Progress with Diamond-II storage ring lattice

Hossein Ghasem

hossein.ghasem@diamond.ac.uk

Diamond Light Source

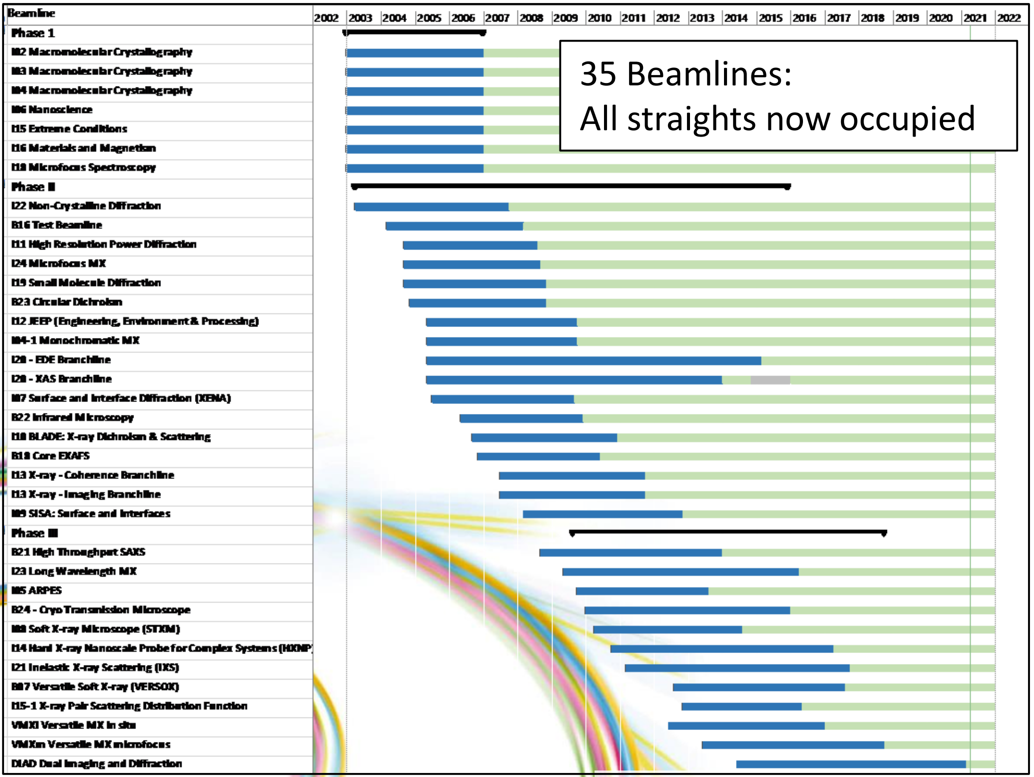
IOP PAB Annual Conference 2021

Outline

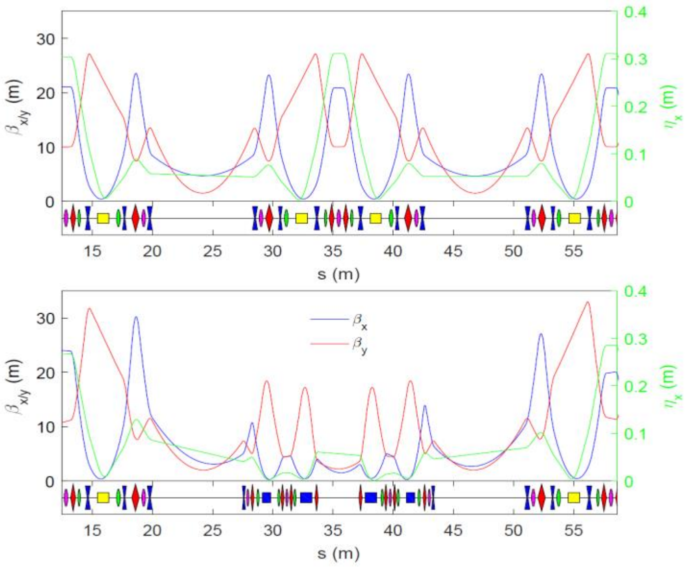
- Introduction to Diamond storage ring
- Motivation, wish-list and constraints for the new storage ring
- Paths to low emittance - general introduction of the techniques being exploited
- Diamond-II storage ring lattice structure and main alternatives
  - CDR (15-1-1)
  - Lattice development after CDR
  - Optimization strategy
  - Baseline lattice 34-1-1 (Off axis injection)
  - Lattice 34-2-2 (On axis injection)
- Overview of lattices
  - Parameters – ID, IBS, 3HC
  - DA
  - Inj. Eff.
  - Lifetime.
- Magnets
- Timeline
- Conclusion

Diamond Light Source

- Diamond is the UK's national **synchrotron radiation facility.**
- Located at **Rutherford Appleton Laboratory**, Oxfordshire
- Commissioning 2005 - 2006
- Start of user operations Jan 2007
- DDBA installed since Nov. 2016



35 Beamlines:
All straights now occupied

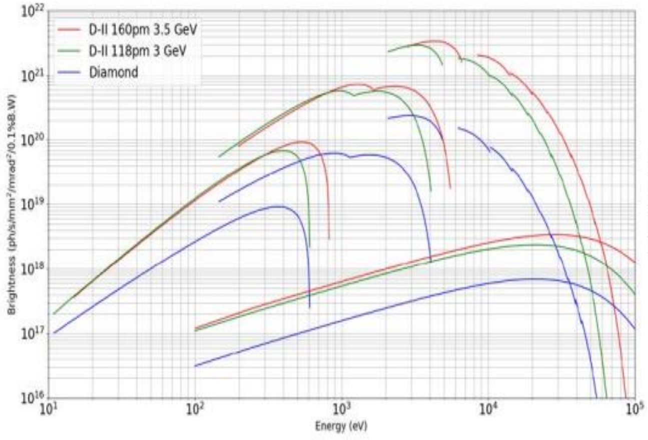


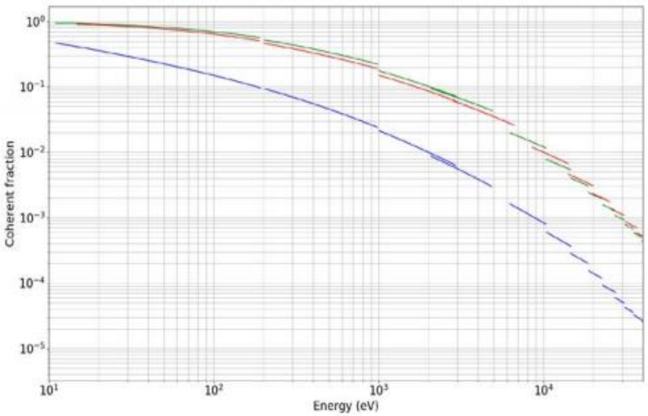
Lattice	Combined DBA/DDBA
Structure	24 cells
Straights	18 × 5.3 m / 6 × 8.3 m / 1 x 3.4 m
Energy	3 GeV
Circumference	561.571 m
H/V Emittance	2.72 nm.rad / 8 pm.rad
Energy spread	0.096 %
Current	300 mA
Lifetime	10 h

Diamond-II upgrade

- ☐ Motivation: Improve quality of photon beams delivered to users:
  - ○ Increase spectral brightness and transverse coherence
  - ○ Reduced source size, line-width
  - ○ Optimise spectral range
  - ○ Space for new beamlines
- ☐ Starting wish-list
  - ○ Low horizontal emittance
  - ○ Increase in number of straight-sections for IDs
  - ○ Maintain existing beamlines
  - ○ Re-use existing hardware where possible (RF, IDs, injector, …)
  - ○ Short pulse capabilities?
- ☐ Constraints:
  - ○ Must fit in the existing tunnel, Source-point changes kept to a minimum
  - ○ Minimize technology risks
  - ○ Minimize shutdown period

