Presented at the COMSOL Conference 2008 Hannover

Highest Pulsed Magnetic Fields in Science and Technology, Assisted by Advanced Finite-Element Simulations

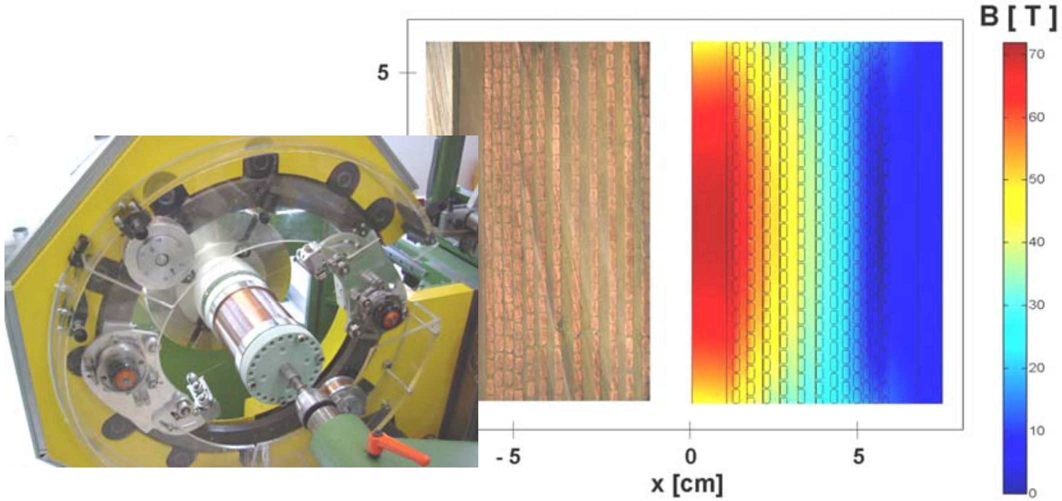
Hochfeld-Magnetlabor Dresden

Forschungszentrum Dresden Rossendorf

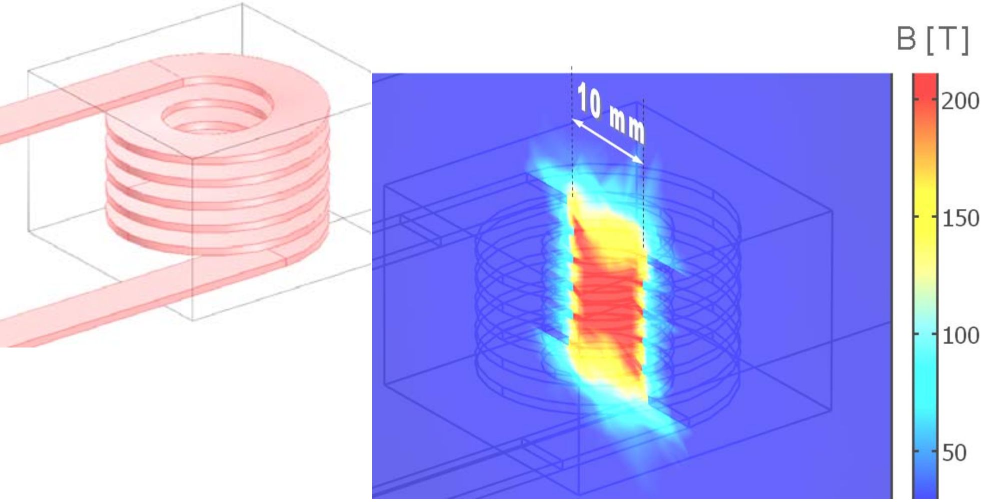
1) Highest magnetic fields for advanced materials studies

1) Highest magnetic fields for advanced materials studies

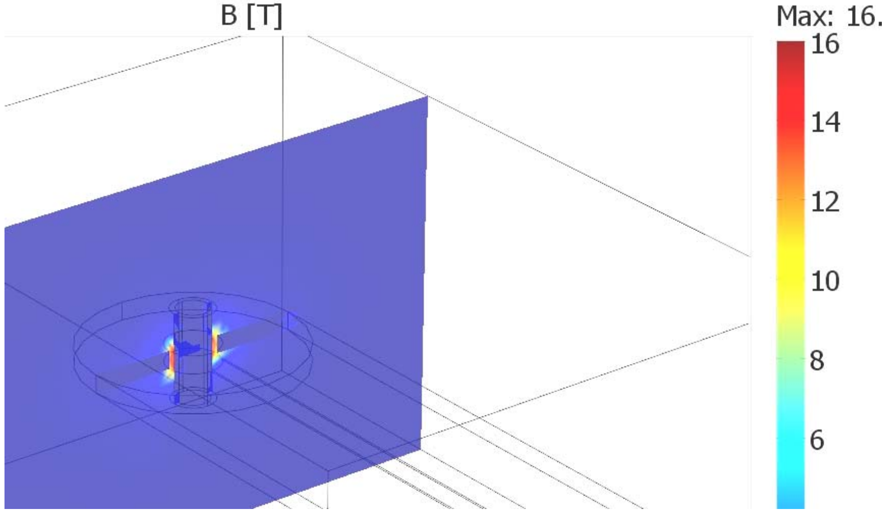
2) Design, fabrication, and use of pulsed-field coils for materials research

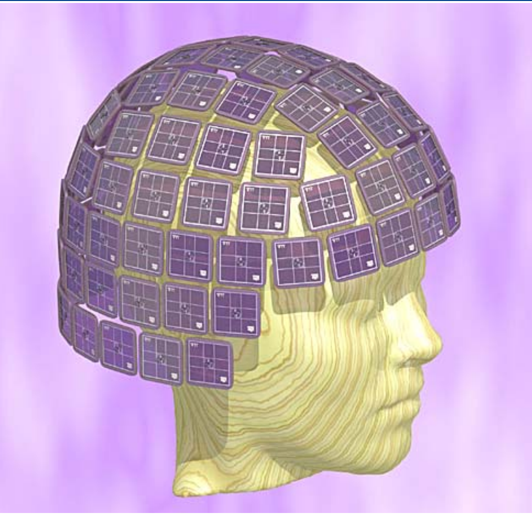


3) Simulation of pulsed-field coils for ultimate flux densities



4) Simulation of electromagnetic pulse-forming processes

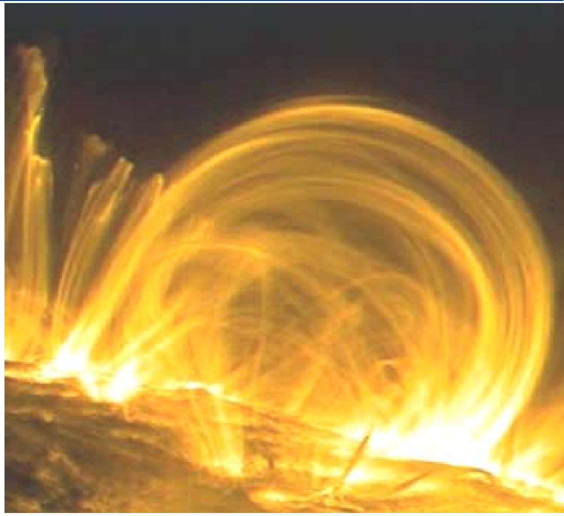




Biology
pT – nT

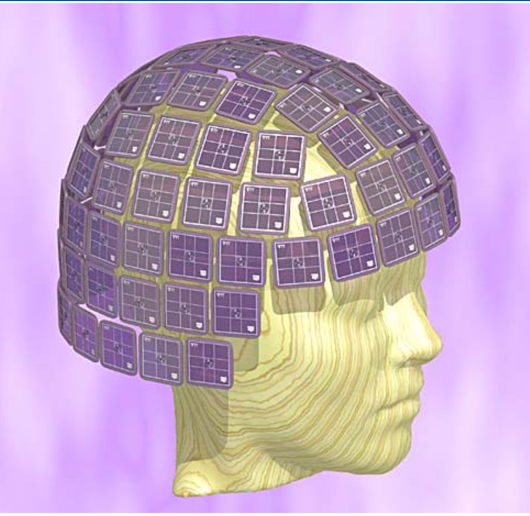
Civilization
~ µT

Earth
45 µT



Sun
0.1 T

Magnetic fields in Nature and Technology [1 T = 1 Tesla = 1 Vs/m^2]



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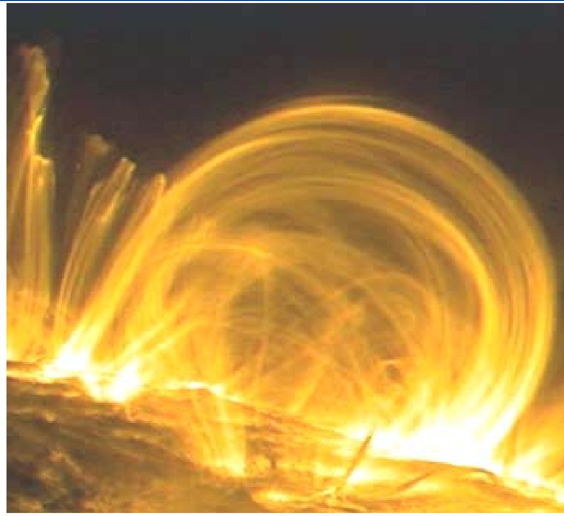
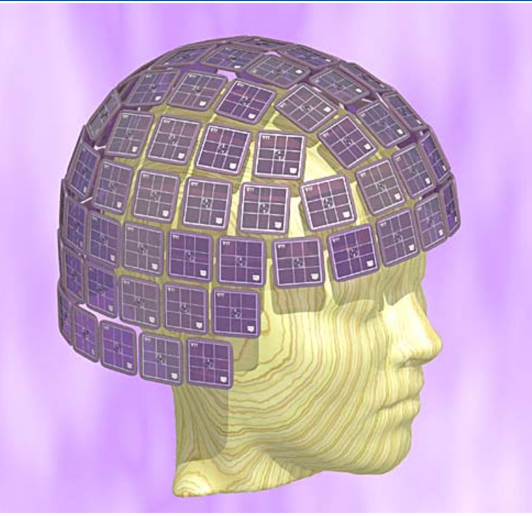


Sun
0.1 T

Diagnostics
~ 1 T



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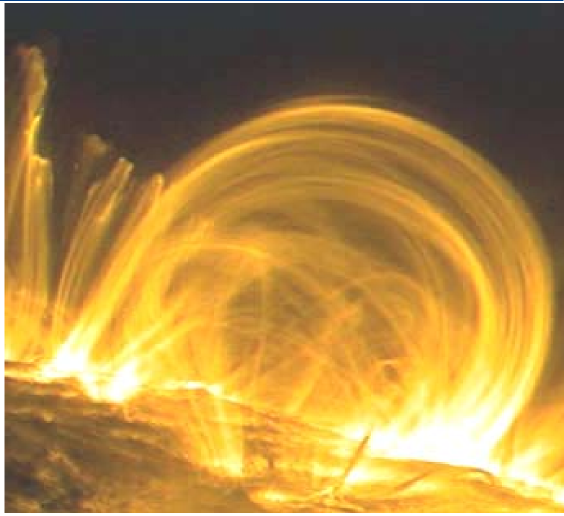

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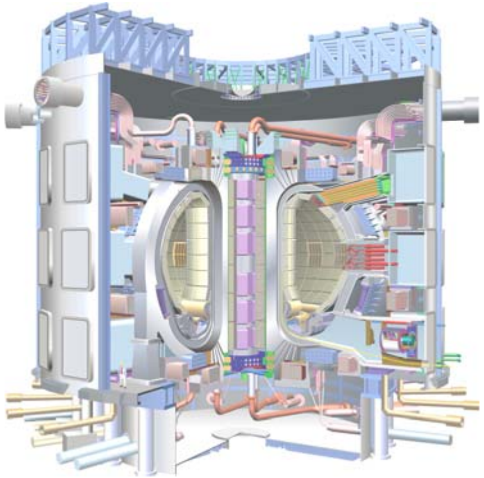
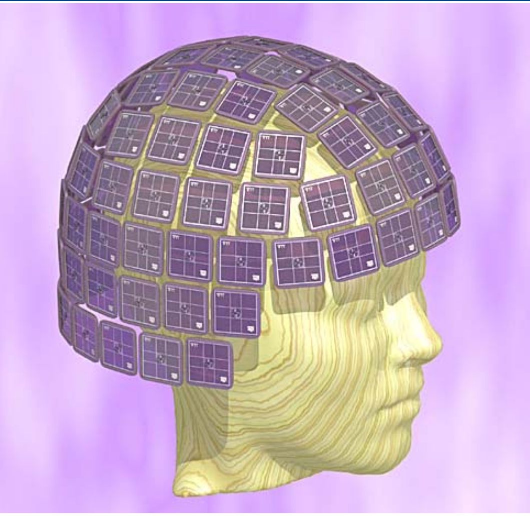


Fusion
~ 10 T

Magnetic fields in Nature and Technology [1 T = 1 Tesla = 1 Vs/m^2]



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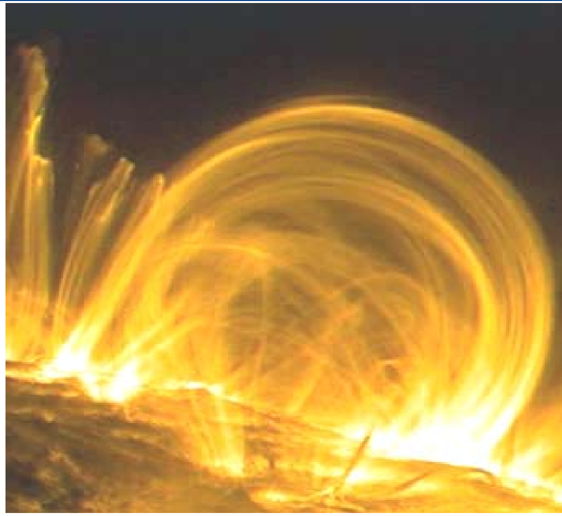

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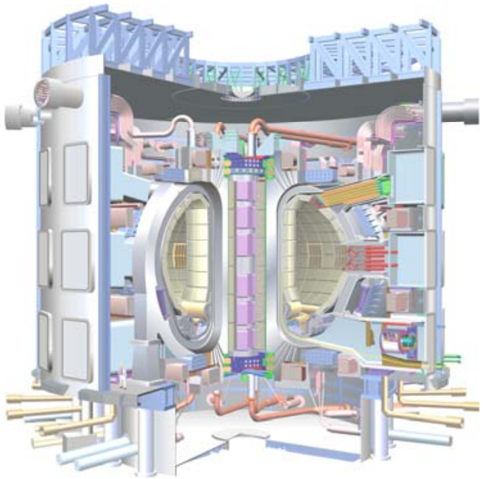
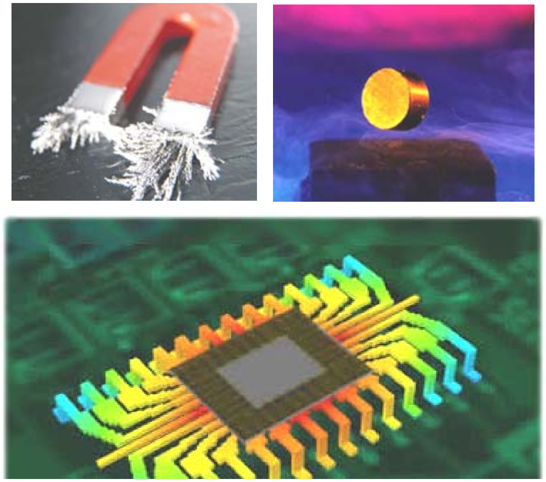
Diagnostics
~ 1 T

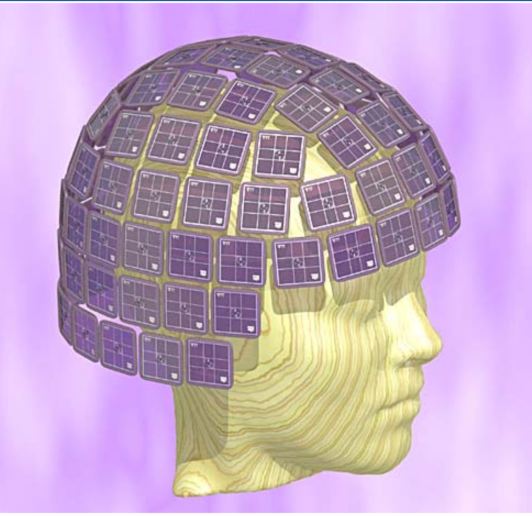


Fusion
~ 10 T



Materials
µT – 1000 T

Magnetic fields in Nature and Technology [1 T = 1 Tesla = 1 Vs/m^2]



Biology
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Civilization
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Earth
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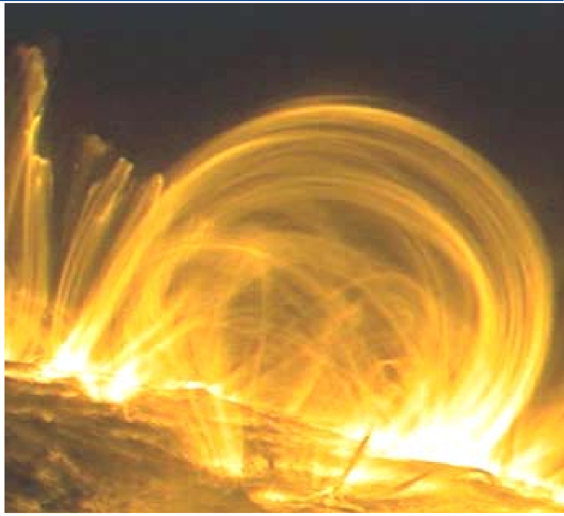

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Diagnostics
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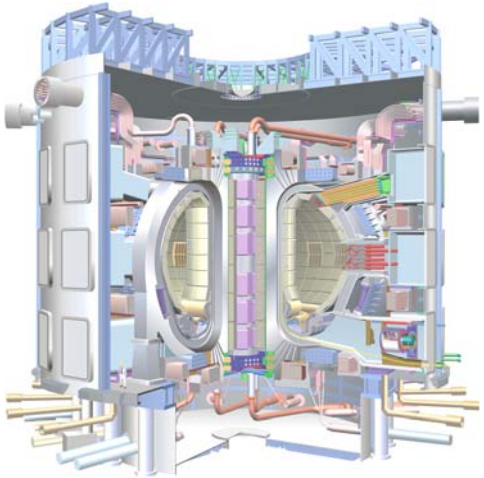
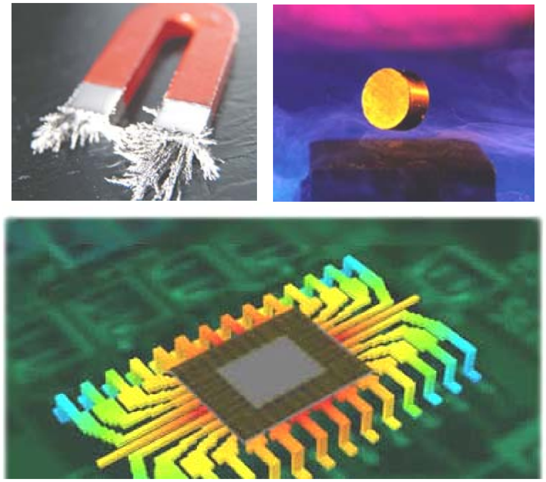
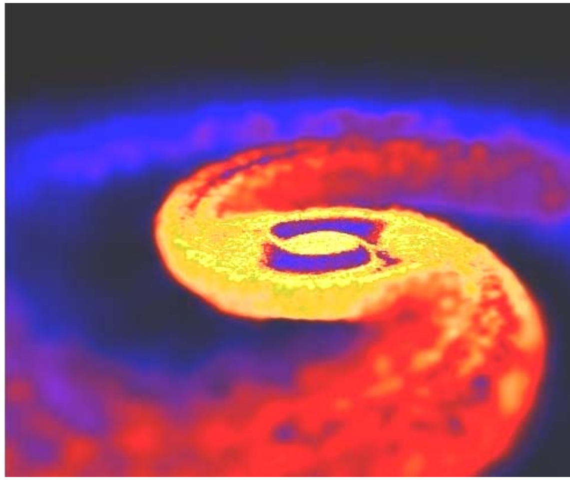


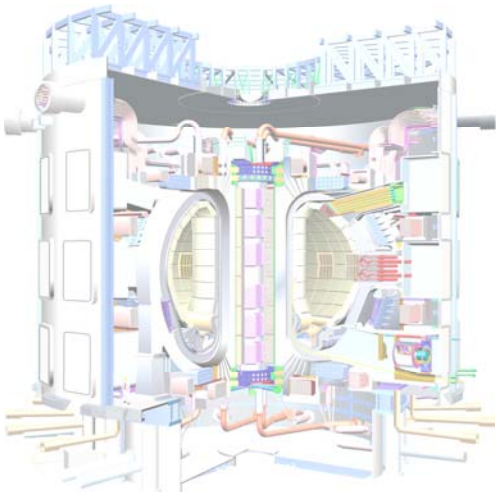
Fusion
~ 10 T

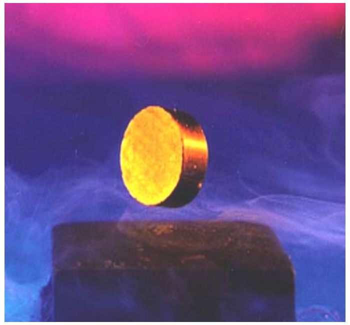


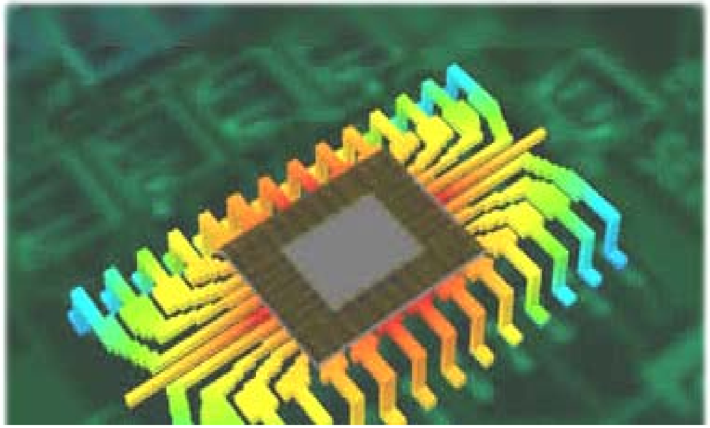
Materials
µT – 1000 T



Neutron stars
$10^8 – 10^{11}$ T







- Ferromagnets
- Antiferromagnets
- Multiferroics
- Strongly correlated electron systems
- Superconductors
- Semiconductors
- Nanoclusters
- Low-D spin systems
- Metal organics
- Proteins
- ...

