Vacuum System for DDBA
and
Lessons Learned for Diamond-II

Matthew Cox
Diamond Light Source, UK

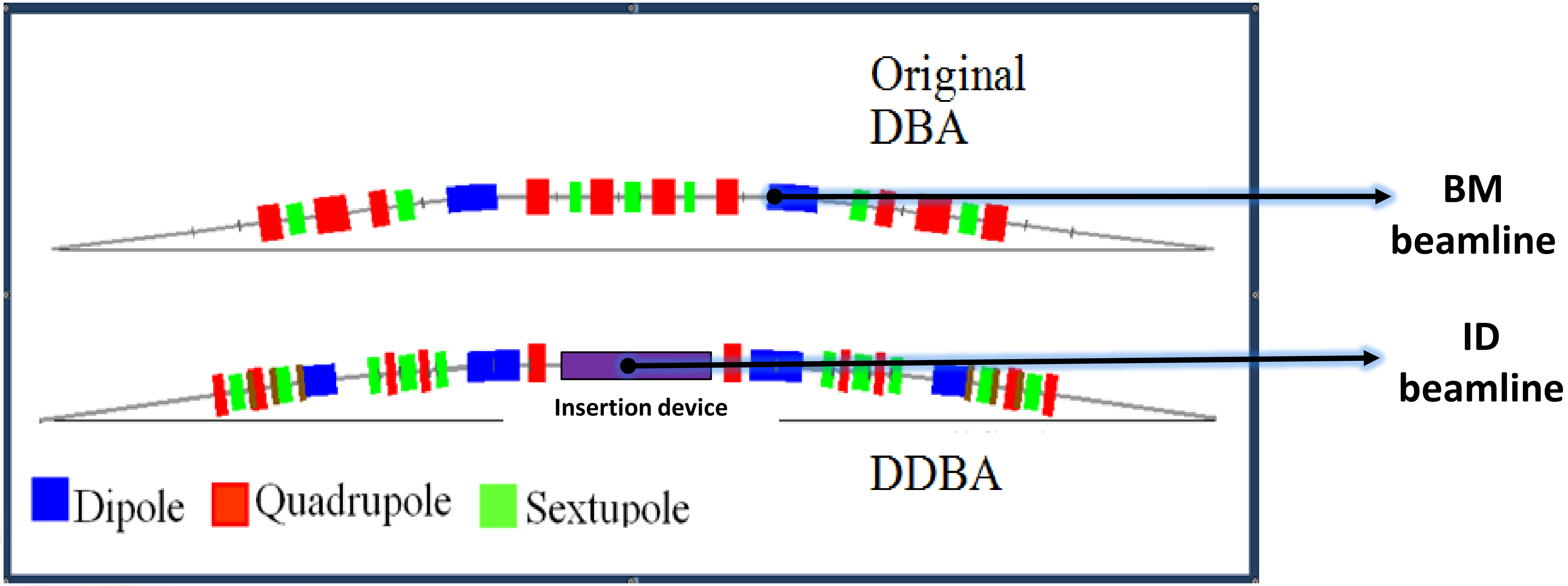
matthew.cox@diamond.ac.uk
www.diamond.ac.uk

Overview

- Requirements
- Vacuum pumping design
- Vessel manufacture
- Build and processing

Why DDBA?

Need for additional insertion devices → Double Double Bend Achromat (DDBA) concept: Replace one or two "DBA" cells with a new "DDBA" cell creating a new mid-cell straight section for an Insertion Device, thus converting a BM beamline into an ID beamline.



+ Exploration of technology needed for a possible major upgrade, Diamond-II with smaller emittance. One contender for Diamond-II has a DTBA lattice which would have many vacuum system similarities with DDBA

Vacuum requirements

- Replace entire vacuum system for one cell (17.35m)
- Beam physics compatible: Impedance, Beam stay clear, RF heating, DC/AC magnets, SR heat loads ...
- CO equivalent $p \leq 10^{-9}$ mbar with stored beam (Z^2 weighted sum of partial pressures)
- No pressure bursts or particles to trip beam
- Installation + beam conditioning in a working machine with $\leq$ 8 weeks downtime

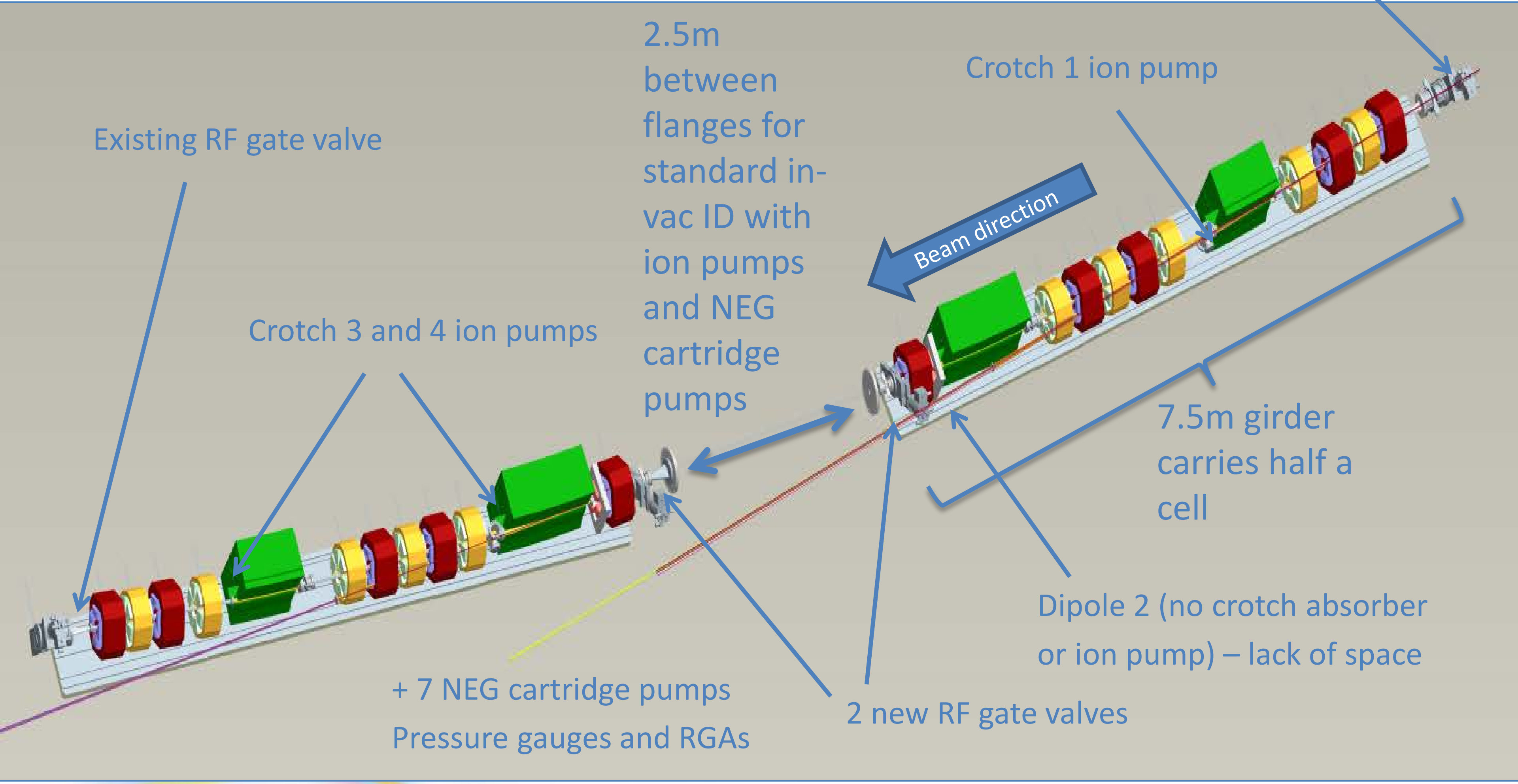
Vacuum pumping design

- Vacuum vessels typically 18 x 27 mm ellipse internal
- No NEG coating. Discrete ion pump and Non-Evaporable Getter (NEG) pumps fitted in where space ... not in optimum places for vacuum.
- Mixture of distributed and lumped photon absorbers

NEG coating	No NEG coating
Better ultimate vacuum Only active gases pumped (in the absence of SR) so may required auxiliary pumping anyway.	Worse ultimate vacuum between pumps – should be good enough though All gases can be pumped
Quicker beam conditioning (few A.h)	Slower beam conditioning (100s A.h)
Always need to bake / reactivate after venting (probably ….)	Don't always need to rebake after venting
Significant R & D and setup time and effort needed for variety of vessel geometries	Much less R & D, time and effort needed
Sensitive to saturation, surface poisoning, flaking etc	No coating to flake off or get poisoned Larger pumping capacity.
Probably more expensive overall (at commercial coating prices). Economics may be different for a whole machine	Probably cheaper overall despite additional discrete pumps, controls, wiring etc

