An Experimental approach to investigating device-level RF reliability

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Used tools

- Circuit simulations: ADS :(
- Parameter extraction: DMT & VerilogAE :)
- Reports and plots: pyLatex :)
- Measurements: pyLab :) => private Gitlab project based on the Python package pyVISA
  - VNA Rohde & Schwarz ZNB 8, 9 kHz - 8.5 GHz, 4 test ports
  - VNA Rohde & Schwarz ZVA 50, 10 MHz - 50 GHz, 4 test ports
  - VNA Keysight N5235A PNA-L, 10 MHz - 50 GHz, 2 test ports
  - SMU Keysight E5270B, 2 medium power channels
  - SMU Keysight B2900 series
  - Signal generator Agilent E8257D, 250 kHz - 20 GHz
  - Signal generator Agilent 83650B, 10 MHz - 50 GHz
  - Power meter Agilent E4418B
  - Spectrum analyzer Agilent E4448A, 3 Hz - 50 GHz
  - Switch controller Keysight 11713B

Outline

- Introduction
- Impedance tuner based experimental setup and selected measurement and HICUM/L2 simulation results
- Selected degradation results

Introduction

Previous investigations

First results reported in:

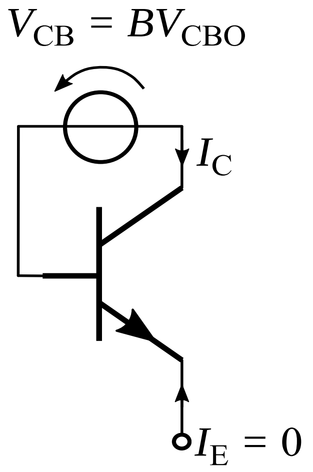
C. Weimer et al., "An Experimental Load-Pull Based Large-Signal RF Reliability Study of SiGe HBTs", BCICTS, 4p., 2021

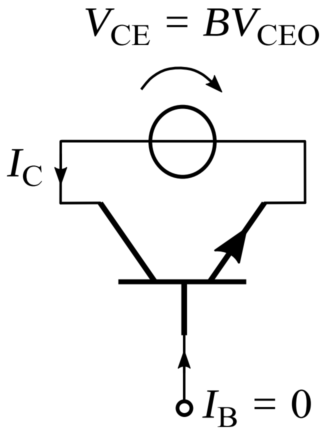
Experimental insights:

- Nonlinear transistor operation causes dynamic i_c and v_{ce} swings and static I_C expansion to regions of the output characteristics that cannot be reached under DC conditions without device destruction
- Symmetric large-signal dynamic i_c and v_{ce} swings do not cause degradation of SiGe HBTs other than the low-injection excess base current
- Strongly nonlinear large-signal transistor operation leads to degradation of SiGe HBTs beyond the low-injection excess base current

=> **This talk:** Continuation of the experimental study, specification of the experimental setup and presentation of selected degradation results

Commonly employed static breakdown voltages

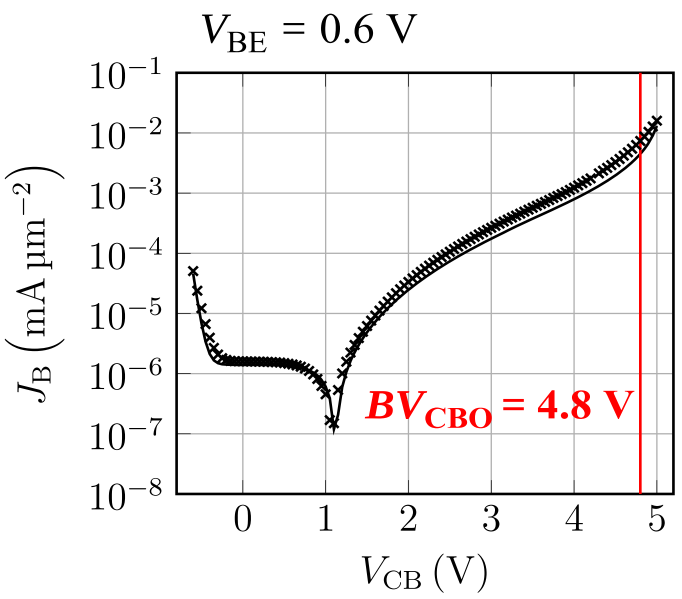


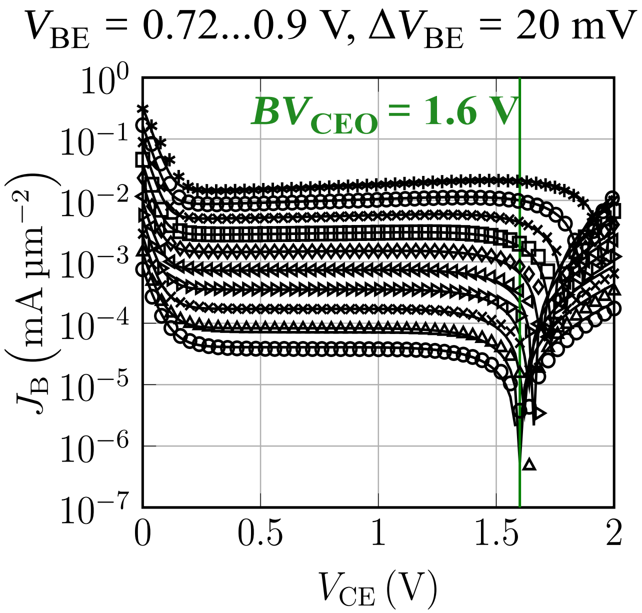


=> BV_{CBO} and BV_{CEO} are statically defined and commonly referred to for estimating the operating limits of SiGe HBTs

Illustration of BV_{CEO} and BV_{CBO}

- BV_{CBO} is the *static* breakdown voltage of the BC junction
- Statically BV_{CBO} can only be reached at very low injection levels
- BV_{CEO} is the V_{CE} at which base current reversal occurs at low injection => Indicator of the onset of high-energy charge carrier effects



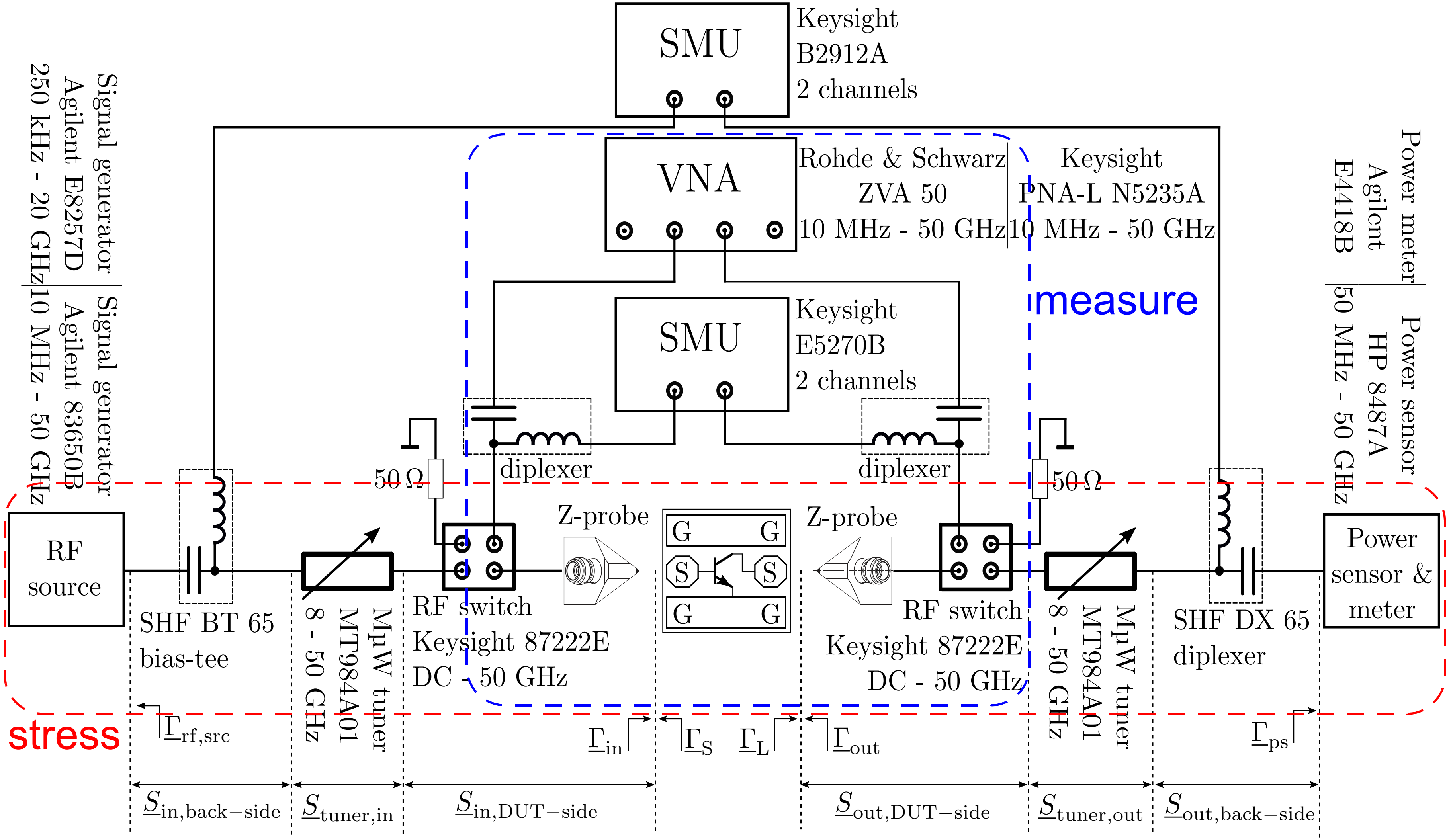


=> BV_{CEO} is often interpreted by designers as the upper limit of V_{CE}!

