Accelerator Laboratory, KEK

Recent Developments of Klystron in Japan/Asia, and Consideration for the High Efficiency Approach

KEK

S. Fukuda

Basic Purpose of this Talk

- Recently high efficiency for the klystron is interested in the world relating with the big project, such as ILC, CLIC, FFC and CEPC.
- Klystron demands in Asian area is increasing not only Japan but other country as China, Korea and India.
- Contents;
  1. High efficiency klystron attempts in KEK is described. ILC related klystrons, Injector linac klystron upgrade, and CPD plan for KEKB klystron are talked.
  2. High efficiency klystron R&D in Korea and China is presented. Klystron collaboration between Japan and India is also presented.
  3. Let's consider "What kind of high efficiency is important for the big project"

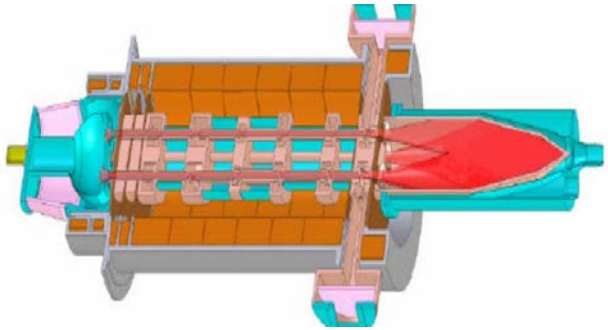
Various Klystron developments in KEK

Main-ILC-Project Klystron

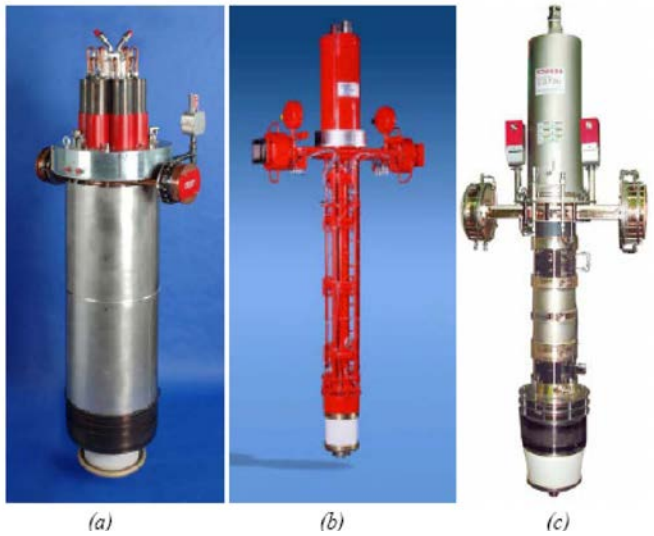
(Multi-beam Klystron)

- **DESY Based Development (Thales)**
- KEK-Toshiba Collaboration /YH Chin & Russian Team

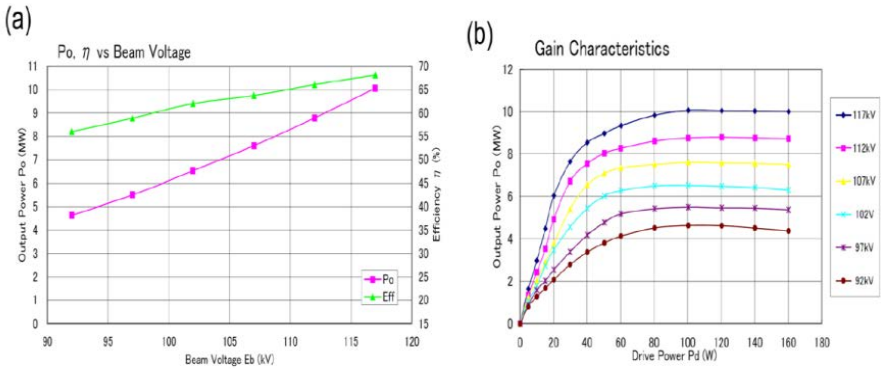
Parameter	Specification
Frequency	1.3 GHz
Peak power output	10 MW
RF pulse width	1.65 ms
Repetition rate	5.0 (10) Hz
Average power output (5 Hz)	82.5 kW
Efficiency	65 %
Saturated gain	> 47 dB
Instantaneous 1 dB BW	> 3 MHz
Cathode voltage	> 120 kV
Cathode current	< 140 A
Filament voltage	9 V
Filament current	50 A
Power asymmetry (between two output windows)	< 1 %
Lifetime	> 40,000 hours



In order to have a h
efficiency, multibea
Approach is inevitab



CPI:VKL-8301 Thales:TH1801 Toshiba:E3736



Toshiba MBK Characteristics

MBK and More Demand from ILC

- MBK (Multi-beam Klystron) uses following 2 functions to mate to the ILC specification.

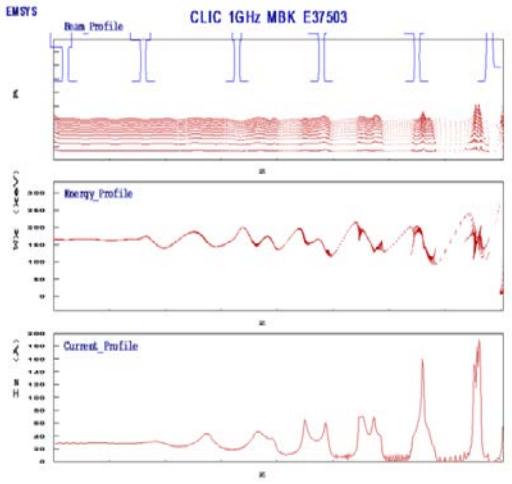
  1. Small perveance beamlet klystron can output high efficiency.
     (Small current, low voltage, low output power)
  2. Adding the powers of several beamlets to have high power.

- ILC MBKs are first successful high power MBK and more than **65%** and **10MW** power was achieved.
- Recently rapid progress of superconducting cavity reaching to **40MV/m** gradient, and more higher efficiency is requested.
- Now, cavity folks desire 71% efficiency of MBK.
- Toshiba recently succeeded in ~70% for DESY MBK.
- Are there more higher demand in future?

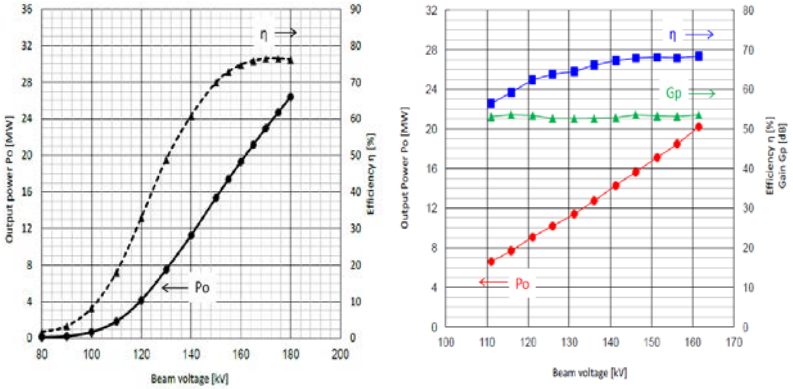
Another MBK by Toshiba

- If ILC project is approved, it is required to raise the tube efficiency more to save the total power dissipation.
  - ➢ Classical way: recent improvement of Toshiba for CLIC MBK ~ reached to 70%
  - ➢ HEIKA way: recent approach to raise the efficiency

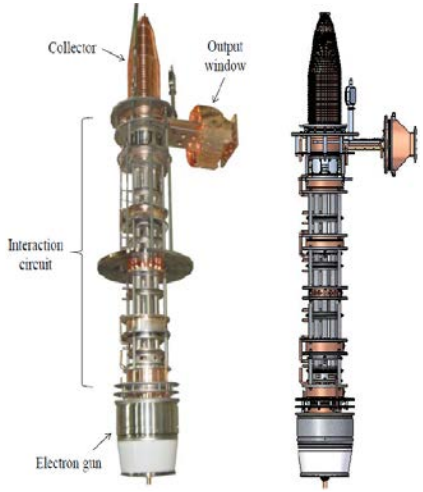
Budget is not approved but try to pursue the way.



- Below is the example of CLIC 1GHz MBK in Toshiba



Simulation and test results



Parameters	Unit	Design	Result
RF frequency	MHz	999.516	999.516
Peak RF power	MW	21.5	20.2
Power efficiency	%	71(*)	68.3
Power gain	dB	50.5	53.5
Peak beam voltage	kV	166	161.4
Peak beam current	A	170.4	183.2
Beam perveance	$\mu A/V^{3/2}$	2.52	2.82

(*) at 20 MW

In the courtesy of Toshiba presented at 2016 Jap. Accl. Meeting

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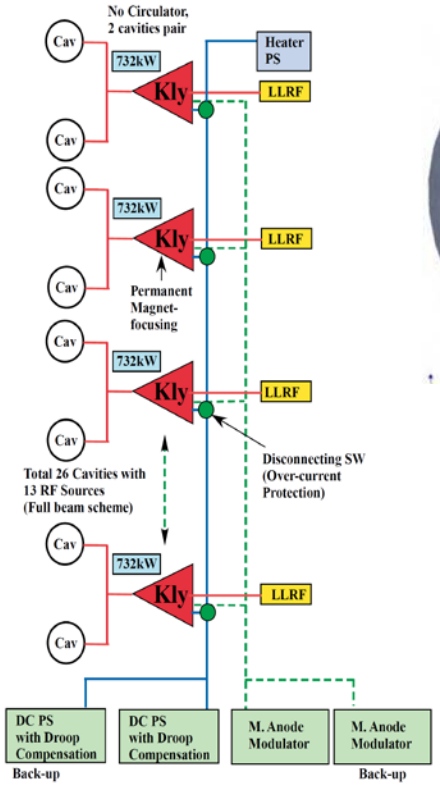
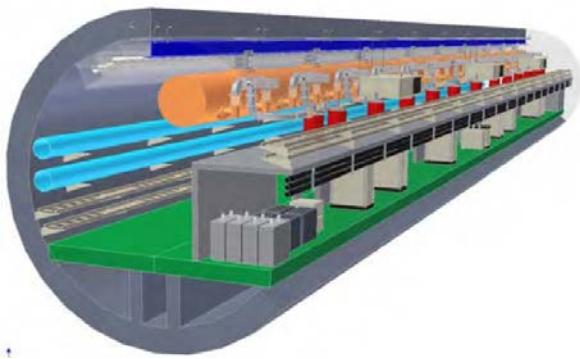
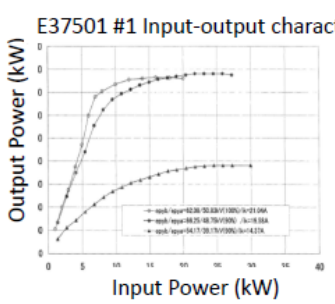
ILC-Project Klystron

