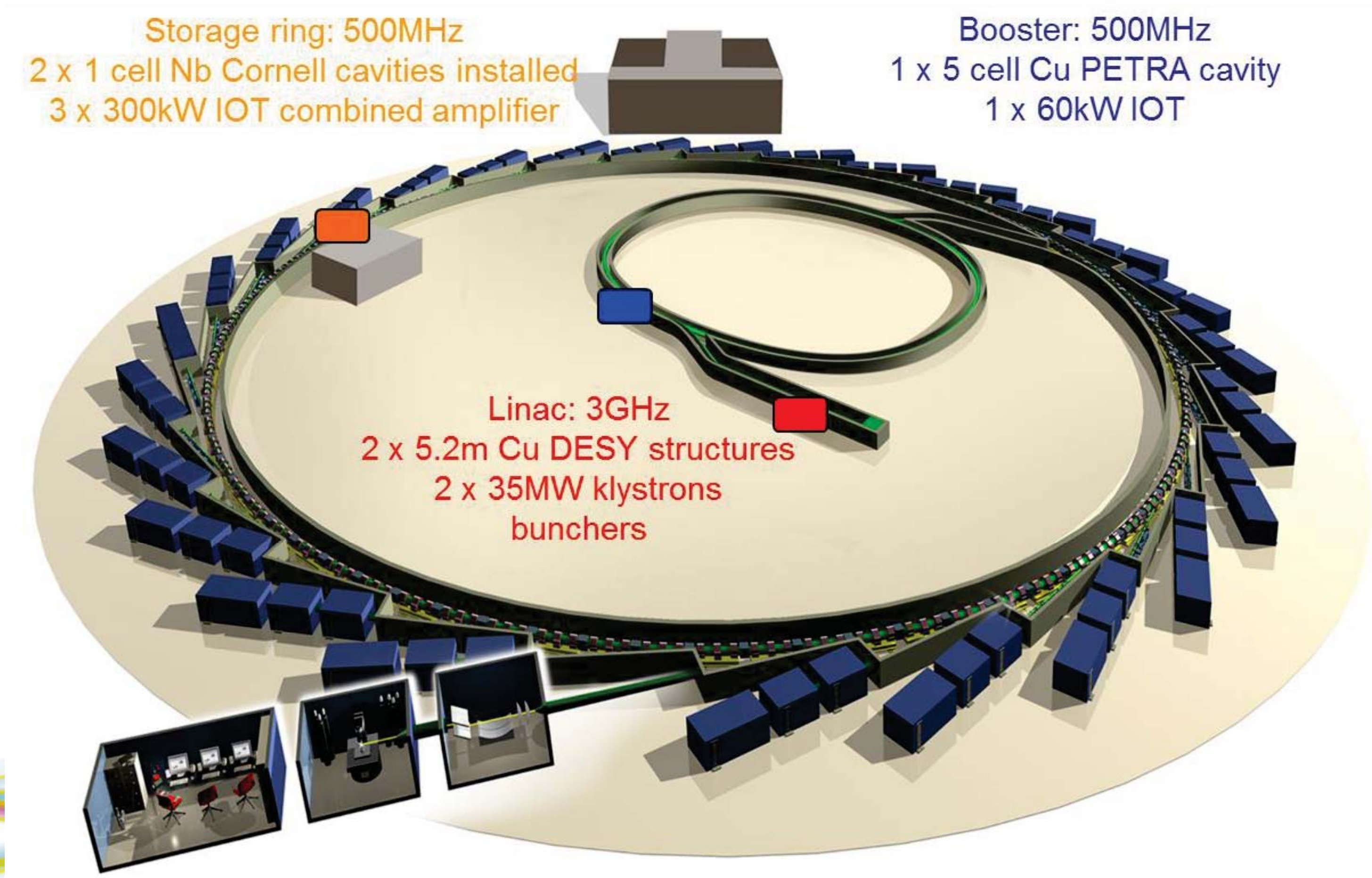
Status of Diamond Light Source RF

Chris Christou, Diamond Light Source

ESLS-RF 18
Synchrotron Soleil
8th November 2018

RF at Diamond Light Source



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

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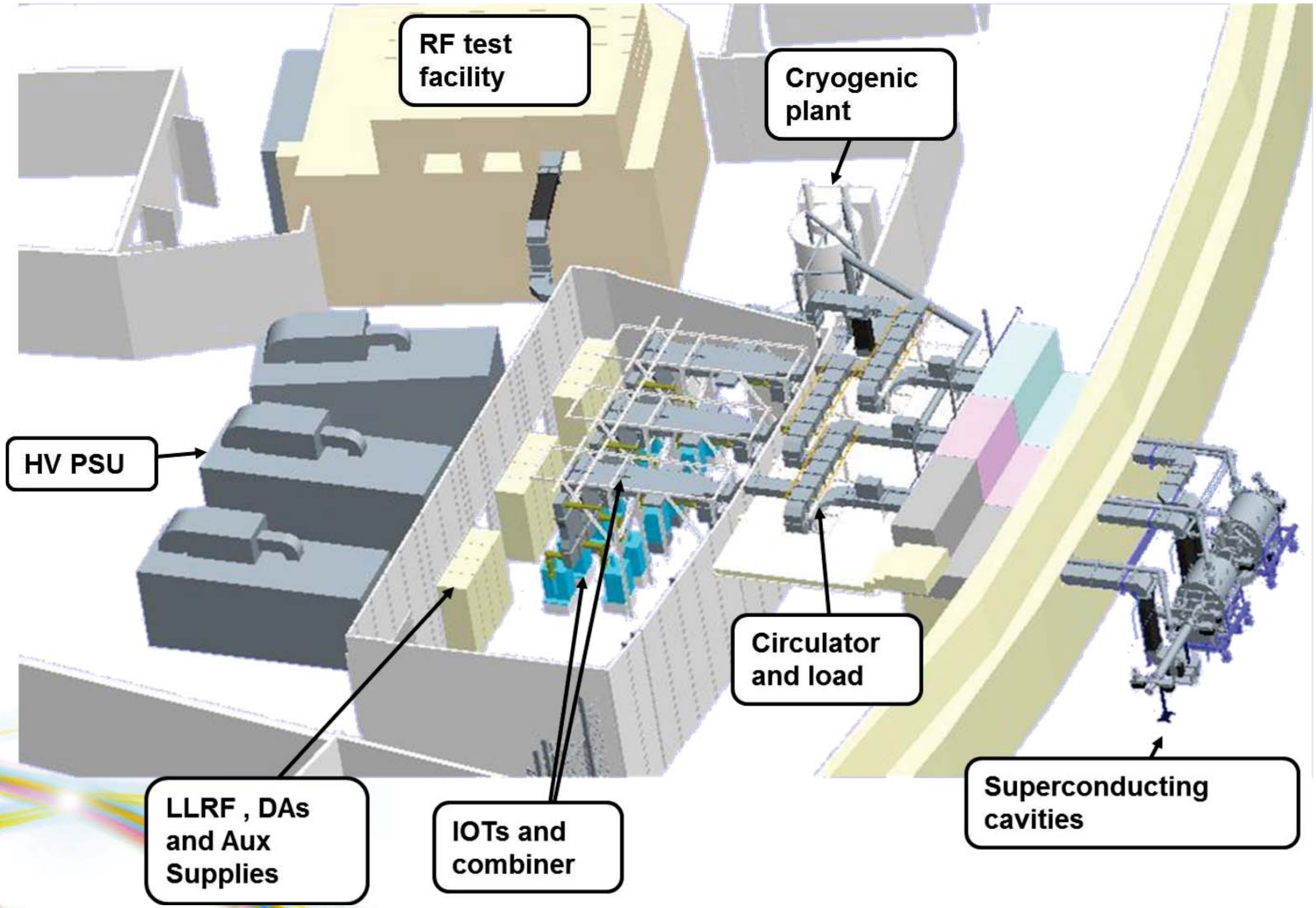
Injector cavities and structures

