Status of Diamond Light Source and Diamond-II

Richard Fielder
on behalf of the Diamond team

30th European Synchrotron Light Source Workshop
14/12/2022

Talk Outline

1) Diamond Status:
   - Operations
   - IDs
   - RF
   - Zepto quadrupole
   - Energy and efficiency

2) Diamond-II Status:
   - Lattice update
   - Commissioning
   - Diagnostics
   - Injection
   - Timeline

3) Conclusions

Diamond Light Source

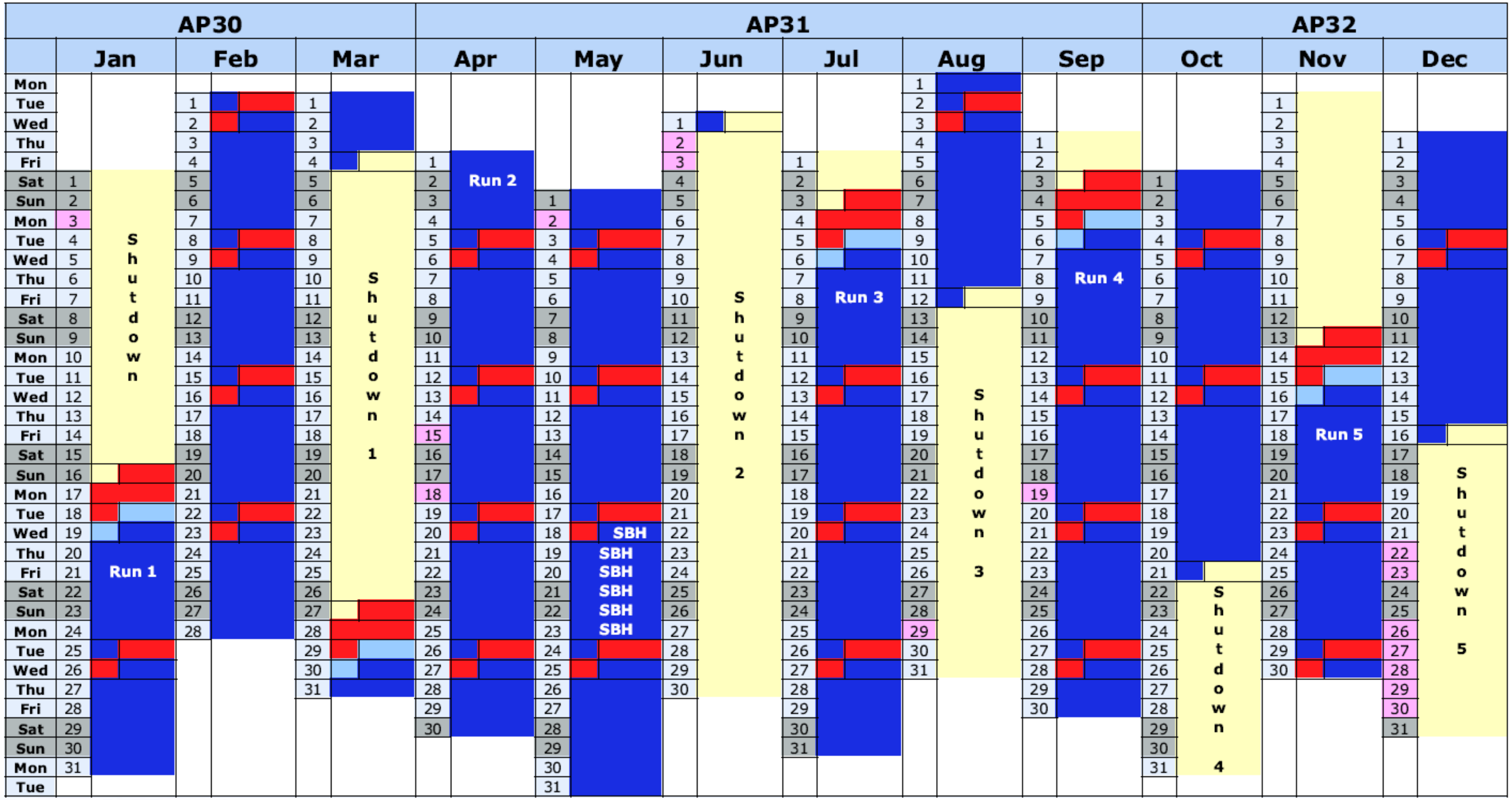
Diamond Operational Statistics

Courtesy C. Bailey

Back to standard operating schedule (4776 user hours)

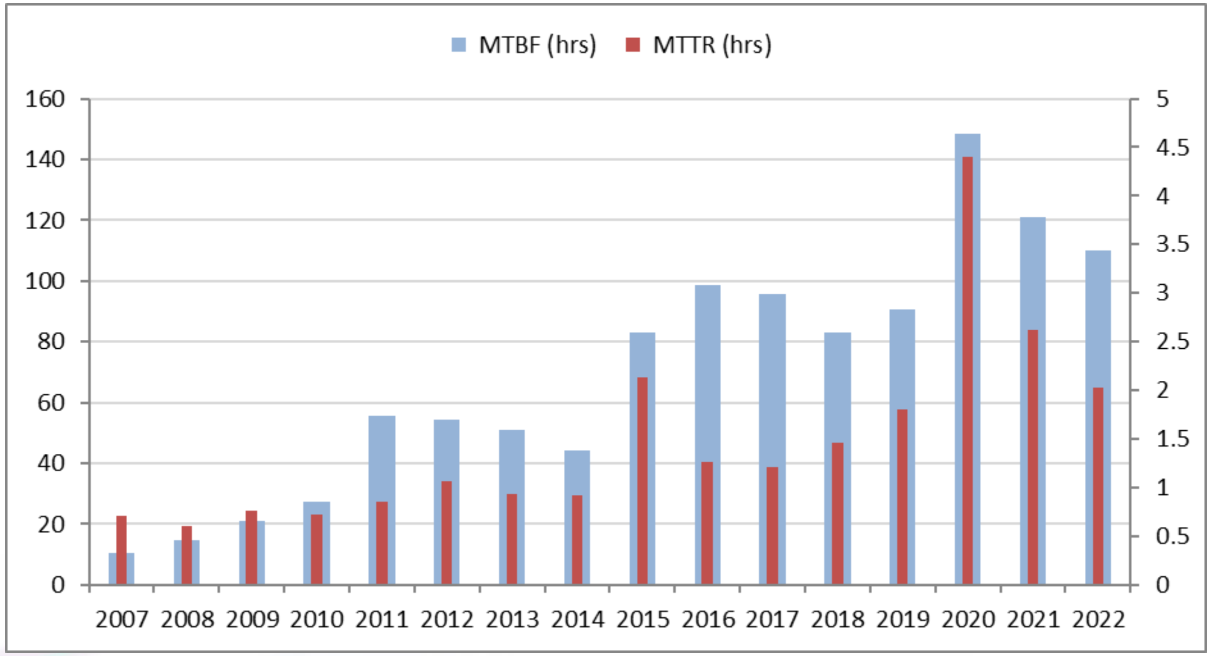
Few requests for non-standard operating conditions, just one week single bunch hybrid

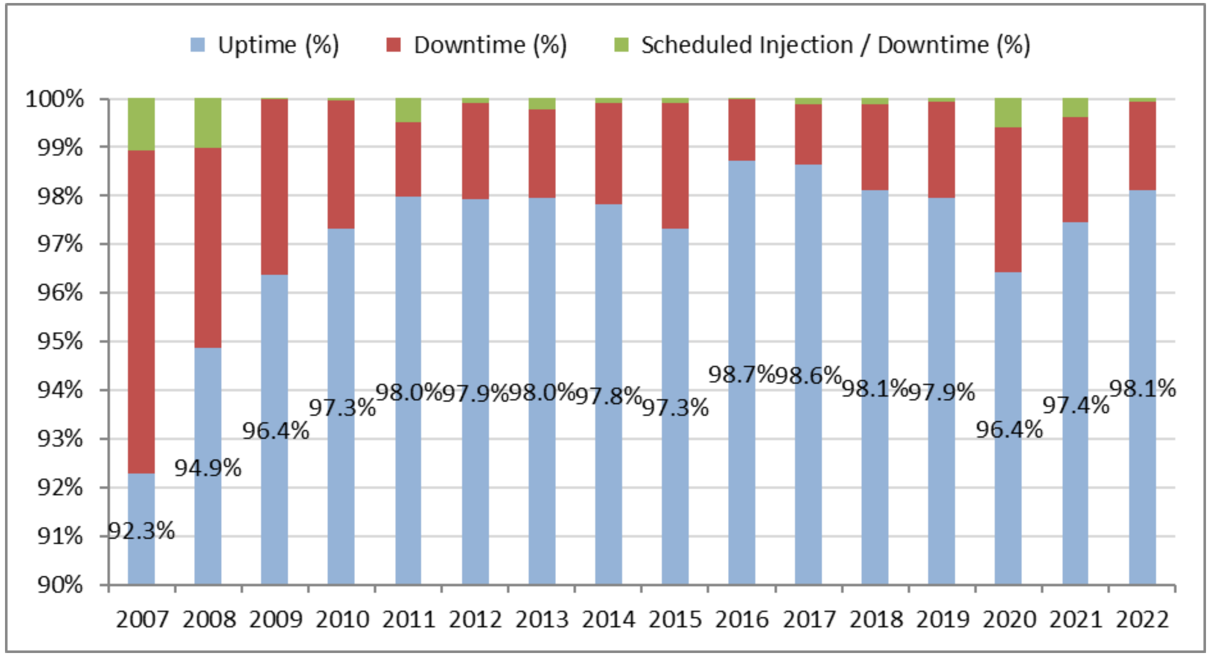
Low alpha request next year for first time in 4 years



Diamond Operational Statistics

- MTBF 116 hrs & 98.3 % uptime after 4416 hrs - 360 hrs to go at time of compilation
- Comparable to last year, higher MTBF than pre-pandemic
- MTBF decreasing, MTTR decreasing - correlation with return to site or just coincidence?





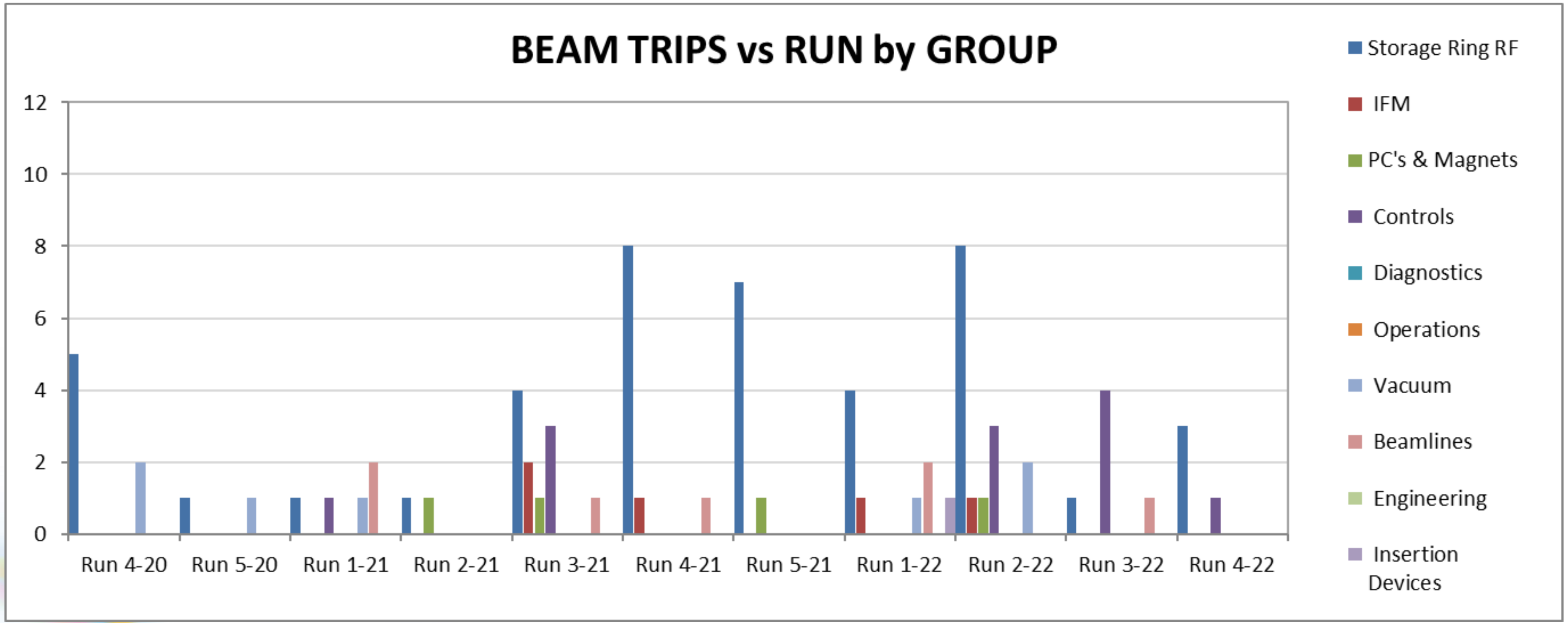
- (As of 12/12/22 MTBF = 113 hrs)

