第41回 高エネルギー加速器セミナー
OHO'24
新奇・革新的な加速技術

KEK

Introduction to High-Efficiency Klystrons

OHO2024 (2023/9/10~11)

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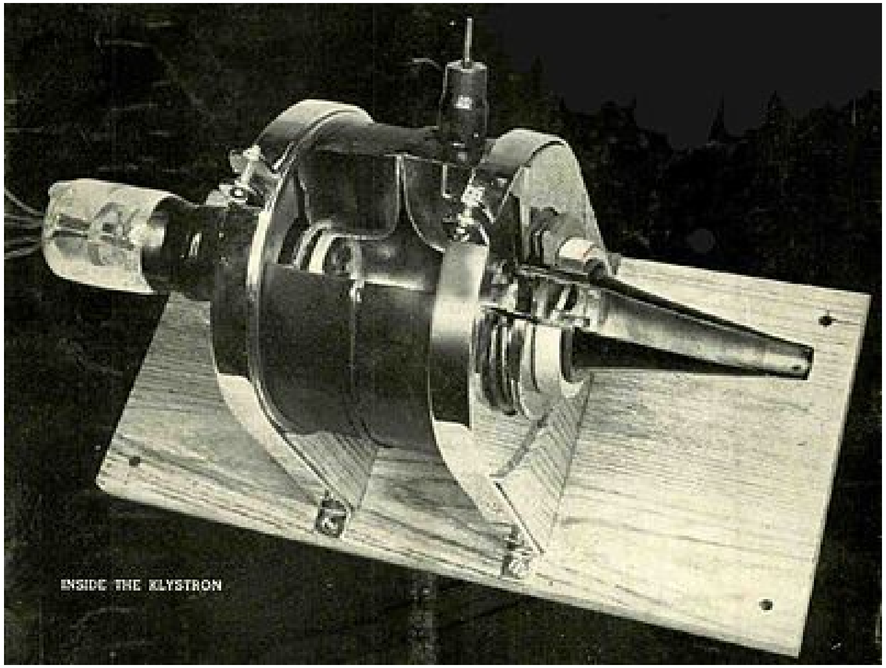
What is a Klystron?

- Klystron, initially developed in the 1930s is an amplifier of microwave power.

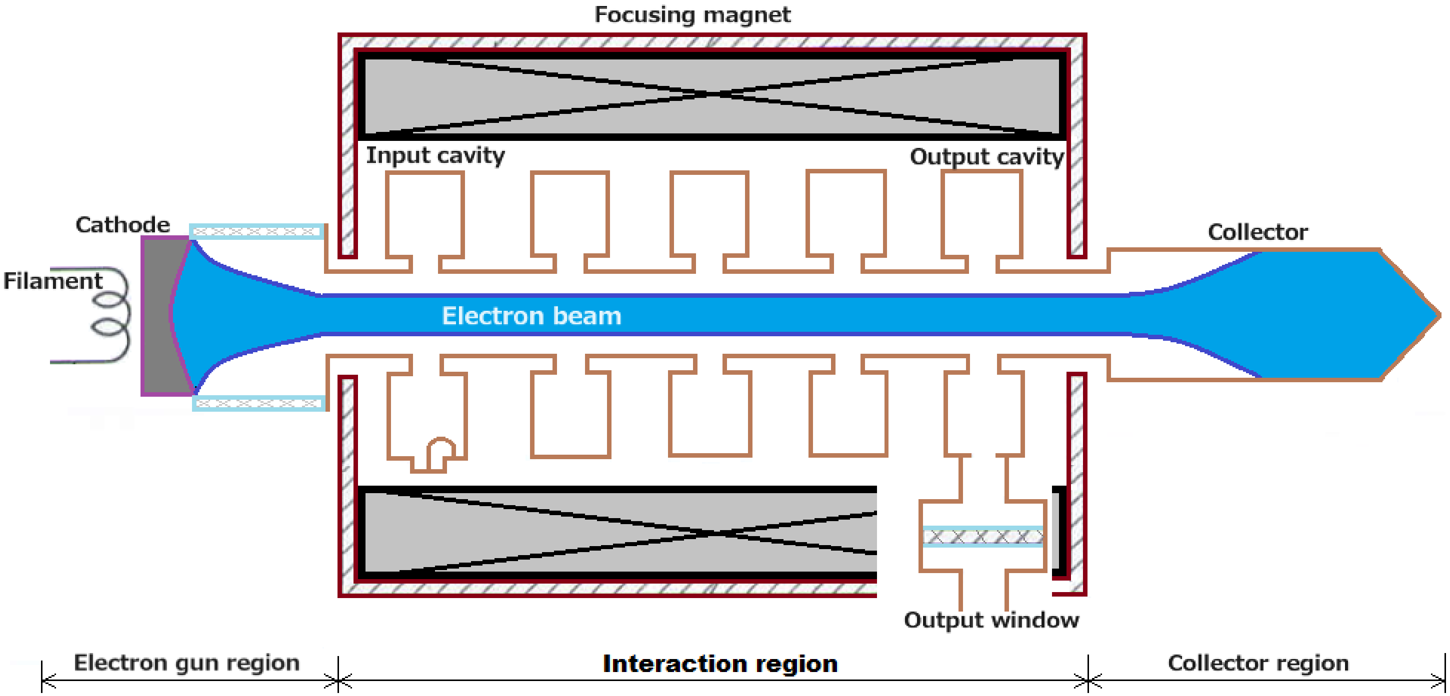


The first commercial klystron in 1940s

*[Ref.*https://en.wikipedia.org/wiki/Klystron]*

- The leftmost part is an electron gun.
- The rightmost tapered part is a beam collector.
- The middle section is the interaction region, which includes two cavities and a drift tube.
- The output RF power is 200 W at a frequency of 750 MHz, and an efficiency of 50%.

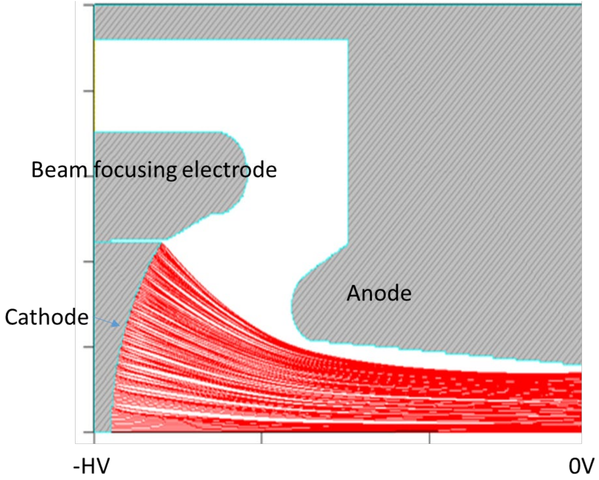
What is a Klystron?



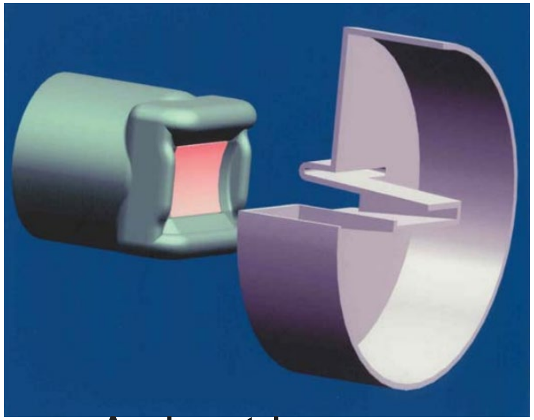
- A klystron is composed of an electron gun region, an interaction region, and a collector region.
- The electron gun primarily includes the cathode, filament, insulating ceramic, and other components. /
- The interaction region is composed of a RF circuit, and a beam focusing magnet.
    - The RF circuit is a cavities-chain, including an input cavity, intermediate cavities, an output cavity and output window.
    - The focusing magnet is to prevent beam from spreading.
- The collector region is to stop the beam with a cooling collector.

What is a Klystron?

- The electron gun of a klystron/



- .The electrons gain energy and form an electron beam with a specific energy level.
  - ○ **Beam voltage, V_0**
  - ○ **Beam current, I_0**

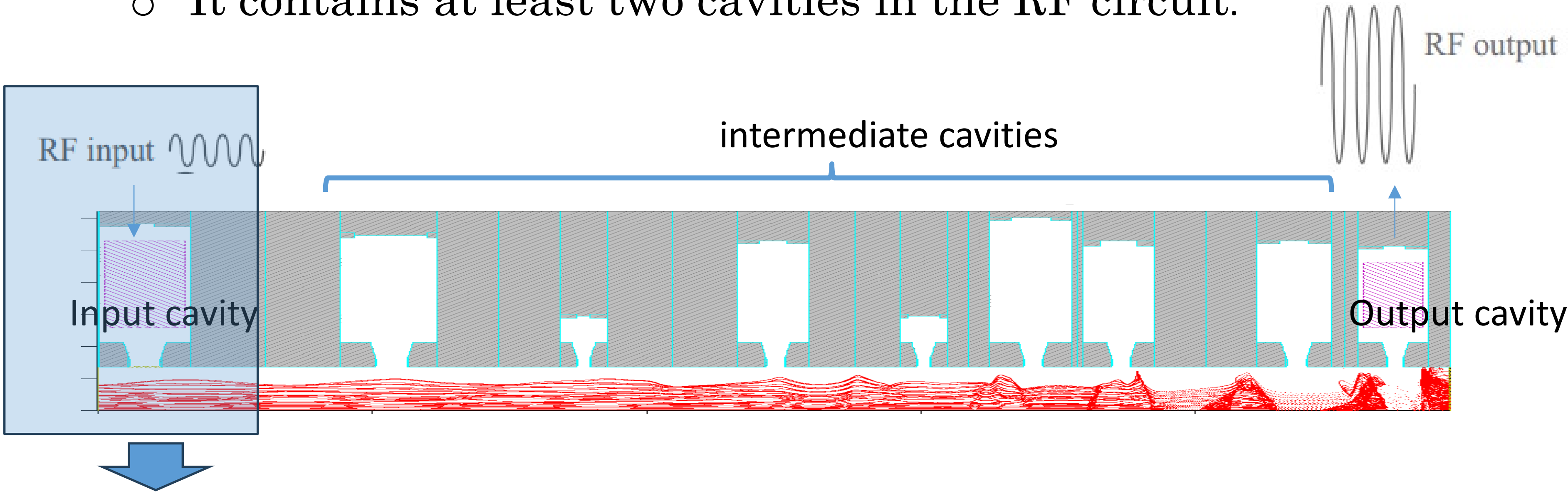


A sheet beam gun

*[Ref.*SLAC-PUB 10620]*

What is a Klystron?

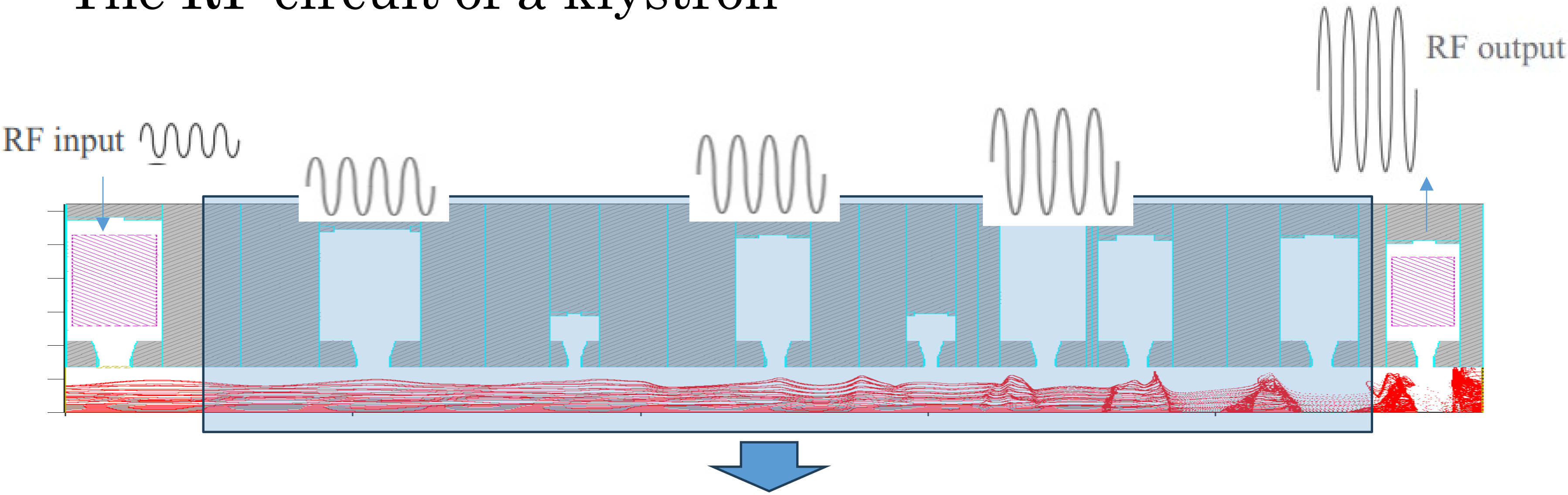
- The RF circuit of a klystron
  - It contains at least two cavities in the RF circuit.



- The beam passes through the **input cavity.**
- Some electrons to accelerate and others to decelerate depending on the phase of the voltage.
- This process is known as **velocity modulation.**

What is a Klystron?

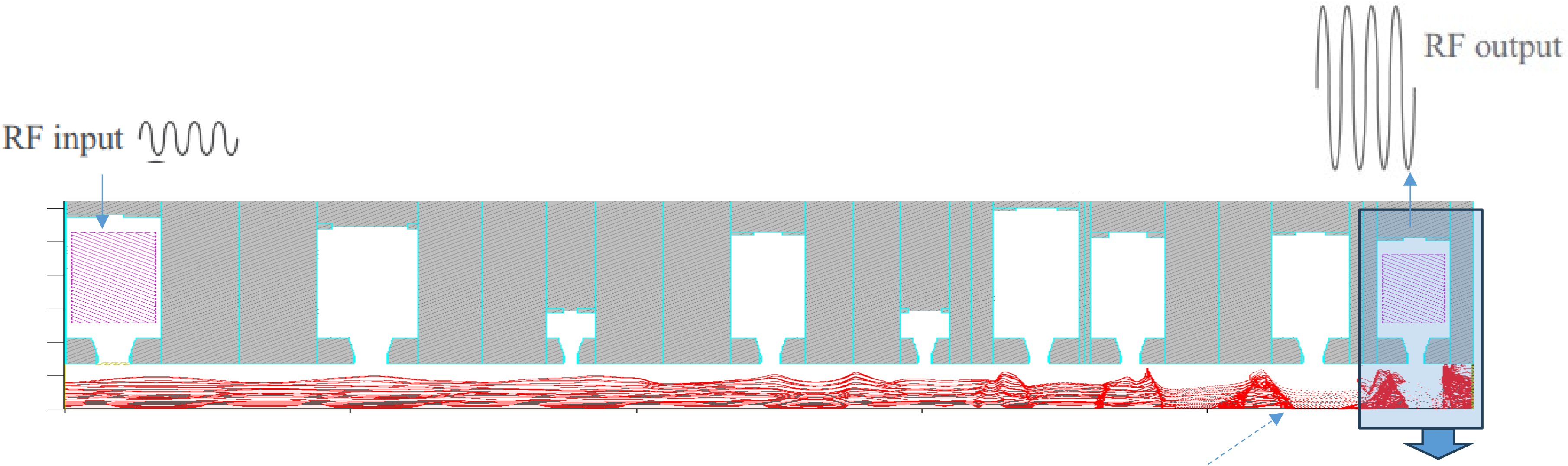
- The RF circuit of a klystron



- The velocity modulation causes **density modulation** through the drift tunnel, forming electron bunches.
- These bunches induce RF in successive cavities, producing gap voltages.
- The velocity modulation is then reinforced, and density modulation is strengthened, to form a well-bunched beam.

What is a Klystron?

- The RF circuit of a klystron



.In simple terms, **a high-efficiency klystron** transfers **more power in the interaction region** rather than **losing it in the collector region.**

- The well-bunched beam induces a great RF power at the output cavity and decelerates. /

What is a Klystron?

