Diamond-II Vacuum System Conceptual Design

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Diamond-II overview

Diamond

- 3rd generation source UK
- 3 GeV 300 mA
- 562 m circumference 24-cell DBA lattice
- 2.7 nm.rad emittance
- Operating since 2007

Diamond-II

- Motivation
  - Increase brightness
  - 24 new mid-straights for additional insertion devices
  - In-place upgrade
- 3.5 GeV
- 160 pm.rad emittance as of CDR
- DTBA - modified 6BA lattice
- Installation ≈ 2025-26 with ≤ 18 month disruption to user operations

Conceptual design from CDR presented here

Some experience from DDBA cell installed 2016

LATTICE STILL DEVELOPING (+ reverse bends?)

VACUUM DESIGNS STILL DEVELOPING

Some references

Diamond-II CDR 2019

https://www.diamond.ac.uk/Home/About/Vision/Diamond-II.html

Conceptual design of the Diamond-II vacuum system (IPAC 2019 TUPMP050)

CONCEPTUAL DESIGN OF THE DIAMOND-II VACUUM SYSTEM

M.P. Cox†, C.W. Burrows, A.G. Day, J.A. Dymoke-Bradshaw, R.K. Grant, N.P. Hammond, X. Liu, A.G. Miller, H.S. Shiers, N.R. Warner, Diamond Light Source, Didcot, UK

DDBA cell 2 upgrade (2016)

R. Bartolini *et al.*, "Double-double bend achromat cell upgrade at the Diamond Light Source: From design to commissioning", *Phys. Rev. Accel. Beams*, vol. 21, no. 5, p. 050701, 2018.

Diamond vacuum system

O. Malyshev and M. Cox, "Design modelling and measured performance of the vacuum system of the Diamond Light Source storage ring", *Vacuum*, vol. 86, p. 1692, 2012.

