CERN

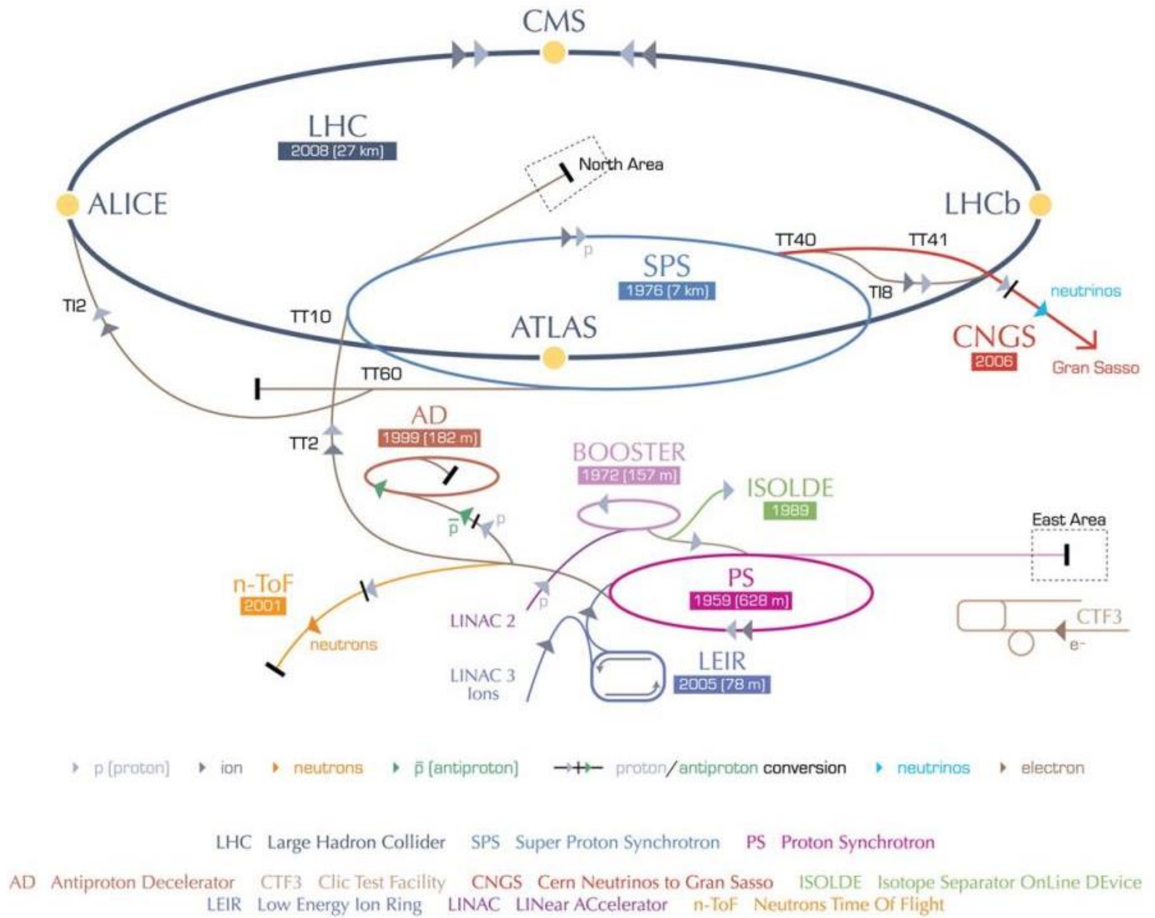
Liesbeth Vanherpe, Olivier Crettiez, Alexey Vorozhtsov, Thomas Zickler

Quadrupole Electro-magnets for Linac4 at CERN

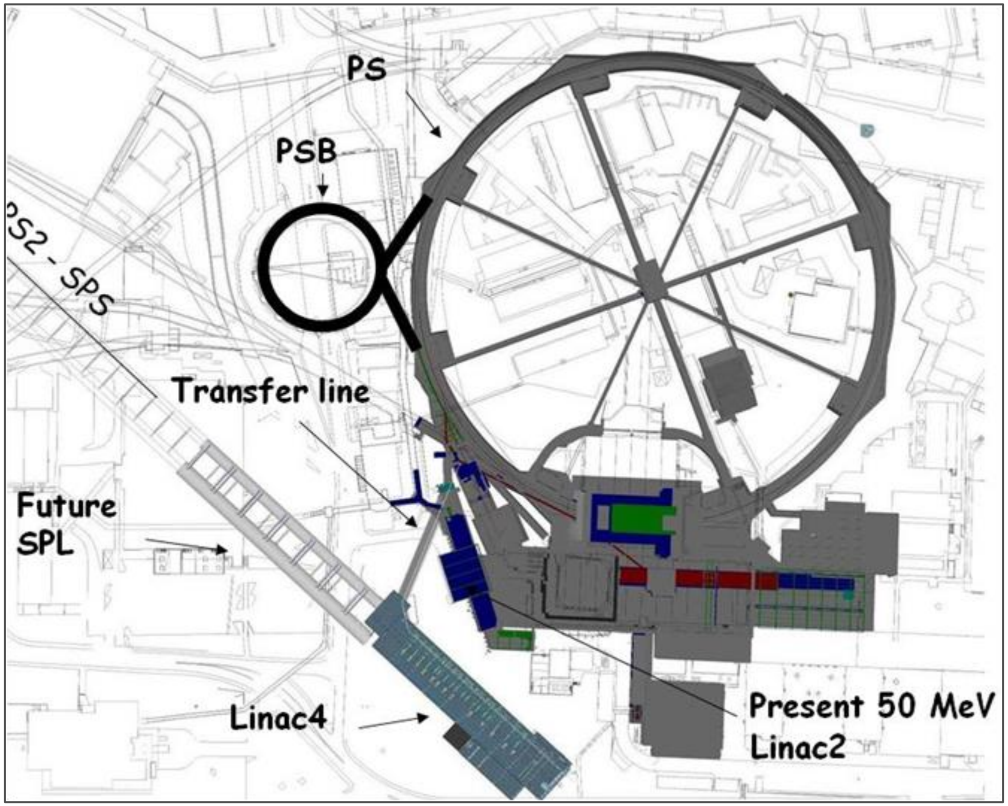
ATS Seminar, CERN, July 11, 2013

Presentation as prepared for the International Conference on Magnet Technology, Boston, MA USA, July 14-19, 2013

