Energy efficient beam transport by means of high current pulsed magnets

Workshop on Special Compact and Low Consumption Magnet Design

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C.Tenholt

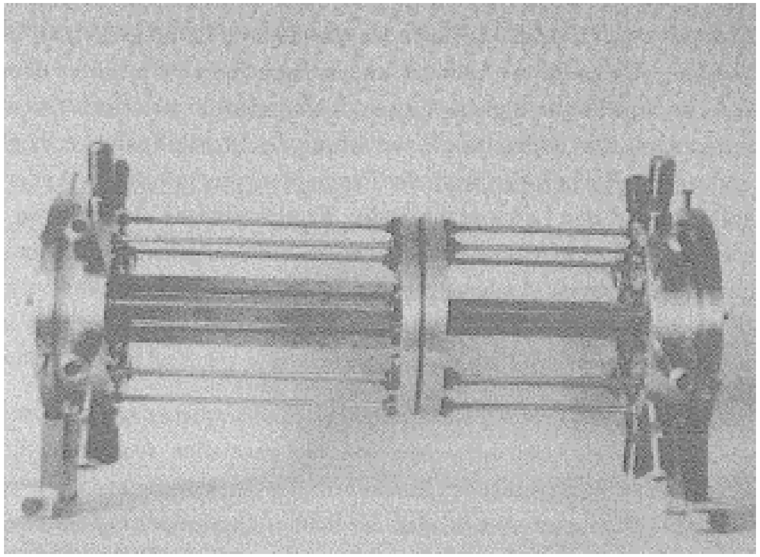
Qualitative Comparison of Different Technologies

	Conventional Magnets	Superconducting Magnets	Plasma- or Lithium Lenses
Operation	Quasi static	Quasi static	Pulsed
Space requirememts	High	High	Moderate
Aperture	High	High	Moderate
Field strength/gradients	Limited	High	High
Average energy dissipation	High	Low	Low
Cost	Low	High	Moderate
Beam shape	bunched/cw	bunched/cw	Bunched

Opportunities of Improvement (bunched mode)

- Increase of magnetic field gradient
  - Independence from magnetic saturation (no iron core)
  - High current pulses
- Energy saving
  - Pulsed currents vs. cw
  - Energy efficient circuit
- Space gain
  - Smaller aperture enabled by higher field gradients

First efforts: Rod conductor quadrupoles



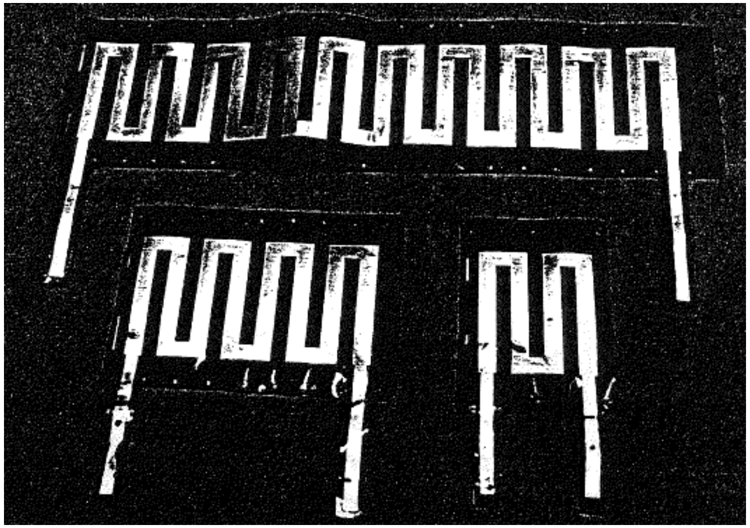
Rod conductor quadrupole

- At least one rod per pole
- Rods supplied symmetrically by pulsed current (homogeneous fields)
- Polarity defined by direction of electric current
- Tested doublet with r_1=0.012m and r_2=0.02m
  - ➢ G_1=92.5 T/m at 42kA
  - ➢ G_2=42.75 T/m at 55kA

→ Focal radius: 150µm at
beam charge 26+, rigidity 6Tm

First efforts: Foil quadrupoles

- Copper conductor etched on fotoresist foils
- High magnetic fields by stacking and filament winding of foils