=> What is the actual safe-operating area of dynamic operation?

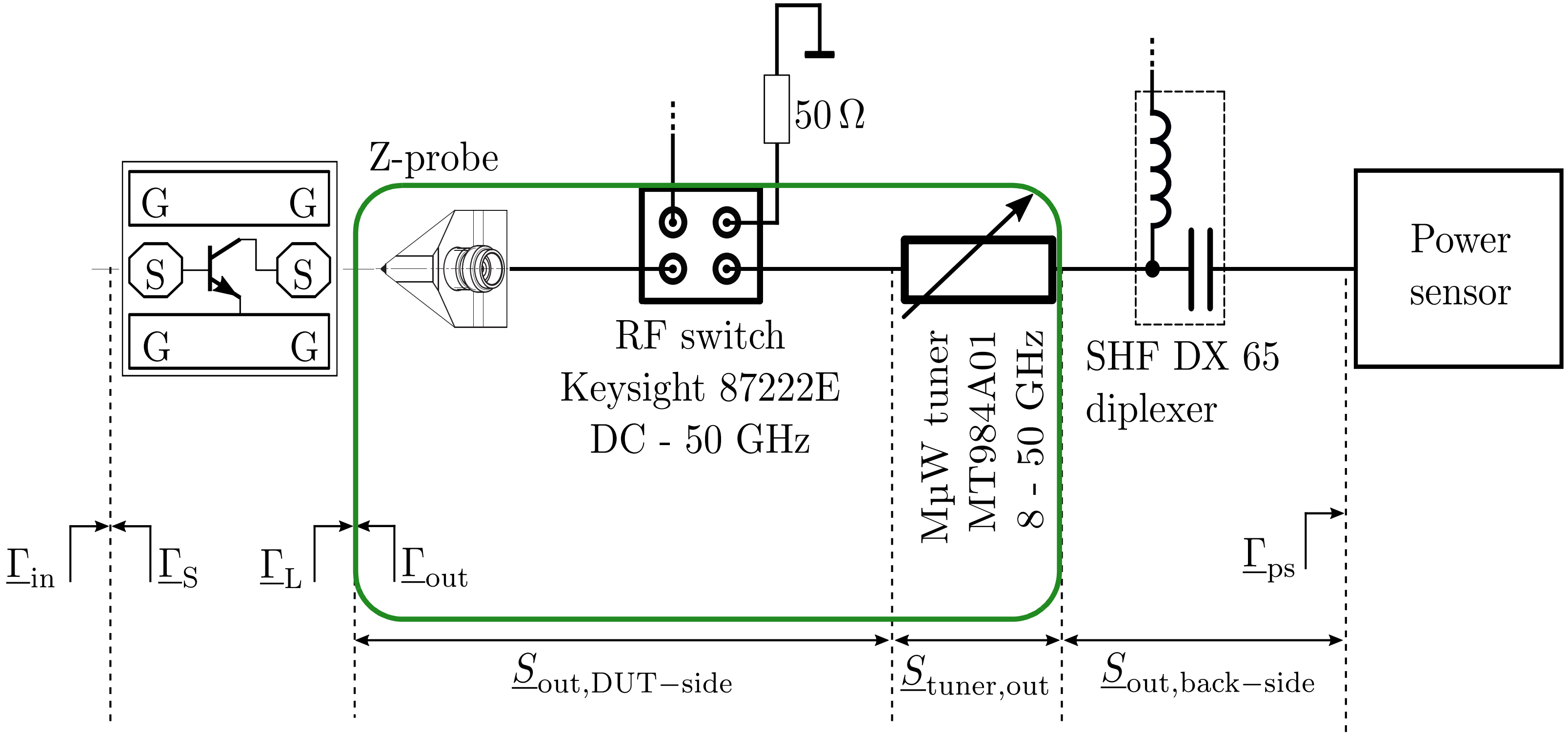
Impedance tuner based experimental setup and selected measurement and HICUM/L2 simulation results

Experimental setup



=> Python-automated stress-measure sequences consisting of dynamic stress and periodic measurements of DC and small-signal characteristics

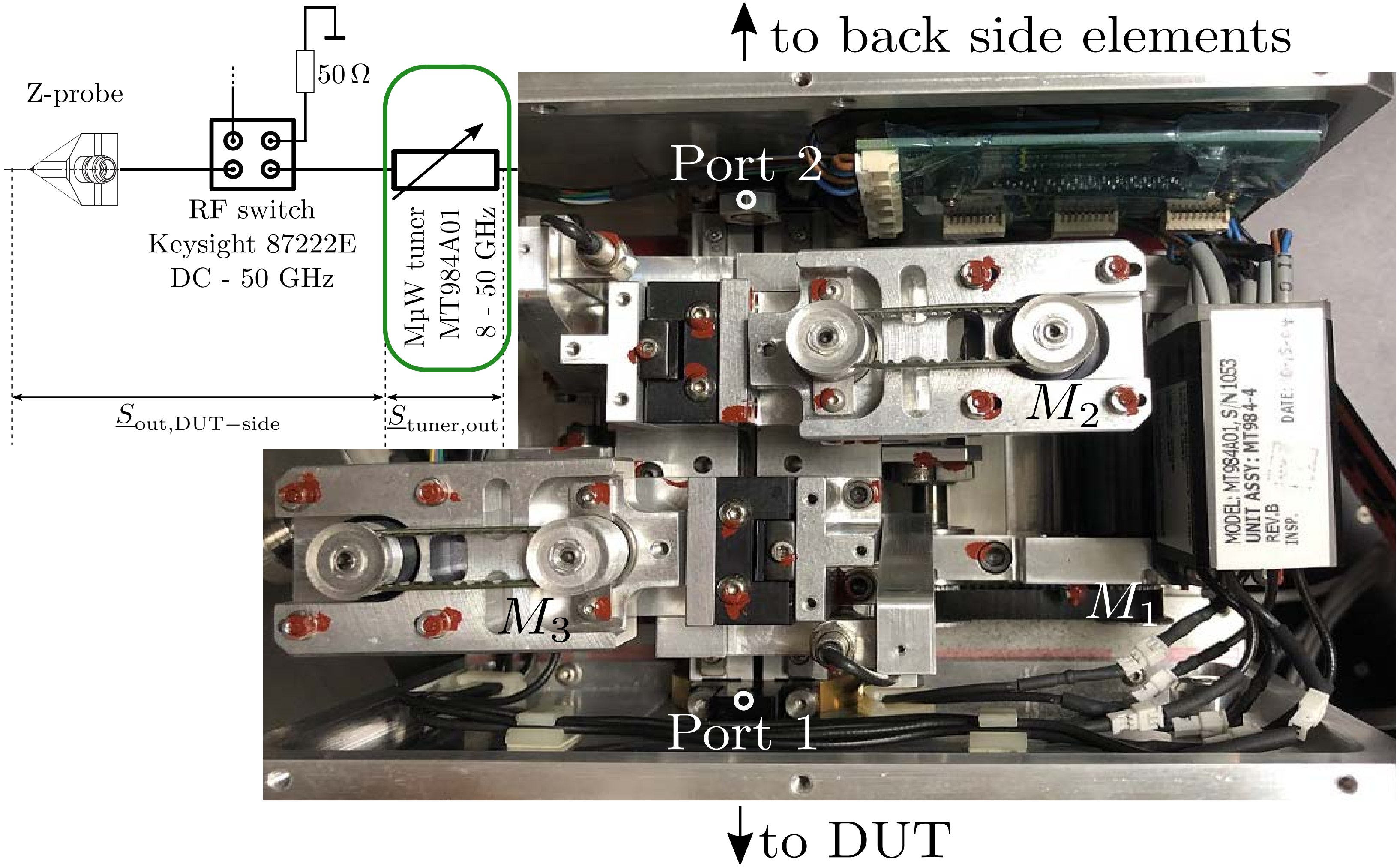
Cascading of *S*-parameters in the load path



$$[\underline{T}_{\mathrm{casc}}](\boldsymbol{M},f) = [\underline{T}_{\mathrm{out,DUT-side}}](f)\cdot[\underline{T}_{\mathrm{tuner,out}}](\boldsymbol{M},f)\cdot[\underline{T}_{\mathrm{out,back-side}}](f)$$

