R&D of the CPD (Collector Potential Depression) Klystron at KEK

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Note:
The purpose of this R&D is improvement of efficiency of a CW klystron.
Target is a proof-of-principle of CPD to apply a CW klystron in the unsaturated region (a maximum rf power of 500 kW) using a KEKB 1.2MW-CW-klystron (Toshiba E3732 or E3786). A CPD klystron (E37703 CPD) was fabricated at 2013.
However, this CPD klystron will not be installed in Super KEKB in the future.
Commercial viability of it is required development of KPS (Klystron Power Supply) to optimize it. At present, this is a future task.

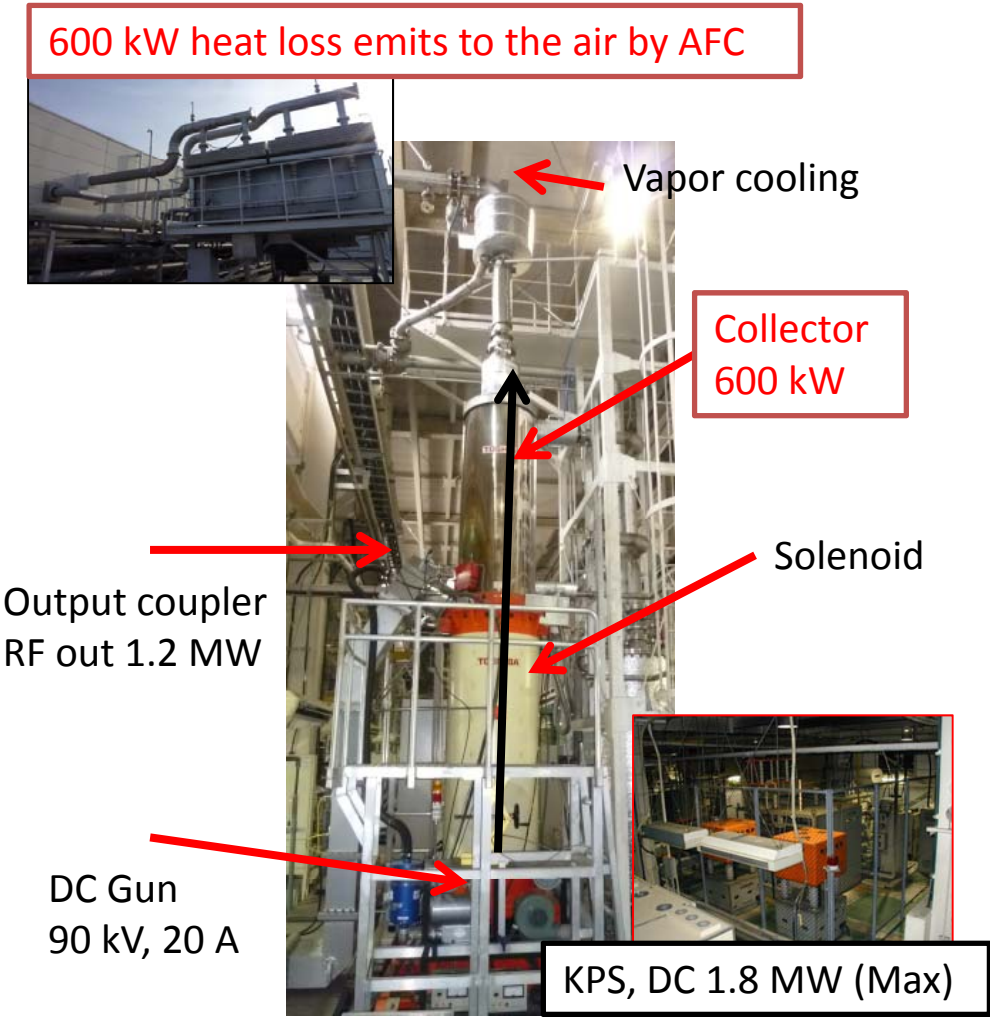
Introduction

A high power RF system always needs large electric power in the operation. An improvement of efficiency is also always required as a technology component for the energy saving.

In case of a CW klystron of MW class output power has ripened technically, improvement in efficiency of a klystron by rf design is difficult.

Therefore, to improve the efficiency of a klystron, a collector loss must reused to do the energy recovery (pick-up as electrical power from it).

Generally, a collector loss is emitted to the air as thermal energy through a cooling devices.



Toshiba E3732 (CW klystron), 508.89MHz
Used for the TRISTAN, the KEKB and the SuperKEKB.

CPD method applied to Gyrotron

To improve an efficiency of a high-power source, the CPD (Collector Potential Depression) method already was developed to apply a Gyrotron. (Up to 10 ~ 20 %)

http://www.toshiba-tetd.co.jp/eng/product/prden.php?type=cat&search=400000200000

In this case, an ceramics insulator is used to insulate between the collector and the body to be applied high-voltage of Vc (~ 30 kV) for an energy recovery.

The energy spread of spent beam at operation is important for it. At saturation, the spent beam has small energy spread through electromagnetic interaction in the cavity. Therefore, ~ 30 kV of Vc can apply on the gap to pick-up as the electrical power from the spent beam to the outside of gyrotron after generating rf power.

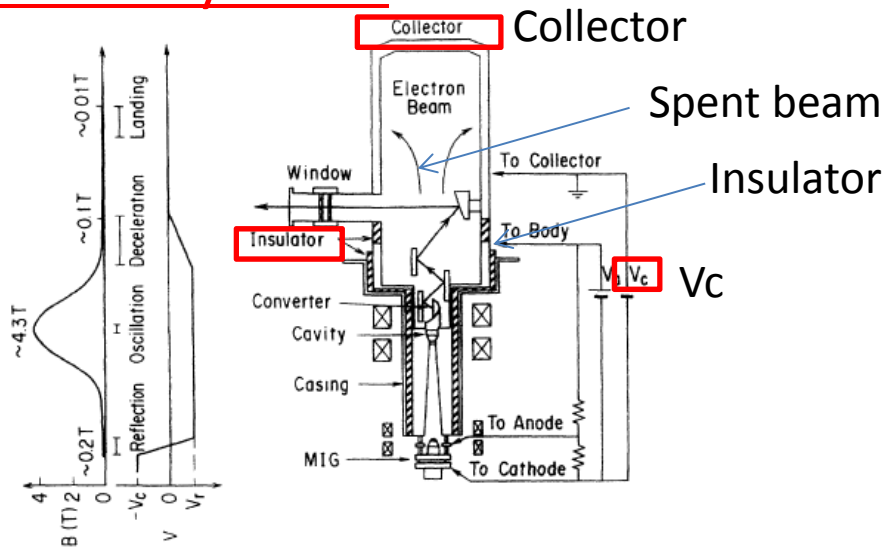


FIG. 1. Conceptual view of the gyrotron and power supply for collector voltage depressio

