The ALS RF systems, upgrades and ALS-U plans

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Outline  Structure of this talk

- RF systems in the Advanced Light Source (ALS)
- 2017 - 2018 work on the ALS storage ring RF
- Plans for the ALS-U RF
**ALs-RF E-Gun**

- **hot deck @ -120 kV**
  - Heater PS
  - Bias PS
  - 25 W RF drive amp. *(ENI 325)*
  - Several optical links for control, monitor and RF

- **125 MHz from master oscillator**

- **Gating from timing system**

- **→ analog optical link to drive amp on hot deck**

- **Gun output**

- **2.5 ns pulses**

**isolation transformer for mains supply**

**gun body**

**cathode of YU-171 triode**
ALS-RF  E-Gun & Linac

<table>
<thead>
<tr>
<th>RF power [kW]</th>
<th>24</th>
<th>18</th>
<th>4000</th>
<th>16000</th>
<th>16000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bunch length [ns]</td>
<td>2.50</td>
<td>0.80</td>
<td>0.20</td>
<td>0.02</td>
<td>0.01</td>
</tr>
<tr>
<td>Energy [MeV]</td>
<td>0.12</td>
<td>25</td>
<td>50</td>
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</table>
**ALS-RF**  E-Gun & Linac

**LLRF**
- In service since 1989, all analog
- Proposing an upgrade to a digital FPGA based system

**Instrumentation**
- Wall current monitor
- Beam position monitors (buttons)
- Scintillator paddle with camera
- Switchable beam dump with Faraday cup

- 3 GHz waveguides
- e-gun
- 3 x buncher
- linac 1
- linac 2
**ALS-RF**

**125 MHz & 500 MHz buncher RF**

**125MHz: 5 x Eimac CV-2222**
- $P_{out} \sim 24\,\text{kW}$ for $\sim 30\,\text{us}$

**500MHz: 5 x Eimac CV-2404**
- $P_{out} \sim 18\,\text{kW}$ for $\sim 30\,\text{us}$

**2018 Maintenance**
- All 10 tubes replaced in 2018
- Sockets cleaned of dust
- All amplifier cavities re-aligned
- 50% increase in gain & output power

**Eimac CV-2222**
125 MHz cavity amplifier

**Eimac CV-2404**
500 MHz cavity amplifier

**Eimac 3CPX800A7**
Lifetime 10-12 years
2 x Thales TV-2002 Klystrons
- 24 MW, 2us, 1 Hz, 50 W avg.
- In service: 1989

Klystron lifetimes [years]
linac 1: 17, 10, 2+
linac 2: 9, 14, 2, 4+

Klystron Failures
- Internal parasitic emission
- Internal arcing
- Low / drifting output power
- 2013: collector water leak, fouled oil, shorted `buck coil` focusing magnet

Modulator Failures
- Thyratron CX-1666
- HV Caps
- HVPS & Cable

Replacement of PFN type modulator by a solid state type funded for FY18/19
Normal HV / RF pulsing

Pulses with suspected arcing

2018 frequent (every few days) modulator trips
suspected arcing in the klystron

oil shows signs of degradation, oil processing equipment on order

... might need to replace the tube soon
Nominal operating parameters

- \( V_k = 32 \) kV
- \( I_k = 2.8 \) A
- \( \text{Eff} = 60\% \)
- \( \text{Gain} = 23 \) dB
- \( P_{\text{out}} = 54 \) kW

IOT lifetimes

#1: 3 yrs failed due to poisoned cathode from HV cable fault

#2: 9+ yrs

Failures

- Grid Bias PS
- HV Cable fault (due to RF standing wave)
- HV Isolation Transformer
- Thyratron
- 2018: resistor went open circuit in analog LLRF system
**ALS-RF** Storage ring RF

**Klystron Operating Parameters**

\[
\begin{align*}
V_k &= -53.1 \text{ kV} & I_k &= 9.55 \text{ A} \\
V_a &= 32.8 \text{ kV} & I_a &= 1.6 \text{ mA} \\
\text{Eff} &= 51.53\% & \text{Gain} &= 41.41 \text{ dB} \\
\mu P &= 1.61 & \text{RF Output} &= 261.7 \text{ kW}
\end{align*}
\]

**RF system**

- Operational since 2012
- Nominal RF output power
  - ~260 kW with a single klystron
    - (500 mA, nominal ID gap)
- In 2019:
  - ~360 kW max. with 2 klystrons

**Issues**

- HV filter capacitor degradation
- Arc detectors not reliable
  - (due to ionizing radiation!)
- Mod anode control system ...

