EXTRACTION KICKER FOR THE CLIC DAMPING RINGS

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On behalf of:
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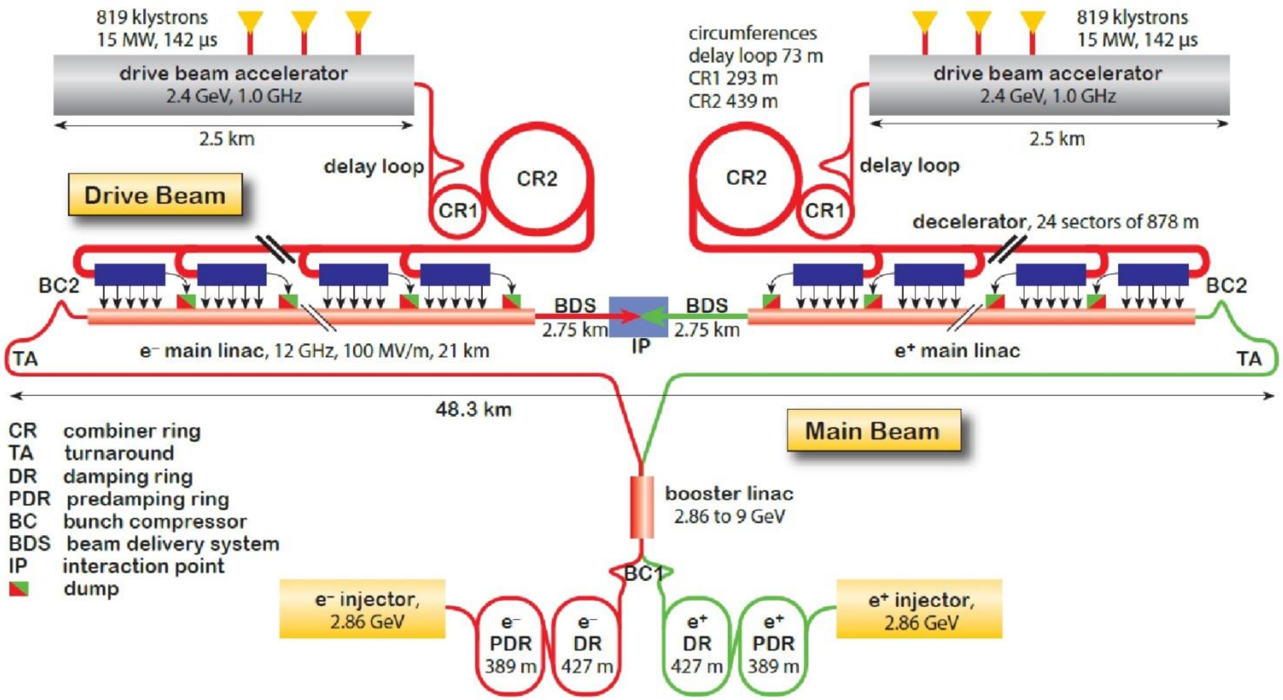
1) INTRODUCTION



- High luminosity at the IP ⇨ very low emittance beams

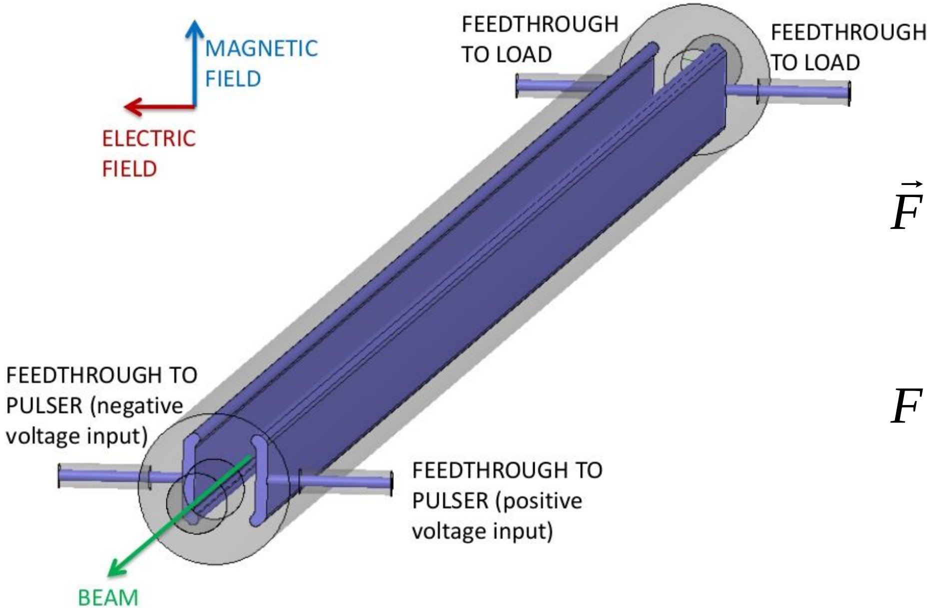
- In CLIC, 2 PDRs and 2 DRs to damp both the electron beam and the positron beam.
  - PDRs: damp to emittances that are small enough to be injected into the DRs without losses (63 μm HP & 1.5 μm VP).
  - DRs: provide the final stage of damping to the required low emittance at a fast repetition rate of 50 Hz (500 nm HP & 5 nm VP).

2) KICKERS PARAMETER CHOICE AND TECHNOLOGY

Beam parameters	CLIC DRs 1 GHz	CLIC DRs 2 GHz
Energy (GeV)	2.86	
Circumference (m)	427.5	
Bunch population [10^9]	4.1	
Normalized emittance (nm)	500 (H) 5 (V)	
Bunches per train	156	312
Bunch length (mm)	1.6	1.8
Bunch spacing (ns)	1	0.5

Kickers parameters	CLIC DRs 1 GHz	CLIC DRs 2 GHz
Deflection angle (mrad)	1.5	
Aperture (mm)	20	
Effective length (m)	1.7	
Field rise and fall times (ns)	560	1000
Pulse flat top (ns)	900	160
Flat top reproducibility	$\pm\ 1 \times 10^{-4}$	
Extraction stability	$\pm\ 2 \times 10^{-4}$	
Extraction uniformity (%)	± 0.01 (over 1 mm)	
Repetition rate (Hz)	50	
Vacuum (mbar)	10^{-10}	
Stripline voltage (kV)	±12.5	
Stripline current (A)	± 250	
Longitudinal beam impedance (Ω/n)	0.05	
Transverse beam impedance (kΩ/m)	200	

