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New Spiral Beam Screen Design for the FCC-hh Injection Kicker Magnets

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Outline

1. FCC-hh injection kicker system parameters
2. Conventional beam screen
   - General features
   - High voltage issues
3. New concept
   - Spiral beam screen
4. Longitudinal beam coupling impedance
   - Conventional beam screen
   - Spiral beam screen (optimized)
   - Impact on longitudinal beam stability
5. Transverse beam coupling impedance
   - Wakefield and Eigenmode simulations
   - FCC impedance budget considerations
6. Field homogeneity and field rise time
7. Summary of achievements and future R&D

FCC-hh injection kicker system

Challanges:

- Injection kicker system must be **highly reliable**
- Machine protection constraints: **max. 80 bunches** can be safely transferred into FCC-hh at a time
- **New pulse power generator topologies** required (i.e. Inductive Adddder or Marx Generator)
- Injection kicker magnets are **installed in the circulating beam**

→ **necessity of the beam screen to reduce beam coupling impedance**

T. Kramer: FCC-hh kicker systems: status and R&D plans (injection, extraction, dilution), Wed. 09:10

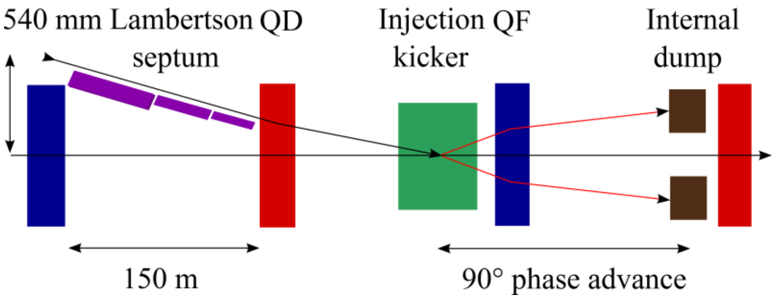
J. Borburgh: FCC-hh Injector Design, Tue. 17:00

A. Chmielinska: FCC-hh Injection and Extraction: Insertions and Requirements, Wed. 09:30

Baseline parameters:

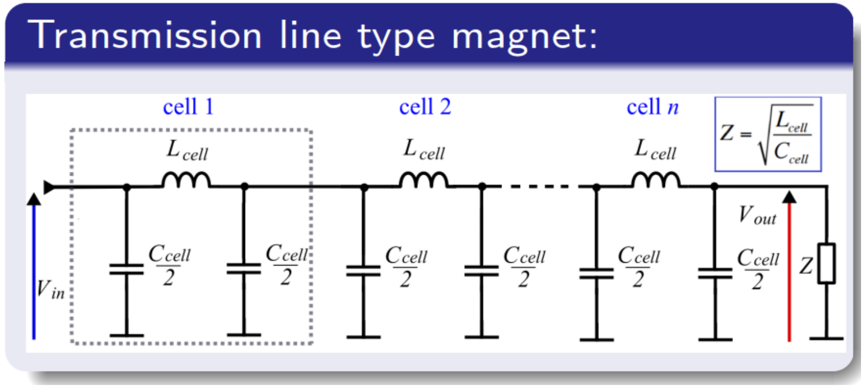
Parameter	Value
Injecton energy [TeV]	3.3
Angle [mrad]	0.18
Pulse duration [μs]	2
Current [kA]	2.4
Voltage [kV]	15
System impedance [Ω]	6.25
System length [m]	40
Field rise time [μs]	0.43
Aperture dimensions [mm]	48
Magnet fill time [μs]	0.355
Good field region (h/v) [mm]	8/8
Flat-top tolerance [%]	±0.5

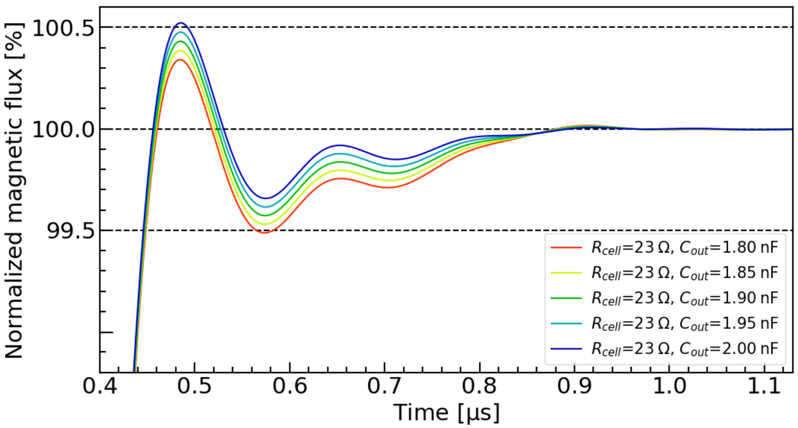
Baseline:
Injection kicker system length **reduced from ~120 m to 40 m** and moved to the end of the half-cell: **18 magnets in total**



FCC-hh injection kicker magnet

- **Transmission line topology** to achieve **fast field rise** time with **low ripple**
- **Number of cells: 20**
  → compromise between complexity and the required cut-off frequency of each cell
- Kicker magnet yoke: **NiZn ferrite**



