John Adams Institute for Accelerator Science

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3 TeV Future Muon Collider:
RCS Acceleration in SPS Tunnel

Student Design Project

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Motivations for a Muon Collider

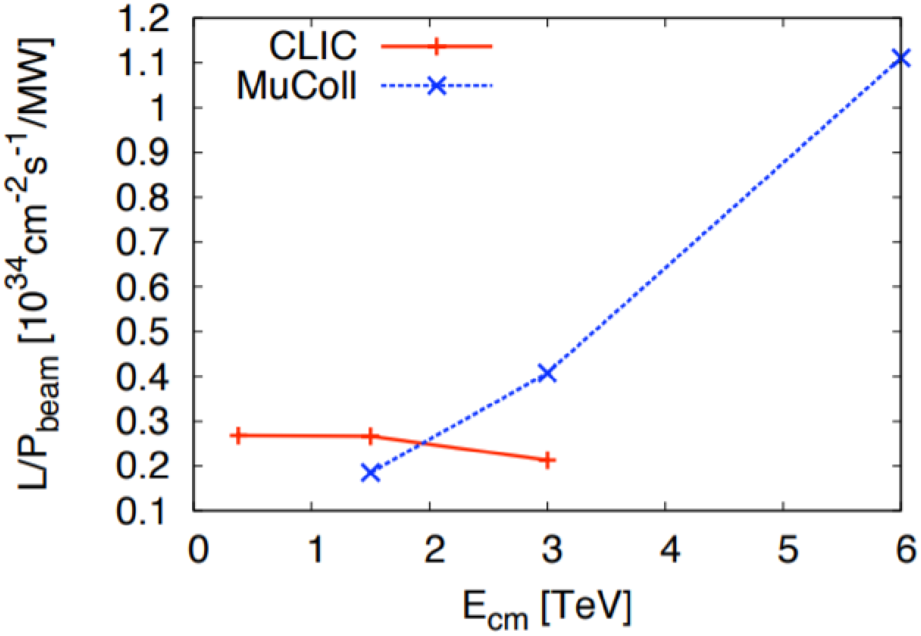
Why do we need a muon collider?

- **We want a lepton colliding machine to explore the energy and precision frontier**
- **A much higher discovery potential than a hadron machine of equivalent energy**
- **Does not suffer from synchrotron radiation**
- **Does not have the large footprint of a linear accelerator - it can reuse infrastructure**

Particle Physics at Muon Collider

Advantages of building a muon collider?

- **A highly synergistic physics programme**
- **Can be built in stages, with interesting physics at each step**
- **A high luminosity per unit wall power**

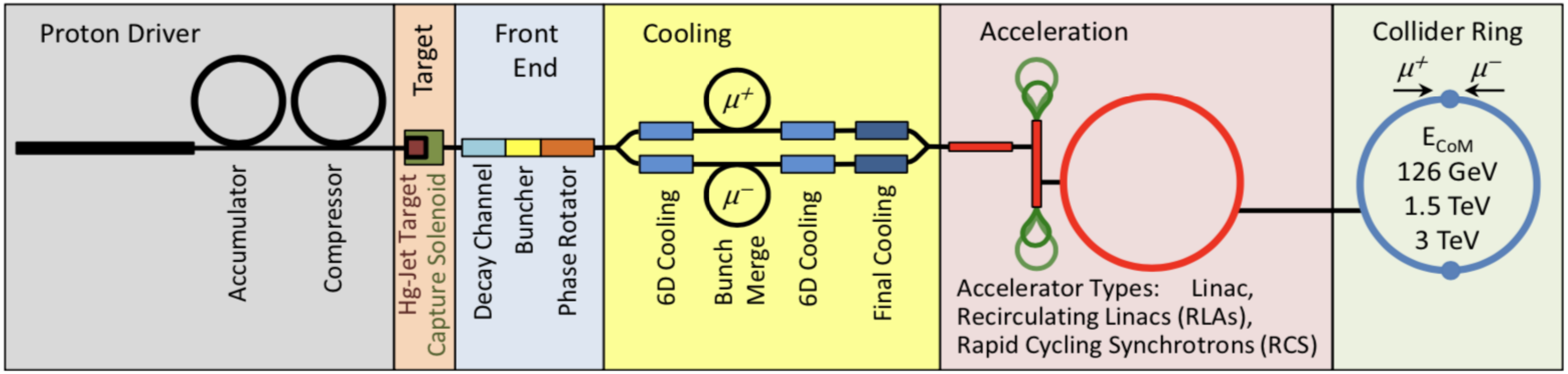


Previous Muon Collider Studies

- **Studies on overall collider scheme and basic machine parameters**
- **Two schemes for muon production**

1. MAP scheme

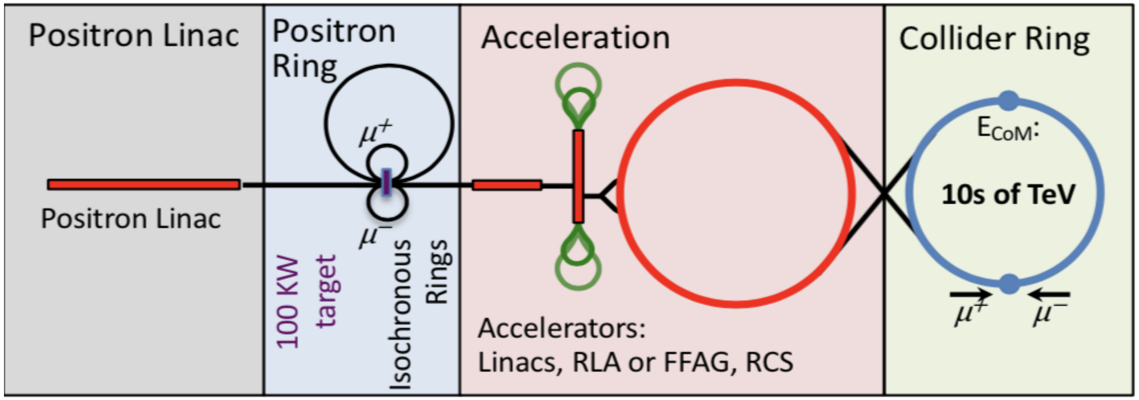
  - **Proton on pion-producing target**
  - **Muons created by pion decay**
  - **Large emittance requires 6D ionization cooling**
  - **Acceleration stage involves linac, RLAs and RCS**



Previous Muon Collider Studies

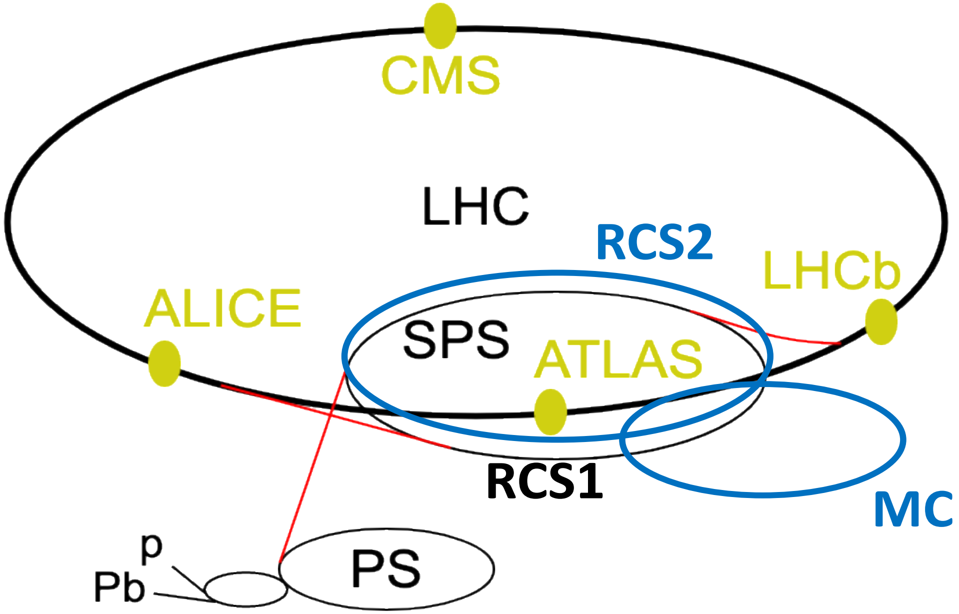
2. LEMMA scheme

- Positron on beryllium target
- $\mu^+\mu^-$ production at threshold
- Low emittance
- Allows lower overall charge in collider ring
- Lower backgrounds in collider detector



Our Studies

- **We focused on acceleration stage for 3 TeV MC**
- **RCS**
  - **Lattice**
  - **Magnets**
  - **RF cavities**
  - **Radiation**



- **Considerations**
  - **Cost and resources**
- **Use existing infrastructure at CERN**
- **Acceleration from 100 GeV to 1.5 TeV**
  - **Divided into two stages RCS1 and RCS2**

RCS Lattice Design

Student Design Project

Jake Flowerdew

Collette Pakuza

Peter Griffin-Hicks

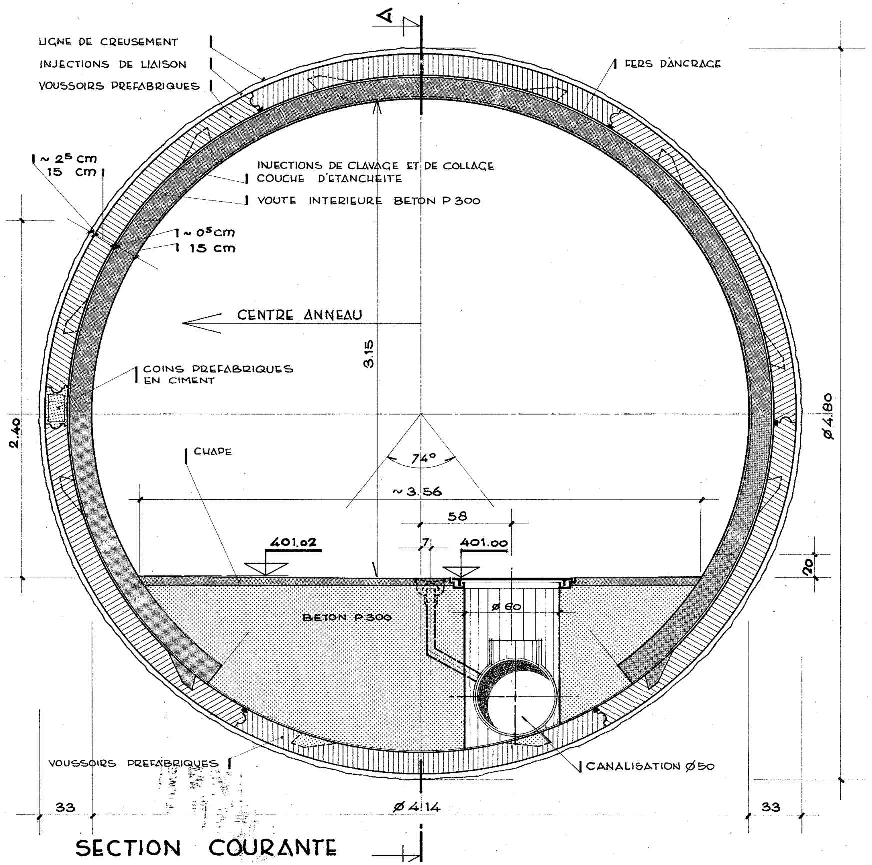
Overview

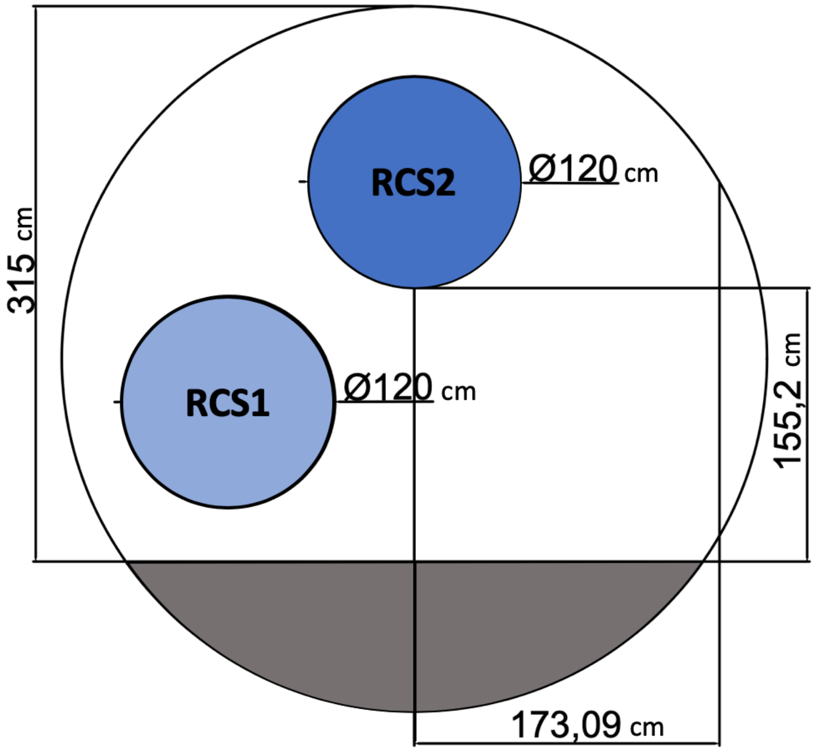
- **Feasibility of RCS1 and RCS2 in current SPS tunnel**

- **First studies of full lattice for both RCSs**

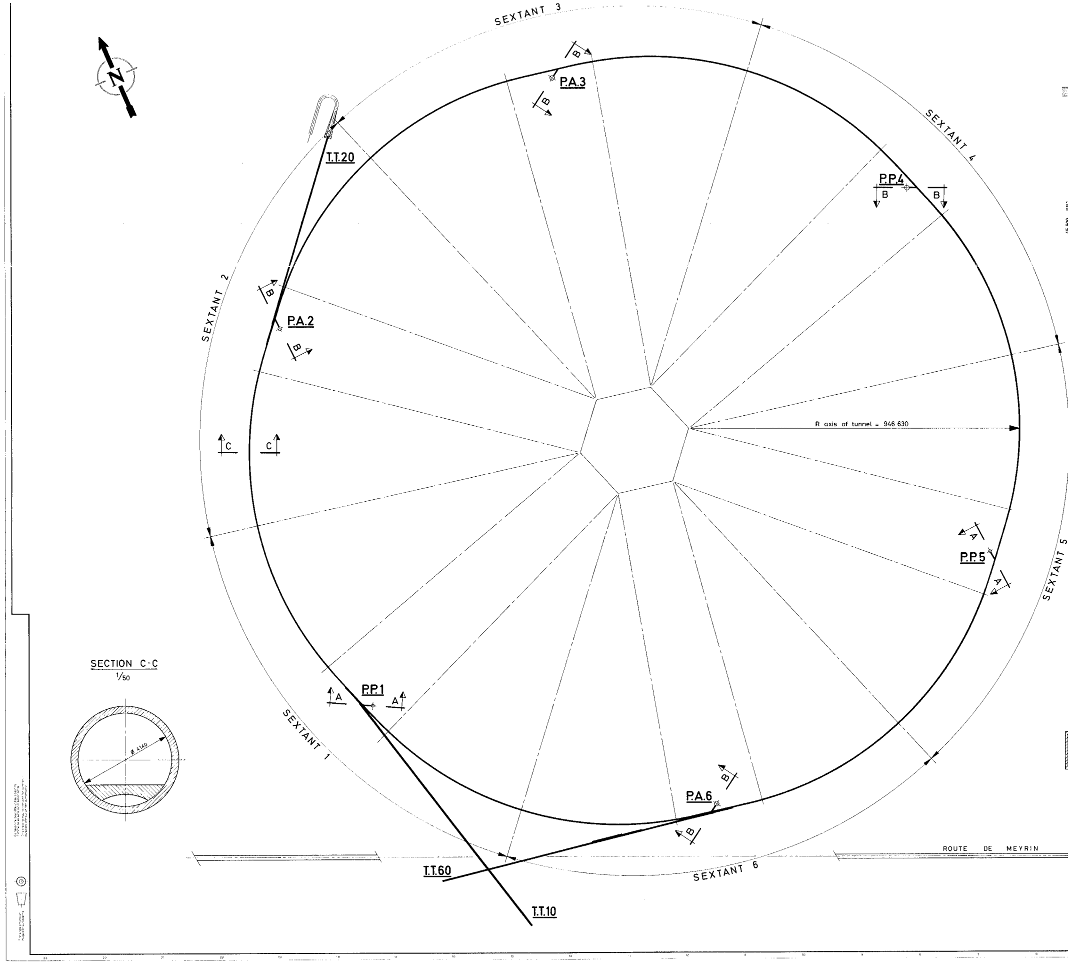
- **Developed dispersion suppressor schemes**

Feasibility of RCSs in SPS Tunnel





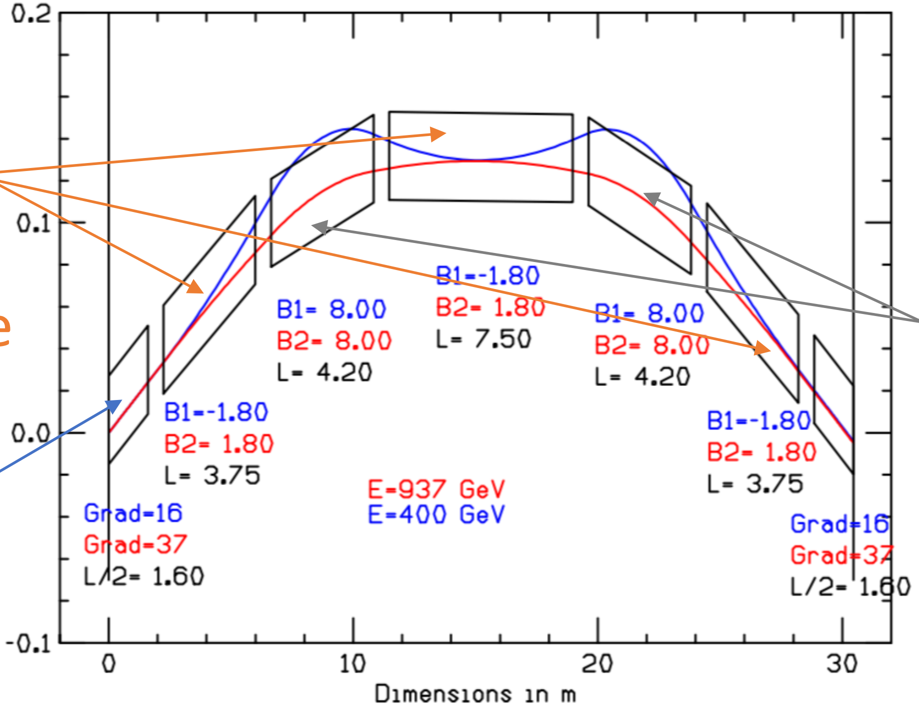
Dimensional constraints



- 6.9 km circumference
- 6 arcs
  - Each ~1 km
- 6 straight sections
  - Each 131 m

