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# Large-signal PHEMT and HBT modeling for power amplifier applications

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# Agenda

- Introduction
- Phemt modeling issues
- Empirical model vs table-based model; Charge model vs ‘no-charge’ model
- Class-inverse-F operation of power PHEMTs
- Models of III-V-based HBTs
  - Modofied GP model
  - VBIC model
  - Modified VBIC model
  - Thermal coupling model
- Small-signal and large-signal HBT model verification
- HBT modeling application to power amplifier

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# Challenges of modeling for power amplifier designs

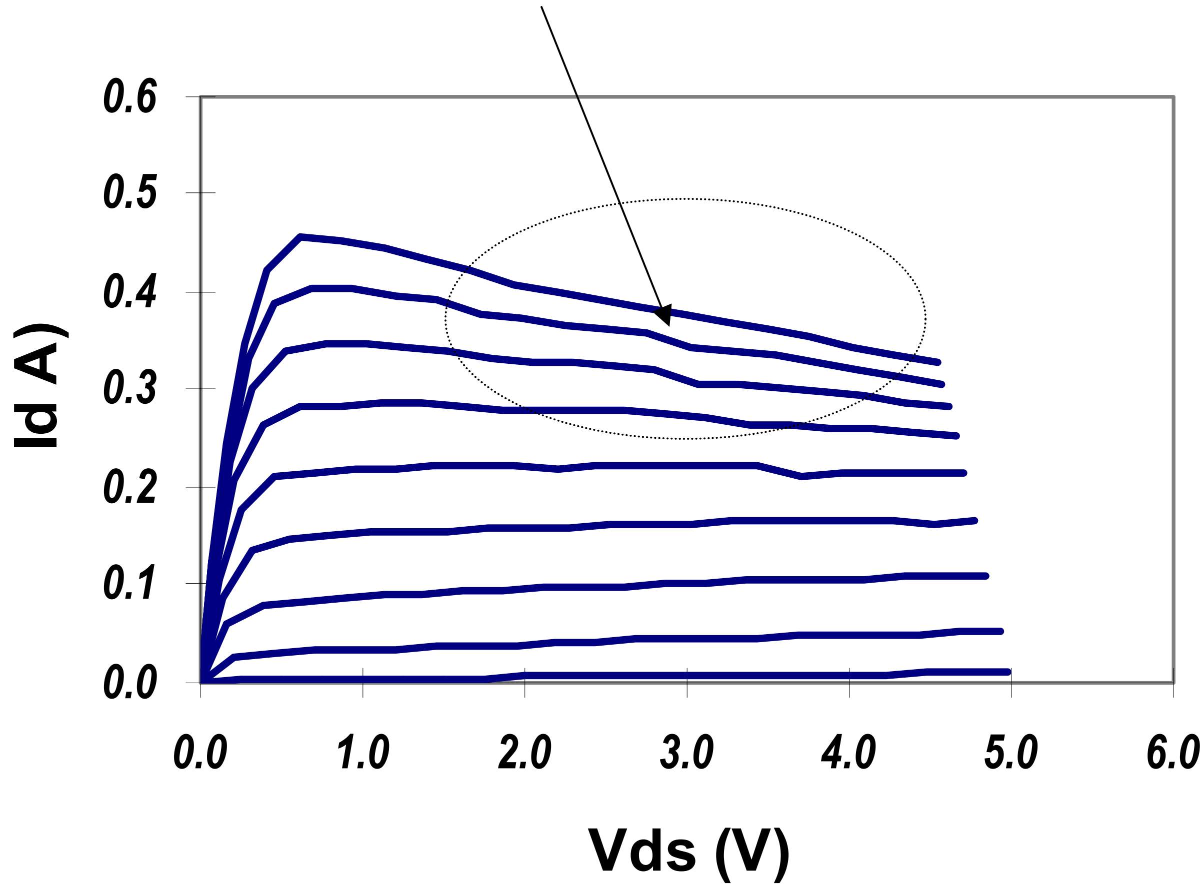
- PHEMT/HBTs feature higher efficiency, high frequency and good linearity and are being widely used in power amplifiers for wireless communications
- Commercial models are difficult to predict consistent small-signal and large-signal power performance including linearity.

The requirements for a good model are:

- Must be capable of reproducing three-terminal dc IV curves over wide range and possible IV collapses
- Must be capable of fitting measured S-parameters over a wide bias range
- Must accurately predict power, efficiency and linearity
- Must be able to predict load-pull behavior
- Must be scaleable to large-size used in power amplifiers
- Good convergence

# PHEMT modeling issue: Self-heating

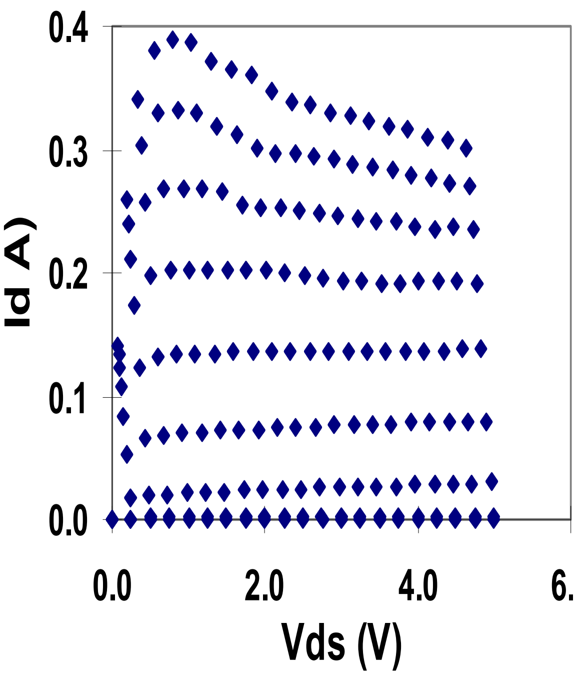
- Positive RF Gds but Negative DC Gdso at Higher Power Dissipation Region



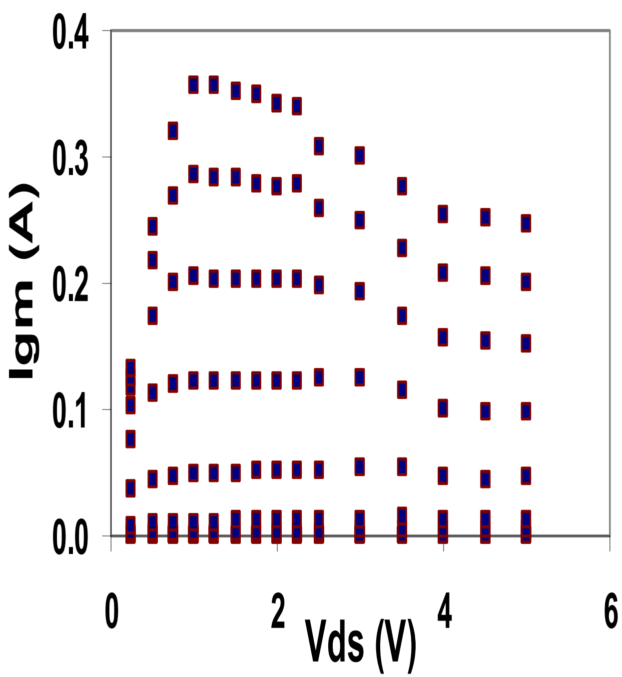
# PHEMT modeling issue: I-V dispersion

- - DC-IV Does Not Mean Equal to RF-IV
- -RF IVs That Fit RF Gm and RF Gds Differ From Each Other

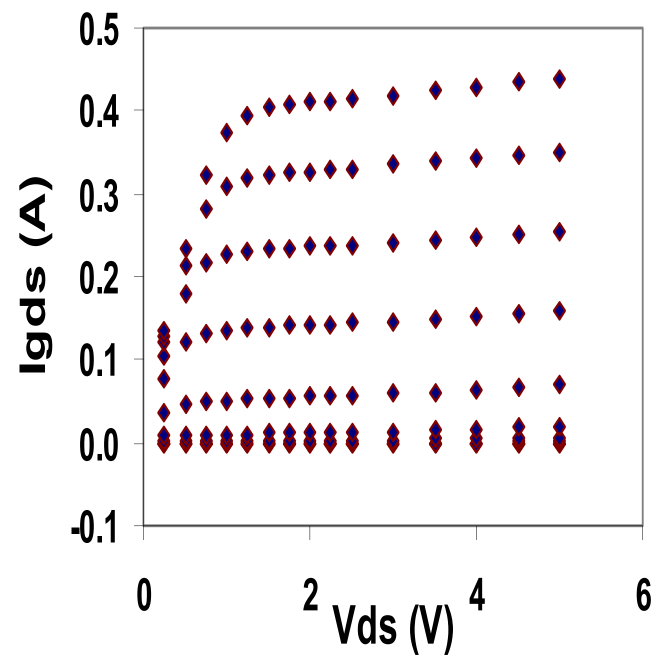
DC IV




RF IV That Fits RF Gm




RF IV That Fits RF Gds

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# PHEMT modeling issue: Charge Conservation?

- 2d-charge Qg Can Be Integrated From Extracted (Based on Measurement Data) Cgs(vgs,vgd) and Cgd(vgs,vgd) and Should Be Path-independent

**Charge Conservation or Path Independence Rule Requires:**

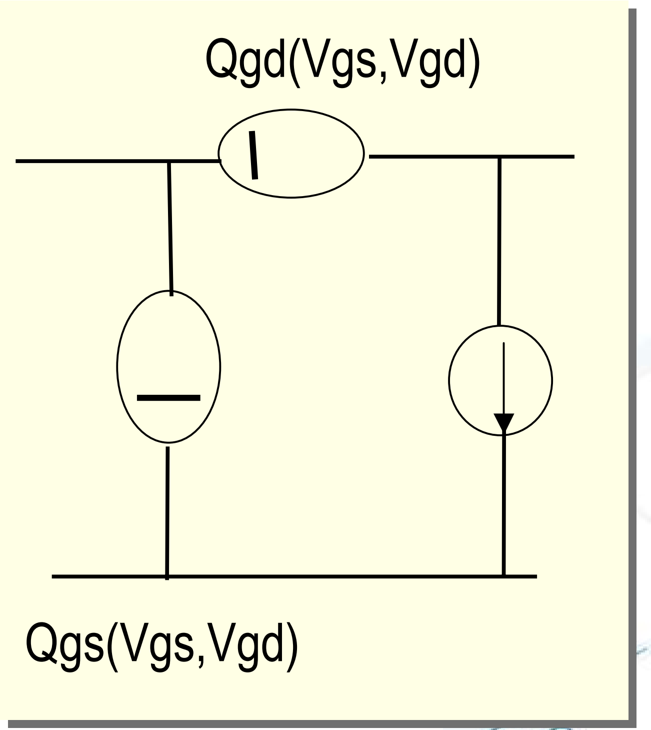
$$Q_g = \int (C_{gs}\, dv_{gs} + C_{gd}\, dV_{gd})$$

$$\partial C_{gs} / \partial V_{gd} = \partial C_{gd} / \partial V_{gs}$$

**For Small Size Devices and No Significant Dispersion, Path Independence Does Hold. In general, it does not hold, because of improper equivalent circuit**

# PHEMT modeling issue: consistence and others

- A derived small-signal model from the large-signal model must be consistent with small-signal models over a wide range of biases
- 2D QV Functions in Large-signal Model Introduce Additional Trans-capacitances that do not exist in small-signal models
- Be continuous up to at least third derivatives of IV and QV curves
- Accurate gate current model including leakage and breakdown



# Empirical model verses Table-based model

- Both models use simple $\Pi$-shaped intrinsic equivalent circuit
- Both models use IV and QV characteristics and assume path-independence
- Both models use simple linear or nonlinear RC-type circuit on drain side to account for low-frequency dispersion
- Empirical models have advantages of approximate mapping onto device physical structure, large-dynamic range independent of measurement range. Their disadvantage is accuracy.
- Table-based models have advantages of least-parameter-extraction, technology-independence, accuracy but the disadvantages are: slower convergence, limited validity in its measurement range in extraction.