100 MeV normal conducting linac

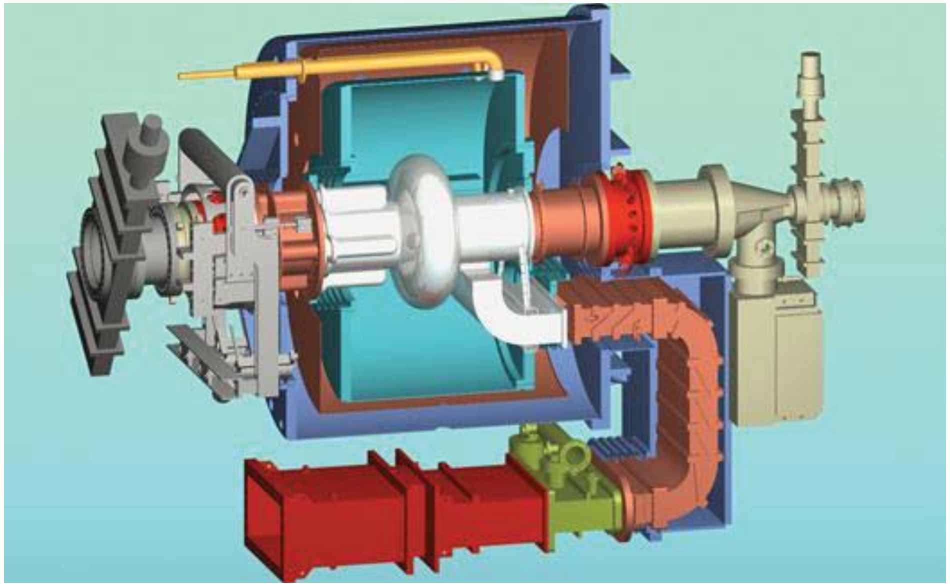
5-cell copper booster cavity

Storage Ring RF

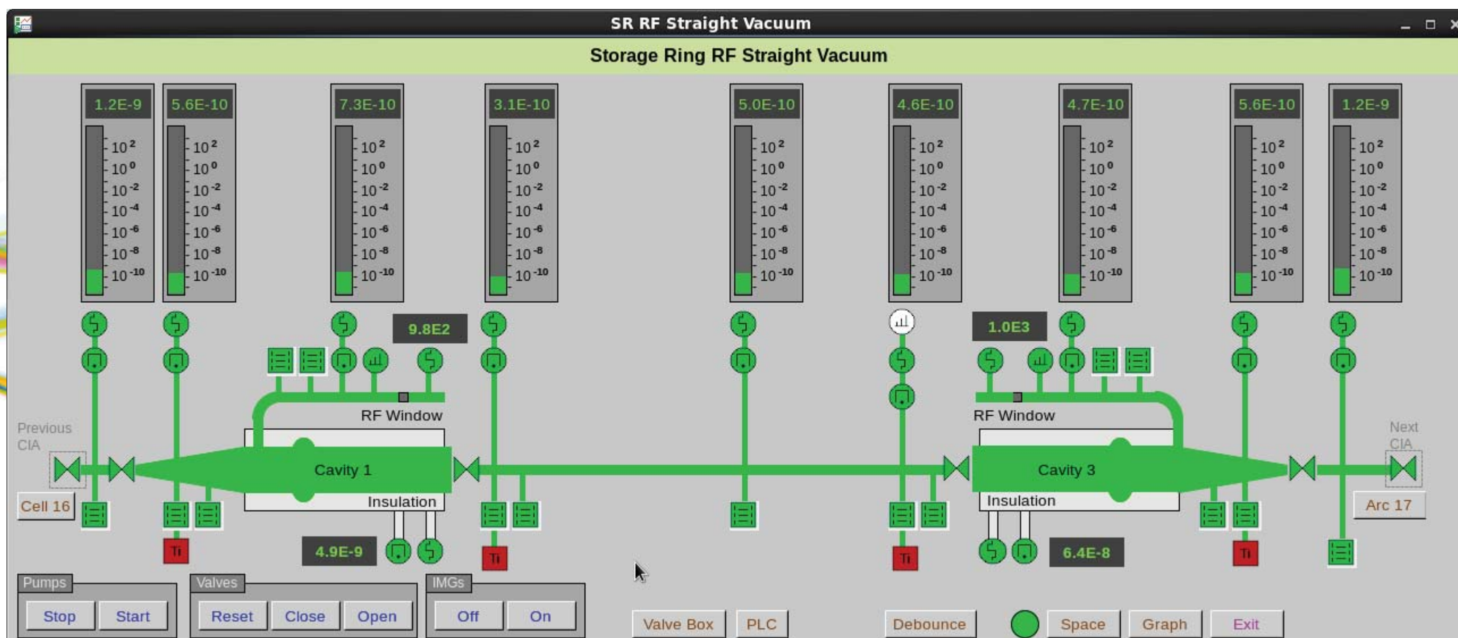


- One high voltage power supply supports four IOTs which are then combined
- Superconducting cavity supported by Air Liquide cryogenic plant
- Space for three cavities in RF straight, usually two operational
- Two extra EU HOM damped cavities installed in 2017-2018

The CESR-B cavity

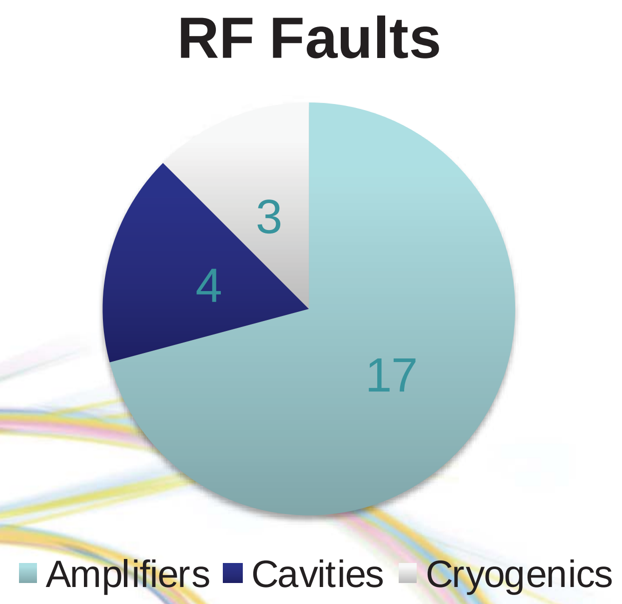


Resonance frequency	499.765 MHz
Maximum accelerating voltage	3 MV
Operating voltage (CESR–III)	1.8 MV
Effective cell length	0.3 m
R/Q ($R = V^2/P$)	89 Ohm
Geometry factor G	265.7 Ohm
Intrinsic cavity quality factor Q_0 at operating conditions	$> 10^9$
External quality factor Q_{ext} of RF input power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



Reliability: year to date

	Hours	Faults	MTBF	MTTR	Downtime
Diamond	4992	55	90.8 hours	1.4 hours	77 hours
Storage ring RF	4992	24	208 hours	1.6 hours	38 hours

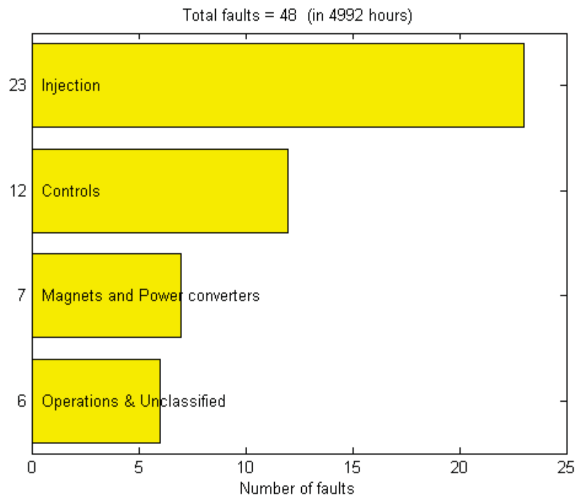


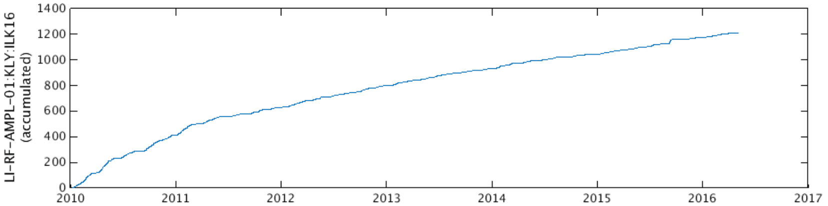
Amplifier		Cavities		Cryogenics	
IOT short circuit	6	Flow meter	1	Coldbox vacuum	2
IOT output coupler	5	Helium pressure gauge	1	Coldbox pump	1
Focus coil supply	4	NC cavity conditioning arc	1		
Filament supply transformer	1	Reflected power	1		
Drive amplifier cooling	1				

