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scSPS Design Project

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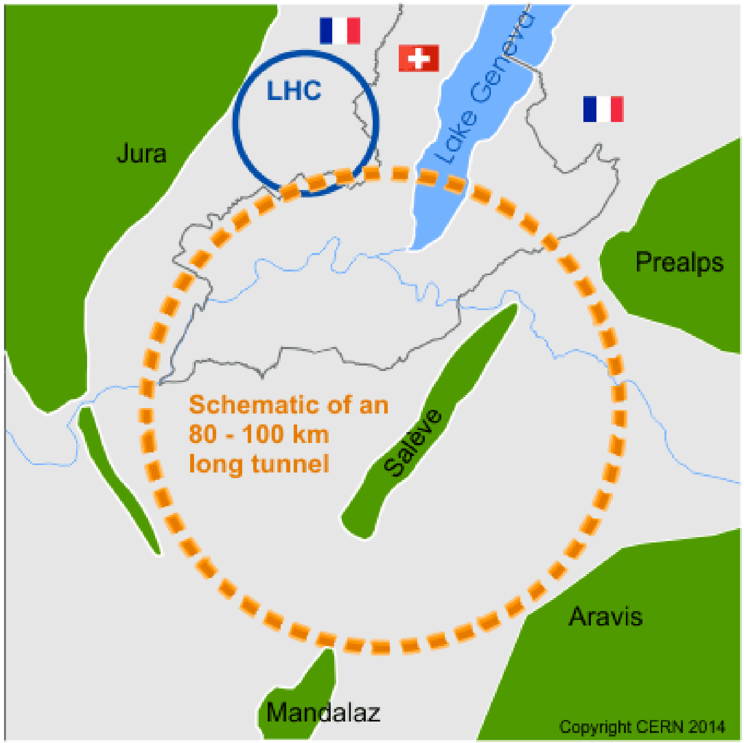
Future of Particle Physics



- **LHC: 14TeV**
- **FCC-hh: 100TeV**
  - **Higgs boson couplings**
  - **Top quark decays**
  - **Quark substructure?**
  - **Supersymmetry?**

Linac4 → Booster → PS → SPS → LHC → FCC-hh

scSPS → FCC-hh

scSPS General Parameters

- **SPS**
  - **6.9km circumference**
  - **26GeV to 450GeV**
- **scSPS**
  - **Same tunnel**
  - **26GeV to 1.3TeV**

- **Previous study: basic machine parameters**
- **Our study:**
  - **Lattice**
  - **Magnets**
  - **RF cavities**

scSPS Lattice Design

Student Design Project

Gian Luigi D'Alessandro

Siobhan Alden

Overview

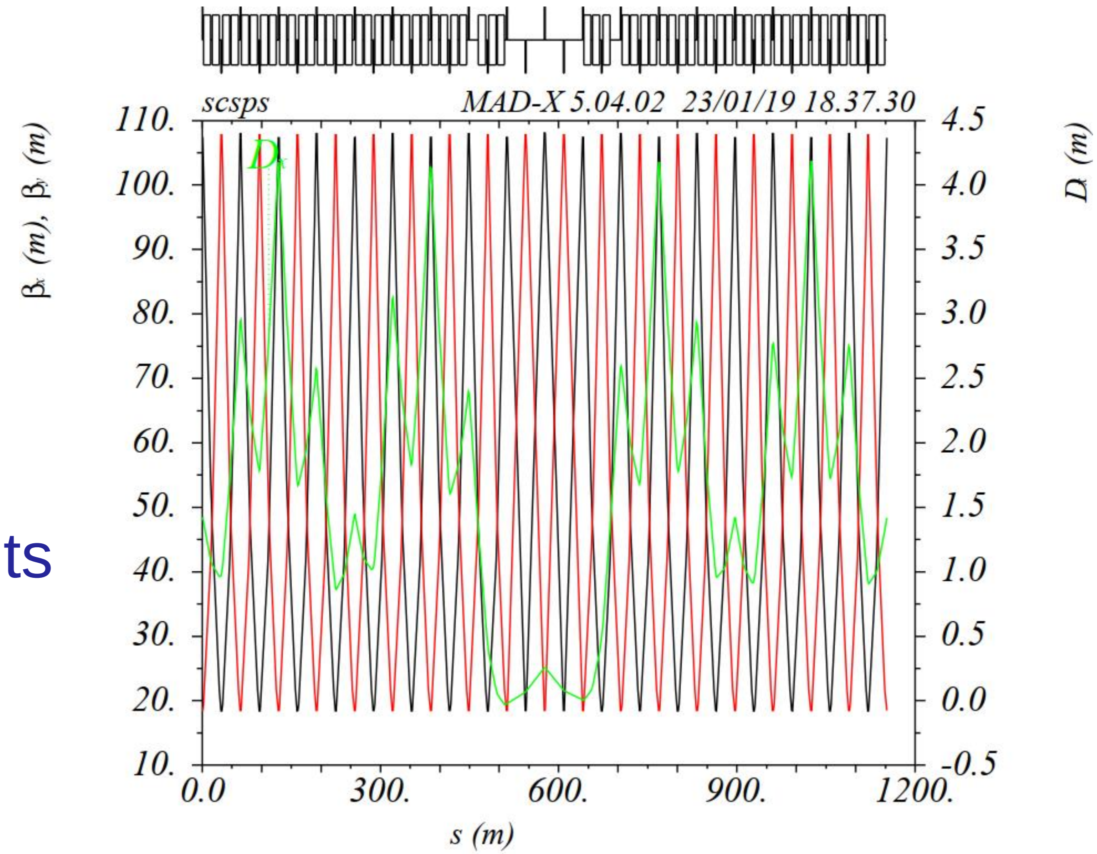
- Investigation of first scSPS design report
- scSPS lattice developed and comparisons made
- Developed dispersion suppressor schemes
- First chromaticity and sextupoles studies
- Global lattice parameters investigated
- Options for alternative machine lattice considered

First Lattice Generation

- Obtained Lattice from scSPS parameters [1]

- Calculated Bending Magnets and Quadrupoles constraints

- Maximum Dispersion ~ 4.1 m
- Min Betas ~ 20 m
- Max Betas ~107 m



Red – Beta y

Black – Beta x

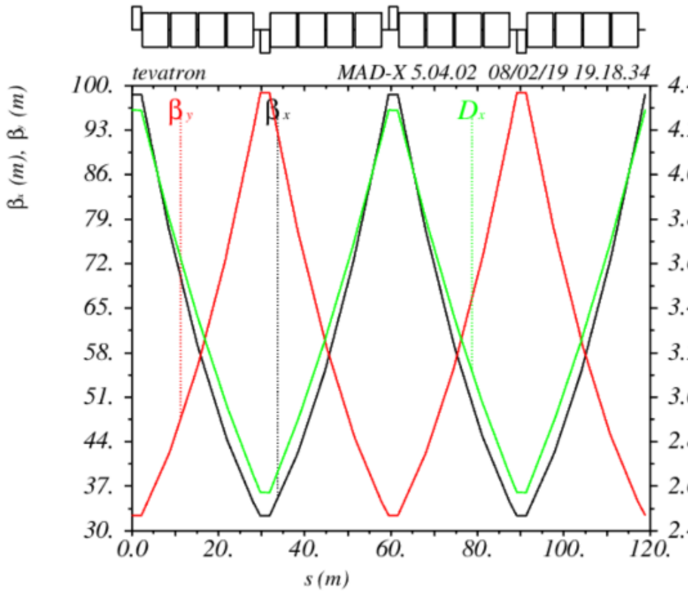
Green – Dispersion x

Global Comparison

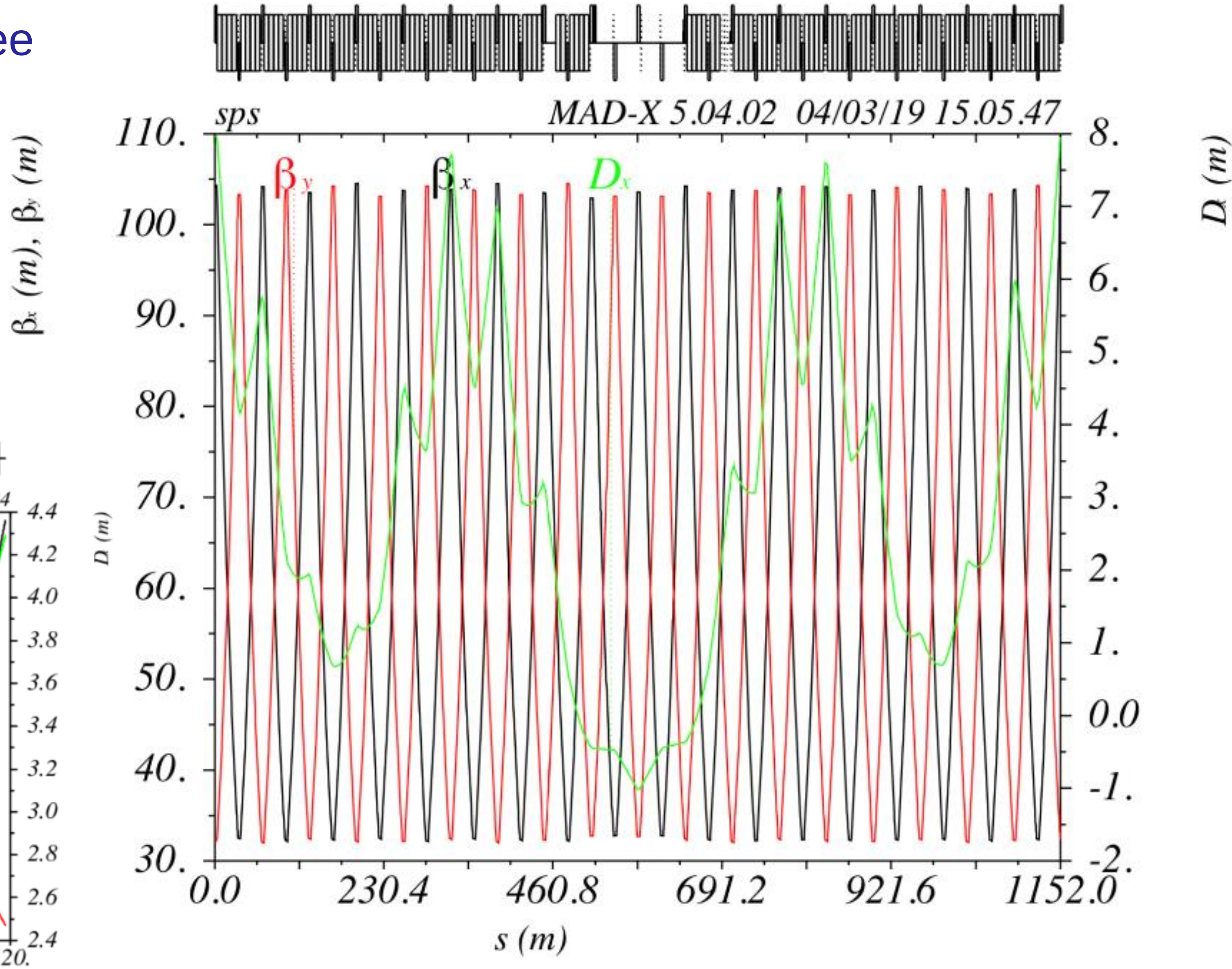
Generated Lattice for three circular accelerators:

- SPS
- scSPS
- Tevatron

Tevatron Two Cells



SPS Lattice – Single Arc



Calculated Parameters

Parameter	SPS (Q=20)	scSPS (Q=26)	Tevatron
β_{max}	107 m	107 m	100 m
Length of Quad – l_Q	3.1 m	1.35 m	2.13 m
Length of cell - L_{cell}	64 m	64 m	59.4 m
Phase advance per cell - μ	71°	89.96°	68°
Quad strength - k_Q	0.0112 m^{-2}	0.033 m^{-2}	0.018 m^{-2}
Dipole length - l_D	6.26 m	12.12 m	6.1 m
Dipole strength	2.02 T	6 T	4.33 T
Max momentum	450 GeV	1300 GeV	980 GeV
Total Length	6900 m	6900 m	6280 m
Min no. dipole per cell	7	4	7