NOTE: Beam energy in Diamond-II storage ring will be to 3.5GeV





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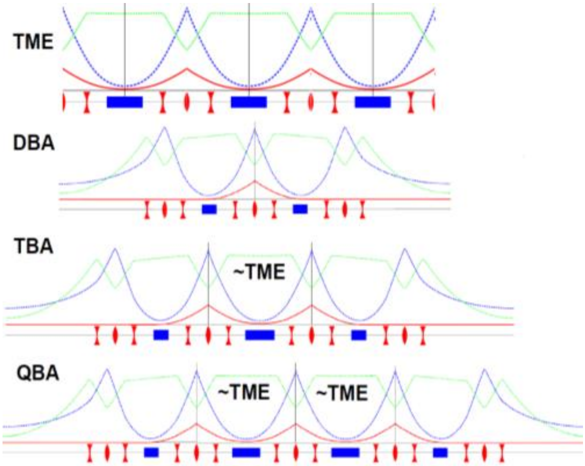
Paths to low emittance

A. increase number of dipoles (MBA)

$$\epsilon_x \propto \frac{1}{N_d^3}$$



- TME-like (Theoretical Minimum Emittance) cells provide lowest possible beam emittance by shaping dispersion and beta-functions to have a waist in the centre of the bending magnets.

- Starting from TME-like cells and increasing number of dipoles lead to substitutional reduction in beam emittance.

B. control Jx with trans. gradient dipoles

- Emittance lowered by increasing J_x

$$\epsilon_x = C_q \gamma^2 \frac{I_5}{J_x I_2}$$

- Damping Partition Numbers:

$$J_x = 1 - \frac{I_4}{I_2}$$

- Emittance adjusted by introducing a vertically-focussing gradient in the dipoles

$$I_4 = \oint \frac{\eta_x(s)}{\rho(s)} \left(\frac{1}{\rho^2(s)} + 2K(s) \right) ds$$

Paths to low emittance

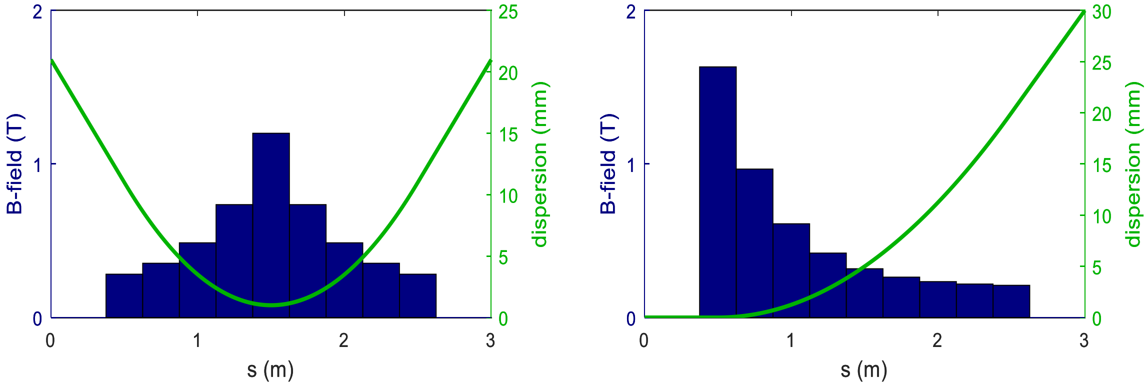
C. use long. gradient dipoles

- Emittance lowered by minimising I_5

$$\epsilon_x = C_q \gamma^2 \frac{I_5}{J_x I_2}$$

$$I_5 = \oint \frac{\mathcal{H}(s)}{\rho^3(s)} ds$$

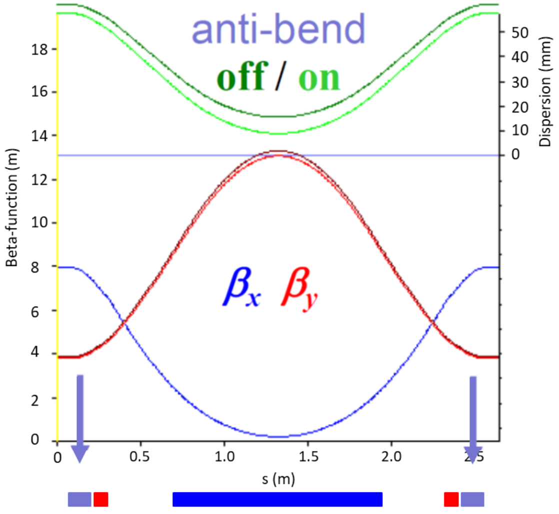
$$\mathcal{H}(s) = \gamma_x \eta_x^2 + 2\alpha_x \eta_x \eta_{x'} + \beta_x \eta_{x'}^2$$



- Make the dipole field strongest where the dispersion is at a minimum
- Total bend angle is kept constant
- Can get below TME of uniform dipole
- Have the benefit of producing hard x-rays where B-field is large

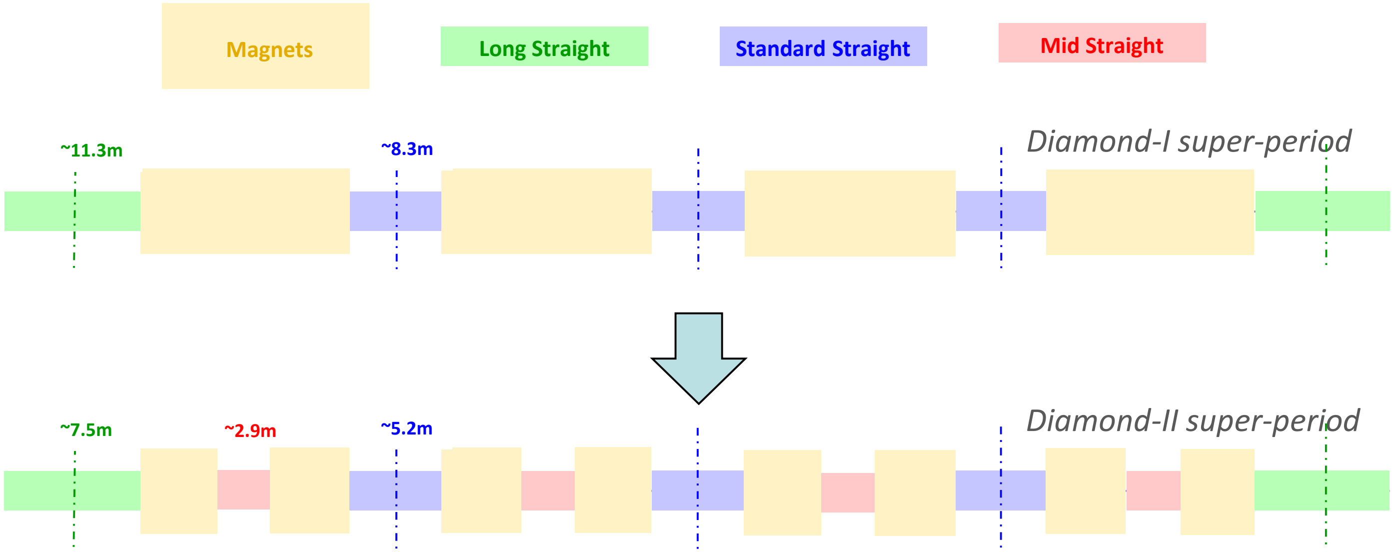
D. employ reverse bending magnets

- Reverse bending magnets can be used as an additional handle to control the dispersion
- Beta-functions largely unchanged
- Located at large $\mathcal{H}(s)$, so also contribute to ε_x.
- Lead to very small or even negative momentum compaction factor
- Impact on bunch-lengthening and instability thresholds to be determined



A. Streun, LER-4, Frascati, 2014

Diamond-II lattice structure



6 long straights, ~7.5 m long:	IDs, injection elements
18 standard straights, ~5.2 m long:	IDs
24 mid straights, ~2.9 m long:	IDs, 3PW/dipole sources, RF, 3HC, diagnostics, stripline kickers