Diamond Operational Statistics

Longest trips:

- Difficult RF reset after power dip, 4.67 & 4.2 hrs
- Drop in water flow to magnet, 4 hrs
- Repairs to Beam off Button Lamps, 2*3.5 hrs
- Cryo-plant trip due to compressed air failure, 3.5 hrs

RF (mainly IOTs) remains most frequent cause of trips



Diamond Covid Response

At time of last ESLS workshop, staff were moving back to office with 2 m spaced desks, masks at all times, PCR and LFT testing on site

As of 13/12/21 all staff advised to work from home where possible

From 31/01/22, staff to resume working on site

Three phase roadmap for relaxing controls:

Phase 1 from 08/03/22 - building swipe access controls relaxed, temperature checking not required

Phase 2 from 01/04/22 - user number limits removed, room occupancy limits removed (spacing remains), masks only required in high-throughput areas, PCR testing no longer done on site

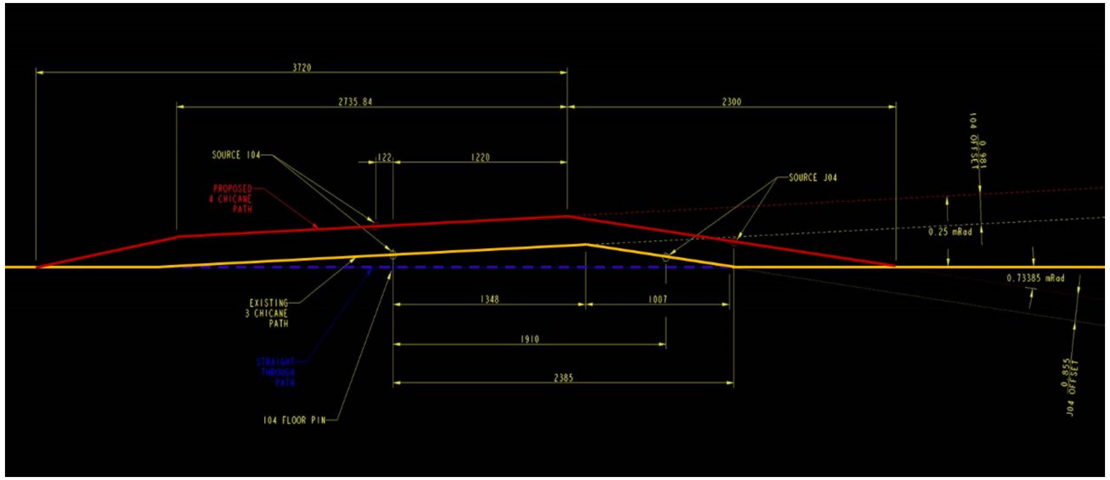
Phase 3 from 03/05/22 - most restrictions lifted, masks not required in most places, spacing requirements lifted, in-person events resume

Flexible WFH with approval, desk spacing and improved ventilation mostly remains in place, LFT tests available for staff

Many meetings still Teams/Zoom for convenience and due to limited meeting space

Diamond Insertion Devices

Courtesy Z. Patel



New IDs installed in straight 04, replacing existing in-vac ID with CPMU and 0.6m ex-vac with 1.5m HPMU

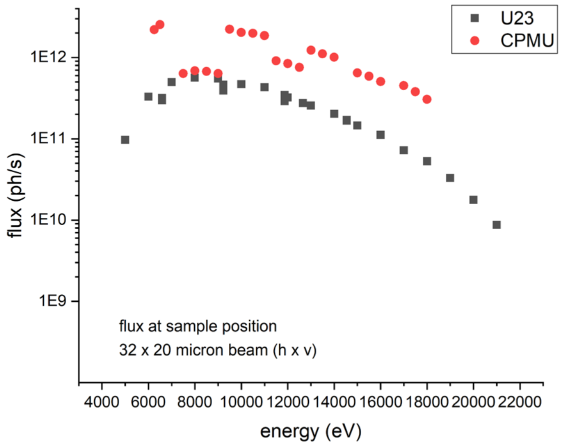
Downstream girder swapped – BPM/valve moved to make space for longer ID

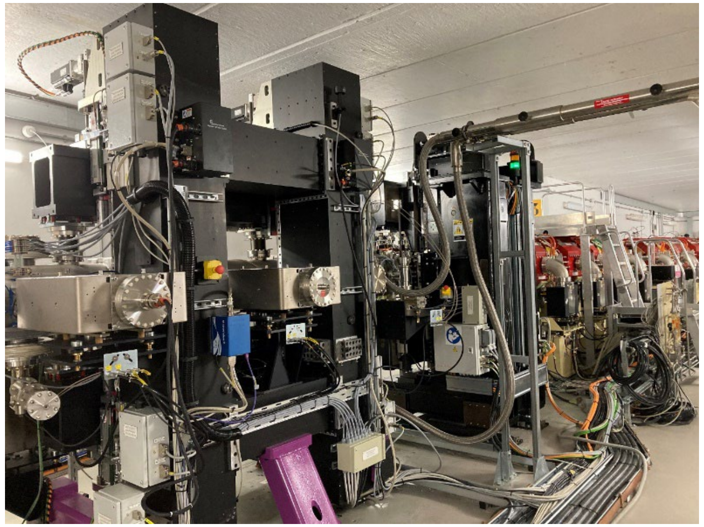
4-chicane bump to allow re-use of existing 3 chicane magnets despite larger angle required

Large effort from many groups to install and commission in normal length shutdown

CPMU-4 designed, built, and measured in-house
17.6 mm period, 2 m long, 113 periods
Beamline report 5 times more flux compared to previous device

HPMU-1 procured from Kyma. 19.7 mm period, 1.5 m long, 78.5 periods
Beamline report 9-10 times more flux





Diamond Insertion Devices

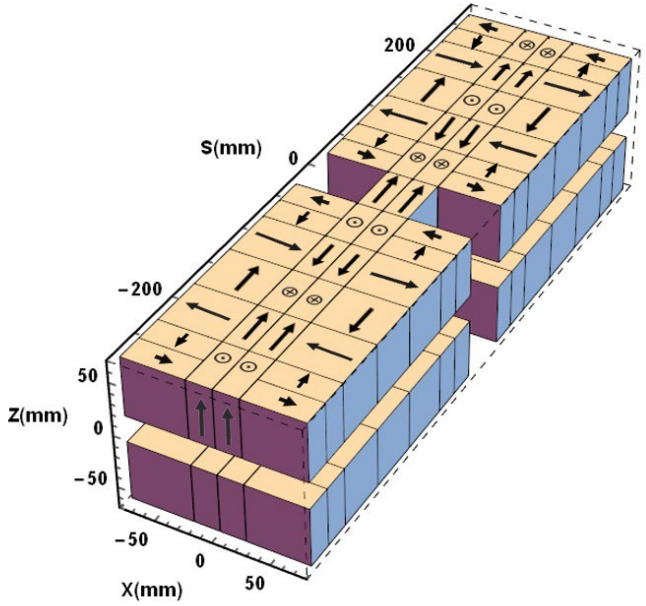
CPMU-3 installed January 2022 to replace CPMU-1 that was installed March 2020. Issue with foil buckling when cooled with CPMU-1. Foil tension increased in response, may not have solved problem
Both 17.6 mm period, 2 m long, 113 periods

CPMU-1 is being reworked and will be installed next year for I11 instead of the SCU ordered from Budker Institute

CPMU-5 is being built and will be installed next year for VMXm (replaces J02)

Working on an APPLE KNOT design for beamline I05 to reduce heat load on the front end and beamline optics at lower photon energies

Paper in Review of Scientific Instruments:
https://doi.org/10.1063/5.0081034

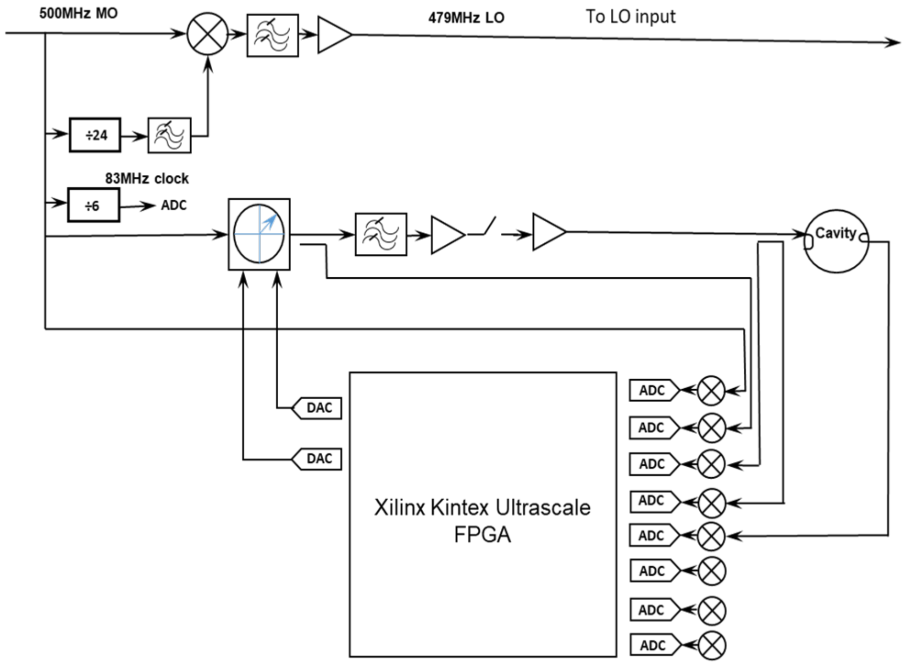


New 3 m long measurement bench (Hall probe & flipping coil) designed, built and commissioned in-house

Diamond RF

Courtesy C. Christou

Solid state amplifier installation is progressing
- 120 kW SSA in storage ring (Cryoelectra) - one NC cavity
- 60 kW SSA in booster (Ampegon) - second cavity for resilience
- 80 kW SSA in RF Test Facility (Ampegon)



SLED cavity installed in linac
- Flexible LLRF allows arbitrary pulse compression to be generated
  - 2 x power multiplication with 1 µs flat top for multibunch
  - > 5 x power multiplication with spike for single bunch

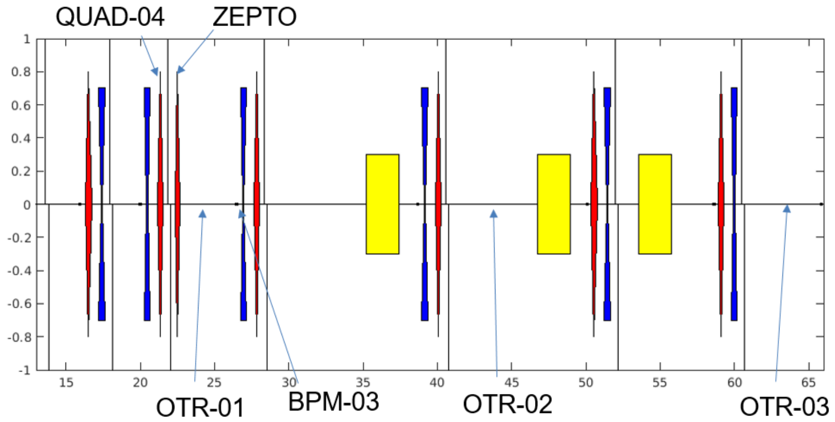
Digital low-level RF installed with all Solid State Amplifiers
- Also installed on IOT-driven NC cavities

Second generation of DLLRF has been developed
- Replacing unwieldy front ends with MTCA RTF modules

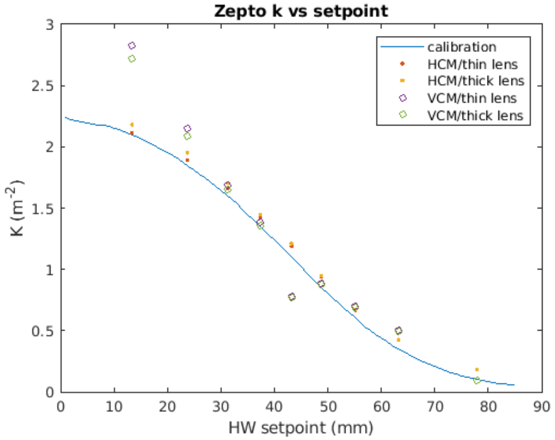
ZEPTO Quadrupole

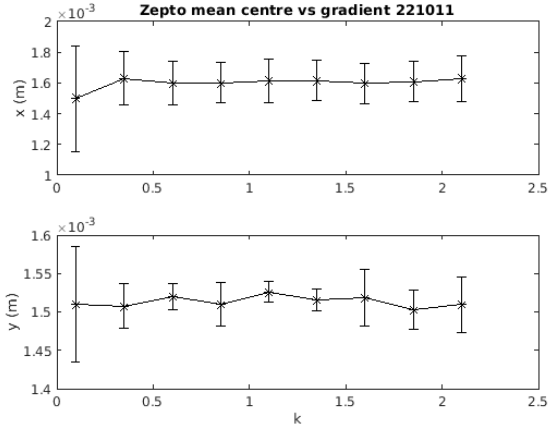
ZEPTO (Zero Power Tuneable Optics) permanent magnet quadrupole developed at STFC Daresbury
Wide tuning range using moveable permanent magnets on fixed yoke - large potential energy savings

Installed in Diamond BTS, with quad-04 turned off



Ongoing measurements of gradient, magnetic centre, etc.