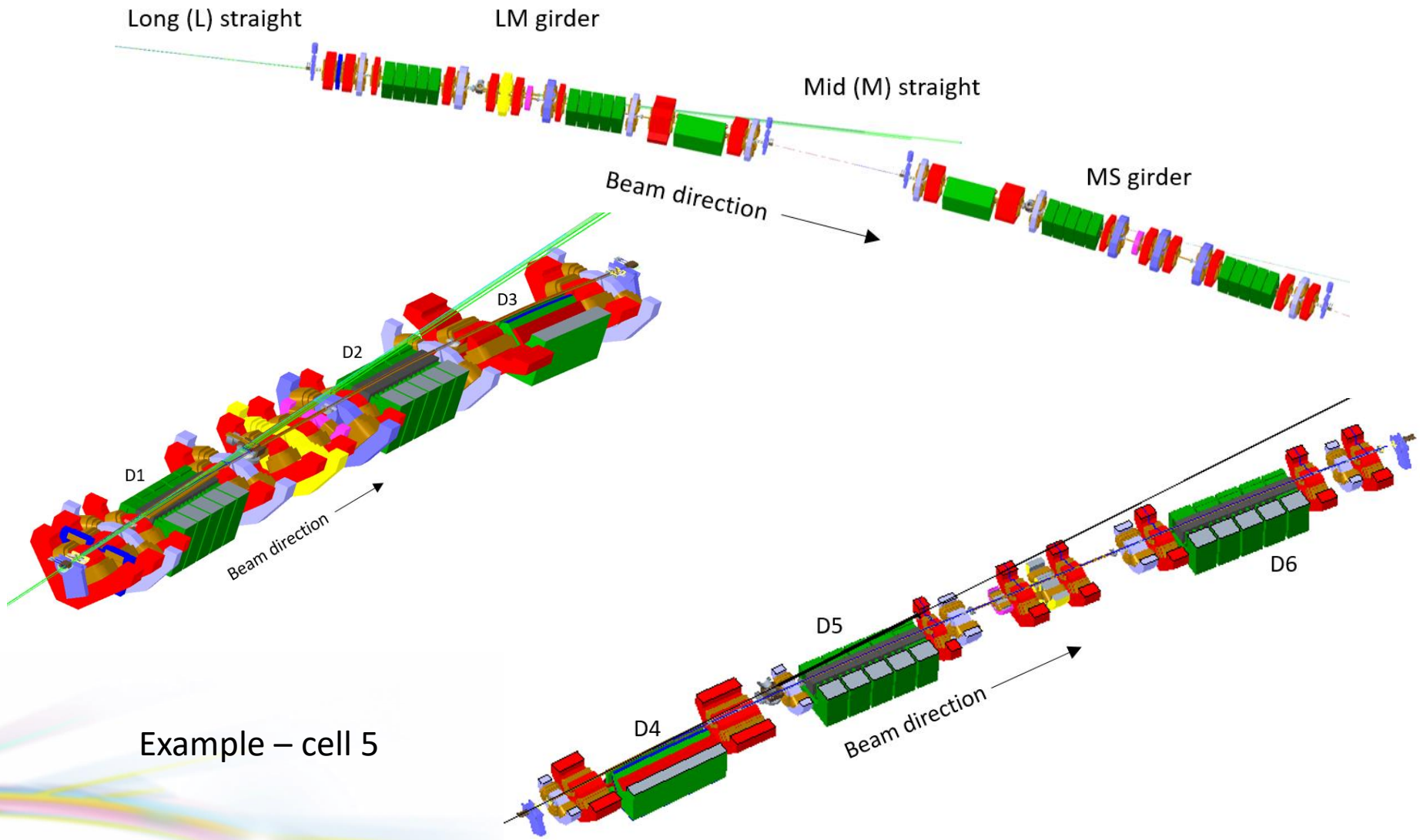
Requirements

Vacuum performance	• Gas lifetime > 10 hours at 300 mA after 100 Ah of beam conditioning • Average pressure of 10^{-9} mbar or better around the storage ring at 300 mA after 100 Ah of beam conditioning
Machine impedance	• Geometry to minimise steps, gaps and cross-section changes and shield RF bellows (also to reduce RF heating effects) • Resistive wall effects are material dependent and can be affected by base material, coating material(s) and surface morphology, e.g. roughness
Electron beam stay clear	• Respect minimum aperture for the vessel interior space so as not to reduce the lifetime
Magnet compatibility	• Vessel external size and shape must allow enough space for the magnet poles, coils and yokes with an allowance, where required, for mechanical decoupling and in-situ bakeout heaters/insulation • Vessel materials must not affect the magnetic field applied to the beam by the magnets (both AC and DC) • In-situ bakeout must not produce excessive temperatures in nearby magnets • Vessel movements, e.g. due to heating and cooling during operations, must not move the magnets by a significant amount
Photon extraction	• Routes for photon beams from bending magnets and insertion devices
Heat load management	• Synchrotron radiation power loading on the vessel wall from bending magnets and insertion devices
Operations	• Reliable, maintainable, energy efficient • Control and monitoring to verify the correct functioning and to give early warning of any problems • Interlocks to protect against damage or incidents

Key features

- Detailed vessel geometry in development
- Preference for simple circular cross section (20mm Inside Diameter) tubes where possible (for reliability, ease of manufacture and coating, low surface area …)
- 20mm ID tubes strongly conductance limited
- Little space for lumped pumps
  → Distributed pumping
  → Non-evaporable getter (NEG) coating wherever possible
- Not all gases pumped by NEG coating
- High gas loads near photon absorbers due to photon stimulated desorption (PSD)
  → Supplementary ion pumps in critical regions
- *In-situ* bakeout / NEG coating activation proposed
- Main construction materials copper and stainless steel

General layout



Example – cell 5

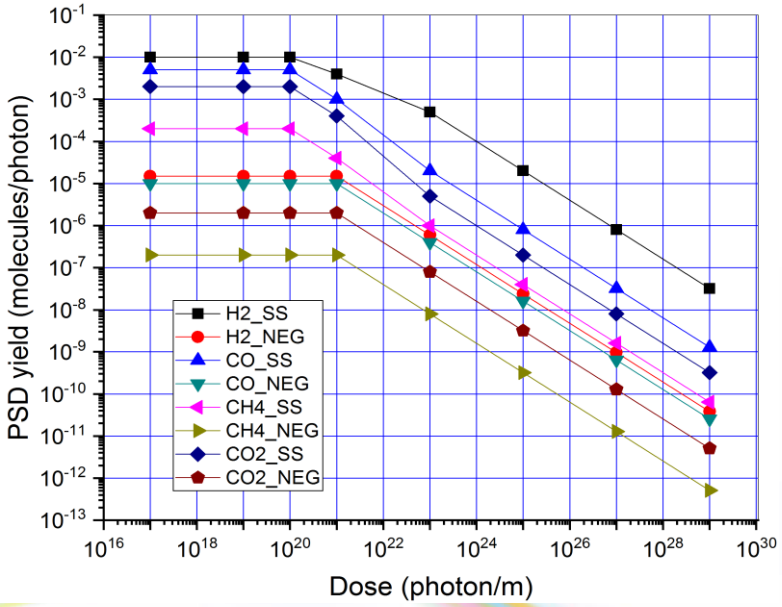
Pumping calculations 1

- Simple tubular vessel with 20 mm internal diameter centred about the electron beam path
- Only bending magnet dipole radiation (insertion devices and other magnets ignored)
- Ion pump at the end of each dipole
- Scattered / reflected / fluorescence radiation ignored
- 3 different vessel wall materials
  - Plain copper/stainless-steel
  - Fully-activated NEG coating
  - CO-saturated NEG coating (as activated NEG coating with s=0)
- Diamond in-house 1D PressureProfile code
- Separate calculation for H_2, CO, CH_4 and CO_2 → Σz^2-weighted CO-equivalent pressure
- Cell 5 taken as typical

