Impact of Ferromagnetism of Materials on Fusion Reactor Design

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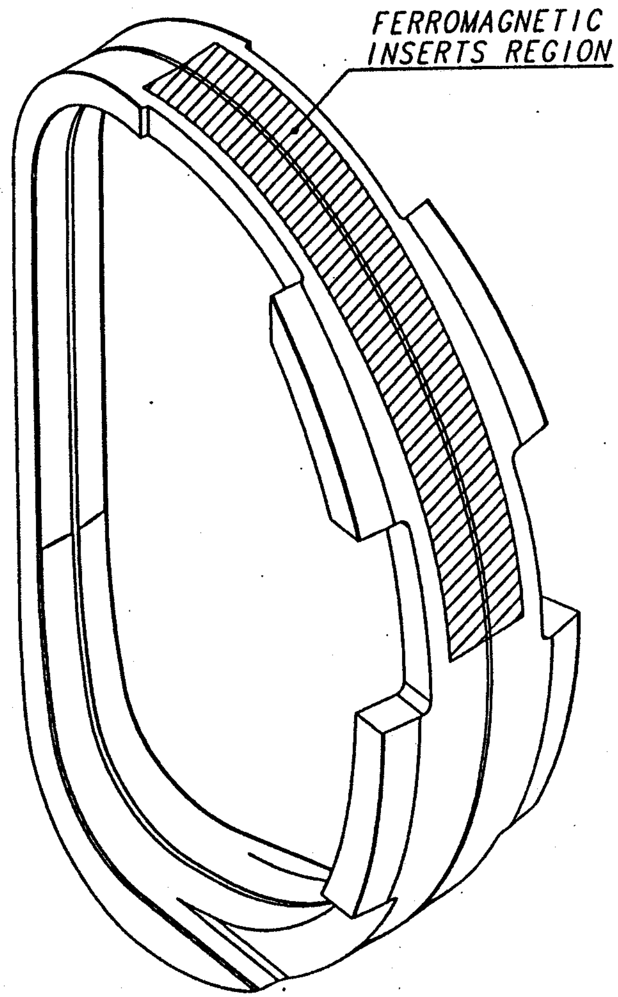
Shielding Design and Material Changes



