Presented at the COMSOL Conference 2009 Milan

COMSOL 2009, Milan, October 2009

Hochfeld-

Magnetlabor

Dresden

Magnetic Fields in

Science and Medicine

Assisted by Advanced Finite-Element Simulations

Forschungszentrum
Dresden Rossendorf

Hochfeld-Magnetlabor Dresden (HLD) • www.fzd.de/HLD • A.Sytcheva

1) Highest magnetic fields for advanced materials studies

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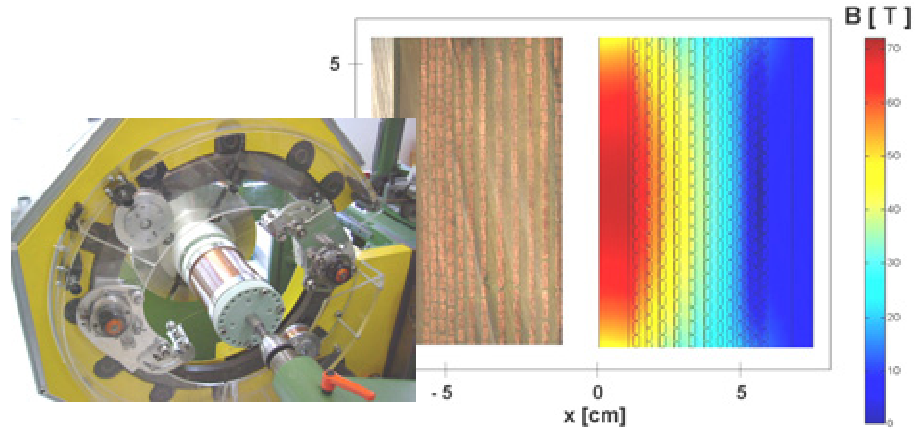
2) **Design, fabrication, and use of pulsed-field coils for materials research**



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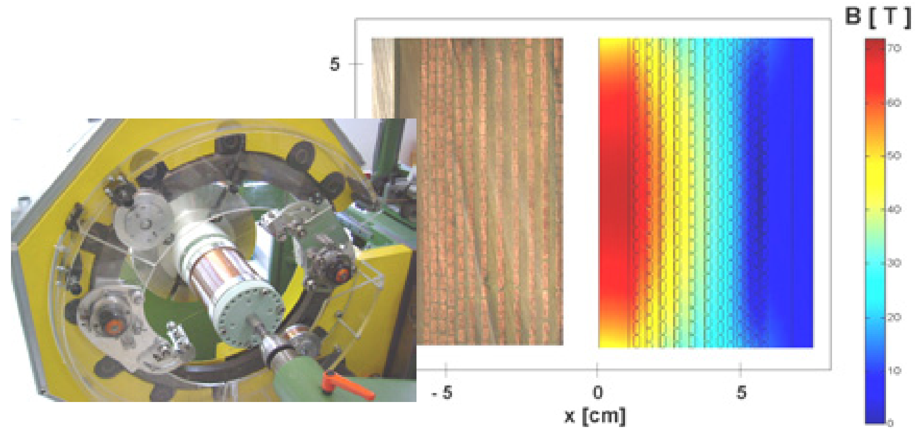
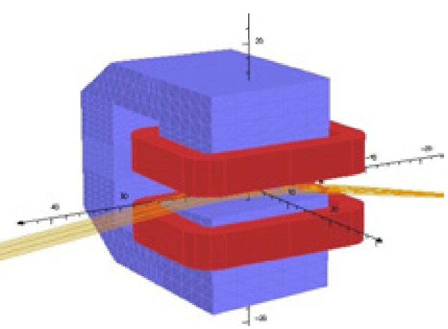


3) **Magnets for ion-beam bending, guiding, focusing at ELBE**



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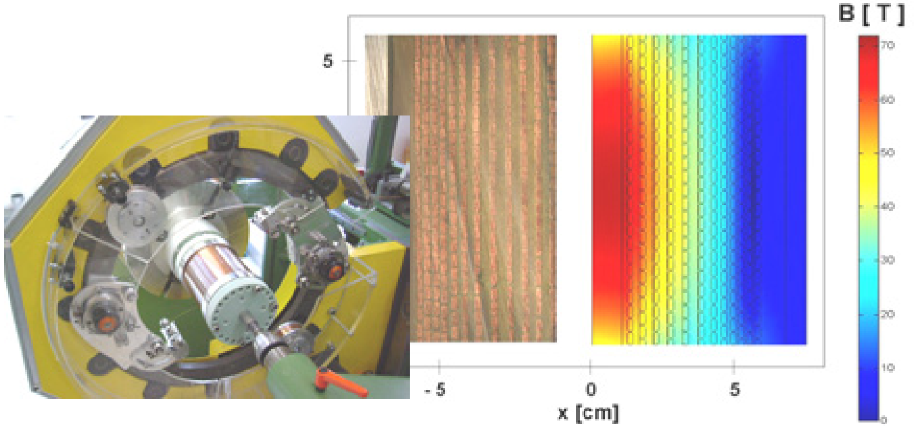

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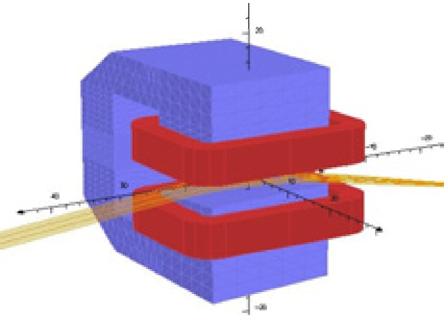
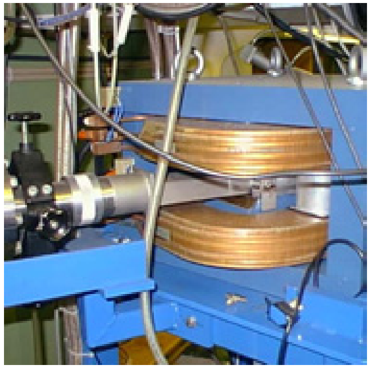
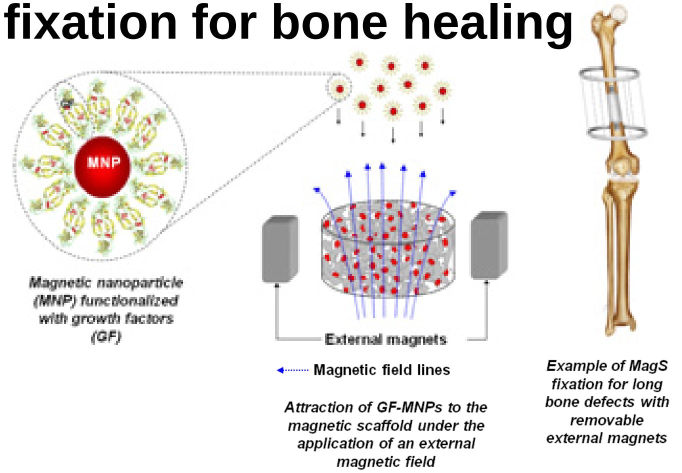




