Nested Magnet Optics for FCC-ee

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Thanks to: K. Oide, J. Kosse, B. Auchmann, A. Thabuis, M. Korazinos and many others

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Motivation

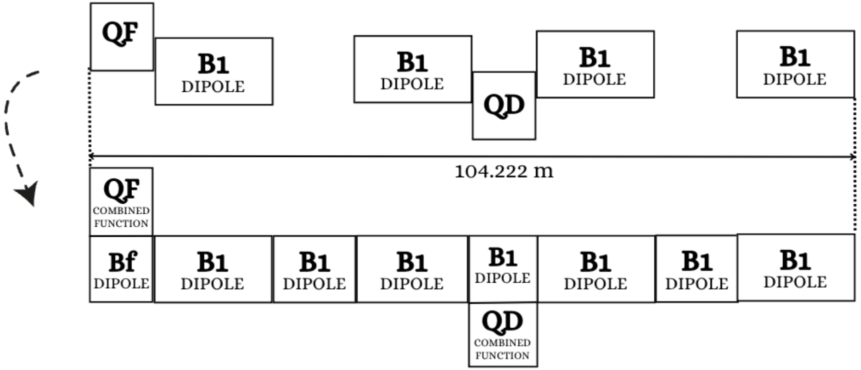
- **Superconducting short straight sections** in arc to replace warm quadrupoles and sextupoles (M. Korazinos)
  - Save energy from **ohmic heating**
  - Allows for **nested magnet designs** that are individually powered
- Nested magnets provide multiple **benefits**
  - Nesting dipoles in place with quadrupoles and sextupoles to **increase fill factor**
    - Increase **bending radius** and **decrease synchrotron radiation** power
    - **Reduce energy consumption** or allow for **higher beam current**
  - Nesting of quadrupoles, sextupoles and/or correctors for improved **relative alignment**
- Potential interest in **alternative technology** for nested or combined function magnets

Damping Partitions and Stability

- **Initial** approach to uniformly distribute integrated dipole field **across all dipoles, quadrupoles and sextupoles** in FODO
  - $B_{new} = B_{old} \frac{L_{dipoles}}{L_{dipoles}+L_{quadrupoles}+L_{sextupoles}}$
- Radiation in focusing quadrupoles, **reduces horizontal damping** partition, leading to **no stability** for horizontal equilibrium emittance
  - $I_4 = \oint \frac{D_x}{\rho}\left(2k_1 + \frac{1}{\rho^2}\right) ds$
  - $J_x = 1 - \frac{I_4}{I_2},\ \epsilon_x = C_q \frac{\gamma^2}{J_x} \frac{I_5}{I_2}$
- **Unique problem** for nested magnets
- Requires **careful choice of dipole field** in nested magnets

Optimised Bending Angle

- Careful **choice** of bending angle required to **optimise emittance**
- **Solution**:
  - **Reduce** dipole field in **focusing quadrupoles** Bf
  - **Uniformly increasing** field B1 in **arc dipoles** and **defocusing** ones
- **Target**:
  - Achieve horizontal emittance in tt lattice **equivalent** to **baseline design**
  - **Alternative** emittances **can be achieved** depending on design requirements



Schematic comparison between baseline and NM option for Z lattice.

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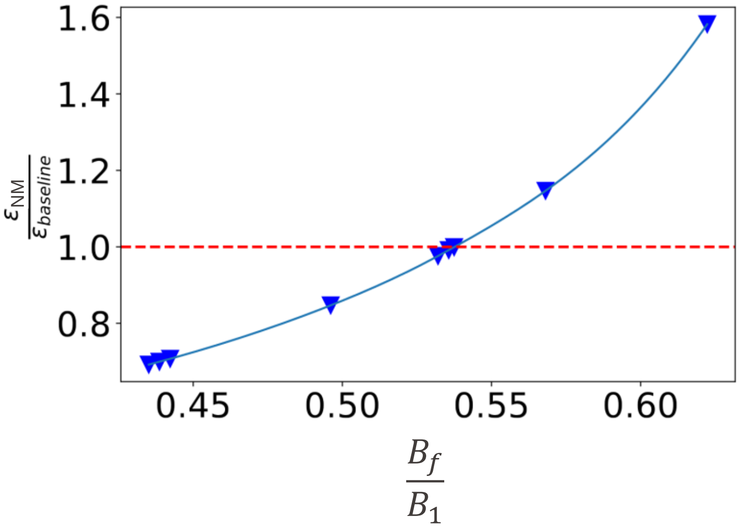
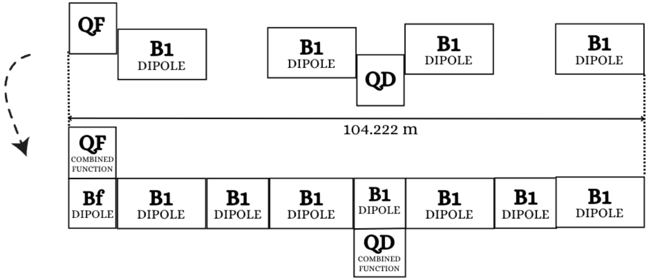


Horizontal emittance compared to baseline for different ratio of dipole field in focusing and defocusing quadrupoles.

