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Microwave reflectometry diagnostic for density profile and fluctuation measurements on Helically Symmetric eXperiment (HSX)

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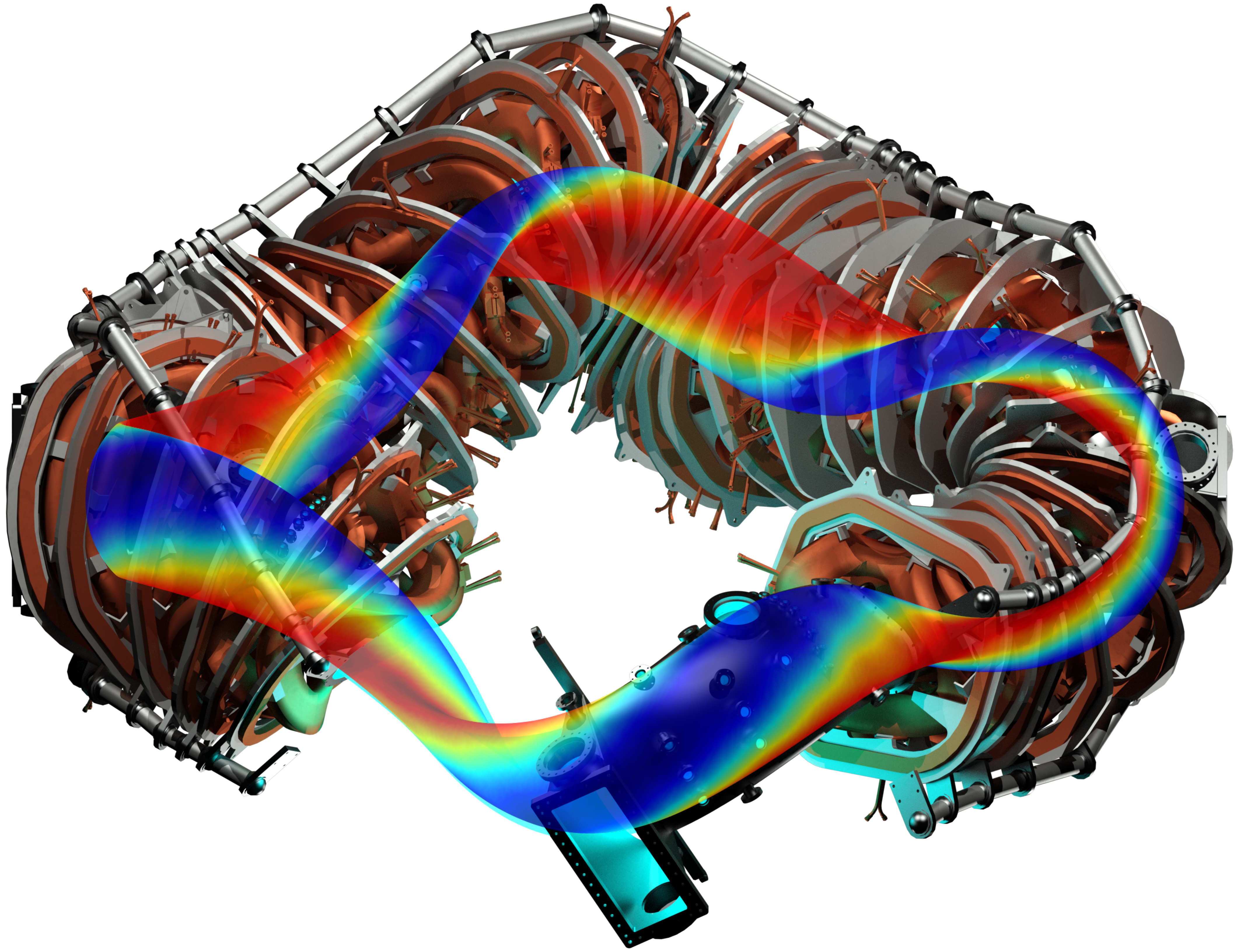
Outline

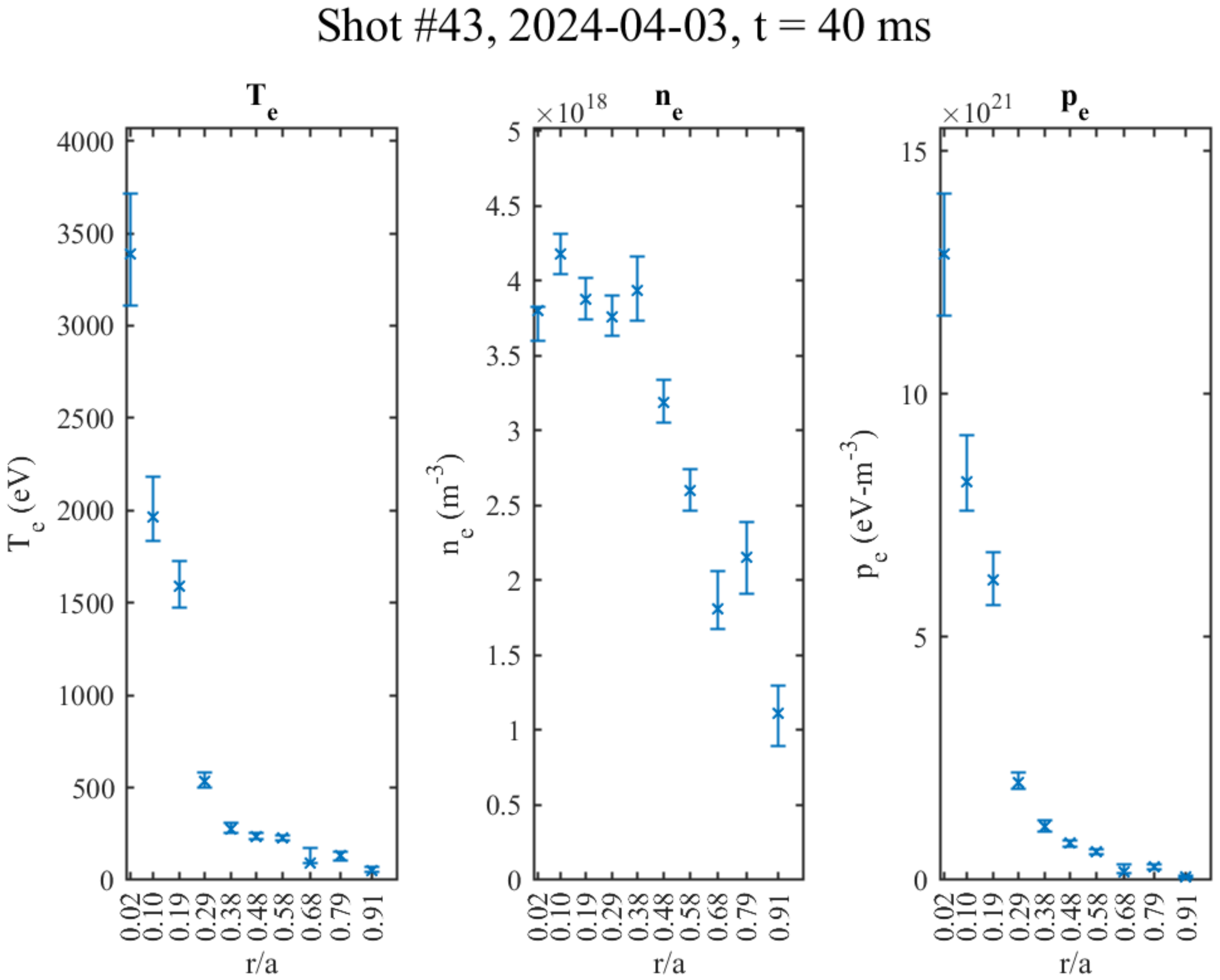
- Introduction
- Observations of density fluctuation
- Profile reconstruction with O-mode regime
- Plan of system renovation
- summary

HSX is an ideal testbed for studies of micro-instabilities and neoclassical transport

Helically Symmetric eXperiment

- **H**elically **S**ymmetric e**X**periment (HSX) is featured a quasi-helically symmetric magnetic configurations (**QHS**)
- 4 field periods (48 modular + 48 planar coils)
- rotational transform $\iota > 1$

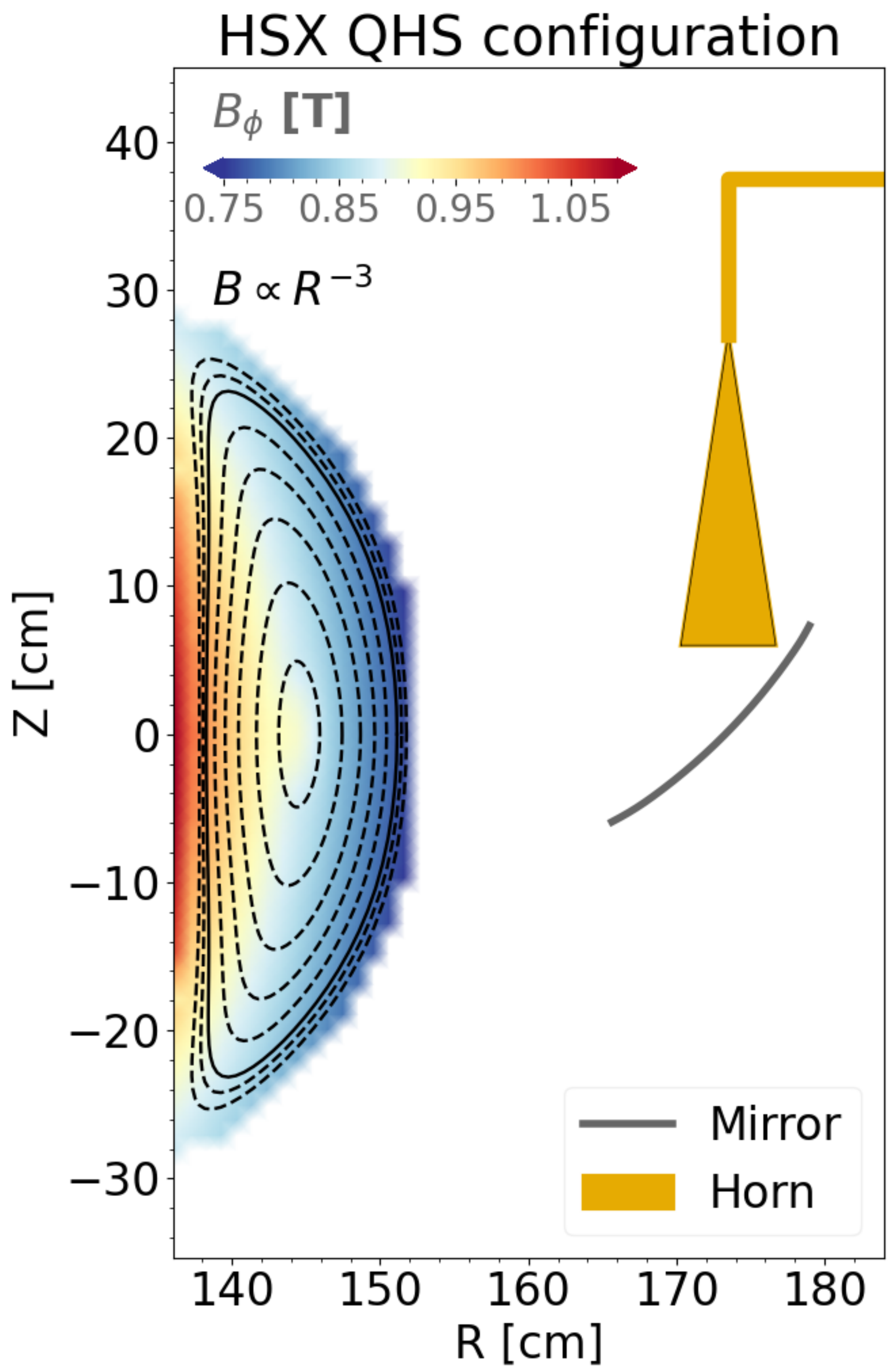




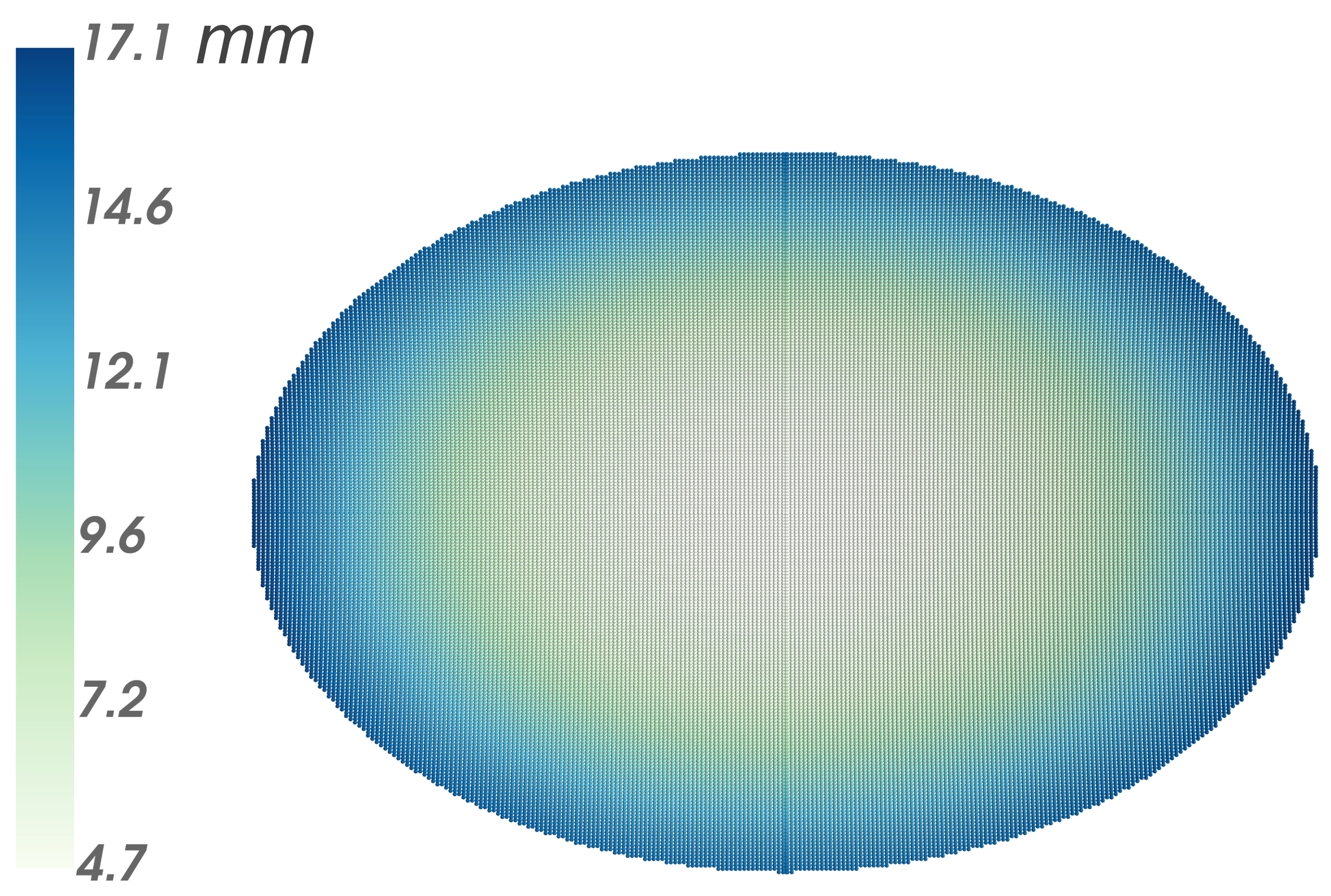
Radius	$R/a = 1.2\ m/0.12\ m$
ECRH	@28 GHz $P_{absorption \sim 20\ kW}$
Pulse length	50 ms
On-axis B field	0.5~1.0 T
Core temperature	$T_e \leq 3\ keV \quad T_i \sim 50\ eV$
Plasma density	$\sim 10^{13} cm^{-3}$
Diagnostics	**Reflectometry**, CECE, TS, Interferometer, fast camera, Mirnov coils, CHER …

https://hsx.wisc.edu/

Reflectometry is designed to measure the electron density fluctuation and profile

