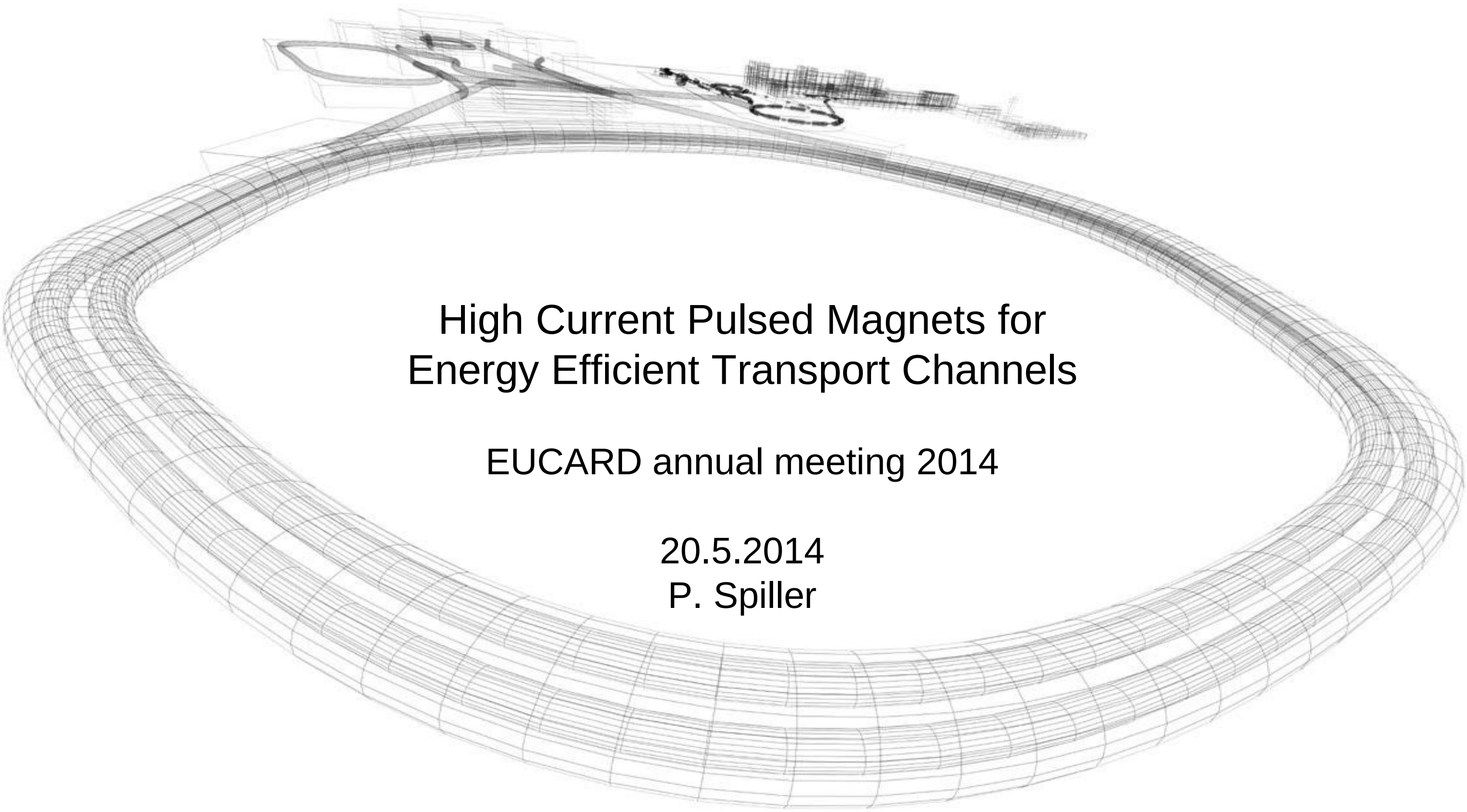


High Current Pulsed Magnets for Energy Efficient Transport Channels

EUCARD annual meeting 2014

20.5.2014
P. Spiller

Advantages of Pulsed Magnets

- Energy efficient
  (field is only on during flight time of ion bunch through magnet)
  Low average energy dissipation

- Low heat release into air or water
  Relaxed technical infrastructure for building (water recooler, air ventilation)

- Potential for very high fields and gradients
  Replacement for superconducting magnets with much less infrastructure effort (cryogenic plant, He distribution system etc.)

