The Diamond-II Project

PSI, Mar. 21st 2024

Richard P. Walker, Technical Director, interim Project Director for Diamond-II

- Introduction
- Machine
- Beamlines
- Buildings
- Timescales

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Diamond Light Source

- The UK's national synchrotron radiation facility, funded by Government (86%) and Wellcome Trust (14%).
- A major piece of UK Research Infrastructure.
- Since starting operations in 2007 it has:
  - served over 14,000 scientists from academia and industry
  - hosted over 220 companies paying for proprietorial access, across multiple sectors
  - provided training for 8,000 PhD students
  - hosted over 6,000 visitors each year

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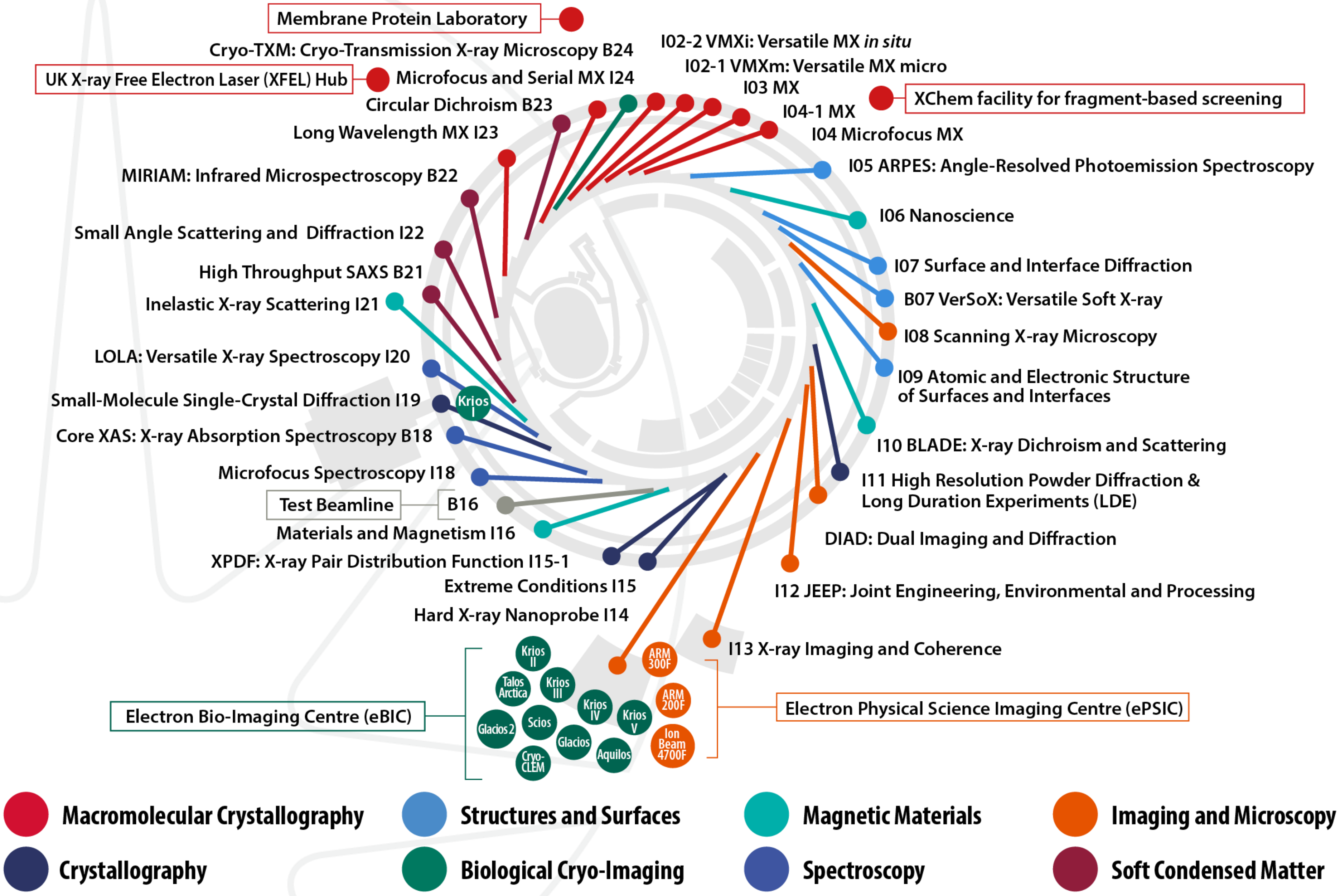
The Diamond Facility



- 33 beamlines
- 36 independently operating instruments
- 11 electron microscopes

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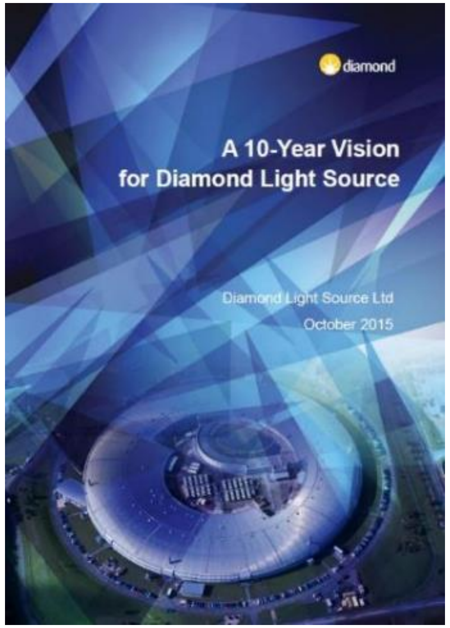
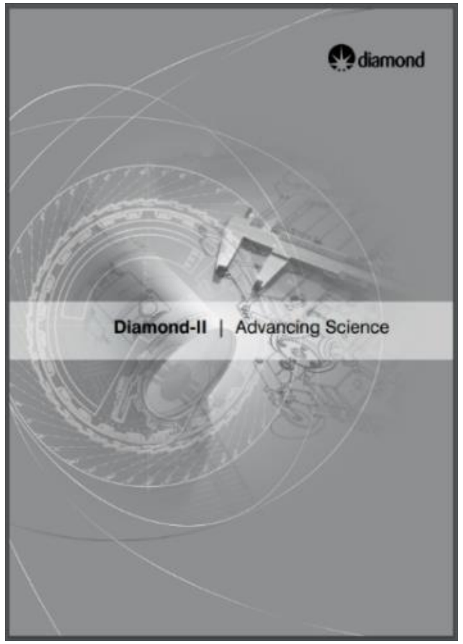
Bacground to Diamond-II

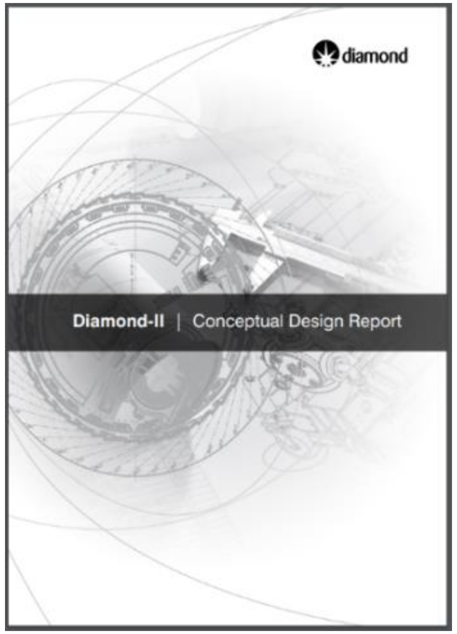
- 10-Year Vision, October 2015
  included a major upgrade: Diamond-II
- Diamond Science Advisory Committee, April 2016

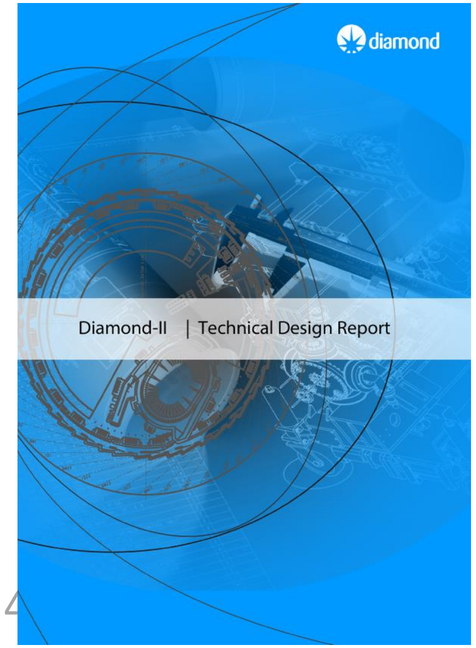
“SAC agree … that a major upgrade of DIAMOND Light Source, to achieve a source of radiation of much higher brightness, is required in order to maintain the excellence of the facility ….”

- Science case endorsed by Science Advisory Committee, November 2018
- Conceptual Design Report endorsed by international review committee, April 2019
- Diamond Board approved proceeding to the Technical Design Report (TDR) phase, June 2019
- Draft Machine TDR successfully reviewed by Machine Advisory Committee, March 2022
- Machine TDR published in August 2022





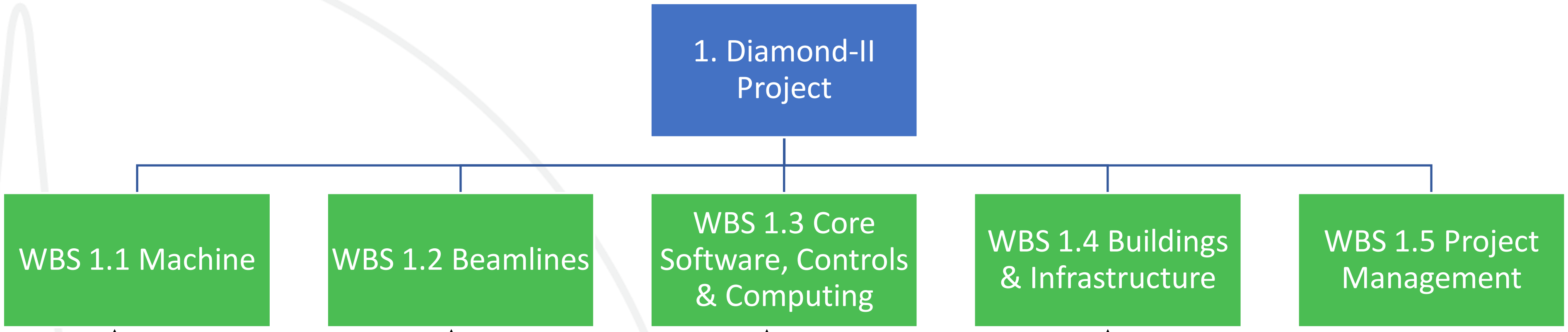




Diamond-II Project Approval

- Confirmation of approval, 21st July 2023
- **Official announcement, 5th September 2023**, at Diamond, by the Secretary of State for Science, Innovation and Technology

Diamond-II Top Level WBS



A major upgrade of the machine, replacing most of the Booster synchrotron and Storage Ring.

3 new ‘flagship’ beamlines + significant upgrades to many existing beamlines.

A boost in data handing and analysis hardware & software, to manage the increased data rates.

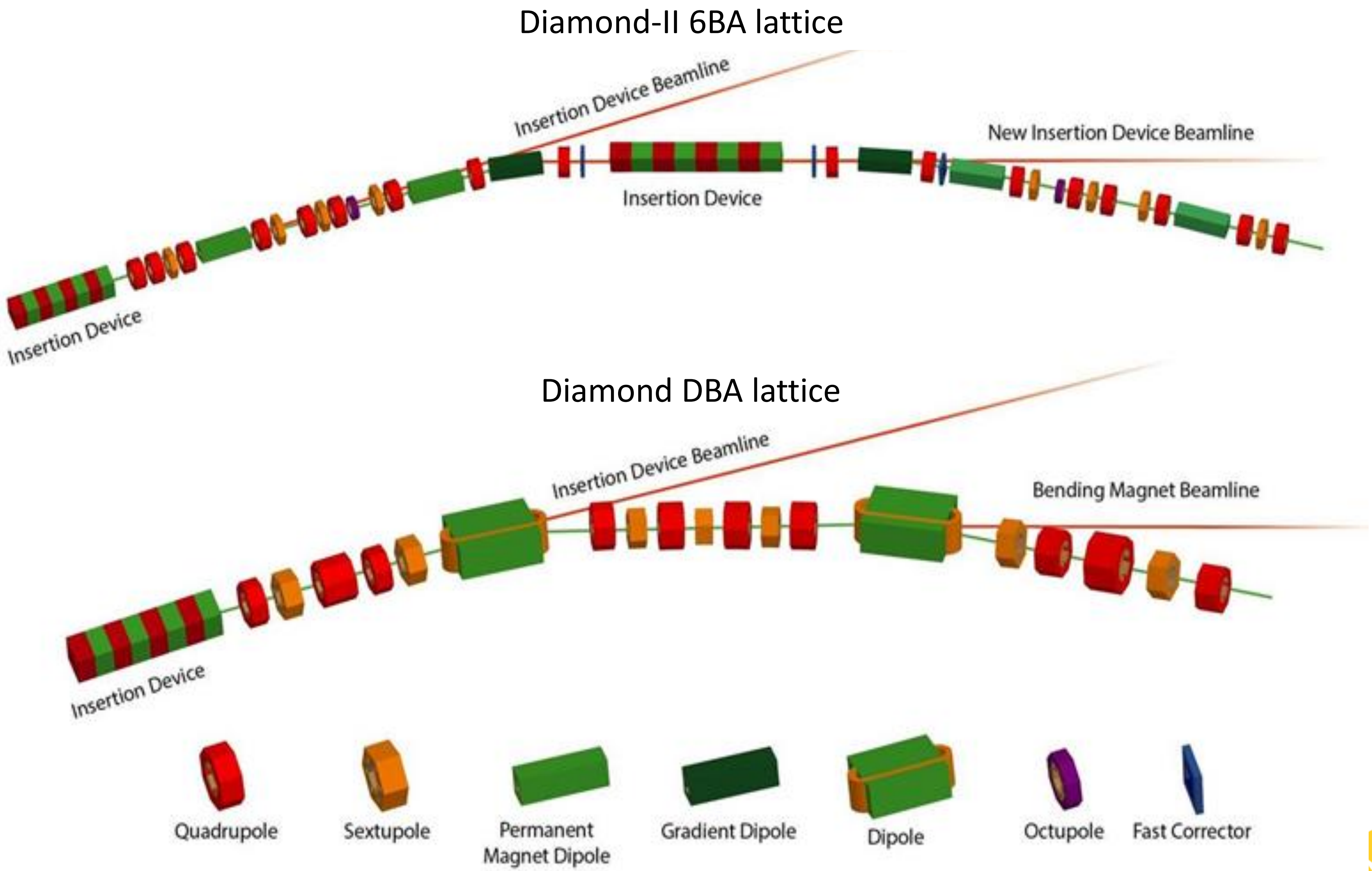
A new Diamond Extension Building for Diamond-II assembly work, as well as several other on- and off-site storage buildings.

Enhanced Project Management processes.

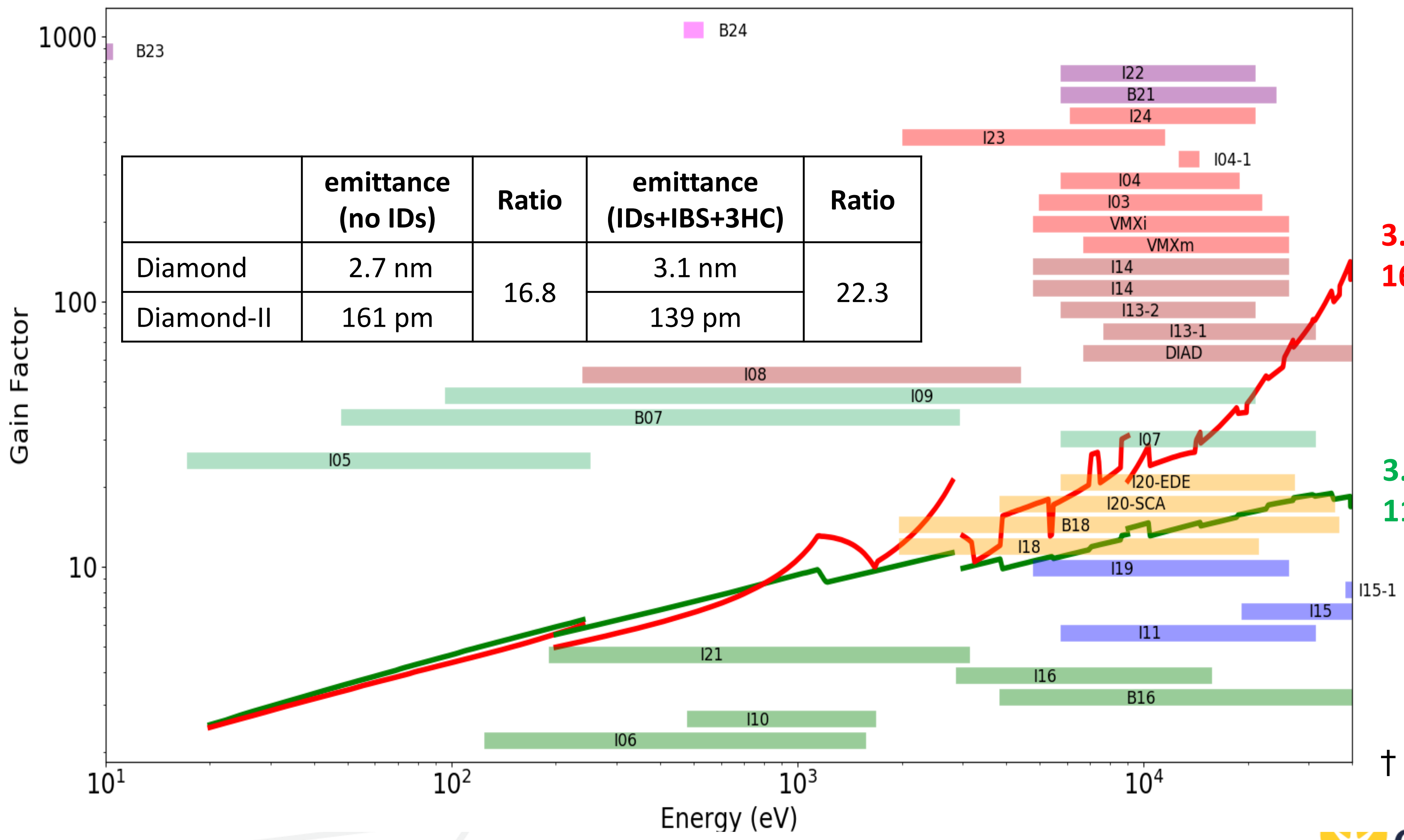
Diamond-II Design Goals and Main Features

- Increased brightness and coherence → modern low emittance MBA lattice
  → increase in energy from 3 GeV to 3.5 GeV
- Increased capacity for insertion devices → inclusion of 'mid straights' in a 6BA lattice
- Maintain ID source points (other than two) → careful adjustment of straight section lengths

Diamond-II Layout



Diamond-II Brightness



	emittance (no IDs)	Ratio	emittance (IDs+IBS+3HC)	Ratio
Diamond	2.7 nm	16.8	3.1 nm	22.3
Diamond-II	161 pm		139 pm	

3.5 GeV, 161 pm

3.0 GeV 118 pm

† bare lattices

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Diamond-II: Use of the 24 mid-straights

- 2 used to maintain two existing mid-straight insertion device beamlines
- 2 for IDs for new Diamond-II beamlines
- 4 will be used to convert existing bending magnet beamlines into ID beamlines
- 5 reserved for future ID beamlines

- 5 will be used for RF cavities
- 1 will be used as part of the injection scheme
- 1 will be used for diagnostics
- 4 unallocated

} Note that none of these straights could be used for new ID beamlines as there is no space on the experimental hall floor for a beamline.

