Diamond-II Progress

Ian Martin,
on behalf of the Diamond-II design team

3rd Workshop on Low Emittance Lattice Design
27/06/2022

Talk Outline

1) Diamond-II Design:
   - Initial goals / design constraints
   - Cell layout
   - Optimisation strategy
   - Main parameters
   - Injection scheme => Talk by Jonas Kallestrup

2) Performance studies carried out for TDR:
   - Magnet cross-talk
   - Collimation
   - Impact of IDs
   - Simulated commissioning
   - Collective effects => Talk by Teresia Olsson
   - Final performance estimates

3) Timeline

4) Conclusions

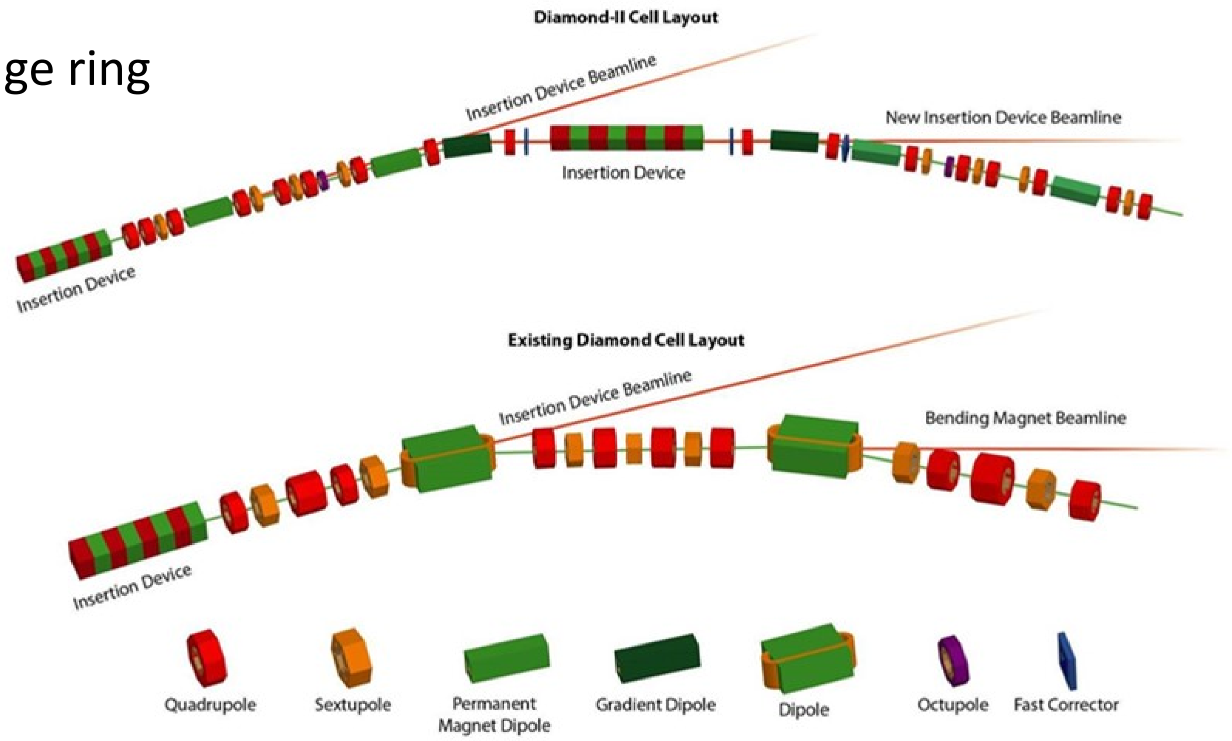
Diamond-II Design Goals

Design Goals for Diamond-II:

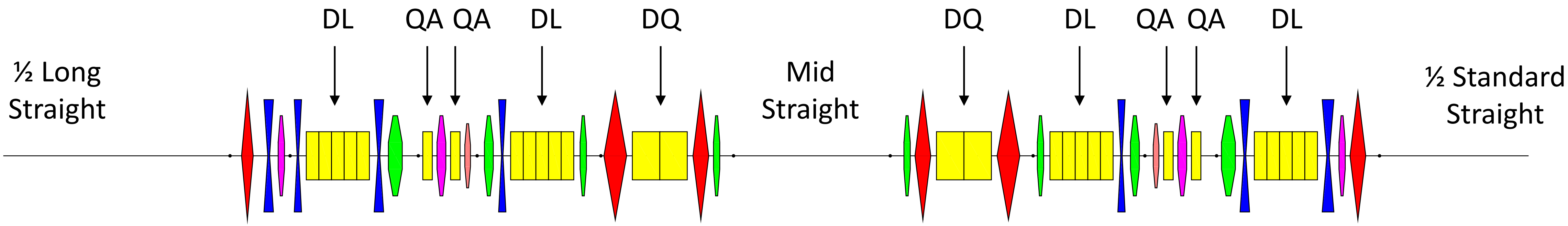
1) Optimise the science enabled at Diamond
2) Maximise the impact it has for researchers both in universities and in industry

Achieved through integrated approach:

- New Modified Hybrid 6-Bend Achromat (M-H6BA) storage ring
  - Combines ESRF-EBS and Diamond DDBA
  - Lower emittance (x17-25, depending on IDs)
  - Double number of straight sections
- Raise energy from 3 GeV to 3.5 GeV
  - increase flux and brightness above 10 keV
- Upgrade IDs / new flagship beamlines
- Improved data handling/computation, automation, ...



Diamond-II Lattice



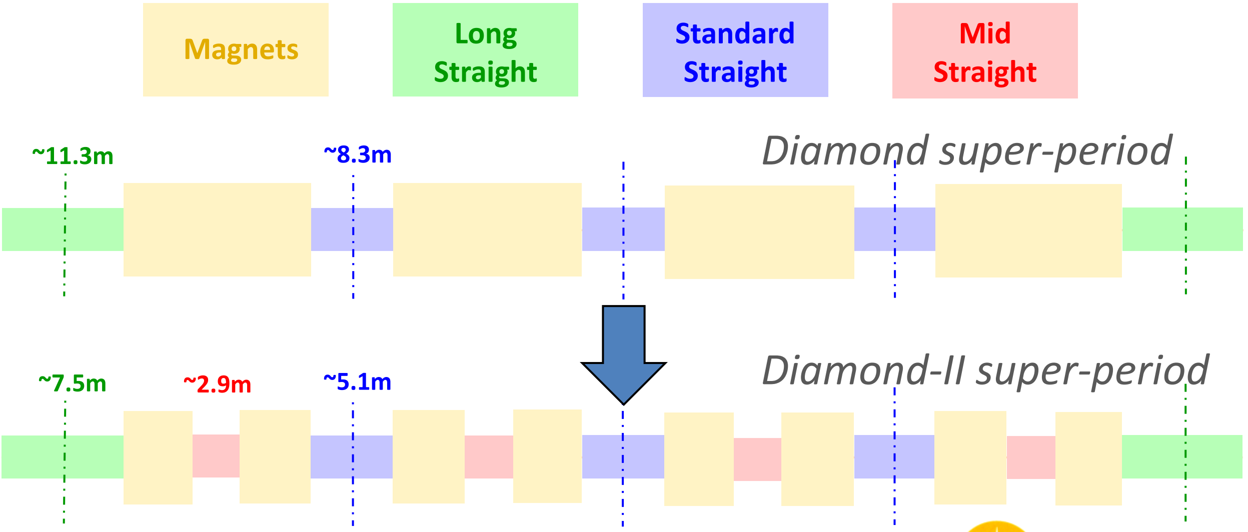
Each cell consists of:

4 longitudinally-varying dipoles (DL)
2 transverse gradient dipoles (DQ)
4 offset quadrupoles producing anti-bends (QA)

12 (13) quadrupoles
12 sextupoles with windings for SQUAD / HCV / VCM
2 octupoles

>35 % of the ring consists of insertion straights (quad to quad)

Combines low emittance with high capacity



Diamond-II Design Constraints

Magnet	Maximum Strength
Quadrupole	90 T/m
Anti-bend (high gradient)	80 T/m (3.6 mm offset)
Anti-bend (low gradient)	60 T/m (7.8 mm offset)
Skew quadrupole	2 T/m
Sextupole (narrow bore)	5,000 T/m^2
Sextupole (wide bore)	3,500 T/m^2
Octupole	70,000 T/m^3