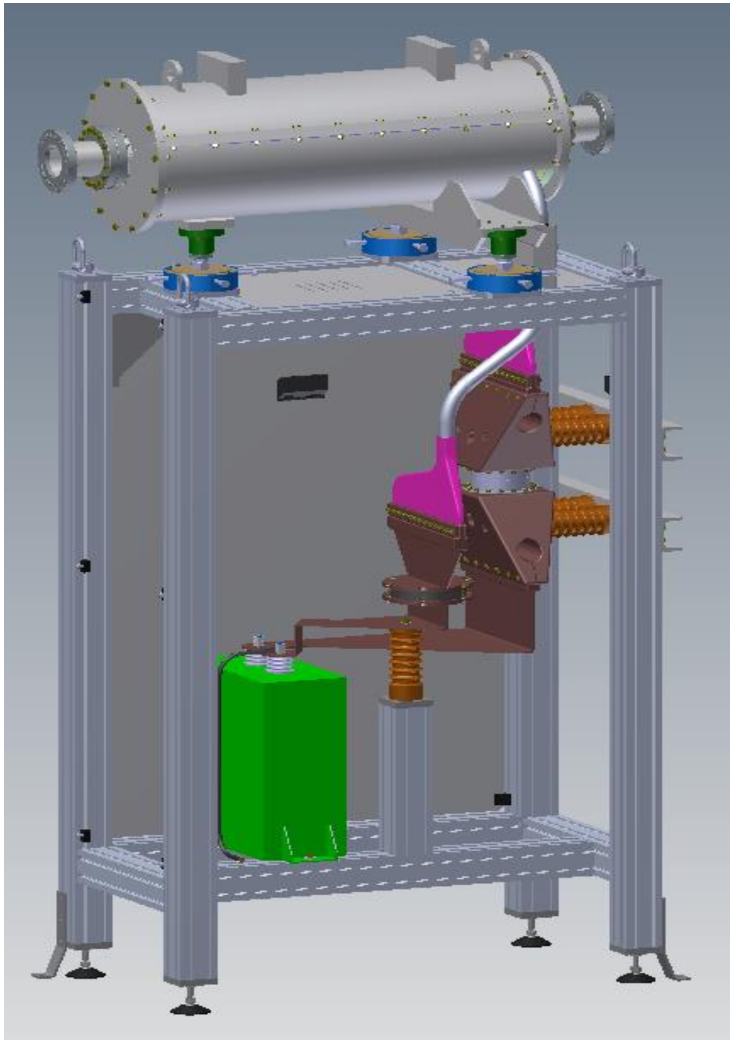
→ **Experiences: Foils are not capable of leading necessary currents**

New approach: Cos(2θ)-shaped wire conductors

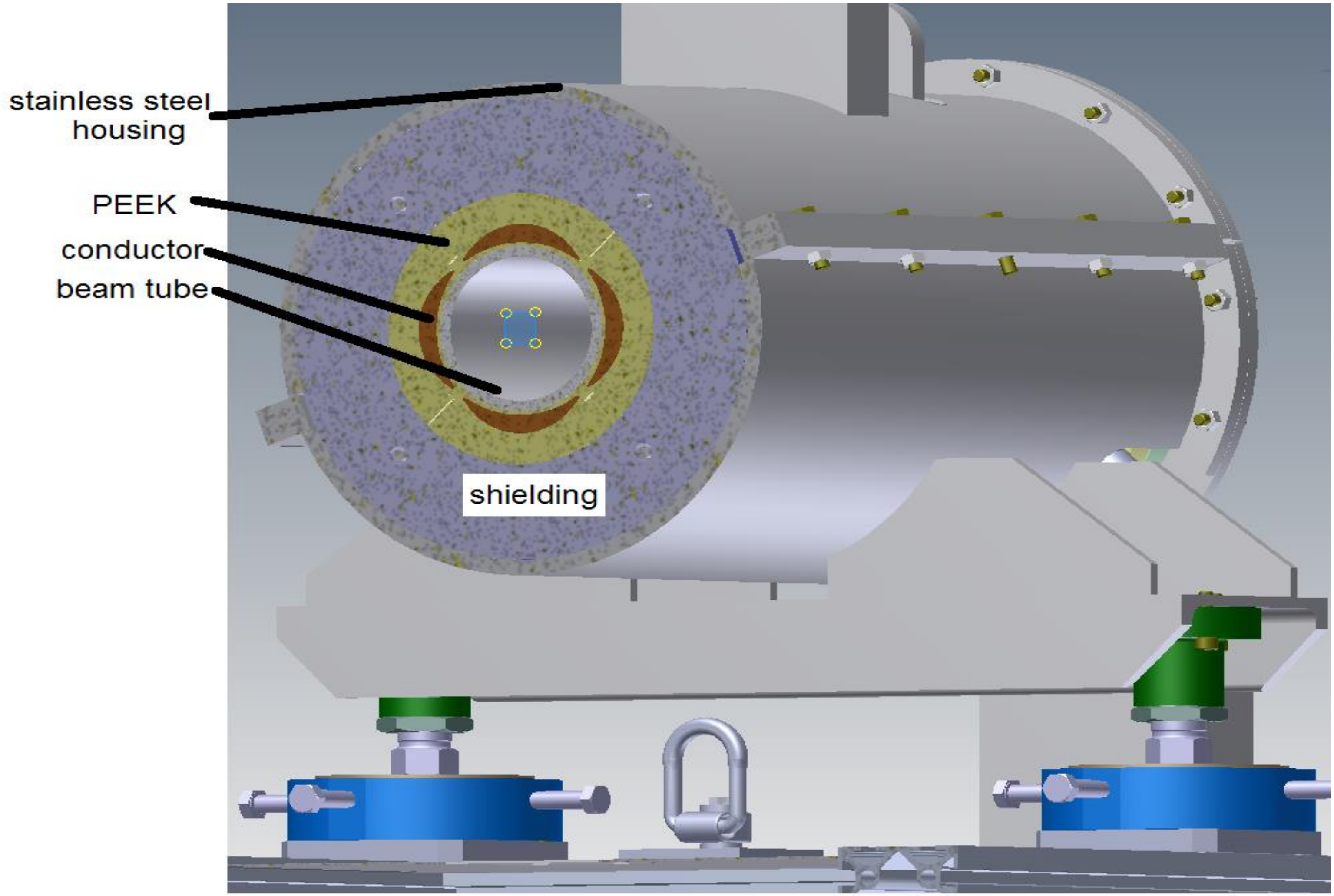
Lens with boxed electrical circuit (electrical shielding and safety) underneath:

- Capacitor (green)
- Disc resistor (black)
- Switch (grey)

All linked by special adaptors for low inductivity and low influence of Skin Effect



New approach: Lens cross section



Target values

	Prototype Quadrupole
Gradient	80 T/m
Length	0.65 m
Pulse length	170 μs
Peak current	400 kA (31 kA)
Peak voltage	23 kV (4.7 kV)
Energy @23 kV	119 kJ (5 kJ)
Inductivity	1,3 μH
Capacitor	450 μF
Forces	200 kN

New approach: Construction characteristics

– Ceramic beam tube

– Cos(2θ)-shaped conductor

600 strands of bunched, drilled copper wires (diameter of 0.355 mm) insulated against each other (providing homogenous current distribution)

– PEEK

Damping of mechanical stress caused by current pulses

– Shielding

Thin silicon iron discs, laminated in beam direction (increase of enclosed magnetic field)

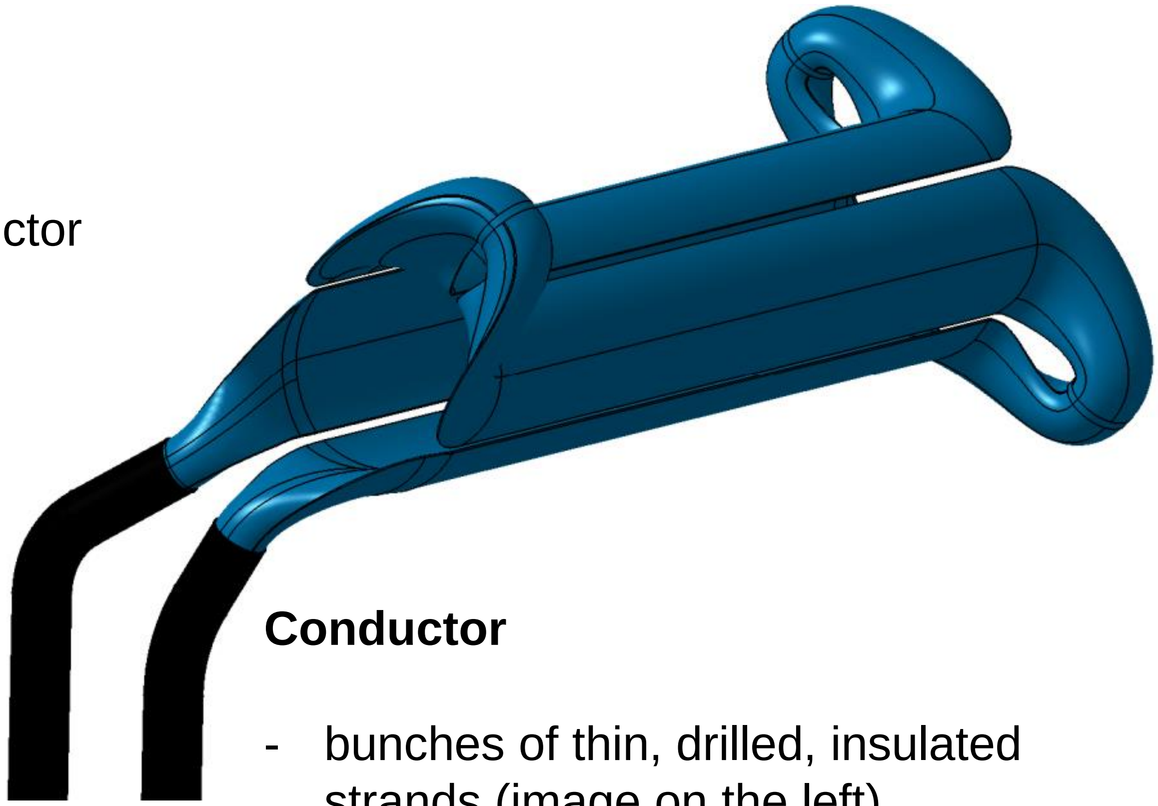
– Housing

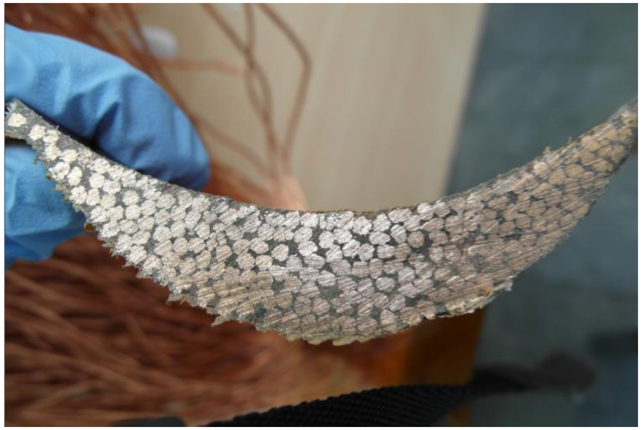
Protection of nearby equipment against electromagnetic noise, absorption of mechanical forces

Conductor

Formation of poles

- winding of one single conductor
- symmetric ends (as far as possible)

