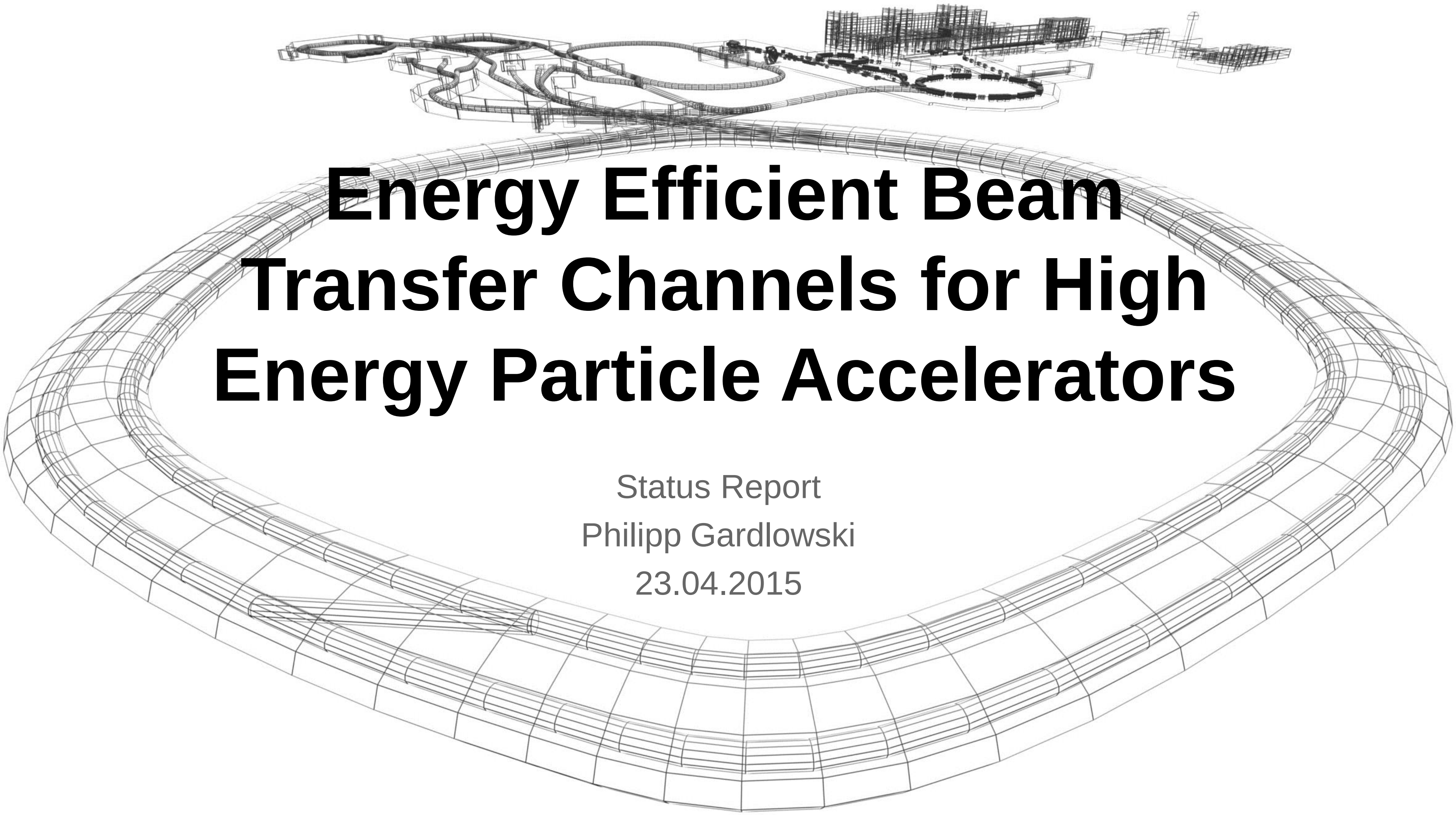

Energy Efficient Beam Transfer Channels for High Energy Particle Accelerators

Status Report

Philipp Gardlowski

23.04.2015

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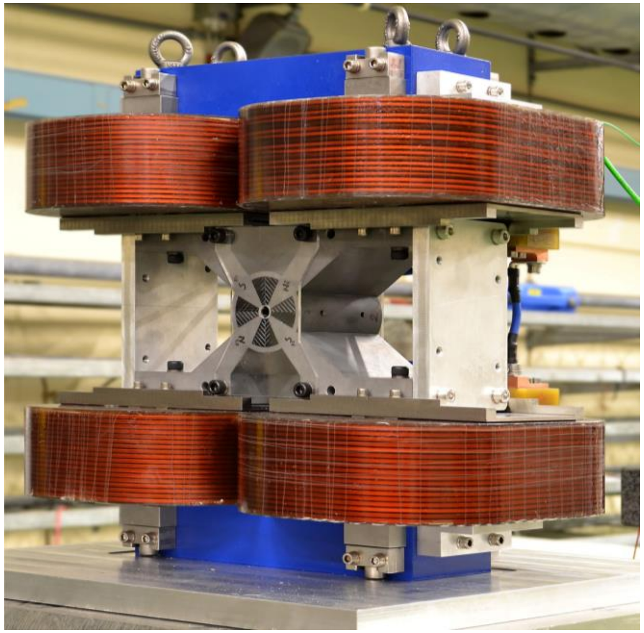
Aims and practice

- There is a variety of different magnet types ...
  ... Which of those types is the “right“ one?

▼ Hybrid quadrupole for CLIC [3].



▲ Normal conducting quadrupoles at J-PARC [2].

