Status of Diamond Light Source RF

Chris Christou, Diamond Light Source

ESLS-RF 18
Synchrotron Soleil
8th November 2018
RF at Diamond Light Source

Storage ring: 500MHz
2 x 1 cell Nb Cornell cavities installed
3 x 300kW IOT combined amplifier

Linac: 3GHz
2 x 5.2m Cu DESY structures
2 x 35MW klystrons
bunchers

Booster: 500MHz
1 x 5 cell Cu PETRA cavity
1 x 60kW IOT

3GeV 300mA third generation synchrotron light source
Diamond has been operating for users since January 2007
Injector cavities and structures

100 MeV normal conducting linac

5-cell copper booster cavity
- One high voltage power supply supports four IOTs which are then combined
- Superconducting cavity supported by Air Liquide cryogenic plant
- Space for three cavities in RF straight, usually two operational
- Two extra EU HOM damped cavities installed in 2017-2018
The CESR-B cavity

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resonance frequency</td>
<td>499.765 MHz</td>
</tr>
<tr>
<td>Maximum accelerating voltage</td>
<td>3 MV</td>
</tr>
<tr>
<td>Operating voltage (CESR–III)</td>
<td>1.8 MV</td>
</tr>
<tr>
<td>Effective cell length</td>
<td>0.3 m</td>
</tr>
<tr>
<td>$R/Q$ ($R = V^2/P$)</td>
<td>89 Ohm</td>
</tr>
<tr>
<td>Geometry factor $G$</td>
<td>265.7 Ohm</td>
</tr>
<tr>
<td>Intrinsic cavity quality factor $Q_0$ at operating conditions</td>
<td>$&gt; 10^9$</td>
</tr>
<tr>
<td>External quality factor $Q_{ext}$ of RF input power coupler</td>
<td>$2 \times 10^5$</td>
</tr>
<tr>
<td>RF power delivered to 1 A beam</td>
<td>325 kW</td>
</tr>
<tr>
<td>$E_{pk}/E_{acc}$</td>
<td>2.5</td>
</tr>
<tr>
<td>$H_{pk}/E_{acc}$</td>
<td>41.6 Oe/(MV/m)</td>
</tr>
<tr>
<td>Loss factor of the module with one taper at $\sigma_z = 13$ mm</td>
<td>0.48 V/pC</td>
</tr>
<tr>
<td>Cryomodule HOM power at 1 A beam current</td>
<td>13.7 kW</td>
</tr>
<tr>
<td>Cavity operating temperature</td>
<td>4.5 K</td>
</tr>
<tr>
<td>Cryostat static heat leak to liquid helium bath</td>
<td>30 W</td>
</tr>
<tr>
<td>Cryomodule length</td>
<td>2.86 m</td>
</tr>
</tbody>
</table>
## Reliability: year to date

<table>
<thead>
<tr>
<th></th>
<th>Hours</th>
<th>Faults</th>
<th>MTBF</th>
<th>MTTR</th>
<th>Downtime</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diamond</td>
<td>4992</td>
<td>55</td>
<td>90.8 hours</td>
<td>1.4 hours</td>
<td>77 hours</td>
</tr>
<tr>
<td>Storage ring RF</td>
<td>4992</td>
<td>24</td>
<td>208 hours</td>
<td>1.6 hours</td>
<td>38 hours</td>
</tr>
</tbody>
</table>

### RF Faults

- Amplifiers: 17
- Cavities: 17
- Cryogenics: 17

### Amplifier Faults

<table>
<thead>
<tr>
<th>Amplifier</th>
<th>Cavities</th>
<th>Cryogenics</th>
</tr>
</thead>
<tbody>
<tr>
<td>IOT short circuit</td>
<td>Flow meter</td>
<td>Coldbox vacuum</td>
</tr>
<tr>
<td>IOT output coupler</td>
<td>Helium pressure gauge</td>
<td>Coldbox pump</td>
</tr>
<tr>
<td>Focus coil supply</td>
<td>NC cavity conditioning arc</td>
<td></td>
</tr>
<tr>
<td>Filament supply transformer</td>
<td>Reflected power</td>
<td></td>
</tr>
<tr>
<td>Drive amplifier cooling</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Faults in injector system