(DRFS Klystron as the Alternative Plan)

- Fukuda proposed the distributed RF Scheme for ILC and discussed, Small system was constructed to show the feasibility)
- KEK-Toshiba Collaboration /Fukuda specify tube and Toshiba manufactured







DRFS based on the many 800kW
Klystron feeding to 2 superconductive cavities

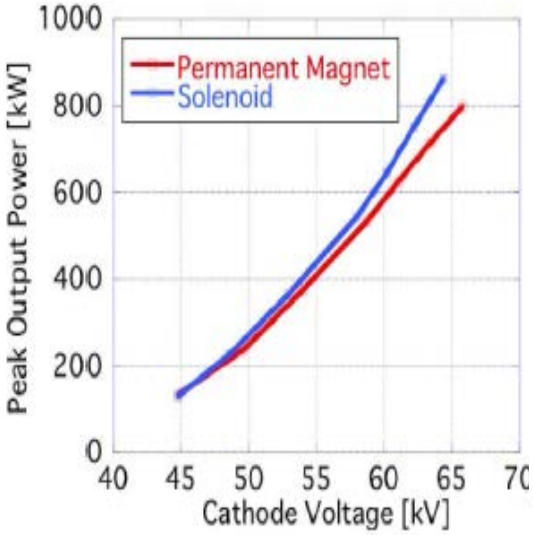
Achieving data
Original design was 750kW but same Design achieved More than 800kW.
No. 1 DRFS klystron: 806.7kW at 67.1kV (Micro-perveance=1.15), Eff.=**60.1%**

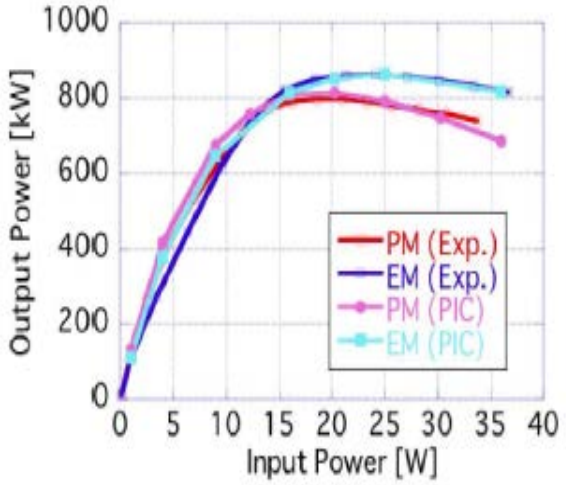
Klystron	Frequency	1.3	GHz
	Peak Power	750	kW
	Average Power Output	7.50	kW
	RF pulse width	1.5	ms
	Repitition Rate	5	Hz
	Efficiency	60	%
	Saturated Gain		
	Cathode voltage	64.1	kV
	Cathode current	19.5	A
	Perveance(Beam@64.1kV	1.2	mPerv
	(Gun@53kV)	1.56	mPerv
	Life Time	120,000	hours
	# in 3 cryomodule	13	
	Focusing	Permanent magnet	
	Type of Klystron	Modulated Anode Type	
DC Power supply per 3 cryomodules			
	# of klystron (3 cryomodul	13	
	Max Voltage	71.5	kV
	Peak Pulse Current	244	A
	Average Current	2.47	A
	Output Power	177	kW
	Pulse width	2.2	ms
	Repitition Rate	5	Hz
	Voltage Sag	<1	%
	Capacitor	26	mF
Bouncer Circuit			
	Capacitance	260	mF
	Inductance	4.9	mH
M. Anode Modulator			
	Anode Voltage	53	kV
	Anode Bias Voltage	-2	kV

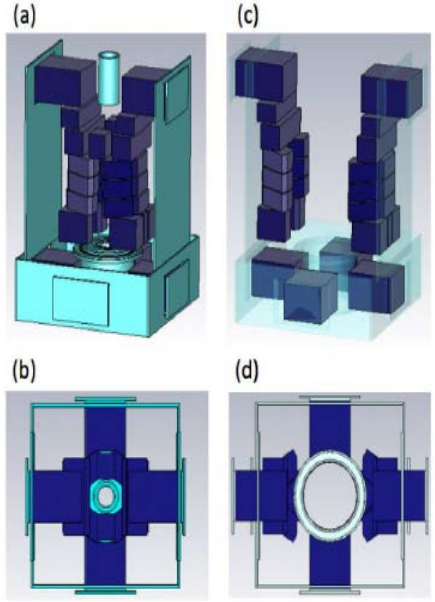
PM Focusing for DRFS Klystron

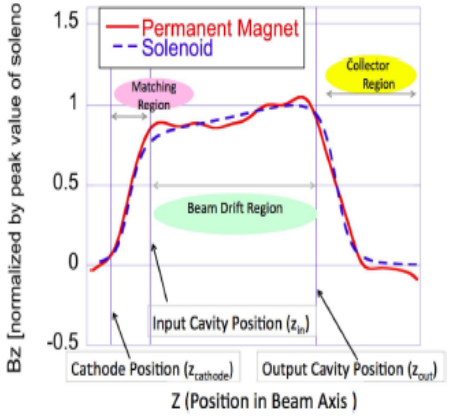
(Power Saving of RF System: Permanent Magnet Focusing by Fuwa)

Using ferrite magnet focusing, DRFS klystron was operated
And obtained the comparable performance as electromagnet.









Mechanically moving to the beam Axis enables to reduce the bulk Volume of the magnet.

Operating power is reduced and ILC needs this technology.

Axial symmetry requirement is the most difficult point
To achieve the comparable efficiency.

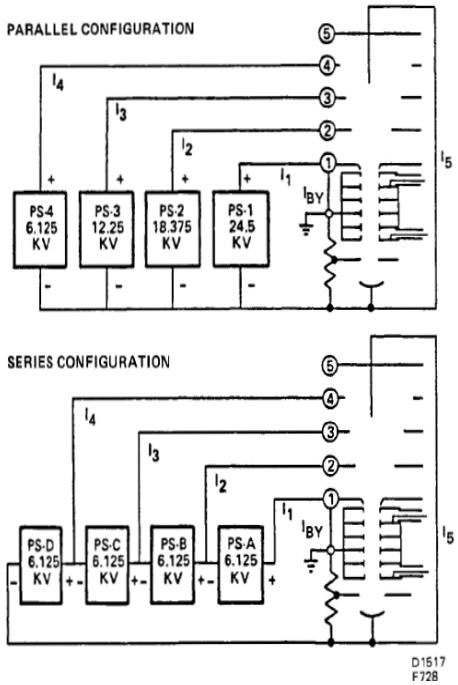
Efficiency Improvement Trial

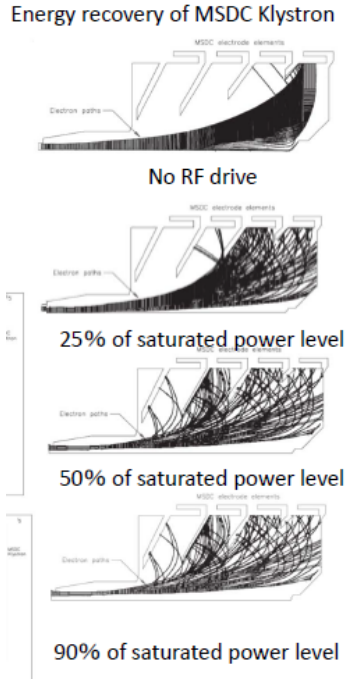
Efficiency Improvement by Collector Potential Depression

- Concept and States of Art

So called MSD (Multi-stage Depressed Collector) klystron was developed to improve the efficiency. Depressed collector/potential depression technology is the way that dissipated power I the collector is back to PS by depressed collector potential.

For high power klystron, KEK tried to develop this technique to raise the efficiency.





