Possibilities for Future SR and FEL Development in the UK.

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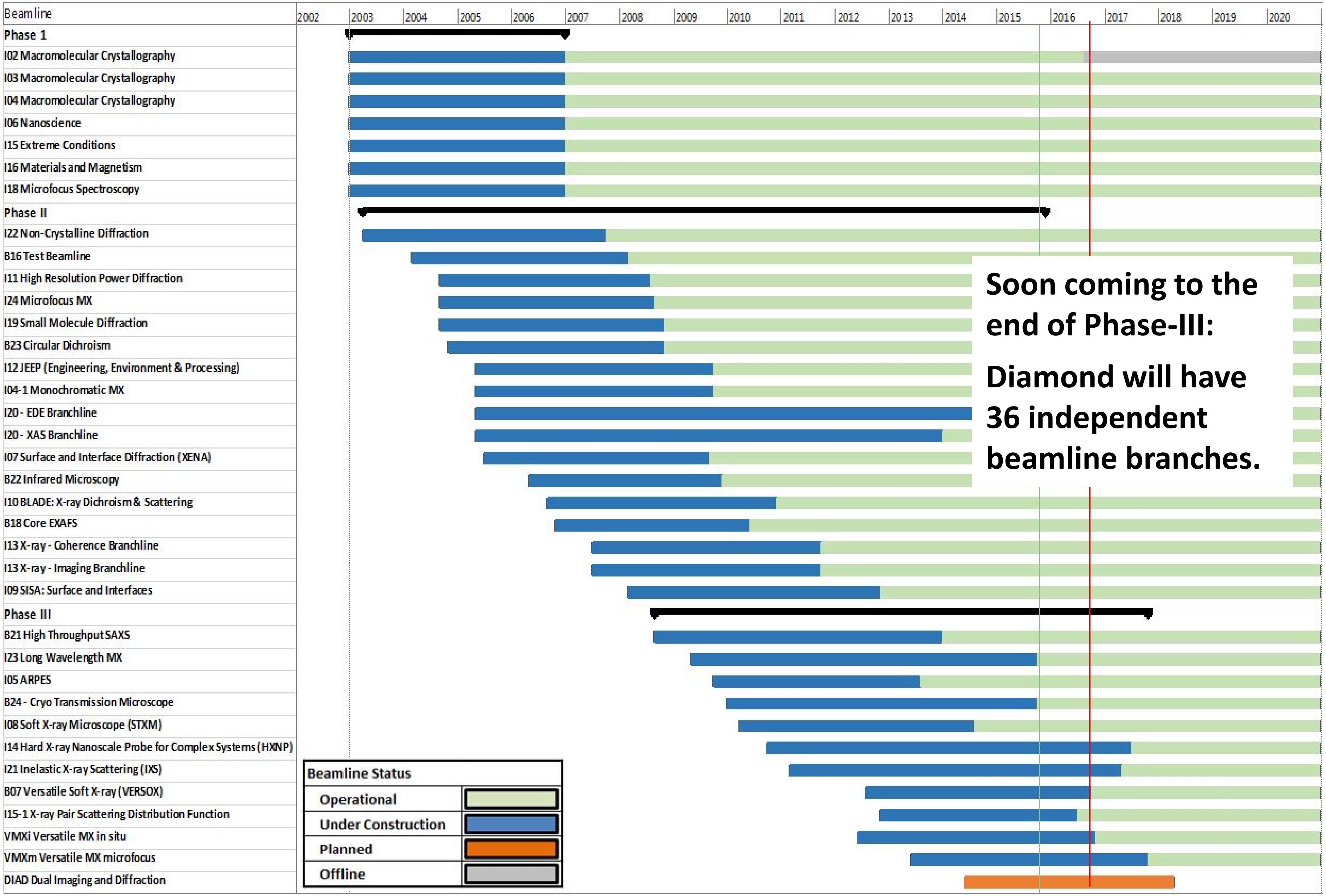
SR-86 … a lot's changed since then !

Diamond Light Source

diamond

Beamline Delivery Schedule BLS-GEN-REP-0011 October 2015



Insertion Devices

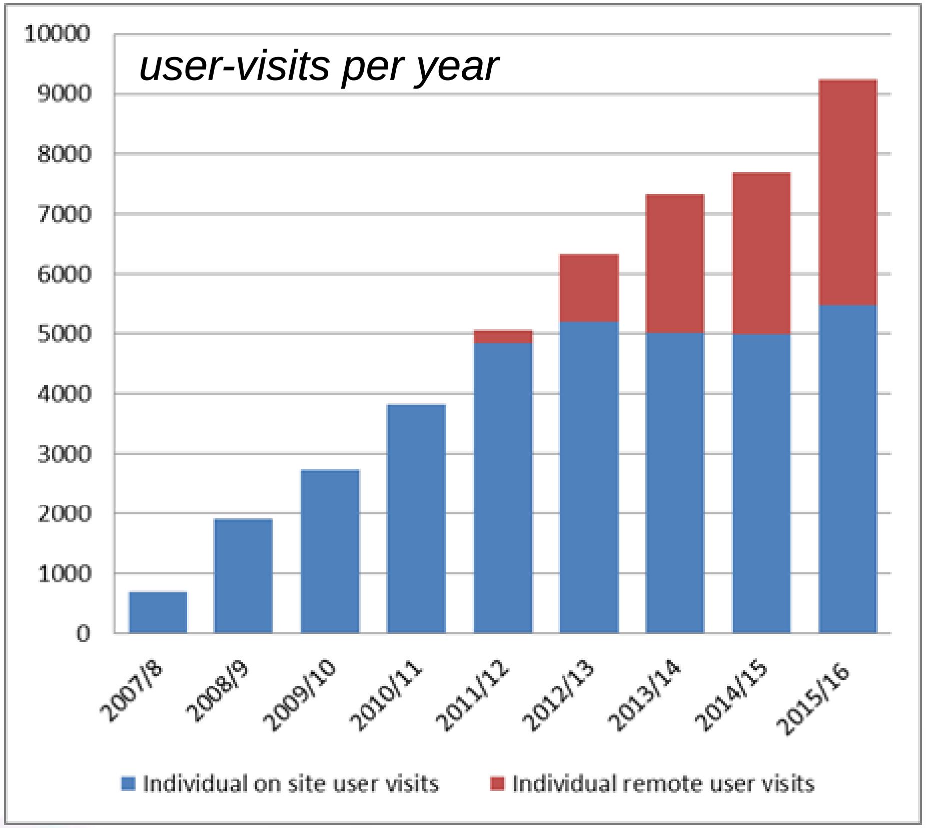
	Type of Device
01	(injection)
02	in-vacuum undulator
03	in-vacuum undulator
04	in-vacuum + short ex. vac. undulators
05	5m APPLE undulator
06	2 APPLE undulators
07	cryogenic in-vacuum undulator
08	4.5m APPLE undulator
09	in-vacuum + APPLE undulators
10	2 APPLE undulators
11	in-vacuum undulator
12	superconducting wiggler

	Type of Device
13	2 in-vacuum undulators
14	in-vacuum undulator
15	superconducting wiggler
16	in-vacuum undulator
17	(RF)
18	in-vacuum undulator
19	in-vacuum undulator
20	2 permanent magnet wigglers
21	5m APPLE undulator
22	in-vacuum undulator
23	in-vacuum undulator
24	in-vacuum undulator

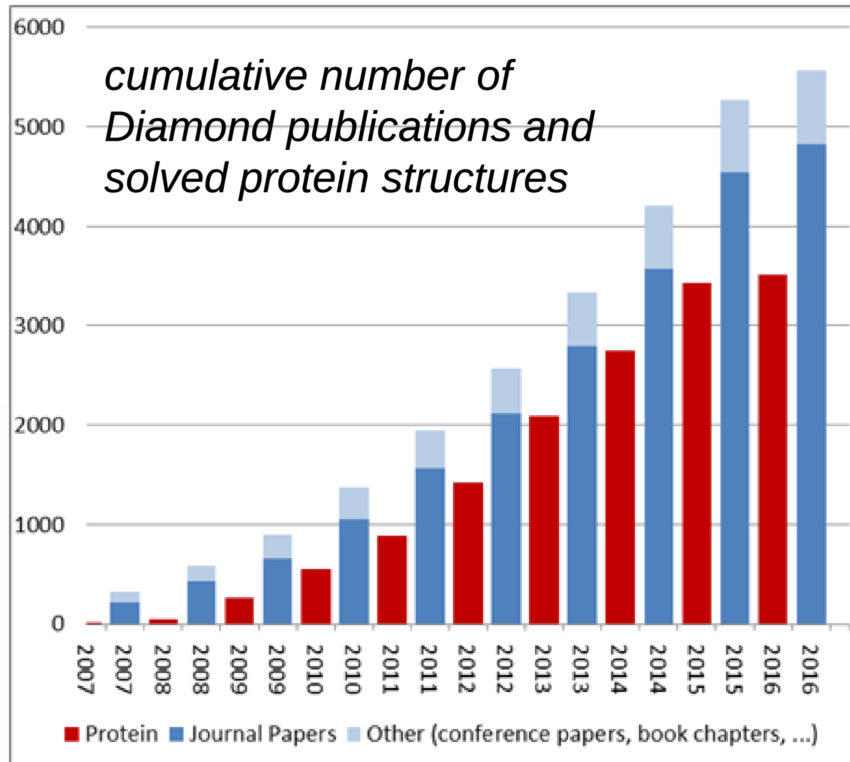
27 discrete IDs … all straight sections are occupied !

Demand and Output

Increasing demand - over 9000 “user-visits” last year:

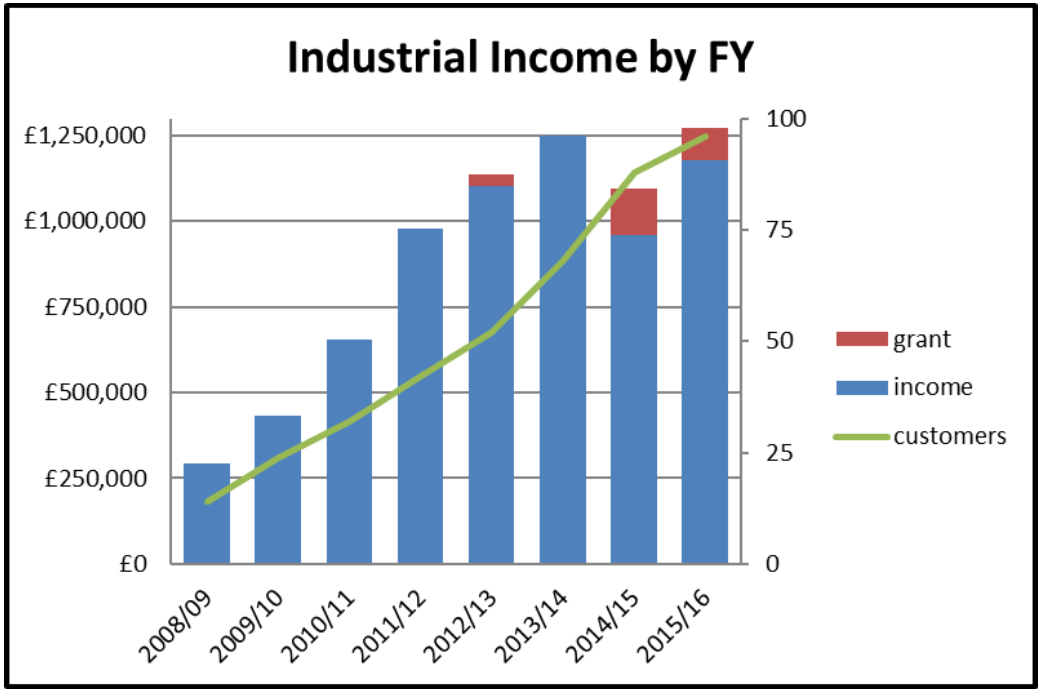


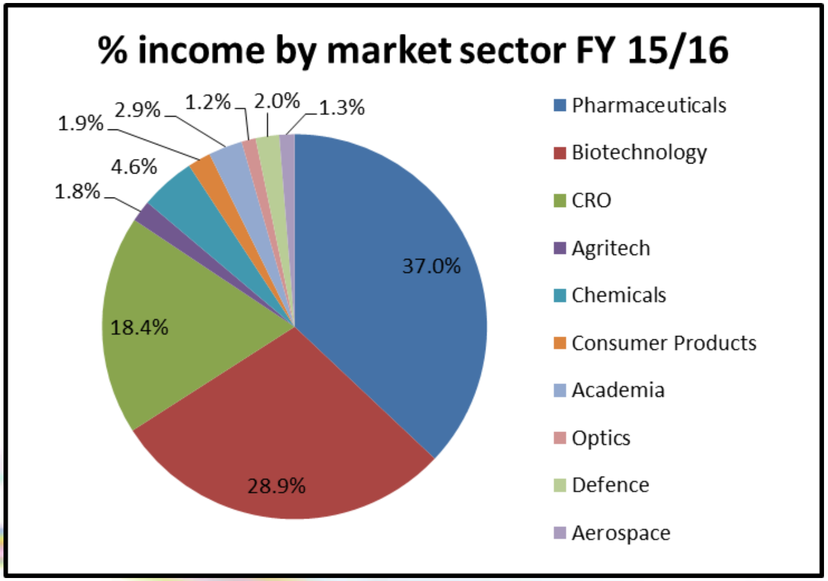
Increasing science output:



Industrial Impact

Increasing impact – now 100 companies engaged in industrial use of Diamond





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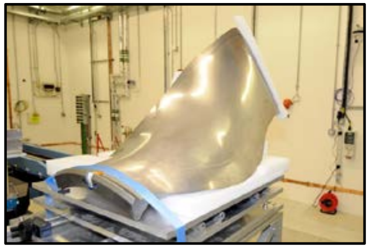
Examples of industrial use of Diamond

Engineering

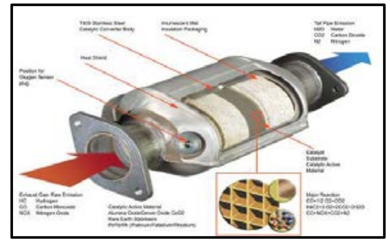


Rolls-Royce
Strain scanning in aerospace components

Consumer products

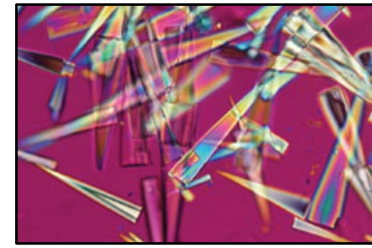
Unilever
Microstructure in a new hair care product

Catalysis



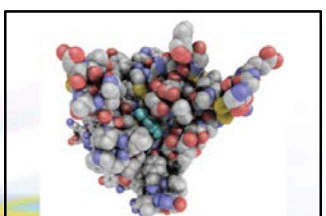
Johnson Matthey
Platinum speciation in three way catalysts

Fuel additives



Infineum
Crystallisation processes in biofuels

Drug design



Heptares
Designing drugs for Parkinson's disease treatment

Drug manufacture

GlaxoSmithKline
Controlling a manufacturing process

Medical devices

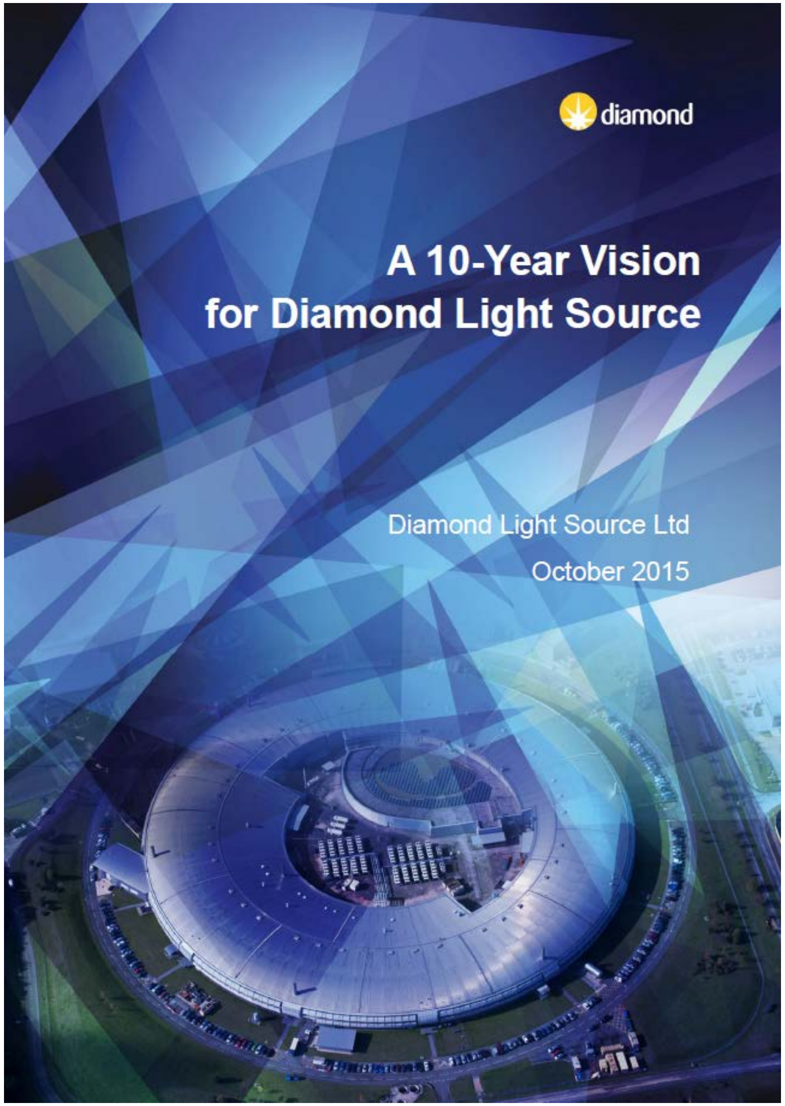
NHS
Understanding failure in MOM hip replacements

Diagnosing disease

NHS
Speeding up cancer diagnosis using IR

Planning for the Future

The 10-year Vision:



available from: http://bit.ly/Diamond10yearvision

The Diamond Upgrade

… which led to the Diamond Upgrade proposal:

presented to the Diamond Science Advisory Committee (27th-28th April 2016) and Board of Directors (1st June 2016).

The Diamond Upgrade

A next generation light source for UK science and innovation

Executive Summary

Diamond has established itself in its tenth year of operation as a world-class synchrotron, enabling research by leading academic and industrial groups in physical and life sciences. However, the technology for light sources, including detectors, optics and scientific computing, is developing at a tremendous pace and Diamond must take advantage of this if it is to continue to provide first-class opportunities to meet the scientific and societal challenges of the future.

This document outlines some of these challenges, shaped by the strategic priorities of our shareholders, STFC and the Wellcome Trust, and informed through input from our user community. It also presents an Upgrade programme for the period 2016-2024, whose timescale is set by the length of time it will take to design, build and commission a new, low-emittance storage ring, and this part of the Diamond Upgrade is called Diamond-II.

The new storage ring will be built within the existing footprint and offer more than 10-fold increase in brightness, with much enhanced coherence. In addition the unique machine design gives the potential to introduce more high performance insertion device beamlines, as well as providing flexibility for implementing other source improvements in the future.

Equally important for effective science delivery will be upgrades at every other stage of the measurement process - from brighter insertion devices, through nanofocus optics to faster detectors offering far greater resolution/range in time and space, and near real-time comprehensive data analysis. These developments will provide transformative opportunities across science, engineering and medicine. Specifically Diamond will build on its position as a leading global centre for materials discovery, processing and integrated structural biology to maximise the impact of the ongoing revolutionary developments.

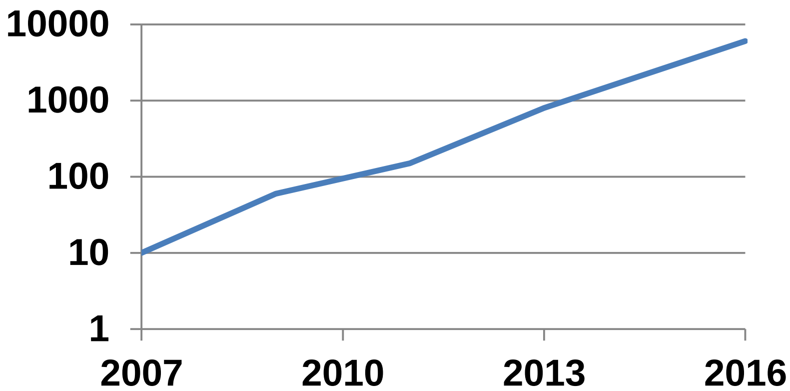
April 2016 1

The Diamond Upgrade 2016-2024

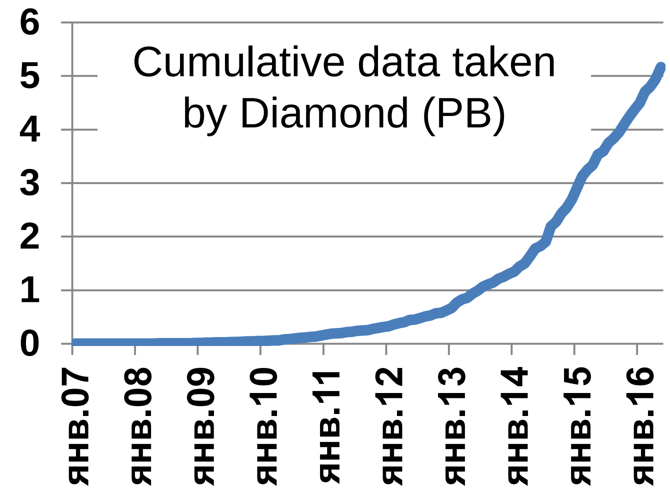
- **Enabling technology to maintain competitiveness:**
  - Improved sources – CPMUs and potentially SCUs
  - Improved optics
  - Improved detectors
  - Improved/greater range of sample environments and sample transfer systems
  - Continuing upgrades to data handling infrastructure
- **Significant upgrades to beamlines**
- **A new low emittance lattice: Diamond-II**

The "Data Deluge"

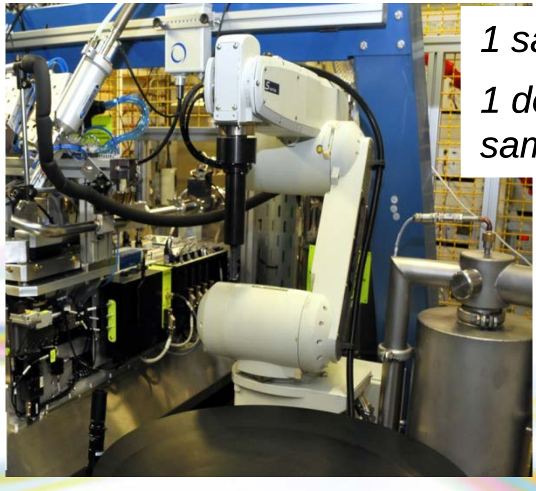
Increasing data rates from detectors (MB/s):



Increasing data storage requirements:

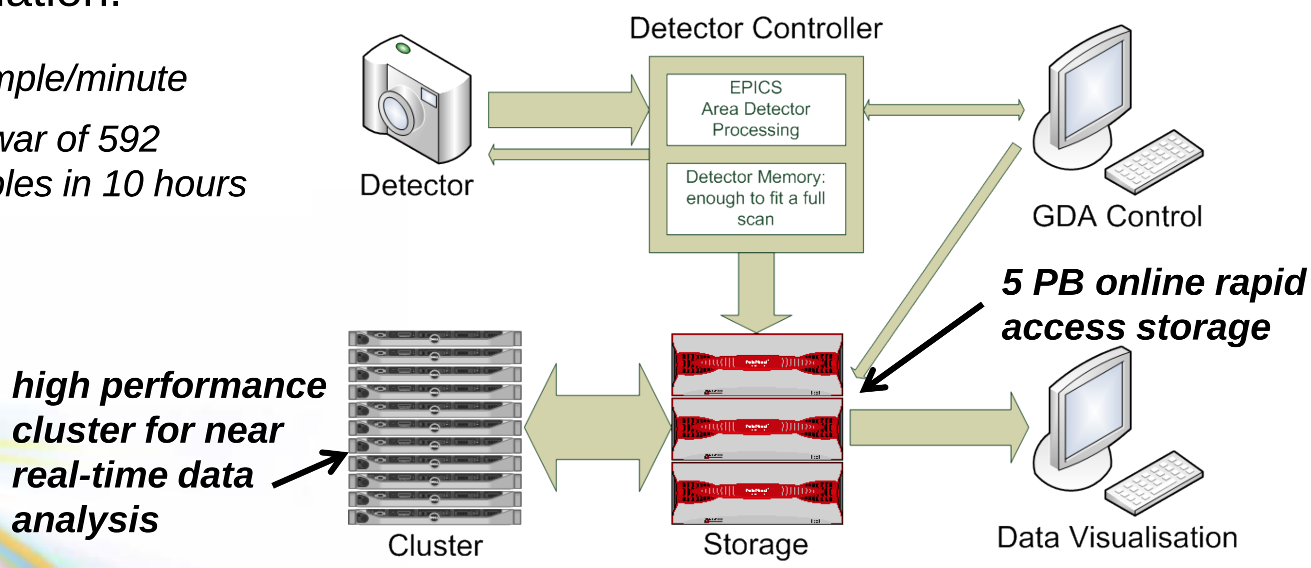


Increasing use of automation:



1 sample/minute

1 dewar of 592 samples in 10 hours



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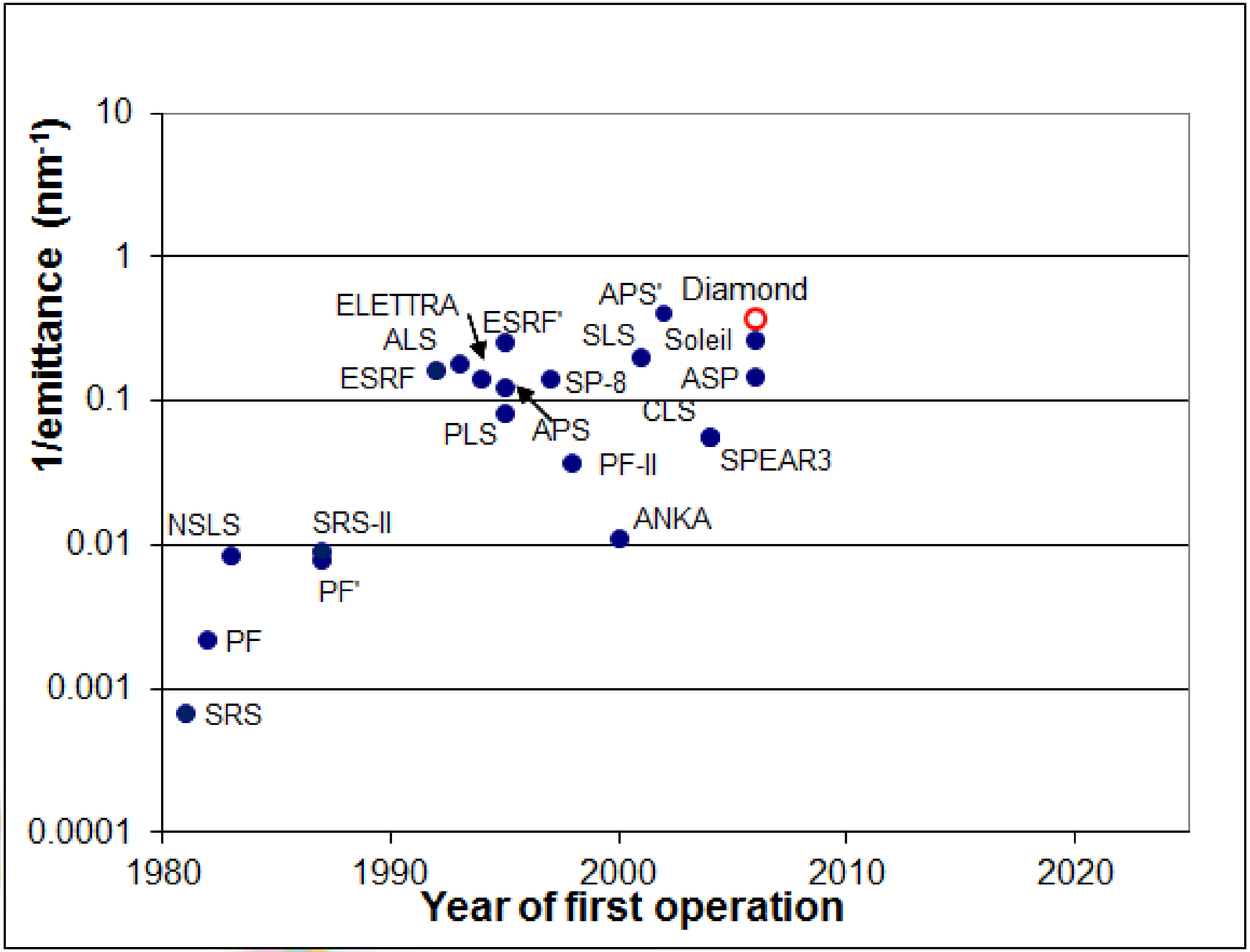
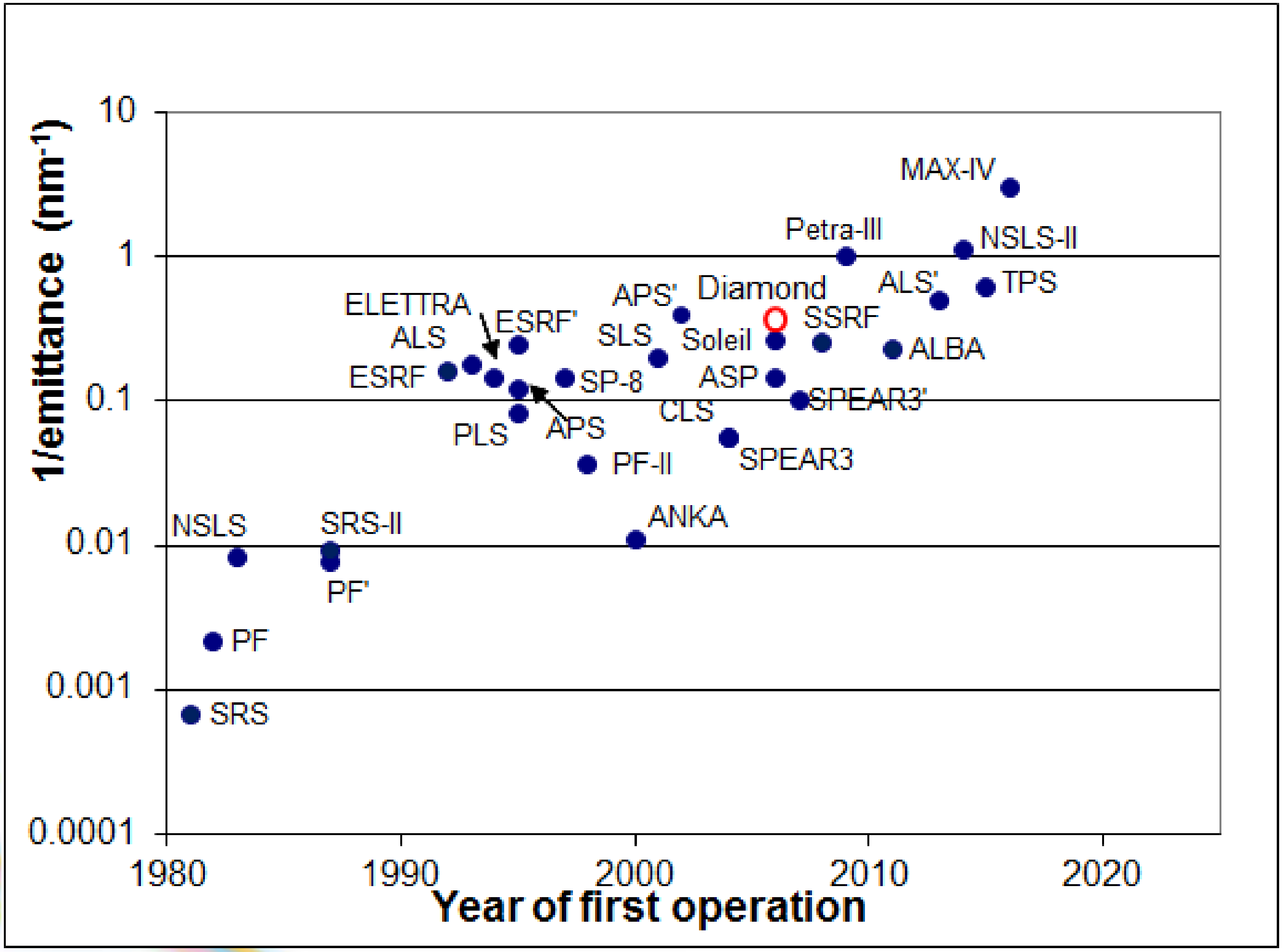
When Diamond was built .. it was the largest, and lowest emittance “medium energy” SR source:

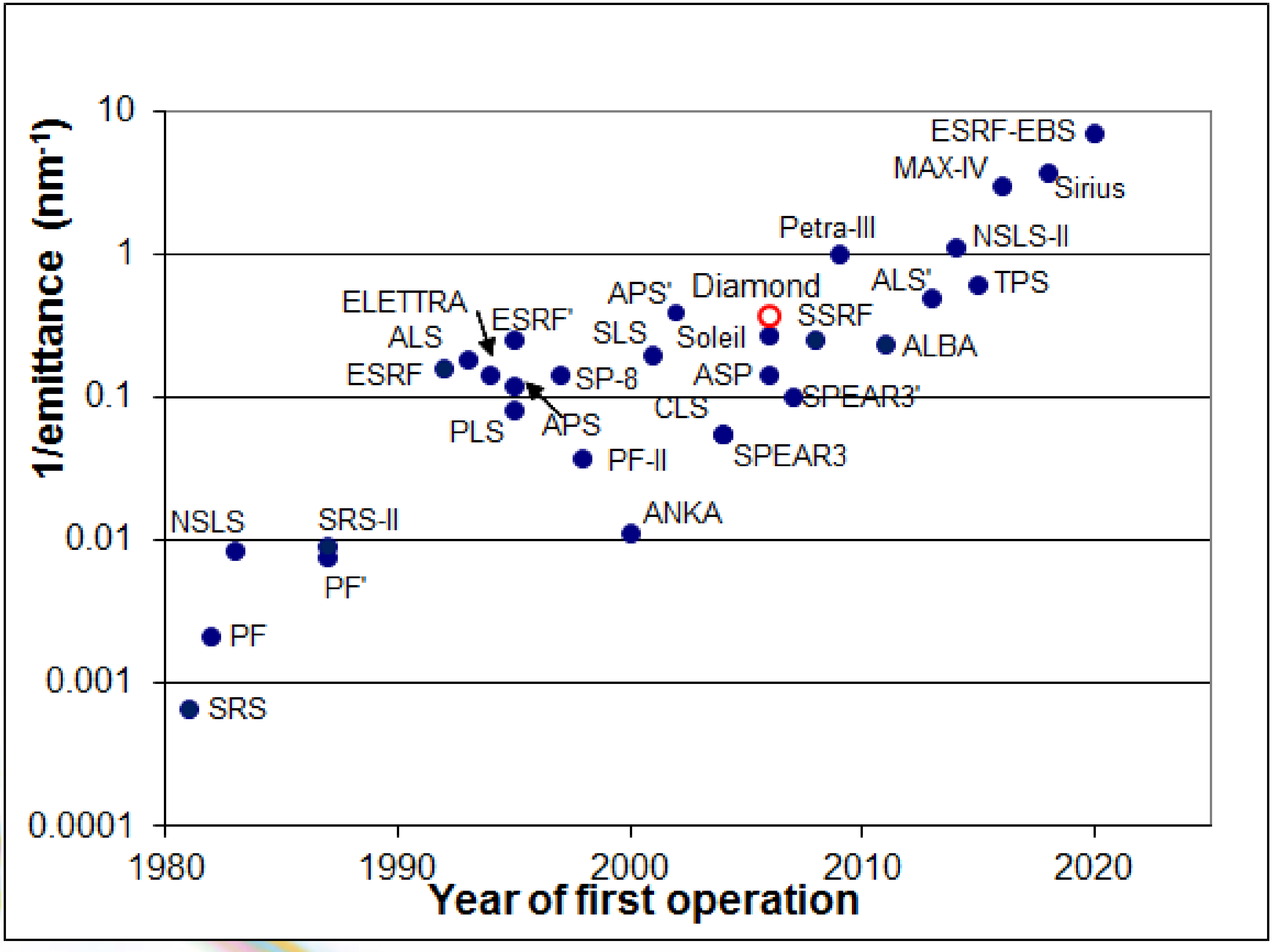


but now …



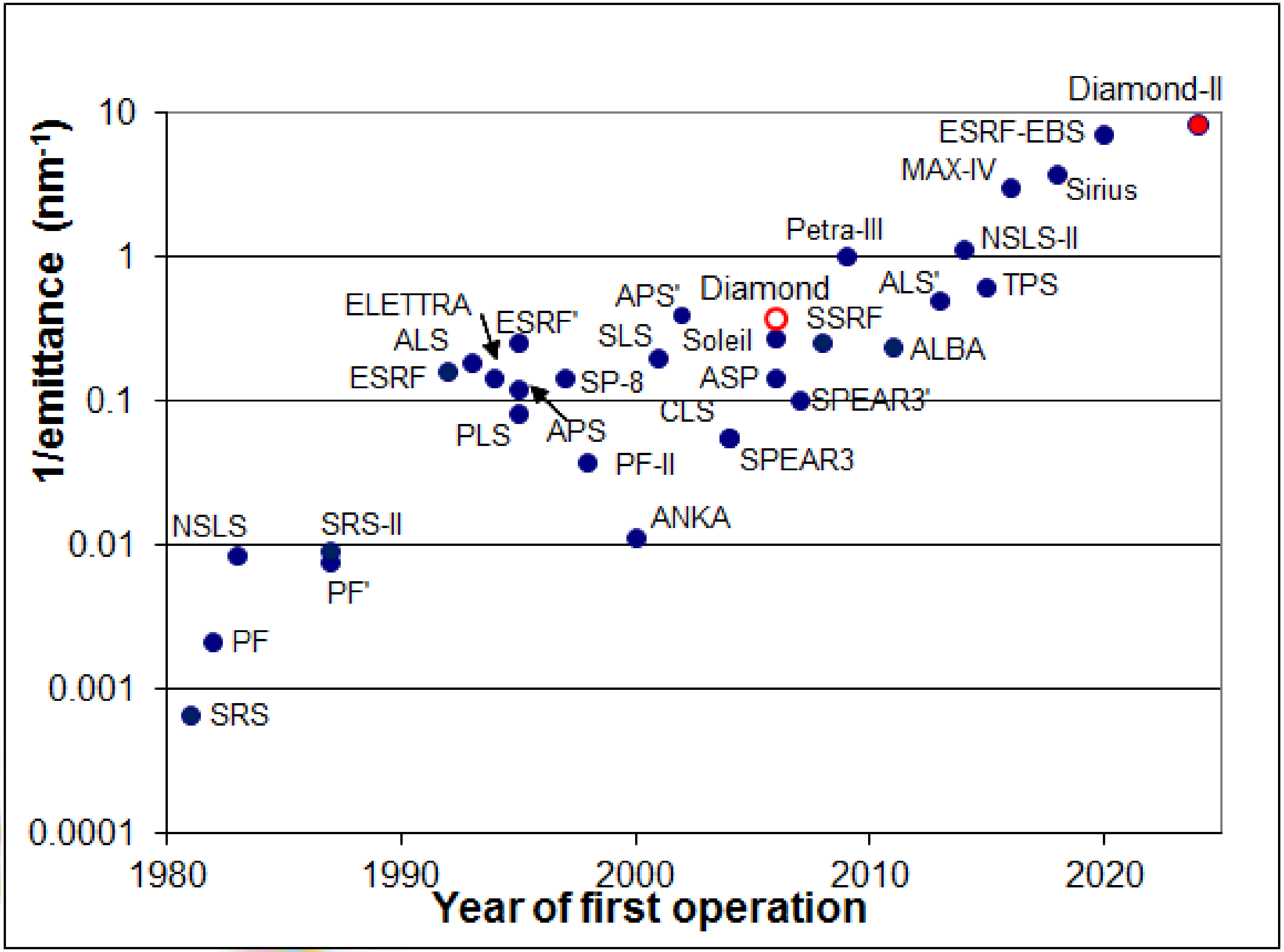
1/emittance (nm-1)
Year of first operation
10
1
0.1
0.01
0.001
0.0001
1980
1990
2000
2010
2020
MAX-IV
Petra-III
NSLS-II
ALS'
TPS
APS'
Diamond
SSRF
ELETTRA
ESRF'
SLS
Soleil
ALBA
ALS
ESRF
SP-8
ASP
SPEAR3'
CLS
PLS
APS
PF-II
SPEAR3
NSLS
SRS-II
ANKA
PF'
PF
SRS

and soon …



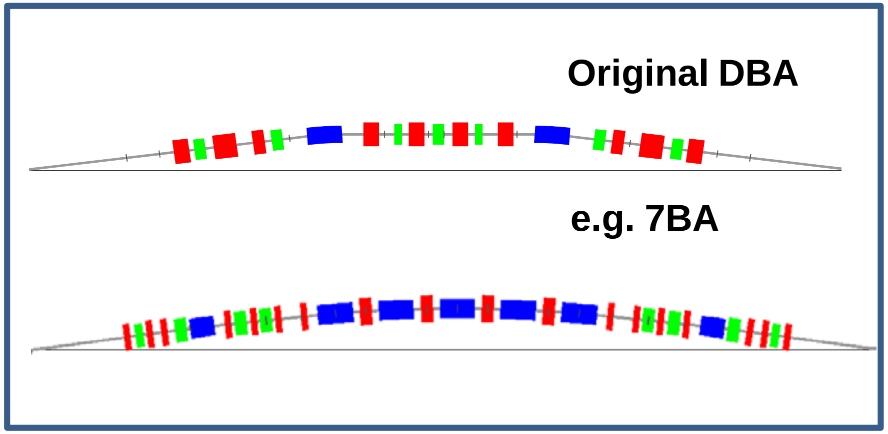
10
1
0.1
0.01
0.001
0.0001
1/emittance (nm-1)
1980
1990
2000
2010
2020
Year of first operation
ESRF-EBS
MAX-IV
Sirius
Petra-III
NSLS-II
ALS'
TPS
Diamond
APS'
SSRF
ALBA
ELETTRA
ESRF'
SLS
Soleil
ALS
ESRF
SP-8
ASP
SPEAR3'
CLS
PLS
APS
SPEAR3
PF-II
ANKA
NSLS
SRS-II
PF'
PF
SRS

so we are beginning to think seriously about Diamond-II …



Initial MBA studies

Initial studies of low emittance lattices started with Multi-Bend Achromats (MBA) with M=4,5,7



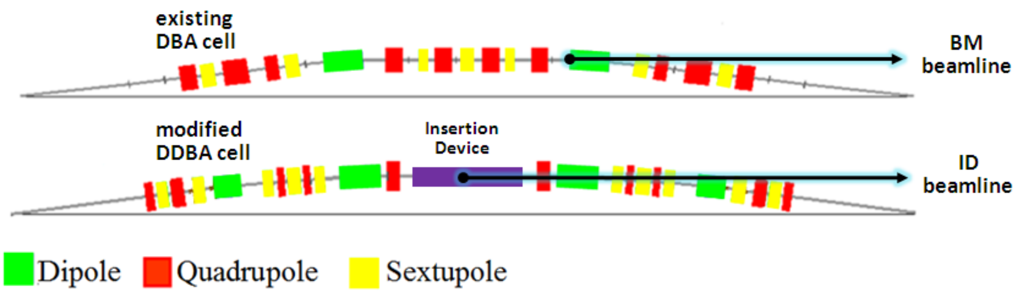
Increasing M reduces emittance, but results in diminishing dynamic aperture:

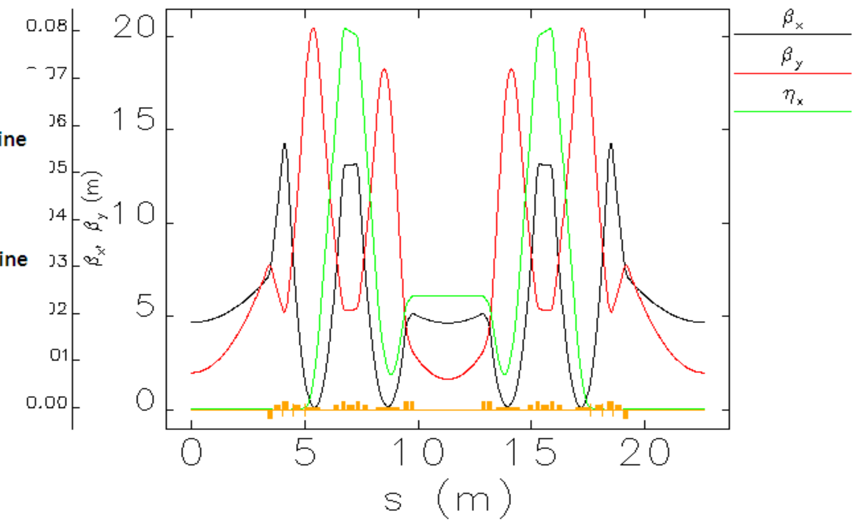
No. of Bends (M)	Emittance	Dynamic Aperture
4	270 pm	± 5 mm
5	140 pm	± 3.5 mm
7	45 pm	± 1 mm

courtesy of R. Bartolini, DLS

DDBA

This led to the concept of a modified 4BA, or "double-DBA" (DDBA)



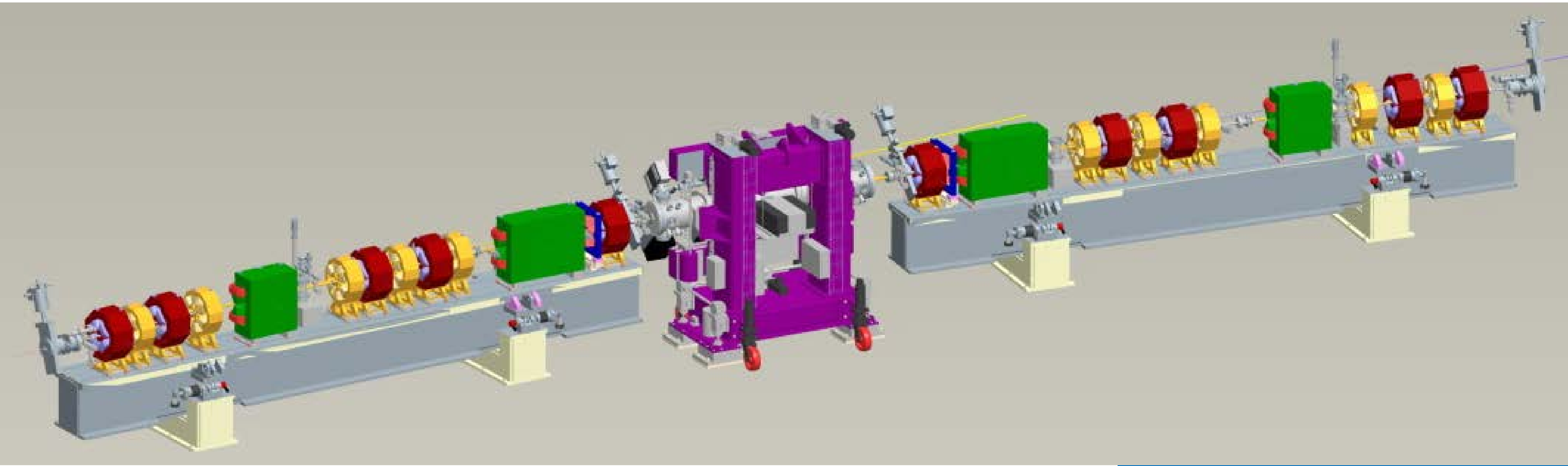


- Allows a bending magnet beamline to become a new insertion device beamline
  - Will be carried out in one cell of the ring in Oct./Nov. 2016 to create a new ID beamline
- Converting the whole ring to DDBA became the initial design for Diamond-II
  - Natural emittance 275 pm.rad (factor 10 reduction on present lattice)
  - 24 additional straight sections for further ID beamlines or other machine components

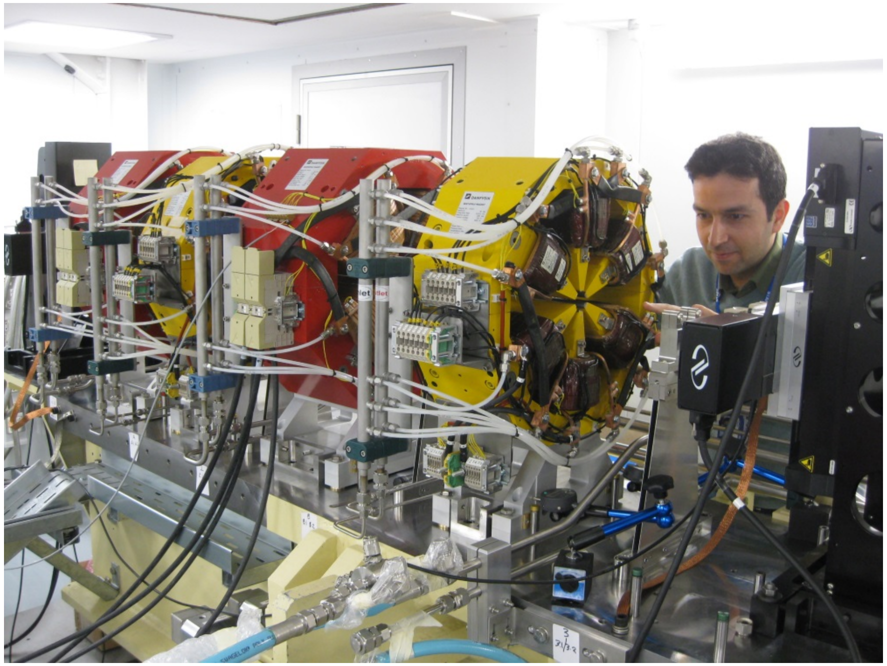
DDBA

take out a complete arc, 3 girders:

and replace it with 2 completely new girders:
(new magnets, vacuum vessels, BPMs, girders, cabling, controls etc.)

