FCC-hh DESIGN REPORT

JOHN ADAMS INSTITUTE

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INTRODUCTION

Hannah Harrison

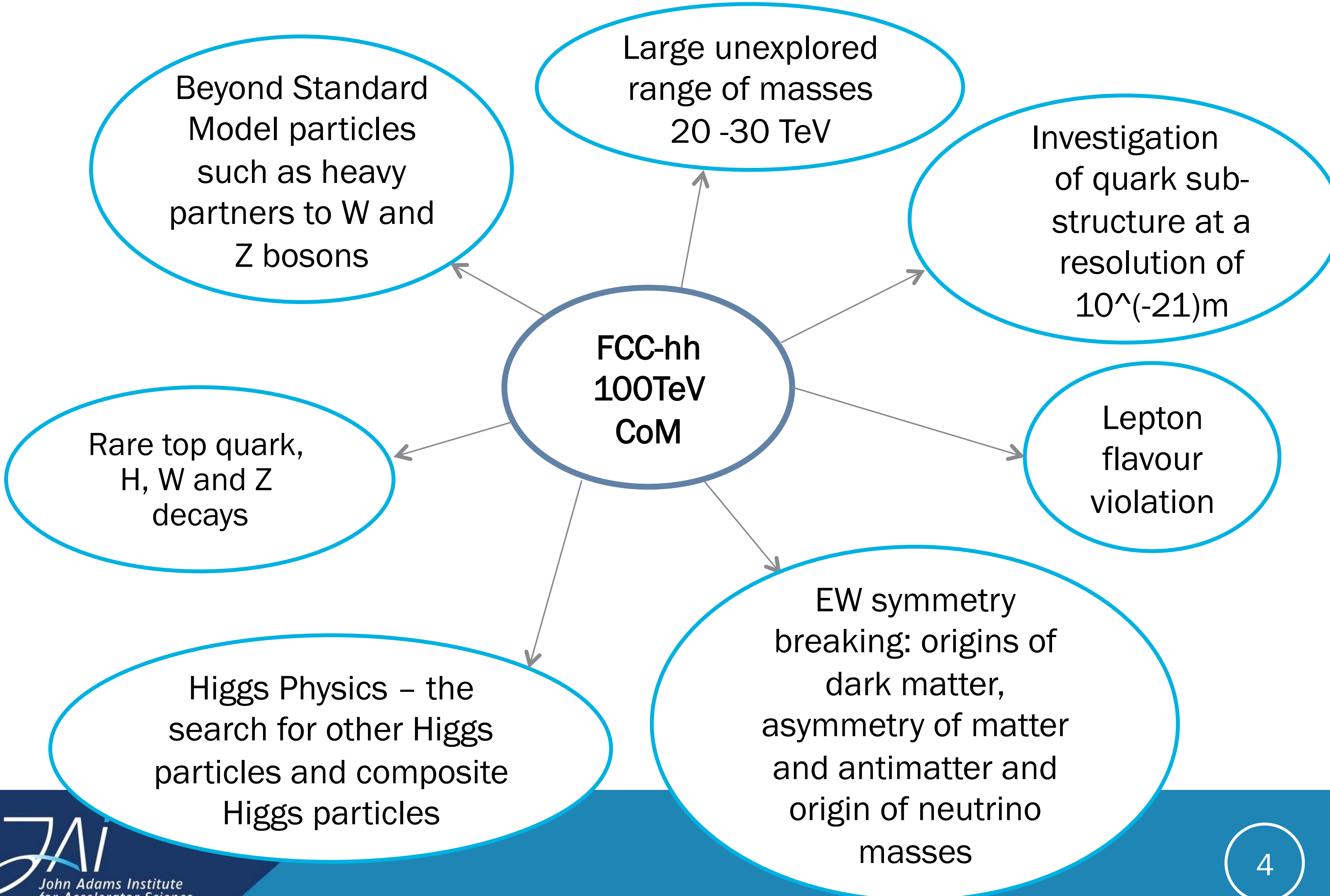
THE FCC-hh PROPOSAL

- Future Circular Collider – Hadron Hadron
- Ring circumference → 100 km (80 km)
- Magnetic field strength → 16T (Nb_3Sn superconductor)
- Centre of mass energy → 100 TeV (80 TeV)
- Location currently not decided

Magnetic Rigidity

$$B\rho = \frac{p}{e}$$

THE PHYSICS JUSTIFICATION FOR THE FCC-hh



THE FCC-ee AND FCC-he

FCC-ee

- High Luminosity → precision physics
- Collisions of Z, W, H and t
- CoM range in the region of 240GeV-500GeV
- Detailed studies of electroweak symmetry breaking

FCC-he

- Investigate deep inelastic scattering
- Electron-deuteron/electron-ion scattering → investigate nuclear structure
- Quark-Gluon plasma formation
- Heavy ion collisions

PROJECT BRIEF

- **Carry out in-depth studies of various aspects of the FCC-hh**

- **Look at possible ways of reducing the cost of building such a machine**
  - Reducing the Aperture
    - Less superconducting material would be needed
    - Reduction in possible centre-of-mass energy
    - Reduction in luminosity

  - Use different material to construct the dipoles
    - Other superconductors are cheaper than Nb_3Sn (e.g. NbTi)
    - Cannot support such high magnetic fields
    - Reduction in possible centre-of-mass energy

Need to examine the trade off between the best possible parameters for the machine to perform physics and the cost of achieving them

ASPECTS OF THE FCC-hh DESIGN CONSIDERED

- Lattice Design
- Synchrotron Radiation and Instabilities
- Magnet Design
- RF cavities
- Conclusion – *how will our ideas impact the physics capabilities of FCC –hh?*

LATTICE DESIGN

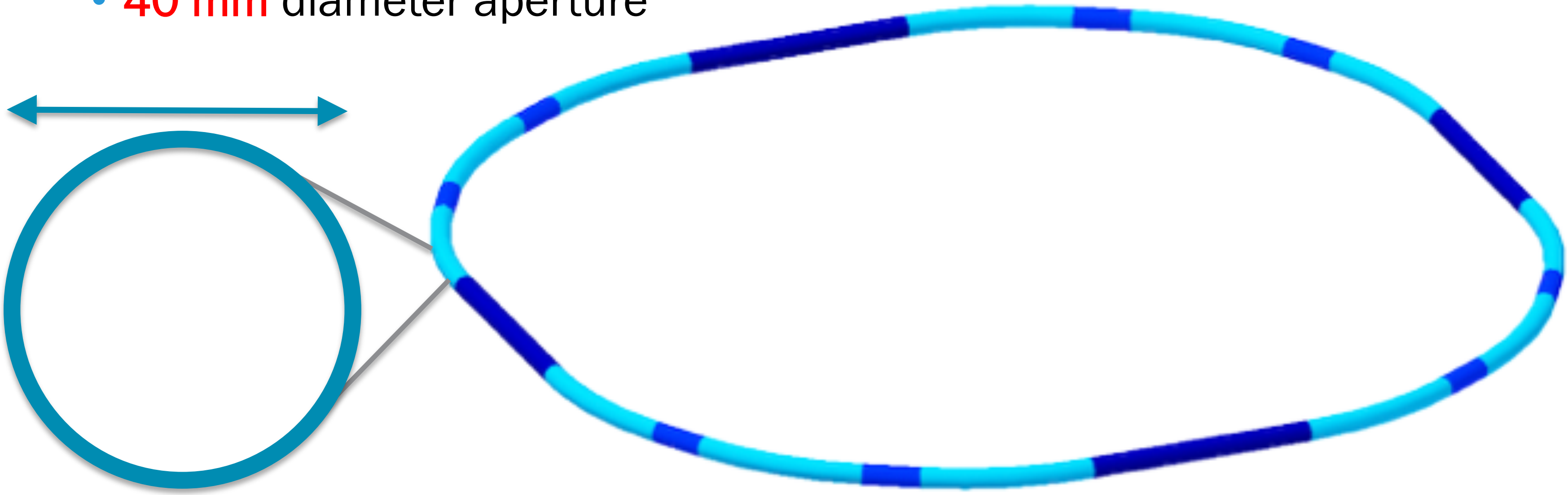
Christopher Arran

- Possible Cost Reductions
- Effect on Beam Energy

STARTING POINT

Reyes Alemany & Bernhard Holzer Design:

- 12 arcs and 12 straights (exaggerated length)
- 4 long straights for Interaction Points, injection etc
- 450 Tm^{-1} quadrupole field gradient (Nb_3Sn)
- 14.7 T dipoles (Nb_3Sn)
- 40 mm diameter aperture



POSSIBLE COST REDUCTIONS

Smaller aperture

- Less superconductor material required
- Consider 40mm, 30mm and 20mm apertures

Cheaper dipole magnets

- Consider NbTi at 10.5T vs Nb_3Sn at 16T

Aperture Diameter	Maximum Twiss Beta
40mm	354.6 m
30mm	199.4 m
20mm	88.6 m

Dipole Strength
14.7 T
10.5 T
16 T

CONSTRAINTS

Physical limits on lattice:

- Space for RF, IP, injection and extraction
- Require space between components

Constraint	
Ring circumference	100 km
Long straight length	≥ 1 km
Dipole length	≤ 14.2 m
Dipole-Dipole spacing	1.3 m
Dipole-Quadrupole spacing	3.6 m

LATTICE AFFECTS BEAM ENERGY

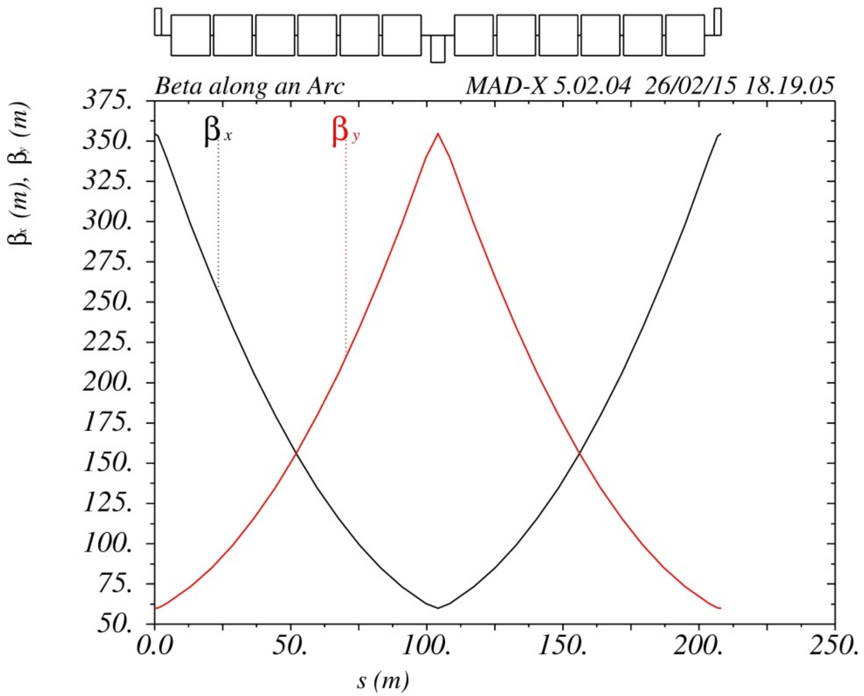
Scaling Laws:

- Aperture ⇒ Maximum Twiss beta
  ⇒ FODO cell length
  ⇒ No. dipoles
  ⇒ Beam energy

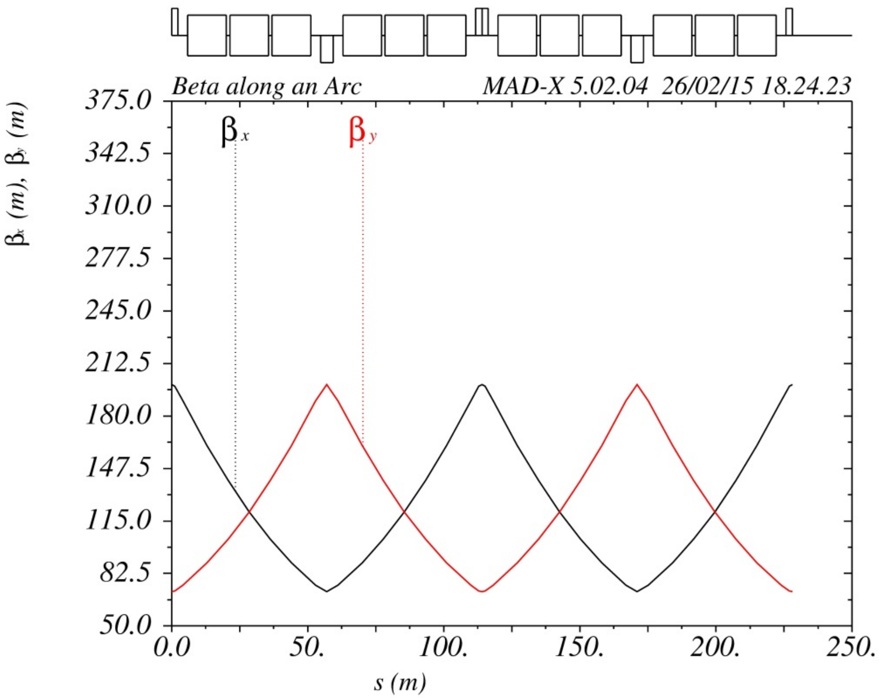
- Dipole strength ⇒ Beam energy

MAD X OUTPUT

40 mm Aperture
12 dipoles per cell



30 mm Aperture
6 dipoles per cell



RESULTS

Energies / TeV	Dipole Field	14.7 T	10.5 T	16 T
Aperture Diameter	40 mm	100	74.6	100
	30 mm	96.4	70.8	100
	20 mm	68.8	53.0	

Dipole Fill Factor	Dipole Field	14.7 T	10.5 T	16 T
Aperture Diameter	40 mm	71%	75%	66%
	30 mm	69%	71%	66%
	20 mm	50%	53%	

CONCLUSIONS

- 30 mm aperture ⇒ only slightly lower energy
- 20 mm aperture is too small

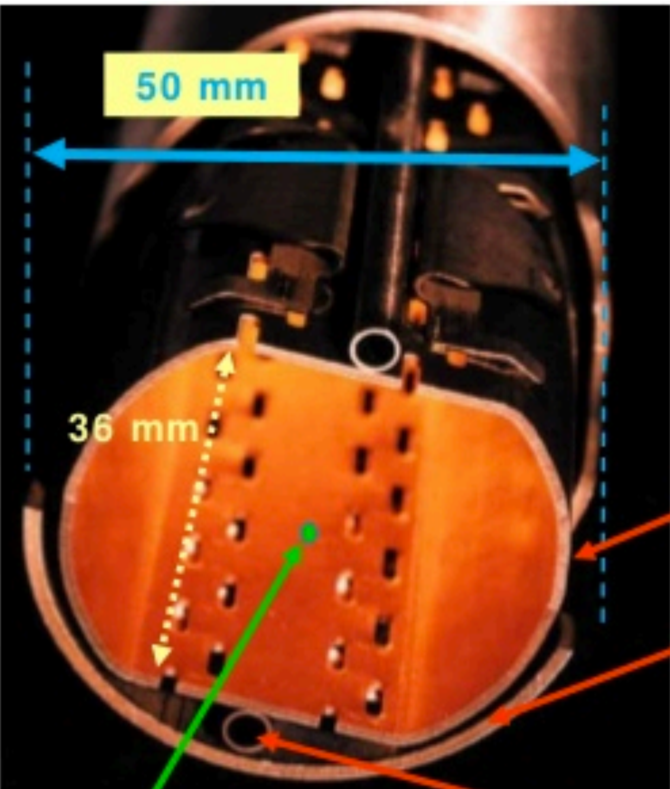
- 10.5 T ⇒ 70-75 TeV centre of mass
- 16 T is stronger than necessary

