Model 4 Tesla Diople Magnet
toward Final Focus Quadrupole

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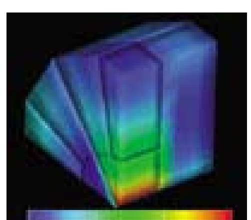
Abstract

- A model permanent magnet exceeding 4 Tesla was recently designed, manufactured and measured. This field level was only achievable by a superconducting magnet or a pulsed high current coil magnet. A modified Halbach magnet'concept is introduced to increase the field strength.
- Cooling the permanent magnet to Liquid Nitrogen temperature further enhance the field.
- The high field DC magnet can be used in a cyclic accelerator or in a Final Focus Quadrupole magnet in Linear Collider.



A new development in Japan that enables powerful magnetic fields to be obtained without using expensive electromagnets could open the door to smaller, special-purpose particle accelerator installations.

While particle accelerators were invented to supply the high-energy beams needed to pierce through nuclear barriers and see the subnuclear world, most of the accelerators now in use are low-energy machines used for a variety of applications, such as radioisotope production, cancer therapy and ion implantation.

In high-energy machines that take beams into the relativistic regime, the magnetic fields have to vary and pulsed electromagnets are the norm.

However, for lower-energy machines and for special-purpose magnets, it can be more economical to use permanent magnets instead, with no requirement for attendant power supplies, cooling or special cryogenics.

This idea was pioneered by Klaus Halbach at Berkeley, who in the late 1970s introduced permanent magnets as "wigglers" and "undulators" to generate synchrotron radiation from a captive high-energy electron beam. The magnetic material of choice was initially a rare-earth/cobalt alloy. Permanent magnets are also used in Fermilab's Antiproton Recycler ring (*CERN Courier* July p16).

Motivated by the need to design compact machines to provide beams for cancer therapy, a team from Japan's National Institute of Radiological Sciences, led by Masayuki Kumada, collaborated with Sumitomo Special Metals to produce a scaled-down, prototype permanent magnet to achieve the required magnetic fields of greater than 4 tesla. So far such fields have only been achievable with large superconducting magnets.

Using suitable magnetic materials such as samarium cobalt, the maximum field that can be attained is about 2 tesla normally. The Halbach-type designs improved on this by using a geometry that effectively amplifies the interior field.

The key innovation in the new idea is to use a saturated iron pole in the magnetic circuit of the permanent magnet to introduce a higher residual field, to compress the magnetic flux, and to weaken the demagnetizing field. Fields of up to 4.45 tesla have been attained when cooled to -25–C (at room temperature the field was 3.9 tesla). With these fields, a machine for handling hadrons (nuclei) for cancer therapy would be less than half the diameter of current machines. The team has begun work on a permanent magnet cyclotron. Another possible application would be high-energy hadron colliders with small beams.

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1. Introduction

- Myth of Permanent magnet(PM):
- Weak field(half of Br)
- Expensive (Nd material)
- Unstable(temperature dependence)
- Small magnet
- Fluctuation in magnetization

Challenge to Schleuter' advantage of PM

- Strongest fields when small
- Compact
- Imersible in other fields
- Analytical material
- No power supplies
- No cooling
- No energy bill

Progress at Fermilab Recycler

- Temperature compensation
- High homogeneity
- Less expensive(ferrite magnet)
- - but low field

Other Progress and Future Direction

- 250T/m Q mag(1985)
- 3 Tesla wiggler U.tokyo(1998)
- MRI

  (large, several kG,

  stable and accurate)

- 4.45 Tesla at NIRS
- PM cyclotron
- PM FFAG
- Variable field PM

  (PM synchrotron)