Parameter	
Magnetic length	300 mm
Good field region	10 mm radius
Max gradient	22.7 T/m
Min gradient	0.3 T/m

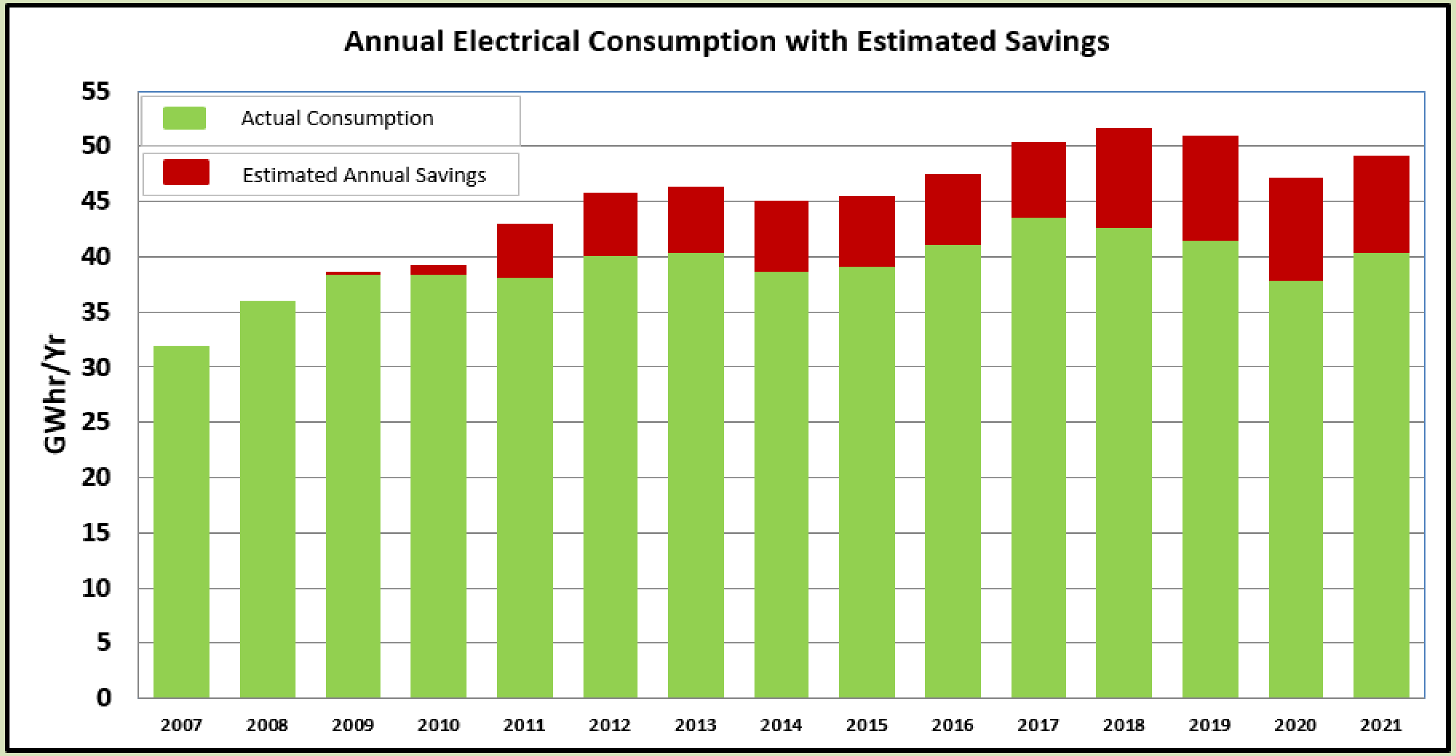
See Bainbridge et. al, doi:10.18429/JACoW-IPAC2022-THOYSP1, doi:10.18429/JACoW-IPAC2021-TUPAB365

Diamond Energy and Efficiency

- Variety of efficiency measures developed since start of operations - greatest savings from lighting improvements and variable speed drives
- >20% savings compared to predicted costs without measures in place
- Currently replacing experimental hall lights and some offices with LEDs
- Increased ventilation for Covid reduces some gain from air handling

Courtesy P. Coll

System	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Light Sensors/Lighting Enhancements	£10,896	£36,322	£89,798	£117,234	£117,234	£117,166	£117,166	£117,166	£141,967	£231,704	£235,973	£266,847	£266,847
Reduction in AHU Operational Hours	£15,603	£31,207	£81,502	£81,502	£81,502	£81,502	£81,502	£81,502	£68,076	£68,076	£68,076	£0	£0
Variable Speed Drive Installation		£793	£209,153	£243,202	£246,911	£254,444	£254,444	£254,444	£357,763	£385,594	£424,646	£546,384	£546,384
Solar Power					£10,878	£10,878	£10,878	£10,878	£10,878	£10,878	£10,878	£10,878	£12,488
Others :													
DH Tx re-tapping			£3,046	£3,046	£3,046	£3,046	£3,046	£3,046	£3,956	£4,300	£4,300	£4,773	£4,773
UPS Replacement					£3,029	£30,294	£30,294	£30,294	£39,343	£39,343	£39,343	£43,671	£43,671
Chiller Efficiencies									£50,000	£100,000	£100,000	£100,000	£100,000
Free Cooling Activation									£20,822	£54,317	£54,317	£60,292	£60,292
Adiabatic Cooling													£12,000
Total Annual Savings	£26,500	£68,321	£383,500	£444,984	£462,601	£497,330	£497,330	£497,330	£692,806	£901,723	£946,655	£1,032,844	£1,046,453
Day/night Averaged Electricity cost (p/kWhr)	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	10.0	10.0	10.0	11.1	12.0
Est. Actual Annual Electricity Costs (exc. Tariffs)	£3,817,627	£3,825,325	£3,789,207	£3,990,495	£4,025,224	£3,852,500	£3,894,061	£4,088,914	£4,349,900	£4,259,700	£4,144,300	£4,205,064	£4,848,000
% of Savings v Actual Cost	0.7%	1.8%	10.1%	11.2%	11.5%	12.9%	12.8%	12.2%	15.9%	21.2%	22.8%	24.6%	21.6%



Diamond Solar Panel Installation

Two small existing solar panel installations on roof of booster (since April 2013) and Active Material Building (since June 2021) providing 134 kWp total

New installation currently in progress on synchrotron building roof

Phase 1 with 1 MWp

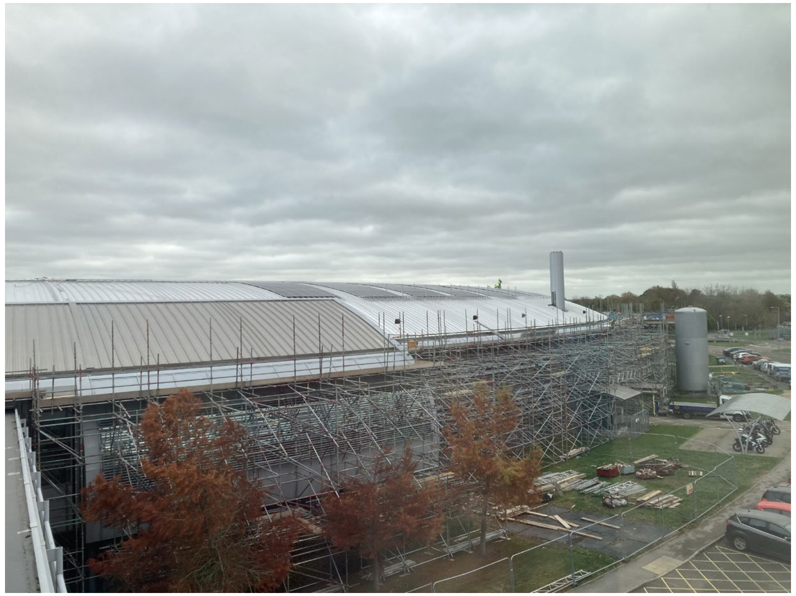
Phase 2 additional 1.7 MWp approved as modification of existing contract

Due to finish May 2023

~5 % of Diamond's power use

Location	**Installed capacity**	**Generated Power (per year)**
Booster Roof	100 kWp	80,000 kWh
Active Material building	34 kWp	27,000 kWh
Currently being installed:		
Synchrotron Roof	2.7 MWp	2.3 GWh

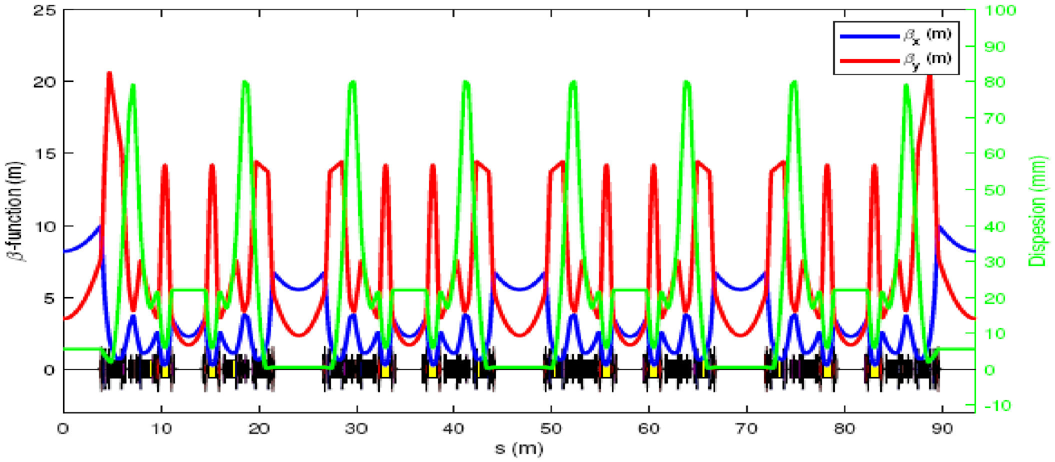
Diamond Solar Panel Installation



Diamond-II

Diamond-II Lattice Update

TDR published October 2022, available for download at - https://www.diamond.ac.uk/Diamond-II.html
Lattice as described at ESLS 2021



Parameter	Units	Diamond @ 3 GeV	Diamond-II @ 3.5 GeV
Circumference	m	561.6	560.560944
Harmonic Number	-	936	934
RF Frequency	MHz	499.654	499.511
Positive bending angle	deg	360.0	374.4
Reverse bending angle	deg	0.0	14.4
Total bending angle	deg	360.0	388.8
Betatron Tunes	-	[27.21, 12.36]	[54.15, 20.27]
Natural Chromaticity	-	[-79.0, -35.6]	[-67.6, -88.5]
Corrected Chromaticity	-	[1.7, 2.2]	[2.0, 2.3]
Momentum Compaction Factor	$\times 10^{-4}$	1.70	1.04
2^{nd} Order M.C.F.	$\times 10^{-4}$	17.6	5.25
Maximum β_x	m	22.7	9.94
Maximum β_y	m	27.0	20.57
Maximum η_x	mm	310.9	80.2
Synchrotron Frequency	kHz	2.29 @ 2.4 MV	1.24 @ 1.42 MV
Natural Emittance	pm.rad	2729	161.7
Effective Emittance in mid-straight	pm.rad	-	237.7
Energy Spread	%	0.096	0.094
Energy Loss per Turn	MeV	1.01	0.723
Natural Bunch Length	ps	11.4 @ 2.4 MV	12.5 @ 1.42 MV
Horizontal Damping Partition	-	1.00	1.87
Vertical Damping Partition	-	1.00	1.00
Longitudinal Damping Partition	-	2.00	1.13
Horizontal Damping Time	ms	11.1	9.67
Vertical Damping Time	ms	11.2	18.08
Longitudinal Damping Time	ms	5.6	16.03
Radiation integral I1	m	0.096	0.058
Radiation integral I2	m^{-1}	0.882	0.342
Radiation integral I3	m^{-2}	0.124	0.019
Radiation integral I4	m^{-1}	-0.001	-0.299
Radiation integral I5	m^{-1}	1.82×10^{-4}	5.76×10^{-6}