Previous Lattice Studies

- **FODO cells with a hybrid design**
- **3 pulsed magnets and 2 SC magnets per half-cell**



Normal-conducting pulsed dipole

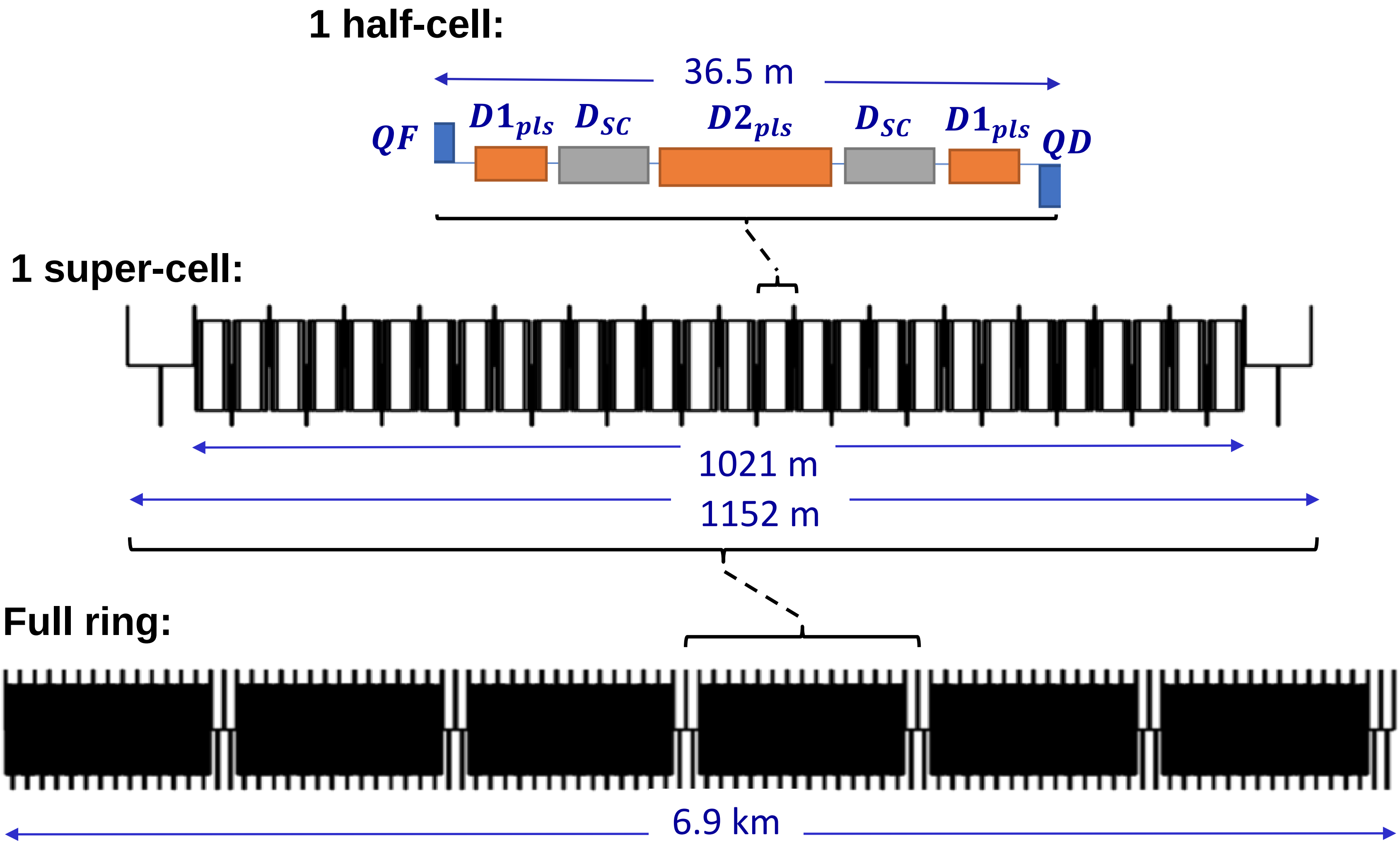
Quadrupole

Fixed superconducting (SC) Dipole

Diagram Ref: Summers, D.J., Cremaldi, L.M., Godang, R., Kipapa, B.R. & Rice, H.E., Muon acceleration to 750 GeV in the Tevatron tunnel for a 1.5 TeV $\mu^+\mu^-$ collider, Particle Accelerator Conference (PAC 07), Albuquerque, NM, 25-29 June 2007, THPMS082.

Our Lattice Design

- **Based on hybrid FODO cell**



Calculated Parameters

Parameter	Units	RCS1	RCS2
Injection Energy	GeV	100	900
Extraction Energy	GeV	900	1500
$D1_{pls}$ length	m	2.0	6.0
$D2_{pls}$ length	m	20.95 (3x7 m)	6.71
D_{pls} initial magnetic field	T	-2.00	-2.00
D_{pls} final magnetic field	T	2.00	2.00
D_{SC} length	m	3.12	6.24
D_{SC} strength	T	10.0	12.0
Quad length	m	2.0	2.0
Quad initial gradient	T/m	6.4	57.6
Quad final gradient	T/m	57.6	96.0
Number of cells		84	84
Number of cells per arc		14	14
Packing factor		0.76	0.76
Total length of straights	m	738	738
Space for RF	m	492	492
Beam aperture	mm	38	28

Dispersion suppressor: Missing Dipoles

- Used MAD-X to plot beta and dispersion functions
- Suppress dispersion in straights

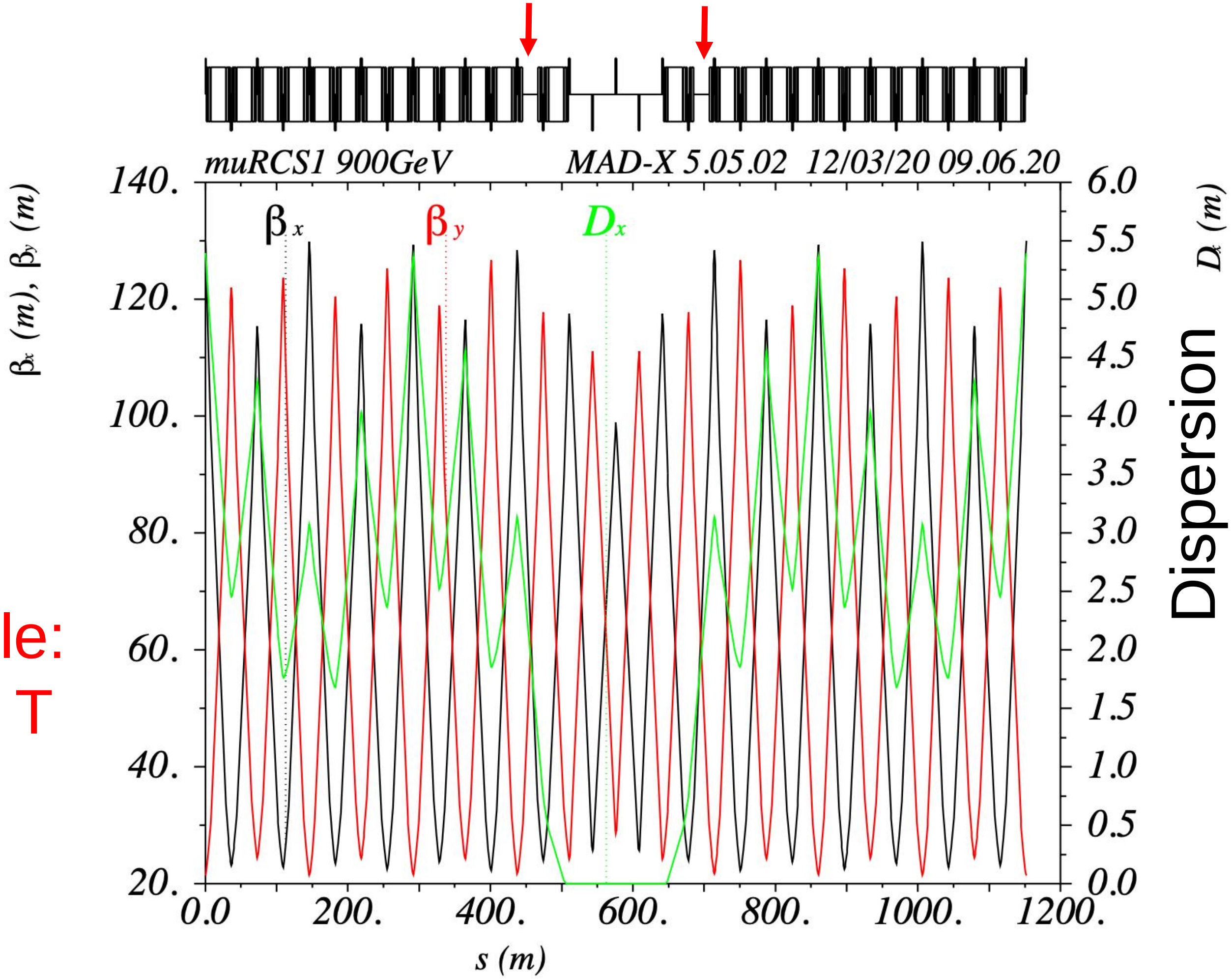
1. Missing Dipoles

- Advantage
  - Beta functions essentially unchanged

- Disadvantage
  - Changes the geometry of the ring or requires extra bending

Dispersion suppressor: Missing Dipoles

RCS1 900 GeV – 1 super-cell



Pulsed dipole:
-0.5 T -> -5 T

Dispersion suppressor: Extra Quadrupoles

2. Extra Quadrupoles

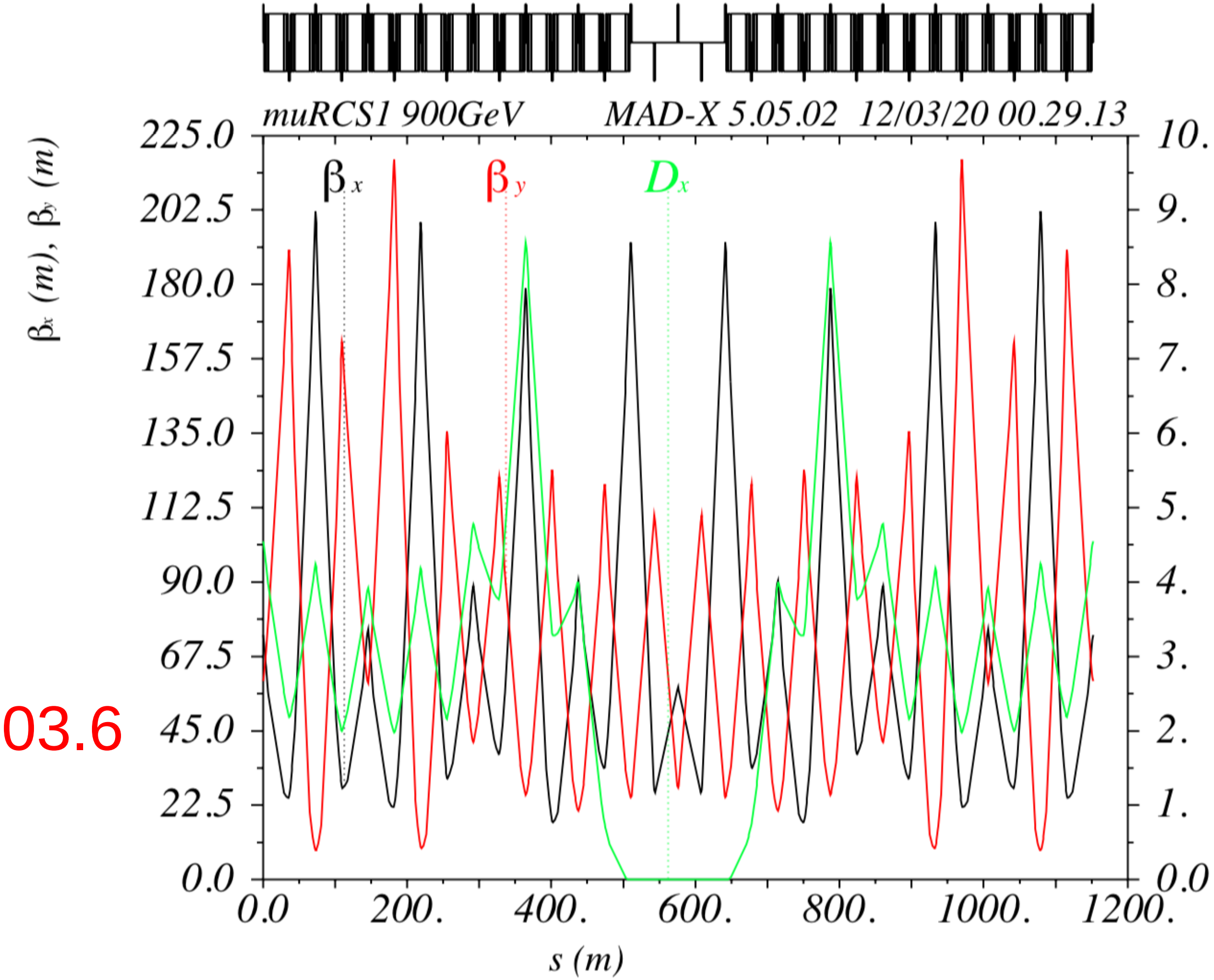
- **Vary the strength of 8 quadrupoles in each half super-cell**

- **Advantage**
  - **Ring geometry doesn't change**

- **Disadvantages**
  - **Increased beta functions**
  - **Individually powered quadrupoles**

Dispersion suppressor: Extra Quadrupoles

RCS1 900 GeV – 1 super-cell



Dispersion

Max Quad strength = 103.6 T/m

Conclusions

- **Utilized existing SPS tunnel which reduces costs**
- **Showed that acceleration of muons from 100 GeV to 1.5 TeV can be achieved with two RCS rings in the SPS tunnel**
- **Provided a lattice design with zero dispersion straights**

Longitudinal Dynamics and Collective Effects

Longitudinal Dynamics

- **Longitudinal dynamics simulations**
  - **From the repetition rate of main magnets:**
    - **Obtain RF voltage required per turn**
    - **Determine muon survival**
  - **Calculate time varying parameters:**
    - **Space charge tune shift**
    - **“Luminosity” of counter-rotating beams**
    - **Beam-beam parameter**

- **Assumptions:**
  - $\boldsymbol{N = 10^{12}}$ **muons per bunch**
  - $\boldsymbol{\epsilon_{x,y} = 25\,\pi\ \mathrm{mm\ mrad}}$
  - $\boldsymbol{\langle \beta_{x,y} \rangle \approx 60\ \mathrm{m}}$

Longitudinal Dynamics

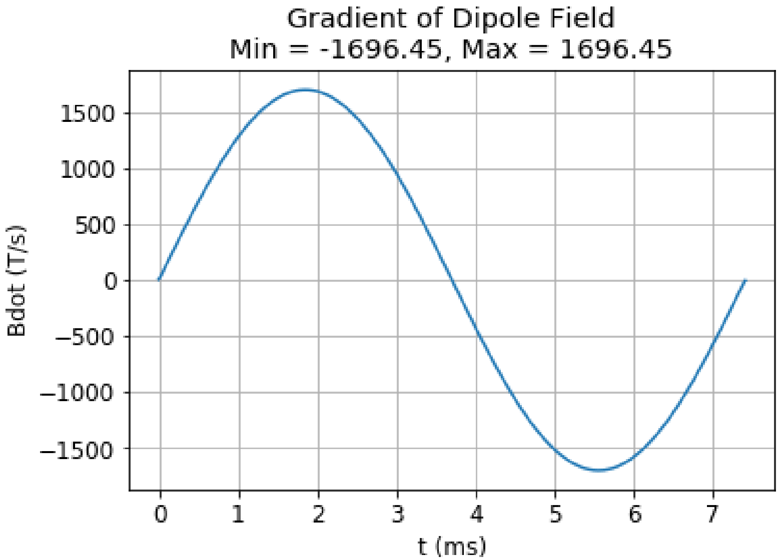
Dynamics synchronous to the rate of change of magnetic flux – the main magnet ramp.

$$B_{\text{fixed–field}} = \text{constant}$$

$$B_{\text{fast–ramping}} = -B_0 \cos(2\pi f_{\text{rep}} t)$$

$$\dot{B} = \frac{dB}{dt}$$

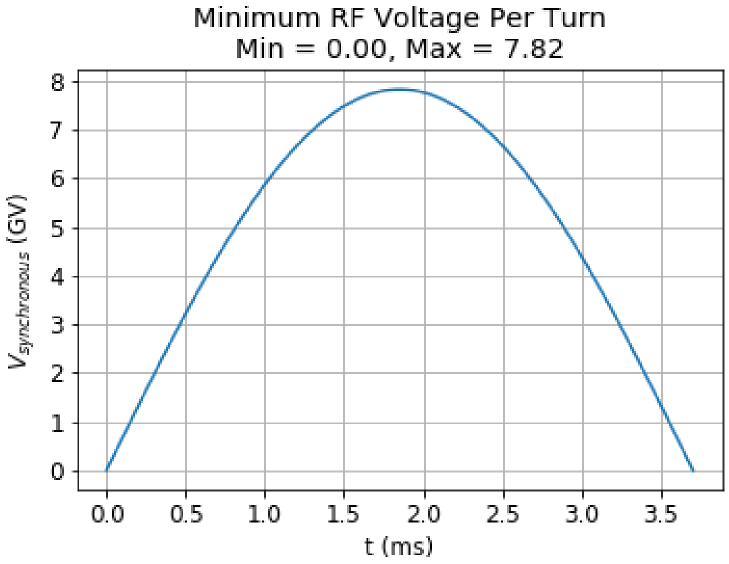
Only linked to ramping magnets

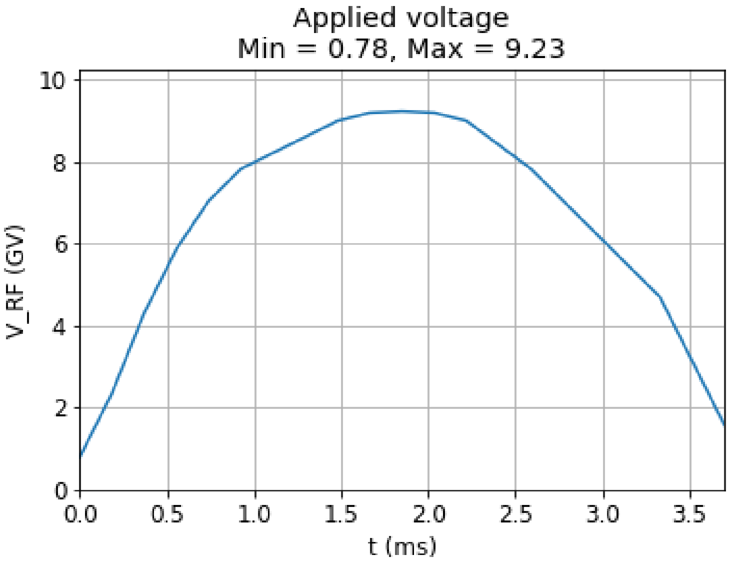


Longitudinal Dynamics

- **As magnet current ramps:**
- **Beam energy must increase to keep beam on design orbit**
- **Minimum RF voltage per turn for ideal synchronous particle**