INSTABILITIES

Rob Williamson

- Resistive Wall
- Aperture Implications
- Coupled Bunch
- TMCI
- Damping Possibilities

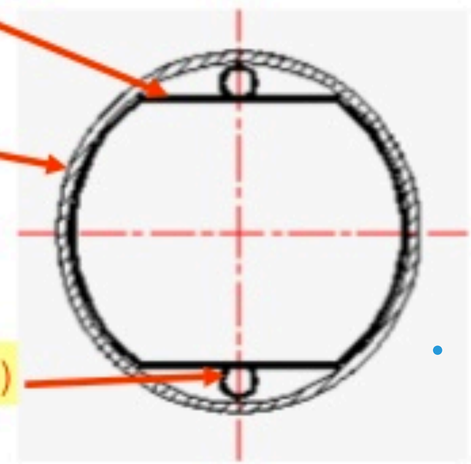
RESISTIVE WALL IMPEDANCE



LHC Beam Screen

- Beam interacts with its environment through impedances
- Transverse impedance dominated by resistive wall:

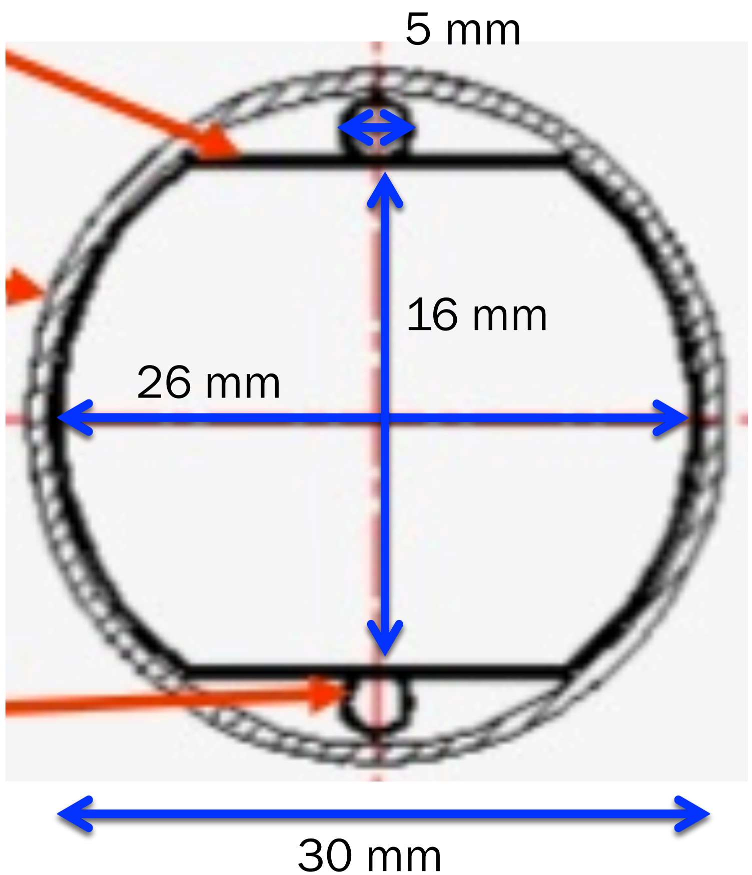
$$Z_{\perp}(\omega) = (\mathrm{sgn}(\omega) - i)\,\frac{Z_0 R \delta_s}{b^3}$$



- b = beampipe radius
- δ_s = skin depth

IMPLICATIONS OF APERTURE REDUCTION

- Assume LHC-style beam screen geometry
- Minimum aperture
  - +/- 8 mm for 30 mm aperture
  - +/- 13 mm for 40 mm aperture
- Impedance proportional to b^{-3}
- Effect on instability growth rates?

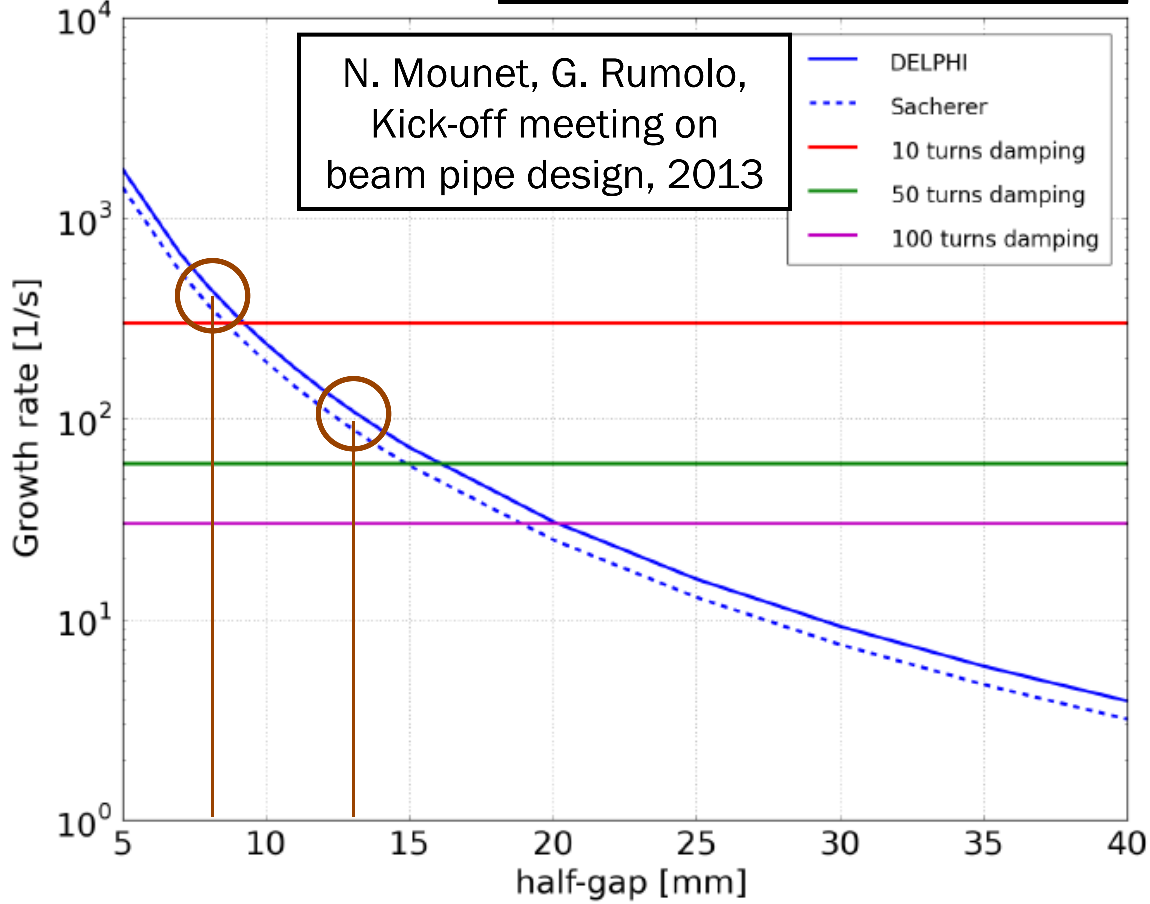


FCC-30mm

COUPLED BUNCH INSTABILITY

25ns bunch spacing
10^{11} protons per bunch
Chromaticity = 0
Copper below 20K
Includes magneto-resistance

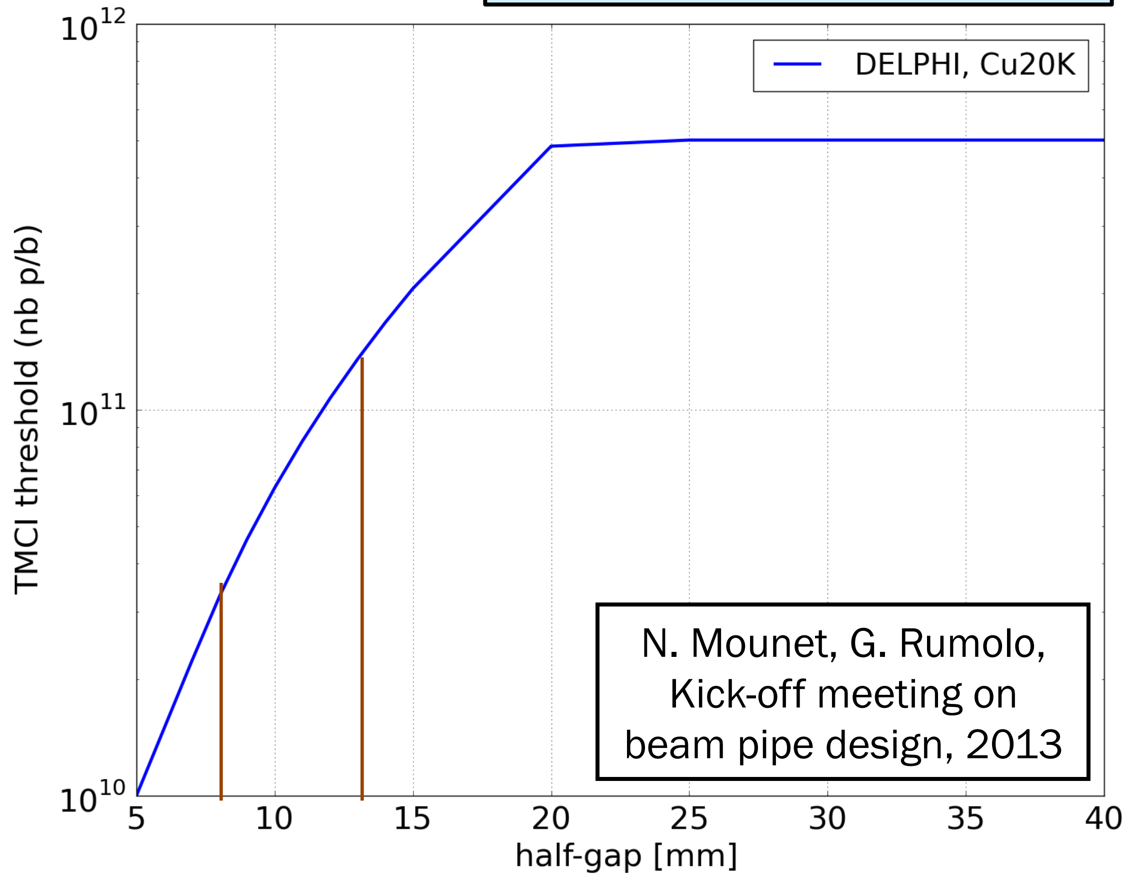
- Growth rate for coupled-bunch instability is proportional to the transverse impedance
- Scales as 1/γ
  - Plot at 3 TeV
- Factor of 4.3 larger growth rate
  - < 10 turns damping



TRANSVERSE MODE COUPLING INSTABILITY

Chromaticity = 0
Copper below 20K
Includes magneto-resistance

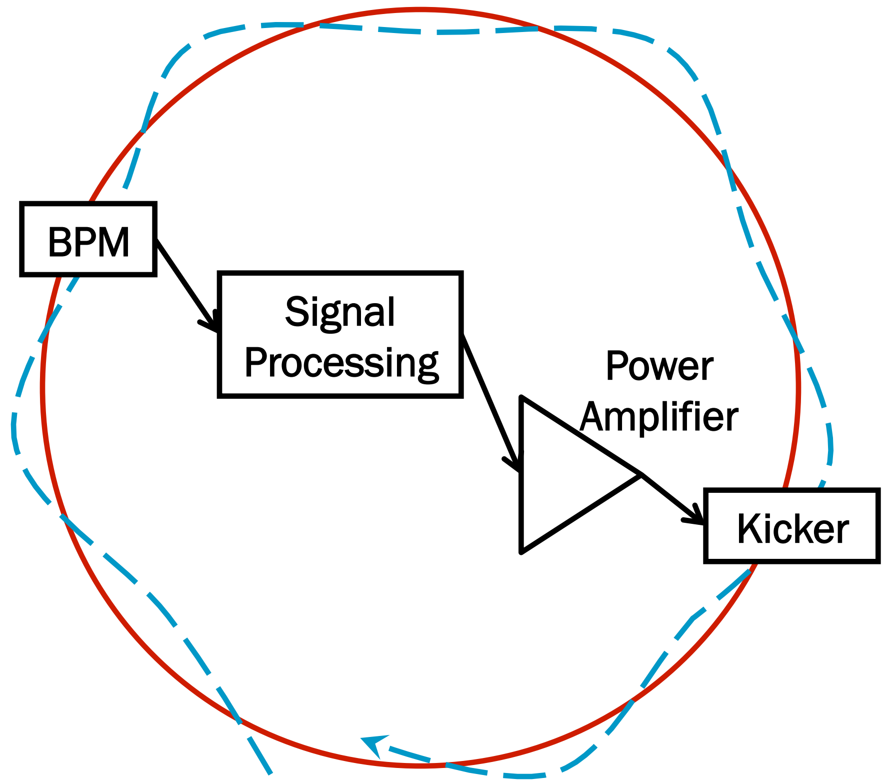
- Headtail instability driven by resistive wall impedance
- Threshold increases with beam energy
  - Plot at 3 TeV
- Maximum intensity
  - ~3×10^{10} ppb
  - ~1.5×10^{11} ppb
- Nominal = 1×10^{11} ppb



N. Mounet, G. Rumolo, Kick-off meeting on beam pipe design, 2013

DAMPING SYSTEMS

- Landau octupoles
- Transverse damper system
- LHC system
  - < 40 turns (3.6 ms)
  - Equates to 11 turns FCC
  - < 10 turns hard limit
- FCC system (30 mm aperture)
  - < 7 turns => multiple kickers
  - Good noise control on BPMs
  - Power available
  - GHz system for TMCI



CONCLUSIONS

- **Reducing the aperture**
  - Increases growth rate for coupled bunch instability by factor 4
  - Damping in <7 turns
  - Reduces threshold to TMCI to 3×10^{10} ppb
  - Reduces luminosity by factor of 10 from design

- **Transverse damping system**
  - Faster damping than LHC
  - GHz intra-bunch system for TMCI

SYNCHROTRON RADIATION

Mehpare Atay

Alternative Considerations for Synchrotron Radiation

SYNCHROTRON RADIATION IN FCC-hh

Machine	Bending radius(m)	Beam energy(GeV)	γ	Beam current(mA)	Critical photon energy(eV)	Total SR power radiated(W)
LHC	2803.95	6500	6928	490	35.1	2431
FCC-hh 15T	11146.32	50000	53306	500	4016	2.18E+06
LEP-2	3096.2	104	203521	4.5	8.06E+05	1.51E+07
ESRF	23.366	6	11742	200	20504	9.81E+05

- The critical energy is in the X-ray region.
- FCC generates 170 times of SR power of the LHC.

