Status of High-power RF system for MR and DR

High-power RF-G
Ken Watanabe (3rd division)

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- Klystron
- Klystron power supply (KPS)
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Introduction

Many equipments, which compose high-power RF systems (including LLRF) used in SuperKEKB, were manufactured for TRISTAN that was constructed in early 1980s.

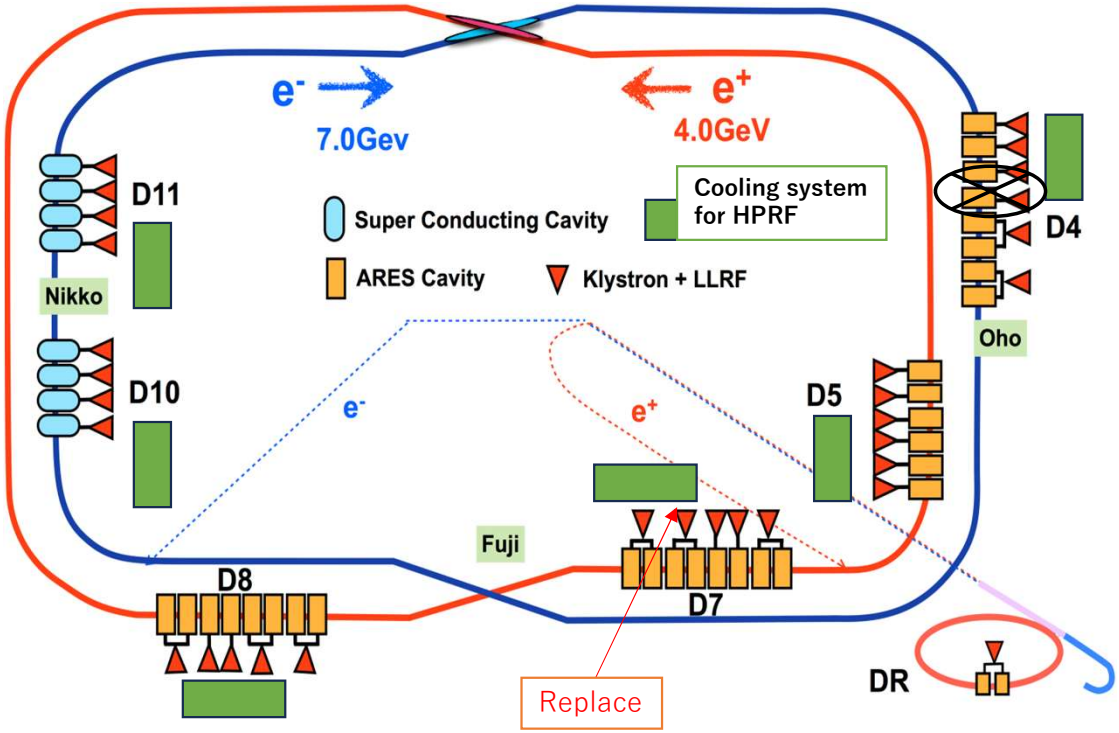
- Used for more than 35 years since manufacturing.
- Used while continuing maintenance systematically within the approved budget.

The development of elemental technologies in the field classified as high-power RF was almost completed by the KEKB.

- Target of research: Evaluation of the lifespan

The number of stations taken off from operation varies depending on the location of the failure.

*Currently,
- One KPS (D04E and D04F) is stopped due to failure of around rectifier, it occurred during startup for 2024ab run.
- One klystron (D07B) replaced in End of Feb 2024 due to breakdown occurred in tube (trip rate gradually increased).



*Number of RF stations in SuperKEKB
Total 31 stations are operating in MR(30) and DR (1).

*In addition, we also have six stations for testing each component.
(508.9 MHz x4, 1018 MHz x1 and 1250 MHz x1)
-> They also serve as spare part for RF stations of MR and DR.

Introduction

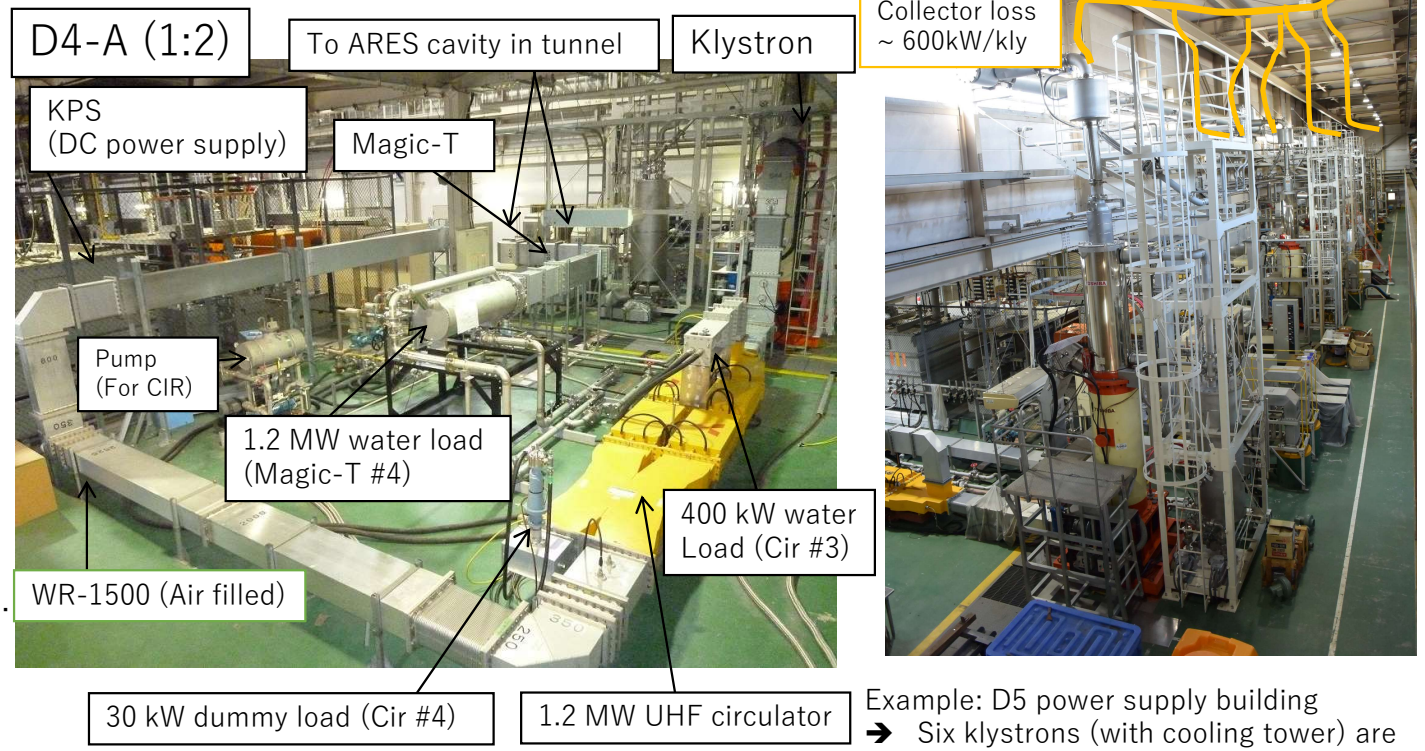
High-power RF (HP RF) system is shown bellow,

*Klystron (MR 30, DR 1) Toshiba E3876, E3732
508.9 MHz, Max= 1.2 MW(CW)
Efficiency 40~60 % in operation

*KPS (Klystron Power Supply): (MR 16, DR 1)
Vk ~90kV, Va ~80kV, Max 20A for a klystron
(A-type for two klys and B-type for one kly)

*Waveguide system (MR 30, DR 1)
-1.2 MW UHF Circulator (4-port)
-Water load (1.2MW and 400kW)
-Dummy load (30kW)
-WR-1500 (Air filled) Total 1.6 km long.

*Cooling system for HPRF (MR 6, DR 1)
-AFC (vapor cooling) for klystron collector losses.
Cooling capacity ~ 8MW
-Pumping system
for Circulator (2.2 kW pump)
for Water loads (22 kW pump)



Example: D5 power supply building
➔ Six klystrons (with cooling tower) are built into one building.
➔ One AFC is placing at outside of building.

