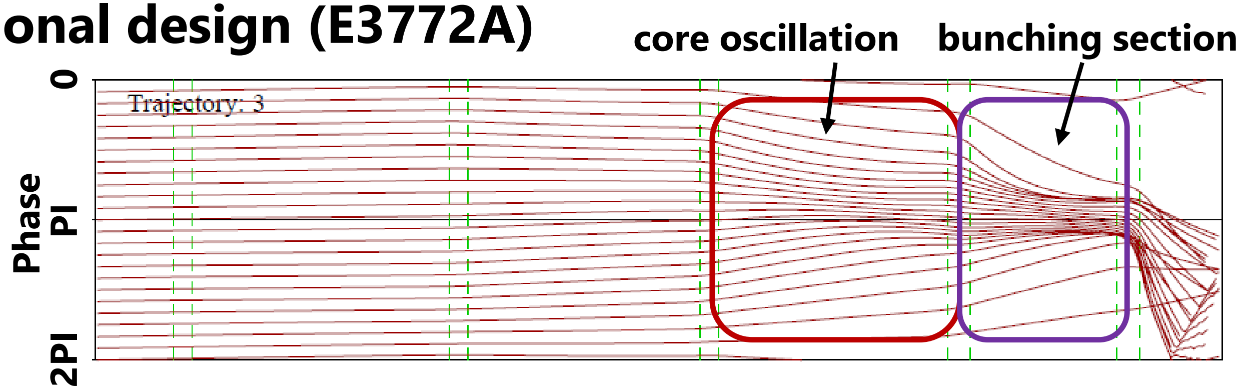
Parameter	E3772A design	High efficiency design	
		Target	Result
Output power [MW]	7.5	>7.5	8.9
Frequency [MHz]	2856	2856	2856
Beam voltage [kV]	155	145	145
Perveance [$\mu A/V^{3/2}$]	1.8	1.8	1.8
Drive power [W]	80	<160	130
Efficiency [%]	45	60	62

The number of electrons in the accelerating phase was decreased.

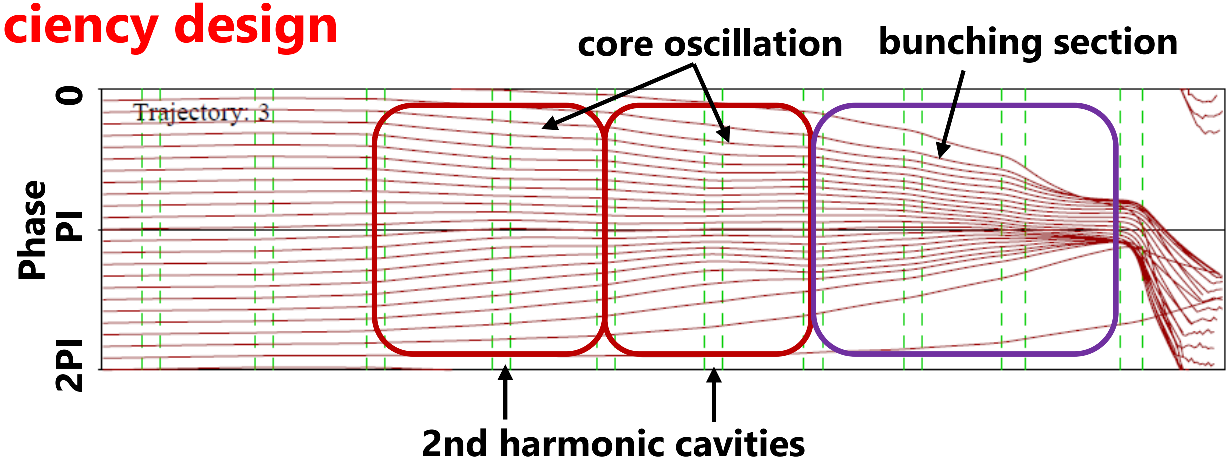
4. Development of High Efficiency S-band Klystron

FCI Simulation

Conventional design (E3772A)



