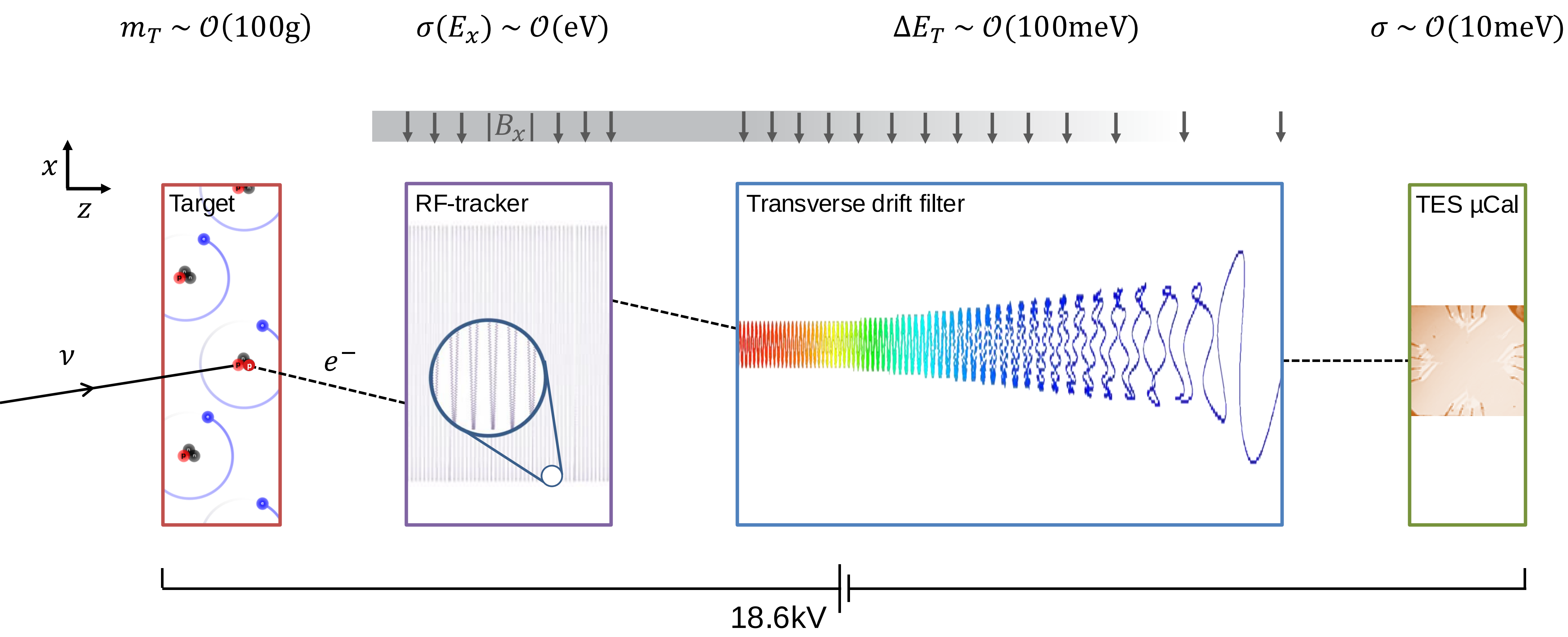
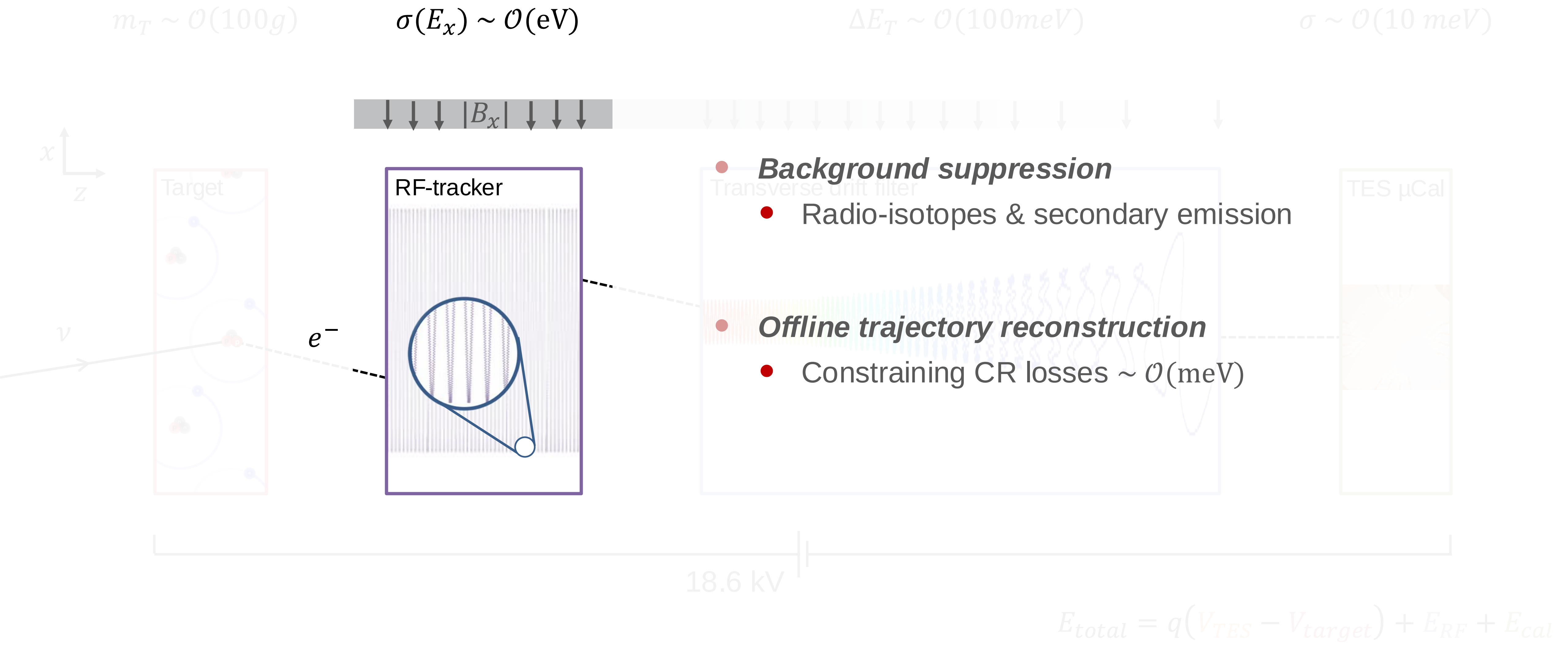
***Amsterdam activities*: Progress report**

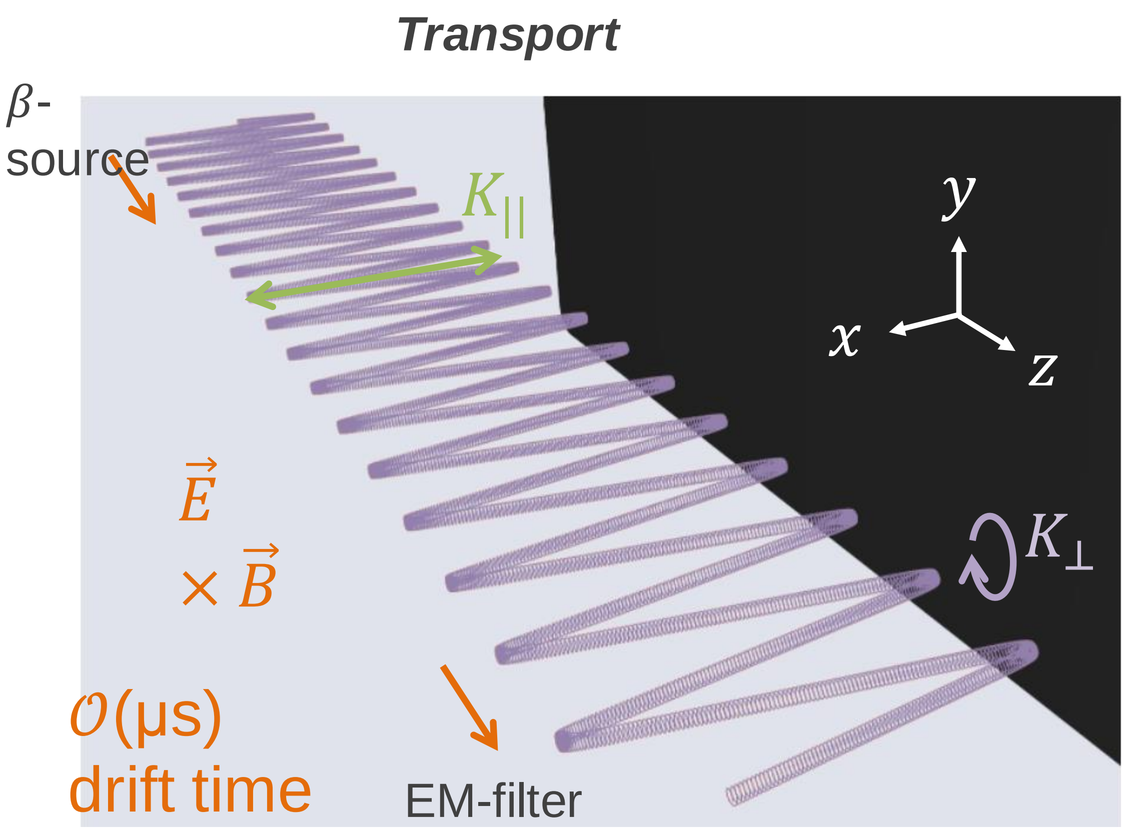
James Vincent Mead

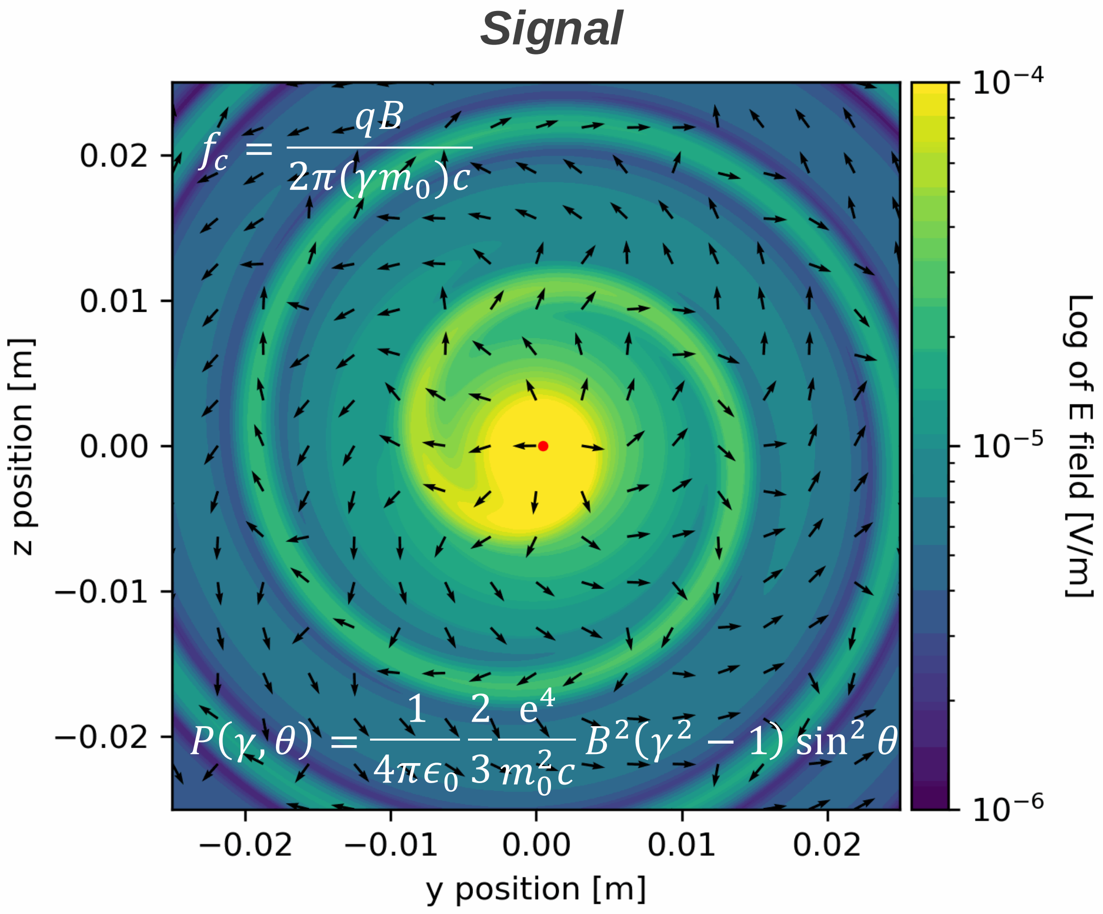


$$E_{total} = q(V_{TES} - V_{target}) + E_{RF} + E_{cal}$$



- ***Background suppression***
  - Radio-isotopes & secondary emission
- ***Offline trajectory reconstruction***
  - Constraining CR losses ~ $\mathcal{O}(\text{meV})$



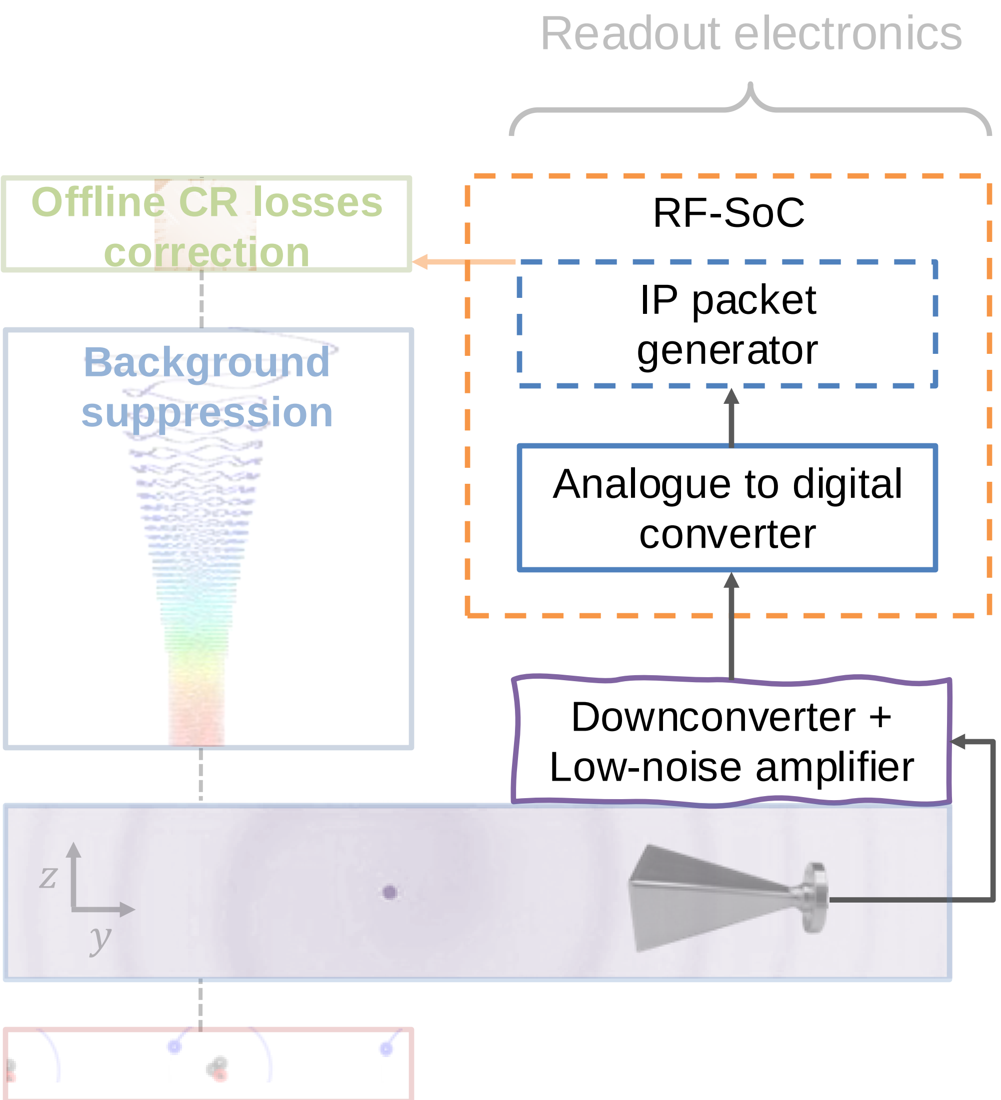


Tan, Princeton

El Morabit, UvA

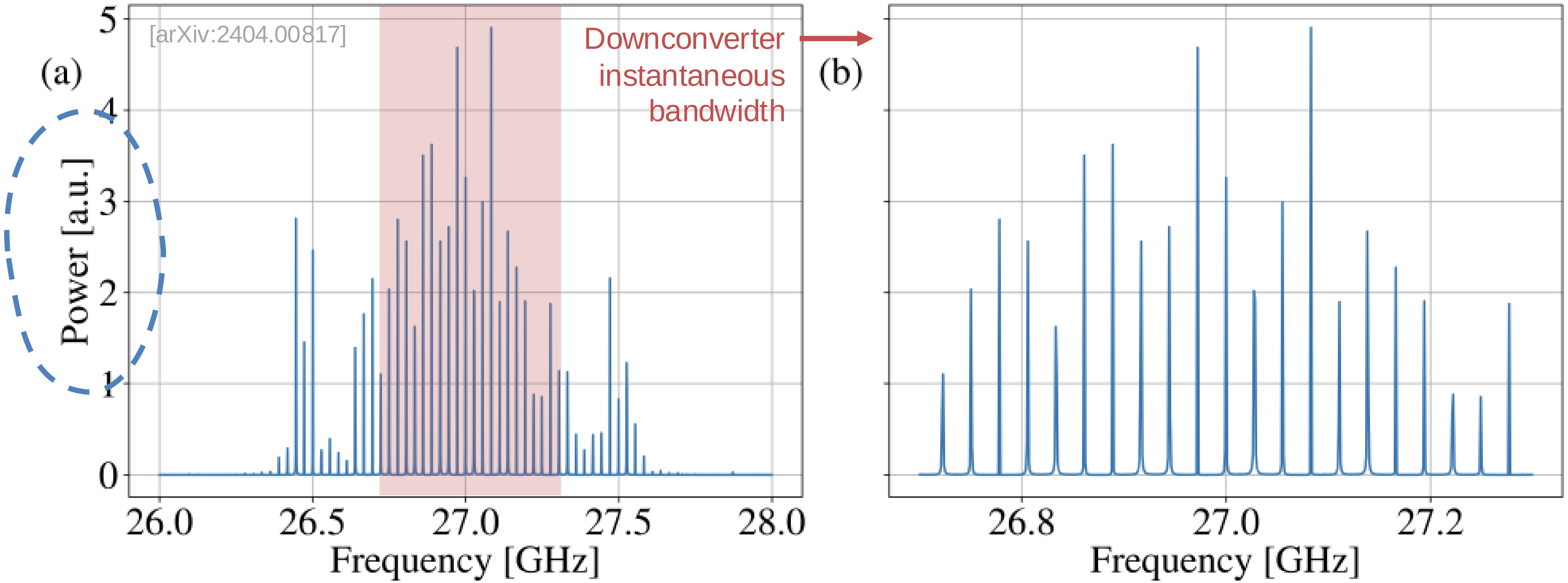
RF readout & electronics

- ***Cyclotron radiation emission spectroscopy***
  - CR power from single electron: $\sim 1\ \mathrm{fW}$
  - CR frequency from 18.6 keV in 1T: $\sim 27\ \mathrm{GHz}$
- ***Cryogenic low noise amplifier***
  - Dominates SNR
  - Gain ~ 28dB
  - Noise figure ~ 1dB
- ***HF analogue electronics***
  - CR signal mixed to 450 MHz in two stages
  - Downconverter gain ~ 55dB
  - Downconverter noise figure ~ 5dB
  - Digitized with 5 GHz sampling rate