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Thales 2161L

Kly. 1

Kly. 2

Mod. anode hot deck

Wg. switch matrix
Since 2012, intermittent loss of filament current / mod anode voltage → trip of klystron interlock system (~ once a month)

Problem really surfaced in 2017 (several trips a day!)

By installing a `Lab-Jack` DAQ module we could narrow down the faulty behavior to the PLC I/O module

Proprietary digital link over plastic fibres

One fiber was found partly damaged
- bad enough to cause I/O glitches due to `bit errors`
- not bad enough for the PLC to signal a link error
Wg. Switch Matrix

- Provides operational redundancy

Operating modes

- Kly. 1 or 2 single drive (shown)
- Dual drive
- Dummy load drive
- Cavity to test port for VNA meas.

Current state

- Wg. switches locked in place as shown
- 2019: finish work on control / interlock system for full 2 klystron operation
Percentage of Scheduled Beam Time Lost to SRRF & Non-Latching Faults by Fiscal Year

Goal for SRRF system based on 5000 hours of User Beam time: 0.3% or less

* Data for partial year
SRRF Reliability - Mean time between faults

SRRF Faults, MTBF (in hours): Mean time between faults, FY2004 - FY2018*

Goal for SRRF system based on 5000 hours of User Beam time: 500 hrs or greater

* Data for partial year
SRRF Reliability - Mean time to recovery

**SRRF Faults, MTTR (in minutes): Mean time to recovery, FY2004 - FY2018**

Goal for SRRF system based on 5000 hours of User Beam time: 90 min or less

* Data for partial year
SR-RF upgrades

Timeline

- **2012**
  - Established Klystron site #2

- **2013**
  - New HVDC power supply

- **2014**
  - Installed IGBT based disconnect switch

- **2016**
  - Finished waveguide switch-matrix

- **2017**
  - Commissioned digital LLRF system

- **2018**
  - RF phase noise improvements

- **2019**
  - Full 2 Klystron operation
**Hardware**

- Xilinx **KC705** eval. board (Kintex 7) + ADC & DAC daughter boards by 4DSP
- Custom made 500 MHz *up / down converter* board

**Features**

- Scalable, distributed design, ≤ 42 input / output channels with ≤ 60 MHz bandwidth
- 1.45 μs interlock latency
- Non - IQ sampling
- Managed through gigabit ethernet interface
- Epics integration / python expert GUI
- Open Source! Code available on github

**In progress**

- Narrow-band network analyzer feature
- System-on-a-chip for initialization & housekeeping
- Timing system integration (Micro-research Finland)
- SRRF loop optimization
  (avoid ‘fighting’ with ALS longitudinal feedback)
SR-RF upgrades

Phase noise hunting

MO replacement selected & ordered

500 MHz master osc.

Upgrade of coax based MO distribution system in conceptual design stage

Timing sys.
E. gun
Buncher

Linac I
Linac II

Buncher
Booster
Storage Ring

LLRF

Klystron

Drive amp.

Replaced in 2018

Old amp.
New amp.