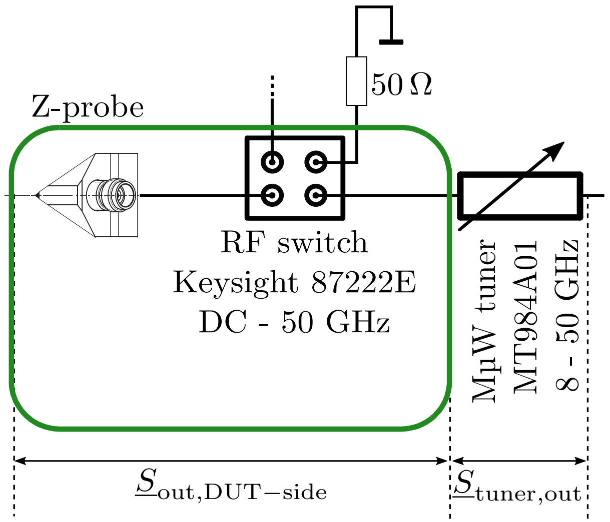
=> Cascading of *S*-parameters over all frequencies within the tuner bandwidth (8 GHz - 50 GHz) and over all tuner motor positions

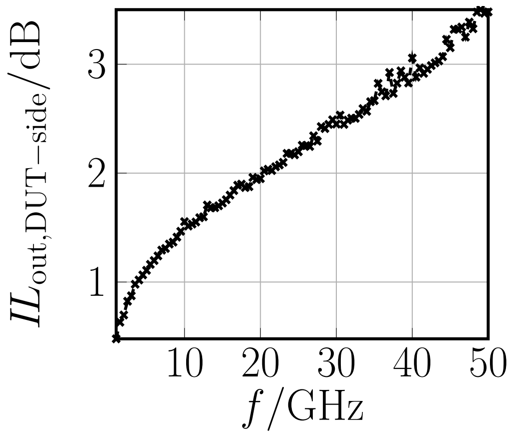
Impedance tuner motors

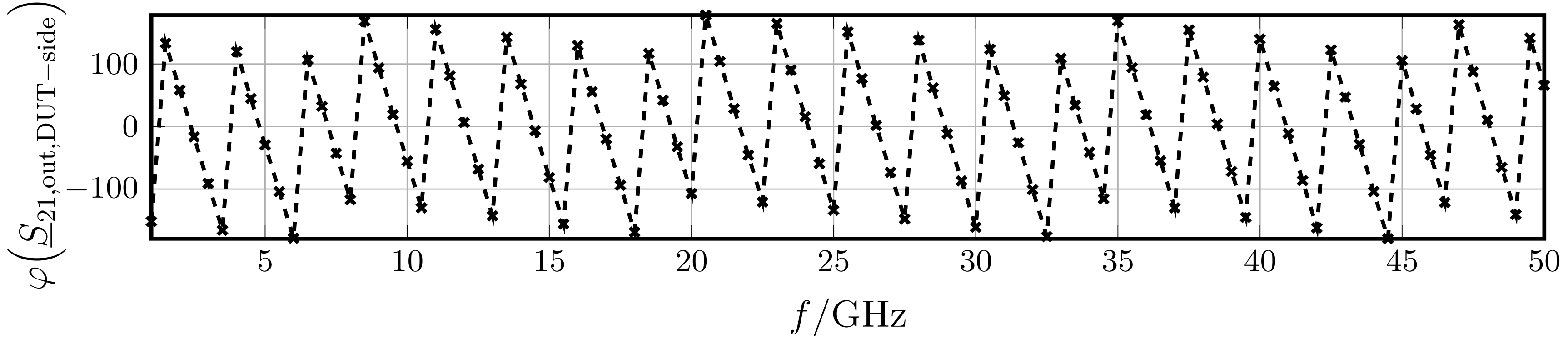


=> The frequency-dependent reflection coefficient presented to the DUT is altered by the three stepper motors $\boldsymbol{M} = (M_1\ \ M_2\ \ M_3)^{\mathrm{T}}$ which determine $\underline{S}_{\mathrm{tuner}}$

Characterization of setup losses



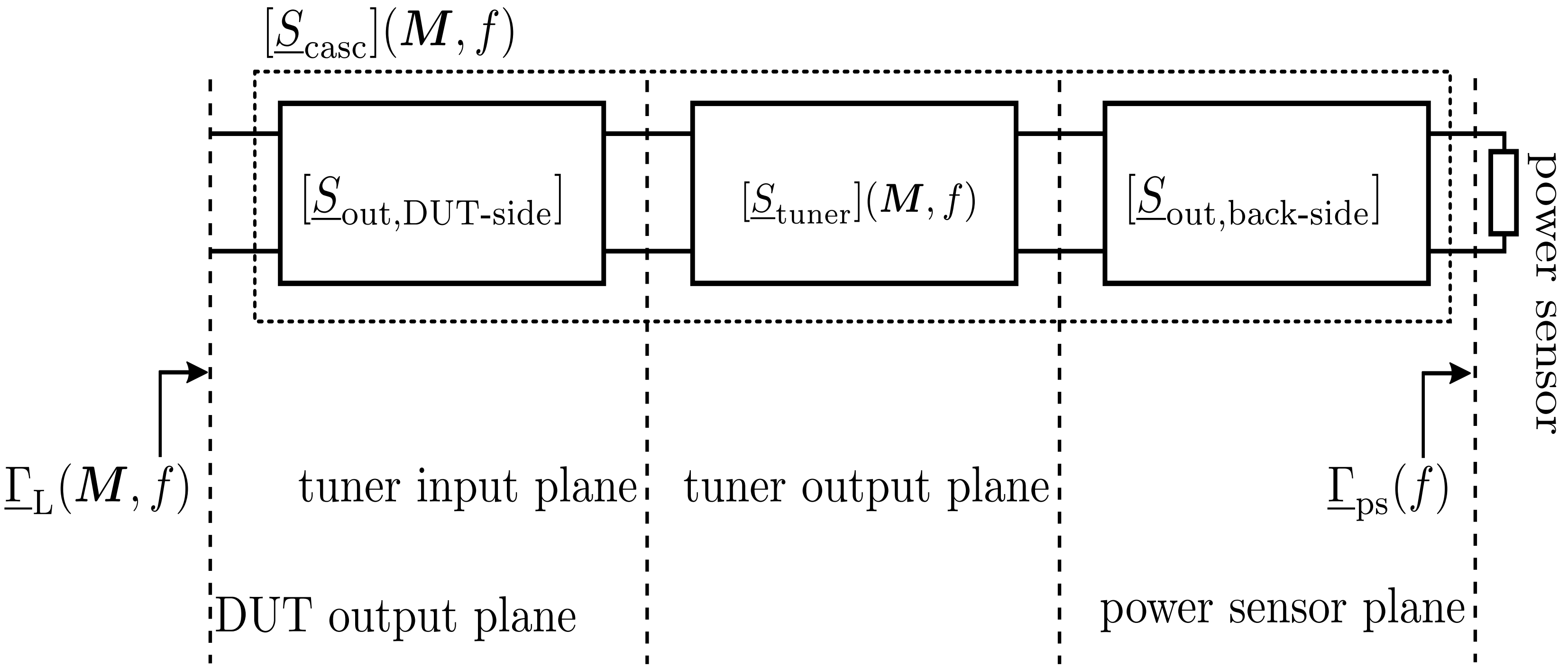




=> Fixture elements cause insertion loss and phase shift and have been characterized and taken into account in the netlist

=> The tunable range in the Smith chart is shrunk due to insertion loss between DUT plane and tuner plane

