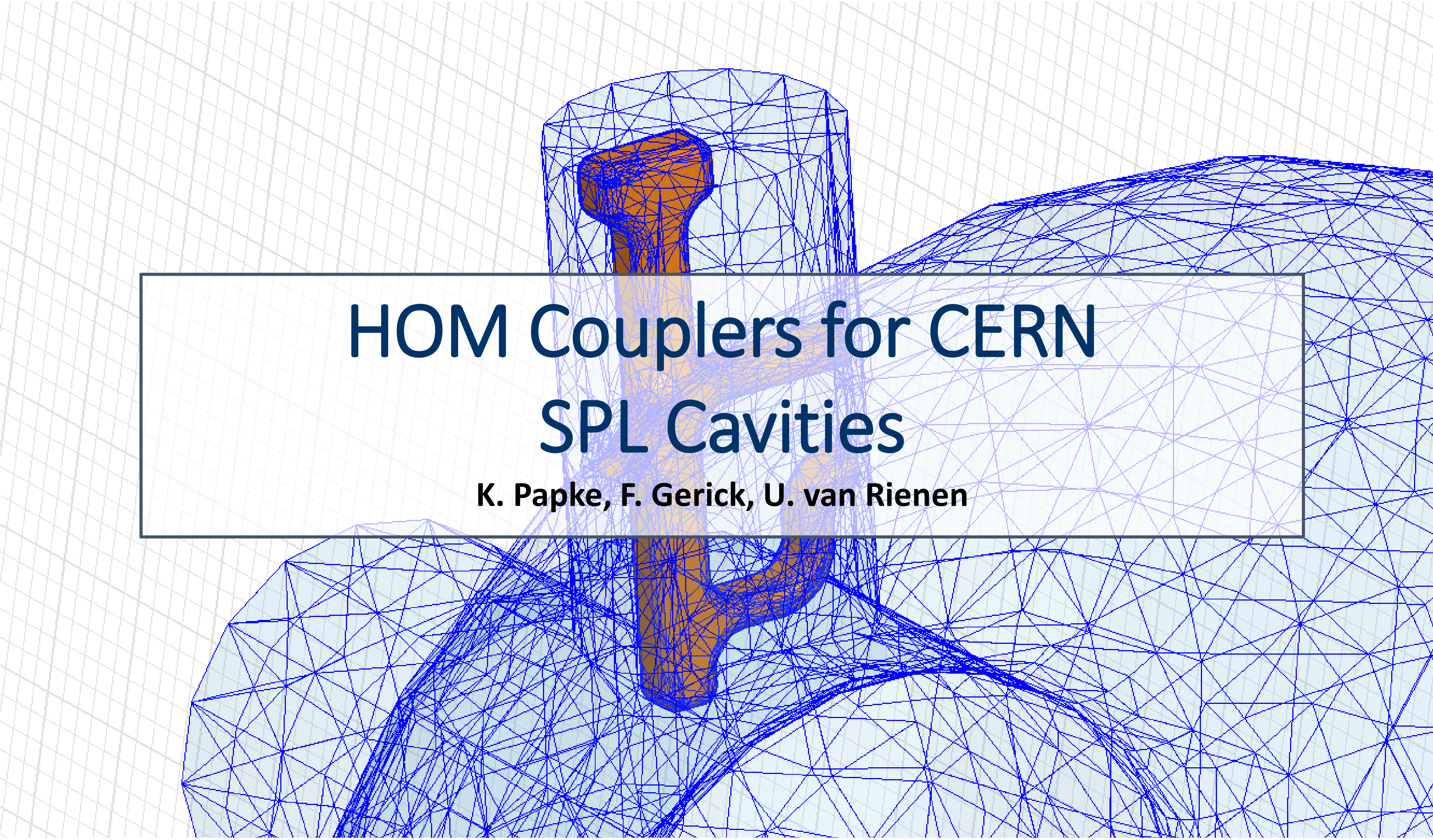
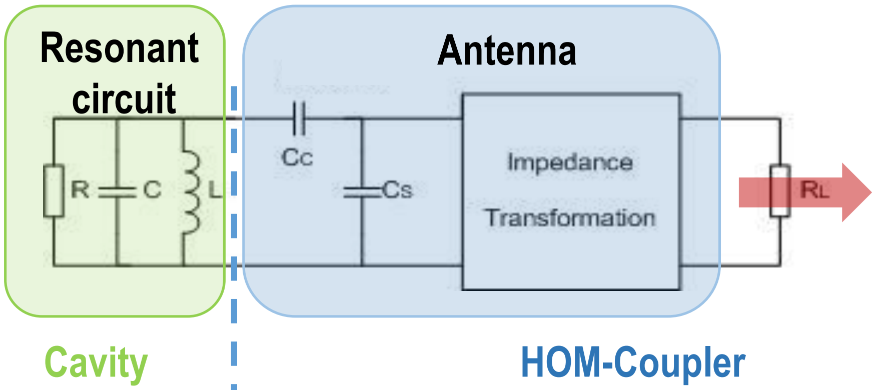


HOM Couplers for CERN SPL Cavities

K. Papke, F. Gerick, U. van Rienen

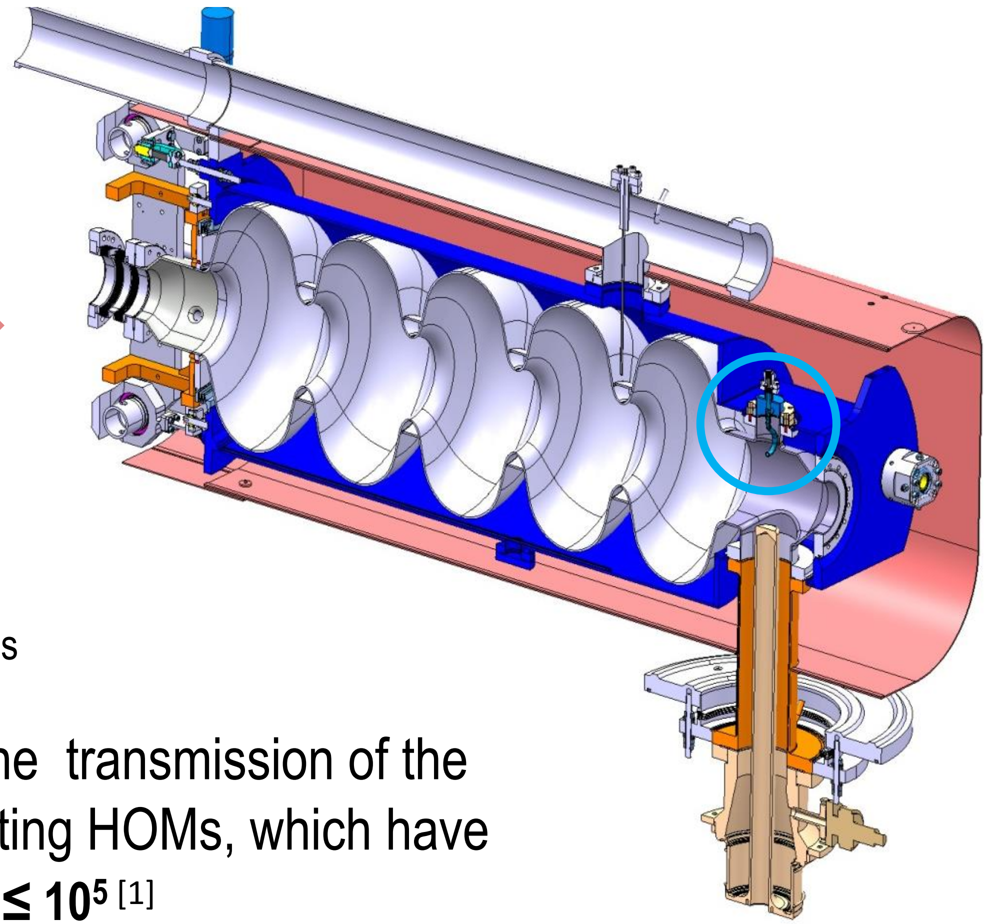
Work supported by the Wolfgang-Gentner-Programme of the Bundesministerium für Bildung und Forschung (BMBF)

- HOM-Coupler used to extract or dissipate unwanted, higher order modes in the cavity induced by the beam



⇐ Very high impedance for the notch frequency (704.4MHz)