Layout developed in close collaboration with engineers:

1) Existing ID source-points to be retained
2) Magnet separation limited to 75 mm (magnetic lengths)
3) Magnet strengths: trade-off between aperture and optics
4) Standardise magnet types / lengths where possible
5) Allow space for absorbers, BPMs, flanges, gate valves, …

Minimum straight lengths:

Long straights: Keep two undulators and chicane in double mini-beta straights (double MB will be lost)

Standard straights: Allow space for 3.5 m APPLE IDs; allows existing chicanes/beamline angles to be kept

Mid straights: Space for 1.5 m long in-vacuum ID

Straight	Requirement	Diamond	Diamond-II
Long	>7.44 m	11.3 m	7.545 m
Standard	>4.884 m	8.3 m	5.065 m
Mid	>2.9 m	3.4 m	2.872 m

Diamond-II Mid-Straights

Straight	Use
K01	Injection stripline kickers
K02	ID for VMXm beamline
K03	ID for flagship new beamline
K04	ID for flagship new beamline
K05	2×main cavities
K06	2×main cavities
K07	ID for K07 beamline
K08	ID for flagship new beamline
K09	electron beam diagnostics
K10	reserved for future new short beamline
K11	ID for DIAD beamline
K12	reserved for future new beamline
K13	reserved for future new beamline
K14	ID for flagship new beamline
K15	Passive SC third harmonic cavity
K16	ID for K16 beamline
K17	2×main cavities
K18	3PW for K18 beamline
K19	ID for flagship new beamline
K20	2×main cavities
K21	ID for K21 beamline
K22	DQ dipole for B22 beamline
K23	DQ dipole for B23 beamline
K24	Injection stripline kickers

Diamond-II contains 24 new mid-straights:

- Pros and cons:
  - adds capacity to the facility
  - limits achievable nat. emittance
  - increases vertical chromaticity
- Allowable dispersion must be carefully controlled (ID effects)

Proposed usage:

- Relocate existing ID beamlines
- Upgrade BM beamlines
- Five new flagship beamlines
- Two straights for injection striplines
- Space for diagnostic equipment
- Five straights for RF (8×main cavities, 1×3HC)
- Space reserved for three future beamlines

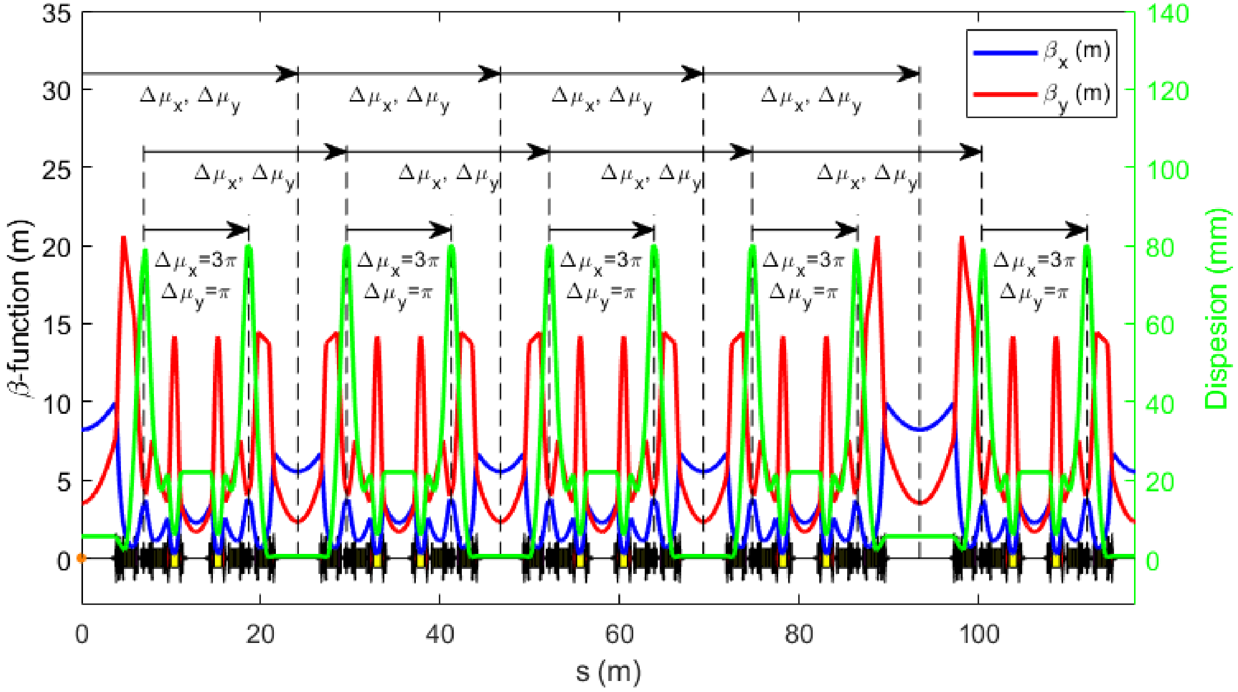
Optimisation Strategy

Linear Lattice:

1) H-function in mid-straight optimised for emittance with IDs
2) Anti-bends used to increase dispersion at sextupoles (used to maximise lifetime rather than lower emittance)
3) Small dispersion leakage in long straights to lower emittance
4) Beta functions at injection point
5) Beta functions at IDs minimised (WIP)
6) DL profile shaped to dispersion function

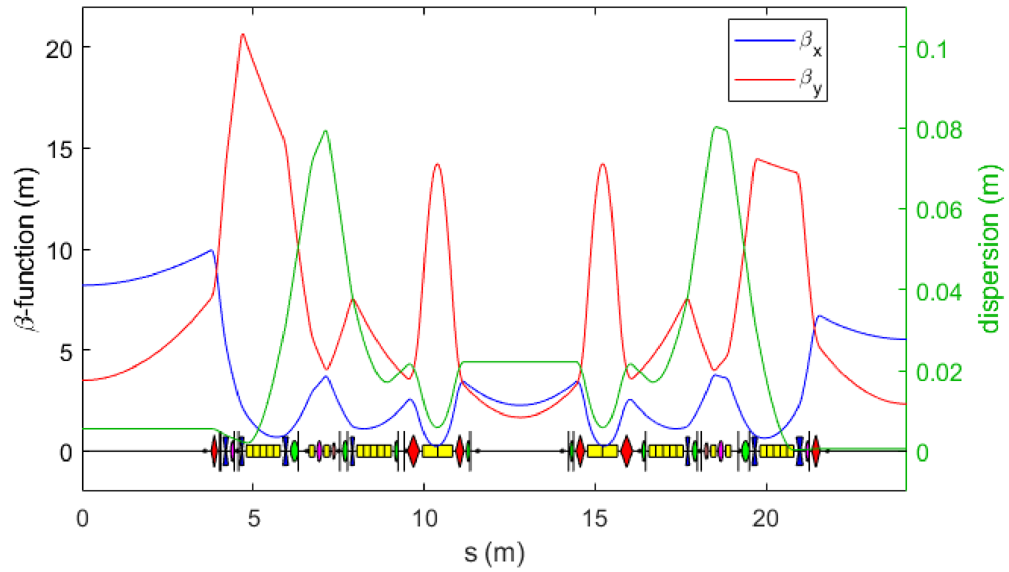
Nonlinear dynamics:

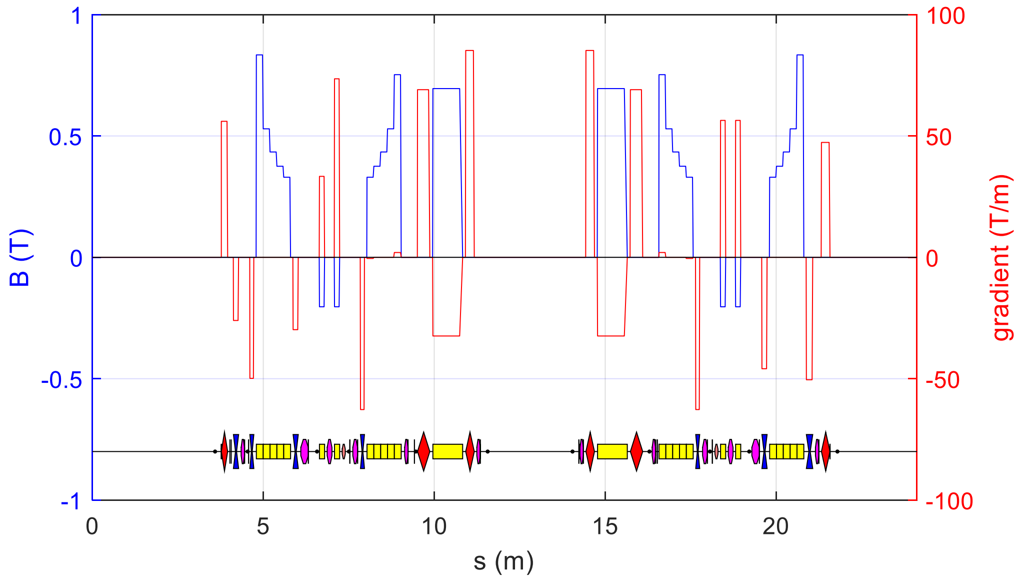
1) '-I transformer' between chromatic sext.
2) Cell tunes chosen to cancel RDTs over 8 cells:
   - μ_x = ~2π*18/8
   - μ_y = ~2π*7/8
3) Symmetry maintained:
   - cell tunes same for long / standard straights
   - cell tunes same f-sext => f-sext
4) Some detuning necessary:
   - ring tunes must avoid main resonances
   - -I transformer drives 2nd order chrom. (Δμ/2π ~ 0.025)
   - tolerance of Δμ/2π ~ 0.01 for cell tunes



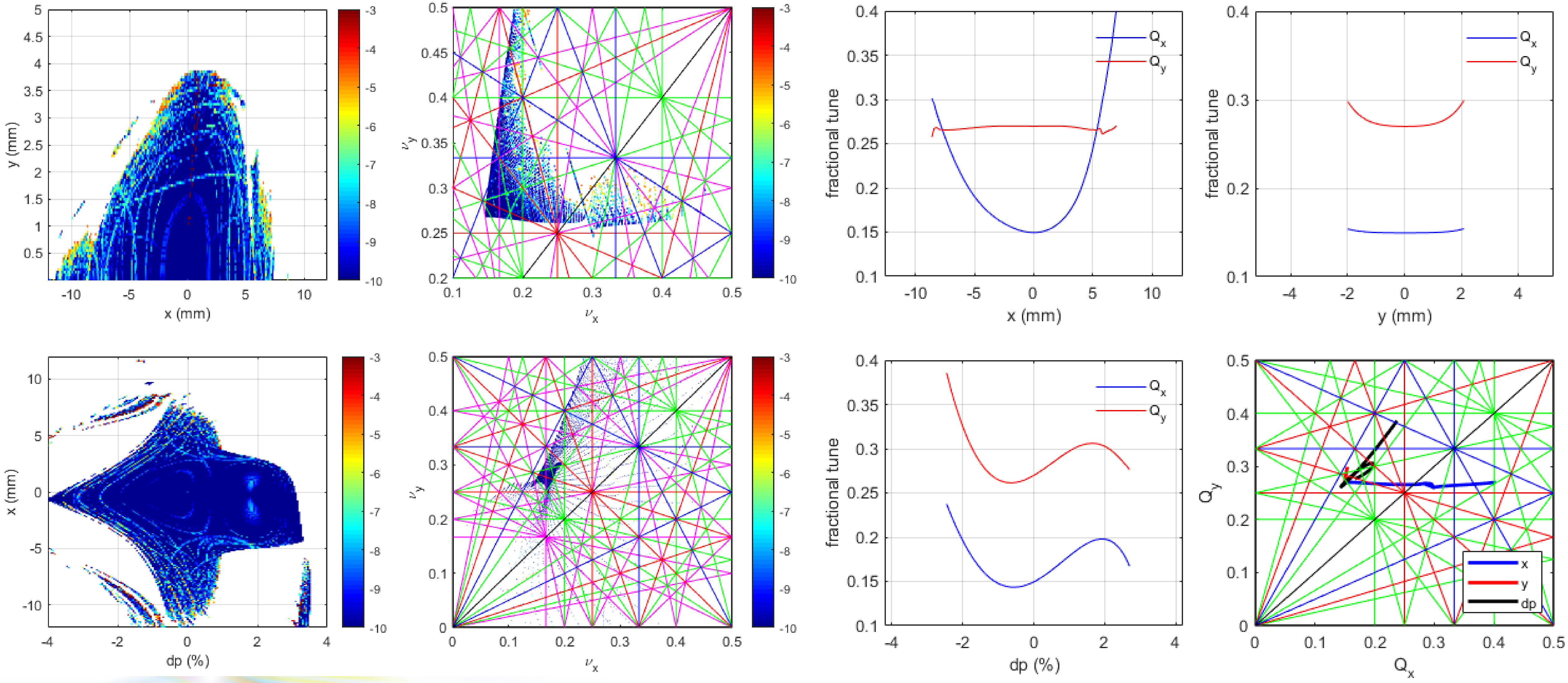
Diamond-II Lattice

Parameter (no IDs)	Units	Diamond	Diamond-II
Energy	GeV	3.0	**3.5**
Circumference	m	561.6	**560.561**
RF frequency	MHz	499.654	**499.511**
Total bend angle	Degree	360	**388.8**
Betatron tunes	-	[27.21, 12.36]	[54.15, 20.27]
Natural chromaticity	-	[-79.0, -35.6]	[-67.6, -88.5]
Momentum compaction	-	1.7×10^{-4}	1.0×10^{-4}
H. damping partition	-	1.00	1.87
Energy loss per turn	MeV	1.01	0.72
Emittance	pm.rad	2730	**162**
Energy spread	%	0.096	0.094
Bunch length	ps	11.4@2.4 MV	12.5@1.4 MV
τ_x	ms	11.1	9.7
τ_y	ms	11.2	18.1
τ_E	ms	5.6	16.0