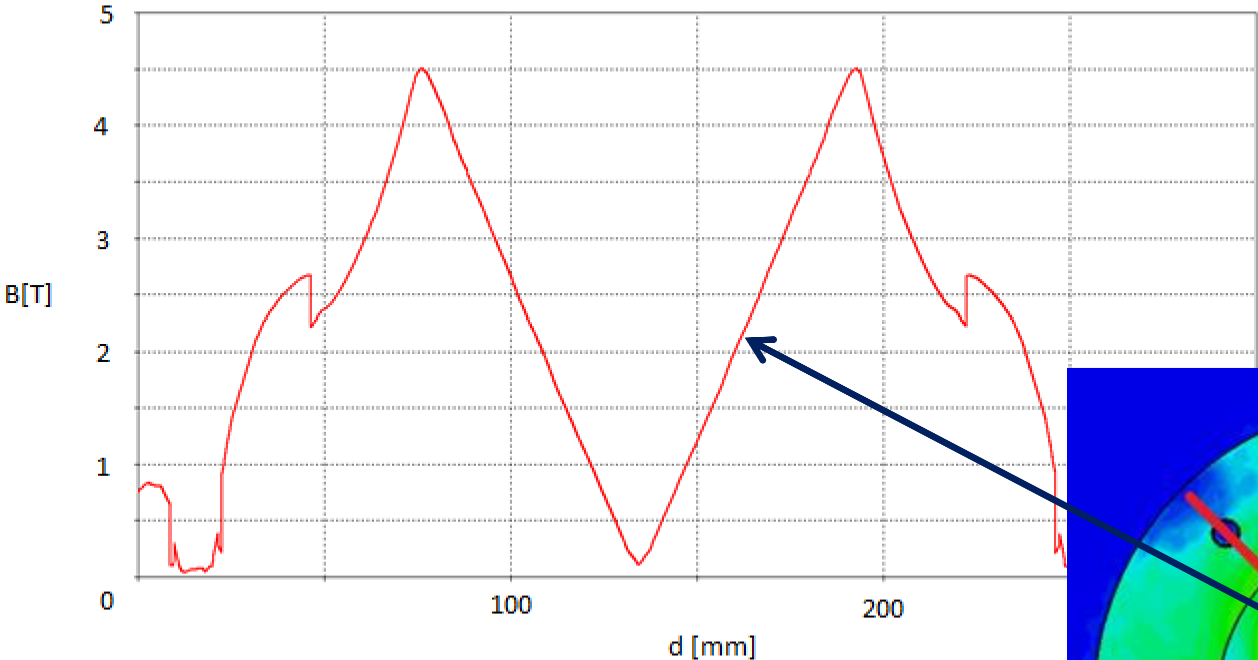


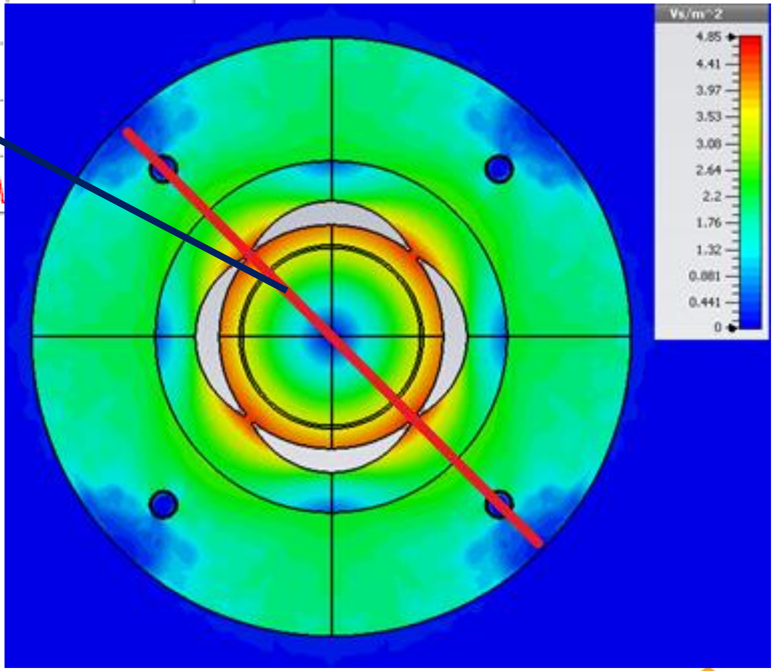


Conductor

- bunches of thin, drilled, insulated strands (image on the left)
- cos(2**θ**) cross section