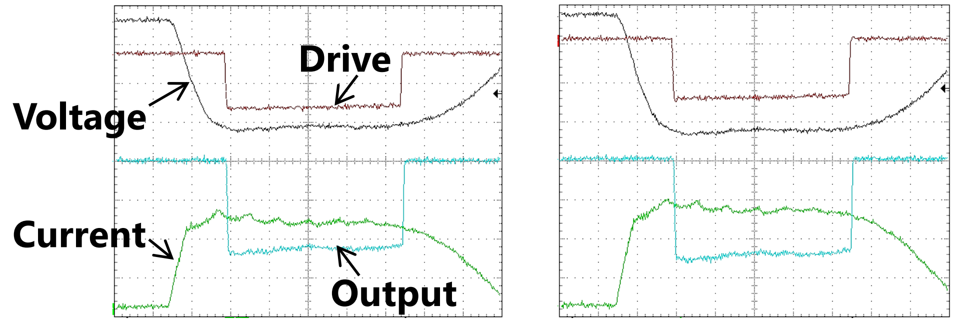
High efficiency design



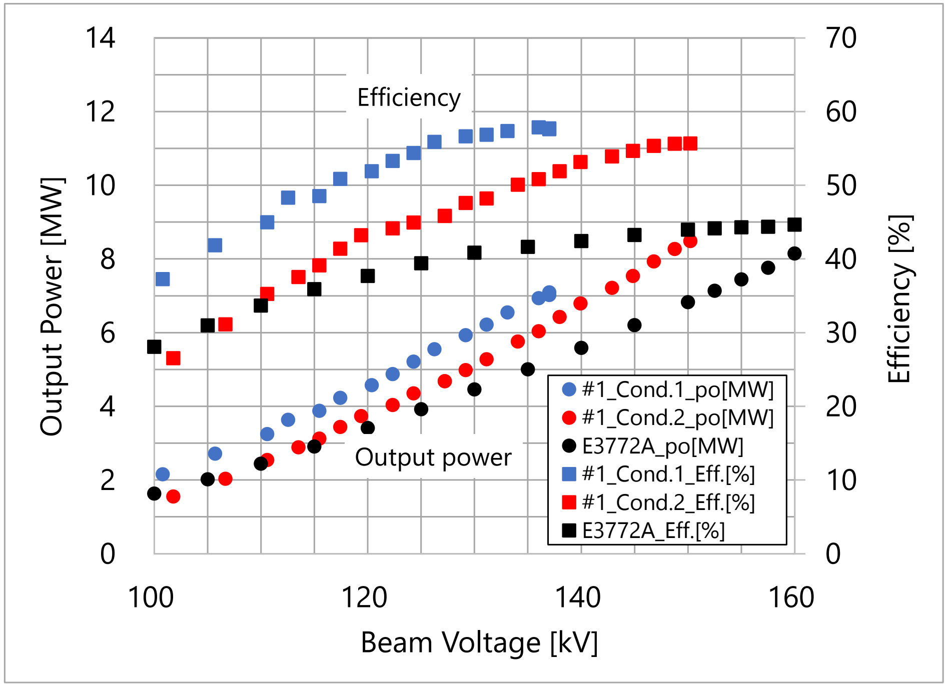
Electrons were smoothly bunched by core-oscillation sections in the high efficiency design.