3) STRIPLINE KICKER OPERATION

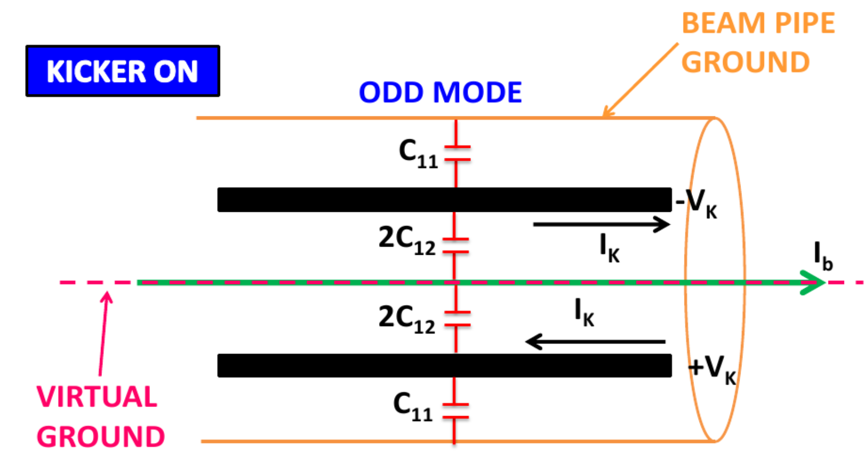


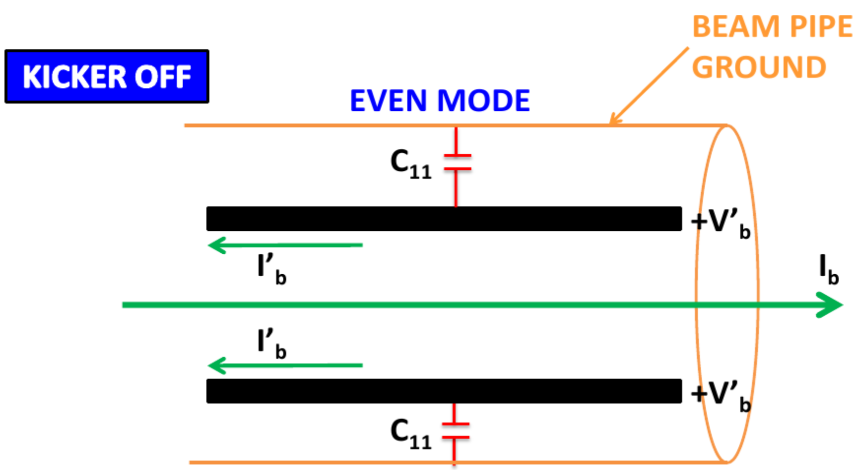
$$\vec{F} = q\left(\vec{E} + \vec{v} \times \vec{B}\right)$$

$$F = q\left(E + c \times \frac{E}{c}\right) = 2qE$$

- Two parallel electrodes housed in a conducting cylinder:
- Each of the electrodes is driven by an equal but opposite polarity pulse:
  - downstream feedthroughs: inductive adder
  - upstream feedthroughs: 50 Ω resistive loads.
- Each of the electrodes with its adjacent ground planes (beam pipe walls) forms a transmission line for TEM waves.

COUPLED LINES → TWO OPERATION MODES:
ODD AND **EVEN** MODE





$$Z_{odd/even} = \frac{1}{cC_{odd/even}}$$

$$\boldsymbol{Z_{odd} < Z_{even}}$$

ODD MODE:

- The electric field lines have an odd symmetry about the centre line, and a voltage null exists between the two electrodes.
- There is a virtual ground plane midway between the electrodes (capacitance = $2C_{12}$)
- The effective capacitance between an electrode and ground is $C_{odd} = C_{11} + 2C_{12}$.

EVEN MODE:

- The two electrodes are at the same potential, so there is no charge stored in the capacitance between them.
- The resulting capacitance of either electrode to ground is $C_{even} = C_{11}$.

4) DESIGN OF THE STRIPLINE GEOMETRY

The most important challenges:

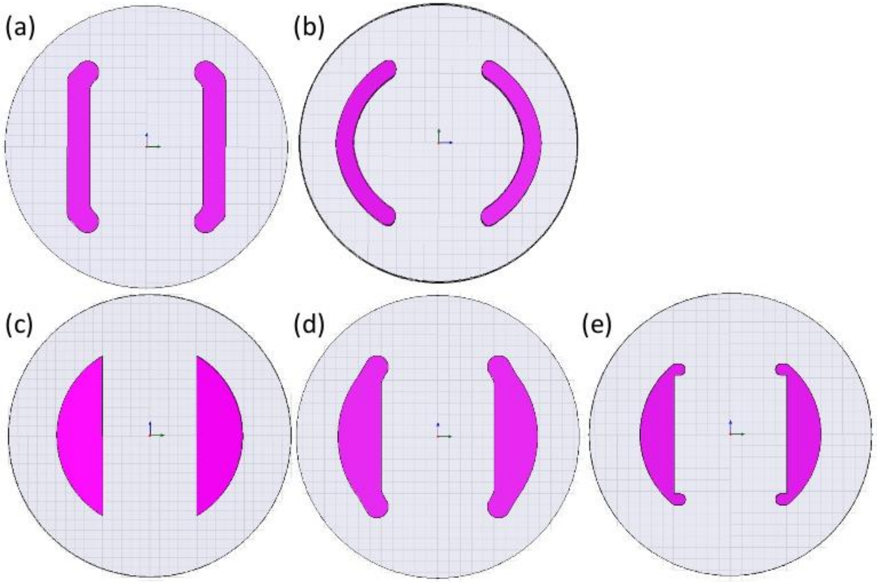
- Field homogeneity
- Good power transmission, with extremely low pulse ripple
- Very low beam coupling impedance

Optimize the striplines studying the dependence of the field homogeneity, as well as the odd and even mode characteristic impedances, upon the cross section geometry of the striplines.

NEW ELECTRODE SHAPE

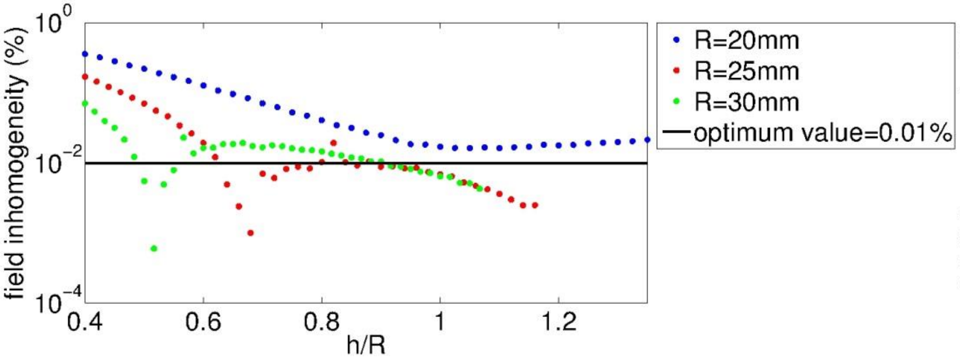
4.1) Characteristic impedance and field homogeneity optimization

- The most common electrode shapes for striplines, used in kickers, are flat and curved electrodes.
  - flat electrodes show good field homogeneity
  - curved electrodes may allow for a better impedance matching between the two operation modes, but with poorer field homogeneity.
- A new geometry was proposed, the half-moon electrode: good field homogeneity and suitable impedance matching.