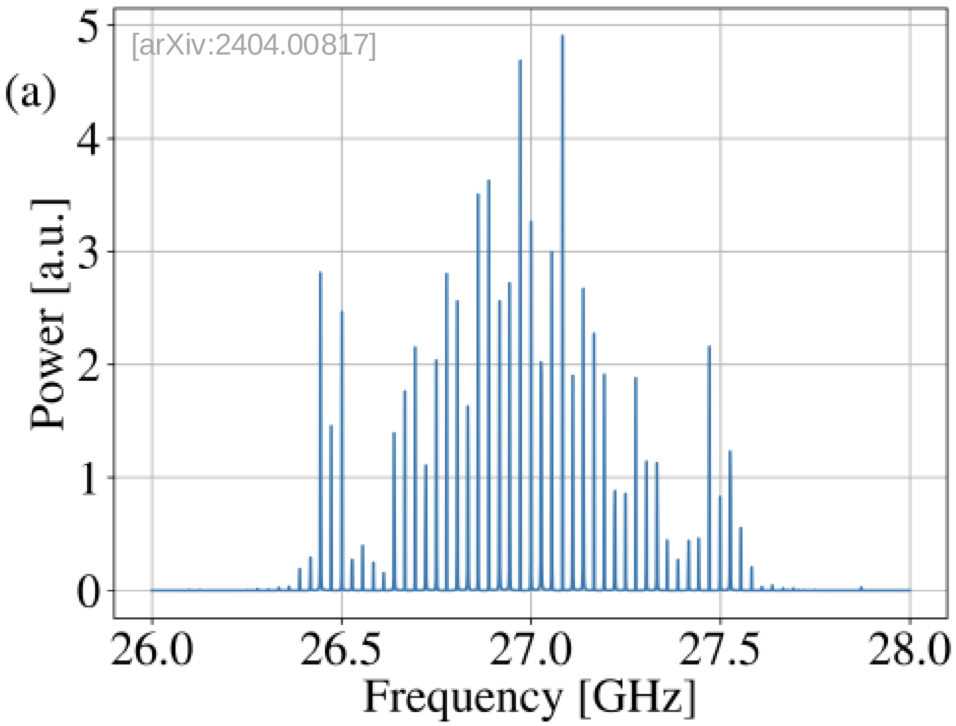
SNR expectation

Detailed CST simulation – electron bouncing at y,z=0 for 1μs

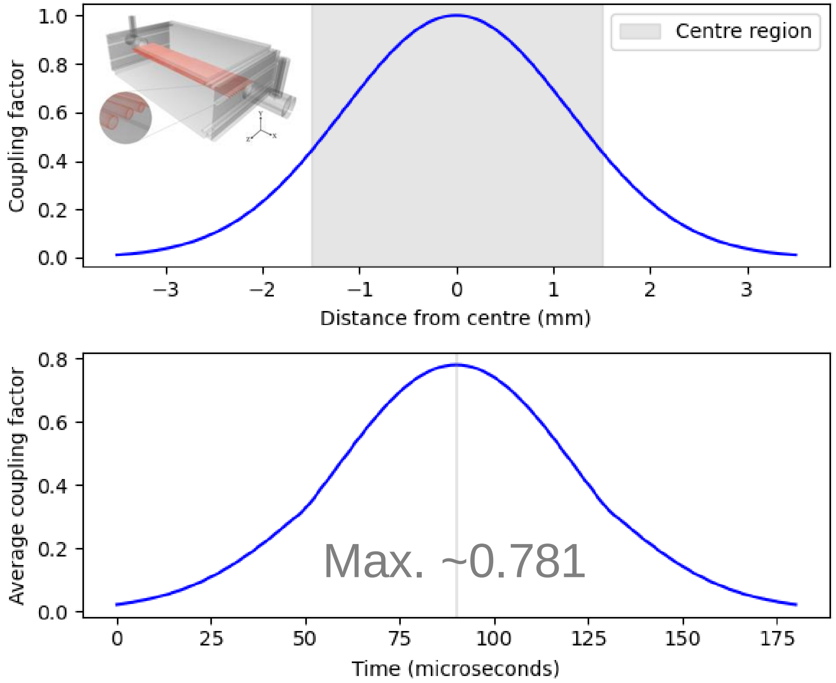


Iwasaki, Princeton

Further sanity check of shape of spectra due to AM from antenna · ExB required



Normalise spectrum to 2x time-averaged power*

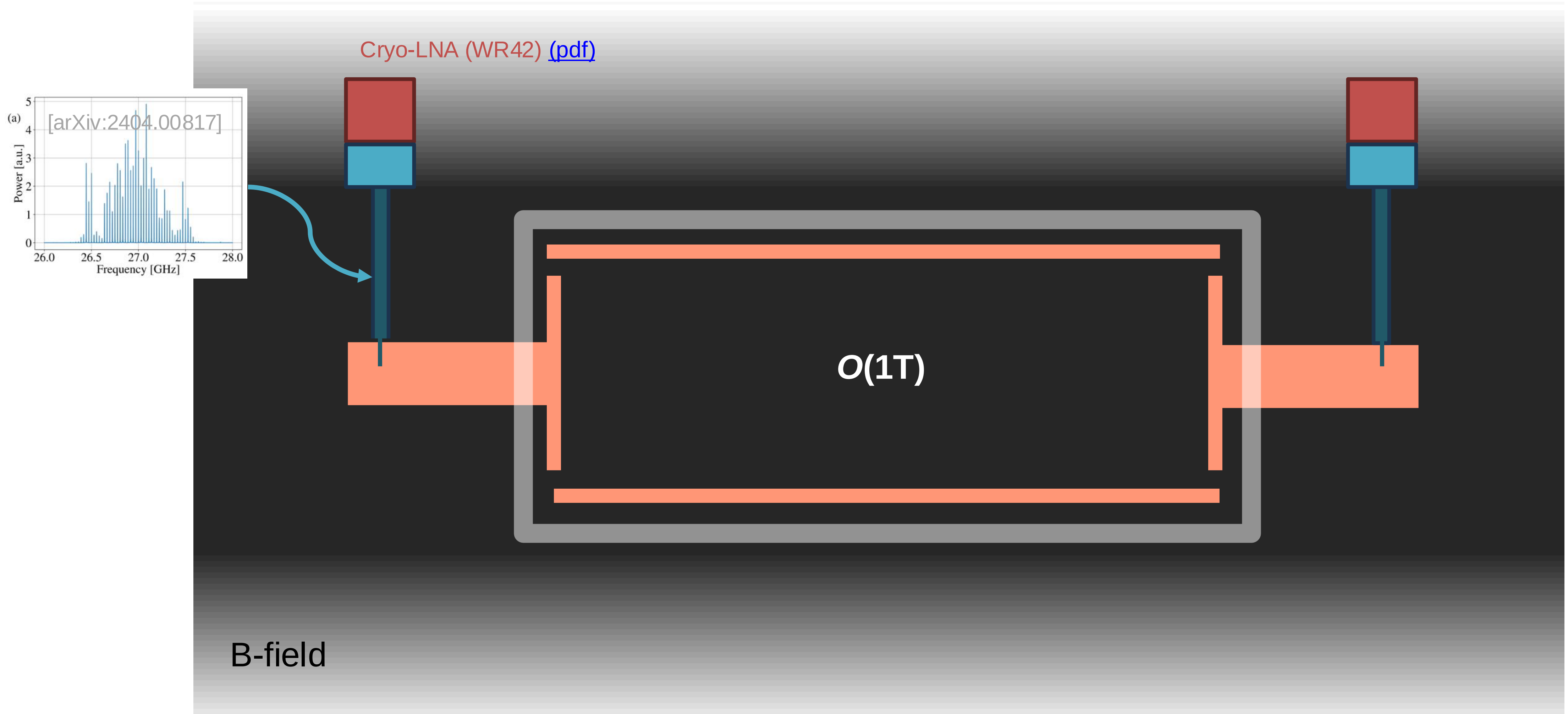


$50ms^{-1}$ ExB drift traversing 3mm in 60µs

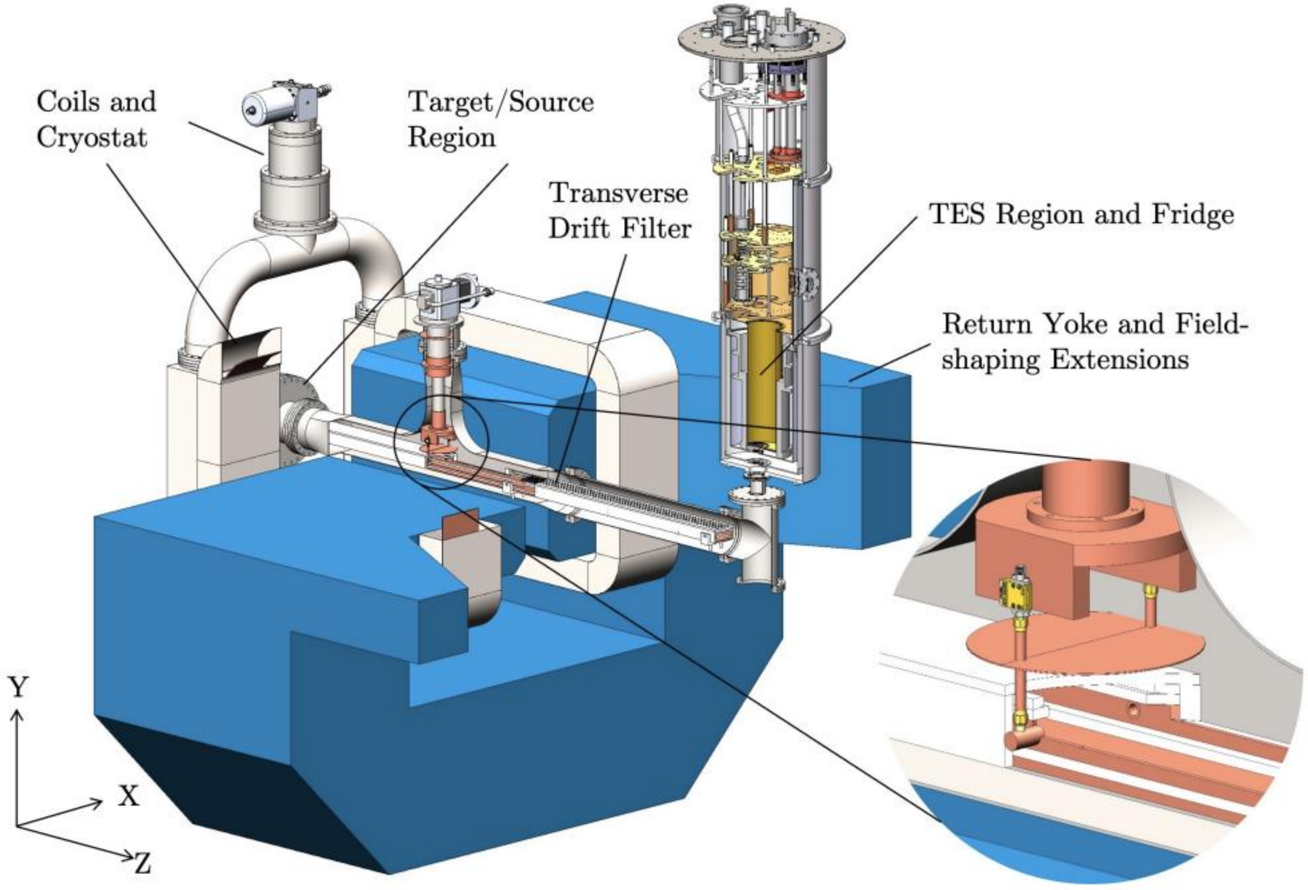
*see backup slides

gitlab

O(1mT)

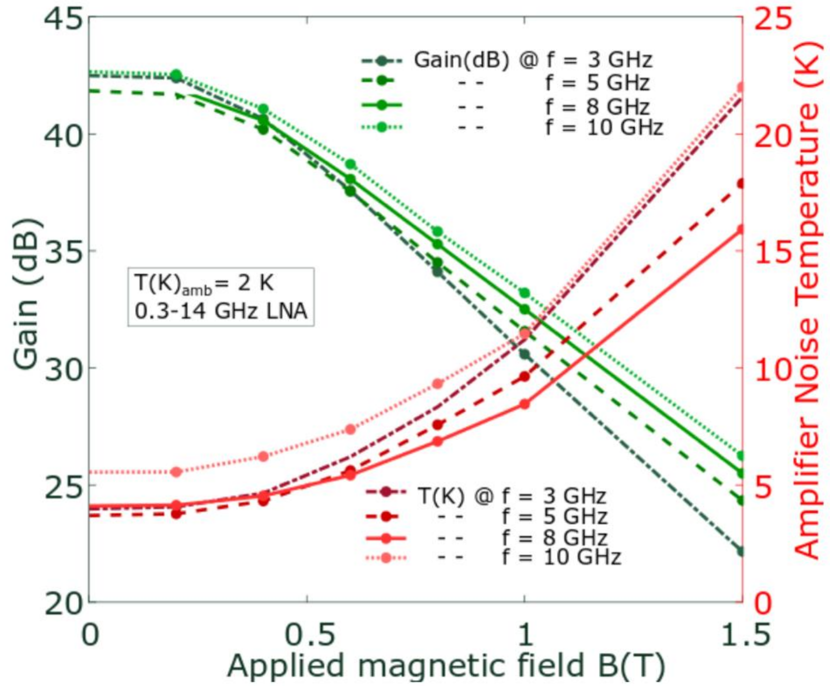

Cryo-LNA (WR42) (pdf)
[arXiv:2404.00817]
(a)
Power [a.u.]
Frequency [GHz]
O(1T)
B-field

LNA noise temperature in a B-field



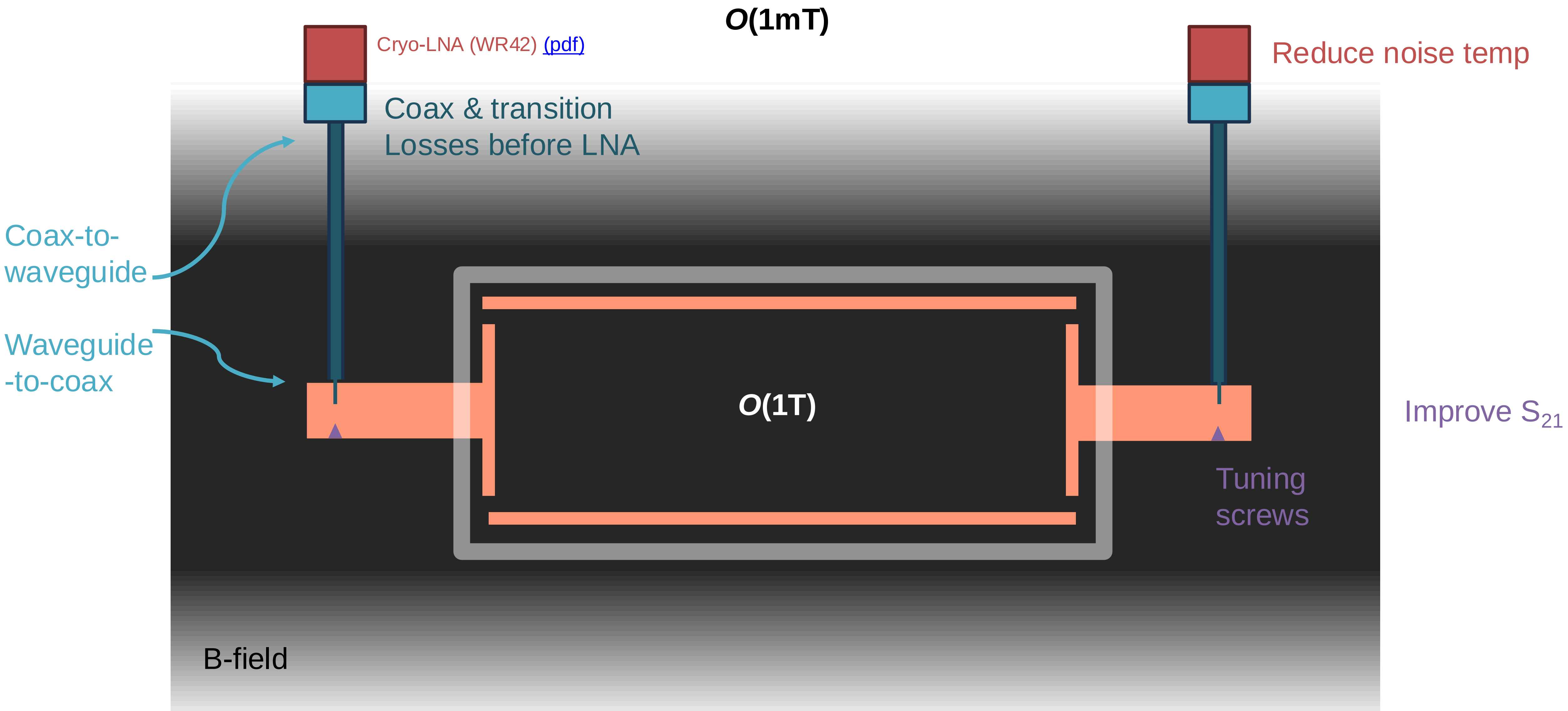
[arXiv:2404.00817]

[AIP Advances 9, 085004 (2019)]

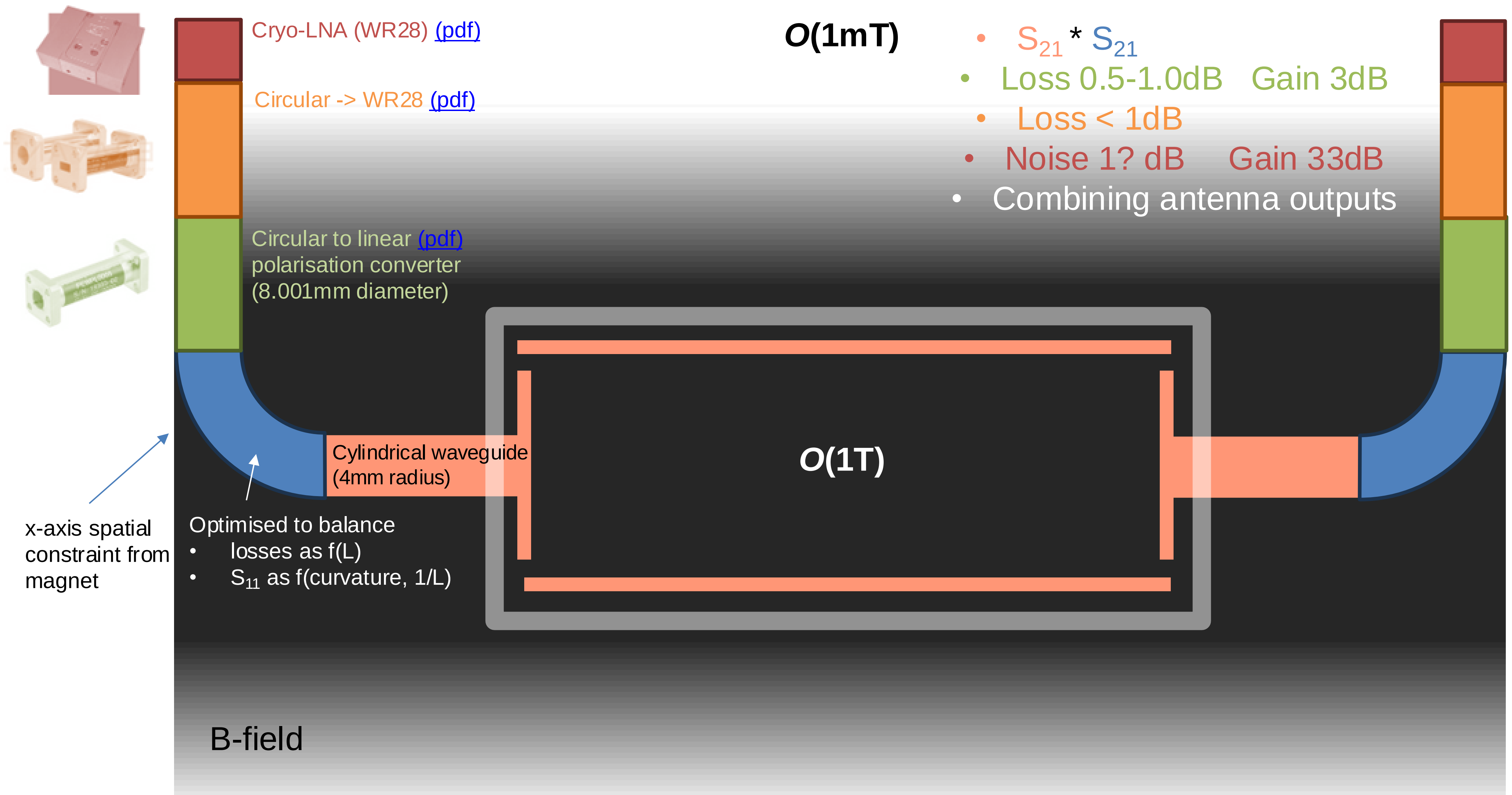


Factor ~2 increase in noise temperature from 0 - 1T

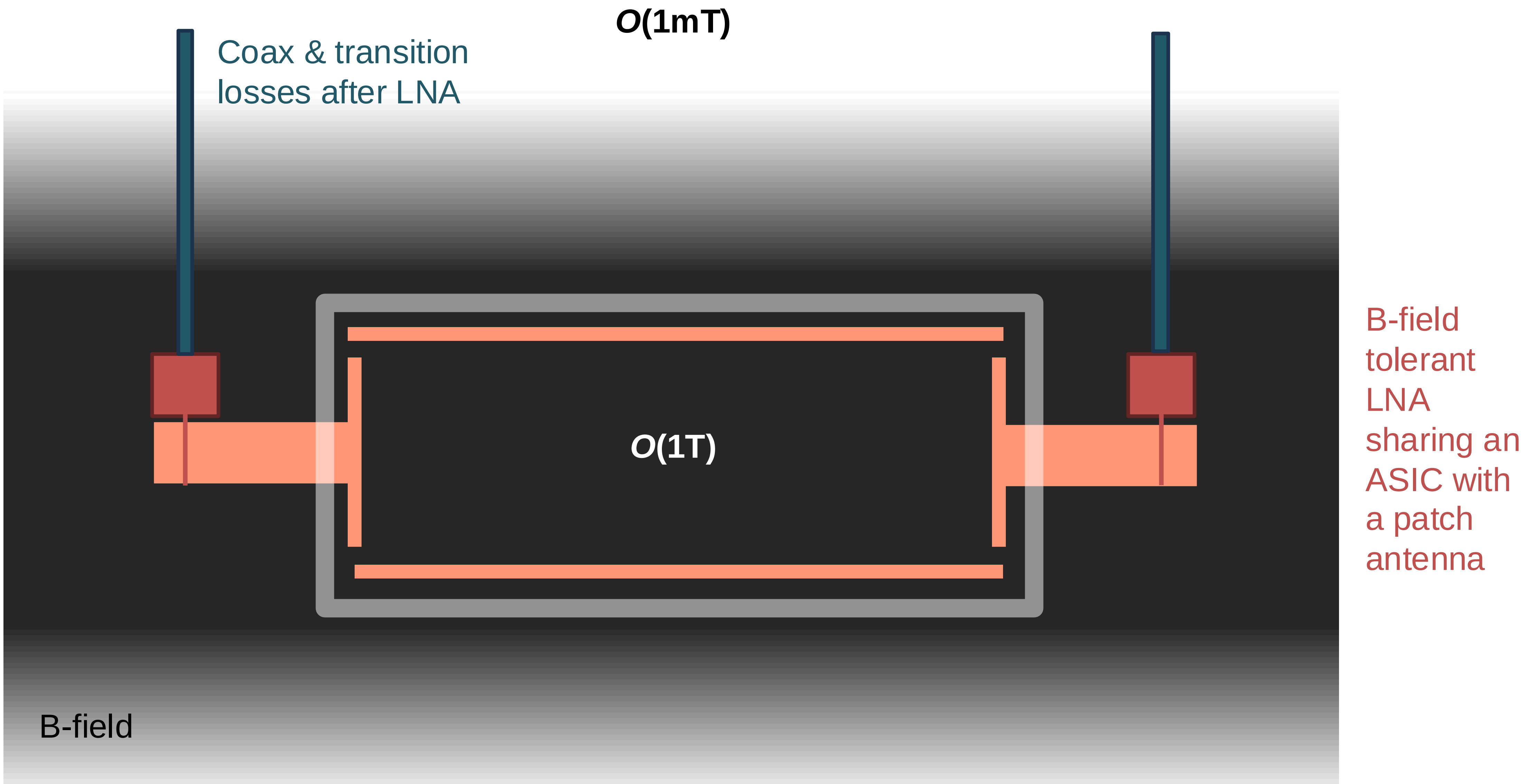
Probable changes



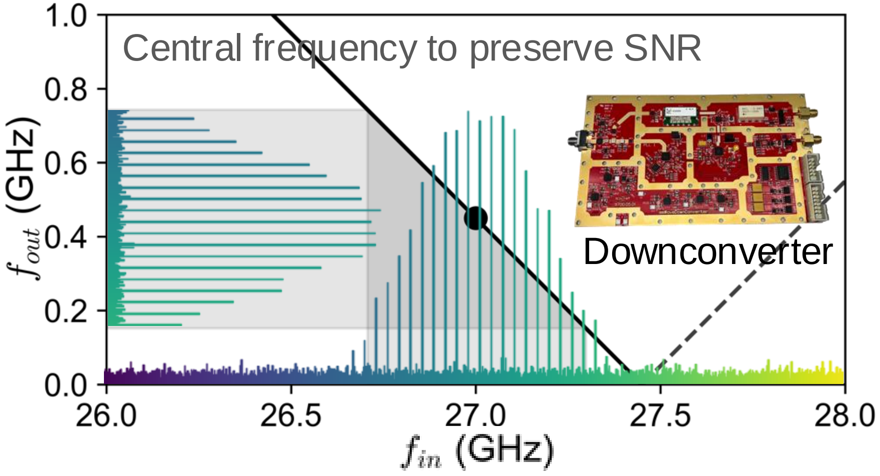
New waveguide toys?

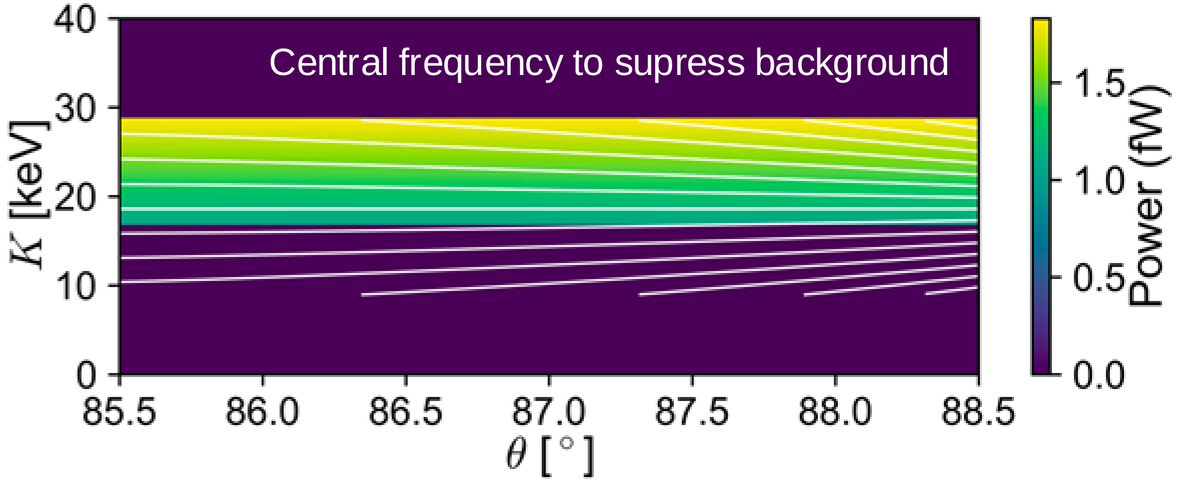


Wish list


O(1mT)
Coax & transition
losses after LNA
O(1T)
B-field
B-field
tolerant
LNA
sharing an
ASIC with
a patch
antenna

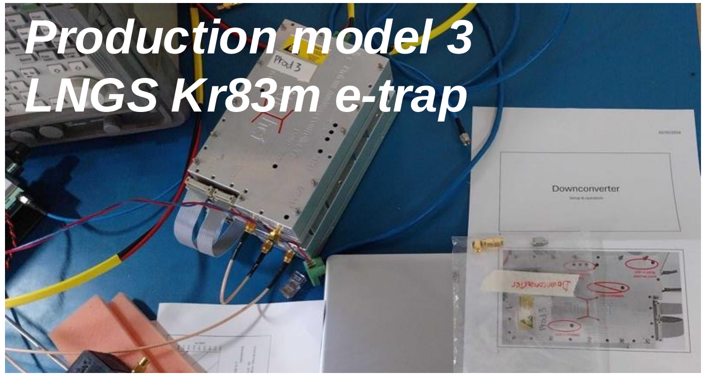
Two-stage mixing produces inversion of the spectrum + central freq. → 0.45 GHz