Arc Cell Solution

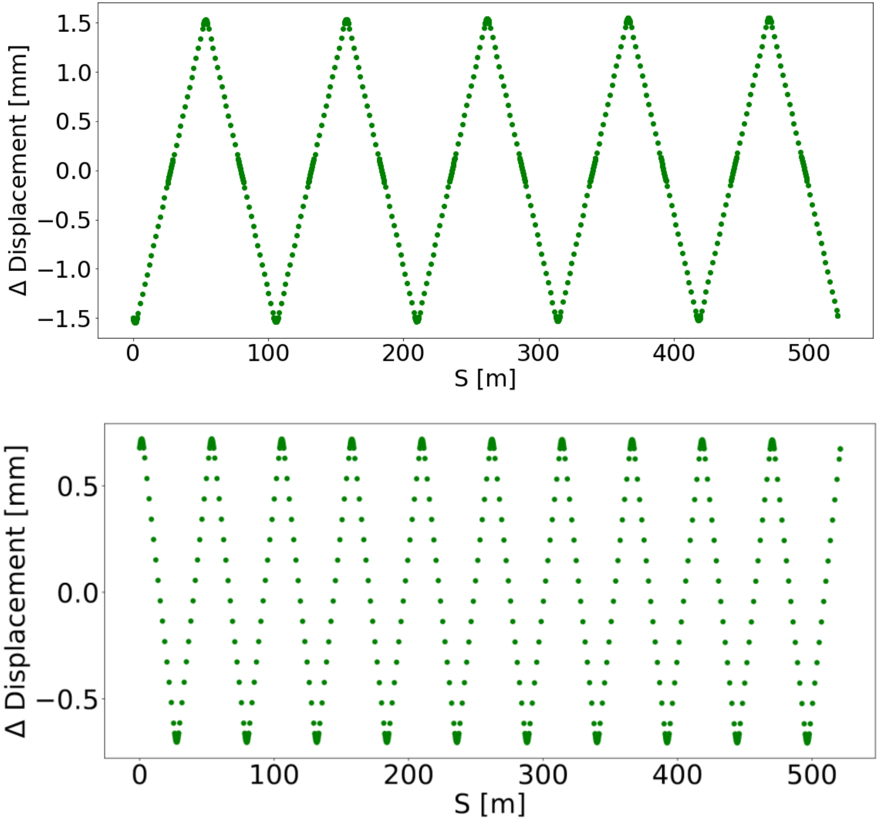
- **tt arc cell** with horizontal equilibrium emittance (**1.39 nm**) close to baseline design (**1.49 nm**)
  - Achieved with dipole field in focusing quads reduced by a **factor of 0.54**
- **Reduction of radiation power by 16.5 %**
  - 9994.85 MeV/turn to 8353.07 MeV/turn
- β and dispersion **beating less than 1 %** compared to baseline
- Optimised dipole field recovers emittance and stability but brings **new complications…**



Schematic comparison between baseline and NM option for Z lattice.

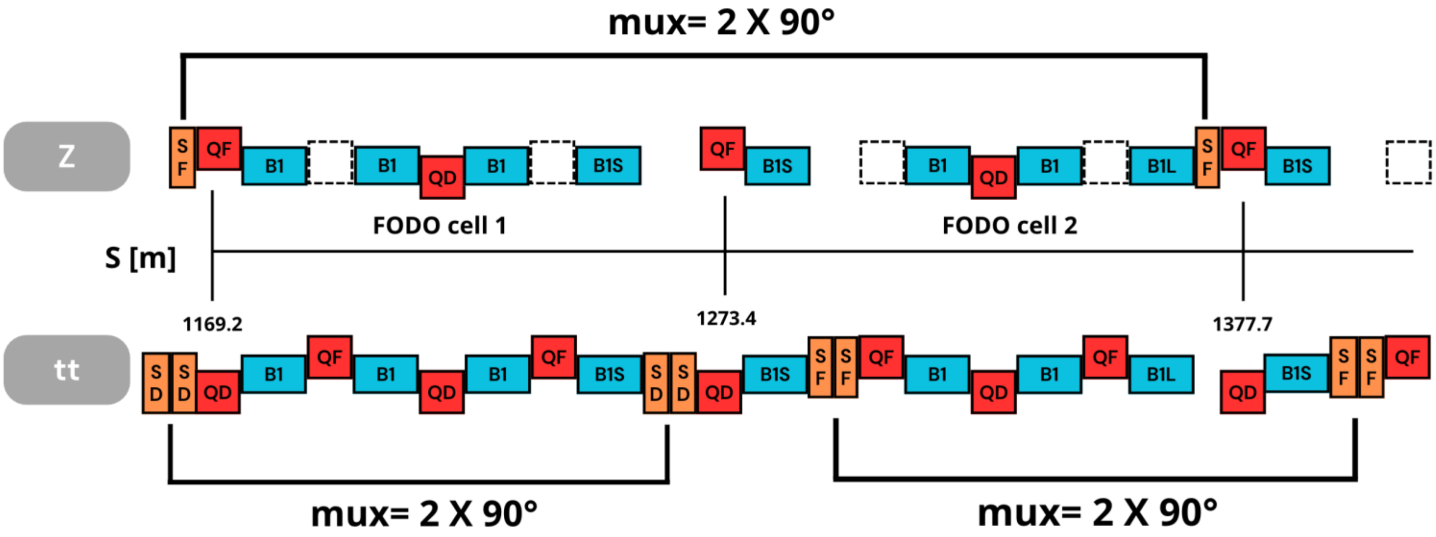
Complication 1: “Zig-zag”