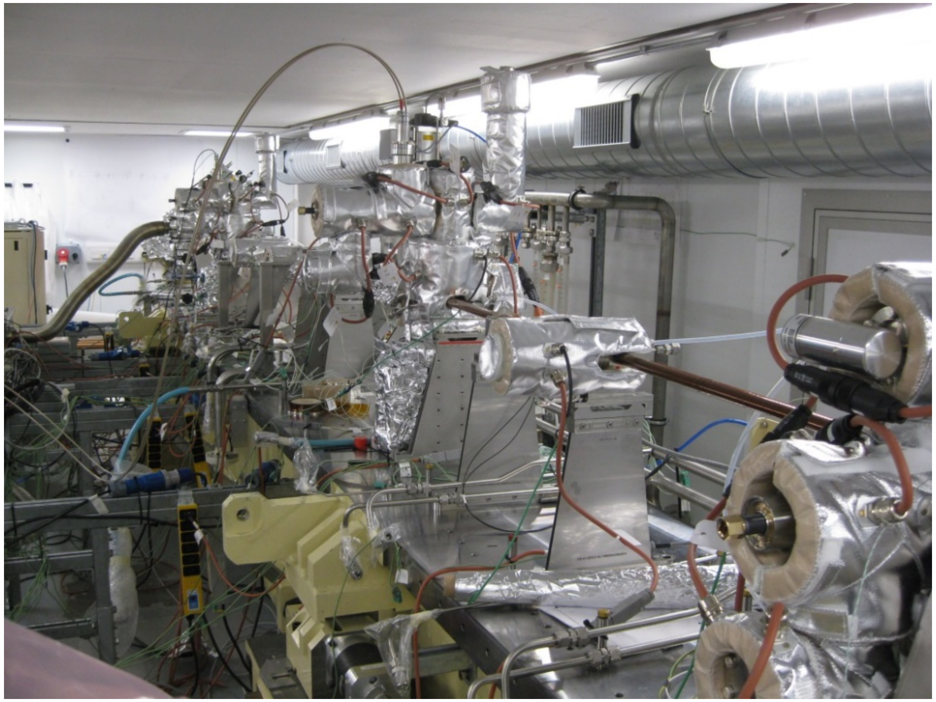


DDBA



Installation of one DDBA in Oct./Nov. 2016

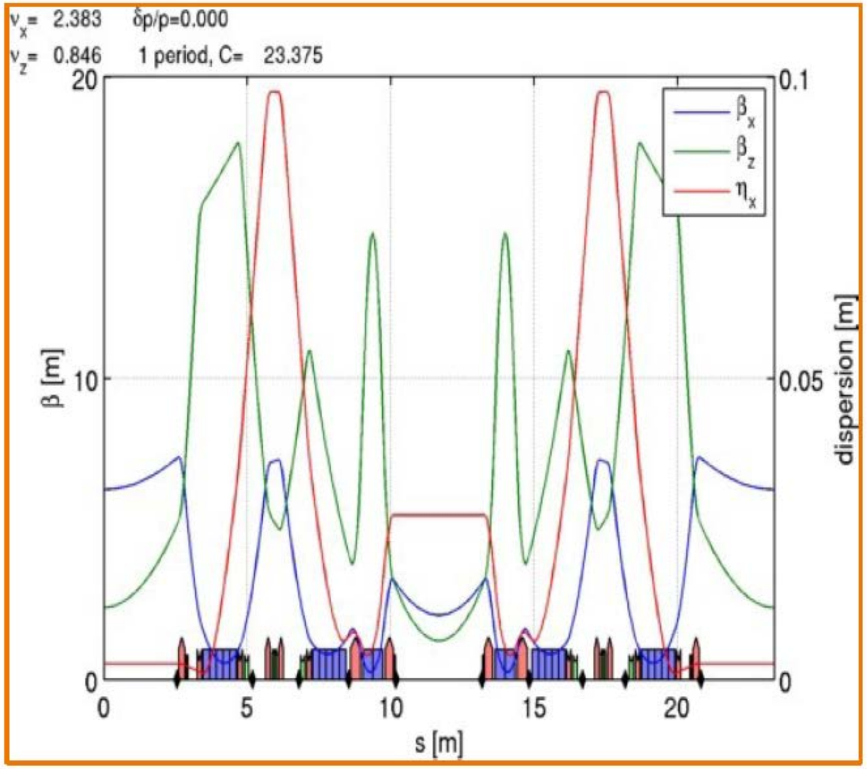
- New magnets & vacuum vessels delivered
- Girder assembly well underway



Diamond-II

**In the summer of 2015 a new concept emerged –
the modified 6BA, or "double triple bend achromat" (DTBA) lattice.**

This has been developed in collaboration with ESRF, adapting their hybrid 7BA lattice, with longitudinal gradient bends, to our 6BA.



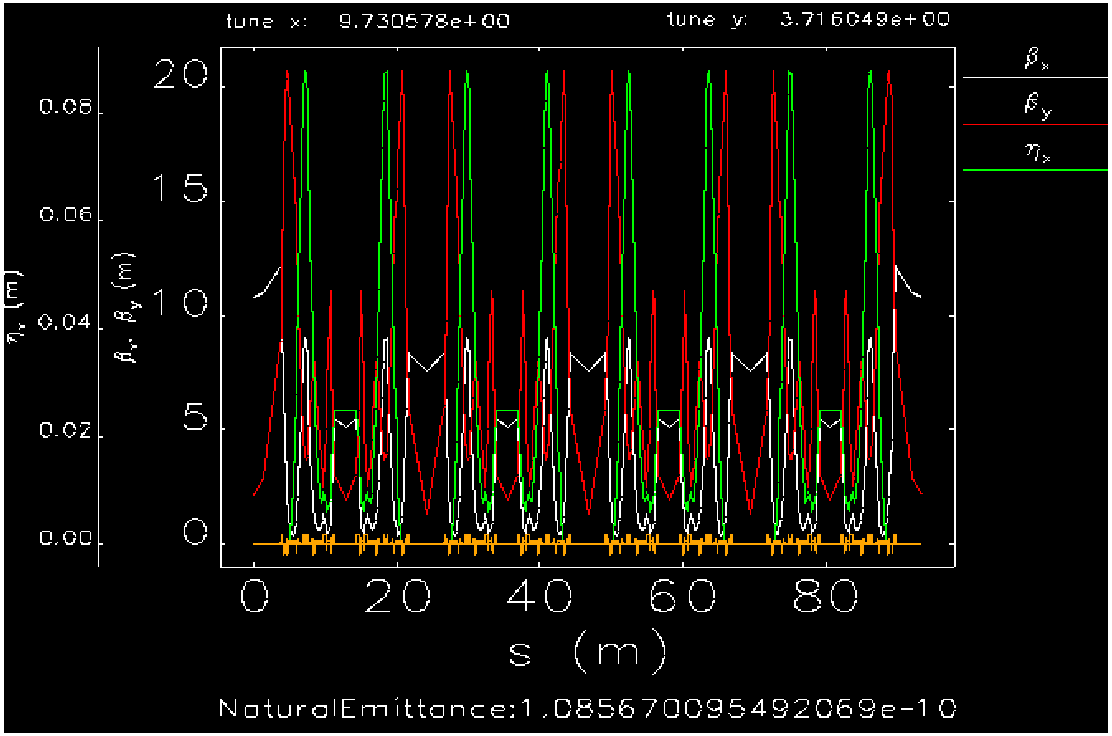
Promising design:

emittance ~120 pm
dynamic aperture ~ 8-9 mm
lifetime ~ 2-3 h

Gives the benefits of both lower emittance and additional straight sections !

Study of a Double Triple Bend Achromat (DTBA) Lattice for a 3 GeV Light Source, A. Alekou et al., Proc. IPAC 2016

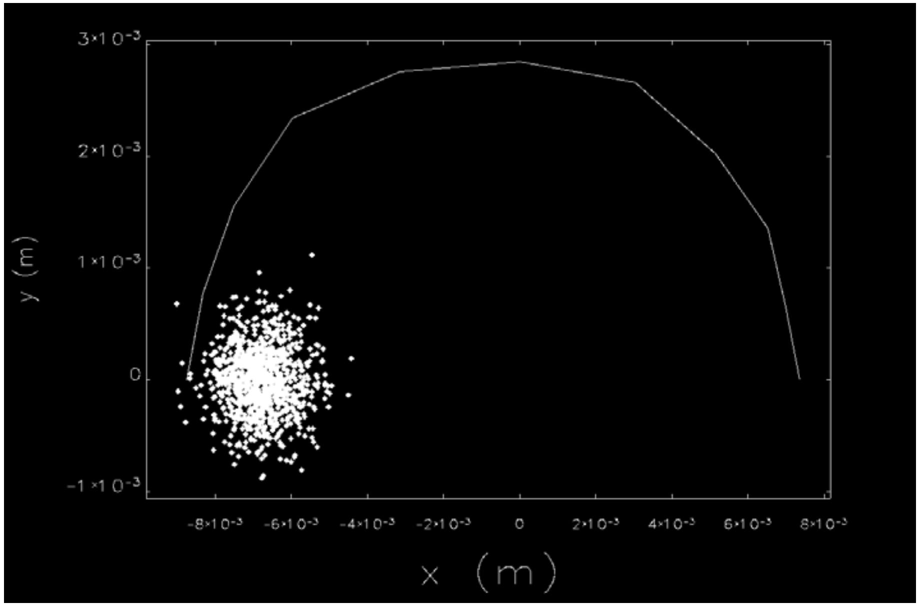
Diamond-II

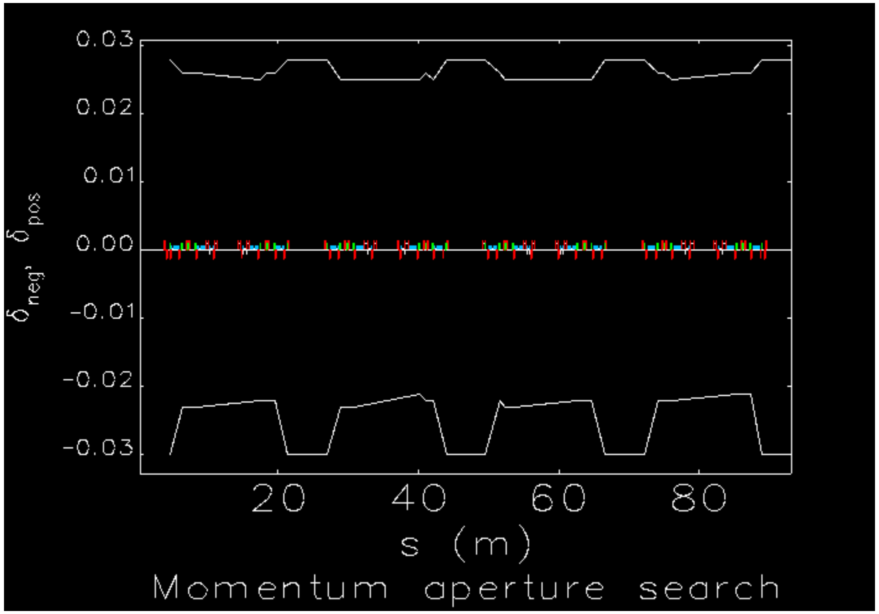


	Diamond	Diamond-II
Emittance	2700 pm	108 pm
Tunes H, V	27.20, 13.36	58.38, 22.30
Chromaticity H,V	-54, -90	-79, -123
Momentum compaction	1.7 10^{-4}	1.1 10^{-4}
Bunch length	3 mm	2.4 mm

Diamond-II

Full ring dynamic aperture and momentum aperture





- Dynamic Aperture of -8.5 +7.5mm, can accommodate the injected beam
- Momentum aperture of ~3% gives a Touschek lifetime of ~2.5h (300 mA 1 % coupling) without bunch lengthening

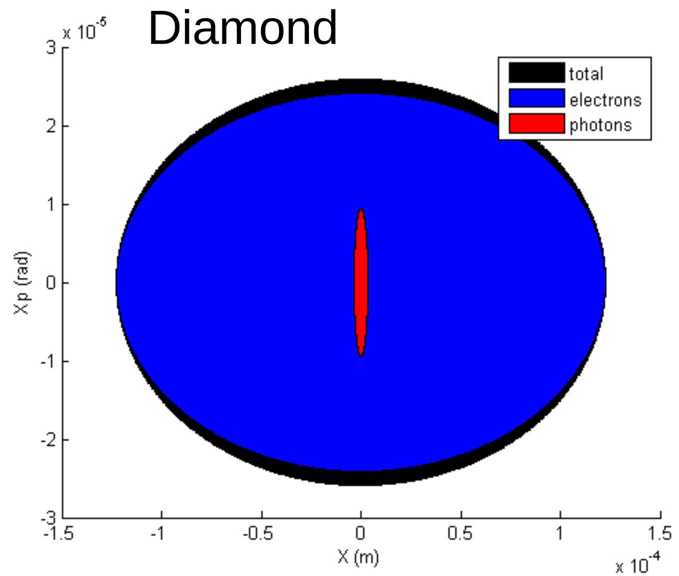
DTBA is a promising candidate for Diamond-II !