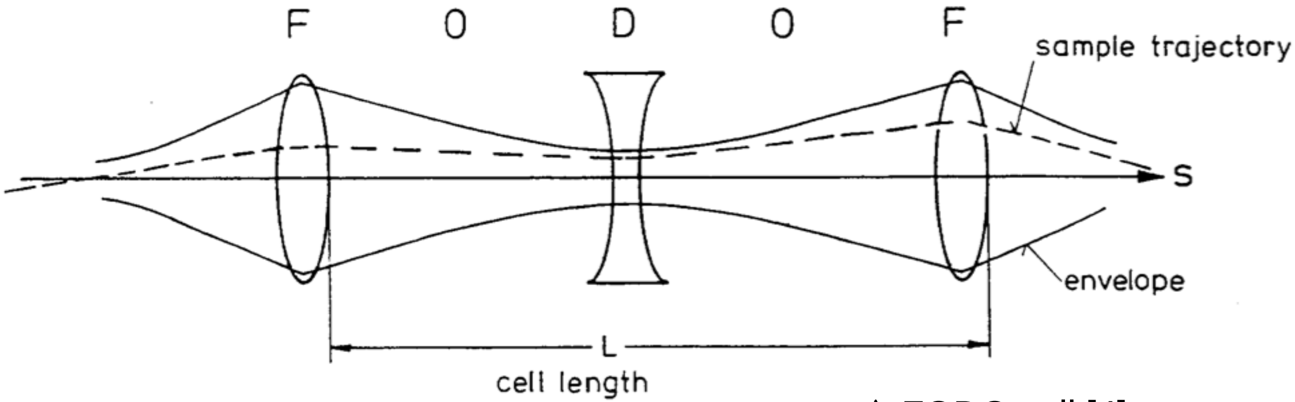
▶ Prototype of a high current pulsed quadrupole at GSI [1].

Aims and practice

→ Develope a rule of thumb for choosing the magnet type for high energy beam transfer channels

- Estimation of costs for a FODO beamline
  - Modelling the different magnet types
    - Compact design
    - Optimization of the energy efficiency
  - Estimation of costs
    - Determine operation costs
    - Determine manufacturing costs
    - Determine total costs for the planned life time

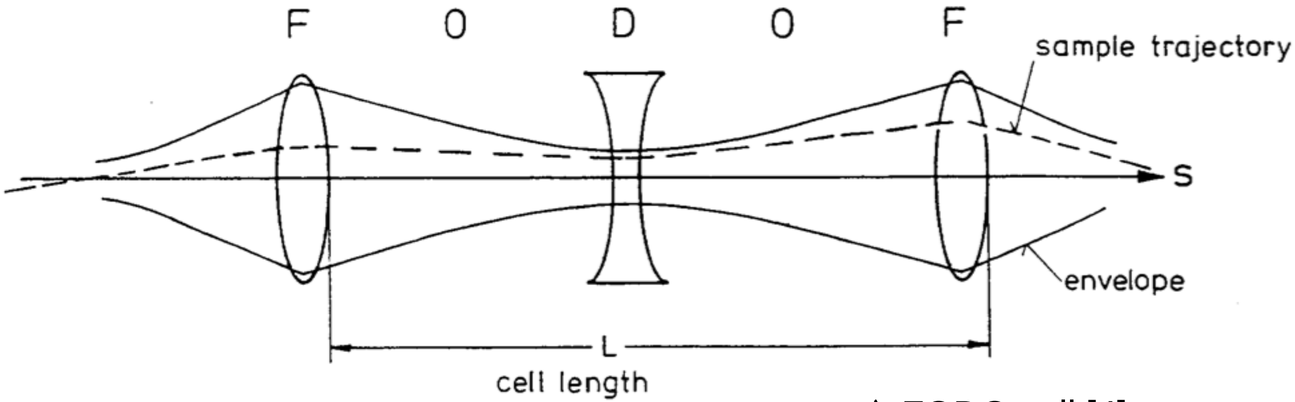
Properties of FODO-transfer channels [5]



▲ FODO cell [4].

- Boundary conditions:
    - **Straight beamline** (no dipoles)
    - **Periodic structure** of the transfer channel
    - **Matching** of the beam parameters is necessary at the start and the end of the transfer line
    - Transport line has to be **long** enough to neglect the matching parts of the transfer line

Properties of FODO-transfer channels [5]

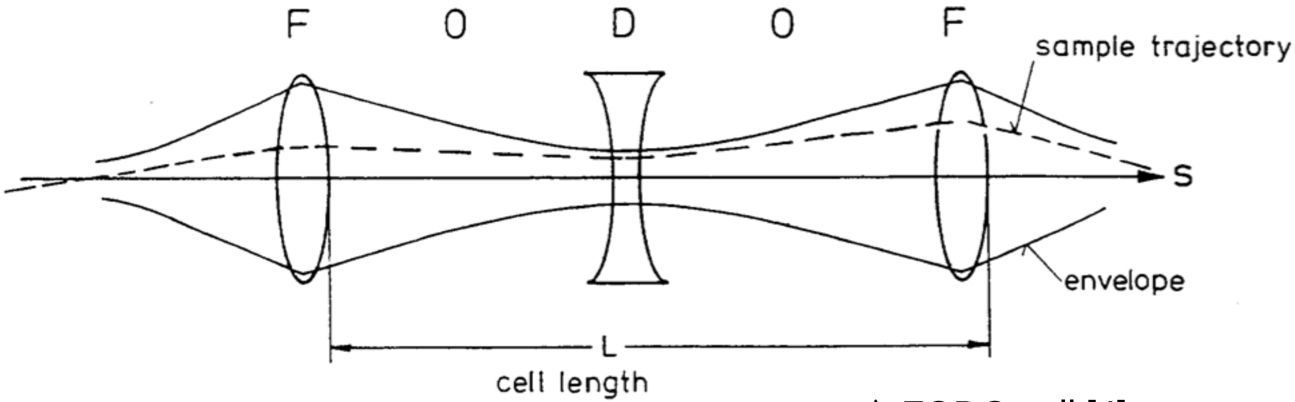


▲ FODO cell [4].