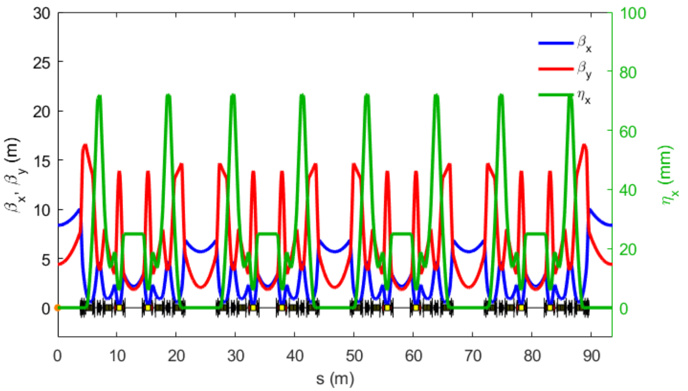
>35 % of the ring consists of insertion straights (quad to quad)

Diamond II CDR

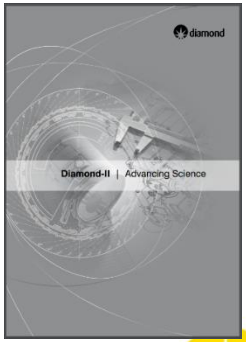
ESRF-EBS Hybrid 7BC cell
Double-Double Bend Achromat cell

Lattice structure is called as ‘Modified-Hybrid 6-Bend Achromat’

- All Diamond-II storage ring options are based on the Modified-Hybrid 6 Bend Achromat structure.
- Version M-H6BA-15-1-1 of the lattice is the one presented in CDR.
- Each cell consists of:
  - 4 long. dipoles + 2 trans. gradient dipoles
  - 16 (17) quadrupoles
  - 12 sextupoles
  - 2 octupoles



Parameter	Values
Energy (GeV)	**3.5**
Betatron tunes	**[57.16, 20.25]**
Natural emittance (pm.rad)	**157**
Emittance with IDs (pm.rad)	**149**
Natural chromaticity	[-75.7, -89.7]
Momentum compaction factor	1.2×10^{-4}
Energy Loss per turn (MeV)	0.67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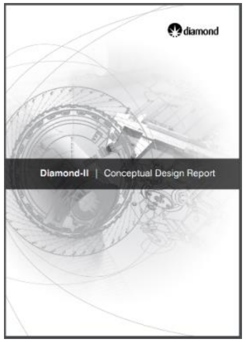
Diamond-II | Advancing Science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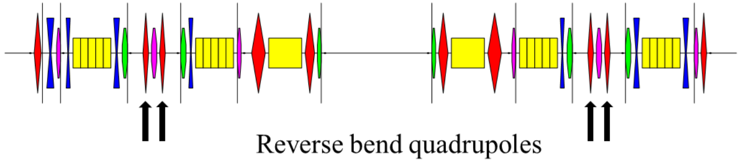
Diamond-II | Conceptual Design Report

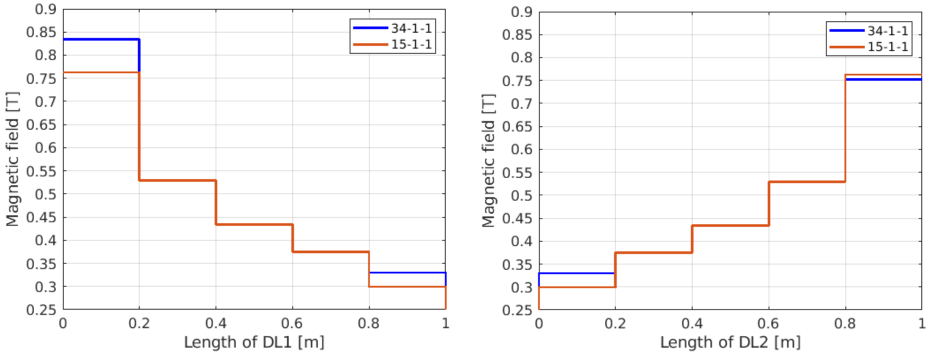
Conceptual Design Report (May 2019):
https://www.diamond.ac.uk/Home/About/Vision/Diamond-II.html

Diamond II lattice development after CDR

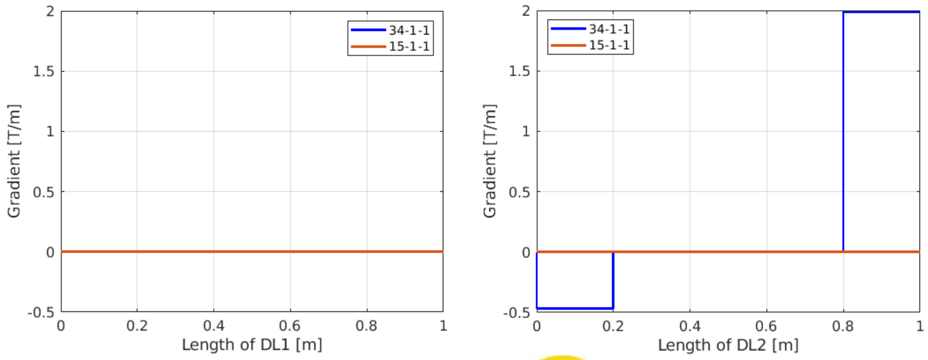
I. Addition of **reverse bend quadrupoles** to control dispersion found to be beneficial, either to:
- increase dispersion at chromatic sextupoles (height of dispersion bump) which results to maximise momentum acceptance (lattice 34-1-1)-> (lifetime gain)
- reduce dispersion in dipoles as well as MSS (emittance reduction)



II. B-field for the Long. Variable bend (DL) dipoles optimised:
- improved variation w.r.t dispersion function
- helps to lower the emittance
- DL2 now different from DL1



III. Tra. gradient added to two pieces of DL2 dipoles:
- Additional knobs to control phase advance for –I transformer and optics in mid-straight



NLBD Optimization strategy

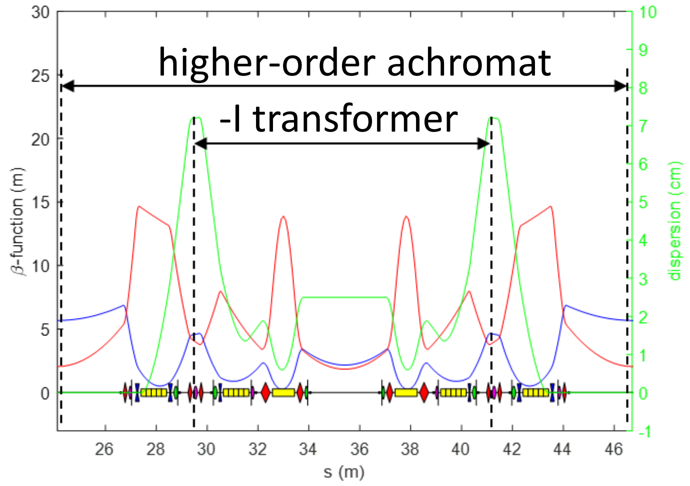
Nonlinear beam dynamic (NLBD) optimization is based on combination of:

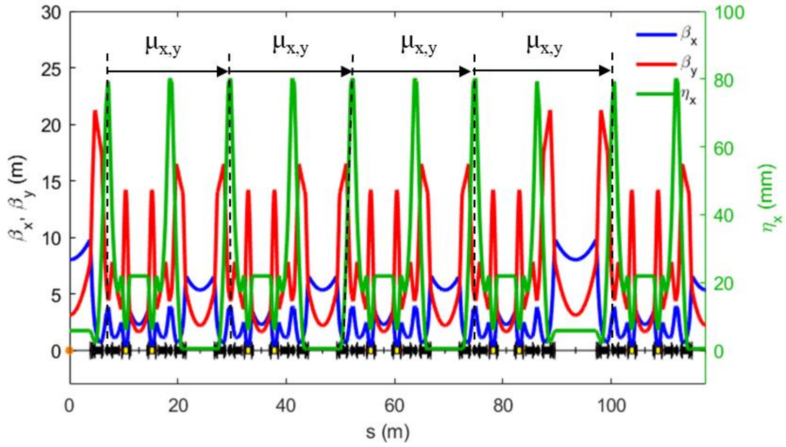
- -I transformer: Phase advance between focussing chromatic sextupoles:
  $\mu_x = \sim 3\pi$
  $\mu_y = \sim \pi$