4) Magnetic targeting, diffusion and fixation for bone healing



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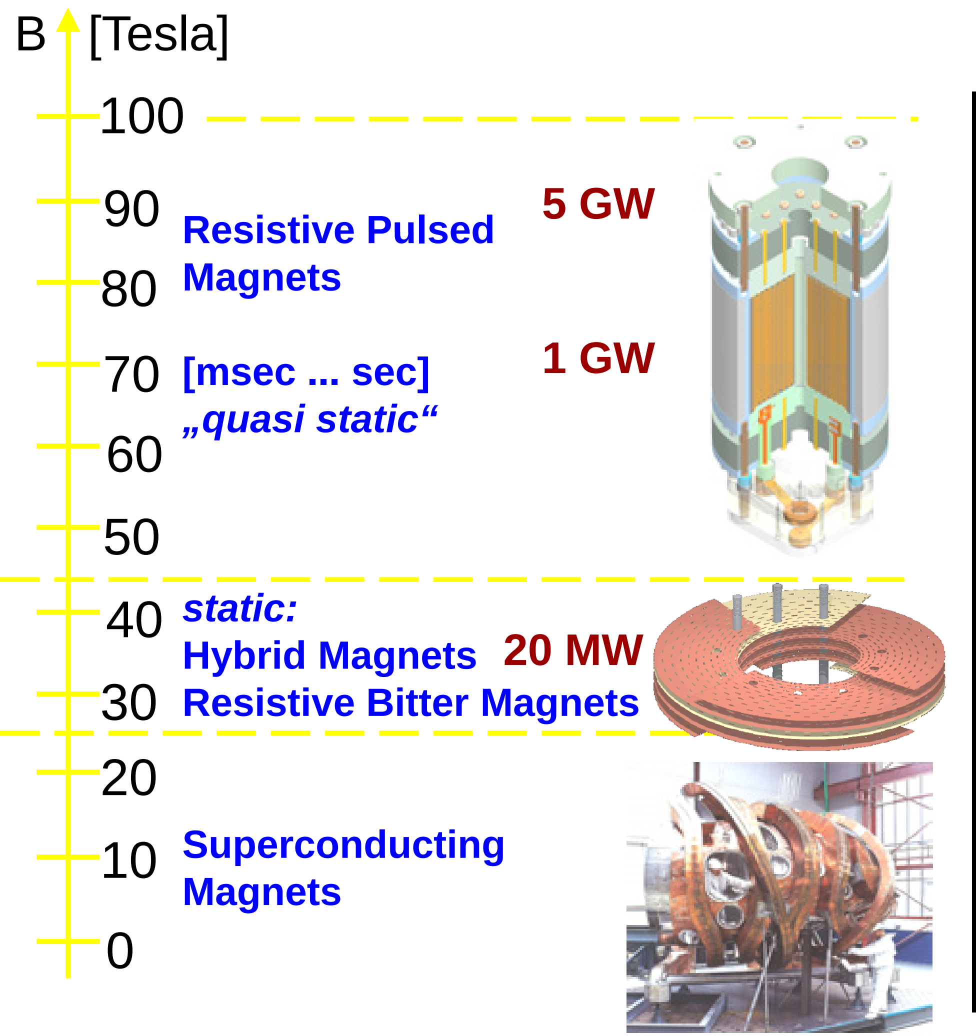


HLD is one of the three user facilities (Los Alamos, Dresden, Tokyo) which reach out for 100 T for research on advanced materials

B [Tesla]

100

90 **Resistive Pulsed Magnets** **5 GW**

80

70 **[msec ... sec]** ***„quasi static“*** **1 GW**

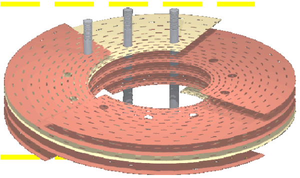
60

50

40 ***static:***

Hybrid Magnets **20 MW**

30 **Resistive Bitter Magnets**



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10 **Superconducting Magnets**

0

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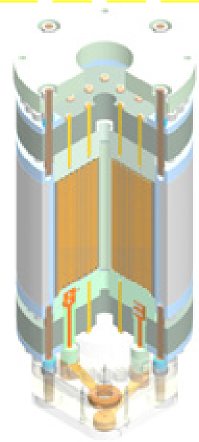

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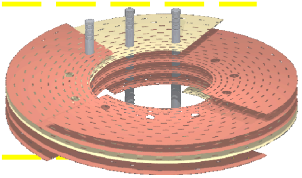

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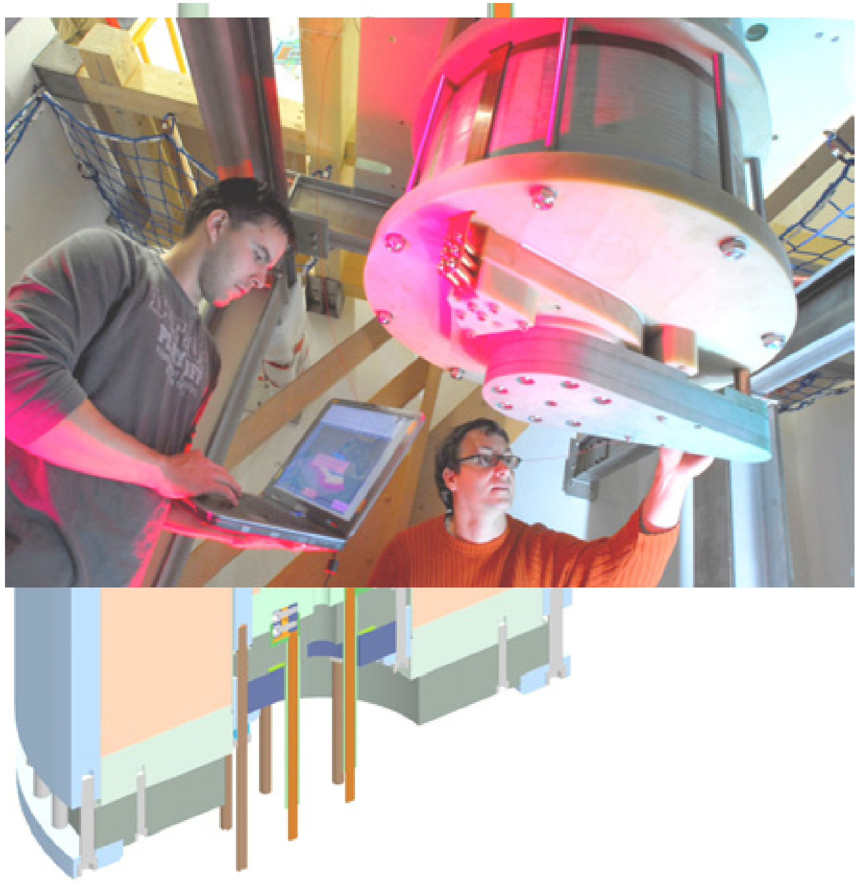
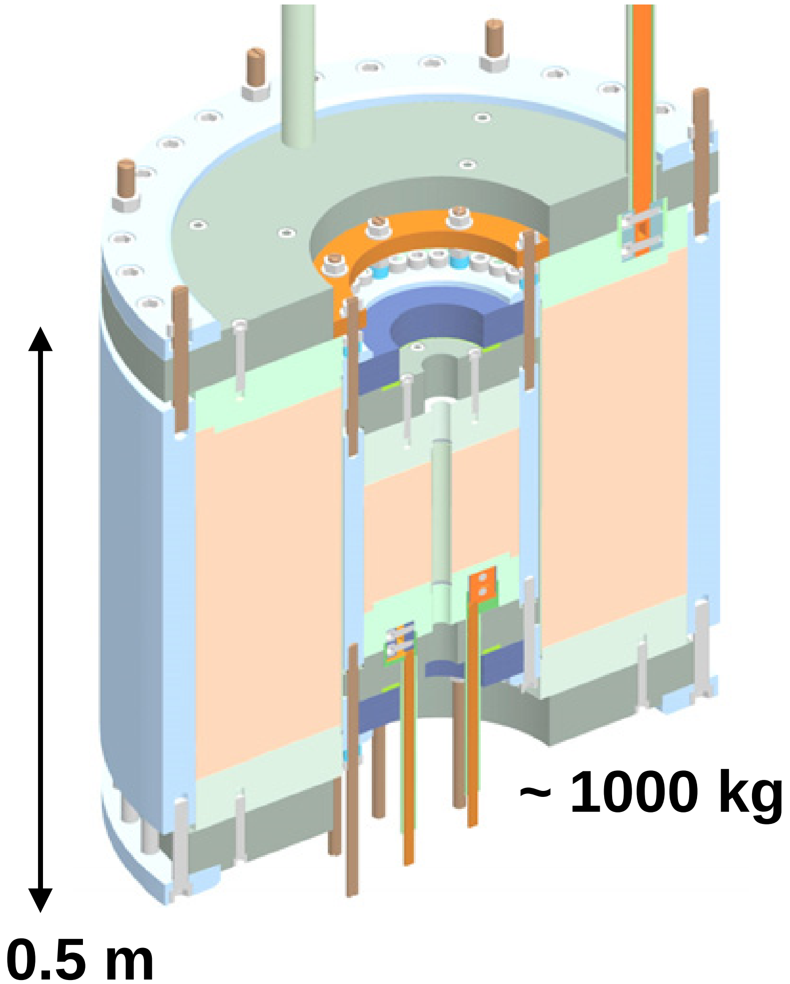
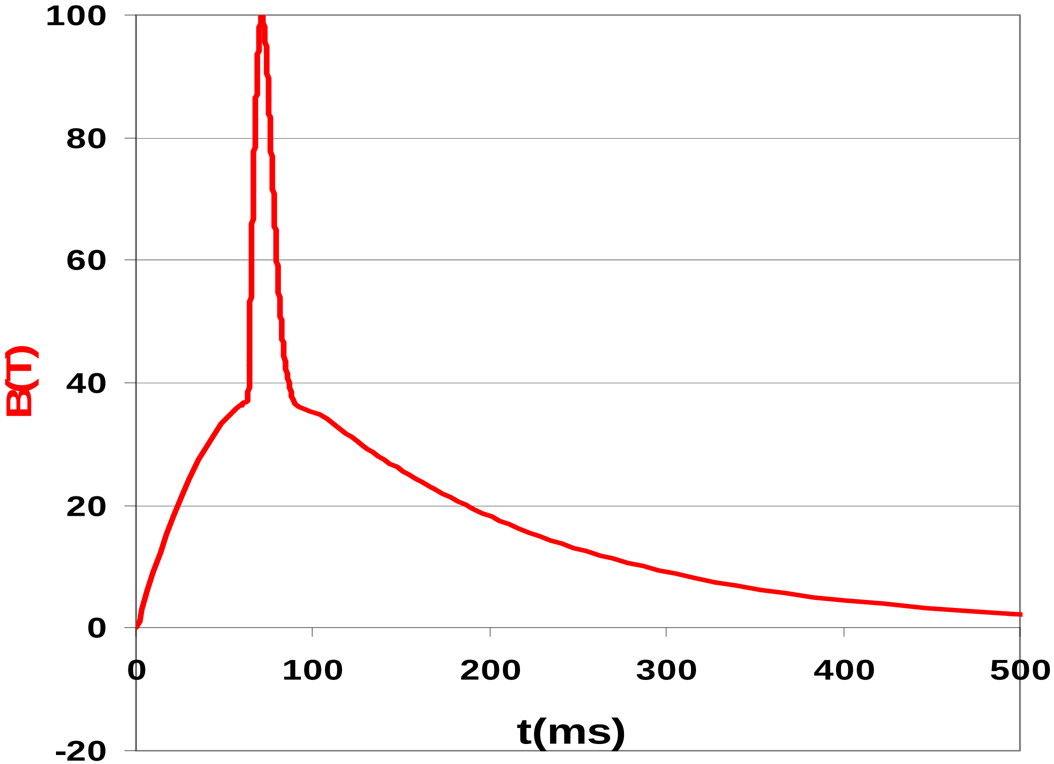