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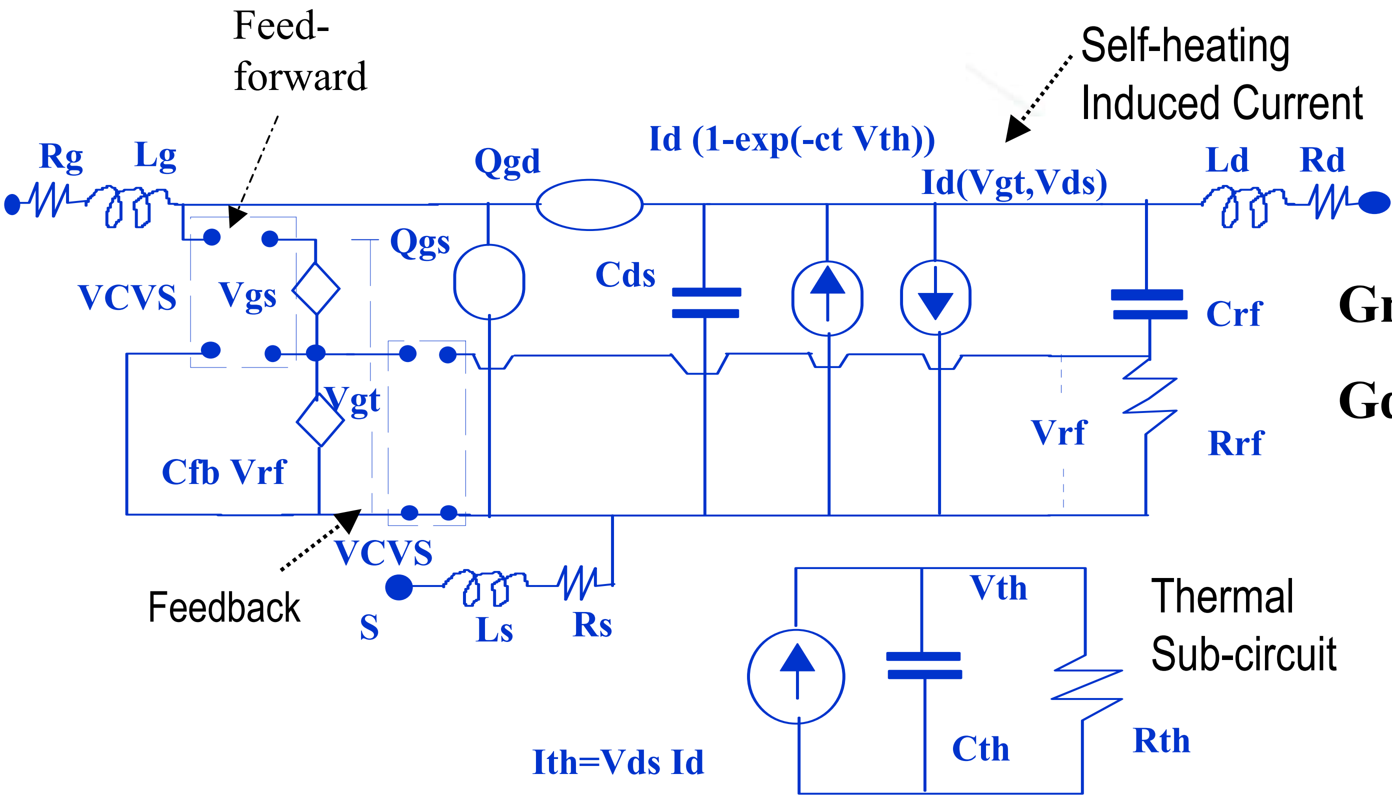
# Dispersion model of PHEMTs

- Instead of Using RC Branch in Drain Port, Alpha Model Uses a Feed-back and Feed-forward Circuit to Modify the RF Gds and RF Gm.
- Self-heating Effects Are Modeled by a Sub-thermal-circuit and a Coefficient of Id Modification

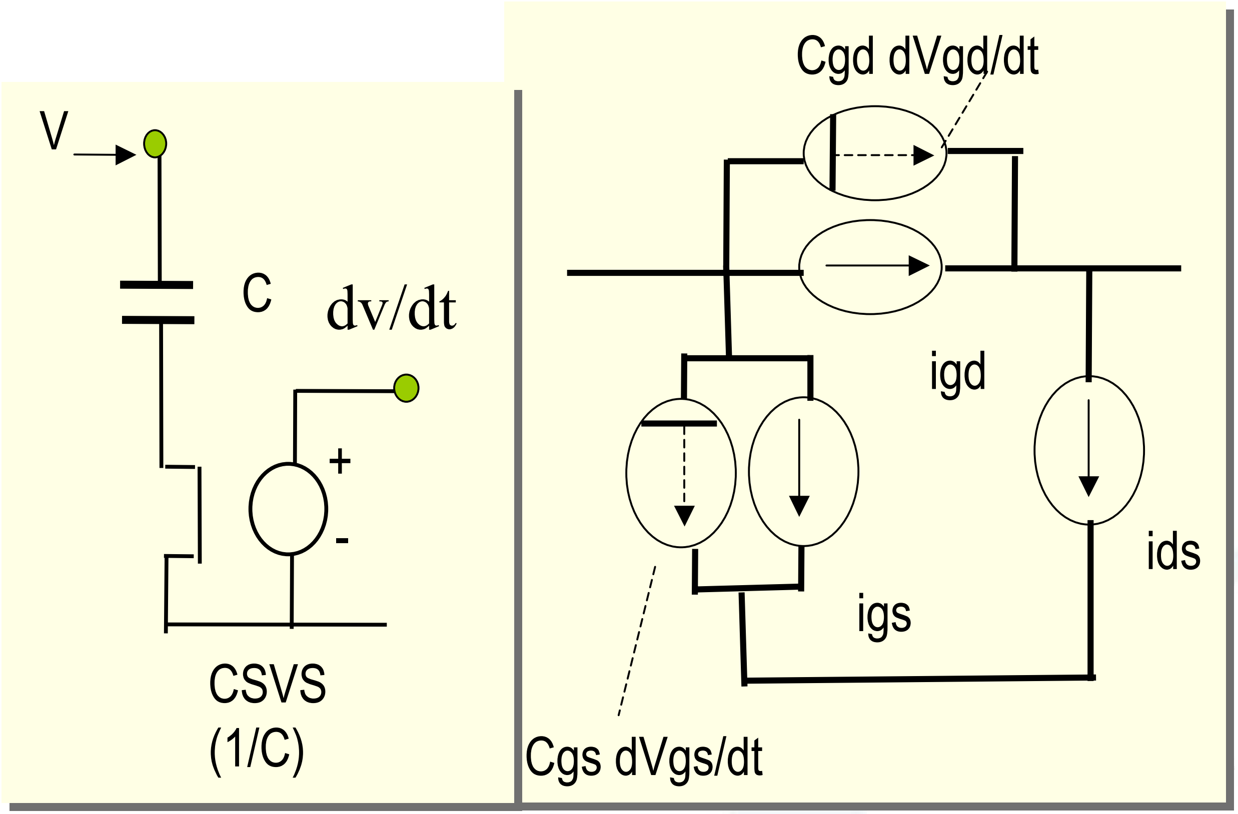



Gm=+GmoCfb

Gds=+GdsoCbk

# ‘No-Charge’ model

- Use Capacitive Current Sources to Replace Charge Sources
- Create a Virtual Node (Voltages dv_dt) That Are Proportional to Time-derivative of Vgs or Vgd. The Capacitance Current, C(Vs)*dV_dt , Is the Nonlinear Function of Vgs,vgd and dV_dt



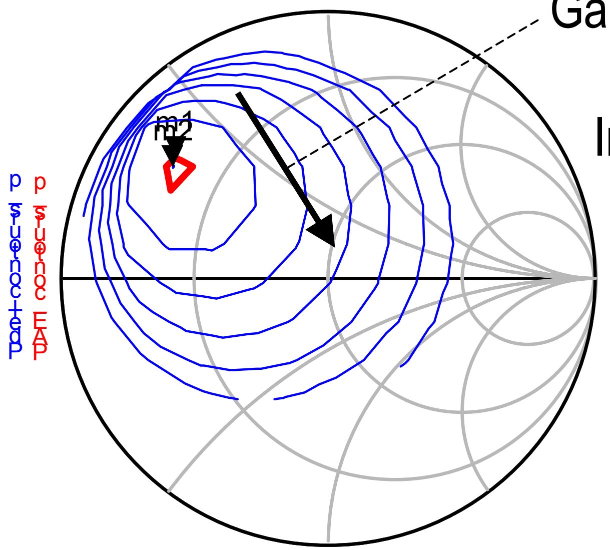
# Charge model verses 'Non-charge' model

- No extra trans-capacitances are involved
- Complete and one-by-one-correspondence consistence with small-signal models over all bias-points measured
- Care must be taken to avoid average component of capacitive currents. Use CR broke circuit for each current
- Charge model is still better in convergence.
- Both models can be table-based or empirical.

# Application: 2-tone Load-pull Simulation

- The Results Are Verified by Comparing the Measured at Several Points

**Gain**

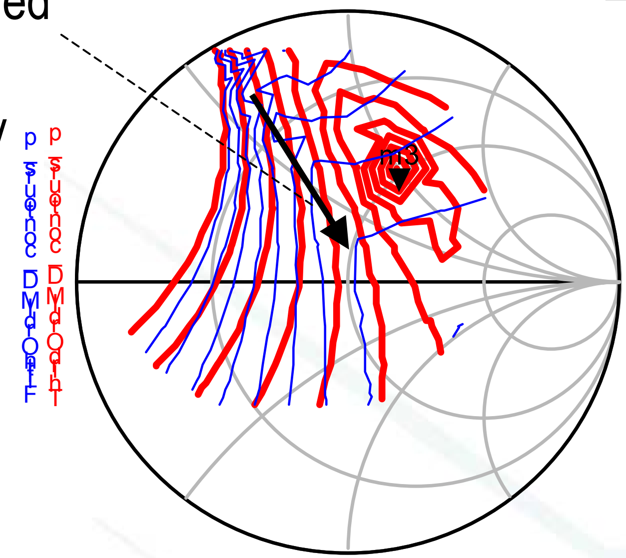



indep(PAE_contours_p) (0.000 to 6.000)
indep(Pdel_contours_p) (0.000 to 57.000)

m1
indep(m1)=6
PAE_contours_p=0.728 / 141.714
level=3.252045, number=1
impedance = Z0 * (0.176 + j0.338

Gain Unchanged but TMD Improved by 8 dB

**TMD & FMD**




indep(ThirdOrdIMD_contours_p) (0.000 to 31.000)
indep(FifthOrdIMD_contours_p) (0.000 to 27.000)

| Minimum 3rd-Order IMD, dBc | Minimum 5th-Order IMD, dBc |
|---|---|
| -83.437 | -100.154 |