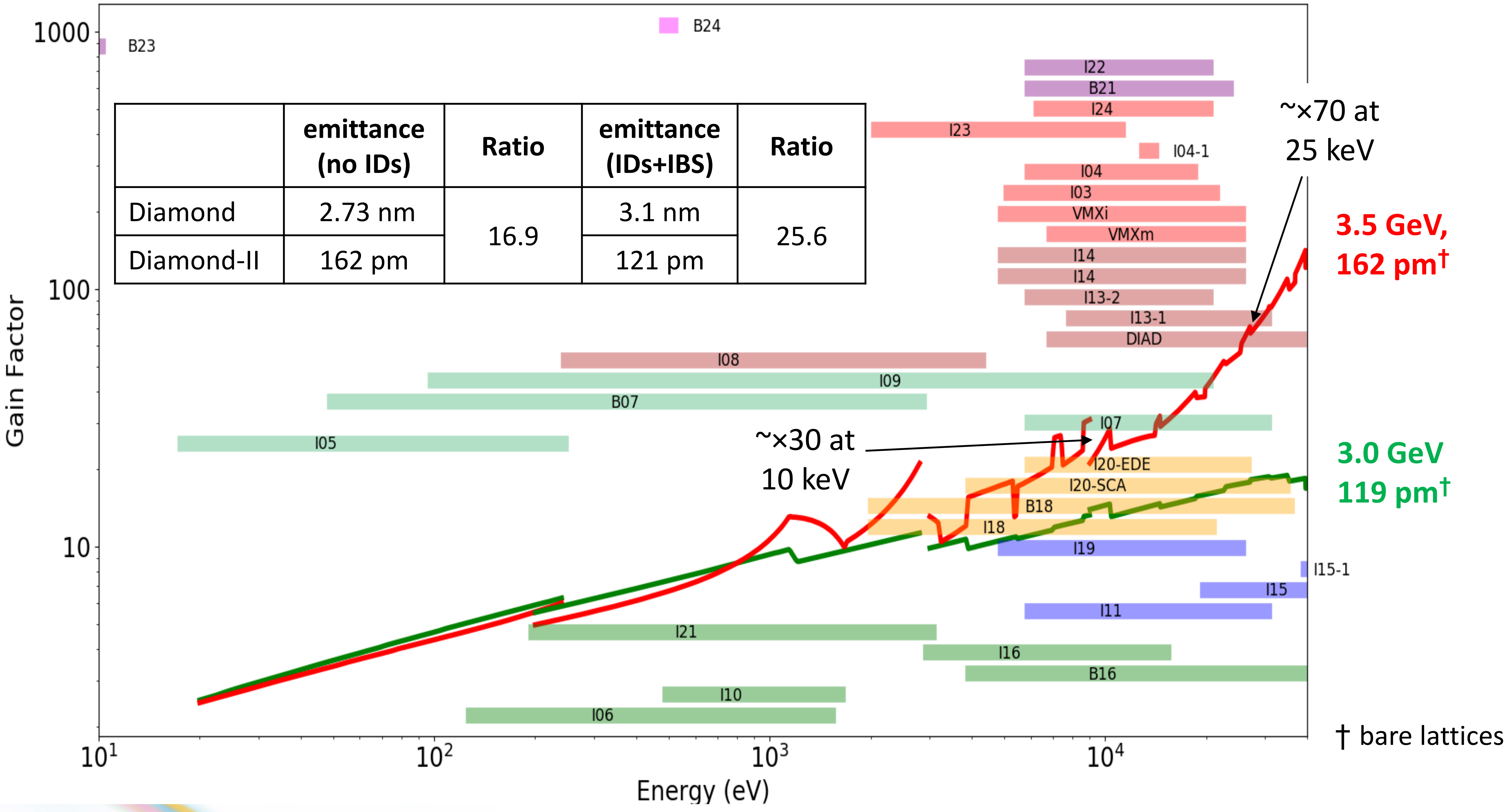


Dynamic Aperture



Brightness Gain From Lattice Change and Beam Energy

	emittance (no IDs)	Ratio	emittance (IDs+IBS)	Ratio
Diamond	2.73 nm	16.9	3.1 nm	25.6
Diamond-II	162 pm		121 pm	

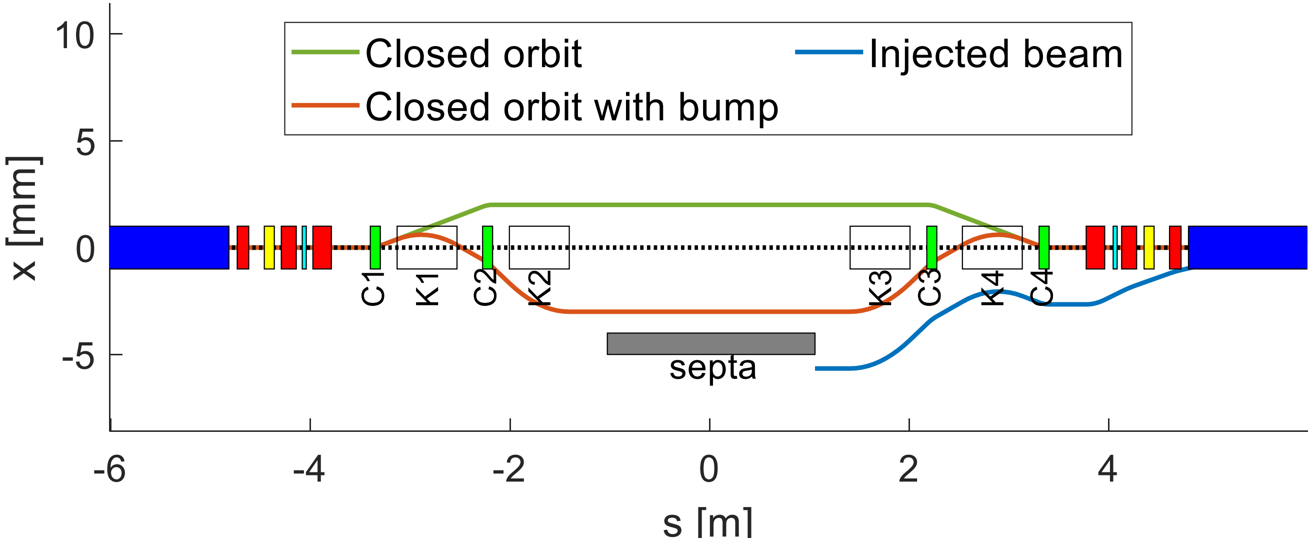


Injection Schemes

The injection straight layout I01 contains:

- 3 mm-thick septum magnet (1.6 m, 1.0 T, 70 µs)
- 1 mm-thick septum magnet (0.3 m, 0.4 T, 10 µs)
- Four 6 µs half-sine bump kickers (K1-K4)
- Four DC chicane magnets (C1-C4)

The DC chicane provides fine-control for the stored beam position and angle w.r.t. the septum plate.



The following stages are foreseen during commissioning and operation:

1) First turns: single-shot injection using the bump kickers set for on-axis injection (multi/single-bunch)
2) First accumulation: multi-shot injection using the bump kickers set for aperture-sharing (multi/single-bunch)
3) Final stages: multi-shot injection using the bump kickers set for closed bump (multi/single-bunch)
4) Top-up injection: aperture-sharing injection using stripline kickers in K01 straight (single bunch only)

Note: the kickers can be used to refill the machine and as a fall-back option in case of failure of the striplines.

More details of aperture-sharing injection scheme given in Jonas Kallestrup's talk on Wednesday.

Simulated Commissioning

Storage ring commissioning modelled using T. Hellert's Simulated Commissioning Toolbox

Phase One (on-axis injection):

- First turn / multi-turn threading
- Ramp up sextupoles
- Turn on RF (adjust phase / frequency)
- Quadrupole scan to maximise transmission

Phase Two (off-axis accumulation w/ mis-matched kickers):

- Initial, coarse BBA + beta-beat correction
- Second BBA + LOCO optics correction
- Third BBA + coupling and optics correction

Phase Three (off-axis accumulation w/ closed orbit bump):

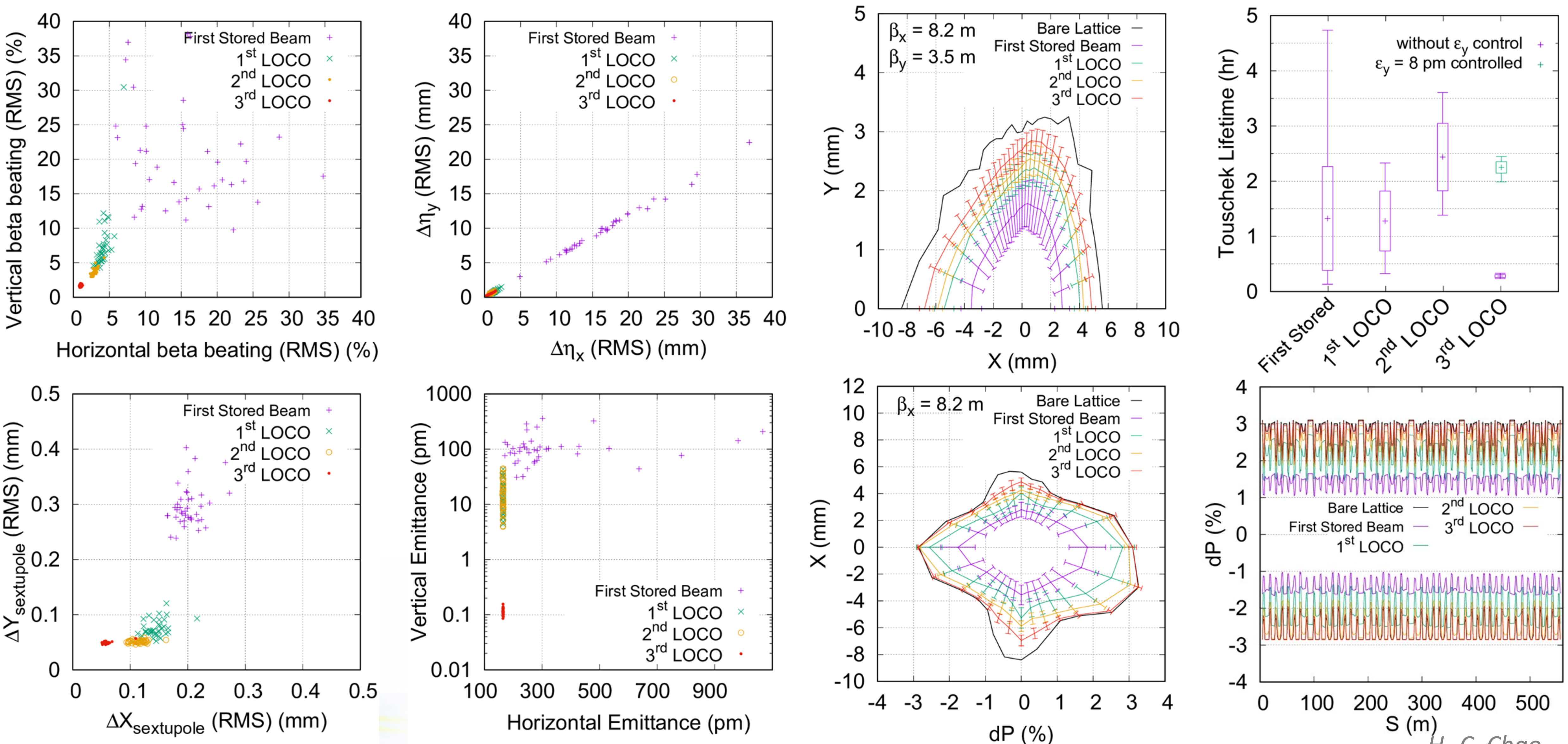
- Optics correction with IDs and collimators