Dispersion suppressor: reduced field

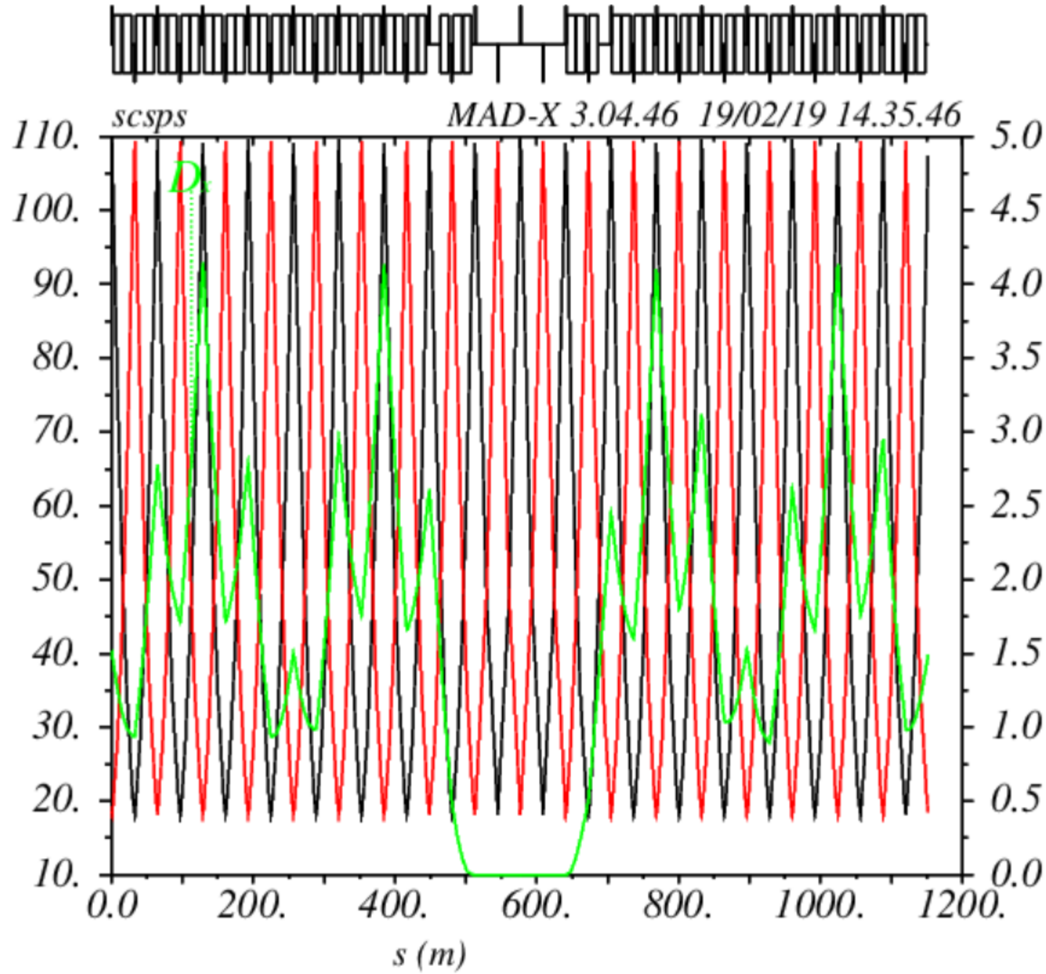
Three different suppressors:

- Reduced field
- Trimmer quadrupoles
- Singularly powered quadrupoles

Reduced Field Suppressor:

- Reduced the field in one of the dipoles close to the IP->reduced bending angle.
- Reached 0 dispersion at IP.
- Slightly changed the geometry of the lattice.

Reduced Field Suppressor



Dispersion suppressor: singularly powered quadrupoles

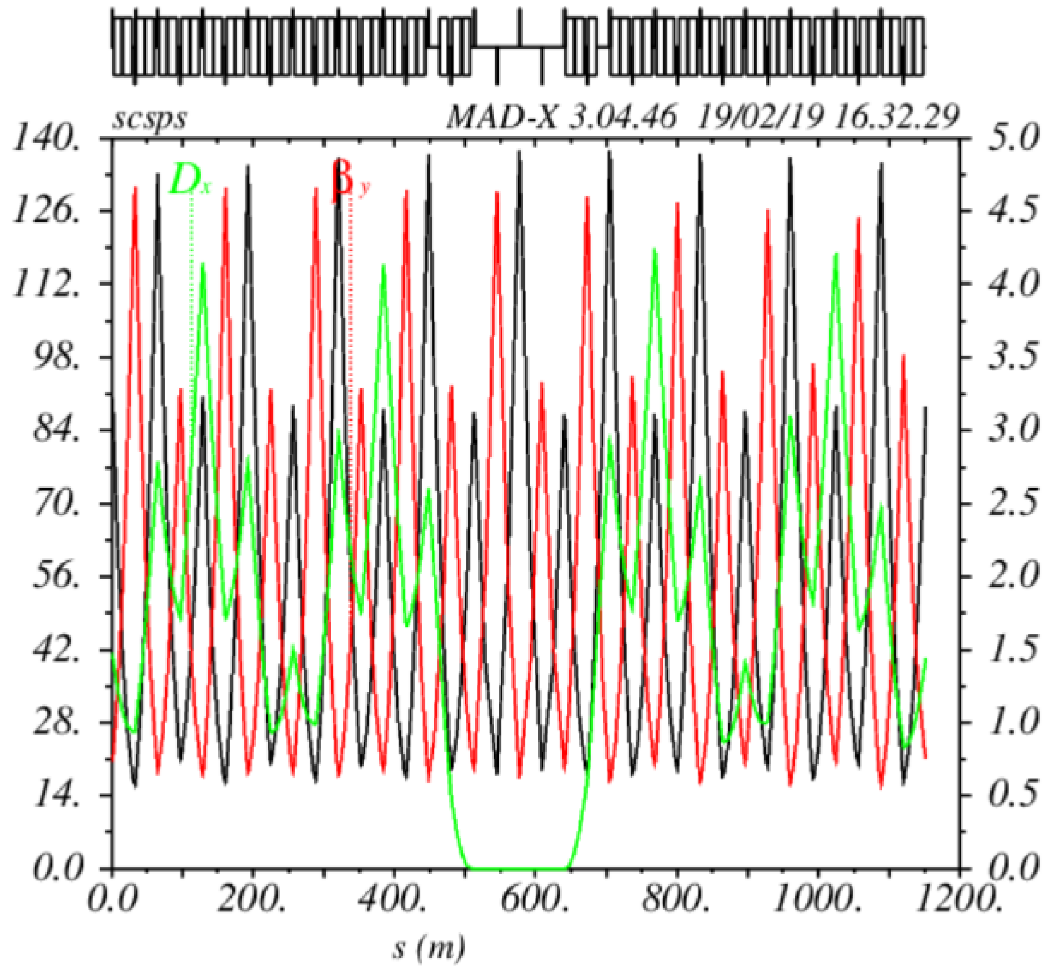
Three different suppressors:

- Reduced field
- Trimmer quadrupoles
- Singularly powered quadrupoles

Singularly powered quadrupoles:

- Changed the field in two of the dipoles close to the IP->increased focusing strength.
- Reached 0 dispersion at IP.
- Slightly changes the betas in the arcs and tune of the machine.
- Would not need to change the confi-guration of the magnets.

Singularly Powered Quads



Dispersion suppressor: trimmer quadrupoles

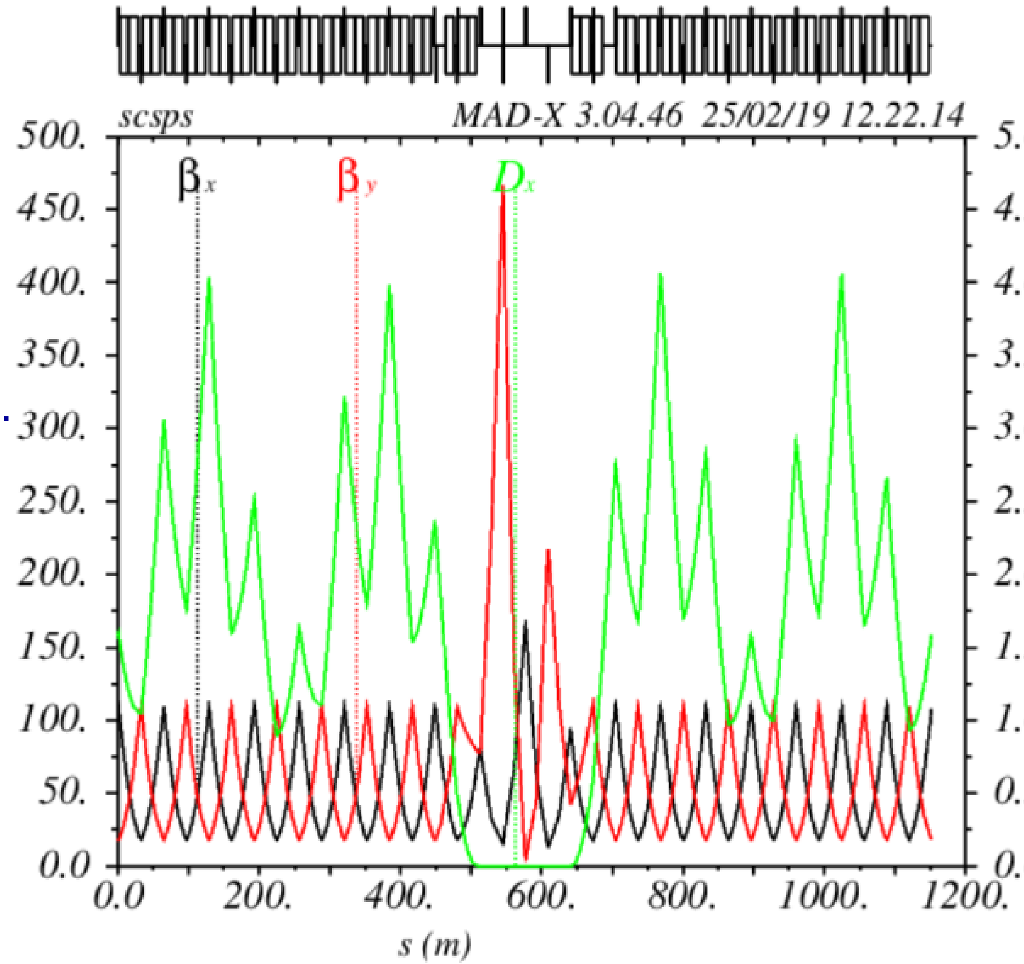
Three different suppressors:

- Reduced field
- Trimmer quadrupoles
- Singularly powered quadrupoles

Trimmer quadrupoles:

- Added 6 quadrupoles called “trimmers”.
- Reached 0 dispersion at IP.
- Slightly changes the betas at the IP.
- Need to insert more magnets.

Trimmer Quads Suppressor



Chromaticity Studies

Chromaticity can be expressed as

$$Q' = \frac{-1}{4\pi} N \frac{1}{f_Q} \left\{ \frac{L \cdot \sin(\varphi/2)}{\sin(\varphi/2)\cos(\varphi/2)} \right\}$$

- N, number of cells,
- f_Q , focal length of the quadrupoles
- L , length of the cell
- φ , phase advance of the cell.

