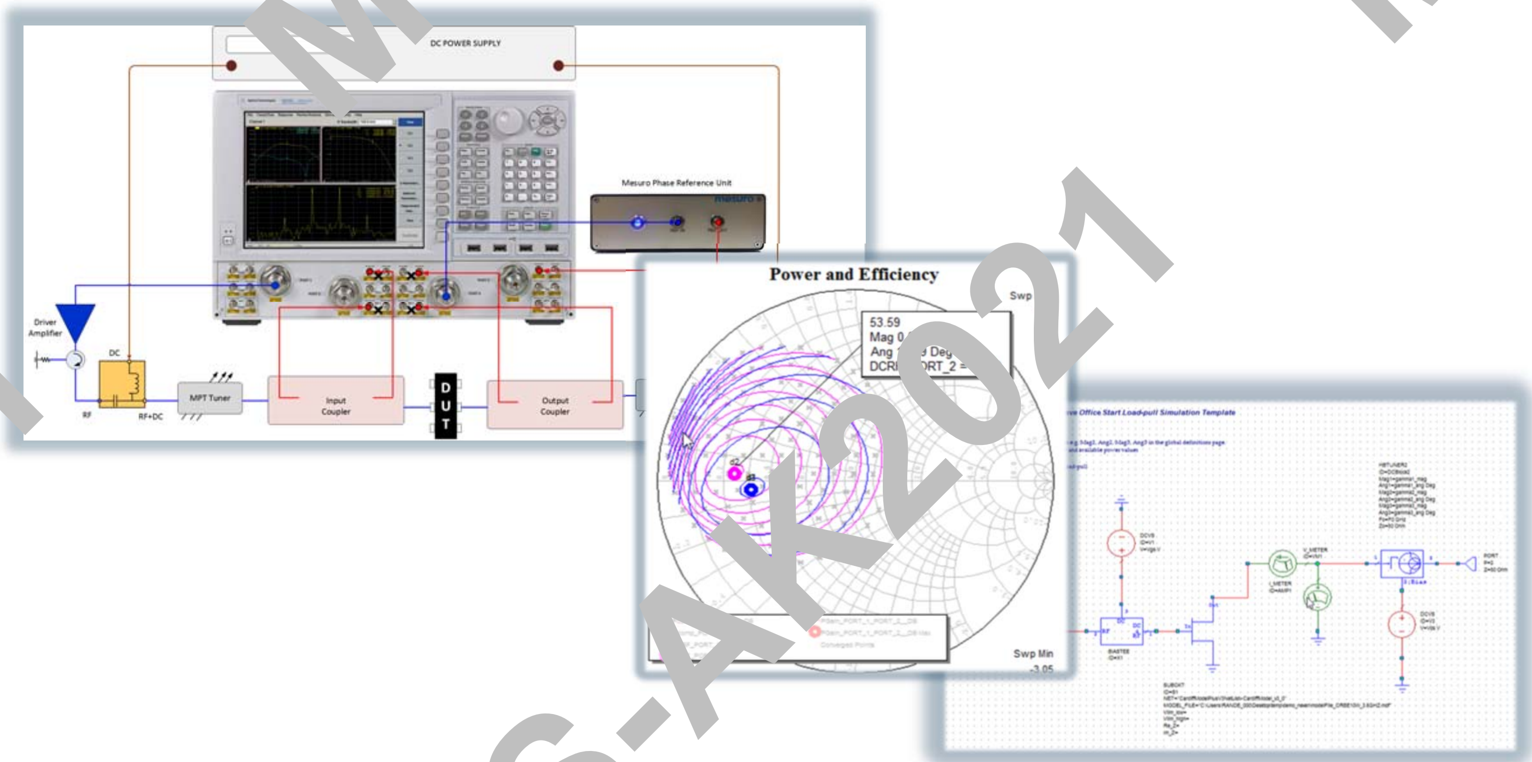
From Wave-based (Vector) Load-pull to Non-linear Behavioural Models



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Outline

- Wave-based Load-pull measurement overview
- CM+ Behavioural model generation
  - Theory of model extraction
  - Measurement strategy
  - Model extraction procedure
- Application – Usage in CAD
- Does Source-pull really affect device performance?
- CM+ Model Interpolation and Extrapolation (Frequency and Bias)
- Conclusions

Wave-based (Vector) Load-pull measurement overview

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Wave-based load-pull measurement: Introduction

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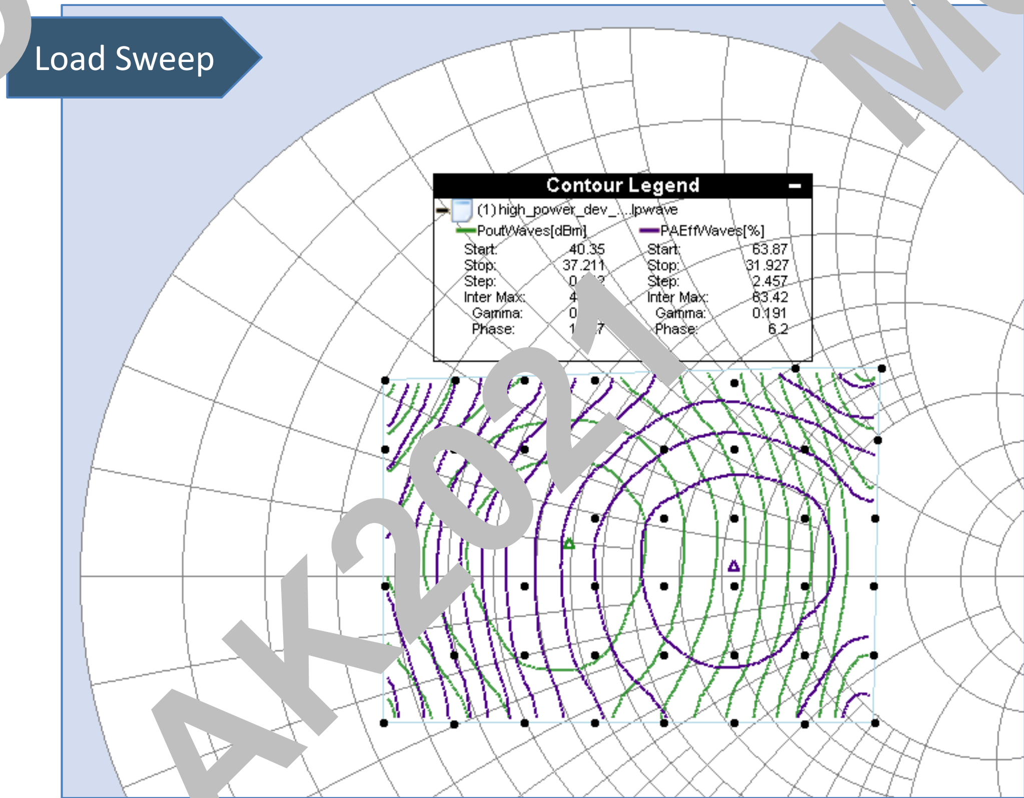
- Load-pull is the measurement of key non-linear parameters indexed as a function of load-impedance
  - Input Power
  - Output power and Gain
  - Drain efficiency and Power added efficiency
- Impedance control is provided by a passive tuner or active tuner.
- Traditionally carried out using a scalar bench e.g. using power sensors and calibrated passive tuners.



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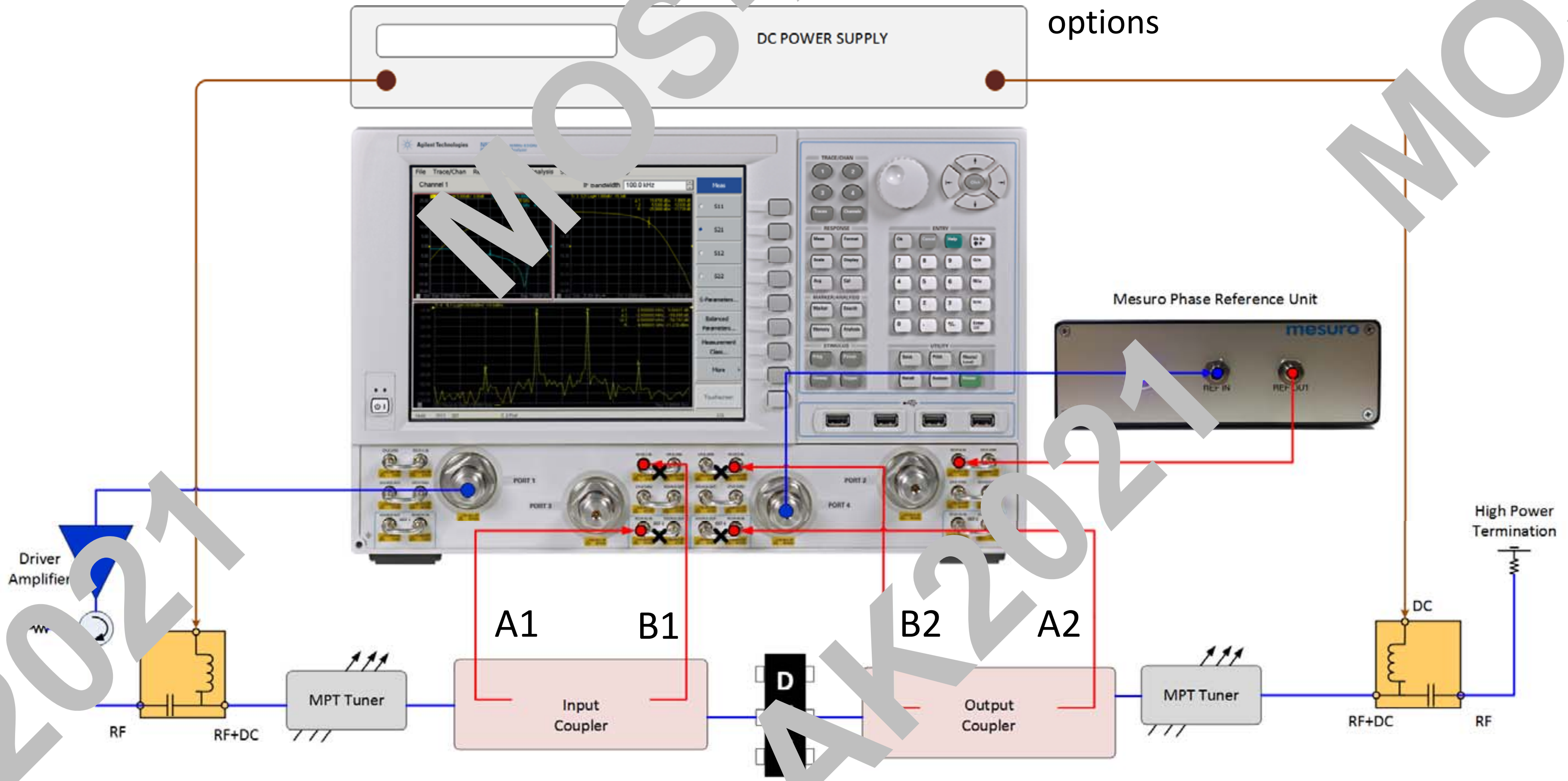
Wave-based (Vector) load-pull measurement Hardware Setup

