Design and RF Measurements of an X-band Accelerating Structure for the Sparc Project

INFN-LNF ; UNIVERSITY OF ROME LA SAPIENZA ; INFN - MI

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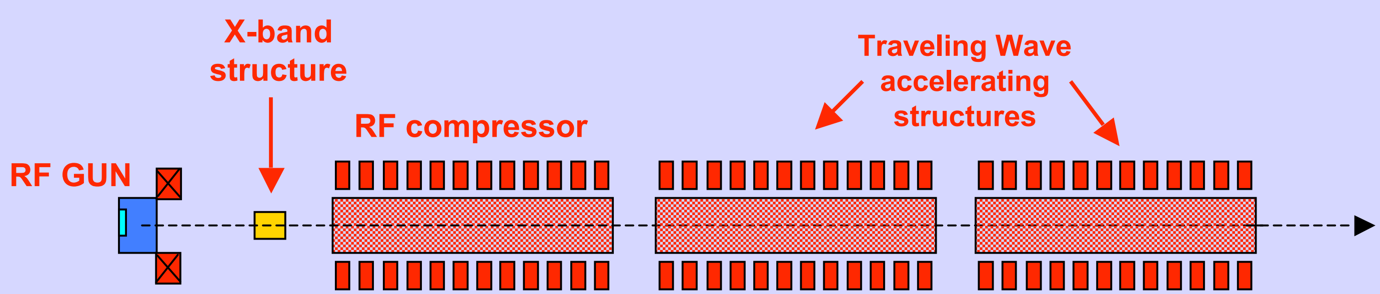
SALAF (**S**trutture **A**cceleranti **L**ineari ad **A**lta **F**requenza)
is the INFN r&d programm on
" multicell resonating structures"
operating at X-band (10 ÷ 12 GHz).

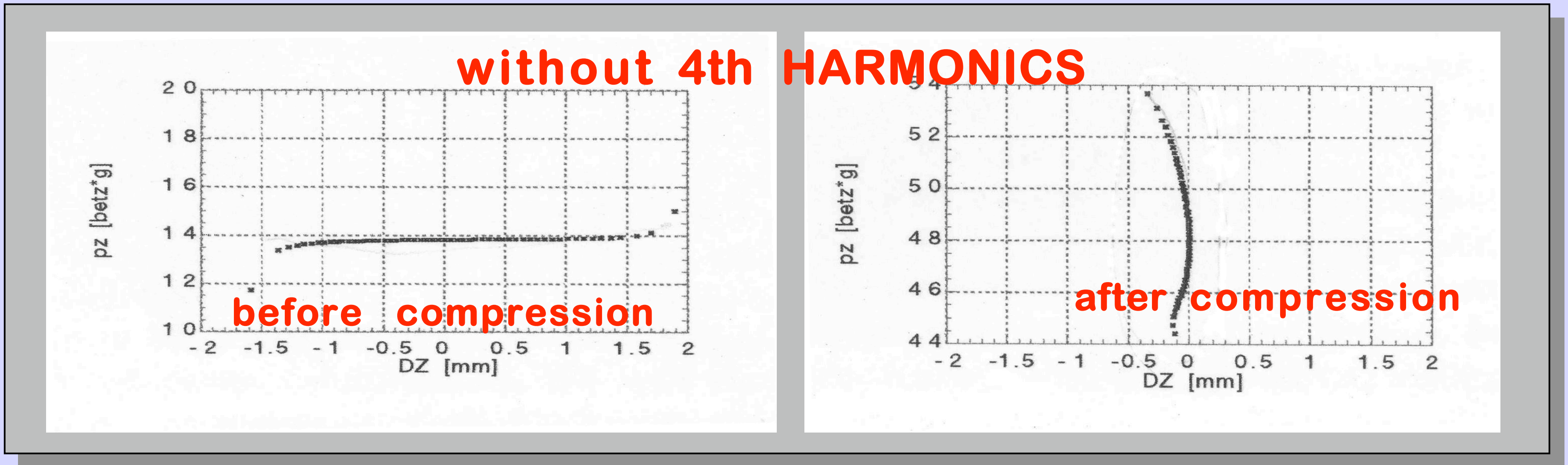
the MOTIVATION …….

- **To use in high brilliance photo-injectors *(SPARC-phase-2)* to compensate for the beam longitudinal phase-space distortion, enhanced by the bunch compression of the acceleration process**
- **To gain know-how in vacuum microwave technologies**

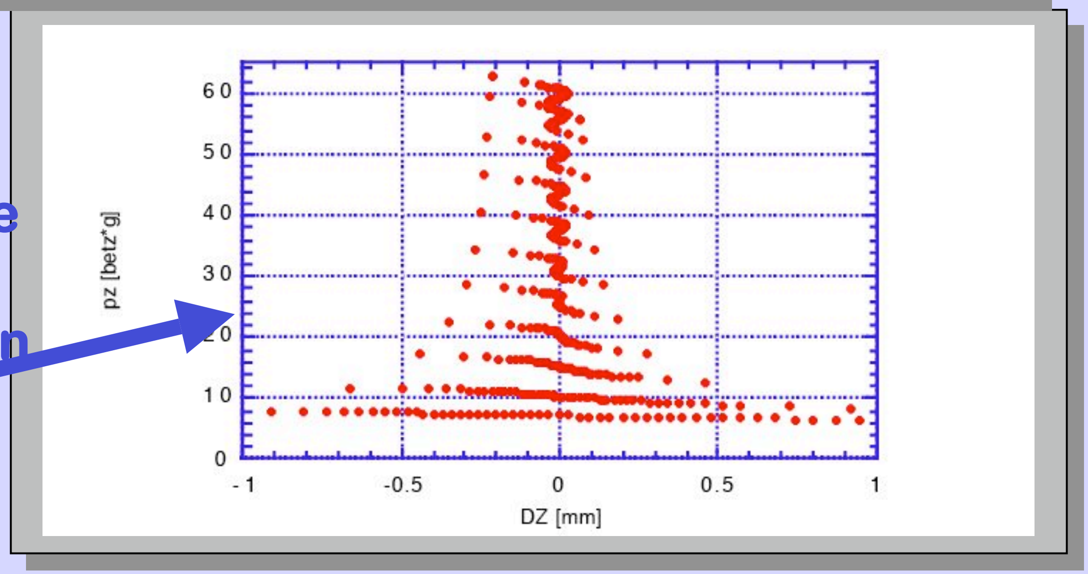


Correction of the Phase-Space distortion

- The 4th harmonic structure provides RF curvature local correction.
- Beam longitudinal emittance hold within limited values.
- Minimum bunch length achieved.



time evolution of the
beam phase-space
with RF compression
+ 4th Harmonics



SUMMARY of the ACTIVITY

ElectroMagnetic Design

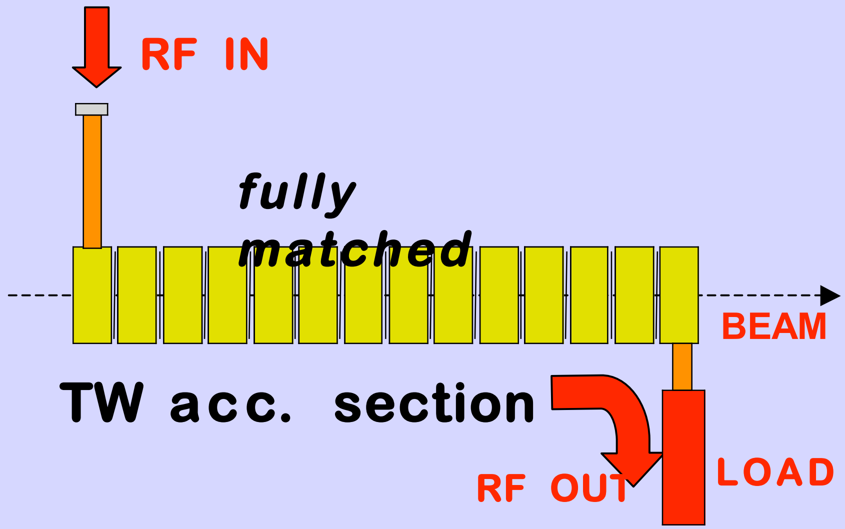
- Travelling or Standing Wave structure ?
- Mode of operation … π or π/2 ?

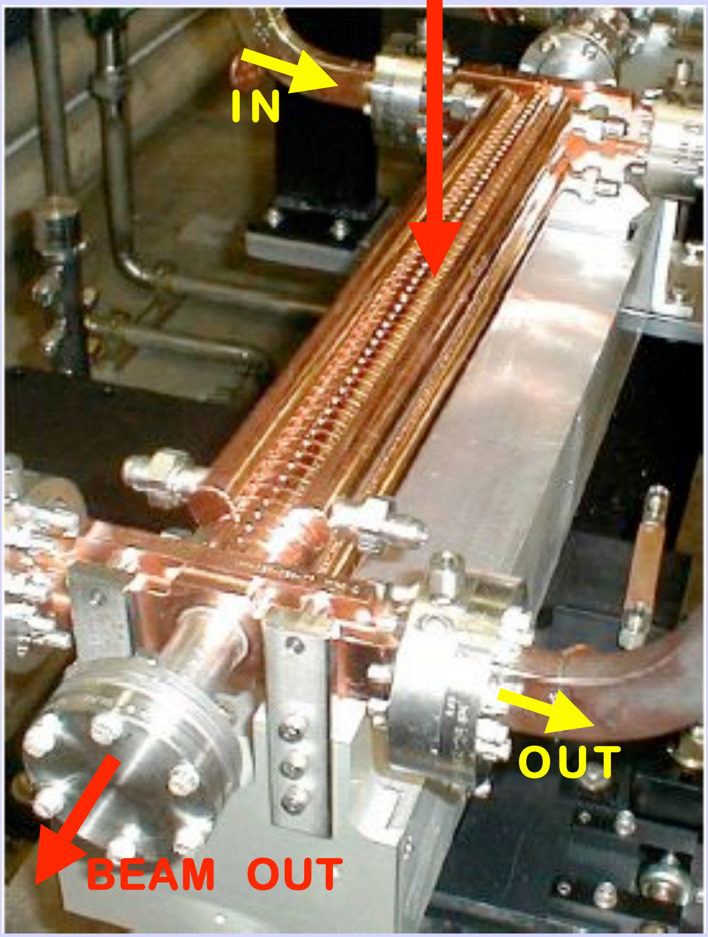
Hardware Design

- Construction of a 11.424 GHz Cu *prototype*
- RF characterization
- Development and test of a real model:
  - → *precise machining*
  - → *brazing*
  - → *vacuum tests*
  - → *RF tests*

E.M. DESIGN

Recent experiences (NLC) have been made at SLAC and KEK Travelling Wave X-band structures.





MultiMegawatts peak power tests, carried out at SLAC, had been showing frequent internal discharges caused by field emission.

… *TW structures*

- ➔ the fully matched condition of TW structures helps the RF generator in feeding the resonator under discharge …. and sustains the power flow throughout it.
- ➔ hence, the inner surface may get damaged.
- ➔ the design accelerating gradient (60 ÷ 70 MV/m) may not be achieved routinely.

To overcome the problem, instead of TW units, Standing Wave structures can be used.
Internal discharges cause strong cavity detuning and generator mismatching.

RF POWER FEEDING ➔ *IMPOSSIBLE* under discharge

… Standing Wave structures

the Standing Wave accelerating section is a disk-loaded guide with the output port *shorted*.

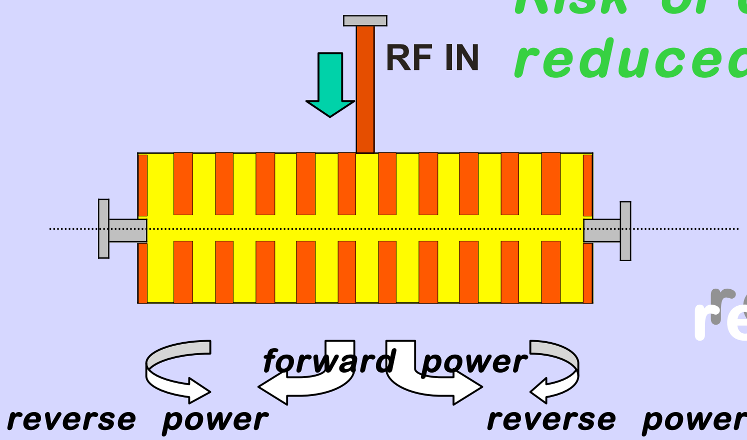
Input RF matching is only possible if the RF power distribution is unperturbed.

Field emission discharges detune the SW cavity

by several bandwidths

Risk of d

reduced.



the Standing Wave section is considered the best structure to achieve reliability and high field operatio at X-band

R&D aims to analyze in details ....

axially coupled π and $\pi/2$ mode SW structures

and

$2\pi/3$ and $5\pi/6$ mode TW structures

Important R&D goals are ....

To study the accelerating structure sensitivity vs mechanical tolerances and assembling errors

To investigate the effects of the power dissipation on the general performances of the structure.

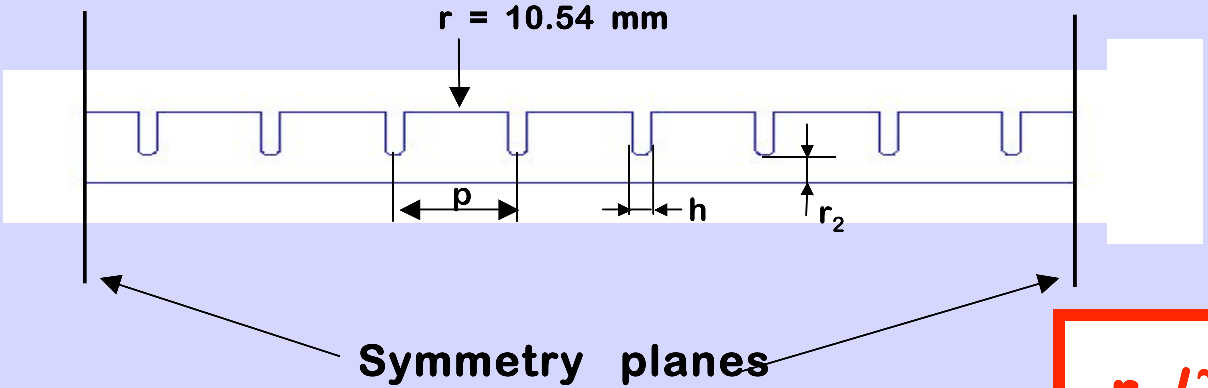
E.M. design guide-lines of 11 GHz accelerating structures

- To get high accelerating field per unit-length to shorten the structure
- To get high shunt impedance to reduce the need of RF po
- To get the lowest E_p/E_0 and B_p/E_0 ratios to minimize dark achieve high break-down free field gradient and low thermal effect
- To get high ratio E_0^2/W to optimize the efficiency of the st
- To reduce accelerating structure sensitivity vs mechanical tolerances and assembling errors by increasing the group velocity (i.e. filling time)
- To reduce the parasitic mode content which affect the bea dynamics
- To shape the structure internal profile in order to avoid multipactoring discharges

Study and simulation of a 9-cell π-mode X-band struc

Simulated structure with no coupling tubes

p = 13.121 mm
h = 2 mm
r_2 = 4 mm

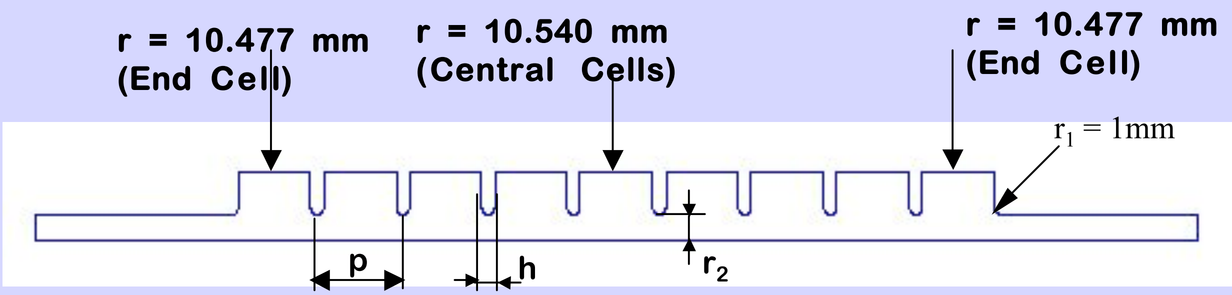


π

$r_2/\lambda = 0.15$

Simulated structure with coupling tubes

p = 13.121 mm
h= 2 mm
r_2 = 4 mm

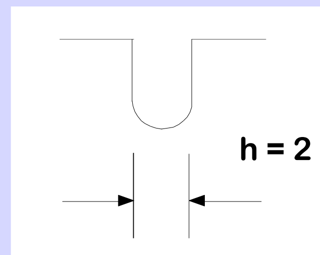


… some basic expressions of the disk-loaded waveguide …

Analytical expression of the dispersion curve:

$$\omega_\phi^2 = \omega_0^2 + 0.5 \cdot (\omega_\pi^2 - \omega_0^2) \cdot (1 - \cos\phi)$$

Coupling coefficient: K = (_π-_0) / _π/2 → **K = 2.42 %**



very similar values

Analytical relation of the coupling coefficient:

(based upon geometric parameters)

Coupling coefficient:

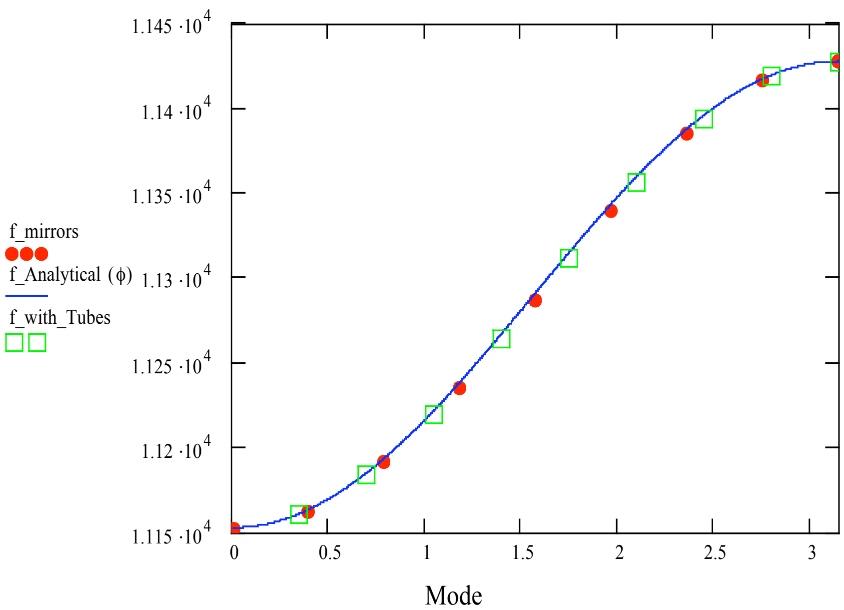
$$K = \frac{\omega_\pi - \omega_0}{\omega_{\omega/2}} \approx k e^{-\alpha h}$$

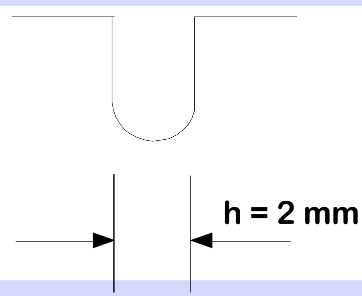
→ **K = 2.27 %**

$$with \quad k \equiv \frac{4a^3}{3\pi J_1^2(2.405) b^2 l} << 1 \quad and \quad \alpha = \sqrt{\left(\frac{2.405}{a}\right)^2 - \frac{\omega^2}{c^2}}$$

... *simulation of 9-cell π-mode* ....

DISPERSION CURVE with and without beam-tubes





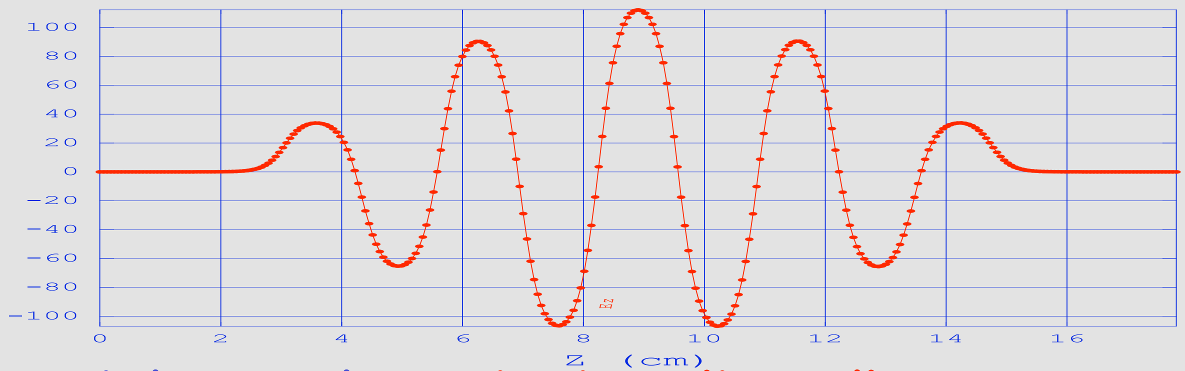
structure with mirrors

Frequency [MHz]	Mode [π]
11152.818	0
11162.906	1/8
11191.717	1/4
11235.333	3/8
11287.522	1/2
11340.448	5/8
11386.000	3/4
11416.834	7/8
11427.704	1

structure with tubes

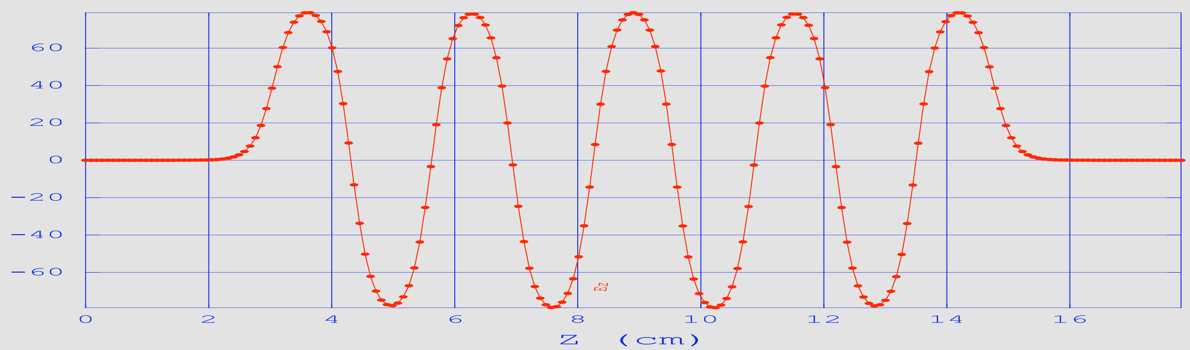
Frequency [MHz]	Mode [p]
11160.784	1/9
11183.868	2/9
11219.481	1/3
11263.701	4/9
11311.225	5/9
11356.593	2/3
11393.989	7/9
11418.634	8/9
11427.465	1

… simulation of 9-cell π-mode ….



With beam-tubes and constant cavity radius

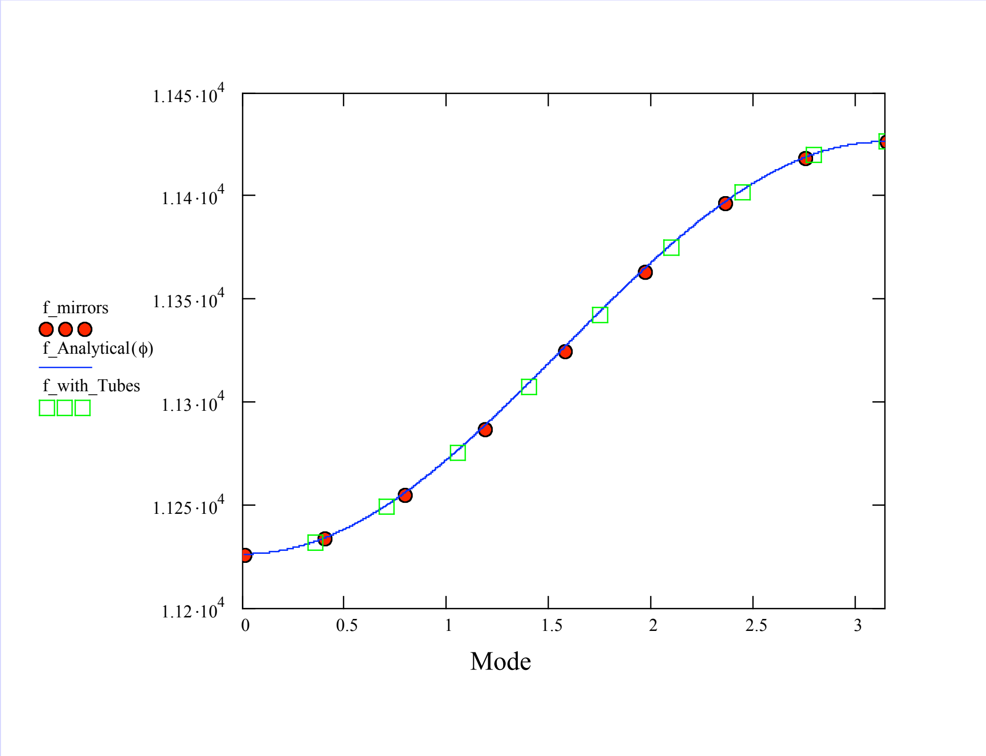
▶ no flatness of the on-axis longitudinal E-field



With beam-tubes and reduced end-cells radius

▶ flatness of the on-axis longitudinal E-field

… simulation of 9-cell π-mode X-band structure with h = 3 mm

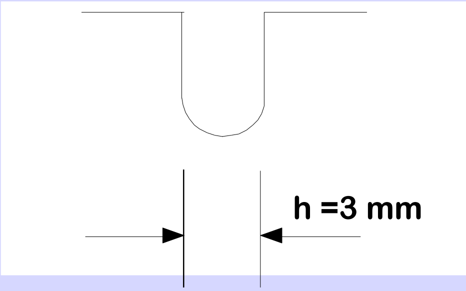


structure with mirrors

Frequency [MHz]	Mode [p]
11226.065	0
11233.518	1/8
11254.808	1/4
11286.885	3/8
11324.981	1/2
11363.477	5/8
11396.442	3/4
11418.442	7/8
11426.240	1

structure with tubes

Frequency [MHz]	Mode [p]
11231.958	1/9
11248.970	2/9
11275.146	1/3
11307.483	4/9
11342.200	5/9
11375.053	2/3
11402.022	7/9
11419.735	8/9
11426.078	1



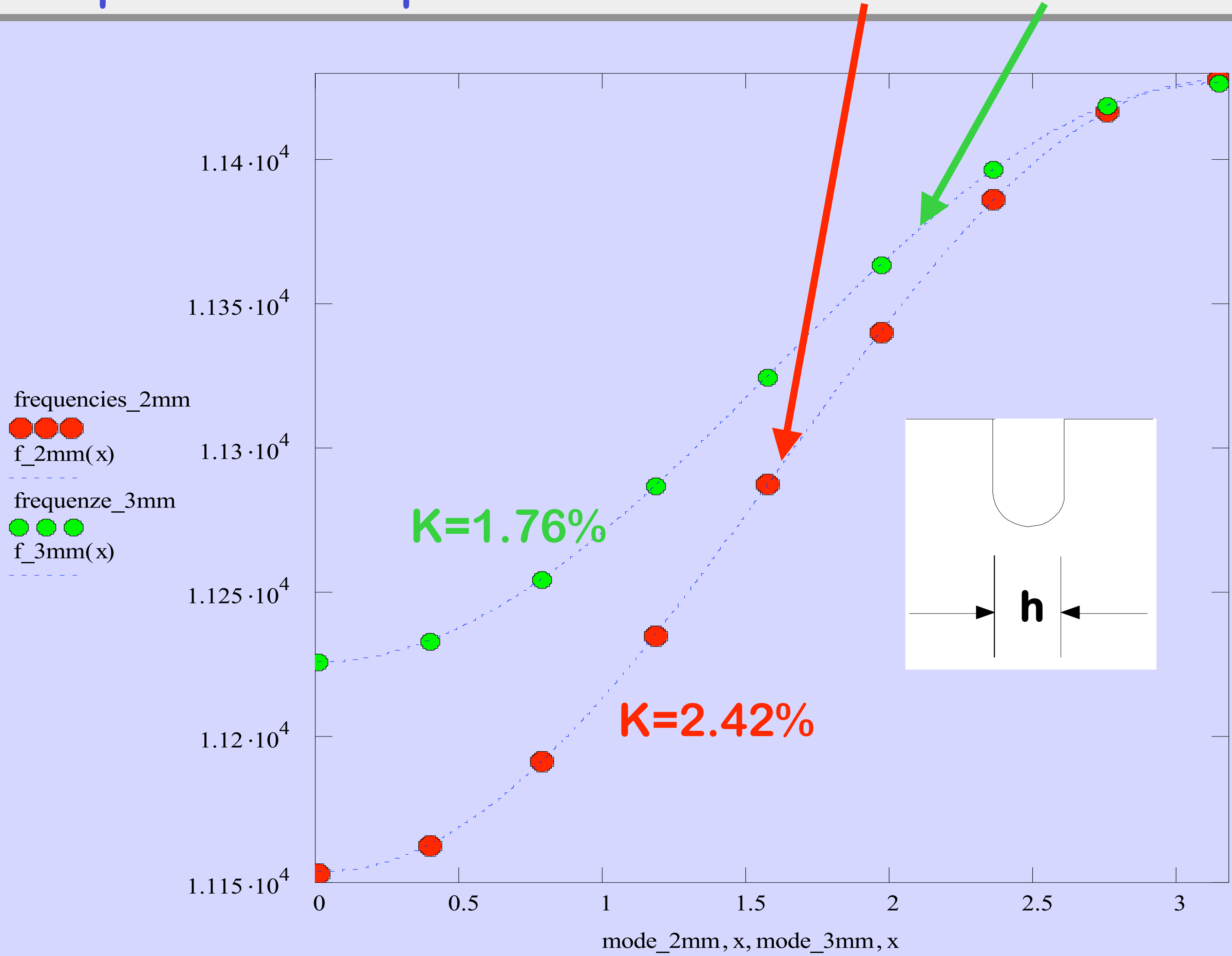
Coupling coefficient:

K = 1.76 %

(with h = 3 mm the thickness iris)

... simulation of 9-cell π-mode .....

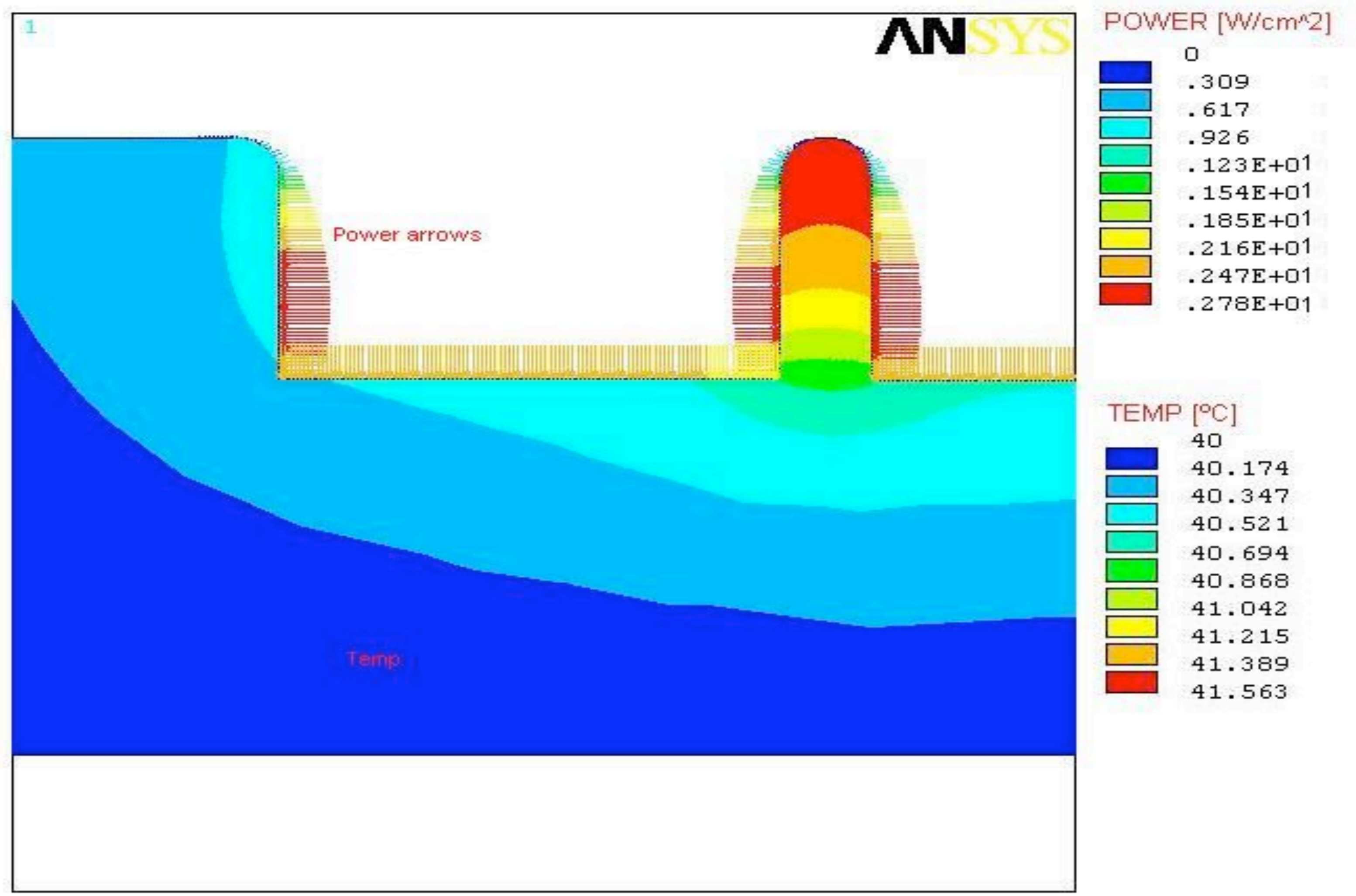
Comparison of dispersion curves for h = 2 and 3 mm thickness



... simulation of 9-cell π-mode .....

Thermal flux and temperature fields of the boundary region of a copper structure.

Study performed with the ANSYS-*code*(TM).



… simulation of 9-cell π-mode …..

Comparison of Standing-Wave X-BAND Structures with different disk-tickness

RF parameter list calculated with SUPERFISH, OSCAR2D and ABC codes

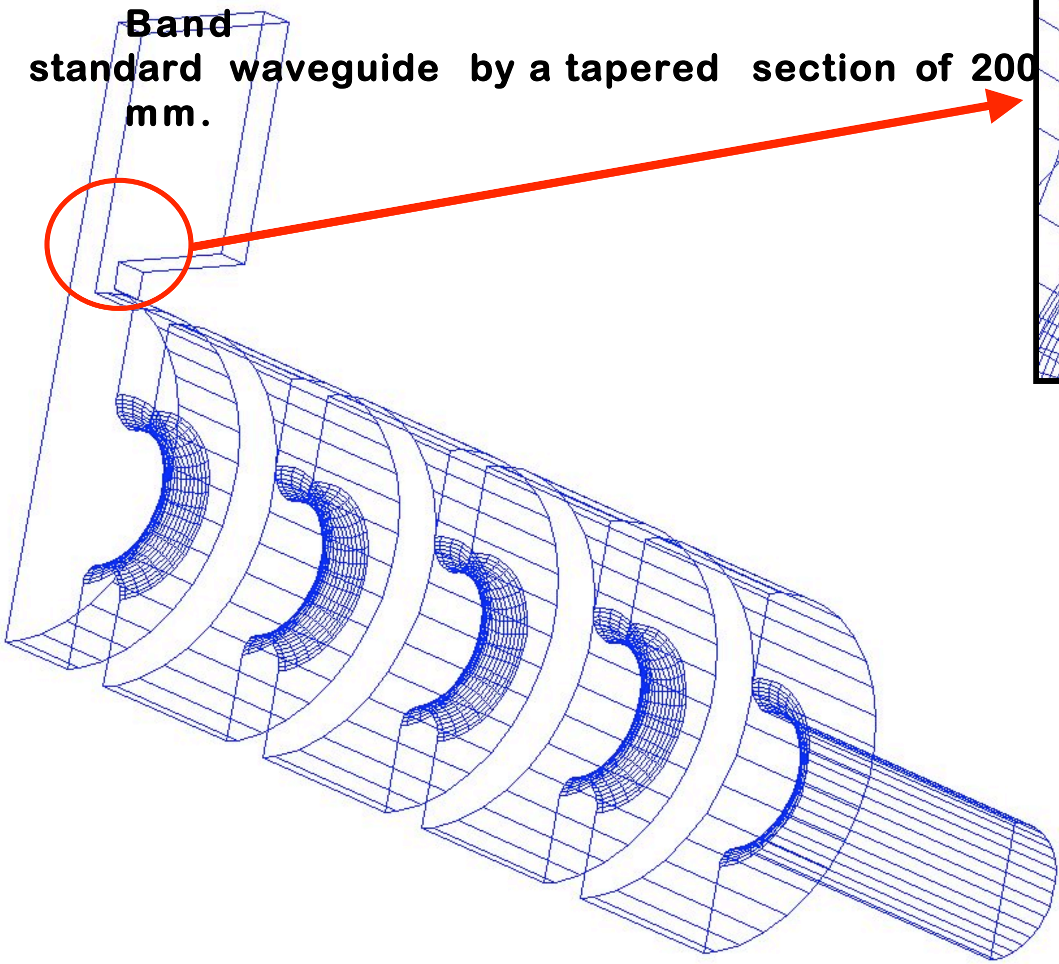
	π mode	π mode
-Frequency, F (MHz)	11426*	11427*
-Length for calculation, L (cm)	11.81	11.81
-Beam tube length, l (cm)	3	3
-Cavity number, n_b	9	9
-Ratio of phase to light velocity, v_φ/c	1	1
-Structure periodicity, L_p (cm)	1.3121	1.3121
-Beam hole radius, r (cm)	0.4	0.4
-Iris Thickness, t(cm)	0.3	0.2
-Transit time factor, T	0.739	0.731
-Factor of merit, Q	8069.46	8413.18
-Form factor, R_{sh}/Q (Ω/m)	9232.34	9165.38
-Shunt impedance, R_{sh} (MΩ/m)	74.5	77.11
- Coupling coefficient, K(%)	1.76	2.42
-Peak power, P (MW)	2.795	2.701
-Energy stored in cavity of length L, W (joules)	0.314	0.316
-Peak power per meter, P/m (MW/m)	23.66	22.87
-Energy stored in cavity per meter, W/m (joules/m)	2.659	2.677
-Duty cycle, D.C.	10^{-4}	10^{-4}
-Repetition frequency, f (Hz)	50	50
-Power dissipation, P_d (Watt)	279.5	270.1
-Average accelerating field, E_{acc}(MV/m)	42	42
-Peak axial electric field, E_{max} (MV/m)	56.84	57.49
-Kilpatrick factor	1.089	1.197
-Peak surface electric field, E_{sur} (MV/m)	95.36	104.84
-Ratio of peak to average fields E_{max}/E_{acc}	1.35	1.37
-Ratio of peak to average fields E_{sur}/E_{acc}	2.27	2.496
-Ratio of peak fields B_{max}/E_{sur}(mT/MV/m)	1.89	1.65
-Pulse charge, C (nC)	1	1
-Pulse length, τ (psec)	10	10
- Number of bunches, n	1	1
-Average beam power, P_{baver} (W)	0.248	0.248
-Energy spread due to the beam loading, %	$\pm$0.788	$\pm$0.783
-Loss parameters due to the HOM's K_p (V/pC)	17.77	16.95
-Loss parameter of the operating mode, K_0(V/pC)	19.57	19.43

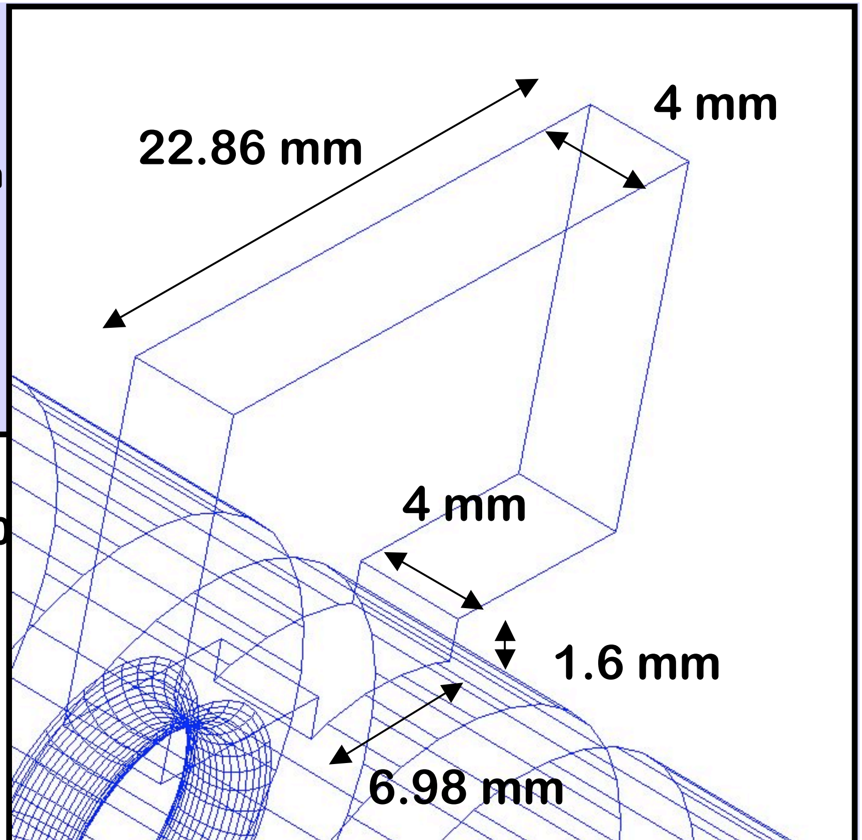
* Mesh 0.03 cm. With a mesh of 0.01 cm, we have too long calculation time, but we have seen that the frequency value converge to 11424 MHz.

3D coupler design (HFSS)

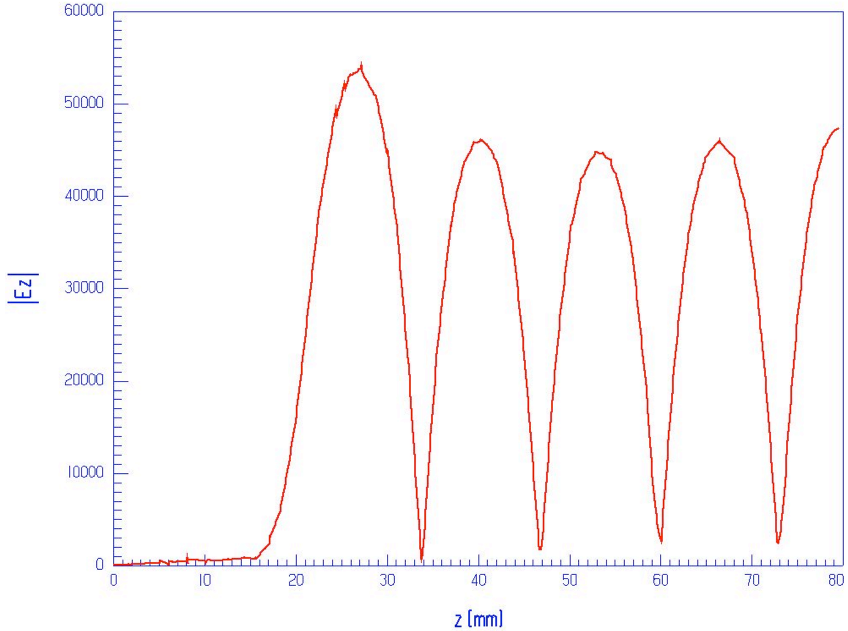
1 The radius of the central coupling cell has been retuned
to compensate for the perturbation induced by the
2 coupling hole;

The waveguide input port is connected to an X Band
standard waveguide by a tapered section of 200 mm.





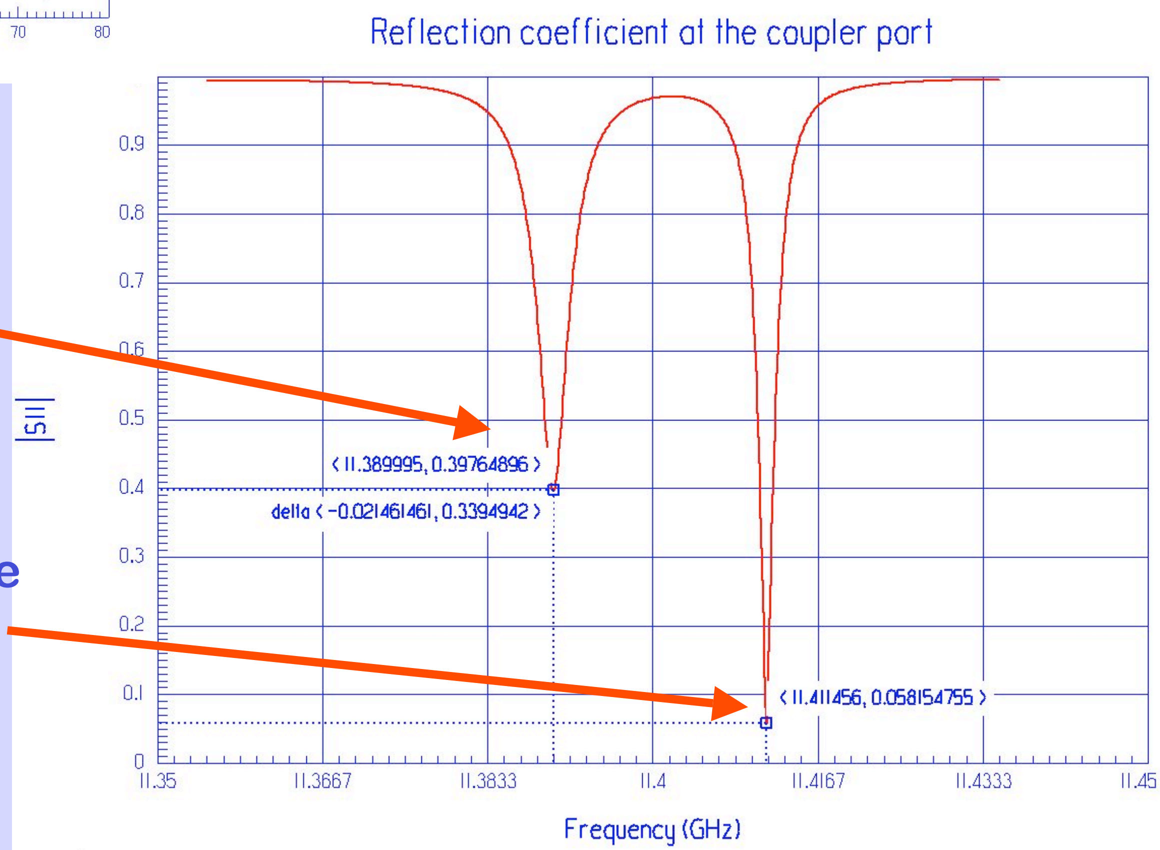
Results



Field flatness after retuning the central cell radius

Nearest mode excited by the coupler (3/4π)

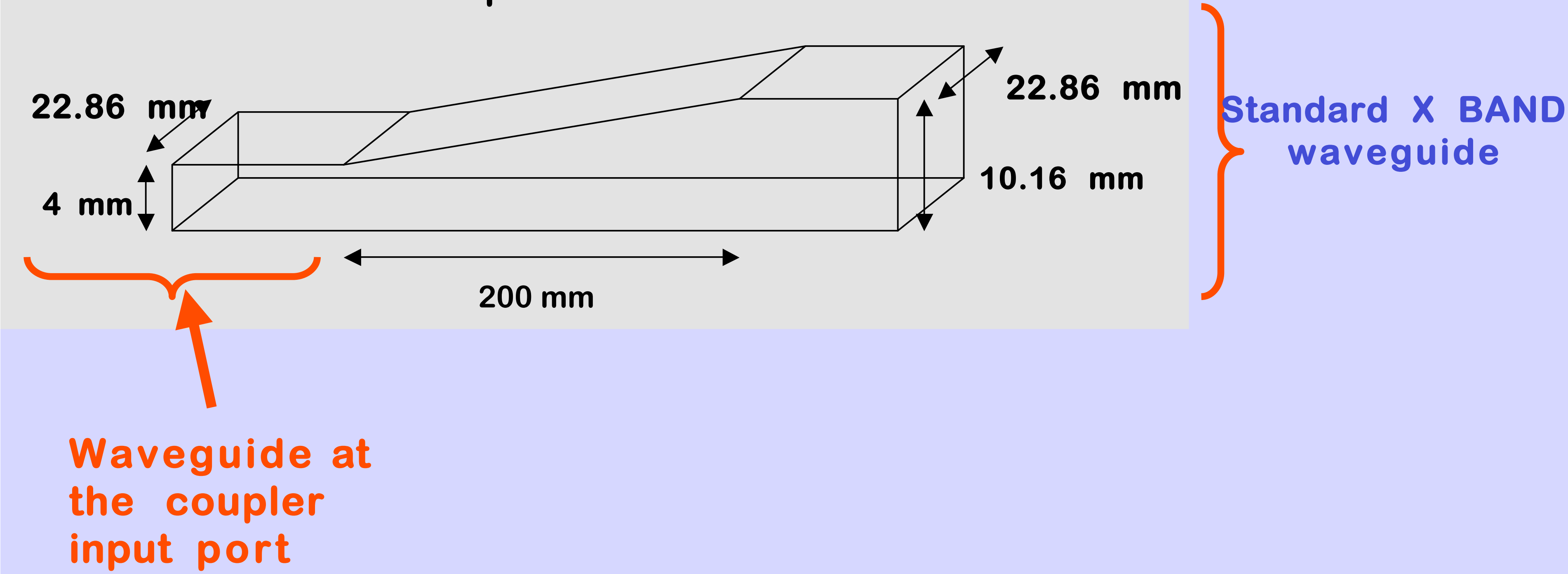
Accelerating mode
$S11=0.06 \Rightarrow \beta=1.12$



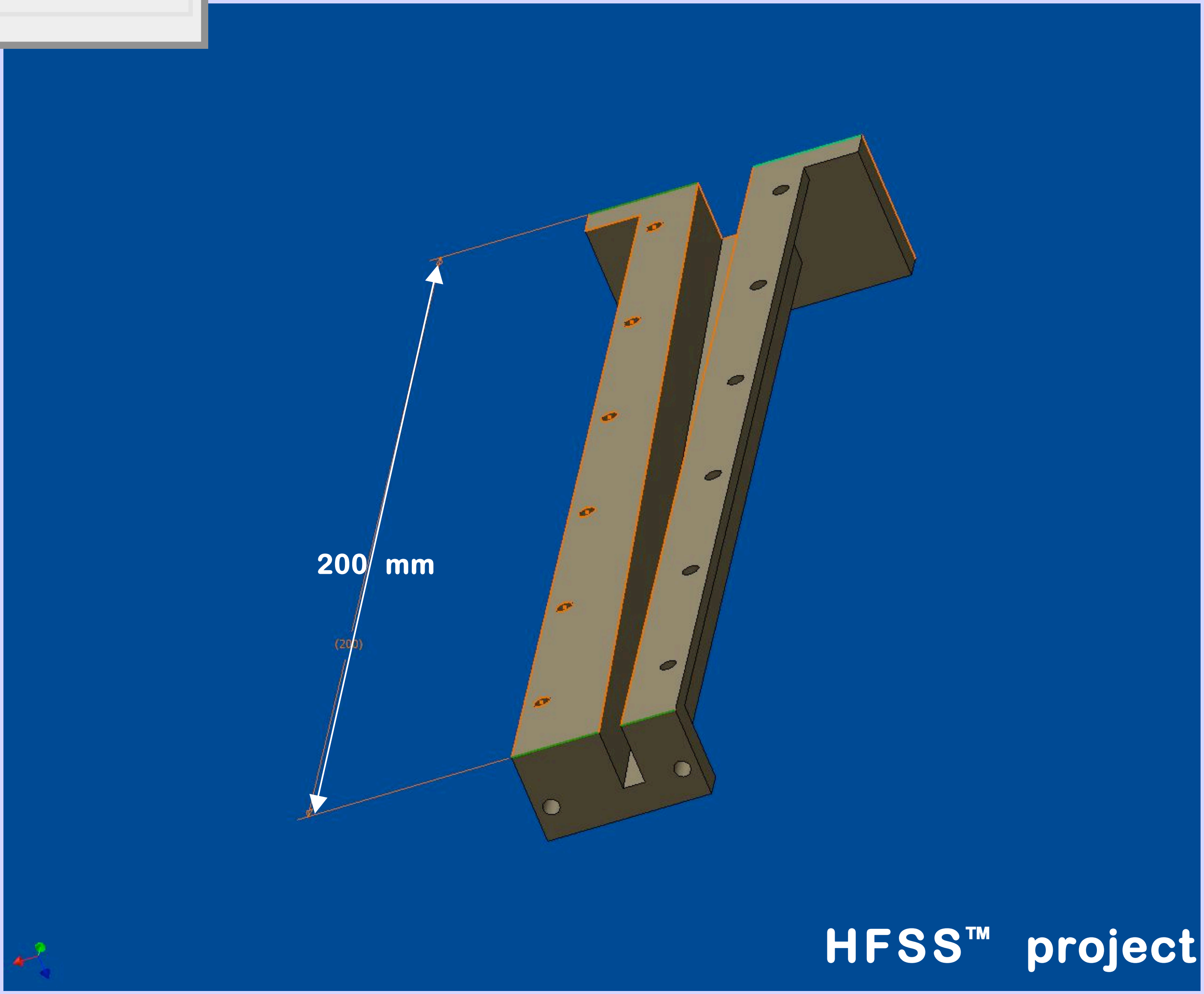
Tapered section

The waveguide input port is connected to an X Band standard waveguide with a 200 mm long tapered section.

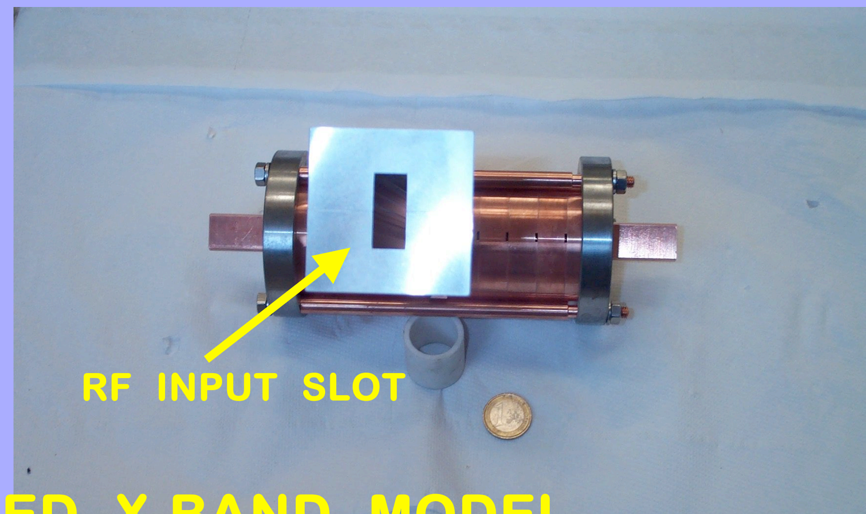
The reflection coefficient (obtained with HFSS) of the tapered section is of the order of 0.01.



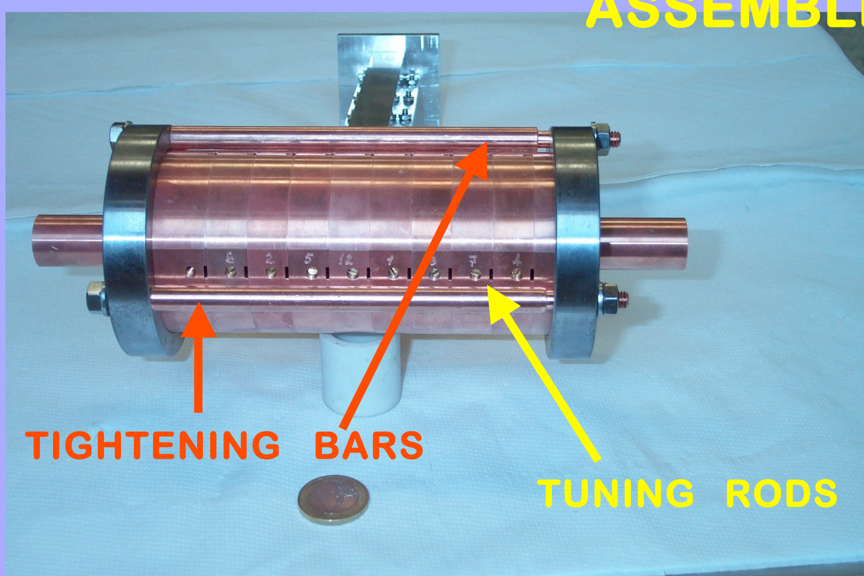
Tapered section

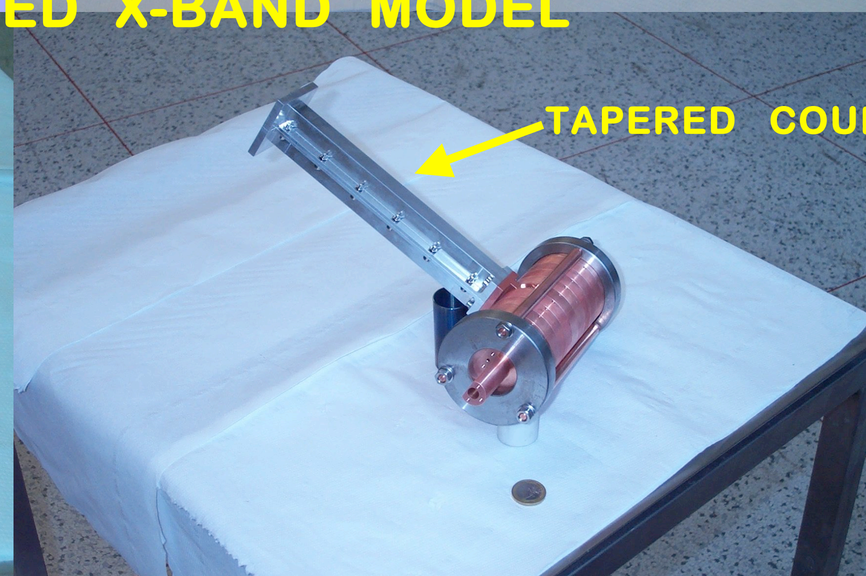


CONSTRUCTION of a π-MODE STANDING-WAVE 11.4 GHz COPPER PROTOTYPE

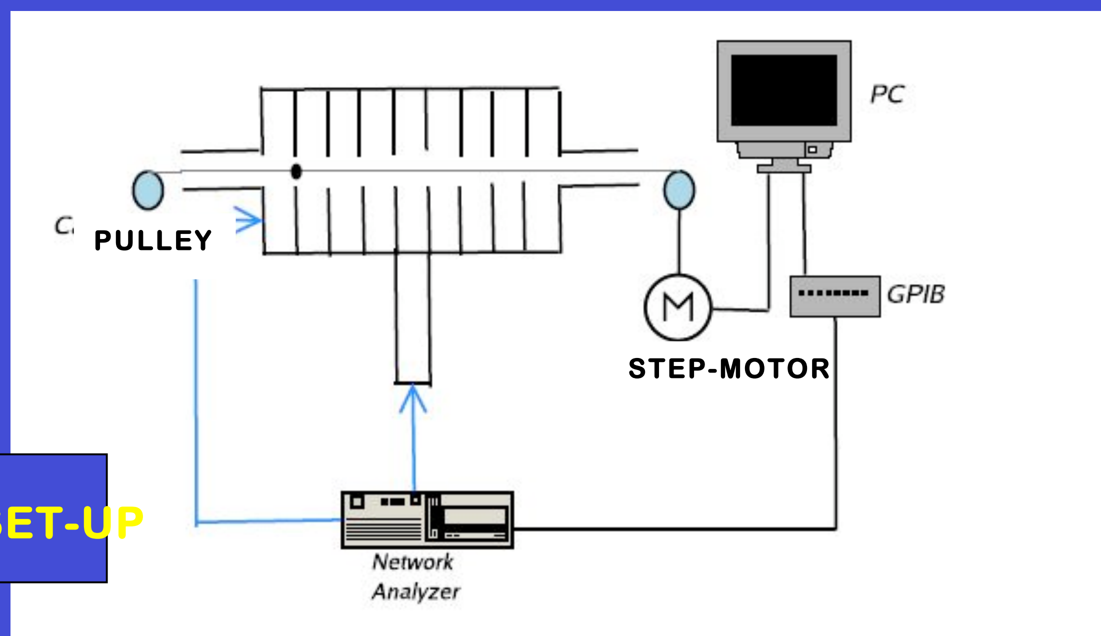


ASSEMBLED X-BAND MODEL

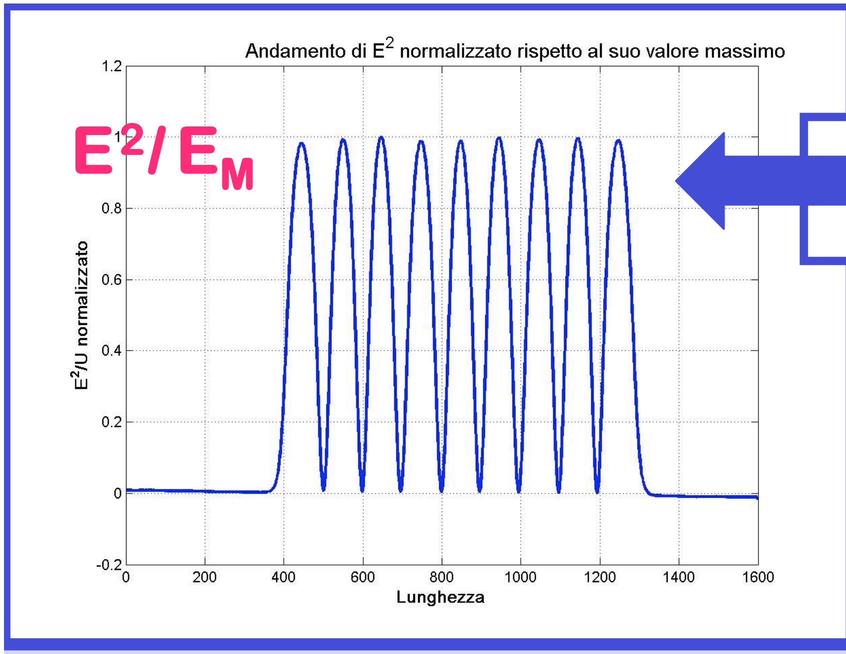




CHARACTERIZATION OF THE X-BAND STANDING-WAVE COPPER MOD



BEAD-PULL MEASUREMENT SET-UP

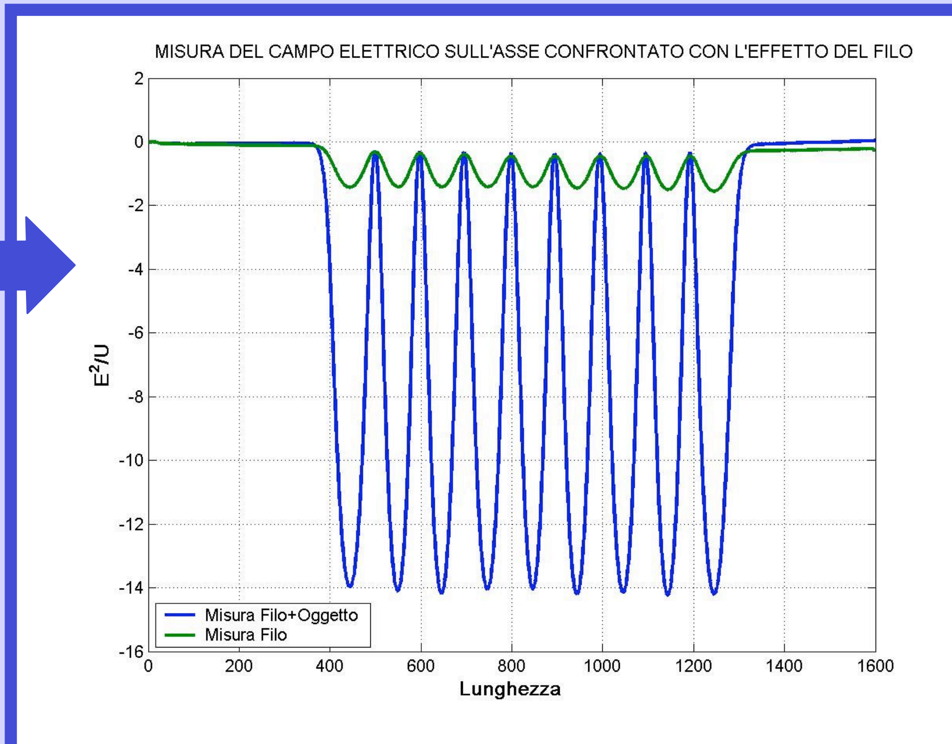


π-mode ACCELERATING ELECTRIC FIELD BEHAVIOR AFTER the 9-CELL TUNING

THE FIELD FLATNESS IS < 1%

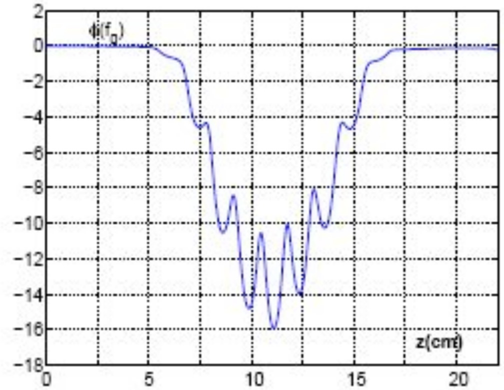
π-mode BEAM AXIS ELECTRIC FIELD

In green, the CONTRIBUTION of the WIRE and the BEAD GLUE

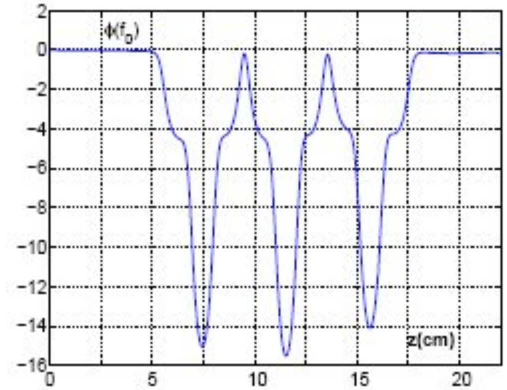


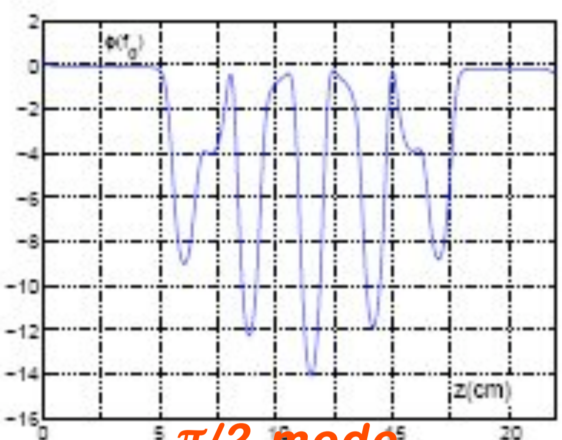
BEHAVIOUR OF OTHER LONGITUDINAL E-FIELD FUNDAMENTAL MODES

0-mode



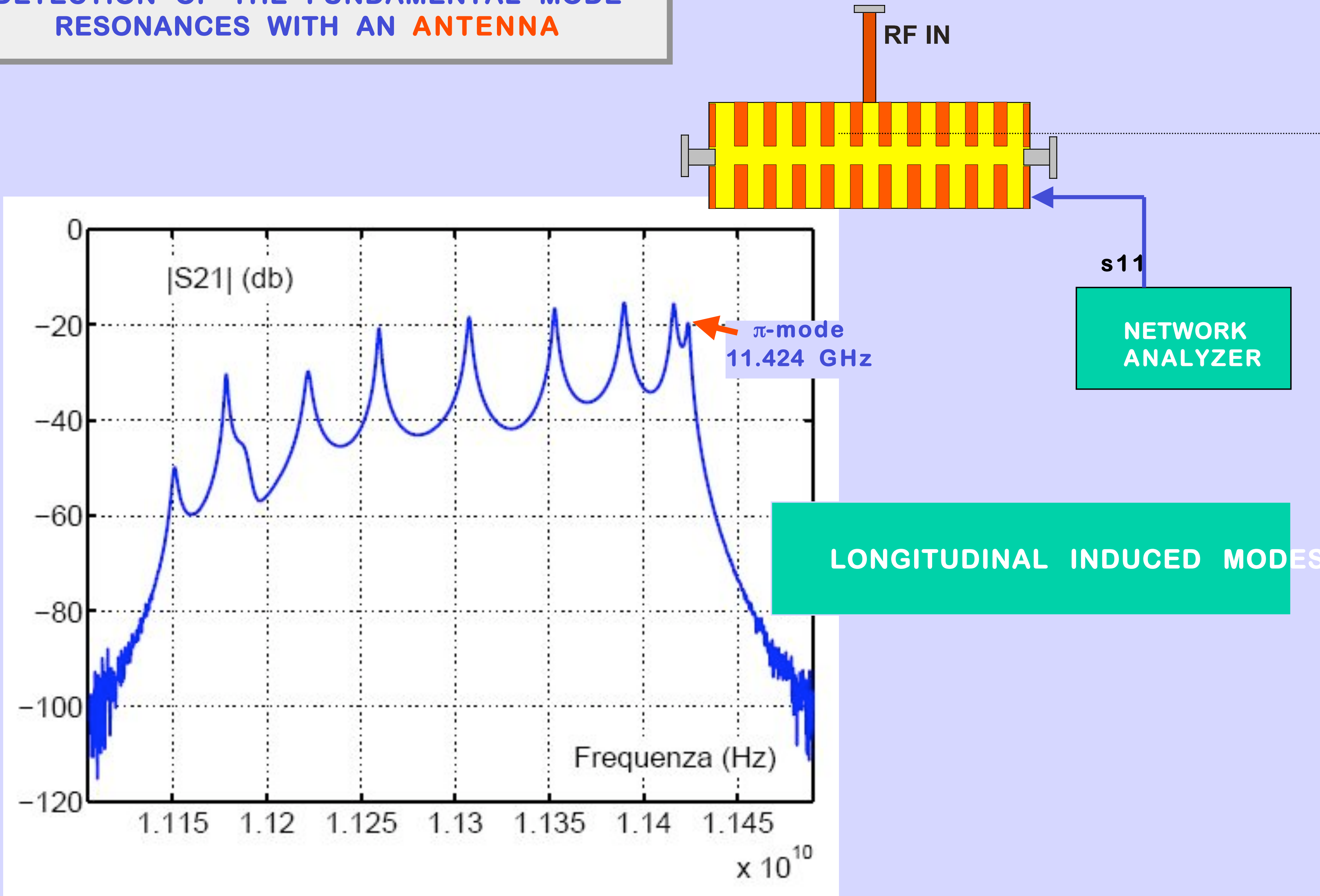
π/4-mode



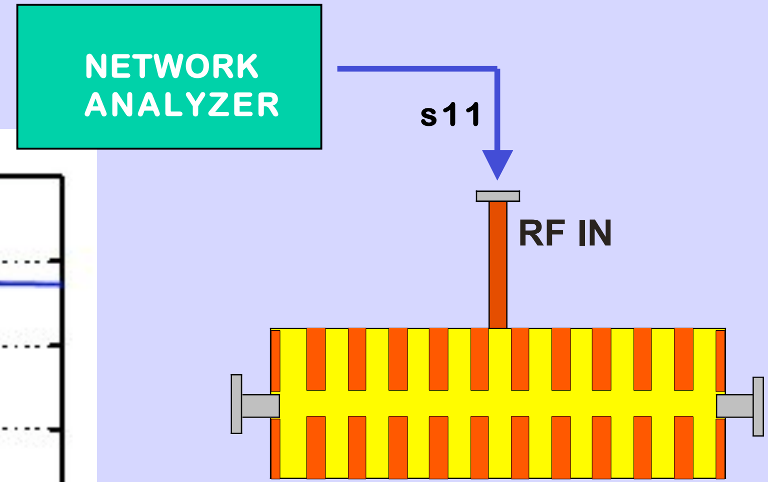


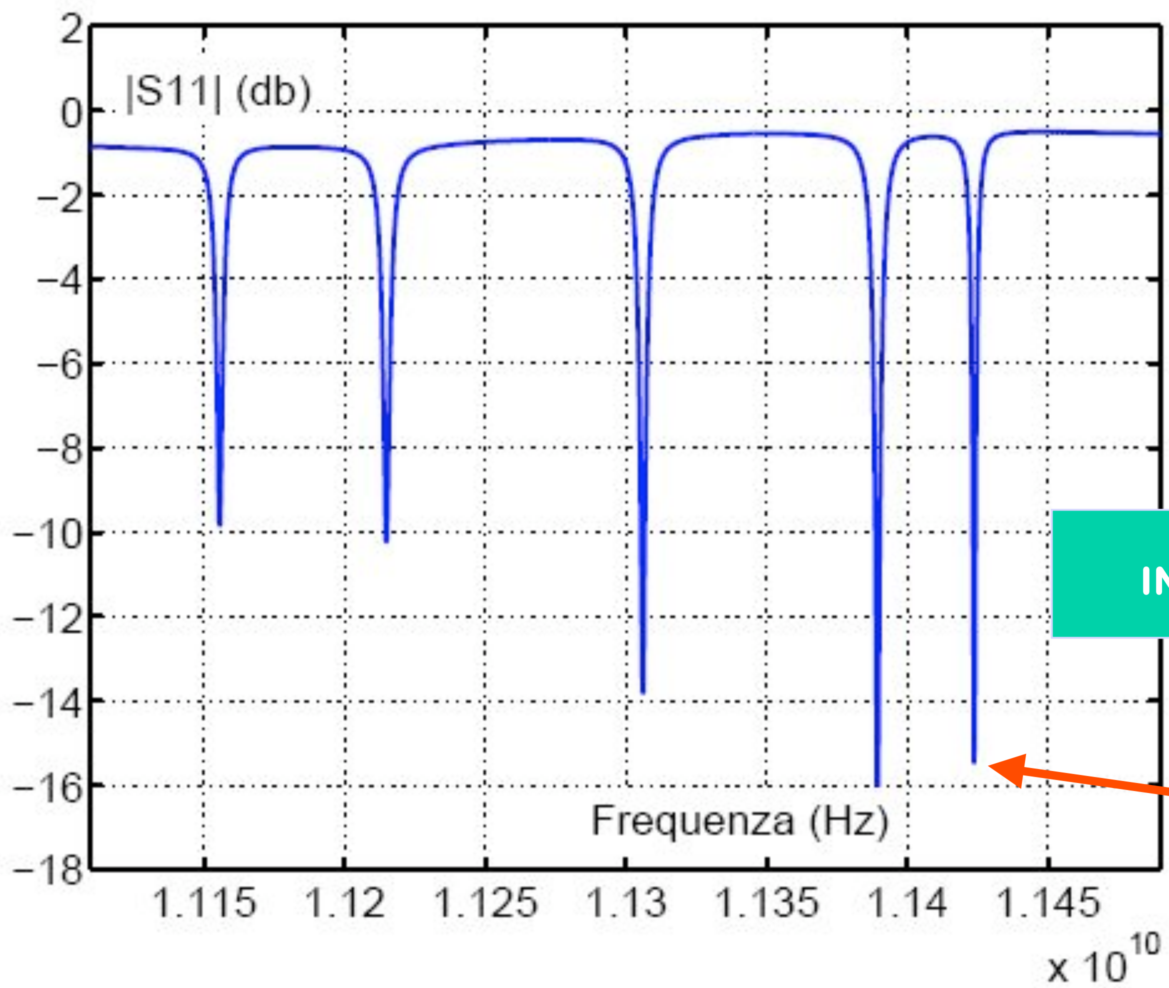
π/2-mode

DETECTION OF THE FUNDAMENTAL MODE RESONANCES WITH AN ANTENNA



DETECTION OF THE FUNDAMENTAL MODE RESONANCES BY THE INPUT COUPLER





INPUT COUPLER INDUCED MODES

π-mode
11.424 GHz

X-BAND COPPER PROTOTYPE MAIN PARAMETERS

π-mode frequency	11.424 GHz
Form factor r/Q	9400 Ω/m (*9165*)
Unloaded Q	7960 (*8413*)
External Q	8000
E-Field flatness	< 1 %
Number of cells	9
Structure length	110 mm

In red, the theoretical values

CONCLUSIONS

- **FIRST R&D ACTIVITY on X-BAND STANDING WAVE DISK-LOADED STRUCTU STARTED SUCCESSFULLY.**
- **IMPORTANT KNOW-HOW ASPECTS of the E.M DESIGN and FABRICATION of X-BAND ACCELERATING SECTIONS HAVE BEEN ACQUIRED**
- **FUTURE ACTIVITY :**
  - **CARRY OUT BRAZING PROCESS to VERIFY the VACUUM PERFORMANCES of a CAVITY**
  - **DEVELOPE a π/2-MODE STRUCTURE TO CH E.M. SENSITIVITY vs FABRICATION ERROR**