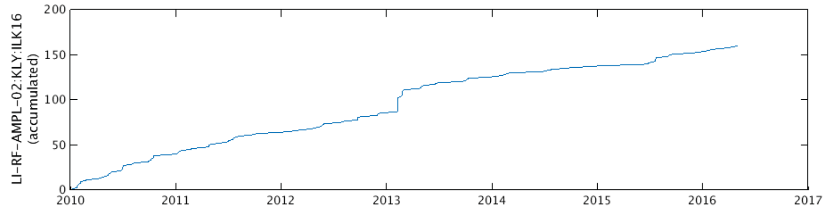
Faults in injector system

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

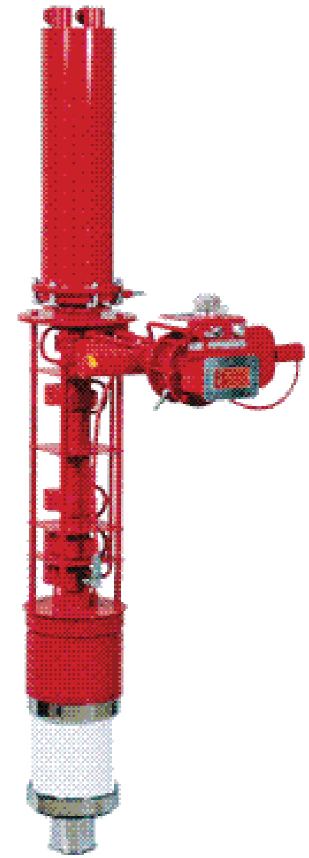
- CPI YU171
- 25,000 hours

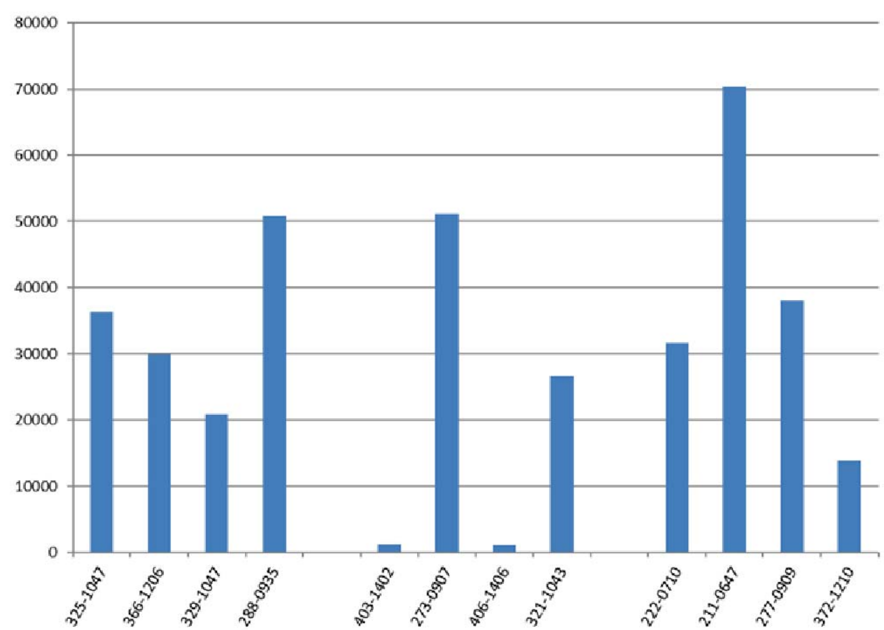
Linac

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

Booster and storage ring

- E2V IOTD2130
- Booster #224-0712: 49,000 hours



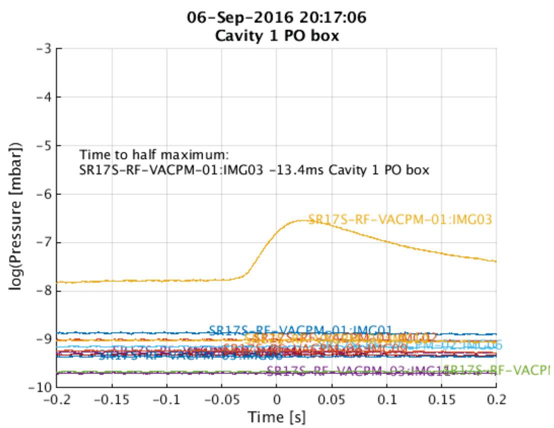


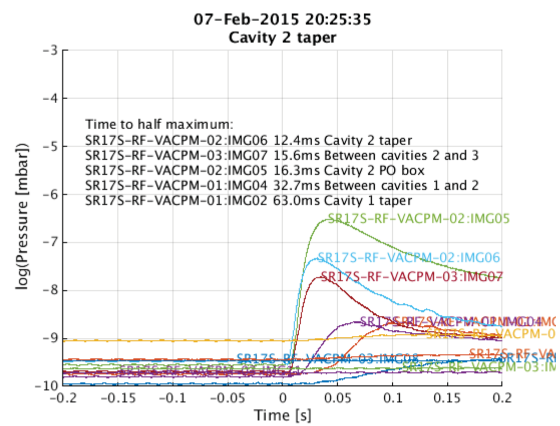
Cavity fast vacuum trips

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

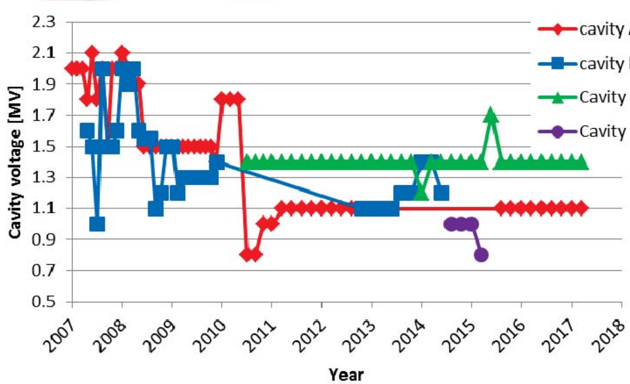
Reliable operating voltages	
Cavity A	1.1 MV
Cavity B	1.2 MV
Cavity C	1.4 MV
Cavity D	0.8 MV

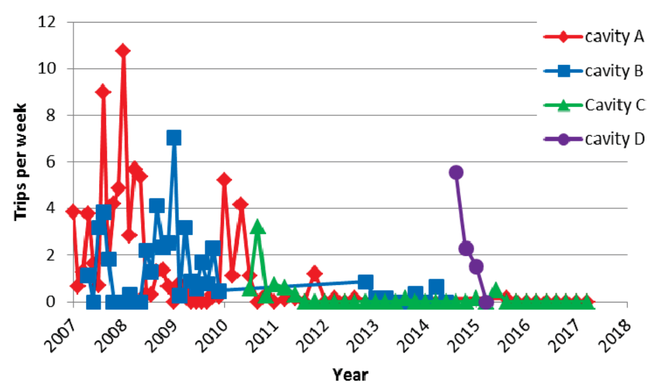




Sequence of events

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?

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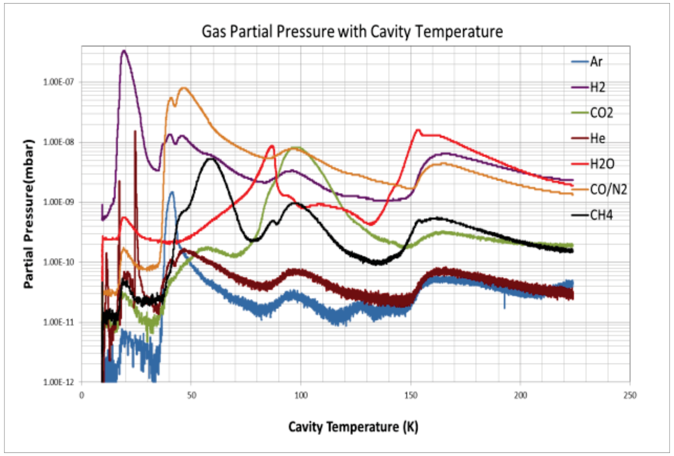
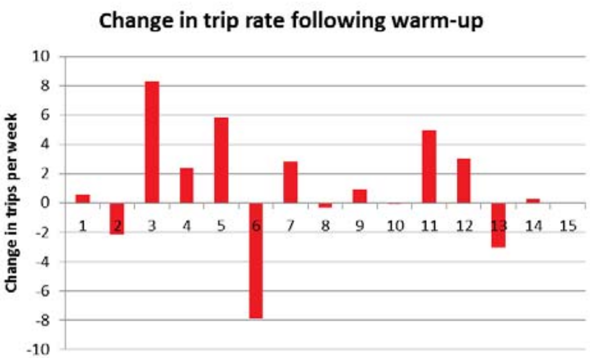
Cavity warm-ups

