# Upgrade status of the RF system for SPring-8 storage ring


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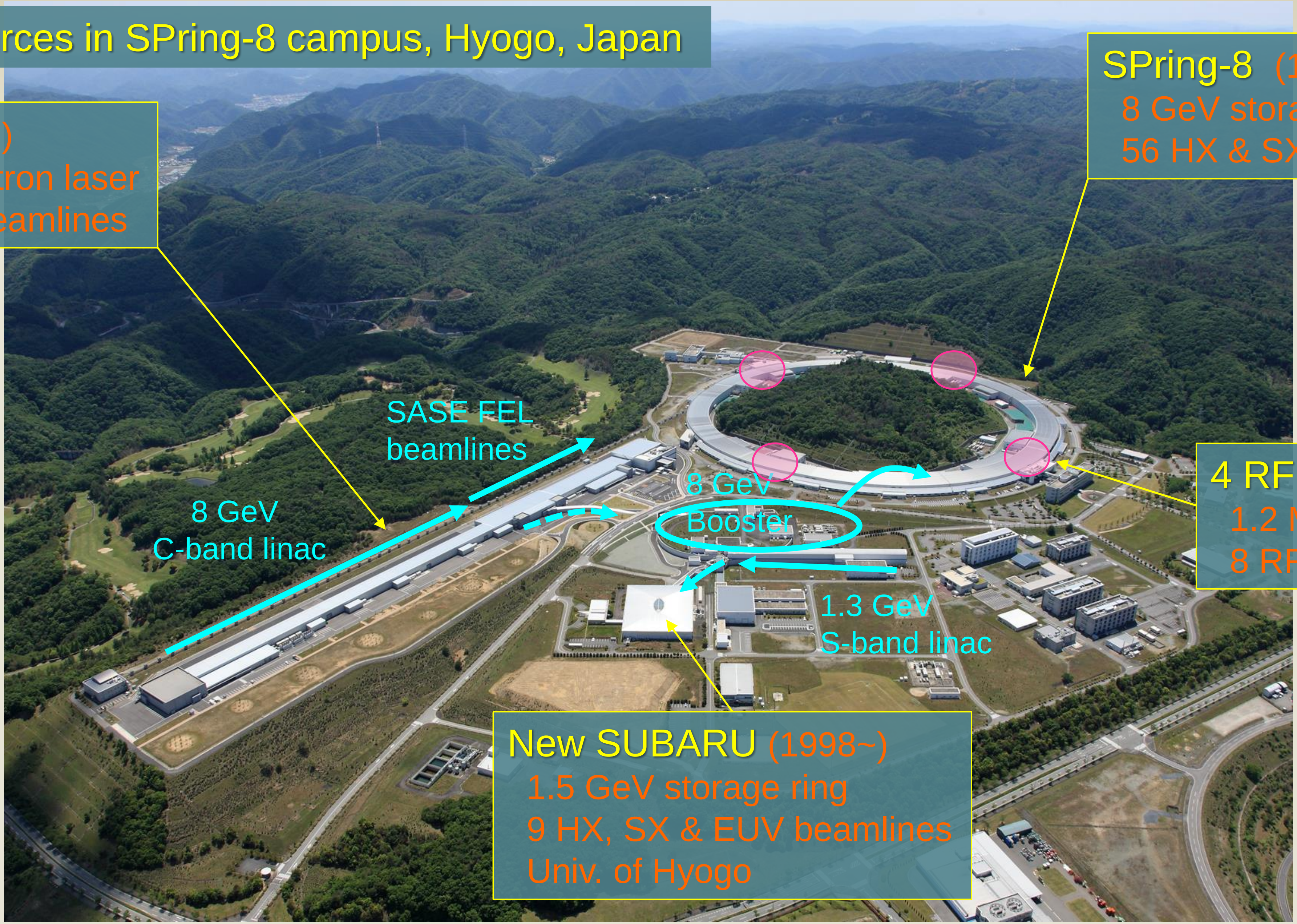
# Outline

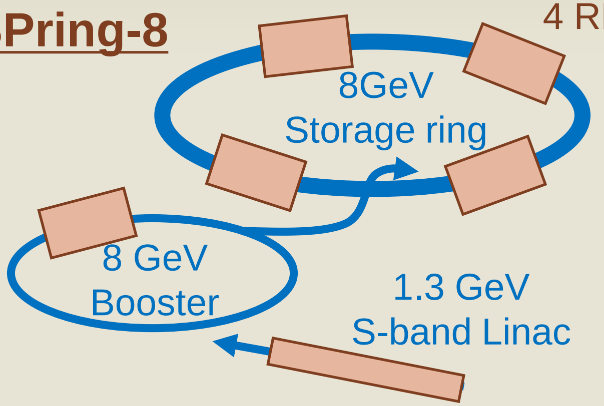
- Overview of SPring-8 upgrade project “SPring-8-II”
- On-going upgrades of RF system
  - Klystron power station
  - Digital low level RF control
- Development for future upgrade
  - HOM damped RF cavity
  - Solid state amplifier (SSA)
- Summary

# Three light sources in SPring-8 campus, Hyogo, Japan

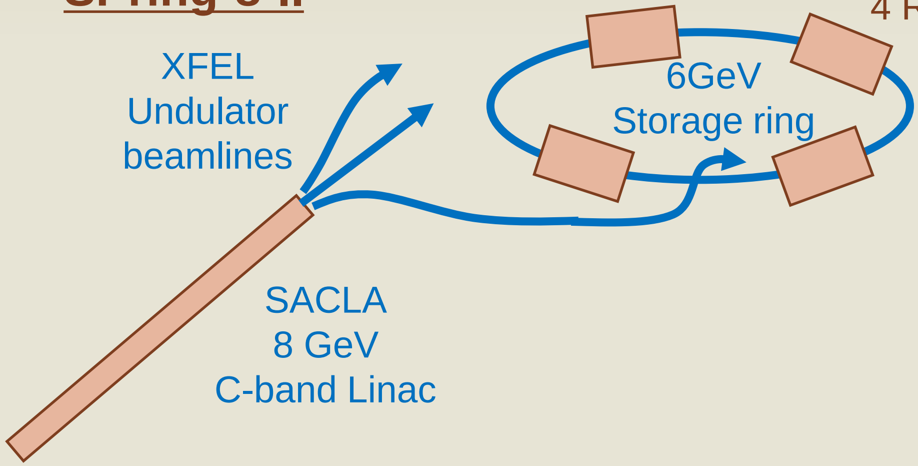


# Upgrade project "SPring-8-II" (planned 2020's)

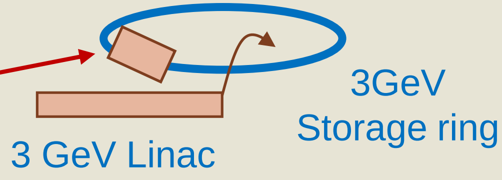
**SPring-8**




**SPring-8-II**




**New 3 GeV storage ring project in Japan**




- Low emittance (~100 pmrad) storage ring
- High brightness X-ray radiation
  - Beam energy 8 GeV → 6 GeV   ($\varepsilon \propto \sqrt{E_{beam}}$)
  - 5-bend achromat beam optics
  - Small beam dynamic aperture and physical aperture
  - Stable beam injection from SACLA   …..First commissioning is planned in this year.
  - Magnets and BPMs should align with high accuracy   ….Half cell mock-up was constructed.
  - RF should be stable and reliable, not to fluctuate the beam more than small beam size.

For future upgrade
- HOM damped RF cavity
- Solid state amplifier

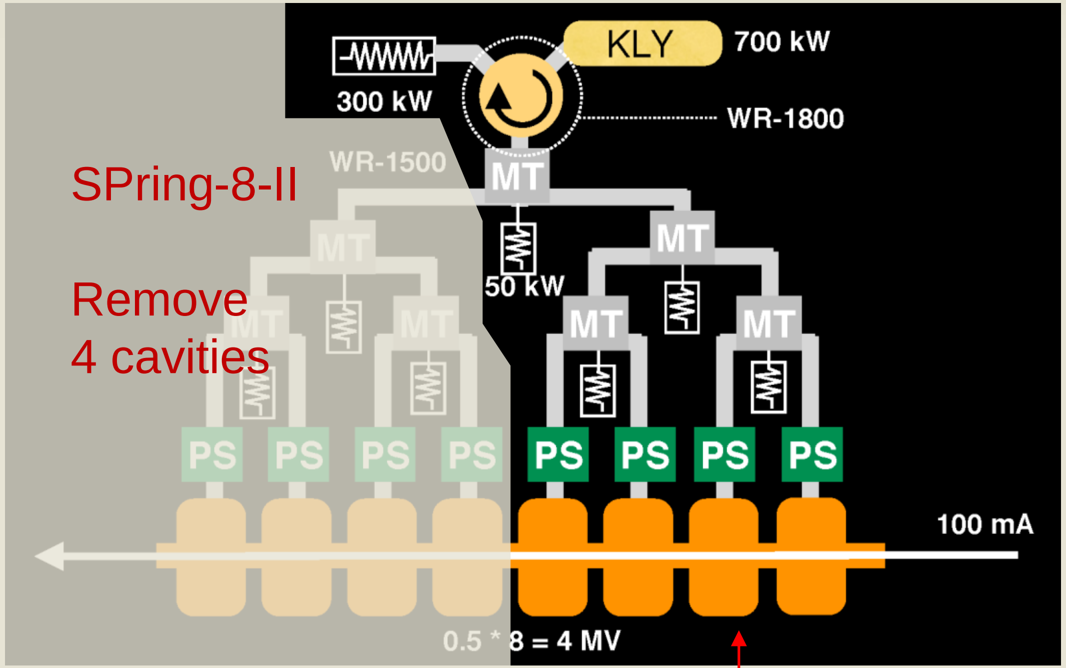
Upgrade of RF system
- Klystron power station
- Low level RF control