	Offset (μm)	Roll (μrad)	Field Error (%)
DL dipole	100	100	0.05
DQ dipole	50	100	0.05
QA anti-bend	35	100	0.05
Multipoles	35	100	0.10
Corrector	150	150	0.10
Girder	150/150	150	-

Error source		Value
BPM	Offset / roll	500 μm / 10 mrad
	Calibration	5 %
	Noise (TBT / closed orbit)	60 μm / 1 μm
RF	RF Frequency	100 Hz
	RF Voltage	0.5 %
	RF phase	90 degrees
Injected beam	Position / angle	100 μm / 10 μrad
	Energy / phase error	0.1 % / 0.1 deg.

H.-C. Chao

Simulated Commissioning

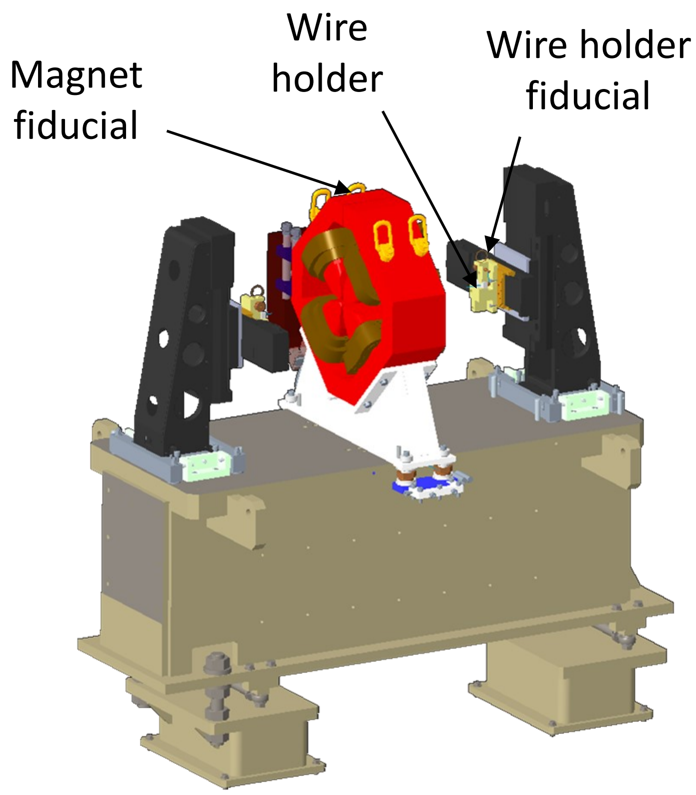


H.-C. Chao

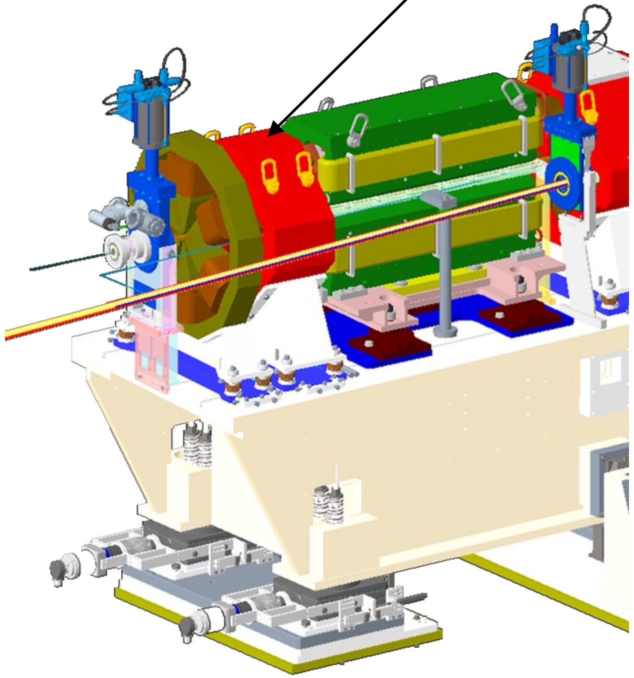
Simulated Commissioning

- 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
- Investigations are in progress to see if relaxing the tolerances is feasible

Error Source	RMS error
Wire holder inspection	2
Magnetic centre	5
Wire holder survey	25
Magnet fiducial survey	10
Magnet survey onto girder	35
Splitting / joining of magnet	8
Survey monument placement	3
Transportation / installation in tunnel	10
Total uncertainty	**46**