- Calculated Q'= -34.64.
- For alternating-gradient machines Q'~ -1.3Q*.
- As the tune is 27.5, expected Q'~-35.75.
- Chromaticity from simulation is Q'=-35.30

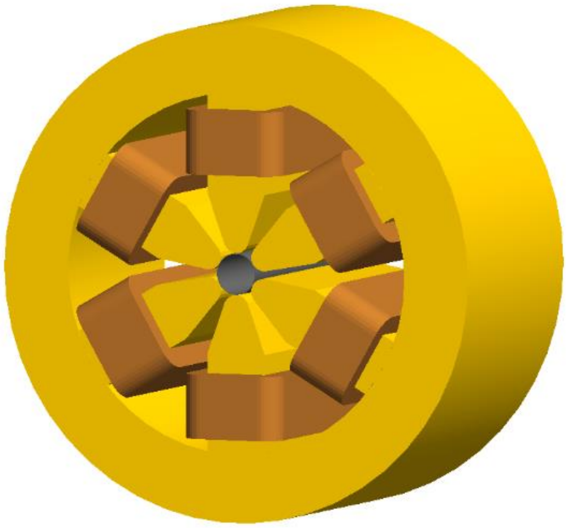
*E.Wilson, an introduction to Particle Accelerators, Oxford University Press

Sextupoles

The Sextupoles correct a term of:

$$\frac{1}{4\pi}\frac{\int B''(s)\beta(s)D(s)ds}{B\rho}$$

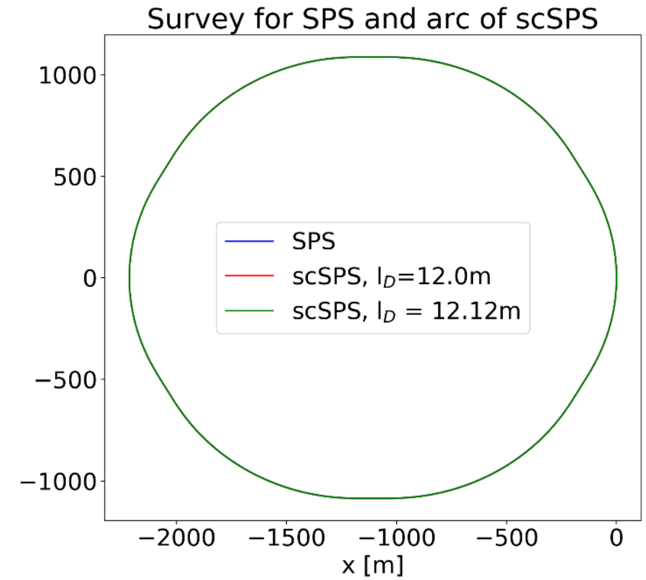
- Assuming D=4m, N=216, Bmax=107 and L=0.4 m: B''= 25.85 T*m^-2
- With and aperture of 4 cm radius B=(B''a^2)/2 B~ 0.2 T.
- Low field, might lower number of sextupoles

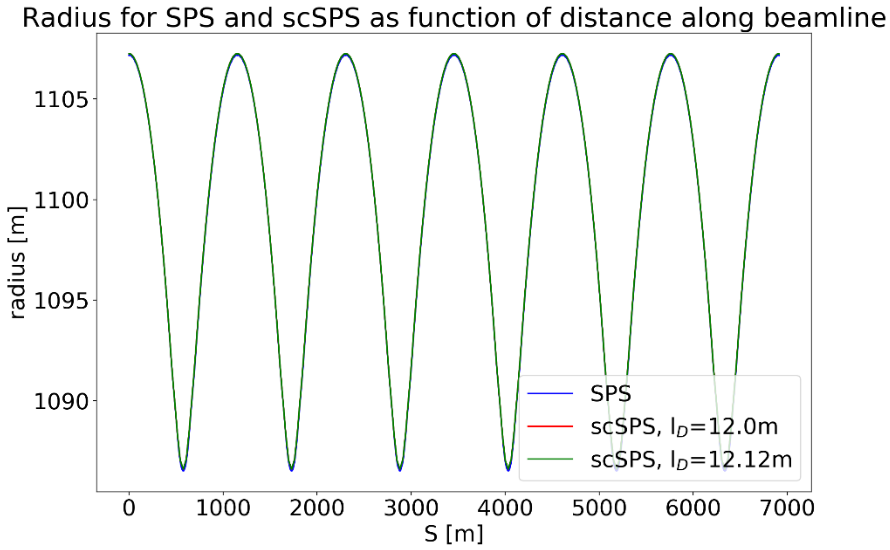


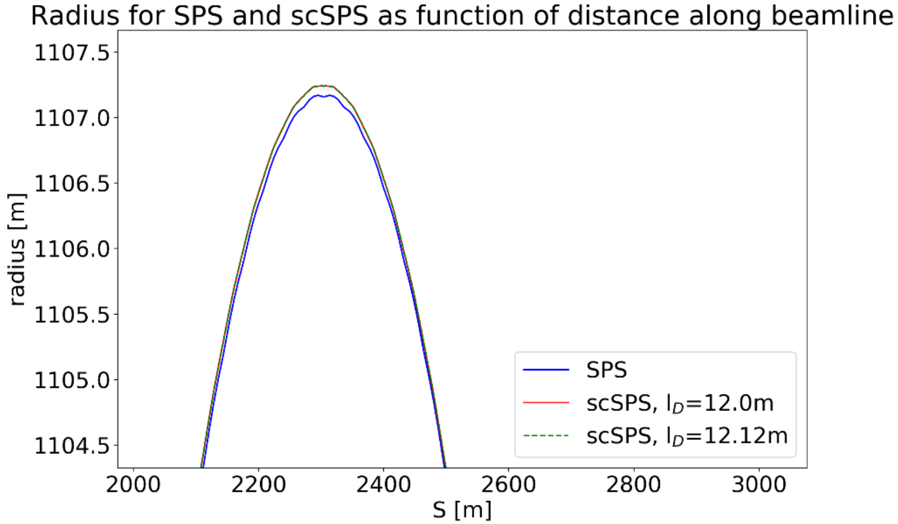
- Madx simulations show that with these values -> Vertical and Horizontal Chromaticity can reach ~0.02.
- Considering the working point this would grant a non resonant system.

Survey

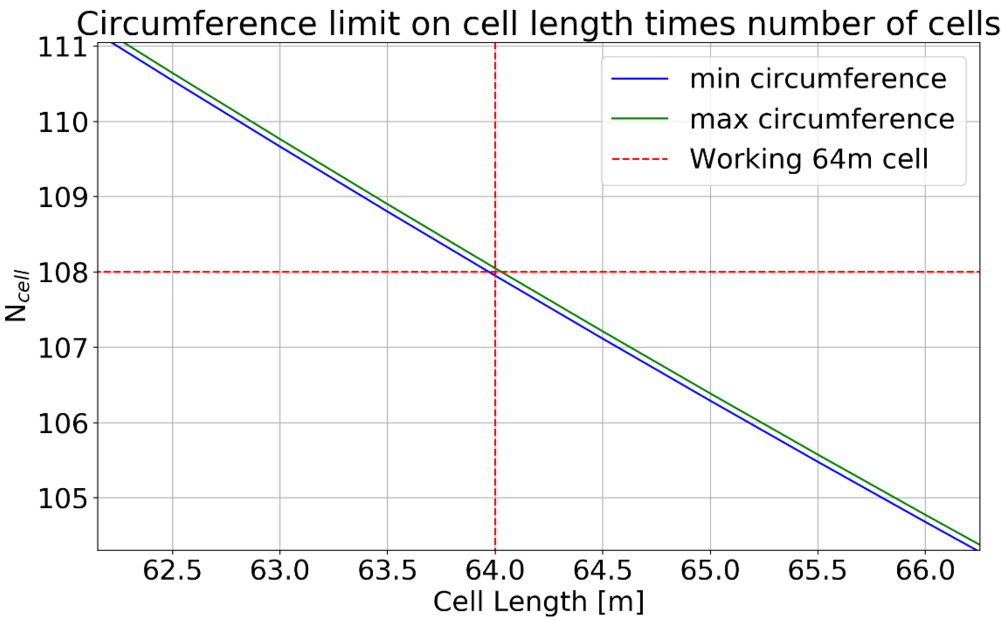
- Extended Optics to full ring
- R(s) for dipole's length of 12.12 m and 12 m (both mentioned in the paper), B=6 T
- Max deviation 8cm for the 12.12 m

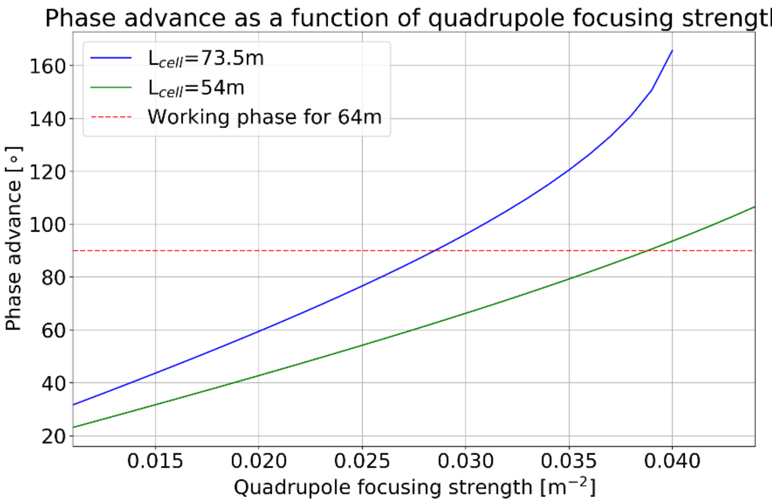


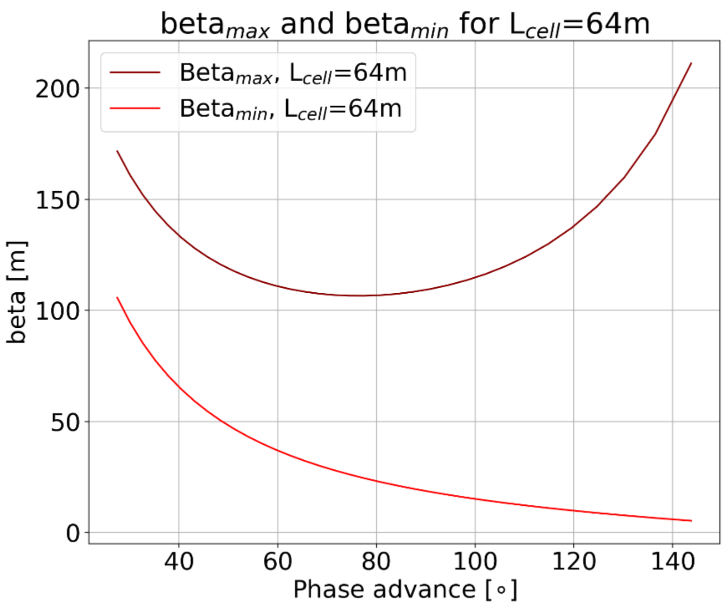




Global Lattice parameters





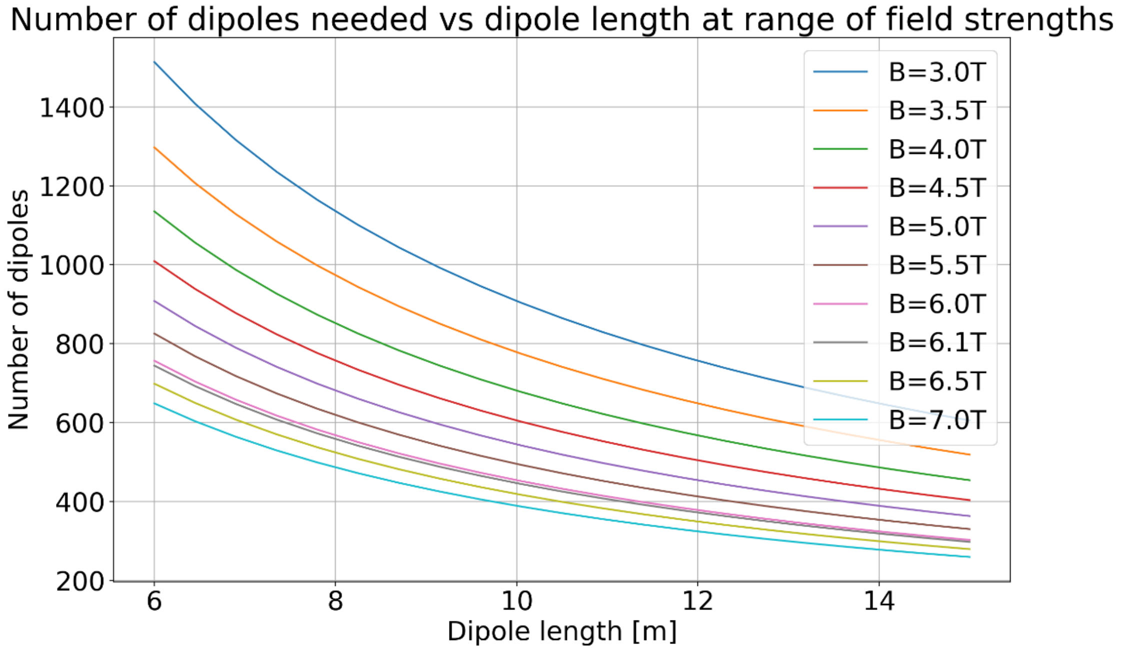


- Different cells' length limited by tunnels' circumference (0.5 m radius tolerance)
- Phase advance VS quads strength
- Resulting Betas for 64 m