# Operation parameters for SPring-8 and SPring-8-II

H. Ego, IPAC'16 MOPMW009

| | SPring-8 (1997 ~) | SPring-8-II (2020s, planned) |
|---|---|---|
| Beam energy | 8 GeV | 6 GeV |
| Natural emittance | 2.4 nmrad (non achromat) | 0.1 nmrad (with undulator) |
| Beam current | 100 mA | 200 mA |
| Multi-bend lattice | 2-bend | 5-bend achromat |
| Beam energy loss | 13 MeV /turn | 5 MeV /turn |
| Acceleration voltage | 16 MV/turn | 7 MV /turn |
| RF frequency | 508.580 MHz | 508.762 MHz |
| Number of RF cavities | 8 x 4 stations | 4 x 4 stations |
| Cavity voltage | 500 kV /cavity | 440 kV /cavity |
| Beam loading | 40 kW /cavity | 60 kW /cavity |
| Klystron output power | ~ 700 kW | ~ 400 kW |

SPring-8 RF station




RF cavities
Bell shaped
single cell cavities
Q0~40,000
Rz ~ 6 MΩ

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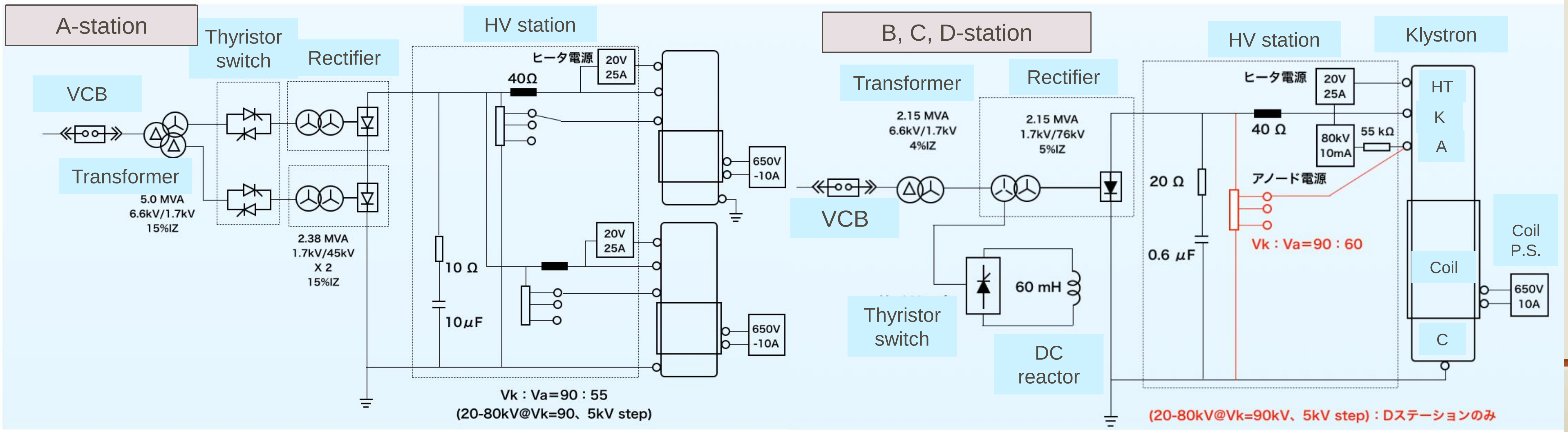
# (1) Replacement of klystron power station

Courtesy H. Ego

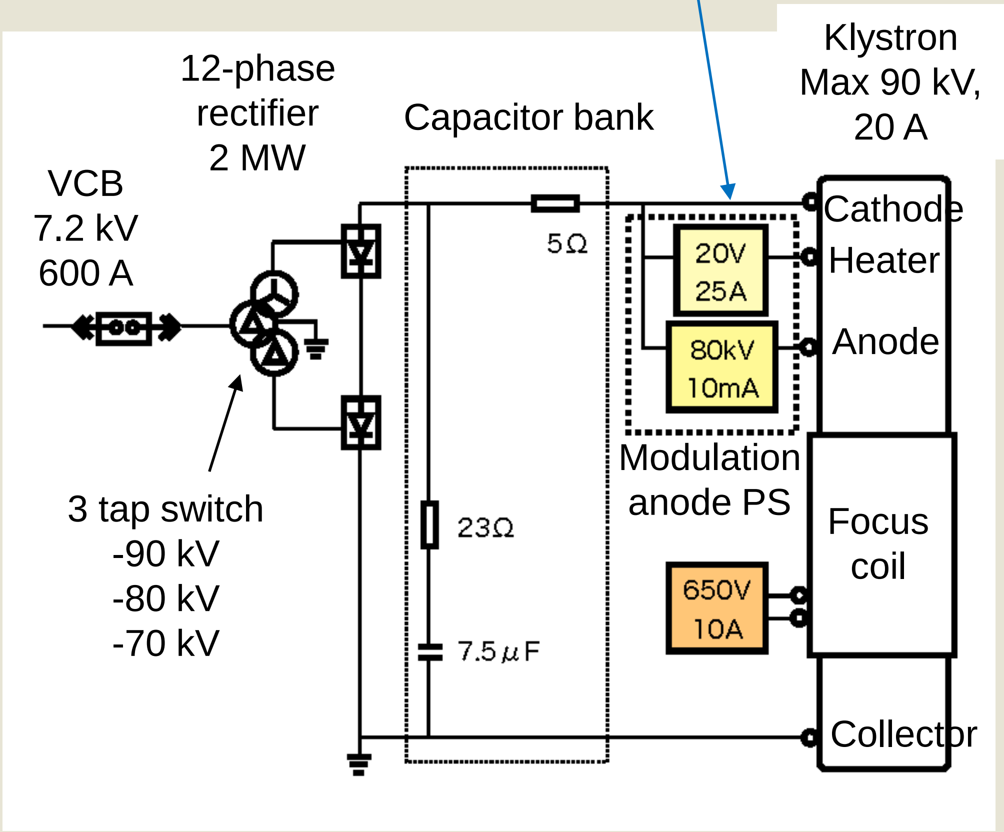
- Stable RF system for low emittance storage ring
  - Beam fluctuation should be small enough compare to small beam size.
- Replace 20 years old power stations
  - Aged problems; bank capacitors, resistors, high voltage cables, …
  - Discontinued products; thyristors, PLCs, panel meters,
  - 3 type of configurations; different response and stability, variety of spare components.



# New power station circuit

- Simple circuit design
  - Reliable and low cost
- No voltage control (thyristor switch or IVR)
  - Thyristor generates switching noise on power line
  - IVR has a mechanical parts, which should me maintained.
  - Voltage variation is compensated by LLRF feedback
- 12-phase rectifier with 3 tap switch
  - Select cathode voltage
- Modulation anode
  - Controls the beam current for better power efficiency
- No crowbar circuit
  - Rarely had a klystron arc, but false firing

| Vc | Power | Purpose |
|---|---|---|
| -90 kV | ~900 kW | 3-station operation for redundancy |
| -80 kV | ~700 kW | Usual 4-station operation |
| -70 kV | ~500 kW | SPring-8-II |