Measurement bench

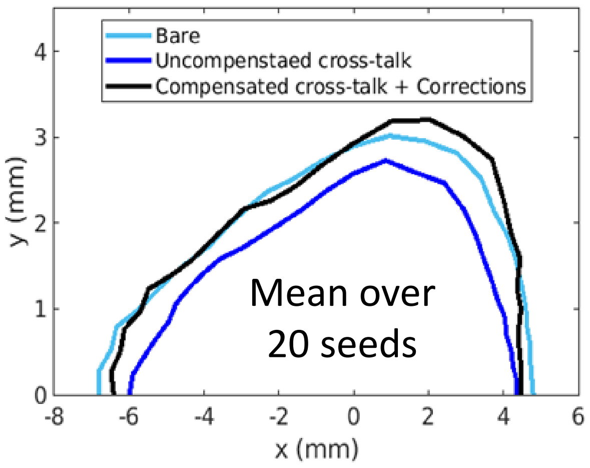


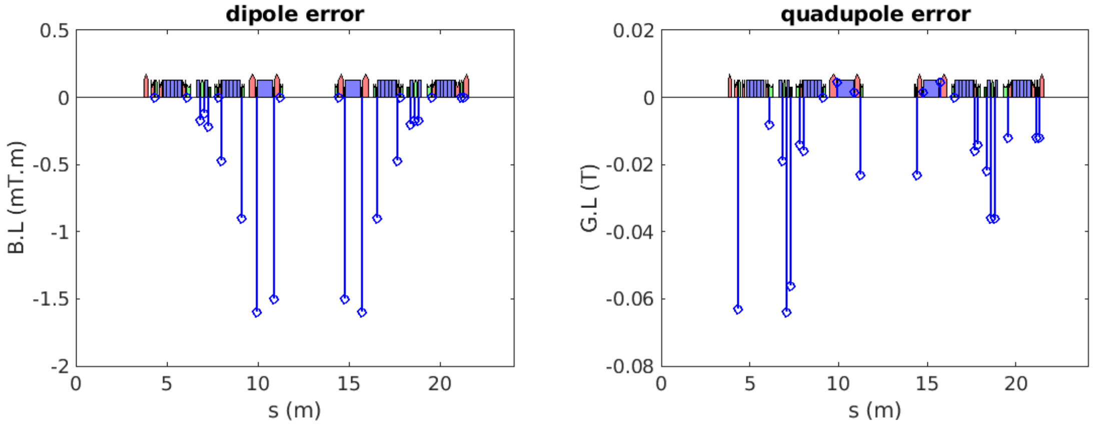
Storage ring girder

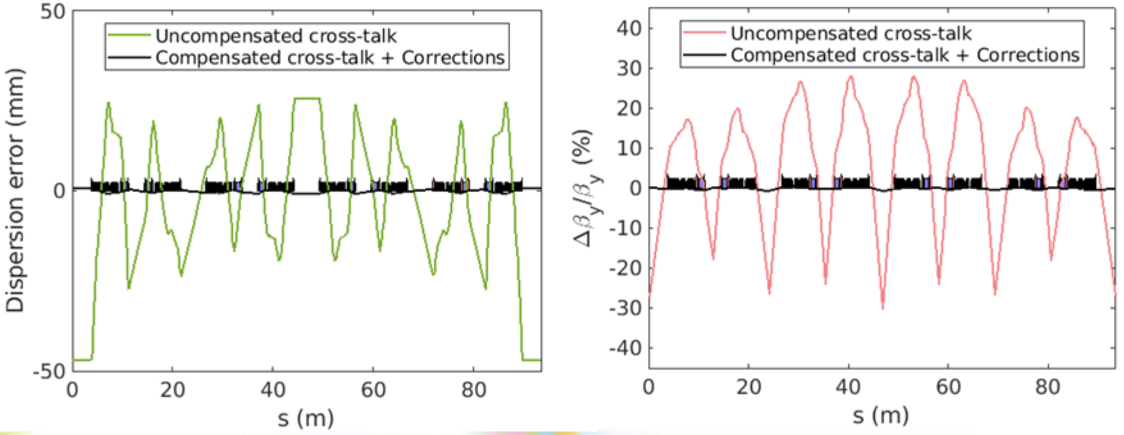
P. Vivian

Magnet Cross-Talk

- Close proximity of the magnets leads to substantial cross-talk and field errors
- Modelled as thin-lenses between magnets; values extracted from OPERA model
- Can be largely compensated by adjusting local dipole and quadrupole set-points
- Modelling of full s-dependent fringe fields in progress







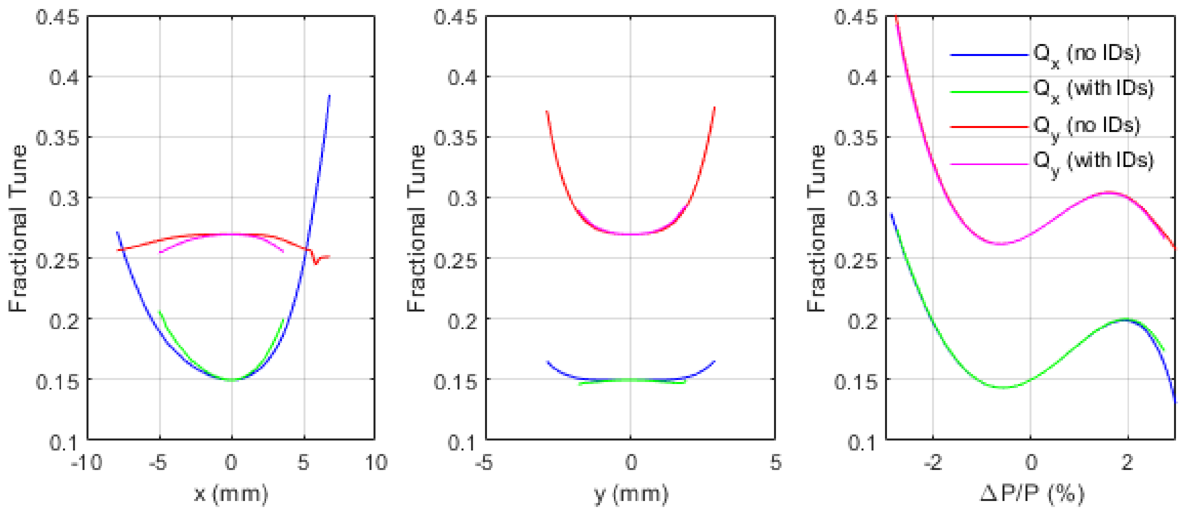
Parameter	Uncompensated	After Correction
Tune-shift [x,y]	[+0.03, +1.02]	[0.00, 0.00]
Chrom. change [x,y]	[+2.8, +11.0]	[0.0, 0.0]
Emittance	269 pm.rad	162 pm.rad
Max orbit [x]	741 µm	29 µm
Max beta-beat [x,y]	[21.4%, 30.3%]	[3.2%, 1.0%]
Max dispersion error	47.0 mm	1.0 mm
Lifetime change	-0.77 h	-0.13 h

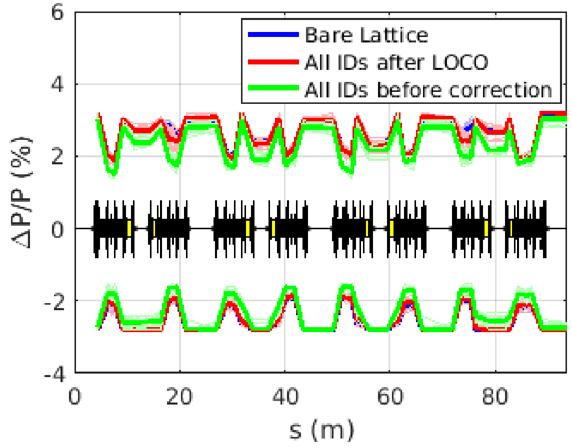
H. Ghasem

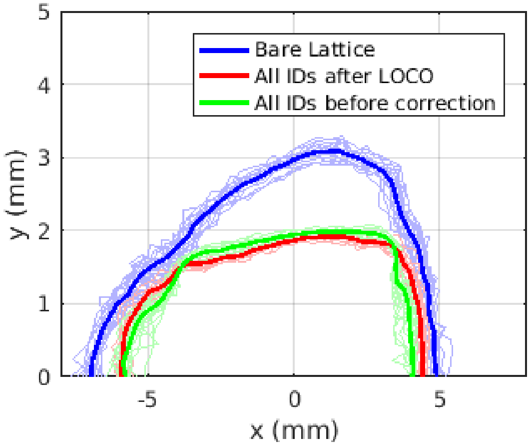
Impact of IDs

- Total number of IDs increases from 28 to 36 in D-II
- Contribute significantly to overall machine parameters
- Mid straight IDs (dispersive location)
    - ➢ Limited to <1.5 T to avoid emittance blow-up
    - ➢ Impact on '-I transformer' found to be negligible
    - ➢ Generally short devices, low beta-functions
- LOCO correction effective at restoring lifetime and DA
- Active shim wires for APPLE II devices under study
- Global tune feedback necessary

	ε_x (pm.rad)	σ_E (%)	U_0 (MeV)	$\Delta\beta_y/\beta_y$ (%)	ΔQ_y
Bare lattice	162	0.094	0.72	-	-
Long Str.	145	0.090	0.88	11	+0.03
Standard Str.	115	0.115	1.39	19.4	+0.07
Mid Str.	178	0.092	0.86	1.3	+0.01
All IDs	121	0.109	1.68	19.7	+0.11