Final Focus Quadrupole

2. HIGH FIELD Permanent Magnet

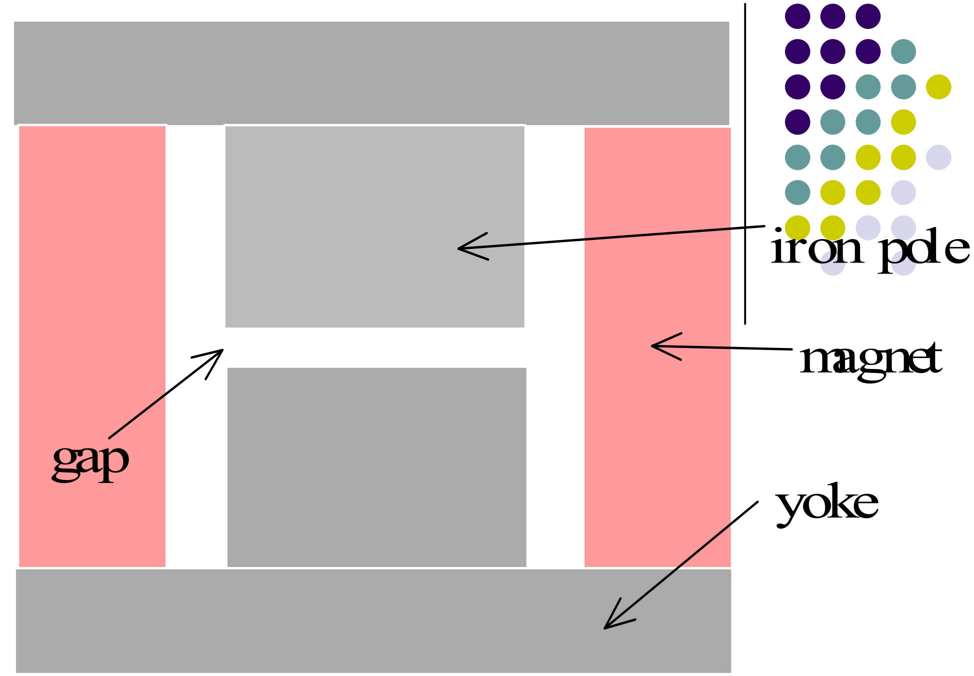
- Neomax $B_{residual}$=1.2 T
  while B_{gap}=0.6 T
  Why so low?
- How can we exceed $B_{residual}$
  In gap field?