Current status: Klystron

Klystron (Two model are used in MR and DR)
- **E3786** is first model. And **E3732** is an improved version of E3786 with countermeasure of breakdown around electron gun.
- In total, more than 100 klystrons were manufactured from 1982-, including proto-types.

- The malfunctioning ones were discarded, and we currently have **"38"** of them for SuperKEKB and a test station of D1-AT.

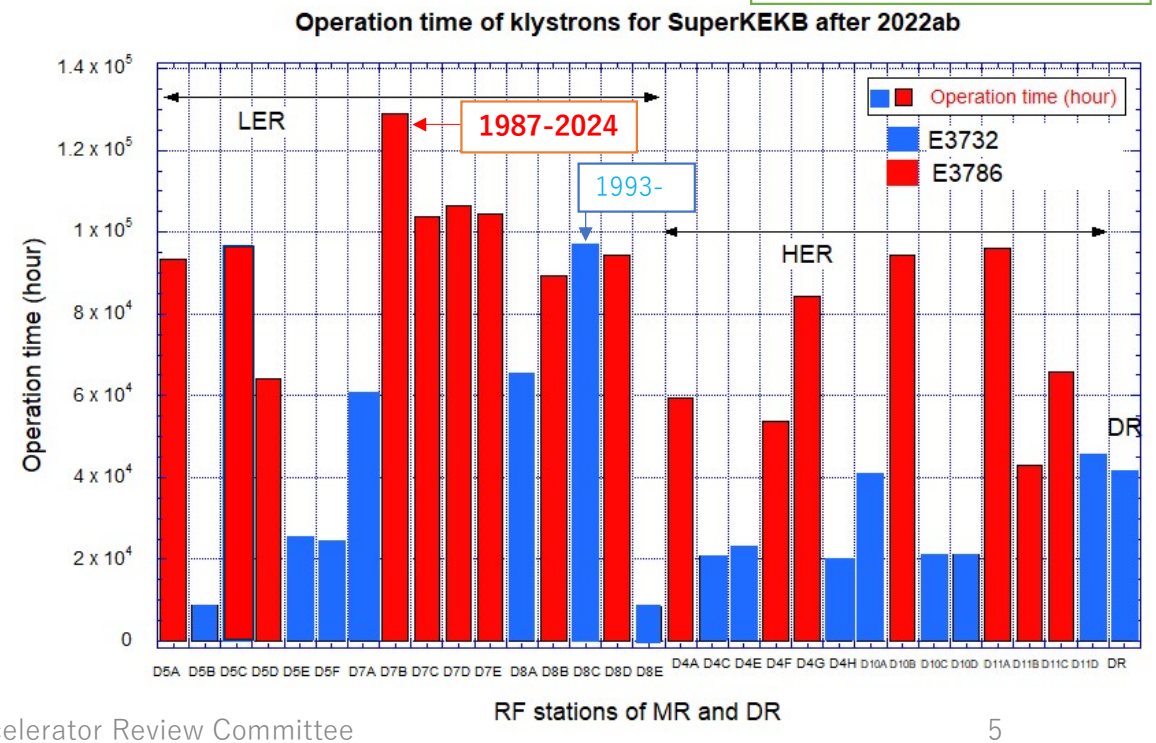
E3786 -> 16 klystrons are working in MR (another one is used at D1-AT).
- Manufactured at 1986~1992 (have 20 klystrons).
  -- A possibility of breakdown (occurrence !!!)
- Most long operation time is over 130,000 hours (D07B).

E3732 -> 15 klystrons are working in MR and DR.
- Total 18 klystrons have,
- 10 klystrons modified to E3732 specification since 1993.
- 8 klystrons manufactured in 2003 to 2013

- Information regarding lifetime is not yet available.
  (because statistical data is not enough.)
- Breakdown at electron gun has never occurred since the specification changed to E3732.
  Most long operation time is about 100,000 hours (D08C).

* Spare: Total 6 klystrons - E3786 x 3, **E3732 x 3 (modified x 2)**

Before starting 2024ab



Long-term operation plan: Klystron

During a recent operation,
a breakdown in tube with sudden increase of klystron output occurred frequently in a short period time at **D07B.** Then, the klystron replaced to spare in one day.
(E3786 manufactured in 1987, just over 130,000 hours).

-- Trip Rate: 8 times in 2 day (End of Feb 2024) --

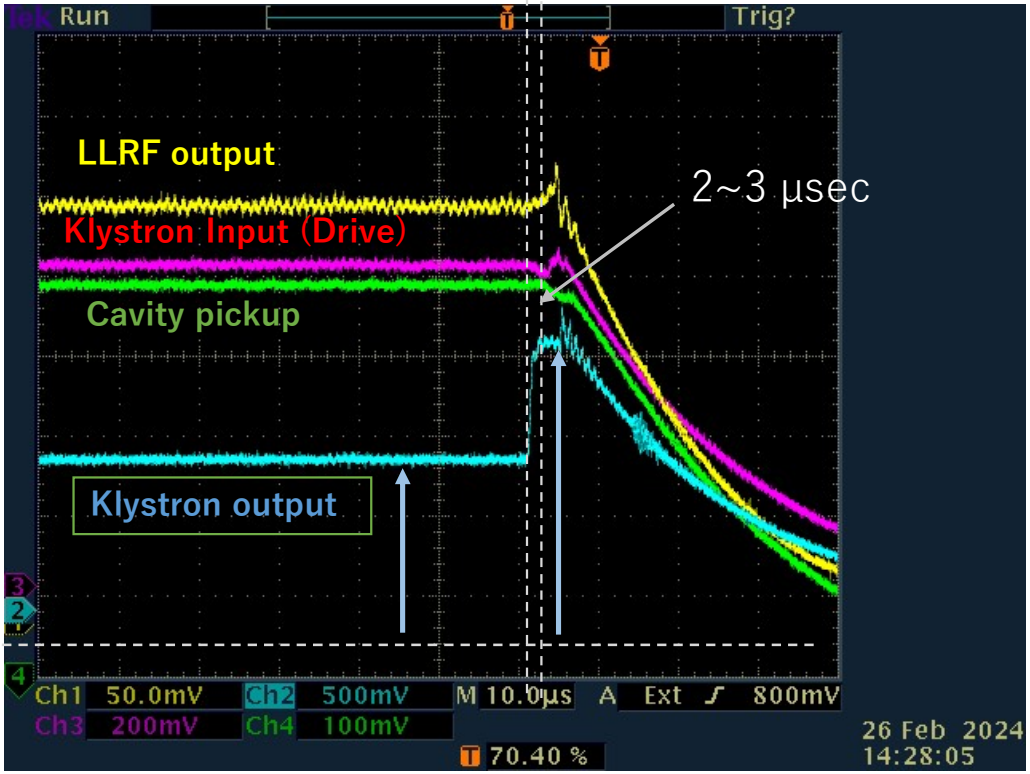
* It could not be used for operating at this trip rate. However, no degrease in emissions from electron gun has been observed.

- It is predicted that the number of such klystrons will gradually increase within ~6 years.

For future long-term operation,
- Necessary to replace E3786 with "E3732-type".
- Necessary to manufacture one klystron every 1~2 years, if 5,000 hours operation time per year is assumed.