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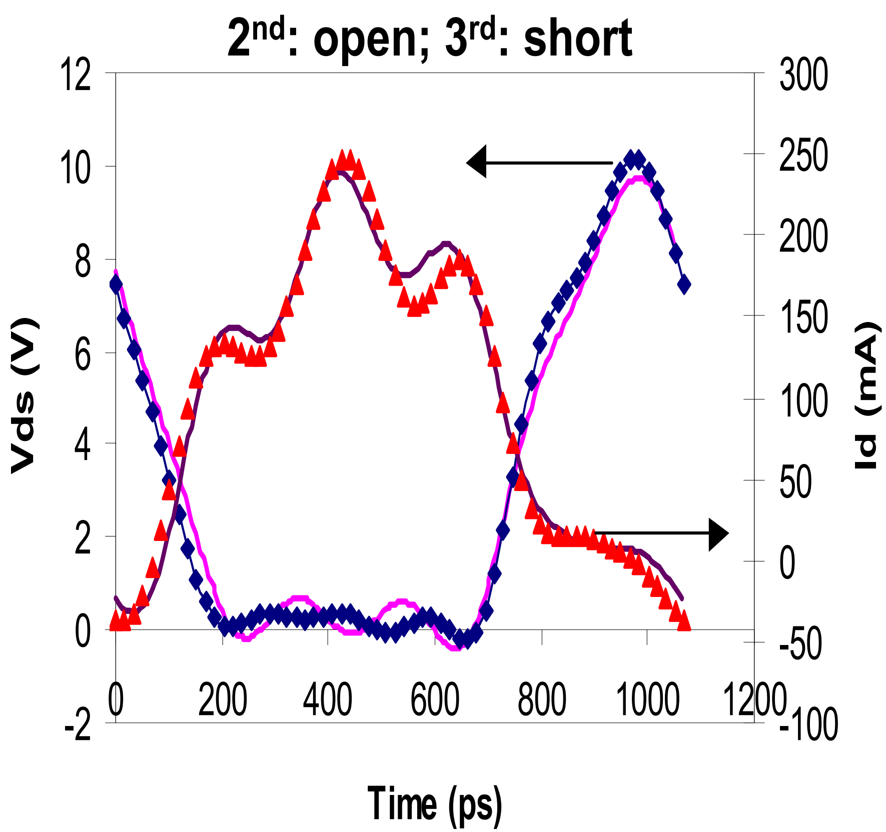
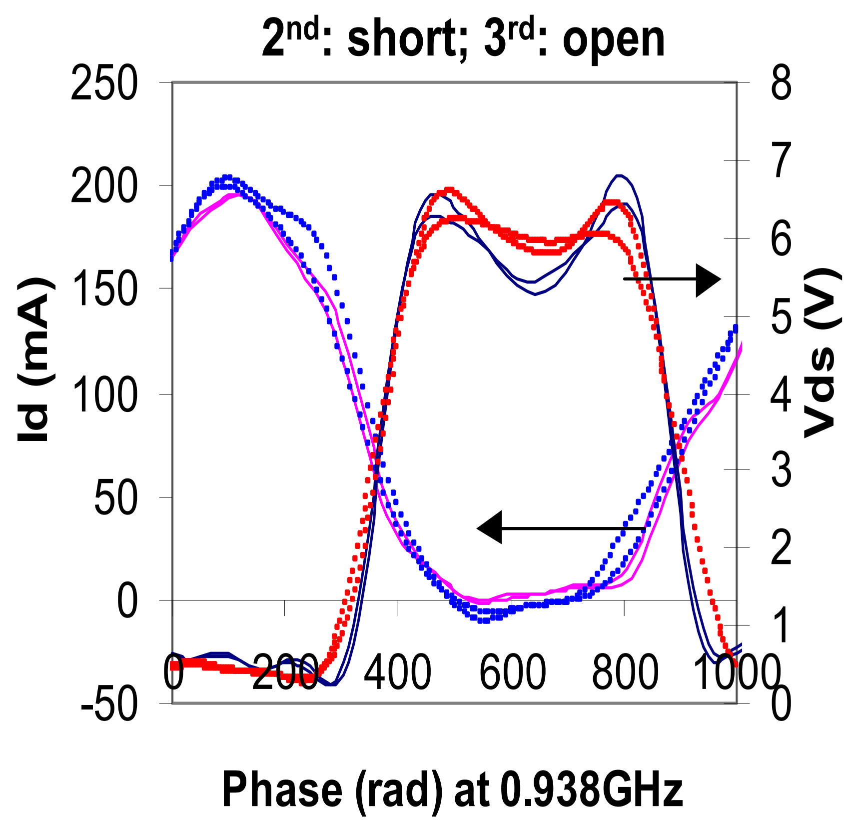
# Application: Waveform at Inverse-F and Class-F Operation

## Class Inverse-F (PAE 80%)




## Class F (PAE 69%)




**Symbol: Measured        Line: Modeled**

**Vds = 3.2 V Vg = -0.88 V (Inverse F), Vg = -1.1 V (Class-F), Total Wg = 2 mm**

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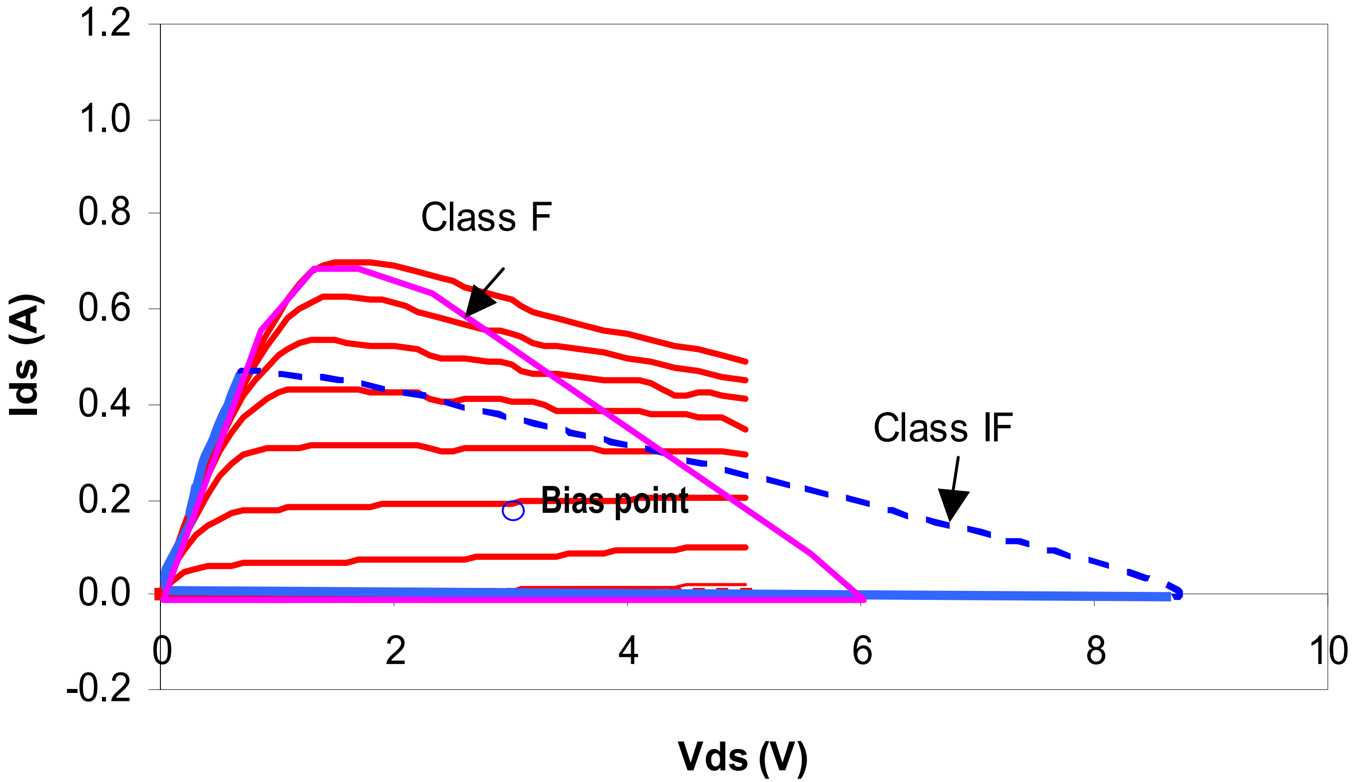
# Application: load-line of ideal Inverse-F and Class-F Operation

High PAE Requirement: - Id ≈ 0 when Vd swings, Vd minimized , when Id swings

- fast transit for Id*Vd ≠ 0 (broken line)

Class F: visit more time on resistive loss area than clss inverse-F



# HBT modeling

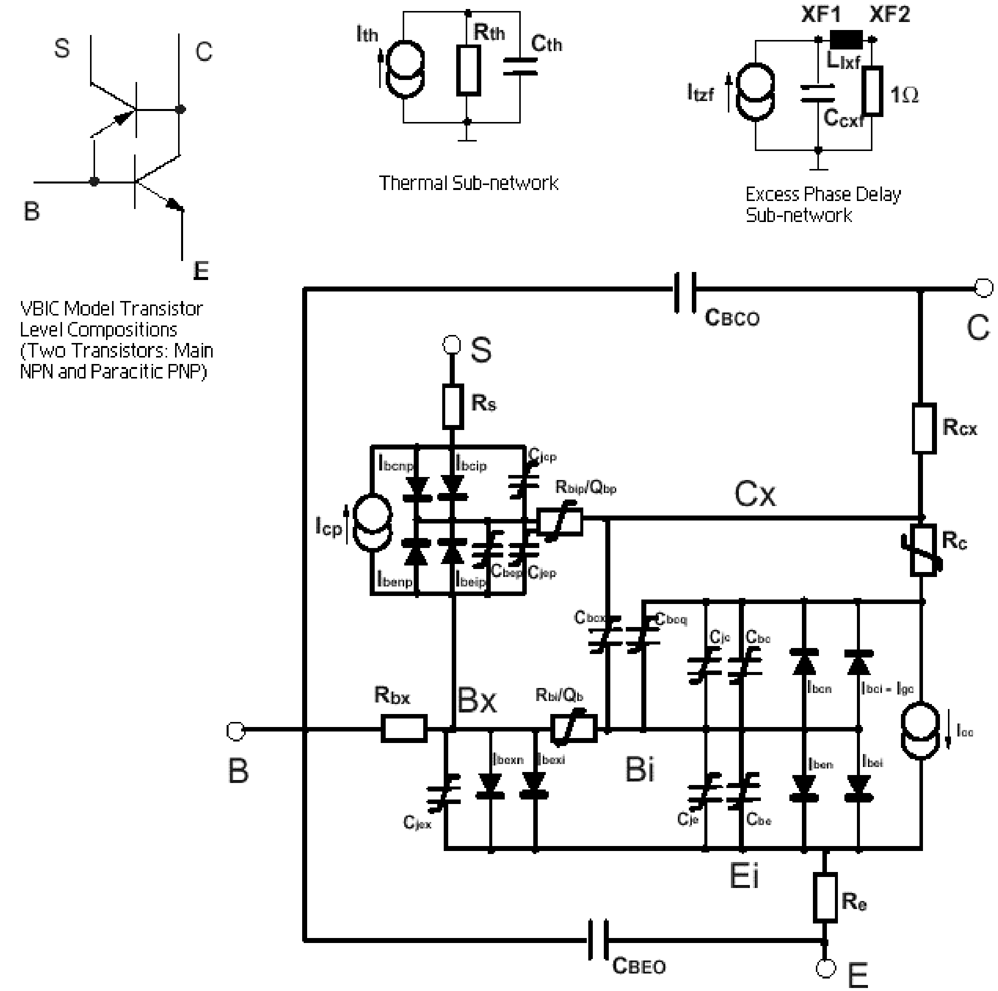
- Most hand-set PA's are using HBTs
- The advantages over PHEMTs: unipolar DC supply, uniformity and high yield, linearity. Caution must be taken on thermal management
- Commercial and non-conmercial models