Additional changes post-TDR:

Removed transverse gradient from longitudinal-gradient dipoles

Minor changes to BPM and corrector positions for engineering reasons

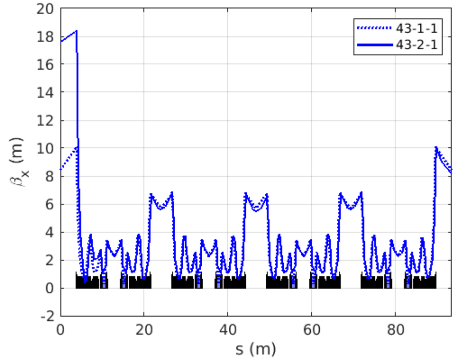
Standalone correctors replaced with octupole at end of long straights (WIP, potential ~10% lifetime increase)

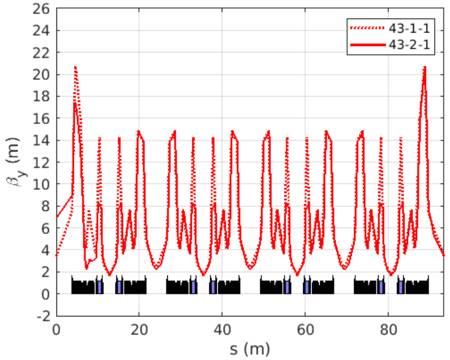
diamond

Diamond-II Lattice Update

Courtesy H. Ghasem

Investigating injection cell with high beta - no new hardware





Parameters	Units	Base line (43-1-1)	Inj. Cell (43-2-1)
Energy	GeV	3.5	3.5
Circumference	m	560.561	560.561
Tune	-	[54. 149,20.269]	[54. 139,20.210]
Beta (x,y)	M	(8.21, 3.50)	(17.62, 7.01)
Nat. emittance	nm	161.5606	164.69
Nat. chromaticity	-	[-68.1,-89.3]	[-68.6, -88.9]
TLT	hrs	1.99±0.14	1.68±0.04
Natural bunch length	mm	3.73	3.73

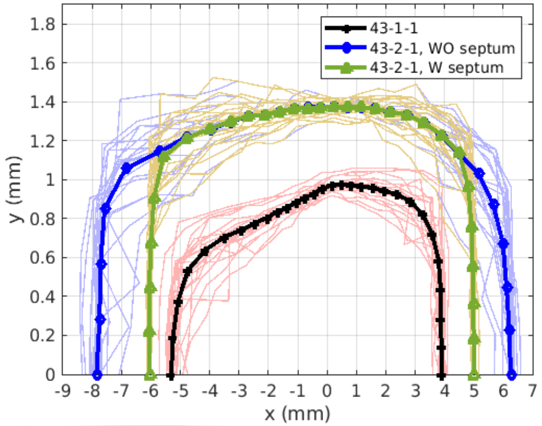
Note: lifetime at natural bunch length, harmonic cavity expected to increase by factor 3-4

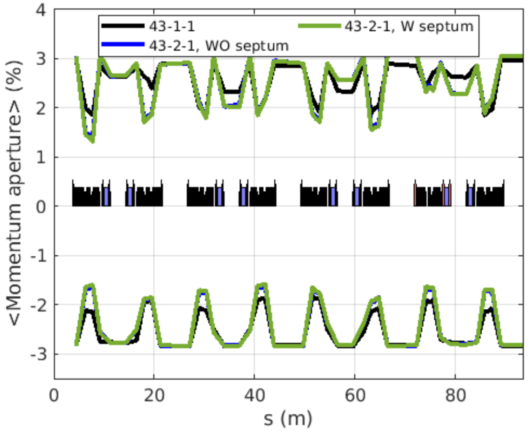
Potential fall-back option in case of injection problems

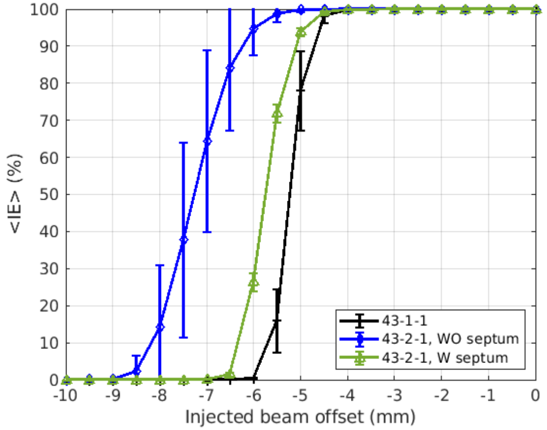
May allow lower emittance lattice options or better Twiss matching at ID source points

Large increase in effective dynamic aperture, but now limited by septum aperture

Significant compromise on lifetime - reduced momentum aperture since phase advance not perfectly matched in injection cell







Diamond-II Commissioning

- Updated errors from TDR
- Reduction in girder misalignment but increase in misalignment of magnets on girder
- Due to more detailed analysis of alignment tolerances by engineering groups (see extra slide)
- Have ordered CMM measurement bench for assessment and comparison with laser tracker system - cost neutral change
  Expected to reduce multipole alignment error from 46.5 -> 38.2 µm

Magnet and Girder Errors

	Misalignment Errors		Relative Field Errors	
	Offset (µm)	Roll (µrad)	Main Field (%)	Secondary Field (%)
Girder	~~150/150~~ **50/50**[1]	150		
DL	100	100	0.05	
Dipole-Quadrupole	~~50~~ **100**	100	0.05	0.10
Anti-bend Quad	~~35~~ **50**	100	0.05	0.10
Quadrupole	~~35~~ **50**	100	0.10	
Sextupole	~~35~~ **50**	100	0.10	
Octupole	~~35~~ **50**	100	0.10	
CM	~~150~~ **70**	150	~~0.10~~ **5.00**	
CM (on sext)				0.10
Skew Quad (on sext)				0.50

Other Error Sources

BPM Errors		
Offsets	500	µm
Roll	10	mrad
Calibration	5	%
Noise (Turn-By-Turn)	60	µm
Noise (Closed Orbit)	1	µm
RF Errors		
Frequency	100	Hz
Voltage	~~0.5~~ **1.5**	%
Phase Offset	90	°
Injected Beam Jitter		
Transverse Displacement	100	µm
Transverse Divergence	10	µrad
Energy Deviation	0.1	%
Phase Shifts	0.1	°
Other Errors		
Circumference	1	µm
Injection Pulsed Magnet Jitter	0.024	%

Diamond-II Commissioning

Courtesy H.-C. Chao

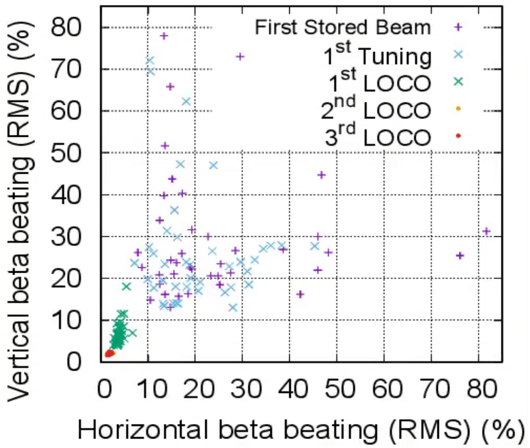
Simulated commissioning based Thorsten Hellert's toolkit

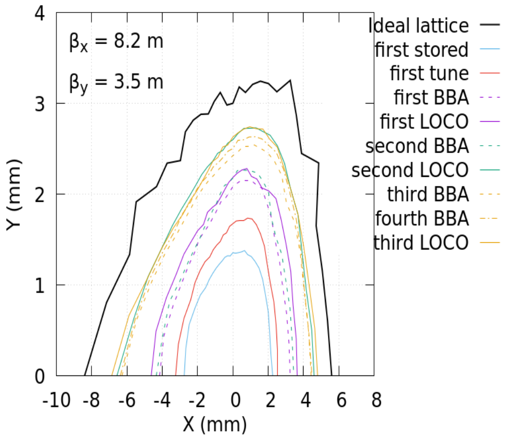
Updated procedure able to work on all error seeds (40) without intervention

Additional octupoles may allow to recover lifetime to TDR values despite larger errors

1. Beam threading
2. RF tuning
3. First tuning (using only 7 quad families)
4. First BBA
5. First LOCO (quads only)
6. Second BBA
7. Second LOCO (include skew quads)
8. Third BBA
9. Fourth BBA
10. Third LOCO* (include anti-bends and DQ)
11. Final tuning* (closed orbit, chromaticity)

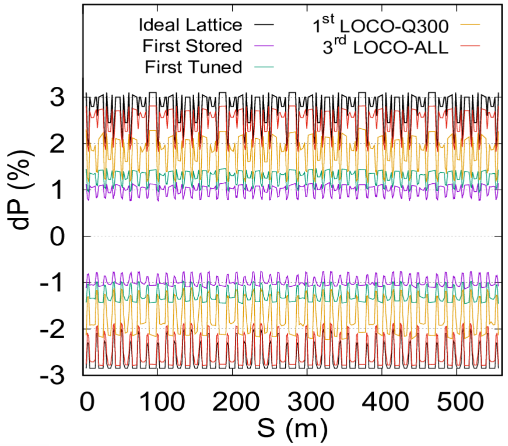
* alternative steps without DQ and AB

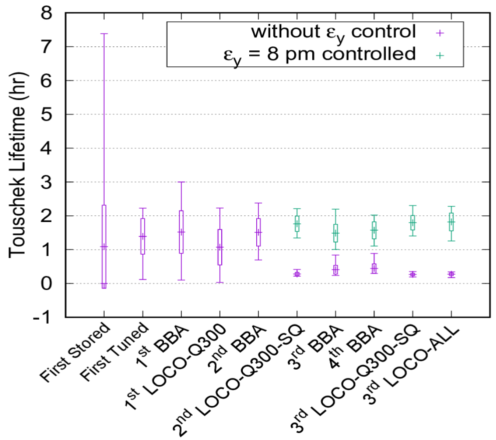




Horizontal dynamic aperture
TDR errors: -6.9 ~ +4.9 mm
New errors: -6.9 ~ +4.8 mm

Average beta-beat @ BPM
TDR errors: 1.0, 1.7%
New errors: 1.8, 2.0%



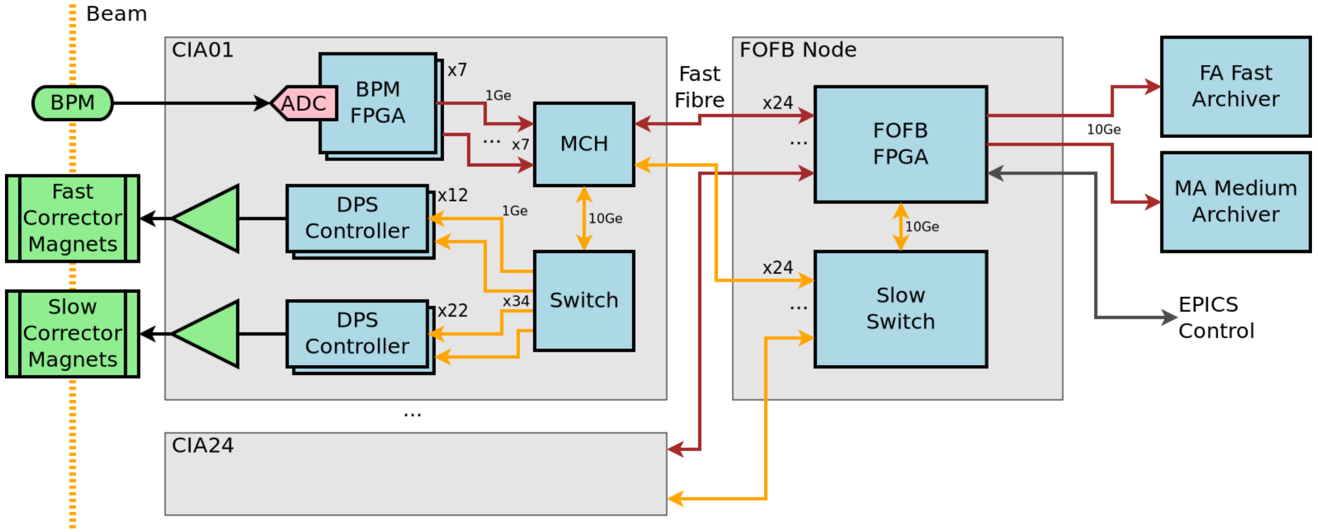


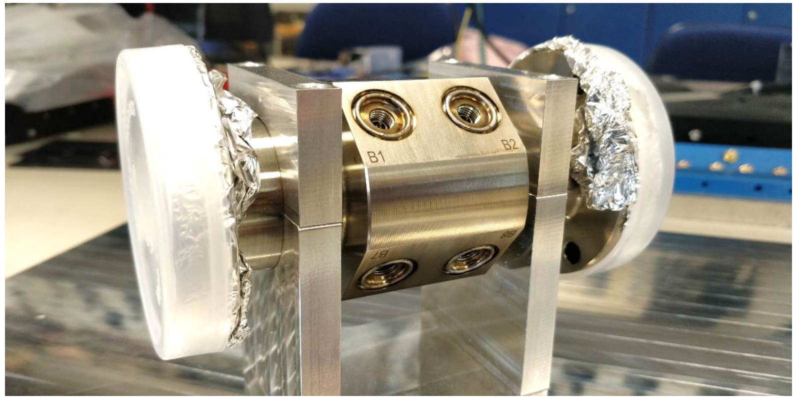
Mean Touschek-lifetime
(without harmonic cavity)
TDR errors: 2.25±0.10 hr
New errors: 1.82±0.26 hr (-19%)