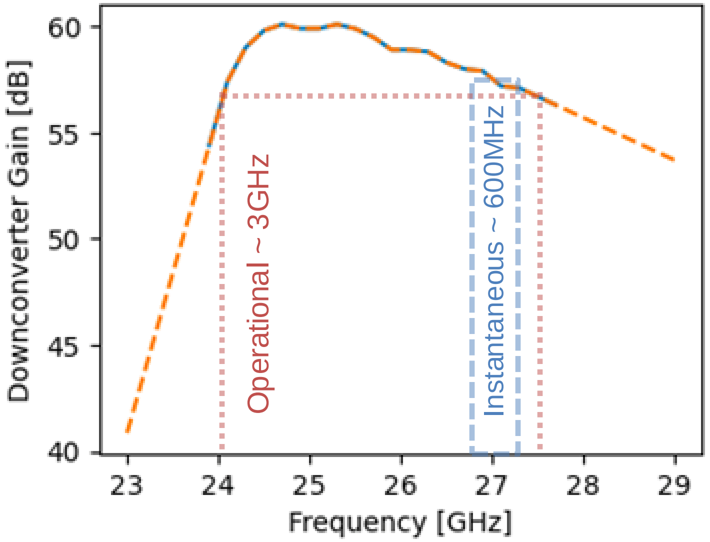




Central frequency range:	24.0 – 27.5 GHz
Instantaneous bandwidth:	0.6 GHz

Naafs, NIKHEF

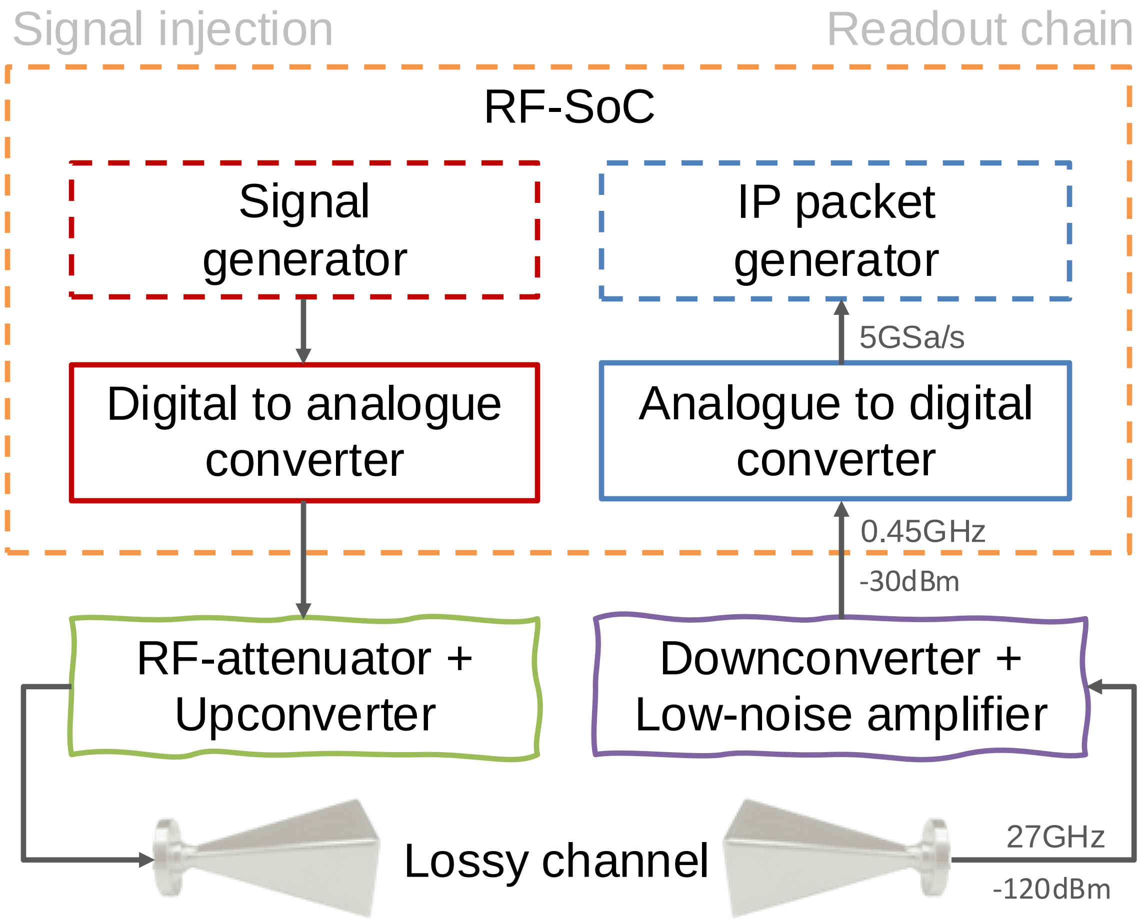




- ***Ongoing***
  - Updating all control boards to latest software version
  - Final consistency checks between downconverters
  - [Documentation]
- ***Future***
  - Full characterisation
    - Measure losses (VNA preferred)
    - Noise figure measurement with calibrated source
    - Measure gains of LNA + downconverter chain (VNA needed)

Closed-loop test

- ***Synthetic signal***
  - 27 GHz central freq., 1fW emission, $\mathcal{O}$(μs) length
  - Approximate CR to test electronics & antennas
- ***Loop test***
  - FPGA transmits & receives simultaneously
  - Testing shielding & characterising noise
  - Measuring losses and interference
  - In air test (high power signal) and vacuum
  - Between two antenna?
- ***Baseline for evolving test setup***
  - Explore antenna configurations
  - Test impact of cavity on CR-signal



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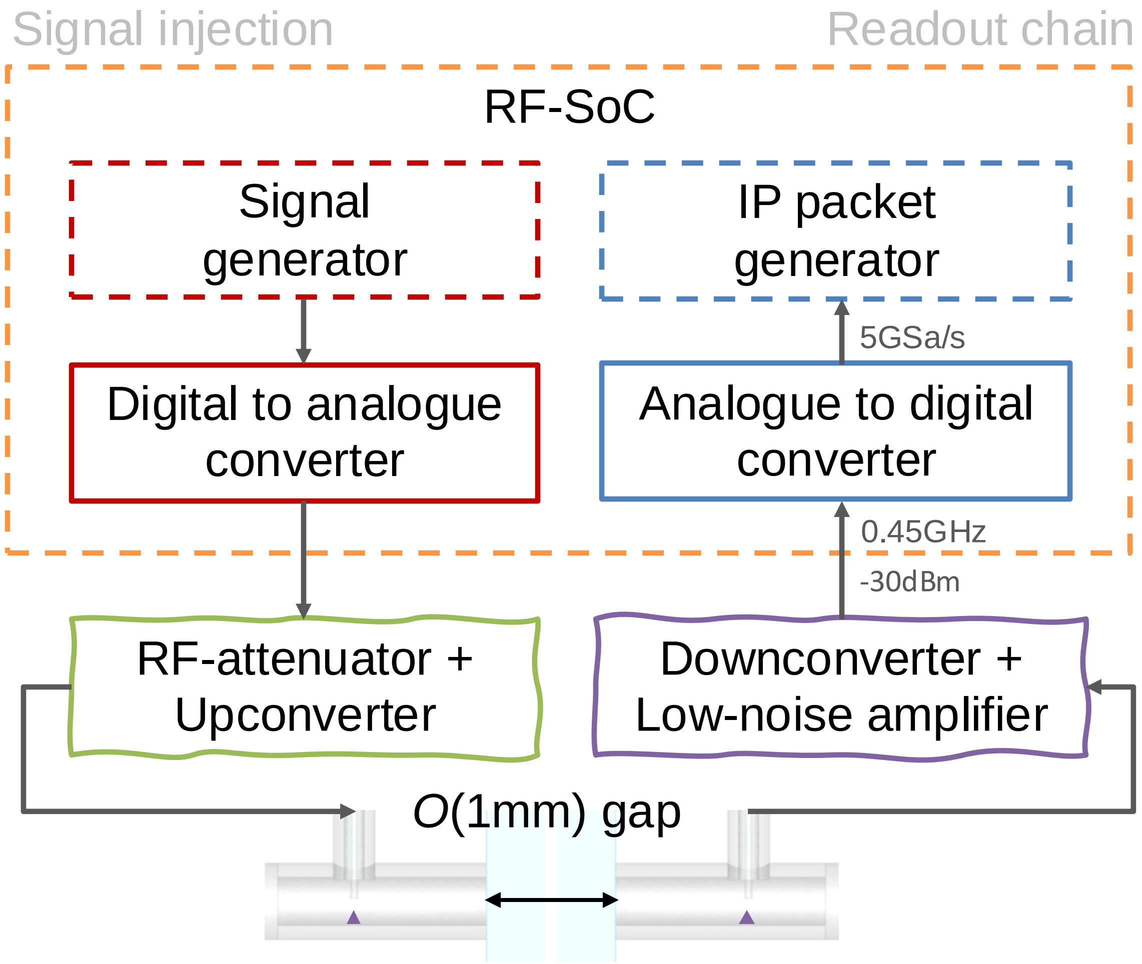
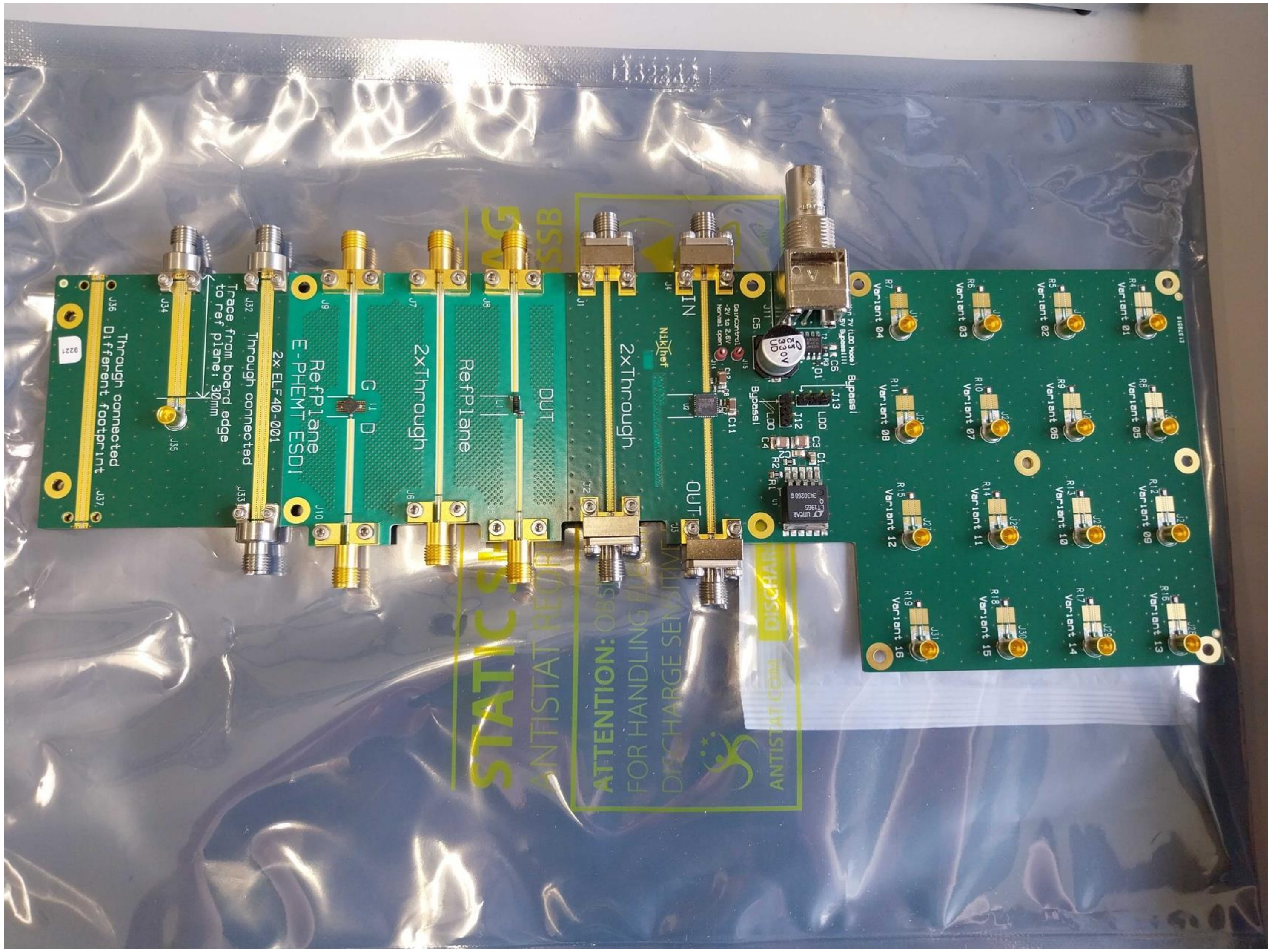


Upconverter status

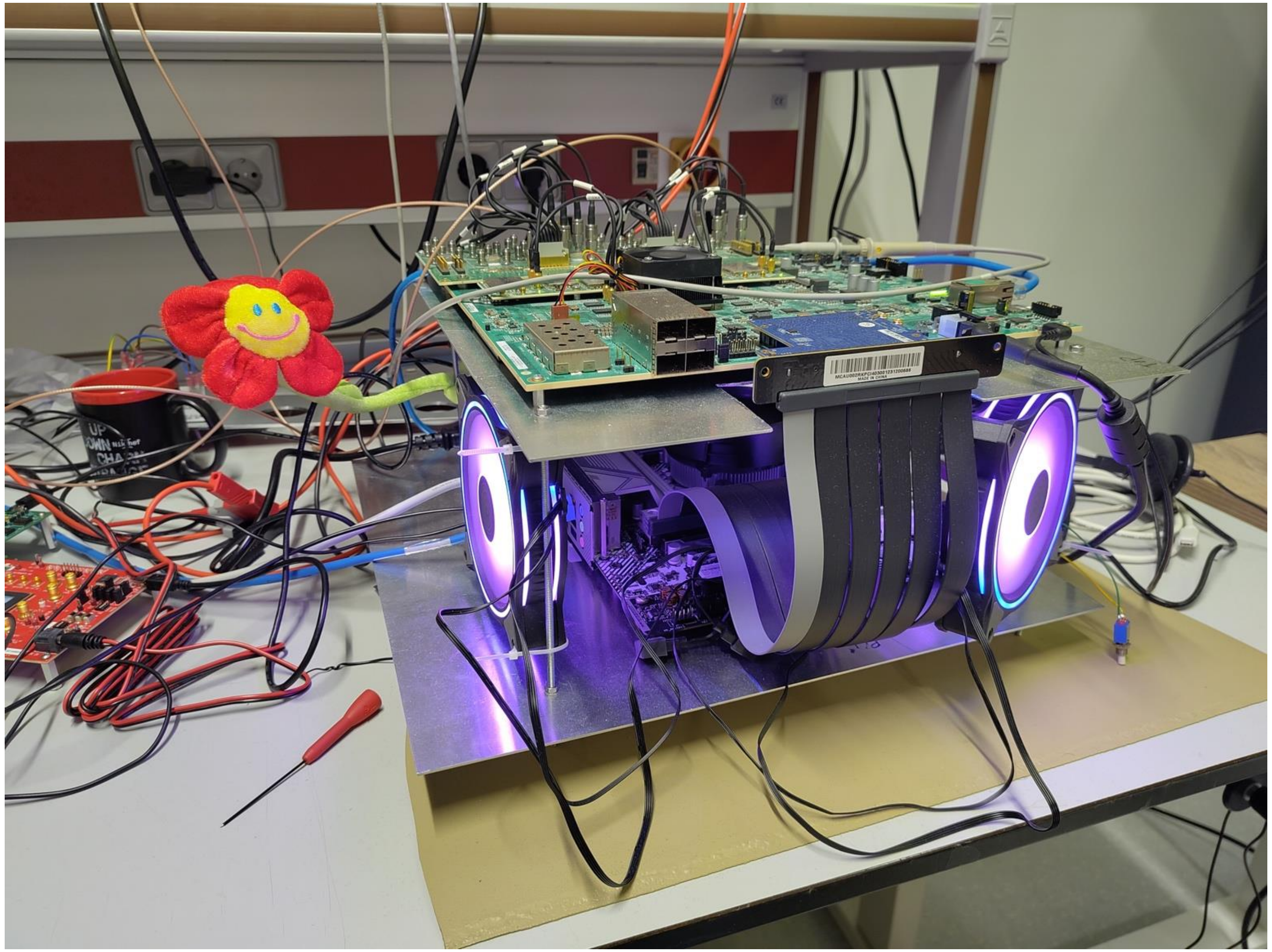


Naafs, NIKHEF

- ***Since last meeting***
  - Footprint tests concluded
  - Moving forward with optimal connectors in next iteration
  - Final architecture adjustments made – delivery expected early next year
- ***Future***
  - Arranging housing fabrication with mechanical engineering department
  - Work on control software in anticipation of deliveries next year

RF-SoC status

Bos, NIKHEF

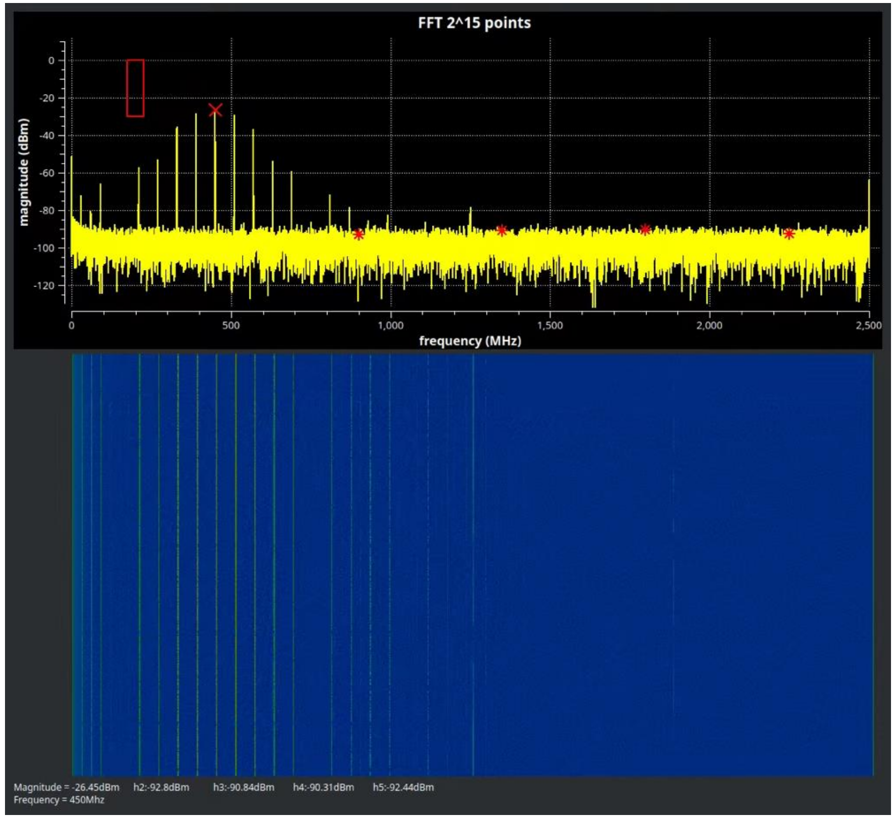


- ***Parts incorporated***
  - Enables continuous readout
  - Enables trigger algorithm development from ‘data’
  - Set up RF-SoC Mattermost with Massimiliano & Pascal (FPGAs)
  - Fun collab opportunity for students interested in algorithm development?
- ***Injecting signal***
  - Toy model (AM/FM generator)
  - LNGS e-trap data from scope (WIP)

Waterfall plot on RF-SoC

Bos, NIKHEF

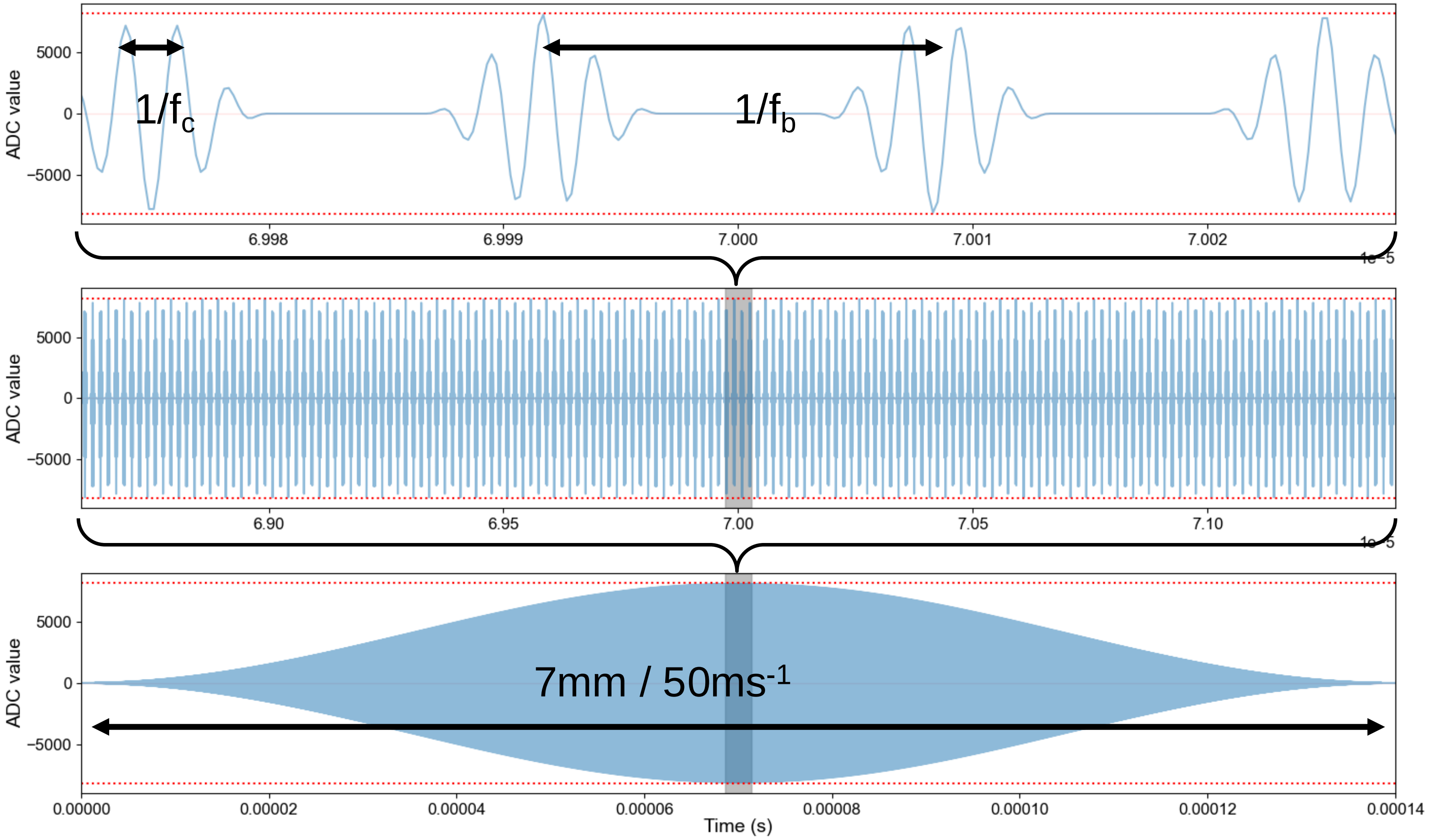
- ***Toy signal input***
  - Sample rate: 5GSps
  - Window size: 2^15 = 16384 samples
  - Time per row: 2^15 / 5GSps = 6.5μs (can be extended to 13μs)
- ***Trigger and analysis***
  - Basic box-trigger enabled
  - Plotting synthesized signal using onboard DAC (can input different parameterisations)
- ***Work in progress***
  - Improving upon dead-time
  - Producing overlapping STFTs (à la Sauron plot)



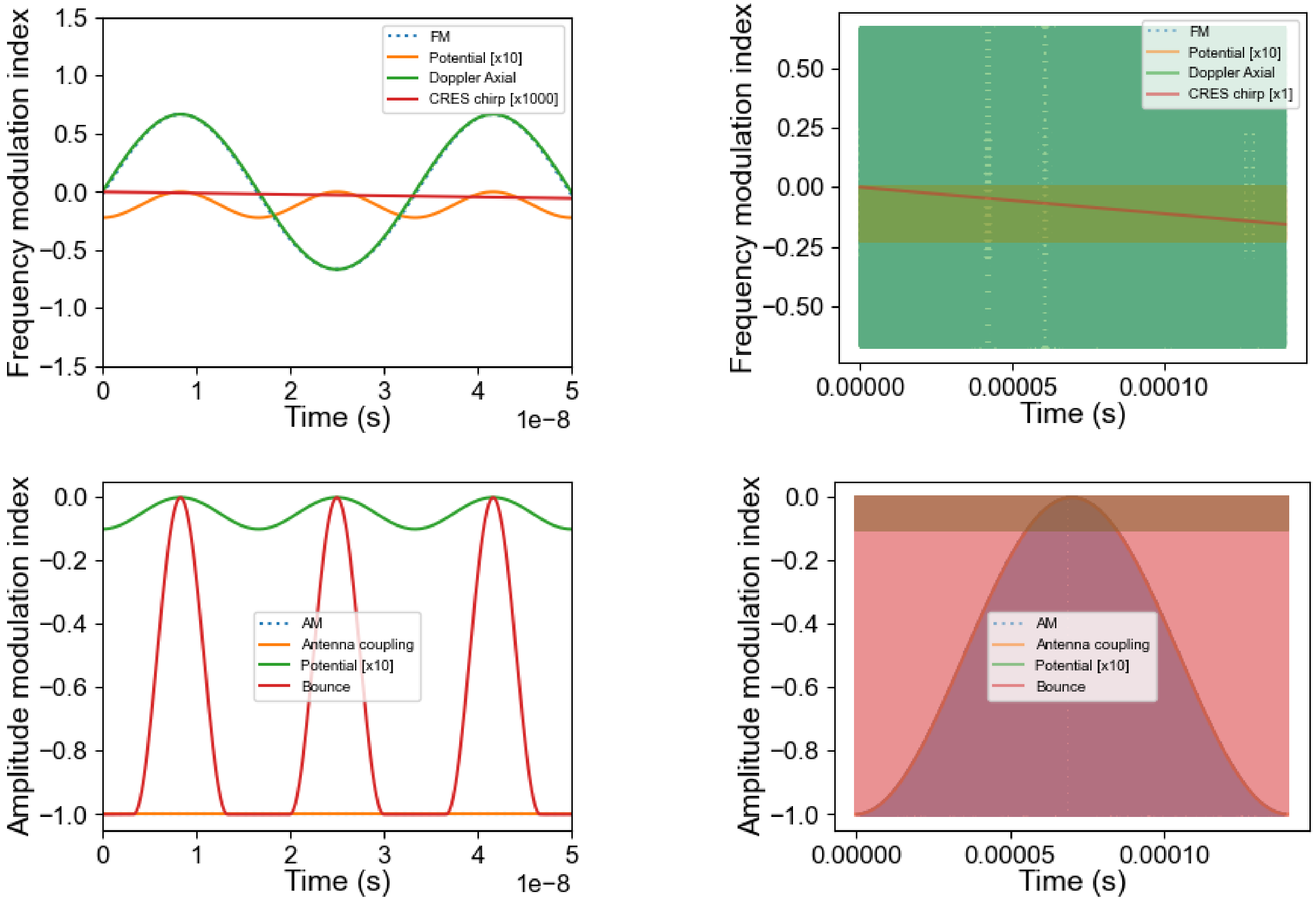
gitlab

Animation

Toy signal over 140μs



Downconverted signal with ‘antenna coupling’