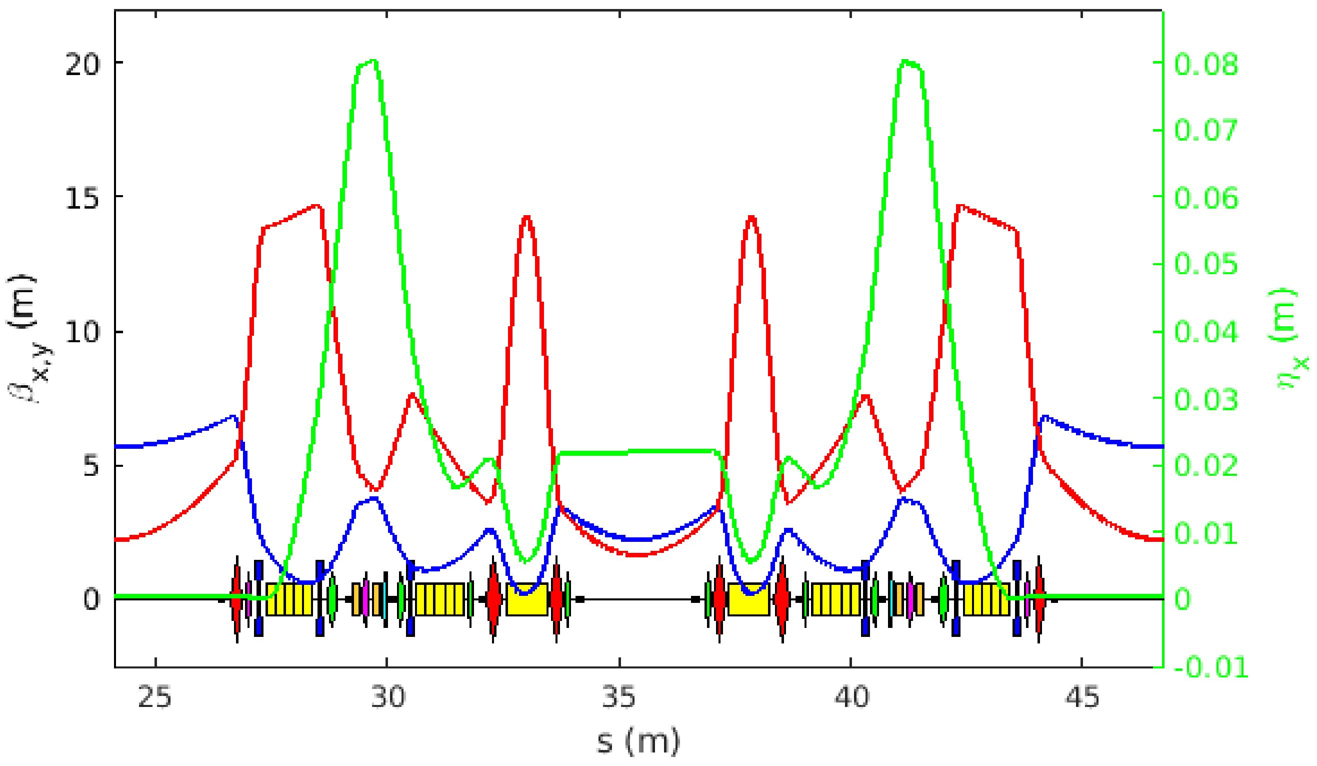
Diamond-II Machine

- Diamond-II Lattice
- Collimation
- Injection
- Magnets
- Vacuum
- Engineering
- RF
- Diagnostics and Feedbacks
- Insertion Devices
- New Booster

Diamond-II Lattice Design

The Diamond-II lattice is a ‘Modified Hybrid 6 Bend Achromat’, which combines two concepts:

- The ESRF-EBS cell (Hybrid 7 Bend Achromat)
- The Diamond Double-Double Bend Achromat (DDBA) cell



	Diamond	Diamond-II
Lattice Type	DBA	M-H6BA
Circumference	561.6 m	560.561 m
Straight Sections	24	48
Energy	3 GeV	3.5 GeV
Beam Current	300 mA	300 mA
Natural Emittance	2.7 nm.rad	161 pm.rad
Equilibrium Emittance	3.1 nm.rad	120 pm.rad
Natural Energy Spread	0.096 %	0.094 %
Equilibrium Energy Spread	0.107 %	0.109 %

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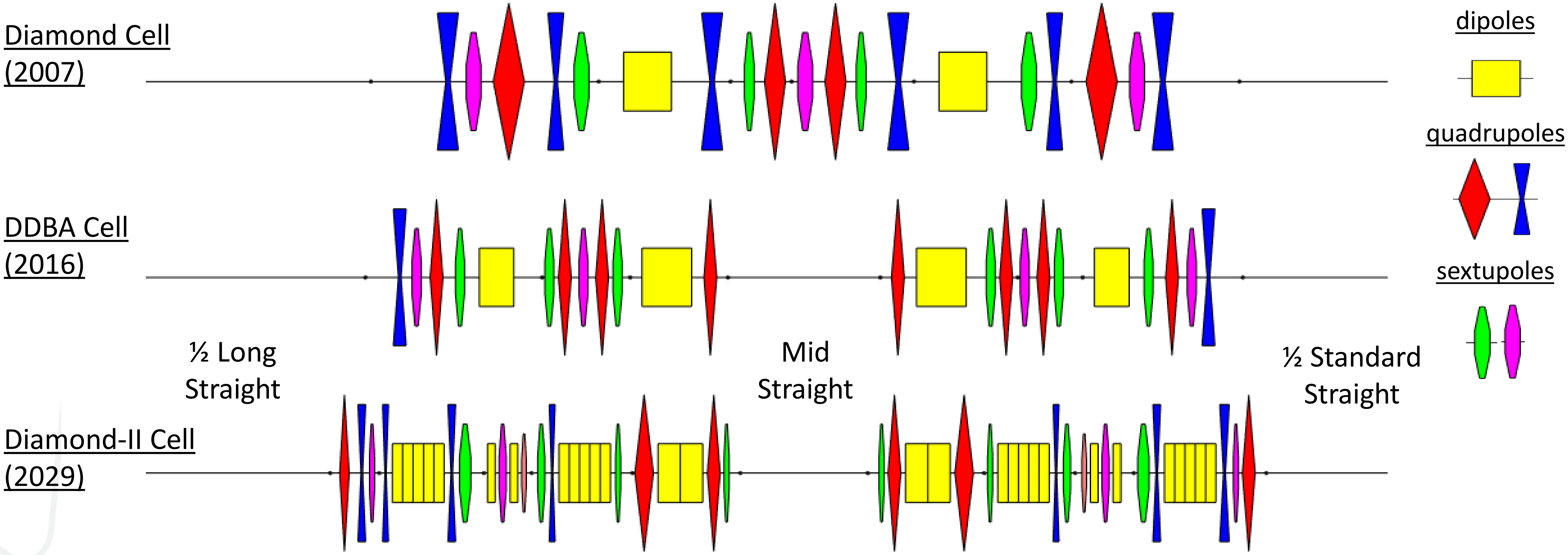
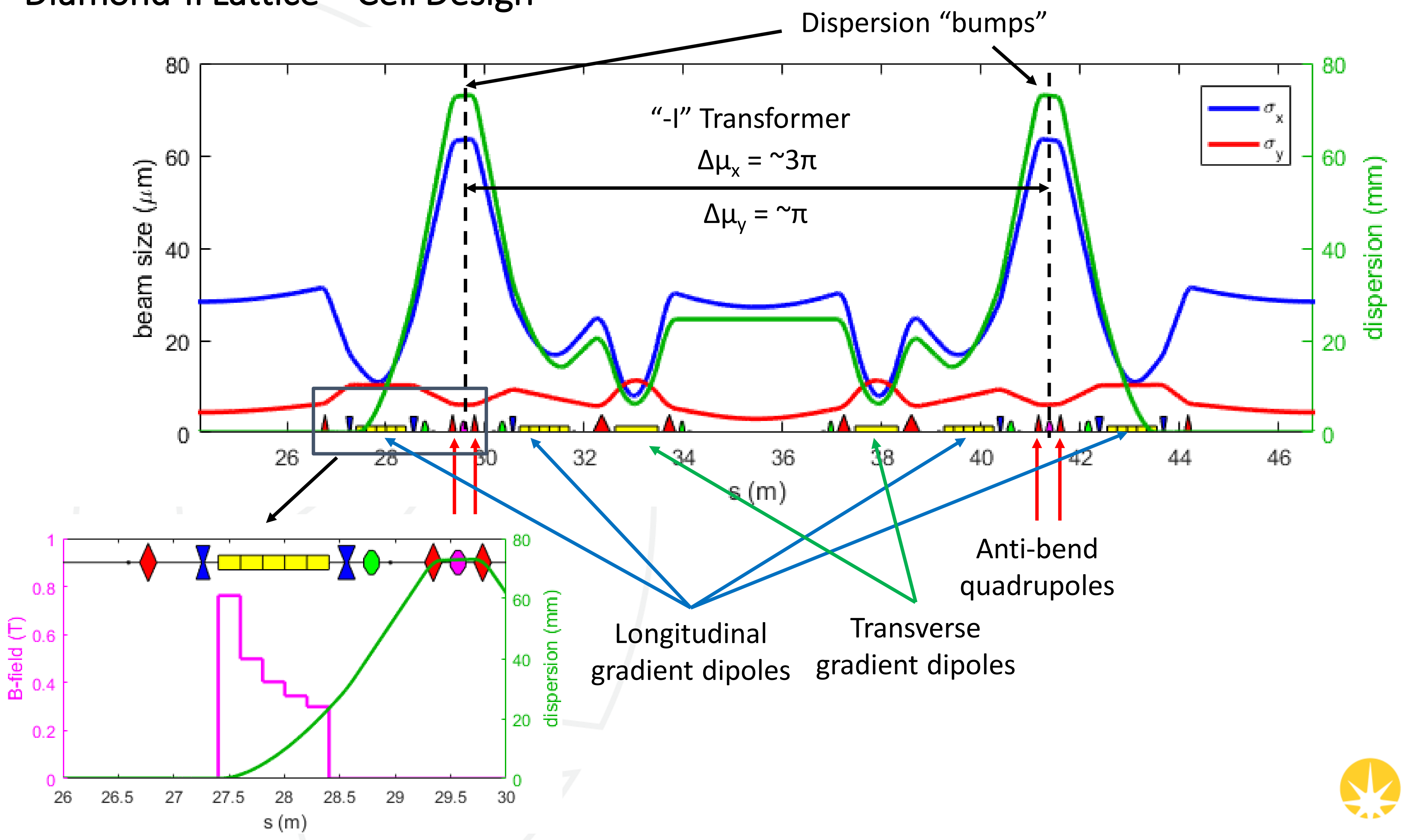
Diamond-II Lattice Evolution

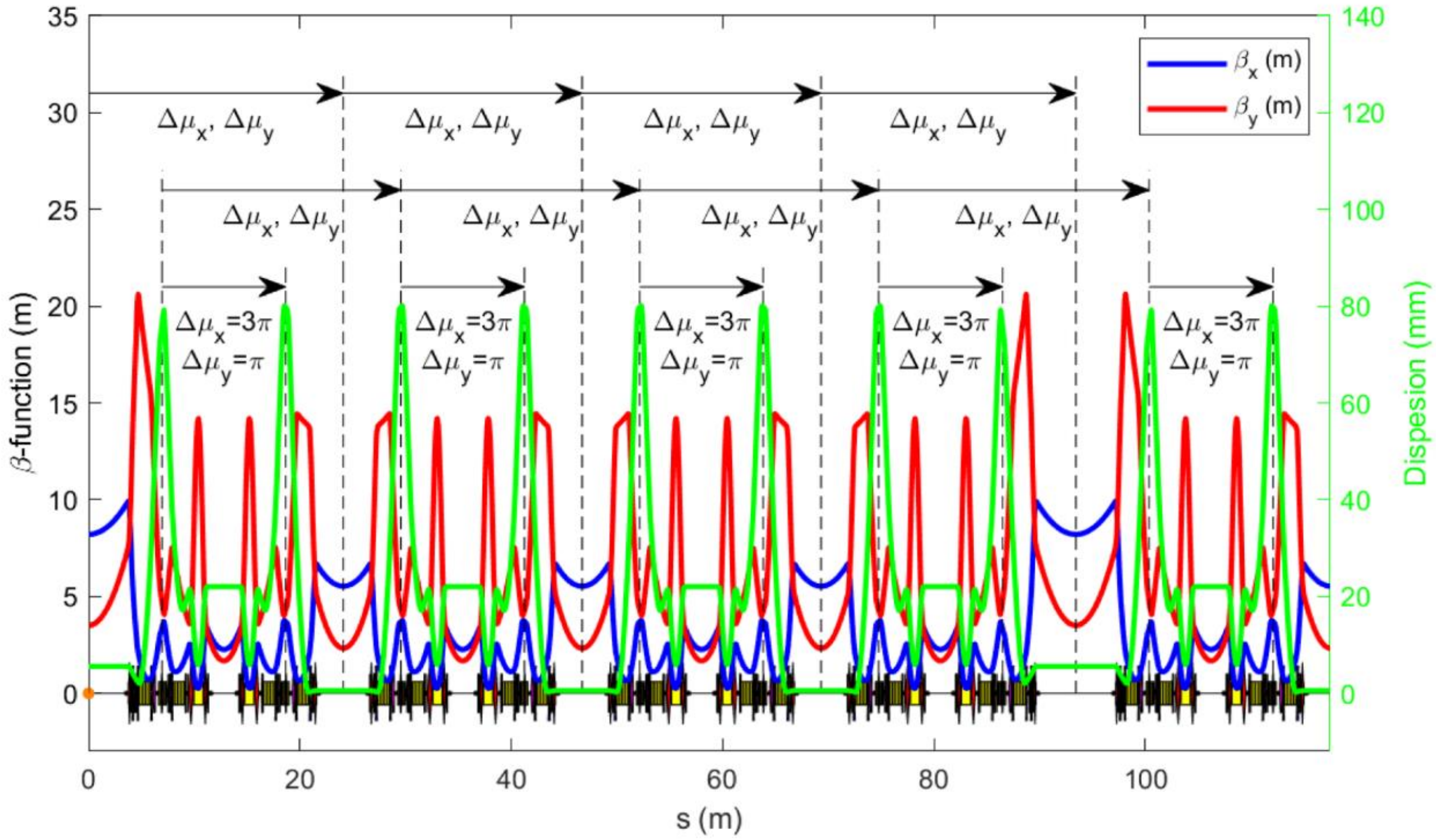


	Diamond	DDBA Cell	Diamond-II
Long straight	11.3 m	-	7.545 m
Standard straight	8.3 m	-	5.065 m
Mid straight	-	3.4 m	2.872 m
# Magnets per cell	19	24	36 (37)