Almost 30,000 top-ups this year: 48 failures
- 23 injector, including 13 linac arcs and 5 linac rack fan monitor faults
- Klystrons arc frequently, usually reset automatically without stopping top-up

2016
- IOT (and spares) failed in booster
- Changed from Thales to e2v IOT

2018
- Capacitors failed in klystron pulse tank
- Replaced all capacitors
Filament hours

**Gun**
- CPI YU171
- 25,000 hours

**Linac**
- Thales TH2100 klystron
- #210052: 61,000 hours
- #210057: 58,000 hours

**Booster and storage ring**
- E2V IOTD2130
- Booster #224-0712: 49,000 hours
Cavity fast vacuum trips

Trips initially dominated by fast vacuum trips
- MTBF is strongly dependent on cavity voltage
- Each cavity has a “safe” operating voltage below which it is unconditionally stable
- Trip rate is independent of power
- Can distinguish between trips at the window and at the cavity by pressure profile

Reliable operating voltages

<table>
<thead>
<tr>
<th>Cavity</th>
<th>Voltage (MV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cavity A</td>
<td>1.1</td>
</tr>
<tr>
<td>Cavity B</td>
<td>1.2</td>
</tr>
<tr>
<td>Cavity C</td>
<td>1.4</td>
</tr>
<tr>
<td>Cavity D</td>
<td>0.8</td>
</tr>
</tbody>
</table>

Sequence of events
1. Discharge in high field
2. Arc crowbars cavity
3. Reflected power trips amplifier
4. Pressure spike follows

Trips eliminated by reducing voltage
- Effective
- Why can’t we operate at higher voltage?
Cavity warm-ups

Cavities have been subjected to warm-ups to room temperature in the past

- Occasional full warm-ups tried in early days and with problematic cavities
- Gas is cleared from surfaces and identified by RGA
- More frequent partial warm-ups have been used with all cavities

Every warm-up carries the risk of disaster!

Very little benefit at Diamond

- Cavities are no better in run following warm-up
- Cavities are no worse in run following no warm-up
- No degradation of reliability if partial warm-ups are stopped for several runs
- Short term improvement apparent following partial warm-up
  - No trips in first few days
  - Trips resume when vacuum returns to normal
Cavity conditioning

Pulse conditioning without beam
- 2.3 MV peak voltage, 10% duty cycle (10 ms/100 ms)
- Detune angle scanned to sweep standing wave
- Carried out when work is going on elsewhere in SR
- X-ray emission reduced after conditioning

Two cavities simplify “with-beam” conditioning
- Sweep cavity phases to move power between cavities
- Beam is restored after violent conditioning events

Gradually reducing frequency of conditioning
- No change in base cavity pressure
- Cavity radiation reaches equilibrium in second week

We can do more important things than conditioning
Storage ring RF history

Diamond has four CESR-B cavities
- Two in operation at any one time
- Cavity failure is a major disruption

Mean Time Between Failures for RF system has improved
- 20 hours in 2007
- 200 hours in 2018

<table>
<thead>
<tr>
<th>Cavity</th>
<th>Failure date</th>
<th>Detail</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>none</td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>2009, 2014</td>
<td>UHV leak</td>
</tr>
<tr>
<td>C</td>
<td>2006</td>
<td>Insulation vacuum leak</td>
</tr>
<tr>
<td>D</td>
<td>2015</td>
<td>Window failure</td>
</tr>
</tbody>
</table>
Recent cavity failures

2014: Leak from helium can into cavity UHV

- Failed during cool-down from room temperature
  - No more warm-ups unless absolutely necessary
- Indium seal at waveguide flange
  - Returned to manufacturer in December 2014
  - Cavity returned to DLS in 2016
  - Failed acceptance test with leak at indium seal on FBT
- Scheduled return from latest repair: January 2019

2015: Failure of ceramic-metal braze at window

- During normal operation after standard conditioning
- Repaired on-site at RAL in February 2016
  - Installed spare window assembly
  - Used RAL Space satellite assembly cleanroom
  - ISO class 5 cleanroom with 5 tonne crane
- Tested to 2.1 MV operation in RF test facility
Normal conducting cavities

Two new normal conducting cavities have been installed in the storage ring:

- Resonant cavity at 500 MHz in centre
- Radially mounted components
  - Coupler, tuner and HOM loads
- Less powerful than superconducting RF but simpler
  - Easily maintained
  - Voltage per cavity will be reduced
  - Power per amplifier will be reduced
- Latest iteration of cavity installed at BESSY, Alba and ESRF (scaled for frequency)
  - Flanged joint at base of HOM damper waveguide removed to address trapped mode
  - Pickup coated at ESRF
- Much smaller longitudinal footprint than SC cavity
  - Can be installed in regular straight
  - SC cavity environment undisturbed
  - Further NC cavities can be installed
New storage ring RF configuration
NC cavity bakeout and conditioning

Both cavities baked at 120°C for two weeks
- First bake before conditioning
- Second bake after installation in ring
- Post-bake RGAs show
  - no evidence of leaks
  - minimal H2O
  - no hydrocarbon contamination of the vacuum

Two weeks available for cavity conditioning
- FPC critically coupled for conditioning
- Similar multipacting barriers
  - 100 W, 11-13 kW, 19 kW, 25 kW, 35-39 kW, 50 kW and 60 kW.
- After two weeks the cavity was able to run continuously at 20 kW, corresponding to a voltage of 300 kV planned for initial operation.

Comprehensive temperature monitoring
- 7 thermocouples on the copper structure
- 14 thermocouples welded to the cooling pipes.
Temperatures rose linearly with conditioning power
- four points exceeding 30°C at maximum power
- highest temperature was recorded on the cavity body at the base of the fundamental power coupler.
Installation in the storage ring

- Installation of two cavities is complete
- Installed upstream and downstream of RF straight
- FPC rotated to $\beta = 5$ for operation
- Baked in storage ring following installation
- Powered from pre-existing IOT-based amplifiers
- Cavity used at 400 kV for high voltage operation (short pulse low $\alpha$) for users
- Parked cavity is invisible to beam
- No instabilities excited in any mode of operation

Measured parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_s = V^2/2P$</td>
<td>3.8 M$\Omega$</td>
</tr>
<tr>
<td>$Q_0$</td>
<td>33,000</td>
</tr>
<tr>
<td>Coupling $\beta$</td>
<td>5.2</td>
</tr>
<tr>
<td>Operational power</td>
<td>Up to 120 kW</td>
</tr>
</tbody>
</table>
Digital Low Level RF

Collaboration with Angela Salom at Alba to adapt the Max IV DLLRF to Diamond

Functionality
- IQ or polar PI loops of the cavity field to control amplitude and phase.
- Cavity tuning
- Fast interlock handling.
- Automatic start-up of the system
- Automatic conditioning of the cavity
- Monitoring of RF signals
- Recording of main digital processing signals for post-mortem analysis

Features
- Digital LLRF offers more flexibility than analogue system and can be upgraded as necessary
- Based on the MicroTCA standard
- Perseus 601X advanced mezzanine card with Virtex6 FPGA from Nutaq is used as the core processor of the control algorithm
- 16 Channel 14-bit ADCs and 8 channel 16-bit DACs FPGA mezzanine cards used as interface

Status
- Tested on booster amplifier
- Installed on both NC cavity systems
- Will be deployed on all systems
NC cavity was first operated for users in low α
- NC cavity at 400 kV
- SC cavity voltages reduced from 1.7 MV to 1.5MV
- Clear reduction in number of SC cavity trips
Must address amplifier reliability now

Good Voltage and phase stability with NC cavity and DLLRF
- No evidence of occasional steps in voltage and phase
- DLLRF has been tested on NC cavity and booster cavity
- To be tested on repaired SC cavity in RF test bunker in early 2019
- Cavity has been tested to 120 kW nominal full power with no problems

Beam can survive when NC cavity is turned off
- Measured at 150 mA beam current
- SC cavity power rings
- Beam is kicked horizontally ±0.5 mm
- Not part of plan but worth investigation
- What happens with two operational NC cavities?
High power solid state amplifiers

- High power IOTs can be replaced by multiple LDMOS power transistors
- System includes multiple redundant modules for robust operation
- Proven to be reliable at Soleil and other synchrotrons
- Two amplifiers have been constructed by Ampegon: 60kW and 80kW
- A development of the SLS booster amplifier
- To be used in Diamond booster and RF test facility
High power solid state amplifiers