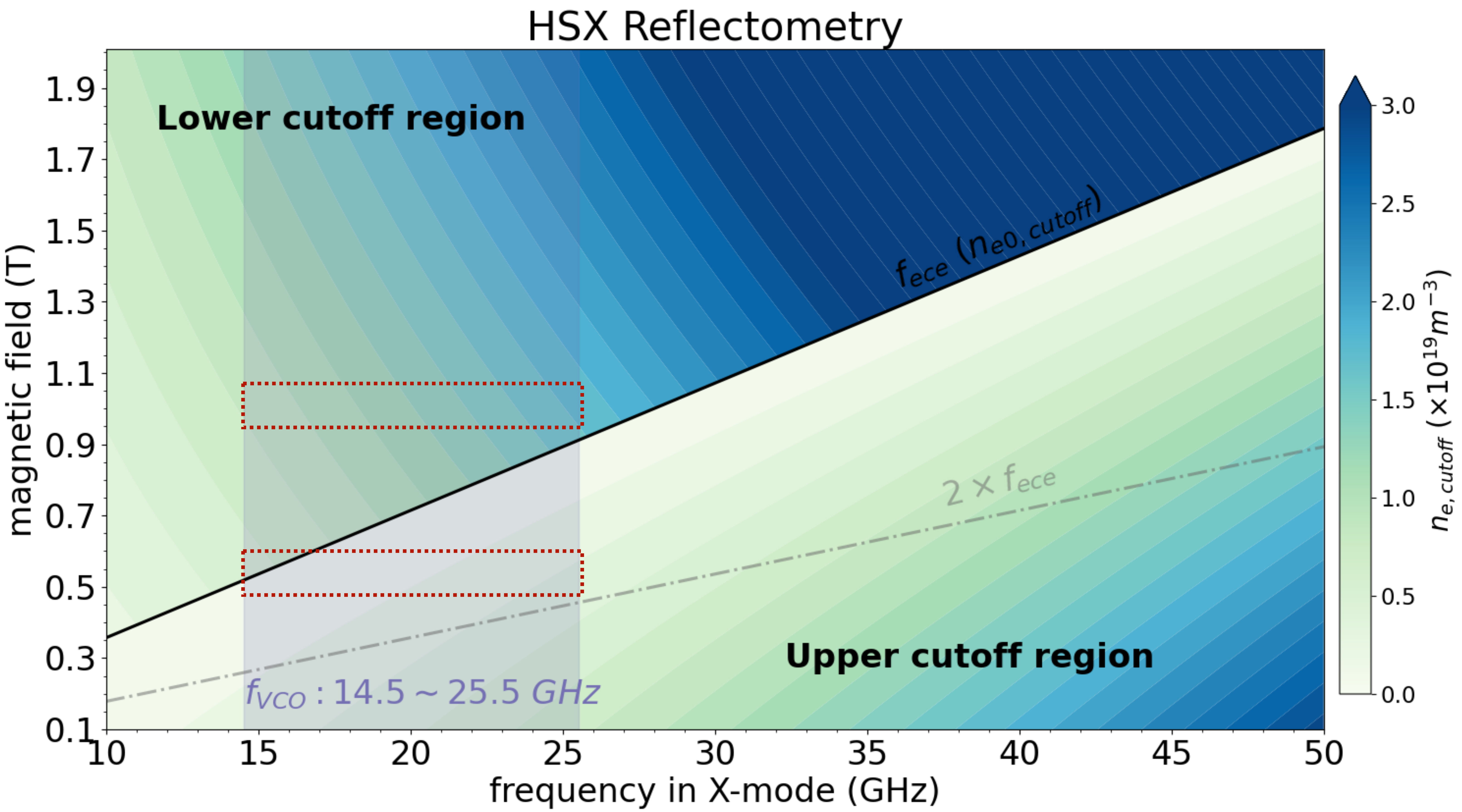


- Monostatic horn at boxport A
  - Major radius at 173.5 cm
  - E-plane 63.5 mm / H-plane 88.5 mm
  - L = 210 mm
  - Waveguide: WR-42
- Vertically-installed horn, facing toward an elliptical mirror at equatorial plane



- Elliptical mirror
  - Distance to the horn 60 mm
  - Focal length 143.16 mm (E-plane), 137.89 mm (H-plane)
  - Incident angle 45^o

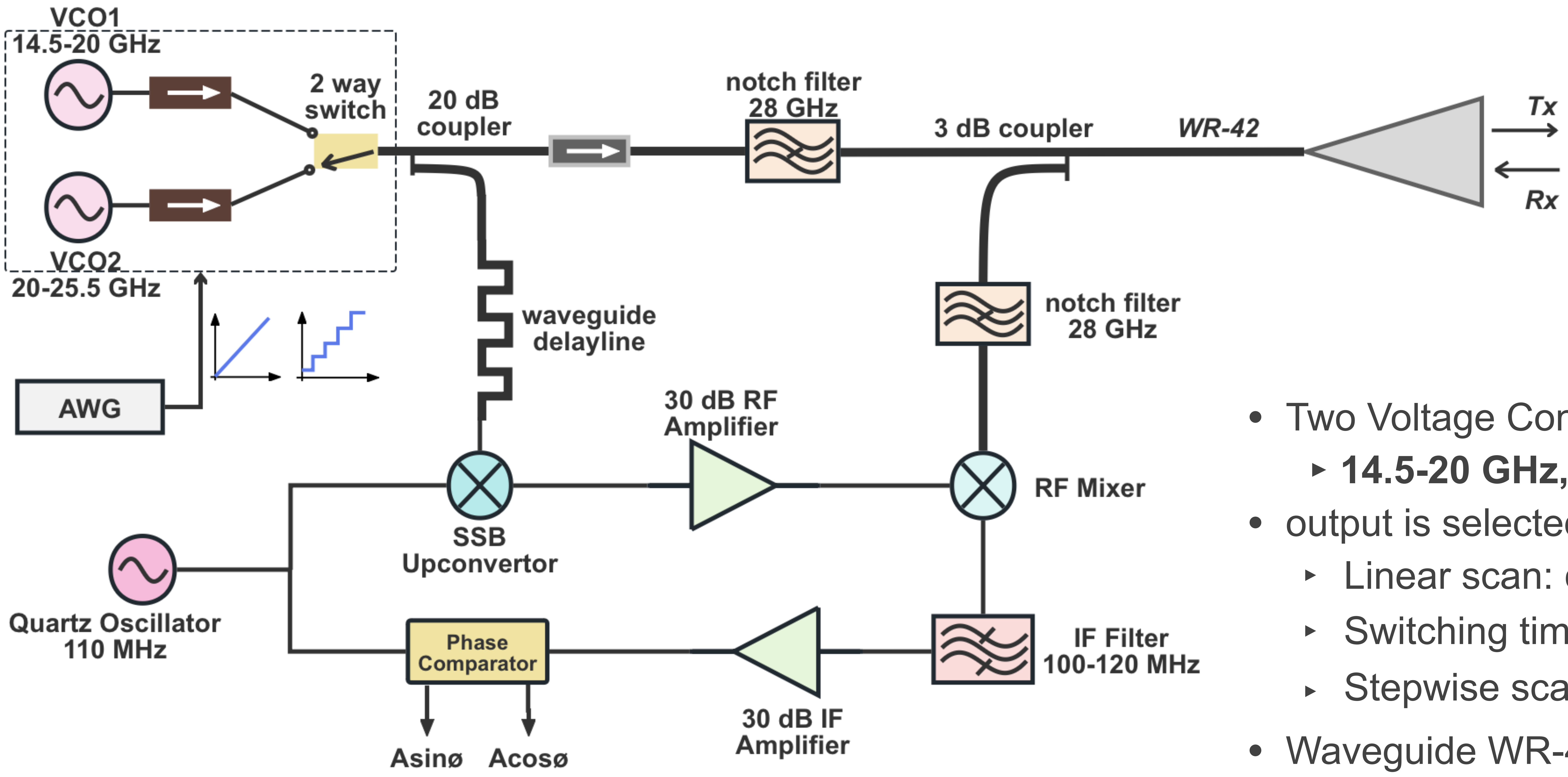
Polarization is selected by rotating the mirror and horn



- Operational frequency range 14.5~25.5 GHz
- **O-mode** operation at B=1 T, corresponding to cutoff density of $2.8 \sim 7 \times 10^{18}\ m^{-3}$
- **X-mode** operation per requirement
  - upper cutoff at 0.5 T: $0.05 \sim 0.36 \times 10^{19} m^{-3}$
  - lower cutoff at 1 T: $0.72 \sim 1.7 \times 10^{19} m^{-3}$

$$|B| \propto R^{-3}$$

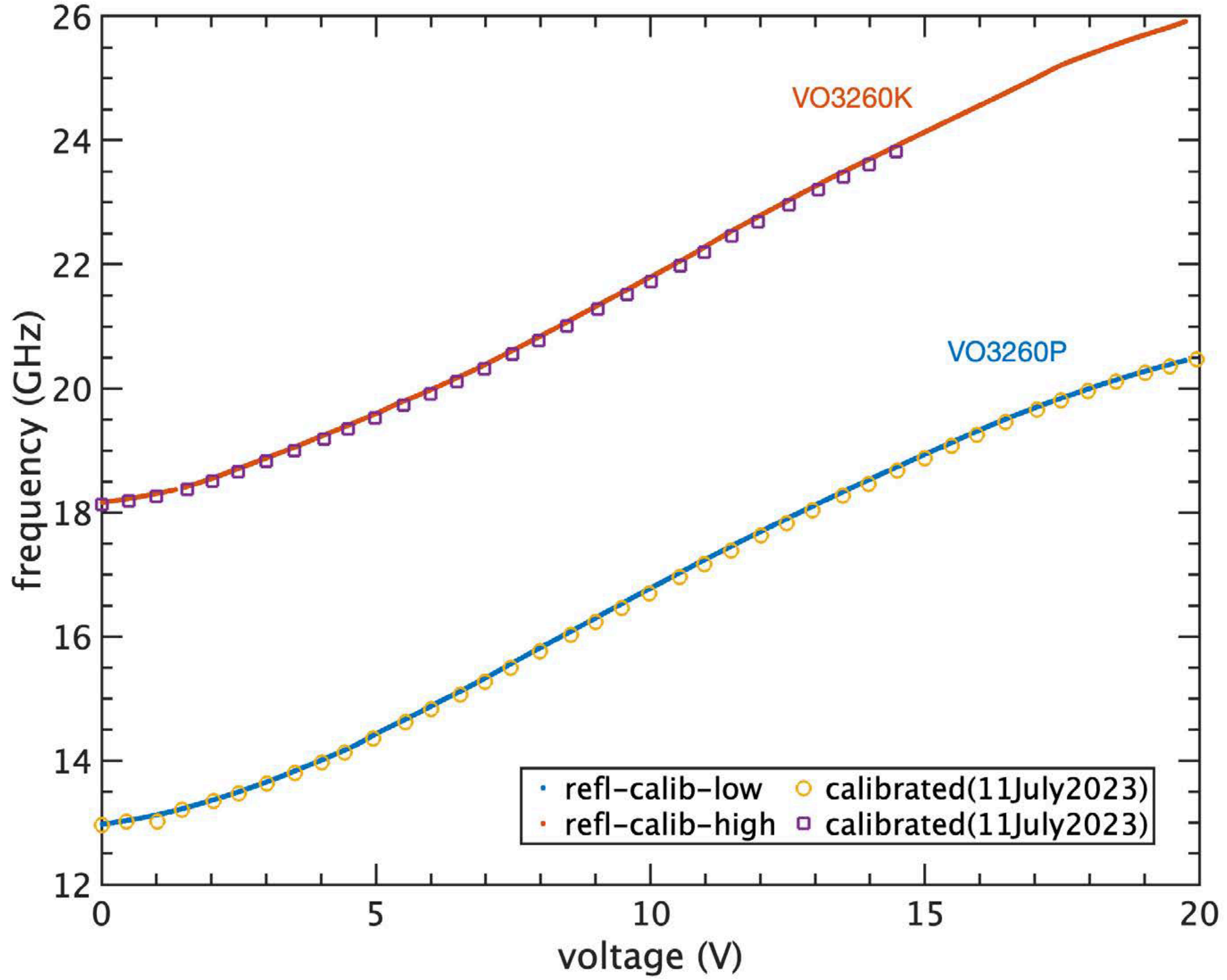
Layout of microwave components: Conventional FMCW heterodyne system



- Two Voltage Control Oscillators (VCO)
  - **14.5-20 GHz, 20-25.5 GHz**
- output is selected by a fast-pin switch
  - Linear scan: **df/dt ~27.7 GHz/ms**
  - Switching time: $\sim 54\ \mu s$ (18.5~20 GHz)
  - Stepwise scan: $N_f = 20,\ \Delta f = 500\ MHz$
- Waveguide WR-42 delayline ~10 m to compensate the phase at LO of RF mixer

VCOs are re-calibrated after the HSX refurbishment

Helically Symmetric eXperiment



- *Dots: original calibrated data*
- *Circle & rectangle: newly-calibrated data*

- HSX was refurbished in 2023 for high density operation planned at late 2024
- Reflectometry system hasn't been operated for decades
- VCO performance is the same as before
- Frequency-voltage curve matched to the original values