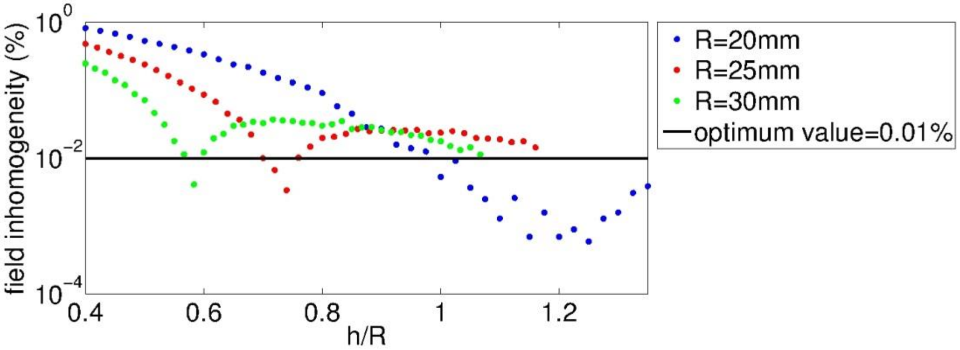


FIELD HOMOGENEITY

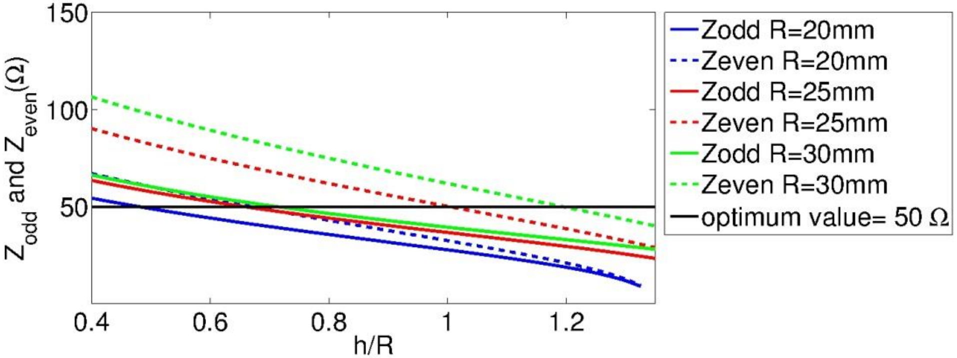
FLAT ELECTRODE

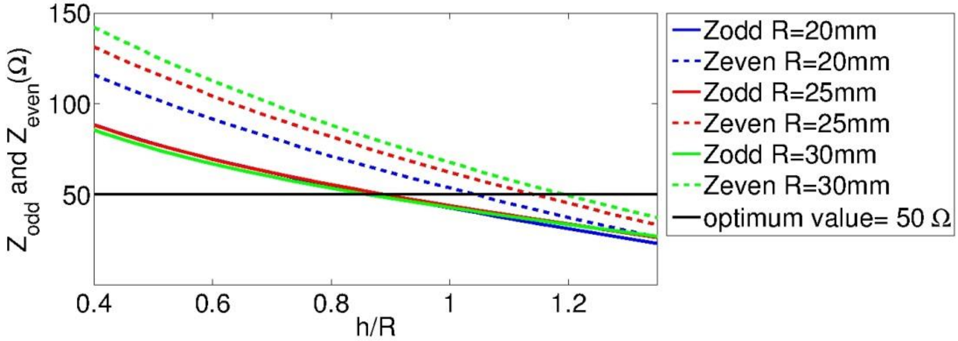


HALF-MOON ELECTRODE



CHARACTERISTIC IMPEDANCE





Simulations with HFSS:

- Flat electrodes: Z_{even} = 50 Ω, Z_{odd} = 36.8 Ω, R = 25 mm.
- Half-moon electrodes: Z_{even} = 50 Ω, Z_{odd} = 40.9 Ω, R = 20 mm.

