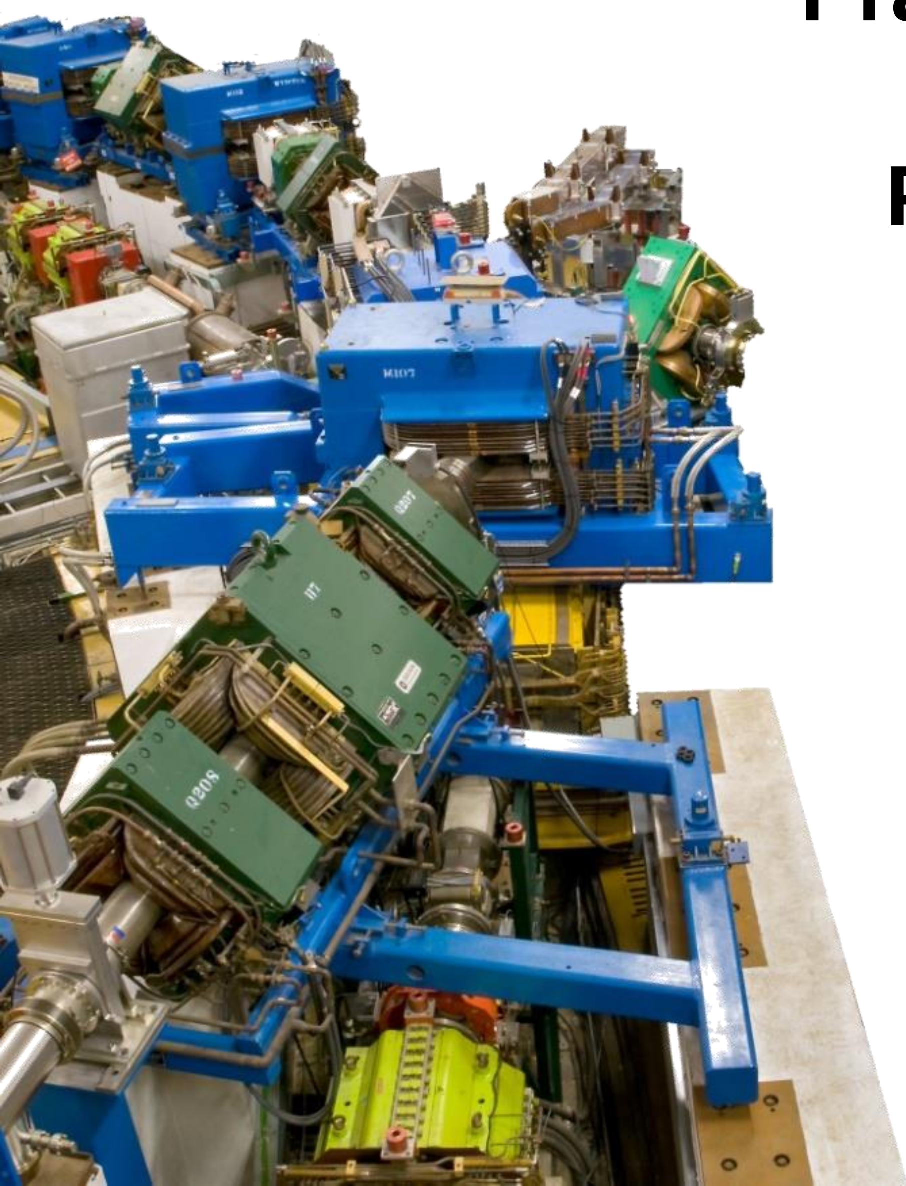
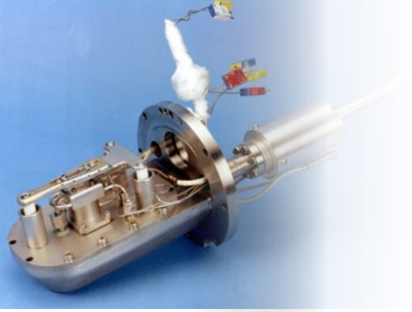
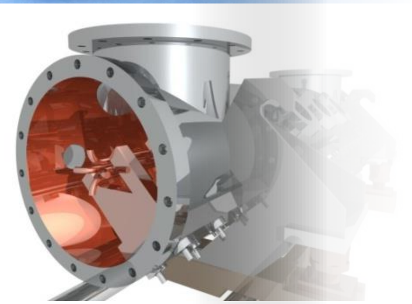


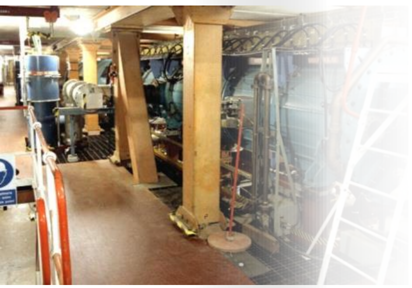
Practical Experience of Running the ISIS Proton Accelerator Spallation Source

John Thomason

ISIS Accelerator Division Head

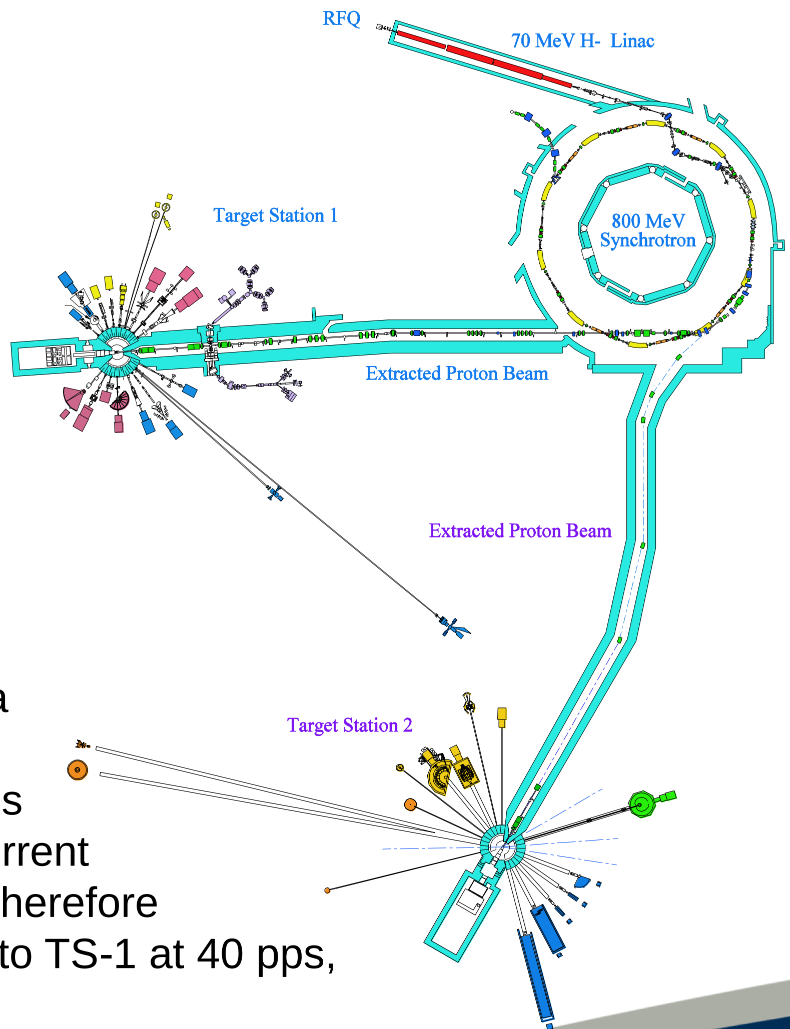






ISIS Accelerators

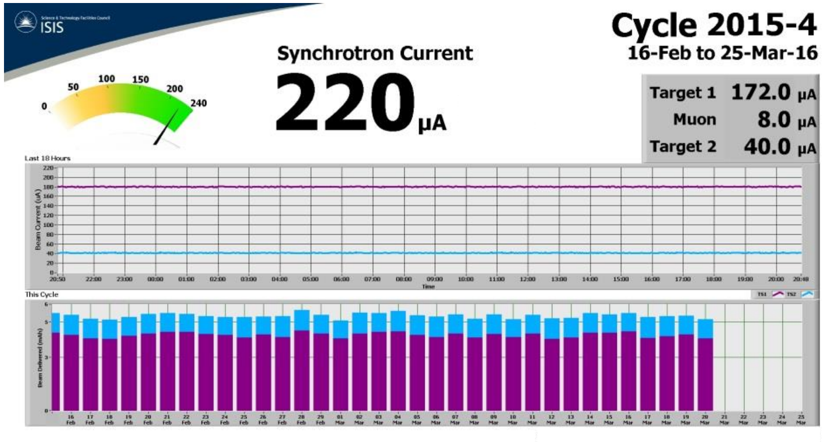
- H^- ion source (17 kV)
- 665 kV H^- RFQ
- 70 MeV H^- linac
- 800 MeV proton synchrotron
- Extracted proton beam lines



