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In-Vacuum Magnet Design and Challenges

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Workshop on Special Compact and Low Consumption Magnet Design, 26th November 2014

Overview

- Motivation
- Additional Challenges
- Current Solutions
- Practical Experience
- Ongoing Improvements
- Future Potential

Disclaimer

- The topic of this talk is undulators for generating synchrotron radiation
- I appreciate that there are other specialised magnets which are also mounted in-vacuum (e.g. kickers and septa) but they will not be covered here

Motivation

- Permanent magnet undulators dominate synchrotron light sources
  - They are able to generate high fields at short periods with acceptable magnet gaps
  - The fundamental wavelength emitted on axis is: $\lambda = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2}\right)$

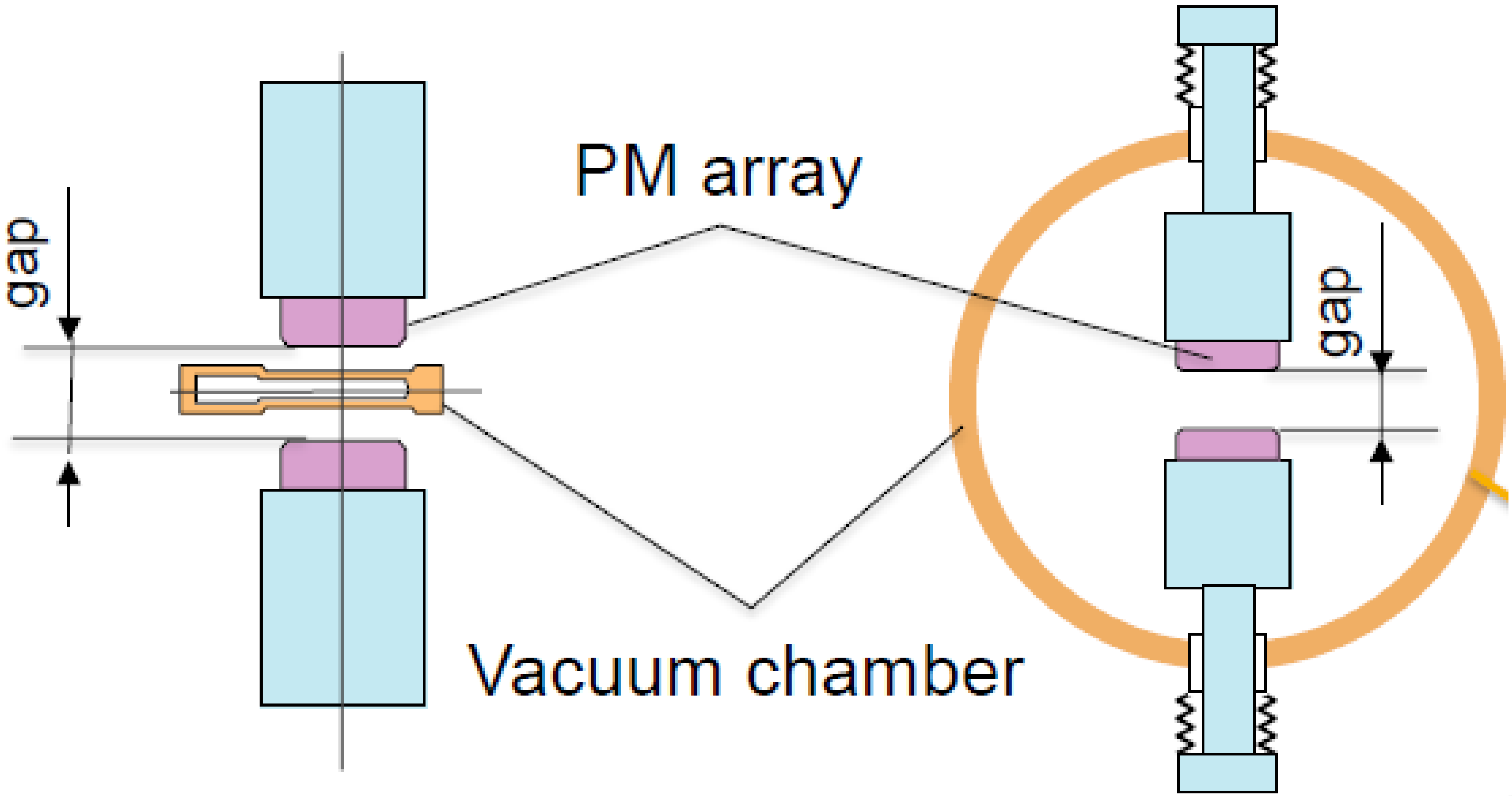
  where λ_u is the period, γ is the relativistic factor, and $K = 0.934 B_0 \lambda_u$ (B_0 in T and λ_u in cm).
  - For the shortest possible wavelengths at a fixed energy the period needs to be reduced and K increased (conflicting requirement)
  - We can't, in general, just have short period and low K because then the tuning range of the undulator is too small and the output photon flux too low