VNA Requirements:

- Standard 4-Port VNA (PNA-X or PNA)
- NO requirement for any non-linear options



Measure Amplitude and Phase of A1,B1,A2 and B2@F0,2F0,3F0

Wave-based load-pull measurement: Capabilities

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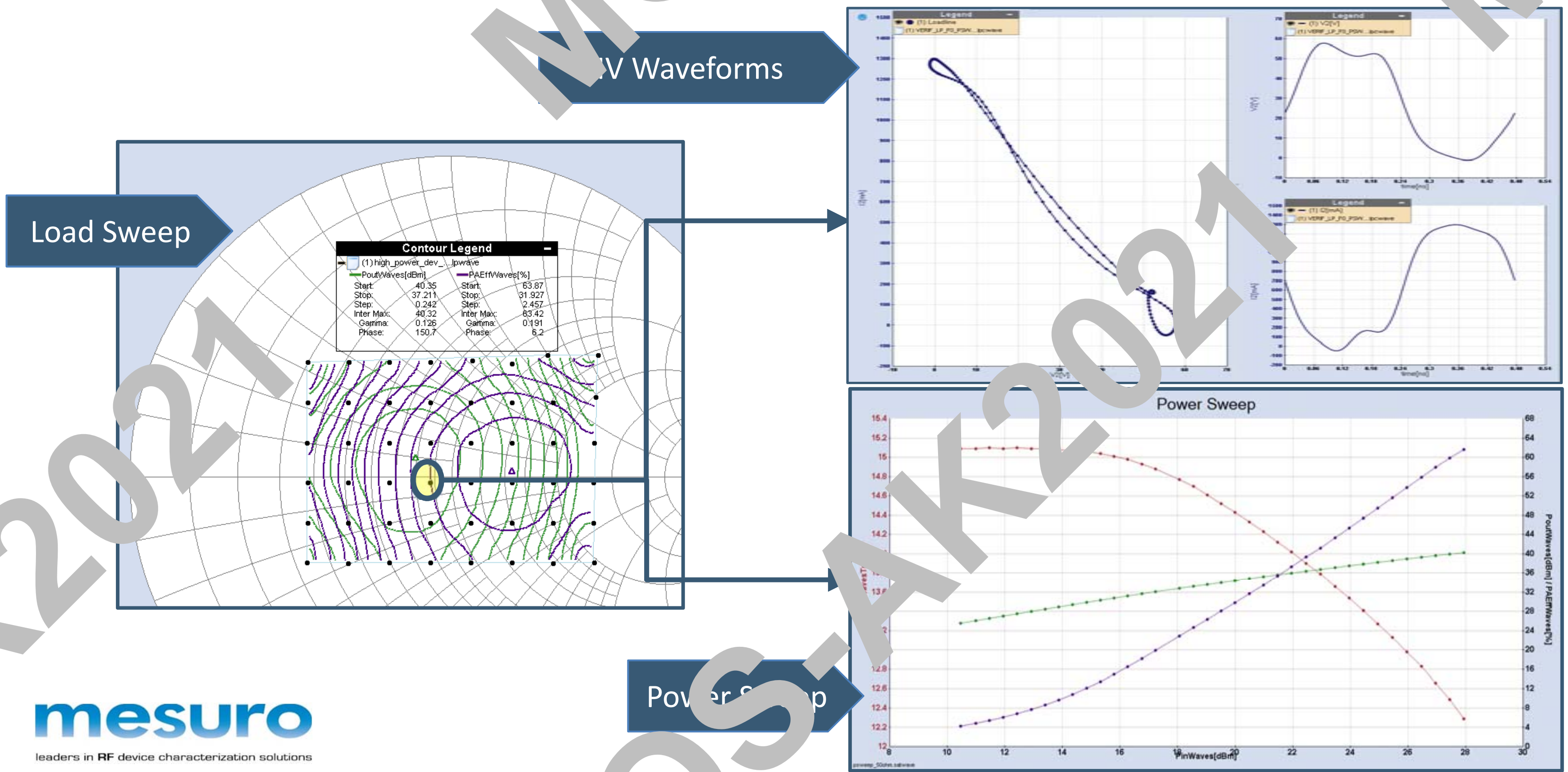
- Load-pull data can be captured by measurement of traveling waves with a calibrated network analyser e.g. a_1, b_1, a_2, b_2 as well as dc terms v_1, v_2, i_1, i_2 allow us to compute <u>additional</u> parameters:
  - Input Gamma of the device under test
  - Accurate measure of load-impedance for the fundamental and harmonic frequencies at the input and output ports
  - Accurate time-domain waveforms (phase reference required).



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Behavioural Model Generation

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Solve Puzzles for RF design engineers

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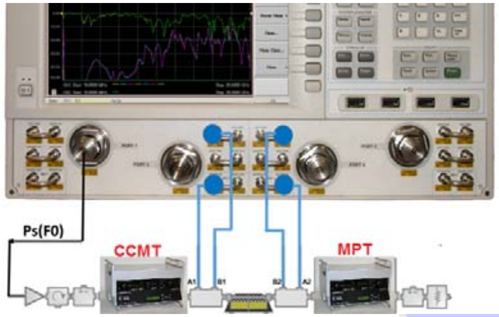
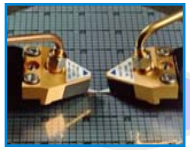
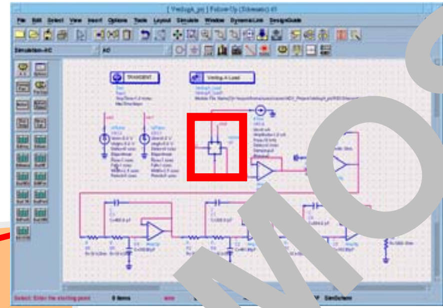




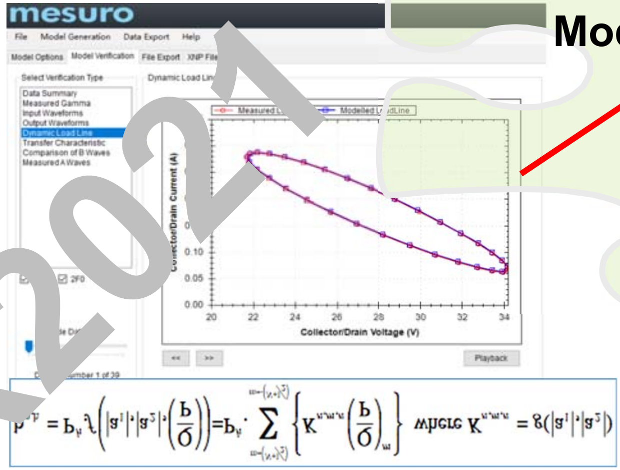
Nonlinear
Measurements

Nonlinear
Simulation & Design



Nonlinear
Modeling

Customer
Applications



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Behavioural Model Generation

Brief theory of Cardiff Model +

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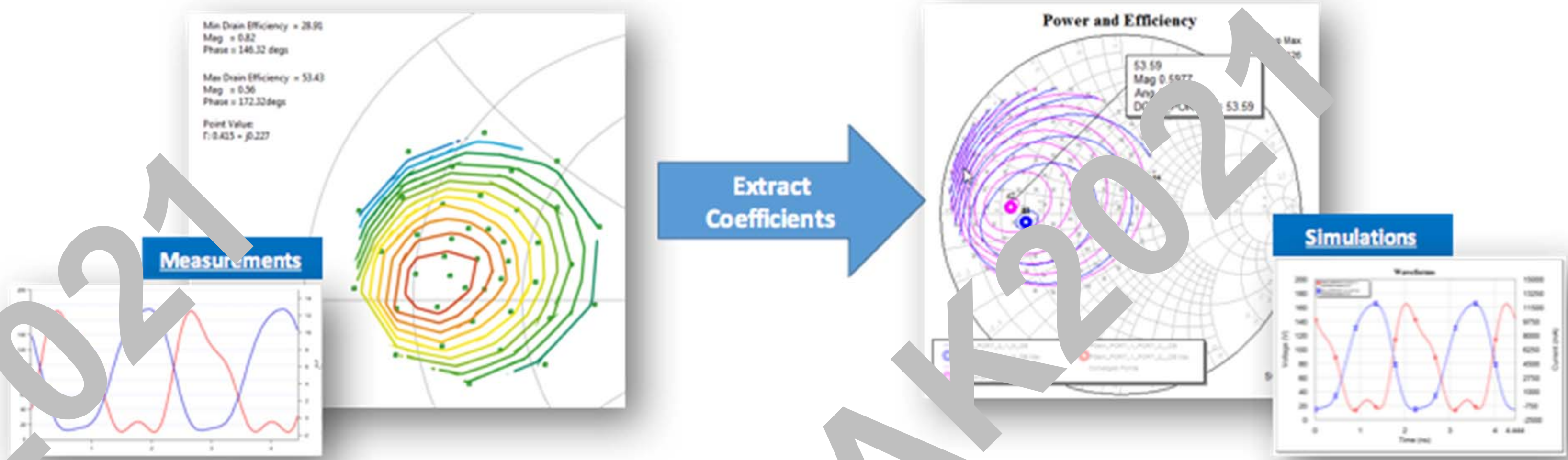
- The Cardiff Model+ is a behavioural modelling strategy, based on a polynomial fit of the load-pull measurement data.
- It is generalized to an Nth odd order in terms of the relative phase component Q/P.

$$b_{n,h} = P^h f\left(|a_1|,|a_2|,\left(\frac{Q}{P}\right)\right) = P^h \cdot \sum_{m=-(N+1)/2}^{(N+1)/2} \left\{K_{n,m,n}\left(\frac{Q}{P}\right)^m\right\} \quad \text{where } K_{n,m,n} = g(|a_1|,|a_2|)$$