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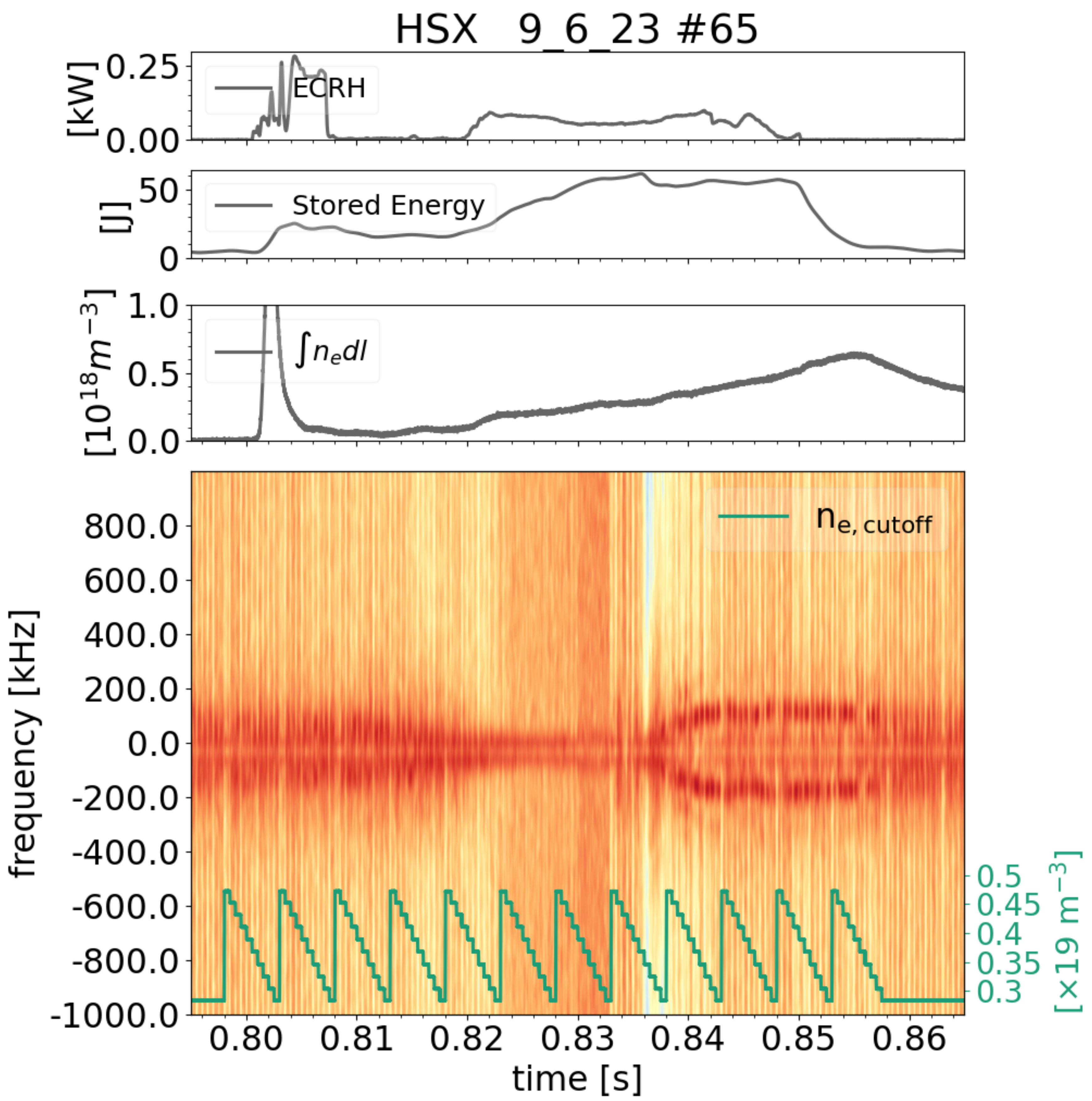
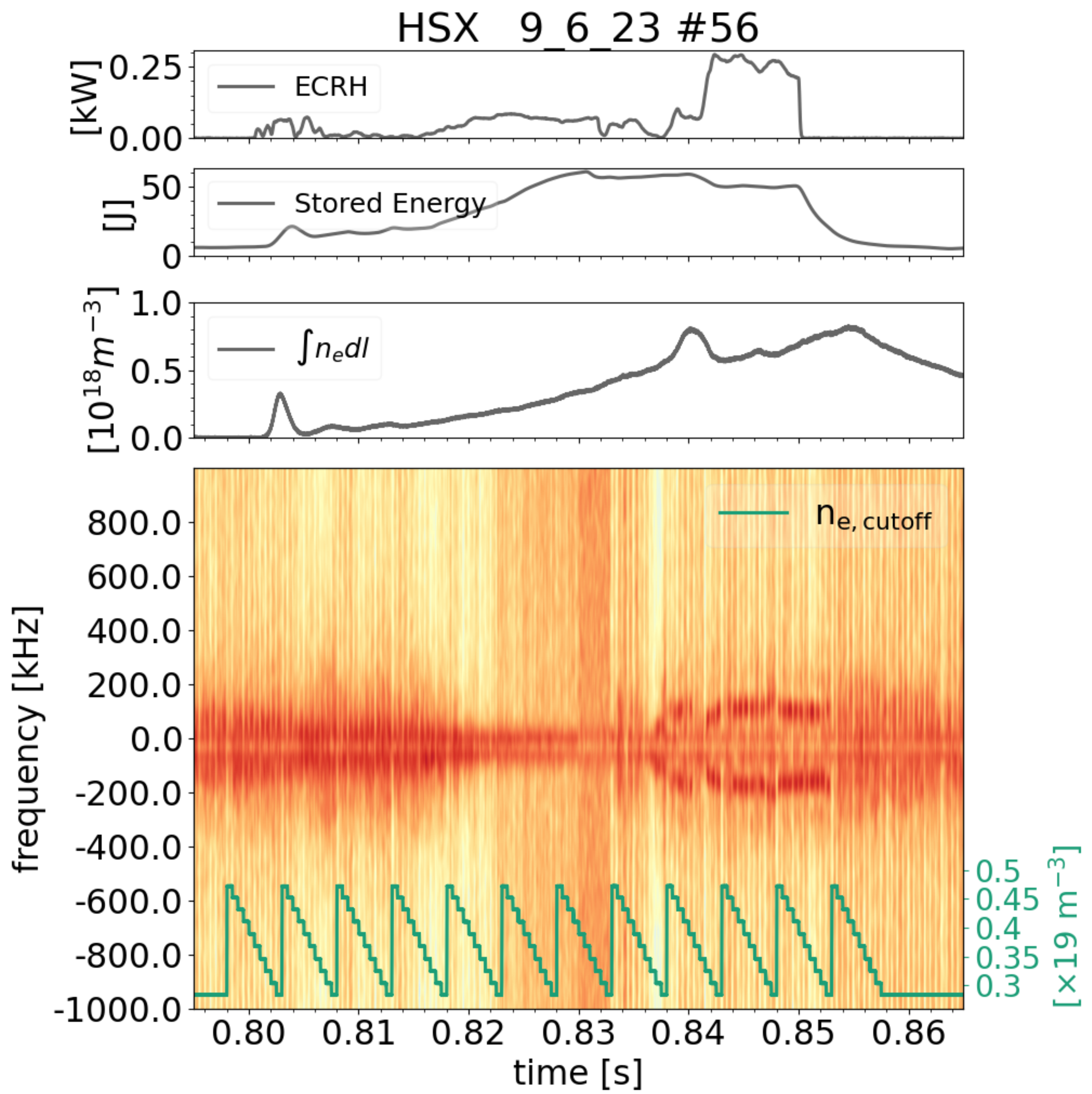
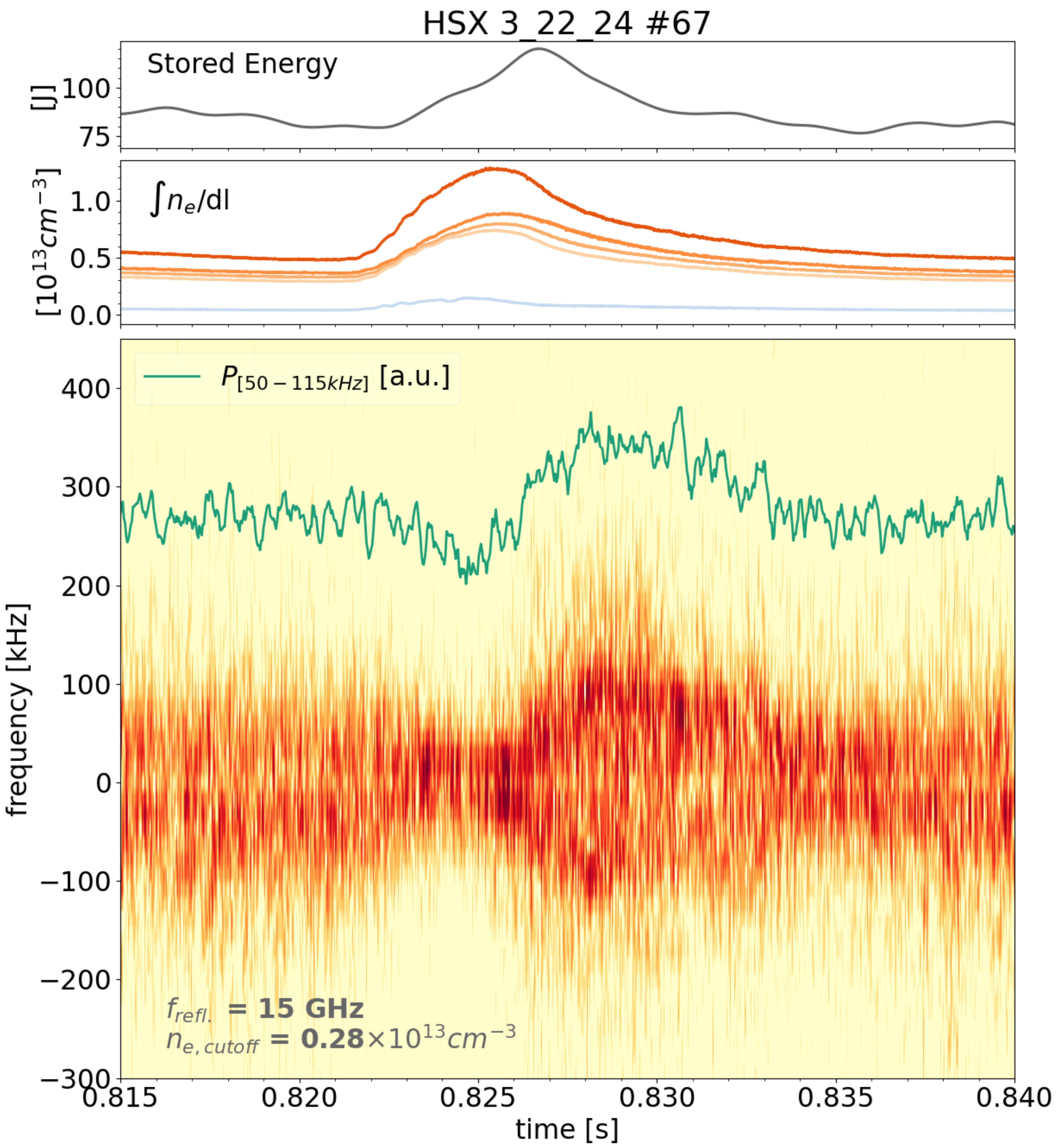
A turbulent mode observed during density ramping

- Mode frequency ~150 kHz
- Appears after 0.835 s, remains the same at all cutoff density
- Could play a role on the profile gradient
- Not clear the mode behavior (electronic-magnetic mode?)