Motivation

- In a typical permanent magnet undulator we have: $B_0 \propto e^{-\pi g/\lambda_u}$ so to keep K (relatively) high whilst reducing the period we have to reduce the gap, g [Remember $K \propto B_0\lambda_u$]
- So, the ***magnet gap is a crucial parameter*** in every undulator and, in a sense, it defines the potential output of every light source
- The magnet gap is dependent upon the needs of the electron beam as well so is not a free parameter
- Undulator designers realised that the beam vacuum chamber always costs valuable **mm** and so they decided to put the undulator itself inside the vacuum chamber for critical applications

Example

- For normal out of vacuum undulators, if an electron beam requires 5mm full vertical gap, say, then typically the vacuum chamber might be 1 to 2mm thick and so with allowance for tolerances the magnet gap could be 8 to 10 mm.
- If the undulator can be put in vacuum the magnet gap will typically be 5.2mm,
  - At 3 GeV, a typical ***out of vacuum*** PM undulator with 20 mm period will generate **2.6 to 4.2 keV** photons in the first harmonic with an **8 mm gap**
  - With a **5.2 mm gap**, the same undulator ***in vacuum*** will generate **1.6 to 4.2keV**.
  - Alternatively, the period could be reduced to **17.2mm** and then the photon range would be **2.6 to 4.9 keV** and the **flux would be increased by approx 30%** compared with the 8mm gap device as well.



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The Challenges of In Vacuum Undulators

- **Maintaining a suitable vacuum for the electron beam**
- **Coping with wakefield issues**
- **Not being able to make magnet measurements or shimming of the final device**

- [Approx double cost of standard undulator]