Diagnostics
~ 1 T

Fusion
~ 10 T

Materials
µT – 1000 T

+Research on advanced techniques in pulsed magnetic fields

1) Highest magnetic fields for advanced materials studies

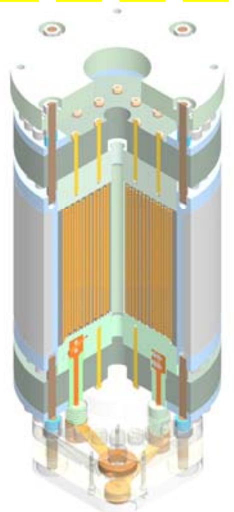
B [Tesla]

100

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

80

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

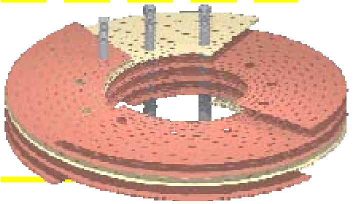


60

50

40 ***static:*** **Hybrid Magnets** **20 MW**

30 **Resistive Bitter Magnets**

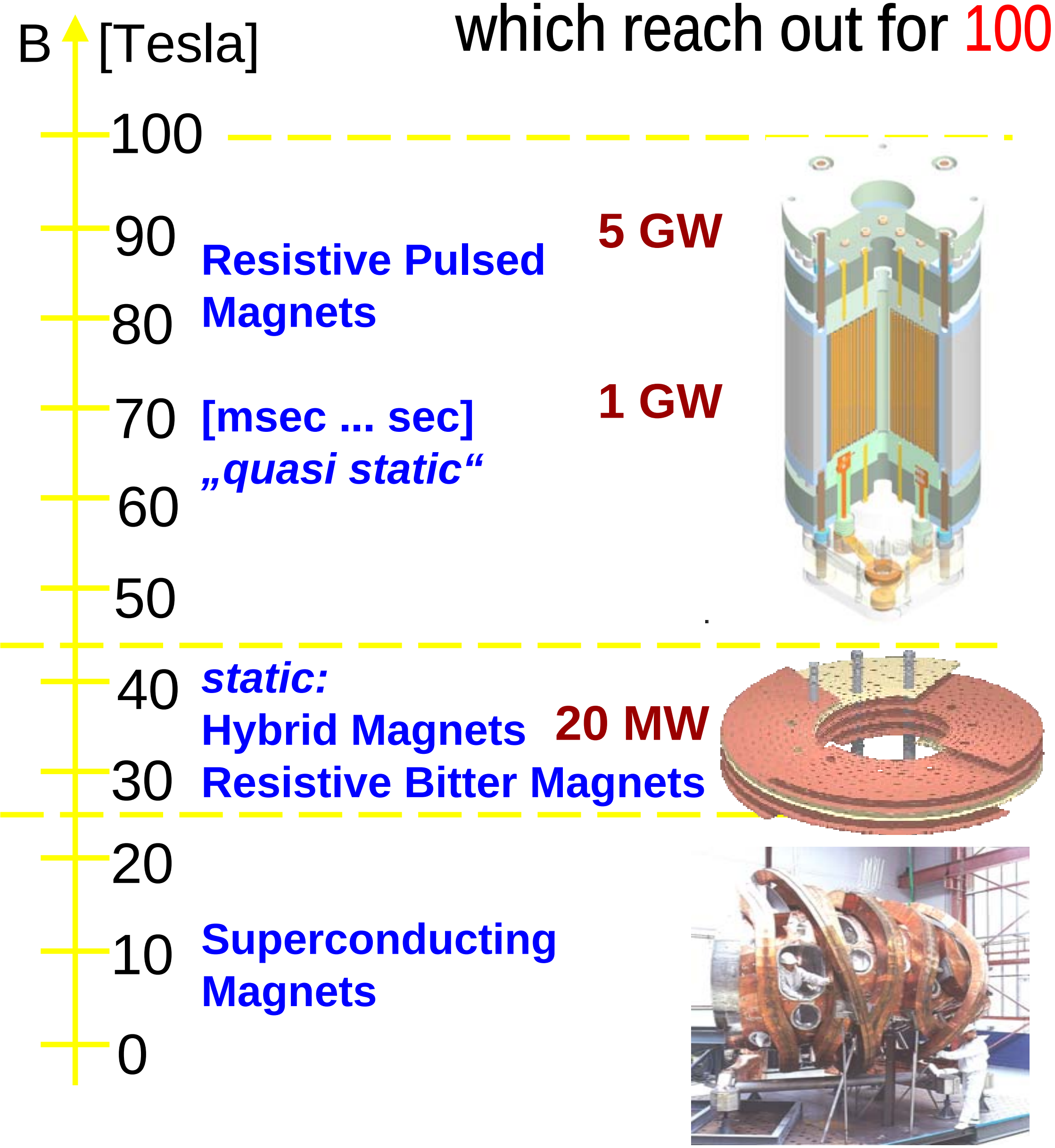


20

10 **Superconducting Magnets**

0

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



1) Highest magnetic fields for advanced materials studies

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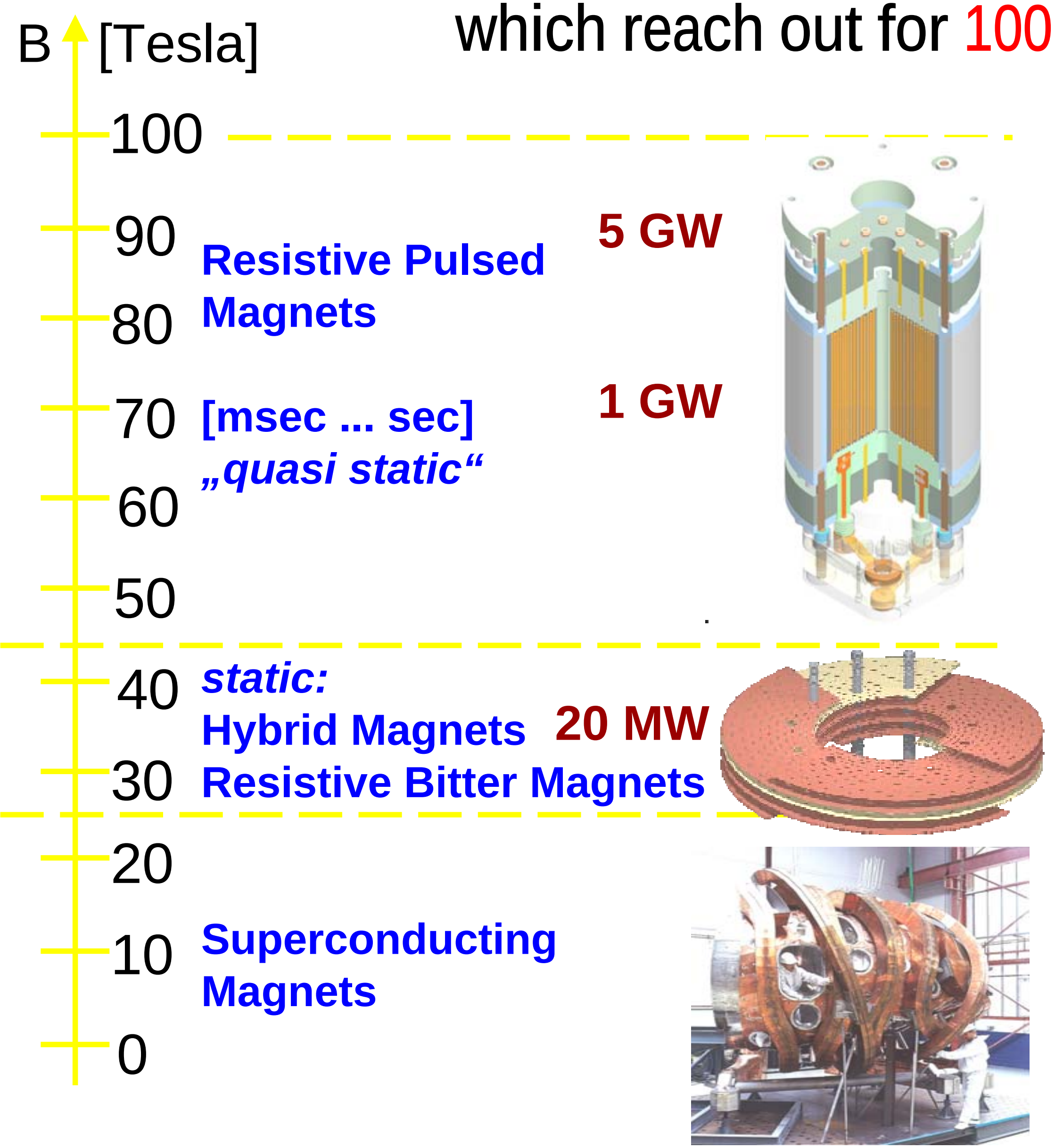

The Quest for 100 T in the quasistatic (0.01 ...1 sec) time range

1) Highest magnetic fields for advanced materials studies

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B [Tesla]

100

90

80

70

60

50

40

30

20

10

0

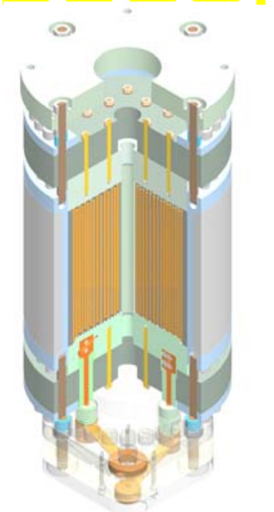
Resistive Pulsed Magnets

[msec ... sec]

„quasi static“

5 GW

1 GW

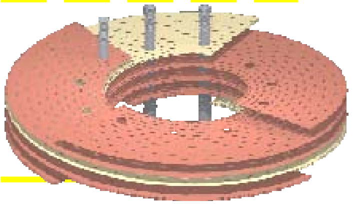


static:

Hybrid Magnets

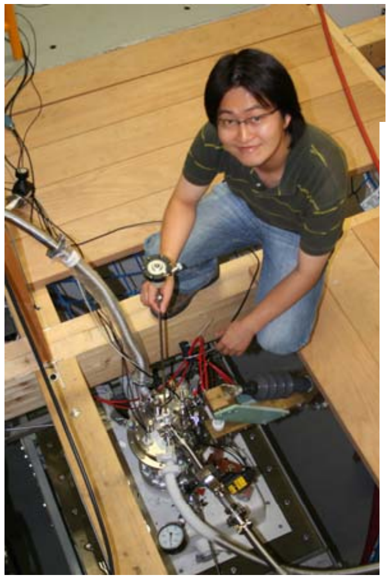
Resistive Bitter Magnets

20 MW

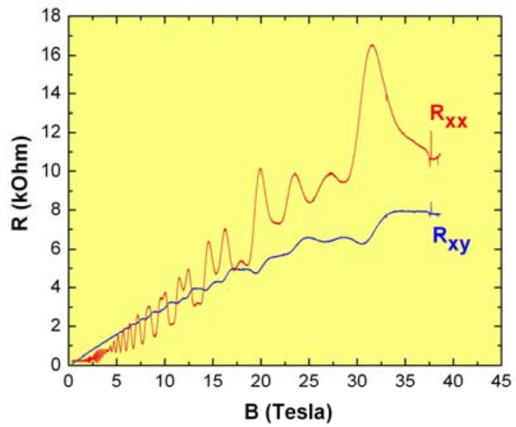


Superconducting Magnets

- **HLD was evaluated and recommended by the German Science Council**
- **HLD is worldwide the only facility which provides combined access to high magnetic fields and intense IR-FIR radiation**
- **HLD is financed by** Bundesministerium für Bildung und Forschung; SMWK



„advanced materials in high magnetic fields“



1) Highest magnetic fields for advanced materials studies

$B \sim \mu_0 N I / l$

B = 50 ... 100 T,

Current I ~ 100 kA

50 MJ / 24 kV / 600 kA / 5 GW modular capacitive pulsed-power supply

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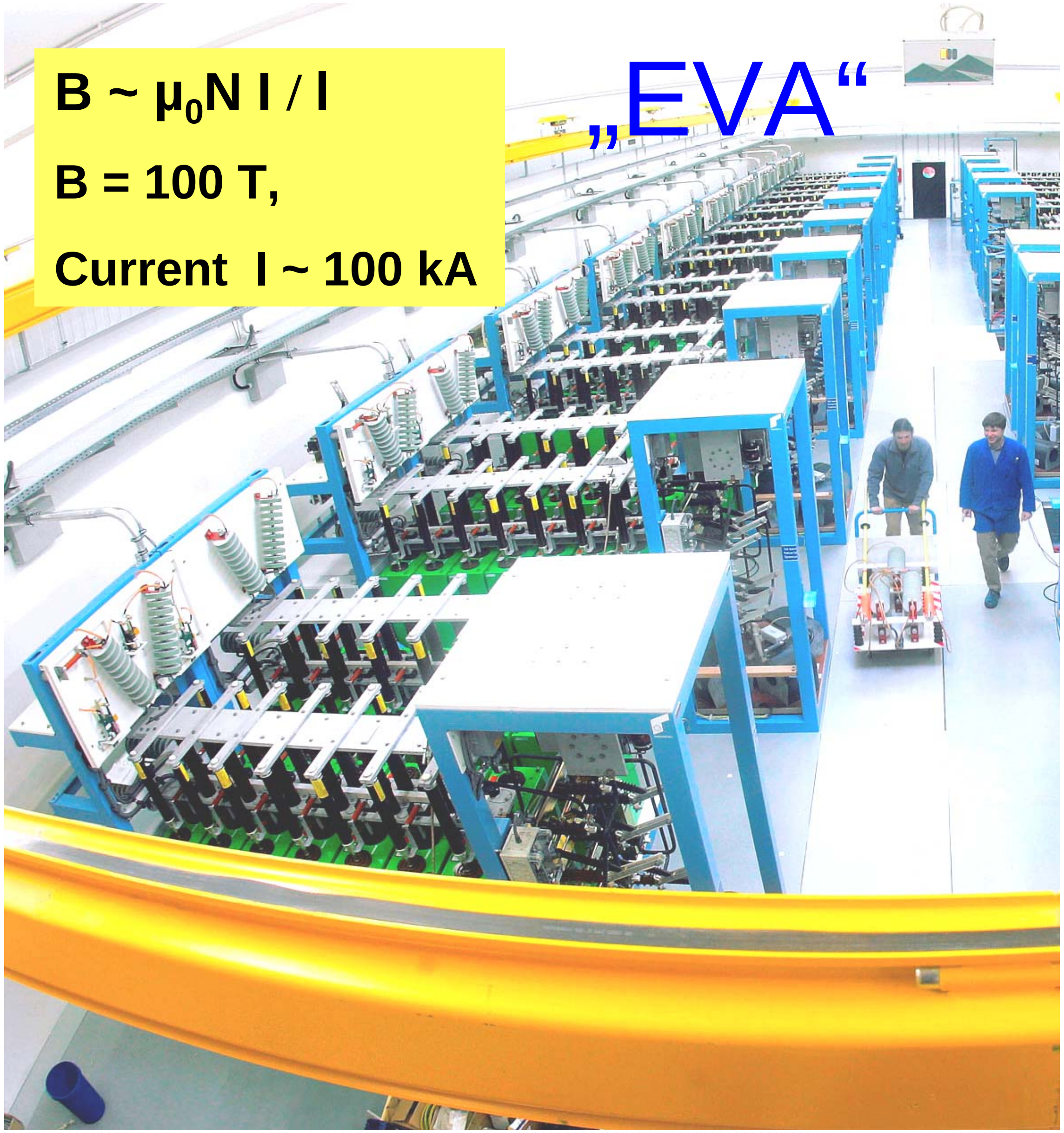
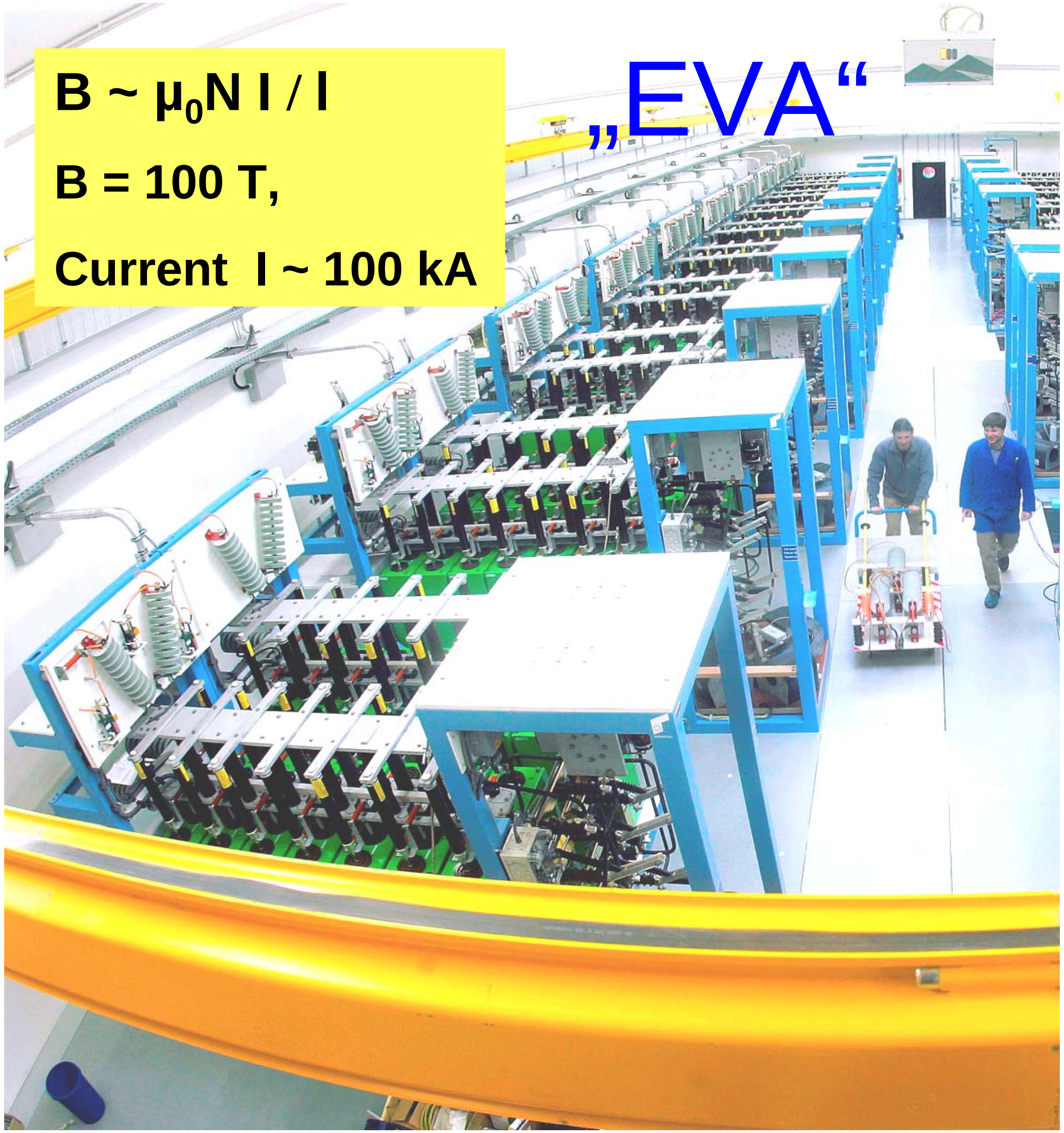