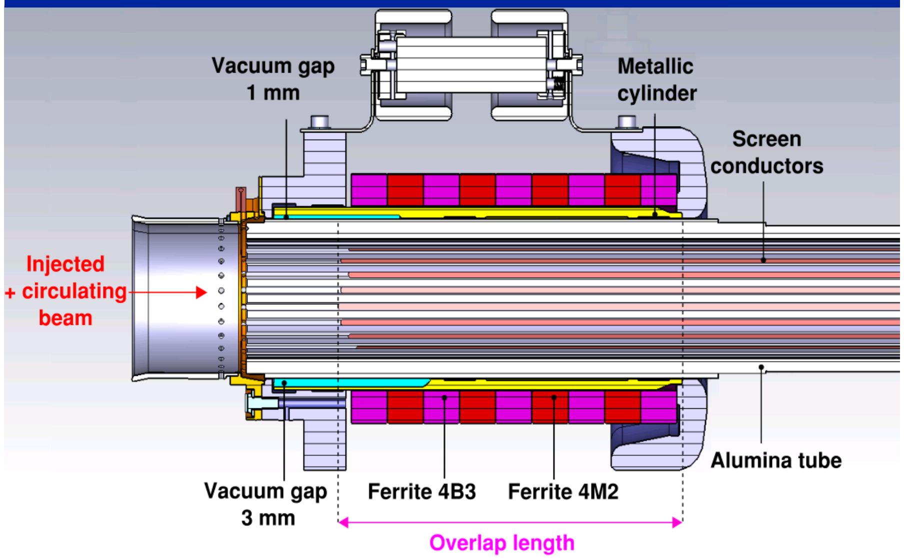


Conclusion:

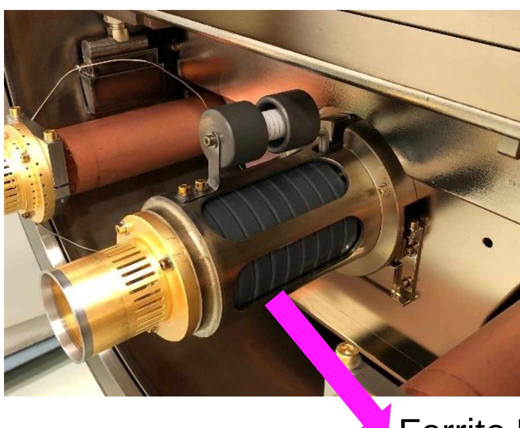
- Detailed **PSpice** model of the FCC-hh injection kicker developed: required field rise time and filed flat-top quality are achieved
- **CST model** developed to study beam coupling impedance

Motivation

Conventional beam screen (Catia model):



Example: LHC MKI.



Ferrite Rings

General features:

- **24 (NiCr) straight screen conductors** inserted into grooved slots of alumina tube to shield ferrite yoke from the EM fields induced by the circulating beam:
  → reduced beam coupling impedance

- **Capacitive coupling** to ground at the upstream end allows to preserve **fast magnetic field rise time:**
  → no major Eddy current loops

- **Overlap length** determines resonances in the longitudinal impedance spectrum
  → possibility to shift resonant modes to higher frequencies [1]:
  i.e.: post LS1 MKI: $L_{overlap}$=130mm [2], upgraded MKI8D: $L_{overlap}$=56mm [3].

$$f_{\mathrm{conv}}^{(n)} = \frac{nc}{2\sqrt{\varepsilon_{r,\mathrm{eff}}}(L_{\mathrm{overlap}} + \delta_{\mathrm{fringe}})}$$

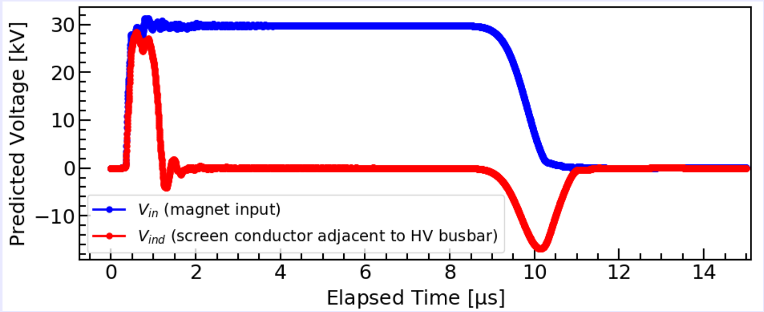
- **Power loss in the ferrite yoke is also reduced** due to the damping provided by the ferrite rings positioned around each end of the beam screen [3].

Motivation

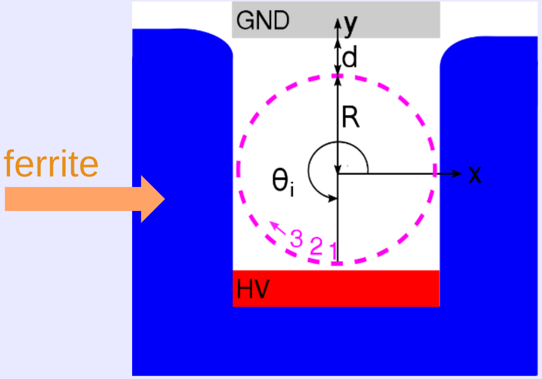
High voltage issues:

- **During magnetic field rise and fall, a significant voltage is induced on the screen conductors [2]:**
  → possibility of HV breakdowns between adjacent screen conductors or/and between screen conductors and metallic cylinder.
- **Non-symmetric vacuum gap** is introduced to reduce the electric field.

