Measurements of RE-driven waves in FTU, TCV and COMPASS

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C.R. ENEA di Frascati

Timeline

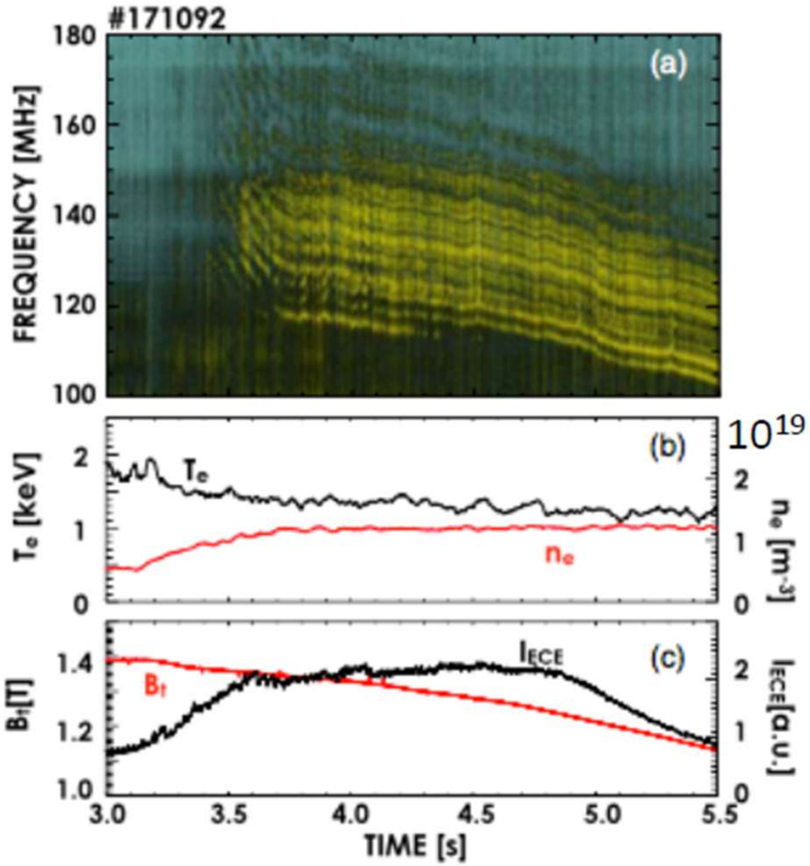
- 2019:
  - FTU – Experimental campaigns C1 and C2 – F09: Waves excitation by REs (ex-vessel antennas)
- 2020:
  - COMPASS – 12° RE experimental campaign (in-vessel and ex-vessel antennas)
  - TCV – MST1 experimental campaign 2020 – T08: Runaway electron beam physics and MGI in support of ITER SPI (ex-vessel antennas)
- 2021:
  - TCV – WPTE experimental campaign C1 – RT05: RE generation and mitigation (in-vessel antenna)
- 2022:
  - TCV – WPTE experimental campaign C2 – RT05: RE generation and mitigation (in-vessel antenna)

People

- Scientific coordinators:
  - Paolo Buratti
  - Carmine Castaldo

- Scientific team:
  - Paolo Buratti
  - Carmine Castaldo
  - Alessandro Cardinali
  - Francesco Napoli
  - Andrea Selce (Borsista ENEA)
  - William Bin (ISTP-CNR)
  - Ocleto D’arcangelo
  - Gian Luca Ravera
  - Daniele Carnevale (Roma Tor Vergata)

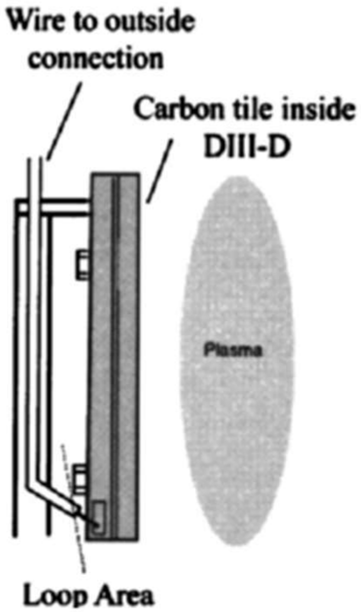
Direct observation of RE-driven whistler waves in DIII-D (2018)



D. A. Spong et al PRL 120 155002 (2018)

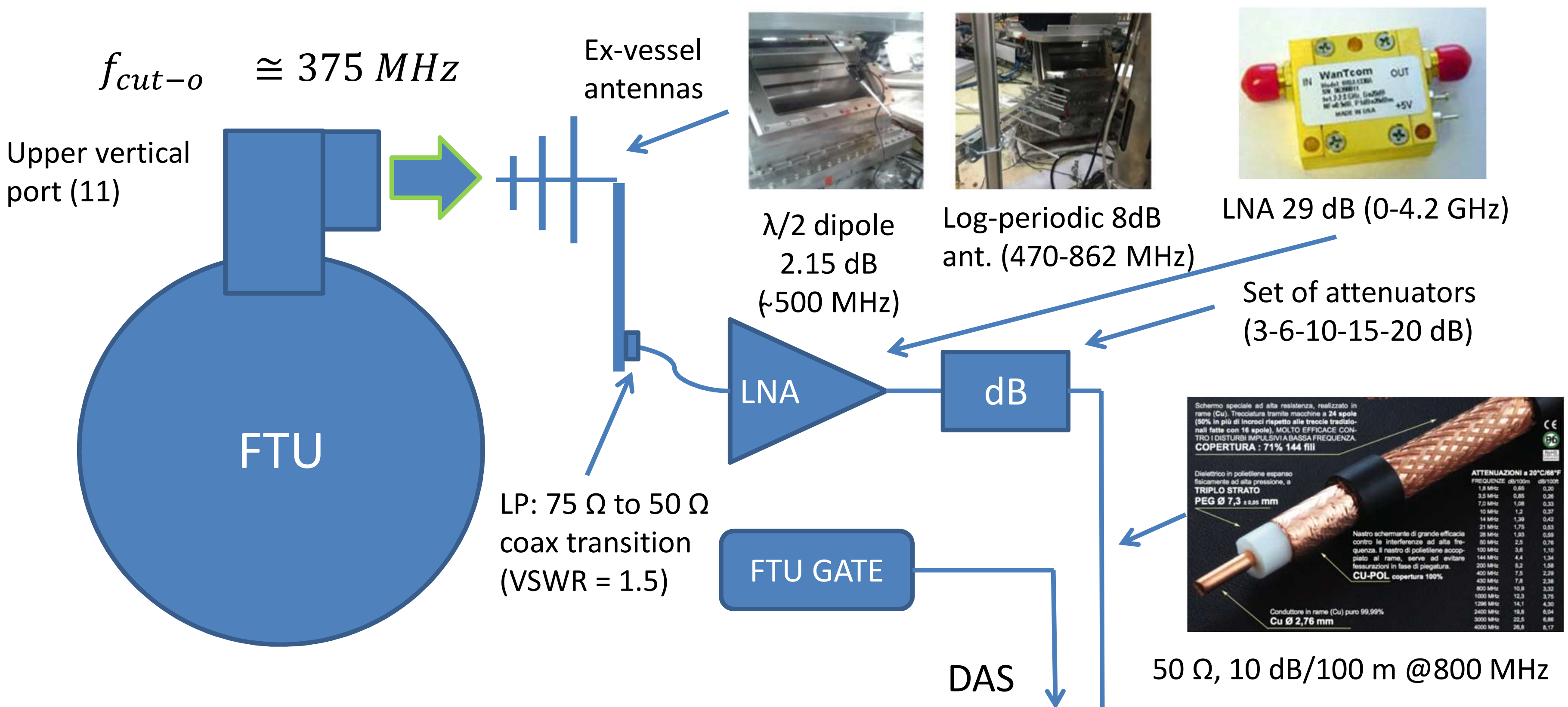
W. W. Heidbrink et al. PPCF 61, 014007 (2019)

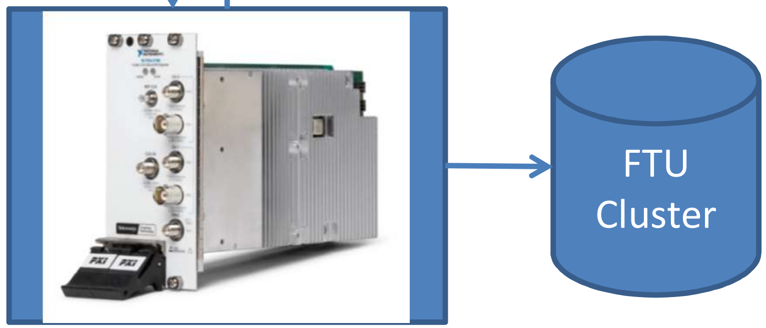
$$\omega = kV_A\sqrt{1 + k_{\parallel}^2 c^2/\omega_{pi}^2}$$



Single rectangular turn of area 16.6 cm^2
Two coils separated by 15° toroidally
28 Ω to 50 Ω transition - 100 m coax cable
200 MS/s digitizer - 5.04 s memory
High-pass filter 100MHz at the input (aliasing)

Detection of RE-driven waves in FTU



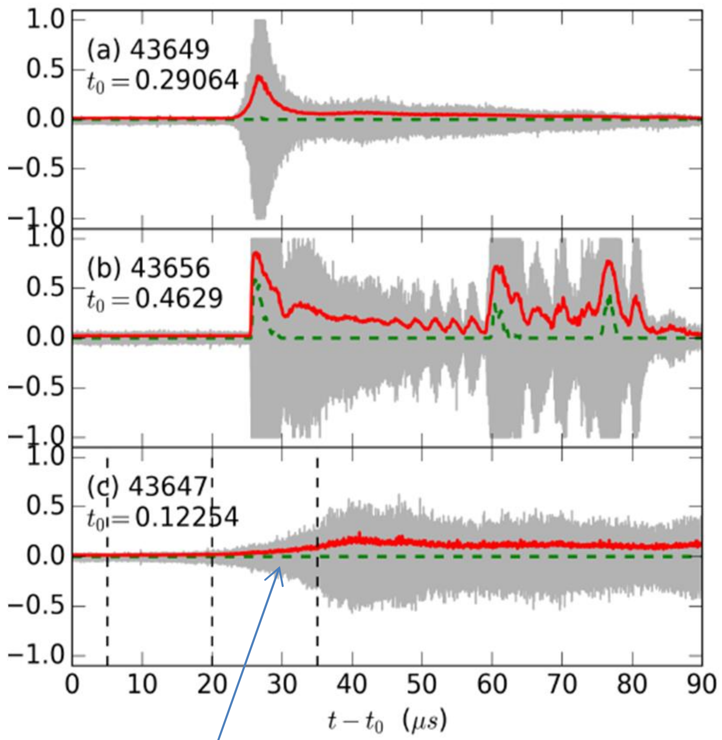


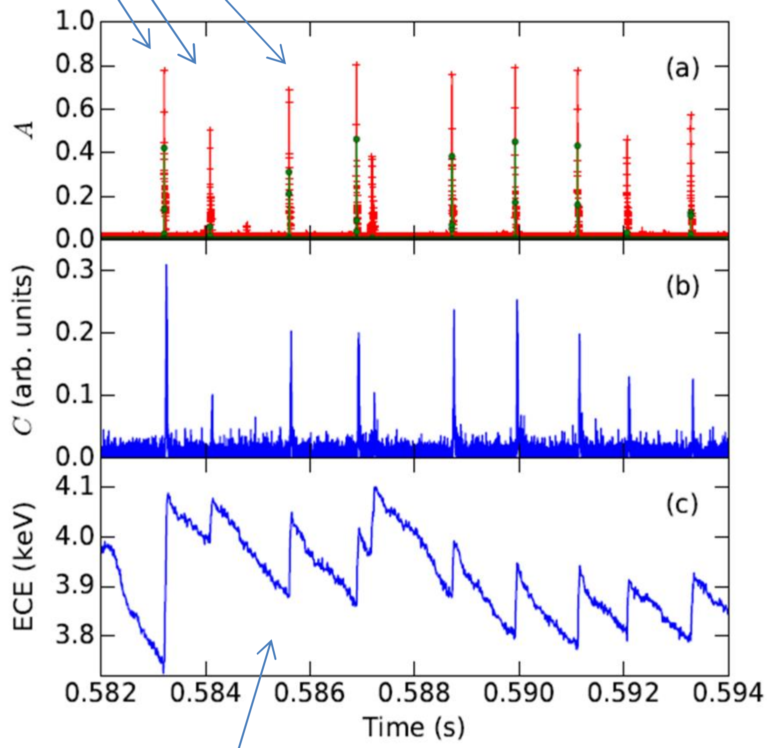
National Instruments PXIe-5186 digitizer
Max sampling rate 12.5 GS/s – 8 bit resolution – 5 GHz BW
PC controlled – LabVIEW interface
two input channels (x1 50 Ω, x1 1MΩ)
limited on-board memory: at 3.12 GS/s (Nyquist freq. 1.56 GHz) we have a 200ms time window

Detection of RE-driven waves in FTU

Anomalous Doppler Instability (ADI)

P. Buratti et al Plasma Phys. Control. Fusion 63 095007 (2021)



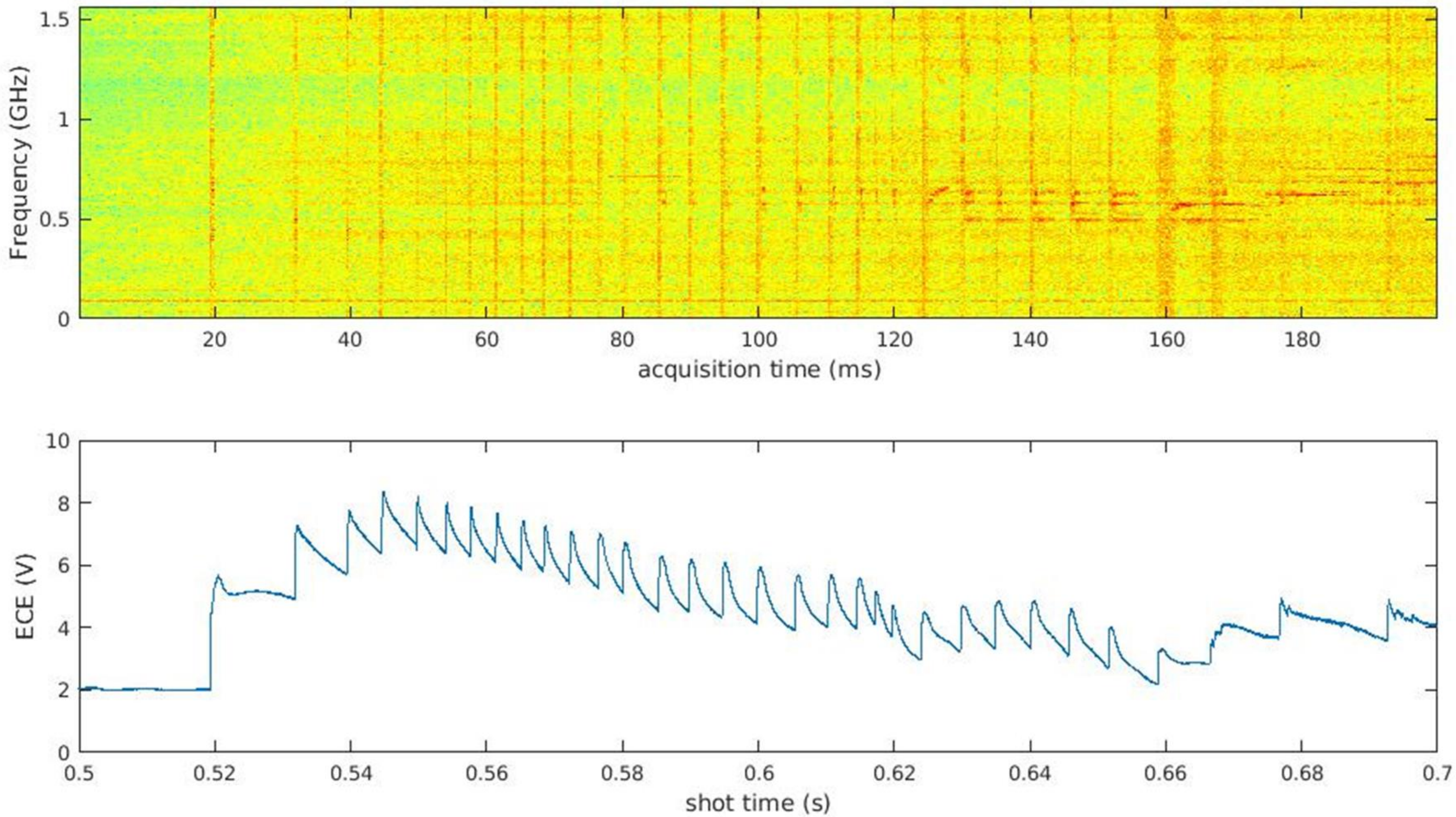


In RED the normalized RMS of the raw RF signal computed over a 100 ns time interval