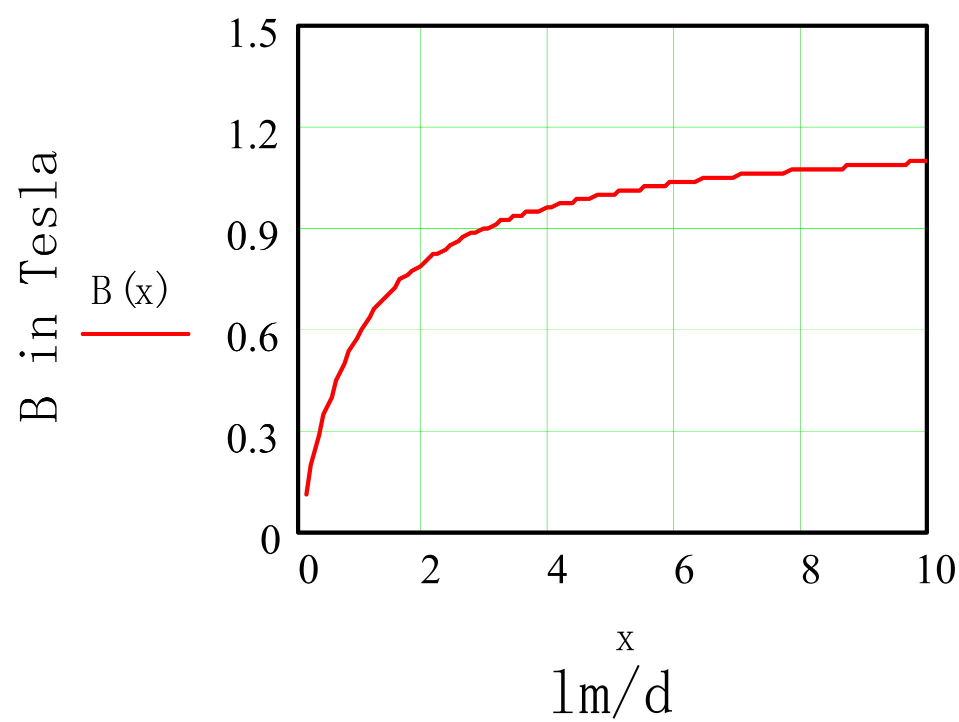
Conventional PM

- Field strength in the gap

$$B_g = \frac{l_m}{l_m + d}\mu_0 H_c$$

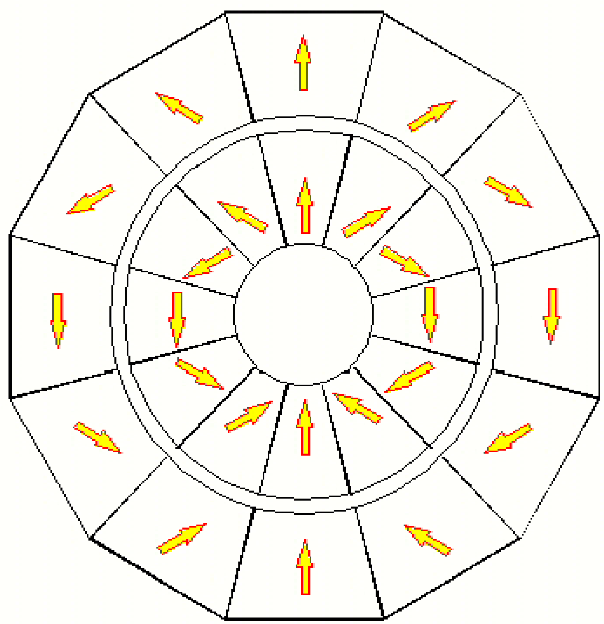
$$\approx \frac{l_m}{l_m + d} B_r$$



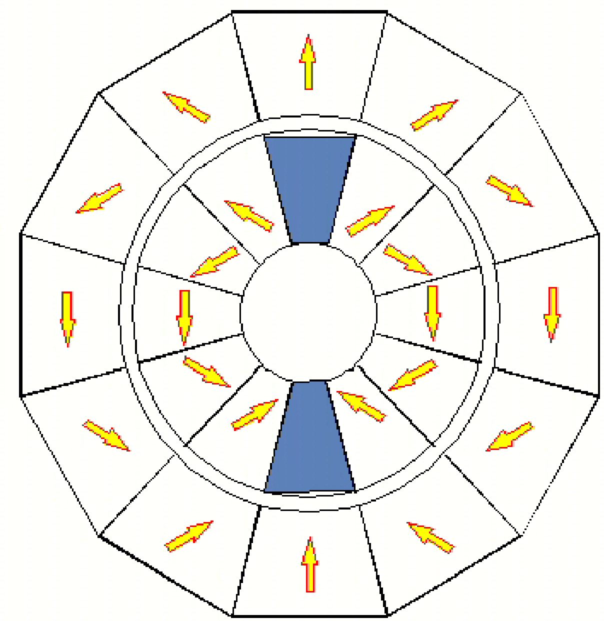


K.Halbach discovered:

$$B_g = B_r l_n \left(\frac{r_2}{r_1} \right)$$



•Halbach circuit



•Our new scheme:

•Extended Halbach circuit

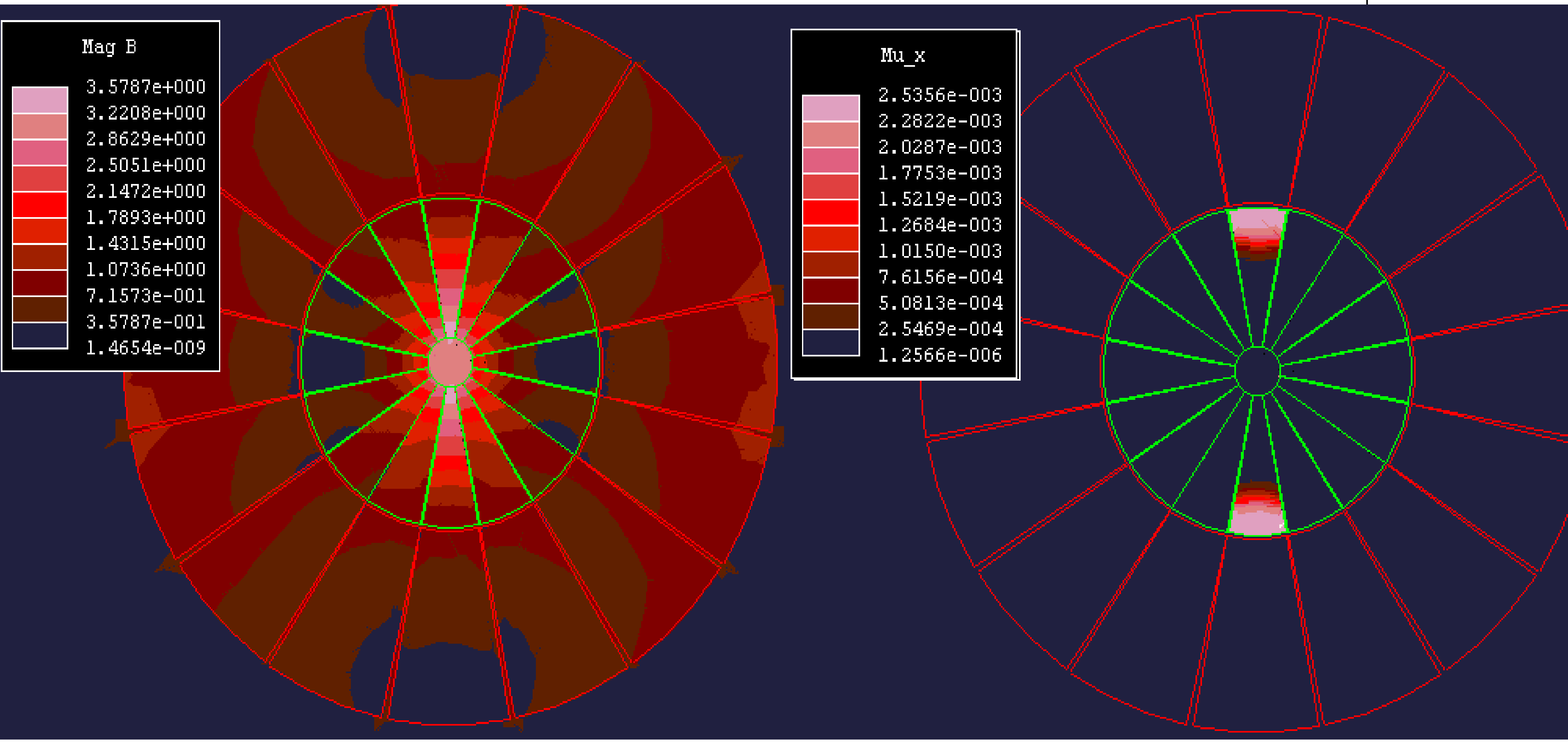
Saturated iron

$$B_g \approx \frac{B_r l_m + \frac{l_i}{\mu^*} B_{s0}}{d + \frac{l_i}{\mu^*}\frac{S_g}{S_i} + l_m \frac{S_g}{S_m}}$$

- **Saturated iron** – contrast to common sense
- Flux compression by partial non-saturated iron
- You may not believe:
- **iron pole is stronger that PM pole!!!**

- Note demagnetization effect.
- Two layer magnet(strong H_c, strong B_r))

Saturation Inside/ Non-saturation Ouside



Model 4 Tesla Dipole Magnet

- Choice of inner radius of 3 mm and outer radius of 100 mm of 1.2 Tesla NEOMAX should generate 4.2 Tesla dipole field. The length is 150 mm. By simple scaling, inner diameter of 30mm, the outer diameter must be 1 meter for this field level. This size could be greatly reduced if the magnet is operated in liquid nitrogen temperature.

Operation at room/cool temperature

- Ex.1 Neomax-50CR

Temp (K)	B (T)	H_{cB} (MAm-1)	$(BH)_{max}$ (kJm^{-3})	H_{cJ} (MAm^{-1})
5	1.52	1.17	429	6.18
77	1.45	1.08	396	5.43
296	1.25	0.91	295	1.13