50 MJ:

18 000 kg at 270 km/h

50 MJ / 24 kV / 600 kA / 5 GW modular capacitive pulsed-power supply



$B \sim \mu_0 N\, I\, /\, l$

B = 100 T,

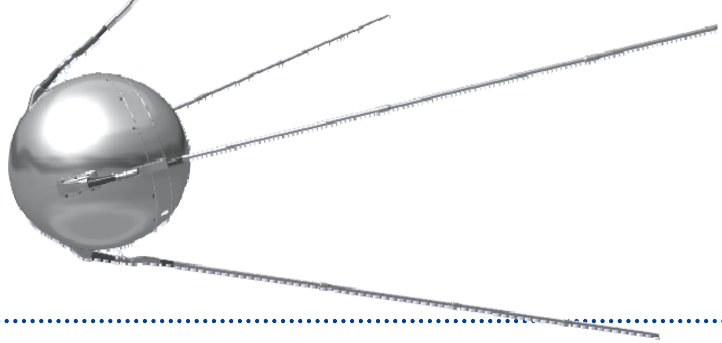
Current I ~ 100 kA

„EVA“

50 MJ:

18 000 kg at 270 km/h

1.8 kg at 27.000 km/h



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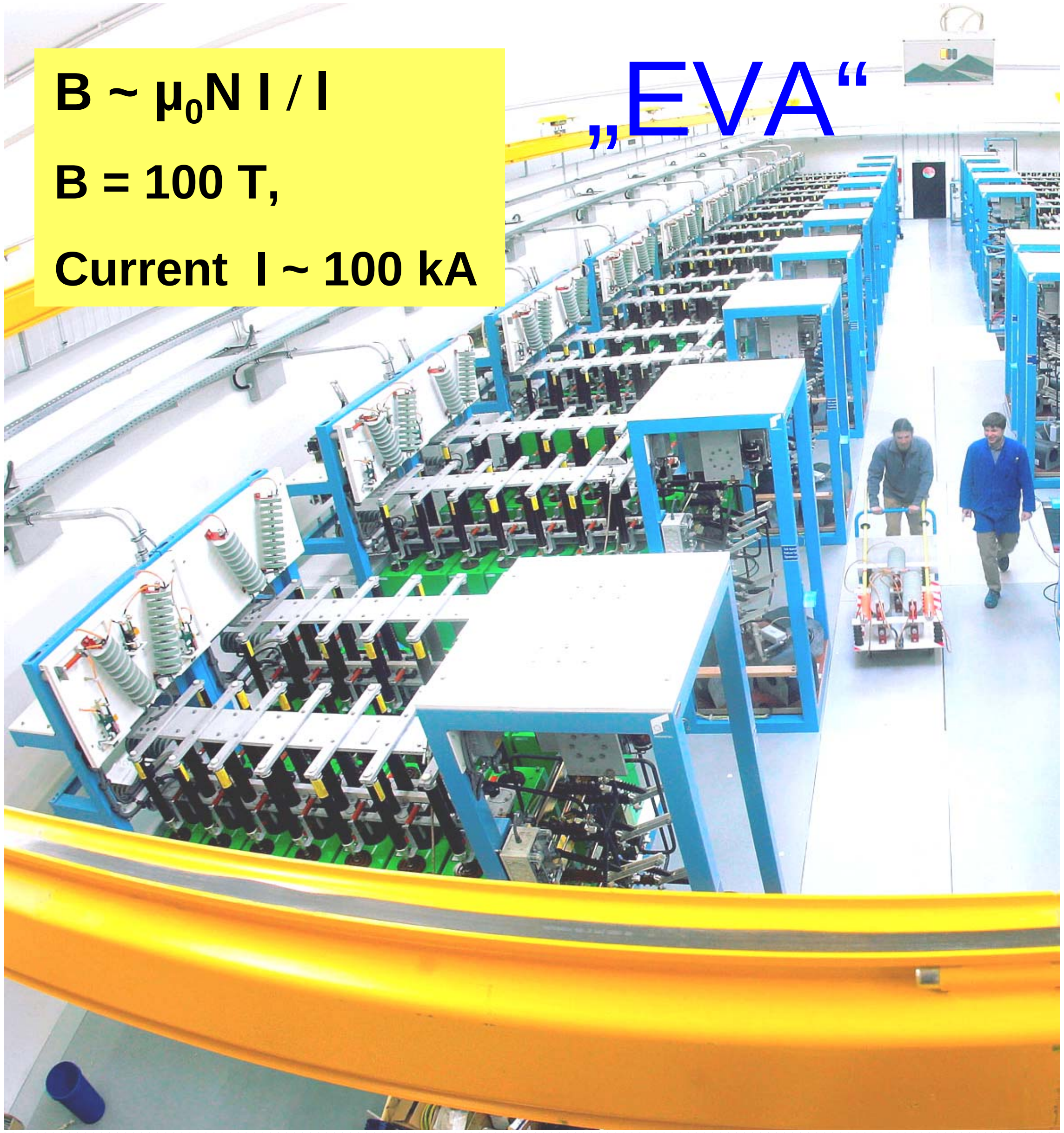

5 GW ~ 7.000.000 Ps

~ power production/ consumption of a few million people

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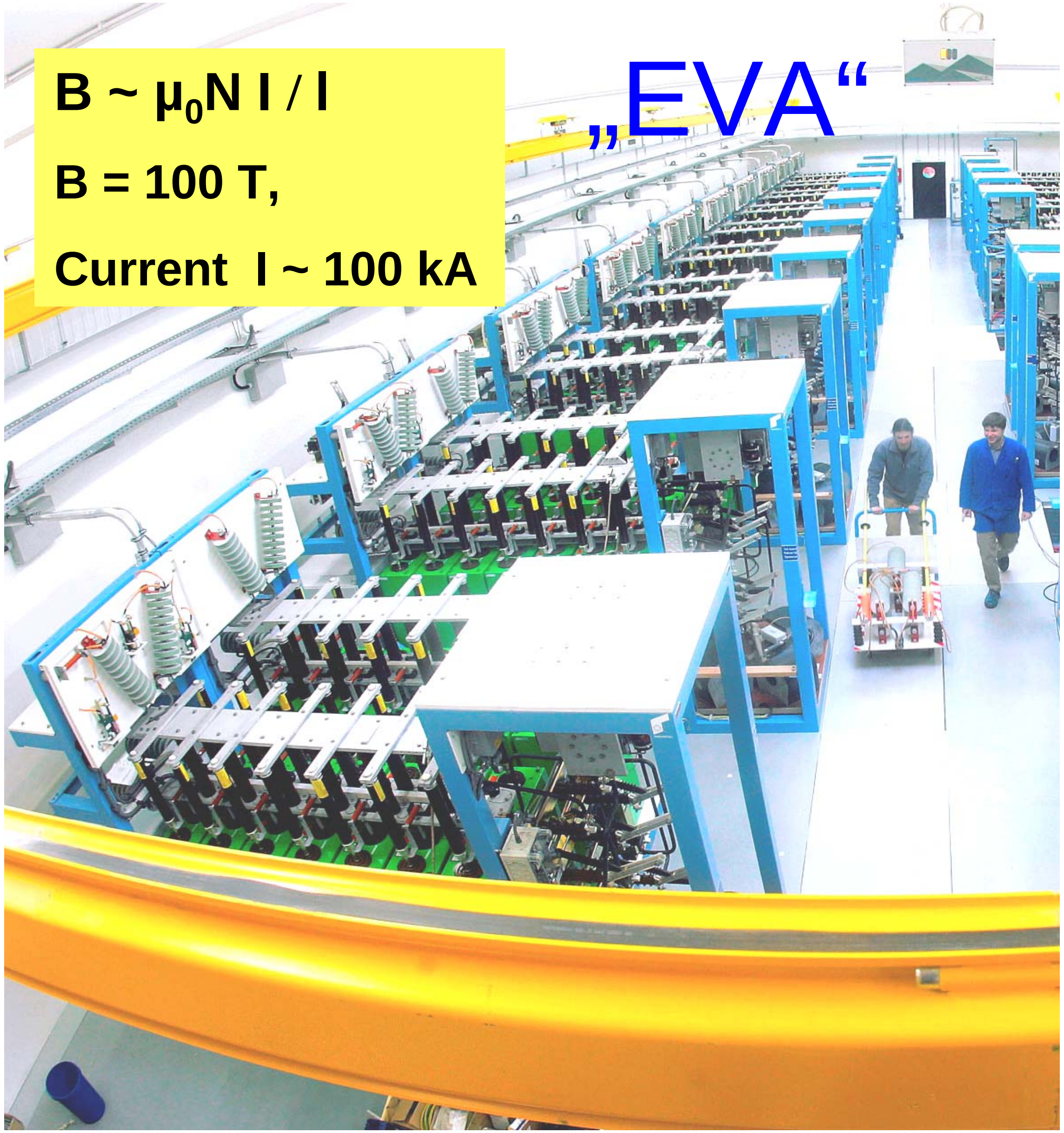
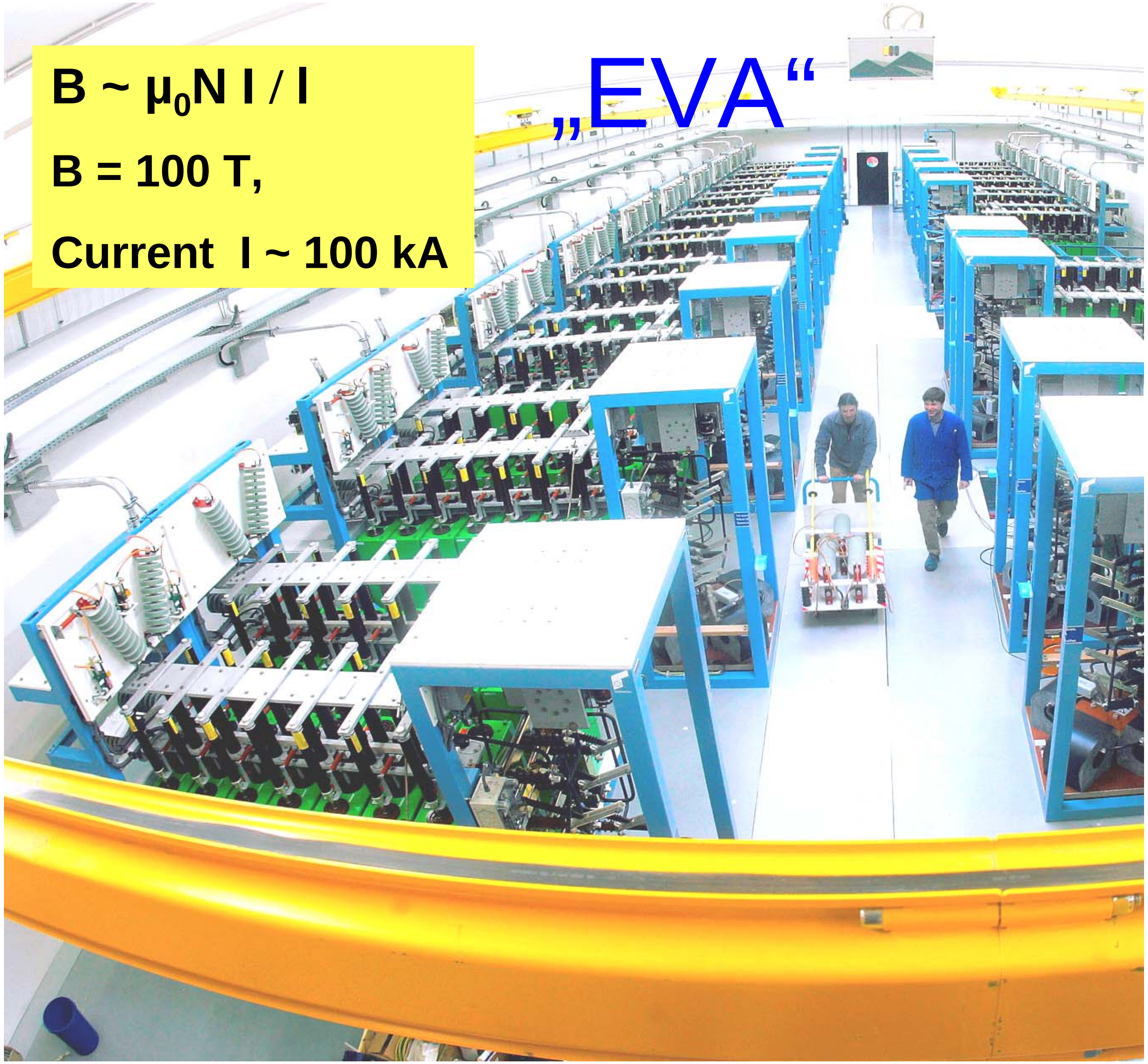


5 GW ~ 7.000.000 Ps

~ power production/ consumption of a few million people

~ or: power of a rocket

50 MJ / 24 kV / 600 kA / 5 GW modular capacitive pulsed-power supply



Costs of 50 MJ ?

50 MJ / 24 kV / 600 kA / 5 GW modular capacitive pulsed-power supply

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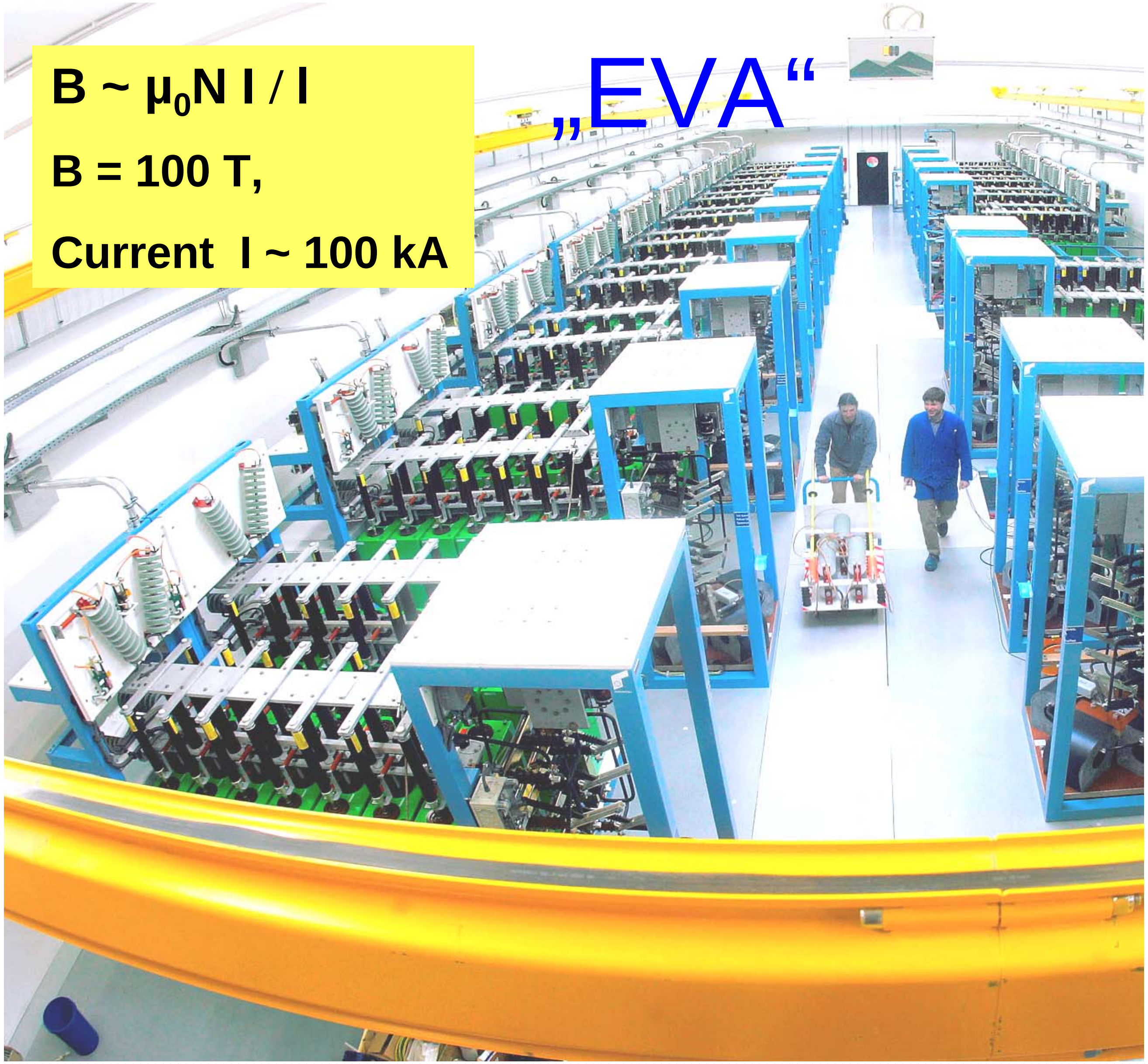
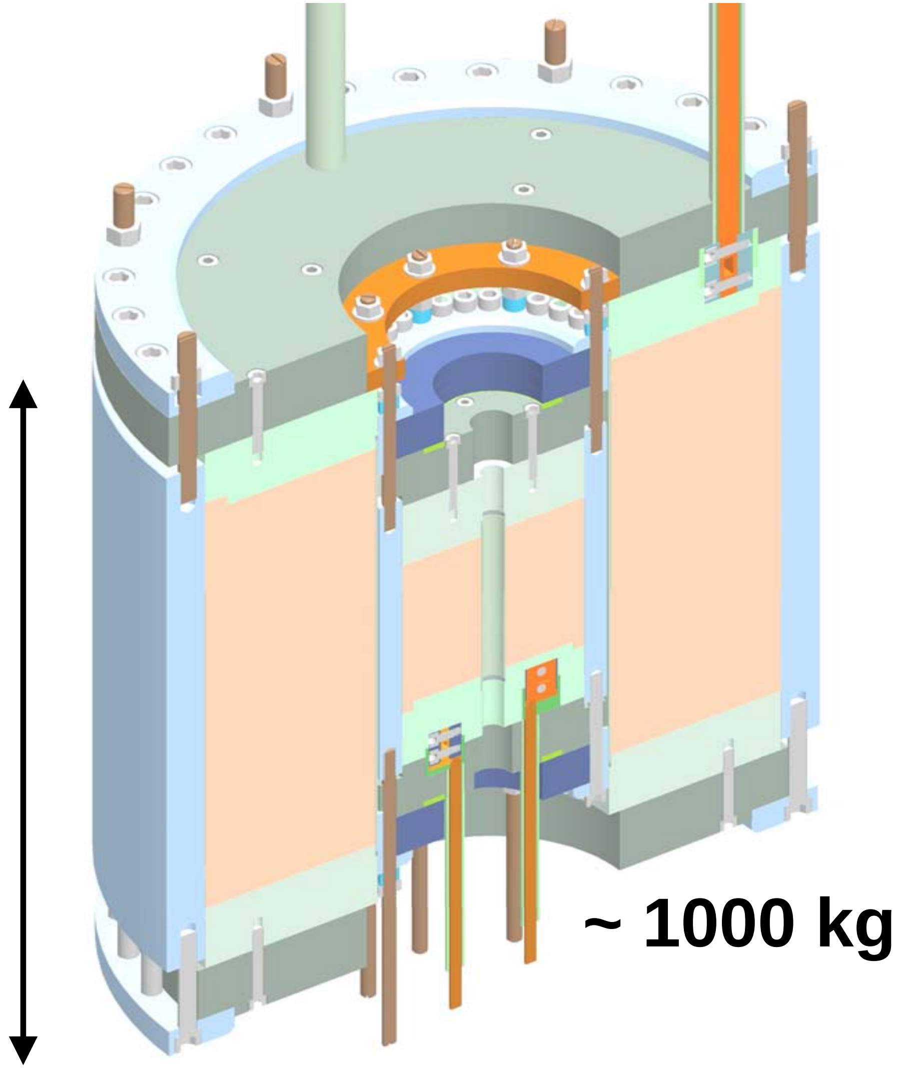


22nd Feb. 2006

Costs of 50 MJ ?

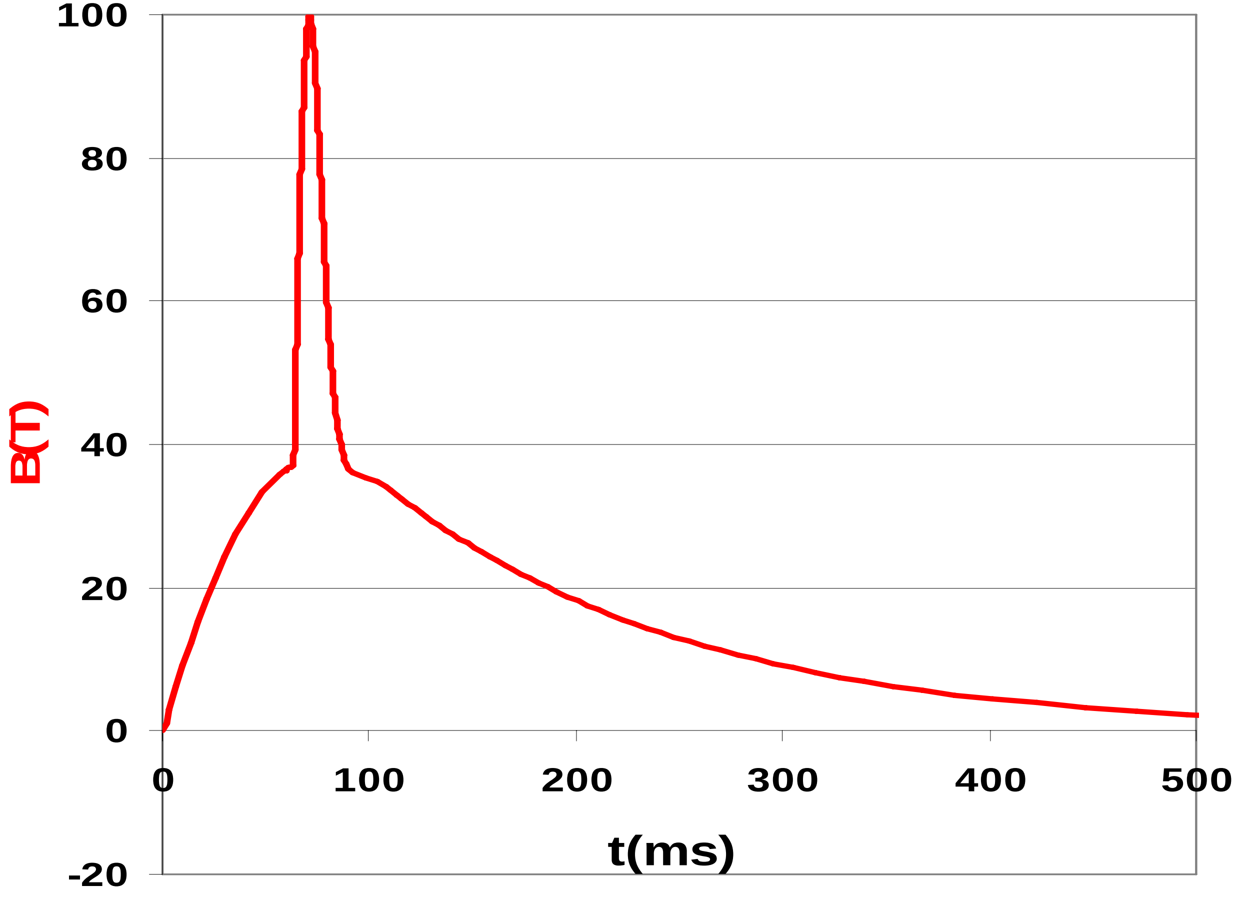
~ 2 € !

