Operational experience of high-power RF at Diamond Light Source

Chris Christou, Pengda Gu, Alun Watkins

Diamond Light Source

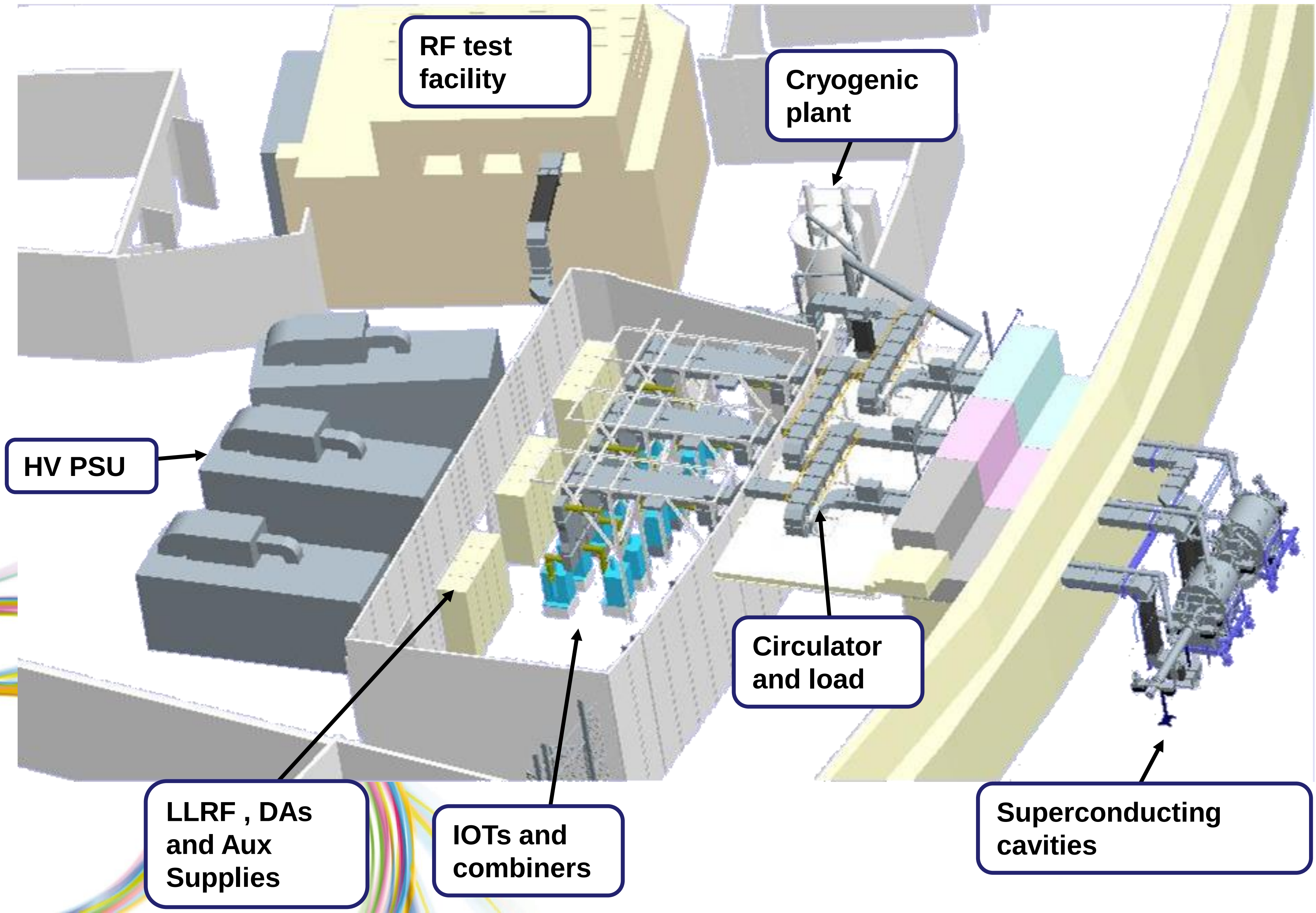
Diamond Light Source

- UK national synchrotron light source
- 3 GeV storage ring, 300 mA beam current
- Full energy booster and 100 MeV linac
- Running user beam since 2007, top-up since late 2008
- 2013 statistics:
    - 5088 hours to beamlines
    - > 98% beam delivery
    - RF is source of 60% of all beam trips

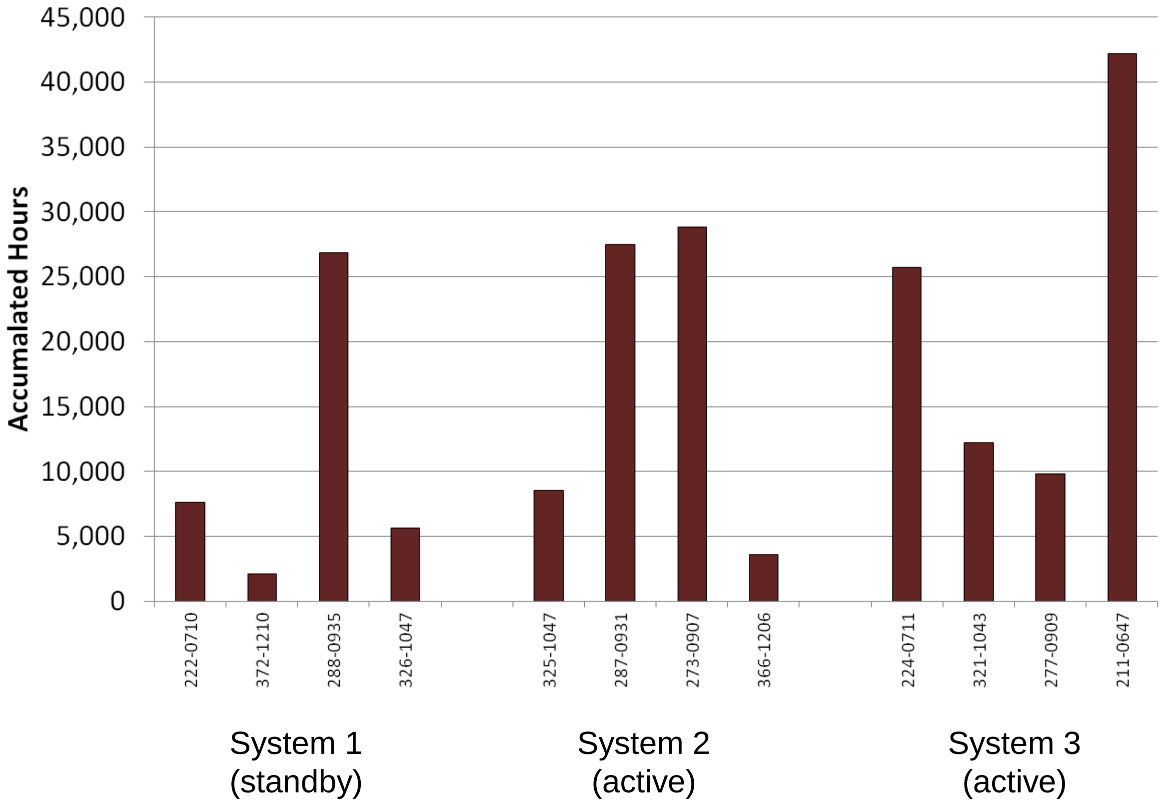
The RF Group

- Chris Christou
- Alek Bogusz
- Pengda Gu
- Matt Maddock
- Peter Marten
- Shivaji Pande
- Adam Rankin
- David Spink
- Alun Watkins

SR RF Systems



Filament hours



SR: e2v IOTD2130

- Two 4-IOT amplifiers driving cavities for normal operation
- One amplifier for test/conditioning/standby
- 300 mA needs > 50 kW per IOT
- Further spares “on shelf”
- Up to 40,000 hours operation