- Ex. 2 more new materials

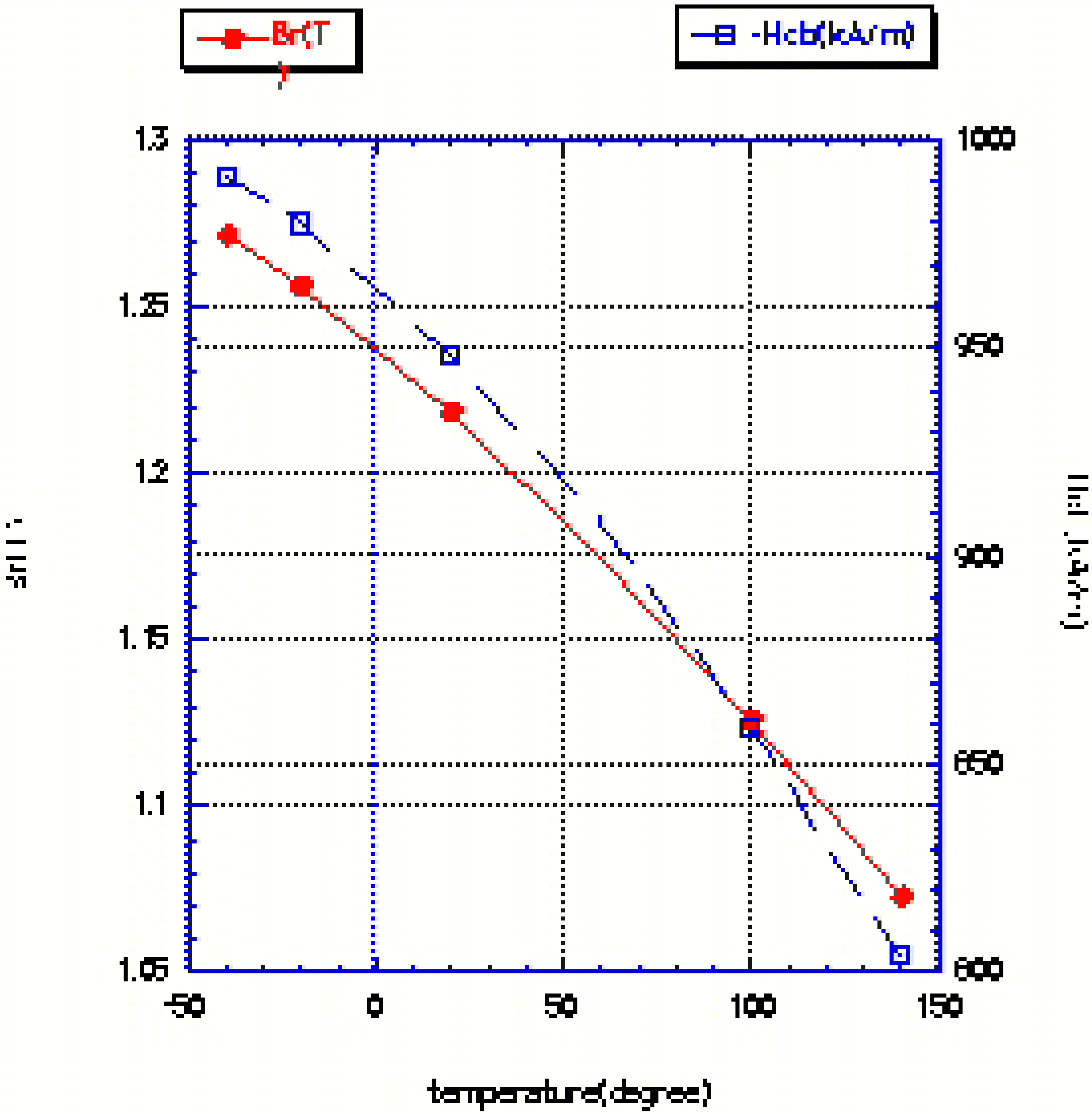
- At 77K

material	Pressing method	B_r (T)	$(BH)_{max}$	H_{cB}
Neomax-53CR	Vertical magnetizing	1.49	53.3MGOe	14.3kOe
Neomax-50CR	Parallel magnetizing	1.45	49.7MGOe	13.7kOe