Test Result

Cond.1 (6.2MW, 56.9%) **Cond.2 (7.5MW, 54.7%)**

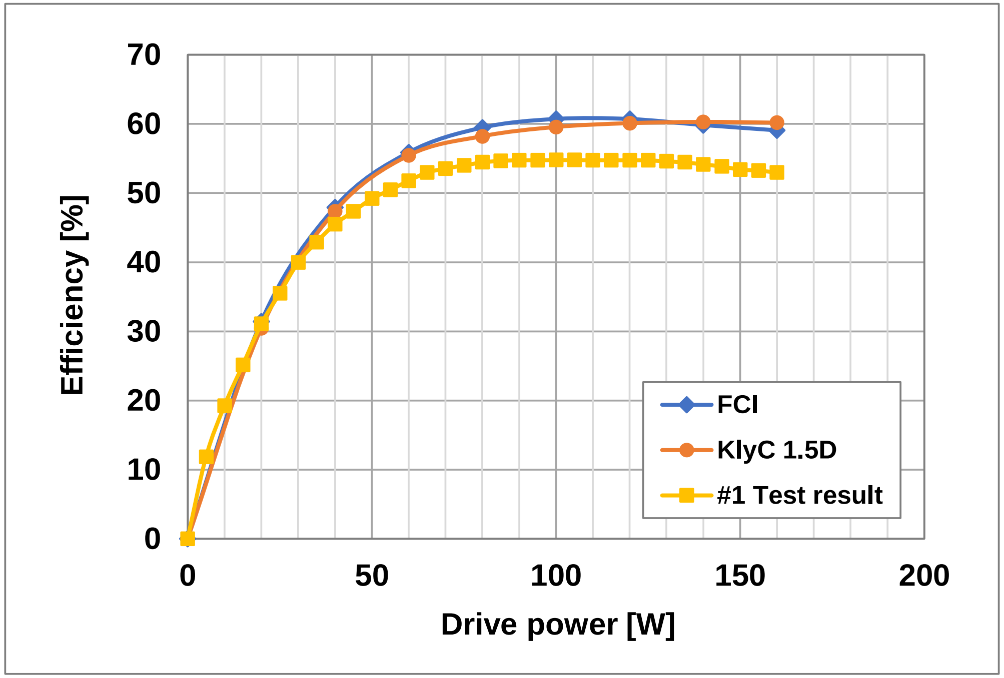


Parameter	Cond.1	Cond.2
Operating frequency [MHz]	2856	2856
Beam voltage [kV]	131.1	144.8
Beam current [A]	83.4	95.2
Output power [MW]	6.2	7.5
RF pulse width [μs]	4.5	4.5
Pulse repetition rate [pps]	100	100
Drive power [W]	60	90
Power efficiency [%]	56.9	54.7
Power gain [dB]	50.5	49.0
Micro perveance [$\mu A/V^{3/2}$]	1.76	1.73
Solenoid power [kW]	2.6	6.5



4. Development of High Efficiency S-band Klystron

Comparison of FCI and KlyC



KlyC was developed by J.C. Cai and I. Syratchev (CERN).

Simulation result

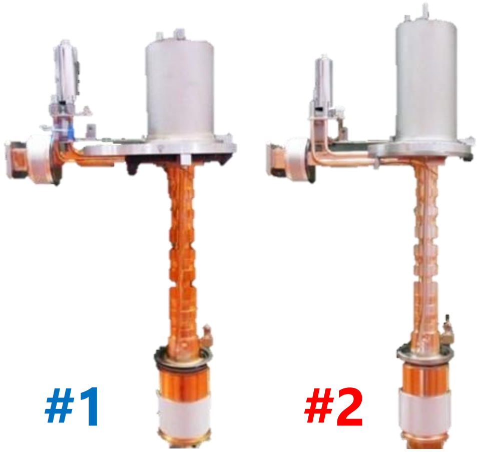
Parameter	FCI	KlyC
Output power [MW]	8.4	8.3
Drive power [W]	100	140
Efficiency [%]	60.7	60.3
Beam voltage [kV]	144.8	
Beam current [A]	95.2	

KlyC config.
Layer Number: 10
Space Charge Field Order: 10
Division Number in RF: 128
Iteration Residual Limit: 0.0001
Iteration Relaxation: 0.3

