Permanent Magnet Diploes and Quadrupoles for FFAGs

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Outline

(1) Permanent Magnet Overview

(2) Some Design Considerations

(3) Radiation Effect

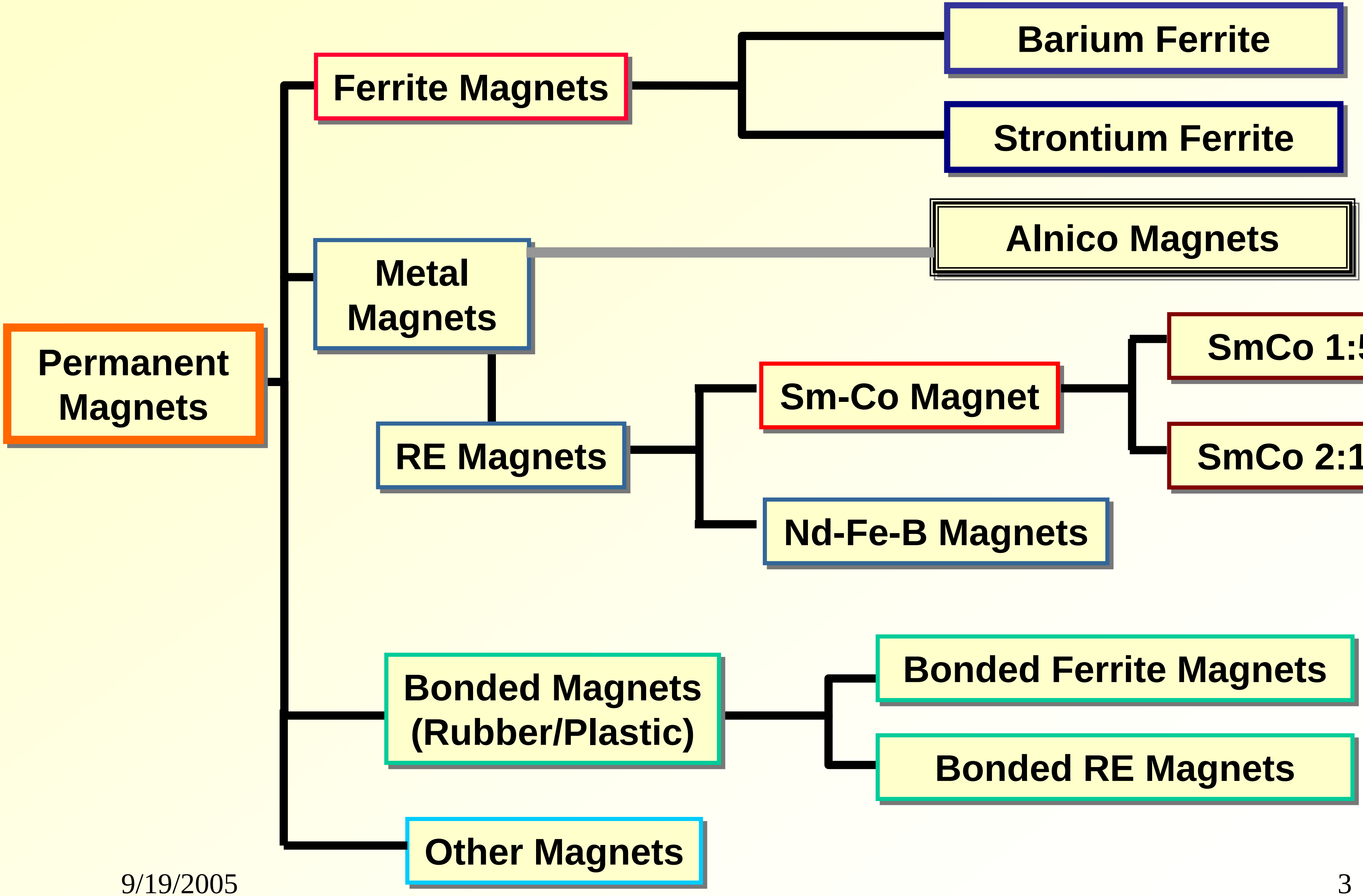
(4) Permanent Magnet Dipoles

(5) Permanent Magnet Mangles

(6) Permanent Magnet Quadrupoles

(7) Summary

Types of Commercial magnets



Permanent Magnets

Ferrite Magnets

Barium Ferrite

Strontium Ferrite

Metal Magnets

Alnico Magnets

RE Magnets

Sm-Co Magnet

SmCo 1:5

SmCo 2:17

Nd-Fe-B Magnets

Bonded Magnets (Rubber/Plastic)

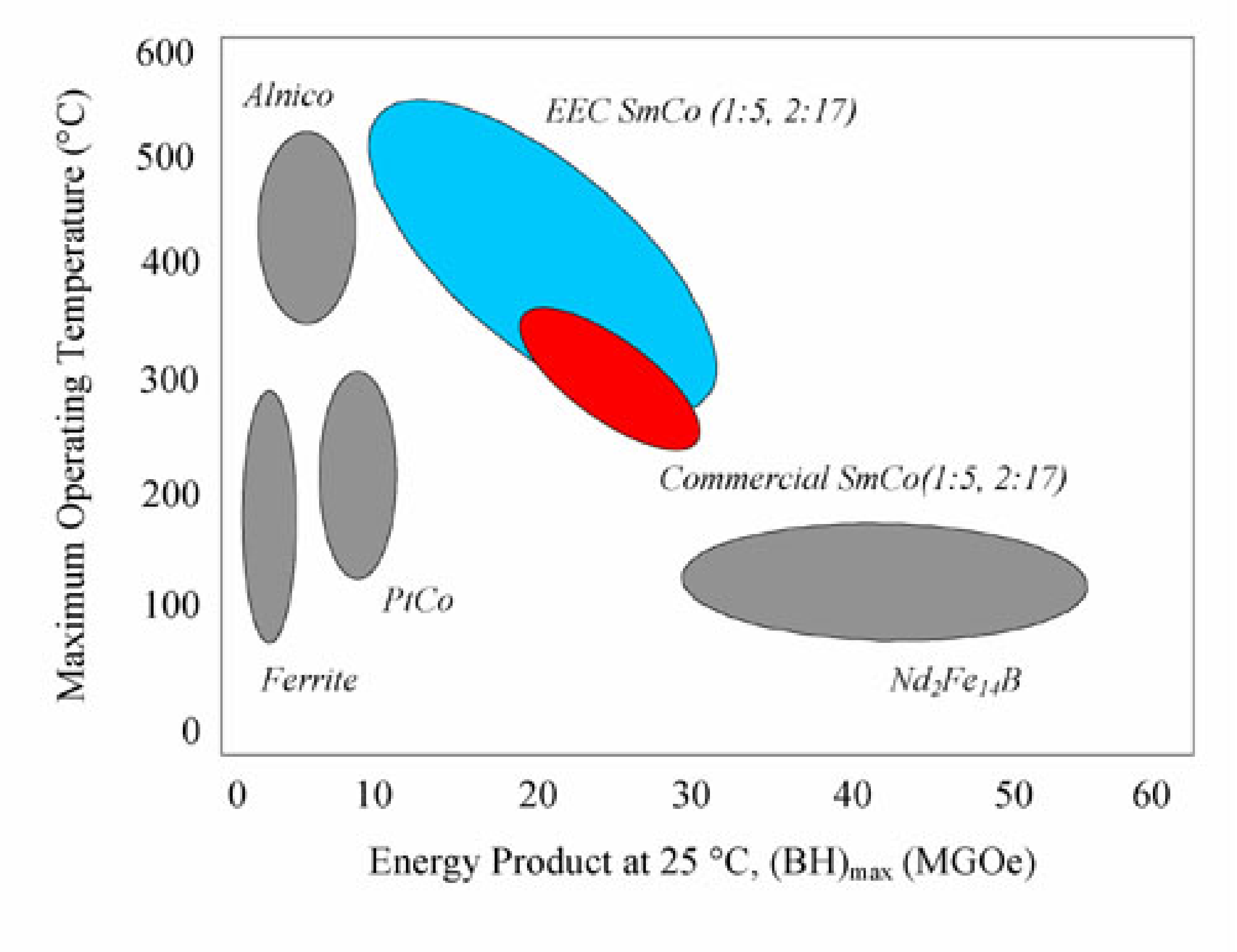
Bonded Ferrite Magnets

Bonded RE Magnets

Other Magnets

$(BH)_{max}$ versus Maximum Operating Temperature

Overview



Permanent Magnet Selection

Some factors to consider:

(1) Magnetic performance
(2) Corrosion resistance
(3) Thermal stability
(4) Radiation resistance
(5) Magnetization direction
(6) Manufacturability
(7) Cost

Permanent magnets --- properties comparison

Typical magnetic properties, in terms of energy product, of selected commercial magnets:

- ✓Sintered Nd-Fe-B magnets: up to 50 MGOe
- ✓Sintered Sm-Co magnets: up to 32 MGOe
- ✓Isotropic bonded Nd-Fe-B magnets: up to 10 MGOe
- ✓Sintered ceramic magnets: up to 4 MGOe
- ✓Cast Alnico magnets: up to 9 MGOe