Interrelation of the modulation indices based on CST parameterisations

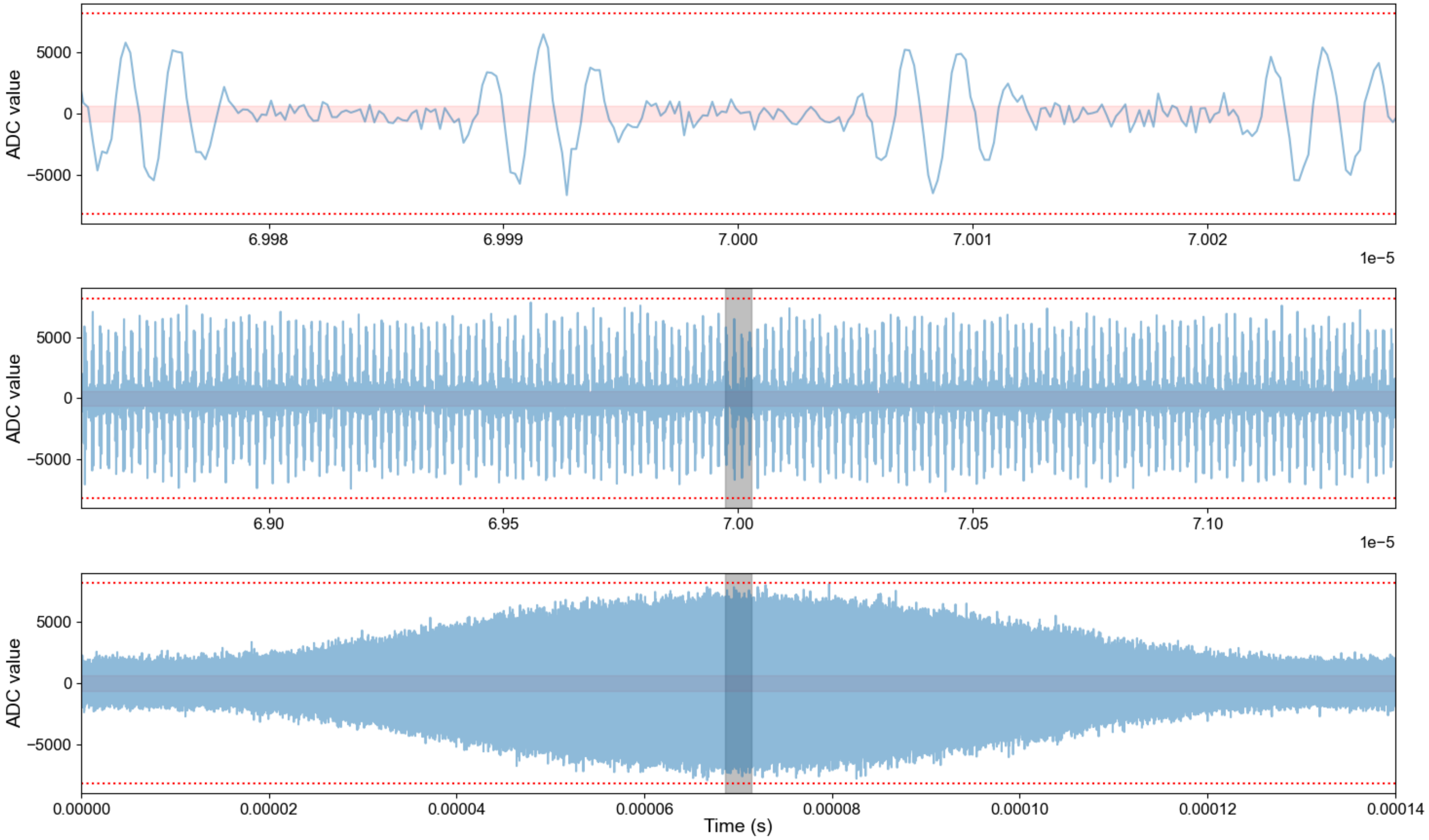
Toy signal for FPGA trigger development at Nikhef and LNGS

Can mimic e-trap transverse observer, can mimic flyby longitudinal observer

Chirp is included (only non-cyclical modulation effect)

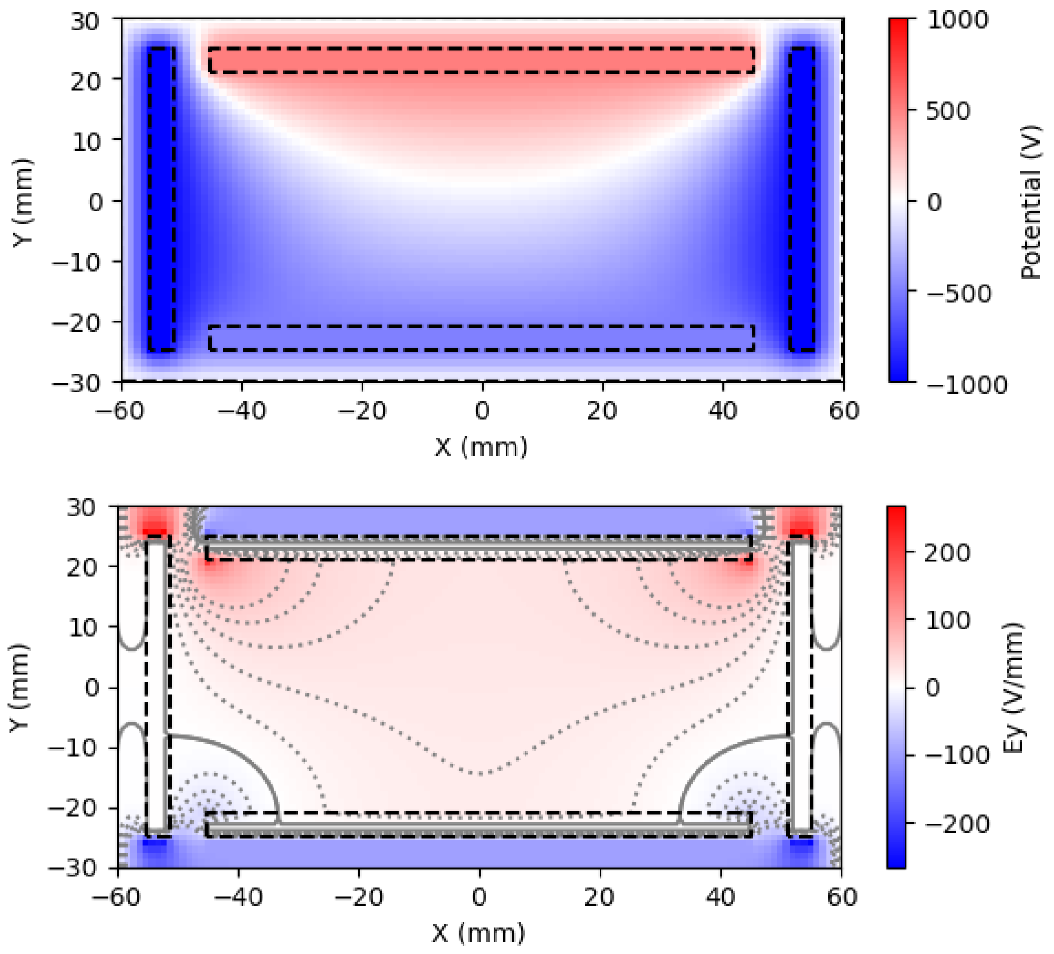
Want to include energy loss effect on modulations (decaying amplitudes)

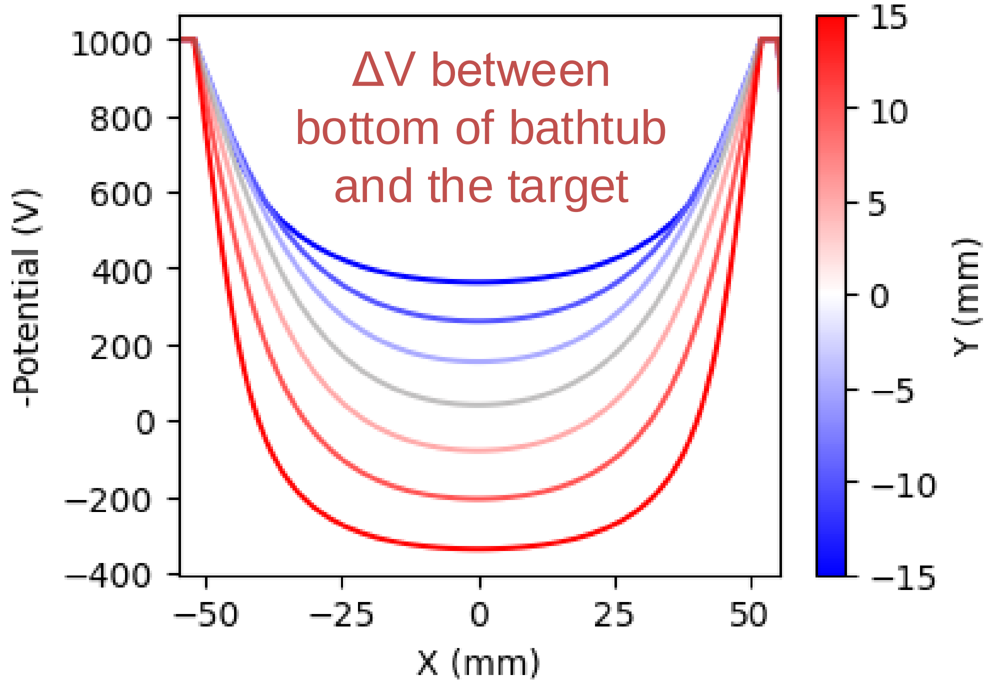
Including noise to mimic LNA temperature



Placeholder for the RF region acceptance

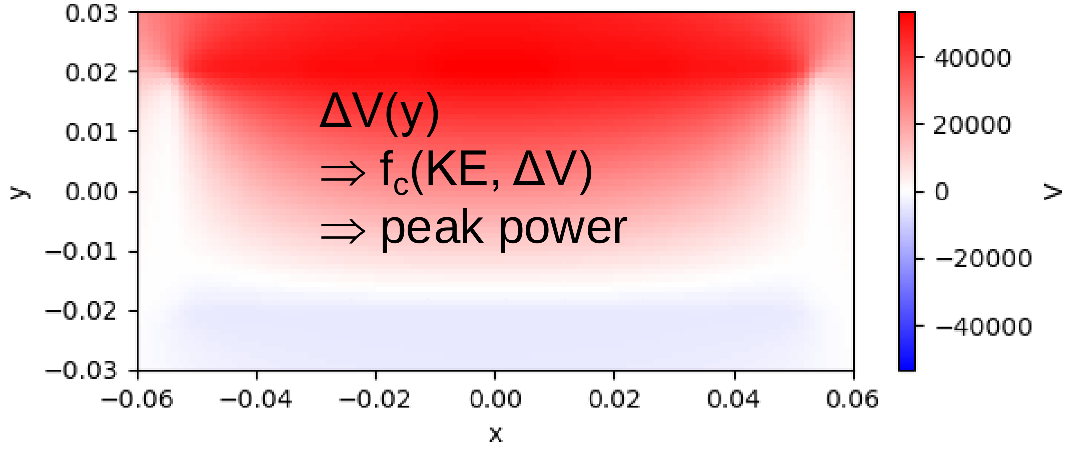
Based on e-trap acceptance studies

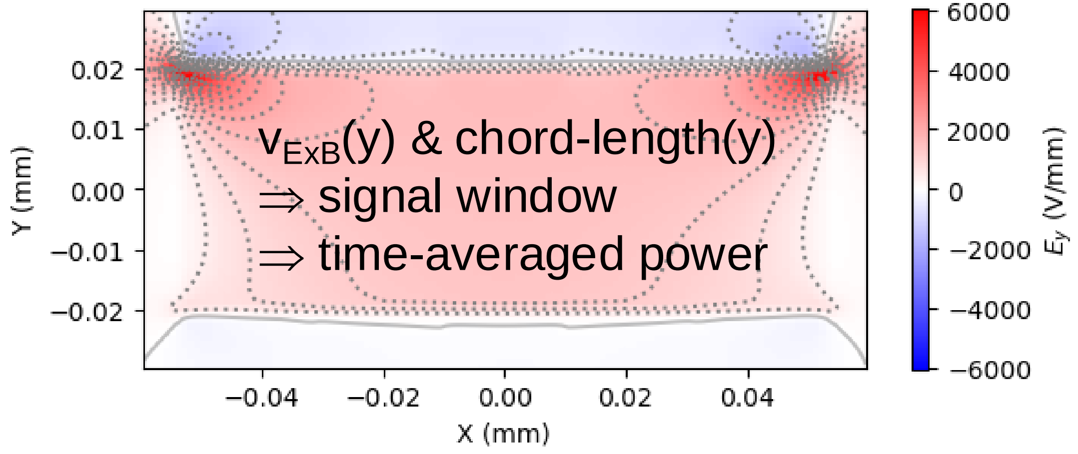


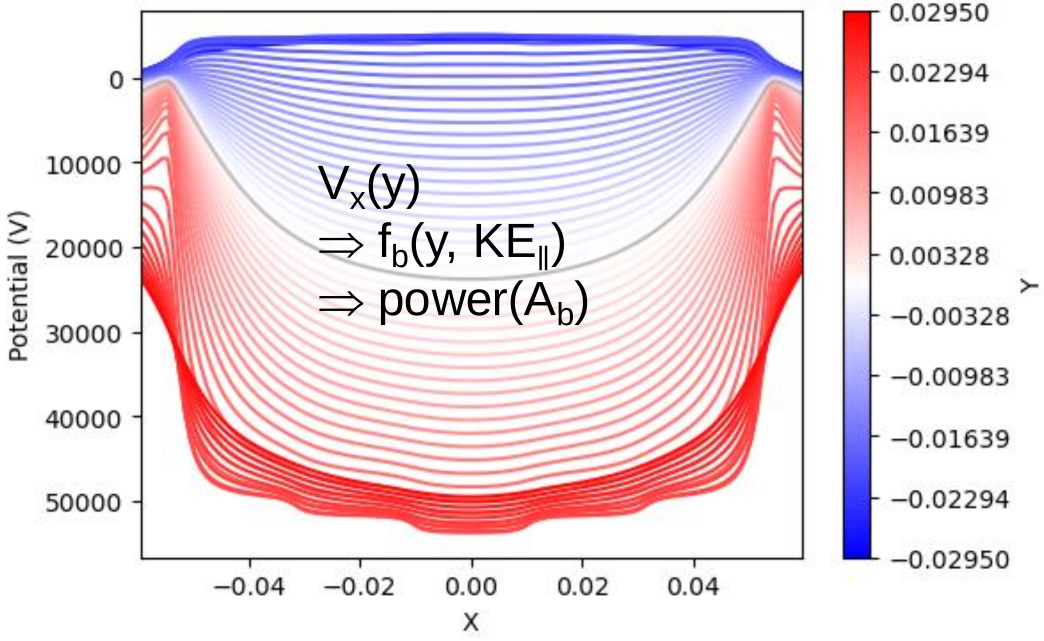


- Variation in central and bounce frequencies
- Integrated ExB drift across antenna face

Update from Wonyong's end-to-end geometry

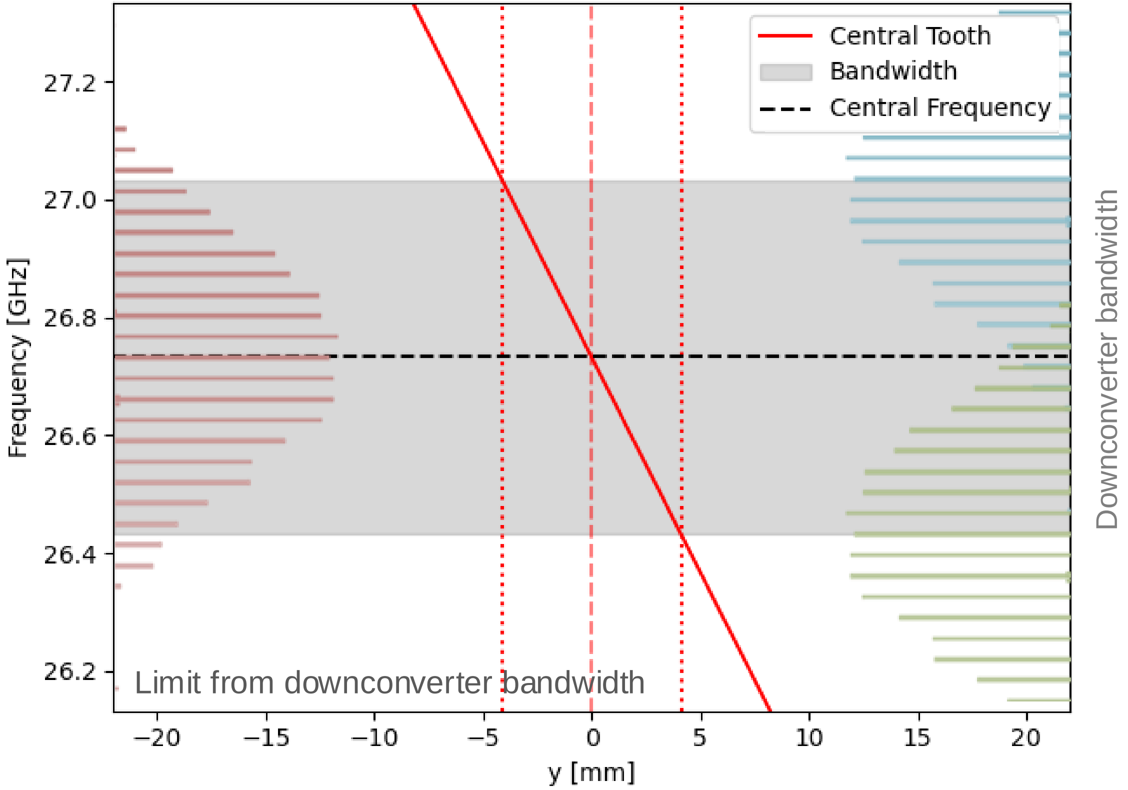


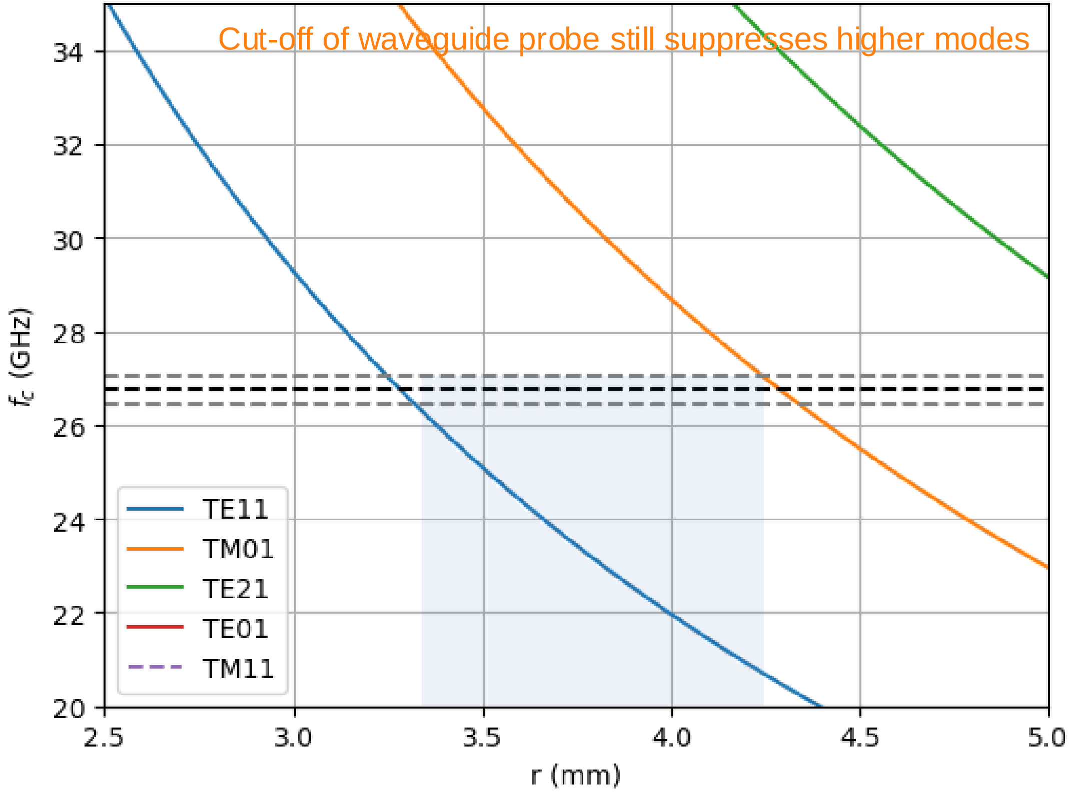




- Relatively little variation in E_y ∴ ExB drift
- Significant offset and y-dependence in ΔV ∴ f_c
- Variation in bathtub shape ∴ bounce frequency

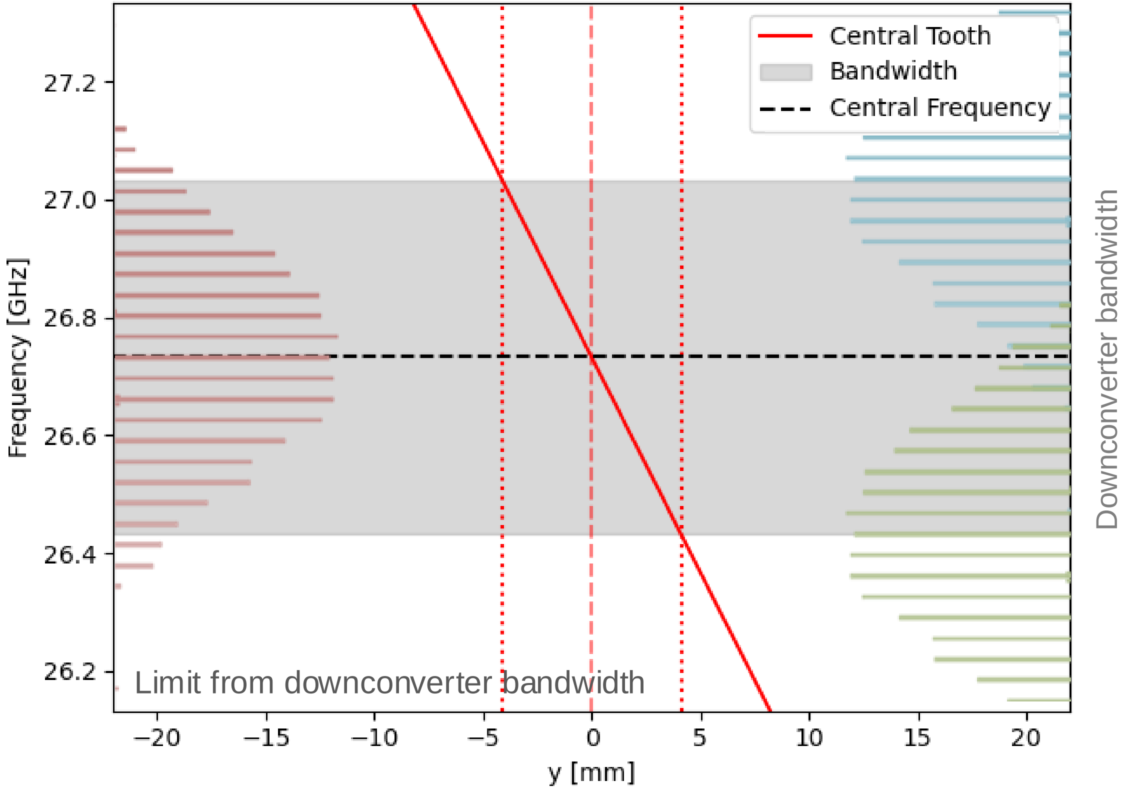
Number of teeth required for SNR threshold or precision on f_b could dictate y-acceptance

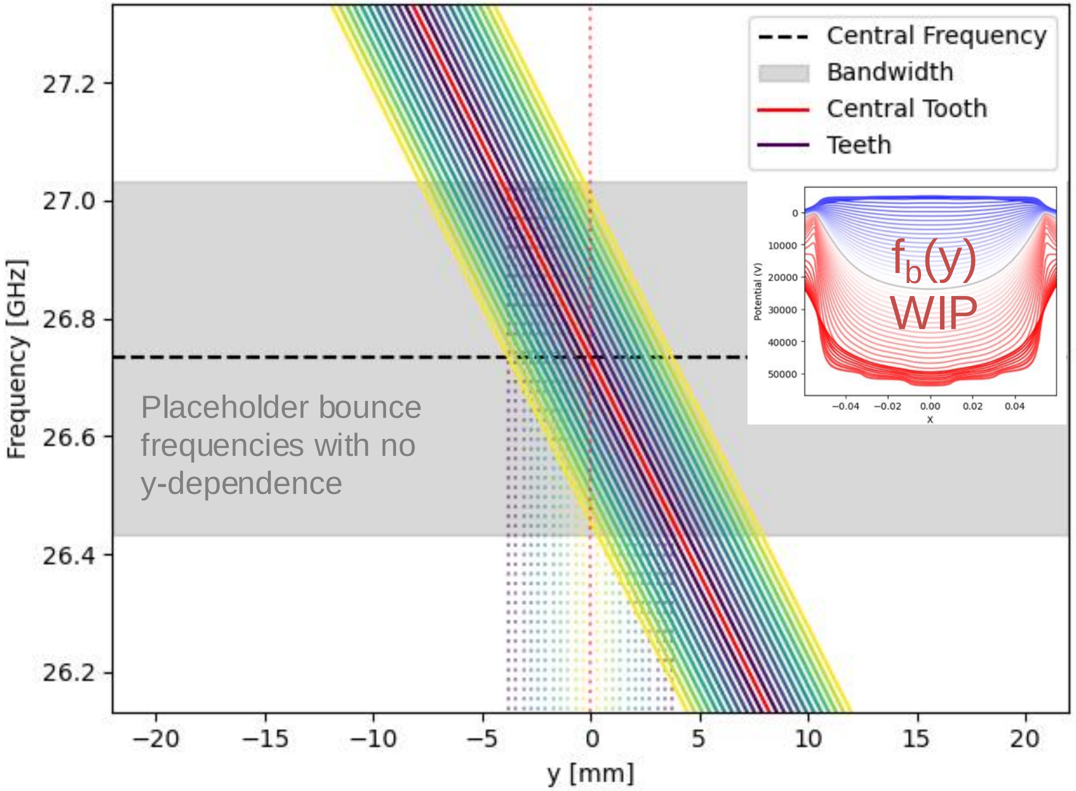




50ms^{-1} across 7mm diameter antenna >60μs signal requires < ±3.16mm from y=0

Does this introduce additional degeneracies with background with electrons with same bounce frequency?