100 T double coil magnet (43 MJ / 3 MJ)





Inner: 20 mm bore, 10 layers CuNb 4x6 mm^2

Outer: 10 layers Cu 8x14 mm^2

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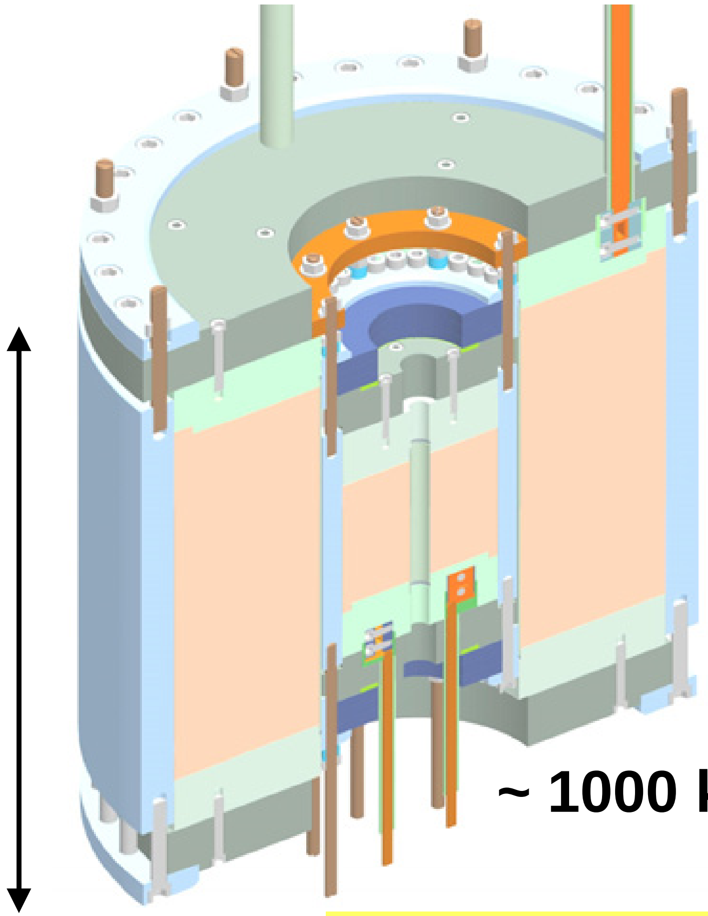
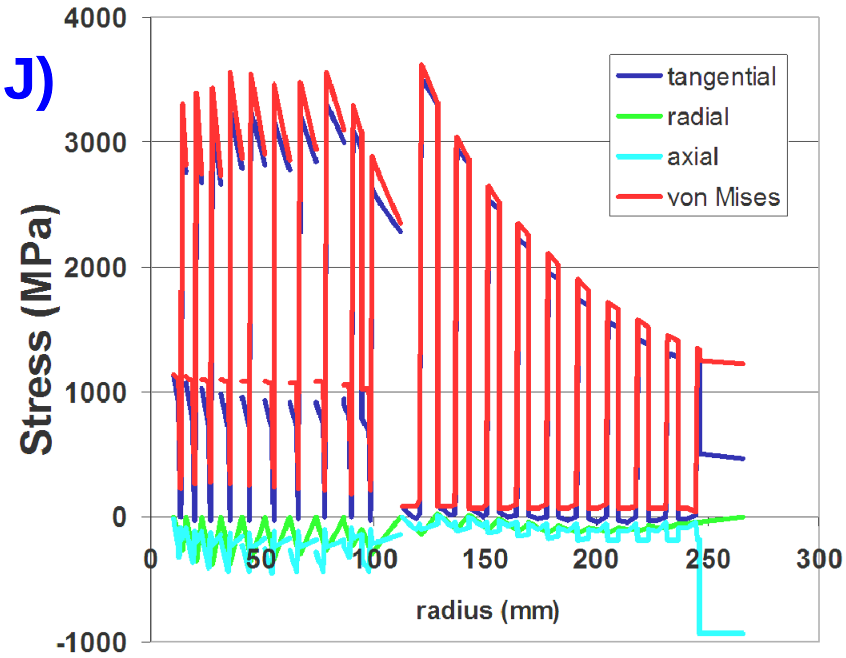


~ 1000 kg

0.5 m



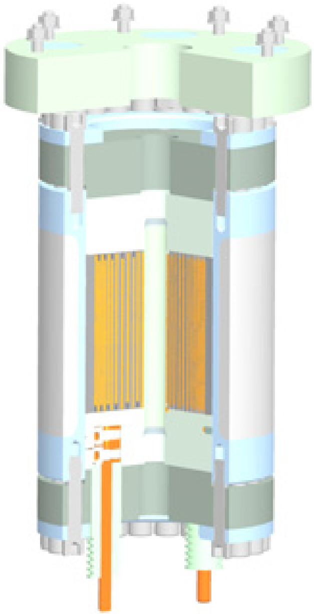
Voltage: 10 ... 30 kV (short pulse!)