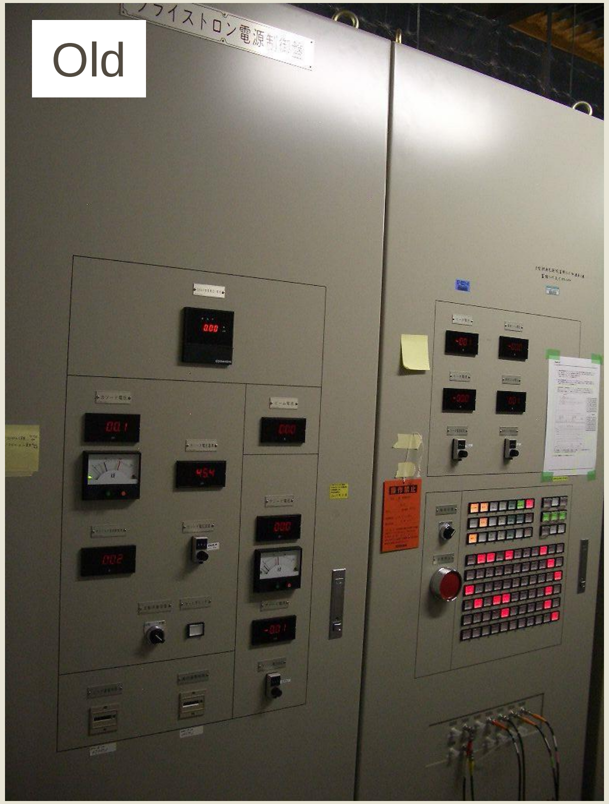


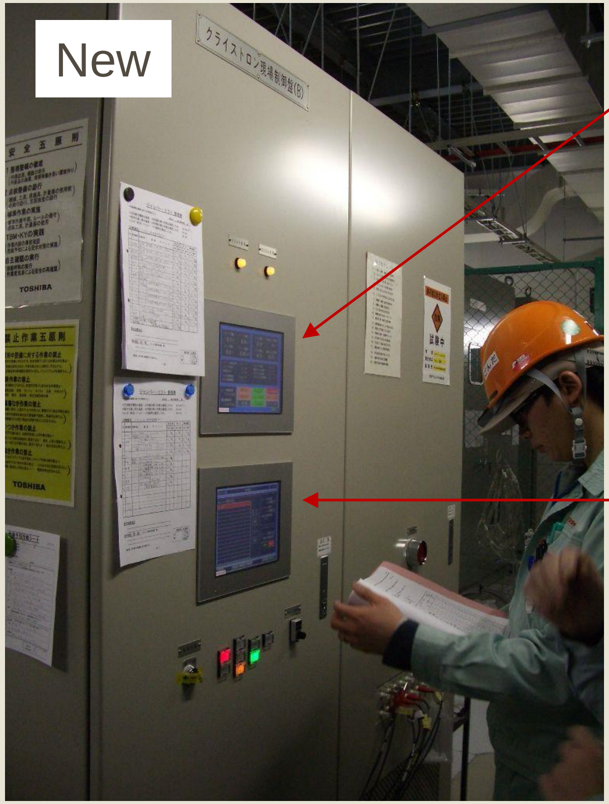
# Photograph of the new power station



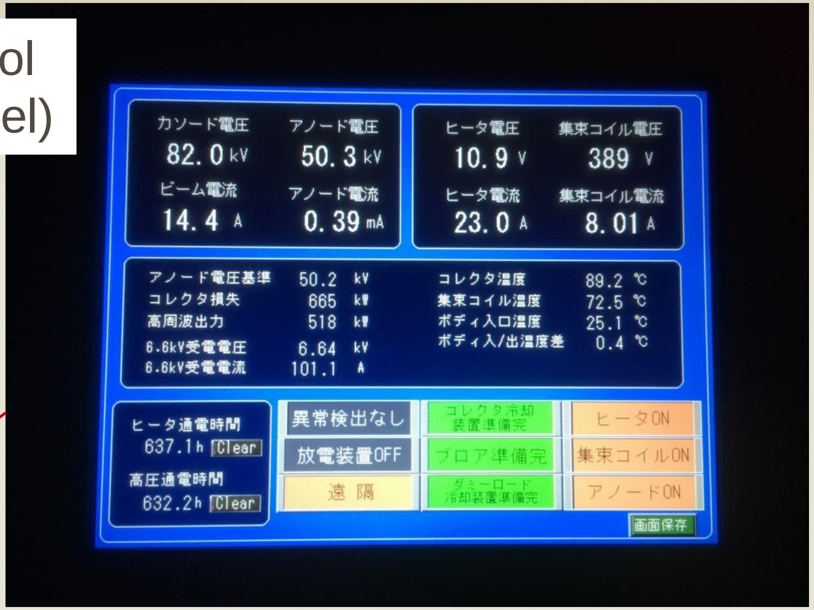
# New control panel

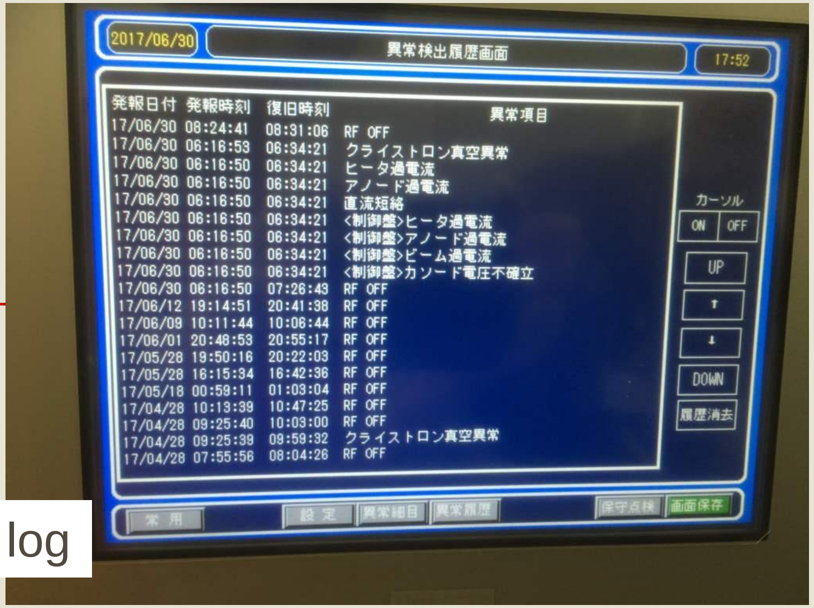
- Graphic touch panel
- PLC: Yokogawa FA-M3,  Network connection: FL-net
- All the data are recorded in the accelerator database.




Local control
(Touch panel)




Alarm log

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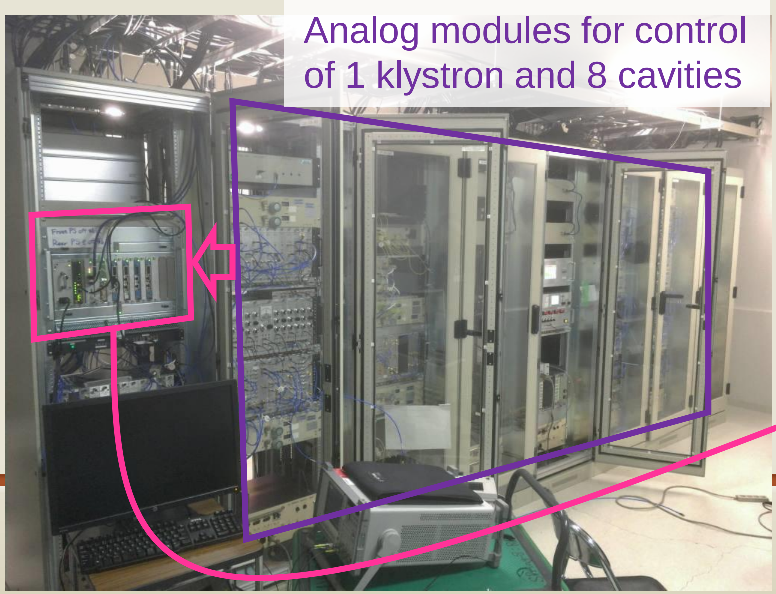
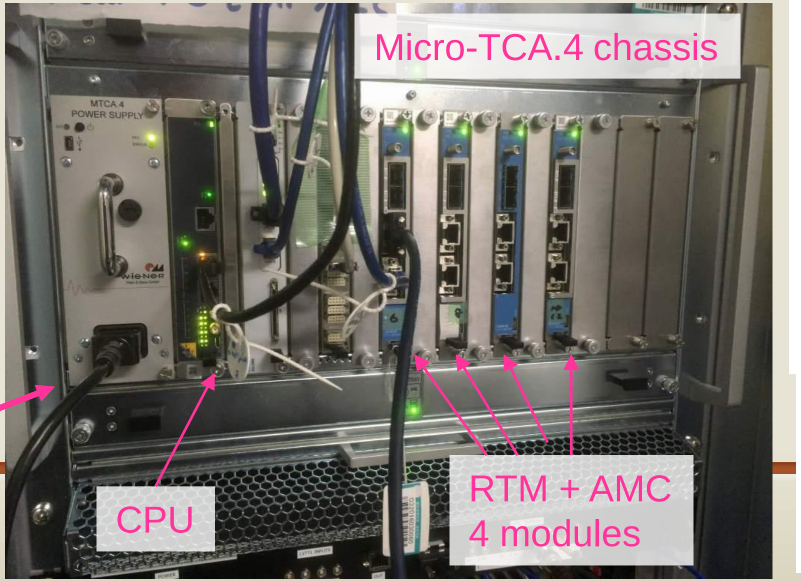
T. Ohshima, IPAC'17 THPAB117