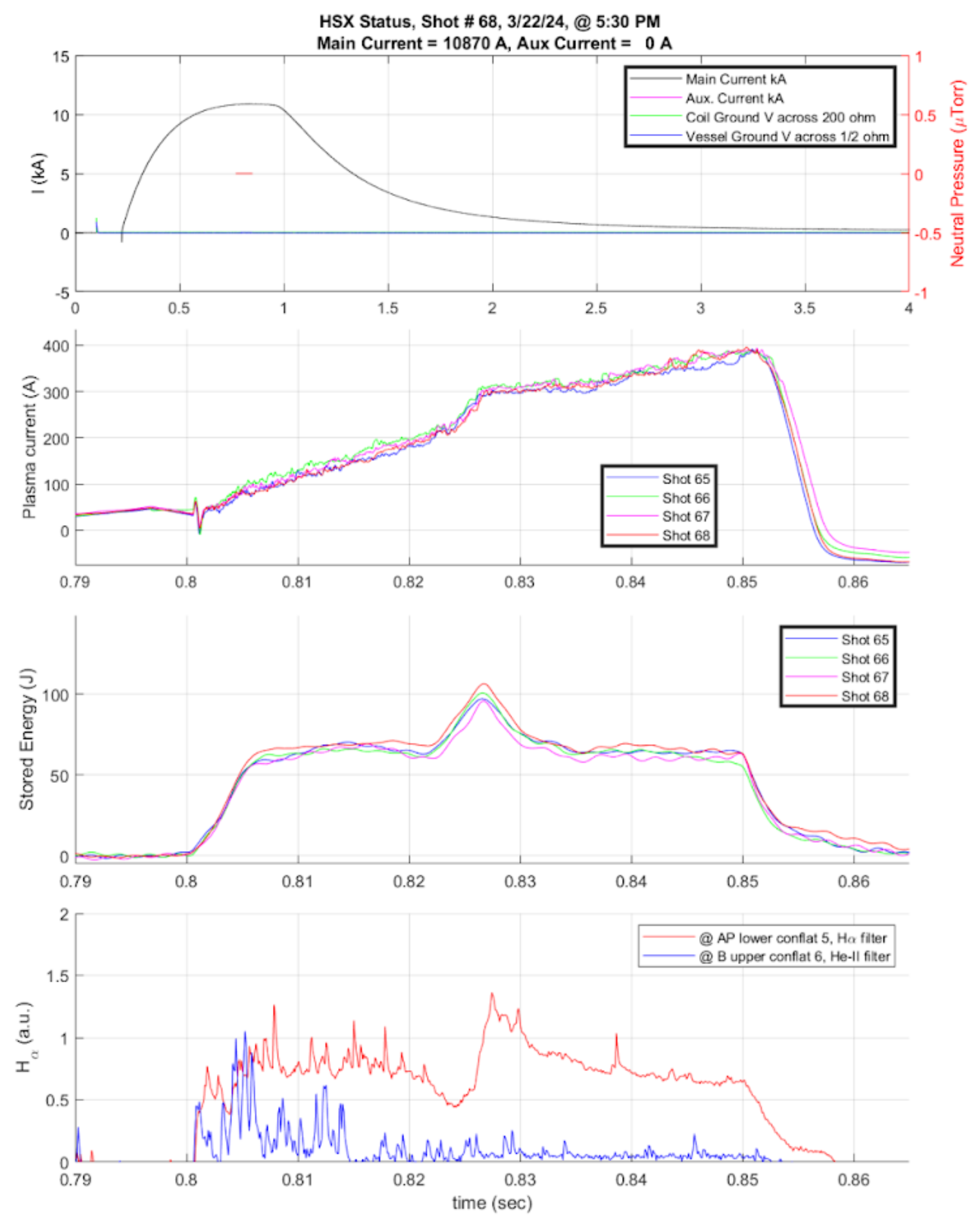


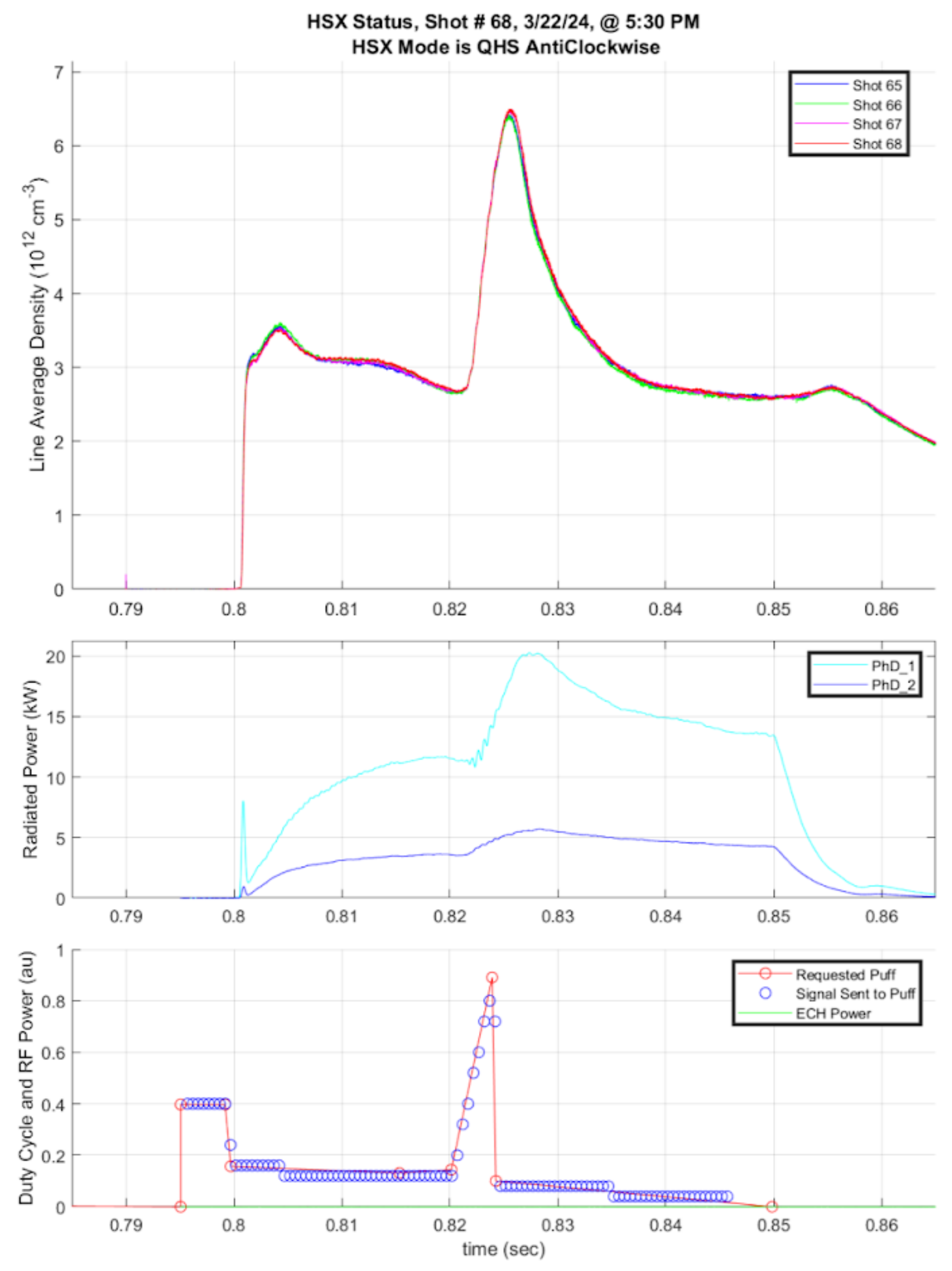


Turbulence modulation is observed during the gas puffing experiment

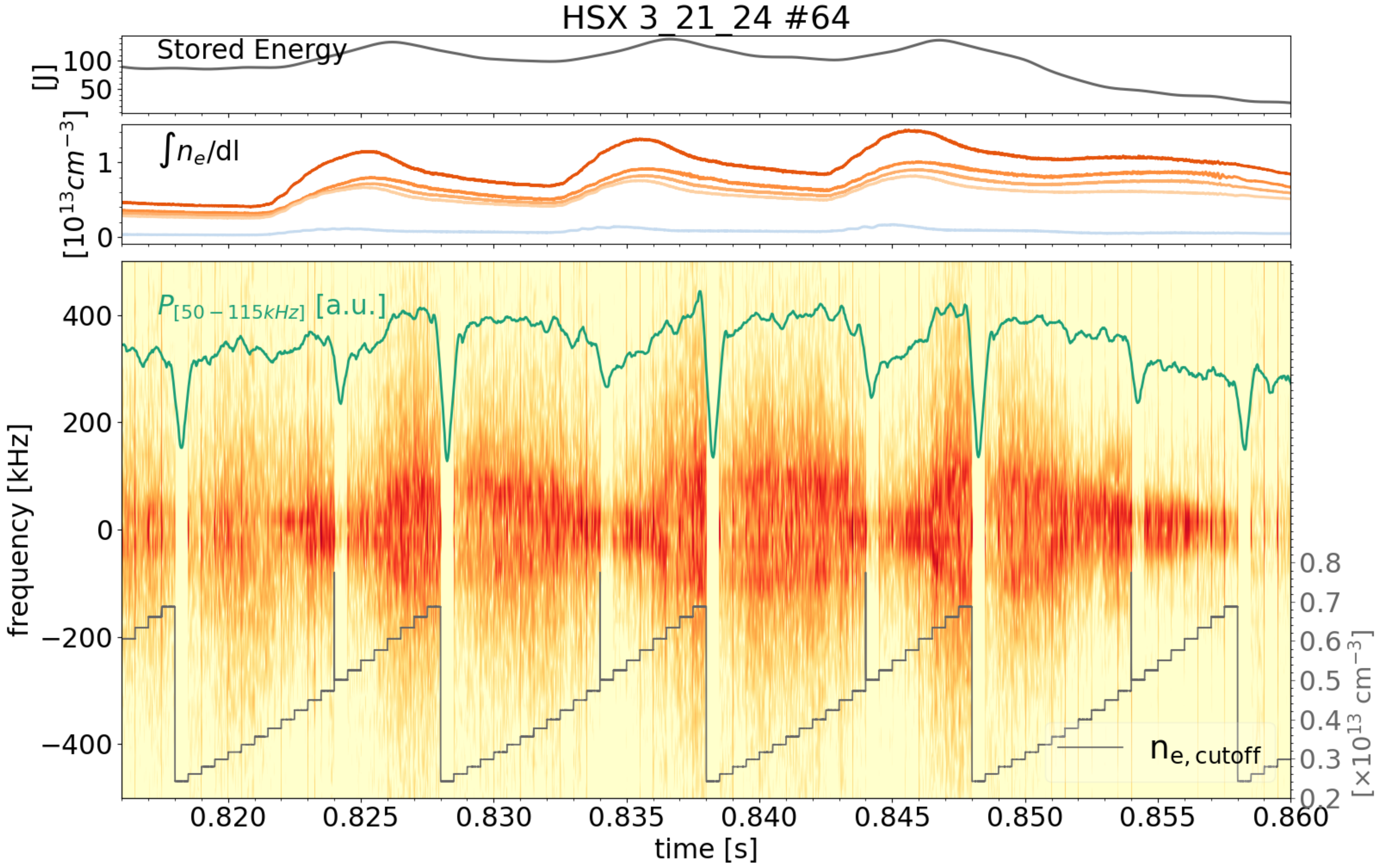


- Gas puffing is applied to modulate plasma density
- At ne rise, turbulence is suppressed (f<50 kHz mode?)
- At ne decrease, spectral power integrated at 50-115 kHz
- Turbulence at 100 kHz appears at the late phase when the density decreases





Radial location of 100 kHz turbulence is determined with stepwise scan



- 100 kHz turbulence regularly appear at the ne-decreasing phase in each gas-puff cycle
- Exist only when ne starts to decrease, yielding a relation between density gradient and the turbulence modulation
- Density profile is needed to confirm the radial coverage of the 100 kHz mode

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Choi-William Distribution (CWD) is applied to extrapolate f_{beat} from time-frequency spectrum

Helically Symmetric eXperiment

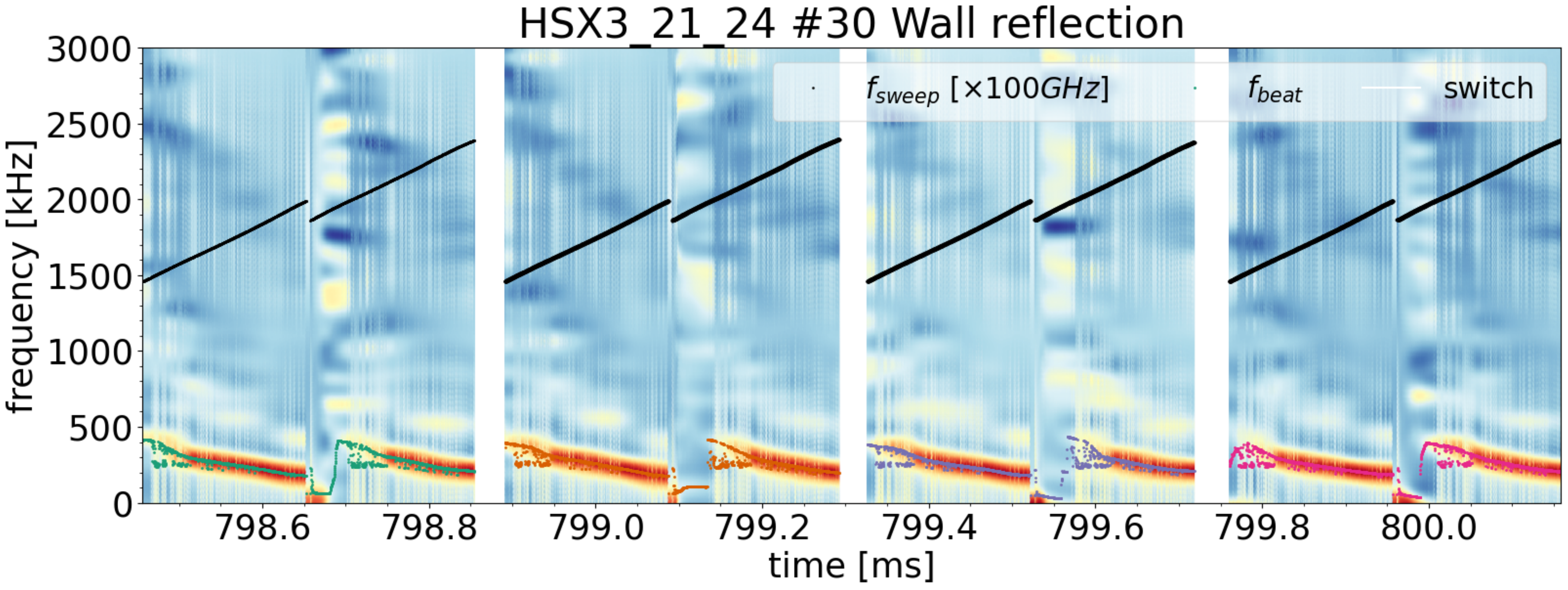
- For HSX reflectometer: $f_s = 8\ Msps,\ 1/dt \approx 2.2\ kHz$. CWD is applied to calculate the beat frequency spectrum
- CWD can improve the time-frequency resolution and suppress the cross-term interference or artifacts

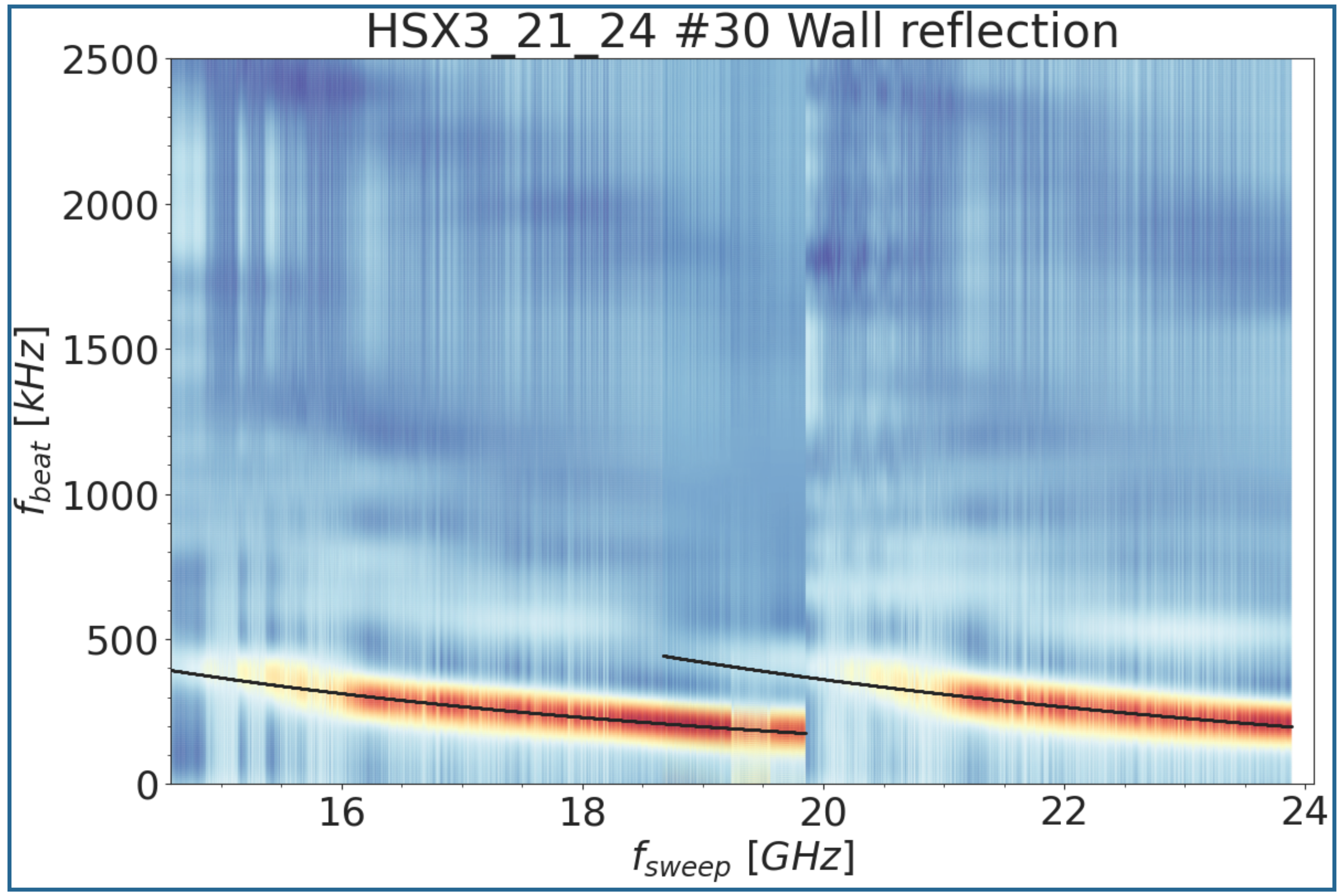
$$P(n,\theta) = 2\sum_{\tau=-\infty}^{\infty} \boxed{h_N(\tau)} exp(-j2\theta\tau)[\sum_{\mu=-\infty}^{\infty} \boxed{h_M(\mu)} \frac{exp(-\mu^2\sigma/4\tau^2)}{(4\pi\tau^2/\sigma)^{0.5}} S(n+\mu+\tau)S^*(n+\mu-\tau)]$$

- Kernel is $\phi(\xi,\tau) = exp(-\xi^2\tau^2/\sigma)$, where $\sigma\ (\sigma > 0)$ is scaling factor
- The time and frequency resolution is determined by $h_N(\tau)$ and $h_M(\mu)$ respectively
- $h_N(\tau)$ is a symmetrical window, $h_M(\mu)$ determines the duration of the time indexed autocorrelation function
- CWD is more robust than the spectrogram especially when data volume is insufficient

H Choi, W Williams, IEEE Trans. Signal Process. 37, 862 (1989)