- Baseline design assumes **twin quadrupole** design for two beams
  - **Focusing QF for e+ and defocusing QD for e-**
  - Allows **sharing of same yoke** to lower power
- Different **dipole fields** results in horizontal **orbit offsets** between two beams
  - Up to **1.5 mm in Z lattice**
- Could be **tolerable** for the **physical aperture**
- **NMs do not impose polarity constraints** between e+ and e-
  - **Change lattice design** to QF/QF and QD/QD



Displacement between horizontal orbit of e+ and e- ring for QF/QD NM layout for z (top) and tt (bottom)

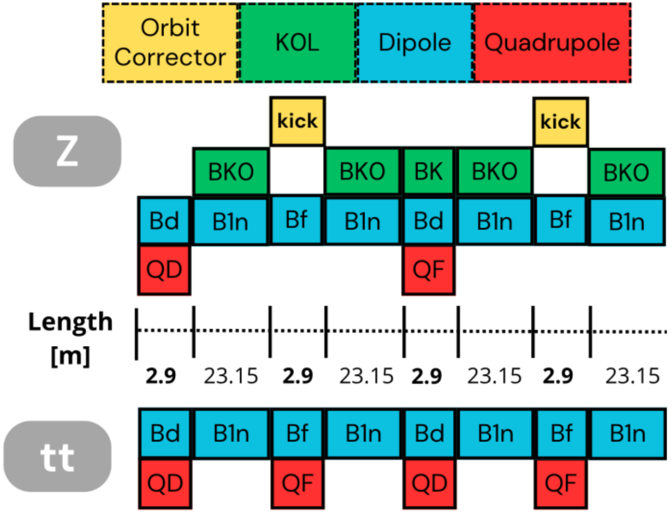
Complication 2: Z vs tt Layout



- **tt lattice** requires arc cells **half the length** of those in **Z lattice**
  - Results in **flipping of polarity** of focusing quadrupoles
- Also **change in dipole** field in quadrupoles **to preserve partitions**
  - Results in a **different geometric layout** of design orbit

Solution 1: Differing Reference and Magnetic Layout

- Solution **without realignment** possible
  - Using **tt-layout as baseline**
- Achieved by
  - **Adjusting magnetic bending angle** (k0)
  - Whilst keeping **reference orbit bending angle unchanged**
  - Using quadrupole gaps in Z-lattice as **kickers to close orbit**
- Results in a **deviation** of about **2 mm** between closed and design orbit in arcs
  - **Complications** due to **feed-down** from sextupoles and quads
  - Possible complication for **synchrotron radiation**



Magnetic layout for non-realigned solution between z and tt

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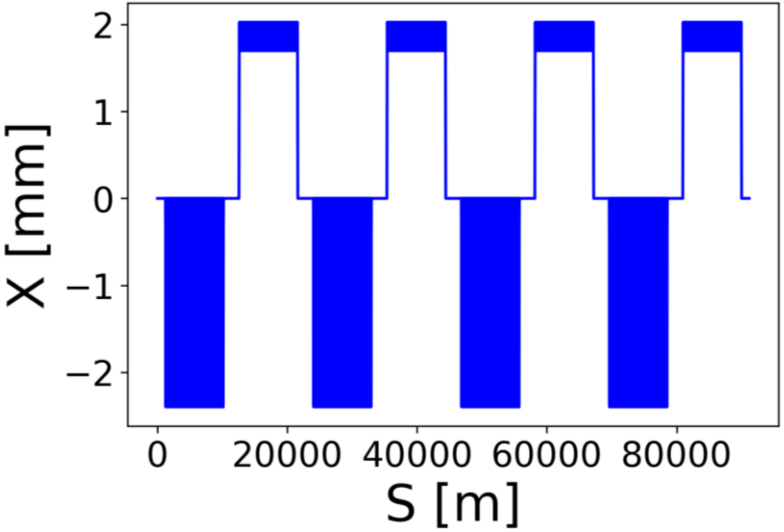
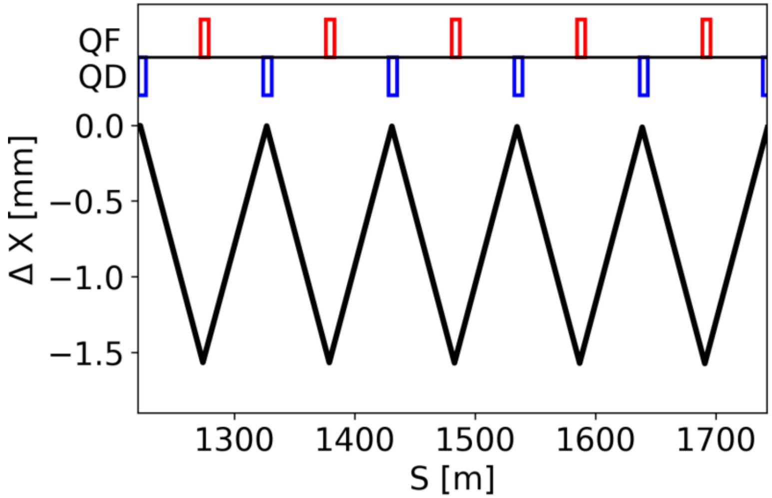