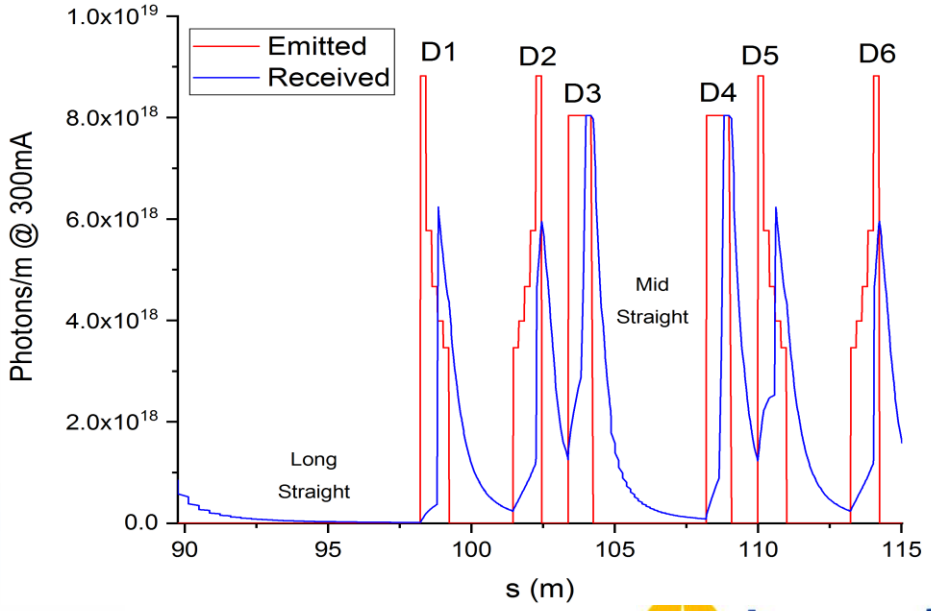
Pumping calculations 2

Material	Cu/StSt	Activated NEG	Saturated NEG
Q H_2 (mbar.l/s/sqcm)	1.0×10^{-11}	1.0×10^{-14}	1.0×10^{-14}
Q CH_4 (mbar.l/s/sqcm)	1.0×10^{-13}	1.0×10^{-16}	1.0×10^{-16}
Q CO (mbar.l/s/sqcm)	1.0×10^{-12}	1.0×10^{-15}	1.0×10^{-15}
Q CO_2 (mbar.l/s/sqcm)	1.0×10^{-13}	1.0×10^{-16}	1.0×10^{-16}
s H_2	0	7.0×10^{-3}	0
s CH_4	0	0	0
s CO	0	0.1	0
s CO_2	0	0.1	0
Initial PSD yield H_2 (molecule/photon)	1.0×10^{-2}	1.5×10^{-5}	1.5×10^{-5}
Initial PSD yield CH_4 (molecule/photon)	2.0×10^{-4}	2×10^{-7}	2×10^{-7}
Initial PSD yield CO (molecule/photon)	5.0×10^{-3}	$< 1 \times 10^{-5}$	$< 1 \times 10^{-5}$
Initial PSD yield CO_2 (molecule/photon)	2.0×10^{-3}	$< 2 \times 10^{-6}$	$< 2 \times 10^{-6}$