- Commercial models: GP, √ VBIC, Mextram, Hicum

- Non-commercial models: √ Modified-GP, √ Modified-VBIC or others

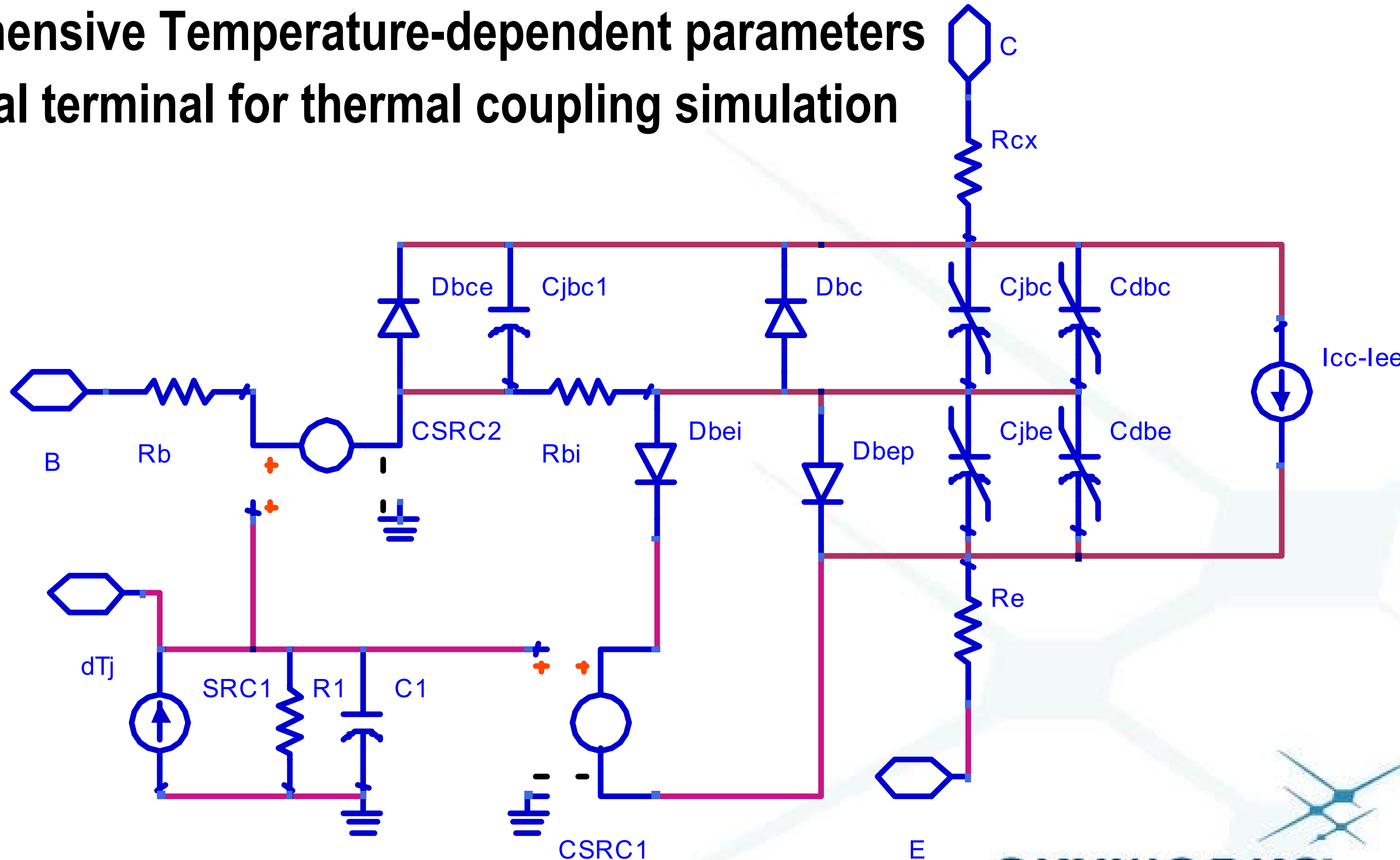
# VBIC model and features

- √Self-heating
- √ Separation of the transfer current and base current
- External BE diode
- Parasitic PNP
- Early effect on Tf
- Quasi-saturation
- √ Comprehensive Temperature-dependent parameters



# Modified GP model and features

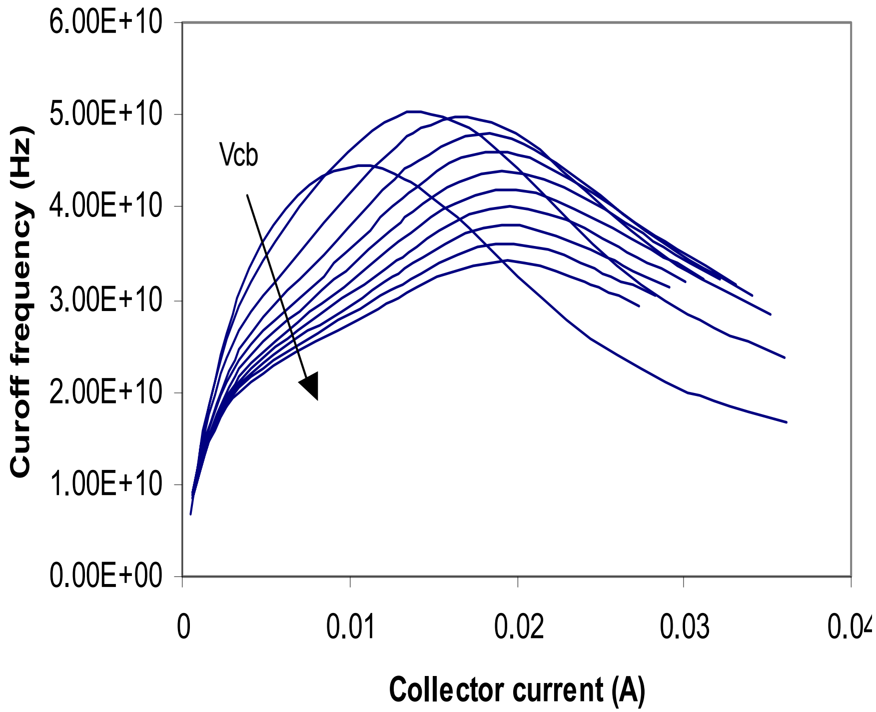
- √major Self-heating effects including nonlinear terms
- √ Separation of the transfer current and base current
- √ Comprehensive Temperature-dependent parameters
- √ Additional terminal for thermal coupling simulation