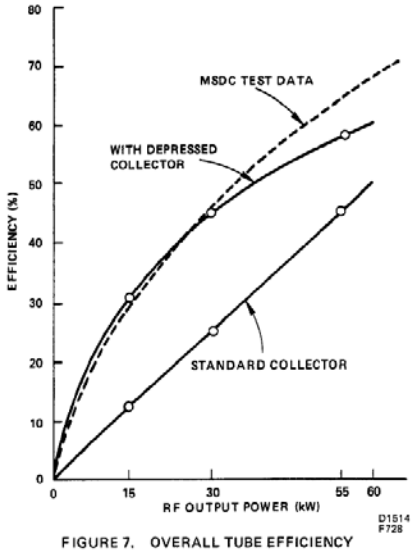


FIGURE 7. OVERALL TUBE EFFICIENCY

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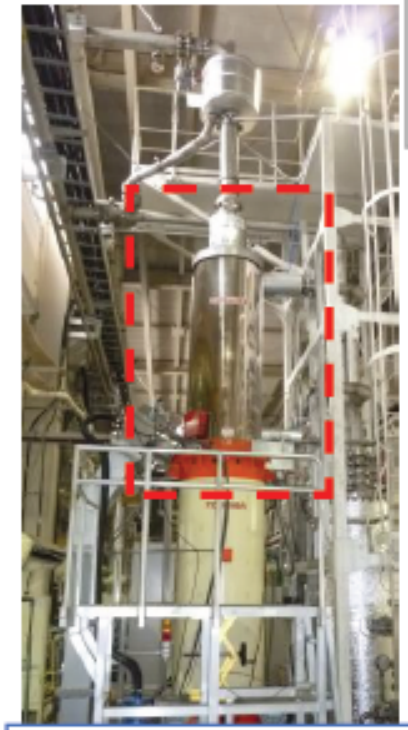
Fabrication of the CPD klystron for the demonstration

CPD (Collector Poteitial Depression) is an energy-saving scheme that recovers the kinetic energy of the spent electrons after generating rf power. Existing klystron was used to fabricate the CPD klystron at 2013 (Toshiba 37703 CPD). Target is a proof-of-principle of CPD to apply the CW klystron in the unsaturated region.

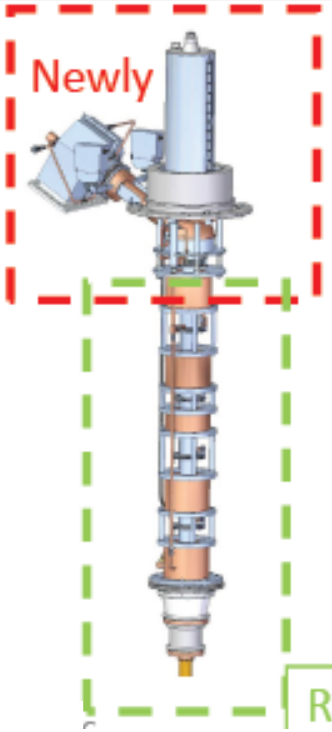
Recycled components were the electron gun, the Input cavity and the middle cavities in drift tube.

Newly fabricated components were the output cavity, the output coupler and the collector with CPD gap.



E3786 (T-44A)
Fabricated at 1989

Toshiba 37703 CPD
June 2014



Concern

***Leak wake field to outside klystron from CPD gap**

***Corona discharge around CPD gap**

***Radiation shield**

Must be clear these items for the operation.

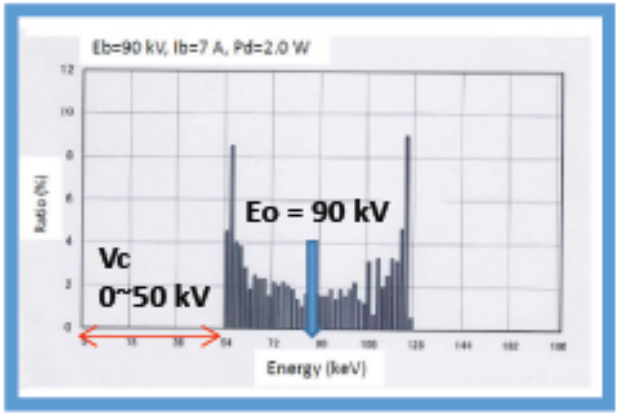
Limitation of the output power by backward electrons

In case of a klystron, the spent electron beam has large energy spread through electromagnetic interaction in the cavities at the saturated operation.

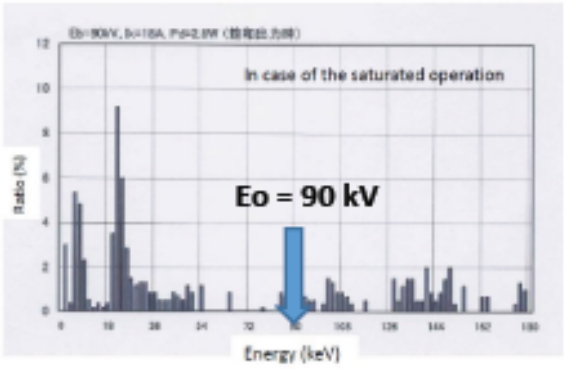
Therefore, the collector potential cannot be increased beyond the lower limit of distribution of the spent electron beam, otherwise backward electrons hit the cavities, and then deteriorate the klystron performance to apply CPD method.

Saturate : 1.2 MW ~ 65 % <- cannot apply CPD

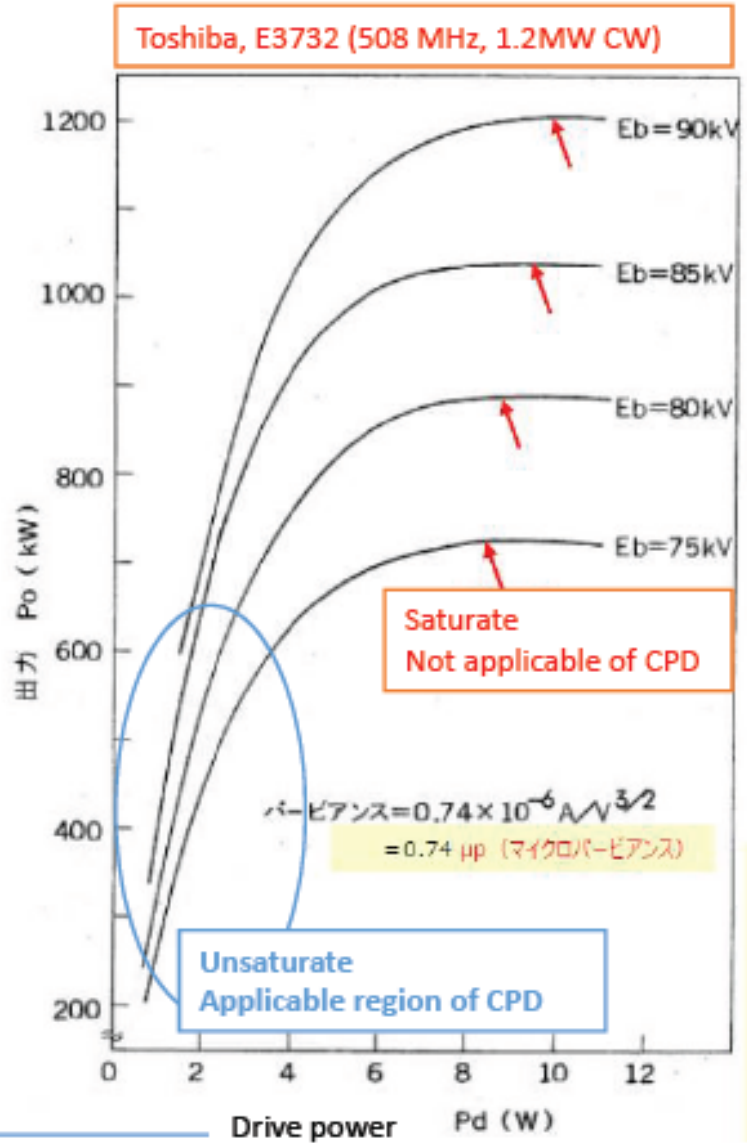
Unsaturate: 200-500 kW 30-50 % <- 50-70 % by CPD



Unsaturate: 200 kW out



Saturate: 1 MW out



Energy distribution of the spent electron beam after pass through the output cavity.

Issues must be addressed for CPD Klystron

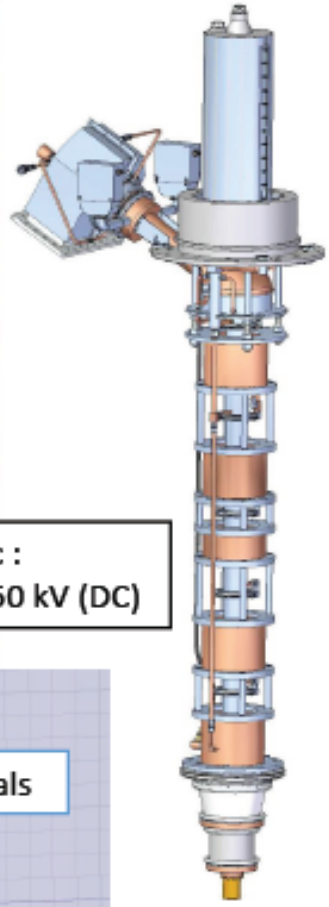
The CPD klystron has an insulator to insulate between the body and the collector for the energy recovery. In this case, three issues must be addressed for the operation. That is;

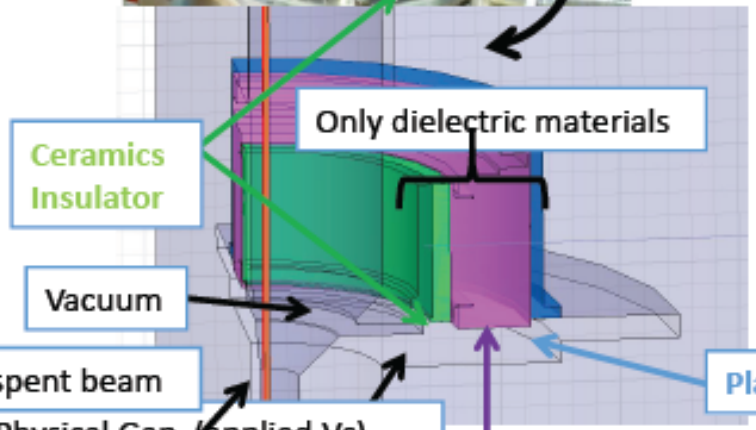
(a) Corona discharge, breakdown;
around the ceramics insulator and the outside of klystron .

(b) RF leakage;
from the physical gap and the dielectric materials.

(c) Structure of the Radiation shield;
to cover the top of the klystron.

Under designing of the RF and radiation shield to optimize for the test of CPD klystron.

