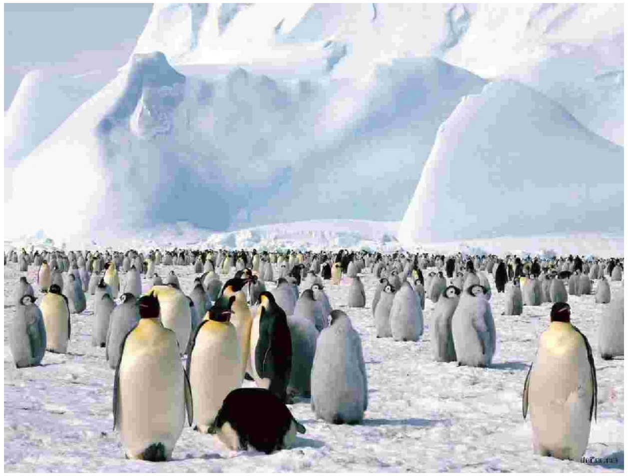
LEADING BEYOND S-PARAMETERS

S-functions
- Measure, Model, Simulate -



An application in ICE

Outline

- Key benefits
- Key capabilities
- Why S-functions?
- What are S-functions?
- Harmonic-related S-functions as an example application in ICE(*)

(*) Integrated Component Characterisation Environment

Key Benefits

S-functions are for nonlinear components ...

... what S-parameters are for linear components

- Improve and speed up the design process
  - Measure and directly simulate RF systems under large-signal conditions
- Simplify and increase RF component sales
  - Provide more complete system-level models for RF components, instead of limited data sheets
  - Reduce the need for evaluation boards to prove proper operation of component
- S-functions are easy because they are a natural extension of S-parameters

Key Capabilities

- Natural extension of S-parameters
  - Reduce to S-parameters for small-signal excitation
  - S-parameters are cascadable, S-functions are cascadable too
- Predict harmonic behaviour of components under different impedances
- Predict modulation behaviour of components under different impedances
  - Under pseudo-static assumption
- Predict component behaviour under arbitrary small-signal spurious signals in different impedances
- Valid for multi-ports, applicable to differential components

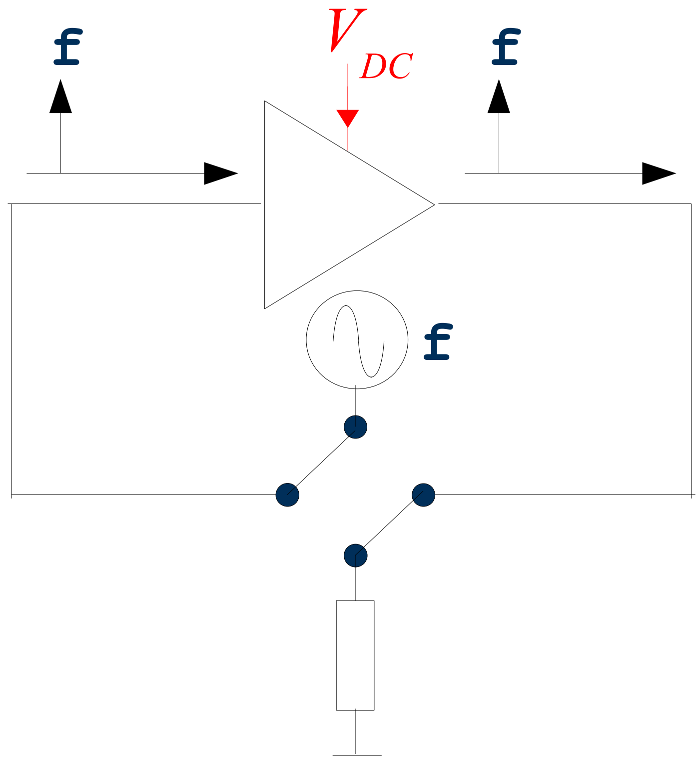
Why S-functions?

- S-parameters are valid for linear mode of operation **only**.
- The success of S-parameters is based on its **uniform** approach for linear RF and microwave problems.
- Unfortunately there is **no uniform** approach yet to deal with nonlinear RF and microwave problems.
- In the scientific world, different approaches are proposed to describe different phenomena.
- S-functions deal with a subset of these phenomena in a **uniform way** as a natural extension of S-parameters.

From S-parameters to S-functions

S-parameters measured at fixed DC bias point

$\rightarrow S(f)$



S-parameters measured at different DC bias points

Linear $\rightarrow S(V_{DC}; f)$

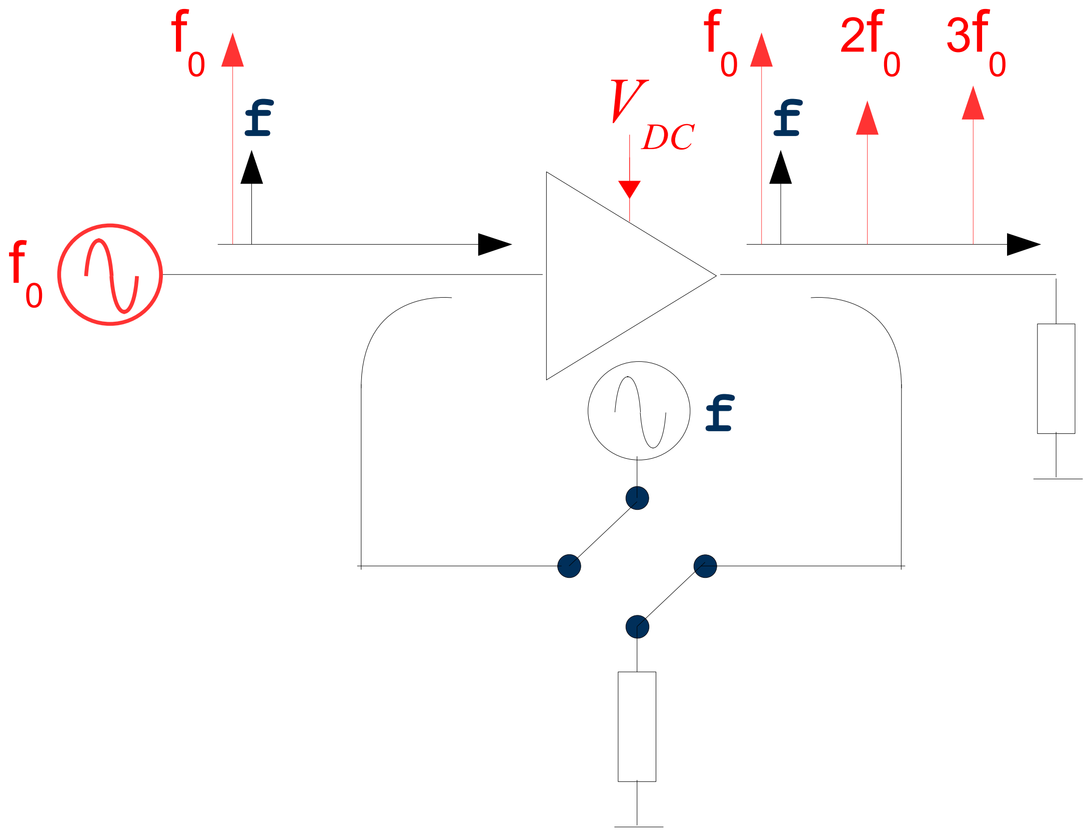
Nonlinear $\rightarrow I(V_{DC})$

Remark: for the sake of intuitive explanation, mathematics is not 100% correct

From S-parameters to S-functions

An additional bias point: large-signal tone at f_0

Assumption: the amplitude of tone at **`f`** is small enough(*)