Calculation of the total load reflection coefficient

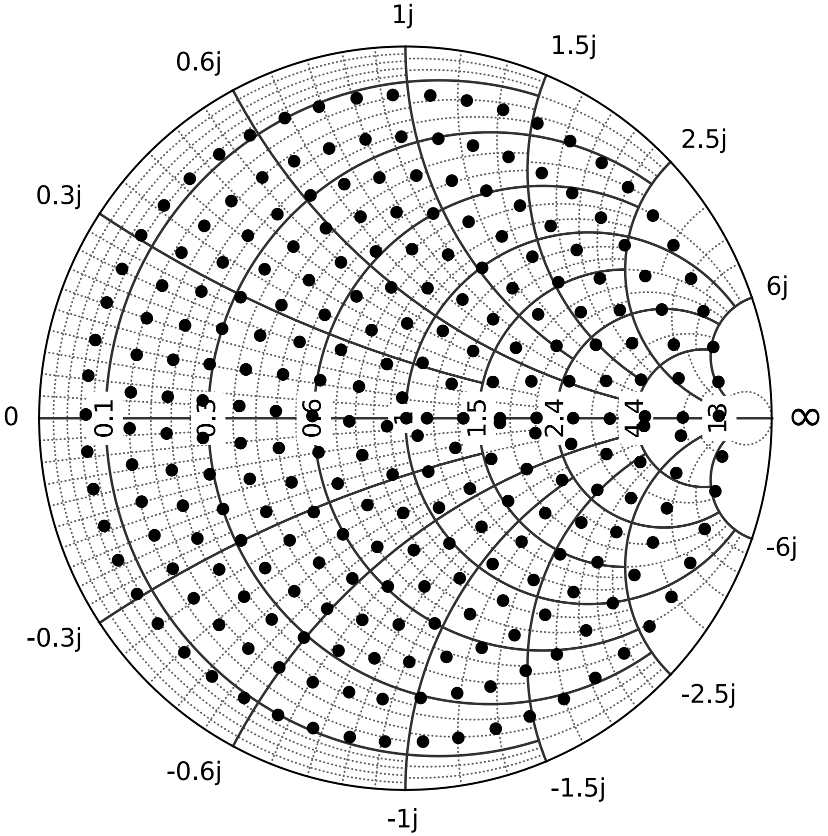


$$\underline{\Gamma}_{\mathrm{L}}(\boldsymbol{M},f) = \underline{S}_{11,\mathrm{casc}}(\boldsymbol{M},f) + \frac{\underline{S}_{12,\mathrm{casc}}(\boldsymbol{M},f)\,\underline{S}_{21,\mathrm{casc}}(\boldsymbol{M},f)\,\underline{\Gamma}_{\mathrm{ps}}(f)}{1-\underline{S}_{22,\mathrm{casc}}(\boldsymbol{M},f)\,\underline{\Gamma}_{\mathrm{ps}}(f)}$$

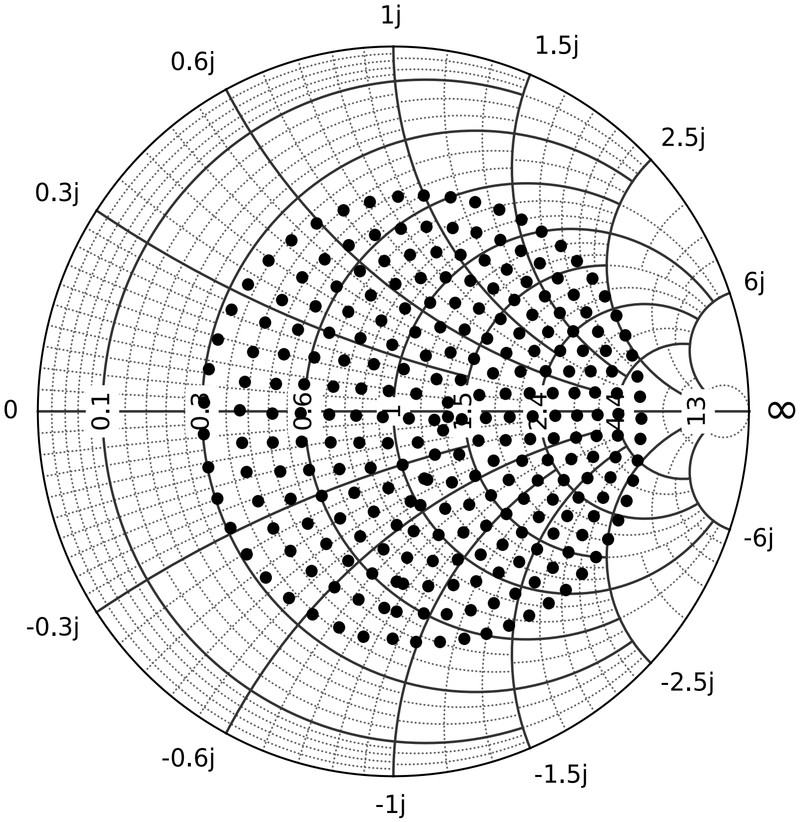
=> Load reflection coefficient calculation over all frequencies within the tuner bandwidth (8 GHz - 50 GHz) and over all tuner motor positions

Total load reflection coefficient of cascaded *S*-parameters

$\underline{S}_{11,\mathrm{tuner}}(\boldsymbol{M}, f = 10\,\mathrm{GHz})$

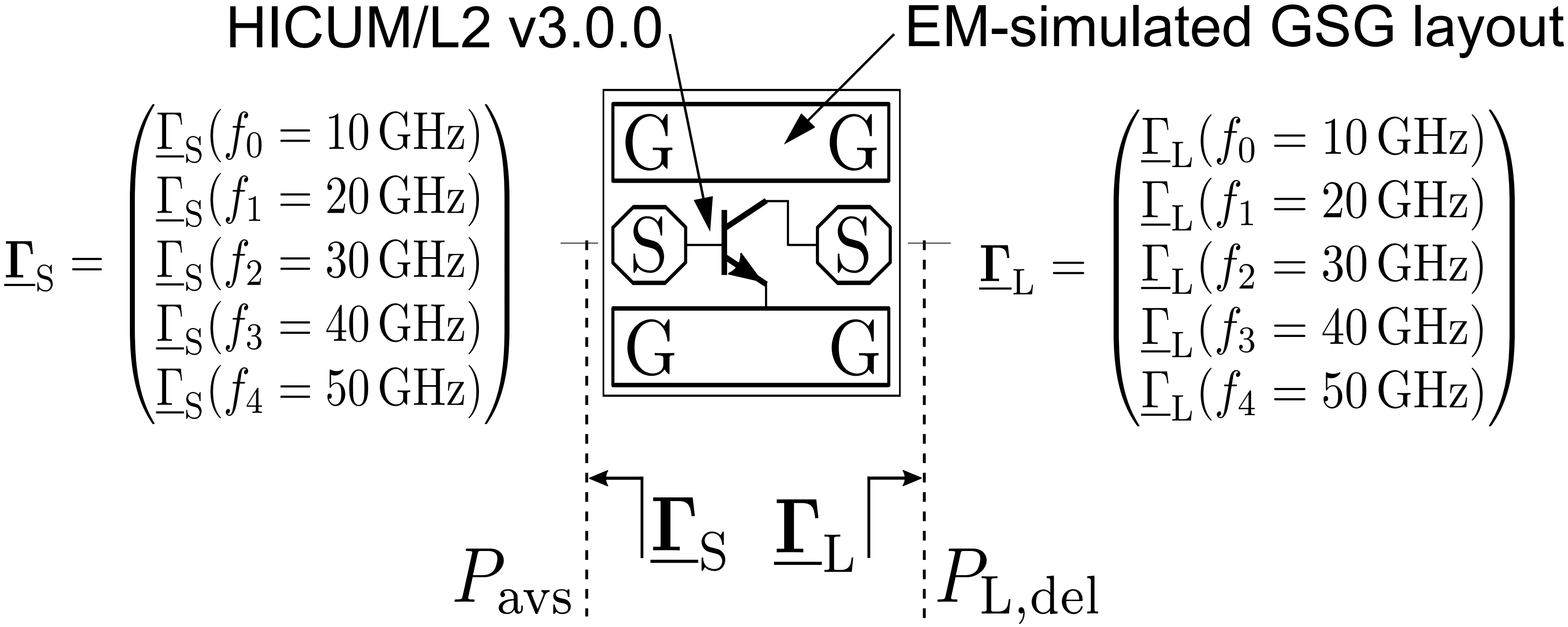


$\underline{\Gamma}_{\mathrm{L}}(\boldsymbol{M}, f = 10\,\mathrm{GHz})$



=> Setup fixtures and tuner reflections determine the total load reflection coefficient presented at the DUT reference plane

