



Elettra Sincrotrone Trieste

RF Plants status for E2.0

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** Retiring at the end of October

¹ Hired this year

² CST and HSFF simulation

³ DLLRF and interlock system

Elettra decommissioned, long shut down started July 4th 2025

Elettra 2.0 project: S6BA-E with 12-fold symmetry operating mainly at 2.4 GeV (400 mA). It will open to external user in 2027

Elettra 2.0 machine installation will start Spring 2026

Elettra 2.0

FERMI

Seeded FEL (HGFG), 1.5 (1.8) GeV, 10 Hz (50 Hz) – First Lasing Dec.13, 2010
Open to external users since 2012 (FEL-1) (100-20 nm, 12 - 62 eV) and 2015 (FEL-2) (20-4 nm, 62 - 320 eV)

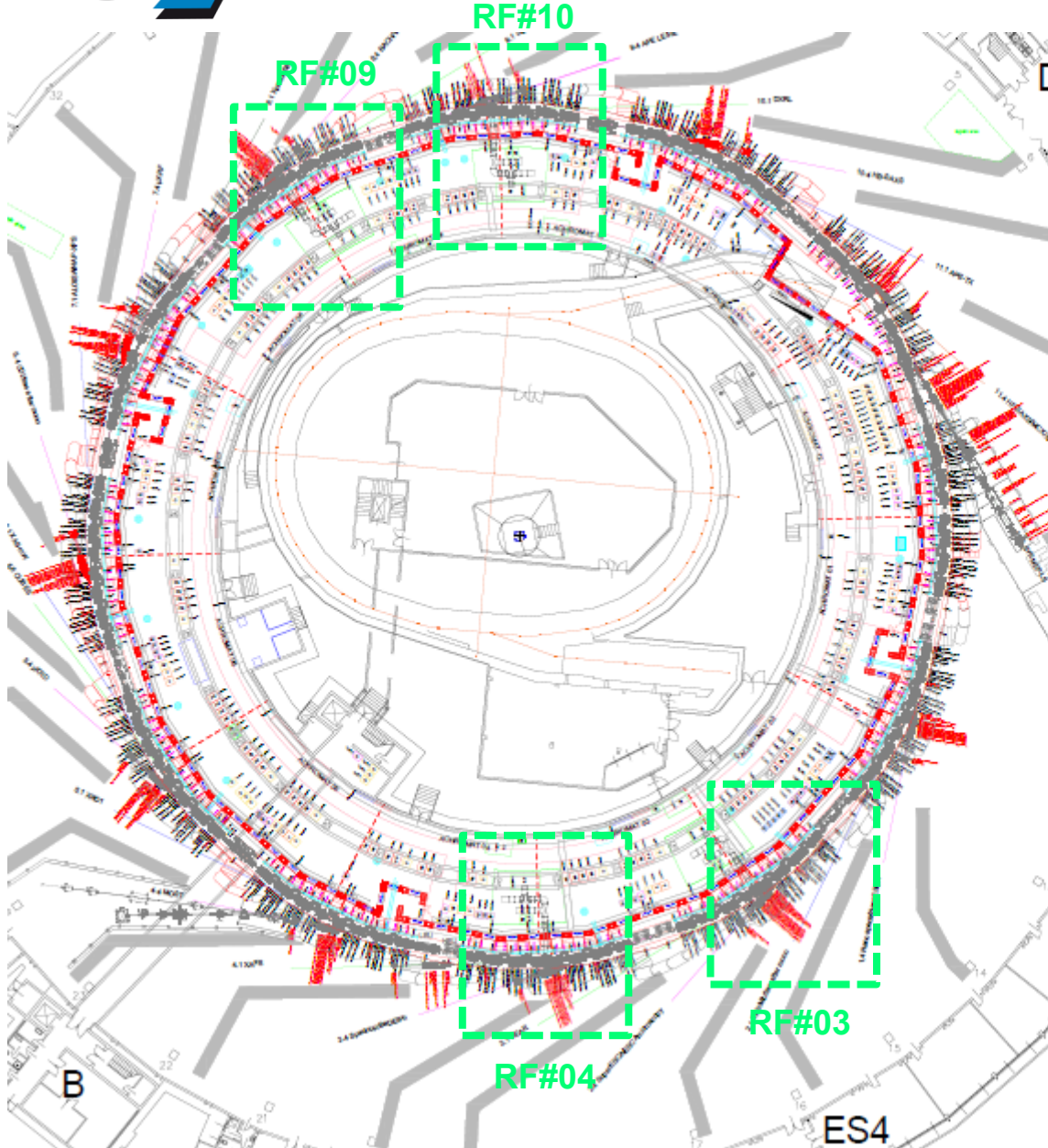
EUROPE





Elettra
Sincrotrone
Trieste

Elettra 2 parameters



Parameters	Value	Unit
Energy	2.4*	GeV
Circumference	259.2	m
Emittance	212	pm rad
Current	400	mA
Momentum compaction	$1.2 \cdot 10^{-4}$	
RF frequency [MHz]	499.654	MHz
Harmonic number	432	
Energy spread	$1.0 \cdot 10^{-3}$	
Energy losses*	620	keV
Beam Power	248	kW
Accelerating voltage [MV]	2.0	MV
Number of RF cavities	4	
Copper losses/ each cavity***	39 (52)	kW
Beam power/each cavity	62	kW
Total power/each cavity***	101 (120)	kW

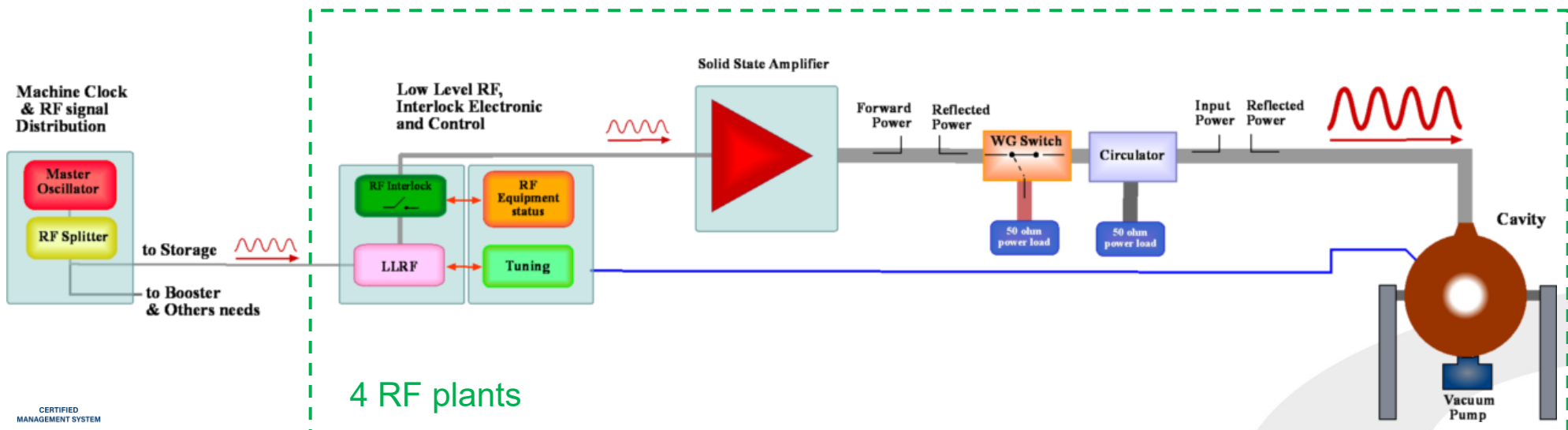
* For some time also at 2 GeV

** Including all IDs and SuperBends

***Maximum attainable value in round brackets

4 RF Plants with the
same Elettra cavities

- ✓ **RF Distribution** : Simplification of the RF signal distribution is foreseen using COTs passive splitters. No more RF signals in control room. All the RF cables will be replaced. Same master oscillator: R&S SMA100 with High Stability option.
- ✓ **4 Storage Ring RF Plants:**
 1. **New DLLRF**: project under development in house
 2. **New Digital RF Interlock**: project under development in house
 3. **130 kW Solid state amplifiers**: installed and already in operation for Elettra
 4. **New wave guide WR1800** run towards the cavity: all components already in house
 5. **Same Elettra cavity**: CBM due to HOMs instabilities investigation started
 6. **Booster RF power upgrade** completed: IOT amplifier installed



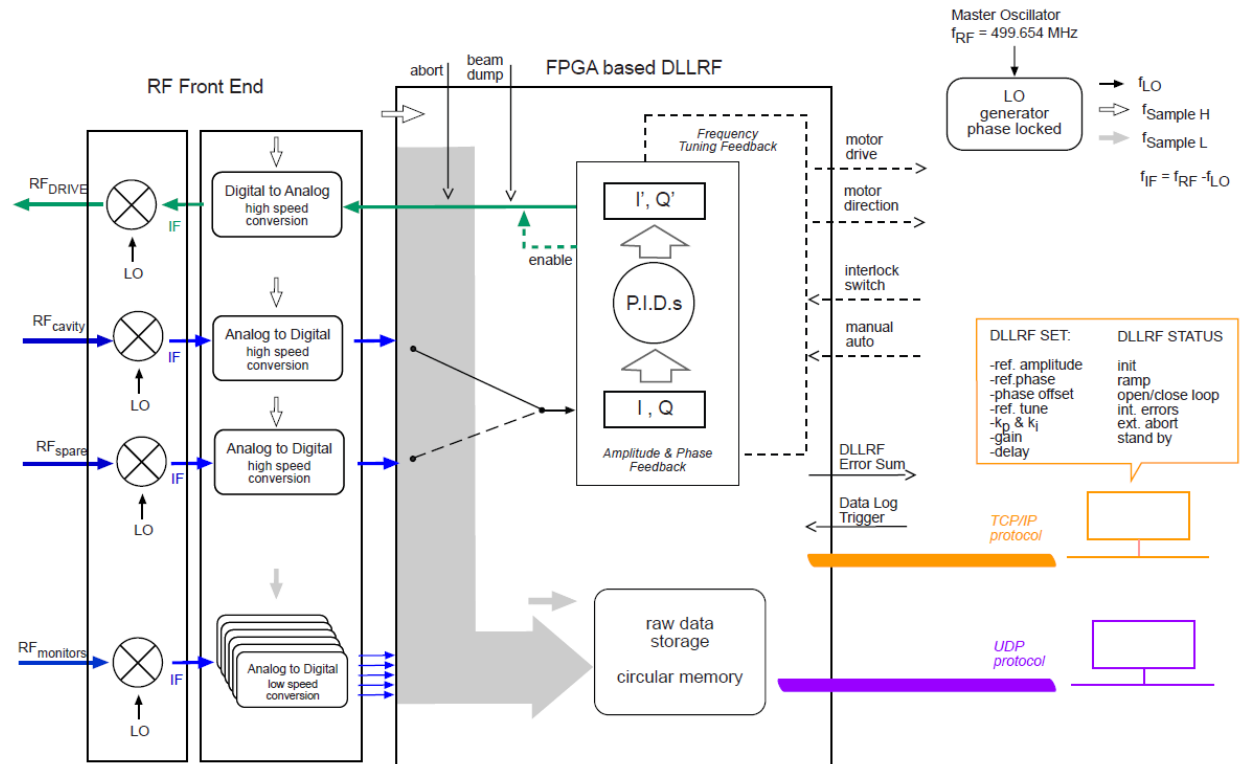
DLLRF : in house development

DLLRF “pizza Like” solution with three main units:

- ✓ **Front-End** to down-convert the 500 MHz signal to 18 MHz IF signal, passive board;
- ✓ **Local Oscillator** and signal clock generator board;
- ✓ **Logic unit “carrier board”** based on SOC FPGA + DAC board & up-conversion + I/O board. In addition it hosts fast DAQ data acquisition, triggered in synch with the storage ring turn of the row data at 10 GB/s to enhance RF operation and diagnostic

Loop parameters	Amplitude	Phase
Stability after transient	$\pm 0.1\%$	$\pm 0.1^\circ$
Accuracy	$< 0.5\%$	$< 1^\circ$
Resolution	$< 0.05\%$	$< 0.05^\circ$
Set points range	$> 5\text{ dB}$	$> 60^\circ$
Dynamic range	$> 26\text{ dB}$	360°
Bandwidth	$> 20\text{ kHz}$	$> 20\text{ kHz}$