Diamond-II Diagnostics

Courtesy L. Bobb

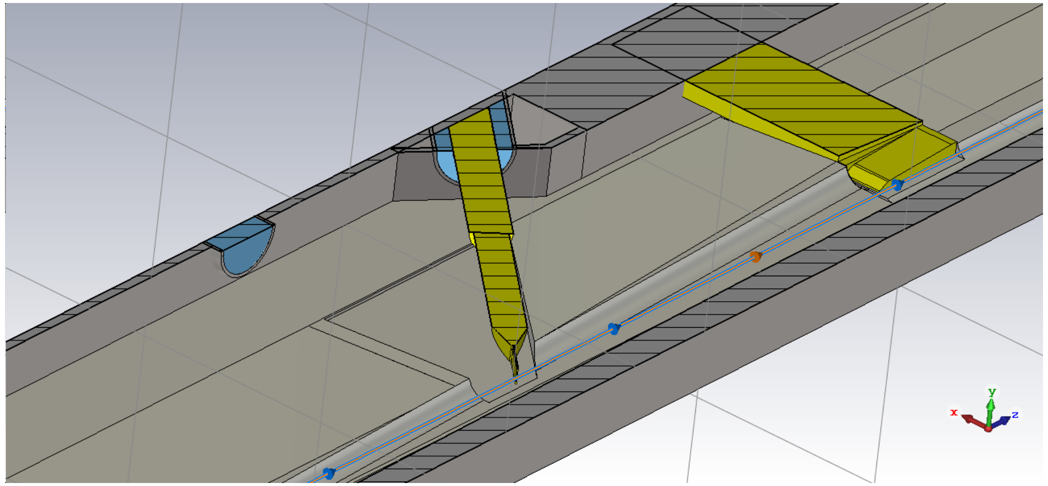
- BPM systems undergoing prototyping – analogue front end with pilot tone compensation
- Fast orbit feedback system - update rate increased from 10 -> 100 kHz, will have two different corrector types operating at different rates





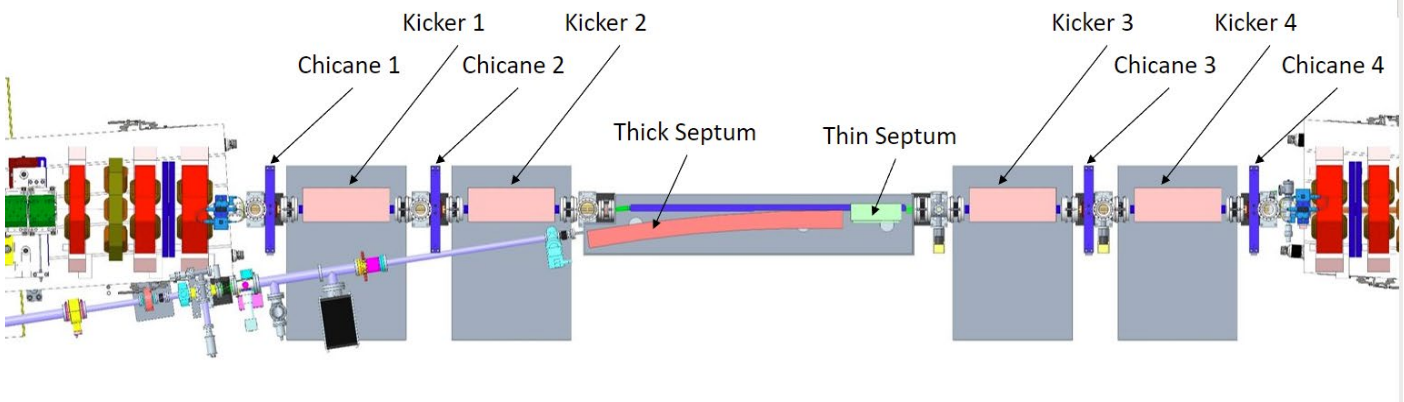
- Front-end x-ray BPMs; will be included in feedbacks
- X-ray pinhole cameras
- Visible light extraction - modified vessel with retractable mirror

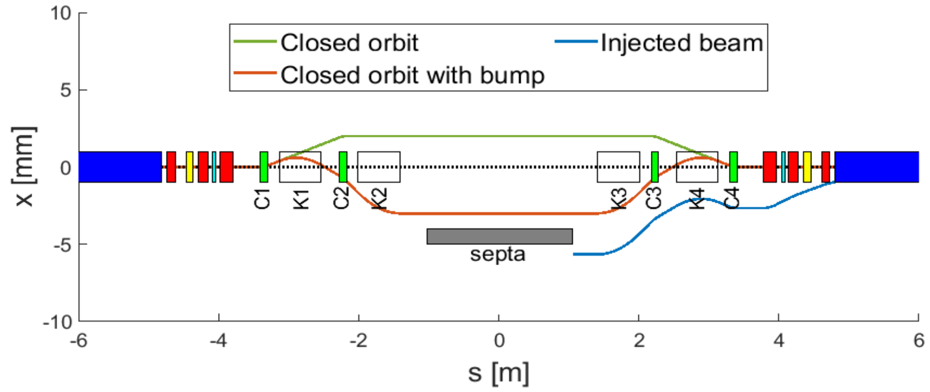
  See L. Bobb talk, FCCee: Diamond-II, 22 Nov 2022



Diamond-II Injection

- 4-kicker bump with thick/thin septum - use for commissioning (on- and off-axis injection)
- Multibunch injection to reach full current faster, but not able to eliminate disturbance to stored beam
- Static chicanes to move stored beam closer/further from septum



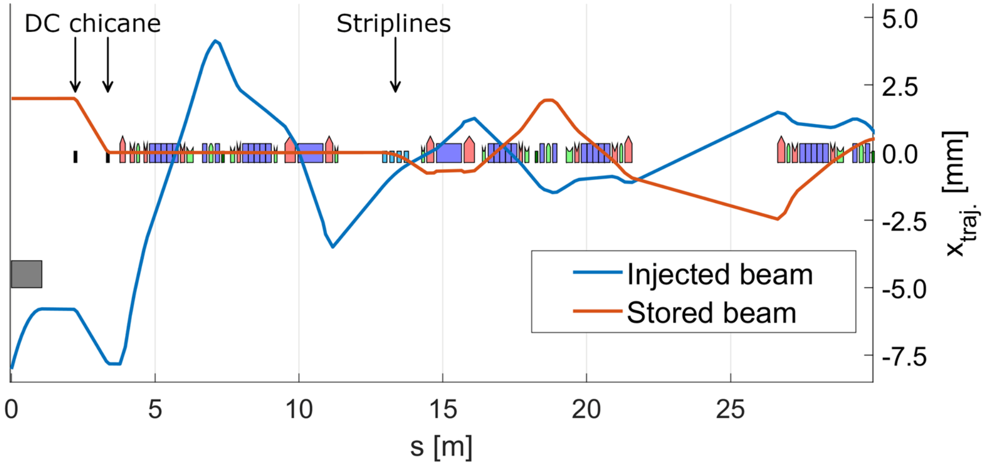


- Investigating permanent magnet for thick septum

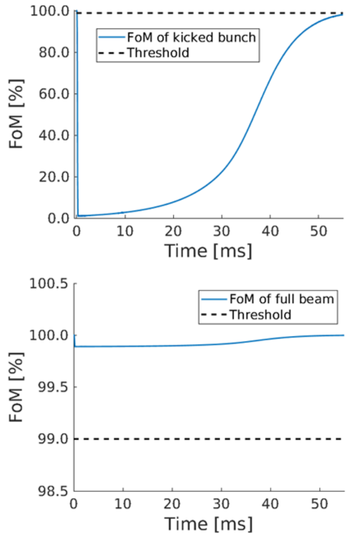
Magnet	Number	Bending angle (mrad)	Pulse shape	Pulse duration (µs)
Thin septum	1	10.5	Sine	>10
Thick septum	1	137.9	Sine	100
Kickers	4	7.2	Half-sine	6
Chicanes	4		DC	n/a

Diamond-II Injection

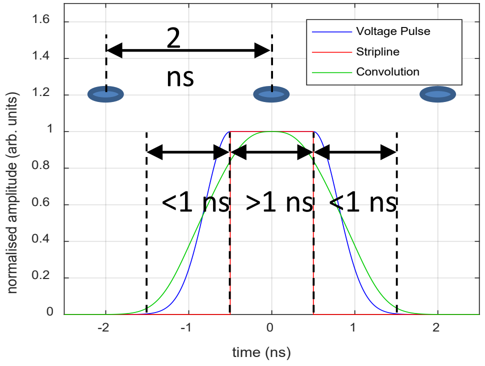
- Requirement -> “Intensity integrated over 100 μs through 2D FWHM slit 45 metre downstream from source point must remain above 99% of nominal at all times at all beamlines”
- Single bunch injection with aperture sharing - injected and stored beam both kicked by striplines, but other bunches see no disturbance

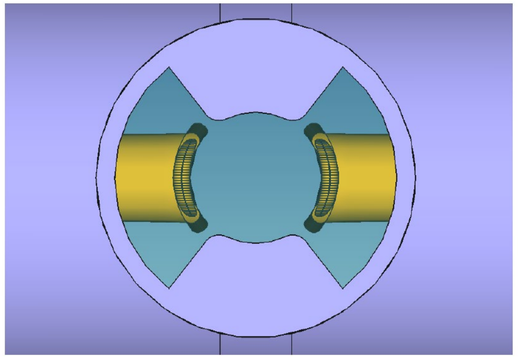


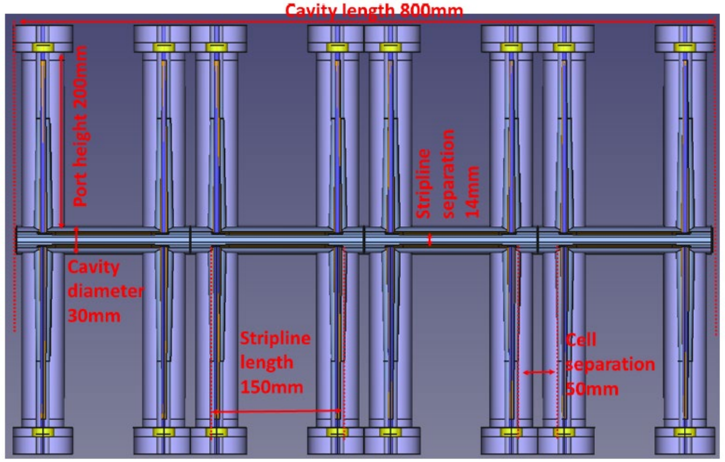
Parameter	Value
Number required	4
Magnetic length	0.15 m
Full gap	14 mm
Rise time (5-95%)	≤ 1 ns
Fall time (5-95%)	≤ 1 ns
Pulse duration (flat stop, 95-95%)	> 1 ns
Total duration	≤ 3 ns
Peak voltage	± 11.8 to ± 21.0 kV



- Striplines and pulsers being prototyped, expect to test in current ring in ~6 months







Diamond-II Timeline and Funding

- November 2021: Outline Business Case (OBC) for Diamond-II approved by the relevant Gov. Dept. and Treasury

- June 2022: first phase of funding for Diamond-II (£95.2m in total) announced, covering 3 years April '22 – March '25, subject to Full Business Case approval

- October 2022: TDR published

- Unfortunately, the total funding cannot increase with respect to what was in the OBC (based on 2020 costs ...), with no allowance for inflation, and the funding profile is a lot flatter than what was planned in the OBC. Consequences of this are:
  - start of Diamond-II shutdown delayed by 1 year to Dec. 2027
  - significant de-scoping e.g. postpone two 'flagship' new beamlines, no linac upgrade etc.