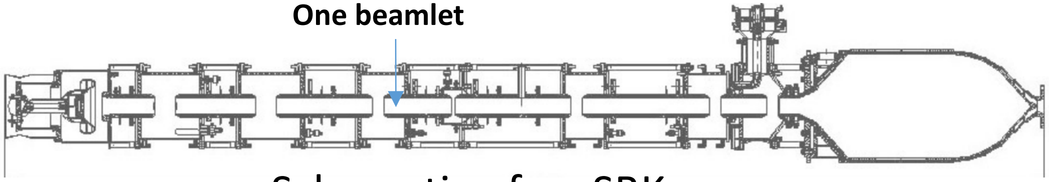
- Depend on the number of electron beams contained in the klystron, it can be classified to a **single-beam klystron(SBK)** and **multi-beam klystron(MBK).**

One cathode for SBK

*[Ref.*A. Rehman, arXiv: Accelerator Physics,2015]*

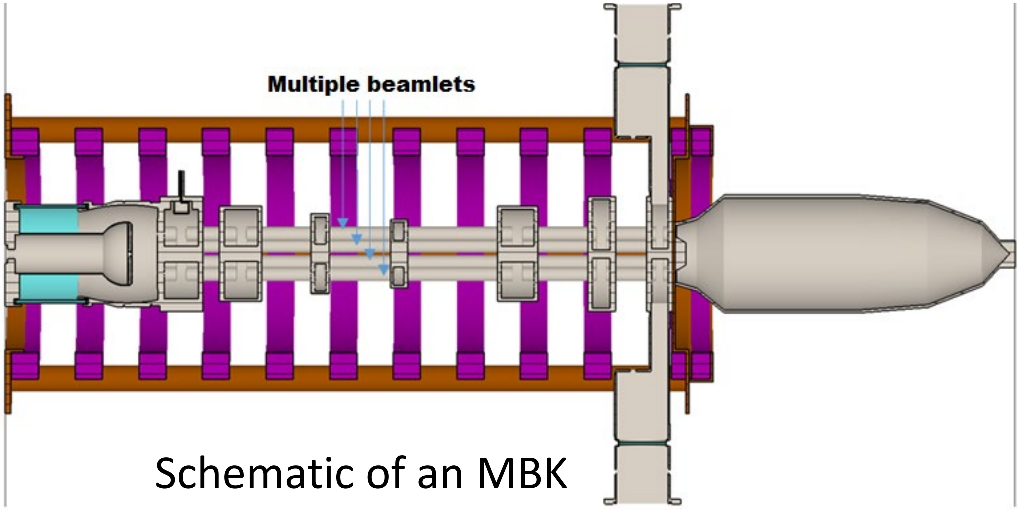
Multiple cathodes for MBK

*[Ref.*https://etd.canon/en/tech/klystron.html]*



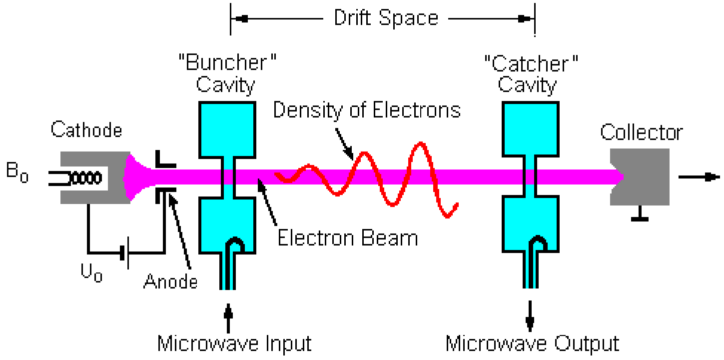
Schematic of an SBK

*[Ref.*SLAC-PUB 10620]*



Schematic of an MBK

What is a Klystron?



*[Ref.*https://en.wikipedia.org/wiki/Klystron]*

- .Some important parameter of a klystron
  - Gain(Power Gain)

$$G = 10\,log_{10}\frac{P_{out}}{P_{in}}$$

    - P_{in} is the drive RF power to input cavity.
    - P_{out} is the output RF power of the klystron

❑ For example, power gain of a S-band pulsed high power klystron could be higher than 50 dB,(500 W → 50 MW)

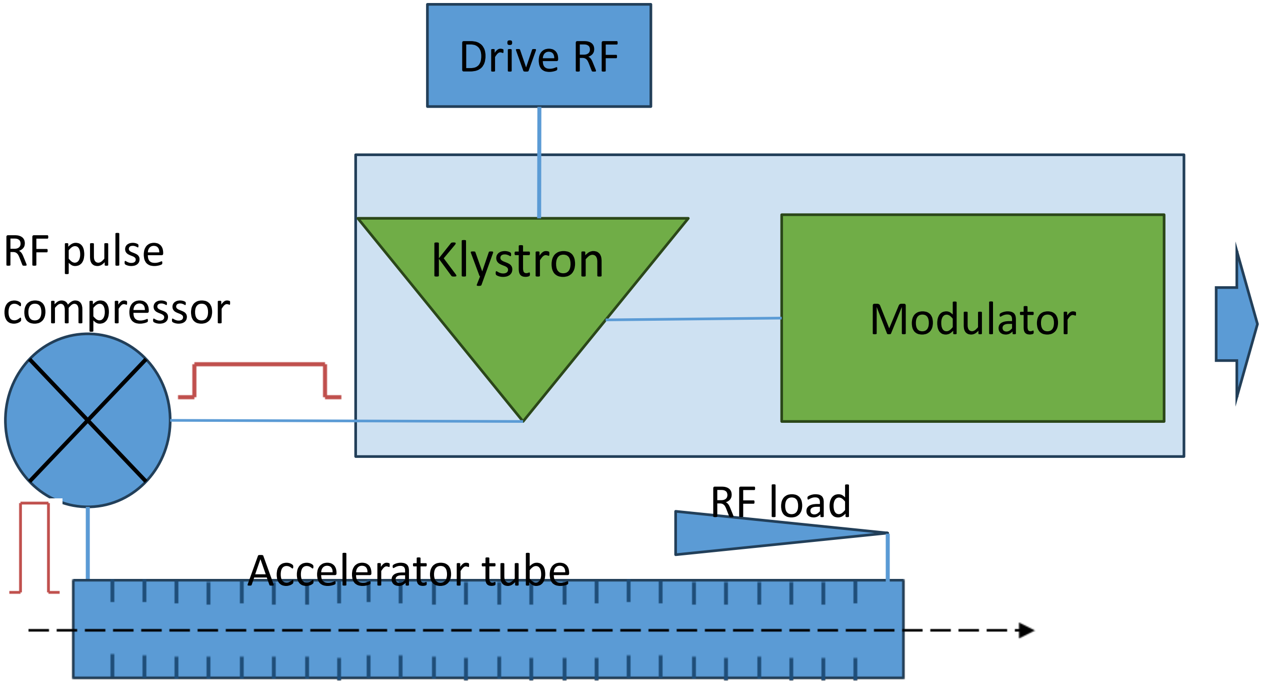
  - Efficiency

$$\eta = \frac{P_{out}}{P_0}$$

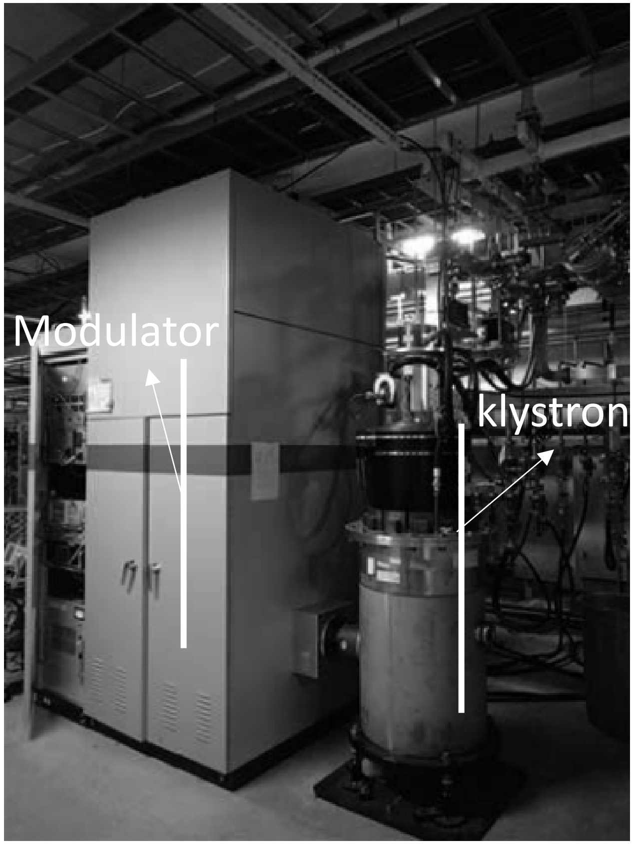
    - P_0 is the beam power (V_0* I_0).

RF Power of a Klystron

- Klystrons are widely adopted by particle accelerators as RF power sources./



Schematic blocks of an RF system in a linac accelerator



*[Ref. *S. Matsumoto, OHO 2017]*

RF Power of a Klystron

- Driven by decades of evolving requirements from particle accelerators, klystrons for scientific use have seen significant advancements in both pulsed output power and average output power.

Vendor	**CANON**	**SLAC**	**SLAC**	**CANON**
Peak power (MW)	**50**	**65**	**150**	**1.2**
Average power (MW)	**0.01**	**0.041**	**0.027**	**1.2**
Frequency (GHz)	2.856	2.856	2.998	0.509
Operation mode	Pulsed	Pulsed	Pulsed	CW
Type	E3730A	5045		E3786

E3730A

*[Ref.*https://etd.canon/en/product/category/microwave/klystron.html]*

RF Power Consumption by Large-Scale Accelerators

- The KEK e^-/e^+ Injector Linac operates with 60 pulsed 50 MW S-band klystrons:
    - The efficiency of those 50 MW klystrons is 45%.
    - The power consumed solely by these klystrons is 1.23 MW.
- If the klystron efficiency could be improved from 45% to 65%, a total power of 0.38 MW would be saved. Over an entire year of operation, this would result in an energy savings of 2,270 MWh.

*[Ref. *https://www-linac.kek.jp/]*

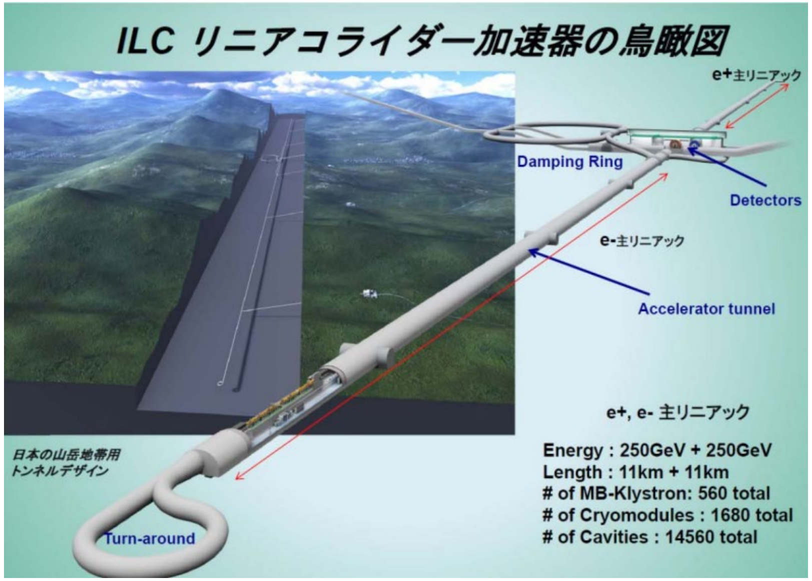
RF Power Consumption by Large-Scale Accelerators

- 32 CW 1.2 MW UHF-band klystrons for the rings of SuperKEKB.
- The state-of-the-art efficiency of these UHF-band klystrons is 65%, resulting in a total power consumption of 20 MW.
- If the efficiency could be improved from 65% to 80%, power of 3.7 MW would be saved --- covering the total power consumption of the KEK e^{-}/e^{+} Injector Linac.

*[Ref.*https://www2.kek.jp/accl/legacy/eng/accl map_superkekb.html]*

RF Power Consumption by Large-Scale Accelerators

- International Linear Collider (ILC)
  - L-band MBK
  - A total of 35 MW of RF power for accelerating electrons and positrons to super-high energies.
  - State of art efficiency of the MBK is 65%.
  - The Klystrons waste the power of 19 MW.



*[Ref. *S. Fukuda, ILC School-High Efficiency RF Source]*

RF Power Consumption by Large-Scale Accelerators

- The efficiency of klystrons has become a worldwide topic
- RF power consumption is a common challenge for future large-scale accelerators, such as the FCC, CLIC, and CEPC. /

Project name	RF power consumption
KEK e^-/e^+ Injector Linac	1.23 MW
Rings of SuperKEKB	20 MW
ILC	54 MW
FCC	160 MW
CLIC	118 MW
CEPC	174 MW

*[Ref. *google searched picture]*

A small thermal power plant generates 50~300 MW of electric power

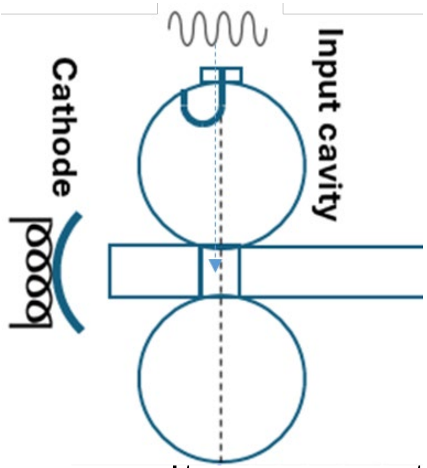
- Any question?

*[Ref.*A. Jensen, et al, 25 Year Performance Review of the SLAC 5045 S-Band Klystron, 2011]*

Key Concepts for High-Efficiency Klystrons

- The principle of the electron bunching process in a klystron is based on the **modulation of electron velocity (velocity modulation)**.
- A **two cavity** and **one-dimensional** model is employed for analysis of the velocity modulation.
- .The space charge is not considered.

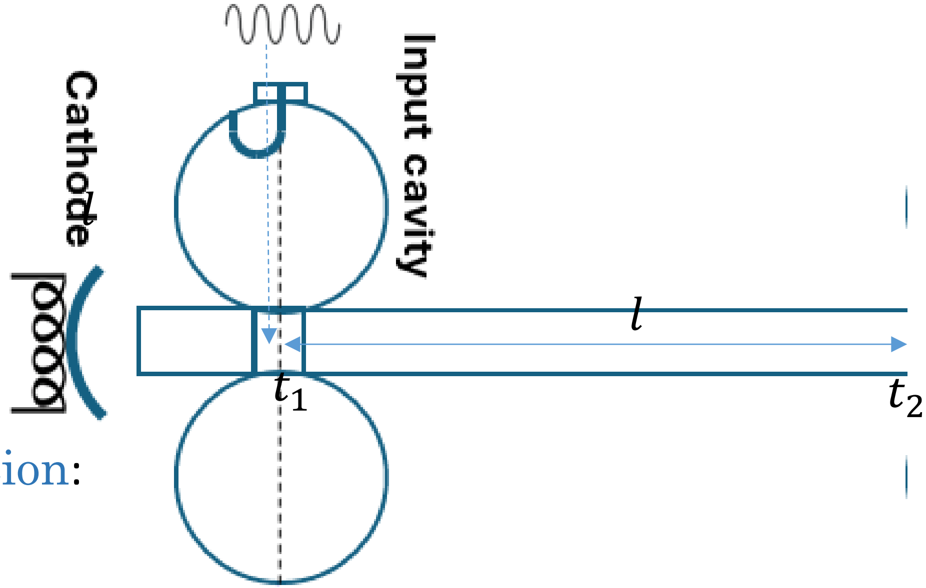
$$V_1 = \hat{V}_1 \sin \omega t$$



- V_1 represents the time-varying voltage across the cavity gap.
- $\hat{V}_1$ is the magnitude of the modulation voltage.
- t is the time.
- ω is the angular frequency of sine wave voltage applied to the modulation gap.

Key Concepts for High-Efficiency Klystrons

- The electron enters the modulation gap at t_1 and drifts a length l downstream of the modulation gap by time t_2.



- Basic equation of velocity modulation:

$$\omega t_2 = \omega t_1 + \theta_0 - X \sin \omega t_1$$

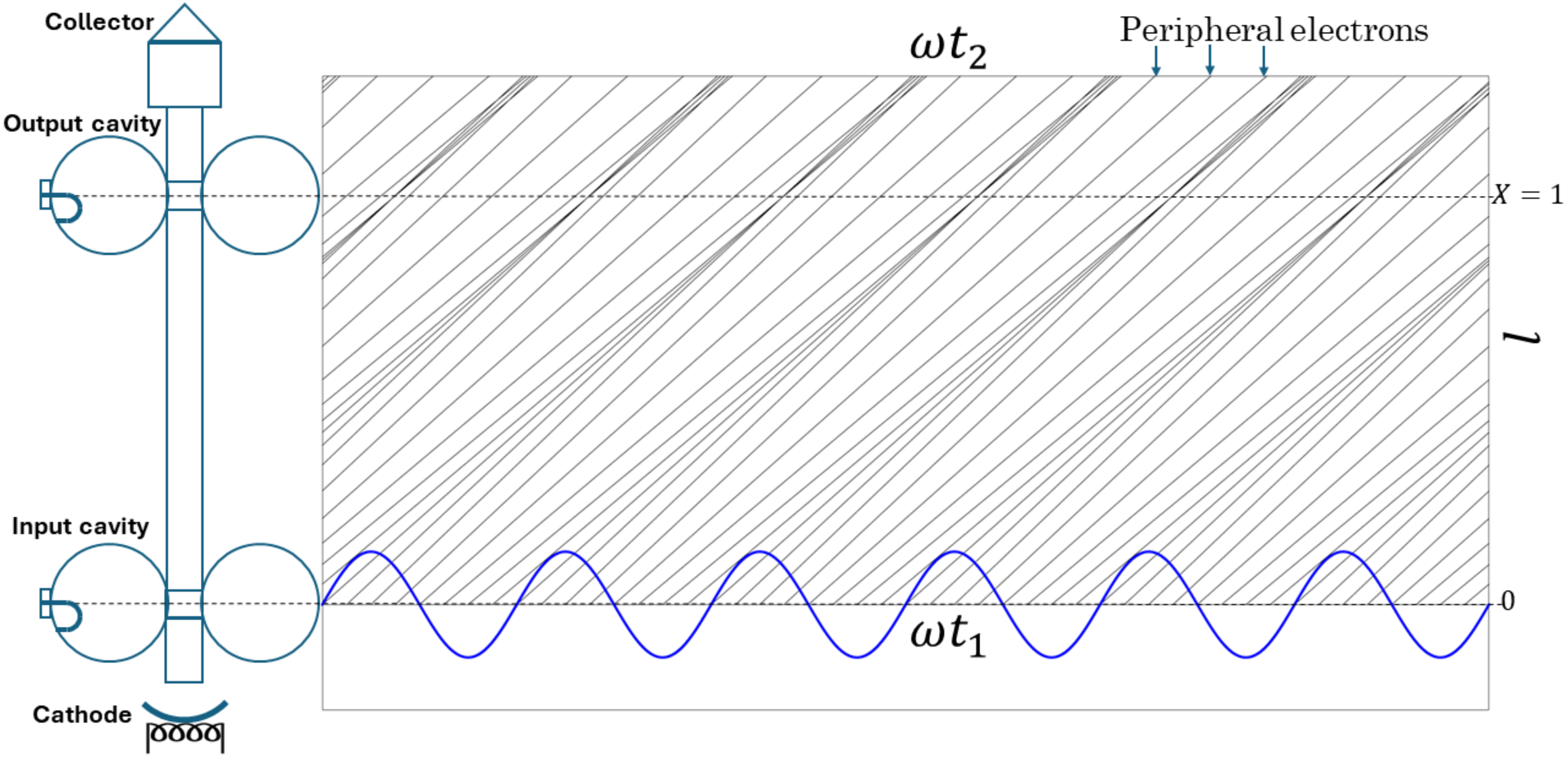
$$\begin{cases} \theta_0 = \dfrac{\omega l}{v_0} \\ X = \dfrac{1}{2} \alpha \theta_0 \\ \alpha = \dfrac{\hat{V}_1}{V_0} \end{cases}$$