Magnet voltage and voltage of screen conductor (#1):

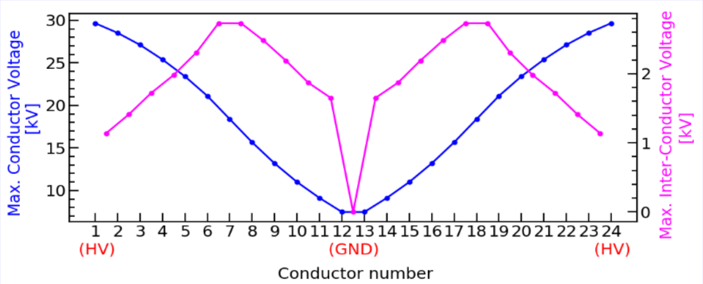


Induced voltage:



Induced voltage: $$V_i = \frac{dB}{dt}(d + R - y_i)L$$

Maximum conductor and inter-conductor voltages (for 60 kV PFN voltage):

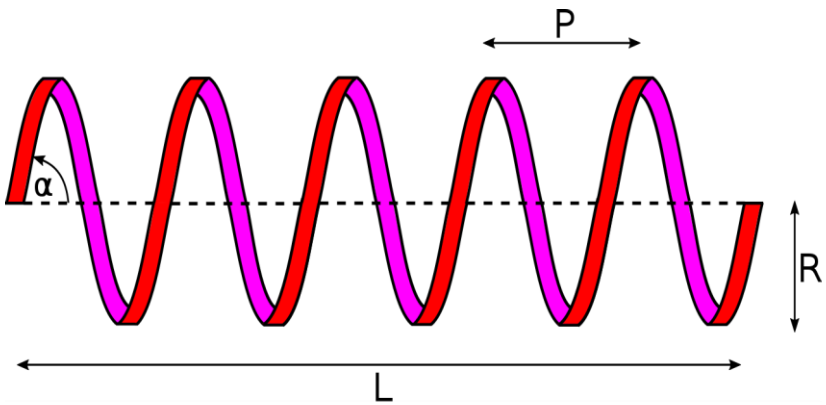


Max. induced voltage: $$V_1 = \frac{dB}{dt}(d + 2R)L$$

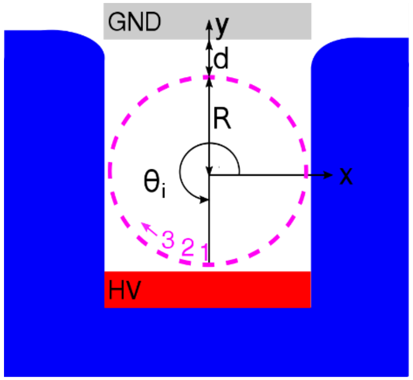
Max. difference between adjacent conductors: for $\theta \sim 0$ and $\sim \pi$.

New concept: spiral beam screen

Each conductor has a form of spiral:



P-pitch, *R*-beam screen radius, *α*-spiral angle.



Spiral beam screen:

The coordinates of the *i*-th spiral screen conductor:

$$\begin{cases} x_i(\theta) = R\cos(\theta + \theta_i) \\ y_i(\theta) = R\sin(\theta + \theta_i) \\ z_i(\theta) = \frac{P\theta}{2\pi};\ \theta \in [0; 2\pi N_{\text{turn}}] \end{cases}$$

where $\theta_i = \frac{3}{2}\pi - \frac{2\pi(i-1)}{24}$ and N_{turn} is the number of turns in the kicker magnet aperture.

For the spiral beam screen, the distance of each screen conductor from the GND busbar changes along the *z* direction:

$$f_i(\theta) = d + R - y_i(\theta).$$

For an integer number of turns along the aperture:

$$V_i = \frac{dB}{dt}(d + R)L$$

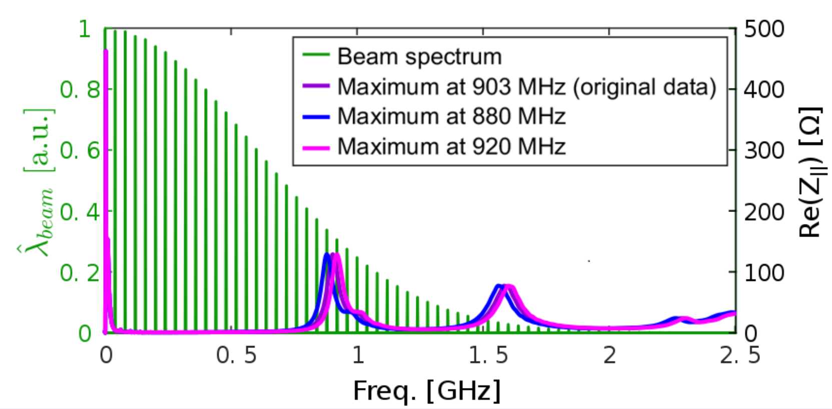
Spiral beam screen is expected to provide significantly improved HV performance

- ✓ **the induced voltage on each screen conductor is the same,**
- ✓ **this is approximately one-half of the worst case straight screen conductor.**