# (2) Digital low level RF control development

- Digital control
  - Flexible control parameters
  - Free from the drift of analog modules
  - Intelligent logical interlock on-board
  - Record waveforms for trouble shooting
- Required accuracy: $\Delta V/V = 0.1\%$ rms
  $\Delta\phi = 0.1$ degree rms

- Micro-TCA.4 platform
  - Commonly used for new BPM system etc.
  - Integrate RF front end, digitizer (ADC/DAC) and FPGA on-board
  - 8 RF signals are measured in 1 module
  - Compact (1/10 of analog systems)
  - Low cost per channel

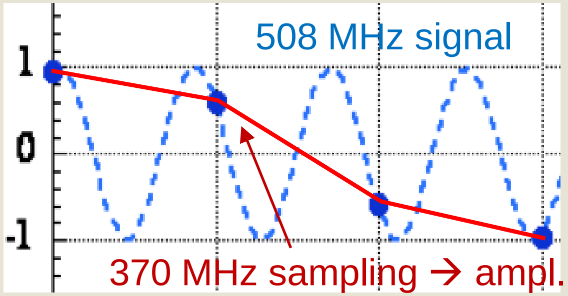


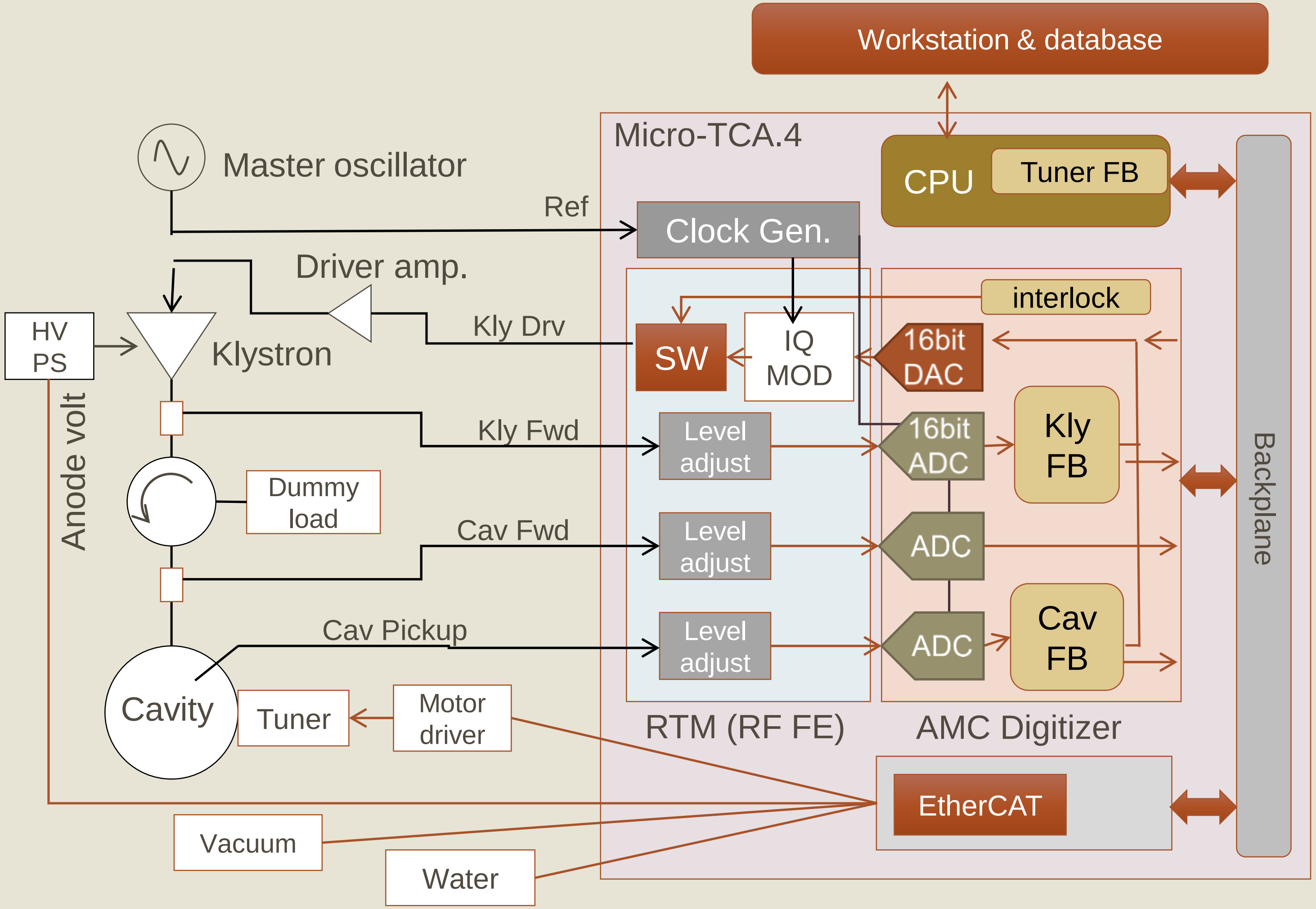

| Under-sampling RTM | Digitizer AMC |
|---|---|
| 8ch RF inputs | 10ch 16-bit, 370 MSPS ADC |
| 1ch Vector modulator | 2ch 16-bit, 500 MSPS DAC |
| CANDOX | Mitsubishi Denki Tokki |

# Block diagram of RF amplitude & phase control

- IQ modulation for ampl. & phase control
- Under sampling measurement, without mixer