New DDBA Arc Layout

Photon beam extraction at crotch 1 and 3 only
Built up on 2 girders

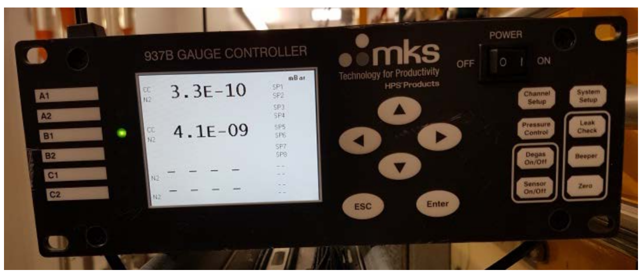


Vacuum pumping design

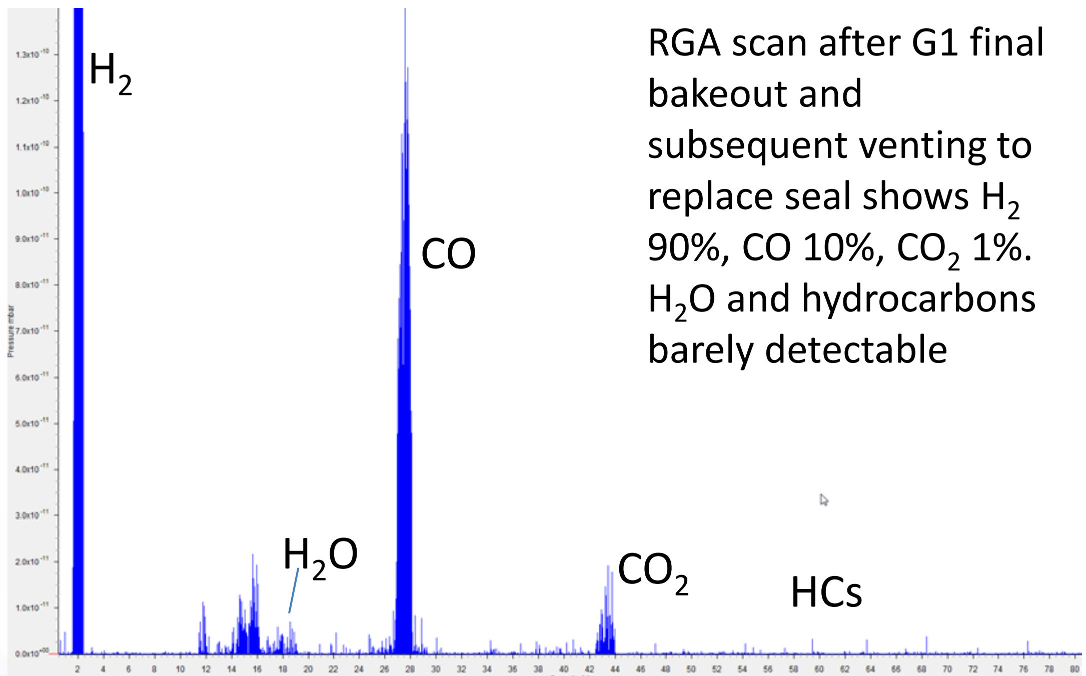
Was it a good choice?

Indications are positive so far:

- Simulations say it will work
- Static pressure and cleanliness (RGA scans) before installation are good
- Yet to be installed and tested with beam – PSD and beam conditioning, Heating (RF and SR), Impedance, Mechanical stability and alignment, Pressure spikes, beam losses and beam trips etc



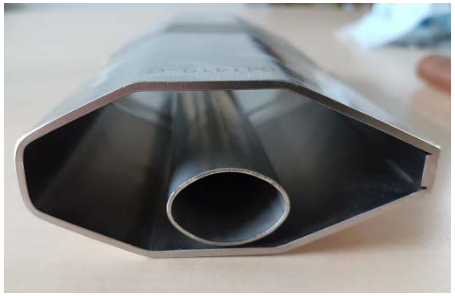
G1 and G2 static pressures (mbar)



RGA scan after G1 final bakeout and subsequent venting to replace seal shows H_2 90%, CO 10%, CO_2 1%. H_2O and hydrocarbons barely detectable

Vacuum vessel design

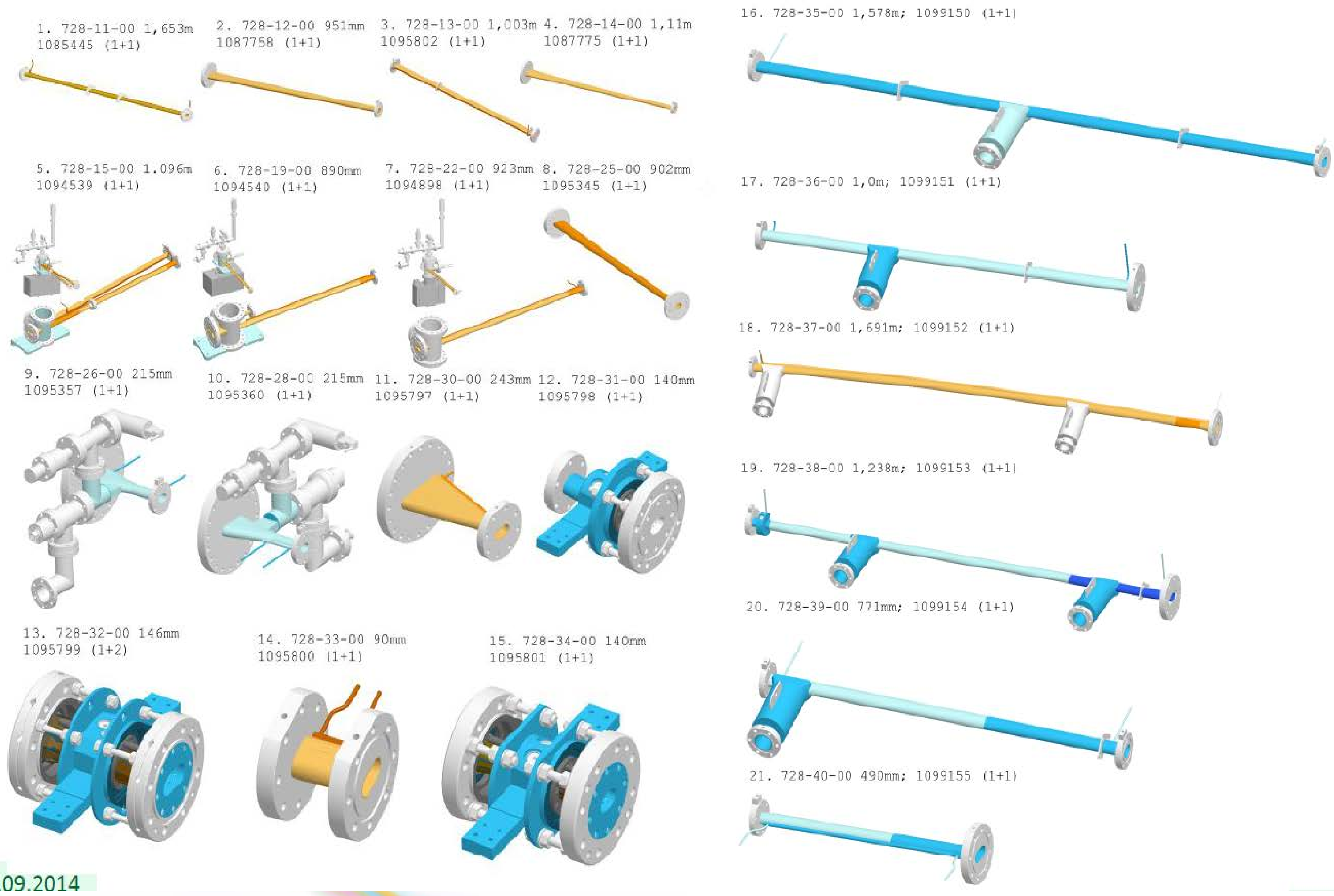
- Vessel materials copper alloy (OFS, OFHC) and stainless steel (316L, 316LN)
- Cross section typically 18 x 27 ellipse internal. Much smaller cross section and more delicate than Diamond-I vessels
- Fabrication by TIG welding, vacuum brazing, e-beam welding
- Incorporate distributed and lumped water cooled absorbers with bumps to shadow flange joints
- Low gap flange joints (Helicoflex® sealed) in e-beam path. Standard CF flanges otherwise.



Typical Diamond-I and DDBA vessel cross sections

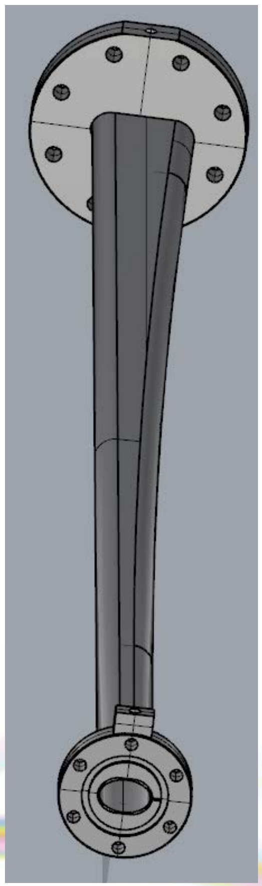
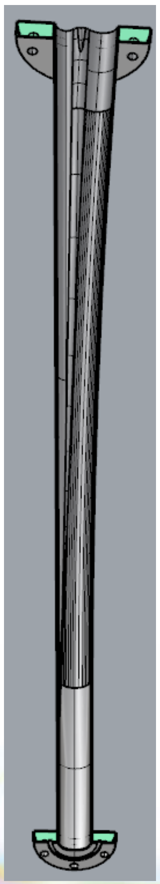
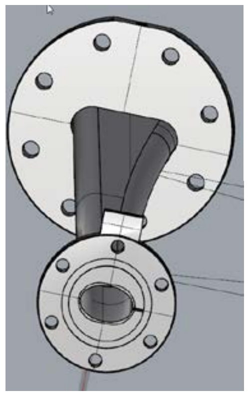
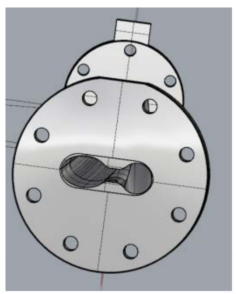
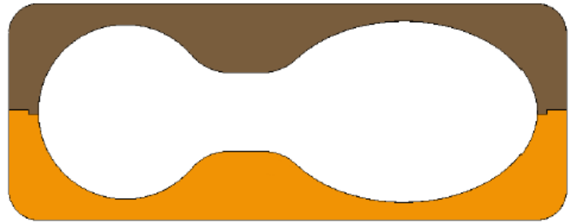
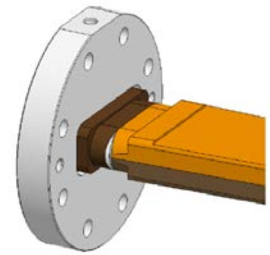
27x18 ellipse section in OFS-copper with e-beam welded cooling channel