Global Lattice parameters: Dipoles

- Fixing different B field values
- Range of lengths and resulting number of dipoles required for the full ring
- Fill factor from this

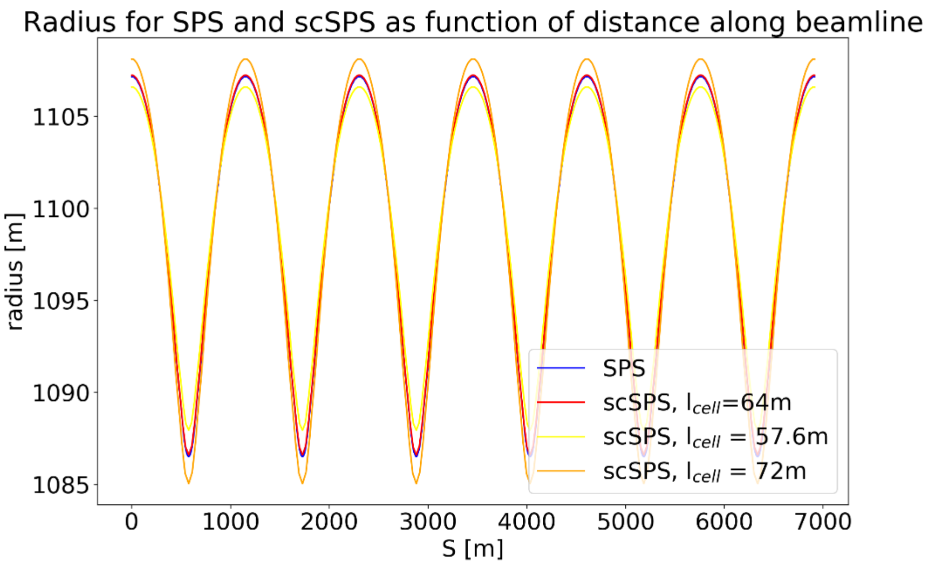
1) $2\pi = N*\theta$
2) $B\rho = 3.33p$
3) $\theta = Bl/B\rho$



Cell Length

Different Cell's Lengths:

- Fixed Drifts length
- Fixed phase advance – 89.96˚
- 6 arcs and even number of cells per arc (respecting symmetry)



Cell Length [m]	Cell Number	K,Quads [m^-2]	Dipole Length [m]	Dipole B peak [T]	α, Dipoles [rad]	Max Betas [m]	Max Deviation [m]
57.6	20	0.036	10.52	6.16	0.014	98	0.5
64	18	0.033	12.12	6	0.016	107	0.08
72	16	0.029	14.12	5.82	0.019	122	1

Conclusions

- Starting from a single arc for the scSPS lattice compared this to the SPS and Tevatron.
- 3 dispersion suppressors examined – that generate 0 dispersion at interaction point.
- Chromaticity calculated as Q'=-35.30 and correcting sextupole peak field strength calculated as B~0.2 T which leads to Q'~0.02.
- Extended the optics to the full ring – checked physical geometry aligns – max deviation 8cm found
- Investigated other lattice options than the SPS cell length – primary look at parameters for 3 cell length options; 57.6 m, 64 m, and 72 m.

Future Work

- Develop dispersion suppressor and chromaticity studies for each of the alternative lattice designs.
- Compare the advantages and disadvantages for the 3 dispersion suppressor options to choose the optimal design
- Consider having a higher sextupole field but fewer – i.e. do not place one after every quadrupole. This reduces cost but impacts the optics quite heavily.

scSPS Magnet Design

Luke Dyks
Daniel Harryman
Michael Backhouse

Outline

- **scSPS requirements**
- **SIS300 fast ramping magnets**
- **Dipole Magnets**
- **Quadrupole Magnets**
- **Sextupole Magnets**
- **Conclusions**
- **Outlook**

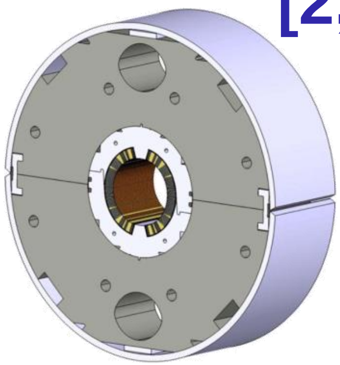
scSPS Requirements

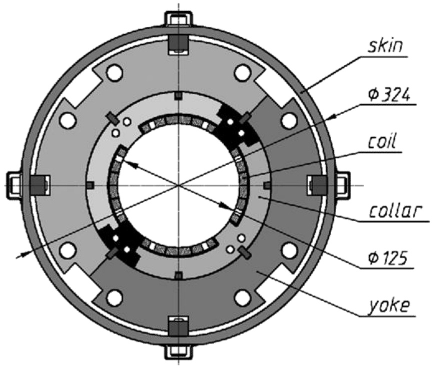
- **Inner coil radius → 45 mm**
- **Operating temp 1.9 K or 4.2 K**
- **Dipoles**
  - **Magnetic field inj – ext → 0.12 – 6.1 T**
  - **Fast Ramping → 0.35 – 0.5 T/s**
- **Quadrupoles**
  - **Gradient inj – ext → 2.8 – 146 T/m**
  - **Pole tip Field → 6.58 T**
  - **Fast Ramping → 8.5 – 12.2 T/m/s**
- **Sextupoles**
  - **Horizontal correction → 0.17 T**
  - **Vertical correction → 0.33 T**
  - **Resistive magnet**

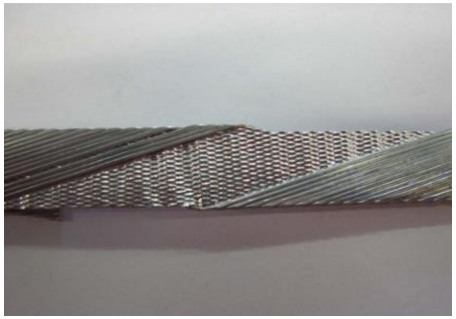
SIS300 Magnets

[2,3]

- **Fast ramping sc magnets designed and tested**
- **Operating temp. → 4.2 K**
- **Dipoles**
  - Magnetic field inj – ext → 1.6 – 4.5 T
  - Ramp rate ~ 1 T/s (LHC ~ 7 mT/s)
- **Quadrupoles**
  - Gradient inj – ext → 16 – 45 T/m
  - Pole tip field → 2.25 T
  - Ramp rate → 10 - 20 T/m/s
- **Cables**
  - NbTi Rutherford cables
  - Main design work to reduce AC losses
  - 2 layers of 0.825 mm diameter wires
  - Ratio Cu to Nb = 1.5

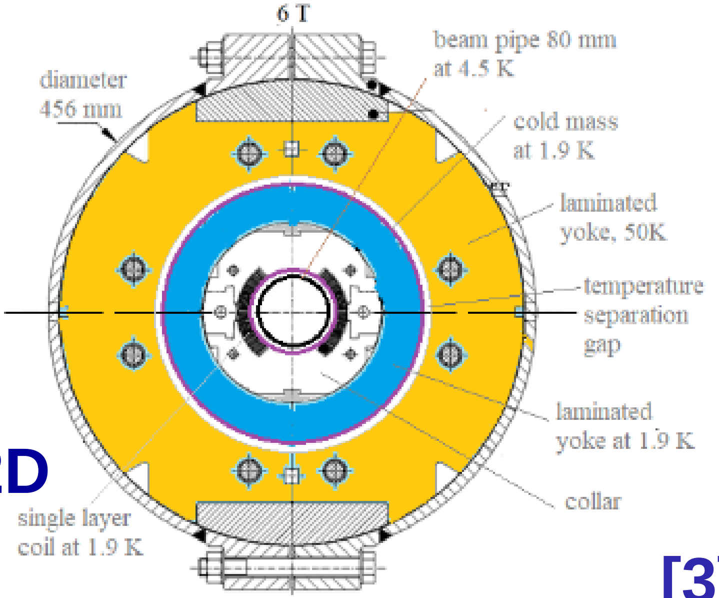






Dipoles

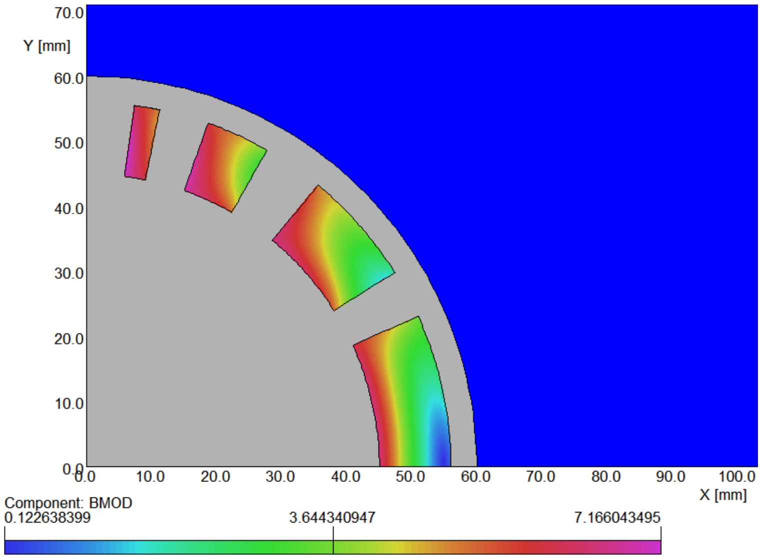
- **Cos(θ) magnet design**
- **Based on preliminary designs**
- **Rutherford cables based on SIS300**
- **3 dipole designs**
  - **Single layer 11 mm wide cables**
  - **Single layer 15 mm wide cables**
  - **Double layer graded cable**
- **1/4th symmetry**
- **Sector approximation**
- **Modelled magnets in OPERA 2D**
  - **Field strength**
  - **Field quality**
  - **Current Densities**



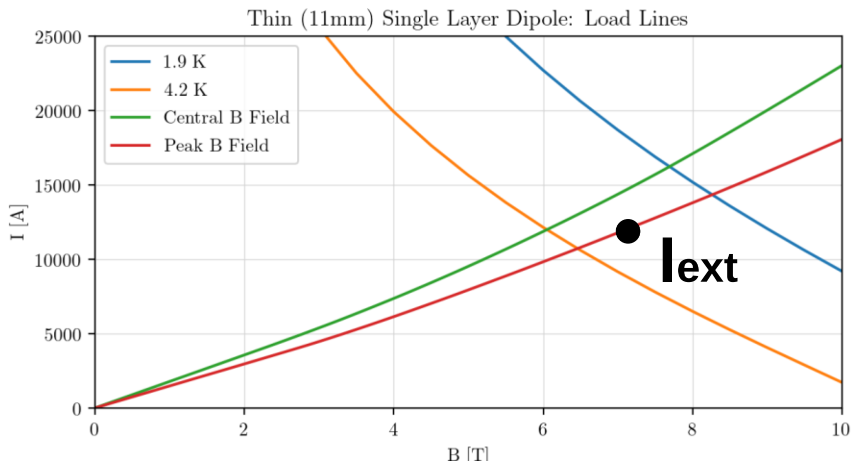
[3]