Diamond-II Lattice – Cell Design

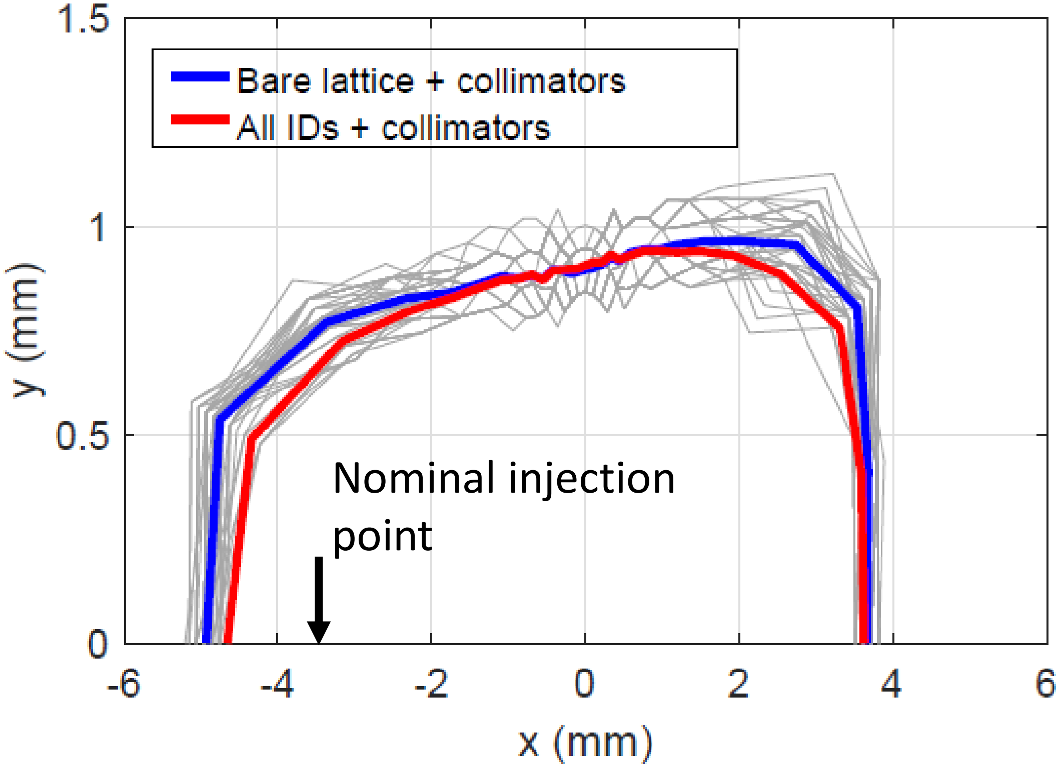


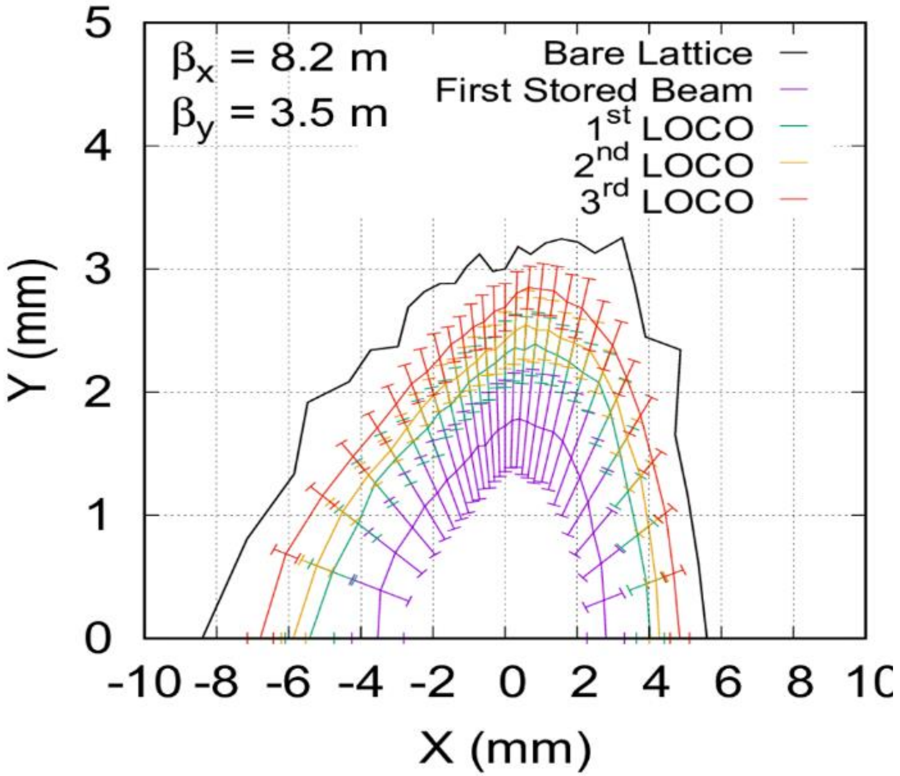
Diamond-II Lattice – Super-period Design



- Diamond (and Diamond-II) has 6-fold symmetry.
- “pseudo- symmetry” - fixing the cell tunes to be the same regardless of whether they contain long or standard straight sections has also been found to be beneficial for non-linear dynamics.

Diamond-II Lattice Performance





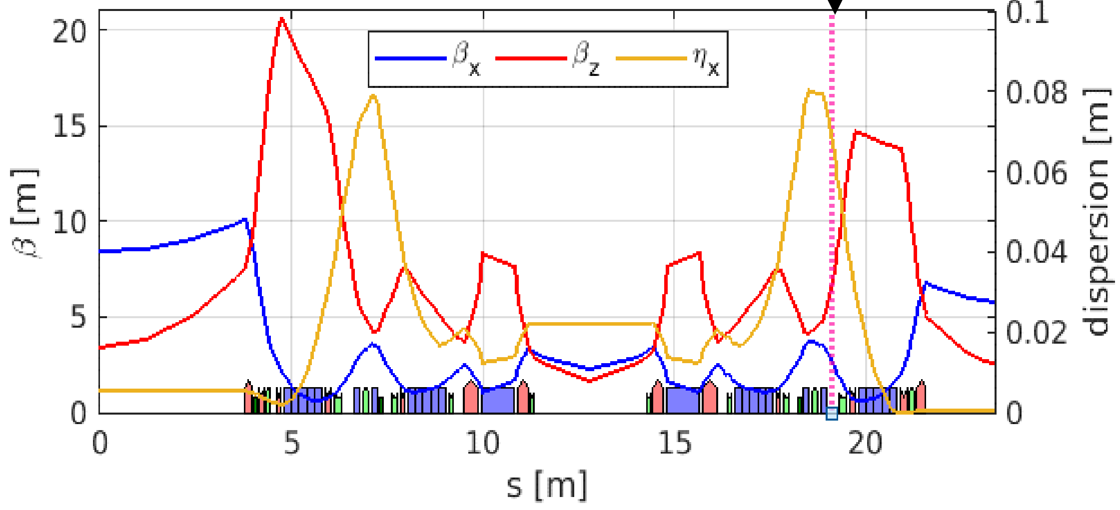
- Dynamic Aperture from 6D tracking including physical apertures (including collimators), magnet alignment and multipole errors after simulated commissioning.
- Detailed Simulated Commissioning calculations have been carried out and are still being refined.

Collimation

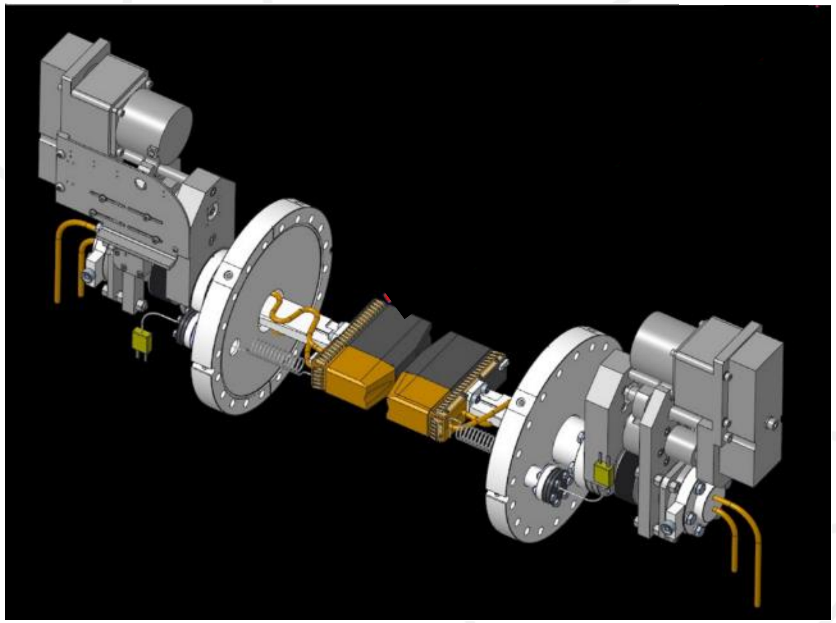
- 3 horizontal and 3 vertical collimators located in identical points in the cell:

Loss Mechanism	% of electrons collected by all collimators
RF off	97.7±6.9
Touschek scatter	71.4±3.4
Elastic gas scatter	74.6±0.8
Inelastic gas scatter	34.7±0.4
All lifetime losses	70.8

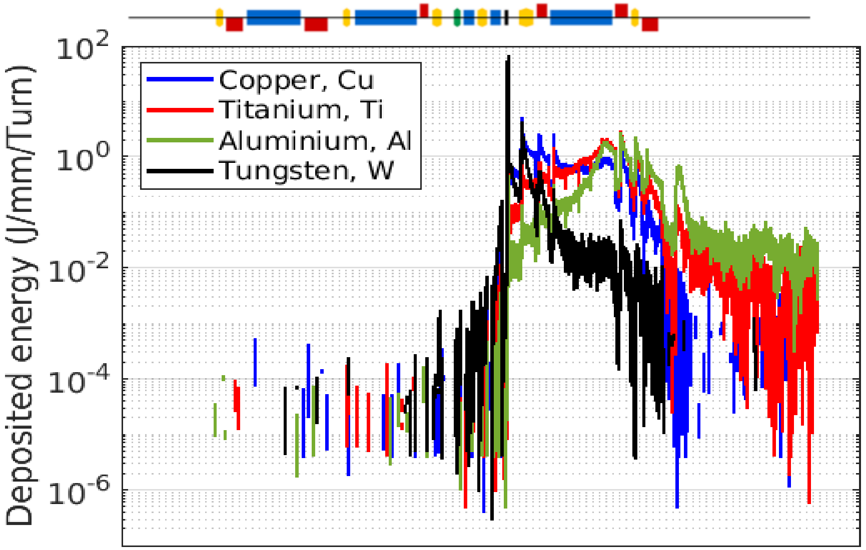
Collimator location



- Simulating energy deposition using BDSIM to assess damage to collimators and downstream components – including permanent magnets.



- New design with cooled copper taper and tungsten blade in progress.

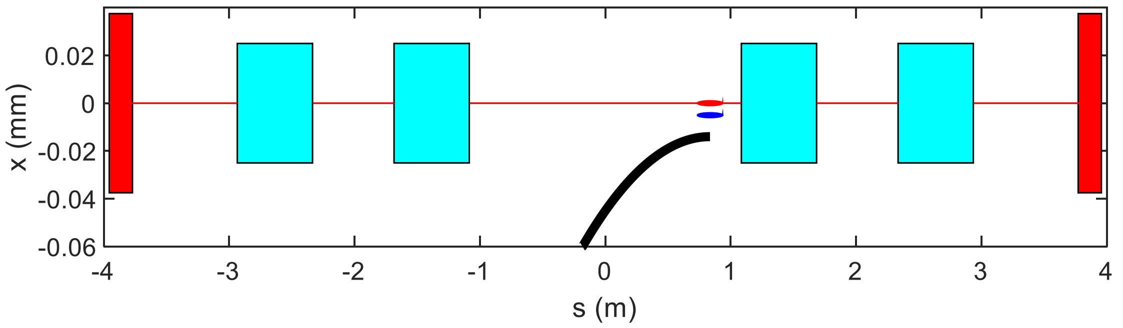


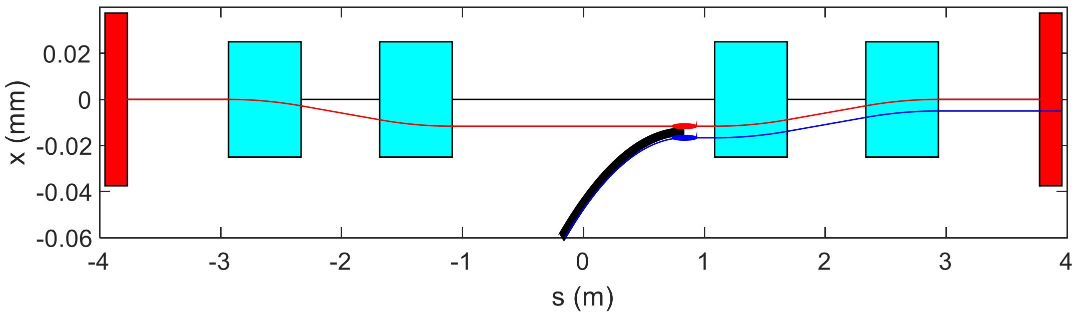
Injection

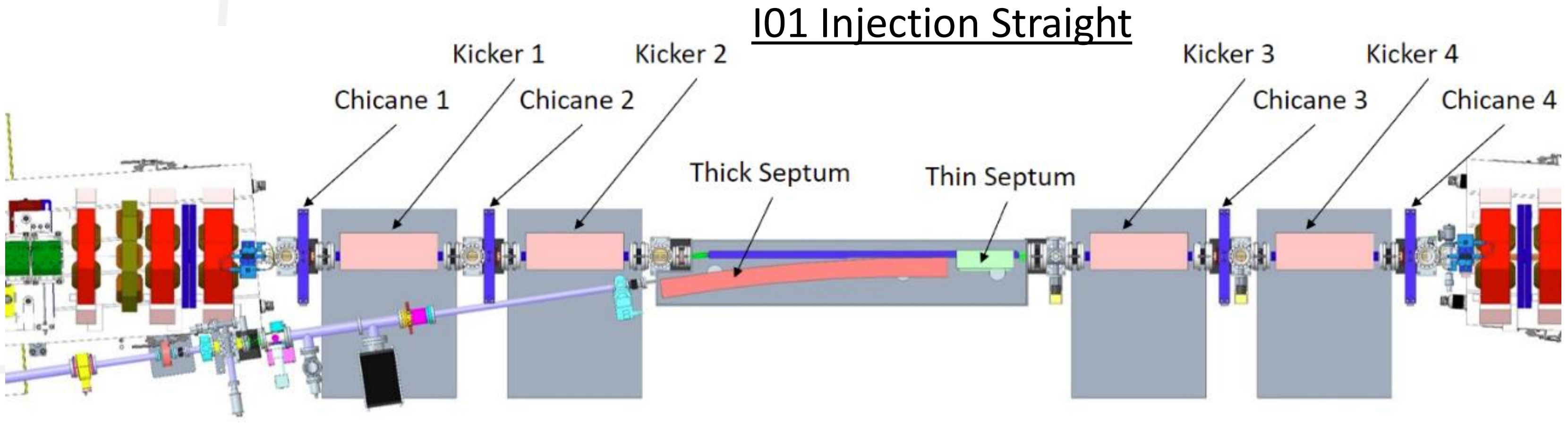
Diamond-II will operate two different injection schemes:

1) <u>Standard four kicker bump (single or multi-bunch)</u>

- Robust, proven technology
- Can be adjusted for different stages during commissioning:
  - ➢ single shot, on-axis injection
  - ➢ off-axis accumulation with closed orbit bump
- Baseline injection scheme for re-filling during operations
- Downside: difficult to make injection invisible to users due to technology limitations



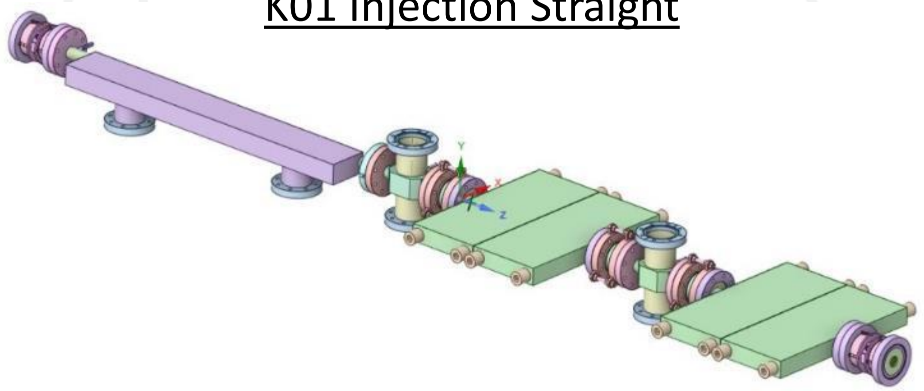


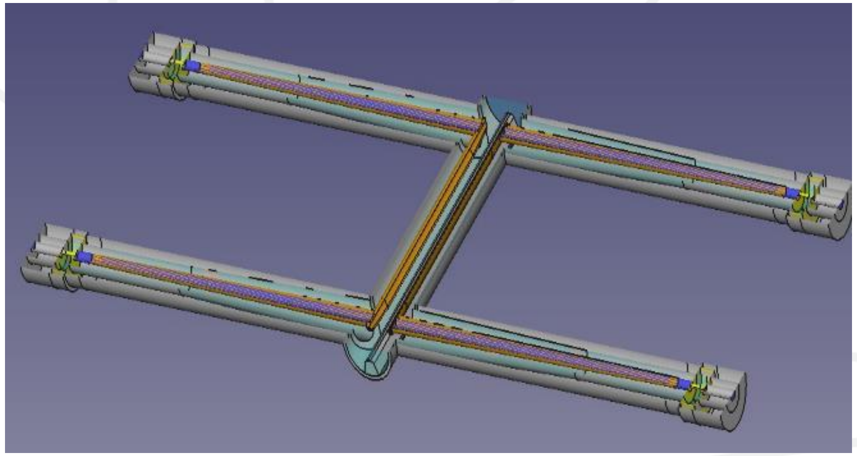


2) Stripline kicker injection (single bunch only)

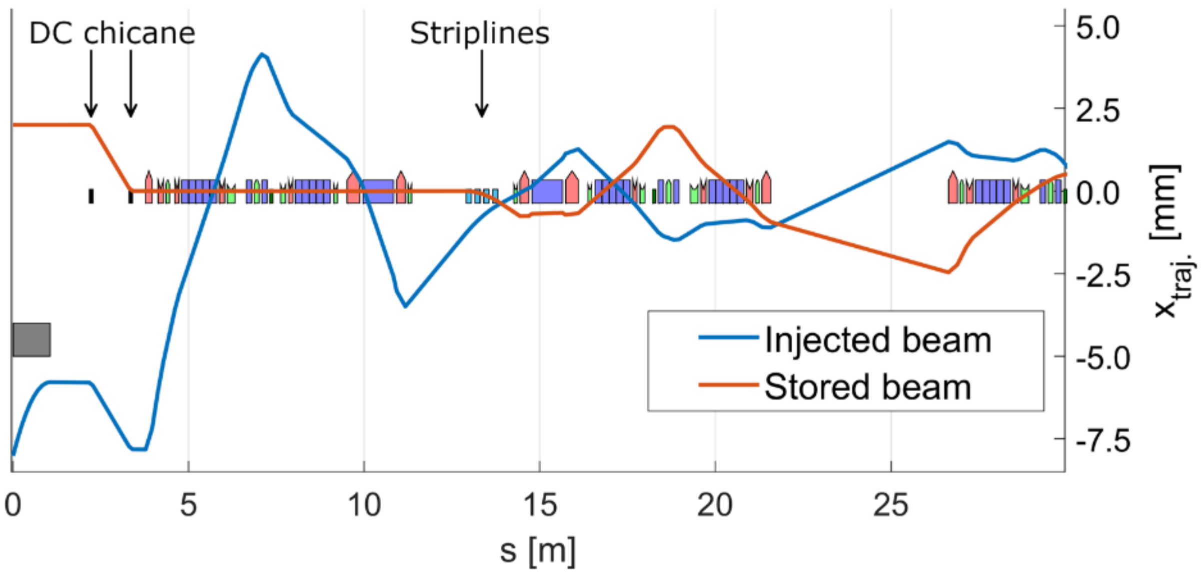
- Used for top-up injection with shutters open (improved transparency: 1-2 bunches in 899 kicked)
- 'Aperture-sharing' or 'kick-and-cancel' configurations