Inner-wall reflected signal is measured as a reference of the system dispersion





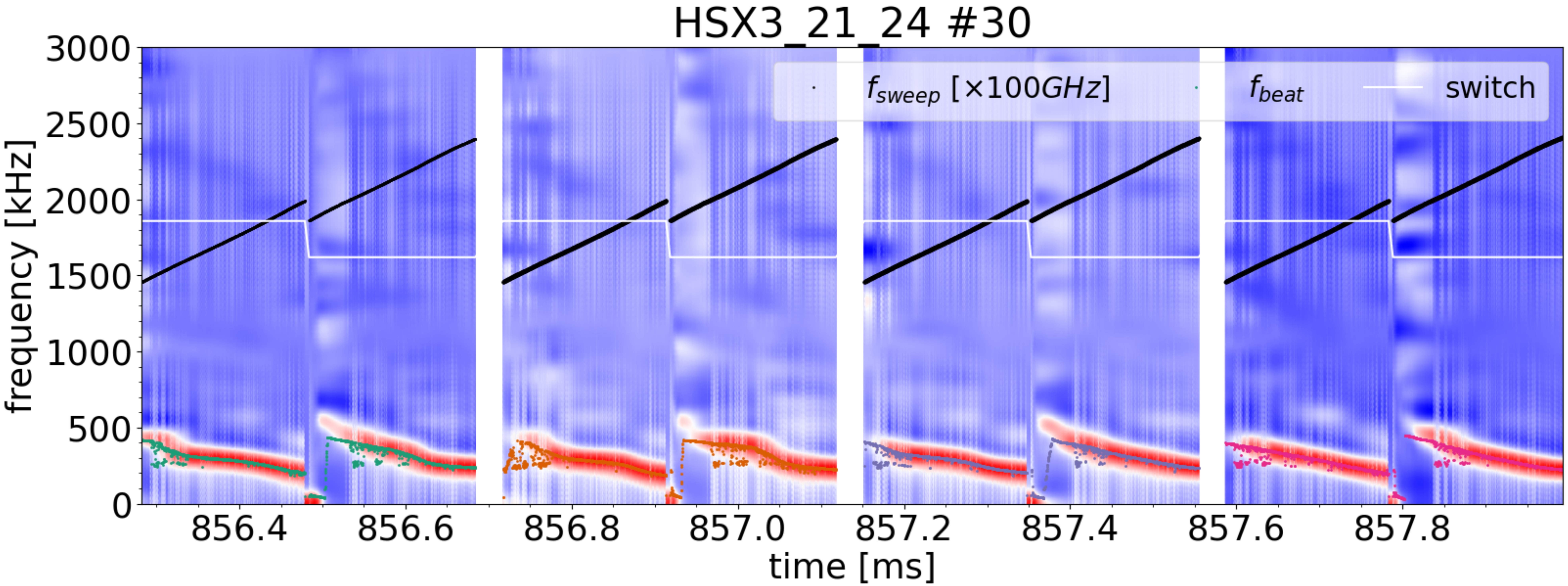
- The first several cycles (before ECRH) are chosen, which are reflected from the inner wall
- Averaged f_{beat} spectrum is obtained, then the system delays are fit to the function:

$$f_{beat,wall} = a + b/(1 - f_{sweep})^{0.5}$$

- Parameters a, b are applied to calibrate the f_{beat} during plasma operation

Low-VCO: a = -1.99e+08, b = 1.99e+08
high-VCO: a = -4.36e+08, b = 4.36e+08

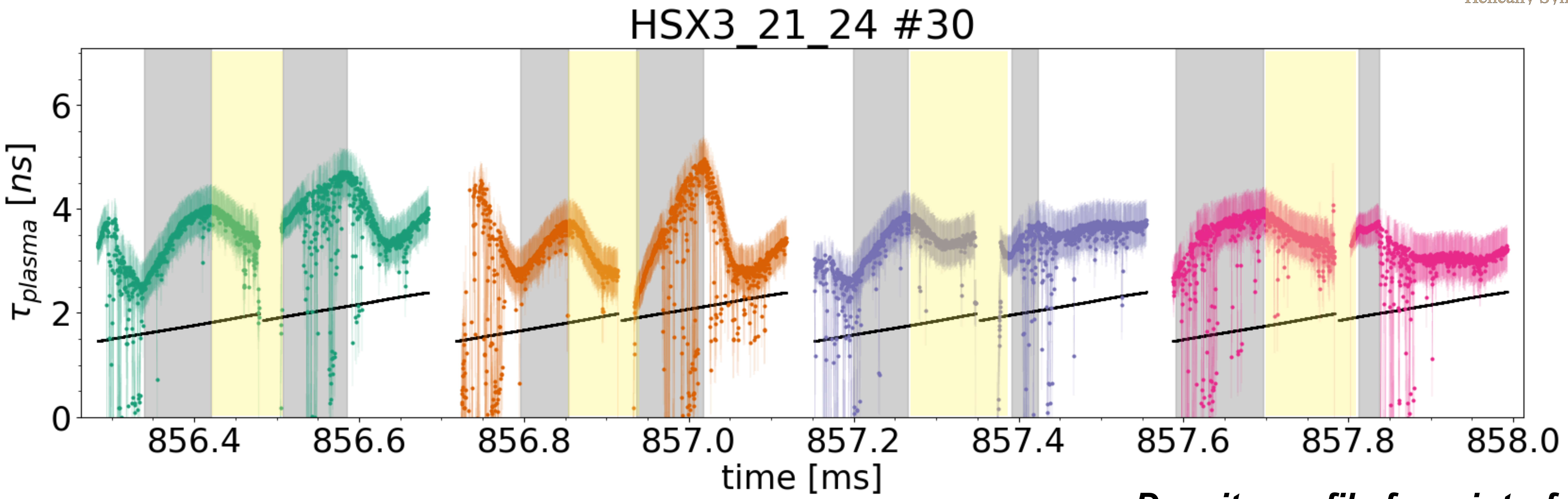
f_{beat} is obtained from the spectrum during plasma operation



- Sweeping rate $1/dt = 2.2\ kHz$, $f_{beat} = 100 \sim 300\ kHz$
- For the O-mode, $f_{beat} = (\tau_{plasma} + \tau_{sys})\dfrac{df_{VCO}}{dt}$

$$f_{beat,wall} = (\tau_0 + \tau_{sys})\frac{df_{VCO}}{dt} \quad (\tau_0 = 2\Delta r/c \approx 2.4\ ns)$$

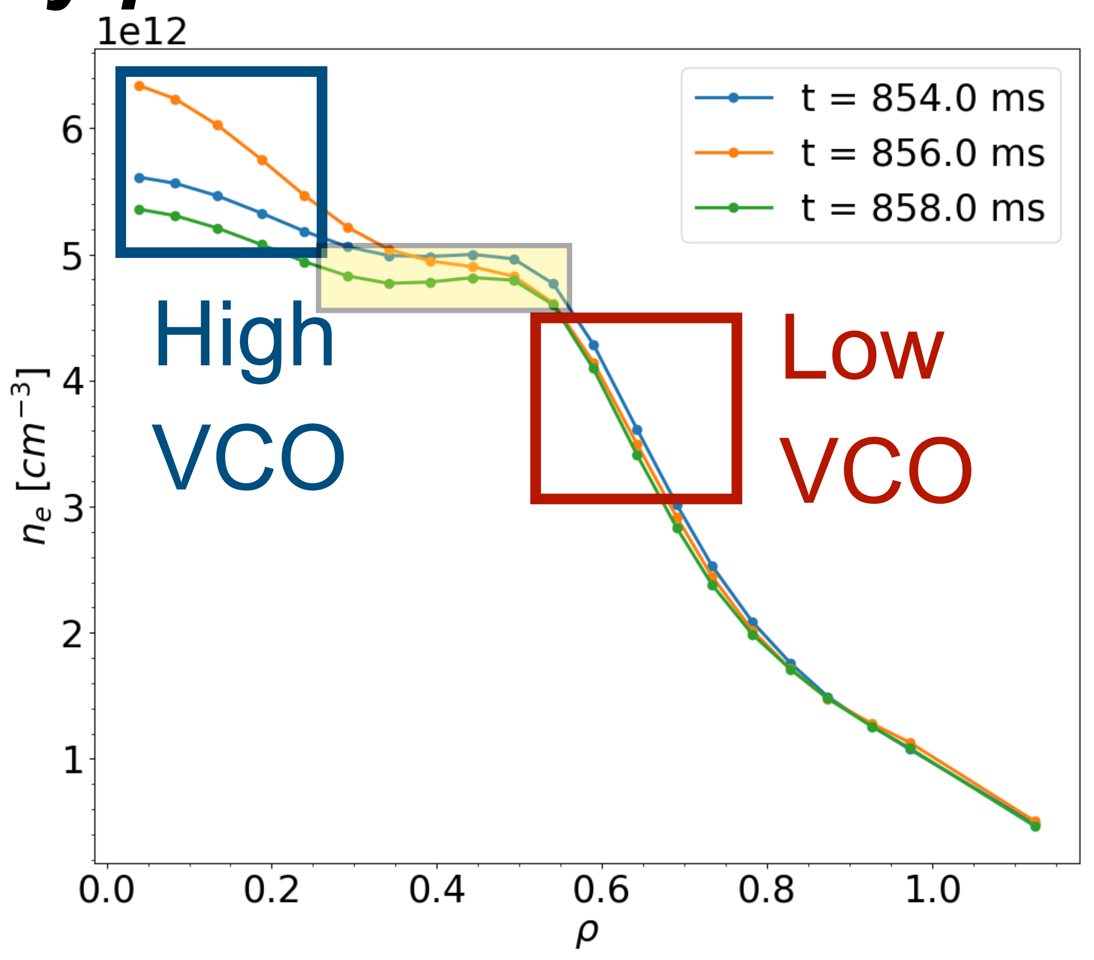
Understanding of the delay time evolution during plasma operation



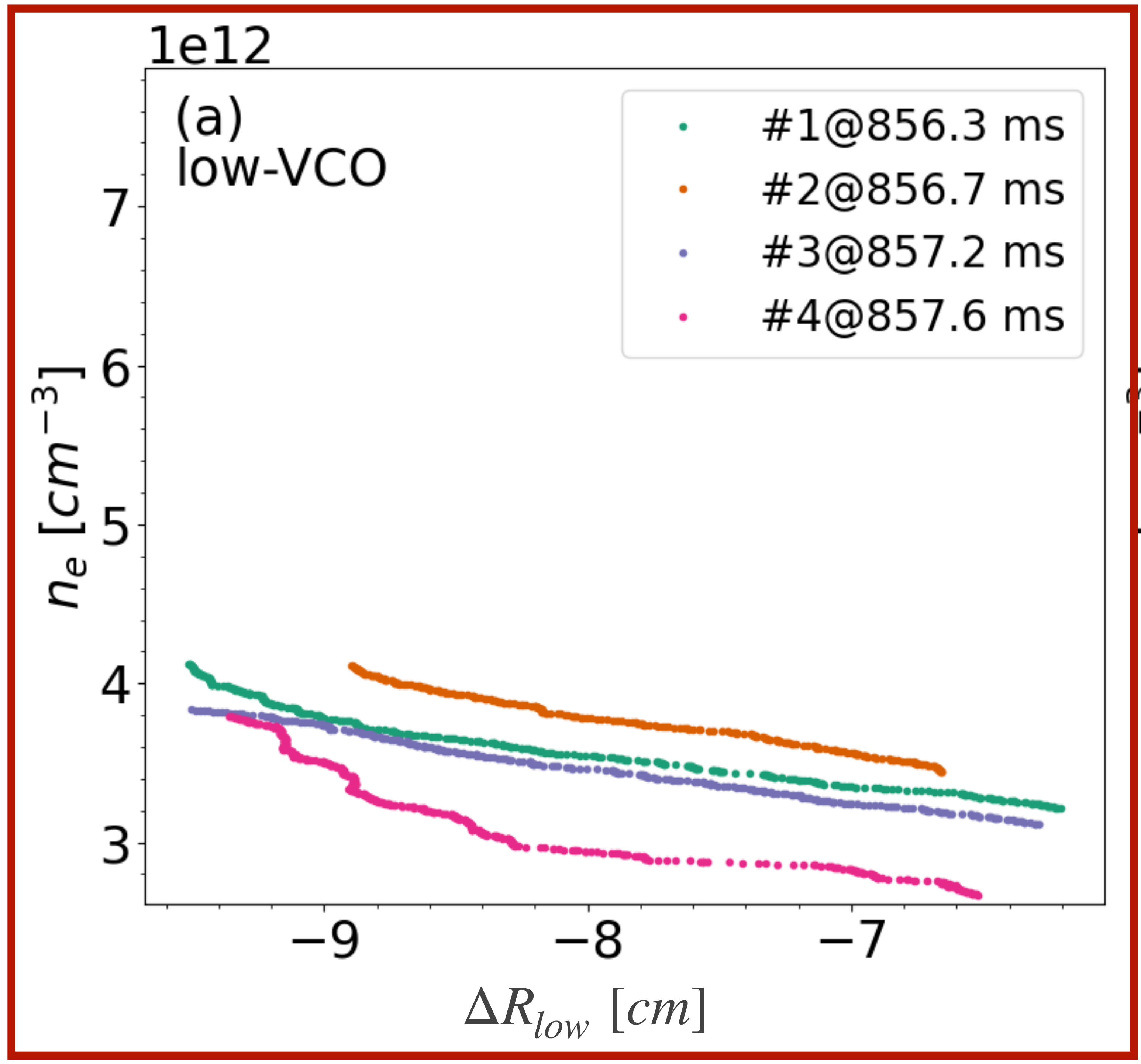
$$\tau_{plasma} = (f_{beat} - f_{beat,wall})(\frac{df_{VCO}}{dt})^{-1} + \tau_0$$

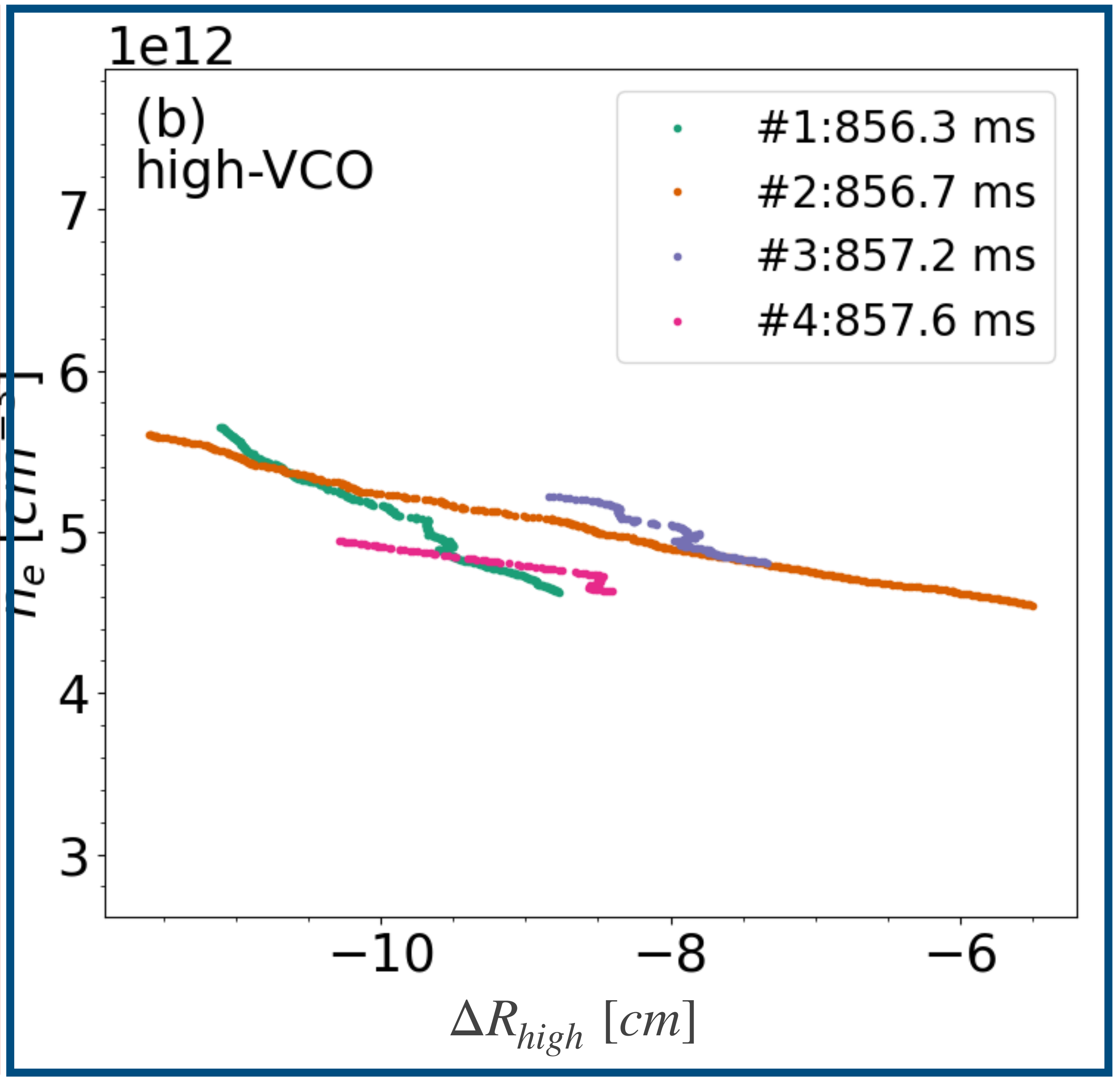
- **Low-VCO:** start from the positive slop
- **Blind area (yellow)**: Neglect the $d\tau/dt < 0$ between low- and high-VCOs
- **high-VCO:** select only the first phase with positive slop