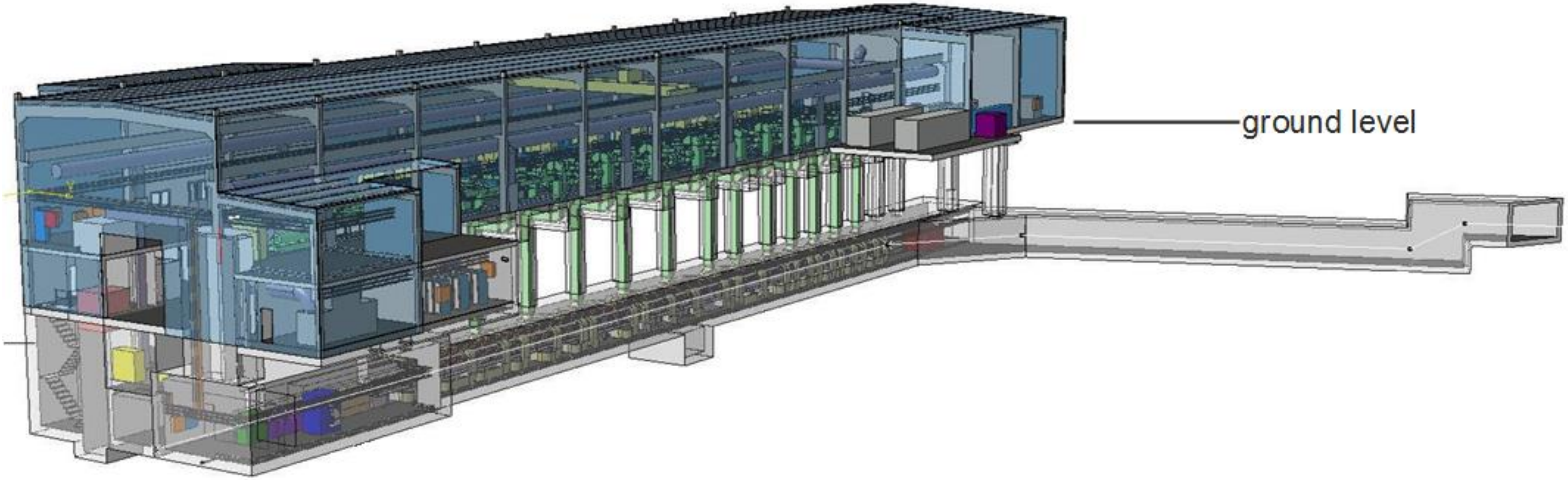
CERN Accelerator Complex



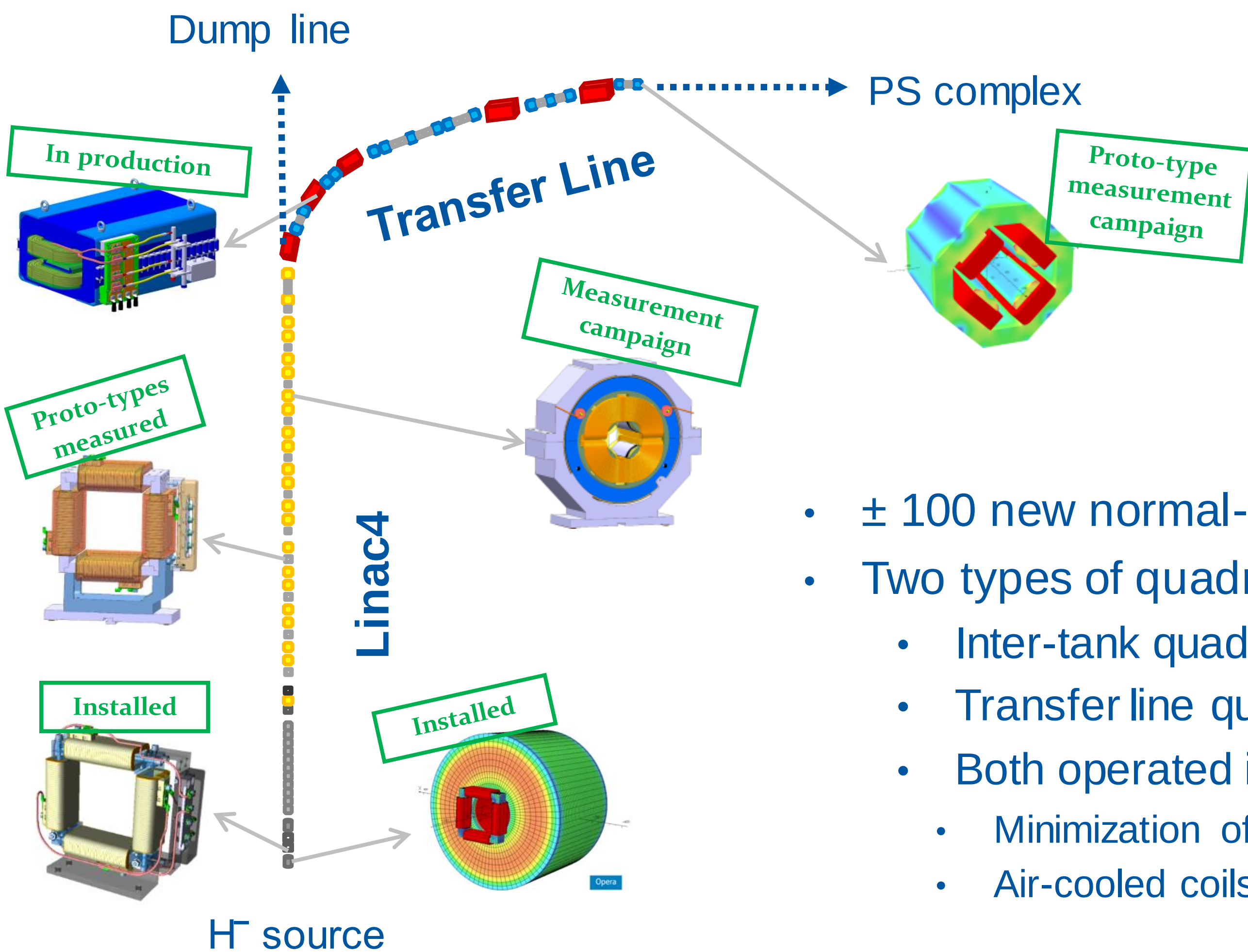
PS Complex


PS
PSB
PS2 - SPS
Transfer line
Future
SPL
Linac4
Present 50 MeV
Linac2

Linac4 and Transfer Line



Linac4 and Transfer Line Layout



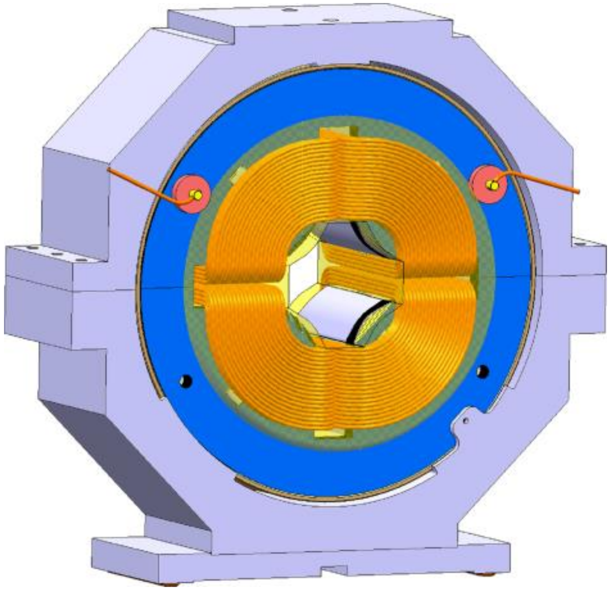
- ± 100 new normal-conducting magnets
- Two types of quadrupole magnets:
  - Inter-tank quadrupole magnet
  - Transfer line quadrupole magnet
  - Both operated in a pulsed mode
    - Minimization of r.m.s. power consumption
    - Air-cooled coils

Inter-tank Quadrupole Magnets

Design requirements and constraints

Parameter	Value	Unit
Aperture radius *r*	27	mm
Overall magnet length	< 105	mm
Overall magnet radius	< 125	mm
