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Vacuum baking test of NdFeB permanent magnet material for ERL undulators*.

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Abstract.

The note describes result of the vacuum baking test of 30cm long magnetic arrays with 25mm period pure permanent magnet (PPM) structure made of NdFeB permanent magnet material of 40SH grade. Magnetic array dimensions and material were similar to what is planned for use in ERL insertion devices.

Analysis based on the magnetic properties of PM material and 3-D magnetic field calculation has shown that the temporary attachment of a steel plate to the magnetic array just for the period of baking can significantly increase the demagnetization temperature. For given PM material and array geometry the predicted increase was from 77degC to 125degC.

In the test, a magnetic array with attached steel plate was placed in a vacuum vessel and baked in vacuum for 48hrs at 120degC. After baking magnetic field measurement showed no change in magnetic field within 2% of measurement precision. The outgassing rate of the baked array scaled to an undulator was equal to $333\ nT \cdot liter/\sec$ per meter length with 96% of hydrogen.

Calculation of the demagnetization temperature, experimental setup, results and analysis are presented.

Introduction.

The most effective in-vacuum style insertion devices (ID) require the baking out cleaning procedure to satisfy UHV conditions. The baking temperature should be chosen very carefully because, from one hand , the higher temperature provides faster and better cleaning, on the other hand, it may cause the PM structure demagnetization. The choice is usually a compromise between these two concerns.

It is known that the demagnetization temperature depends on PM material grade and applied demagnetizing field, which, in turn, depends on ID magnetic design. Magnetic design for ERL IDs can differ from one that used for storage ring. Because ERL is a one pass machine, the beam does not require additional space around for newly injected particles and also there are no limits on the aperture implied by the beam life

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time requirement. Thus ID's aperture and magnetic design could be different. Given the difference in the magnetic design, there should be difference in backing out recipe.

To confirm our understanding of the baking out procedure and to obtain data which can be applied for ERL in-vacuum ID design, we assembled two 30cm length PM arrays and with one of them went through the full procedure. The acquired experience as well as a test results are described in the following sections.

The baking temperature limit consideration.

As it was mentioned above, the choice of the baking temperature is probably the most important issue. The higher the temperature, the faster cleaning and better results can be expected. On the other hand, higher temperature may cause PM demagnetization. The later implies very hard limit. In our test, using PM material specifications, we estimated temperature limit for single PM blocks, and then measured it. Since the measurement result has been found in good agreement with prediction, we calculated, in the similar way, the temperature limit for the magnetic assembly and used this limit for the magnetic array baking-out procedure as described below.

Description of PM material demagnetization characteristics.

Left plot in Fig. 1 depicts demagnetization curves for NdFeB permanent magnetic material of N40SH grade at different temperature. Data was copied from website: www.maurermagnetic.ch. Here vertical scales are intrinsic magnetic field in direction of magnetization (blue) and specific magnetic moment (red), horizontal is magnetic field induction applied in direction opposite to magnetization. Knees seen in curves indicate points of irreversible demagnetization. For example, the 120^0C curve indicates that PM material will be irreversibly demagnetized if ~7.8kOe are applied opposite to the magnetization direction. The intrinsic magnetic field under this conditions will be ~3800kG, see right scale. This is a minimum of the intrinsic field that can be reached without irreversible demagnetization at 120^0C of temperature.