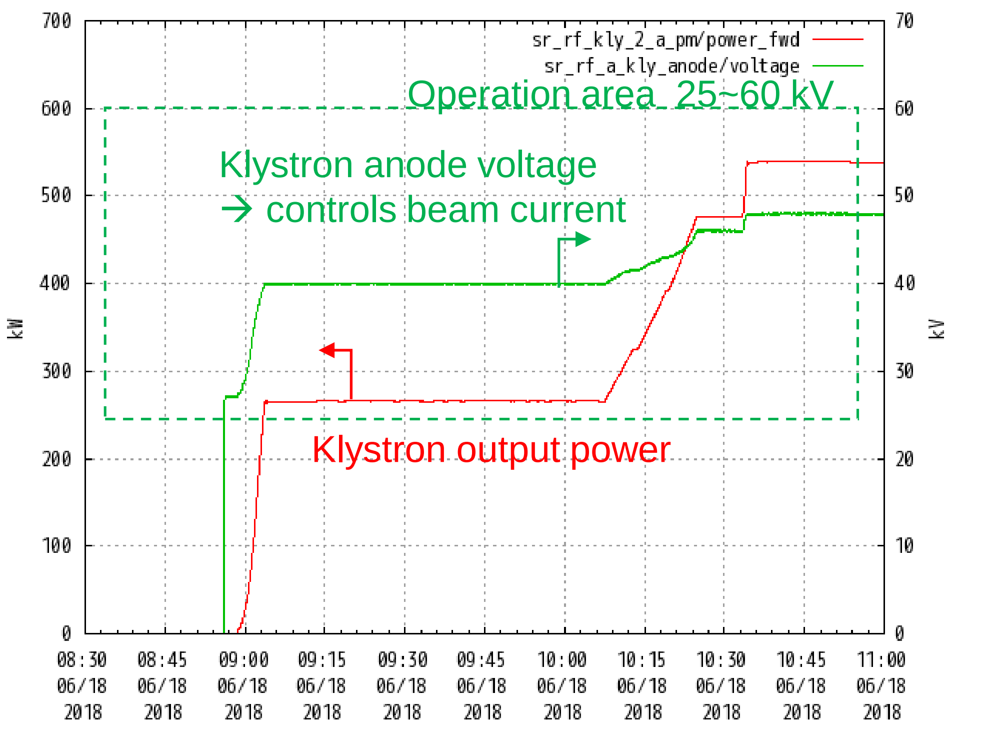


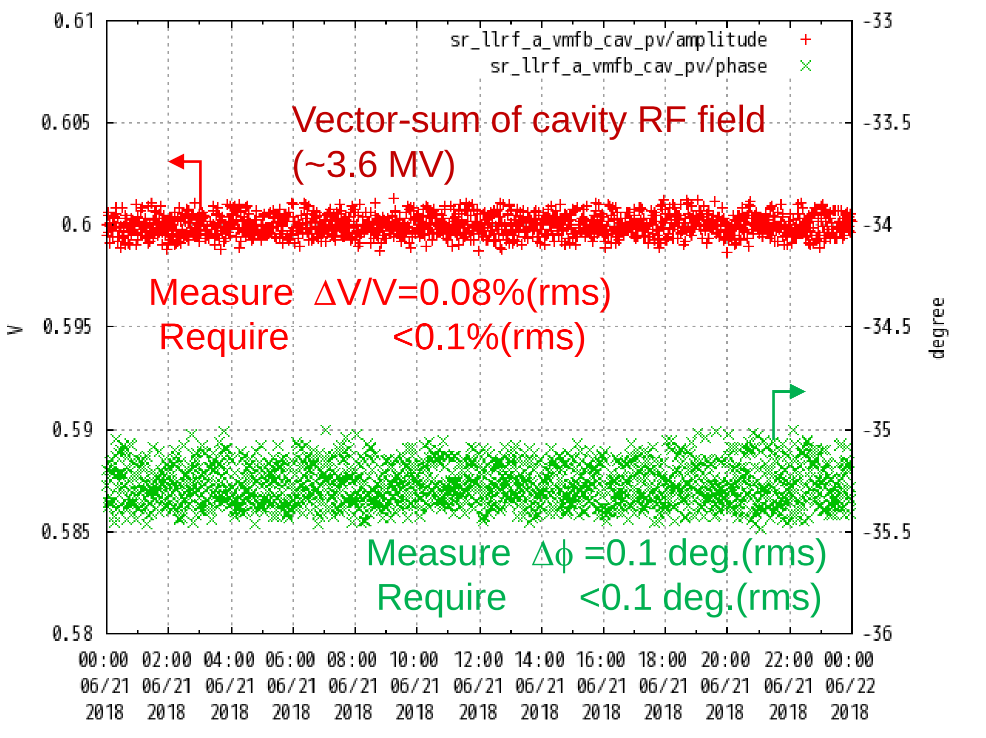

- Digital feedback on FPGA
  - Klystron FB (several 10 Hz ~ kHz)
    - Compensate voltage ripple etc..
  - Cavity FB (~several 10 Hz)
    - Compensate beam loading etc...
- Control via EtherCAT
  - Klystron anode voltage
  - Cavity tuner



# Operation status

- New LLRF system was installed at A-station in April this year.
- The new system has been operated for 3 months.
- Measured stability and accuracy of the cavity voltage satisfy the requirement.
- We plan to install the same system to other 3 RF stations by next year.

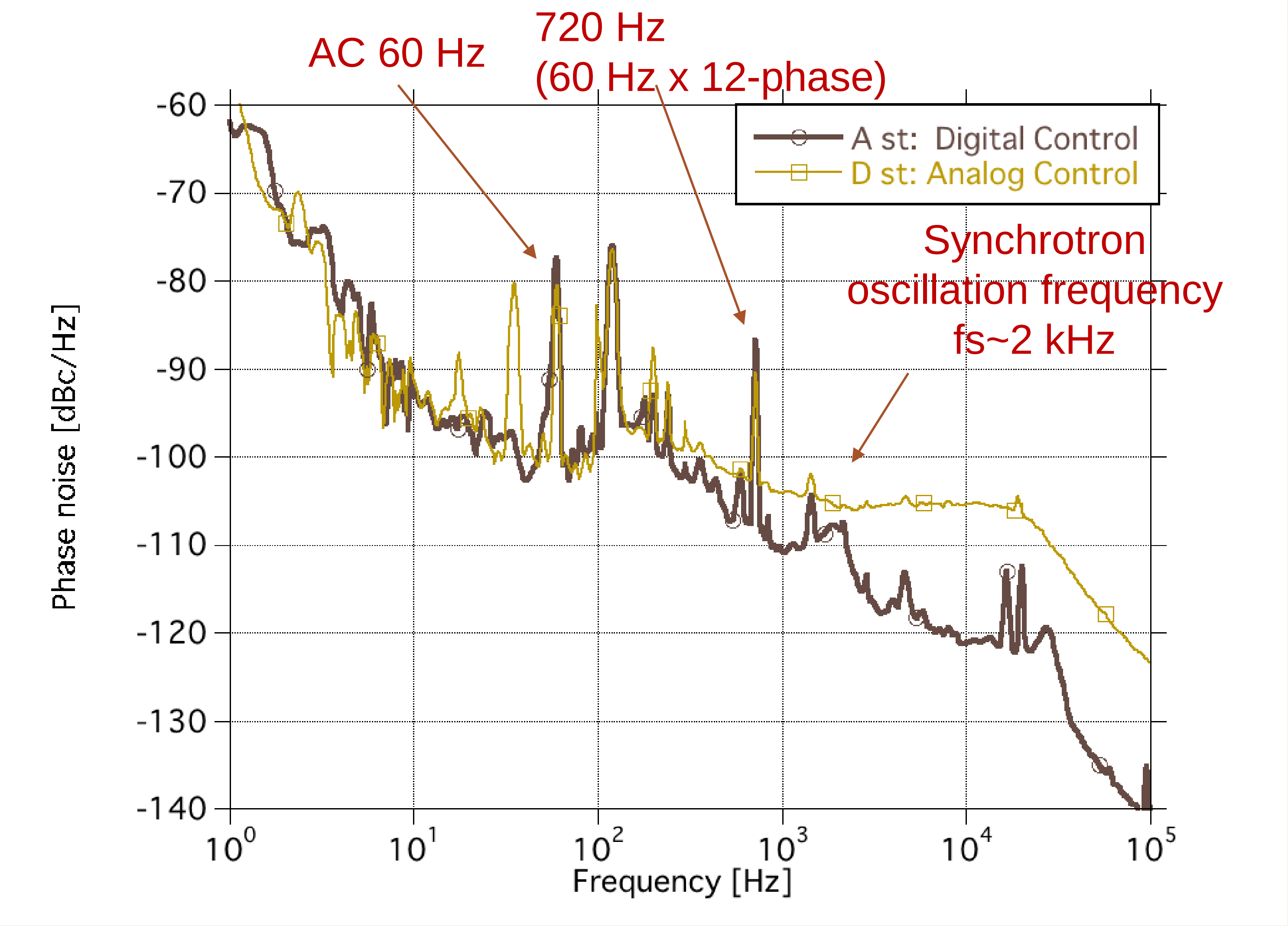


# Phase noise on cavity pickup signal

- Phase noise was measured and compared to the data for analog system.
- New system effectively reduces the phase noise over kHz.

  (fs~ 2 kH)
- 60 Hz and its harmonics are around -80 dBc/Hz. This is acceptable level.

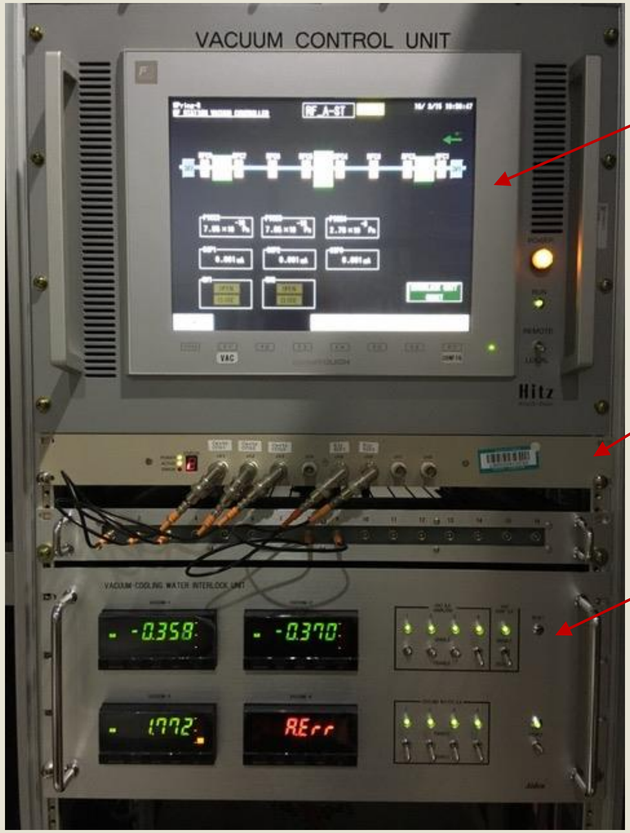


Courtesy T. Asaka

# New vacuum control / interlock system

- Replace old hardwares
  - Discontinued PLC modules
  - Analog (NIM) interlock modules
  - GPIB data collection

- New system
  - PLC with touch panel
  - Vacuum pressure info. to LLRF
  - Redundant interlock system




PLC with touch panel

EtherCAT to LLRF

Hardwired interlock system (Vacuum, water)