- Higher order achromat: Cell tunes chosen to cancel resonance driving terms over 8 cells:
  $\mu_x = \sim 2\pi * 19/8$
  $\mu_y = \sim 2\pi * 7/8$

Some detuning necessary:
ring tunes must avoid main resonances
-I transformer drives 2nd order chromaticity ($\Delta\mu/2\pi \sim 0.025$)
tolerance of $\Delta\mu/2\pi \sim 0.01$ for cell tunes

- Phase advance symmetrisation between sextupoles

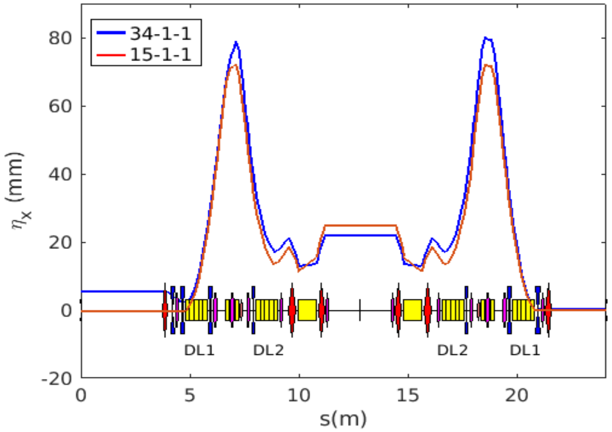


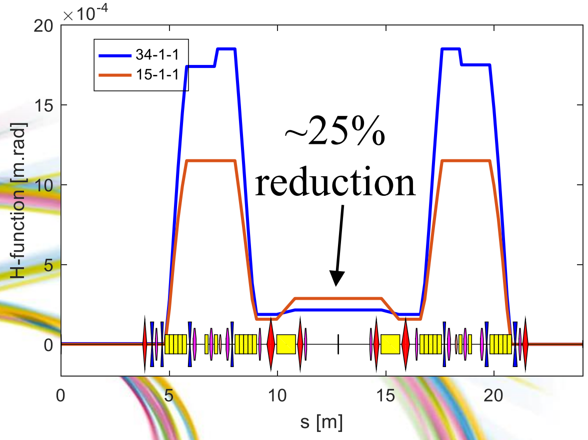


Baseline lattice 34-1-1 _OFF axis INJ.

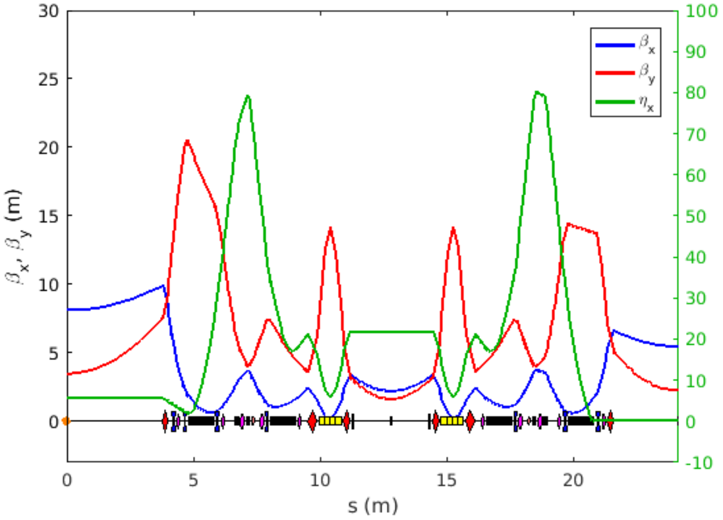
- Increase margin of safety for off-axis injection
- Improve the lifetime
- Maintain brightness achieved during CDR

Parameter	Values
Energy (GeV)	3.5
Betatron tunes	[54.15, 20.27]
Natural emittance (pm.rad)	161
Emittance with IDs (pm rad)	139
Natural chromaticity	[-67.5, -88.6]
Momentum compaction factor	1.0×10^{-4}
Energy Loss per turn (MeV)	0.72
Peak dispersion (mm)	80 mm



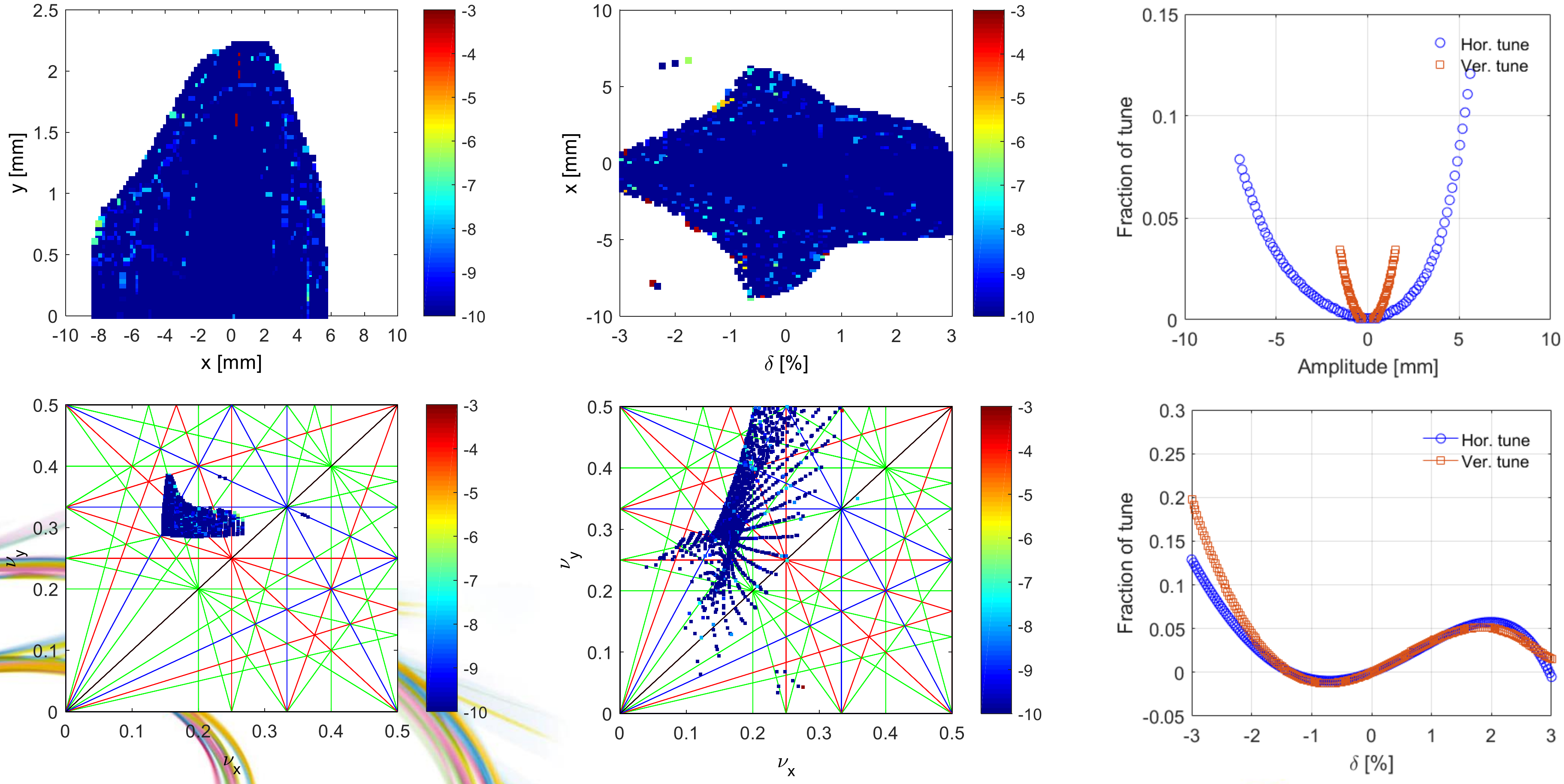


~25% reduction



Baseline lattice 34-1-1 _OFF axis INJ.