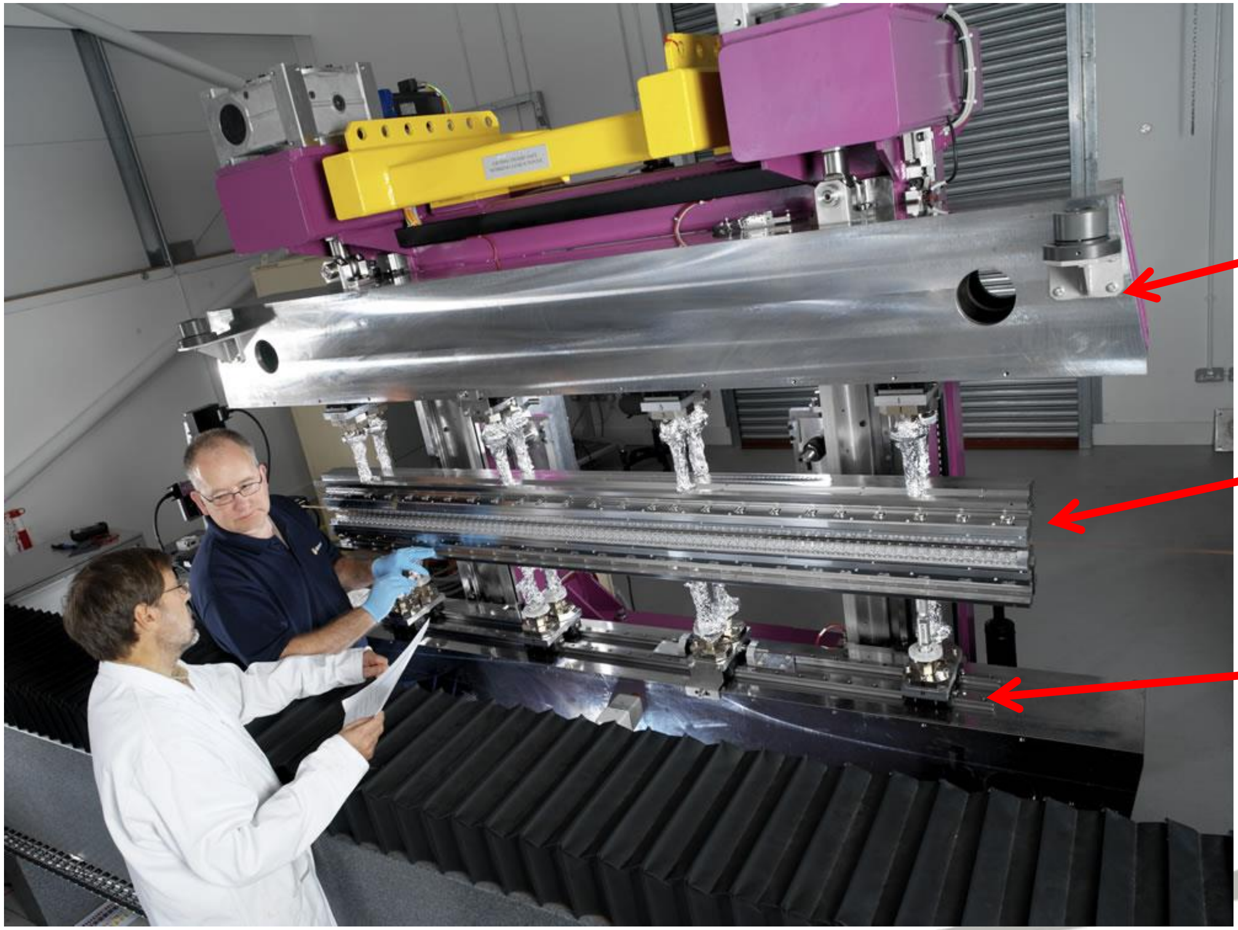
The Beam Vacuum

- Storage ring vacuum is very important for beam lifetime and permanent magnets are porous so there was a lot of concern that they could not be used in vacuum in large numbers (a 100 period undulator typically uses ~800 individual PM blocks).
- Each PM block is individually coated (~5 μm of Titanium nitride often used but nickel or aluminium also possible)
- The undulator design of stacking blocks next to each other and holding them in individual holders against a backing beam naturally creates trapped volumes of gas
- UHV engineering practices implemented, trapped volumes minimised as far as possible
- Installed pumping of ~7000 l/sec used (ion pump & NEG)

ALS in vacuum undulator – plenty of pumps and vacuum instrumentation

The Beam Vacuum

- To attain UHV, baking to several hundred °C is common practice – this is not compatible with PM blocks as causes unwanted and poorly controlled demagnetisation
- Bake to ~125 °C still possible with NdFeB (grade dependent – some limitations) and beneficial to vacuum. SmCo can go to higher temperatures but magnetisation strength lower so no overall benefit in terms of peak field.
- Need to allow for thermal expansion of arrays during bake.
- PM blocks are pre-baked prior to use to make sure even low temperature bake has no effect (stabilising effect).



Diamond in vacuum undulator

Out of vacuum part

In vacuum part

Rails allow for thermal expansion

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Wakefield Issues

- PM Blocks present high resistance surface adjacent to electron beam – resitive wall wakefield very significant, leading to overheating of PM blocks and damage to undulator
- Therefore must have continuous conducting surface on top of blocks so electron beam does not see high resistance
- Furthermore, must have continuous conducting surface connecting adjacent fixed gap vessels to (moving) magnet arrays of undulator
- Lay thin copper foil (50 μm) coated with nickel (50 μm) so held in place over surface of all blocks so beam sees high conductivity surface and wakefields then manageable – early in-vacuum undulator did suffer from damage due to heating effect
- Use flexible RF transitions which provide good conducting path from adjacent vessel to moving arrays