ECE of suprathermal electrons time correlated with ADI events

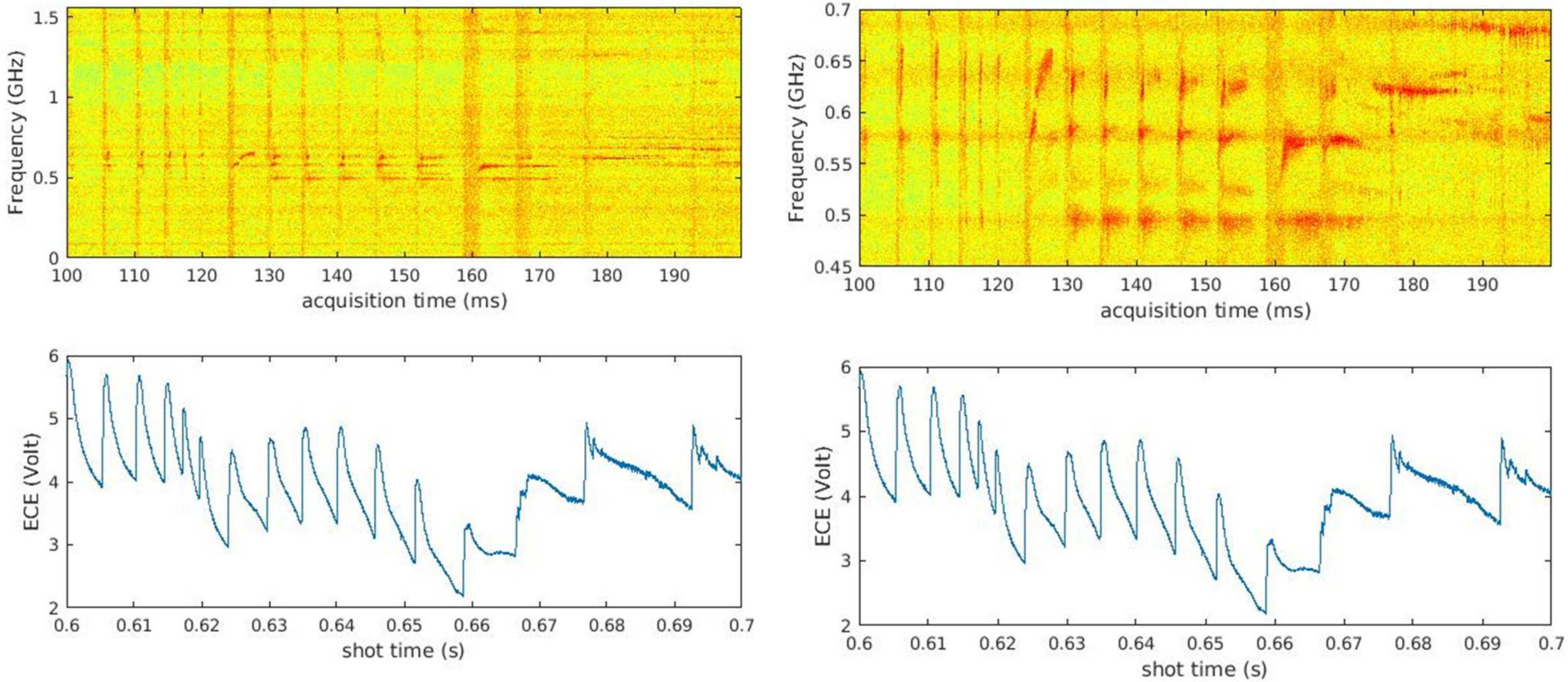
Detection of RE-driven waves in FTU

42927

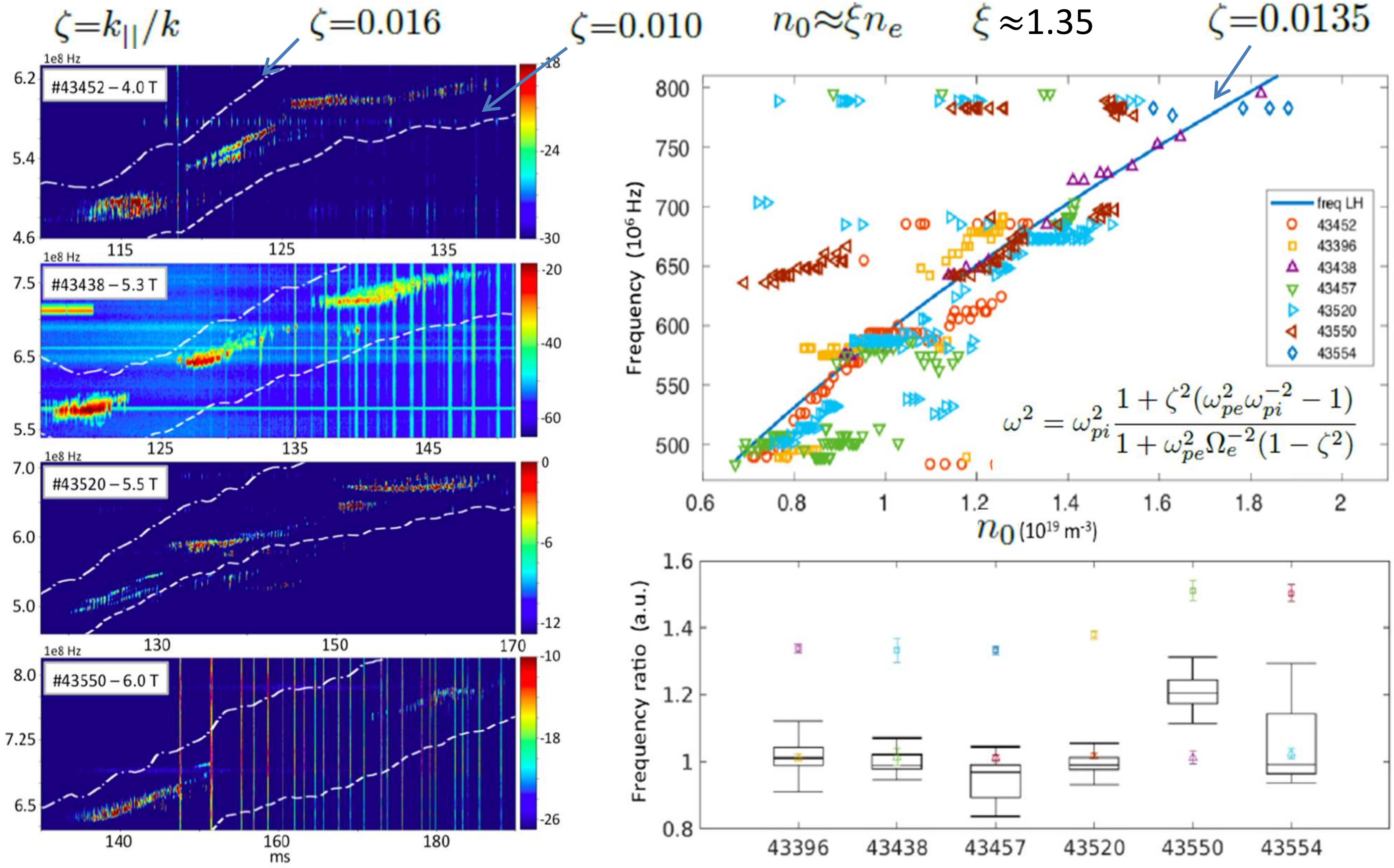


Detection of RE-driven waves in FTU

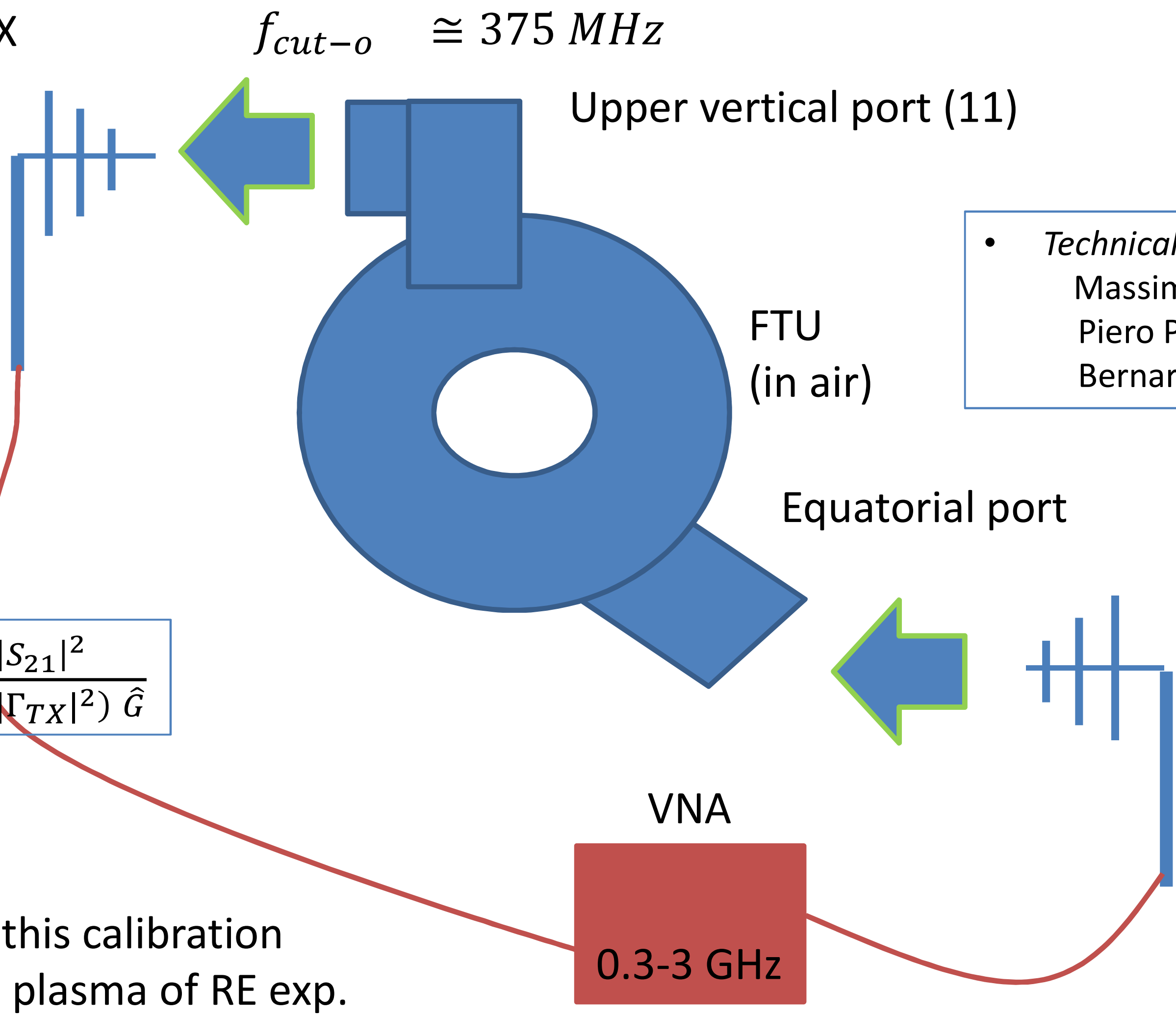
42927



First identification of RE-driven lower hybrid waves (submitted to PRL 2021)



De-embedding of the transfer function of the measurement channel



Ex-vessel log-periodic antenna placed on FTU cryostat in the same position of data acquisition during the experiment.

In-vessel twin log-periodic antenna

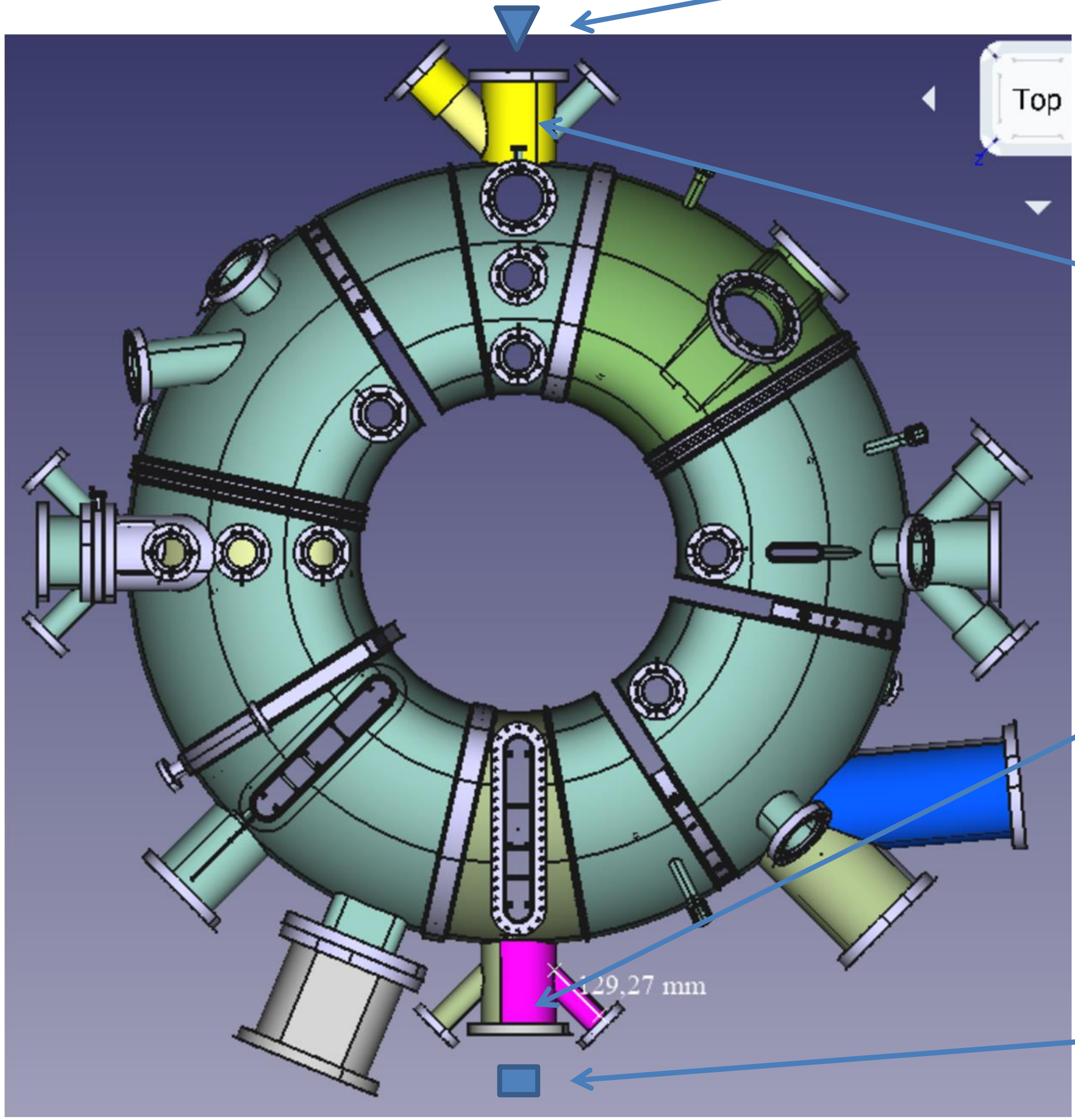
- *Technical support*:
  Massimo Aquilini
  Piero Petrolini
  Bernardo Raspante

Transfer function:

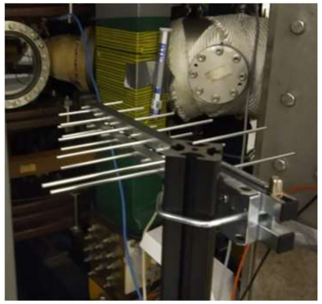
$$F_{TRASF} \propto \hat{F} = \frac{|S_{21}|^2}{(1-|\Gamma_{TX}|^2)\ \hat{G}}$$

Main drawback:
we could perform this calibration without the target plasma of RE exp.