- DA: Physical stable area
- Natural chromaticity has been corrected by the chromatic sextupoles to +2.3/+2.7.
- Single particle tracking has been done for 2500 turns through the ring.

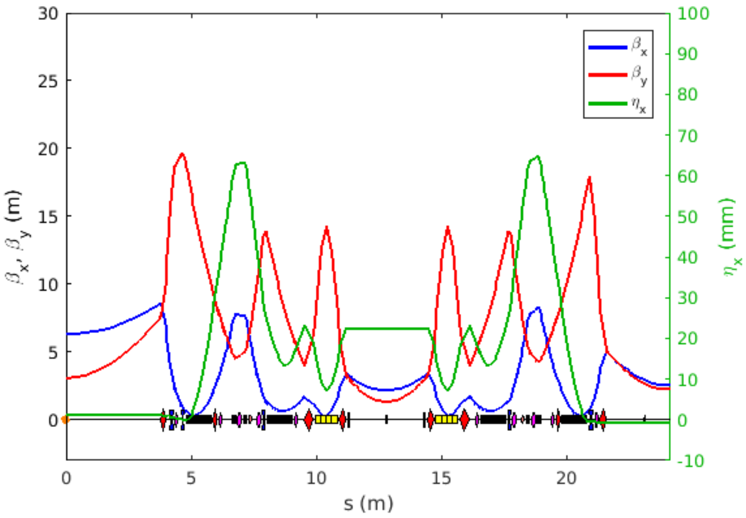


Lattice 34-2-2 _ ON axis INJ.

- Keep the same physical structure as 34-1-1
- Lower the equilibrium emittance (with IDs)
- Set β-functions at IDs to increase brightness
- Define machine optics that can be possible later upgrade path once storage ring commissioning is complete and injection performance limits are known.

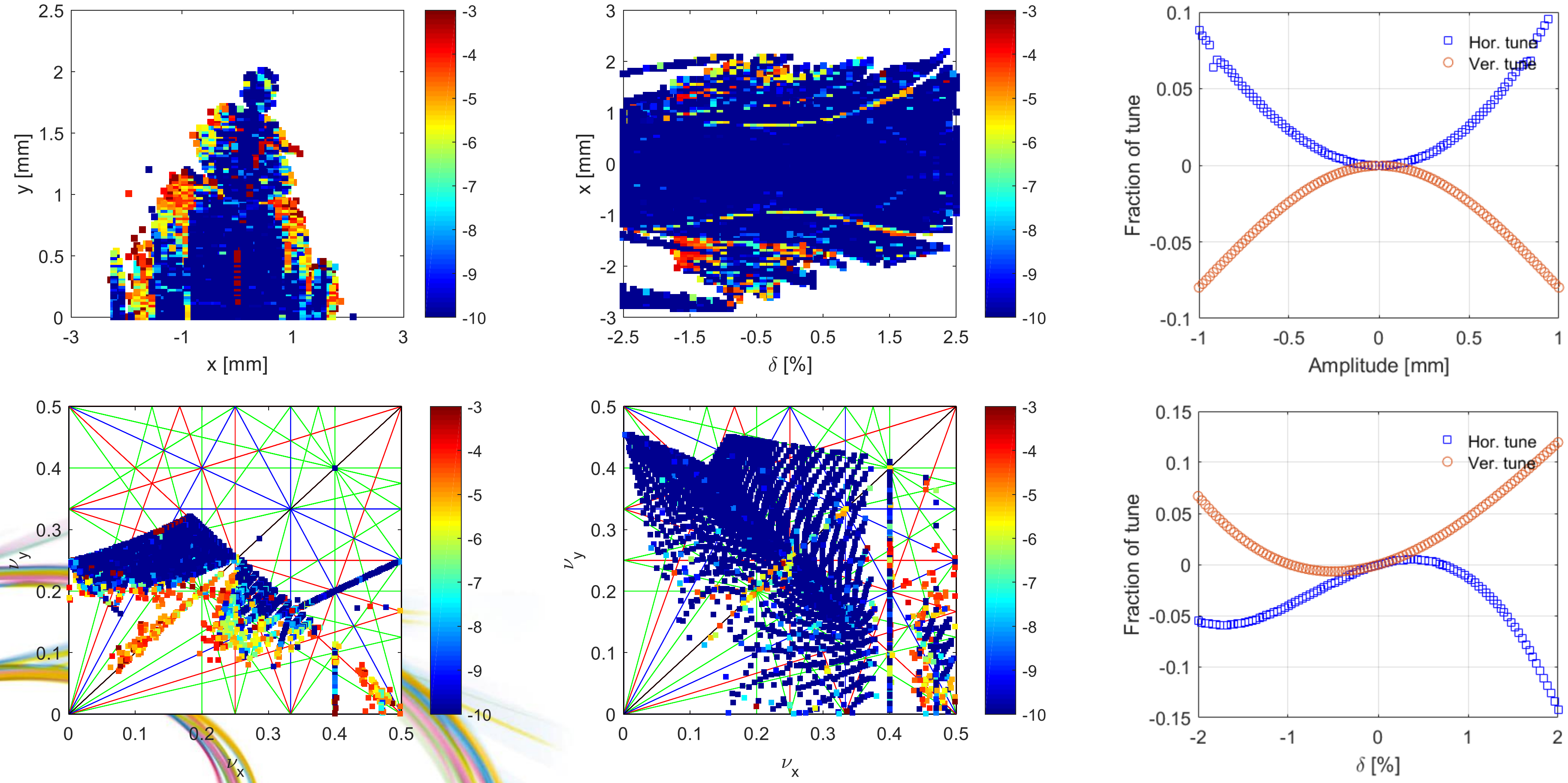
- Constraints / challenges:
  - Keep source points fixed; same circumference
  - Anti-bends must be re-aligned to maintain the same bend angle following change in gradient
  - Shorter lifetime / more frequent injections
  - On-axis injection only (single bunch swap out)
  - Increased sensitivity to ground motion / vibrations

Parameter	Values
Energy (GeV)	3.5
Betatron tunes	[62.19, 20.30]
Natural emittance (pm.rad)	106
Emittance with IDs (pm.rad)	106
Natural chromaticity	[-90.4, -111.7]
Momentum compaction factor	1.0×10^{-4}
Energy Loss per turn (MeV)	0.72
Peak dispersion (mm)	65



Lattice 34-2-2 _ON axis INJ.

- Natural chromaticity has been corrected by the chromatic sextupoles to +2.0/+2.3.
- Single particle tracking has been done for 2500 turns through the ring.



