FCC-ee Energy Efficient Beam Optics Design

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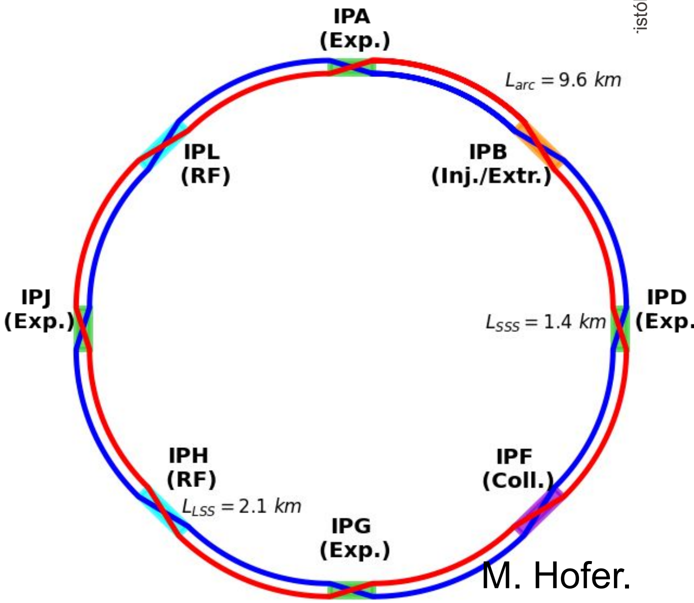
CHIPP/CHART Workshop on Sustainability in Particle Physics 2023

FCC-ee: Big size big problems

- The Future Circular electron-positron Collider (FCC-ee) is an international feasibility study to probe new phenomena coupled to the Higgs and electroweak sectors.
- It is a lepton collider in a tunnel with a circumference of about 90.65 km.
- The FCC-ee will collide beams with four different energies of 45 to 182.5 GeV (corresponding to the energies of Z, WW, HZ and tt modes) with 4 Interaction Points.
- The maximum RF power supplied to the beam to compensate synchrotron radiation at each mode is limited to 50MW



M. Hofer.

Synchrotron Radiation

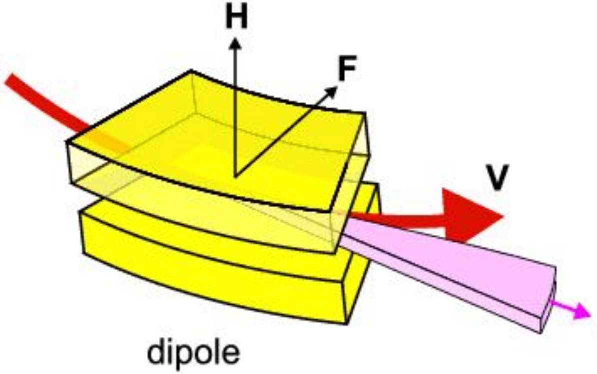
- Synchrotron Radiation (SR) is the electromagnetic radiation emitted by a charged particle beam when bent.
  In a circular accelerator this happens at every dipole.
  The total energy loss per turn per particle is:

$$U_0 = \frac{e^2}{3\epsilon_0}\frac{\beta^3\gamma^4}{\rho} \quad \dashrightarrow \quad \langle P_s \rangle = U_0 \frac{I}{e}$$