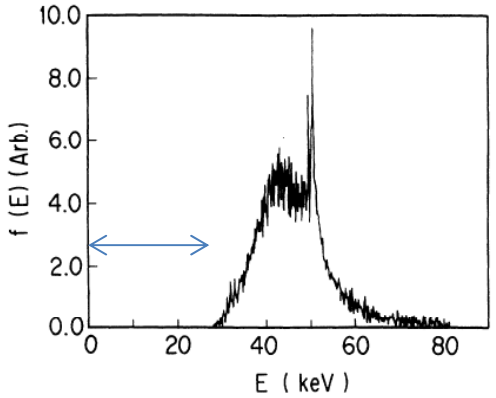
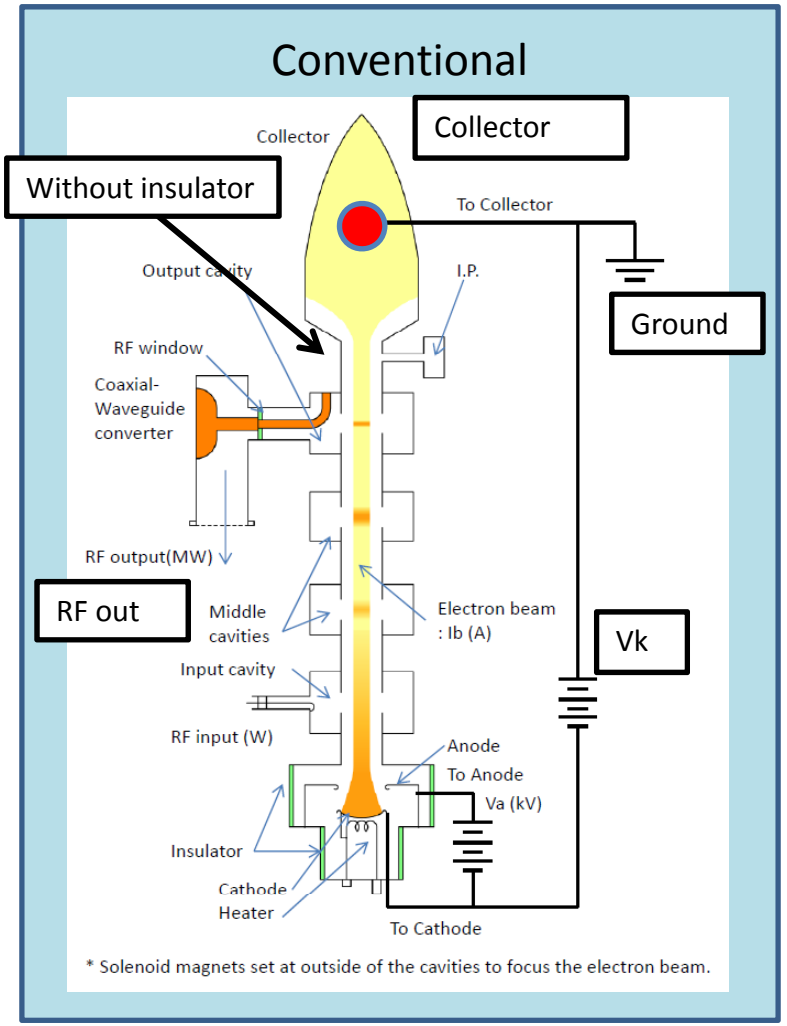


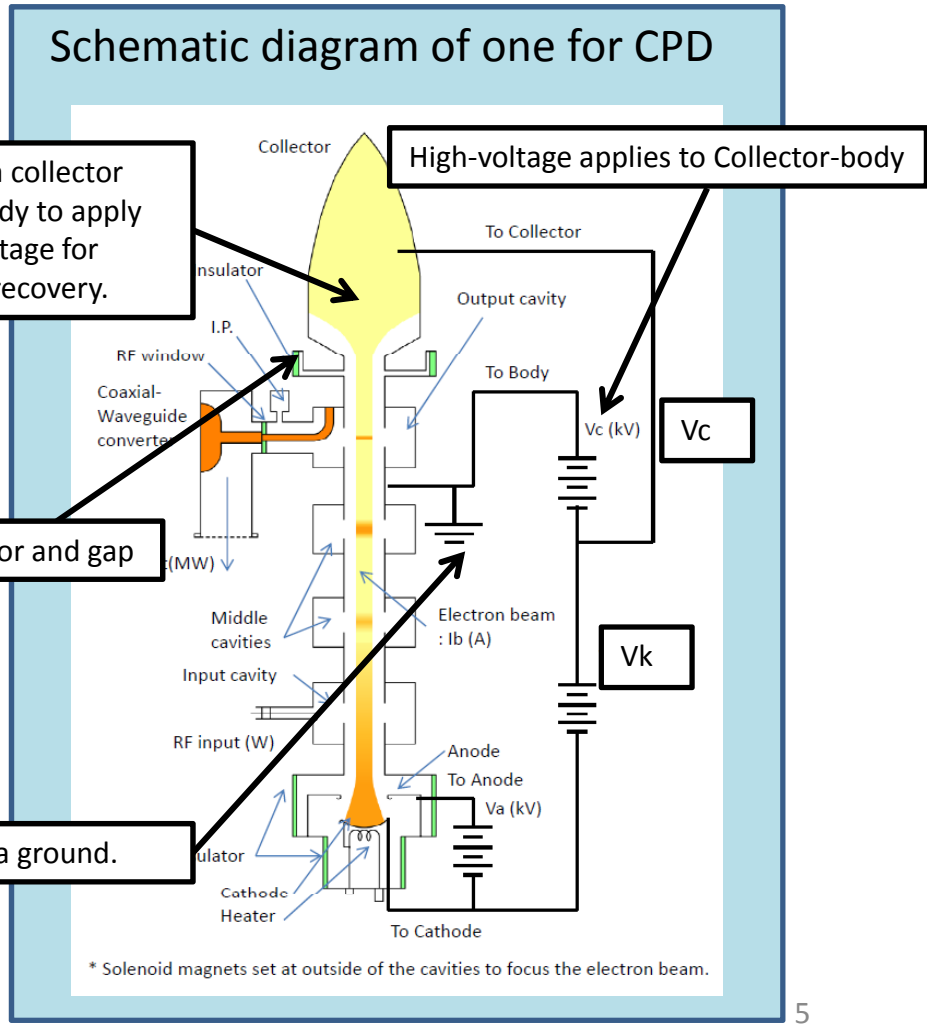
FIG. 3. Simulation result of the energy distribution of the spent beam. $I_c = 26.5$ A, $B_c = 4.33$ T, $\alpha = 1.4$, and $\Delta v_\perp / v_\perp = 8\%$. Beam energy $E_b = 76$ keV.