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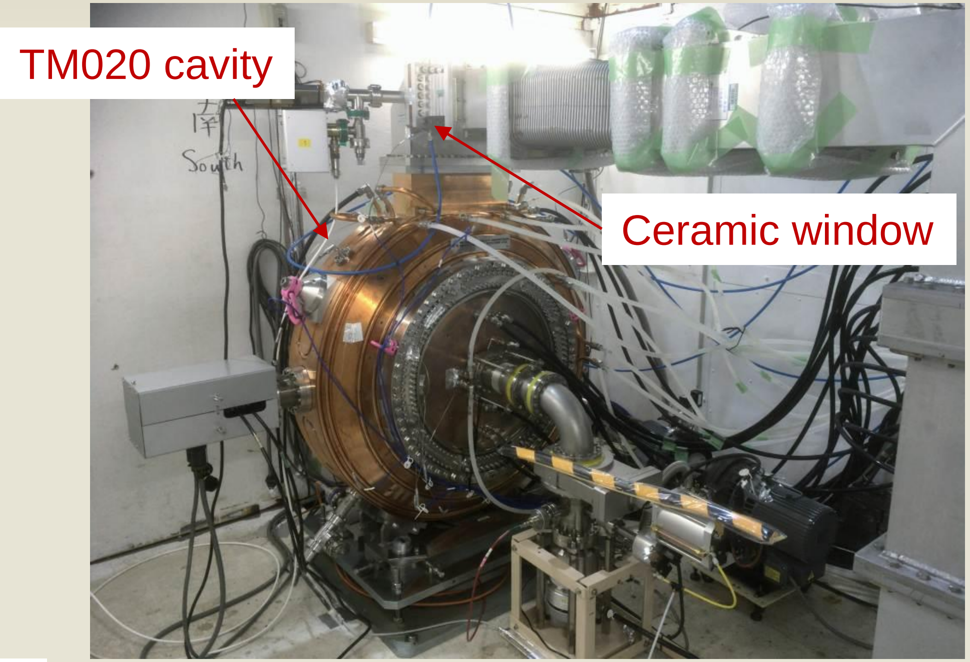
  - HOM damped RF cavity
  - Solid state amplifier (SSA)

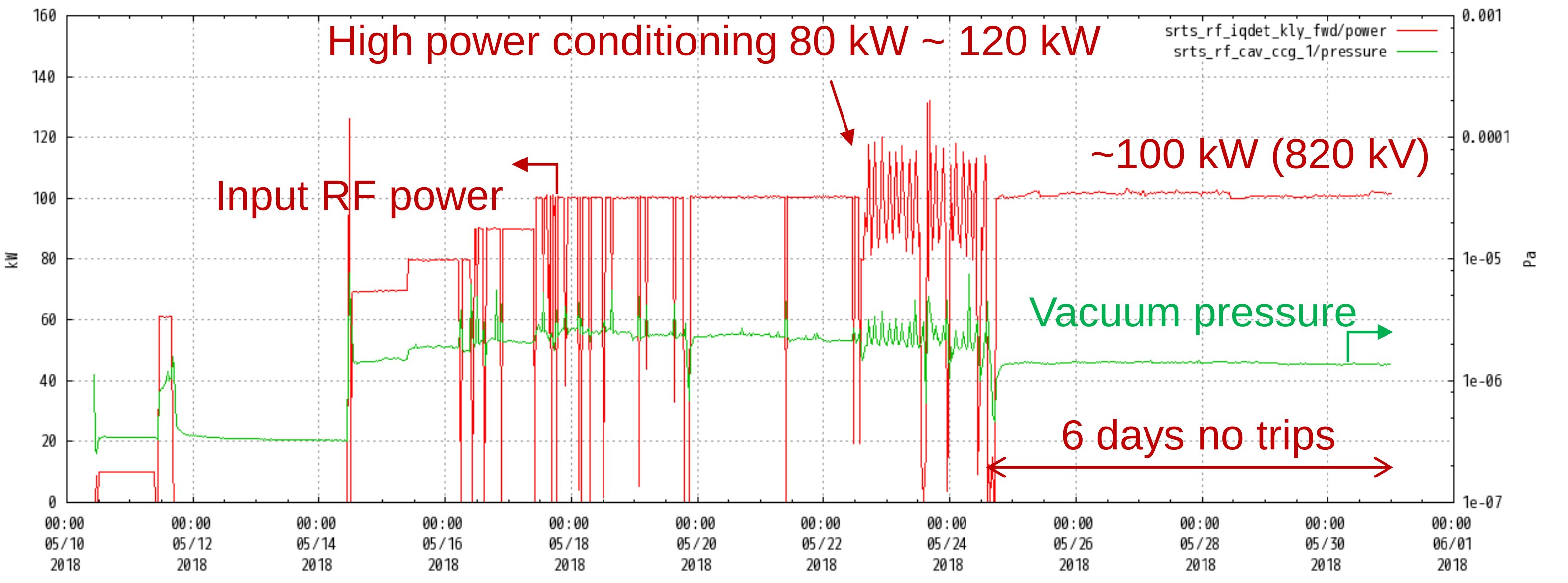
- Summary

Courtesy H. Ego
See SPring-8-II CDR

# (4) TM020 cavity with HOM damped structure

- Damp parasitic resonances (monopole, dipole)
  - HOM absorbers (ferrite) installed at magnetic node
- High Q (60,000) and Rz (6.8 MΩ) → High acceleration voltage
- The cavity will be used at new 3 GeV storage ring project in Japan.
- High power test
  - Without absorber:  up to 135 kW (960 kV)
  - With absorber:  will be tested in next year.




HOM absorber (Ferrite)
Brazing on copper plate has been established.

# (5) Solid state amplifier (SSA) development

Collaboration with
Mitsubishi Denki Tokki Systems

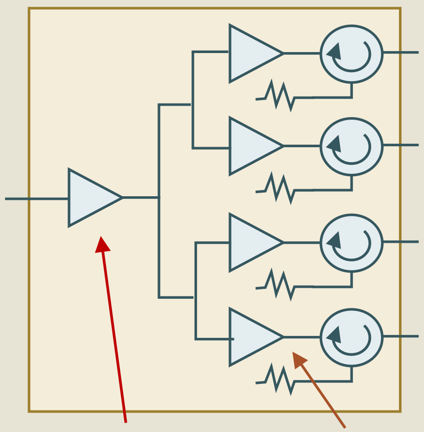
- For future option of 508 MHz RF source, a SSA was developed.
- In design, RF power of 160 LDMOSs are combined with a cavity combiner.

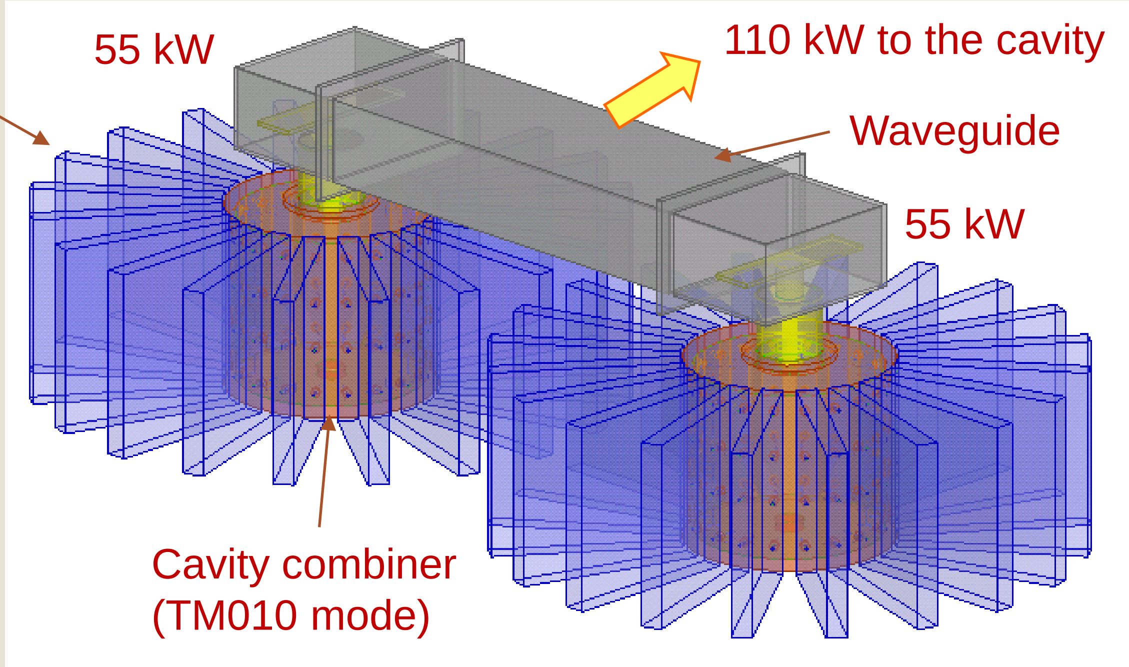
Already reported in CWRF 2016

- We performed a high power test of a prototype cavity combiner and one SSA module.

New

| Target specifications and design parameters | |
|---|---|
| Frequency | 508.762 MHz |
| Output power | 110 kW |
| Power efficiency | > 60% |
| Main amplifier | 160 LDMOSs |
| Pre-amplifier | 40 GaN-HEMTs |
| Power combining | Cavity combiner |
| -3dB band width | 5 MHz |



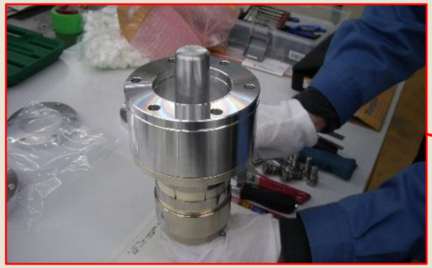



# Low power test of prototype combiner

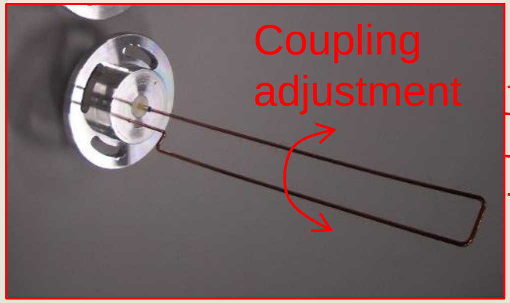
- Prototype aluminum cavity was fabricated.
- 4-port power combining was demonstrated.
- Coupling of 4-port was adjusted by rotation of the antenna.
- Combining power efficiency of 94% was obtained.