Frequency Tuning Loop	
Dead band	$\pm 100\text{ Hz}$
Hysteresis	$\pm 500\text{ Hz}$
Resolution	$< 100\text{ Hz}$
Dynamic range	$\pm 200\text{ kHz}$
Speed	100 Hz/s to 700 Hz/s



DLLRF : design choices

Front –End (non IQ sampling) and Local Oscillator design:

Chosen frequencies:

$$f_{RF} = 499.654 \text{ MHz}$$

$$f_{IF} = f_{RF} \frac{1}{27} = 18.506 \text{ MHz}$$

$$f_{LO} = f_{RF} \frac{26}{27} = 481.148 \text{ MHz}$$

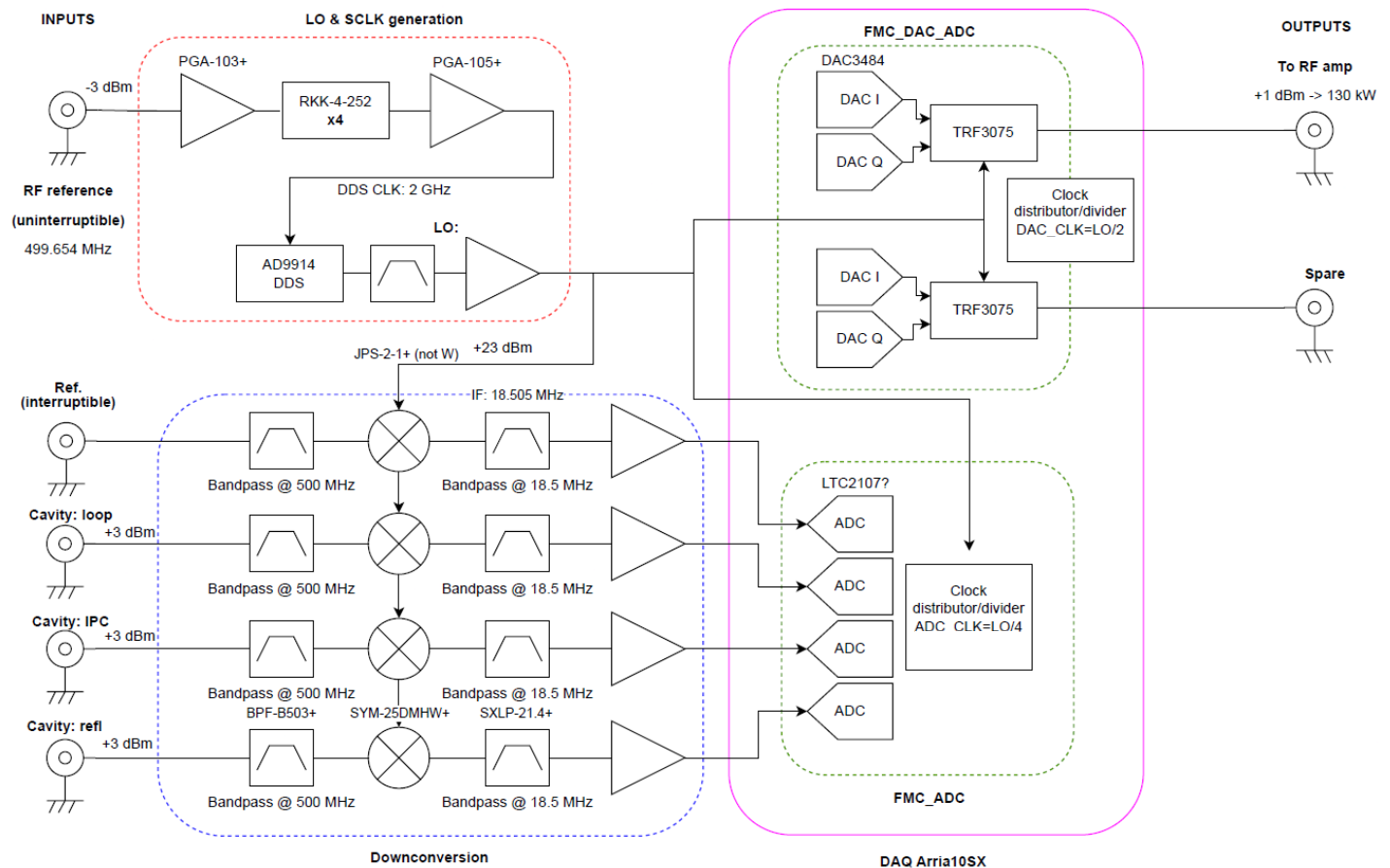
$$f_{ADC} = f_{RF} \frac{261}{274} = 120.287 \text{ MHz}$$

and given this choice

$$f_{revolution} = f_{IF} \frac{1}{16} = 1.1566 \text{ MHz}$$

f_{IF} is therefore a multiple integer of the revolution frequency f_{rev} .

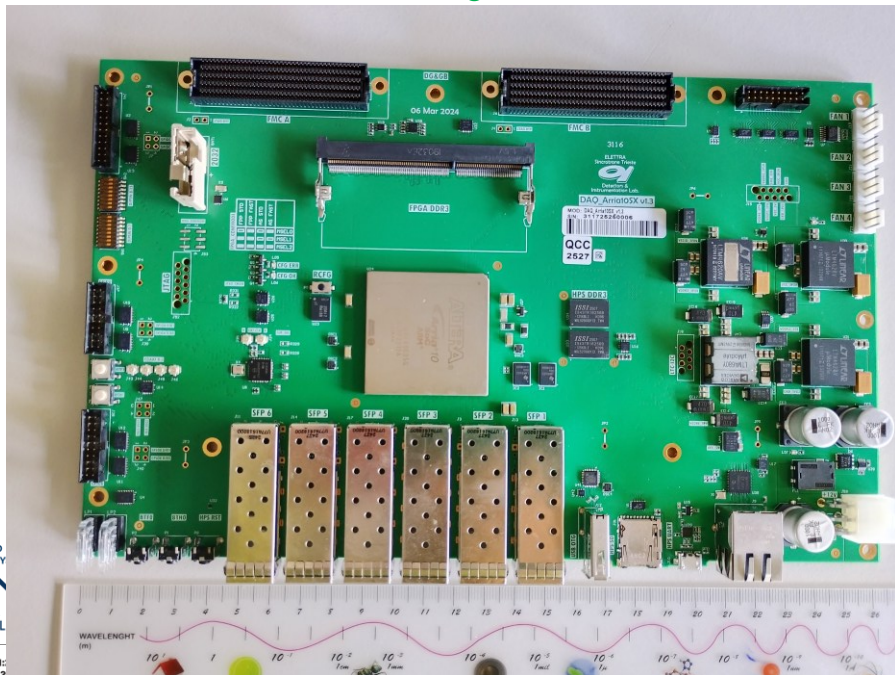
Turn by turn RF row data log will be done.



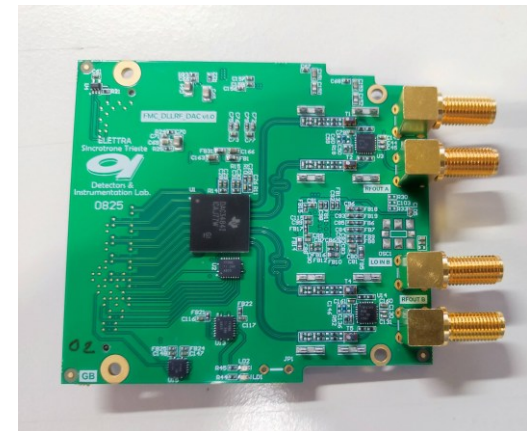
DLLRF : design choices

- ✓ DLLRF will use a considerable part of hardware ARRIA 10SX board and firmware developed in-house for the **eBPM unit**.
DAQ Arria 10SX hardware is a SOC & FPGA unit, based on Intel Arria 10 SoC FPGA with ARM processor inside, 217.000 logic elements and 1.523 DSP blocks. On board memory 8 GB of DDR3 , buffers – raw for data post off-line collection, triggered with beam dump events or by user.
- ✓ Two FMC boards – 4 channels each - for the IF RF signals:
 DLLRF firmware : 4 CHs OUT for RF output signal, room for spares;
 4 CHs IN for the IF signals to be digitalized;
- ✓ One board for 16 in - 16 out digital signals: frequency tuning motor signals
 and external abort – beam dump
- ✓ eBPM unit is full integrated for the E2.0 remote control
 and fast data acquisition → 1 GB/s and 10 GB/s

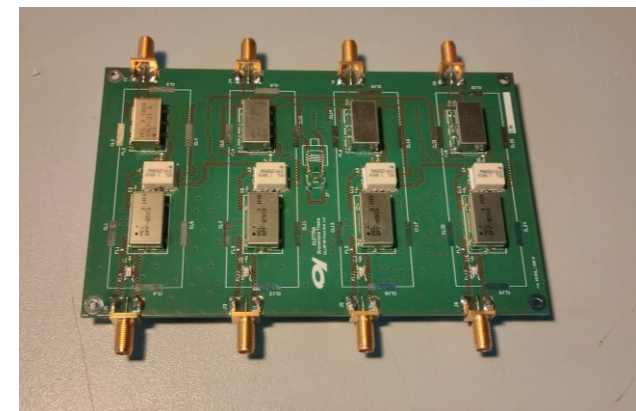
DAQ Arria 10SX digital board



DAC board

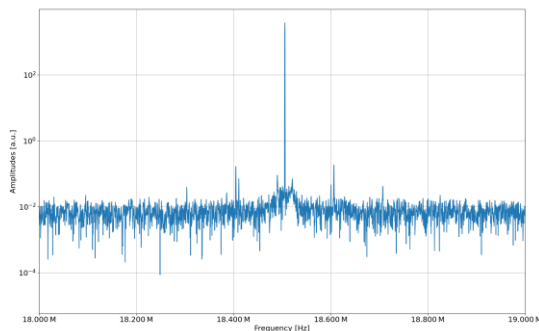


500 MHz to 18 MHz FE board.
Passive board – single unit

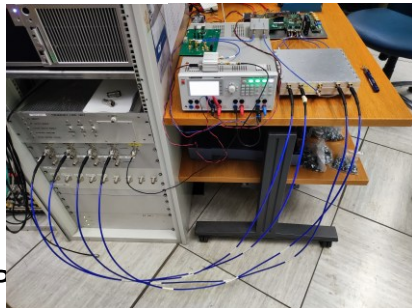
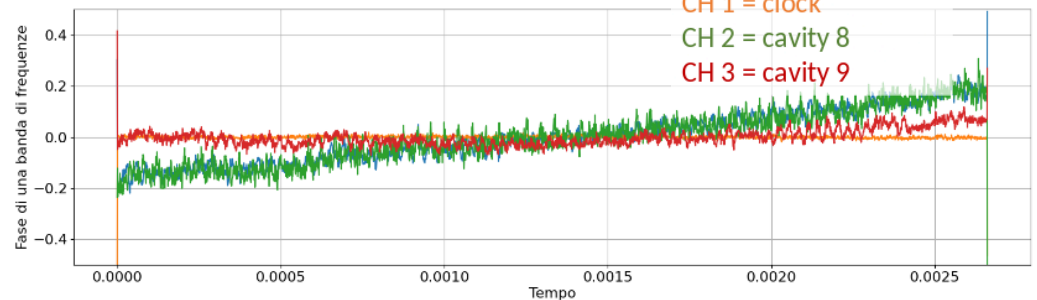
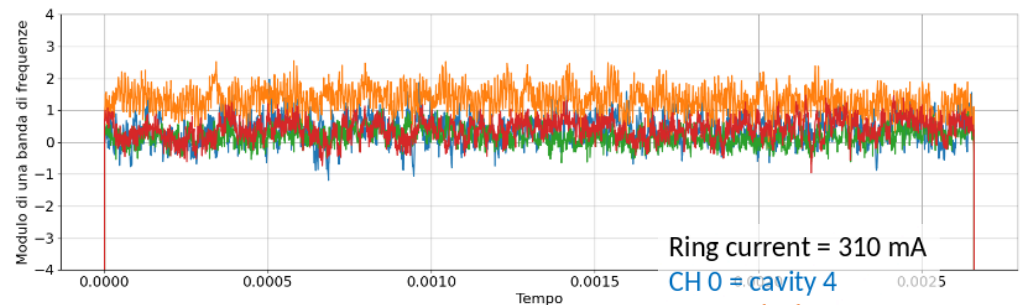