Initial scSPS Dipole Design

Single Layer – 11 mm Cables

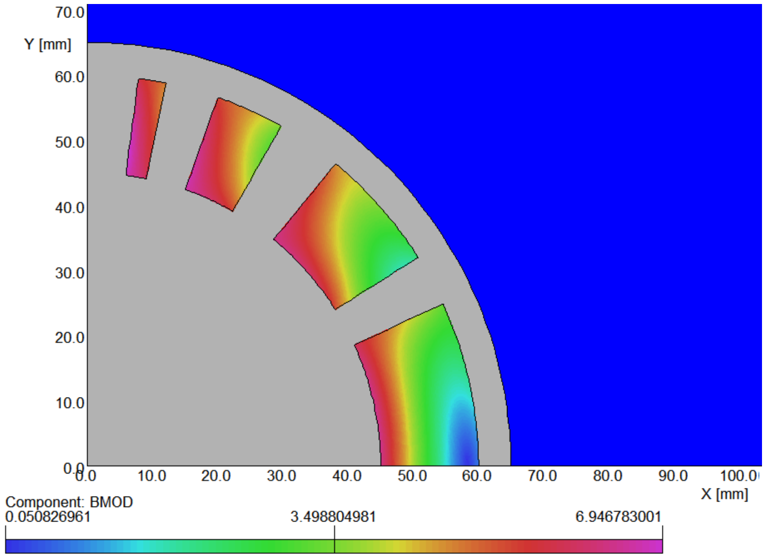


- Extraction current → 12119 A
- Injection current → 214 A
- B peak → 7.16 T
- Load margin → 84 % @ 1.9 K
- Harmonics ~ 10^{-2} - 10^{-4}

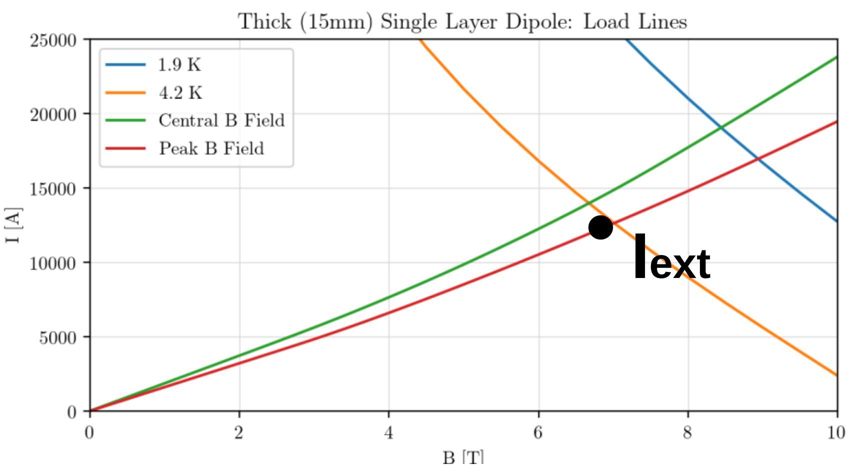


		I = 214 A	I = 12119 A
b1	[1e-4]	10,000	10,000
b3	[1e-4]	-178.84	-40.68
b5	[1e-4]	82.07	90.16
b7	[1e-4]	4.17	5.57
b9	[1e-4]	6.09	6.68
b11	[1e-4]	-0.46	-0.49

Single Layer – 15 mm Cables

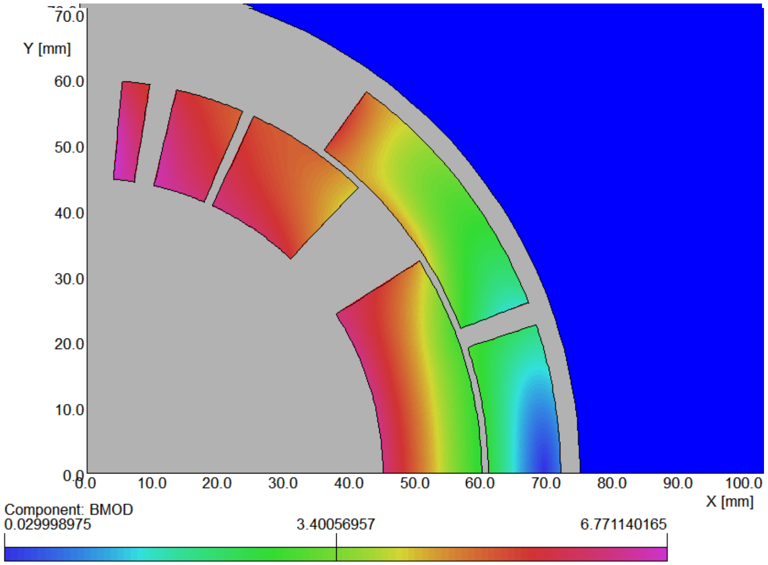


- Extraction current → 12500A
- Injection current → 224 A
- B peak → 6.95 T
- Load margin → 74 % @ 1.9 K
- Harmonics ~ 10^{-2} - 10^{-4}

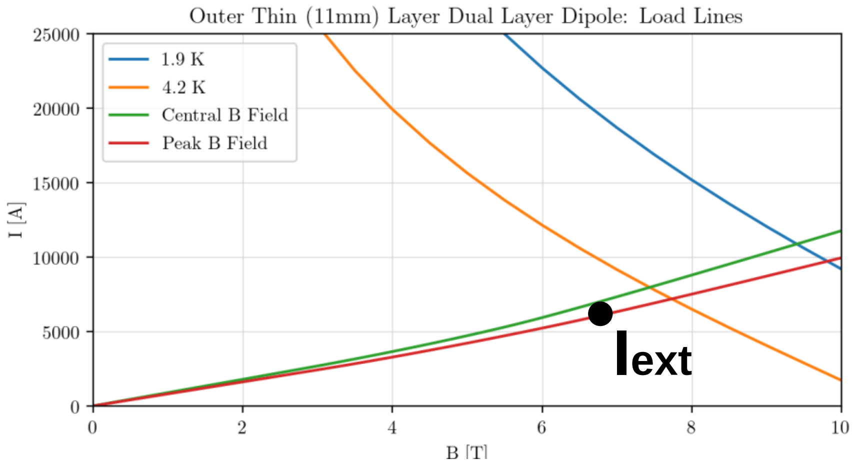


		I = 224 A	I = 12500 A
b1	[1e-4]	10,000	10,000
b3	[1e-4]	-138.50	-34.04
b5	[1e-4]	70.64	77.23
b7	[1e-4]	3.75	4.56
b9	[1e-4]	4.88	5.33
b11	[1e-4]	-0.39	-0.42

Double Layer Graded



- Inner layer 15 mm cables
- Outer layer 11 mm cables
- Grading → 1.36
- Extraction current → 6068 A
- Injection current → 107 A
- B peak → 6.77 T
- Load margin → 84 % @ 4.2 K
  → 62 % @1.9 K
- Harmonics ~ 10^{-2} - 10^{-4}

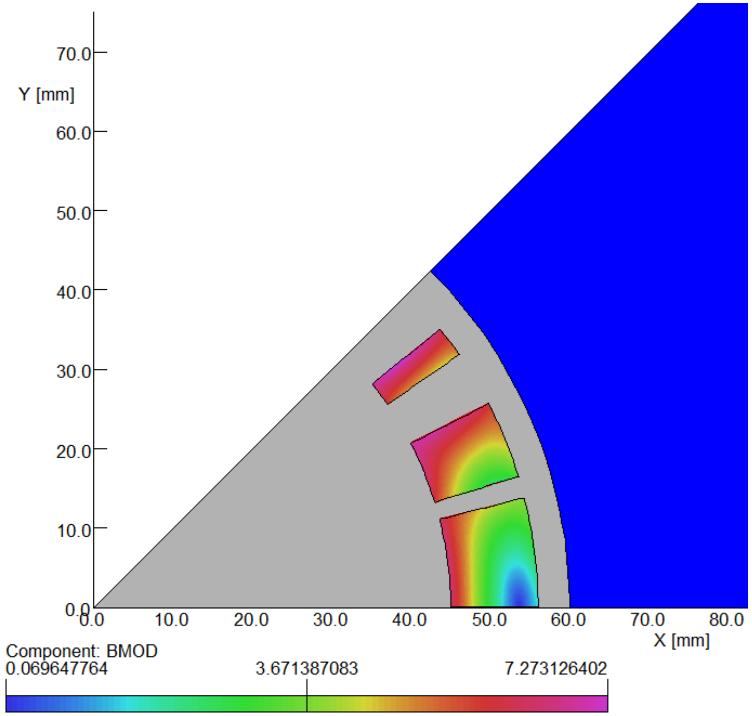


		I = 107 A	I = 6068 A
b1	[1e-4]	10,000	10,000
b3	[1e-4]	-89.50	-57.85
b5	[1e-4]	64.93	75.56
b7	[1e-4]	-4.19	-4.90
b9	[1e-4]	-3.35	-3.78
b11	[1e-4]	-0.49	-0.55

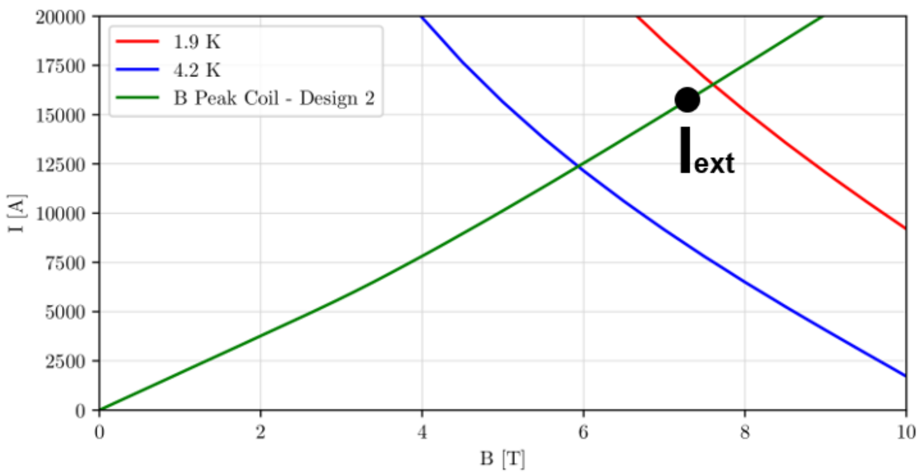
Quadrupole Magnets

- Cos(2Θ) coil layout gives quadrupole field
- 3 quadrupole designs
  - Single layer 11 mm wide cables
  - Single layer 15 mm wide cables
  - Double layer graded cable
- 1/8th symmetry
- Sector approximation
- Modelled magnets in OPERA 2D
  - Field strength
  - Field quality
  - Current Densities

Single Layer – 11 mm Cables

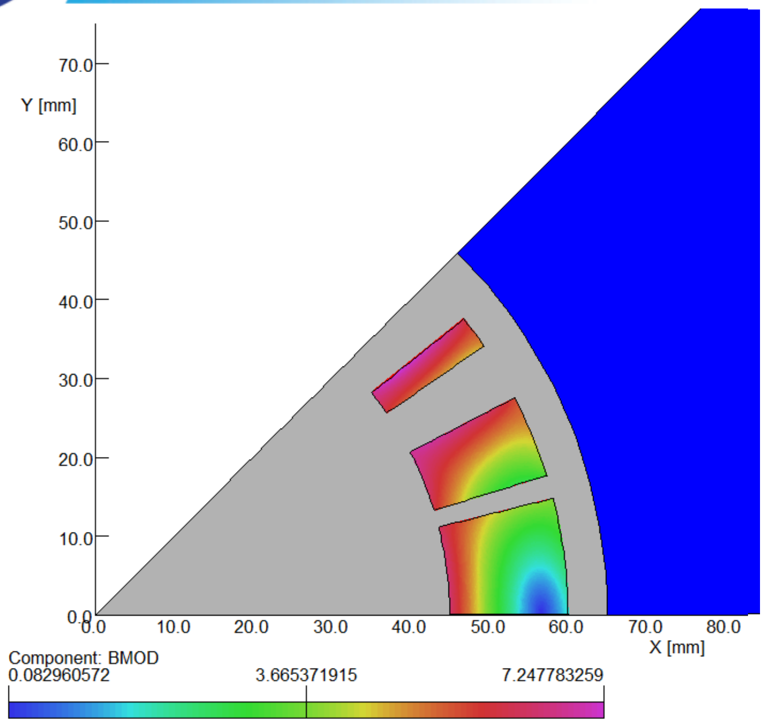


- **Extraction current → 15697 A**
- **Injection current → 276 A**
- **B peak → 7.27 T**
- **Load margin → 95 % @ 1.9 K**
- **Harmonics ~ 10^{-4} - 10^{-3}**