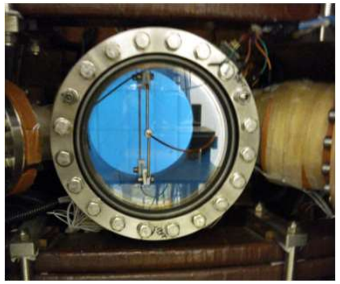
RF probes in COMPASS



Ex-vessel log-periodic antenna:

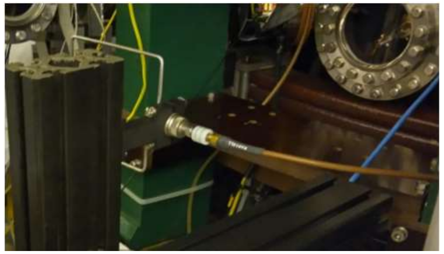


In-vessel north antenna (passive):

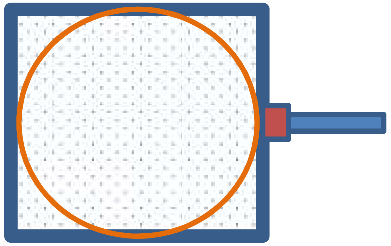


In-vessel south antenna (active/passive):

Ex-vessel loop (twin) antenna:

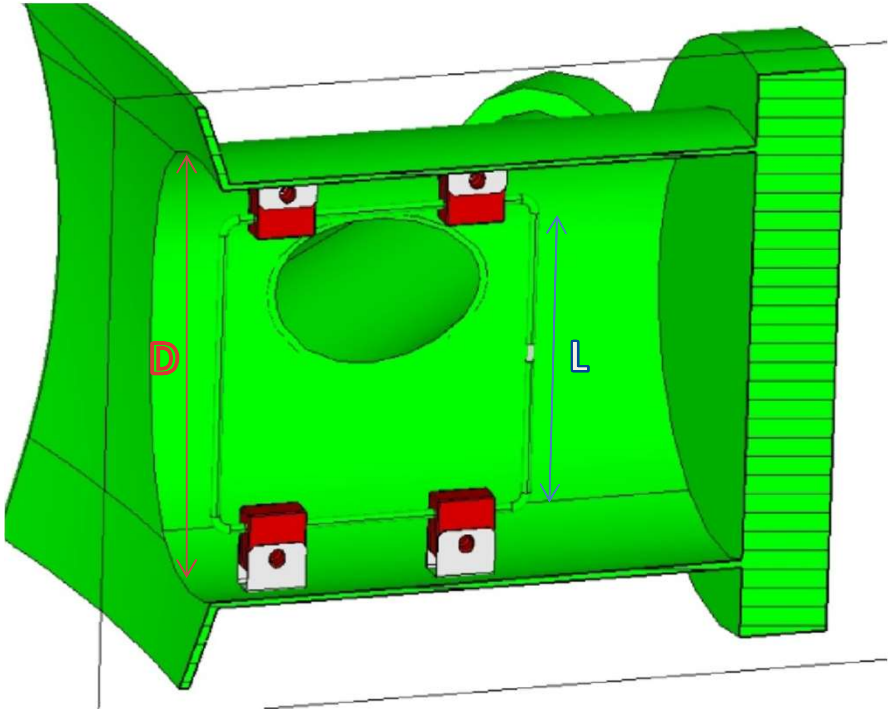


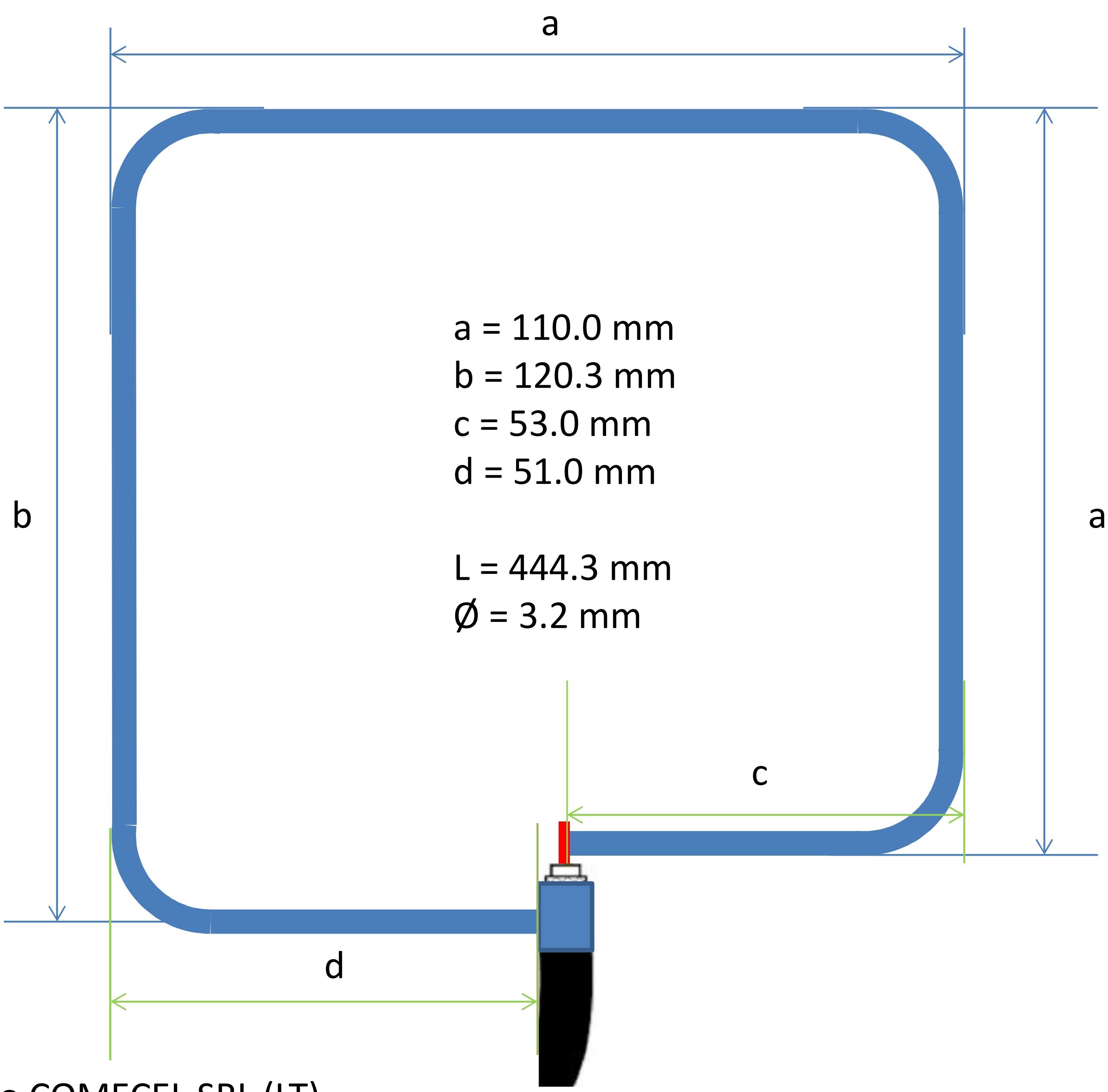
Loop antenna design



- A *rectangular shape* is easier to build than a circular one.
- Moreover, for a given space, a square shape maximizes the loop area, i.e. the loop sensitivity.
- The antenna is oriented with the loop plane parallel to the vertical plane as done in DIII-D.
- RF measurements to be done with an high cut-off frequency of the cylindrical port (about 1.17 GHz).

- Design based on COMPASS's reference toroidal magnetic field for REs experiments:
  $B_o = 1.15$ T
- Deuterium cyclotron frequency:
  $f_c \approx 8.77$ MHz @ **1.15 T**
- Selected harmonic numbers:
  N = 1 - 10
- Target frequency band:
  Δf = 8.77 MHz – 87.7 MHz
  BW = **78.9 MHz**
  f_0 = BW/2 = 39.5 MHz
- Horizontal port's diameter:
  D ≈ 150 mm
- Square loop side (A = 121 cm^2):
  L = 110 mm
- Small loop antenna:
  $P \approx 0.06\ \lambda_0$





Design sent to COMECEL SRL (LT)

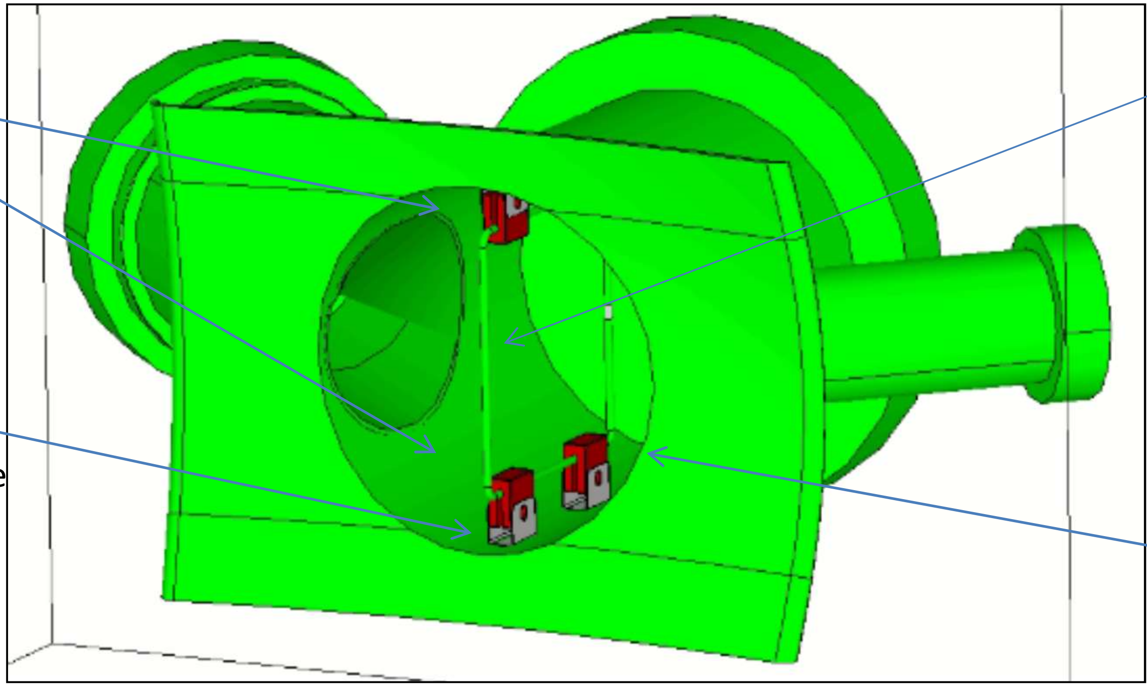
CST Simulations

Square loop compatible with holders:
Area: 121 cm^2
Material: aisi 316L stainless steel
Ø = 3.2 mm

Freq/BW	Port Att.
[8.77 87.7] MHz	-25 dB
478.9 MHz	-4 dB

Loop holders

U shape holder made from 0.5 mm SS 304/316 plate which is point welded to the port surface (Martin Jerab).

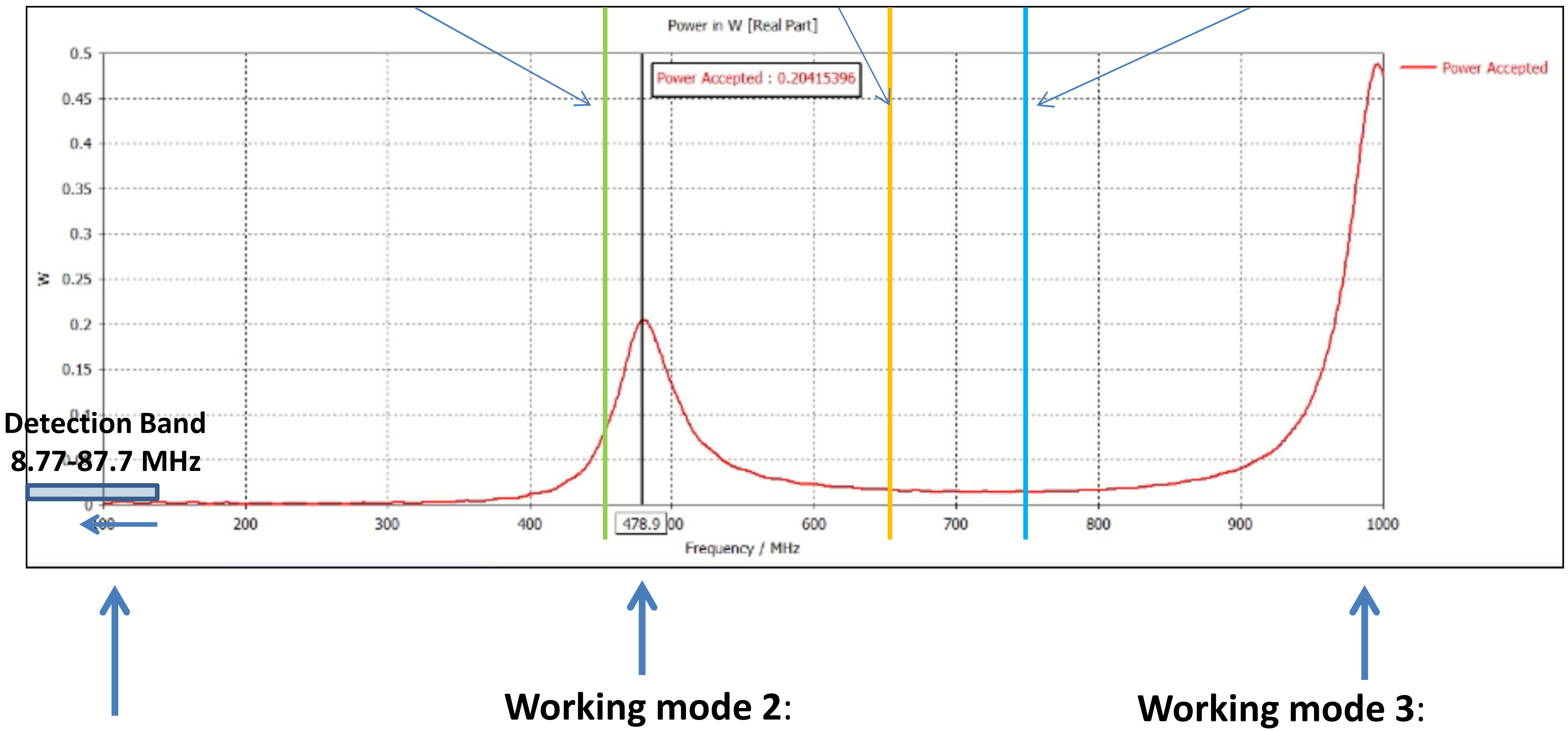


To minimize port attenuation the antenna has been aligned to the port-vessel interface.

Second part is from PTFE (TEFLON) insulator. In the hole there is M5 screw/nut/washer set to hold the loop on position (Martin Jerab).