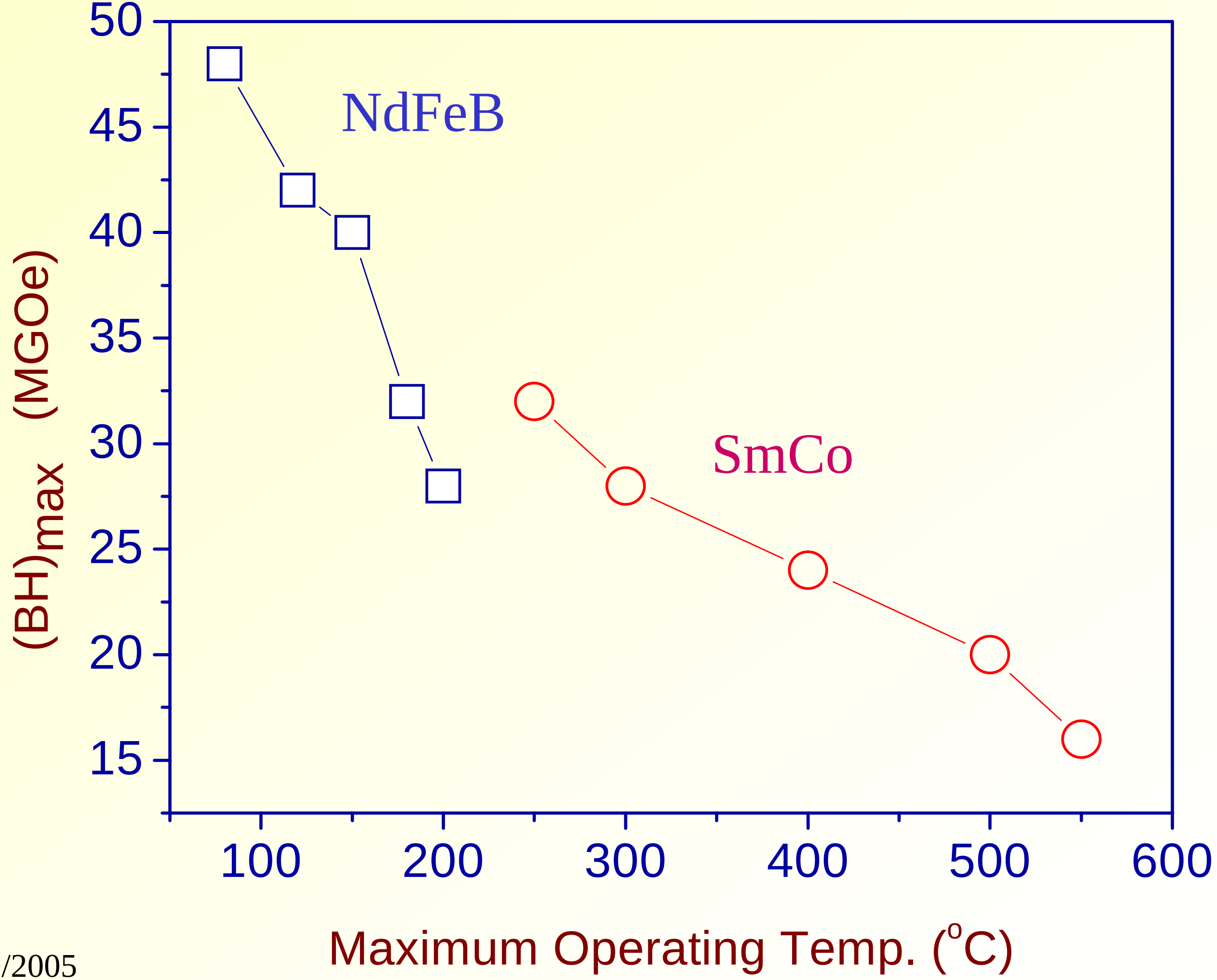
Rare Earth Magnets

Maximum operating temperature of sintered magnets

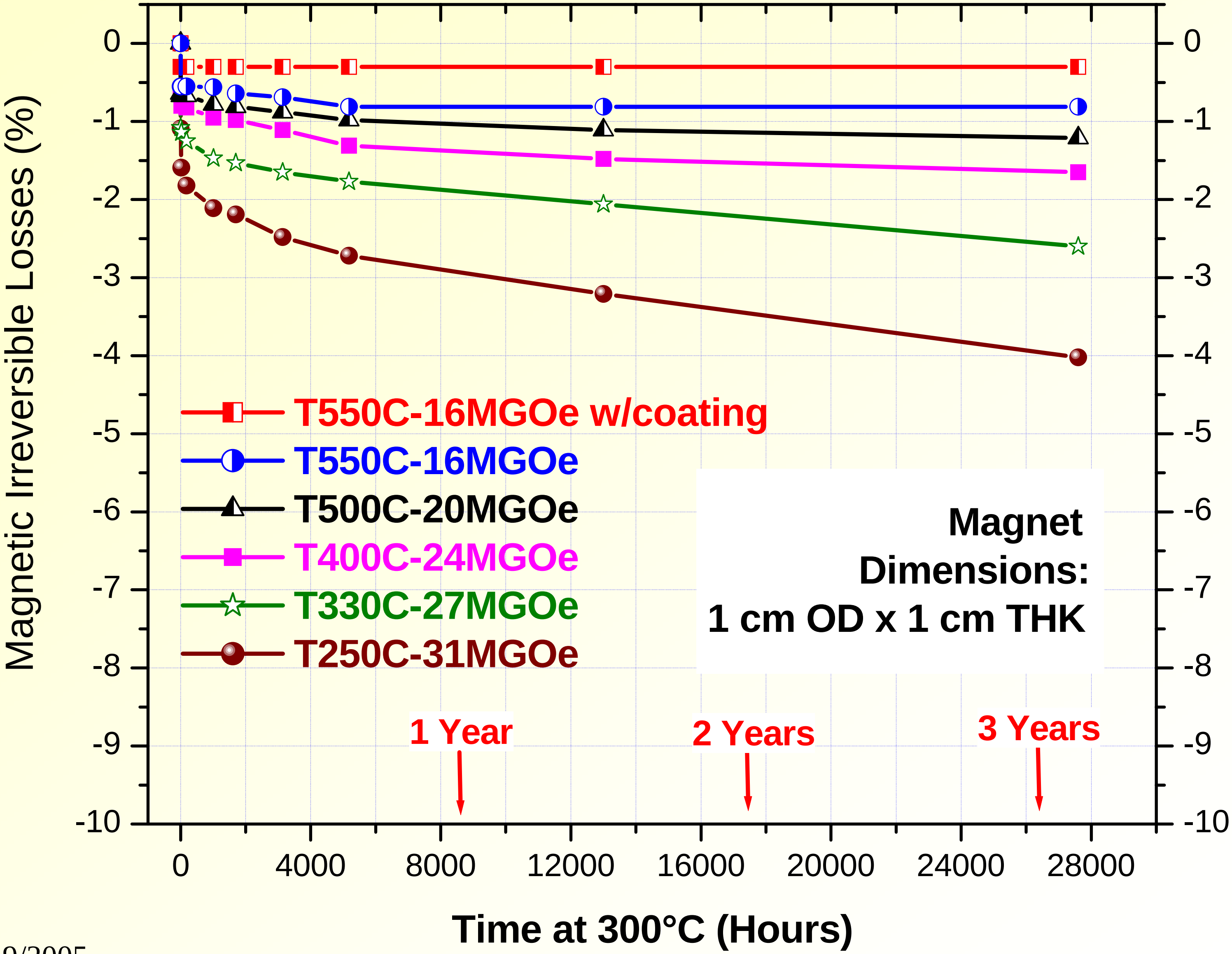
Magnets	Maximum Operating Temp.*
NdFeB with ${}_iH_c$ =12 kOe	80°C
NdFeB with ${}_iH_c$ =17 kOe	120°C
NdFeB with ${}_iH_c$ =20 kOe	150°C
NdFeB with ${}_iH_c$ =25 kOe	180°C
Conventional SmCo magnets	300°C
EEC24-T400 magnets (patented & available)	**400°C**
EEC20-T500 magnets (patented & available)	**500°C**
EEC16-T550 magnets (patented & available)	**550°C**

Rare Earth Magnets --Properties vs. Temperature

$(BH)_{max}$ Versus Maximum Operating Temperature



Long-term Thermal Stability of SmCo Magnets at 300°C in Air



Magnet Dimensions: 1 cm OD x 1 cm THK

High temperature magnets

- DoD initiated the More Electric Aircraft program, which requires magnets with maximum operating temperature more than 400°C
- Funded by the Department of Defense, a series of sintered SmCo 2:17 magnets were developed at EEC with maximum operating temperature as high as 550°C
- These patented SmCo UHT magnets were introduced to the industry in 1999.

SmCo Rare Earth Magnets

PM Grades	B_r (kG) (kG)	$(BH)_{max}$ (MGOe)	Max. operating temp (^oC)
EEC2:17-31	11.6	31	250
EEC2:17-27	10.8	27	300
EEC24-T400	**10.2**	**24.5**	**400**
EEC20-T500	**9.3**	**21**	**500**
EEC16-T550	**8.6**	**17**	**550**

Nd-Fe-B sintered magnets

Key features:

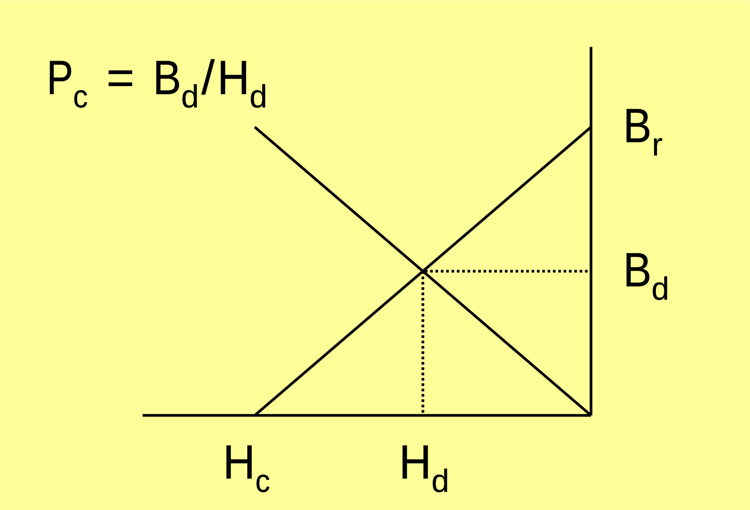
- Highest $(BH)_{max}$ available (up to 50 MGOe)
- Less expensive than Sm-Co magnets
- Corrosion resistance is not good
- Special coating is required
- Maximum operating temperature is very low compared to SmCo magnets

Nd-Fe-B Type Rare Earth Magnets

PM Grades	B_r (kG) (kG)	$(BH)_{max}$ (MGOe)	Max. operating temp (°C)
N50	14-14.5	48-51	70
N45	13.2-13.8	43-46	70
N45M	13.2-13.6	43-46	100
N42SH	12.8-13.2	40-43	120
N33UH	11.3-11.7	31-34	180