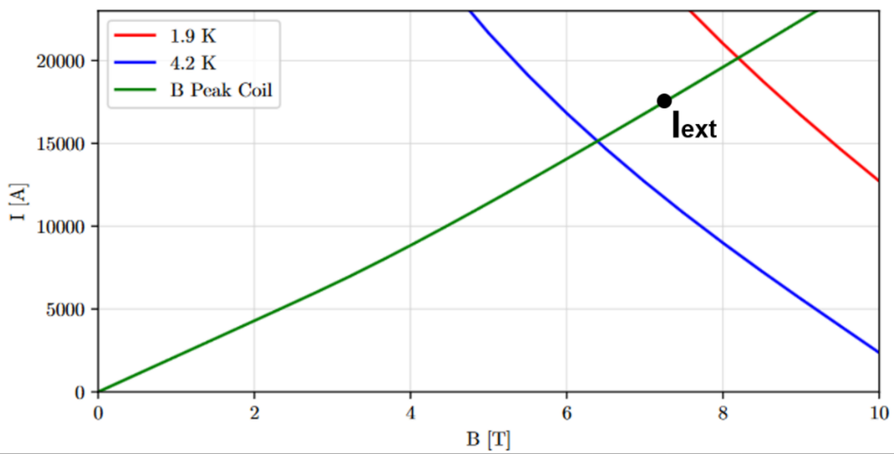


		I = 276 A	I = 15697
b2	[1e-4]	10,000	10,000
b6	[1e-4]	-9.92	7.41
b10	[1e-4]	1.79	2.31
b14	[1e-4]	0.02	0.03
b18	[1e-4]	0.09	0.10

Single Layer – 15 mm Cables

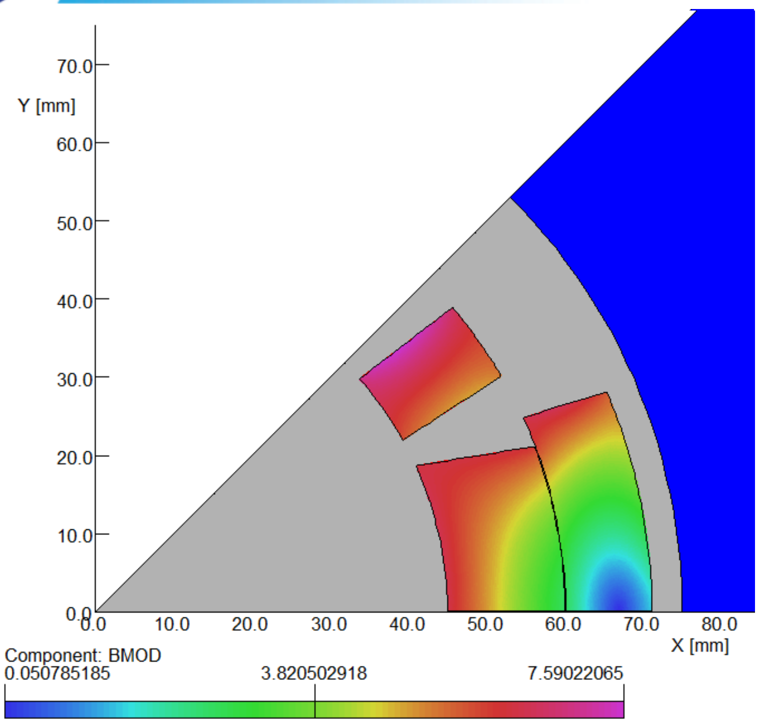


- **Extraction current → 17500 A**
- **Injection current → 305 A**
- **B peak → 7.24 T**
- **Load margin → 86 % @ 1.9 K**
- **Harmonics ~ 10^{-4} - 10^{-3}**

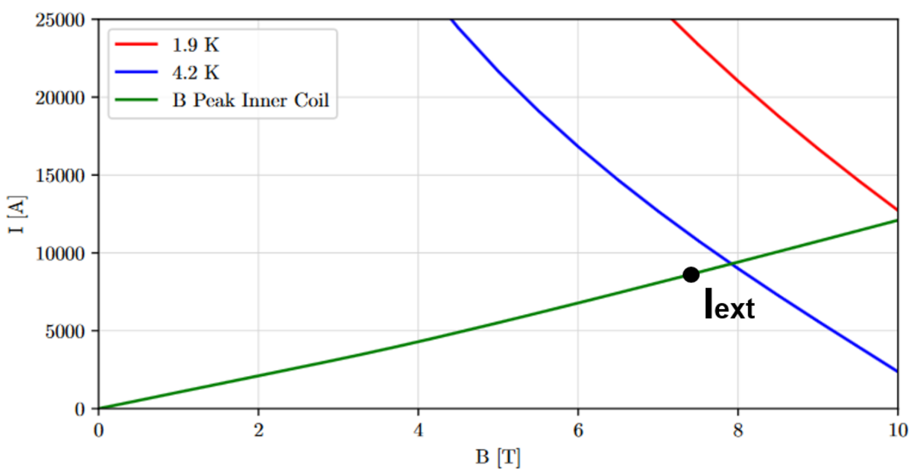


		I = 305 A	I = 17,500
b2	[1e-4]	10,000	10,000
b6	[1e-4]	-9.08	2.08
b10	[1e-4]	1.55	1.86
b14	[1e-4]	0.01	0.02
b18	[1e-4]	0.07	0.08

Double Layer Graded



- Inner layer 15 mm cables
- Outer layer 11 mm cables
- Grading → 1.36
- Extraction current → 8865 A
- Injection current → 161 A
- B peak → 7.6 T
- Load margin → 96 % @ 4.2 K
  → 69 % @1.9 K
- Harmonics ~ 10^{-4} - 10^{-3}

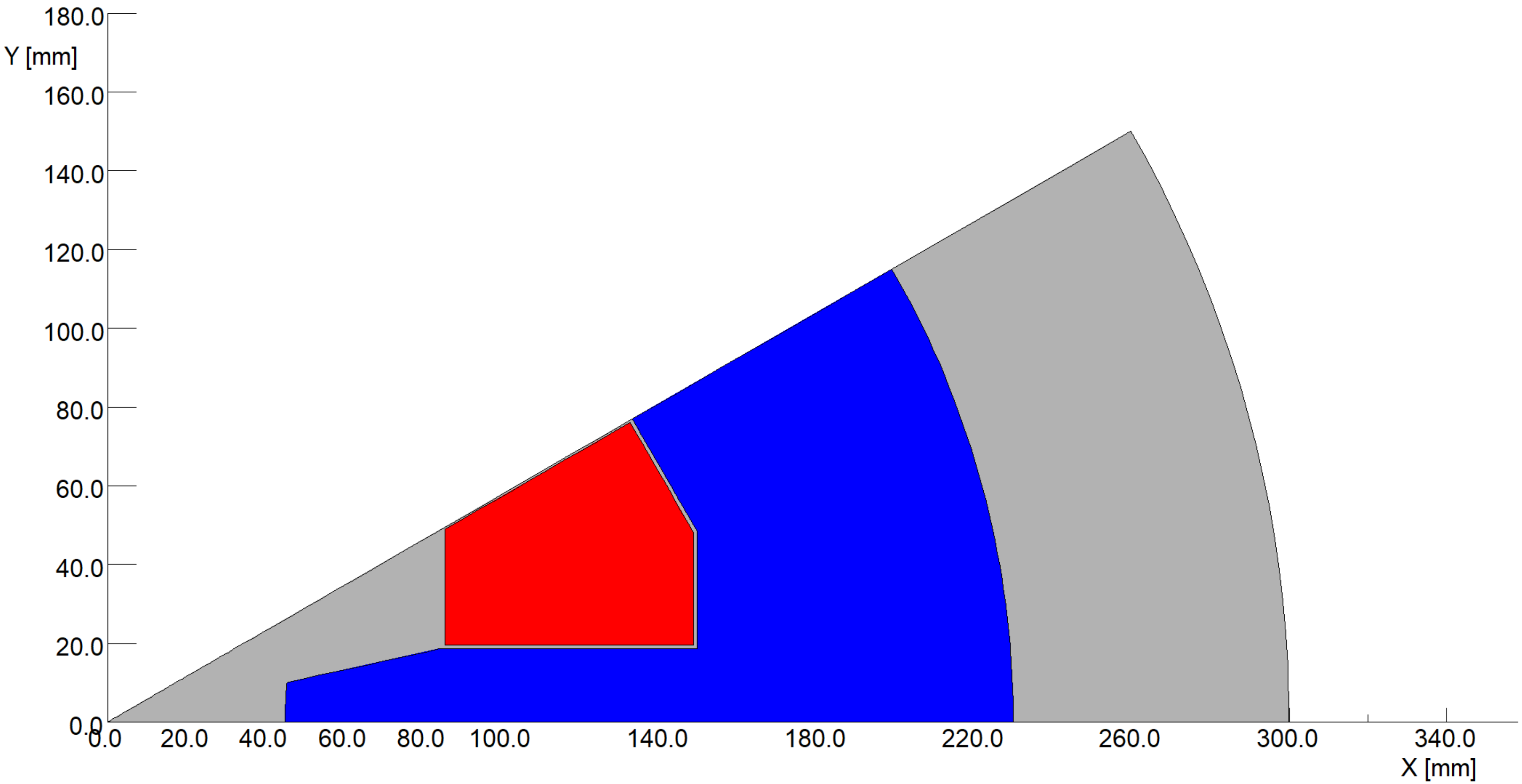


		I = 305 A	I = 17,500
b2	[1e-4]	10,000	10,000
b6	[1e-4]	-9.24	-8.67
b10	[1e-4]	5.28	5.95
b14	[1e-4]	-0.86	-0.96
b18	[1e-4]	0.04	0.04

Sextupole Magnets

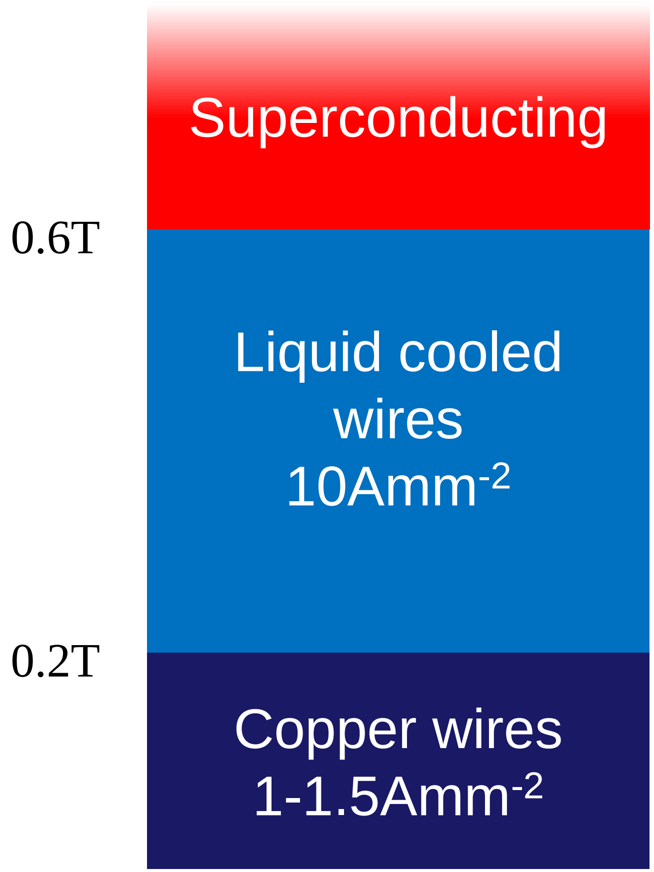
- **Iron dominated resistive magnet**
- **2 sextupole designs**
  - **Air cooled cables**
  - **Water cooled cables**
- **1/12th symmetry**
- **Sector approximation**
- **Modelled magnets in OPERA 2D**
  - **Field strength**
  - **Field quality**
  - **Current Densities**

Yoke geometry



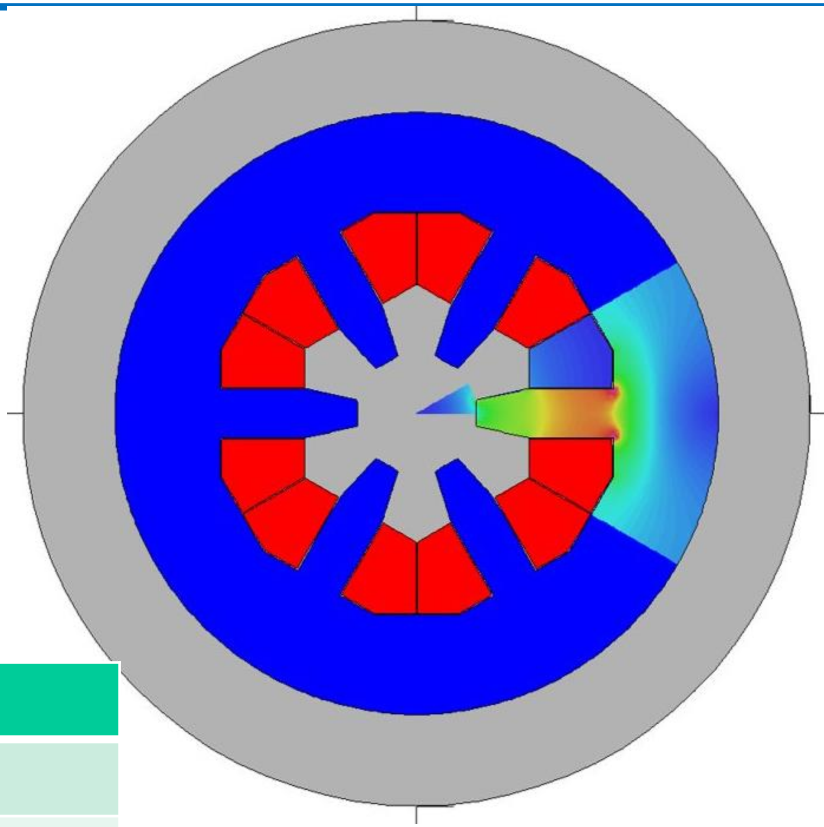
Field thresholds

Given reasonable yoke geometries, the peak field is limited by the wire type.