Heat up: 77 K ⟶ 350 K in msec

Stress: $P = B^2/2\mu_0 \sim 4$ GPa at 100 T

➡ Realistic Multi-Physics FEM Simulation is needed!

FEA example 1 (azimuthal symmetry):

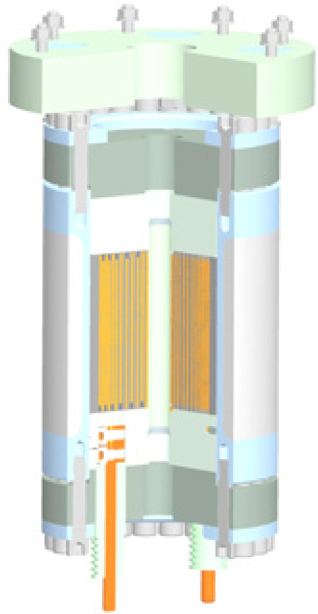


30 turns, 12 layers, 3 mH,
t_{Pulse} = 100 msec; B ~ 70 T

FEA example 1 (azimuthal symmetry):

Challenging conditions in pulsed high-field (70 T) coils

- extremely high Lorentz forces and resulting mechanical load
- extreme heat load
- extreme electrical environment



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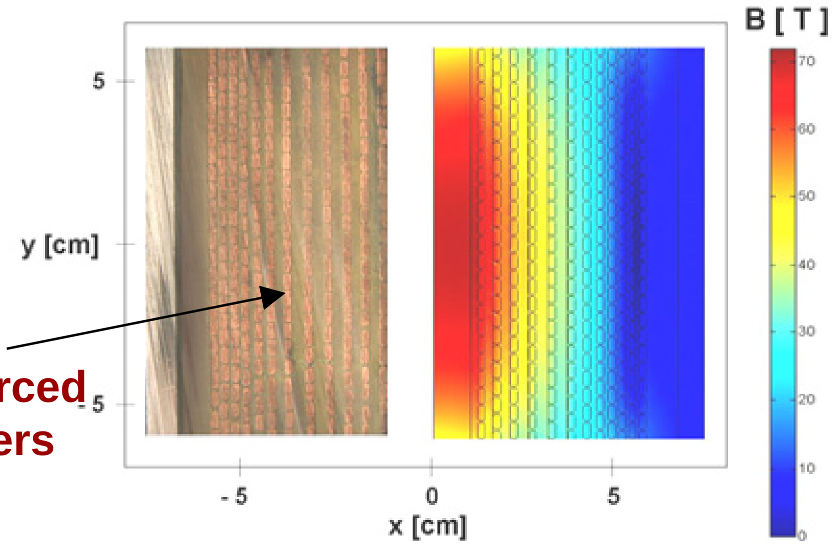
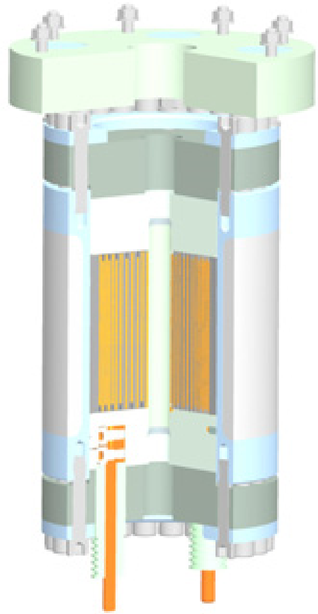
Wires reinforced by fibers





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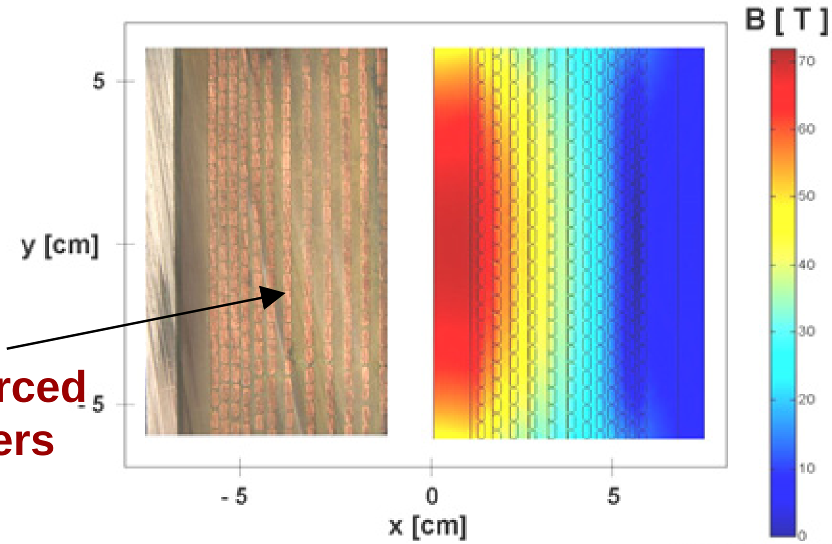

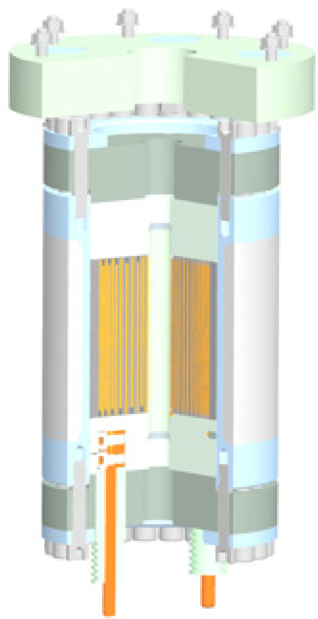

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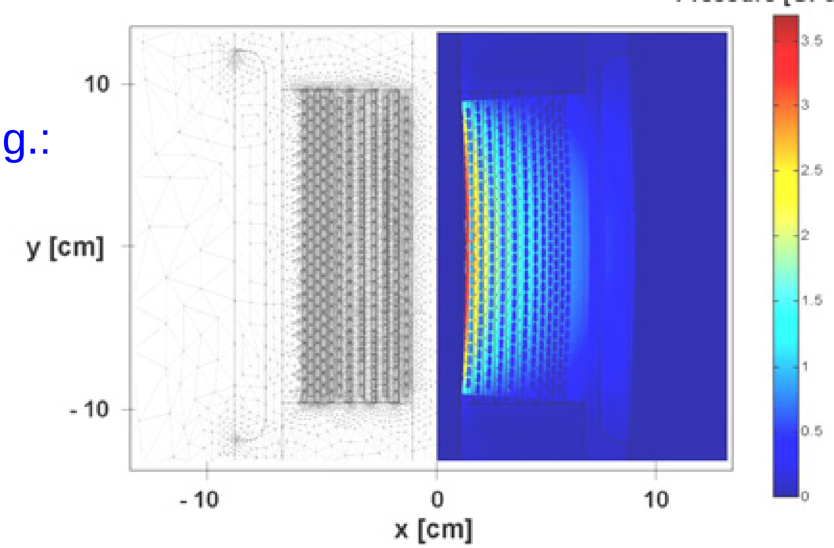
FEA allows for calculation of, e.g.:

B(x, y, z, t) up to 72 T

T(x, y, z, t) up to 350 K

P(x, y, z, t) up to ~ 3.7 GPa

Deformation dx(t), dy(t), dz(t)