Reason for changes

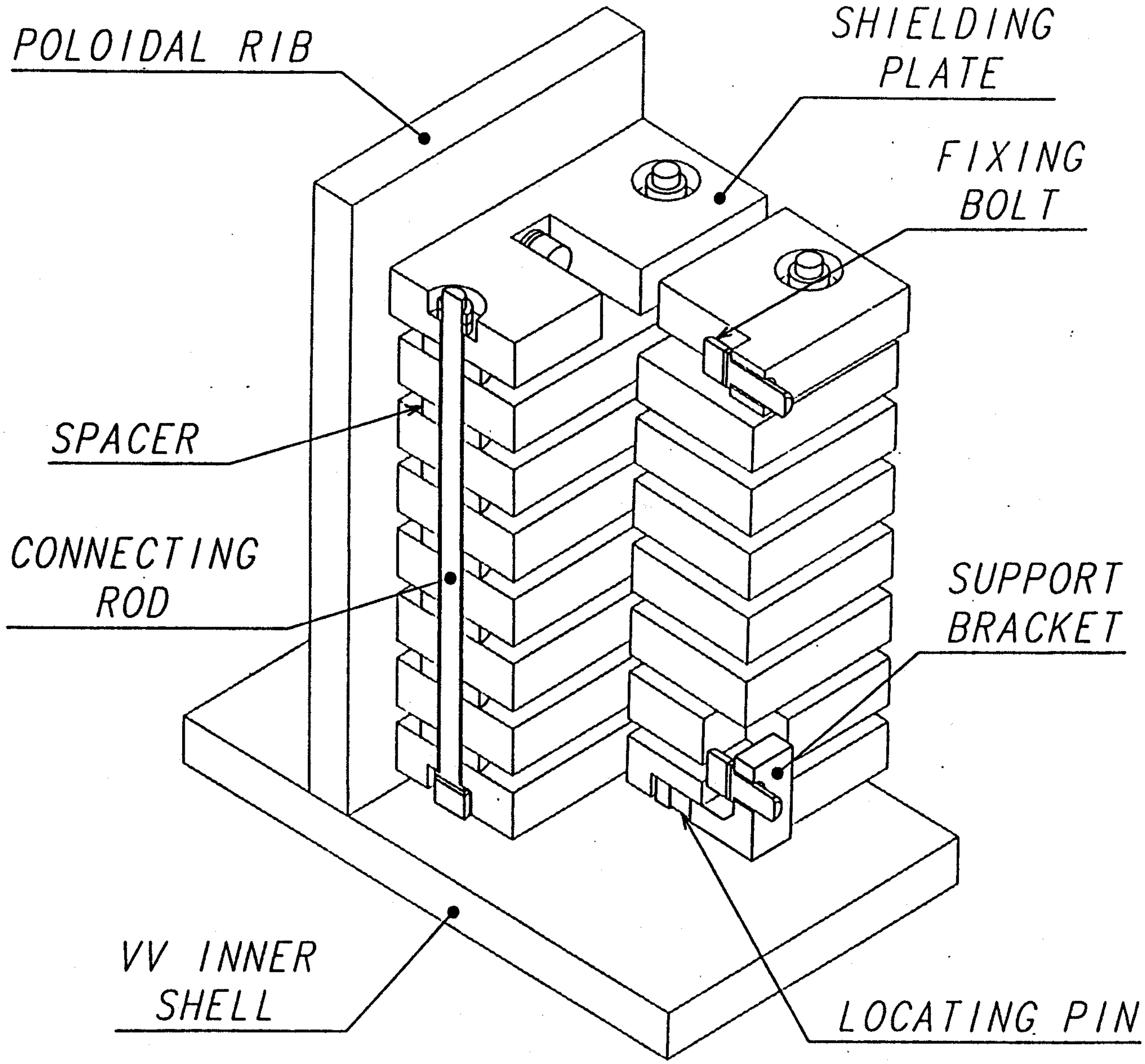
- Ferromagnetic inserts added to reduce toroidal field ripple at plasma edge
- 2 % boron added to main vessel shielding to improve shielding effectiveness

Changes

- Shielding under TF coil from 12:00 to 3:00 changed to ferromagnetic SS 430
- Shielding in other areas changed to SS 304 (with 2% boron)

Results

- Toroidal field ripple reduced by factor of 2.3 times (from 1.6 to 0.7 %)
- Boron addition reduced TF coil nuclear heating by factor of 2 times



Schematic view of the shielding structure.

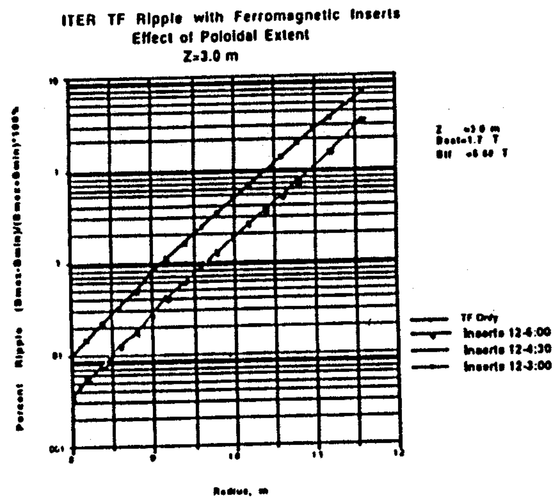
Ferromagnetic Insert Design

Material: Ferritic Stainless Steel (SS430)