Overview of lattices: parameters

Parameter		**Units**	**15-1-1 (CDR)**	**34-1-1**	**34-2-2**
Circumference		m	560.573856	560.560644	560.560644
Betatron tunes			[57.16, 20.25]	[54.15, 20.27]	[62.19, 20.30]
Natural chromaticity			[-75.7, -89.7]	[-67.5, -88.6]	[-90.4, -111.7]
Momentum compaction factor			1.2×10^{-4}	1.0×10^{-4}	1.0×10^{-4}
Energy Loss per turn (without/with IDs)		MeV	0.67 / 1.71	0.72 / 1.76	0.72 / 1.76
Total absolute bend angle		**degrees**	**360**	**388.8**	**388.8**
Number of anti-bend dipoles		-	0	96	96
Emittance (bare lattice)		pm.rad	157	161	106
Energy spread (bare lattice)		%	0.078	0.094	0.091
Bunch length (bare lattice)		mm	3.5	3.8	3.8
Emittance (with IDs, IBS, 3HC*)		**pm.rad**	**147.5**	**138.7**	**106**
Energy spread (with IDs, IBS, 3HC*)		**%**	**0.10**	**0.11**	**0.11**
Bunch length (with IDs, IBS, 3HC*)		**mm**	**10.9**	**10.3**	**10.6**
Anti-bend gradient / offset / angle	QF4	Tm^{-1} / mm / deg	-	56.4 / 3.61 / 0.150	53.1 / 3.84 / 0.150
	QF4L	Tm^{-1} / mm / deg	-	73.3 / 3.24 / 0.175	58.7 / 4.05 / 0.175
	QF4_C1	Tm^{-1} / mm / deg	-	33.5 / 5.06 / 0.125	48.3 / 3.52 / 0.125

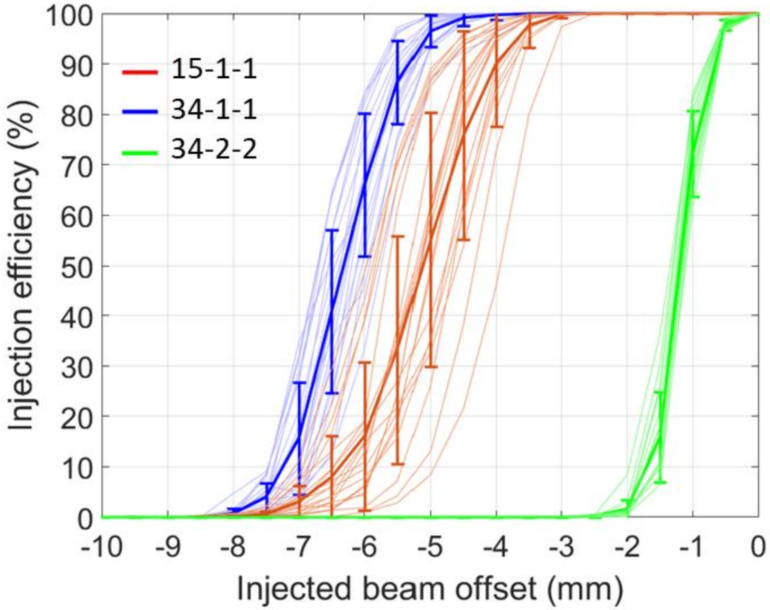
*Assumes factor 3 bunch lengthening for all bunches

Overview of lattices: Inj. Eff.

- Injection efficiency calculations carried out in ELEGANT over 2048 turns, with physical apertures
- Injected bunch parameters taken from latest Booster-II parameters

Inj. Bunch Parameter	Unit	Value
Horizontal emittance	nm.rad	17.7
Vertical emittance	nm.rad	1.8
Energy spread	%	0.086
Bunch length	mm	11.6

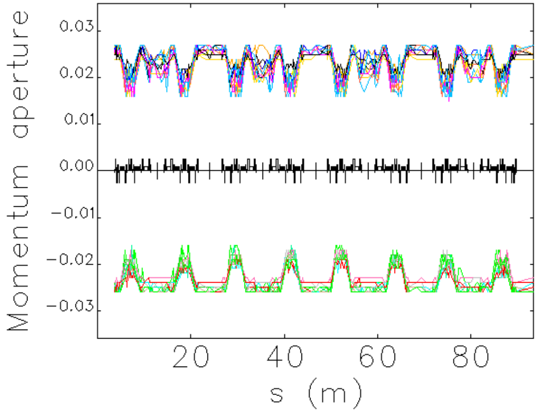
- Transfer line optics re-optimised for each lattice and each injected beam offset



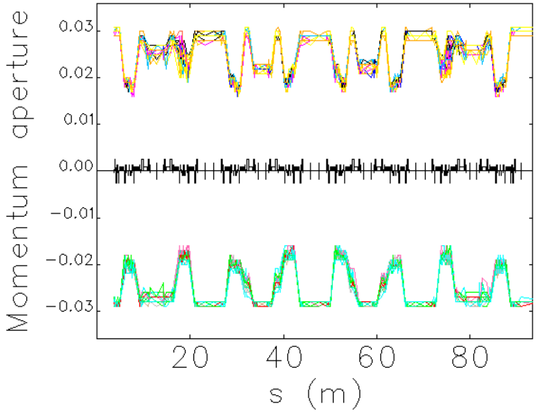
- Lattice 34-1-1:
  - Clear improvement over 15-1-1 in terms of available dynamic aperture
  - Less sensitive to individual seeds
- Lattice 34-2-2 would require on-axis swap-out injection

Overview of lattices: Lifetime

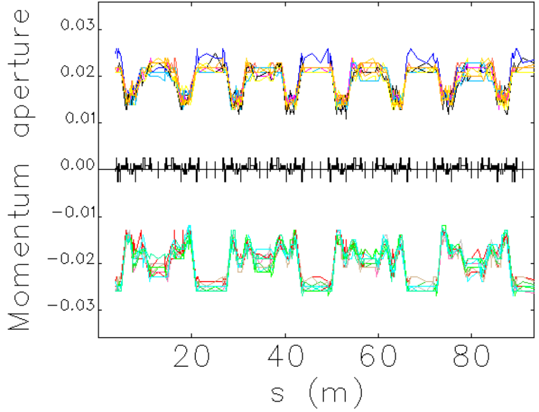
15-1-1



34-1-1



34-2-2



- Lifetime is calculated in ELEGANT using calculated dynamic and momentum apertures
- Uniform pressure distribution: 100 % CO, pressure = 1×10^{-9} mbar

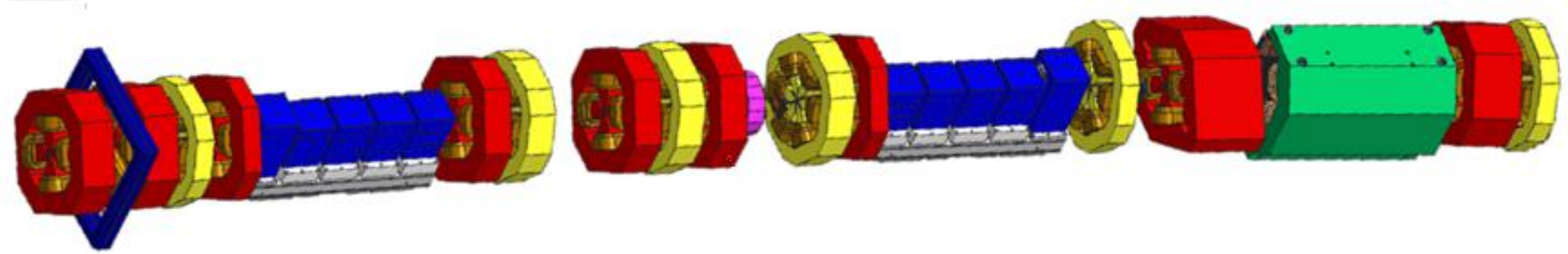
Larger dynamic and momentum apertures for 34-1-1 lead to increased gas lifetime compared to 15-1-1

Parameter	Units	15-1-1	34-1-1	34-2-2
RF voltage	MV	1.27	1.42	1.25
Bunch length	mm	3.51	3.75	3.83
Bunch current	mA	0.33	0.33	0.33
Average Touschek lifetime	**h**	**1.16**	**1.80**	**0.65**
Coulomb lifetime	h	33.01	48.99	9.17
Bremsstrahlung lifetime	h	72.64	73.56	68.45
Total gas	h	22.70	29.41	8.09
Averafe Touschek lifetime (with IDs, IBS, 3HC)	h	4.07	5.04	2.14
Overall lifetime	**h**	**3.45**	**4.30**	**1.70**