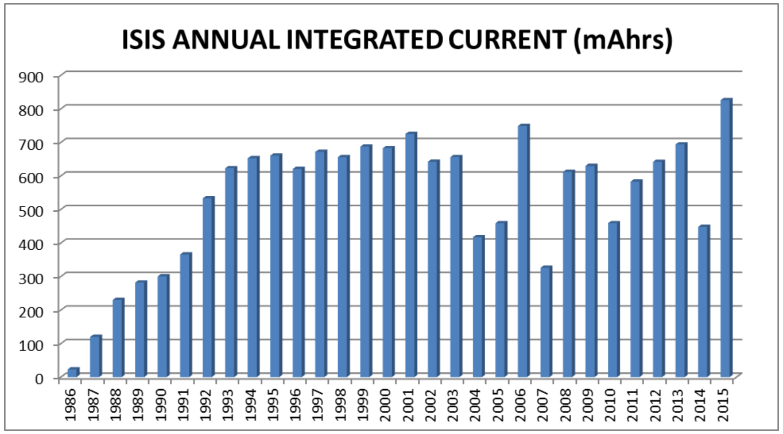
The accelerator produces a pulsed beam of 800 MeV (84% speed of light) protons at 50 Hz, average beam current is 220 μA (2.8×10^{13} ppp) therefore 176 kW on target (140 kW to TS-1 at 40 pps, 36 kW to TS-2 at 10 pps)

Performance

- 220 µA to two target stations
- Synchrotron efficiency = 93-95 %
- Beam availability = 90±5 %



- ~£50M/year operating budget
  (£8M/year for accelerator operation/sustainability)
- ~400 staff - 120 in accelerator division
- 160 - 200 operating days per year split into 4 or 5 cycles
- Long (6-9 month) shutdown every ~3 years for upgrades



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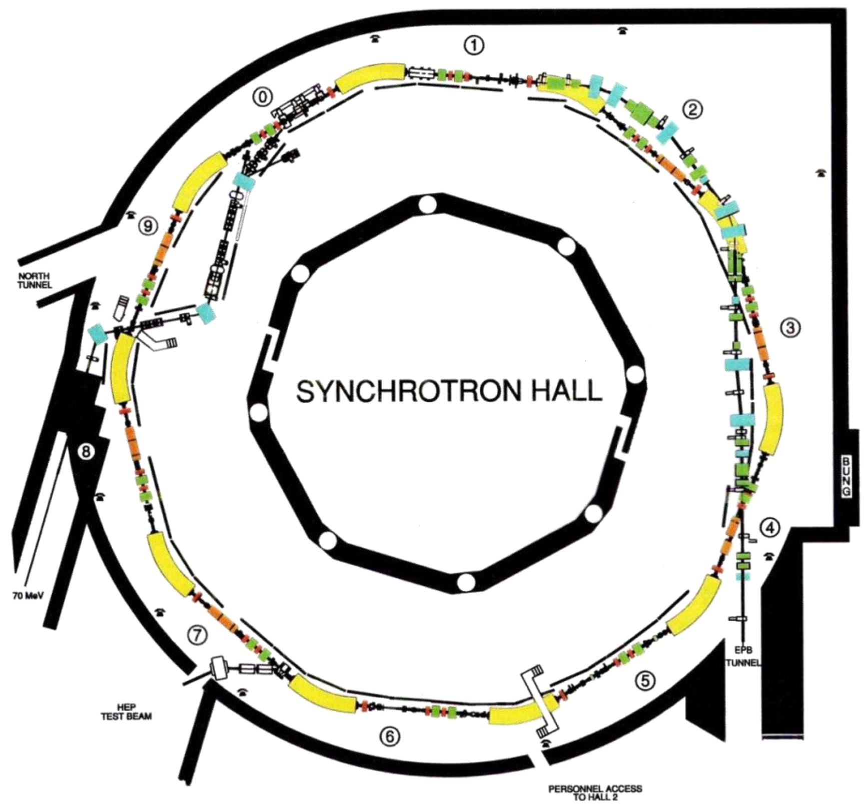
What lies behind the statistics

date	failed dipole	spare coils upper/lower
03/10/13	SP4	5/4
19/11/13	SP3	4/3
24/11/13	SP4	3/3
01/02/14	SP2	2/3
27/05/14	SP9	1/3



Dipole recovery – SP3

SP3 dipole failure - 19th November 2013 - Continued

Dipole 3 (yellow magnet) buried underneath the elevated section of EPB1 and EPB2
(Viewed from the outer side of the synchrotron)

View of Dipole 3 (yellow magnet) from the inner side of the synchrotron

R4QC singlet (22nd November 2013), R3QC singlet (24th November 2013) & SP3 doublet (1st December 2013) bus bar sparking damage - various images

Dipole recovery – SP4

R4QC singlet (22nd November 2013), R3QC singlet (24th November 2013) &
SP3 doublet (1st December 2013) bus bar sparking damage - Continued

SP3 doublet magnet bus-bar damage

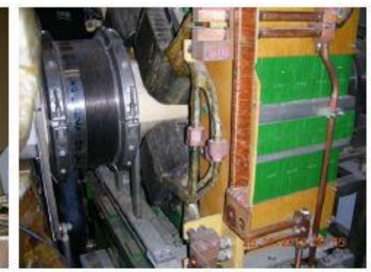
SP3 doublet bus-bars replaced with cable

Dipole 4 failure - upper coil - (new design) - 24th November 2013

View of Dipole 4 with failed top coil removed showing beam pipe curvature and some superficial spark damage to vacuum vessel.