Good field region radius r_0	18	mm
Integrated magnetic flux density gradient $\int G dz$	1.83 – 2.22	T
Harmonic content B_n/B_2 at r_0 for $n = 3, 4, \ldots, 10$	< 0.01 (= 100 units)	
Maximum power converter current	100	A
Maximum voltage on power converter	900	V
Operation mode	Pulsed	
Repetition frequency	2.0	Hz
Total duty cycle	500	ms

Inter-tank Quadrupole Magnets

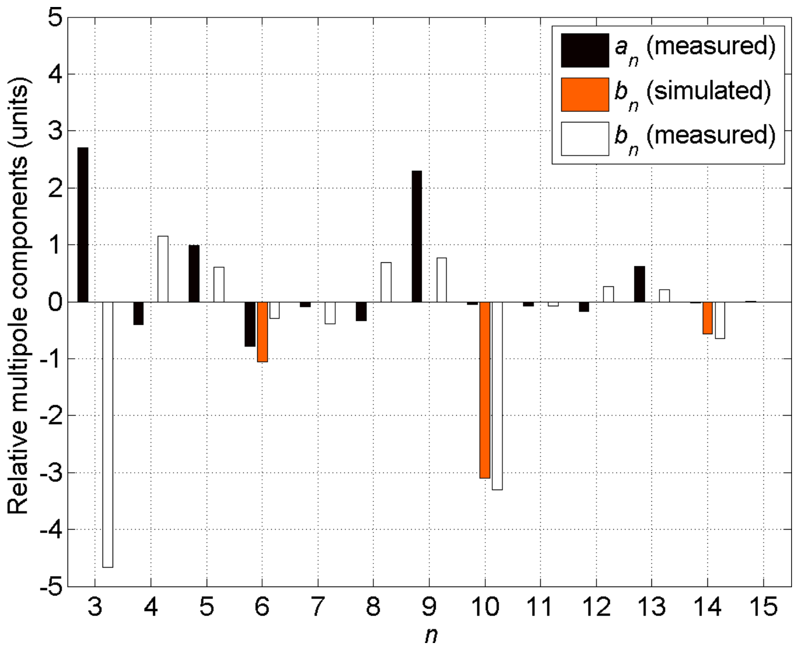


- Magnetic design
  1. Pole profile with 2D simulations
  2. 45°-chamfer of 4 mm height validated with 3D simulations
- Mechanical design
  1. Yoke halves manufactured with EDM
  2. Shrink-fitted stainless-steel ring
  3. Impregnated after assembly
  4. Holder of anodized aluminium