Inserted Region: Under TF coil from 12:00 to 3:00

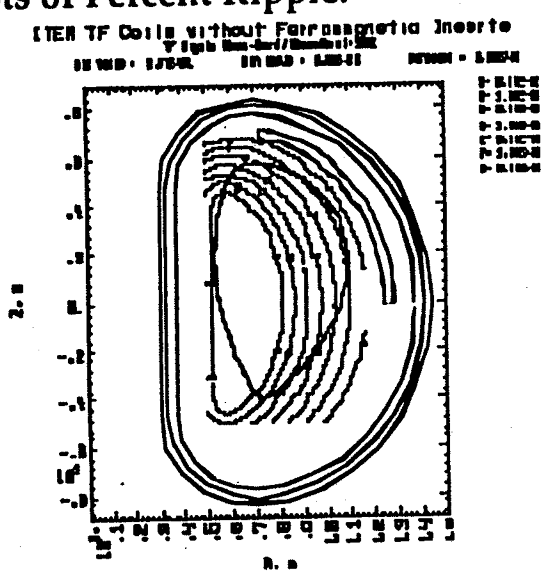
Toroidal Field Ripple Reduction:

Case	Maximum Ripple (%)	Ripple Reduction Factor
Without ferromagnetic inserts	1.6	1.0
With ferromagnetic inserts	0.7	2.3



Percent Ripple vs. Radius at Z=3.0m

Contour Plots of Percent Ripple:



Without Ferromagnetic Inserts

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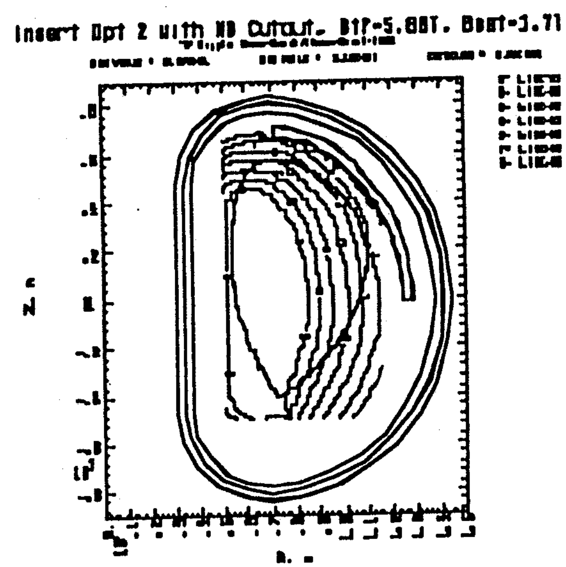

With Ferromagnetic Inserts

REF. M. ONOZUKA. "ITER VACUUM VESSEL DESIGN STATUS" MAR 1998

Ferromagnetism R&D Needs

- The effect of **realistic geometries** on field ripple should be assessed, including asymmetries and realistic penetrations.
- The **allowable** perturbation in the **poloidal** field should be determined.
- The interaction with **transient** magnetic fields should be assessed
  e.g., during start-up and disruptions
  - forces
  - delays in field penetration
  - impact on the vertical stability system
- The **loads and stresses** on a realistic blanket and associated ducting, piping, and manifolds should be re-evaluated. This can be done with existing, commercial finite element codes.
- The **stored energy** associated with the magnetization of these materials and their effects on source terms for safety calculations should be assessed.
- The **magnetic properties** vs temperature, radiation damage, etc. should be confirmed

Ref: A. Hishinuma et al, "Current Status and Future R&D for Reduced-Activation Ferritic/Martensitic Steels"

Conclusions

- Ferromagnetic material can be used to advantage
  - Lower activation
  - Can be used to reduce toroidal field ripple in tokamaks

- Plasma initiation, stability, control, etc. are not significantly impacted, but
  - Ports and other discontinuities in ferromagnetic material should be as axisymmetric as possible to avoid low order error fields
  - Care should be taken with placement of magnetic probes

- Forces can be high, especially on piping and other components that pass through high field gradients, but it is possible to provide adequate support

- R&D may be useful to study specific reactor configurations and materials

Presentation Outline

- Why use ferromagnetic materials?
- What are the concerns?
- What have we concluded in the past?
- What are the results of recent experiments and studies?
- Conclusions

Why use ferromagnetic materials?