R3QC - Super period 3 singlet quadrupole failure - 24th November 2013

Top view of R3QC quadrupole singlet magnet

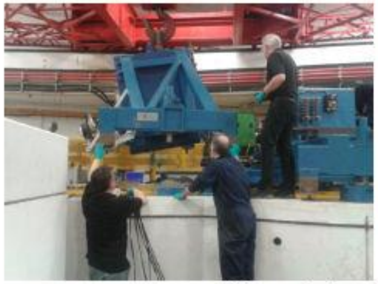


Lower right coil failure on R3QC

Spark damage to R3QC windings

R3QC damage to upper left windings

Dipole recovery – SP2



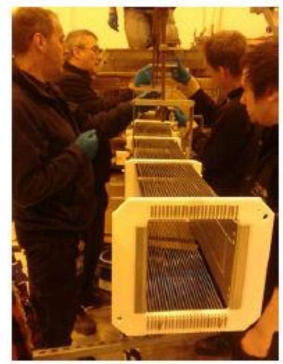

EPB magnet elements being removed

Dipole 2 removed

Damage to Dipole 2 ceramic upon removal

Damage to Dipole 2 upper coil

Dipole 2 disconnected



Inserting Spare Dipole RF Screen

Inspecting the finished RF screen assembly

Dipole 2 being lifted

Dipole 2 showing winding water connections

Spare Dipole being craned in

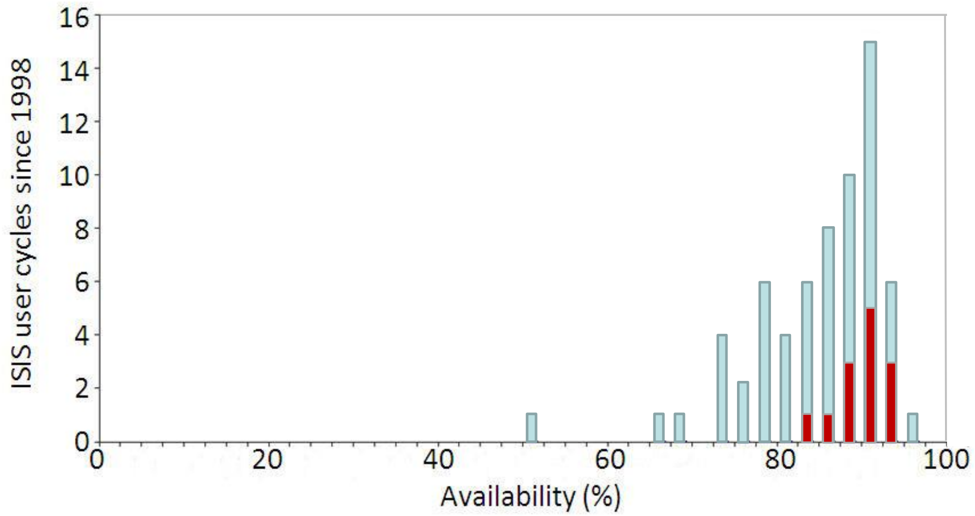
Spare Dipole being placed

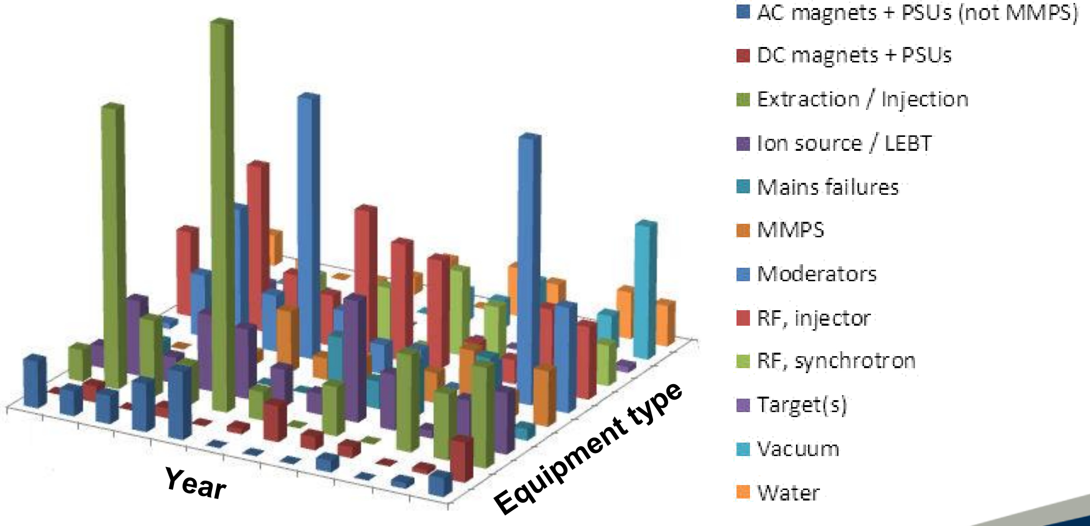
Aftermath

- Difficult work over a sustained period carried out under strong time pressures with radiation doses to staff that need to be carefully managed
- Additional active waste to be dealt with
- Significant unexpected post-mortem and redesign work
- Worryingly low stock of spare upper coils with at least 12 month lead time on getting more (now have ‘full’ spares stock, but are tendering to replace entire inventory with a new design re-introducing mica layers in insulation)
- Have had to run parts of some user cycles at 700 MeV (rather than usual 800 MeV) and introduce much stricter regime for Main Magnet Power Supply run-up/run-down in order to protect the coils

Availability

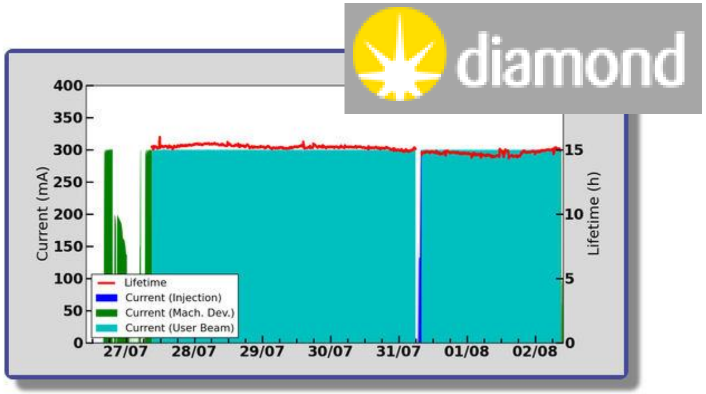
- It is vital that we maintain the confidence of our user community
- Need to target available effort and resource at improving (variability of) availability





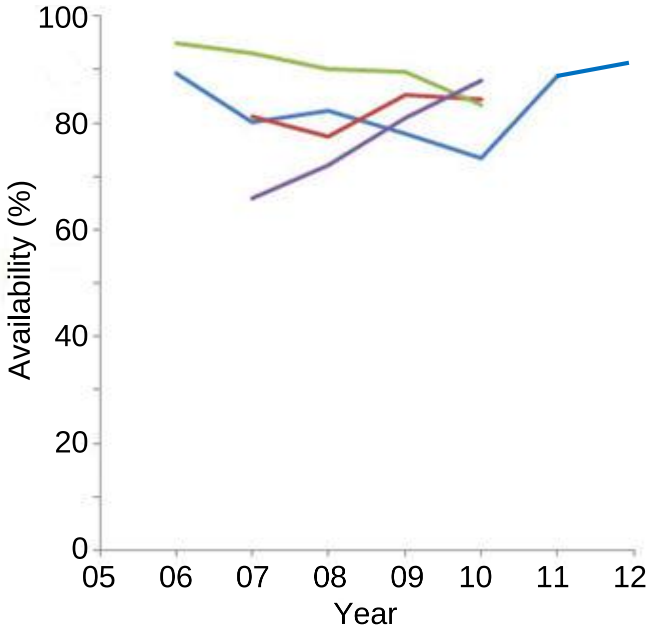
- Analysing trends and predicting problems is non-trivial

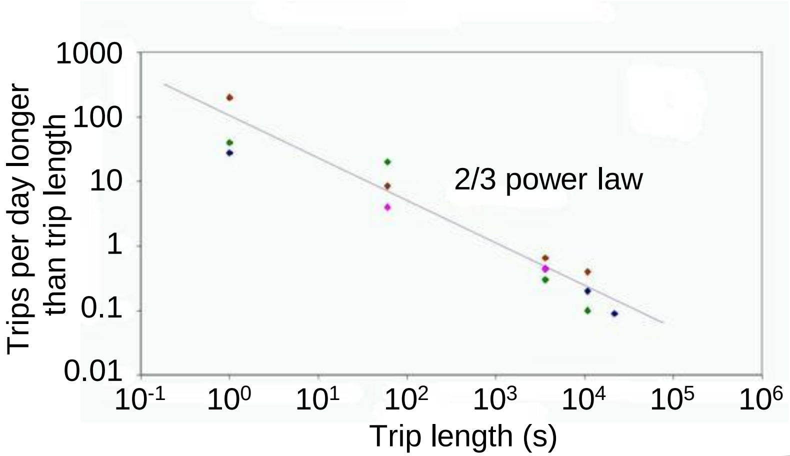
Availability



- The ISIS accelerator performs comparably with similar machines worldwide (and should not be compared with synchrotron light sources or the LHC)

- *"In the period following TS1 the LHC was operating for about 80% of the total scheduled time, with only 20% of the time spent recovering from faults. This is an outstanding result for a machine as complex as the LHC…"* - LHC report 11 Jun 2016





If it can go wrong…

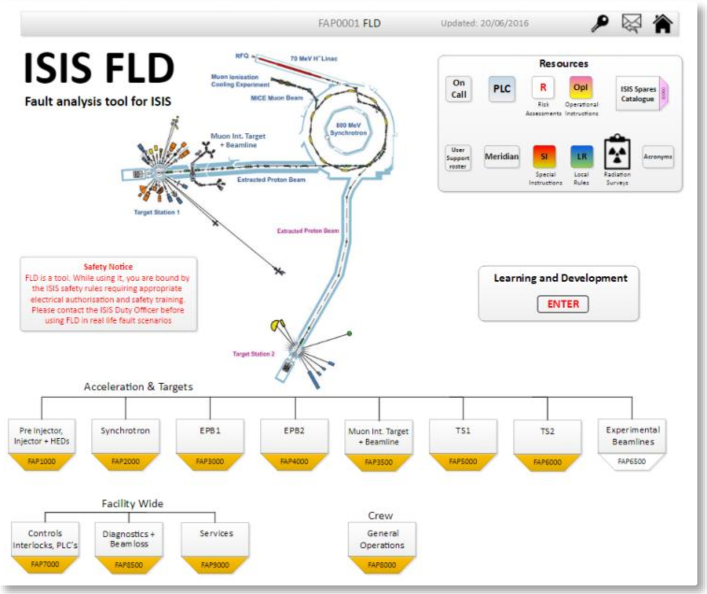
- Rabbits/rats gnaw through cables
- Lightning strike on site/facility input transformer
- Swan flies into power lines
- Unexplained power brown/black-out from National Grid
- Contractors step on and break deionized water feed
- Water / vacuum leaks
- Flooding of tunnels due to rise in water table
- High ambient temperature compromises cooling
- Finger trouble / human error / new staff under training
- Things that ‘never go wrong’ go wrong
- Site emergency
- Newly installed kit cannot be fully pre-tested off-line