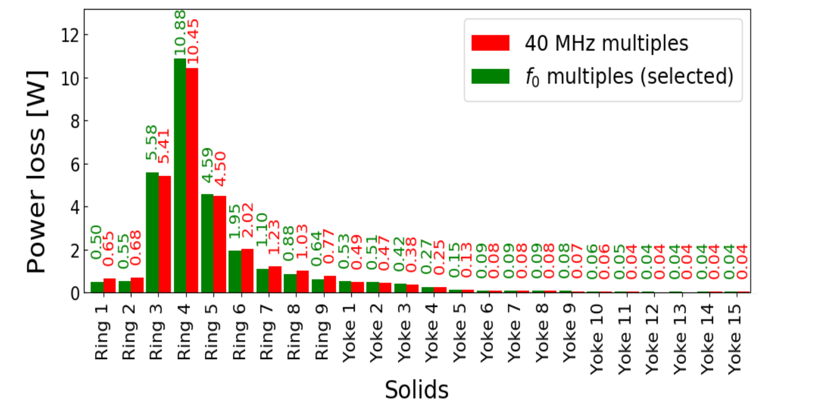
Longitudinal beam coupling impedance

Conventional beam screen*

Longitudinal impedance spectrum:



Power deposition distribution:



Total power loss
(evaluated also for worse case scenarios)

✓ 30.2 W/33.4 W/29.3 W
(smaller than for the LHC MKI8D [3])

Power deposition distribution evaluated using 2 methods:

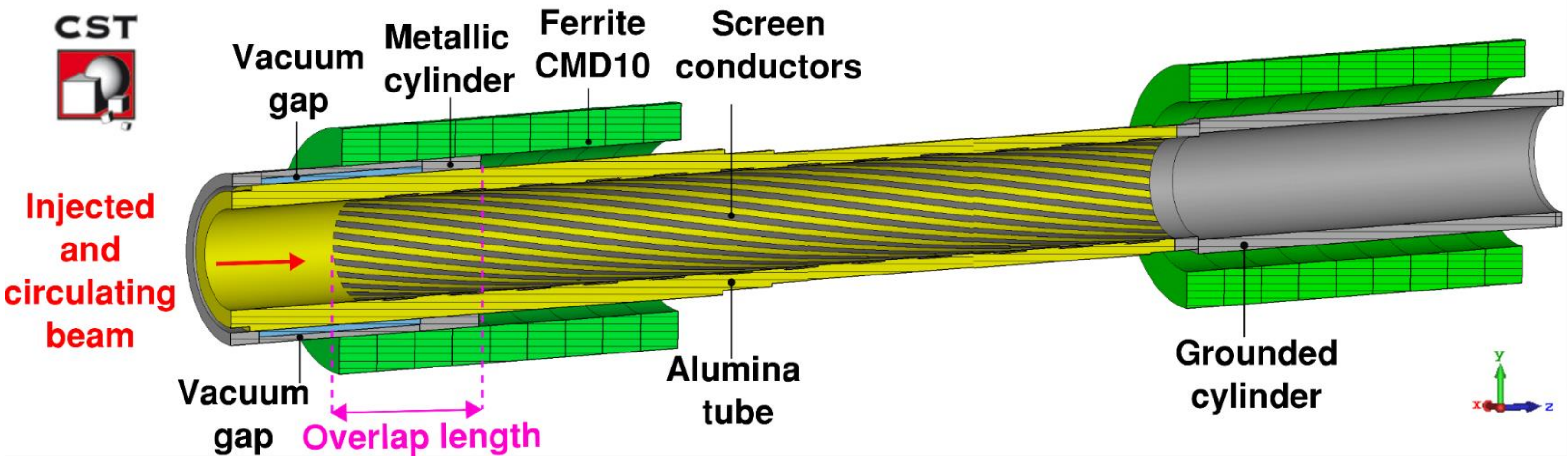
✓ Distribitions very similar to the upgraded LHC MKI8D, which was verified experimentally [3]

✓ new method of calculating the power deposition distribution [4] improves the accuracy by about 10%

Conclusion:
Upgraded magnet LHC MKI8D did not limit LHC operation [5], hence no heating issues are expected for the FCC-hh injection kickers during operation with nominal beam parameters.

*$L_{overlap}$=56 mm + non symmetric vacuum gap as in the upgraded LHC MKI8D installed in YETS 2017/2018.

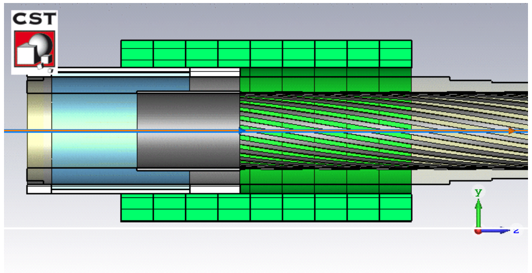
Spiral beam screen



Features:

- ✓ Integer number of turns in the aperture
- ✓ Symmetric vacuum gap (2 mm width)
- ✓ Ungraded lengths of screen conductors
- ✓ Reduced overlap length (40 mm)

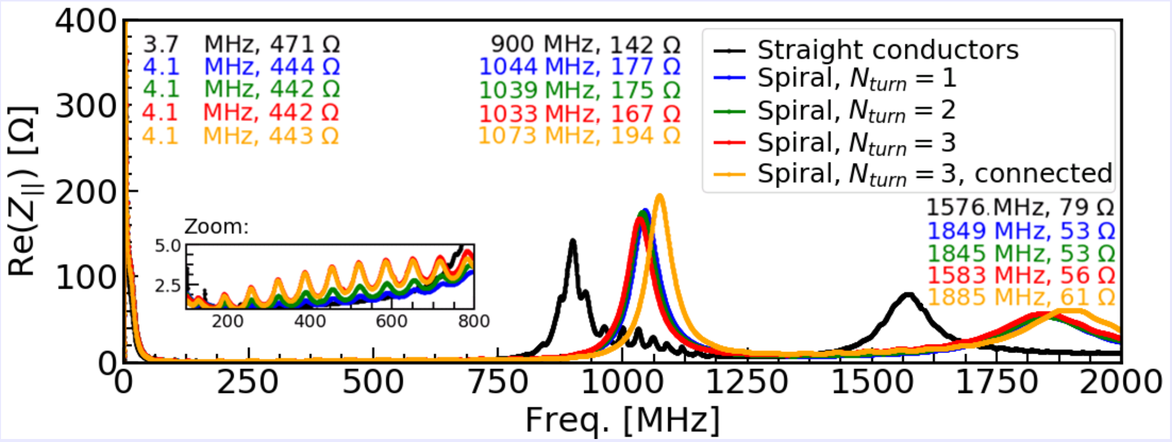
Alternative options:



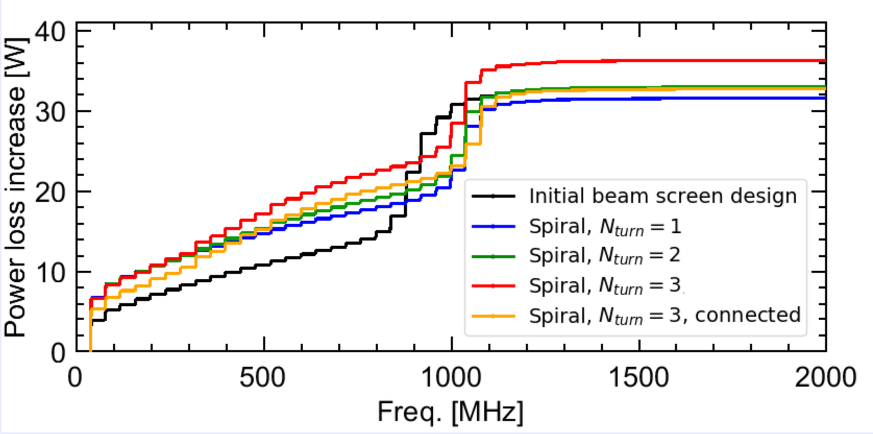
- ✓ Possibility to connect all spirals together
- ✓ Future option to use switch and minimize beam coupling impedance once machine is filled

Spiral beam screen (optimized design):

Longitudinal impedance spectrum:



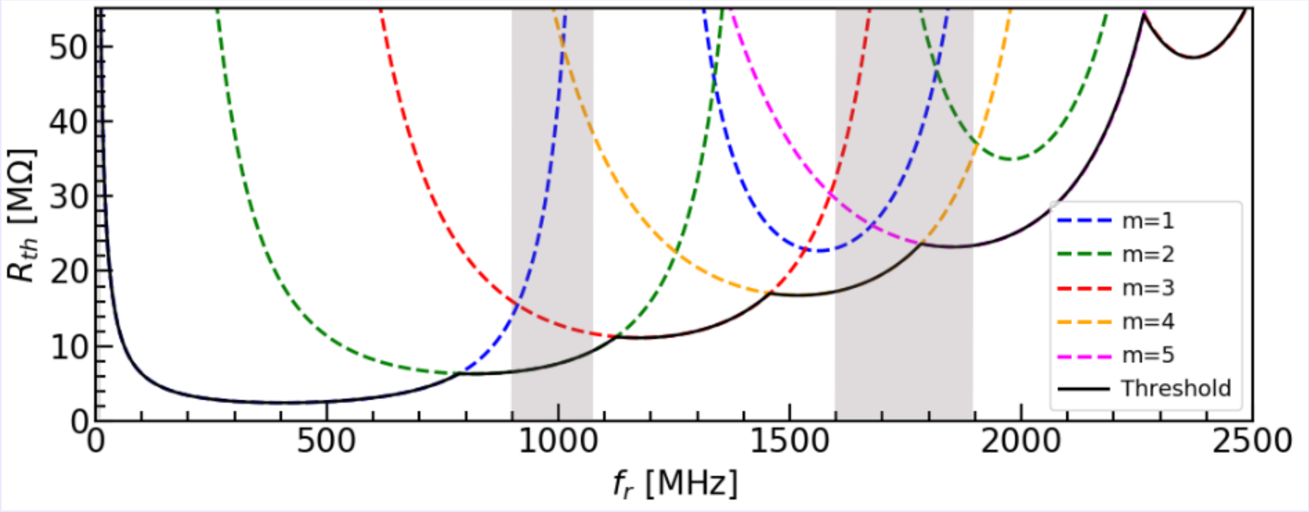
Power loss increase:



Conclusion:
No heating issues are expected for the FCC-hh injection kickers with the spiral beam screen.