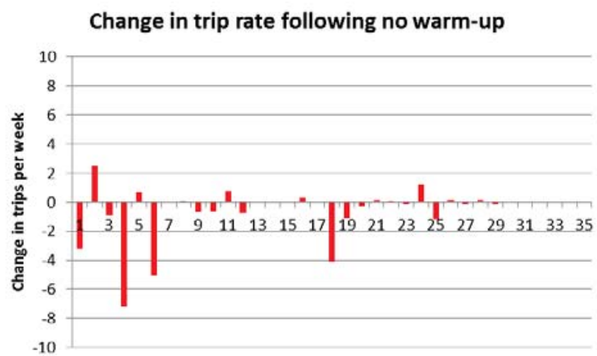
Cavities have been subjected to warm-ups to room temperature in the past

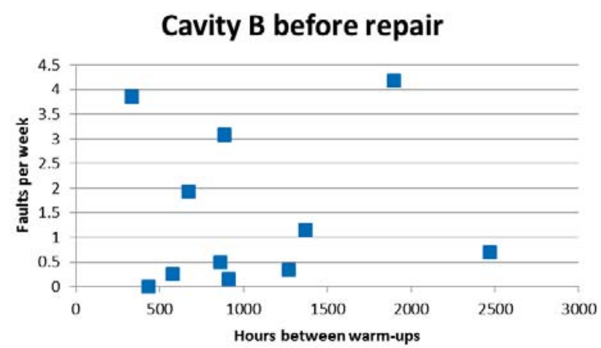
- Occasional full warm-ups tried in early days and with problematic cavities
- Gas is cleared from surfaces and identified by RGA
- More frequent partial warm-ups have been used with all cavities

Every warm-up carries the risk of disaster!



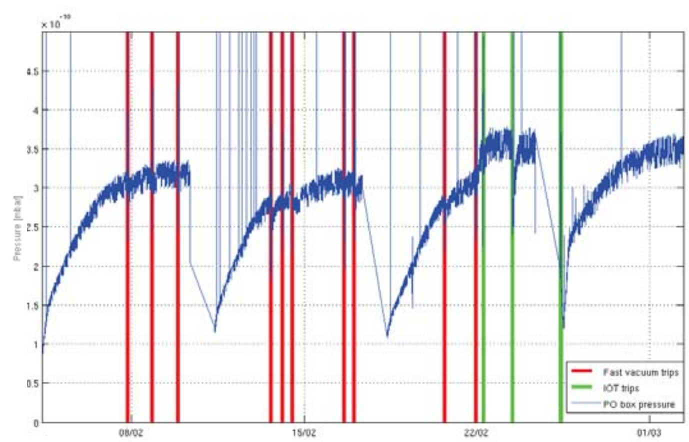






Very little benefit at Diamond

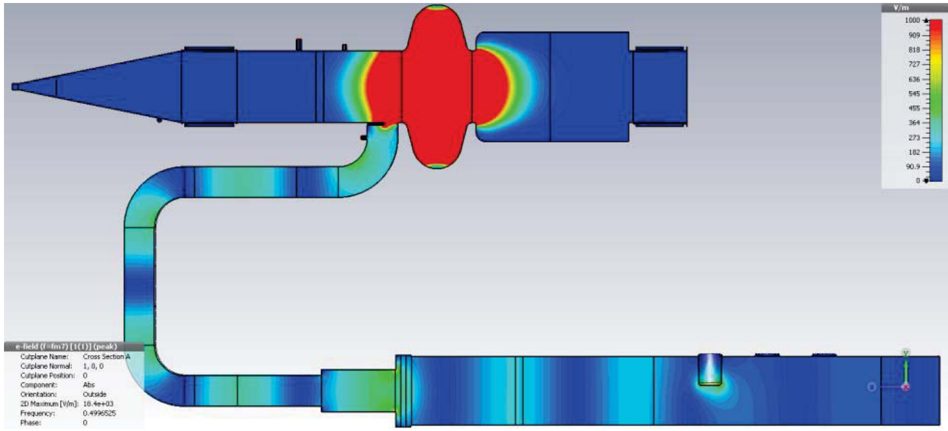
- Cavities are no better in run following warm-up
- Cavities are no worse in run following no warm-up
- No degradation of reliability if partial warm-ups are stopped for several runs
- Short term improvement apparent following partial warm-up
  - No trips in first few days
  - Trips resume when vacuum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



Cavity conditioning

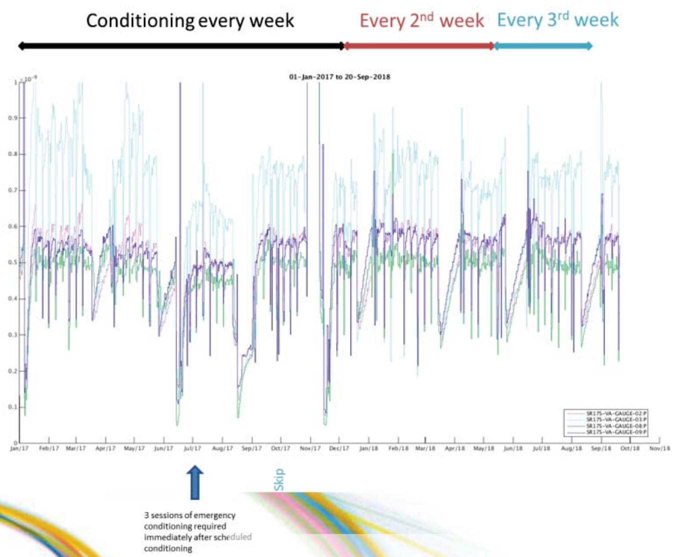
Pulse conditioning without beam

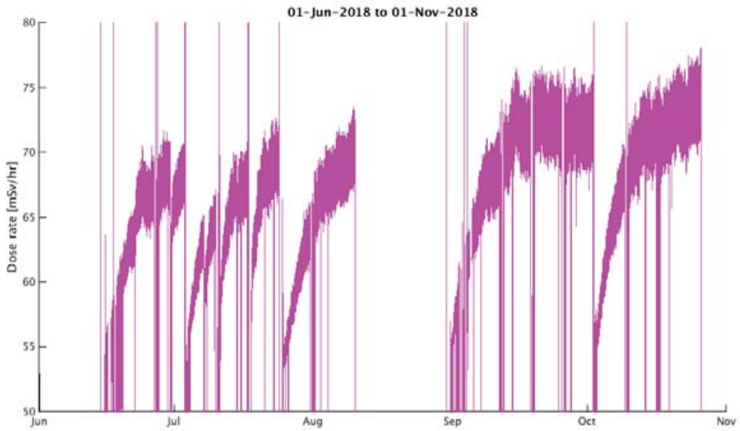
- 2.3 MV peak voltage,10% duty cycle (10 ms/100 ms)
- Detune angle scanned to sweep standing wave
- Carried out when work is going on elsewhere in SR
- X-ray emission reduced after conditioning