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



~ 1000 kg

0.5 m



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

Outer: 10 layers Cu 8x14 mm^2

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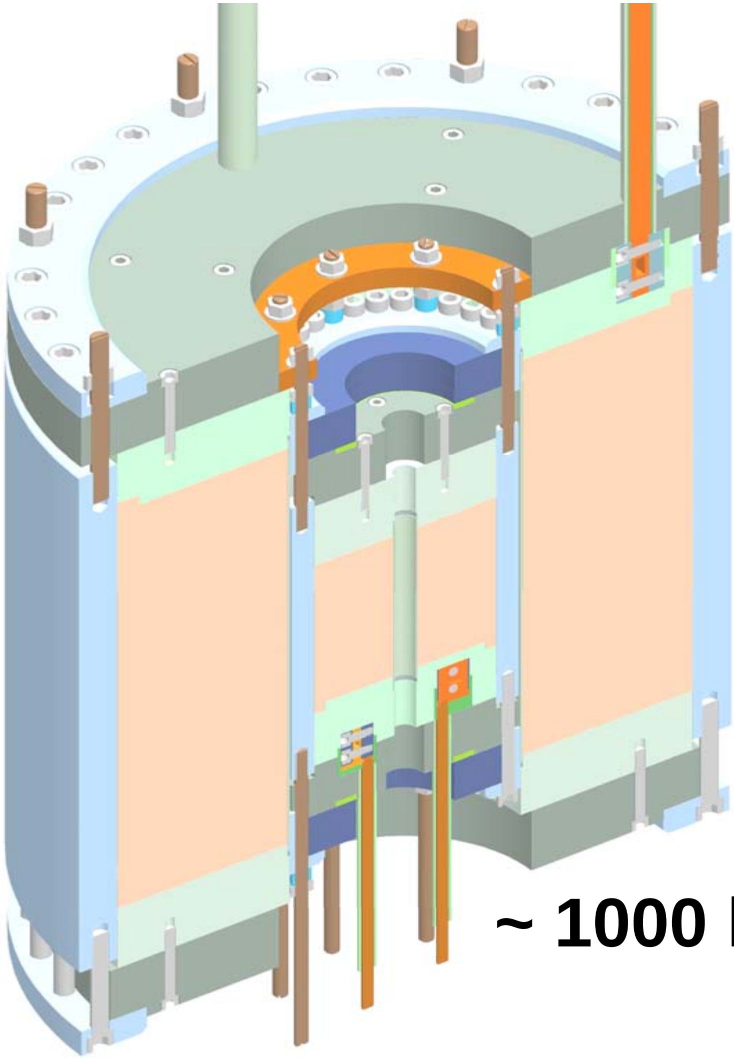

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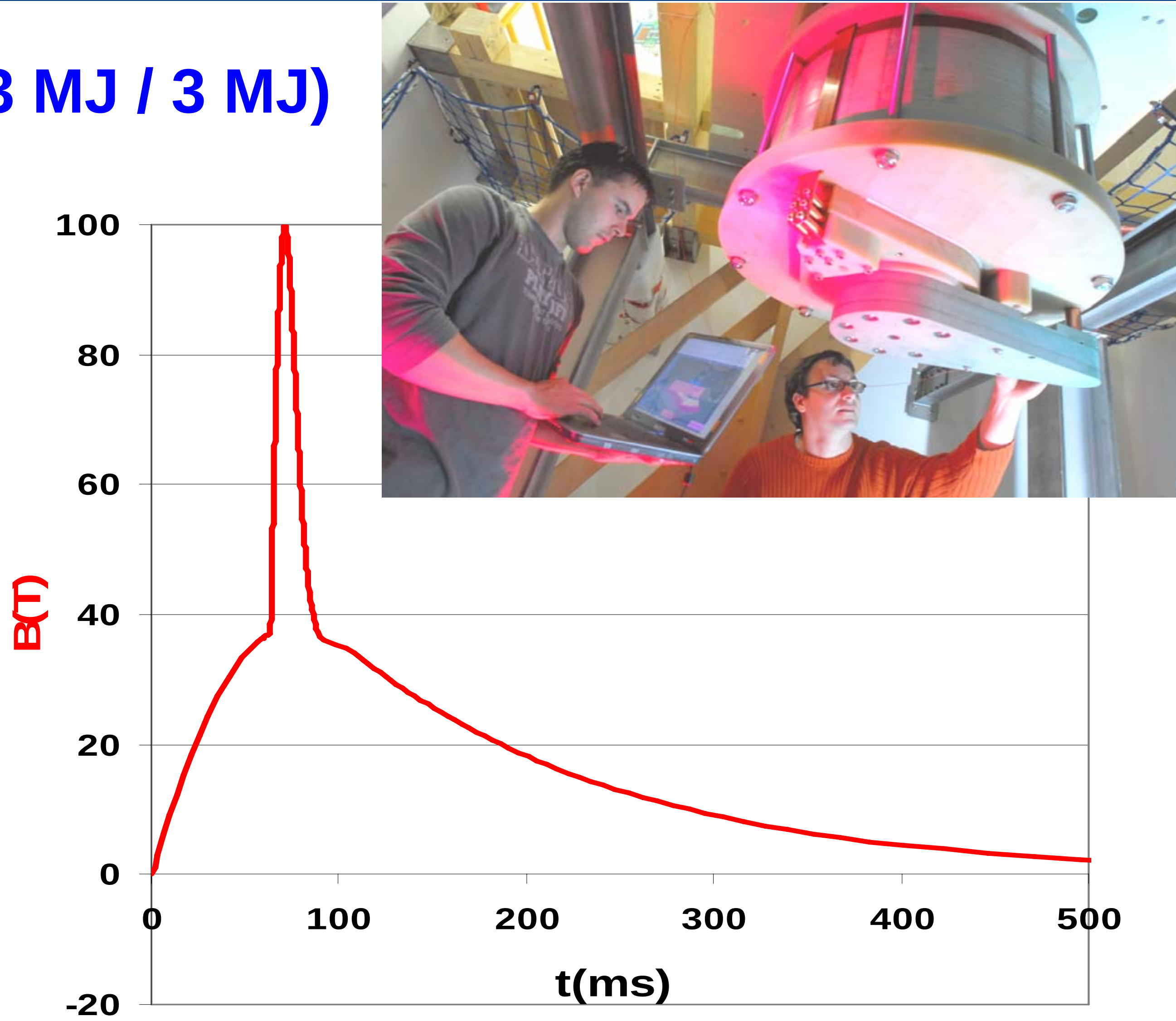

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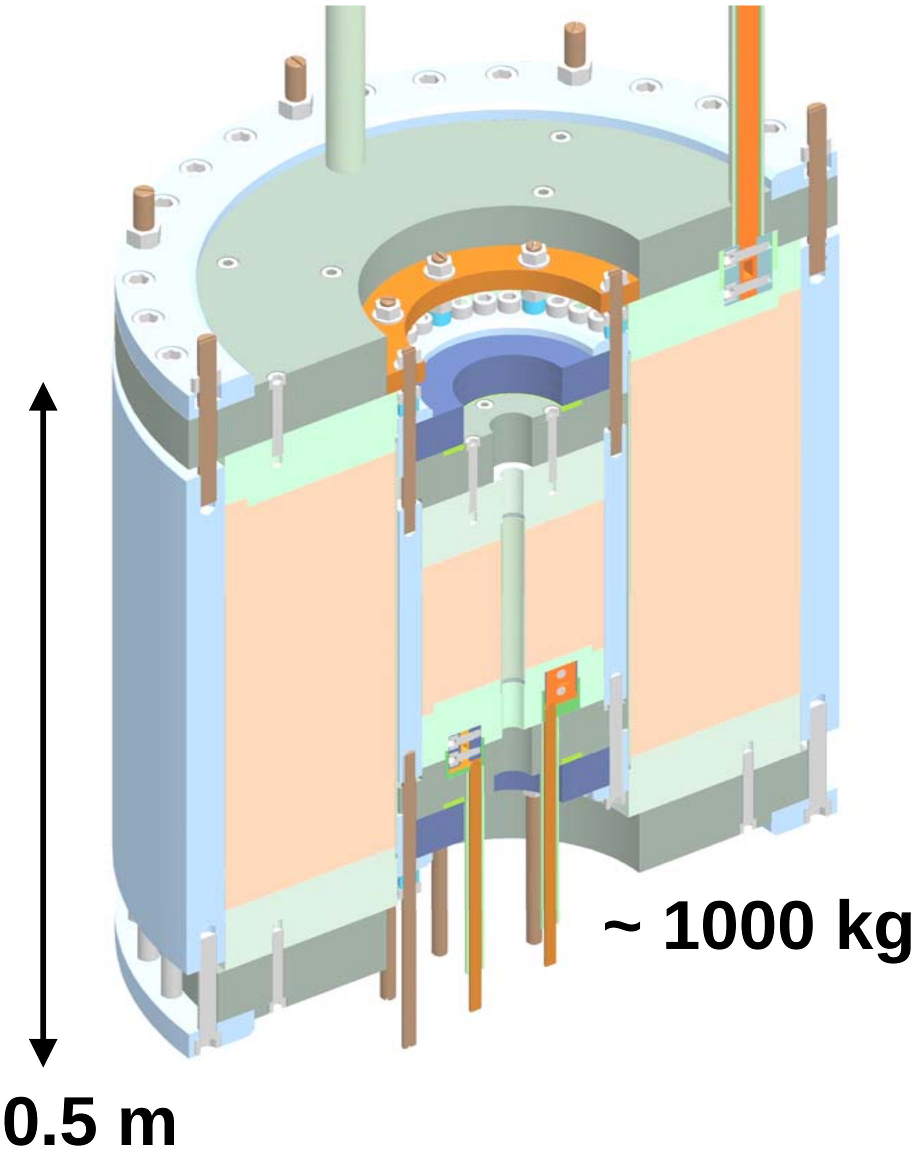

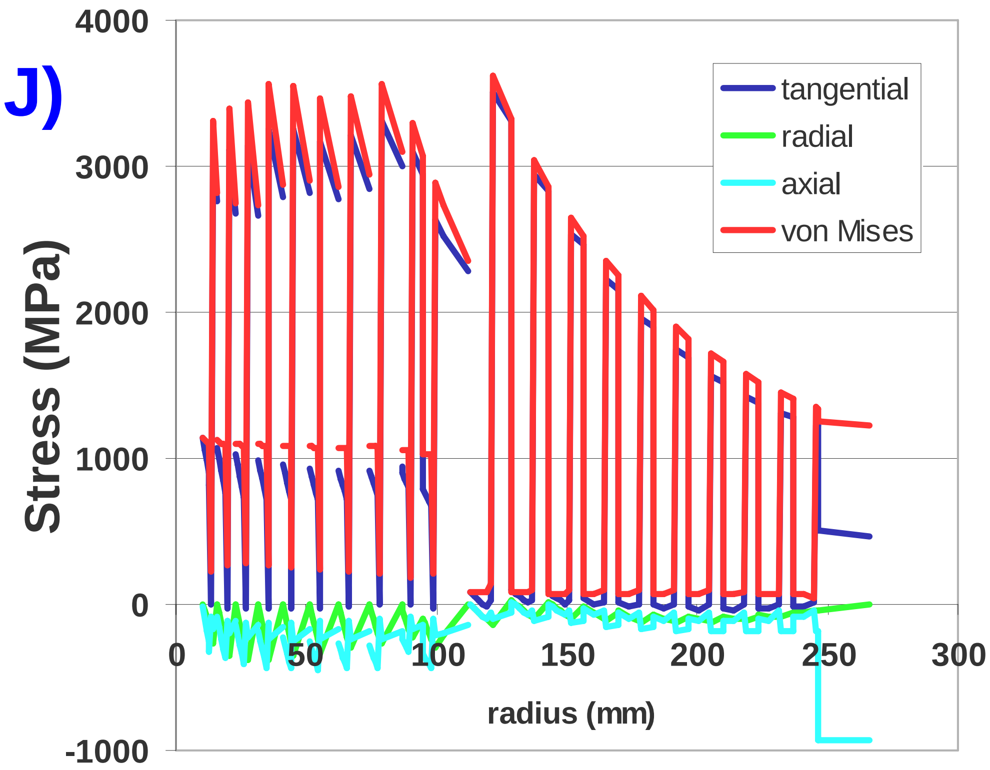

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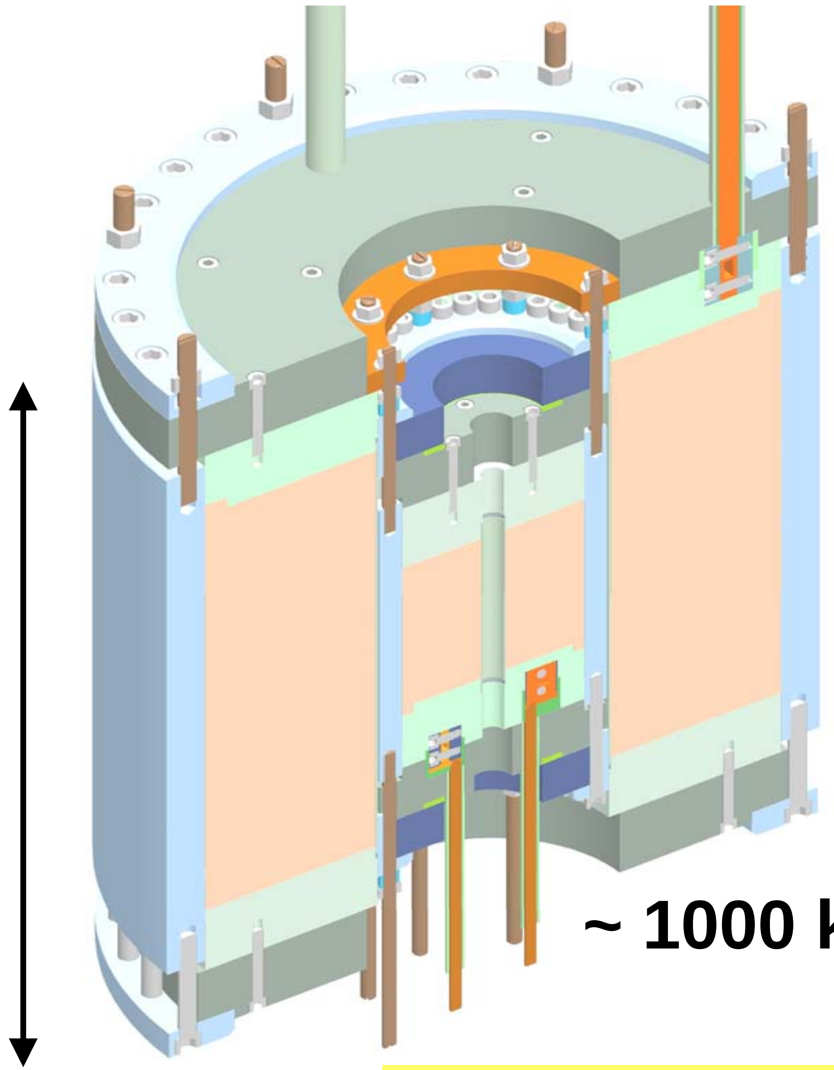

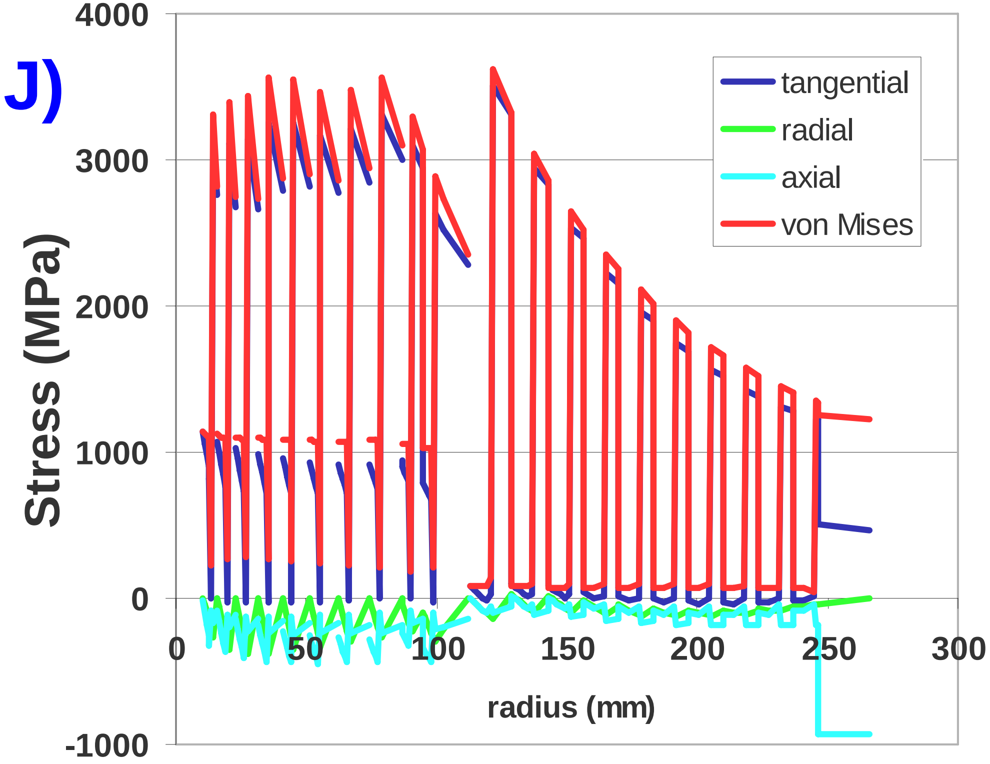

~ 1000 kg

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!

a) Simple estimates ... give limits: $P = B^2/2\mu_0$

B = 50T, P ~ 1.0 GPa = upper limit of ultimate tensile strength of most steels

B = 100T, P ~ 4.0 GPa = limit of ultimate tensile strength of fibre reinforcement

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b) Analytical solution using Biot-Savart law

- **allows for precise and fast computation,**

... but requires complex analytical solutions in restricted geometry segments

(see e.g.: L. Urankar et al., IEEE Transactions)

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(see e.g.: L. Urankar et al., IEEE Transactions)

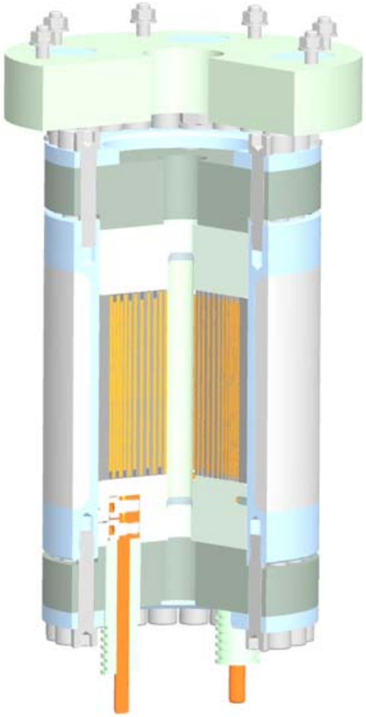
c) Numerical approach using Finite-Element Analysis (FEA)

- solves coupled partial differential equations under boundary conditions

- no restrictions in geometry, allows for multiphysical solutions ... but requires a considerable amount of computation time: fast solvers are needed

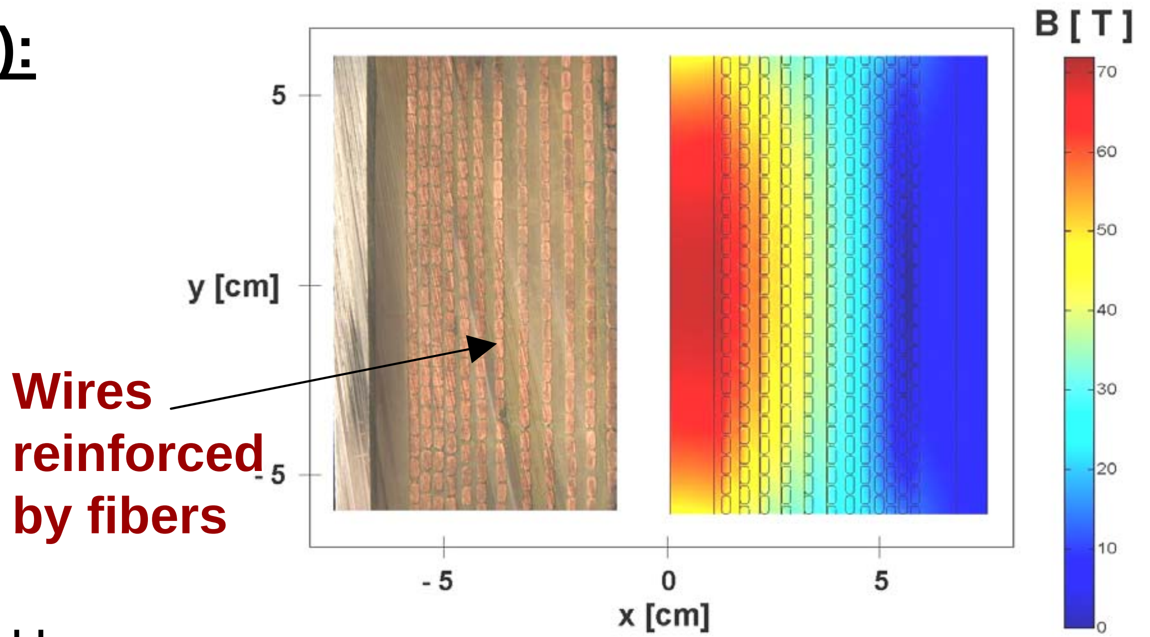
Multiphysics FEA via COMSOL

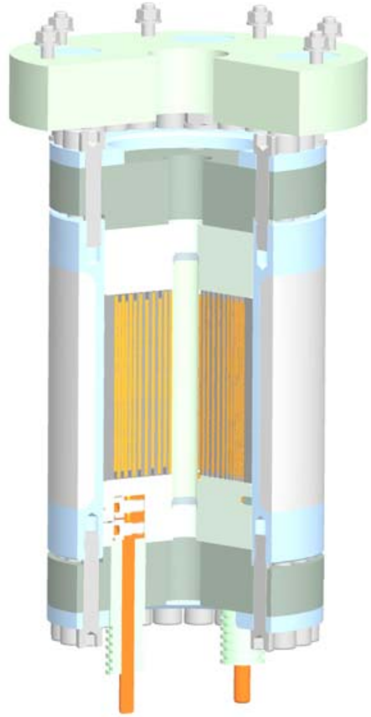
FEA example 1 (azimuthal symmetry):