- Ampleon BLF578 50 V LDMOS power transistor
- 2 x 850 W RF out per module
- Built in circulator
- LDMOS and RF PCB vapour soldered into housing for lowest possible thermal resistance
- All modules snap fit into 128 port RF cavity combiner
- Combiner is 99% efficient
- Tuneable with >4 MHz 3 dB bandwidth

80kW acceptance tests
- > 80 kW output
- > 57% efficiency
- Module redundancy demonstrated
- CW, AM and pulsed operation
- Harmonics > 30 dBc
- Spurious emissions >80 dBc
Solid state amplifiers at Diamond

80 kW amplifier installed in RF hall
- Will power RF test facility
- On 200 A fused supply
- Using water supply for aluminium circuit
- Passed all acceptance tests
- Water cooled load rated at 150 kW but failed at 50 kW
- Mezzanine platform installed to support transmission line to test facility

60 kW amplifier installed on BTS roof
- Will power second booster cavity
- On 200 A fused supply
- Using water supply for aluminium circuit
- Awaiting delivery of amplifier modules
- Acceptance test scheduled for January 2019
- Transmission line penetration in BTS roof is shielded by steel labyrinth
Second booster cavity

Diamond booster operates with a single 5-cell copper cavity
- Cavity and amplifier are both single points of failure
- Install second cavity in vacant length of booster ring
- 5 cell Petra cavity from DESY
- Baked in tunnel in summer 2018
- Installation progressing in November 2018
- Powered by solid state amplifier, controlled by digital LLRF
Linac SLED cavity upgrade

Linac RF
- Thales TH 2100 klystron amplifies 3 GHz RF pulse from LLRF
- PPT (now Ampegon) modulator generates high voltage pulse to power the klystron

The problem
- If either modulator fails, linac fails
- Top-up stops immediately and storage ring cannot be filled from empty

A partial solution
- Linac can run at reduced energy on one modulator
- Transmission through booster is zero to dismal

Ideal solution
- 100 MeV beam from one klystron and modulator
The Stanford Linac Energy Doubler

- Cavity in waveguide to compress the RF pulse
- Two cavities coupled to waveguide with hybrid combiner
- Water cooled
- UHV maintained with two ion pumps
- Cavities tuned or detuned by elastic deformation of base
- First part of pulse charges up the cavity
- Cavity is discharged during second part of pulse and power is added to klystron pulse
- RF pulse is compressed, peak power rises and linac energy increases

Energy gain

- Simple phase switch loses pulse flat top and puts multibunch operation at risk
- Programmed phase and voltage can correct waveform
- Use IQ modulation of klystron drive with MicroTCA DLLRF
- New DLLRF must control 3 GHz RF
**Helium Recovery**

**Scope of project**
- Recycling exhaust from beamlines and wigglers
- Reducing waste of a limited resource
- Significant cost saving to DLS
- 15% average helium price rise per annum
- STFC will liquefy gas at ISIS
- High pressure pipe run from DLS to ISIS
- Dewars of LHe returned for beamline use

**Project status**
- Ring main has been installed around Diamond
- First beamlines have been connected (I05, I06, I09, I10, I21)
- Plant room at Diamond is nearly complete
- High pressure line across site has been installed and tested
Summary and outlook

• Maintain good reliability
  – Diamond is a user facility, reliability and continuity is paramount
  – Year to date for Diamond
    – 4992 hours of user beam, 90.8 hours MTBF, 208 hours RF MTBF
    – RF responsible for 24 of 55 faults

• Complete ongoing projects
  – Normal conducting cavities, Digital LLRF, Solid State Amplifiers, Booster RF upgrade, Helium recovery, Linac upgrade

• Continue minor projects
  – IOT isolation switches, IOT isolation and beam survival, Beam purity and noise reduction, cavity reliability, fault mode operation…

• Future possibilities
  – Further NC cavities and SS amplifiers, SC cavity operational improvements, Higher harmonic cavities…
The Diamond RF Group

- Chris Christou
- Pengda Gu
- Peter Marten
- Shivaji Pande
- Adam Rankin
- David Spink
- Laurence Stant
- Anton Tropp

Thank you for your attention

Any questions?