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

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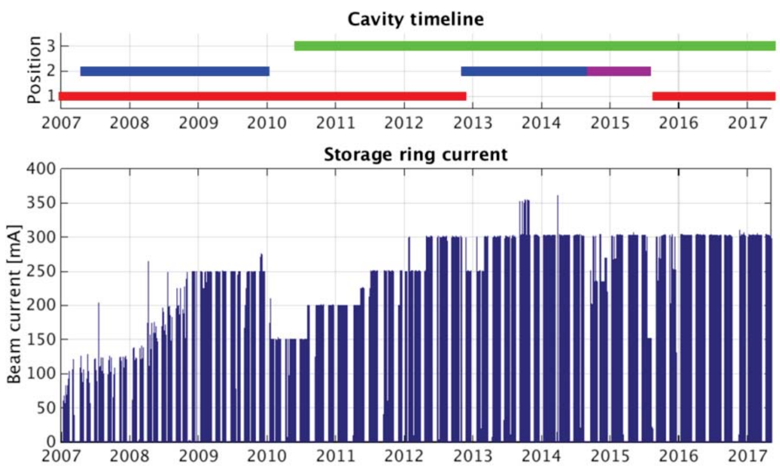
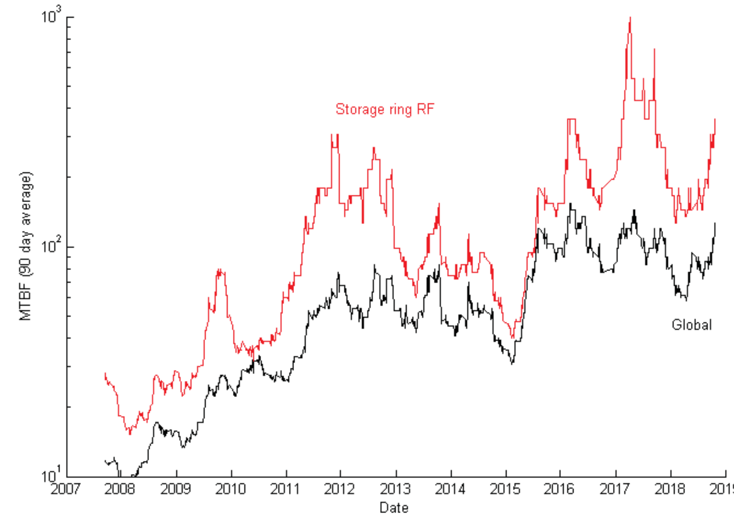
Storage ring RF history





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

Cavity	Failure date	Detail
A	none	
B	2009, 2014	UHV leak
C	2006	Insulation vacuum leak
D	2015	Window failure

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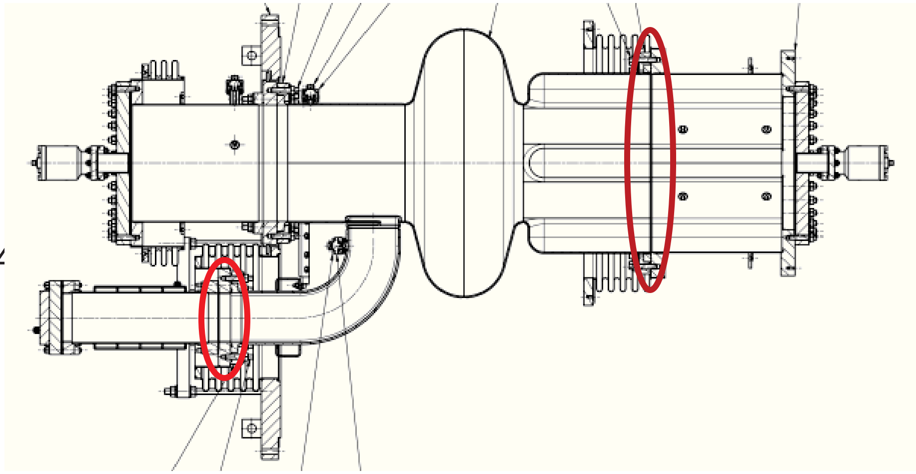
Recent cavity failures

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

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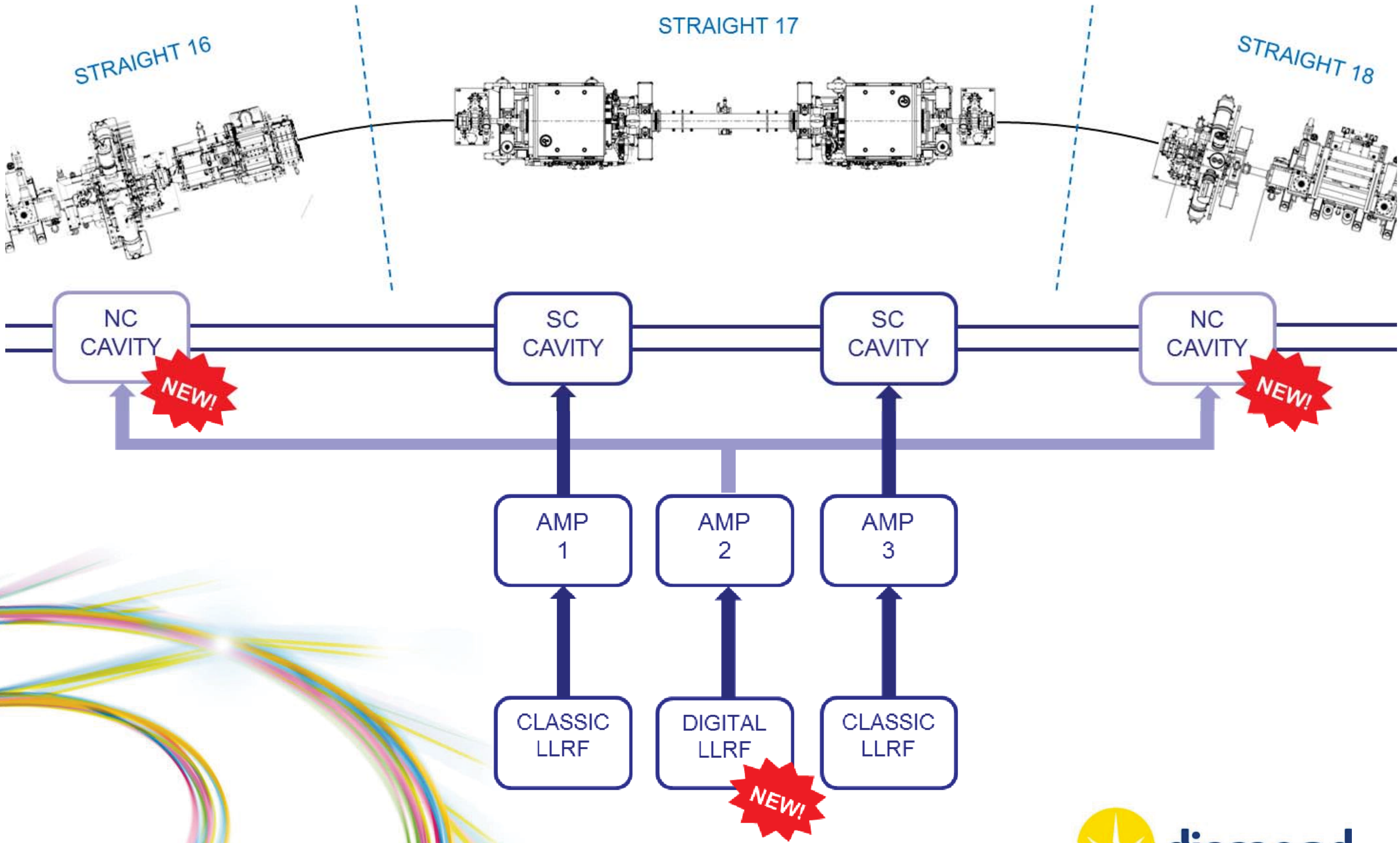
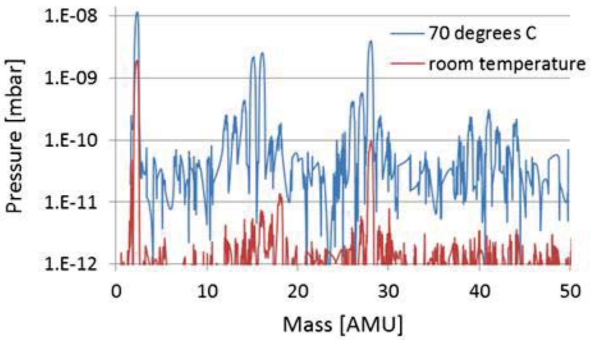
New storage ring RF configuration

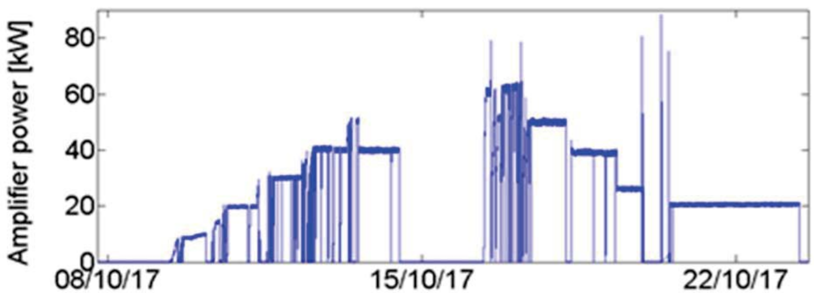


NC cavity bakeout and conditioning

Both cavities baked at 120ºC for two weeks

- First bake before conditioning
- Second bake after installation in ring
- Post-bake RGAs show
  - no evidence of leaks
  - minimal H_2O
  - no hydrocarbon contamination of the vacuum