Ref. PHYSICAL REVIEW LETTERS, Volume 74, Number 26, pp 3532-3535, 26 December 1994
K. Sakamoto et al., "Major Improvement of Gyrotron Efficiency with Beam Energy Recovery"

How to apply CPD method to klystron

* CPD is an energy-saving scheme that recovers the kinetic energy of the spent electrons after generating rf power.





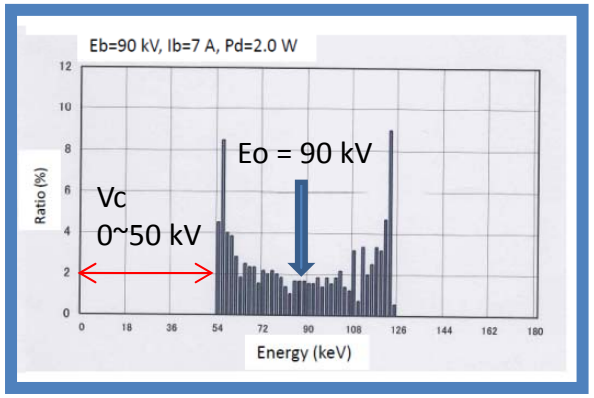
Limitation of the output power by backward electrons

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

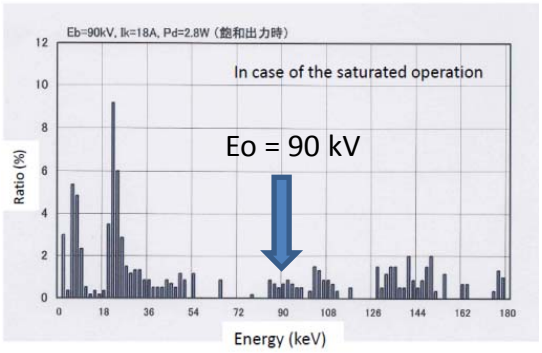
Therefore, the collector potential cannot be increased beyond the lower limit of distribution of the spent electron beam, otherwise backward electrons hit the cavities, and then deteriorate the klystron performance to apply CPD method.

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

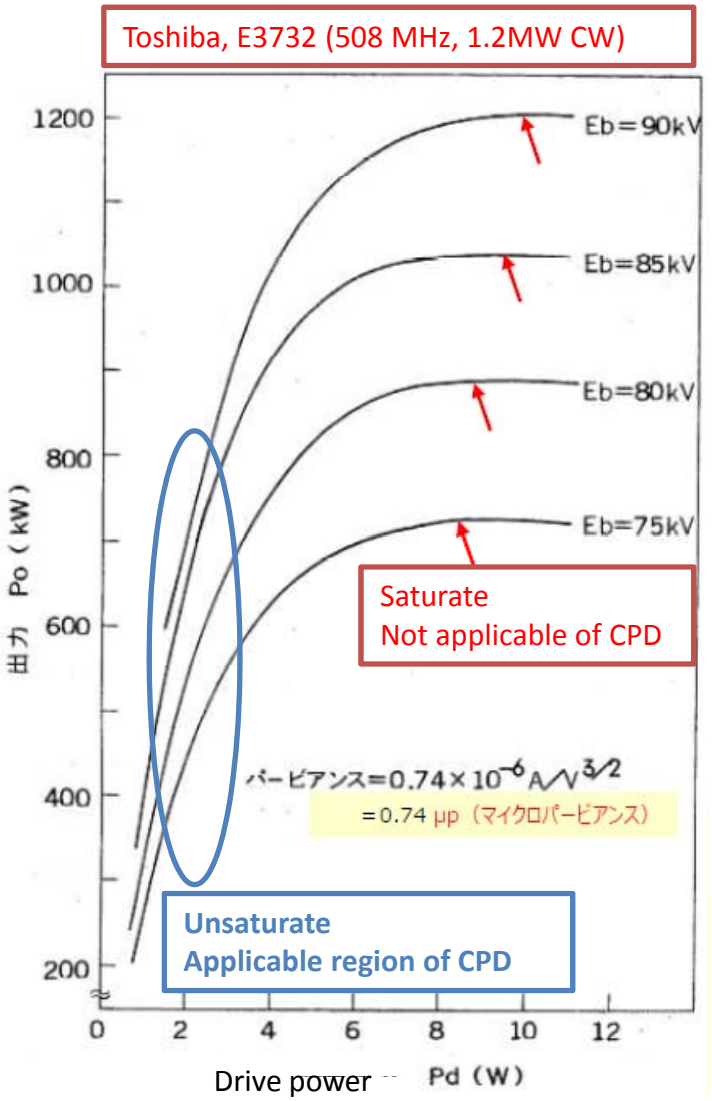
Unsaturate: 200-500 kW 30-50 % <- 50-70 % by CPD