⇐ Low impedance for "all" other modes

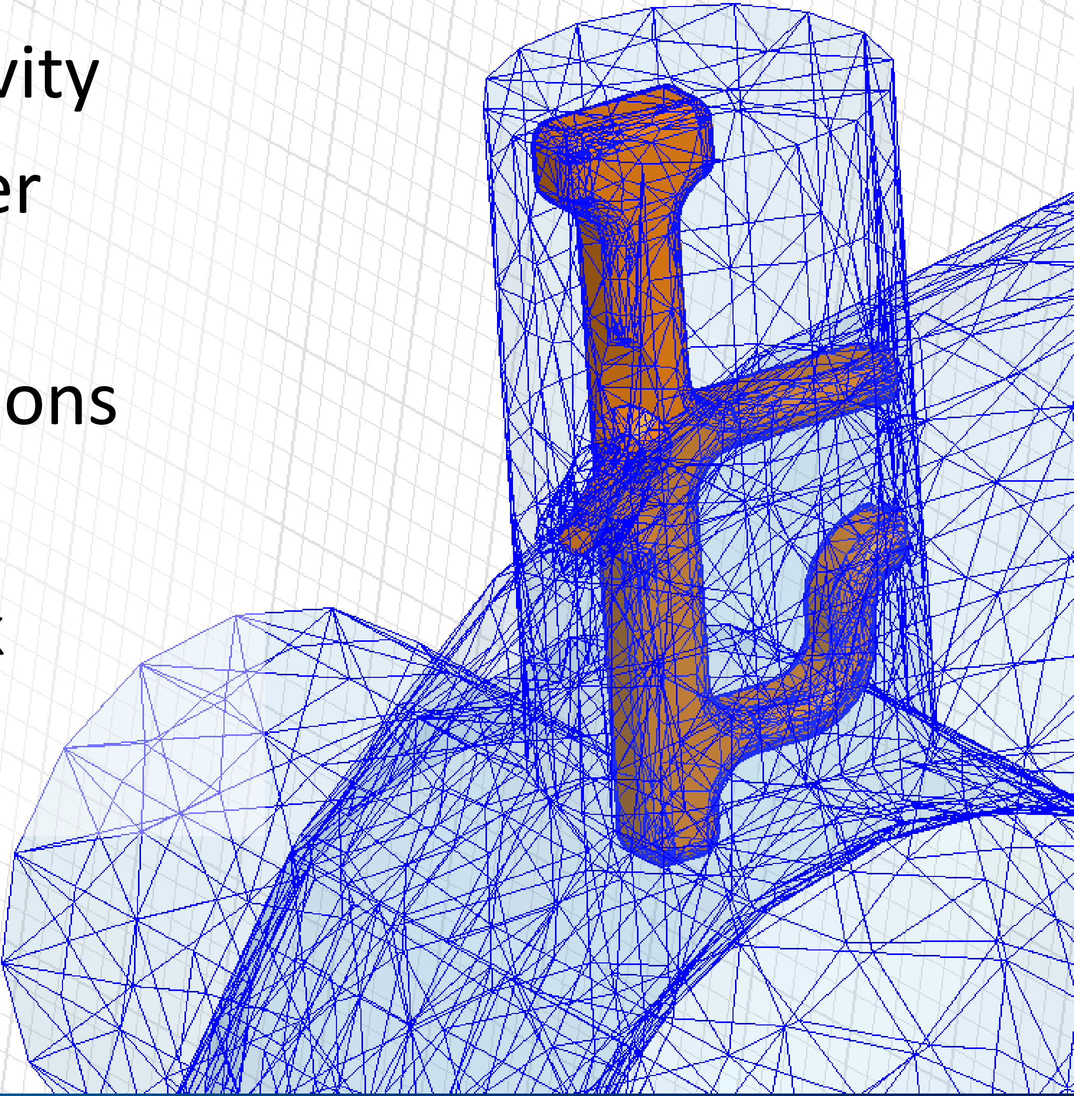


O. Capatina, SPL Seminar 2012

- Design goal of HOM filter: block the transmission of the accelerating mode, while transmitting HOMs, which have significant (R/Q) values with **Qext ≤ 10^5** [1]

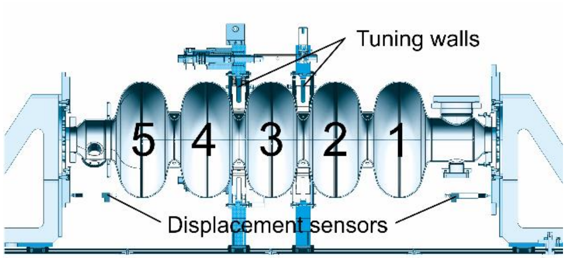
Outline

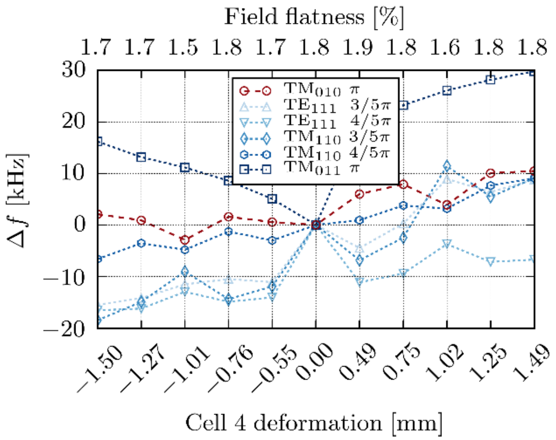
- Cavity Mode Sensitivity
- Tests of HOM coupler prototypes
- Heat Loss Investigations
- Multipacting
- Summary & Outlook

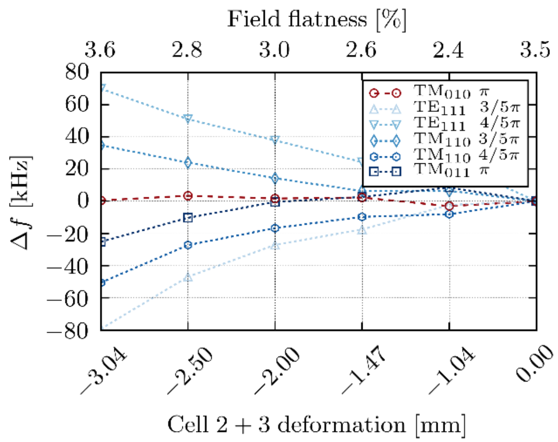


Cavity Mode Sensitivity [3]

- Single cell plastic deformations (~1.5 mm) and subsequent retuning yield residual HOM frequency shifts of up to several 10s of kHz
- Frequency shift is not always systematic
- Due to large frequency shift during cool-down (> 1MHz), shifting of HOMs via single cell detuning/retuning is probably not precise enough to displace single HOMs away from machine lines