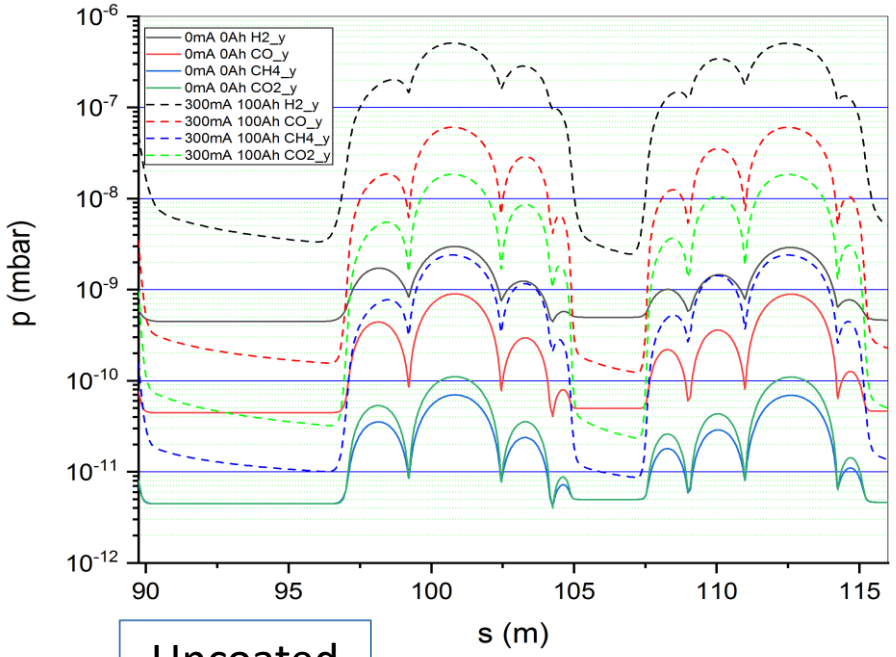
Material properties



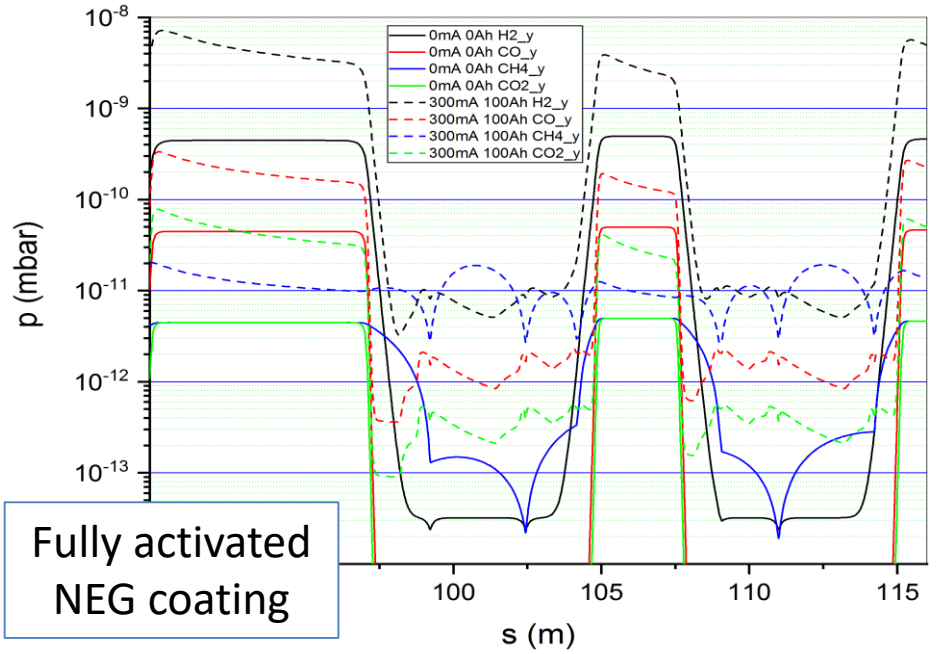
Photon flux on wall



Pumping calculations 3

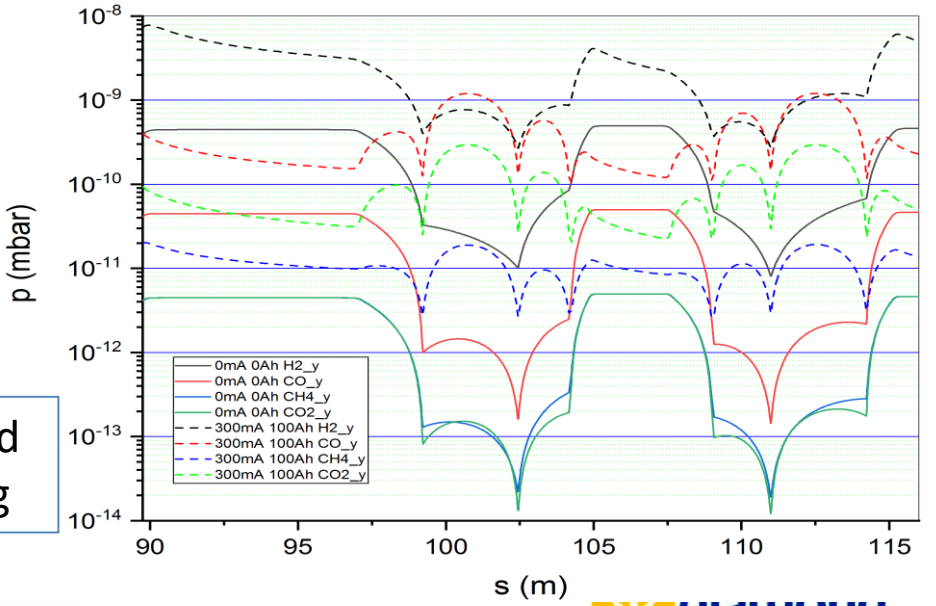


Uncoated



Fully activated NEG coating

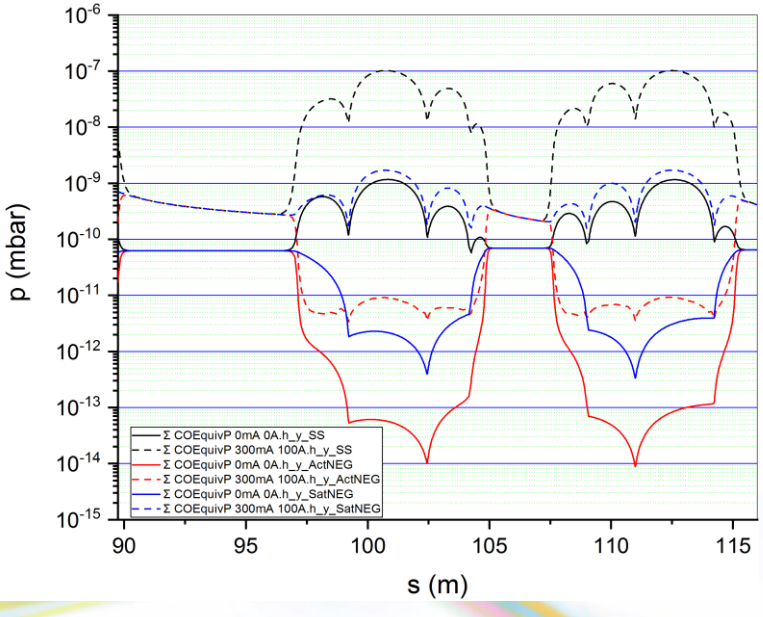