- θ_0 is called the DC transit angle of the electron reaching the distance of l.
- X is called the bunching parameter.
- α is a depth of modulation. (α<<1)

Key Concepts for High-Efficiency Klystrons

From equation $\omega t_2 = \omega t_1 + \theta_0 - X \sin \omega t_1$ we can draw the Applegate diagram/

(The code for generating the diagram can be found in the OHO lecture)



- .The Applegate diagram illustrates that electrons with a DC beam velocity enter the modulation gap of the input cavity, resulting in the electrons arriving at the output cavity in bunches. /

Key Concepts for High-Efficiency Klystrons

$$\omega t_2 = \omega t_1 + \theta_0 - X \sin \omega t_1$$

Solution

$$\omega t_1 = (\omega t_2 - \theta_0) + \sum_{n=1}^{\infty} \frac{2}{n} J_n(nX) \sin n(\omega t_2 - \theta_0)$$

$I_2 = I_0 \frac{dt_1}{dt_2}$

$$I_2 = I_0(1 + \sum_{n=1}^{\infty} 2J_n(nX) \cos n(\omega t_2 - \theta_0)$$

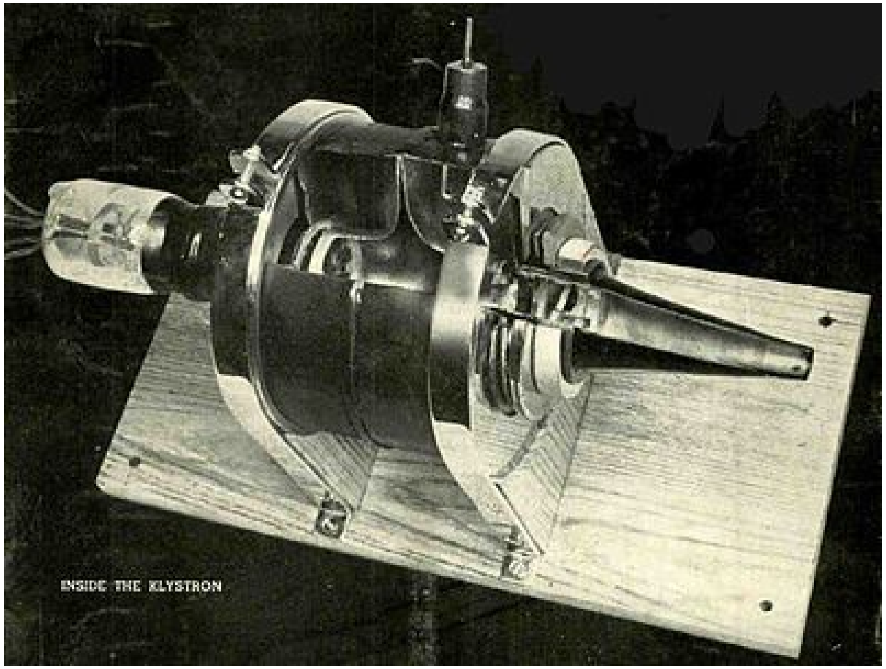
- J_n is the Bessel function of the nth order.
- I_0 is the DC beam current.
- I_2 is current components in the beam downstream the modulation gap

- Once $X = 1.84$, J_1 reaches its maximum value of $J_1(1.84) = 0.58$.
- Maximum value of the fundamental component of the current will be $i_{1,MAX} = 1.16 I_0$

The theoretical maximum electron efficiency of a two-cavity klystron is

$$\boxed{\eta = \frac{P_{out}}{P_0} == \frac{1}{2} \frac{i_{1MAX}}{I_0} = 58\%}$$

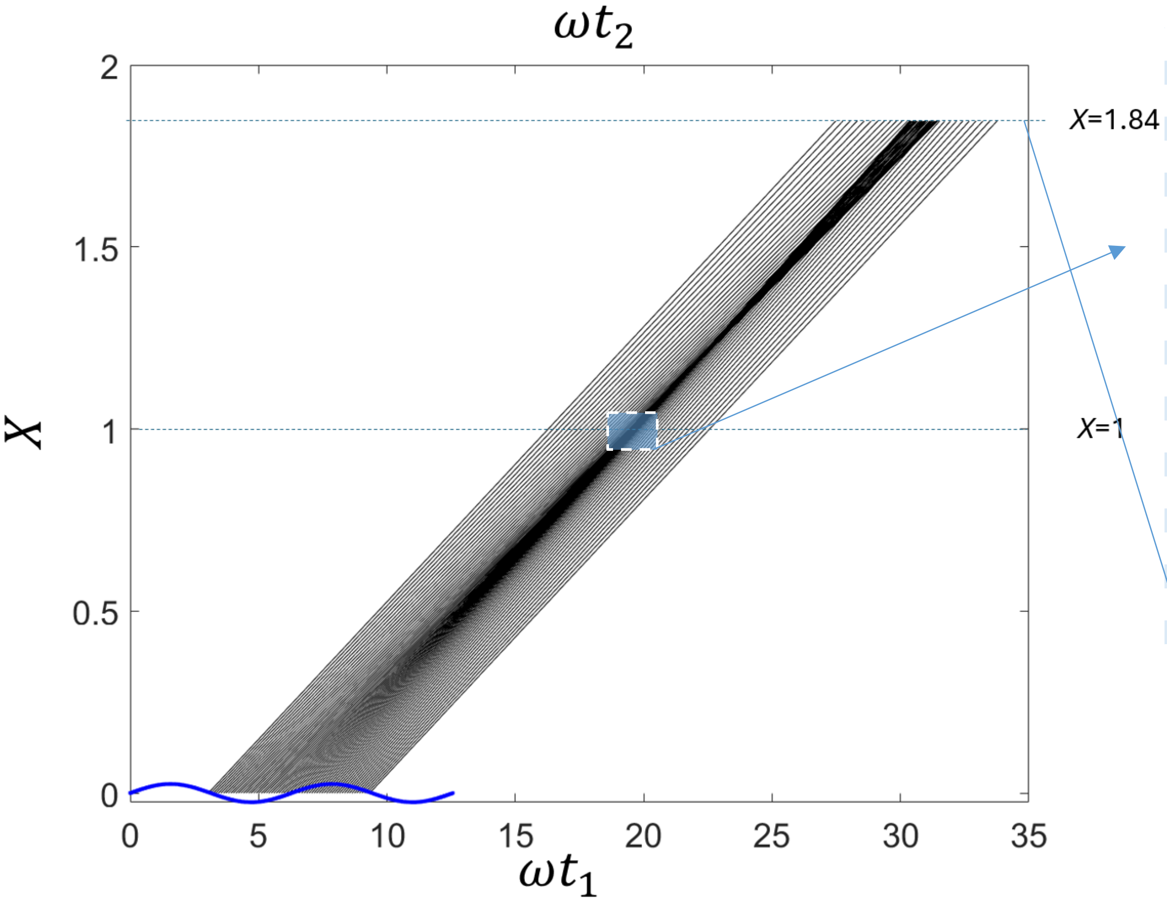
- Output RF power is 200 W
- Frequency is 750 MHz
- **Efficiency is 50%**



The first commercial klystron in 1940

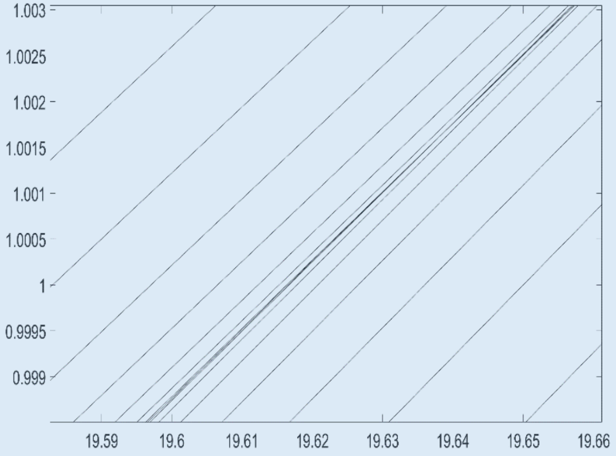
*[Ref.*https://en.wikipedia.org/wiki/Klystron]*

Key Concepts for High-Efficiency Klystrons



Applegate diagram of $\omega t_2 = \omega t_1 + \theta_0 - X \sin \omega t_1$

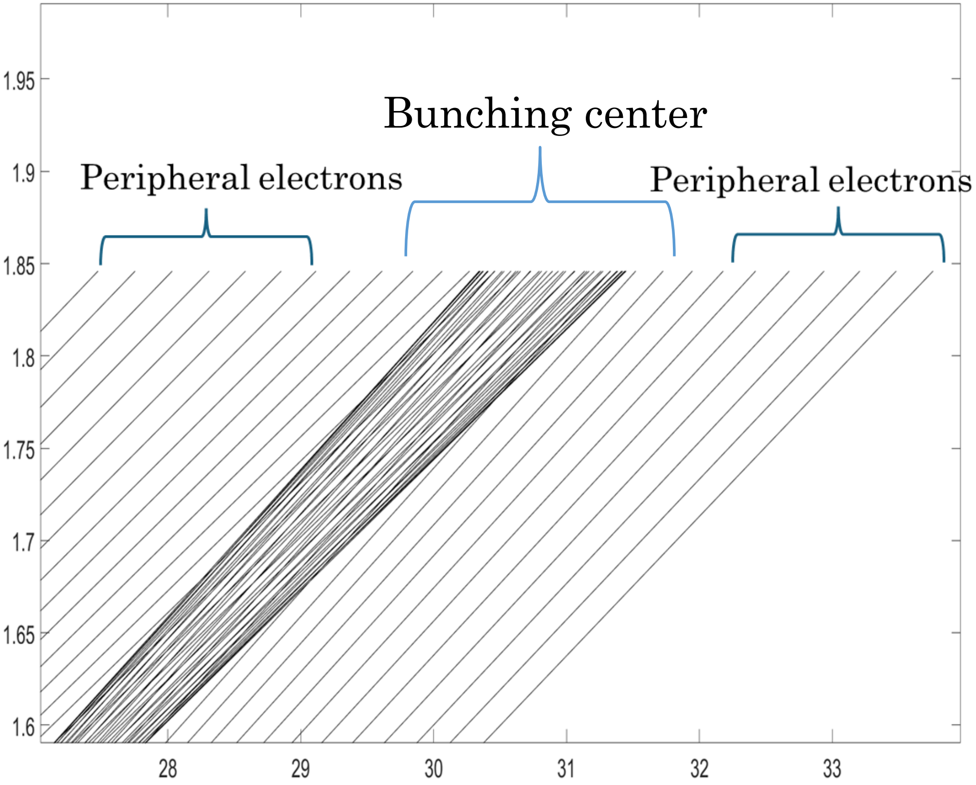
- .Electrons begin to “overtake" each other, at $X = 1$.



- The output cavity should be placed at $X = 1.84$ to achieve maximum efficiency (58%).
- Why not a higher efficiency?/

Key Concepts for High-Efficiency Klystrons

- -Why not have a higher efficiency of 58% for the two cavities analysis?/



- .Peripheral electrons or “outsiders” can not enter the gap of output cavity at a right decelerating phase
- They are accelerated in the output cavity, limiting the overall electron efficiency

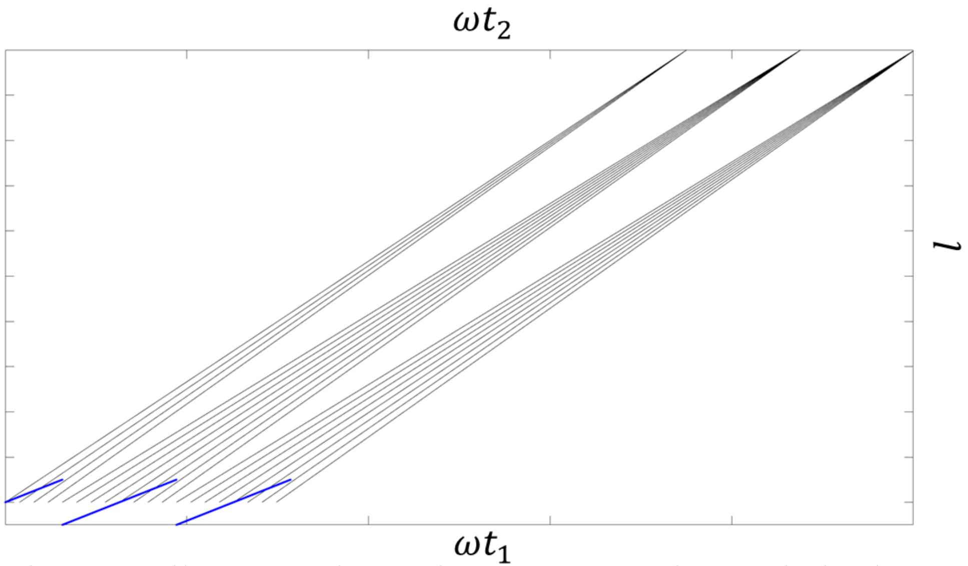
Key concept for a high-efficiency klystron:

To improve the efficiency of a klystron, the peripheral electrons should be collected into the bunching center as much as possible.//

Key Concepts for High-Efficiency Klystrons

- For a higher efficiency, image the ideal bunching scenario for the two-cavity klystron:
  - All the electrons enter output cavity gap at one phase with the maximum negative voltage.
- To achieve this, We have to change the modulating signal from a sine function to a sawtooth function.

$$V_1 = \hat{V}_1 \sin \omega t \quad \Rightarrow \quad V_1(t_1) = V_0 \frac{2\omega t_1}{\theta_0} \qquad t_1 \in \left[\frac{-\pi + 2n\pi}{\omega}, \frac{\pi + 2n\pi}{\omega}\right], n = 0,1,2 \ldots$$



Applegate diagram based on sawtooth modulation

- No peripheral electrons.
- All the electrons arrive at the output cavity at the same phase,
- All the beam power is transferred to the RF, efficiency ~ 100%

Key Concepts for High-Efficiency Klystrons

- The sawtooth voltage is difficult to realize in an RF cavity.

- Sawtooth function can be represented as a Fourier series.

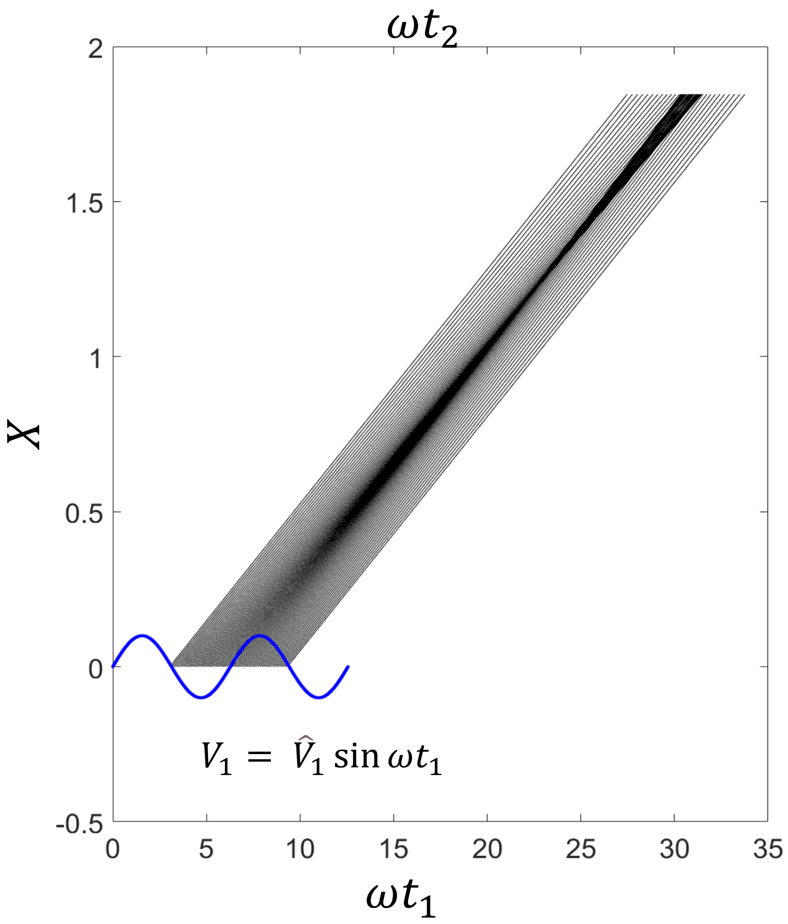
$$V_1(t_1) = V_0 \frac{2\omega t_1}{\theta_0} \xrightarrow{\text{Fourier}} V_1(t_1) = -\frac{4V_0}{\theta_0}\sum_{n=1}^{\infty}\frac{(-1)^n}{n}\sin n\omega t_1$$

$$\Big\downarrow \ \mathit{Only\ considering}\ n = 1,2,3$$

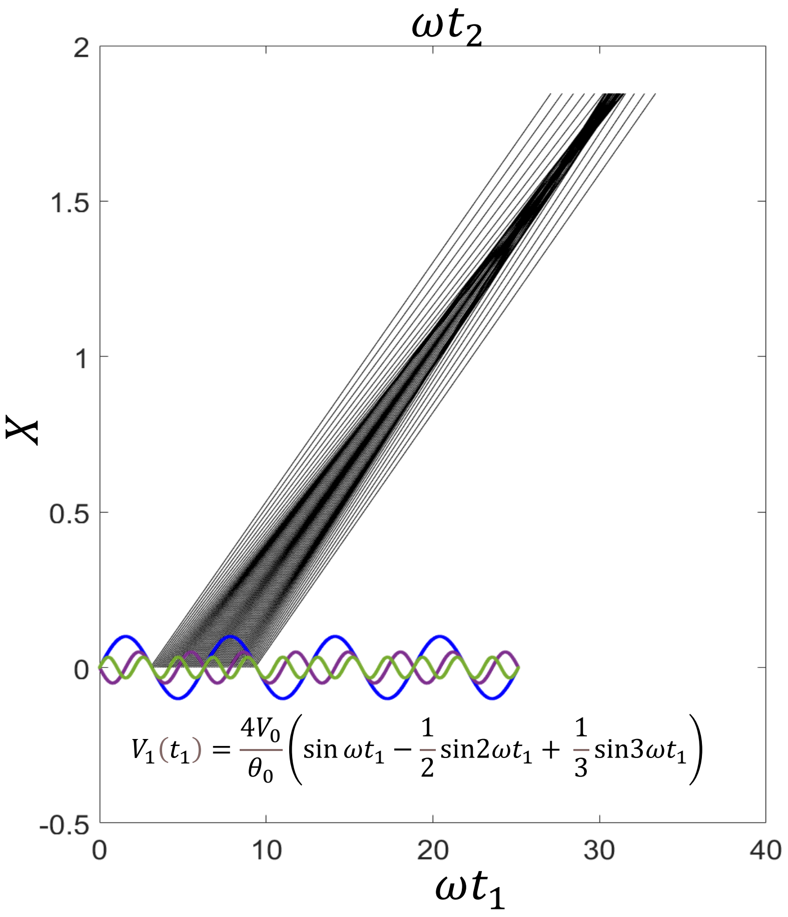
$$V_1(t_1) = \frac{4V_0}{\theta_0}\left(\sin \omega t_1 - \frac{1}{2}\sin 2\omega t_1 + \frac{1}{3}\sin 3\omega t_1\right)$$