Impact on longitudinal beam stability (I)

Thereshold for the longitudinal coupled bunch instability:
(assuming Gaussian bunch distribution):



$$R_{||} < \frac{|\eta| E_0}{I_0 \beta^2} \left(\frac{\Delta E}{E_0}\right)^2 \frac{\Delta\omega_{s0}}{\omega_{s0}} \frac{F_{CB}}{f_0 \tau_L} G(f_r \tau_L)$$ (see Ref. [6])

I. Karpov: Requirements for longitudinal HOM damping in FCC-hh, Tue. 08:45

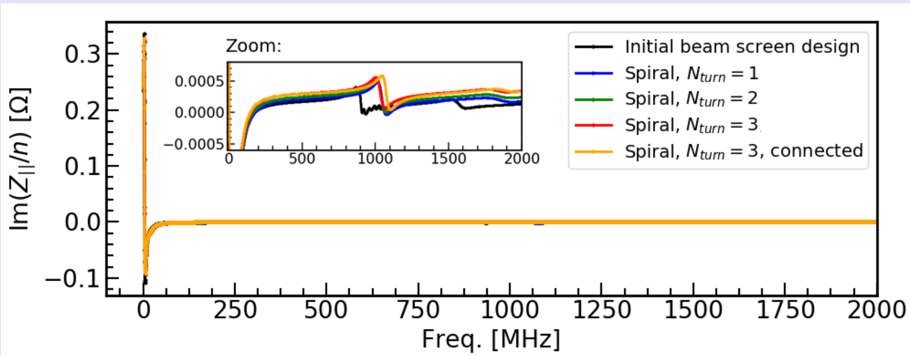
Contribution to the threshold at ~1000MHz:
18 kickers x 200 Ω / 8 MΩ ≅ 0.05%

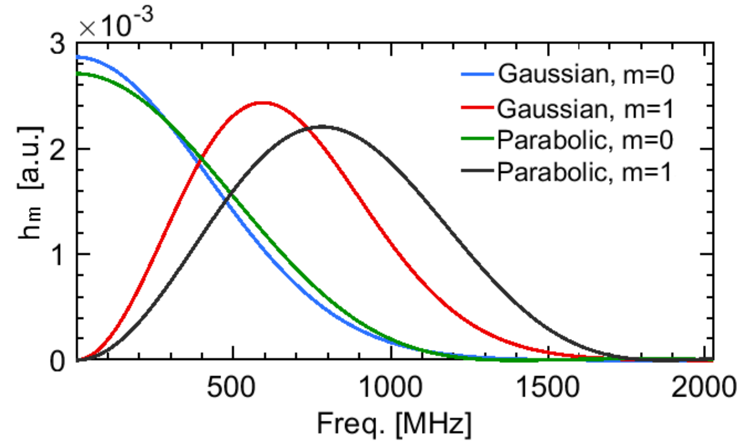
Conclusion:
Kicker magnets are very unlikely to drive coupled bunch instability in the longitudinal plane.

Impact on longitudinal beam stability (II)

Total impedance budget for the loss of Landau damping in FCC-hh: 200 mΩ (assuming margin of a factor of 2 in comparison with LHC) [7].

Im (Z/n):





Effective impedance:

$$\mathrm{Im}\left(\frac{Z_{||}}{n}\right)^{m}_{\mathrm{eff}} = \frac{\sum_{p=-\infty}^{\infty} \frac{\mathrm{Im}Z_{||}(\omega_p)}{n} h_m(\omega_p)}{\sum_{p=-\infty}^{\infty} h_m(\omega_p)} \qquad h_m(\omega) = \begin{cases} (\omega\sigma_{RMS})^{2m}\exp(-\omega^2\sigma_{\mathrm{RMS}}^2) & \text{for a Gaussian bunch,} \\ (m+1)^2 \frac{1+(-)^m\cos(\omega\tau_L)}{[(\omega\tau_L)^2-\pi^2(m+1)^2]^2} & \text{for a parabolic bunch.} \end{cases}$$

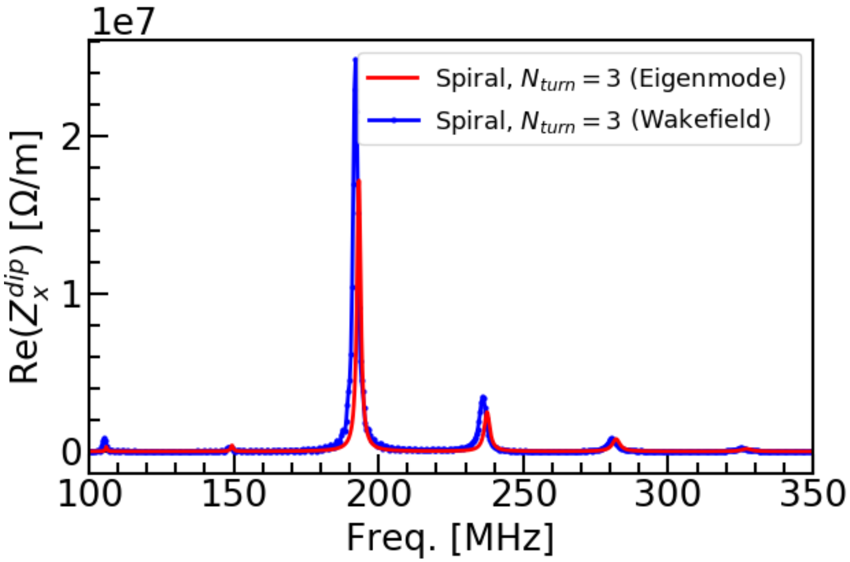
Conclusions:

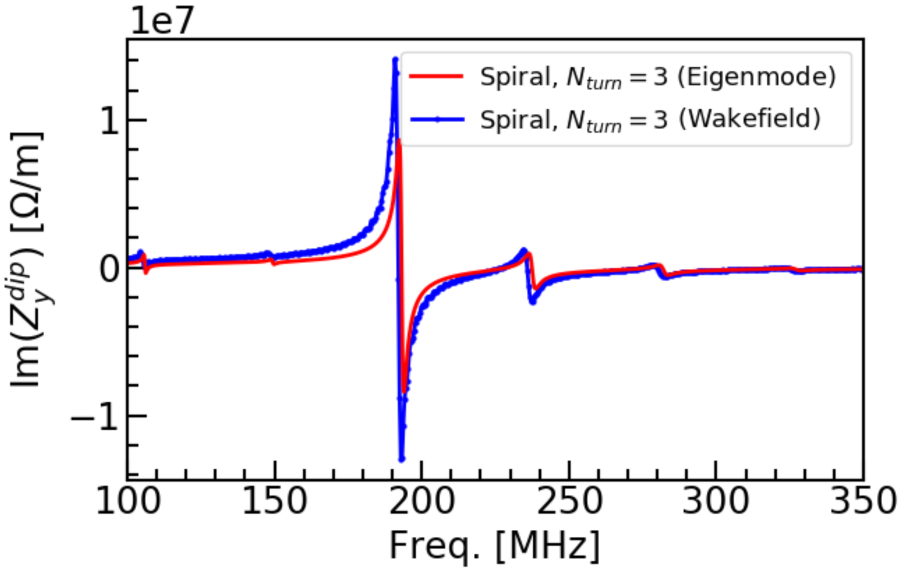
- For 18 kicker magnets with the conventional beam screen, the contribution to the total impedance budget is between 2.5% to 3%.
- In the worst case, for the spiral with 3 turns, the contribution is between 5.4% to 5.7% (not critical)
- For 120 m long injection system (as initially assumed), without optimization, the contribution would be around 18%

Transverse beam coupling impedance

Results:

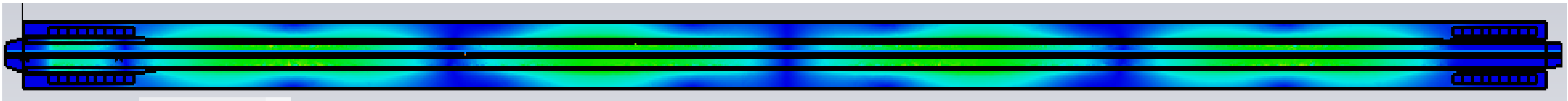
New method to disentangle dipolar and quadrupolar impedance using Eigenmode Solver
(S. Arsneyev, see Ref. [8])





- Very good agreement between Eigenmode and Wakefield simulations
- Modes at approximately: 105 MHz, 150 MHz, 193 MHz, 237 MHz.
- In addition: spiral beam screen with symmetric vacuum gap cancels out quadrupolar component of transverse impedance.

Mode at 193 MHz:



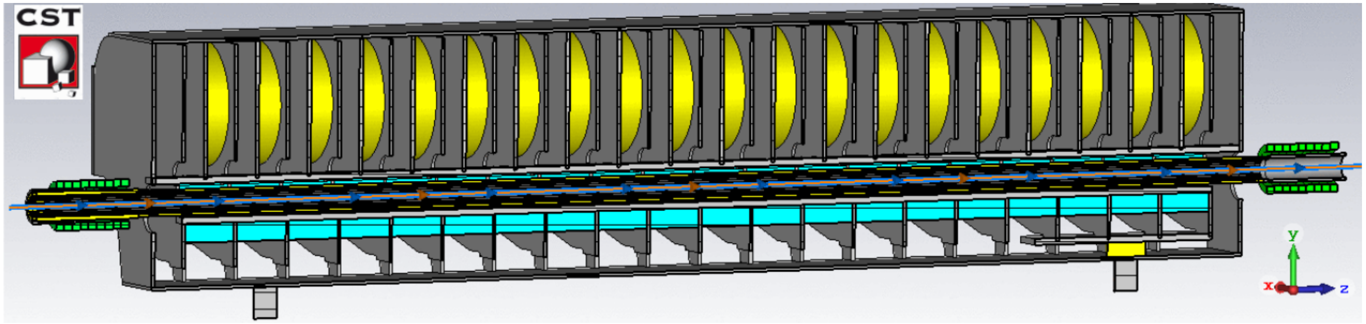
FCC-hh transverse impedance budget

1. 18 kicker magnets with a conventional or a spiral beam screen will not fit into impedance budget for coupled bunch instability in the transverse plane

2. However, 2 magnets with a 3 turn spiral will fit

S. Arsenyev: Impedance budget and stability, Tue. 09:42

3. For the spiral design, the frequency of the resonant modes can be tuned, several options can be considered: i.e:
   - magnets with a different integer number of turns along the aperture
   - magnets with the same integer number of turns along the aperture, but with more turns outside the aperture
   - magnets with a different length of the beam screen
   - perhaps spiral beam screen with a non-integer number of turns



✓ 9 pairs of detuned kicker magnets will fit into impedance budget.

4. There is **no possibility of tuning the frequency of the conventional beam screen** design without a destructive impact on the longitudinal impedance.