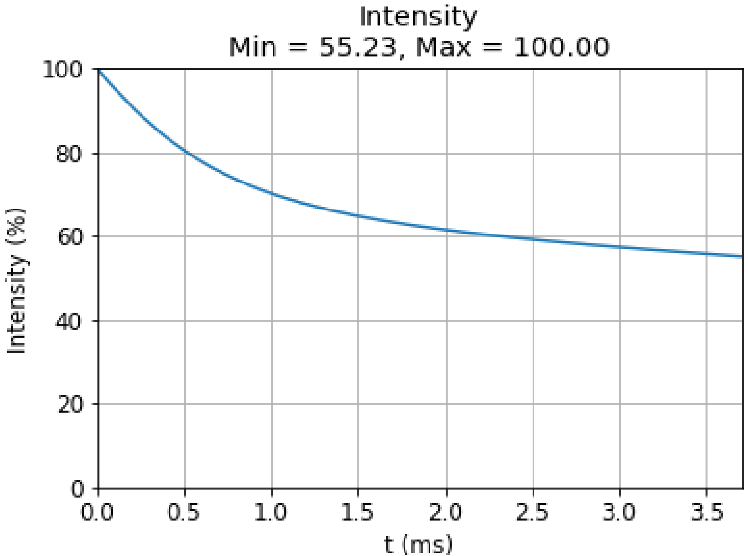
- **In reality, need more than this to create potential well in which to store accelerating particles**


Minimum RF Voltage Per Turn
Min = 0.00, Max = 7.82


Applied voltage
Min = 0.78, Max = 9.23

RCS1

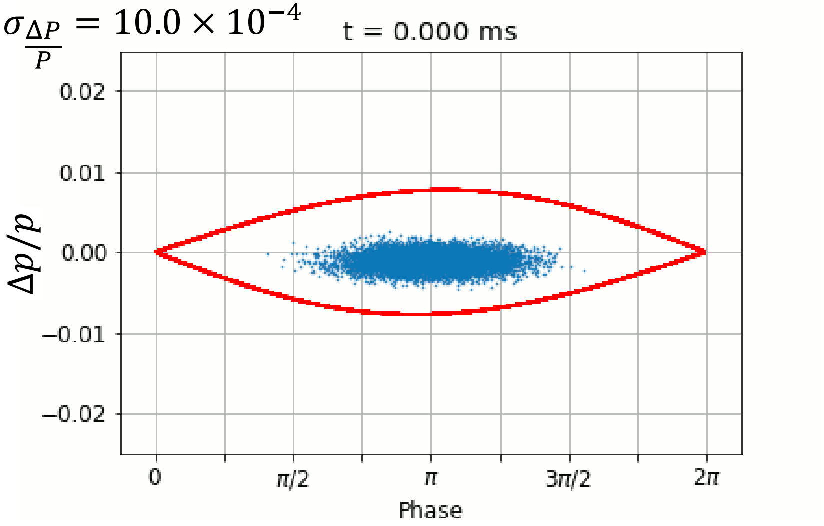
Injection energy	100	GeV
Extraction energy	900	GeV
Repetition rate	135	Hz
Time in lab frame	3.704	ms
Time in beam frame	1.304	μs
Number of turns	161	
Muon survival	55.2	%
Bucket losses	>0.1	%
Mean rev. frequency	43.373	kHz
$\Delta f_{revolution}$	2.4e-5	kHz
RF Harmonic	29 973	
RF frequency	1300.011	MHz
Max RF voltage / turn	9.23	GV



At $t = 0$ ms

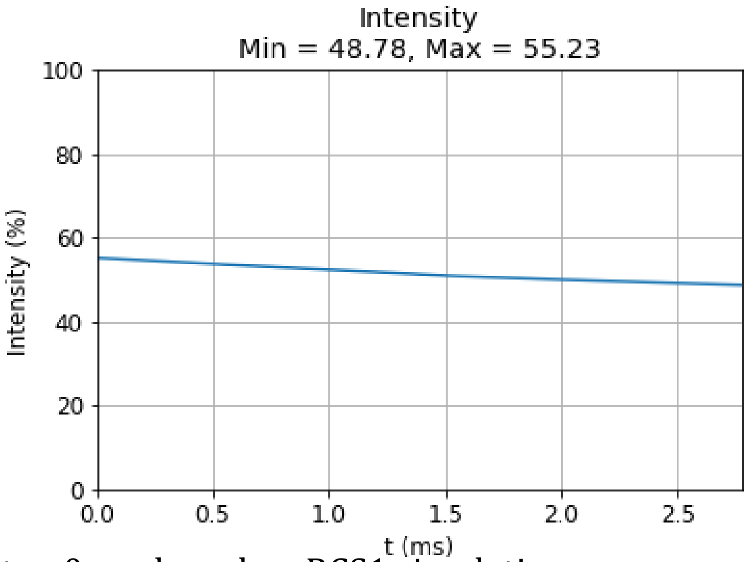
$\sigma_\phi = 0.15\,\pi$

$\sigma_{\frac{\Delta P}{P}} = 10.0 \times 10^{-4}$



RCS2

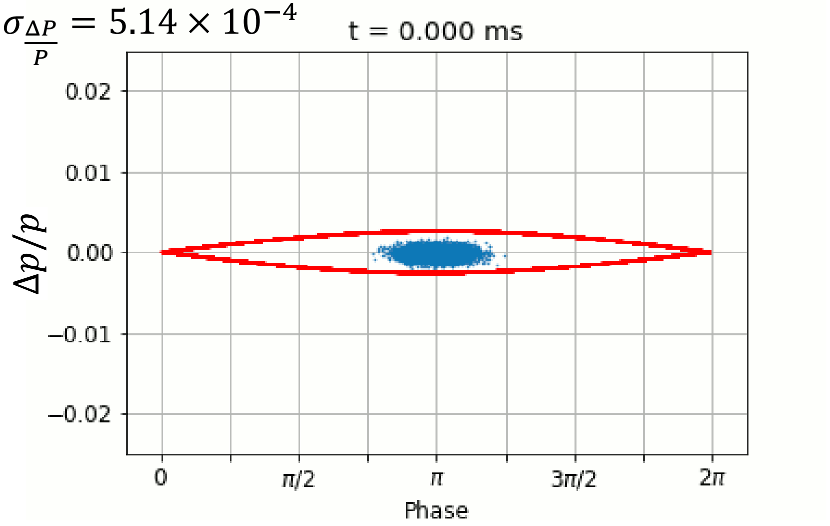
Injection energy	900	GeV
Extraction energy	1500	GeV
Repetition rate	180	Hz
Time in lab frame	2.778	ms
Time in beam frame	0.253	μs
Number of turns	108	
Muon survival	89.1	%
Bucket losses	0.9	%
Mean rev. frequency	43.373	kHz
$\Delta f_{revolution}$	1.9e-7	kHz
RF Harmonic	29 973	
RF frequency	1300.011	MHz
Max RF voltage / turn	9.23	GV



At $t = 0$ ms, based on RCS1 simulation

$\sigma_\phi = 0.0615\,\pi$

$\sigma_{\frac{\Delta P}{P}} = 5.14 \times 10^{-4}$



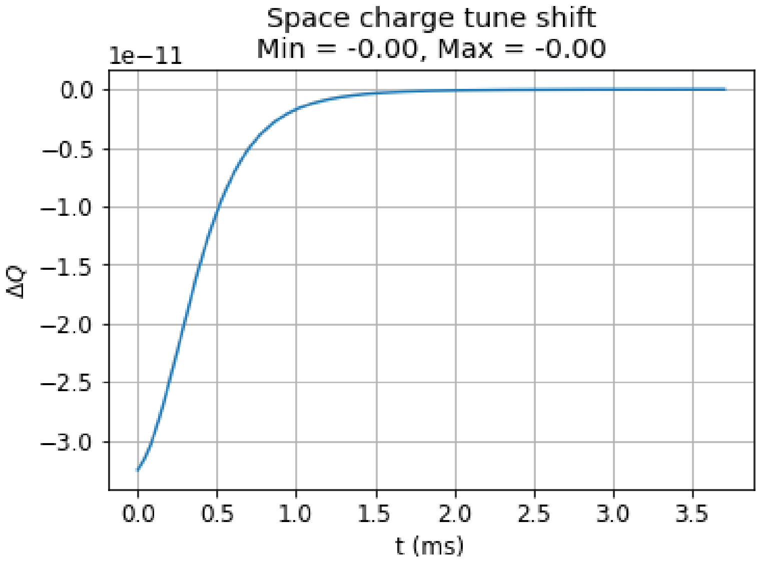
Space charge in RCS1

Transverse

Linear tune shift:

$$\Delta Q = -\frac{r_0 N}{2\pi\epsilon_{x,y}\beta^2\gamma^3}$$

Negligible

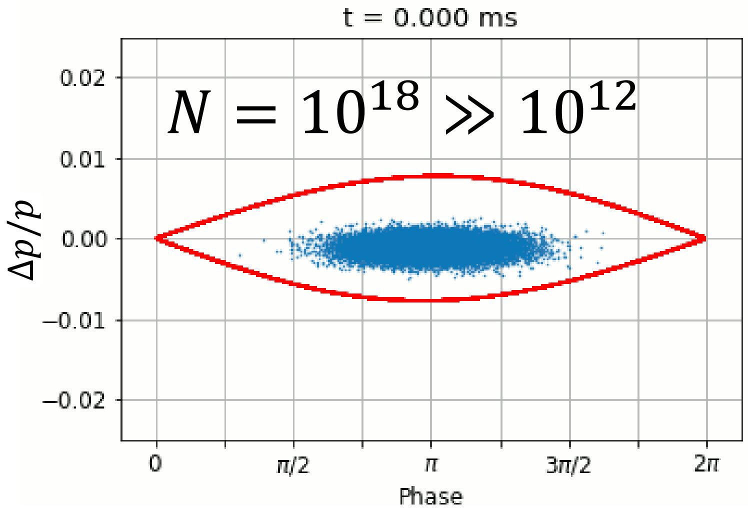


Longitudinal

Voltage drop per turn:

$$\Delta U = -e\beta cR\frac{\partial\lambda}{\partial s}\left[\frac{g_0 Z_0}{2\beta\gamma^2} - \omega L\right]$$

Negligible until $N > 10^{17}$



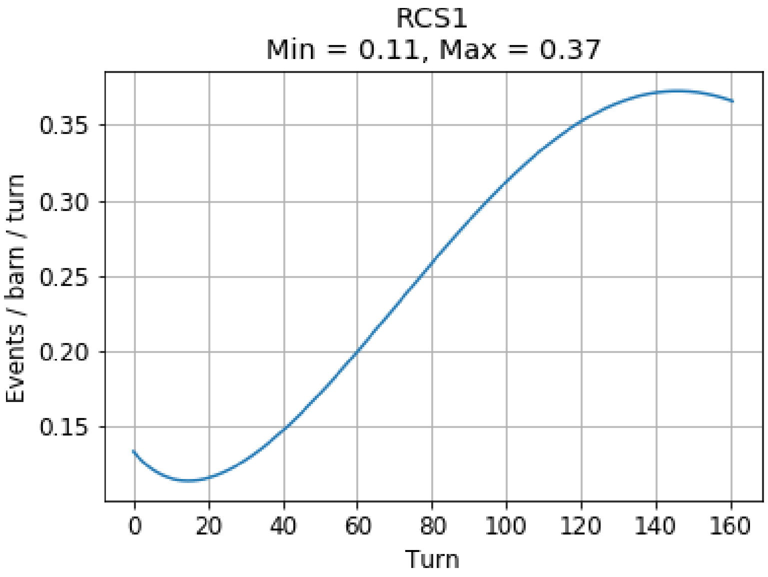
$N = 10^{18} \gg 10^{12}$

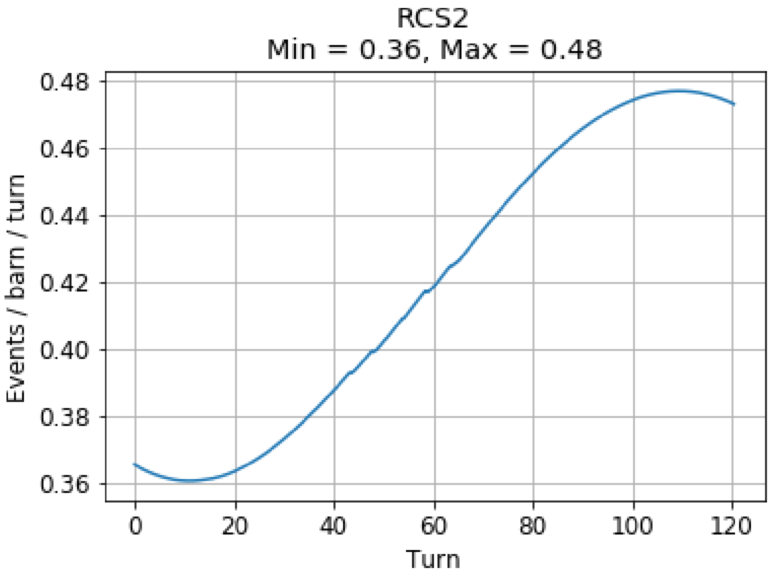
Counter-rotating beams

Collisions between counter-rotating beams of μ^+ and μ^- should not cause significant losses. Beams are not focussed and accelerate over a very quick time scale.

$$\text{Events per turn} = L \cdot T \cdot \sigma_\mathrm{X} = \frac{N_1 N_2 f_{rev} N_B N_{IP}}{4\pi\sigma_{x,y}^2} \cdot \frac{1}{f_{rev}} \cdot \sigma_\mathrm{X}(E)$$

$$\text{Events per turn} = \frac{(N_0 \exp(-t/\tau))^2 N_B^2}{4\pi\sigma_{x,y}^2(E)} \cdot \sigma_\mathrm{X}(E)$$





Counter-rotating beams

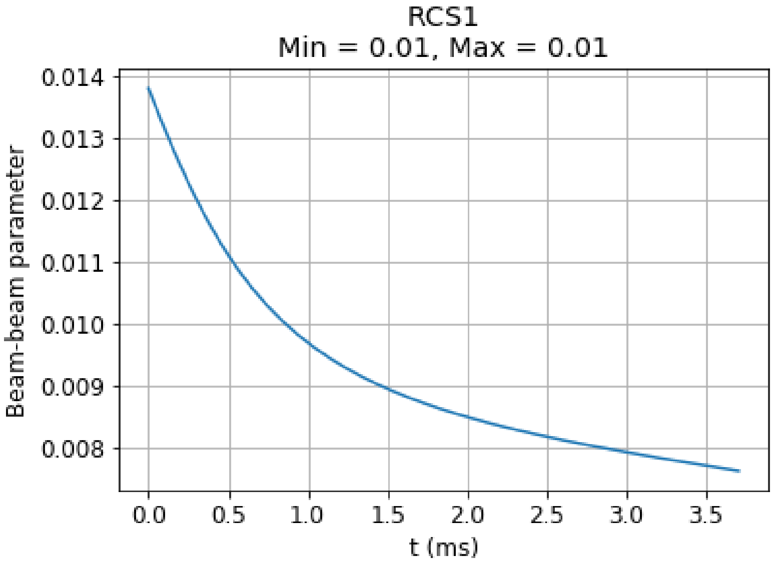
Beam-beam effects:

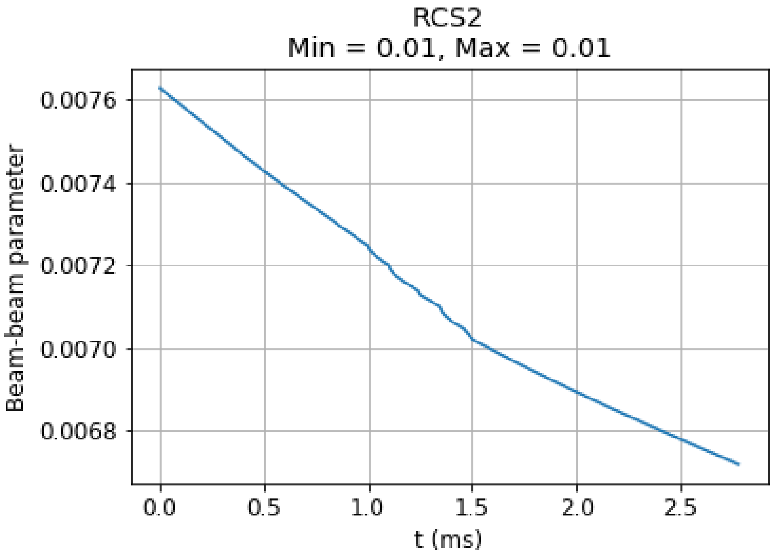
$$\xi = \frac{r_0 N \beta_{x,y}}{4\pi\gamma\sigma_{x,y}^2} < 0.014$$

$$\xi_{LHC} = 0.0037^{\dagger}, \qquad \tau_{bb} = 55 \text{ hours}^{\ddagger}$$

† Beam-beam effects, Werner Herr, Cockroft Institute Lectures

‡ LHC Beam Parameters, Mike Lamont, LHC Collimation Project


RCS1
Min = 0.01, Max = 0.01


RCS2
Min = 0.01, Max = 0.01

Conclusion

- **RF voltage is minimized while keeping losses low**
  - **Can be optimized further**
- **First order collective effects are negligible**
  - **Proper simulation studies should be carried out to determined effects of counter-rotating beams**

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UNIVERSITY OF OXFORD

RCS Cavity Design

Student Design Project

Max Topp-Mugglestone

Laurence Wroe

RF Requirements

Main factors affecting RF design:

- **A large voltage gain (for μ-decay):**
  - **Maximise acceleration gradient**
- **Low cost/power**
- **NC or SC**
- **Available technology/frequency**
- **Space available**
  - **Radially limited by SPS tunnel**

Super-Conducting vs Normal-Conducting

- **Large amount of RF operated at high-gradient, high duty factor**
  - **Need to maximise power efficiency**
    - **Effective limit on CW NC cavities ~2MV/m**
    - **High gradient NC structures limited to <1% duty**
- **SC enables larger aperture**

- **Disadvantages of SC:**
  - **Refrigeration requirements**

Frequency Choice

- **Choose standard frequency to enable use of off-the-shelf powerline components**
  - **352 MHz (LEP)**
  - **704 MHz (RHIC electron cooling ring)**
  - **1.3 GHz (ILC)**

Frequency choice

- **Cavity diameter scales as 1/f**
  - **Large amount of RF required (material requirements)**
  - **Limited space available (~90cm between RCS1 beam pipe and RCS2 beam pipe)**
- **Available aperture scales as 1/f too**
  - **Need to ensure cavity bore is wide enough to fit the beam!**
  - **Wider beam pipe reduces wakefield effects**