3.75 kHz

Significant improvement for IR beamline users
ALS-U Plans

Overview

- **> 100 fold** increase in soft x-ray brightness
- Requires **new lattice** in the storage ring, diffraction limited emittance
- Unique: **on axis swap out injection** to satisfy the smaller dynamic apertures of the new lattice
- New **accumulator** ring for topping-up the swapped-out bunch train

![Beam profile](image)

![Diagram](image)
Storage ring

There is a real chance of reusing the existing 500 MHz ALS RF system + cavity

- **But** optimum coupling factor ~10, existing coupler only achieves < 3.2
- **Option 1** live with reflected RF power (and larger electricity bill)
- **Option 2** develop a new RF coupler
- Simulation work in progress

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Accumulator

- Severe space constraints → will need to modify the concrete shielding
- Exploring existing cavity options
  - ALS SRRF cavity
  - Research Instruments - EC “Dampy” cavity
  - Toshiba ASP cavity
- RF Performance & Cooling: RI & Toshiba have no big differences
- Fit: Toshiba cavity would be a leading candidate if coupler coaxial section is extendable. NDA?
ALS-U Plans

Accumulator RF

- **2 amplifiers** (one for each cavity)
- Optional: 3rd amplifier to improve reliability (might not be needed with SSAs)
- Simplified switch matrix
ALS-U Plans

Major specs.

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<table>
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<tbody>
<tr>
<td>CW output power [kW]</td>
<td>60 - 80</td>
</tr>
<tr>
<td>Frequency [MHz]</td>
<td>499.6</td>
</tr>
<tr>
<td>1 dB bandwidth [MHz]</td>
<td>&gt; 4</td>
</tr>
</tbody>
</table>

Additionally, we would like

- High Reliability / Fault Tolerance: continue to operate with N failed transistors, amp. modules or power supplies (PS)
- Maintenance: modular design, dripless quick disconnects, hot-swappable DC PS
- Fail-Safe Controls & Interlocks

→ can be met by commercial SSA’s

Example: VHF solid state amplifier for the LCLS-II Gun B collaboration

Two 60 kW CW SSA at 186 MHz preparing for test at factory

See poster by K. Baptiste on Thursday
Booster IGBT magic-smoke was released

Booster Bend Magnets
- 1 cycle per second
- 1.2 MJ capacitor bank for energy storage between cycles

Power converter
- based on Semikron IGBT bridge modules
- rated 1.7 kV, 2.4 kA, switches @ 2 kHz

11. April 2018
- upper half-bridge switch failed closed during its conduction period, root cause not clear
- short across the DC bus in the next half-cycle
- IGBT module went through rapid unscheduled disassembly
- 12 x 100 A fuses blew in the cap. bank and prevented worse
- replacing IGBT module and a DC bus filtering cap. allowed us to start back up
Booster: IGBT magic-smoke was released

- 4 x IGBT arrays on cold-plate
- IGBT dies
- Failed short
- Arcing damage on back of a failed module
- Burned bus bar / transducer
The injector and its RF systems will still be needed for a long time. Legacy systems are being replaced step by step. (S-Band PFN modulators, analog LLRF, etc.)

Storage ring RF system upgrade very close to completion (Outstanding: Arc detector issues, control and interlock integration for second klystron)

There’s a good chance we will need a new solid state amplifier + cavity for the ALS-U accumulator ring soon
Thank you!
## Booster cavity

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Center Frequency</td>
<td>499.64 MHz</td>
</tr>
<tr>
<td>Harmonic #</td>
<td>125</td>
</tr>
<tr>
<td>Peak acc. voltage (@ 66 kW)</td>
<td>813 kV</td>
</tr>
<tr>
<td>Beam current (multibunch)</td>
<td>4 mA</td>
</tr>
<tr>
<td>Synch. rad. loss (dipoles)</td>
<td>5 kW</td>
</tr>
<tr>
<td>Shunt imp. (ZT$^2$)</td>
<td>5 MΩ</td>
</tr>
<tr>
<td>RF power required</td>
<td>54 kW</td>
</tr>
<tr>
<td>RF power installed</td>
<td>80 kW</td>
</tr>
</tbody>
</table>

**Beam configuration**

- **Waveguide**: WR1800
- **Window**: Cylindrical ceramic
- **Flange**: Iris
- **Power installation**: 80 kW

**Remote control**

- **Coax to wg. trans.**
- **Beam port**
- **HOM port**
- **Piston tuner**

**RF power requirements**

$\text{RF power required} = \text{beam loading} + \text{cavity loss} + \text{return loss} + \text{transmission loss}$