RF System Upgrade for the New Extremely Brilliant Light Source at the ESRF,
Operation Experience with Klystrons and Solid State Amplifiers

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352 MHz 1.3 MW Klystron

Thales TH 2089
Existing Storage Ring
1992: commissioning
1994: external users
since then:
• many upgrades
• brilliance increase by about a factor 1000

New Extremely Brilliant Source: EBS
• further brilliance increase by a factor 40
2019: installation
2020: commissioning resume user service
Main features:
- 2 regions with large dispersion for efficient chromaticity correction
- Rough sextupole compensation by having a $\approx \pi$ phase advance between the 2 sections

Performance:
- Natural equilibrium emittance: $\epsilon_{x0} = 134 \text{ pm}$
- Emittances with 5 pm coupled into the vertical plane and 0.5 MV radiation losses from ID’s:
  - $\epsilon_x = 107 \text{ pm}$
  - $\epsilon_z = 5 \text{ pm}$

[Courtesy: L. Farvacque]
DL
0.17 ➞ 0.67 T
permanent magnets,
5 modules

Quadrupole
91 T/m, ∅25.4 mm

[Courtesy: Gael Le Bec]
DQ
0.55 T, 37 T/m

[Courtesy: Gael Le Bec]
### MAIN MACHINE PARAMETERS

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Existing ESRF</th>
<th>ESRF-EBS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Same energy, current and filling patterns</td>
<td>E, Ibeam</td>
<td>6 GeV, 200 mA</td>
</tr>
<tr>
<td>Emittance</td>
<td>$\varepsilon_x / \varepsilon_z$</td>
<td>4000 pm / 5 pm</td>
</tr>
<tr>
<td>Energy loss (incl. 0.5 MeV for ID's)</td>
<td>U</td>
<td>5.4 MeV/turn</td>
</tr>
<tr>
<td>Same ID position $\Rightarrow \Delta f_{rf} = +170\ kHz$</td>
<td>$f_{rf}$</td>
<td>352.20 MHz</td>
</tr>
<tr>
<td>Longitudinal damping time</td>
<td>$\tau_s$</td>
<td>3.5 ms</td>
</tr>
<tr>
<td>Momentum compaction factor</td>
<td>$\alpha$</td>
<td>$17.8 \times 10^{-5}$</td>
</tr>
<tr>
<td>Energy spread</td>
<td>$\sigma_E/E$</td>
<td>$1.06 \times 10^{-3}$</td>
</tr>
<tr>
<td>Nominal RF voltage</td>
<td>$V_{acc}$</td>
<td>8 MV (max 12 MV)</td>
</tr>
<tr>
<td>$\Rightarrow$ RF Energy acceptance (incl. ID's)</td>
<td>$\Delta E/E$</td>
<td>2.9 %</td>
</tr>
<tr>
<td>Synchrotron frequency</td>
<td>$f_s$</td>
<td>1.86 kHz</td>
</tr>
<tr>
<td>$I_{\text{threshold}}$ for HOM driven instabilities (LCBI) [for a given HOM]</td>
<td>ratio</td>
<td>1.9 to 1</td>
</tr>
<tr>
<td>Number of cavities</td>
<td>$N_{cav}$</td>
<td>5 (five-cell cav's $\Rightarrow$ 25 cells)</td>
</tr>
<tr>
<td>Cavity Coupling</td>
<td>$\beta$</td>
<td>4.4</td>
</tr>
<tr>
<td>Total RF power at 200 mA</td>
<td>$P_{\text{tot-200mA}}$</td>
<td>$\approx 1400$ kW</td>
</tr>
</tbody>
</table>
Total energy loss including ID radiation: 3.1 MeV/turn
Maximum RF Voltage: 6.6 MV
RF transmission losses: 15 %
   including RF losses, spurious mismatches
Stored current with operational margin: 220 mA
RF frequency: 352.371 MHz

15 HOM damped cavities:
3 prototypes validated for 0.6 MV / 150 kW
12 cavities in fabrication

5-cell cavities: strong HOM!