# Tf and Cbc characteristics that commercial models can not fit

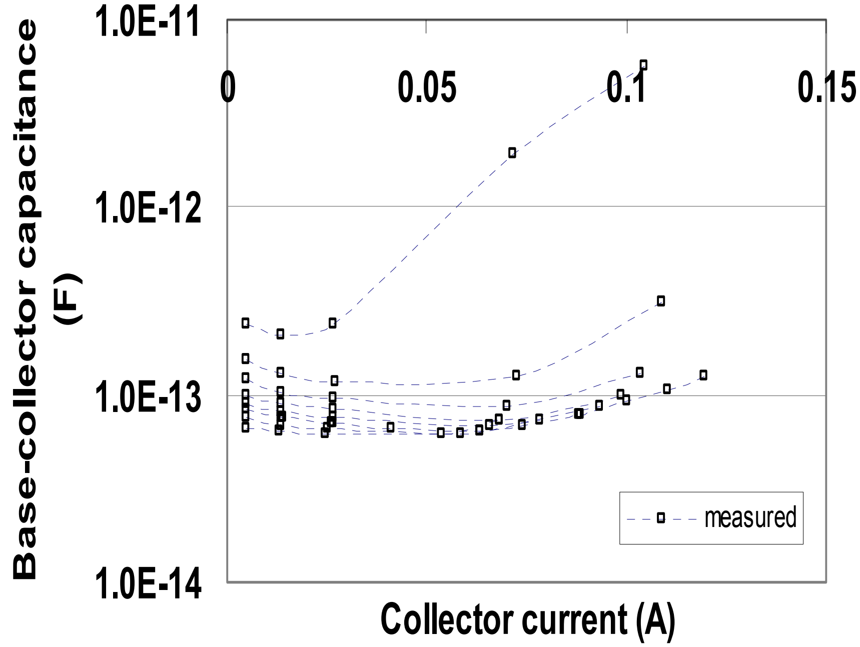
Ft as function of Vcb & Ic

Vcb=-0.8, & -0.5 to 4 V step 0.5 V



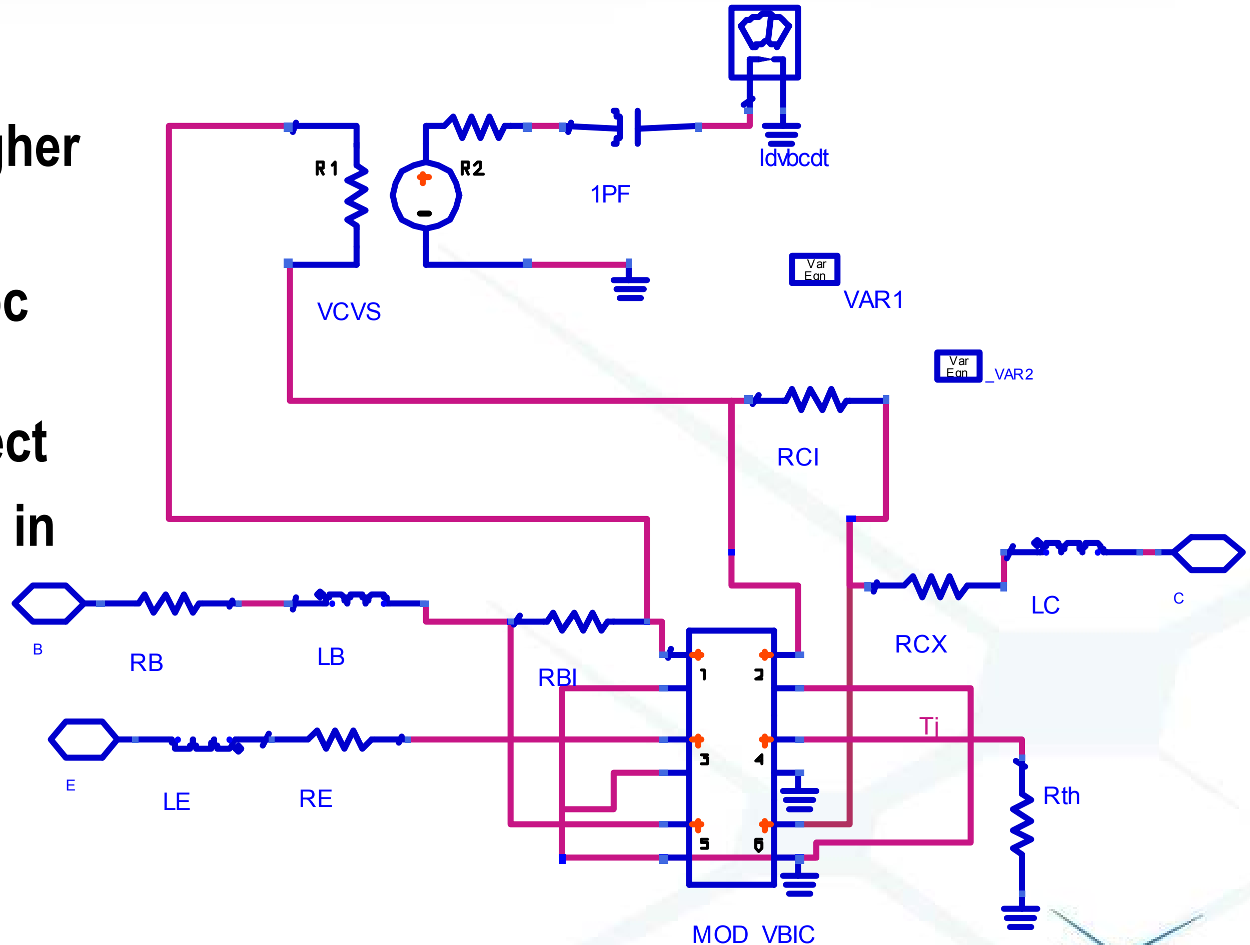

Cbc as finction of Vbc & Ic

Vbc=0.5 to 3.5 V step 0.5 V



# Modified VBIC model and features

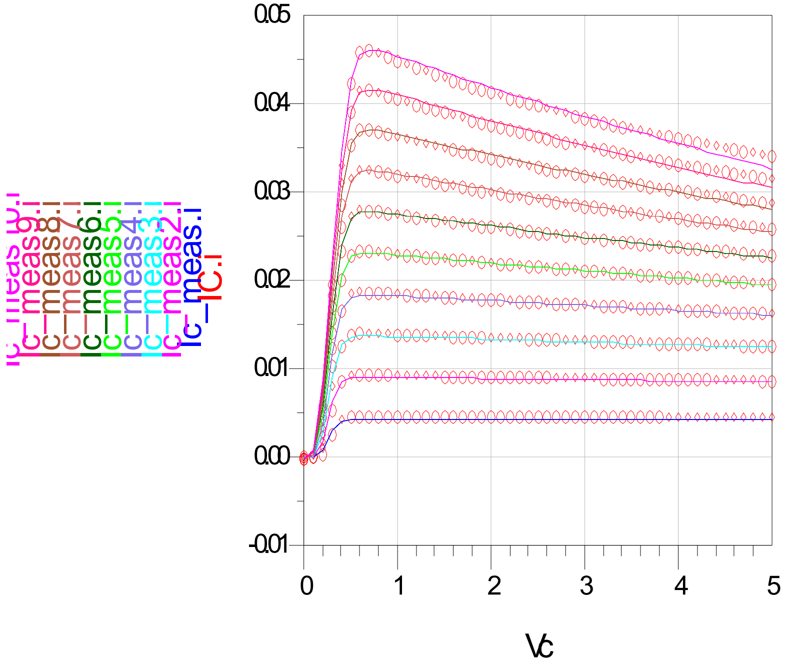
- √Self-heating
- √ accurate Tf model to account for ft drop at higher current (Kirk Effect)
- √ Vbc & Ic dependent Cbc due to mobile-charge modulation and Kirk Effect
- √ Implemented with SDD in ADS

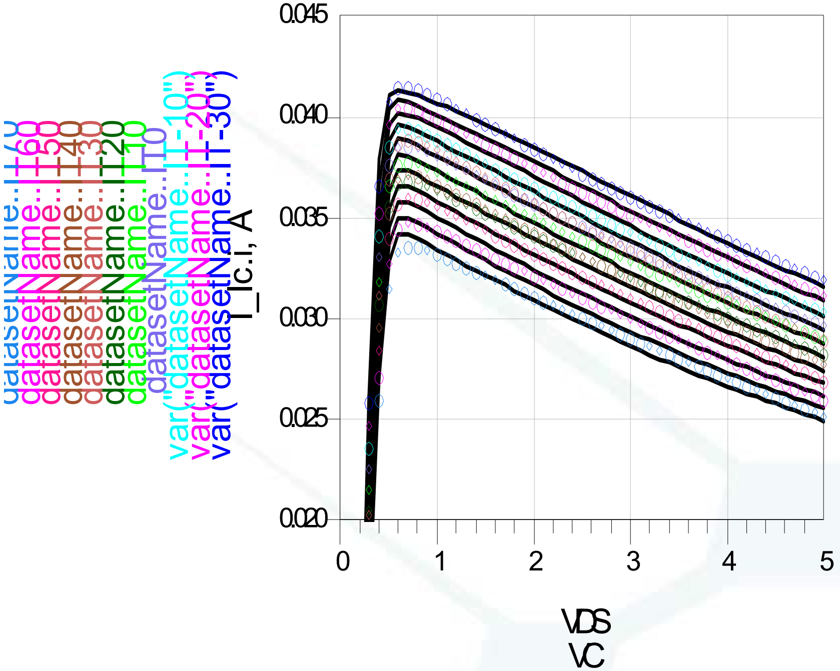


# Ic-Vc and Vb-Vc curves at constant Ib modeled vs measured

Ae=56um^2   Ic-Vc

Vb-Vc




Symbol:Modeled, Solid line:Measured

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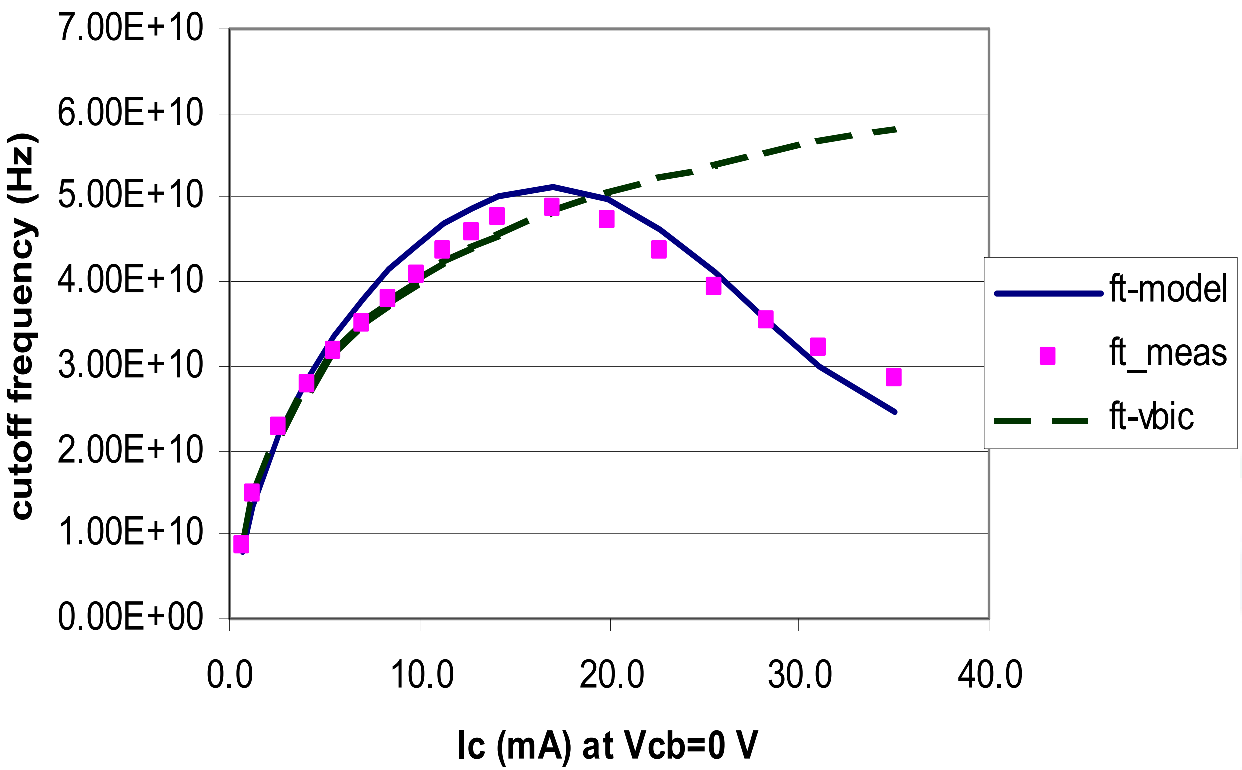
# Modified VBIC fits ft at higher current

Ft as function of Vcb & Ic Vcb=0V Solid line: Modified VBIC Broken line: VBIC model

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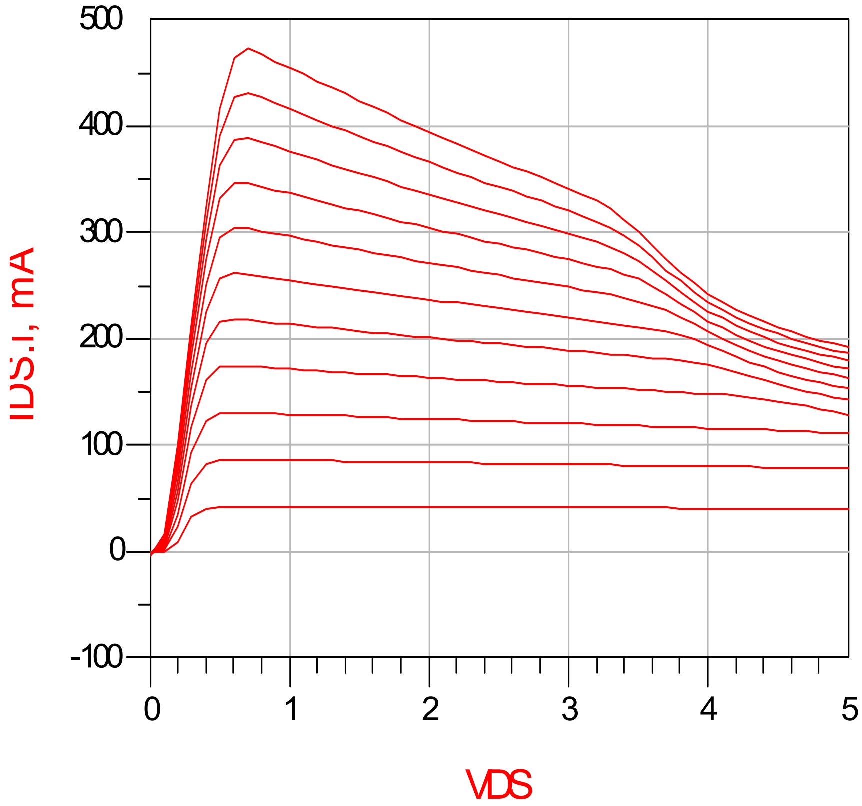
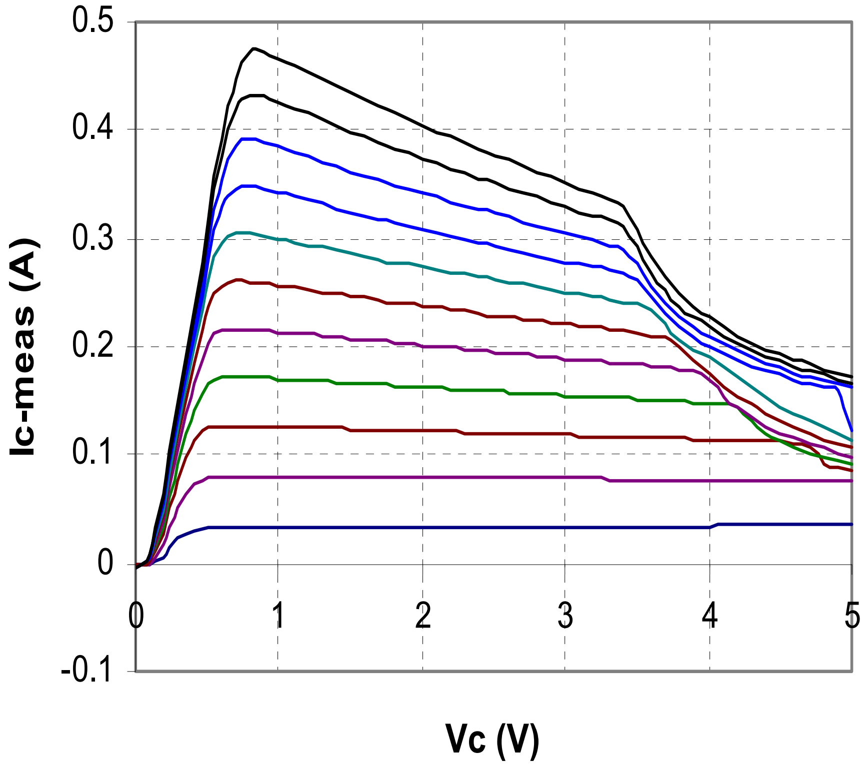
# IV collapse modeled vs measured