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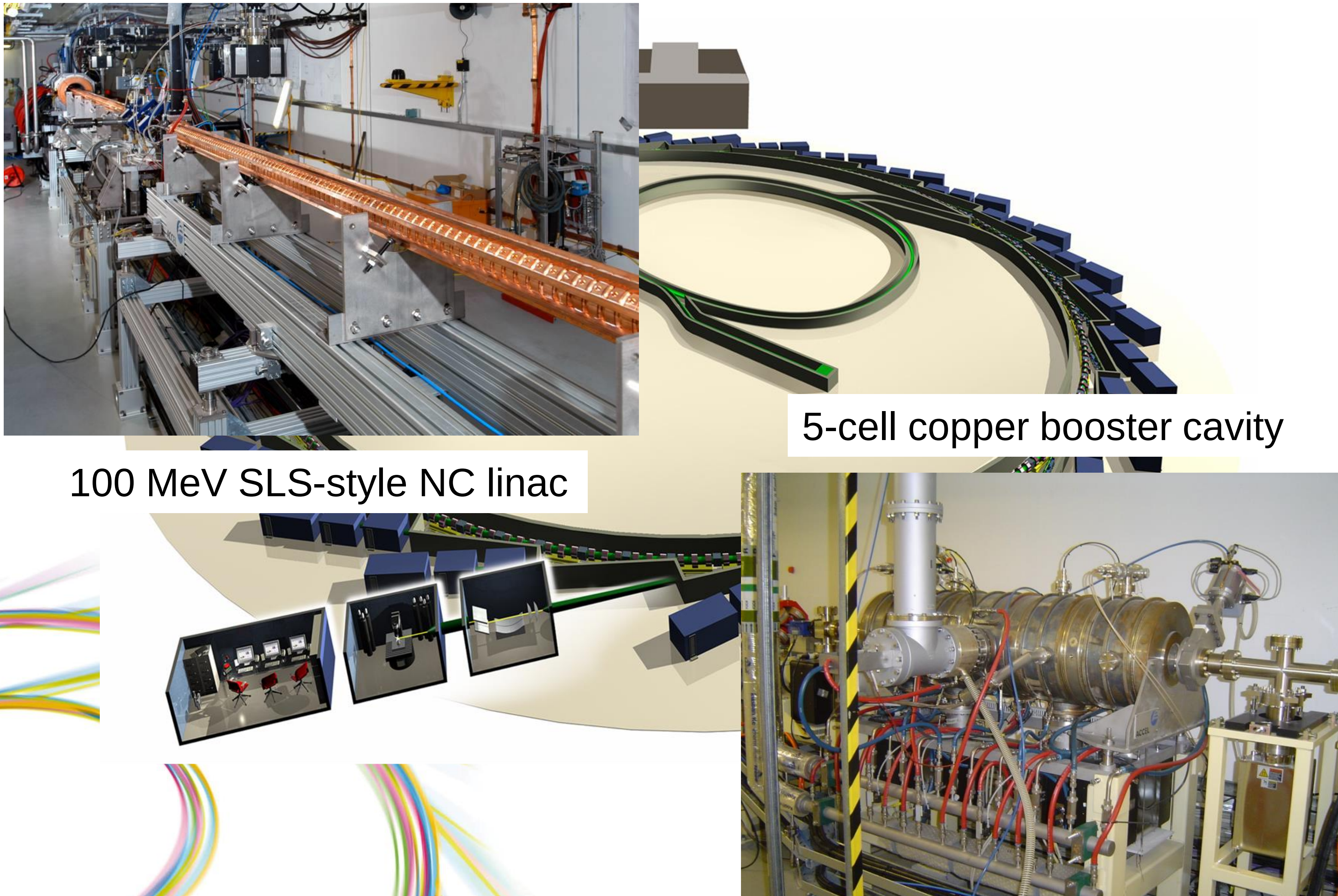
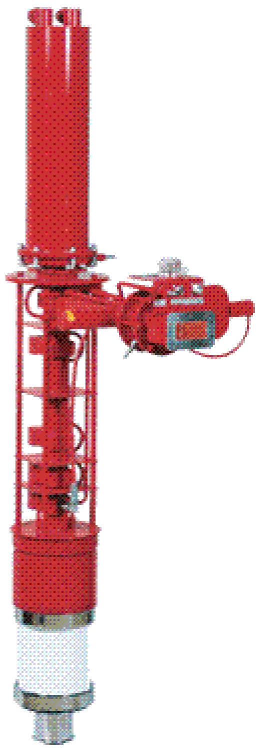
Other RF Systems



100 MeV SLS-style NC linac

5-cell copper booster cavity

Injector RF



Linac: Thales TH2100 klystrons

- Rated at 37 MW, 100 Hz
- Running at 16 MW, 5 Hz

- Running open loop
- Initial pair of klystrons replaced after 17,000 & 20,000 hours
- Current pair of klystrons have run for over 30,000 hours each
- Manage occasional arcs to minimise effect on machine operation
- Triode gun with dispenser cathode
    - Changed once in August 2013

Booster: Thales TH793

- Single IOT cycling to 50 kW at 5 Hz
- 41,000 filament hours
- “Second hand” spares from SR
- Very reliable at low average power