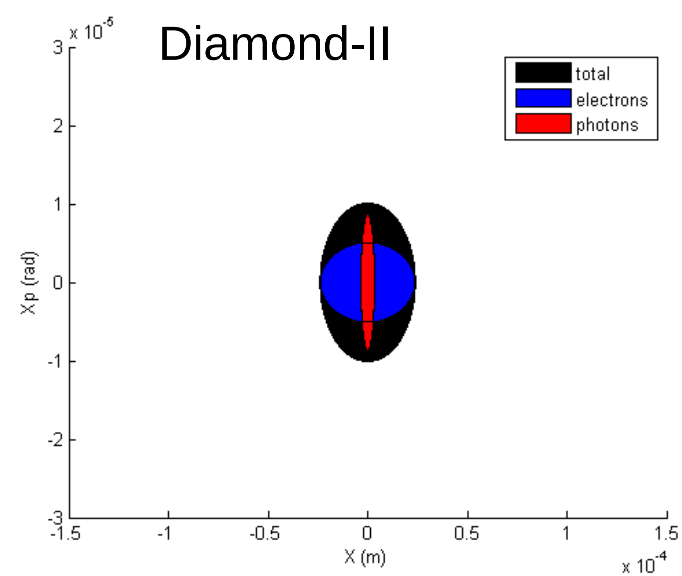
Electron beam sizes and photon phase space

Parameter (rms values)	Diamond	Diamond-II
Horizontal size, σ_x [mm]	123.5	23.6
Vertical size, σ_y [mm]	3.5	3.5
Horizontal divergence, $\sigma_{x'}$ [mrad]	24.1	5.1
Vertical divergence, $\sigma_{y'}$ [mrad]	2.3	2.3
Product	$2.38\ 10^4$	$9.60\ 10^2$
Electron beam brightness ratio	1	24.8

NB] with the same vertical emittance of 8 pm.

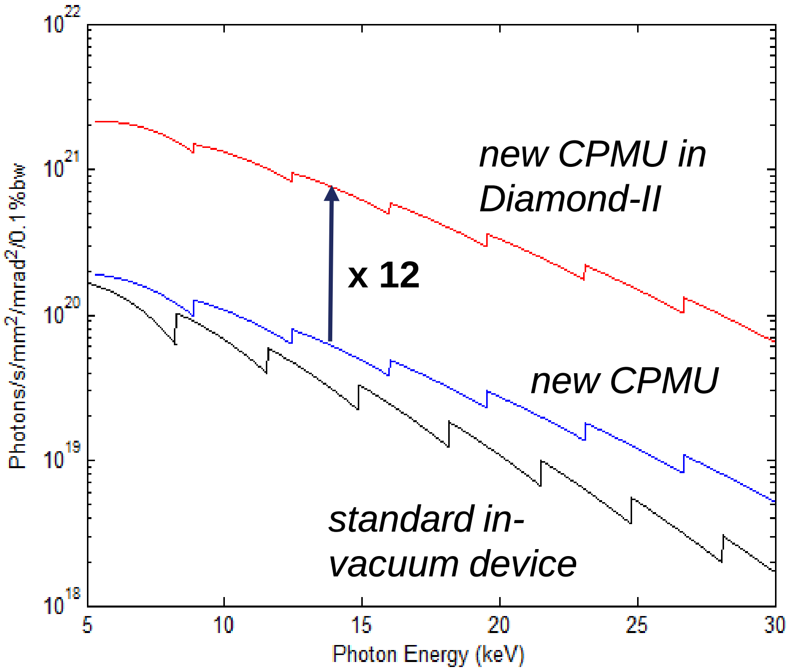
electron & photon horizontal phase space at 1Å



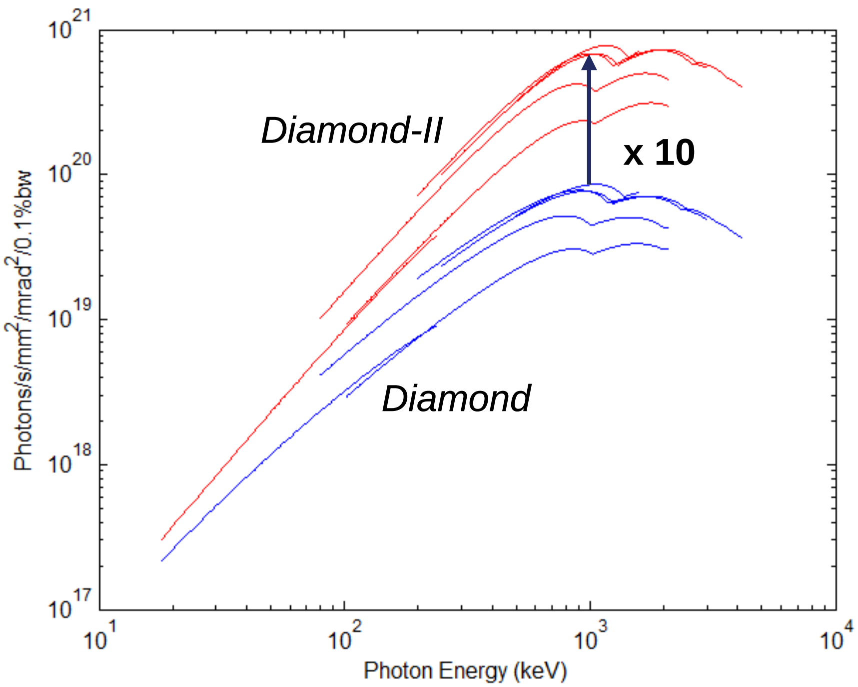


Brightness improvement with Diamond-II (120 pm)

Hard X-ray undulator



Soft X-ray undulators
(APPLE-II for I05, I06, I08, J09, I10 and I21)



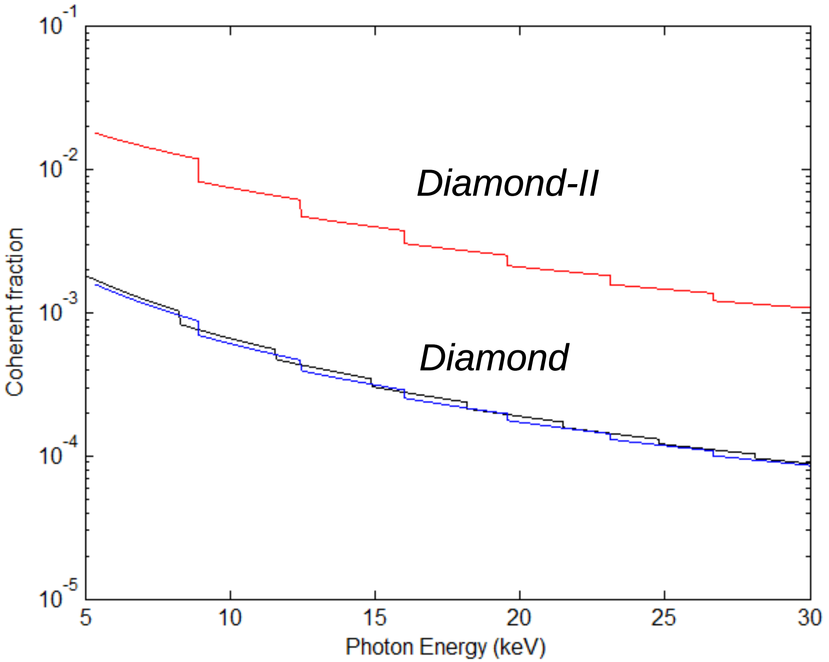
NB] this assumes the same vertical emittance of 8pm in Diamond-II
brightness ratio = x 17 at 20 keV for emittance of 2 pm

Transverse Coherence

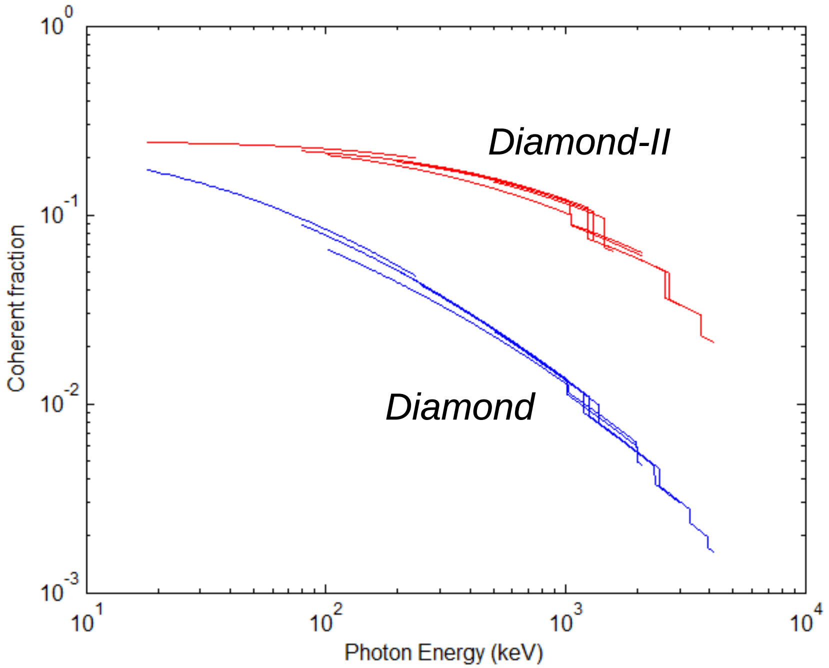
Coherent fraction improvement with Diamond-II (120pm):

$$F = \frac{\lambda^2/(4\pi)^2}{\Sigma_x \Sigma_{x'} \Sigma_y \Sigma_{y'}}$$

Hard X-ray undulator

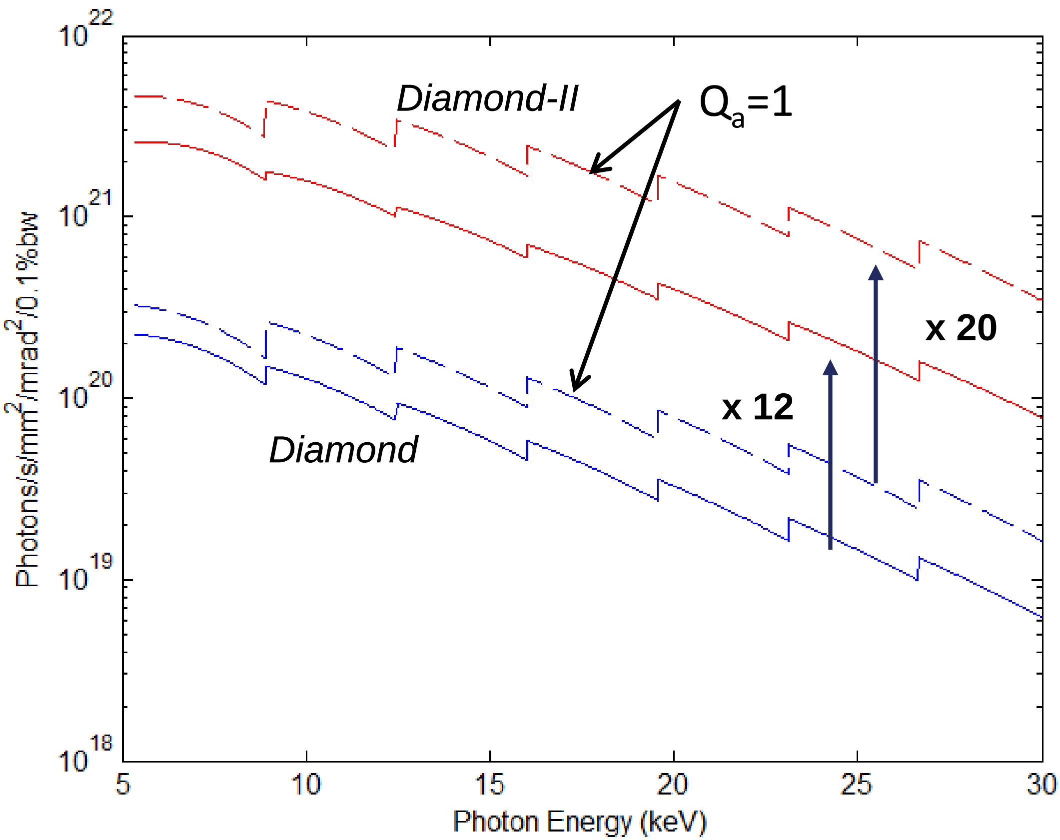


Soft X-ray undulators
(APPLE-II for I05, I06, I08, J09, I10 and I21)