300 turns, 12 layers, 3 mH,
t_{Pulse} = 100 msec

FEA example 1 (azimuthal symmetry):





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FEA allows for calculation of, e.g.:

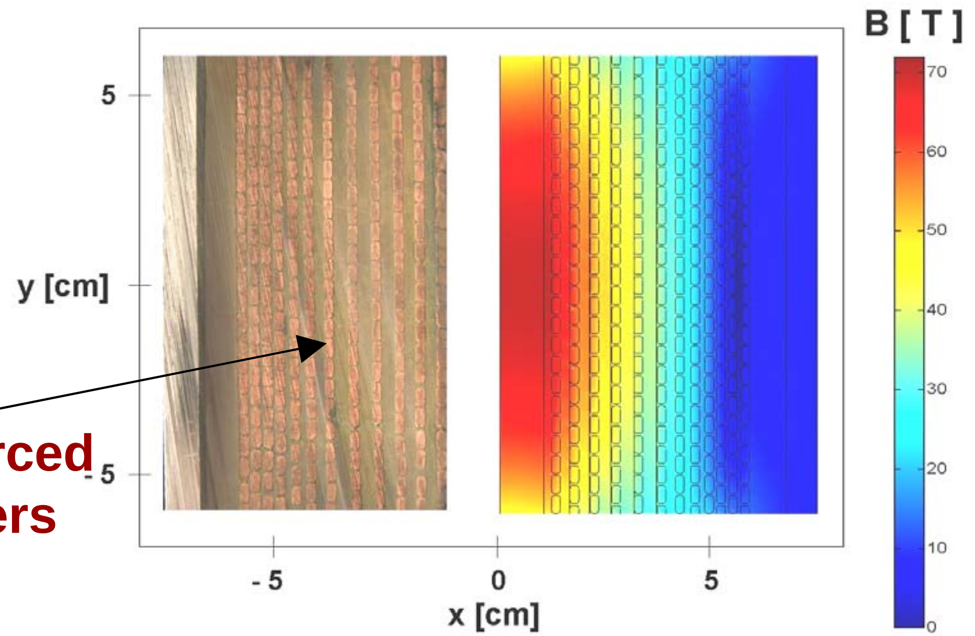
B(x, y, z, t) up to 72 T

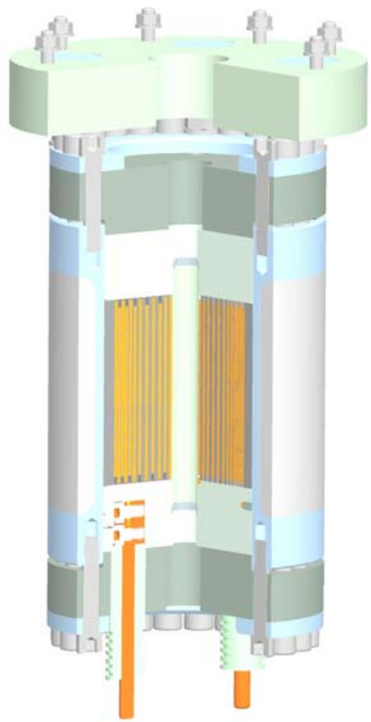
FEA example 1 (azimuthal symmetry):

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

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

Wires reinforced by fibers





300 turns, 12 layers, 3 mH,
t_{Pulse} = 100 msec

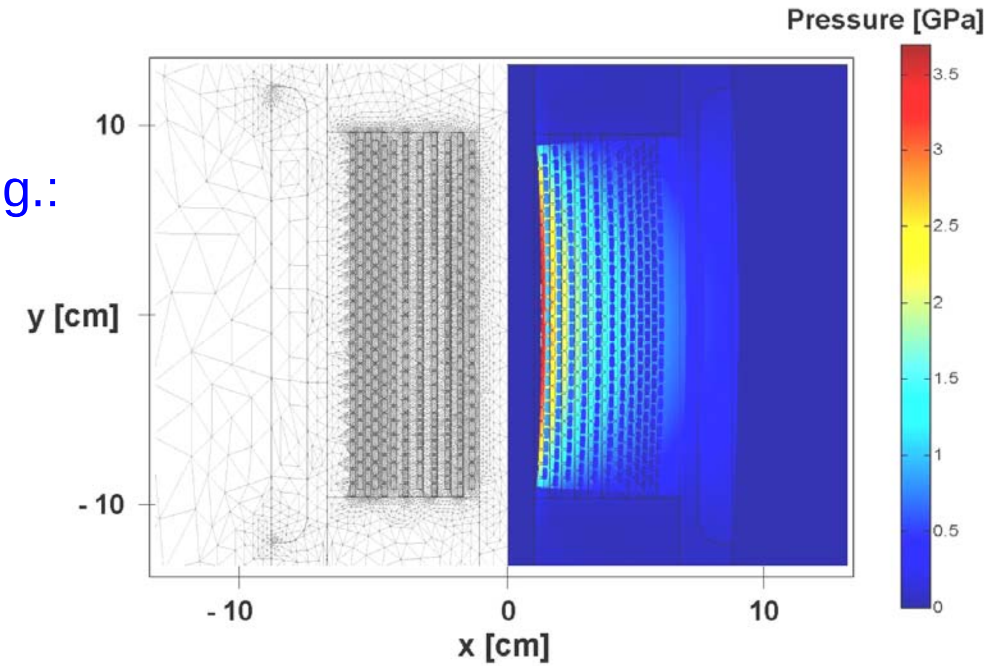
FEA allows for calculation of, e.g.:

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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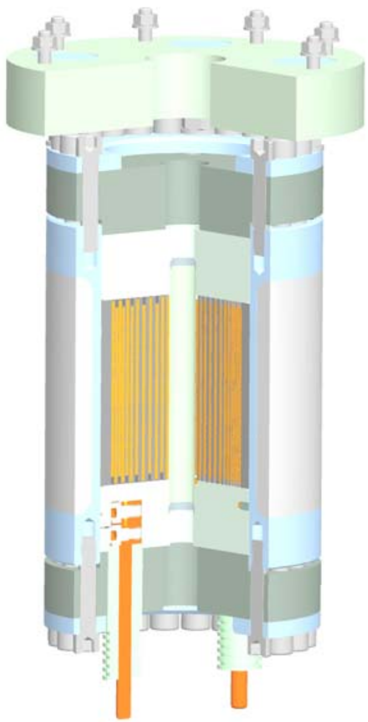

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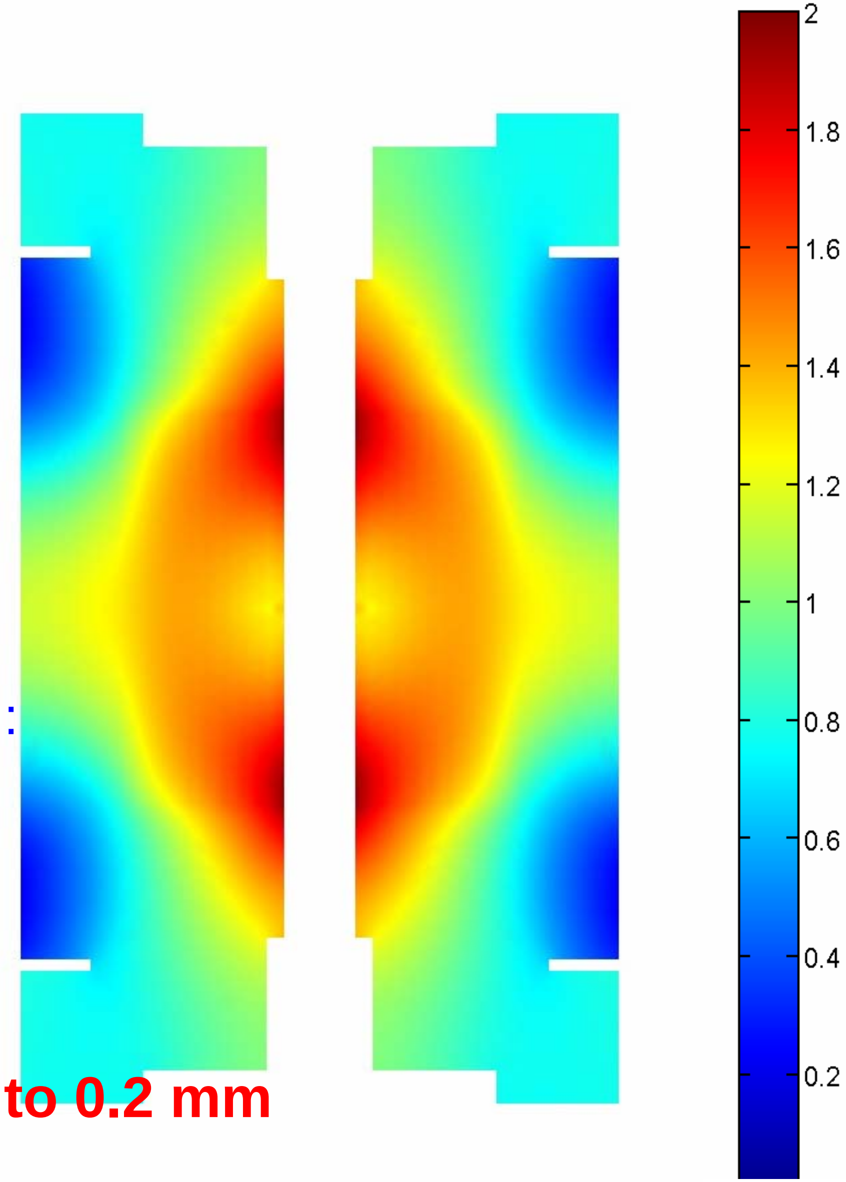
P(x, y, z, t) up to ~ 3.7 GPa

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

Deformation [10^{-4} m]



Challenges

- extremely high Lorentz forces and
- resulting mechanical load
- materials in plastic regime
- extreme heat load
- extreme electrical environment

Special conductors up to ~1 GPa:

- CuSn, CuBe alloys
- $CuAl_2O_3$ composites
- steel-copper macro composites
- CuAg micro composites
- CuNb nano filament composites

Special Fabrication techniques:

Challenges

- extremely high Lorentz forces and
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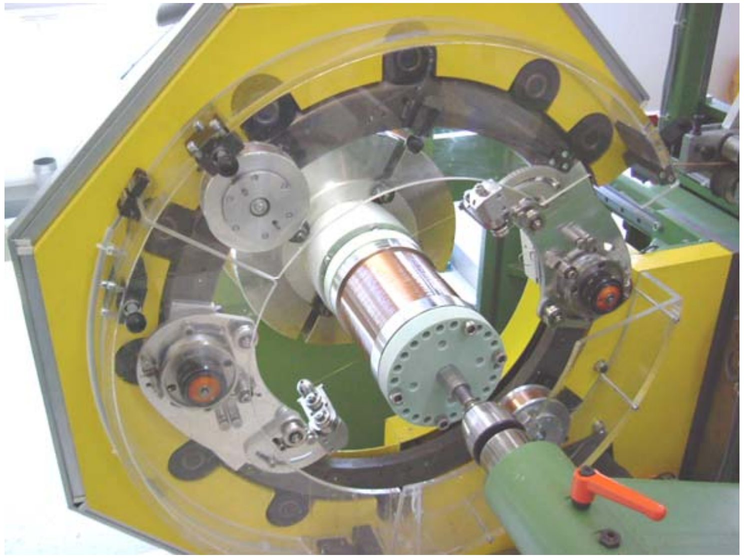
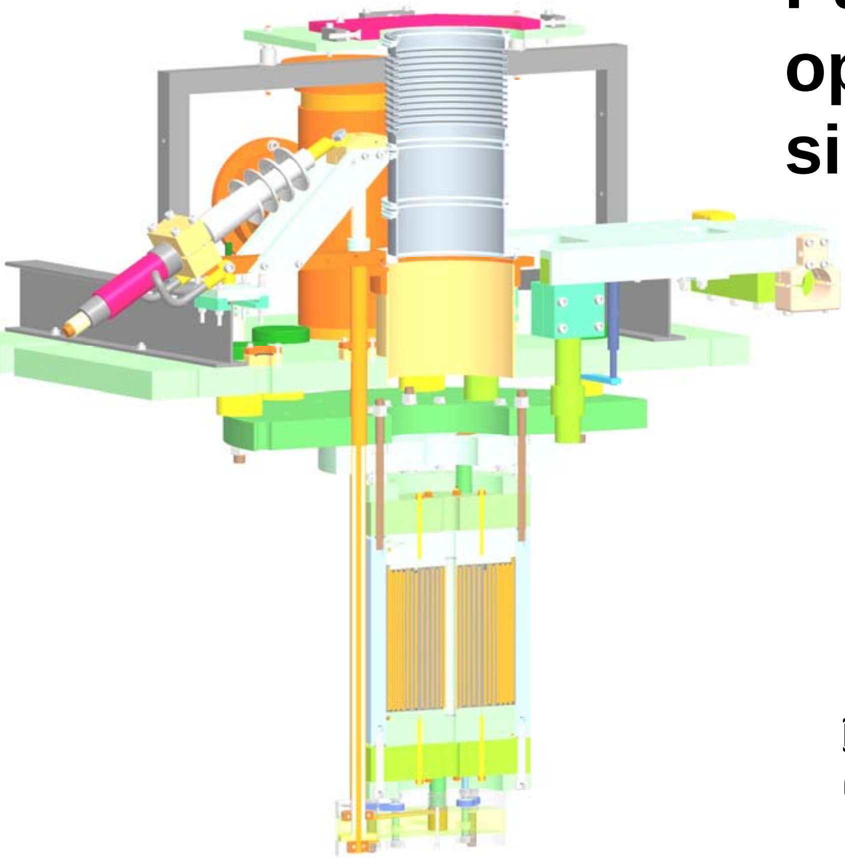


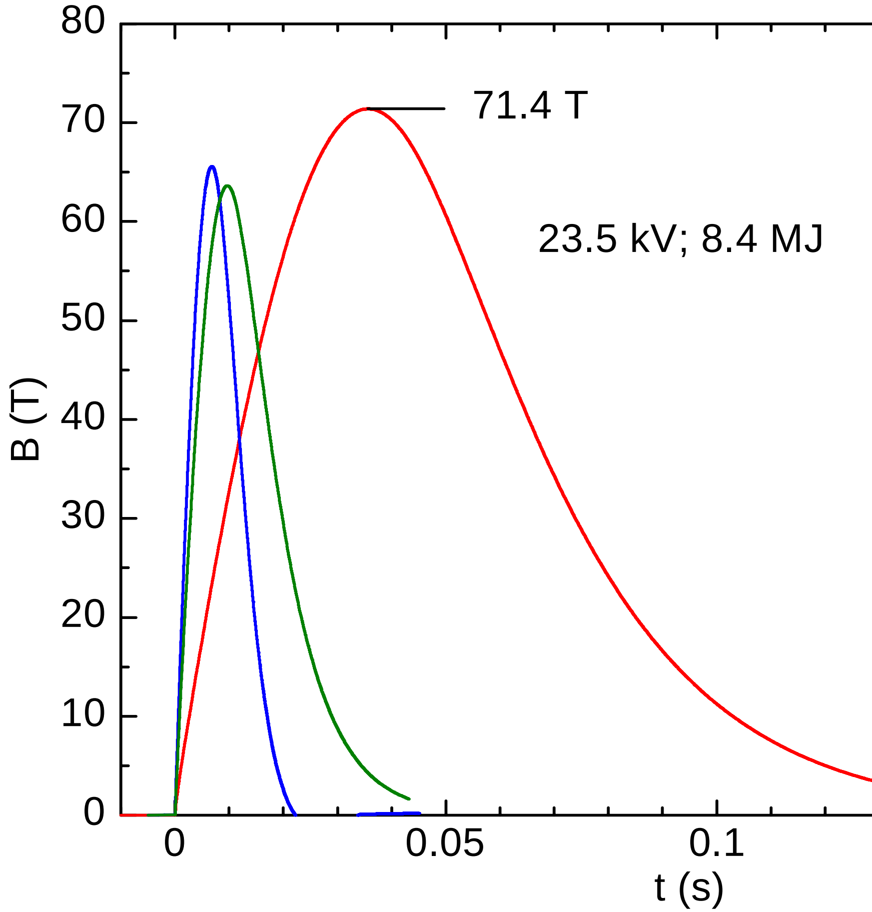
Special fiber reinforcement:

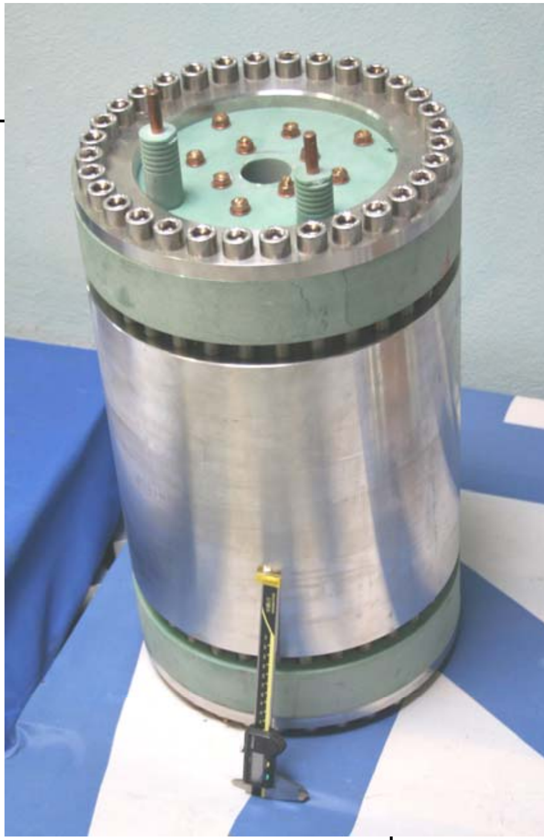
- „Zylon“ (PBO) fiber
- high tensile strength (5 GPa along fibre)
  highly anisotropic (consider in FEA !)
- high thermal stability and conductivity
- high-voltage electrical insulation

Steel reinforcement: „MP35N“



Pulsed-field coils of the HLD in continous operation for internal and external users since 2006:





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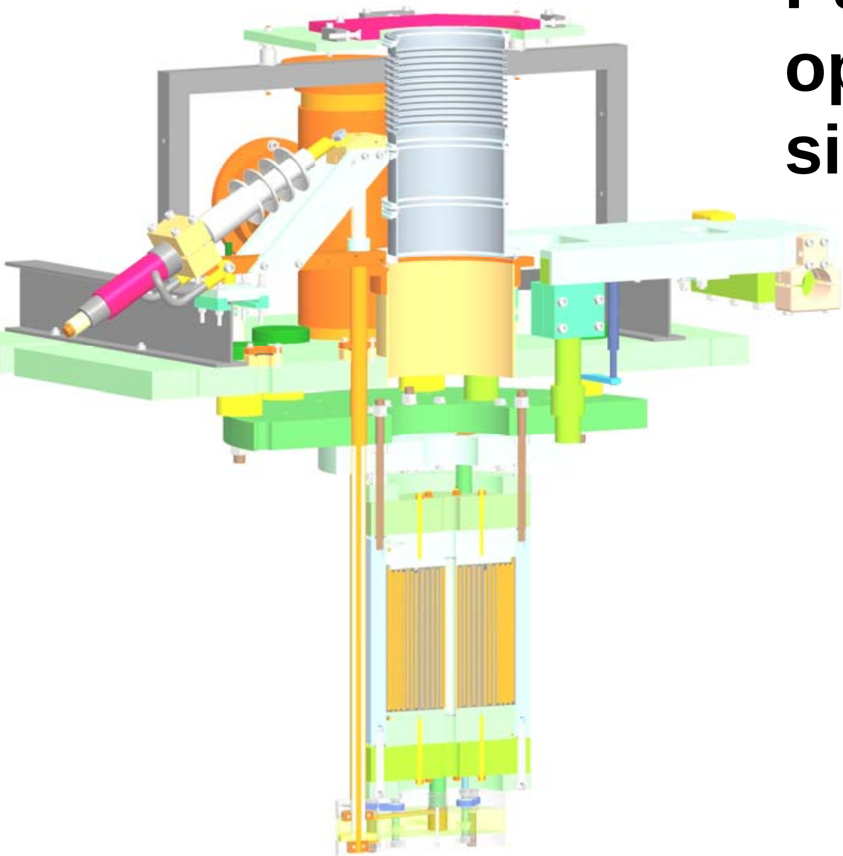

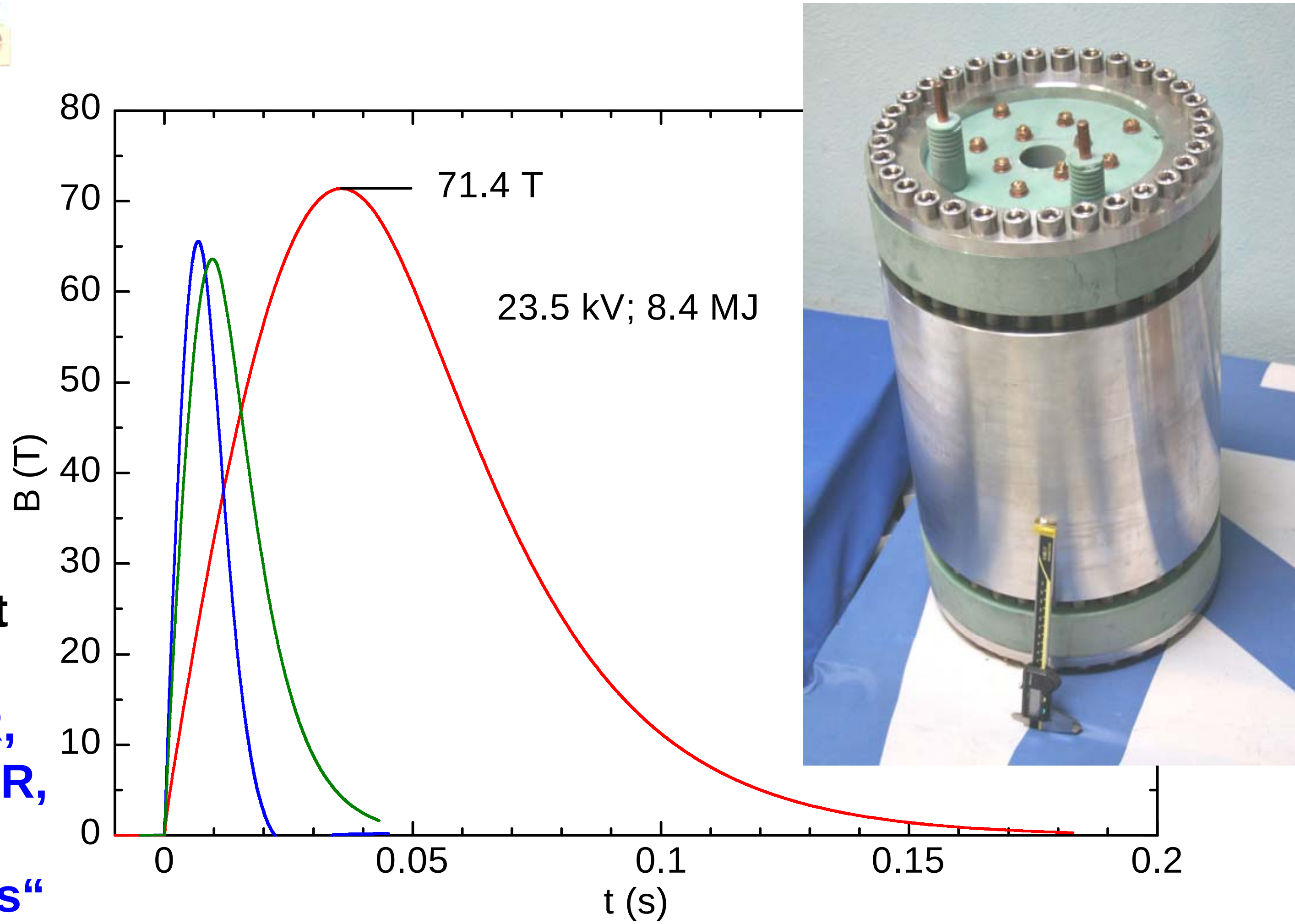

Many experimental measurement techniques available at HLD:
el. transport, magnetization, ESR, IR spectroscopy, ultrasound, NMR, heat capacity, ...