DLLRF : Test and status

- ✓ DLLRF carried board tested and ready.
- ✓ Front End prototype board + LO & SLCK generator board + FPGA board data acquisition tested on real RF signals “cavity+beam” last June.
- ✓ The first FE pre-series board under test these days.
- ✓ The first LO pre-series under design and realization within end of October.
- ✓ Modulator prototype board will be tested beginning of November.
- ✓ DLLRF firmware under development.
- ✓ DLLRF remote control firmware and DAQ ready (same as eBPM board)
- ✓ **First DLLRF unit pre-series in December this year in the RF power lab (dry run).**

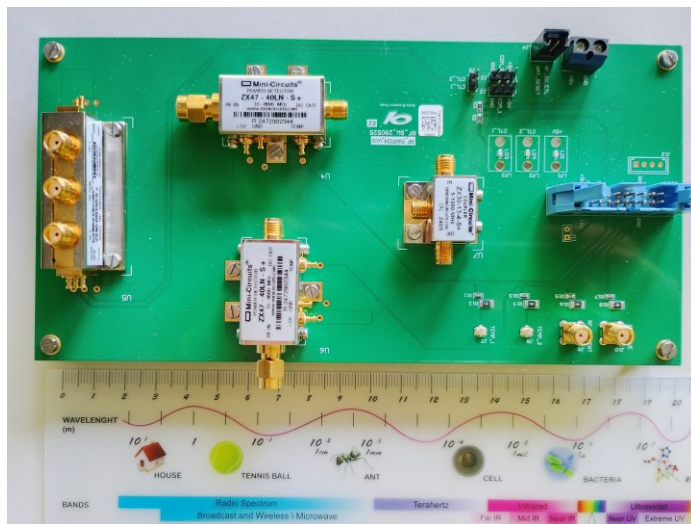


First data: 18.5
MHz IF signal
sampled data.
Modulations at
 ± 100 kHz and
 ± 15 kHz occur.

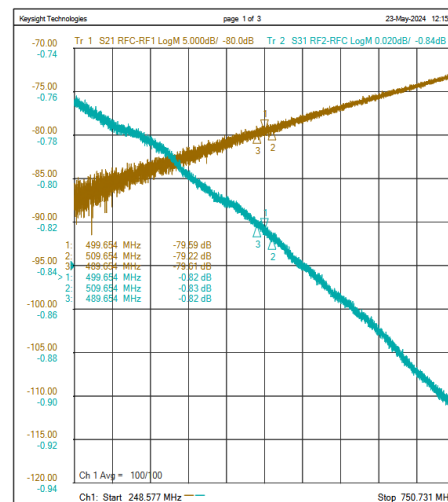


RF Interlock Unit

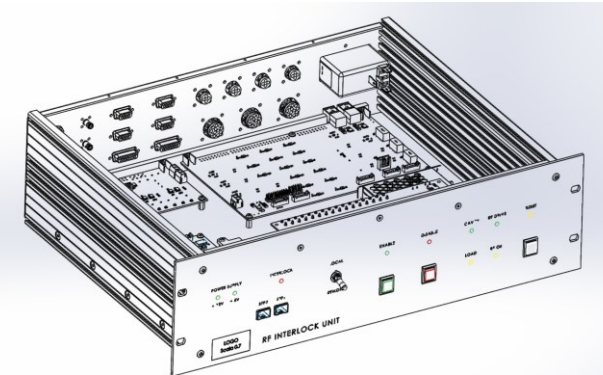
- ✓ RF plant interlock and DLLRF are deployed on two different and separate systems.
- ✓ All relevant RF plant variables and status data – more than 20 PV (vacuum pressure, flow switches, arc detectors, etc) are monitored by a FPGA based unit (evaluation board).
- ✓ Any failure triggers the fast RF switch that stops the RF amplifier driving signal.
- ✓ At the same time the RF plant failure status is delivered to the Machine Protection System via optical fiber to safely dump any stored beam.
- ✓ The implemented RF switch is the **ZX80-DR230** from Mini-Circuits among several possibilities (HMC546MS8G Analog Devices, GRF6011 Guerrilla RF, SKY12255-708LF Skyworks). **Fail-safe** + RF connectors already assembled.
- ✓ RF Switch position feedback will be given by dedicated power detector ZX47-40 from Mini-Circuits



RF switch to protect and interlock the RF plant



RF switch performances @ 500 MHz
Open path isolation > -79 dB
Close path insertion loss = 0.83 dB
Return loss > 17 dB

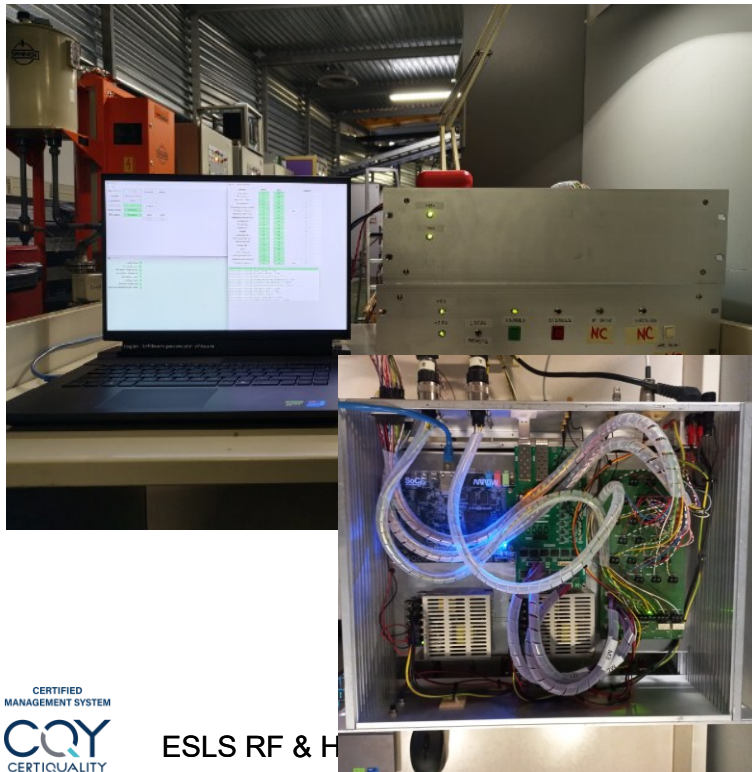


Interlock data monitoring unit

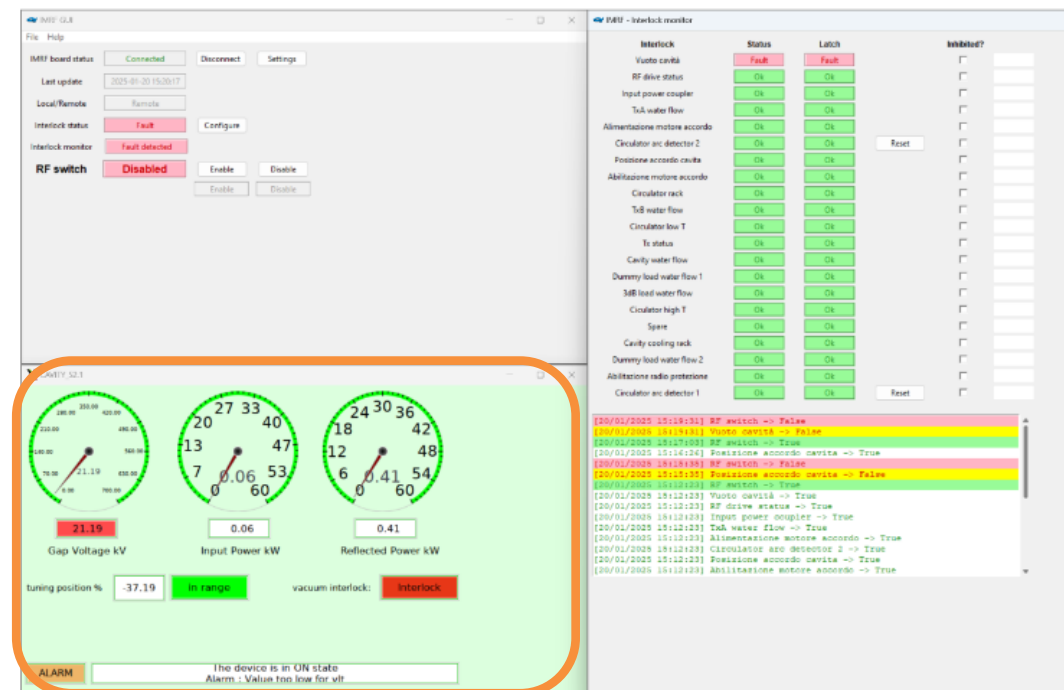
RF Plant Interlock test and status

- ✓ RF plant interlock prototype has been tested on real data last March on one RF plant of Elettra during user operation.
- ✓ All the Elettra RF interlock signals have been duplicated because the test shall have no impact on the machine operation.
- ✓ Dry test on each interlock signal was OK. Firmware ready.
- ✓ “Mass production” of the RF switch and interlock data acquisition units started.
- ✓ The RF interlock system pre-series will be tested in RF lab within December.

RF interlock: RF switch (bottom) and digital board (top) units in test on one plant in Elettra during user operation



RF interlock based on FPGA board user interface. Dry run on each interlock is OK. The orange square highlights the analogic RF interlock data implemented in the Elettra control room.



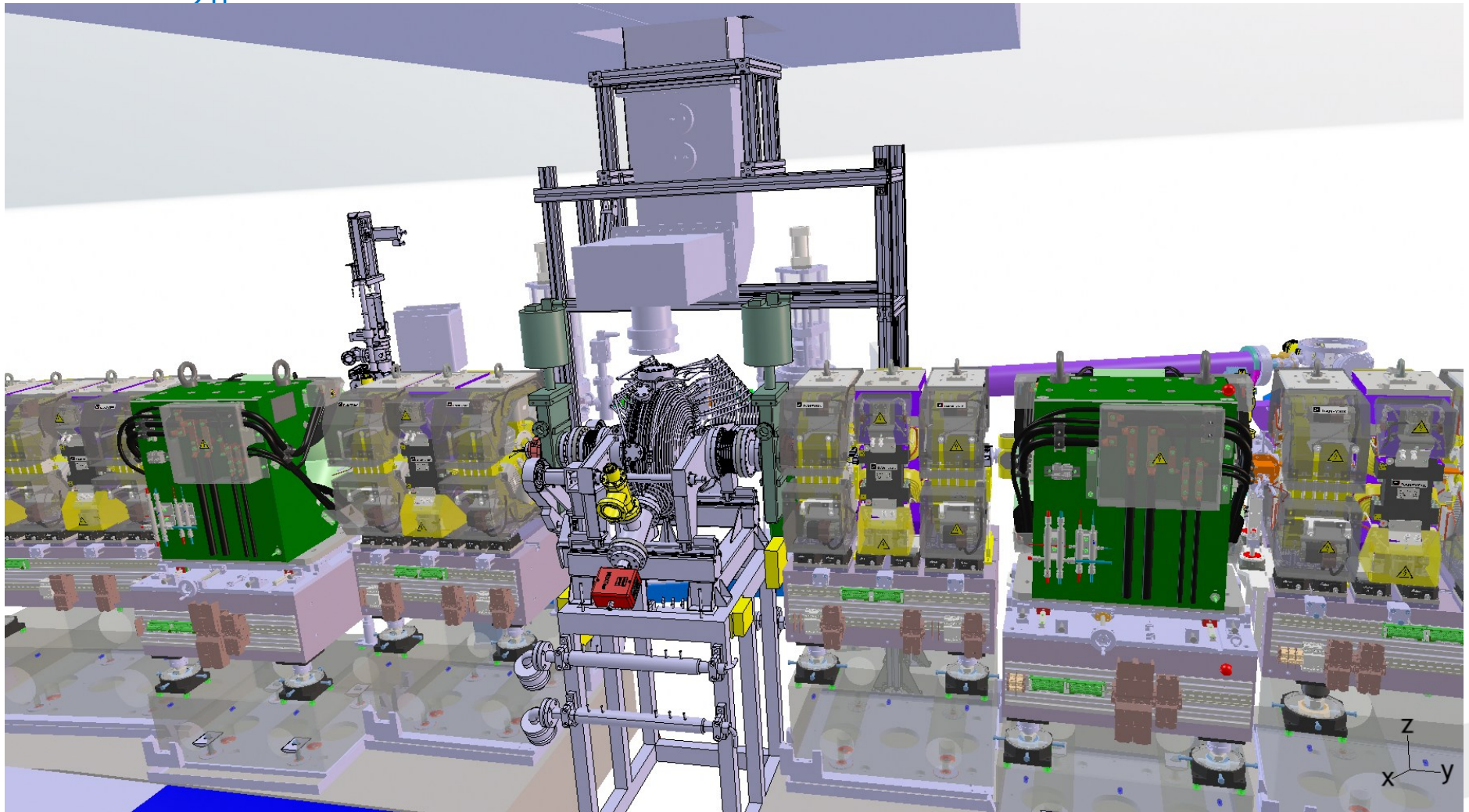


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Elettra Cavity & HOM investigation