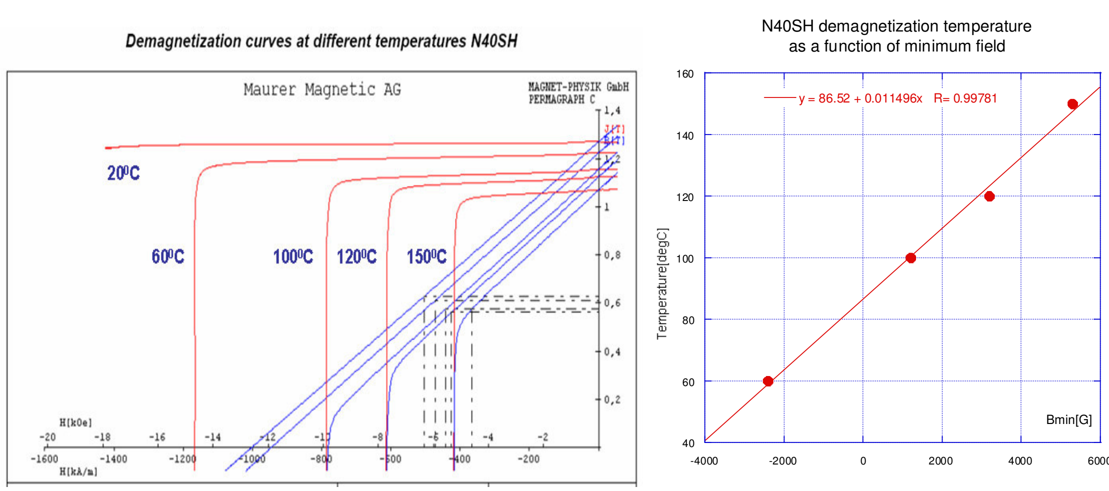

Figure 1. N40SH demagnetization curves at different temperature, left plot, and demagnetization temperature as function of intrinsic magnetic field in direction of magnetization, right plot.

The dependence of minimum reachable magnetic field as a function of temperature was extracted from data depicted on left plot and plotted on right side in Fig.1 in the form of temperature as a function of the minimum field. The linear fit for the temperature dependence on the field gives:

$$T_{demag}[^{0}C] = 86.52 + 0.0115 \cdot B_{\min}[G] \qquad (1)$$

So to estimate the temperature limit for given magnetic assembly, one should first calculate the magnetic field, then identify regions with minimal magnetic field in direction of magnetization. These will be regions with strongest demagnetizing field. After that, using expression (1) one can calculate the temperature limit. The baking temperature should be slightly lower.

Prediction and measurement of the baking temperature limit for single PM blocks.

The strategy described above for the baking temperature choice has been tested on two PM rectangular blocks made of NdFeB material of N40SH grade. The blocks had dimensions 1.0 x 0.5 x 0.125”. One block, “V” type, was magnetized in 0.5” direction, another, “H” type, in 0.125” direction.

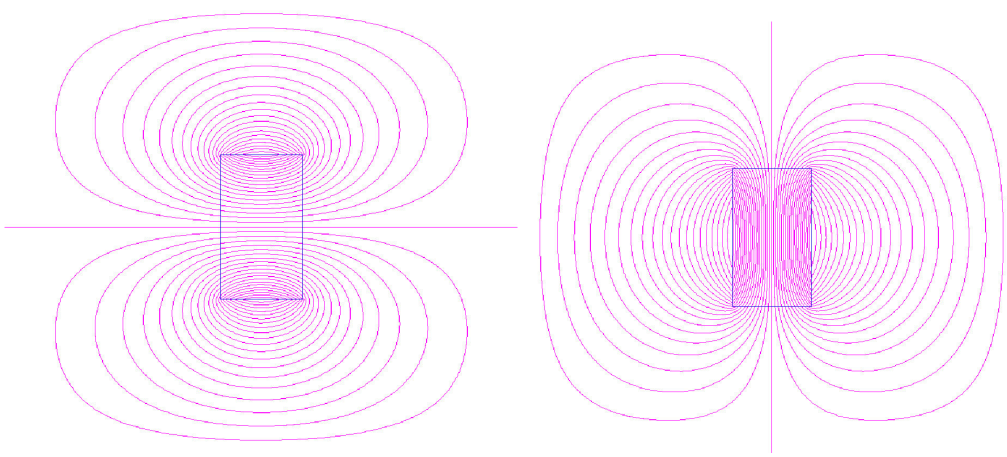

Figure 2. Magnetic field lines blocks magnetized in 0.125” direction, left plot, and in 0.5” direction, right plot.

Figure 2 shows magnetic field for both. Calculation with 3D magnetic modeling program “Vector Field” indicated that the PM block of “H” type had a minimum field of 3.38kG and “V” type a minimum field of 5.3kG. Using expression (1), one can predict that the demagnetizing temperatures for “H” and “V” blocks should be close to 125^{0} C and 148^{0} C respectively.

Results of the demagnetizing temperature measurements are depicted in Fig. 3. Each point represents the change in magnetic moment of the blocks caused by the baking out cycle at different temperatures. The baking out time was ~30min, magnetic moments were measured with Helmholtz coils apparatus at room temperature before and after each cycle. The baking temperature is shown on horizontal axes, open circles show data for "H" block, solid squares are for "V" type.

