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# Electromagnetic design of a re-entrant cavity- BPM for the ILC Main Linac

Laura Karina Pedraza, Daniel González, Nuria Fuster, Daniel Esperante,  
Benito Gimeno, César Blanch, Juan Carlos Fernández

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[laura.pedraza@ific.uv.es](mailto:laura.pedraza@ific.uv.es)

[daniel.Gonzalez-Iglesias@uv.es](mailto:daniel.Gonzalez-Iglesias@uv.es)



# Introduction

## ILC Project:

- Next large particle accelerator for high energy physics
- Two  $\approx 10$  km long superconducting LINACS
- Collide  $2 \times 250$  GeV electrons and positrons beams at the interaction point (IP)
- Potential Higgs Factory

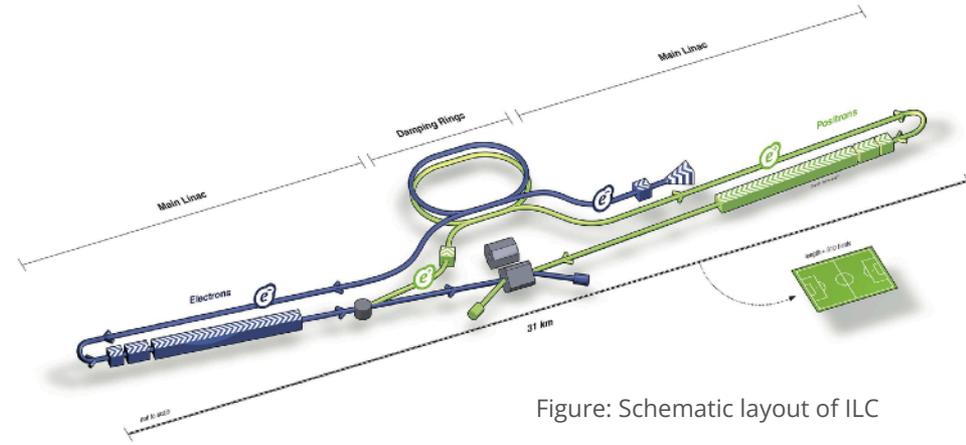


Figure: Schematic layout of ILC

## Beam diagnosis:

Measure and evaluate the properties and behaviour of the beam (current, position, momentum...)

## ILC's demands:

Achieve high luminosity at the IP

To guide and stabilise the beam, we require high-resolution **beam position monitors (BPM)** with spacial resolution  $< 1 \mu\text{m}$

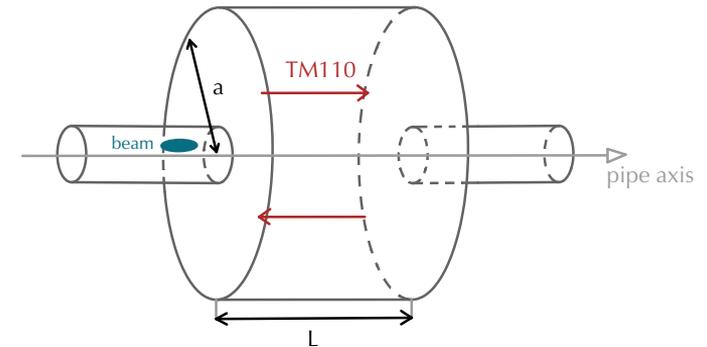


Figure: pill-box cavity BPM scheme

## Development of a **re-entrant cBPM for the ILC Main Linac**

Project in collaboration with KEK and CIEMAT: development of the cryostat for a BPM and a super-conducting quadrupole

### Mechanical requirements:

Mechanical fit of the BPM and the SC quadrupole magnet  
Cryogenic and UV conditions have to be met

### Measurement requirements:

Spatial resolution  $< 1 \mu\text{m}$

Temporal resolution  $< 369 \text{ ns}$

The designed BPM will initially be tested at ATF (Accelerator Test Facility)

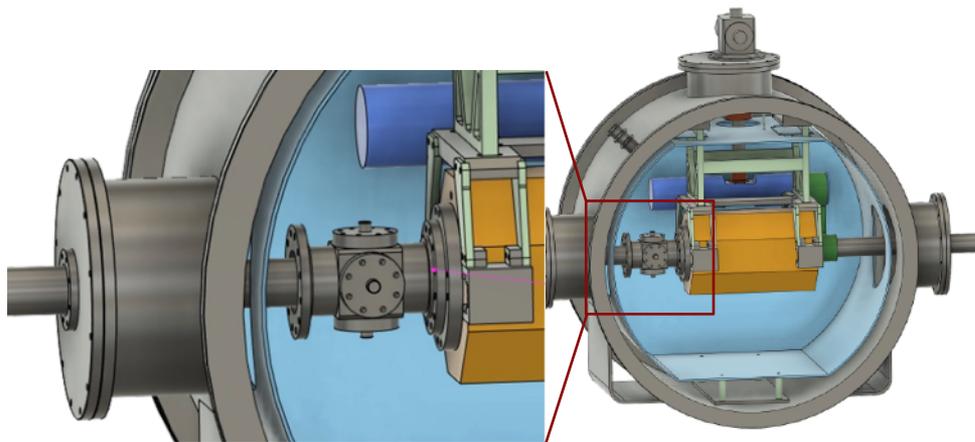


Figure: Cryostat accommodating BPM and SC quadrupole

Beam parameters	ATF	ILC
Beam energy (GeV)	1,3	250
Bunch charge (nC)	1,6	3,2
Bunch spacing	0,33 s	369 ns
Bunch length (mm)	7	0,3

# I. Resonant cavity Beam Position Monitor

## A) Pillbox cavity BPM

### → Working principle

Cavity BPMs are resonant systems crossed by the beam pipe. EM modes are induced on the cavity by the beam and their amplitude depends on the beam position.

Two modes in particular are of interest:

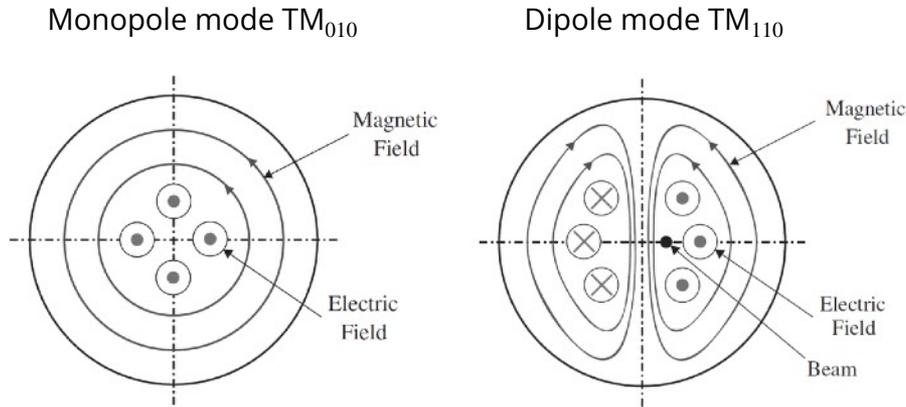
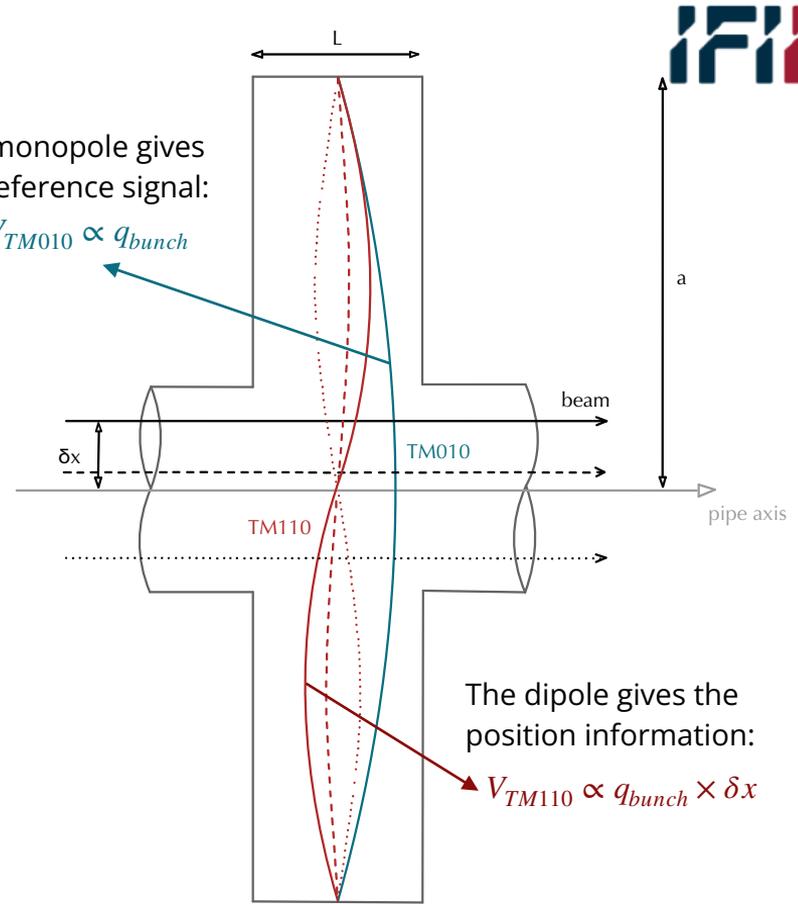


Figure: Cross-sectional view of the TM modes in a pillbox cavity

The monopole gives the reference signal:

$$V_{TM010} \propto q_{bunch}$$



The dipole gives the position information:

$$V_{TM110} \propto q_{bunch} \times \delta x$$

Figure: Representation of the E-fields induced in the cavity

## II. Performance of the cBPM

### A) Existing model developed by CEA Saclay

**Operation frequency:** 1.725 GHz

**Resolution :** around  $4 \mu\text{m}$

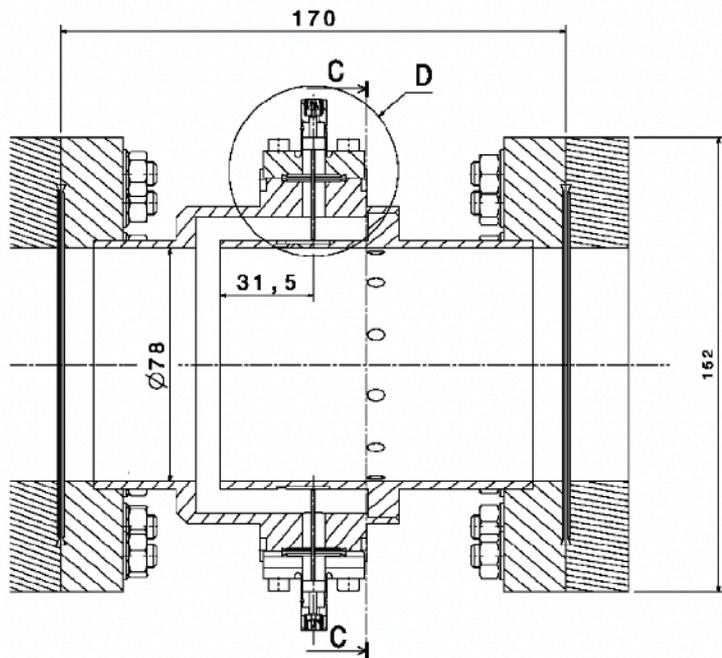


Figure: Drawing of the CEA Saclay cBPM

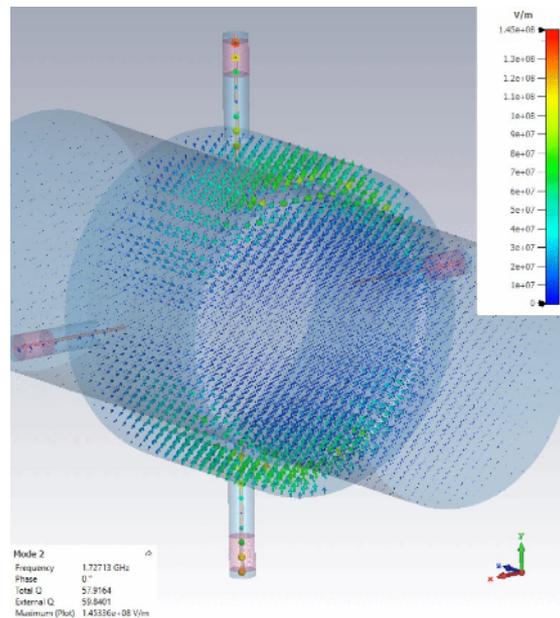


Figure: CST simulations of the CEA Saclay cBPM

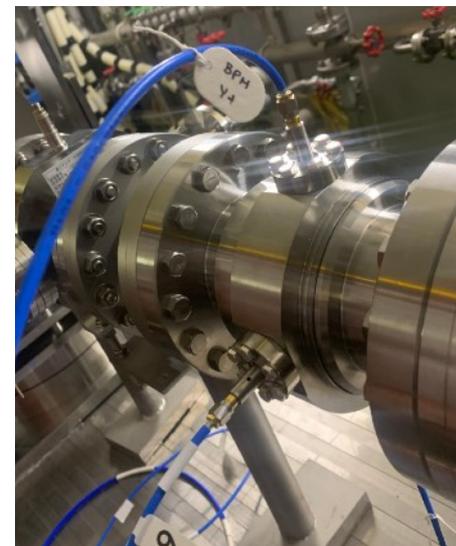


Figure: CEA Saclay cBPM installed at ATF

- **Resonance frequency**  $f_m$ : Operation frequency of the BPM (two modes) → Mainly determined by the electronics and repetition frequency of the accelerator

depends on the geometry of the cBPM

- **Loaded quality factor**  $Q_L$ : Determines the coupling of the cavity with the exterior but also the length of the waveforms in time

$$\tau = 2Q_L / \omega_{mnp}$$

- **Normalized shunt impedance**  $(R/Q)_m$ : Evaluates the effect from the beam in the cavity. This factor determines the sensitivity of the observed output signals.

$$(R/Q)_{monop} = \text{constant} \Rightarrow (R/Q)_{monop, \delta x} = (R/Q)_{monop, x_0} \quad (R/Q)_{dip} \propto \delta x \Rightarrow (R/Q)_{dip} = (R/Q)_{dip, x_0} \times \frac{\delta x}{x_0}$$

- **S-parameter**  $S_{21}$  (at the dipole mode frequency): Determines the coupling between orthogonal ports. A high coupling will produce a reading on the y-port when there is beam shifted on the x-axis only, known as **cross-talk**.

- **Resonance frequency**  $f_m$ : Operation frequency of the BPM (two modes) → Mainly determined by the electronics and repetition frequency of the accelerator

Because of filters specifications:  $1.610 < f_{dip} < 1.638$  GHz

- **Loaded quality factor**  $Q_L$ : Determines the coupling of the cavity with the exterior but also the length of the waveforms in time

To have the right length of signals:  $10\text{ns} < \tau < 100\text{ ns} \Rightarrow 10\text{ ns} \times \pi f_m < Q_L < 100\text{ ns} \times \pi f_m$

- **Normalized shunt impedance**  $(R/Q)_m$ : Evaluates the effect from the beam in the cavity. This factor determines the sensitivity of the observed output signals.

$(R/Q)_{monop}$  should be kept similar to  $(R/Q)_{dip}$   $(R/Q)_{dip} > 0.27\ \Omega \rightarrow$  increases the sensitivity of the measurements

- **S-parameter**  $S_{21}$  (at the dipole mode frequency): Determines the coupling between orthogonal ports.

To keep the cross-talk to a minimum:  $|S_{21}(f_{dip})| < -30\text{ dB}$

### III. Design and development of a NEW re-entrant cBPM

#### A) New BPM requirements

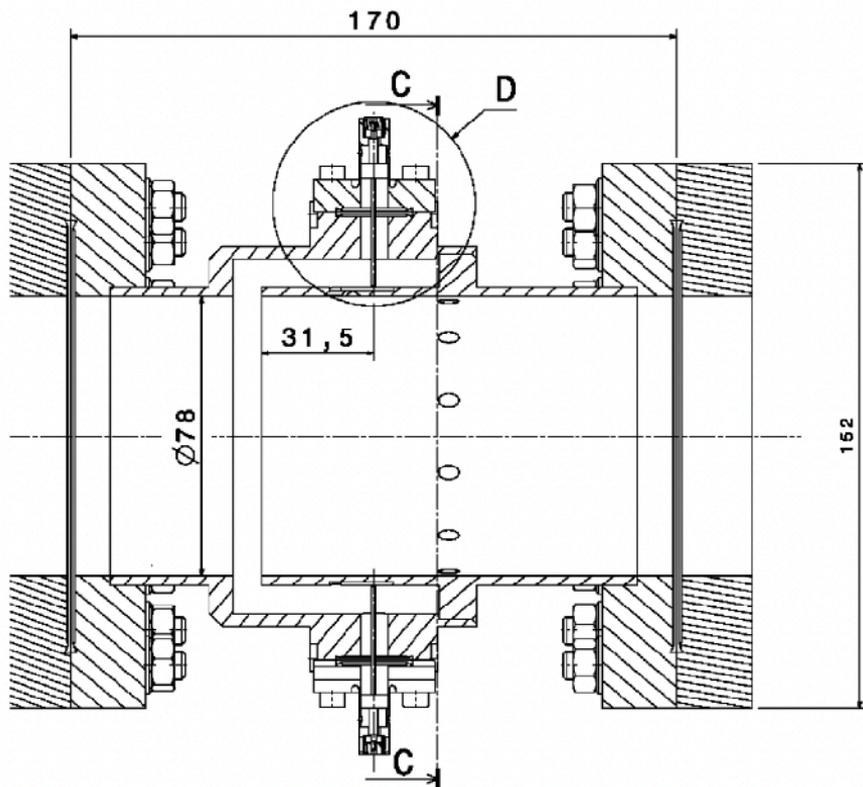


Figure: Drawing of the CEA Saclay cBPM

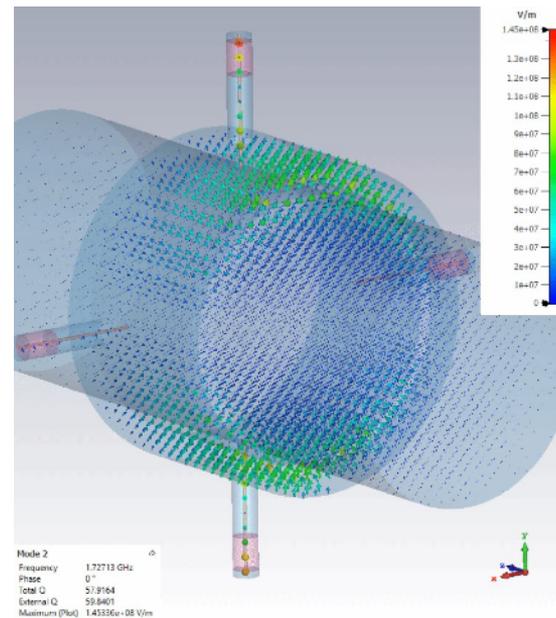


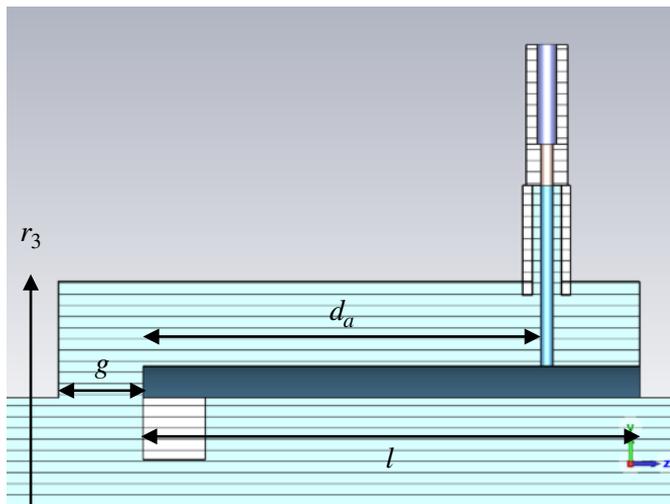
Figure: CST simulations of the CEA Saclay cBPM

#### Global requirements:

- High precision BPM with a time nanometer resolution ( $< 369$  ns) and a spatial resolution  $< 1 \mu\text{m}$
- ILC beam bunch by bunch measurements (low enough  $Q_L$ )
- Low beam dynamics impact (wakefields studies)
- Ultra high-vacuum and cryogenic temperatures performance
- Attachment with SCQ

# III. Design and development of a NEW re-entrant cBPM

## B) Latter BPM design



**Parameters of optimisation (mm):**

Uses a commercial feedthrough

Modification of parameters  $r_3$ ,  $l$ ,  $d_a$  and  $g$  to obtain desired performance

Mode	Monopole					Dipole (on x)				
	Freq (GHz)	$Q_L$	R/Q ( $\Omega$ ) @ 5 mm	$S_{11}$ (dB)	$S_{12}$ (dB)	Freq (GHz)	$Q_L$	R/Q ( $\Omega$ ) @ 5 mm	$S_{11}$ (dB)	$S_{12}$ (dB)
<b>SACLAY</b>	1.255	23.8	12.9	-5.7	-6.5	1.724	59	0.27	-25.0	-33
<b>Our Optimization</b>	1.120	37.65	14.47	-5.4	-6.6	1.626	72.30	0.357	-16.3	-30.6

Increases signal length

Proper frequency for ATF

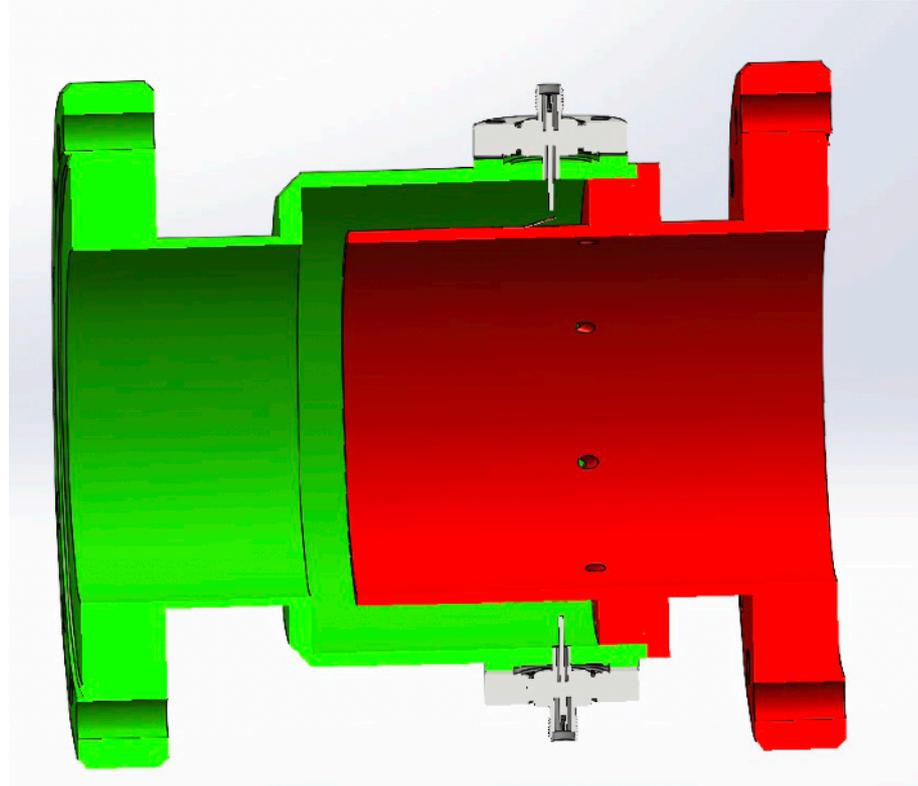
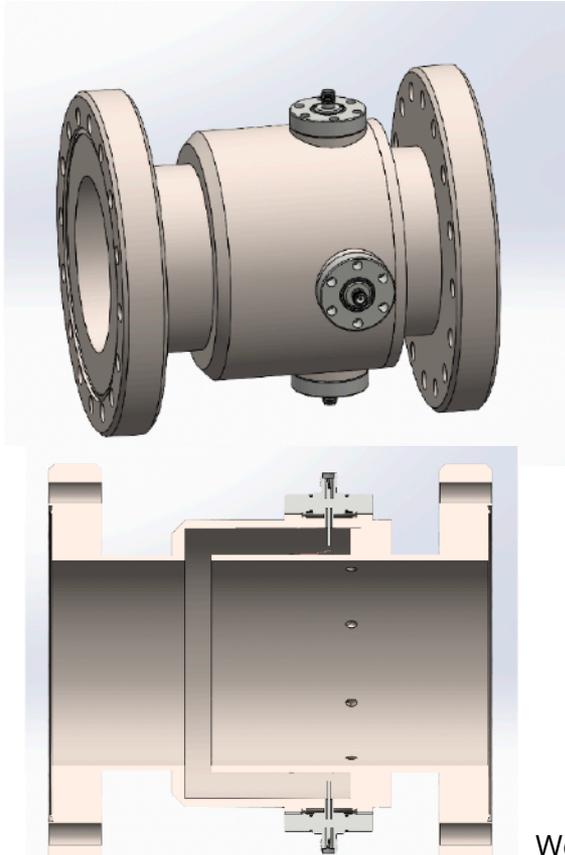
Increases sensitivity

Avoids cross-talk

### III. Design and development of a NEW re-entrant cBPM

#### B) Latter BPM design

The contact of the feedthrough with the BPM is being evaluated



We are working with Neptury Technologies for the construction of the new cBPM. 10

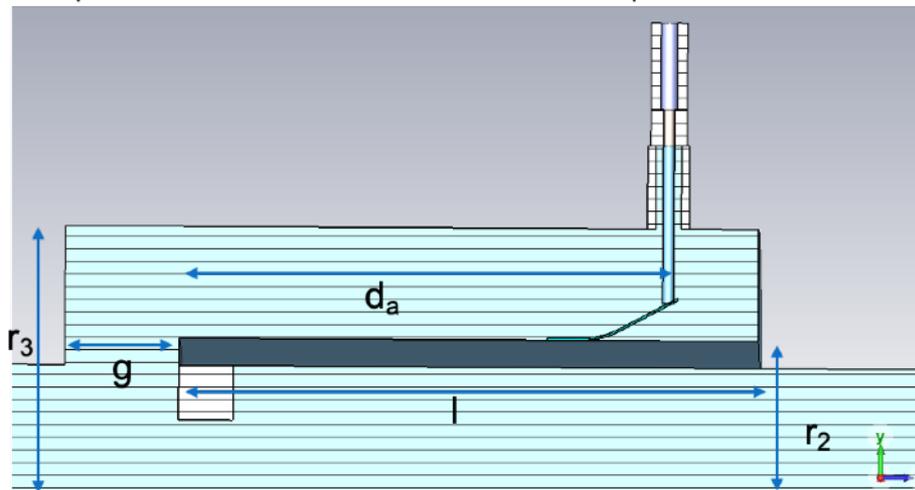
- En el proceso de fabricación del BPM existen imperfecciones en el mecanizado de las piezas que componen el dispositivo, de manera que las dimensiones finales del prototipo pueden diferir ligeramente de los valores ideales del diseño, el efecto de estas variaciones deben ser tenidas en cuenta para verificar que su impacto en los parámetros de funcionamiento del BPM son pequeños y no comprometen el rendimiento óptimo del mismo

- Tomamos el BPM con el conector, con las siguiente dimensiones correspondientes al diseño final optimizado:

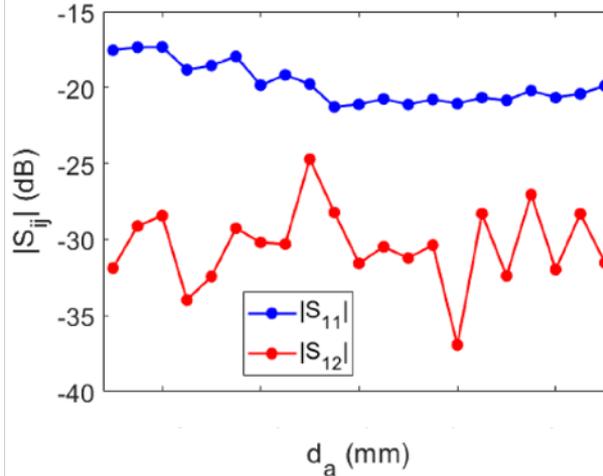
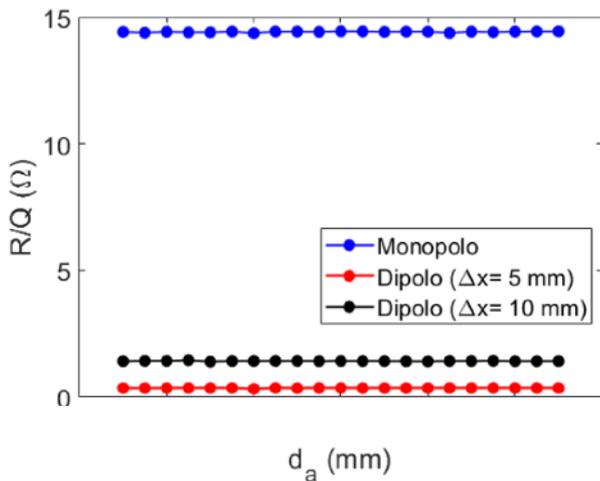
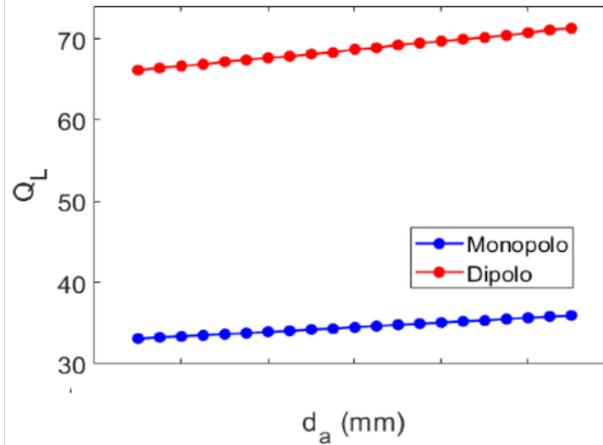
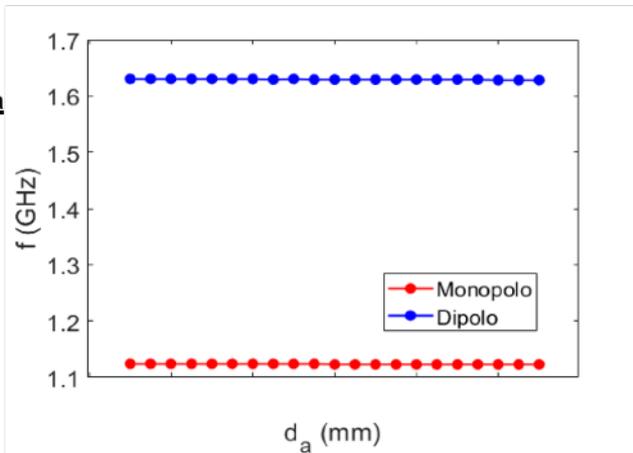
$$g = \quad \text{mm} \quad r_3 = \quad \text{mm} \quad r_2 = \quad \text{mm}$$

$$l = \quad \text{mm} \quad d_a = \quad \text{mm}$$

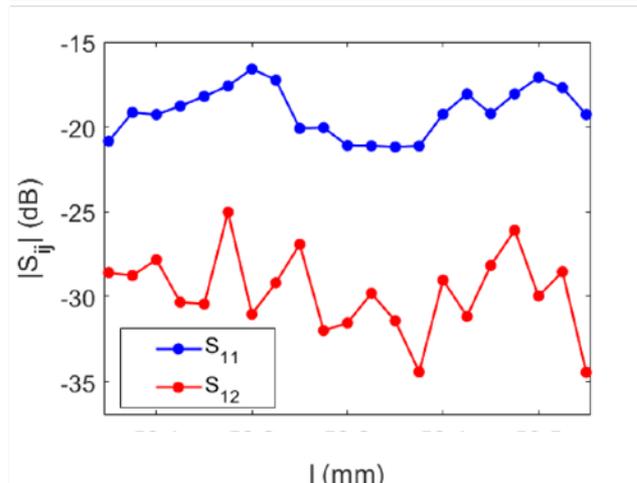
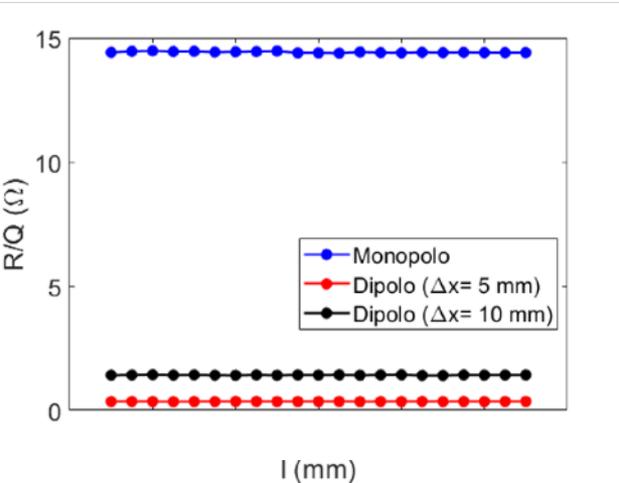
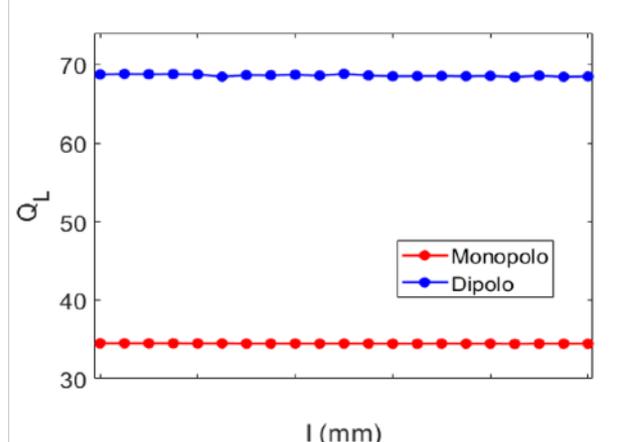
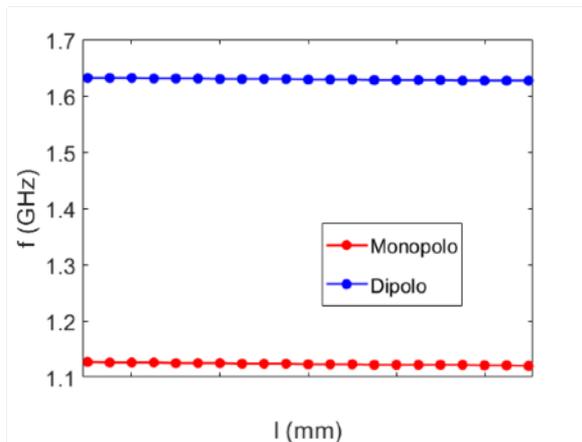
- Evaluaremos pequeñas variaciones de las dimensiones del componente respecto al valor óptimo de diseño, concretamente, se tendrán en consideración:  $d_a$ ,  $l$ ,  $r_2$ ,  $r_3$ ,  $g$ ; con pasos de  $25 \mu\text{m}$
- En esta última versión del diseño ha sido necesario añadir una pestaña metálica (cobre-berilio) para que se produzca el contacto eléctrico entre el conductor interno de la antena coaxial del acoplador y el conductor interno de la cavidad reentrante, debido a que el conductor interno del acoplador resulta demasiado corto al ensamblar en el cuerpo del BPM



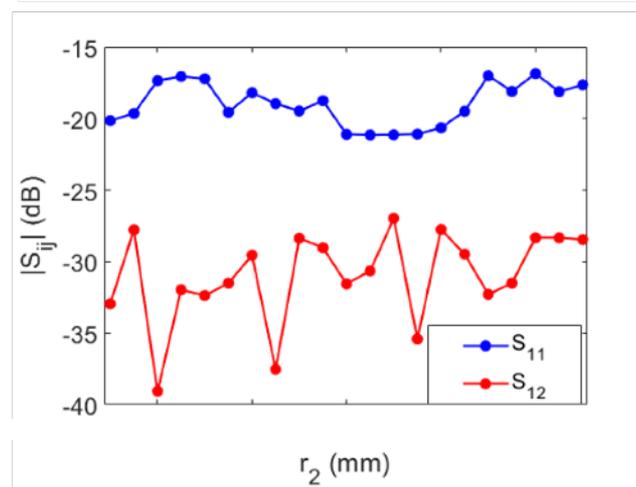
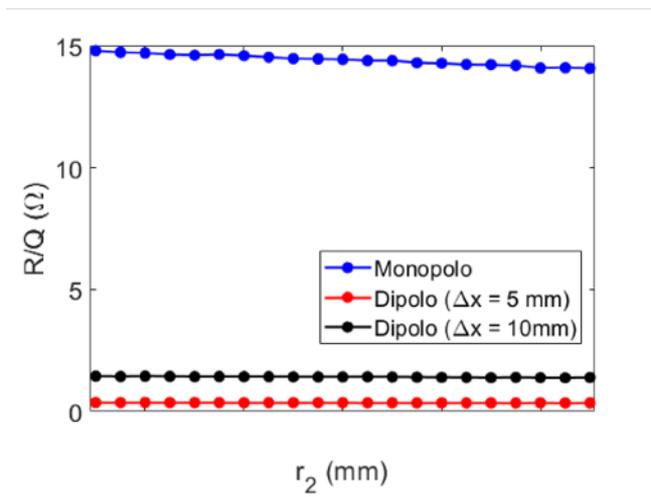
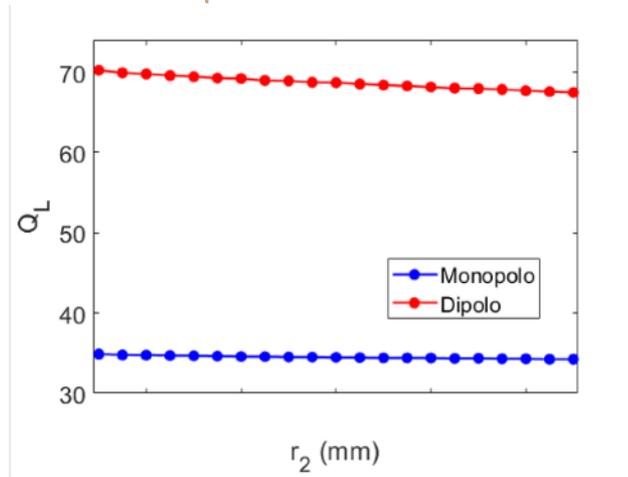
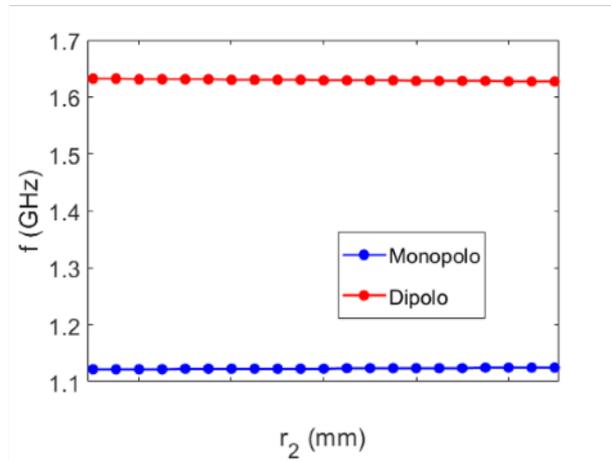
### Variación de $d_a$



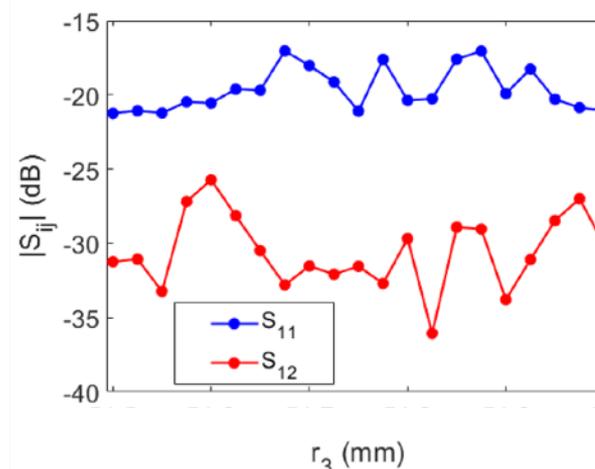
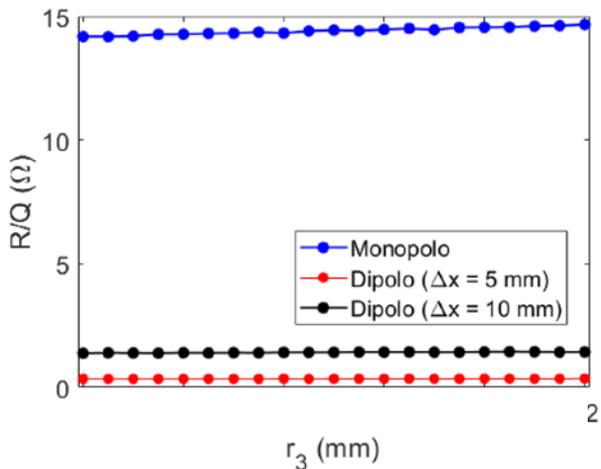
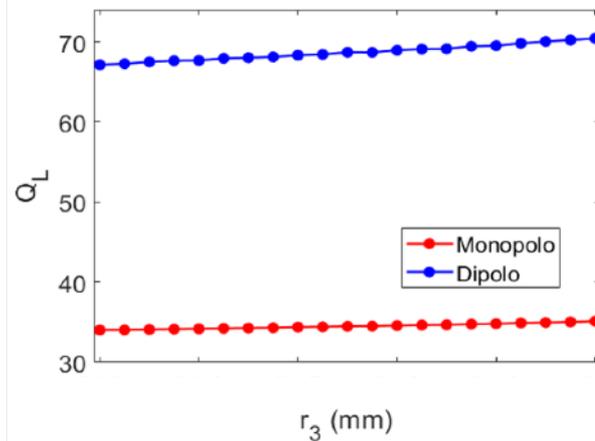
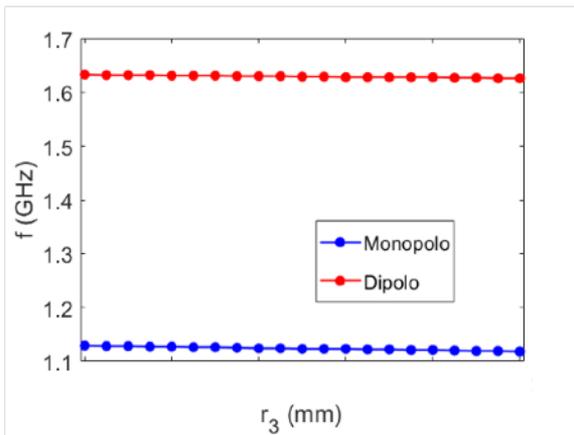
### Variación de l



### Variación de $r_2$



### Variación de $r_3$

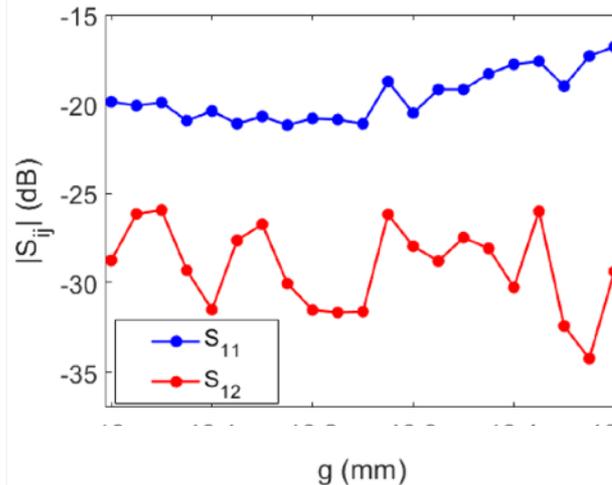
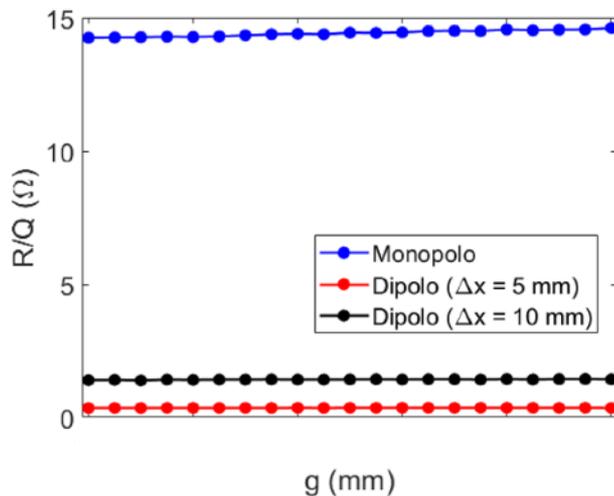
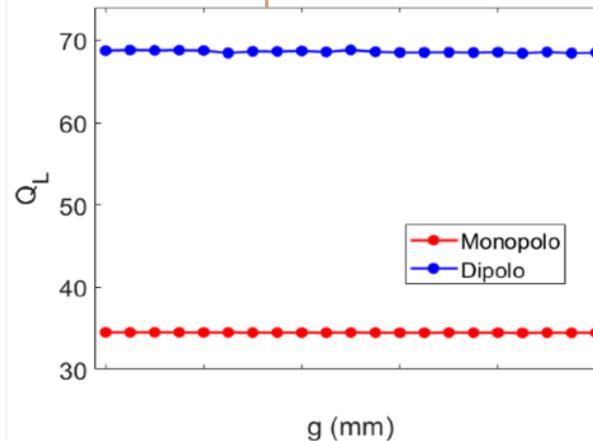
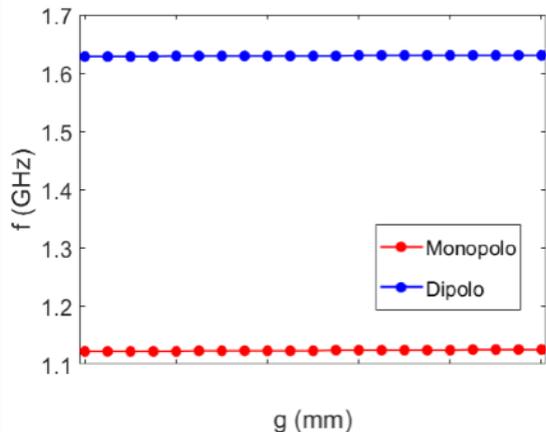


# IV. Análisis de las tolerancias del BPM

## A) Variación de un solo parámetro

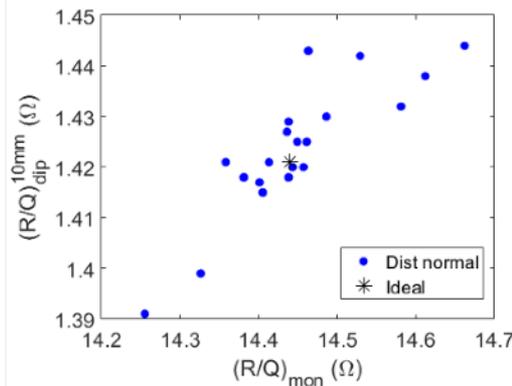
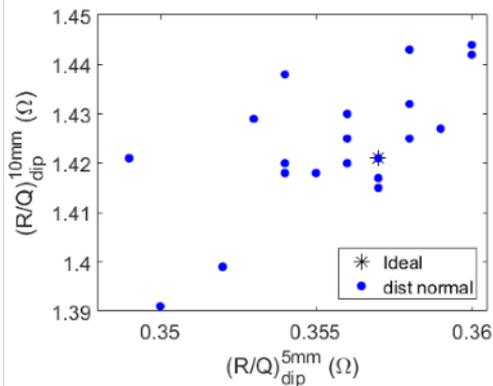
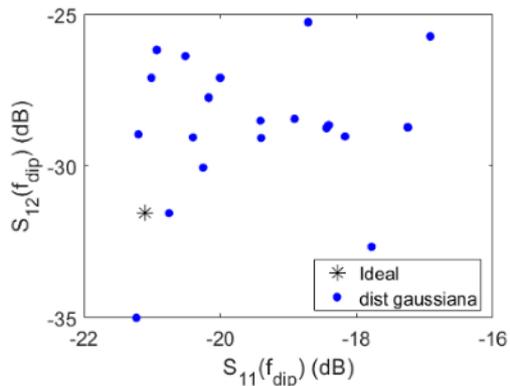
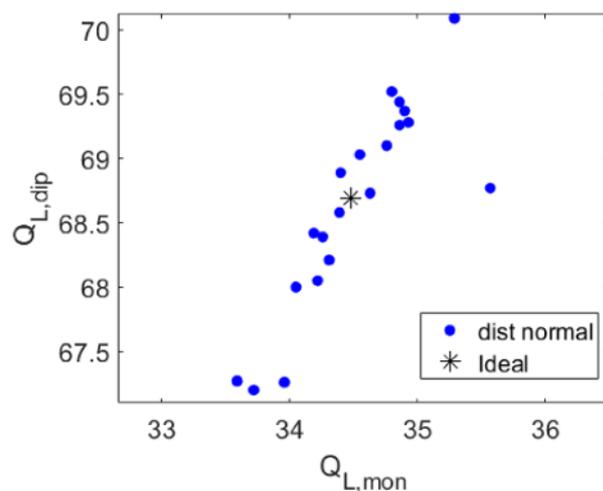
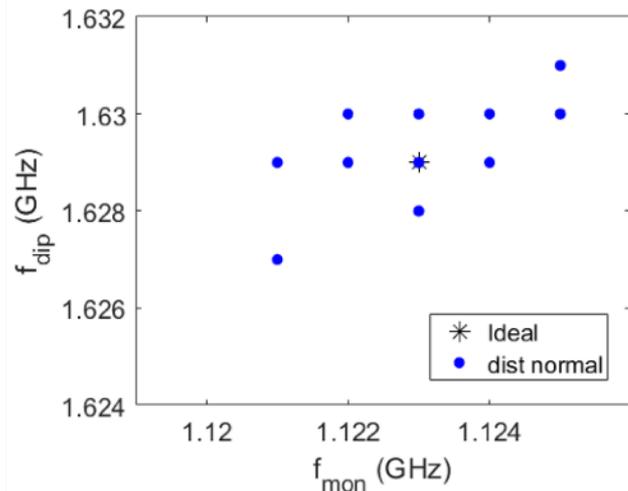


### Variación de g



- En este apartado vamos a estudiar cual es el efecto en los parámetros de funcionamiento del BPM de variar todas las dimensiones del diseño anteriores de manera simultánea, simulando el efecto que tendrían las incertidumbres reales debidas a las tolerancias de los procesos de fabricación del componente
- Para ello, consideraremos que las tolerancias de fabricación tienen una desviación estándar de 50  $\mu\text{m}$ , y que los errores de fabricación siguen una distribución normal centrada en el valor ideal de diseño
- Tomaremos 20 muestras diferentes para las cuales examinaremos los parámetros de funcionamiento del BPM y analizaremos cuanto se alejan de los valores ideales

caso	g (mm)	l (mm)	r <sub>3</sub> (mm)	d <sub>a</sub> (mm)	r <sub>2</sub> (mm)
1					
2					
3					
4					
5					
6					
7					
8					
9					
10					
11					
12					
13					
14					
15					
16					
17					
18					
19					
20					



Variación de  $a_1$ : suponemos que la beam pipe se deforma y pasa de tener geometría circular a elíptica, con semiejes mayor y menor,  $a_1$  y  $b_1$ , respectivamente. Variamos los valores de  $a_1$  (semieje horizontal, dirección x) manteniendo  $b_1$  constante (con el valor de  $r_1$  del diseño óptimo)

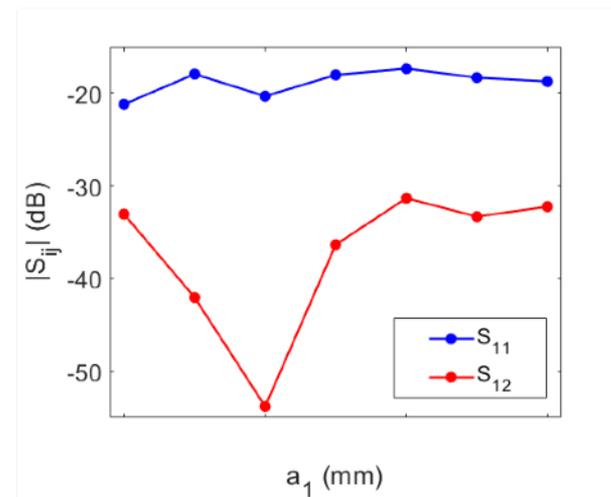
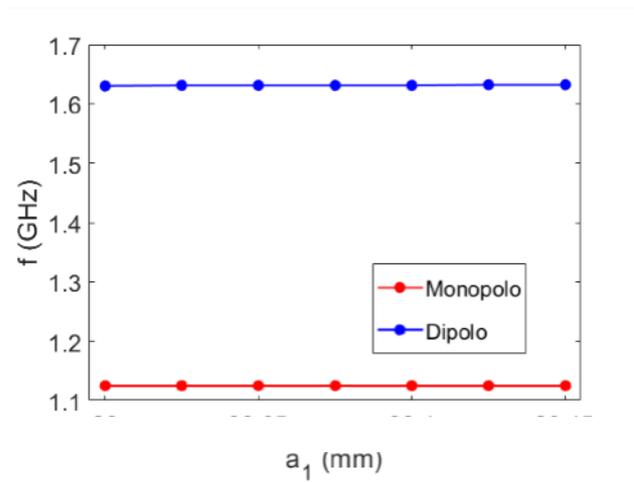
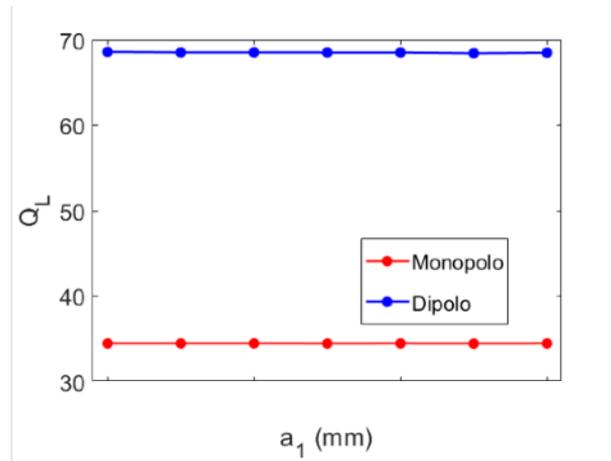
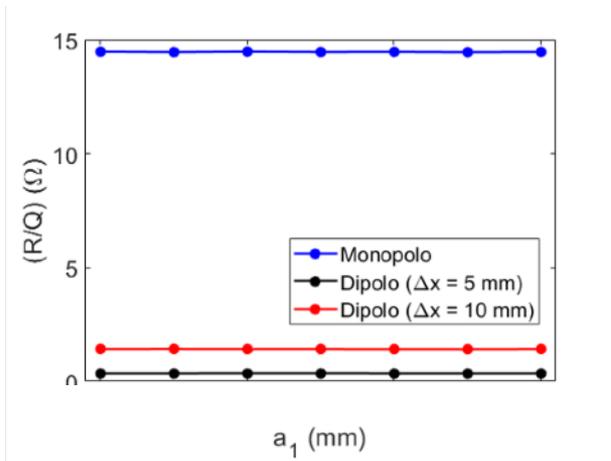
$a_1$ (mm)	$f_{mon}$ (GHz)	$f_{dip}$ (GHz)	$Q_{L,mon}$	$Q_{L,dip}$	$(R/Q)_{mon}$ ( $\Omega$ )	$(R/Q)_{dip}^{5mm}$ ( $\Omega$ )	$(R/Q)_{dip}^{10mm}$ ( $\Omega$ )	$S_{11}$ (dB)	$S_{12}$ (dB)
1.125	1.630	1.630	34.47	68.58	14.479	0.355	1.428	-21.21	-33.06
1.125	1.163	1.163	34.47	68.52	14.458	0.355	1.431	-17.96	-42.05
1.125	1.631	1.631	34.48	68.59	14.450	0.356	1.424	-20.34	-53.80
1.125	1.631	1.631	34.46	68.51	14.483	0.356	1.426	-18.05	-36.35
1.125	1.631	1.631	34.47	68.51	14.470	0.355	1.420	-17.37	-31.34
1.125	1.632	1.632	34.45	68.42	14.459	0.352	1.418	-18.34	-33.33
1.125	1.632	1.632	34.47	68.48	14.466	0.354	1.417	-18.76	-32.15

**Rangos de funcionamiento requeridos para el BPM**

$f_{dip} \in [1.610, 1.638]$  GHz       $(R/Q)_{mon} > 12.8 \Omega$   
 $Q_{L,mon} > 31.8$        $(R/Q)_{dip}^{10mm} > 1.15 \Omega$   
 $Q_{L,dip} > 46.1$        $S_{12}(f_{dip}) < -33$  dB

- No se observan variaciones sustanciales de los parámetros de funcionamiento del BPM dentro del rango de valores estudiado

## Variación de $a_1$



Variación de  $a_2$  y  $a_3$ : suponemos que la cavidad reentrante se deforma, pasando de tener geometría coaxial circular a coaxial elíptica, con semiejes mayor y menor del conductor interno,  $a_2$  y  $b_2$ , respectivamente, y con semiejes mayor y menor del conductor externo,  $a_3$  y  $b_3$ , respectivamente. Variamos simultáneamente los valores de  $a_2$  y  $a_3$  (semiejes horizontales, dirección x) manteniendo  $b_2$ ,  $b_3$  constantes (con valores de  $r_2$  y  $r_3$  del diseño óptimo)

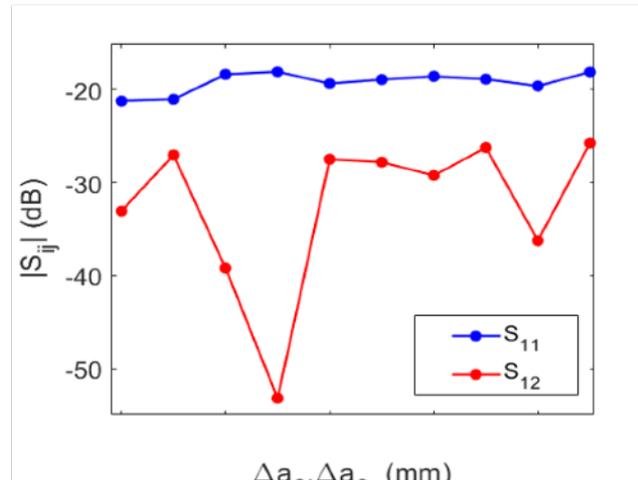
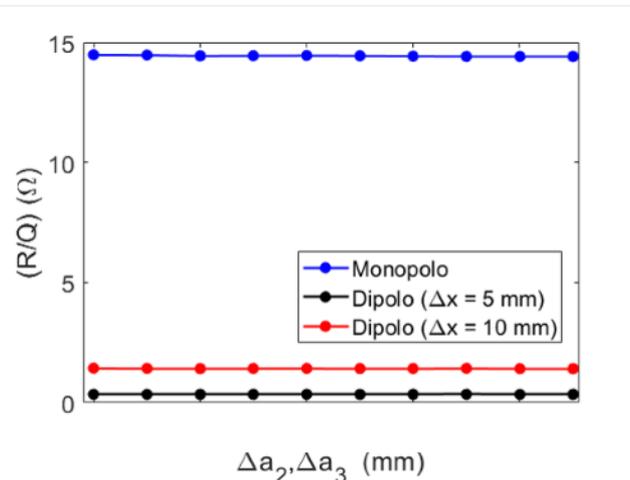
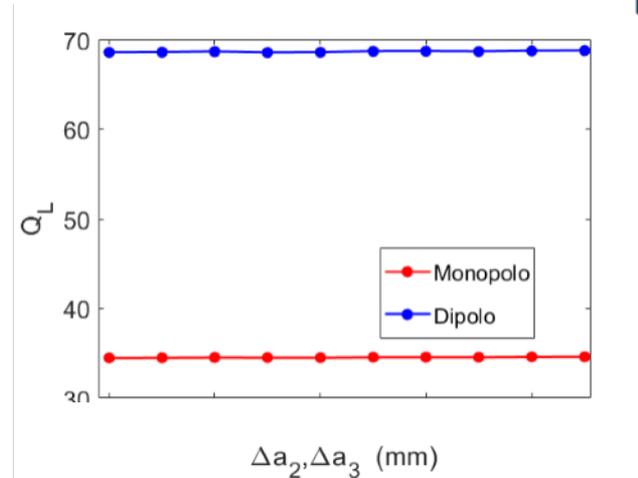
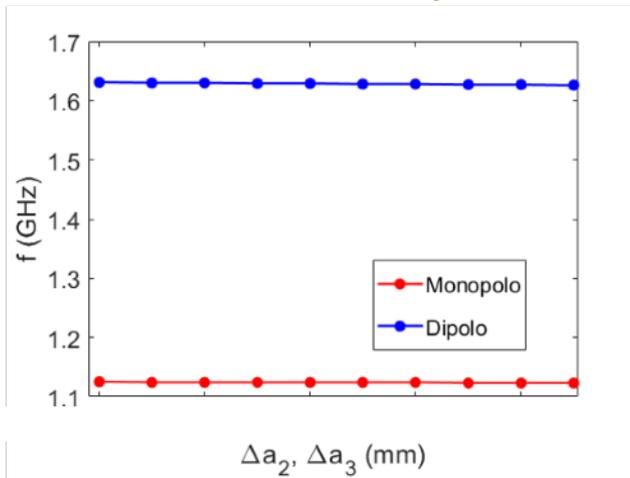
$a_2$ (mm)	$a_3$ (mm)	$f_{mon}$ (GHz)	$f_{dip}$ (GHz)	$Q_{L,mon}$	$Q_{L,dip}$	$(R/Q)_{mon}$ ( $\Omega$ )	$(R/Q)_{dip}^{5mm}$ ( $\Omega$ )	$(R/Q)_{dip}^{10mm}$ ( $\Omega$ )	$S_{11}$ (dB)	$S_{12}$ (dB)
		1.124	1.630	34.49	68.60	14.468	0.354	1.419	-21.03	-27.04
		1.124	1.630	34.52	68.67	14.433	0.353	1.412	-18.36	-39.21
		1.124	1.629	34.51	68.56	14.441	0.355	1.418	-18.08	-53.20
		1.124	1.629	34.50	68.59	14.449	0.354	1.420	-19.34	-27.49
		1.124	1.628	34.55	68.70	14.437	0.353	1.414	-18.91	-27.80
		1.124	1.628	34.55	68.71	14.422	0.353	1.415	-18.57	-29.23
		1.123	1.627	34.55	68.68	14.411	0.357	1.423	-18.87	-26.24
		1.123	1.627	34.59	68.75	14.409	0.351	1.411	-19.61	-36.25
		1.123	1.626	34.60	68.78	14.409	0.354	1.410	-18.10	-25.74

**Rangos de funcionamiento requeridos para el BPM**

$f_{dip} \in [1.610, 1.638]$  GHz       $(R/Q)_{mon} > 12.8 \Omega$   
 $Q_{L,mon} > 31.8$        $(R/Q)_{dip}^{10mm} > 1.15 \Omega$   
 $Q_{L,dip} > 46.1$        $S_{12}(f_{dip}) < -33$  dB

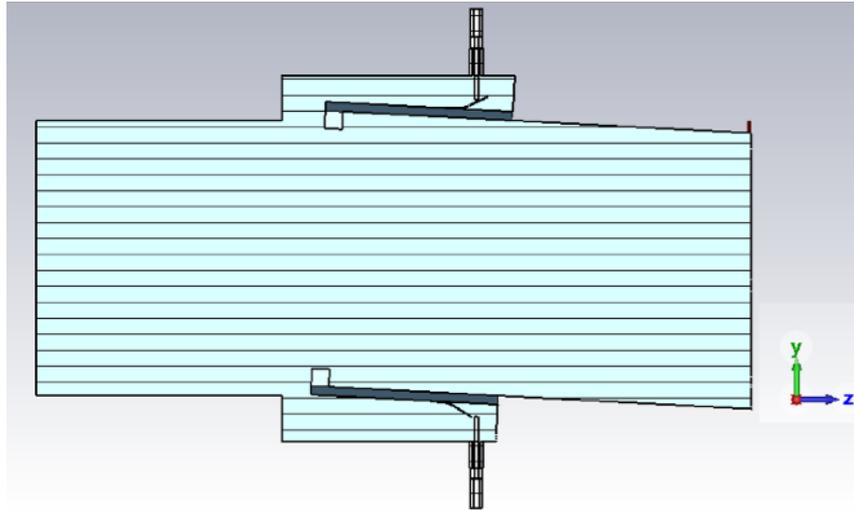
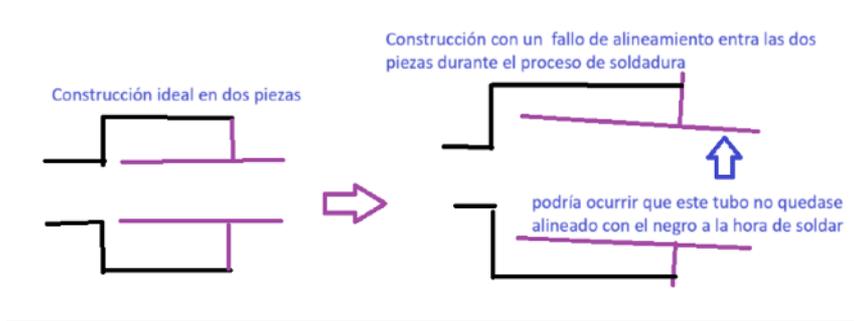
- No se observan variaciones sustanciales de los parámetros de funcionamiento del BPM dentro del rango de valores estudiado

## Variación de $a_2$ y $a_3$



# IV. Análisis de las tolerancias del BPM

## D) Estudio del desalineamiento al soldar las piezas del BPM



Esquema del BPM en CST con el desalineamiento al soldar las piezas

- El desalineamiento entre las piezas se caracteriza por el ángulo  $\theta$  que forma el eje axial con respecto a la orientación de la pieza correspondiente a la cavidad reentrante

## IV. Análisis de las tolerancias del BPM

### D) Estudio del desalineamiento al soldar las piezas del BPM

Variación de  $\theta$  (en el eje y)

$\theta$ (°)	$f_{mon}$ (GHz)	$f_{dip}$ (GHz)	$Q_{L,mon}$	$Q_{L,dip}$	$(R/Q)_{mon}$ ( $\Omega$ )	$(R/Q)_{dip}^{5mm}$ ( $\Omega$ )	$(R/Q)_{dip}^{10mm}$ ( $\Omega$ )	$S_{11}$ (dB)	$S_{12}$ (dB)
0.0	1.125	1.631	34.55	68.63	14.453	0.355	1.416	-18.980	-45.080
0.1	1.124	1.631	34.57	68.68	14.452	0.357	1.422	-22.240	-66.450
0.2	1.124	1.631	34.54	68.67	14.455	0.354	1.422	-20.880	-44.040
0.3	1.124	1.630	34.54	68.70	14.457	0.355	1.420	-21.520	-58.250
0.4	1.124	1.631	34.53	68.67	14.454	0.355	1.421	-24.900	-35.100
0.5	1.124	1.631	34.51	68.62	14.459	0.355	1.422	-19.930	-31.660
0.6	1.124	1.631	34.48	68.67	14.443	0.352	1.414	-23.750	-29.900
0.7	1.124	1.631	34.45	68.65	14.439	0.359	1.416	-27.670	-30.830
0.8	1.124	1.631	34.50	69.21	14.420	0.361	1.428	-20.080	-37.270
0.9	1.124	1.631	34.38	68.65	14.423	0.359	1.431	-30.800	-33.540
1.0	1.124	1.631	34.34	68.68	14.415	0.358	1.426	-22.200	-34.000
1.1	1.124	1.631	34.34	68.71	14.392	0.358	1.424	-22.450	-37.220

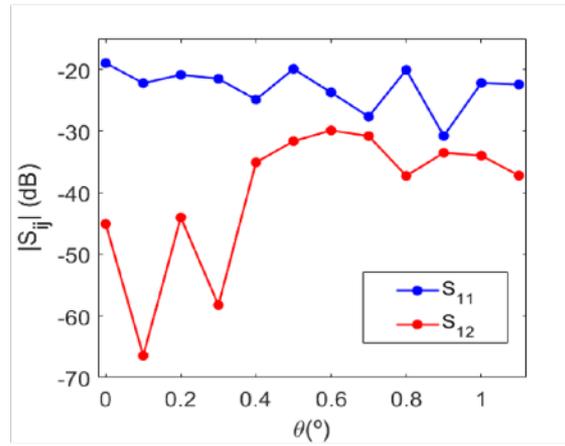
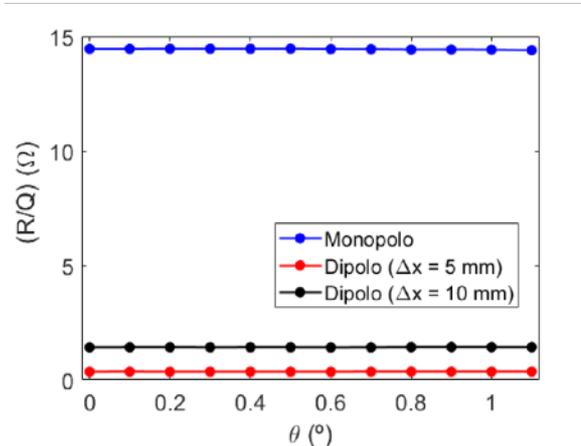
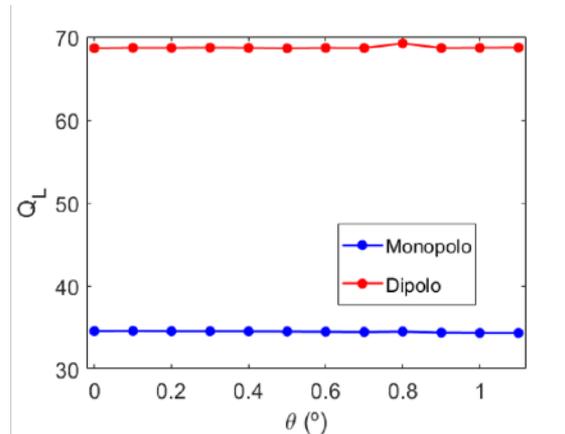
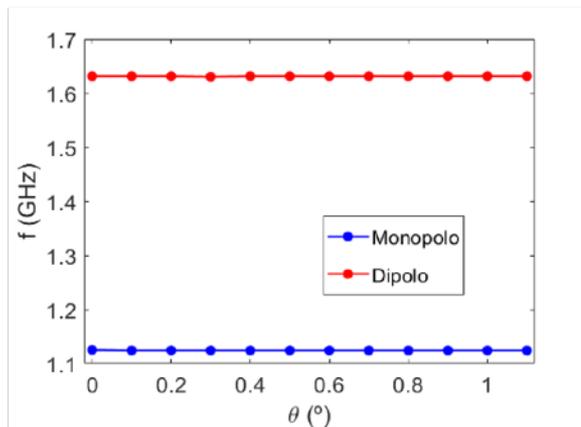
- Para valores de  $\theta < 1.2^\circ$  los parámetros de funcionamiento del BPM se mantienen estables
- Para valores de  $\theta \geq 1.2^\circ$ , la reflexión aumenta mucho ( $S_{11} > -1\text{dB}$ ) debido a que el desalineamiento provoca que la antena del conector coaxial deje de hacer contacto con la pestaña ubicada en el conductor interno de la cavidad reentrante

Rangos de funcionamiento requeridos para el BPM	
$f_{dip} \in [1.610, 1.638]$ GHz	$(R/Q)_{mon} > 12.8 \Omega$
$Q_{L,mon} > 31.8$	$(R/Q)_{dip}^{10mm} > 1.15 \Omega$
$Q_{L,dip} > 46.1$	$S_{12}(f_{dip}) < -33 \text{ dB}$

# IV. Análisis de las tolerancias del BPM

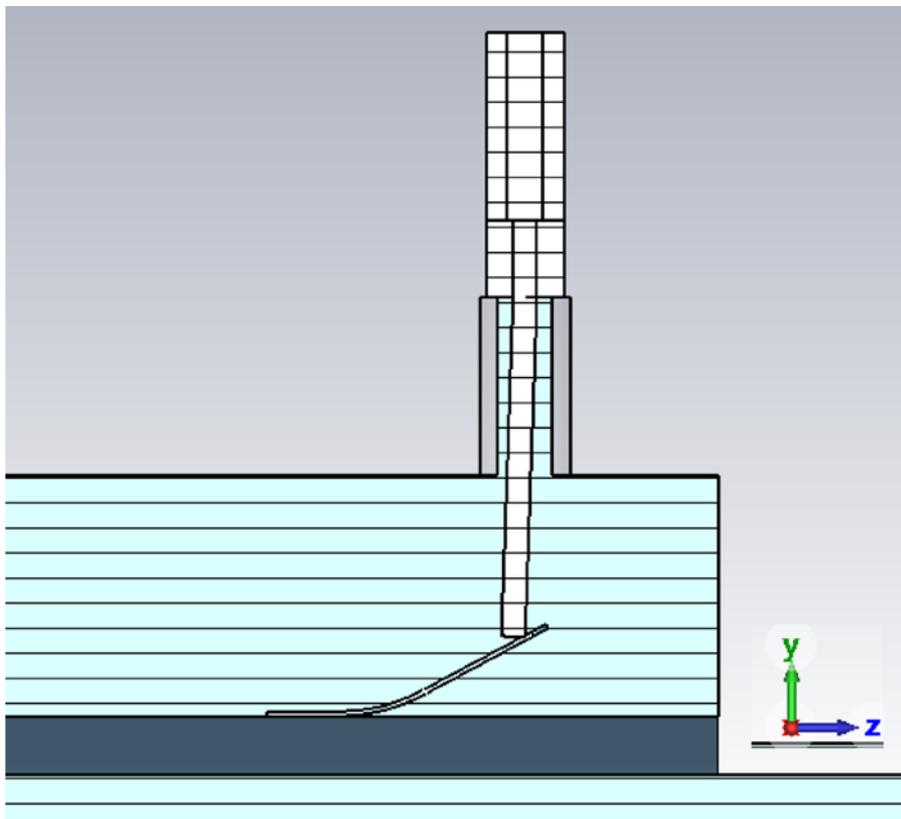
## D) Estudio del desalineamiento al soldar las piezas del BPM

### Variación de $\theta$



## IV. Análisis de las tolerancias del BPM

### E) Estudio del efecto que las antenas del conector coaxial estén torcidas



Esquema del BPM en CST con la antena torcida

- El efecto de que la antena esté torcida se parametriza con el ángulo  $\Phi$  que forma la antena con la posición de la antena “recta”, en el caso de la figura, con respecto al eje  $y$
- Para este estudio supondremos que las cuatro antenas están torcidas el mismo ángulo  $\Phi$  e iremos variando este ángulo

## IV. Análisis de las tolerancias del BPM

### E) Estudio del efecto que las antenas del conector coaxial estén torcidas

#### Variación de $\Phi$

$\phi$ (°)	$f_{mon}$ (GHz)	$f_{dip}$ (GHz)	$Q_{L,mon}$	$Q_{L,dip}$	$(R/Q)_{mon}$ ( $\Omega$ )	$(R/Q)_{dip}^{5mm}$ ( $\Omega$ )	$(R/Q)_{dip}^{10mm}$ ( $\Omega$ )	$S_{11}$ (dB)	$S_{12}$ (dB)
0.0	1.124	1.631	34.53	68.56	14.452	0.355	1.422	-19.84	-32.63
0.2	1.124	1.631	34.57	69.01	14.444	0.356	1.433	-19.32	-62.43
0.4	1.125	1.631	34.55	69.30	14.466	0.355	1.426	-18.31	-55.80
0.6	1.125	1.630	34.52	69.53	14.449	0.356	1.423	-20.44	-51.12
0.8	1.125	1.630	34.52	69.85	14.443	0.356	1.421	-20.32	-45.27
1.0	1.125	1.630	34.50	70.17	14.470	0.356	1.430	-20.89	-48.90
1.2	1.125	1.630	34.47	70.43	14.452	0.357	1.428	-21.20	-57.27
1.4	1.124	1.630	34.45	70.74	14.462	0.356	1.429	-21.23	-53.42
1.6	1.124	1.630	34.41	71.03	14.428	0.357	1.426	-19.67	-39.69
1.8	1.125	1.630	34.35	71.18	14.460	0.356	1.419	-17.26	-33.55
2.0	1.125	1.630	34.32	71.48	14.483	0.355	1.423	-19.49	-42.60

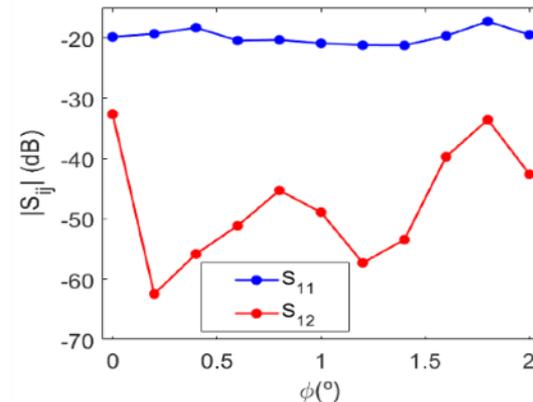
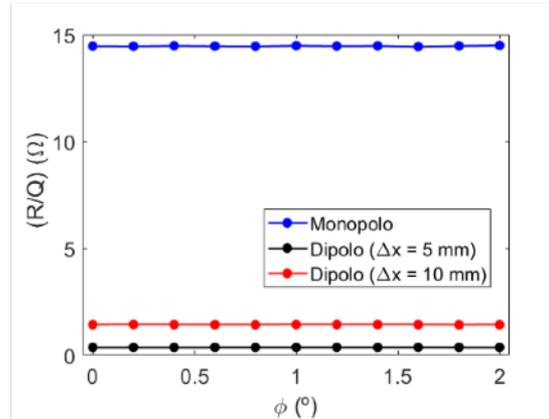
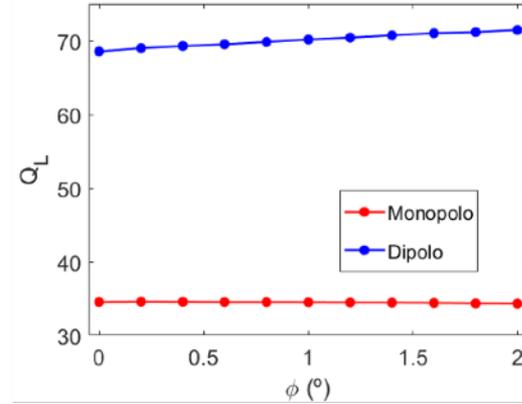
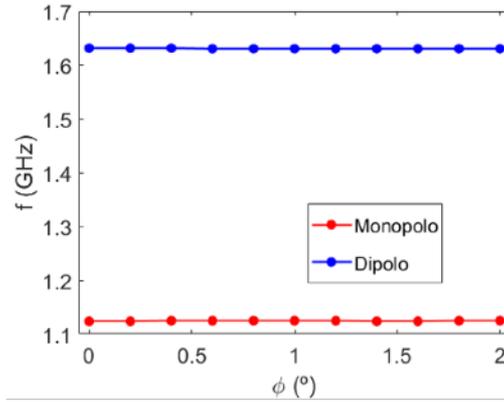
- No se observan variaciones sustanciales de los parámetros de funcionamiento del BPM dentro del rango de valores estudiado, con excepción de  $Q_L$  para el modo dipolar, que tiende a aumentar con el ángulo  $\Phi$

<u>Rangos de funcionamiento requeridos para el BPM</u>	
$f_{dip} \in [1.610, 1.638]$ GHz	$(R/Q)_{mon} > 12.8 \Omega$
$Q_{L,mon} > 31.8$	$(R/Q)_{dip}^{10mm} > 1.15 \Omega$
$Q_{L,dip} > 46.1$	$S_{12}(f_{dip}) < -33$ dB

# IV. Análisis de las tolerancias del BPM

## E) Estudio del efecto que las antenas del conector coaxial estén torcidas

### Variación de $\Phi$



## IV. Análisis de las tolerancias del BPM

### F) Estudio del desalineamiento de los ejes de la beam pipe y la cavidad reentrante

Variación de  $\Delta x$ : suponemos que existe un offset en la dirección horizontal entre el eje de la beam pipe y el eje de la cavidad reentrante

$\Delta x$ (mm)	$f_{mon}$ (GHz)	$f_{dip}$ (GHz)	$Q_{L,mon}$	$Q_{L,dip}$	$(R/Q)_{mon}$ ( $\Omega$ )	$(R/Q)_{dip}^{5mm}$ ( $\Omega$ )	$(R/Q)_{dip}^{10mm}$ ( $\Omega$ )	$S_{11}$ (dB)	$S_{12}$ (dB)
0.0	1.125	1.631	34.55	68.63	14.453	0.355	1.416	-18.98	-45.09
0.1	1.124	1.631	34.57	68.65	14.456	0.333	1.382	-18.73	-29.81
0.2	1.125	1.631	34.59	68.70	14.465	0.315	1.336	-18.08	-37.76
0.3	1.124	1.630	34.65	68.97	14.450	0.296	1.305	-18.88	-27.83
0.4	1.119	1.624	45.11	69.08	14.459	0.00027	0.00009	-18.82	-28.18
0.5	1.113	1.617	50.03	70.12	14.487	0.00008	0.00007	-18.61	-27.57

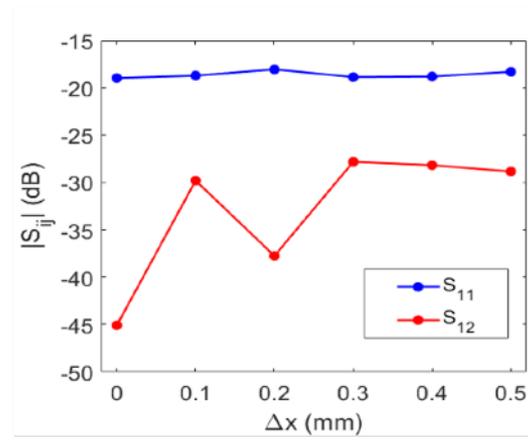
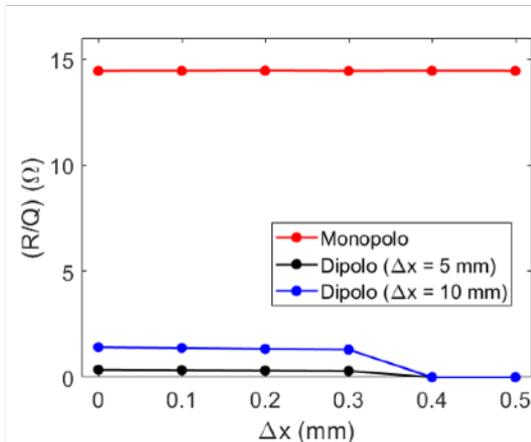
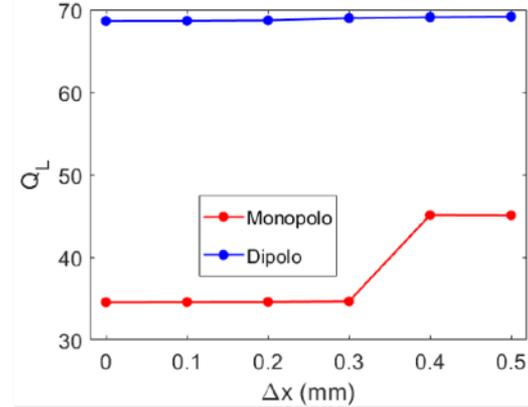
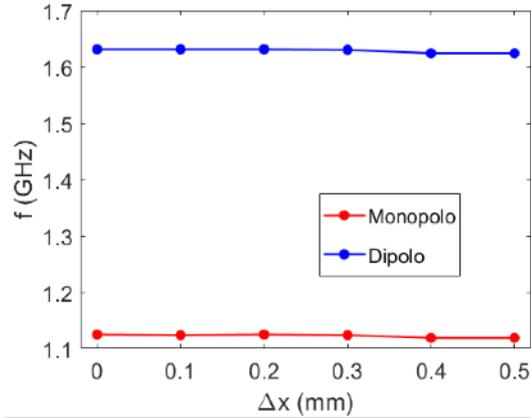
- Para valores de  $\Delta x < 0.4$  mm los parámetros de funcionamiento del BPM se mantienen estables, se observa una ligera disminución en el  $(R/Q)$  del modo dipolar
- Para valores de  $\Delta x \geq 0.4$  mm, el  $(R/Q)$  del modo dipolar cae prácticamente a cero debido a que se pierde el contacto entre una de las pestañas y la antena del acoplador coaxial

<b>Rangos de funcionamiento requeridos para el BPM</b>	
$f_{dip} \in [1.610, 1.638]$ GHz	$(R/Q)_{mon} > 12.8 \Omega$
$Q_{L,mon} > 31.8$	$(R/Q)_{dip}^{10mm} > 1.15 \Omega$
$Q_{L,dip} > 46.1$	$S_{12}(f_{dip}) < -33$ dB

# IV. Análisis de las tolerancias del BPM

## F) Estudio del desalineamiento de los ejes de la beam pipe y la cavidad reentrante

Variación de  $\Delta x$ :





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# Thank you for your attention

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[laura.pedraza@ific.uv.es](mailto:laura.pedraza@ific.uv.es) [daniel.gonzalez-iglesias@uv.es](mailto:daniel.gonzalez-iglesias@uv.es)

