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

SPring-8 (1997–)
- 8 GeV storage ring
- 56 HX & SX beamlines

SACLA (2011–)
- X-ray free electron laser
- 3 HX & EUV beamlines

New SUBARU (1998–)
- 1.5 GeV storage ring
- 9 HX, SX & EUV beamlines
- Univ. of Hyogo

8 GeV
- C-band linac
- SASE FEL beamlines

1.3 GeV
- S-band linac

4 RF stations
- 1.2 MW klystron
- 6 RF cavities
Upgrade project “SPring-8-II” (planned 2020’s)

- Low emittance (~100 pmrad) storage ring
- High brightness X-ray radiation
  - Beam energy $8 \text{ GeV} \rightarrow 6 \text{ GeV}$ ($\varepsilon \propto \sqrt{E_{\text{beam}}}$)
  - 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

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

**SPring-8 RF station**

**Remove 4 cavities**

**RF cavities**
Bell shaped single cell cavities
Q0~40,000
Rz ~ 6 MΩ
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- Summary
(1) Replacement of klystron power station

- Stable RF system for low emittance storage ring
  - Beam fluctuation should be small enough compared 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.

![Diagram of klystron power station configuration]
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

<table>
<thead>
<tr>
<th>Vc</th>
<th>Power</th>
<th>Purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>-90 kV</td>
<td>~900 kW</td>
<td>3-station operation for redundancy</td>
</tr>
<tr>
<td>-80 kV</td>
<td>~700 kW</td>
<td>Usual 4-station operation</td>
</tr>
<tr>
<td>-70 kV</td>
<td>~500 kW</td>
<td>SPring-8-II</td>
</tr>
</tbody>
</table>
Photograph of the new power station

VCB
12-phase transformer & rectifier
Focus coil
Power supply

High voltage capacitor bank

Modulation anode
Power supply

New control panel

- Graphic touch panel
- PLC: Yokogawa FA-M3, Network connection: FL-net
- All the data are recorded in the accelerator database.
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• Summary
(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: $\frac{\Delta V}{V} = 0.1\% \text{ rms}$
  - $\Delta \phi = 0.1\ \text{degree rms}$

- 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
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.

Klystron anode voltage \(\rightarrow\) controls beam current

**Klystron output power**

**Operation area** 25~60 kV

**Klystron anode voltage**

- **Operation area**: 25~60 kV
- **Measure** \(\Delta V/V = 0.08\%\) (rms)
- **Require** <0.1\% (rms)

**Klystron output power**

- **Vector-sum of cavity RF field** (~3.6 MV)
- **Measure** \(\Delta \phi = 0.1\) deg. (rms)
- **Require** <0.1 deg. (rms)
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 kHz)
- 60 Hz and its harmonics are around -80 dBc/Hz. This is acceptable level.
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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• Summary
(4) TM020 cavity with HOM damped structure

- Damp parasitic resonances (monopole, dipole)
  - HOM absorbers (ferrite) installed at magnetic node
- High Q (60,000) and $R_z$ (6.8 $\text{M}\Omega$) \(\rightarrow\) 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

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

Target specifications and design parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>508.762 MHz</td>
</tr>
<tr>
<td>Output power</td>
<td>110 kW</td>
</tr>
<tr>
<td>Power efficiency</td>
<td>&gt; 60%</td>
</tr>
<tr>
<td>Main amplifier</td>
<td>160 LDMOSs</td>
</tr>
<tr>
<td>Pre-amplifier</td>
<td>40 GaN-HEMTs</td>
</tr>
<tr>
<td>Power combining</td>
<td>Cavity combiner</td>
</tr>
<tr>
<td>-3dB band width</td>
<td>5 MHz</td>
</tr>
</tbody>
</table>

40 modules

GaN-HEMT ~120 W
LDMOS (BLF578) ~800 W

55 kW

110 kW to the cavity

Cavity combiner (TM010 mode)

Waveguide

Collaboration with Mitsubishi Denki Tokki Systems

Already reported in CWRF 2016

New
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.

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

Output port : Coax. WX-77D

Input port : loop antenna

Coupling adjustment

Frequency bandwidth of the power efficiency

- Theoretical ~95%
- Tuner 25 mm
- Tuner 23 mm
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.

Target frequency 508.762 MHz
3dB bandwidth ±400 kHz

Theoretical ~95%
Pulsed RF operation

- 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.

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

Theoretical ~95%
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 ($\Delta V/V=0.08\%$, $\Delta \phi=0.1\text{deg}$).
    • 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.