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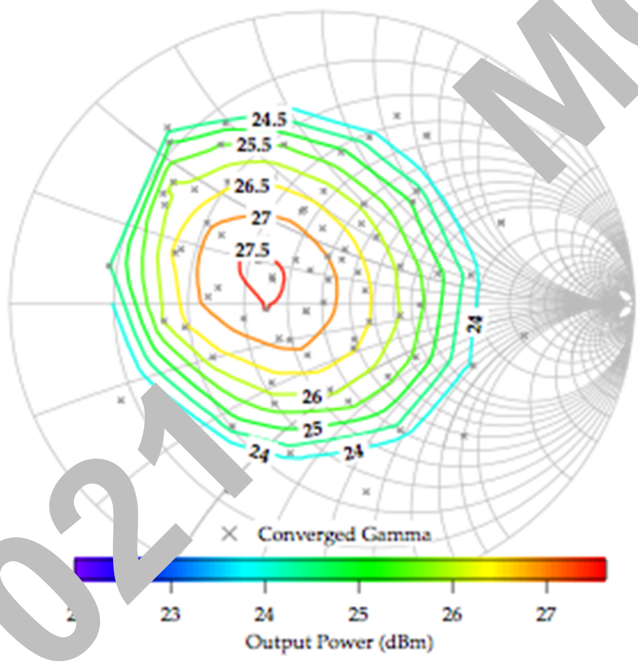
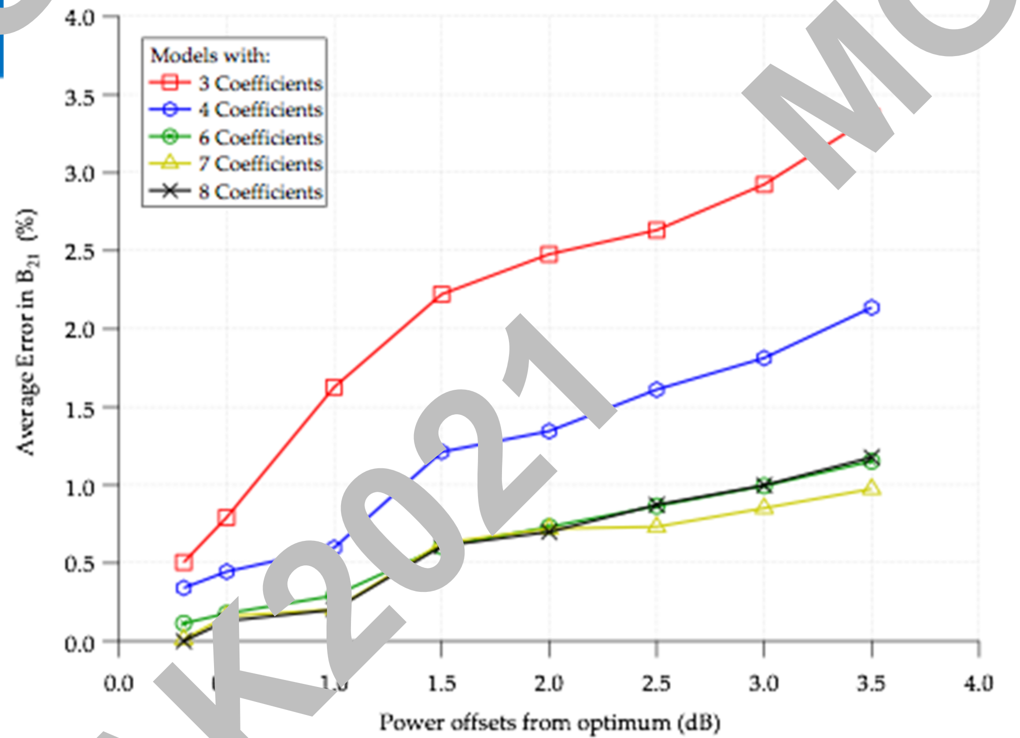
Behavioural Model Generation

Brief theory of Cardiff Model +

How many coefficients do we need to model this load-pull grid accurately?





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Harmonic Behavioural Model

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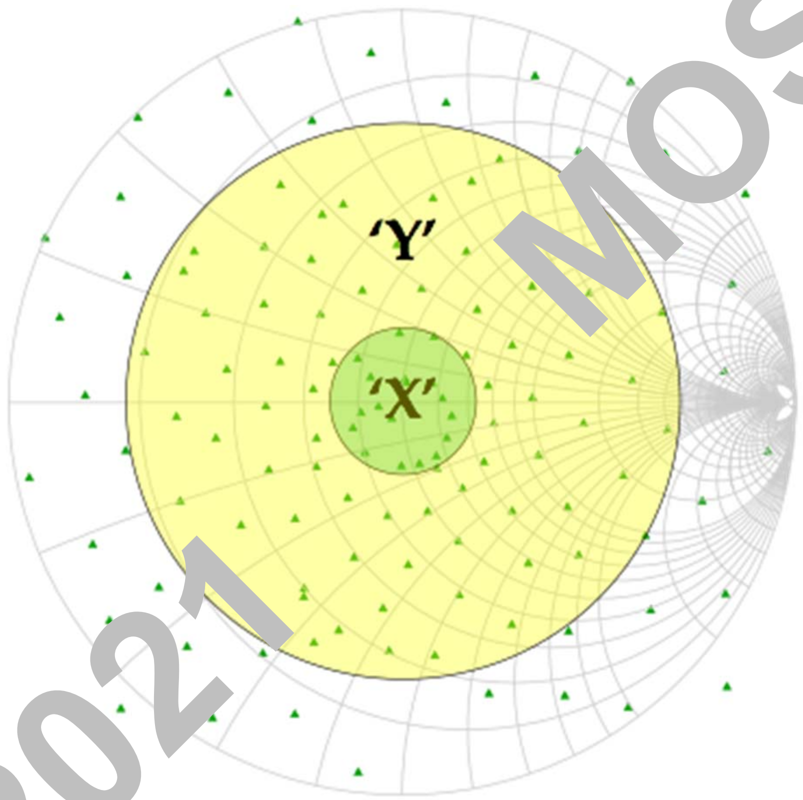

In order to test the 2F0 model extrapolation behaviour, 2nd harmonic coefficients were extracted from measurement data contained within two subsets:

For 2F0 impedances with $|\Gamma_{22}|$ <= 0.2 – [Model 'X']
For 2F0 impedances with $|\Gamma_{22}|$ <= 0.7 – [Model 'Y']

These two conditions are shown on the right. Each model was then required to predict the measured behaviour of the device in impedances spread all over the smith chart including points at the edge of the smith chart i.e. $|\Gamma_{22}|$ <= 1.

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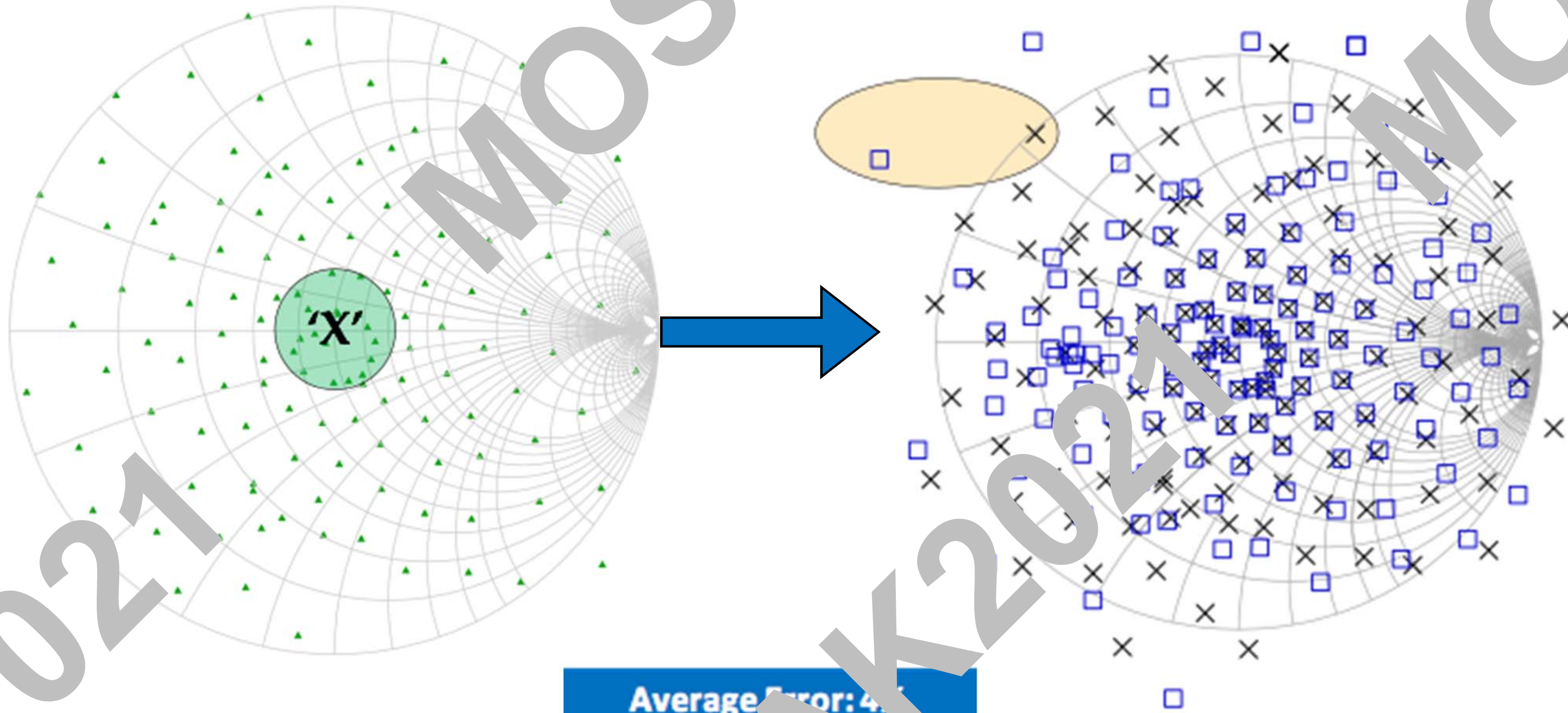
Harmonic Behavioural Model