Partial pressures of the main gases

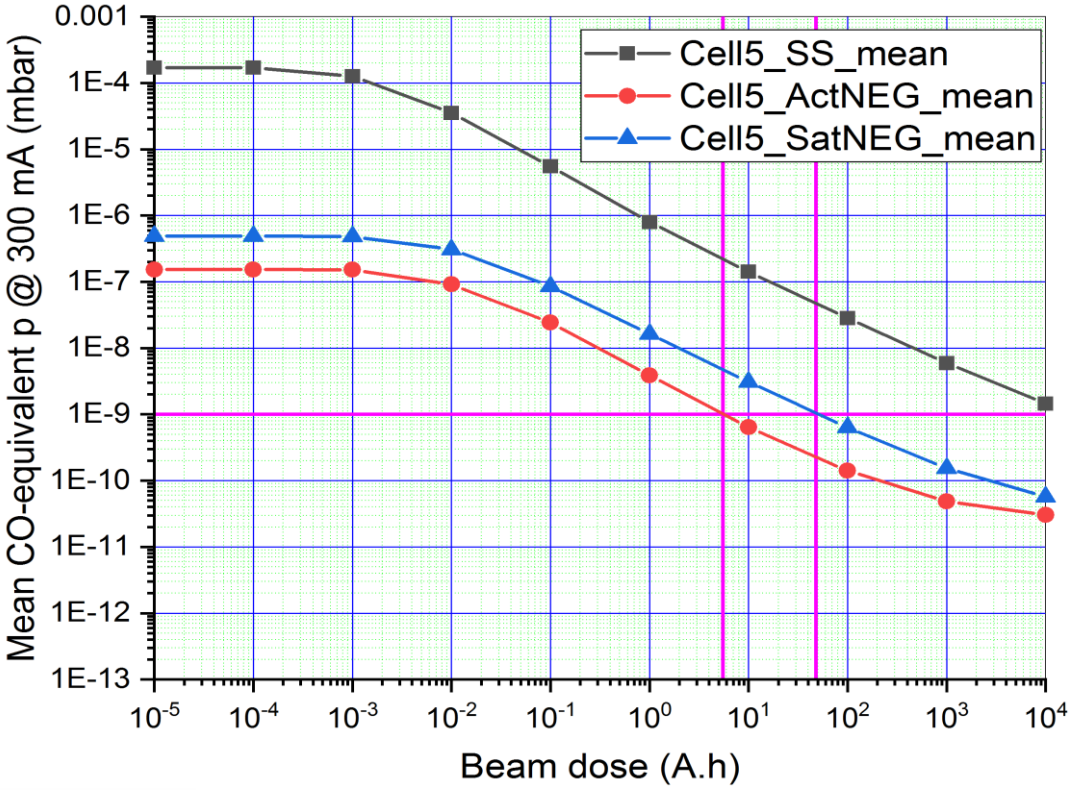


CO-saturated NEG coating

Pumping calculations 4

- Time to achieve 10^{-9} mbar at 300 mA
  - Uncoated > 1000 A.h: (>7 years at 300 mA)
  - Fully-activated NEG coating: 6 A.h
  - Saturated NEG coating: 50 A.h
- Target < 100 A.h