Unsaturate: 200 kW out



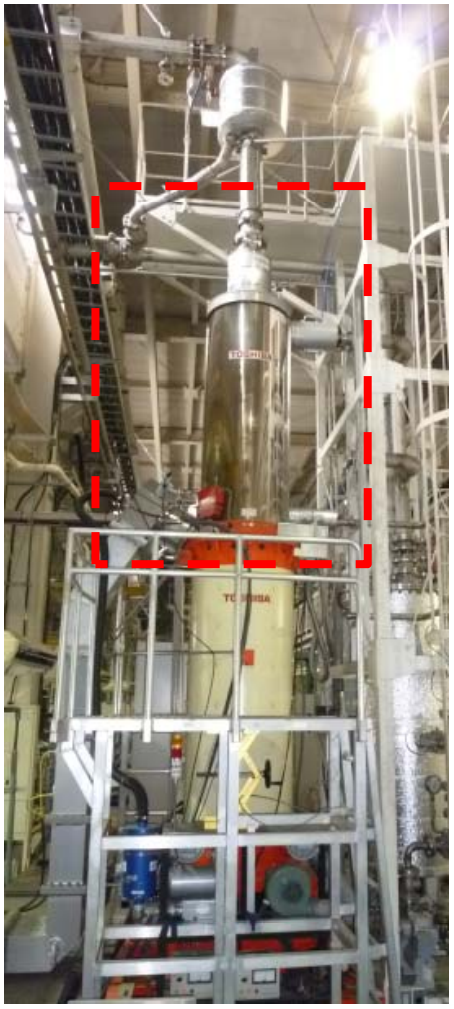
Saturate: 1 MW out



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

Fabrication of a CPD klystron for the demonstration

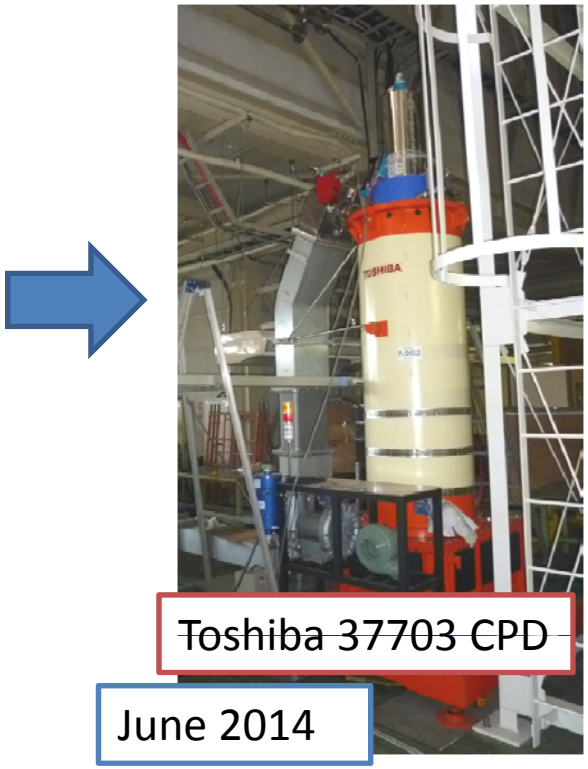
E3786 (T-44A)
Fabricated at 1989



Existing klystron was used to fabricate a CPD klystron at 2013.
(Toshiba 37703 CPD)

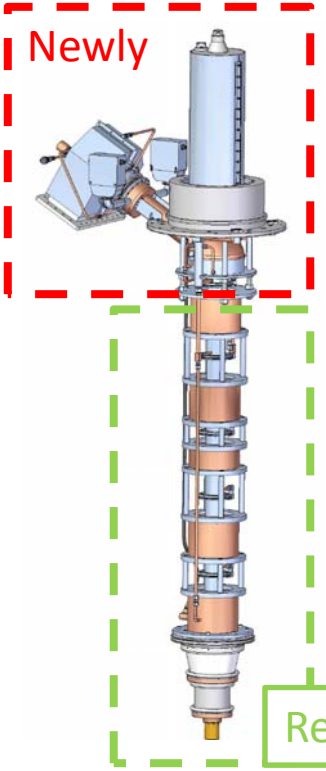
※Recycled components were the electron gun, the Input cavity and the middle cavities in drift tube.

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



~~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.

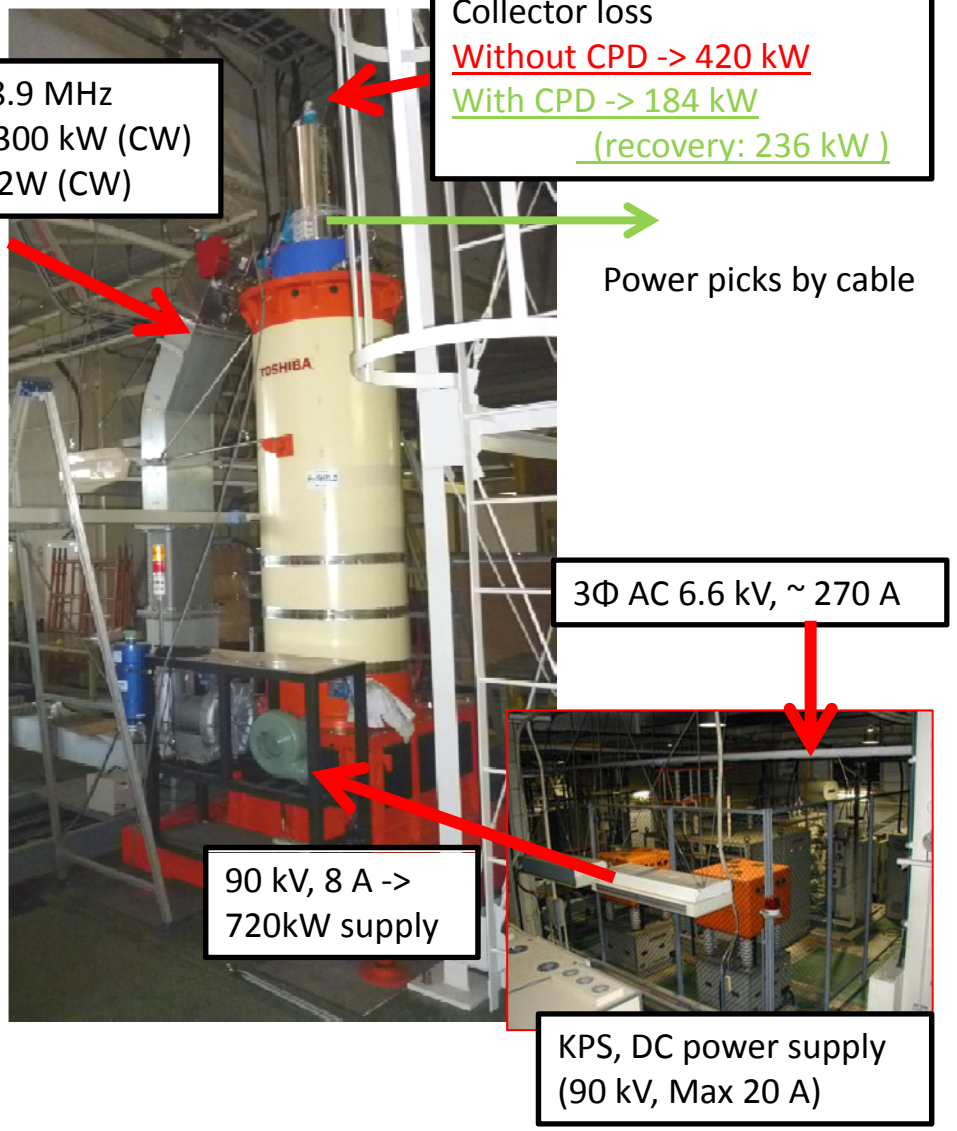
The parameters compared with E3732 and E37703 CPD