Two weeks available for cavity conditioning

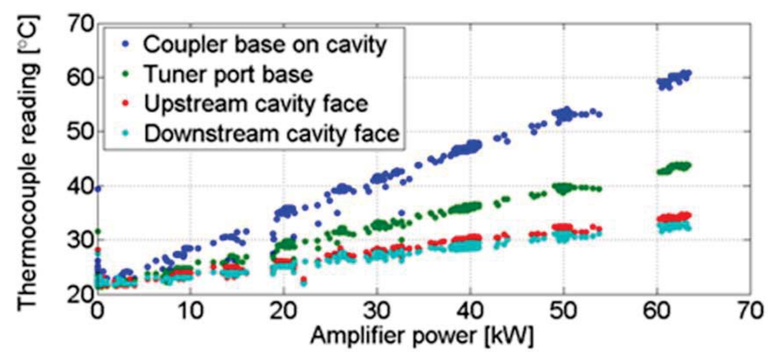
- FPC critically coupled for conditioning
- Similar multipacting barriers
  - 100 W, 11-13 kW, 19 kW, 25 kW, 35-39 kW, 50 kW and 60 kW.
- After two weeks the cavity was able to run continuously at 20 kW, corresponding to a voltage of 300 kV planned for initial operation.

Comprehensive temperature monitoring

- 7 thermocouples on the copper structure
- 14 thermocouples welded to the cooling pipes.

Temperatures rose linearly with conditioning power

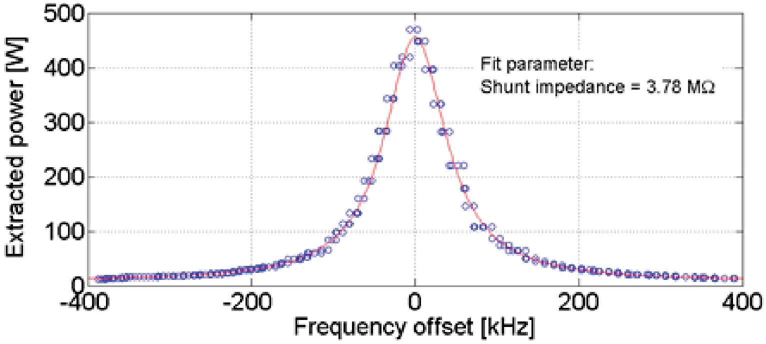
- four points exceeding 30°C at maximum power
- highest temperature was recorded on the cavity body at the base of the fundamental power coupler.

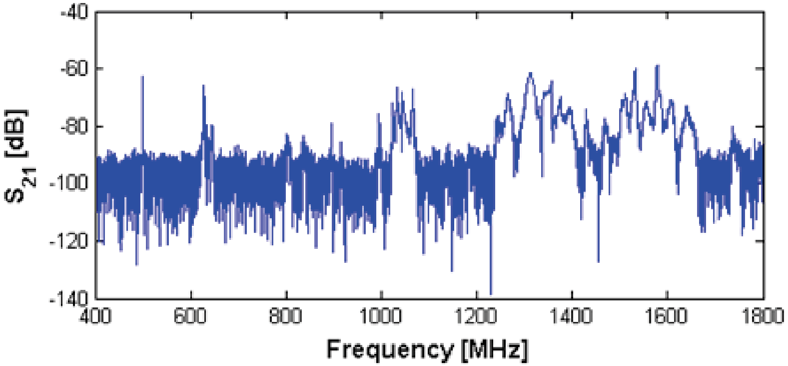


Installation in the storage ring

Installation of two cavities is complete

- Installed upstream and downstream of RF straight
- FPC rotated to β = 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 α) for users
- Parked cavity is invisible to beam
- No instabilities excited in any mode of operation





Measured parameters	
$R_s = V^2/2P$	3.8 MΩ
Q_0	33,000
Coupling β	5.2
Operational power	Up to 120 kW

Digital Low Level RF

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

Functionality

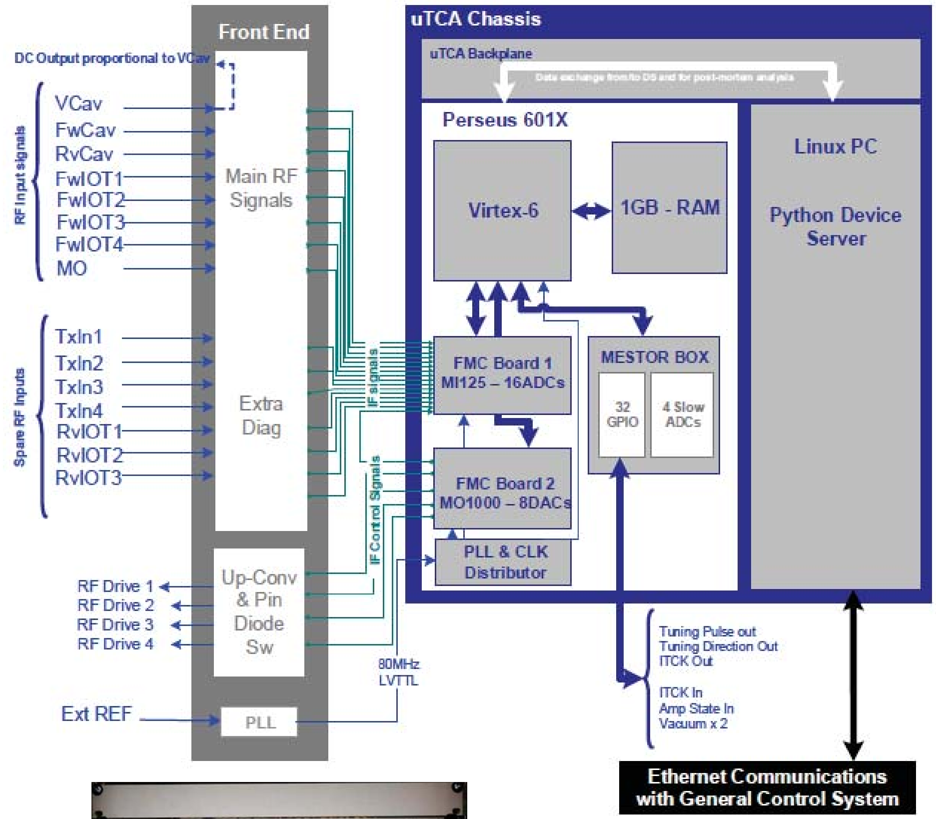
- IQ or polar PI loops of the cavity field to control amplitude and phase.
- Cavity tuning
- Fast interlock handling.
- Automatic start-up of the system
- Automatic conditioning of the cavity
- Monitoring of RF signals
- Recording of main digital processing signals for post-mortem analysis

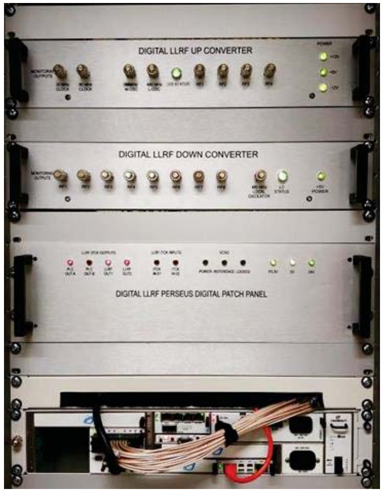
Features

- 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





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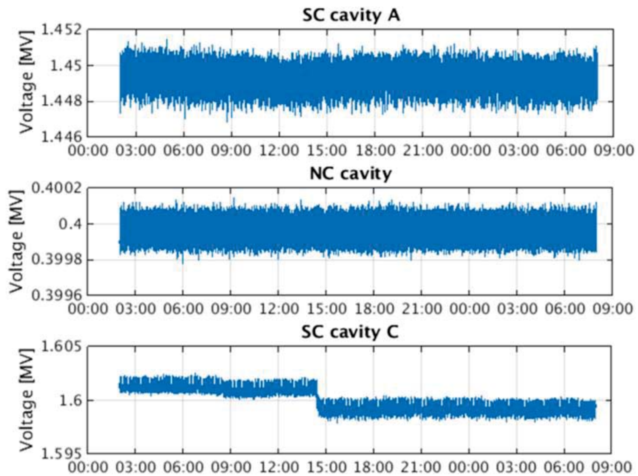
Operation with NC cavity and DLLRF