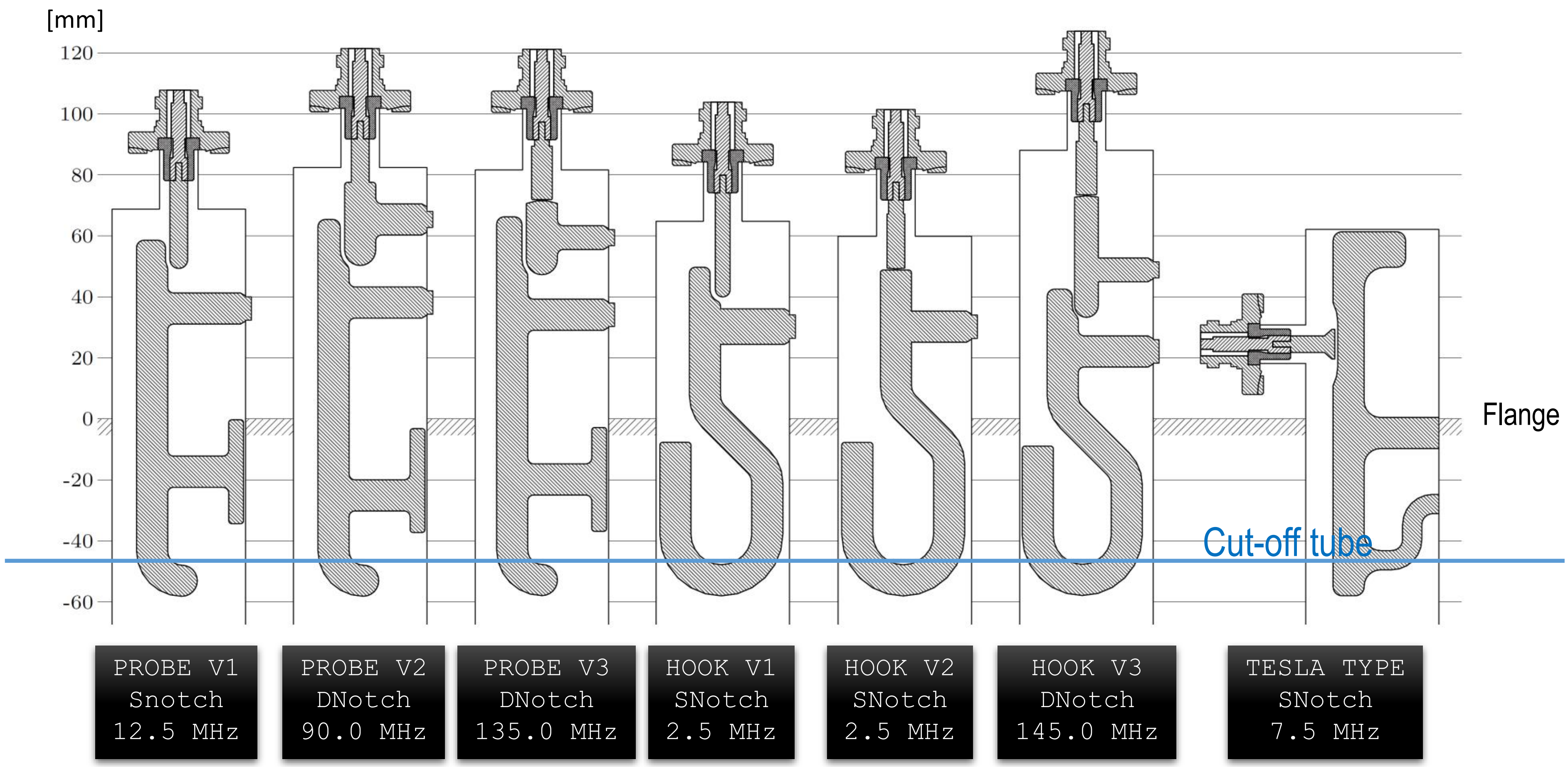






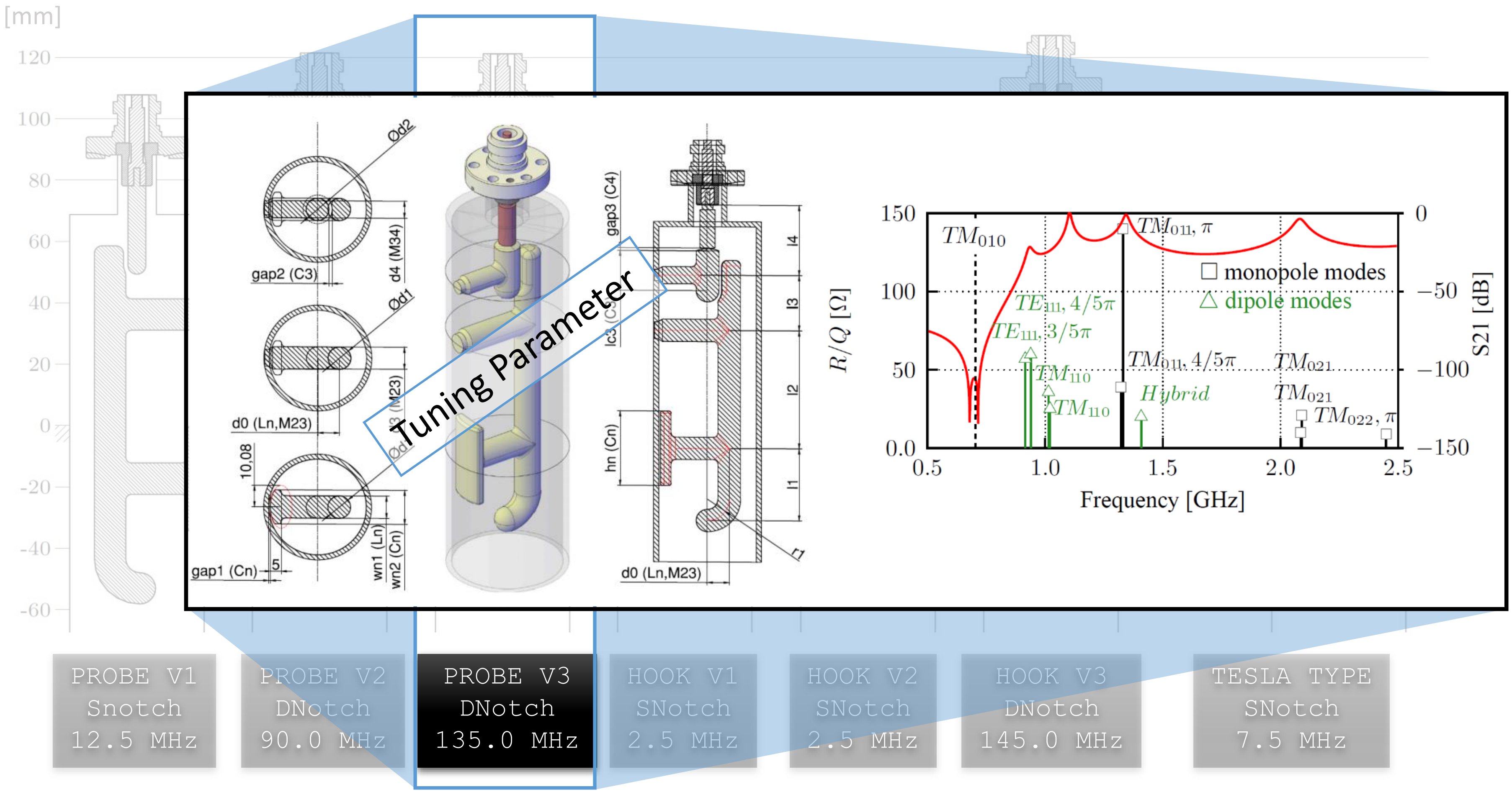
Monopole modes			Dipole modes		
Type	Freq [MHz]	R/Q [Ω]	Type	Freq [MHz]	R/Q [Ω]
$TM_{010}\pi$	704.4	566	$TE_{111}3/5\pi$	918	57
$TM_{011}4/5\pi$	1322	39	$TE_{111}4/5\pi$	943	60
$TM_{011}\pi$	1331	140	$TM_{110}3/5\pi$	1014	36
TM_{021}	2087	10	$TM_{110}4/5\pi$	1020	25
TM_{021}	2090	21	Hybrid	1409	20
$TM_{022}\pi$	2449	9			

Design approaches and prototype choice



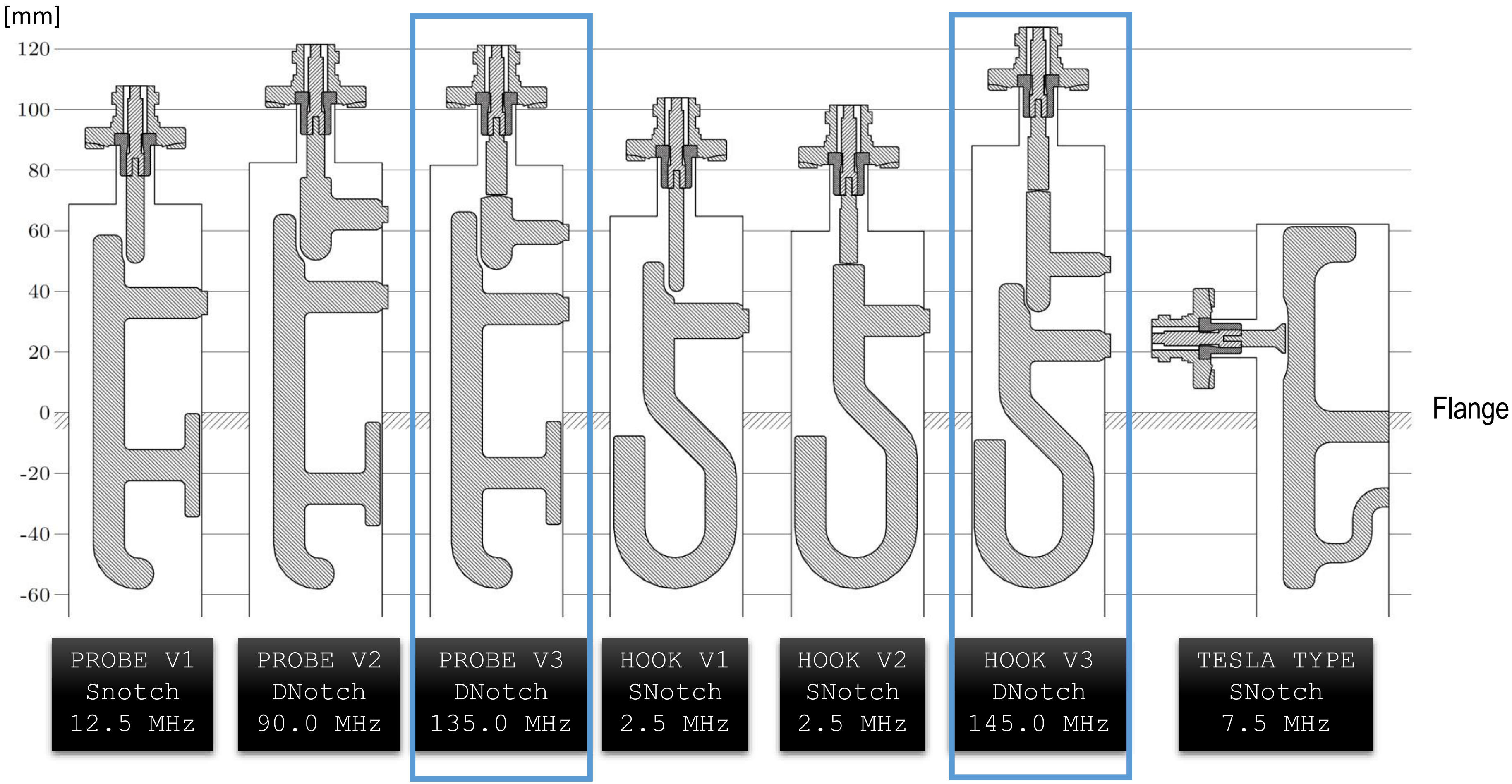
- Single notch designs easier to fabricate but they are more sensitive and have a lower selectivity
- Hook designs have a better coupling to dipole modes/ Probe designs better for monopole modes
- Notch filter of the TESLA design nicely tunable but design is not reasonable for SPL cavity