Currently, "new manufacturing" has the lowest cost for this issue.
Modification of old klystrons is no longer a good policy…

2024-02-26 14:27 RF D07B trip

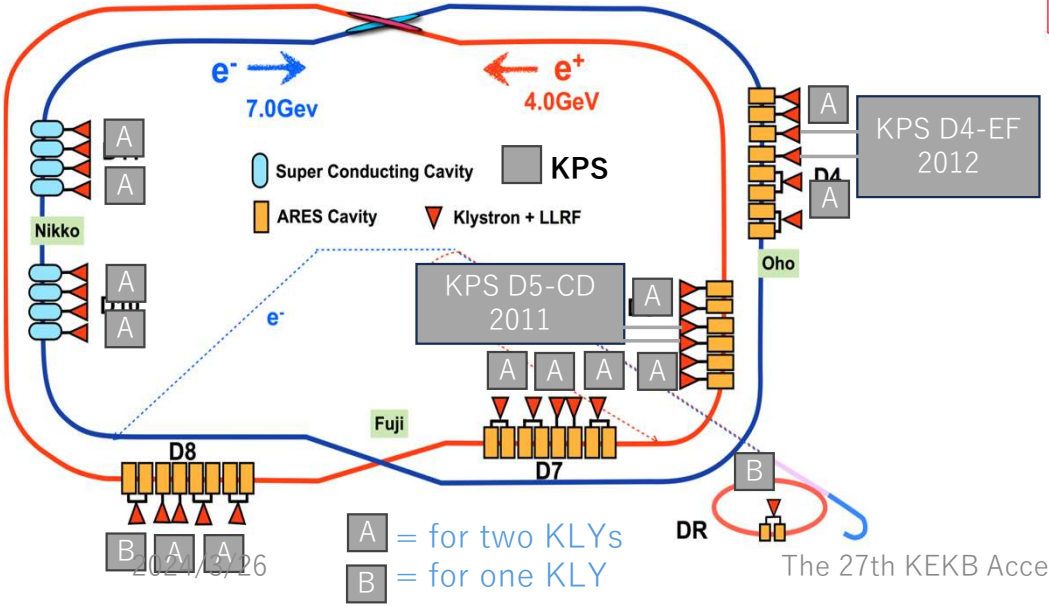


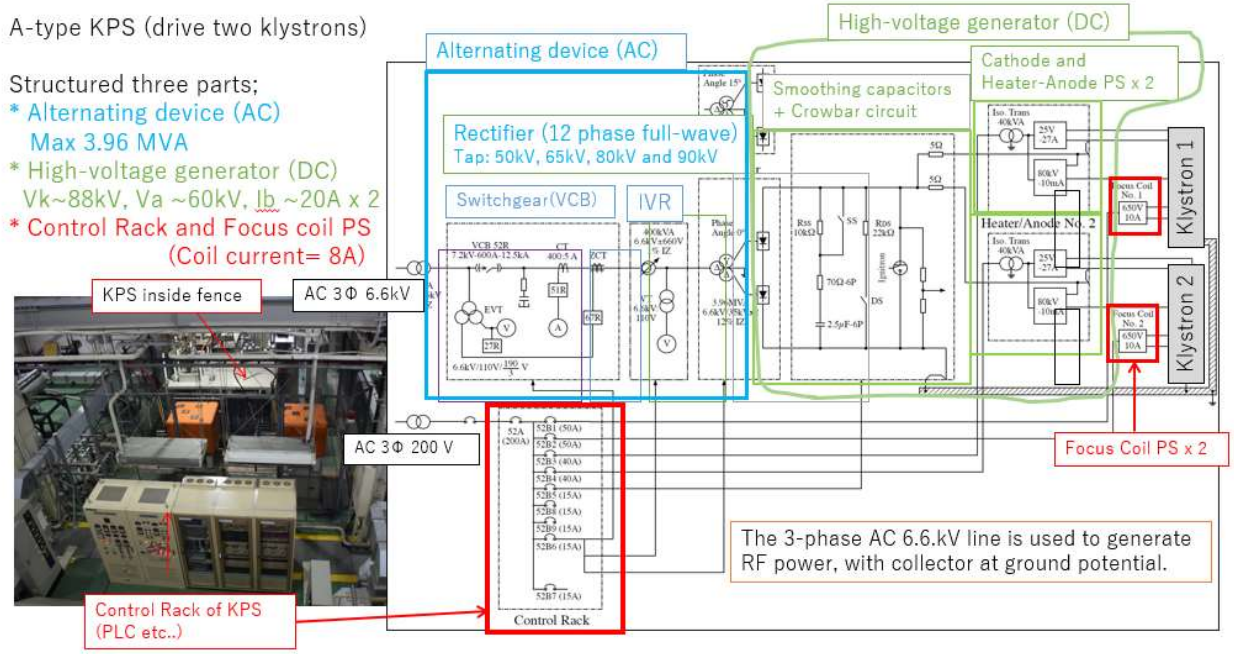
The klystron output was responded first by breakdown around electron gun. At this time, the instantaneous amount of change in klystron output was more than double.
(V_a is increased by breakdown, then I_b is also increased.)

Current status: KPS

Currently, we have total 21 power supplies.

- 19 power supplies manufactured in the 1980s (A-type x 12 + B-type x 7)
  *Since then, it has been relocated as appropriate depending on the configuration of the KEKB and SuperKEKB.
- 2 power supplies manufactured in 2011-2012 to reinforce RF power for SuperKEKB





For DC part and Control Rack
- Completely updated from the original devices until 2012 (define as 2nd generation).
  *PLC, control boards, small control power supply and instruments with contacts etc..
- For the AC section, we have been updating the aging components since 2020.
  * VCB (Vacuum circuit breaker) etc.. -> 40 years since installation.

Long-term operation plan: KPS

AC section (Target item -> 40 years since installation)

- VCB (Vacuum circuit breaker)
  Total: 15 stations (12 stations updated in 2023).
  Remaining three units will be updated in 2024.

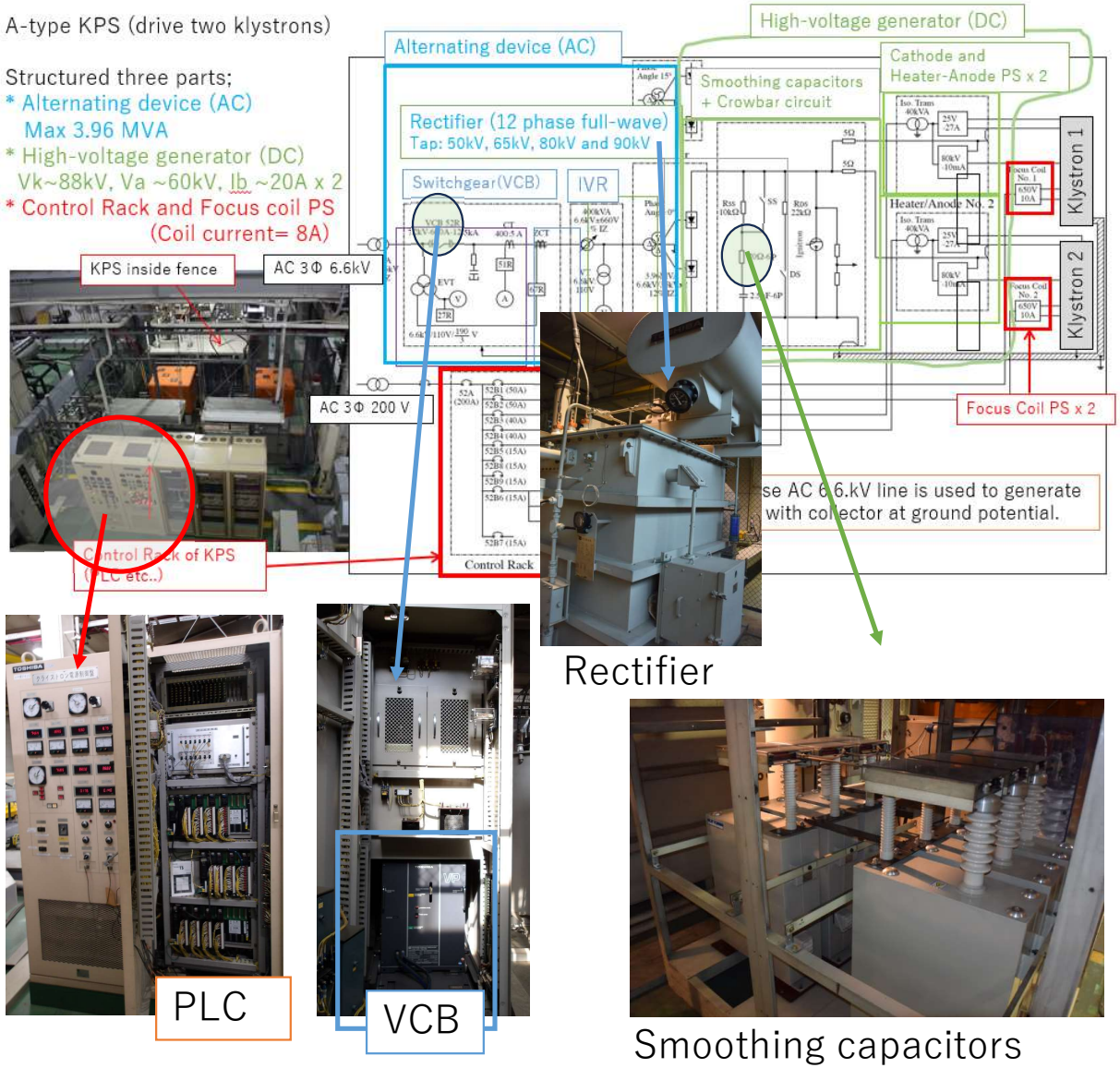
- IVR and Rectifier
  Performing continuous monitoring of insulation oil.
  Insulation oil will change as necessary.
  (Volume-> IVR: 560 L, Rectifier: 7850 L)

Other (Control rack and DC part)

- PLC (more than 20 years since installation).
  Total: 14 stations
  Updating work will being in 2024.