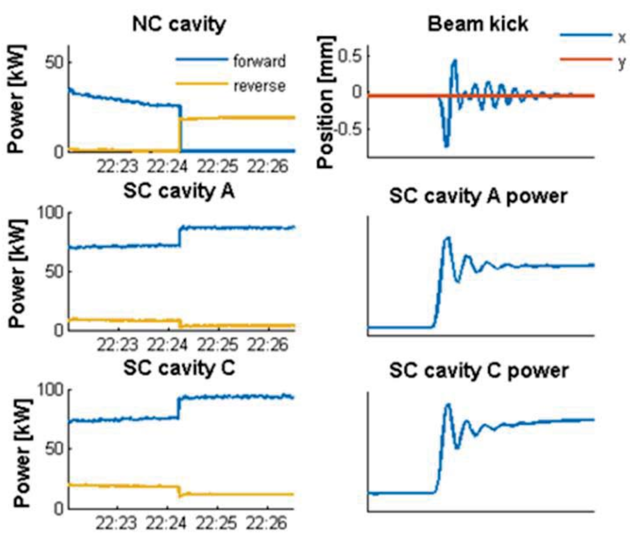
NC cavity was first operated for users in low α
- NC cavity at 400 kV
- SC cavity voltages reduced from 1.7 MV to 1.5MV
- Clear reduction in number of SC cavity trips

Must address amplifier reliability now

Low α run	Cavities	Cavity faults
2015 run 4	2 SC	6
2016 run 1	2 SC	7
2018 run 1	2 SC + 1 NC	0



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?

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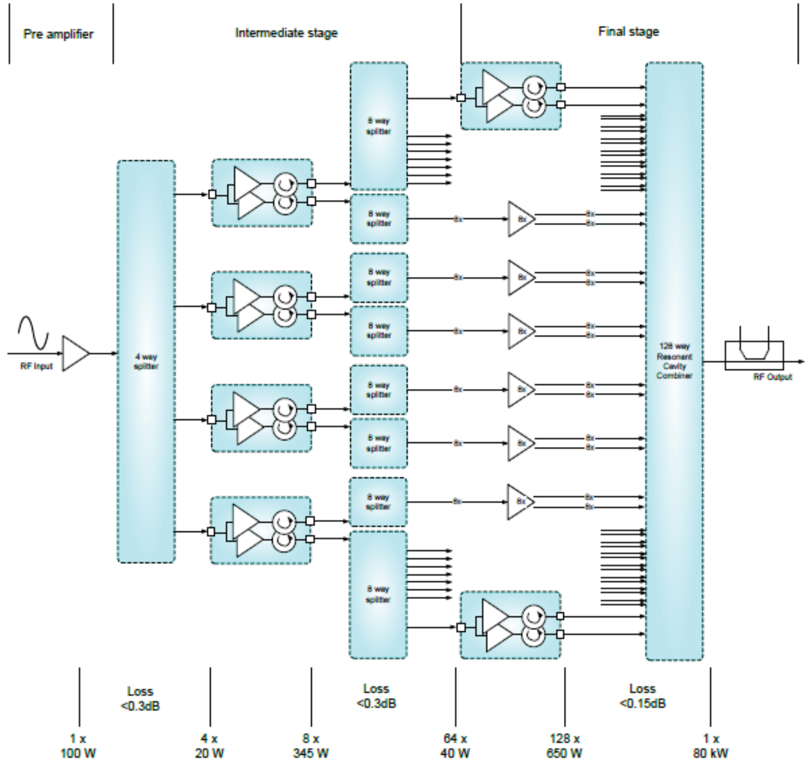
High power solid state amplifiers



High power IOTs can be replaced by multiple LDMOS power transistors

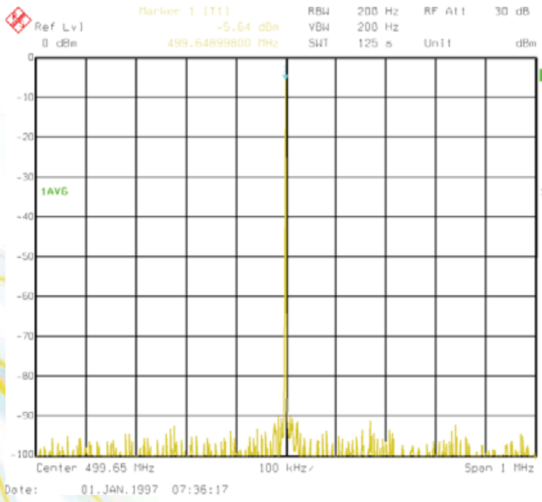
- System includes multiple redundant modules for robust operation
- Proven to be reliable at Soleil and other synchrotrons
- Two amplifiers have been constructed by Ampegon: 60kW and 80kW
- A development of the SLS booster amplifier
- To be used in Diamond booster and RF test facility

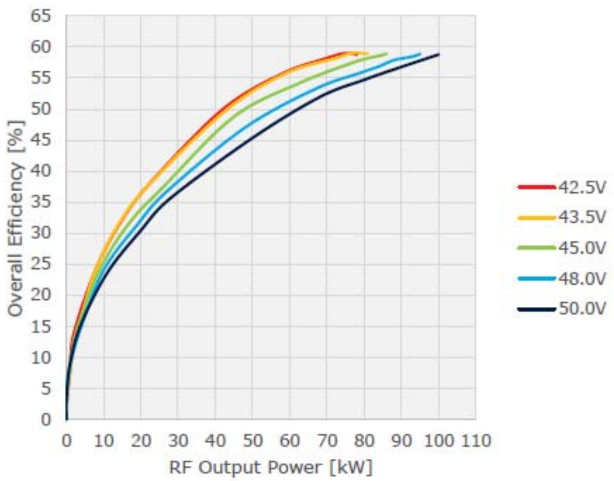
High power solid state amplifiers

- 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

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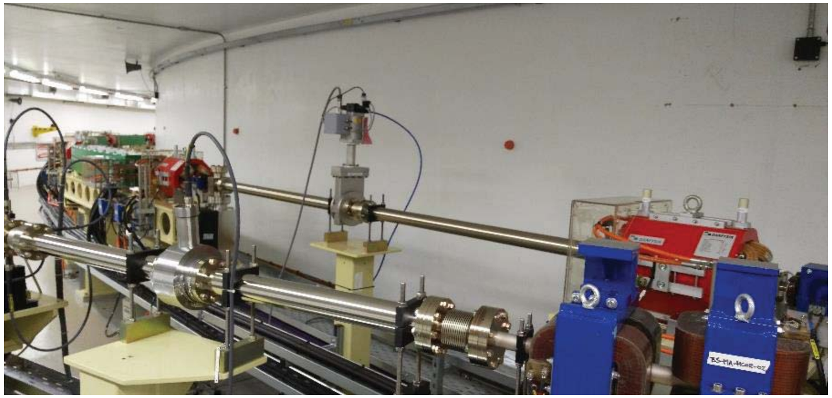
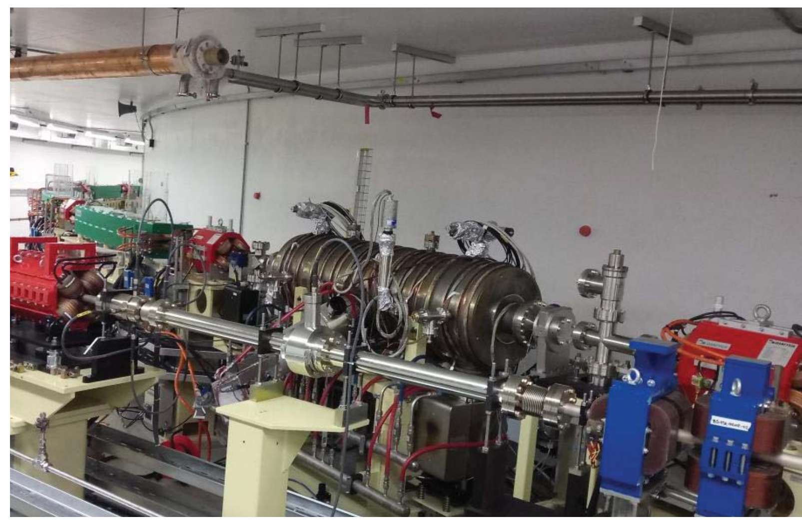
Second booster cavity