- Transport matrix for FODO cell: $M = \begin{pmatrix} 1 - \frac{d^2}{2f^2} & 2d\left(1 + \frac{d}{2f}\right) \\ -\frac{d}{2f^2}\left(1 - \frac{d}{2f}\right) & 1 - \frac{d^2}{2f^2} \end{pmatrix}$

- Twiss matrix: $M = \begin{pmatrix} \cos\Phi + \alpha\sin\Phi & \beta\sin\Phi \\ -\gamma\sin\Phi & \cos\Phi - \alpha\sin\Phi \end{pmatrix}$

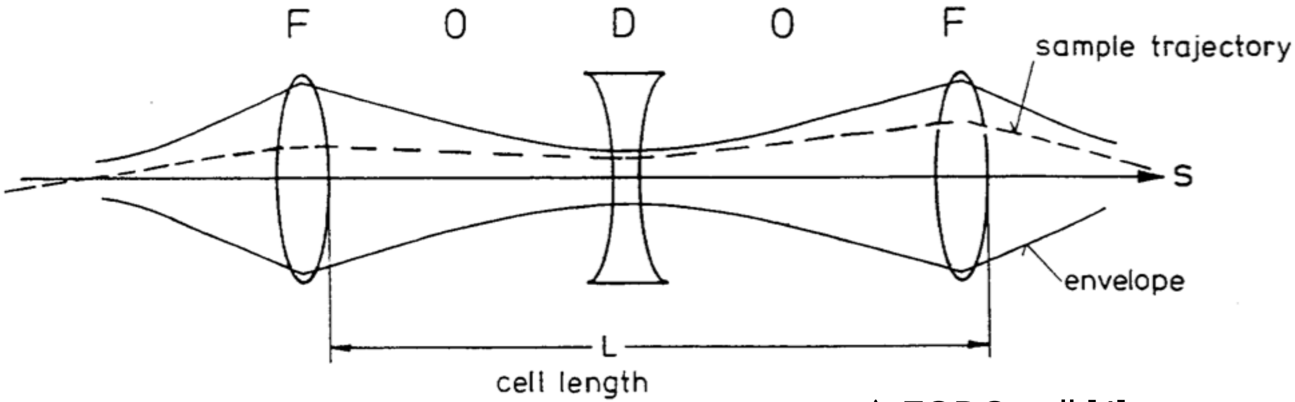
Properties of FODO-transfer channels [5]



▲ FODO cell [4].

- Beta function in focussing quadrupole: $\beta_{\max} = \frac{2f\left(1+\frac{d}{2f}\right)}{\sqrt{1-\frac{d^2}{4f^2}}}$
- focal length: $f = \frac{g}{l} B\rho$
- For large values of f or Bρ: $\beta_{\max} \propto f \propto B\rho$

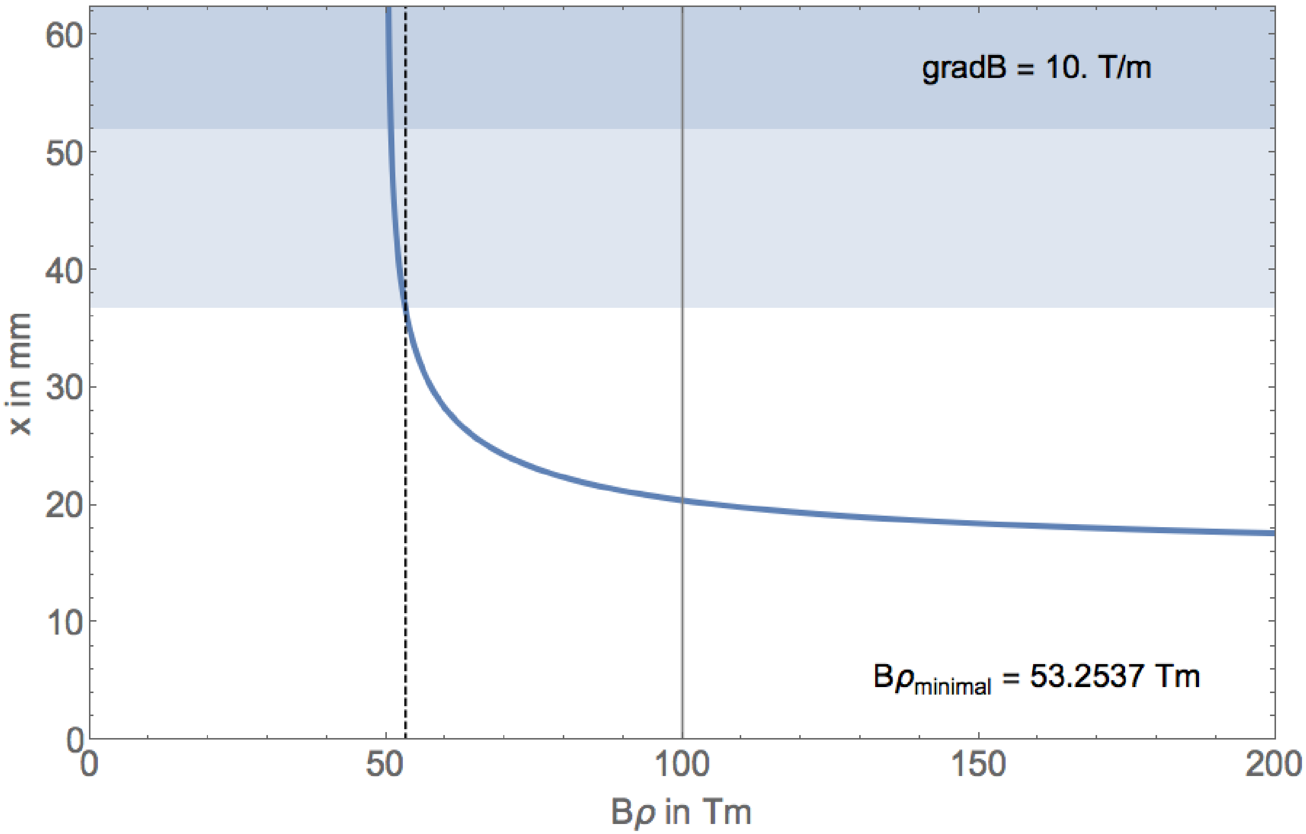
Properties of FODO-transfer channels [5]