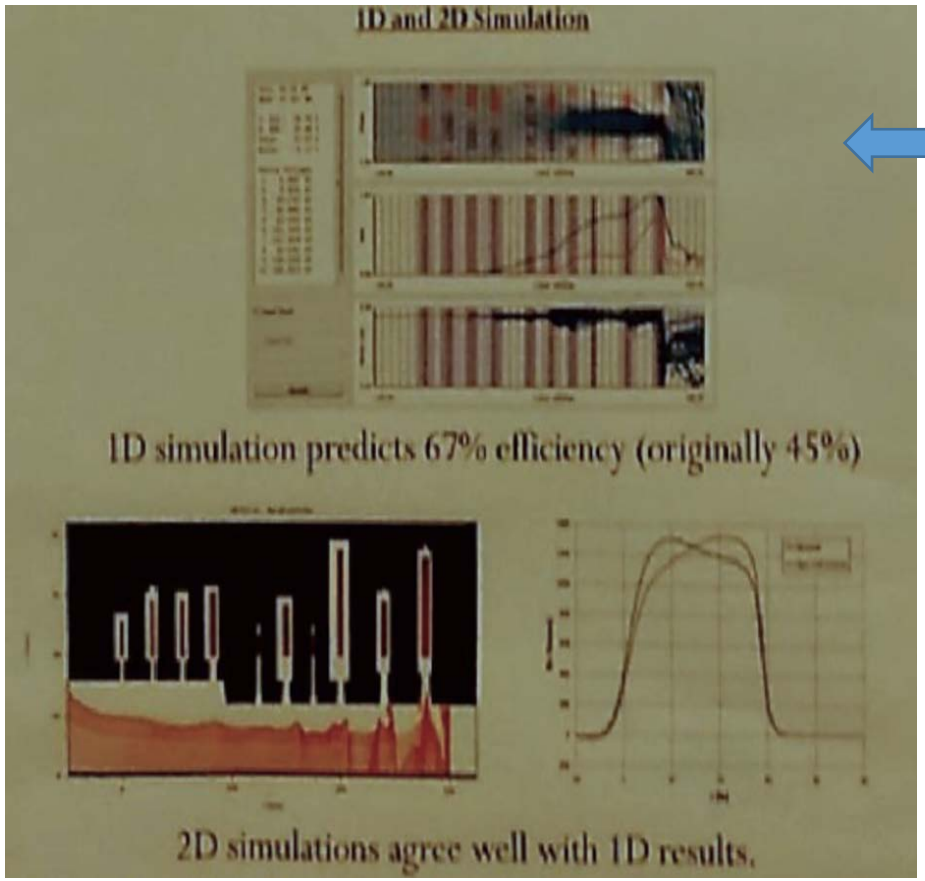




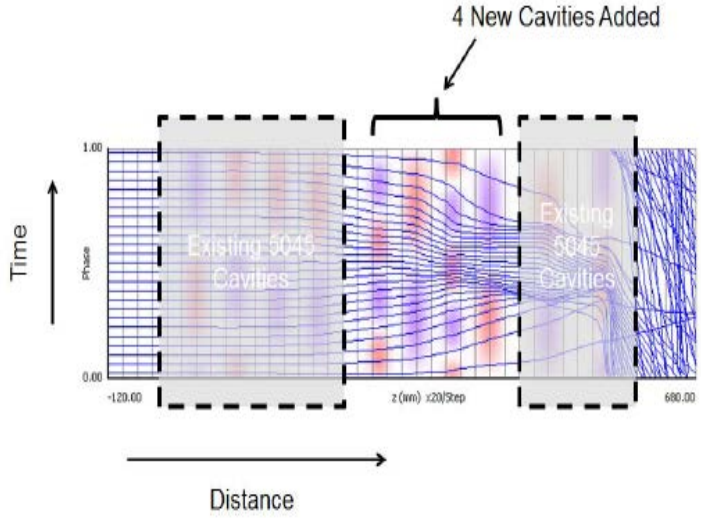
Recent Trend for the High Efficiency Approach

- One possible approach is applying the BAC technology to S-band 50 MW klystron (just started for next fiscal year).
- In KEKB injector linac, we need to have an energy margin to get more stand-by klystron.
- Another likely approach is to apply to the efficiency improvement for ILC klystron for the electron-driven position source: 1.3 GHz 50 MW klystron and 2.6 GHz 80 MW klystron.
- Hints are come from A. Jensen's approach for 5045 klystron presented at IVEC 2015 in Beijing. **BAC approach is especially effective for high perveance klystron with ~2 μperv.**

A. Jensen applied BAC tech. to 5045 klystron to raise efficiency



A. Jensen's poster at the IVEC2015



Four cavities are inserted to Long drift tube section to raise the efficiency. New cavities are called BAC function, bunching, aligning and collecting the bunch.

First attempt was not succeeded, but after some revisions, he obtained then good results. (IVEC2016, informed by the person).

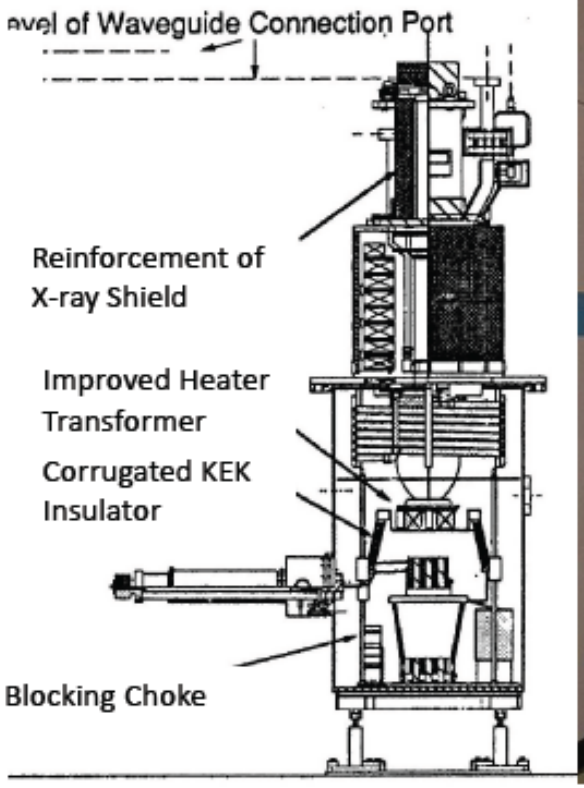
Particular feature is that even in the high perveance tube as 2 micro perveance, more than 60 % of efficiency was achieved.

S-band 50 MW Pulsed Klystron in KEK

boratory, KEK

Toshiba E3730

MELCO PV3050



60 of both klystrons are operated in KEKB linac. Specifications are completely same and both are compatible.

Pulse transformer, tank assembly and installation way were designed by S. Fukuda.

Attempt to apply BAC to KEK 50 MW klystron

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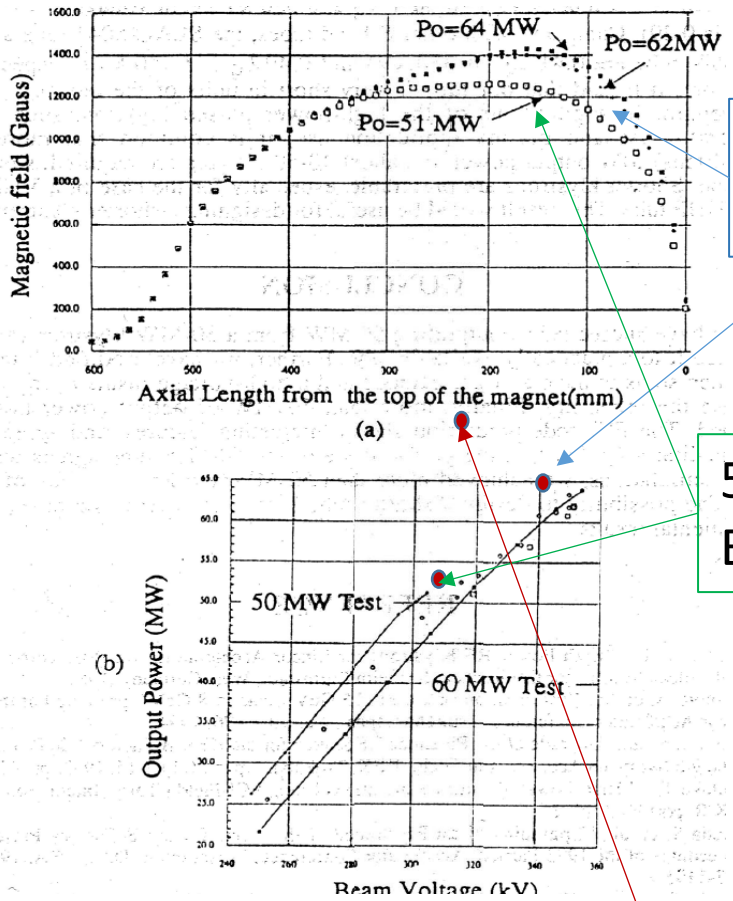


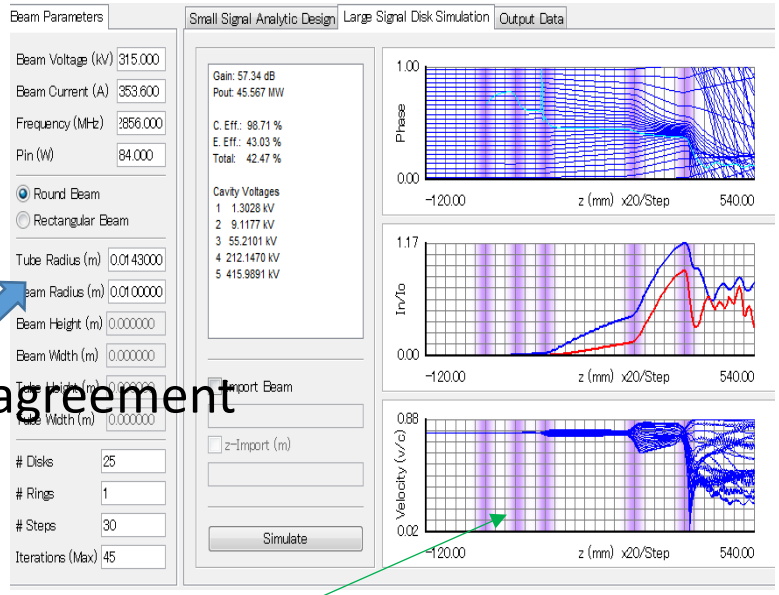
S-band 50 MW
Test data

64MW @354kV
Eff.=41% (1996)