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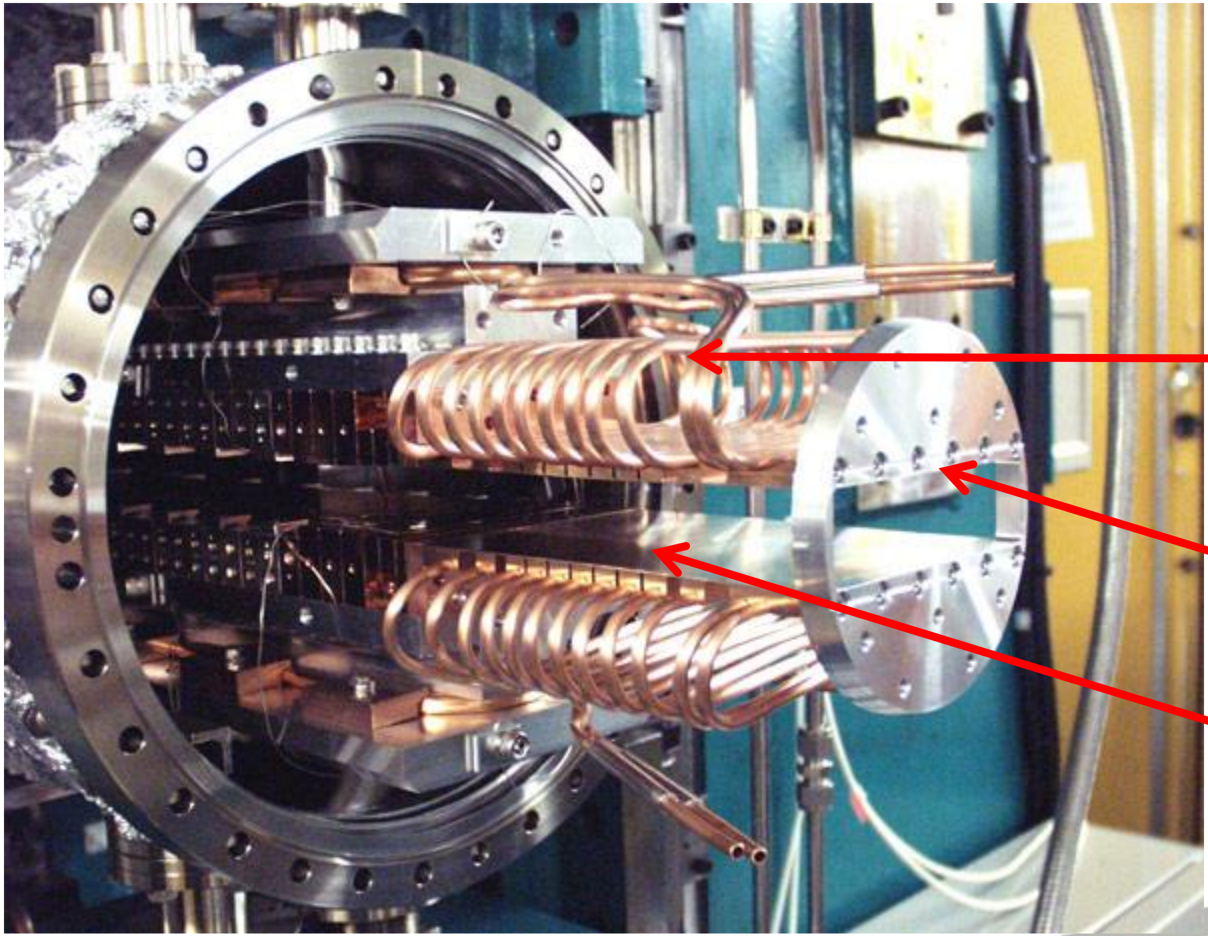
In vacuum examples