- Full Business Case in preparation on this basis

- Many reviews have to take place next year along the route to funding, aiming for funding approval in July 2023

Conclusions

- ❖ Diamond
- Back to normal working on site for most staff
- Resumed normal operation schedule for users
- ID and RF upgrades continuing - overlap with Diamond-II
- Solar panel installation in progress

- ❖ Diamond-II
- TDR published!
- Diamond-II lattice “frozen” - still pursuing options for further improvements
- Commissioning and injection looking promising
- Focus now on engineering designs, prototyping in progress for many parts
- Challenges with costs and supply chain

Backup Slides

EXTRA SLIDES

Diamond-II IDs

IDs currently under design:

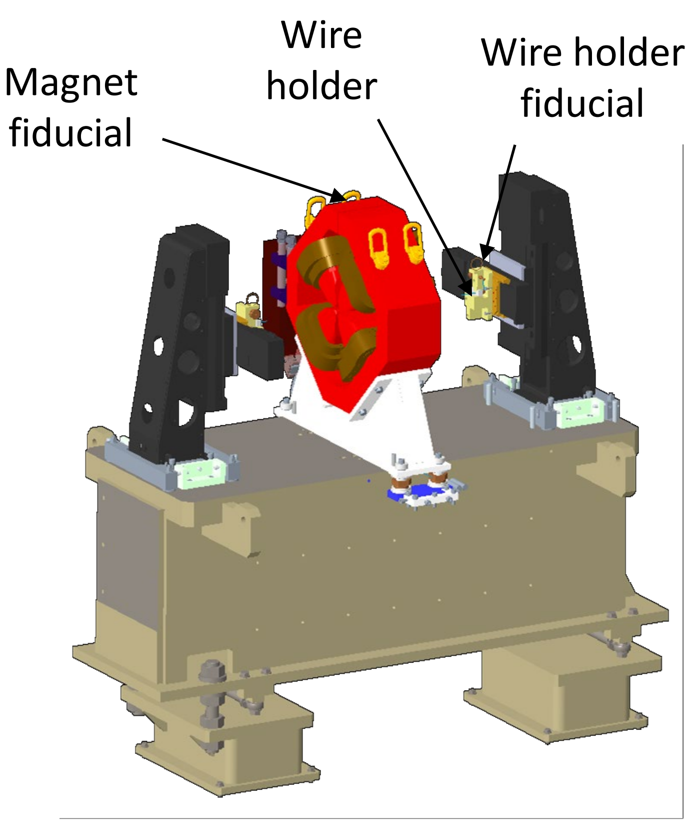
Purple - flagship beamlines
Red - others to be replaced in dark period
Green - upgrades before Diamond-II

Beamline	ID	Period (mm)	N	L (m)	Gap (mm)	B (T)	K	Diamond-II energy range (keV)	Ptot (kW)
I11	CPMU-1	17.6	113	2	4	1.4	2.3	9 – 35	9.06
I04	CPMU-4	17.6	113	2	4	1.36	2.24	5 – 30	8.55
K02 (VMXm)	CPMU-5	17.6	113	2	4	1.4	2.3	5 – 30	9.06
K04 (XChem)	HPMU-1	19.7	78.5	1.6	4	1.31	2.4	10 – 25	8.01
I05	APPLE K-1	200	25	5	21	0.57	10.7	0.010 – 0.24	3.65
I02 (VMXi)	CPMU-5*	17.6	113	2	4	1.4	2.2	5-30	8.6
K02 (VMXm)	CPMU-6	17.6	85	1.5	4	1.4	2.3	5 – 30	6.8
I09.1	HPMU-3	23	87	2	6.4	0.97	2.1	2.1 – 18	4.4
K21	HPMU-4	18.7	80	1.5	4	1.17	2.1	6 – 14.5	4.8
K16	HPMU-5	18.7	80	1.5	4	1.17	2.1	6 – 45	4.8
I06	APPLE II-1 EMPHU	56 65	33 24	2 1.75	19.5 12.5	0.73 0.265	3.82 1.61	0.25 - 2.1 0.5 - 1.7	2.29 0.51
I08	APPLE II-2	56	70	3.97	19.5	0.732	3.82	0.25 – 4.2	4.8
I10	APPLE II-3	56	70	3.97	23	0.6	3.1	0.35 – 1.6	3.2
K07(B07-2)	APPLE II-4	64	28	1.94	18	0.87	5.2	0.125 – 4.0	3.38
K18	3PW	_	1	2	12	1.4		2 – 30	0.4
I17 CSXID	APPLE II-6	52	94	5	16.5	0.82	3.99	0.25-3.0	7.66
K14 SWIFT	MPW	116	6	0.7	15	1.3	14.1	4 – 35	1.7

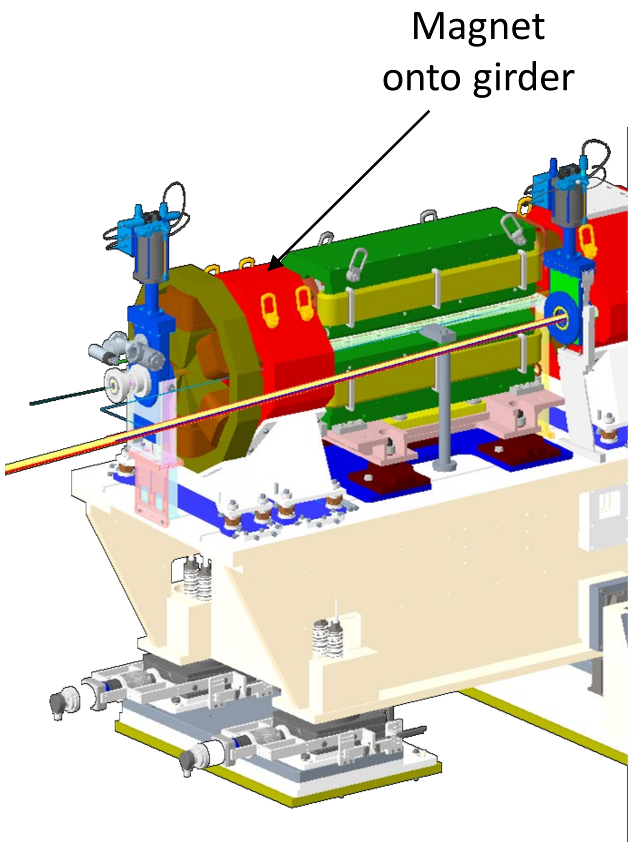
Diamond-II Errors

- Analysis of magnet alignment tolerance is in progress by magnet, survey and engineering groups
- Combined uncertainty is currently larger than has been assumed in the commissioning simulations
- Wire holder survey could be improved by replacing laser tracking with CMM bench - 17% reduction

Stretched wire		CMM Bench	
Wire holder inspection	2	Wire position measurement	5
Magnetic measurement	5	Magnetic measurement	5
Wire holder survey	25	Survey Feature position measurement	5
Magnet fiducial survey	10		
Magnet surveyed into position on girder	35	Magnet surveyed into position on girder	35
Splitting/joining Of Magnet	8	Splitting/joining Of Magnet	8
Survey ball in cone repeatability	3	Survey ball in cone repeatability	3
Transport	10	Transport	10
SMR Centring	3	SMR Centring	3
Combined Uncertainty of magnet position on Girder	**46**		**38**



Measurement bench



Storage ring girder

Diamond-II Girder Prototyping

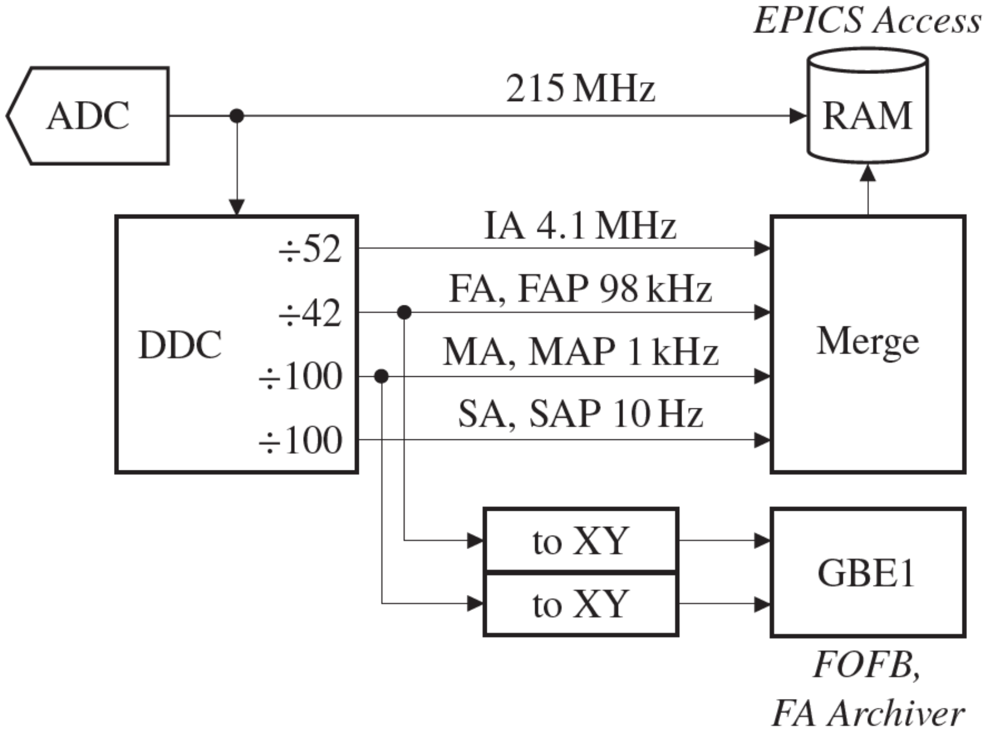
Prototyping underway

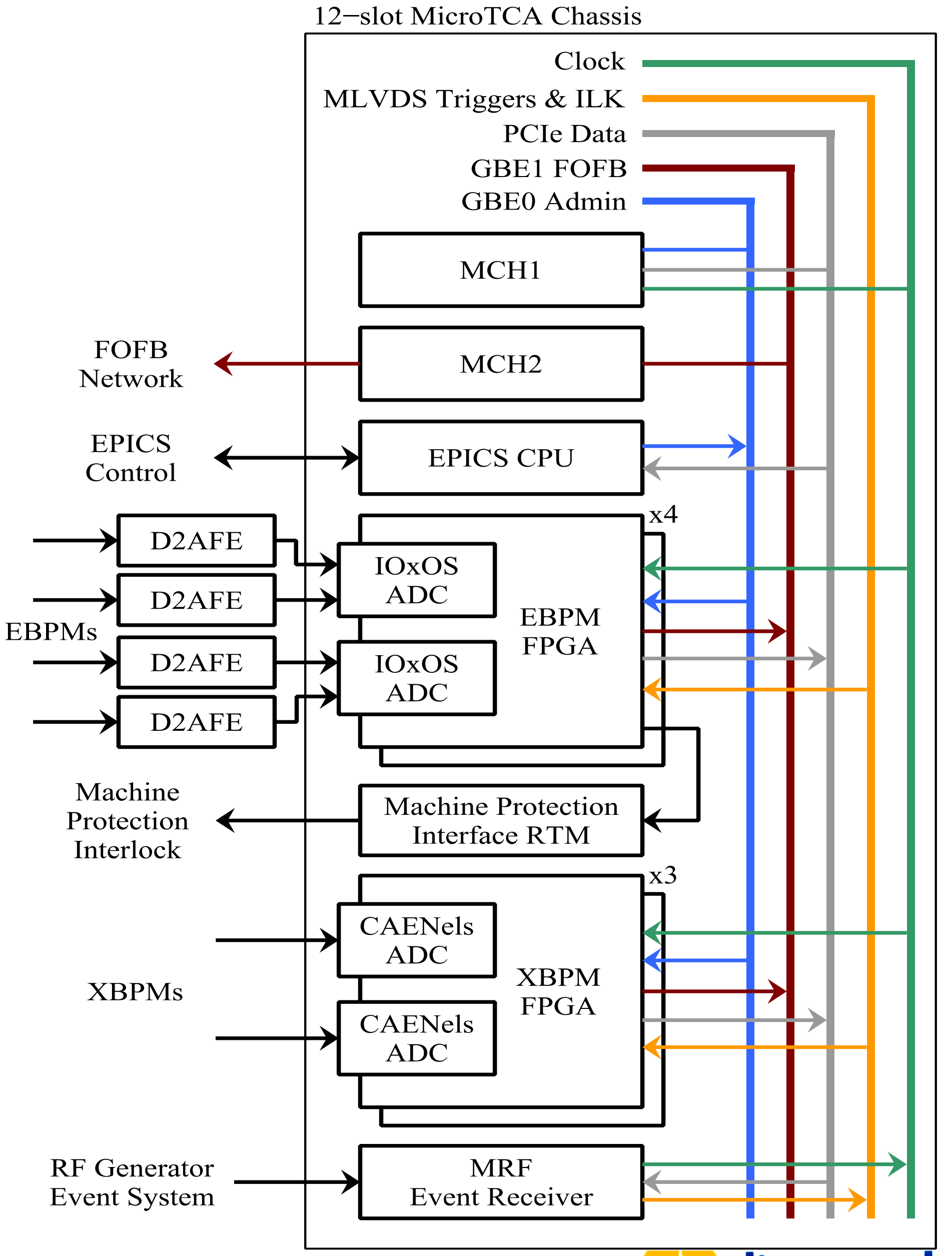
Prototype 8m girder with dummy magnets for vibration tests, alignment trials etc.