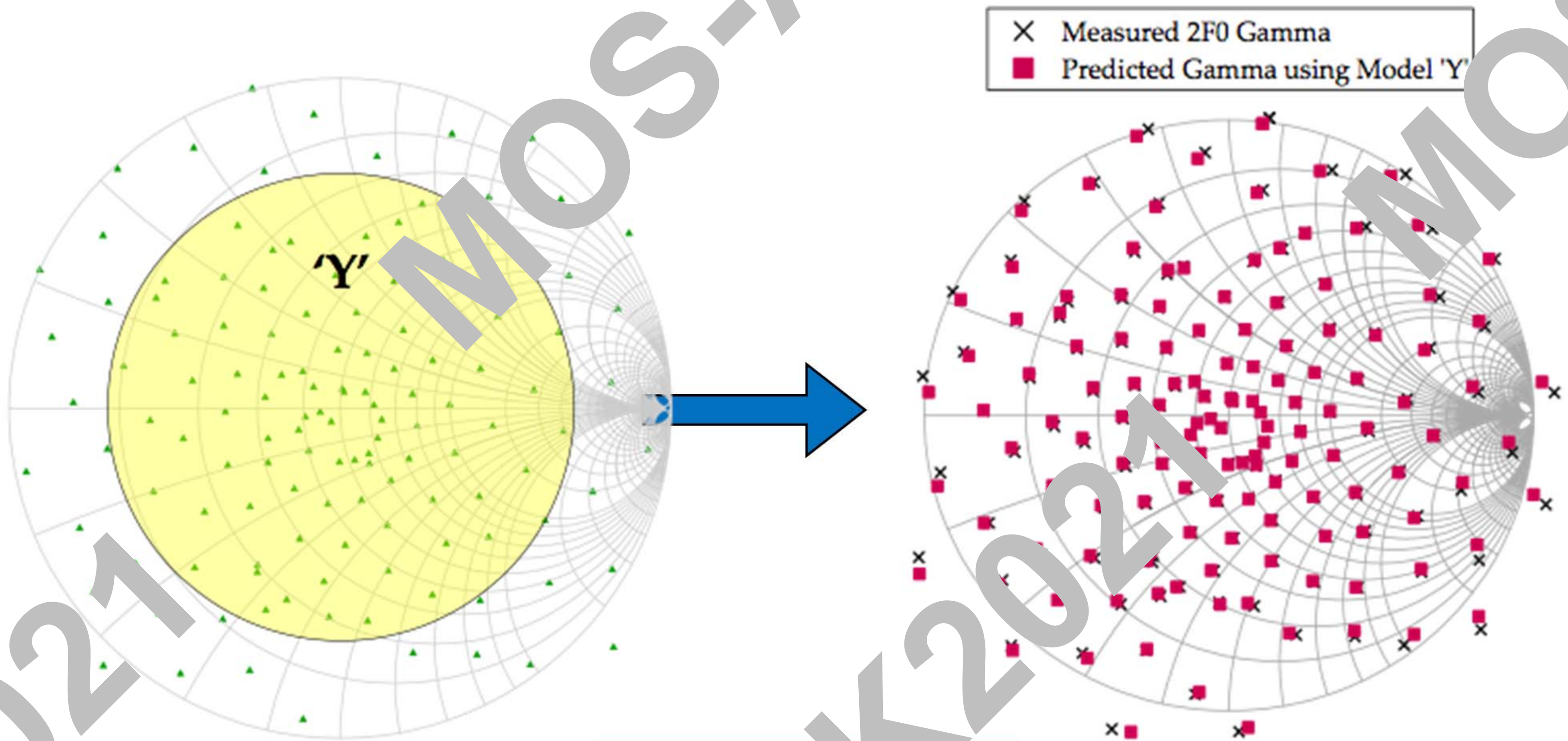
Harmonic tuning limited 0.2



Average Error: 4[illegible]
Worst case error: [illegible]8%

Harmonic Behavioural Model

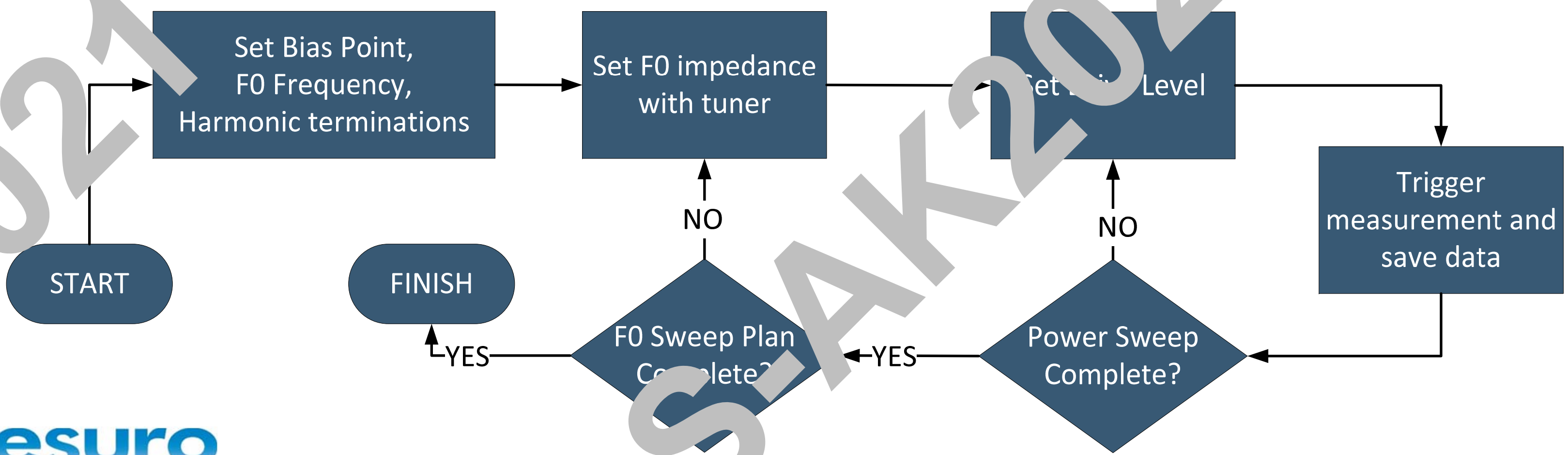
Harmonic tuning limited 0.7



Average Error: 1.1%
Worst case error: 4.6%

Behavioural Model Generation: Measurement Strategy (F0 Only)

- For fundamental-only (F0) model generation, the load-F0 impedance is swept through a pre-defined sweep plan; centred around the optimum for power and efficiency performance.
- The harmonic frequencies e.g. 2F0 and 3F0 are kept at a constant impedance.
- Measurements of a_1, b_1, a_2, b_2 at all calibrated frequencies and dc values v_{1dc}, v_{2dc}, i_{1dc}, i_{2dc} are captured and stored in a file indexed by fundamental load impedance and input drive.
- We usually recommend carrying out an input drive power sweep with a ~20dB dynamic range.
- Fundamental source-pull is not necessary however it can aid in minimising the input return loss and thus provide a facility for driving the DUT into compression.

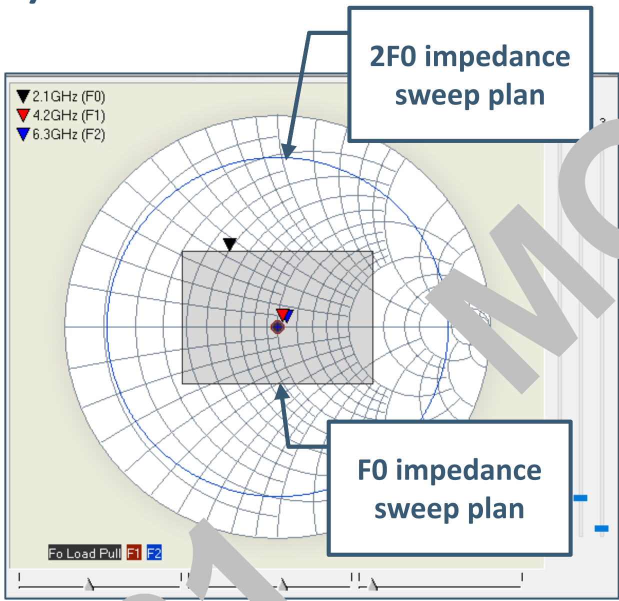


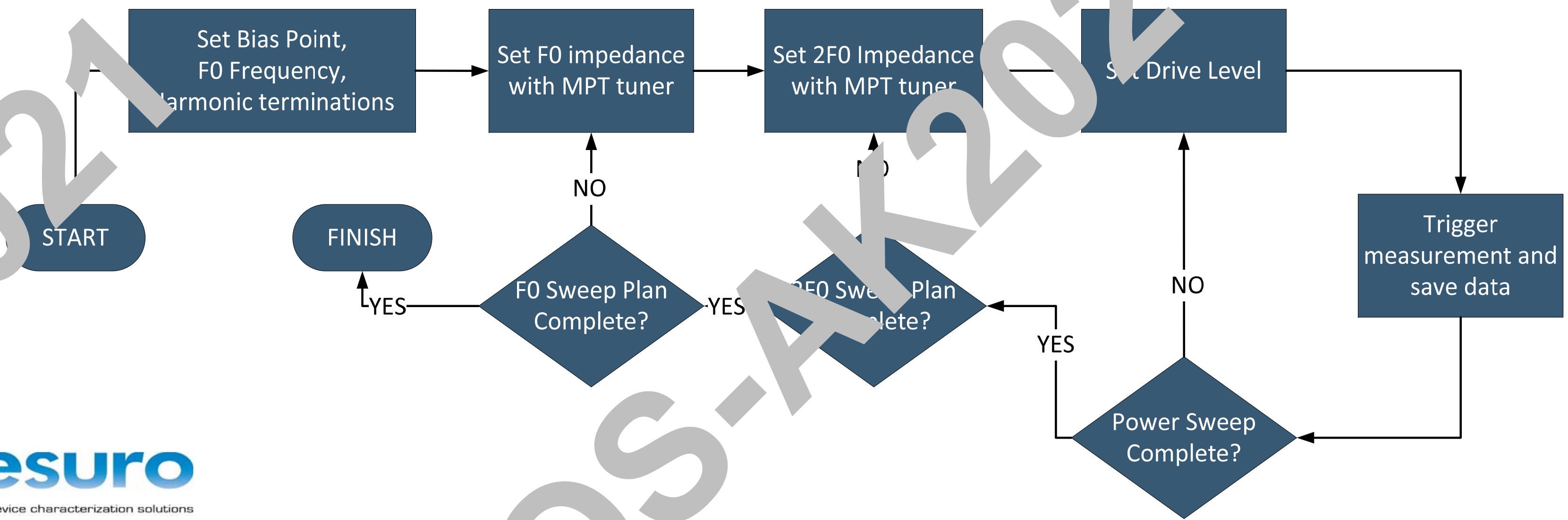
Behavioural Model Generation: Measurement Strategy (harmonics)

- For harmonic model generation, the load-F0 impedance is swept through a pre-defined sweep plan. This is "nested" with another sweep plan at each harmonic required within the model.

- MPT Tuner can be used to simultaneously change the fundamental and harmonic impedance for the above plan.

- Gamma@2F0 is around 0.6-0.8 with 6 to 12 points.





Behavioural Model Generation: Importing data

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Import Wave-based LP Data

Measurement Data processing…

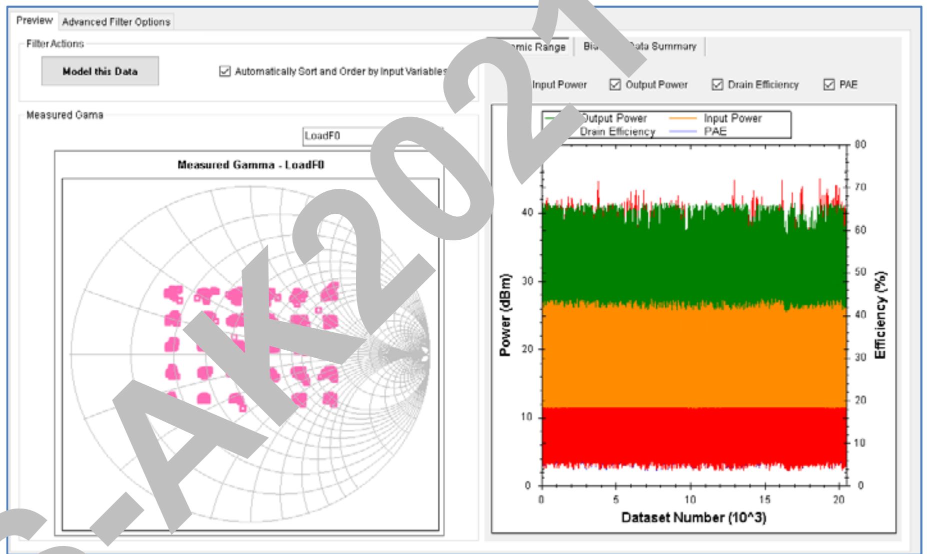
Determine the complexity (w) required to fit a global model for the given load-pull space.