Netlist definition



$$\underline{\mathbf{\Gamma}}_{\mathrm{S}} = \begin{pmatrix} \underline{\Gamma}_{\mathrm{S}}(f_0 = 10\,\mathrm{GHz}) \\ \underline{\Gamma}_{\mathrm{S}}(f_1 = 20\,\mathrm{GHz}) \\ \underline{\Gamma}_{\mathrm{S}}(f_2 = 30\,\mathrm{GHz}) \\ \underline{\Gamma}_{\mathrm{S}}(f_3 = 40\,\mathrm{GHz}) \\ \underline{\Gamma}_{\mathrm{S}}(f_4 = 50\,\mathrm{GHz}) \end{pmatrix}$$

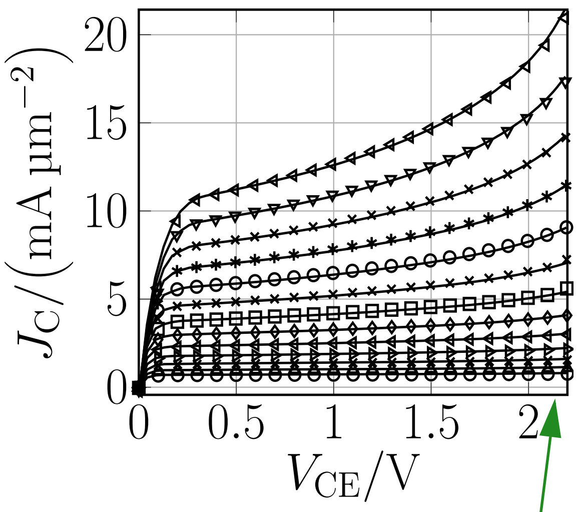
$$\underline{\mathbf{\Gamma}}_{\mathrm{L}} = \begin{pmatrix} \underline{\Gamma}_{\mathrm{L}}(f_0 = 10\,\mathrm{GHz}) \\ \underline{\Gamma}_{\mathrm{L}}(f_1 = 20\,\mathrm{GHz}) \\ \underline{\Gamma}_{\mathrm{L}}(f_2 = 30\,\mathrm{GHz}) \\ \underline{\Gamma}_{\mathrm{L}}(f_3 = 40\,\mathrm{GHz}) \\ \underline{\Gamma}_{\mathrm{L}}(f_4 = 50\,\mathrm{GHz}) \end{pmatrix}$$

- 50 GHz is the highest frequency measurable with Keysight's 85056A 2.4 mm calibration kit used for the setup fixture characterization
- A fundamental frequency of f_0 = 10 GHz enables to characterize the setup fixtures up to the fifth harmonic
- Vectorial defintion of the source and load reflection coefficient as specified in: A. Howard, “Load pull simulation using ADS”, Agilent Technologies, 2002

Modelcard of the DUT

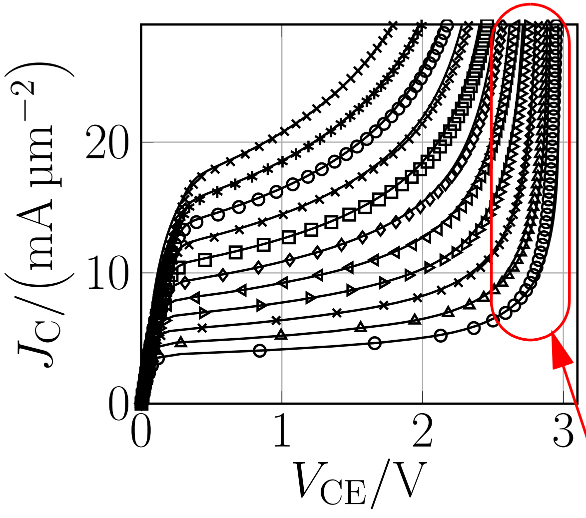
IHP, SG13G2, emitter size: $b_{E0} = 0.12\ \mu m$, $l_{E0} = 2.65\ \mu m$

$V_{BE} = 0.8$ V...0.92 V, $\Delta V_{BE} = 10$ mV



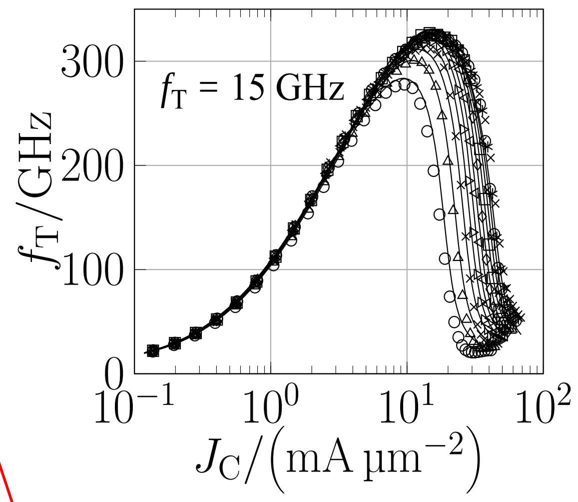
Forced V_{CE}, sensed I_C

$V_{BE} = 0.86$ V...0.96 V, $\Delta V_{BE} = 10$ mV



Forced I_C, sensed V_{CE}

$V_{BC} = 0.5$ V...-0.5 V, $\Delta V_{BC} = -100$ mV

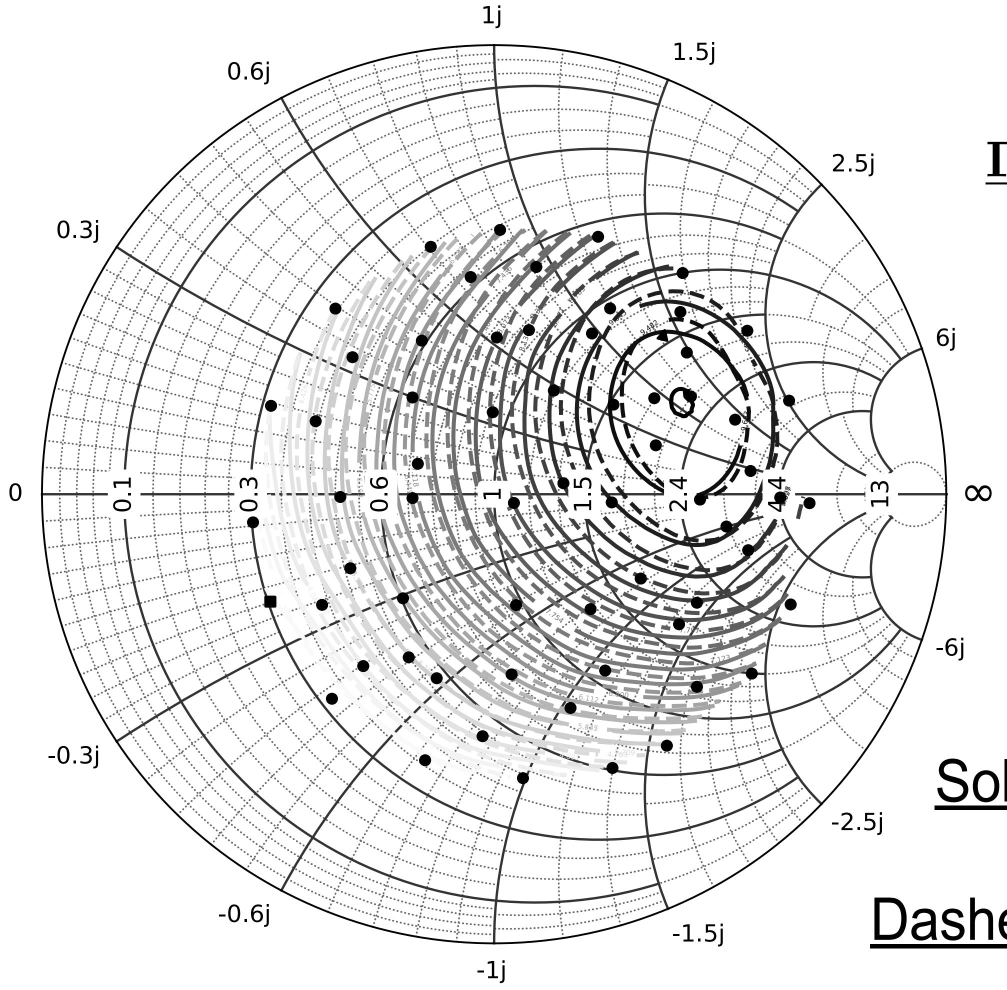


typical V_{CE} range for parameter extraction

interaction between avalanche multiplication and self-heating

=> Modelcard calibration at all collector injection levels within and beyond the V_{CE} range typically used for parameter extraction