Orbit in arcs of Z lattice without realignment

Solution 2: Full Realignment

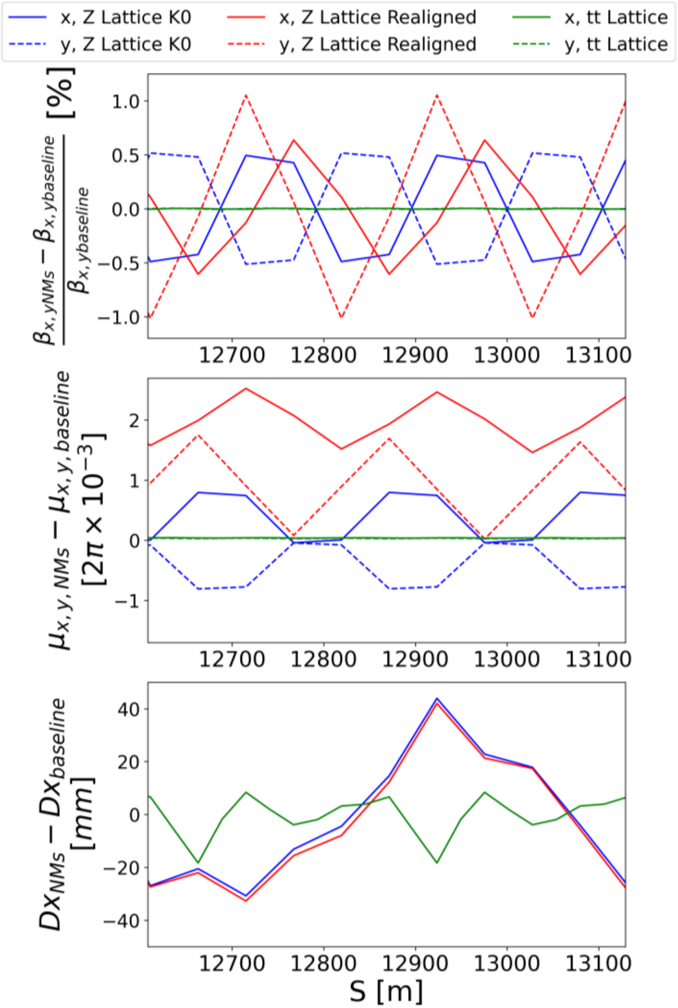
- More **costly and labour intensive** solution would be to fully **realign** the entire machine **when changing operation mode** from Z to tt (or vice versa)
  - Requires a **realignment of every focusing** quadrupole by 1.5 mm
  - **Manually** or through **automated** movers
- More **favorable** solution from **beam-dynamics** point of view
  - No complicated sextupole feed-down to correct



Realignment requirements when switvching between Z to tt mode.

Comparison with Baseline FODO

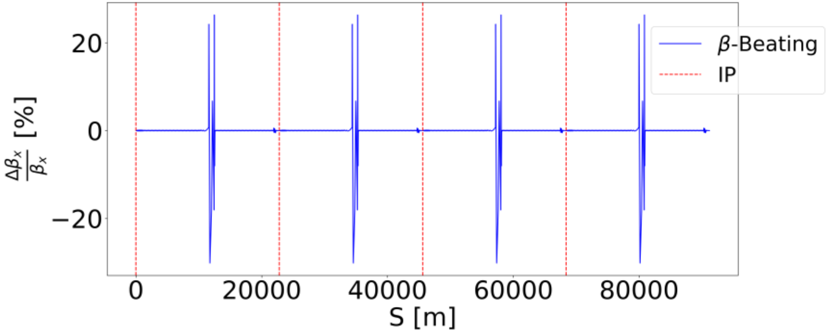
- Almost **no difference** between **baseline** optics and optics obtained with NM
  - **Less than 1 % β-beating**
  - **Few mm dispersion beating**
- Closeness to baseline means
  - **Simpler integration** of baseline **insertion regions** for full ring design
  - **Baseline sextupole** configuration should be compatible
    - For **chromaticity** correction and **dynamic aperture** optimisation
    - **Avoids** complex **re-optimisation**
    - **More difficult** for **non-realigned** layout due to sextupole feed-down



Optics beating between baseline and NM lattices.