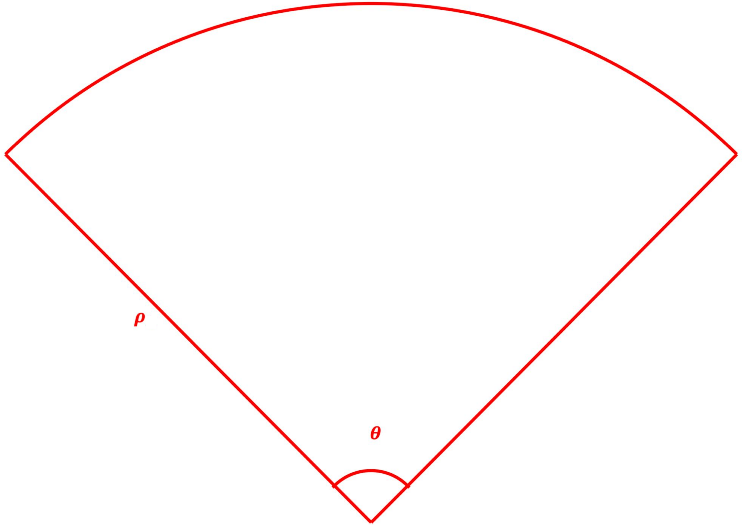
- Therefore the synchrotron radiation power per beam in MW is proportional to:

$$P_b \propto \frac{\gamma^4}{\rho}$$

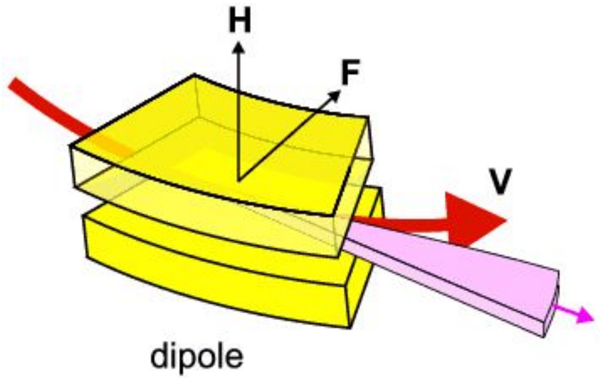
- In the case of the FCC-ee this power is about 50 MW and has to be **recovered by the RF cavities**. The only way we can reduce the power loss is to increase the bending radius.



http://pd.chem.ucl.ac.uk/pn/inst2/prop.htm



Synchrotron Radiation



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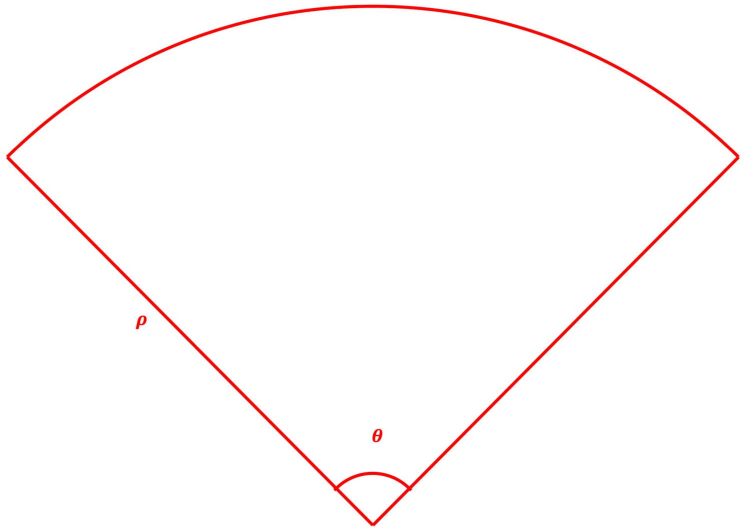
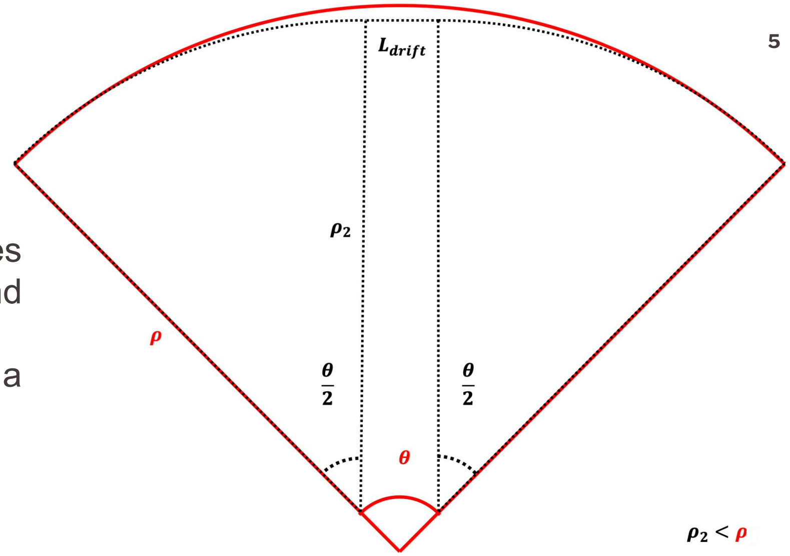
- The bending radius is the ratio between the length of the dipole arc and the angle over which the beam is bent