- Smoothing capacitors (~100 pieces)
  Completed. -> MR (2012) and DR (2023)

- DC part
  Necessary to update to 3rd generation,



Trouble (D4-EF KPS manufactured in 2012)

2024/01/12 PM at D04EF-KPS

- During startup of RF system for 2024ab run,
  A discharge occurred around the bushing of the HV-cable connected between the rectifier and cathode power supply while raising the rated voltage to 88 kV DC (A discharge occurred at 85 kV).

**History of this KPS,
- Manufacturing in 2012.
  An inspection after manufacturing -> applied a high-voltage of 110 kV DC for this line (no abnormalities).
- The rated voltage of 88 kV DC was applied every started up to confirm that there were no abnormalities (worked w/o any problem until 2022ab).
- This failure occurred after 21,000 hours of operation since the manufacture.
  Most of the time of this KPS was operated at around 75 kV.
  (due to the storage beam current in HER is not maximum).

- It is clear that, this is not an initial defect.
  The cause of the discharge is currently under investigation.
  The situation of rectifier cannot be decided until the disassembled.

**Future action (Note, currently under consideration with company)
- Replace with spare (but, currently in use at the D1-AT) for this issue

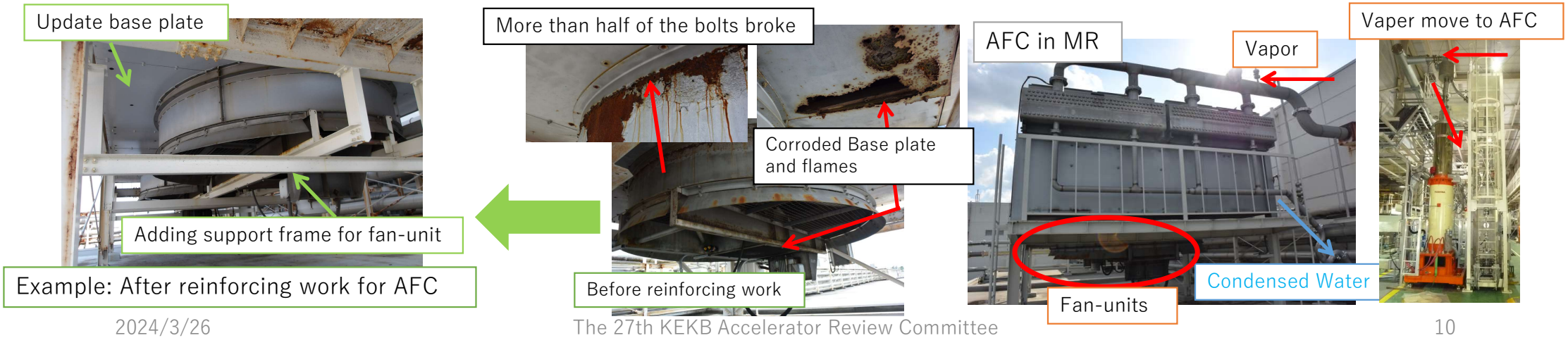
Current status and plane: Waveguide and Cooling system for HPRF

Waveguide system
- Worked well without serious failure.
  Maintenance is caried out in a planned manner based on the aged deterioration of components.

Cooling system for HPRF
- The most serious problem was the aging of AFC (Air fin-cooler) for cooling the collector loss from klystrons.
  There was in danger of collapsing due to corrosion of the steel materials used in structures (with poor water drainage).
- Reinforcing work over the past few years had put the situation out of the way.

- Ongoing of additional repair works:
  Reinforcing work for the flames with painting work, updating the invertor-units and motor to drive the cooling fans.

- This will ensure that the cooling system for HPRF can withstand operation for more than 15 years.

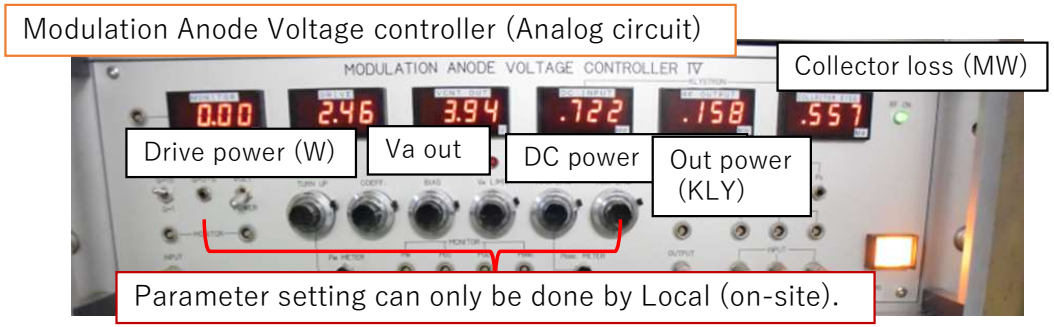


Considering for energy saving in HPRF systems

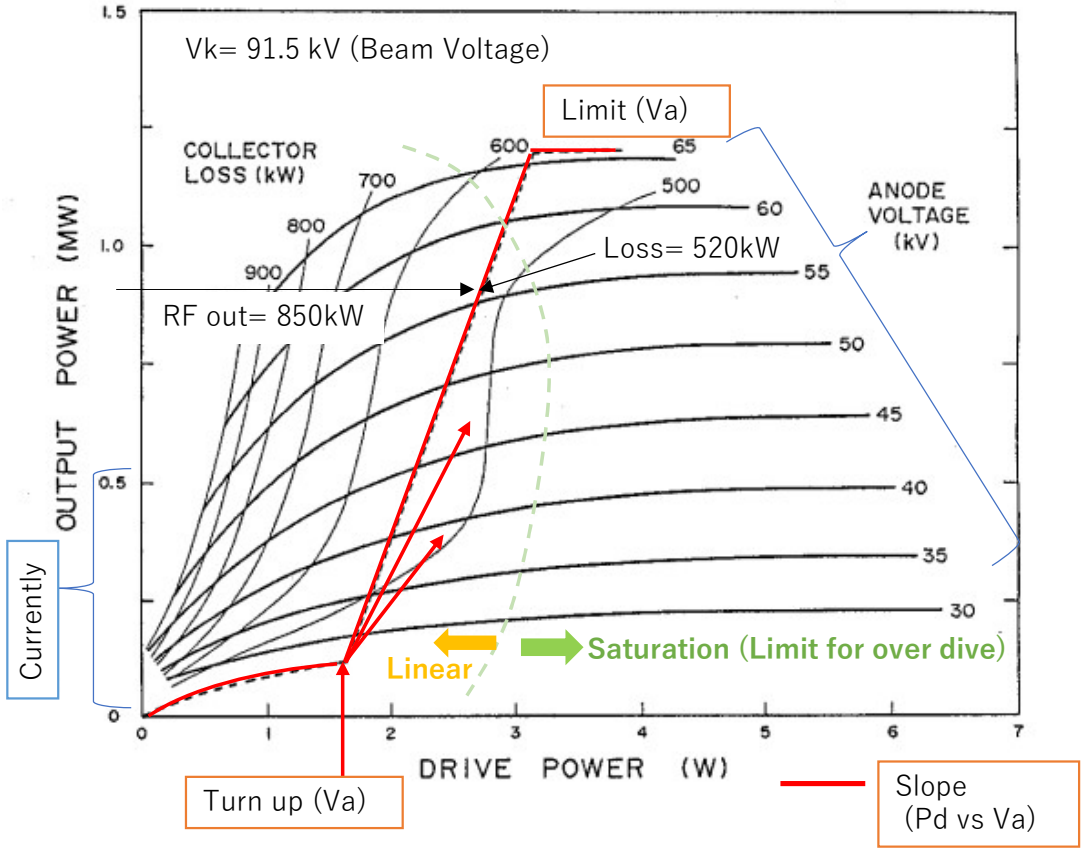
Currently,
- Analog circuits use to control the klystron output by a slope of Va. (Developed at TRISTAN)
- They must be set on-site, and it is difficult to constantly make fine adjustments to all of them.