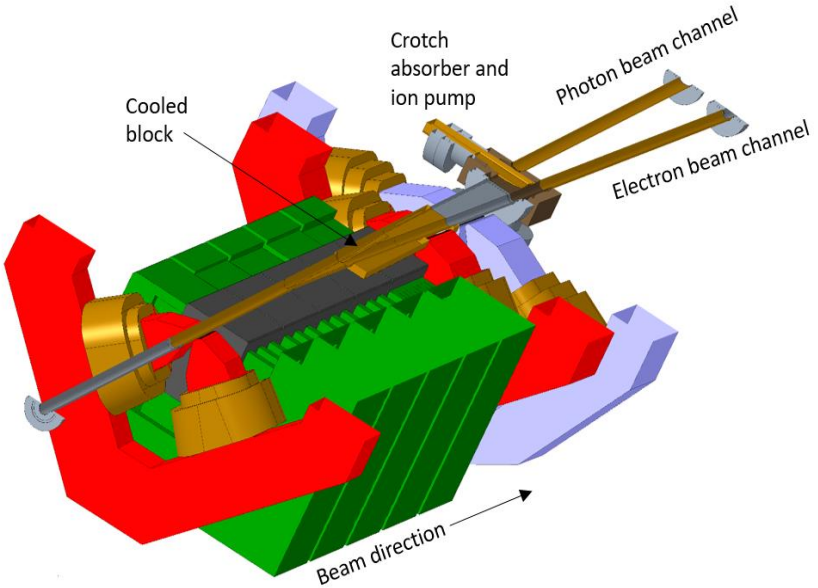


Σz^2-weighted CO-equivalent p at 300 mA vs distance and vs beam dose

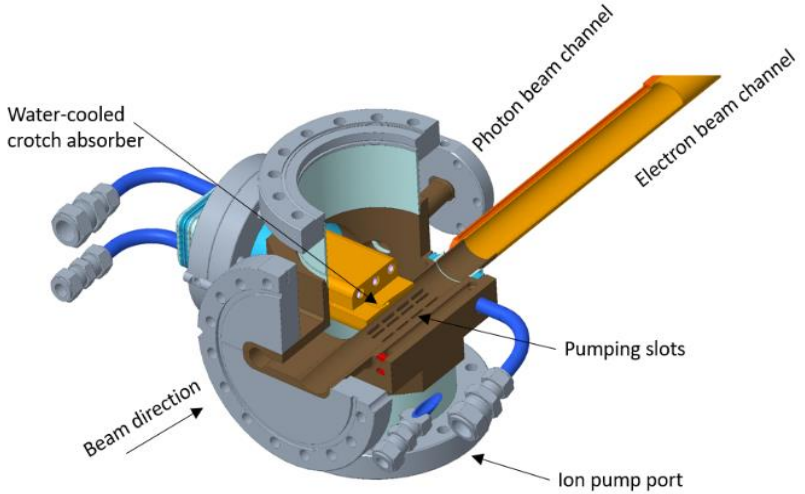
Vacuum vessel materials / construction

- Geometry
  - Circular with 22 mm outside diameter, 1 mm wall thickness.
  - Magnet inscribed diameter 24 mm = 1 mm clearance for in-situ bakeout system.
  - Special cross-sections where needed
  - Avoid gaps and steps for impedance
  - As few vessel variants as possible for manufacturing scale
- Materials
  - Copper alloy, e.g. OFS copper with Ag loading as used in DDBA
  - Stainless steel in the region of fast corrector magnets. 316LN material is preferred for its higher strength and low magnetic permeability
  - Aluminium for ex-vacuum IDs (extruded, NEG coated) and could be considered elsewhere but unsuitable for fast corrector magnet regions and has relatively high thermal expansion coefficient
  - CuCrZr for absorbers can integrate knife-edge flanges
- Standard techniques
  - Welding (TIG, e-beam, laser …)
  - Vacuum brazing
- Things to watch
  - Additive manufacturing

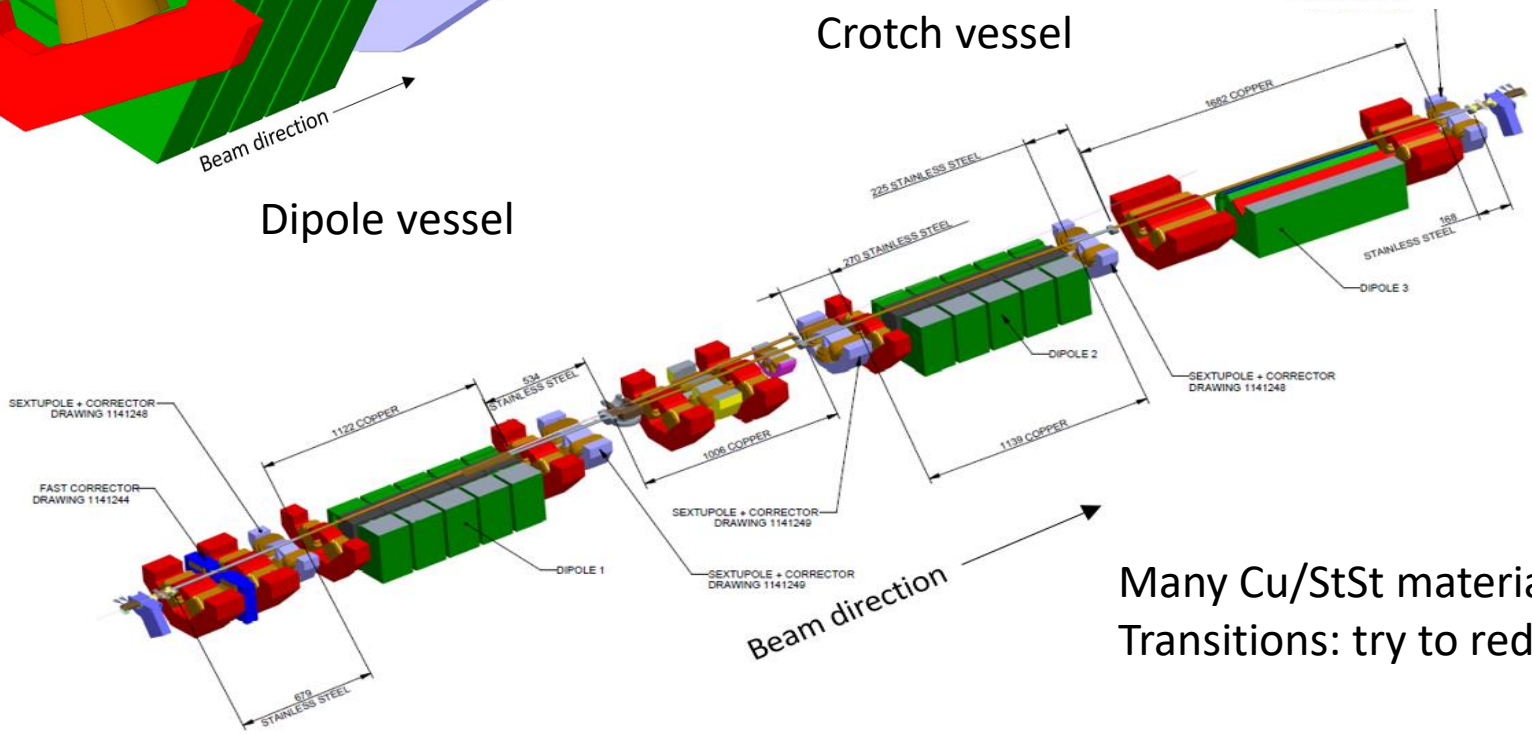
Vacuum vessel concepts



Dipole vessel



Crotch vessel



Many Cu/StSt material
Transitions: try to reduce

NEG coating

- Active metal coating (commonly Ti-Zr-V) on the vacuum vessel interior
- Typically 1µm thick (< 0.5 to 2 µm possible)
- Can be applied to Cu, StSt, Al etc
- Used successfully at many facilities to a greater or lesser extent
- Requires thermal activation under vacuum typically to 180°C for 24 hours to achieve full benefits (possibly quaternary alloys available in future with lower activation T)