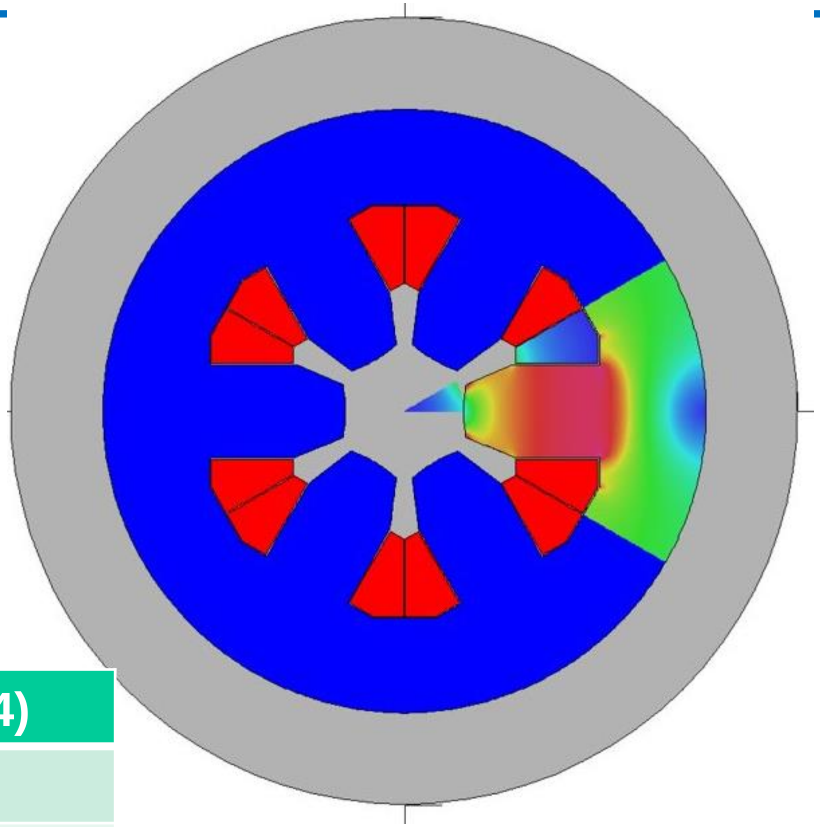
0.17T design

Achievable with $1Amm^{-2}$ (non-liquid cooled wires)



Coefficient	Value (10^-4)
b3	10000
b9	3.8
b15	2.7
b21	1.7
b27	1.4

0.33T design



Current density of $3.2 Amm^{-2}$ requires liquid cooled cables

Coefficient	Value (MOD, 10^-4)
b3	10000
b9	7.9
b15	5.7
b21	1.7
b27	1.4

Conclusions

- **Dipoles and quadrupoles must be superconducting**
- **Use similar Rutherford cables to SIS300**
- **Single layer 11 mm design for dipole @ 1.9 K**
- **40 mm aperture of magnet makes 11 mm quadrupole challenging**
- **Single layer 15 mm design adequate for both @ 1.9 K**
- **Double layer may be improved to operate at 4.2K**
- **Weigh up cryogenic vs. cabling costs.**
- **Chromaticity correction achievable with resistive magnets**

Outlook

- **Further improve quality and load limit**
- **Investigate low field losses**
- **Calculate mechanical stresses**
- **Calculate thermal properties**
- **3D magnet design**
- **Investigate 50 GeV injection**
- **Reduce number of sextupoles and increase field, possibly SC**

scSPS RF cavity design considerations

David Posthuma de Boer and Aimee Ross

Our objectives

- **Choose between NC and SC cavities**
- **Decide on a frequency, voltage and shape of cavity**
- **Optimise characteristics using Superfish and CST Microwave studio**

scSPS RF design constraints

- **Must capture beam from PS**
  - **4.2 ns bunch length**
  - **26 GeV energy**
- **Must accelerate to 1.3 TeV**
  - **Ramp rate of dipoles ($\dot{B}_{max} = 0.5$ T/s)**
  - **Energy increase of ~2.5 MeV per turn**
  - **Cavity field at 11 MV/m**
- **FCC requires 25 ns bunch spacing**

Super-Conducting vs Normal-Conducting

- **High voltage, high energy machine**
- **Other advantages of sc cavities:**
  - **Low power losses**
  - **Allows larger aperture**
- **Disadvantages of sc cavities:**
  - **Cryogenic cooling required**
  - **Very small natural frequency bandwidth**


[5]

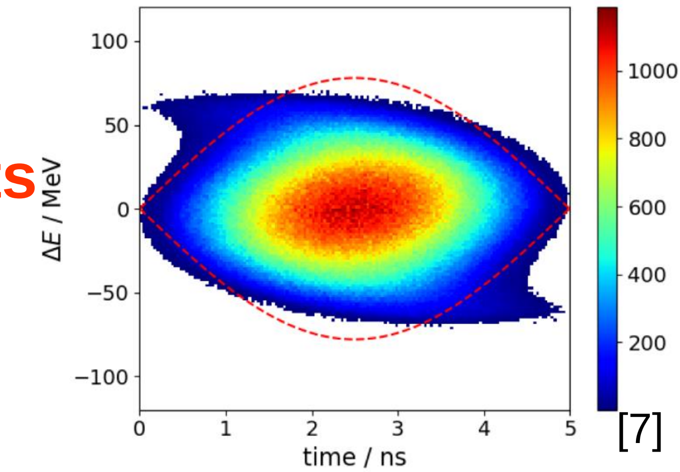
SPS Cavity


[6]

LHC Cavity

200 MHz vs 400 MHz

- **Advantages of 200 MHz vs 400 MHz**
  - Better beam capture efficiency
  - Reduced bandwidth requirements
- **Disadvantages of 200 MHz vs 400 MHz**
  - Larger diameter (1.4 m) ⇒ larger cryogenics, waveguides
  - Very little experience with 200MHz sc
- **A 200 MHz sc cavity has been prototyped at CERN**



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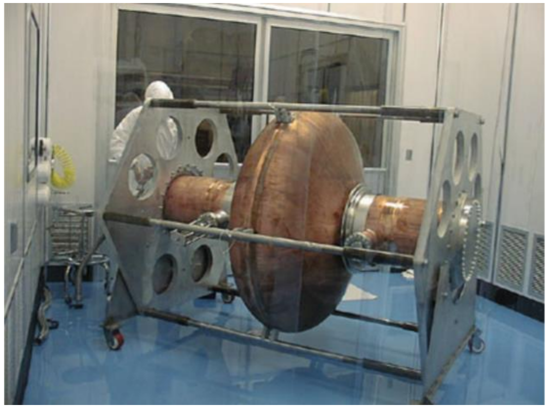
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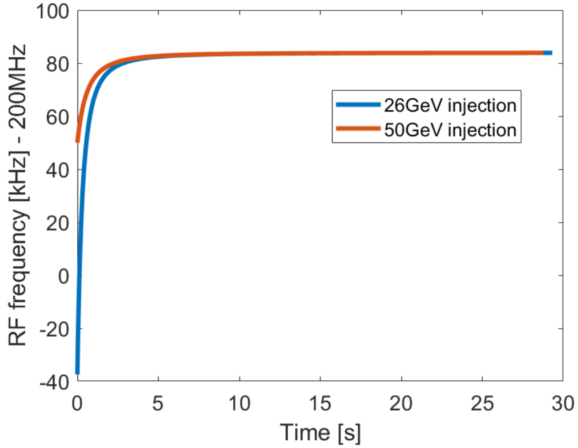
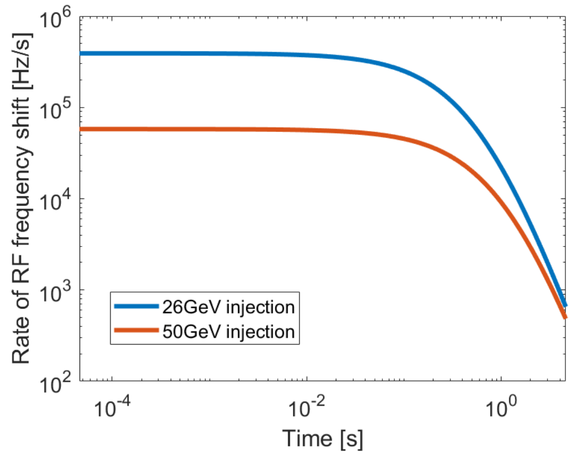
Constraints on bandwidth

- sc cavities have natural bandwidth of order few Hz
- Tuners are used to vary bandwidth:
  – Fast, small bandwidth - piezo tuner 3 kHz
  – Slow, large bandwidth - for LHC 180 kHz, 9 kHz/s

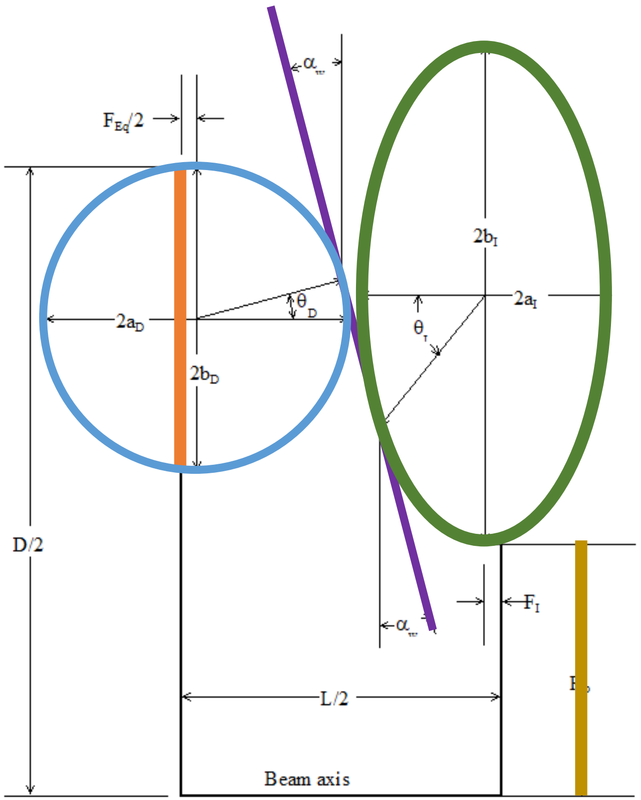




- Such a tuner should be possible, but requires R&D

Parameter Study

- **Parameters that we have to vary**
  - **Dome vertical radius**
  - **Dome radius ratio (A/B)**
  - **Wall angle**
  - **Iris radius ratio**
  - **Aperture radius**