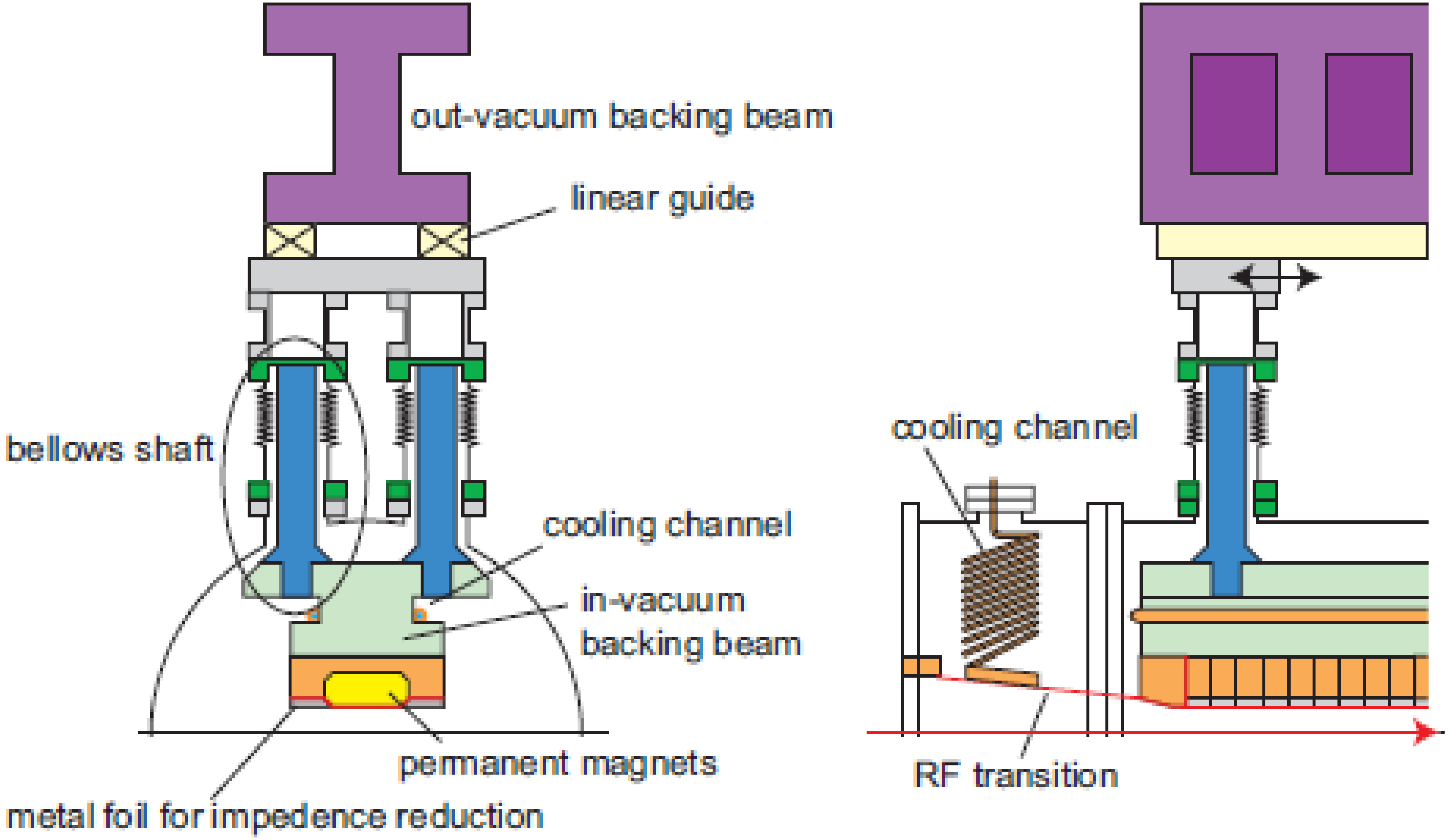


Diamond in vacuum undulator

Cooling water for any wakefield heating or synchrotron radiation absorption

Fixed aperture for adjacent vacuum vessel

Flexible transition



Proceedings of the 27th International Free Electron Laser Conference

IN-VACUUM UNDULATORS

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Magnet Measurements

- Undulator magnet measurement systems move Hall probe around volume of interest by accessing from the side – far easier than accessing from the end due to aspect ratio – short probe arms!
- Can’t measure undulator with this system when outer vacuum vessel in place
- Can’t apply shims to undulator when outer vacuum vessel in place
- Measure and shim before outer vessel is in place – extra complication – have to make sure demounting the arrays and reinstalling them is ***very*** reproducible
- Alternative of changing the measurement system so enters lengthways has been developed later when essential for specific applications – results good but certainly more complex