Qualitative Comparison of Different Technologies

	Conventional Magnets	Superconducting Magnet Systems	Plasma- or Lithium Lenses	High Current Pulsed Magnets
Degree of engineering	High	High	Moderate	Low
Operation mode	Static/ramped	Static/ramped	Pulsed	Pulsed
Aperture	High	Limited	Limited	Limited
Geometr. size	Small-large	Moderate (cryostat)	Moderate	Small
Field strength/gradients	Limited	High	High	High
Average energy dissipation	High	Moderate (heat load to cryogenics)	Low	Low
Electr. stray field	Low	Low	High	Moderate
Technological complexity	Low	High	High	Moderate
Cost	„Low“	High	Moderate	„Low“
Reliability	High	High	Moderate	Moderate
Beam time structure	bunched/cw	bunched/cw	bunched	bunched

Application of Pulsed Magnets

No need for c.w. operation of e.g. n.c. beam transport magnets if the beam pulse length is in the order of e.g. < 1 μs and the repetition frequency is moderate

Application in transport systems for bunched ion- or electron beams e.g.

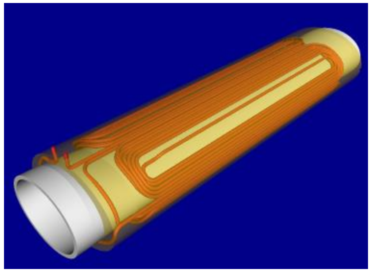
- inbetween circular accelerators (synchrotrons, storage rings etc.)
- final focusing of bunched beams
- linacs in pulse mode operation

Application in circular accelerators for fast processes e.g.

- controlled short term linear coupling during multi turn injection processes
- gamma T jump

History

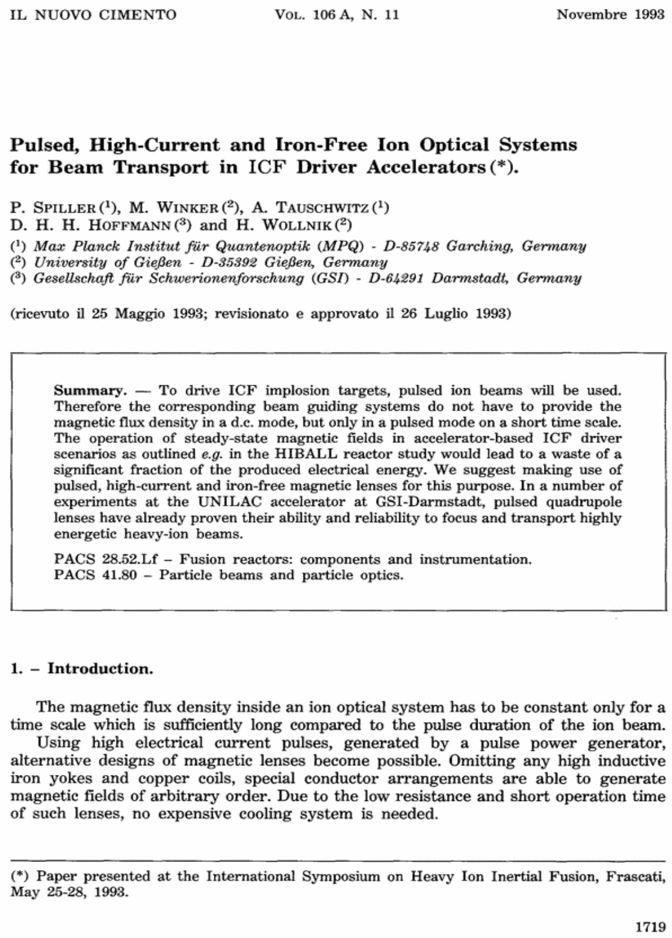
At LBNL for IFE



Pulsed quadrupole magnets developed

For HIF, and other non-DC magnetic applications, pulsed magnets offer high fields at lower cost than superconducting (SC) magnets, and at lower energy consumption than DC resistive magnets. They are compact and have a high degree of design flexibility. These might include very-short-latticeperiod transport, final focus in high neutron and radiation environments, beam steering and corrections between transport sections, and time dependent focusing.