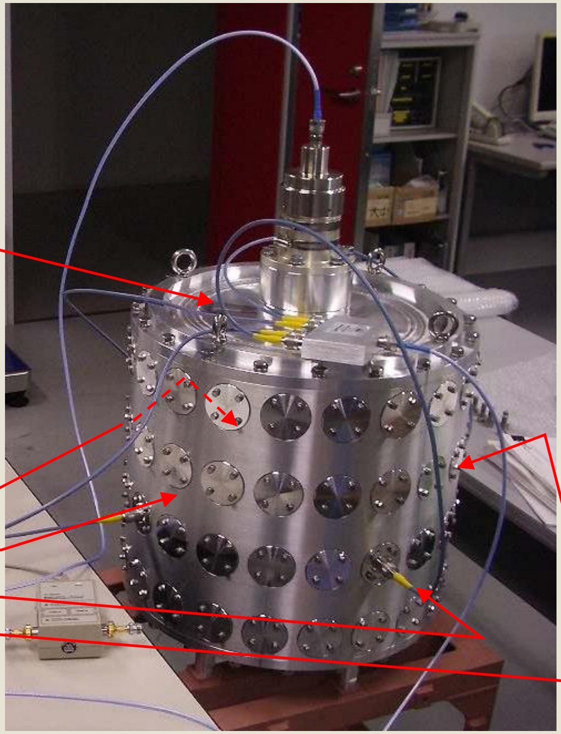
| | Real combiner | Prototype |
|---|---|---|
| Cavity material | Copper | Aluminum |
| Unloaded Q ($Q_0$) | 46,600 | 27,600 |
| Input antenna | 80 | 4 |
| Input coupling ($\beta_{in}$) | 2.9 | 4.8 |
| Output coupling ($\beta_{out}$) | 233 | 19 |
| Power efficiency | >99% | 94% |
| -3dB band width ($\Delta f_{3dB}$) | 5.1 MHz | 0.7 MHz |

Output port : Coax. WX-77D

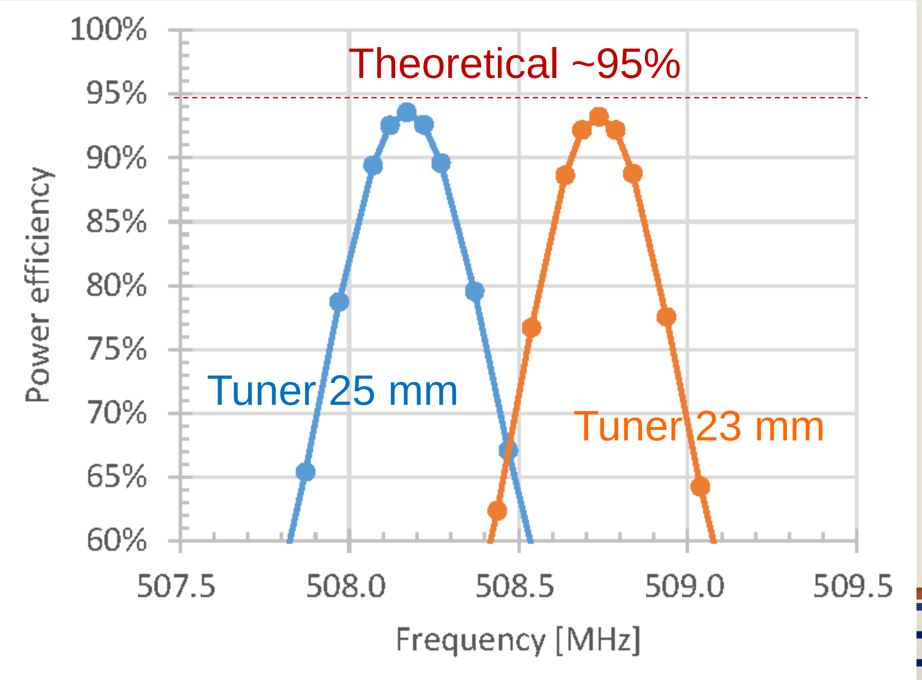


Input port : loop antenna



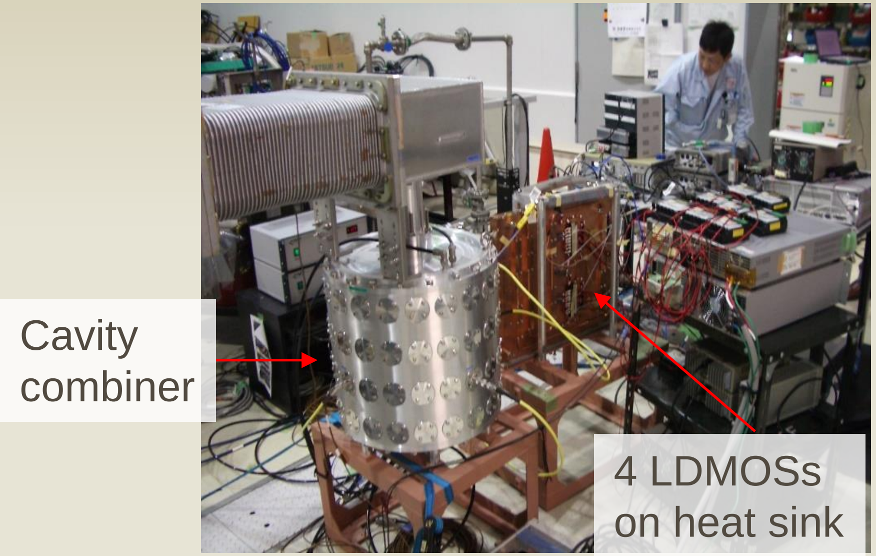



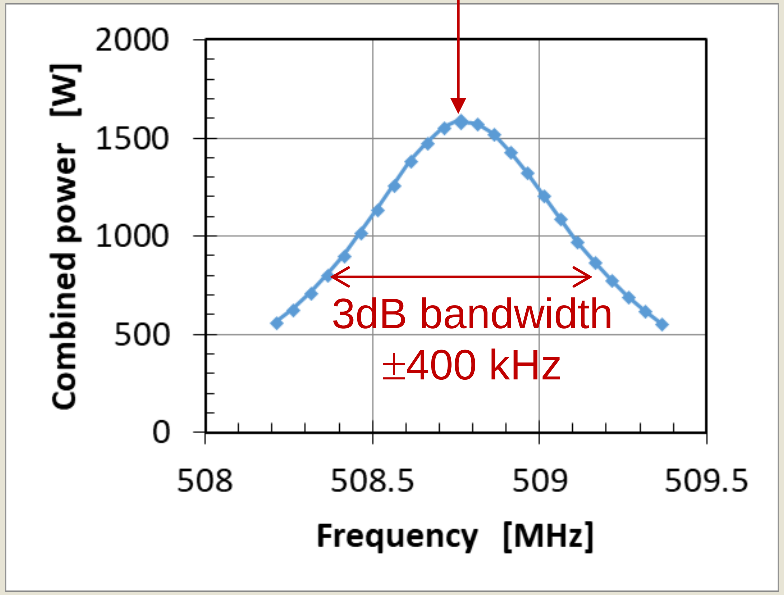
Frequency bandwidth of the power efficiency