- **Aim**
  - **Optimise r/Q**
  - **Minimise peak fields**
  - **Suppress Higher Order Modes**

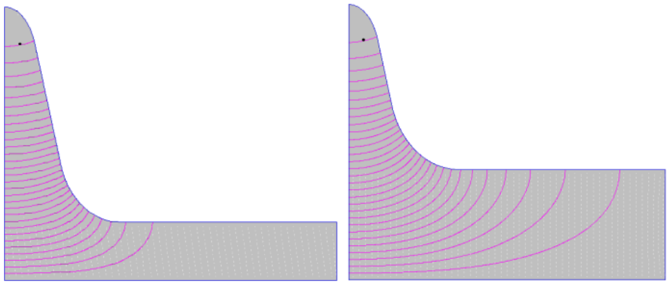
Parameter Study

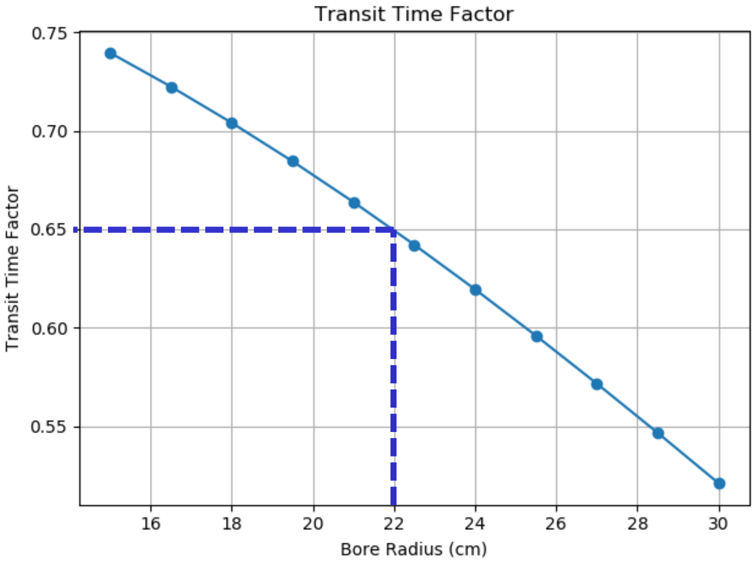
Beam Pipe Aperture

- As large as possible for HOM suppression
- Fields to "leak" into beam pipe

Transit Time Factor (TTF) Limit

- Max field and acceleration rate limit the TTF
- Previous 200 MHz cavity reached 11MV/m
- Taking that as limit gives $T > 0.6$
- The radius of 22cm was investigated





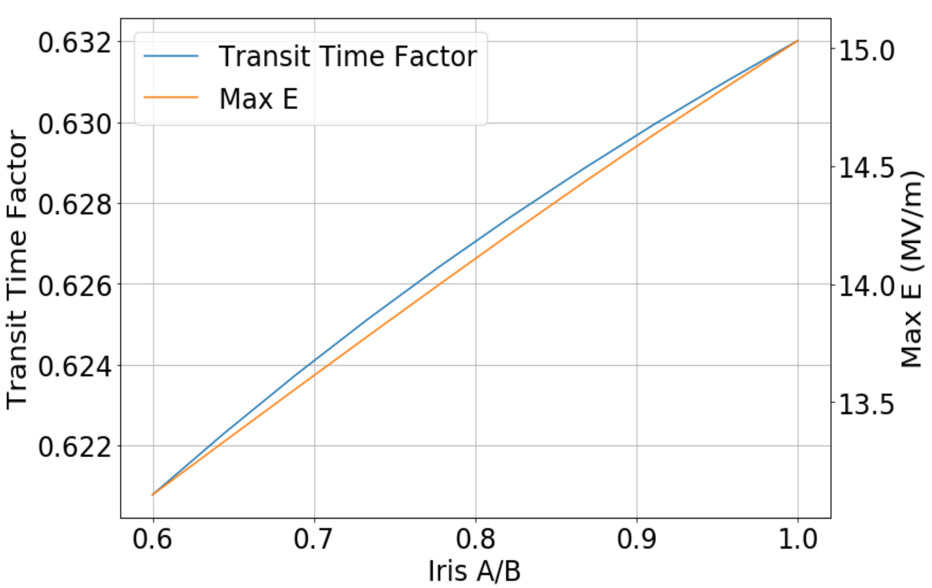
Parameter Study

Iris A/B

- Small Transit Time Factor (TTF) change
- Large variation in E_{peak}

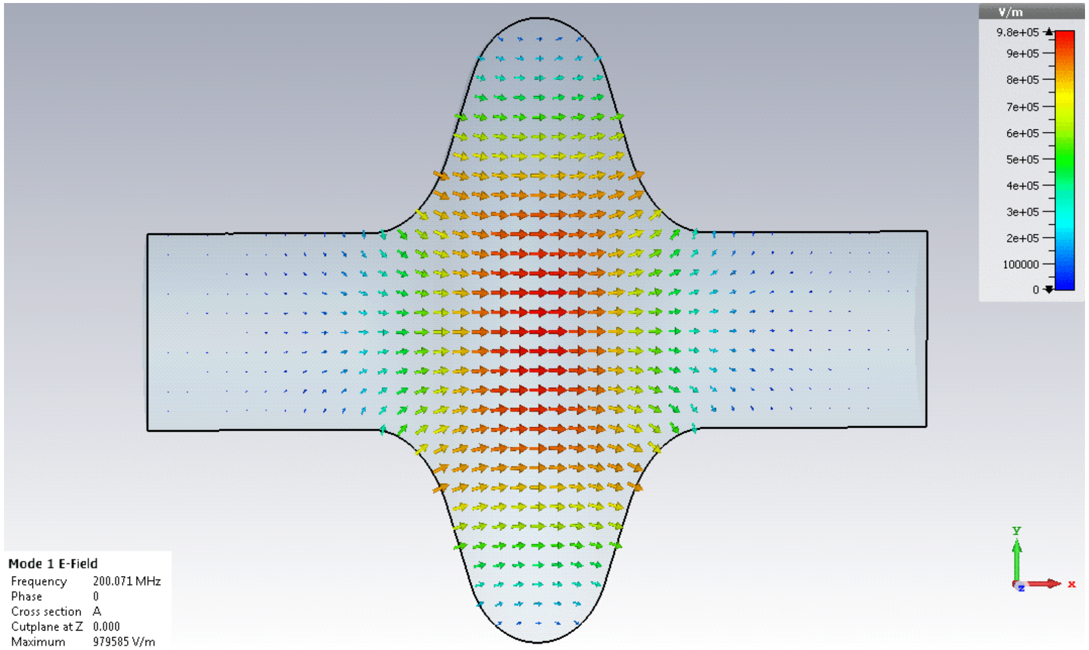
Other parameters chosen to

- Maintain required TTF
- Reduce peak fields
- Increase HOM frequencies

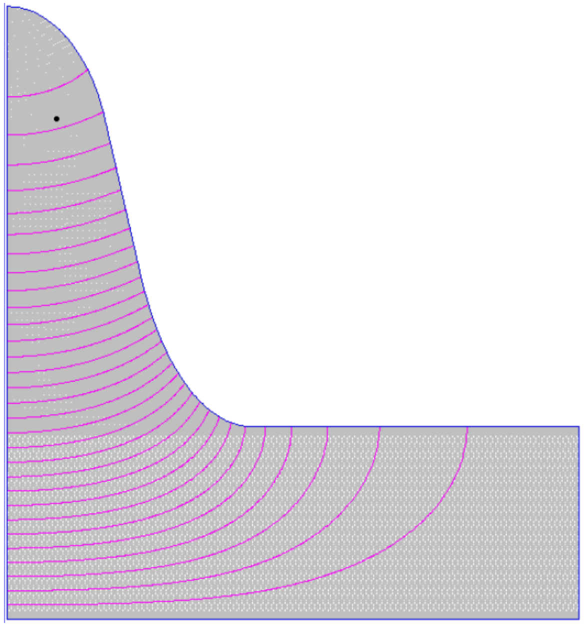


Would also need to consider engineering and material constraints

The final model



CST E-field animation for TM010



Superfish half-cavity

	Our cavity	**CERN's prototype**
E_{peak}/E_{acc}	1.07	1.69
B_{peak}/E_{acc}	3.24 mT/(MV/m)	4.34 mT/(MV/m)
r/Q	106 Ω	121 Ω

Conclusion

- Fundamental properties of the required cavity have been calculated.
- A 200 MHz single cell superconducting elliptical cavity has been optimized with SUPERFISH and validated with CST.
- Practical realization would require R&D into tuning techniques for bandwidth & swing rate.

- Future work could look at:
  - Adding asymmetric pipes to improve the transit-time factor
  - Higher order mode suppression by increasing cut-off pipe apertures
- If a shorter bunch could be injected at 50 GeV from an upgraded PS
- then it could be possible to use a 400 MHz cavity and reduce the required frequency swing and swing rate.

Summary of scSPS design project

- **Dispersion suppressors and chromaticity studies conducted for existing scSPS lattice design. Alternative lattices proposed.**
- **Superconducting dipole and quadrupole designed with different cable and temperature parameters. Resistive sextupoles designed.**
- **A single-cell superconducting cavity is proposed, with considerations of tuning bandwidth and HOM suppression.**
- **PS upgrade would make many of these challenges more manageable (higher energy, shorter bunch).**

Thank you for listening

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Back up slide - tuner

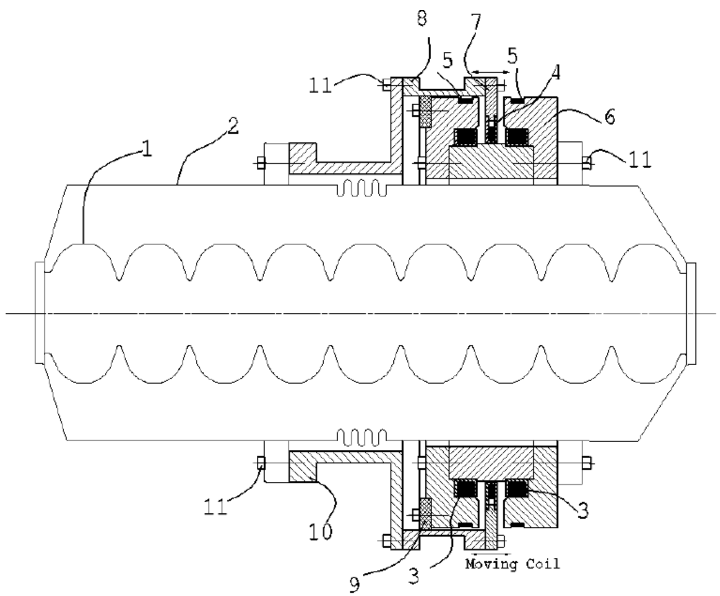
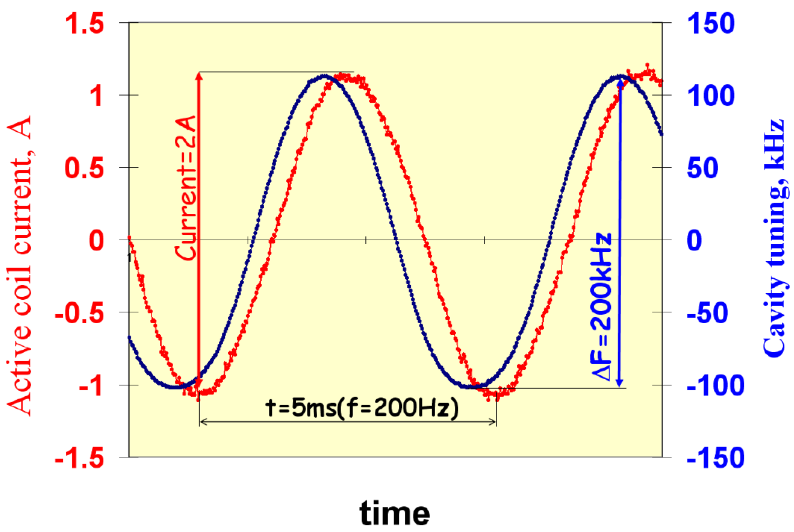


Figure 1: Electromagnetic Tuner cross-section.



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