Prototype storage ring vacuum vessels

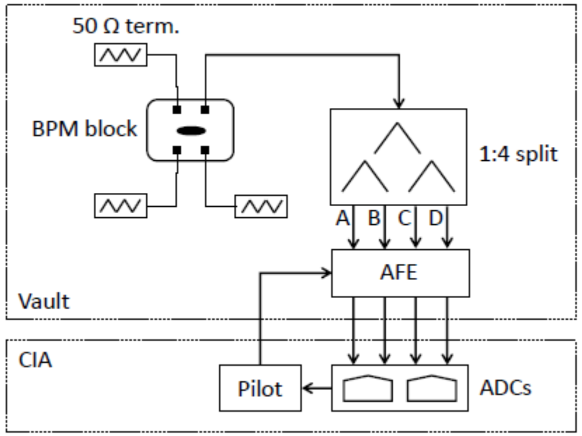
BPM Digitisation and Processing

Data Stream	Used for
Intermediate Acquisition (IA)	Converted to turn-by-turn data
Fast Acquisition (FA)	Fast orbit feedback (FOFB) and fast archiver
Medium Acquisition (MA)	Additional archiver/fault detection
Slow Acquisition (SA)	Live EPICS data



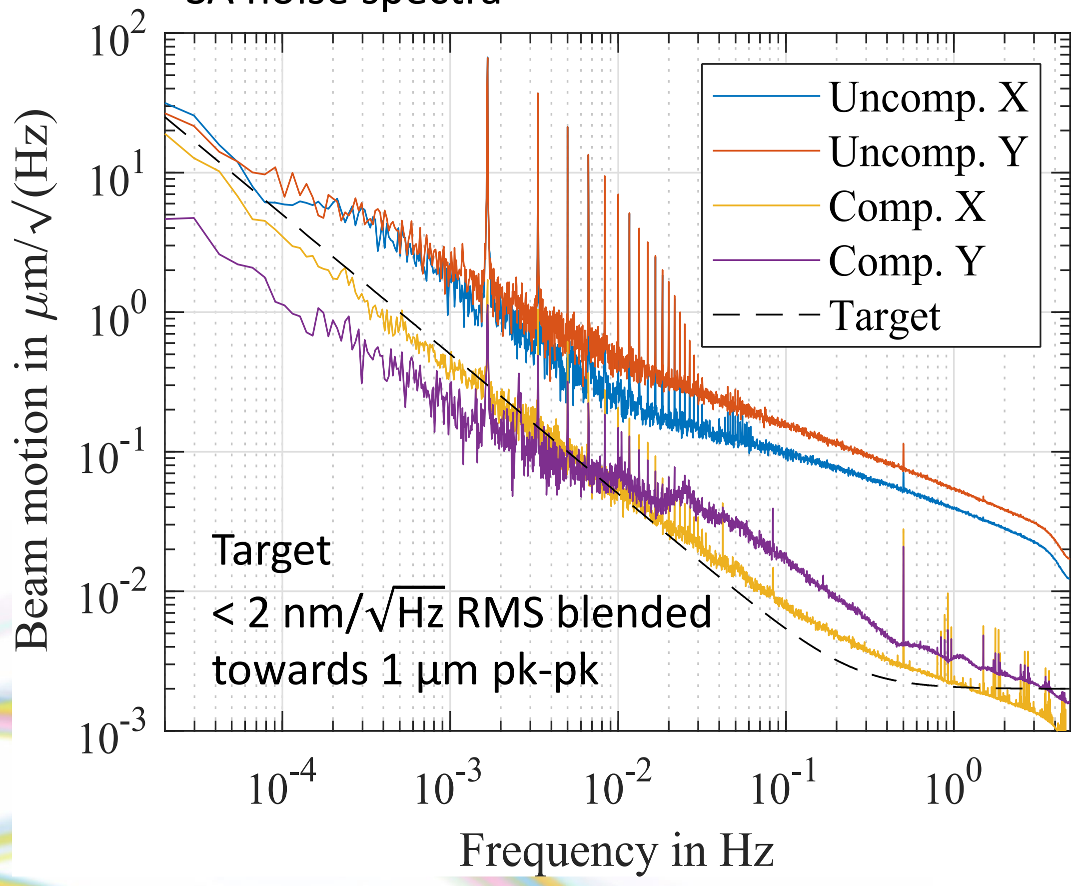


BPM System Measurements

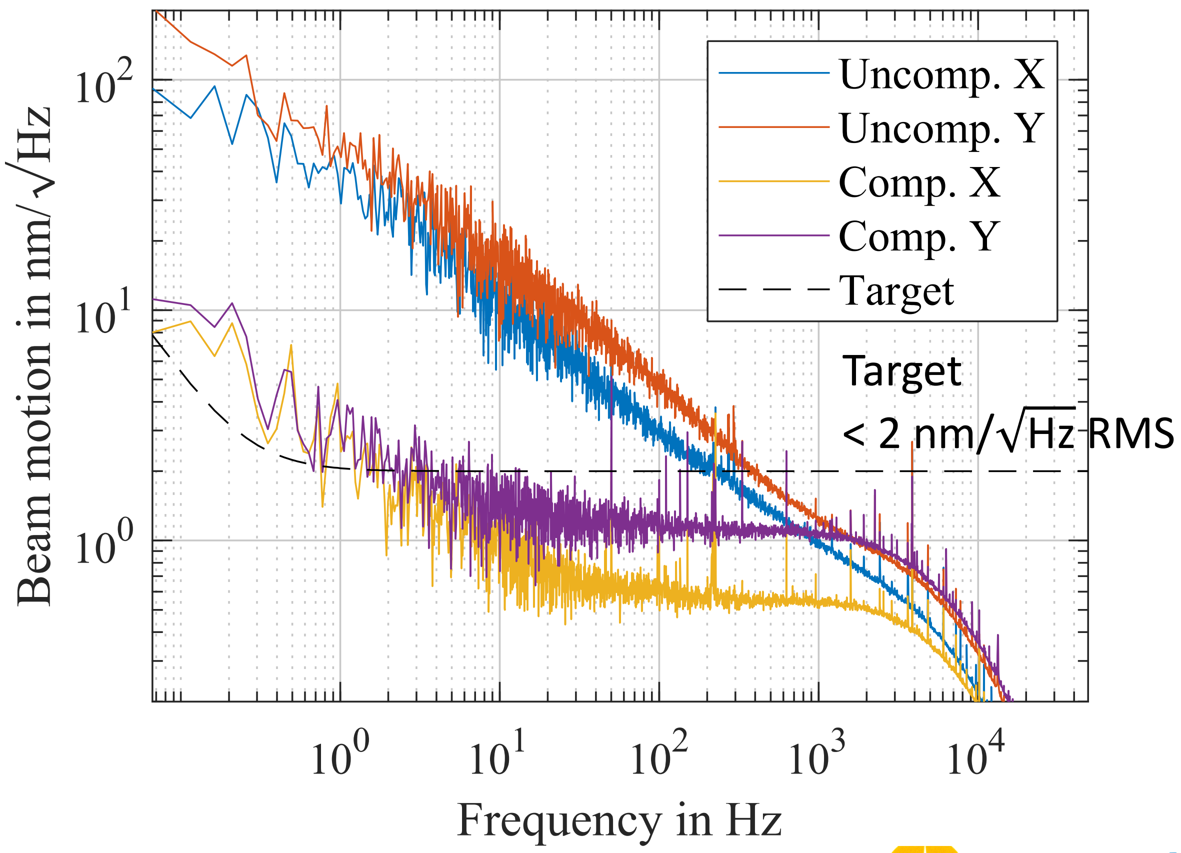


- Demonstrates efficacy of pilot-compensation.
- Line at 1.67 mHz and its decaying harmonics are caused by the 10 minute top-up, and are reduced by increasing the attenuation in the D2AFE to improve the linearity.
- Line at 0.5 Hz is the flash rate of a status LED on the AFE modulating the power supply, shows high sensitivity!