Magnets

courtesy A. Shahveh

Magnet Type	Description	Max Strength	Type
CFDL	Combined function longi. gradient dipole	0.33 to 0.83 T -0.5 to 2 T/m	Permanent
DQ		0.6951 T -32.397 T/m	Electromagnet
Quadrupole		85.2 T/m	Electromagnet
Antibend Quads	Offset quadrupole, 3.2<dx<5.1	73 T/m 3.24 mm	Electromagnet
Sextupole	Sextupoles with correctors	4186.29 T/m^2	Electromagnet
Octupole	Simple octupoles	45401.77 T/m^3	Electromagnet



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Possible Timeline for Diamond-II

Event	Date
CDR Published	May 2019
Draft TDR	Dec. 2021
Start of funding and procurement	Apr. 2022
Start of shutdown	Dec. 2025
Resume full User Mode	Jun. 2027

Conclusion

- Unique: combines low emittance with high-capacity
- Lattice design exploits many advanced techniques.
  - MBA
  - anti-bends
  - longitudinal variable bends
  - transverse gradient dipoles
- Several lattice alternatives have been investigated and the propose lattice is 34-1-1.
  - CDR 15-1-1
  - 34-1-1 (Baseline solution - Off axis injection)
  - 34-2-2 (High brightness lattice as possible later upgrade path -On axis injection)
- Diamond-II is aiming for off axis injection.
- High brightness mode is under consideration. This would require on axis injection scheme.
- Engineering, vacuum and magnet design are in progress. No significant problems are foreseen.

Acknowledgments

Diamond-II Lattice Design Team:

R. Fielder, A. Jury, J. Kallestrup, I. Martin, T. Olsson, B. Singh, R. Walker,

Former Members:

A. Alekou, M. Apollonio, R. Bartolini, J. Bengtsson , T. Pulampong, F. B. Taheri

Thank you for your attention

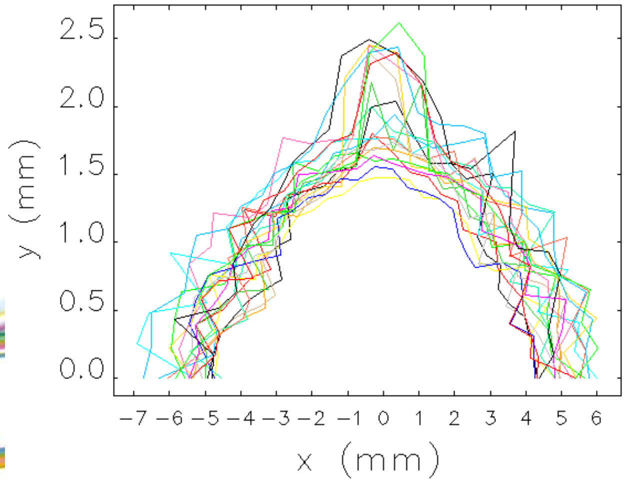
Back up slides

Overview of lattices: DA

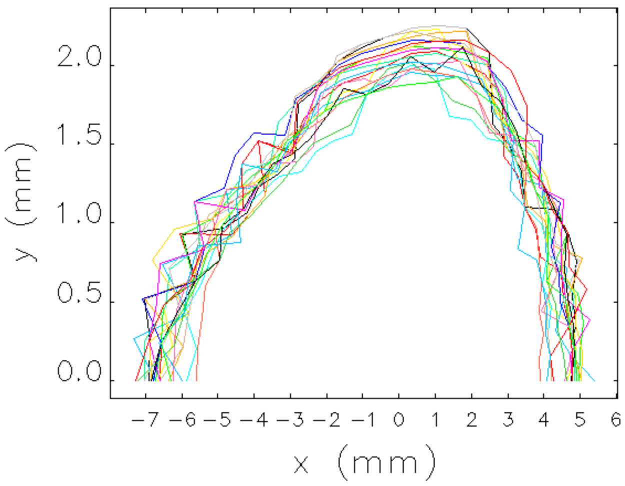
- Initial characterisation of lattices uses reduced errors
- Orbit, tunes and chromaticity correction only (no beta-beat or coupling correction)
- Physical apertures are included, with s-dependent ID gaps down to 4 mm taken into account
- DA, injection efficiency and lifetime values validated using full errors in AT2 with Simulated Commissioning Toolbox.

	Δx, Δy (μm)	**Roll (μrad)**	**Strength error**
Dipole	15	100	1×10^{-4}
Quadrupole	15	100	1×10^{-3}
Sextupole	15	100	1×10^{-3}
Octupole	15	100	1×10^{-3}
BPM	20	10	-

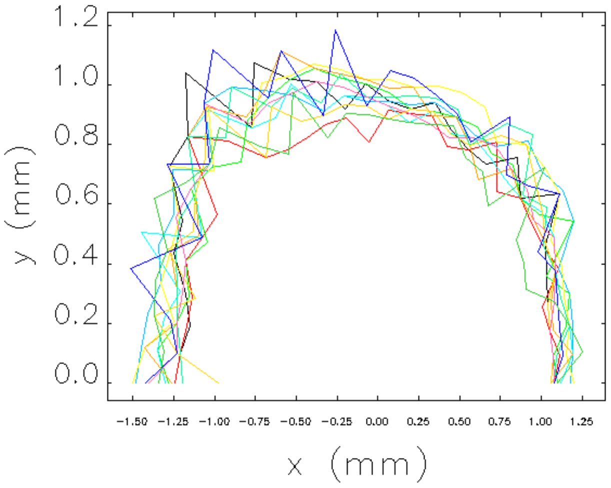
15-1-1



34-1-1



34-2-2



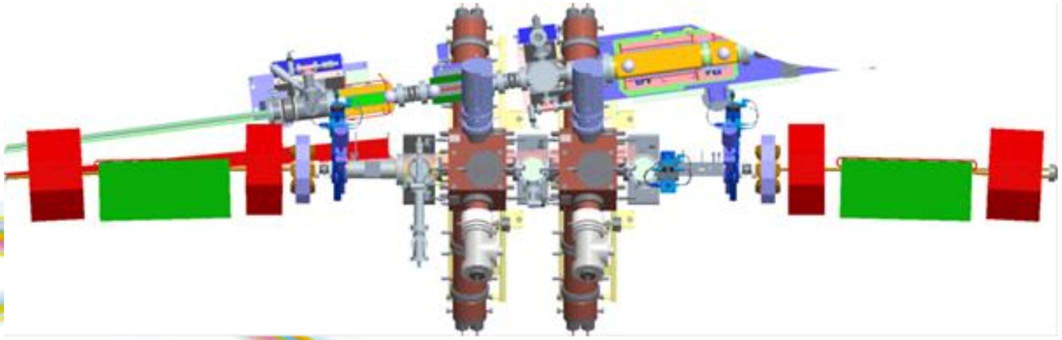
Diamond-II RF system

Use **HOM-damped normal-conducting cavities (500 MHz):**

- More robust and more easily repaired than superconducting cavities
- Releases current long RF straight for a new flagship beamline ID
- Broader frequency tuning range allows Diamond-I NC cavities to be used in Diamond-II
- Latest iteration of cavities used in BESSY, ALBA and ESRF (scaled for frequency)
- Smaller footprint than superconducting cavities in cryostats
- Effective HOM-damping has been demonstrated in Diamond-I

Eight RF cavities arranged in pairs in mid-section straights:

- Multiple low-voltage cavities gives lower wall losses
- Use of multiple cavities introduces redundancy of operation



Courtesy C. Christou

Diamond-II RF system

Amplifiers

Each cavity powered by single **solid state amplifier**

- 100 kW amplifier many 800 W power transistors
- Redundancy ensures continuity of operation
- Several commercial suppliers exist

Amplifier/cavity operation regulated by **digital LLRF**

- IQ or polar PI loops for cavity ampl./phase
- Based on the MicroTCA standard
- Digital (functionality can be added as required)
- Based on system developed at ALBA

Higher harmonic cavity

- Minimise storage ring heating
- Alleviate collective instabilities
- Maximise beam lifetime