Generate the Model

Model Verification: Immediate feedback of model vs. measurement performance

Export model coefficients as MDF file or XNP File

- The generator requires measured *a* and *b* waveforms for all the harmonics and ports.
- It also requires the measured DC parameters v_{dc} *and* i_{dc}.
- Generator sorts the datasets in sub-sets of input power, frequency and bias.
- Indexing of the data-sets in |ap,h| and Q/P is carried out for each load-pull point.
- User can remove *erroneous data points* before attempting to create a model using the advanced filtering options.



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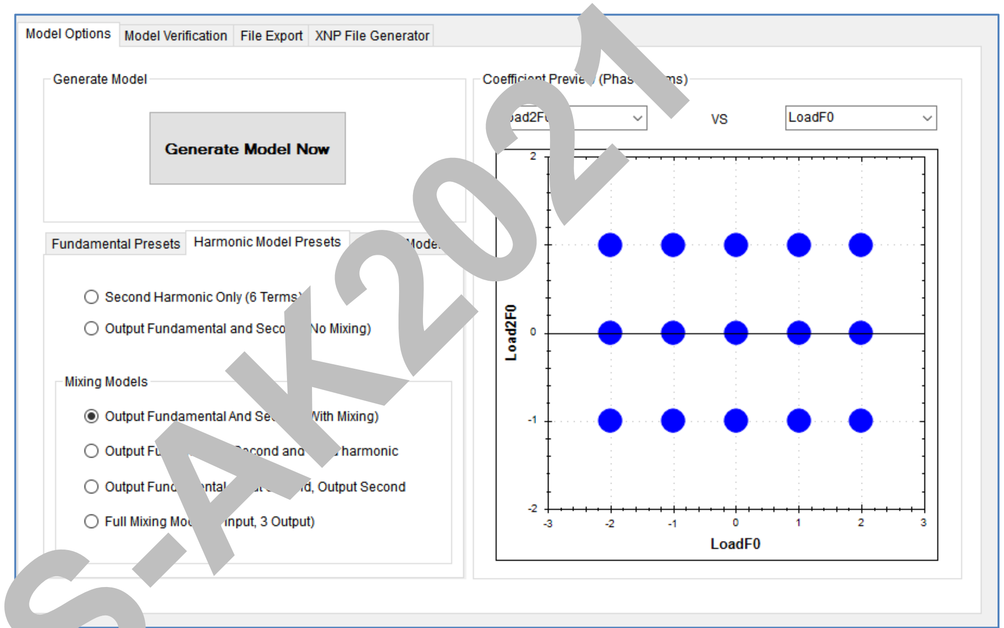
Behavioural Model Generation: Selecting the order

1. Import Wave-based LP Data
2. Measurement Data processing…
3. Determine the complexity (w) required to fit a global model for the given load-pull space.
4. Generate the Model
5. Model Verification: Immediate feedback of model vs. measurement performance
6. Export model coefficients as MDF file or XNP File

- Based on user requirements, the generated model can be conditioned to a coefficient pattern e.g.
  - Fundamental Only,
  - Fundamental and Second Harmonic Mixing model, etc.
- Users can also define custom patterns for the behavioural model



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Behavioural Model Generation: Built-in Verification

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Import Wave-based LP Data

↓

Measurement Data processing…

↓

Determine the complexity (w) required to fit a global model for the given load-pull space.

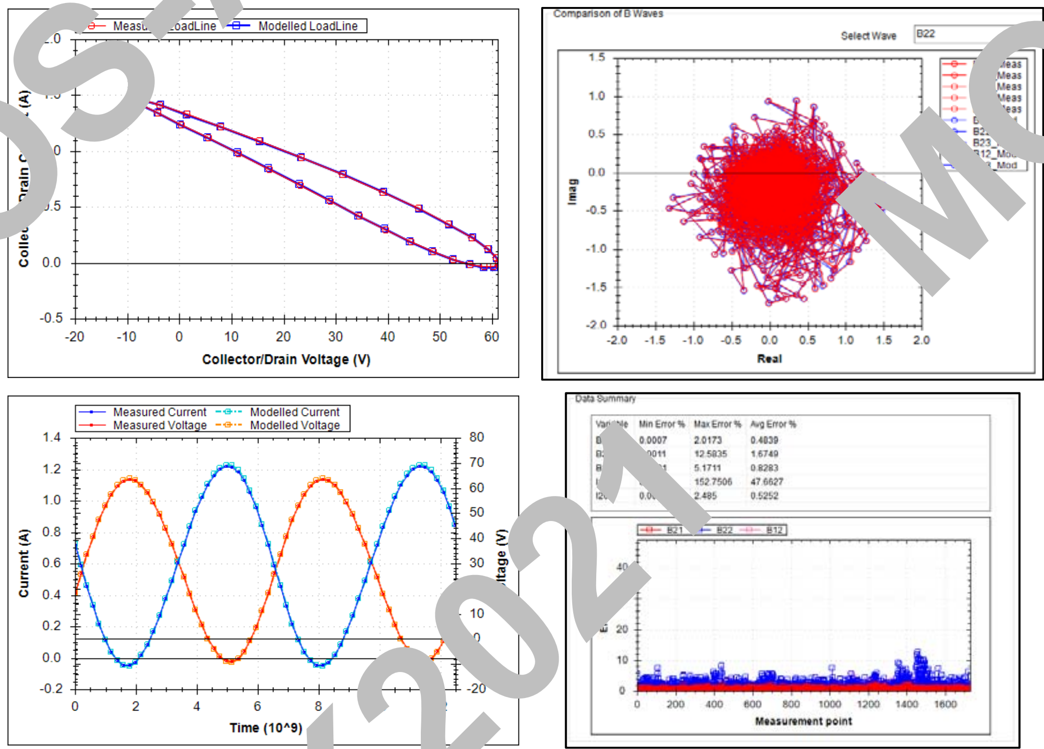
↓

Generate the Model

↓

Model Verification: Immediate feedback of model vs. measurement performance

Export model coefficients as MDF file or XNP File



- Once the model is generated, the coefficients are used to simulate measurement conditions.
- Error bars, time-domain waveforms and other plots are displayed to check the accuracy of the model.

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Behavioural Model Generation: Model files

Import Wave-based LP Data

Measurement Data processing…

Determine the complexity (w) required to fit a global model for the given load-pull space.

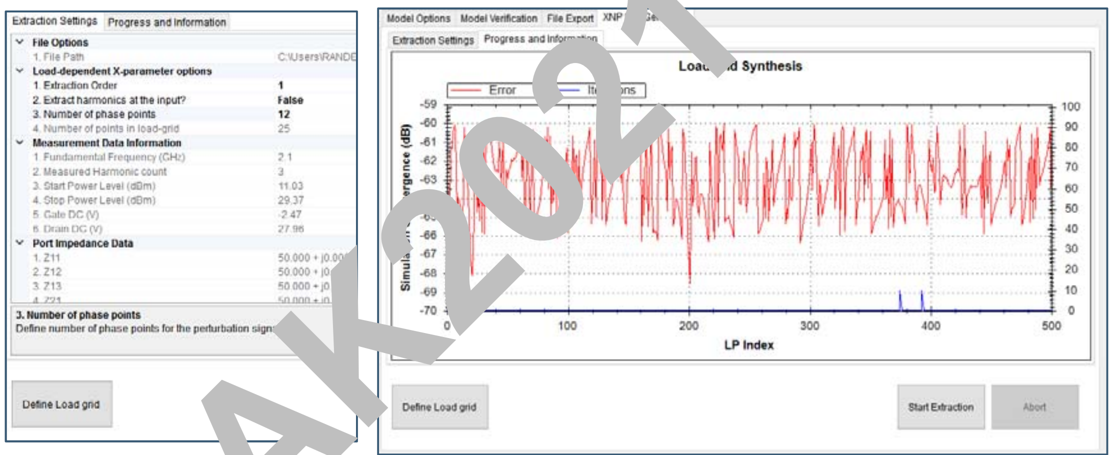
Generate the Model

Model Verification: Immediate feedback of model vs. measurement performance

Export model coefficients as MDF file or XNP File

- CM+ Model files are in MDF format with a very small file size (<100kiB) compatible with
  - Keysight ADS v2009-2015
  - AWR Microwave office v9.0-12.0

- CM+ Models can also be saved as *.xnp files with the built-in XNP Model file generator



Performance of Model in CAD

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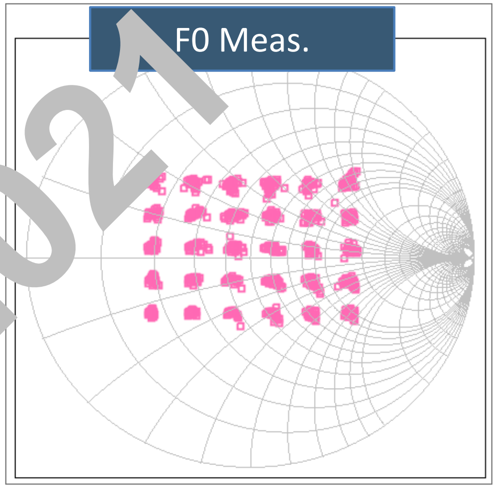
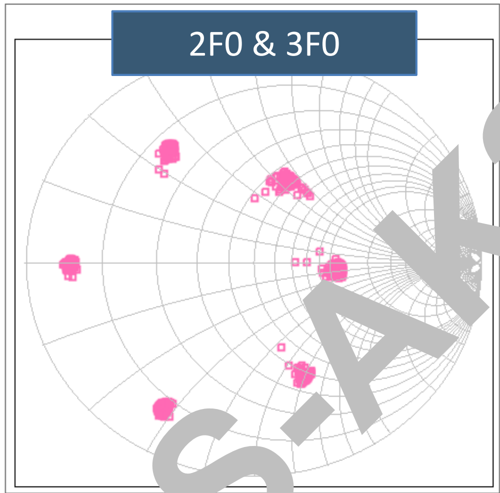
Performance in CAD:
Model extraction parameters

- Model extraction was carried out for a 10W CREE Device (CGH40010).
- The F0, 2F0 and 3F0 impedances were used in a nested pattern.
- Bias point was chosen to provide i_d = 390mA with V_{ds} = 28V
- Fundamental frequency 2.1GHz
- PNA-X was used with a Mesuro Phase reference unit
- RF Signal was in CW Mode.