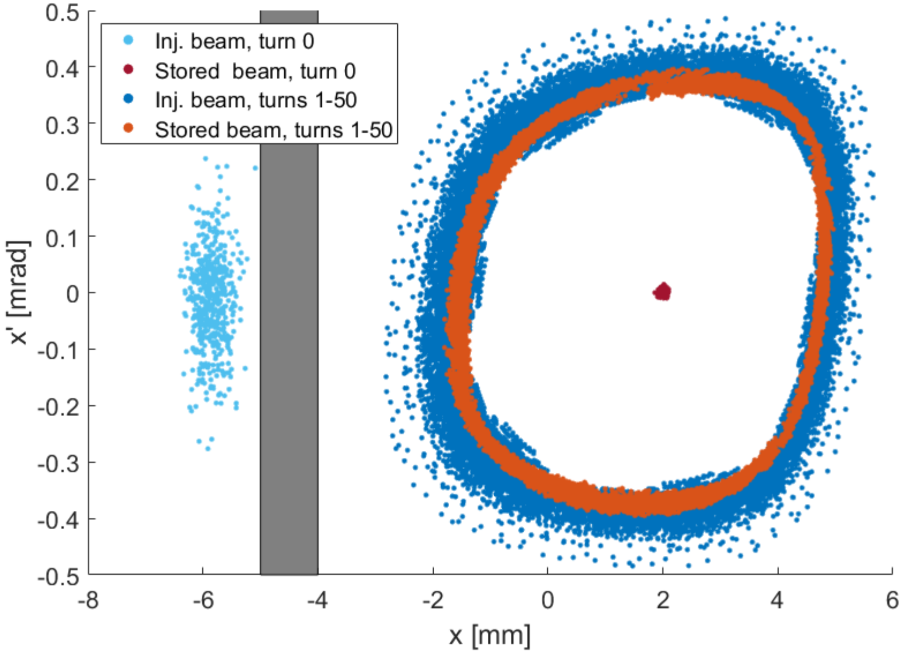
K01 Injection Straight





Aperture-sharing injection





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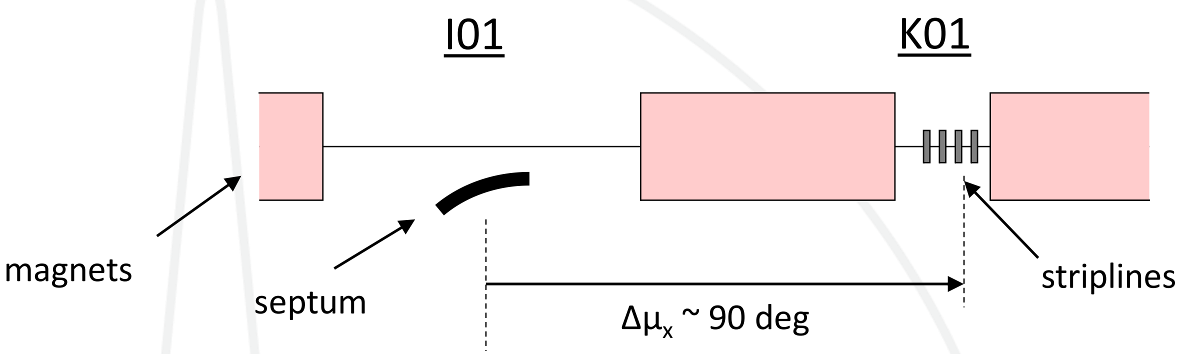
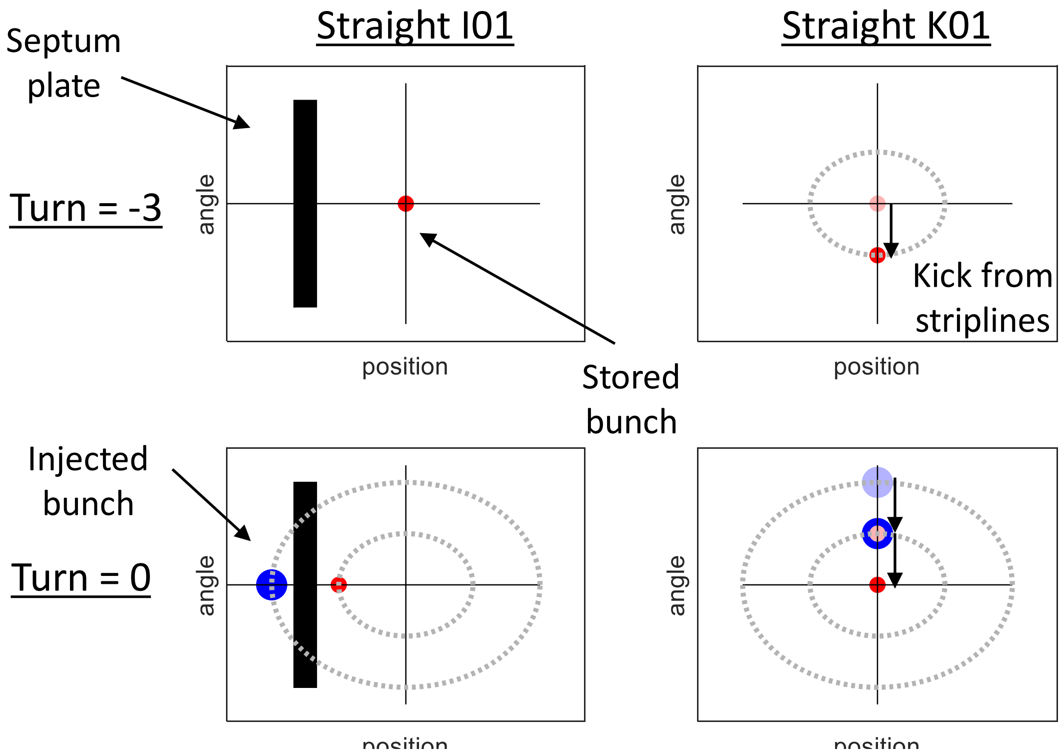
‘Kick and Cancel’ injection



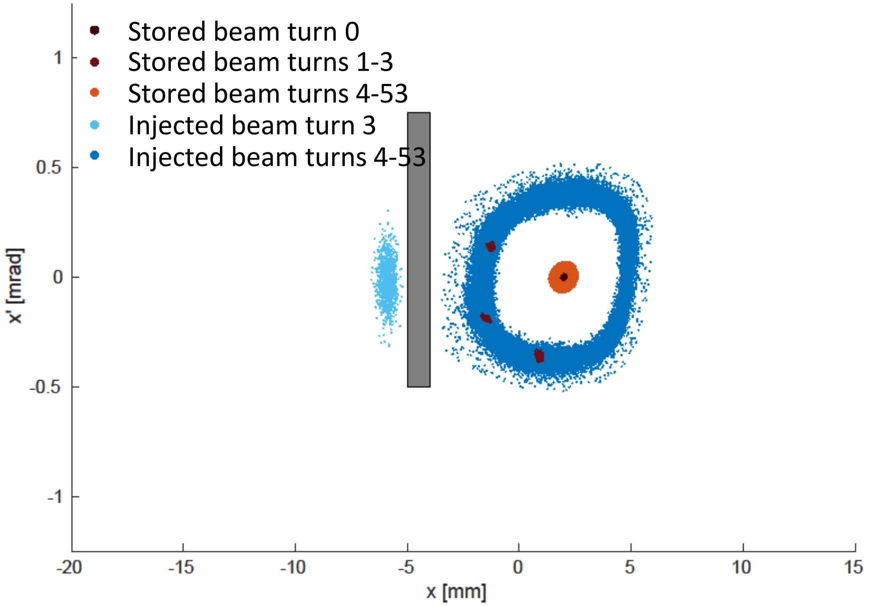


Pros:

- Improved overall transparency as only injected bunch continues to oscillate
- Reduced transverse wakefields / interaction with TMBF as stored bunch is back on-axis
- Potential to do further aperture sharing by over-kicking the stored bunch

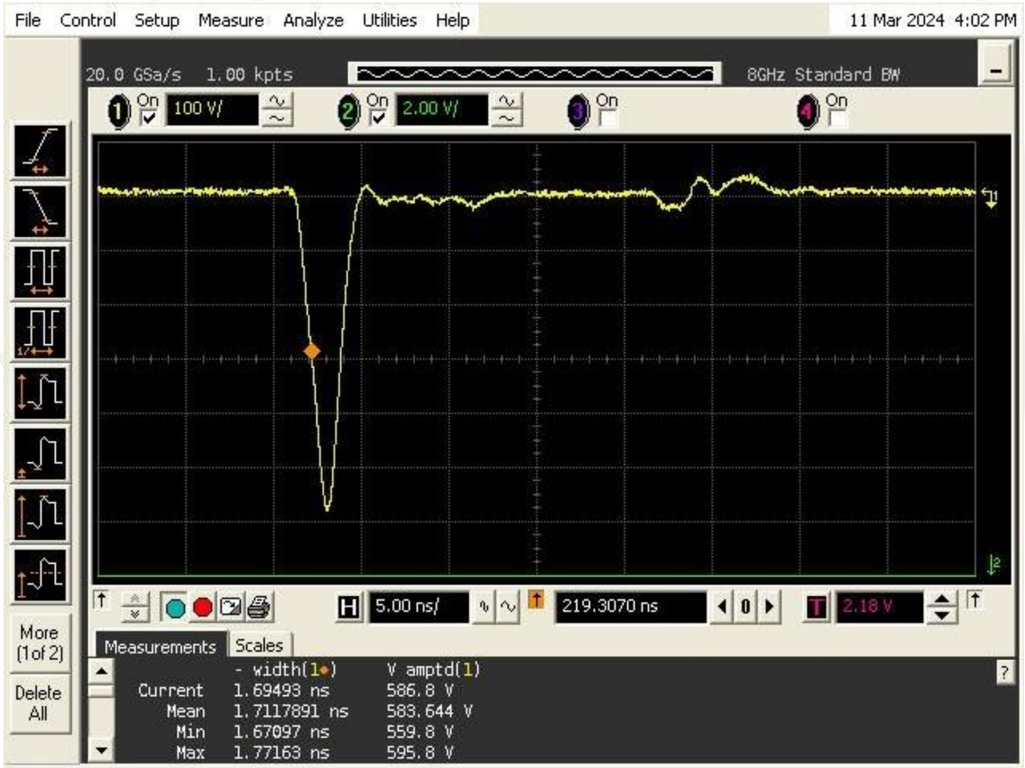
Cons:

- Pulser needs to deliver multiple pulses
- 3 ns pulses in multi-pulse mode not possible ? Longer pulses mean more bunches are kicked
- Sensitive to decoherence for stored bunch
- Cancellation not perfect for nominal betatron tune but still pretty good



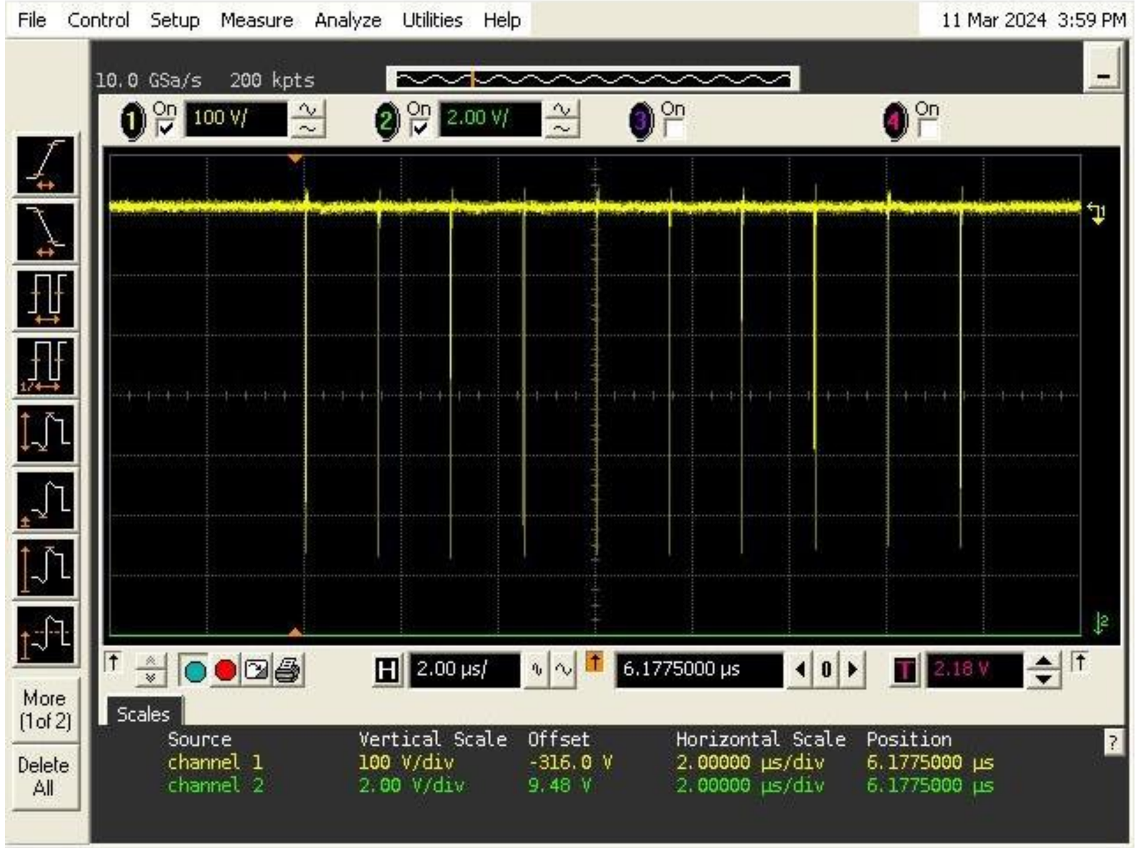
Pulser development

- A multi-pulse, high voltage pulser is under development by Kentech Instruments Ltd.
- The second stage prototype is currently being built:
  - ± 4 kV,
  - bursts of up to 10 pulses with programmable amplitude and spacing,
  - 5%-5% width ≤ 4 ns (best effort for 3 ns).



One of the pulses, shown at 5 ns/div.

Recent status:



Bursts of 10 micropulses with 1.5 us pulse separation at 1 kHz

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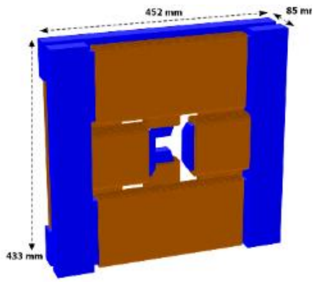
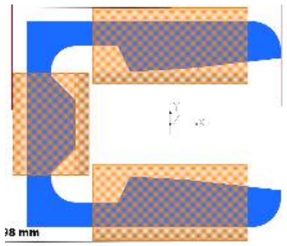
Magnets

Magnet type	Max. strength
Longitudinal gradient dipole (DL)	0.82 T
Transverse gradient dipole (DQ)	0.7 T, 33 T/m
Quadrupole	90 T/m
Sextupole	5,000 Tm^{-2}
Octupole	70,000 Tm^{-3}

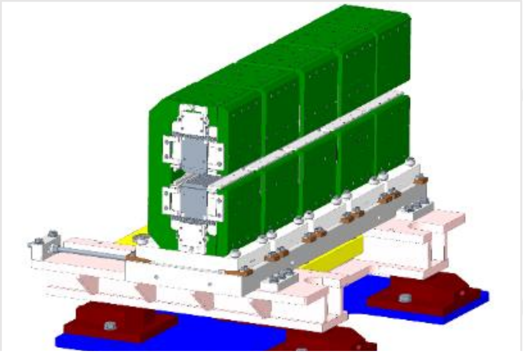
1032 magnets (excl. spares)
(456 in Diamond)