Compatibility with IRs

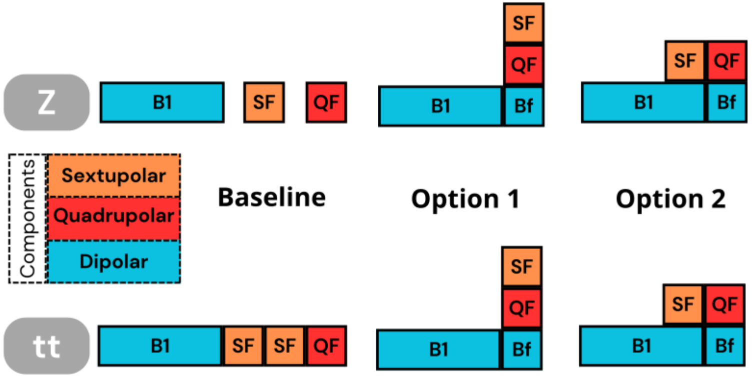
- Small differences in optics require **rematching of IRs**
  - To obtain **baseline optical functions** in RF and experimental insertions
- Rematching can be achieved with using **first few quadrupoles** in IR
  - **Maximum change** in β function of **about 20%**
    - **Limited to matching region**
  - **Fully recover baseline optics** for full integration
- In the case of **no realignment** kickers required to **close orbit** at IR interface



Change in β function due to rematching of straight sections

Sextupoles and First Dynamic Aperture Studies

- **Two options** for nested sextupoles:
  - Option 1: **All coils nested**
  - Option 2: Sextupoles nested with **dipoles only**
- **Scaled** in two steps:
  - Same **integrated sextupole field** as baseline
  - **Uniformly scaled** to achieve baseline **chromaticity**
- **First DA** studies performed without any further optimisation
  - **Reduction of horizontal dynamic** aperture but **not zero**
  - **Slight increase in vertical**
  - **More** higher order amplitude and momentum **detuning**
  - **Further optimisation required**



Options for nested sextupole layouts

Sextupoles and First Dynamic Aperture Studies

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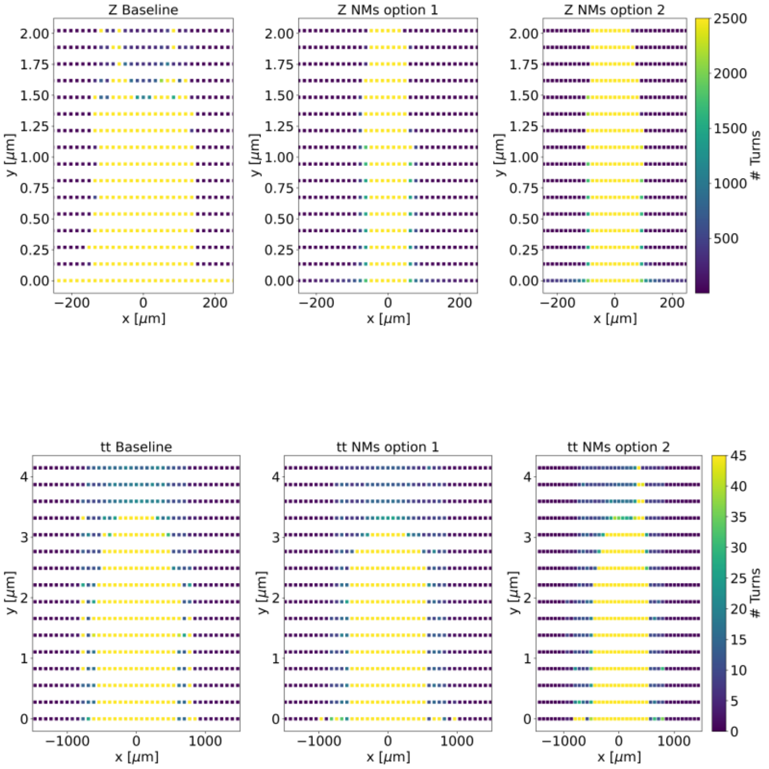
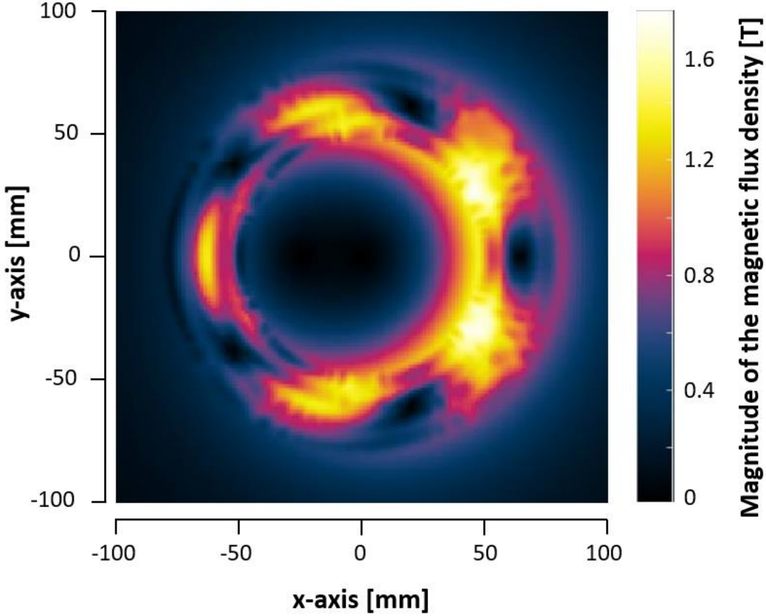