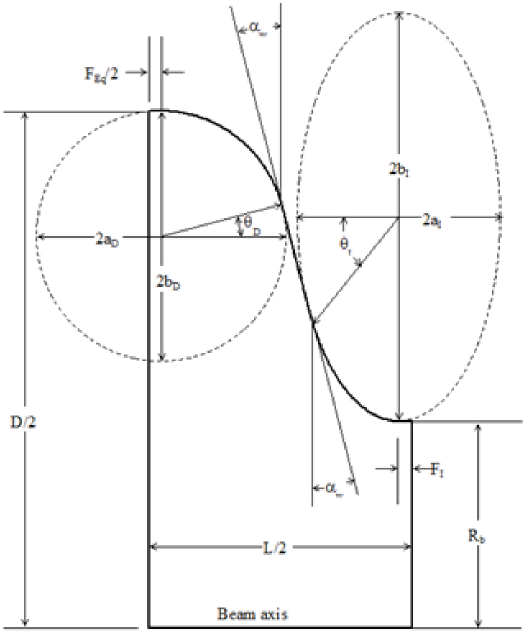
Frequency choice

Freq [MHz]	Cavity Radius [cm]	Bore radius [cm]
352	37.55	10
704	18.98	3
1300	10.25	2

1300 MHz is the best option!

Cavity Optimisation

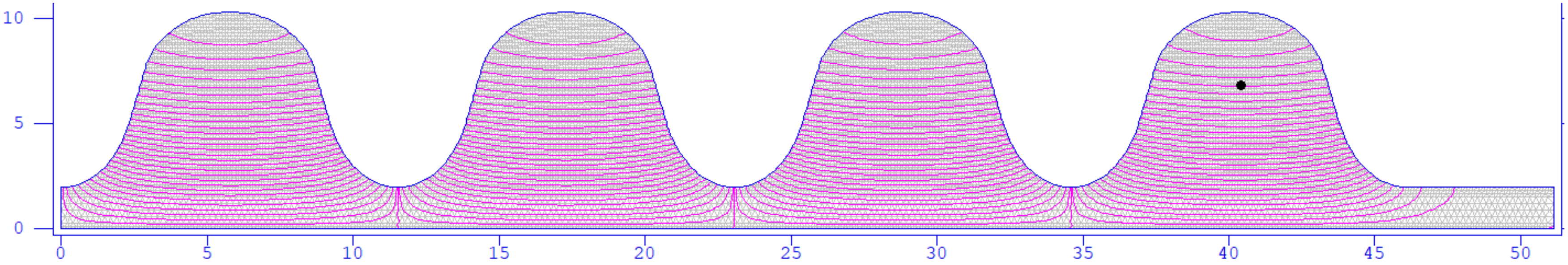
- **Goals:**
  - Minimise peak fields
  - Minimise Bmax/Emax and Emax/E0
  - Minimise power losses
  - Maximise field flatness
- **Input variables**
  - Dome ellipse axes
  - Iris ellipse axes
  - Wall angle
  - Bore radius

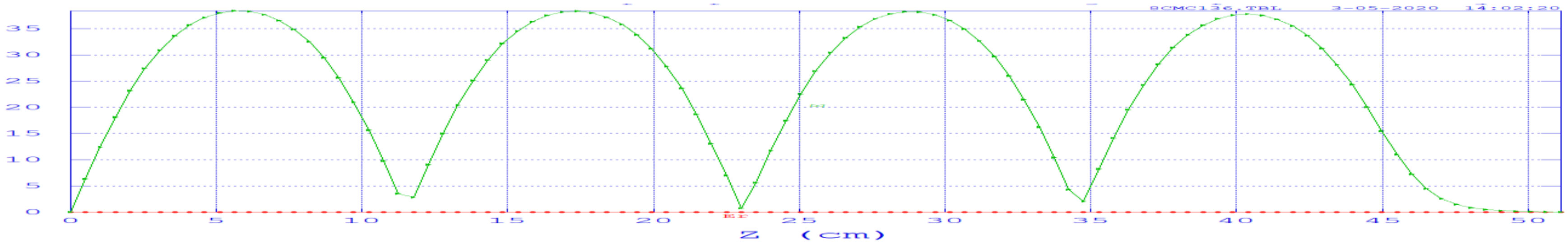


Cavity Optimisation

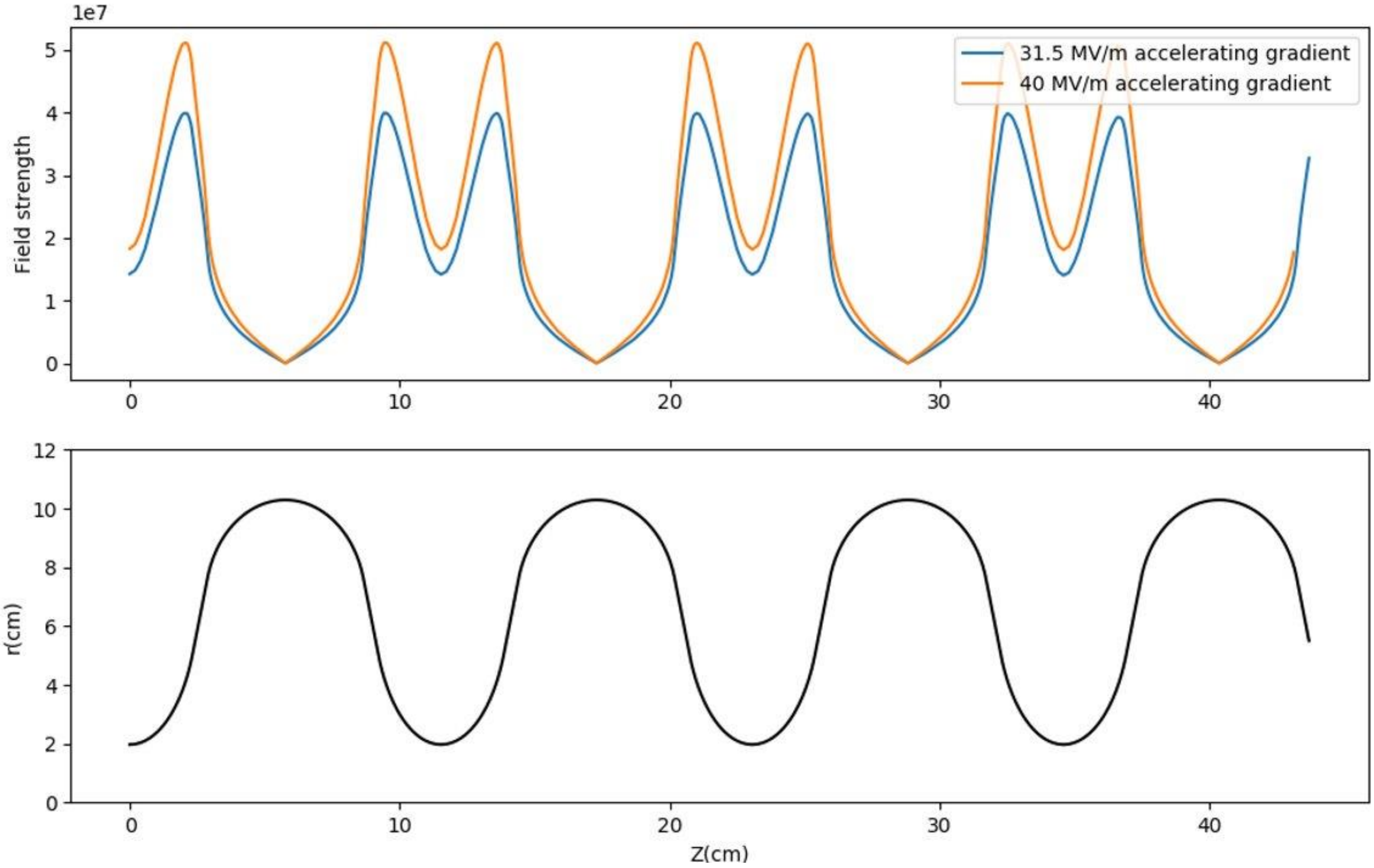
- **Our design:**

Cavity name	Length [cm]	Radius [cm]	Q [e+11]	R_s/Q [Ω/m]	B_{max}/E_{max} [mT/(MVm^{-1})]	E_{max}/E_0	Power dissipated (W)
1300 MHz 8 cell cavity	92.24	10.29	0.0826	221	2.7051	1.2690	18.3563
TESLA (from SFISH)	143.57	10.33	0.101	272	2.09	2.04	67.34
TESLA (9 cell cavity data)	127.6	10.33	>0.05	518	4.26	2.0	1400