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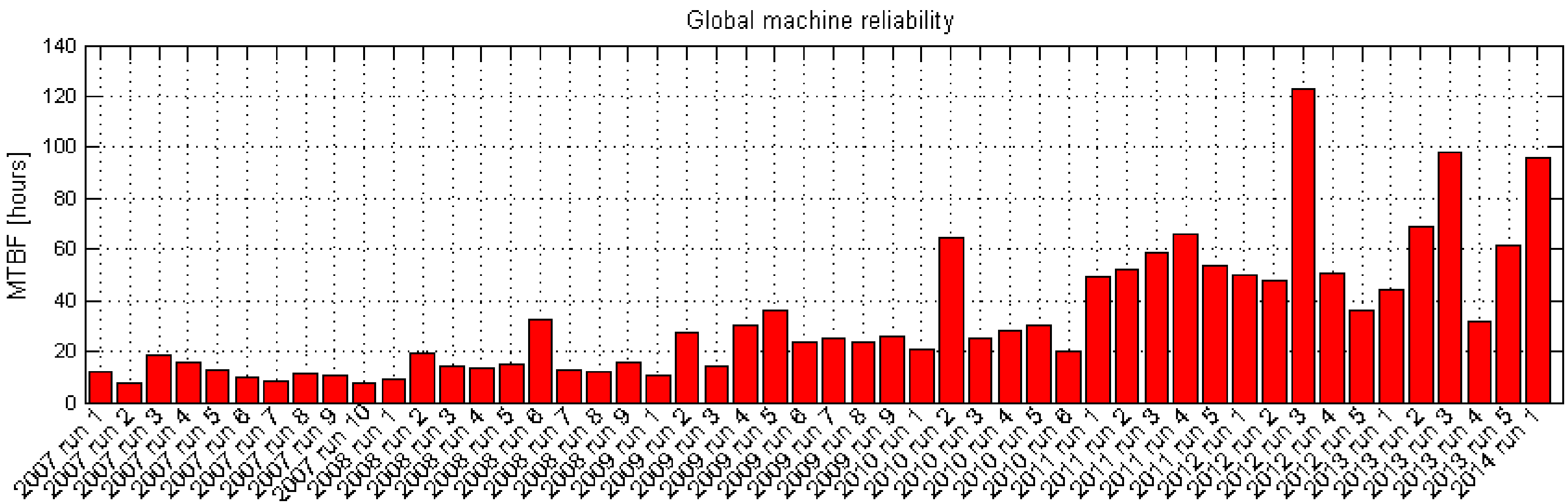
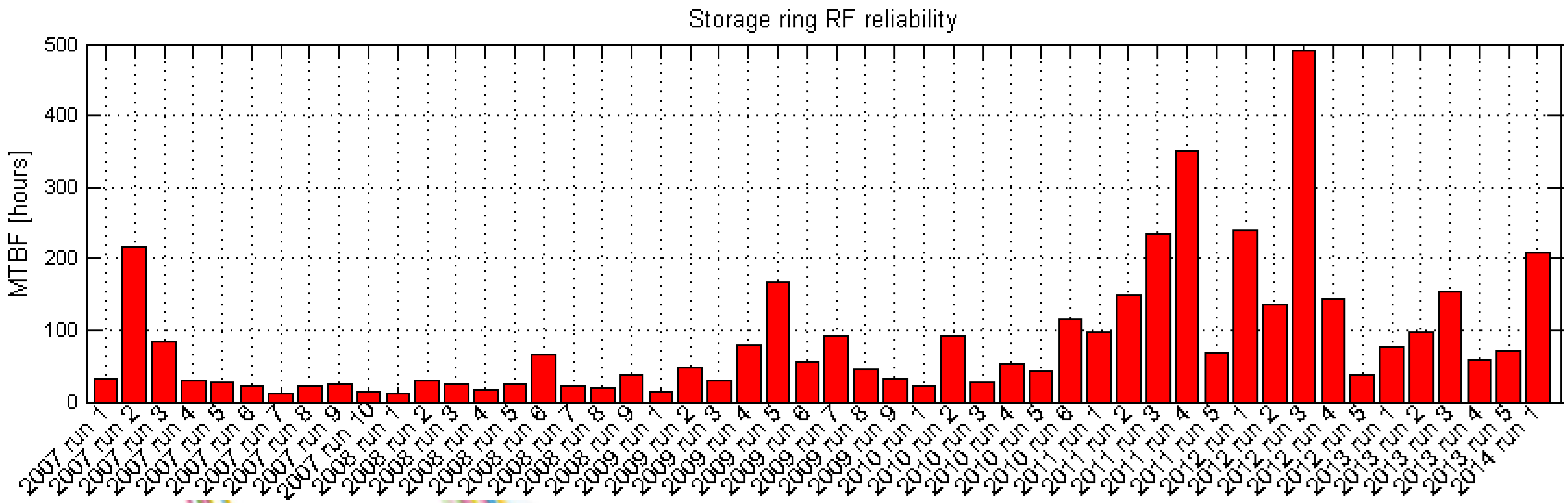
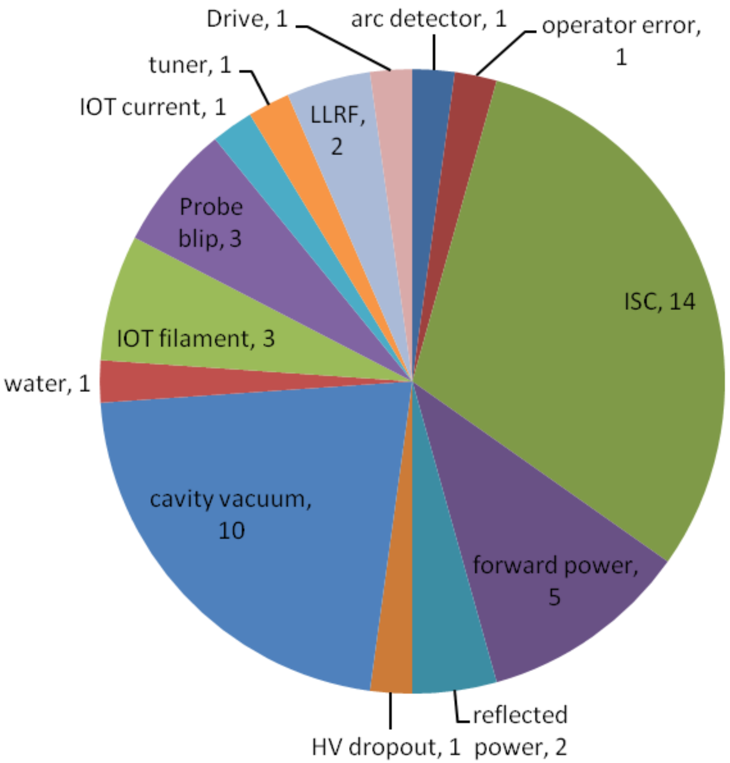
Machine Reliability

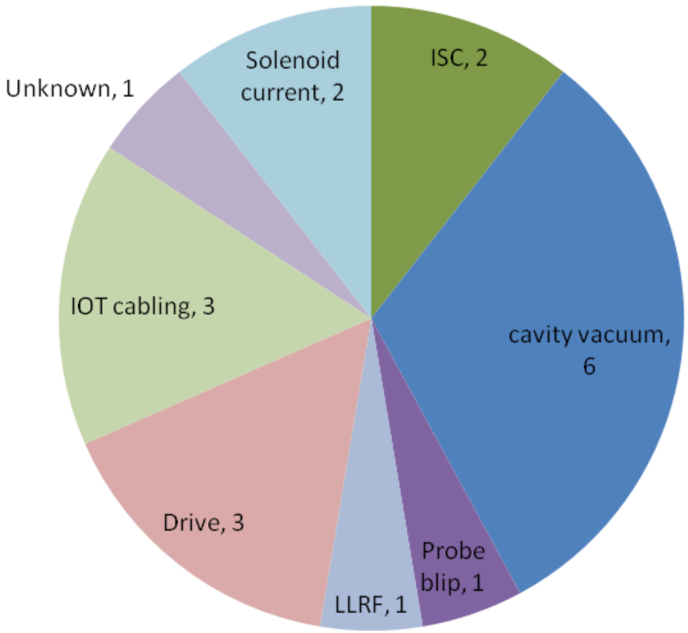




RF faults



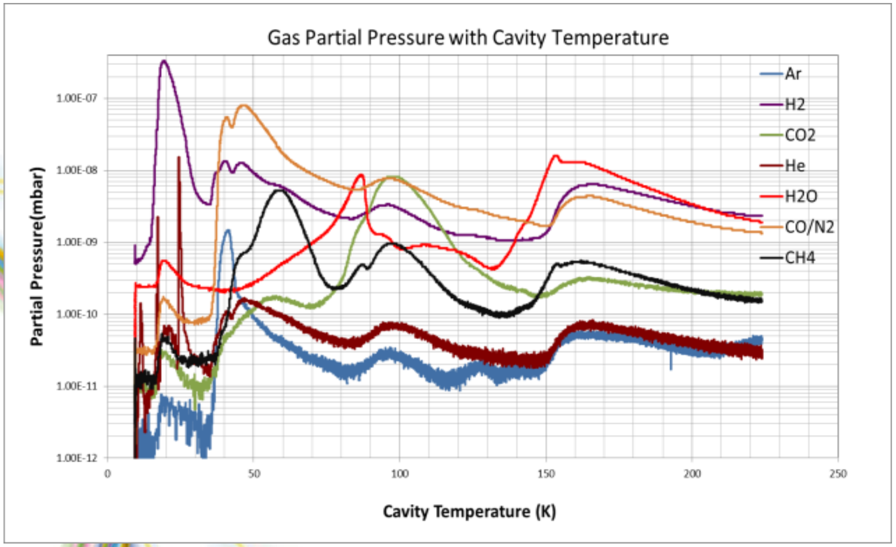
2013
46 faults



2014 so far
19 faults

Cavity conditioning

- Cavities are fully warmed up each shutdown
- RF windows are baked each shutdown
  - Taken to 120°C and held for three days
- Cavities are partially warmed up to 50 K several times each run
  - Every three weeks so far this year
- Pulse conditioning every week in run-time
  - 2.5 MV peak voltage,10% duty cycle (10ms/100ms)
- Pulse conditioning with detuned cavity every week in run-time
  - Detune angle scanned to sweep standing wave in waveguide
- NEG & TSP pumping of RF straight for H and He
  - Operating pressure 1 to 5 x 10^{-10} mbar at 300 mA
  - TSPs fired every week, NEG cartridges regenerated every shutdown