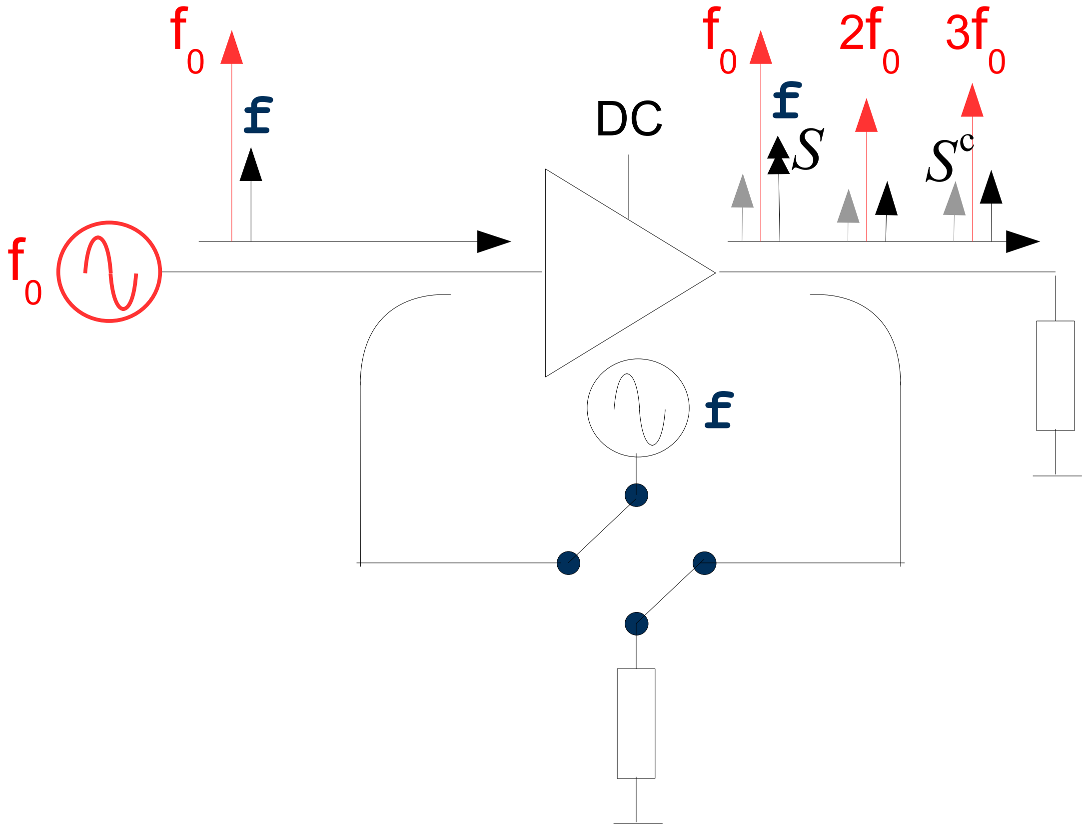
Linear ➡ $S(V_{DC}, f_0, |a_1(f_0)|; f)$

Nonlinear ➡ $b_i(h f_0) = Mapping^{l}_{ih}(V_{DC}, f_0, a_1(f_0))$

(*) to have linear contribution at output of `f` only

From S-parameters to S-functions

Increase the amplitude of tone at **f**



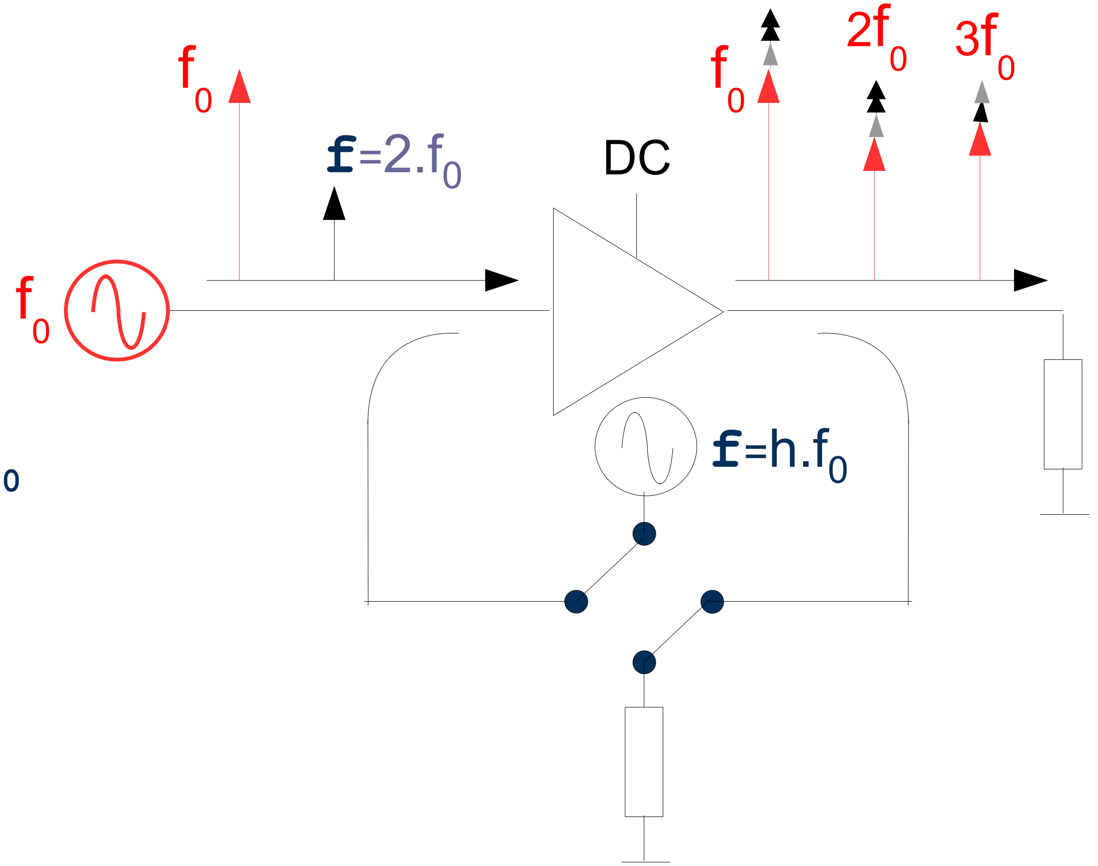
Linear ➡ S is extended to predict additional frequencies(*)