▲ FODO cell [4].

- For large values of f or Bρ: $\beta_{\max} \propto f \propto B\rho$
- Beam envelope: $x_{\max} = \sqrt{\varepsilon \beta_{\max}}$
- Emittance changes due to adiabatic damping: $\varepsilon_1 = \varepsilon_0 \dfrac{(B\rho)_0}{B\rho}$
- For large values of Bρ: $x = const.$

Beam envelope as a function of the magnetic rigidity



▲ Beam envelope as a function of the magnetic rigidity for a straight **FODO-transfer channel without dipoles**.

Beam parameters:

- $B\rho_{Design}$: 100 Tm
- ε_{Design}: 12 mm mrad

Beamline parameters:

- Magnet length: 1,0 m
- Apertur radius: 52 mm
- Pole radius: 56 mm
- Poletip field: 0,56 T
- Gradient: 10,0 T/m
- Drift length: 10,0 m

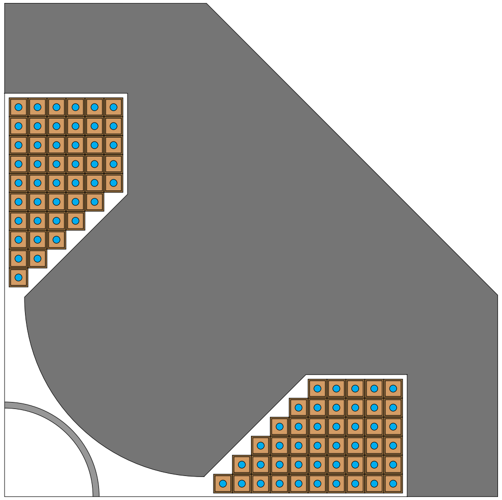
Modelling the energy requirement

- What is included in the magnet models?
    - Power loss of the magnets
    - Power loss of the power converters and cables
    - Cooling of the magnets (water and LHe), watercooled components in power converters, and watercooled cables

- What has not been implemented yet?
    - Air cooling
    - Water consumption
    - Dipole magnets

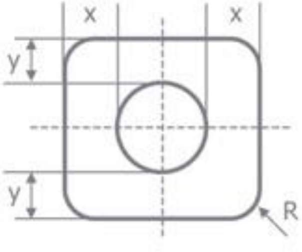
Normal conducting quadrupole (NC)

- Coil geometry:
  - Trapezoidal coil-cross section (less saturation of magnetic flux density in the joke)
- Criteria for choosing the coil cable:
  - Maximum current density of 5 A/mm^2
  - Determine minimum necessary cooling channel diameter caused by a pressure drop of up to 10 bar
  - Choose cable with minimum power loss of the magnet



▲ Cross section of the normal conducting quadrupole.

▼ Cable cross section [6].

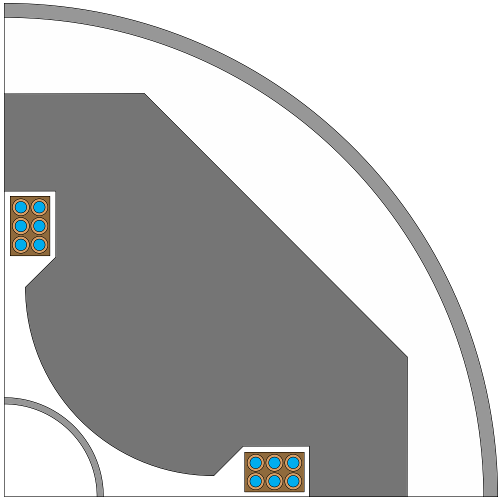


Superferric quadrupole (SF)

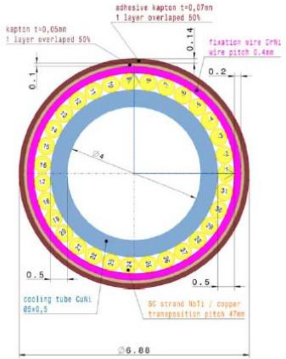
- Design of the SF quadrupole is similar to the SIS100 quadrupoles for FAIR [7]

- Coil geometry/joke geometry:
  - Up to 10 turns: rectangular coil-cross section
  - More than 10 turns: trapezoidal coil-cross section
  - Minimize cold mass (joke mass)

- SIS100 quadrupole cable
  - Up to 14,680 A per turn [7]
  - Cooling channel for LHe