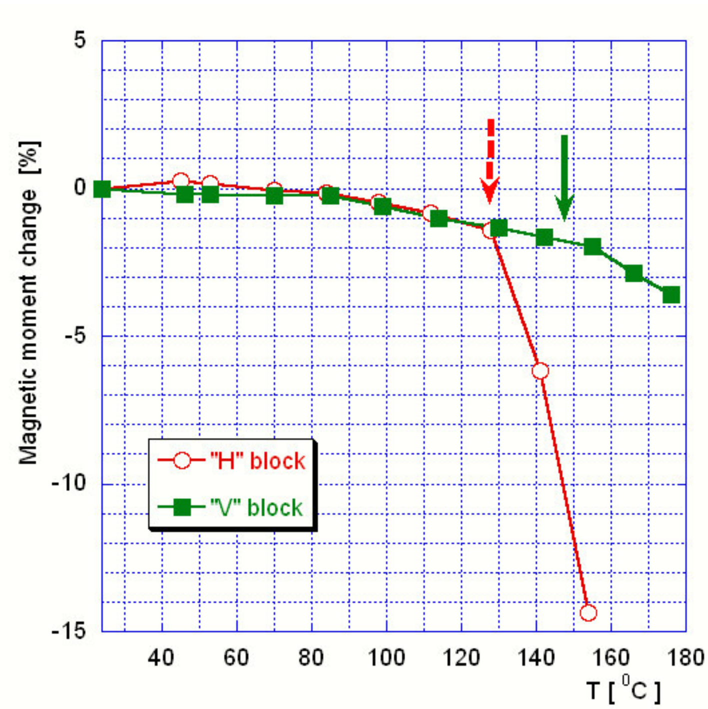

Figure 4. The measured dependence of irreversible demagnetization on temperature for "H" (open circles) and "V" (solid squares) blocks. Arrows show predicted demagnetizing temperature.

Dashed and solid arrows show the predicted demagnetizing temperature for "H" and "V" blocks respectively. In "H" block data there is obvious "knee", which indicates a demagnetizing temperature close to 128^0 C. This is in good agreement with predicted 125^0 C, see dashed arrow. In the "V" block data the knee is not so apparent. At the point corresponding to 155^0 C baking temperature one can see the small change in slope, which can be the indication of the irreversible demagnetization. This temperature is slightly higher than predicted. But taking into account the possible errors in magnetic moment measurement (+-0.2%) and in baking temperature (+-2^0C) the agreement with predicted 148^0 C , see solid arrow, can be considered as satisfactory.

This simple experiment proved that the baking temperature limit, which is in fact the demagnetization temperature, can be reliably predicted with few degrees precision from magnetic material demagnetization curves and accurate magnetic field calculation.

Prediction of the baking temperature limit for magnetic array.

The tested magnetic array consisted of 48 rectangular PM blocks made of NdFeB of N40SH grade from Stanford Magnets Company. Blocks had dimensions 1.0x0.5x0.125" and were magnetized in 0.5" and in 0.125" direction. Magnetic field for two periods of the magnetic array calculated with program POISSON is shown on left plot in Fig. 5. Here arrows indicate direction of the PM block magnetization, the gap side on the bottom. From the plot one can identify the critical regions with strongest demagnetizing field, i.e., with minimum field in the direction of magnetization. These are at the bottom of horizontally magnetized blocks. Here one can see a minimum of line density, and at the corners, direction of the magnetic lines is perpendicular to magnetization. Plot on the right side is a result of 3D magnetic field modeling with "Vector Field" software. It shows dependence of horizontal magnetic field at H-block bottom on position along assembly. The ends of the horizontal axes correspond to H-block corners. The data indicate -800G magnetic field there. Negative sign means the field is opposite to magnetization. For this field, expression (1) gives demagnetizing temperature 77^0C.