$S(V_{DC}, f_0, |a_1(f_0)|; f)$ and $S^c(V_{DC}, f_0, |a_1(f_0)|; f)$

Nonlinear ➡ $b_i(h f_0) = Mapping^l_{ih}(V_{DC}, f_0, a_1(f_0))$

(*) theoretically expressed through the Volterra theory

S-functions, limited to Harmonic Behaviour



`f = h . f`$_0$

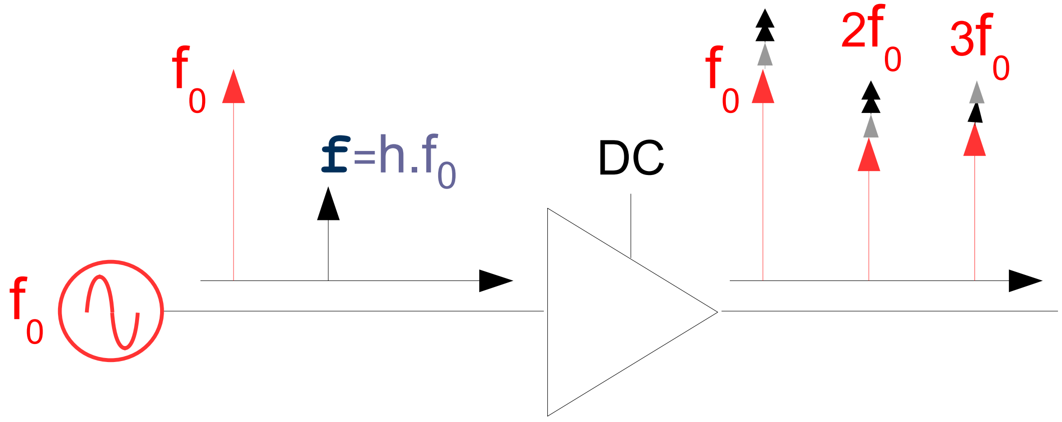
Linear ➡ S is extended to predict additional frequencies(*)

$$S(V_{DC}, f_0, |a_1(f_0)|; h f_0) \quad \text{and} \quad S^c(V_{DC}, f_0, |a_1(f_0)|; h f_0)$$

Nonlinear ➡ $b_i(h f_0) = Mapping^l_{ih}(V_{DC}, f_0, a_1(f_0))$

(*) theoretically expressed through the Volterra theory

S-functions, focused on Harmonic Behaviour



$b_p(h.f_0)$ can be expressed as function of DC, f_0 and $|a_1(f_0)|$

The complete model is based on three contributions:

Linear →
$$S(V_{DC}, f_0, |a_1(f_0)|; h f_0)$$
$$S^c(V_{DC}, f_0, |a_1(f_0)|; h f_0)$$

Nonlinear →
$$b_i(h f_0) = Mapping^l_{ih}(V_{DC}, f_0, a_1(f_0))$$

S-functions in ICE(*)

- S-functions focussed on harmonic and modulation(**) behaviour
- Sweepable Large-Signal Operating Point (LSOP)
- Auto or user-defined tickle signal level
- From simple push-the-button solution to access to expert-level details
- Visualization of component behaviour during data collection
- Easy model verification (no EDA tool required)
- Sufficient sanity checks included
- Easy export to and integration in Agilent™ ADS

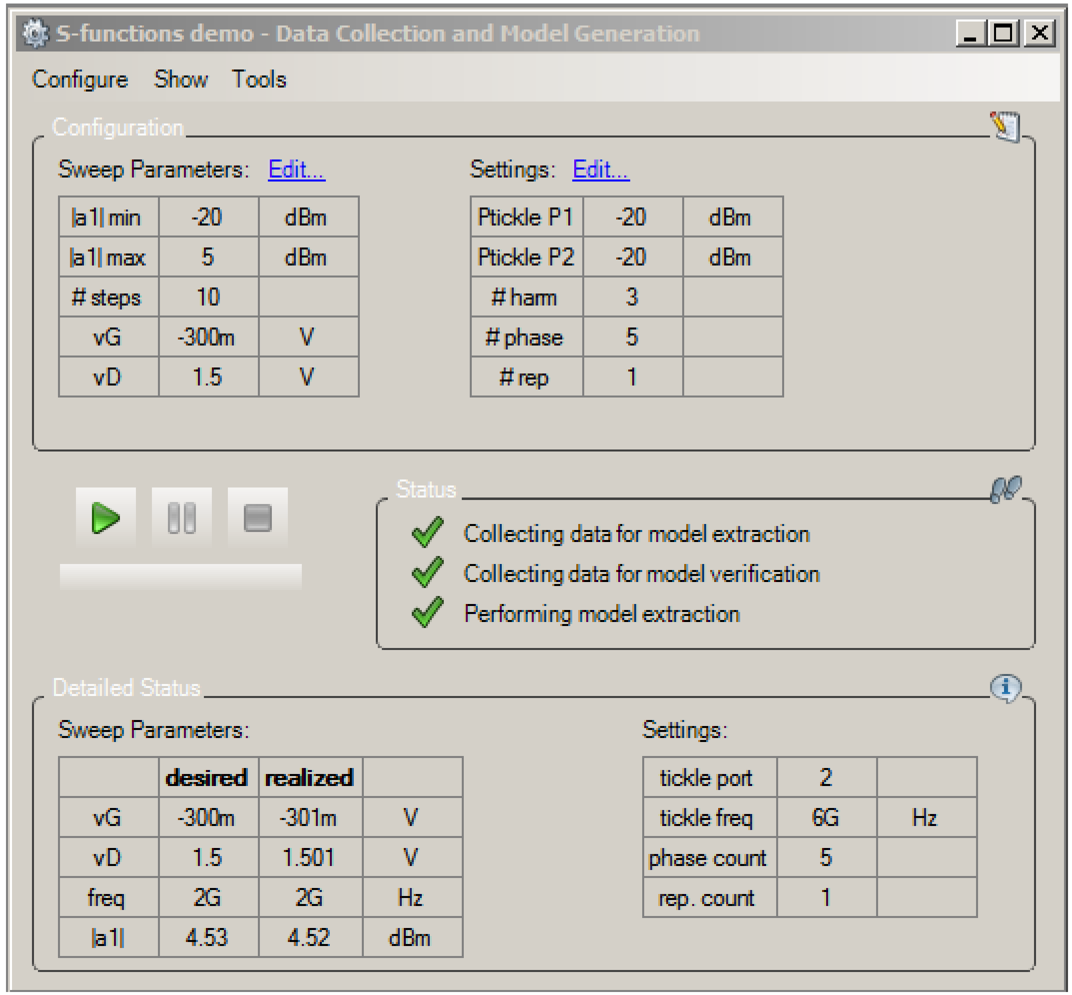
- Support for mismatched environments
- Harmonics generated by RF sources don't cause any problem
- Simple output prediction does not require EDA tool
- Support for both sampler-, mixer- and scope-based Large-Signal Analysers
- Runs both on PC and on supported instruments
- Export to and integration in other EDA tools on request
- Possible to extend the LSOP variables, e.g. temperature

(*) Integrated Component Characterisation Environment
(**) Pseudo-static behaviour