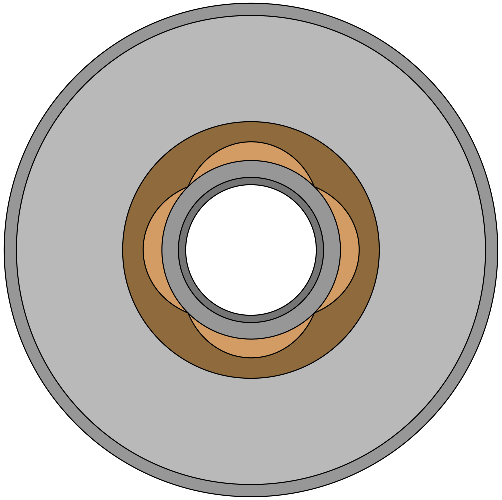
▲ Cross section of a superferric quadrupole.



▶ Cross section of the SIS100 quadrupole cable [7].

High current pulsed quadrupole (HCPQ)

- Coil design:
  - constant current density in conductor
  - cos(2Θ) distribution of the conductor width causes cos(2Θ) distribution of the current



▲ Cross section of a HCPQ [8].

- Energy consumption:
  - Get inductivity from approximation
  - Get capacity, damping resistor and voltage from risetime and “flat top” time of the oscillating circuit
  - Partial energy recovery possible (efficiency η)
  - Energy consumption per shot: $E = \frac{1}{2}(1-\eta)CU^2$

▼ Conductor-cross section [8].

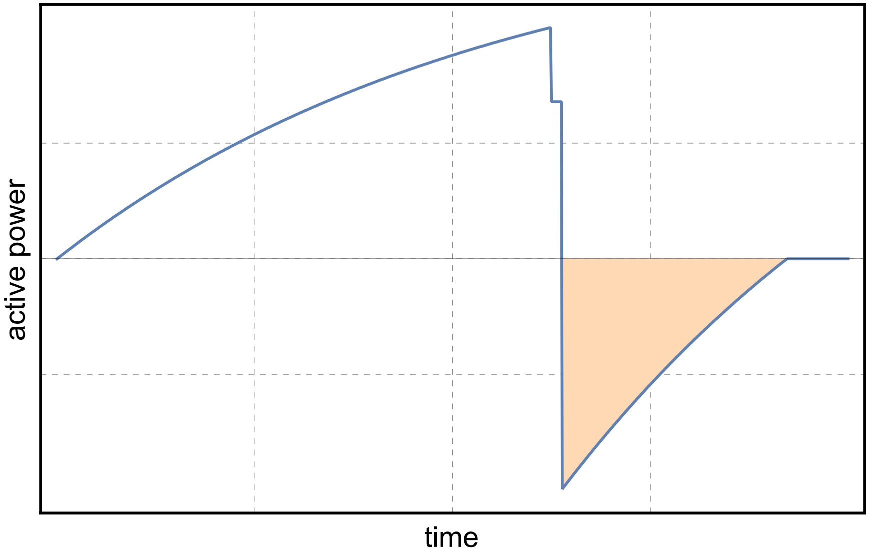
Power converters and supply cables

- Two types of power converters for NC and SF:
  - Switch Mode (SM2): I ≤ 2 kA, U ≤ 600 V
  - Silicon Controlled Rectifier (SCR): I > 2 kA, U > 600 V
  - Losses scale with current and risetime (1 s for NC & SF)
- Connection cable from power converter to magnet:
  - assume a length of 100 m
  - Cross section scales with current

- NC: Connect *n* magnets in series to one power converter
- SF: One power converter powers all magnets in the transfer line (no losses in SC bypass line and magnets)
- HCPQ: assume10% of the magnet losses as power converter losses

Energy Recovery

- HCPQ:
  - Alternative design of the oscillating circuit with second inductivity leads to **energy recovery up to 80%**
- NC & SF:
  - SM2 power converters store energy of ramp-down process
  - assume that **up to 80% of this energy can be stored**



▶ Active power of SM2 power converters. Orange area represents the energy that can be stored with an efficiency of up to 80%.

Water recooling

- Power loss of the water recooling
  - 100% of the power loss of the watercooled components is cooled by water
  - Hybrid water recooling technology
  - $P_{el,water} = 0{,}25\ W/W_{el,magnet} * P_{el,magnet}$

- water pumps: 0,9 kW/pump
- Pumps run while shutdown in order to keep the magnets‘ cooling channel clean

▶ Hybrid water recooling [9].

Cooling of superconducting magnets

- Continous cryostat, no cold-warm transitions

Quadrupole	Losses (4 K)	Losses (50-80 K)
Static losses	1,2 W/m	4,6 W/m
Dyn. losses (>0,5 Hz)	26,2 W/m	
Dyn. losses (<0,5 Hz)	4,9 W/m	

Cryogenic infrastructure	Losses (4 K)	Losses (50-80 K)
Connecting cryostats	1,0 W/m	5,0 W/m
Vacuum barrier (1x pro 130 m)	2,0 W/piece	4,0 W/piece
Connection box (1x pro 130 m)	4,0 W/piece	10,0 W/piece
LHe-Feedbox	20,0 W/box	85,0 W/box
LHe-Endbox	10,0 W/box	50,0 W/box
Current-Feedbox	5,0 W/box	20,0 W/box
Current Leads (2 pieces per familiy)	5,0 W/piece	31,5 W/piece