CHALLANGES DUE TO SYNCROTRON RADIATION

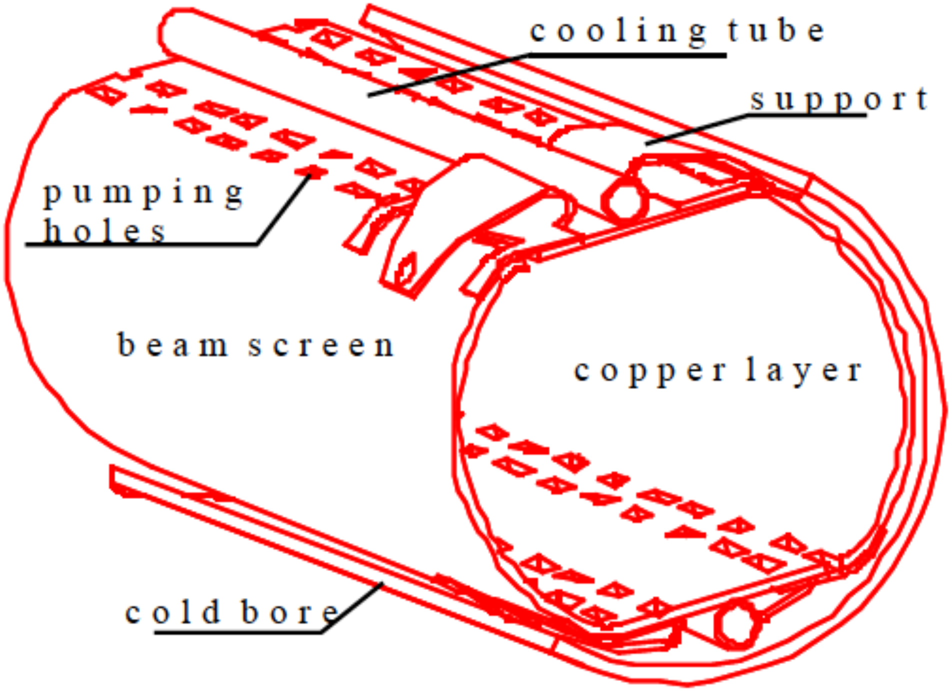
Power radiated per mrad	0.35	kW
SR line power density	31.18	W/m
Photon flux	1.54E+17	ph/s/m
Critical angle for SR emission	1.88E-05	rad
SR energy loss	4.67	MeV/turn

- High temperature of the beam pipe; *due to the SR power density*
- Large gas load; *due to the large photon flux*

➡SR needs to be absorbed by the designed beam pipe.

LHC BEAM SCREEN DESIGN

- Why is the beam screen effective in absorption?
- Impedance of the beam pipe; *exciting strong beam instabilities*



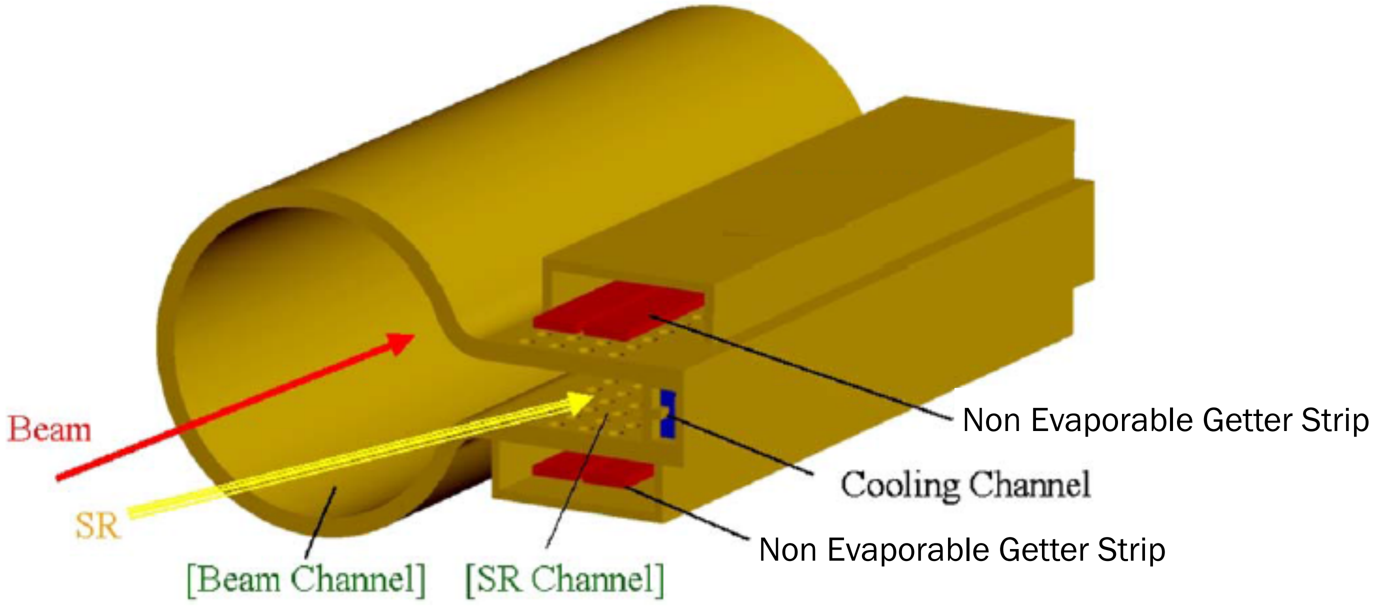
P. Cruikshank et al. / Mechanical Design Aspects of the LHC Beam Screen

ANTECHAMBER

- It can reduce the power density of the SR on the walls of the beam pipe:

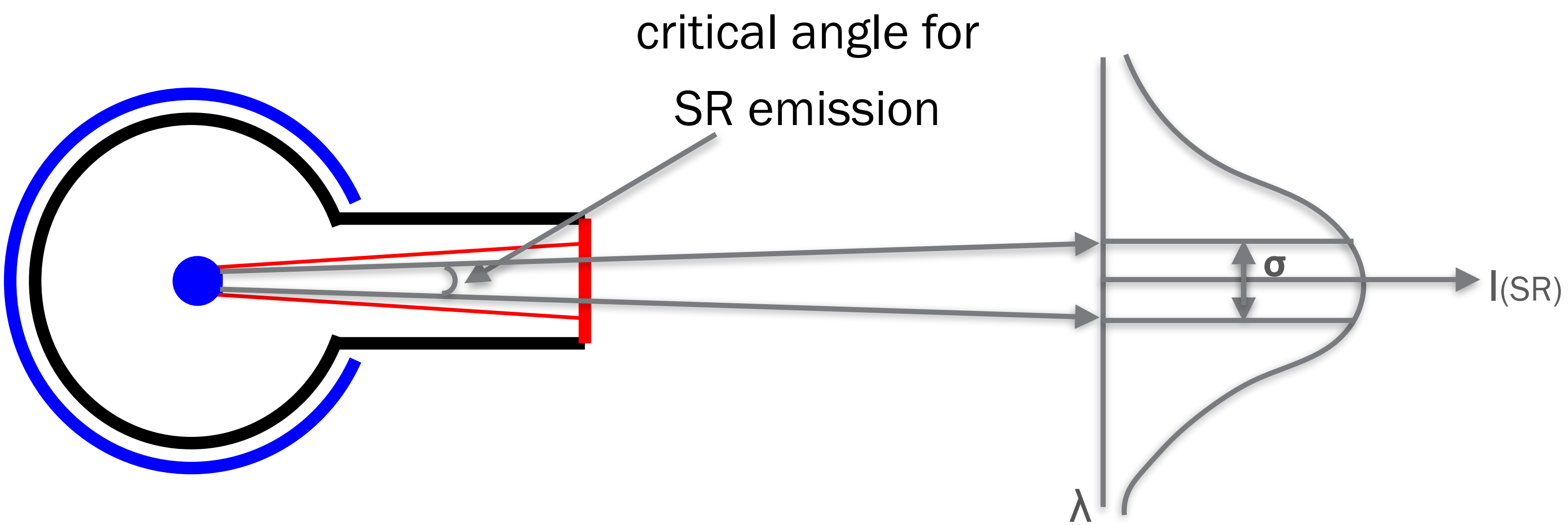
➡ SR is diluted due to its vertical spread; *the chamber has a wider outer half-aperture*

➡ The horizontal spread contributes to reduce the maximum power density; *SR from bending magnet hits the outside of the magnet*



Y. Suetsugu et al. / Nuclear Instruments and Methods in Physics Research A 538 (2005) 206-217

ANTECHAMBER PARAMETERS



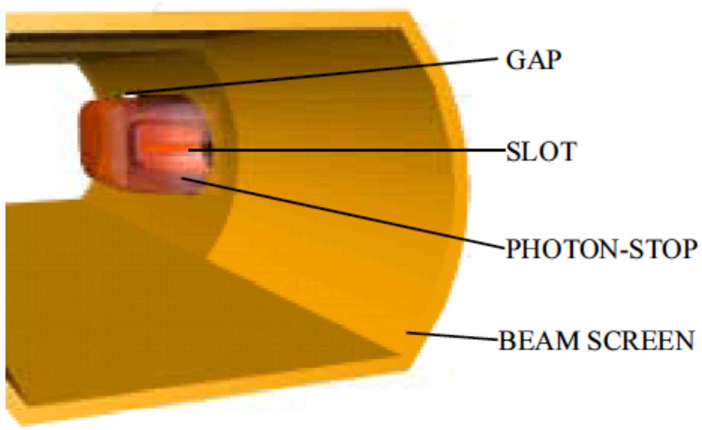
- Small beam impedance:

➡ The effect of the pumping slots on the beam is decreased.

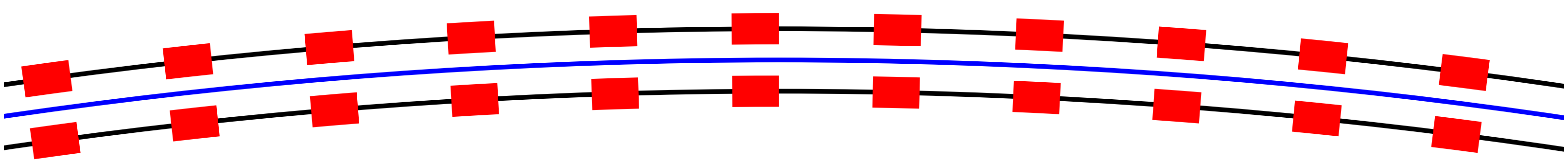
- Reduced photoelectron density in the beam channel; *diminishes the electron cloud effect*

PHOTON STOP

- Absorbs the SR power at the room temperature with water cooling
- Commonly used in synchrotron light sources



- Inserted in the beam tube at the end of each magnet



T. K. Kroc/Synchrotron Radiation in the VLHC

CONCLUSIONS

- FCC-hh makes a powerful source of SR with total radiated SR power of 2.18 MW.

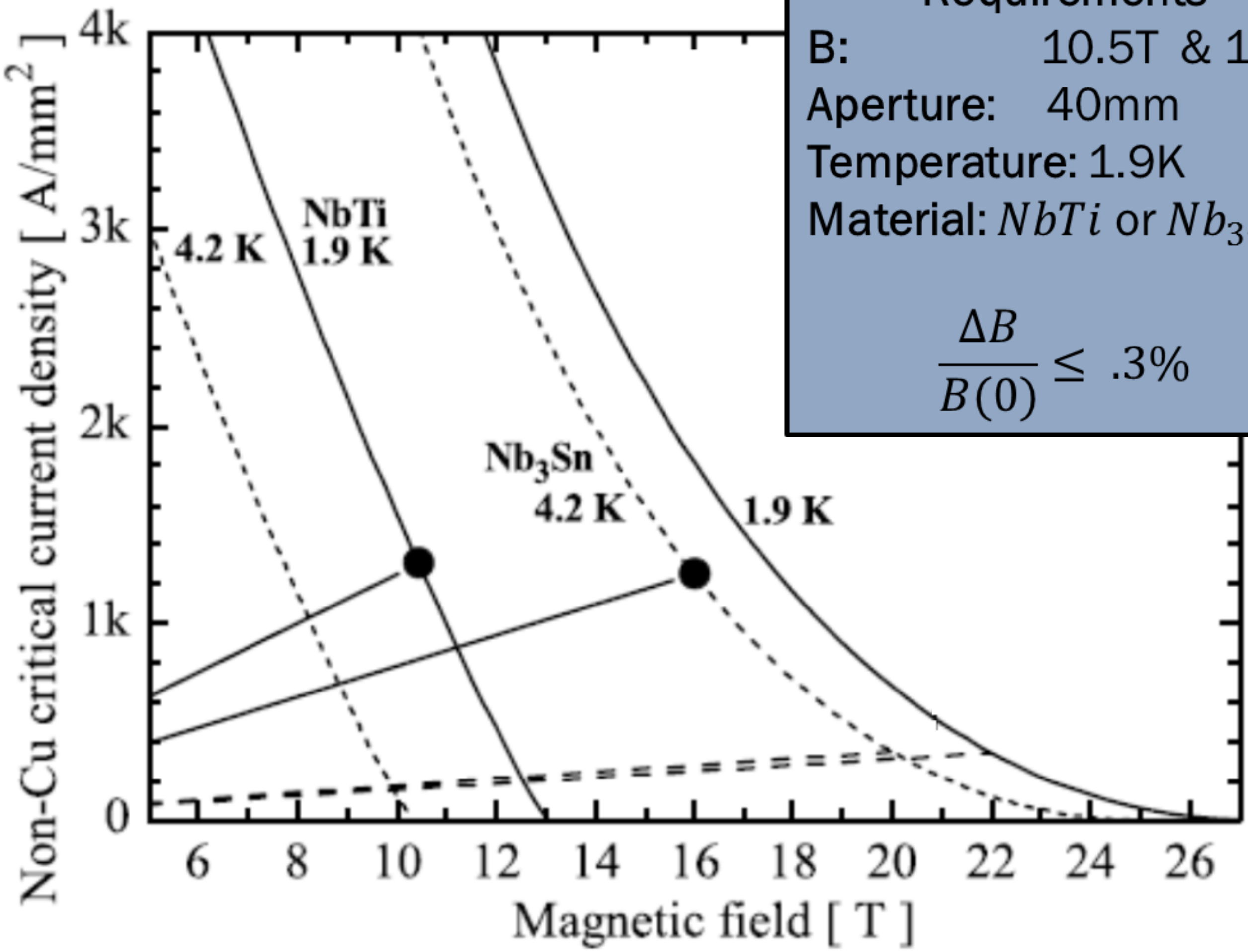
- Antechamber and photon stop solutions have been considered for the high SR problem in FCC-hh.

- However, the geometry of the beam pipe also needs to be optimized to minimize the cost of the superconductive magnets.