Diamond in vacuum undulator

Out of vacuum part

In vacuum part

Hall probe arm

Rotating coil system

Measurement bench

Experience

- The Spring-8 facility in Japan played a major role in making in-vacuum undulators part of the mainstream (~mid 1990s)
- Worldwide they are implemented in most modern storage ring light sources and some FELs
- They are available from industry and are very reliable
- Very good vacuum levels are achieved (10^{-9} mbar) and beam lifetime has not suffered from their introduction
- A typical minimum magnet gap would be ~4 to ~5mm for a 2m long magnet
- Many storage rings 'top-up' continuously 24 hrs/day with these magnets in use at minimum gap – electron beam very well controlled
- Operating costs low – a few more vacuum pumps but no extra water cooling needed

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Figure 10: 25-m long IVU installed in the LSS in SPring-8.

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SACLA X-Ray FEL in Japan

18 x 5m undulators
18 mm period
3.7 mm gap
SwissFEL will also rely on in-vac undulators

Improvements

- In-vacuum undulators have successfulluy transitioned from R&D in the 1990s to mainstream off the shelf systems today
- There have been incremental improvements but fundamentally the same principles are still used
- The most significant enhancement has taken advantage of the in-vacuum technology to cool down the PM blocks to increase the magnetisation of the material and so enhance the magnetic fields – so-called cryogenic PM undulators (CPMUs)

Cryogenic PM undulators

- **Magnetisation increases as temperature decreases, coercivity increases even more** – ***selection of stronger grades possible***
- Better performance, better vacuum because cold, better radiation damage resistance – lots of advantages
- **PrFeB** better than **NdFeB** because good at 77K which is easy temperature to generate stably (LN2)
- CPMUs have been implemented successfully ***unbaked***

- Operating costs increased because of LN2 cooling loop (~250 litres/day)
- Operational experience good

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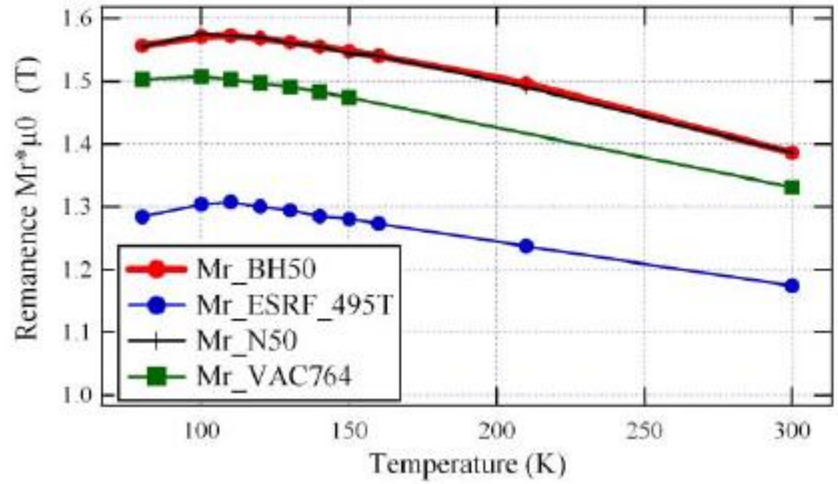
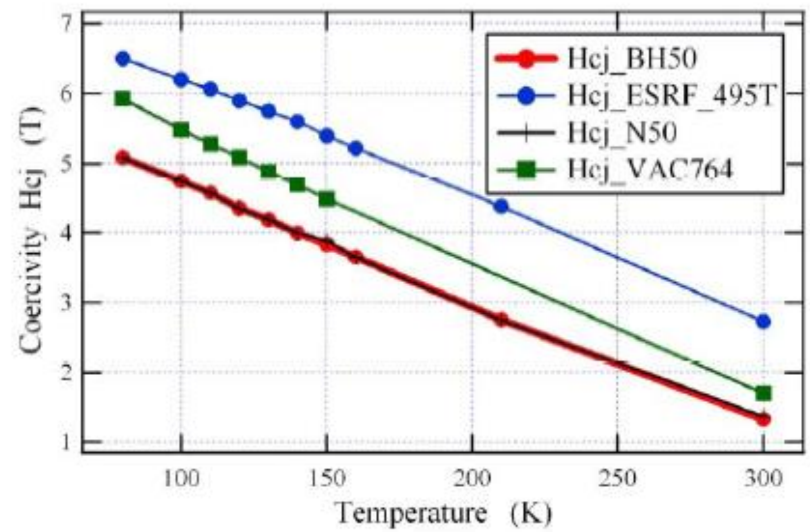
PM Materials