HOM damped mono-cell cavities
developed at ESRF, based on BESSY/ALBA design
RE-USE OF EXISTING RF POWER SOURCES FOR ESRF-EBS

3 x 150 kW SSAs feeding prototype cavities in existing storage ring: re-used for EBS

352 MHz 1.3 MW Klystron

85 kW SSA with cavity combiner, developed at ESRF [M. Langlois’ talk]

2 of 3 existing klystron transmitters: re-used for EBS
- Storage Ring

- **Cell 5**
  - 75 kW tower
  - 75 kW tower
  - 75 kW tower

- **Cell 7**
  - 75 kW tower
  - 75 kW tower
  - 75 kW tower

- **Teststand**
  - In house SSA
  - Compact 85 kW SSA with cavity combiner

- **KLYS 1**
- **KLYS 2**
- **3rd harmonic cavities**
  - Still under study: Passive SC or active NC

- **Existing klystron transmitters operational for EBS**
- **Will be refurbished**
- **Including full control upgrade**
- **Further SSAs after EBS commissioning**

- **3x existing 150 kW SSAs**

- **Base line: 13 cavities**
- **Use only existing RF sources**
- **14th cavity fed by in house SSA**
- **Operating SSA on machine for validation as long term alternative to klystrons**
- Even with 5 cavities in fault (1 complete cell) operation at 4.5 MV / 200 mA still possible
- Also room left for performance upgrade
New lattice: same operation modes as existing machine:

<table>
<thead>
<tr>
<th></th>
<th>Multibunch</th>
<th>16-bunches</th>
<th>4-bunches</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total current</td>
<td>200 mA</td>
<td>90 mA</td>
<td>4 x 10 mA</td>
</tr>
<tr>
<td>Nb. Bunches</td>
<td>868</td>
<td>16</td>
<td>4</td>
</tr>
<tr>
<td>Bunch length</td>
<td>23 ps</td>
<td>64 ps</td>
<td>77 ps</td>
</tr>
<tr>
<td>Lifetime for $\varepsilon_{\text{vert}} = 5 \text{ pm}$</td>
<td>19 h</td>
<td>1.8 h</td>
<td>1.2 h</td>
</tr>
</tbody>
</table>

Implementation of 3rd harmonic cavities at 1057.1 MHz for bunch lengthening and increased Touschek lifetime under study.

Alternatives:

1. Passive SC cavity, Super3HC type like at Elettra or SLS: collaboration with CEA / IRFU / SACM in Saclay, France
2. Active NC cavities: scaling of ESRF HOM damped accelerating cavity
Strong detuning $\Delta f$ of Super3HC like cavity:
- $Z_{\text{cav}} \approx jX$, with $X \gg R$, $X \neq f(QL)$
- $\Delta f$ such that: $2 I_{\text{beam}} X = V_{\text{harm}}$
- $\Delta f \approx 3.5$ kHz for $I_{\text{beam}} = 70$ mA

Smaller $I_{\text{beam}} \Rightarrow$ larger $X \Rightarrow$ smaller $\Delta f \Rightarrow$ larger $R^+$

$\Rightarrow$ Problem of AC Robinson instability for $I_{\text{beam}} < 70$ mA!
(off resonance, $\Phi_{\text{harm}}$ follows rigid bunch motion at $f_s \neq 0$)

Bunch lengthening:
$V_{\text{harm}} = 1.7$ MV for $V_{\text{acc}} = 6$ MV
EXAMPLE OF AC ROBINSON INSTABILITY ON 3RD SYNCHROTRON SATELLITE

SIMULATION:
- Bunch center of mass: unstable oscillation at $3f_s$ for large $QL$
- Strong Amplitude & phase oscillation of $V_{harm}$ at $3f_s$

Tentative explanation: beating between
- Nominal harmonic voltage driven by the beam at $3f_{rf}$
- Strong voltage from tiny $3f_s$ synchrotron sideband close to SC-cavity resonance

[Multiparticle tracking simulation using AT with beam loading effects in cavities by N. Carmignani in collaboration with B. Nash, ESRF]
Initially since 1991:
- 1 klystron powered 2 five-cell cavities
- via 2 couplers/cavity
- 600 kW in total
- Total $V_{\text{acc}}$ up to 8 MV

April 2012 upgrade:
- 4 x 150 kW SSAs powered 2 cavities

January 2016 upgrade:
- 4 x 150 kW SSAs feed 4 cavities
- 1 SSA/cavity via 1 coupler/cavity
- Total $V_{\text{acc}}$ up to 11 MV
- Redundancy: 8 MV operation with 3 systems (i.e. if 1 cavity or SSA fails)

Ready for safe frequent top up operation started in 16 bunch in April 2016
**OPERATION EXPERIENCE WITH 7 X 150 KW SSA**

- **Booster \(\rightarrow\) 4 SSA 150 kW each. In operation since January 2012 (4500 hours)**
  - Top-up since April 2016
- **SR \(\rightarrow\) 3 x SSA 150 kW each. In operation since October 2013 (17400 hours)**
  - 1 is out of operation because of cavity failure
- **So far no transistor failure (BLF578 from NXP, now produced by AMPLEON)**
- **Nominal Power Efficiency 58% Gain 63.3 dB – No variation in time (last control March 2016)**