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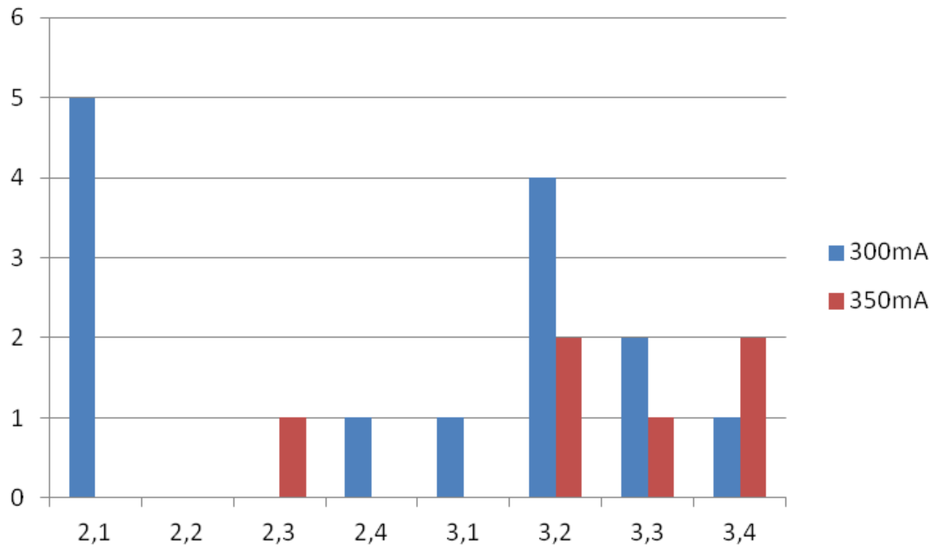
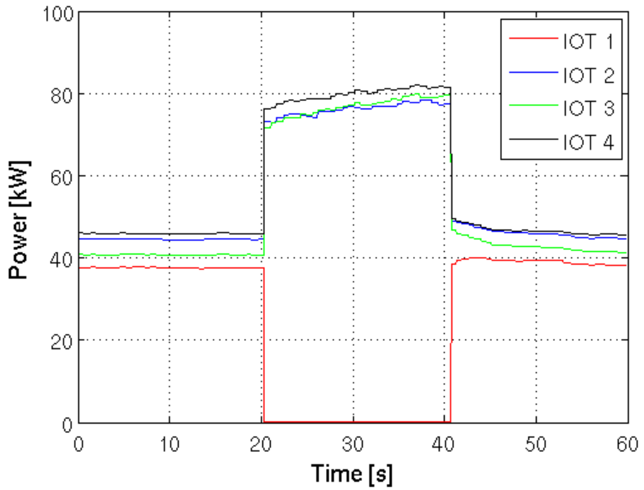
IOT conditioning



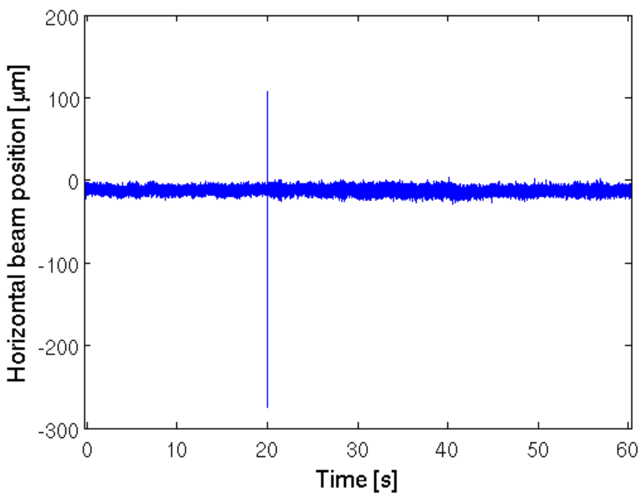
- IOT internal short was the biggest single cause of beam trips in 2013
- Increase in beam current to 350mA was disrupted by IOT reliability
- 350mA requires 65kW per IOT
- Two weeks of 350mA running caused ~1/3 of all IOT trips
- IOT 2/1 was replaced in May 2013

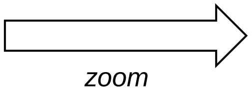
- Condition selected IOTs every shutdown
- Emergency conditioning following ISC fault when appropriate
  - Using in-house spark box
  - Ramp to 45 kV and hold
- 2 ISC trips so far in 2014
- 14 + 6 ISC trips in 2013
- Not tested 350mA in 2014
- High power RF conditioning is an option

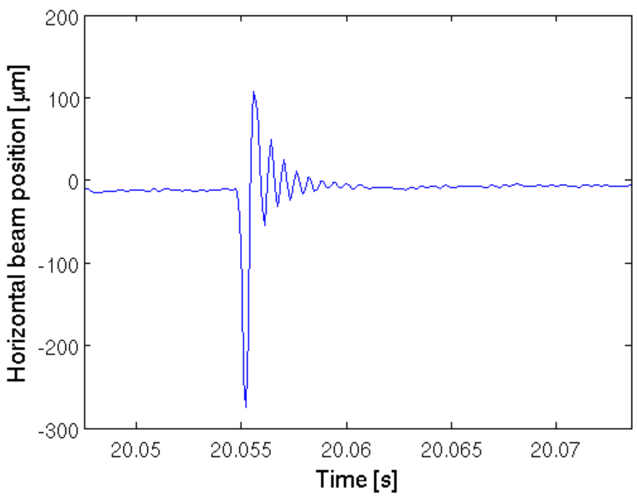
IOT fault tolerance



- Can maintain beam when single IOT is switched off
  - 240 mA with IDs, 250 mA without
  - No interlocks violated
- Beam disturbance of several hundred microns in the horizontal plane
- Can we introduce fast switching to give a resilient system?
  - Suitable fast solid state switches available
    - Behlke, …
- LLRF is critical
  - Speed of response and multiple cavities
  - Protect IOT and save beam within 500 turns



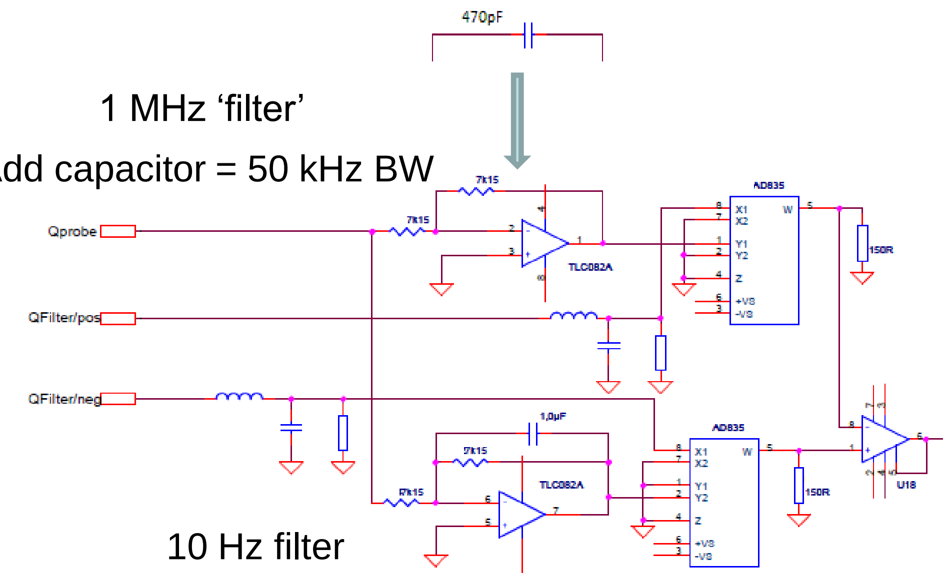




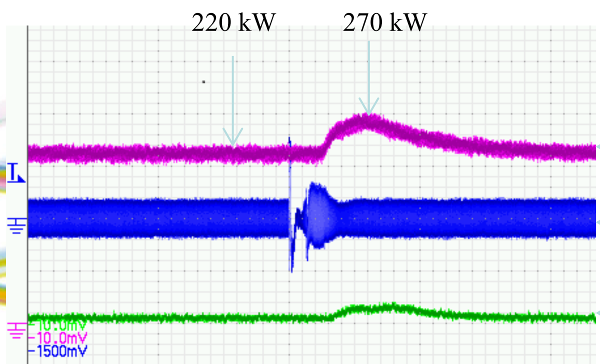
Cavity probe blips

Probe blips

- Appear as fall in cavity voltage
- LLRF increases power
- Can trip on P_{max} or P_{rev} interlock
- Address with LLRF bandwidth control