A. Vorozhtsov, "Linac4 Inter-tank Electromagnetic Quadrupole," CERN,Tech. Rep. EDMS 1183024, 2012

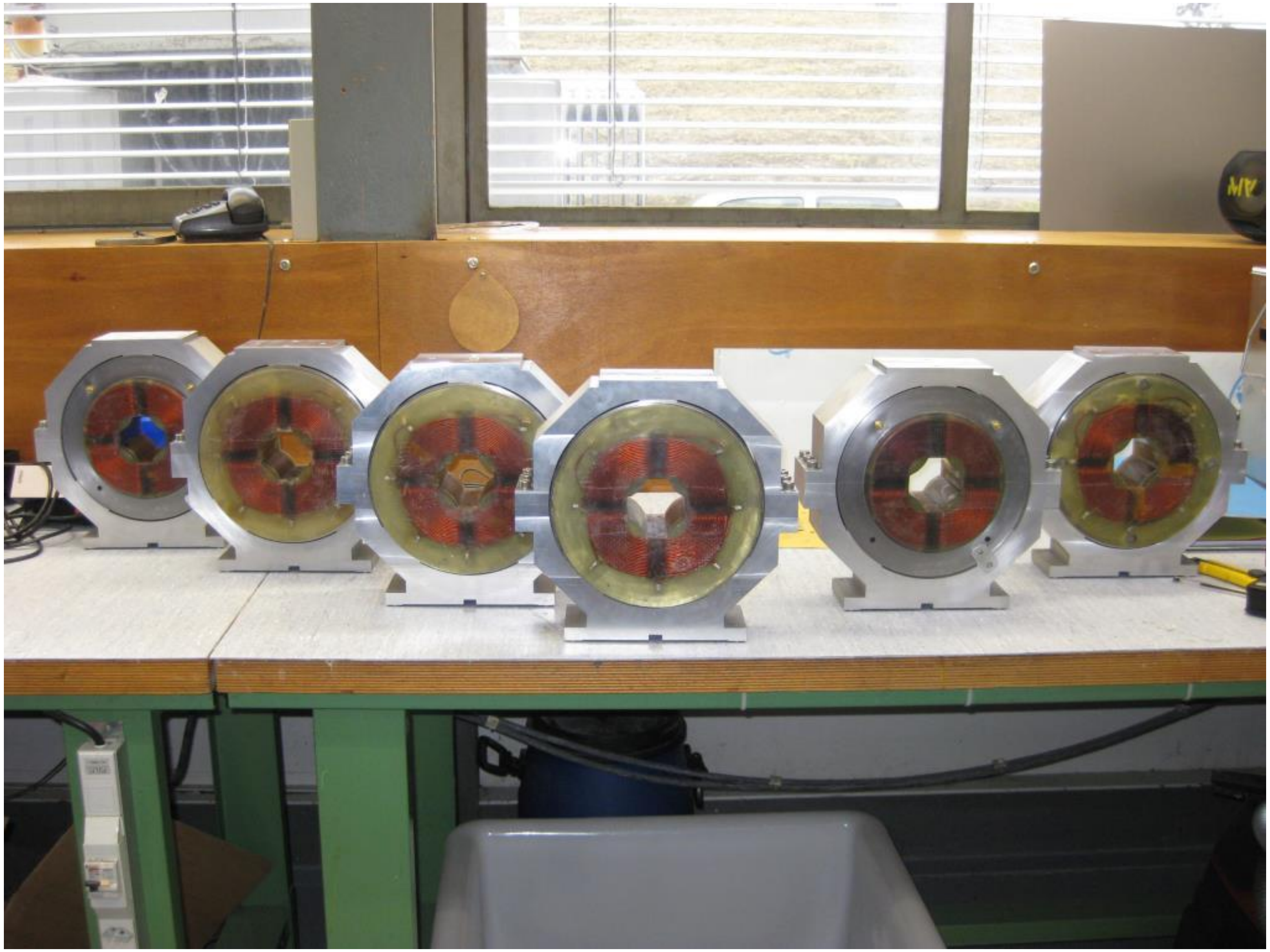
Inter-tank Quadrupole Magnets

- Magnetic measurements of prototype
  - Rotating coils
  - 18% of nominal current
  - Averaged over measurements at opposite current levels
- Field quality
- Field delay
  - Stabilization time of 1 ms



M. Buzio, R. Chritin, and P. Galbraith, "Magnetic measurements of Linac4 intertank electromagnetic quadrupole prototype," CERN, Tech. Rep. EDMS 1265033, 2013

Inter-tank Quadrupole Magnets



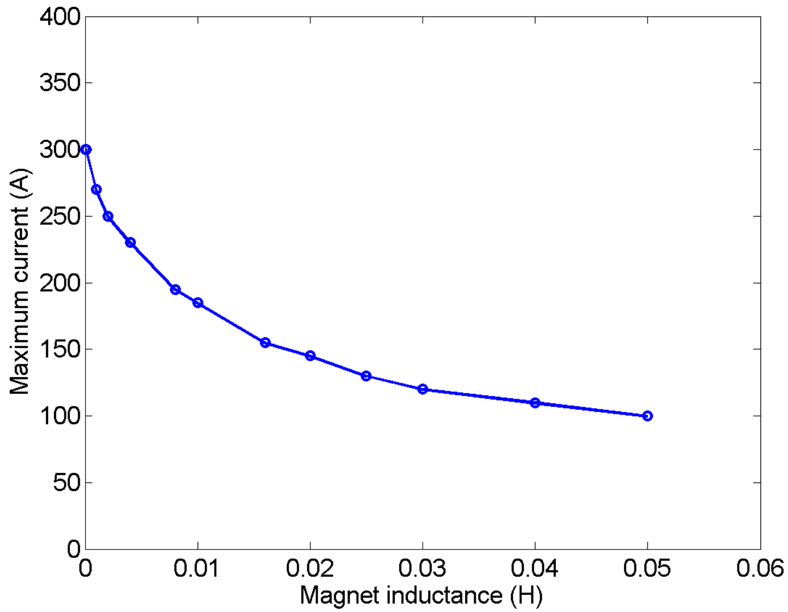
Transfer Line Quadrupole Magnets

Design requirements and constraints

Parameter	Value	Unit
Aperture radius r	50	mm
Good field region radius r_0	37.5	mm
Magnetic length l_m	300	mm
Magnetic flux density gradient $\int Gdz$	4	T
Harmonic content B_n/B_2 at r_0 for $n = 3, 4, \ldots, 10$	< 0.01	
Maximum voltage on power converter	1	kV
Operation mode	Pulsed	
Repetition frequency	1.111	Hz
Total duty cycle	900	ms