- We get a new modulating function composed by a fundamental sine function, and its 2nd and 3rd harmonics.
- Expecting to get a higher efficiency with the new modulating function.

Key Concepts for High-Efficiency Klystrons



$$V_1 = \hat{V}_1 \sin \omega t_1$$



$$V_1(t_1) = \frac{4V_0}{\theta_0}\left(\sin \omega t_1 - \frac{1}{2}\sin 2\omega t_1 + \frac{1}{3}\sin 3\omega t_1\right)$$

From the comparison:

- The peripheral electrons are effectively collected into the bunching center
- A high efficiency, by applying a combination of the fundamental, 2nd, and 3rd harmonics.

Key Concepts for High-Efficiency Klystrons

So far, the two-cavity kinematic theory has not included space charge, limiting its applicability for designing a (high power) two-cavity klystron. However, some concepts derived from the above discussion are still beneficial for designing a high-efficiency klystron:

1) **To achieve a high-efficiency klystron, peripheral electrons should be collected into the bunching center as much as possible./**
2) **.Bunching with harmonics improves efficiency by helping to collect peripheral electrons.**

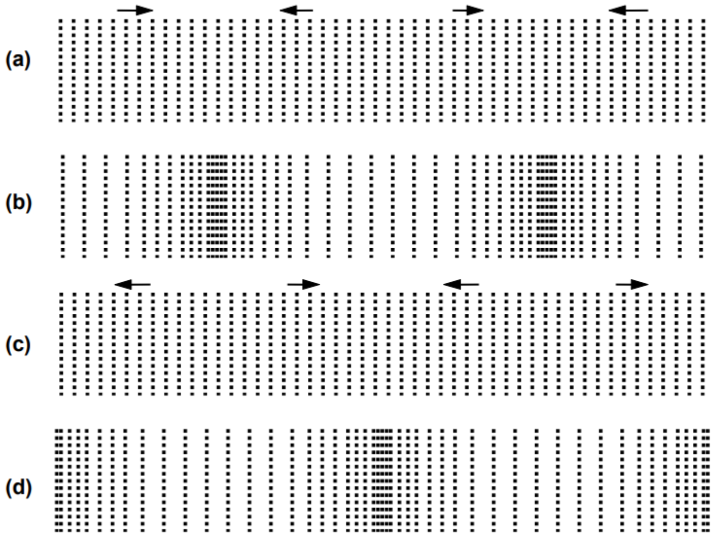
Space Charge in Klystrons

- The two-cavity ballistic theory dose not consider the space charge, but the bunching is strongly affected by space charge.
- The space charge wave theory introduced the **plasma frequency** ω_p

$$\omega_p = \sqrt{\frac{e\rho_0}{m\varepsilon_0}}$$

- ρ_0 is the uniform electron density in a free space
- ε_0 is the vacuum permittivity
- m and e are the mass and electric charge of an electron

- The longitudinally modulated electron beam can be viewed as an oscillating plasma in a free space, with a plasma frequency ω_p



(a–d) Electron distributions during plasma oscillations.

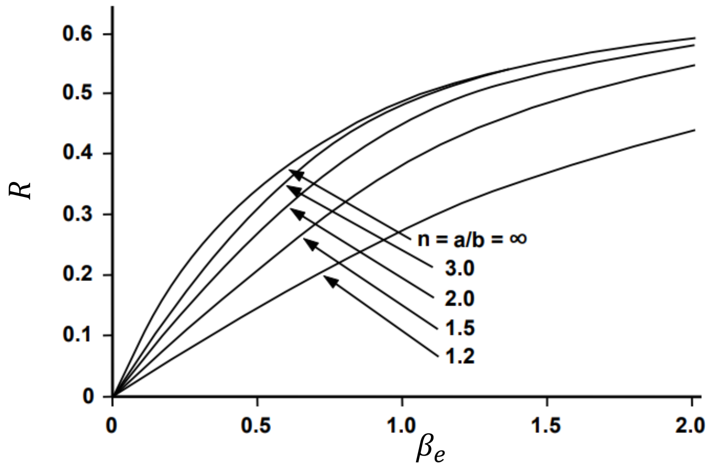
*[Ref. *A.S. Gilmore, "Klystrons, Traveling Wave Tubes, Magnetrons, Cross-Field Amplifiers, and Gyrotrons"]*

Space Charge in Klystrons

- Considering plasma in a conductive tunnel, the plasma frequency ω_p is modified to the reduced plasma frequency ω_q by multiplying it by a plasma reduction factor R

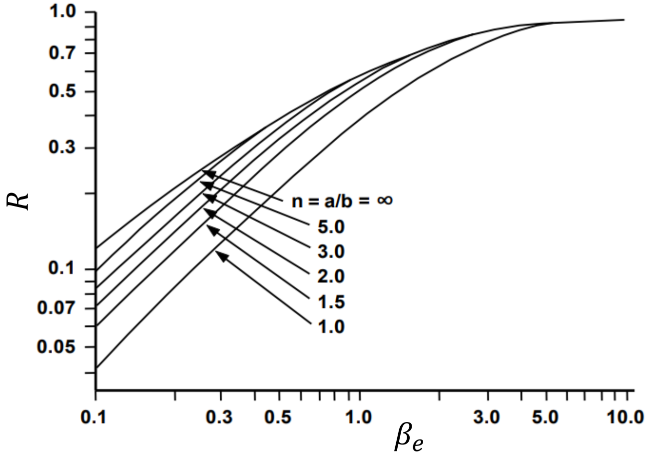
$$\omega_q = \omega_p * R$$

- R is plasma reduction factor



Plasma reduction factor vs electron propagation constant for a Brillouin beam

*[Ref. *A.S. Gilmore, "Klystrons, Traveling Wave Tubes, Magnetrons, Cross-Field Amplifiers, and Gyrotrons"]*



Plasma reduction factor vs electron propagation constant for a confined beam

*[Ref. *A.S. Gilmore, "Klystrons, Traveling Wave Tubes, Magnetrons, Cross-Field Amplifiers, and Gyrotrons"]*

- Reduced plasma propagation constant β_q

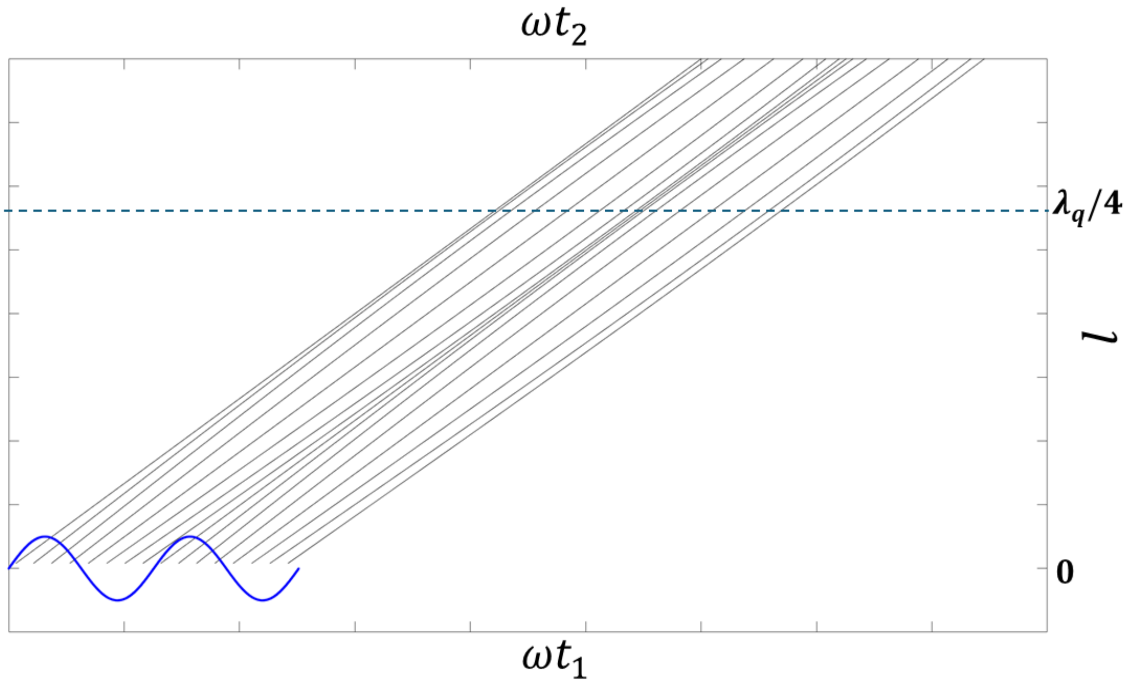
$$\beta_q = \frac{\omega_q}{v_0}$$

- β_e is electron propagation constant (ω/ v_0)
- v_0 is electron velocity

Space Charge in Klystrons

- Basic equation can be modified by multiply a factor of $\sin\beta_p l / \beta_p l$, to include the space charge effect.

$$\omega t_2 = \omega t_1 + \theta_0 - X\sin\omega t_1 \quad\Rightarrow\quad \omega t_2 = \omega t_1 + \theta_0 - \frac{\sin\beta_q l}{\beta_q l} X\sin\omega t_1$$



- The Applegate diagram with space charge effect.
- The phase traces of electrons are bent.
- .The electrons are pushed back before they can overtake each other--- the "anti-bunch effect"
- Length to the bunch core is a quarter of the reduced plasma wavelength $\lambda_q/4$

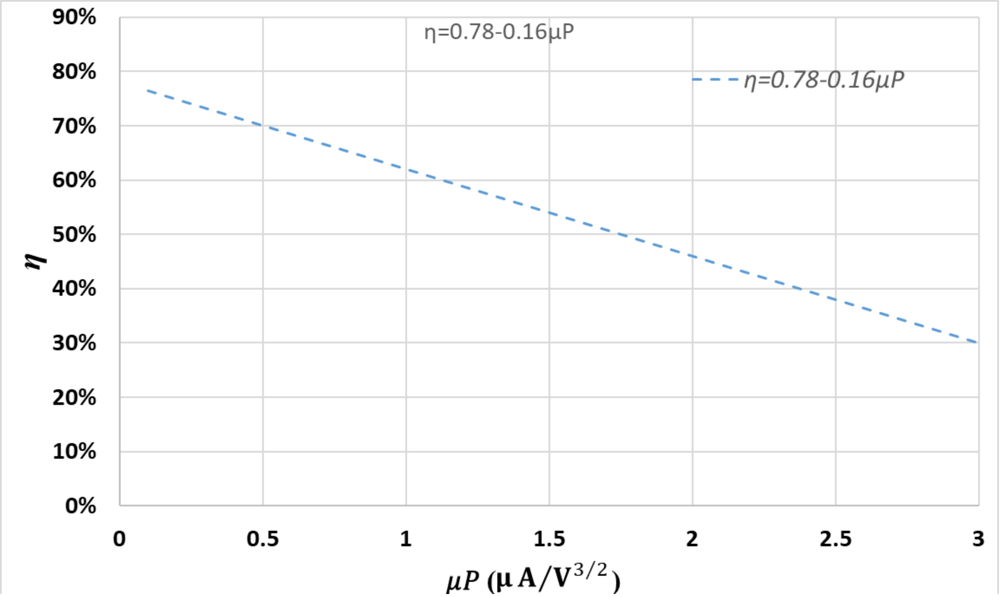
Space Charge in Klystrons

- **.The beam (micro) perveance μP** is an important parameter that indicates the magnitude of the space charge effect in a beam

$$\mu P = 10^6 \frac{I_0}{{V_0}^{3/2}}$$

- An inverse relationship between the beam perveance and the efficiency of a klystron. (Empirical relationship)

$$\eta = 78 - 16 \times \mu P$$

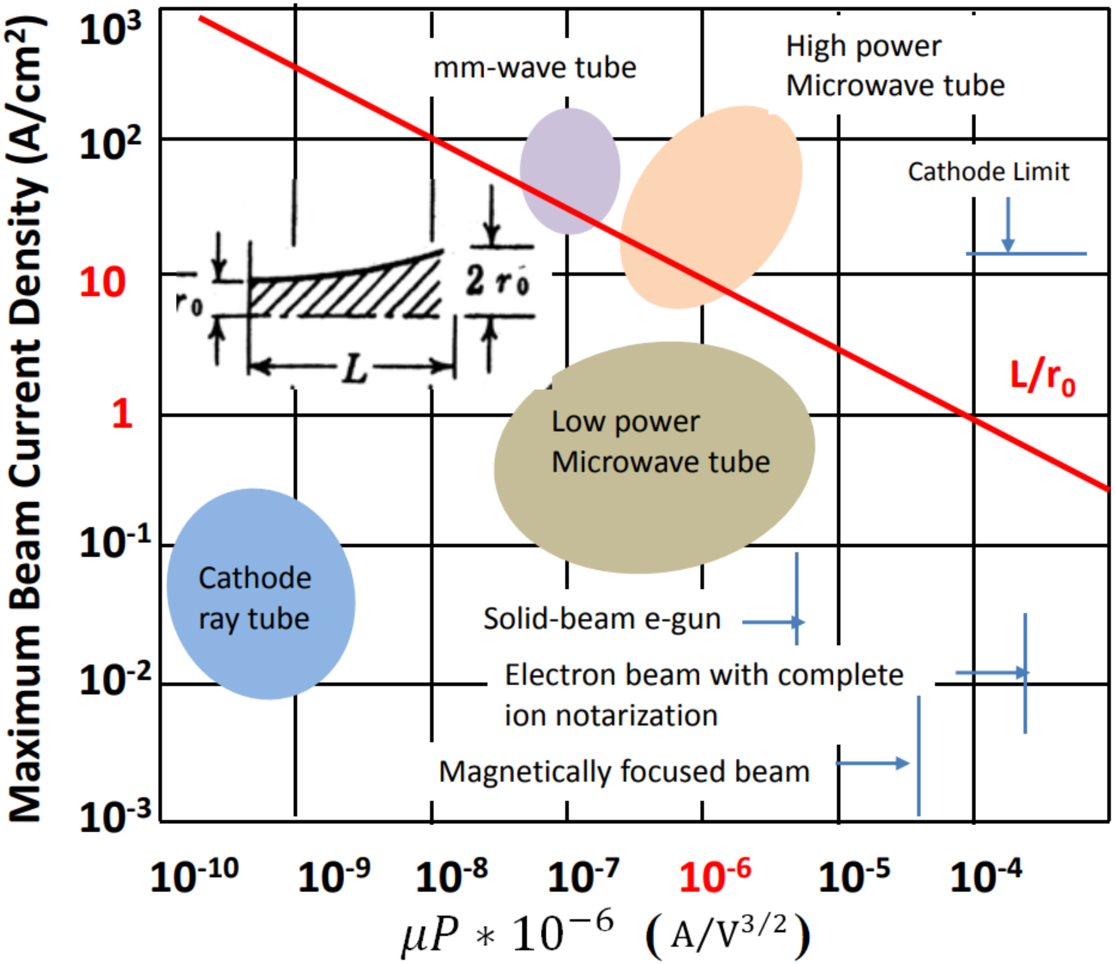


Space Charge in Klystrons

- The beam perveance is of great importance in the wider usage of vacuum devices involving electron beams./

- Microwave tubes (klystron, IOT, TWT, etc.) are located in a region with a perveance range from 10^{-7} to 10^{-6} $\mathrm{A/V^{3/2}}$ and a maximum beam current density from 10^{-1} to 10^{2} $\mathrm{A/cm^2}$.