Some Design Considerations

Permeance Coefficient P_c

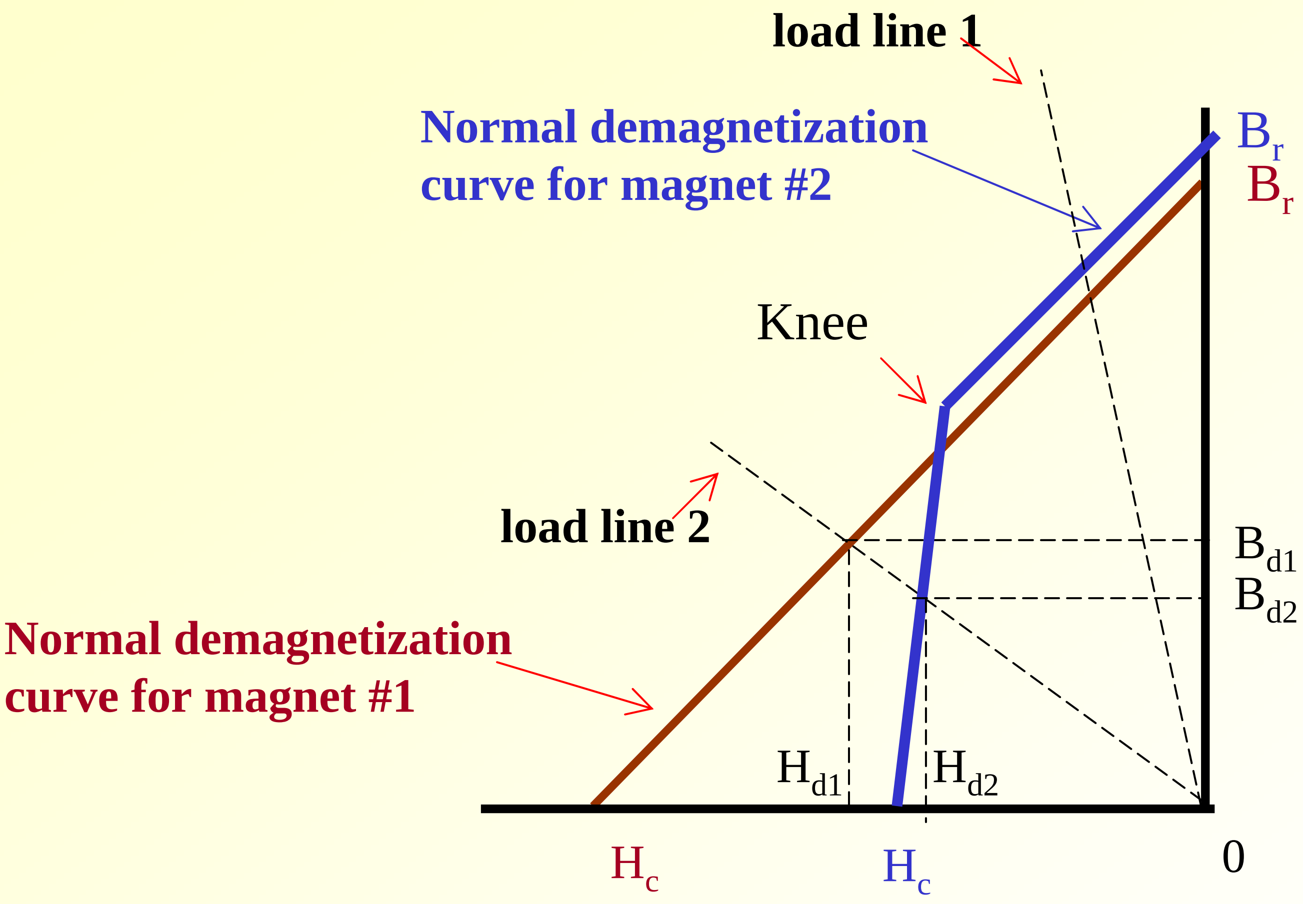


In the magnetic circuit, a magnet will operate at a specific point on its extrinsic demagnetization curve:

$$P_c = B_d/H_d$$

- Also known as **load line** or **operating point**
- It is related to the dimensions of the magnets and the associated magnetic circuit

Why straight-line demagnetization curves?



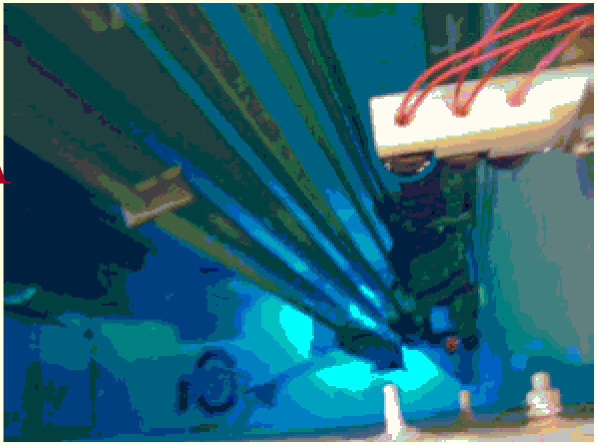
Application with load line #1: Both magnets are okay to use

Application with load line #2: Only magnet #1 is suitable

Radiation Effect

The effects of radiation on permanent magnets was studied at EEC under a NASA STTR Contract

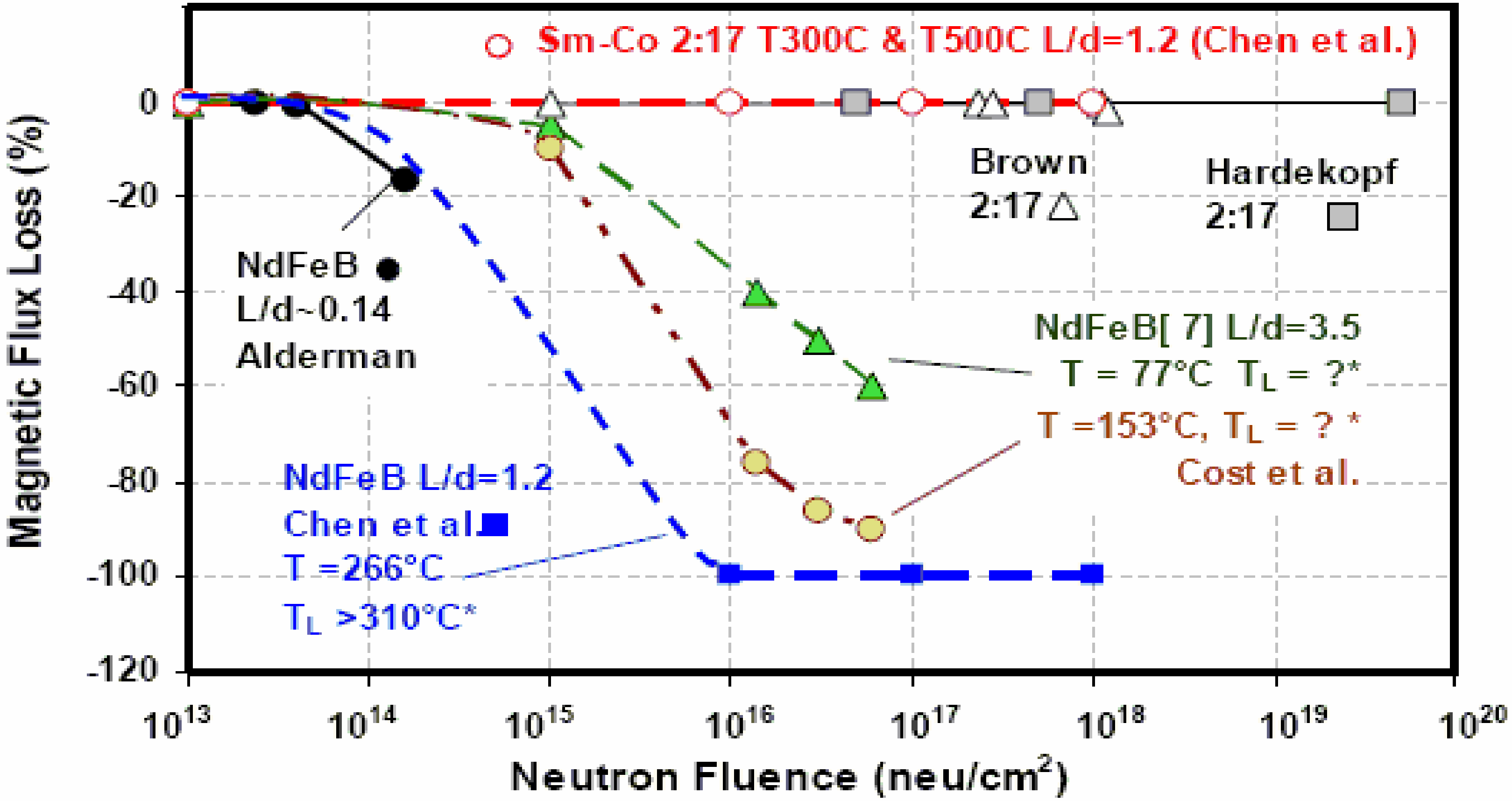
- All Samples have a L/D ratio of 1.25
- Permanent Magnets Studied:
  - EEC T500 and T300 SmCo 2:17 magnets
  - Nd-Fe-B Magnets
- Radiation Source: Ohio State University Research Reactor