Transfer Line Quadrupole Magnets

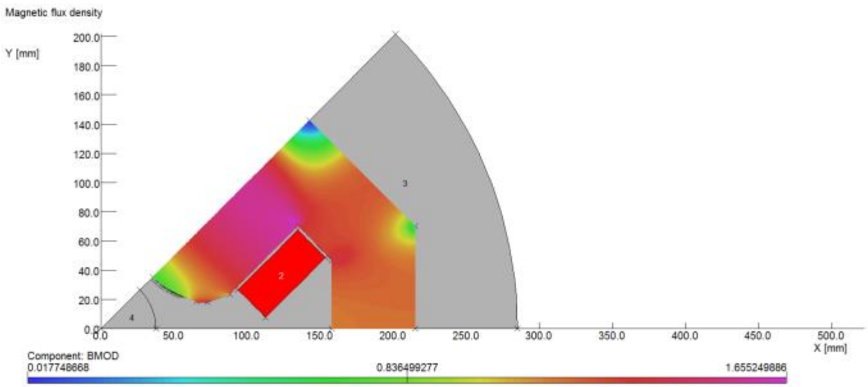
Design requirements and constraints



Operation range MaxiDiscap power converter

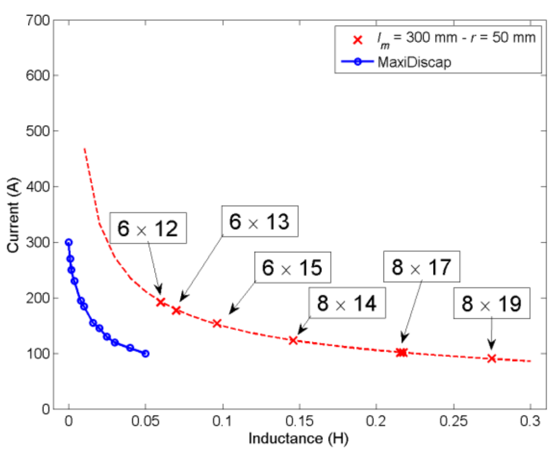
J.-M. Cravero, “MaxiDiscap operation range,” Private communication, 2010, CERN

Transfer Line Quadrupole Magnets

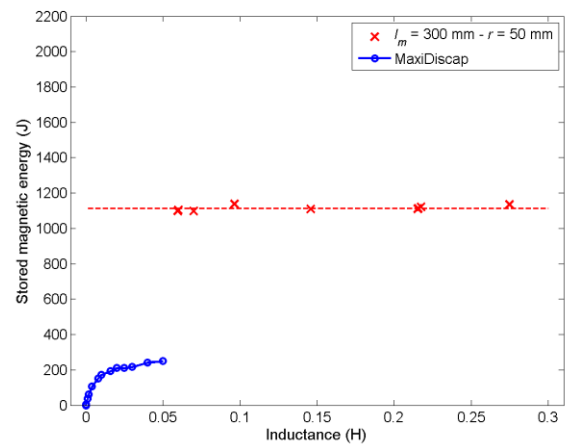


$$E_s = \frac{LI^2}{2} \qquad (1)$$

1. Excitation current is set
2. Stored energy E_s is obtained from 2D model
3. Inductance L is calculated

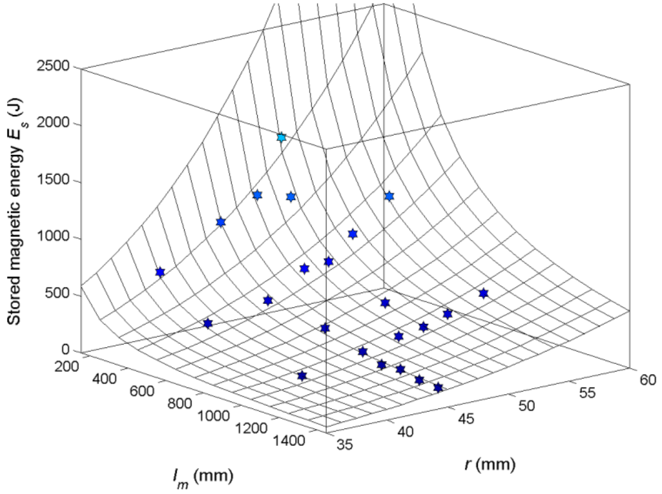


(1)



Transfer Line Quadrupole Magnets

Goal 1: Find magnet characteristics that match power converter



1. Use stored energy E_s to characterize quadrupole magnet
2. Compare with power converter operation range

Goal 2: Fast parameter analysis without need for lengthy simulations!

Transfer Line Quadrupole Magnets

$$E_s = \frac{LI^2}{2}$$

$$I = \frac{G_0 r^2}{2\eta\mu_0}\frac{1}{N} \text{ with } G_0 = \frac{\int_{+\infty}^{-\infty} G dz}{l_m}$$

transfer function of quadrupole iron-dominated electro-magnet [1]

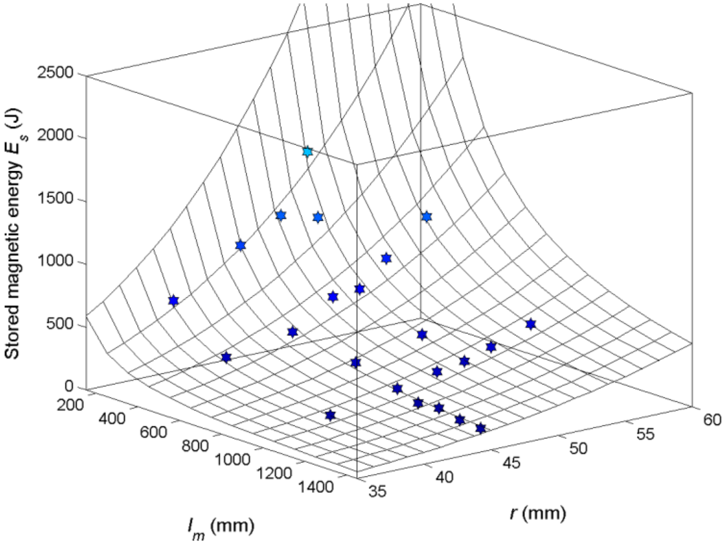
$$L = 8\pi\mu_0 N^2 \left(l + \frac{2}{3}r\right)\sqrt{\frac{d}{r}}$$

yoke length *l* and distance centre-coil *d* [1]

$$E_s = \pi\frac{1}{\mu_0\eta^2}\left(\int_{-\infty}^{+\infty} G(0,0,z)dz\right)^2 {l_m}^{-1} r^4$$