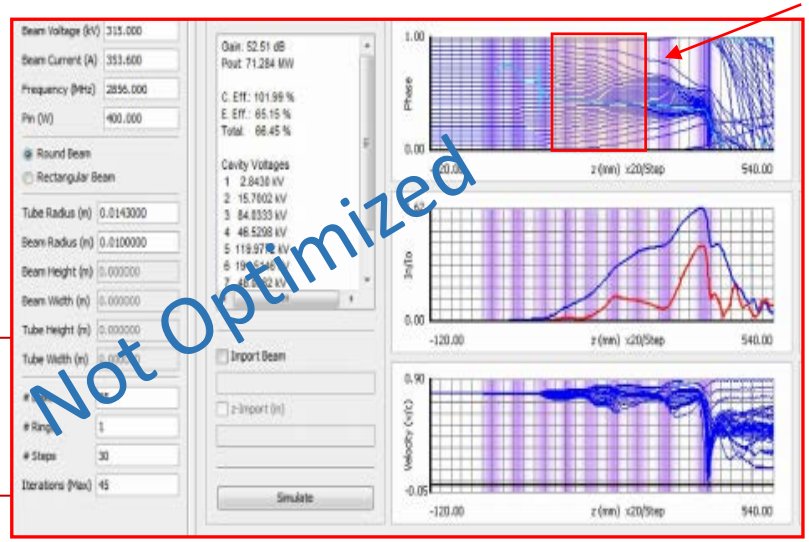
51.5MW @305kV
Eff.=46% (1995)

71MW @315kV
Eff.=66% (2017)

Ajdisk not good agreement



Existing Cavity Layout



BAC Cavity

Penultimate cavity is
Moved to output cavity
Side but same total
length

Need optimization

Need 2.5D simulation

BAC Cavity Layout (Trial)

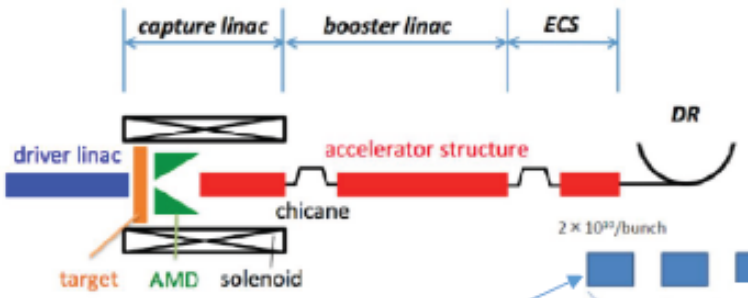
We can obtain higher efficiency anyway.

Main-ILC-Project Klystron for Positron-Source

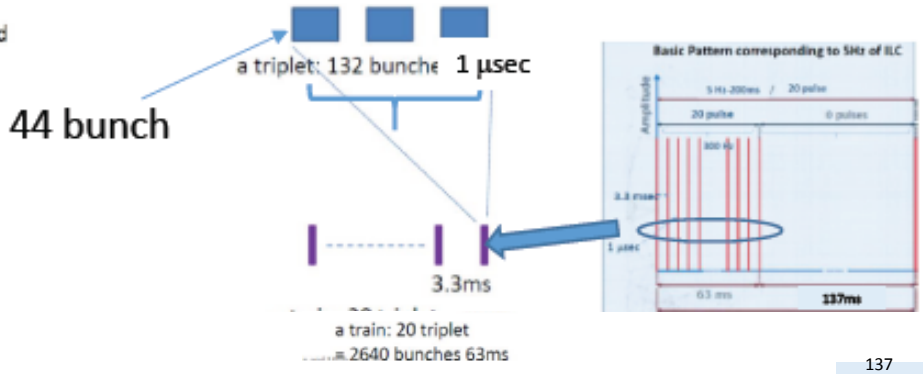
(Back-up plan of Electron Driven Accelerator)

- ILC basic design for positron source is adulator scheme, while this technology is not well matured. Back-up plan by electron driven accelerator is checked.
- New klystrons with higher efficiency are desirable and it will be the future task. Budget is not approved and trying to look for the solution.

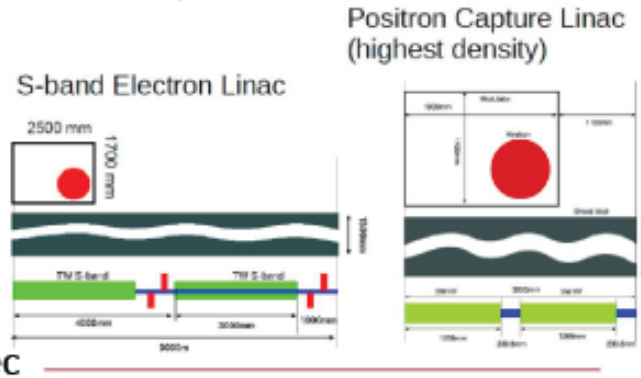
300 Hz rep. rate for klystron, 1.3 and 2.6 GHz frequency for main L-band superconductive cavity.



20 pulse for 63msec
(~300 Hz)
No pulse for 137msec



RF Unit Layout



High Density Layout

RF unit

Large number of tubes

Component	Specifications	Number (1 by 1)	Number(2 by 1)
Accelerator	1.27 m L-band SW	28	28
Accelerator	2.0 m L-band TW	71	116+4
Accelerator	2.0 m S-band TW	48	76
~~Accelerator~~	~~2.0 m S-band TW~~	~~190~~	~~190~~
Klystron	50 MW L-band	85	74
Klystron	80 MW S-band	108	98

137 ms

Klystron, modulator and layout plan

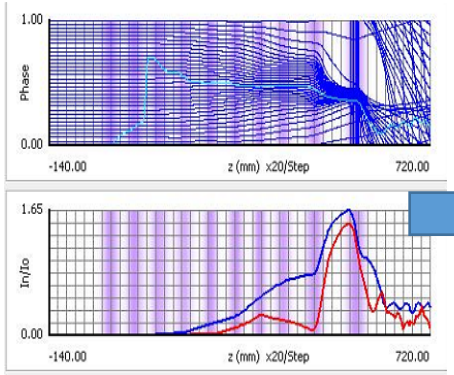
(Back-up plan of Electron Driven Accelerator)

Accelerator Laboratory, KEK

New L-band/High efficiency is required

Main Parameters	Value	Unit
RF Frequency	1300	MHz
Peak Power	50	MW
Average RF Power	22.5 (0.3)[1]	kW
Pulse width	0.5 - 1.5	μs
Pulse Repetition	1 - 300 (3.8)[1]	Hz

[1] Corresponding to 3,8Hz op



New S-band /High efficiency is required

BAC Method Tentative 65% Design

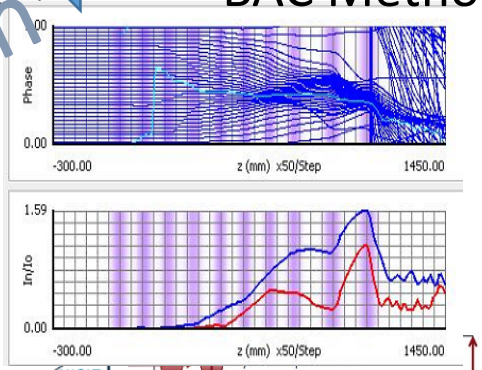
Main Parameters	Value	Unit
RF Frequency	2600	MHz
Peak Power	80	MW
Average RF Power	36 (0.4)[1]	kW
Pulse width	0.5 - 1.5	μs
Pulse Repetition	1 - 300 (3.8)[1]	Hz

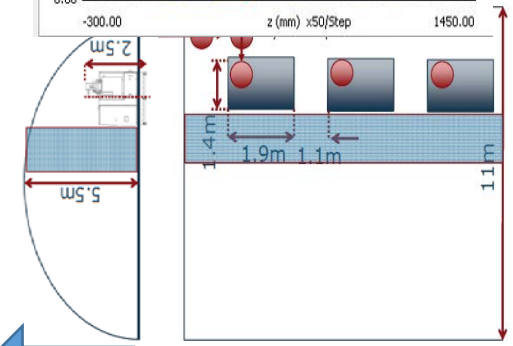
[1] Corresponding to 3,8Hz operation

BAC Method Tentative 65% Design

L-band system

S-band system



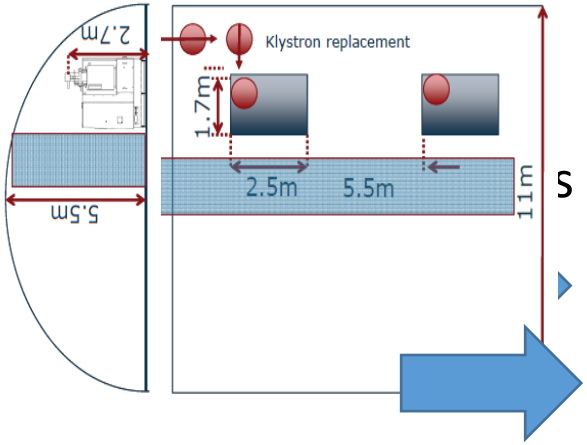


KEK CONCEPT DESIGN 50MW C-BAND
– SOLID STATE MODULATOR PARAMETERS

Main Parameters	Value	Unit
Peak Power	127	MW
Average Power	95 (2)[1]	kW
Klystron Voltage	370	kV
Klystron Current	344	A
Pulse width (FWHM)	2 - 2.7	μs
Mains current at 420VAC	230 (4)[1]	A
Single phase current	7	A