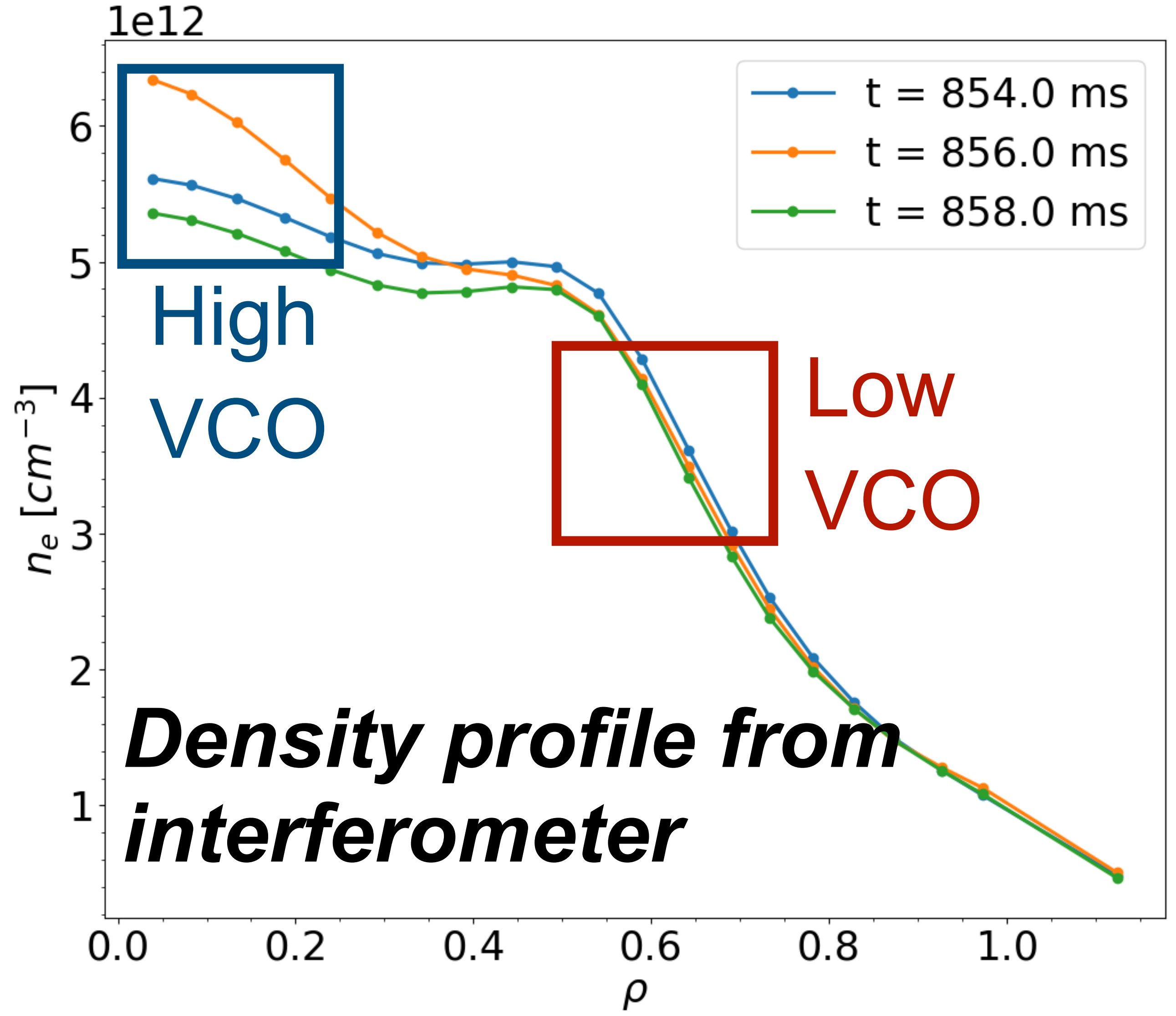
Density profile from interferometer



Abel integral is performed to obtain the relative cutoff position (ΔR)







Abel integral is performed to calculate the cutoff position:

$$\Delta R = -\frac{c}{2\pi^2}\int_{f_0}^{f_c} \tau_{plasma}(f_c^2 - f^2)^{-0.5} df$$

- For O-mode, beat signal from low- and high-VCO is uncorrelated
- Density profile is obtained as a function of relative radius, consistent with the interferometer profile
- Mapping profile to major radius is ongoing, with the help of TS

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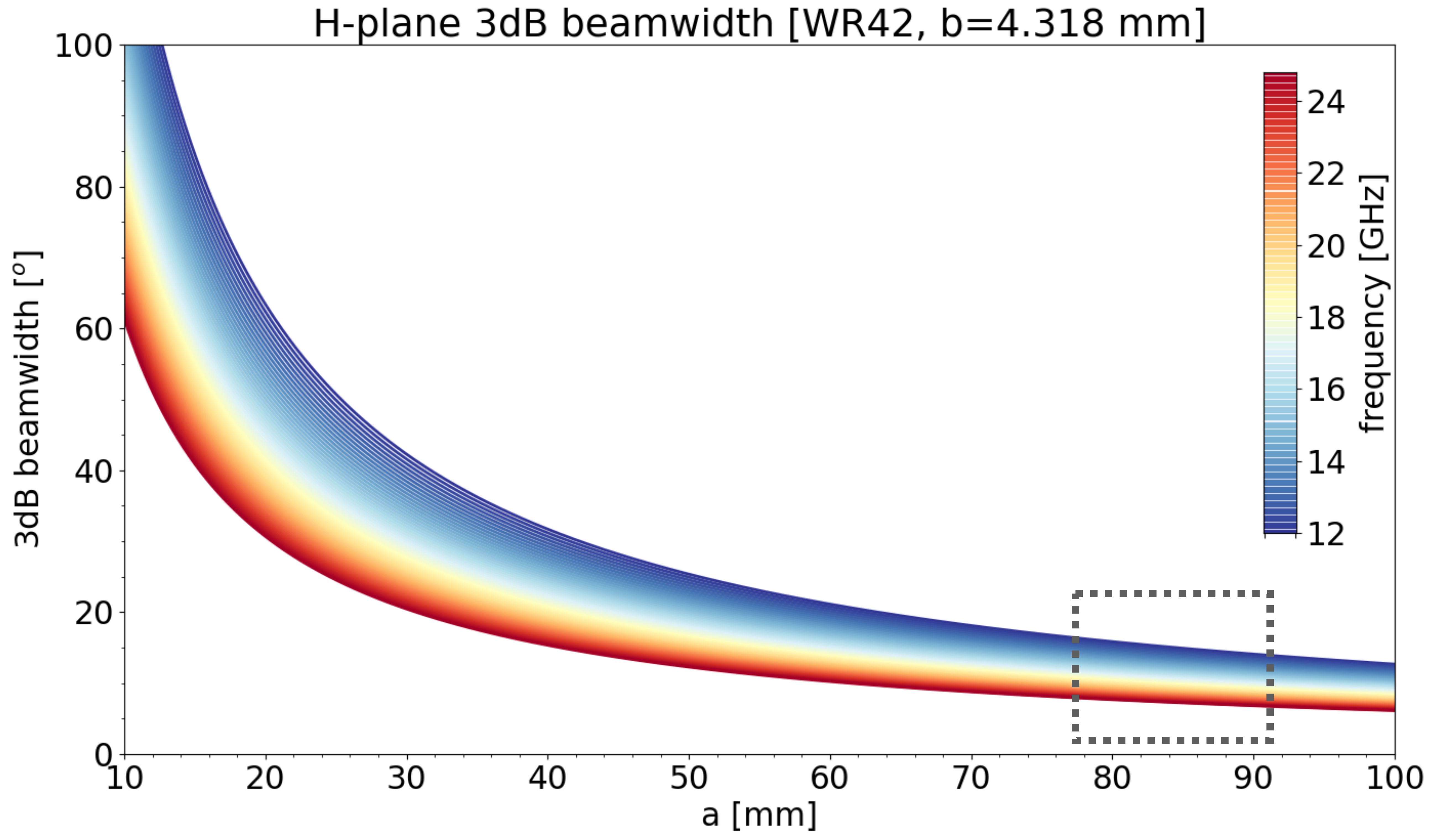
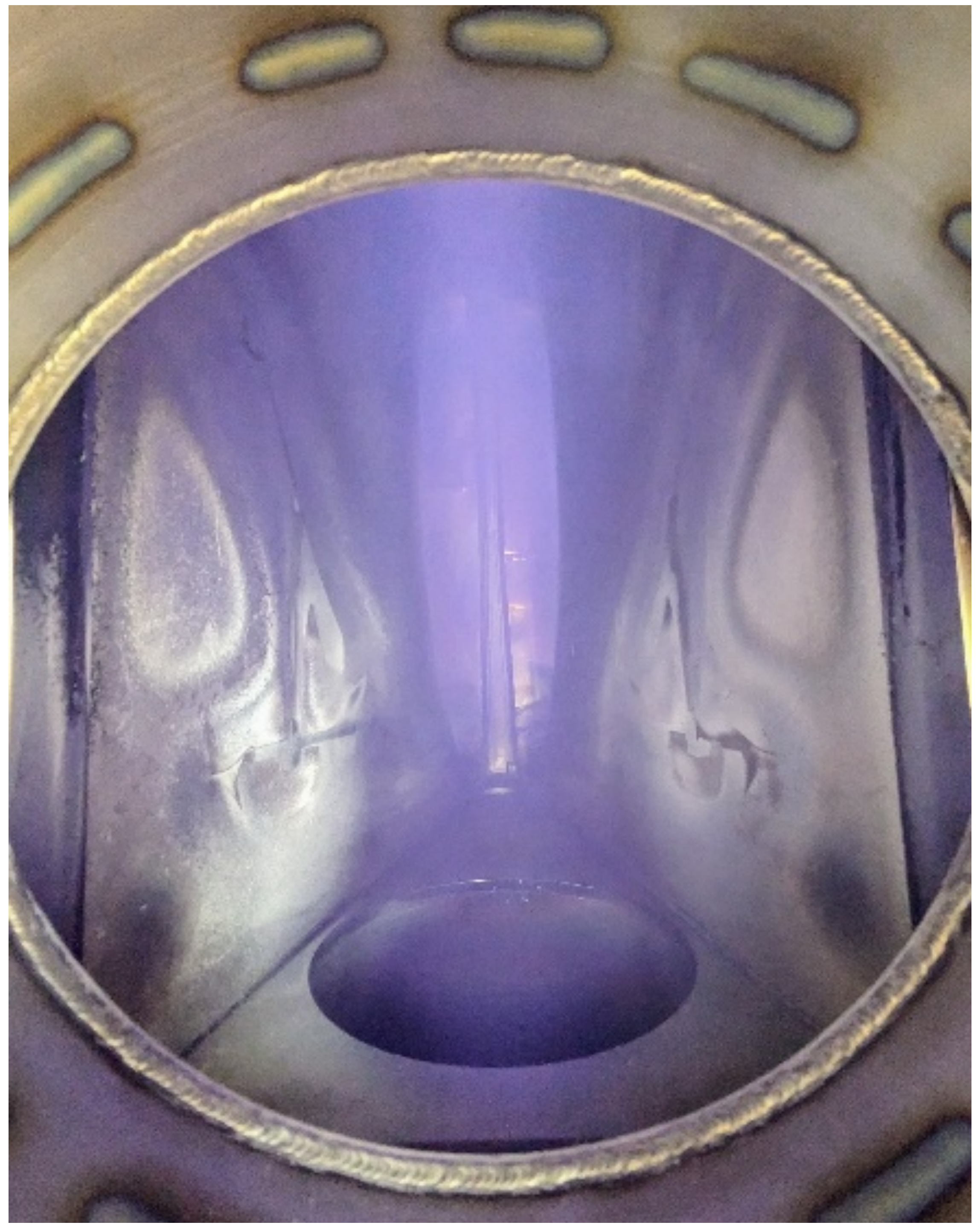
Replacing the antenna by a bi-static H-plane sectoral antenna pair