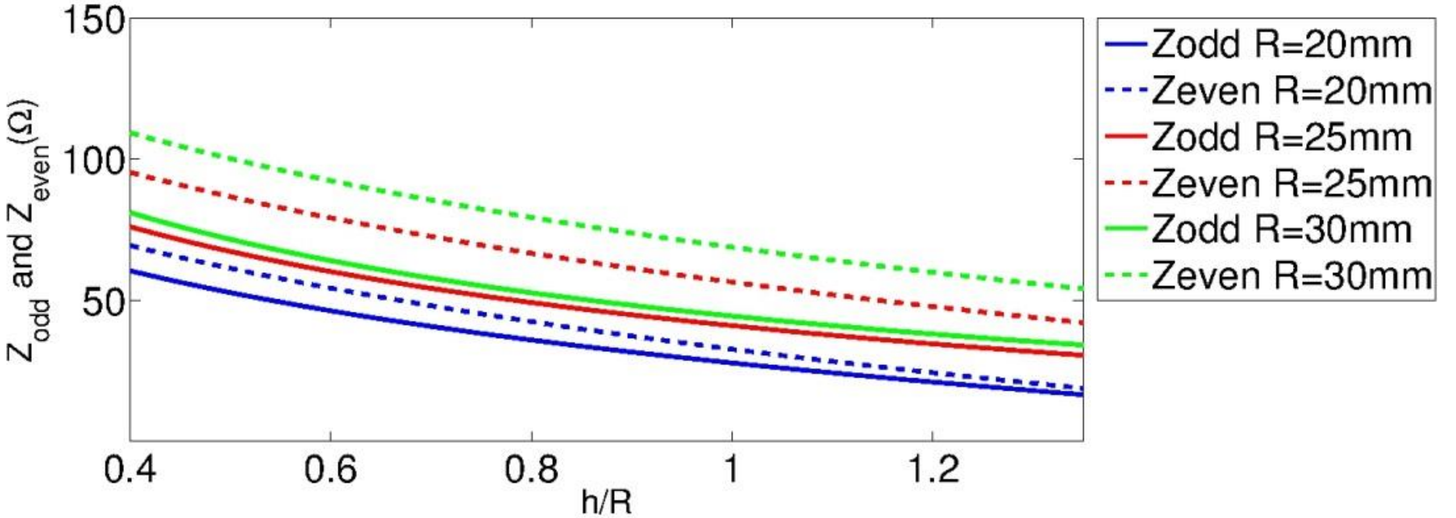
FIRST-ORDER ANALYTICAL APPROXIMATION

- The electrodes can be considered as parallel plate capacitors

$$C_{12} = \epsilon_0 A/a$$

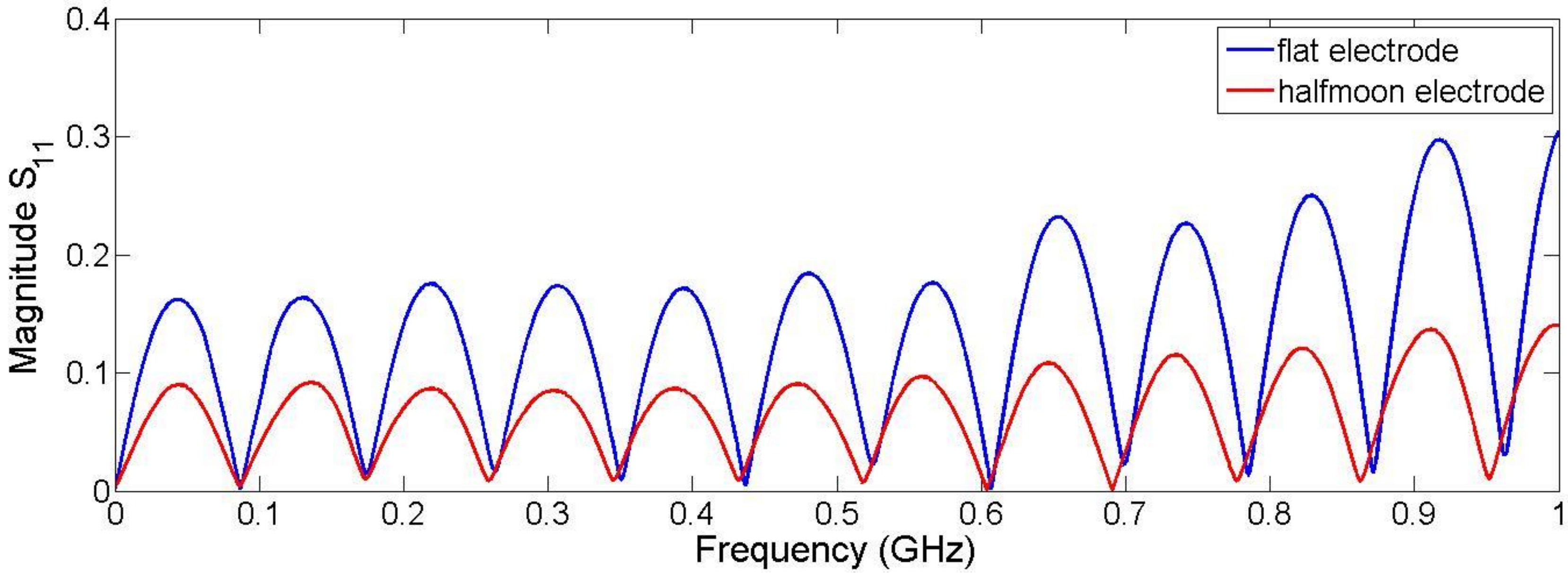
- The capacitance between an electrode and the beam pipe can be thought as the capacitance between a strip conductor and an infinite ground plane

$$\frac{1}{C_{11}} = \left(\frac{87}{\sqrt{\epsilon_r + 1.41}}\right) \ln\left(\frac{5.98d}{0.8h + \omega}\right)$$



4.2) Power transmission through the striplines

- Impedance mismatches result in reflections:
  - the characteristic impedance of the connection from a feedthrough to an electrode is not 50 Ω,
  - the odd mode characteristic impedance is lower than 50 Ω.
- CST MS has been used to calculate the reflection parameter S_{11}, looking into an input port when the corresponding output is terminated with 50 Ω.

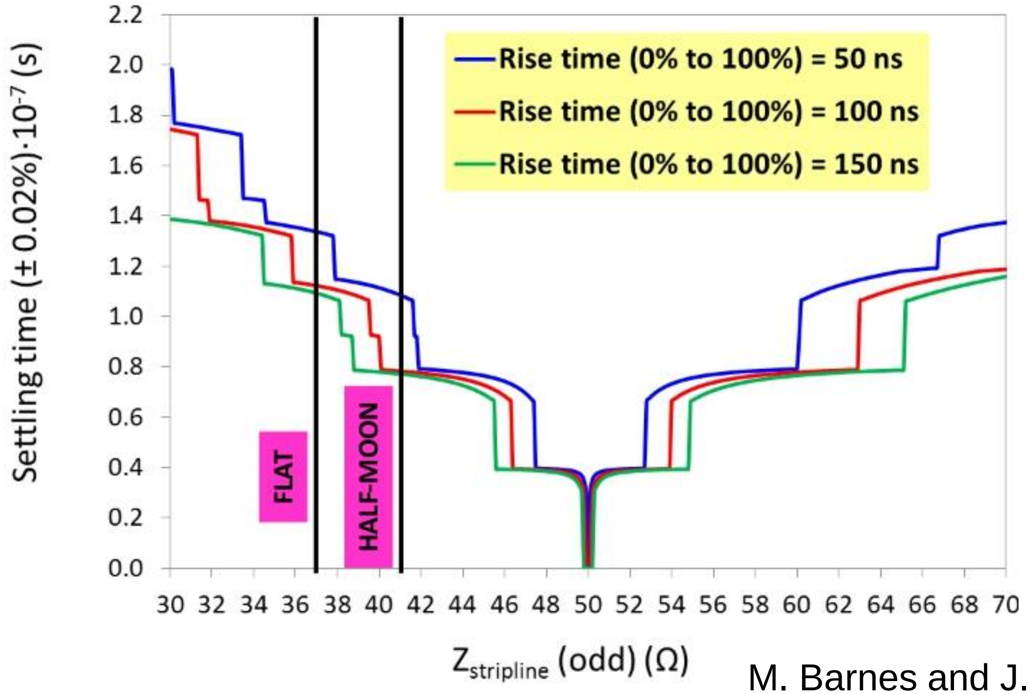


- The peaks of the S_{11} parameter increase with frequency
- The frequency difference between peaks is related to the electrode length as $\Delta f = c/2L \approx 90\ \mathrm{MHz}$.