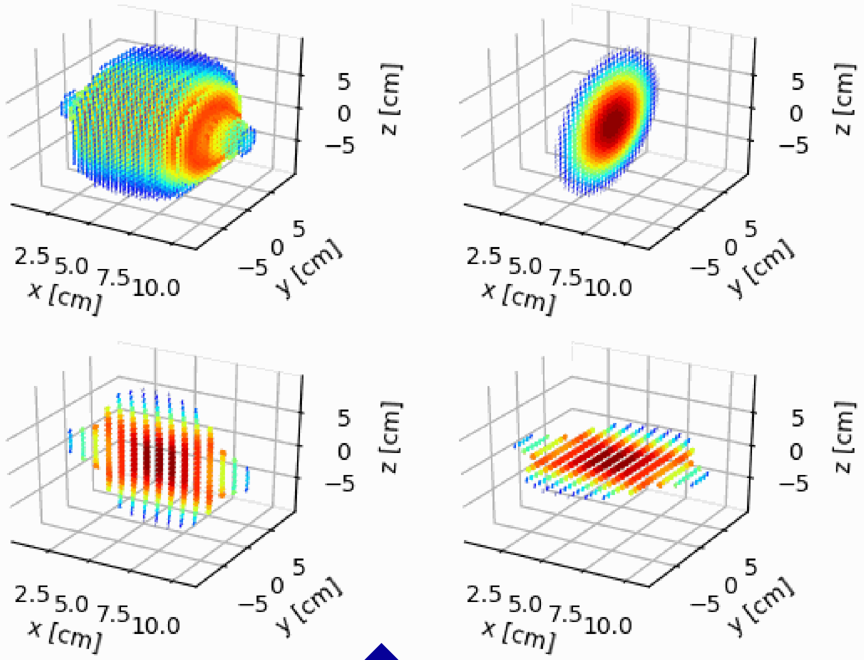


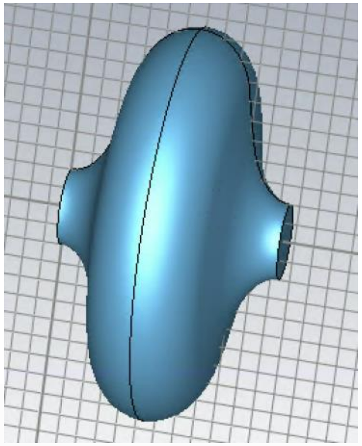


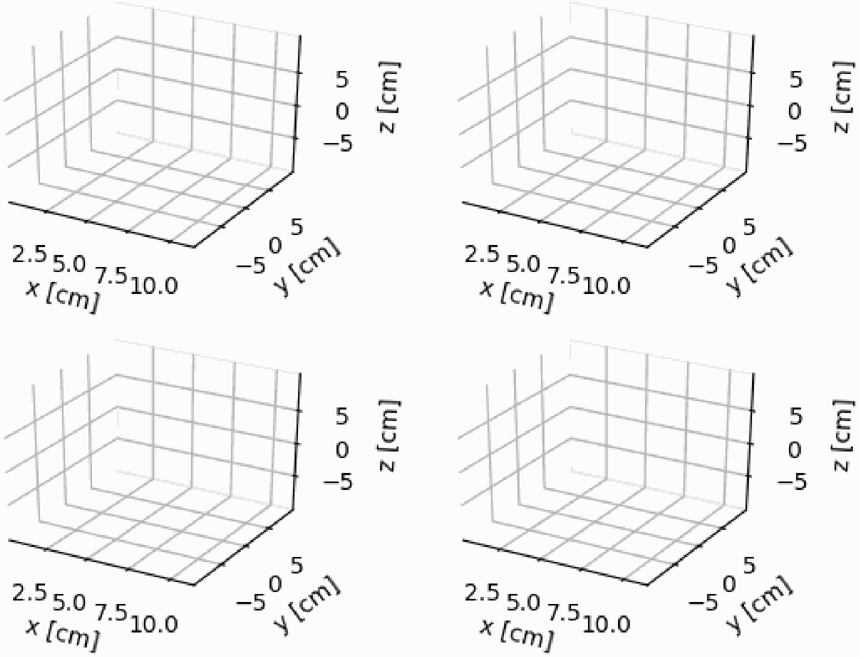
Cavity Gradient Studies



3D design in CST – Single Cell

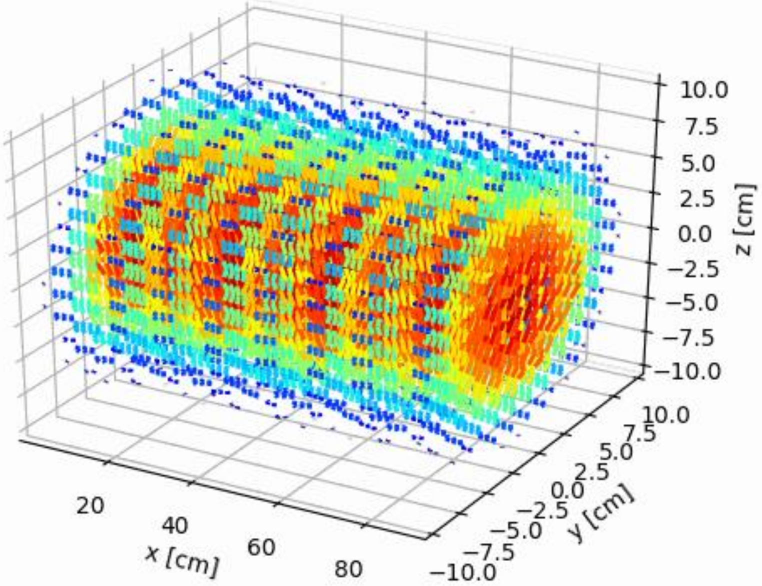


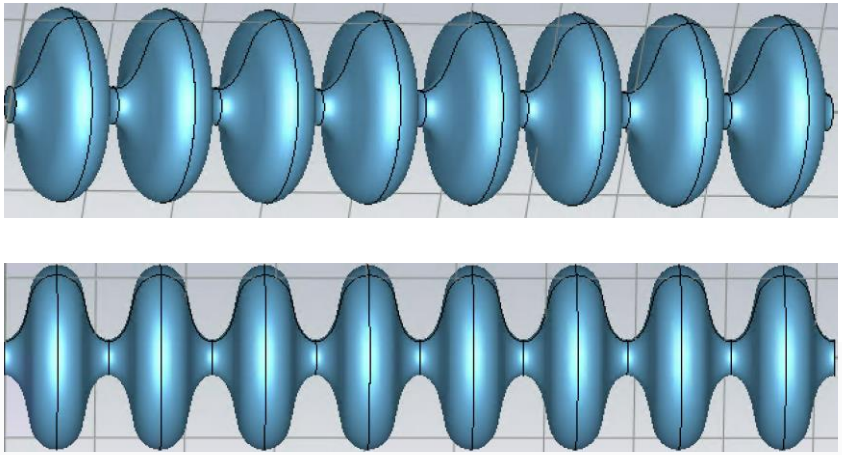


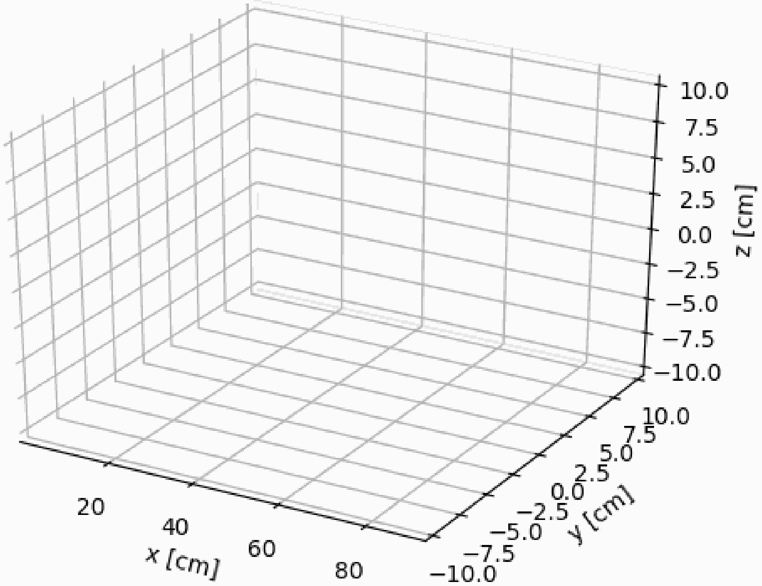


- E-field
- H-field

3D design in CST – 8 Cell

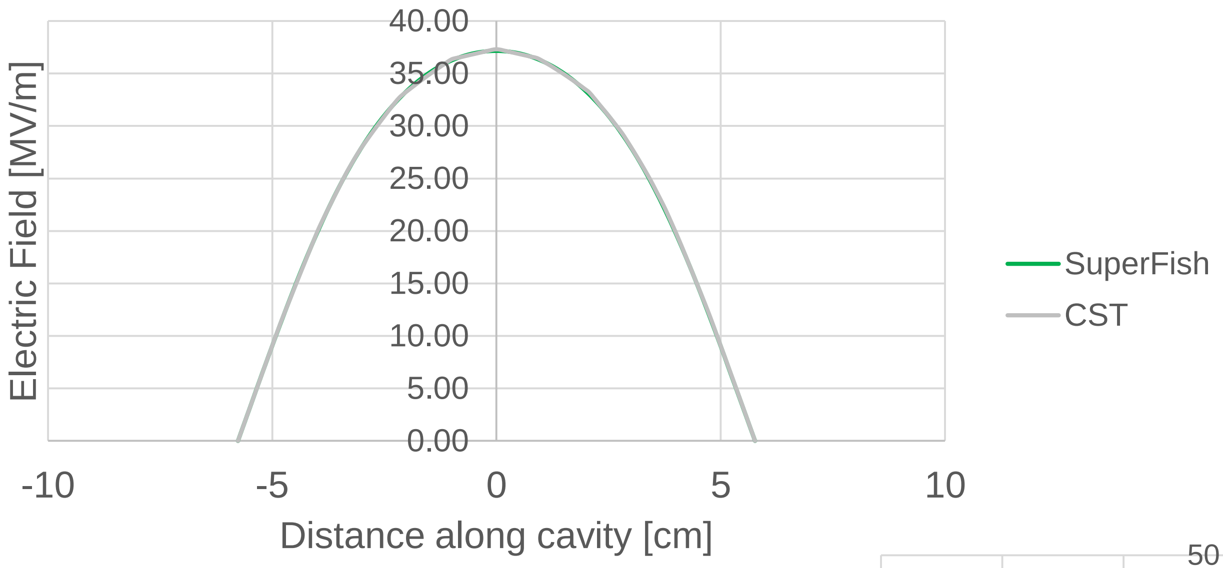




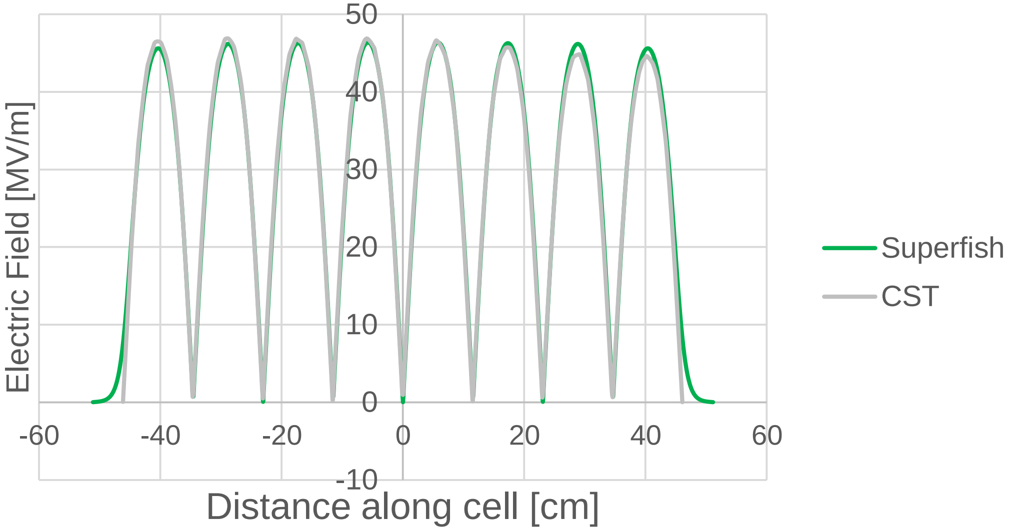


- E-field
- H-field

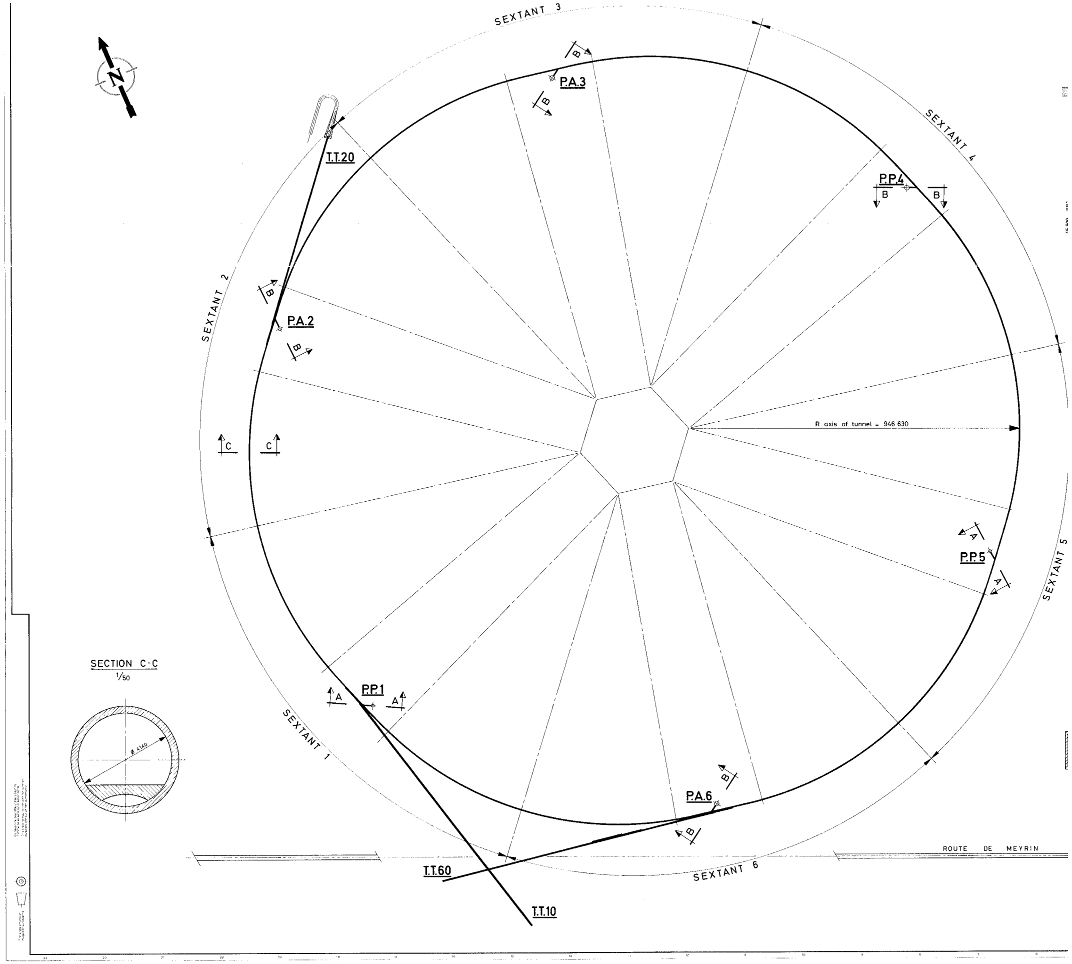
Superfish to CST Comparison



- Similar flatness
- Add in beam pipe to improve!

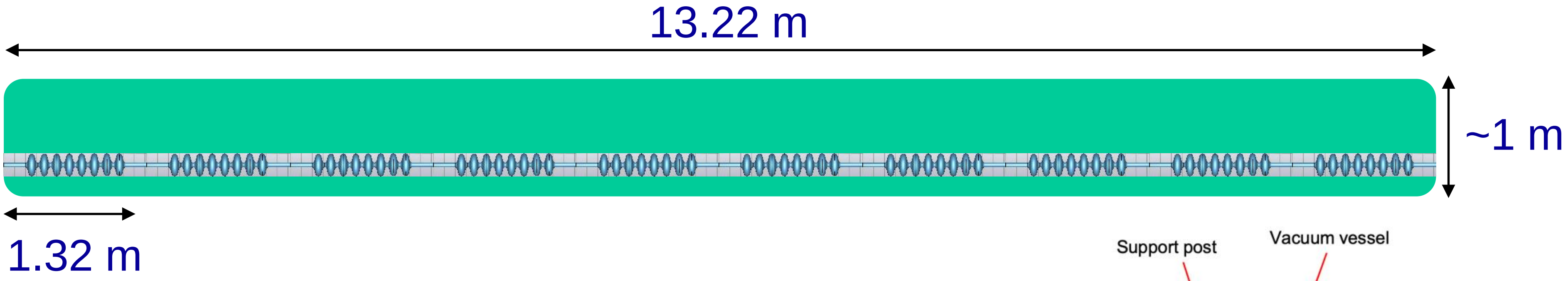


Dimensional constraints

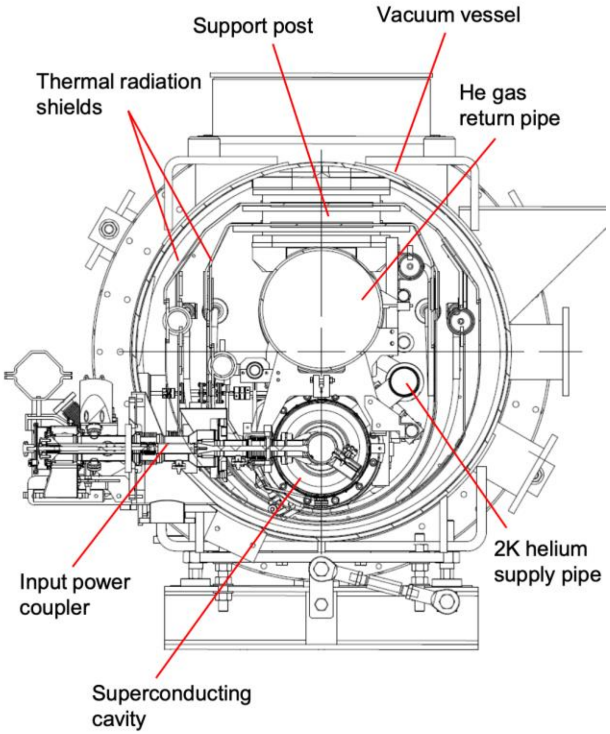


- **6.9km circumference**
- **6 straight sections**
  - **Each 131m**
- **6 arcs**
  - **Each ~1km**

Cryomodule Design



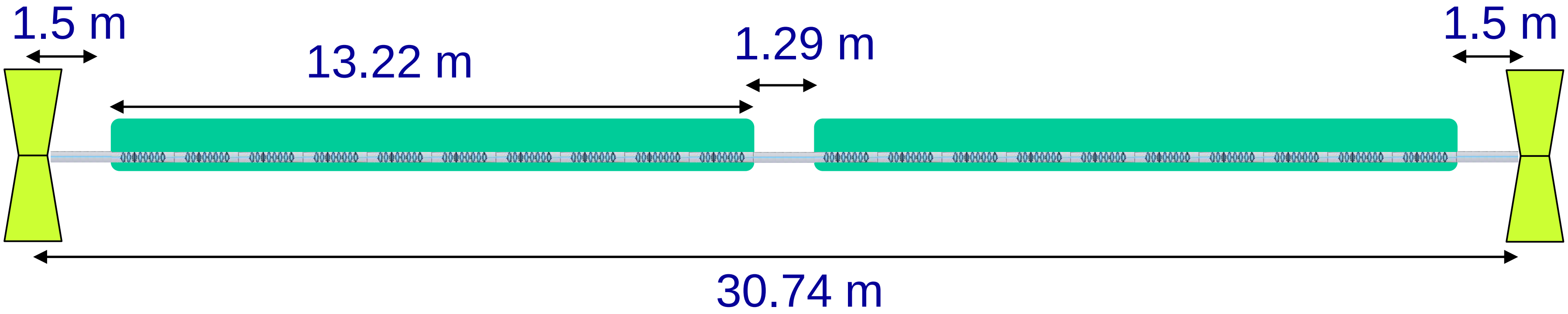
- 10 8-cell cavities in one cryomodule
    - Maximises packing factor
- Packing factor of cryomodule is 69.7%
- Thorough cryomodule design not complete…!



DESY-TESLA-TYPE-III Cryomodule Cross Section

RF Design

- **6 straight sections of L = 131 m**
- **Quads separated by 30.74 m**



- **Actual packing factor: 60%**
- **Voltage gain per 30.74 m section: 581 MV**
- **V gain per turn (4/6 straights): 9.3 GV**
- **Have 1 straight for injection, 1 for extraction – achieves required 9.23 GV**

Luminosity Considerations

$$\mathcal{L} = \frac{c}{4\pi}\,\frac{\gamma}{l}\,\frac{N_1 N_2}{\varepsilon_N \beta^*} \Longrightarrow \frac{c}{4\pi}\,\frac{\gamma}{l}\,\frac{1}{\varepsilon_N \beta^*} N_{0_{\mu-Coll}}^2\, e^{-\frac{2t}{\gamma t_\mu}}$$

$$\boxed{\langle\mathcal{L}\rangle = \frac{c}{4\pi}\,\frac{\gamma}{l}\,\frac{1}{\varepsilon_N \beta^*}\,\frac{\gamma t_\mu}{2}\,\frac{1}{t_b} N_{0_{\mu-Coll}}^2}$$

$$\therefore N_{0_{\mu-Coll}} = 2.36e12$$

Using $N_0^{MAP} = 2e12 \quad \Longrightarrow \quad \boxed{P_{RCS1\to\mu-Coll} = \frac{N_{0_{\mu-Coll}}}{N_0^{MAP} P_{MAP\to RCS1}} = \frac{1.18}{P_{MAP\to RCS1}}}$

Where:

$\boxed{\langle\mathcal{L}\rangle = 2e34\ \mathrm{cm}^{-2}\mathrm{s}^{-1},}$ $\quad \gamma = \frac{1.5}{105.66}\,\frac{\mathrm{TeV}}{\mathrm{MeV}},$ $\quad l = 4500\ \mathrm{m},$ $\quad \varepsilon_N = 25\ \pi\,\mu\mathrm{m\ rad},$

$\beta^* = 0.5\ \mathrm{cm},$ $\quad t_\mu = 2.2\ \mu\mathrm{s},$ $\quad t_b = {}^{1}/_{12}\ \mathrm{s}$

Source: *Muon Colliders*, The Muon Collider Working Group – Input to the European Particle Physics Strategy

- **Proves maximization of muon survival in our acceleration is key: need closer to 100% than 1%!**
- **More work needed on the production and collider processes to maximise average luminosity**

Conclusion

- Literature review completed and suitable design identified
- High gradient (31.5 MV/m) cavity design has been demonstrated in Superfish and CST
- Allows fast acceleration (50% survival) from RCS1 to μ-collider

To Do:

- Detailed physics reach study needed
- Optimise in CST and adding in further components into design:
  - Detailed cryomodule design
  - HOM couplers
  - Power source and transfer design

Magnet Design

Titus-Stefan Dascalu
Adam Hughes
Wei-Ting Wang

Pulsed Dipole Design

Outline:

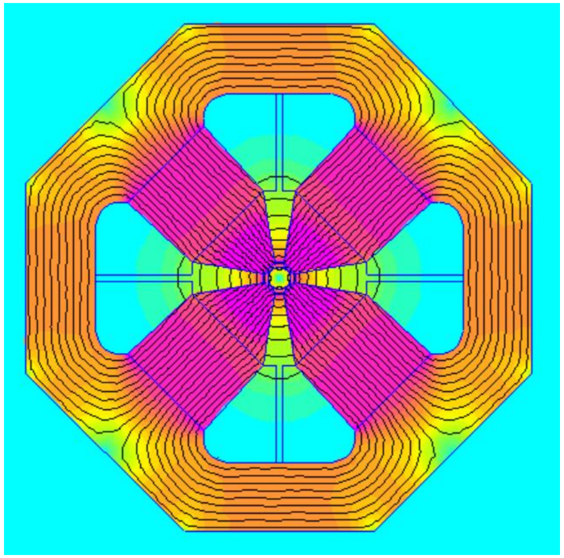
- Design Requirements
- Material Selection
- Dipole Geometry
- Field Strength
- Field Quality
- Power Consumption
- Conclusions

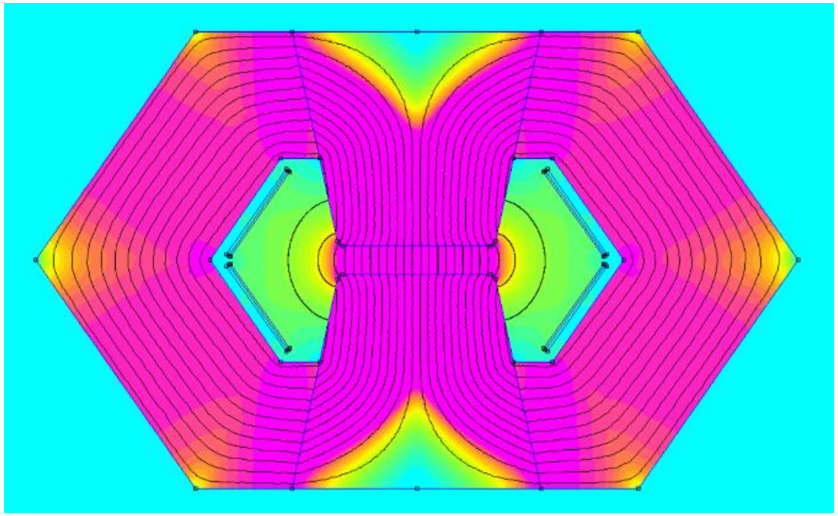
Design Requirements

- **Magnetic Flux Density of 2 T**
- **Field Quality**
  - **Condition for “good field” region: $\frac{\Delta B}{B} \leq 10^{-4}$**
- **Functionality**
  - **Work against superconducting dipoles at low energy**
  - **Work with superconducting dipoles at high energy**
  - **Max. ramp rate of 200 Hz**
- **Dimensions**
  - **Smaller than tunnel diameter of 1.2 m**
  - **Aperture width of 30 mm**
- **Power Consumption**
  - **Current density of 1.5 A/mm^2 for resistive power losses**
  - **Dipole power consumption in order of kW**

FEMM Simulations

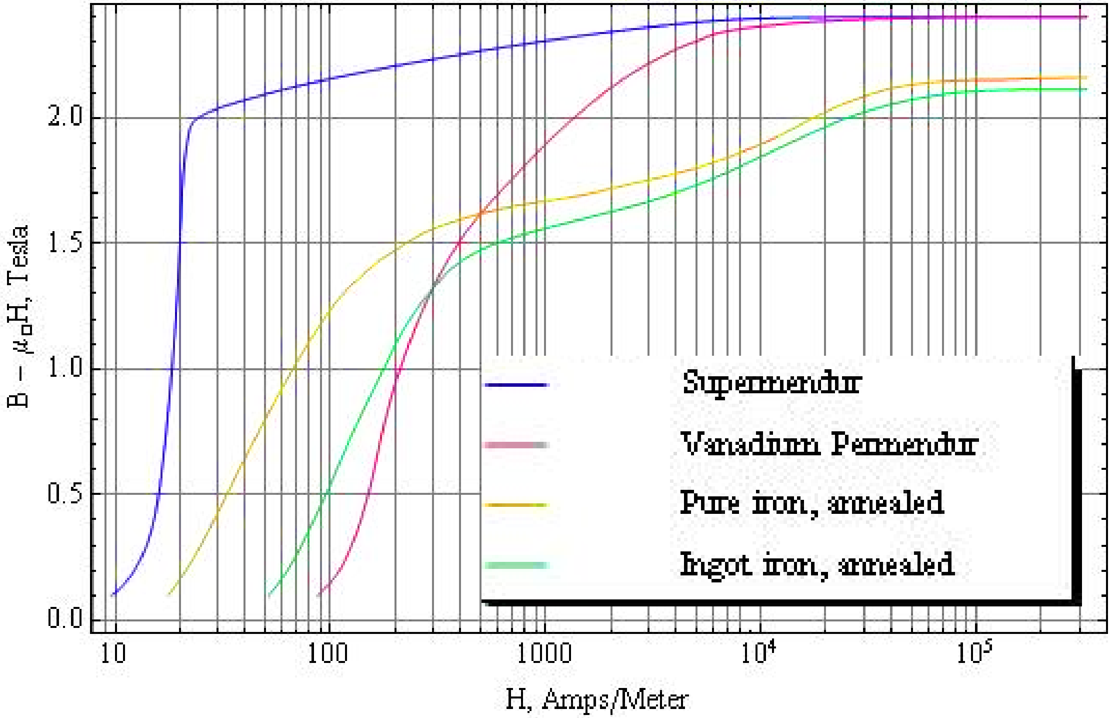
- **Finite Element Method Magnetics**
  - **2D planar domain**
  - **Low frequency**
  - **Linear/nonlinear magnetostatics**
  - **Linear/nonlinear time harmonic magnetics**





Material Selection

- **Material Options for Poles**
  - **Permendur: 50% Steel, 48% Cobalt, 2% Vanadium**
  - **Supermendur: 50% Steel, 48% Cobalt, 2% Purified Vanadium**
  - **M-15 Steel (SiFe): 96% Steel, 2-4% Silicon**



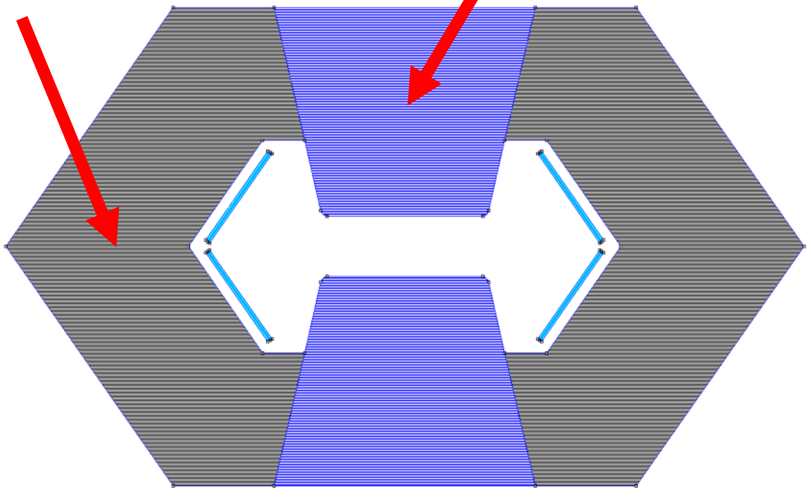
FEMM Magnetics, "DC Magnetization Curves of Soft Magnetic Materials," FEMM Magnetics, 15 June 2016. [Online]. Available: http://www.femm.info/wiki/SoftMagneticMaterials. [Accessed 8 March 2020].