MAGNET DESIGN

Alberto Arteche & Rob Shalloo

DESIGN BRIEF



Requirements

B: 10.5T & 16T

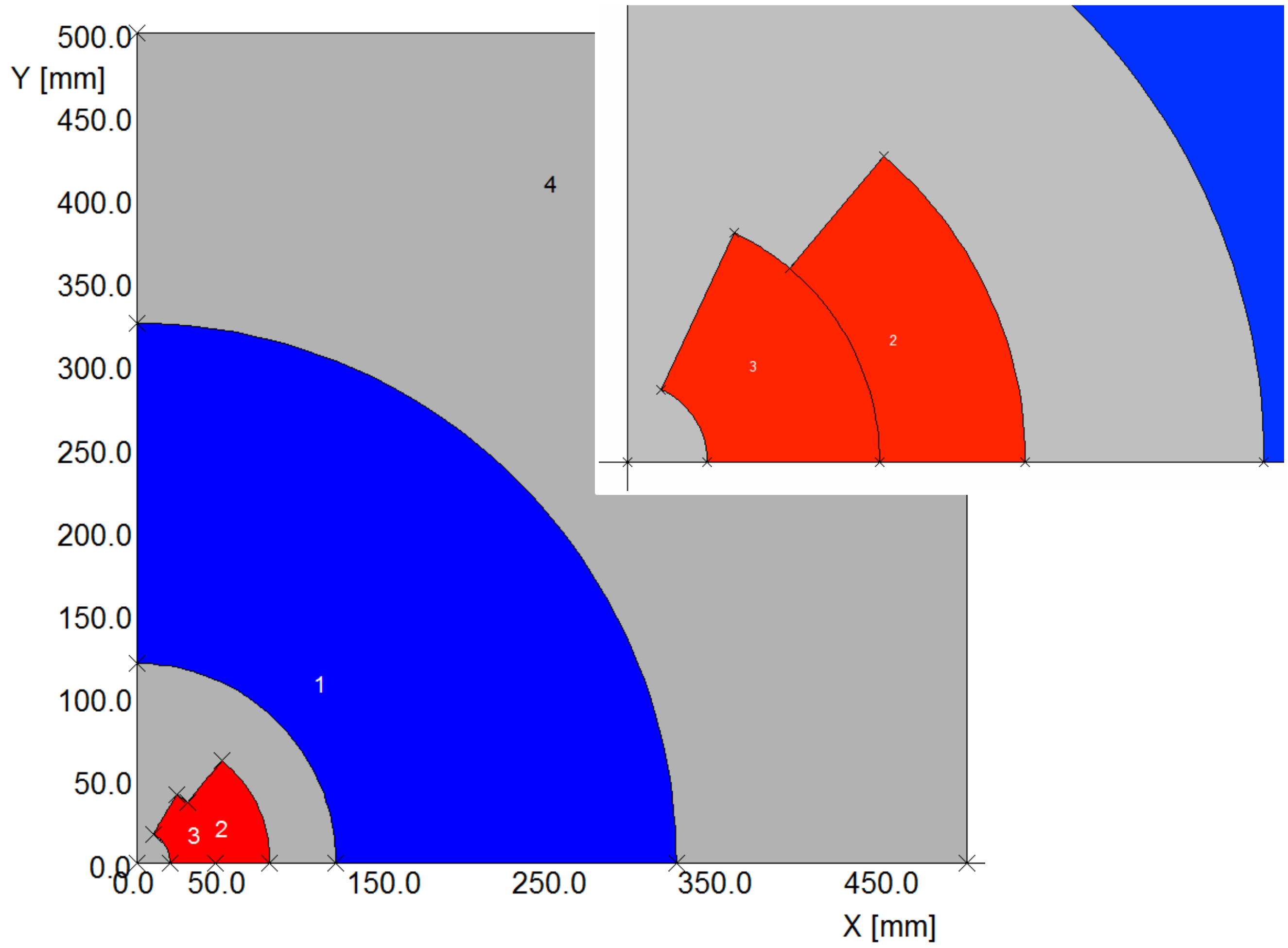
Aperture: 40mm

Temperature: 1.9K

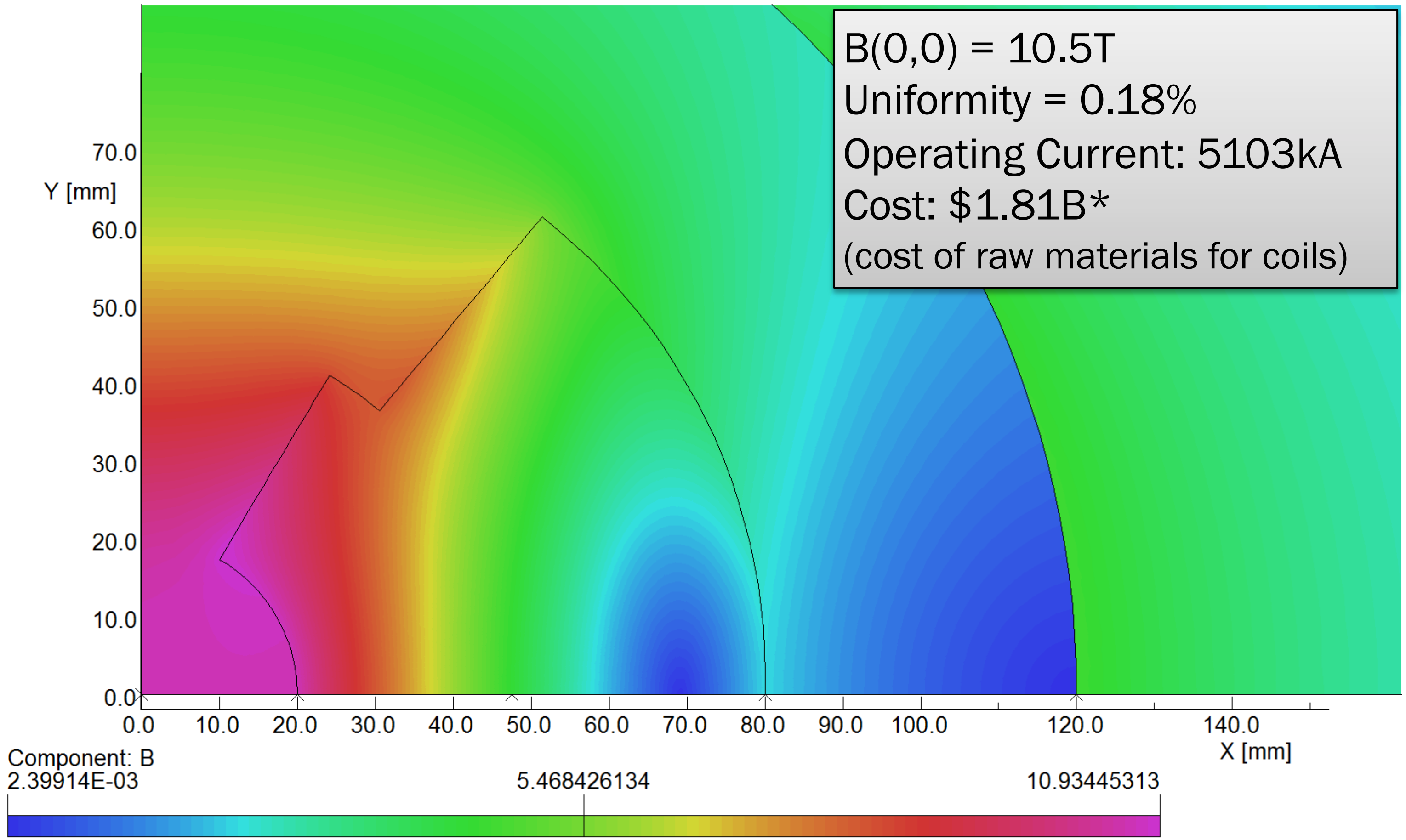
Material: $NbTi$ or Nb_3Sn

$$\frac{\Delta B}{B(0)} \leq .3\%$$

SUPERCONDUCTING MAGNETS

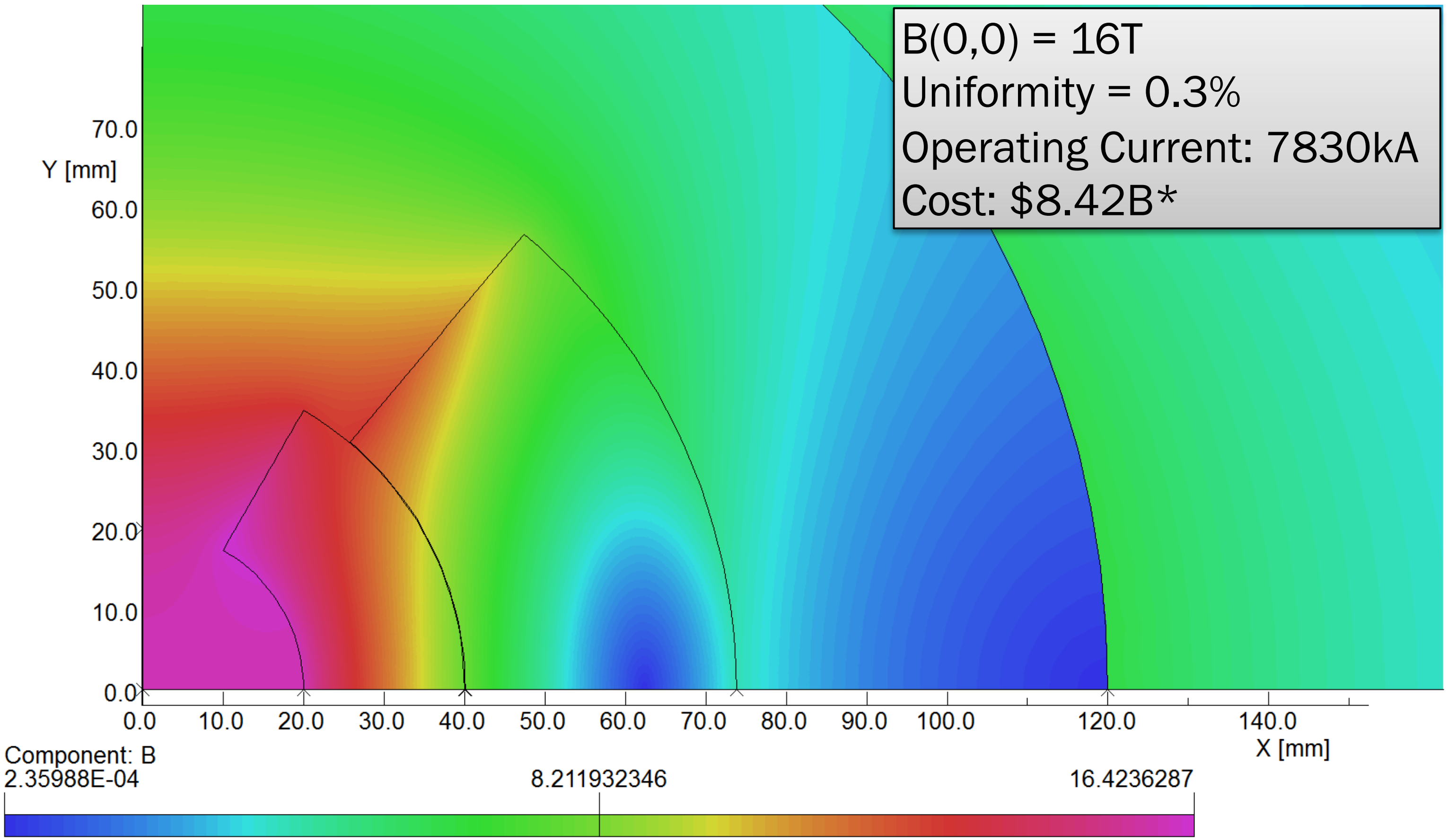


10.5T NIOBIUM TITANIUM



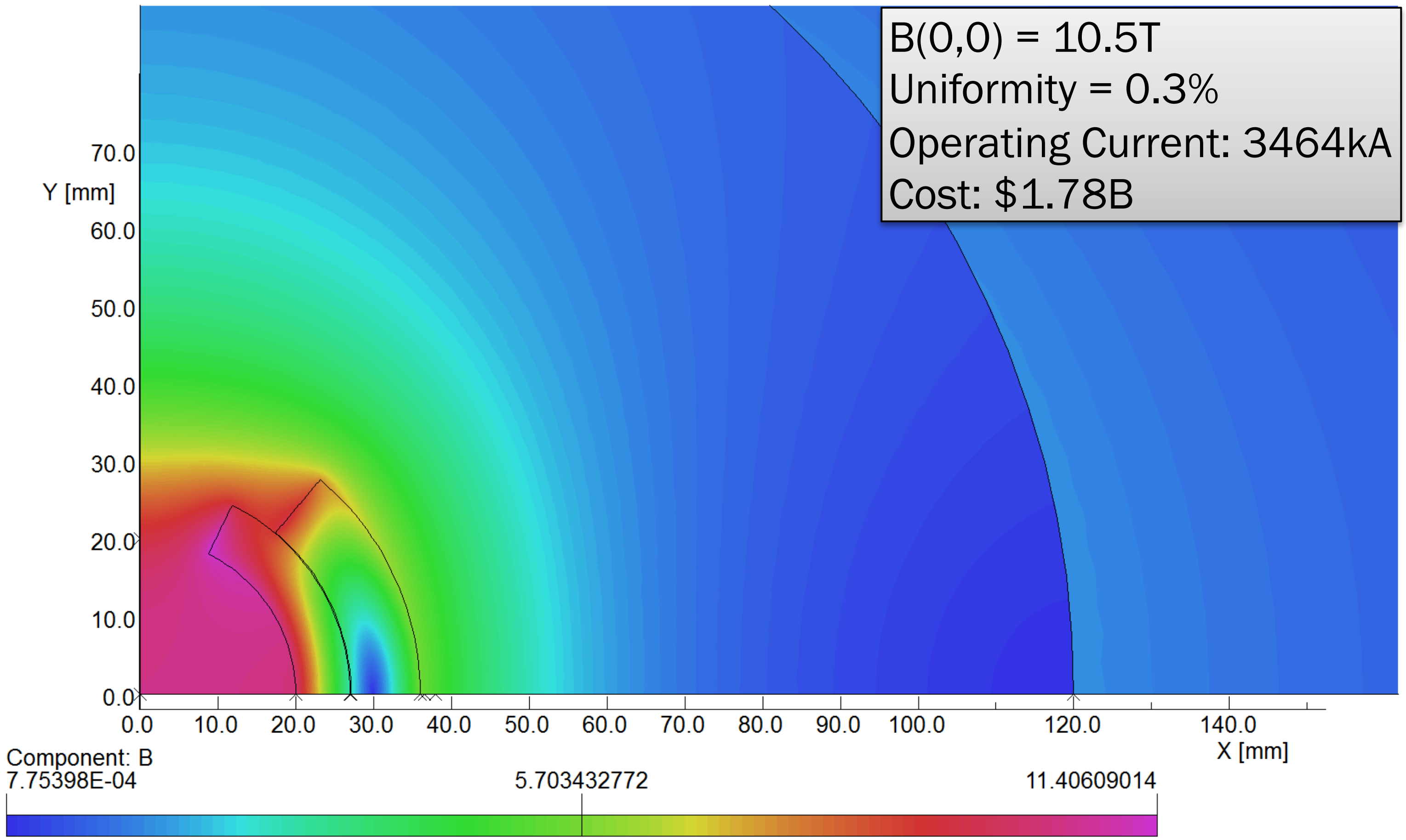
*L. Rossi and E. Todesco. Conceptual design of 20 T dipoles for high-energy LHC. 2011.

16T NIOBIUM TIN

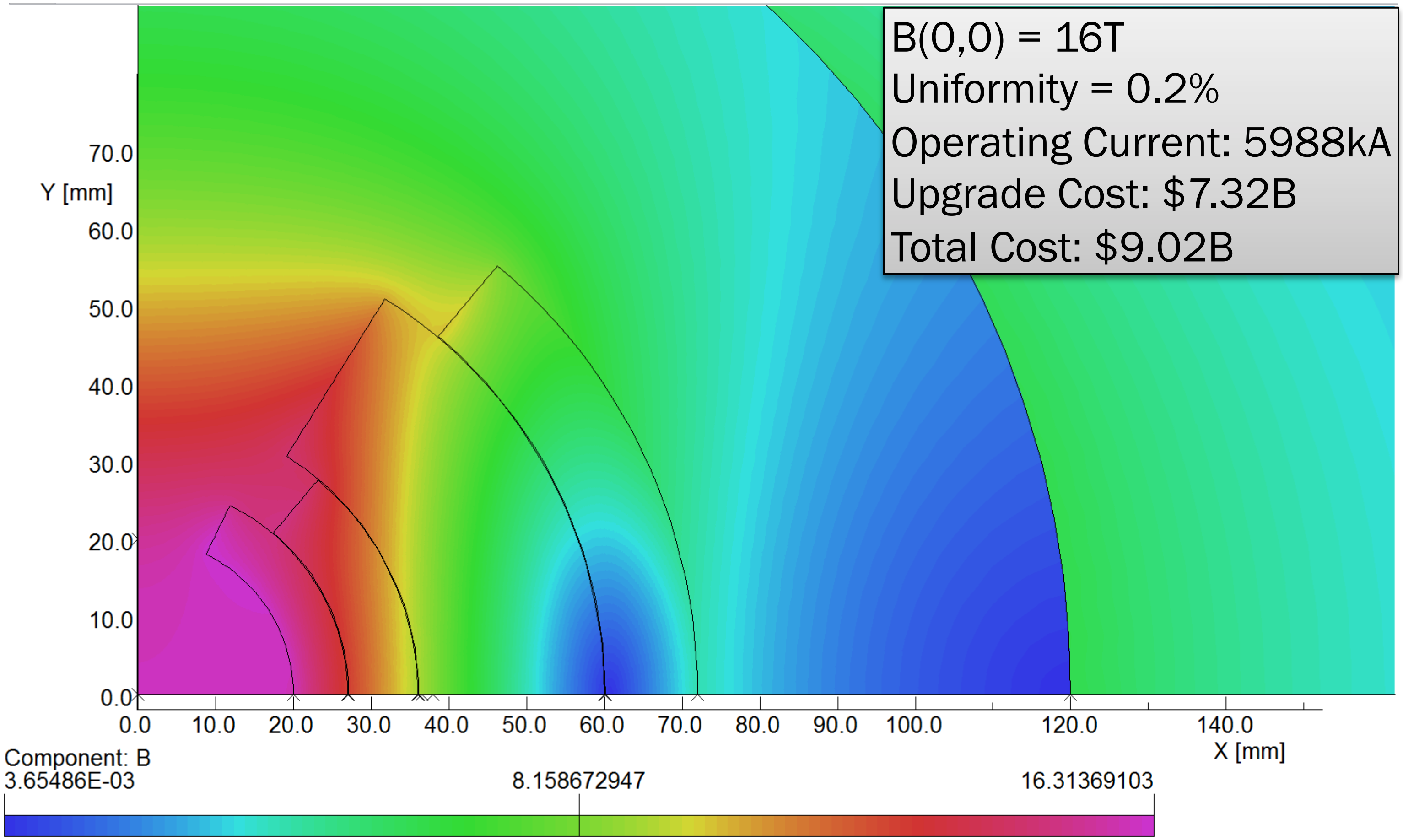


*L. Rossi and E. Todesco. Conceptual design of 20 T dipoles for high-energy LHC. 2011.