Design approaches and prototype choice



- Transmission behavior optimized according to the HOM spectrum of the cavity by adjusting all design parameters

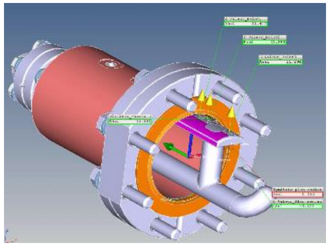
Design approaches and prototype choice

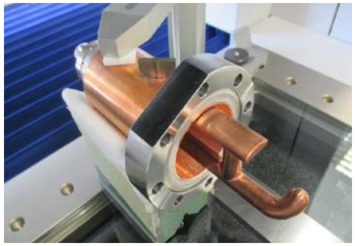


- 3D-prints of the PROBE V3 and HOOK V3 (copper coating)
- PROBE V3 solid prototype made of copper

Prototype Tests

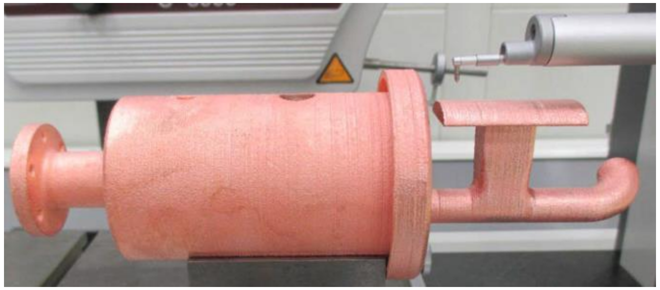
- Dimensional control of the notch plate:
  - Tolerance of the couplers: ±0.2 mm
  - Surface roughness test of a 3D-print: 0.24 mm
  - Gap distance of notch filter of solid prototype slightly out of tolerance (+0.246 mm), however adjusted by bending

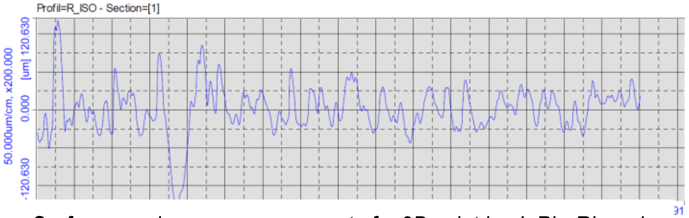




Mechanical Design by T. Renaglia, F. Pillon, N. Alonso

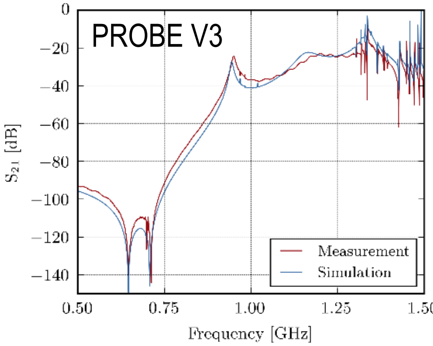
Dimensional control of the solid prototype by D. Pugnat

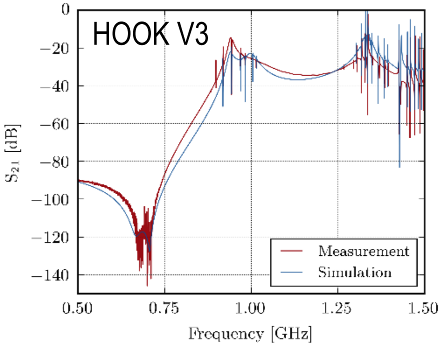




Surface roughness measurement of a 3D-print by J. Ph. Rigaud

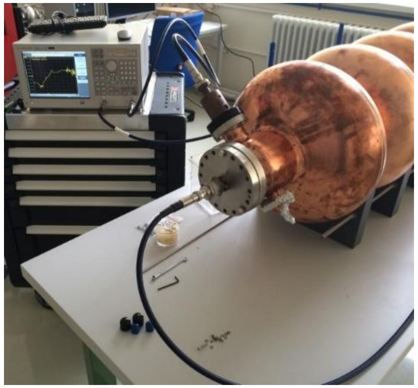
- RF Transmission tests on a copper SPL cavity
  - S21 parameter in good agreement with the simulations
  - Rotatable flange allows fine tuning of gap distance





PROBE V3

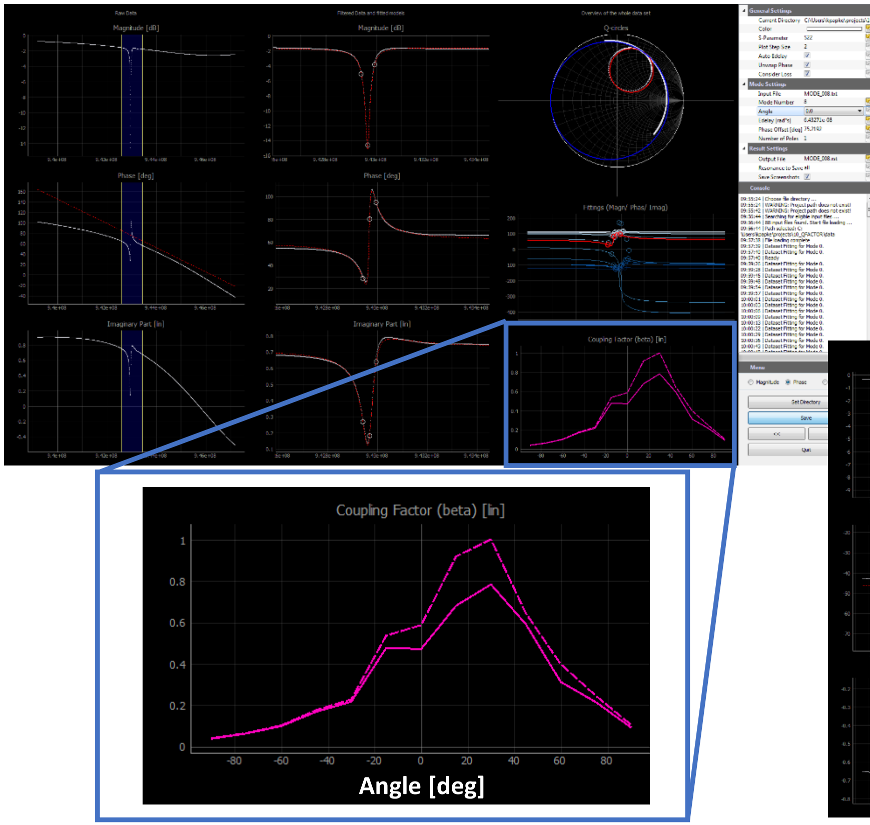
HOOK V3



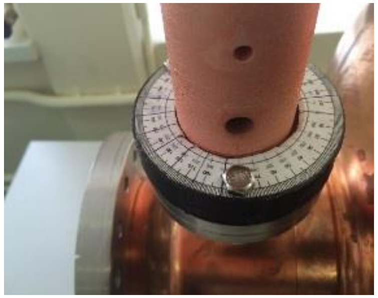
S21 and Qext measurements at warm

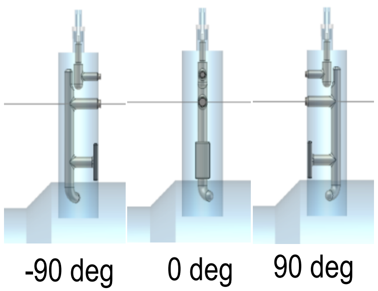
Prototype Tests

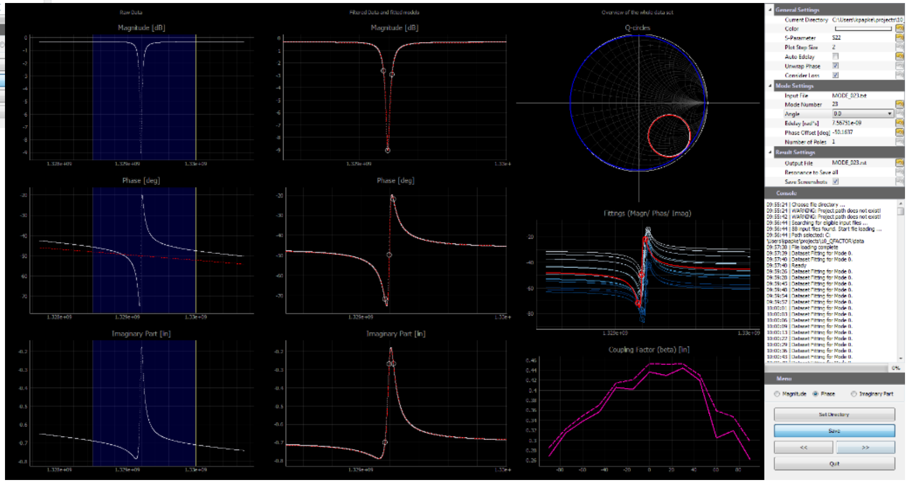
- Q external measurements for different coupler orientations with respect to the beam line
  - Program was written to simplify the evaluation of measurements (~80 modes, ~1000 data sets/ coupler)
  - Uses complex pole fitting algorithm to extract resonance frequency and bandwidth [4,5]



TE$_{111}$ 4/5 π Measurement







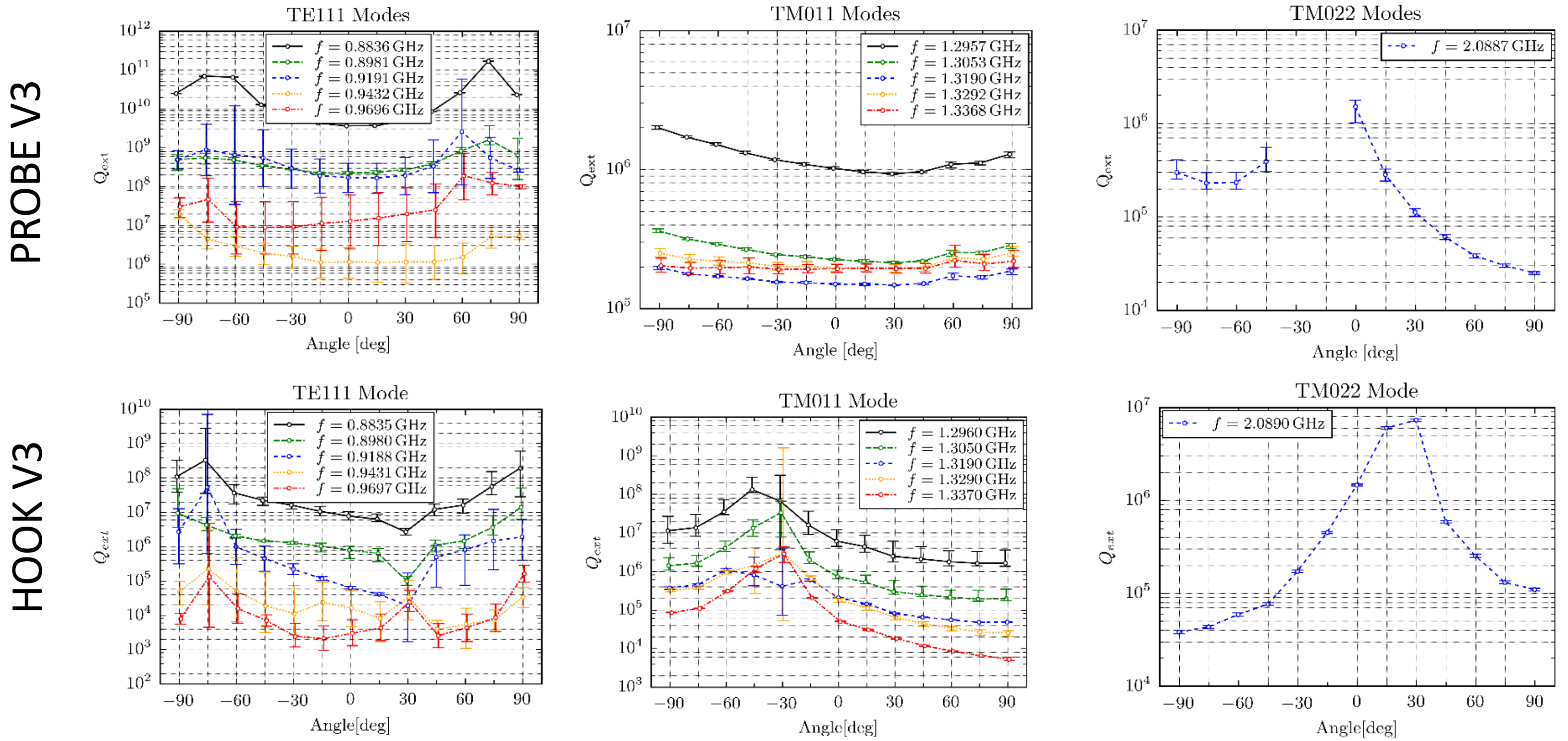
TM$_{011}$ 4/5 π Measurement

Prototype Tests

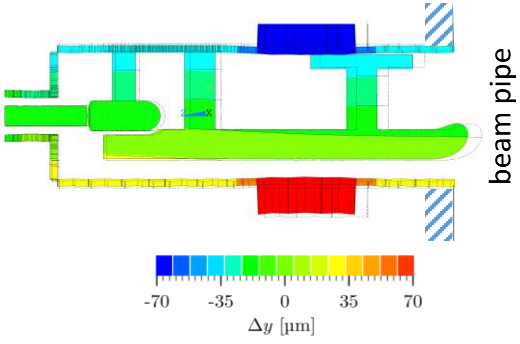
- Q external measurements for different coupler orientation with respect to the beam line
  - Coupling factor measured directly over S11 and over reference antenna
  - Preferable positions: 30 deg for PROBE V3 and 0 deg for HOOK V3
  - HOOK V3 shows for most of the selected HOMs lower Qext

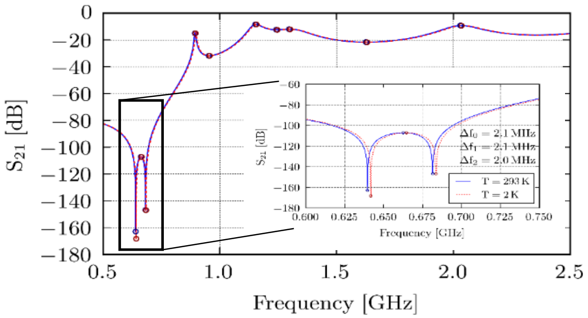
$$\beta_{hom} = \frac{1 \pm S_{11}}{1 \mp S_{11}}$$

$$\beta_{hom} = \frac{|S_{21}|^2}{\frac{4\beta_{ref}}{(\beta_{ref}+1)^2} + |S_{21}|^2}$$

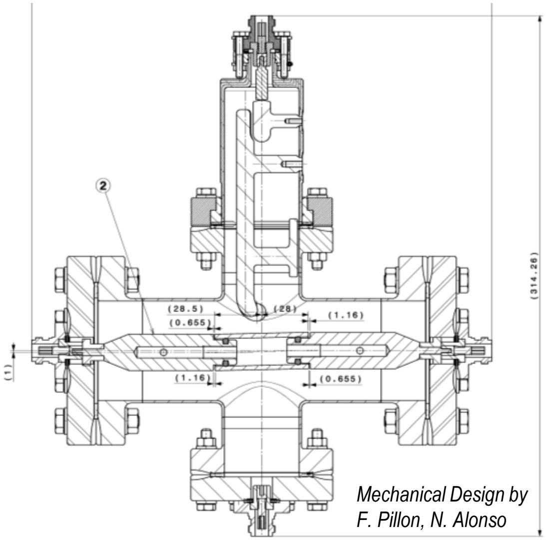


- Thermal Contraction
  - How much detuning of the notch filter at room temperature would be necessary to achieve the aimed behaviour at cold?





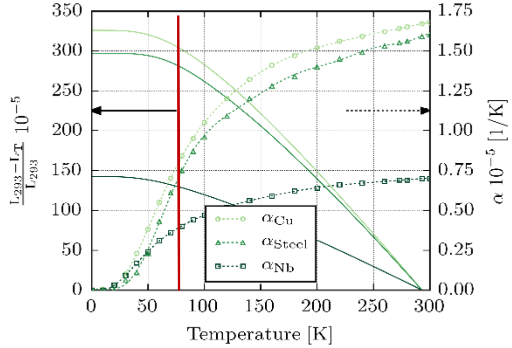
  - Investigation of the robustness of the HOM couplers
  - Contraction and RF simulations combined in Ansys APDL
  - Different materials of flange and coupler yield stresses that have notable effect on the resonance shift (gap distance varies)
  - For experimental tests, a coaxial transmission line was fabricated
  - Test facility is also used for leakage tests and later high power tests

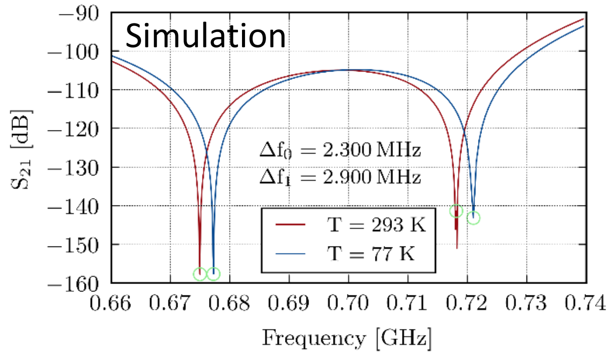


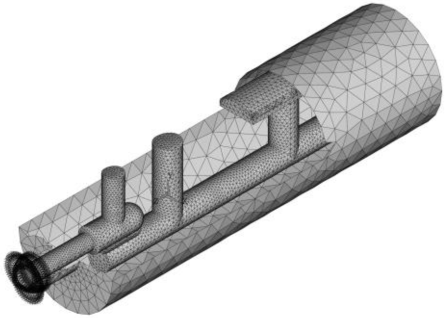
Mechanical Design by F. Pillon, N. Alonso

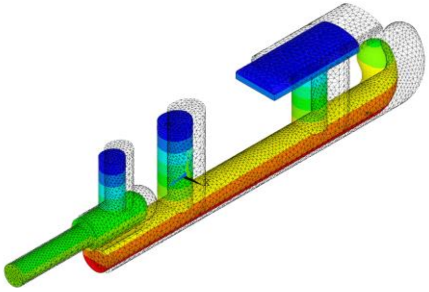
Prototype Tests

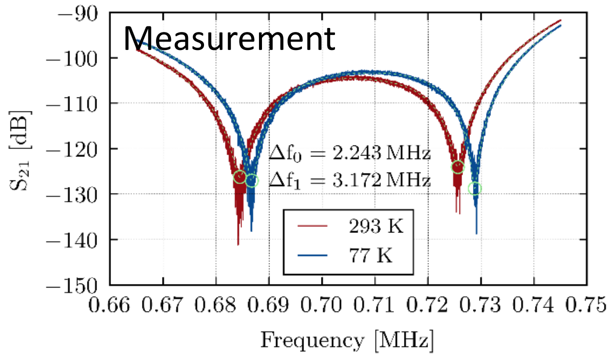
- Thermal Contraction
  - At 77 K more than 90 % of the maximum contraction is done
  - Liquid nitrogen used to cool down the coupler mounted on the cross
  - Agreement between simulations and measurements within 10 %
  - assuming only copper in the simulation, the error would rise to 50 %
  - According to simulation, a Nb coupler would have a negative f-shift







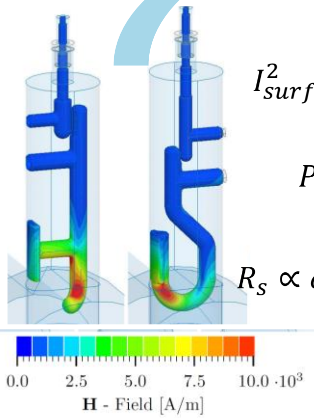




Heat Loss Investigation

- Power dissipation caused by accelerating mode yields moderate heat loss in the lower mW range

	PROBE V3	HOOK V3
I_{surf} [A]	298	227
Rs [μΩ]	10	10
Duty cycle [%]	10	10
$P_{estracted}$ [mW]	0.045	0.21
P_{loss} [mW]	44.4	25.8
$TM_{022}\pi$	2449	9



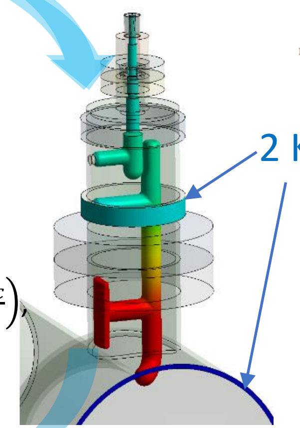
$$I_{surf}^2 = \frac{1}{2} R_S \oiint HH^* \, ds$$

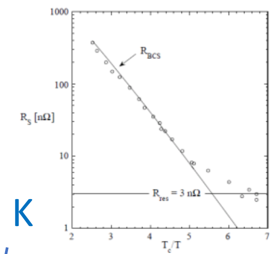
$$P_{loss} = \frac{1}{2} R_S I_{surf}^2$$

$$R_S \propto \omega^2 RRR \exp\left(-\frac{1.76 T_c}{T}\right),$$

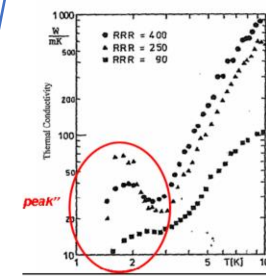
$T < T_c/2$

$\lambda \propto RRR$





B. Aune et al. PRSTAB 3, 092001, 2000

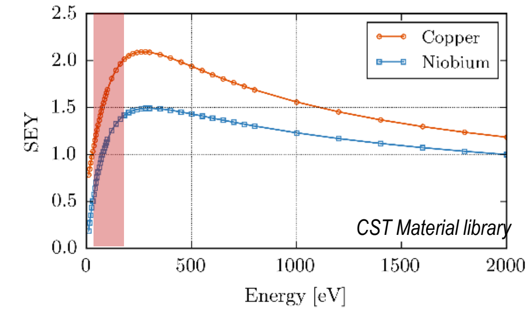


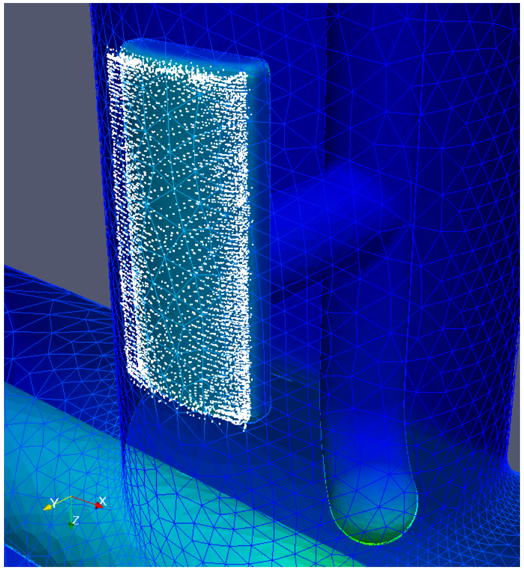
FermiLab: Technical Division Note TD-06-048

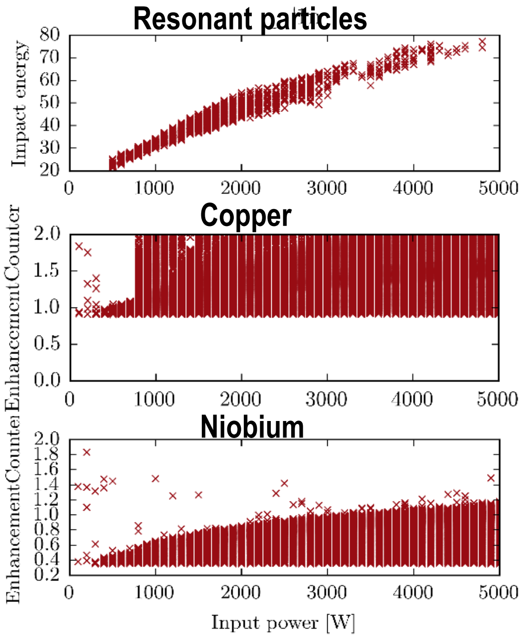
- Power dissipation due to HOMs to be expected in the same order
- Thermalisation at the fixations increase the allowable maximum surface resistance by a factor of 2
- no active cooling by liquid helium inside the antenna foreseen
- Hook design shows a better thermal behavior
- Integration in the cryo modul for the next year is in progress

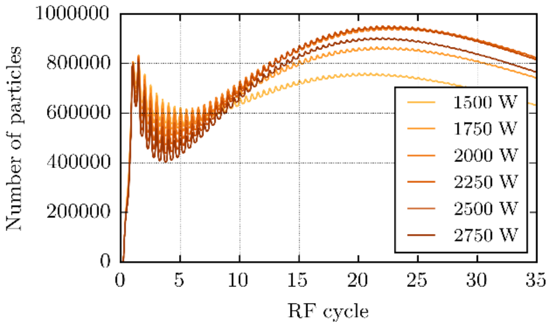
Multipacting

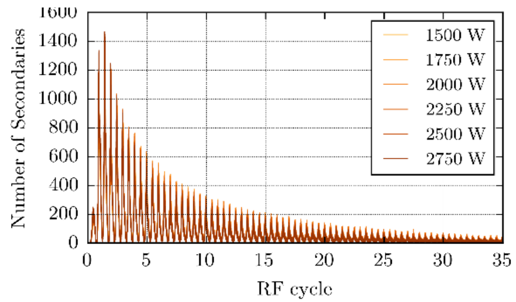
- Solid prototype mounted on the test facility (Cross) simulated with track3p (ace3p) and CST PIC solver
- Different materials to classify hard and soft barriers
- Multipacting at 704.4 MHz
  - Resonant particles found at impact energies between 20 – 80 eV which corresponds to 500-5000 W input power for the cross and 50-500 kV/m accelerating gradient
  - No indications for an exponential increase, rather the particle are dying out slowly





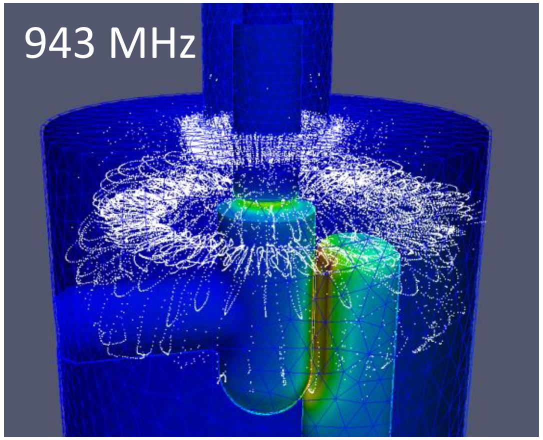


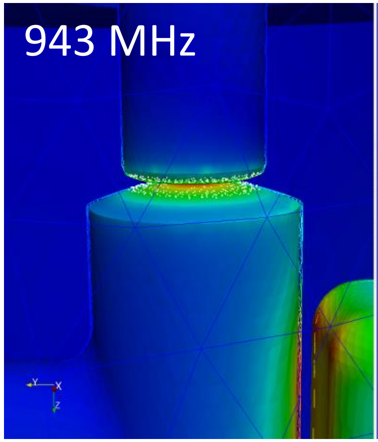


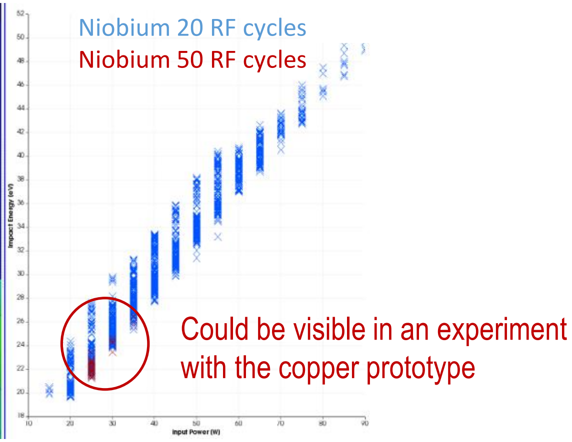


Multipacting

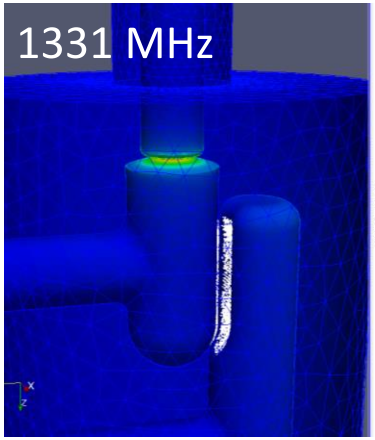
- Multipacting at higher frequencies
  - At 943 MHz (TE_{111} pi-mode) , resonance at 25 -35 W input power (comparable to an energy level inside the cavity which is 6 orders of magnitude lower than the one of the accelerating mode)

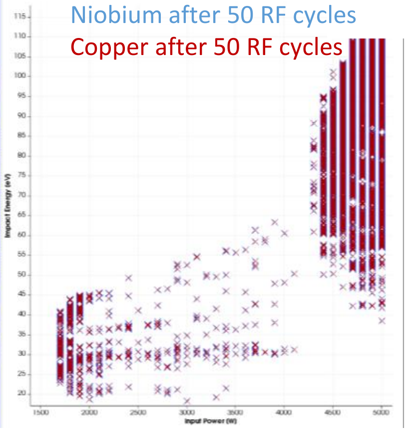






  - Concave shape of the central capacitor should be removed to avoid potential MP which appears for both, copper and niobium
  - At 1.33 GHz (TM_{011} modes) , behavior is similar for the upper capacitor at lower input power (6-25 W)
  - Central capacitor at 1.33 GHz shows a wide range for resonant trajectories: 1–5 kW



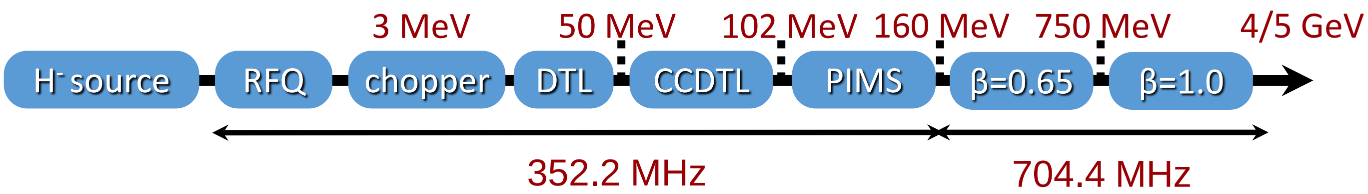


Summary and Outlook

- After calibration all prototypes have shown a correct RF transmission
  - Solid prototype required a little mechanical correction (bending)
  - Rotational flange allows fine tuning of the notch frequency
  - No vacuum leaks observed
- Measured Qext for the selected HOMs below 2e5 if at least one hook coupler is used (hook design seems to be a bit better)
- Shift of the notch resonances during cool-down experimentally verified
  - Double notch filter very robust against contraction
- Multipacting studies have not shown any problematic regions
  - Small changes will be considered for the next version
- Plans for integration of one coupler inside the cryo module initiated
- High-power tests with the current solid prototype will start soon
- Mechanical design for a niobium prototype could start in June

Thank you for your attention

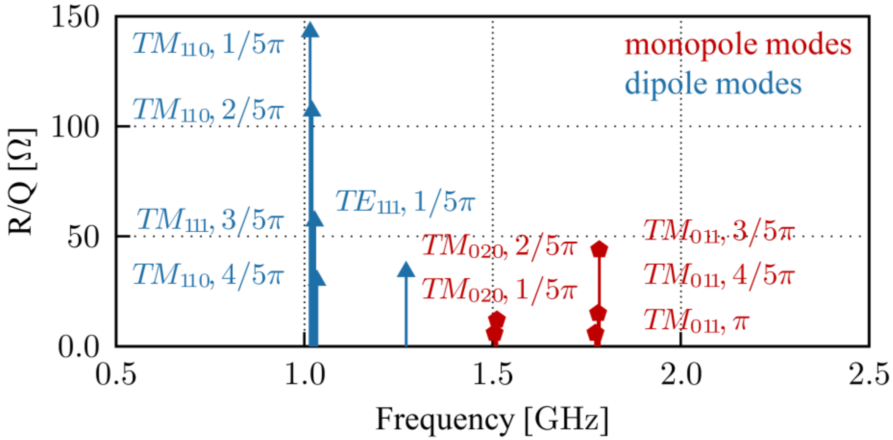
[1] M.Schuh, “Study of Higher Order Modes in Superconducting Accelerating Structures for Linac Applications“, PhD thesis, 2011.
[2] M.Schuh, F. Gerigk. “Influence of higher order modes on the beam stability in the high power superconducting proton linac“, Phys. Rev. ST Accel. Beams, 2011.
[3] K.Papke et. al., “Mode sensitivity analysis of 704.4 MHz SC RF cavities“, MOPB078, SFR 2013, 2013.
[4] B. Gustavsen and A. Semlyen, "Rational approximation of frequency domain responses by Vector Fitting", IEEE Trans. Power Delivery, vol. 14, no. 3, 1999.
[5] P. Reinhold. “Duplication of the Fast Relaxed Vector-Fitting algorithm in python”, URL: https://github.com/PhilReinhold/vectfit_python



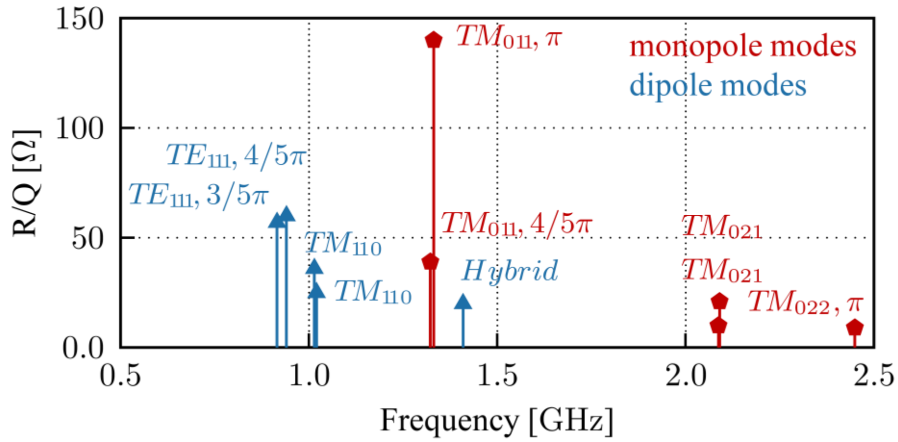
Schematic layout of the linac
(Conceptual design of the SPL II)

- For SPL dipole HOMs are considered less problematic
- In case of recirculators or synchrotrons should be also considered
- Design goal for relevant HOMs: **Qext < 10^5**
- HOM spectra for the medium and high beta Cavities:

Medium beta cavity (beta = 0.65)