Item	E3732 (E3786)	E37703, CPD
Frequency	508.58 - 508.89 MHz	508.58 - 508.89 MHz
Max output	1.2 MW	500 kW
Efficiency	20~65% (Max efficiency at the tome of saturation)	Without CPD 20-60% (Unsaturation) With CPD 40-80% (10-20 % improved)
Collector size	1 MW	500 kW
Cooling method for collector	Vapor cooling (130 l/min + AFC)	Water cooling (360 l/min)
Cooling item	Klystron body Output coupler Focusing coil	Klystron body Output coupler Focusing coil
		Ceramics insulator, Microwave absorver
KPS	B-type x 1	B-type x 1 PS for CPD x 1
Vk	47-90 kV	47-90 kV
Va	25-60 kV, Max Ib 20 Adc	25-65 kV, Max Ib 20Adc
Vc (CPD)	none	0 ~ -50 kV

We were examined that to demonstrate the CPD method to apply a klystron modification by existing klystron.
Moreover, the parameters were determined as a result of restrictions that the KPS also uses the existing thing.

Power balance of a CPD klystron within without CPD

Example of
: Toshiba E37703, CPD



In case of 300 kW output (η = 42%) operation,

* Without CPD (Vk = 90 kV、Ib = 8 A)
  Required DC power is 720 kW
-> RF out 300 kW, Collector loss 420 kW

* With CPD (Vk = 90 kV、Ib = 8A、Vc = 30 kV)
  η = 42 -> 62%

-> RF 300kW, Collector loss 184 kW
  Recovery power 236 kW <- Pick-up by cable from collector, then reuse to drive a klystron

After driving CPD, the required DC power is shifted to about 500 kW using by recovery power from the collector.

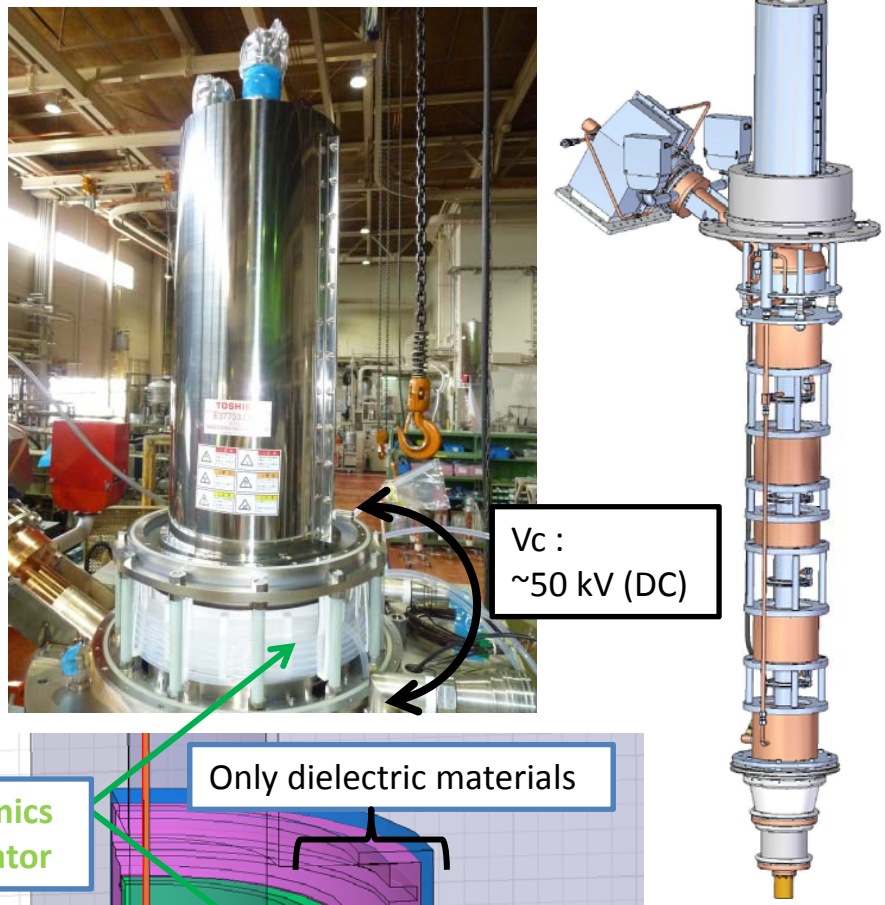
Issues must be addressed for CPD Klystron

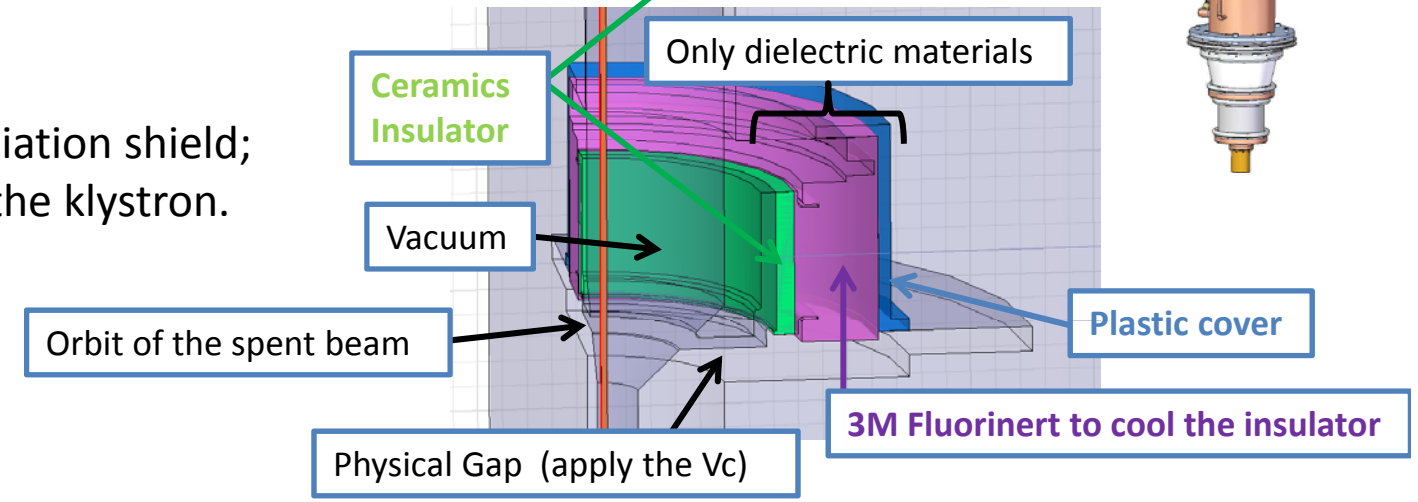
The CPD klystron has an insulator to insulate between the body and the collector for the energy recovery. In this case, three issues must be addressed for the operation. That is;

(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.