- Limited lifetime of components cannot always be dealt with by maintenance regime
- Components catch-fire/explode/fail/radiation-damage
- Network failure crashes controls system
- Diagnostic failure (e.g. target thermocouples) leads to danger of ‘flying blind’
- PPS challenged
- HSE inspection into something else (e.g. asbestos)
- Terrorist attack / act of God / sabotage / plane crash / epidemic disease

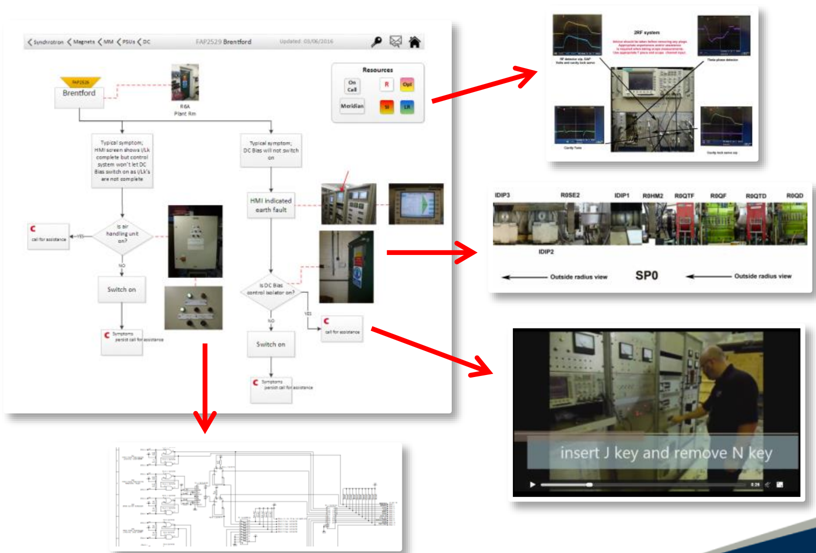
Achieving > 90% availability: short term, immediate response

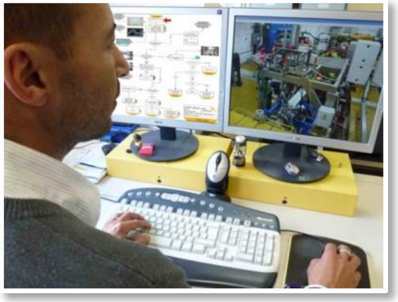
- Maintaining 32 years of skill & knowledge
- ISIS breaks down and needs fixing
- Always unforeseen circumstances
- Fault-finding required just to stand still
- A limit of crew specialist knowledge
- Skilled engineers at a premium
- Recruitment and retention ongoing process
- Training constantly required

FLD: part of the solution



- Fault analysis software tool
- Available to crew site wide 24/7
- Content supplied by equipment owners
- Fault pathways for analysing faults
- Access to specialist information
- Helps increase availability





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Achieving > 90% availability: medium term maintenance

ISIS Maintenance Period Work-list

1^{st} – 28^{th}* August 2016

INJECTOR

Task/Title of work	Proposed dates	Responsible person	Comments
Debuncher Feedline investigate window	4^{th} Aug	JL	
Tank 2 o ring vacuum leak repair	2^{nd} Aug	JL/GM	
Tank 4 Vac check (recent blip)		GM	
Mod 4 timing crate		PAH/SRS	
Mod 1 & 2 enclosure modification	1^{st} →	SRS & Sect.	Contract & electrical support
Mod 4 303 maintenance		Linac Sect	
Mod 1 tune up / 4616 change		Linac Sect	
RFQ Tune up		Linac Sect	
Mod 3 cleaning		Linac Sect	
Remove cathode modulator water from M1		Linac Sect	
Fit 40kV volt meters		Linac Sect	
Interlock checking	28^{th} August	Mark A.	Requires ion source operational please !
Install new heat exchanger for Mod 4	1^{st} - 5^{th}	S. Morse	No RF water to Mod 4
New PM9 installation.	17^{th} Aug	Alex Pertica / Tony Kershaw	Pre-alignment required against the rails system frame.
Work on Injector BLM Argon system	2^{nd} – 12^{th}	Tony Kershaw	
Check oil level/condition on injector rotary and all roughing pump	3 Aug	SP	
Test operation Tank 3 roughing pump	3 Aug	SP	
Test RGA operation all Tanks	3-5 Aug	SP	
Test HEDS pump 1 operation	4 Aug	SP	

SYNCHROTRON / EPB1 & 2

Task/Title of work	Proposed dates	Responsible person	Comments
Run RF systems/LOI HPD in synch	15^{th} – 28^{th}	A Seville	Water and all necessary ILKS required!
JEMA connection to system 2	1st	NF/DG	all necessary ILKS required
Liquid Resistor tests	1^{st} Aug	AS/RM	Access to cavities & running them up/down
HPD servicing – 1RF2, 1RF8, 1RF9, 2RF5, 2RF6 drain down, 1RFHPD5 service, 1RF8 inspection	WC 8^{th}	DG	
HPD servicing – 1RFHPD6 service, 1RF9 inspection, IRFHPD7 service, 1RF2 inspection	WC 15^{th}	DG	
HPD servicing – 2RFHPD2 service, run up all RF equipment	WC 22^{nd}	DG	
Hall 2 patch panel connections			
Replace the egg flow meters on the bat cave panel	15^{th} – 26^{th}	P Masterson	
Break into the main magnet circuit to install the tee pieces and valves for the adiabatic upgrade	1^{st} – 14^{th}	D Couchman	Must be finished on the 14^{th} to allow RF work!!
Replace SP7 flow panel	1^{st} – 14^{th}	S.Lees	No water supply to SP7
Replace SP8 flow panel	15^{th} – 26^{th}	P.Masterson	No water supply to SP8
Flush extract septum 1	16^{th} – 18^{th}	P.Masterson	Septum 1 water off
Install water supply for new steering magnet SP3	17^{th} – 18^{th}	P.Masterson	No trim quad/ steering magnet water SP3
Install Vacuum port in shutter void ventilation	17^{th} Aug	G.Field / P.Masterson	Shutter void ventilation off
R80 process water glycol fill	22^{nd} – 25^{th}	P.Masterson	R6 link plant off, not EPB2 magnet / PS water
Upgrade E1Q1 power supply from 200A to 300A including new supply cable	Flexible (1 week)	A Black	
Install new Musr power supply including new supply cables	1^{st} – 5^{th}	A Black	
Choke oil top up, clean & inspection	25^{th} & 26^{th} August	S Reeves	Dependant on new DC bias switch on / testing date
Coil Clamp checks	24^{th} Aug	Jim Loughrey	
Air sampling equipment set up	8th Aug	Jim Loughrey	
EPB Position monitor install	15^{th} Aug	Jim Loughrey	
Check vibration on K2 magnet	15^{th} Aug	Jim Loughrey	
Commission EPB1 MOLs	1^{st} - 28^{th} Aug	Tim Carter / Andy Sanders	Requires access to EPB1 & EPB1 PSUs to be switched off/on.
Upgrade inner sync water panel interlocks SP7 (possibly SP8)	1^{st} - 28^{th} Aug	P Masterson / Tim Carter	Cannot run / test MMPS during this time.
Confirm correct operation of North Tunnel EPB1 water panels during devicenet fault.	1^{st} - 28^{th} Aug	Tim Carter / Andy Sanders	Will require EPB1 PSUs to be switched off.
Measure injection dipole magnet temperatures, resistance and inductance	1^{st} and 4^{th}	J Ranner	
Measure trim quad currents	15^{th}	J Ranner	Needs water
Modify MMPS control system for new DC Bias PSU	8^{th} and 9^{th}	J Ranner	
Trim Quad Power Supplies. Maintenance & Calibration	1^{st} – 28^{th} Aug	M Julian / B Orton	
Extract Kickers Maintenance	1^{st} – 28^{th} Aug	M Julian/ J Tydeman	
EC Muon Kicker Installation	1^{st} – 28^{th} Aug	M Julian	
HEDS Chopper Install	1^{st} – 28^{th} Aug	M Julian/ B Orton	
MMPS Danfysik DC Bias Commission	23^{rd}- 28^{th} Aug	S West	
New double position monitor installation next to EPM26 or EPM26A.	18^{th} Aug	Alex Pertica	
Replace Scintillators in Dipole 2	15^{th} – 26^{th}	Tony Kershaw / Alex Pertica	Being done at end of shutdown when Rad levels lowest