Loop Antenna in Port Geometry

fp$_{Deuterium}$: 468 MHz @ 1e19 m-3 663 MHz @ 2e19 m-3 741 MHz @ 2.5e19 m-3

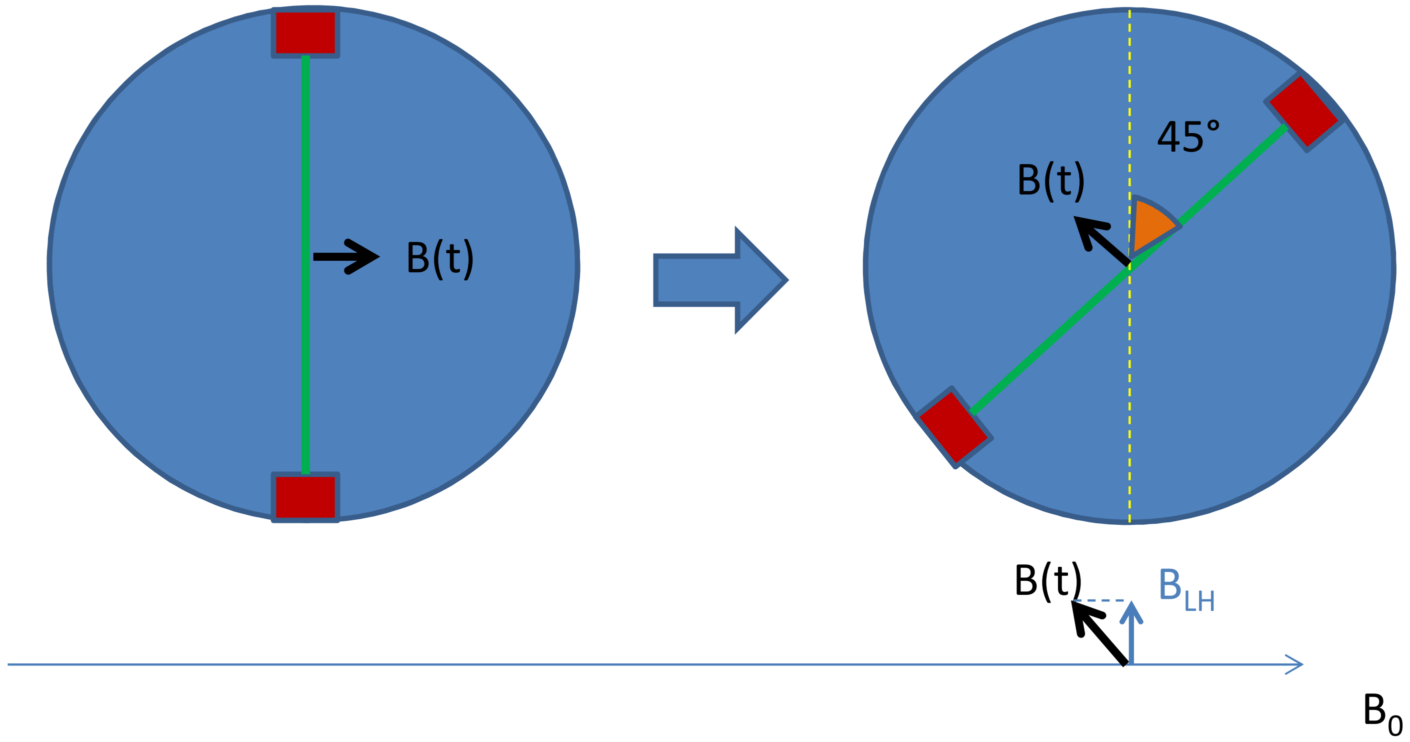


Working mode 1:
not resonant antenna
tuned with a matching network

Working mode 2:
first resonance without network
usefull to couple RF power

Working mode 3:
second (main) resonance
without network

Antenna Polarization for Rx/Tx

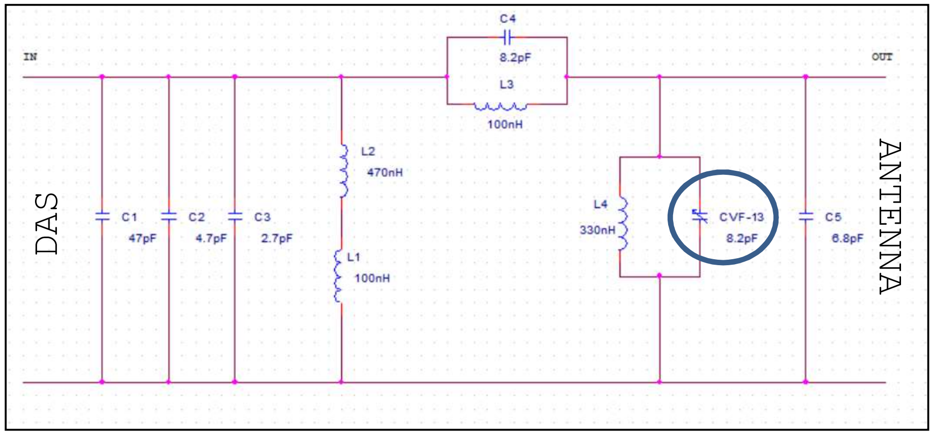


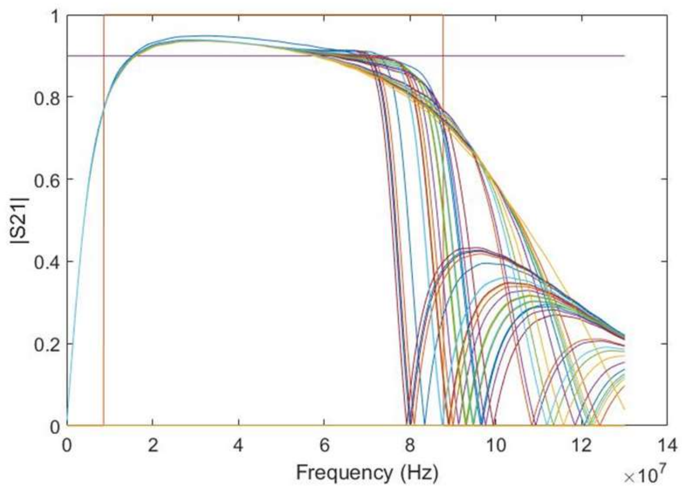
LH coupling @ 479 MHz:
n_cutoff ≈ 2.8e+15 m^-3
n_opt = 2*n_cutoff = 5.6e+15 m^-3

Power transfer estimation
Spectrum estimation
n// > n//_crit (accesibility)
n//~ 1.2 (interaction with beam)

Matching network design

- Since the loop antenna is not resonant in the lower working band, it is necessary to use a matching network to tune the antenna to operate in the selected working band.
- The matching circuit can add additional resonances to the loop antenna and thus make it more broadband.
- The matching circuit has been designed using a direct synthesis method (**The Cambrian Algorithm, author: F. Napoli**) and the antenna impedance has been obtained from CST simulations (VNA measurements resulted noisy and therefore useless).
- CST simulations are realistic since they considered the loop antenna inside the COMPASS port and with the antenna holders (considering the real used materials and the real port geometry by means of FreeCAD descriptions).
- The matching circuit has been realized with dicrete passive components for RF applications soldered on a test board (no PCB due to time limitations) and with a variable capacitor (trimmer) on the output port (load/antenna side) to compensate the real antenna impedance on site.
- A prototype of the antenna with its matching network has been tested in air at ENEA before shipment.



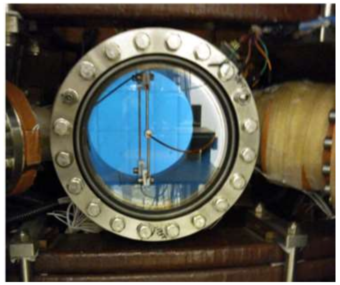


Rx Layout

x2

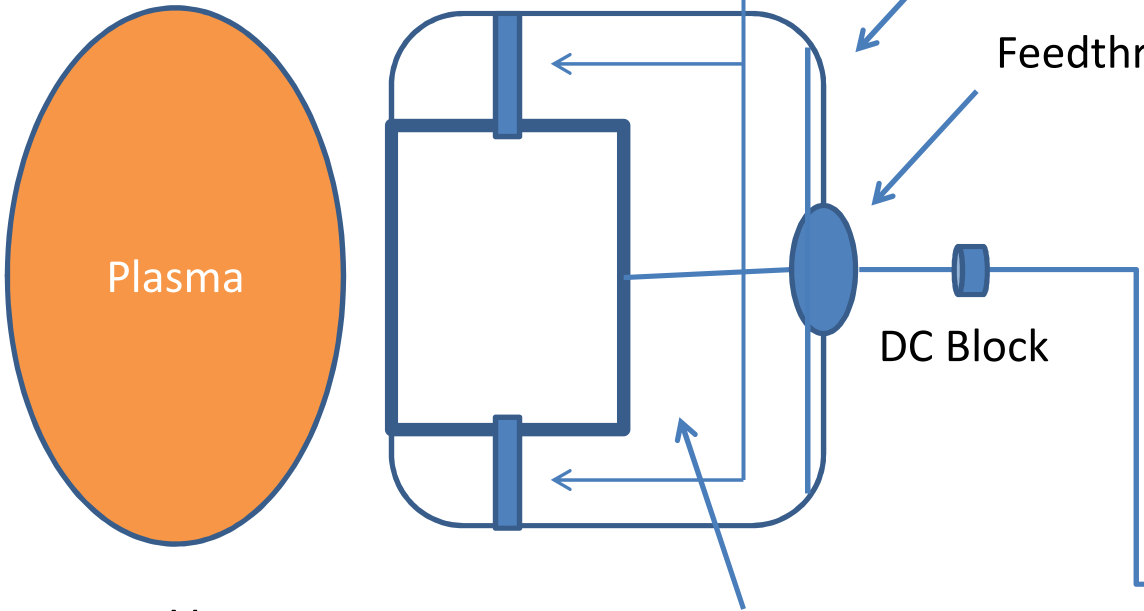
Antenna holders

Port Flange



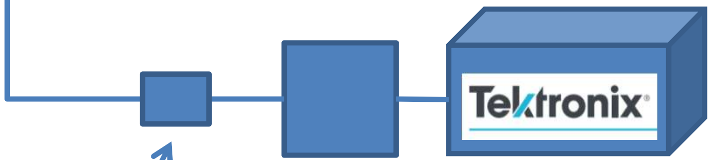
Feedthrough

Coax
(FTU-like cable)



DC Block

DAS

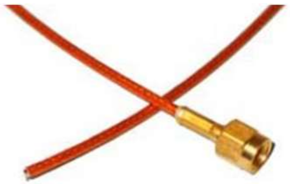


Matching
Network

Input Protections
(several attenuators)

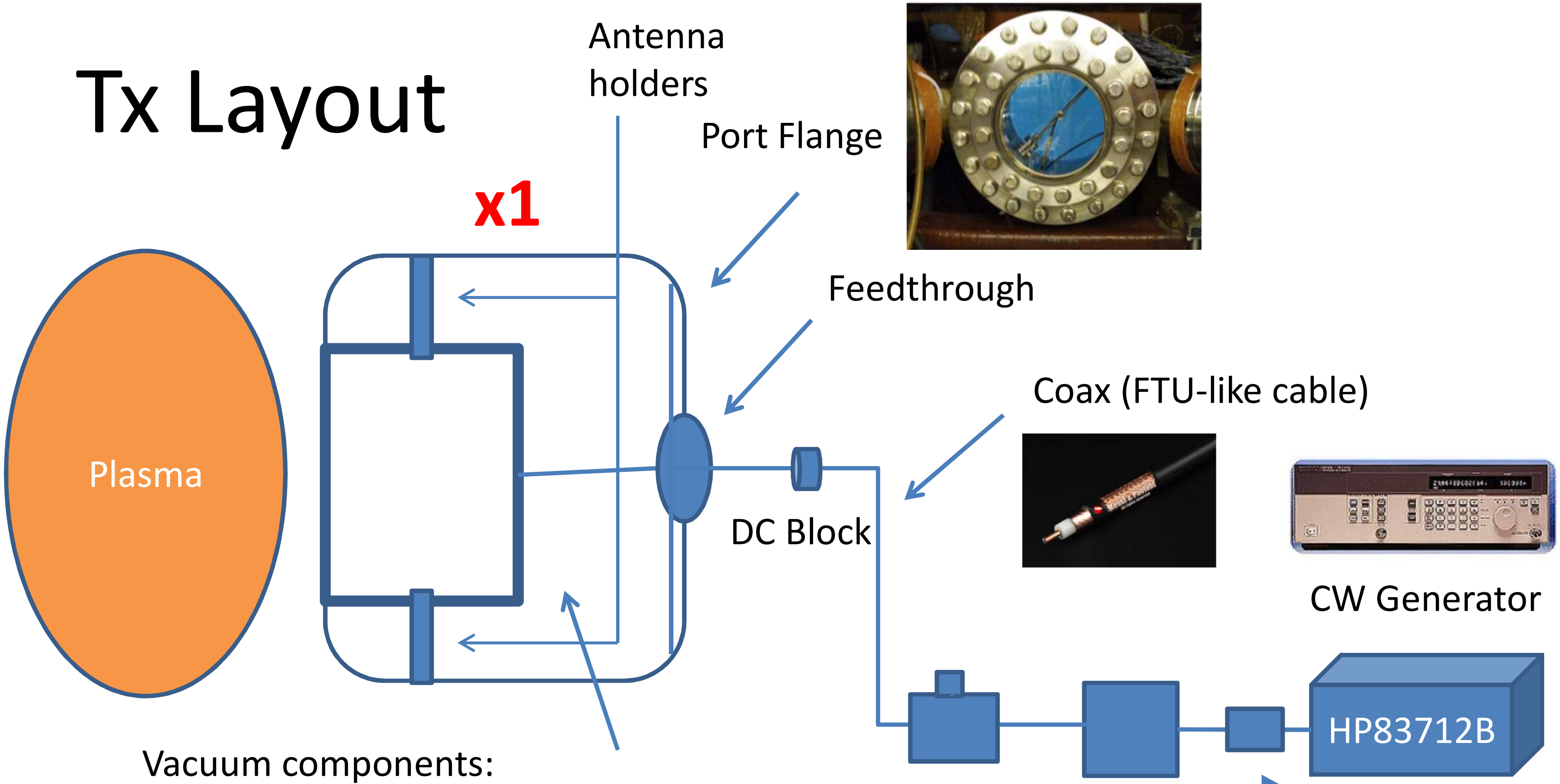
Vacuum components:

- 1 Loop (AISI 316L stainless steel)
- 1 UHV coaxial cable with SMA connectors



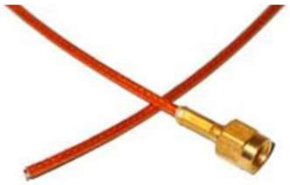
DAS: 8ch, 12-bit, 2.5GHz, 25GS, 500M

Tx Layout

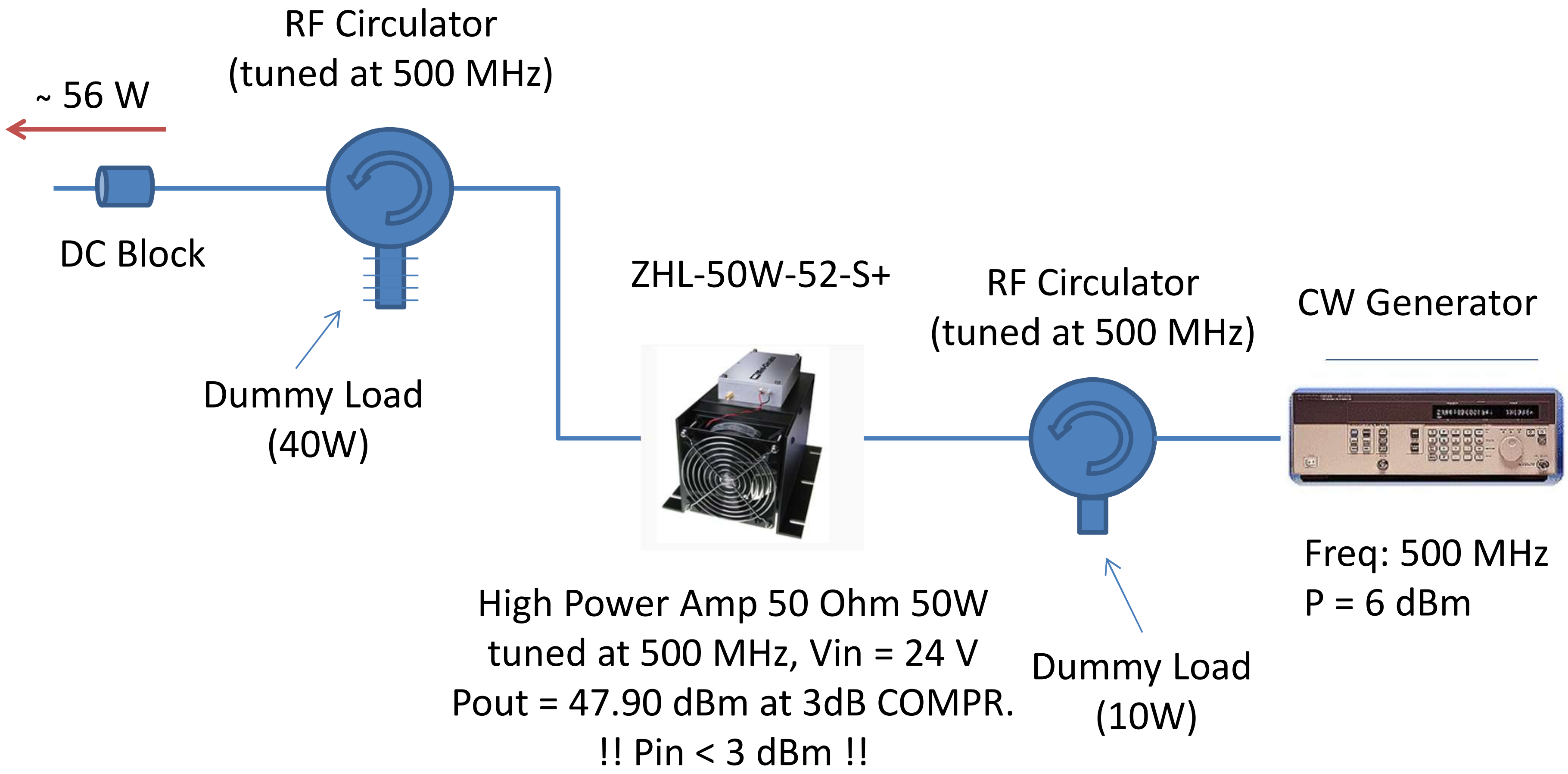


Vacuum components:

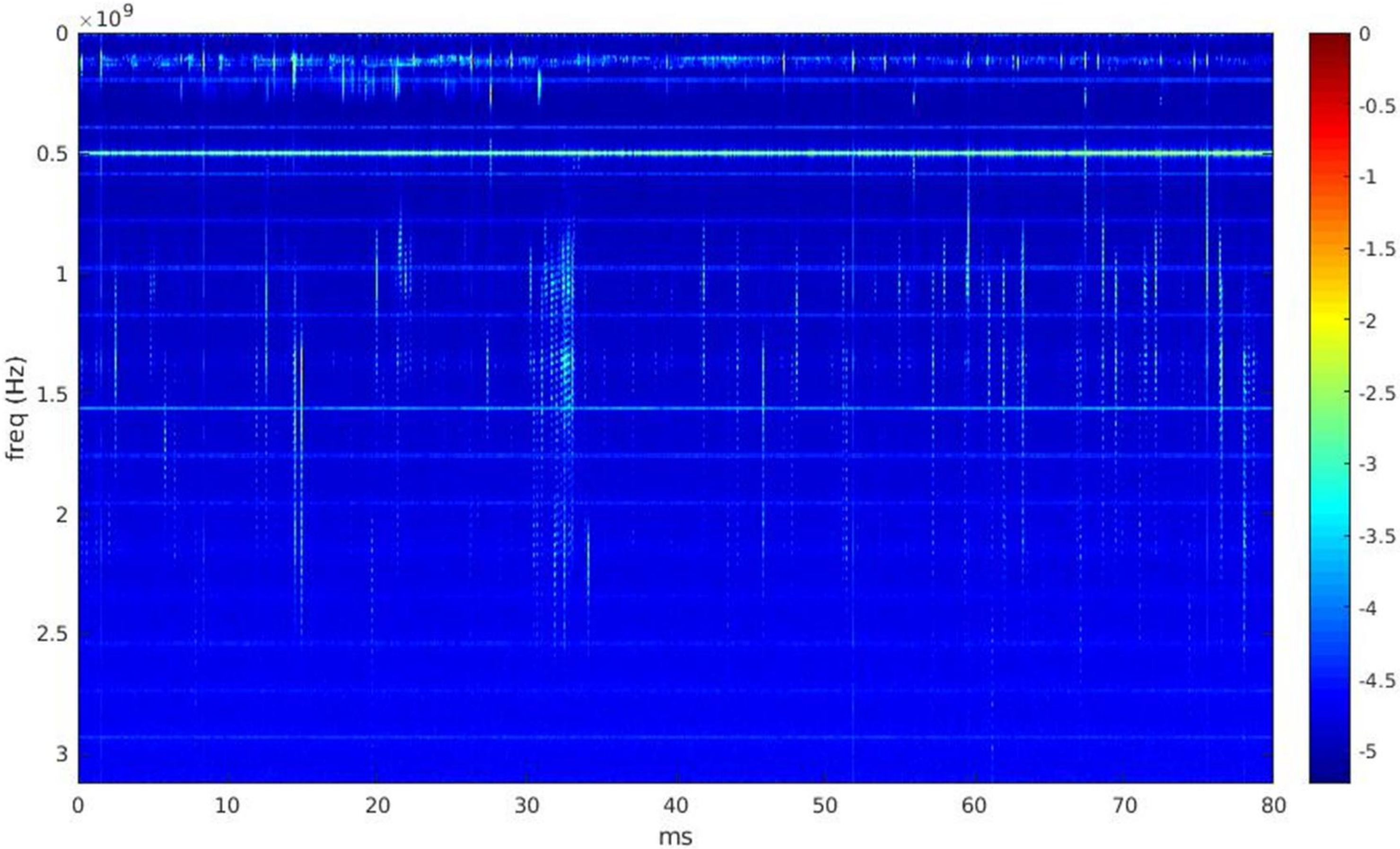
- 1 Loop (AISI 316L stainless steel)
- 1 UHV coaxial cable with SMA connectors



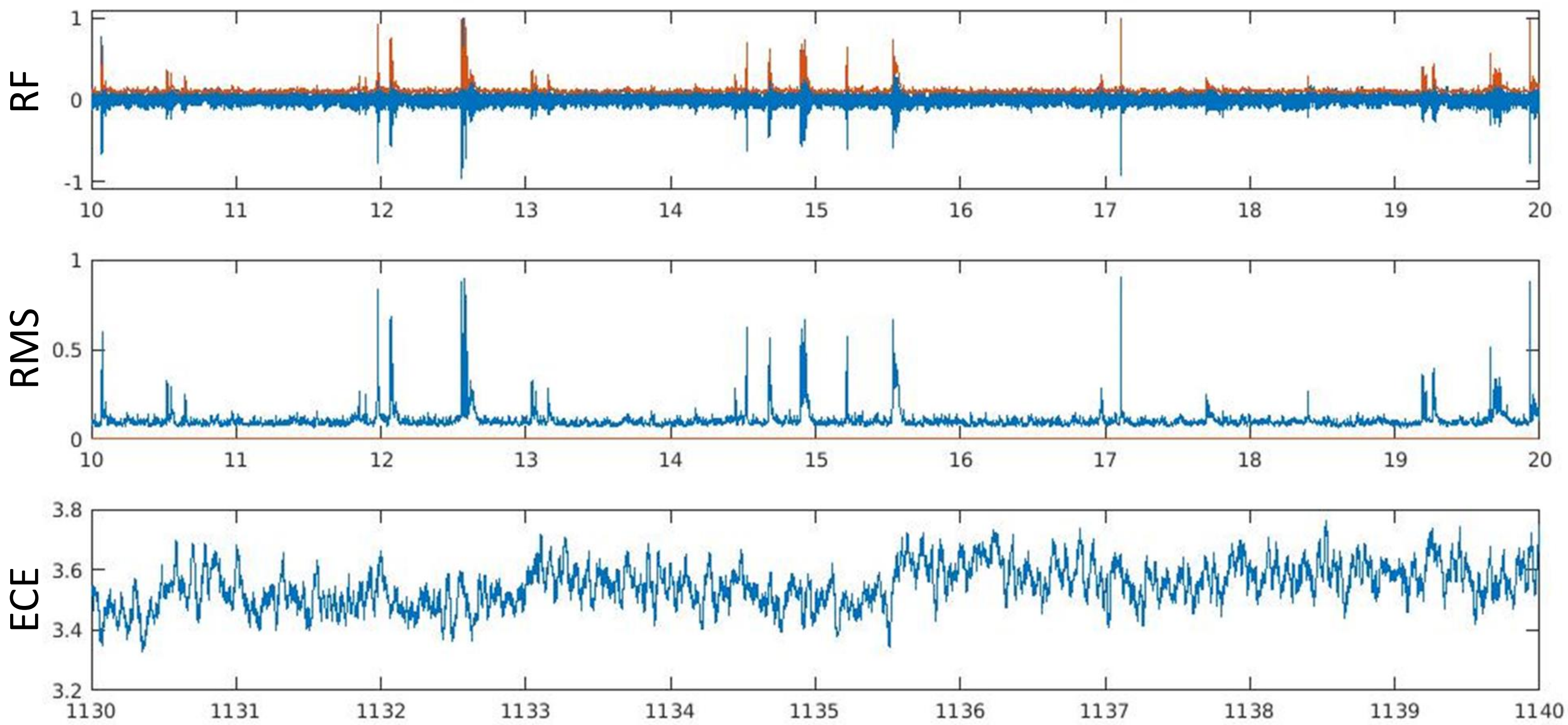
Final Tx Layout



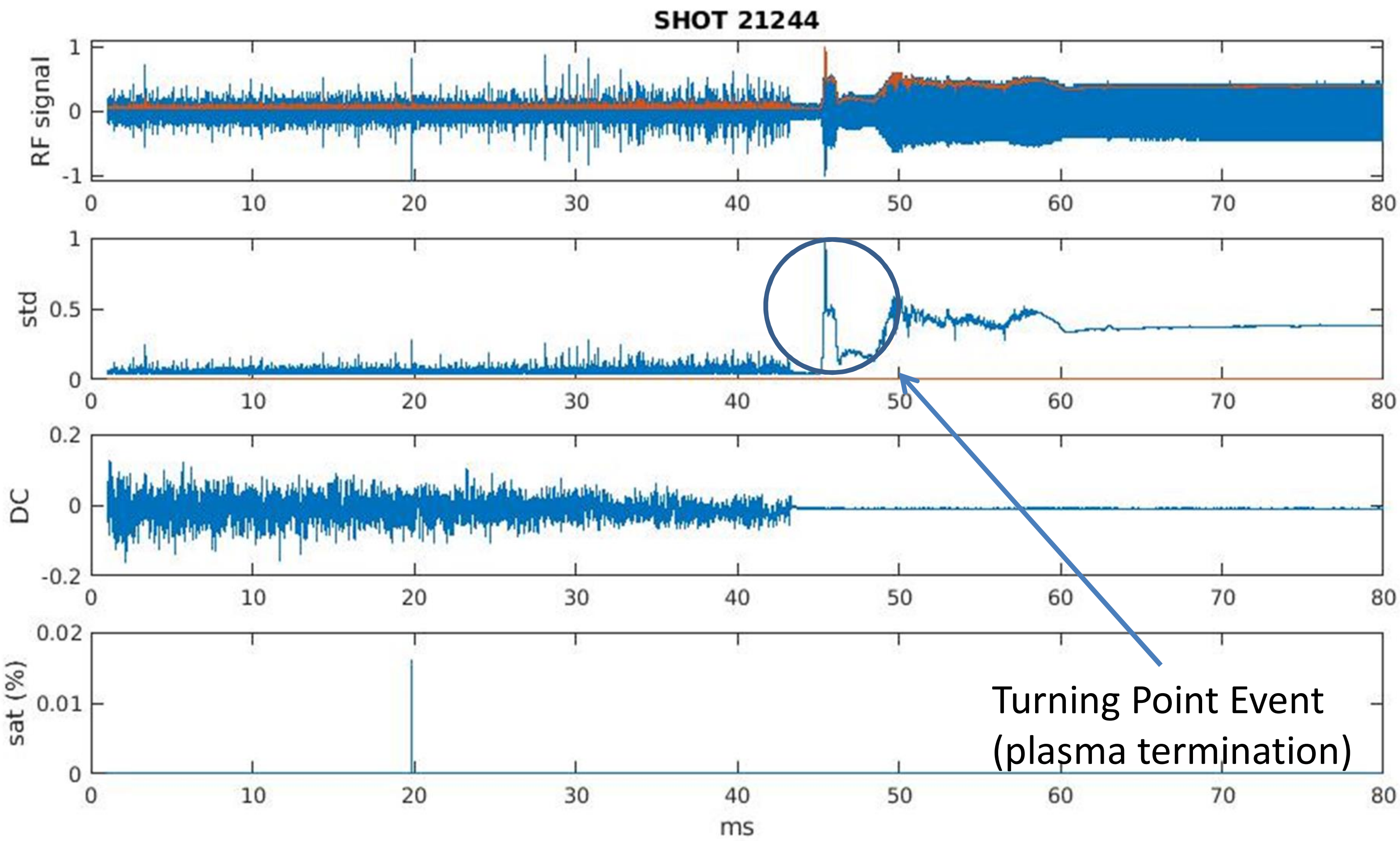
21246 – In-vessel Antenna (N)



RF Signal vs ECE

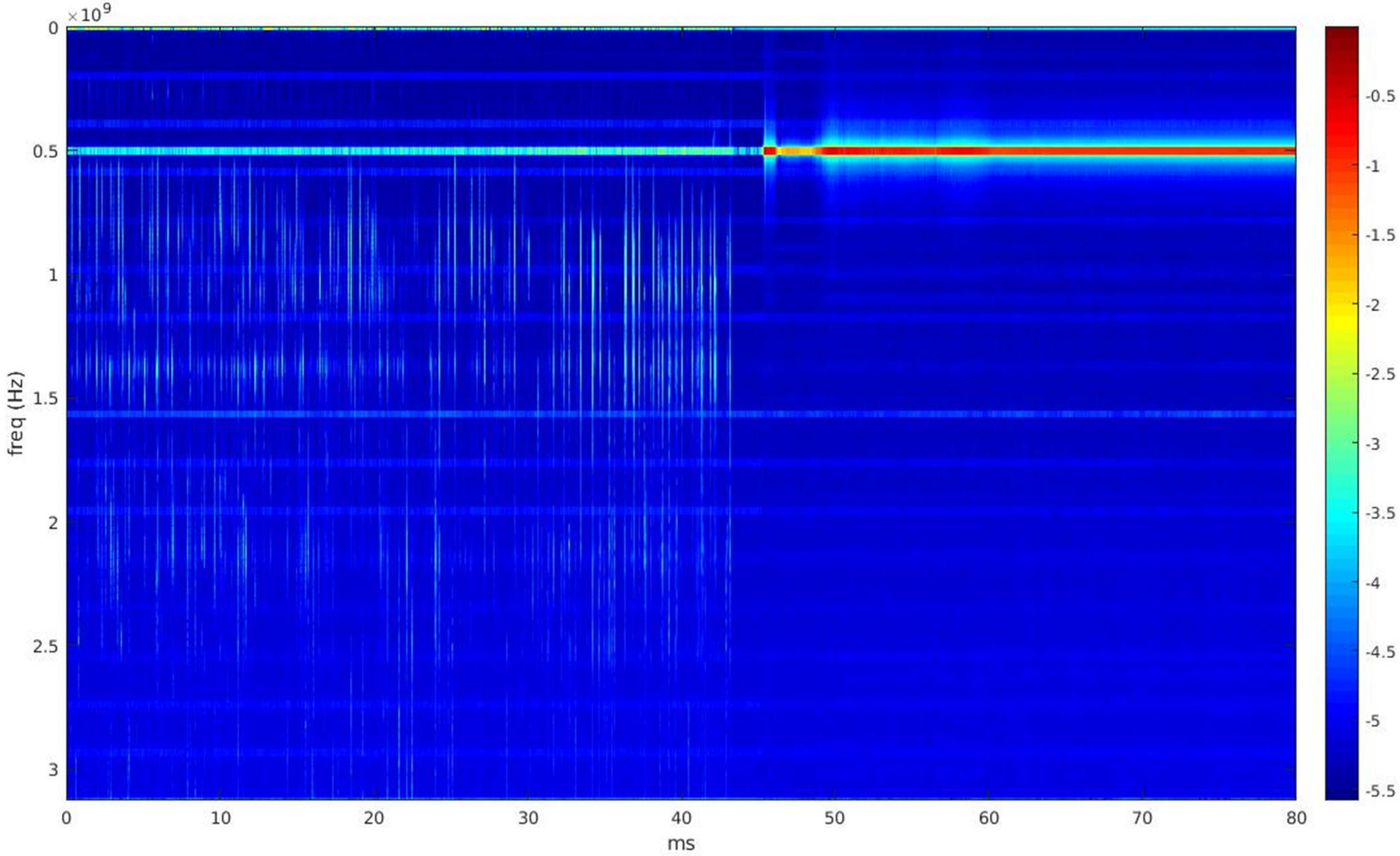


Shot 21244 - In-vessel Antenna (N)