At GSI for ICF



IL NUOVO CIMENTO Vol. 106 A, N. 11 Novembre 1993

Pulsed, High-Current and Iron-Free Ion Optical Systems for Beam Transport in ICF Driver Accelerators (*).

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(ricevuto il 25 Maggio 1993; revisionato e approvato il 26 Luglio 1993)

Summary. — To drive ICF implosion targets, pulsed ion beams will be used. Therefore the corresponding beam guiding systems do not have to provide the magnetic flux density in a d.c. mode, but only in a pulsed mode on a short time scale. The operation of steady-state magnetic fields in accelerator-based ICF driver scenarios as outlined *e.g.* in the HIBALL reactor study would lead to a waste of a significant fraction of the produced electrical energy. We suggest making use of pulsed, high-current and iron-free magnetic lenses for this purpose. In a number of experiments at the UNILAC accelerator at GSI-Darmstadt, pulsed quadrupole lenses have already proven their ability and reliability to focus and transport highly energetic heavy-ion beams.

PACS 28.52.Lf – Fusion reactors: components and instrumentation.
PACS 41.80 – Particle beams and particle optics.

1. – Introduction.

The magnetic flux density inside an ion optical system has to be constant only for a time scale which is sufficiently long compared to the pulse duration of the ion beam.

Using high electrical current pulses, generated by a pulse power generator, alternative designs of magnetic lenses become possible. Omitting any high inductive iron yokes and copper coils, special conductor arrangements are able to generate magnetic fields of arbitrary order. Due to the low resistance and short operation time of such lenses, no expensive cooling system is needed.

(*) Paper presented at the International Symposium on Heavy Ion Inertial Fusion, Frascati, May 25-28, 1993.

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Prototype Quadrupole Magnet

Prototyping is in the responsibility of the Group „High Voltage Pulse Power“

- GSI designs and builds a prototype high current pulsed quadrupole magnet for a final focusing for SIS18 beams

- Design studies and conceptual engineering design has been completed

- EUCARD deliverable 3.2. „design study“ has been completed.

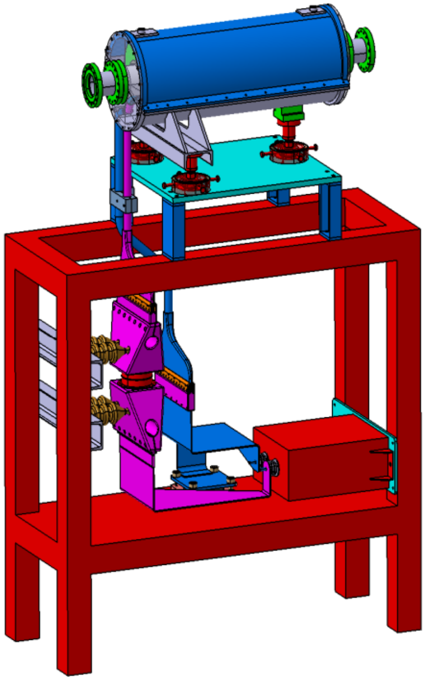
- Tendering for the final engineering design and manufacturing of the prototype lens completed.

Potential Driver Technologies

High power switches	
Pseudospark switch	Plasma lens operated with six parallel 60 kA switches. However not reliable under variable operation conditions.
Spark gap	Restricted life time.
Ignitron	Mercury
Semi conductor stacks	Available for very high currents
Thyratrons	Reliable and proven. Limited number manufacturers. Limite current
Energy storage	
Capacitors	Periodic discharge, „Flat top“ may be sufficient
Pulse cable	Rectangular current pulse
PFN	Rectangular current pulse

Prototype Quadrupole Magnet – Parameters

	Prototype Quadrupole
Gradient	80 T/m
Length	0.65 m
Pulse length	90 µs (beam 1 µs)
Peak current	400 kA (35 kA)
Peak voltage	17 kV (5 kV)
Energy @17 kV	65 kJ (5.6 kJ)
Inductivity	535 nH
Capacitor	450 µF
Forces	200 kN