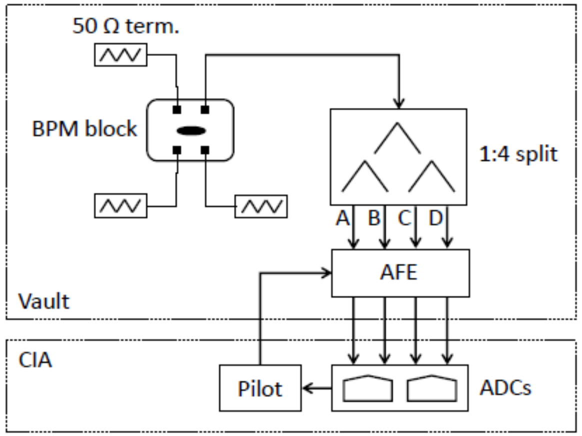
SA noise spectra



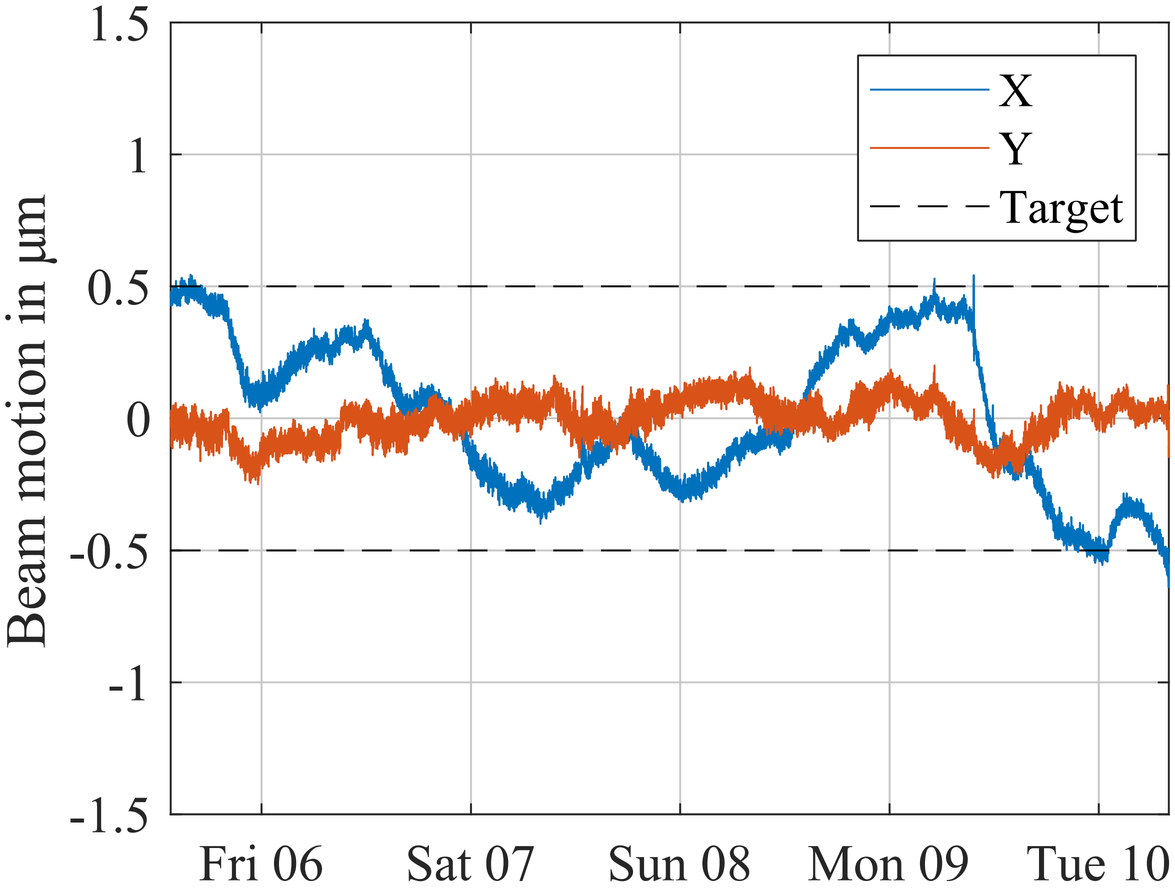
FA noise spectra

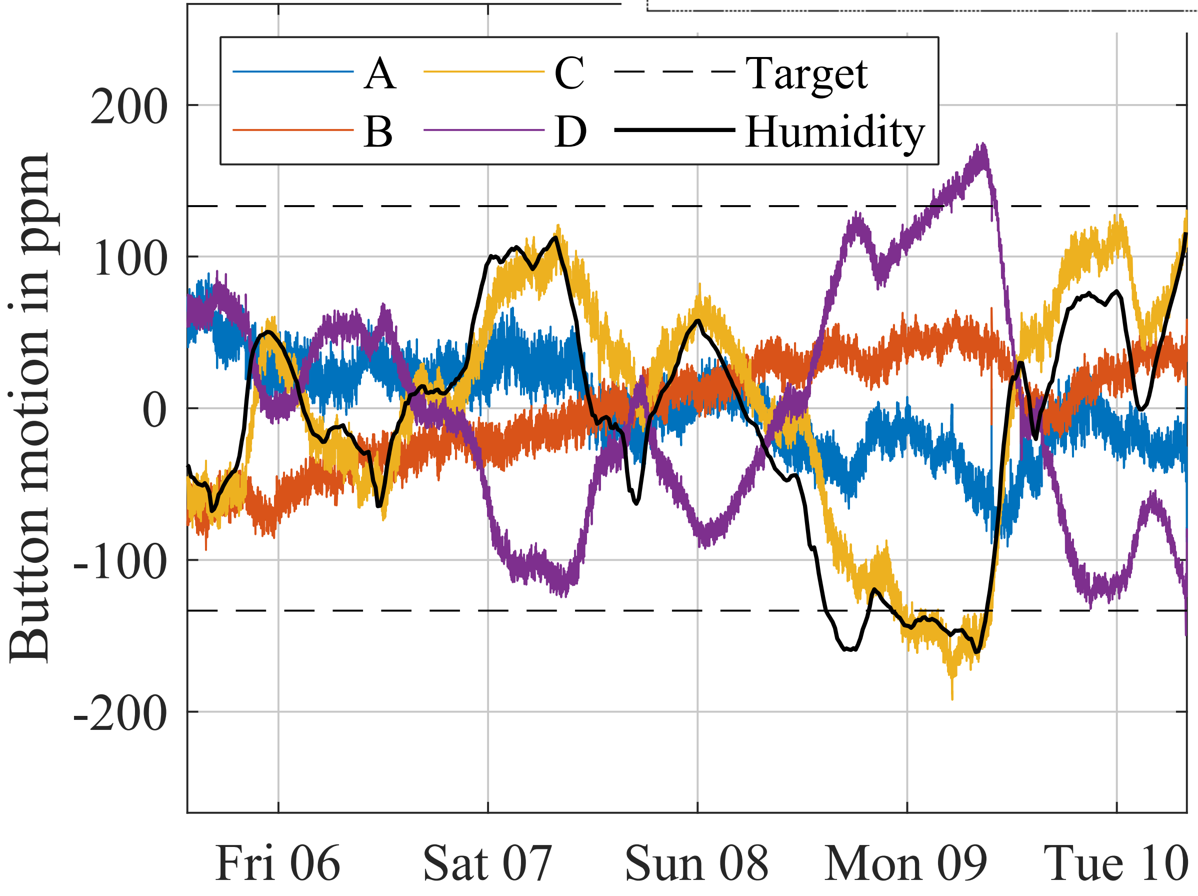


BPM System Measurements



- Performance of the Y signal is satisfactory, the X signal is drifting significantly, at times exceeding the target.
- Explained by correlation of channels C and D with humidity
- Investigations underway to answer if this comes from the AFE (under test) or the 1:4 splitter (used for testing)





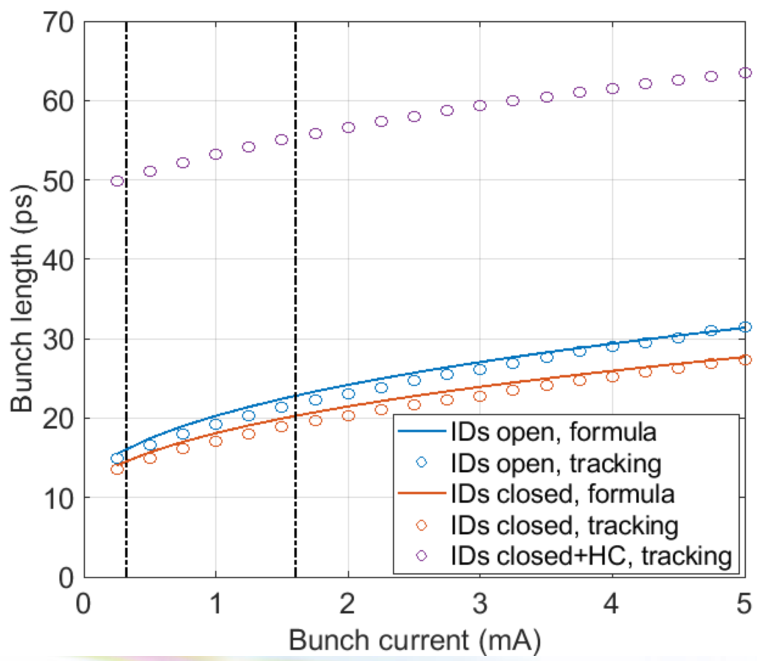
Diamond-II Collective Effects

Single bunch dynamics simulated in Elegant - one turn map with lumped impedance

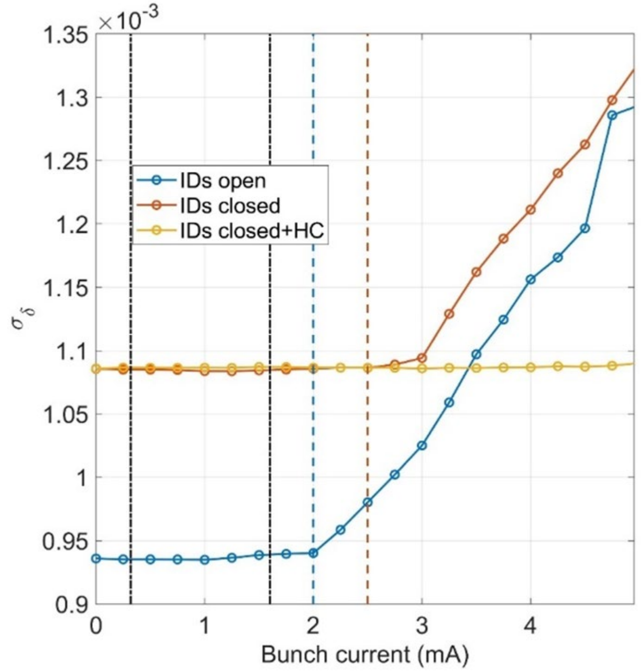
Resistive wall, geometric impedance calculated using 0.5 mm bunch length, flat-potential harmonic cavity

Stable for standard (0.3 mA) and hybrid (1.6 mA) fill bunch charge conditions at nominal 2/2 chromaticity

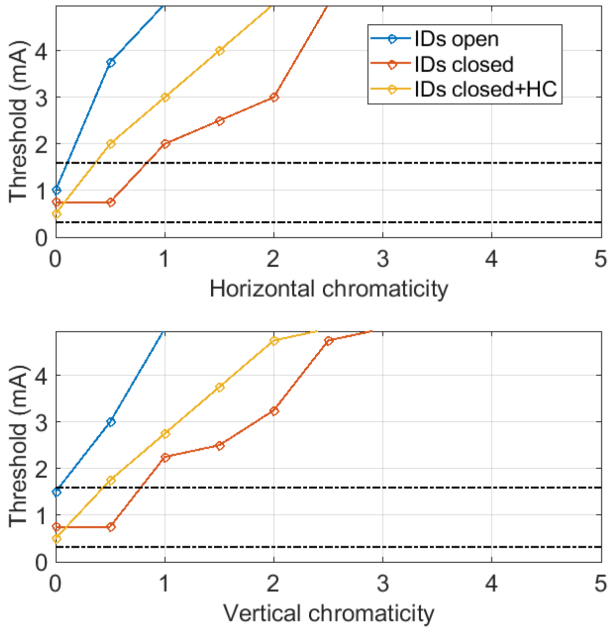
Bunch lengthening



Microwave instability



Head-tail instabilities



Diamond-II Collective Effects

Multibunch dynamics also mainly simulated in Elegant

Resistive wall impedance greatest effect

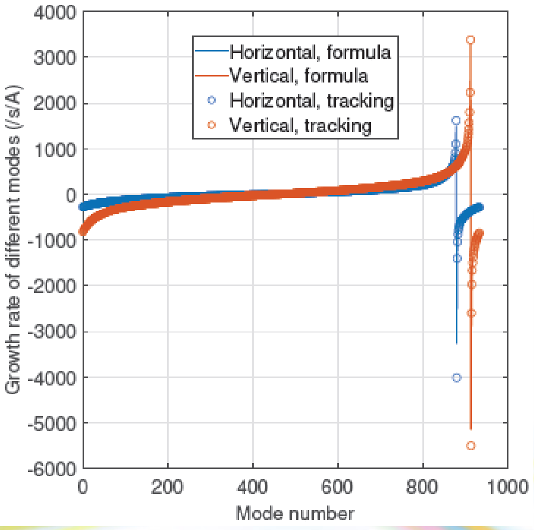
Investigating length of geometric wakes required - multiple turns?

RF cavities included as modes from S-parameter analysis - too big for wakefield simulation

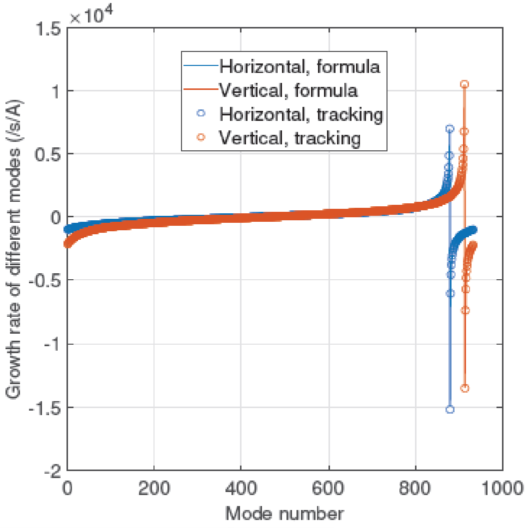
Stable when including harmonic cavity and with chromaticity 2/2

Detailed simulations including realistic multibunch feedback in progress

IDs open



IDs closed



Uniform fill, chromaticity 0, long range impedance only		Radiation damping rate (/s)	Largest growth rate (/A/s)	Estimated threshold (mA)
Open IDs	Horizontal	103.5	1622	**63.8**
	Vertical	55.2	3390	**16.3**
Closed IDs	Horizontal	176.7	6993	**25.3**
	Vertical	128.5	10505	**12.2**

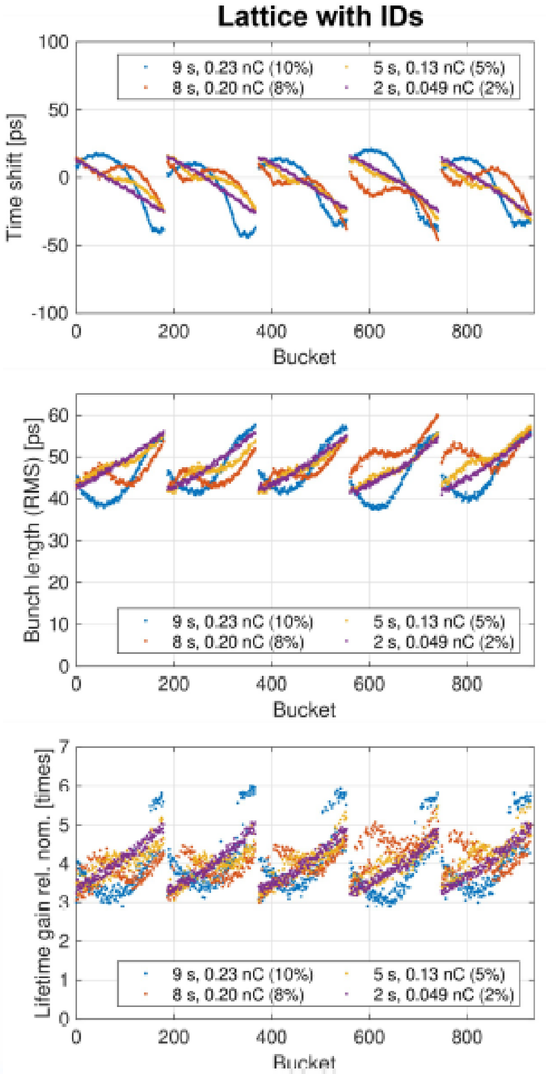
Diamond-II Collective Effects

Transient beam loading and bunch charge variation with harmonic cavity

5 bunch trains with gaps of 7 buckets

Charge variation depending on injection frequency, lifetime

Single bunch hybrid more challenging - may require higher charge guard bunches



Ion simulations ongoing, investigating best way to spread interaction points - very compute intensive

Stable with same gaps required for beam loading