Vacuum vessels



Dipole 1,3,4 vessels

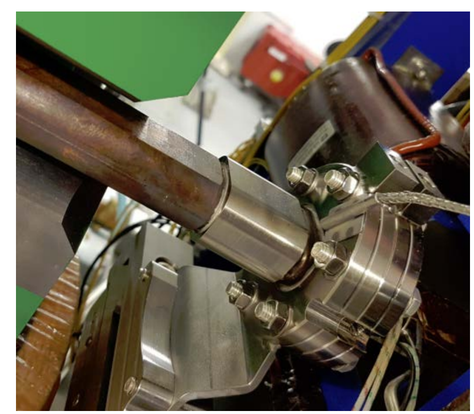
Copper
Antechamber to allow SR - BM (+ ID for dipole 1 and 3) to exit to downstream crotch
No water cooling needed

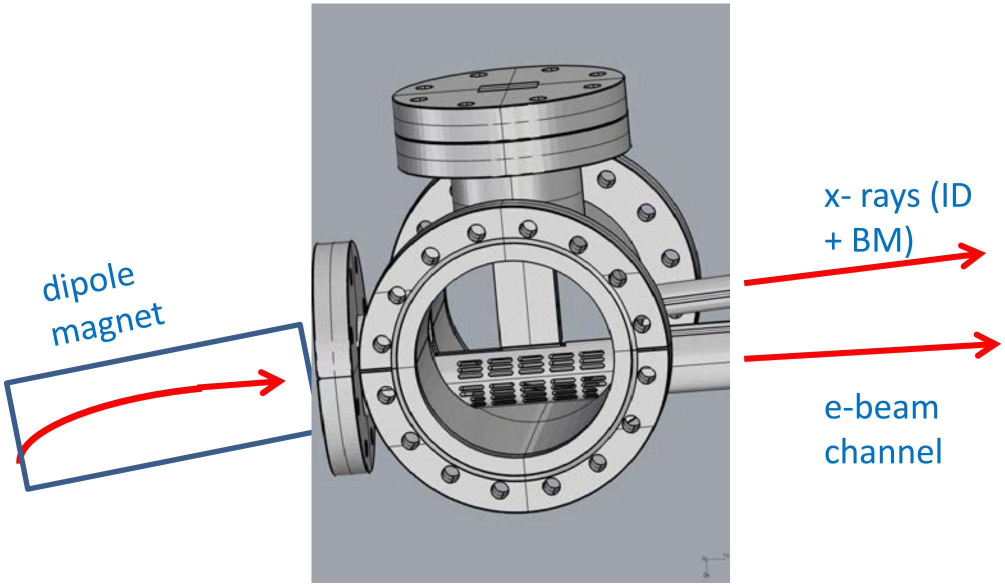
Manufacturing method to reduce distortion:
Machine 2 halves
E-beam weld together
Vacuum braze adapter into flange
Cu-Cu TIG weld vessel to flange adapter. Late stage problems with weld cracking led to change to vacuum braze with stainless steel intermediate piece. Needed to re-run thermal FEA. Trial welds had not been not fully representative.

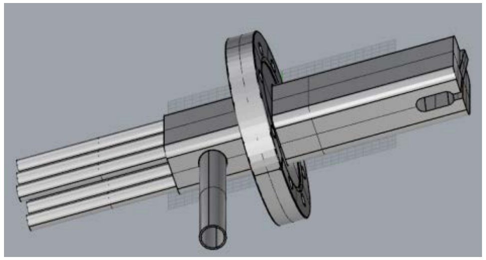
Weld cracking

Additional stainless steel intermediate piece



Crotch 1,3,4 assembly

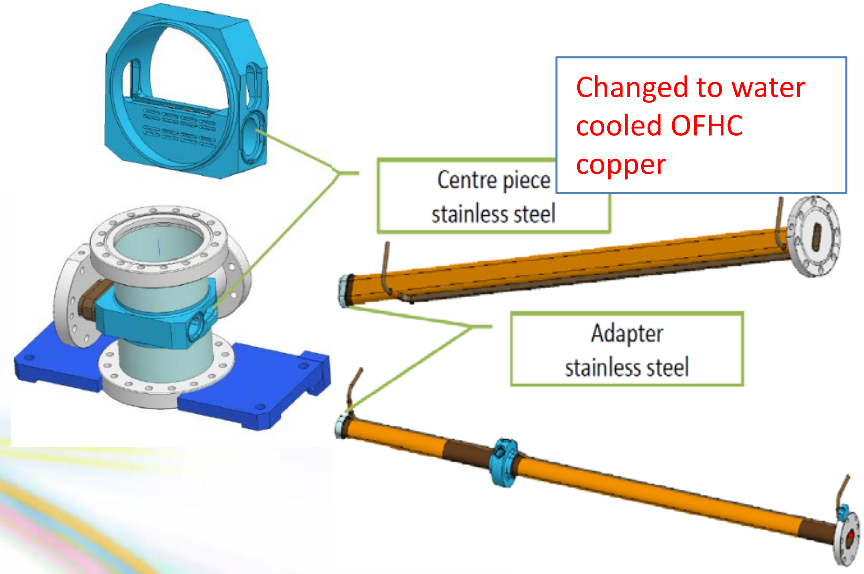




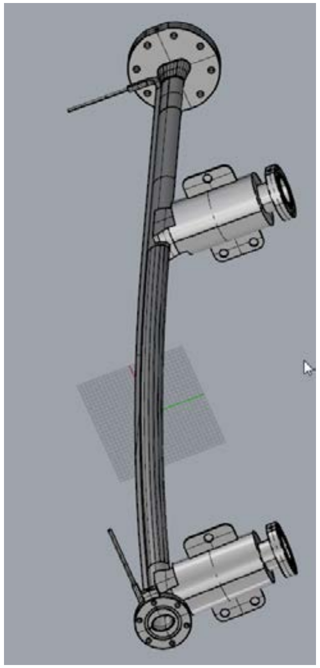
Crotch absorber
Copper, vacuum
brazed (similar to
Diamond-I)
N.B. Crotch 4 has
no beam through
hole

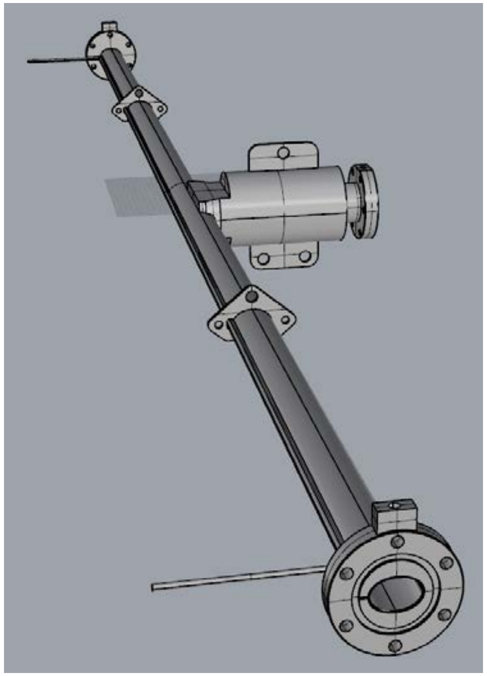
Manufacture was relatively unproblematic

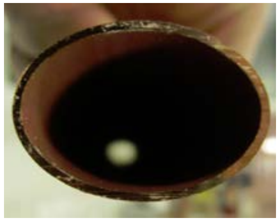
Some parts had to be re-made after burn through of the e-beam welded cooling channel in production despite successful earlier trials



Dipole 2 vessel and straight vessels

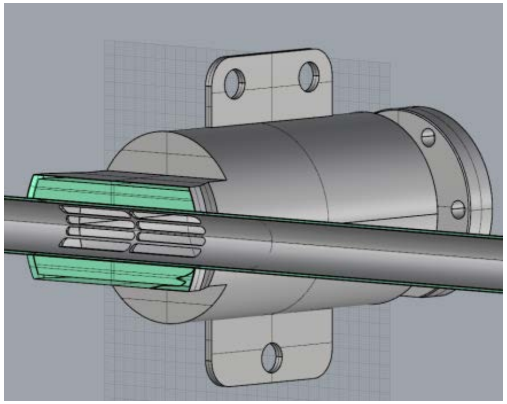




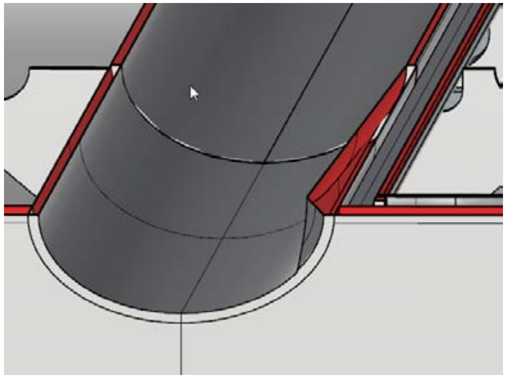


Copper / stainless steel elliptical tube - curved
E-beam welded external water cooling channel
NEG cartridge pump ports
Internal cooled bumps to shield flange joints from SR