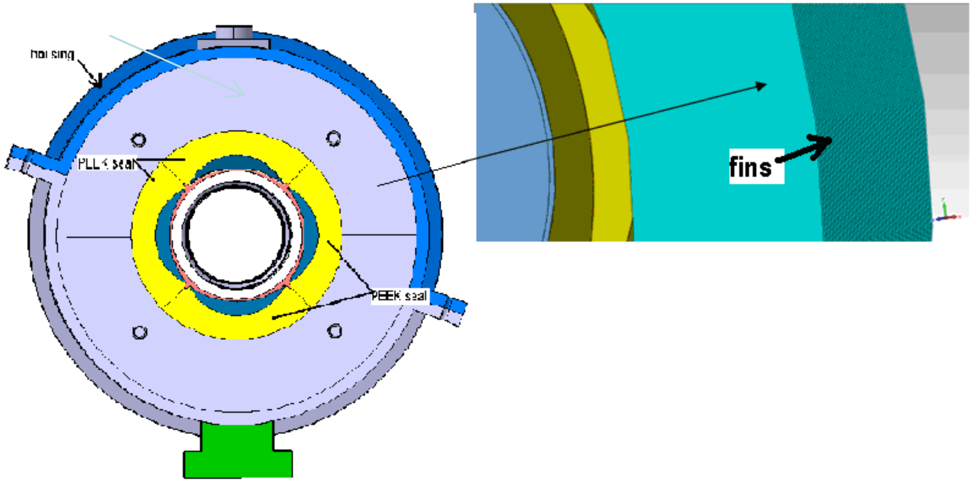


Engineering model of the prototype quadrupole magnet incl. support

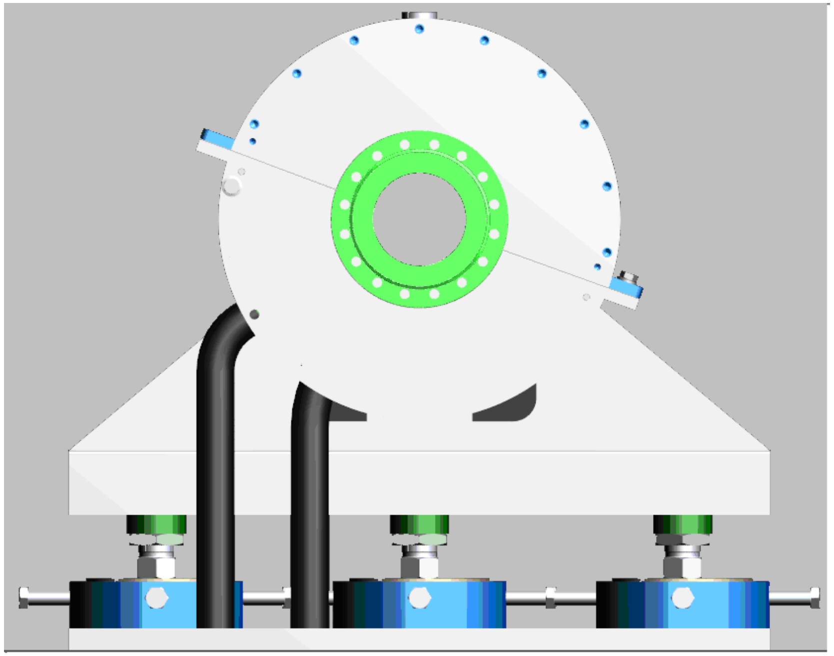
Comparison Pulsed Quadrupole – Conventional Quadrupole

	Conventional Quadrupole	**Pulsed Quadrupole**
Gradient	10 T/m	15.38 T/m
Length	1 m	0.65 m
G x L	10 T	10 T
Apertur radius	0.065 m	0.056 m
Peak current	270 A	77 kA
Peak voltage		4.7 kV
Stored energy	5,5 kJ (in magnet gap)	5 kJ (in capacitor)
	SIS18 repetition rate: 1 Hz	
Power	18 kW	5 kW