10.5T NIOBIUM TIN



(10.5+5.5)T NIOBIUM TIN



CONCLUSION

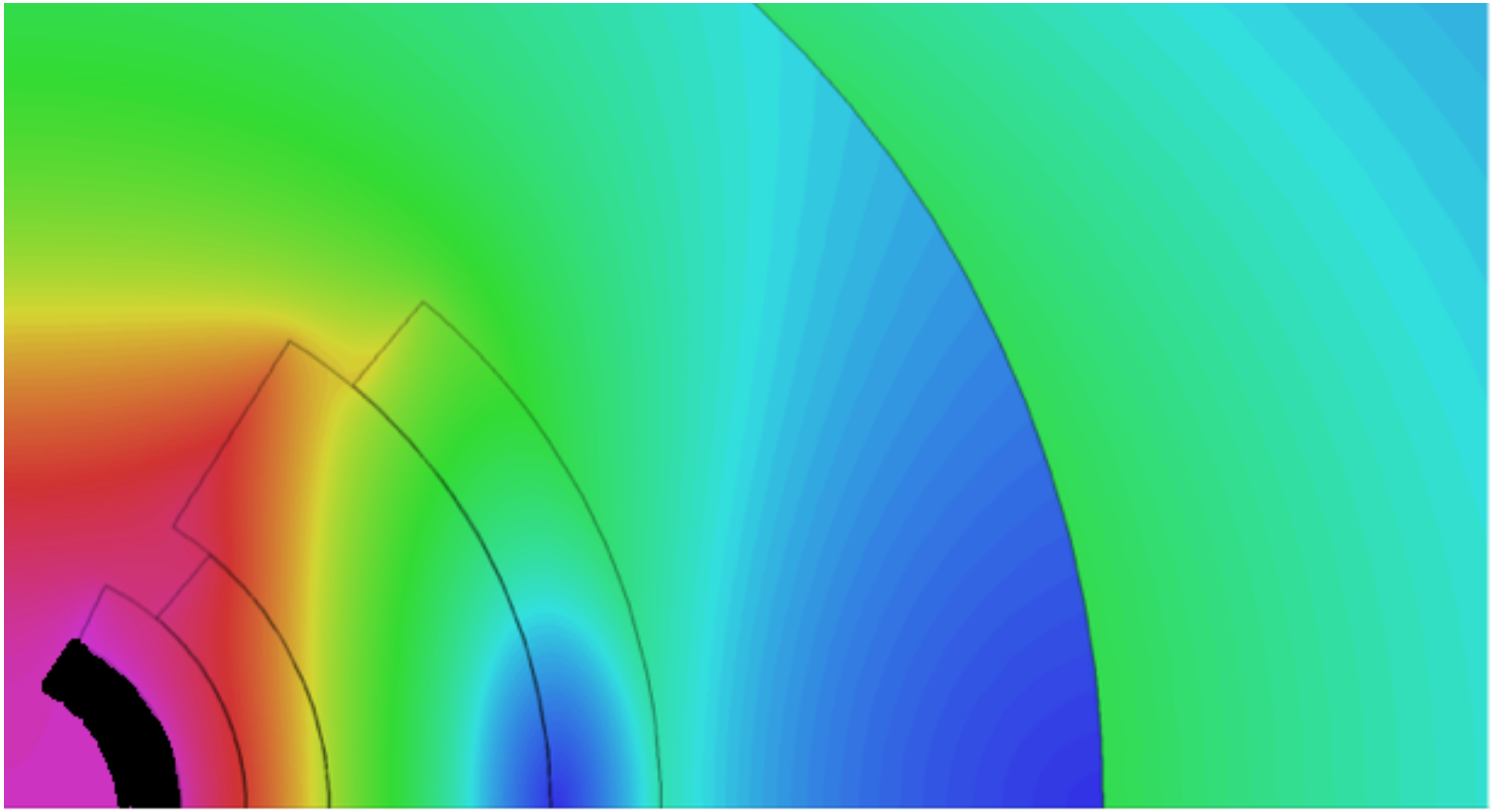
Design	Current (kA)	Amount Required (Tonnes)	Years to Acquire* **	Cost	C.O.M Energy (TeV)
10.5T NbTi	5103	9026	5	$1.81B	75
16T Nb3Sn	7830	7322	73	$8.42	100
10.5Nb3Sn	3464	1546	15	$1.78	75
(10.5+5.5)T Nb3Sn	5988	1546+6363 =7909	15+63 = 78	$(1.78+7.32)B	100

* G. Donnier-Valentin – NEEL Institut

** C. Sborchia - ITER Magnet Design

WHAT IF?

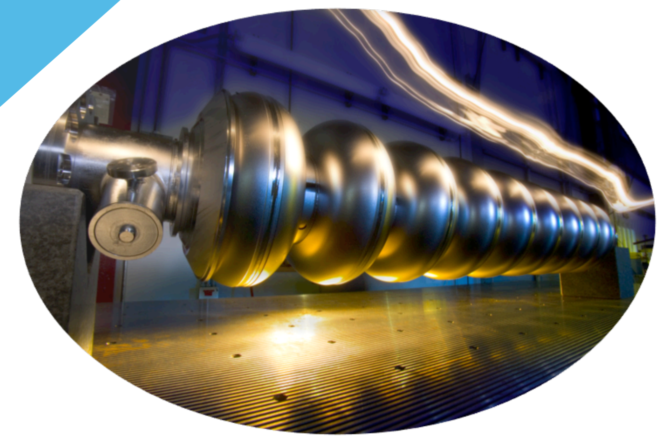
20+T Machine with 30mm Aperture?



RF CAVITIES

Talitha Bromwich & Huibo Zhang

Superconducting RF cavity
© Fermilab



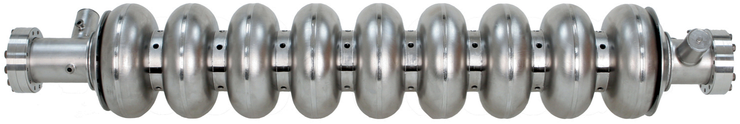
Design of the RF structures for particle acceleration

- Accelerating voltage required per turn
- Optimisation of cavity geometry
- Cavity models in 2D and 3D

SUPERCONDUCTING ELLIPTICAL RF CAVITY

Calculating total RF voltage per turn required to meet accelerator design parameters

Ring circumference	100 km
Max KE (per beam)	50 TeV
Max field strength	16 T
Max injection energy	3.3 TeV
Magnetic field ramp time	25 minutes
Phase	70 degrees
Accelerating gradient	20 MV/m
Accelerating frequency	400.8 MHz
Accelerating voltage	29.8 MV/turn
SR energy loss	4.67 MeV/turn
Total voltage	34.2 MV/turn



Nine-cell Niobium superconducting cavity © ILC

← Match LHC timing

← SC cavity frontier

← Match LHC RF system

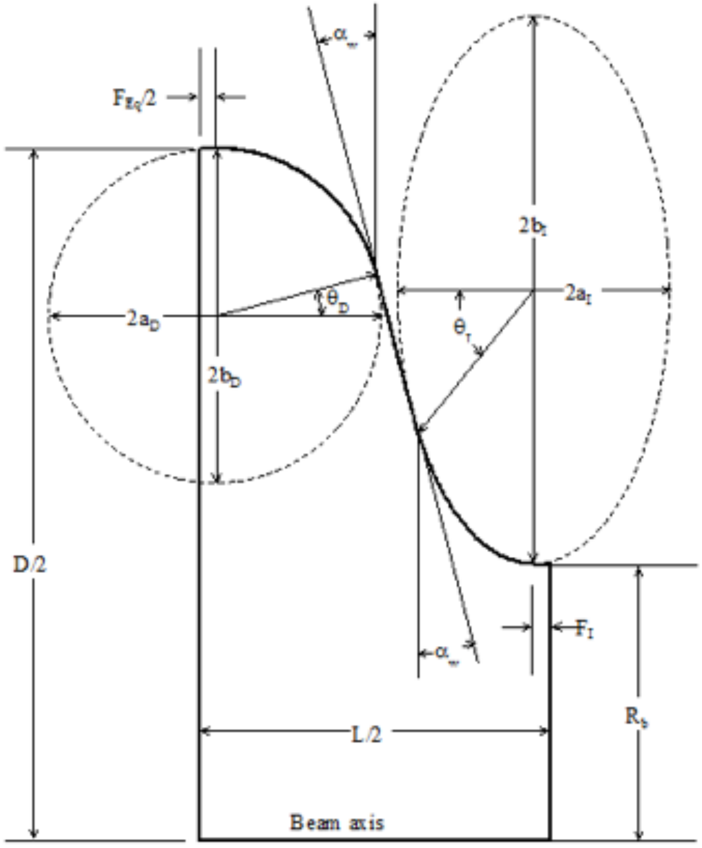
CAVITY GEOMETRY OPTIMISATION

FACTORS TO CONSIDER:

- Electric field on cavity surface - high fields might cause electric breakdown or field emission – *minimise and avoid peaks*
- Magnetic field on cavity surface - high field peaks might cause quenching or thermal breakdown – *minimise and avoid peaks*
- Quality factor Q – ratio of the stored energy in the cavity to energy dissipated along the walls - *maximise*
- Emax/Eo –*minimise*

TRY ALTERING:

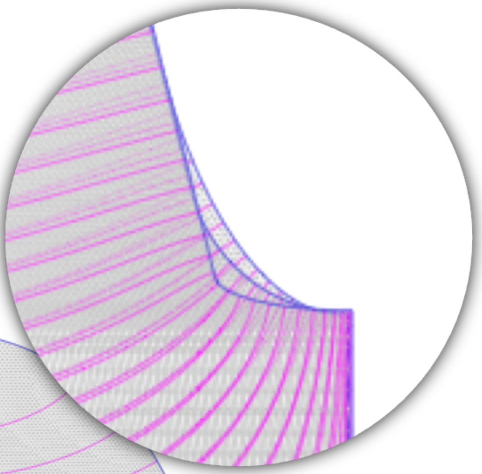
- Iris ratio a/b
- Dome ratio a/b and dome height