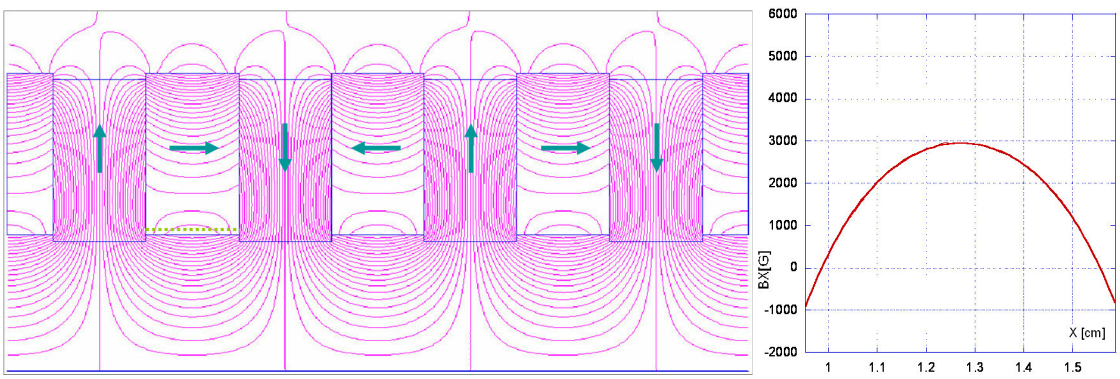

Figure 5. On left magnetic field lines for two periods of magnetic array. Right plot is horizontal magnetic field inside of "H" blocks at cross section marked by dotted line in left plot.

This temperature limit is certainly too low for effective baking out..

One obvious way to increase the temperature limit, i.e., decrease demagnetizing field would be switching to "less aggressive design". Calculation shows that reduction of PM block height from 0.5" to 0.25" results in the change of magnetic field at the "H" block corners from -800G to 1000G. It, in turn, results in the increase of baking temperature limit from 77^0C to 98^0C. A negative side effect of this change is the reduction of magnetic field in undulator gap. In a 4mm gap the field will be reduced from 12.8 to 10.7kG.

Another way to decrease demagnetizing field, i.e., increase the baking temperature limit, is a temporary redistribution of the magnetic field for the baking out period. The left plot in Fig. 6 shows the magnetic field for the magnetic array with a steel plate attached at the bottom. This plate redistributes magnetic field in such a way that regions with minimum horizontal magnetic field in "H" blocks move closer to block centers and the minimum field strength increases to 3380G - see plot on right side. For this field, according to expression (1), demagnetization temperature should be 125^0C.

Thus the effect of the steel plate attachment is the temperature limit increase from 77^0C to 125^0C. It is assumed that after baking out steel plate should be removed.

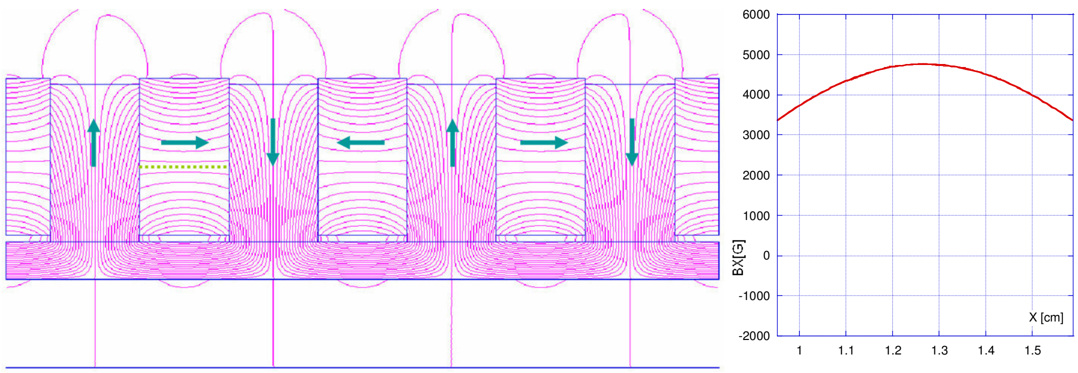

Figure 6. On left magnetic field lines for one half of magnetic assembly with attached iron plate. Right plot is horizontal magnetic field inside of "H" blocks at cross section marked by dotted line in left plot.

During the baking described in the following section, a steel plate of 0.125" thickness was attached to the magnetic array as it is shown schematically in Fig.6. To be on the safe side the baking temperature was chosen to be 120^0C, which is slightly lower than the predicted limit.

Undulator model baking result.

For the baking out procedure, 30cm long magnetic array, see picture in Fig.7, with 0.125" thickness steel plate attached to the top was placed in cylindrical vacuum vessel of 11.1 liter volume, see Fig.8. The vessel has been pumped with turbo-pump, residual gas pressure was measured with cold cathode gauge and RGA apparatus was used for the residual gas content analysis.