Dynamic aperture for NM magnet lattice and sextupoles scaled for chromaticity correction.

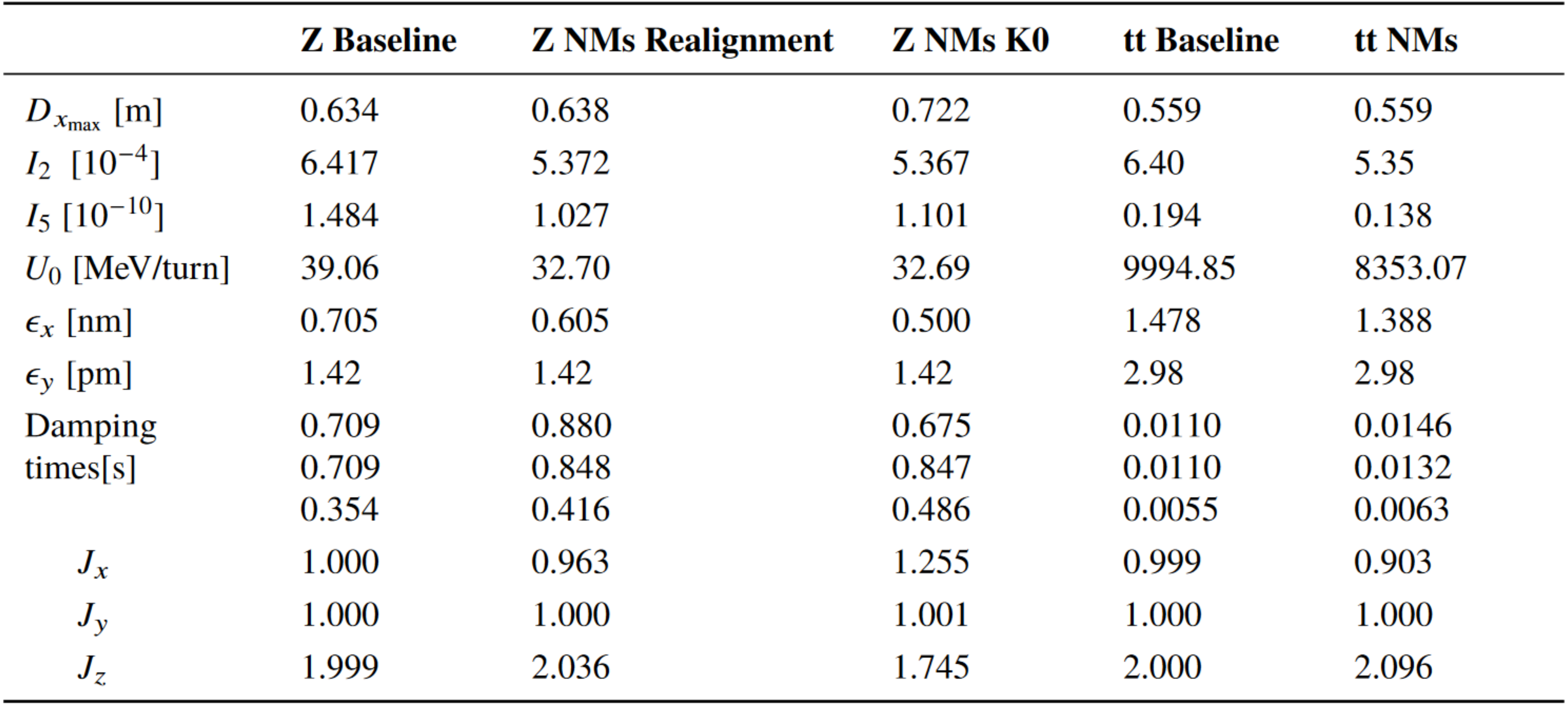
Magnet Design

- Close **collaboration** with **magnet experts** from **CERN** and **PSI**
  - J. Kosse, B. Auchmann, A. Thabuis, M. Korazinos…
- **Bi-weekly meetings** discussing hardware requirements and constraints
- Aim to **build prototype** based on designs
- IPAC24 paper “*Parameter space for the magnetic design of nested magnets in the FCC-ee arc cell*”
- See also M. Korazinos *“Design of HTS magnets for the short straight sections, the HTS4 project”* today