For energy saving,
- Modification of klystrons is not realistic in our case.
- Optimization of Va control is the most practical.
- Development of new module to control the parameters by remote (using FPGA and EPICS), stating from this year.

- Expected reduction-> ~50 kW/KLY for the collector loss
- In total, ~1.5 MW of electricity can save in intermediate output range .
  ** Electricity varies the range of 20~30 MW for HPRF depending on the storage beam currents in both ring (from Idol to max currents).



P_d vs P_o (E3786)

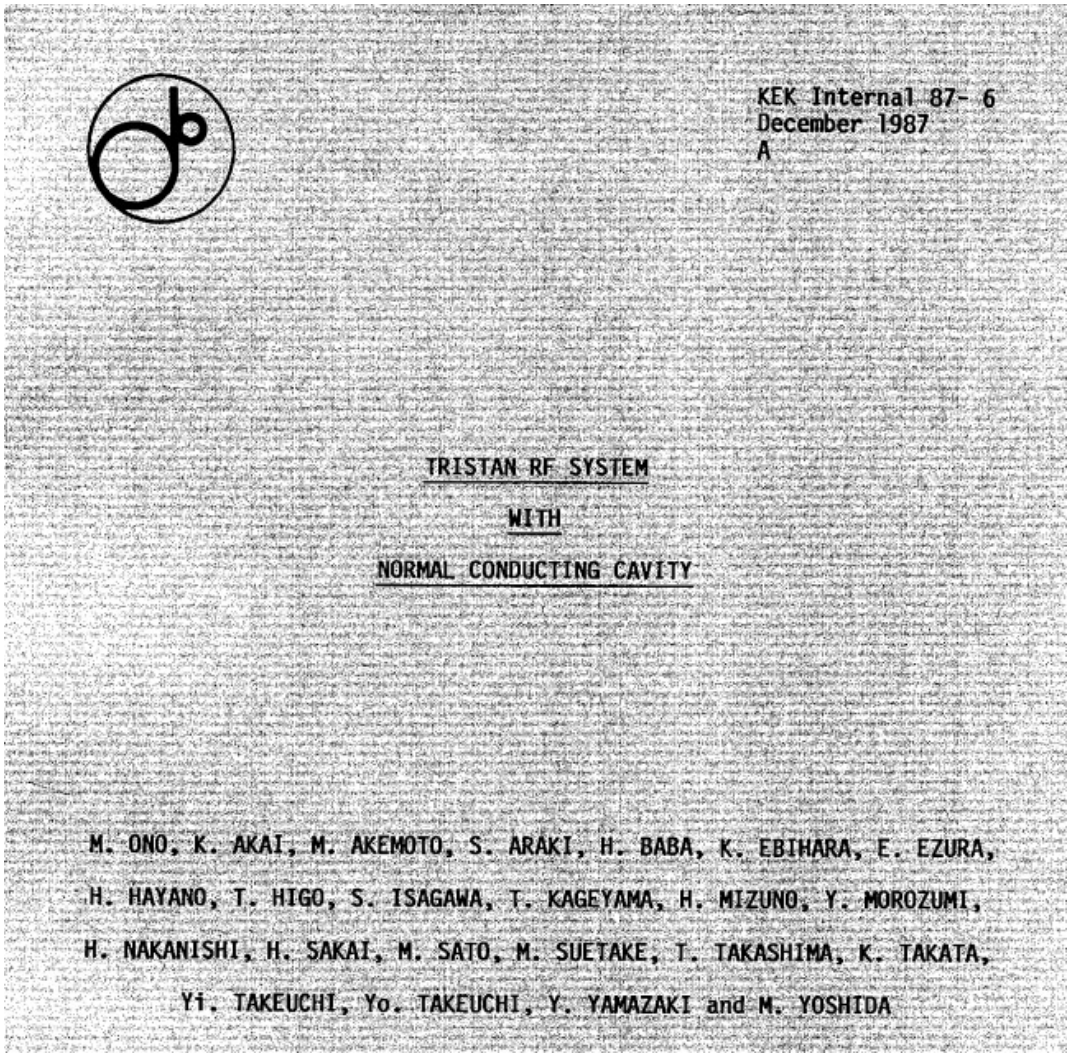


- Simple control method was applied to increase Va voltage at an arbitrary slope relative to the drive power (KLY input).

Summary (For continues operation from 2024 to more than +15 years)

Item	Require	Additional cost for +15 years	Maintenance cost / year
Klystron	- Requires at least "seven" E3732 type klystrons. It is necessary to purchase at least one klystron every 1~2 years (during in 2024~2034)	600 million yen for seven klystrons	15~20 million yen
KPS	- Requires update again to 3rd generation for DC part. - Requires update of PLCs for 14 racks	500~600 million yen for updating PLCs and other	50~60 million yen
Klystron and KPS control	- Requires new anode voltage control system for energy saving. It is possibility that we can expect to save ~150 million yen in electricity cost/year.	~50 million yen for updating this controller (31 stations)	Now estimating.
Waveguide system	- Requires spare components for HPRF at least Circulator (2), Water load (4) and dummy load (10)	100 million yen for spare components	40~50 million yen
Cooling system	- Requires additional repair work for AFCs.	100~150 million yen for repair work for AFCs.	5~10 million yen
Total		~ 1.5 billion yen (divide in 10 years ?)	~ 140 million yen (achieved every year)

Backup



KEK Internal 87- 6
December 1987
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TRISTAN RF SYSTEM WITH NORMAL CONDUCTING CAVITY

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Klystron

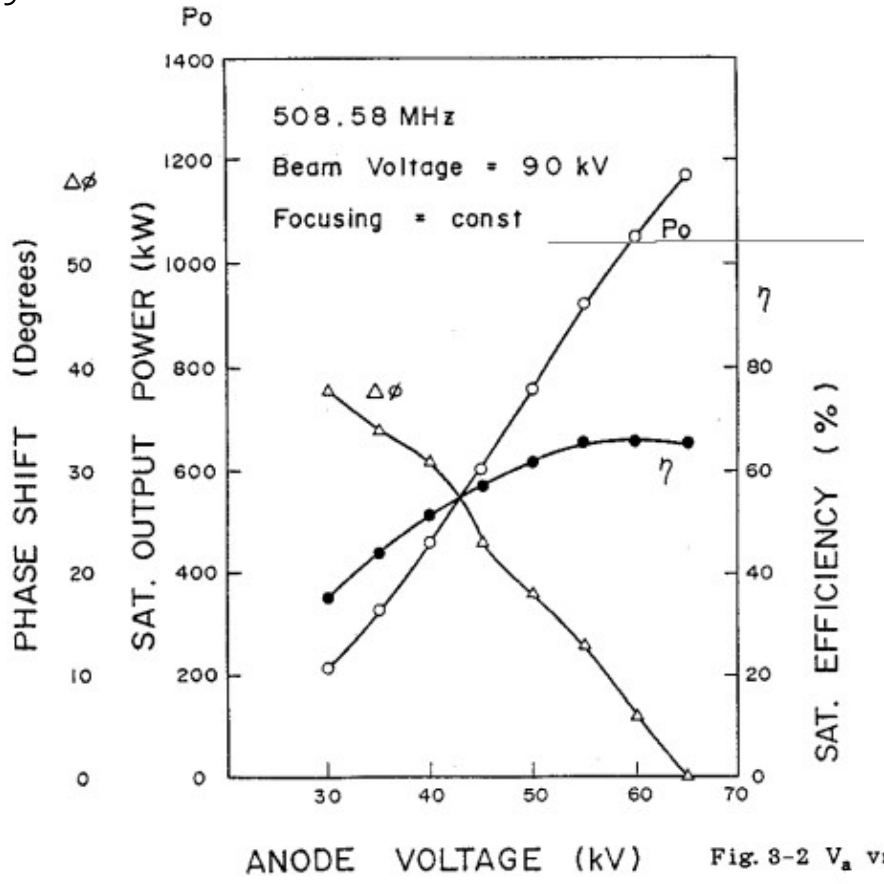


Fig. 3-2 V_a vs. P_o, η and $\Delta\Phi$ at saturation. (E3786)