<table>
<thead>
<tr>
<th>Component</th>
<th>Event count</th>
<th>Disturb Operation</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>HPA 650W (filter)</td>
<td>SR 10, SY 9</td>
<td>No, No</td>
<td>CMS filters stressed when soldering on the PCB. Youth problem, now fixed with time. Last failure: April 27 2015.</td>
</tr>
<tr>
<td>DC/DC Converter 280V/50V</td>
<td>SR 4, SY 3</td>
<td>No, No</td>
<td>Fuse blown. OK after replacing the fuse</td>
</tr>
<tr>
<td>Pre-Driver</td>
<td>SR 0, SY 5</td>
<td>Yes, 1</td>
<td>Conception problems, which have been fixed: Gain loss, bad soldering, bad logic circuitry …</td>
</tr>
<tr>
<td>MUXBOX Control Interface</td>
<td>SR 3, SY 4</td>
<td>Yes, 2, No</td>
<td>The SSA trips when the fuse blows because the relays for cooling interlocks are fed by this interface. This is a weakness of the system, which can be improved.</td>
</tr>
<tr>
<td>Water Cooling</td>
<td>SR 1, SY 2</td>
<td>No, Yes, 1</td>
<td>Fortunately it happened outside of machine operation</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td>SR 18, SY 23</td>
<td>2, 2</td>
<td>1 in 2014 + 1 in 2015 (\rightarrow) Beam loss 2 in 2012 (\rightarrow) Refill postponed</td>
</tr>
</tbody>
</table>
KLYSTRON TRANSMITTERS

- **STORAGE RING** - 3 RF stations with **1.1 MW and 1.3 MW klystrons**
  - RF station #1 feeding 4 five-cell cavities
  - RF station #2 as backup for #1 or for RF Power Test Stand
  - RF station #3 feeding 1 five-cell cavity (formerly 2 cavities)
- Stations #1 and #2 in operation since 1991, station #3 since 1997
- Stations #1 and #2: control refurbished year 2000 following the standard of station #3
- Obsolescence of VME / linux computers comprising measurement and digital I/O boards
  - New control is under refurbishment using PCI and independent measurements and digital I/O
- Klystron EEV2-2 dead at 21770 hours in October 2015
- Station #3 will be dismantled end of 2018 for new ESRF-EBS machine
<table>
<thead>
<tr>
<th>RF Station</th>
<th>Klystron Id</th>
<th>HV time</th>
<th>Average/year</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1</td>
<td>EEV4</td>
<td>65,087</td>
<td>6,100</td>
</tr>
<tr>
<td>#2</td>
<td>EEV1</td>
<td>34,121</td>
<td>5,000</td>
</tr>
<tr>
<td>#3</td>
<td>PHILIPS</td>
<td>22,775</td>
<td>4,500</td>
</tr>
<tr>
<td>Spare Klystrons</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>EEV3</td>
<td>8,374</td>
<td></td>
</tr>
<tr>
<td></td>
<td>TH89022-2</td>
<td>18,428</td>
<td></td>
</tr>
<tr>
<td></td>
<td>TH89018-2</td>
<td>36,340</td>
<td></td>
</tr>
<tr>
<td></td>
<td>EEV5</td>
<td>10,631</td>
<td></td>
</tr>
</tbody>
</table>

Potential time of 110,000 hours assuming a life time of 40,000 hours / klystron corresponding to **11 years of operation** (9 years on EBS).
## KLYSTRON VERSUS SSA FAILURES

<table>
<thead>
<tr>
<th>Year</th>
<th>Klystrons + ancillaries*</th>
<th>SSA</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Beam losses</td>
<td>% of total RF failures</td>
</tr>
<tr>
<td>2012</td>
<td>2</td>
<td>8%</td>
</tr>
<tr>
<td>2013</td>
<td>3</td>
<td>14%</td>
</tr>
<tr>
<td>2014</td>
<td>3</td>
<td>9%</td>
</tr>
<tr>
<td>2015</td>
<td>1</td>
<td>4%</td>
</tr>
</tbody>
</table>

* Modulating Anode PS, Focusing PS, Filament PS, IP
WHAT COULD BE IMPROVED ON 150 KW SSA

Interlocked cooling water flow controllers:

- 1 Kobold flow controller per cooling plate, supporting 16 HPA of 650 W or drivers
- 18 cooling plates per SSA

### Erosion issue

Alternative to Kobold

7x18 = 126
to be replaced
≈ 40k€

### Design issue

When the Control Interface fuse is blown the SSA is tripped only because the flow and temperature interlocks are conditioned by this interface (relay).

Interlock should be processes independently.
Thank you !!!