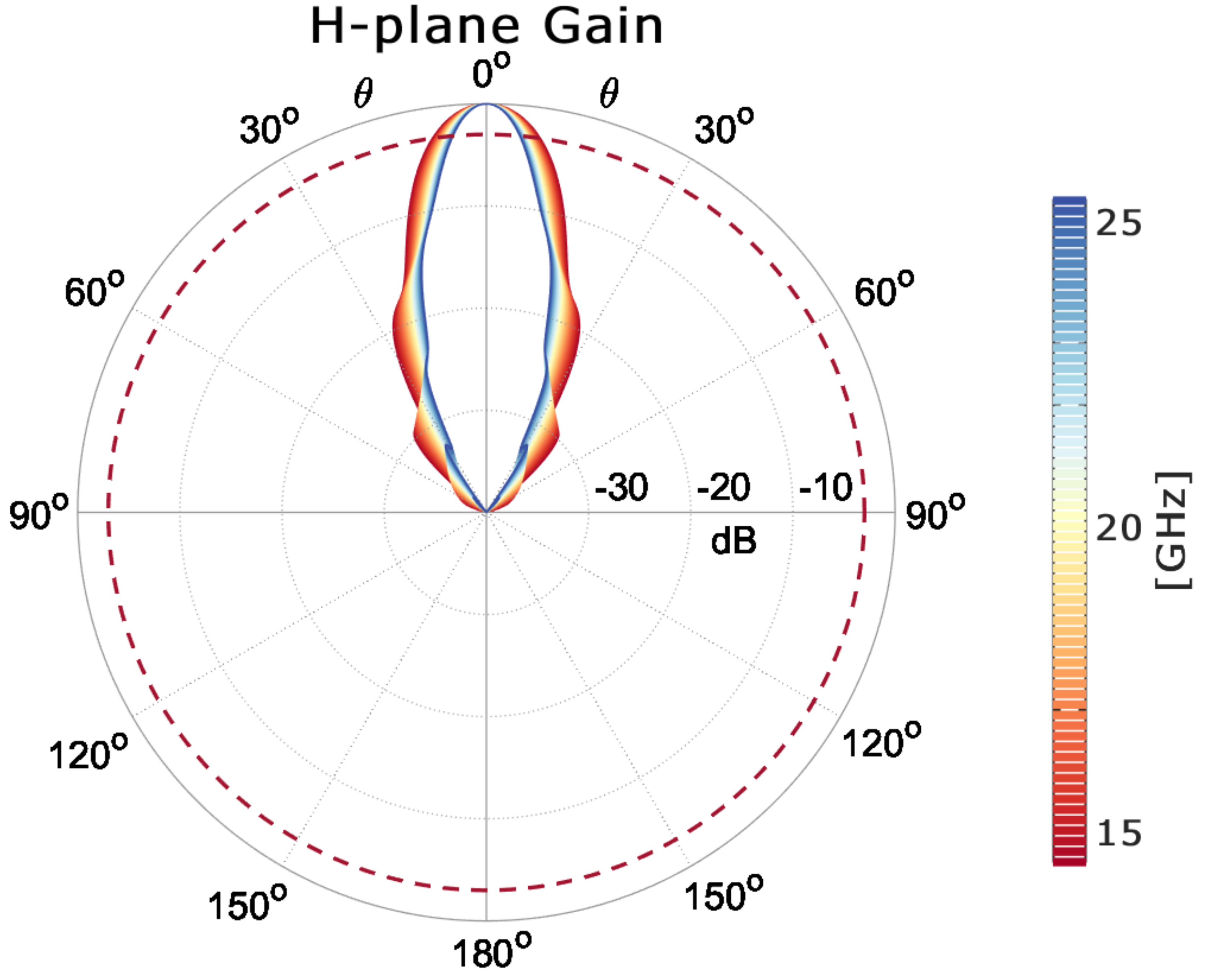


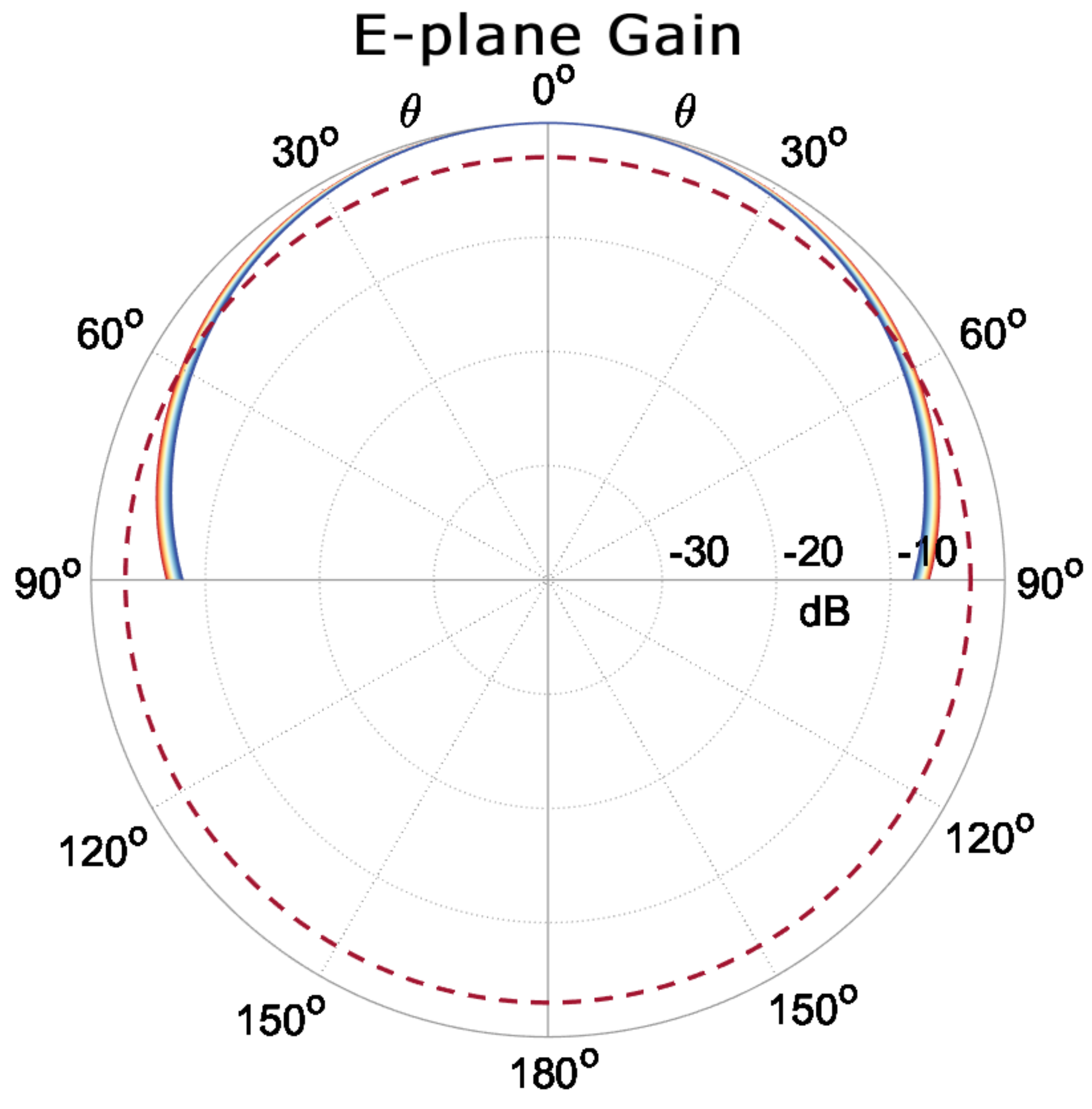
plasma viewing window from the port of glow discharges

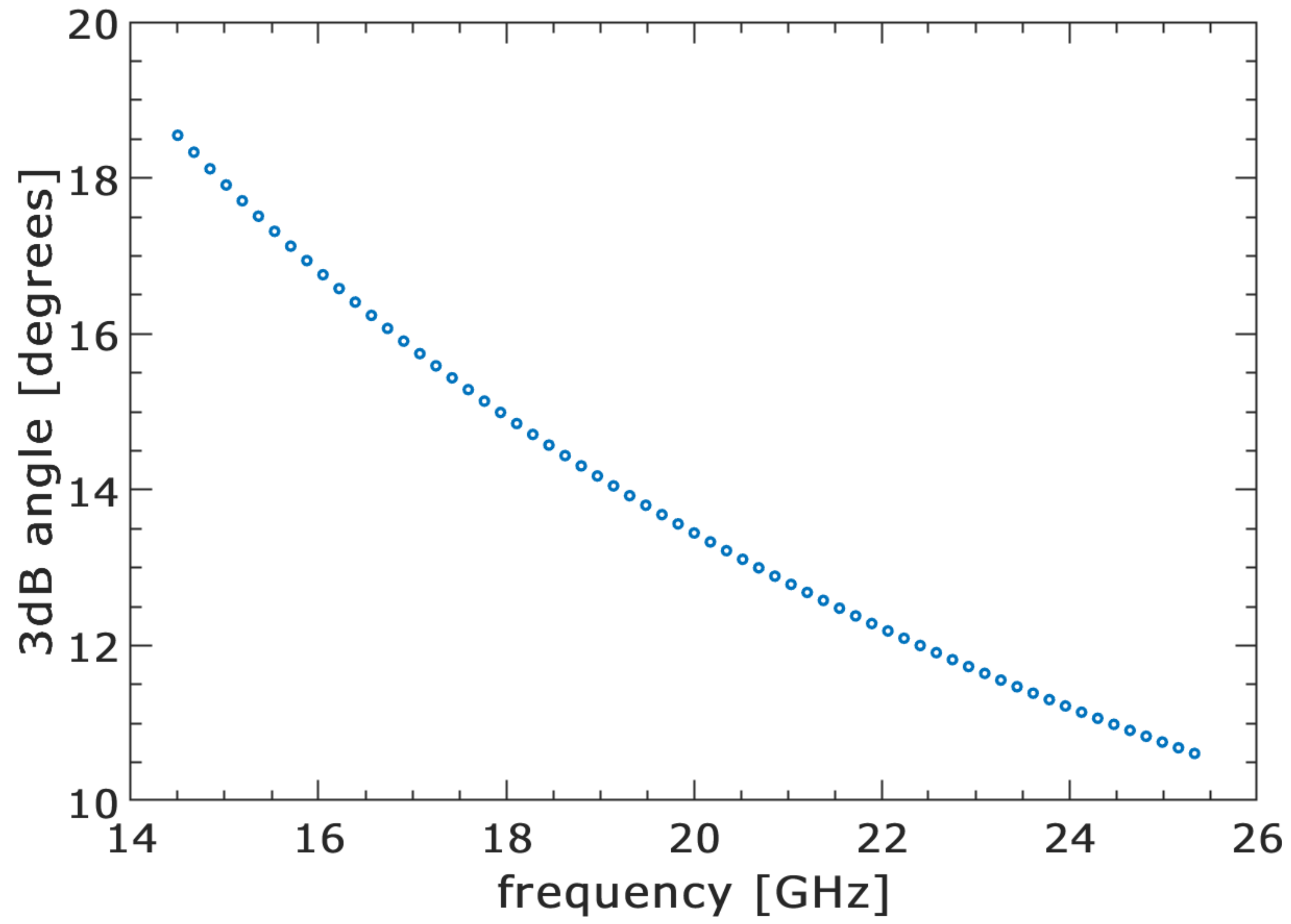


- Separate the Tx and Rx beam using a bi-static antenna pair
- Due to the limited space at the port, H-plane sectoral antenna pair is preferable
- Keep E-plane at 4.318 mm and extend the H-plane width of the antenna
- 80~90 mm of H-plane reduces the 3dB pattern below 20^o

Radiation pattern calculation indicates a finite beam width and gain



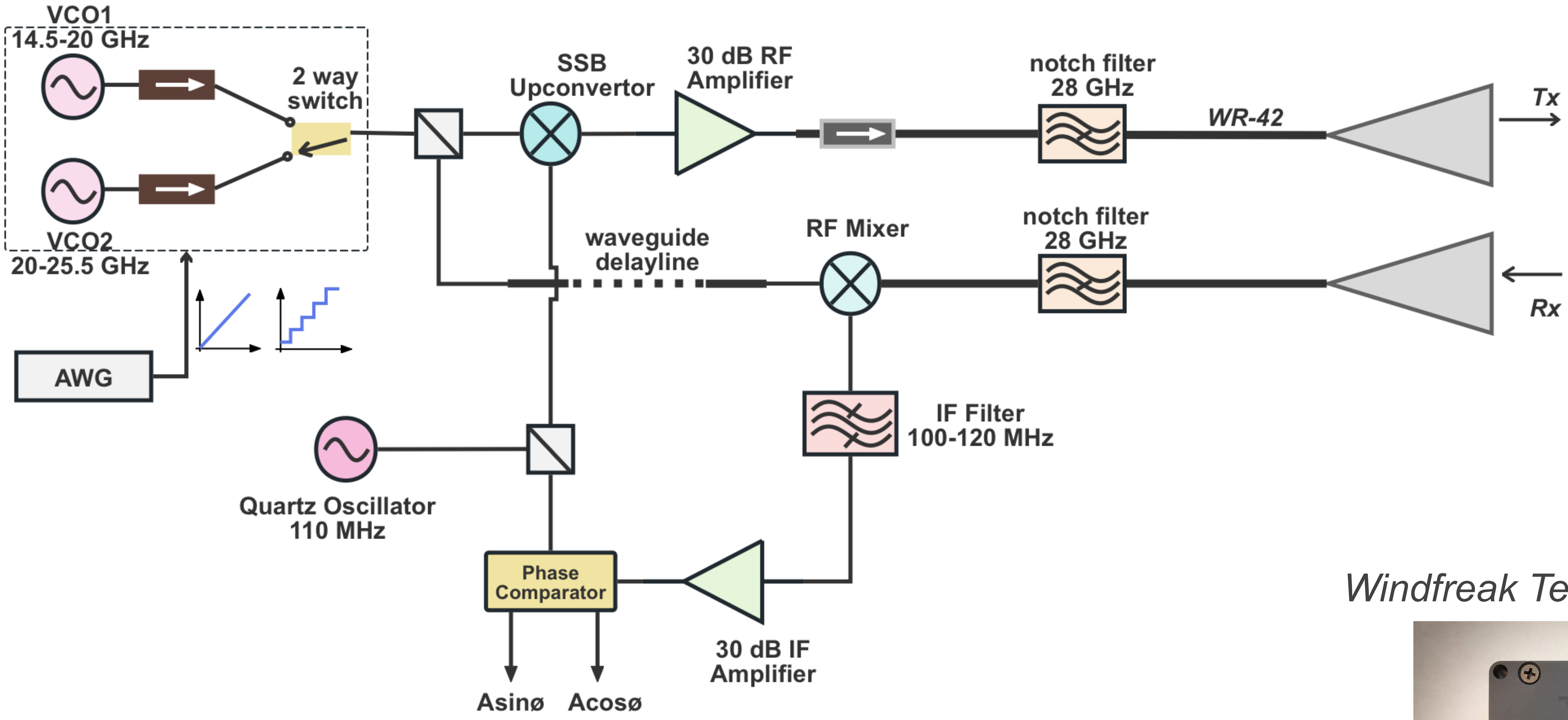




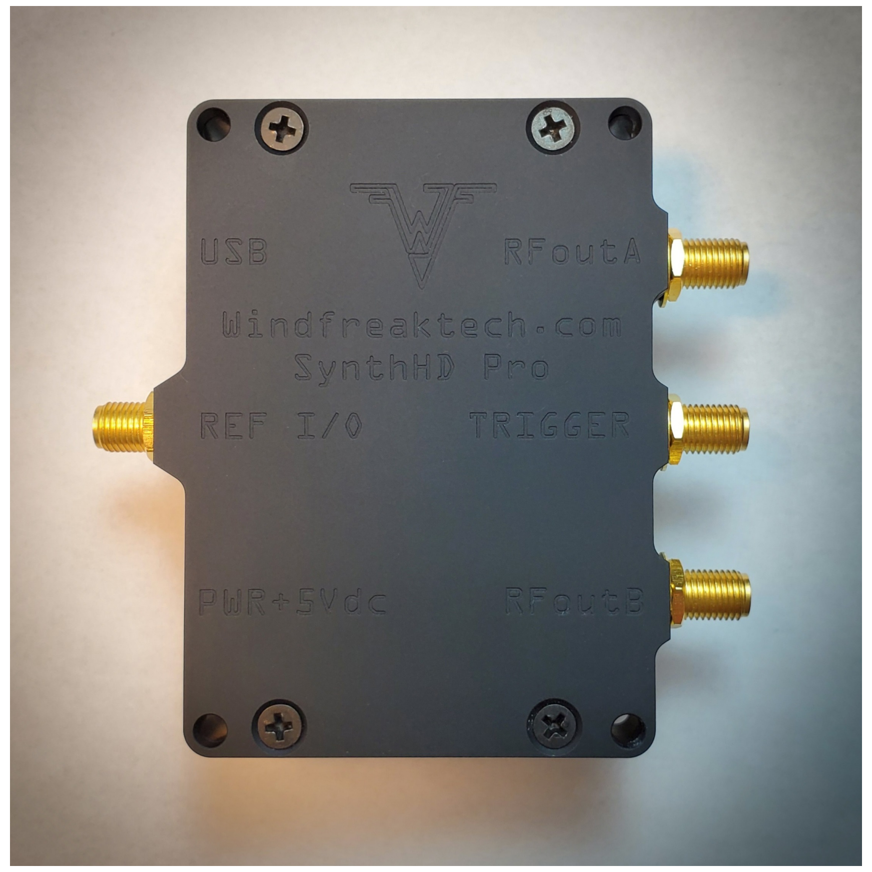
- H-plane sectoral antenna: a = 4.318 mm, b = 88.5 mm
- Frequency scan from 14.5 to 25.5 GHz
- H-plane beam width reduces as increasing the frequency
- Finite H-plane beam width, broadened in E-plane
- Future work: estimate the angle of viewing window, and compare with the beam width