Dipole - Geometry

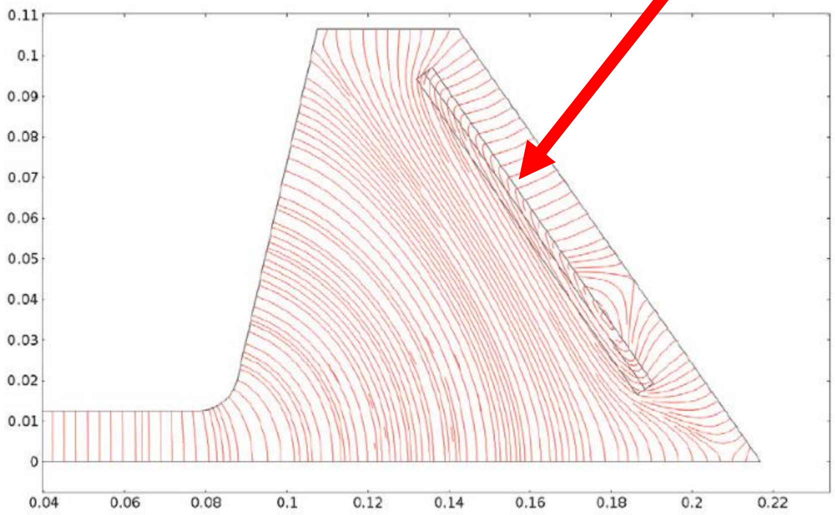
- **Model based on previous design[1]**
  - **Multiple materials**
  - **Coil config. minimizes eddy current losses**

Low losses at high freq.

High saturation field



Excitation coil



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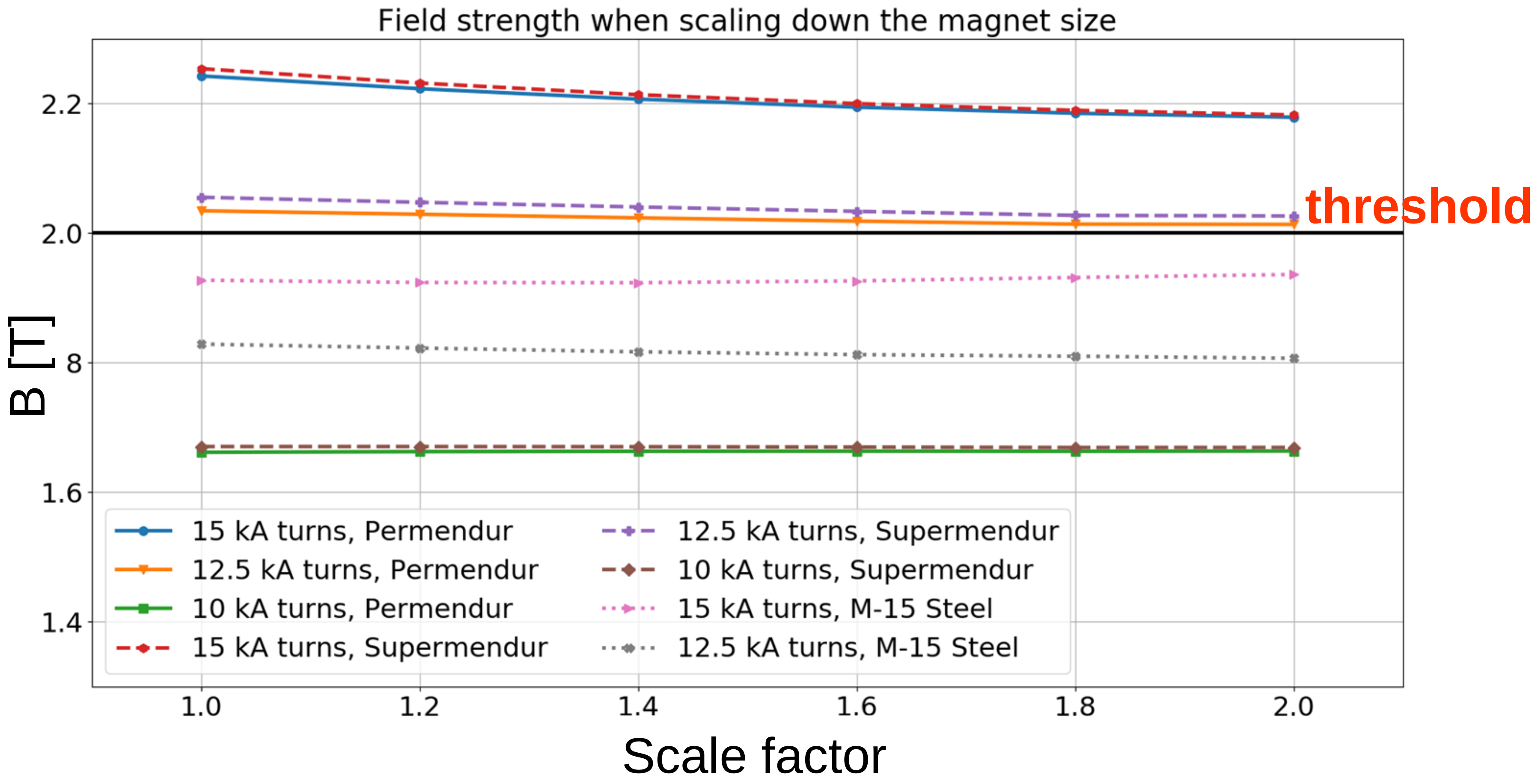
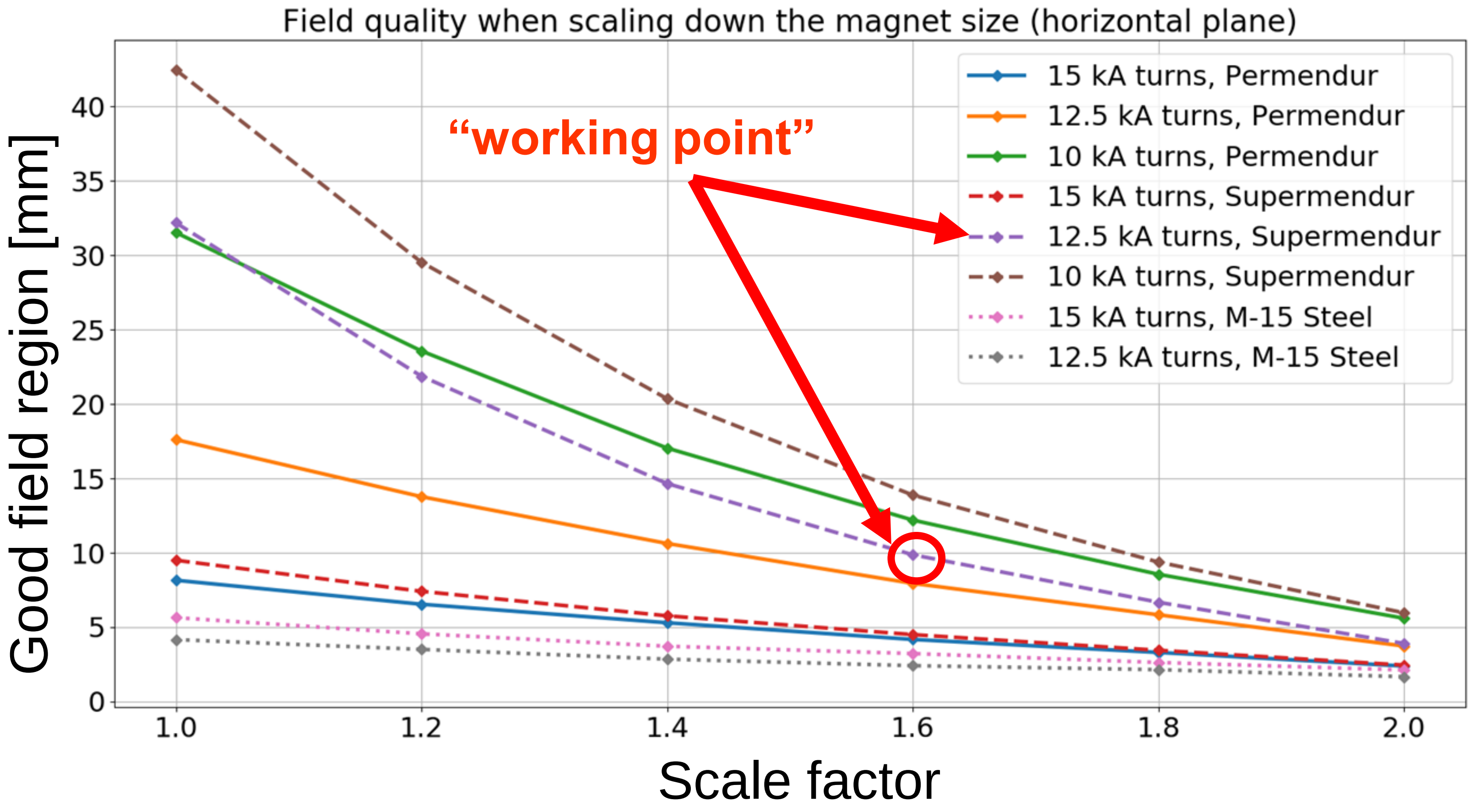
[1] Berg, J. Scott, and Holger, Witte. "Pulsed synchrotrons for very rapid acceleration". *AIP Conference Proceedings* 1777, no.1 (2016) https://doi.org/10.1063/1.4965683

Field Strength



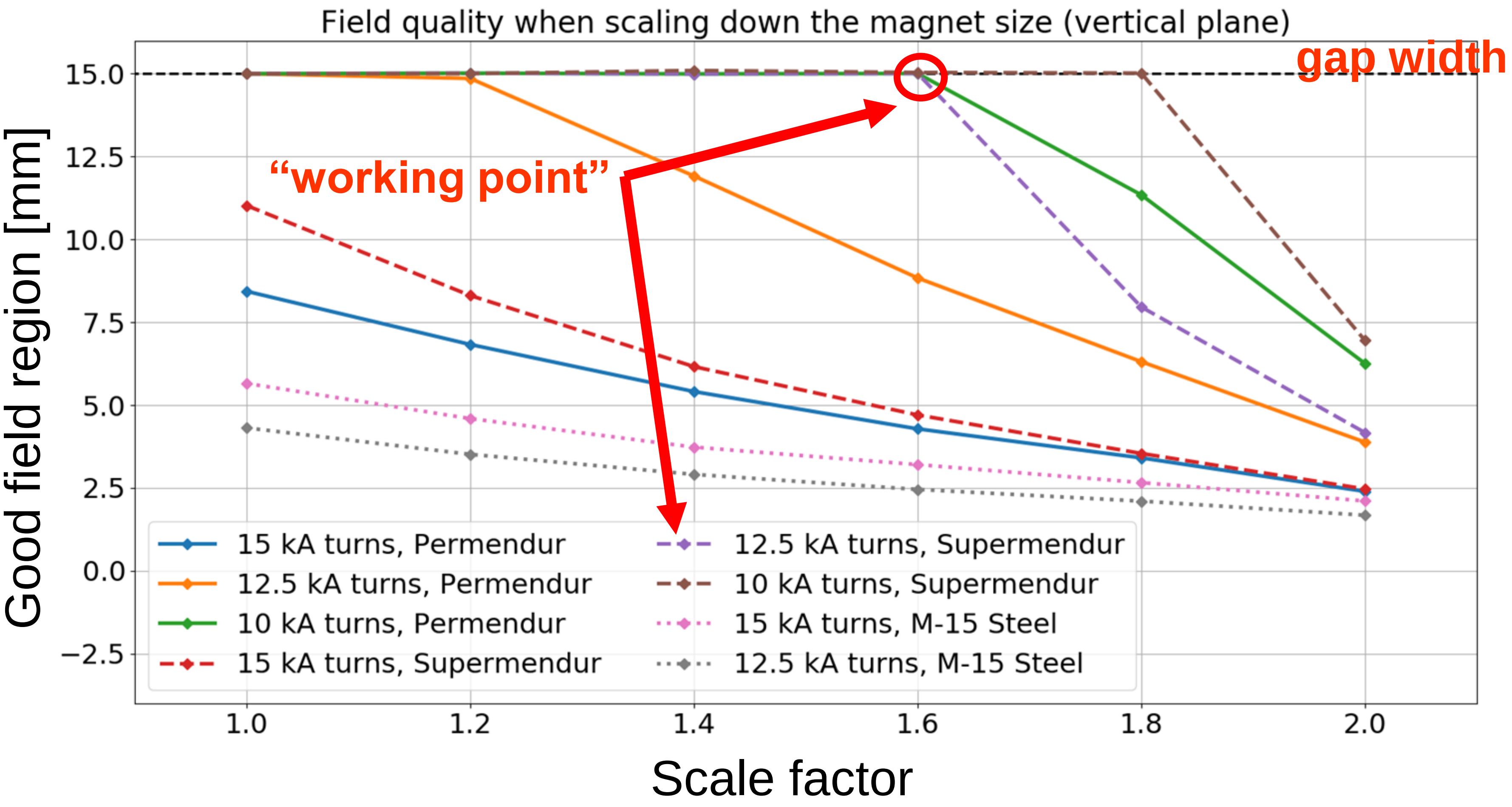
- **Small variation of field strength with dipole size**
- **Small difference between the proposed materials**

Field Quality – Horizontal Plane



- **Significant reduction in horizontal field quality with size**
- **Supermendur maintains the field quality better**

Field Quality – Vertical Plane



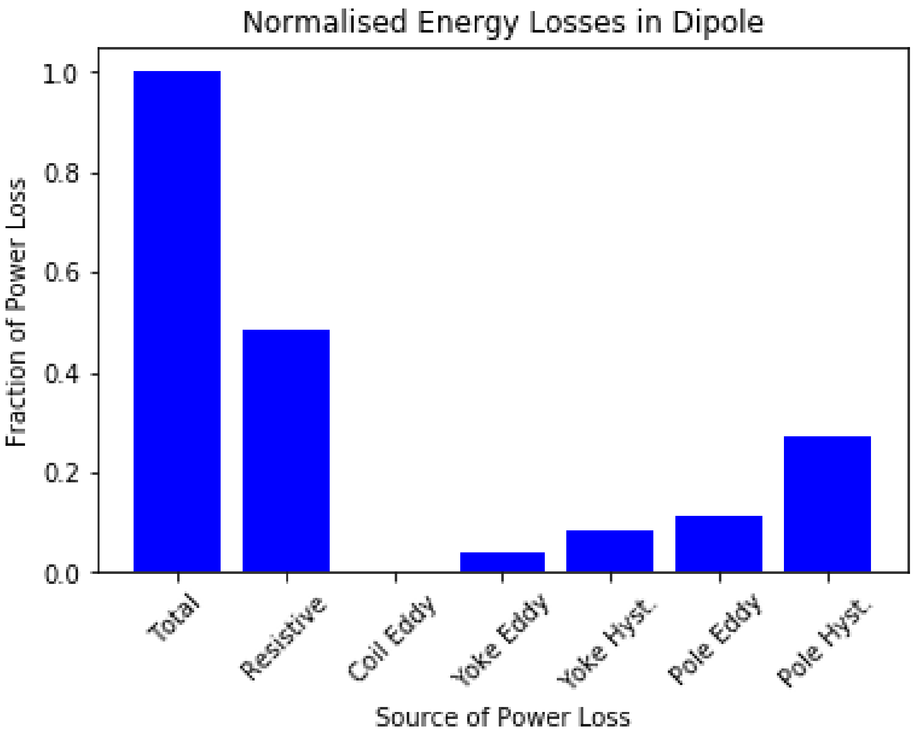
- **Vertical field quality less sensitive to size**
- **Supermendur maintains the field quality better**

Dipole – Final Design

Dipole specification	
Dimensions	500 x 300 mm^2
Gap size	30 mm
Maximum field B_{max}	2.0 T
Field quality at B_{max}	1 x 10^{-4}
Good field region (h x v)	20 x 30 mm^2
Number of bus bars	4
Current per bus bar	12500 A turns
Average peak current density cable	5.3 A/mm^2
Ramp rate	200 Hz

Power Consumption

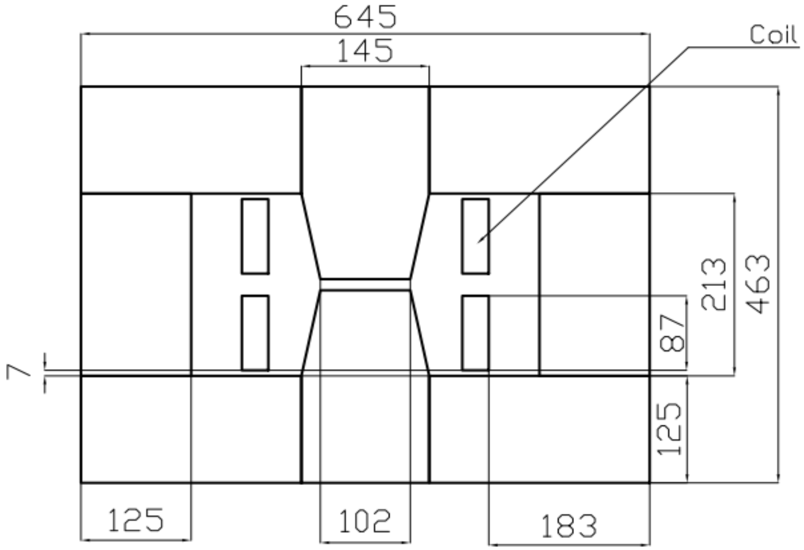
- **Overall Power Consumption**
  - **113 kW per dipole**
  - **23 MW consumption by entire system of dipoles**

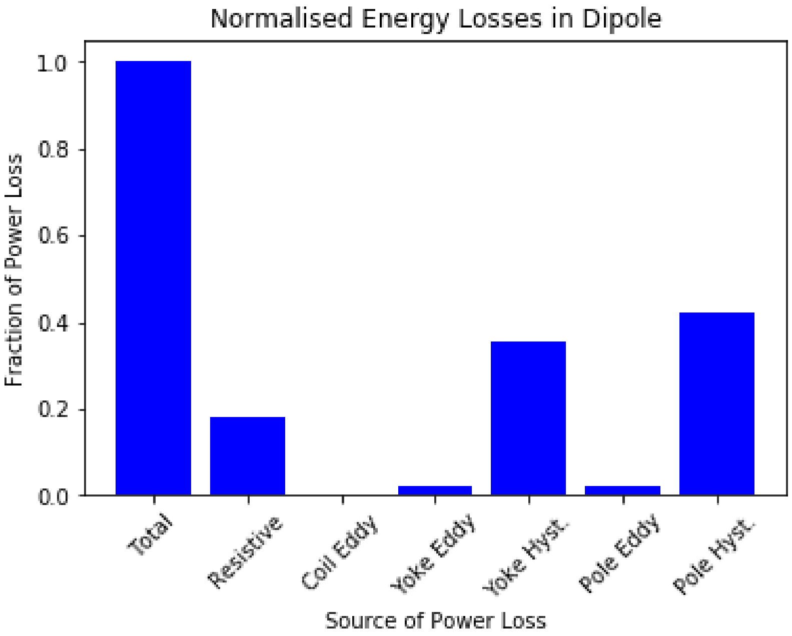


- **High resistive losses**
  - **Current Density of 5.3 A/mm^2**
  - **Limited space for wire with large cross-sectional area**
- **Low eddy current losses**
  - **Magnets arranged in stacked 0.27 mm laminate sheets[2]**
- **Low hysteresis losses**
  - **High proportion of permendur in regions of high magnetic field**

Power Consumption

- **Alternative Design[2]**





- **63 kW power consumption per dipole**
- **Higher eddy current and hysteresis losses**
- **Resistive losses of 6 kW per dipole**
  - **Copper mesh cross-sectional area can be as large as 8 cm^2**
  - **Current density of 1.5 A/mm^2**

[2] H. Witte, J. Berg, P. Kovach, M. Anerella and M. Lopes, "Rapid Cycling Dipole Magnet," in Proceedings of PAC2013, Pasadena, CA USA RAPID, Pasadena, 2013.