- The beam with an original radius of r_o expands to a radius of $2r_o$ after drifting a length of L.



*[Ref. *S. Fukuda, ILC School-High Efficiency RF Source]*

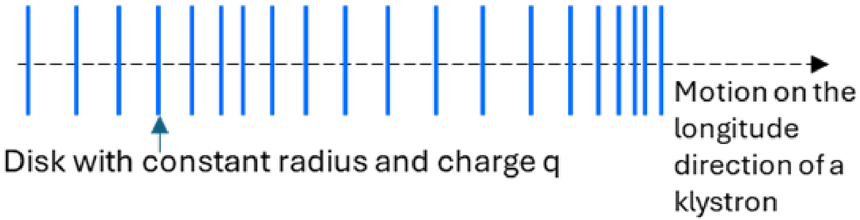
Space Charge in Klystrons

- **The space charge effect is the most dominating factor influencing the new bunching methods.**
- Due to its complexity, **computer simulation** is the most reliable tool for designing a high-efficiency klystron.

- DAY1 (9/11)

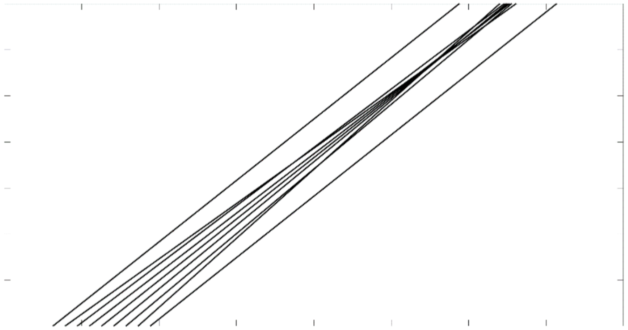
Simulation Methods

- **One-dimensional disk model** programs are among the most popular simulation tools, such as JPNDISK, AJDISK.

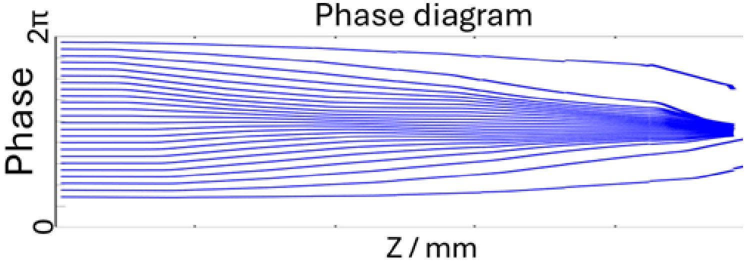


- The electron beam is divided into multiple electron layers, or disks.
- All electrons within the disk undergo the same longitudinal motion.
- Transverse motion is not considered (one-dimensional).
- The space charge force is treated as electric forces between those disks.

Applegate diagram



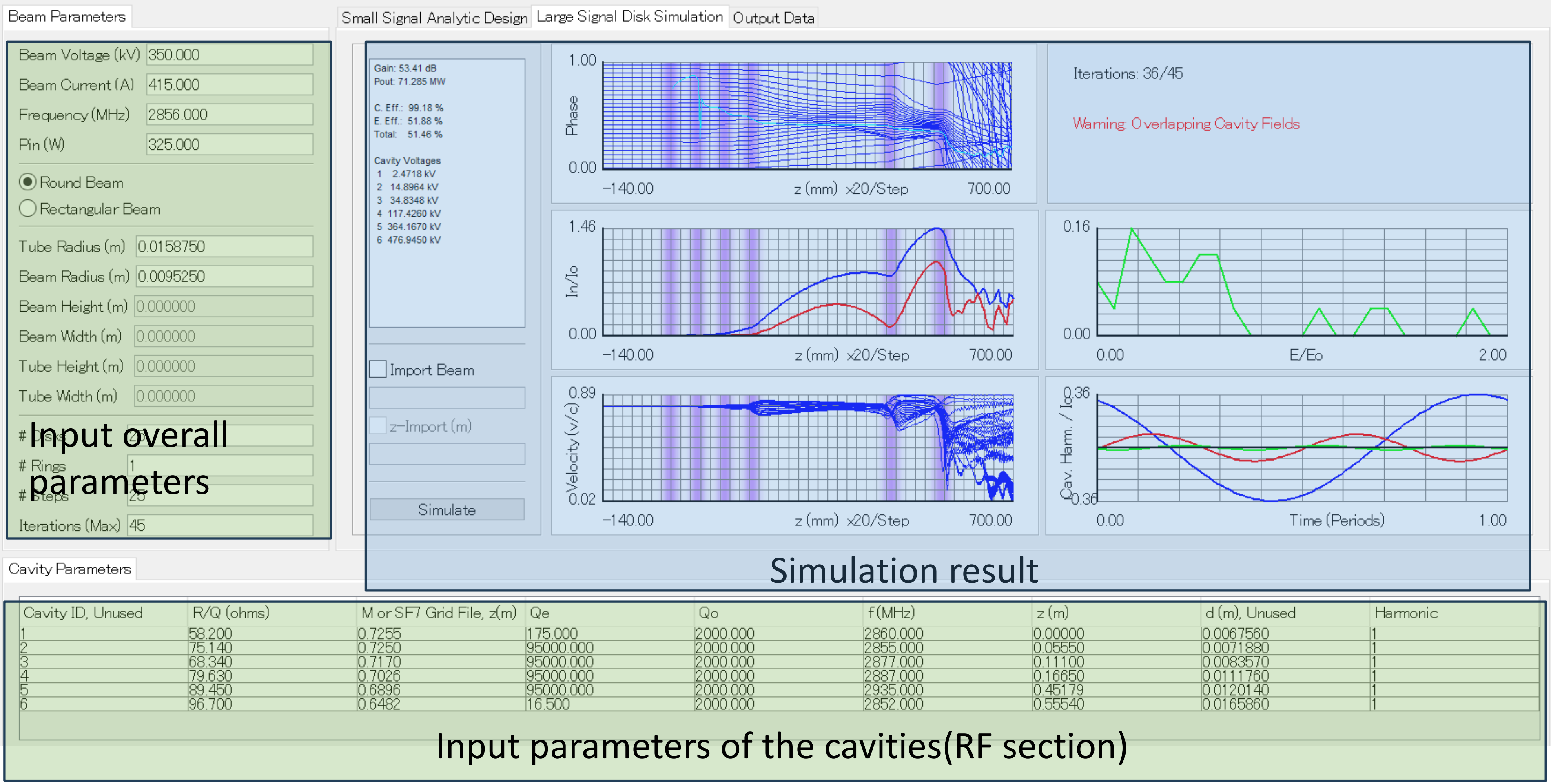
Phase diagram



- Phase diagram (similar toApplegate diagram) is the result from the disk simulation.

Simulation Methods

- Example of one-dimensional disk code--AJDISK



Beam Voltage (kV) 350.000
Beam Current (A) 415.000
Frequency (MHz) 2856.000
Pin (W) 325.000

● Round Beam
○ Rectangular Beam

Tube Radius (m) 0.0158750
Beam Radius (m) 0.0095250
Beam Height (m) 0.000000
Beam Width (m) 0.000000
Tube Height (m) 0.000000
Tube Width (m) 0.000000

Disks 25
Rings 1
Steps 25
Iterations (Max) 45

Input overall parameters

Gain: 53.41 dB
Pout: 71.285 MW

C. Eff.: 99.18 %
E. Eff.: 51.88 %
Total: 51.46 %

Cavity Voltages
1 2.4718 kV
2 14.8964 kV
3 34.8348 kV
4 117.4260 kV
5 364.1670 kV
6 476.9450 kV

☐ Import Beam

☐ z-Import (m)

Iterations: 36/45

Warning: Overlapping Cavity Fields

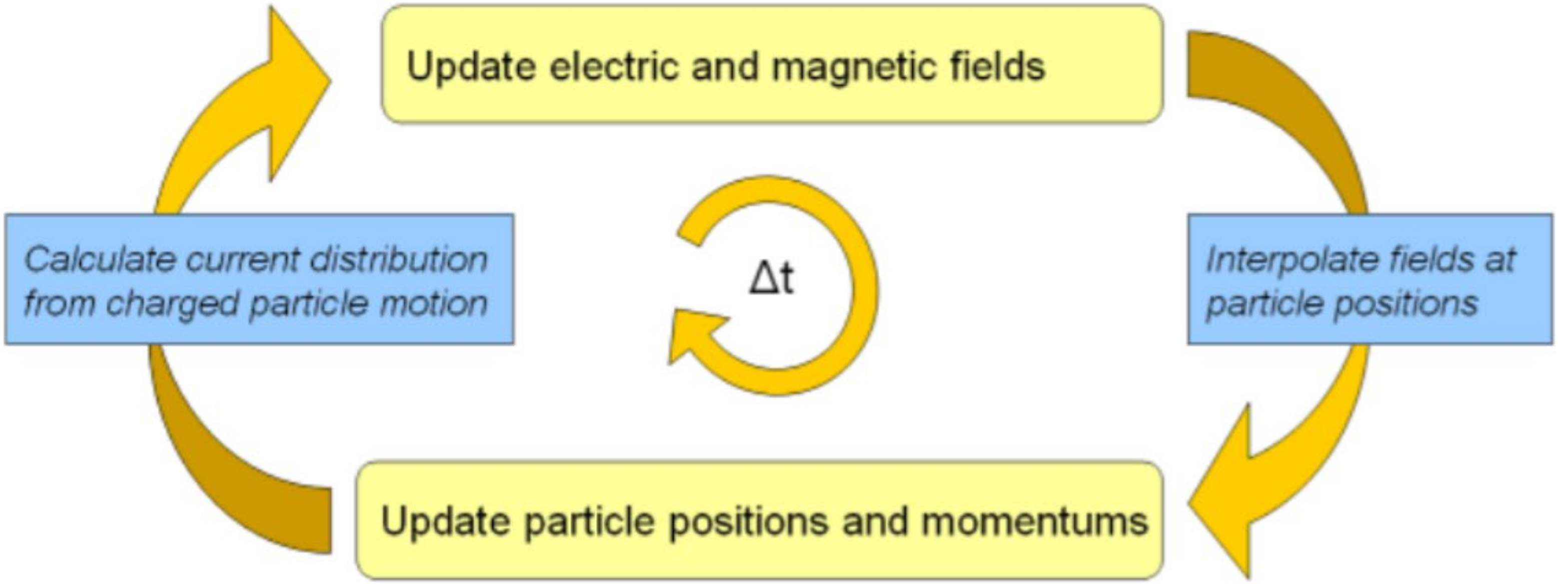
Simulation result

Cavity ID, Unused	R/Q (ohms)	M or SF7 Grid File, z(m)	Qe	Qo	f(MHz)	z (m)	d (m), Unused	Harmonic
1	58.200	0.7255	175.000	2000.000	2860.000	0.00000	0.0067560	1
2	75.140	0.7250	95000.000	2000.000	2855.000	0.05550	0.0071880	1
3	68.340	0.7170	95000.000	2000.000	2877.000	0.11100	0.0083570	1
4	79.630	0.7026	95000.000	2000.000	2887.000	0.16650	0.0111760	1
5	89.450	0.6896	95000.000	2000.000	2935.000	0.45179	0.0120140	1
6	96.700	0.6482	16.500	2000.000	2852.000	0.55540	0.0165860	1

Input parameters of the cavities(RF section)

Simulation Methods

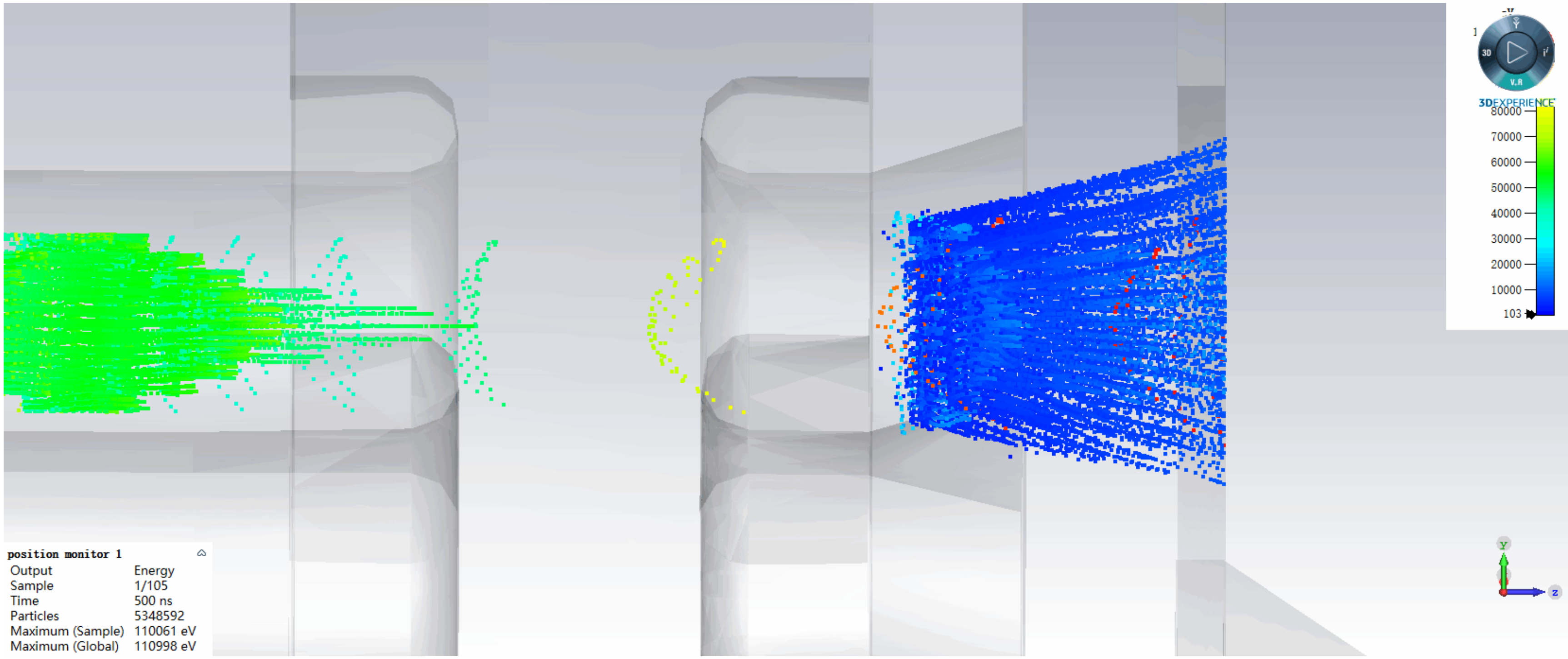
- **Particle-in-Cell (PIC) simulation** is most sophisticated tool for klystron design.
  - Allowing a realistic 2D/3D boundary
  - CST, EMSYS…/



*[Ref.*CST Studio Suite Help Document)*

Simulation Methods

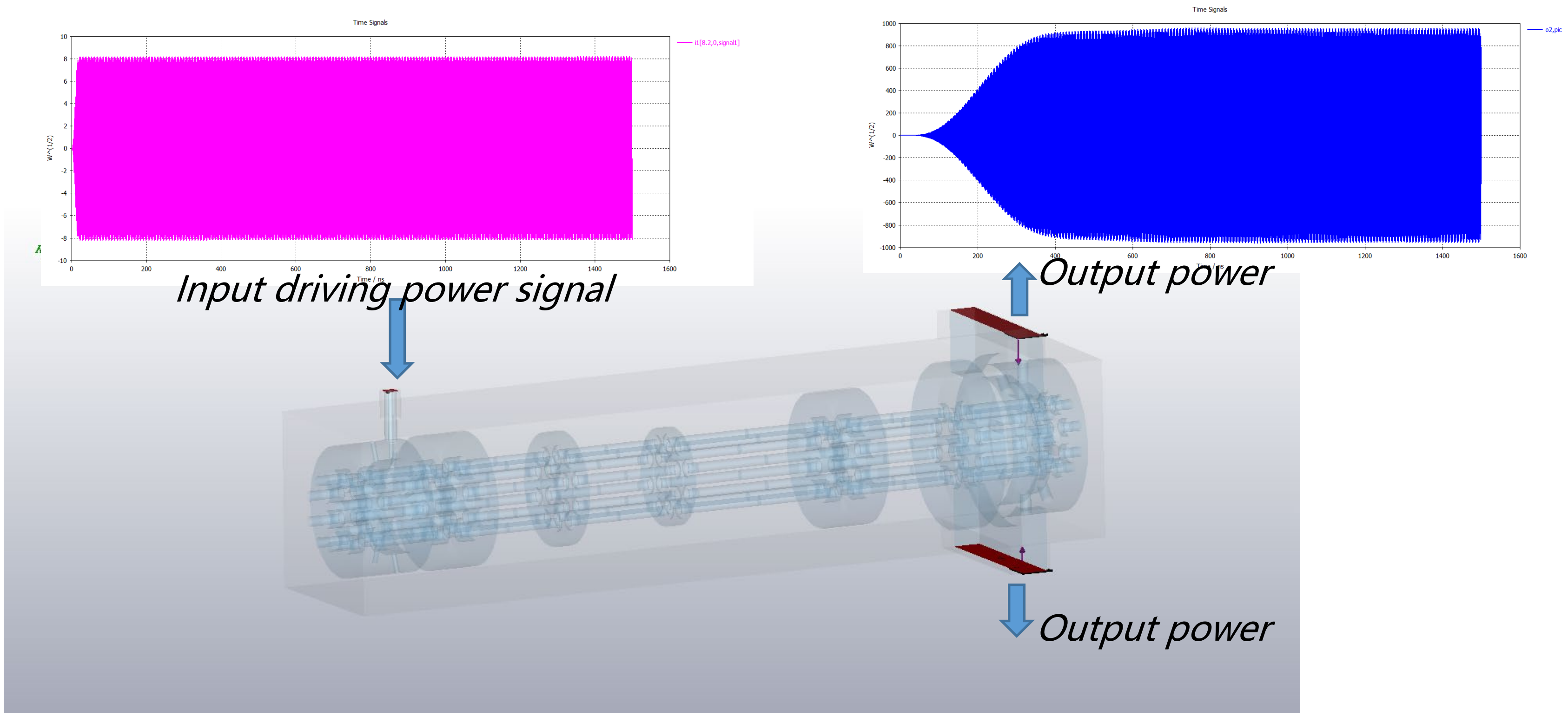
- Example of 3-D **PIC simulation--CST**
  - Time-dependent beam motion
  - Realistic cavities boundary



```
position monitor 1
Output              Energy
Sample              1/105
Time                500 ns
Particles           5348592
Maximum (Sample)    110061 eV
Maximum (Global)    110998 eV
```