Load-pull with tuned source reflection coefficient



$$\underline{\mathbf{\Gamma}}_\mathrm{S} = \begin{pmatrix} \underline{\Gamma}_\mathrm{S}|_{10\,\mathrm{GHz}} = 0.233 + 0.3\mathrm{j} \\ \underline{\Gamma}_\mathrm{S}|_{20\,\mathrm{GHz}} = -0.091 - 0.44\mathrm{j} \\ \underline{\Gamma}_\mathrm{S}|_{30\,\mathrm{GHz}} = 0.179 + 0.179\mathrm{j} \\ \underline{\Gamma}_\mathrm{S}|_{40\,\mathrm{GHz}} = -0.204 - 0.071\mathrm{j} \\ \underline{\Gamma}_\mathrm{S}|_{50\,\mathrm{GHz}} = -0.262 + 0.032\mathrm{j} \end{pmatrix}$$

f_0 = 10 GHz
V_BE = 0.92 V
V_CE = 2.0 V > BV_CEO = 1.6 V
P_avs = -4.15 dBm

Points: $\underline{\Gamma}_\mathrm{L}(\boldsymbol{M}, f = 10\,\mathrm{GHz})$

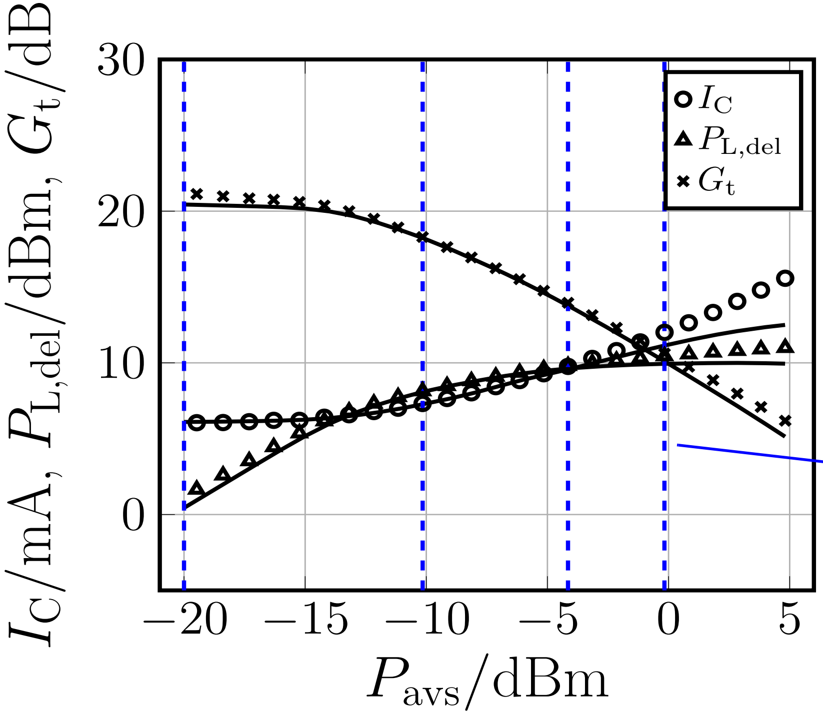
Solid lines: isopower contours from measured $P_\mathrm{L,del}$

Dashed lines: isopower contours from simulated $P_\mathrm{L,del}$

=> Innermost constant-power contour indicates the Smith chart area in which maximum power is delivered to the load

Power sweep with tuned source/load reflection coefficient

$$\underline{\mathbf{\Gamma}}_{\mathrm{S}} = \begin{pmatrix} \underline{\Gamma}_{\mathrm{S}}|_{10\,\mathrm{GHz}} = 0.233 + 0.3\mathrm{j} \\ \underline{\Gamma}_{\mathrm{S}}|_{20\,\mathrm{GHz}} = -0.091 - 0.44\mathrm{j} \\ \underline{\Gamma}_{\mathrm{S}}|_{30\,\mathrm{GHz}} = 0.179 + 0.179\mathrm{j} \\ \underline{\Gamma}_{\mathrm{S}}|_{40\,\mathrm{GHz}} = -0.204 - 0.071\mathrm{j} \\ \underline{\Gamma}_{\mathrm{S}}|_{50\,\mathrm{GHz}} = -0.262 + 0.032\mathrm{j} \end{pmatrix} \qquad \underline{\mathbf{\Gamma}}_{\mathrm{L}} = \begin{pmatrix} \underline{\Gamma}_{\mathrm{L}}|_{10\,\mathrm{GHz}} = 0.533 + 0.166\mathrm{j} \\ \underline{\Gamma}_{\mathrm{L}}|_{20\,\mathrm{GHz}} = -0.417 - 0.054\mathrm{j} \\ \underline{\Gamma}_{\mathrm{L}}|_{30\,\mathrm{GHz}} = 0.394 - 0.066\mathrm{j} \\ \underline{\Gamma}_{\mathrm{L}}|_{40\,\mathrm{GHz}} = -0.071 - 0.135\mathrm{j} \\ \underline{\Gamma}_{\mathrm{L}}|_{50\,\mathrm{GHz}} = 0.131 - 0.2\mathrm{j} \end{pmatrix}$$