Before

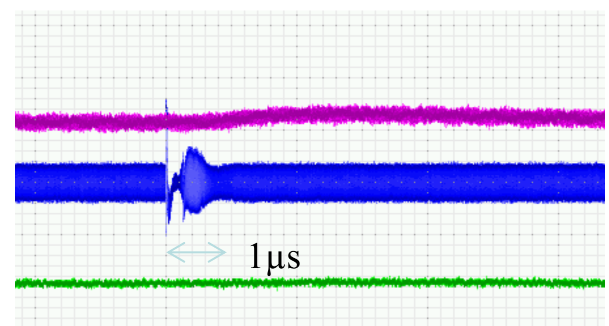


P_{fwd}

Cavity Probe

P_{rev}

After

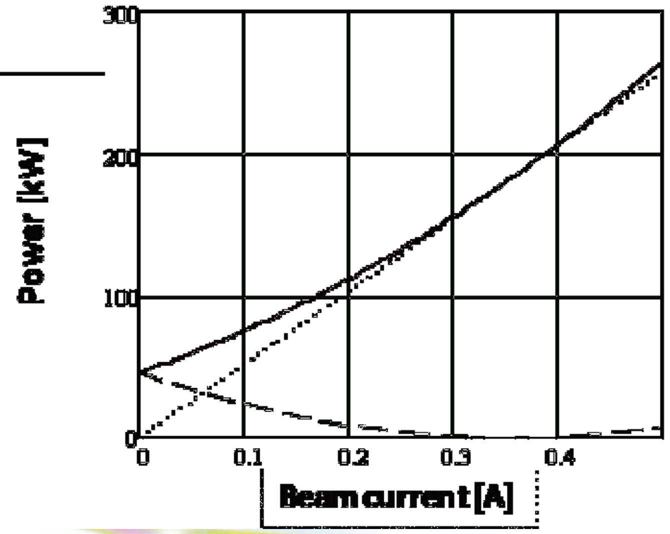


Long events(~5 µS) can still cause cavity trips

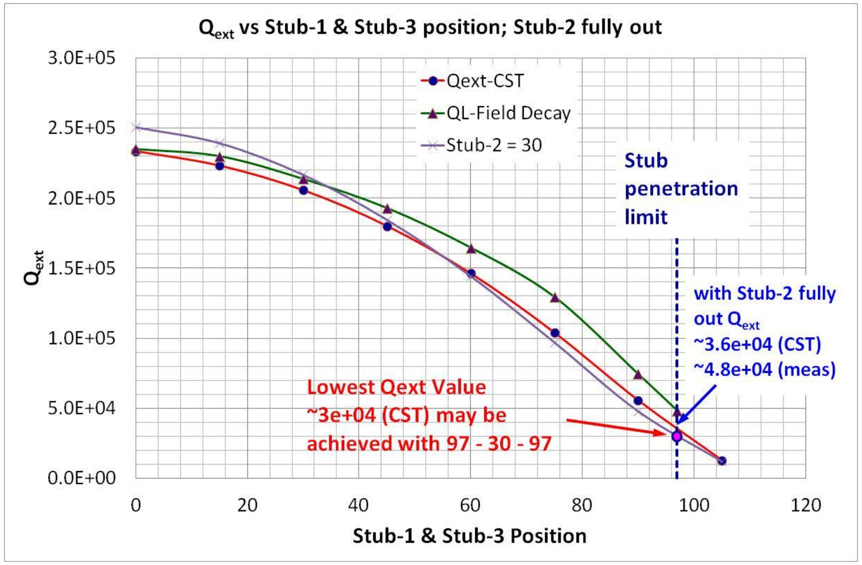
- a circuit to detect blips and reduce LLRF gain is being developed

Beam current upgrade

- Desire for storage ring beam current to be raised
  - Driven by ever increasing beamline flux demand
  - Radiation shielding is rated for 500 mA operation
- 500 mA operation requires a third cavity and lower external Q

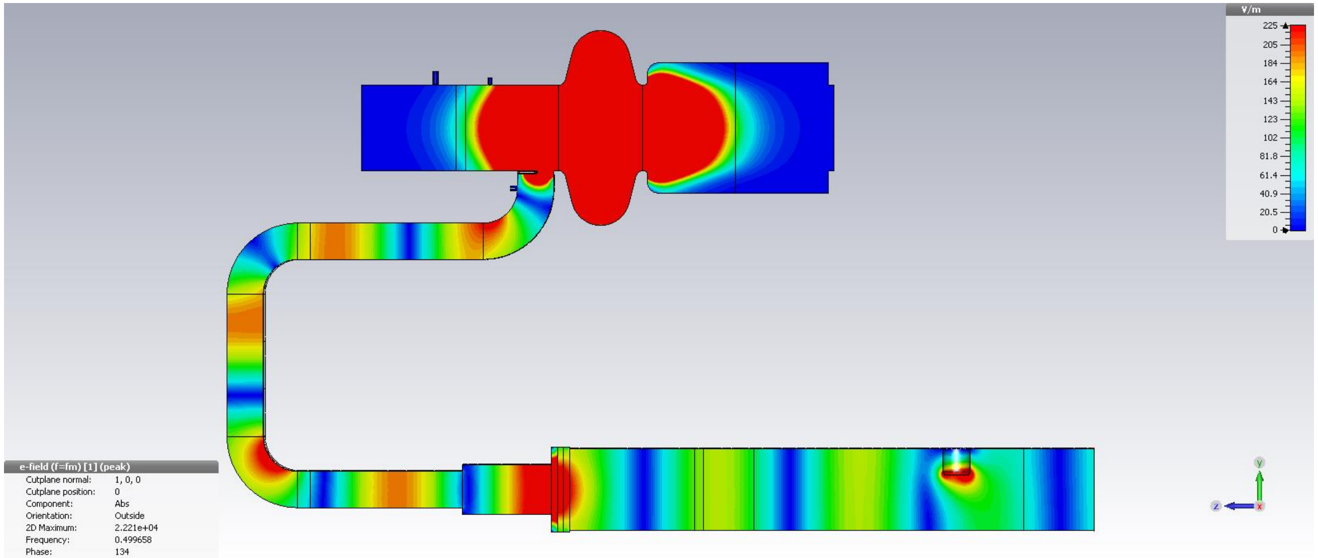


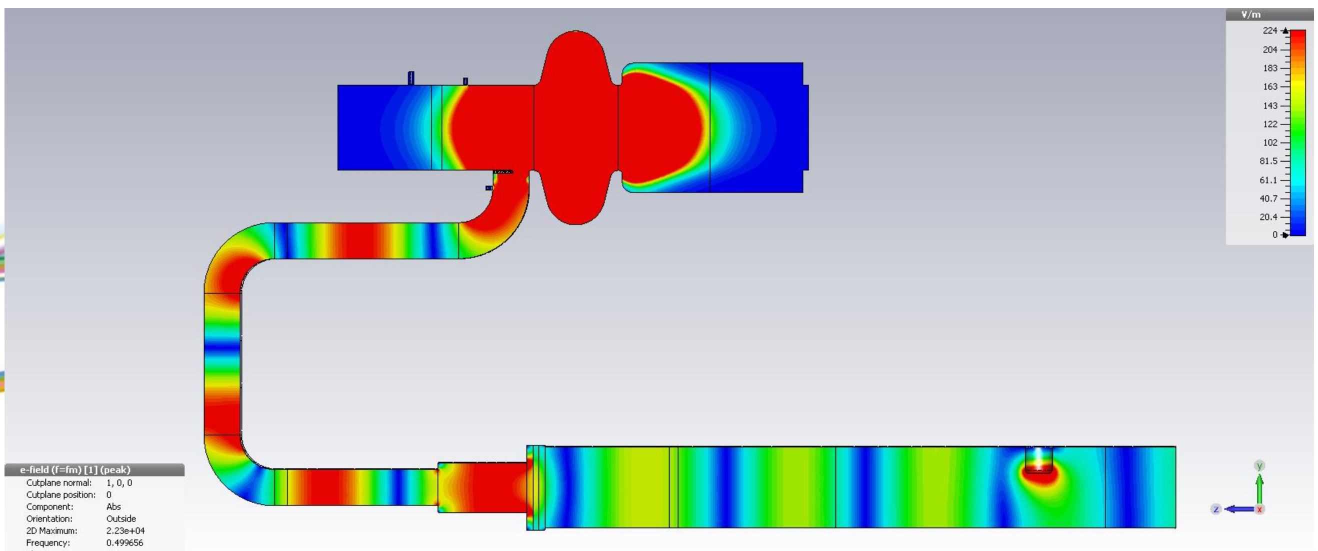
Typical three cavity configuration
1.4MV, $Q_0 = 6x10^8$, $Q_{ext} = 1.2x10^5$