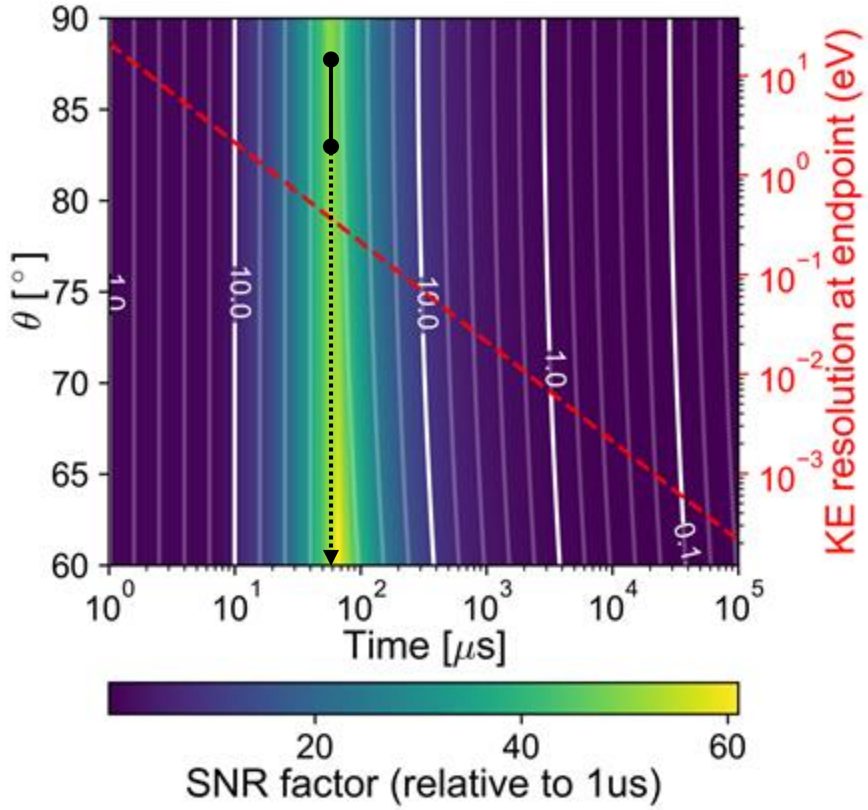




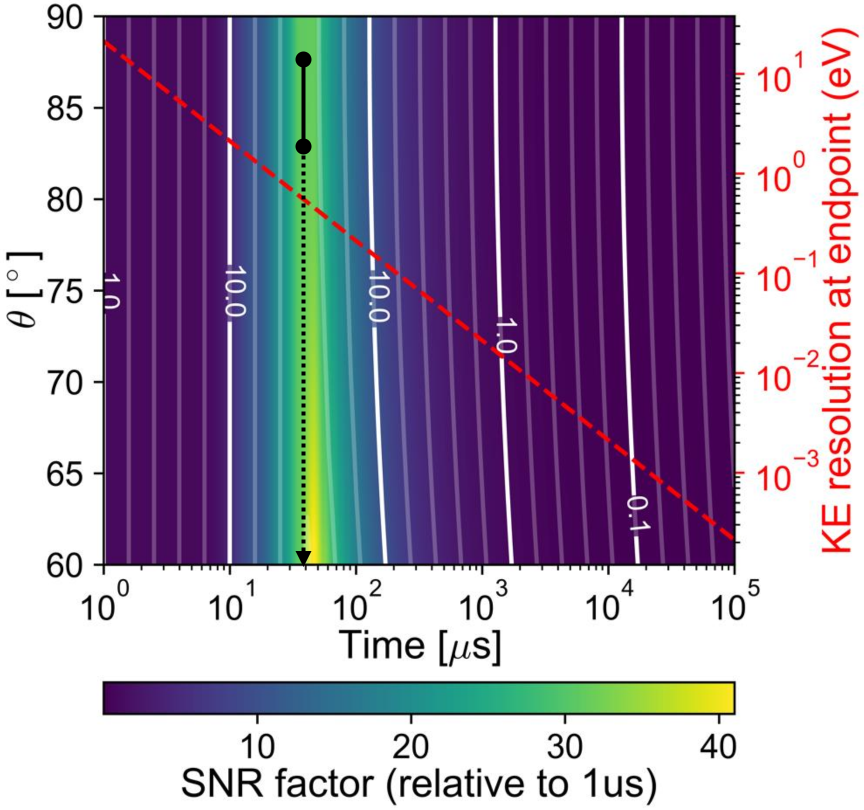
Length of signal could give abs(y), combine with f_c & f_b to give signal & background hypotheses

Adjusting chirp expectation to new KE

18.6 keV, θ ~ 85°, 60μs FFT



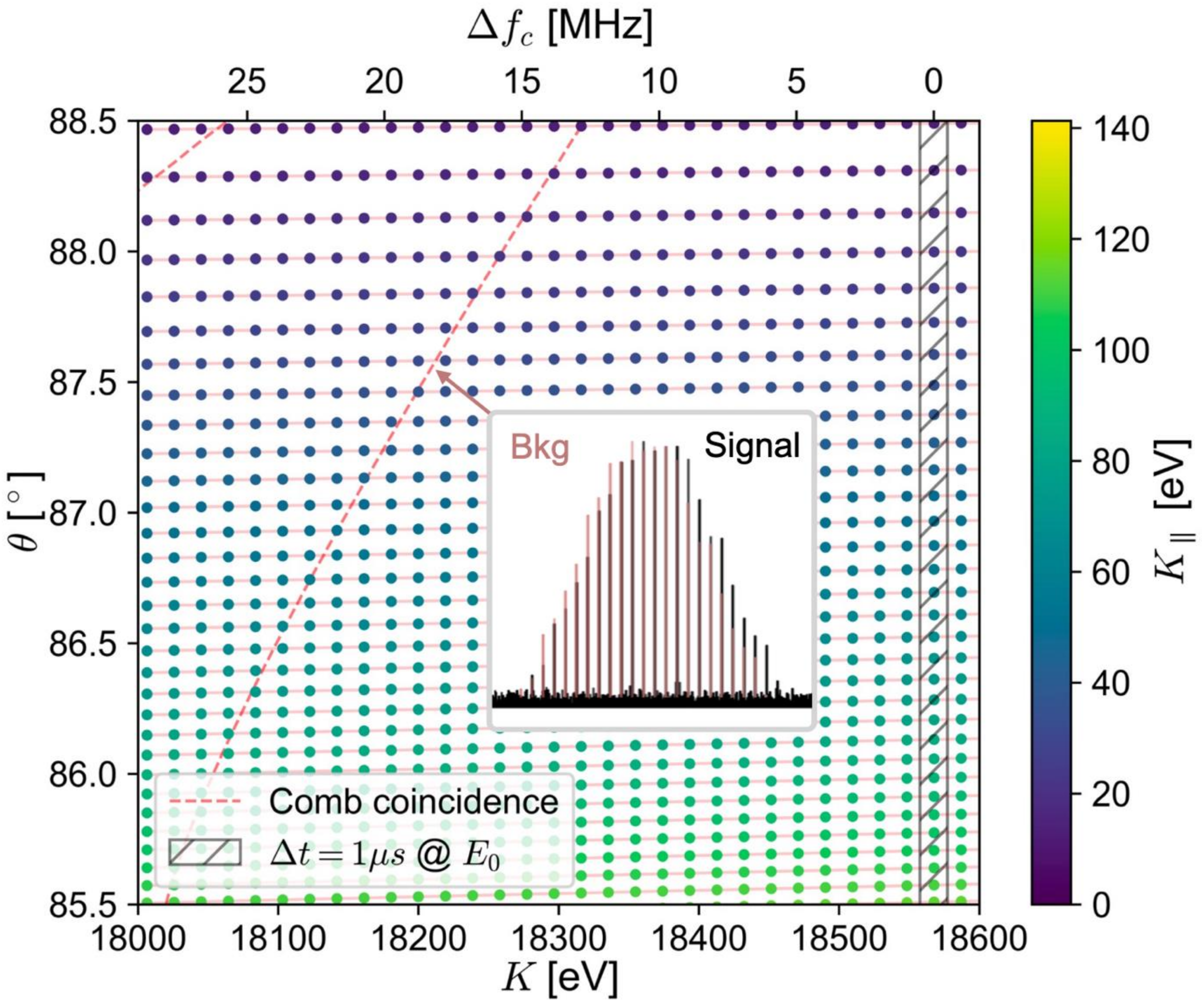
40.0 keV, θ ~ 85°, 40μs FFT



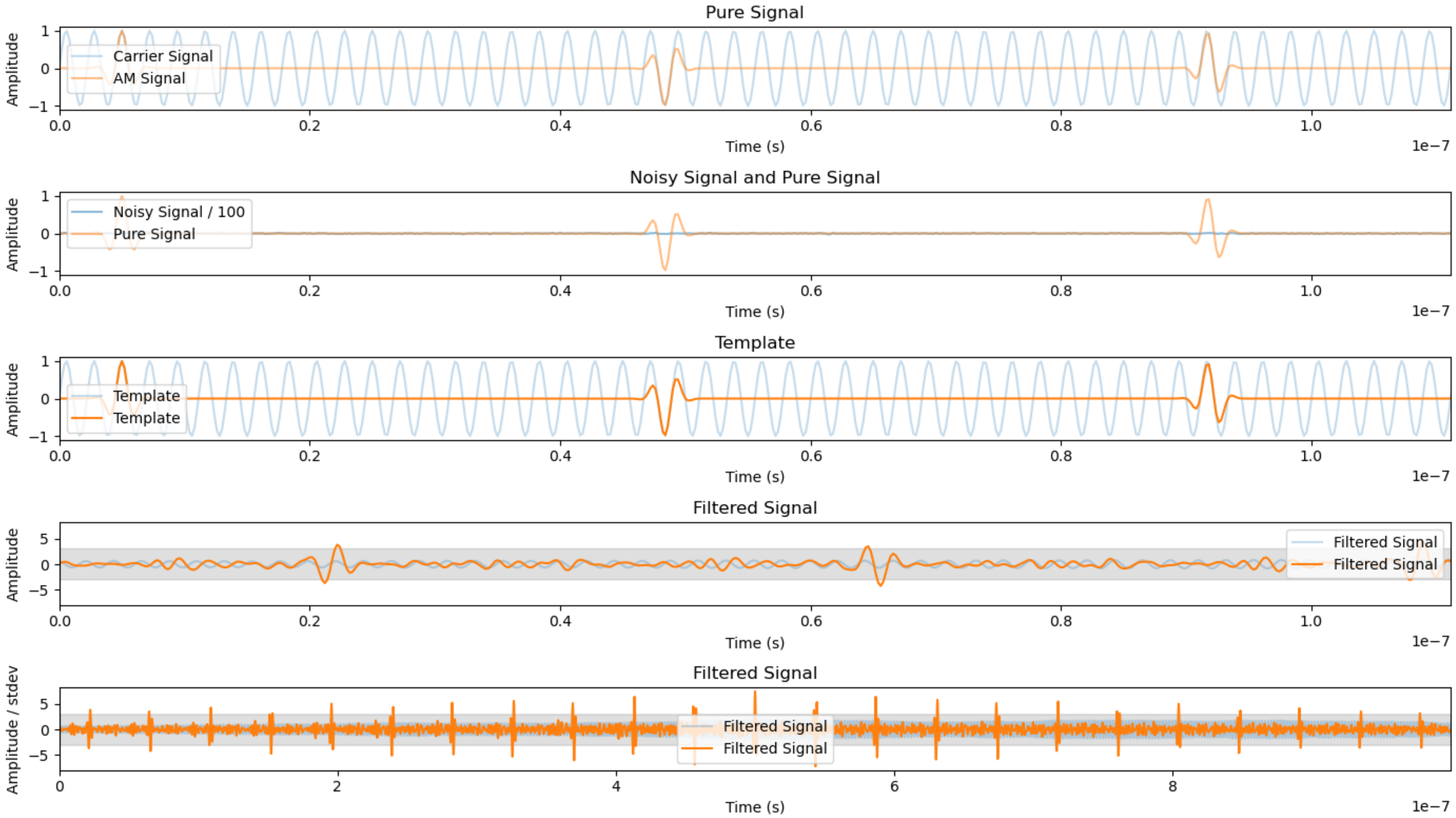
WIP: replacing θ-dependence w. y-dependence for KE range

Matched filtering algorithm template bank

Assuming y=0, filter passively deals with background



- ***Reproduce this style of plot for frequency comb template bank (disentangles from specific config.)***
  - x-axis = Central frequency
    y-axis = Bounce frequency
    (can show freq. grid on KE and $KE_\parallel$ axes for specific configuration)
  - z-axis = SNR for specific noise temp.
    = int(conv.) given signal input
    (can assess algorithm performance)
  - Define as SNR of central tooth?
    SNR is now f(KE, $KE_\parallel$, ΔV_{RF}, v_{ExB})



- Single antenna has a coherent signal as cumulative phase offset returns to zero due to cyclical FM (long Δt for narrow Δf precision)
- Chirp is non-cyclical: also has damping effect on other modulations (we intentionally choose FFT window too short to see the chirp for SNR)
- Does relative phase of opposite antenna pairs have V_x ∴ y-position encoded?

Summary

- ***Nikhef deliverables***
  - Final push to closed loop test underway
  - Renting VNA and SA for full characterisation
  - Trigger development underway (learn hls4ml and make Pascal’s life miserable)

- ***Looking into***
  - Algorithm assessment akin to Project-8 JINST paper [arXiv:2310.02112v1]
  - Disentangling y-offset in the signal analysis (anticipating target→RF transfer functions)
  - RGA outgassing measurement of 3D printed RF components from LNGS

~~NWO Veni grant to investigate B-field tolerant LNA & cavity resonators~~ Unsuccessful

RF-group book-keeping

[Nikhef Indico – RF meetings]

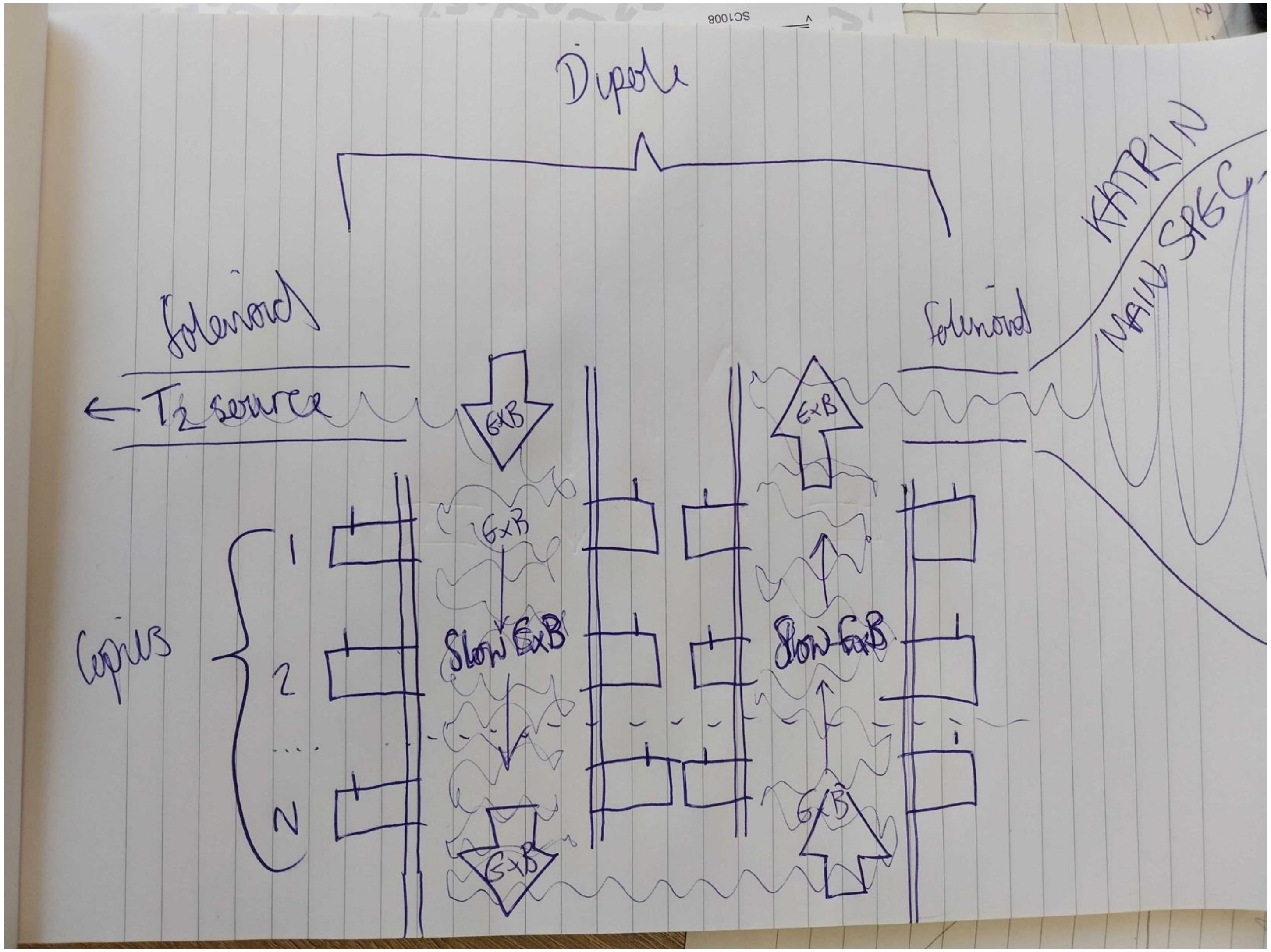
[LNGS Wiki – RF group page]

[LNGS Cloud – RF meetings]

[Ptolemy Github – RF project]

(Late) Christmas present for KATRIN?

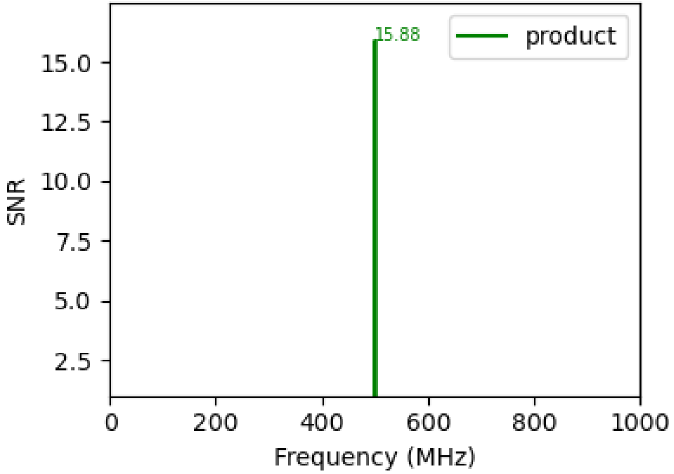
Mature state of my transport electron transport studies

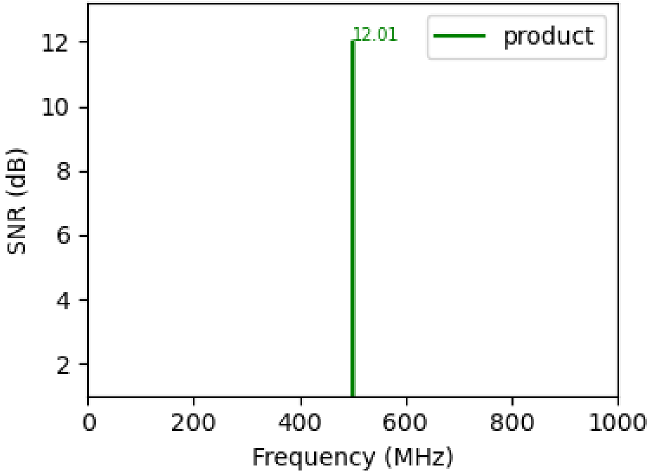


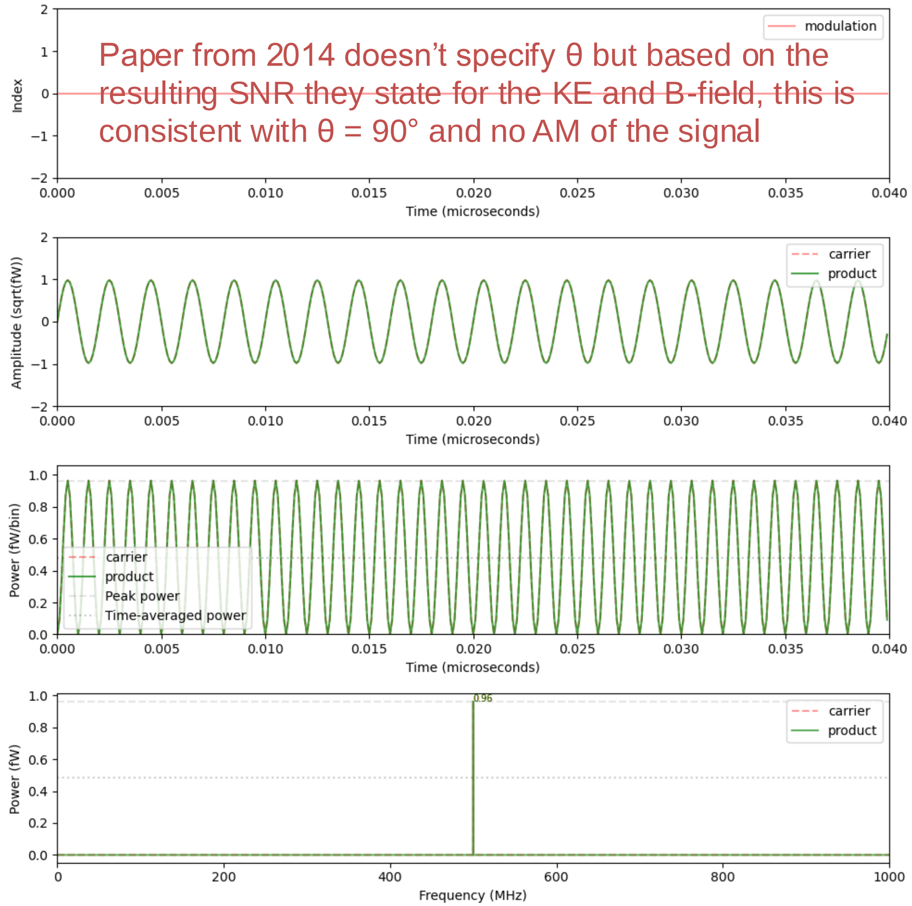
Sanity checking SNR expectation

[Phys. Rev. Lett. 114, 162501]

- ***Project-8 paper example***
  - KE = 18 keV
  - Power = 0.825 fW
  - Duration = 33 μs
  - Sampling rate = 10 GHz
  - Carrier freq. = 0.5 GHz
  - RBW = ~ 30kHz
  - Temp = 145K
  - Noise = ~ 0.06fW/bin
  - SNR = 15.8
  - SNR = 12 dB







Paper from 2014 doesn't specify θ but based on the resulting SNR they state for the KE and B-field, this is consistent with θ = 90° and no AM of the signal

[gitlab]

Sinusoidal amplitude modulation

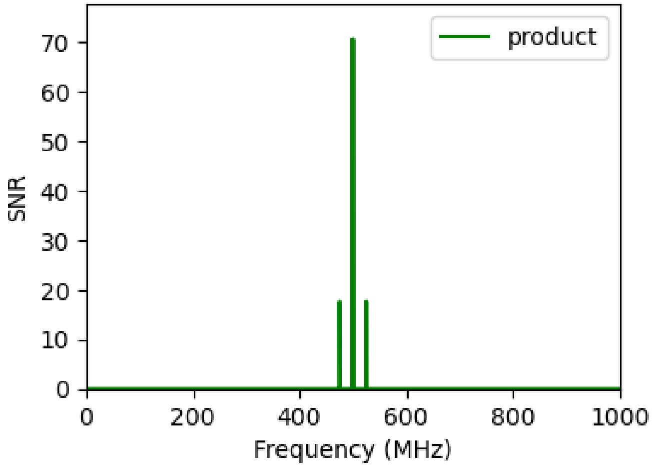
I should have set the power to reflect θ < 90° implied by non-zero f_b but it's the time-averaged power normalisation that matters here, not the absolute SNR values

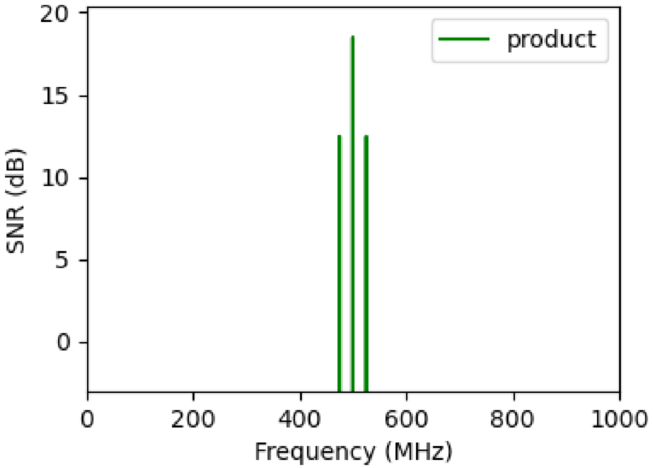
- ***PTOLEMY signal with AM***
  - KE = 18.6 keV
  - Power = 1.17 fW
  - Duration = 50 μs
  - Sampling rate = 10 GHz
  - Carrier freq. = 0.5 GHz
  - AM freq. = 25 MHz