V_{BE} = 0.92 V

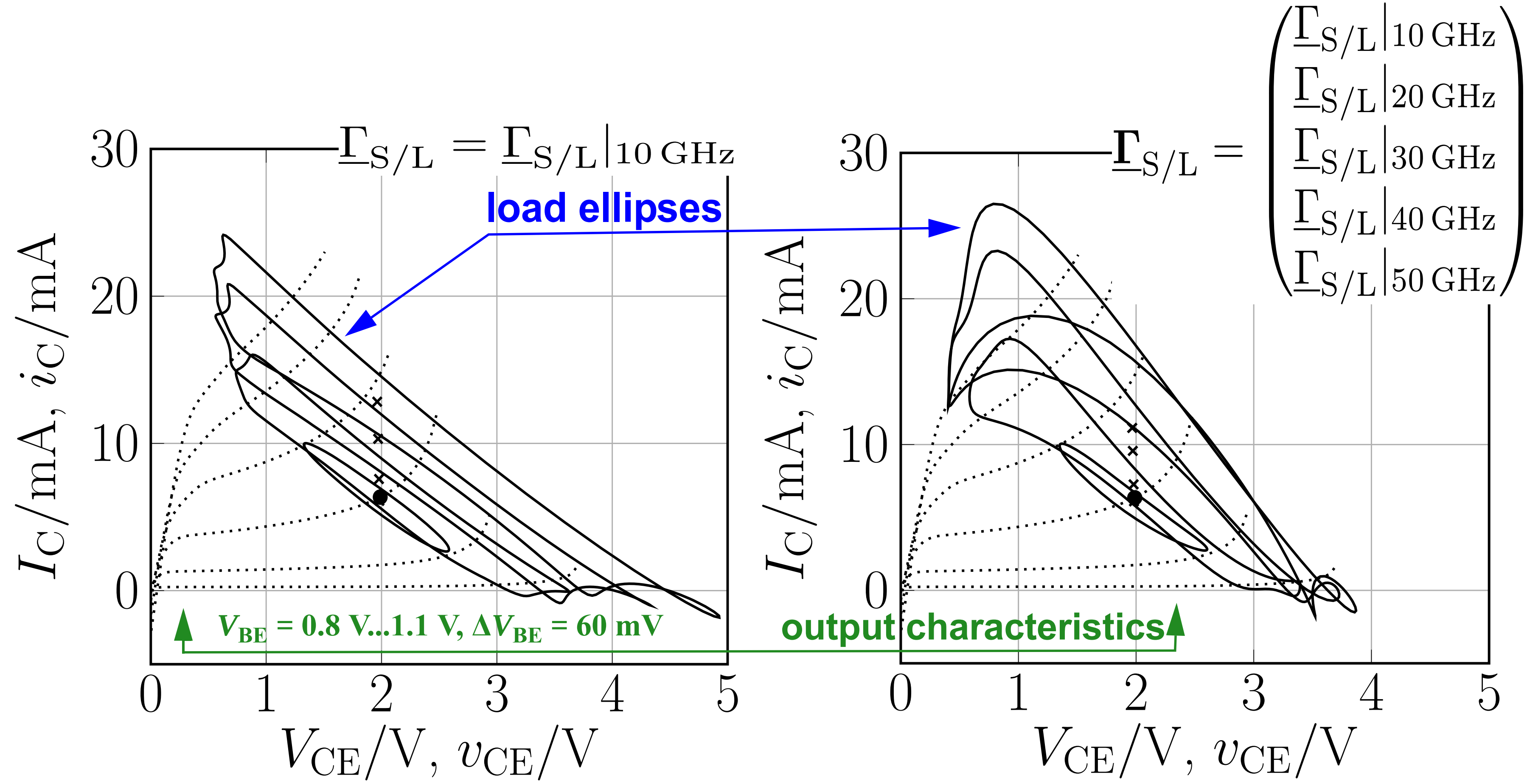
V_{CE} = 2.0 V > BV_{CEO} = 1.6 V

f_0 = 10 GHz

Time-domain signal swings shown on the next slide

=> Very good agreement over a wide range of P_{avs}

Time-domain signal swings

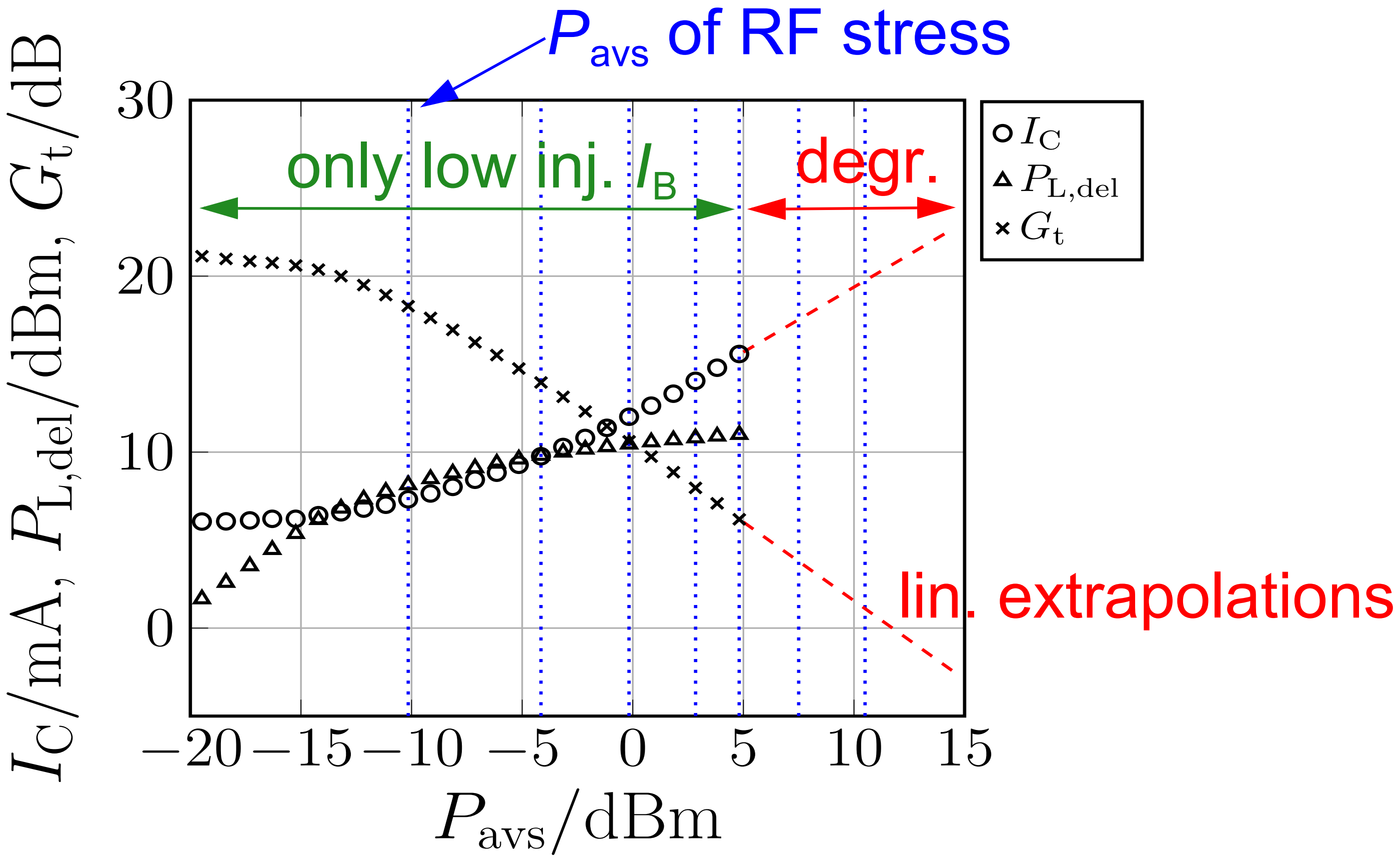


=> An accurate description of the fundamental and harmonic reflection coefficients at the DUT reference planes is necessary to simulate with sufficient accuracy the time-domain $i_C(t)$ and $v_{CE}(t)$ swings of distorted signals

Selected degradation results

RF stress conditions

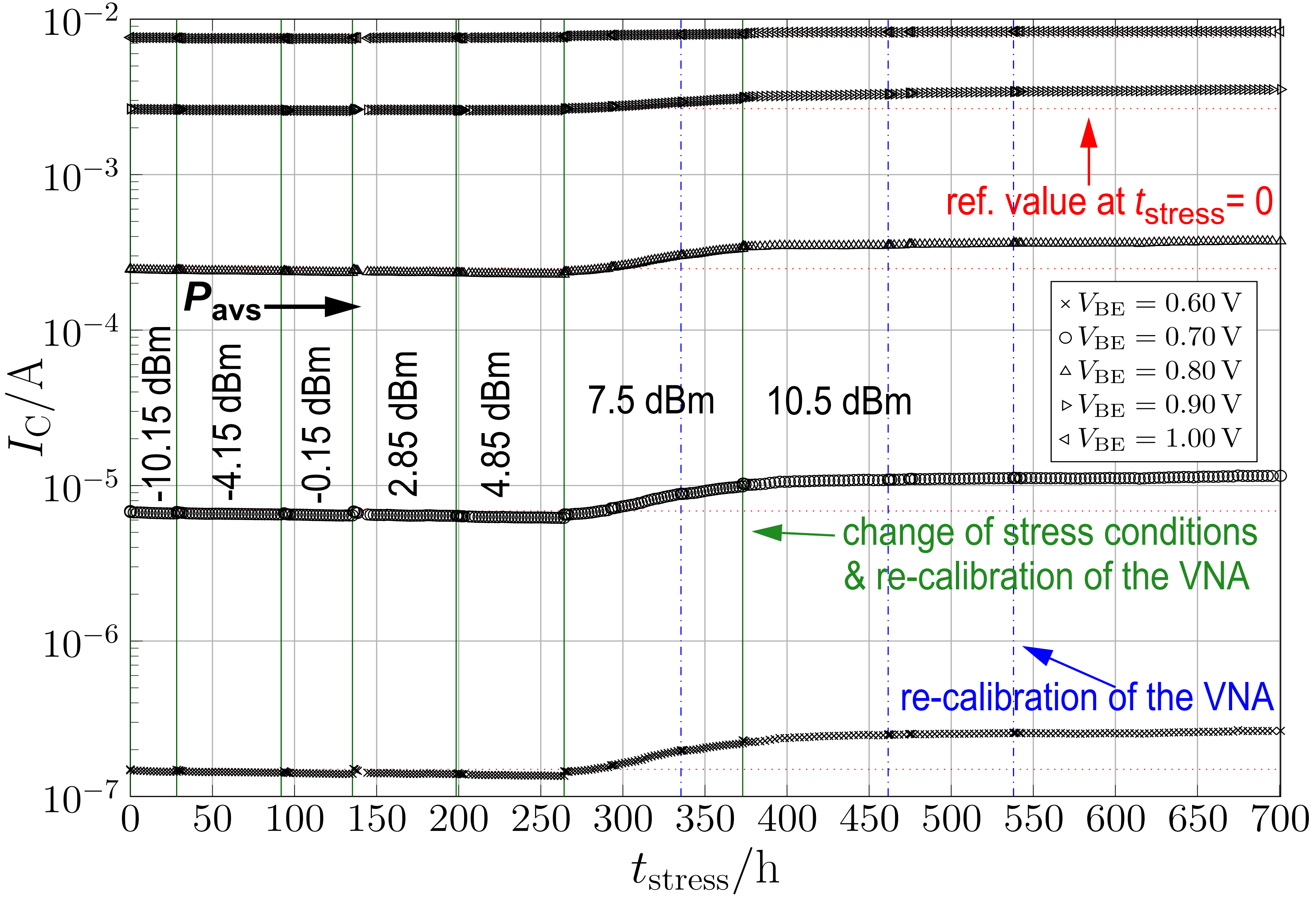
$V_{CE} = 2.0\ \mathrm{V} > BV_{CEO} = 1.6\ \mathrm{V}$
$V_{BE} = 0.92\ \mathrm{V}$
$f_0 = 10\ \mathrm{GHz}$