4.3) Settling time

- Impedance mismatches create reflections and thus ripple.
- **Settling time**: the time for the ripple to reduce within specification (±0.02%), measured from the end of the rise time (0% to 100%) of the idealized trapezoidal current pulse produced by the inductive adder.

↑settling time ⟶ ↑pulse width ⟶ ↑power dissipation $T_s < 100$ ns



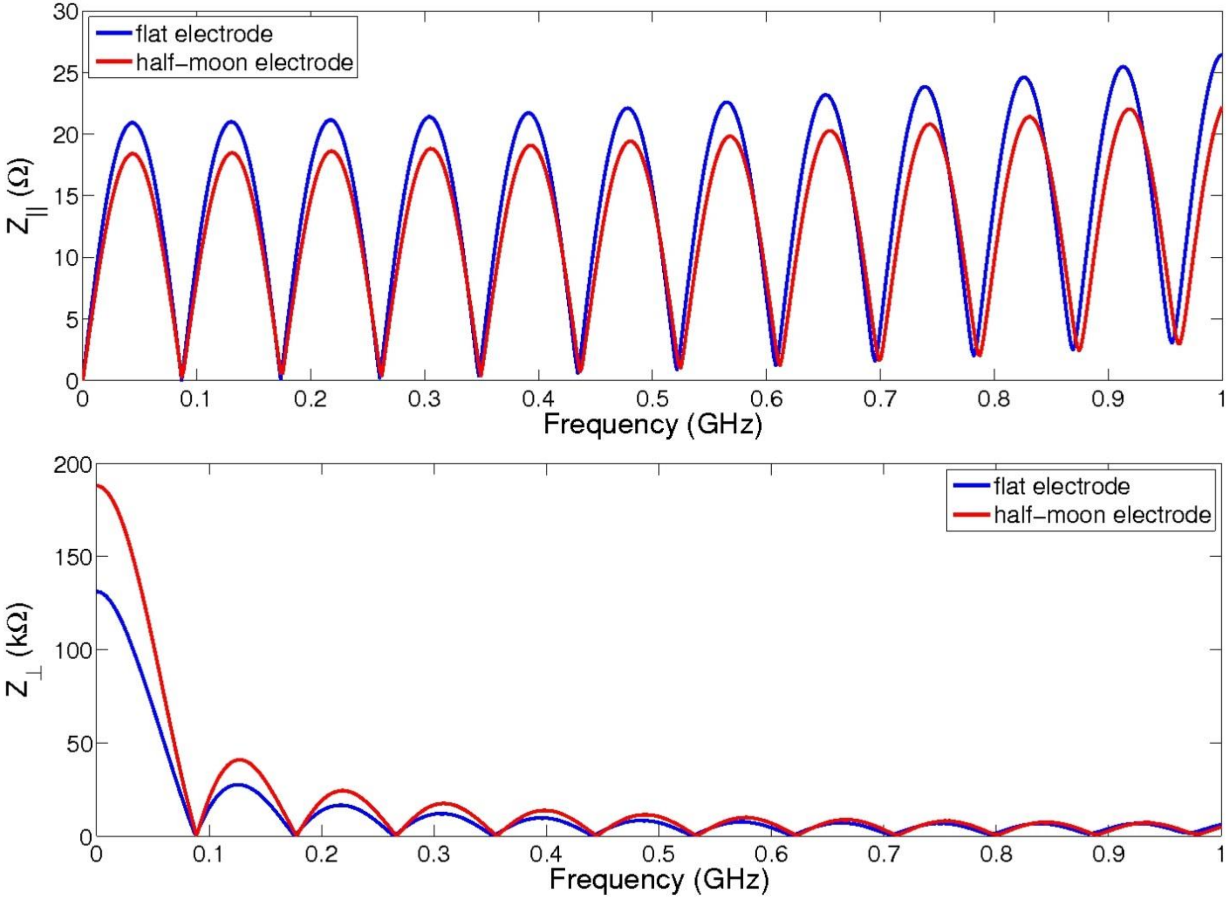
M. Barnes and J. Holma

$T_r = 100$ ns

- Flat electrode
  $T_s = 113$ ns
- Half-moon electrode
  $T_s = 78$ ns

4.4) Beam coupling impedance

- A charged particle beam traveling inside a vacuum chamber induces wakefields which act back on the beam itself.
- It is important to reduce as much as possible the effect of the wakefields in order to diminish the perturbation of the circulating beam.
- By using CST PS, the beam coupling impedance at low frequencies has been studied.



At low frequencies:

$$\omega/2\pi \ll c/4l \approx 44 \text{ MHz}$$

- Longitudinal impedance per harmonic:

$$\frac{Z_{\parallel}}{n} \simeq jZ_{even}\left(\frac{\phi_0}{\pi}\right)^2 \frac{L}{r}$$

$\approx \boldsymbol{j0,09\Omega}$ flat electrode

$\approx \boldsymbol{j0,06\ \Omega}$ half-moon electrode

where $r = 427{,}5\ \text{m}$ is the DR radius.

- Transverse impedance:

$$Z_{\perp} \simeq j\frac{8Z_{even}L}{\pi^2R^2}\sin^2\frac{\phi_0}{2}$$

$< \boldsymbol{j150\ \text{k}\Omega}$

$< \boldsymbol{j200\ \text{k}\Omega}$

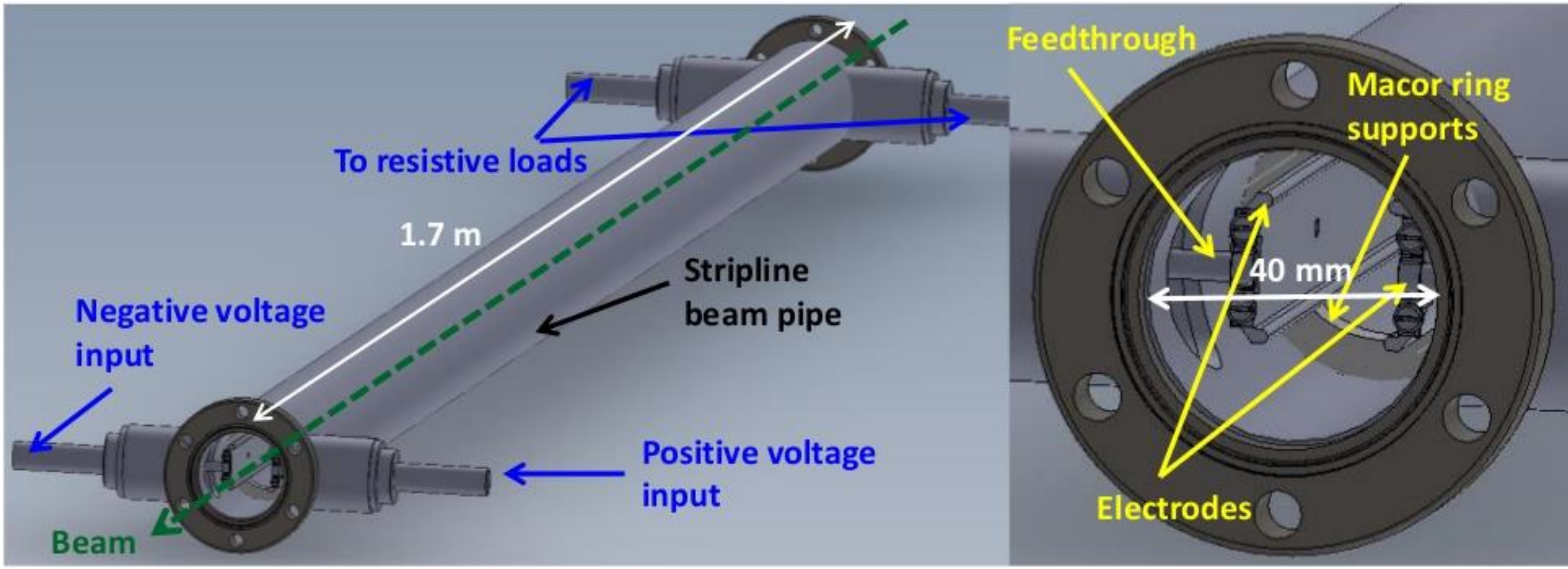
High frequency beam coupling impedance is an open question to be studied.

4.5) Discussion and choices of the striplines geometry

	FLAT ELECTRODE	HALFMOON ELECTRODE
Matching characteristic impedances		✓
Field homogeneity		✓
Signal transmission		✓
Settling time		✓
Untapered longitudinal beam coupling impedance		✓
Untapered transverse beam coupling impedance	✓	

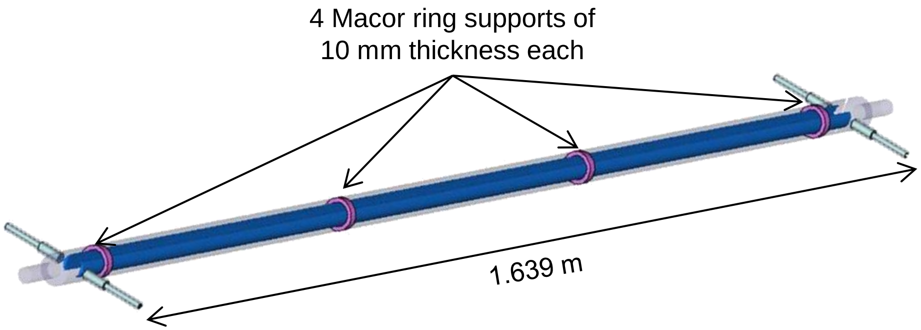
The half-moon electrodes are considered as the best choice for the cross-section of the striplines for the extraction kicker of the CLIC DRs.

5) MATERIALS AND COMPONENT STUDIES
5.1) Material choices

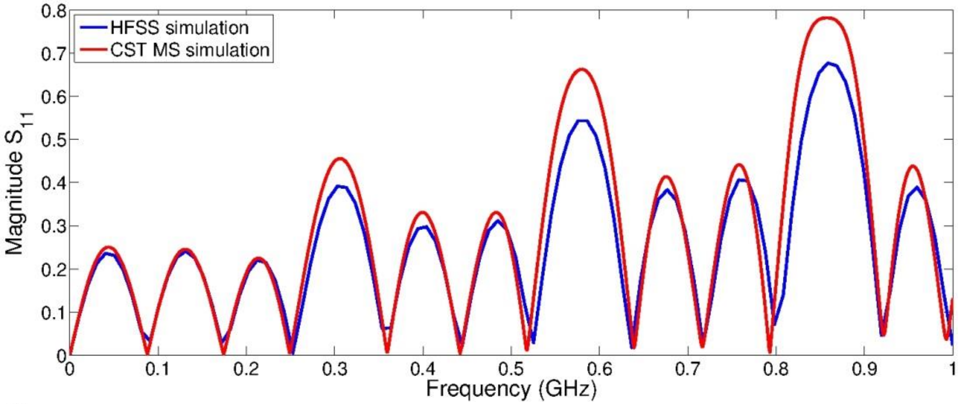


- The beam pipe housing the stripline electrodes is a stainless steel tube of 1.712m length, and an internal diameter of 40.0 ± 0.2 mm.
- Aluminum has been chosen for the electrodes, because it is relatively easy to achieve the tight tolerances required during manufacturing.
- The electrode supports have been manufactured using ceramic (Macor).

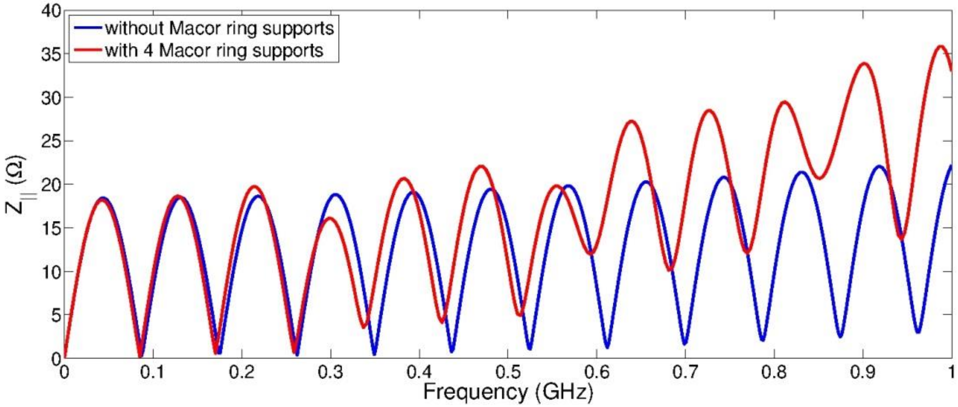
5.2) Study and optimization of electrode supports