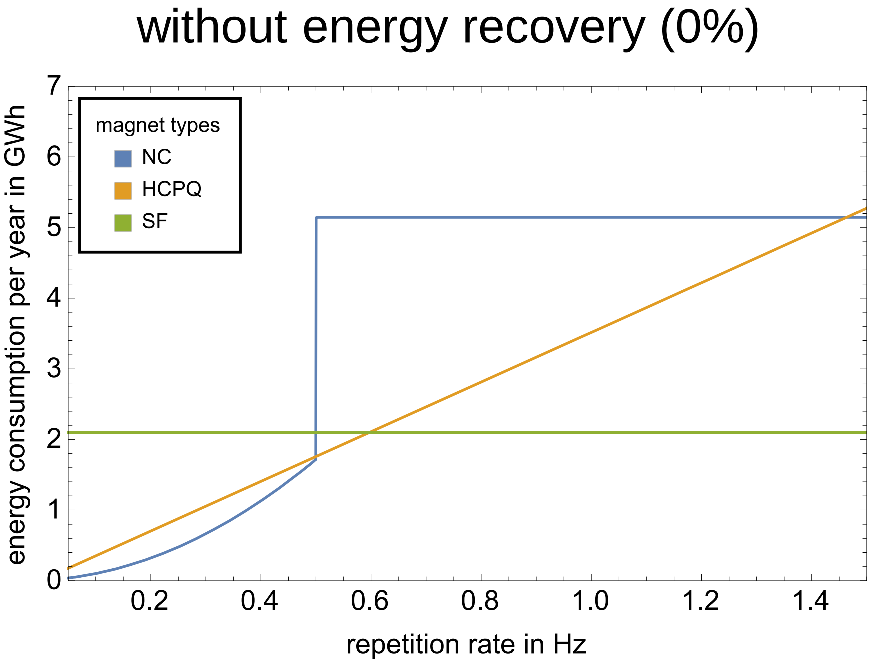
Cooling of superconducting magnets

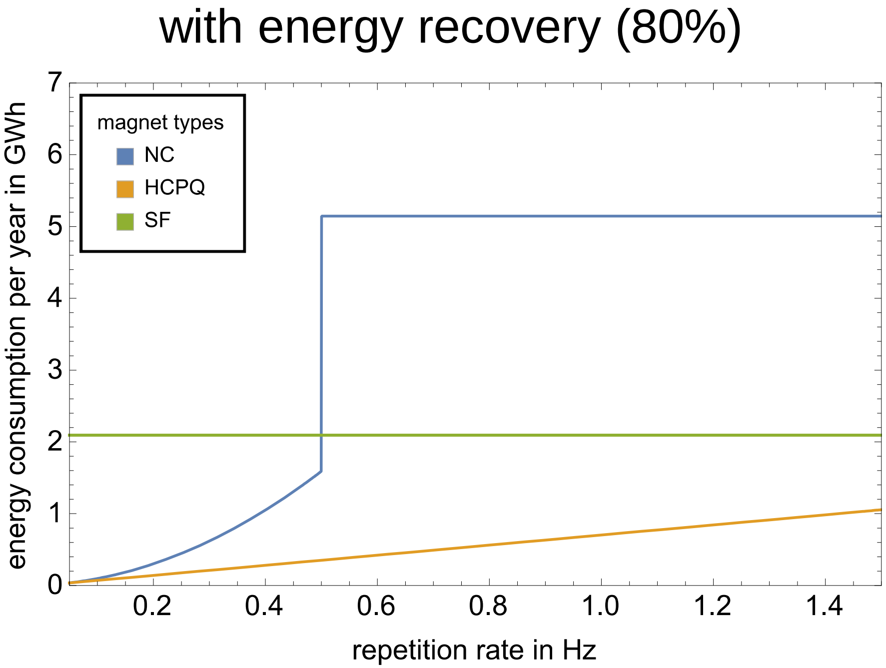
- Calculation of electrical power loss from cryo losses:
  - Losses caused by refrigeration of Helium and water
  - $P_{el,4K} = (250\ W/W_{4K} + 56{,}3\ W/W_{4K}) * P_{4K}$
  - $P_{el,50\text{-}80K} = (15\ W/W_{50\text{-}80K} + 3{,}4\ W/W_{50\text{-}80K}) * P_{50\text{-}80K}$

- Scale cryo losses with cold mass of the joke

- Cryo cooling runs all year with DC load (as well while shutdown)