Detailed three-stub tuner modelling is ongoing

Verification of 3-stub tuner models





- Control of Qext is vital for optimal operation at high power
- Model verification continues
- Note field at coupling tongue
- Need to establish electrical length to tuner

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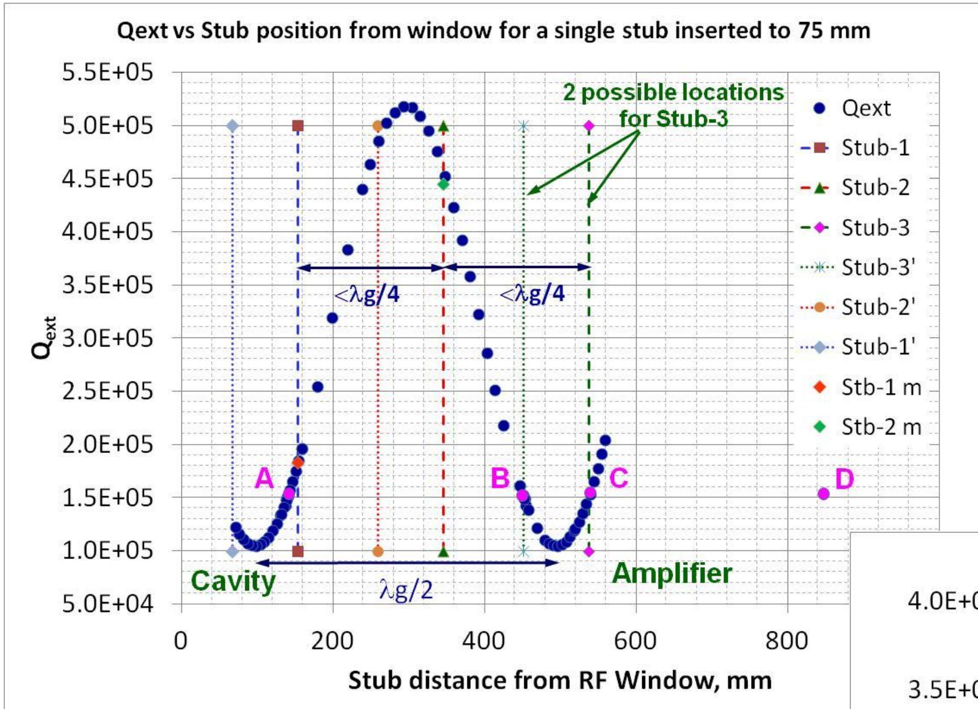
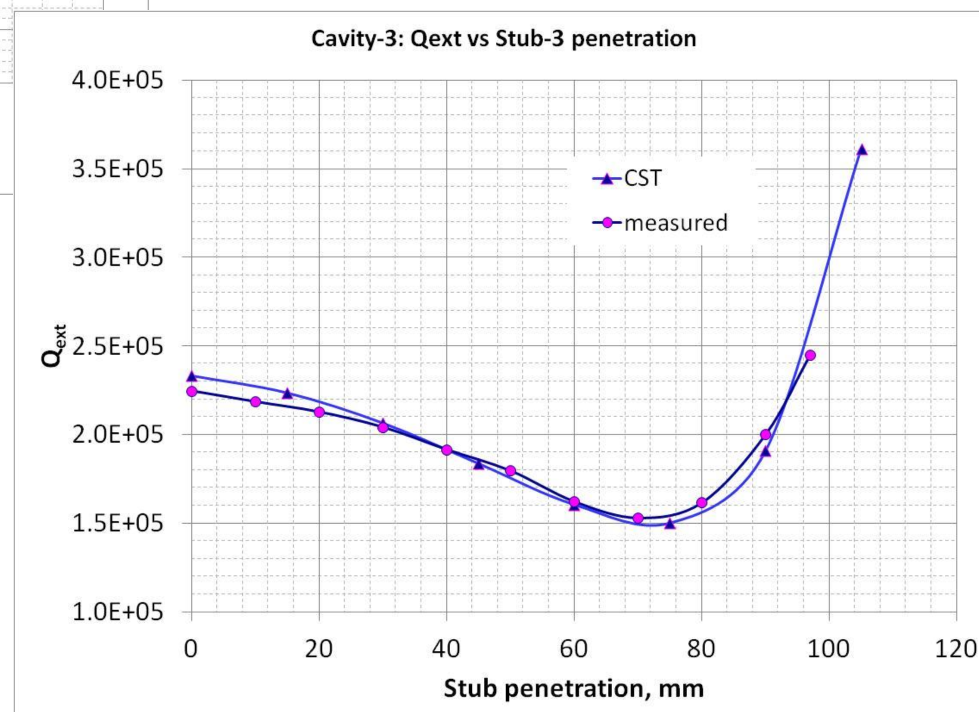
Verification of 3-stub tuner models



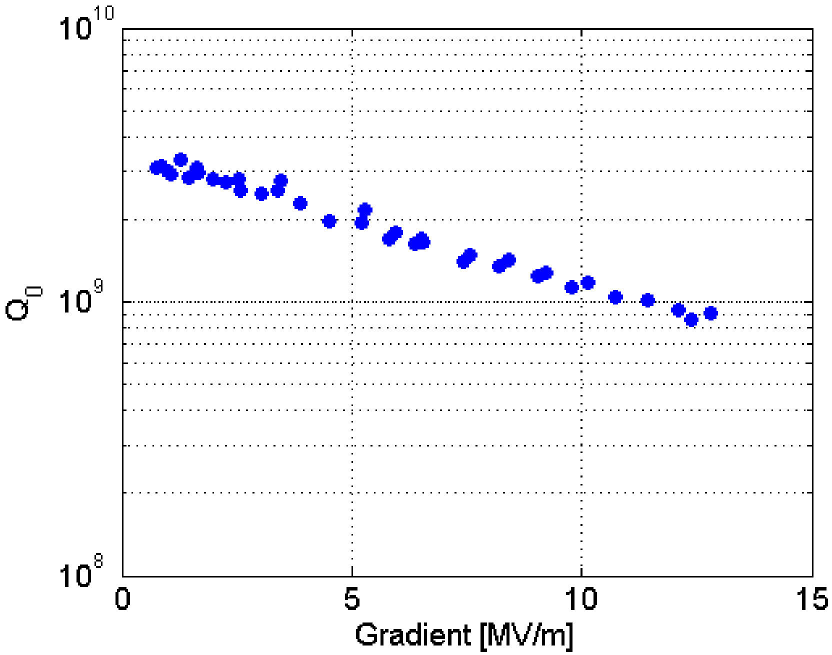
Measurements of Qext for three independent stub insertions has allowed exact geometry to be established