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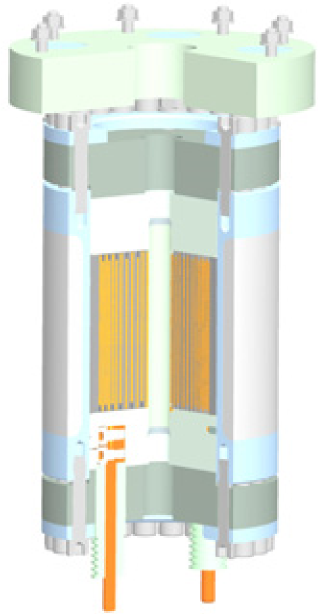

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T(x, y, z, t) up to 350 K

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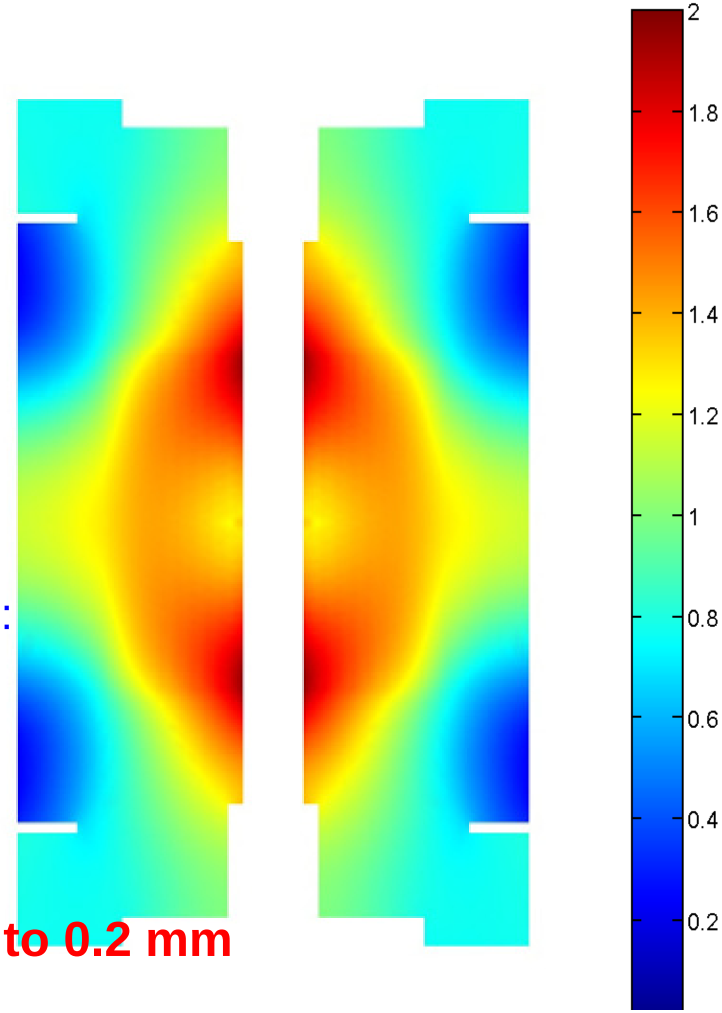
Deformation dx(t), dy(t), dz(t) **up to 0.2 mm**

Deformation [10^{-4} m]



Finite Element Analysis (FEA) has emerged to an important tool

- **to evaluate pulsed-magnetic field techniques which are a technology platform for modern research (and novel industrial innovations)**

- **Thanks to the multiphysics, COMSOL offers many features to simulate the physical behavior of pulsed magnetic field coils made of various parts of materials or composites with very different quantities (iso- or anisotropic functions of temperature, field, pressure, …)**

- **The simulations allow for predicting „weak" points in the coils and avoiding some failure modes.**

- **COMSOL also allows for a computation of quantities which are associated with the design of electrical circuits, such as the inductance of components without any restriction of their shape.**

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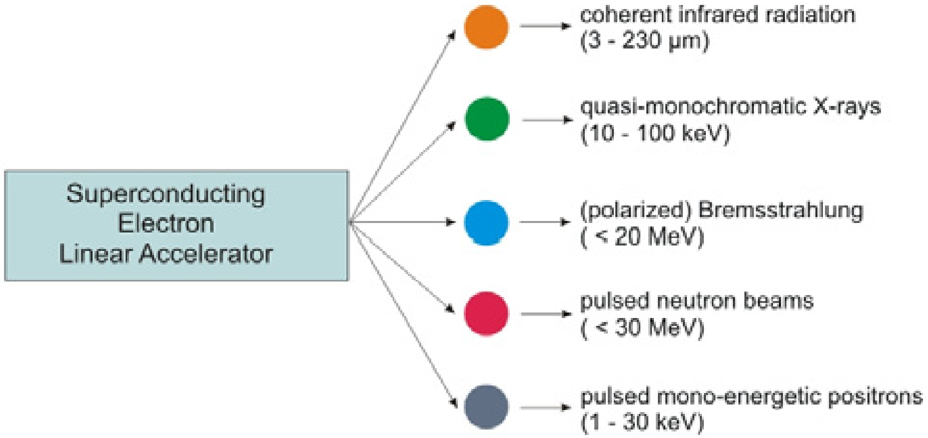
3) Simulation of a separator magnet for ion-beam facility ELBE

ELBE = Electron Linac for beams with high Brilliance and low Emittance

delivers multiple secondary beams
- electromagnetic radiation
- particles



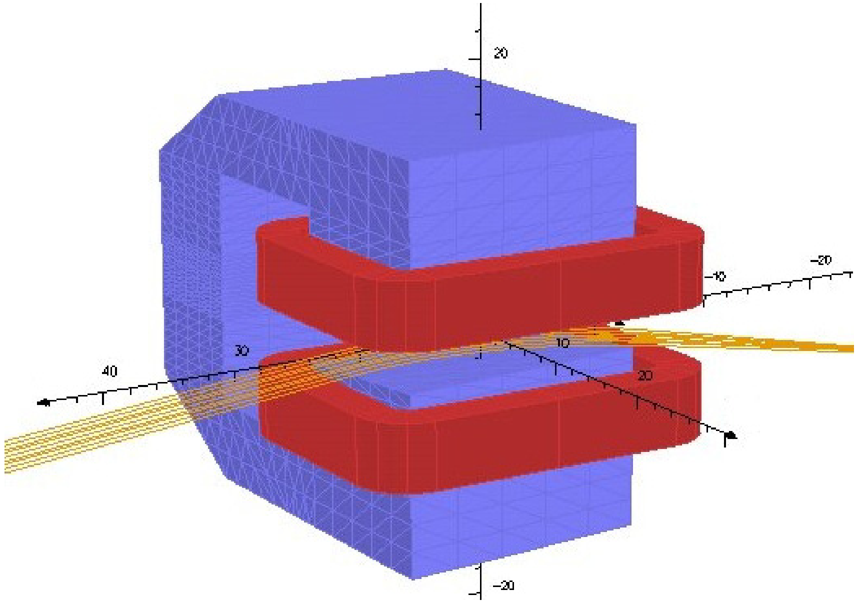
Requirements fo separator magnet:

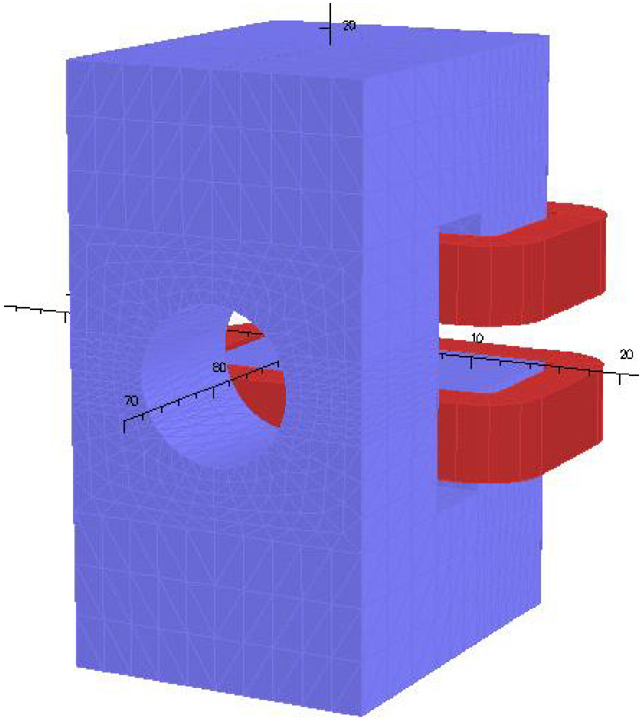
- **to operate e^- and e^+ accelerated up to 50 MeV**
- **to bend them at 45-50 degrees**
- **to have dimensions about $\geq$ 1 m**