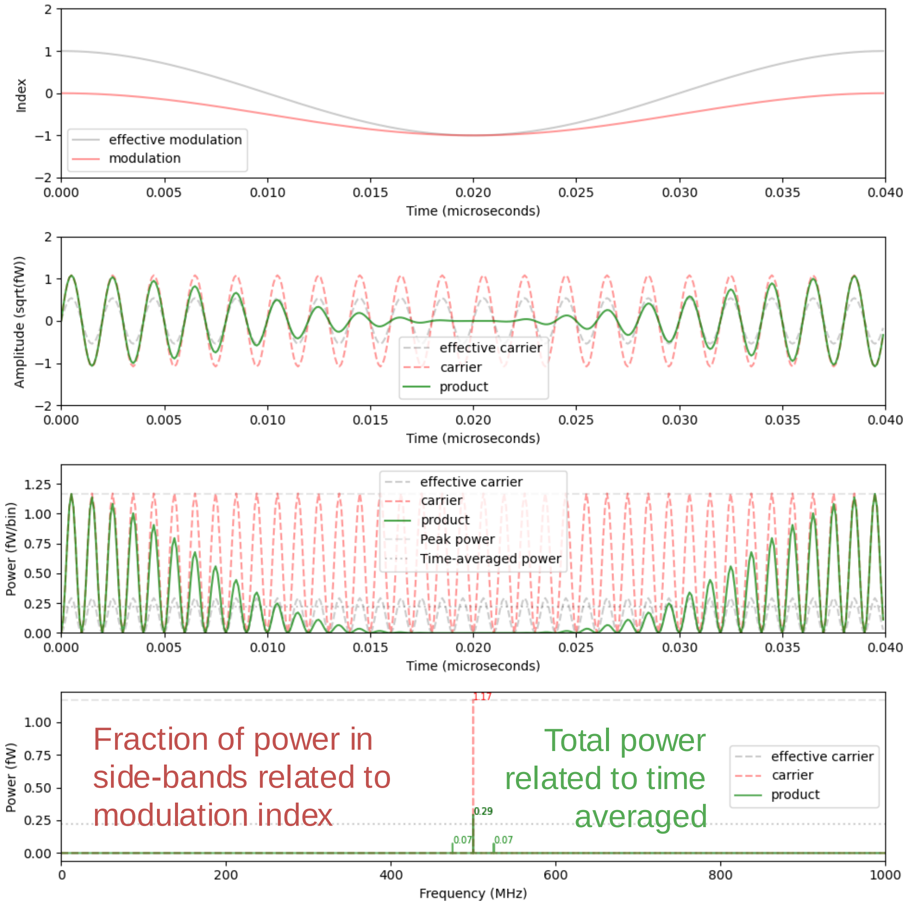
- RBW = ~ 25kHz
- Temp = 15K
- Noise = ~ 0.004 fW/bin

- SNR = 232 ~70
- SNR = 23 dB ~19 dB

No AM







gitlab

Short range sensing with bouncing motion

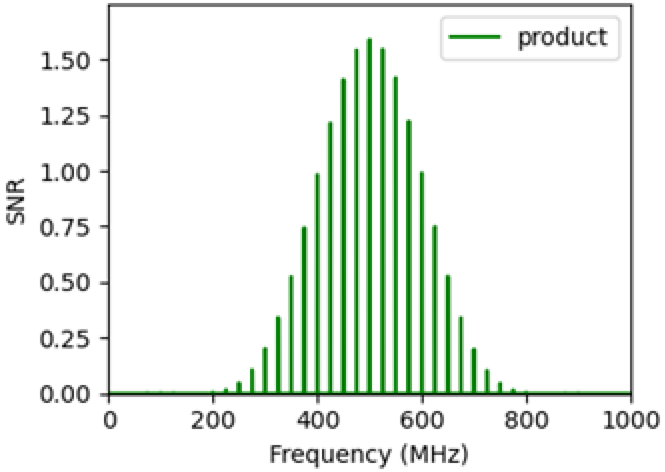
I should have set the power to reflect θ < 90° implied by non-zero f_b but it's the time-averaged power normalisation that matters here, not the absolute SNR values

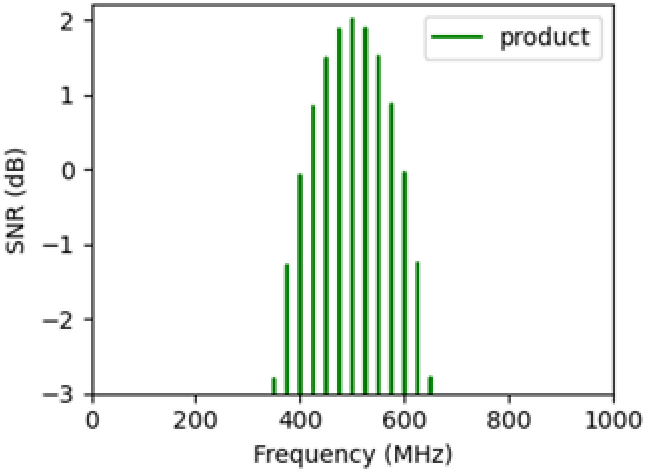
- ***PTOLEMY signal with AM***
  - KE = 18.6 keV
  - Power = 1.17 fW
  - Duration = 50 µs
  - Sampling rate = 10 GHz
  - Carrier freq. = 0.5 GHz
  - AM freq. = 25 MHz

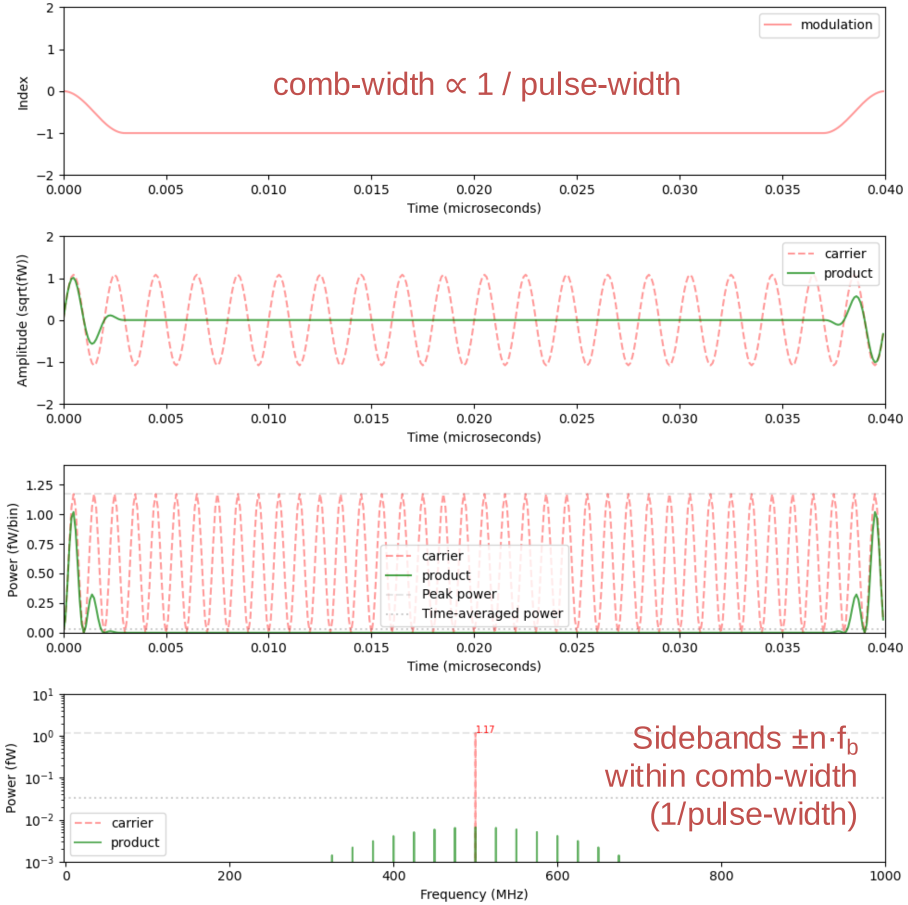
- RBW = ~ 25kHz
- Temp = 15K
- Noise = ~ 0.004 fW/bin

- SNR = 232 ~1.5
- SNR = 23 dB ~2 dB

No AM

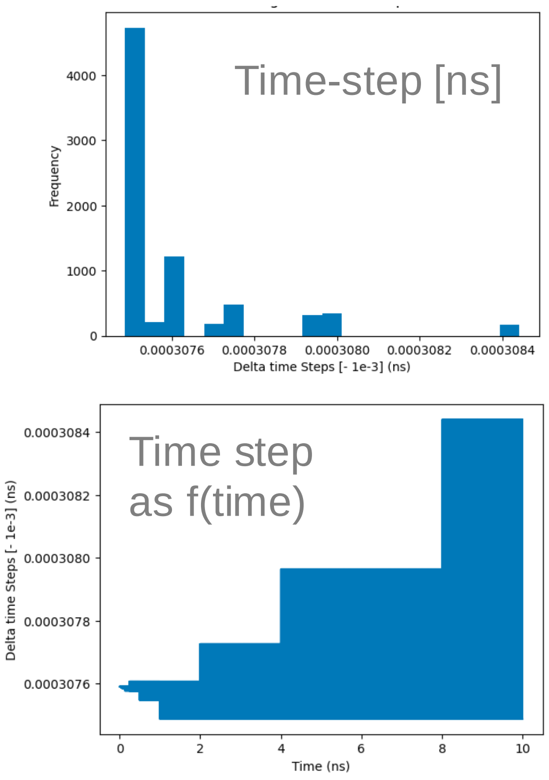






gitlab

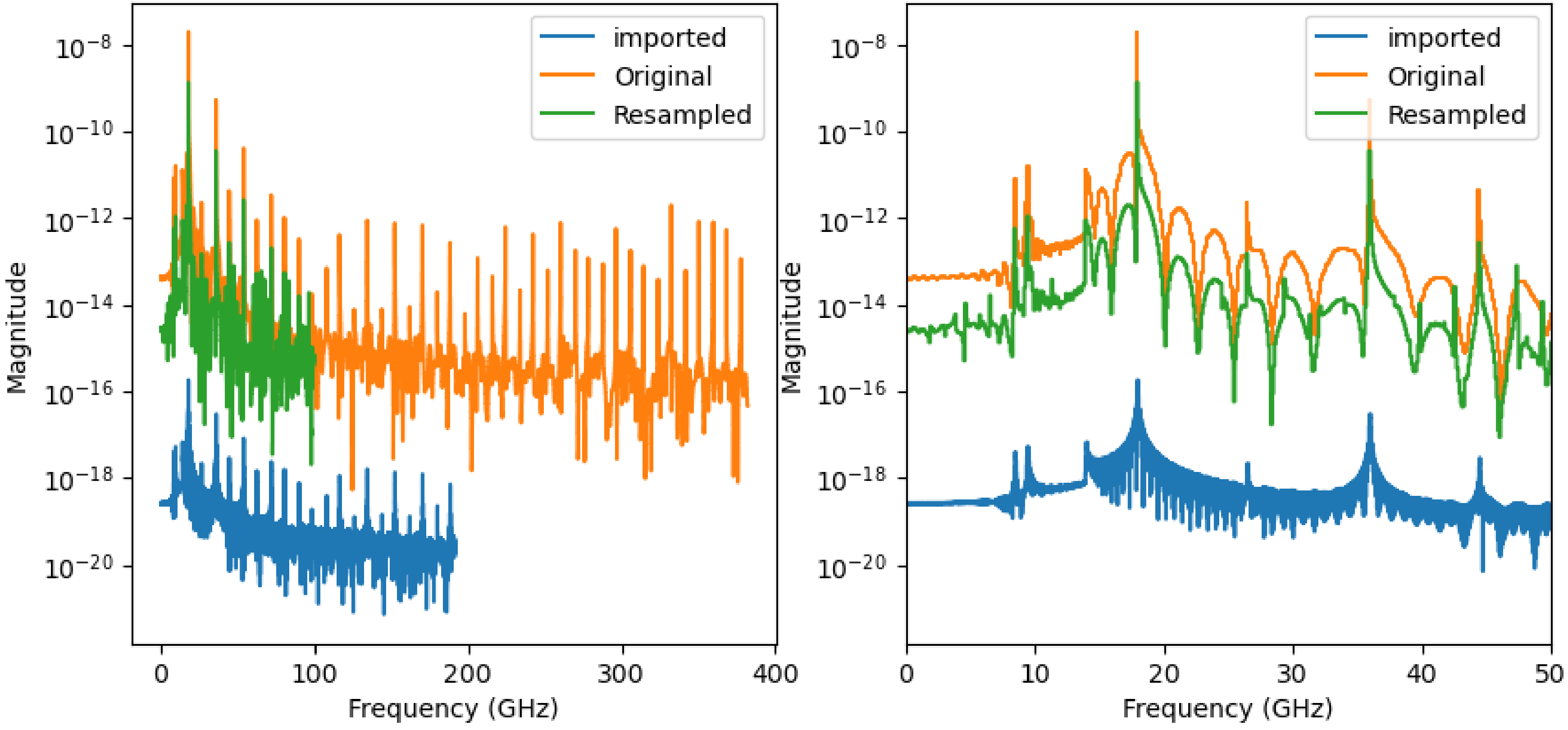
Exported time series data from CST



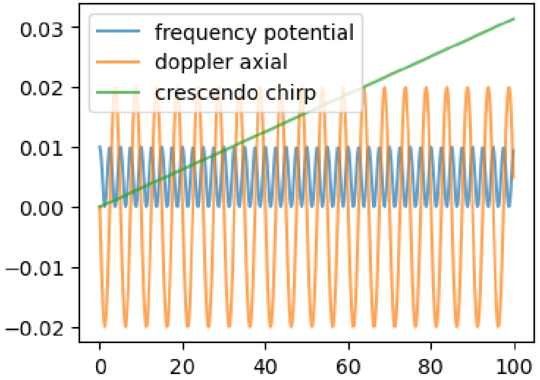
CST time-series exported

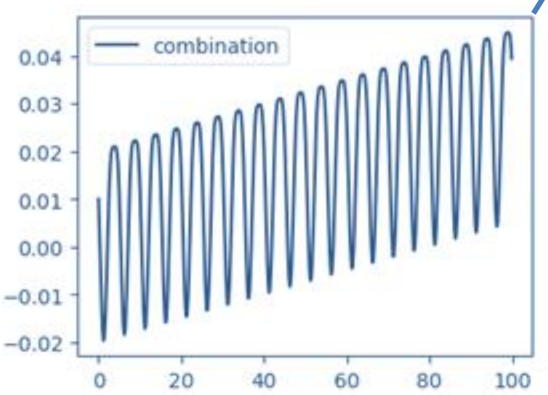
CST time-series exported & resampled

CST's FFT exported

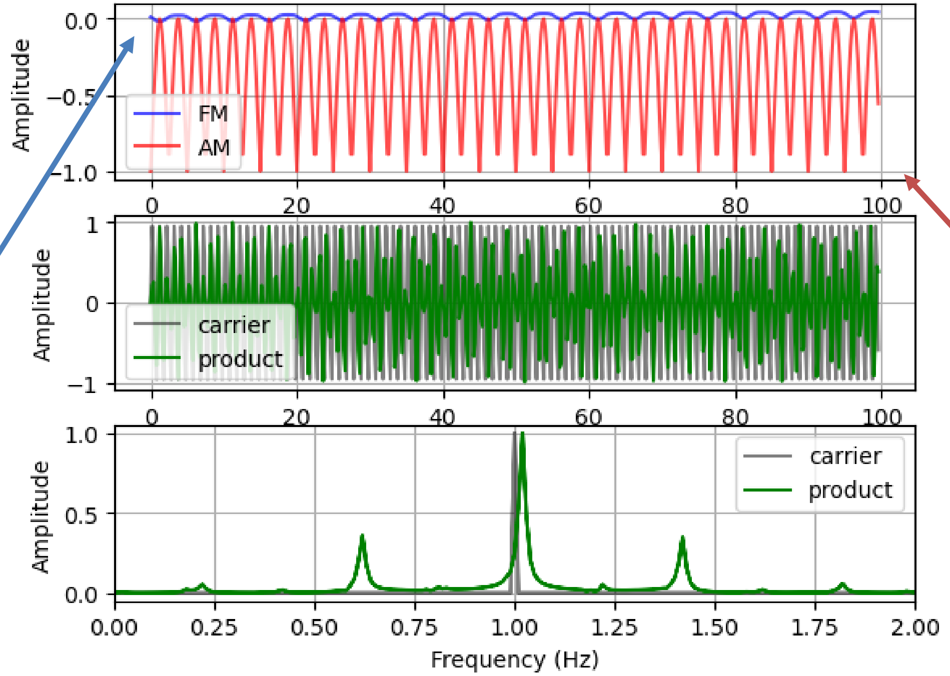


FM



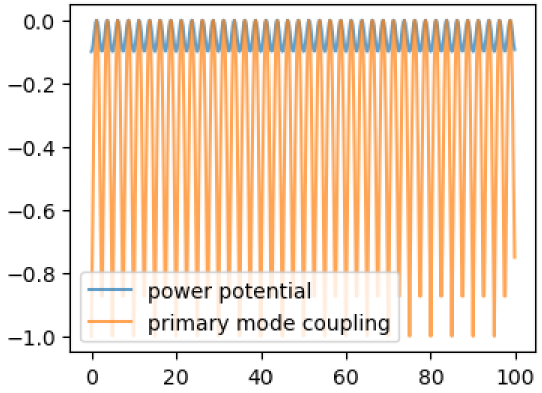


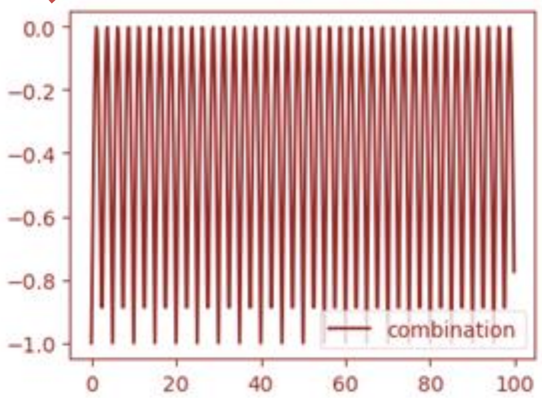
Analogous to e-trap transverse observer



Exaggerated features – not to scale

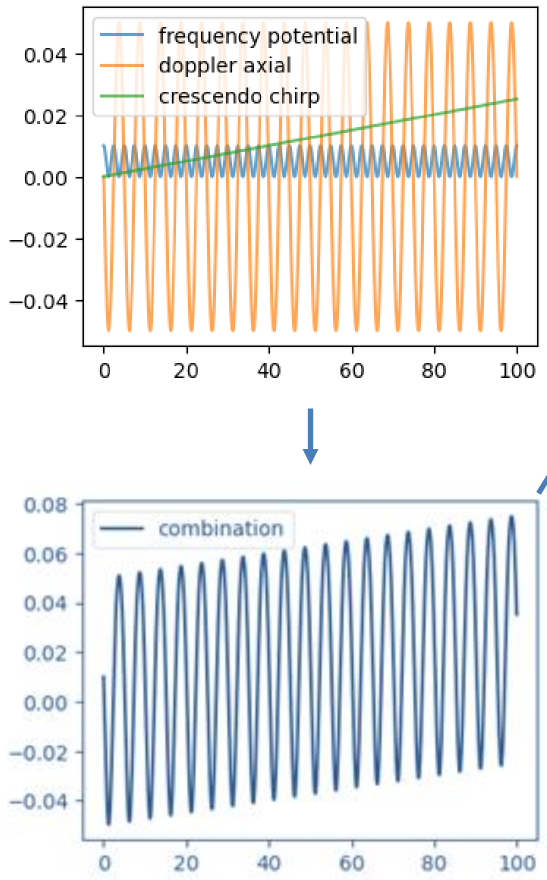
AM



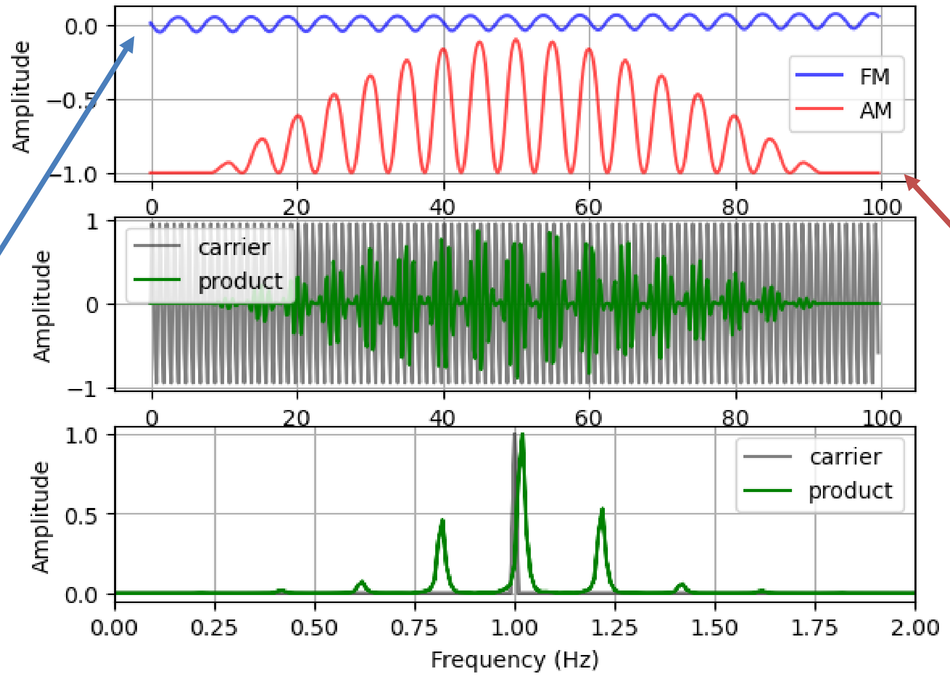


Toy model – longitudinal analysis

FM

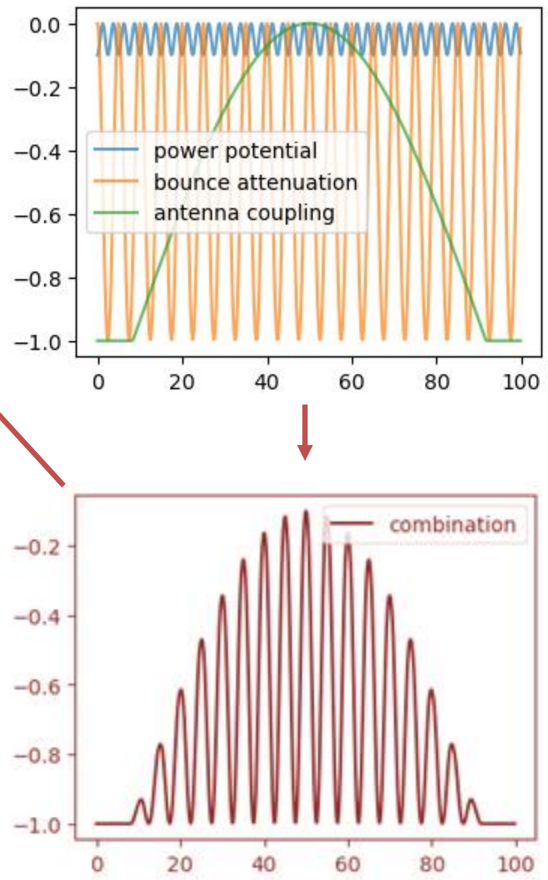


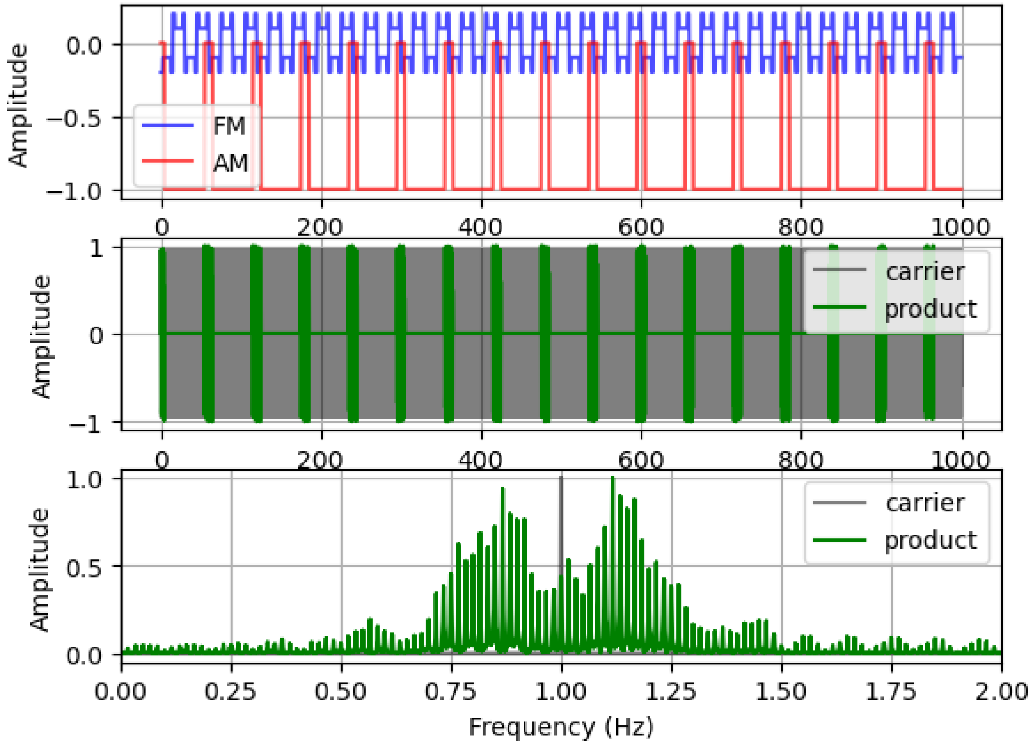
Analogous to flyby longitudinal observer