„allows for a lot of physics“

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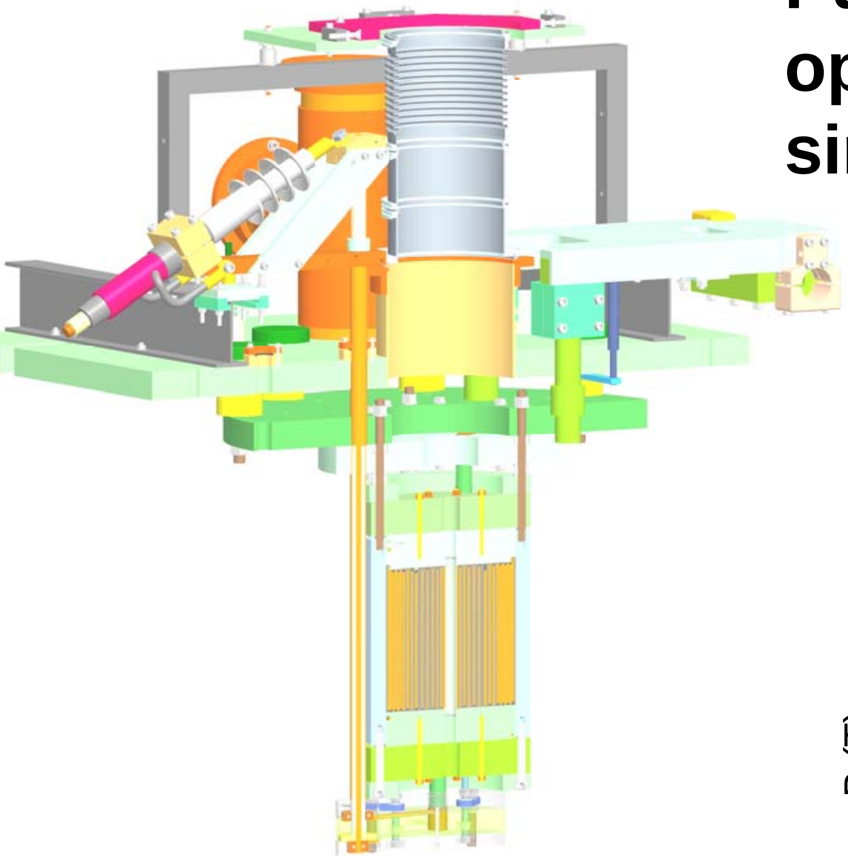
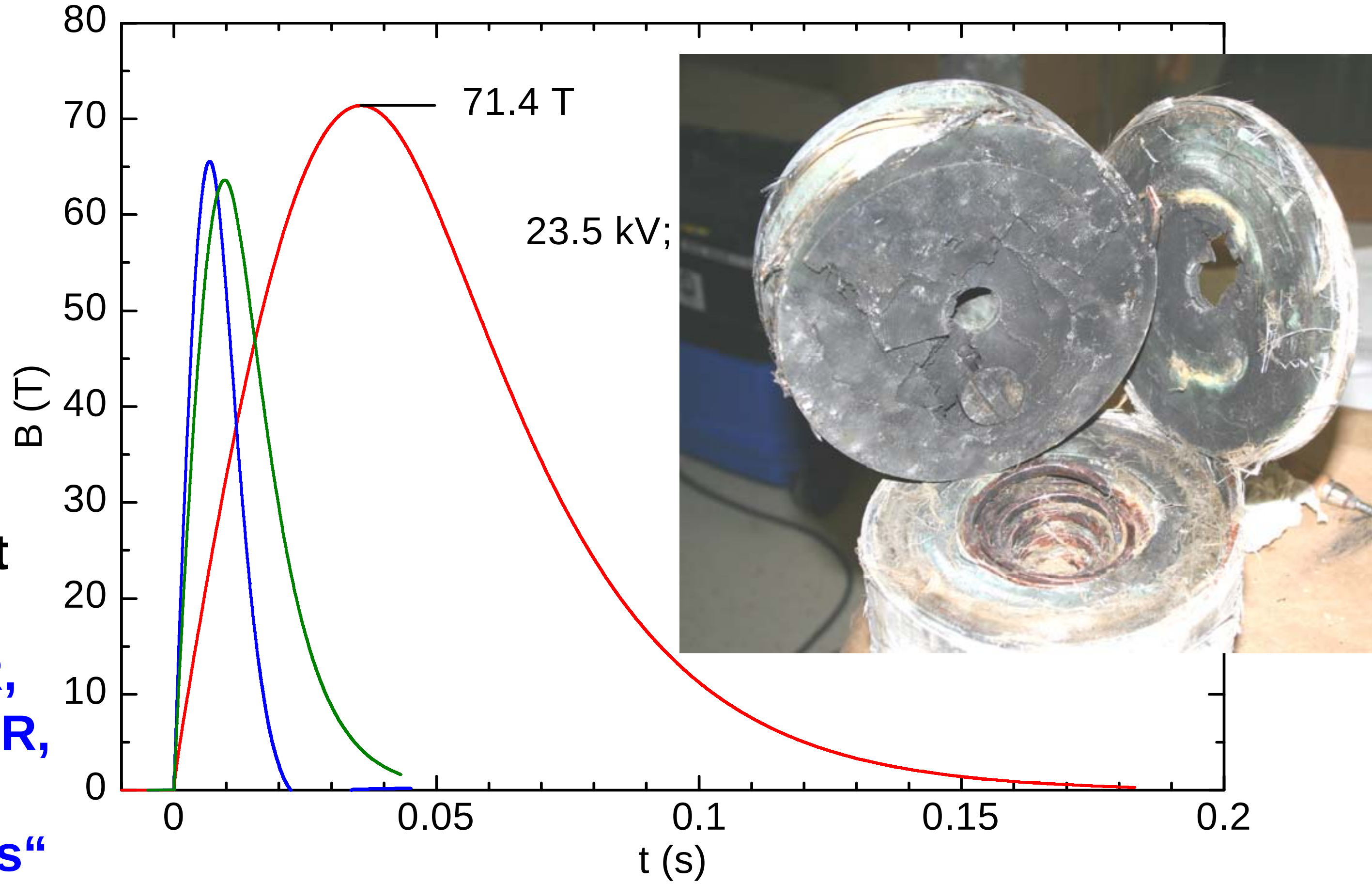
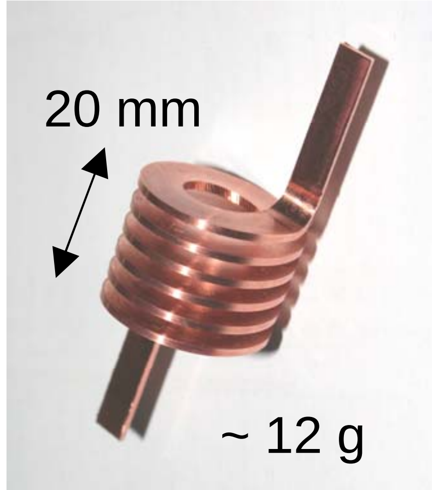


Many experimental measurement techniques available at HLD:
el. transport, magnetization, ESR, IR spectroscopy, ultrasound, NMR, heat capacity, ...
„allows for a lot of physics"

Study of a failure case, ...
„feedback and motivation for realistic FEA"





FEA example 2 (2D azimuthal and 3D symmetry):

Five-turn test coil: 5.5 turns, 10 mm bore, I = 250 kA, t_{pulse} = 10 µsec

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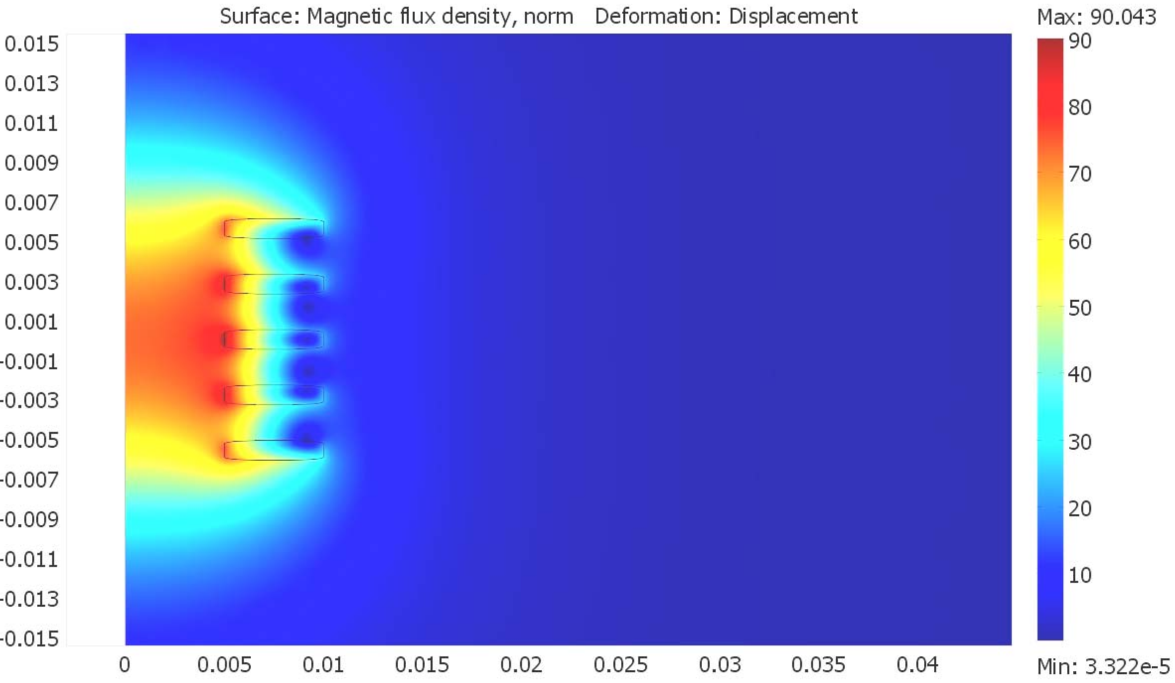

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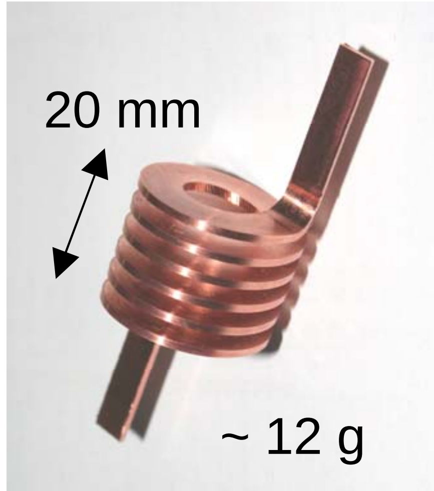
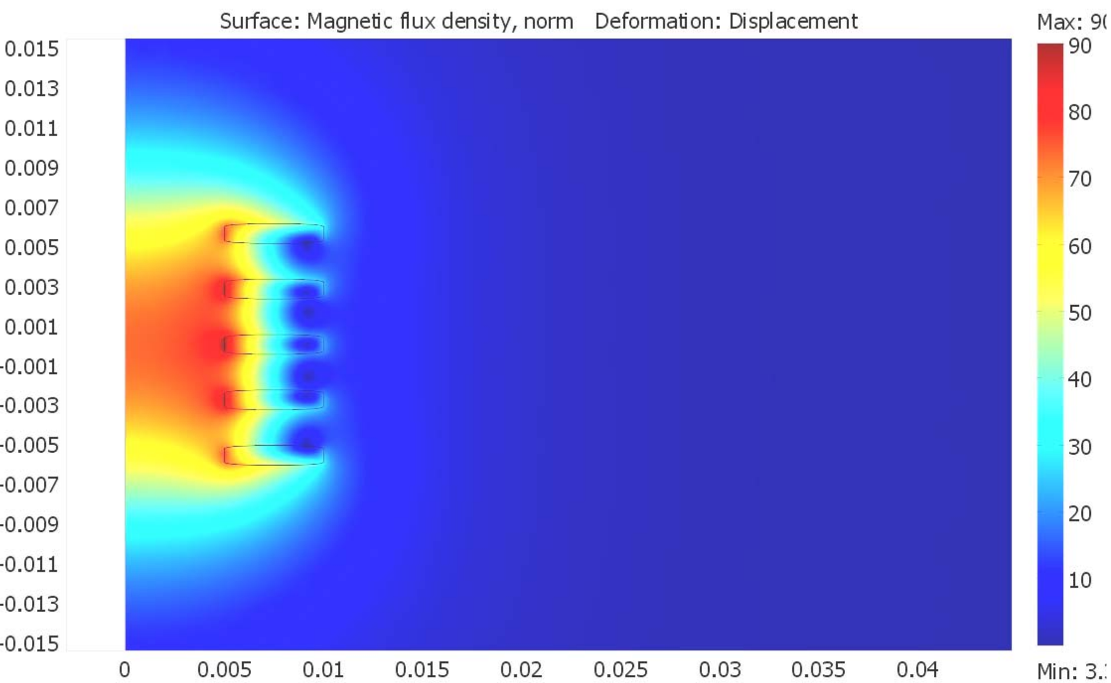
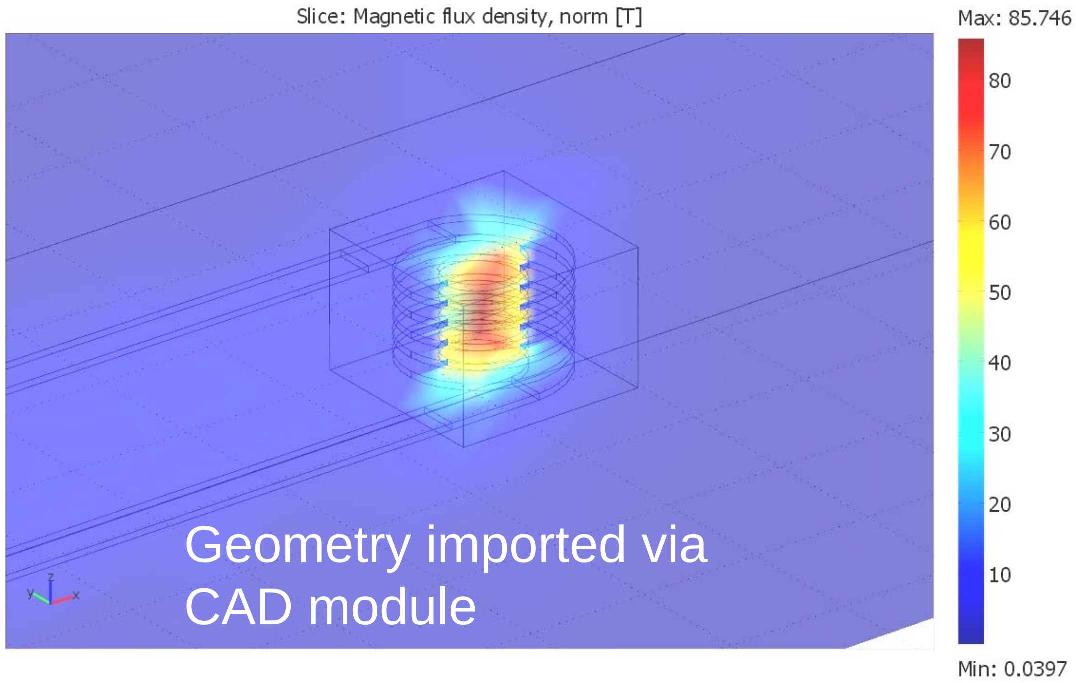


Good agreement between 2D and 3D simulation results of B(r,t)





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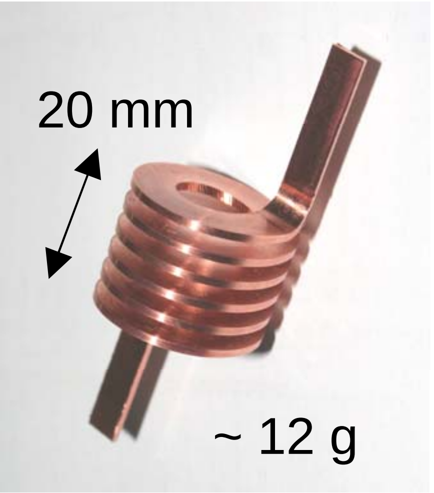
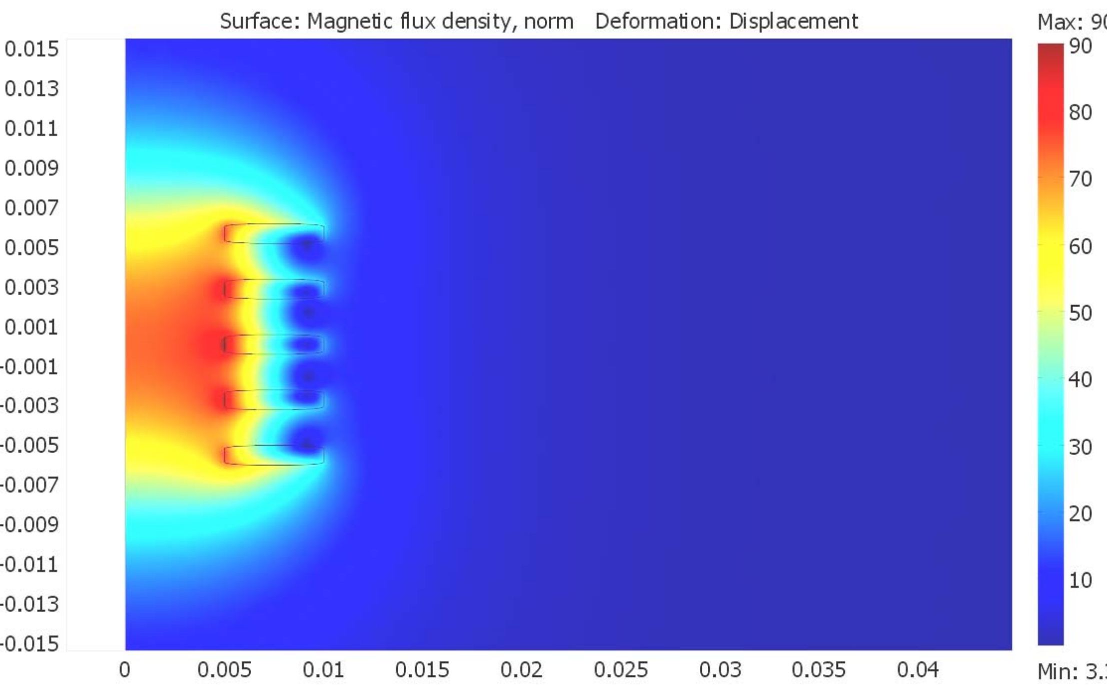
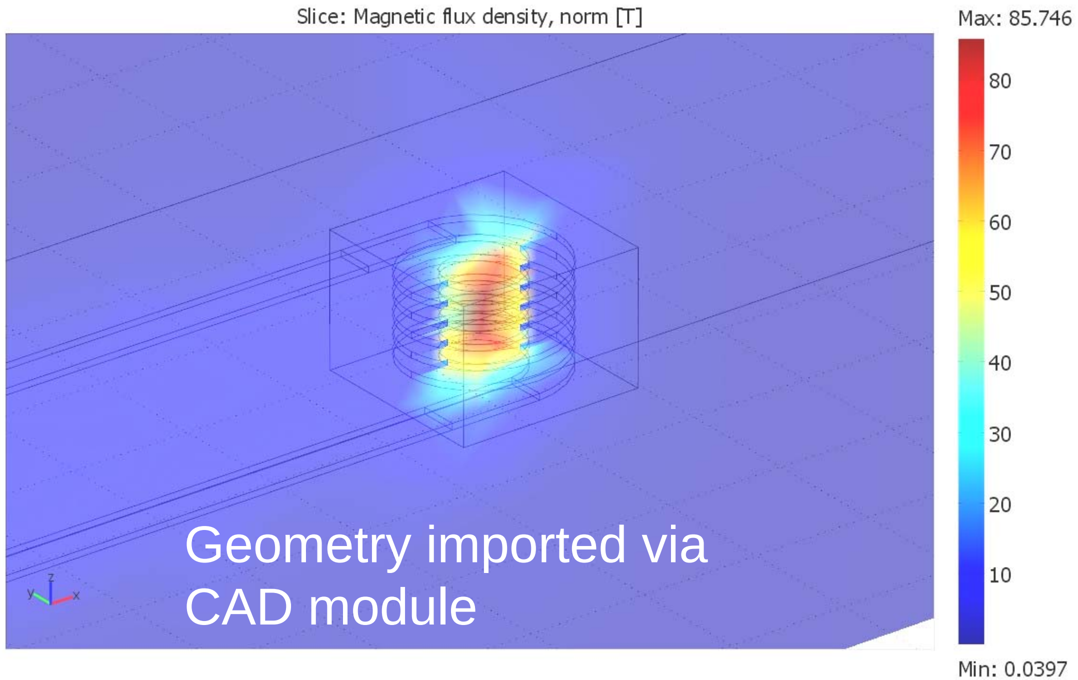