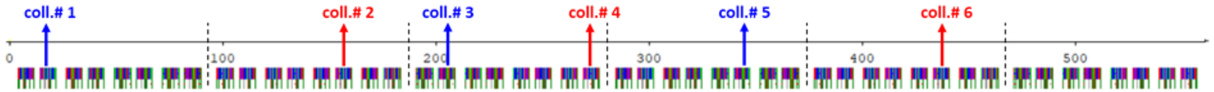


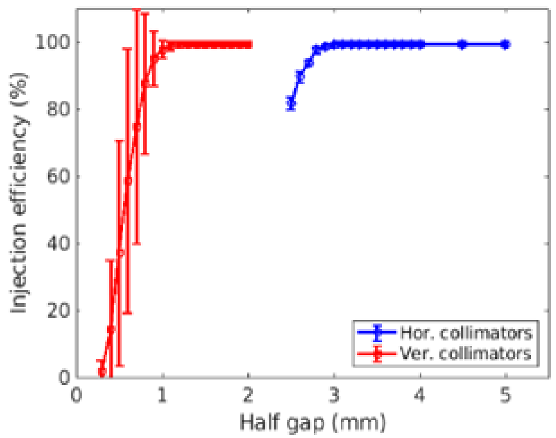


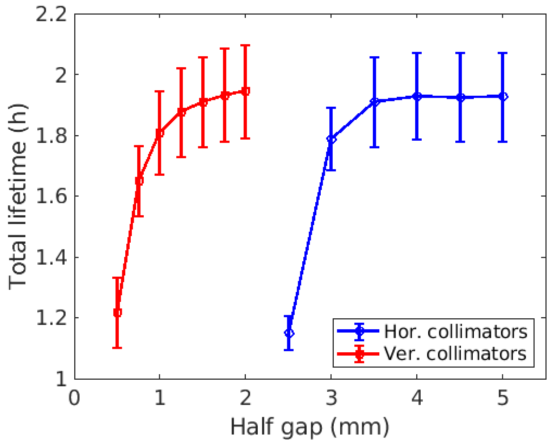
B. Singh

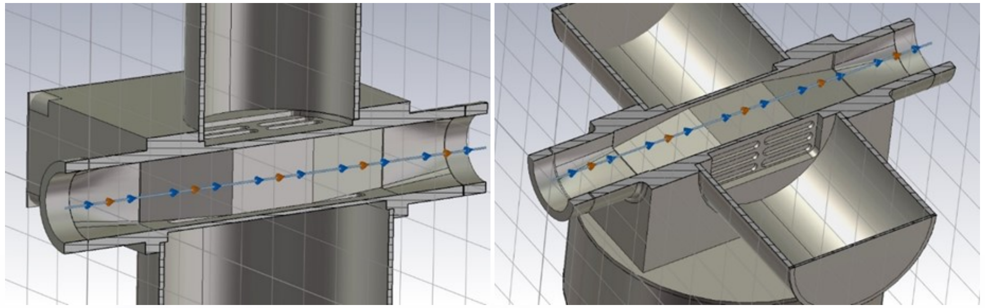
Collimation

- Storage ring contains 6 collimators (3 per plane)
- Located downstream of dispersion bump
- Nominal half-gaps set based on lifetime impact:
  - H = ±3.5 mm
  - V = ±1.5 mm
- Anticipated to collect ≈75 % of all losses
- Collection efficiency can be increased at expense of drop in lifetime

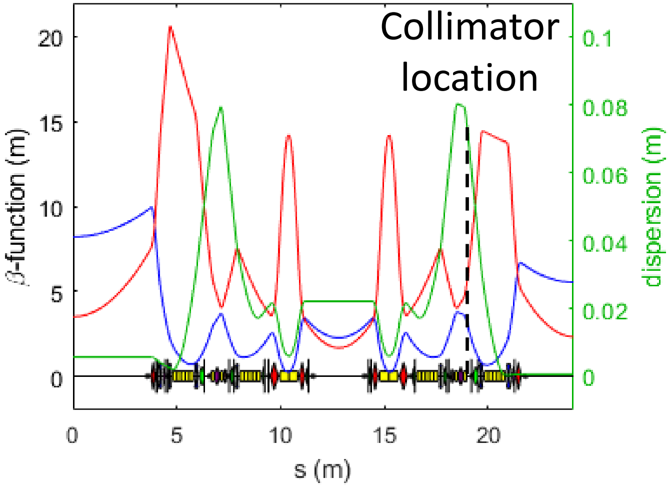








	Loss factor (V/pC)	H kick factor (V/pC/mm)	V kick factor (V/pC/mm)
Horizontal	0.36	-0.22	-0.06
Vertical	0.32	-0.20	-1.03



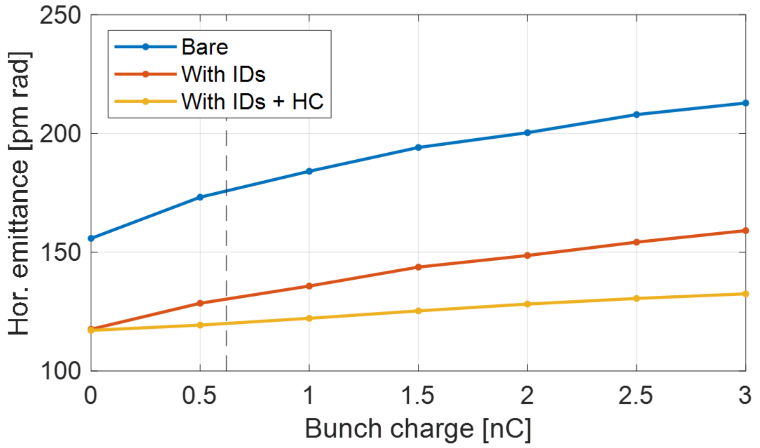
Loss Mechanism	Lost at collimators
RF switch-off	96.0 ± 5.0 %
Touschek scatter	68.8 ± 3.6 %
Elastic gas scatter	21.4 ± 0.4 %
Inelastic gas scatter	34.5 ± 0.3 %
H. injection mis-steer	81.4 ± 16.6 %
V. injection mis-steer	99.9 ± 0.2 %

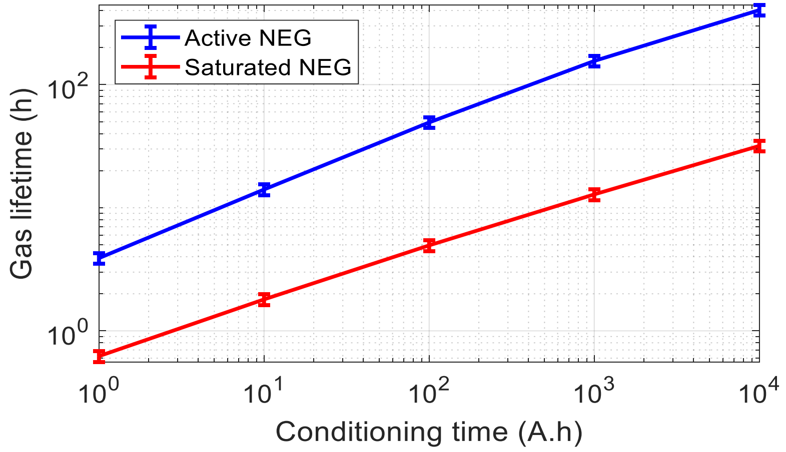
H. Ghasem

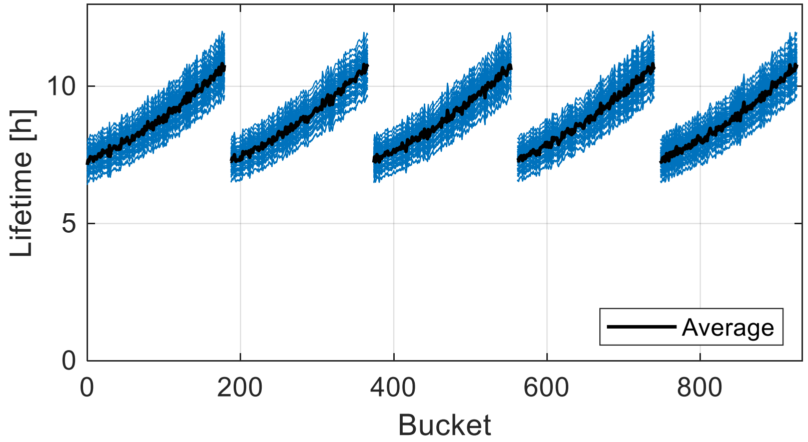
diamond

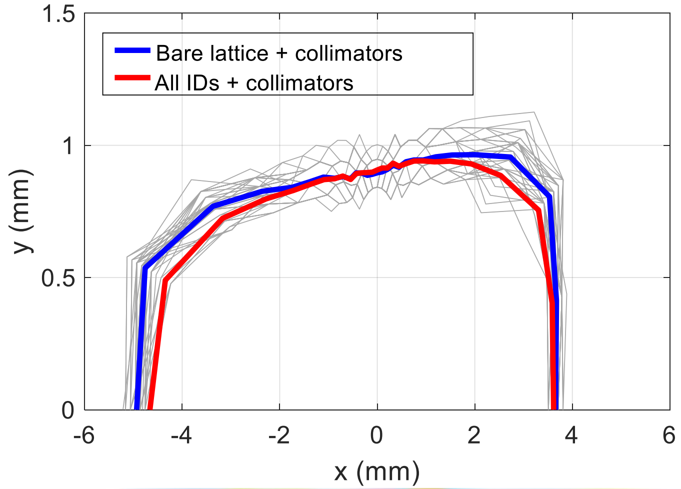
Final Machine Performance

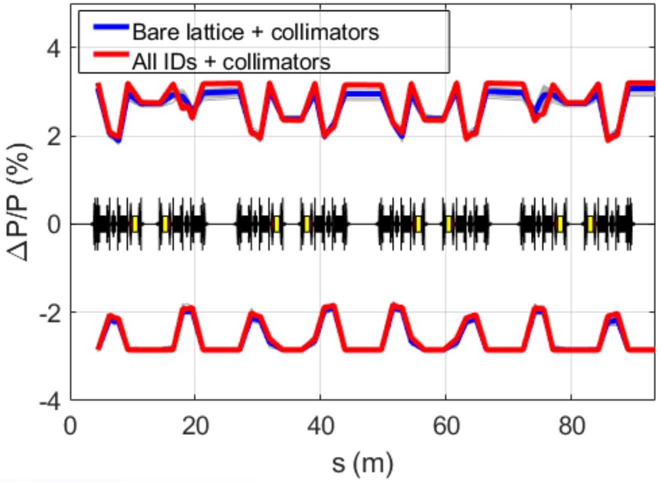
Final performance estimated for ε_y = 8 pm.rad, including IBS, harmonic cavity and vacuum chamber impedance







