FCC injection kicker magnet design, impedance and heating aspects

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Acknowledgements:

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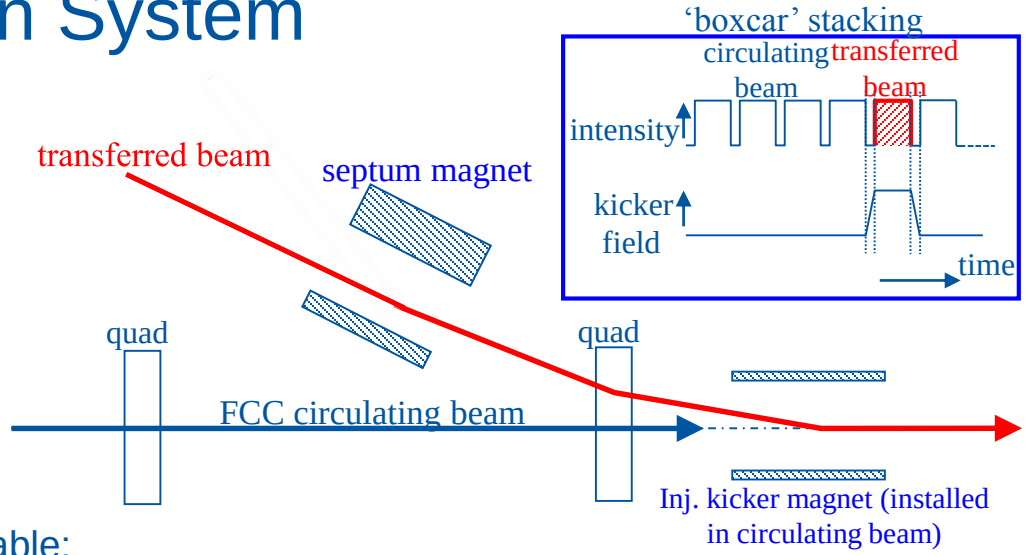
Outline

- Parameters of injection system
- Pulse generators
- Kicker magnets
  - Electrical impedance
  - Beam coupling impedance
  - FCC beam spectrum
  - Measured electromagnetic properties of ferrite
  - Beam induced power deposition
  - Ongoing R&D

Parameters of Injection System

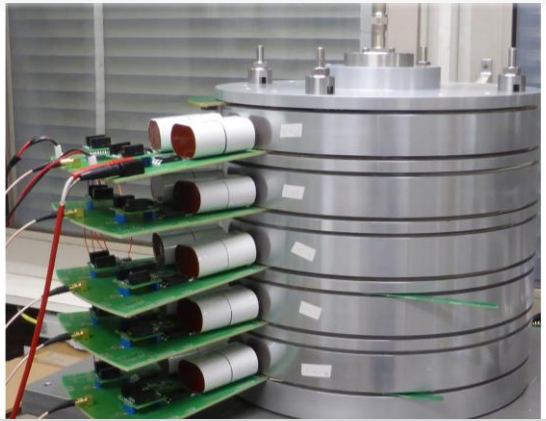
Hardware parameter	Unit	Kicker
Deflection	mrad	0.18
Integrated field	T·m	2.0
Total magnet length	m	40
Good field region (h/v)	mm	32/32
Field rise time	μs	0.43
Flattop length	μs	2.0
Flattop stability	%	±0.5

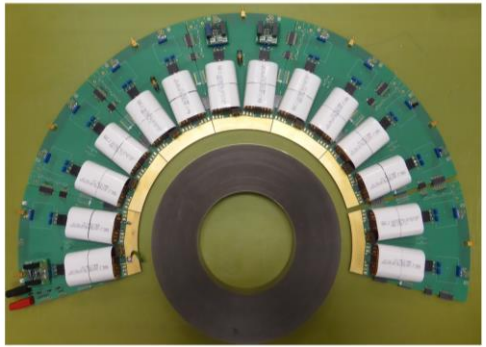


- Injection kicker system must be highly reliable;
- The baseline injection energy for the FCC-hh is 3.3 TeV;
- For machine protection reasons, a maximum of 80-100 bunches can be accepted by the injection protection system and hence safely transferred into FCC at a time;
- Each ring will be filled with 130 batches of **80** bunches (separated by 25 ns) ⇨ **2 μs** pulse;
- **Injection kicker magnets are installed in the circulating beam**.