$$\rho = \frac{L}{\theta}$$



Synchrotron Radiation

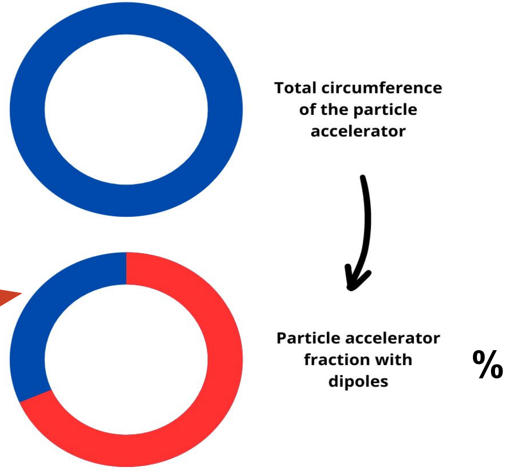
- In practice, the entire arc cannot be made of dipoles because we need space for other magnets and instrumentation
  - This means we need to install dipoles with a shorter bending radius in the same space
  - This increases the synchrotron radiation



$$U_0 = \frac{e^2}{3\epsilon_0}\frac{\beta^3\gamma^4}{\rho}$$

- For a fixed length of tunnel, to increase the $\boldsymbol{\rho}$ we need to maximize the Filling Factor, which is the fraction of the tunnel that is filled with dipoles:

$$Filling\ Factor\ [\%] = \frac{2\pi\rho}{C_0}$$

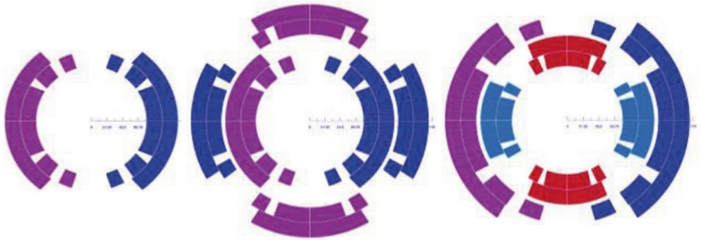


Combined Function Magnets for FCC-ee

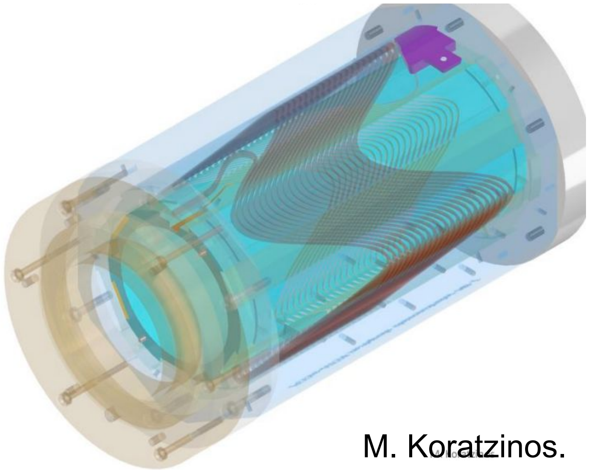
- One way we can increase the filling factor is by extending the dipole field region to the other magnets by using Combined Function Magnets (CFMs).