List of tasks

Now (2013-2014),

(0) Fabrication of a CPD klystron using by the existing klystron (KEKB)
Design of the RF and radiation shield to optimize it

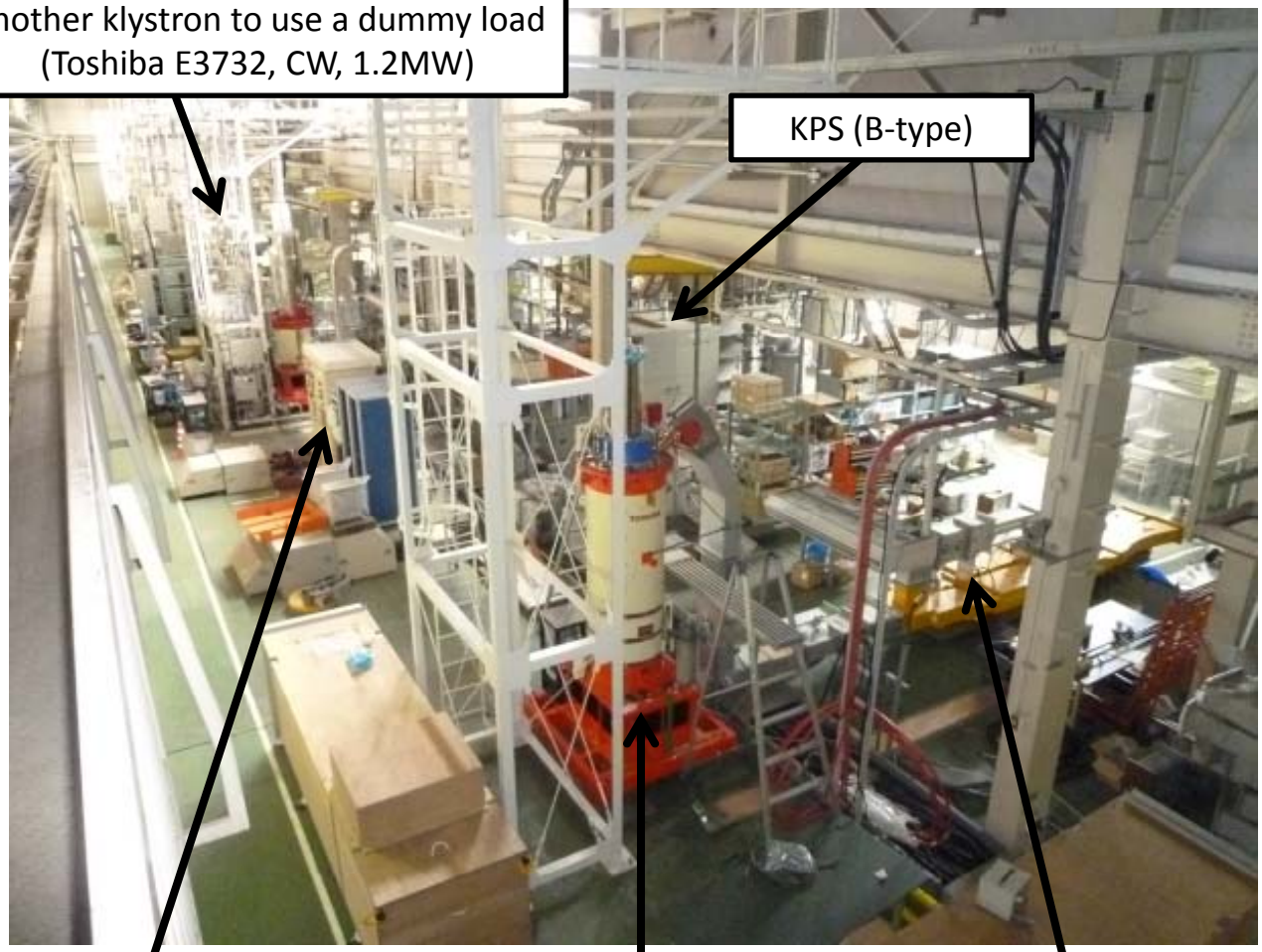
Future plan,

(1) Commissioning starts to drive a normal klystron (2015)
* DC aging (until collector loss of 300 kW)
* RF out (RF out of 300 kW with the collector loss of 420 kW)
(Note, not insulate between the body and the collector to be connecting a cable)
Check the amount of RF leakage and Radiation level

(2) Check the output signal from collector without Vc (2015-2016)
* Small collector loss (~ 100 kW ?)
* Check the output signal from the collector
(The output signal will be terminated to a water cooling type high-power dummy load)

(3) Energy recovery test with Vc for the proof-of-principle (2016-2018)
* Apply the high-voltage (Vc) to recovery the kinetic-energy of spent beams.
* Measures amount of the recovery power dependence on each parameters.
(Another klystron with Marx-circuit will be used for the high-power Dummy load)

RF test station at KEK (D2-A)



Red one is a cable to connect between the body and collector for commissioning.