<u>Optimised Tuning Mode with MPT</u>
20 x Power Levels
30 x F0 L.P. Points
6 x 2F0 L.P. Points
6 x 3F0 L.P. Points
= 21,600

Measurement time ~ 2 Hours

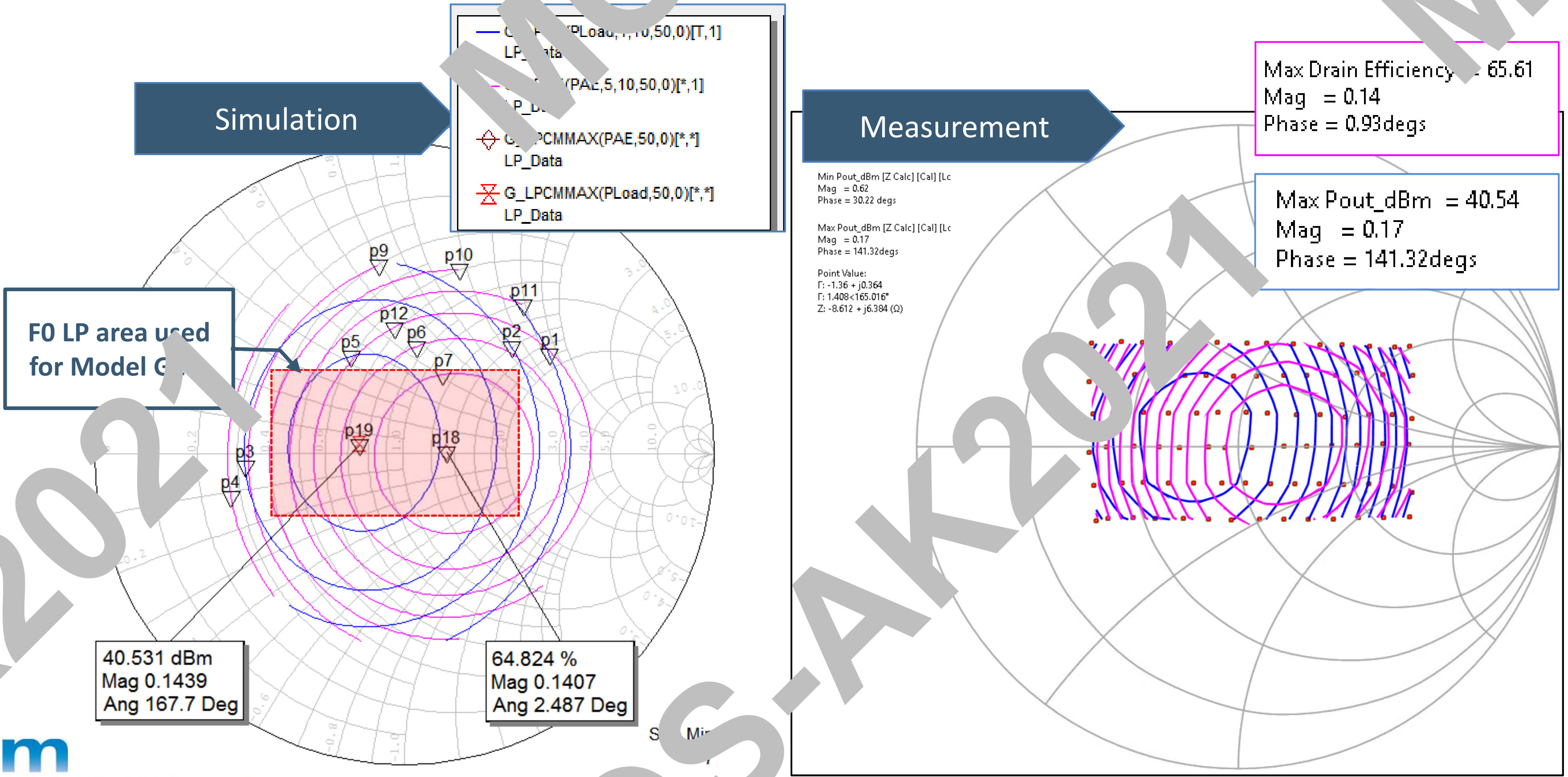




Variable	Min	Max
Fundamental Frequency	2.1	-
Input Power (dBm)	11.401	28.915
Drain Voltage (V)	27.978	28.001
Gate Voltage (V)	-2.354	-2.35
Output Power (dBm)	25.546	41.537
Drain Efficiency (%)	3.599	72.092
PAE (%)	3.567	71.26

Performance in CAD: Fundamental load-pull performance

- Measured vs. Modelled power contours
  - Source F0 and Harmonics 2F0 and 3F0 locked to 50 ohms
  - Load F0 swept and Harmonics 2F0 and 3F0 locked to 50 ohms
  - Fixed available input power = 2?.43dBm. [3dB compression pt. at optimum]



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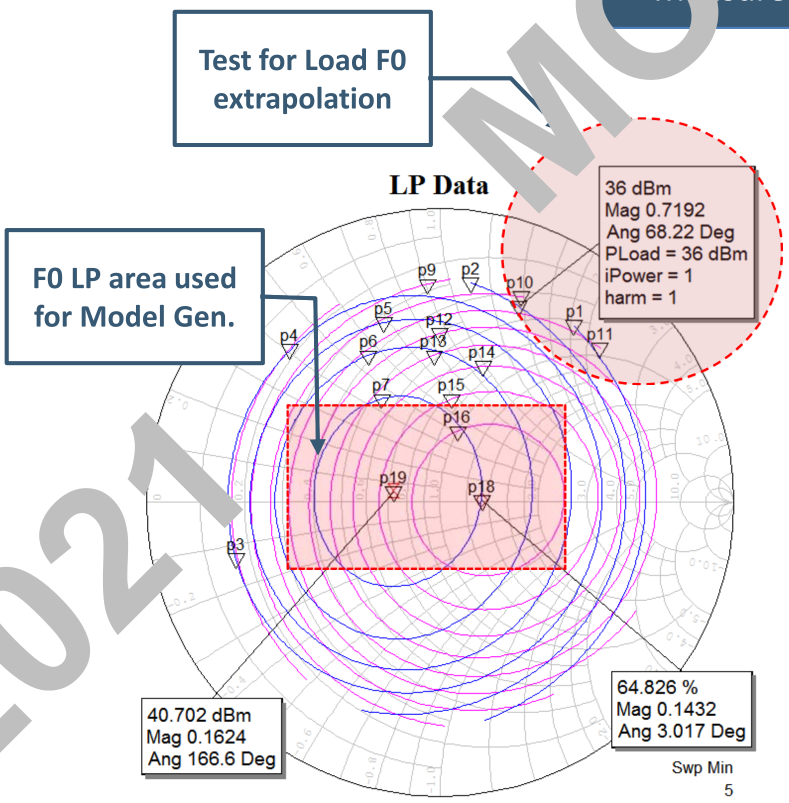
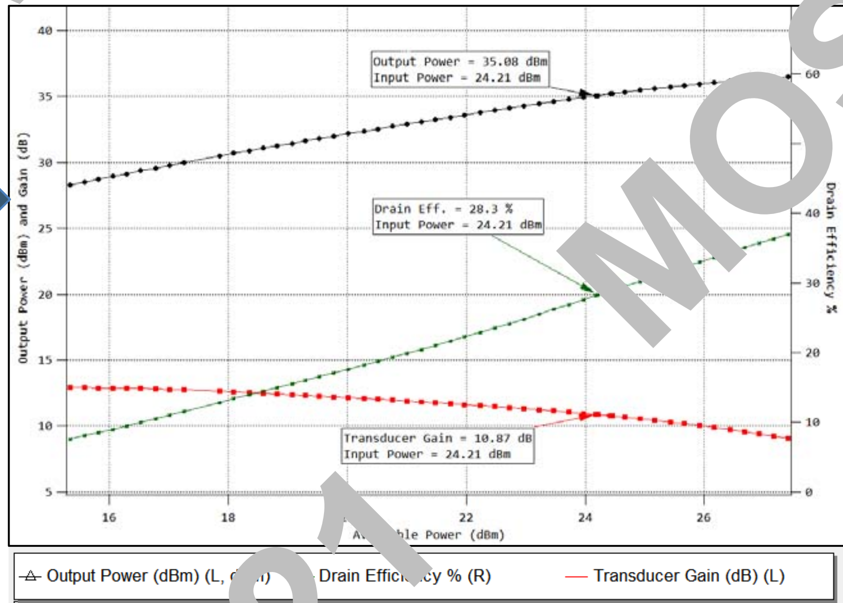
Performance in CAD: Fundamental load extrapolation

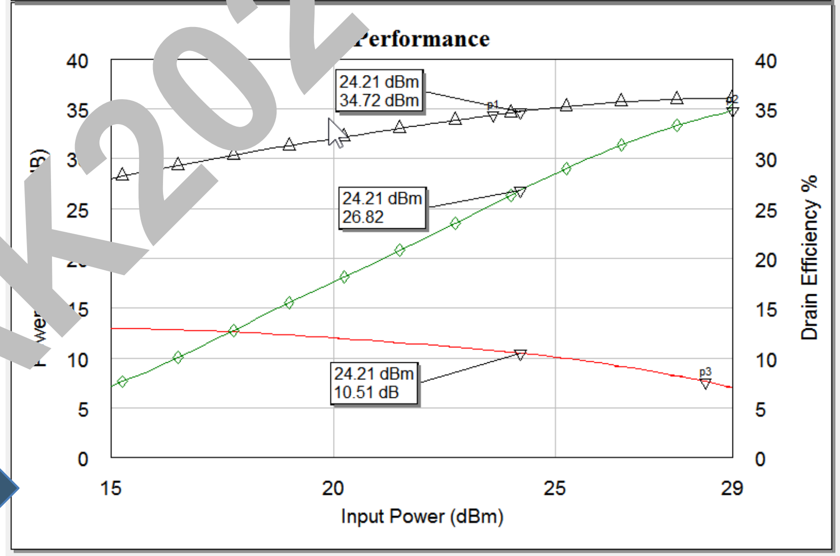
- Measured power sweep in an impedance where the model was not captured