*Should aim to be finished by 16:30 on Friday 26^{th} Aug

Achieving > 90% availability: long term sustainability

Long shutdown work

Main magnet capacitor bank

Collector straight replacement

Radio frequency quadrupole

Second harmonic RF

Downstream EPB1 and muon target collimator

EPB2

Linac tanks 2 and 3 deep clean

Synchrotron re-cabling

Downstream EPB1 and beam entry window

2001 2002 2003 2004 2005 2006 2007 2008 2009 2010 2011 2012 2013

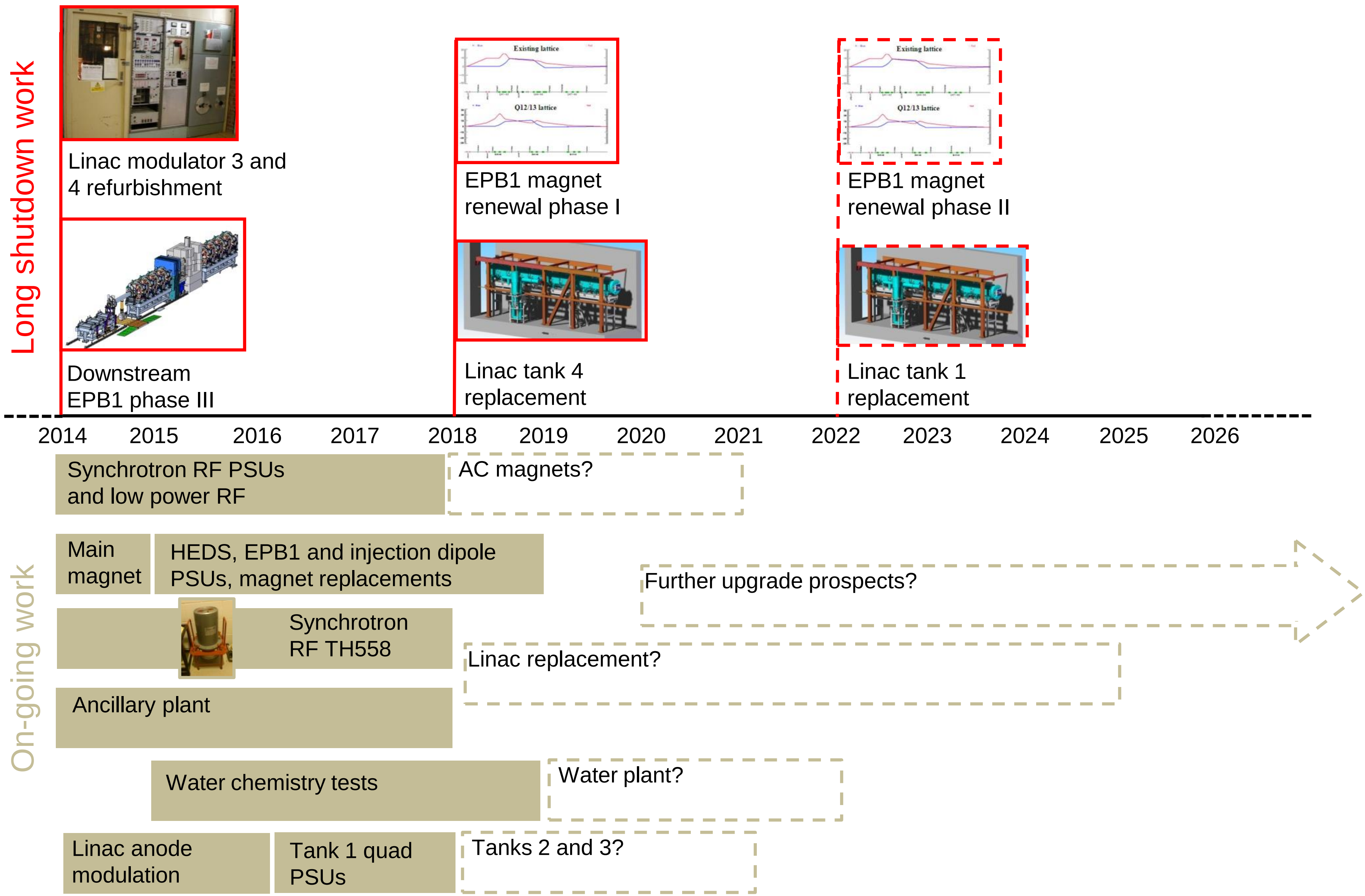
On-going work

Synchrotron RF PSUs

Main magnet chokes and DC PSU

Trim quad and steerer PSUs

Linac anode modulation


Long shutdown work
Linac modulator 3 and 4 refurbishment
Downstream EPB1 phase III
Existing lattice
Q12/13 lattice
EPB1 magnet renewal phase I
Linac tank 4 replacement
Existing lattice
Q12/13 lattice
EPB1 magnet renewal phase II
Linac tank 1 replacement
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023
2024
2025
2026
On-going work
Synchrotron RF PSUs and low power RF
AC magnets?
Main magnet
HEDS, EPB1 and injection dipole PSUs, magnet replacements
Further upgrade prospects?
Synchrotron RF TH558
Linac replacement?
Ancillary plant
Water chemistry tests
Water plant?
Linac anode modulation
Tank 1 quad PSUs
Tanks 2 and 3?

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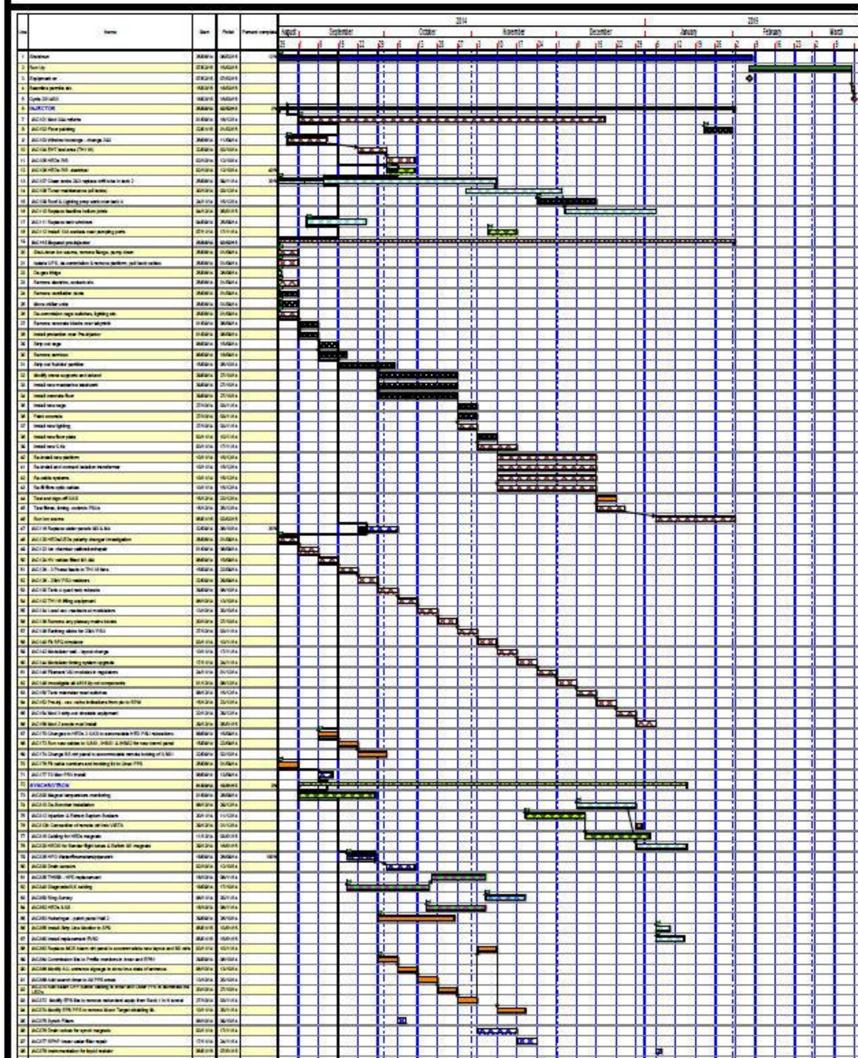
2014 Long Shutdown