[1] D. Tommasini, “Practical definitions and formulae for magnets,” CERN, Tech. Rep. EDMS 1162401, 2011

Transfer Line Quadrupole Magnets



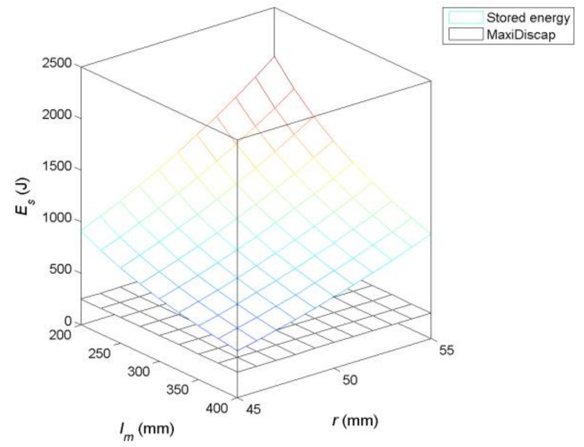
$$E_s = \pi \frac{1}{\mu_0 \eta^2} \left(\int_{-\infty}^{+\infty} G(0,0,z)\,dz \right)^2 l_m^{-1} r^4$$

- Explore parameter space (l_m, r) for given integrated gradient
- Show feasible solutions for given power converter

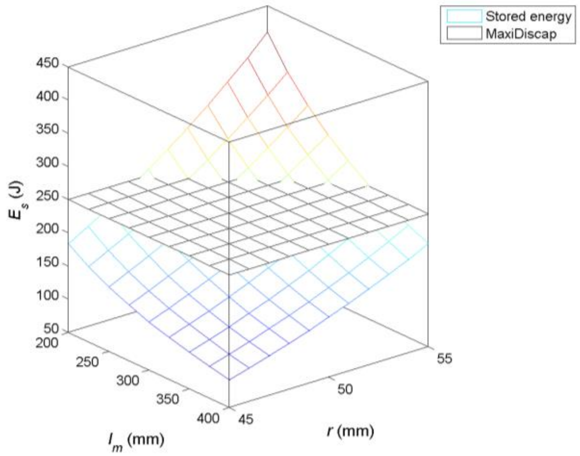
L. Vanherpe and T. Zickler, "A predictive software tool for compatibility assessment of magnet design requirements and power converter constraints based on the stored magnetic energy," *IEEE Trans. Magn.*, to be published