Mass Requirements

- **Main Design**

Material	Mass Required (One Dipole)/Tonnes	Mass Required (System)/Tonnes
Coils (Copper Wire)	0.11	22.71
Yoke (3% Si-Fe)	4.28	857.22
Poles (Supermendur)	4.11	823.43

- **Alternative Design**

Material	Mass Required (One Dipole)/Tonnes	Mass Required (System)/Tonnes
Coils (Copper Wire)	0.62	124.74
Yoke (3% Si-Fe)	10.91	2181.78
Poles (Supermendur)	3.87	775.46

Larger amounts of M-15 Steel and Copper wire required

Dipole – Conclusions

- **Magnetic Flux Density**
  - Magnetic flux density of 2 T achieved in FEMM

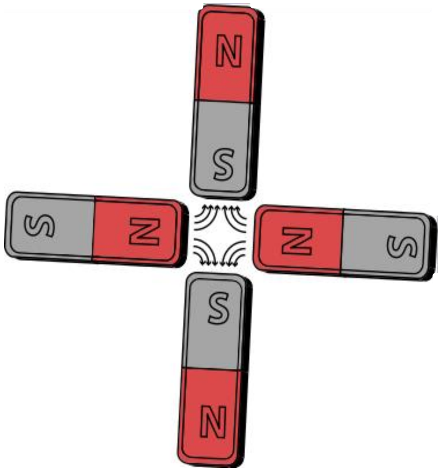
- **Field Quality**
  - Field quality of $\frac{\Delta B}{B} \leq 10^{-4}$ obtained with supermendur poles at 12500 A turns

- **Power Consumption**
  - 113 kW per dipole (23 MW total)
  - Limited by cross-sectional area of copper wire
  - Magnet size has been minimised to reduce power consumption and mass requirements

Quadrupole Magnets

Outline:

- Design Requirements
- Material Selection
- Design Layouts
- Performance
- Power Loss
- Conclusions



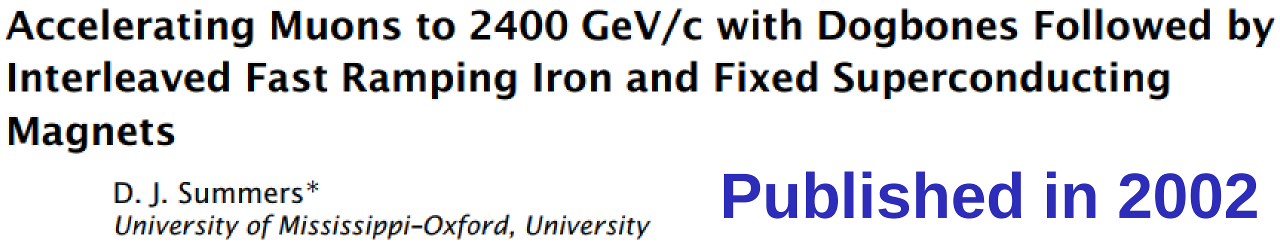
Design Requirements

Extra Quadrupole scheme

	Quads In RCS1	Quads in RCS2	DS quads in RCS 1	DS quads in RCS 2
Number	96	96	96	96
Ramping rate (Hz)	135	180	135	180
Aperture size (mm)	**38**	**28**	**38**	**28**
Gradient (T/m)	**57.6**	**96**	**57.6**	**103.6**

DS: dispersion suppression

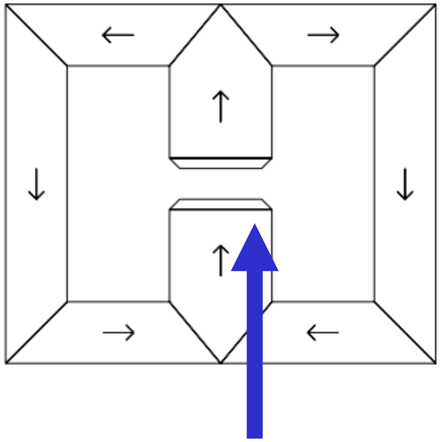
Material Selection



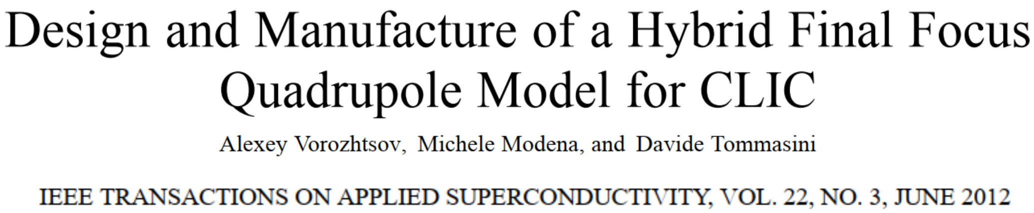
Accelerating Muons to 2400 GeV/c with Dogbones Followed by Interleaved Fast Ramping Iron and Fixed Superconducting Magnets

D. J. Summers*
University of Mississippi-Oxford, University

Published in 2002



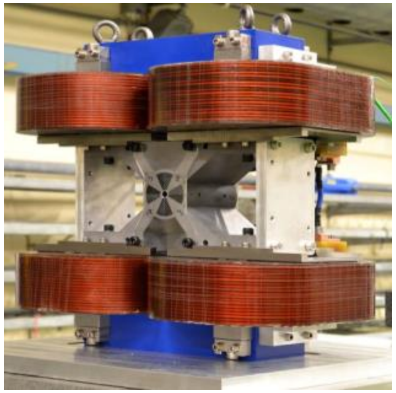
Supermendur

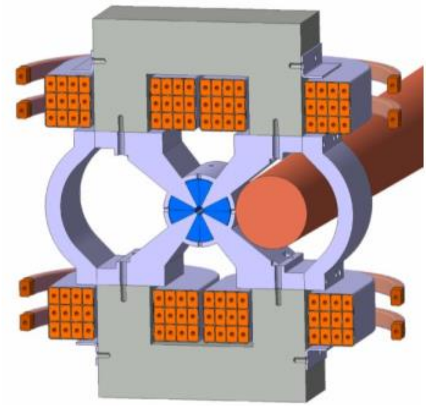


Design and Manufacture of a Hybrid Final Focus Quadrupole Model for CLIC

Alexey Vorozhtsov, Michele Modena, and Davide Tommasini

IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 22, NO. 3, JUNE 2012





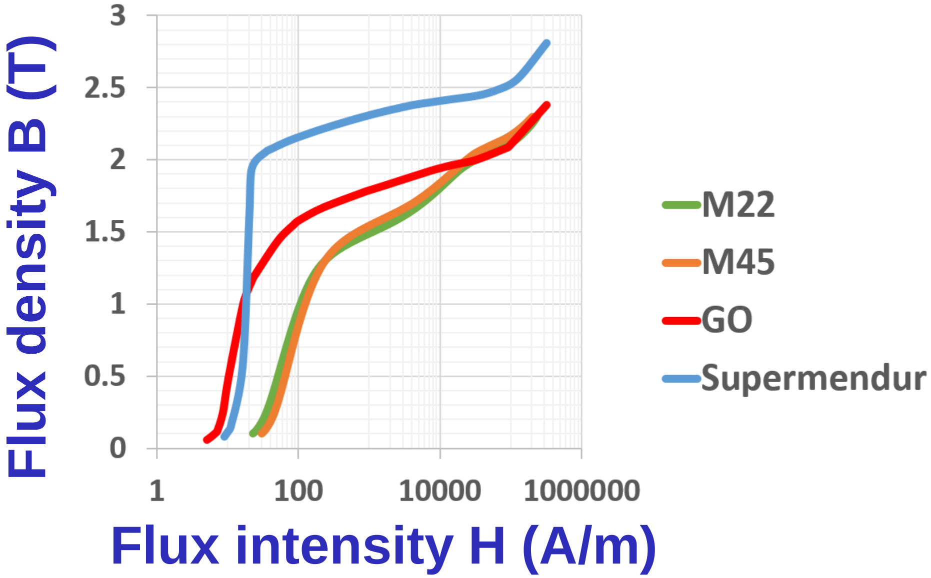
🟪 **Permendur**

◼ **1010 steel**

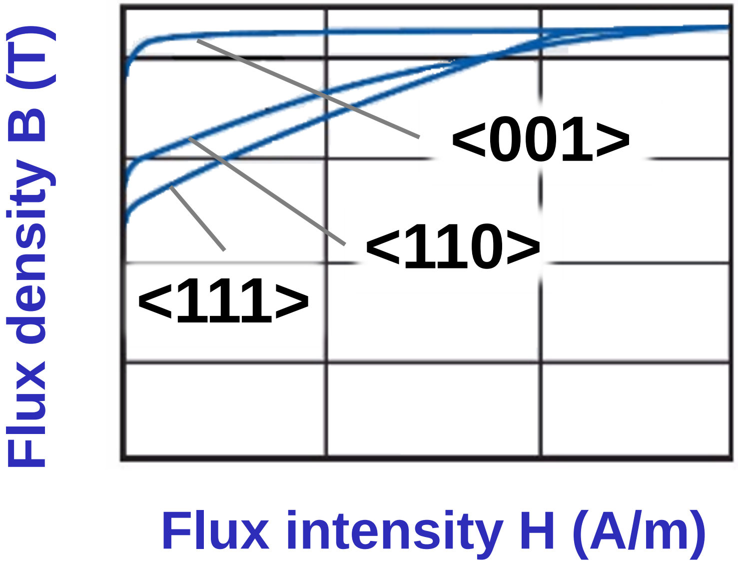
🟦 **$Nb_2Fe_{14}B$**

Material Selection

BH curves



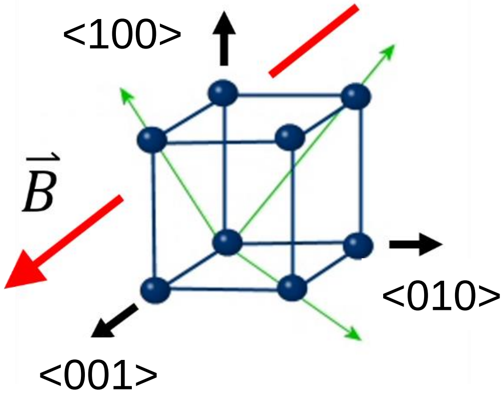
BH curves of crystal orientations



Hysteresis effect $P_{loss} = C_m B^{\alpha} f^{\beta}$

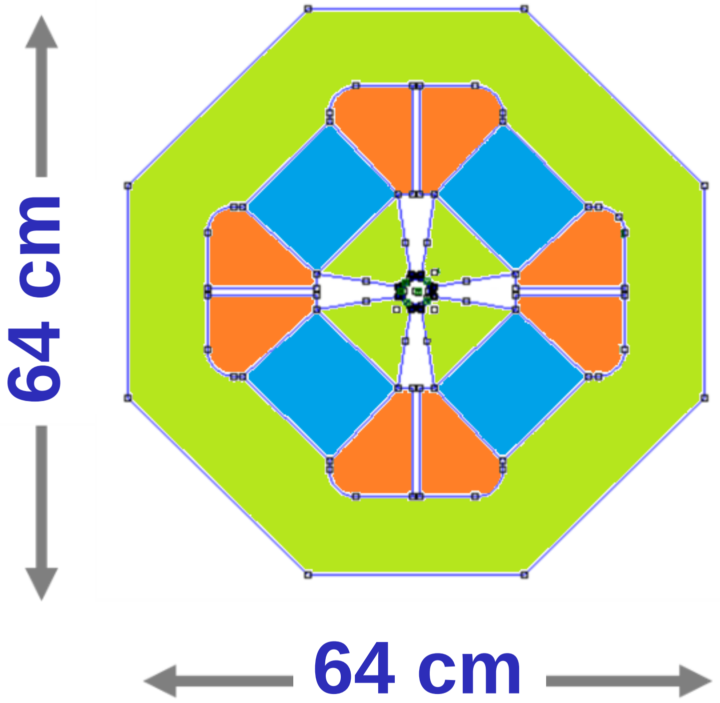
	$C_m \times 10^{-3}$	α	β
GO Si	1.2	2.3	1.5
AISI M22	8.2	2.2	1.3
AISI M45	13.5	1.8	1.3

Crystal structure of Si

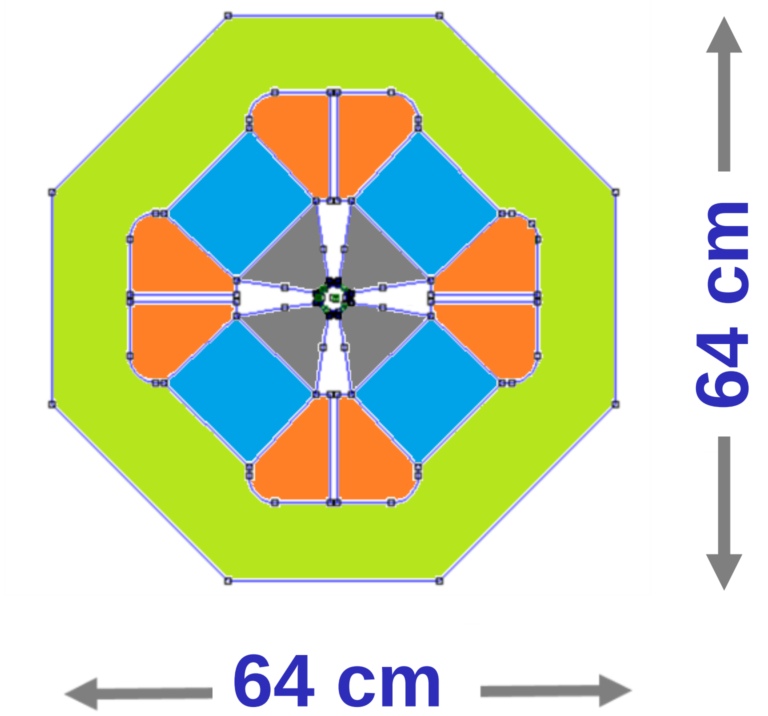


Design Layouts

RCS1



RCS2



● M22 Si steel ● 3% GO Si steel ● Copper wire ● Supermendur

Performance

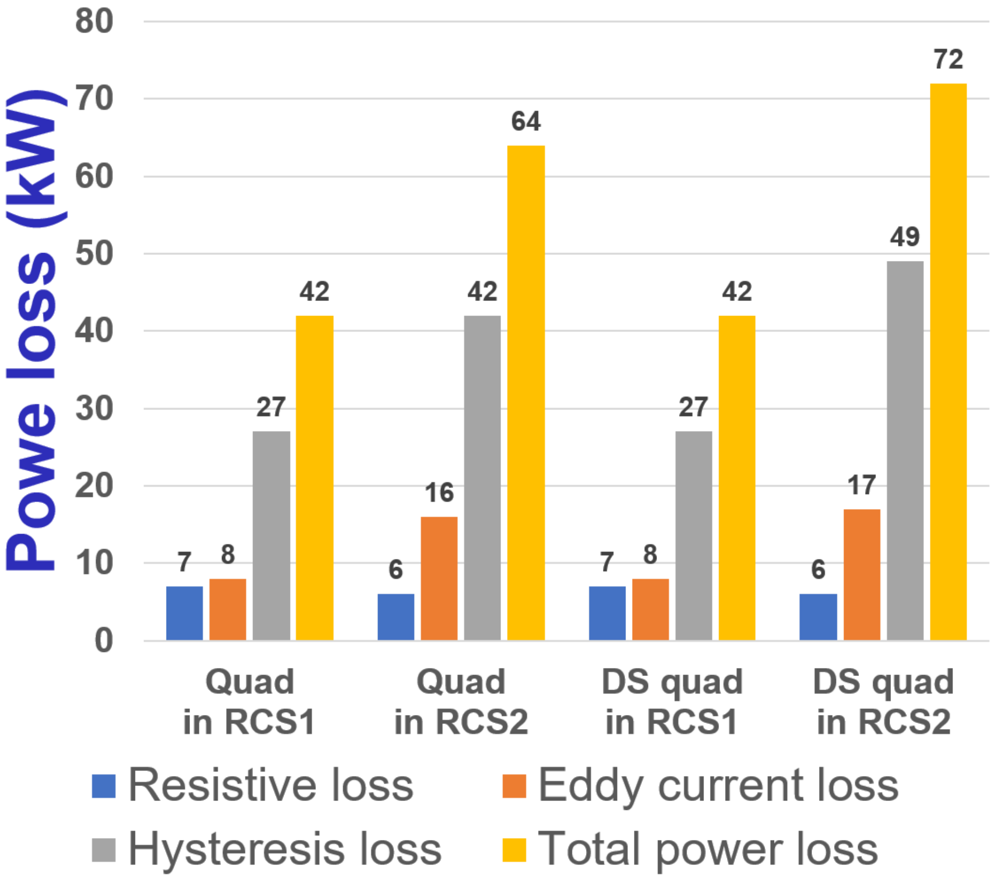
Extra Quadrupole scheme

	Quad in RCS1	Quad in RCS2	DS quad in RCS1	DS quad in RCS2
Ramping rate (Hz)	135	180	135	180
Gradient (T/m)	57.6	96	57.6	103.6
Aperture size (mm)	38	28	38	28
Pole tip field (T)	0.8	1.34	0.8	1.45
Current (A)	**8820**	**7740**	**8820**	**8600**
Efficiency (%)	**98**	**96**	**98**	**93**
Field quality $\Delta g/g$ in $\frac{2}{3}R$	6×10^{-4}	5×10^{-4}	6×10^{-4}	5×10^{-4}