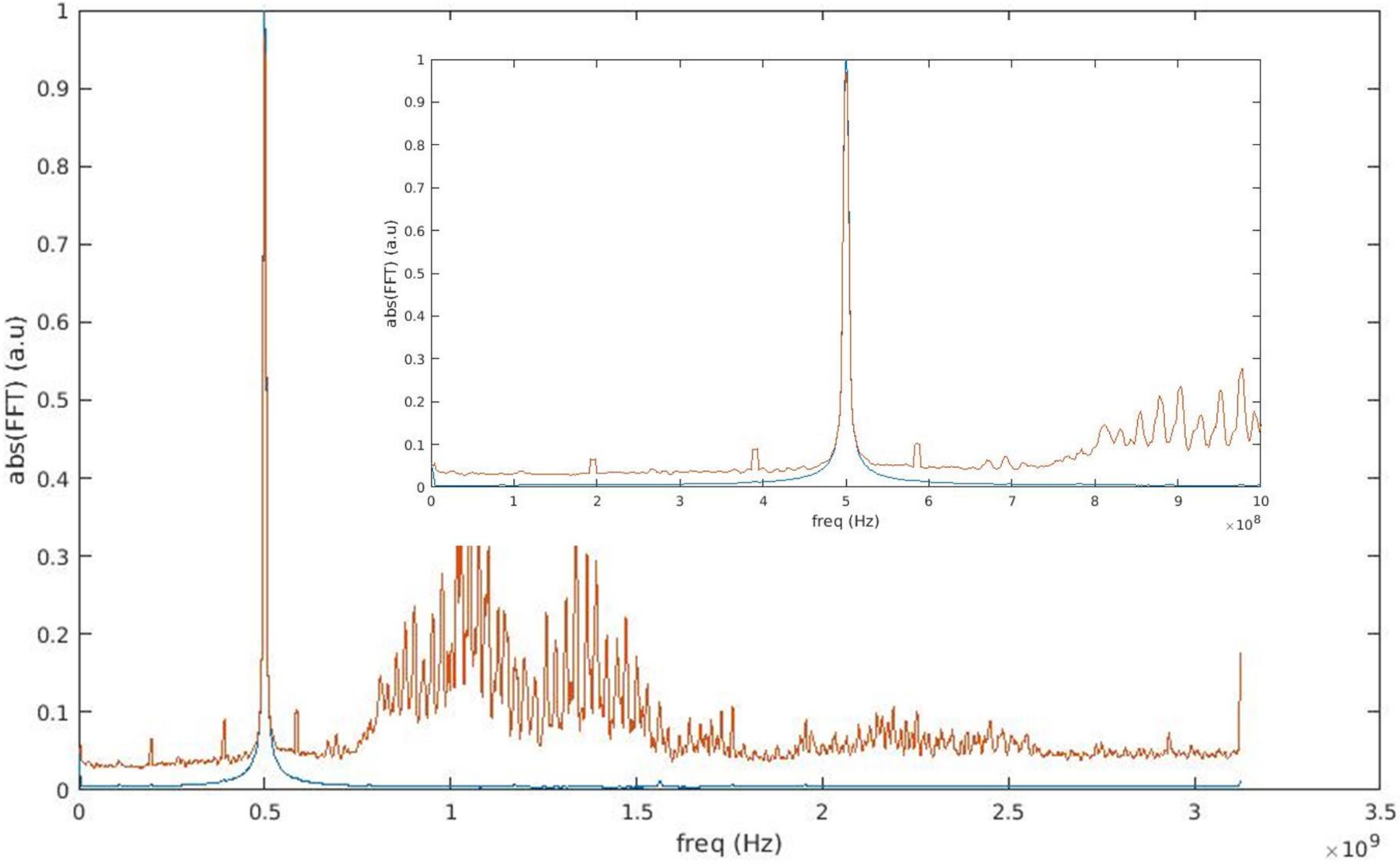
SR: 6.25 GS/s RL: 80 ms t0: ?? ms delta_t = 1 us

Spectrogram – In-vessel Antenna (N)

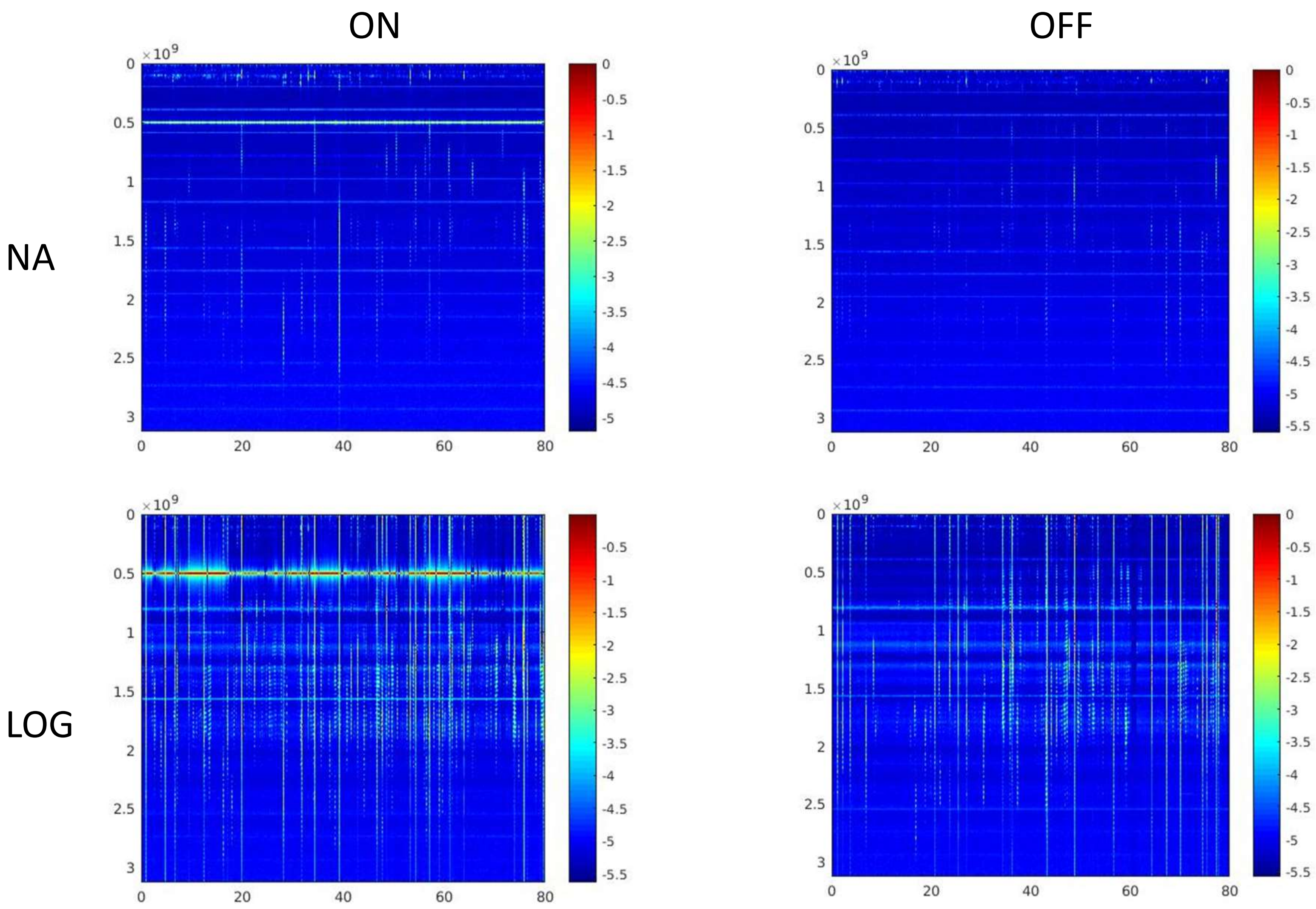


NFFT = 2048

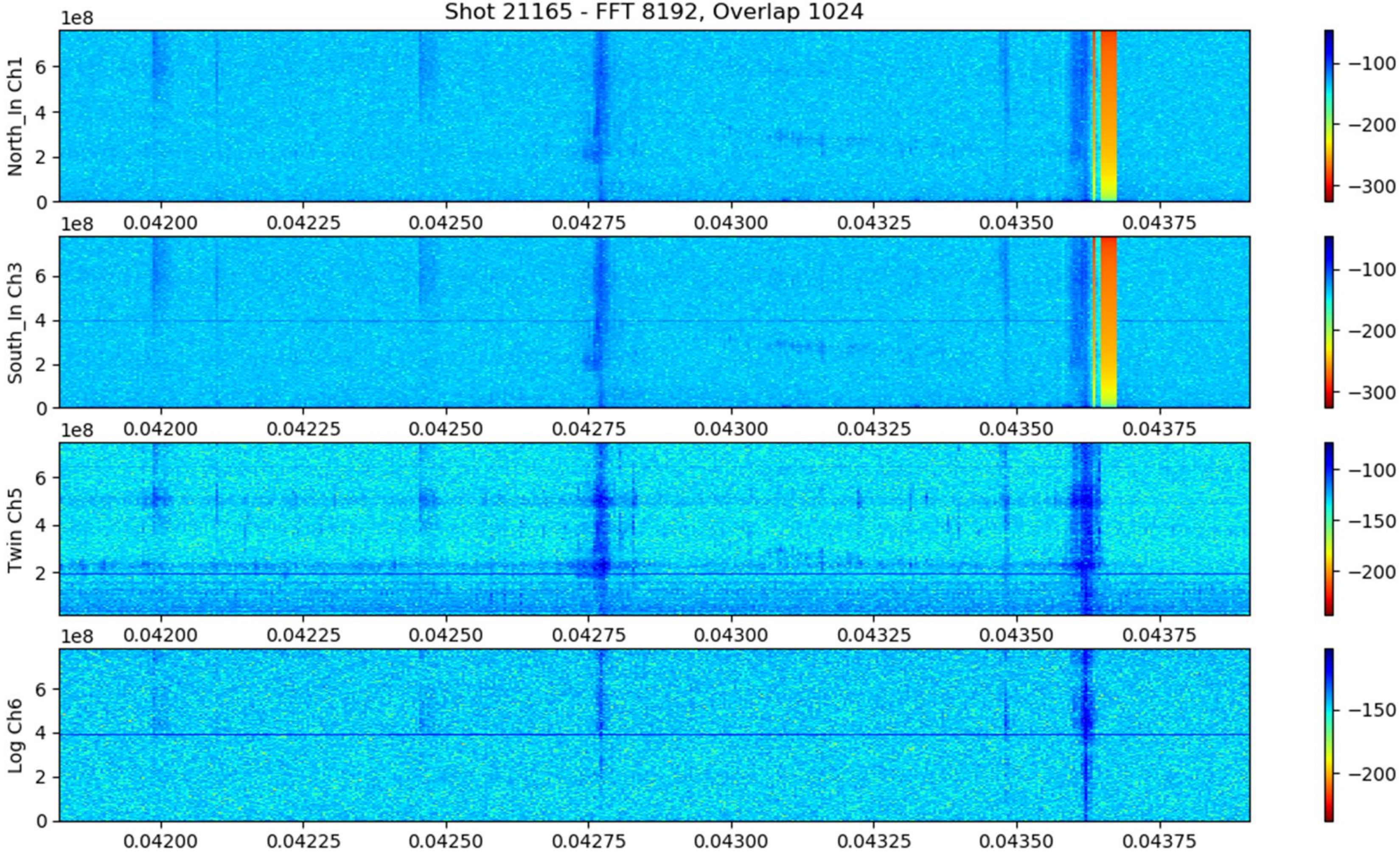
Comparison Before/After Disruption



21256 (SA on) vs 21257 (SA off) - RMPs in-vessel ant. (N) & ex-vessel ant. (LOG)

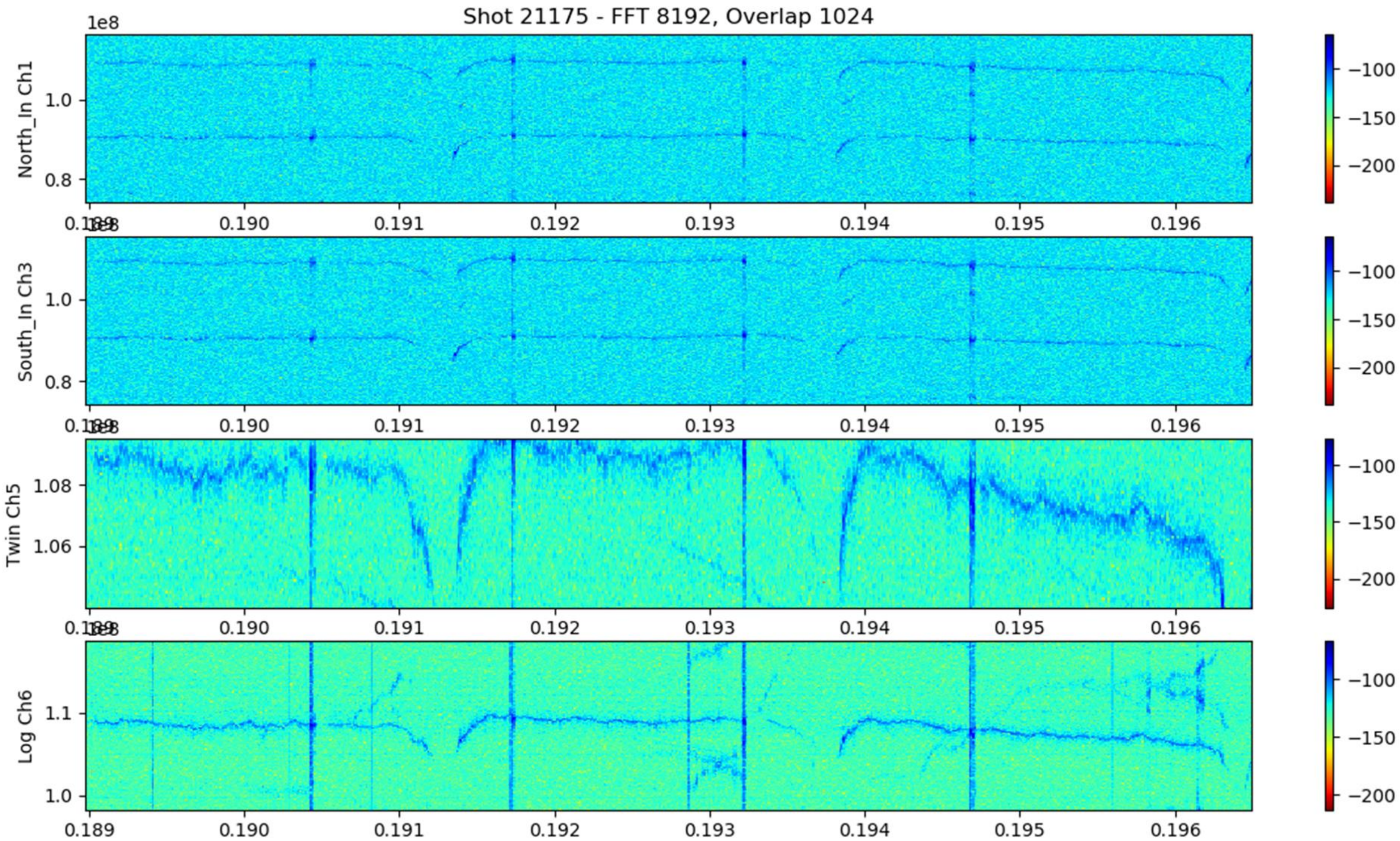


#21165



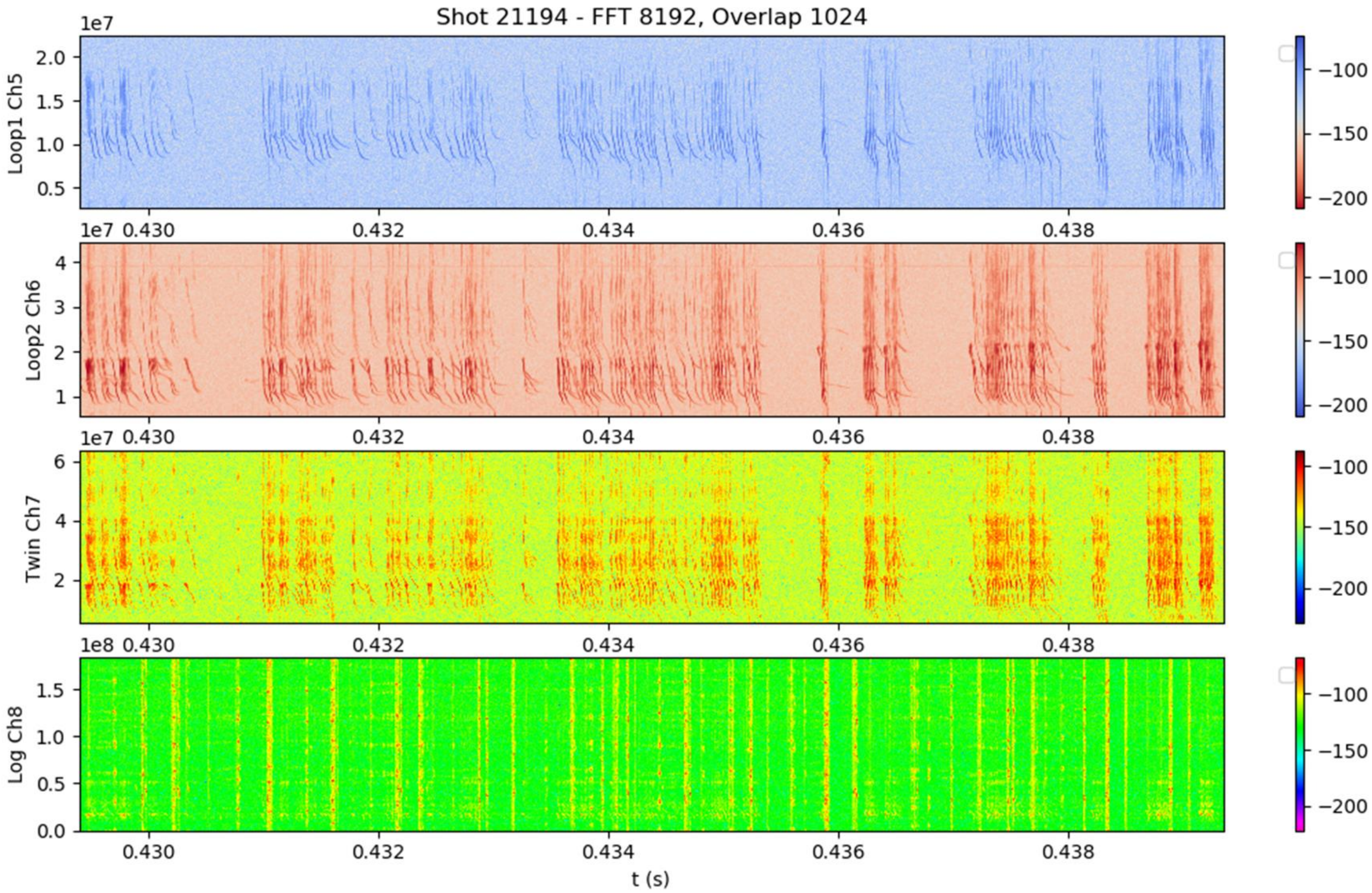
Shot 21165 - FFT 8192, Overlap 1024
North_In Ch1
South_In Ch3
Twin Ch5
Log Ch6
1e8
0.04200
0.04225
0.04250
0.04275
0.04300
0.04325
0.04350
0.04375
−100
−200
−300
−150