Next step

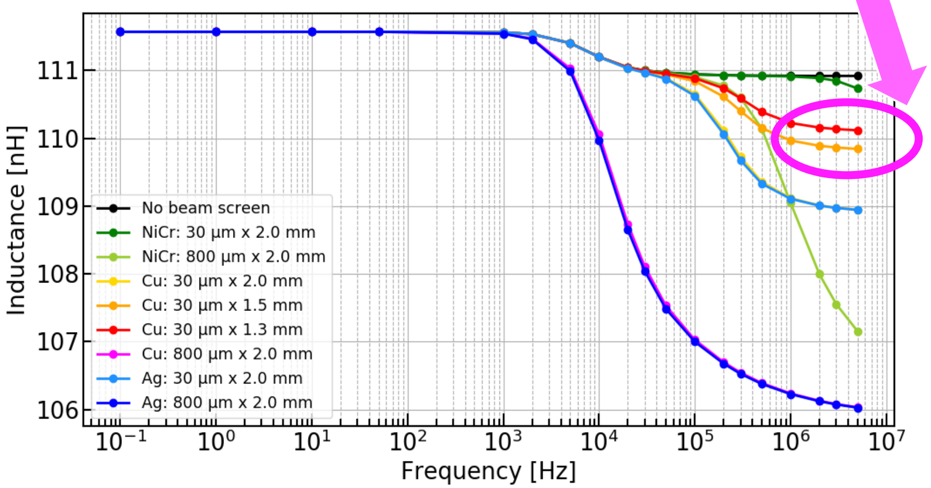
Prototype alumina tube with spiral screen conductors applied using copper paint:
→ measurements ongoing.

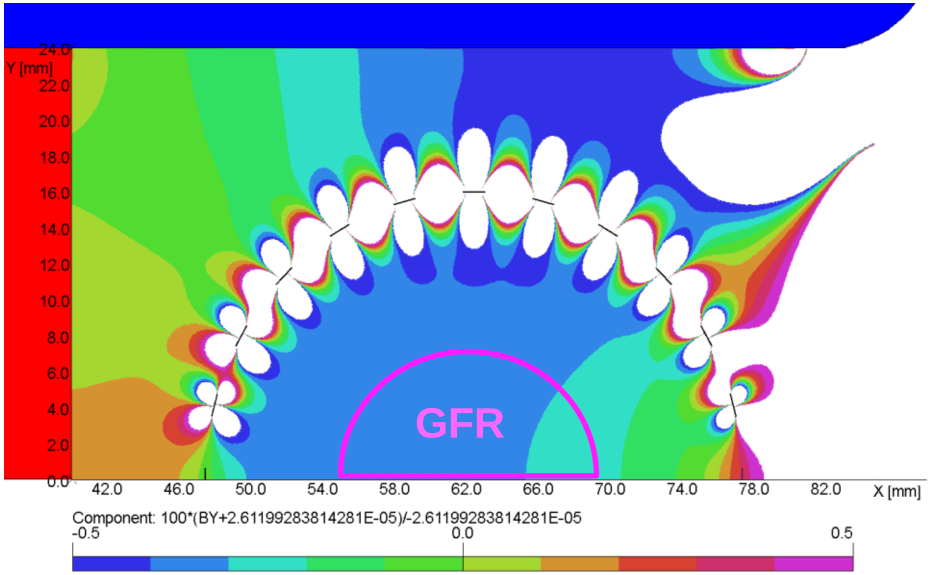
Field homogeneity,
rise time and flat-top quality
of the FCC-hh injection kicker magnet
with the beam screen

Field homogeneity/rise time/flat-top quality

OPERA AC and transient simulations (without including delay time of the kicker magnet)
- investigation of the optimum material/width/thickness of the screen conductors
- Baseline: Cu, 30 µm x 1.5 mm

BEST option





PSpice simulations (including delay time of the kicker magnet)
- ➢ Field flat-top quality and field rise time satisfied for the selected baseline parameters.

Conclusions:
Opera simulations and Pspice simulations confirm that FCC-hh kicker magnet with the beam screen will satisfy field-flat top quality and field rise time requirements.

Summary of achievements

- Optimization of the total injection kicker system length
  - ✓ 120m reduced to 40m
  - ✓ **18 magnets** in total
  - ✓ **significantly reduced total impedance contribution**
- Optimization of system impedance, in conjuction with pulse generator design
- Very well understood power deposition distribution in the kicker magnets (CST simulations, measurements, on-line analysis of the LHC MKI)
- Development of new concept of a **spiral beam screen**
  - ✓ **improved high voltage performance**
  - ✓ **low longitudinal impedance**
  - ✓ **flexibility in terms of different design options**
  - ✓ **possibility to tune transverse resonant modes**
  - ✓ **no quadrupolar component of transverse impedance**
  - ✓ **good field homogeneity** (Opera simulations)
  - ✓ **fast field rise and fall times** (Pspice simulations)

Summary of achievements

- Optimization of the longitudinal beam coupling impedace of the conventional and spiral beam screen design:
  - ✓ **no heating issues** expected for the FCC-hh injection kickers
  - ✓ **very low probability to drive longitudinal coupled bunch instability**
  - ✓ **small contribution to the impedance budget for the loss of Landau damping**
- Very good agreement between new Eigenmode method and Wakefield simulations for transverse impedance:
  - ✓ the spiral beam screen, with possible tweaks, is the **only solution to fit into FCC transverse impedance budget**

Future R&D

- **Field rise-time measurements**: to verify the influence of the spiral beam-screen upon field rise and fall times
- **Sensitivity of influence of small errors in induced voltage** upon field rise time (for conductors coupled in overlap region)
- **High-voltage tests**
- **Analysis of "tuning" of frequency** of transverse impedance resonances
- **Impedance measurements:**
  - **Concept of "switch" to connect all screen conductors to the beam pipe**, once injection is complete ⇨ verify low beam coupling impedance
  - **Concept of "tuning"** of frequency of transverse impedance resonances
  - **Possibly in a test facility, e.g. CLEAR** ?

- **Prototyping,** test and measurement of an FCC injection kicker magnet.

References

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Thank you for your attention.