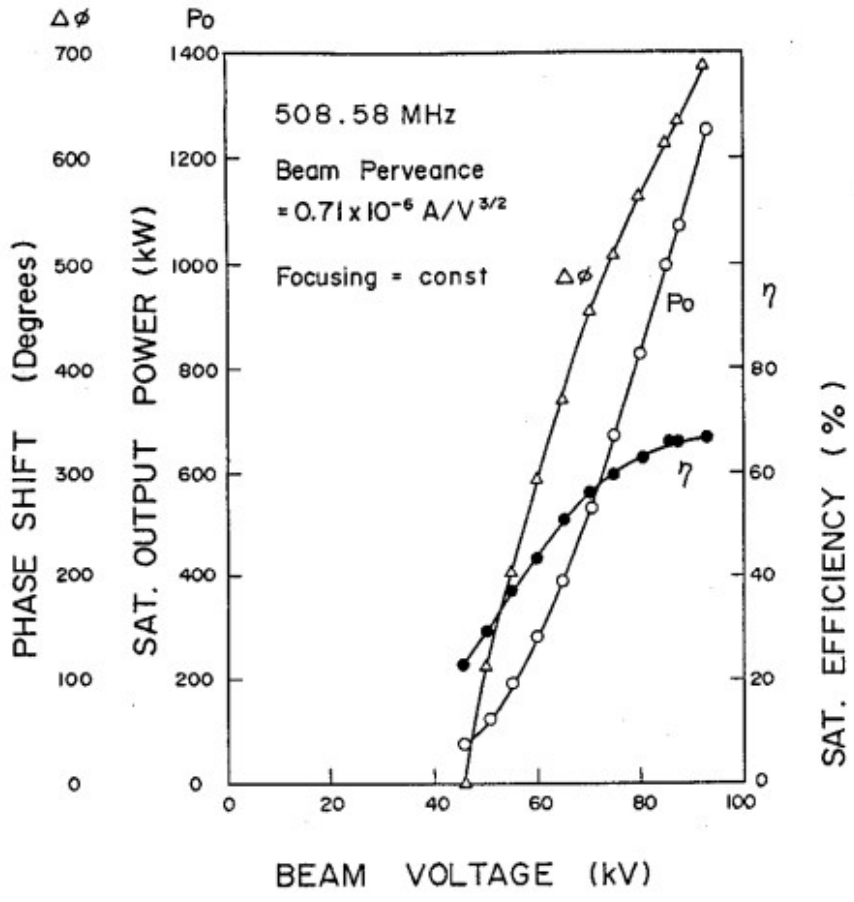
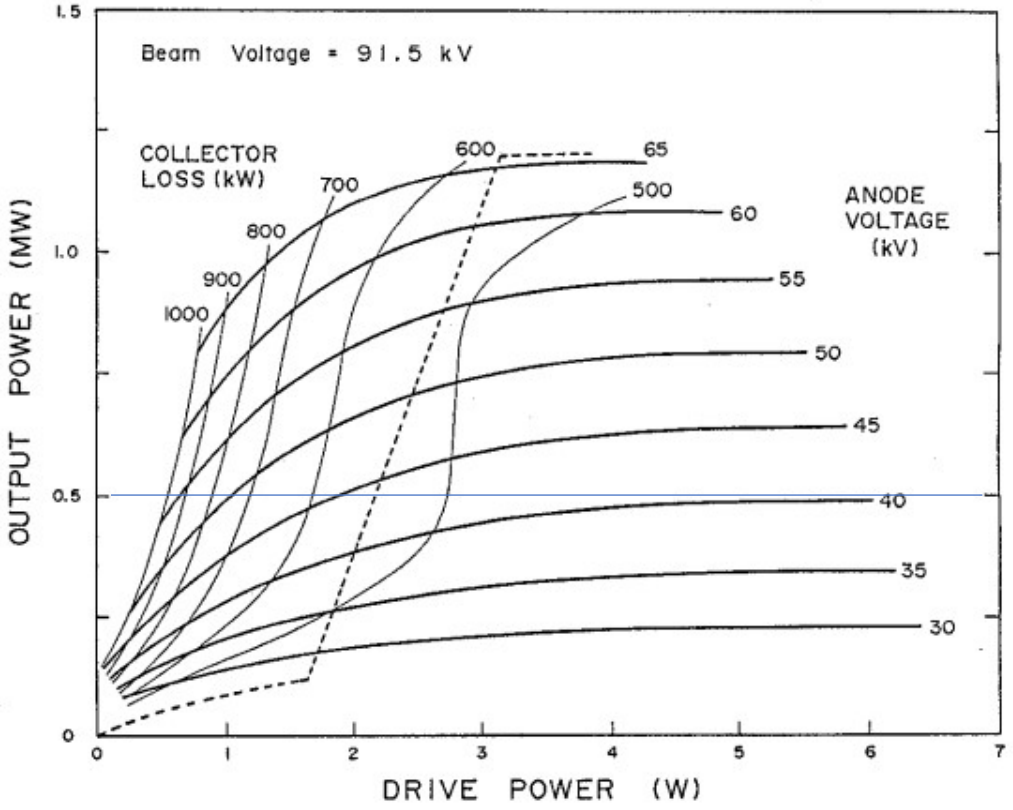


Fig. 3-4 V_B vs. P_o, η and $\Delta\Phi$ at saturation. (E3786)

Klystron

P_d vs P_o (E3786)



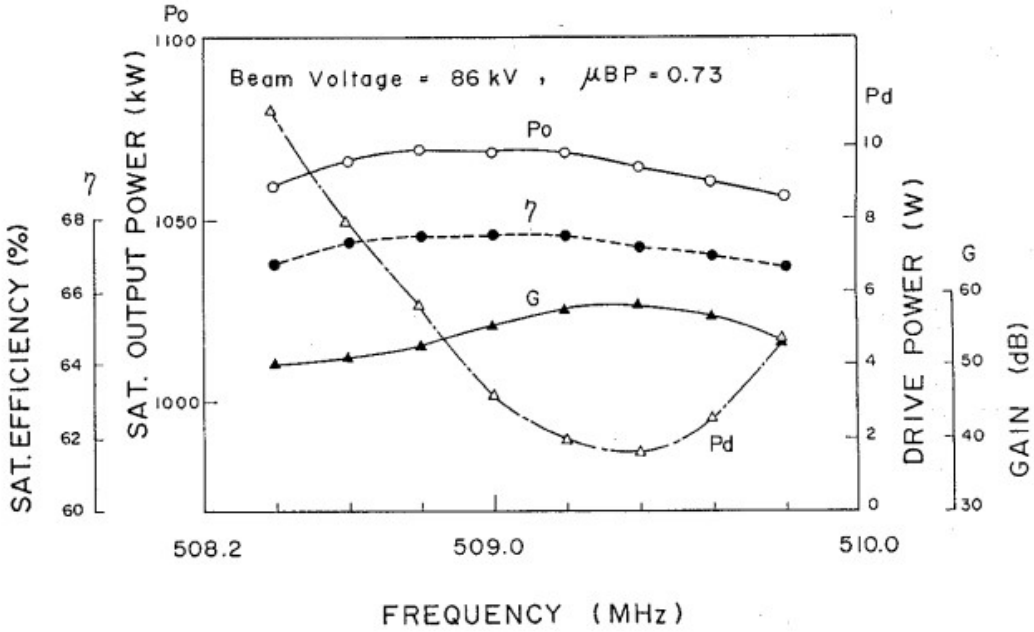


Fig. 3-6 Freq. vs. P_o, η, P_d and Gain at saturation.
(E3786)

Fig. 3-8 P_d vs. P_o
(E3786)