- Ferritic / martensitic steels may offer some advantages over austenitic steels as a structural material

    - Lower activation
    - Higher thermal conductivity
    - Lower thermal expansion
    - Better swelling resistance
    - Large database and experience in reactors
    - ......

- Ferromagnetic properties can be useful to reduce toroidal field ripple

    - Material placed in bore of TF magnets on outboard side
    - Ripple can be reduced by factors of 2 or 3

What are the concerns with ferromagnetic material?

- Error fields during assembly and checkout of machine

  - interferes with low field measurements for coil alignment

- Field perturbations during operation

  - impact on plasma initiation
  - asymmetric error fields due to ports, non-uniform magnetic properties, etc.
  - impact on magnetic diagnostics and plasma control system
  - impact on magnetic reconstruction of separatrix shape

- Ferromagnetic forces during operation (on primary structures and piping)

- Other concerns

  - Compatibility with austenitic structures (different CTE)
  - Vacuum outgassing properties
  - Complications of the magnetic analysis (changes from linear to non-linear)

What has been concluded in the past?

- Starfire study and Lechtenberg, et al, said:

  - Toroidal field ripple effects are small
  - Poloidal field effects can be ~3%, but can be compensated by control system
  - Field penetration should not be a problem, since iron is saturated by TF
  - Forces are high on piping, which is located in regions of high field gradient, but these forces can be accomodated with proper supports

- Attaya et al, and MARS study said:

  - Forces and field errors from ferromagnetic material must be considered, but "should in no way prevent the use of ferromagnetic steels in fusion reactors"
  - For typical blanket structures, field errors are at most a few percent
  - The iron is saturated, except in piping that exits the magnets, which simplifys the calculations
  - Magnetic forces contribute to the stresses on the same order as the coolant pressure and the component weight

ref T. Lechtenburg et al, "An assessment of Magnetic Effects in Ferromagnetic Martensitic Steels for Fusion Machines"
H. Attaya et al, "Implications of Using Ferromagnetic Steel in Mirror Fusion Reactors"

Starfire/Lechtenberg study - Pipe forces

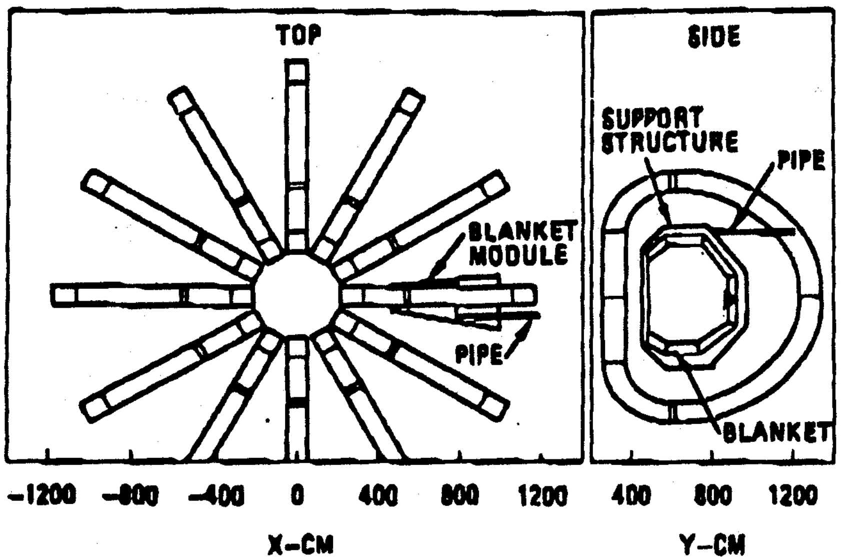

Fig. 4 Schematic of the location of module and coolant pipe with respect to the toroidal field magnets in (a) top view and (b) side view