FCI config.
Number of mesh: 15 x 300
Focusing coil current: #1 tube, cond.2

4. Development of High Efficiency S-band Klystron

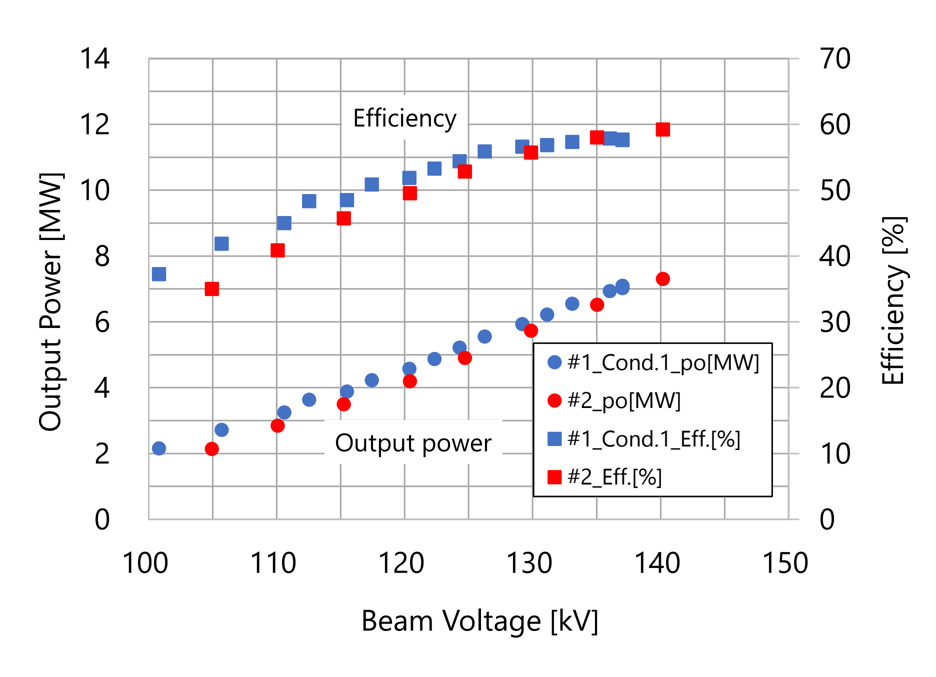
Test Result



#2: Collector length and cavity frequencies were modified from #1.

- **59.2% efficiency at 7.3 MW output power was achieved.**
- **Further adjustment of solenoid coil current will increase efficiency.**

Parameter	#1	#2
Operating frequency [MHz]	2856	2856
Beam voltage [kV]	131.1	140.2
Beam current [A]	83.4	88.0
Output power [MW]	6.2	7.3
RF pulse width [μs]	4.5	4.0
Pulse repetition rate [pps]	100	100
Drive power [W]	60	72
Power efficiency [%]	56.9	59.2
Power gain [dB]	50.5	49.0
Micro perveance [μA/V$^{3/2}$]	1.76	1.68
Solenoid power [kW]	2.6	2.6



5. Consideration

<u>Efficiency estimation of other tubes (simulation)</u>

L-band 10MW MBK

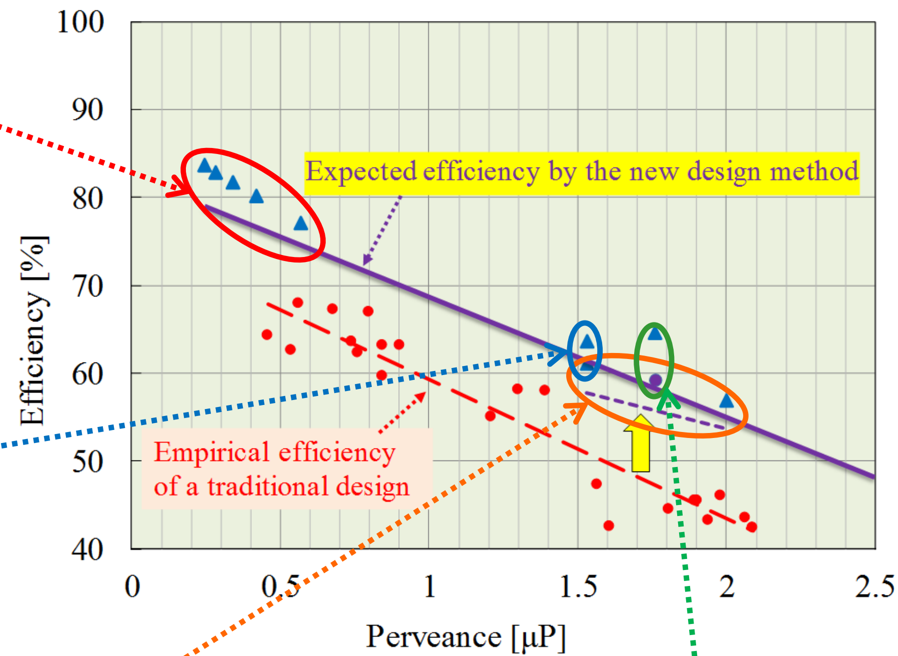
- 6-beam design
  67% → 71%
- 10-beam and extended body length
  67% → 75%

C-band 50MW

- Extended body length
  45% → 60%

S-band 50MW

- Same body length
- 2nd harmonic cavities
  45% → 58%



S-band 7 MW

- Same body length
- 2nd Harmonic cavities
  45% → 60%   (Test: 59.2%)

6. Summary

- Power efficiency of high-perveance klystron was increased by 14% and efficiency of 59.2% was achieved by new bunching design.
- Instabilities were found when beam voltage was increased. Adjustment of solenoid current suppressed instabilities.
- Application of new design to scientific and industrial klystrons to reduce power consumptions or increase output power are expected.

CETD started the collaboration with CERN in the high-efficiency X-band klystron development.

CANON ELECTRON TUBES & DEVICES CO., LTD.