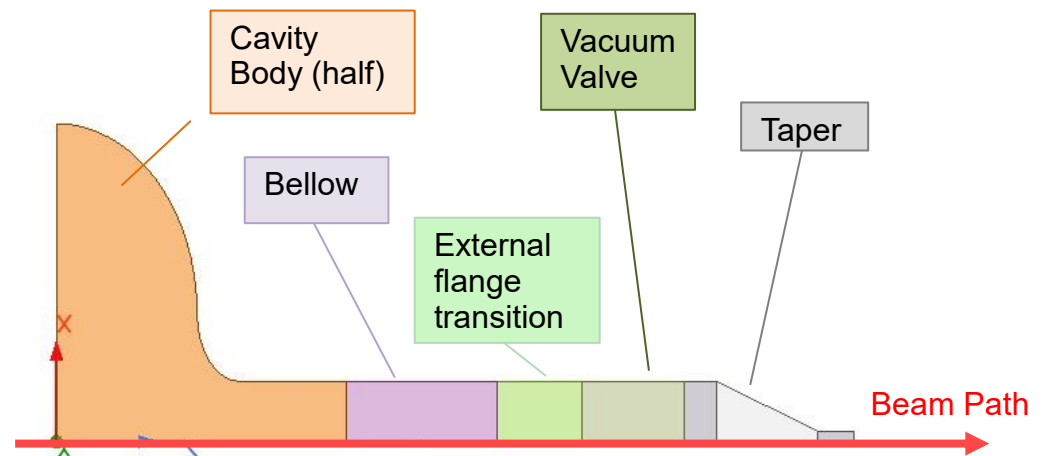
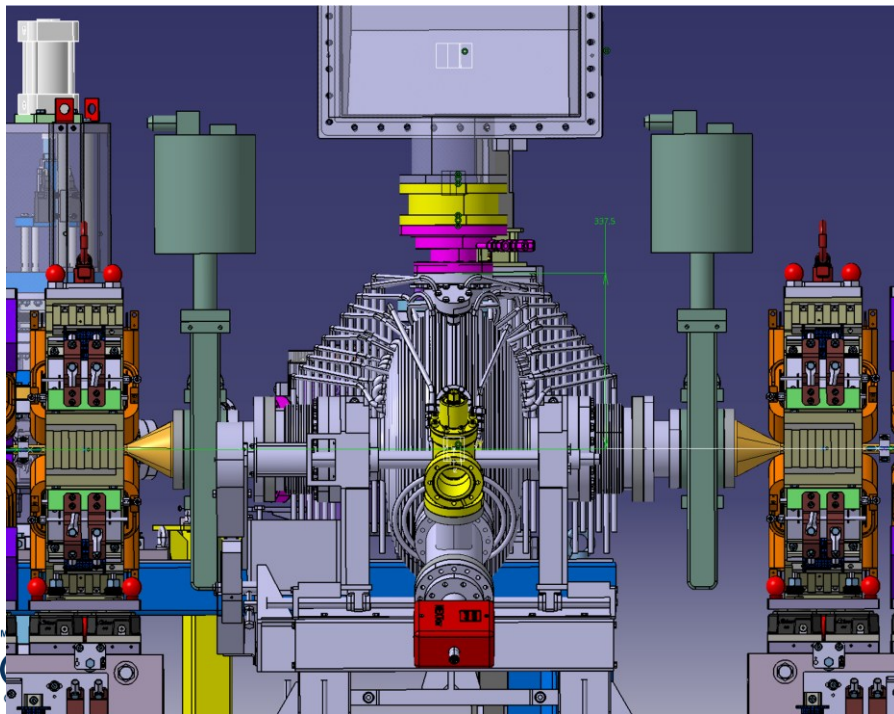
Elettra type cavity as installed in the short vacuum chamber section of Elettra

2.0



Elettra Cavity & HOM investigation

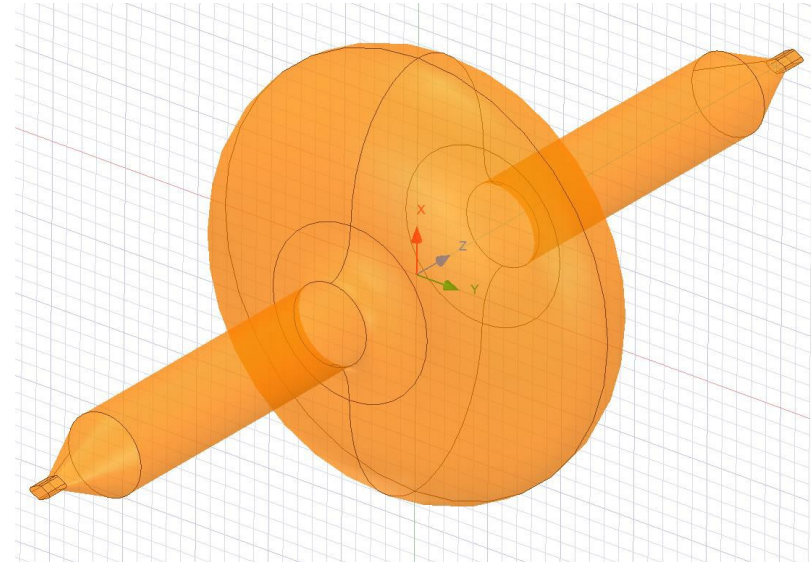
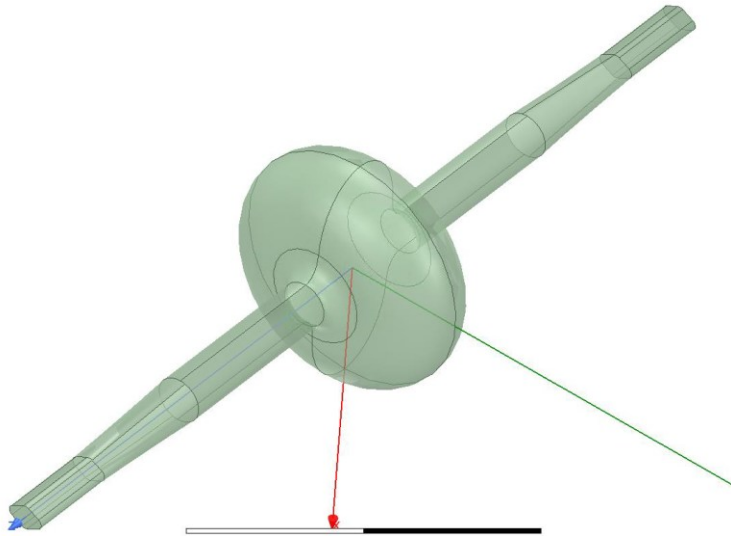
- ✓ Elettra type cavity is a non- HOM damped cavity. CBM instabilities are averted and their effect mitigated by setting the cavity's temperature far from the HOMs resonances.
- ✓ Elettra type cavity will be implemented in the new Elettra 2.0 storage ring.
- ✓ The available room for the cavity installation in the short sections, is **1260 mm**, including the required tapers. This forces very sharp tapers.
- ✓ Elettra 2.0 vacuum chamber cross section is 8.8 times smaller than the Elettra one, having the electromagnetic field propagation lowest cut off frequency around 6.5 GHz (lowest cut off for Elettra is 2.2 GHz).
- ✓ Evaluation of any possible harmful source of CBM instability shall cover the frequency range up to 7 GHz and deal with the complete volume made by “cavity + bellows + vacuum valves + tapers”.



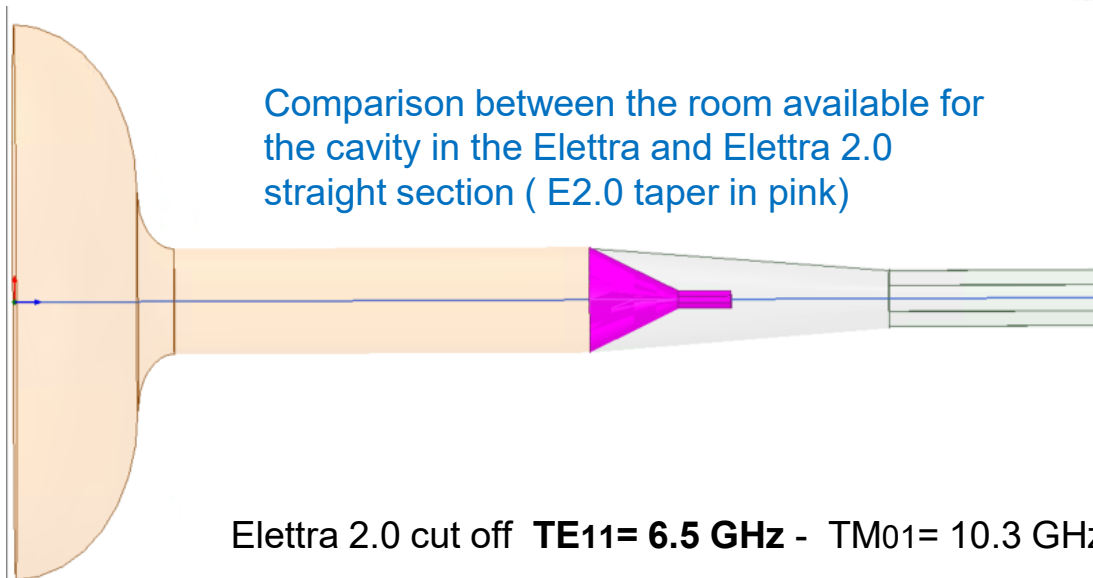
“All-inclusive” cavity model profile as seen by the beam has been implemented for the EM simulation (CST and HFSS).

Elettra & Elettra 2.0 cavity's model

- ✓ A “simplified cavity” model including the tapers has been simulated. The three equatorial ports are omitted since their impact on the impedance seen by the beam traveling close to the ideal orbit is negligible.