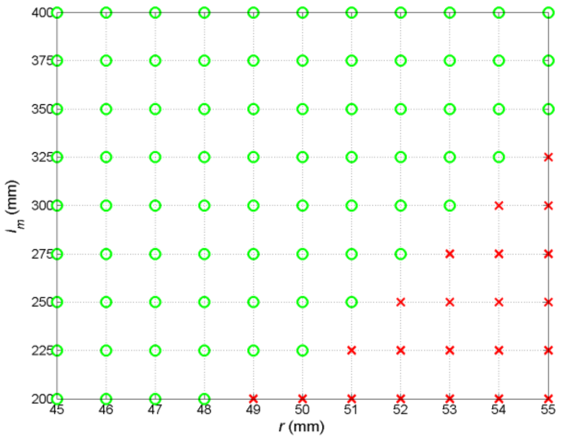
Transfer Line Quadrupole Magnets

- Original required integrated gradient
  $\int G dz$ = 4 T



- New required integrated gradient
  $\int G dz$ = 1.8 T



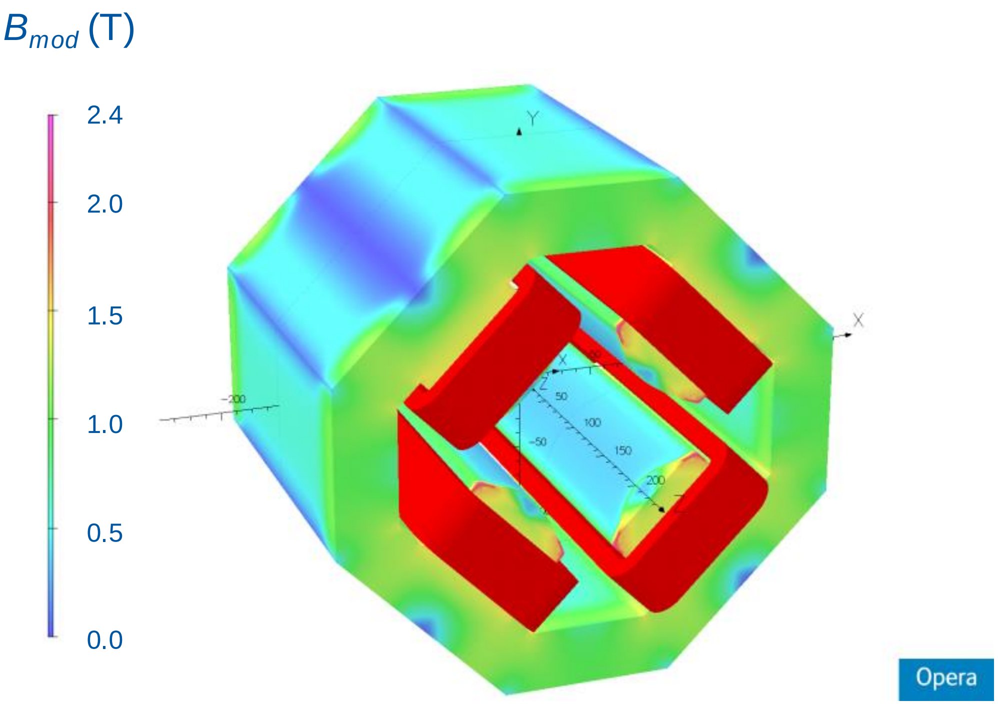


Transfer Line Quadrupole Magnets

Design requirements and constraints

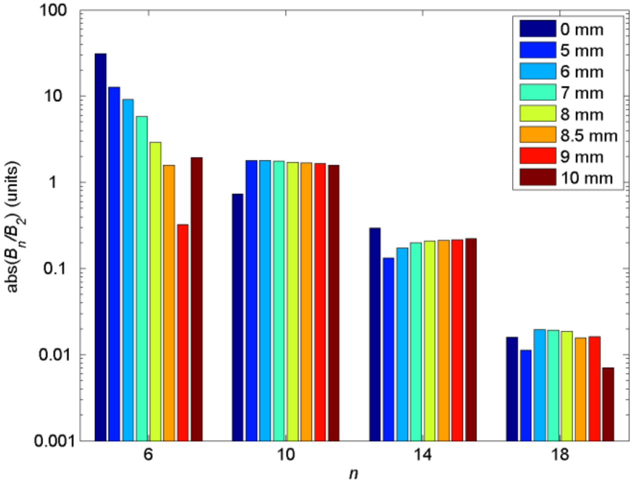
Parameter	Value	Unit
Aperture radius r	50	mm
Good field region radius r_0	37.5	mm
Magnetic length l_m	300	mm
Magnetic flux density gradient $\int G dz$	1.8	T
Harmonic content B_n/B_2 at r_0 for $n = 3, 4, \ldots, 10$	< 0.01	
Maximum voltage on power converter	1	kV
Operation mode	Pulsed	
Repetition frequency	1.111	Hz
Total duty cycle	900	ms

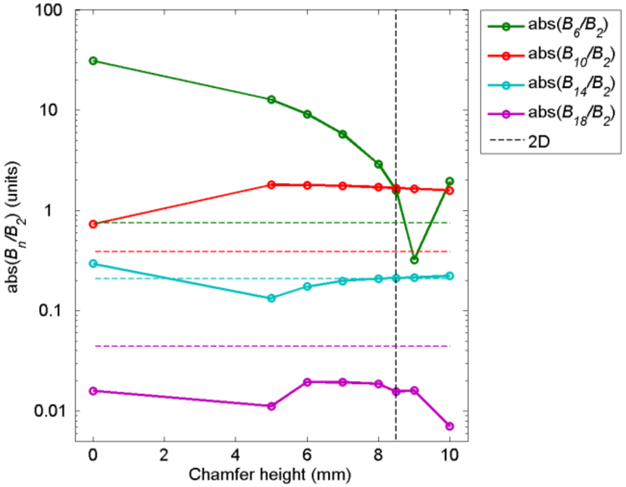
Transfer Line Quadrupole Magnets



- Magnetic design
  - Pole profile with 2D simulations
  - 3D model with magnetic flux density on yoke surface

Transfer Line Quadrupole Magnets

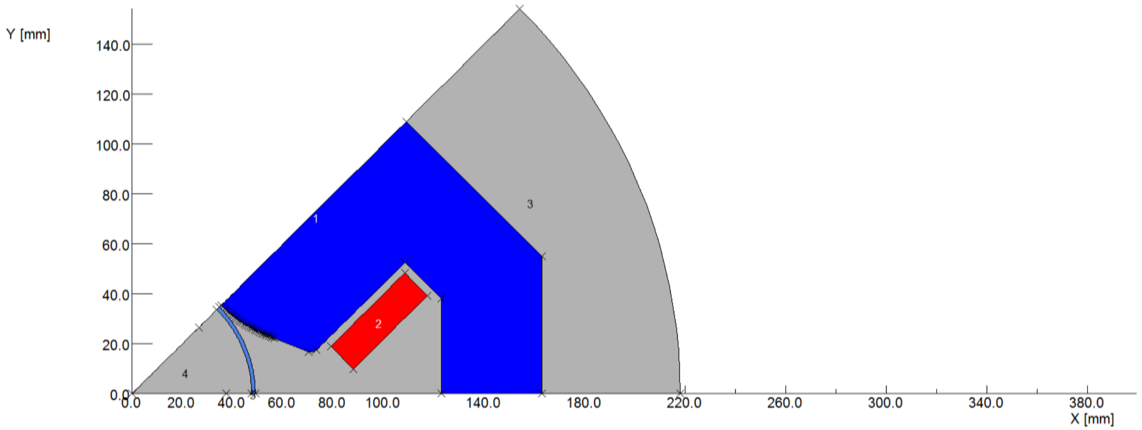




- Magnetic design
  - 45˚-chamfer of 8.5 mm height validated with 3D simulations
- Mechanical design
  - Four quadrants