Passive superconducting HHC

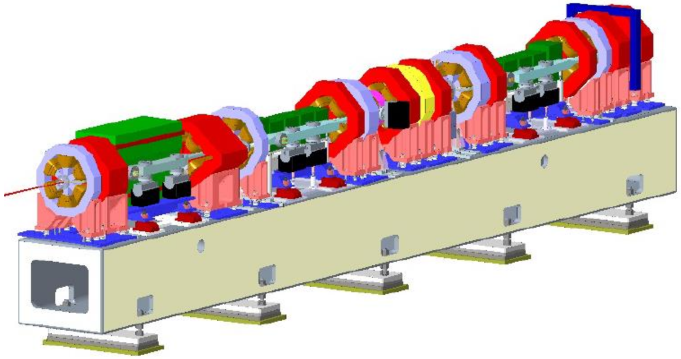
- Needs no new amplifier
- Operates across all beam currents
- Can fit in mid-section straight
- Available from industry (CEA design: SLS, Elettra)
- Can use the existing Diamond-I cryogenic plant

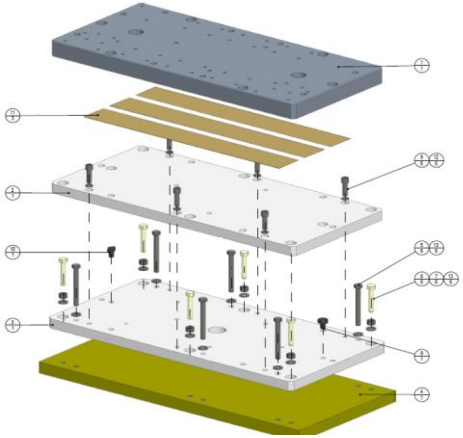
Courtesy C. Christou

Diamond-II Girders

Present solution:

- Magnets to be supported on single girder per half-cell (~8 m long)
- Manual adjustment system (screw-thread adjustment in each plane))
- Aim to achieve overall transmissibility of ~1 in 1-100 Hz band
- Electron beam is most sensitive to vertical girder motion
- Use viscoelastic tape in baseplates
  - stiff at high frequency to reduce transmissibility
  - Soft at low frequencies to allow expansion and contraction
- Choice of material from trial girders
  - steel fabrication (same as existing girders, good stiffness)
  - cast grey iron (better damping properties, easy to produce, cost-effective)
  - carbon composite (lightweight, high natural frequency, expensive)





Test girders will inform final choice of material and support system (in progress).

Courtesy J. Dymoke Bradshaw

Diamond-II vacuum chamber

Requirement: Target average pressure ≤ 10^{-9} mbar at 300 mA after 100 A.h beam conditioning

<u>Current solution (WIP)</u>

Vessel cross-section: Mainly circular (20 mm inner diameter)
Antechamber in those dipole vessels with photon beam extraction

Pumping: Non-evaporable getter (NEG) coated apart from antechamber vessels
Plus discrete ion pumps and NEG cartridge pumps
3D vacuum sims to confirm vacuum (Synrad+, Molflow+, Comsol Multiphysics®)

Heat load management: Mix of discrete and distributed absorbers

Materials/manufacturing: Most vessels copper; antechamber vessels aluminium
CuCrZr discrete absorbers possibly with some additive manufacturing
Fully RF-shielded gate valves, flanges and bellows
NEG coating by industry

Assembly process: Ex-situ bakeout only
Vacuum strings (~7m) built up, baked out and NEG activated on assembly trolleys
Remain under vacuum during installation

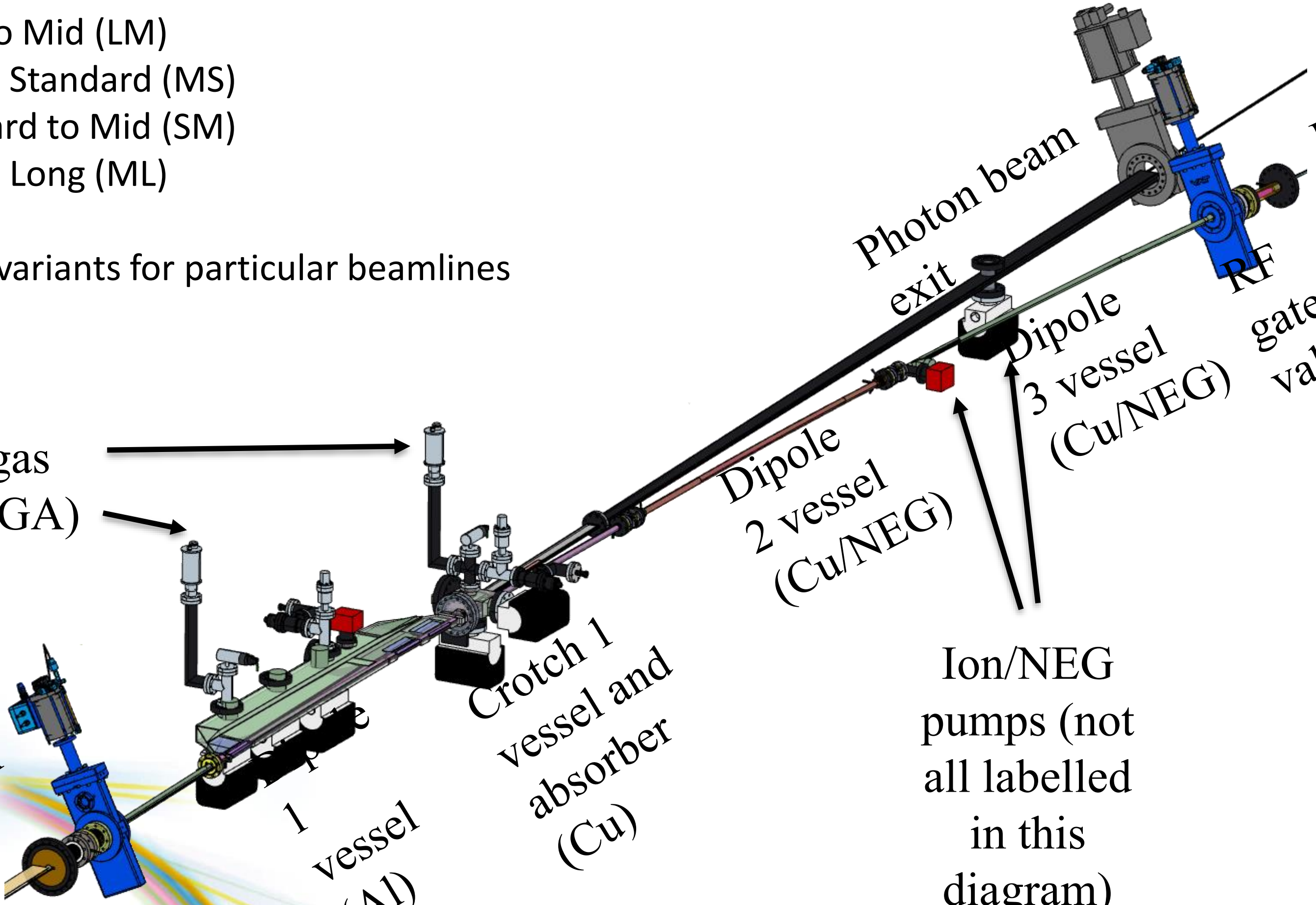
Courtesy M. Cox

Diamond-II vacuum chamber

Four different girder types:

- Long to Mid (LM)
- Mid to Standard (MS)
- Standard to Mid (SM)
- Mid to Long (ML)

plus some special variants for particular beamlines



Photon beam exit

Electron beam exit

RF gate valve

Dipole 3 vessel (Cu/NEG)

Dipole 2 vessel (Cu/NEG)

Residual gas analyser (RGA) ports

Ion/NEG pumps (not all labelled in this diagram)

Crotch 1 vessel and absorber (Cu)

1 vessel (Al)

Beam direction →

Courtesy M. Cox