- ***M. Richardson's talk for more details***

Renovate the component layout to improve the system SNR



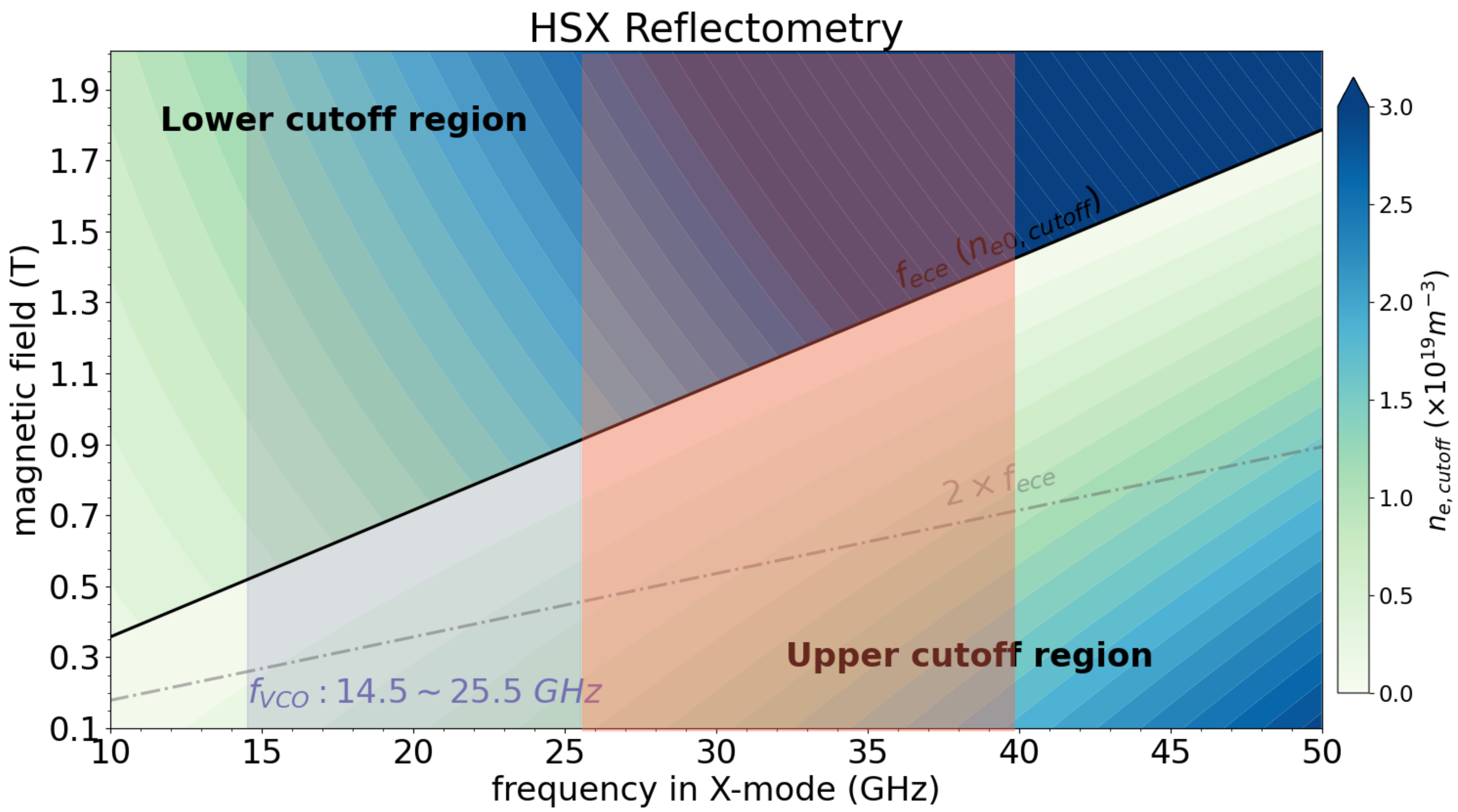
Windfreak Technologies, LLC



- Move the SSB and RF amplifier to the Tx branch
- Separated VCO signal to the RF mixer to reduce the noise at the LO
- Replace the VCO sources + switch by a broad band low-noise synthesizer
- ***M. Richardson's talk for more details***

Future plan on the system development

1. **Ka-band extension**: broaden the radial coverage, especially for X-mode (lower and upper cutoff regions, preferable for 1.25 T)
2. **Doppler reflectometry branch**: turbulent rotation and radial electric field measurements based on current regime and a rotatable mirror - see **M. Richardson's talk**
3. **Ray-tracing and full-wave simulation** - see **H. Miller's talk**
4. **Position reflectometry**: multi-poloidal positions for plasma shape measurement (monostatic, X-mode)
5. **synthetic reflectometry diagnostic**

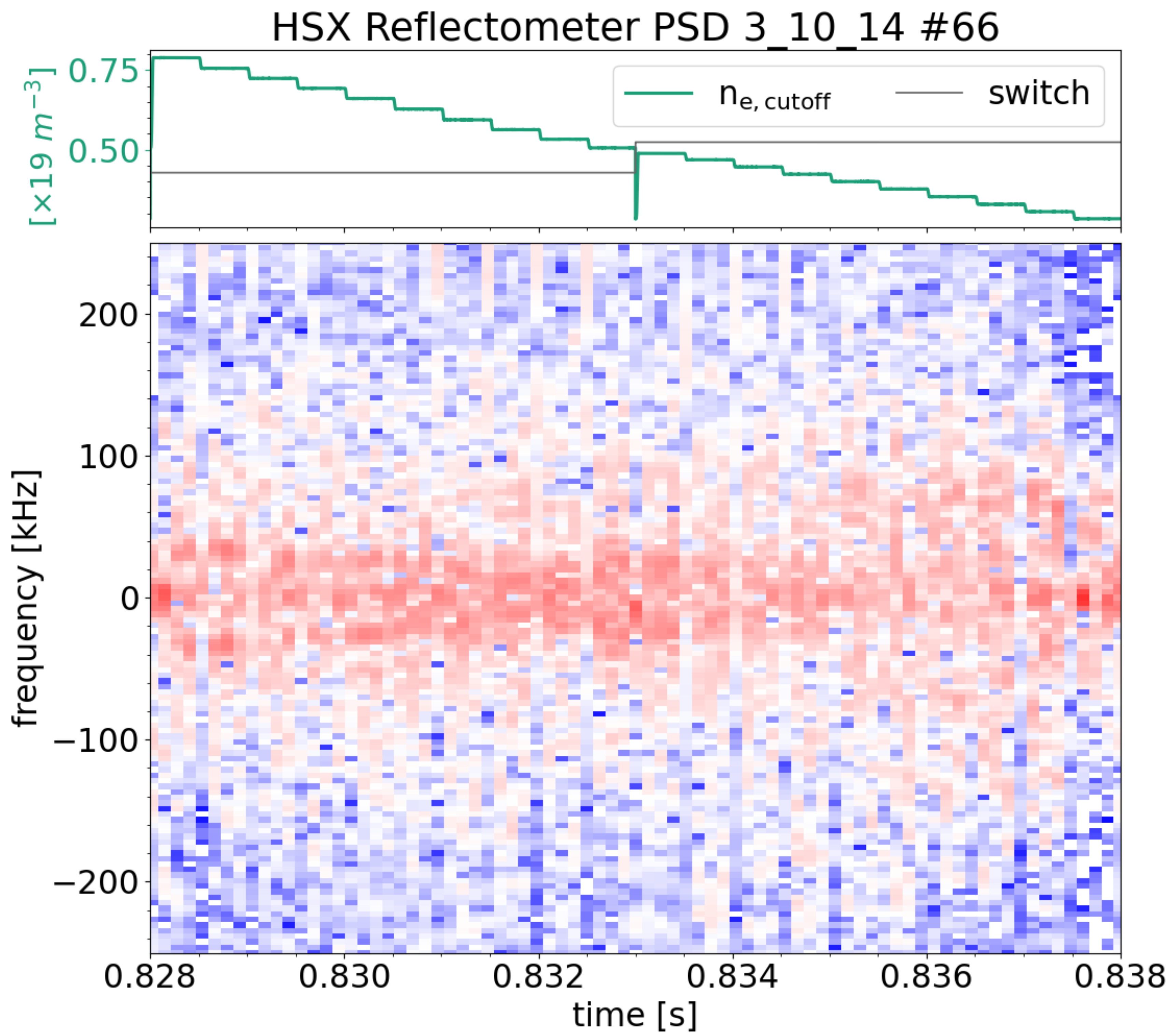


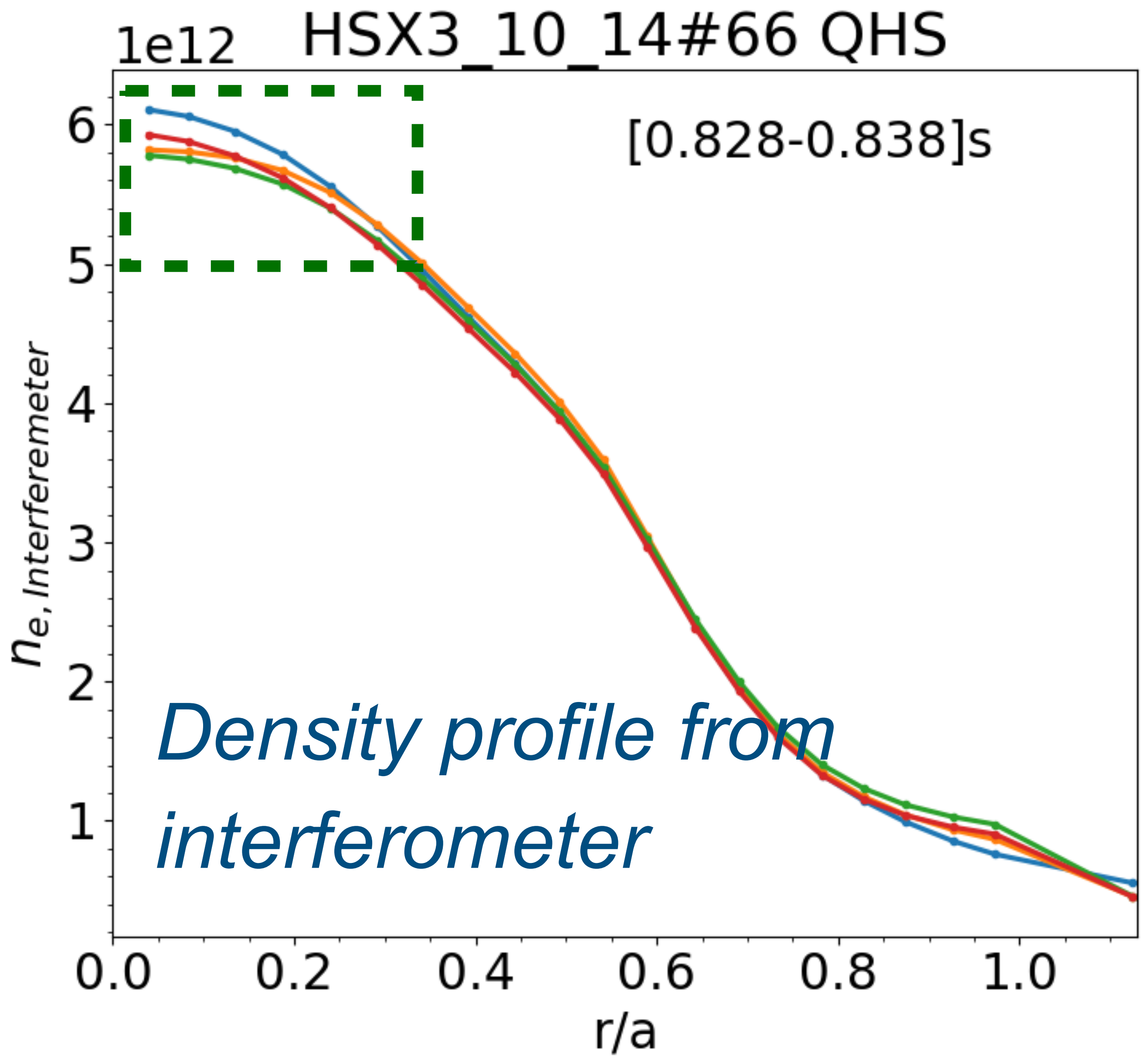
Summary

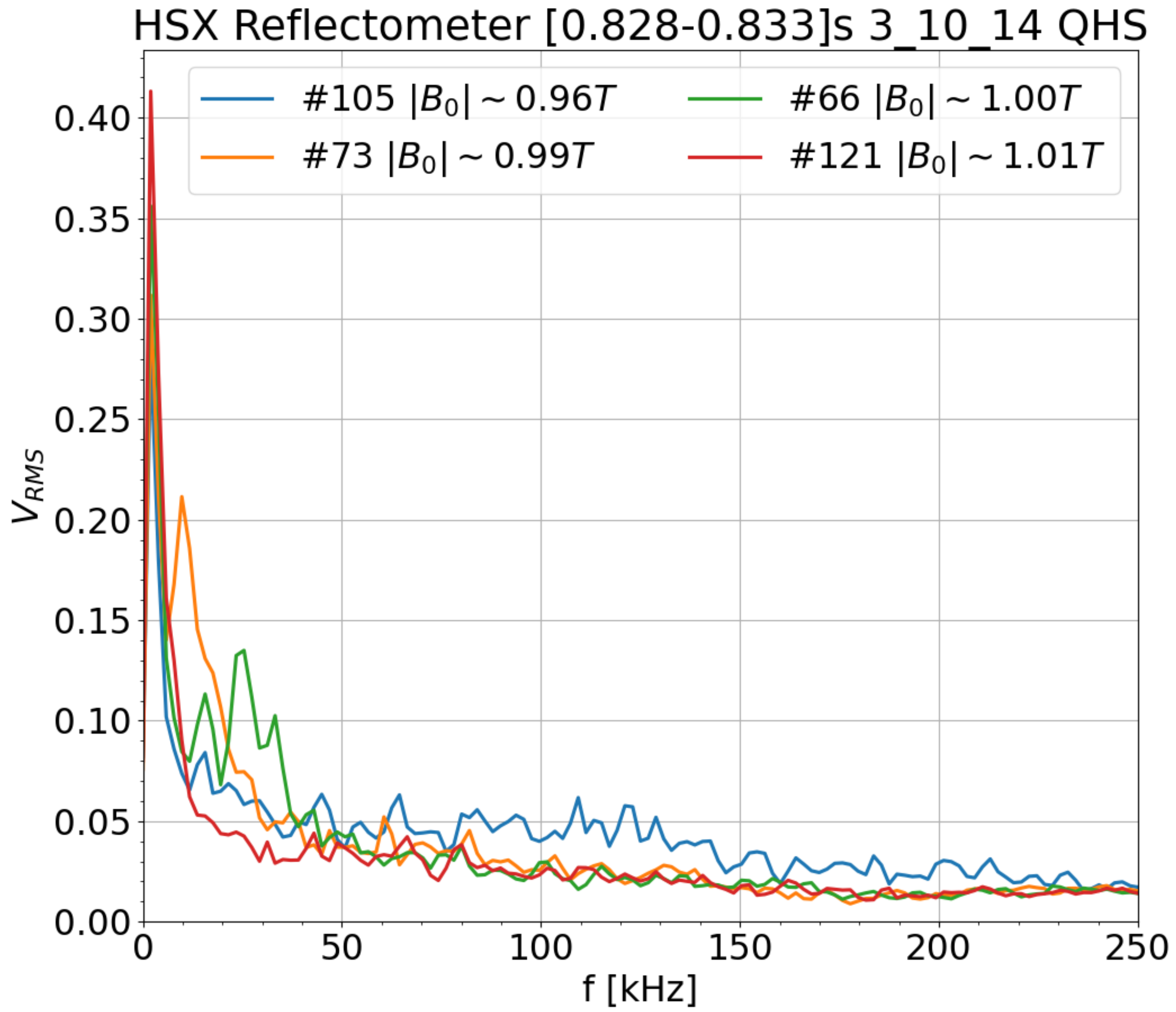
- HSX reflectometry is capable of measuring the density fluctuation and profile, and is flexible for 0.5 T and 1 T plasma operation by tuning the polarization between O- and X-mode
- Fluctuations at low frequency are observed during the resonant scan
- 100 kHz fluctuation is observed during the gas puffing modulation, responding to a density gradient change
- O-mode linear frequency scan is performed for profile inversion
- Relative density profile is obtained. Mapping to the major radius will be done with the help of TS
- Renovation plan includes: H-plane sectoral antenna pair, component layout modification, replacing the frequency source…
- A mirror rotation structure is designing, aiming for the Doppler reflectometry branch - see **M. Richardson's talk**
- Ray tracing is performed using Travis code for both angled (Doppler) and straight incident beam - see **H. Miller's talk**

Backup

Low frequency mode appears in plasma core during the resonance scan







G Weir, PhD thesis

- Mode frequency 10~30 kHz at $n_{e,cutoff} > 0.5 \times 10^{19} m^{-3}$
- Core-localized mode. Radial position of the mode is confirmed from the interferometer
- f = 10 and 30 kHz with on-axis heating (#66, #73)
- Broadband fluctuation at 50-150 kHz rises with outboard-side heating (#105)
- No clear mode observed at inboard side heating (#121)