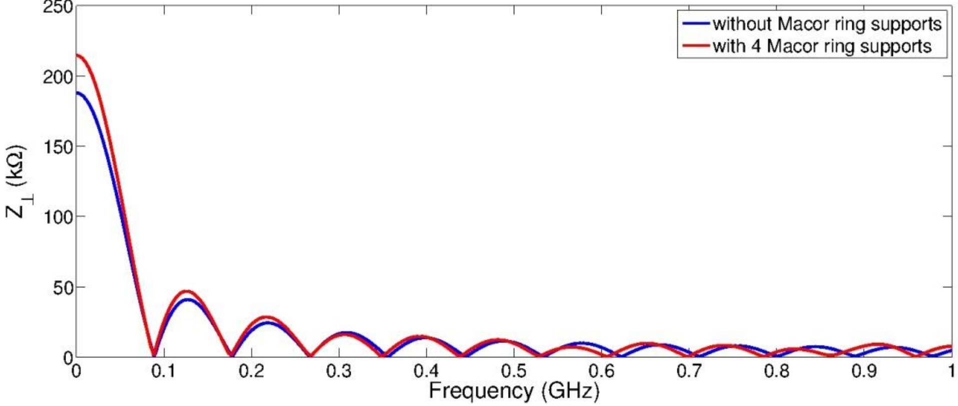


To ensure the alignment of the long electrodes, they have been fixed outside the aperture by using four equally-spaced Macor rings, of 10 mm length each.

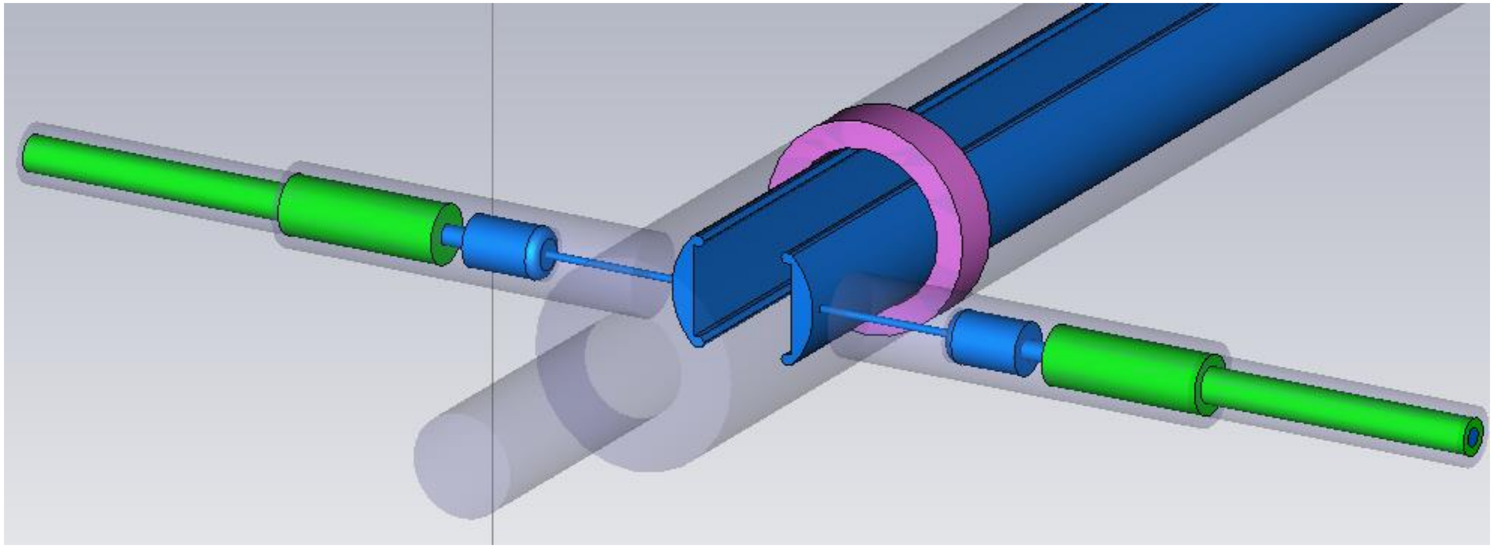


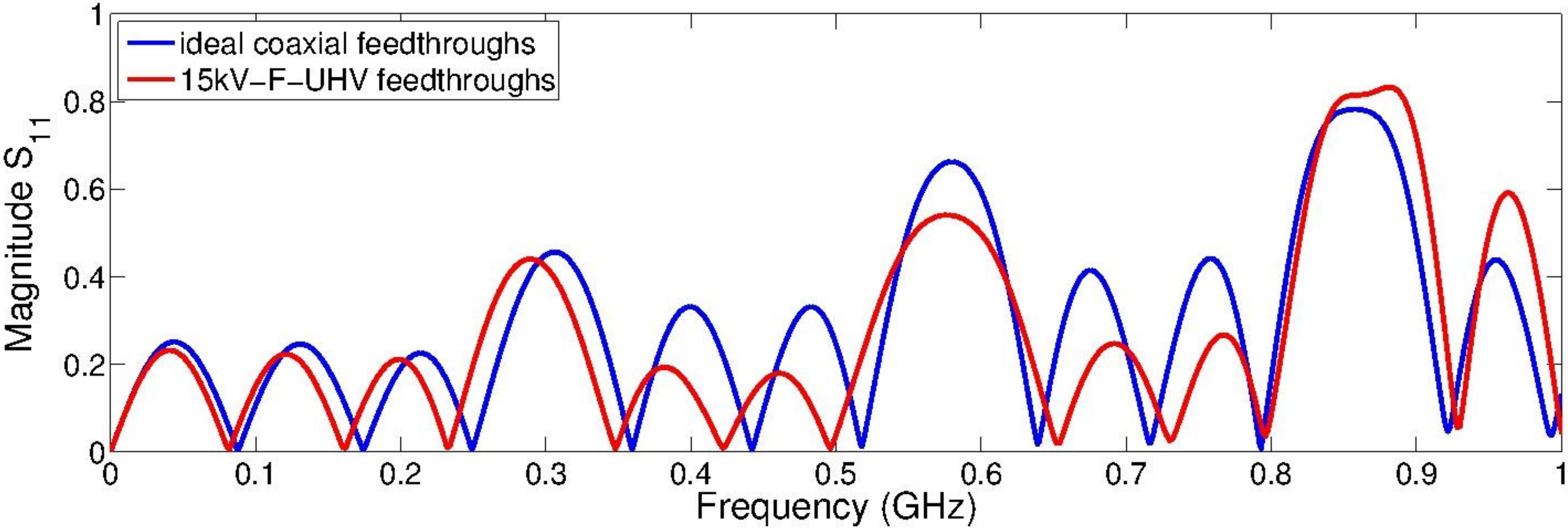
- Macor rings increase the magnitude of the reflection parameter, starting from 300 MHz, of every third peak.
- There is an increase of the longitudinal beam coupling impedance, whereas the transverse one is not significantly affected.