Prototype Quadrupole Magnet – Cross Section

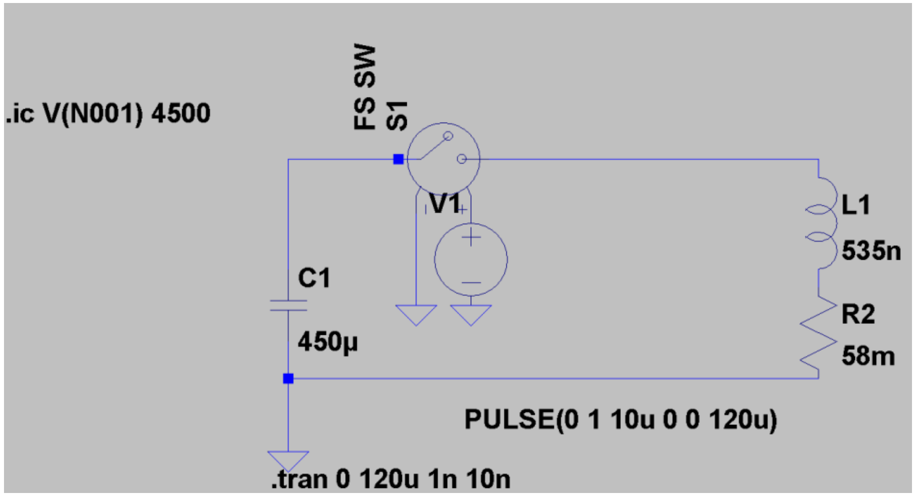


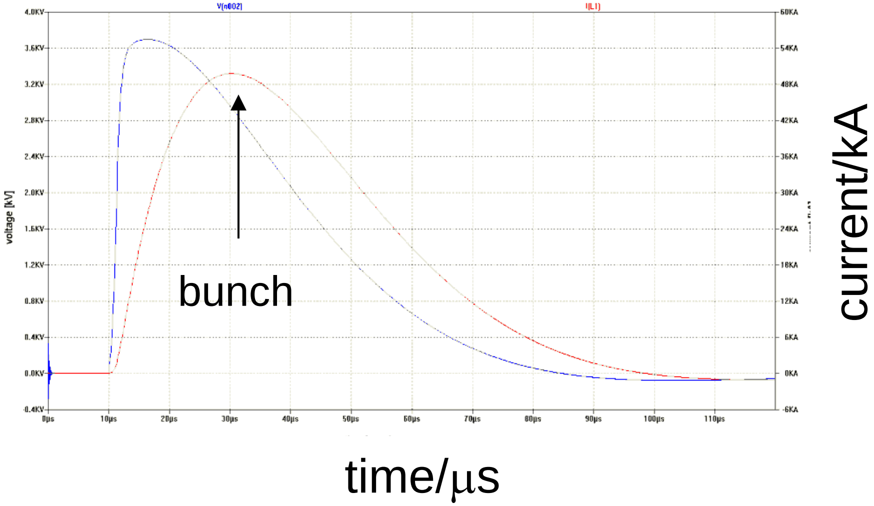
Cross section of the pulsed quadrupole magnet with
- stainless steel collar
- laminated yoke
- peek spacers
- single turn coil
- ceramics beam pipe