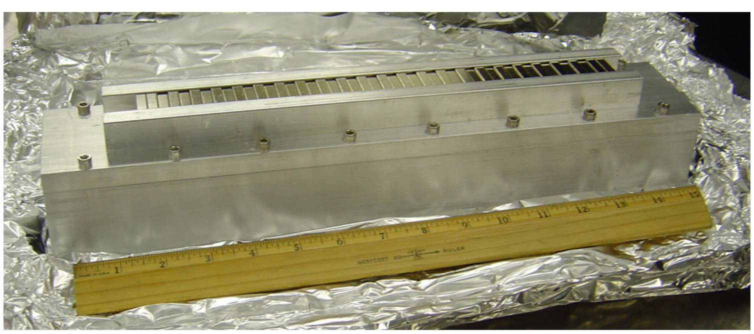

Figure 7. Magnetic array used in the test.

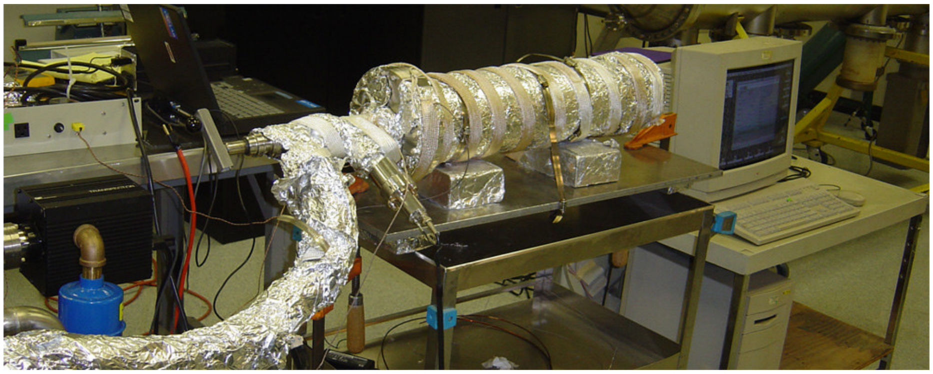

Figure 8. Vacuum vessel prepared for baking out.

The temperature profile during baking is shown in Fig.9. There was a 10hr temperature ramp from room temperature to 120^{0}C, then 48hr dwelling and ~10hr ramp back.

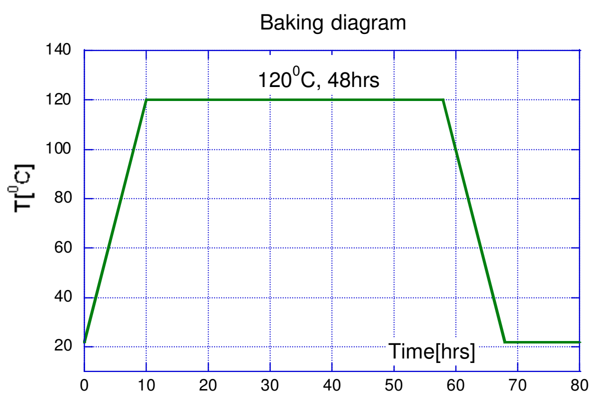

Figure 9. Temperature dependence on time during baking out procedure.

After-baking magnetic properties.

After the baking out was completed and steel plate removed, the magnetic field of the baked array was measured using a Hall probe and compared with the magnetic field of the second, identical not-baked unit. With 2% measurement precision, there was no observable PM material demagnetization and the magnetic field change. Note that without steel plate 120degC baking would certainly cause demagnetization of "H" blocks.

After-baking vacuum related properties.

The residual gas pressure measured with cold cathode gage was reduced during the baking from 10^4 nT in the beginning to 2nT at the end, see plot in Fig.10.