Magnetic field in nested quadrupole and sextupole magnet design

Parameter Overview



	Z Baseline	Z NMs Realignment	Z NMs K0	tt Baseline	tt NMs
$D_{x_{\max}}$ [m]	0.634	0.638	0.722	0.559	0.559
I_2 [10^{-4}]	6.417	5.372	5.367	6.40	5.35
I_5 [10^{-10}]	1.484	1.027	1.101	0.194	0.138
U_0 [MeV/turn]	39.06	32.70	32.69	9994.85	8353.07
ϵ_x [nm]	0.705	0.605	0.500	1.478	1.388
ϵ_y [pm]	1.42	1.42	1.42	2.98	2.98
Damping times[s]	0.709	0.880	0.675	0.0110	0.0146
	0.709	0.848	0.847	0.0110	0.0132
	0.354	0.416	0.486	0.0055	0.0063
J_x	1.000	0.963	1.255	0.999	0.903
J_y	1.000	1.000	1.001	1.000	1.000
J_z	1.999	2.036	1.745	2.000	2.096

Summary of Benefits

- **Reduced power** consumption due to
  - **No ohmic heating** in arc quadrupoles
  - **16.5 % reduced synchrotron** radiation requires lower RF power
- FCC-ee estimated **lifetime** power consumption **20 TWh**
  - Superconducting nested magnets reduce this by **4 TWh**
  - **Including** first estimates of **cooling power** for cryo systems
- Only **one arc dipole family** required
- **Individually powered coils** can be used for **correction** and **tapering**

Summary and Outlook

- **Alternative lattice** design using **nested magnets** presented
  - **Fully integrated** to **linear** level including integration of IRs
- **Stability** achieved by **tuning dipole fields** in focusing quadrupoles
  - Gives rise to layout **complications** between beams and different energy machines, however, **multiple solutions presented**
- Many **potential benefits** from superconducting nested magnets
  - Including about **20 % lifetime power** saving
- **Compatibility** with **baseline sextupole** powering tested
  - First **DA plots promising**
- **Next steps** focused on **full sextupole integration**
  - **Rematching quadrupoles** to **compensate feed-down** in misaligned lattice option
  - Full independent optimisation of sextupoles for **dynamic aperture, including synchrotron radiation**
- In future full study on how **NM affect alignment and tunability**
- Aim to explore similar concept and port methods to LCC optics

Relevant Publications

- C. GARCIA JAIMES, L. van Riesen-Haupt, R. Tomas, and T. Pieloni, “Exploring FCC-ee optics designs with combined function magnets”, in *Proc. 14th Int. Particle Accelerator Conf. (IPAC'23)*, Venice, Italy, May 2023, paper MOPL066, pp. 698-701.
- C. GARCIA JAIMES, L. van Riesen-Haupt, M. Seidel, R. Tomas, and T. Pieloni, “Impact of dipole quadrupolar errors in FCC-ee”, in *Proc. 14th Int. Particle Accelerator Conf. (IPAC'23)*, Venice, Italy, May 2023, paper MOPL065, pp. 694-697.
- C. M. Garcia Jaimes, L. van Riesen-Haupt, M. Seidel, R. Tomas, and T. Pieloni, “First FCC-ee lattice designs with Nested Magnets”, presented at the 15th Int. Particle Accelerator Conf. (IPAC'24), Nashville, TN, USA, May 2024, paper WEPR10, this conference.
- C. M. Garcia Jaimes, T. Pieloni, L. van Riesen-Haupt, M. Seidel, and R. Tomas, “First comparison studies in Dynamic Aperture for Nested Magnets and baseline lattice in the FCC-ee”, presented at the 15th Int. Particle Accelerator Conf. (IPAC'24), Nashville, TN, USA, May 2024, paper WEPR12, this conference.
- C. M. Garcia Jaimes *et al.*, “Parameter space for the magnetic design of Nested Magnets in the FCC-ee arc cell”, presented at the 15th Int. Particle Accelerator Conf. (IPAC'24), Nashville, TN, USA, May 2024, paper WEPR11, this conference.