OSU Reactor

Samples in quartz tubes

Permanent Magnets and Radiation Effect

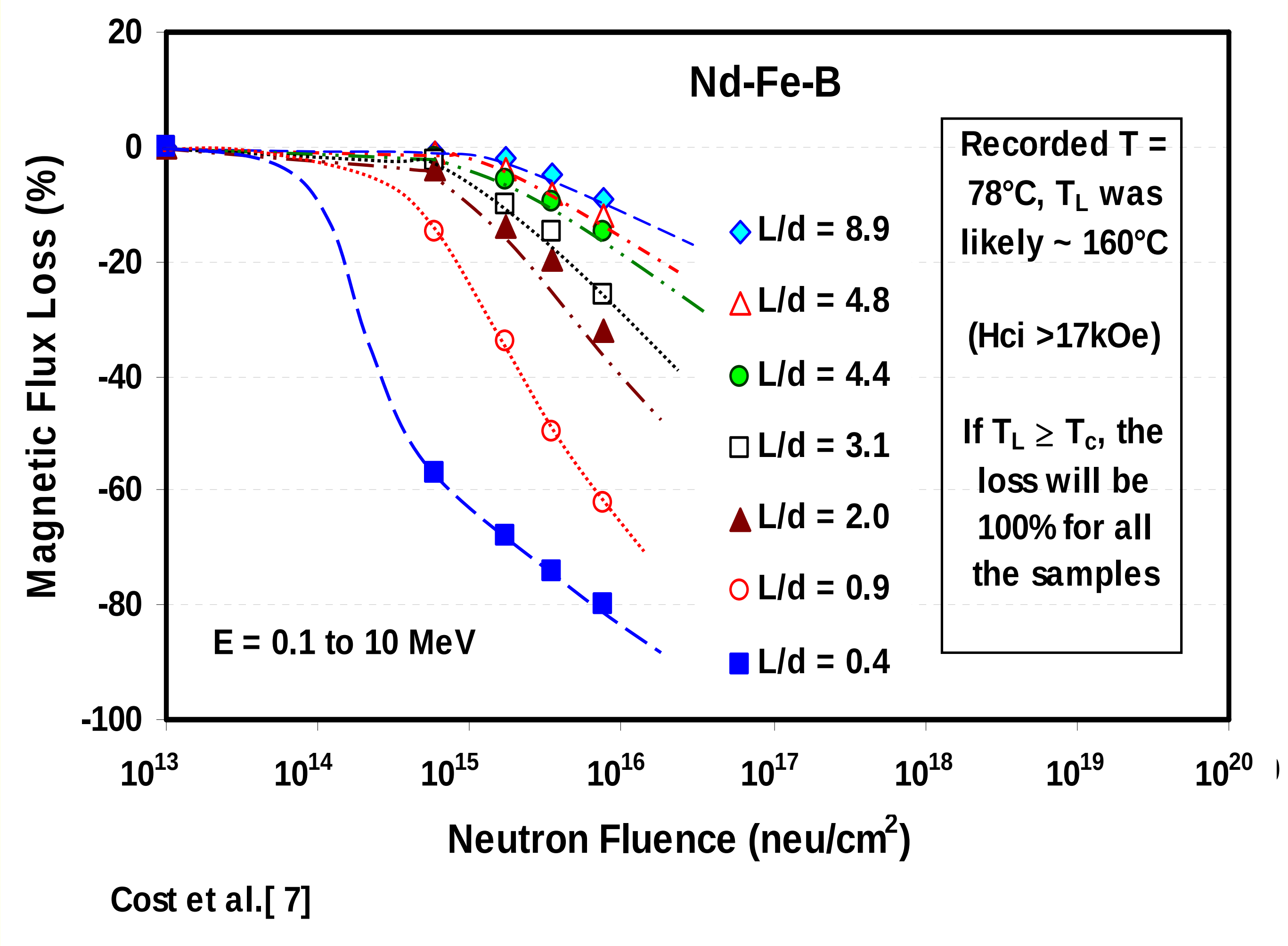


All reports had Neutron E = 0.1-10 MeV.

Neutron flux: 4×10^{12} (Cost) and 2.1×10^{13} n/(cm2.s) (Chen et al)

C.H. Chen, J. Talnagi, J.F. Liu, P. Vora, A. Higgins and S. Liu, IEEE Trans. Magn. 41(2005)3832

Working Point and Radiation Effect



Cost et al.[7]

*J.R. Cost et al, IEEE Trans. Mag.**24** (3), 2016-2018 (1988).*

Radiation Effect

The major radiation damage is caused by radiation-induced thermal spikes

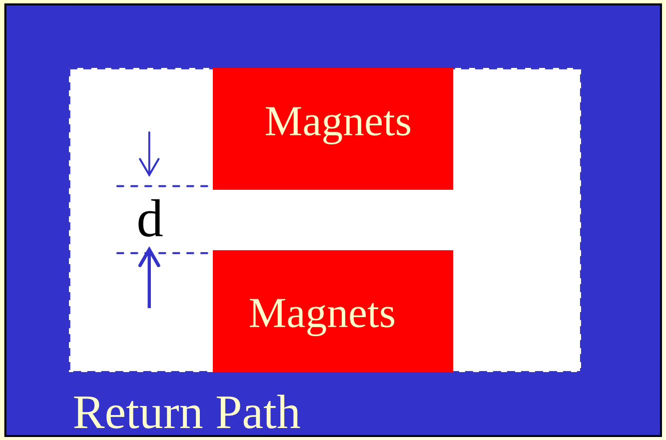
The dominant factor for radiation tolerance is thermal stability, which is related to the following factors:

(1) Curie temperature of permanent magnets

(2) Working point of permanent magnet in the system

(3) Intrinsic coercivity

Permanent Magnet Dipoles



$$B_g = \frac{B_m A_m}{k_1 \mathbf{A_g}}$$

A_m =Magnet area perpendicular to the direction of magnetization;

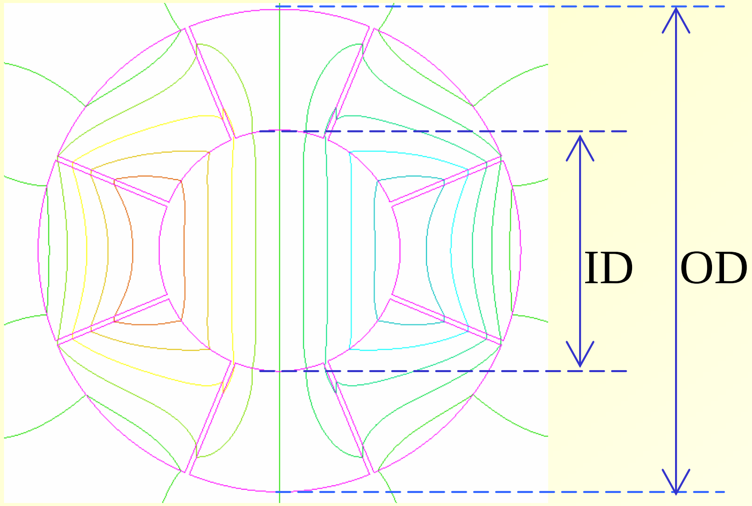
B_m =Flux density of the magnet corresponding to the operating point of the demagnetization curve;

B_g =Flux density desired in the air gap;

A_g =Cross section area of the air gap perpendicular to the flux lines.

The Air Gap Flux Density Is A Lot Lower Than The B_r Of The Permanent Magnets

Permanent Magnet Dipoles



Halbach PM Dipole Structures:

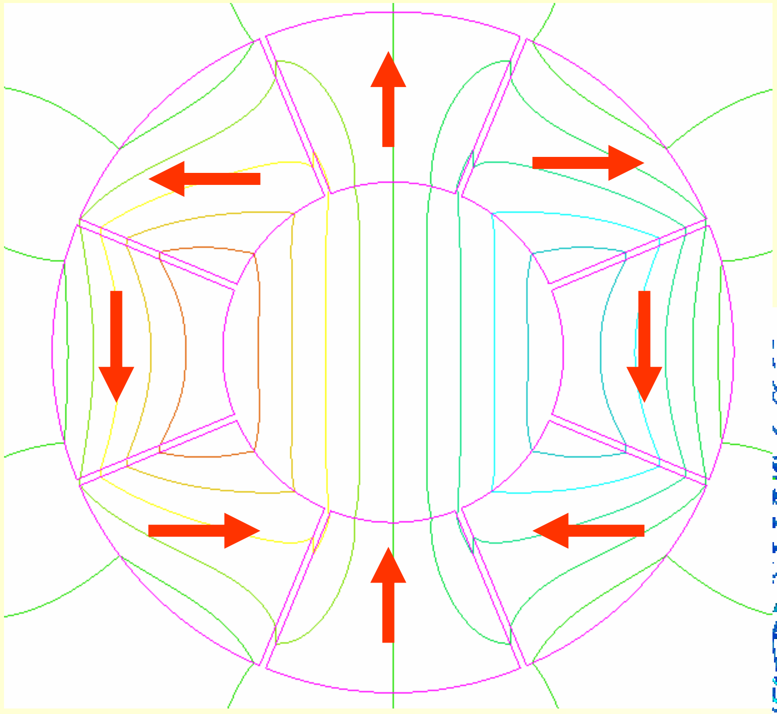
$$B_g = B_r \ln(OD/ID)$$

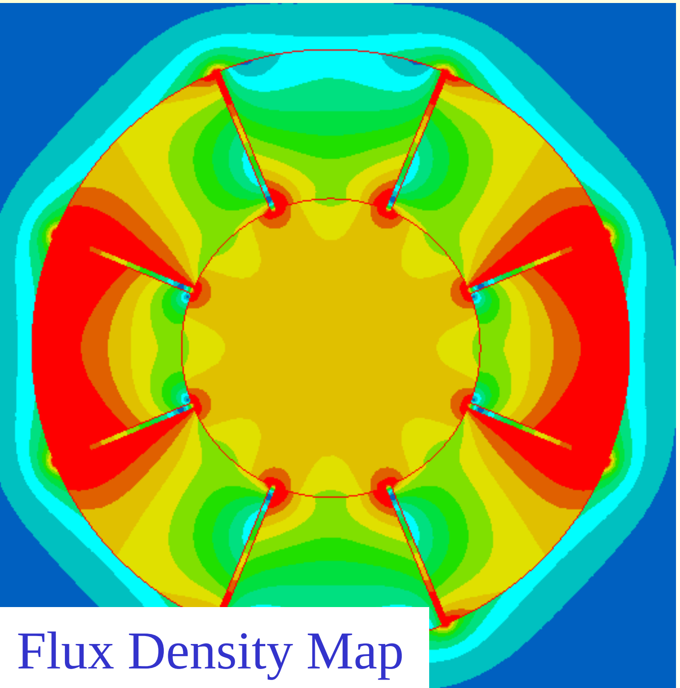
There is no upper limit for air gap flux density in Halbach dipole structures according to above equation. But in reality it would be limited by:

(1) The realistic size

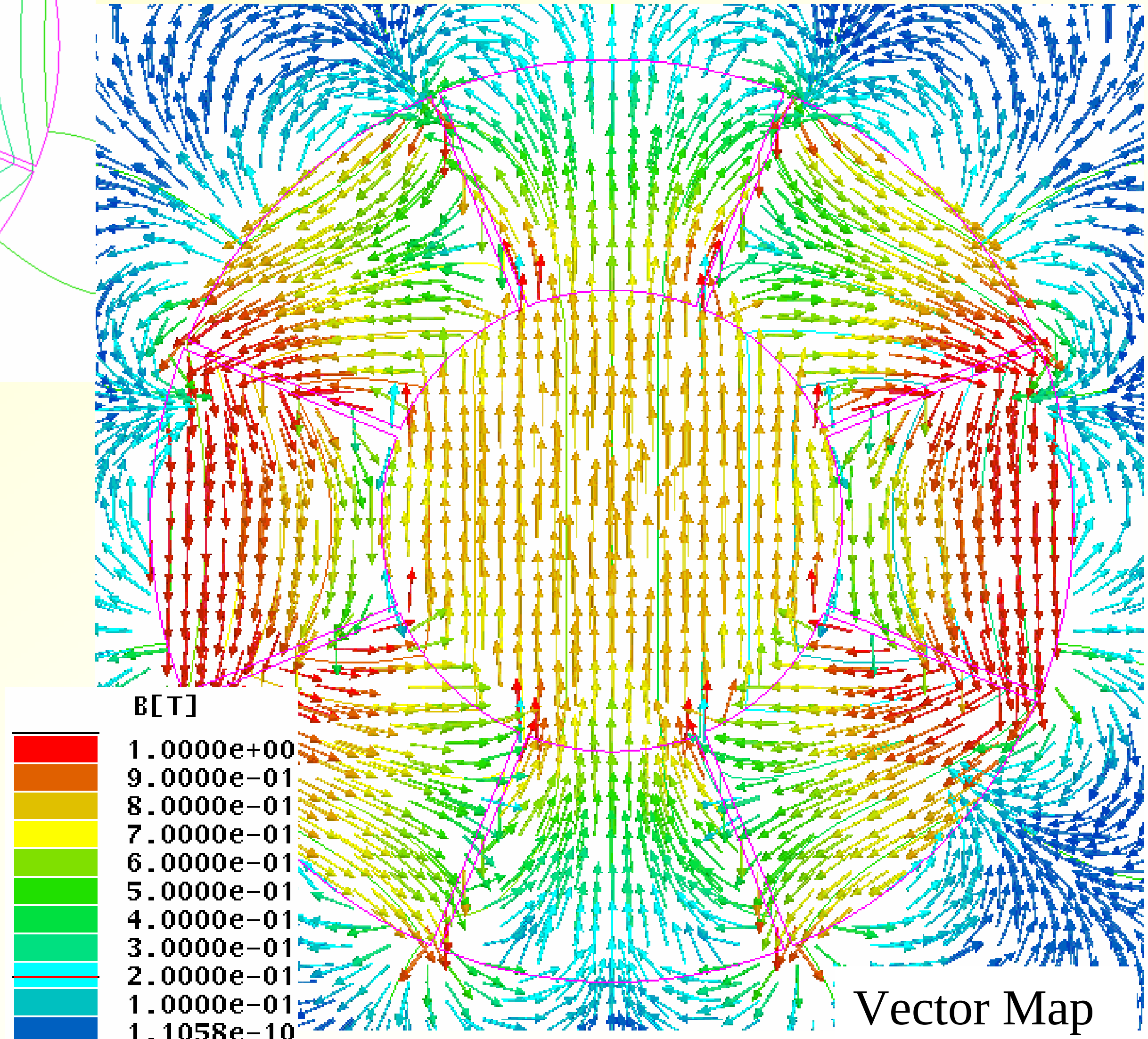
(2) The demagnetization effect

Halbach Dipole Example



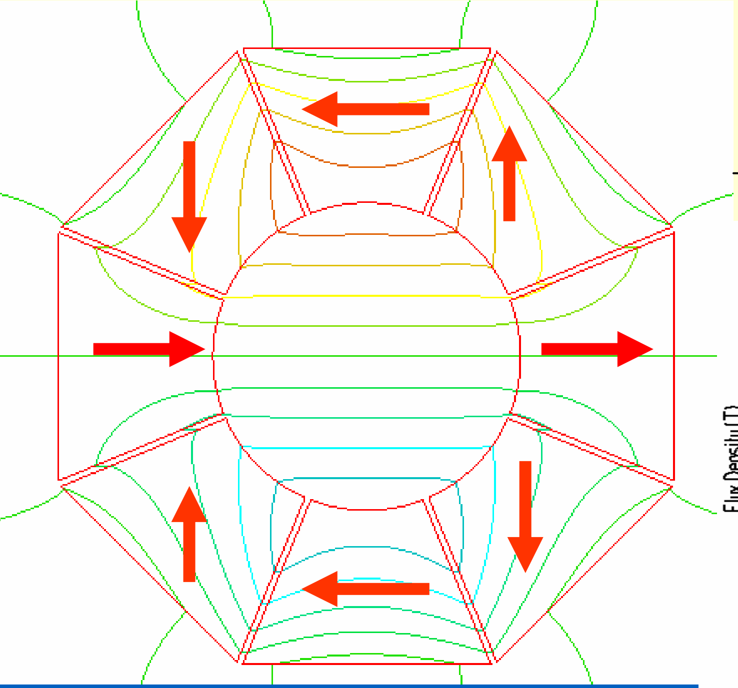


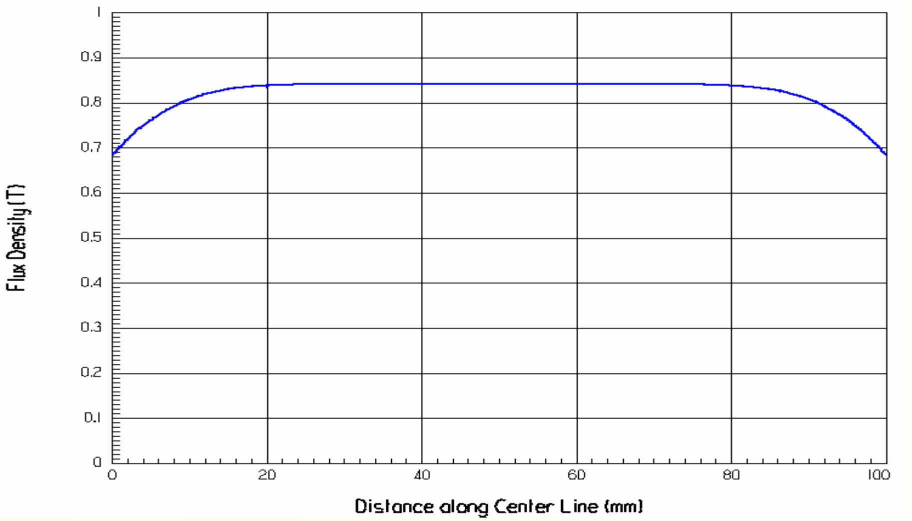
Flux Density Map

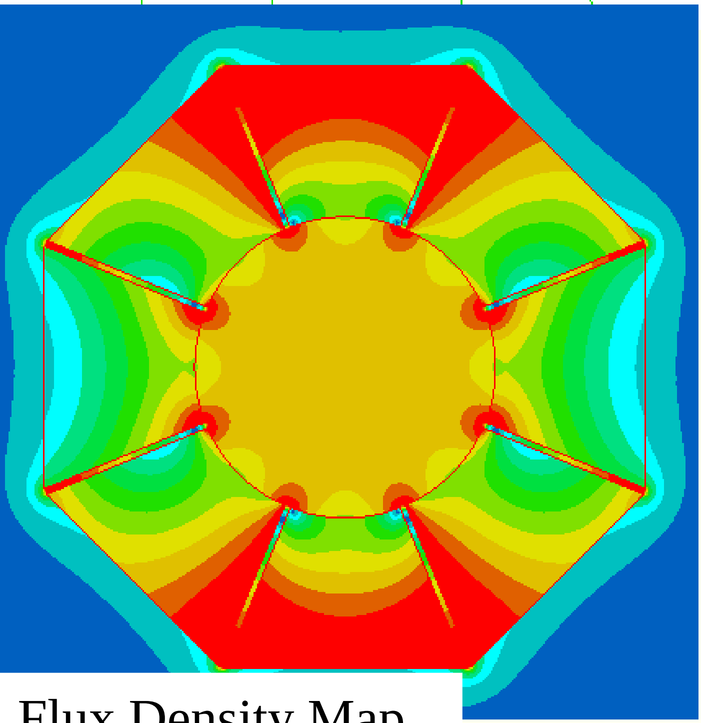


Vector Map

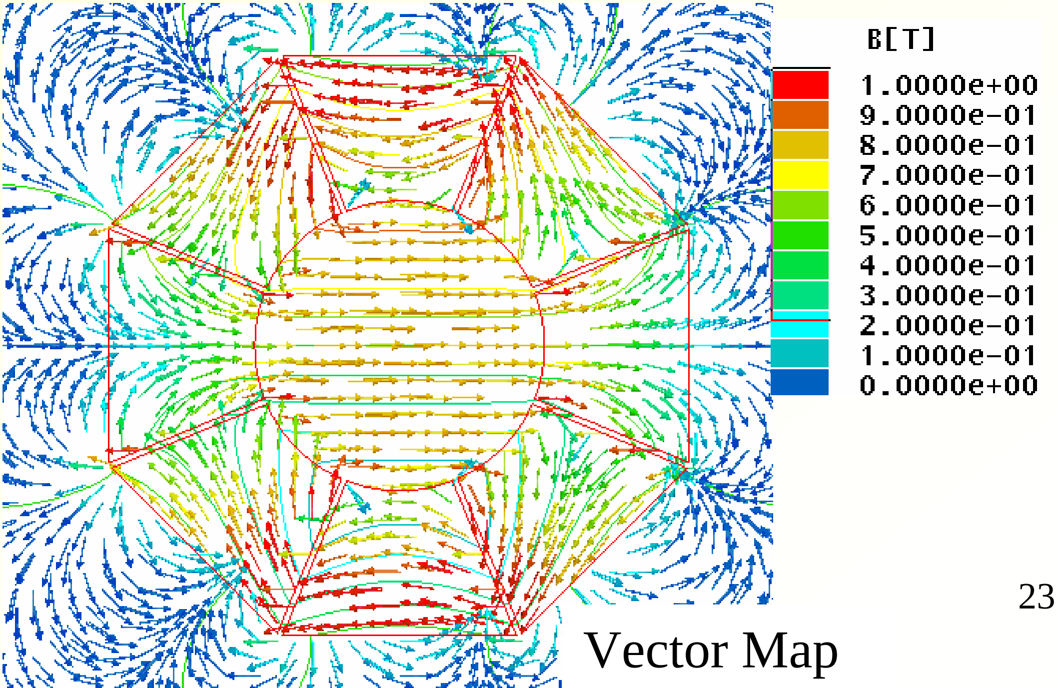
Halbach Dipole Structure