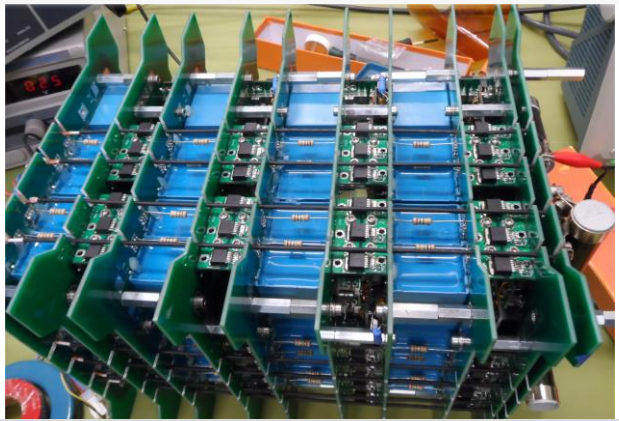
Injection kicker system – pulse generators

- Many kicker systems today use thyratron (gas tube) switches and pulse forming networks/lines;
  - Long-term availability of thyratrons is a real concern;
  - Thyratrons can exhibit unwanted, spontaneous, turn-on.
- Solid-state technology and topologies such as the Inductive Adder or Marx Generator permit series and parallel connection of power semiconductors to achieve high pulsed power:
  - \+ Scalable, reliable, modular, maintainability, ….





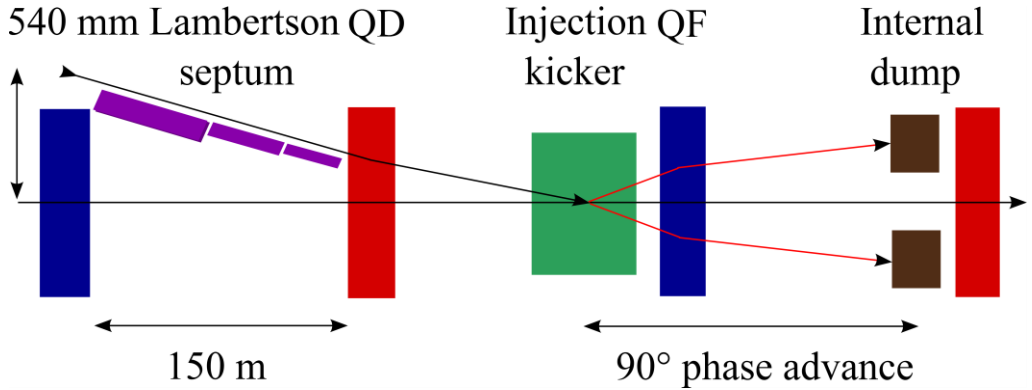
Oral presentation: “Inductive adder prototype pulse generator for FCC-hh kickers”, D. Woog, 11/04/2018, 11:10hrs.



Oral presentation: “Marx prototype pulse generator design and initial results”, M. Barnes, 11/04/2018, 09:30.

Injection system – kicker magnets (1)

The injection region has a FODO lattice with a half-cell length of 150m, to provide space for a normal-conducting septum, vacuum equipment and protection devices;



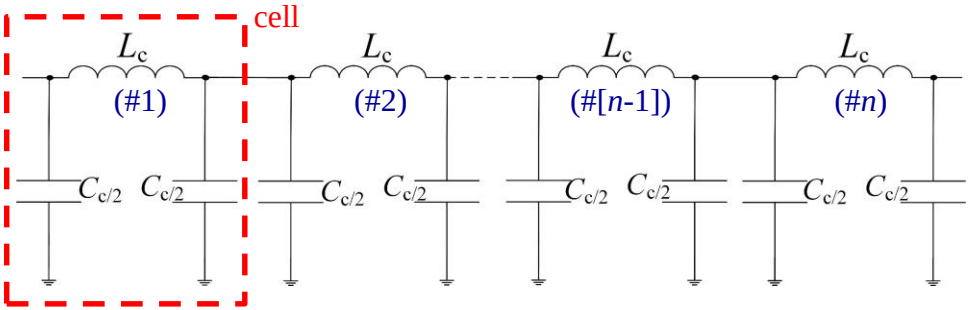
A length of **120m** is available for injection kickers: however it is desirable to utilize a shorter kicker system length for both beam impedance and beam stability reasons:

- ✓ However the length must be **consistent with the ability of the pulse generator to supply the required current**;
- ✓ In the present design, the kicker magnet system will be reduced to **~40m** and moved to the end of the half-cell, with a phase advance of 90° in both planes, to the internal dump.