Work of necessity
* Stages
* Cooling water line
* Interlock system
* Set-up of LLRF system
* Radiation shield
* RF shield

Etc…

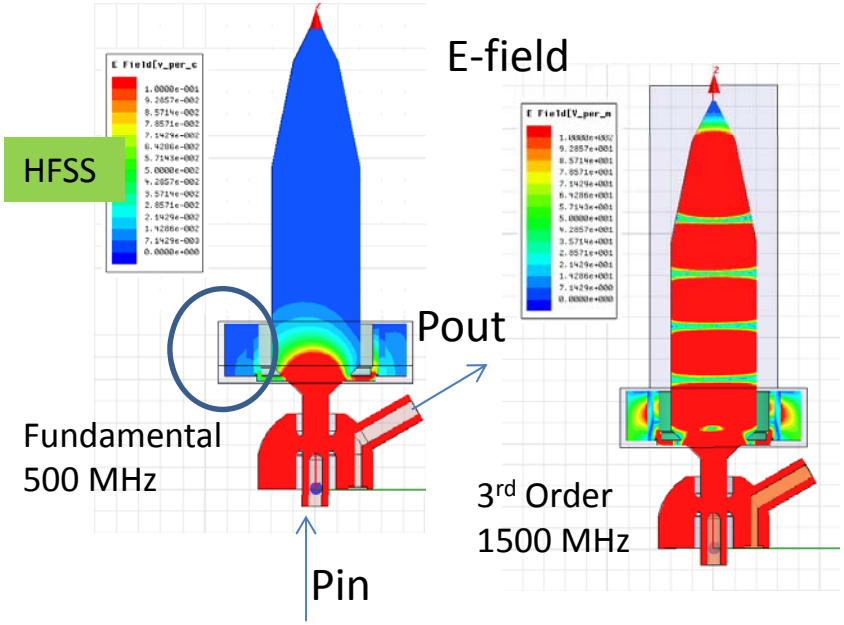
Calculation of the RF leakage from CPD gap

* RF leakage from output cavity (by HFSS)

Check the cutoff performance from fundamental to 3rd Order of output cavity.

Resonant frequency: Fundamental -> 500 MHz
2nd -> 1000 MHz
3rd -> 1500 MHz

Result: Fundamental and 2nd Order are no problem at 1 MW output.
The 3rd Order must be care (-> ~ 100 V/m)



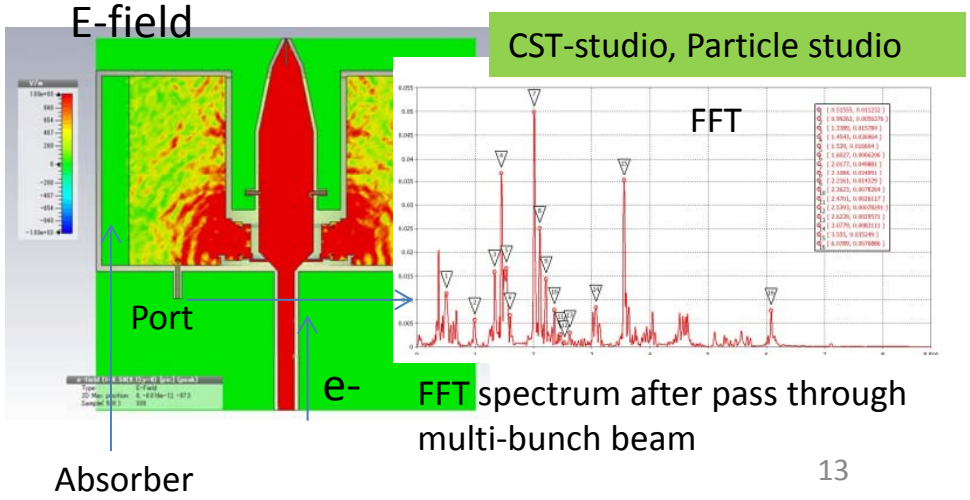
* RF leakage by wake field (by particle studio)

When the electron beams passes through at CPD gap, the wake field excites in klystron.

Frequency range: 500 MHz ~ 6000 MHz

: In case of DC aging -> No problem

* Issue is at RF out (do the velocity modulation)
: In case of the multi-bunch beam (Ib=10A) that is a possibility to build the high voltage (~ kV) near klystron.
But, under calculation to obtain accurate result.



FFT spectrum after pass through multi-bunch beam

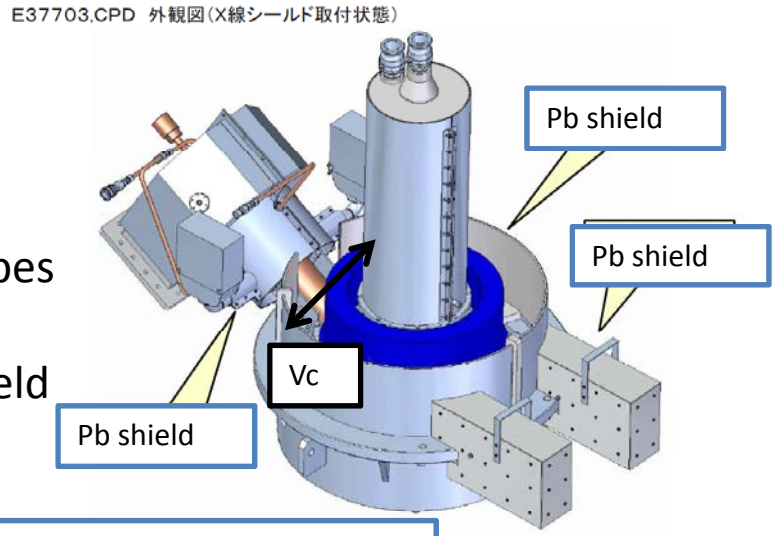
Drawing of the Radiation shield and RF shield

* Radiation shield is already designed by Toshiba lately.