Model Extraction Process – Data Collection

LSOP(*) sweep

"tickle" settings



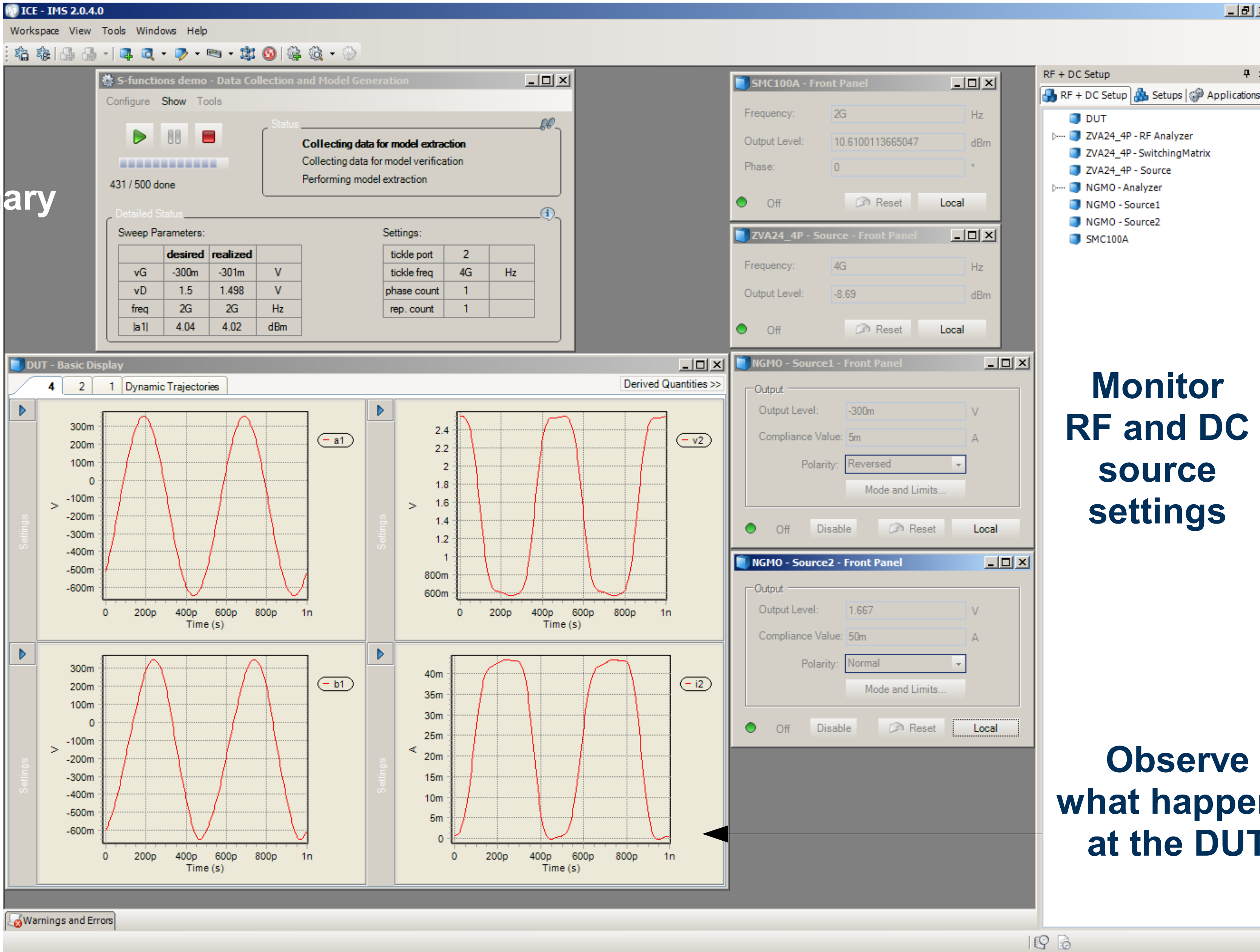
detailed feedback of LSOP for actual measurement