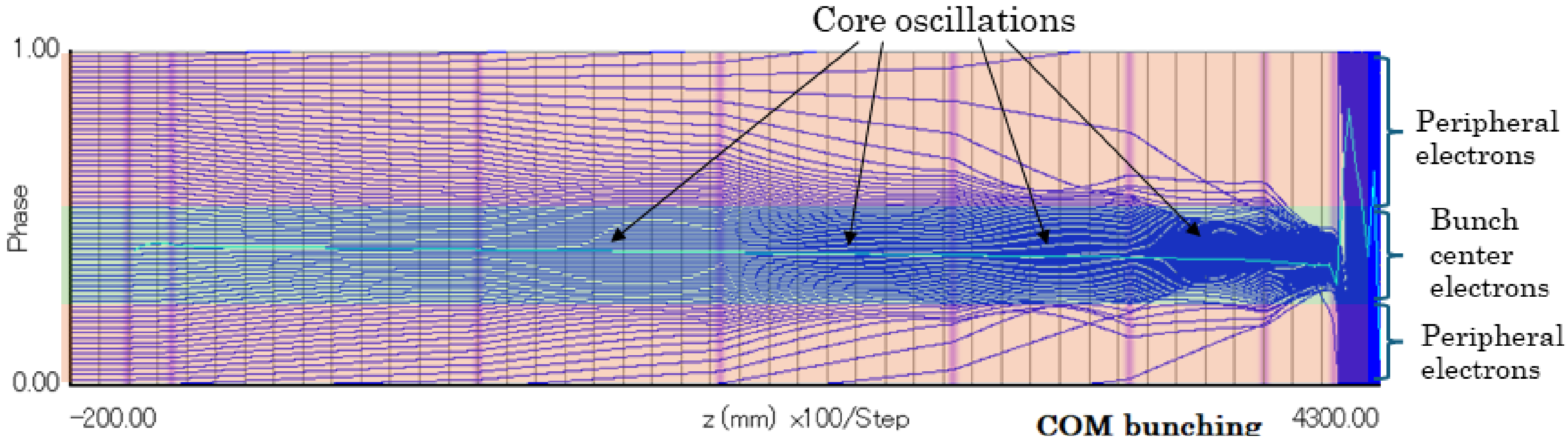
Simulation Methods

- Example of 3-D **PIC simulation--CST**
  - Time-dependent drive signal and resulted output signal



New Bunching Methods for High-Efficiency Klystrons

- Core Oscillation Method (COM) [A. Y. Baikov]
  - A gentle **bunch core oscillation**, due to modulation and space charge forces
  - **Peripheral electrons** slowly approach the bunching center, during the core oscillation.
  - After several core oscillation processes, the peripheral electrons enter bunching center.

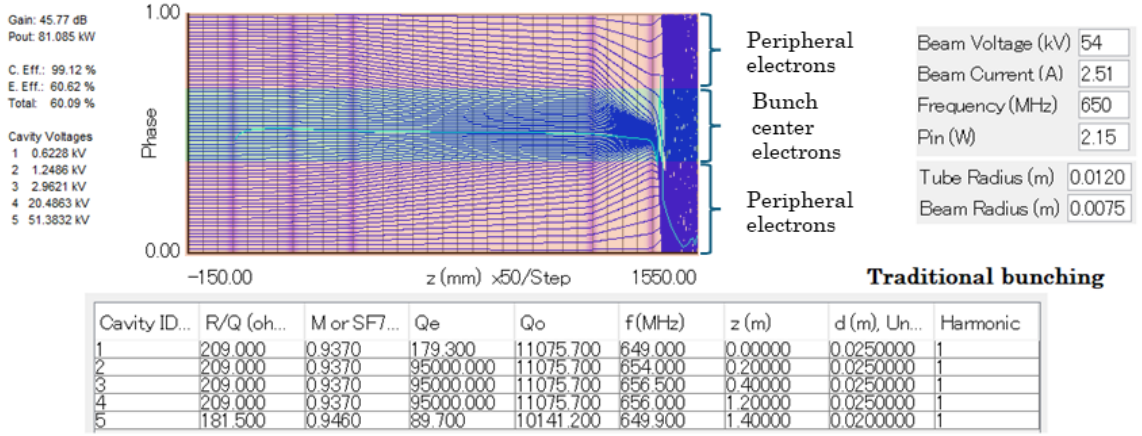


COM bunching

New Bunching Methods for High-Efficiency Klystrons

Traditional bunching

- Gives up the peripheral electrons
- Short interaction section



Gain: 45.77 dB
Pout: 81.085 kW

C. Eff.: 99.12 %
E. Eff.: 60.62 %
Total: 60.09 %

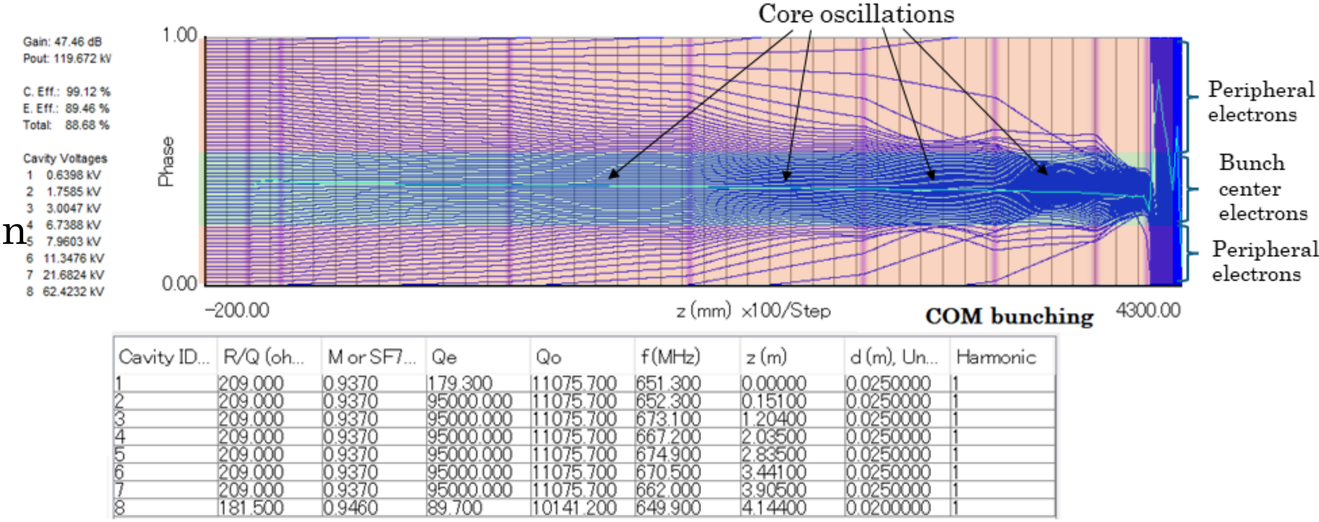
Cavity Voltages
1 0.6228 kV
2 1.2486 kV
3 2.9621 kV
4 20.4863 kV
5 51.3832 kV

Beam Voltage (kV) 54
Beam Current (A) 2.51
Frequency (MHz) 650
Pin (W) 2.15
Tube Radius (m) 0.0120
Beam Radius (m) 0.0075

Cavity ID...	R/Q (oh...	M or SF7...	Qe	Qo	f (MHz)	z (m)	d (m), Un...	Harmonic
1	209.000	0.9370	179.300	11075.700	649.000	0.00000	0.0250000	1
2	209.000	0.9370	95000.000	11075.700	654.000	0.20000	0.0250000	1
3	209.000	0.9370	95000.000	11075.700	656.500	0.40000	0.0250000	1
4	209.000	0.9370	95000.000	11075.700	656.000	1.20000	0.0250000	1
5	181.500	0.9460	89.700	10141.200	649.900	1.40000	0.0200000	1

COM bunching

- Repeated and gentle core oscillation
- Peripheral electrons slowly enter bunching center
- Very long interaction section

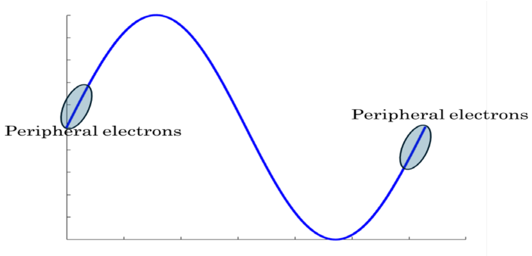


Gain: 47.46 dB
Pout: 119.672 kW

C. Eff.: 99.12 %
E. Eff.: 89.46 %
Total: 88.68 %

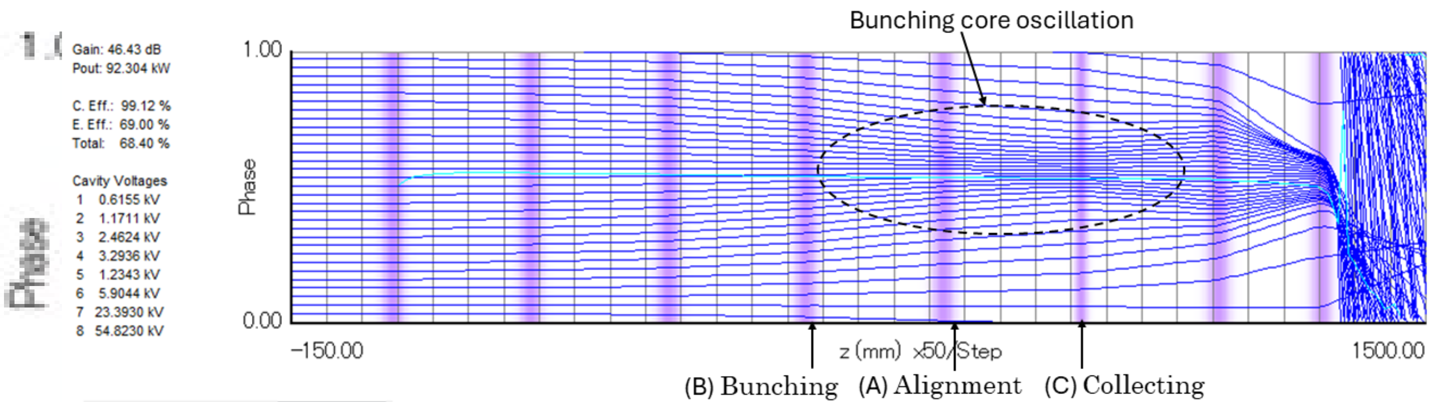
Cavity Voltages
1 0.6398 kV
2 1.7585 kV
3 3.0047 kV
4 6.7388 kV
5 7.9603 kV
6 11.3476 kV
7 21.6824 kV
8 62.4232 kV

Cavity ID...	R/Q (oh...	M or SF7...	Qe	Qo	f (MHz)	z (m)	d (m), Un...	Harmonic
1	209.000	0.9370	179.300	11075.700	651.300	0.00000	0.0250000	1
2	209.000	0.9370	95000.000	11075.700	652.300	0.15100	0.0250000	1
3	209.000	0.9370	95000.000	11075.700	673.100	1.20400	0.0250000	1
4	209.000	0.9370	95000.000	11075.700	667.200	2.03500	0.0250000	1
5	209.000	0.9370	95000.000	11075.700	674.900	2.83500	0.0250000	1
6	209.000	0.9370	95000.000	11075.700	670.500	3.44100	0.0250000	1
7	209.000	0.9370	95000.000	11075.700	662.000	3.90500	0.0250000	1
8	181.500	0.9460	89.700	10141.200	649.900	4.14400	0.0200000	1



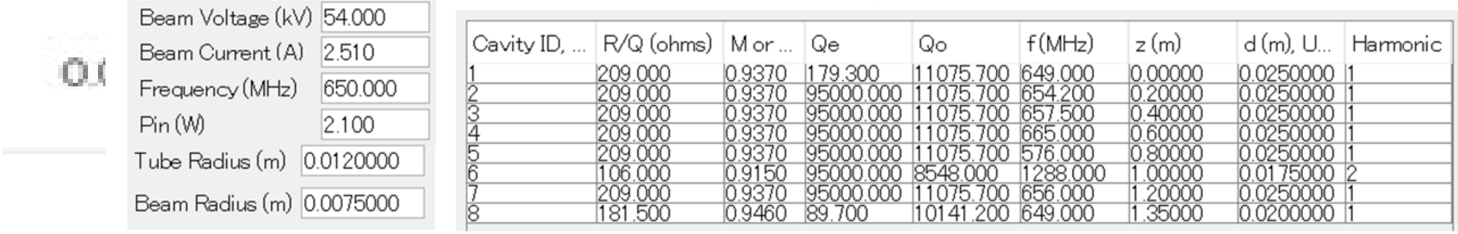
New Bunching Methods for High-Efficiency Klystrons

- Bunching-Alignment-Collecting (BAC) [I. A. Guzilov]
  - ○ Uses additional cavities to actively control core oscillation and collect peripheral electrons/
  - ➢Bunching--- a fundamental resonant cavity to achieve electron bunching
  - ➢Alignment--- corrects the velocity of the bunching center electrons
  - ➢Collection--- a second harmonic cavity, exerts a strong bunching effect on peripheral electrons


Gain: 46.43 dB
Pout: 92.304 kW

C. Eff.: 99.12 %
E. Eff.: 69.00 %
Total: 68.40 %

Cavity Voltages
1 0.6155 kV
2 1.1711 kV
3 2.4624 kV
4 3.2936 kV
5 1.2343 kV
6 5.9044 kV
7 23.3930 kV
8 54.8230 kV

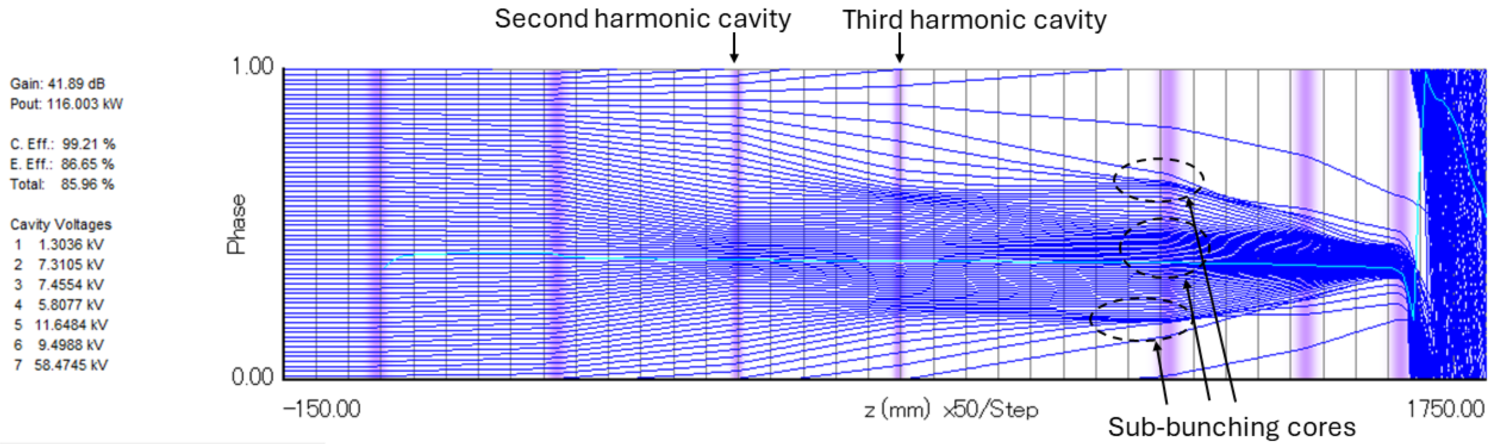


Beam Voltage (kV)	54.000
Beam Current (A)	2.510
Frequency (MHz)	650.000
Pin (W)	2.100
Tube Radius (m)	0.0120000
Beam Radius (m)	0.0075000

Cavity ID, ...	R/Q (ohms)	M or ...	Qe	Qo	f (MHz)	z (m)	d (m), U...	Harmonic
1	209.000	0.9370	179.300	11075.700	649.000	0.00000	0.0250000	1
2	209.000	0.9370	95000.000	11075.700	654.200	0.20000	0.0250000	1
3	209.000	0.9370	95000.000	11075.700	657.500	0.40000	0.0250000	1
4	209.000	0.9370	95000.000	11075.700	665.000	0.60000	0.0250000	1
5	209.000	0.9370	95000.000	11075.700	576.000	0.80000	0.0250000	1
6	106.000	0.9150	95000.000	8548.000	1288.000	1.00000	0.0175000	2
7	209.000	0.9370	95000.000	11075.700	656.000	1.20000	0.0250000	1
8	181.500	0.9460	89.700	10141.200	649.000	1.35000	0.0200000	1