- Different NdFeB grades
- Spin reorientation at ~100K, don't want to work at 77K





Proceedings of EPAC08, Genoa, Italy WEPC098

DEVELOPMENT OF CRYOGENIC UNDULATOR CPMU AT SOLEIL

C. Benabderrahmane*, N. Béchu, P. Berteaud, M.E. Couprie, J.M. Filhol, C. Herbeaux, C. Kitegi, J.L. Marlats, K. Tavakoli, A. Mary
Synchrotron SOLEIL, St Aubin, France.

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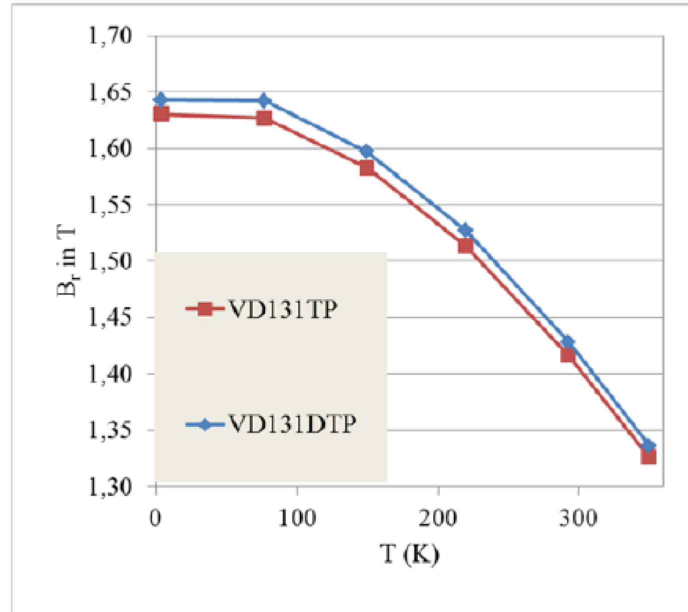
PM Materials

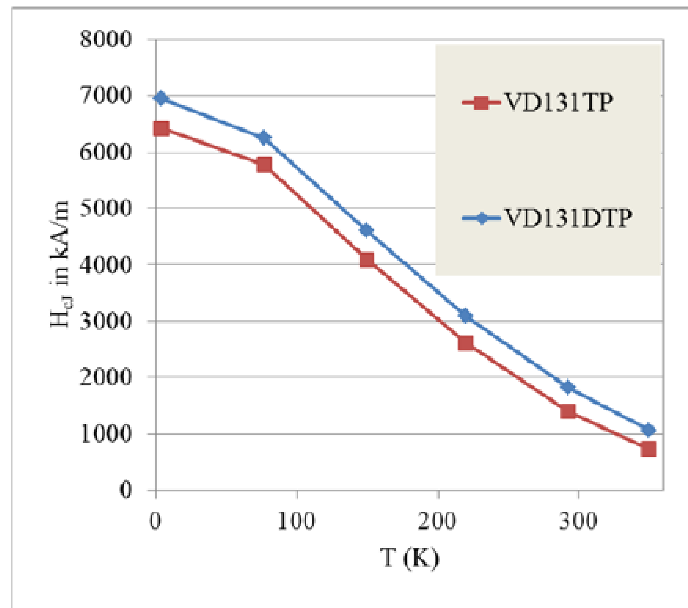
- PrFeB or mixed (PrNd)FeB alloys
- No spin reorientation
- Stable performance, good at 77K