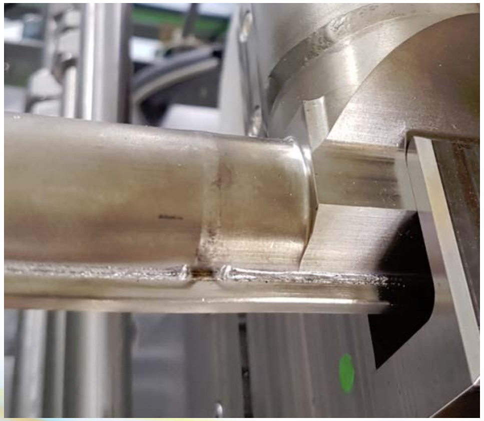
NEG pump interface



SR shadowing bump



Manufacture relatively unproblematic
Development of orbital welding equipment for elliptical tube took much longer than expected

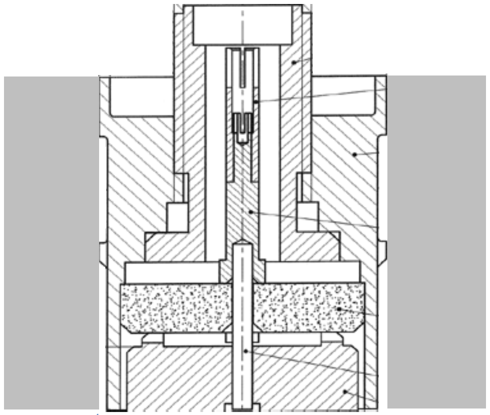


Orbital weld

BPMs

Improved design compared with previous BPM buttons at DIAMOND to reduce RF heating

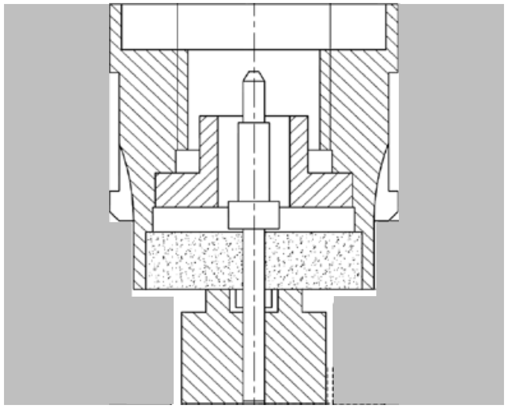
Existing 10.7mm DLS button



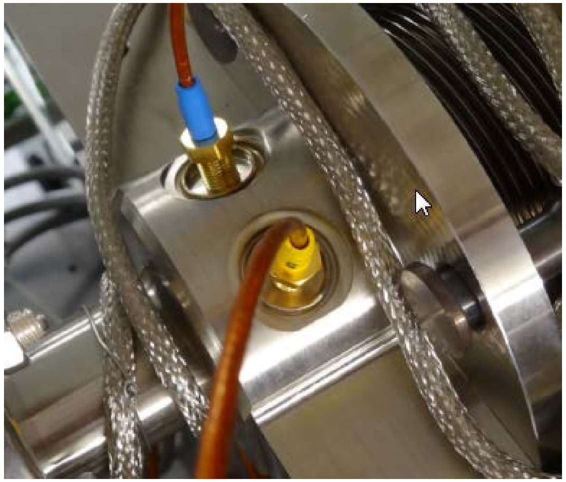
Outer gap between shroud and vessel

Inner gap around button

6mm button – new ESRF type



Only one gap between button and vessel



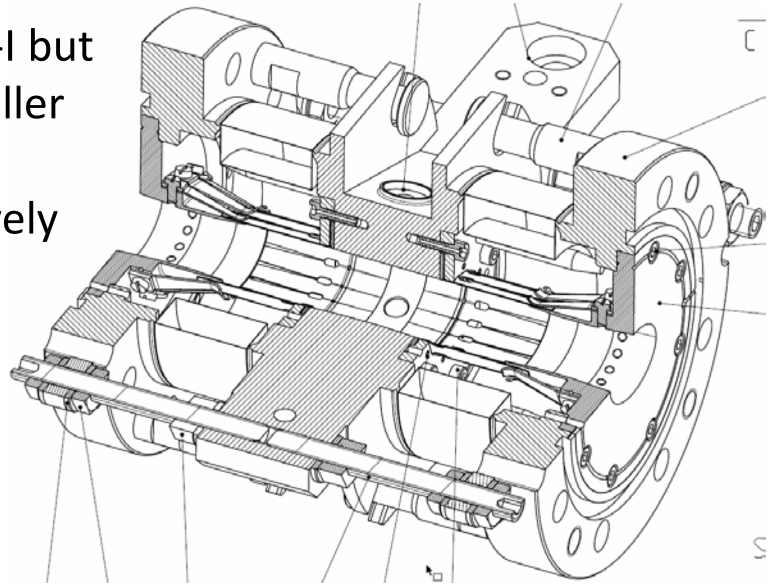
BPM station fitted with bakeable Kapton insulated cables

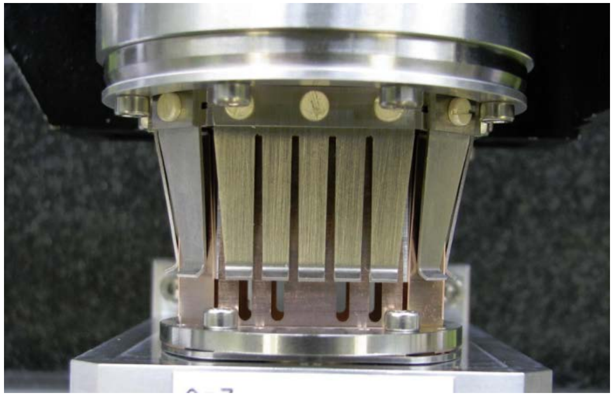
Manufacture and welding-in relatively unproblematic – yet to be tested with beam

RF bellows

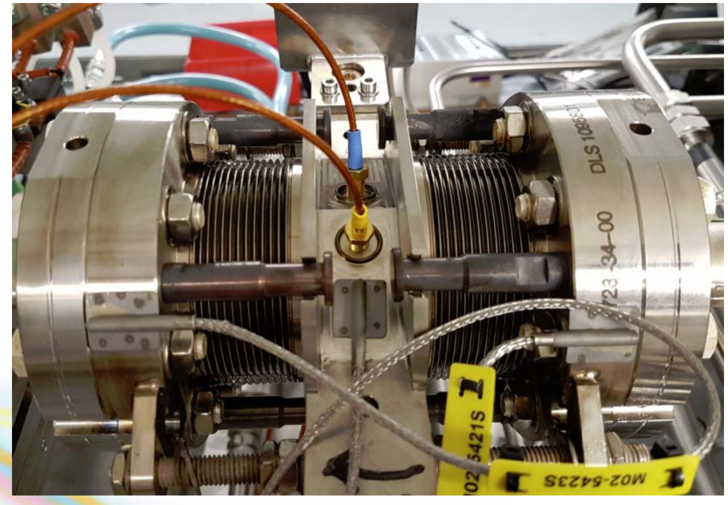
Similar to Diamond-I but scaled down to smaller cross section

Manufacture relatively unproblematic

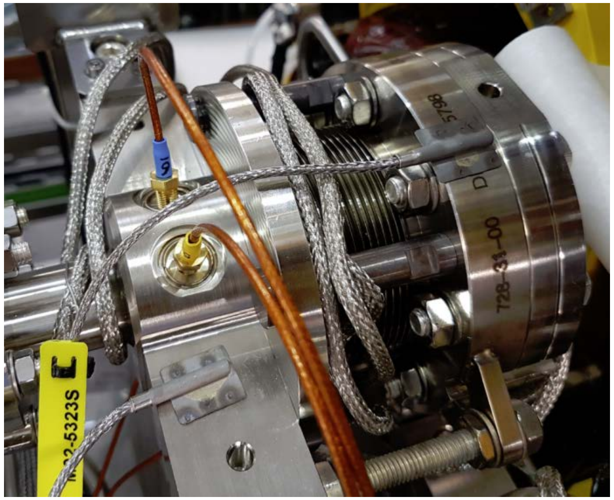




Flexible RF contact assembly on test

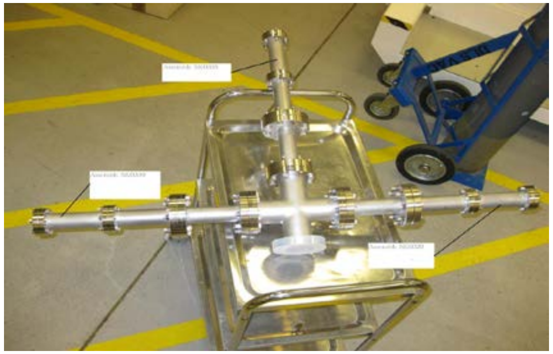


BPM with double RF bellows



BPM with single RF bellows

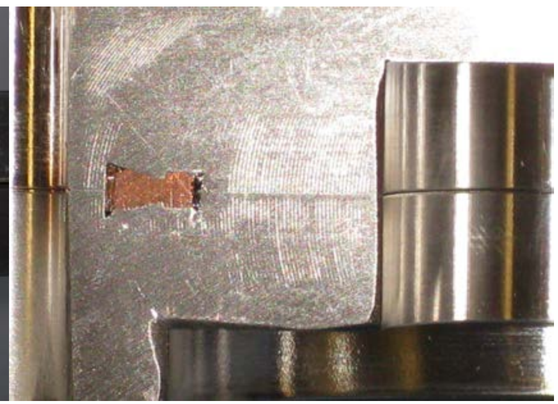
RF Compatible Helicoflex® Flanges: Lab Tests