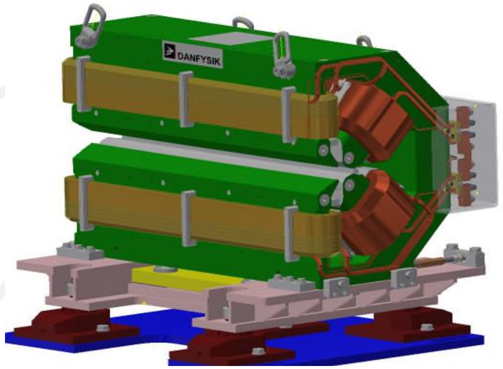
12 slow correctors



144 fast correctors

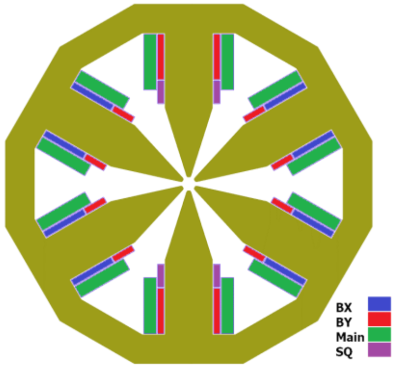


96 DLs

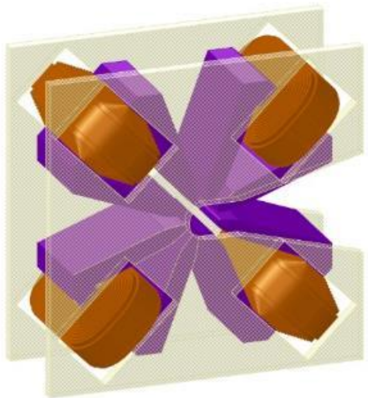


48 DQs

396 Quadrupoles



288 Sextupoles



48 Octupoles

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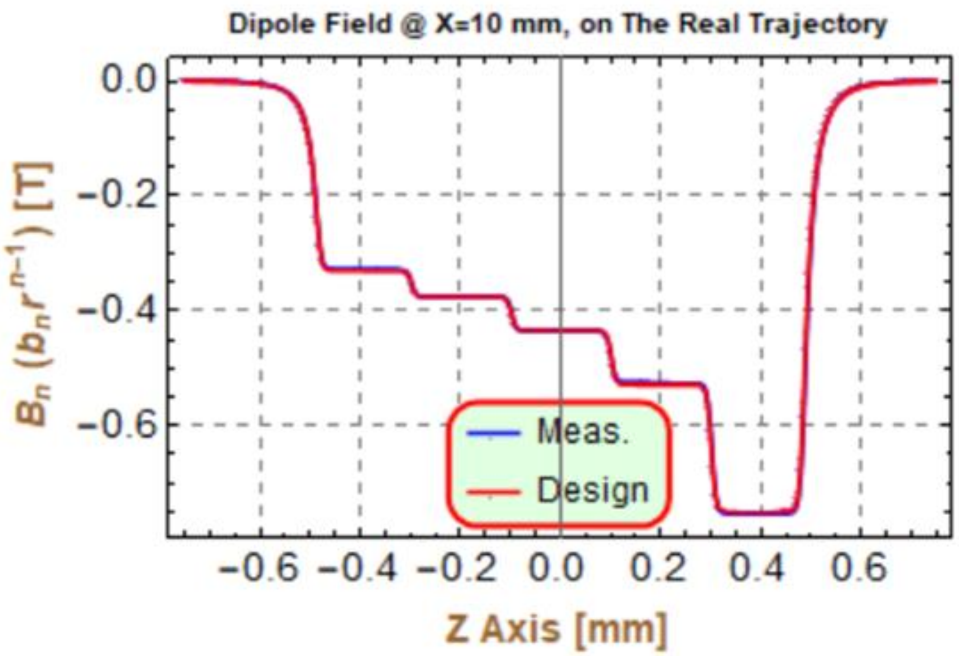
Magnets (ii)

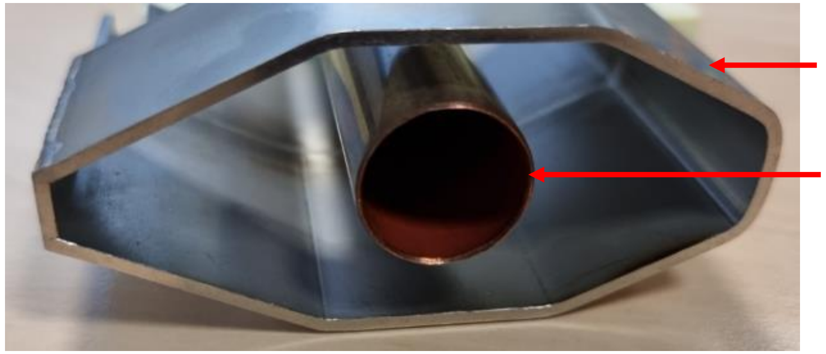
Status:

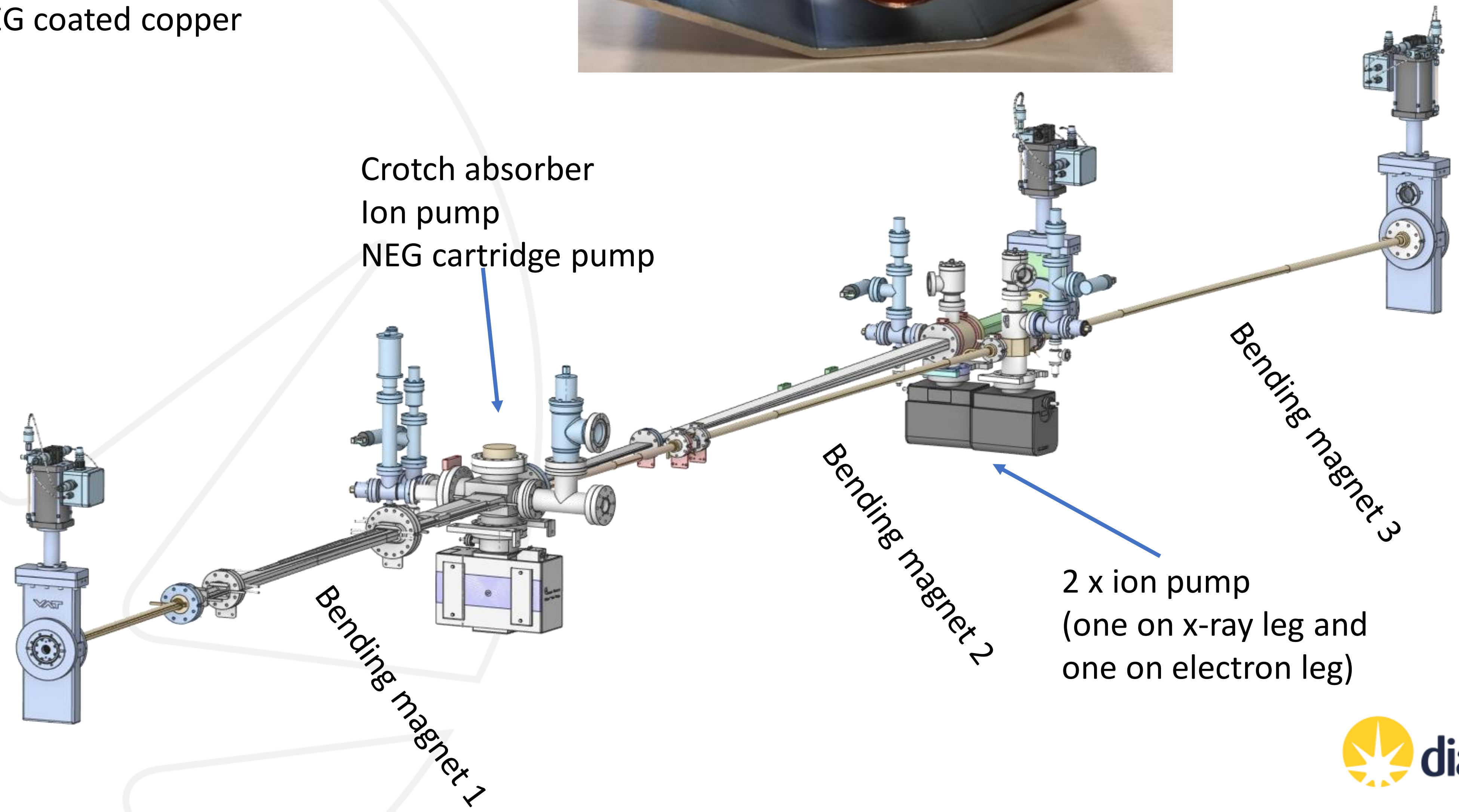
- DQ prototype built and tested
- DL prototype built in-house and tested
- Contract for quadrupole magnets imminent
- ITT for sextupole magnets has been launched
- Other ITTs to be issued soon



Vacuum

- Typical girder vessel string, of 4 different types
- ~ 8m long
- ~ 90% NEG coated copper





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Vacuum (ii)

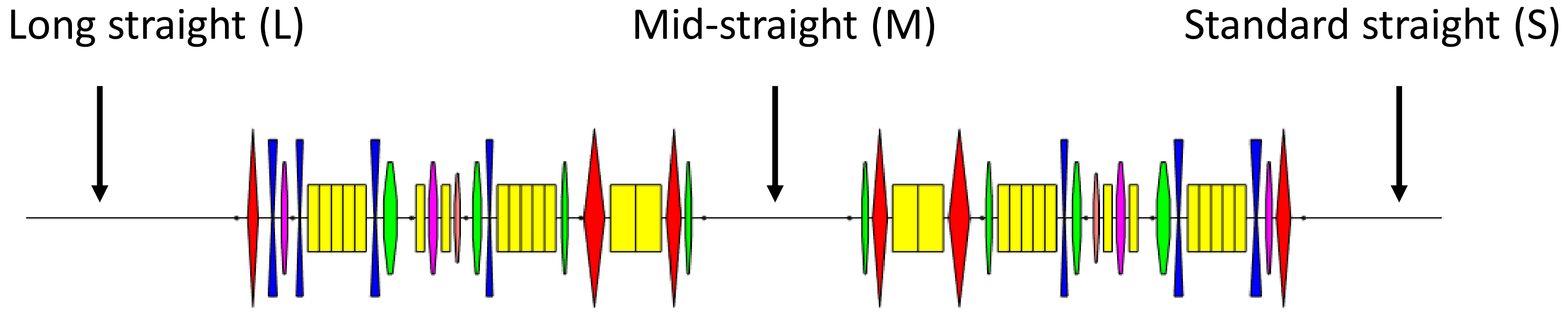
Status:

- A lot of prototyping and NEG coating trials are underway.
- Complete 8m vacuum string assembled and successfully baked-out (with previous Aluminium vessel 2).
- New copper vessel 2 due in March.
- Prototype kicker ceramic vessels produced and flange welding trials underway prior to Ti coating.

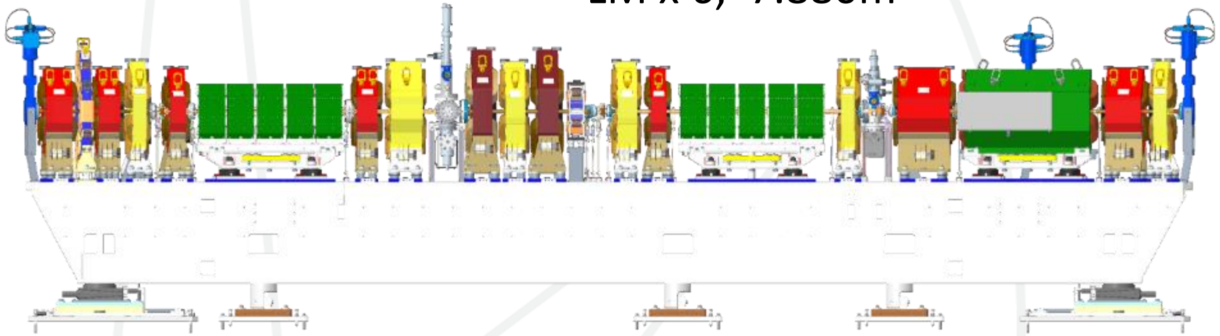
Vessel 2 the most complex vessel
~ 2m long, machined copper and stainless steel
integrated water cooling channels
made in 3 parts, joined then NEG coated

Engineering

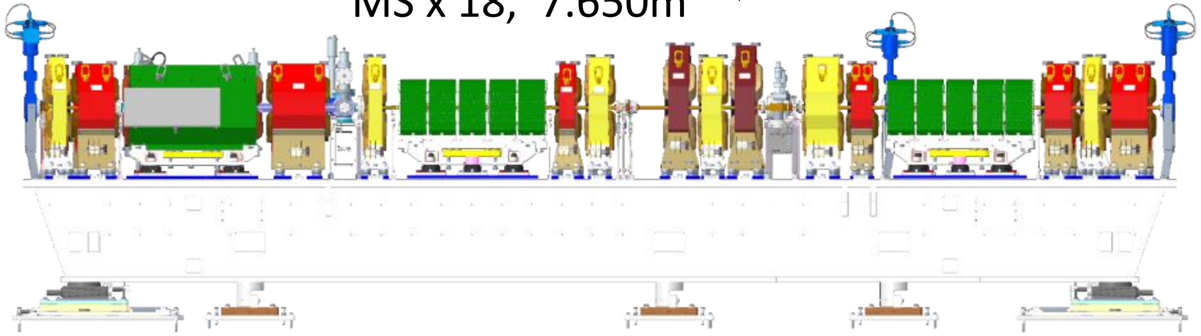
- The lattice design with mid-straights suggests use of two girders per cell, hence 4 girder types depending on what type of straight it connects.



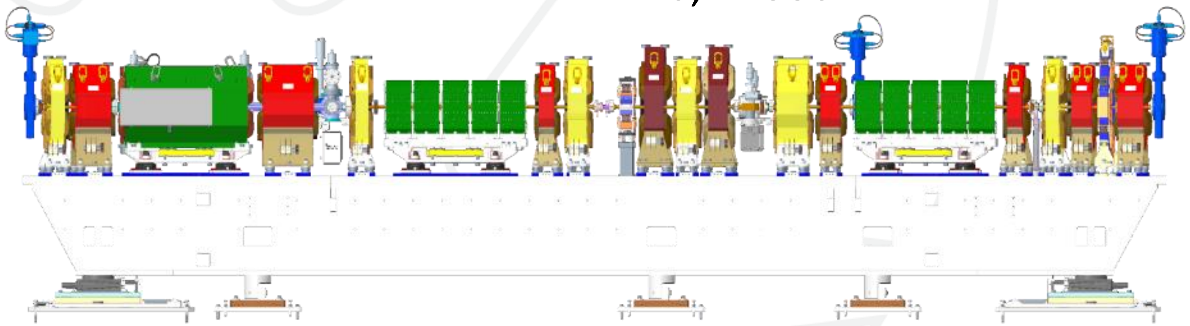
LM x 6, 7.880m



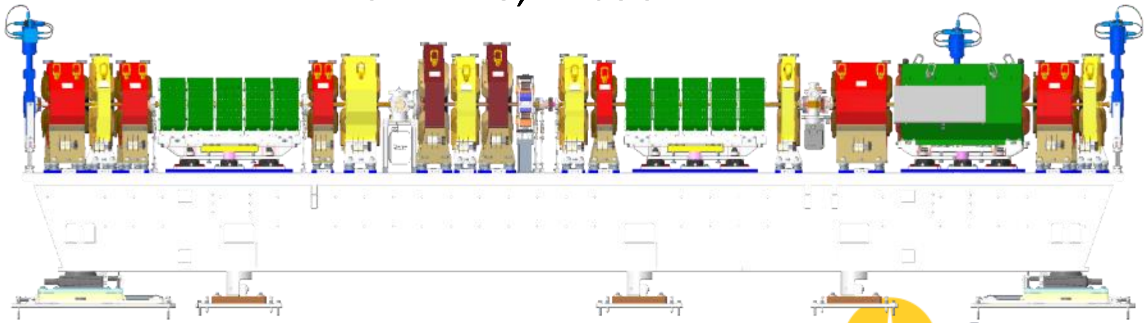
MS x 18, 7.650m



ML x 6, 7.880m



SM x 18, 7.650m



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- Prototype LM girder with dummy magnets, used for extensive vibration and alignment tests

- Vibration performance has been fed into detailed modelling of the effects on the electron beam and are acceptable to meet orbit stability requirements.
- It has been decided that motorization of girder movement is not required. It can be done quickly enough (within a few hours), and accurately, manually.
- Girders will have 8/10 supports but only 4 used for adjustment.

- Now being used to mock-up cooling water manifold, cable trays, cabling and patch panel

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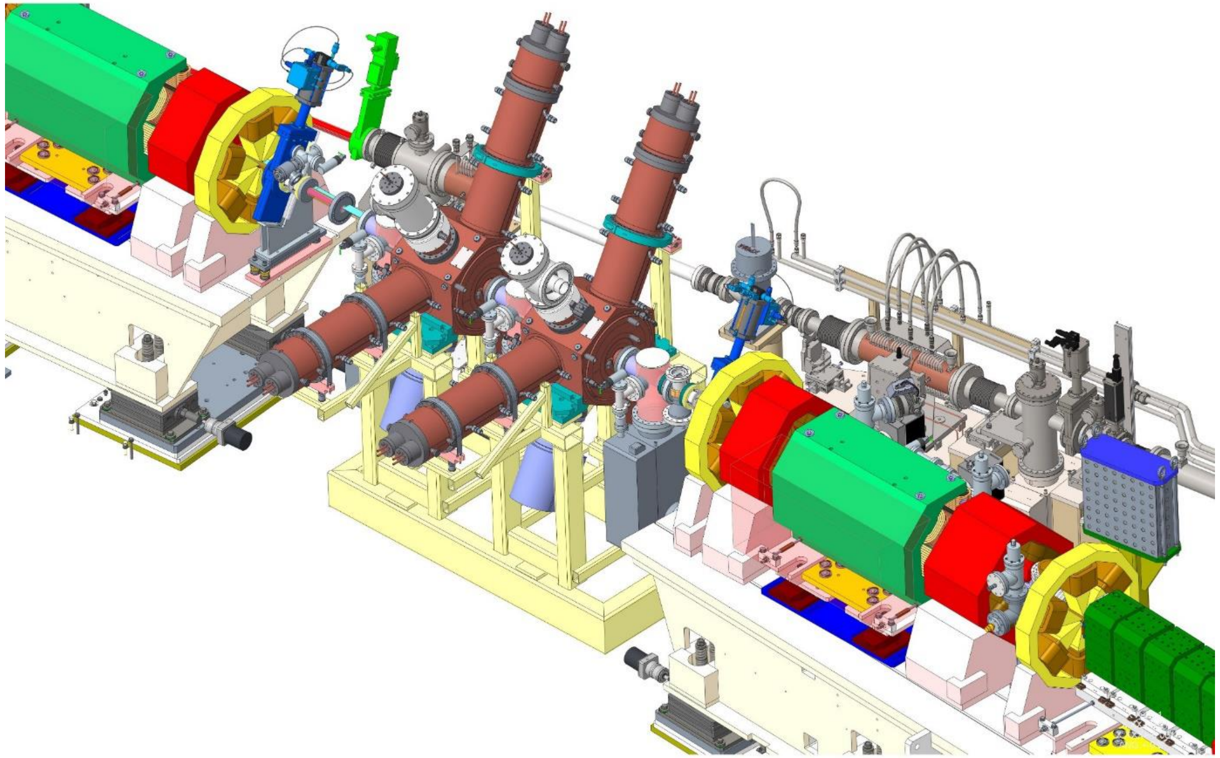
Radiofrequency

- Nominally 8 x 500 MHz EU normal conducting HOM damped cavities, initially 7, to replace the existing superconducting cavities which can't operate at the new storage ring RF frequency.

- The new cavities will be distributed around the ring, in pairs in the mid-straights. This frees the current RF long straight for use for one of the new 'flagship' beamlines.