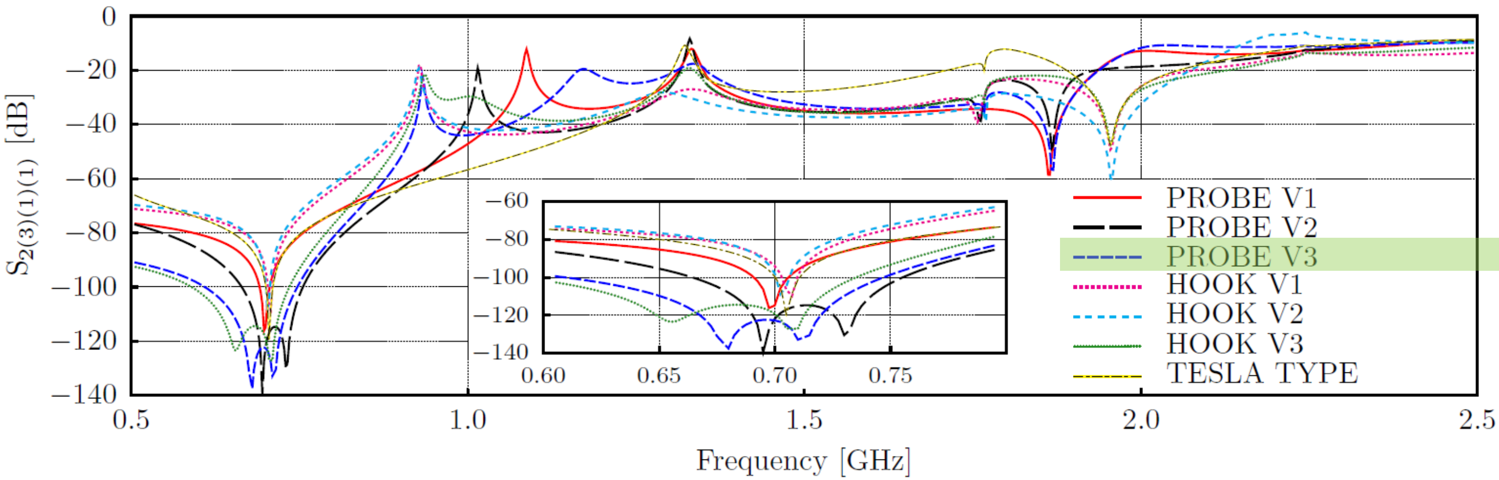


High beta cavity (beta = 1)



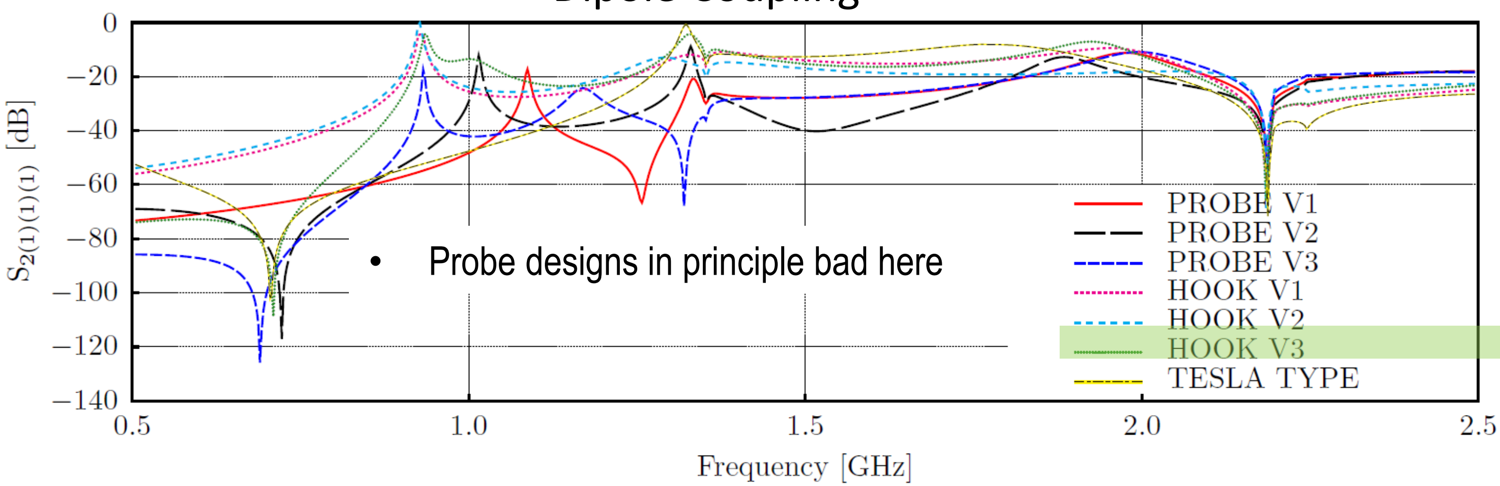
RF Characteristics

Monopole Coupling



Best option

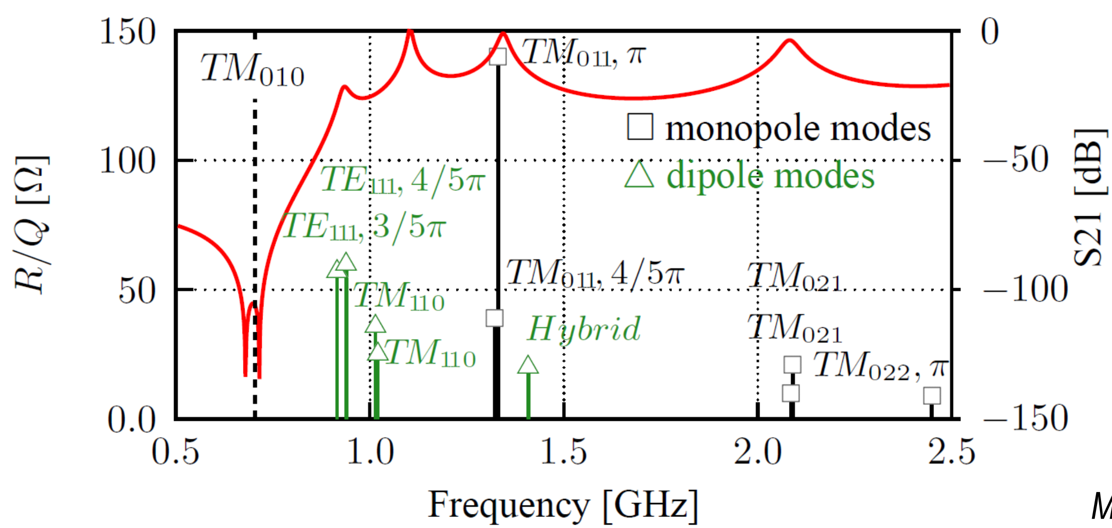
Dipole Coupling

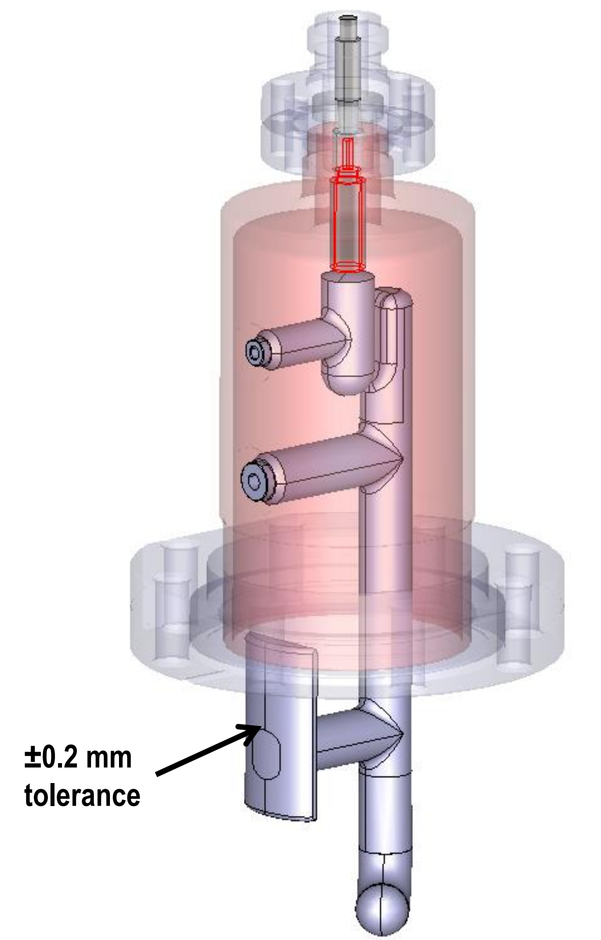


- Probe designs in principle bad here

Best option

- As the 1st Prototype the Probe Coupler (V3) with 3 stages was chosen
  - Notch filter with a relative high bandwidth (135 MHz @-100dB) and therefore very robust
  - High selectivity (steep transition between stop band and or notch filter and pass band)
  - Best coupling to the monopole HOMs at 1.3GHz.
  - No active cooling of the antenna necessary.





Mechanical Design by T. Renaglia, F. Pillon, N. Alonso