Hot S22 Measurement of LHC Circulators

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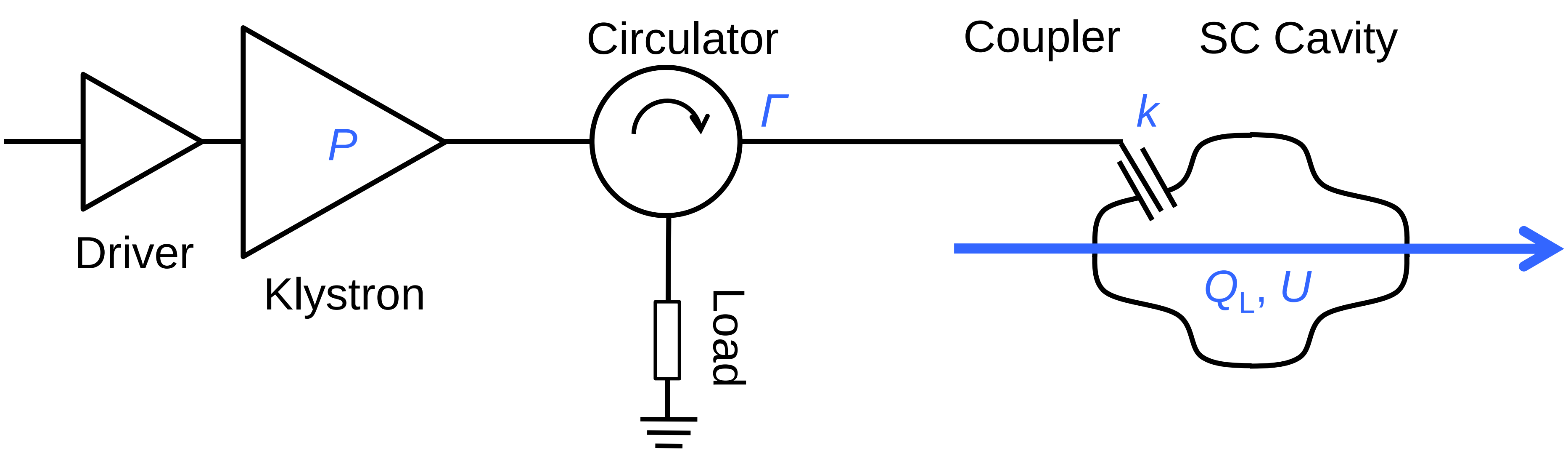
Motivation from LHC Operation

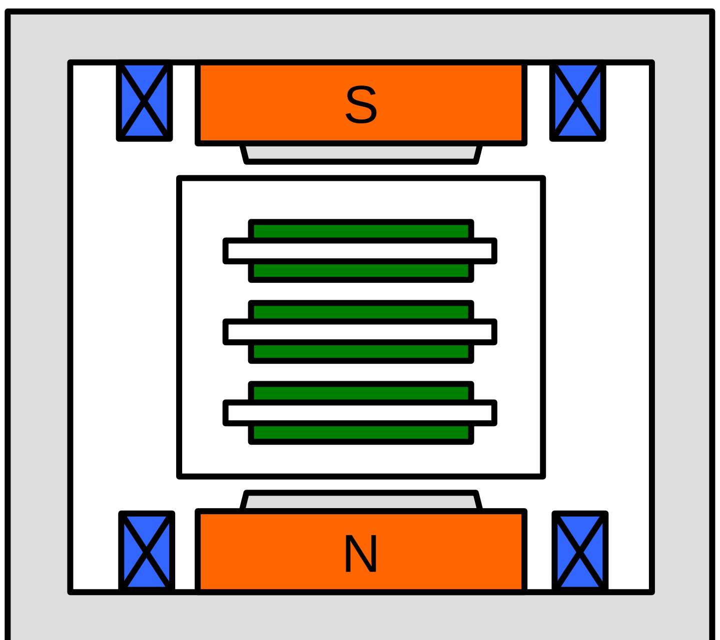
- Loaded Q depends on the coupling k and the reflection Γ of the circulator
  - Couplers calibrated on a 50 Ω load

$$Q_L = f(k,\Gamma)$$

- During ramping of the beam energy Q_L has to change from 20k to 60k
  - Injection: low voltage U of 1 MV/cavity, but low Q in order to increase bandwidth for damping of injection phase and energy error
  - Nominal: high voltage U of 2 MV/cavity → need to raise Q given that the klystron power is limited to around 300 kW
- Uncertainty in Q_L results in variations in Klystron Power P and risk of saturation