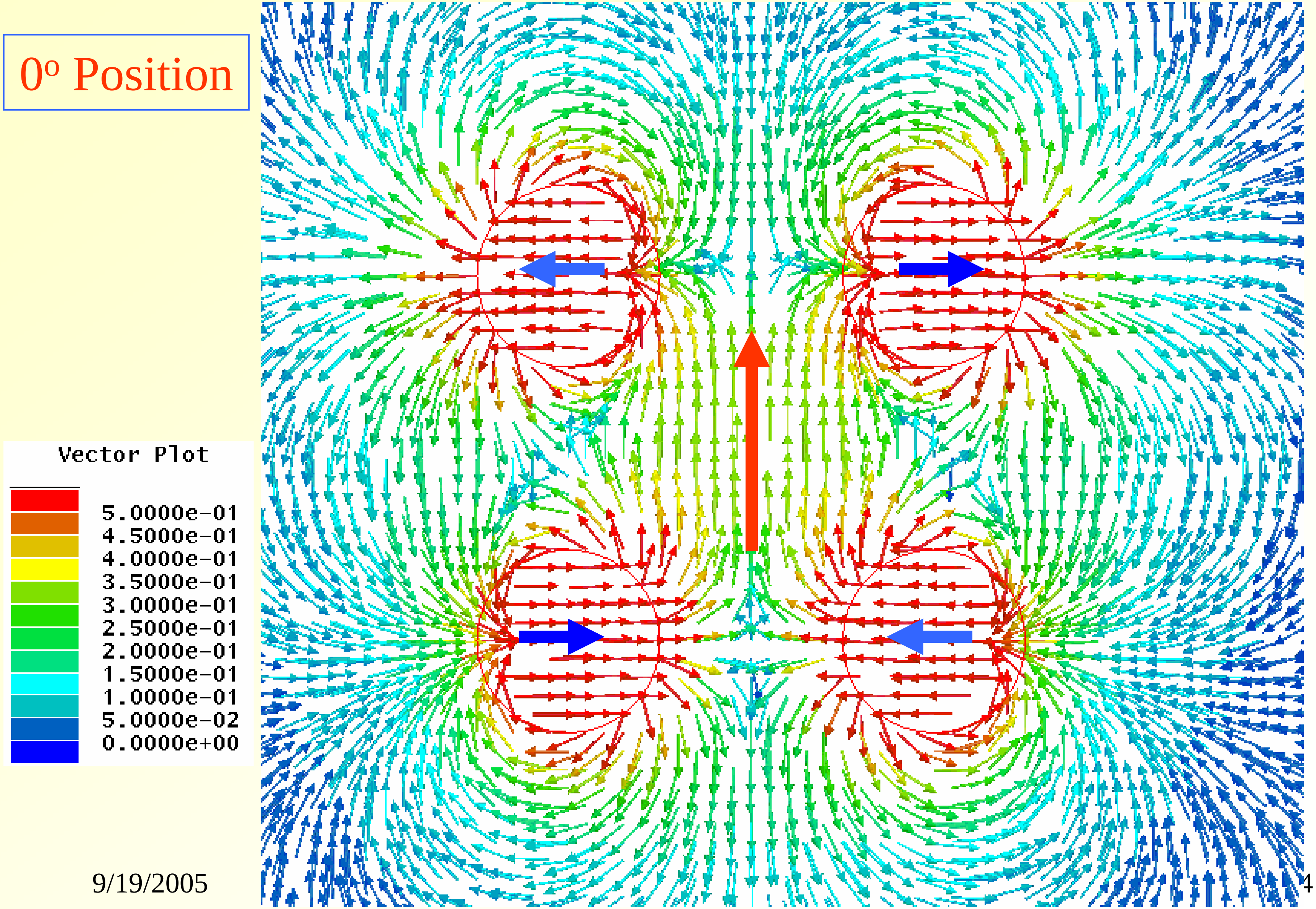
Flux Density Map



Vector Map

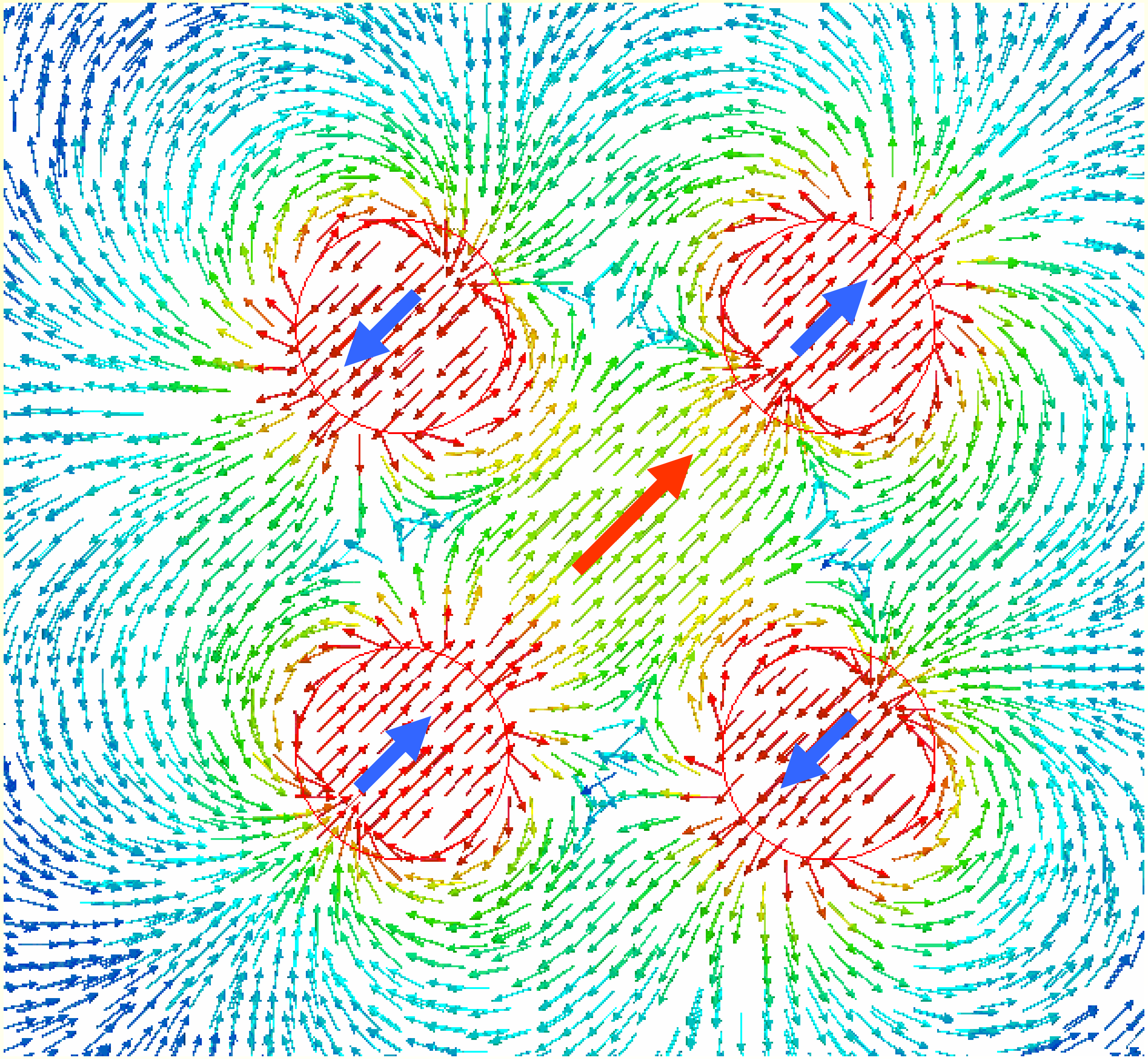
Magnetic Mangles

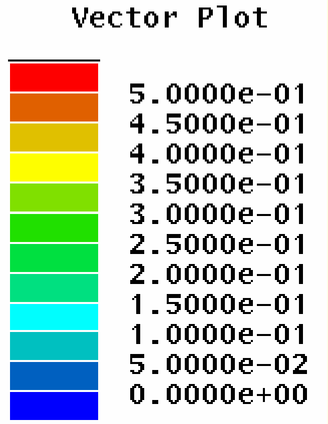
0º Position



Magnetic Mangles

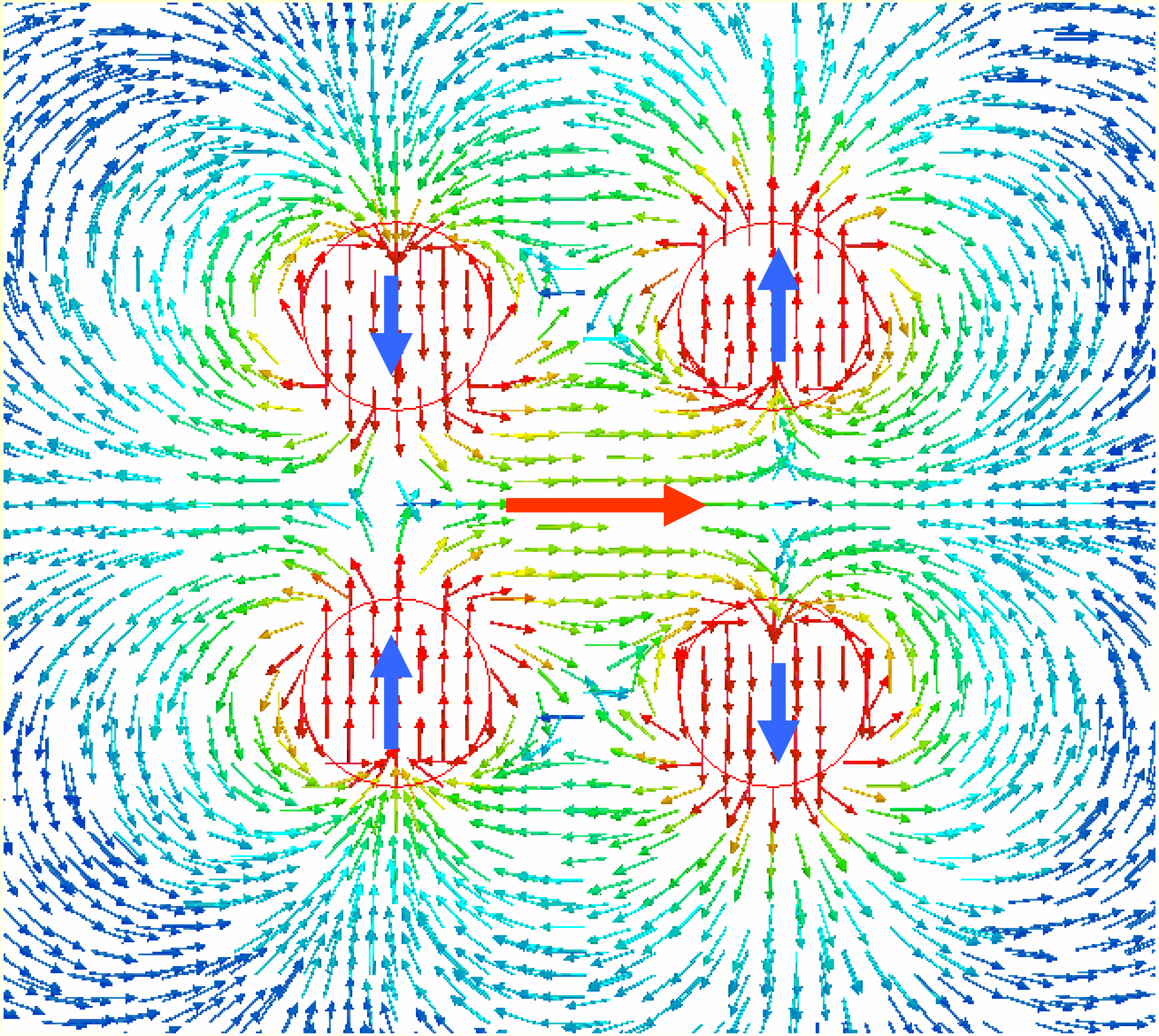
45° Position

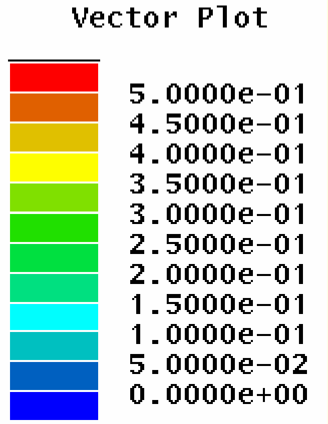




Magnetic Mangles