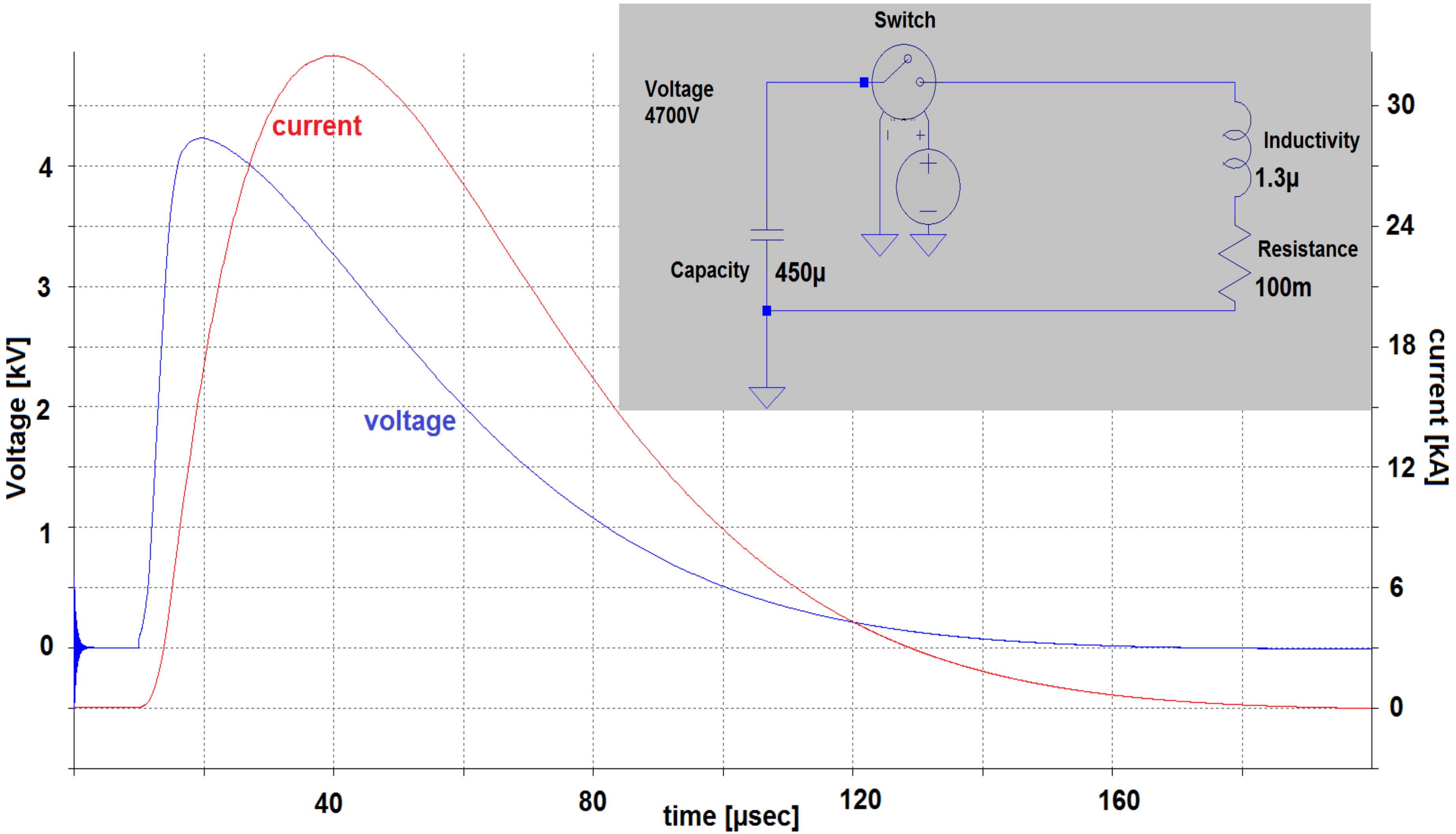
CST-Simulation: magnetic field





homogeneous distribution of the magnetic field inside the beamline for precise focusing