#21175



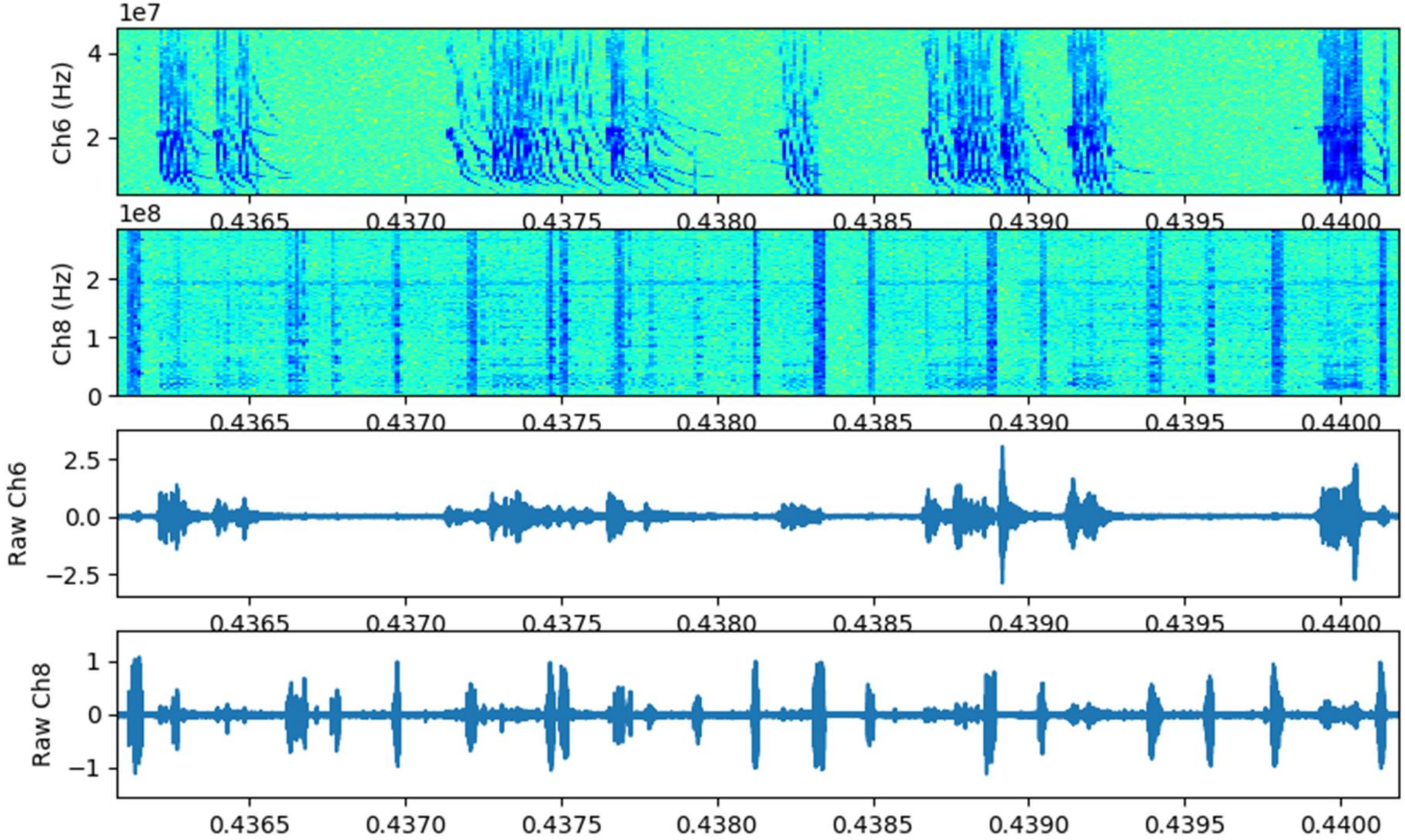
Shot 21175 - FFT 8192, Overlap 1024
1e8
North_In Ch1
South_In Ch3
Twin Ch5
Log Ch6
0.189
0.190
0.191
0.192
0.193
0.194
0.195
0.196
−100
−150
−200

#21194



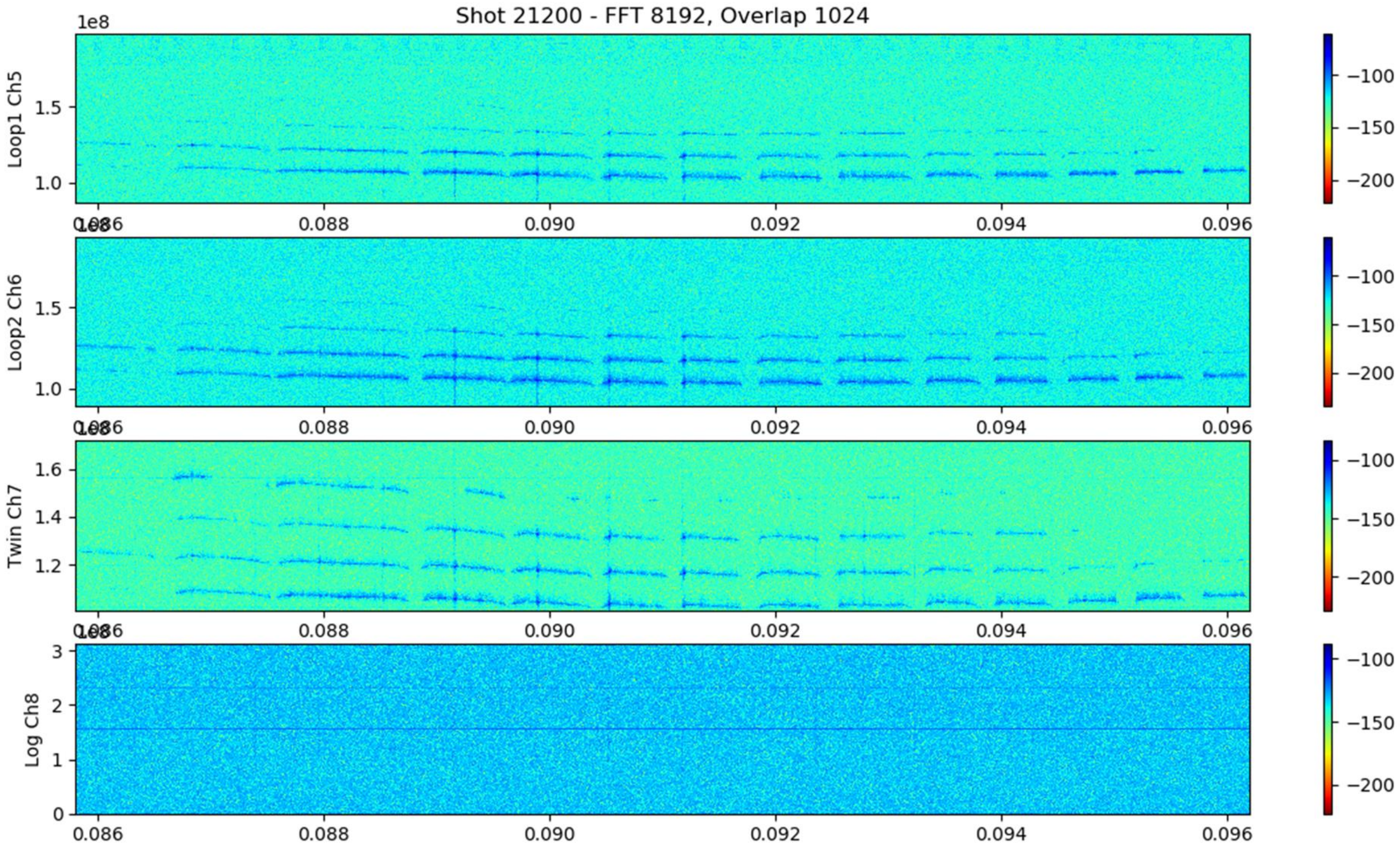
Shot 21194 - FFT 8192, Overlap 1024
1e7
2.0
1.5
1.0
0.5
Loop1 Ch5
−100
−150
−200
1e7
0.430
0.432
0.434
0.436
0.438
4
3
2
1
Loop2 Ch6
−100
−150
−200
1e7
0.430
0.432
0.434
0.436
0.438
6
4
2
Twin Ch7
−100
−150
−200
1e8
0.430
0.432
0.434
0.436
0.438
1.5
1.0
0.5
0.0
Log Ch8
−100
−150
−200
0.430
0.432
0.434
0.436
0.438
t (s)

#21194



1e7
Ch6 (Hz)
4
2
1e8
Ch8 (Hz)
2
1
0
Raw Ch6
2.5
0.0
−2.5
Raw Ch8
1
0
−1
0.4365
0.4370
0.4375
0.4380
0.4385
0.4390
0.4395
0.4400

#21200

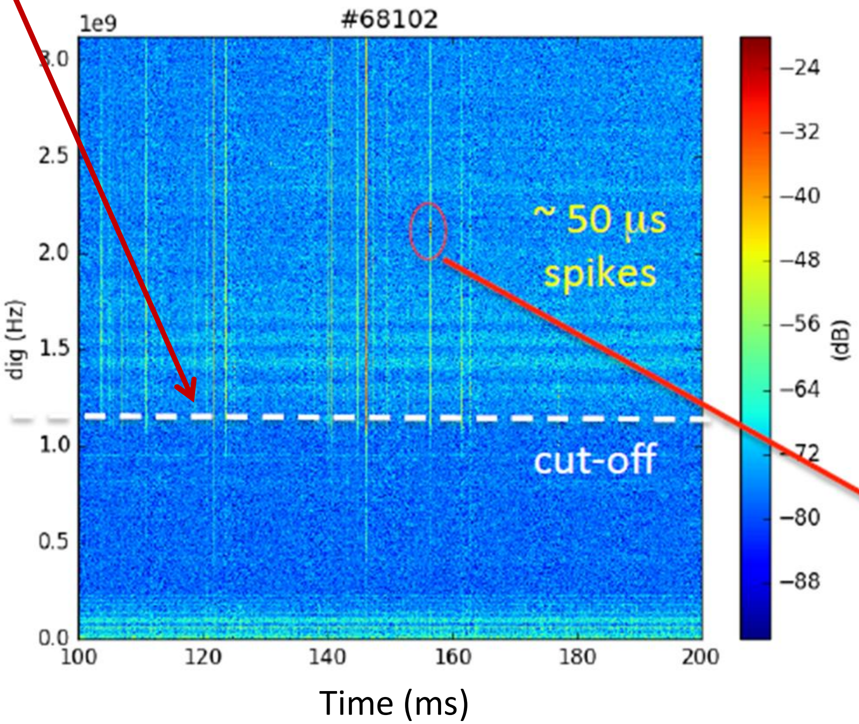


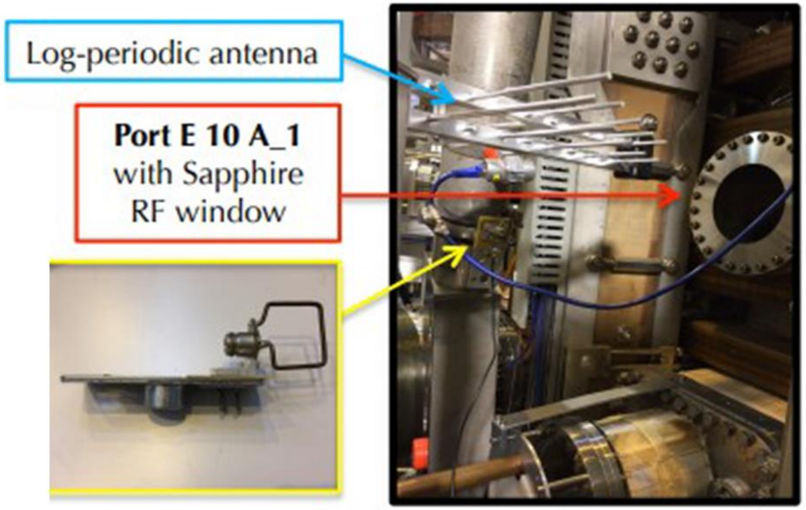
Shot 21200 - FFT 8192, Overlap 1024
1e8
Loop1 Ch5
Loop2 Ch6
Twin Ch7
Log Ch8
0.086
0.088
0.090
0.092
0.094
0.096
−100
−150
−200

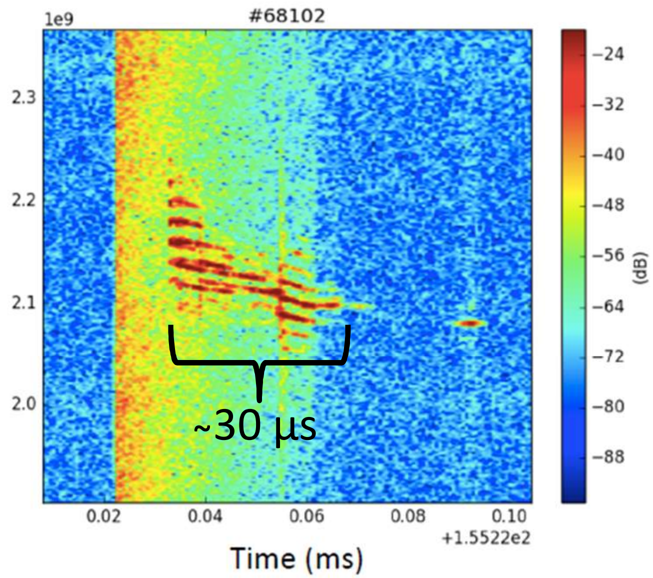
TCV – ex-vessel antennas (2020)

Log-periodic antenna, double-shielded 50 Ohm coaxial cable and DAS as in FTU setup;

TCV port with higher cut-off freq. ~1.17 GHz.