detailed feedback on tickle for actual measurement

(*) LSOP = Large-Signal Operating Point

Expert Details If Desired @ Data Collection

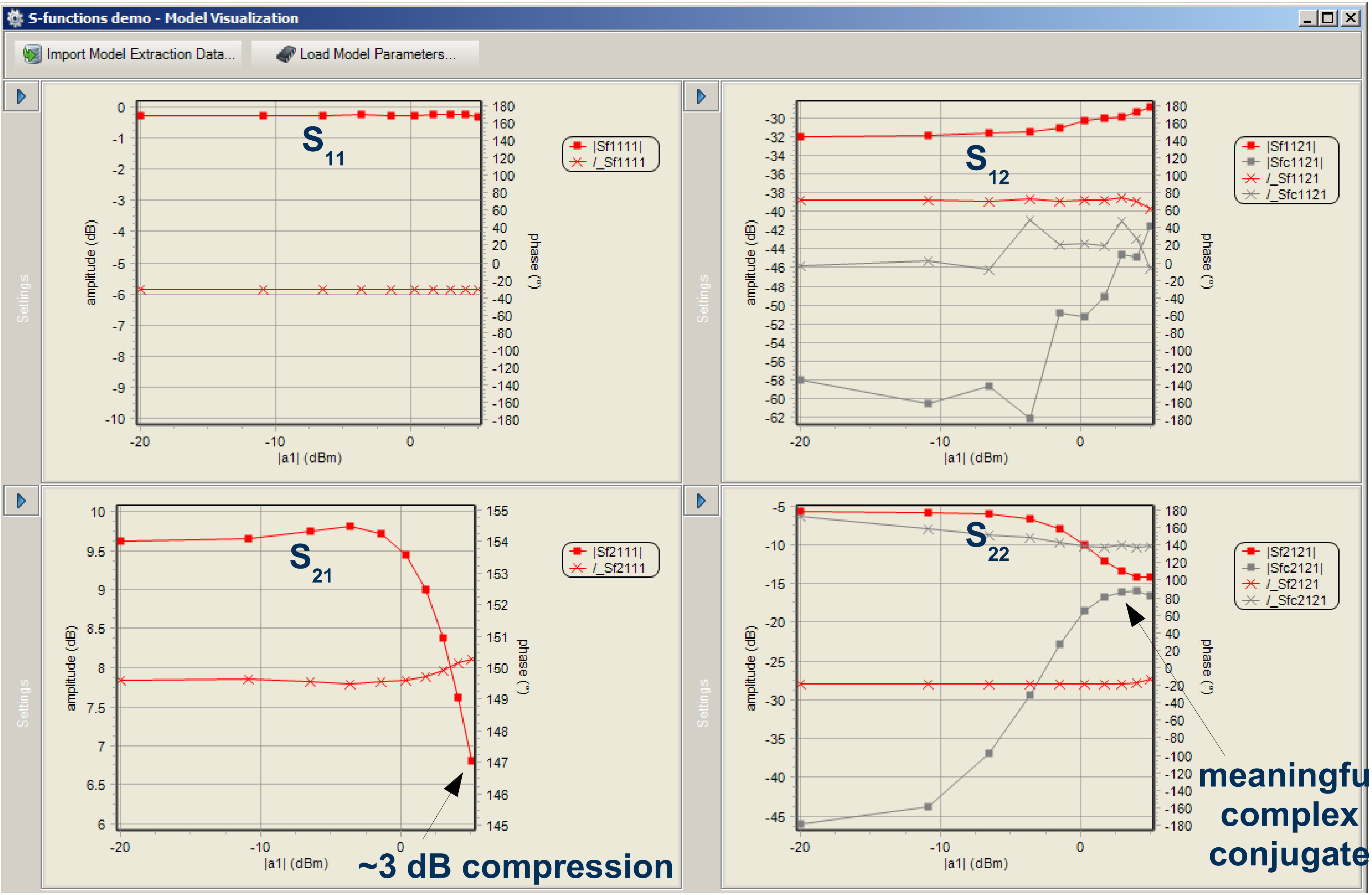
Summary



Monitor RF and DC source settings

Observe what happens at the DUT

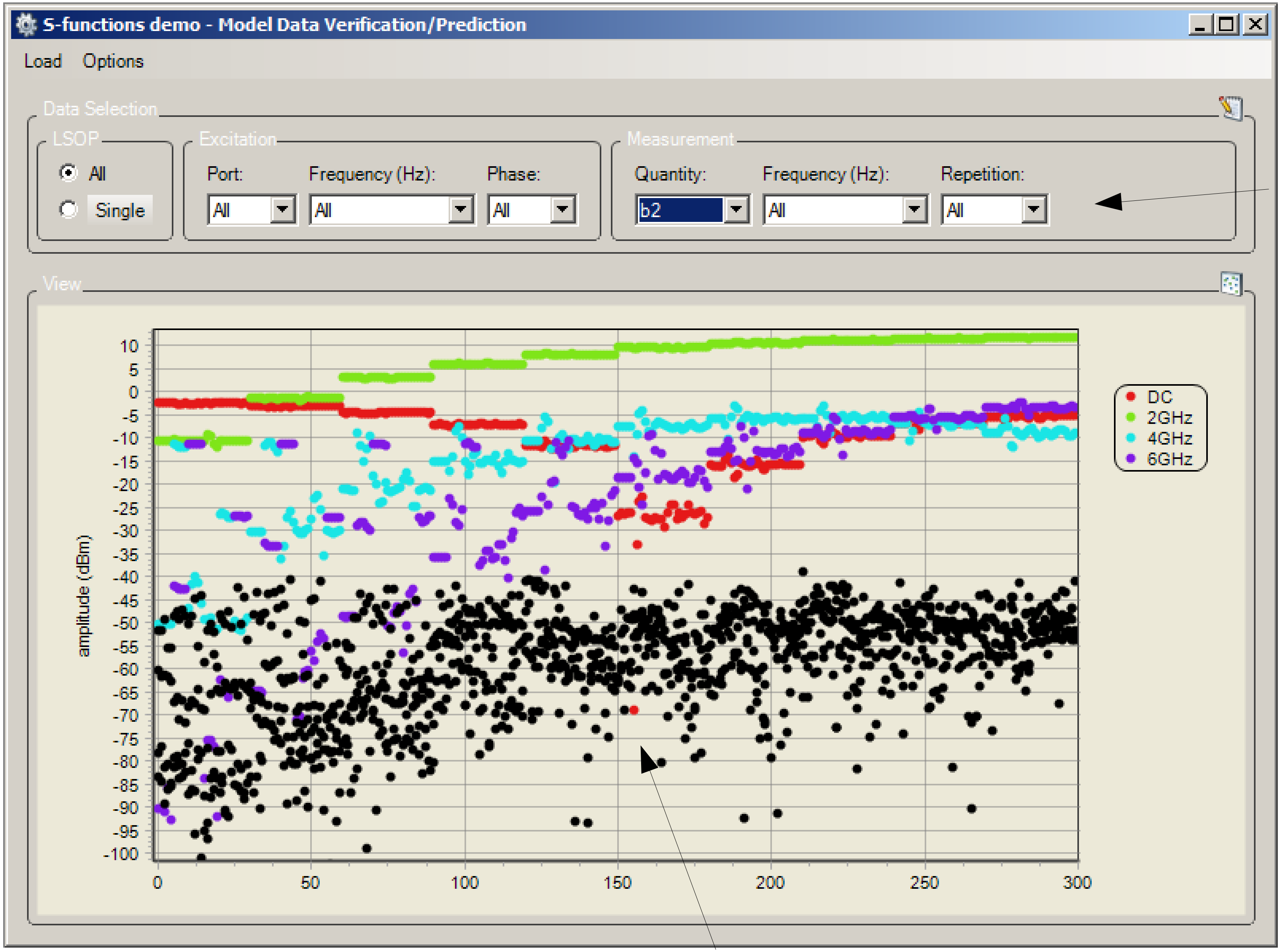
Model Extraction Process – Model Extraction & Visualization



Model verification process

- **1st sanity check:** data collection for model extraction
  - model extraction assumes data collection at constant LSOP
    - flexible control loops to adjust LSOP-related sources (if necessary)
    - summary of variation based on mean, stdev, min/max
    - zoom in if necessary (visual inspection)
  - model assumes sufficient variation of tickle signal
    - condition number for each LSOP setting
    - zoom in if necessary (visual inspection)
  - model assumes linear contribution of tickle signal
    - user-defined or automatic tickle power level
    - user-defined or automatic characteristic impedance
- **2nd sanity check:** verify quality of model (incl. linearization)
  - compare model prediction to measurements used for model extraction
  - look at amplitude of complex error for all measurements in one plot
  - zoom in if complex error too large for certain measurements
  - compare to uncertainty on measurements
- **3rd sanity check:** verify interpolatibility of model
  - compare model prediction to 2nd set of measurements
  - independent set of measurements at in-between values of LSOP (e.g. $|a_{11}|$)