Test setup

Requirements
- Low RF impedance (zero gap)
- Lateral alignment <100µm
- Reliable seal
- Tolerant to thermal cycling

DN63CF



DN40CF

A number of options explored

Helicoflex® Standard seal selected

Helicoflex® seals widely used in other industries, e.g. nuclear, fusion and are generally regarded as reliable

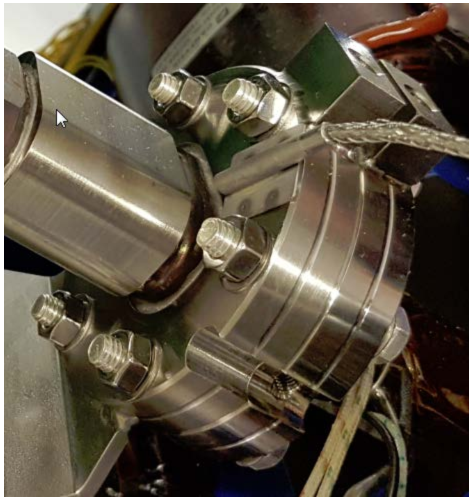
Positive lab tests in all different sizes needed - gaps, steps, leak rate, thermal cycling

Helicoflex DN63

RF Compatible Helicoflex® Flanges: In Practice

In practice not quite so straightforward

- Sealing problems at vessel supplier
  - Surface finish seems critical - milled / turned / polished
  - Different size seals behave differently
  - Not fully understood
  - Seems reliable with correct surface finish
- More sensitive to particles than standard CF type seals
- Leak testing was slow and difficult – add leak testing grooves!
- Expensive, long delivery, single source supplier (more recently second source)



DN40 Helicoflex® sealed flange on dipole vessel showing groove for removable alignment dowel pin, spot welded temperature sensor and survey monument blocks

On the plus side

- Removable dowel pins for lateral alignment work well
- Only one leak at Diamond which was due to inadequate clean assembly conditions

Imprint of machine groove pattern on DN40 Helicoflex® seal (5 mm graph squares)

- Further R & D needed to understand the sealing behaviour before it could be selected for a major project diamond

Vessels contract

Milestone	Target	Actual/Current	Delay (months)
Vessels contract placed	Aug 2014	Aug 2014	0
Vessels final design review	Dec 2014	Jan 2015	1
Vessels first complete set delivered	Jul 2015	Feb 2016	7
Installation	Aug/Sep 2016	Oct/Nov 2016	2

Build time compressed

Delays mainly due to:

- Several different challenges with welding in production (TIG, e-beam)
- Supplier had to develop orbital welding machine for elliptical tube butt welds which tool much longer than expected
- Helicoflex seal issues

- A few components had mechanical errors when received despite factory inspection and had to be worked around / reworked
- Experiences still to be explored in more detail with supplier. Lessons to learn on both sides.

Lessons learned:

- More allowance to sort out problems with first production batch. No opportunity to catch up on series production in this case.
- Challenge supplier assumptions on manufacturing methods and timescales
- Define trials better in the tender / contract. More representative trials early on
- Define factory inspection requirements better. More detailed inspection drawings. Improve site inspection.
- Diamond technician training on handling delicate vessels at the supplier factory was very valuable

Build and installation sequence

- Completed
  - Fully tested and qualified vessels (200°C bakeout) delivered from supplier(s)
  - Vessels and vacuum equipment trial-assembled on the 2 girders without magnets or NEG cartridges
  - Pump down and 200°C bakeout. Vessels uninstalled
  - Magnets aligned on girders and magnet tops removed
  - Vessels and vacuum equipment final-assembled on the 2 girders with magnet bottoms and NEG cartridges.
  - Pump down and 200°C bakeout. Remain under vacuum
  - Magnet tops re-fitted

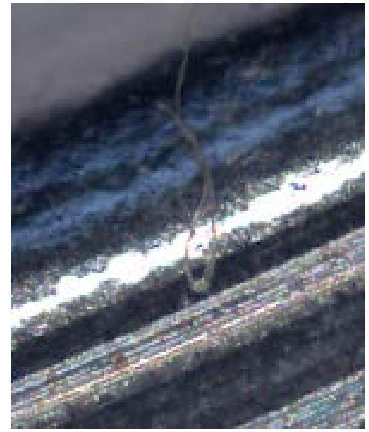
Build and installation sequence

- Next steps
  - Final preparations for installation
  - Installation in the storage ring tunnel under vacuum without venting and without re-baking
  - Connect up to adjacent vacuum sections and front end (re-bake these sections if necessary)
  - Open gate valves, inject beam and carry out beam vacuum conditioning

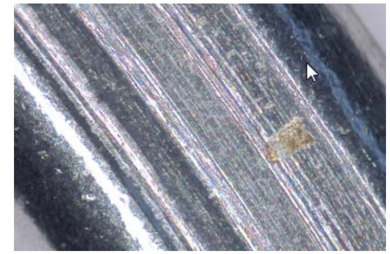
Vacuum build sequence Lessons Learned

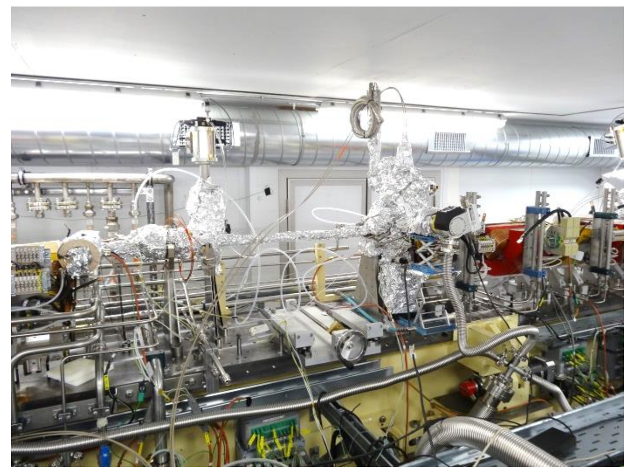
- Difficult to achieve required cleanliness with open vessels on the girder and other activities around. A leak seems to have been caused by particles / fibres trapped in the Helicoflex seal
  - Need to improve clean conditions around open vacuum vessels
  - Better housekeeping from all teams

- Due to shortened build time and cramped space there were issues with too many different teams working in the same area at the same time with inefficiency and risk of damage
  - Better coordination of different teams’ activities
  - More space for working and storage



Small fibre (ca 10µm dia) and particle (ca 200µm) on Helicoflex® seal



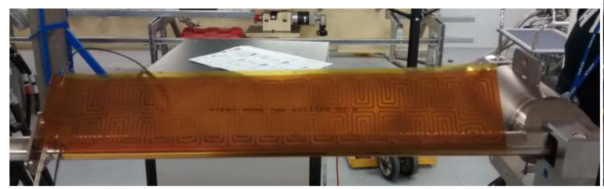


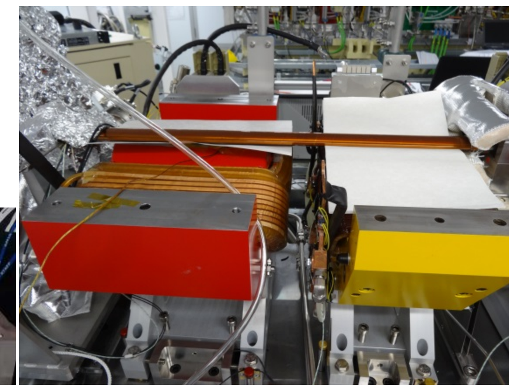
On-girder bakeout in practice

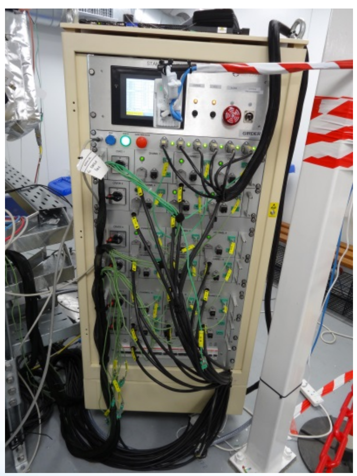
- Combination of Kapton film heaters (≤50VDC), heated jackets, braided heaters and flange band heaters (230VAC) with Al foil in places
- PLC-based control system
- Trial bakeout 200°C without magnets
- Final bakeout (target 200°C) with magnet bottoms only and dipole magnets retracted – in practice limited to 180°C to keep magnet poles below 70°C.