FEA example 2 (3D geometry):

Two variants have been suggested:

- **a conventional model**
- **a model with the back leg yoke serving as a radiation shield. The beam enters the field aperture from behind the back leg yoke through a hole**





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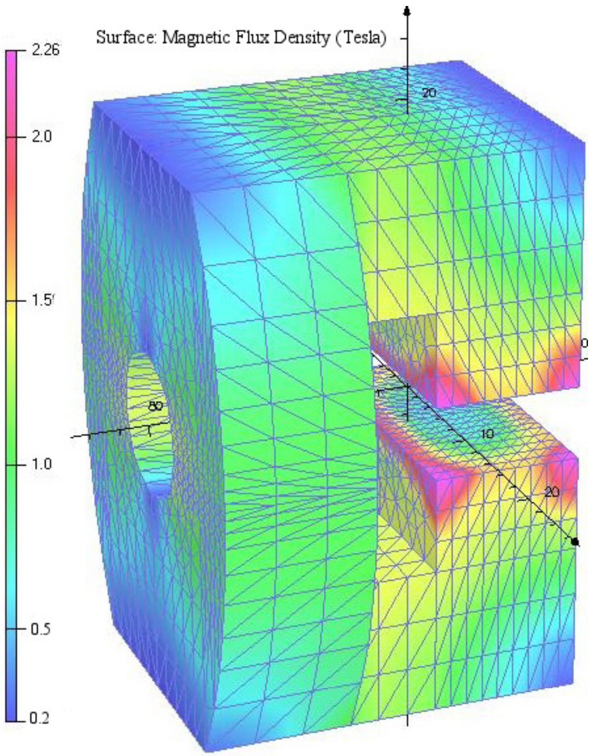

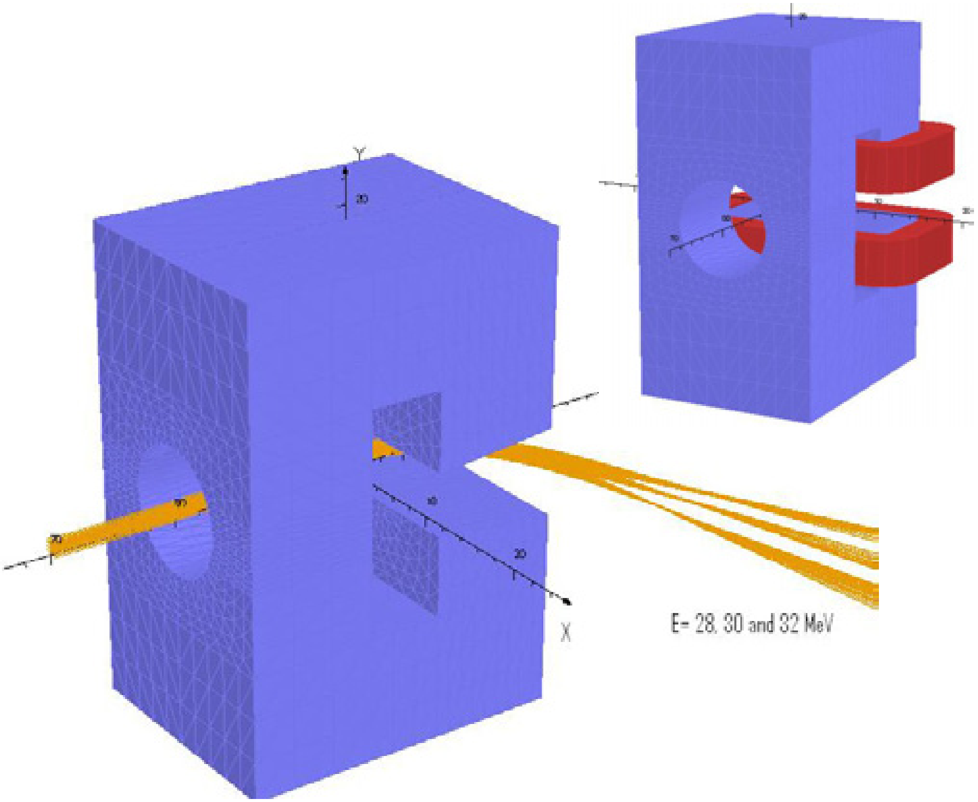

Conclusion to the example:
- possibility to make particle tracing
- possibility to optimize focus position with respect to dimensions of the magnet
- possibility to export 3D field map for further simulation of particle-material interaction (geant 4)

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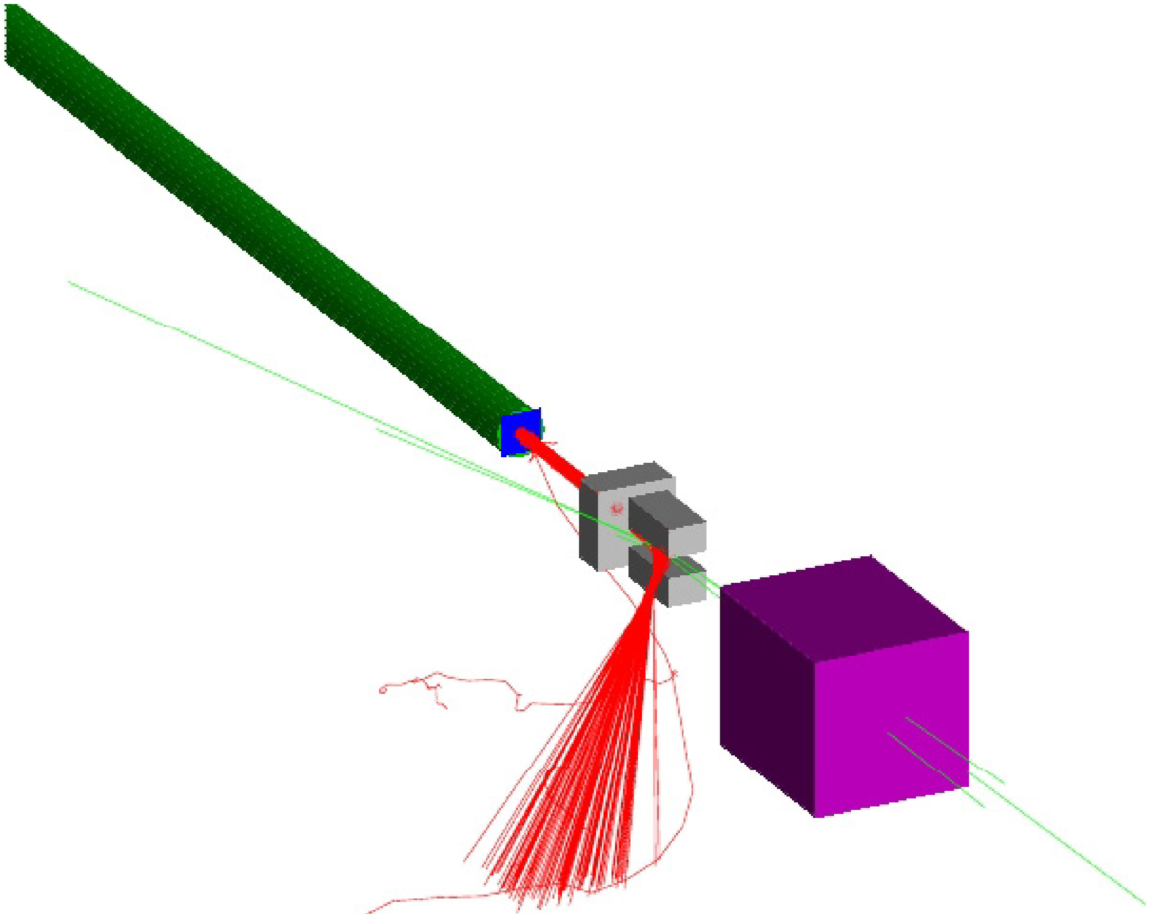

Conclus

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- possibility to optimize focus position with respect to dimensions of the magnet
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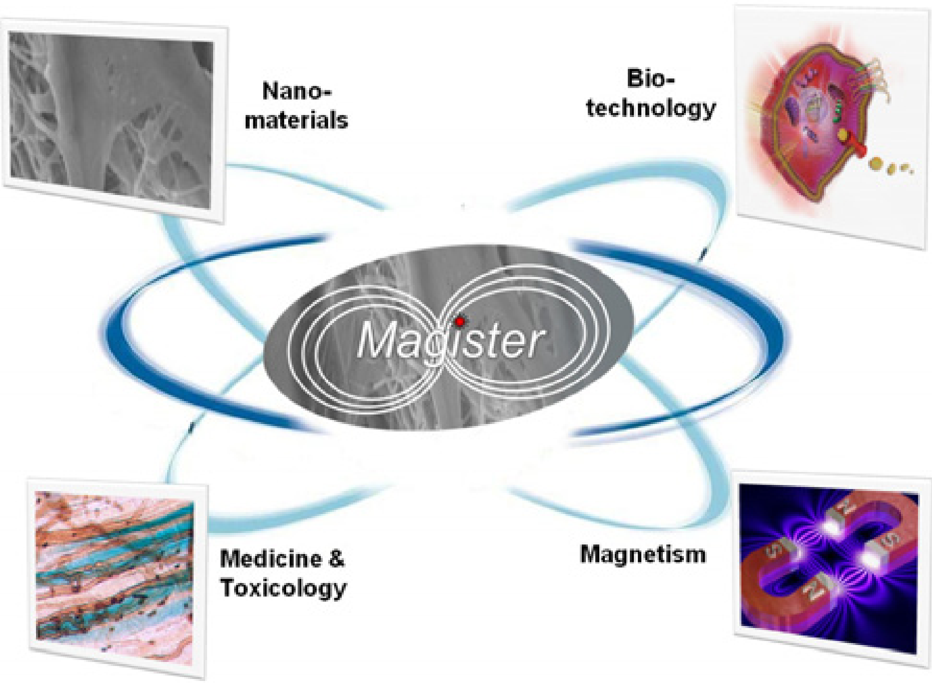
3) Magnetic targeting, diffusion and fixation

MAGISTER is a frontier research project aiming to develop conceptually new type of **Magnetic Scaffolds** for tissue regeneration and orthopaedic surgery.



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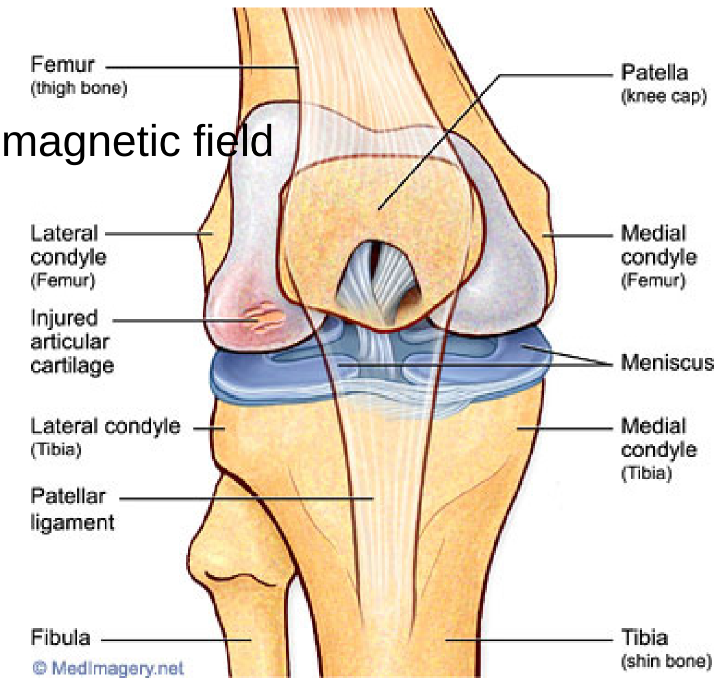
Magnetic Scaffolds:
- are reloadable with magnetic nanoparticles
- should be fixed at certain position with the external magnetic field



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- are reloadable with magnetic nanoparticles (MNPs)
- should be fixed at certain position with the external magnetic field

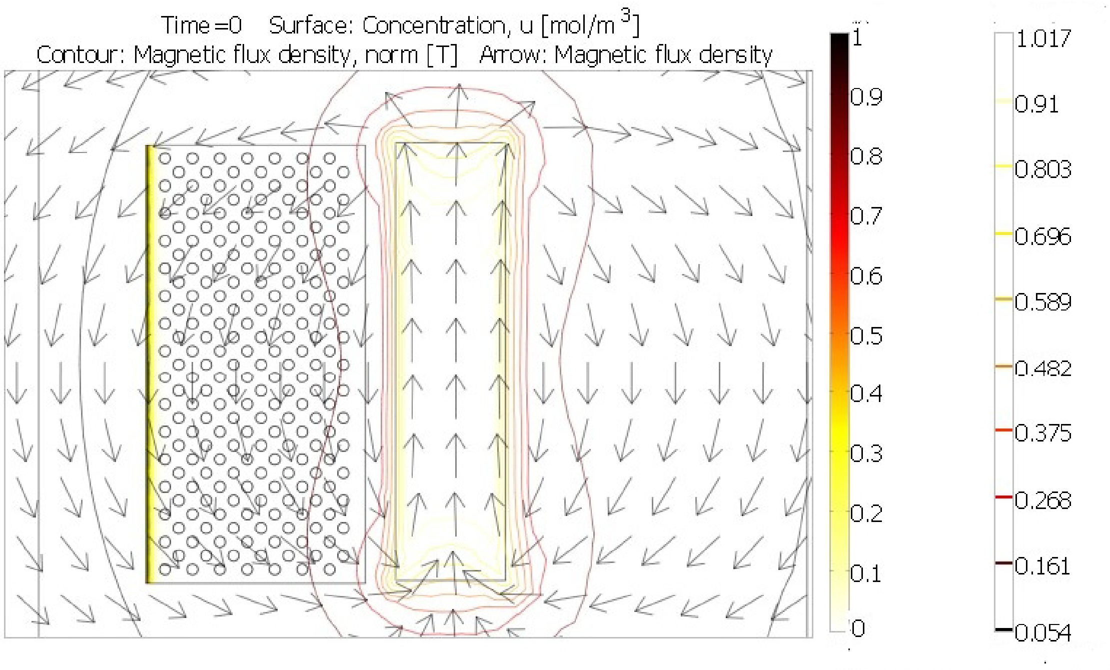
We study:
- manetic targeting, i.e. delivery of magnetic nanoparticles to the specific site
- penetration of MNPs into the scaffold or microvsculture
- fixation of magnetic scaffolds

3) Magnetic diffusion

F ~ **M** ∇**B**

Magnetic force modifies the particle flux and this way enters the diffusion equiation:

$c' = -\nabla (D\nabla c) - \nabla(c\, \mathbf{v}_{mag})$



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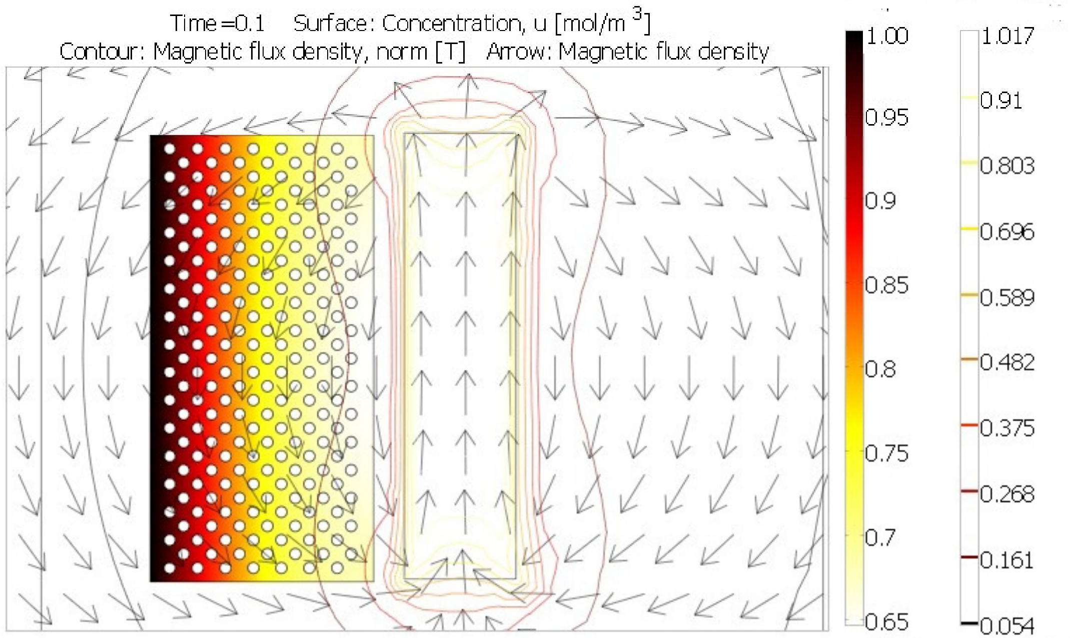

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$\mathbf{F} \sim \mathbf{M}\, \nabla \mathbf{B}$

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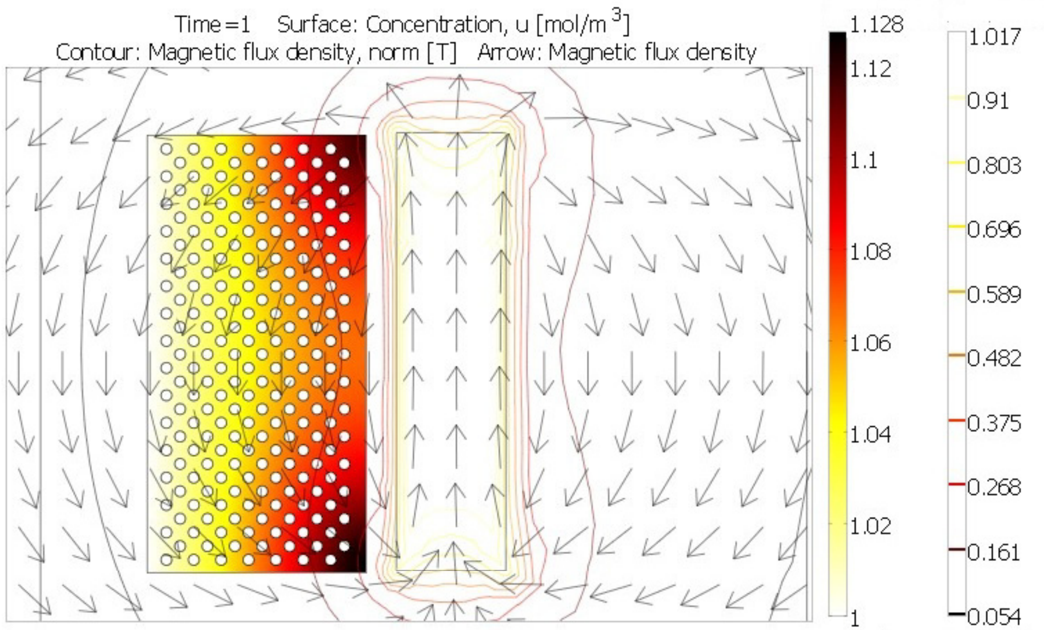
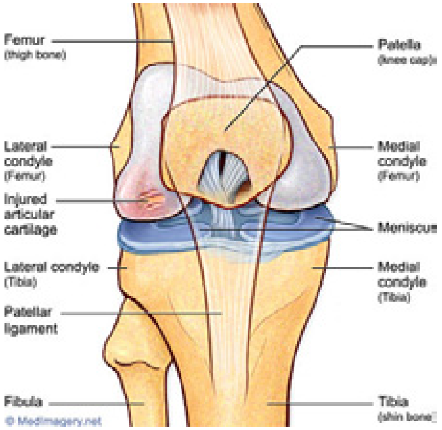
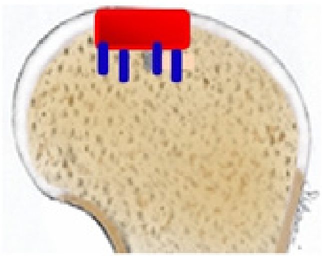
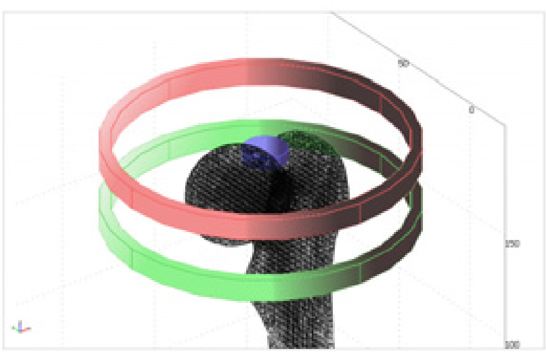
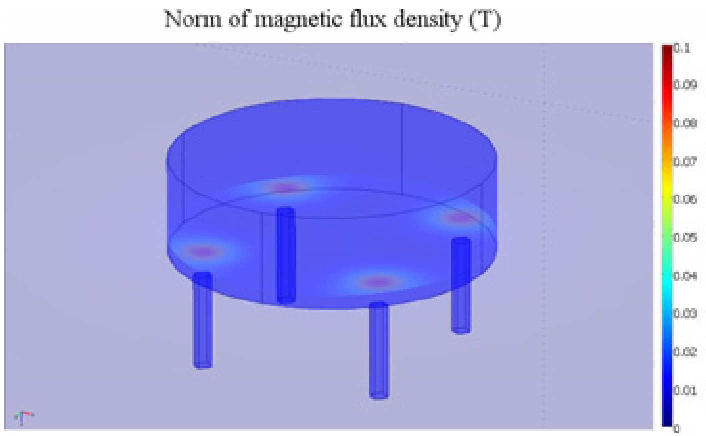



Femur
(thigh bone)
Patella
Lateral condyle (Femur)
Medial condyle (Femur)
Injured articular cartilage
Meniscus
Lateral condyle (Tibia)
Medial condyle (Tibia)
Patellar ligament
Fibula
Tibia
© MedImagery.net






Norm of magnetic flux density (T)
0.1
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0

4) Conclusion to the example

- COMSOL allows for modeling of complex processes related to tissue engineering

- In conjunction with image-data processing software Comsol can serve as a useful simulation platform for medicine

- In the case of bone and osteochondral treatment, as investigated in the framework of MAGISTER project, it may provide a unique possibility to simulate and, thus, adjust the scaffold activity to the personal needs of the patient.

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SMWK

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- EuroMagNET
- DeNUF
- MAGISTER
- EuroMagNET-II

Thank you for your attention!