Electrical Circuit of the Prototype

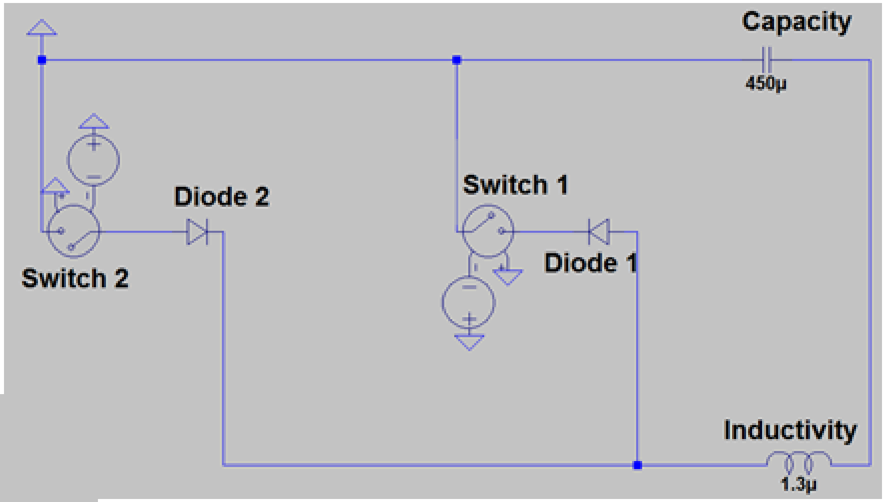


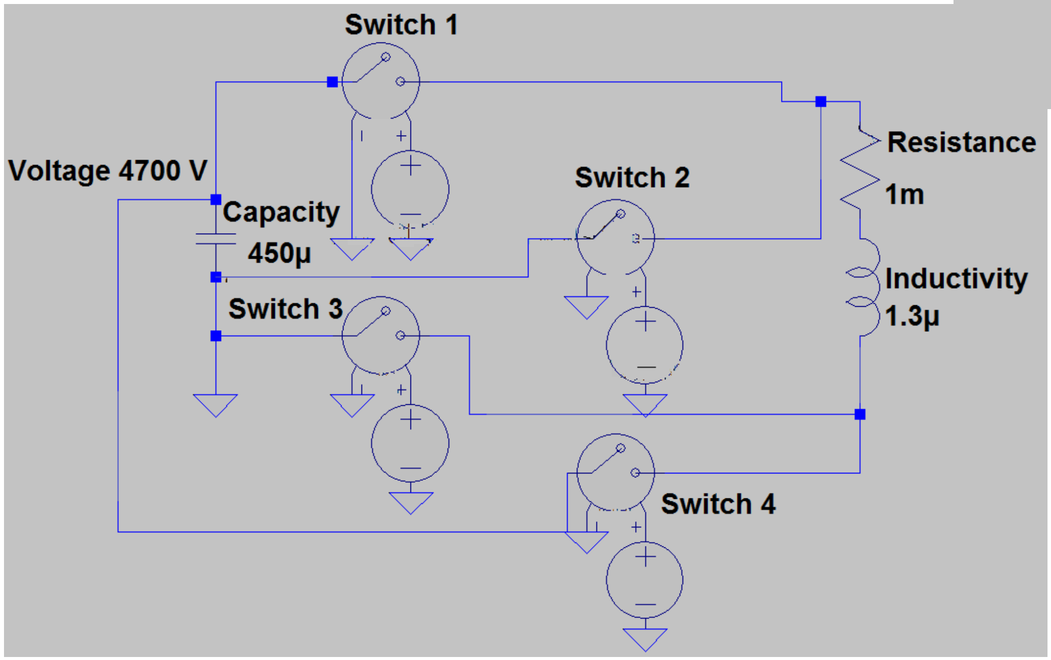
Energy recovery

Problem:

current changes direction through the lens

price: two switches necessary for high currents

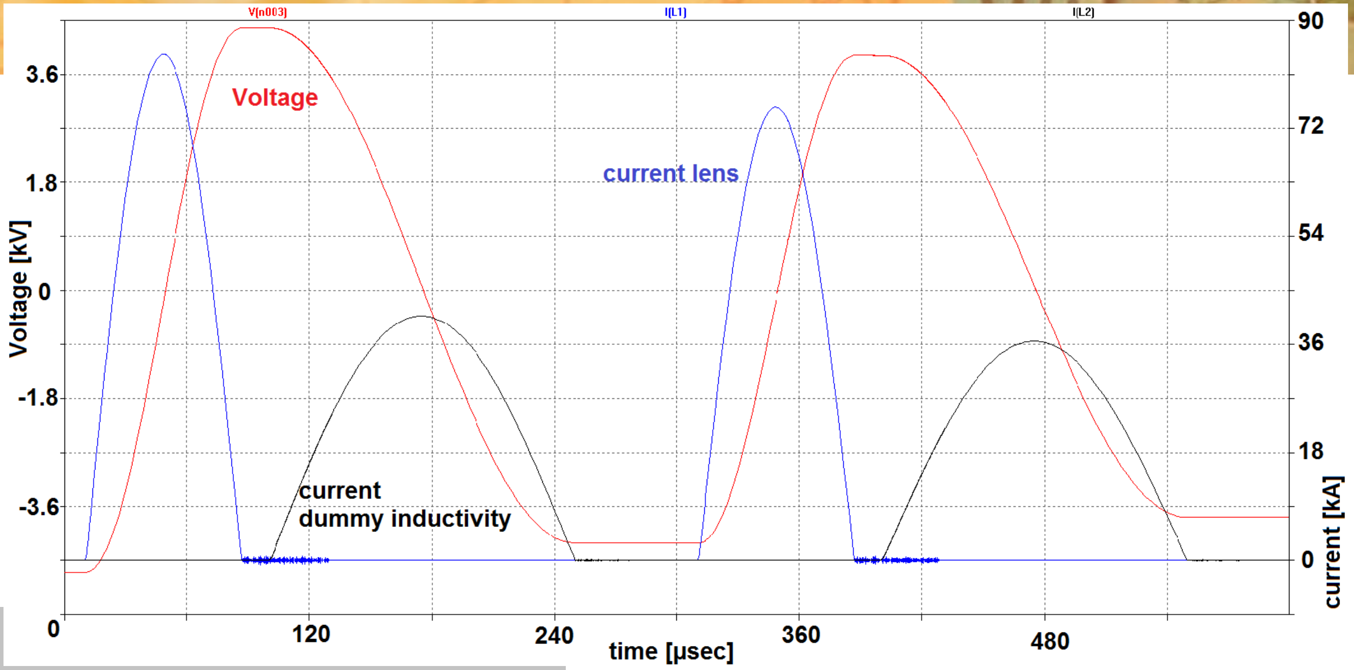


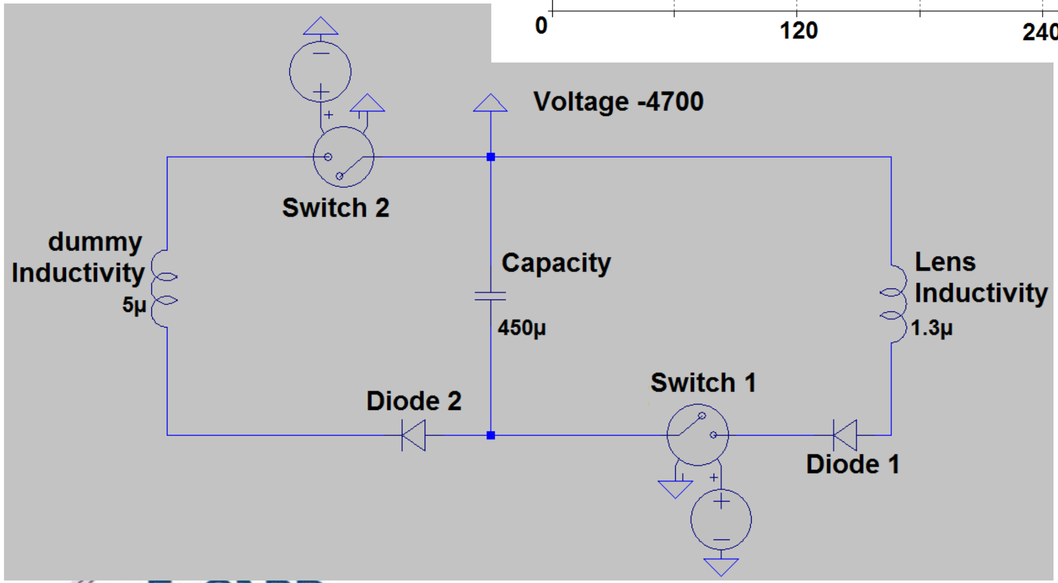


Problem:

price: 4 high voltage/current switches

Energy recovery





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 (810W with energy recovery circuit)

Estimation of maximal pulse repetition rate

Repetition rate

Prototype

(decisive factor: supplying power):

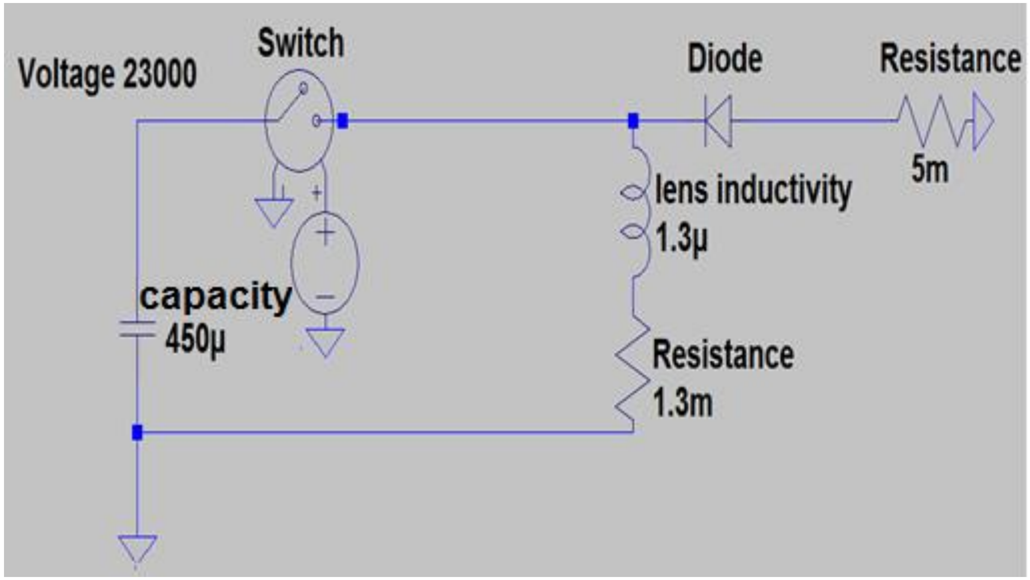
- 4500 V/30 kA

200 sec reloading of capacitor

- 1500 V/10 kA

67.5 sec reloading of capacitor

→ cooling of damping resistor necessary



Maximum value

(decisive factor: lens‘ cooling) see picture on the right

- 23 kV/400kA

21 sec (complete cooling of the lens)

→ (no damping resistor – antiparallel Diode)

Outlook

November 2014: Delivery of lens to GSI

- tests (low performance max. 4500V/31000)
- magnetic field measurments (dc and pulsed mode as far as possible)

Future

- tests with beam
- assembling of energy recovery circuit → test with lens and dummy inductivity