Transfer Line Quadrupole Magnets

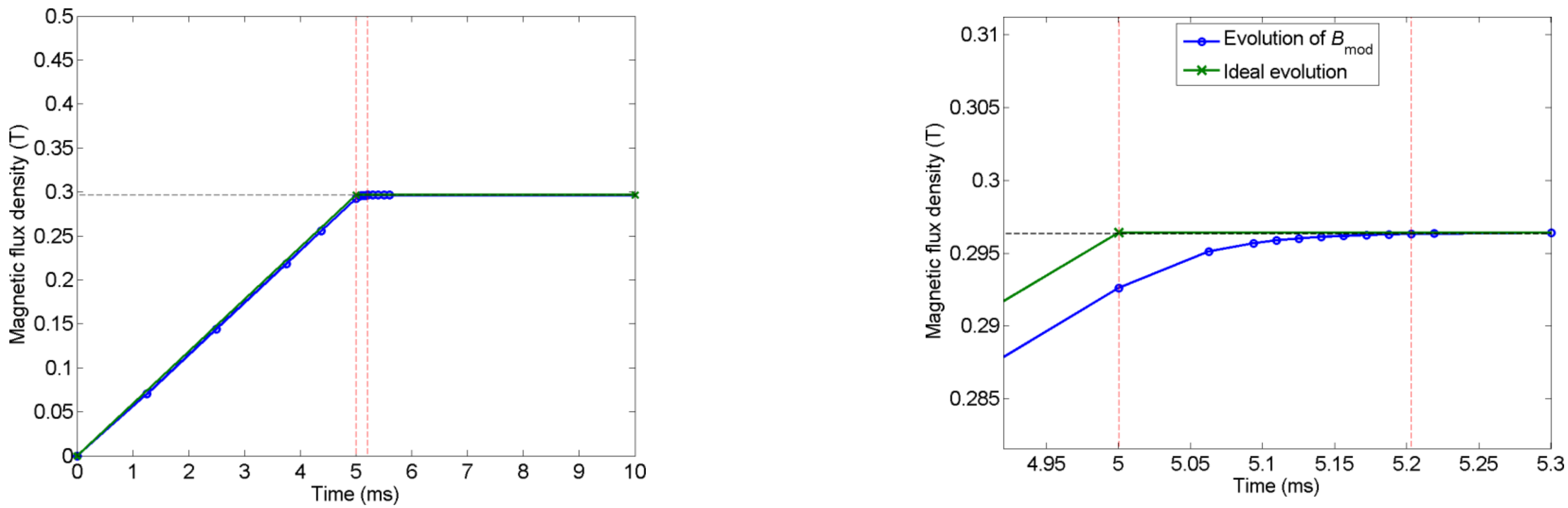
Effect of the vacuum chamber



Parameter	Value	Unit
Wall thickness	1.5	mm
Insulation gap	1	mm
Material	SS 316LN	
Conductivity	1.33×10^3	S/mm
Relative permeability	1.001	

Transfer Line Quadrupole Magnets

Effect of the vacuum chamber



- Eddy currents cause field delay
- Evolution at point inside vacuum chamber, close to pole tip
- Stabilization time t_{vc} = 0.2 ms for $\varepsilon = 10^{-4}$

L. Vanherpe, “Design report of the Linac4 Transfer Line Quadrupole Electromagnets,” CERN, Tech. Rep. EDMS 1291572, 2013

Transfer Line Quadrupole Magnets

Summary

Quadrupole Electro-magnets for Linac4 at CERN

- **Inter-tank quadrupole magnets**
  - Design & prototype measurements
  - Status:
    - All magnets have been manufactured
    - All magnets will be tested both electrically and magnetically at CERN

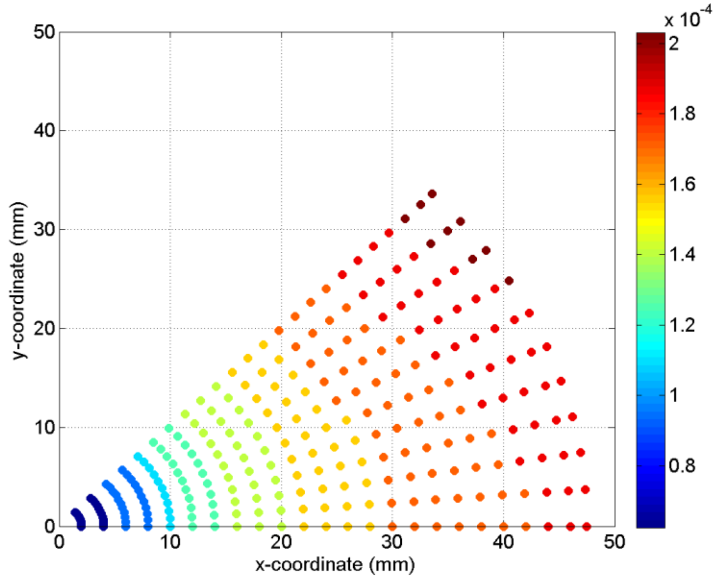
- **Transfer Line quadrupole magnets**
  - Design process
    - Stored energy as basis to compute the main magnet characteristics that match a given power converter, without the need for lengthy simulations
  - Status:
    - Prototype magnet manufactured and ready for testing at CERN

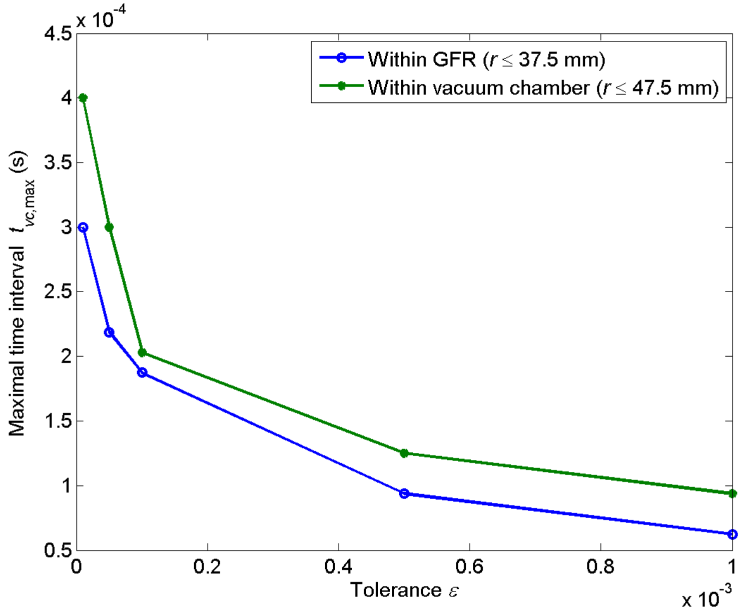
Questions?

www.cern.ch

Transfer Line Quadrupole Magnets

Effect of the vacuum chamber





- Stabilization time
  - as a function of position with vacuum chamber
  - as a function of the tolerance ε