Measurement



Simulation



Performance in CAD: Fundamental Source-pull

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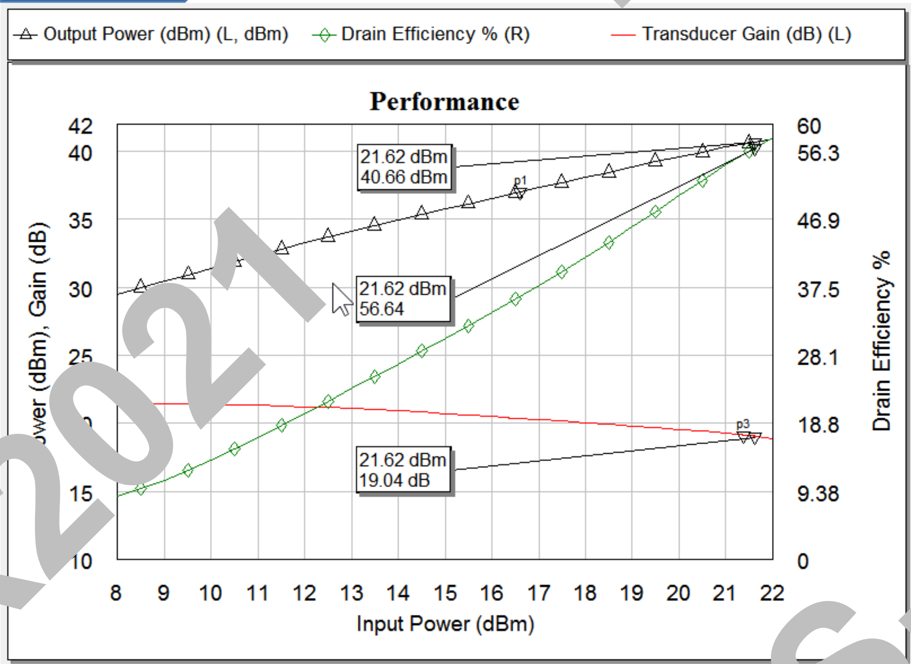
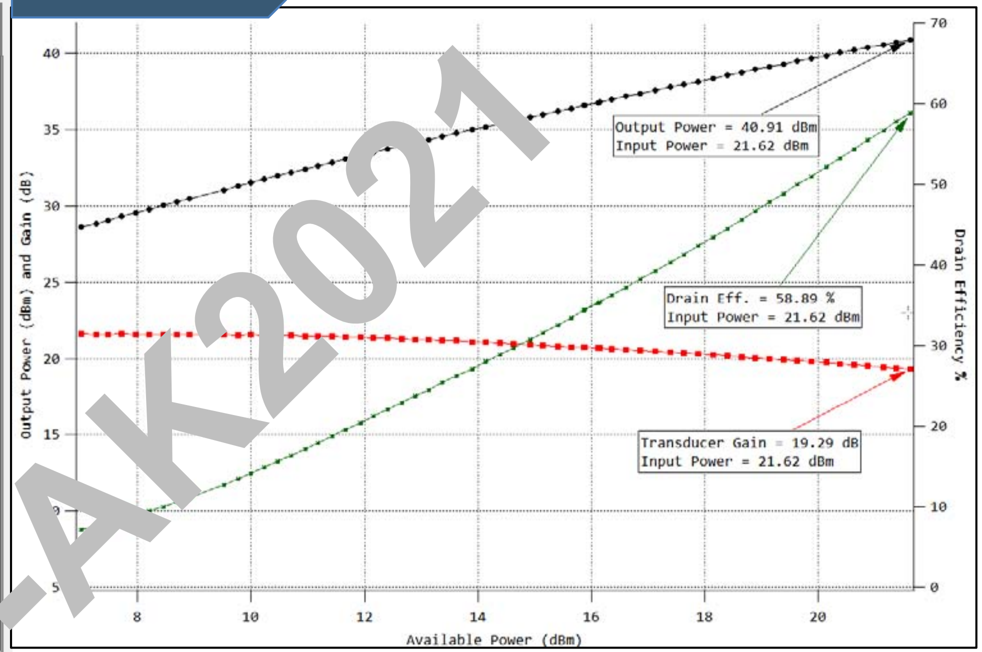
- Measured power sweep in different Source F0 Impedance settings.
  - Model was generated at $|\Gamma_{source}| = 0$ and $\angle\Gamma_{source} = 0$
  - This test was done with $|\Gamma_{source}| = 0.85$ and $\angle\Gamma_{source} = -168$

Simulation



Measurement



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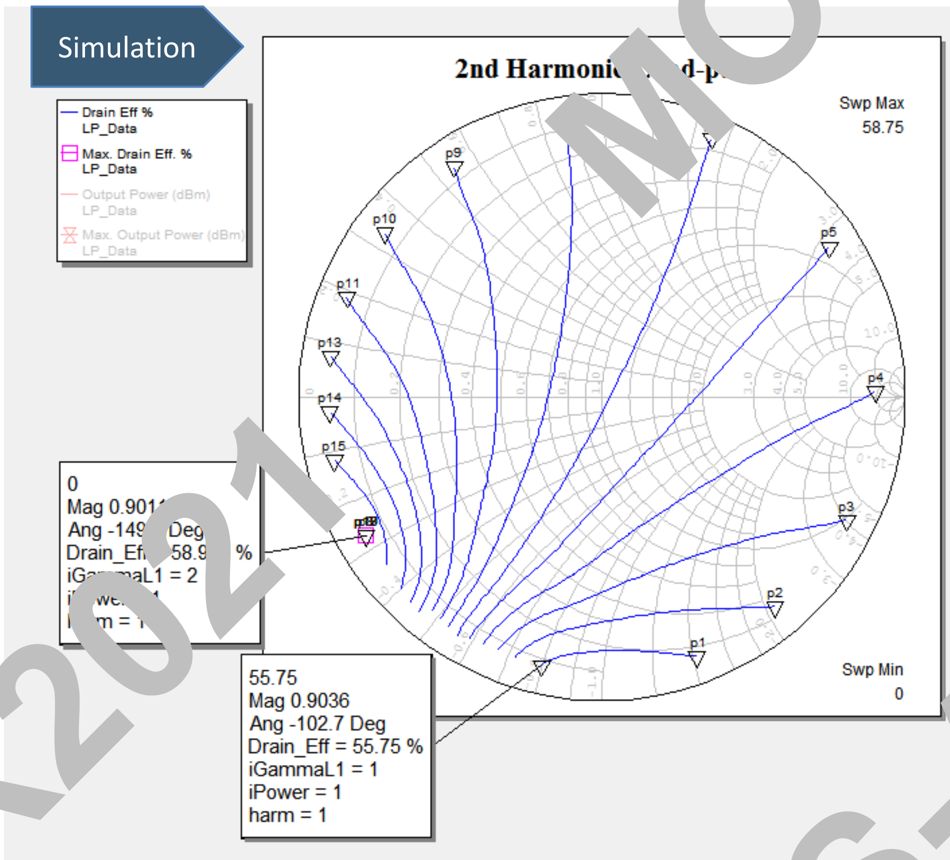
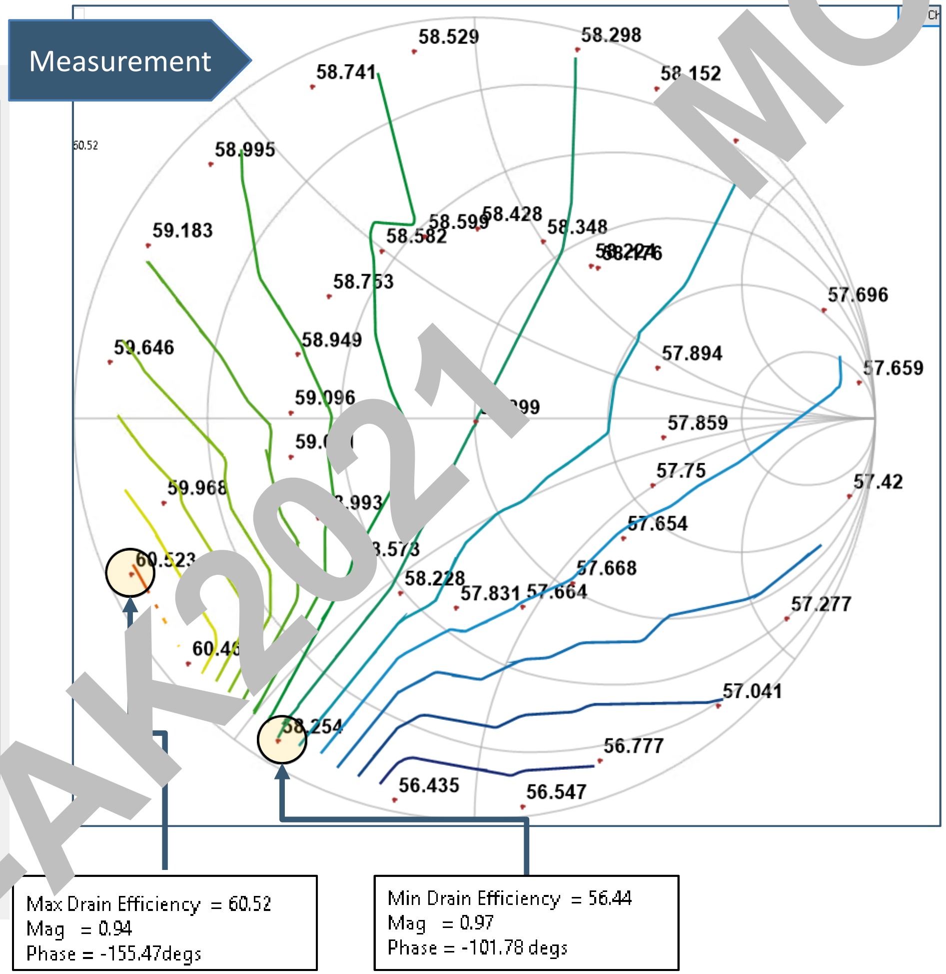
Performance in CAD:
Second Harmonic Load-pull (efficiency)

- The 2[nd] Harmonic Load-pull contours shown were acquired using an active load-pull setup; with the F0 gamma at $|\Gamma_{Load}|$=0.21 and $\angle\Gamma_{Load}$=168°