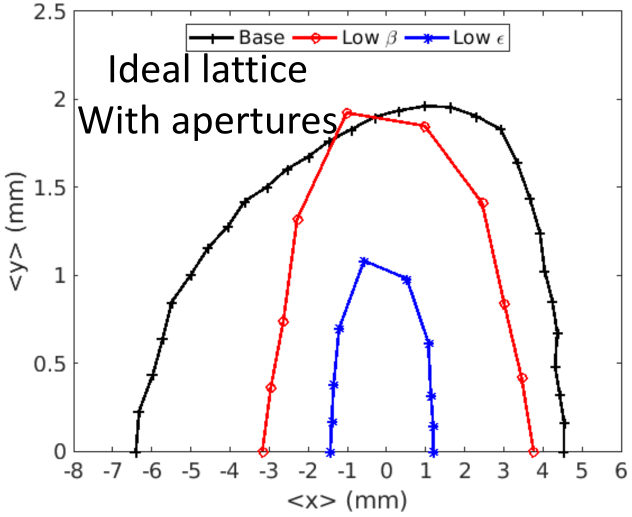


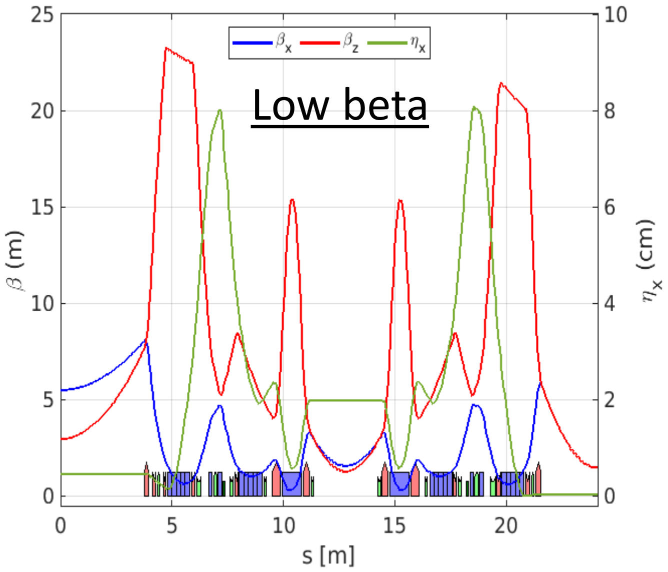


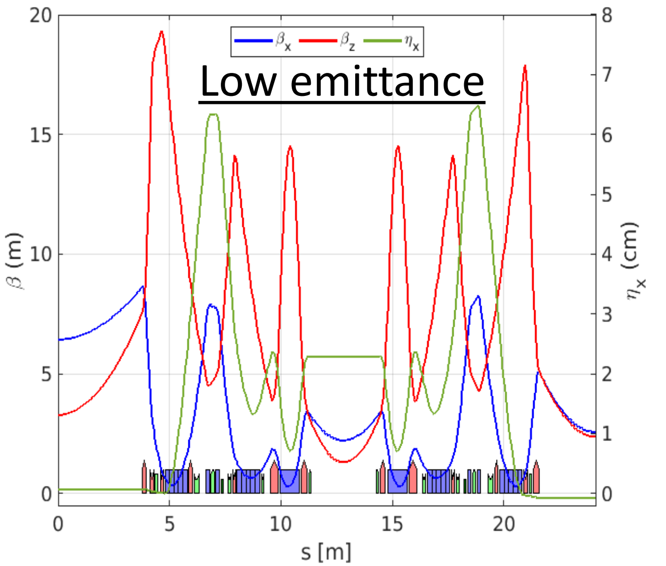
	Bare Lattice	IDs closed
Horizontal emittance	163 pm.rad	120 pm.rad
Energy spread	0.095 %	0.109 %
Bunch length (with HC)	49.1 ps	48.1 ps
Touschek (without HC)	2.8 ± 0.1 h	2.8 ± 0.1 h
Touschek (with HC)	8.2 ± 0.3 h	8.8 ± 0.5 h
Coulomb	60.0 ± 7.2 h	59.7 ± 7.4 h
Bremsstrahlung	277.5 ± 0.5 h	276.6 ± 0.7 h
Total (with HC)	7.0 h ± 0.2 h	7.5 ± 0.4 h

Alternative Optics?

- The same hardware can be retuned to increase photon beam brightness:
  - Low-beta optics
  - Low emittance optics
- Dynamic aperture currently considered too small to adopt as baseline
- Considered for future 'brightness-upgrade'







Parameter		Nominal	Low-beta	Low-emit
Betatron Tune		[54.15,20.27]	[58.14,21.27]	[62.18,20.30]
Emittance (wo, w IDs)		162, 121 pm	152, 115 pm	106, 87 pm
Tous. Lifetime (no HC)		2.2 h	1.2 h	0.8 h
Long	β_x	8.21 m	5.53 m	6.45 m
	β_y	3.50 m	2.99 m	3.30 m
Standard	β_x	5.53 m	1.50 m	2.58 m
	β_y	2.32 m	1.50 m	2.39 m
Mid	β_x	2.26 m	1.60 m	2.24 m
	β_y	1.68 m	1.30 m	1.32 m

Diamond-II Timeline

Diamond-II to be funded as a Joint Venture between two sources (UK Govn./STFC 86% and Wellcome Trust 14%)

Funding Announcements:

- April 2021: Wellcome Trust approve funding, subject to final approval from UK Government
- June 2021: UKRI announced pre-funding for Diamond-II (£2.5M, April 2021 until April 2022)
- June 2022: UKRI confirmed first phase of funding contingent on FBC (£81.5M April 2022 until April 2025)

Event	Date
CDR Published	May 2019
Outline Business Case approved by UK Government	Oct. 2021
TDR Published	Jul. 2022
Submit Final Business Case to BEIS Project Investment Committee	Dec. 2022
Start of main project funding and procurement	Apr. 2023
Start of shutdown	Sep. 2026
End of booster commissioning	Jul. 2027
End of storage ring commissioning	Dec 2027
Resume full User Mode	Mar. 2028

Summary

Performance studies and engineering design of Diamond-II are well-advanced:

- Technical Design Report to be published in next few weeks
- Prototyping of key components either already underway …
  - ➢ DQ dipole and prototype girder received, DL dipole ordered, magnet alignment, power supply controller, BPM electronics, FOFB, girder motion system
- … or planned
  - ➢ injection striplines + pulser, MBF, ceramic kicker vessels, fast corrector + power supply

Upgrades / refurbishment of injector complex also required:

- New low emittance / high-charge booster (ε_x = 134 nm, σ_L = 100 ps $\Rightarrow$ ε_x = 17 nm, σ_L = 38 ps)
- Increase linac energy from 100 MeV to 150 MeV
- New transfer line layout, including dispersion-free section for BTS

Alternative optics also possible using same storage ring hardware:

- 'low-beta' optics has beta-functions at IDs better matched to photon phase-space
- 'low emittance' optics looks feasible (<100 pm.rad)

Requires improvements to injection scheme to implement (enhanced aperture-sharing, swap-out)

Vacancies at Diamond

We now have an opportunity for new members to join the group and contribute to Diamond-II studies:

- 1 × **Accelerator Physicist** or **Senior Accelerator Physicist** (full time / permanent)
- 2 × **PDRA** or **Senior Researcher** (full time / 3-year fixed term)

Working with existing team members to contribute across many different topics:

- numerical optimisation of the Diamond-II storage ring optics
- studying alternative or future machine optics or special operating modes
- modelling of collective effects
- study performance of harmonic cavity
- injection studies
- booster and transfer line development
- machine studies of existing Diamond accelerators

https://www.diamond.ac.uk/Careers/Vacancies.html