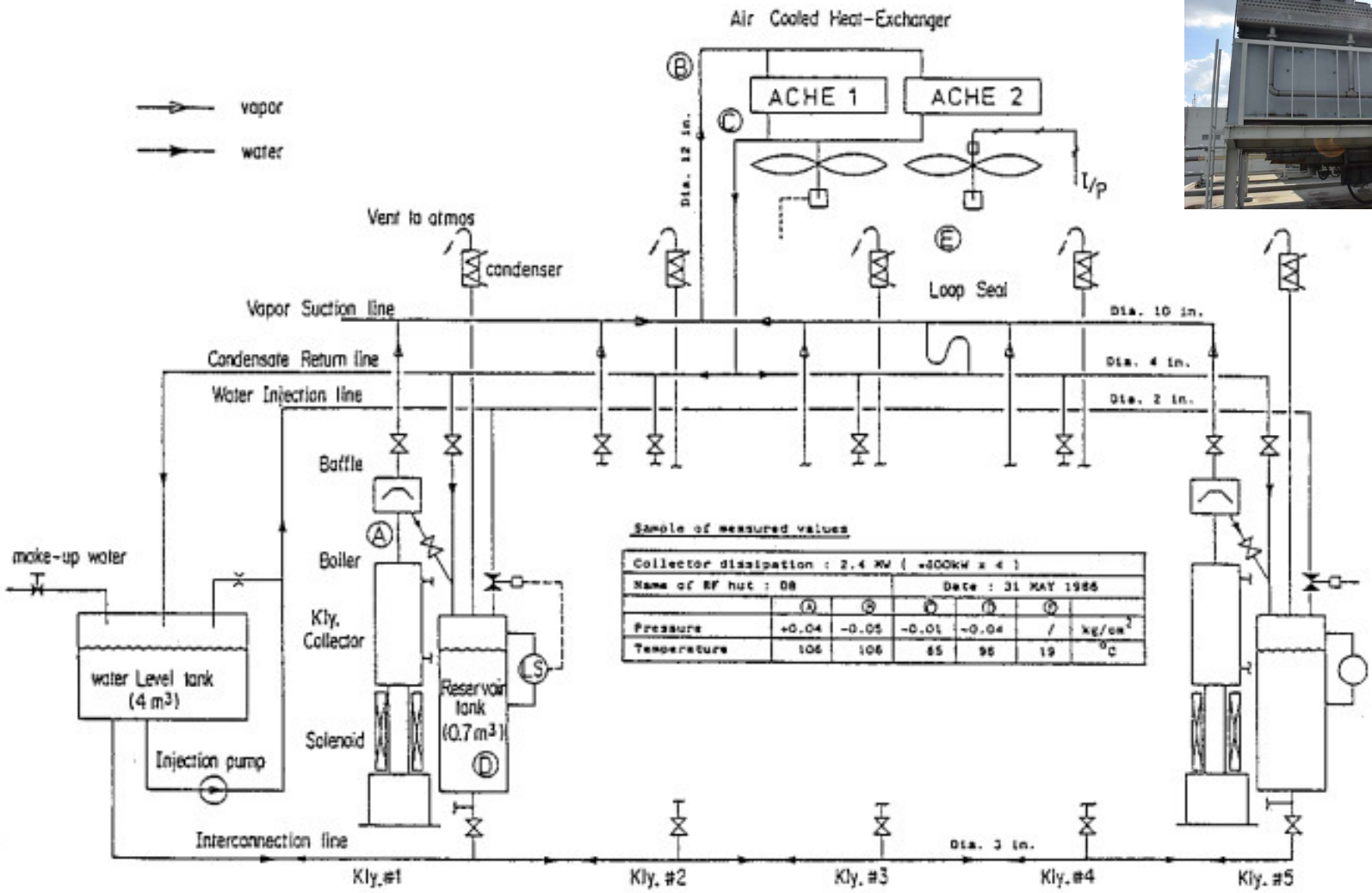


Fig. 5-1 Vapor Cooling System

Modification of klystron from E3786 to E3732 (509 MHz, CW 1.2MW)

1) Input/output hysteresis investigation and countermeasures

- Presumed the multipacting around the gap of second cavity
- Countermeasures -> A crown structure was machined on the gaps.

2) Breakdown around the electron gun with sudden increase of klystron output

- Estimated the creeping discharge of ceramics between the anode and the body.
- Measures have been taken to prevent ceramic stains that can cause creeping discharge.

(A) Suppression of barium evaporation from electron guns

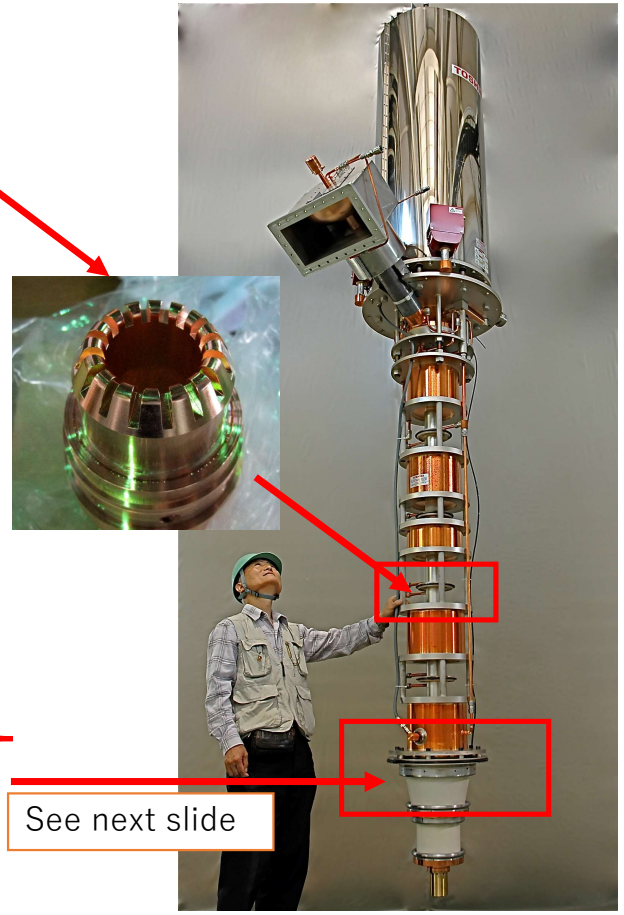
- When barium adheres to copper, the melting point of copper decreases and the firing voltage decreases.
- Countermeasure: Adopt a low-temperature cathode that prevents barium from scattering.

(B) Preventing copper sputtering on ceramics and suppressing direct discharge

- Countermeasure: Coating high melting point chromium oxide on the anode surface

(C) Suppression of direct discharge between the anode and body electrode

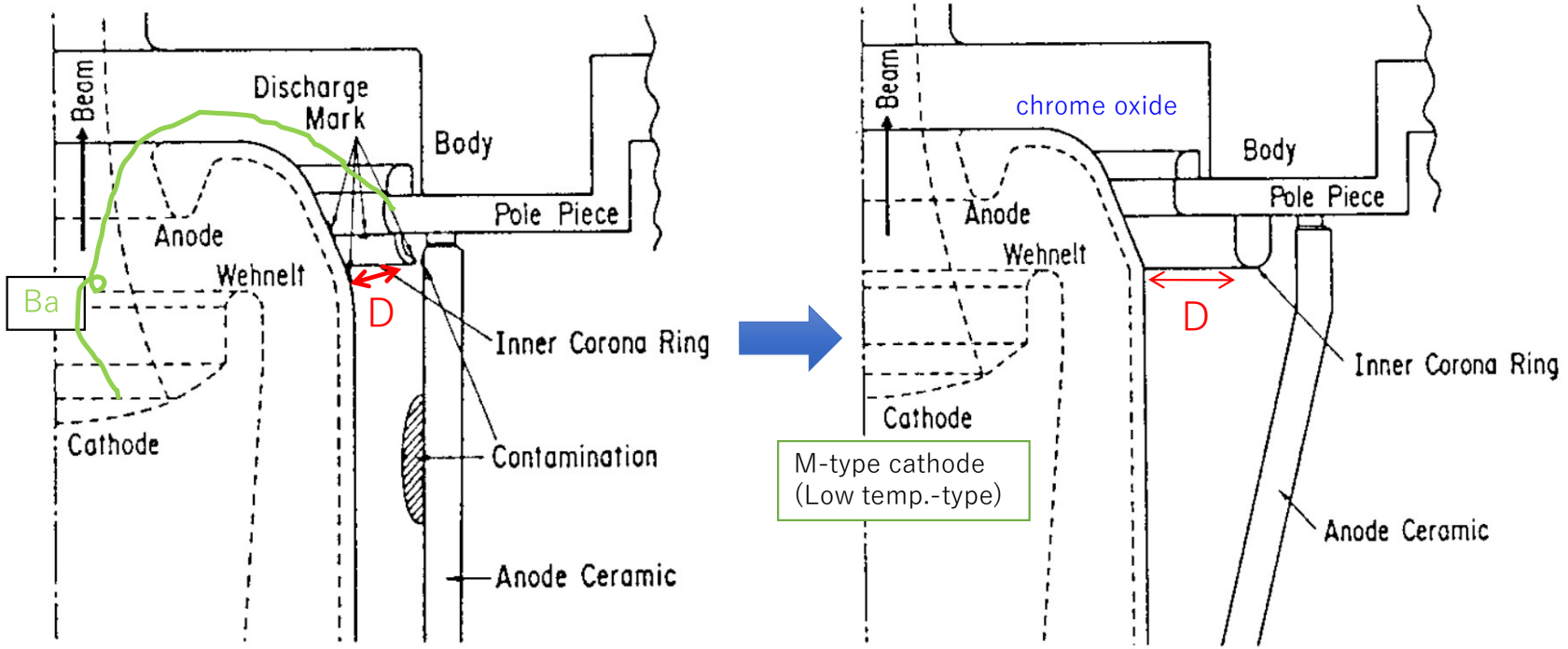
- Countermeasure: Adopts tapered ceramic to increase the distance between the anode and body electrode