Measurements of 3-stub tuner operation now agree well with the model

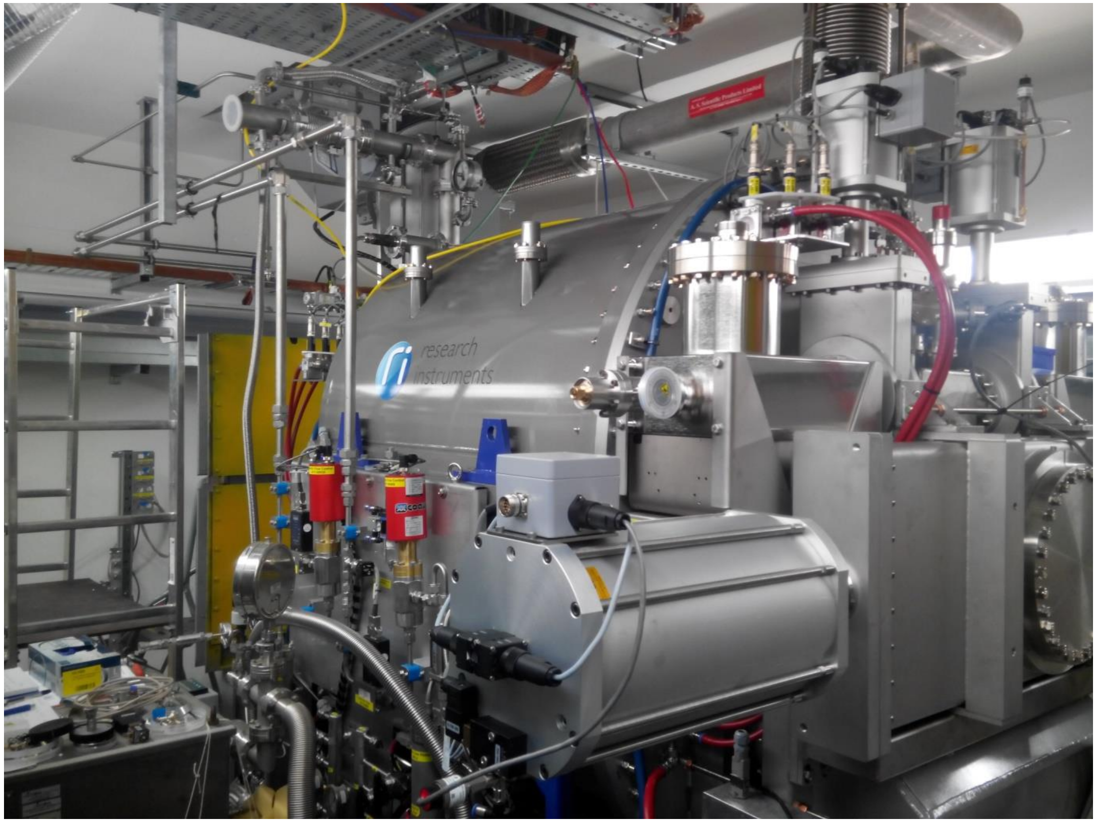
Stubs can be set for arbitrary beam currents and amplifier powers required for all modes of user beam operation

Cavity 4 procurement



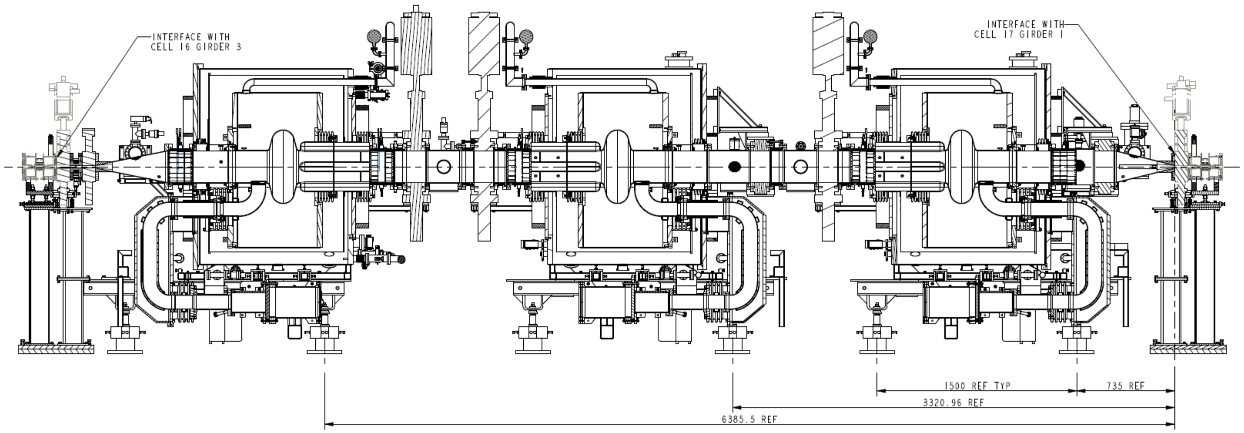
- Cavity 4 contract placed with RI Research Instruments GmbH
- Use SSRF coupler tongue design and CLS pump-out box to give $Q_{ext} = 1.2 \times 10^5$
- Vertical test at Cornell University carried out in July 2013
- Rapid conditioning to full field
- Q_0 exceeded specification
- $Q_0 > 1 \times 10^9$ at $V_{acc} < 6.67$ MV/m
- $Q_0 > 5 \times 10^8$ at $V_{acc} < 9.33$ MV/m

Cavity 4 procurement

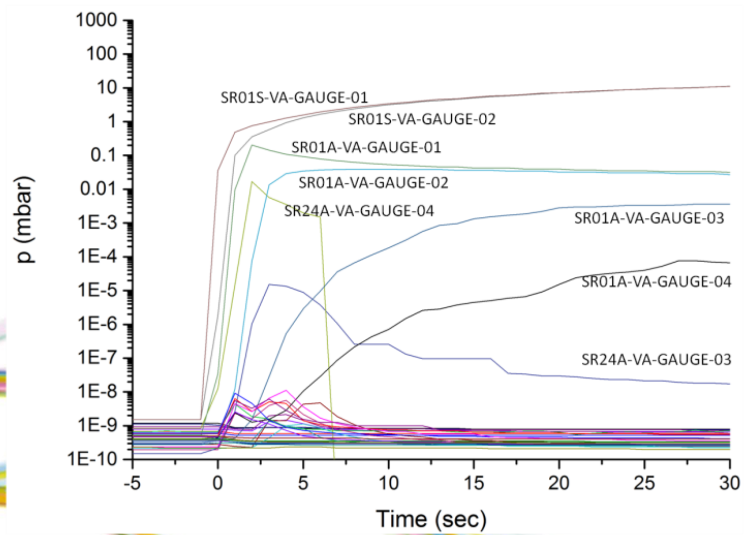


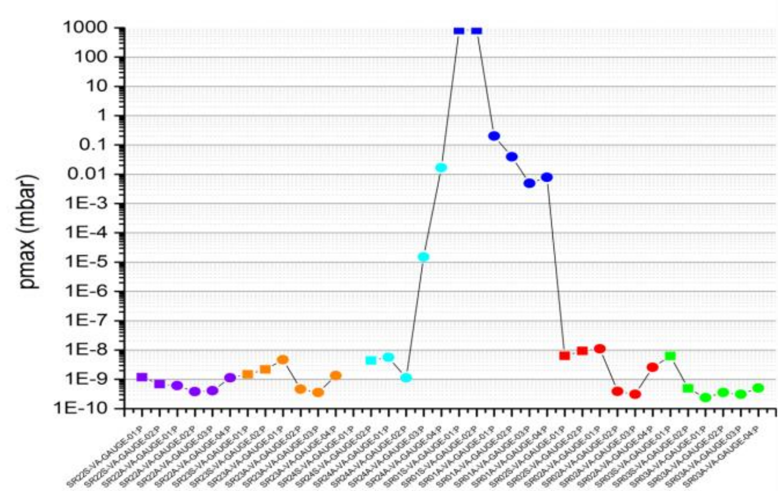
- Cavity 4 delivered to DLS in May 2014
  - Currently installed in the RF test bunker
- Acceptance tests have begun
  - First cooldown scheduled for May 13th
  - High power tests to begin in June

Location of new cavity



Are we at risk of catastrophic failure if all three cavities are in a single straight?