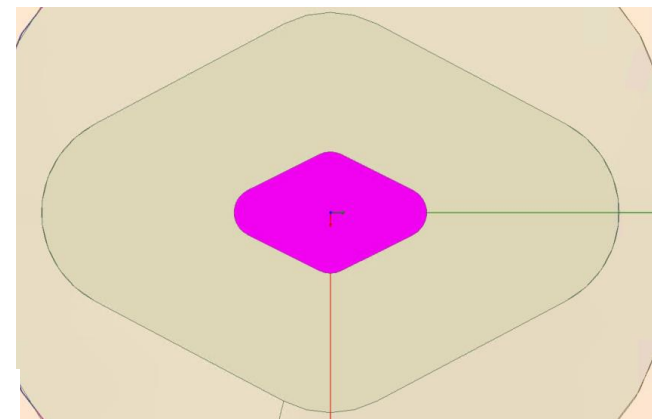
Elettra and E2.0 vacuum chamber
(E2.0 pink cross section)



Comparison between the room available for
the cavity in the Elettra and Elettra 2.0
straight section (E2.0 taper in pink)

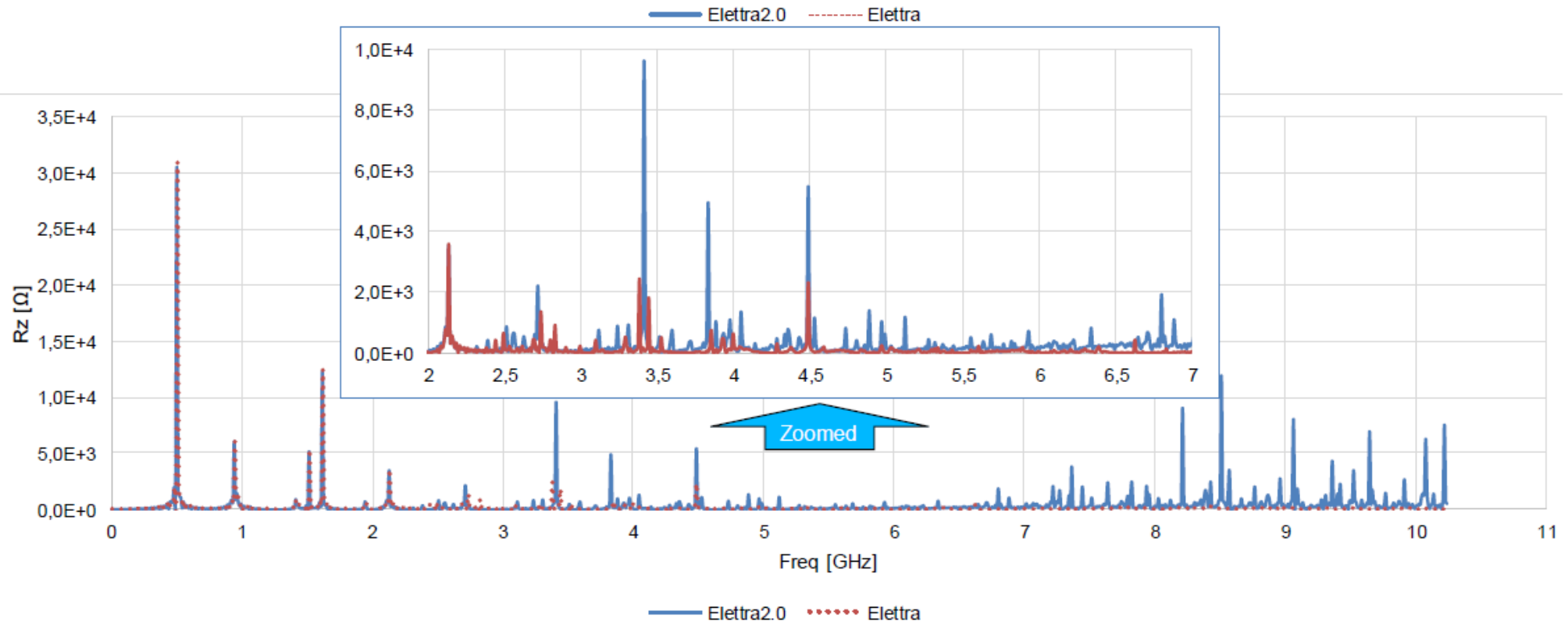
Elettra 2.0 cut off **TE₁₁= 6.5 GHz** - TM₀₁= 10.3 GHz

Elettra cut off TE₁₁= 2.2 GHz - TM₀₁= 3.1 GHz



Time Domain simulation

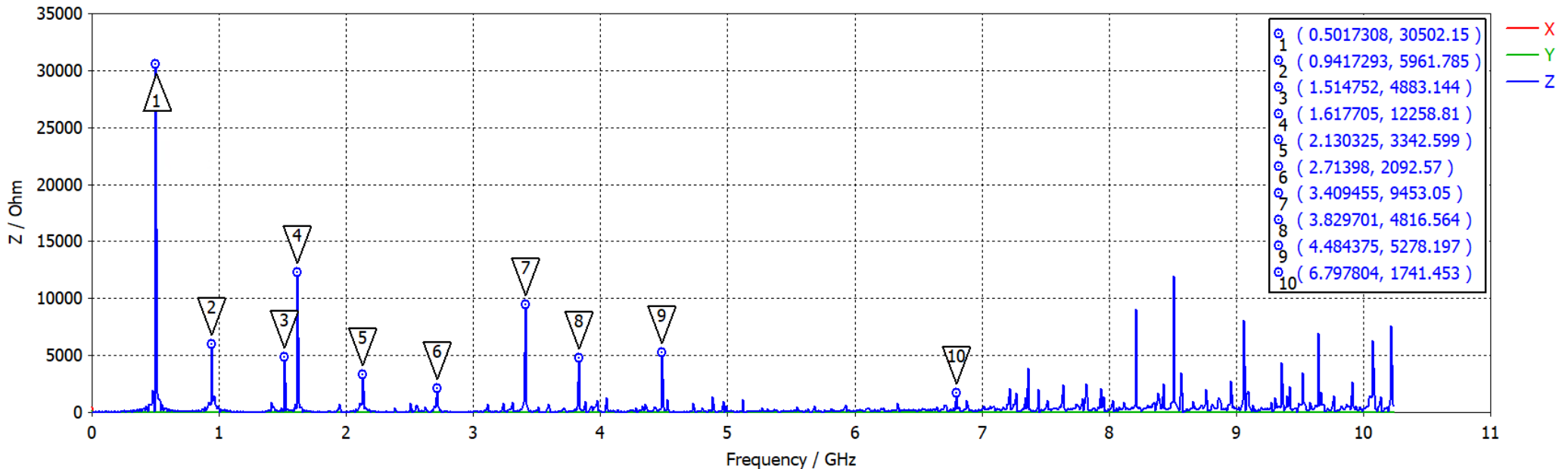
Elettra 2.0 and Elettra Longitudinal Impedance



- ✓ CST Wake Solver: bunch length =10 mm, gaussian distribution, charge 1.753 nC, WF distance 100 m.
- ✓ Up to 2.2 GHz Elettra and Elettra 2.0 the impedance's peaks occur at same frequency. These frequencies are the well known longitudinal HOMs.
- ✓ From 2.2 GHz to 7 GHz there are several still "unknown" longitudinal HOMs.

Time Domain simulation

E2.0 longitudinal impedance: **10 peaks** due to “trapped modes” up to **7 GHz**, including the accelerating mode



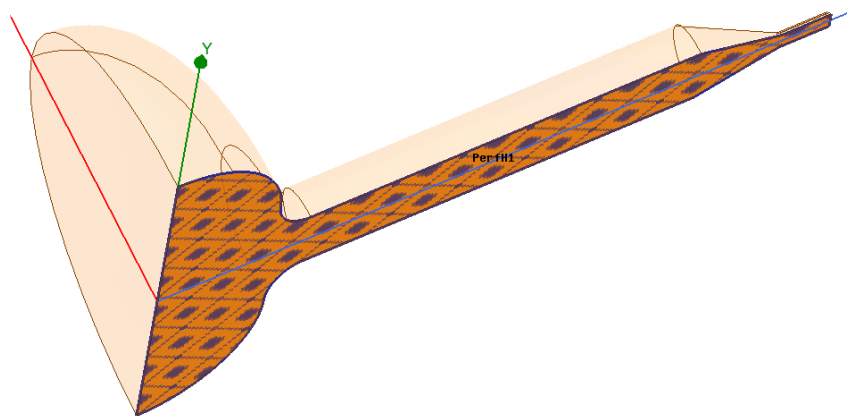
- ✓ **Main impedance peak occurs at 4.5 GHz**, well below the vacuum chamber cut off frequency , 6.5 GHz.
- ✓ Up to 2.2 GHz the impedance peak frequencies match very well the longitudinal modes.
- ✓ Wake field solver vs frequency domain solver and R/Q measurement: **good accuracy** for the frequencies but **poor accuracy** for the impedance's evaluation.

Frequency Domain			Time Domain		
Mode frequency		Mode Impedance	Impedance peak frequency		Impedance
Label	[GHz]	[MΩ]	Label	[GHz]	[MΩ]
L1	0.95	1.32	2	0.94	0.0060
L2	1.06	0.04			
L3	1.42	0.26			
L4	1.51	0.31	3	1.51	0.0049
L5	1.62	0.67	4	1.62	0.0123
L6	1.87	0.02			
L7	1.95	0.13			
L8	2.09	0.00			
L9	2.13	0.64	5	2.13	0.0033

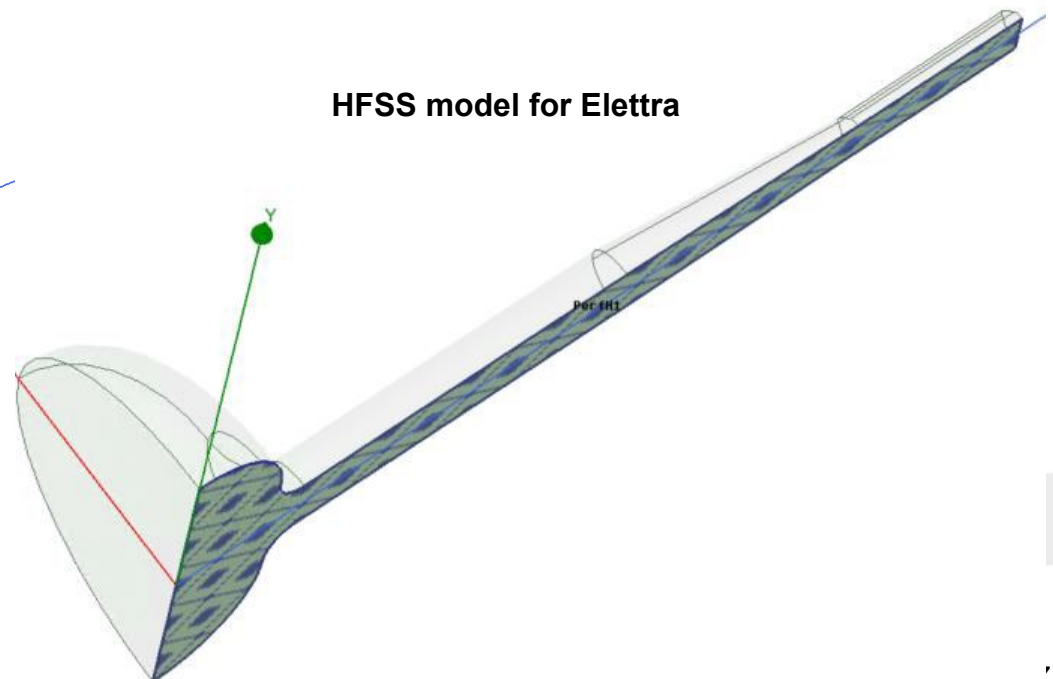
Frequency Domain simulation

- ✓ The new huge “*closed volume*” made by cavity + beam ports up to the tapers has been simulated in the frequency domain (CST and HFSS) to have a better assessment of the impedance due to the EM field trapped modes. The aim is the right estimation of the longitudinal impedance on the beam axis so the cavity equatorial ports are not simulated.
- ✓ $\frac{1}{4}$ of the resonator volume is modelled with a symmetry plane along the beam axis with two boundary conditions for the even and odd modes with respect to the cavity's center.
- ✓ Simulation have been done with CST and HFSS solvers to double check the results (very good matching) .
- ✓ Both Elettra and Elettra 2.0 cavity's lay-out have been simulated: perfect match of the HOMs up to 2.2 GHz!
- ✓ **The 0.5 GHz – 7.0 GHz frequency range has been scanned to identify all longitudinal modes + any HOMs with the same boundary symmetry.**

HFSS model for Elettra 2.0

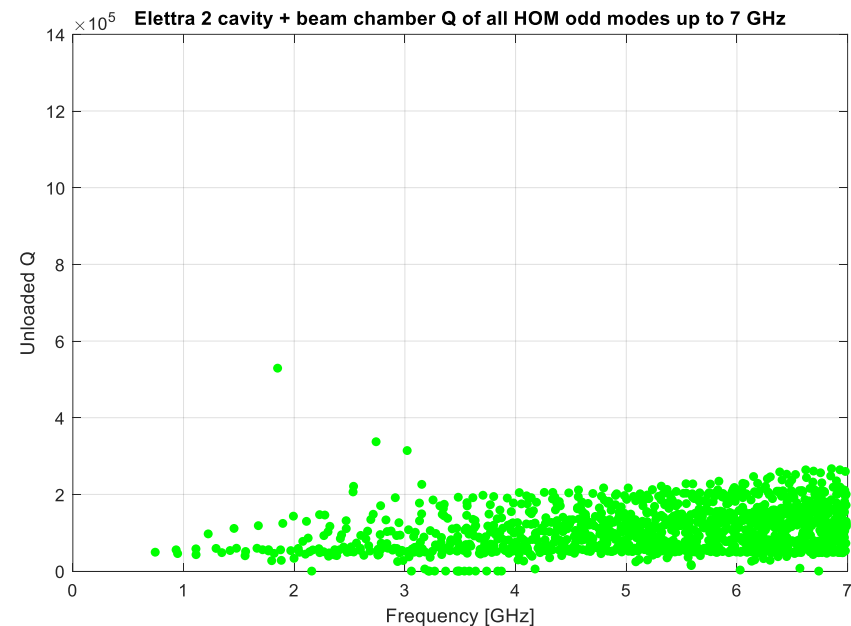
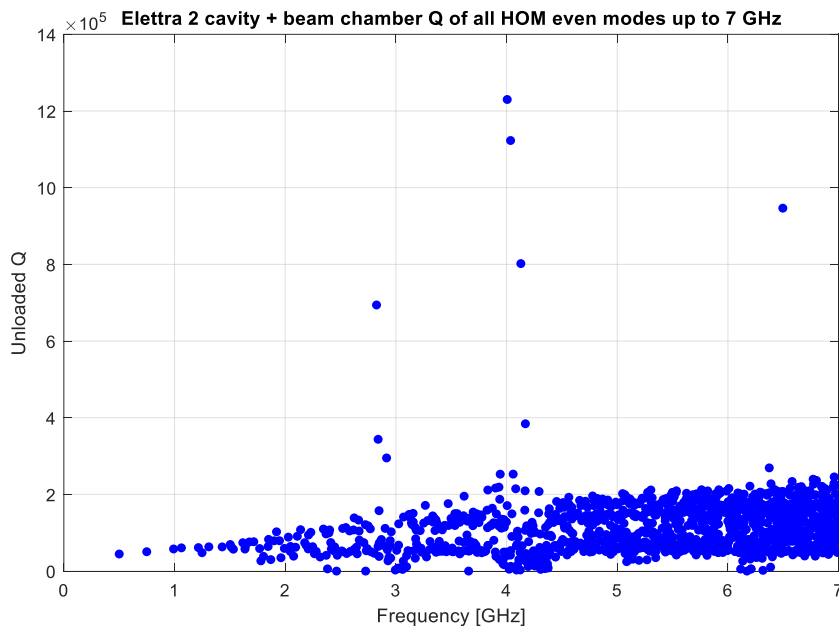


HFSS model for Elettra



Eigen Mode Solver (HFSS)

- ✓ More than **1200 EVEN** HOMs up to 7 GHz as shown in the picture: each dot is a cavity mode quality factor and frequency.
- ✓ More than **1200 ODD** HOMs up to 7 GHz as shown in the picture: each dot is a cavity mode quality factor and frequency.
- ✓ A “smart method” to identify the longitudinal modes among them is needed, starting with the “anomalous” unloaded quality factor.



Even and odd HOMs with unloaded $Q > 2.5 \cdot 10^5$, that means a high efficiency to storage the electromagnetic field energy, do not raise any instability having a very low shunt impedance R :

Mode at 2.8 GHz has $R = 20 \, \Omega$

Mode at 4.1 GHz has $R = 11 \, \Omega$

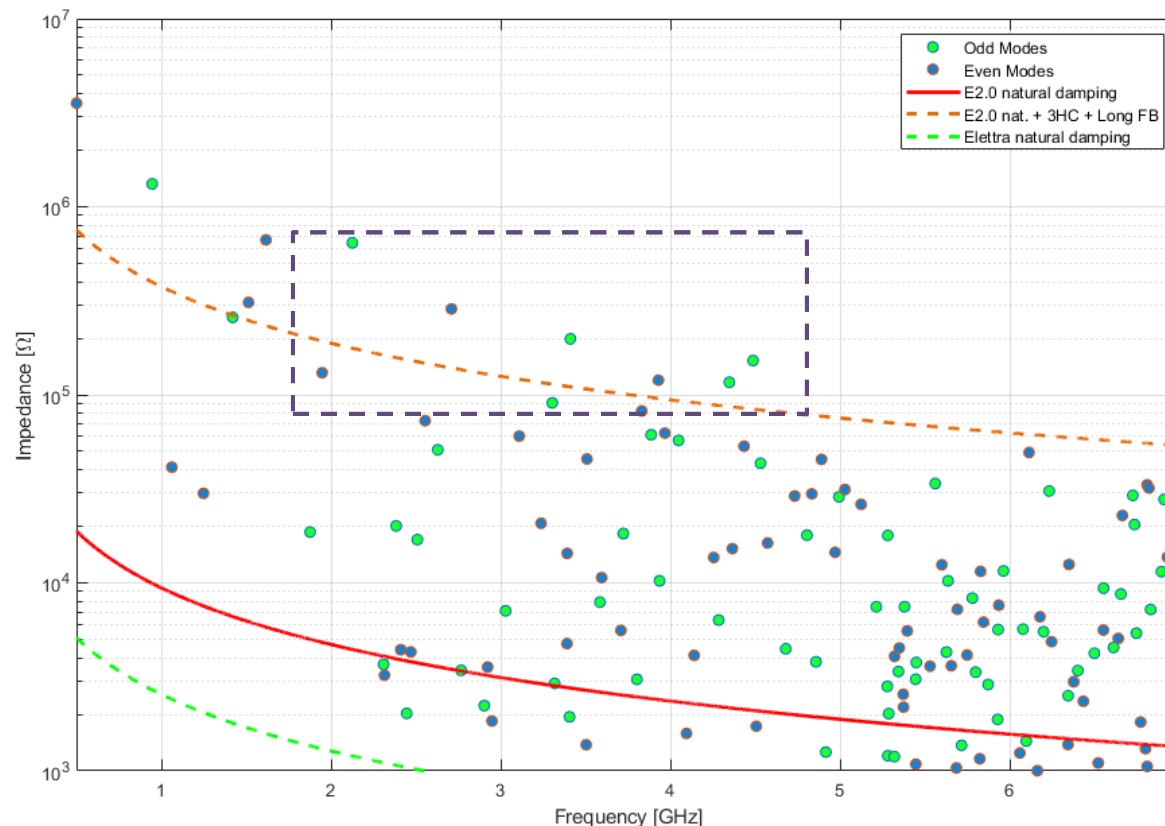
Mode at 6.4 GHz has $R = 8 \, \Omega$.

HOMs Longitudinal Impedance

- ✓ From 0.5 GHz up to 7 GHz there are ~130 modes with longitudinal impedance above the Elettra 2.0 natural threshold.
- ✓ Worse case scenario: the HOMs frequency overlaps the positive synchrotron frequency sideband $f_{HOM} = (pM + n)f_{riv} + f_{syn}$.

Less HOMs survive under the assumption that the impedance threshold is raised **40 times** thanks to 3HC and the longitudinal multibunch feedback (improvement of the threshold to be confirmed).

Nevertheless very few modes are still above the threshold that can be potentially dangerous for the multibunch beam stability. It's advisable to start the design of dedicated dampers for those modes.

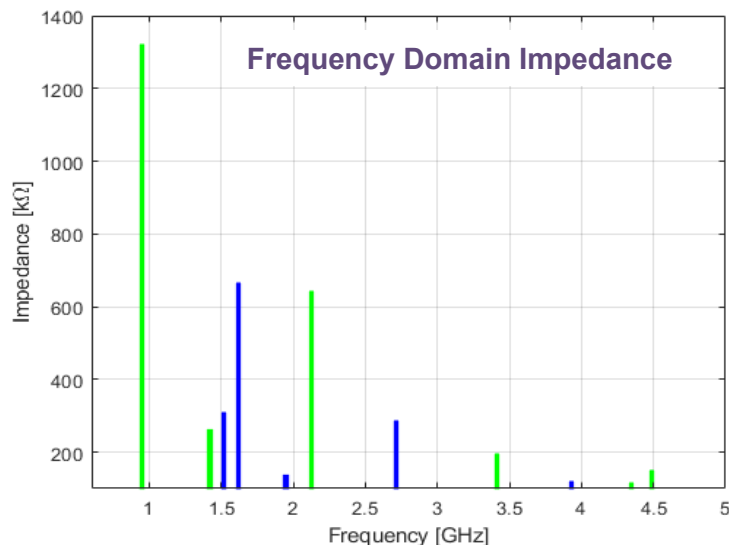
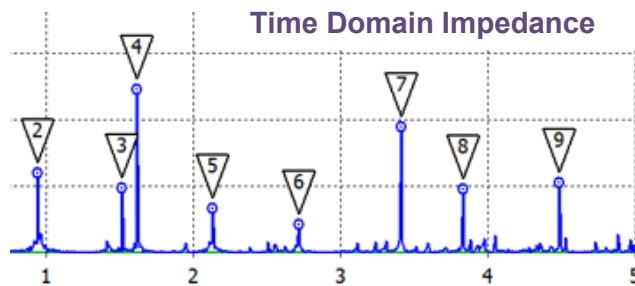


Elettra 2.0 Impedance threshold
given by the natural damping at
2.4 GeV – 0.4 A.

Elettra Impedance Threshold
given by the natural damping at
2.0 GeV – 0.3 A.

Harmful HOMs

- ✓ Out of 130 HOMs only 11 have a longitudinal impedance greater than 100 k Ω from 0.9 to 7 GHz that can drive multibunch instabilities.
- ✓ Six of them are the well known Elettra longitudinal modes.
- ✓ Up to 2.2 GHz these HOMs have been successfully “get rid off” in Elettra thanks to the cavity temperature HOMs frequency shifting, 3HC and LMFB.
- ✓ Frequency domain impedance Z_L shows the expected attenuation as the frequency increases $Z_L \sim \frac{1}{\text{Frequency}}$ and the 4.5 GHz as the highest HOM frequency.



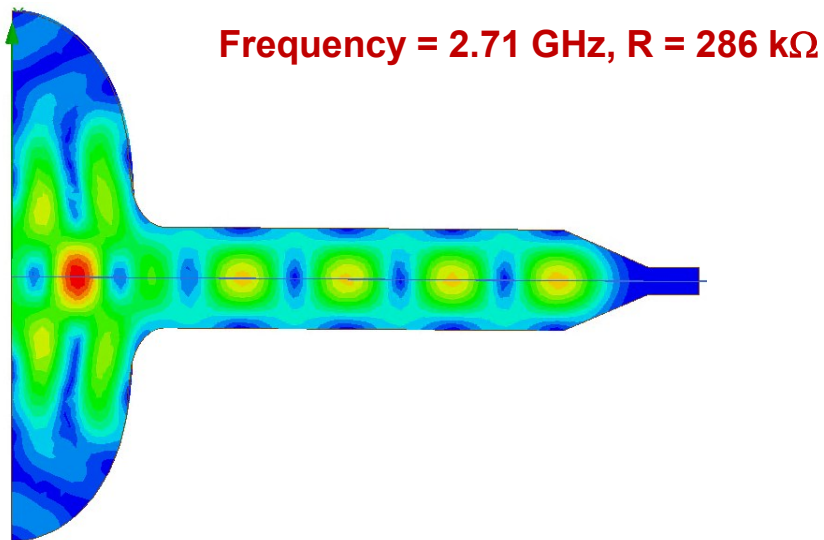
Comparison between the frequency and time domain results

Frequency Domain			Time Domain		
Mode frequency		Mode Impedance	Impedance peak frequency		Impedance
Label	[GHz]	[k Ω]	Label	[GHz]	[k Ω]
L1	0.95	1322	2	0.94	6.0
L4	1.42	258			
L5	1.51	310	3	1.51	4.9
L6	1.62	667	4	1.62	12.3
L7	1.95	131			
L9	2.13	643	5	2.13	3.3
	2.71	286	6	2.71	
	3.41	198	7	3.41	9.5
			8	3.83	4.8
	3.93	120			
	4.35	117			
	4.49	152	9	4.48	5.3

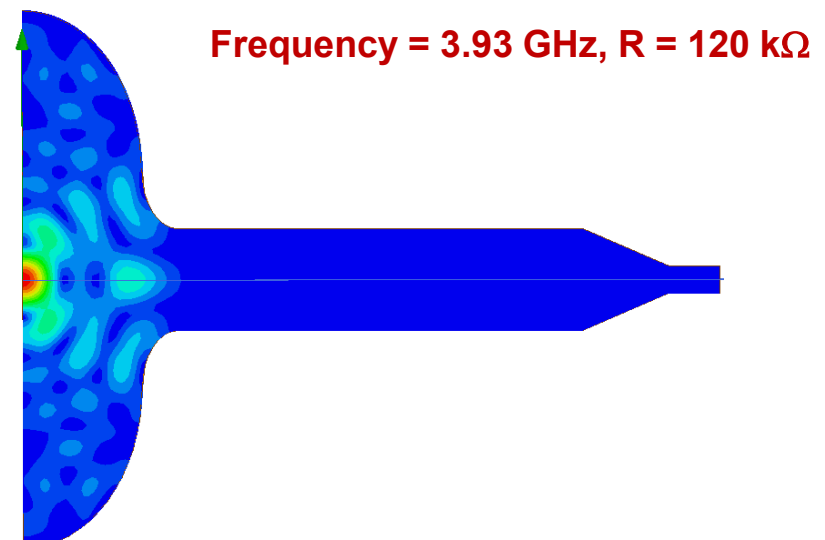
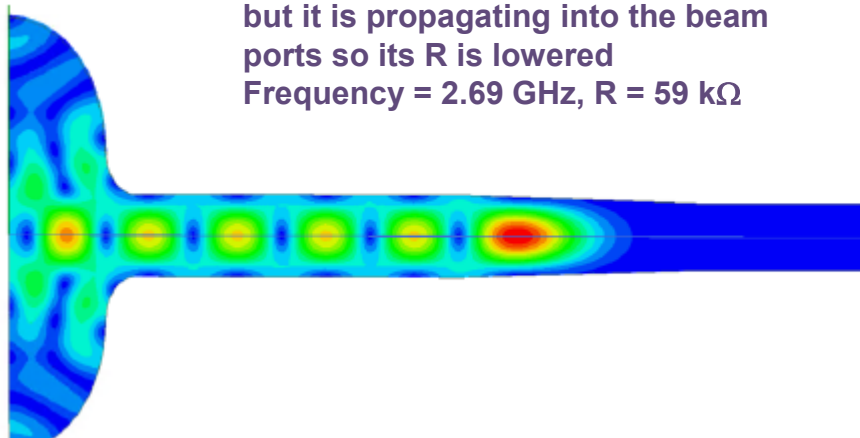
LBA

Mode Field Pattern

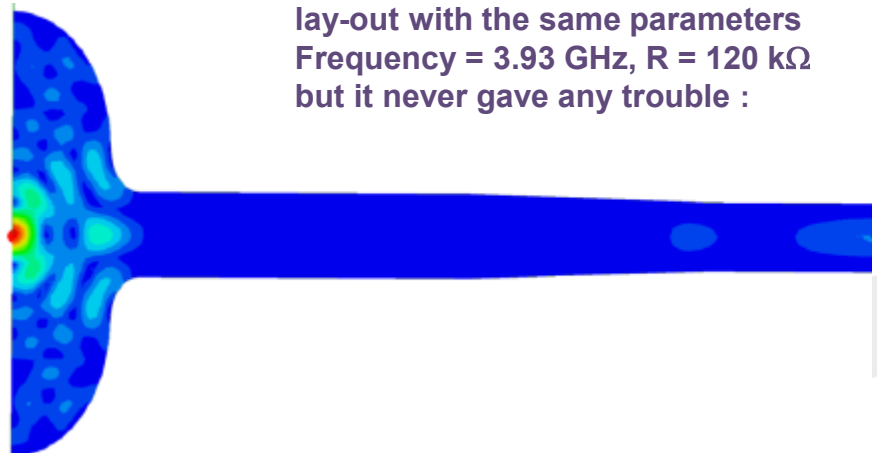
- ✓ Higher efficacy of any dampers shall cover the 2 GHz to 5 GHz frequency range.
- ✓ The magnitude and location of the electric field of the harmful modes shows the direction to design the HOM dampers.



This mode occurs also in Elettra but it is propagating into the beam ports so its R is lowered
Frequency = 2.69 GHz, R = 59 k Ω

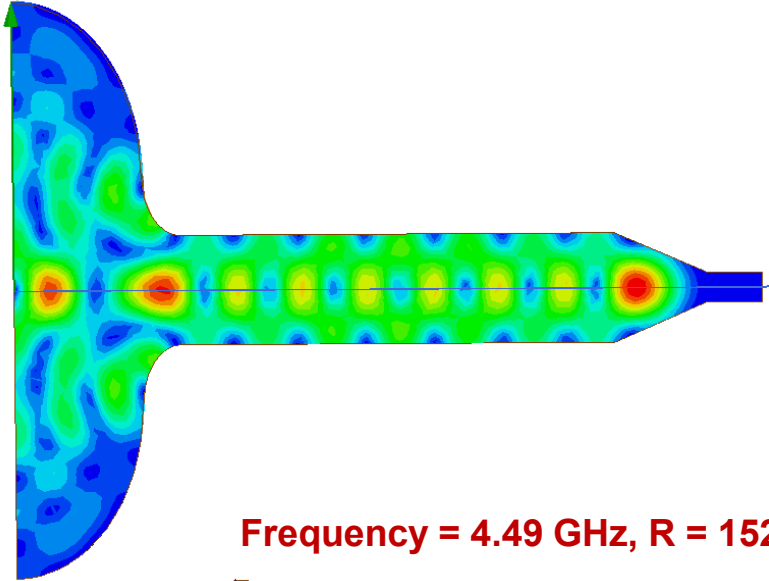


This mode occurs also in the Elettra lay-out with the same parameters
Frequency = 3.93 GHz, R = 120 k Ω
but it never gave any trouble :

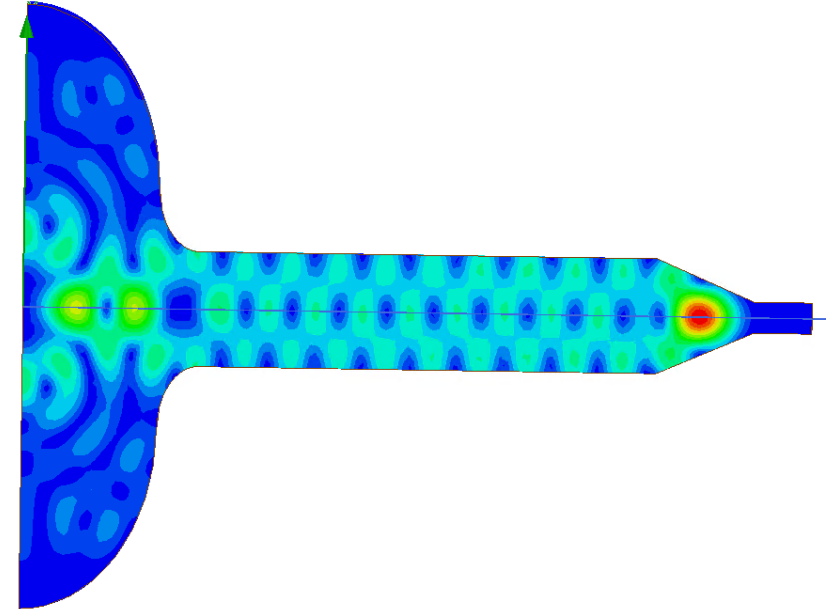


Mode Field Pattern

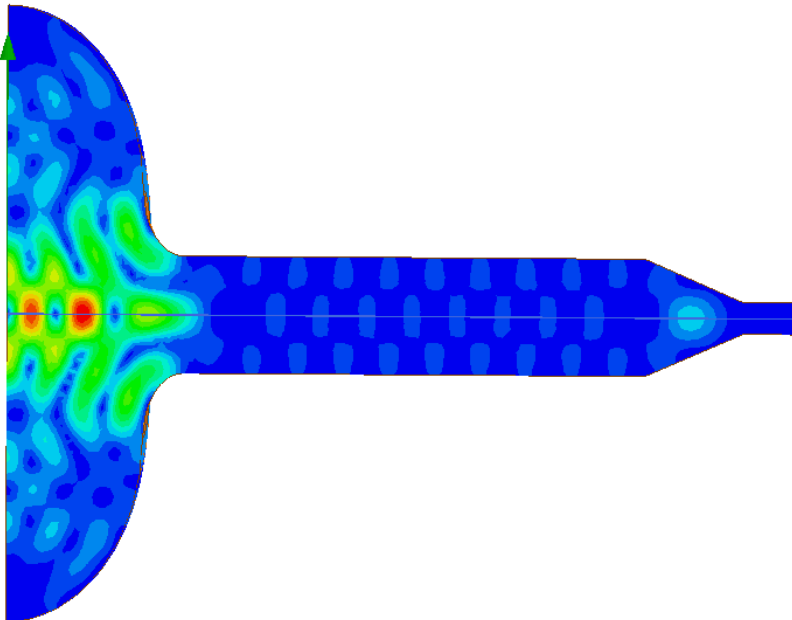
Frequency = 3.41 GHz, R = 198 k Ω



Frequency = 4.35 GHz, R = 117 k Ω



Frequency = 4.49 GHz, R = 152 k Ω



- ✓ Some mode are well confined within the cavity body, some propagates along the beam port effectively.
- ✓ The tapers are equipped with cooling channels already.
- ✓ The action to lower the longitudinal impedance shall take place in two locations: the cavity body itself and the beam ports.

HOM dampers

HOM-Dampers with almost zero-impact of the current cavity lay-out:

One circular waveguide (WG)

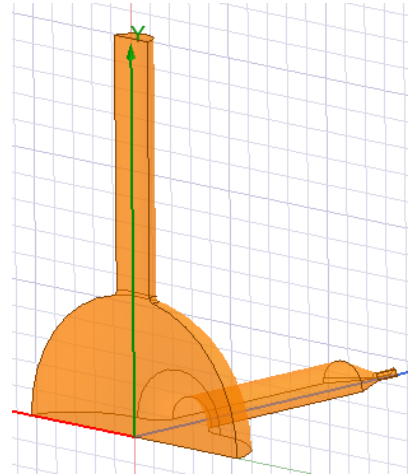
can be connected to the third equatorial cavity port $\varnothing = 84$ mm mainly to extract those mode having EM field confined into the cavity body.

WG Cut off frequency:

TE₁₁ = 2.1 GHz

TM₀₁ = 2.7 GHz

No 500 MHz rejection is needed

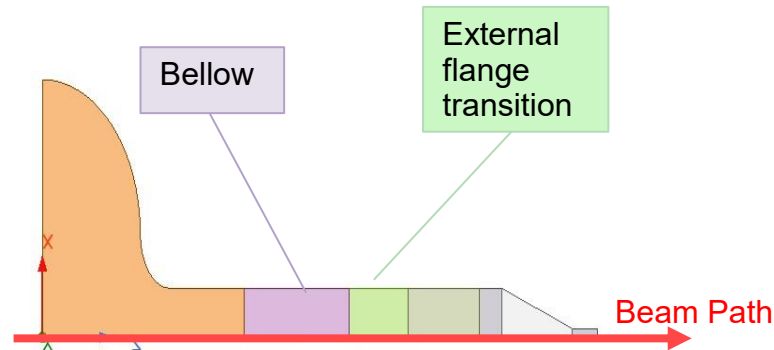


Effect on the 1st HOM at 2.71 GHz:

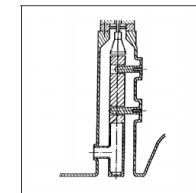
w/o WG $R/Q = 3.87 \Omega$
and $R = 286 \text{ k}\Omega$

w WG $R/Q = 2.80 \Omega$
and $R = 35 \text{ k}\Omega$

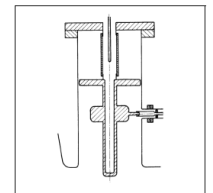
Coaxial couplers on beam tubes to pick up the propagating EM fields. The “external flange transition”, $L=70$ mm, to be replaced with a custom made transition with probe or loop. (standard solution for the Superconducting Cavities).