[1] Corresponding to 3,8Hz operation

OPTIONS: Integration of ...
- Solenoid Power Supply
- Ion Pump Power Supply
- RF Drive amplifier
- Cooling of Klystron (Collector, Body), Solenoid
- All diagnostics and interlocks



S

KEK CONCEPT DESIGN 80MW S-BAND
– SOLID STATE MODULATOR PARAMETERS

Main Parameters	Value	Unit
Peak Power	200	MW
Average Power	150 (3)[1]	kW
Klystron Voltage	400	kV
Klystron Current	500	A
Pulse width (FWHM)	2.3 - 2.9	μs
Mains current at 420VAC	350 (6)[1]	A
Single phase current	7	A

[1] Corresponding to 3,8Hz operation

OPTIONS: Integration of ...
- Solenoid Power Supply
- Ion Pump Power Supply
- RF Drive amplifier
- Cooling of Klystron (Collector, Body), Solenoid
- All diagnostics and interlocks

International Collaboration on Klystron (With China and India)

Collaboration between KEK and IHEP in China

- Since 1995, after Fukuda's visit to China, klystron collaboration has started.
  - S-band pulsed klystron improvement and vendor's education for manufacturing system (ex. 4404 Company)
  - Gifting the MELCO PV3030 – 30MW Klystron (no use in KEK after KEKB)
  - Gifting the X-band old-model klystron developed in KEK
  - Collaboration of developing 5045-like klystron
  - Consulting for the IHEP's 50-MW Klystron Procurement; KEK's system is introduced via Toshiba
  - Helping the procurement of MELCO S-band klystron as the competitive tender
  - C-band klystron magnet collaboration with Shanghai Light Source

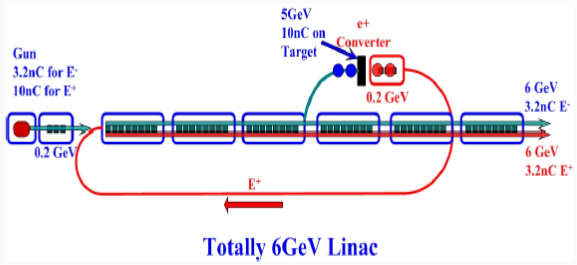
China Recent Accelerator Status & RF

Accelerator Laboratory, KEK

Current Leading Plan by IHEP （中国高能研究所）in China

- **BEPCII** Linac Operation
  Power, Energy Upgrade plan
- **CEPC Project as the future big plan**
  (Chinese Electron-Positron Collider)
- NSC KIPT （China-Mongol plan）
- **ADS** commissioning d

Linac power source



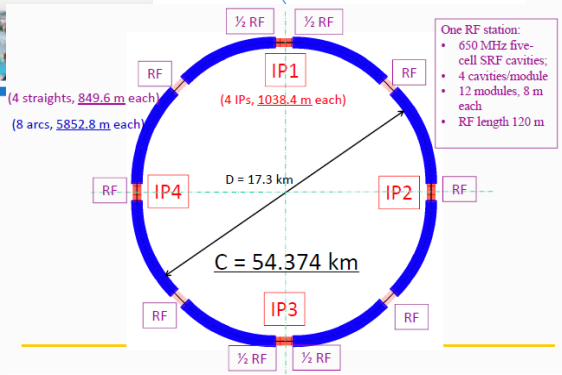
Linac includes 35 set RF power sources, klystron output power more than 65MW （ 80MW ） and related modulator is about 200MW。

Collider power source

CEPC collider SRF system parameters

Parameters mode	Value
Operation frequency	650MHz+/-5MHz
Cavity Type	650MHz 5-cell
Cavity number	384
RF input power (kW)	260 CW
RF source number	384

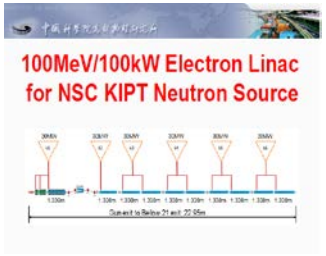
Considering klystron lifetime and power redundancy, each cavity will be individually powered with a CW klystron capable to deliver more than 400 kW.



Parameters of 80MW klystron (TOSIBA E3712)

Parameters mode	Value
Frequency(MHz)	2856
Output power(MW)	80
Efficiency(%)	42
Gain(dB)	53
Pulse length(us)	4
Pulse rate(pps)	100
Beam voltage(kV)	400
Beam current(A)	488
Drive power(W)	350

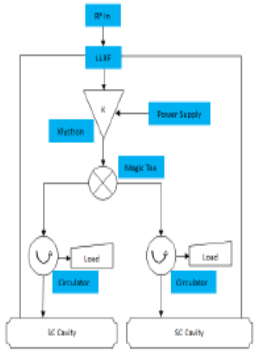
sed 80MW klystron is a mature technology and several nufacturers can meet or exceed the power requirement.



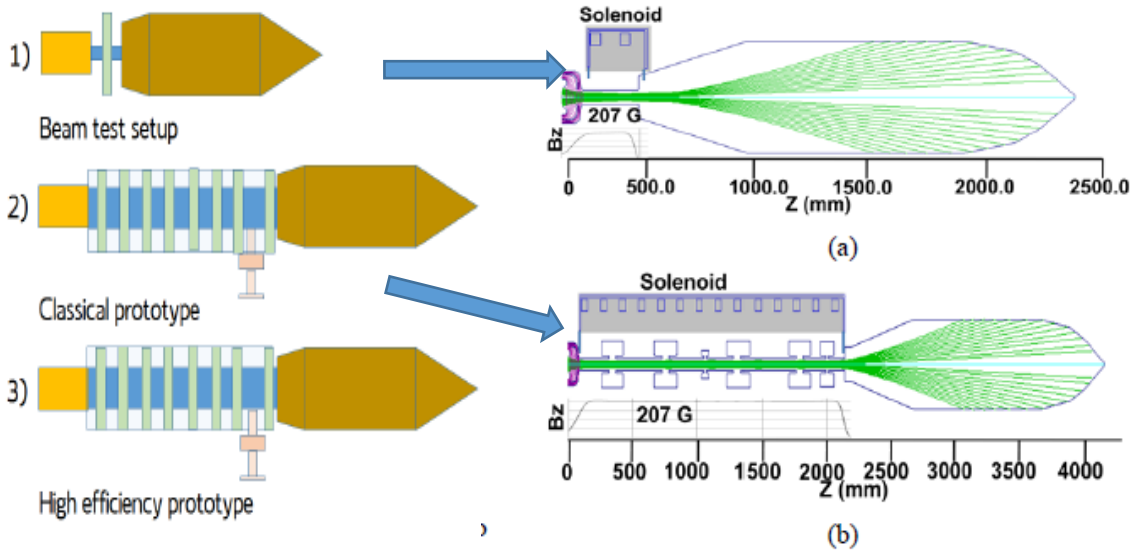
CEPC Project and Klystron (under going)

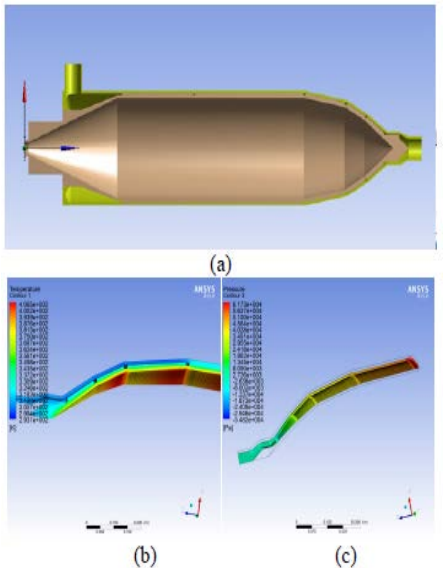
CEPC Collider SRF System Parameters

Frequency	MHz	650
Cavity type	5-cell	5-Cell
Cavity No.		384
Kly. No.		192
Kly. power	kW	800

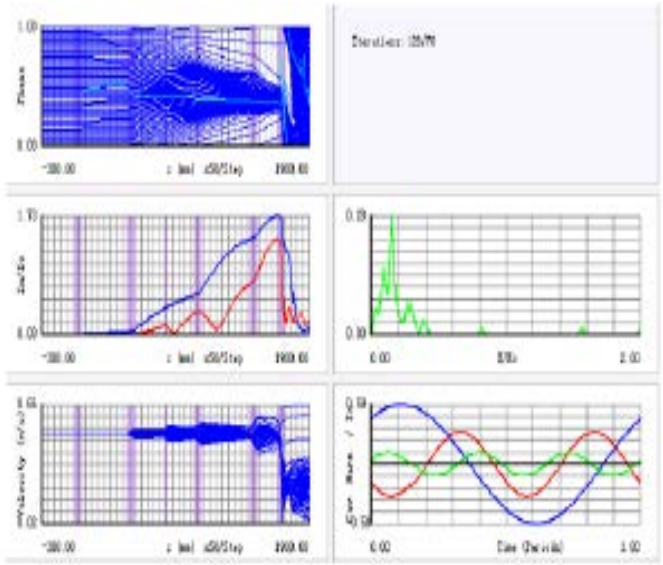


: RF power source configuration.