Interlock protected neighbouring straights in Diamond's only previous vacuum event

- Put new cavity in remote location?
- Third harmonic cavity in RF straight?

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Cryogenic issues for high current operation

As beam current rises and number of insertion devices increases we will bring the new cavity into operation and introduce a third harmonic cavity

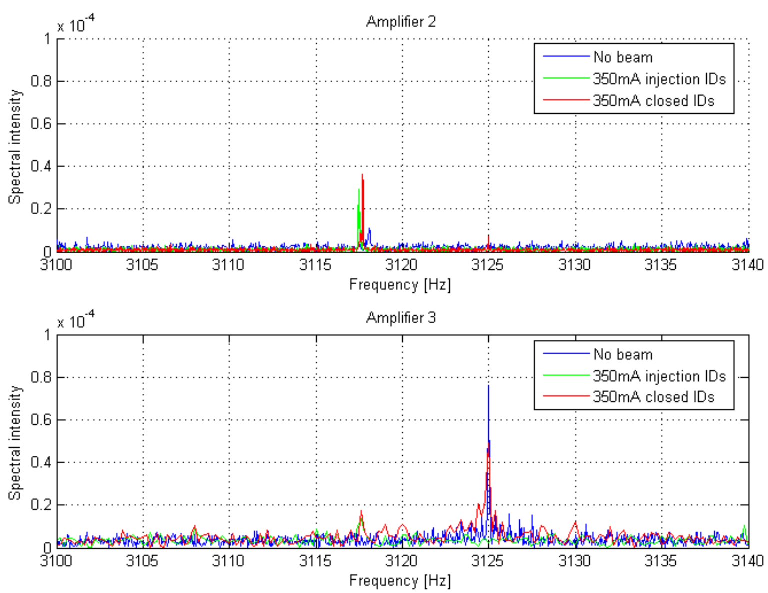
What are the implications for the cryogenic system?

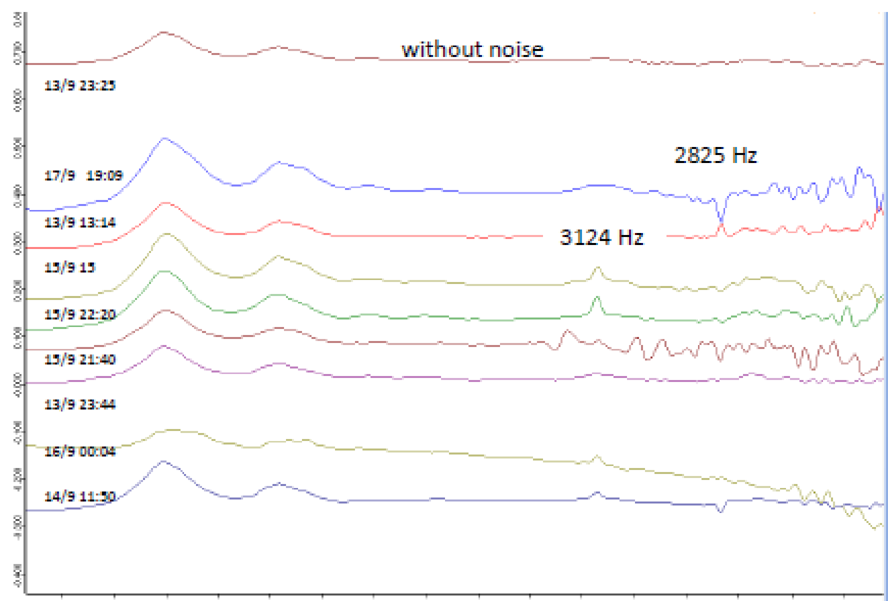
- Capacity of installed cryogenic system is 500 W
- Cold Box load is 82% of capacity with 2-cavity 300 mA operation and 1.8 MV on cavity in RF test facility
- Must consider the following factors for high-current operation
  - Losses in third cavity
  - Change in configuration of multichannel lines
  - Introduction of third harmonic cavity
  - Continued operation of cavity in test facility
- If we are to install the new cavity remote from the RF straight
  - Machine restrictions may force us some distance from the cryogenic system
  - We will need another valve box for the remote cavity
- Gas storage space for cool-down of all three cavities will also be an issue

RF noise on infrared beamline

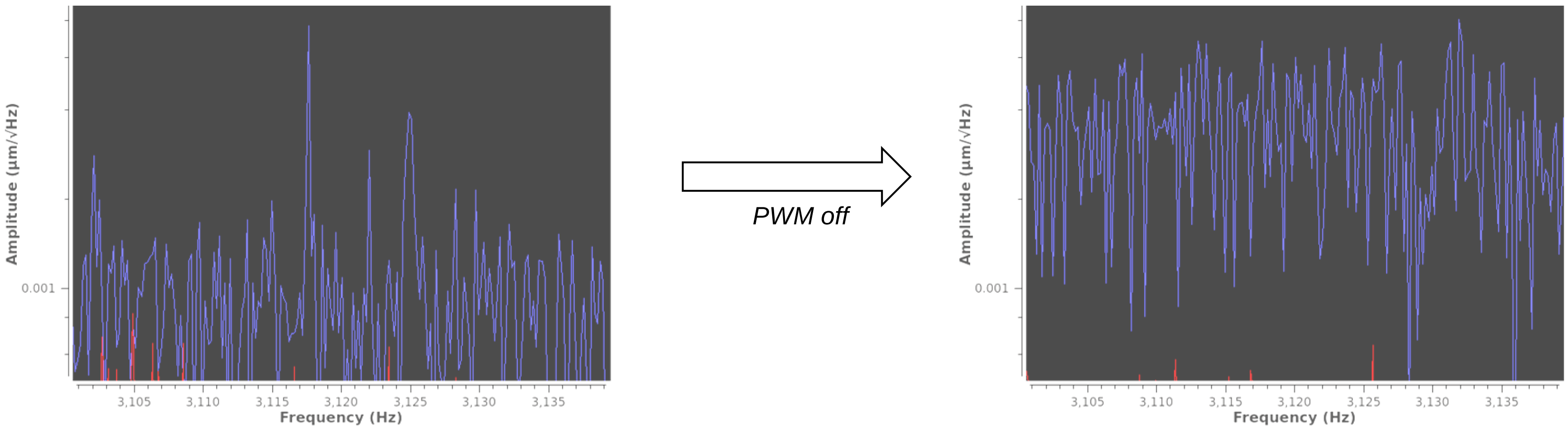
The high voltage power supply for the IOTs is a switched mode supply and as such generates noise on the voltage at the IGBT switching frequency and its harmonics

- Visible in HV spectrum
- Infra-red beamline notice the noise in their interferograms
- Broad-band measurement, so shifting frequency is not an option





Removing the switching noise



Switching noise can be removed by disabling the PWM operation

- Works for klystrons (at SLS) but IOT current drifts with power and system is destabilised during dither at integral module changeover
- Power drawn from IOTs depends on beam current
  - Varies during a fill and at different points in the top-up cycle
- Power drawn from IOTs depends on configuration of insertion devices
  - Out of control of RF group!

Must control switching of integral modules

- Dither must be removed by introducing a large hysteresis in HVPS current-control
- Possibly remove switching entirely and take up slack with LLRF loop
- Occasional shuffling of modules to ensure longevity
  - Weekly during periodic maintenance or during to-up when kickers dominate disturbance

Trials scheduled for June 2014…

Summary

Diamond is a user facility and the RF group must cater to the beamline users

- **Reliability is paramount**
  - Multiple single points of failure in SR RF system
  - Noise or drifts are noticed immediately by beamlines
  - Injector faults will disrupt top-up
- **We are preparing for future machine developments**
  - RF system must develop as beam current increases
  - Continuity of supply must be ensured for IOTs, klystrons and critical smaller components

Thank you for your attention

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