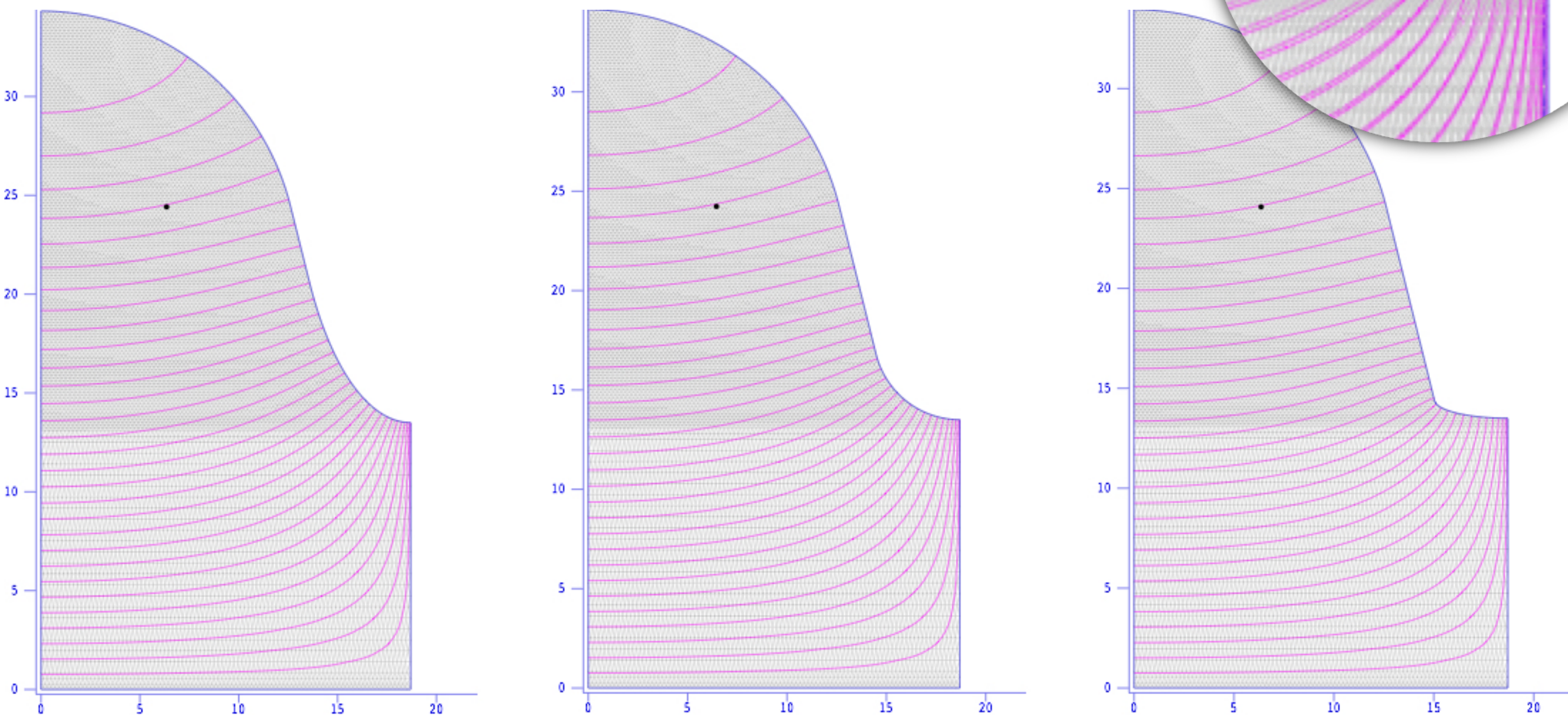


John Adams Institute for Accelerator Science

IRIS SHAPE OPTIMISATION

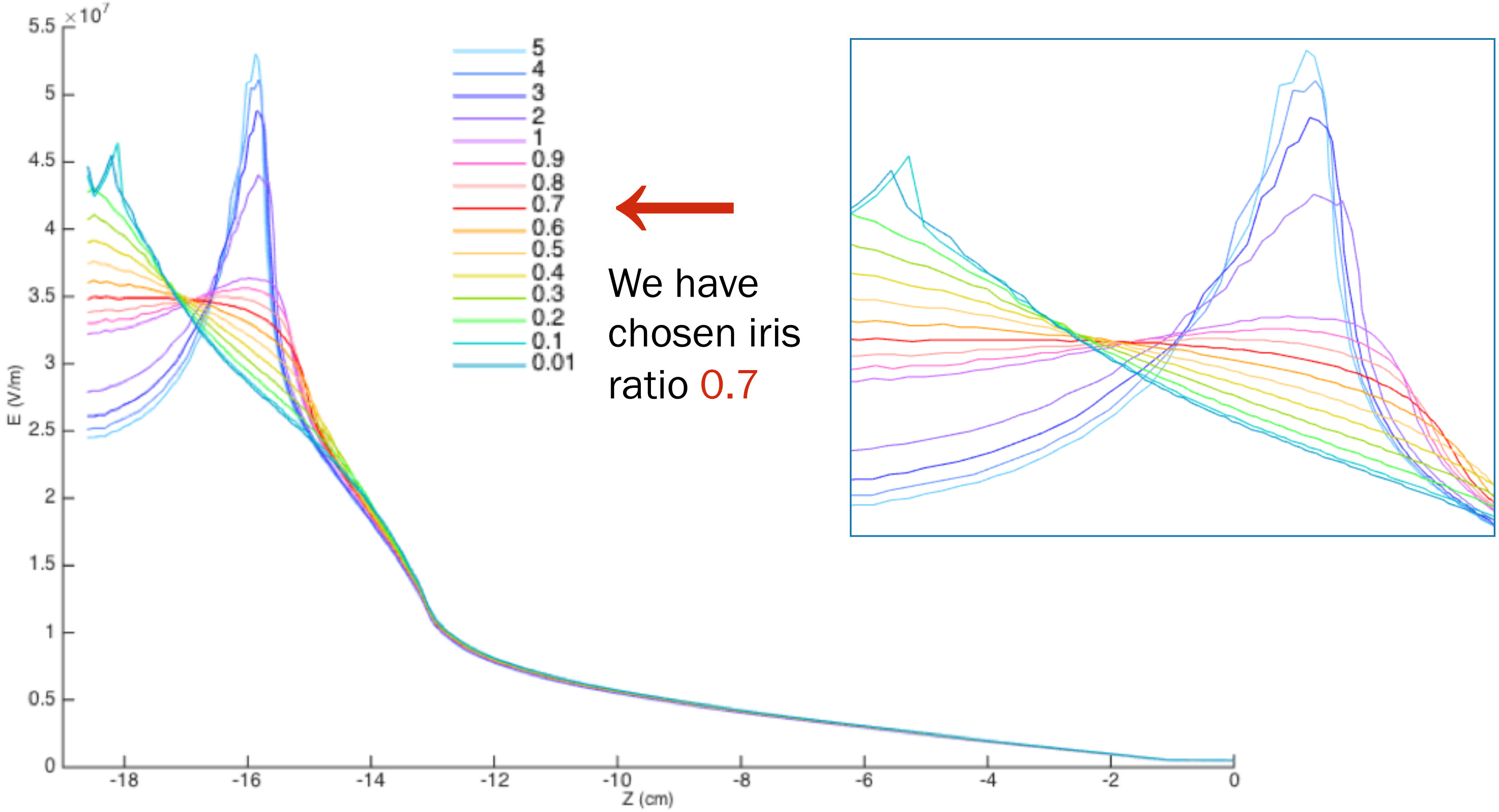
Examples of varying iris a/b ratio to change cavity geometry





0.4 1 4

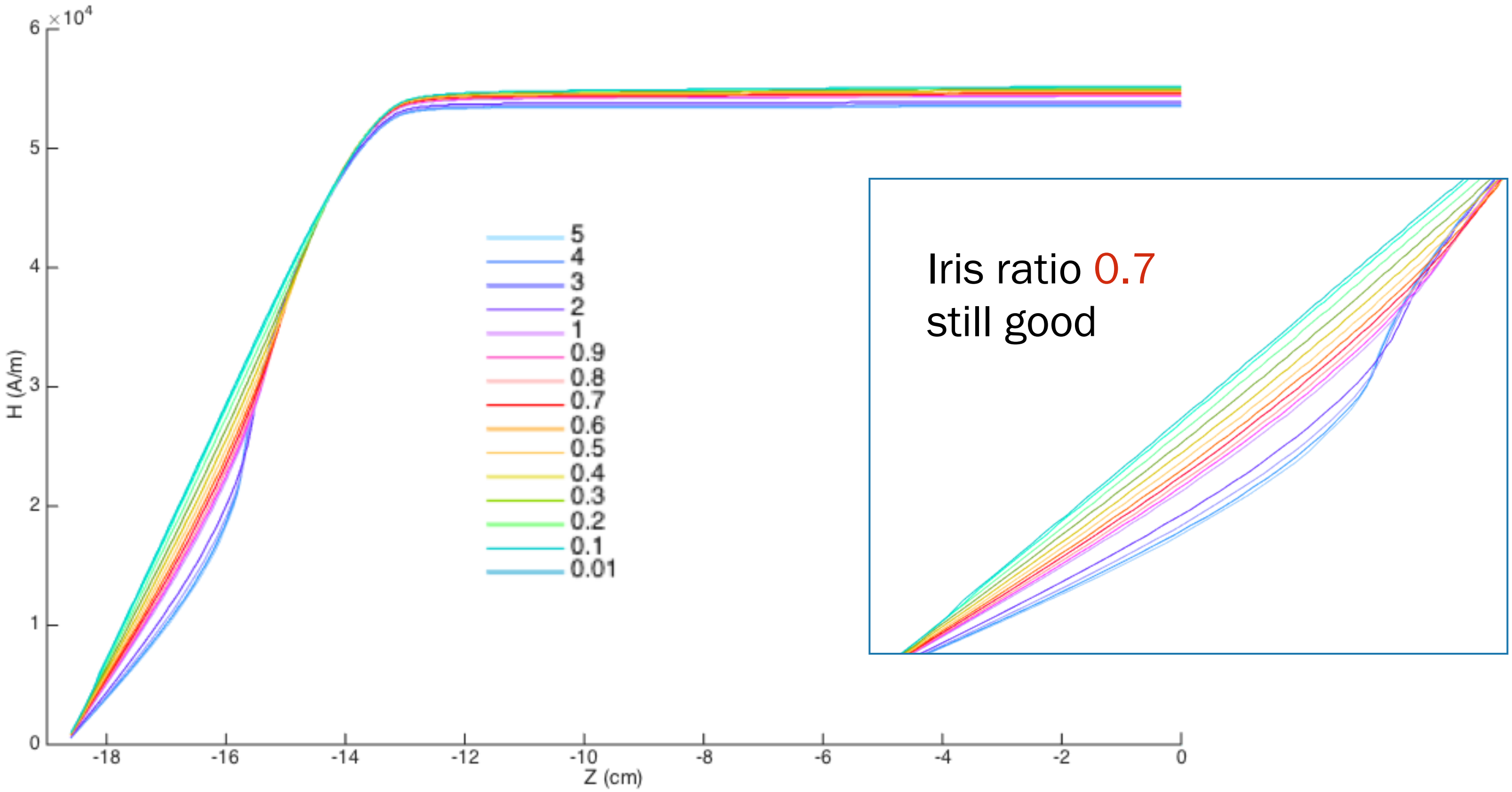
IRIS OPTIMISATION: E FIELD ON SURFACE



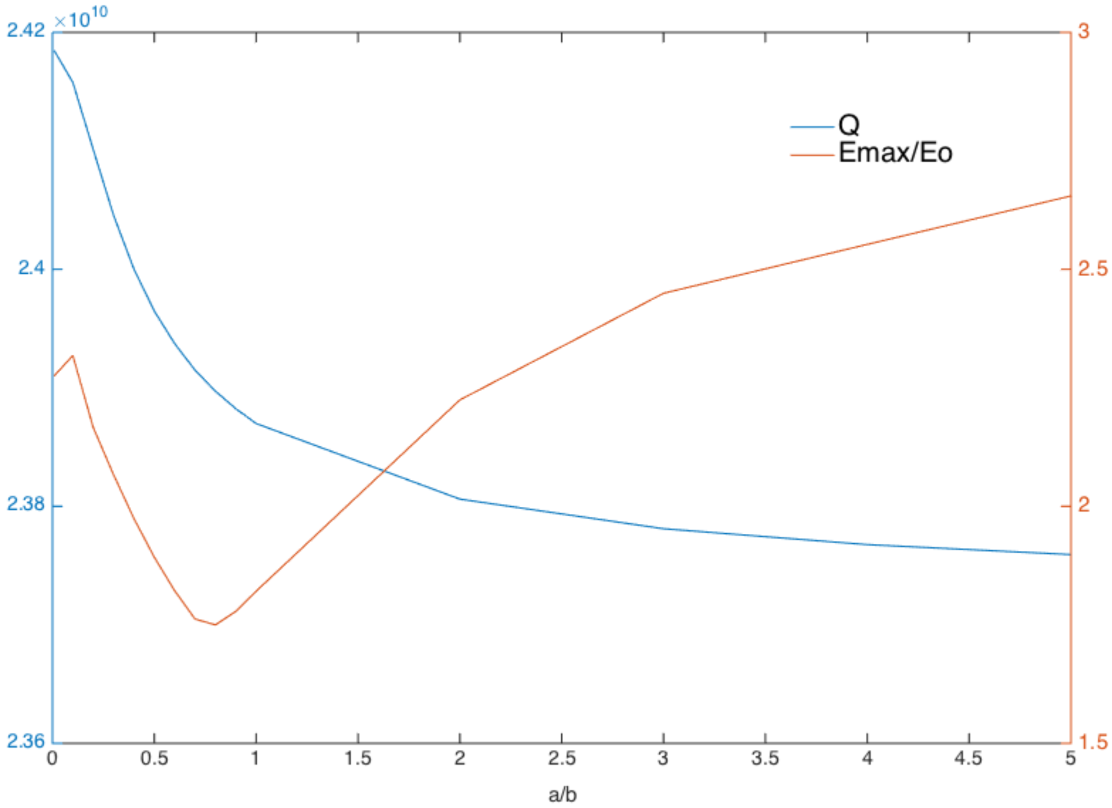
We have chosen iris ratio 0.7

IRIS OPTIMISATION: MAG FIELD ON SURFACE

All values acceptable - the surface magnetic field does not seem to vary significantly very much with changing iris dimensions



IRIS OPTIMISATION: CAVITY Q AND EMAX/EO

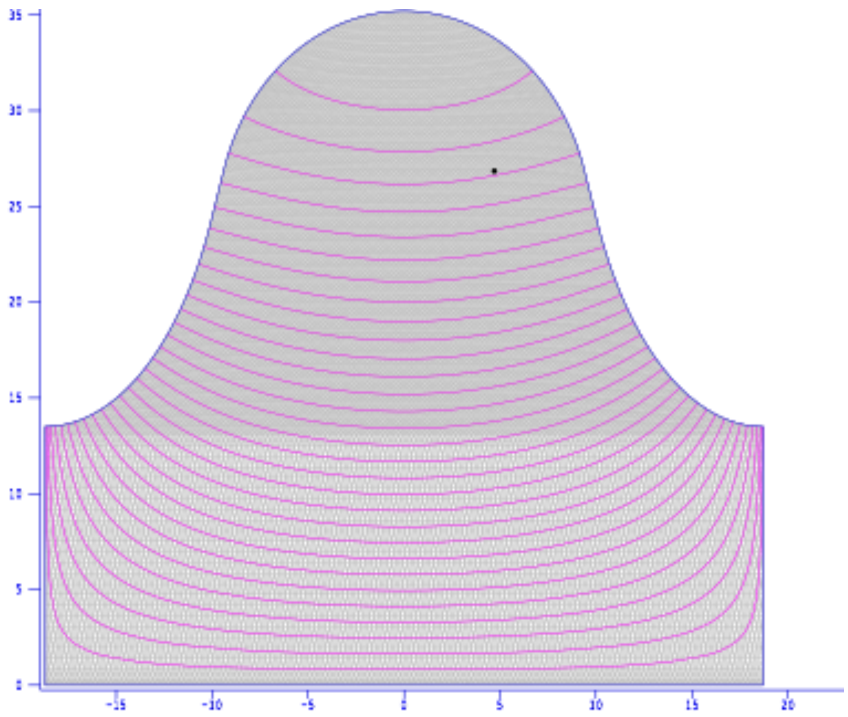


0.7 is a good compromise between maximising Q and minimising Emax/Eo

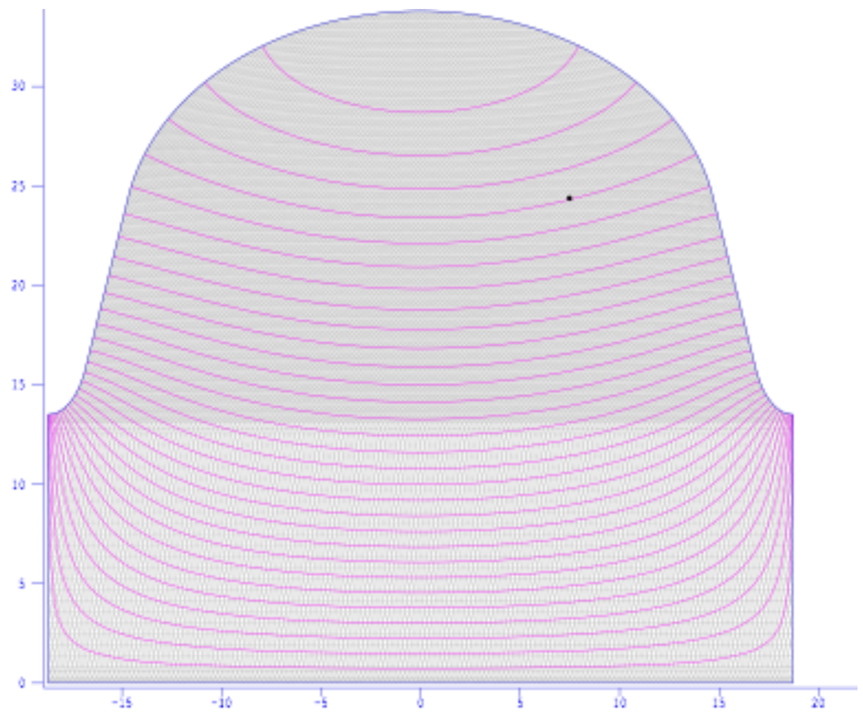
IRIS RATIO: 0.7

DOME SHAPE OPTIMISATION

Examples of varying dome a/b ratio and changes to the cavity geometry



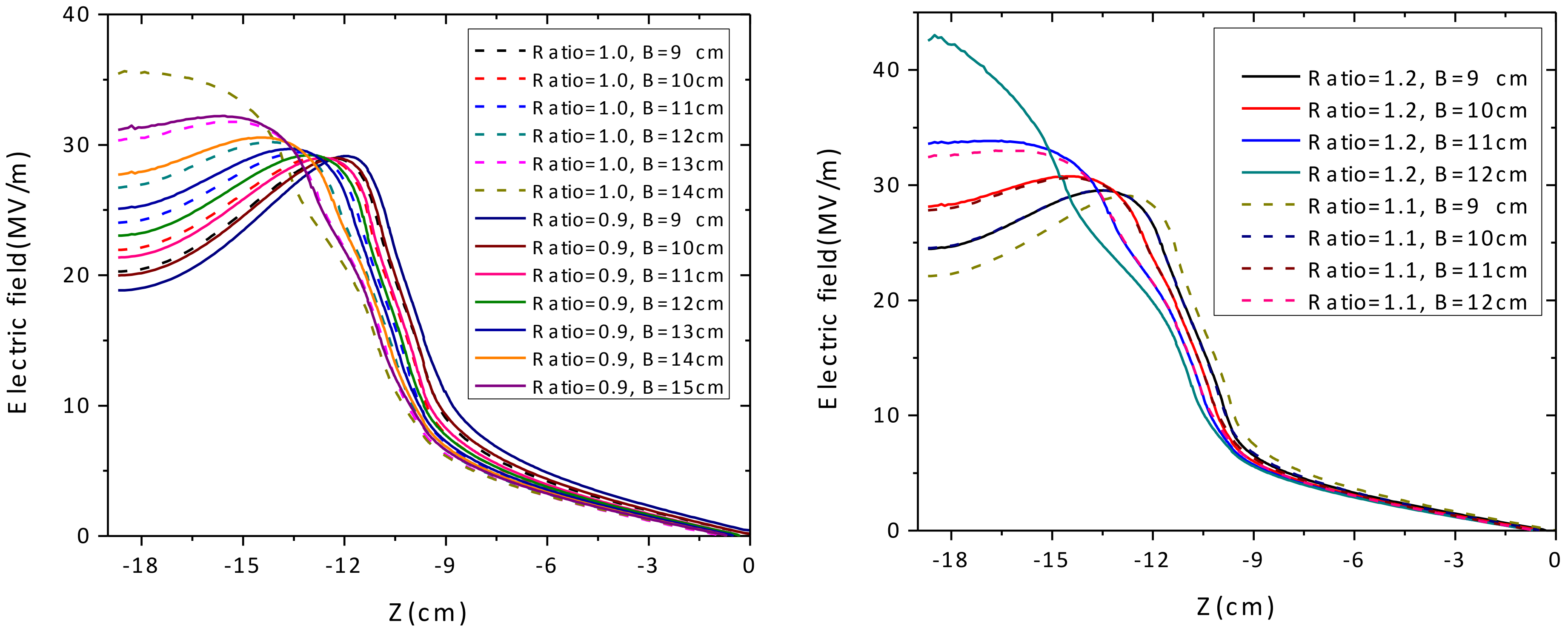
Dome a/b = 0.85



Dome a/b = 1.3

DOME OPTIMISATION: E FIELD ON SURFACE

Dome ratio varied 0.9 to 1.2, dome height 9 cm to 15 cm, iris ratio fixed at 0.7



Fixed dome ratio: maximum electric field increases with the increasing of dome height
Fixed dome height: the maximum electric field increases with the increasing of dome ratio