Oral presentation: FCC-hh transfer line and injection design, E. Renner, 11/04/2018, 15:30hrs.

Injection system – kicker magnets (2)

To achieve a fast field rise time with low ripple, a transmission line type kicker magnet, as used for injection into the LHC, has been chosen;
The number of π (L-C) cells, per magnet, has been optimized to be 20:

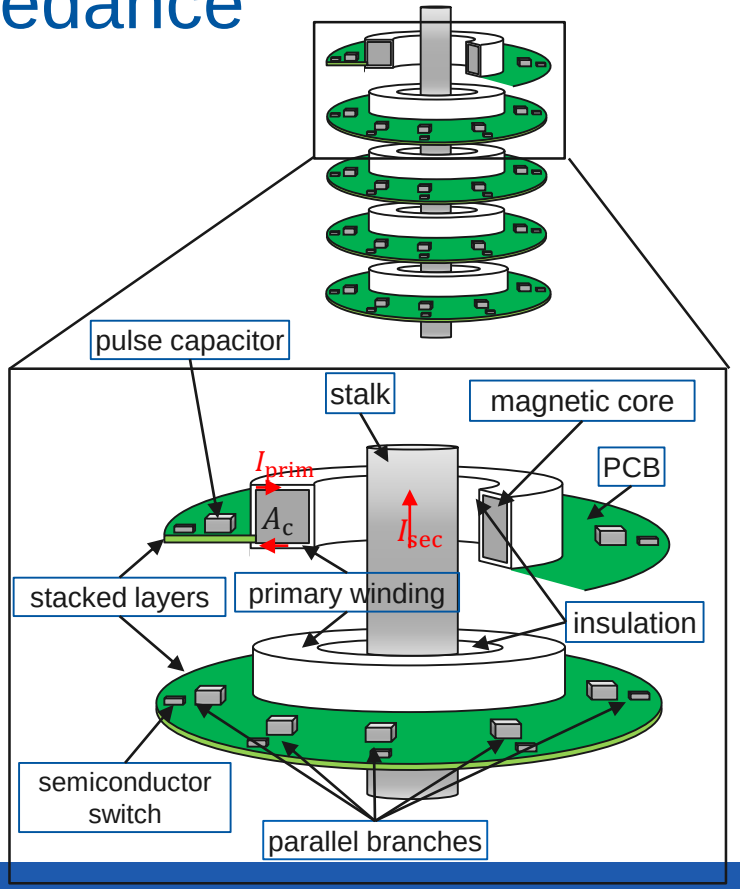


Twenty cells gives a good compromise between complexity of the magnet and the required cut-off frequency of each cell;
The yoke of the kicker magnet will use a NiZn ferrite;
The characteristic impedance (Z) of the kicker magnet is given approximately by:

$$Z = \sqrt{\frac{L_c}{C_c}} \ ,$$

Injection system – electrical impedance

- The electrical impedance of the FCC injection kicker magnet has been optimized together with the inductive adder operational requirements.
- An inductive adder uses magnetic cores. To limit the size, cost and propagation delay through the adder, the output voltage must be kept at a reasonably low value.
- Hence the kicker system must have low characteristic impedance, but consistent with rise time requirements;
- A characteristic impedance of **6.25Ω** has been chosen: in comparison with a lower impedance (e.g. 5Ω), 6.25Ω gives a larger gap of the secondary insulation - significantly reducing the electrical field in this region.