Braided heater on x-ray extraction leg

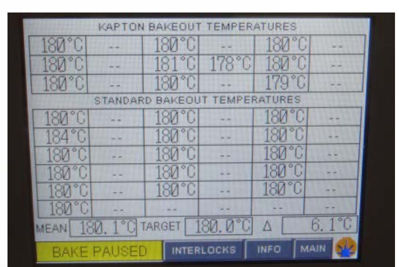
Kapton film heater on elliptical vessel







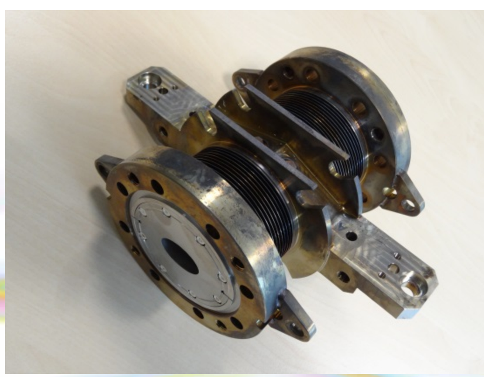
PLC bakeout control racks and display



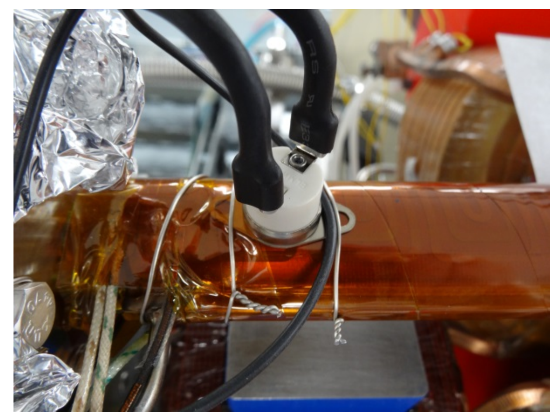
Heated jacket on NEG pump housing

On-girder bakeout in practice

- Lessons learned
  - Generally worked well, however
  - Wiring was complicated and not well thought out
  - It took a lot of adjustment to get uniform ramp up and temperatures ±10°C
  - Due to bug in PLC code – one trial bake overheated and caused some damage to heaters and vessels
    - Hardware over-temperature protection added
    - PLC code testing improved
  - Vessel was not exactly centred in magnet poles reducing clearance for heaters
    - Review tolerances
  - Magnet poles got hotter than expected



Over-temperature damage



Hardware over-temperature protection added

Industry R & D

- Diamond-II
  - Design input, prototyping and series production of vessels and vacuum components (on time please !!!). Improved tolerances and inspection.
  - Coatings and surface treatments (low outgassing, low PSD/ESD, low SEY, pumping …)
  - Novel materials, manufacturing and joining techniques (e.g., additive manufacturing ...)
  - Cost reduction of expensive processes for series production e.g. NEG coating

Thanks to ....

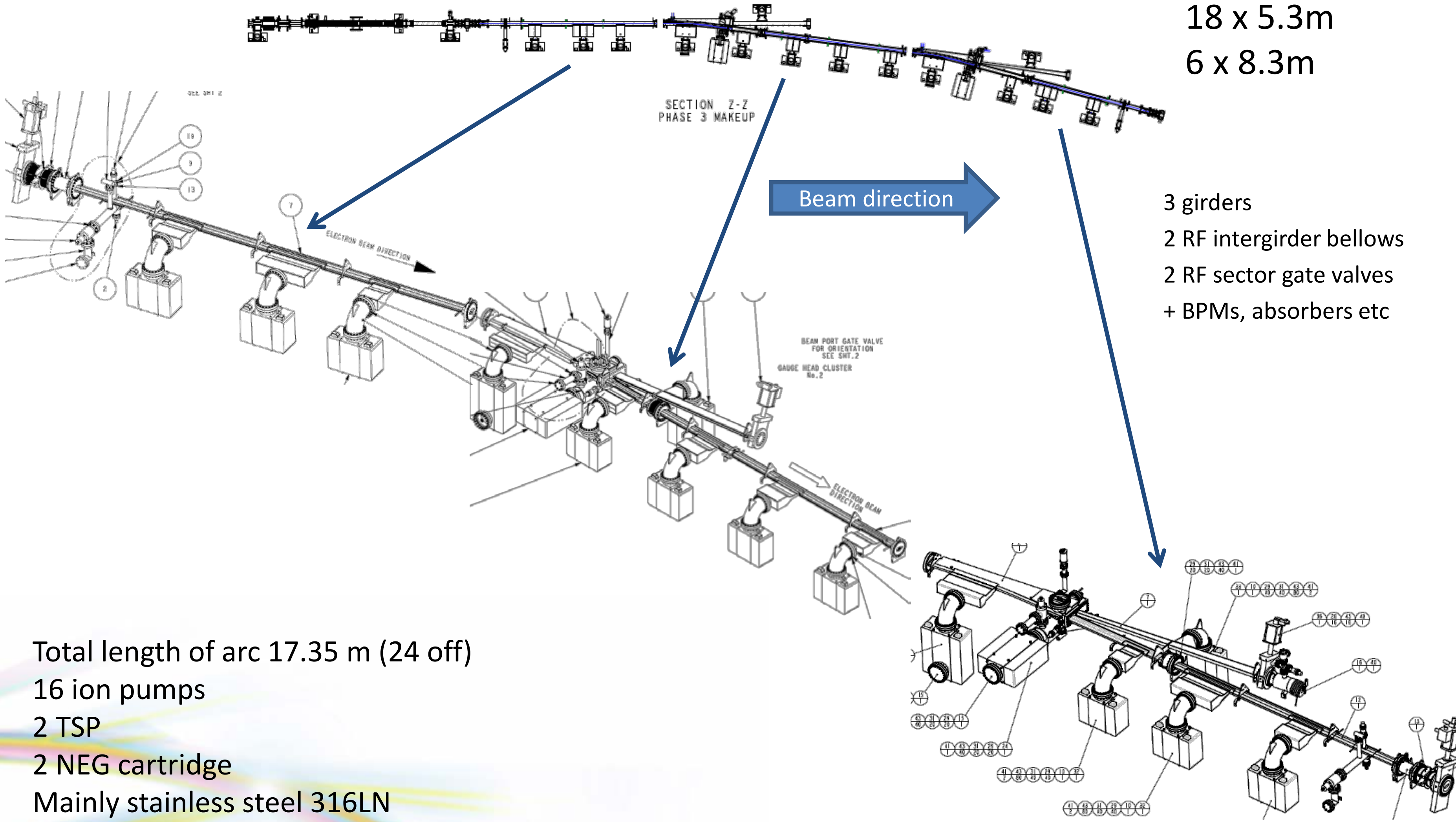
Diamond Vacuum Group

Diamond DDBA Team

Suppliers

Backup slides

Existing (DBA) Arc Layout



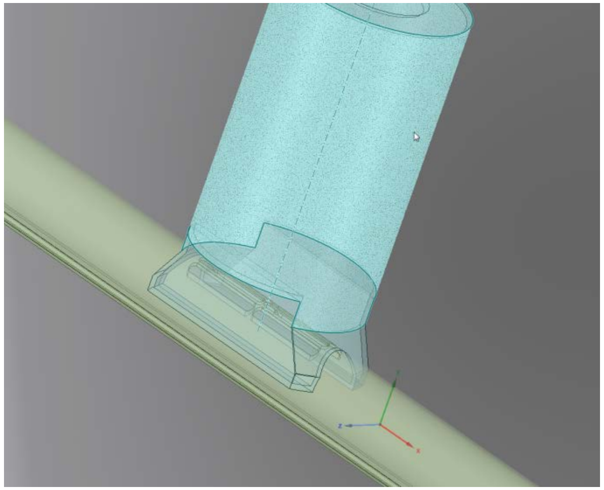
Straight section
18 x 5.3m
6 x 8.3m

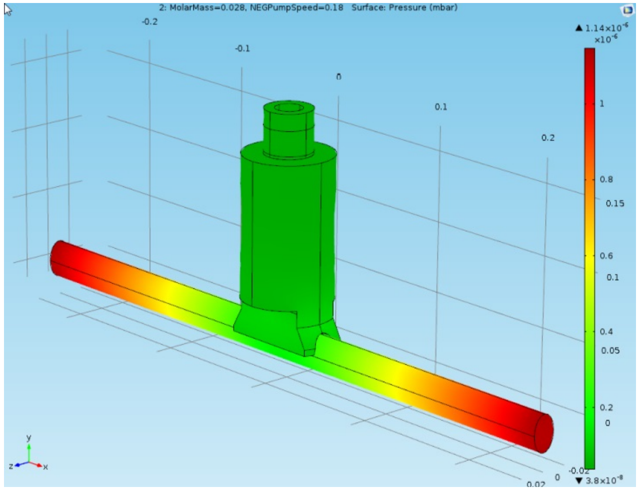
3 girders
2 RF intergirder bellows
2 RF sector gate valves
+ BPMs, absorbers etc

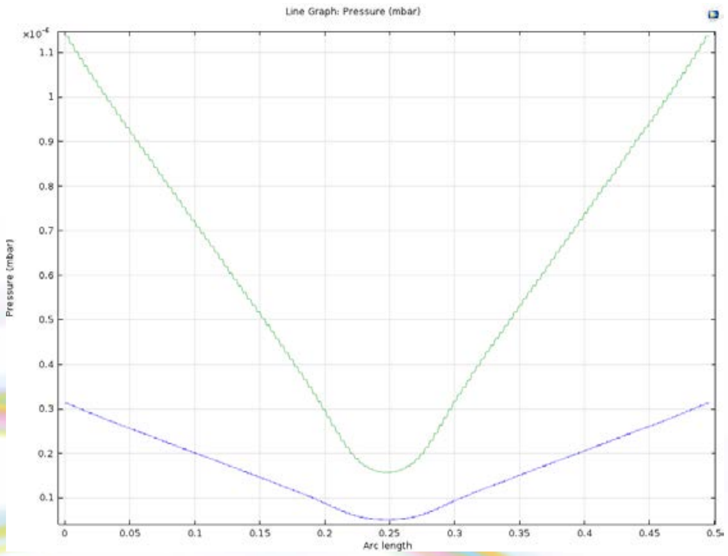
Total length of arc 17.35 m (24 off)
16 ion pumps
2 TSP
2 NEG cartridge
Mainly stainless steel 316LN
4 IMGs
2 RGAs