TUPRO085 Proceedings of IPAC2014, Dresden, Germany

PROPERTIES, OPTIONS AND LIMITATIONS OF PRFEB-MAGNETS FOR CRYOGENIC UNDULATORS

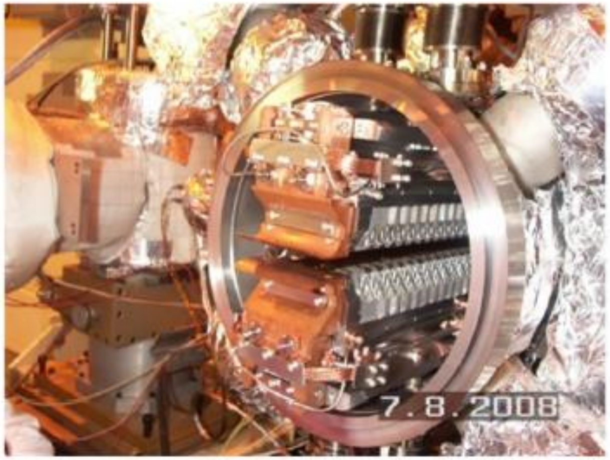
F.-J. Börgermann, C. Brombacher, K. Üstüner, Vacuumschmelze GmbH & Co KG, Hanau, Germany



CRYOGENIC PM UNDULATORS (CPMUS)

CPMU= IVU+ cryogenic cooling of PM arrays (*)

- Higher performance PM materials
- Higher stability
- Better vacuum
- NdFeB or PrFeB
- Liquid nitrogen or cryocooler
- Several devices in operation in different 3GLS

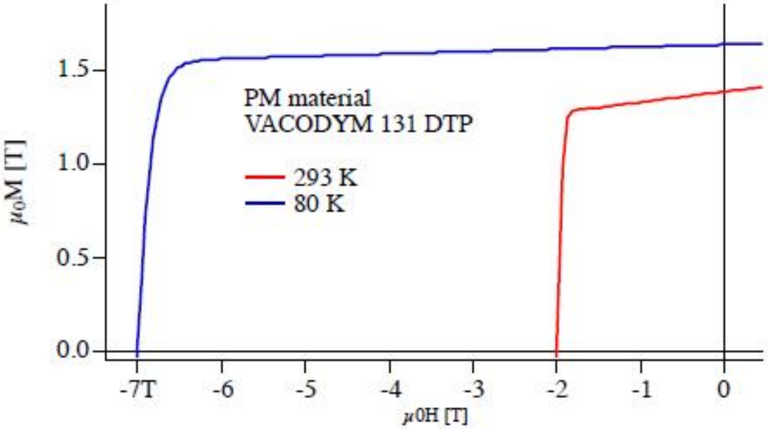


3rd CPMU under construction @ ESRF

PM material: Vacodym 131 DTP (PrFeB)

Br =1.62 T,| $\mu_0 Hc_J$|~ 7 T @ 80 K

Min. gap=4 mm
period 14.5 mm
B_{max}=1.26 T



(*) SPRING 8 proposal : Phys. Rev. ST AB,Vol. **7**, 050702 (2004)

Summary

- There is a significant driver to minimise the magnet gap of undulators as far as possible
- ***This has been achieved by putting the magnets inside the beam vacuum***
- The challenges of maintaining UHV, coping with wakefields, and having to measure and shim before the vacuum vessel is fitted have **all been successfully met**
- Smaller magnet gaps mean **lower electron energies (less GeV!)** needed for the same wavelength **– big energy savings in light sources already generated with this shift to in-vacuum undulators – good news story!**
- In-vacuum magnets are now considered routine and are available from industry
- Putting the arrays in-vacuum has enabled them to be cooled down to take advantage of enhanced PM properties – another beam energy reduction now possible
- **Remaining Issue:** There are many more complex undulator systems (e.g. variably polarising) which could also benefit from smaller gaps but because of the extra degrees of freedom required these are still out of vacuum only (except for one or two prototypes)

Acknowledgements

- Thanks to everyone who helped with providing material for this talk, especially Joel Chavanne, ESRF, for his detailed comments on his experiences with IVU & CPMUs