- 3 benefits for vacuum system
  - Reduces thermal outgassing
  - Reduces PSD
  - Pumps active gases – truly local pumping

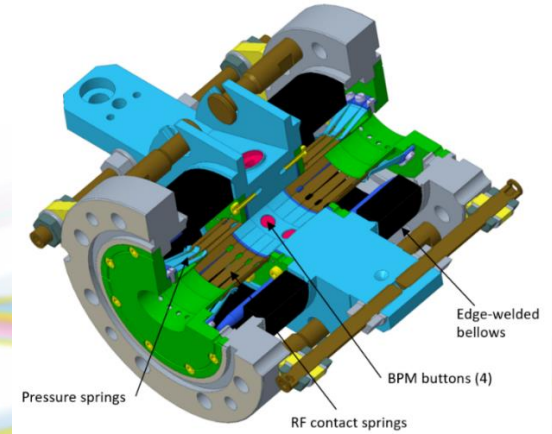
- However
  - Low capacity leads to saturation and pumping stops
  - Easily poisoned or contaminated and can peel off
  - Deposition on complex vessels and with exacting specifications requires significant development and Quality Assurance
  - Usually needs reactivation after intervention (but note high purity neon venting)
  - Some evidence of at least partial activation by synchrotron radiation
  - Relative high surface resistivity (impedance) → fine tune thickness and morphology

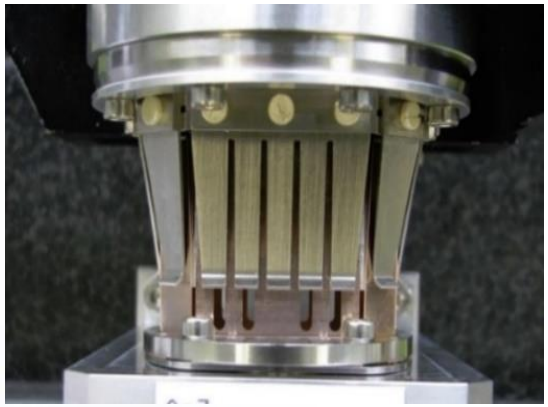
Other vacuum components

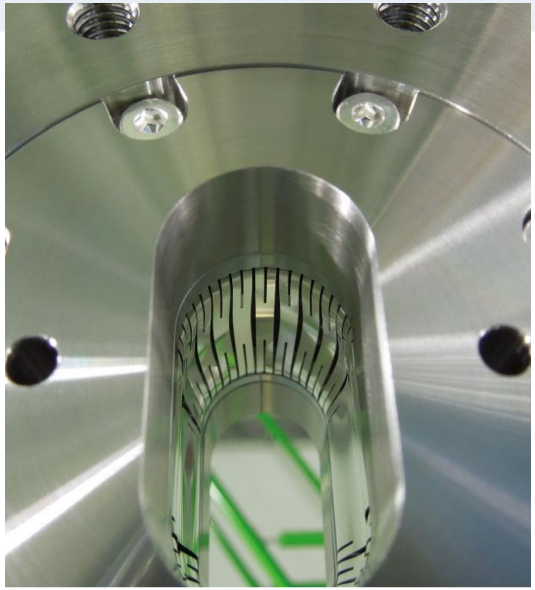
Demountable flange joints

MO seal	Variants in use at a number of different facilities. Specially shaped copper gasket makes vacuum seal and RF continuity.
Flat seal	Thin etched aluminium gasket with sealing ridge makes vacuum seal and RF continuity. Flat flange faces. Originally developed by the VAT company but now also available from third party sources.
Helicoflex® seal	Spring energised C ring makes vacuum seal. Internal flange spigot or land closes RF gap.
CF flange with RF insert	Standard CF gasket makes vacuum seal. Insert makes RF continuity. A number of variants have been used some with spring inserts and some with elasto-plastically-deformed metal insert.

RF shielded bellows and commercially-available valves







Bakeout

- *In-situ,* on-girder bakeout is proposed
- Pros
  - Faster recovery from vacuum incident / intervention during build / operations
  - Saves time and space for assembly and during time critical dark period
  - Avoid handling long vacuum strings under vacuum / constructing large ovens
- Cons
  - Needs additional bellows for thermal expansion
  - Risk of overheating magnet poles
  - Have to develop bakeout system and install on each girder
  - Has to be reliable … radiation damage

- Similar to system developed and implemented on Diamond DDBA
  - Thin-film Kapton heaters
  - Plus “conventional” heaters and jackets (mineral-sheathed heaters)
  - PLC-based control system