Injection kicker magnets – beam coupling impedance

- In the transverse and longitudinal planes, the imaginary and real parts of the beam coupling impedance might critically affect beam stability.
- The real part of the longitudinal beam impedance determines energy loss of beam particles and thus the beam induced heating.
- The power deposition in a kicker magnet may provoke temperature rise of the ferrite yoke beyond the Curie point.
- The power deposition induced by a beam composed of n bunches, each populated by N_b protons, travelling through the structure of longitudinal impedance of Z_l is:

$$\Delta P = 2q^2 n^2 f_o^2 N_b^2 \sum_{p=1}^{\infty} \left| \hat{\lambda}_{beam}\left(pf_o\right) \right|^2 \mathrm{Re}\left[Z_l\left(pf_o\right) \right]$$

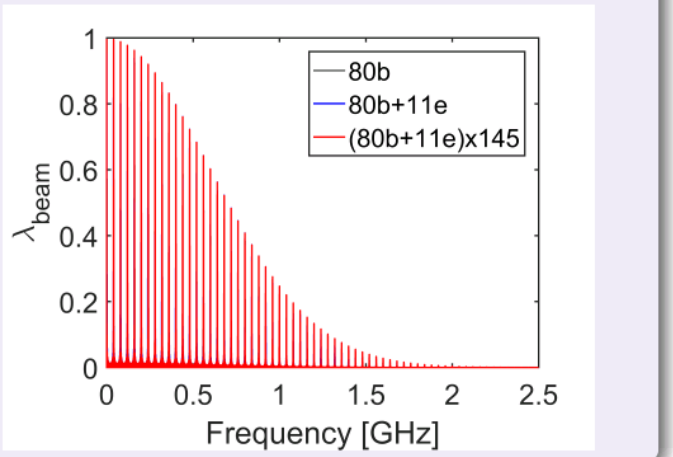
where q is proton charge, f_0 is the revolution frequency, p is an integer and $\hat{\lambda}_{beam}$ is the Fourier transform of the normalized beam charge distribution.

FCC beam spectrum

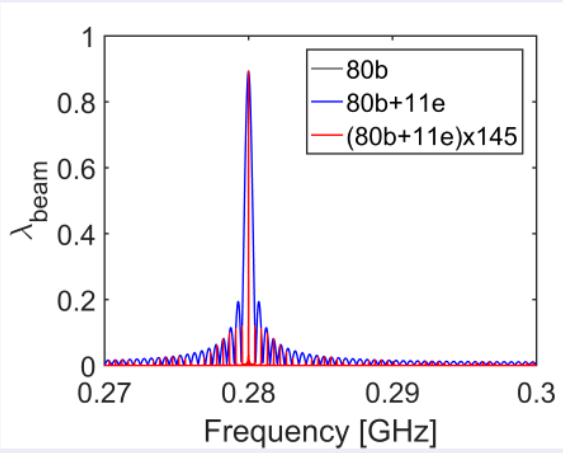
Bunch spacing: 25 ns, Bunch length: 0.08 m

Filling pattern: (80b+4e) x 130 + 10μs (gap, including pilots)⇨10,400 bunches, ~80% filling

FFT:



FFT - Zoom:

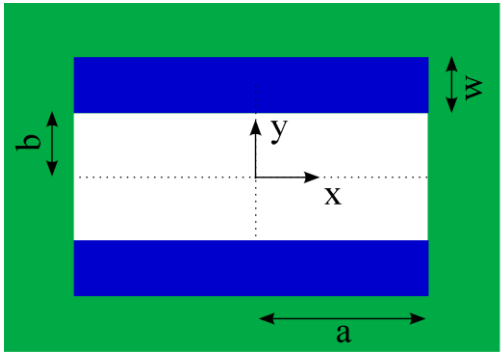


Fundamental harmonics: f_{h0}=40 MHz

Side-band harmonics: f_{h1}=0.439 MHz, f_{h2}=0.00303 MHz

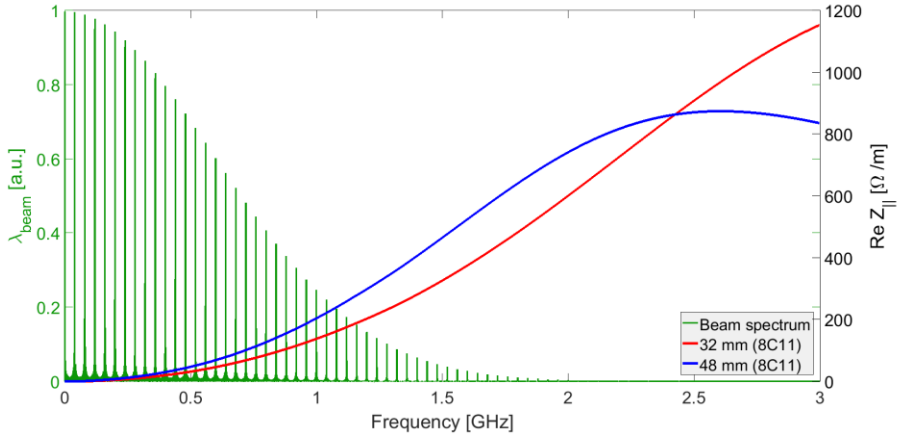
Injection kicker magnets – beam induced power

Analytical approach (Tsutsui model):



- Valid for an unshielded ferrite kicker magnet and for an ultra-relativistic beam.
- The model does not take into account the C-shape of the magnet yoke, but has been shown to be in good agreement with results of impedance measurements.

Longitudinal impedance (@25°C) and beam spectrum:

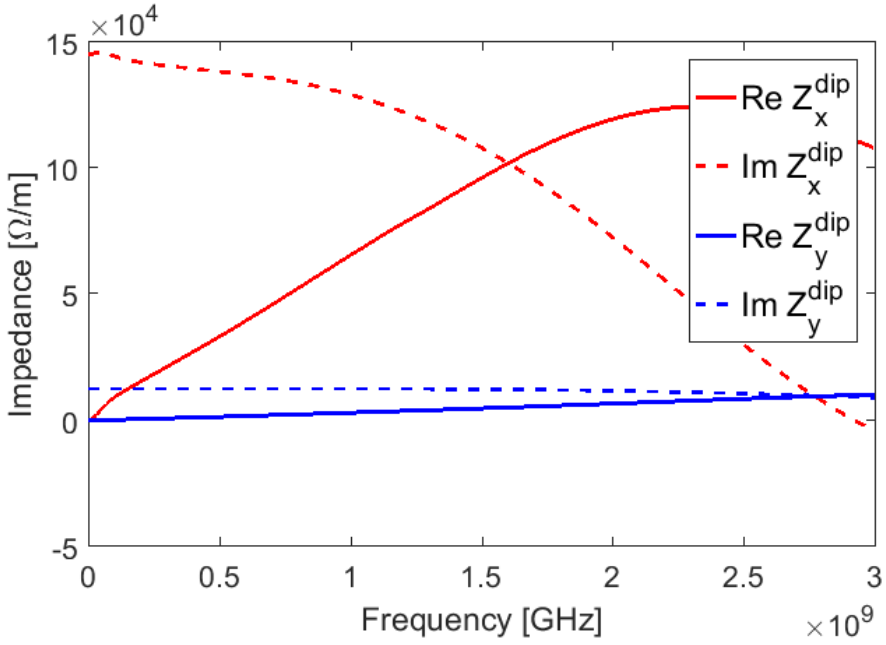


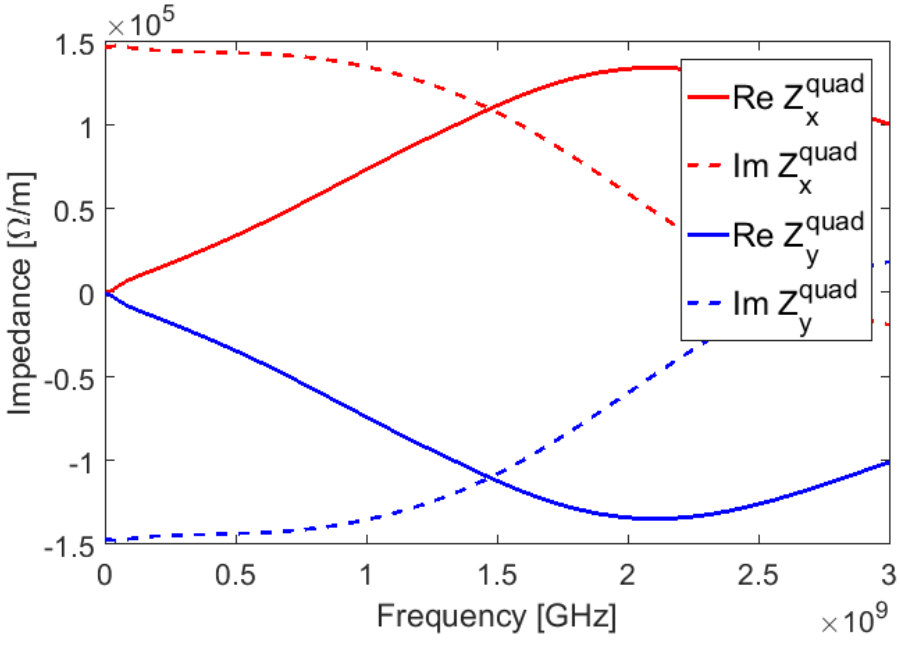
Nominal aperture is 32x32 mm. A beam screen is necessary ⇨ aperture size of ~48x48 mm.

Aperture (mm)	Power Deposition (W/m)
32	202
48	301

Injection kicker magnets – transverse impedance

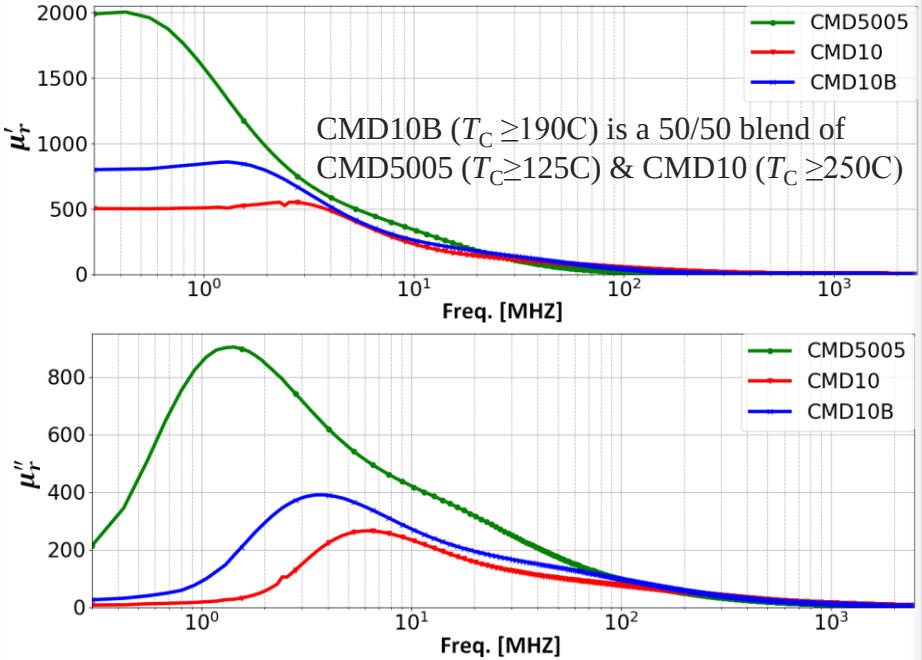
From the Tsutsui model, the transverse impedance of injection kicker magnets is very large, and needs to be significantly reduced (to be studied):