DOME OPTIMISATION

Optimal dome geometry combinations to avoid electric field peaks on the surface

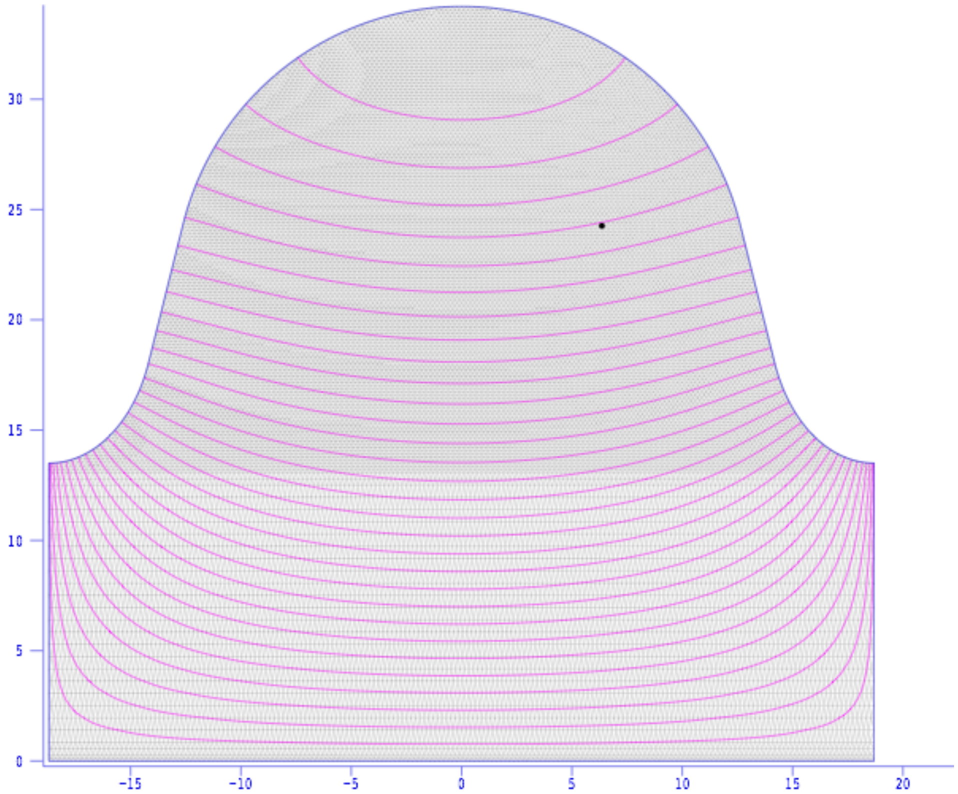
	Emax	Q (E+11)	Emax/E0
dome ratio=0.9, dome height=15cm	32.415	0.2336	1.621
dome ratio=1.0, dome height=13cm	31.98	0.2323	1.599
dome ratio=1.1, dome height=12cm	33.208	0.236	1.6615
dome ratio=1.2, dome height=11cm	34.153	0.2377	1.7072

Weighting of geometric parameters is complex: concentrate on reducing electric field on the surface, maximising Q and minimising Emax/Eo

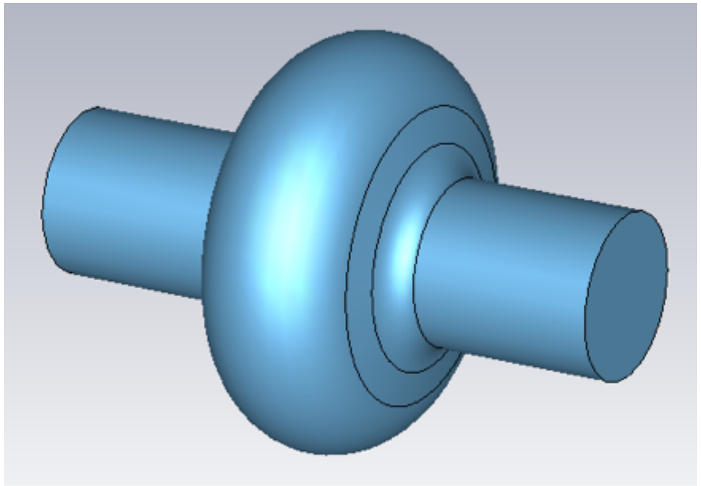
DOME RATIO 1.0, DOME HEIGHT 13 CM

CAVITY DESIGN

Single-cell elliptical cavity modelled in 2D Superfish and 3D in CST Studio



Diameter	68.415 cm
Length	37.399 cm
Iris ratio a/b	0.7
Iris horiz half axis a	4.79 cm
Iris vert half axis b	6.85 cm
Dome vert half axis a	13 cm
Dome a/b	1.0



CAVITY DESIGN PARAMETERS

	Our cavity	*TESLA cavity*
Accelerating structure	Standing wave	Standing wave
Accelerating mode	TM_{010}, Pi mode	TM_{010}, Pi mode
Fundamental frequency	400.8 MHz	1300 MHz
Accelerating gradient	20 MV/m	25 MV/m
Quality factor	2.323×10^{10}	$> 5 \times 10^{9}$
Active length	2.618 m	1.038 m
Geometry factor	269.440 Ohm	270 Ohm
R/Q	48.256 Ohm	518 Ohm
Emax/Eo	1.599	2
Bmax/Eo	3.53 mT/(MV/m)	4.26 mT/(MV/m)

B. Aune, et al, The Superconducting TESLA cavity, Phys.Rev.ST Accel.Beams (2000)

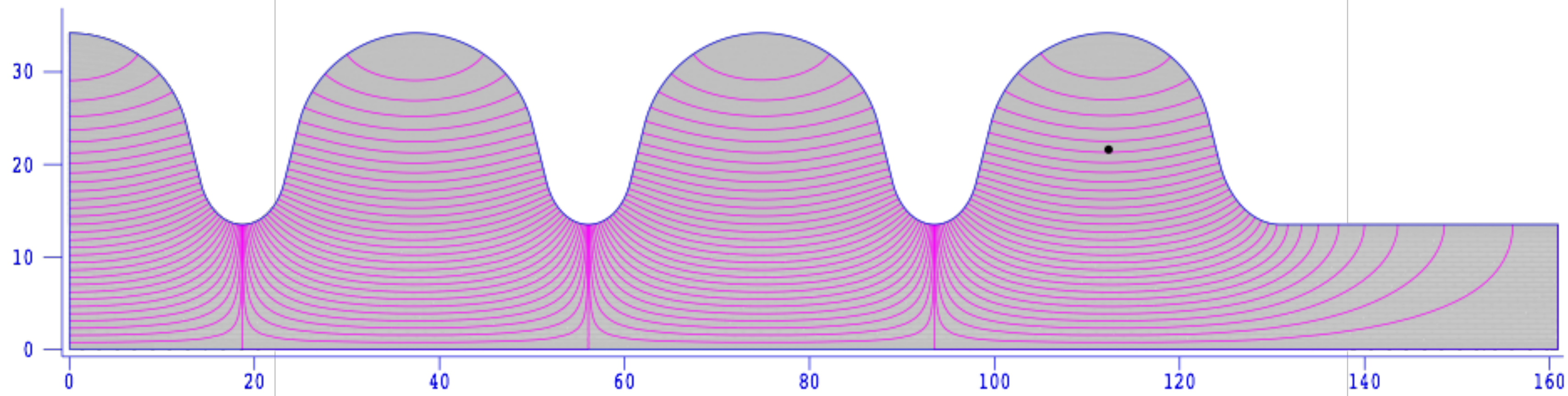
ACCELERATING GRADIENTS

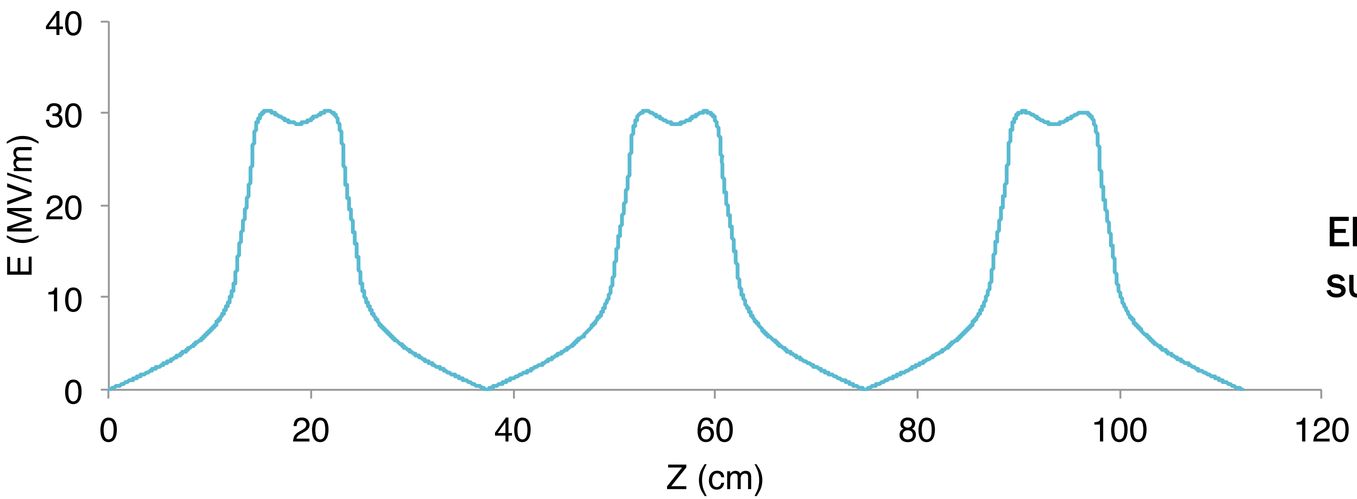
Number of cells required to achieve 34.2 MV/turn with different accelerating gradients

ACCELERATING VOLTAGE GRADIENTS	5 MV/m	10 MV/m	20MV/m	31.5MV/m
Voltage per cell (MV)	1.87	3.74	7.48	11.8
Transit Time Factor	0.778398	0.778398	0.778398	0.778398
Effective Voltage (MV)	1.37	2.74	5.47	8.62
No. cells	25	13	7	5

We have chosen 20 MV/m for our model, as it minimises RF space - which in the FCC-ee (~500 cavities) is vital - and is on the frontier of the superconducting RF cavity technology, soon to be achievable at the 400.8MHz accelerating frequency

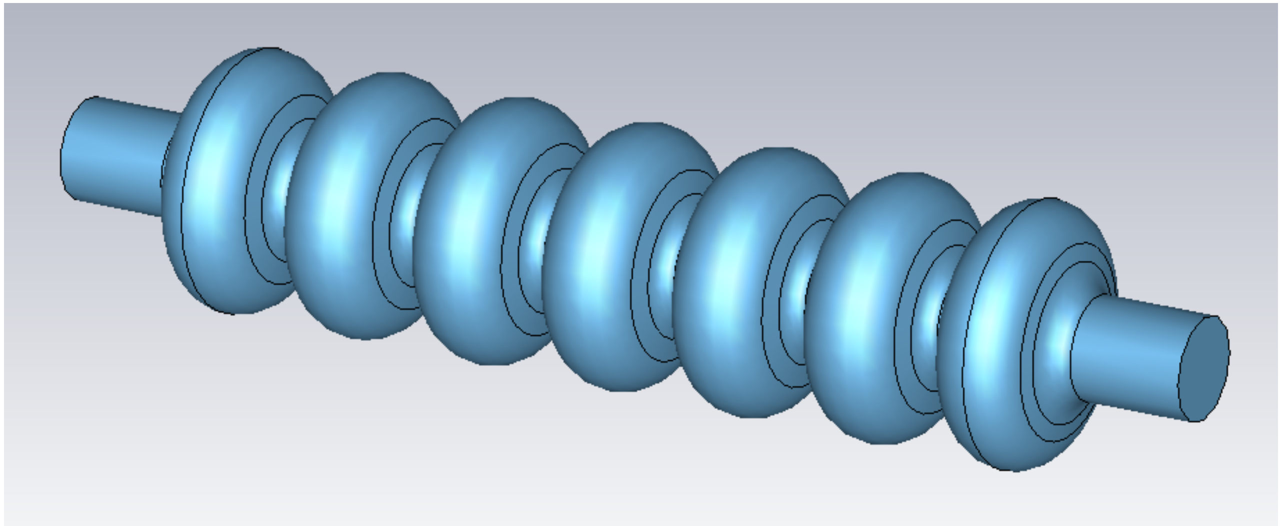
7-CELL CAVITY: SUPERFISH 2D MODEL



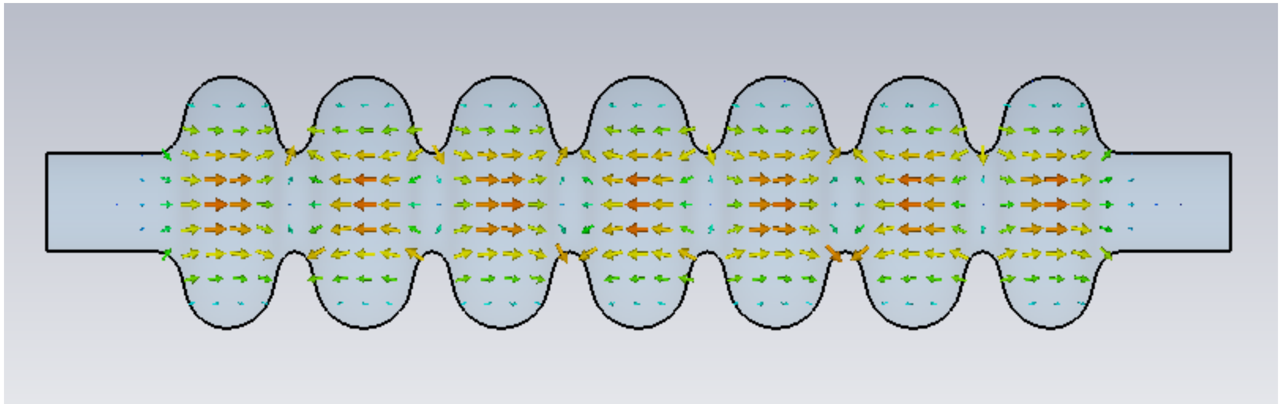


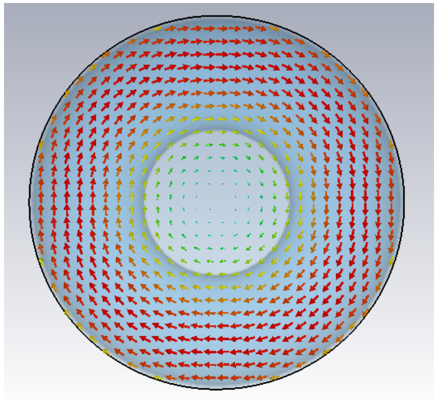
Electric field along the surface of the cavity