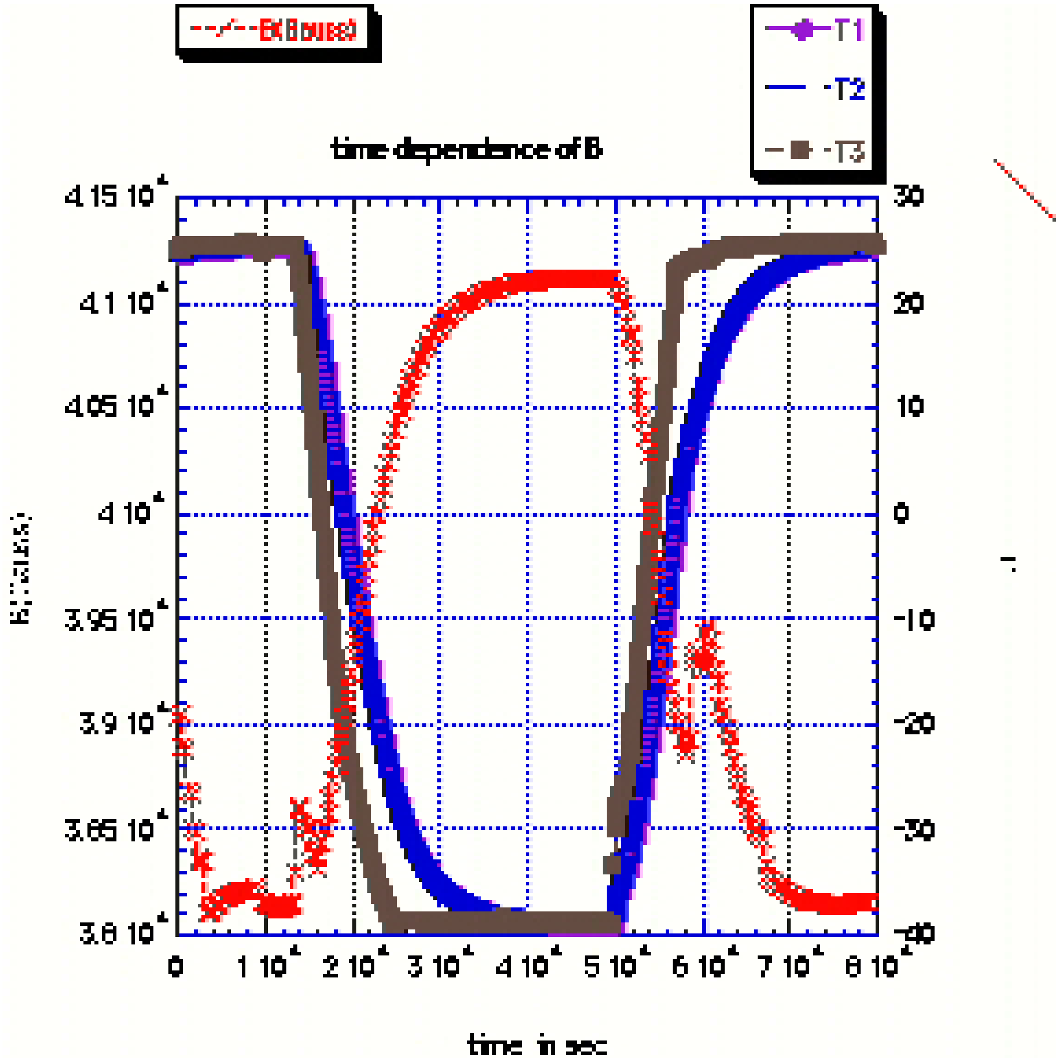
- Ex. 3 more new materials

material	Br(T) at room temperature	Br(T) at liquid temperature
$Nd_2Fe_{14}B$	1.6	1.86
$Pr_2Fe_{14}B$	1.56	1.83