New Bunching Methods for High-Efficiency Klystrons

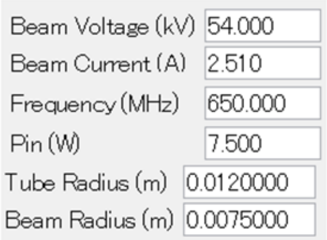
- Core Stabilization Method (CSM) [C. Victoria, et al]
  - Employing 2nd and 3rd harmonic cavities to rapidly incorporate peripheral electrons into the bunching center while reducing the space charge forces at the bunching center. /
  - .Suitable for L-band or UHF-band klystrons
  - Suitable for low-perveance electron beams



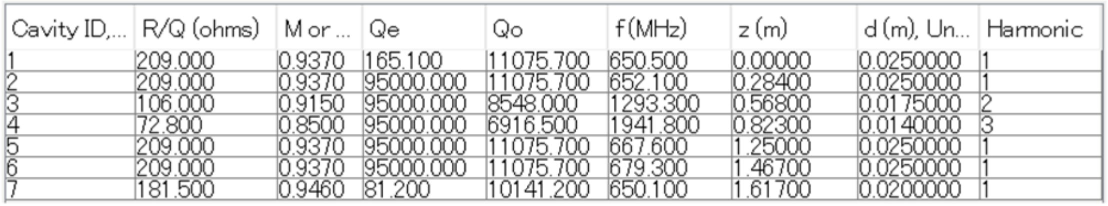
Gain: 41.89 dB
Pout: 116.003 kW

C. Eff.: 99.21 %
E. Eff.: 86.65 %
Total: 85.96 %

Cavity Voltages
1 1.3036 kV
2 7.3105 kV
3 7.4554 kV
4 5.8077 kV
5 11.6484 kV
6 9.4988 kV
7 58.4745 kV



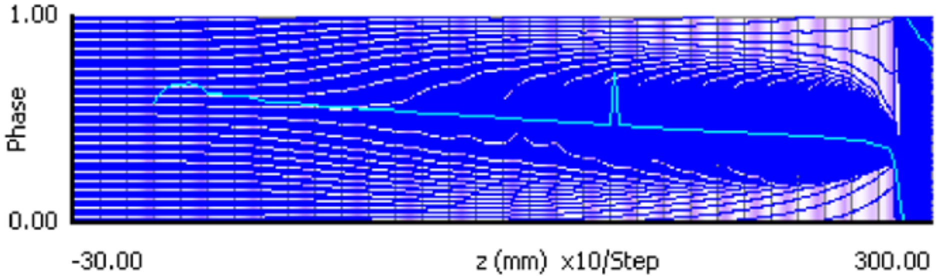
Beam Voltage (kV)	54.000
Beam Current (A)	2.510
Frequency (MHz)	650.000
Pin (W)	7.500
Tube Radius (m)	0.0120000
Beam Radius (m)	0.0075000



Cavity ID,...	R/Q (ohms)	M or ...	Qe	Qo	f (MHz)	z (m)	d (m), Un...	Harmonic
1	209.000	0.9370	165.100	11075.700	650.500	0.00000	0.0250000	1
2	209.000	0.9370	95000.000	11075.700	652.100	0.28400	0.0250000	1
3	106.000	0.9150	95000.000	8548.000	1293.300	0.56800	0.0175000	2
4	72.800	0.8500	95000.000	6916.500	1941.800	0.82300	0.0140000	3
5	209.000	0.9370	95000.000	11075.700	667.600	1.25000	0.0250000	1
6	209.000	0.9370	95000.000	11075.700	679.300	1.46700	0.0250000	1
7	181.500	0.9460	81.200	10141.200	650.100	1.61700	0.0200000	1

New Bunching Methods for High-Efficiency Klystrons

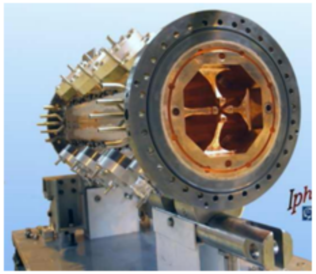
- Adiabatic Bunching (Kladistron) [F. Peauger]
  - Bunching process by numerous low characteristic impedance resonant cavities
  - Each cavity has a low cavity voltage---minor velocity modulation for the electrons/

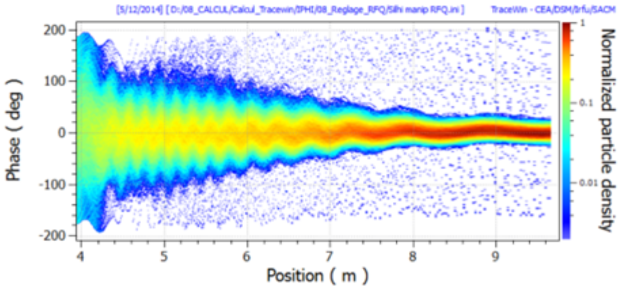


.For the left example:

- A total 20 cavities are used for the layout

- Similar to an RFQ cavity and the phase diagram of protons in an RFQ cavity.

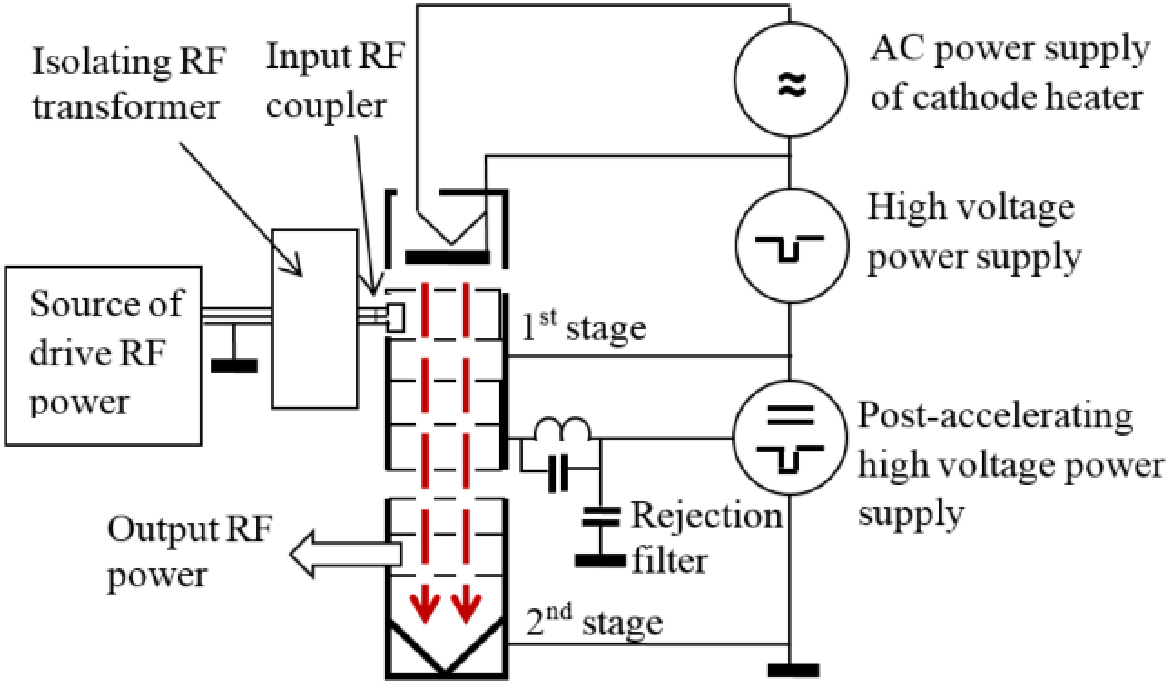




*[Ref.*F. Peauger, EnEfficiency RF sources Workshop, 2014]*

New Bunching Methods for High-Efficiency Klystrons

- Two-stage method [V. E. Teryaev]
  - Adopting two DC accelerating gaps for a klystron
  - Achieving an ultra-low beam perveance after the second acceleration/

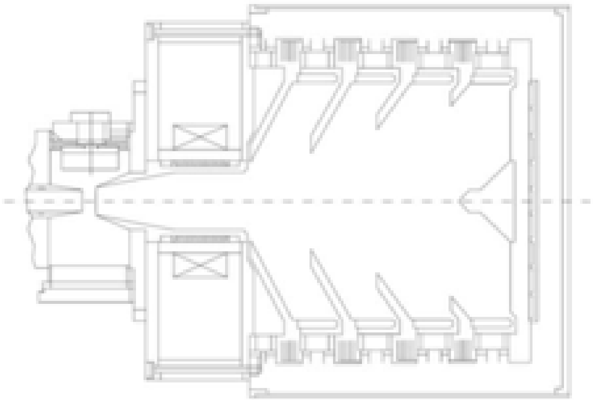


.Technical challenges:
- RF feed to the input cavity on the high voltage state.
- Insulation of the second accelerating gap while preventing the RF leak.
- Beam focusing magnet that accommodate the two-stage structure.

*[Ref.*V. E. Teryaev, et.al, IEEE Transactions on Electron Devices, 2020]*

Depressed Collector

- The depressed collector is used to enhance the overall efficiency of a klystron
- Unlike a normal collector, where the spent beam hits the wall and dissipates heat, the depressed collector aims to recover the power of the spent beam and convert it back into electrical power.



*[Ref. *S. Fukuda, ILC School-High Efficiency RF Source]*

Advantages of a Multi-Beam Klystron

- Single-beam klystrons (SBK): most common type, simple structure, a range of applications
- Multi-beam klystrons (MBK): multiple cathodes, a more complex overall structure, a greater potential for high efficiency.

$$\eta = 78 - 16 \times \mu P \qquad \mu P = 10^6 \frac{I_0}{{V_0}^{3/2}}$$

- SBK : higher-efficiency → lower perveance→ higher gun voltage → higher risk on operational stability

$$V_0 = \left(\frac{P_{\text{out}}}{\eta N_b \mu P * 10^{-6}}\right)^{\frac{2}{5}}$$

- N_b is the number of electron beams

- MBK: higher-efficiency→ lower perveance and acceptable gun volage

Advantages of a Multi-Beam Klystron

- Comparison of perveance and beam voltage between S-band pulsed SBK and MBK/

Output power (MW)	80	80
Efficiency	70%	70%
Total beam power (MW)	114.3	114.3
Number of beams	**1**	**8**
Perveance ($\mu A/V^{3/2}$)	0.29	0.29
Electron gun voltage (kV)	**689**	**300**

Too high

Acceptable

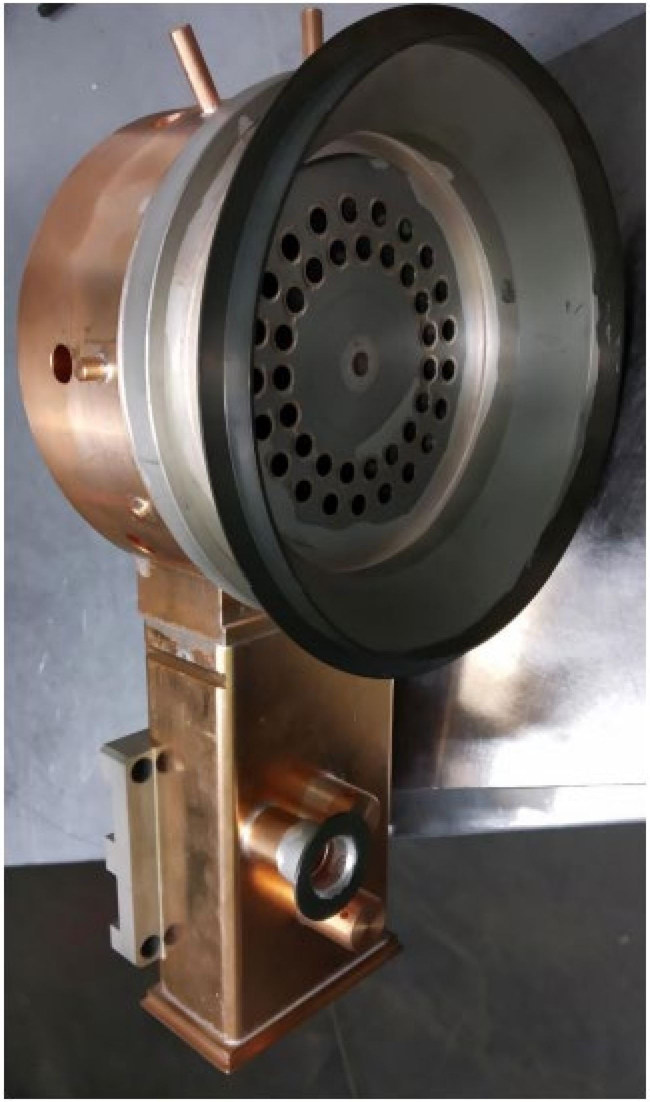
- .MBK can achieve the dual advantages of low perveance and acceptable electron gun voltage.

Global Research Activities

- The existing high-efficiency klystrons

Frequency band	Vendor / Type	Frequency (GHz)	Peak power (MW)	Average power (MW)	MBK or SBK	Efficiency	Perveance $(\mu A/V^{3/2})$	Beam voltage (kV)
S-Band	VDBT / BT267	2.856	16	0.03	MBK	**60%**	0.51	75
	SLAC / 5045(retrofit)	2.856	72		SBK	**54%**	2	350
	CANON / E3772A(retrofit)	2.856	7.3		SBK	**59.2%**	1.68	140
	CPI / VKS-7773	2.45	0.05	0.05	SBK	**74.4%**	0.51	28
L-Band	CANON / E37503	1	20.5	0.077	MBK	**71.5%**	0.42	160
	Thales / TH1803	1	21	0.079	MBK	**73.5%**	0.34	147
	CANON / E3736	1.3	10	0.15	MBK	**65%**	0.56	115
	Thales / TH1801	1.3	10	0.15	MBK	**65%**	0.51	110
	CPI / VLK8301B	1.3	10	0.15	MBK	**65%**	0.57	115
UHF-Band	CPI / VKP7952A	0.7	1	1	SBK	**65%**	0.6	92
	CANON / E3786	0.509	1.2	1.2	SBK	**65%**	0.74	93

Input and intermediate cavities



Output cavity

[Ref.[32]   I. Guzilov, CLIC Workshop 2019]*

CANON / E37117

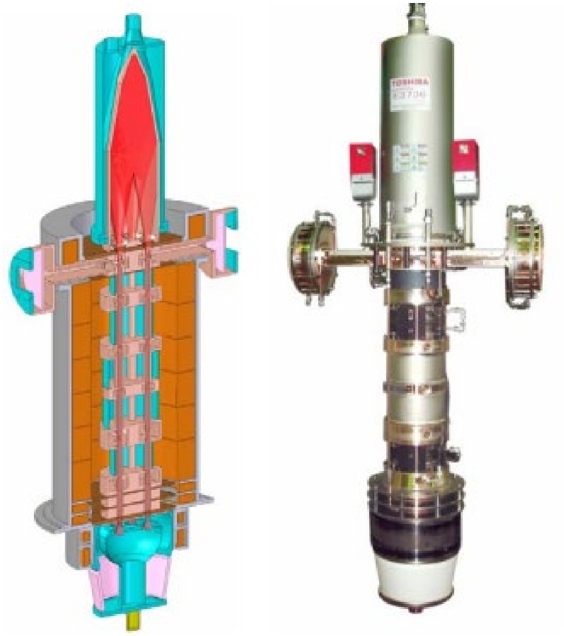
*[Ref.*T. Anno, CLIC Workshop 2019]*

CANON MBK for CLIC project

[Ref.*T. Anno, CLIC Workshop 2019]

THALES MBK for CLIC project

[Ref.*S. Döbert,, CLIC workshop 2018]