The improvement in brightness/coherence is approximately a factor of x3 at 100 eV x10 at 1 keV, x12 at 10 keV, the main benefit coming from the reduction in horizontal source size

Note – effect of energy spread on the radiation brightness is increased for low emittance, with high harmonic numbers !



$$B = \frac{F}{\Sigma_x \Sigma_{x'} \Sigma_y \Sigma_{y'}}$$

$$\Sigma_{x',y'} = \left(\sigma^2_{x',y'} + Q_a^2 \sigma^2_{R'}\right)^{1/2}$$

$$Q_a(x) = \left(1 + \frac{2x^2}{\pi}\right)^{1/4}$$

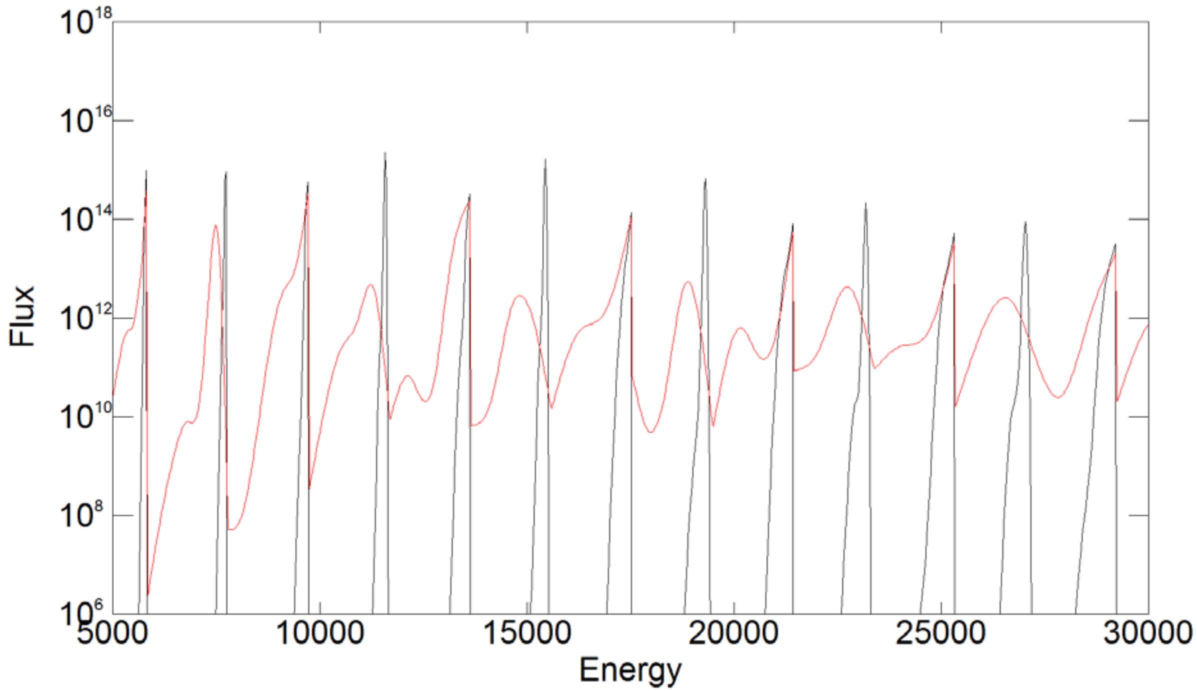
$$x = 2\pi n N \sigma_E$$

Pinhole Flux

Smaller pinhole needed to collect the same fraction of flux:

⟶ smaller mirror sizes, higher quality

⟶ reduced power loading, better thermal stability



*Flux through a 40 μrad * 40 μrad aperture for the CPMU in the existing ring (red) and in Diamond-II (black).*

Impact of Diamond-II on Beamlines

- Several existing Bending Magnet beamlines can convert to Insertion Device beamlines.
- Some lower intensity beamline branches based on short ex-vacuum, Insertion Devices can move to longer in-vacuum IDs.
- New beamlines can be built without impact on existing beamlines.
- Higher brightness/coherence will provide more flux and/or better resolution for nanoprobe beamlines:

  - tender/hard Xray experiments at 10 nm resolution will become routine

  - challenging experiments with < 10 nm resolution will become possible
- Greater exploitation of coherence e.g. ptychography, CDI, CXRD, XPCS etc.
- For crystallography, higher brightness will lead to better signal to noise in diffraction data, higher throughput and increased use of micro-beams.

Impact of Diamond-II on Beamlines

Beamline Name and Number	Diamond II	Insertion device	Optics	Detectors	Sample environments
Macromolecular Crystallography					
I02-1 - Versatile MX micro (VMXm)	New opportunities	New opportunities	New opportunities	New opportunities	New opportunities
I02-2 - Versatile MX in situ (VMXi)	Clear science benefit	New opportunities	Clear science benefit	New opportunities	New opportunities
I03 - MX	Clear science benefit	New opportunities	Modest benefit	New opportunities	New opportunities
I04 - Microfocus MX	New opportunities	New opportunities	New opportunities	New opportunities	New opportunities
I04-1 - Monochromatic MX	Clear science benefit	New opportunities	Modest benefit	New opportunities	New opportunities
I23 - Long Wavelength MX	Clear science benefit	New opportunities	New opportunities	New opportunities	New opportunities
I24 - Microfocus MX	Clear science benefit	New opportunities	New opportunities	New opportunities	New opportunities
B24 – Cryo Transmission	Modest benefit	Modest benefit	Modest benefit	Modest benefit	Clear science benefit
Soft Condensed Matter					
B21 - High Throughput SAXS	New opportunities	New opportunities	New opportunities	New opportunities	Clear science benefit
I22 - Small Angle Scattering and Diffraction	New opportunities	New opportunities	New opportunities	New opportunities	Clear science benefit
B22 - MIRIAM: Multimode InfraRed Imaging And Mircrospectroscopy	New opportunities	New opportunities	Clear science benefit	New opportunities	Clear science benefit
B23 - Circular Dichroism	New opportunities	New opportunities	Modest benefit	New opportunities	Clear science benefit
Surfaces & Interfaces					
I05 - ARPES	Modest benefit	New opportunities	New opportunities	Modest benefit	Modest benefit
I06 - Nanoscience	New opportunities	New opportunities	Clear science benefit	New opportunities	New opportunities
I07 - Surface and Interface Diffraction	New opportunities	Clear science benefit	Clear science benefit	New opportunities	Clear science benefit
B07 - VERSOX: Versatile Soft X-ray	New opportunities	New opportunities	New opportunities	Clear science benefit	Clear science benefit
I09 - SISA: Surface and Interface Structural Analysis	New opportunities	New opportunities	New opportunities	Clear science benefit	Clear science benefit
I10 - BLADE: Beamline for Advanced Dichroism Experiments	New opportunities	Clear science benefit	New opportunities	New opportunities	Clear science benefit

Beamline Name and Number	Diamond II	Insertion device	Optics	Detectors	Sample environments
Engineering and Environment					
I11 - High Resolution Powder Diffraction	New opportunities	New opportunities	Clear science benefit	New opportunities	New opportunities
I12 - JEEP: Joint Engineering, Environmental and Processing	No benefit	Clear science benefit	Clear science benefit	New opportunities	Clear science benefit
I15 - Extreme Conditions	No benefit	Clear science benefit	Clear science benefit	New opportunities	New opportunities
I15-1 - XPDF: X-ray Pair Distribution Function	Clear science benefit	Clear science benefit	Clear science benefit	New opportunities	New opportunities
Spectroscopy					
I08 - Scanning X-ray Microscopy	New opportunities	Clear science benefit	Clear science benefit	New opportunities	New opportunities
I14 - Hard X-ray Nanoprobe	New opportunities	New opportunities	New opportunities	New opportunities	New opportunities
I18 - Microfocus Spectroscopy	New opportunities	New opportunities	New opportunities	New opportunities	Clear science benefit
B18 - Core EXAFS	New opportunities	New opportunities	New opportunities	New opportunities	Clear science benefit
I20 - LOLA: Versatile X-ray Spectroscopy	New opportunities	New opportunities	New opportunities	New opportunities	Modest benefit
I21 - Inelastic X-ray Scattering	New opportunities	Clear science benefit	New opportunities	New opportunities	New opportunities
Materials					
I13 - X-ray Imaging and Coherence	New opportunities	New opportunities	New opportunities	New opportunities	Clear science benefit
I16 - Materials and Magnetism	New opportunities	Clear science benefit	New opportunities	New opportunities	Clear science benefit
B16 - Test beamline	New opportunities	New opportunities	New opportunities	Clear science benefit	Clear science benefit
I19 - Small-Molecule Single-Crystal Diffraction	New opportunities	Clear science benefit	New opportunities	New opportunities	Clear science benefit

KEY: NEW OPPORTUNITIES | CLEAR SCIENCE BENEFIT | MODEST BENEFIT | NO BENEFIT

Comments from the Diamond Science Advisory Committee (April 2016)

"… there are major opportunities both for scientists to exploit the beam coherence and to improve the flux density and hence move to higher spatial, temporal or spectral resolution on beamlines (especially those already using micro-focussing) which exploit the brilliance of the storage ring."

"SAC agree with the conclusion of the upgrade document: that a major upgrade of DIAMOND Light Source, to achieve a source of radiation of much higher brilliance, is required in order to maintain the excellence of the facility … and recommends that a decision on the trajectory towards an upgrade of DIAMOND is urgent."

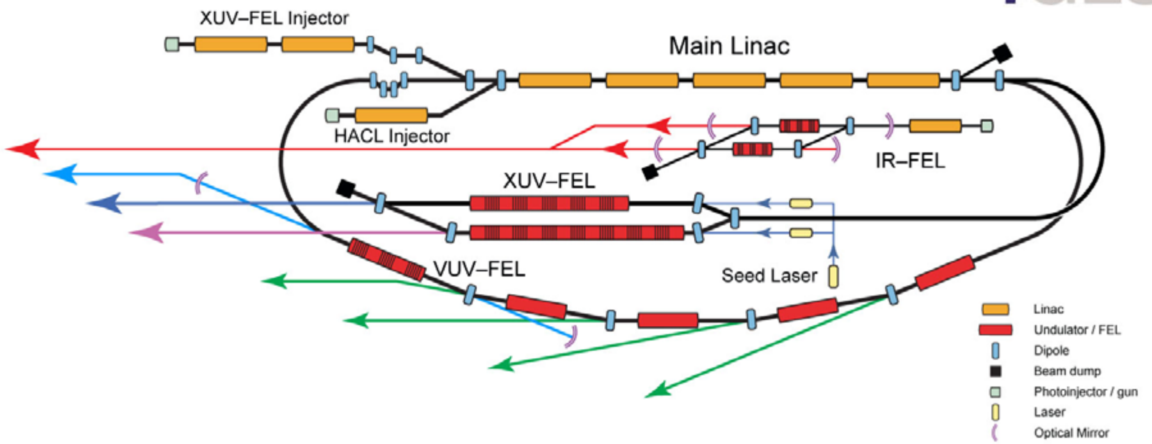
Prospects for an Advanced FEL-based Light Source for the UK

diamond

Two Previous Proposals:

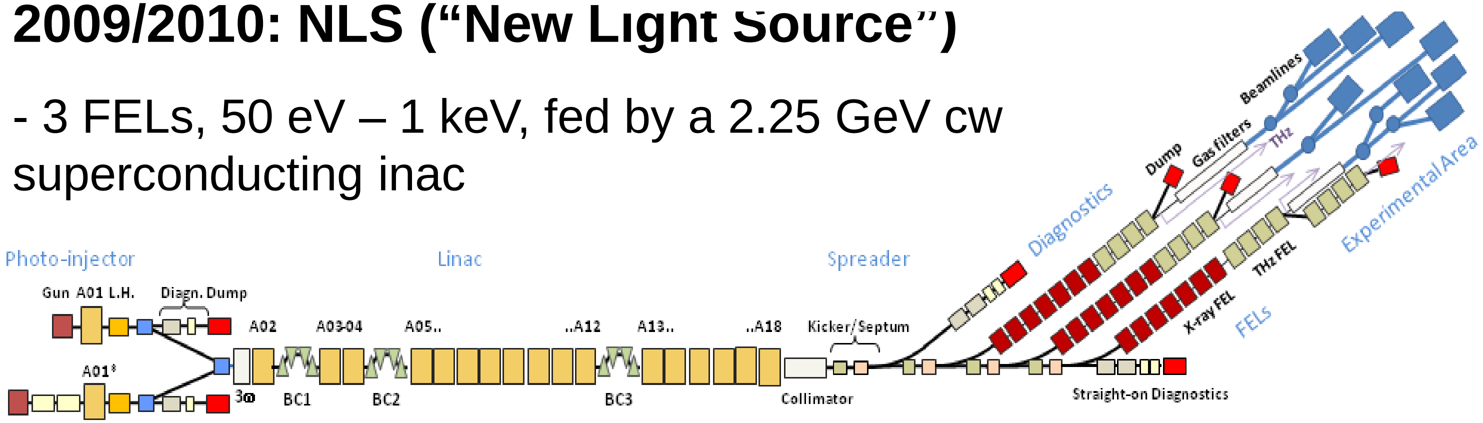
2006: 4GLS

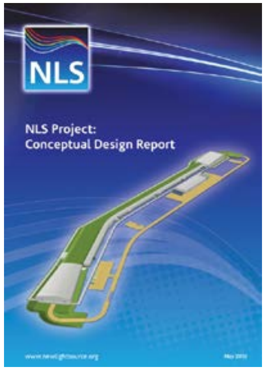
- combination of ERL and FELs



2009/2010: NLS (“New Light Source”)

- 3 FELs, 50 eV – 1 keV, fed by a 2.25 GeV cw superconducting inac





Since then:

- Dec. 2014 – announcement that UK will join European XFEL
- Mar. 2015 – STFC started a Review of provision of FEL radiation for the UK:

FEL Strategic Review

STFC is carrying out a review to determine a strategy for the UK's Provision of Free Electron Laser (FEL) facilities.

The purpose of the FEL strategic review is to develop:

- a 15 – 20 year vision for UK FEL science;
- a 7 year strategy for FEL access, UK FEL facility provision, community development, and underpinning technology/skills.

The major focus of the review will be X-rays, but it will also examine the UK community's needs for lower energy machines and incorporate this into the strategy. The UK has committed to becoming a full member of the European XFEL facility (now under construction near Hamburg, Germany), and so this review will provide the framework for making decisions on any further FEL commitments the UK may make.

http://www.stfc.ac.uk/about-us/our-purpose-and-priorities/planning-and-strategy/fel-strategic-review/

diamond

FEL Review Summary

(as presented to STFC Science Board Feb. 2016)

Needs

"The UK needs to increase its investment in the XFEL.EU …recognising that there will be the need for a UK facility in the future"

"In the long term, the UK's capacity requirements will be best served by constructing a UK FEL facility"

"Doing nothing is not an option. FEL science is advancing rapidly..."

Timescales

"STFC should be in a position to take the final decision on whether to build an X-ray FEL in the UK, and what kind of machine to build, in five years"

"The time taken form fully committing to the construction of a UK FEL facility to it being operational is likely to be at least six years. The final decision on whether to build an X-ray FEL in the UK and to what specification to build could be taken in five years, around 2020.

FEL Review Summary (ii)

(as presented to STFC Science Board Feb. 2016)

Type of machine

“In order to address the majority of the key science challenges, a UK facility would need to deliver hard X-rays.

To further broaden the range of science which could be tackled, the ideal machine would also have a high repetition rate. However, this is likely to be unaffordable as a national facility, so a best compromise specification will need to be defined to fit UK science.

This is expected to be an enhanced SwissFEL like facility: a high-energy non superconducting Xray FEL”

FEL Review Summary (iii)

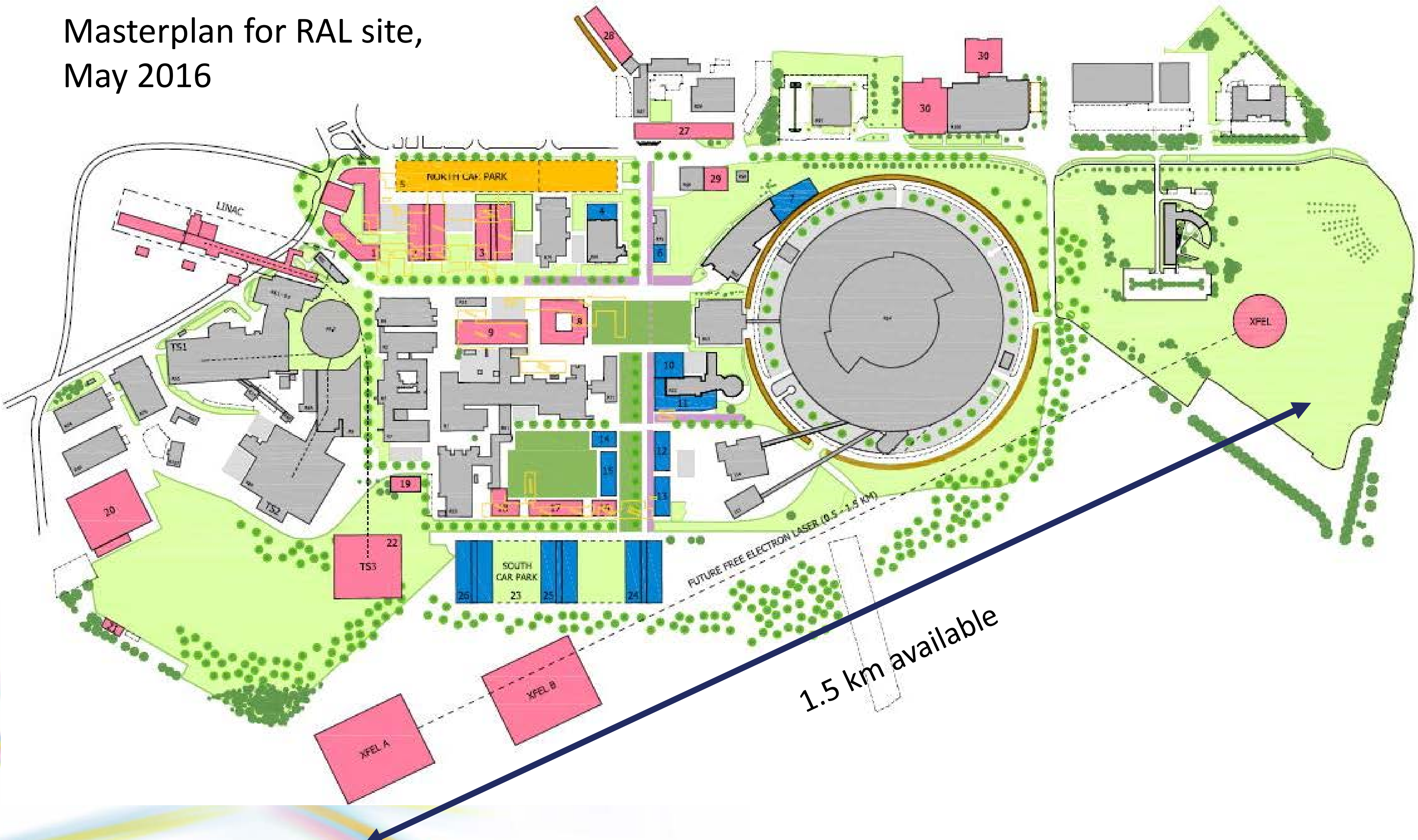
(as presented to STFC Science Board Feb. 2016)

Location

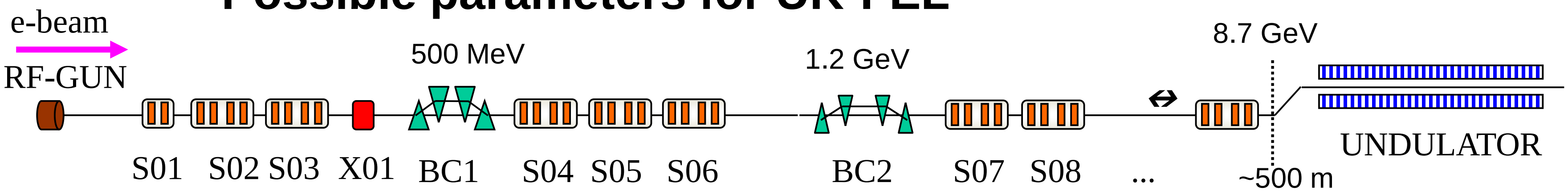
“The UK has a unique opportunity to co-locate an X-ray FEL with the state-of-the-art ultrafast, high-energy and high-powered auxiliary laser sources currently located at the Harwell Campus.

This would equip the UK with world-leading facilities for creating and probing matter at extreme conditions, unmatched by any equivalent facility in the foreseeable future.”

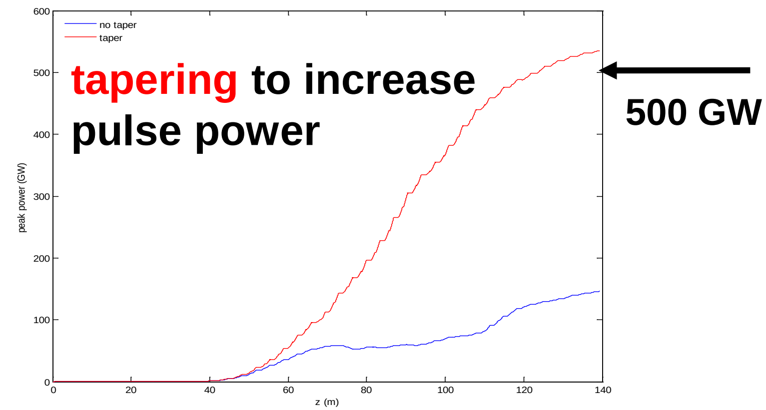
Masterplan for RAL site, May 2016

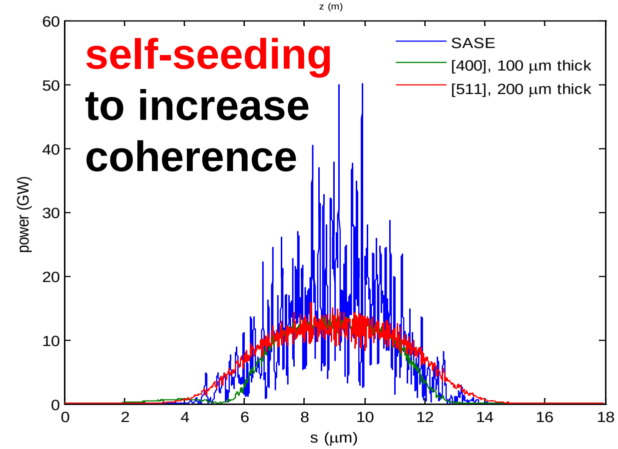


Possible parameters for UK-FEL



Energy	8.7 GeV
Repetition rate	100 Hz (each FEL)
Max. photon energy	~ 18.6 keV
Pulse duration	20-30 fs
Photons/pulse (10 keV)	>~ 10^{12}
No. of FELs	up to 4 (?)
Possible FELs	SXR (0.1 – 2 keV)
gap tuneable	MXR (1.5 – 6 keV)
	HXR (5 – 15 keV)
Experimental stations	3 per FEL
Facility length	~ 850 m
Power consumption	~ 7MW





preliminary calculations by R. Bartolini, I. Martin, DLS

Desired enhancements / R&D topics:

- increased peak power (~TW) and photons/pulse (~10^{13})
- improve temporal coherence and pulse shape uniformity
- sub-fs / attosecond pulses
- two-pulse and two-colour operation
- reduce timing and wavelength jitter; improve laser & FEL synchronisation

FEL Review Summary (iv)

(as presented to STFC Science Board Feb. 2016)

Actions

"To prepare for this decision in five years' time the following actions are recommended in parallel with the development of the community:

- initiate a programme to define the specification that is required …
- develop a fully coordinated FEL R&D programme…
- strategically plan the development of the skills base required to deliver the necessary technologies."

The UK FEL Community looks forward to a positive response from STFC !

Conclusion

Despite some dark clouds … we remain optimistic for a bright future !

Thanks for Your Attention !

SFR-2016