Estimation of energy consumption





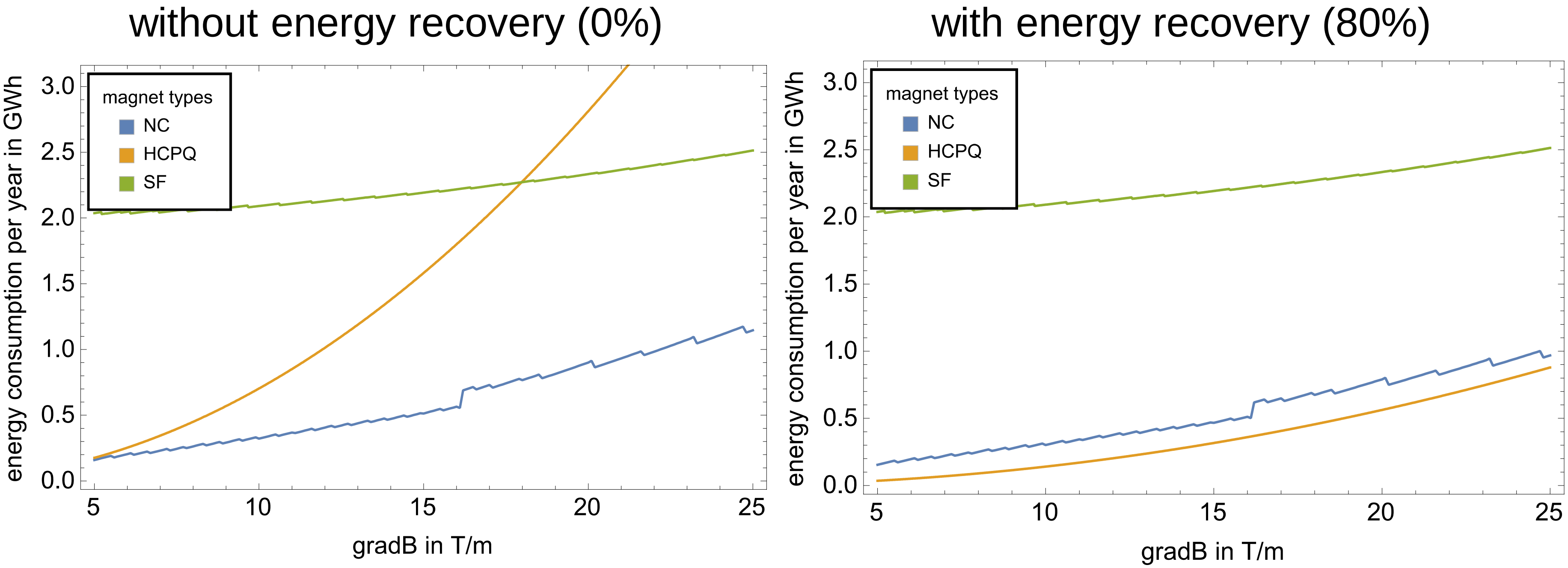
▲ **Energy consumption as a function of the repetition rate** (HCPQ with 0% energy recovery, SM2 power converters with 0% energy recovery, SF in DC operation).

▲ **Energy consumption as a function of the repetition rate** (HCPQ with 80% energy recovery, SM2 powerconverters with 80% energy recovery, SF in DC operation)

Beamline parameters

- Magnet length: 0.65 m
- Gradient: 10 T/m
- Aperture radius: 47 mm
- Drift length: 10.0 m
- 25 FODO cells (500 m)
- Fast extraction: 10 µs

Estimation of energy consumption



▲ **Energy consumption as a function of the gradient** (HCPQ with 0% energy recovery, SM2 power converters with 0% energy recovery, SF in DC operation).

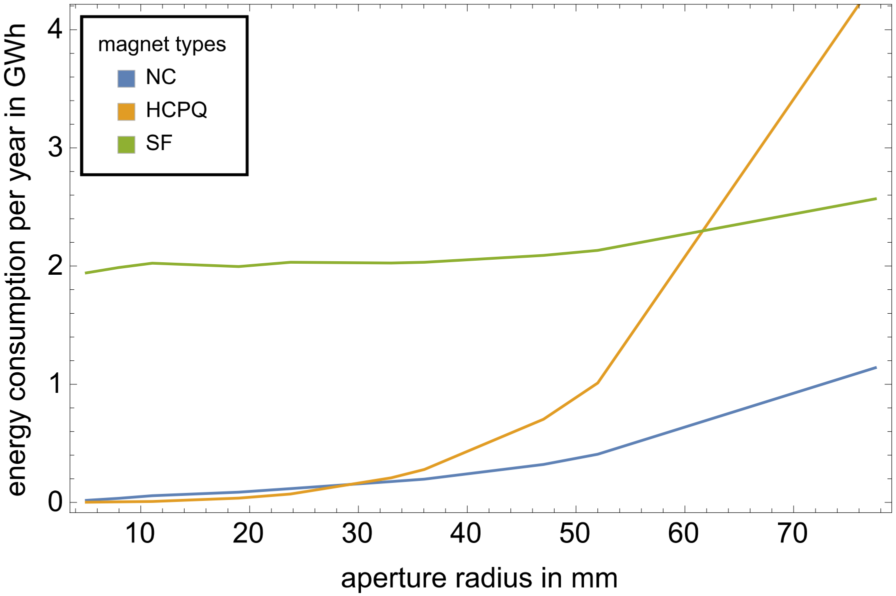
▲ **Energy consumption as a function of the gradient** (HCPQ with 80% energy recovery, SM2 power converters with 80% energy recovery, SF in DC operation).

Beamline parameters

- Magnet length: 0.65 m
- Aperture radius: 47 mm
- Drift length: 10.0 m
- Repetition rate: 0.2 Hz
- 25 FODO cells (500 m)
- Fast extraction: 10 µs

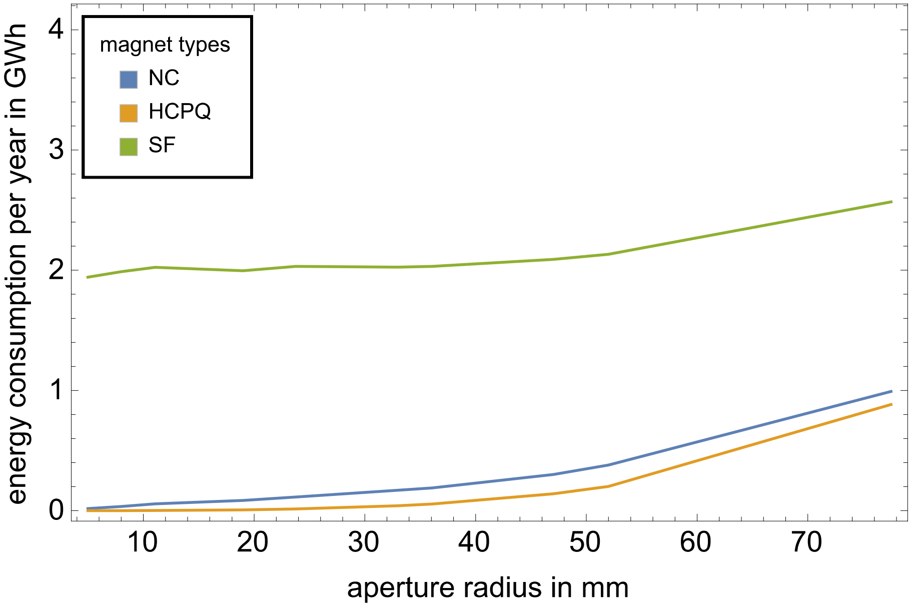
Estimation of energy consumption

without energy recovery (0%)