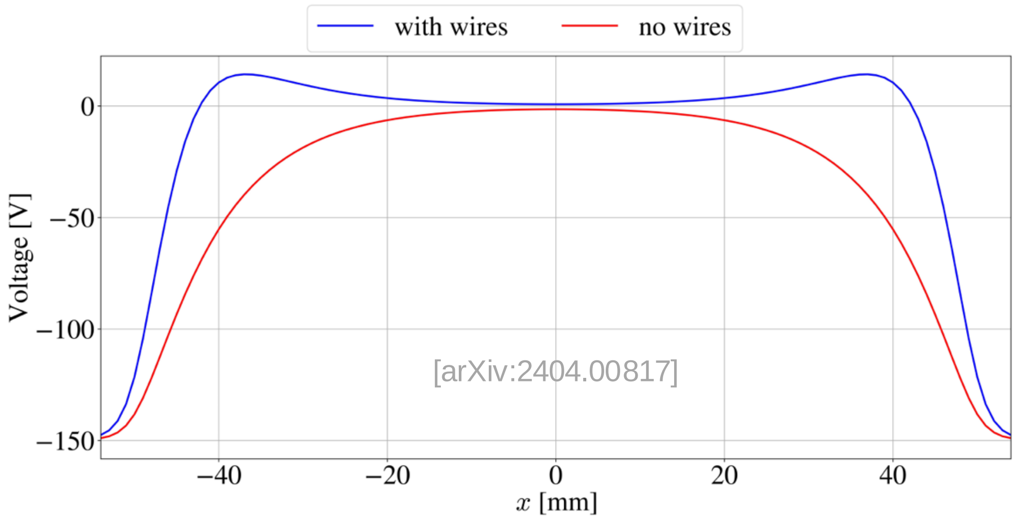


Exaggerated features – not to scale

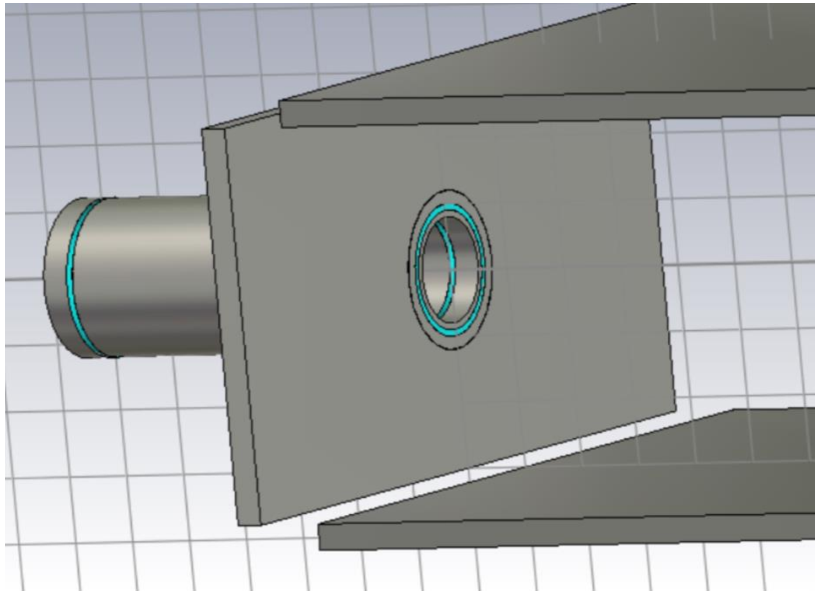
AM

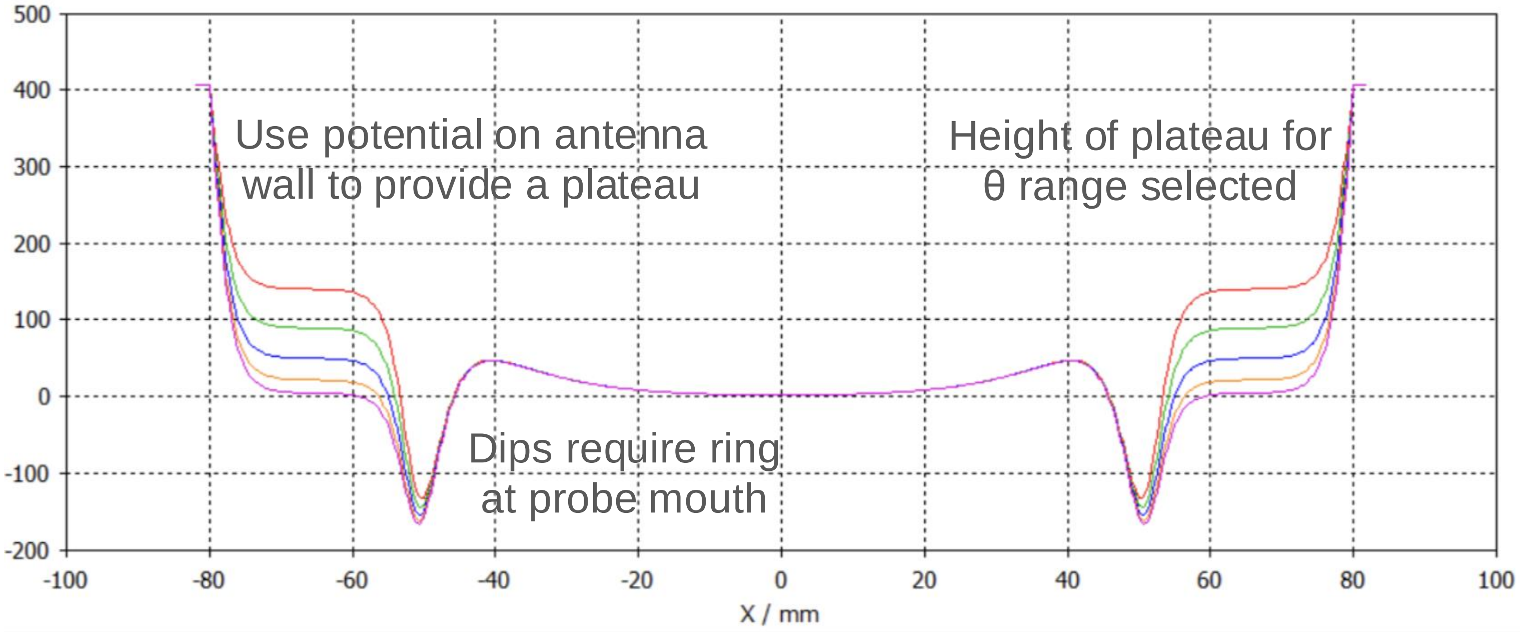


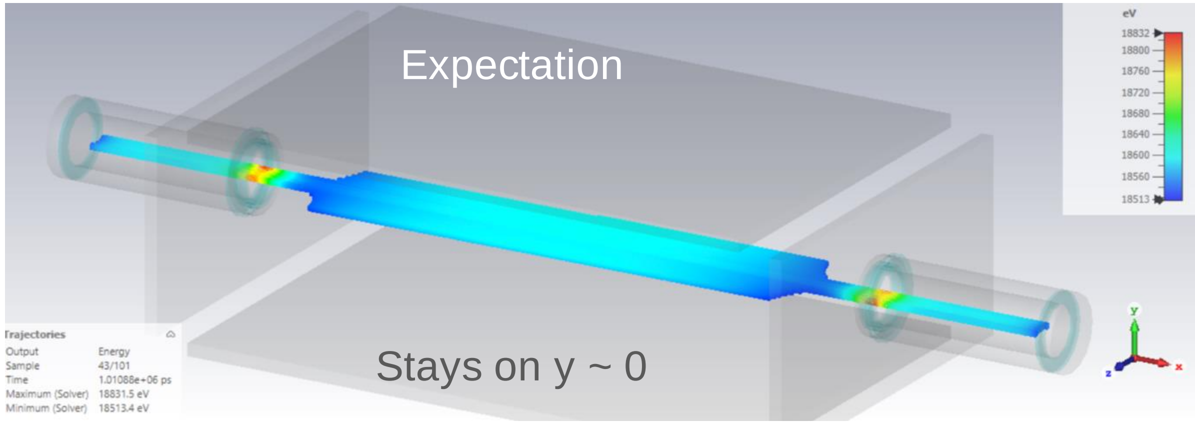


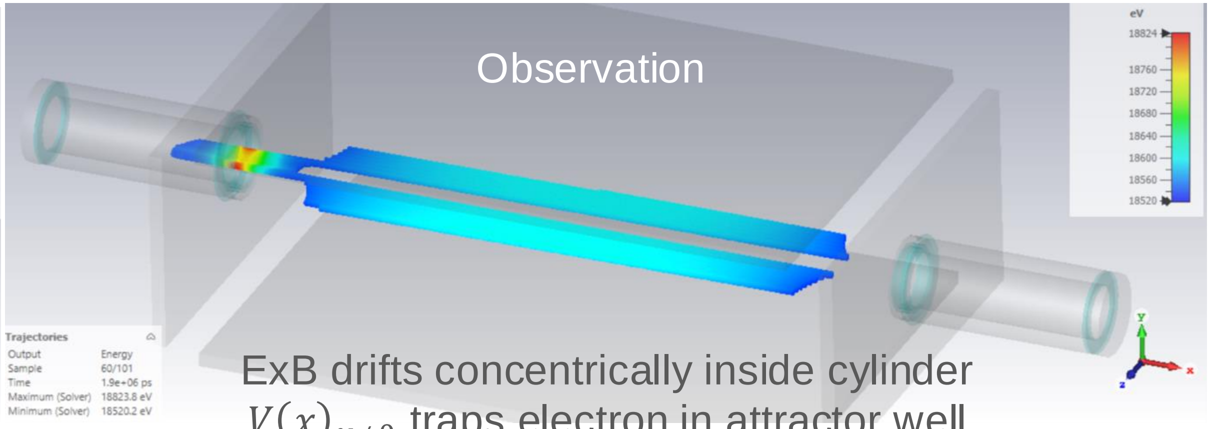


Spike in FM approaching the wall mimicking parallel motion from potential shaping wires



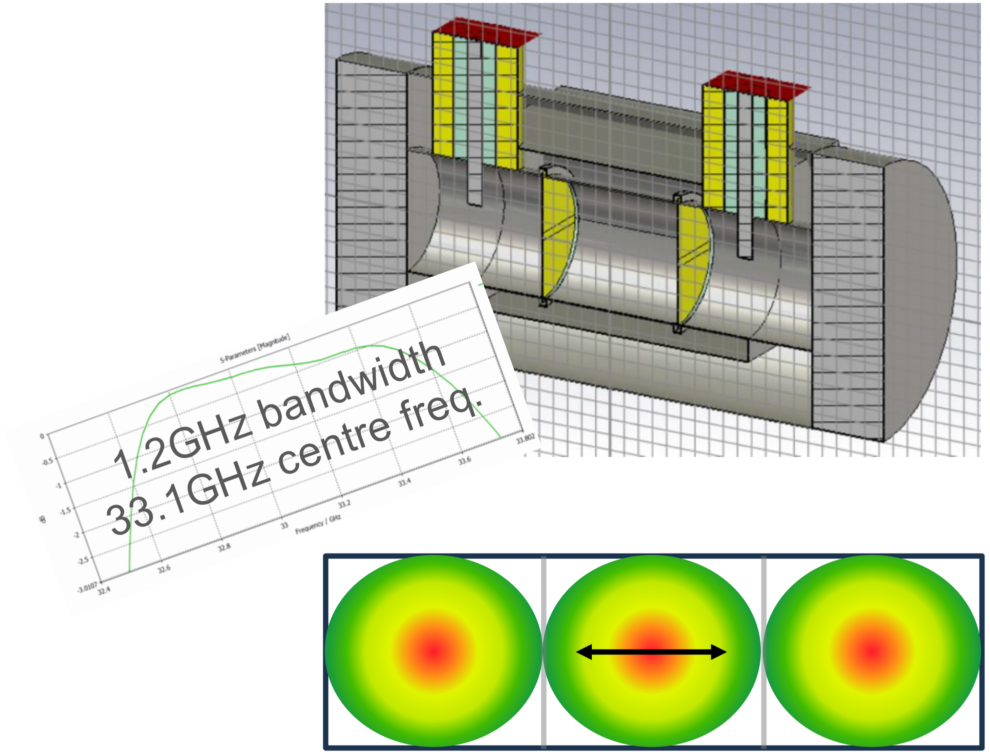




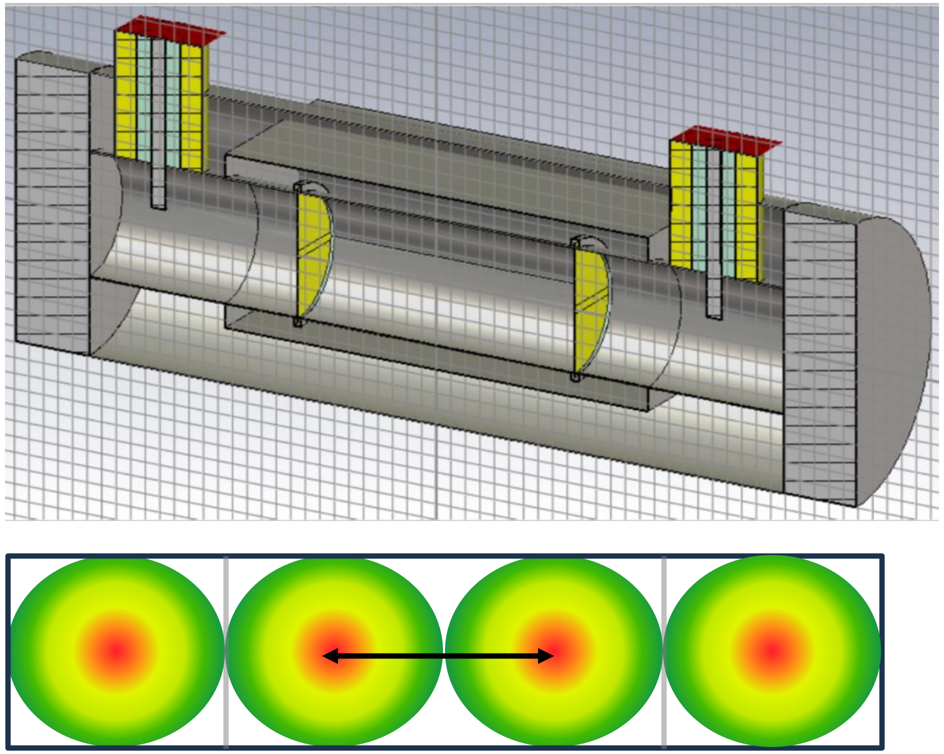


ExB drifts concentrically inside cylinder
$V(x)_{y\neq 0}$ traps electron in attractor well

Electrodes at nodes to preserve mode structure but transport window would support TE10



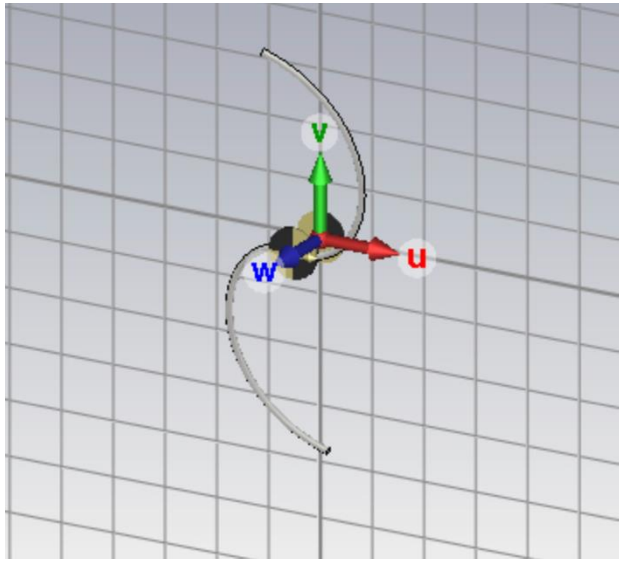
Couples to Doppler freq.



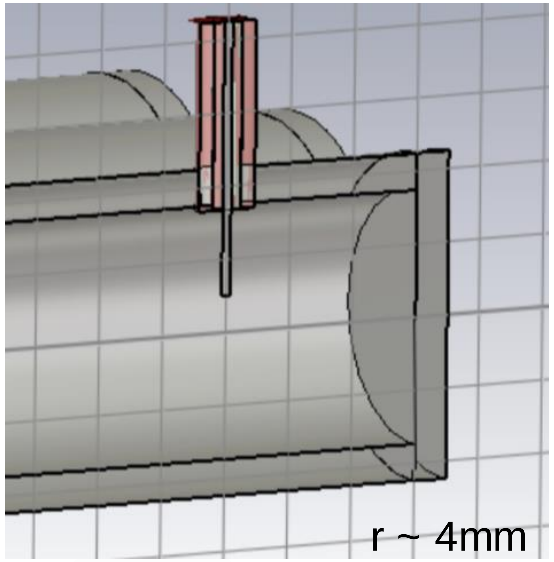
Couples to stationary freq.

Simple mode-specific antennae

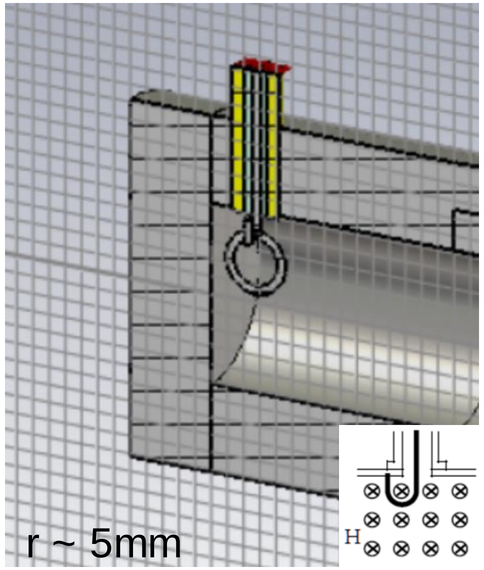
Spiral



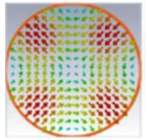
Pin



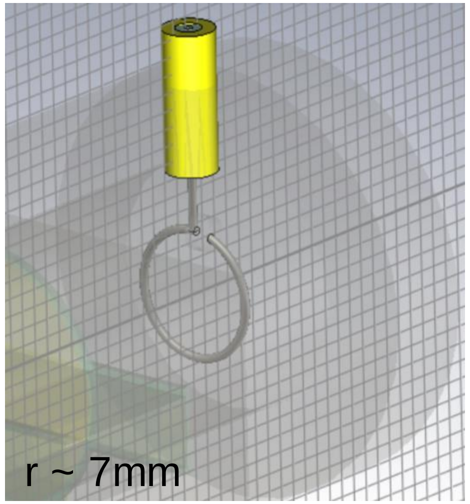
B-loop



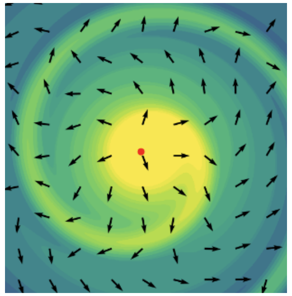
TE21



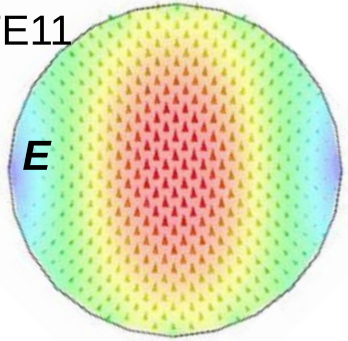
E-loop



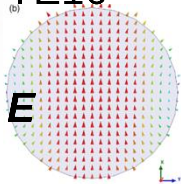
Free space



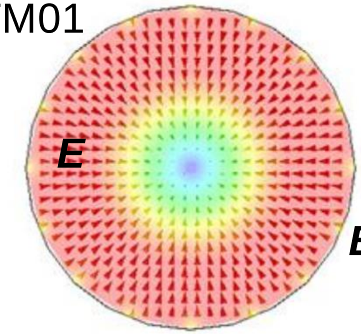
TE11

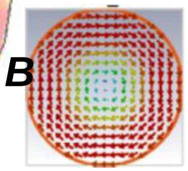


TE10

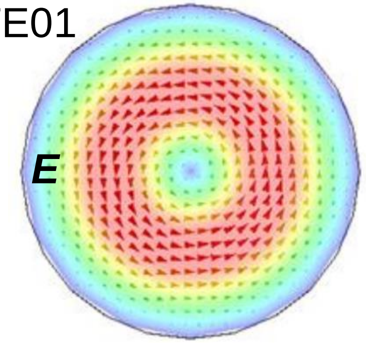


TM01

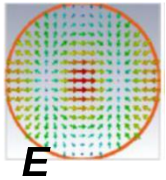


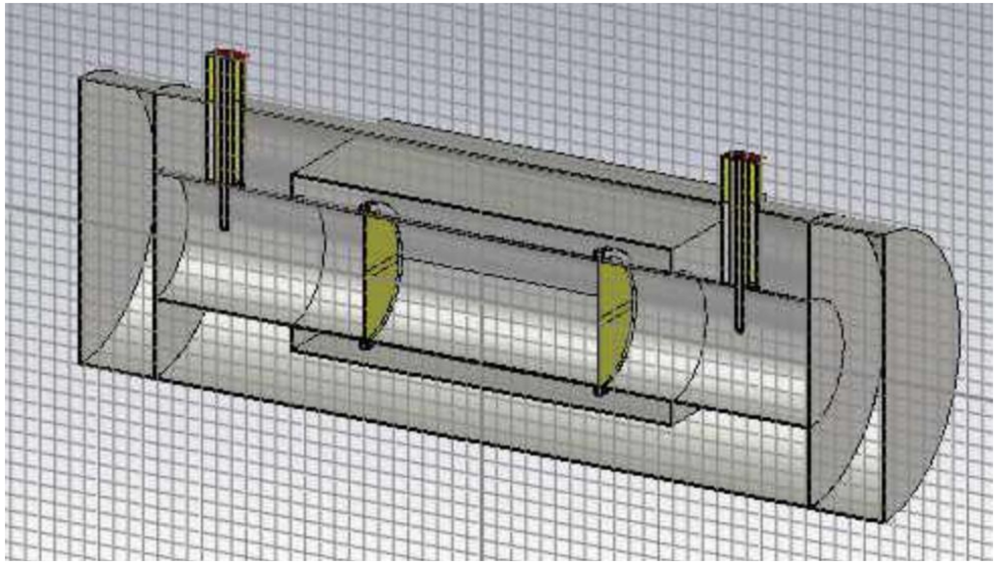


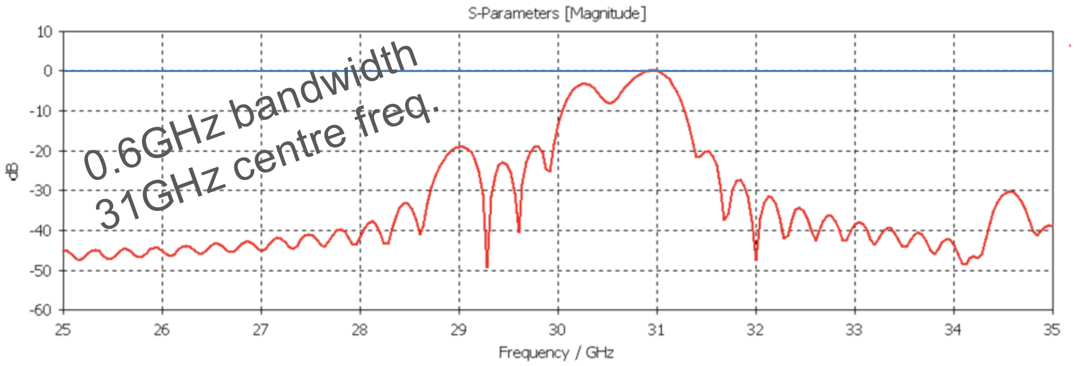
TE01



TM11

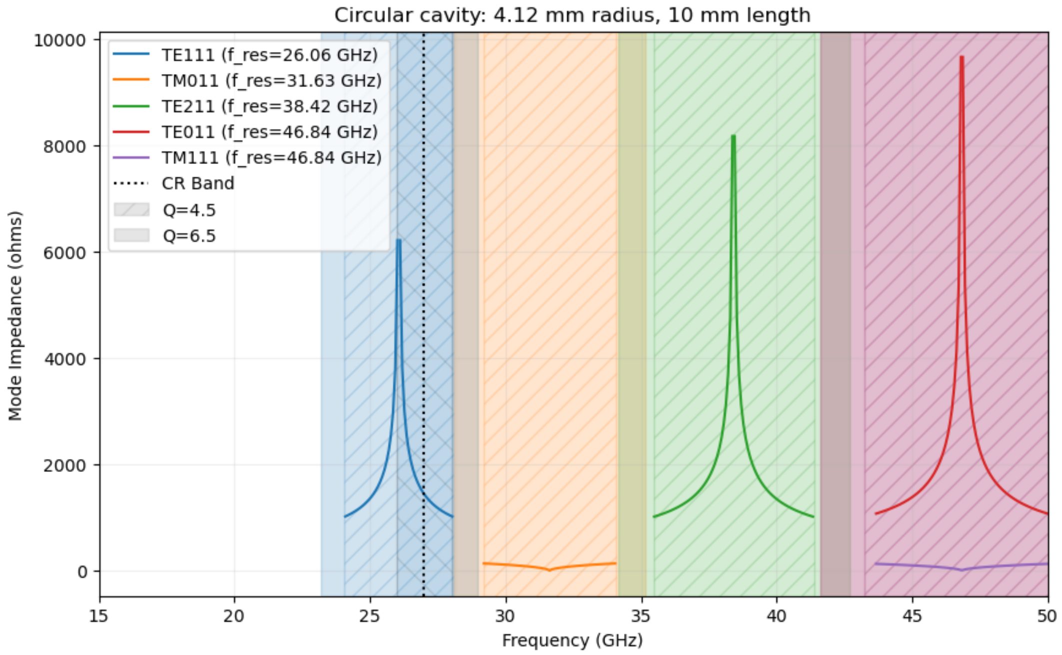




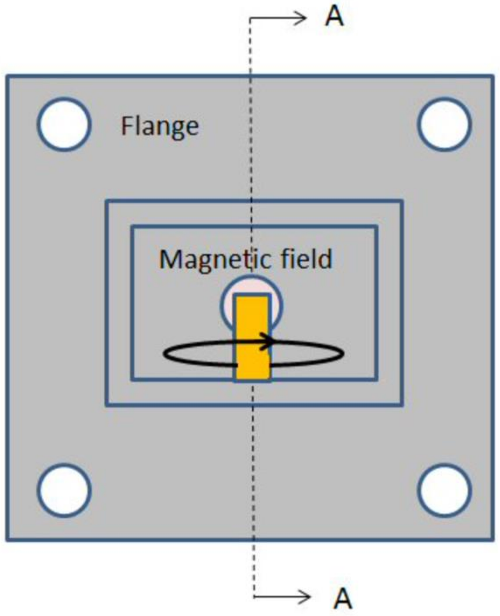


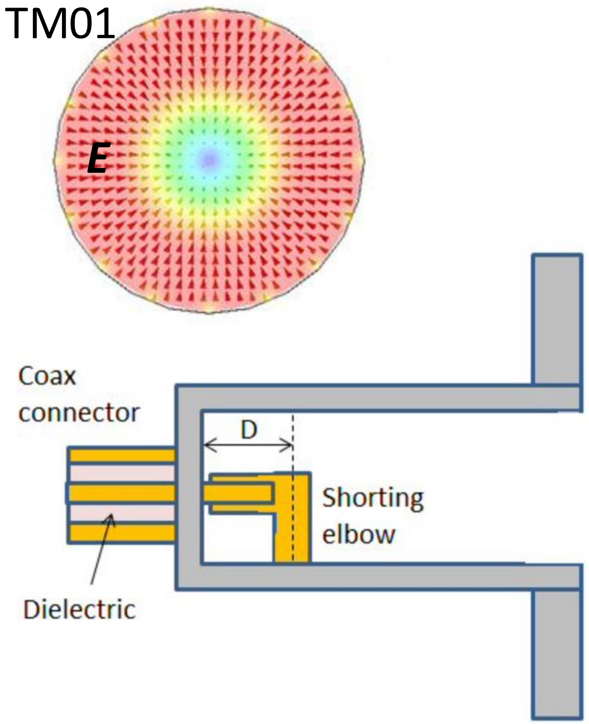
Ongoing: Parameter sweep calculating S_{21}