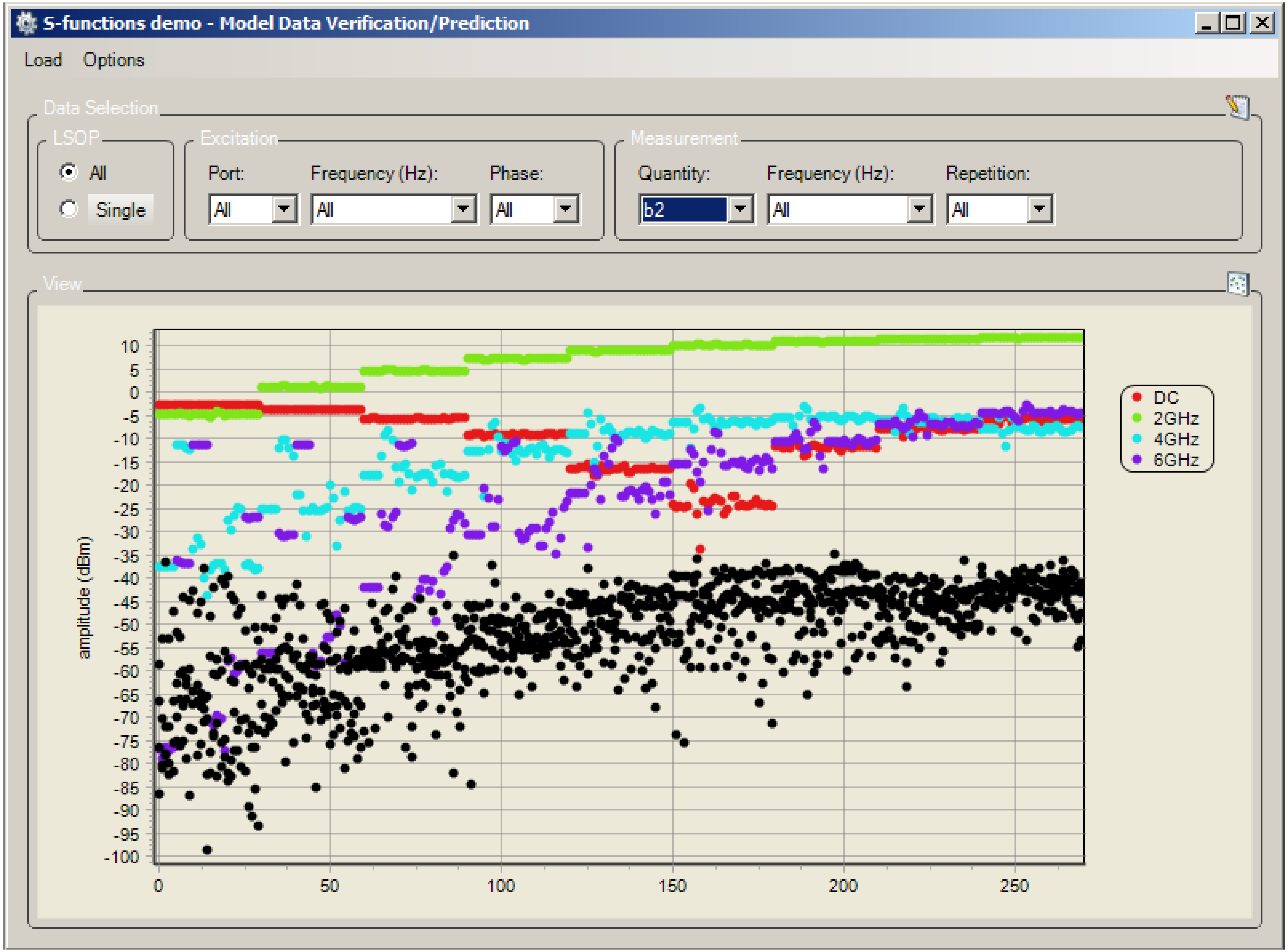
Model Prediction – Data Used for Model Extraction