- Usually in particle accelerators CFMs is when a dipolar magnetic component is superimposed on a quadrupolar one. For FCC-ee we study the use of CFMs to increase the filling factor.

- Additionally, we will study the use of High Temperature Superconductors (HTS) instead of normal conducting magnets (as used in the baseline lattice) and evaluate their impact on power consumption.



M. Koratzinos. 150th FCC-ee Optics Design Meeting & 21st FCCIS WP2.2 Meeting

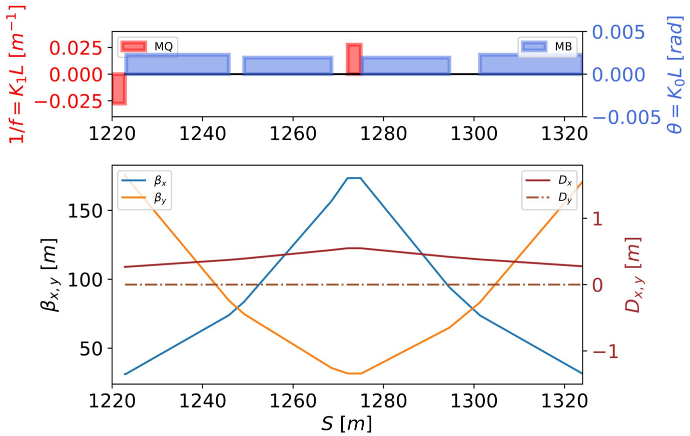


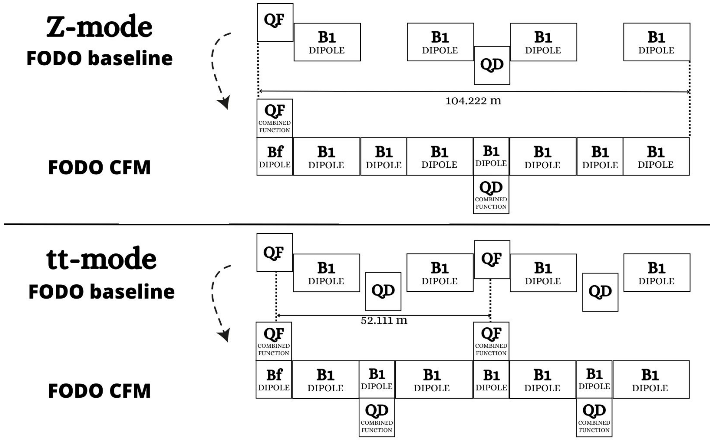
M. Koratzinos.

CFM FODO cell design

- The basic unit of an arc is known as a FODO cell and consists of dipoles placed between **Focusing** and **Defocusing** quadrupoles.
- Usually the total bending angle is distributed among the dipoles.
- We propose a new FODO that distributes the bending among the dipoles and combined function quadrupoles.

- The ratio of the dipole field between the focusing and defocusing CFM has to be optimised to achieve the correct damping behaviour and emittance.
- The design should be compatible for the Z-mode and tt-mode and the electron and positron ring.





CFM FODO cell design: equilibrium emittance behaviour

When CFMs are introduced into the lattice, the Damping Partition change due to the **introduction of a dipolar component** in the quadrupoles.
The problem comes from the radiation integral I4, that depends on the sign of K1 (quadrupole strengths).

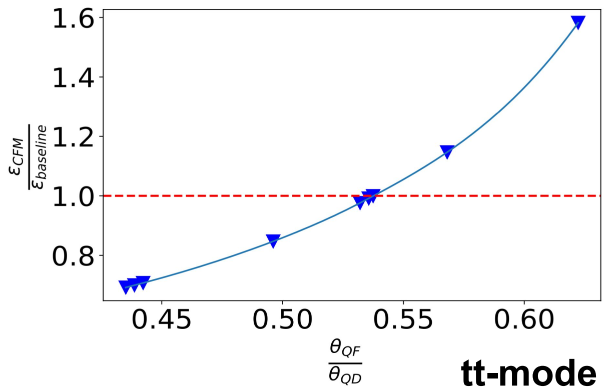
$$I_2 = \oint \frac{1}{\rho^2} ds \,, \qquad I_4 = \oint \frac{D_x}{\rho}\left(2\,k_1 + \frac{1}{\rho^2}\right) ds \,,$$

$$I_5 = \oint \frac{\mathcal{H}(s)}{|\rho^3|} ds \,, \qquad J_u = 1 - \frac{I_4}{I_2} \,,$$