DS: dispersion suppression

Power Loss

Power loss of a quad



Estimation for both rings		
	RCS1	**RCS2**
Number of quads	192	192
Weight (tonne)	784	782
P_{loss} **(MW)**	10	11
Overall Weight (tonne)	1564	
Overall P_{loss} **(MW)**	**21**	

Quadrupole – Conclusions

- **A hybrid material design**
- **Target gradients of B-field achieved**
- **The average Field quality is 6×10^{-4}**
- **Total weight is 1564 tonnes**
- **Total power loss of quads is 21 MW**

John Adams Institute for Accelerator Science

Imperial College London

Royal Holloway University of London

University of Oxford

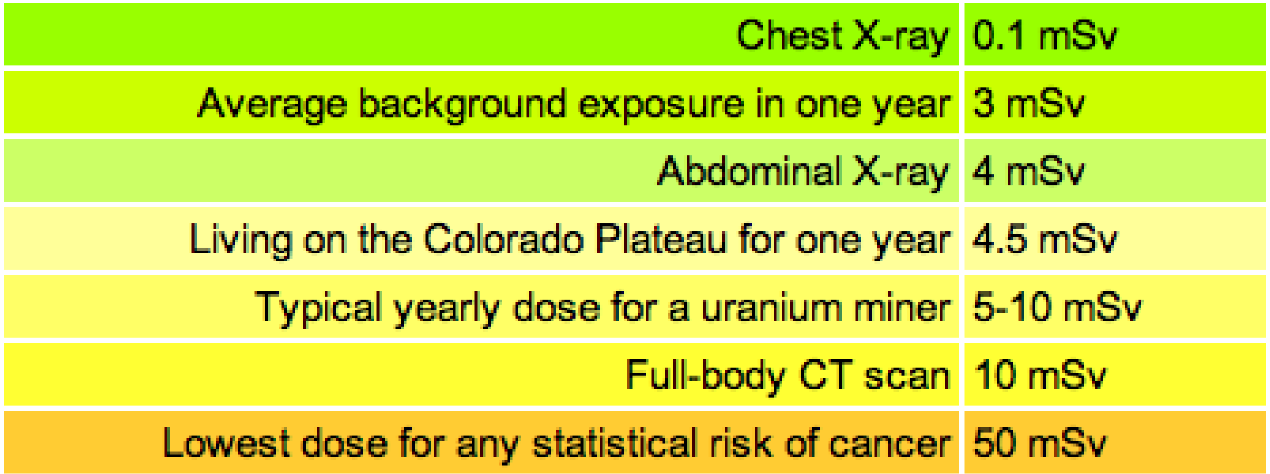
Radiation Considerations

Student Design Project

Carlo Mussolini

How do radiation regulations work?

- **The Sievert (Sv) is a unit describing the effects of radiation on an organism**
- **The regulations we are interested in are aimed towards the protection of individuals, so in Sv**
- **The limits to the general population are 0.3 mSv for people and 1mSv for the environment**

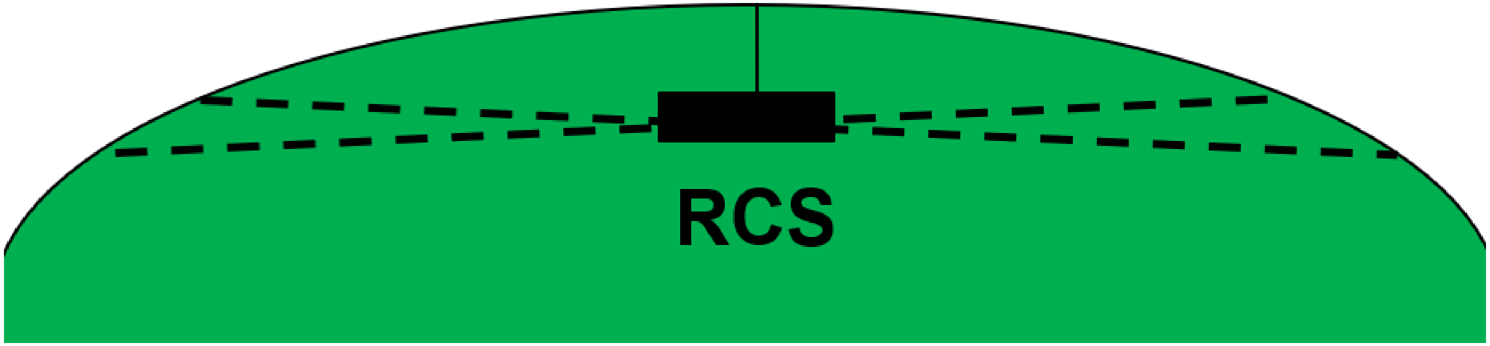


Chest X-ray	0.1 mSv
Average background exposure in one year	3 mSv
Abdominal X-ray	4 mSv
Living on the Colorado Plateau for one year	4.5 mSv
Typical yearly dose for a uranium miner	5-10 mSv
Full-body CT scan	10 mSv
Lowest dose for any statistical risk of cancer	50 mSv

The Neutrino Problem

The neutrino problem (!?)

- Muon decays produce neutrinos each with about 1/3 of the muon’s energy
- Travel straight through the Earth and emerge in a cone in the plane of the accelerator
- The radiation is highly focused in straight sections



The neutrino problem

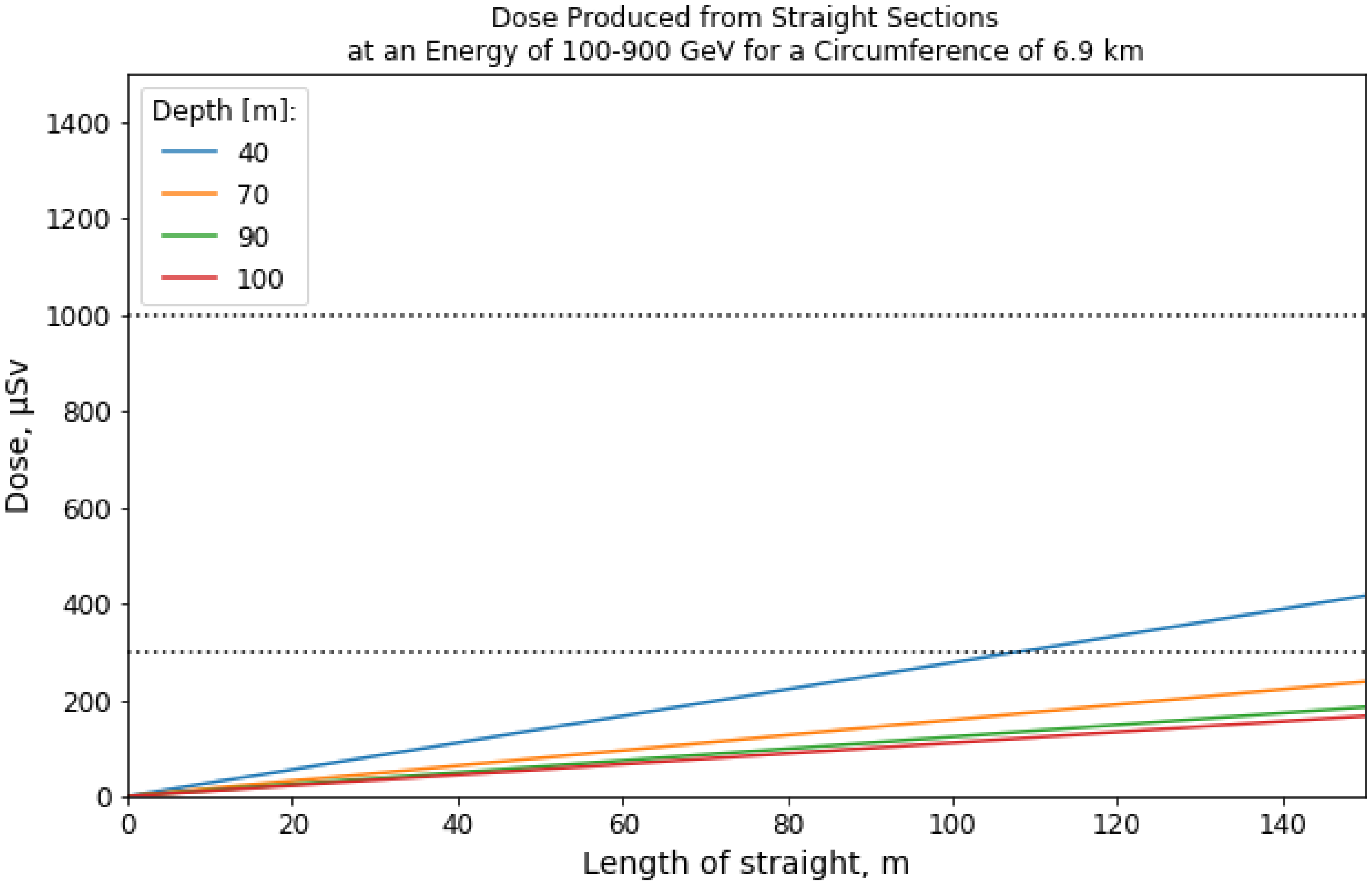
- **Problems arise with muon colliders as the energy frontier**
- **As the energy of the accelerator is increased the neutrino beam becomes more focused**
- **Flux and energy are high enough that with the conversion tables the effects are significant**

$$\theta \sim \sqrt{\epsilon/\gamma\beta} + 1/\gamma$$

$$\log(C) = 2\log(E) - 15$$

Emittance: $\epsilon \sim 25\ \mu m$
Beta function: $\beta \sim 350\mathrm{m}$
Rel. Gamma: $\gamma \sim 1000 - 15000$

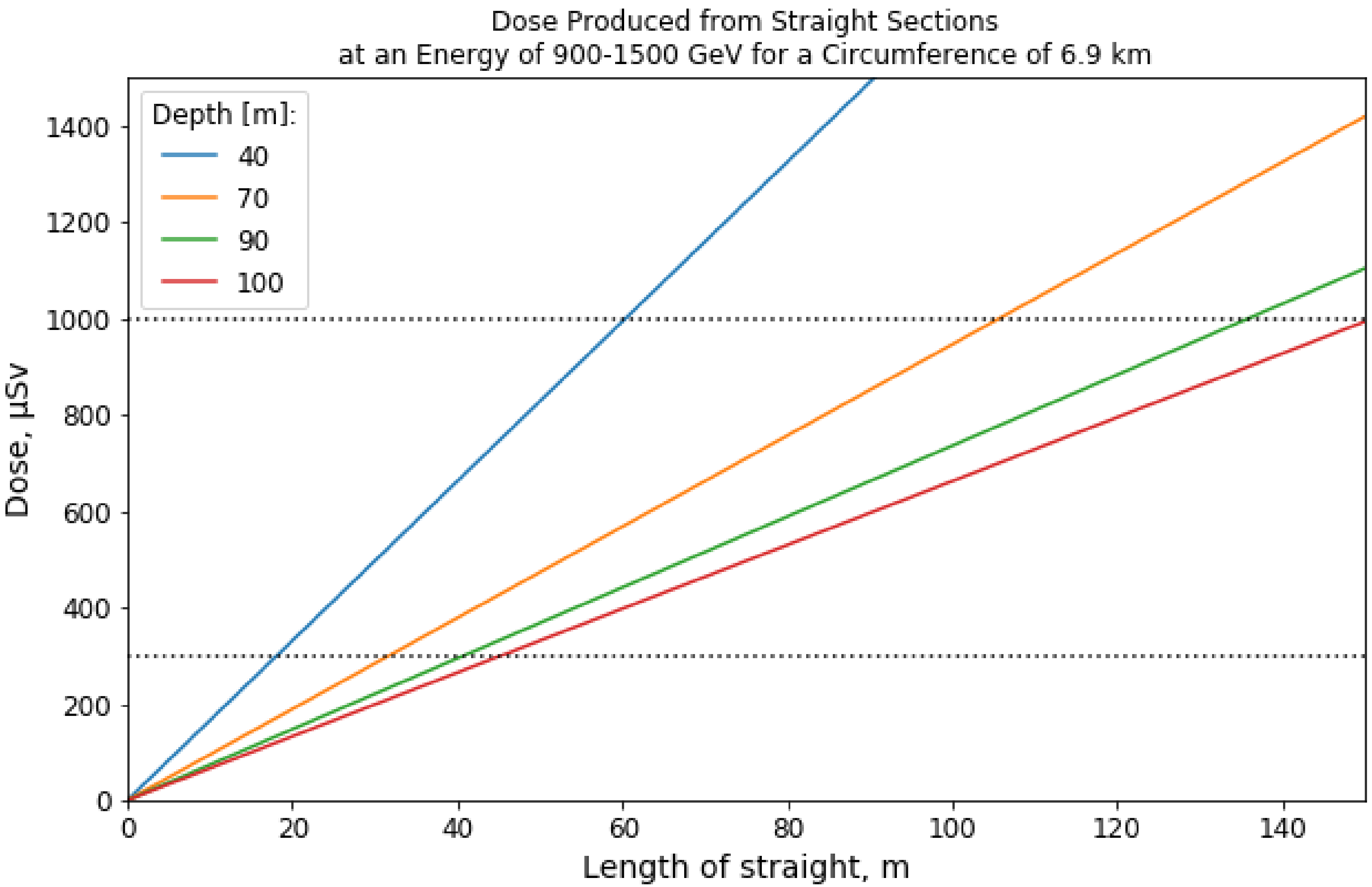
The neutrino problem



Depth SPS: 40 m

Length of straights in RCSs: 130 m

The neutrino problem



Depth SPS: 40 m **Length of straights in RCSs: 130 m**

Solutions to the neutrino problem

The parameters that affect the radiation:

- Time the accelerator is ran for
- Depth of accelerator
- Emittance of the beam
- Length of straights
- Number of muons being accelerated

Not sensible to change

Add small bends or wigglers

Change from the MAP scheme to the LEMMA scheme

The Electron Problem

The electron problem

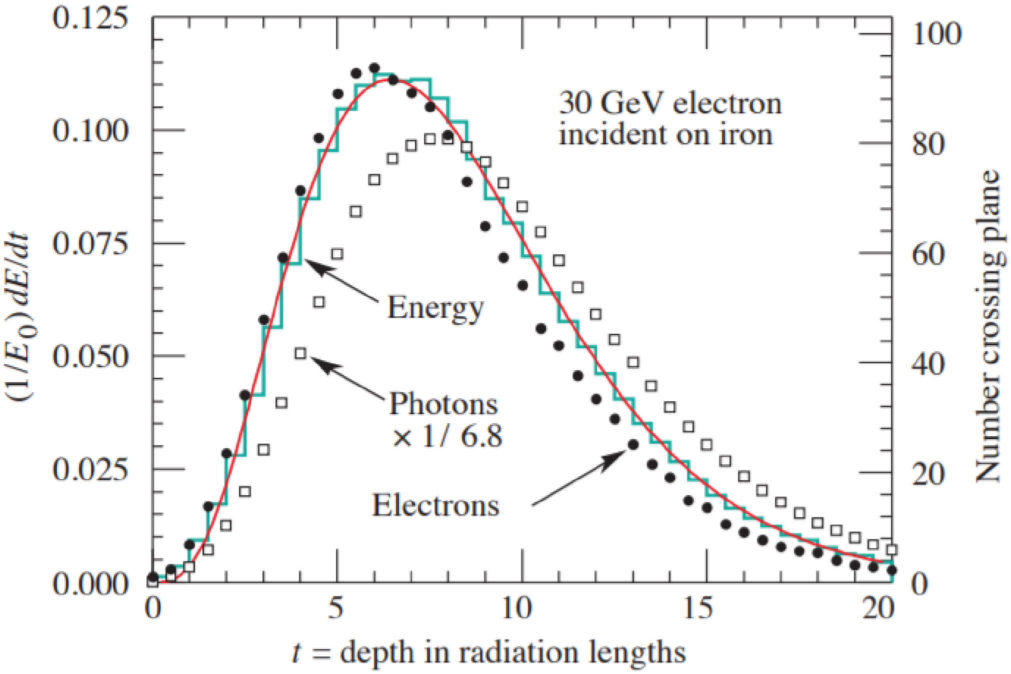
- As the muons decay, electrons are produced
- These electrons do not have the right energy to go around the accelerator
- They fall out of the bunches, depositing energy in the accelerator

Why is this important and how do we evaluate the effects of the electrons on the machine itself?

The electron problem

There are no simulations available for the desired energy range – Especially not in geometries we are interested in

Assuming about 12 cm of material, which is 6 radiation lengths, 25% of energy is deposited in machine



The electron problem

Accelerator	Energy Deposited per Year
RCS1	1.4 TJ
RCS2	1.1 TJ
LEP	0.1 MJ

- **LEP ran for 11 years and was one order of magnitude below significant radiation damage**
- **Clearly if nothing is done about the electrons, the components of the accelerators would be damaged extremely quickly**

Solutions for the electron problem

- There are designs for shielding for a Higgs factory and for magnets to reduce energy deposition
- Would need to check the efficacy of these at higher energies
- It may be possible to extract the electrons, since these act differently in the magnets compared to the muons
- Minimising materials used can also help to minimise the energy deposited

Summary of radiation

- **Difficult quantities to investigate**
- **Clearly there is the need for more in depth studies**
- **The effects of neutrinos are surprisingly significant and may prove to limit the energies a muon collider can reach**
- **Electron damage needs to be investigated to ensure the accelerator would be functional for a sensible length of time**
- **While these issues are significant, they are not insolvable and muon colliders still offer a unique opportunity to probe the high energy frontier**

Conclusion

Student Design Project

Summary of RCS MC design project

- **A lattice that works for all energy ranges, with zero suppression sections and with low tune shift has been designed**
- **Longitudinal dynamics and collective effects to first order are acceptable and further RF optimisation may reduce the already low losses**
- **Existing magnets already provide enough bending but further studies may increase the field strength and further reduce power losses**
- **Radiation and energy deposition are issues that must be carefully considered but can be mitigated**
- **All of this was achieved with the constraint of using the SPS tunnel to significantly lower costs**

Thank you to Emmanuel and Ciprian for their help

Thank you for listening