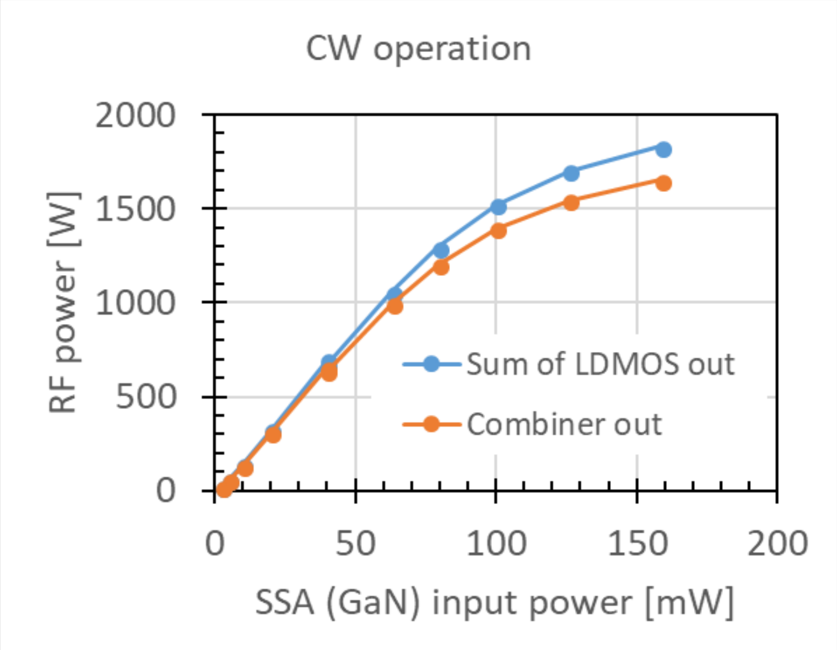


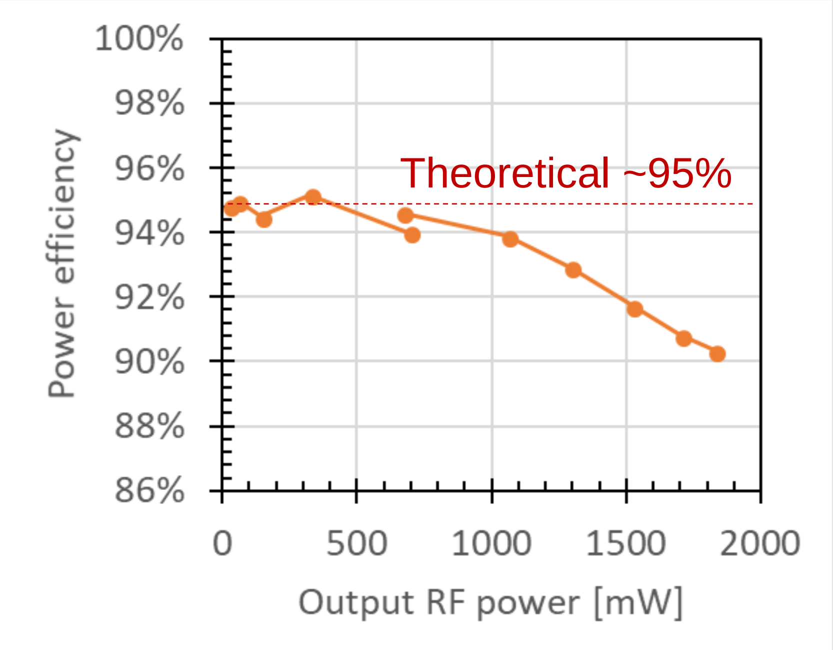
# High power test

- RF power of LDMOS output (470 W x 4 modules) was combined.
- Power efficiency of 95% was obtained at low power.
- But the efficiency was decreased at high power range.



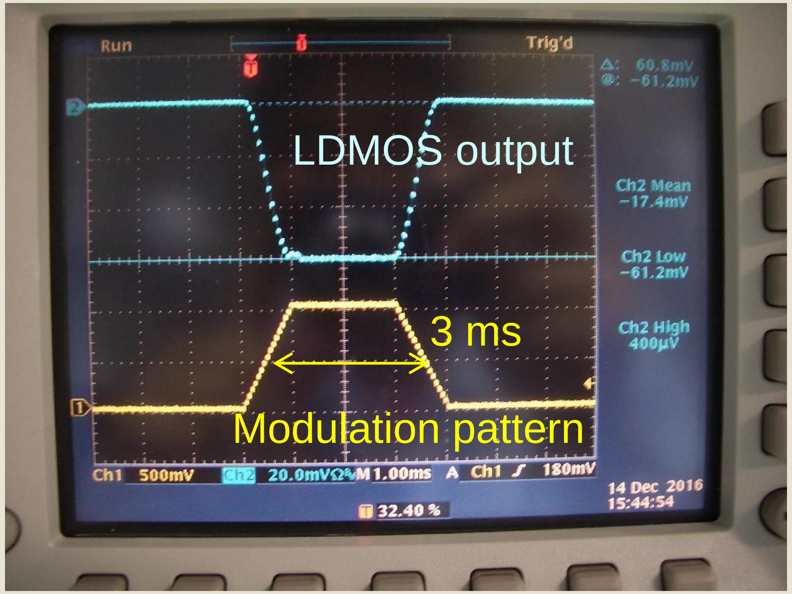



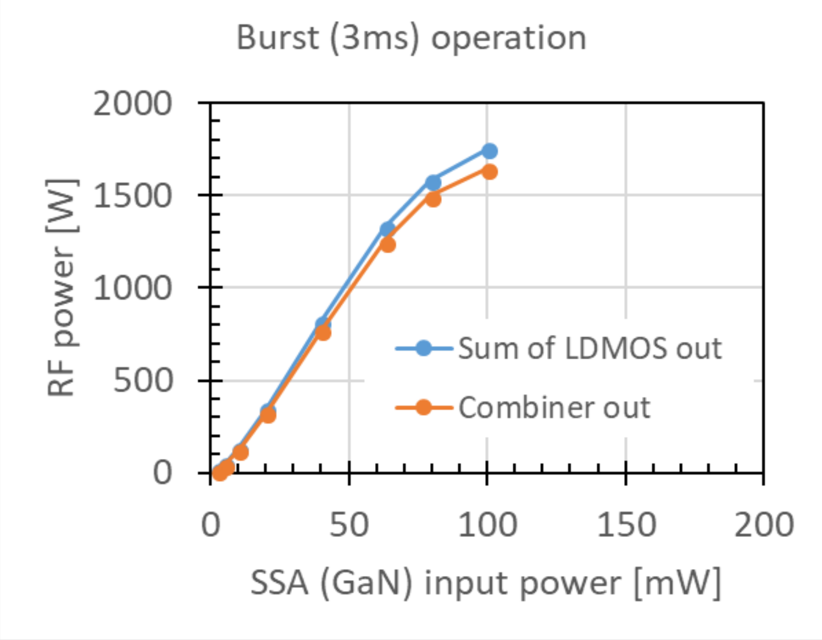



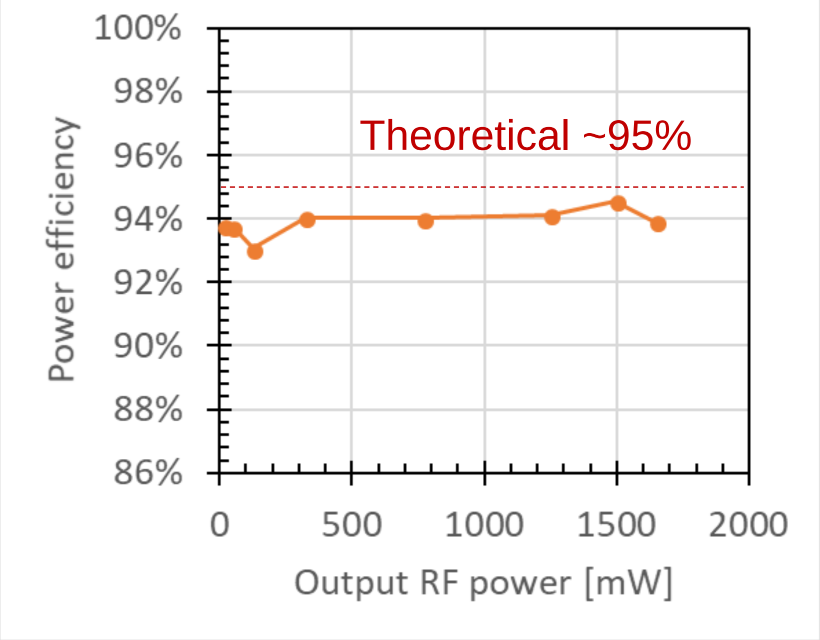
# Pulsed RF operation

Temperature with CW 470 W
LDMOS~110°C
Cable~35°C
Connector~50°C

- We tested with pulsed RF power. (3 ms, 1 Hz)
- The combining power efficiency was constant around 94%.
- Power loss in CW mode was due to the thermal problems (LDMOS, circulator, cable, antenna) ?
- During the investigation, pre-amplifier (GaN-HEMT) was broken
- Due to the budget priority, the study was interrupted.
- Instead of it, we have developed 476 MHz, 90 kW pulsed SSA for buncher cavity of SACLA.



# Summary (1)

- For better stability and reliability, many of old components and systems should be replaced.
- We have replaced/upgraded…
  - klystron power station
    - Simple and reliable circuit design.
    - So far no trouble at the power station.
  - Digital low level RF control system
    - Micro-TCA.4 based system runs well with a required accuracy ($\Delta V/V$=0.08%, $\Delta\phi$=0.1deg.).
    - New vacuum control system and interlock system was installed combined with LLRF system.

# Summary (2)

- We have developed…
  - TM020 cavity with HOM damped structure
    - High power operation test up to 135 kW.
    - HOM absorber will be fabricated and tested in next year
  - Solid state amplifier
    - High power combining test up to 1600 W was performed.
    - But the development was paused due to the priority of budget.
    - We focused to develop 476 MHz, 90 kW pulsed SSA for buncher cavity of SACLA.