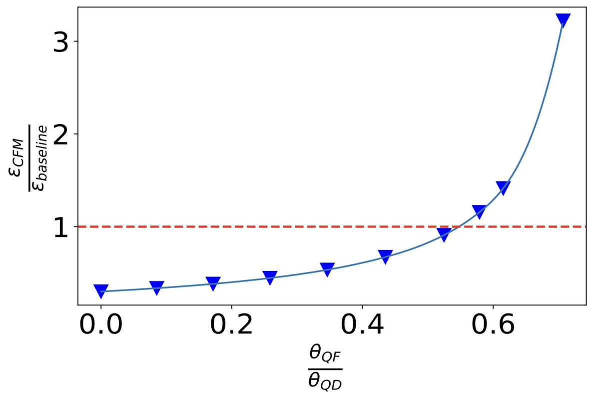
$$\epsilon_u = C_q \frac{\gamma^2}{J_u} \frac{I_{5u}}{I_2} \,, \qquad \tau_u = \frac{2E}{J_u U_0} T_0 \,,$$

We studied different ratios of bending angles in QF and QD CFMs
→ The ratio of fields (or bending angles) must be 0.53 to achieve the nominal emittance.

Z-mode

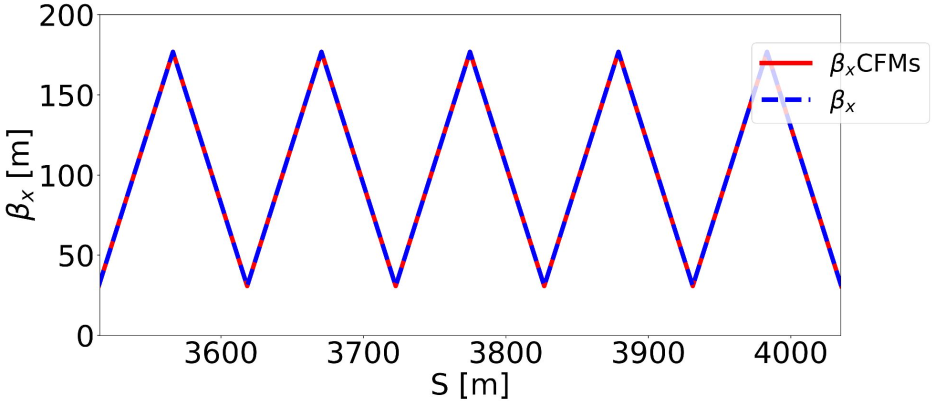


tt-mode



CFM FODO cell design: optics mismatch and elements strengths

Applying the found solution to the lattice results in similar behaviour in the optics.



The magnetic field strengths for the baseline and CFM cell in the Z mode are shown.

The **dipole field** in the main dipoles can be **reduced by almost 20%**

Element	Magnetic component		Baseline Fields		CFMs	
	Dipole	Quad	Dipole [T]	Quad [T/m]	Dipole [T]	Quad [T/m]
Mian Dipoles	B1	- - -	0.0137	- - -	0.0113	- - -
Quad F	Bf	QF	- - -	1.306	0.0060	1.306
Quad D	B1	QD	- - -	-1.306	0.0113	-1.306

Cristóbal García-Jaimes

Pros and cons of this first solution:

Pros:

-A possible reduction of 17% in the U0 for the Z and tt modes is achievable.