▲ **Energy consumption as a function of the aperture radius** (HCPQ with 0% energy recovery, SM2 power converters with 0% energy recovery, SF in DC operation).

with energy recovery (80%)



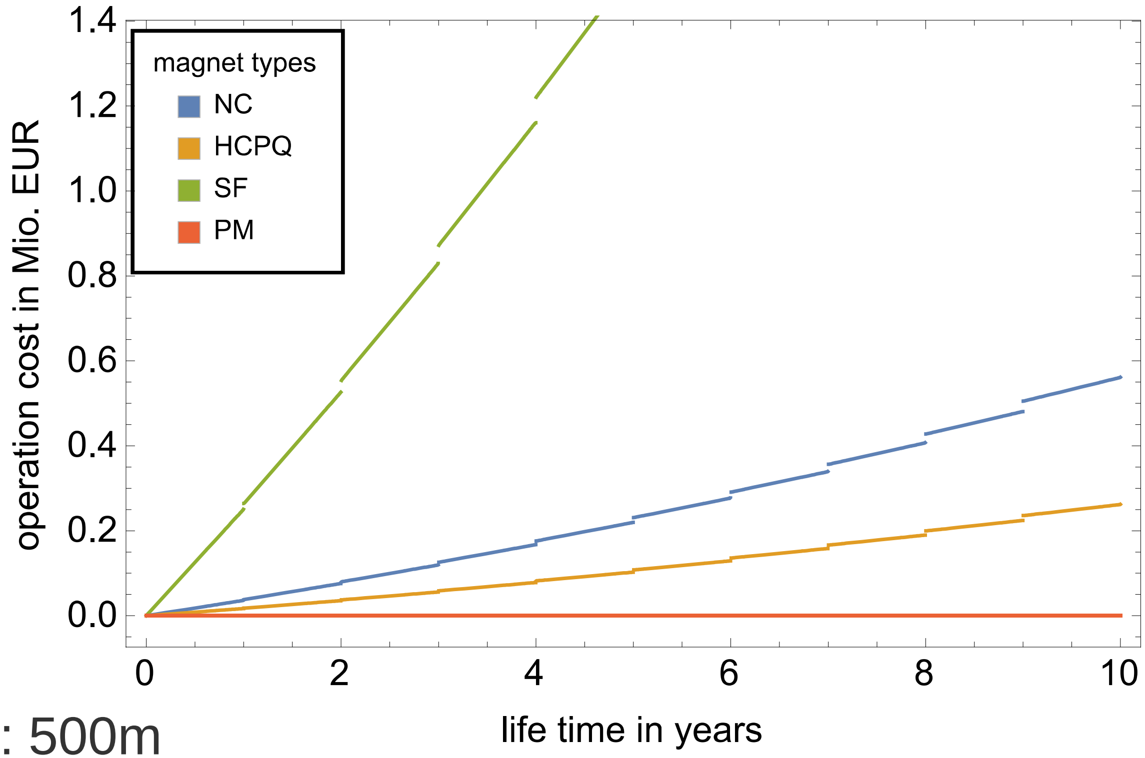
▲ **Energy consumption as a function of the aperture radius** (HCPQ with 0% energy recovery, SM2 power converters with 0% energy recovery, SF in DC operation).

Beamline parameters

- Magnet length: 0.65 m
- Gradient: 10 T/m
- Drift length: 10.0 m
- Repetition rate: 0.2 Hz
- 25 FODO cells (500 m)
- Fast extraction: 10 µs

Estimation of operation costs

- Beam parameters:
  - ε_{Design} = 12 mm mrad
  - $B\rho_{Design}$ = 100 Tm
- Beamline parameters:
  - Magnet length: 0.65 m
  - Apertur radius: 47 mm
  - Gradient: 10,0 T/m
  - Drift length: 10,0 m



- Repetition rate: 0.2 Hz
- Transfer channel length: 500m
- Assumptions:
  - 6000 operating hours per year
  - Energy prices increase of 5% per year

Preliminary results

- NC:
  - AC operation is considerably more energy efficient than DC operation
  - good for low repetition rates (<0.5 Hz), small apertures, and small gradients

- HCPQ:
  - field of application depends on energy recovery
  - with energy recovery: capable for low and high repetition rates (<1.5 Hz), gradients <u>up to 80 T/m</u> and small apertures
  - without energy recovery: sometimes less efficient than NC quadrupole

- SF:
  - DC operation is capable for transfer channels
  - AC operation causes additional losses
  - energy efficient solution for large apertures and high repetition rates

TODO list

- Expand model by SC, PM, and hybrid quadrupoles
- Expand model by dipoles
- Mixing different technologies in one transfer channel:
  - e.g. PM quadrupole + NC dipole
- Determine production costs and total costs
- Optimize drift length
- Field quality

→ Generate a map: “Which magnet type is the most energy efficient type for which requirements?”

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Thank you for your attention!