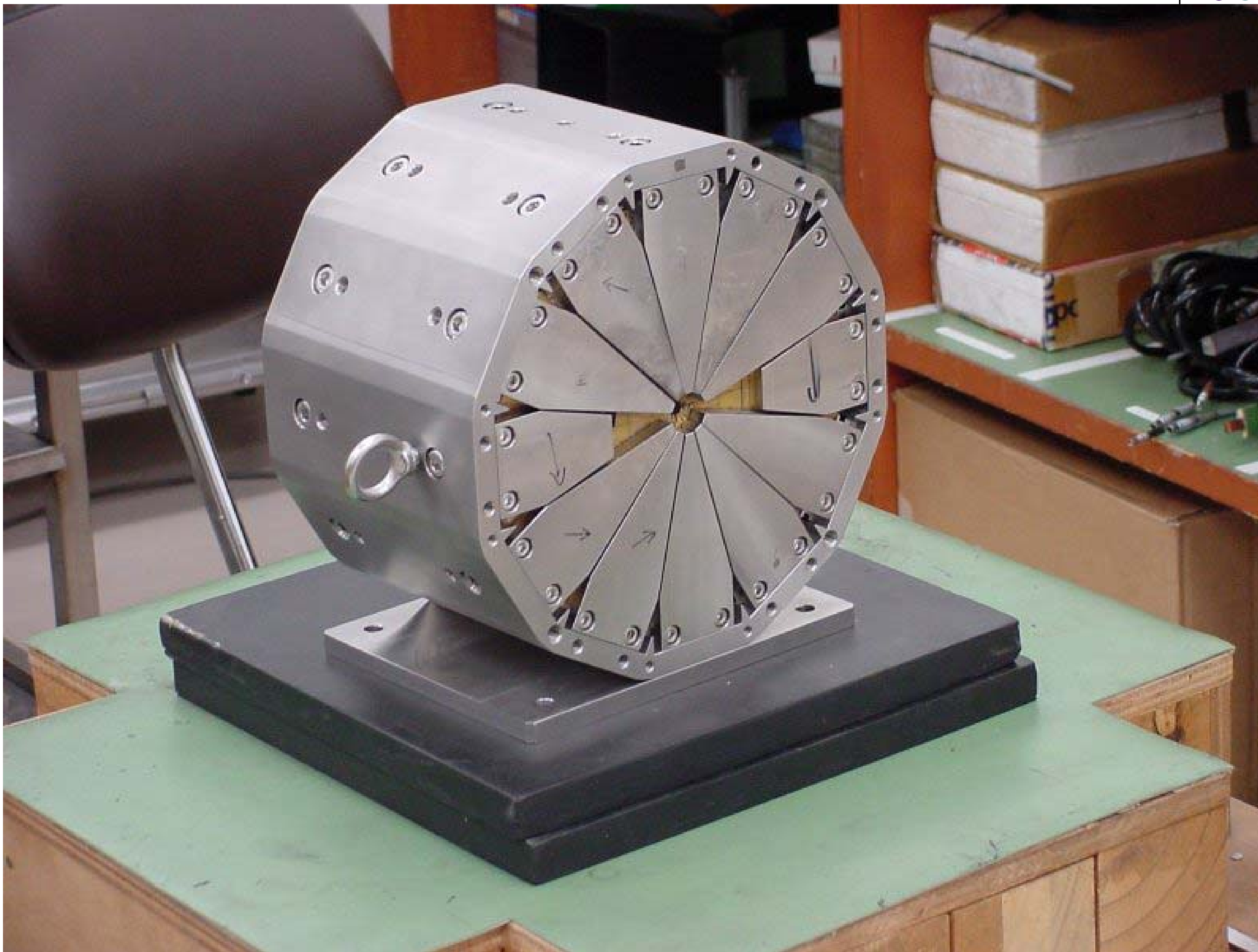
B_r gets stronger with cool down



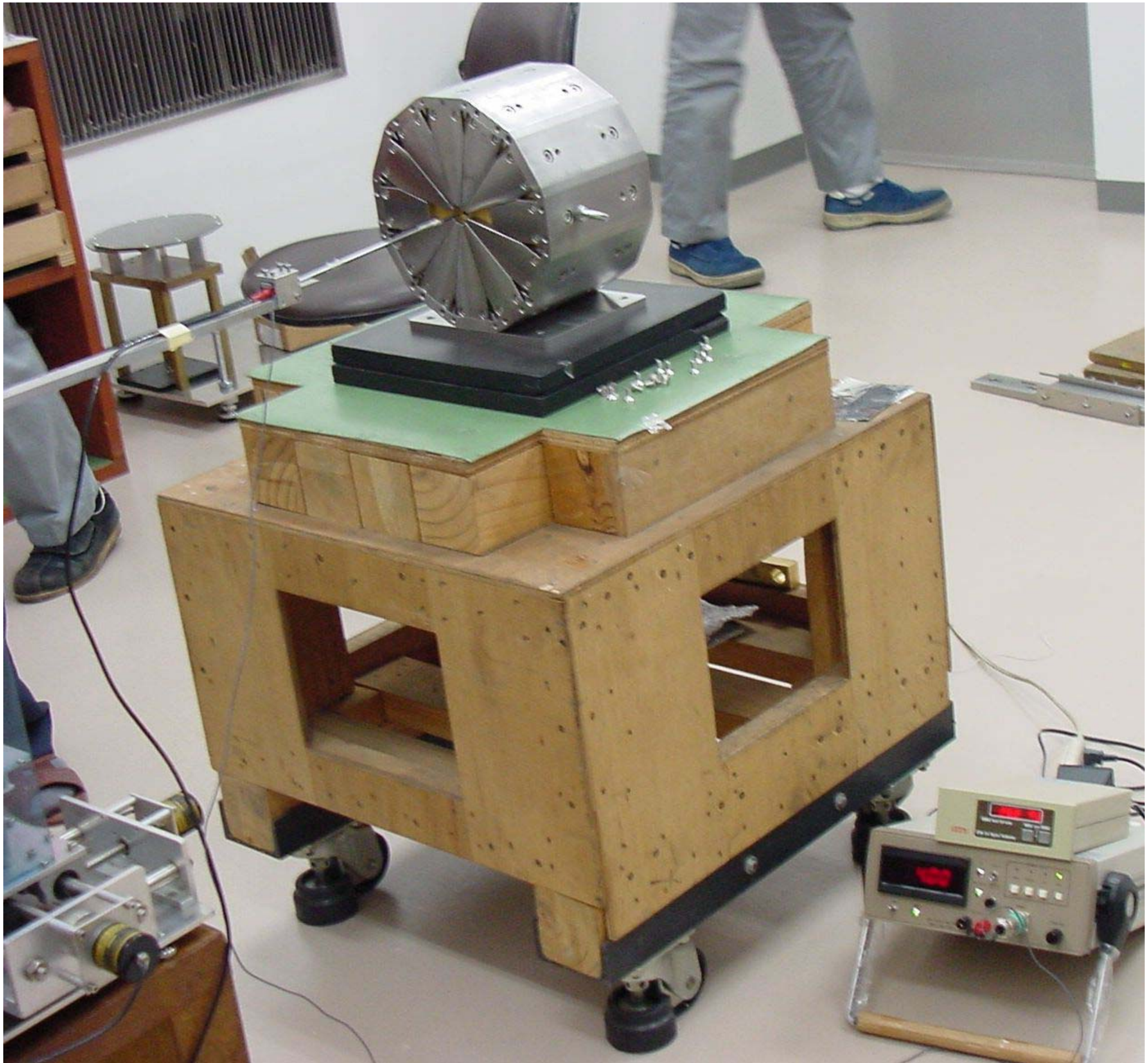
Varying field PM with temperature



4.45 Tesla PM

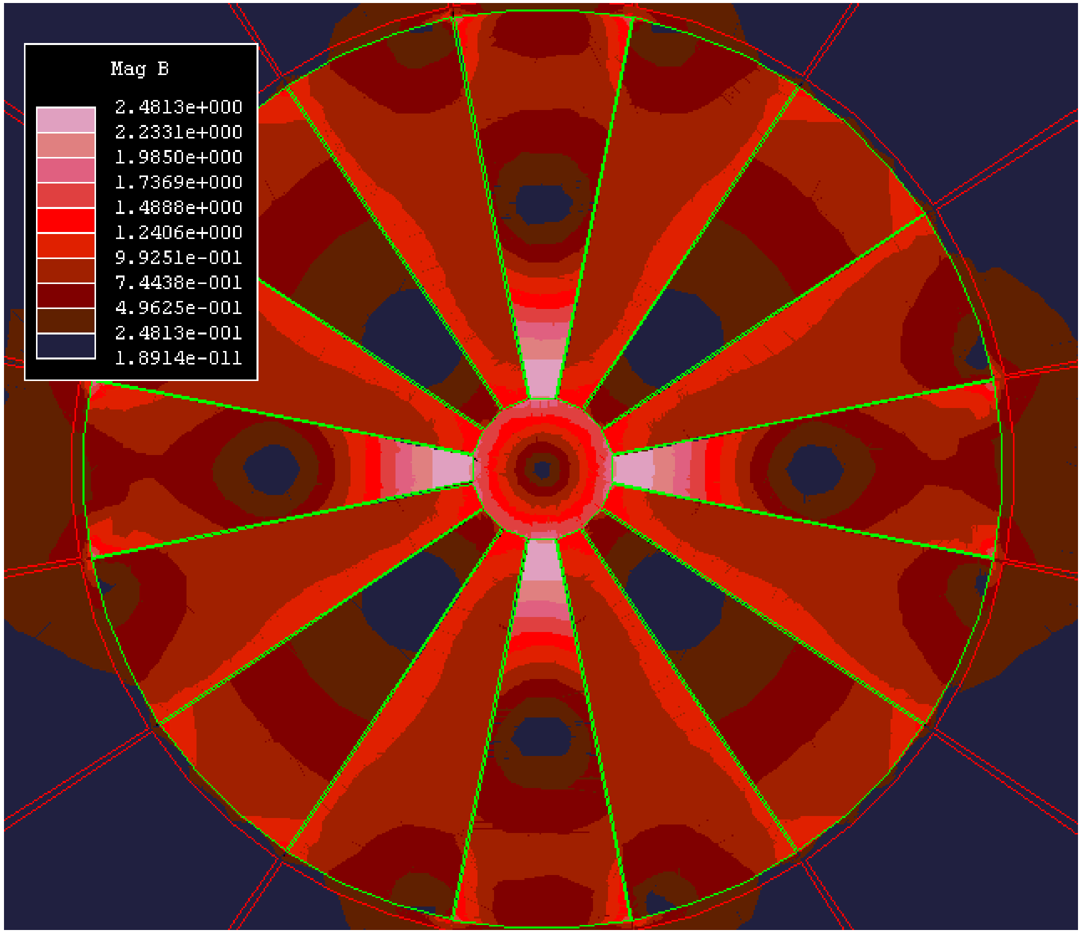


Measurement of 4.45T PM



2 layers variable magnet adjustable by 10% with magnetic axis fixed

Quadrupole


Mag B
2.4813e+000
2.2331e+000
1.9850e+000
1.7369e+000
1.4888e+000
1.2406e+000
9.9251e-001
7.4438e-001
4.9625e-001
2.4813e-001
1.8914e-011

Conclusion

- PM can be stronger than 4 Tesla
- By Saturated iron(Extended Halbach)
- Cool PM can open new applications
- Highest field gradient for final focus Quadrupole possible

Latest information at apac01

5 tesla wiggler magnet

(5T non superconducting wiggler)

Another Magnet in Magnet in progress

Conception by Evgeny I.Antokhin(Budker Institue of Nuclear Physics,WEP010,apac01)

Acknowledgement

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