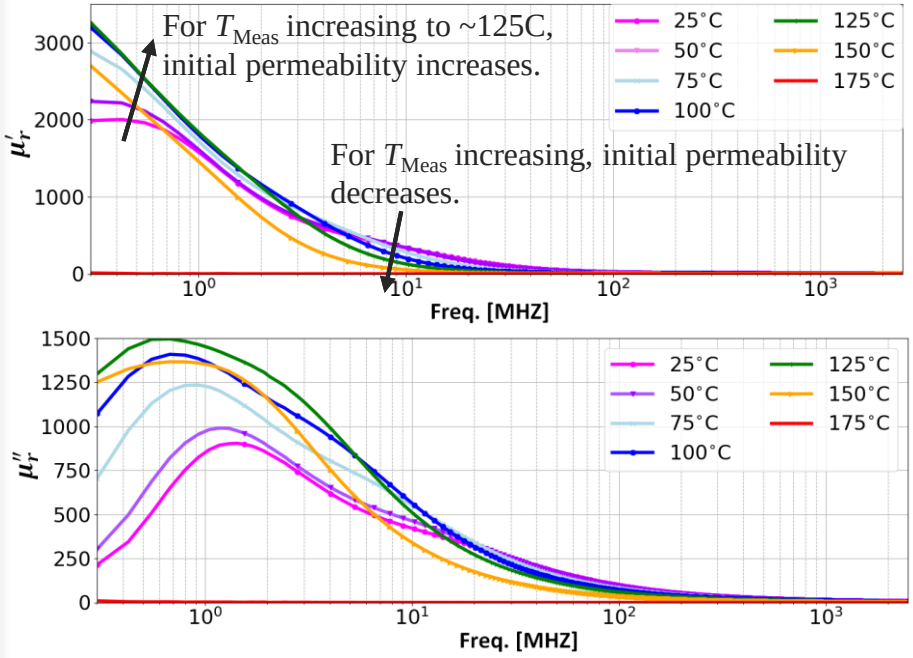
Ferrite – measured electromagnetic properties

Ferrites with various Curie temps. (T_C), @ 25°C:



Note: from datasheet, CMD5005 ≈ 8C11

CMD5005 at various "measured" temperatures:



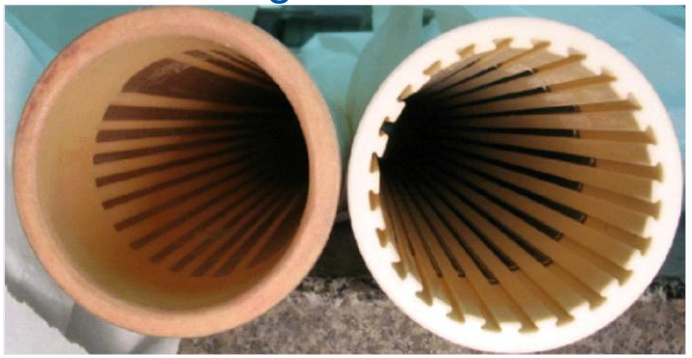
Note: actual ferrite temperature < measured

Kicker magnet – ongoing R&D

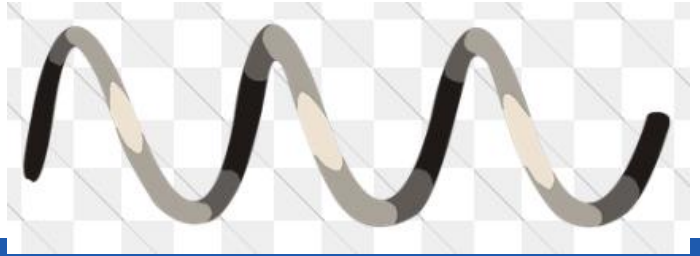
CST simulations of both longitudinal and transverse beam coupling impedance.

Compare predicted impedance for beam screens consisting of:

- ✓ straight conductors (e.g. 24 parallel, as per the LHC injection kicker beam screen):



- ✓ helix serigraphy (e.g. 24 parallel – only one shown):



Conclusion and Outlook

- ✓ **Length of injection kicker systems significantly reduced – greatly reducing contribution to beam coupling impedance;**
- ✓ **Characteristic impedance of injection kicker system has been optimized (6.25 Ω) together with the number of cells per magnet;**
- ✓ **Main harmonics and side harmonics of FCC spectrum have been analyzed;**
- ✓ **Beam coupling impedance has been determined analytically, without a beam screen:**
  - ✓ **A beam screen is necessary to limit beam induced heating;**
  - ✓ **Transverse impedance is high and needs to be significantly reduced.**
- ✓ **CST simulation of various beam screens has commenced.**

Thank you for your attention !!

Questions ?

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- Beam transfer technology challenges, including dump and dilution system design (W. Bartmann, FCC Week 2017).
- LHC at 3.3 HEB (W. Bartmann, FCC Week 2017).
- New design concepts for suppressing erratic triggering of solid state switch stacks (P. Van Trappen et al, FCCWeek 2017).