Five-turn test coil: 5.5 turns, 10 mm bore, I = 250 kA, t_{pulse} = 10 µsec

- **Lorentz forces and mechanical load cause plastic deformation at fields > 50 T**
- **heat up to T_{max} > 400 K critical for fiber composite**
- **critical electrical-field gradients between windings (kV/mm)**

Good agreement between 2D and 3D simulation results of B(r,t)

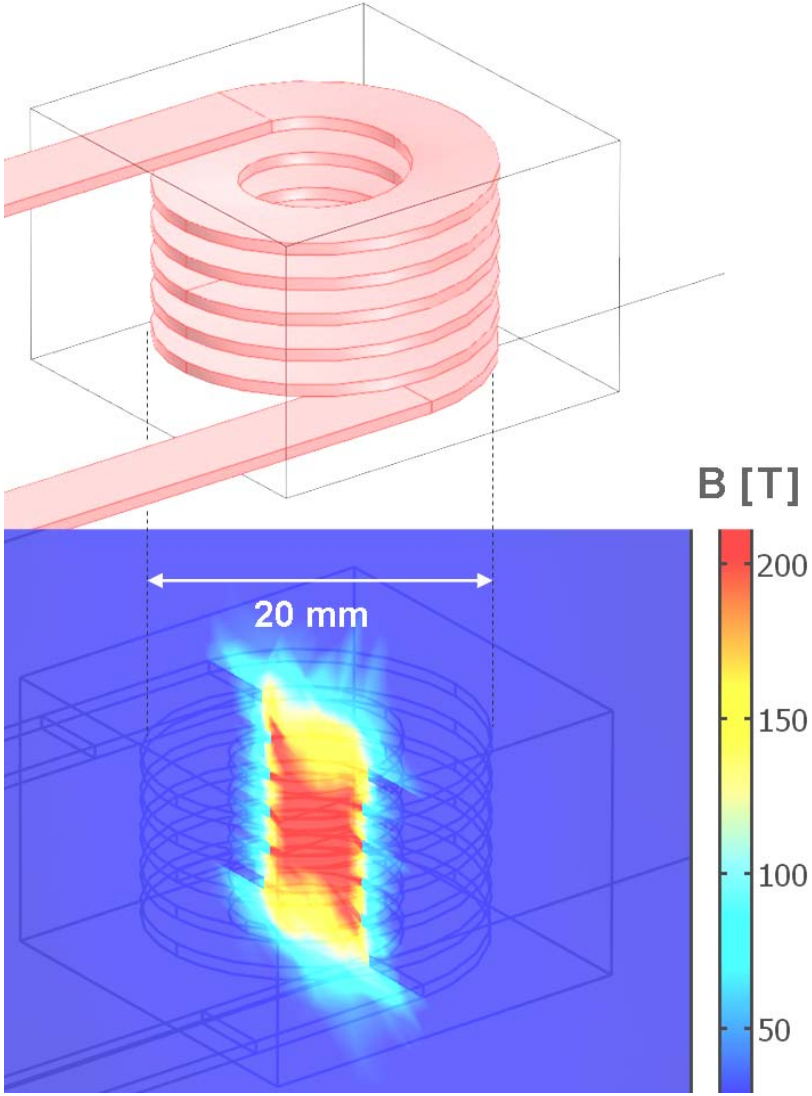




FEA example 2 (2D azimuthal and 3D symmetry):

Five-turn test coil: 5.5 turns, 10 mm bore, **I = 600 kA**, t_{pulse} = 10 µsec

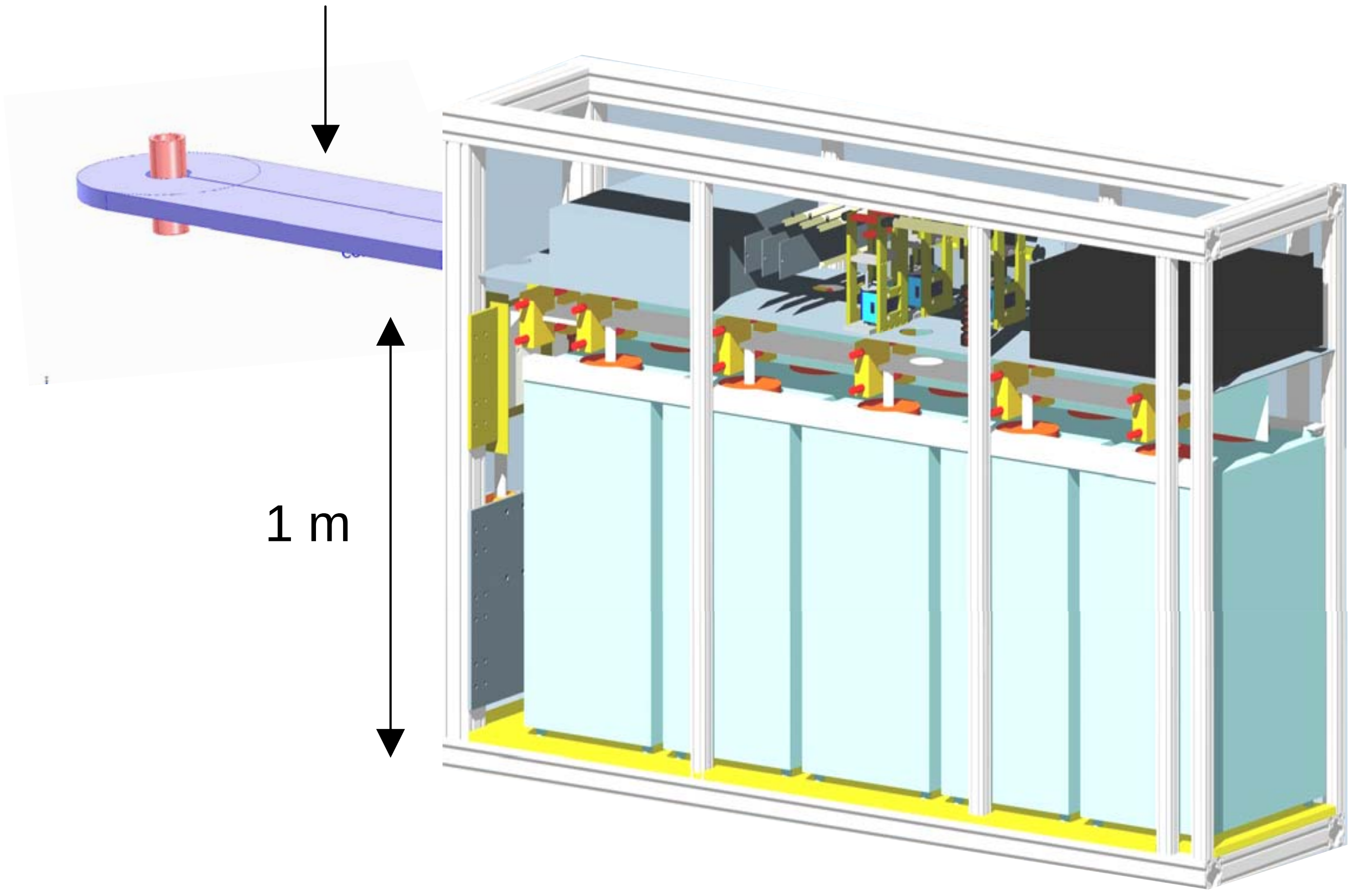
- **magnetic flux densities > 100 T feasible in the µsec time range**
  B = 220 T
- **Lorentz forces beyond destructive limits,**
  P > 5 GPa
- **possible melting and evaporation of coil**
- **critical electrical-field gradients between windings (kV/mm)**

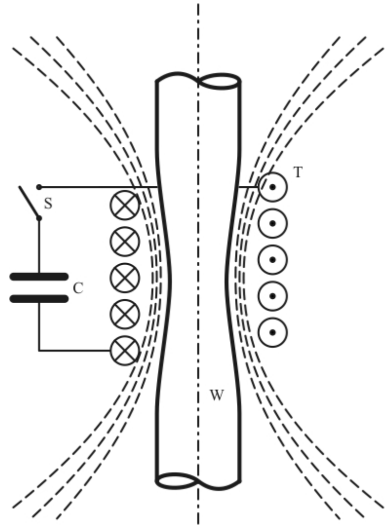


Multiphysics FEA needed for modelling and optimization of the field pulse and burst of the coil

<u>FEA example 3 (3D simulation):</u>

Single-turn pulse deformation coil:

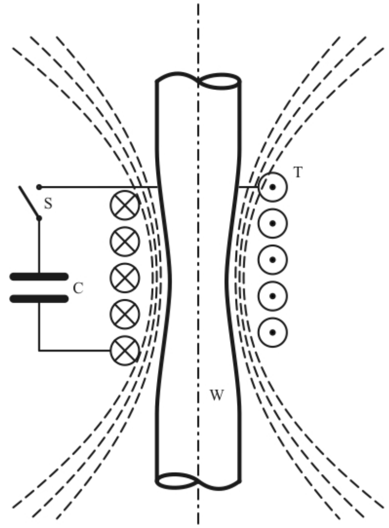




Pulse-current generator

(discharge capacitor bank)

FEA example 3 (3D simulation):



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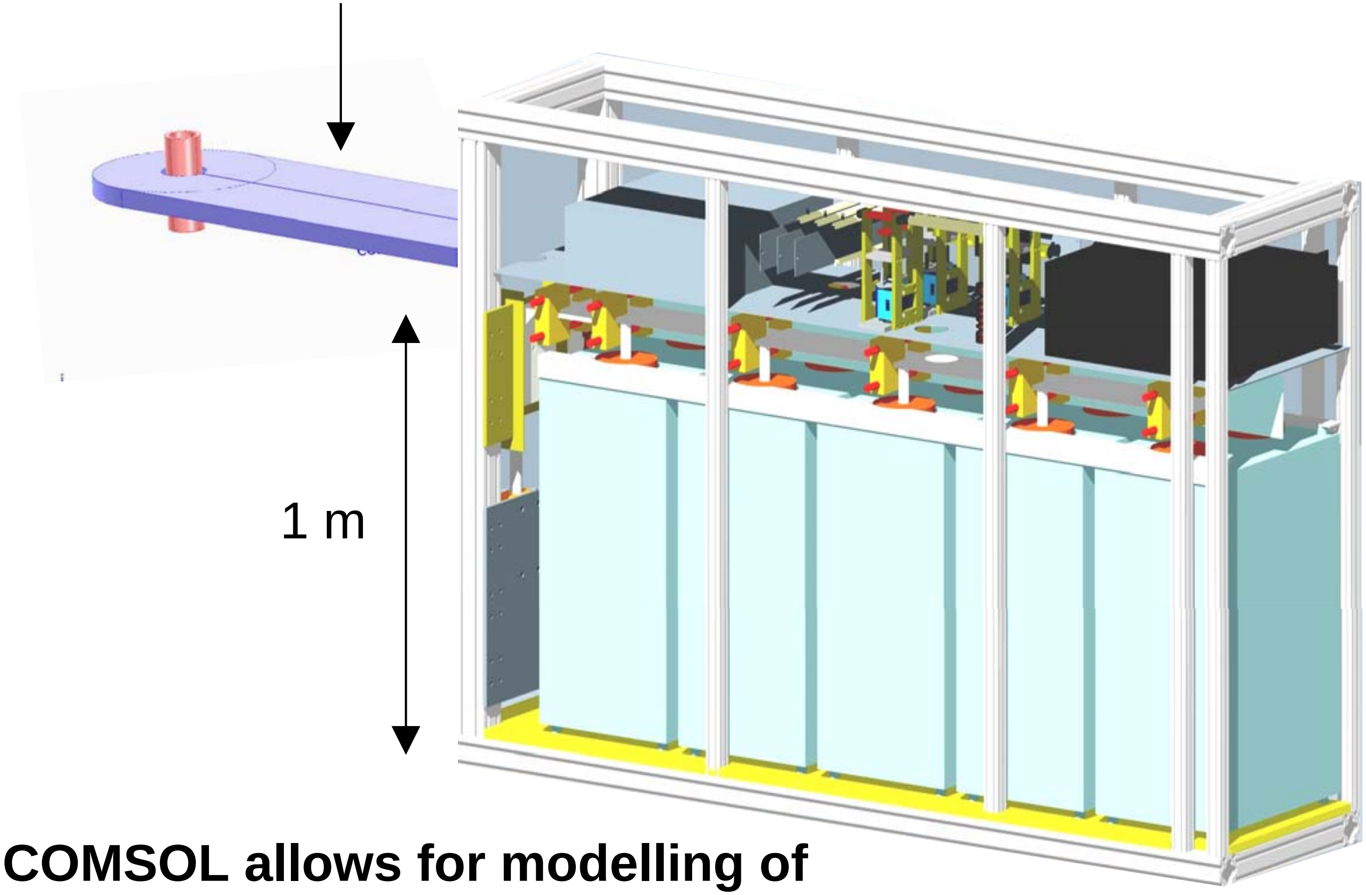


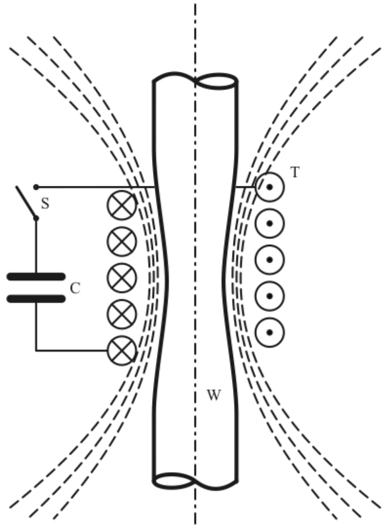
Pulse-current generator

(discharge capacitor bank)

COMSOL allows for modelling of

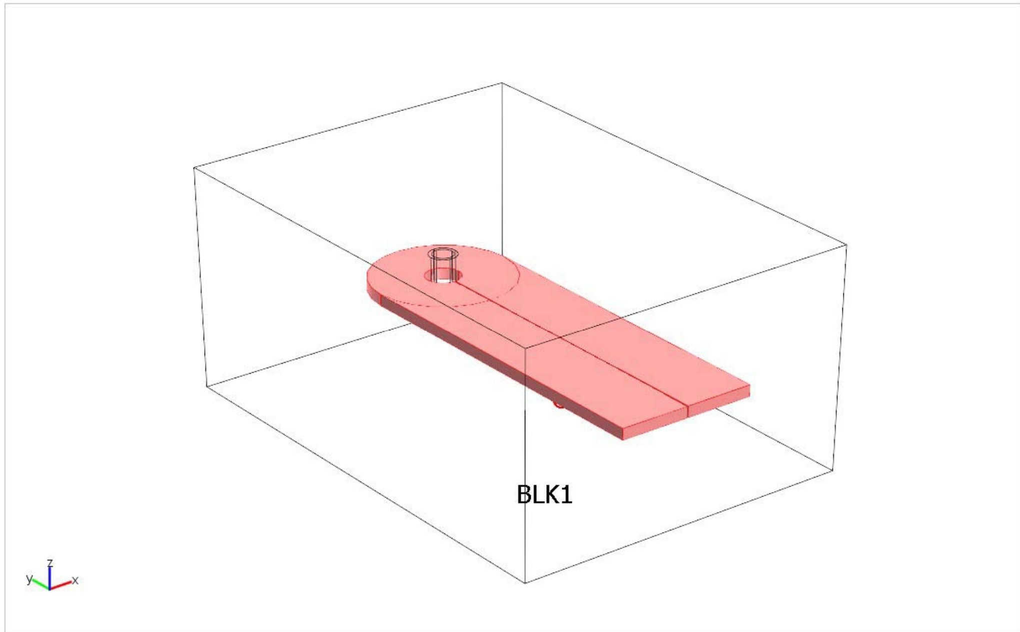
- electromagnetic pulse forming process, i. e. Lorentz forces on induced eddy currents
- basic properties of the pulse generator: inductance ~ 100 nH of the high-power circuit

FEA example 3 (3D simulation):



Single-turn pulse deformation coil:

single turn, 52 mm (2 inch) bore, 2mm slit, 20 mm x 100 mm bars, 600 mm length, I = 500 kA, t_{pulse} = 10 µsec



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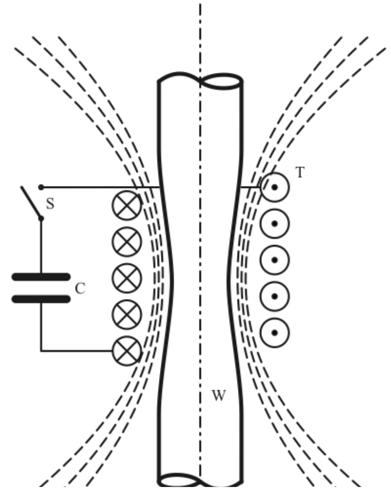

Single-turn pulse deformation coil:

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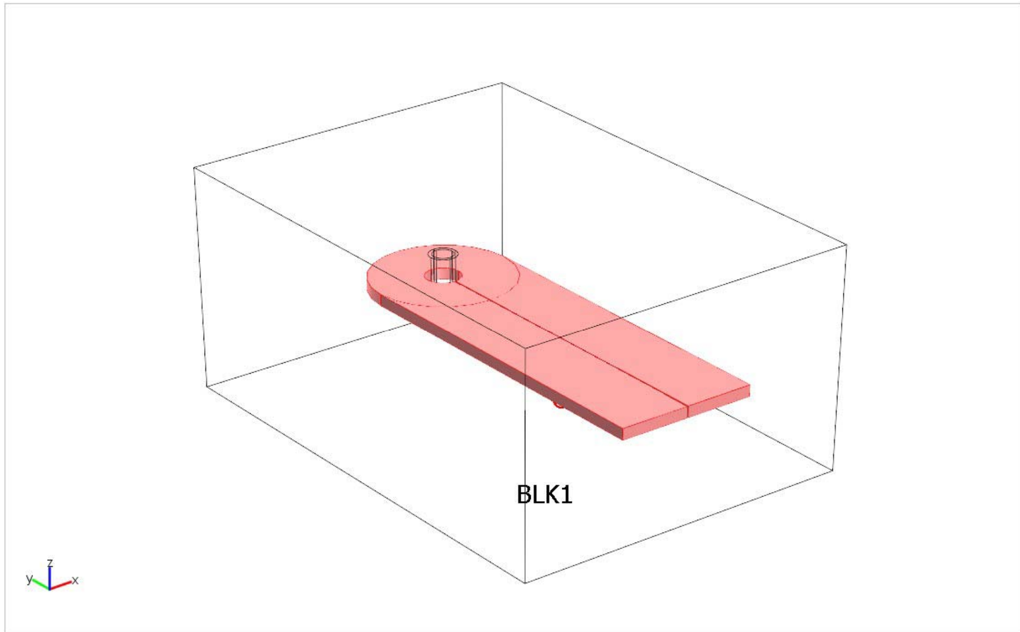
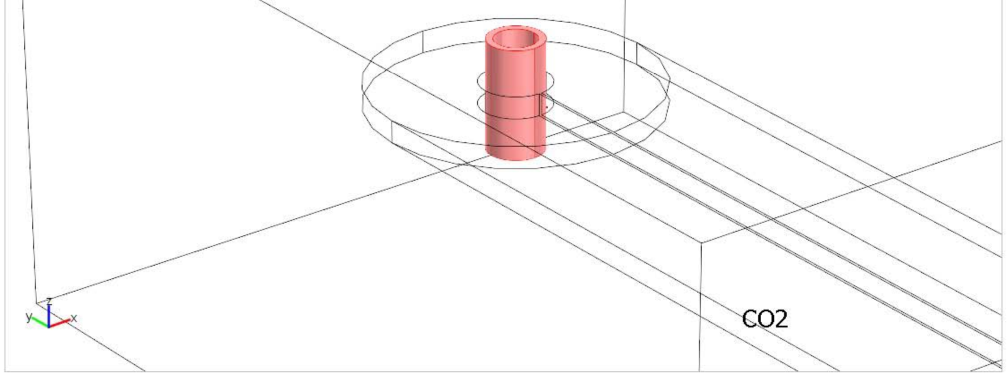
- **Lorentz forces on induced eddy currents cause plastic deformation of work piece**
- **challenging electrical environment**