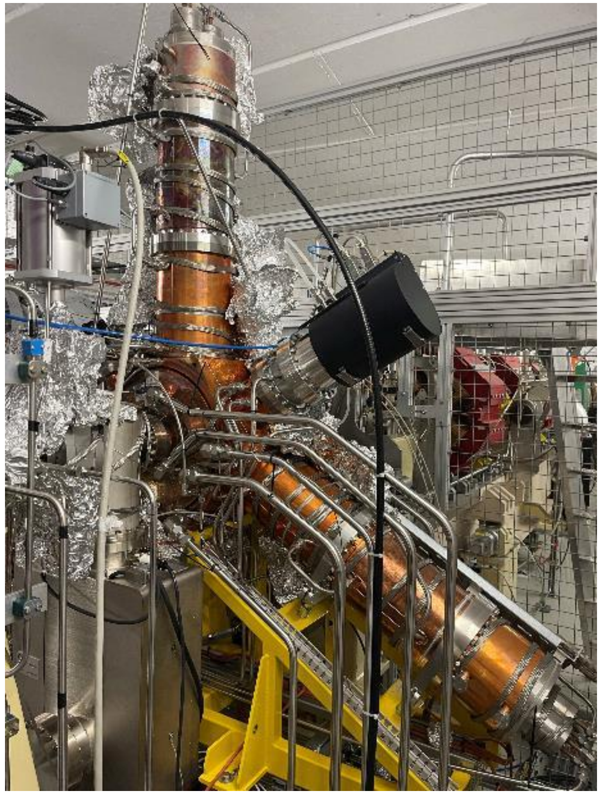
- Each cavity will be powered by an individual solid-state amplifier, replacing the unreliable and now obsolete IOT amplifiers.

- Passive superconducting 3^{rd} harmonic cavity will also be installed, potentially Super-3HC like, or alternative.



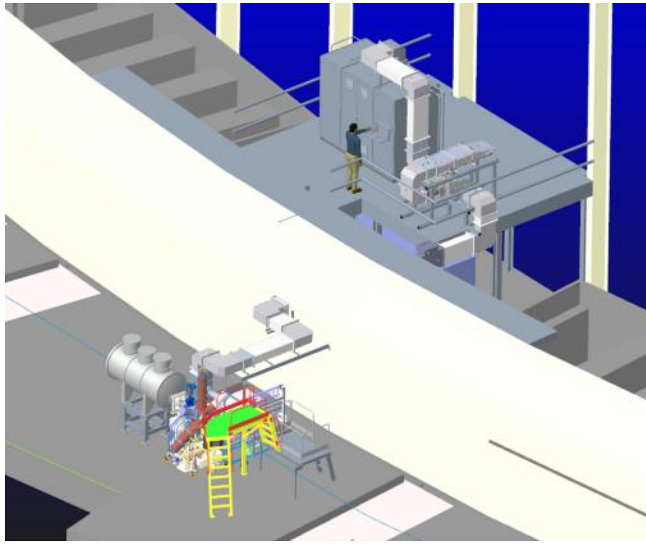
Radiofrequency (ii)

- We already have 3 normal conducting cavities in Diamond. These are for resilience of operation given numerous problems with superconducting cavities and IOT amplifiers.
- One set-up is identical to one the we will use for Diamond-II:
  - EU HOM damped cavity
  - 120 kW solid-state amplifier located on a "RF platform"
  - Digital Low-Level RF



Status:

- Contract placed for 6 solid state amplifiers.
- Tenders returned 18th March for the 3rd harmonic cavity.
- ITT for cavities to be issued soon.
- Aim is to have all equipment received and tested, and where possible installed (e.g. platforms and amplifiers), before the 'dark period'.



Diagnostics & Feedbacks

- Challenges for beam stability and emittance measurement

Parameter	Diamond	Diamond-II
Emittance H/V	2700 pm rad / 8 pm rad	160 pm rad / 8 pm rad
Beam size at sourcepoint H/V (standard straight)	123 µm / 3.5 µm	30 µm / 4 µm
Beam Position Monitor (BPM) block aperture H/V	80 mm / 22 mm	20 mm round 24 mm keyhole 26 mm round
Number of BPMs	175	252
Relative orbit stability (short term)	10% of H/V size up to 100 Hz	3% of H/V size up to 1000 Hz
Absolute orbit stability (short term) H/V (centre of standard straight)	12 µm / 0.35 µm	0.9 µm / 0.12 µm

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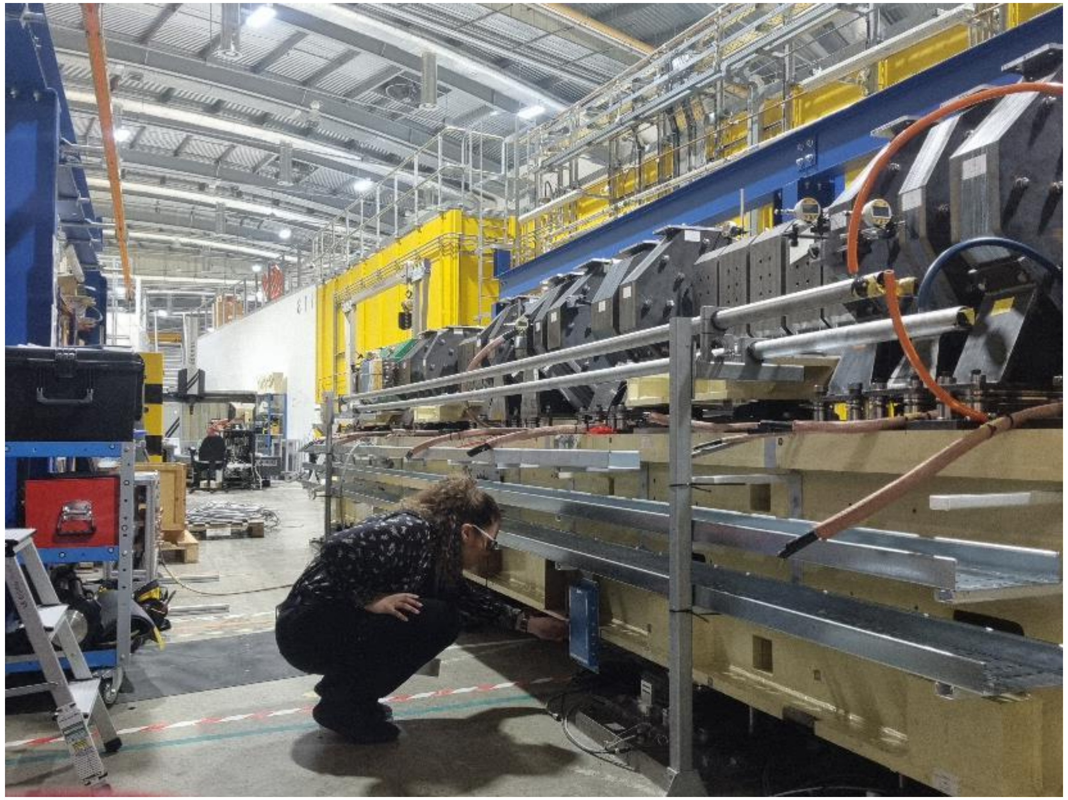
Diagnostics & Feedbacks (ii)

New requirements	New approaches
Improved short- and long-term orbit stability	In-house designed beam position monitor electronics using pilot tone compensation scheme to eliminate drift. Order of magnitude increase in feedback bandwidth. Analogue front-end in tunnel for best signal-to-noise ratio. Low latency centralised fast orbit feedback with 2 loops for slow and fast correctors. Invar supports for primary beam position monitors to mitigate thermal drift.
Beam size stability in both planes	Emittance feedback based on sideband excitation using the multi-bunch feedback system.



Diamond-II Analogue front-end location

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Insertion Devices

- 13 new Insertion Devices are needed for Diamond-II:
  - 2 for new ‘flagship’ beamlines
  - 4 for beamlines switching from an existing bending magnet to an insertion device source
  - 5 to replace existing devices which are too long to fit in Diamond-II
  - 2 to replace existing devices to maintain (or improve) the energy tunability with the new machine energy

- These comprise:
  - 1 x CPMU
  - 4 x HPMU
  - 5 x APPLE-II
  - 1 x 3PW
  - 1 x EMPHU
  - 1 x APPLE-Knot

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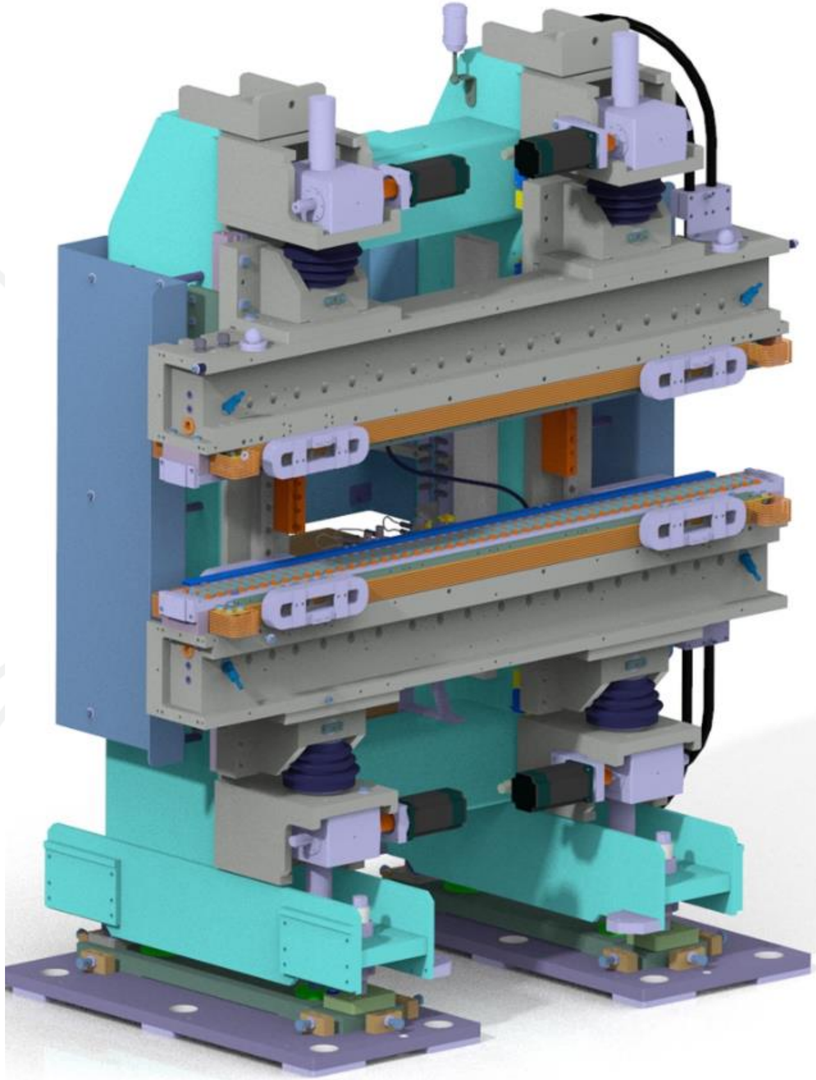
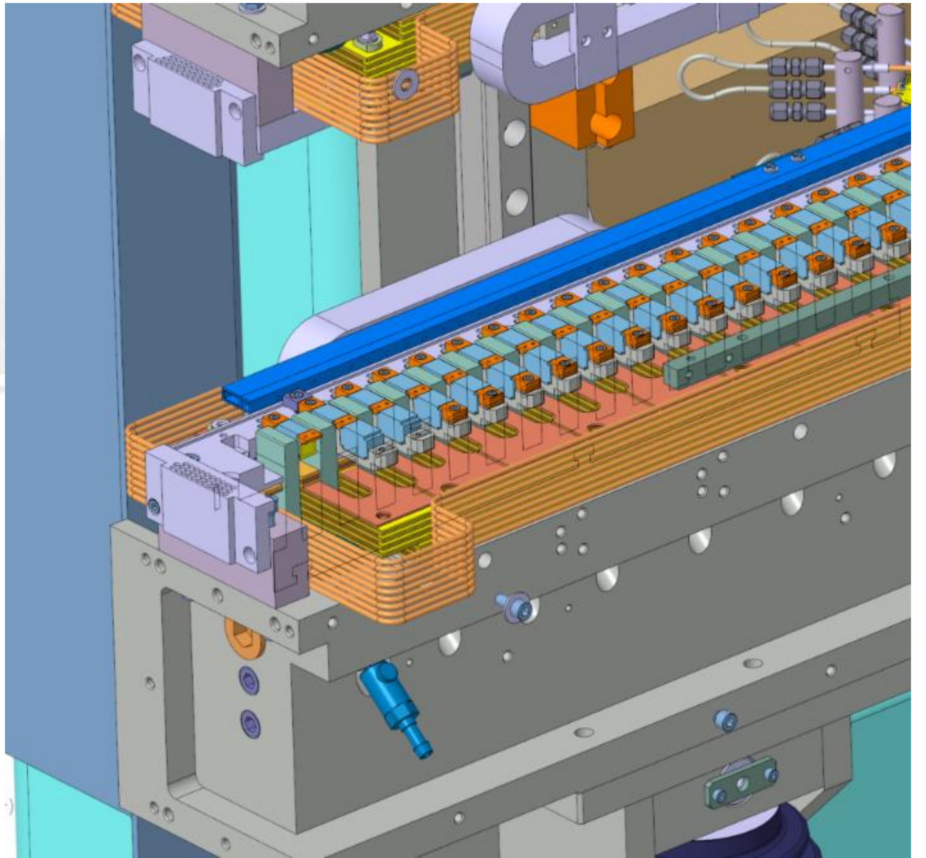
Insertion Devices (ii)

Electromagnetic/Permanent Magnets Helical Undulator (EMPHU)

- Based on the existing SOLEIL device.
- Vertical field produced by coils around poles.
- Horizontal field produced by permanent magnets.
- Produces pure helical field with ‘fast’ switching R/L or static linear vertically polarized radiation.
- SOLEIL device employs air cooled coils, we are aiming to avoid that with water cooled coils.

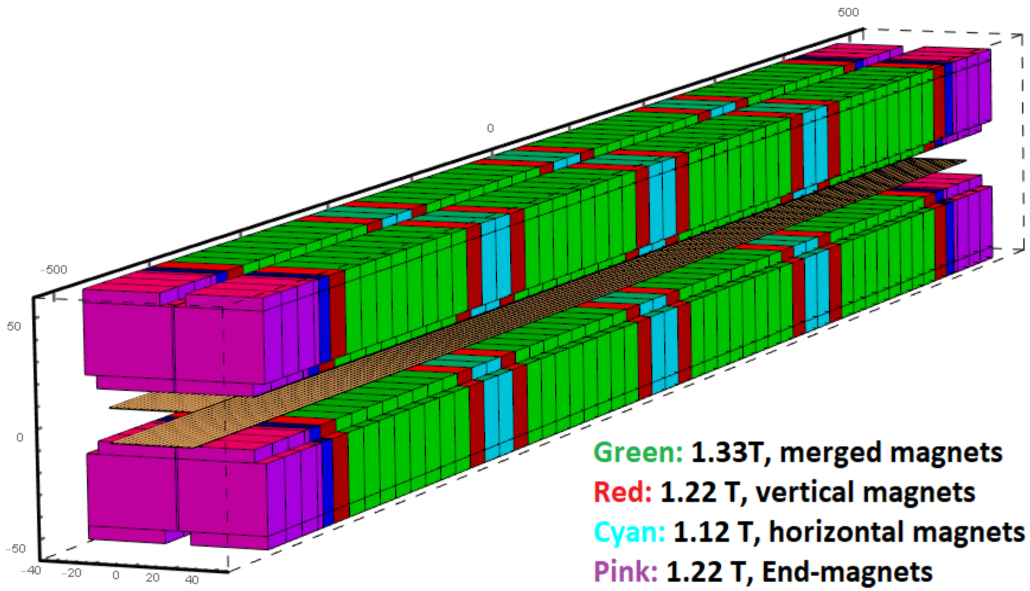




Insertion Devices (iii)

APPLE-Knot

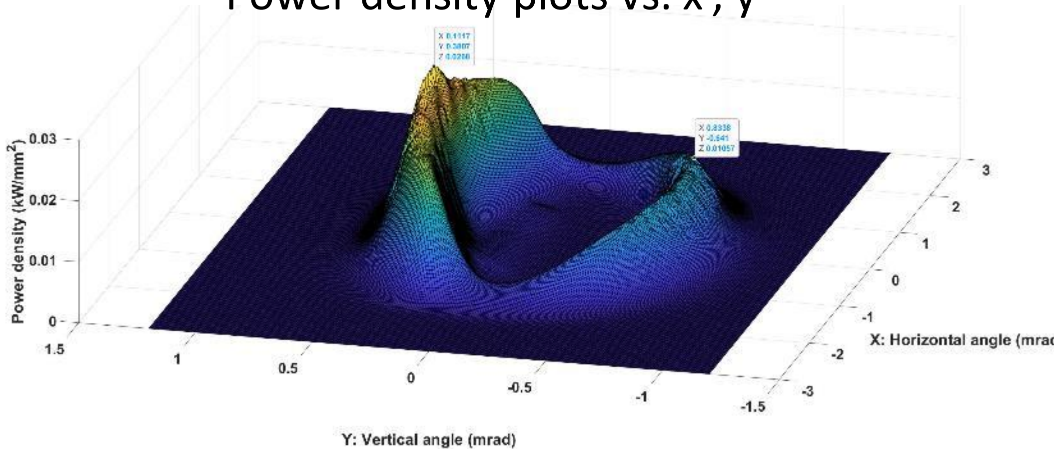
- Required to reduce the power density on-axis because of increased machine energy
- Opportunity will be taken to improve performance: current APPLE device operates down to 18 eV at 3 GeV, new APPLE-II device designed to reach **10 eV at 3.5 GeV**
- Slightly modified design from the original concept with end sections to compensate the trajectory deviation.