Example of coaxial couplers from SC



(c)
CEA: 'Probe'



(d)
CERN: 'Type-I'

Work is in progress to verify the effective damping of these two solutions on the HOMs with highest impedance.

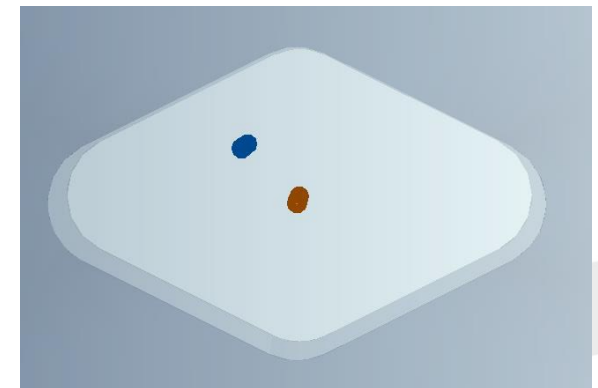
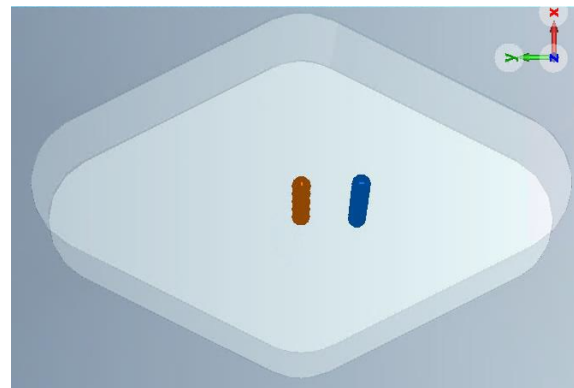
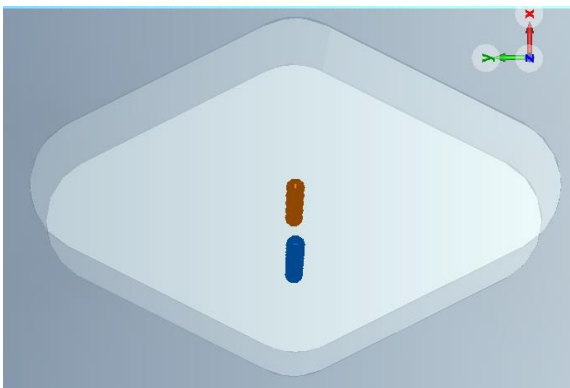
If these solutions fail, the possibility to implement SiC or AlN absorbers on beam pipe replacing the existing bellows will be checked. This forces a different tuning of the cavity and it is not so straightforward implemented.

Transverse Wake Field

Initial results on the transverse impedance Z_T are presented.

- ✓ Elettra 2.0 vacuum chamber transverse sizes are $H_x = \pm 13.5$ mm, $V_y = \pm 8.5$ mm.
- ✓ The transverse wake field is calculated running three different scenarios:
 - ✓ leading particles offset in $x = 3$ mm only
 - ✓ leading particles offset in $y = 3$ mm only
 - ✓ leading particles offset in $x = 3$ mm and $y = 3$ mm (diagonal offset)
- ✓ Setting for the cavity model, bunch charge, mesh resolution and integration length is the same implemented for the longitudinal wake field simulation.
- ✓ On - axis and off- axis field integration along the beam path.
- ✓ Transverse impedance Z_T can be evaluated thanks to the Panofsky-Wenzel formula $Z_T \left[\frac{\Omega}{m} \right] = \frac{Z_L(r_o)}{kr_o^2}$

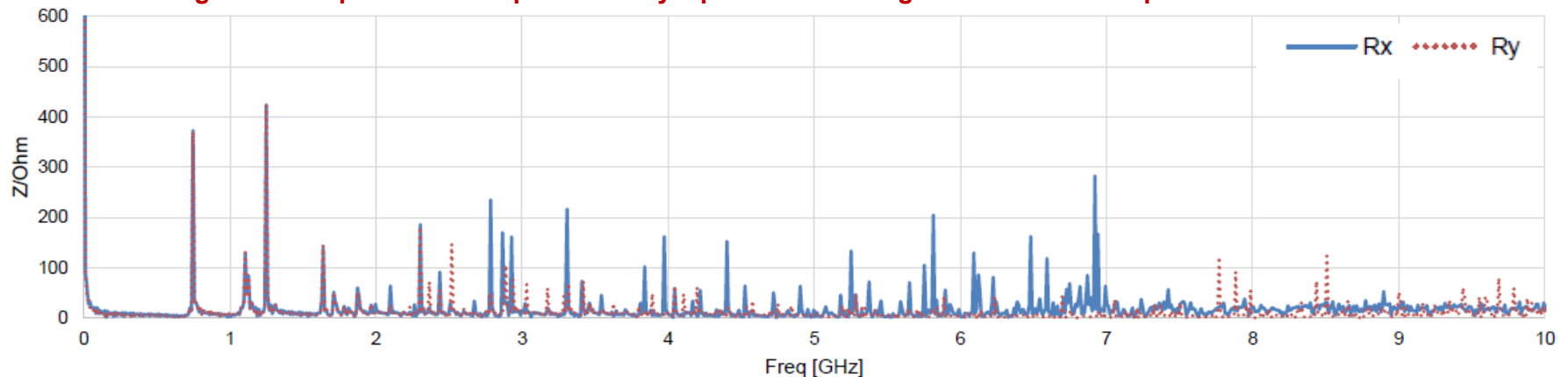
Offset implemented for the transverse wake field simulation. Blu dot the off axis particle, red dot the test particle.



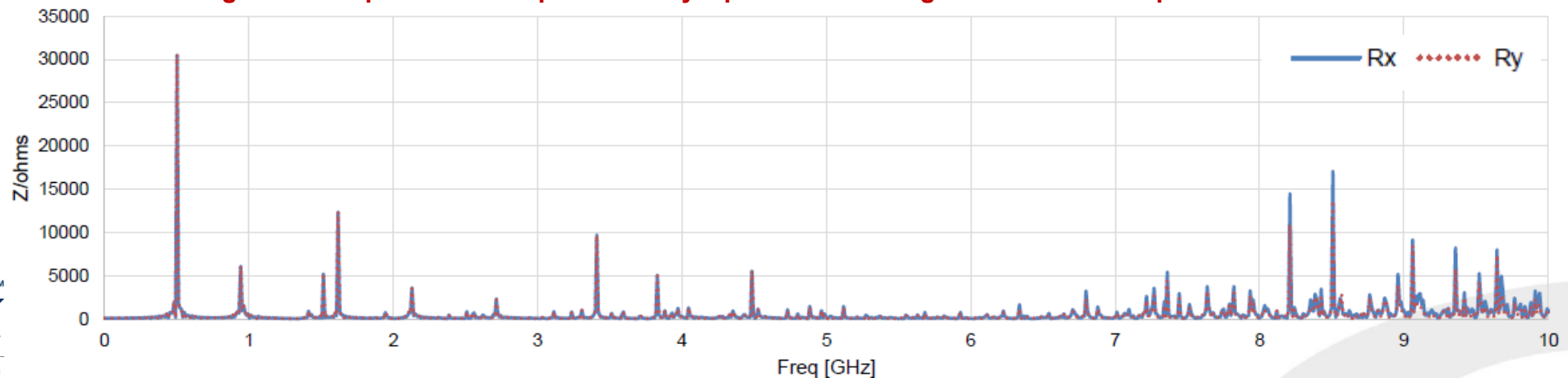
Transverse Impedance

- ✓ Longitudinal impedance data with offset in x=3 mm (red line) and offset in y=3 mm (blue line)
- ✓ The on-axis impedance is still the dominant one and matches perfectly the longitudinal impedance due to the on-axis beam.
- ✓ Largest impedance peak - 430Ω at 1.2 GHz - leads to a $Z_T = 1900 \text{ k}\Omega \text{ m}^{-1}$
- ✓ Highest frequency of the impedance peak - 300Ω at 7 GHz - leads to a $Z_T = 230 \text{ k}\Omega \text{ m}^{-1}$
- ✓ Up to 2 GHz the x and y plot shares same peaks whose frequency can be associated to some already known cavity dipole's modes.

Longitudinal Impedance Z_L experienced by a particle travelling off-axis when the particle source has an offset



Longitudinal Impedance Z_L experienced by a particle travelling on-axis when the particle source has an offset



Dipoles Mode and Frequency Domain

- ✓ Transverse impedance threshold for Elettra 2.0 - 2.4 GeV , 0.4 A , zero chromaticity - is greatly improved by the Multibunch Transverse Feedback (MBF) *

Elettra 2.0 w/o MBF	Elettra 2.0 w MBF
$Z_{T,x} = 93 \text{ k}\Omega \text{ m}^{-1}$	$Z_{T,x} = 2350 \text{ k}\Omega \text{ m}^{-1}$
$Z_{T,y} = 197 \text{ k}\Omega \text{ m}^{-1}$	$Z_{T,y} = 2780 \text{ k}\Omega \text{ m}^{-1}$

- ✓ Only the few highest peaks detected with the time domain solver will be analyzed in the frequency domain to assess the transverse impedance value. Scanning all the frequency range is not an option.
- ✓ Providing that the cavity center is well aligned with the beam optic center (magnetic center) , the Elettra 2.0 beam can't be stored when travelling with an offset larger than $\pm 3 \text{ mm}$. due to the very tight optic.
- ✓ Transverse impedance shall be evaluated at lower offset.

Old data: frequency domain analysis with only the cavity body (no beam port).

The offset of the impedance is evaluated at $r = 50 \text{ mm}$.

There's still a some work to do!

* MBF with standard amplifier 250 W but the system is ready to be upgraded up to 500 W – replacement of the amplifier only - if more damping is needed (Rif. M. Lonza MAC 2023)

Frequency Domain		
Mode Frequency		Transverse Impedance
Label	[GHz]	[k Ω / m]
D1	0.748	3867
D2	0.751	12381
D3	1.12	12283
D4	1.23	178
D5	1.25	5169
D6	1.31	485
D7	1.57	0
D8	1.65	4443
D9	1.73	4457
D10	1.73	1135

✓ RF plant status

- ✓ RF distribution needs a simple makeover.
- ✓ RF power amplifier already installed and in operation for Elettra.
- ✓ RF power run -waveguides, WG switch, circulators and high power loads- already in house ready to be installed.
- ✓ **New DLLRF:**
 - ✓ FPGA board and digital part already specified.
 - ✓ Carrier board validated
 - ✓ FE and ADC prototype validated
 - ✓ Modulator board under test soon
 - ✓ Firmware in progress
- ✓ **New digital RF interlock**
 - ✓ Prototype has been tested, firmware included.
 - ✓ All the components are in house and have been validated.
 - ✓ First pre-series (out of 6) tested within December.
- ✓ Booster RF power upgraded with IOT transmitter and procurement new SSA for the Booster is in the project pipeline

✓ HOM Cavity investigation

- ✓ Longitudinal HOMs investigation with respect to the multibunch instabilities is completed. A key to understand the time domain and frequency domain data has been found.
- ✓ Two different HOMs dampers to mitigate the few dangerous HOMs are being investigated, mainly between 2 GHz and 5 GHz. Analysis starts from the ones having the smaller impact on the Elettra 2.0 current lay-out.
- ✓ The huge number of dipole and multipole resonances deters the use of the frequency domain tools. Some investigation at the wake field 's peak frequency should be enough to obtain the transverse impedance largest value.
- ✓ If needed, the improvement of the MBF is easily achieved .

Thank you!



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