DDBA Kapton-heater wrapped vessel and PLC-based control system

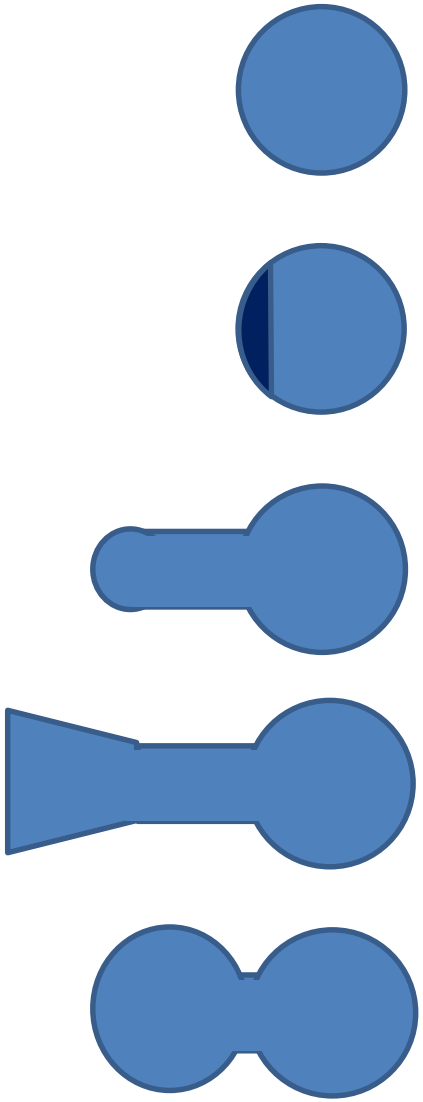
Instrumentation, Controls and Interlocks

- Each standard storage ring cell is divided into four vacuum sections by RF gate valves (2 straights and 2 arcs)
- Each vacuum section has
  - ≥ 2 total pressure gauge sets (Pirani and Cold Cathode Gauge)
  - ≥ 1 Residual Gas Analyser (RGA) or at least a port where an RGA can be connected without breaking the vacuum
  - Many temperature sensors on vacuum vessels and components

- Connected to
  - EPICS Control, monitoring and archiving system
  - Machine protection system (high pressure, loss of vacuum, overtemperature ….)

Next steps 1

- General strategy
  - Use round tube (with external cooling channel) where possible
  - Use absorber “bump”, extended cross-section, antechamber where necessary
- Finalise vessel cross sections and geometries with consideration of
  - Photon beam extraction
  - Photon beam absorbers and heat load management
  - Machine impedance (resistive wall and geometric)
  - Waveguide effect of antechamber
  - Vacuum pumping design and performance
  - Magnet mechanical compatibility
  - Bakeout
  - Vessel manufacturability, number of variants and coatings
  - Flanges, BPMs, bellows …
  - Interfaces to IDs, RF cavities, crotches …



Next steps 2

- Finalise locations and geometries for lumped and distributed pumps and absorbers
- Full 3D calculations with real vessel geometries including photon beam scattering / reflection and beam extraction to optimise and verify vacuum designs (Synrad, Molflow, Comsol®, Ansys®)
- Include all types of insertion device and straights. All straights have to include additional pumping to avoid gas loading of the adjacent NEG-coated sections
- Calculate times for beam conditioning including initial conditioning following installation. The beam current will need to be increased slowly to prevent the pressure increasing above a safe level (normally taken to be around 10^{-6} mbar)
- Develop manufacturing, build and installation sequences and processes
- Select pumps and instrumentation

Some possible topics for discussion

- NEG coatings
  - Specifications are becoming ever-more demanding wrt. machine impedance – thickness, homogeneity, morphology, composition, roughness – and complex geometries
    - Make sure not to over-specify
    - Needs more R&D to develop recipes other labs or industry?
    - Ability of industry to deliver more challenging specs plus increased cost and delivery time and risk of delays
  - Different labs are facing the same issues
    - How can we collaborate more effectively: NEG coating workshop/LinkedIn/e-mail groups etc? Needs organising or it won't happen.
  - Many upgrade projects running in parallel
    - Limited worldwide industry capacity
  - Can we improve the impedance properties of getter coatings with new materials?
  - Multilayer coatings e.g. StSt/Cu/NEG
  - Lower activation temperatures
  - Synchrotron radiation activation from scratch or after venting – how effective?
  - Database of reliable parameters for vacuum simulations – thermal desorption, stimulated desorption (unactivated, activated, and with different degrees of saturation), sticking probabilities
  - Maximum surface power density
  - Coatings on multi-material vessels with brazed joints and difficult geometries
  - Experience with high purity inert gas venting for interventions outside CERN/MaxLab?

Some possible topics for discussion

- Vacuum and heat loads simulation tools and methods
  - Synrad good for dipoles and wigglers but undulator model is not accurate – has anyone assessed its accuracy and what were the findings? How to improve it?
  - Synrad / Molflow pre- and post-processing tips
  - Synrad / Ansys® interface – proving tricky – any tips?
  - Comsol Multiphysics® – a good workhorse tool and in principle can do "everything" in conjunction with SRW/XOP/Spectra but needs work to set up and not optimised for any one task
- *In-situ* bakeout yes or no
  - Balance of costs vs benefits – decisions from different labs
  - How much space to allow between vessels and magnet poles?
  - Types of heaters, temperature inhomogeneity …
  - How hot do the magnets get? Do we have to remove magnet tops for bakeout?
  - Radiation damage and reliability
- Solutions to challenging photon extraction areas, e.g. IR beamline
- Vessel manufacturing
  - Some vessels / components are looking complicated to manufacture and with tight tolerances
  - Many upgrade projects running in parallel – supplier overload
  - Large vacuum vessel contracts always seem to run late – how can we do better?
- RF compatible flanges – what are best available designs?
- RF bellows and inserts – what are the best available designs?

Finally

Thanks to all the people at Diamond too numerous to mention who contributed to this work