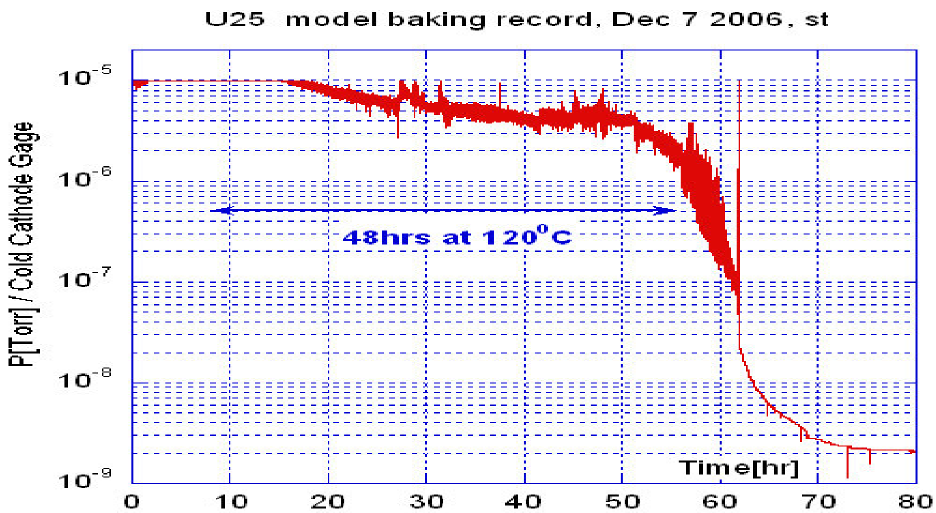

Figure.10 The pressure record.

After the baking was completed and assembly cooled down to room temperature, we measured outgassing rate and outgassing gas spectra. For that, we stopped pumping by closing the valve on vacuum line connecting vessel with pump and measured the rate of the pressure rise. One example of the data is shown in Fig.11.

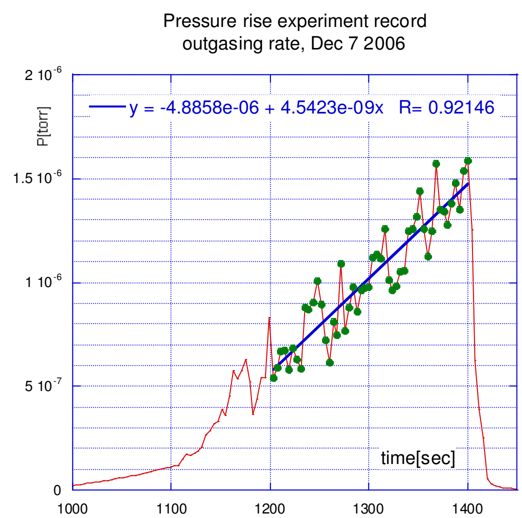

Figure 11. Example of the pressure rise when vacuum pumping was stopped. At time corresponding t = 1400sec, pumping was resumed.

The data linear fit gives the pressure rise rate:

$$P' = 4.5 nT / \sec$$

For 11.1 liter of vacuum vessel volume it gives an outgassing rate:

$$Q_{array}' = 4.5 \cdot 11.1 = 49.95 nT \cdot liter / \sec$$

The outgassing rate of the full undulator structure consisted of two arrays, per unit length will be:

$$Q_{und}' = 2 \cdot \frac{49.95}{0.3} = 333\, nT \cdot liter / \sec / m$$

This number means that to provide required, say 10nT or lower, pressure one should design vacuum system with pumping capability of

$$S = \frac{Q}{P} = 33\, liter / \sec / \, m$$

or higher.

The outgassing gas spectra measured with RGA apparatus is shown in Fig.12. The highest peak is at AMU = 2 corresponding to H2 and a group of peaks of two order magnitude lower are around AMU = 16 and AMU = 26. The possible peak identification is shown on plot.