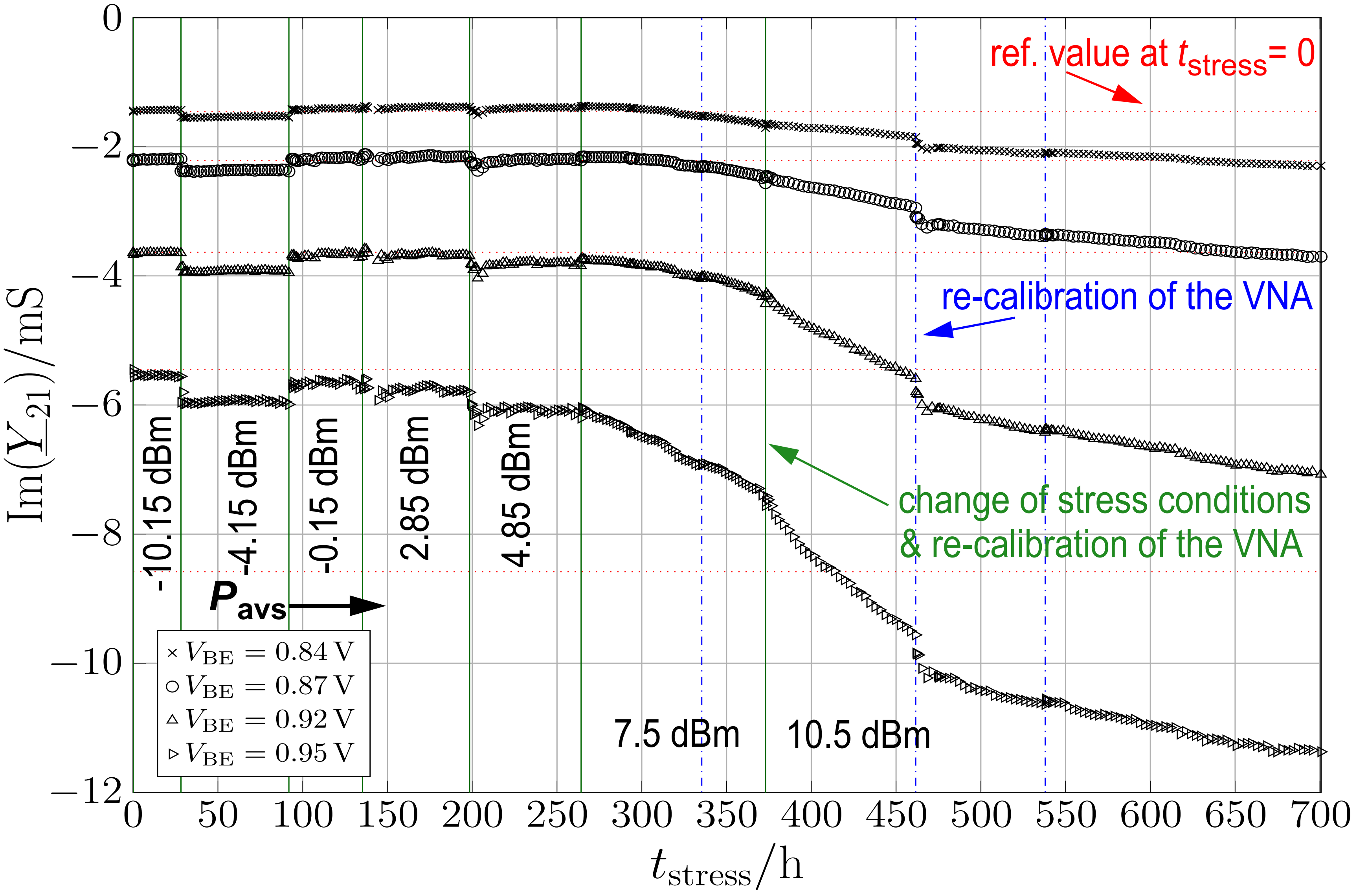
=> Degradation in *Y*-parameters measurable only under strongly nonlinear large-signal operating conditions (=> gain compression)

=> SiGe HBTs can be operated **far beyond** statically defined operating limits

Periodic measurements: Static collector current



Periodic measurements: Embedded Im($\underline{Y}_{21}$)



Conclusions and outlook

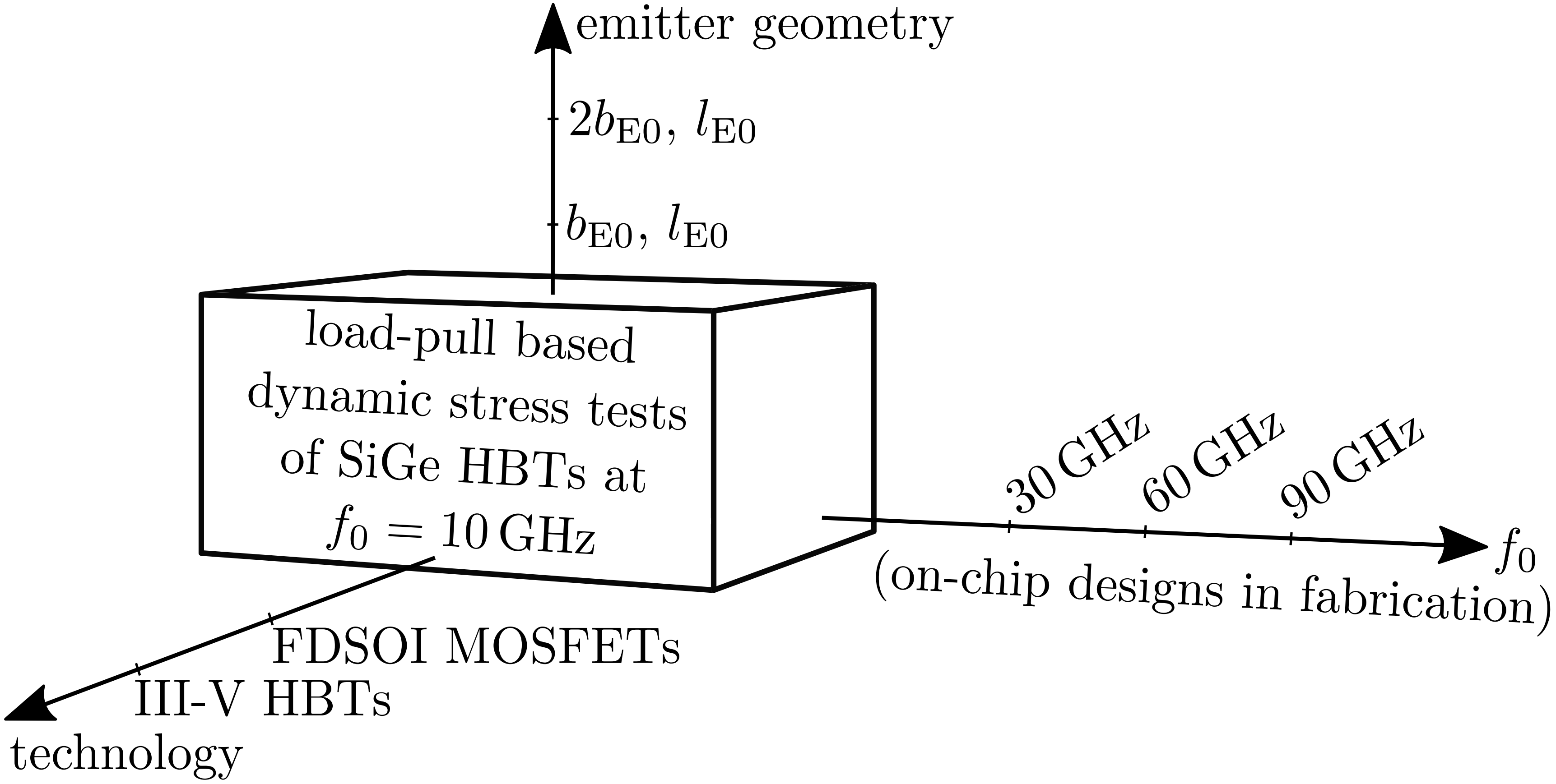
Conclusions

- Long-term RF reliability investigations are an insane project which only an insane engineer would agree to do as a doctoral thesis

- In dynamic large-signal operation, SiGe HBTs are reliably operable far beyond statically defined operating limits such as BV_{CEO}

- Strongly nonlinear dynamic large-signal operation can cause damage beyond base current degradation

Outlook



=> Stress tests with different emitter geometries, frequencies and technologies

=> Find the reason for the observed degradation in SiGe HBTs

Acknowledgements

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