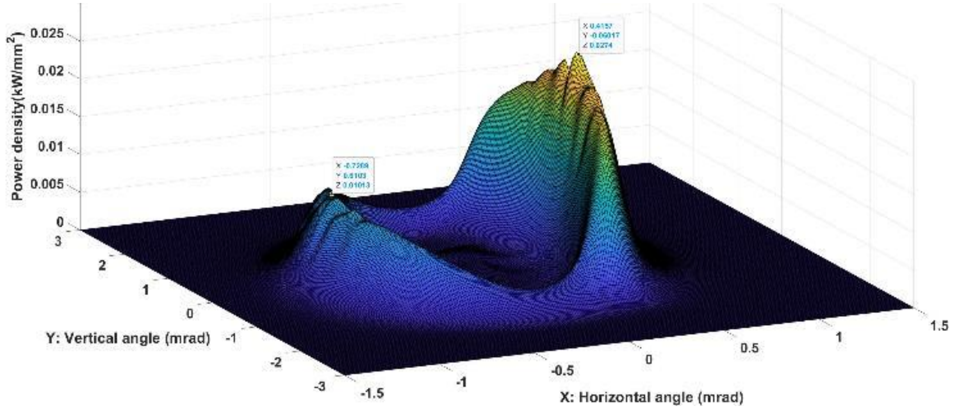
Power density plots vs. x', y'

Polarization

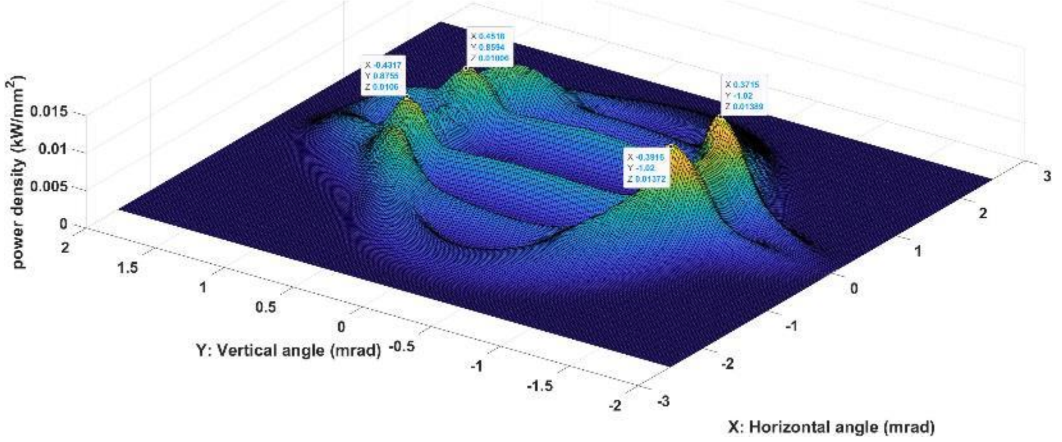
H



V



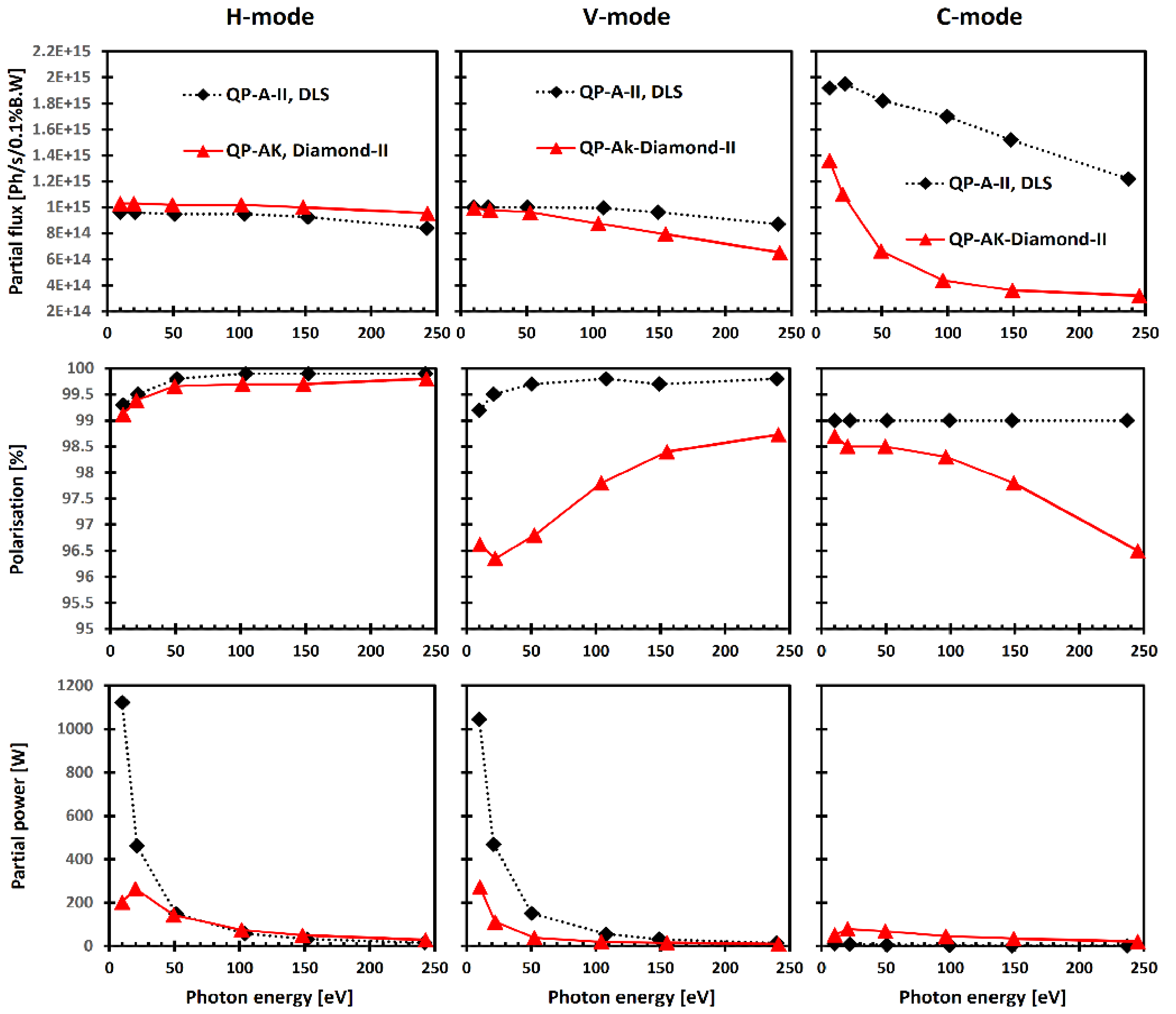
C



Insertion Devices (iv)

APPLE-Knot performance

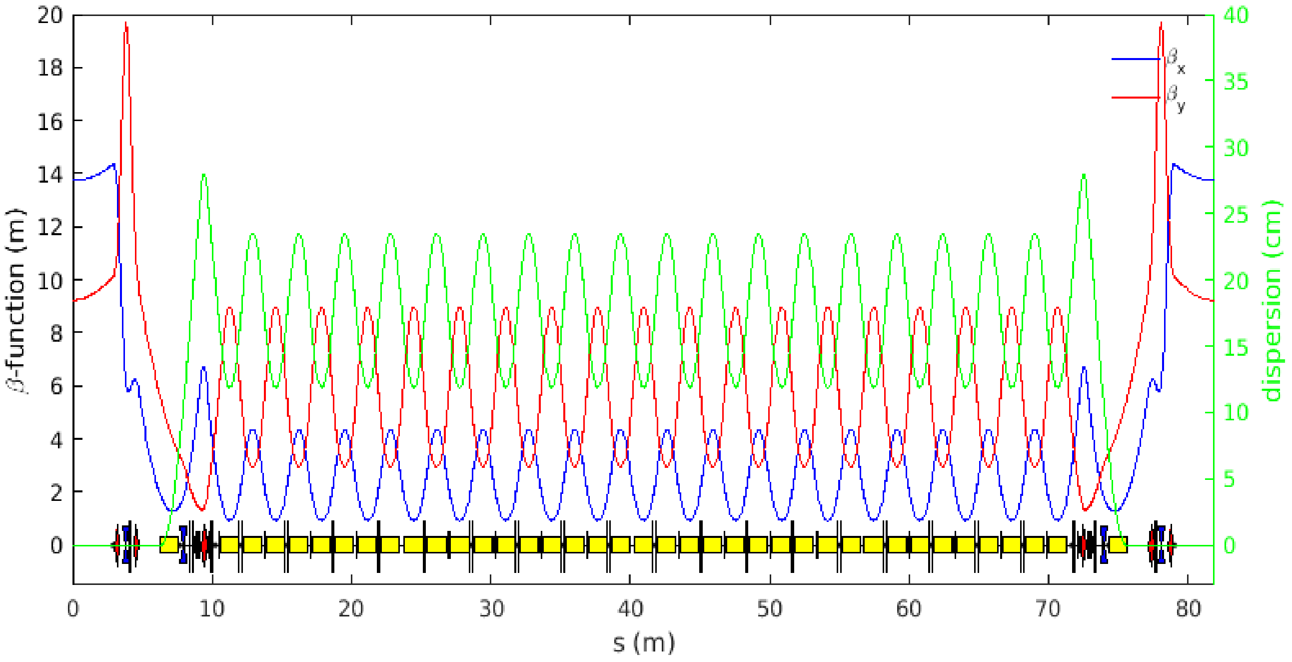
- Slightly worse performance than APPLE device in Diamond in terms of Polarization and Flux in V and C mode
- Much reduced power at low photon energies
- Accepted by the beamline.



New Booster

- New booster ring required with smaller emittance and bunch length to allow injection in Diamond-II

Parameter	Units	Diamond	Diamond-II
Energy Range	GeV	0.1 - 3.0	0.15 - 3.5
Number of Cells	-	22	36+4
Repetition Frequency	Hz	5	5
Circumference	m	158.4	163.8
Betatron Tunes	-	[7.18, 4.27]	[12.41, 5.38]
Emittance	nm rad	**134.4**	**17.4**
Energy Spread	%	0.073	0.086
Energy Loss per Turn	MeV	0.58	0.95
Nat. Bunch Length	ps	**99.3**	**38.0**



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Diamond-II Beamlines

- **3 Flagship new Beamlines**
  - SWIFT: Fast Operando Spectroscopy
  - K04: Ultra-high throughput for MX and Xchem
  - CSXID: Coherent Soft X-Ray Imaging and Diffraction

- **4 Bending Magnet Beamlines converting to ID Beamlines**
  - B07: Versatile Soft X-ray (VerSoX) Beamline
  - B16: Test Beamline
  - B18: Core XAS
  - B21: High-throughput small-angle X-ray scattering

- **3 Bending Magnet Beamlines with extensive front-end changes**
  including mirrors in the front end, but not to the beamlines
  - B22: Multimode InfraRed Imaging and Microspectroscopy
  - B23: Circular Dichroism
  - B24: 3D Correlative Cryo-Imaging

- **Critical Beamline Upgrades**
  - Upgrades required to optics, shielding, slits, diagnostics, collimators, windows etc., to enable the beamlines to operate in Diamond-II.

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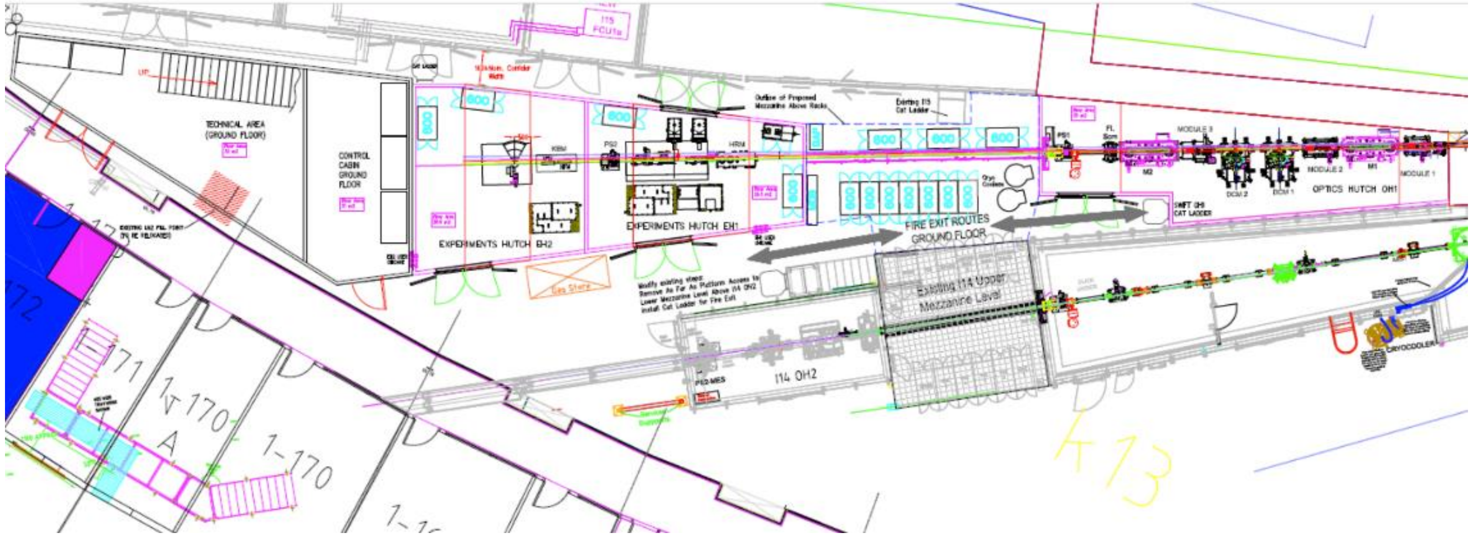
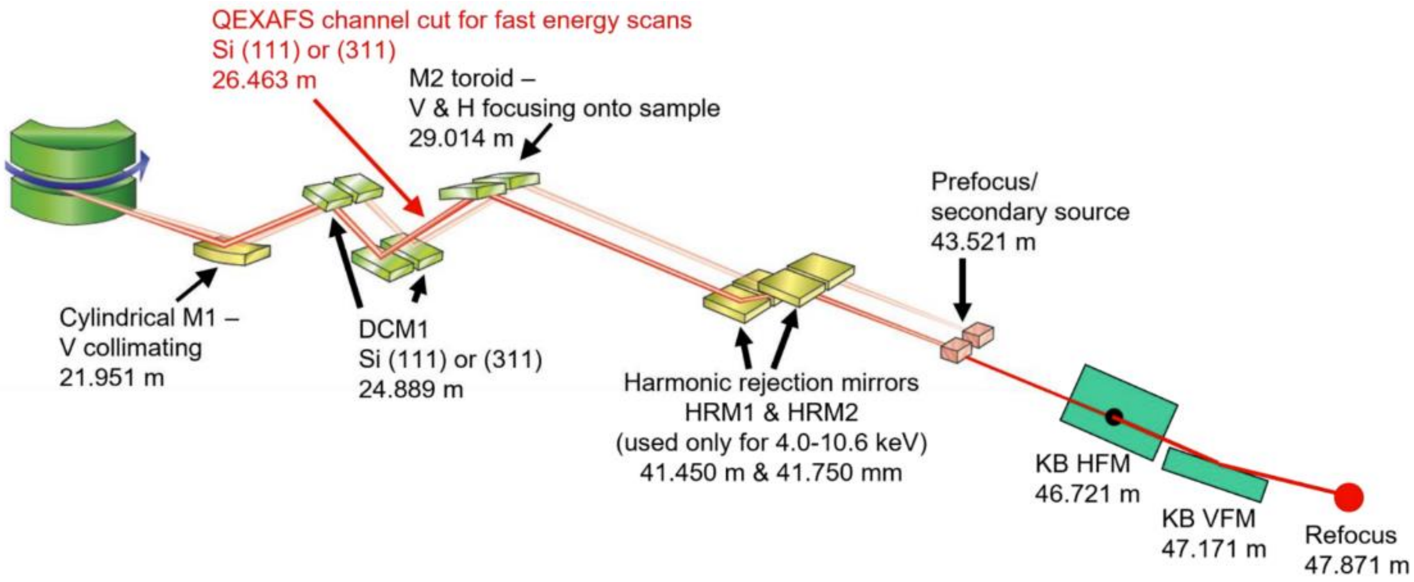
SWIFT – Spectroscopy WIthin Fast Timescales

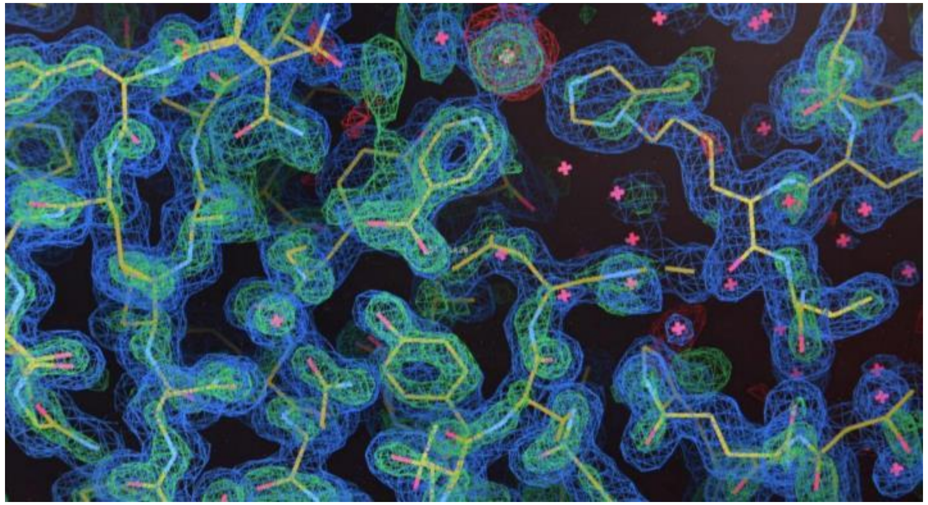
- Studies of dynamic phenomena with Quick-EXAFS in the Hard X-ray region
- Nanoparticle chemistry, metalloenzymes, catalysis, battery research, environmental and earth sciences
- Multipole wiggler source
- Fast-scanning DCM (50Hz, 4-35 keV), fast detectors and data acquisition
- End-station 1: high flux, operando studies, dilute systems, 100 μm x 100 μm
- End-station 2: microfocus 20 μm x 20 μm , chemical mapping, tomography
- Operando sample environments:
  - high temperature (1000 ^{o}C furnace)
  - gas flow reaction cells
  - liquid flow reaction cells
  - electrochemistry