Ae=960 um2  Ib=0.4mA to 4.4 mA step 0.4mA

simulated

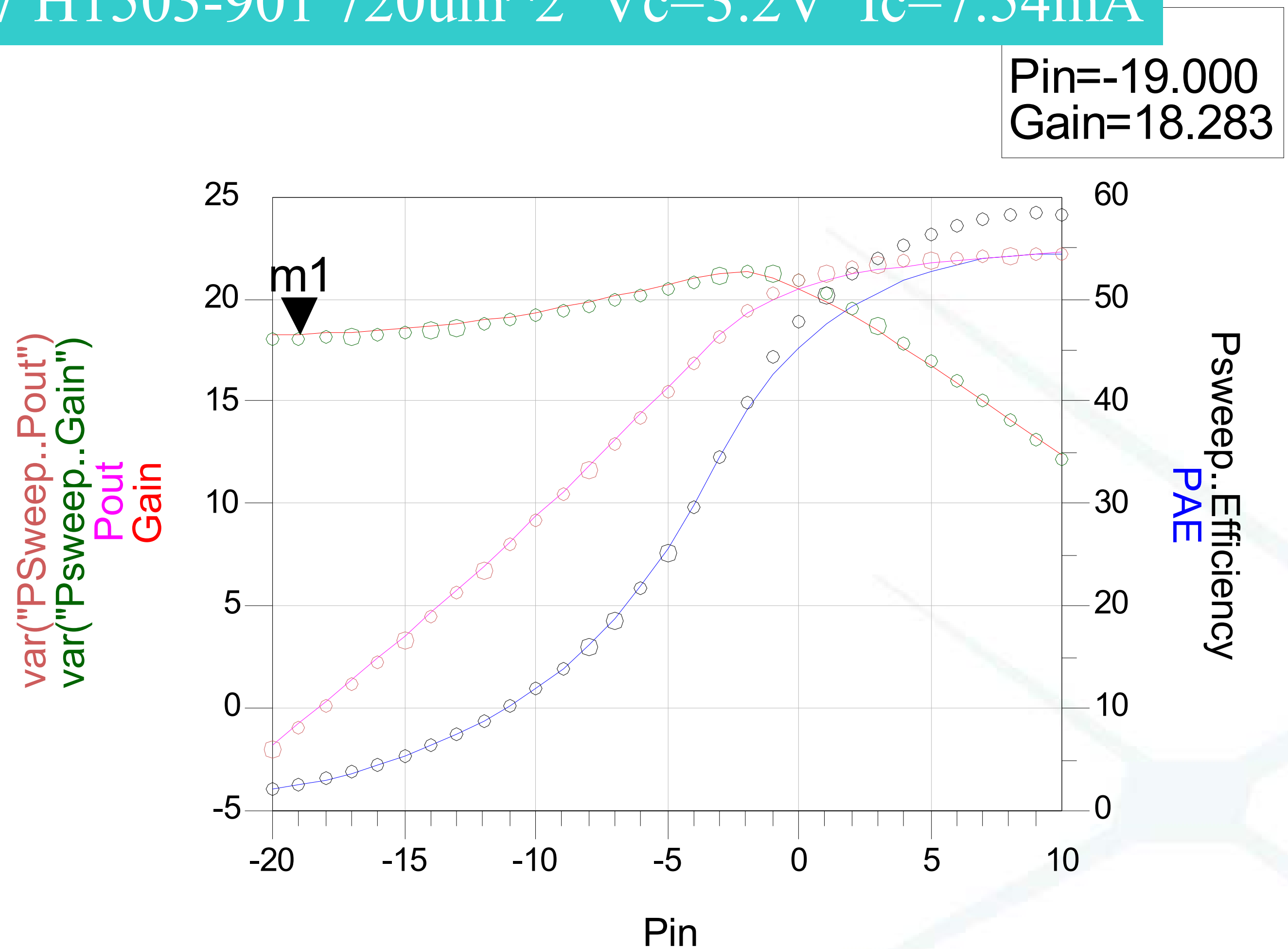



measured



# Power performance Modeled vs Measured

V27 H1503-901 720um^2 Vc=3.2V Ic=7.54mA

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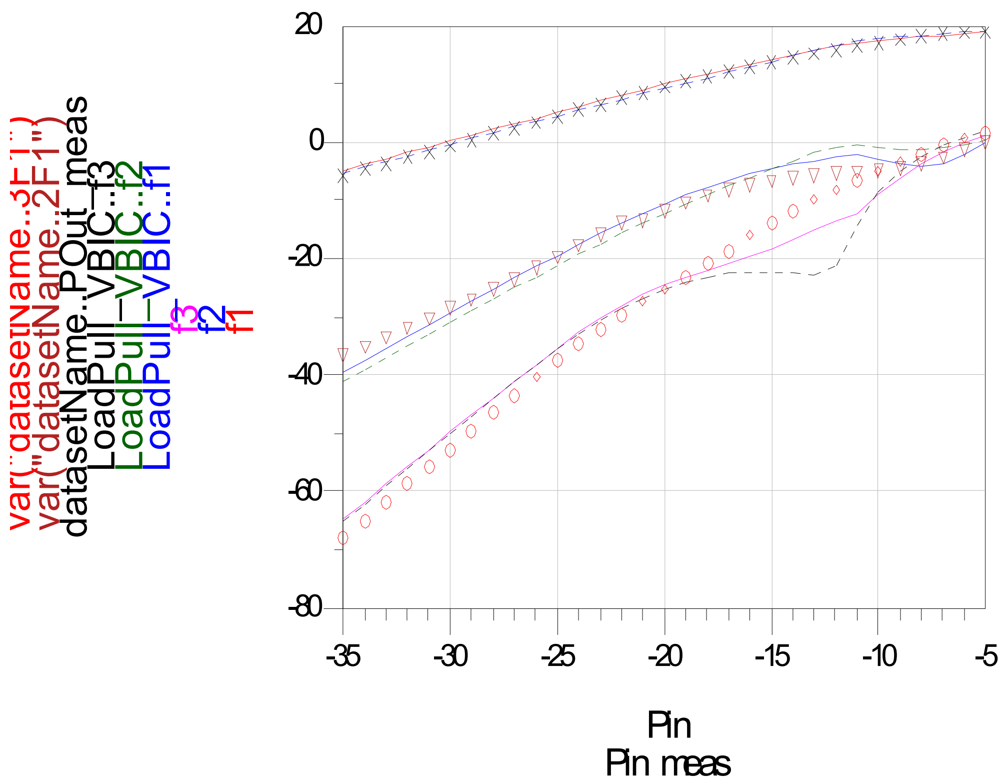
# Harmonics performance Modeled vs Measured

V27 H1503-901 60um^2  Vc=3.5V  Ic=7mA




Vc=3.5 V Vb=1.357 V

Ic=6.98 mA
Rbext=600ohm

Source: f1: 0.78∠26.7

F2: 0.6 ∠6.8

F3: 0.17 ∠168

Load: f1 0.32 ∠26.7

F2: 0.77 ∠-88.4

F3: 0.67 ∠-137.5

**Symbol:measured, solid line:new model, broken lin:VBIC**

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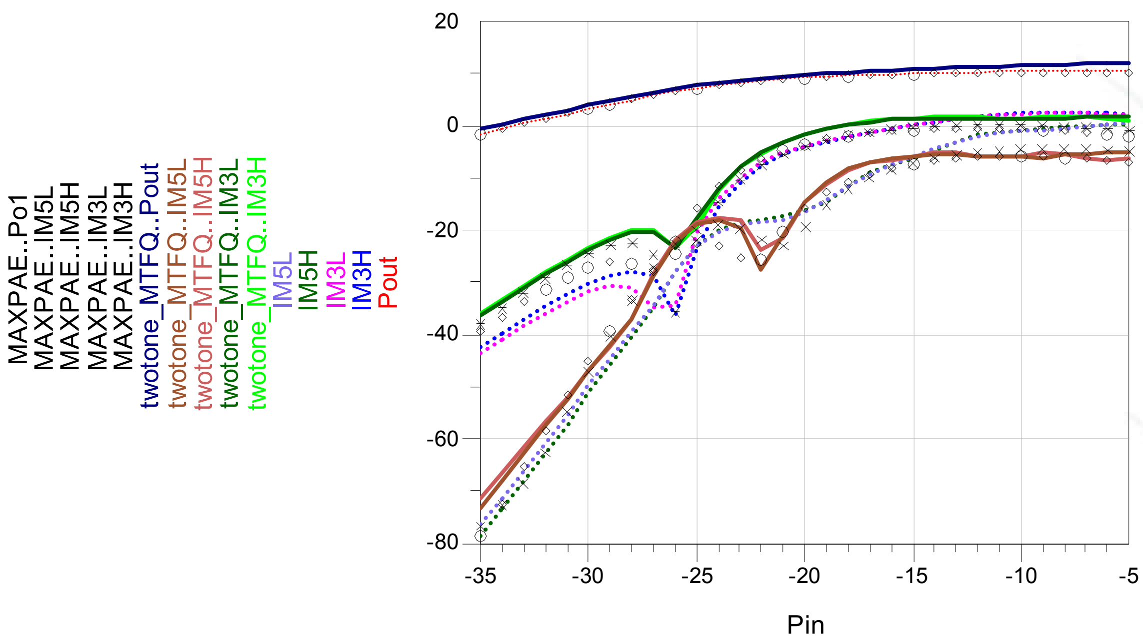
# IM3 & IM5 performance Modeled vs Measured