zoom in if necessary

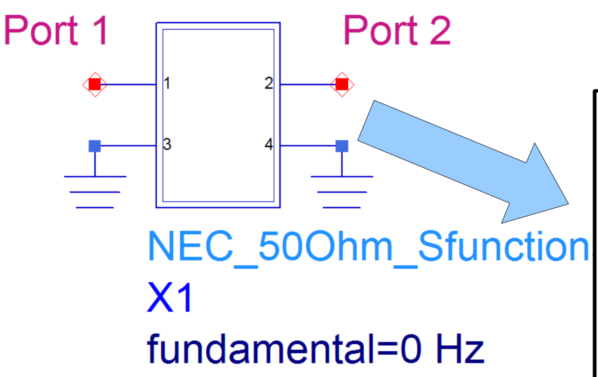
amplitude of complex error for b_2

Model Prediction – Data Used for Model Verification

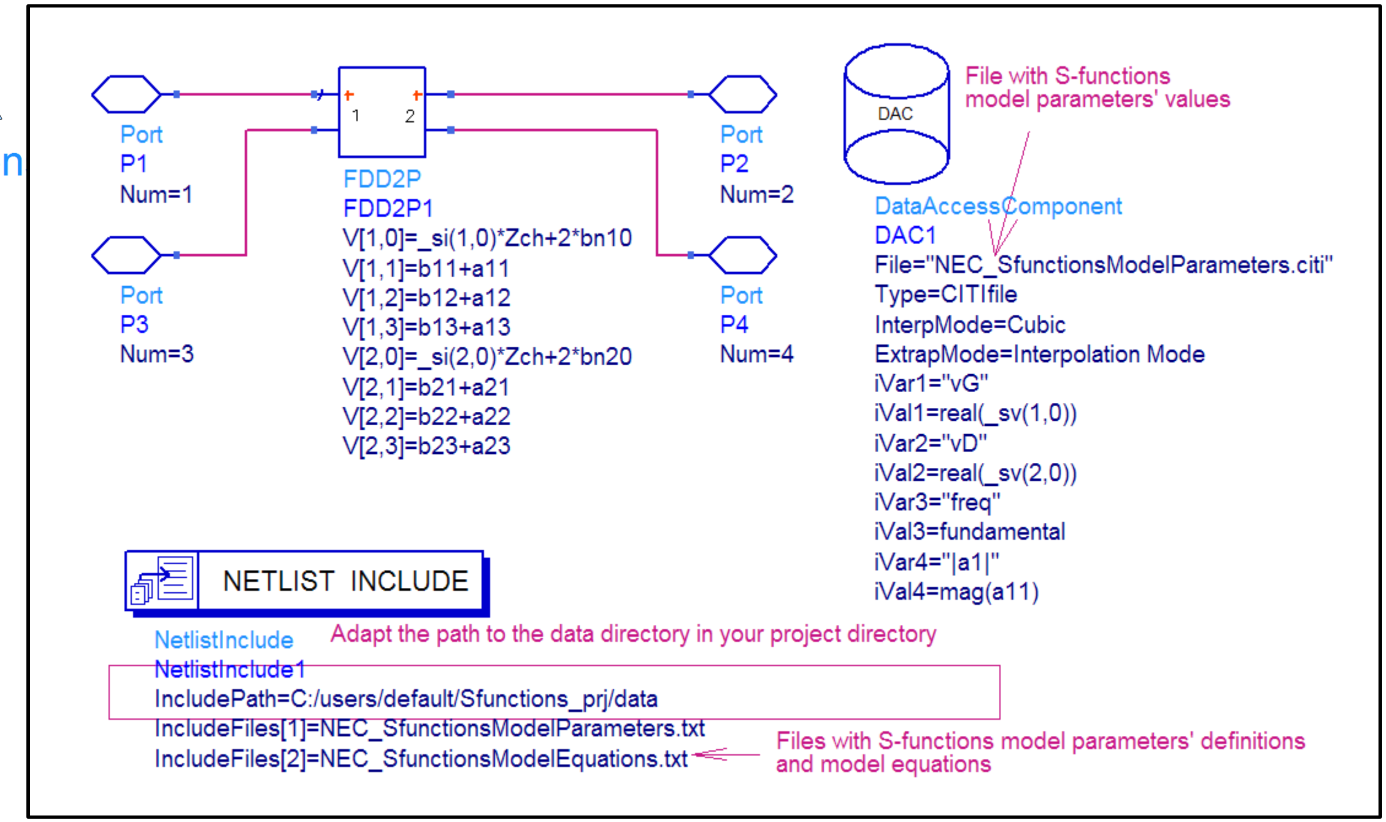


verify interpolation of b_2 with respect to $|a_{11}|$

S-functions in Agilent ADS

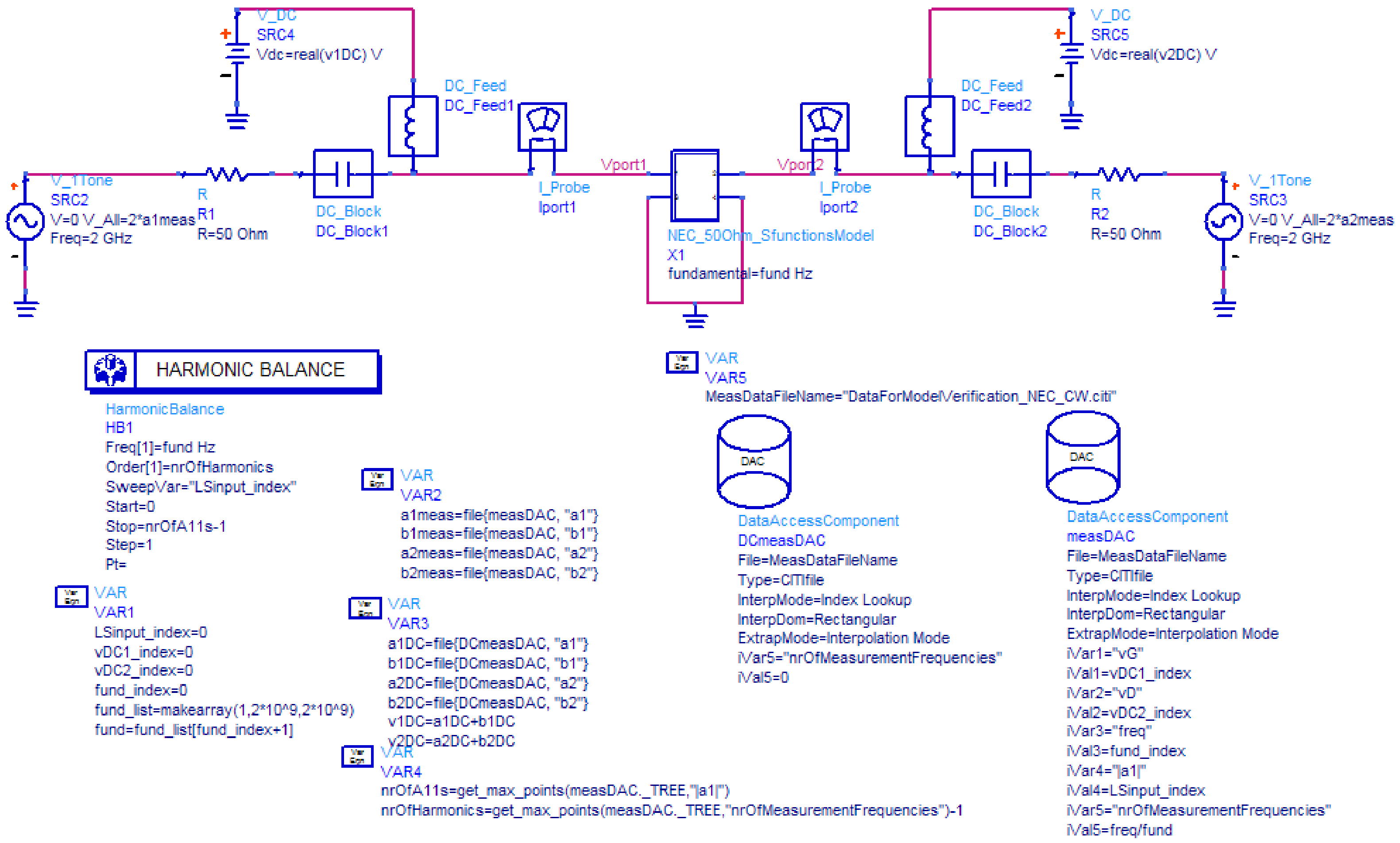


NEC FET device
with 50 Ohm load



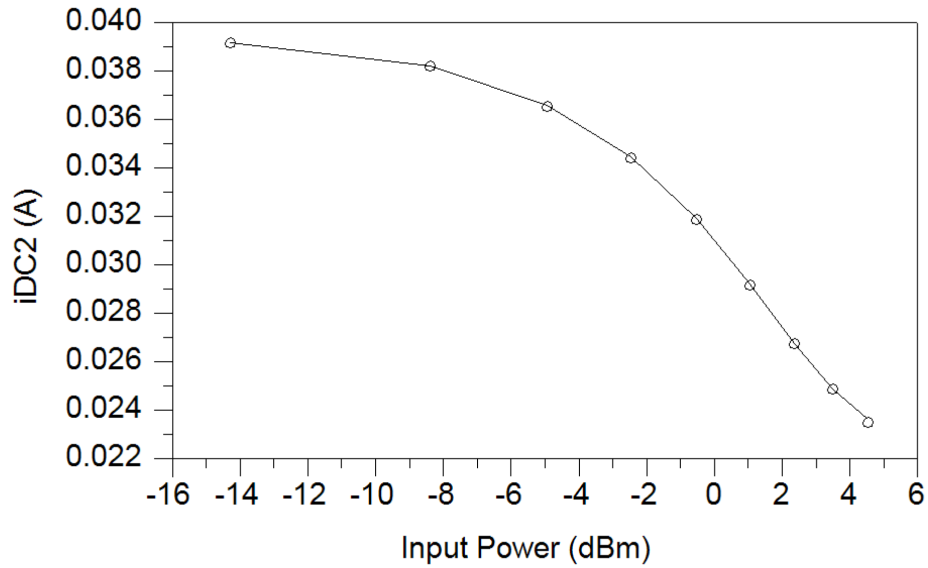
Model Verification in ADS - Schematic

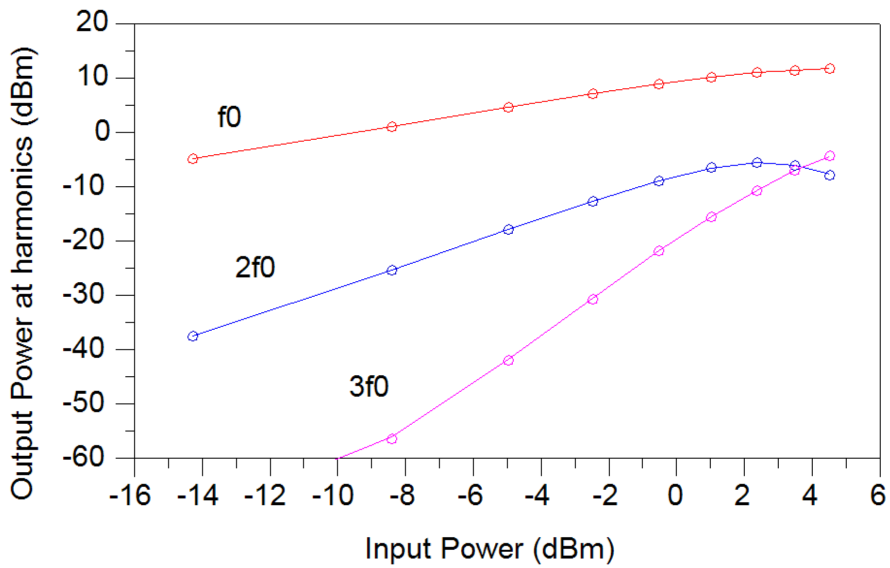
- Example: Harmonic Balance simulation with measured a1 and a2 spectra
- Excitation: CW RF signal at 2 GHz, Input Power sweep
- DC Bias: VDC1= -0.3 V, VDC2= +1.5 V