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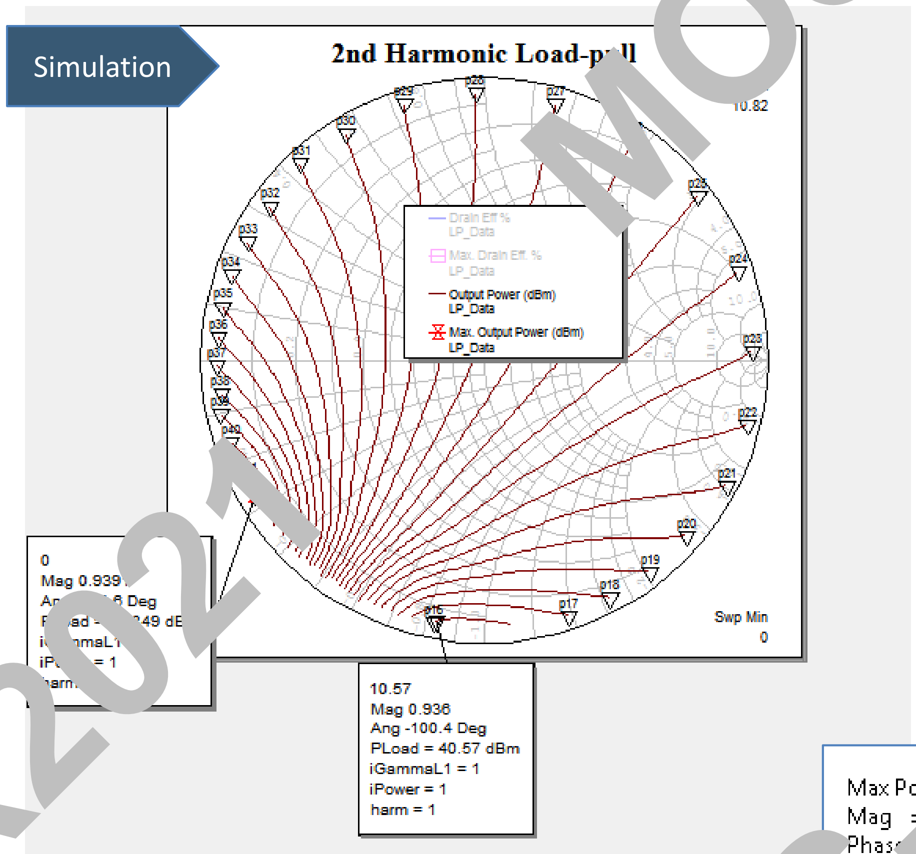
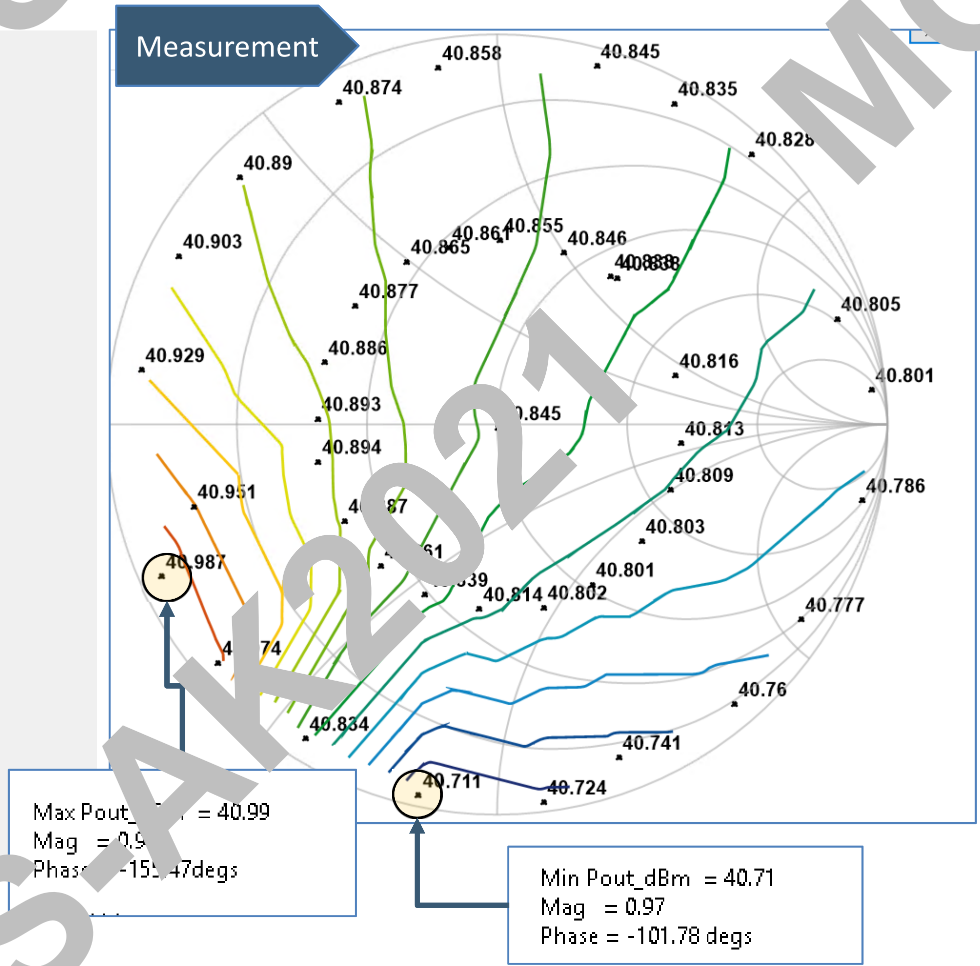
Performance in CAD:
Second Harmonic Load-pull (power)

- The 2nd Harmonic Load-pull contours shown were acquired using an active load-pull setup; with the F0 gamma at $|\Gamma_{Load}|=0.21$ and $\angle\Gamma_{Load}=168°$





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Performance in CAD:
Time Domain Waveforms – Load Lines

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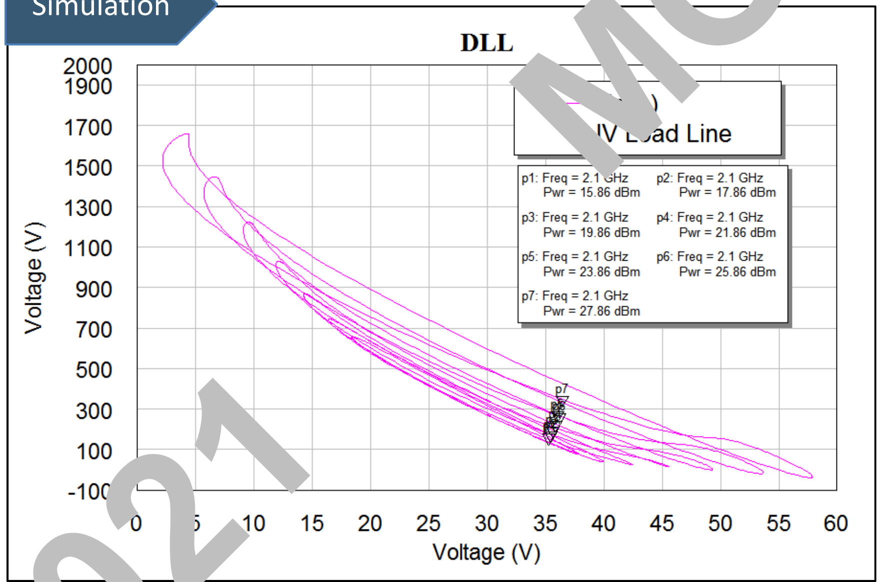
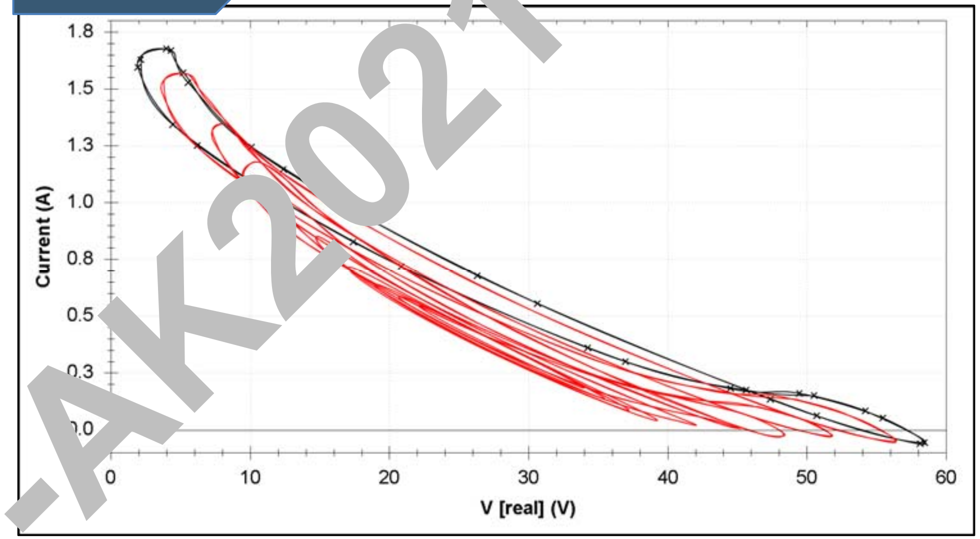
- The 2F0 gamma target was set to $|\Gamma_{Load}|=0.94$ and $\angle\Gamma_{Load}=-150°$
- The F0 gamma target was set to $|\Gamma_{Load}|=0.20$ and $\angle\Gamma_{Load}=168°$
- A power sweep was carried out to 3dB compression point

Simulation



Measurement



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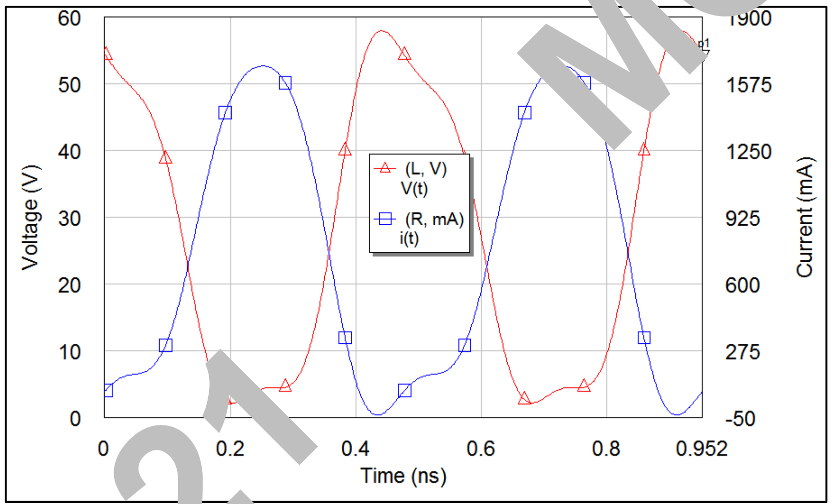
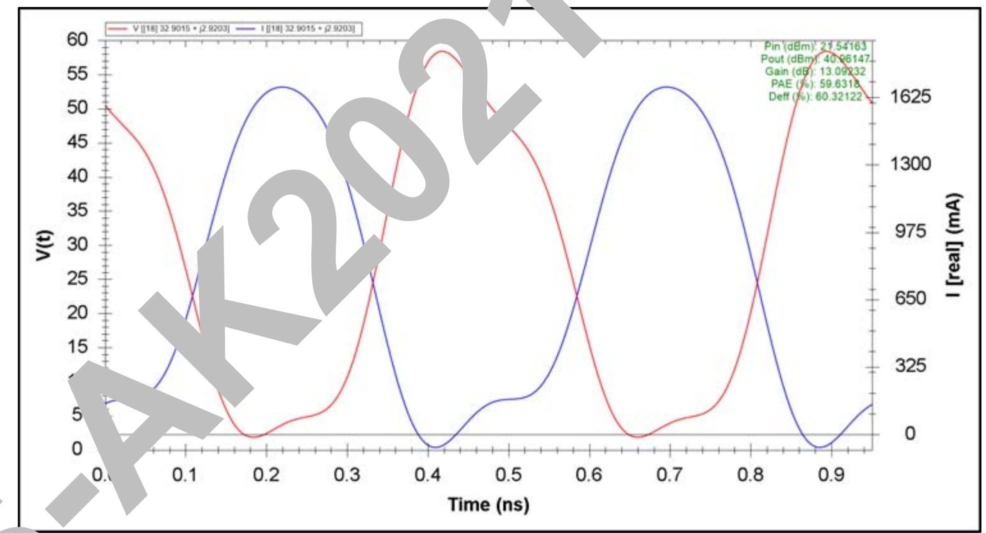
Performance in CAD:
Time Domain Waveforms – IV Waveforms

- The 2F0 gamma target was set to $|\Gamma_{Load}|=0.94$ and $\angle\Gamma_{Load}=-150°$
- The F0 gamma target was set to $|\Gamma_{Load}|=0.20$ and $\angle\Gamma_{Load}=168°$
- A power sweep was carried out to 3dB compression point

Simulation



Measurement



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Conclusions

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- CM+ is a behavioural modelling strategy, based on a polynomial fit of the load-pull measurement data.
- CM+ can support fundamental and harmonic load extrapolation
- Model file size is around a few hundreds kB, faster simulation in CAD
- Built-in model verification
- Easy to upgrade from existing load pull system

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