V27 H1503-901 60um^2  Vc=3.5V  Ic=7mA




Vc=3.5 V Vb=1.357 V

Ic=6.98 mA
Rbext=600ohm

Source: f1: 0.78∠26.7

F2: 0.6 ∠6.8

F3: 0.17 ∠168

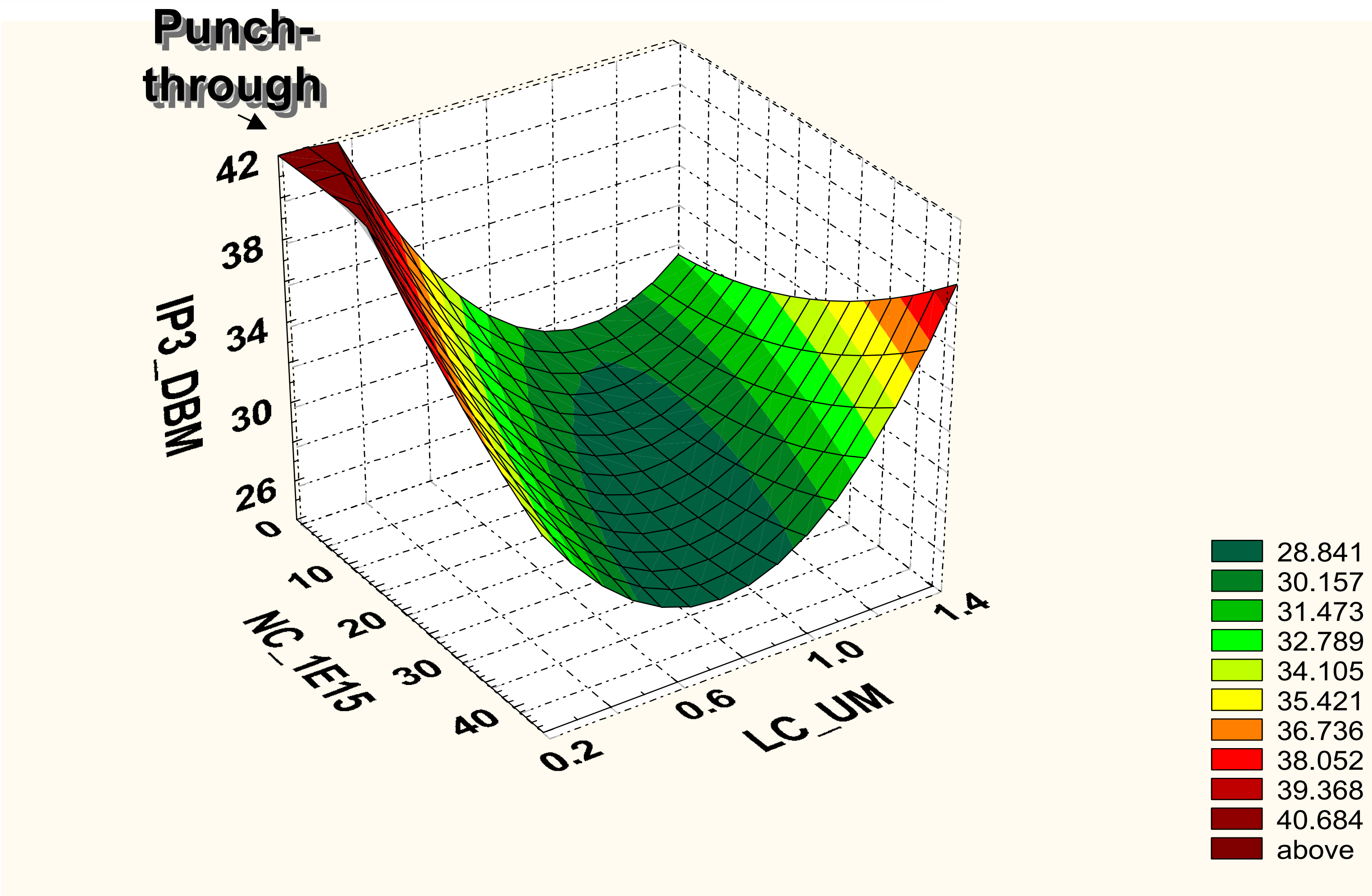
Load: f1 0.32 ∠26.7

F2: 0.77 ∠-88.4

F3: 0.67 ∠-137.5

**Symbol:measured, solid line:new model, broken lin:VBIC**

# Linearity improves for punch-through structure

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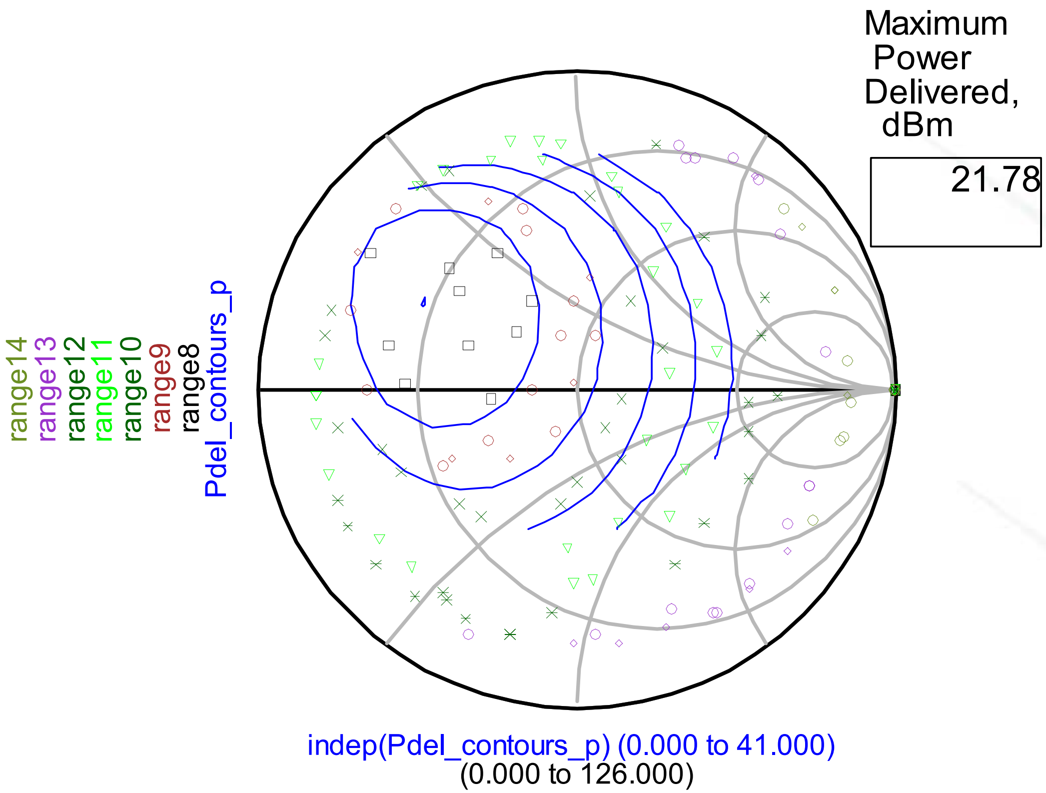
# Pout load-pull, Modeled vs Measured

V27 H1503-901 720um^2 Vc=3.2V Ic=37mA
Pin=0dBm Gamm(2)=0.52<-117




Pout_step=1

Range8 ■ >max-1

Range9 O: max-2

Range10 ×: max-3

Range11 ∇: max-5

Range12 Δ: max-7

Range13 ◇:max-10

Range13 □ :max-15

Max=21.4

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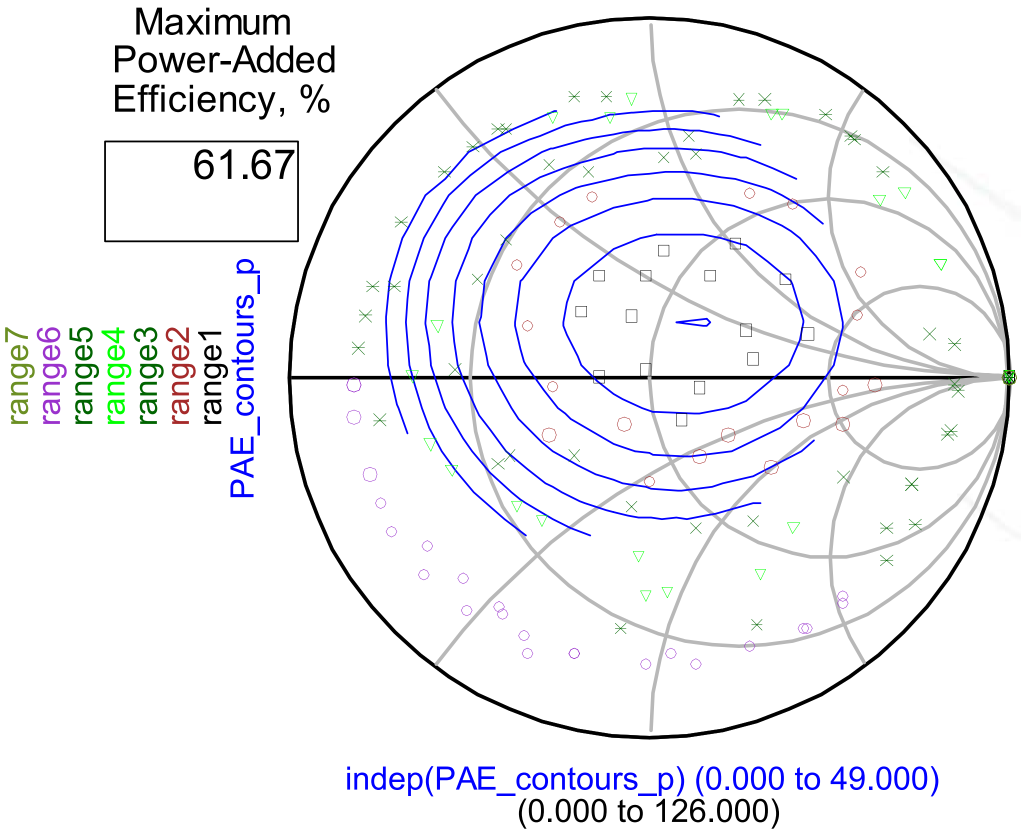
# PAE load-pull, Modeled vs Measured

V27 H1503-901 720um^2 Vc=3.2V Ic=37mA
Pin=0dBm Gamm(2)=0.52<-117




PAE_step=5

range1 ☐ : >max-6

range2 O : max-15

range3 × : max-25

range4 ▽ : max-35

range5 Δ : max-45

range6 ◇ :max-55

Max=61.6

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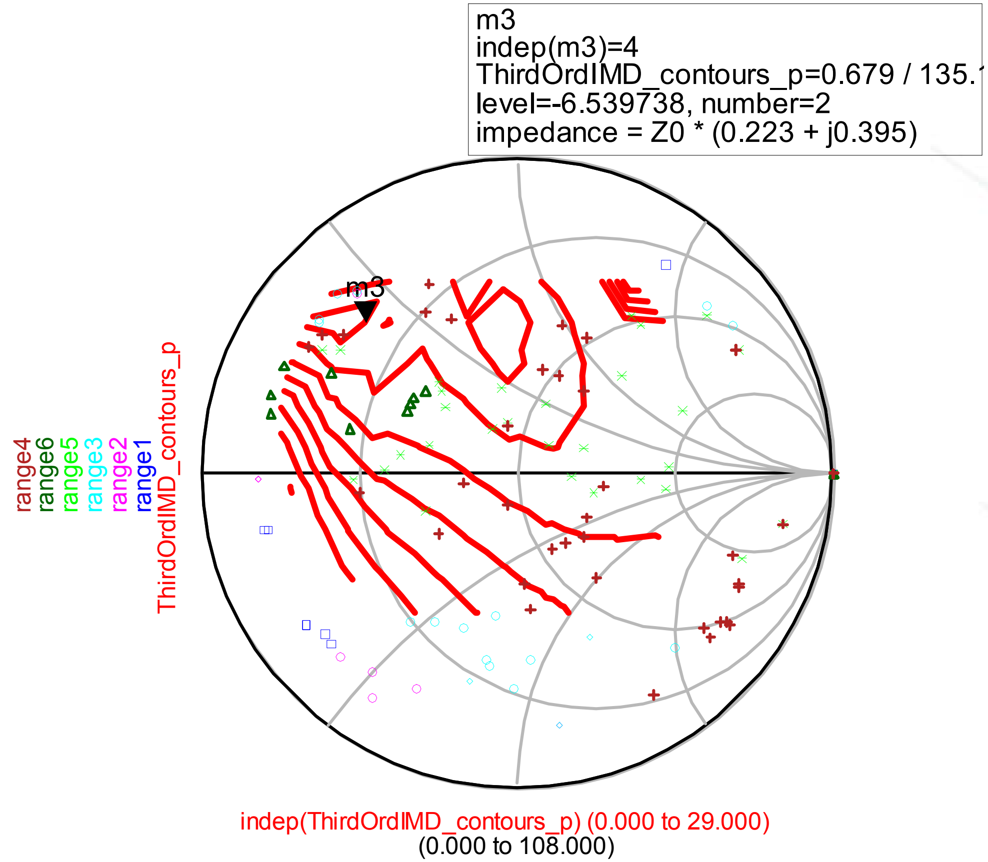
# IM3 load-pull, Modeled vs Measured