Connection side of the lense

Electrical Circuit for the Prototye Tests



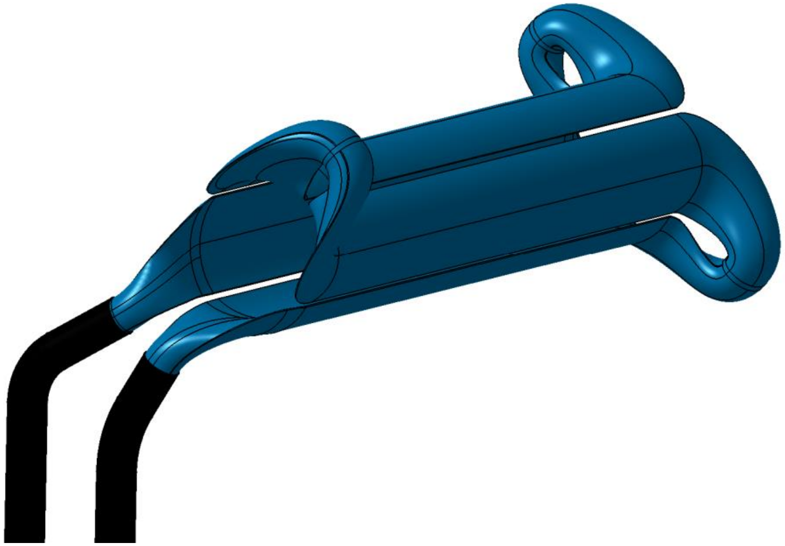


Equivalent electrical circuit

Voltage and electrical current

Conductor Geometry

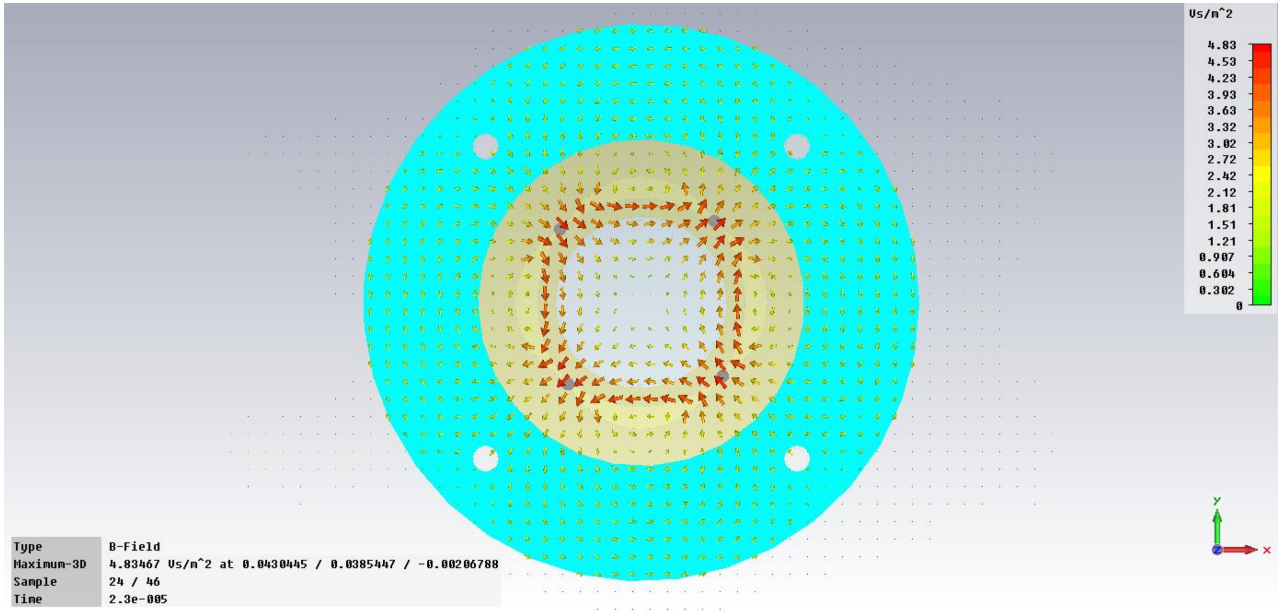
Generates a cos2theta current distribution along the cirumference similar to a superconducting magnet



Cross section of the optimized conductor

Layout of the prototype coil

Field Quality



```
Type         B-Field
Maximum-3D   4.83467 Vs/m^2 at 0.0430445 / 0.0385447 / -0.00206788
Sample       24 / 46
Time         2.3e-005
```

Calculated field distribution for the optimized conductor geometry

Transient Effects

To avoid transient effects (e.g. skin effect) in the conductor,
special effort has to be take to assure a homogenous current distribution in the shown conductor cross section (model has been build).

Patent in prepartion for special components

Next Steps

Prototype Project
Manufacturing of the prototype lens. Contract signed.
Procurement of capacitors, switches, HV power supply etc.
Preparation of field measurements via an inductive coil probe.
Preparation of a beam test with heavy ion beams from SIS18.

Perspectives

- Evtl. development of a pulsed skew quadrupole for linear coupling during MTI into SIS18.

- Increased repetition frequency by adapting the design to water cooling

Transport System Design Study (EnEfficient Transport)
Start of a comparison of beam transport technologies from the system design point of view and with respect to energy efficiency.

(Master thesis Philip Gardlowski)

Members of the Pulse Quadrupole Development Team

- Carmen Tenholt (phd thesis)
- Udo Blell
- Isfried Petzenhauser