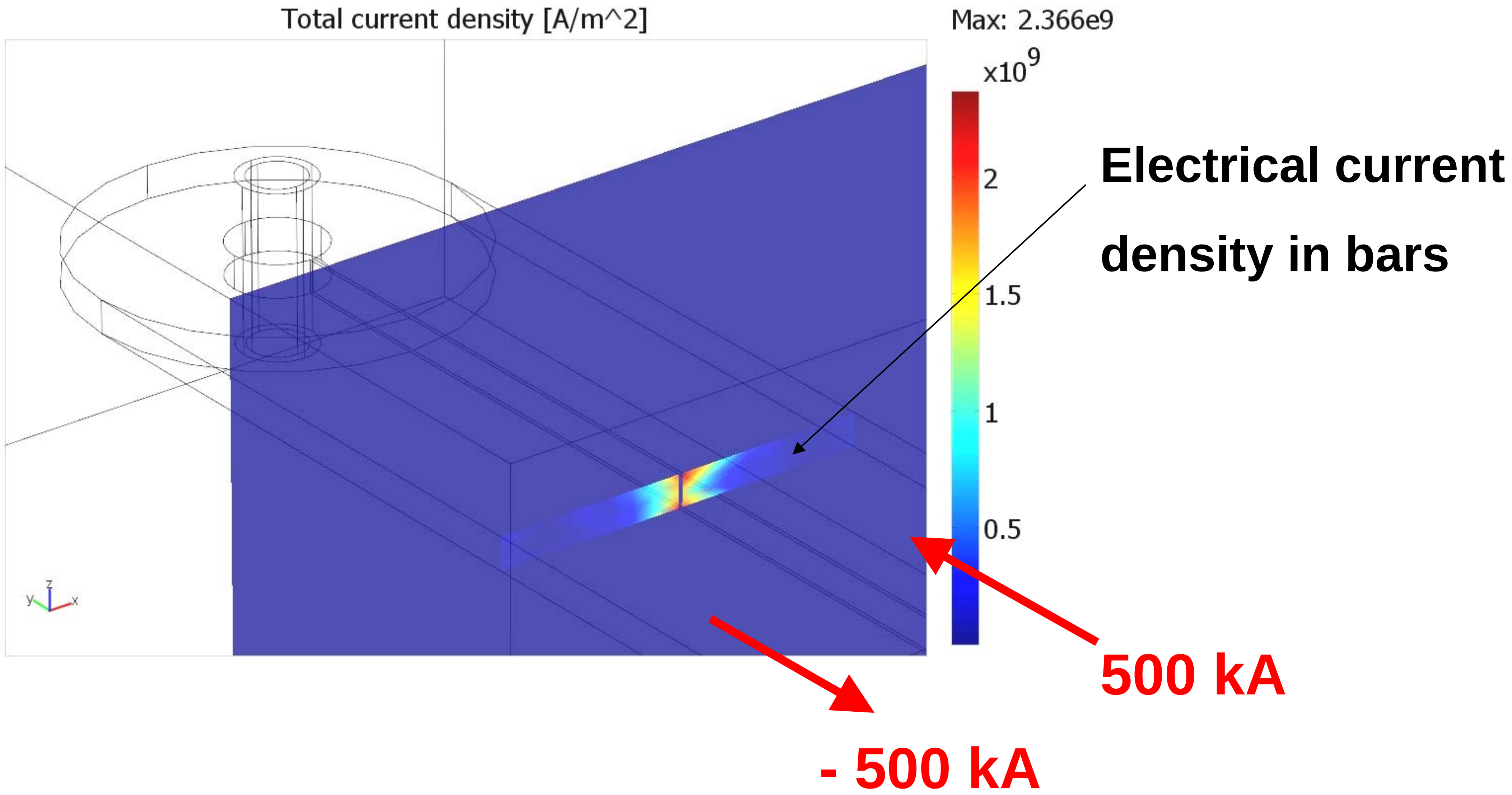


Work piece:

Cu cylinder, 40 mm outer diameter, 5 mm wall thickness



FEA example 3 (3D simulation): **Single-turn pulse deformation coil:**



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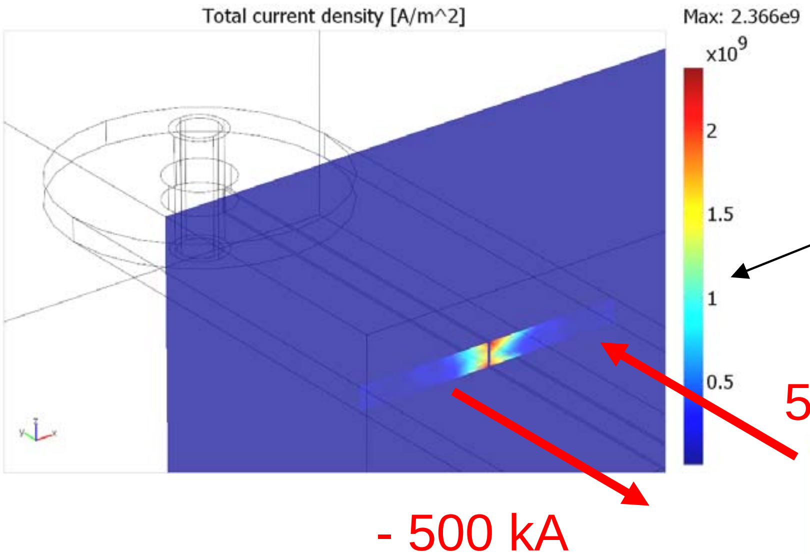
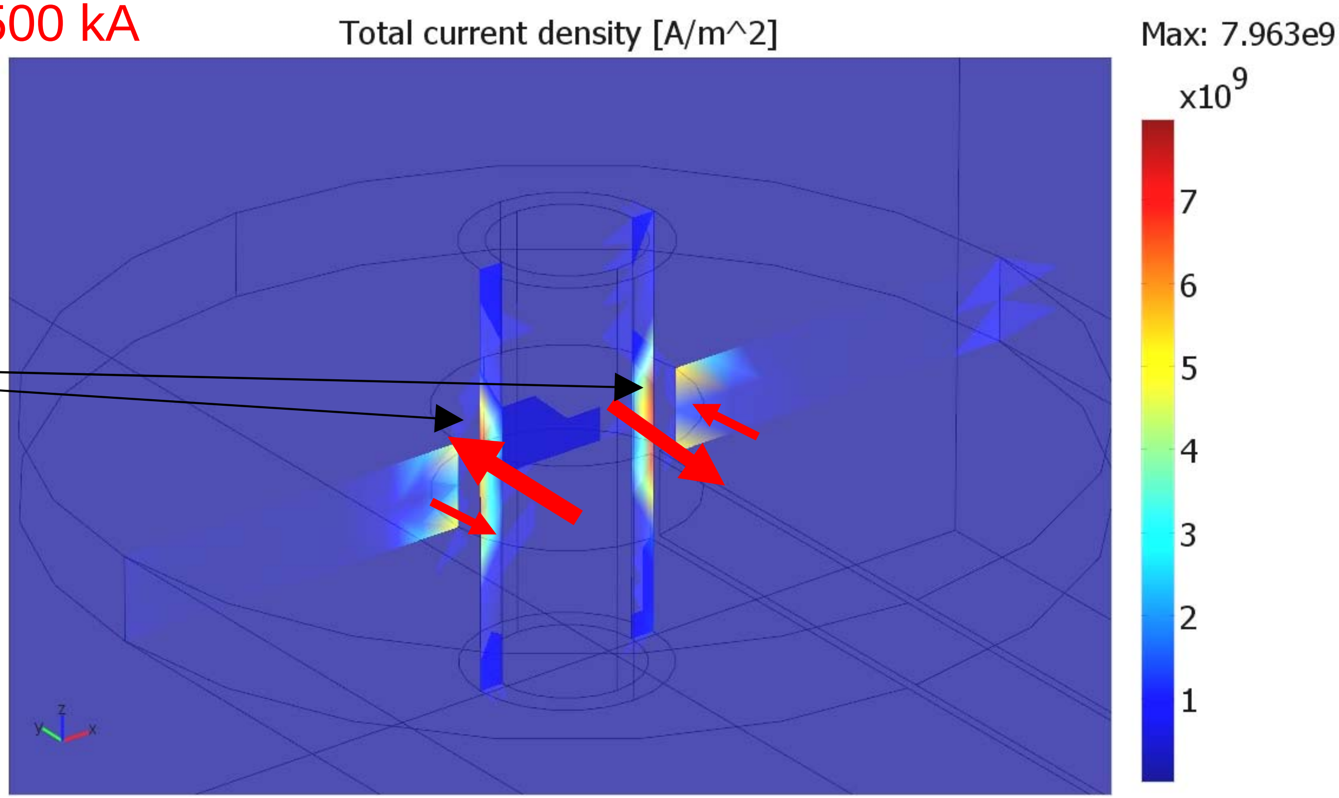


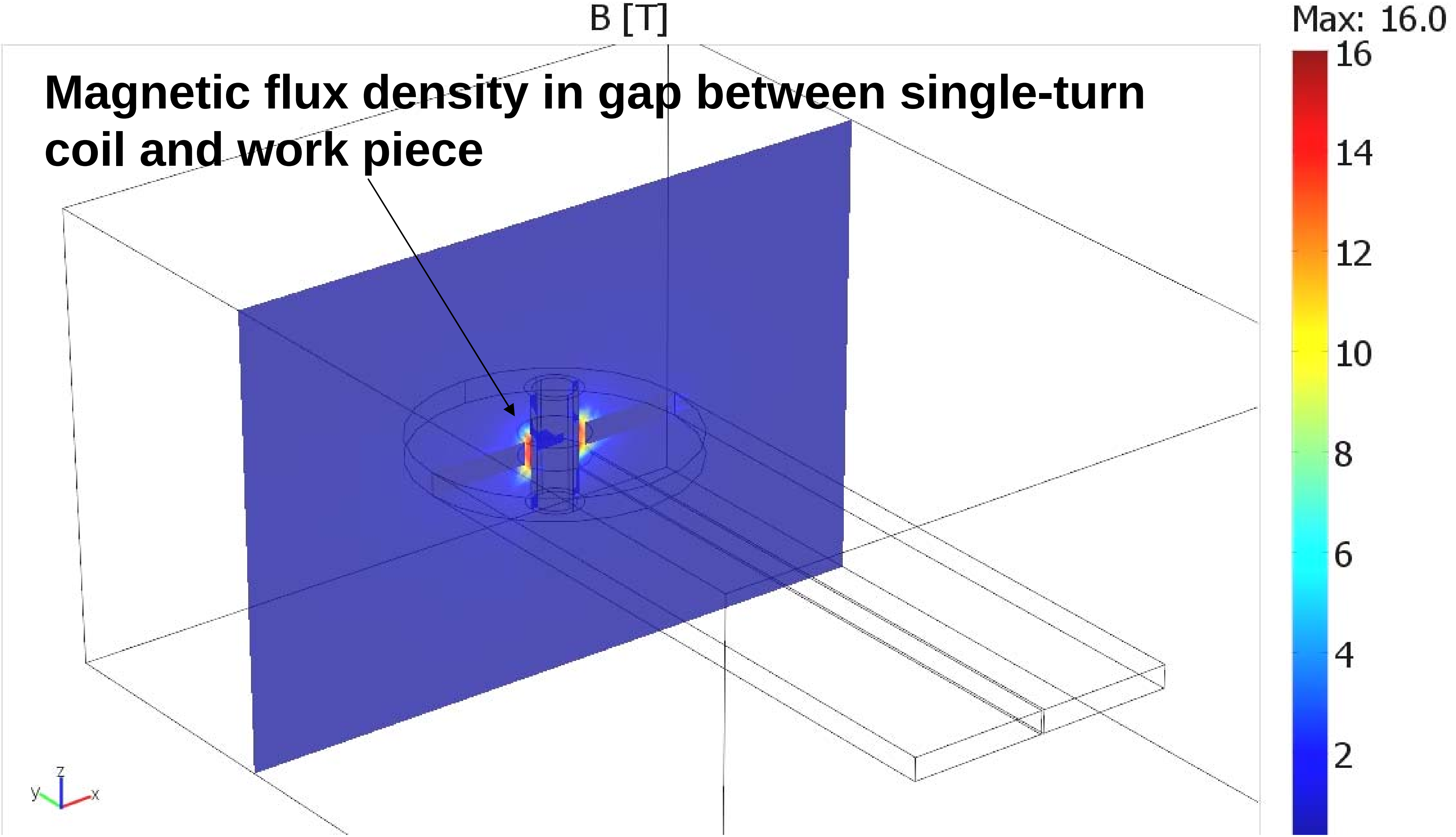
Electrical current density in bars



Induced electrical current density in work piece

$\sim (dB/dt)^2$

FEA example 3 (3D simulation): **Single-turn pulse deformation coil:**



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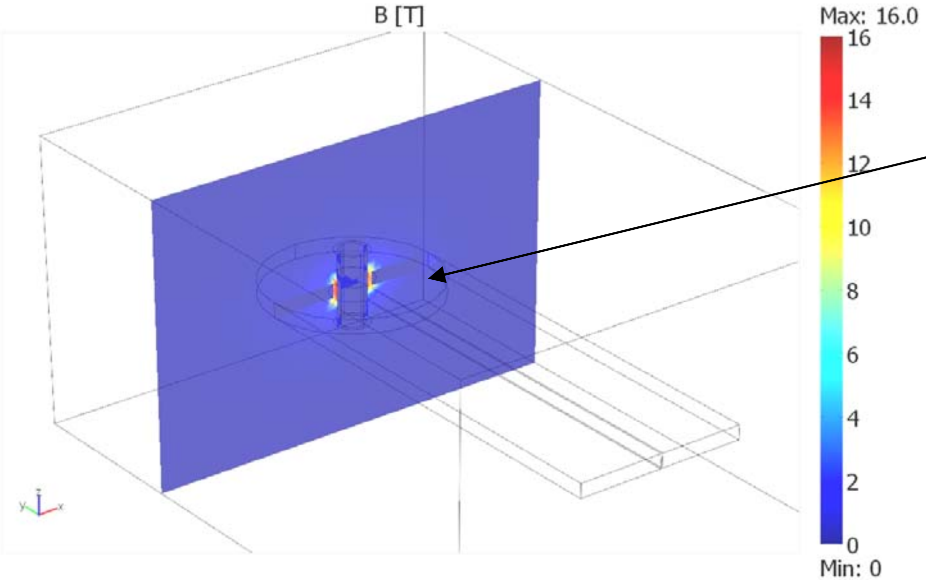


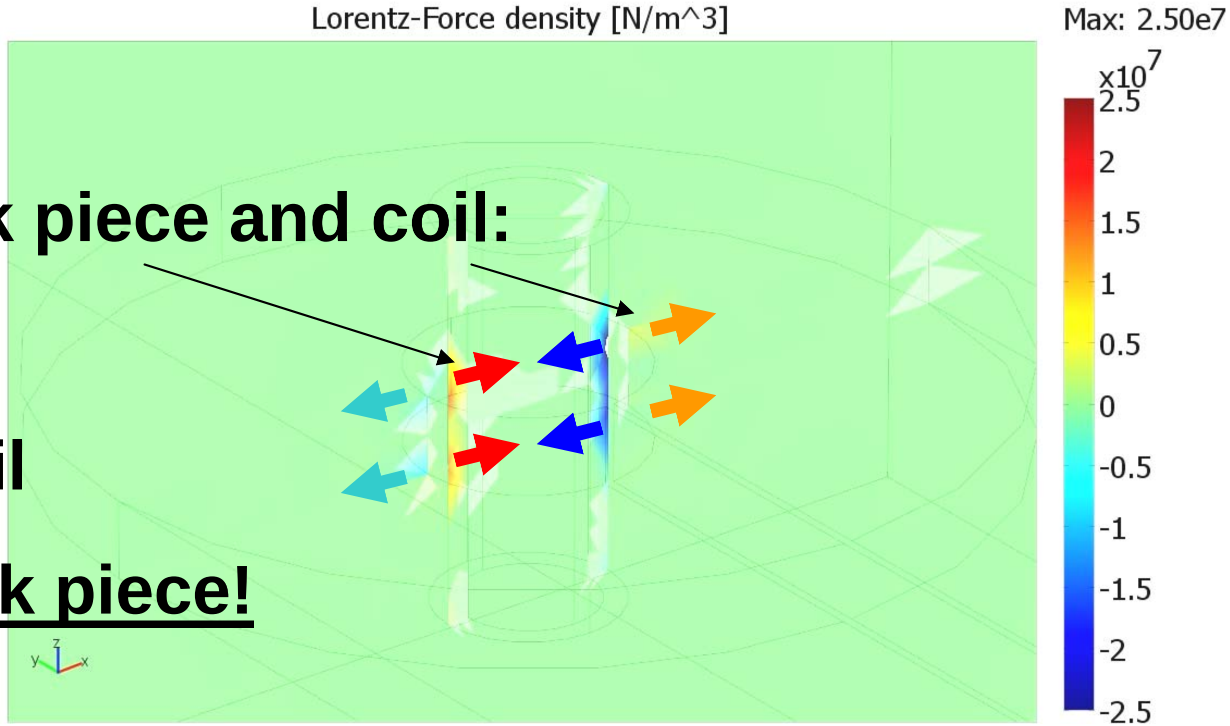
Magnetic flux density in gap between single-turn coil and work piece

Lorentz force density in work piece and coil:

F / V = J x B

-> radial expansion of the coil

-> radial compression of work piece!



FEA example 3 (3D simulation): Single-turn pulse deformation coil:

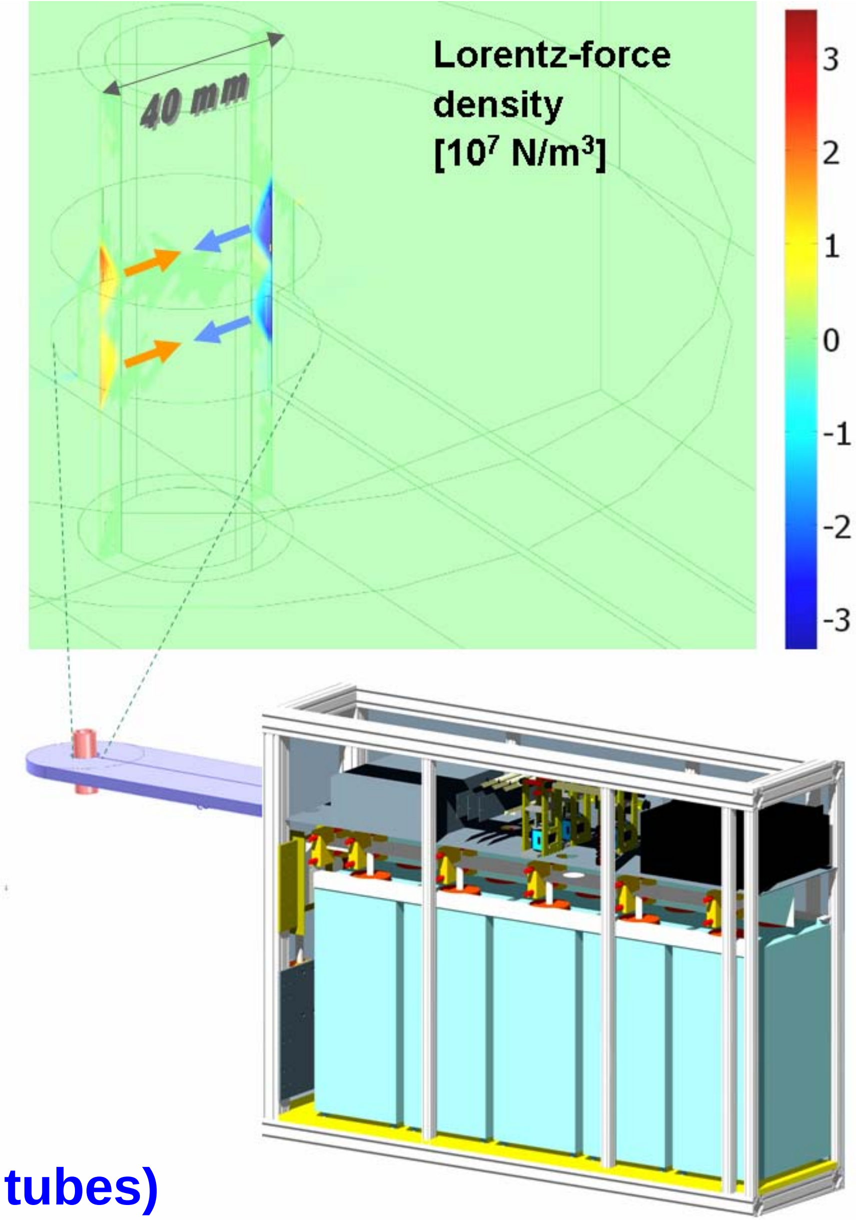
Lorentz force density in work piece and coil:

F / V = J x B

-> radial expansion of the coil

challenges:
- high repetition rate (≤ 10 sec)
- long life time (≥ 10^6 pulses)
- coil needs elastic regime

-> radial compression of work piece!



Next steps:

FEA of mechanical load:
- workpiece needs plastic regime
- use of real stress-strain curve
- calculation of plastic deformation

No limits for geometry !

Future: FEA of welding processes (e. g. of coaxial tubes)

Conclusion

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

- to evaluate pulsed- power and pulsed-magnetic field techniques which are a technology platform for modern research and novel industrial innovations.

-Thanks to its stepwise improvement during the recent years, COMSOL offers many features to simulate the physical behavior of even larger structures, such as pulsed magnetic field coils made of various parts of materials or composites with very different quantities (iso- or anisotropic functions of temperature, field, pressure, …)

- For this purpose, the possibility to perform simulations which comprise several differential equations from many disciplines of physics (multi-physics), such as electrodynamics, mechanics, and thermo-dynamics is beneficial.

- 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. For this reason, COMSOL can be also used to describe pulsed power generators and the technique of electromagnetic pulse forming, joining and possibly welding.

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EU projects:

- EuroMagNET
- DeNUF
- MAGISTER
- EuroMagNET-II
- Upgrade
  ESFRI roadmap

International conference
"Research at High Magnetic Fields"
HLD, Dresden, July 2009

ICAM-I2CAM Institute for Complex Adaptive Matter

Institute for Complex Adaptive Matter