V27 H1503-901 720um^2 Vc=3.2V Ic=37mA
Pin=0dBm Gamm(2)=0.52<-117




IM3_modeled_step=2

range1 □ : -18→ -16

range2: O -16→ -14

range3 ∇ : -14→ -12

Range4 +: -12→ -10

Range5 x: -10→ -8

Ranger6 ϰ:>-8

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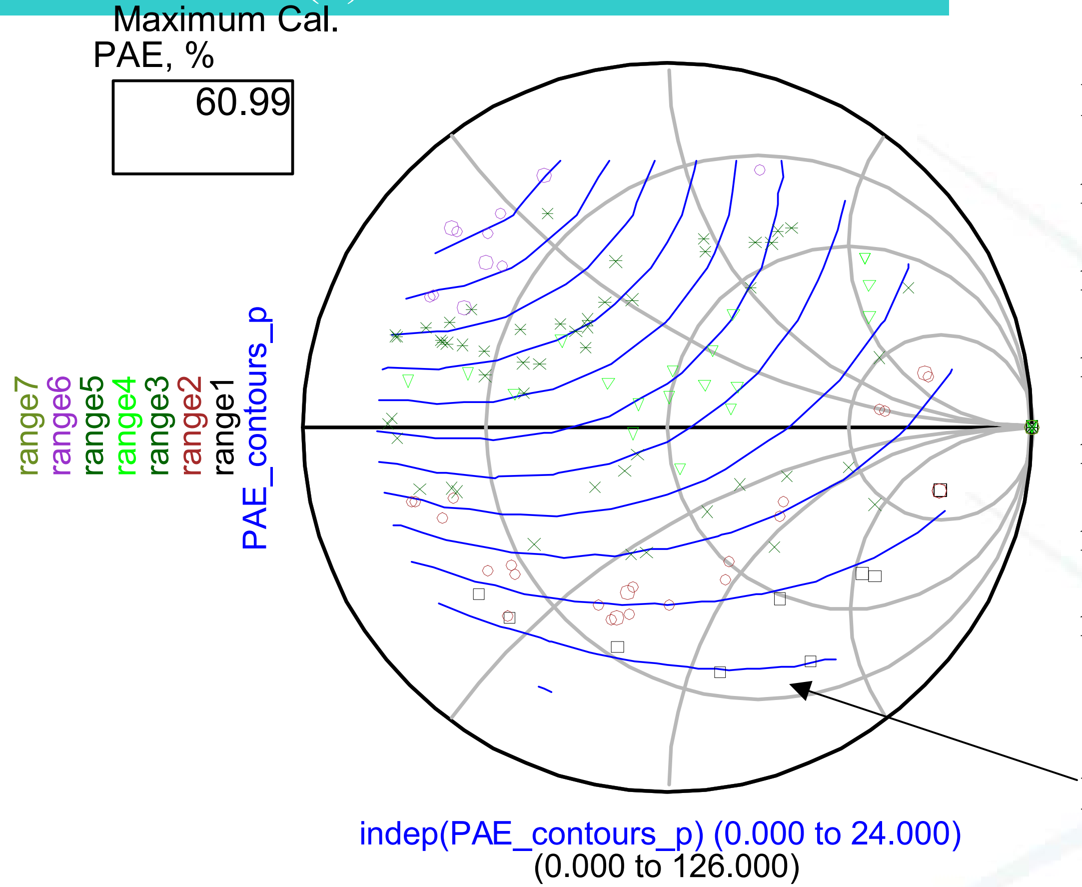
# PAE load-pull for 2nd harmonic, Modeled vs Measured

V27 H1503-901 720um^2 Vc=3.2V Ic=37mA
Pin=3dBm Gamm(1)=0.558<111

No obvious difference of class F and inverse-F!




PAE_modeled_step=2.5

range1 □: max-3→ max

range2 O : max-6 → max-3

range3 × : max-10→ max-6

range4 ▽ : max-15→ max-10

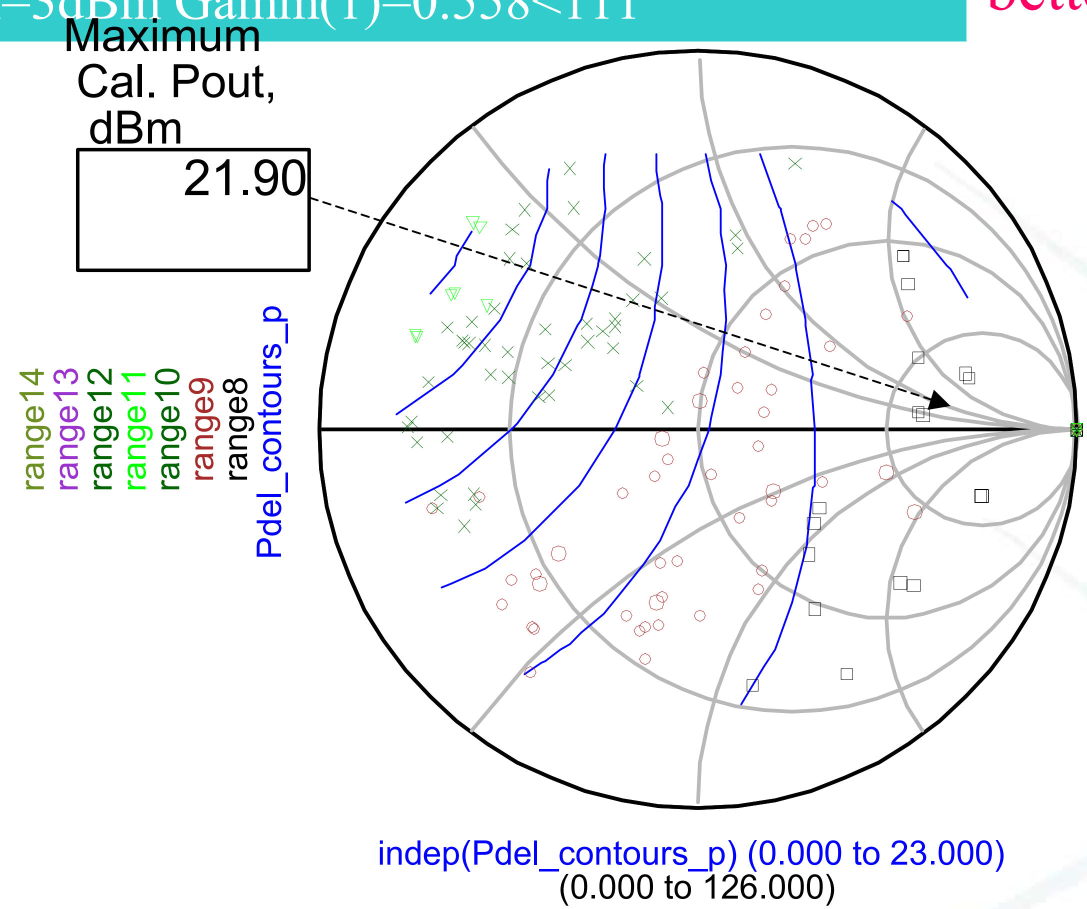
range5 Δ : max-20→ max-15

ranger6 ◇:<max-20

# Pout load-pull for 2nd harmonic, Modeled vs Measured

V27 H1503-901 720um^2 Vc=3.2V Ic=37mA
Pin=3dBm Gamm(1)=0.558<111

For Pout inverse-F is better than class F!




Pout_modeled_step=0.5

**Range8** □ : 19.9→ 20.9

range9 O : 18.9→ 19.9

range10 × : 17.9→ 18.9

range11 ∇ : 15.9→ 17.9

range12: 13.9→ 15.9

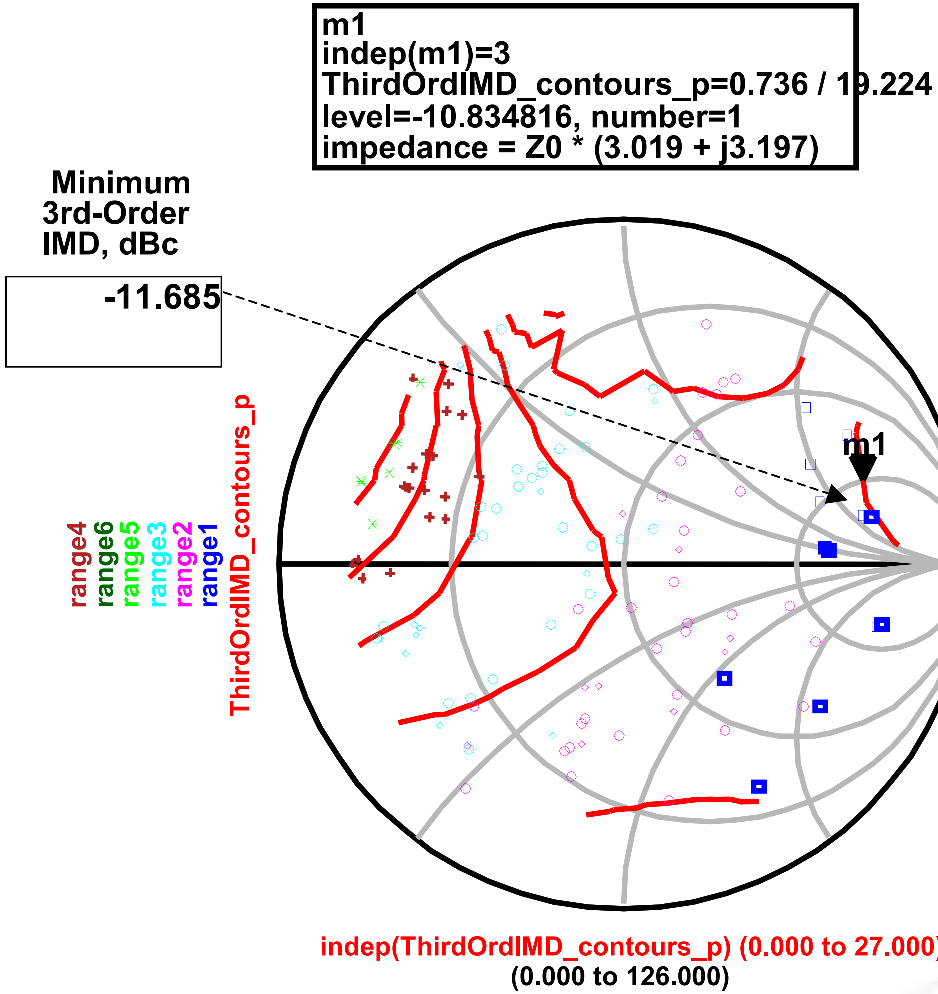
range13: 10.9→ 13.9

ranger13: <10.9

# IM3 load-pull for 2nd harmonic, Modeled vs Measured

V27 H1503-901 720um^2 Vc=3.2V Ic=37mA
Pin=3dBm Gamm(1)=0.558<111

For IM3 inverse-F is also better than class F!




IM3_modeled_step=0.5

range1 ☐ : -13→ -12.5

range2 O : -12.5→ -12

range3 ▽ : -12→ -11

Range4 +: -11→ -10

Range5 x: -10→ -8

ranger6:>-8

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# Conclusion

- The problems with conventional large-signal PHEMT models are addressed that include: dispersion, ‘non-charge-conservation’ originated from use of simple equivalent circuit, etc
- Dispersion and ‘no-charge’ models are presented that overcome the difficulties
- The issues in HBT modeling in terms of mobile charge-modulation and Kirk effects are addressed and modified MP and VBIC models are presented
- The models are verified with comprehensive load-pull results
- Class inverse-F with 2nd harmonic tuned at high impedance is recommended for PHEMT PA design due to its higher PAE over class-F and is likely useful due to its better linearity for HBT power amplifiers.

# Acknowledgement


- Dr. Gene Tkachenko, Dr. Ding Dai for his support
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