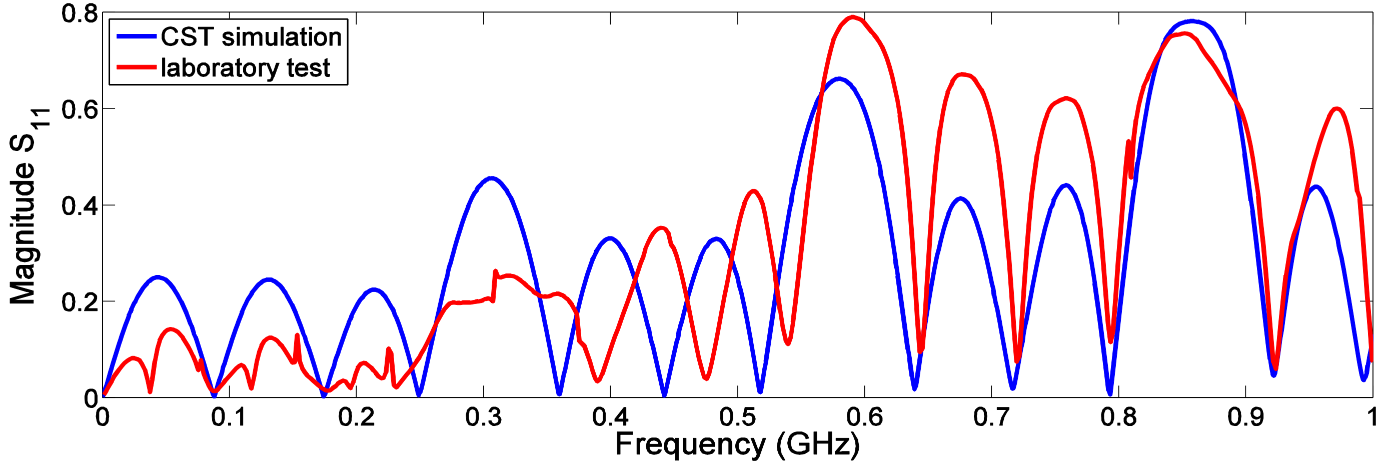


5.3) Feedthroughs study and optimization

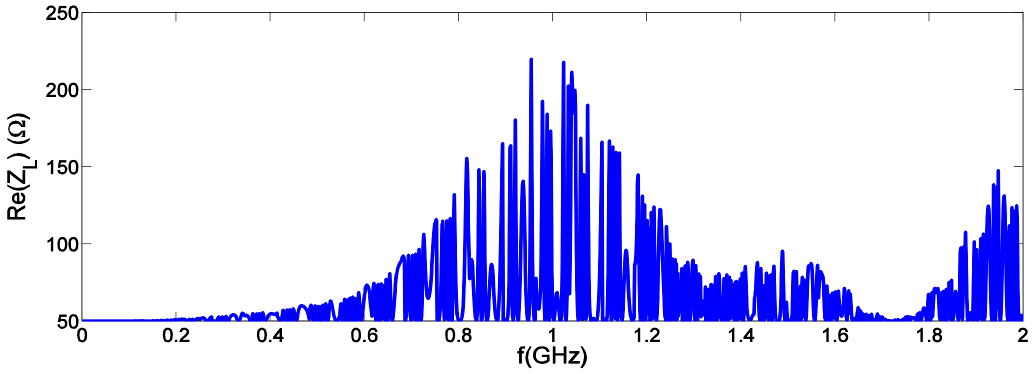




6) FIRST TESTS AT CERN (DECEMBER 2013)

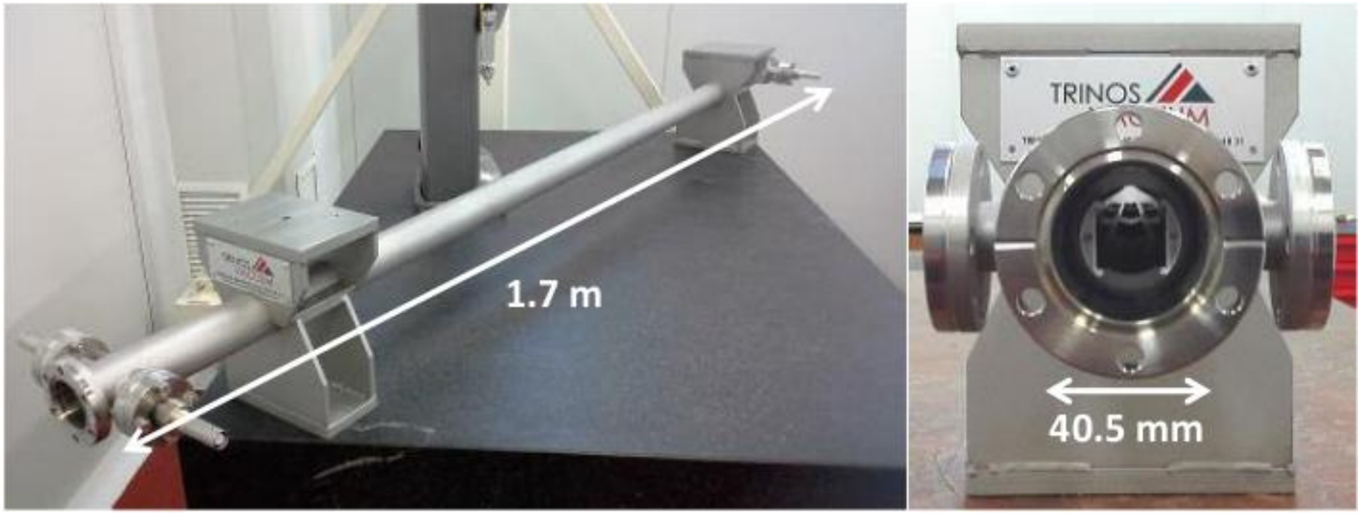


- Only one electrode was connected to the network analyzer and terminated with the resistive load, while the second electrode was “floating”.
- The resistive load has been measured and is not 50 Ω for the whole frequency range considered.



- New results using an hybrid to drive both electrodes will come up soon.

7) SUMMARY



- The stripline design provides the **performance** specified for the extraction kicker of the CLIC DRs: excellent field homogeneity, good power transmission and reasonable broadband beam coupling impedance.

- The **stripline design** has been carried out by using analytical approximations and simulations to optimize the **stripline geometry**.

- A **prototype** of the extraction stripline kicker for the CLIC DR **has been manufactured** by Trinos Vacuum Projects (Valencia, Spain) and is being tested at CERN lab.