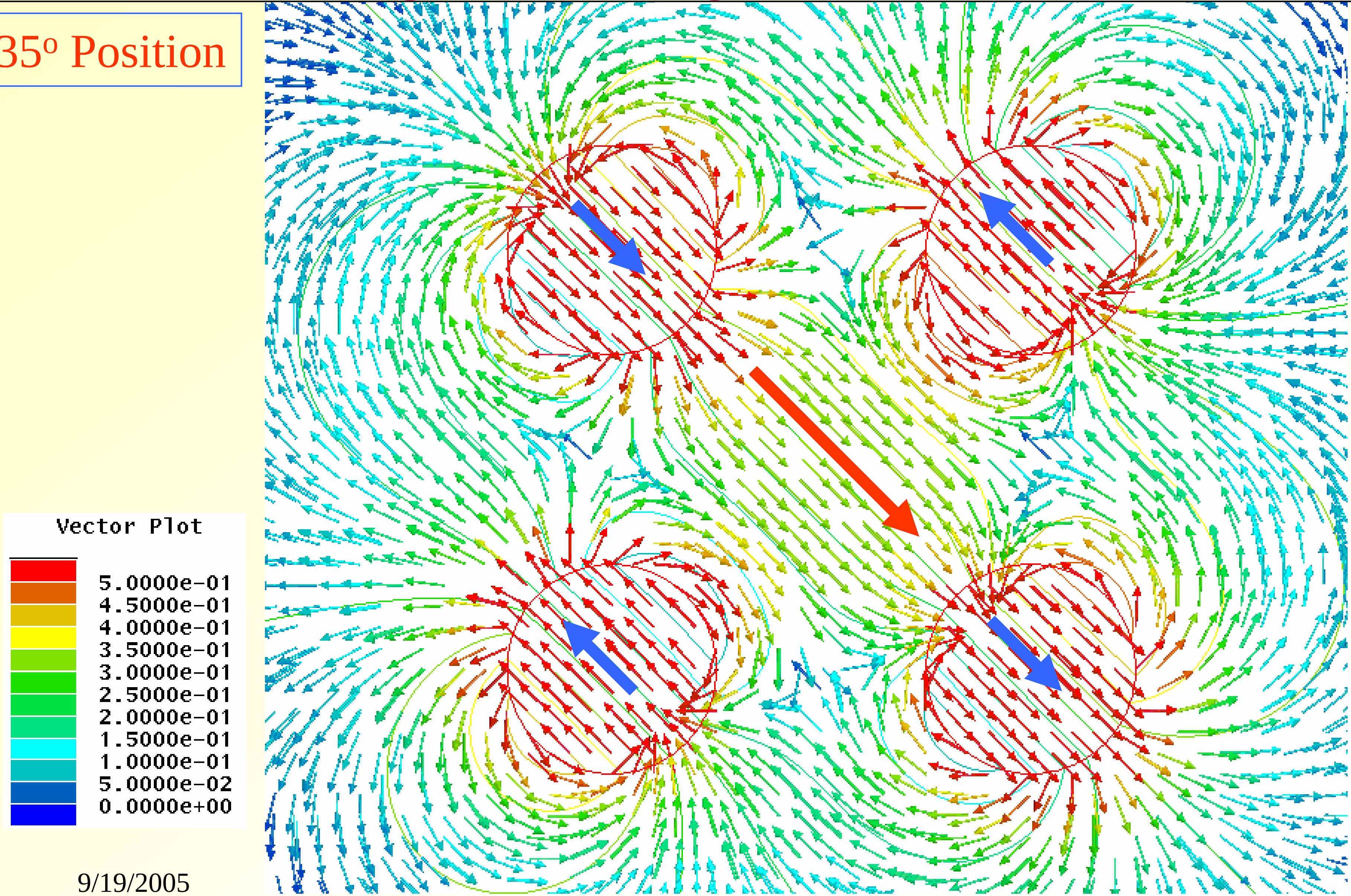
90º Position





Magnetic Mangles

135° Position



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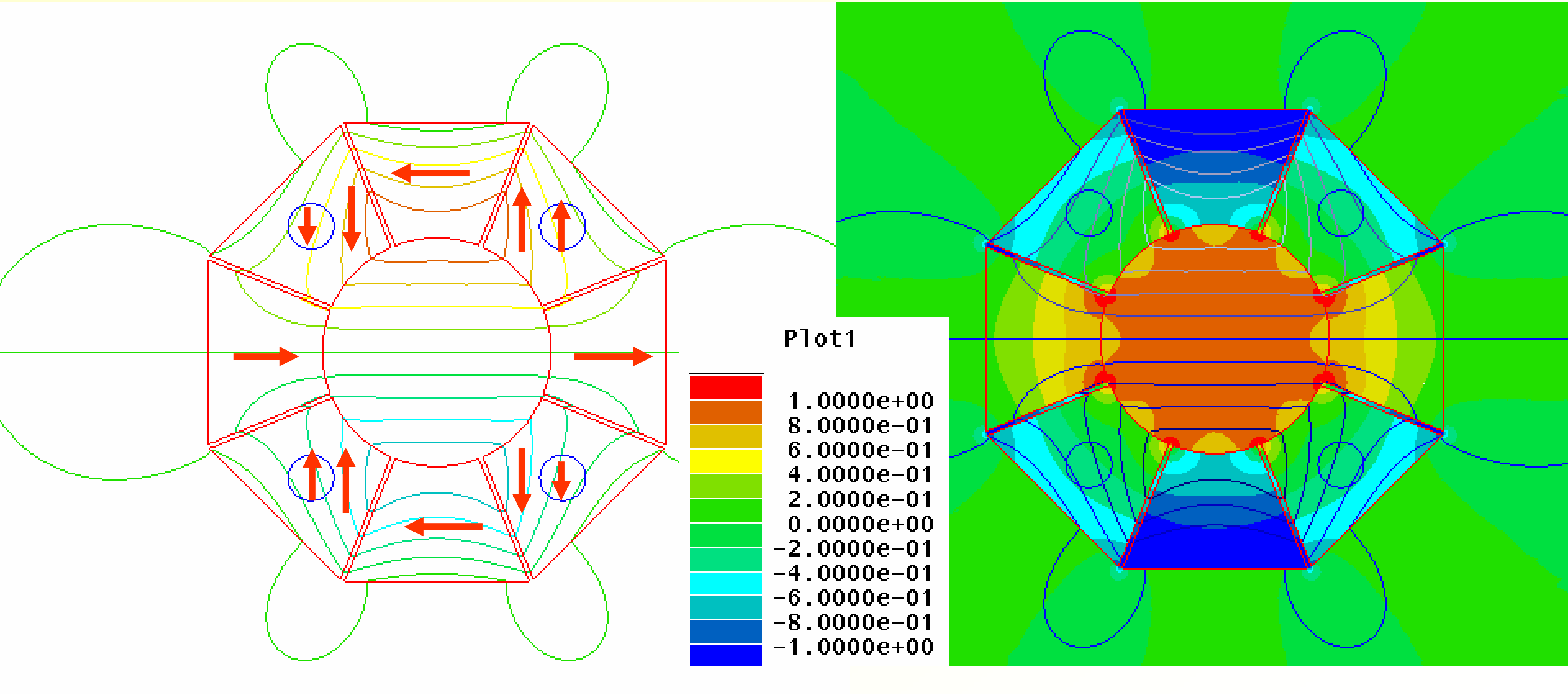
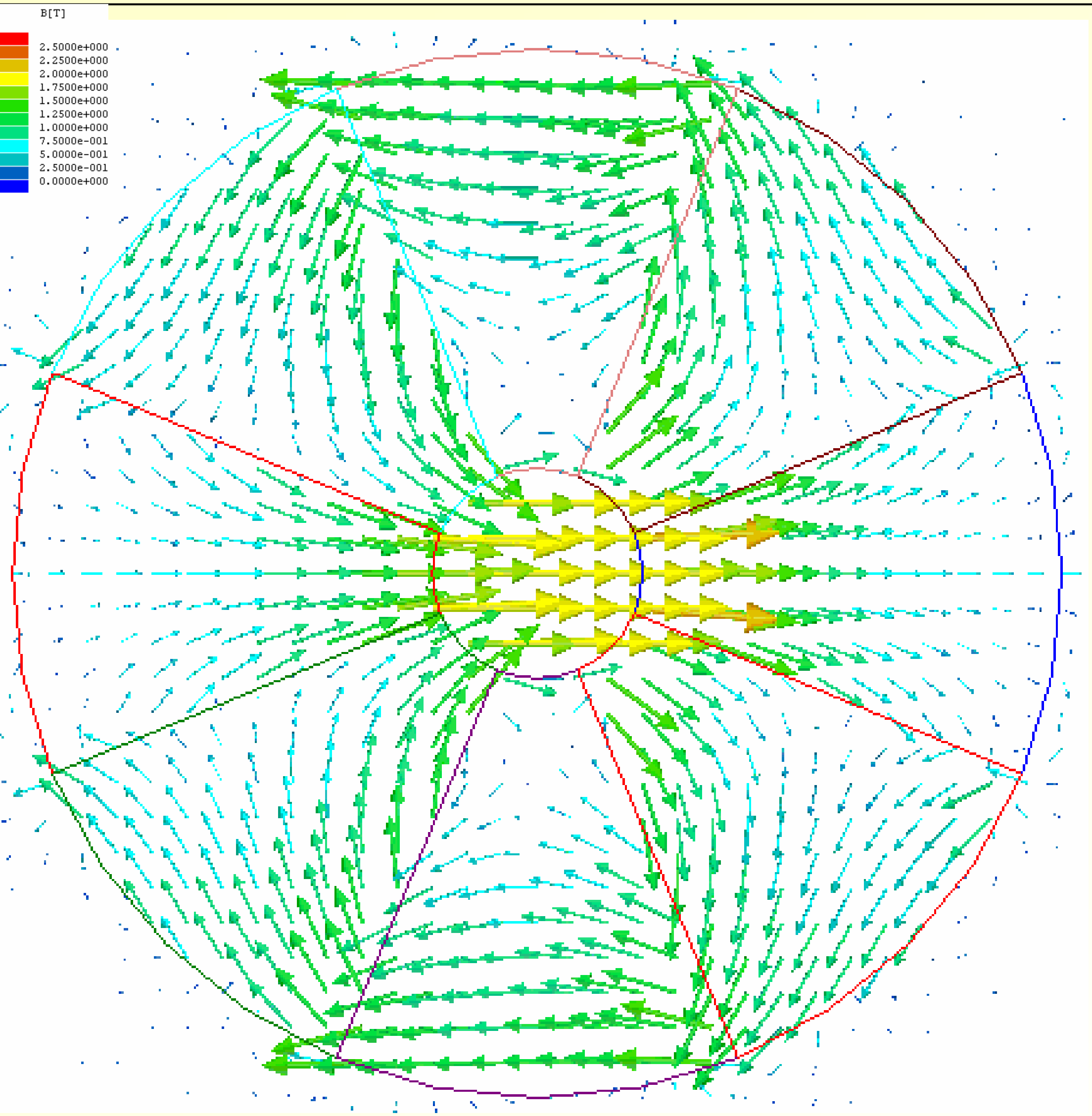
Combination of magnetic mangles and Habach structures can make the air gap flux density adjustable to some degree