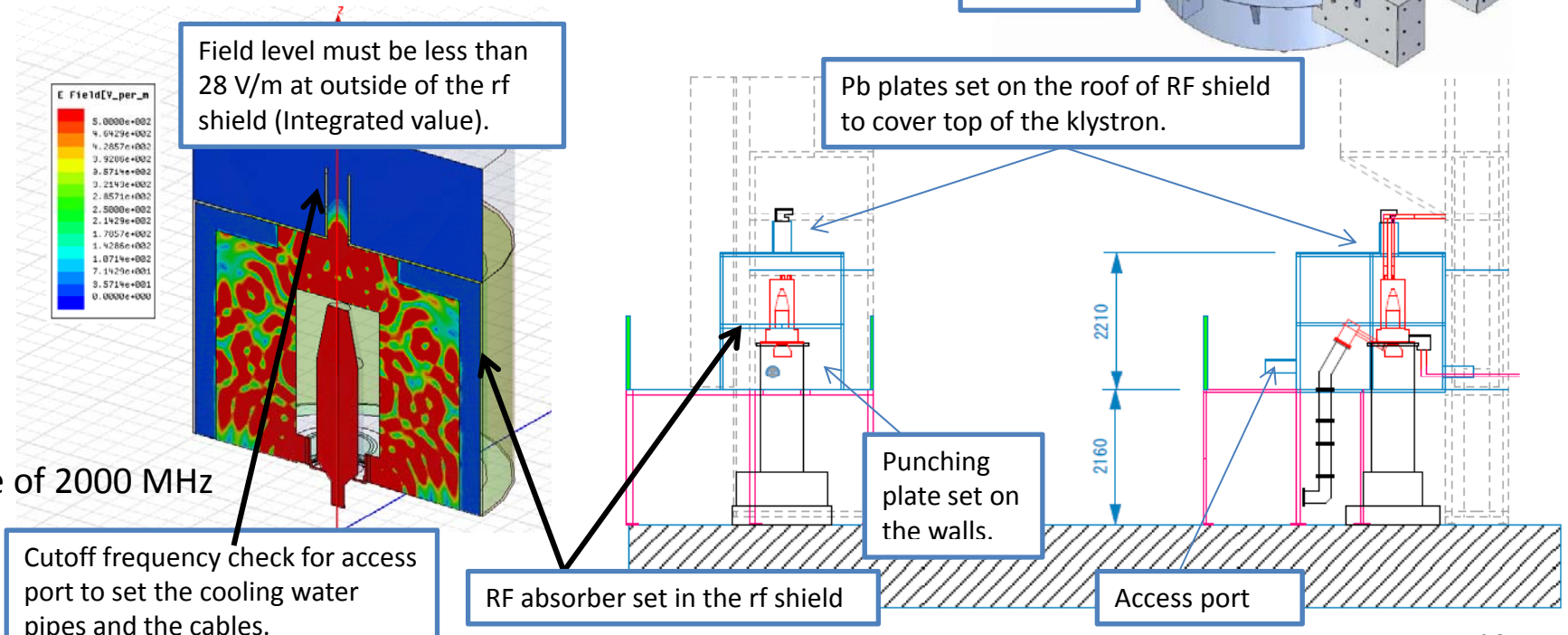
* RF shield is under designing using by simulator.

(i) to make the access ports for the cables and cooling pipes

(ii) to set an absorber for reducing the field level in rf shield

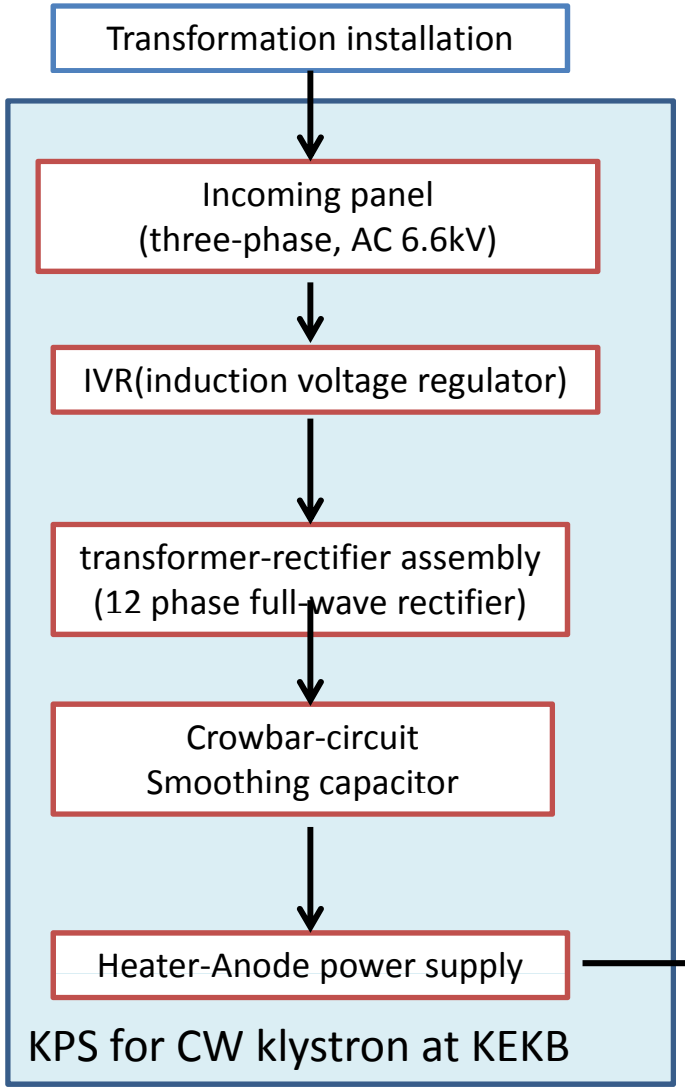


In case of 2000 MHz



Future task: how to design the KPS to optimize the CPD klystrons

Where does the recovery power returned ? (to AC line ?, in KPS ?)



Energy recovery system

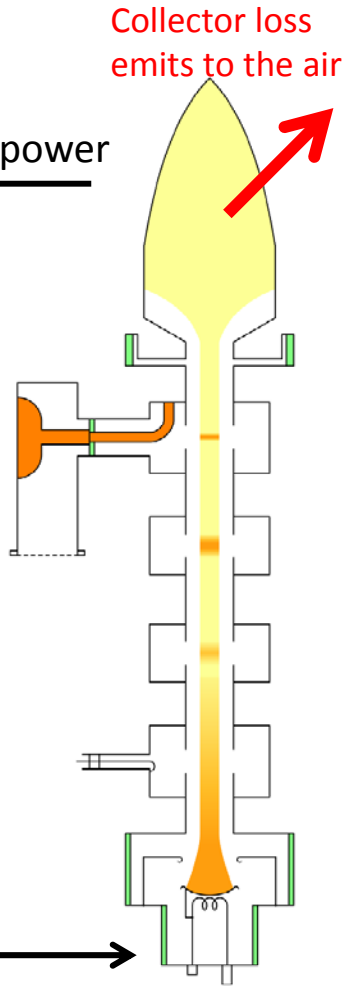
Recovery power

Go to ???

- To AC line with DC-AC convertor ?
- To the DC line ?
- To the DC line with the marx-circuit ?

Must be consider it.

DC power supply to the klystron



Summary

* The introduction of the plane of R&D of CPD klystron at KEK is reported.

* A CPD klystron was fabricated at 2013, to recycle an existing klystron of Toshiba E3786. (It was used to TRISTAN and KEKB.)

* Now, we are doing the design of RF and radiation shield to optimize the CPD klystron.

* The test to demonstrate the proof-of-principle of the CPD method for a klystron is planning to carried out until 2018.

* Commercial viability of a CPD klystron is required development of KPS to optimize it. At present, this is a future task.