CANON E3736

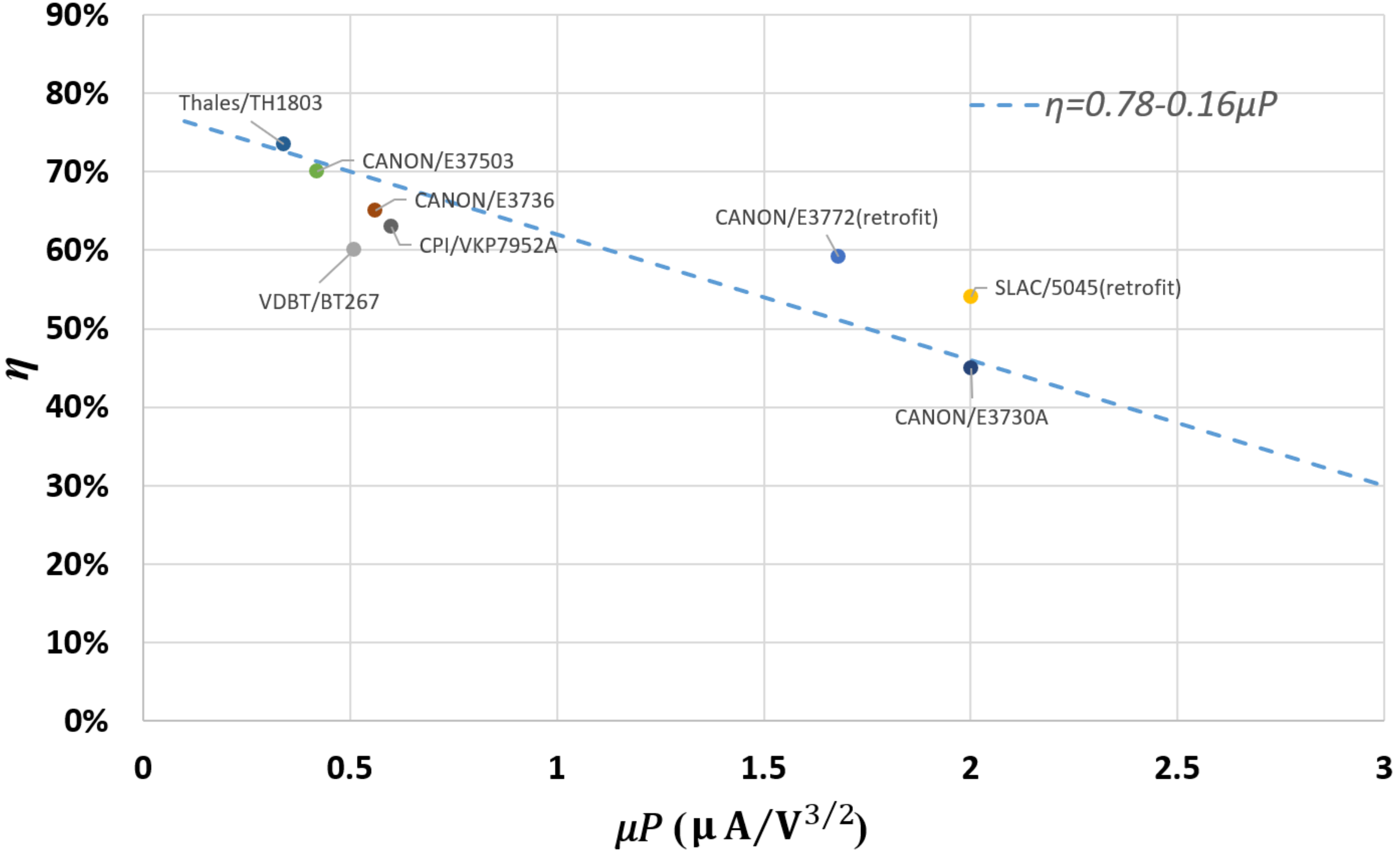
Thales / TH1801

CPI / VLK8301B

*[Ref.*Y.H. Chin, Proceedings of LINAC08, Victoria, BC, Canada, 2008]*

Global Research Activities

- The existing high-efficiency klystrons



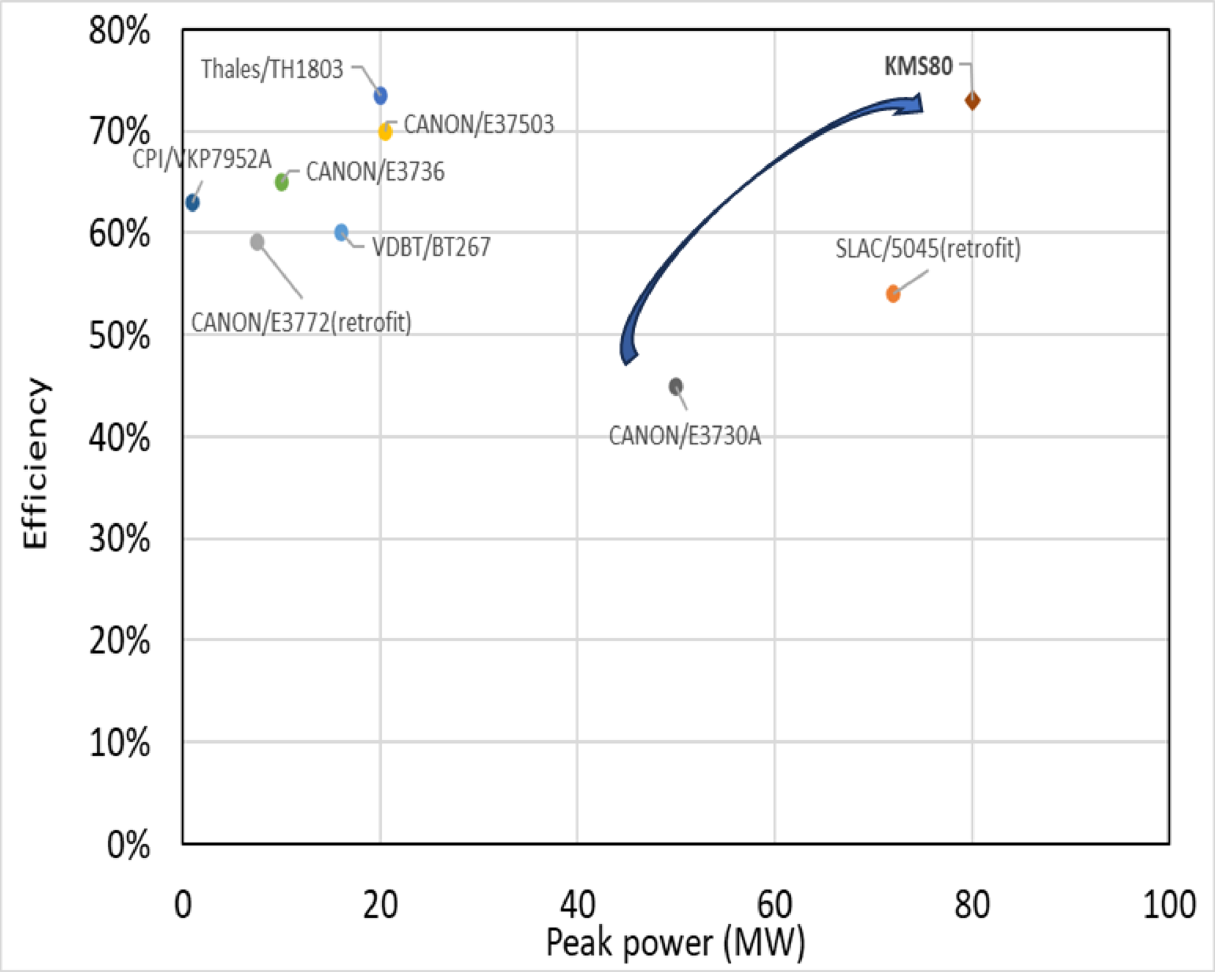
Global Research Activities

- Research activities at KEK
  - An S-band high-efficiency MBK is currently under development to modernize the existing 50MW klystron utilized in the KEK e^{-}/e^{+} Injector Linac.
  - The RF-section of this MBK is designed to achieve a target efficiency of 73%, improving from 45% of the current 50 MW klystron.

Parameters	E3730A	MBK design
Frequency (GHz)	2.856	2.856
Gun voltage (kV)	312	300
Total gun current (A)	362	366.4 (45.8*8)
Beam No.	1	8
Output power (MW)	**50**	**80**
Efficiency	**45%**	**73%**

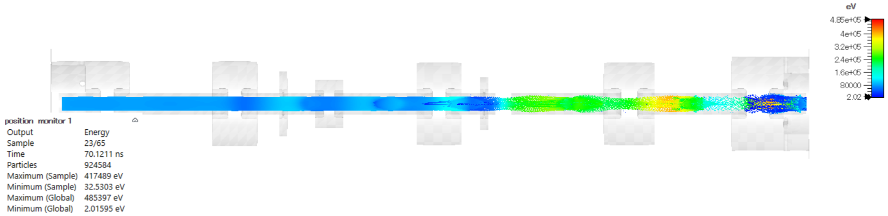
Global Research Activities

- Research activities at KEK



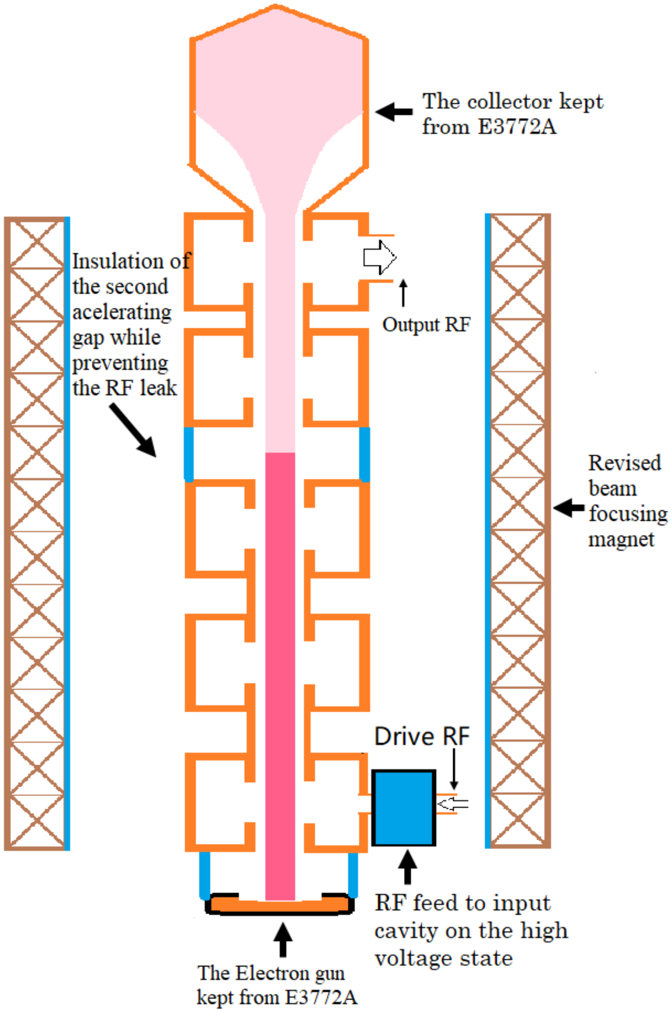
Global Research Activities

- Research activities at KEK
  - Based on a 7.5 MW klystron E3772A from CANON, a S-band two-stage klystron is designed.



```
position monitor 1
Output              Energy
Sample              23/65
Time                70.1211 ns
Particles           924584
Maximum (Sample)    417489 eV
Minimum (Sample)    32.5303 eV
Maximum (Global)    485397 eV
Minimum (Global)    2.01595 eV
```

Parameters(unit)	E3772A	Two-stage klystron (design)
Efficiency	45%	72%
Frequency (GHz)	2.856	2.856
Beam voltage (kV)	150	80 (gun)+170 (post accel. gap)
Beam current (A)	110	41
Output power (MW)	7.5	7.5



Global Research Activities

- Research activities at CERN
  - CERN collaborating with CANON, is developing the X-band high-efficiency klystron.
  - The prototypes are based on CANON E37113.
  - The efficiency is improved from 39% to 56% after testing several protypes.

Parameters(unit)	E37113	HE E37113 (design)
Efficiency	39%	56%
Frequency (GHz)	11.994	11.994
Beam voltage (kV)	157	153
Beam current (A)	96	93
Output power (MW)	6	8

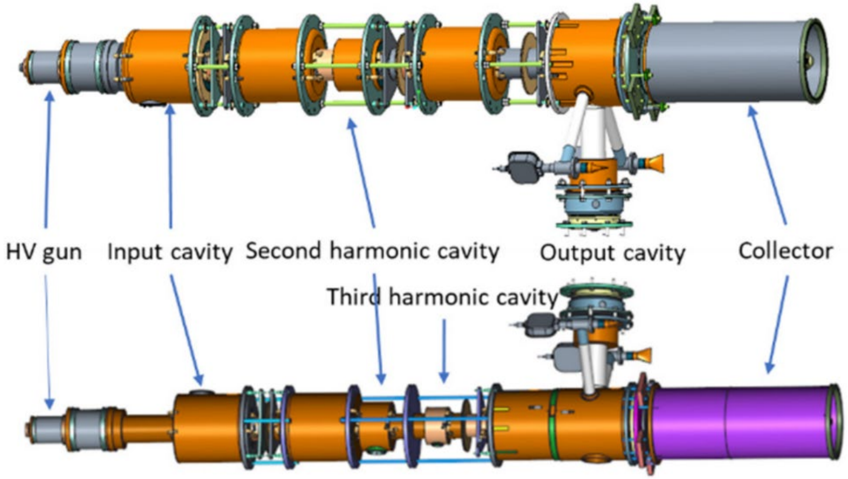
First prototype

[Ref. T. Anno, Workshop on Efficient RF Sources, 2022]*

Global Research Activities

- Research activities at CERN
  - A CW UHF-band klystron is under development as a spare unit for the TH2169 Thales, which operates at the Large Hadron Collider (LHC).
  - The designed efficiency of the new klystron is improved from 62% to 70 %.
  - **The CSM bunching method.**

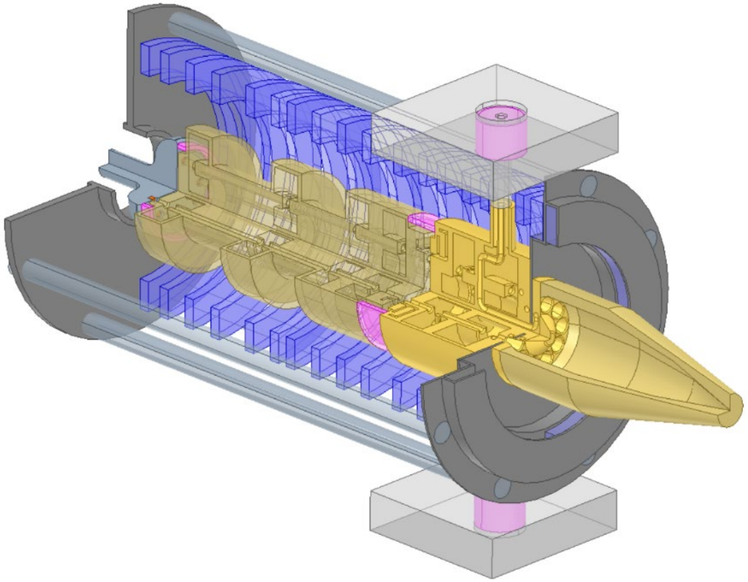
Parameters (unit)	**TH2169**	**HE TH2169**
Efficiency	62%	**70%**
Frequency (MHz)	400.8	**400.8**
Beam voltage (kV)	58	**58**
Beam current (A)	8.4	**9**
Output power (kW)	**300**	**365**



*[Ref.*N. C. Lasheras, et al, 15th International Particle Accelerator Conference, 2024]*

Global Research Activities

- Research activities at CERN
  - For the future FCC project, CERN presents a design of a CW UHF-band MBK operating at 400MHz and an output level of 1 MW.
  - The design adopts the **two-stage method** and the efficiency from simulation is 82%.



*[Ref.*N. C. Lasheras, et al, 15th International Particle Accelerator Conference, 2024]*

Global Research Activities

- Research activities at CEA
  - CEA, with a collaboration of Thales, has developed a klystron prototype adopting the Adiabatic Bunching method.
  - The Thale TH2166 was chosen for retrofitting as a demonstration of the Adiabatic Bunching.
  - The original 6 cavities were increased to 16 cavities. /
  - .The prototype was tested, with the highest measured efficiency at 41%, compared to the 50% efficiency of the TH2166.//

Parameters	**TH2166**	**New prototype**	
		Design	Test
Efficiency	50%	60%	41%
Frequency (GHz)	4.9	4.9	4.9
Beam voltage (kV)	26	26	27.8-30
Beam current (A)	4.3	4.3	

Fig. 11. Left: partial cavities assembly. Center: interaction line and output waveguide ready for brazing. Right: tube closed.

*[Ref.*J. Plouin, et al, IEEE Transactions on Electron Devices, 2023]*

Global Research Activities

- Research activities at CPI
  - CPI is developing an X-band 50MW high-efficiency klystron.
  - CPI proposed a design in 2022 that achieves over 60% efficiency in simulations.
  - The second harmonic cavities and multi-cell output cavity are used to improve the efficiency.

Parameters	value
Efficiency	**>60%**
Frequency (GHz)	**11.994**
Beam voltage (kV)	**400**
Beam current (A)	**190**
Output power (MW)	**52**

Global Research Activities

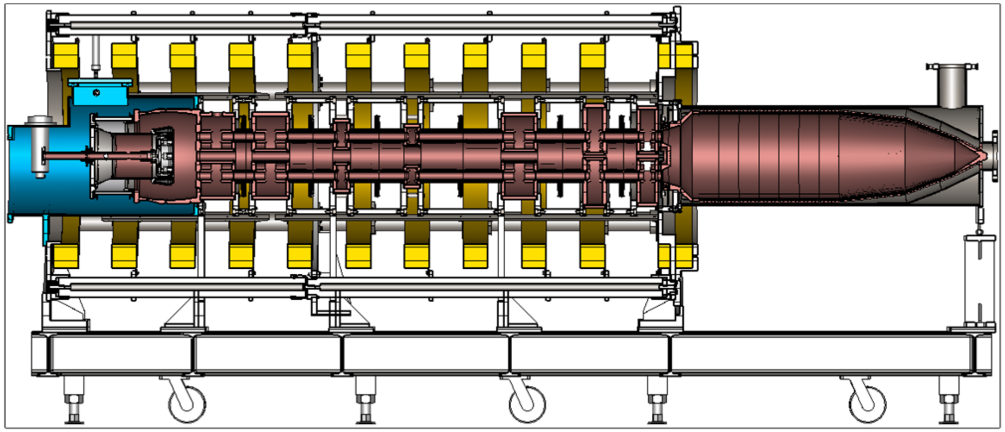
- Research activities at Calabazas Creek Research Inc
    - Calabazas Creek Research Inc. is developing an L band CW klystron with an output power of 100 kW.
    - The COM bunching method is adopted for this design.

Parameters	value
Efficiency	79%
Frequency (GHz)	1.3
Beam voltage (kV)	53.5
Beam current (A)	2.46
Output power (kW)	100

Global Research Activities

- Research activities at IHEP
  - UHF-band CW klystrons with output level of 800 KW for the CEPC project
  - Both single beam and multi-beam design are launched.
  - The CSM bunching method is adopted to improve efficiency, meaning that both second harmonic and third harmonic cavities are used in the RF section

Parameters	MBK	SBK
Efficiency	80%	78%
Frequency (MHz)	650	650
Beam voltage (kV)	54	110
Beam current (A)	20.8 (2.51×8)	9.1
Output power (kW)	800	800



Summary

- Introduction of the **motivation, background** of enhancing klystron efficiency.
- Discussion of the basics of a klystron, highlighting **concepts critical to high-efficiency klystron** design.
- Review of various **bunching methods** for improving klystron efficiency.
- Review of the **global research activities** of high-efficiency klystron.