Halbach Dipole for FFAGs



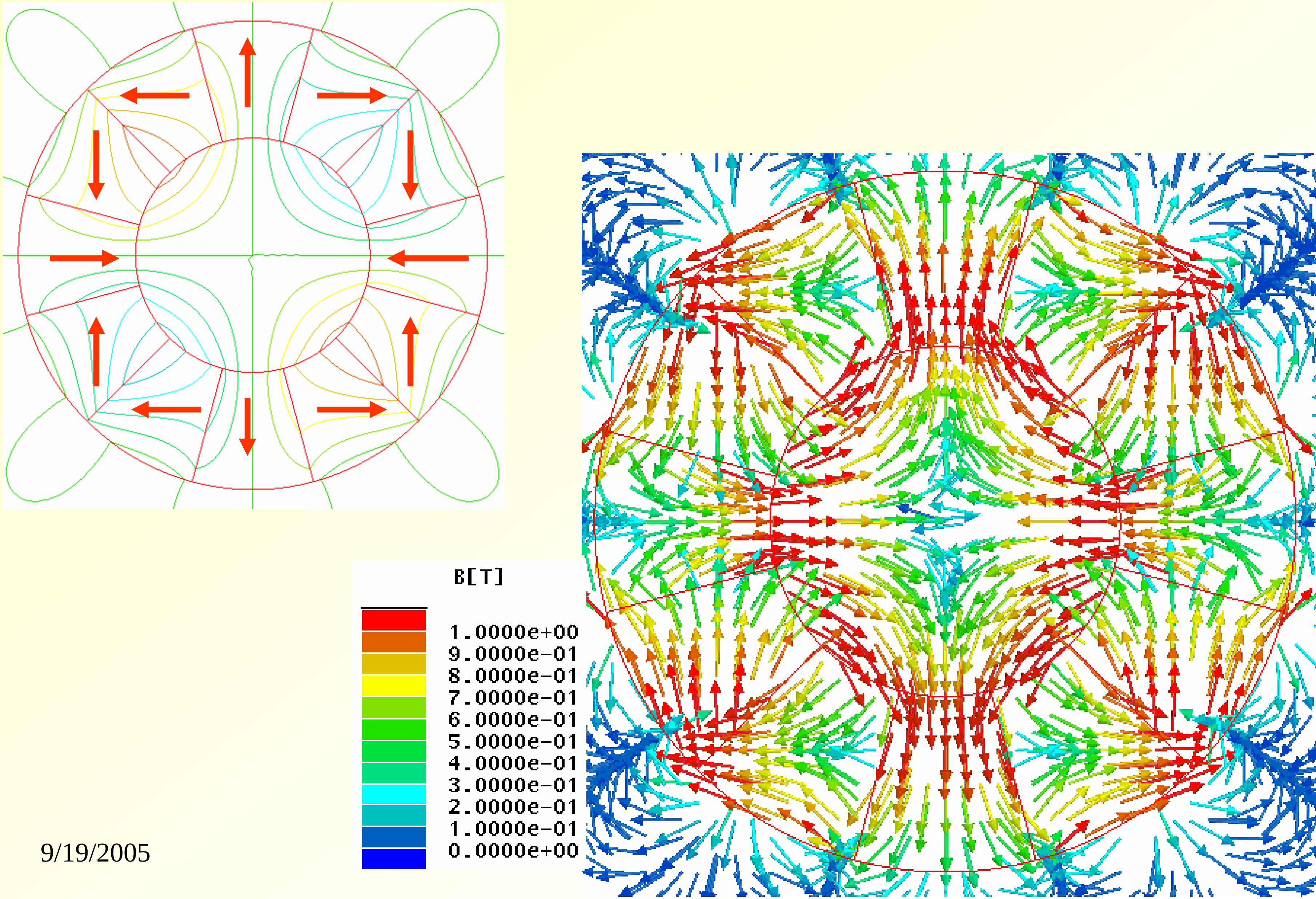
- ✓*4 Tesla PM prototype Halbach cylinder was made in Japan.**

- ✓*EEC has produced many Halbach structures for a variety of applications.*

- ✓*Sintered SmCo or high H_{ci} NdFeB magnets are good choices*

**M. Kumada et al, PAC2001, 3221.*

A Example of Halbach PM Quadrupole



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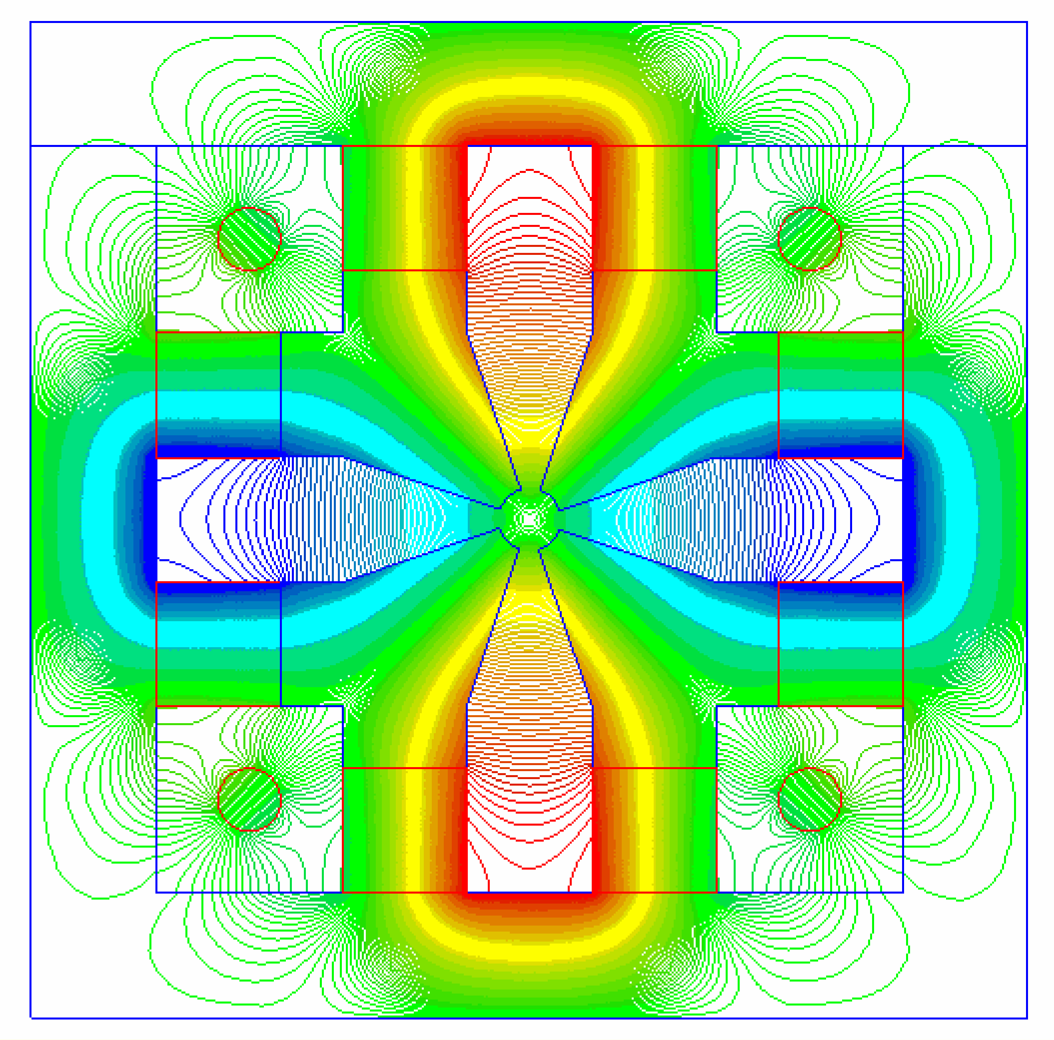
Adjustable Magnetic Quadrupoles



Adjustable magnetic quadrupoles as reported by Fermi lab and SLAC:*

- ➢Diametrically magnetized SmCo 2:17 tuning rods
- ➢Tuning rods rotation changes the strength of field gradient

* *J. T. Volk et al, PAC2001, p217*

Summary

- ✓Permanent magnet dipoles and quadrupoles can have high air gap flux density if designed with Halbach principles.
- ✓Innovative designs can make the air gap flux density adjustable.
- ✓Permanent magnet selection might include trade-offs between cost and performance.
- ✓SmCo magnets are far superior to NdFeB magnets with respect to radiation resistance.

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