NEG cartridge pump interface studies

- Elliptical tube 27 x 18 internal x 1 mm WT
- 8 pumping slots 3 mm wide x 33.5 mm long
- Compromise between vacuum pumping and beam impedance
- NEG cartridge SAES Getters Capacitorr D400-2
- Does not pump CH_4 or inert gases

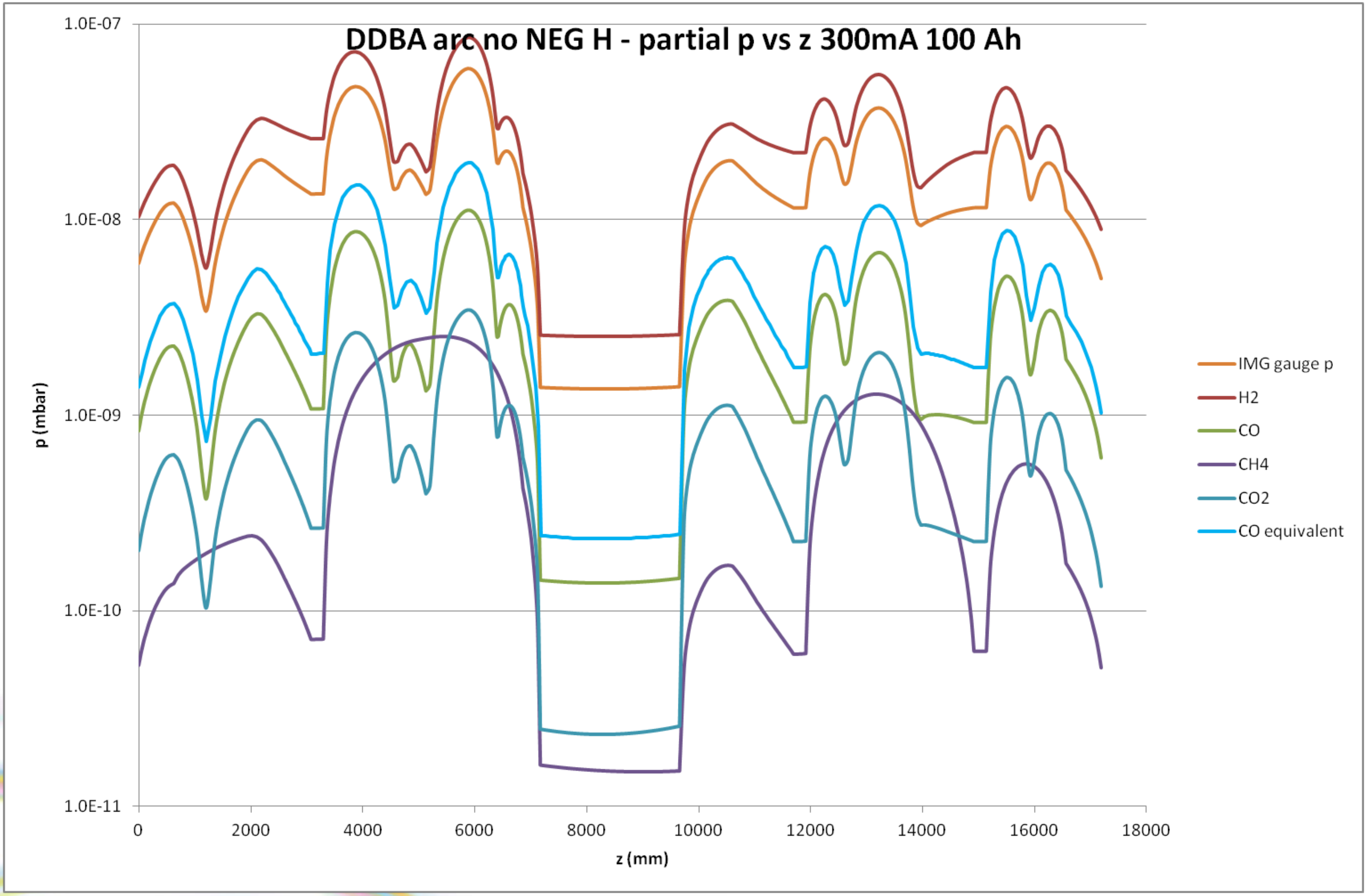




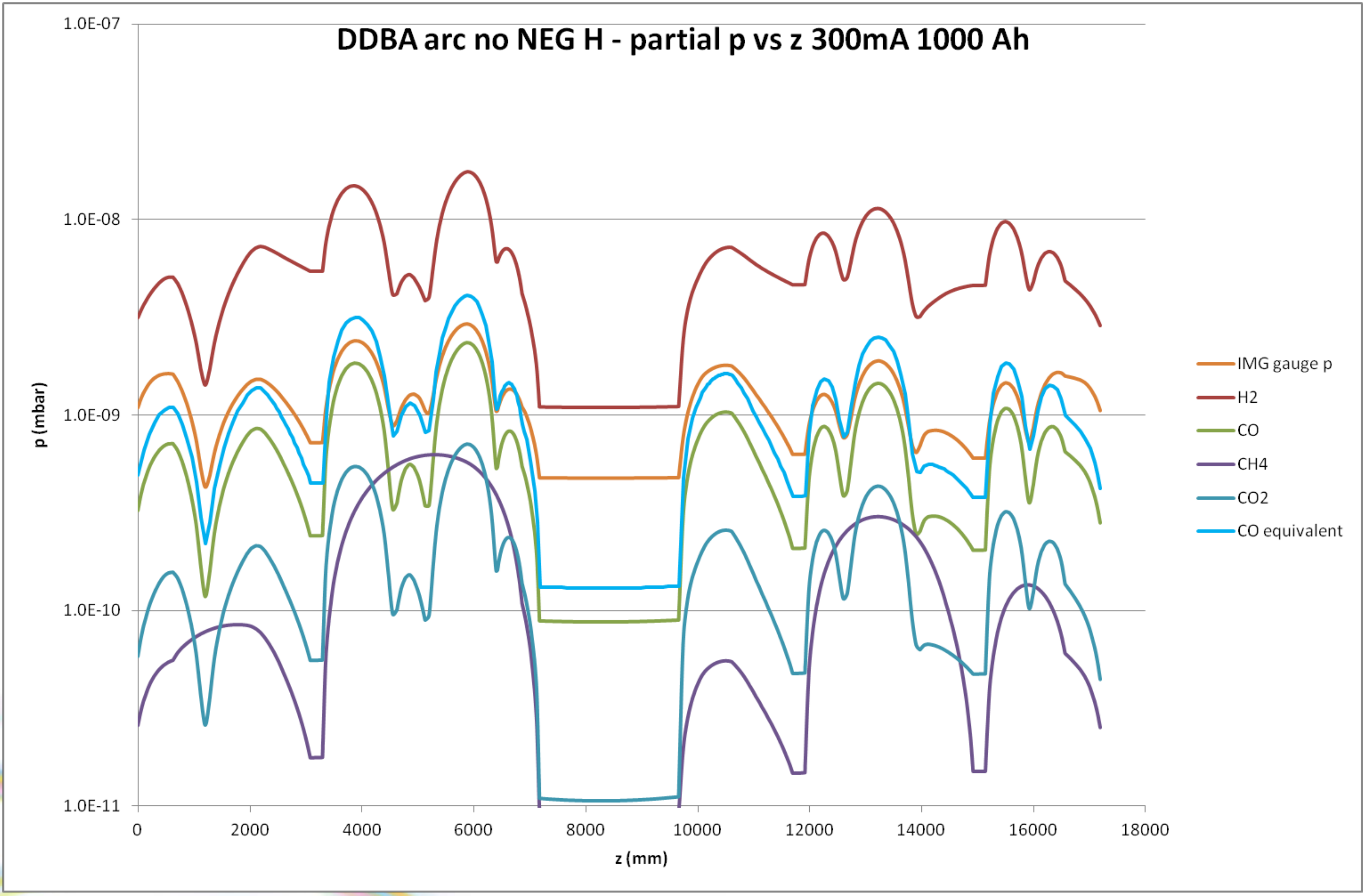


Comsol fmf results	H_2	CO
Naked NEG cartridge pump speed	400 l/s	180 l/s
Gas flow in	1E-5 mbar l/s	1E-5 mbar l/s
P in pump body	2.21E-8 mbar	4.88E-8 mbar
Effective pump speed within pump body	452 l/s	205 l/s
P at pump port	5.32E-8 mbar	1.65e-7 mbar
Effective pump speed at beam tube	188 l/s	61 l/s