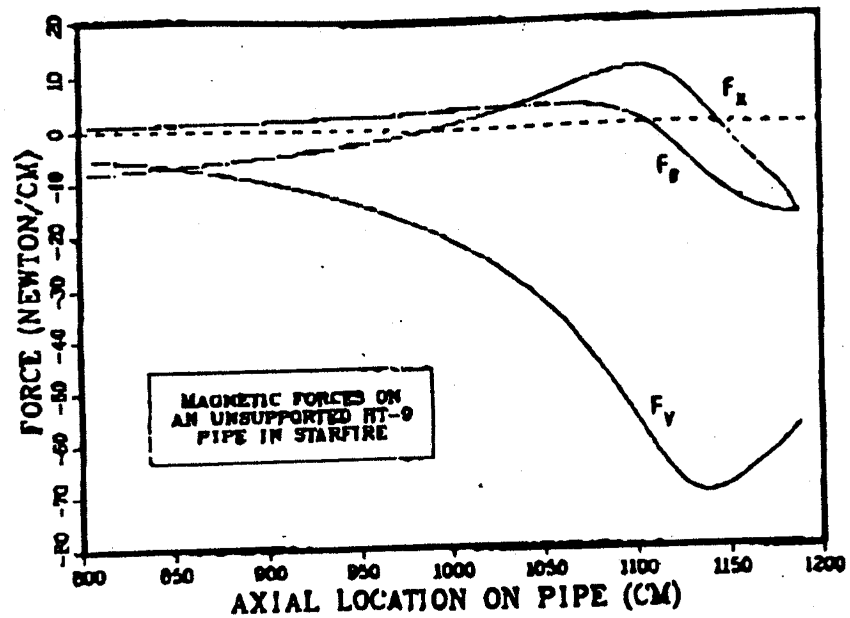

Fig. 5 Magnetic force distribution for a coolant pipe in Starfire at 0.86 m from the center of the TF magnet

ref T. Lechtenburg et al, "An assessment of Magnetic Effects in Ferromagnetic Martensitic Steels for Fusion Machines"

What are the results of recent studies/experiments?

- Abe, Nakayama have inserted ferritic first wall into the HT-2 tokamak
  - F82H plates placed between ports
  - "Error" fields of ~ 1.5E-3 T produced in poloidal and toroidal directions
  - Poloidal field reconstructed including effects of plates
  - Control system was not modified, discharges were successful
  - 1500 discharge cleaning shots were needed to condition F82H, similiar to original experience with 304 sst.

ref. M. Abe, T. Nakayama, "Discharge and Poloidal Magnetic Field Reconstruction in a Ferritic First Wall Tokamak" 17th SOFE, Oct 6-10, 1997.

F82H first wall experiment on HT-2

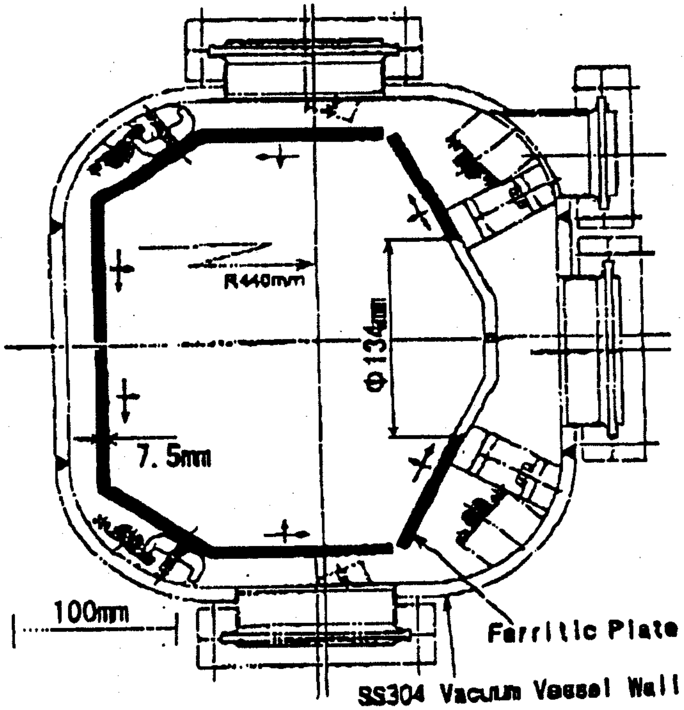

Fig.1 Poloidal cross section of HT-2 in this experiment. The HT-2 vacuum vessel is modified to have a ferritic plate first wall. The arrows denote magnetic sensors and measurement directions. SS304 denotes stainless steel 304.

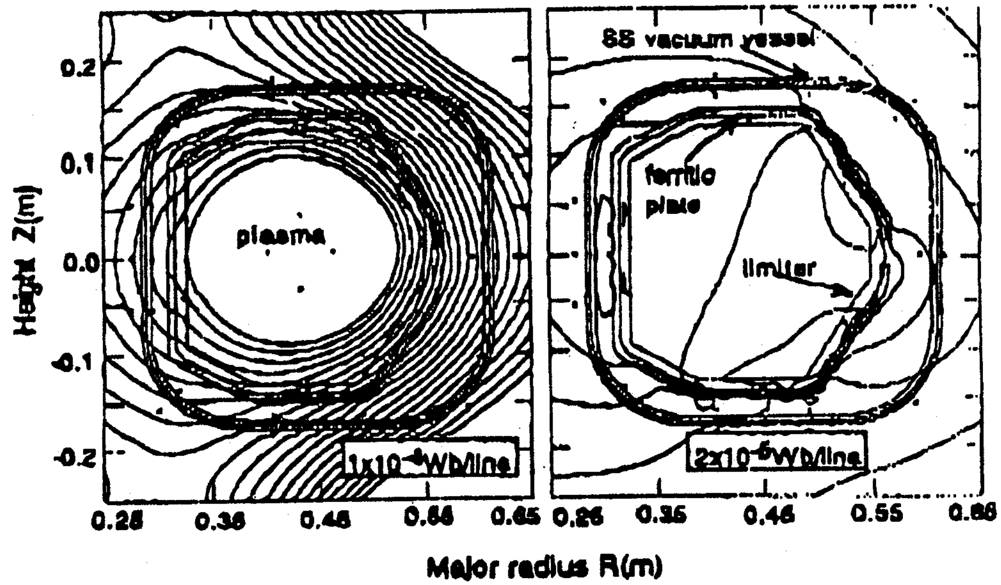

Fig.6 A magnetic fitting result with ferritic first wall. Left shows total poloidal field at time of 20ms in discharge of Fig.4. Right shows magnetic field due to the ferritic plate. The vertical magnetic field at plasma center is $9x10^{-4}$T to reduce the externally applied vertical field. SS denotes stainless steel.

ref. M. Abe, T. Nakayama, "Discharge and Poloidal Magnetic Field Reconstruction in a Ferritic First Wall Tokamak" 17th SOFE, Oct 6-10, 1997.

What are the results of recent studies/experiments?

- JCT, RF and US home teams have investigated effects of ferromagnetic inserts on ITER forces, control fields, etc.

  - *Plasma initiation* not a problem, max magnetic field from inserts in regions of initiation is only half of stray field from PF coils and passive structures

  - *Plasma equilibrium* not affected, field due to inserts < 1% of vacuum field

  - *Plasma shape control* not effected significantly

  - *Plasma boundary magnetic reconstruction* is not a problem, since inserts are not between plasma and magnetic probes

  - *Error fields* insignificant for n=1 radial location error of 10 mm (B2,1/B0 ~1E-6)

  - *Forces* are manageable, global stresses in vacuum vessel < 15MPa due to ferromagnetic forces on inserts

Ref. Y. Gribov, "Report on Acitons Arising from TAC comments", and
B. Riemer, B. Nelson, "Global stresses in Vacuum Vessel due to ferromagnetic shielding material"