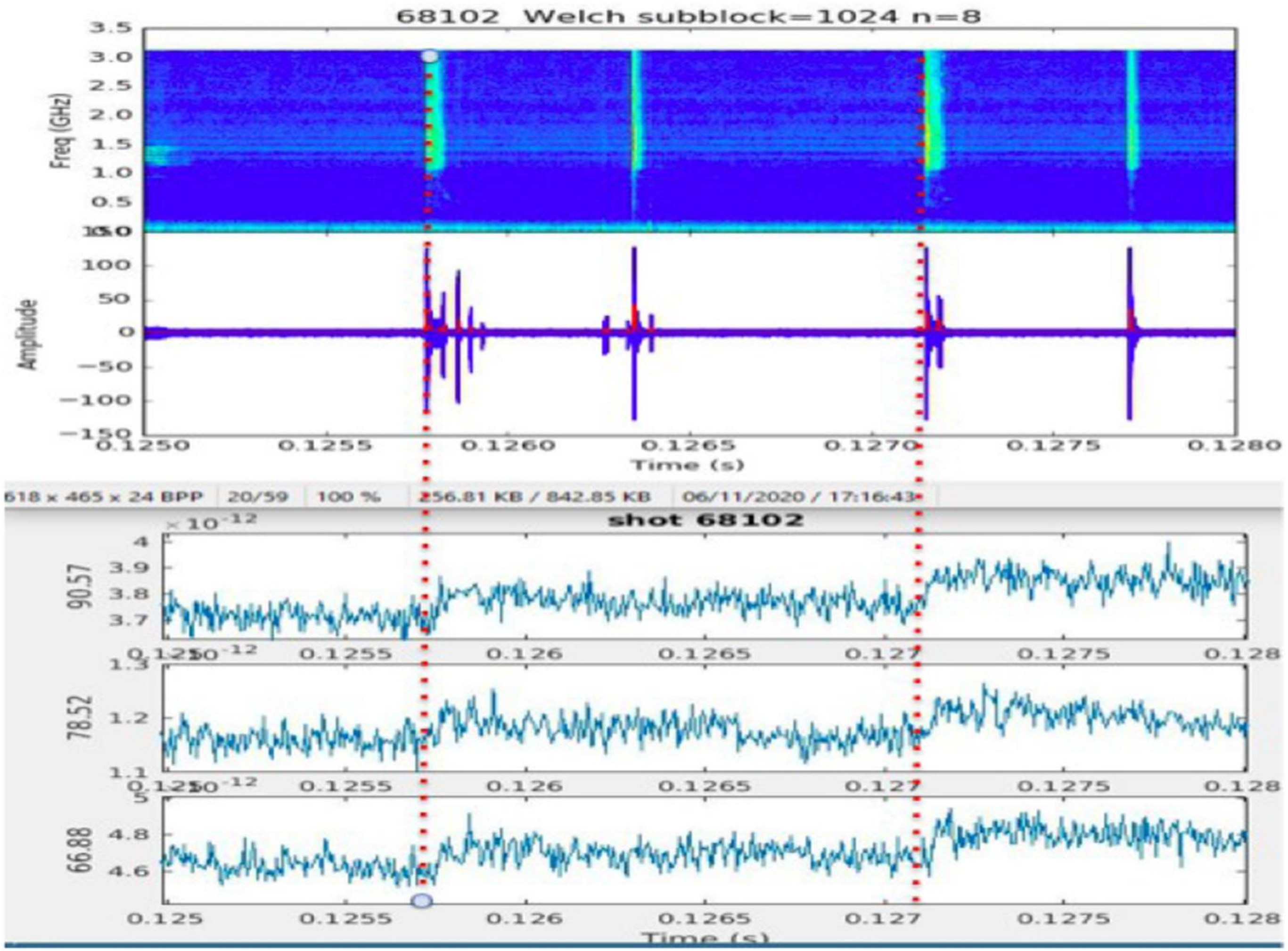






Two ex-vessel antennas:
One small loop antenna (resonant at ~2.5 GHz – gain 3.41 dB – 20% imp. mismatch)
One log-periodic antenna (UHF – gain 8 dB – 2% imp. mismatch)

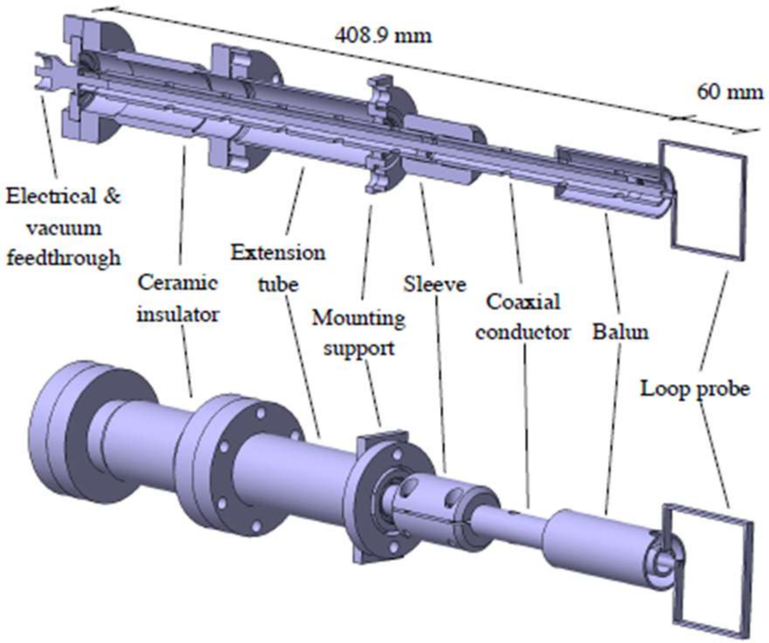
TCV

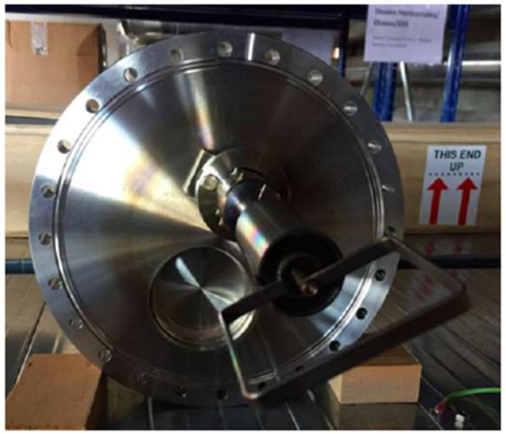


Longer broadband events seem correlated to jumps in ECE signals (ADI)

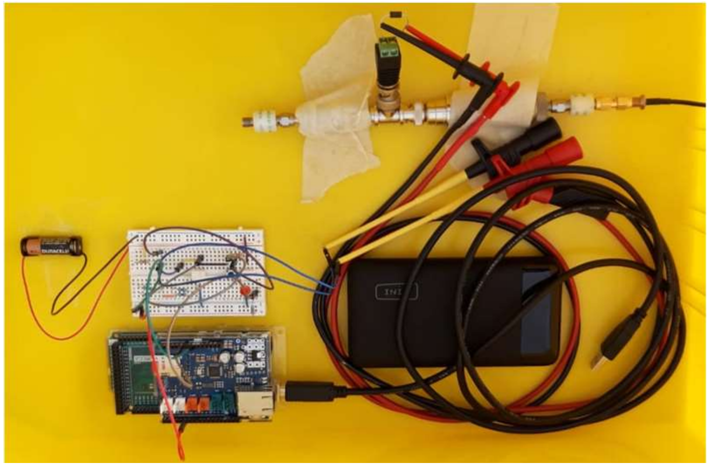
TCV in-vessel antenna (2021-2022)

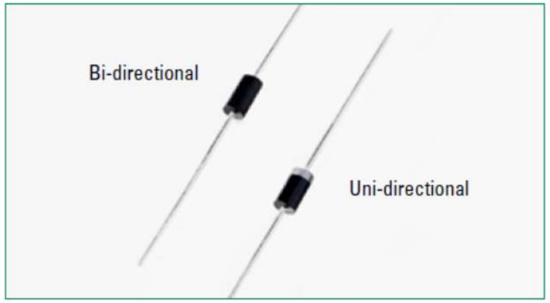
- The LHPI loop-antenna was designed and built (AISI 316L) in the Swiss Plasma Center (SPC) to work as an in-vessel antenna of TCV in the frequency range of 0.1-3.0 GHz;
- Originally designed to detect LH decay waves generated by parametric instabilities in O-X-B mode conversion experiments;
- The antenna is a square loop 60 mm x 60 mm, made of a folded 1.5 mm-tick 5 mm-wide plate in order to have a low self-inductance;
- A rigid coaxial cable of length 40.2 cm with a 53 Ohm characteristic impedance is connected with the loop-probe and at the other end is welded with a type-N electrical feedthrough mounted on a port flage; the internal rod is held in place by two PEEK insulating rings;
- A simmetry coupler (balun) is welded on the outer part of the coaxial cable, designed at 1 GHz (expected LH decay frequency at X-B mode experiments);
- The LHPI antenna is connected to the NI PXIe-5186 fast digitizer (8 bit, 12.5GS/s, 5GHz) with a shielded low attenuation coaxial cable;
- The LHPI antenna is at the same ground of the acquisition system (different from TCV vessel ground), i.e. It is electrically isolated from the vacuum vessel: a ceramic insulator is inserted between the port flange and the antenna flange.
- DC blocks, attenuators and transient-voltage-suppression (TVS) diodes has been used to protect the data acquisition system;

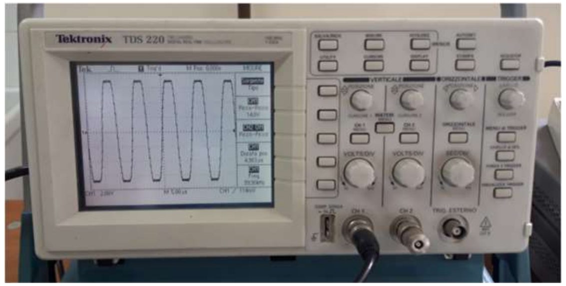


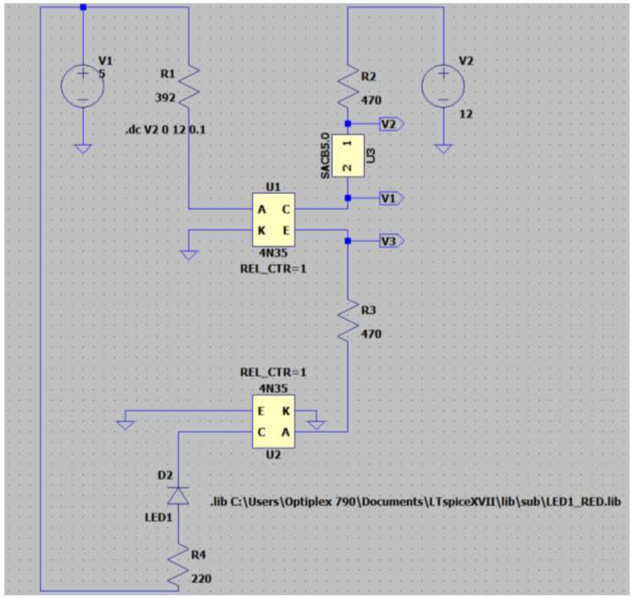


Electronic Diagnostic Circuit for TVS Protection Status

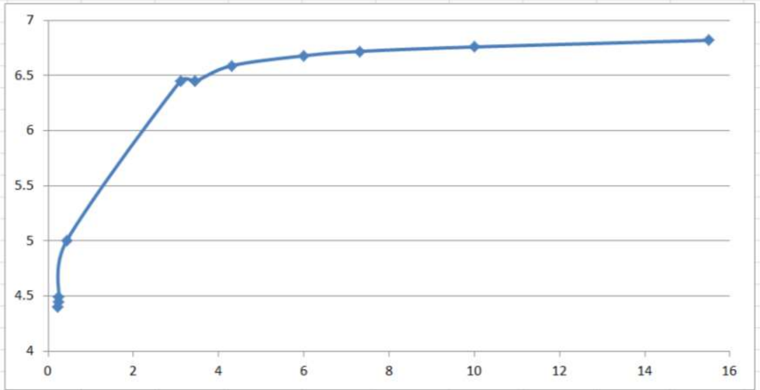




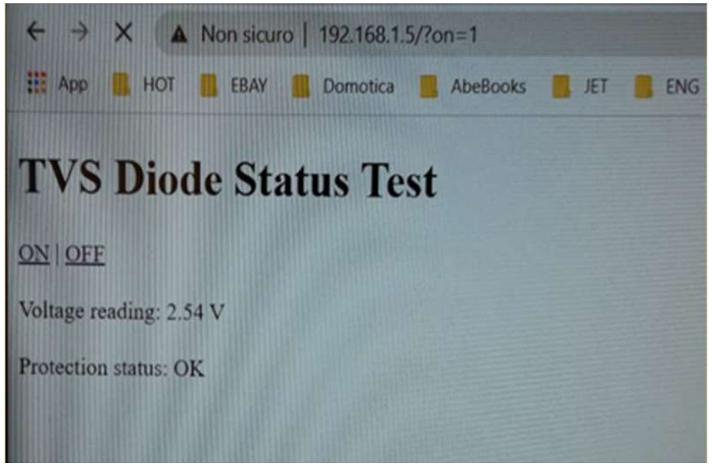


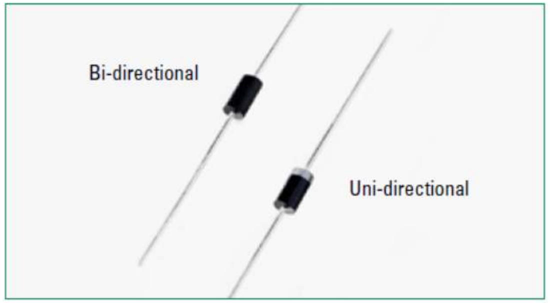


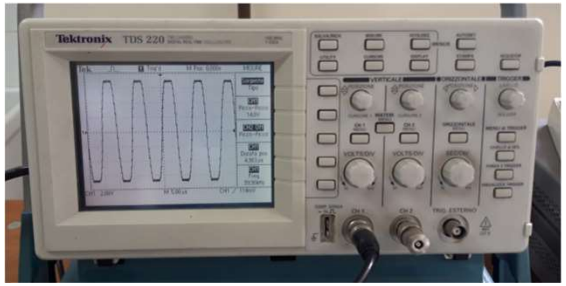
Rs (Ohm)	Is (mA)	Vd (V)
110	15.5	6.82
220	10	6.76
330	7.32	6.72
440	6	6.68
660	4.3	6.59
880	3.45	6.45
1000	3.1	6.45
2000	0.43	5
3000	0.25	4.49
4000	0.24	4.45
5100	0.23	4.4

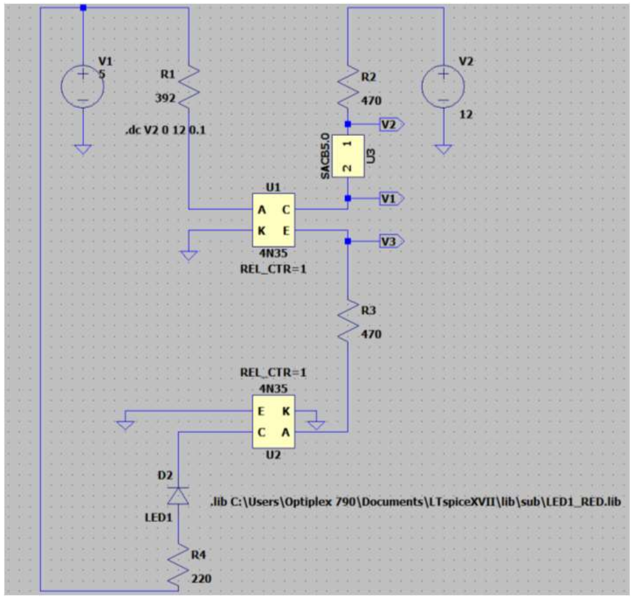


Electronic Diagnostic Circuit for TVS Protection Status









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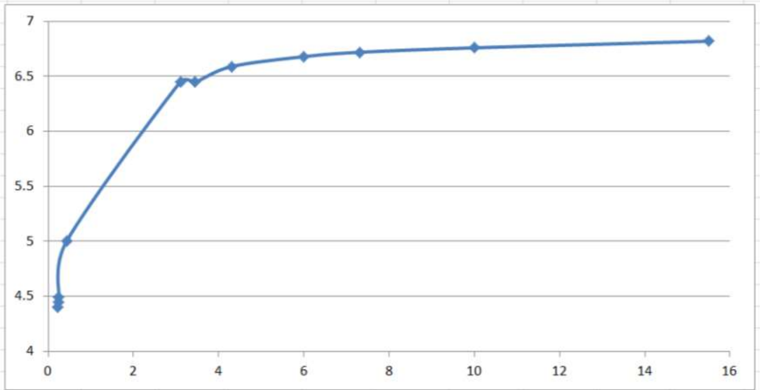

Conclusions

- More work on modeling and data analysis is needed;
- We need more manpower!
- We have enough expertise to build new experiments and new diagnostics in this field;
- In the near feature, for COMPASS-U and DTT, it is likely that we can design and test new RE mitigation systems based on RF tools.


THANK YOU