ISIS



Drawn by: Mike Krendler	Programme Number: Progress 1	Comment:	Date : 16/09/2014

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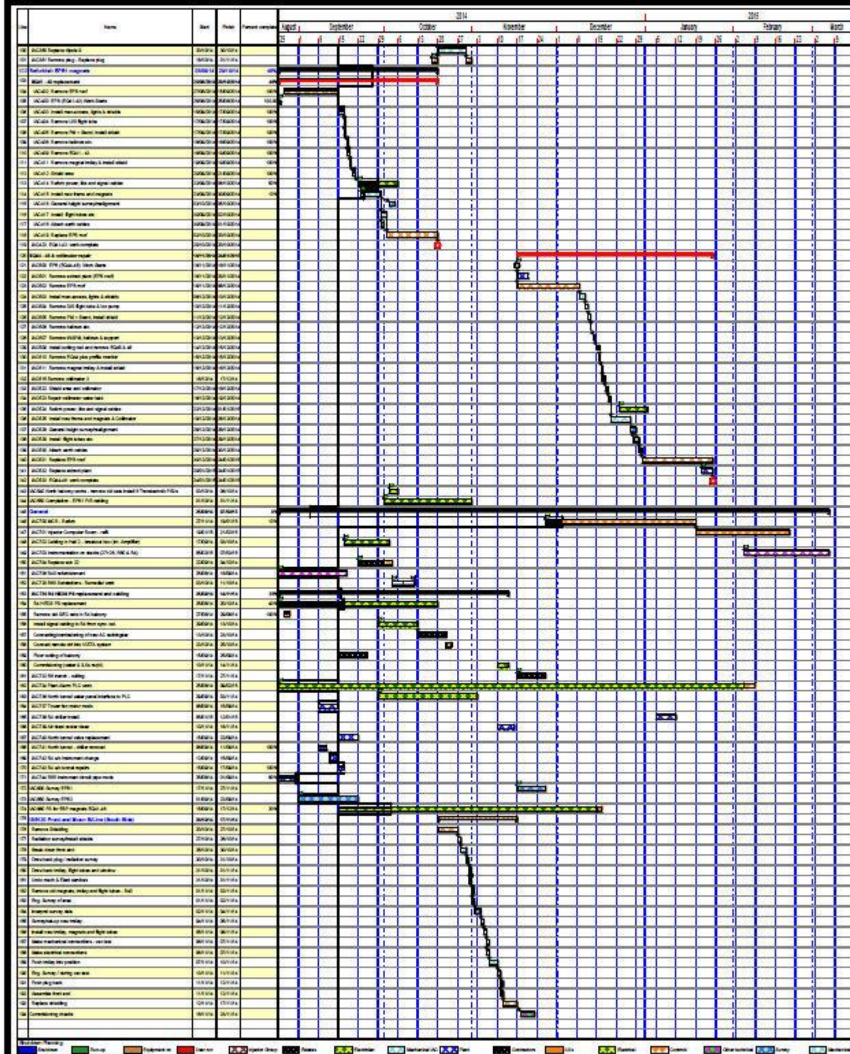
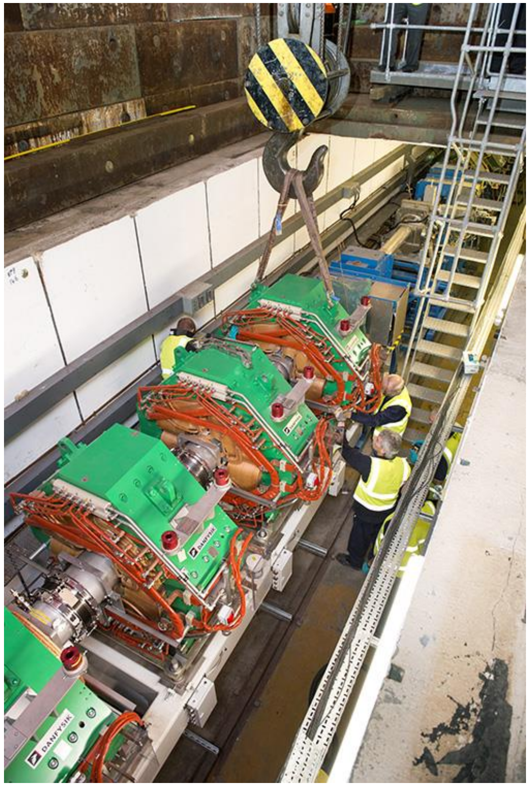
2014 Long Shutdown

ISIS



Drawn by: Mike Krendler	Programme Number: Progress 1	Comment:	Date : 16/09/2014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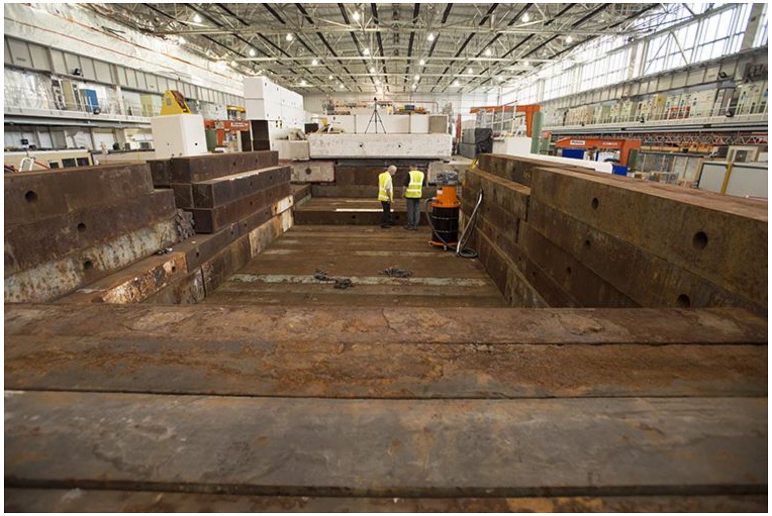
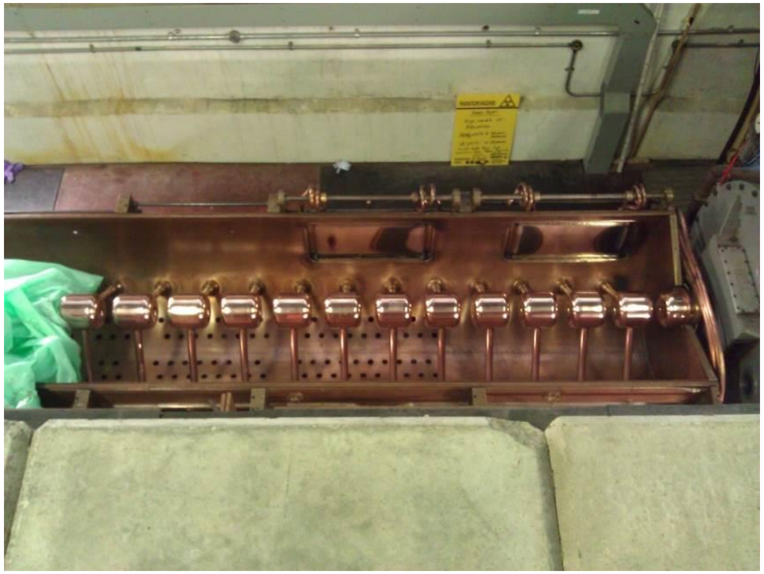
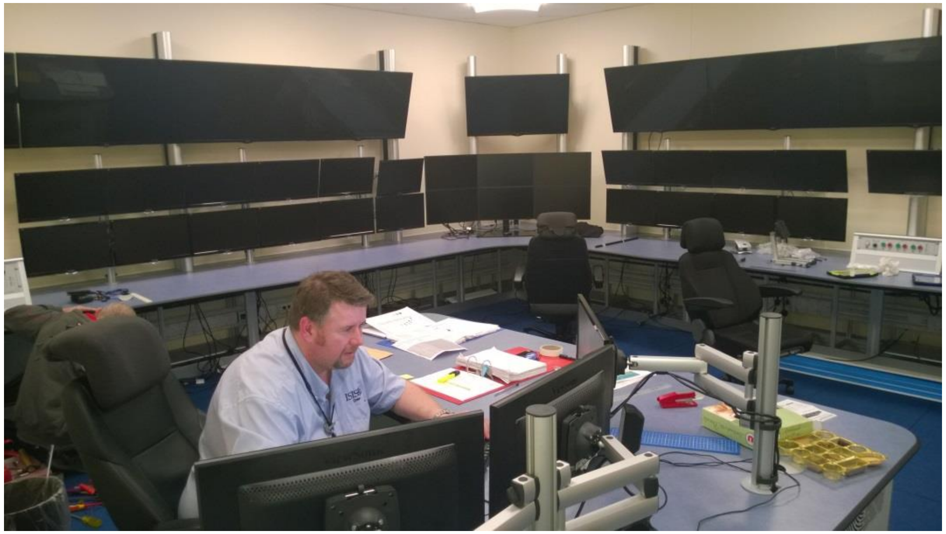
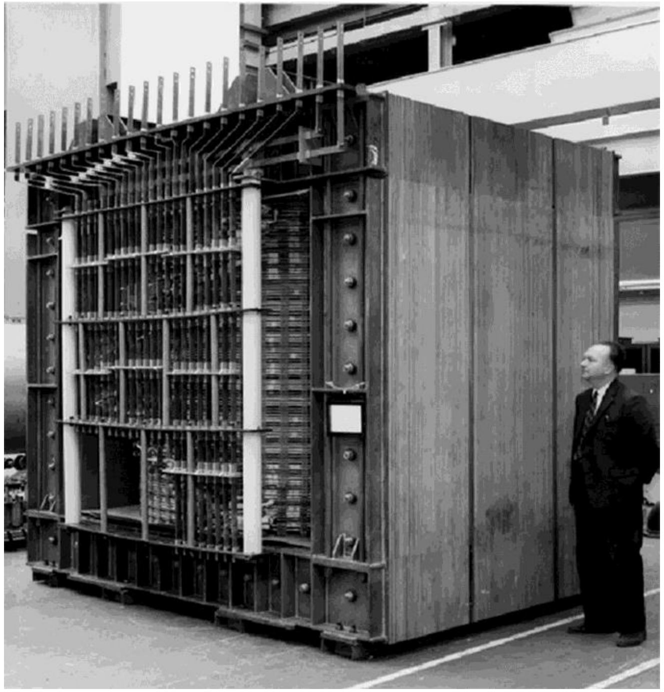