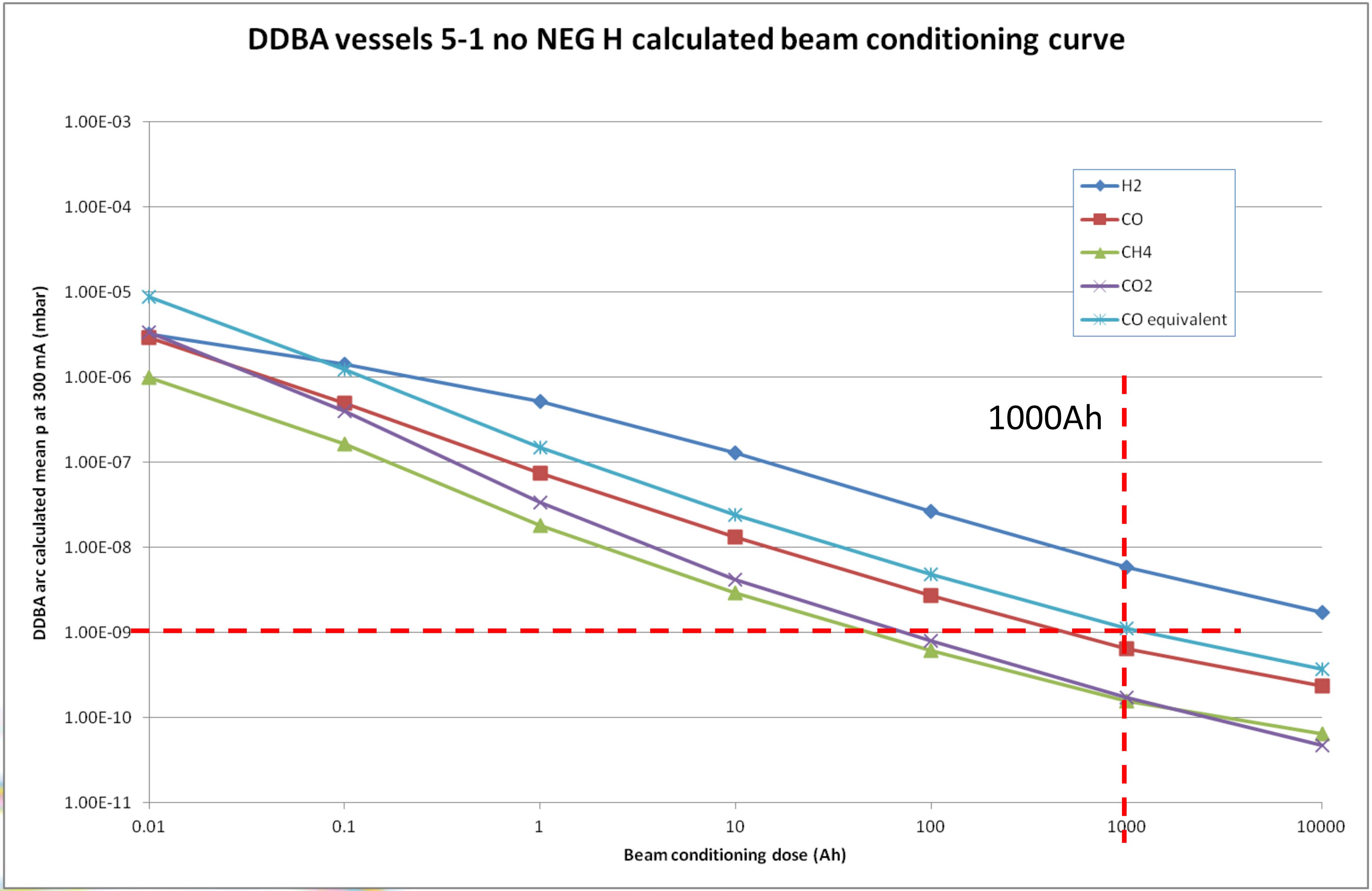
Calc pressure profile 100Ah no NEG coating



Calc pressure profile 1000Ah no NEG coating

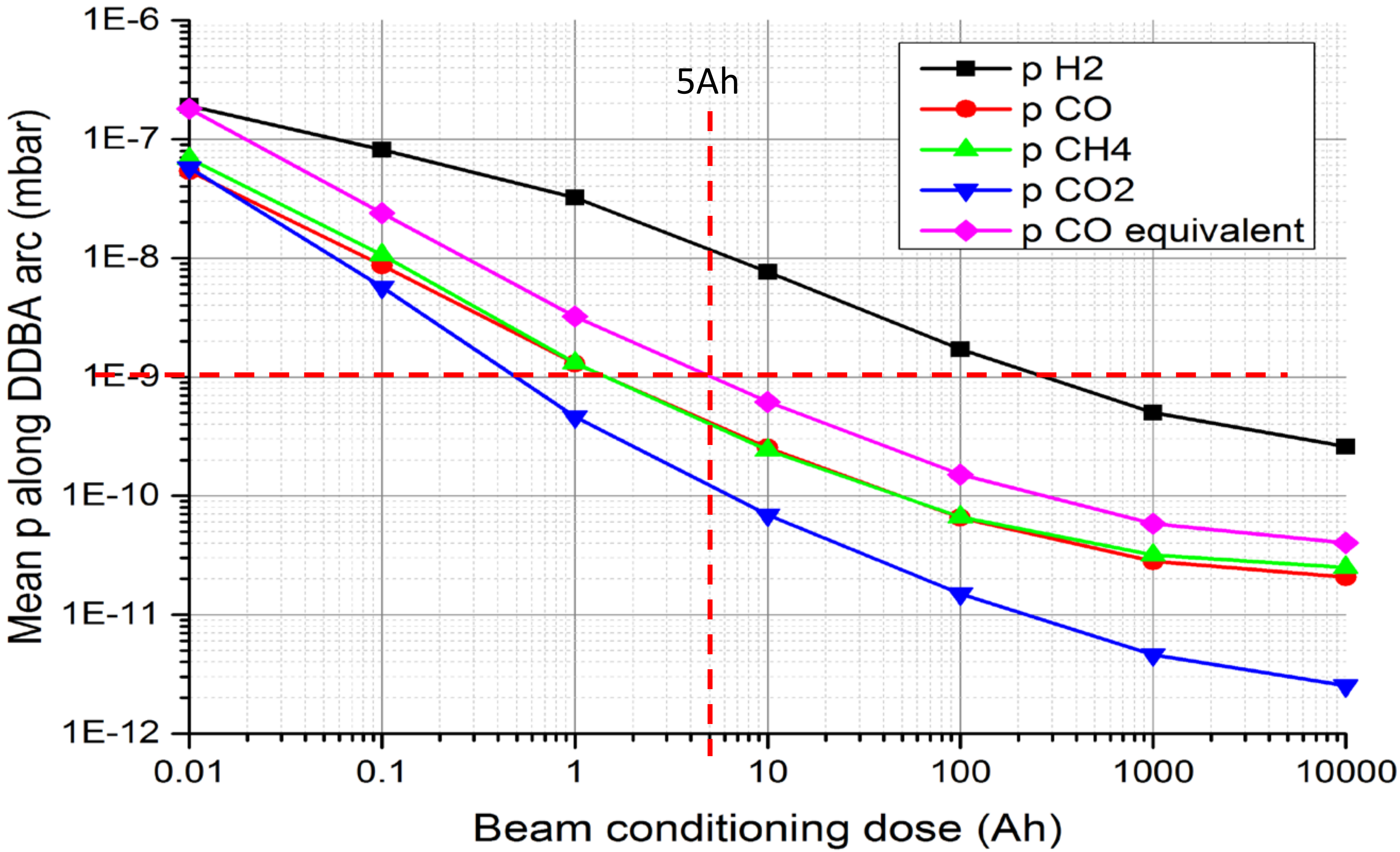


Calc beam conditioning no NEG coating



I_{beam} = 300mA

Calc beam conditioning NEG coating

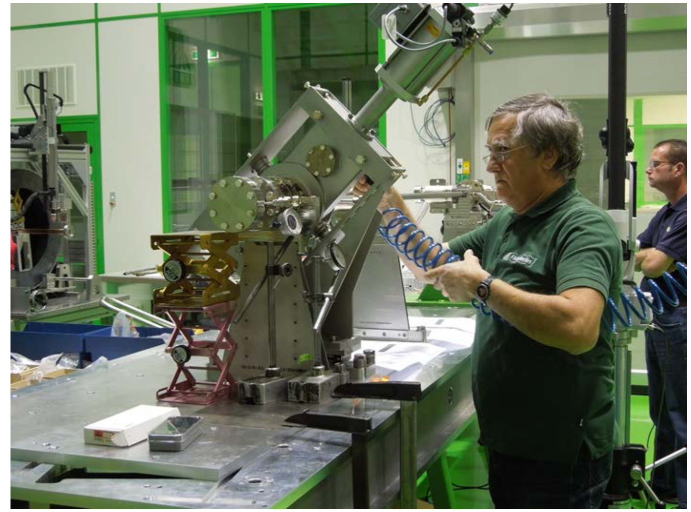


I_{beam} = 300mA

Vacuum vessel tests at supplier

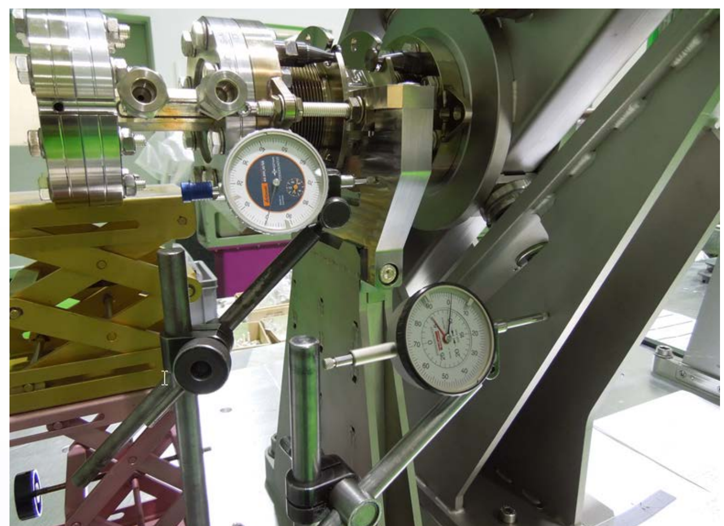
Building up of vacuum strings

Flexible bellows / BPM units



RF gate valve alignment

Survey of vessel string assembly



Measurement of deflection on pump down