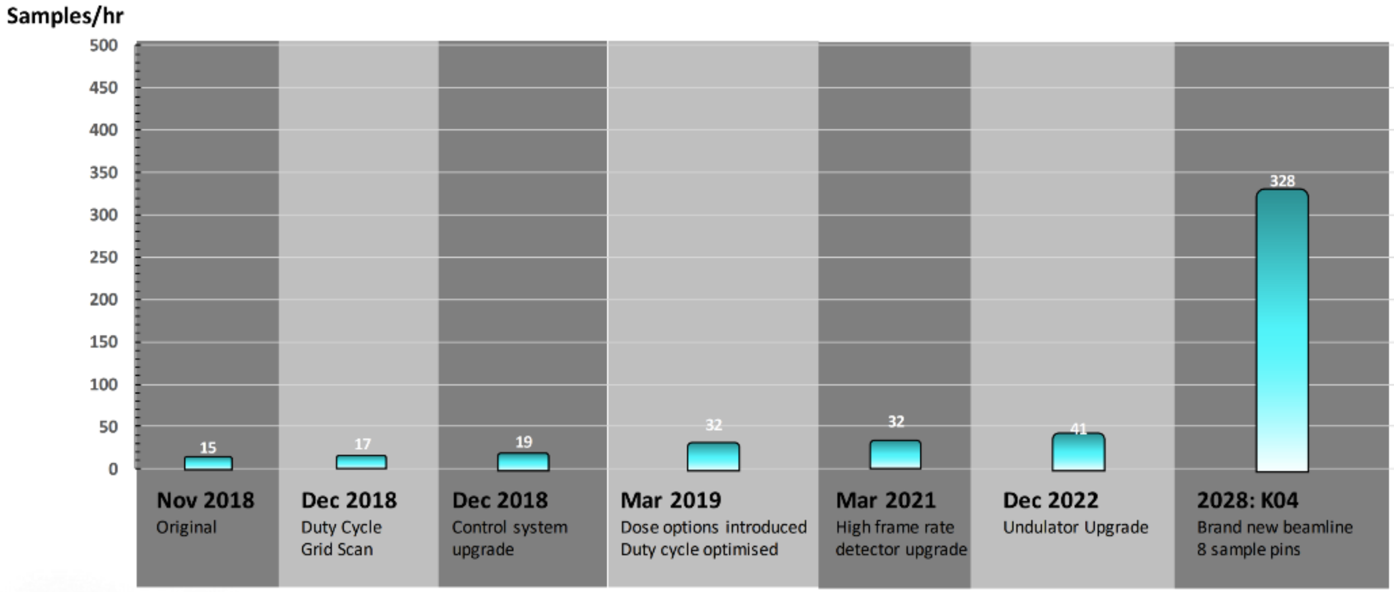


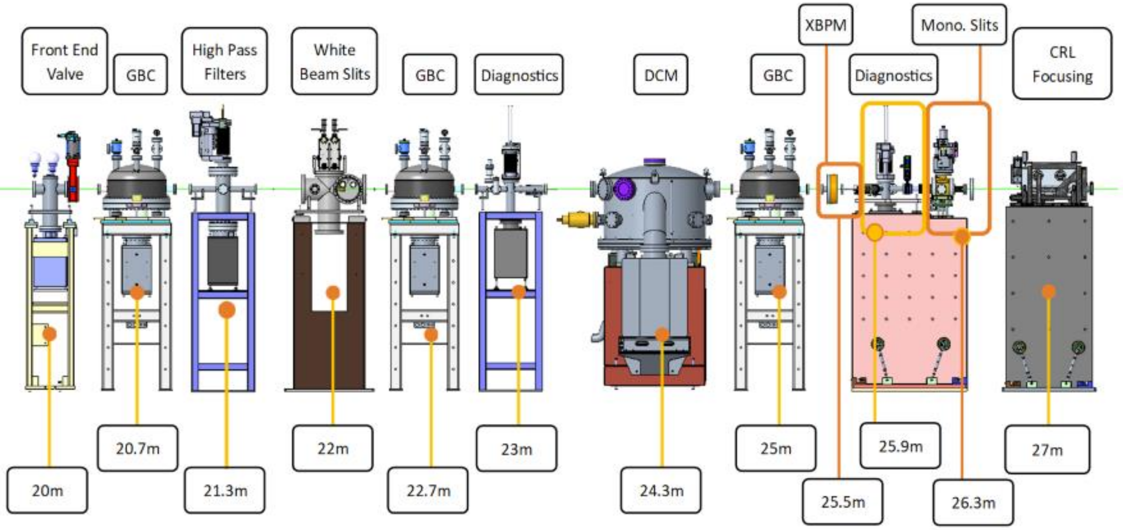


K04 – Macromolecular Crystallography and Fragment Based Drug Discovery

- New beamline as part of a suite of 7 MX beamlines
- Replacement of the existing I04-1 Xchem fixed-energy side-station with a new variable energy beamline in a different location
- Massively increased throughput and automated data collection: 1,500 single crystal samples per day, or > 5,000 of multiple crystal samples per day
- Beam sizes 5-50 μm, crystals down to 10 μm in size.

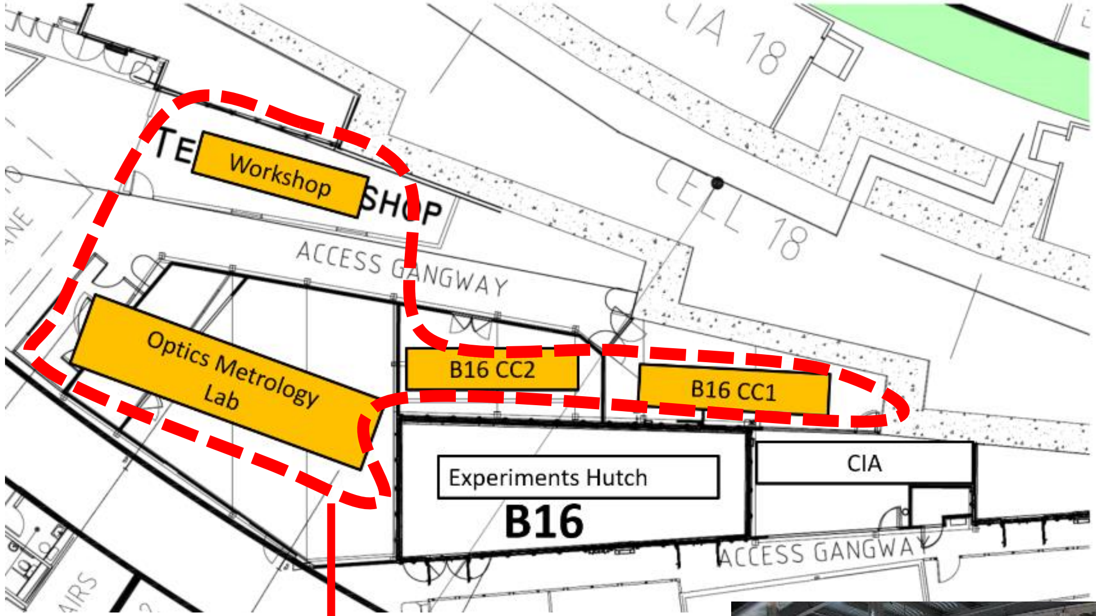


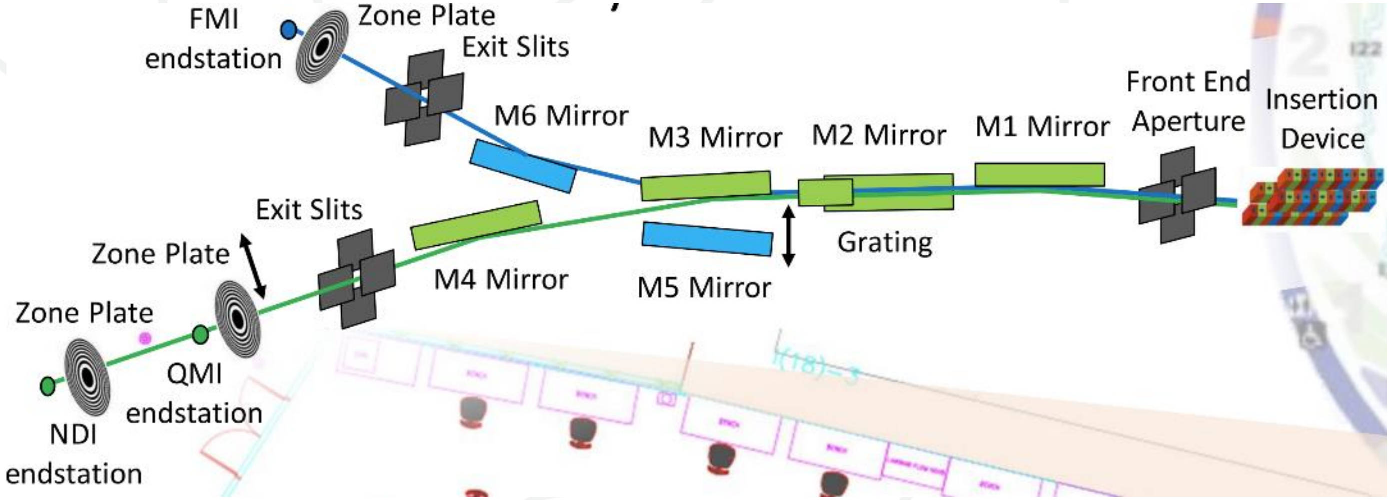




CSXID – Coherent Soft X-ray Imaging and Diffraction

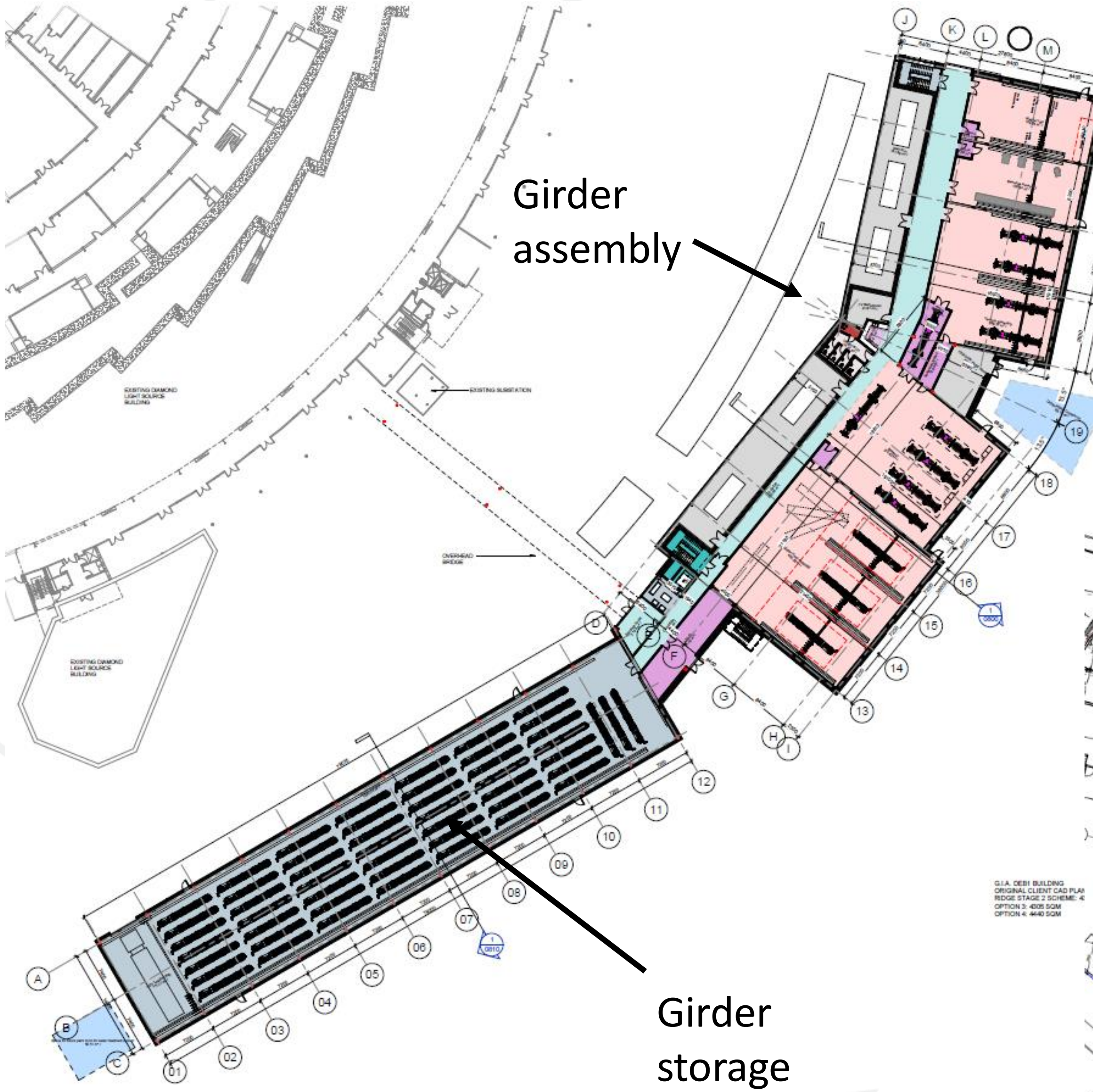
- 5m APPLE-II undulator source using the current long RF straight (I17)
- 0.25 – 3.5 keV
- End-station 1: quantum materials imaging
  - 0-250 mT, 20-300K, electrical excitation and biasing
- End-station 2: functional materials imaging
  - gas mixing cell for catalysis studies etc.
  - liquid flow cell for battery research etc.

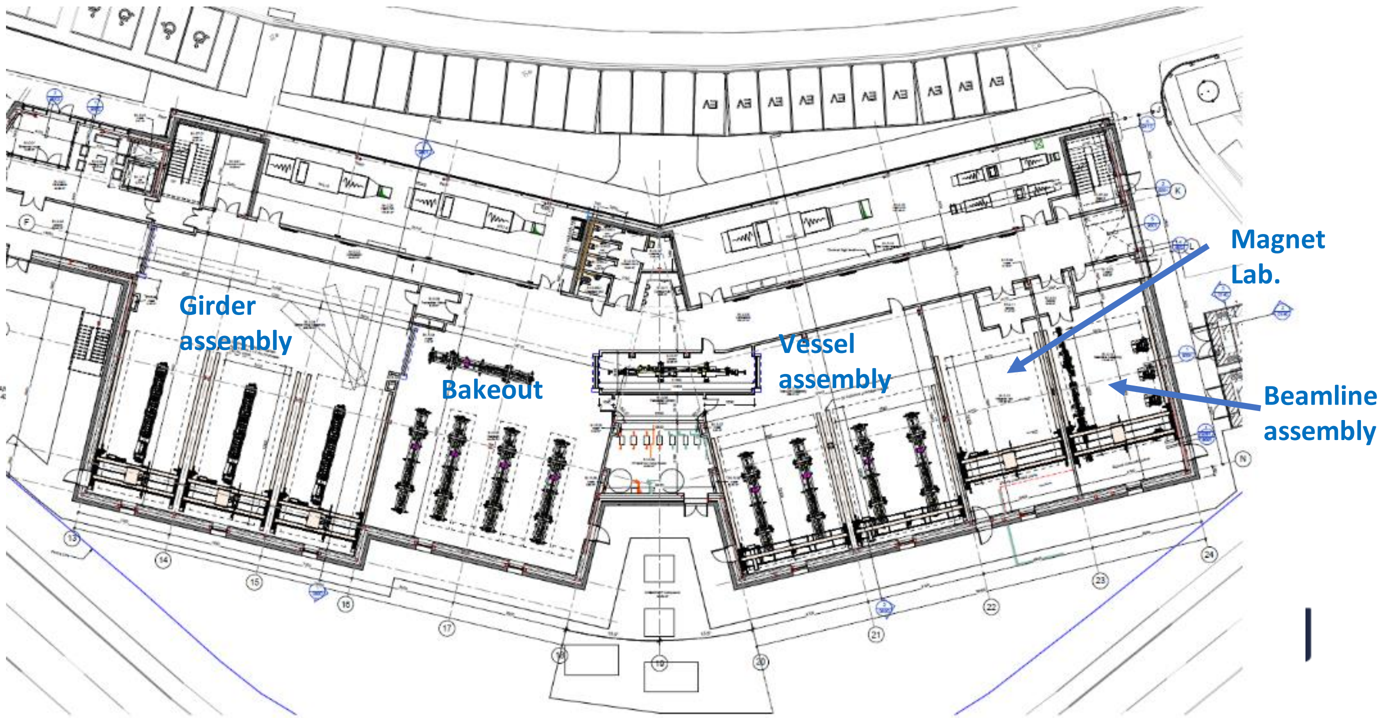




All of these have been relocated and now ready to start hutch construction

Diamond Extension Building





Diamond Extension Building (ii)

- ❑ Contract award 12th December 2023
- ❑ Completion February 2025

DEB1:
- ground floor: magnet measurement, vacuum assembly and bakeout, girder assembly etc.
- 1st floor: offices and labs etc.

DEB2:
- girder storage and girder mock-up
- will be re-purposed after Diamond-II

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Key Project Milestones

- Project approval and first Calls For Tender – Jul. 2023
- Completion of Diamond Extension Building – Feb. 2025
- Start of the Diamond-II shutdown (the 18-month “dark period”) – Dec. 2027
- Start of machine commissioning – Dec. 2028
- Start of regular beamline X-ray commissioning – Jun. 2029
- First phase of operational beamlines – Sep. 2029
- First User on a flagship beamline – Jan. 2030
- Diamond-II Project completed – Mar. 2030

Acknowledgements

- Accelerator Physics: Ian Martin
- Beamlines: Andy Dent
- Buildings & Infrastructure: Pete Coll
- Diagnostics & Feedbacks: Lorraine Bobb
- Engineering: Paul Vivian
- Insertion Devices: Steve Milward
- Magnets: Chris Bailey
- RF: Arash Kaftoosian
- Vacuum: Mathew Cox

... and many others in the Diamond-II Team

Thanks for Your Attention

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