THE VAUGHAN CRANE

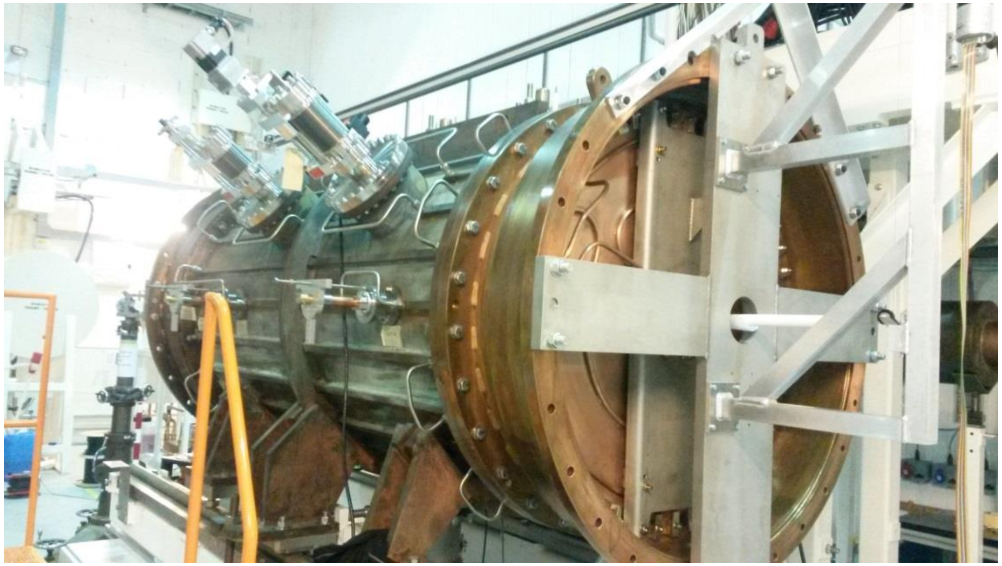


Main Magnet Power Supply



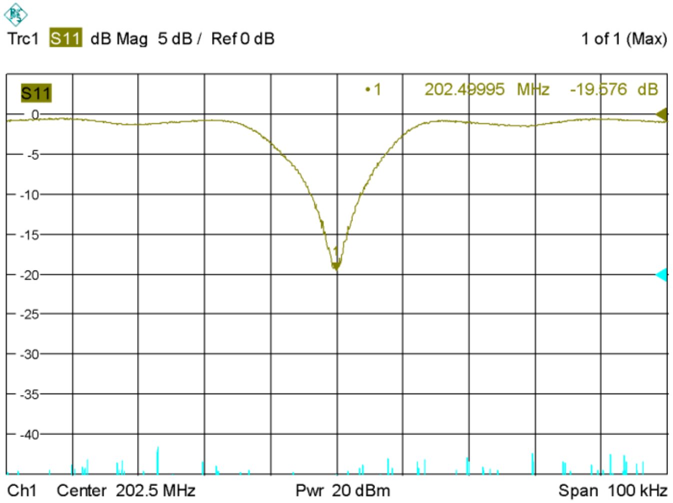
www.richannel.org/powering-a-particle-accelerator

Tank IV replacement



The 1/6 length Tank IV test vessel is complete and the first RF measurements have been made.

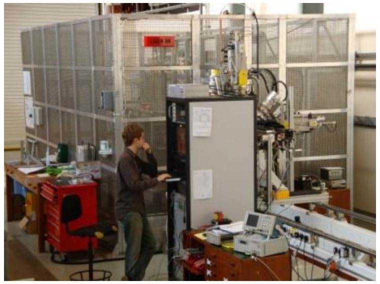
The un-tuned frequency was correct to 2 parts in 100,000.



The tuning mechanisms operated exactly as designed and brought the vessel on tune at 202.5 MHz.

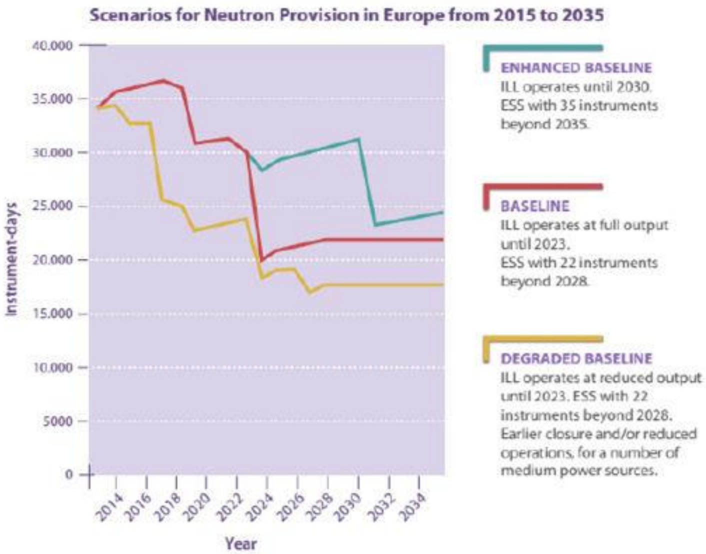
Test facilities

- Whenever possible ISIS downtime from commissioning new equipment should be minimised by using suitable off-line test rigs
- Direct effect on availability




ISIS upgrades

- We have been looking at upgrades to ISIS for many years, but now is a good time to refocus given the advent of ESS, but impending ‘neutron drought’ in Europe



- ESFRI Physical Sciences and Engineering Strategy Working Group Neutron Landscape Group - Neutron scattering facilities in Europe: Present status and future perspectives

- ISIS-II Working Group has been set up, and consists of experts from accelerator, target, neutronics, instrument science, detector and engineering. *Important to stress that this must be envisaged as a facility upgrade, not simply an accelerator upgrade*

- Seven meetings held so far, working from ‘ideal instrument suite’ backwards looking at all aspects of the facility. Intention is to report optimised recommendations to the ISIS Facility Board in December

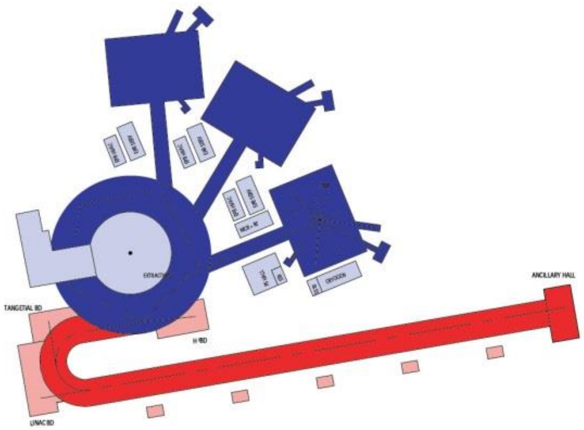
- Multiple day-one target stations, variety of repetition rates, FFAG options and muon production all important topics of discussion

- Looking at:

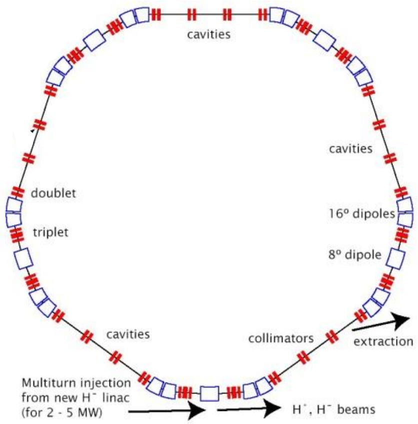
  1) Stand alone facility
  2) Maximum reuse of ISIS infrastructure
  3) Compact neutron sources

Upgrade scenario 1)
1 - 2 MW, upgradable, higher power option

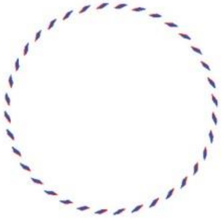
- Stand alone only option
- Provision for multiple optimised targets (3+?) with different powers, repetition rates, *etc.* dependent on user requirements
- Ideally upgradable depending on future needs to 5 or even 10+ MW (using *e.g.* stacked RCS rings)
- Some options:
  – 0.8 GeV superconducting linac + 0.8 - 3.2 GeV Rapid Cycling Synchrotron, baseline machine now under detailed study
  – Fixed Field Alternating Gradient machine could be an important alternative (ASTeC Intense Beams Group), smaller, lower injection energy, higher efficiency and reliability, but will it work at high intensity?
  – Higher energy linac + accumulator ring



0.8 – 3.2 GeV RCS



0.4 – 3.2 GeV FFAG



Upgrade scenario 1)
1 - 2 MW, upgradable, higher power option

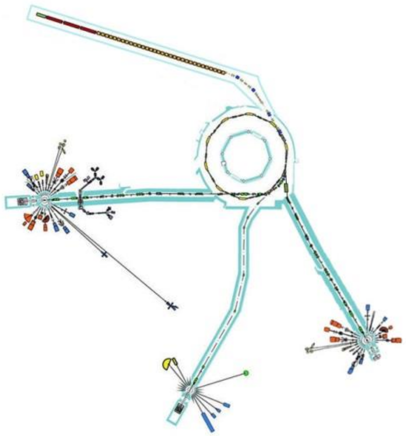
- Essential to undertake corresponding high power target/neutronics studies, maintain dialogue with the user community and iterate with accelerator studies

- Should be designed (and sold) on the basis of scientific output, *not* 'my accelerator is bigger than yours'

- Ideas to study:
  - can we design upgradeable facilities without making them much more expensive?
  - can we save power, reduce costs?
  - would smaller and cheaper with optimised targets be a better fit to the funding envelope and ultimately be better for the community…

Upgrade scenario 2)
0.5 MW lower power option

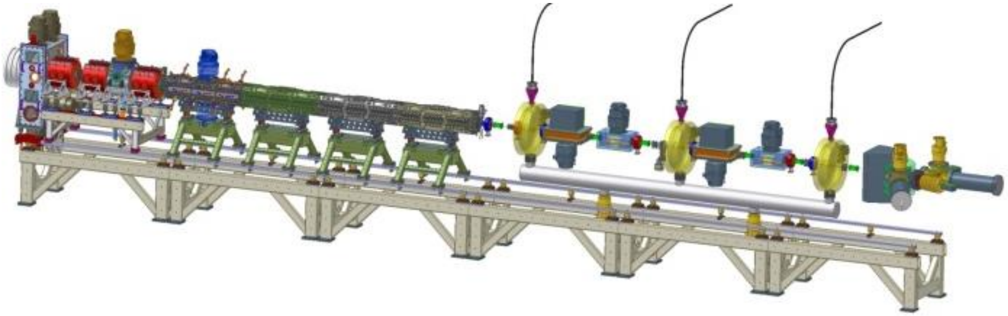
- 180 MeV linac replacement now a well studied, well understood option, but shouldn’t base a new facility on a 30+ year old RCS
- Could be baseline for a new stand alone facility
- Or could house completely new accelerator within existing ISIS infrastructure (provided we can tolerate the consequent off-time)
  - Probably cheapest possible option
  - Only ISIS-II option that guarantees the facility stays in the UK (and at RAL)
- Look at FFAG alternatives (ASTeC Intense Beams Group)
- Know that there are effective target options available in this regime, but again need to optimise fully
- May choose multiple optimised targets even at 0.5 MW



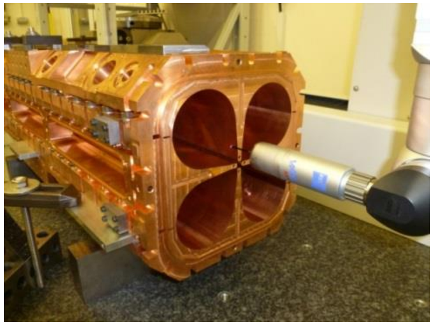
Compact neutron source

- Recent interest in a compact short pulse option with proton energy in the range 14 – 20 MeV

- Could be an extension of the Front End Test Stand in R8 at RAL, which is likely to be handed over to ISIS at the end of Programmes Office funding in 2017

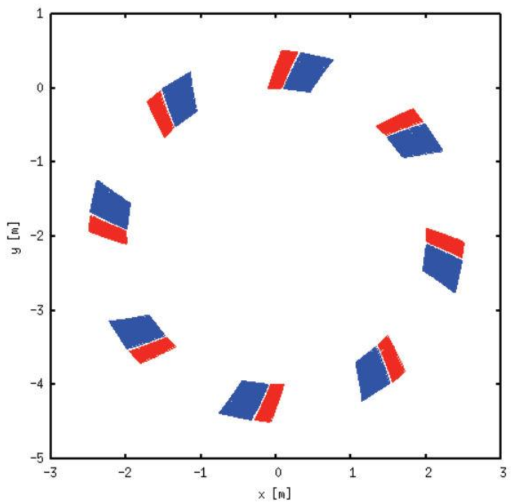


- Other alternative uses (e.g. fusion materials irradiation, single event effect testing with protons) could be considered, but should not be allowed to detract from a unique opportunity to do accelerator development towards ISIS2



Compact neutron source

- Look at FFAG alternatives (ASTeC Intense Beams Group) to take output from FETS (3 MeV) directly to required energy and pulse structure
  - Ties in with Paul trap experiment being set up at RAL by ASTeC IB
  - Study high intensity beam dynamics to establish whether FFAGs are really a possibility for ISIS2
  - Prototype relevant components



Type	DF-Spiral
Kinetic energy	3 - 27 MeV
Pex/Pin	3
Cell number	8
Packing f	0.31
Spiral angle	20
Field index	3
Orbit excursion	0.48 m
Rex/Rin	2.1 / 2.6 m
Bmax@orbit	1.7 (1.9) T
Straight	1.1 m

- Lower risk (but less interesting) alternative is warm DTL to required energy, followed by an accumulator ring.

- Should be used to allow us to demonstrate technology readiness in areas we are not covering under another banner (ISIS sustainability, other UK proton R&D).

Technology readiness

Staffing	Currently have strong leadership in most areas, but would need to retain this and hire lots of new engineers. Could we get them on STFC salaries?
Simulation codes	Lots of expertise and optimised codes within ISIS, ASTeC and universities.
Ion source, RFQ, MEBT, chopper	Covered by FETS programme.
Warm DTL	Tank IV replacement, 4616 and TH116 replacements in hand.
SC Linac	ASTeC efforts towards ESS and engagement with PIP-II at Fermilab should put UK in a much stronger position.
Stripping foils	Recent investigations of carbon foils are encouraging.
Vacuum	Nothing particularly new required, recent efforts to re-establish production of ceramic vacuum vessels, interest in new methods of RF screening at J-PARC and CSNS.
Large AC magnets	MMPS replacement, lots of recent work on dipole coils(!), important to re-establish manufacture of large AC magnet yokes, but hope to cover under sustainability programme.
DC magnets	Lots of expertise built up within ISIS, also on PSUs.
Synch RF	Transition to TH558 going well, watching brief on MA cavities.
Pulsed magnets	Lots of expertise built up within ISIS, but retention of staff has become an issue
Diagnostics	ISIS is world-leading in many areas.
Collimation	Recent HL-LHC work.
High power beam dumps, target windows, etc.	Probably OK.
FFAG magnets, injection and extraction, RF systems	Need to design, prototype and build a real system to give sufficient credibility to pitch for this as a high-power solution.

Summary

- ISIS availability of >90% is generally achieved and satisfies the expectations of our user community, but we need to paddle very hard just to stay still, with concentration on short, medium and long term strategies and enough resource to back them up
- ISIS availability is limited by the age of some components and the design of others, but engineering and design solutions cannot remove every possibility for unscheduled downtime
- Good people and good training are essential
- Future plans are essential to continued neutron provision in Europe beyond 2030