*After taking the above measures (E3732), the klystron did not experience the breakdown.

Increased distance between body and anode electrode

- Countermeasures for the breakdown around electron gun



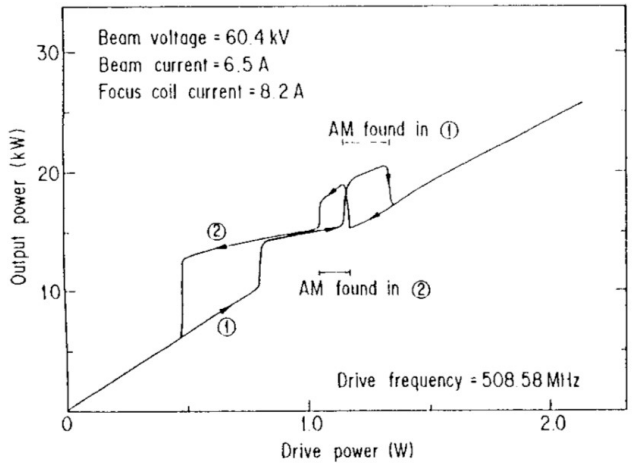
First model（E3786）

Improved（E3732-type）

Maximum electric field strength（Vk: 90kV、Va: 65kV) was shifted from 44 kV/cm (E3786) to 13 kV/cm (E3732)

** Reference: Breakdown electric field strength of electrode with barium coating (evaporates from gun filament)= 100 kV/cm

1) Input/output hysteresis investigation and countermeasures



(a) E3786 T13

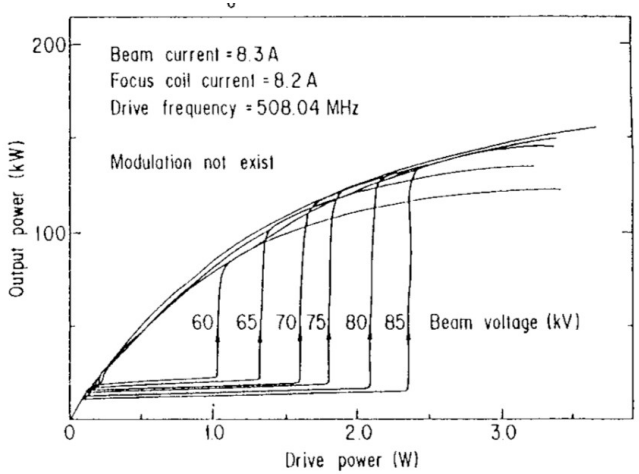


Fig. 3 Dependence of hysteresis on beam voltage of E3786 T13.

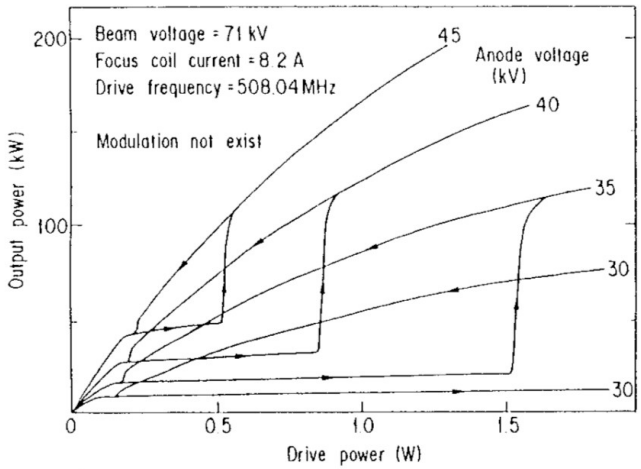
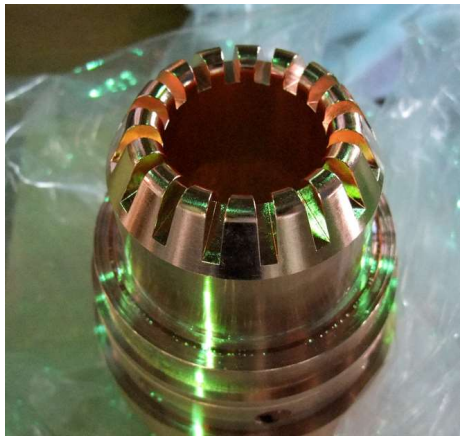


Fig. 4 Dependence of hysteresis on anode voltage of E3786 T13.



Crown structure

* When changing the magnetic field of focusing coil near the second cavity, the characteristics of klystron changes.

List of klystrons
- Time occurred breakdown (Specification of E3786)

- If the initial treatment of the electron gun is done well, its lifespan will be extended.

No.	Klystron	Year of manufacture	Time occured breakdown (hours)	Year in breakdown occurred after manufactue	Remark
1	T26	1986	12,304	3	Occurred in Nov 1989. Modified to E3732 in 1999. Currently, keep as spare (LV on= 49,000 hours)
2	T29	1986	9,594	3	Occurred in Nov 1989. Modified to E3732 in 1993. Currently, use in D08C (LV= 96,000 hours)
3	T32	1988	12,333	1	Occurred in Nov 1989. Modified to E3732 in 1993. Currently, use in D05C (LV= 94,000 hours)
4	T36	1988	8,194	0	Occurred in June 1989. Repair to bellow, T36A
5	T36A	1989	55,032	14	Breakdown occurred again after repair. –> Discard
6	T39	1988	11,391	14	Occurred in Apr 2002. Modified to E3732 in 2005. Currently, keep as spare (LV on= 26,000 hours)
7	T40A	1988	10	0	Occured at the time of delivery. Two time repiared. –> In the third time modified to E3732 in 2005. Currently, use in D11D (LV= 45,000 hours)
8	T43	1989	7,408	0	Occurred in Nov 1989. Currently, use in D08D (LV= 94,000 hours) E3786
9	T34B	1989	2,006	0	Currently, discard
10	T40B	1989	4,320	2	Currently, discard
11	T44A	1989	51,222	21	Occurred in 2010. Modified to a CPD-type klystron with E3732 specification in 2013.
12	T47	1989	4,321	1	Occurred in 1990. Repaired in 1990. Currently, use in D08C (LV= 106,000 hours)
13	T50	1990	4,261	12	Occurred in 2002. Repaired in 2007. Currently, use in D05D (LV= 64,000 hours)
14	T53	1990	20,000	8	Occurred in Mar 1993. Currently, use in D07E (LV= 104,000 hours)
15	T52	1991	89,000	29	Occurred in Dec 2020. Move to test station.
16	T56	1991	85,000	30	Occurred in Apr 2021. Currently, use in D05A (LV= 94,000 hours)
17	T49	1990	77,000	27	Occurred in Nov 2017. Currently, use in D11A (LV= 95,000 hours)
18	T27	1986	130,028	38	10 times occurred in two day at end of Feb 2024. Move to test station.

D07B