Strategy to manufacture tube in China



Ajdisk: 74%

Current Status

- Mechanical design of test tube
- Coaxial window design to manufacture and test
- Director requests us to have more than 80% efficiency, and 2.5D simulation will be desirable using FCI, Magic and CST
- Manufacturing infrastructure such as backing and exhausting furnace is needed

S. Fukuda Talk in IAS2017

- Longer interaction region

-> Bigger furnace required

- MBK as alternative design
- How to increase efficiency in Linear region?

- Possibility to collaborate with company other than China……..

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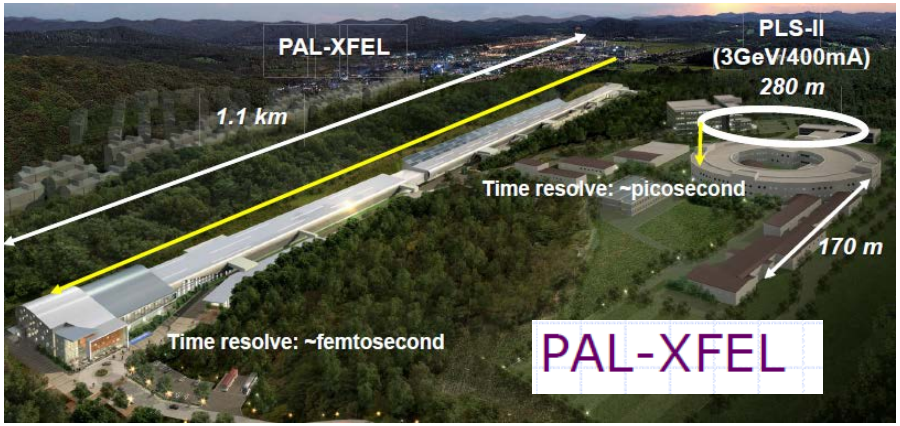
S-band High Efficiency Klystron R&D in POSTECH KOREA



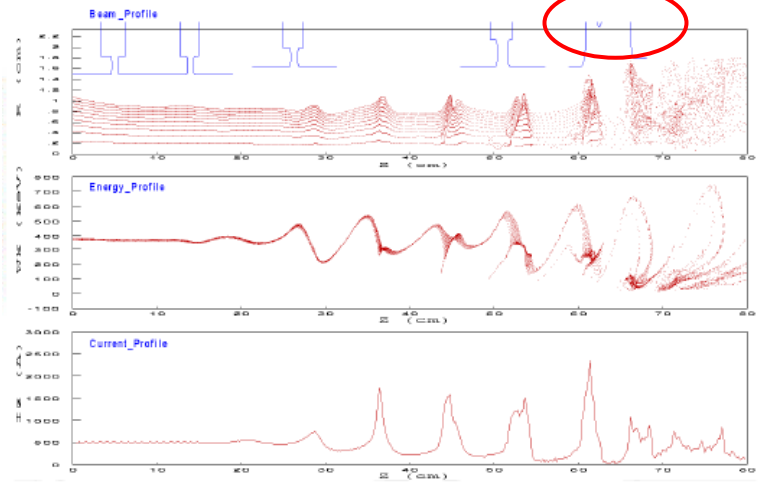
In POSTEC 2 facilities use S-band 80-MW klystrons which are manufactured by in Toshiba.
They have in-house manufacturing facility which repairs some of the failure tube.

Recently high efficiency 80-MW klystron aiming for more than 60% is started.

Their approach is using the TW structure output cavity
And tentatively they got the 60% efficiency.

Needs to check by another Simulation code.

TW structure



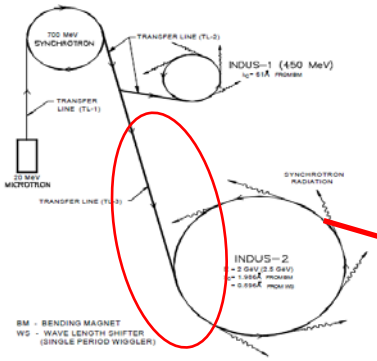
P_{out} = 120 MW, efficiency = 60%

India Recent Accelerator Status & RF

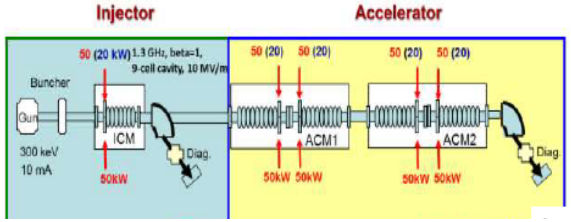
Accelerator Laboratory, KEK

- India is one of advanced accelerator country and there are many small accelerator facility. Domestic medical accelerators are intensively progressed. Japan-India collaboration on accelerator had been promoted by Japanese government.

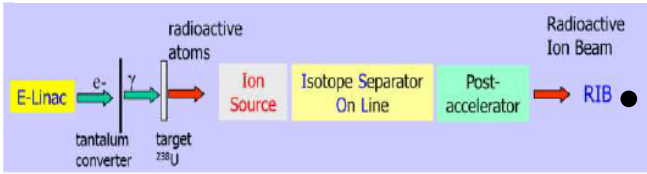
- **Indus2 Upgrade Plan (RRCAT)**



India biggest light source
Indus reformation plan
Introducing Linac
And use the S-band
50MW Klystron

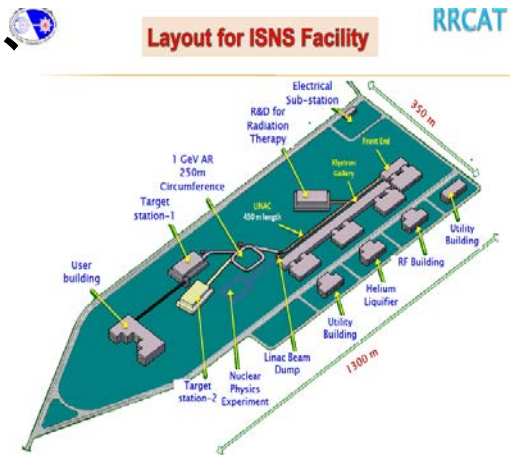


VECC electron linac + Ion Accelerator
50MeV/100kW CW Superconducting : 1.3GHz



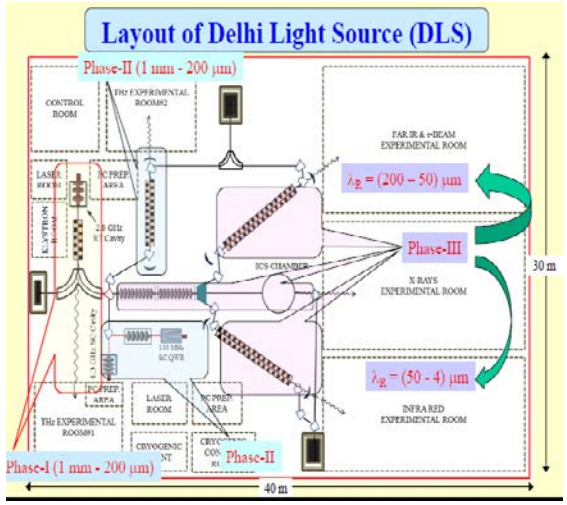
IUAC Future plan

RRCAT Indian SNS Plan
Superconducting
650MHz



DLS : FEL
Phase1:2860MHz
RF-Gun
S-band Klystron
(Toshiba+Scandinova)

Phase2:1.3 GHz SC



What kind of high efficiency is important for the big project?

Important Remarks for High Efficiency Hunting(1)

1. Usual attempt to higher efficiency in klystron is to raise the efficiency at saturation point.

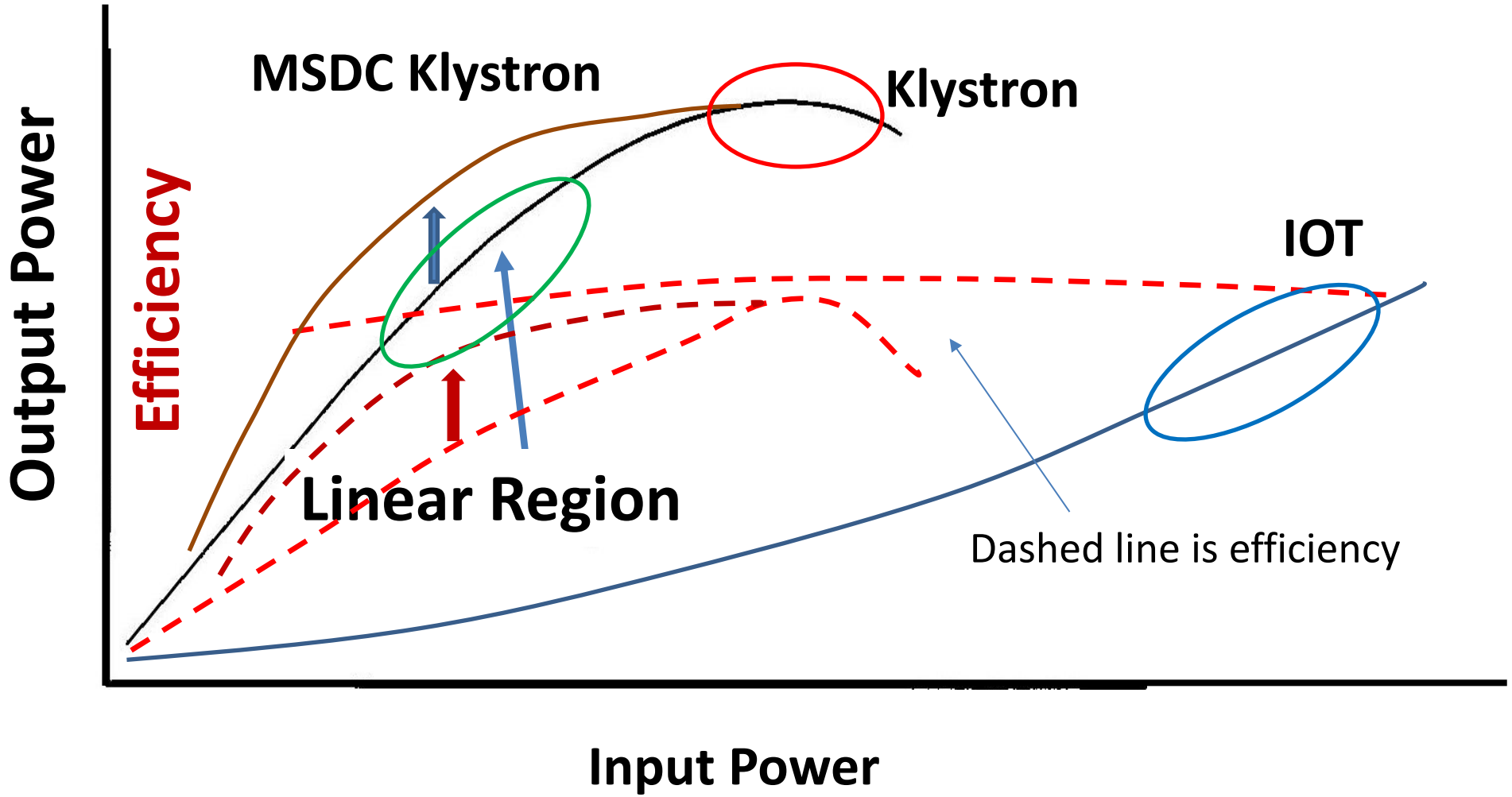
   While, actual operating point is in the linear region in the transfer curve and efficiency is lower than saturation point.