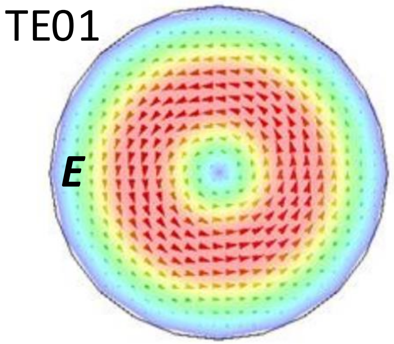
Soon: Parameter sweep calculating Q-factor

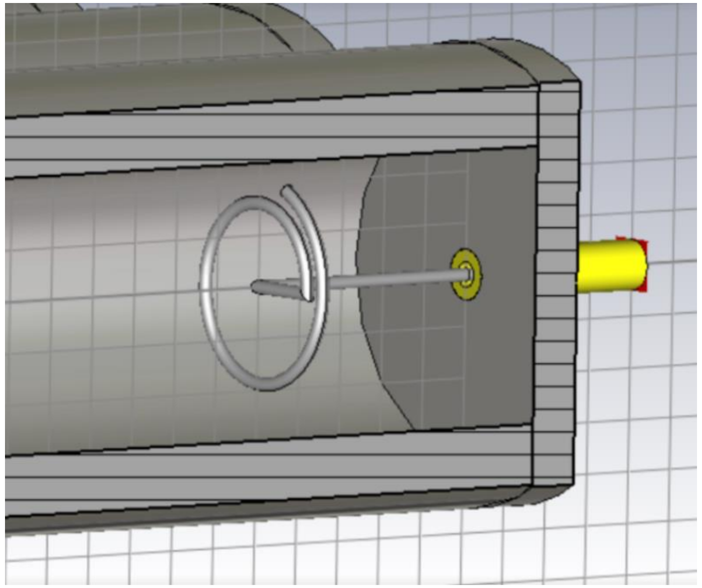


In-line transitions

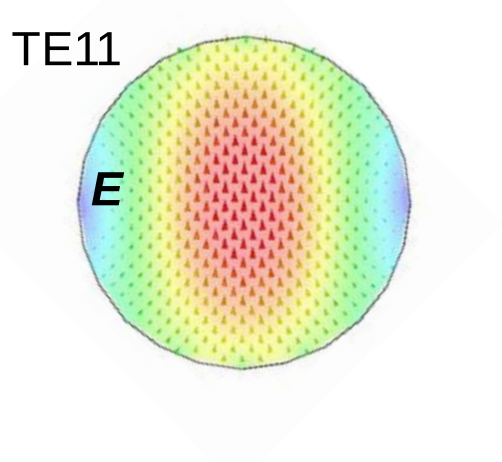






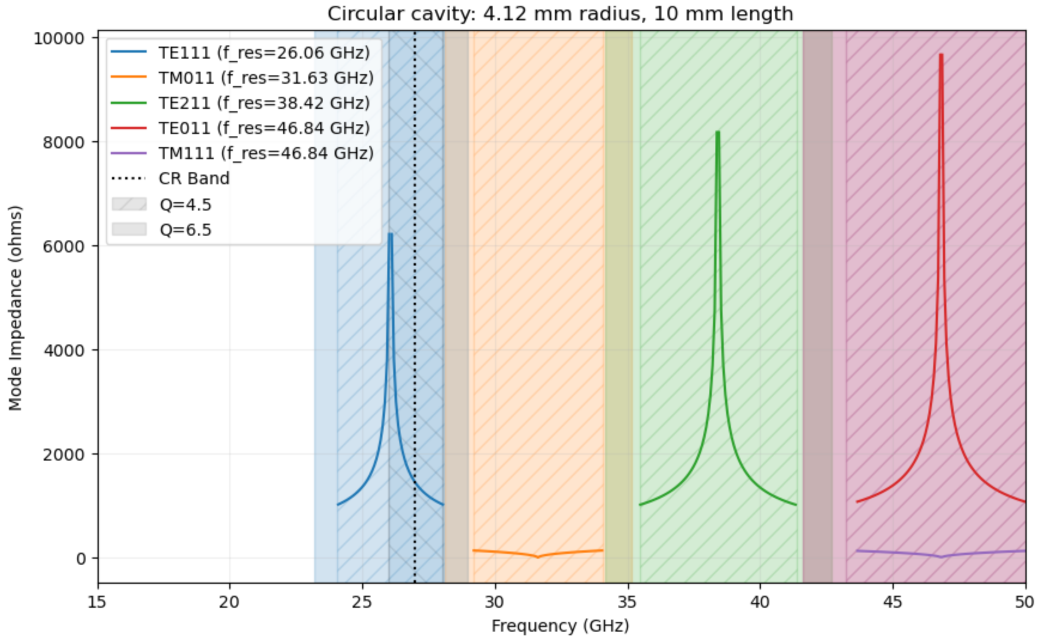


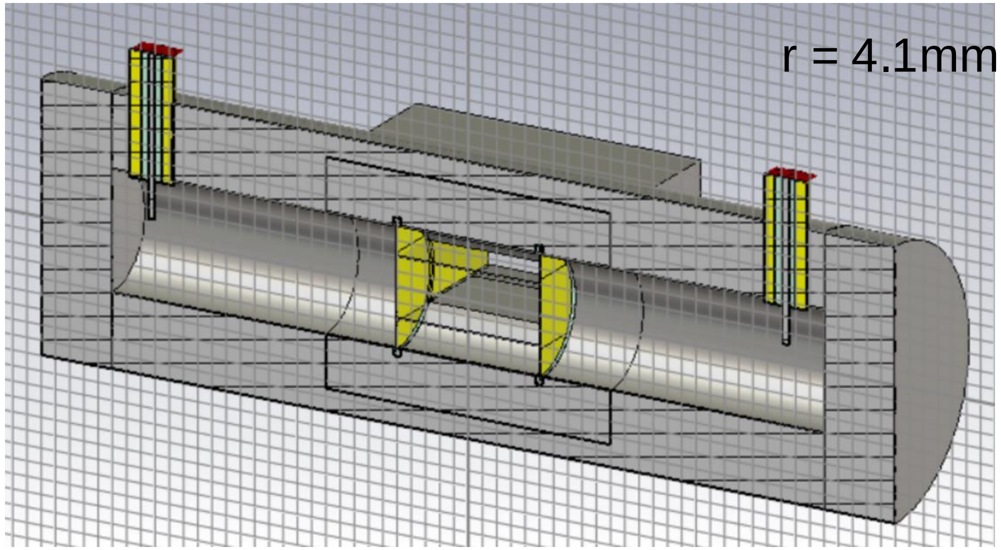
Considered but limited by space between the dipole faces

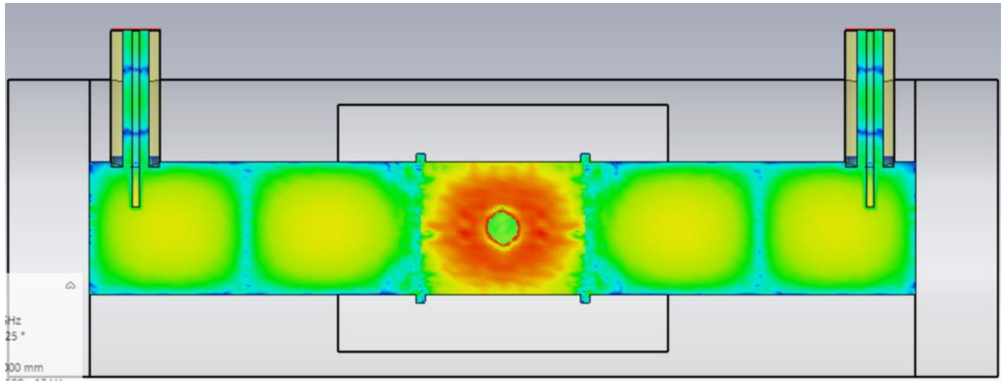


Currently investigating:

- The impact of modelling the electrodes with zero width has on signal
- Tuning for S_{21} between coax ports
- Q-factor dependence of the transport window

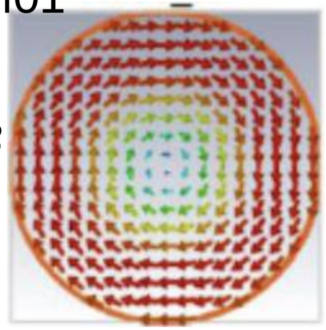






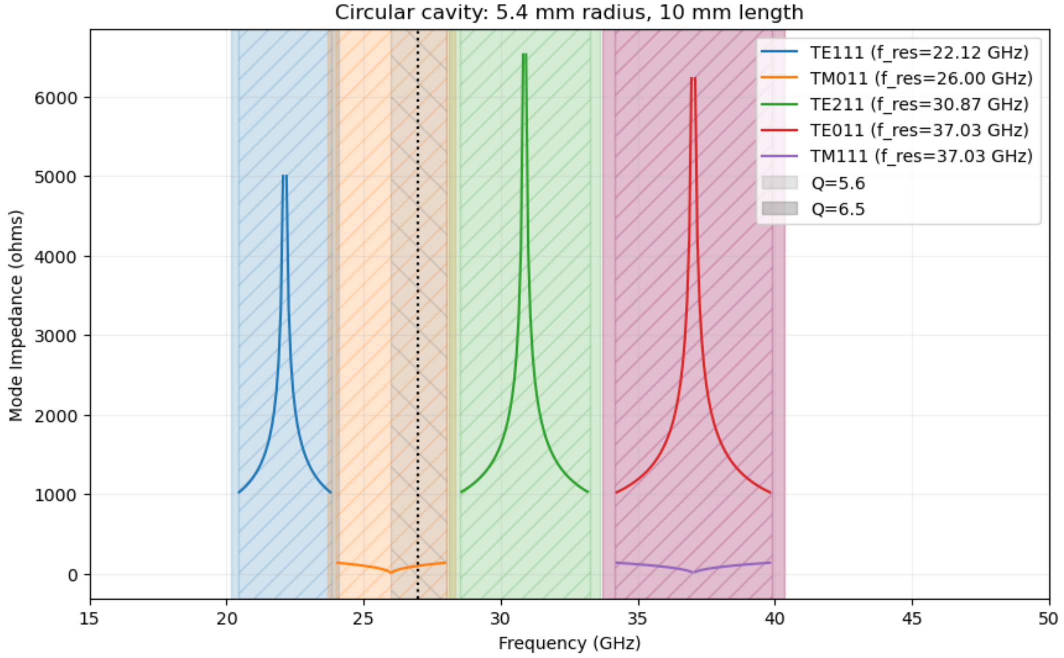
TM01

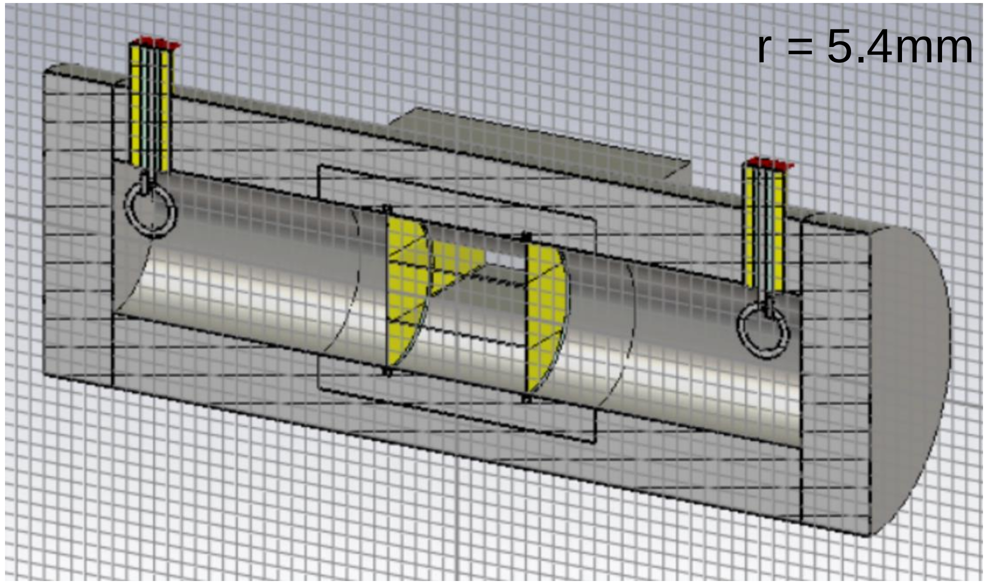
B

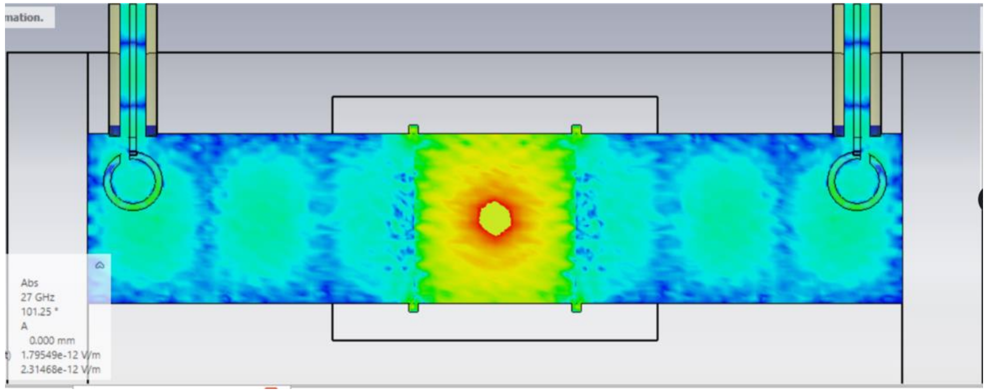


Currently investigating:

- Tuning for S_{21} between coax ports
- Bandwidth dependence of loop radius

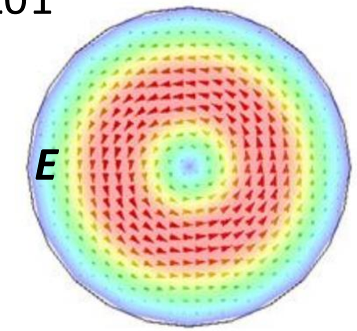






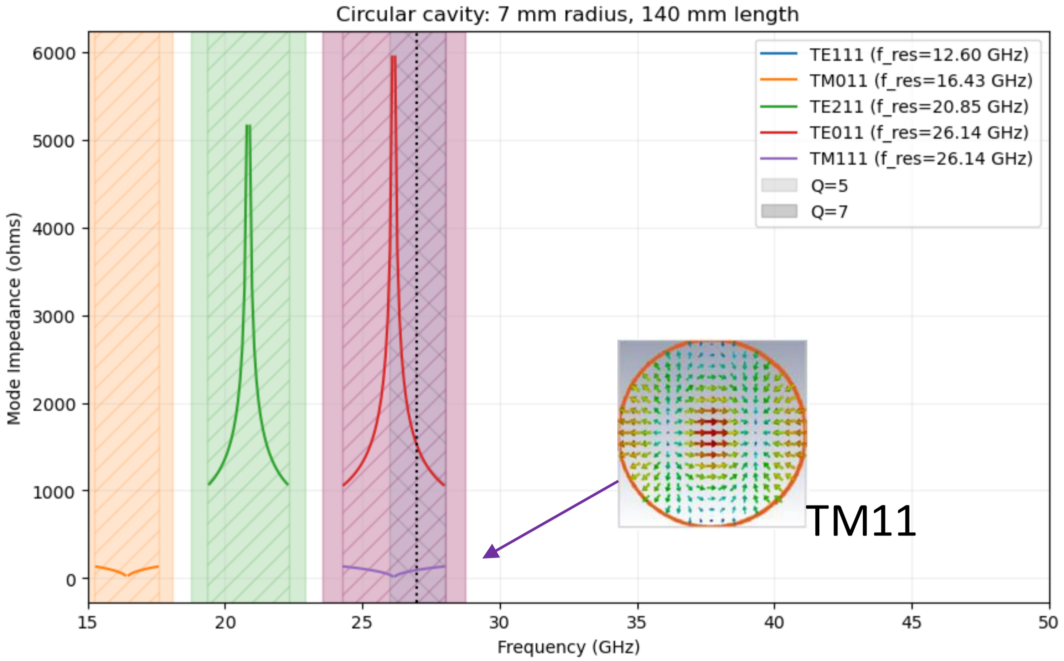
TE01… additional modes?

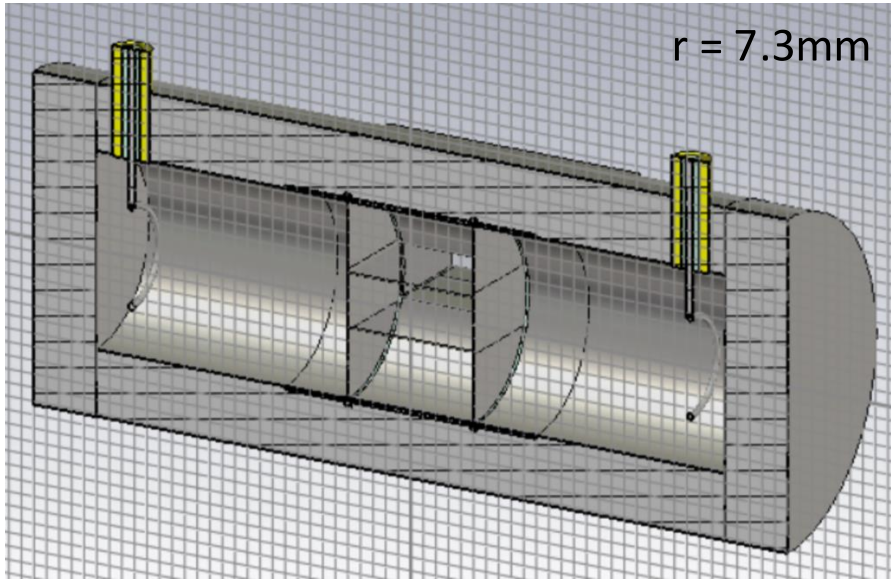
TE01

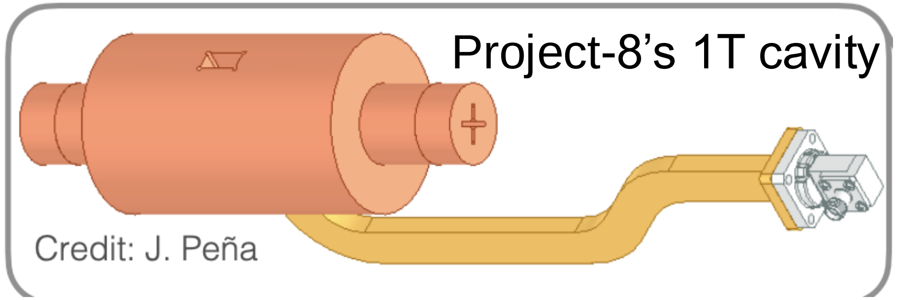


Currently investigating:

- Tuning for S_{21} between coax ports
- Are these modes expected to hybridise?



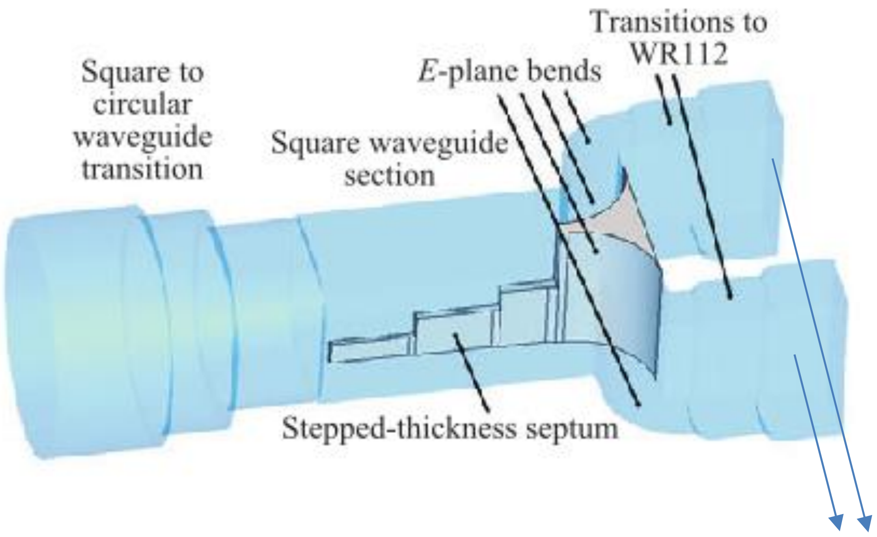




Juliana Stachurska, NuMass 2024

IN-LINE TRANSITION

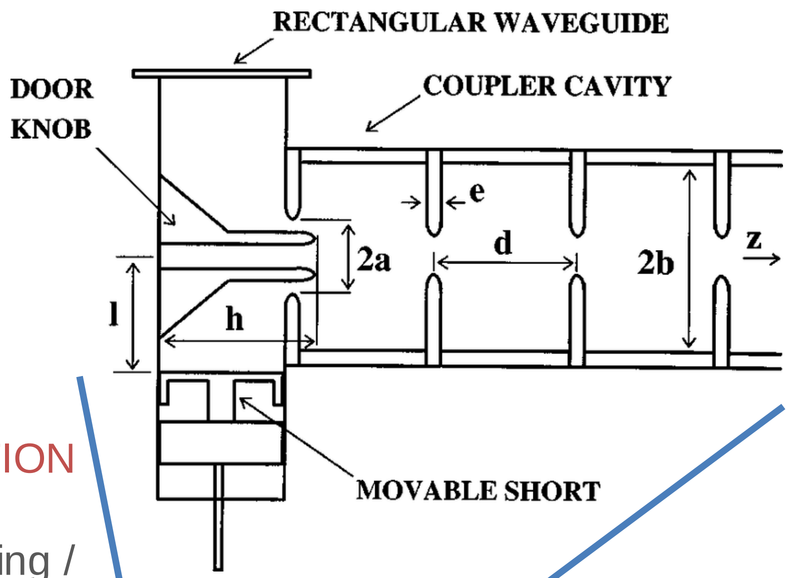
Waveguide less lossy than waveguide
Reduces number of coax-waveguide transitions



Merge rectangular outputs
Direct transition to LNA

Short on space inside current/new magnet? (50mm - 150mm)

RIGHT ANGLE TRANSITION



Impedance matching / Tuning elements built in

Spare-rib compatible?