Model Verification in ADS

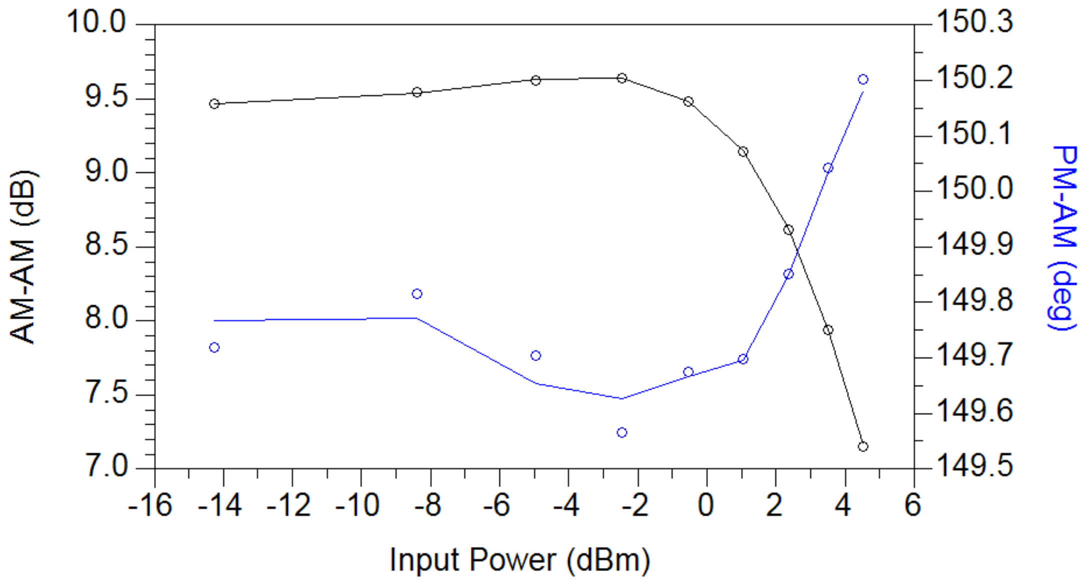
Frequency = 2 GHz, VDC1= -0.3 V, VDC2= +1.5 V





Measurements at <u>different</u> input powers than those which were used for S-functions model extraction!

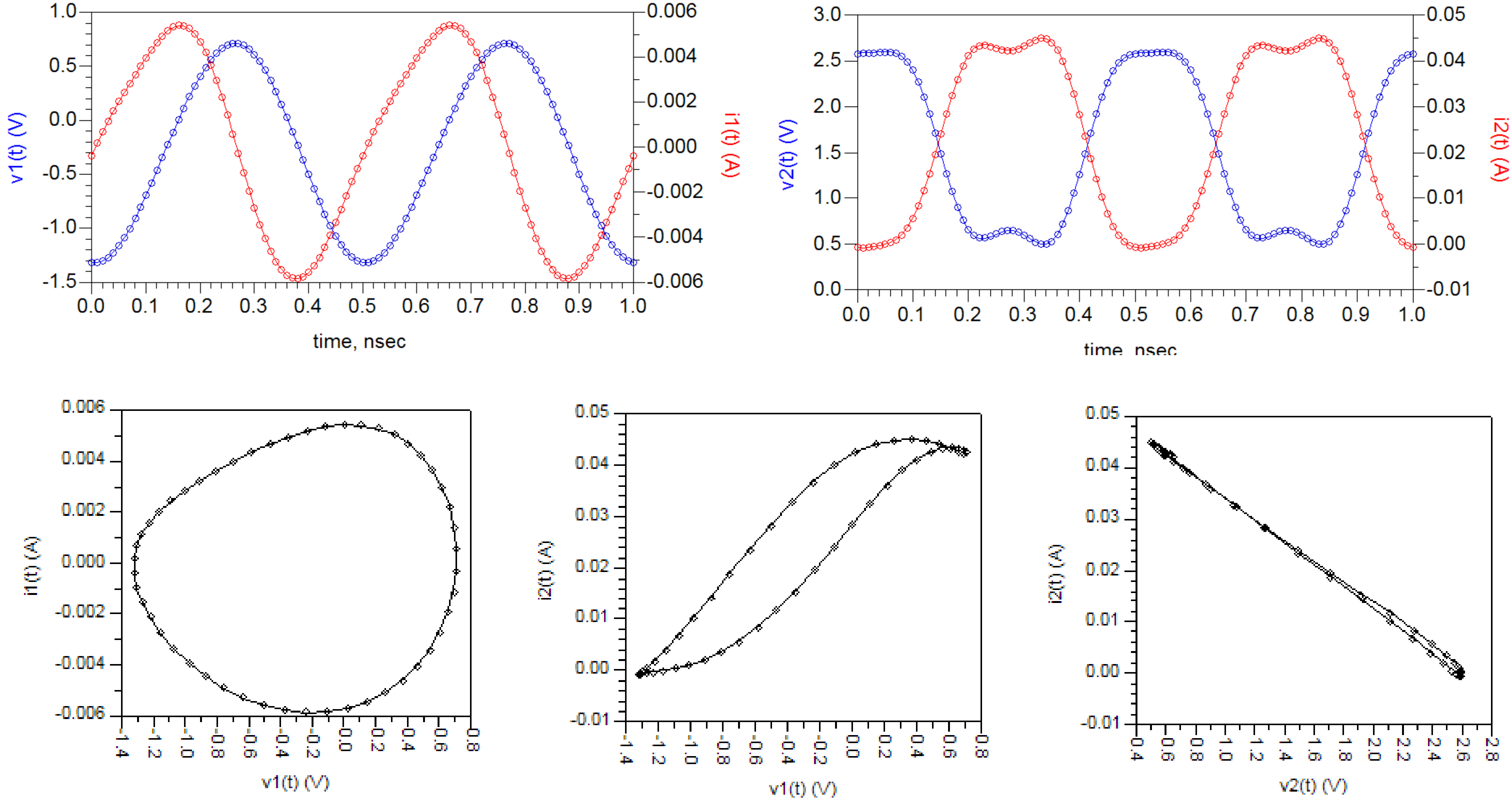
circles – measurements
solid lines - simulations



Model Verification in ADS – Time Domain

Frequency = 2 GHz, VDC1= -0.3 V, VDC2= +1.5 V, Pa1 = +4.5 dBm

circles – measurements
solid lines - simulations



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Conclusion

- S-functions are a natural extension to S-parameters
- S-functions aren't much more complex than S-parameters
- S-function extraction is supported on R&S network analysers
- S-function extraction can be offered for other sampler-, mixer- and scope-based Large-Signal Analysers on customer demand

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