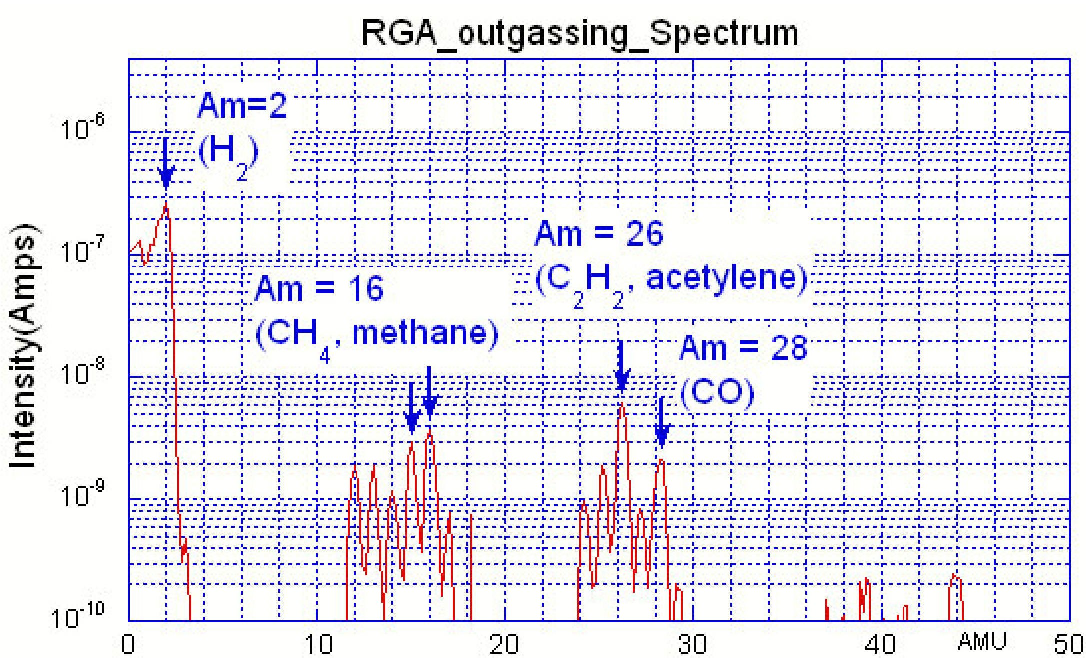

Figure 12. RGA spectrum

Percentage of the residual gas contents extracted from the RGA spectra is shown in form of the "pie" diagram in Fig. 12.

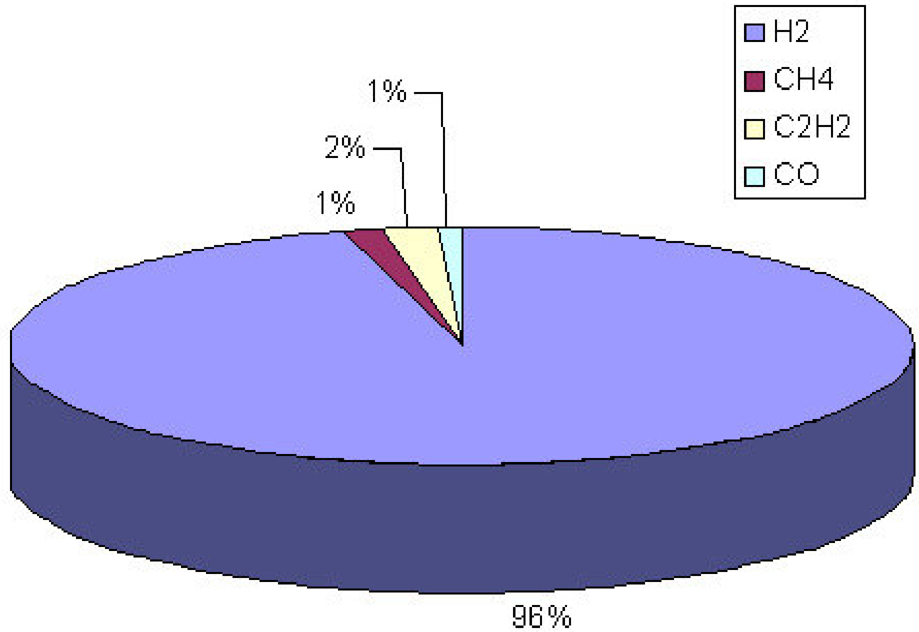

Figure 12. “Pie” diagram of the residual gas contents.

Here one can see that 96% of the residual gas is a molecular hydrogen, so the vacuum system should be designed to provide effective pumping of this species.

Conclusions

Experiments with single PM blocks confirmed that the baking-out temperature limit can be reliably predicted from the PM material demagnetization curves for different temperature and accurate magnetic field calculation.

It was shown in calculation and confirmed in practice baking out that the attachment of the steel plate to the magnetic array for baking period can significantly increase demagnetization temperature limit. This method makes possible to use more aggressive design for in-vacuum IDs with higher magnetic field in gap.

The measured outgassing rate of the baked magnetic array scaled to full undulator was $333\ nT \cdot liter/\sec$ per meter length with 96% of hydrogen (H_2). This number can be used for the design of the vacuum system of in-vacuum IDs.

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