7-CELL CAVITY 3D MODEL: CST STUDIO



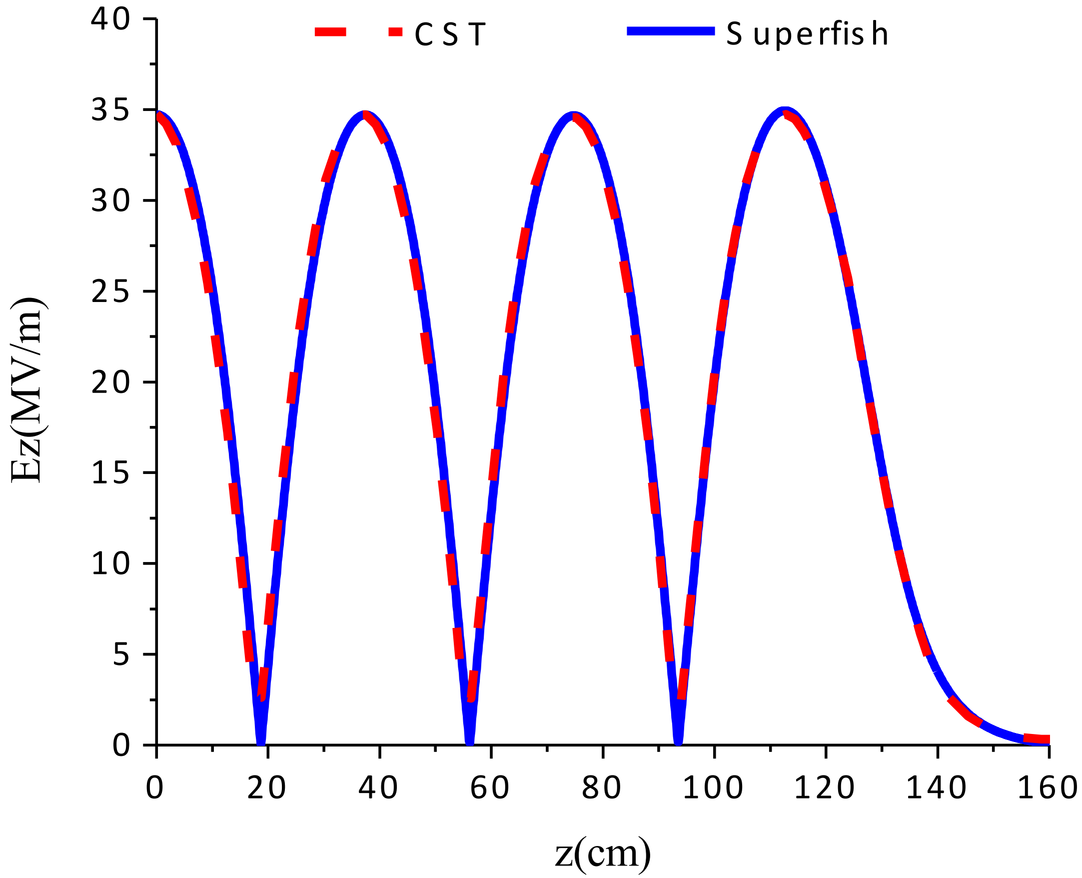
ACCELERATING MODE FREQUENCY
400.7886 MHz





2D & 3D ACCELERATING FIELD

Comparing the accelerating electric field strength of the SUPERFISH and CST STUDIO models on the axis of the cavity



Good agreement!

CONCLUSIONS

- Calculated accelerating voltage required - 34.2 MV/turn.
- Optimised the cavity geometry to achieve this at 400.8MHz by altering elliptical cavity iris and dome shape to minimise peak electric and magnetic fields, and maximise quality factor, Q.
- 2D and 3D models in Superfish and CST Studio.
- Good agreement between models.

- Also shown cavity model is quite flexible and can be adjusted in geometry and number of cells to accommodate different voltage requirements and accelerating gradients etc.

CONCLUSION

Hannah Harrison

- Ideas proposed
- Physics Implications

IDEAS PROPOSED

- **Lattice design →** reduction of aperture from 40mm to 30mm without reduction in beam energy
- **Instabilities →** loss of luminosity and huge increase in instabilities for aperture reduction from 40mm to 30mm
- **Magnet design →** high costs of installing Nb_3Sn dipoles, two solutions proposed - both at lower energy of 80TeV
- **RF cavities →** flexible to changes to design, don't impose constraints on the machine

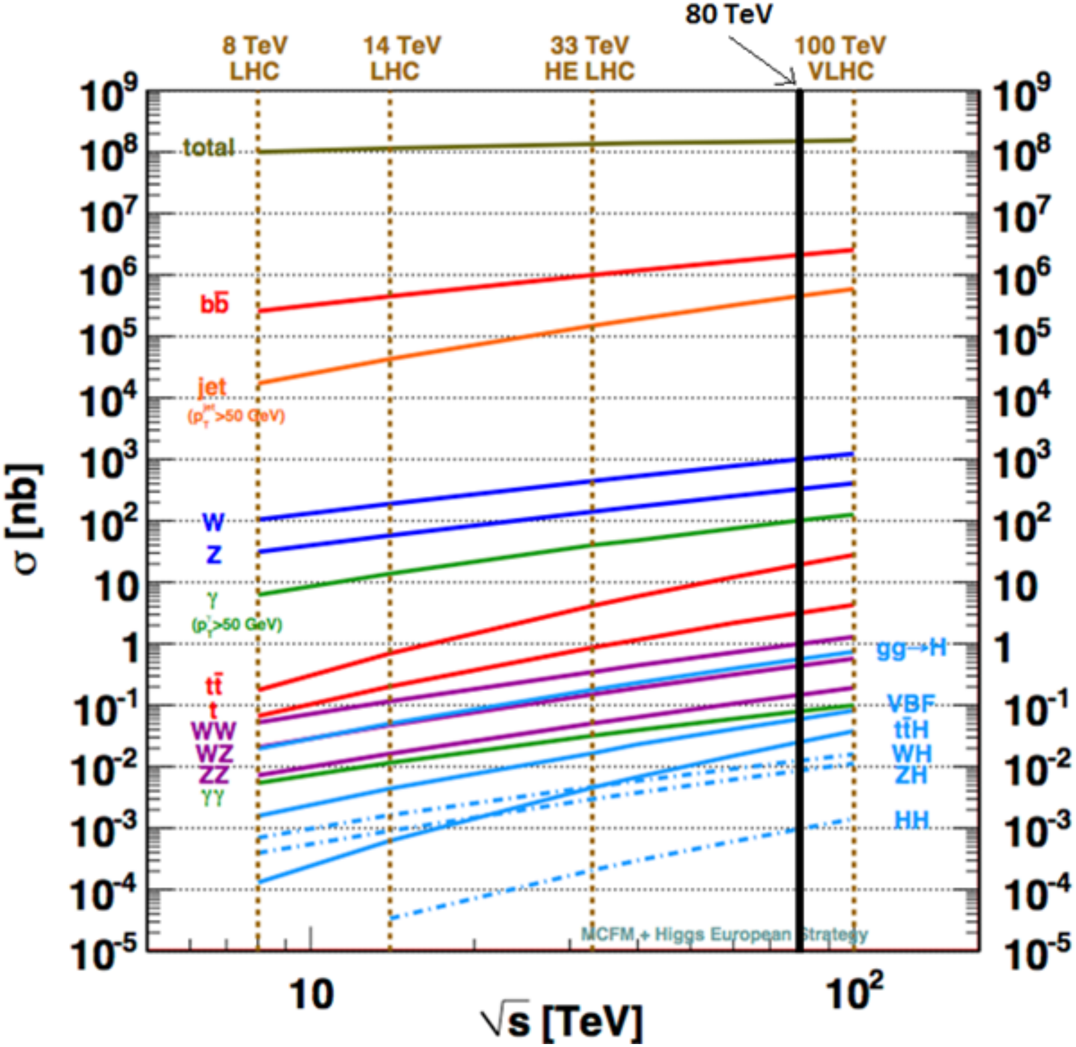
IMPORTANCE OF…

- **High Energies**
- Higher masses
- As a rule of thumb →

  "At fixed luminosity, discovery reach scales like 2/3 E_{beam}" (Presentation – Mangano (2014) CERN)

- **High Luminosities**
- Smaller Couplings (for smaller masses)
- *Luminosity particularly important as it is unknown if any particles of higher mass will be discovered.*
- The suggested changes to the Aperture would result in a large drop in luminsity → a possible deal breaker from a physics perspective

CONSEQUENCES OF LOWERING THE ENERGY



Cross section predictions at proton-proton colliders as a function of centre-of-mass operating energy $\sqrt{s}$

From: Report of the Snowmass 2013 energy frontier QCD working group

Campbell et al.

CONSEQUENCES OF LOWERING THE ENERGY

Process	σ(14 TeV)	R(33)	R(40)	R(60)	R(80)	R(100)
$gg \to H$	50.4 pb	3.5	4.6	7.8	11	15
$qq \to qqH$	4.40 pb	3.8	5.2	9.3	14	19
$q\bar{q} \to WH$	1.63 pb	2.9	3.6	5.7	7.7	10
$q\bar{q} \to ZH$	0.90 pb	3.3	4.2	6.8	10	13
$pp \to HH$	33.8 fb	6.1	8.8	18	29	42
$pp \to ttH$	0.62 pb	7.3	11	24	41	61

Evolution of the cross sections for different Higgs production processes in *pp* collisions with centre-of-mass energy. The cross sections at $\sqrt{S}$ = 14TeV are given in the 2nd column and the ratios $R(E) = \frac{\sigma(E\ TeV)}{\sigma(E=14TeV)}$ in the following columns. All rates assume M_H = 125 GeV and SM couplings.

From: Future hadron Colliders – From physics perspectives to technology R&D. Barletta et al. (2014)

FINAL CONCLUSIONS

- **Analysis of various aspects of the FCC-hh design**
  - Lattice Design
  - Instabilities
  - Magnet Design
  - RF cavities
- **Considered possible alterations to the original design proposal**
  - Aperture Reduction
  - Change of superconducting material
  - Proposal of phased construction to limit initial costs
- **Highlighted various issues and limiting factors facing the project**
  - High cost of constructing dipoles with Nb_3Sn
  - Damaging effects of luminosities at smaller apertures
  - Reduction in physics applications → especially from reduced luminosity

FUTURE WORK

- **Lattice Design**
  - Include Mini-Beta Insertions
  - Controlling Chromaticity
  - Add Kickers and BPMs
- **Instabilities**
  - Increase complexity of the models for the instabilities analysed
  - Look at more instabilities → for example electron cloud instabilities
- **Magnet Design**
  - Further optimisation of designs to reduce materials and improve quality
  - Feasibility study of staged magnet design
  - Design for quadrupoles (and sextupoles and octupoles!)
- **RF Cavities**
  - Check other modes do not interfere with accelerating mode
  - Look at other factors → such as the electric field input, polishing of the surface
  - In-depth study of magnetic field on cavity surface
  - The possibility of using multiple frequencies

THANK YOU

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LATTICE FURTHER INFORMATION

Christopher Arran

EFFECT OF DIPOLE NUMBER

- **Lattice ⇒ Bending radius:** $N_D l_D = 2\pi\rho$
- ⇒ Magnetic rigidity ($p \gg m$): $B\rho = p/e \approx E_{eV}/c$
- ⇒ Beam energy: $E_{eV} = N_D l_D Bc/2\pi$

EFFECT OF APERTURE SIZE

Smaller aperture, diameter D

- Smaller maximum beta $D \geq 14\sigma \propto \sqrt{\beta}$
- Shorter FODO cells $L \propto \beta$
- Stronger quadrupoles $k l_Q = f^{-1} \propto \beta^{-1}$
- But quadrupole strength: $k \propto dB_x/dy \propto D^{-1}$

More length in quadrupoles and spacing

⇒ Less dipole per unit length of cell

EFFECT OF APERTURE SIZE

Less dipole per unit length of arc:

- Longer arcs required
- Shorter straights

Reduces number of dipoles N_D

Reduces beam energy $E \propto N_D$

EFFECT OF DIPOLE STRENGTH

Reduces magnetic rigidity

Reduces possible beam energy

BUT:

- Increases quadrupole strength $k \propto (B\rho)^{-1}$
- Reduces quadrupole length $l_Q \propto k^{-1}$
- Slightly reduces cell length
- Slightly increases dipole fill factor

14.7 T RESULTS:

Aperture	40mm	30mm	20mm
Maximum Beta	354.6 m	199.4 m	88.7 m
Beam energy	**50 TeV**	**48.2 TeV**	**34.4 TeV**
Dipoles per cell	12	6	2
Quadrupole field gradient	450 Tm^{-1}	600 Tm^{-1}	900 Tm^{-1}
Quadrupole strength	0.002698 m^{-2}	0.003732 m^{-2}	0.007844m^{-2}
Quadrupole length	5.17 m	4.62 m	5.55 m
Cell length	208.14 m	114.04 m	53.3 m
No. Dipoles	5016	4836	3532
Dipole Fill factor	71%	69%	50%
No. Quadrupoles	948	1708	3628
No. Arc Cells	442	828	1788
Average Arc Length	7654 m	7869 m	7942 m
Short Straight Length	416 m	114 m	53 m
Long Straight Length	1203 m	1109 m	1042 m

10.5 T RESULTS:

Aperture	40mm	30mm	20mm
Maximum Beta	354.6 m	199.4 m	88.7 m
Beam energy	37.3 TeV	35.4 TeV	26.5 TeV
Dipoles per cell	12	6	2
Quadrupole field gradient	450 Tm^{-1}	600 Tm^{-1}	900 Tm^{-1}
Quadrupole strength	0.003617 m^{-2}	0.005081 m^{-2}	0.01018 m^{-2}
Quadrupole length	2.65 m	3.27 m	3.83 m
Cell length	203.1 m	111.34 m	50.46 m
No. Dipoles	5256	4980	3740
Dipole Fill factor	75%	71%	53%
No. Quadrupoles	972	1756	3820
No. Arc Cells	462	854	1896
Average Arc Length	7819 m	7905 m	7973 m
Short Straight Length	203 m	111 m	50 m
Long Straight Length	1136 m	1006 m	1006 m

16 T RESULTS:

Aperture	40mm	30mm
Maximum Beta	354.6 m	199.4 m
Beam energy	**50 TeV**	**50 TeV**
Dipoles per cell	12	6
Quadrupole field gradient	450 Tm^{-1}	600 Tm^{-1}
Quadrupole strength	0.002698 m^{-2}	0.003598 m^{-2}
Quadrupole length	5.17 m	4.82 m
Cell length	208.14 m	114.44 m
No. Dipoles	4632	4620
Dipole Fill factor	66%	66%
No. Quadrupoles	948	1684
No. Arc Cells	410	768
Average Arc Length	7078 m	7553 m
Short Straight Length	1040 m	229 m
Long Straight Length	1584 m	1368 m