-Single dipole family, (current design contemplates B1, B1S, B1L)

Cons:

-Δdisplacement between e+-e- layouts is observed but can be reduced

-Incompatibility between the Z & tt modes (offset)

-Small changes in the damping partitions and times respect to baseline

	Baseline	**CFM**
Length [m]	91174.117	91174.117
$D_{x_{\max}}$ [m]	0.634	0.679
U_0 [MeV/turn]	39.06	32.33
ϵ_x [nm]	0.705	0.705
Damping times[s]	0.709 0.709 0.354	1.041 0.857 0.394
J_x J_y J_z	1.000 1.000 1.999	0.823 0.999 2.176

Power consumption – collider main magnet systems

See presentation of Jean-Paul Burnet (CERN) at FCC week 2022:

We pay twice for normal conducting magnets: one through ohmic losses, and again for removing the heat with our cooling and ventilation (CV) system.

CV needs to remove the heat of the storage and booster magnets (100MW at top), storage and booster RF (148 at top) and experiments (8MW). Total is 256MW
The share of storage ring magnets on CV is 35%, or **14MW**

Total contribution of the collider ring magnets is therefore **~100MW** at the top, 76% of which comes from the quads and sextupoles

Storage Ring	Z	W	H	TT
Beam Energy (GeV)	45.6	80	120	182.5
Magnet current	25%	44%	66%	100%
Power ratio	6%	19%	43%	100%
Dipoles (MW)	0.8	2.6	5.8	13.3
Quadrupoles (MW)	1.4	4.3	9.8	22.6
Sextupoles (MW)	1.3	3.9	8.9	20.5
Power cables (MW)	1.2	3.8	8.6	20
Total magnet losses	4.8	14.7	33.0	76.4
Power demand (MW)	5.6	17.2	38.6	89

Cooling and ventilation		Z	W	H	TT
Beam energy (GeV)		45.6	80	120	182.5
Pcv (MW)	all	33	34	36	40.2

M. Koratzinos

https://indico.cern.ch/event/1202105/contributions/5385376/attachments/2661124/4610047/HTS4_London_final.pdf

Conclusions and outlook

- First attempt to integrate CFMs in FCC-ee
  - Unbalanced bending angle to achieve optimal emittance and damping
  - 17% reduction in Synchrotron Radiation
  - Review of possible issues attributed to CFMs
    - Solutions under investigation (same quad polarity in the quads and off-set quadrupoles)

- Next steps include:
  - Introduction of sextupoles (they will be more “efficient”) in combined function magnets
  - Full integration of cells in lattice
  - Studies of machine properties with this cell, e.g. Dynamic Aperture.

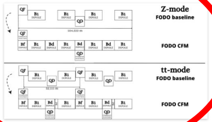
For further details:

https://acceleratingnews.web.cern.ch/news/issue-43/future-circular-collider-fcc/combined-function-magnets-constant-partition-numbers

54 magnets: The High-Luminosity LHC receives its first in-kind contribution

The completion of the High Order Corrector Magnet project was only made possible by the collaborative efforts of INFN, CERN, and industry.

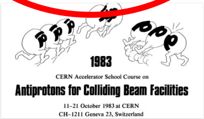
Issue 43 | High-Luminosity LHC (HL-LHC) | 14 March, 2023



Combined function magnets with constant partition numbers lattice for the Future Circular lepton Collider

Optics developments with CFMs show promising results to improve the FCC-ee performance and efficiency.

Issue 43 | Future Circular Collider (FCC) | 13 March, 2023



Collaboration and knowledge sharing: CERN Accelerator School turns 40!

Over the past 40 years, CAS has played a significant role in the advancement of accelerator science and technology and continues to be an important resource.

Issue 43 | Communication, Outreach (ACO) | 13 March, 2023

https://www.ipac23.org/preproc/pdf/MOPL066.pdf

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EXPLORING FCC-ee OPITCS DESIGNS WITH COMBINED FUNCTION MAGNETS

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Merci

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More about Beam Optics: