DESIGN OF A SUBMICRON RESOLUTION CAVITY BPM FOR THE ILC AND CLIC MAIN LINAC

Nikolay Solyak

on behalf of the team:

N. Solyak, A. Lunin, M. Wendt, V. Yakovlev – Fermilab

Nicolas Chritin, Lars Soby - CERN

Nobuhiro Terunuma, Junji Urakawa - KEK

Introduction

- The proposed CERN linear collider (CLIC) requires very precise measurement of transverse beam position in order to preserve extremely low emittance during the beam transport through the ML
- An energy chirp within the bunch train will be applied to measure and minimize the dispersion effects, which also requires high resolution (both in a time and space) of BPM along the beam-line.
- The design is based on a well known TM_{110} selective mode coupling idea [*see, for example, V. Balakin, et al, Proc of PAC1999*].

The BPM design process consists of several aspects:

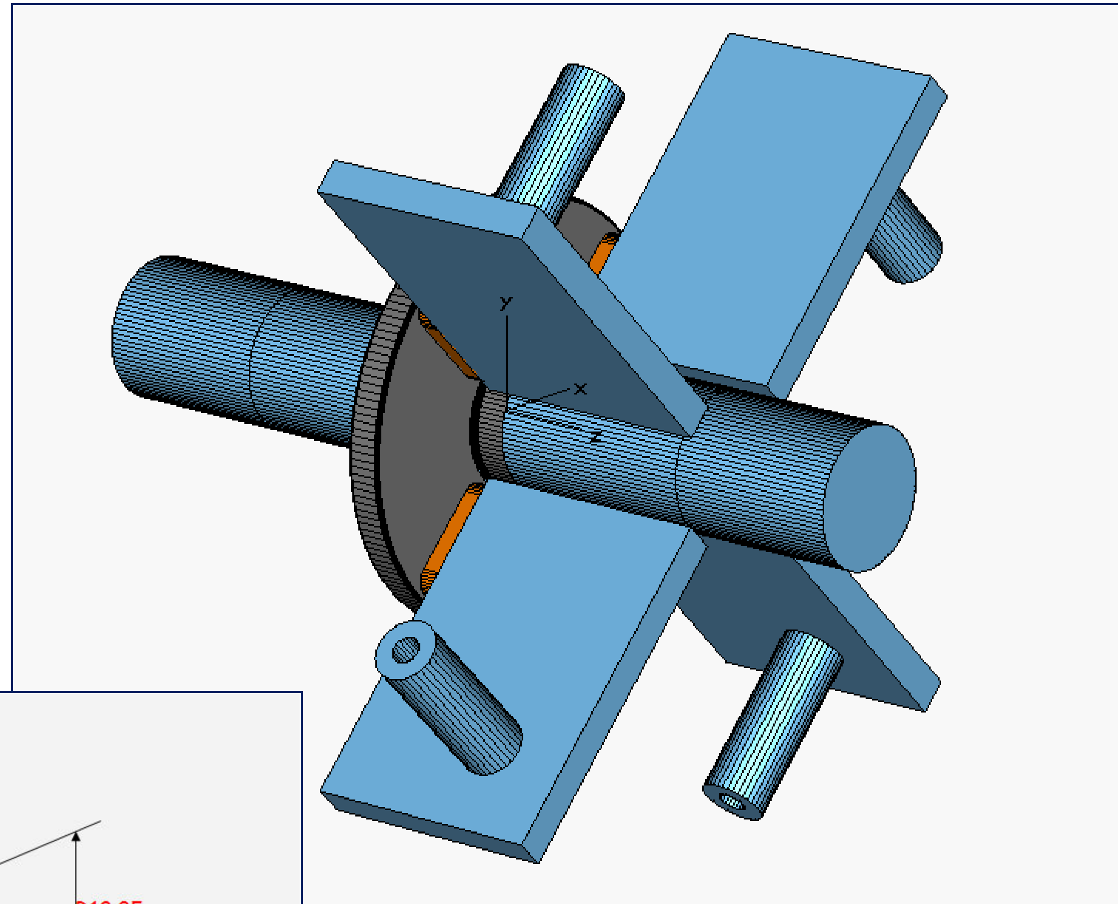
- *cavity spectrum calculations*
- *estimation of parasitic signals of monopole, dipole and quadroupole modes.*
- *orthogonal ports cross-coupling calculation and finally*
- *analysis of the mechanical tolerances of the geometric structure.*

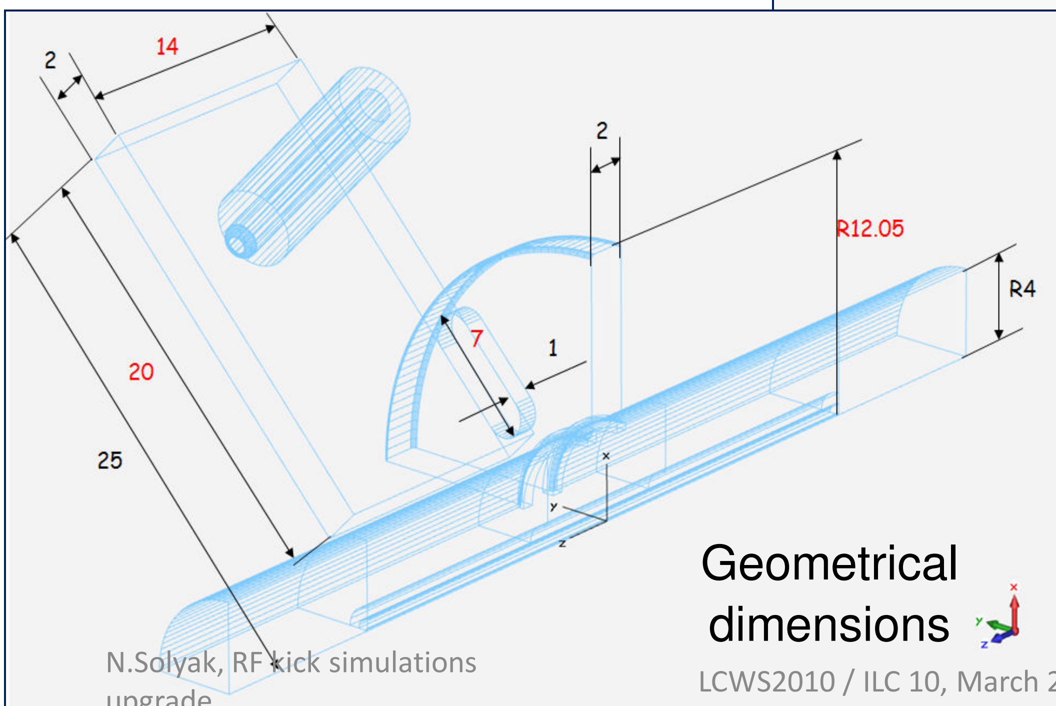
CLIC / CTF Main Linac BPM

	CLIC	CTF
Nominal bunch charge [nC]	0.6	?
Bunch length (RMS) [μm]	44	?
Batch length, bunch spacing [nsec]	156, 0.5	?, 0.333564
Beam pipe radius [mm]	4	4
BPM time resolution [nsec]	<50	<50
BPM spatial resolution	<0.1	<0.1
BPM dynamic range [μm]	±100	±100
BPM dipole mode frequency f_{110} [GHz]	14.0000	14.98962
REF monopole mode frequency f_{010} [GHz]	10.0000	8.993774

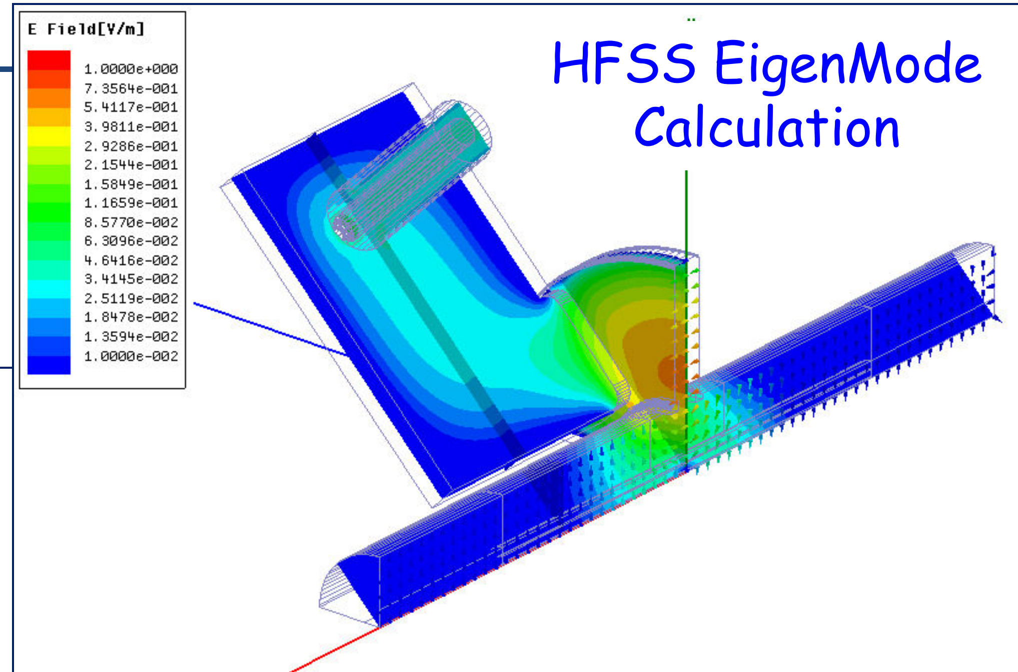
- **WG-loaded, low-Q X-Band design (Fermilab-CERN)**
  - **Q_l ~ 300, resonator material: 304 stainless steel**
  - **CTF prototype includes a monopole mode reference cavity (same frequency)**
  - **~50 nsec time resolution, <100 nm spatial resolution**
- **EM design, tolerances, signal characteristics, etc. finalized.**
- **CTF prototype mechanical design underway (see next slides).**

Concept of the sub-micron resolution cavity type BPM for CLIC (14 GHz)

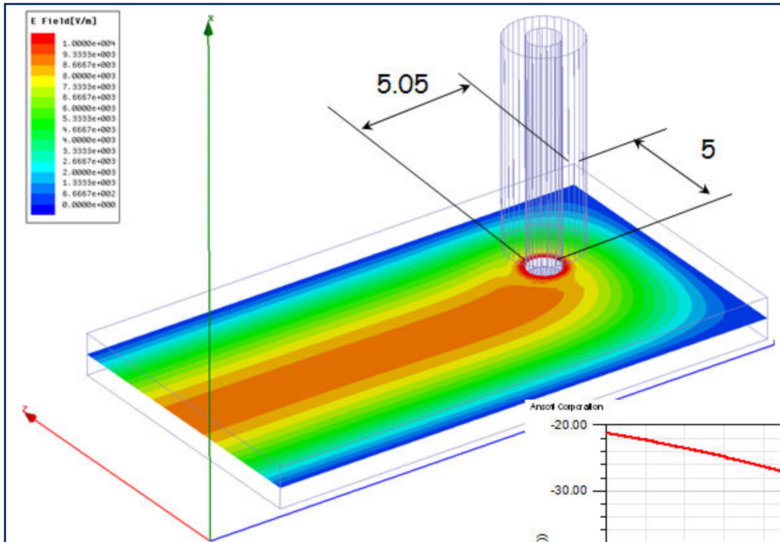


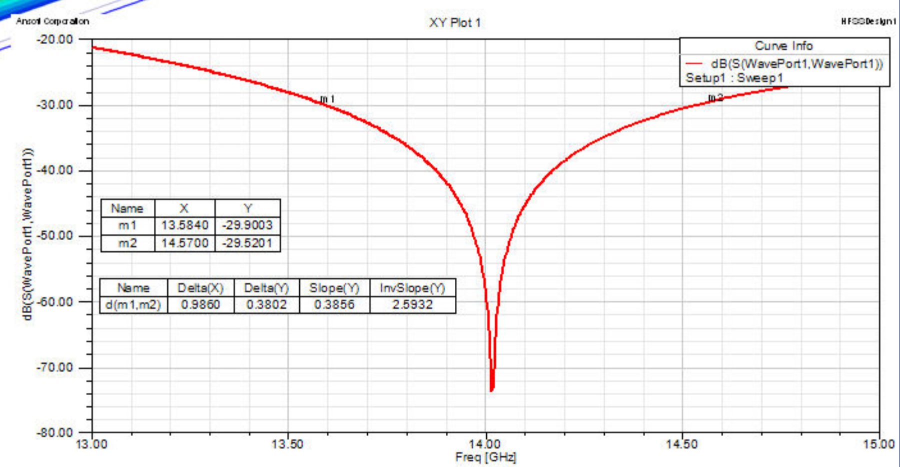


RF design



HFSS EigenMode Calculation





Waveguide to coaxial transition

14 GHz BPM cavity spectrum calculation

Mode Type		Freq. [GHz]	Q_{tot}[1], (Q_{ext})	R/Q, [Ω], [Ω /mm^2], [Ω /mm^4],	Output Voltage[2,3], [V], [V/mm], [V/mm^2]	Freq. Filter Rejection	Phase Filter Rejection[4]	Multi-bunch Regime Rejection
TM_{010}		10.385	380, (>1E9)	45	< 0.001	0.005	0.1	0.1
TM_{110}		13.999	250, (540)	3	17	-	-	-
TM_{210}		18.465	80, (100)	0.05	5	0.025	0.1	0.1
TM_{020}		24.300	680, (>1E9)	12	< 0.001	0.001	0.1	0.05
WG1	TM_{11}	12.285	6	-	3	-	-	-
	TM_{21}	12.285	6	-	0.3	-	0.1	-
WG2	TM_{11}	15.878	4	-	5	-	-	-
	TM_{21}	15.880	4	-	1.2	-	0.1	-
WG3	TM_{21}	21.610	7	-	-	-	-	-

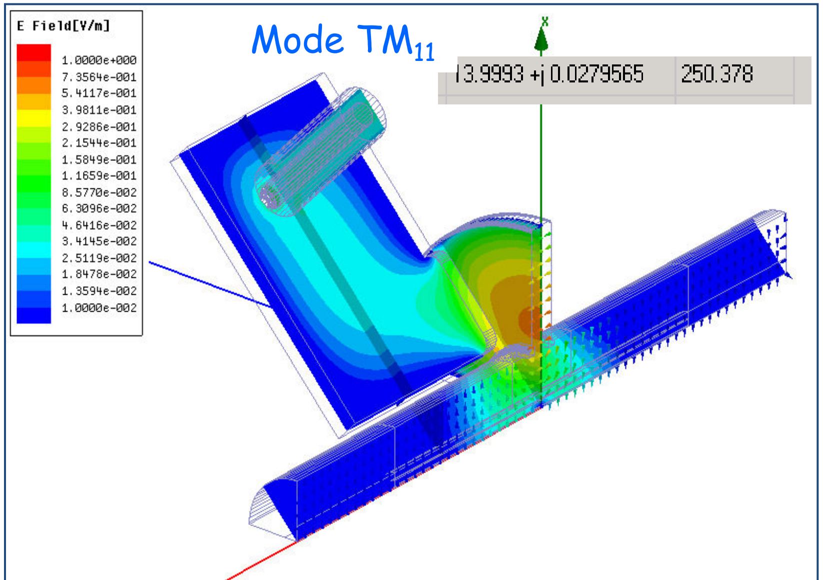
1 - Stainless steel material

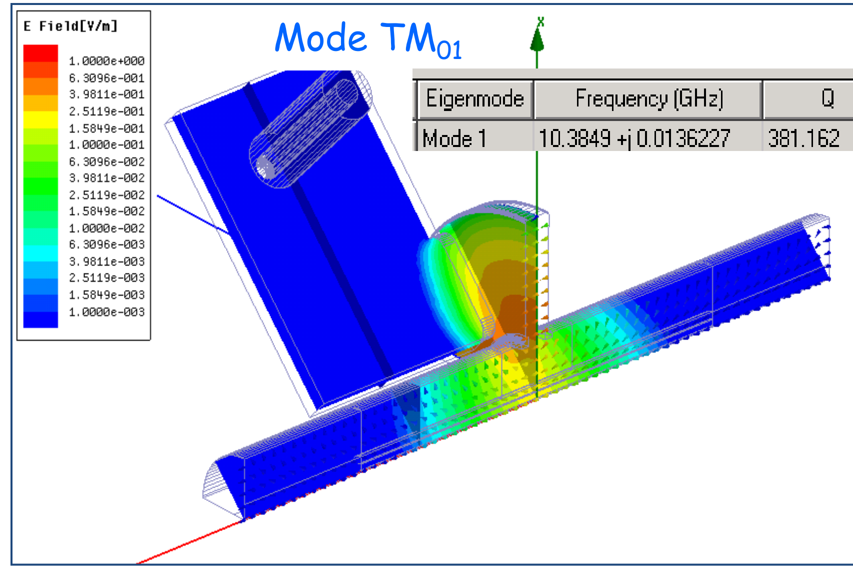
2 – RMS value; normalized to 1 nC charge

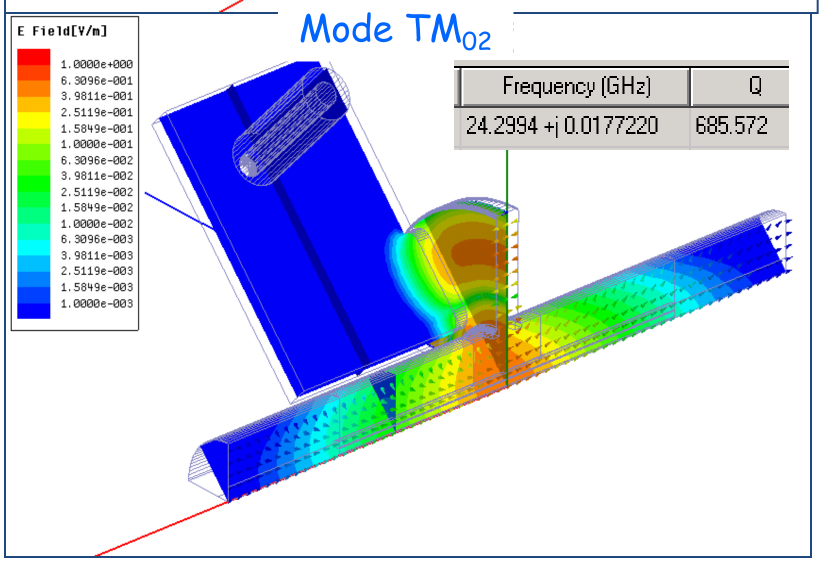
3 - Signals are from a single coaxial output at the eigenmode frequency. Multipole modes are normalized to 1 mm off-axis shift

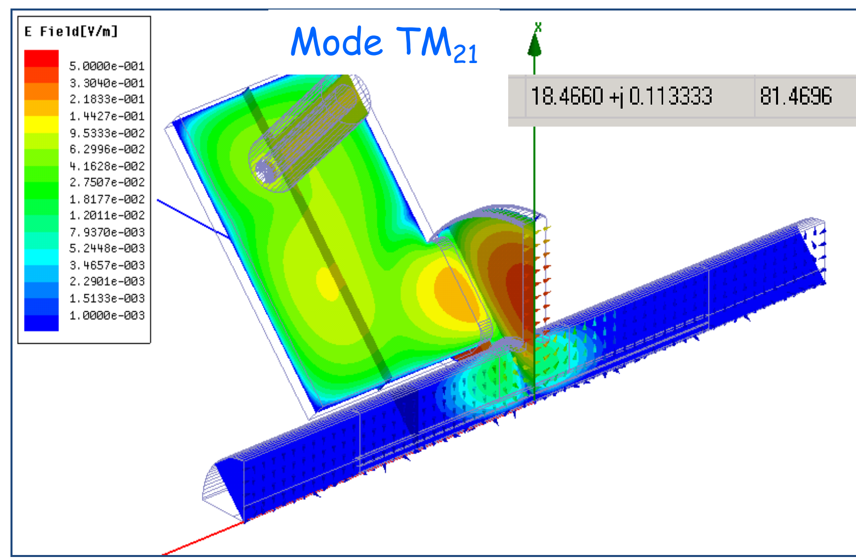
4 – If applicable

BPM Cavity Modes

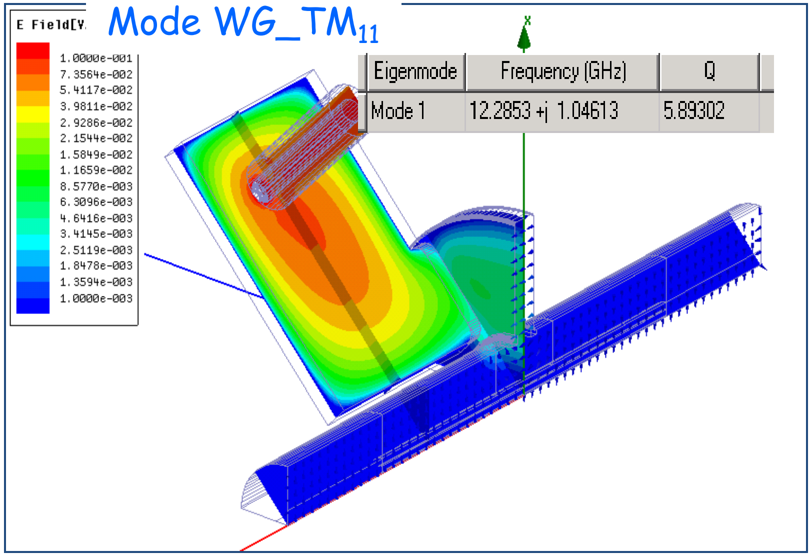


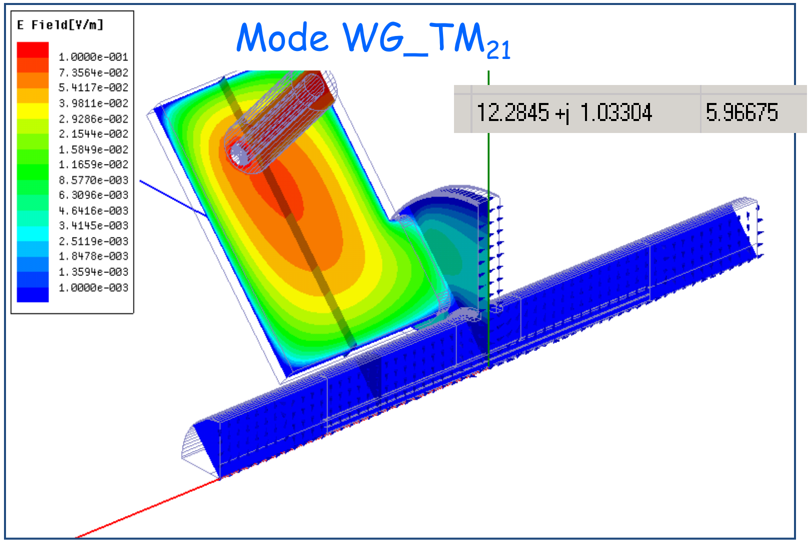


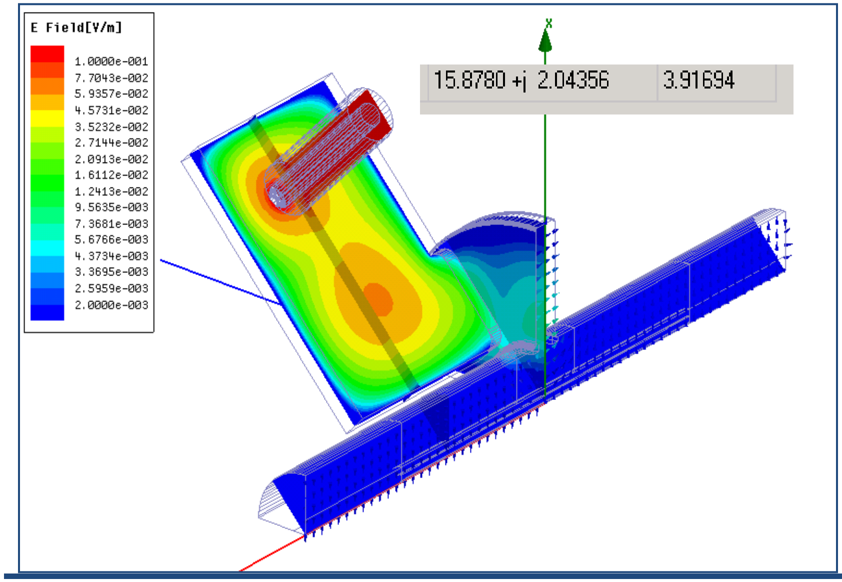


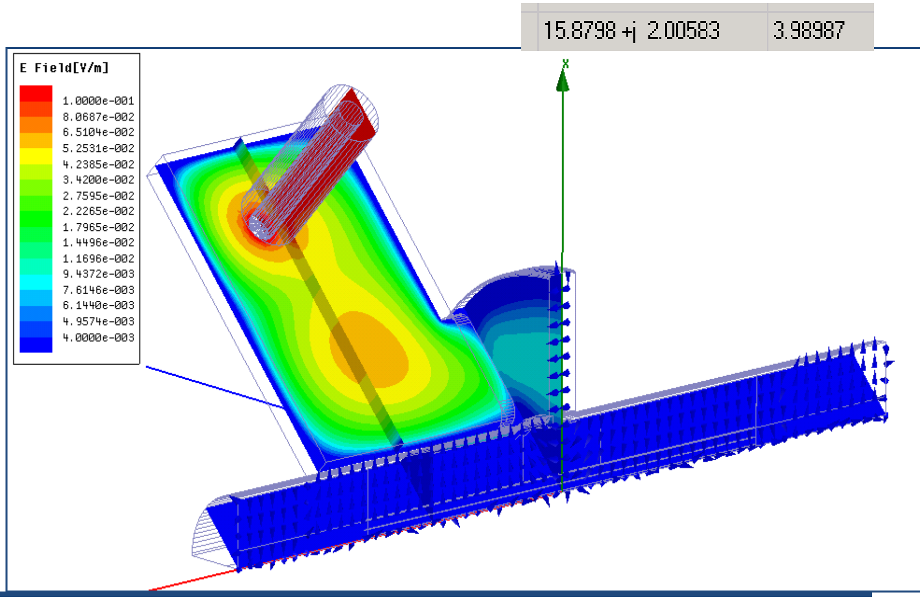


Waveguide Low-Q resonances

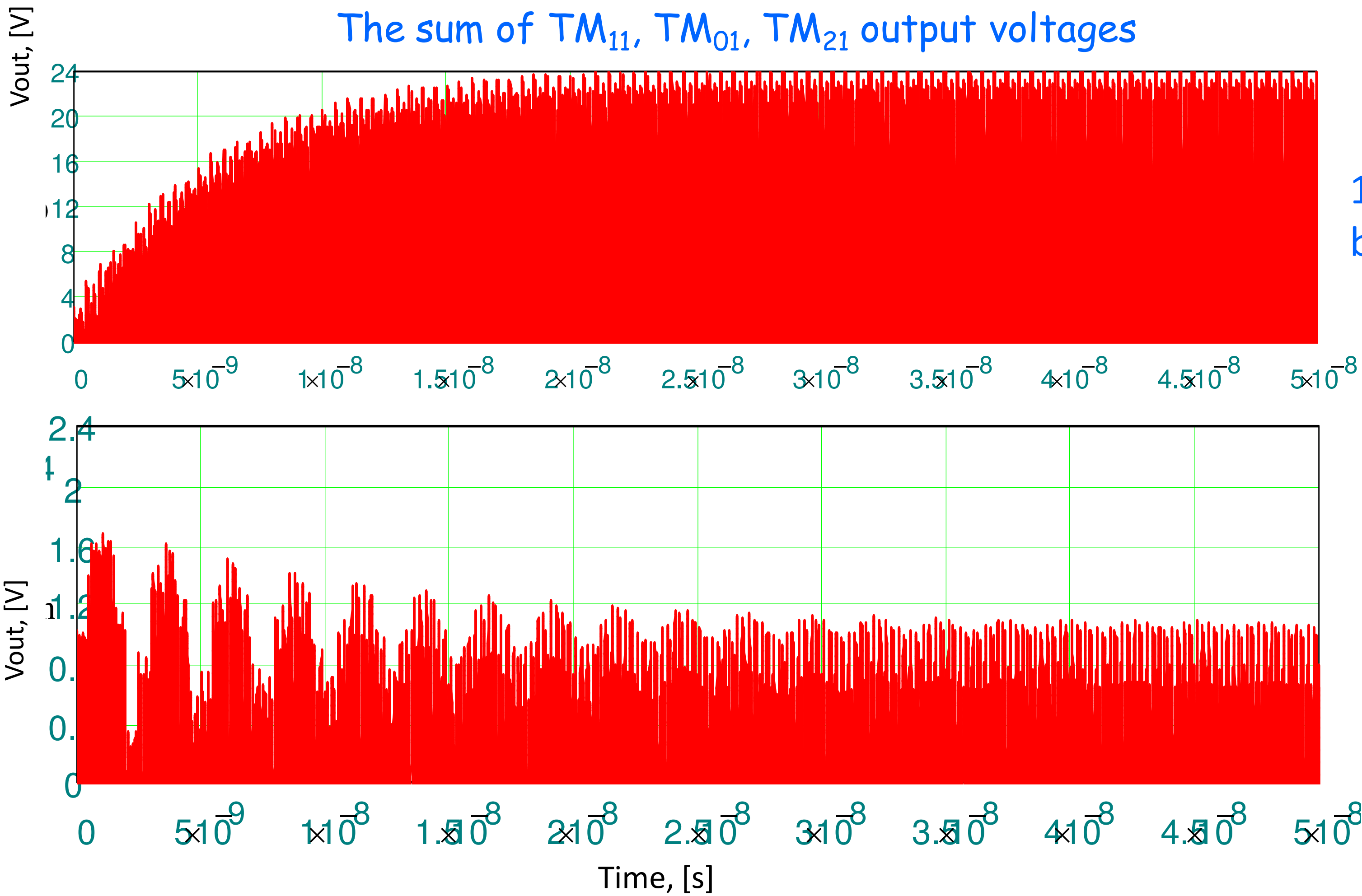








Multi-bunch Regime



100 µm off-axis beam shift

0.1 µm off-axis beam shift

Limitations of the 14 GHz BPM resolution due to TM_{010} & TM_{210} modes leakage.

Mode Type	Freq., [GHz]	Qtot[1]	Beam Shift, [μm]	Maximum Output Voltage[2,3] [mV]		BPM Resolution (Limited by TM_{010} & TM_{210} modes leakage), [nm]	
				Single bunch	Multi-bunch	Single bunch	Multi-bunch
TM_{010}	10.385	380	0	< 1		~ 40	~4
TM_{110}	13.999	250	0.1	2.4	24	-	
TM_{210}	18.465	80	100	< 0.18		~ 8	~ 1
TM_{210}	18.465	80	500	< 4		~ 200	~ 20

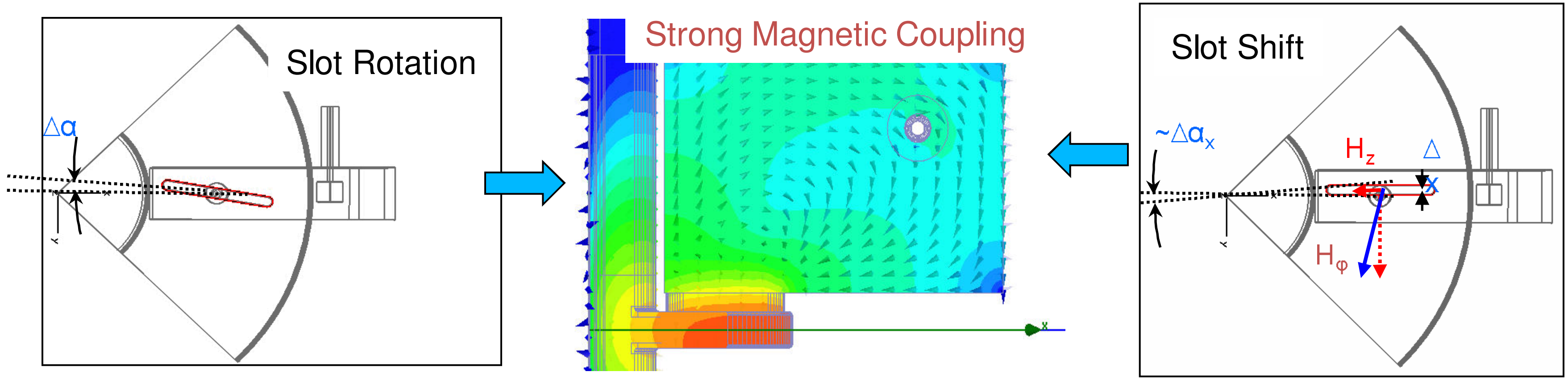
1 - Stainless steel material was used.

2 – RMS value; signal is normalized to 1 nC charge

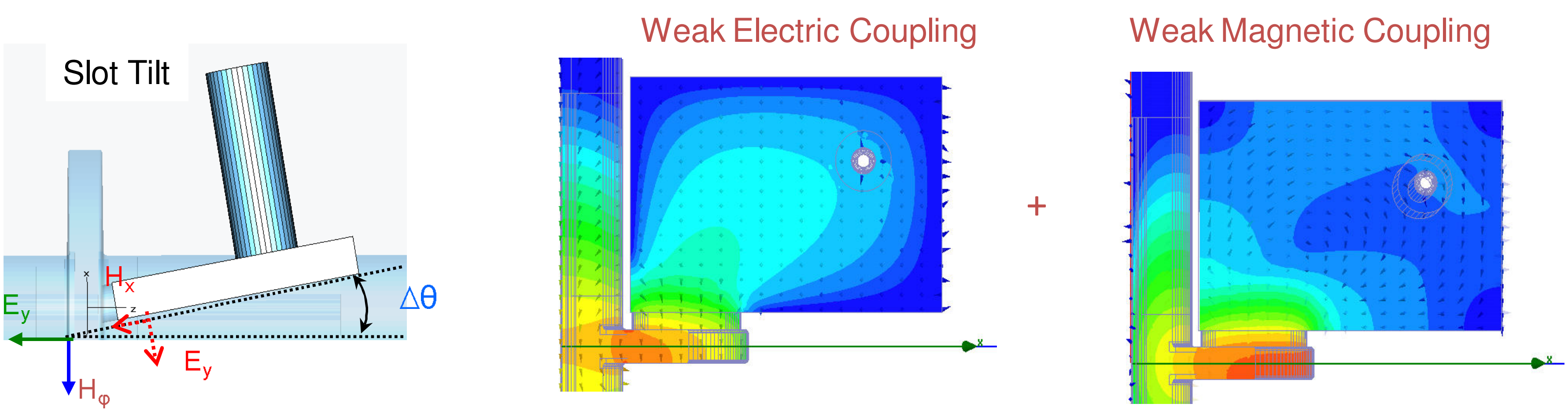
3 - Sum of the signals from two opposite coaxial outputs at operating frequency 14 GHz after all filters applied

Monopole Mode Coupling due to Mechanical Errors

1. Slot rotation causes the non zero projection of TM01 azimuth magnetic field component ($H\phi$) in the cavity to a longitudinal one (H_z) of TE10 mode in the waveguide. Small slot shift is equivalent to rotation with angle: $\alpha_x \sim \arctan(\Delta x/R_{slot})$. Therefore both slot rotation and shift cause strong magnetic coupling of monopole mode to waveguide.



2. Slot tilt causes the non zero projection of TM_{01} azimuth magnetic (H_ϕ) and longitudinal electric (E_z) filelds components in the cavity to a transverse (H_x) and vertical (E_y) components of TE_{10} mode in the waveguide. Because both H_x and E_y are close to zero near the waveguide wall tilt error causes the weak electric and weak magnetic coupling of monopole mode to waveguide.



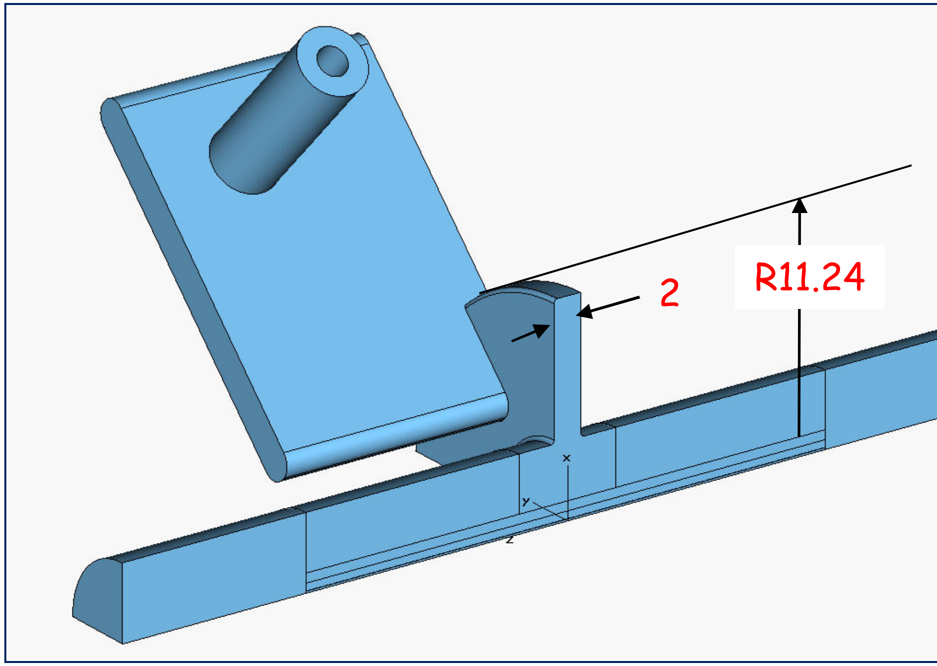
Limitations of 14 GHz BPM resolution due to TM_{110} modes cross-coupling.

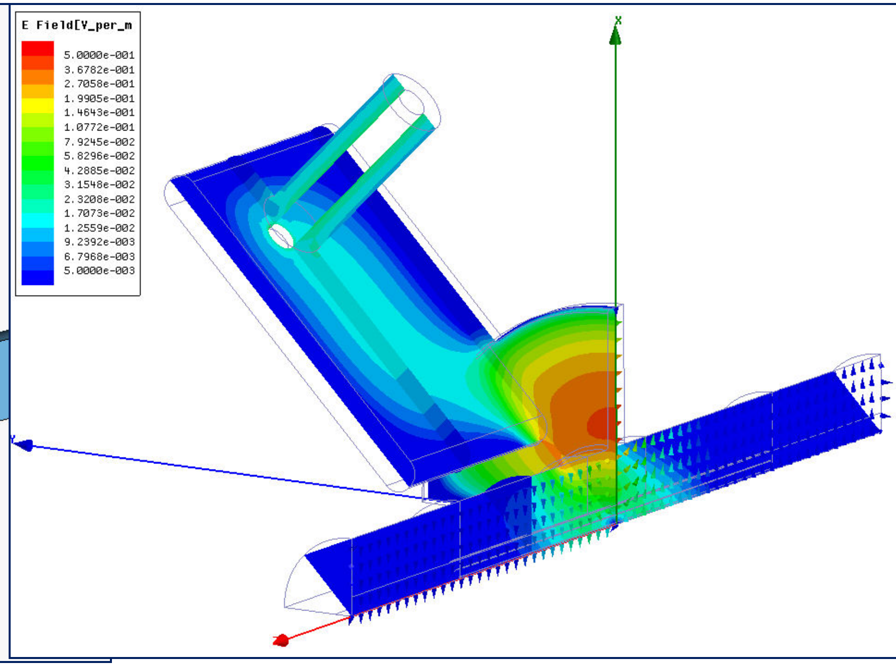
Mechanical Tolerances[1,2]	Cross Coupling -40 dB	Cross Coupling -30 dB	Cross Coupling -20 dB
Slot Rotation, [deg]	< 0.05	< 0.2	< 0.6
Slot Shift, [μm]	< 5	< 15	< 40
Max Dynamic Range , [μm]	100	25	10

[1] - In-phase signals reflection (worse case) is taken into account

[2] - The reflection from LLRF part is assumed less than -20 dB.

BPM cavity prototype for CTF (15 GHz)





no ohmic losses, Q_ext

Eigenmode	Frequency (GHz)	Q
Mode 1	15.0023 +j 0.0119015	630.270

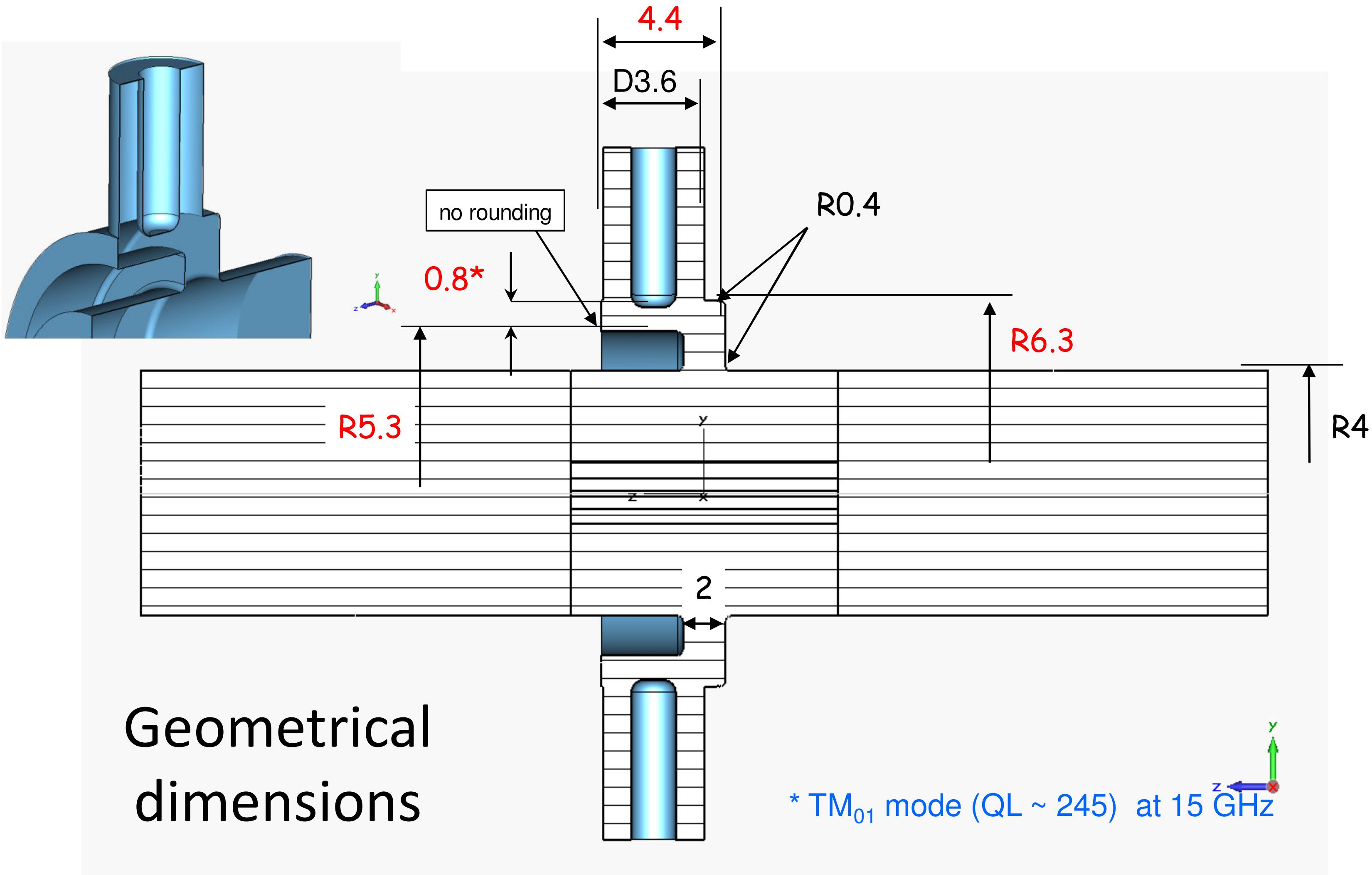
with ohmic losses (steel), Q_load

Eigenmode	Frequency (GHz)	Q
Mode 1	14.9855 +j 0.0286758	261.292

The output voltage is about the same as for initial 14 GHz BPM design :

V_out ~ 24 mV/µm (single bunch)

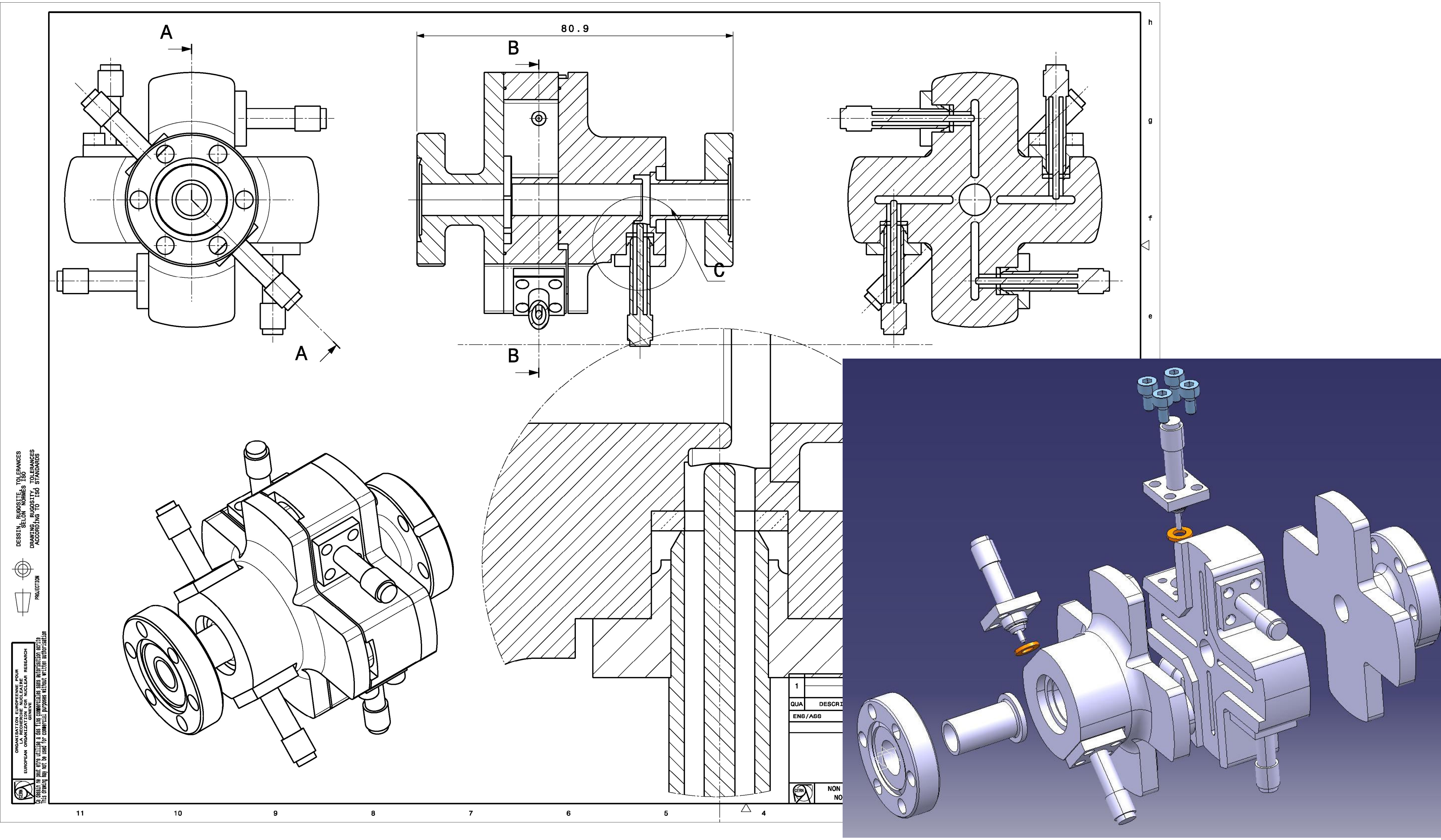
Monopole Cavity (15 GHz)



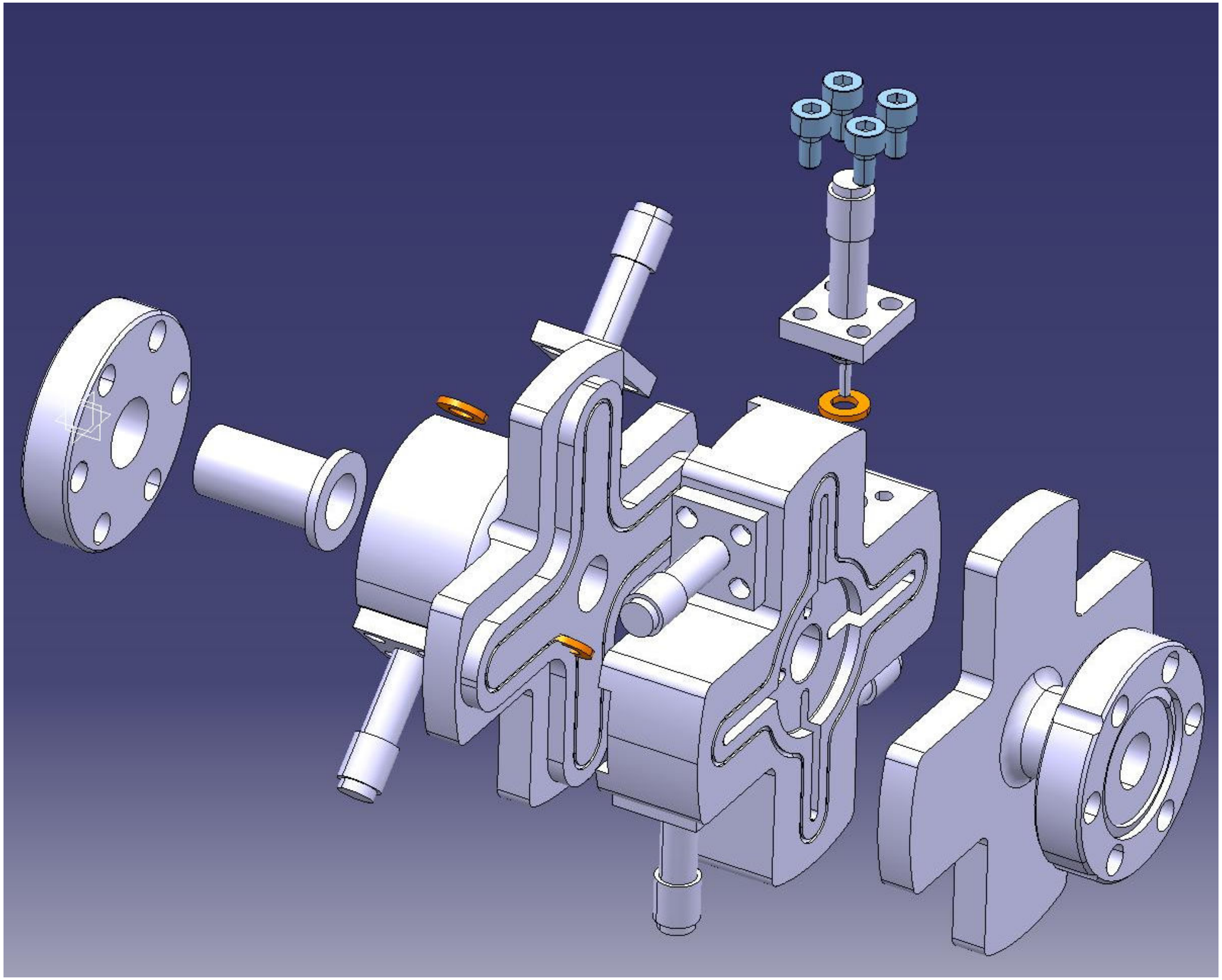
Geometrical dimensions

* TM_{01} mode (QL ~ 245) at 15 GHz

CTF Cavity BPM (preliminary!)

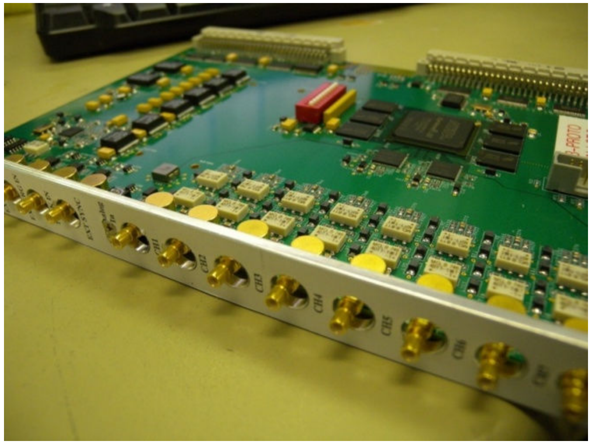


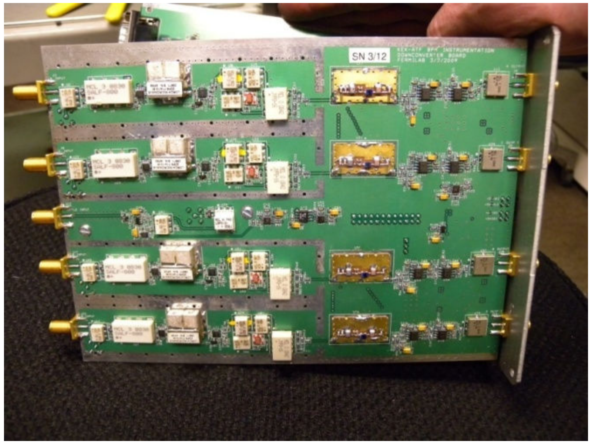
CTF Cavity BPM (cont.)

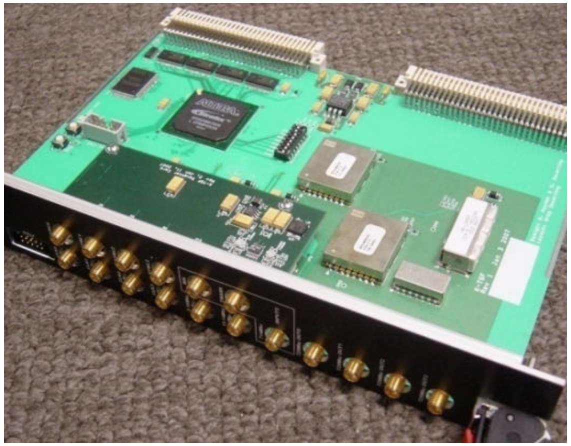


BPM Read-out System

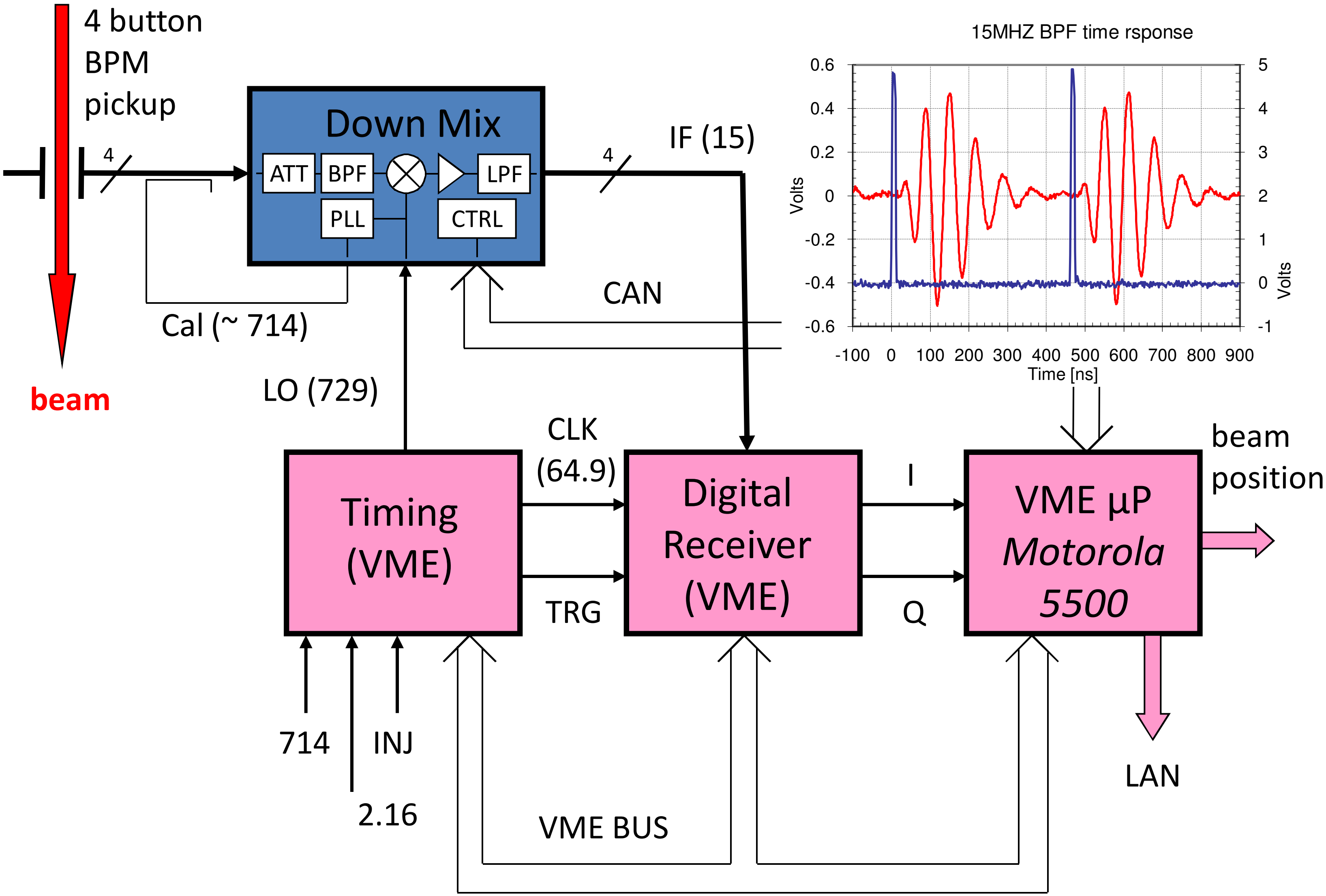
- Based on in-house developed analog & digital signal processing hard- and firmware
  - Implemented this June at the ATF damping ring (to a total of 96 BPMs)
  - Demonstrated <200 nm resolution (narrowband), <10 μm TBT resolution (broadband, ~400 nsec)
  - Integrated calibration system
- Modified versions to be applied for
  - Linac / transport-line button-style BPMs (electrons / hadrons)
  - Cavity BPMs, HOM signal processing, etc.







BPM Read-out Hardware (ATF)



Summary

- A X-Band cavity BPM R&D for the CLIC Main Linac and ILC has been initiated in collaboration with CERN
- Design is presented for a high resolution 14 GHz cavity BPM for CLIC project. After modifications it will built and tested at CTF3 (15 GHz)
- It operates in single and multi-bunch regimes with required time resolution.
- A submicron beam position resolution can be achieved with acceptable mechanical tolerances.
- BPM activities include detector and read-out systems.
  - *The prototype design operates at CTF bunch frequencies.*
- ILC/LC collaboration activities are focused on the KEK ATF damping ring BPM upgrade project.
  - *With minor modifications this read-out system can be applied to other BPM detectors and systems, also for HOM signals.*