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



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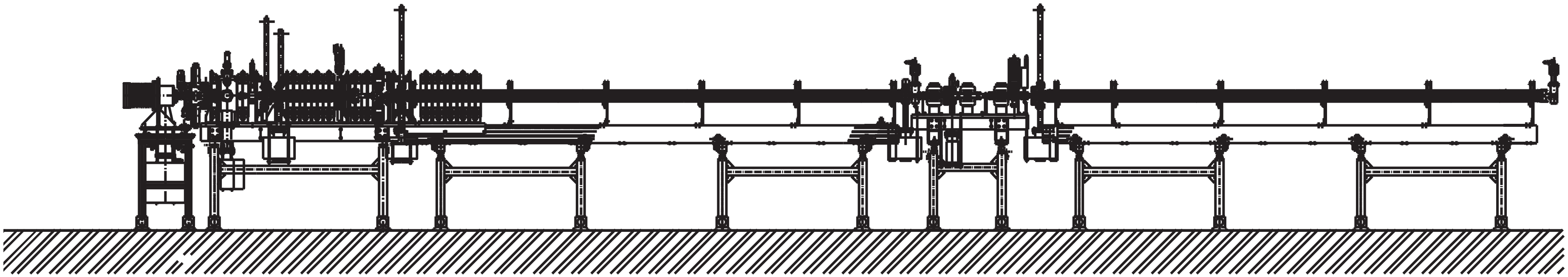
Linac SLED cavity upgrade



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

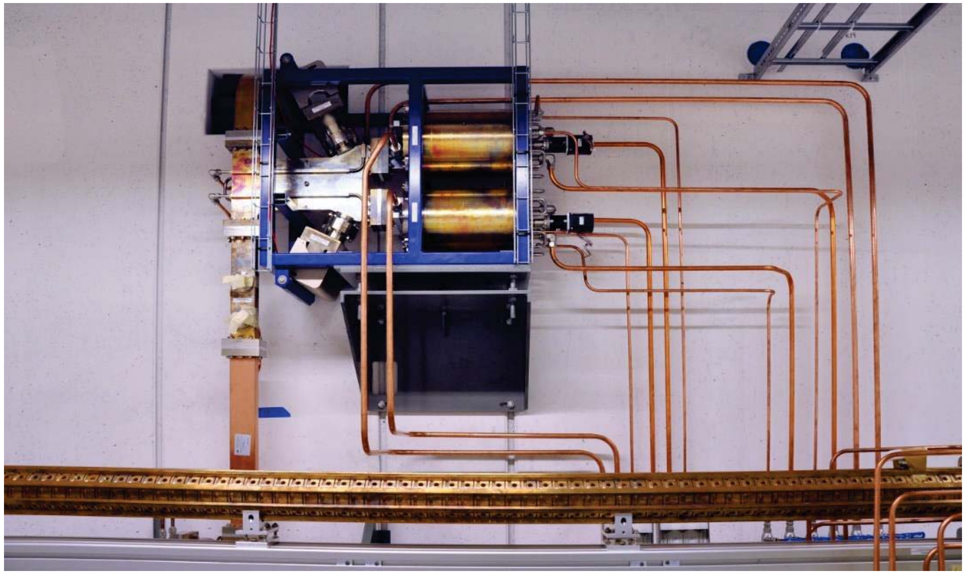
Ideal solution

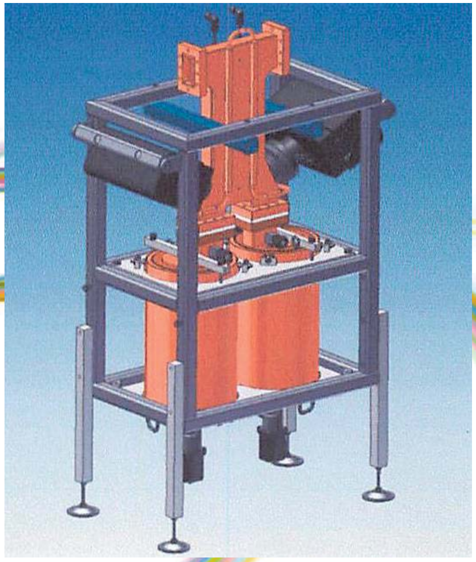
- 100 MeV beam from one klystron and modulator

SLED Cavity

The Stanford Linac Energy Doubler

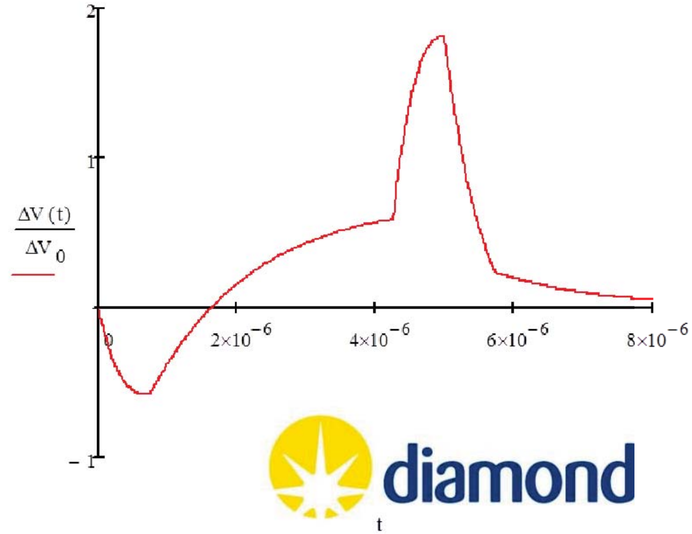
- Cavity in waveguide to compress the RF pulse
- Two cavities coupled to waveguide with hybrid combiner
- Water cooled
- UHV maintained with two ion pumps
- Cavities tuned or detuned by elastic deformation of base
- First part of pulse charges up the cavity
- Cavity is discharged during second part of 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



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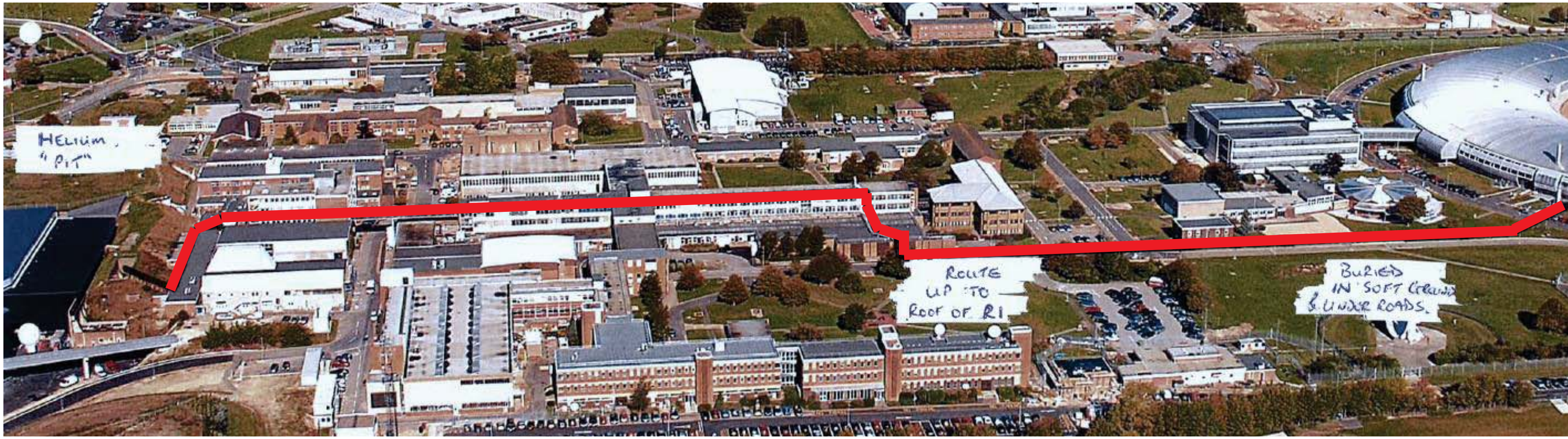
Helium Recovery



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

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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…

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Thank you for your attention

Any questions?