Merci

Questions

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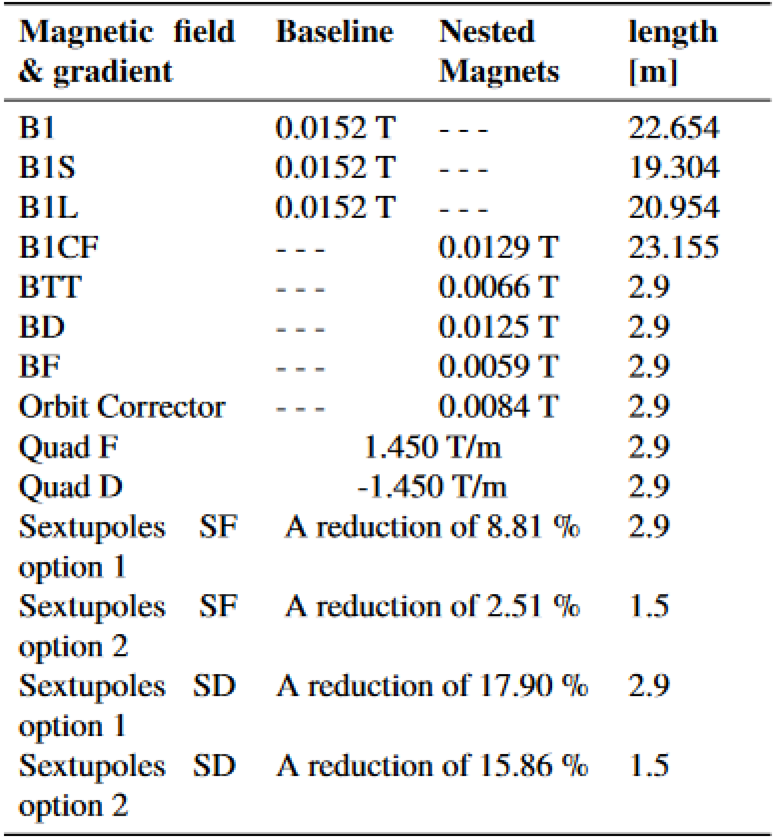
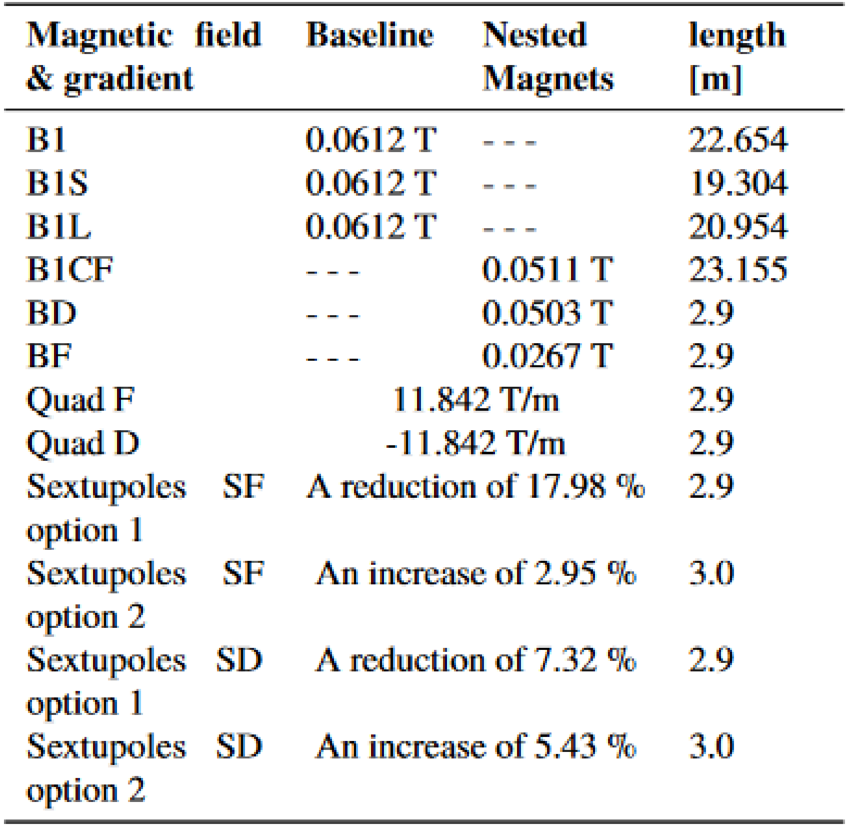
Magnetic Fields



Magnetic field & gradient	Baseline	Nested Magnets	length [m]
B1	0.0152 T	- - -	22.654
B1S	0.0152 T	- - -	19.304
B1L	0.0152 T	- - -	20.954
B1CF	- - -	0.0129 T	23.155
BTT	- - -	0.0066 T	2.9
BD	- - -	0.0125 T	2.9
BF	- - -	0.0059 T	2.9
Orbit Corrector	- - -	0.0084 T	2.9
Quad F	1.450 T/m		2.9
Quad D	-1.450 T/m		2.9
Sextupoles SF option 1	A reduction of 8.81 %		2.9
Sextupoles SF option 2	A reduction of 2.51 %		1.5
Sextupoles SD option 1	A reduction of 17.90 %		2.9
Sextupoles SD option 2	A reduction of 15.86 %		1.5



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B1S	0.0612 T	- - -	19.304
B1L	0.0612 T	- - -	20.954
B1CF	- - -	0.0511 T	23.155
BD	- - -	0.0503 T	2.9
BF	- - -	0.0267 T	2.9
Quad F	11.842 T/m		2.9
Quad D	-11.842 T/m		2.9
Sextupoles SF option 1	A reduction of 17.98 %		2.9
Sextupoles SF option 2	An increase of 2.95 %		3.0
Sextupoles SD option 1	A reduction of 7.32 %		2.9
Sextupoles SD option 2	An increase of 5.43 %		3.0