   Raising the efficiency in the linear region is obtained by IOT, while MB-IOT R&D is required.

   MSDC or CPD described here is another possible way but still needs R&D.

Transfer Curve of Klystron and IOT

Klystron: Efficiency at saturation point is high but operation point (linear region) is lower efficiency. MSDC possibly raises the efficiency in linear region.
IOT: Efficiency is high in wide range. Output power is lower than klystron



Important Remarks for High Efficiency Hunting(2)

2. High efficiency approach requires extra cavities to employ COM method or BAC method to collect the peripheral electrons.

   Extra cavities introduction resulted in the longer interaction region, and then especially for the klystron operating at lower frequency long klystron is manufactured. **Baking furnace is a bottle neck.**

   One of solving this shortage is using MBK. But still sometimes long tube is required.

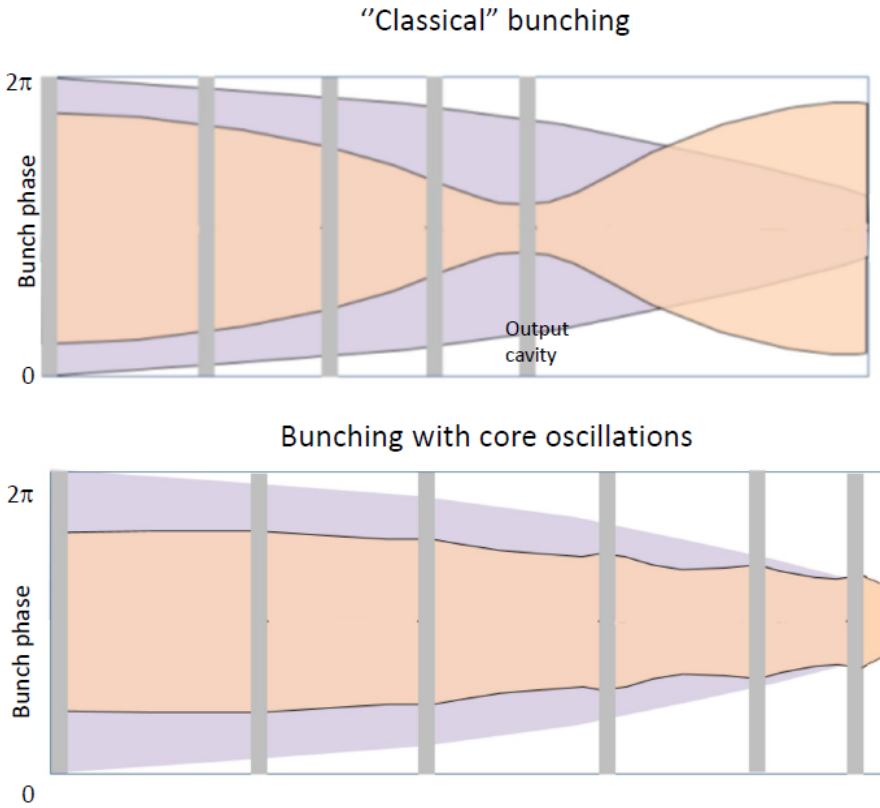
   BAC is very good way for higher frequency with higher perveance tube.

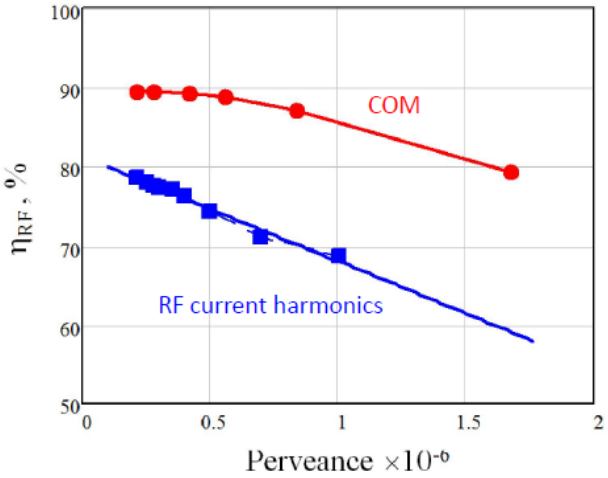
Accelerator Laboratory, KEK

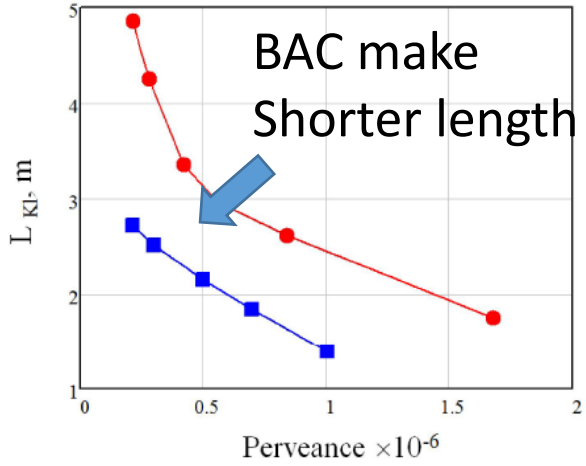
COM Approach
Efficiency and Tube Length Relation

- COM (Core Oscillation Motion)

From "High-efficiency_klystron_development_-_HEIKA", By I. Syrchev, etc @HG2015.







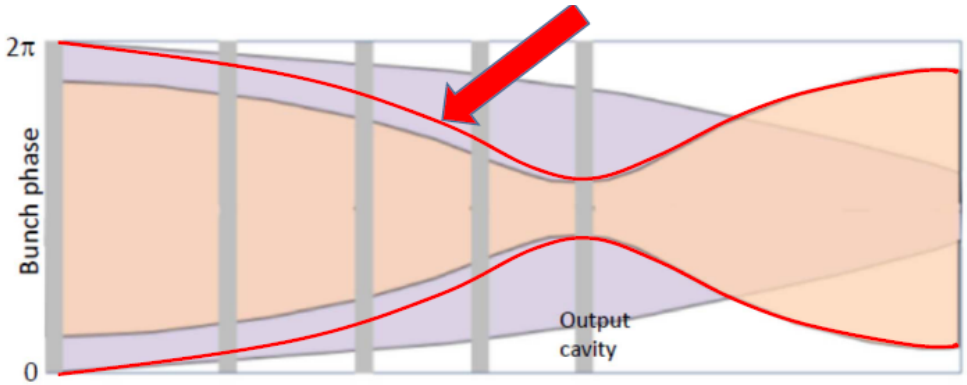
Since the COM prolong the main component of bunch to forward position **where peripheral beam are collecting.** Therefore efficiency is higher and tube is longer than classical design.
BAC is another way to raise efficiency…….

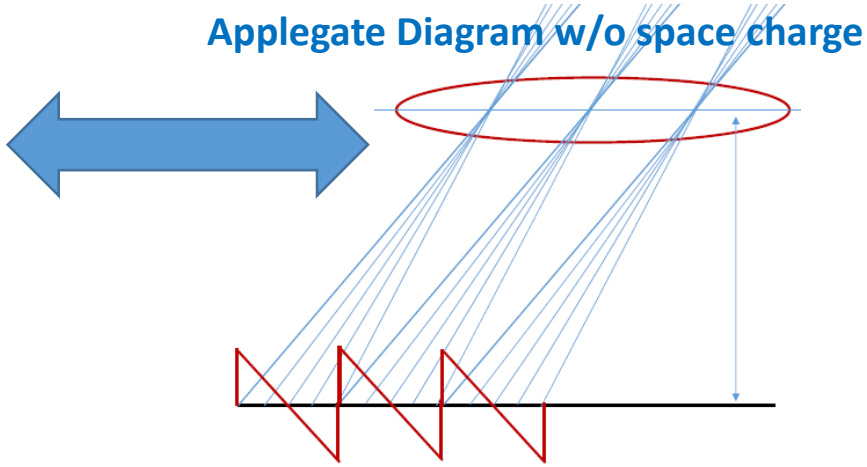
Important Remarks for High Efficiency Hunting(3)

3. Input gap modulation is changed to collect the peripheral electrons at the first COM. This does not required the longer tube length.

   Most simple idea is using the gridded gap applied the saw-tooth wave voltage modulation. Principally it is possible to get the high efficiency.

   It is necessary to consider the beam loss in the grid section.





Thanks for Listening my Talk !