$$P \sim U^2 / Q_L$$





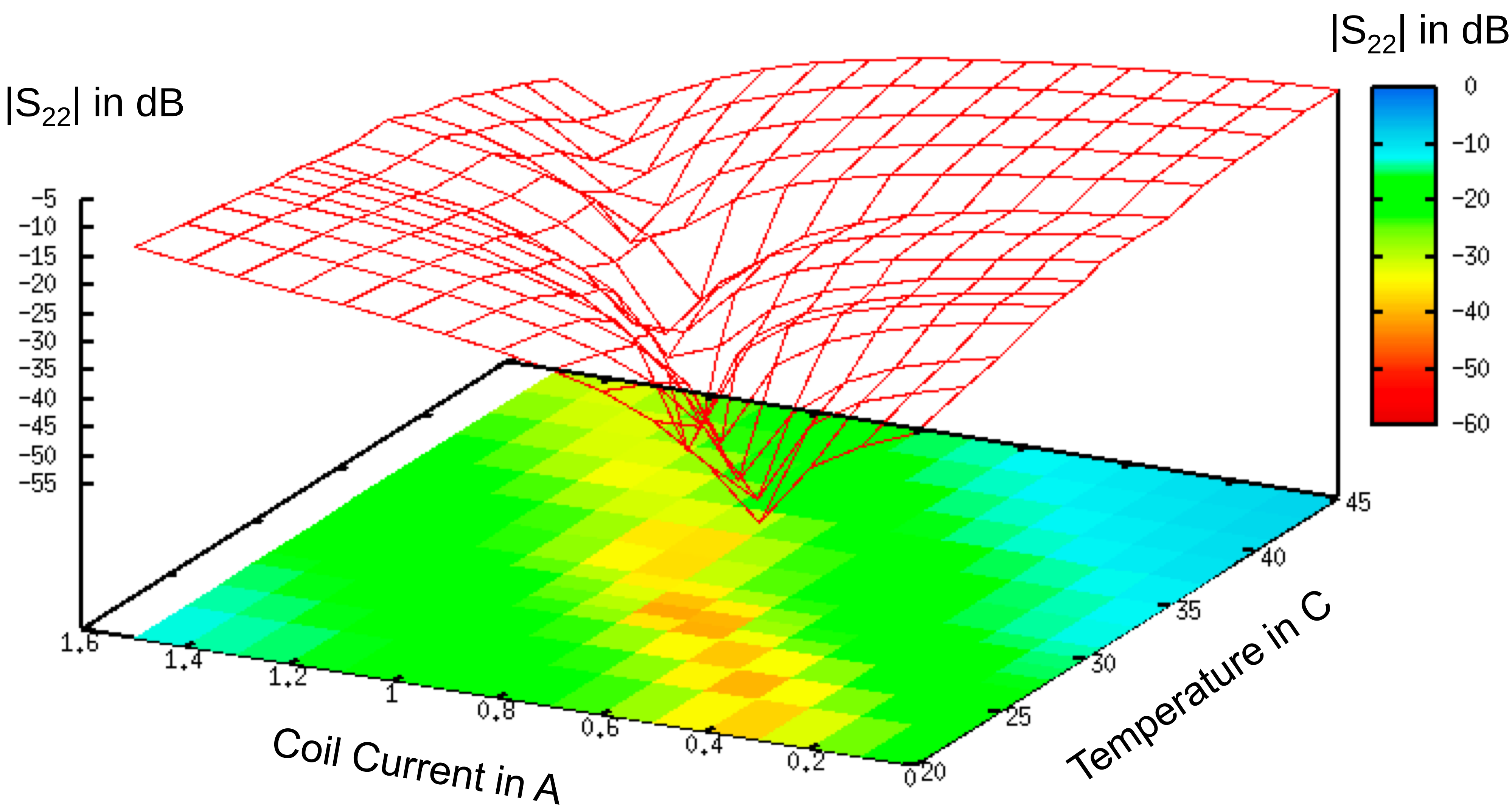
AFT Circulator for 400.8 MHz and 330 kW

- **Ferrite Disks**
  - Power dissipation depending on the phase of the reflected wave
  - Thermal drift due to dissipated power
- **Permanent Magnet**
  - Provides magnetic field for the ferrite disk
  - Subjected to hysteresis and thermal drift with ambient temperature
- **Electromagnet – Coil-Field**
  - Compensation field for thermal drift in ferrites and permanent magnet
- **TCU – Temperature Compensation Unit**
  - Provides current for electromagnet depending on ferrite and permanent magnet temperature

Separate Low-Power Measurements

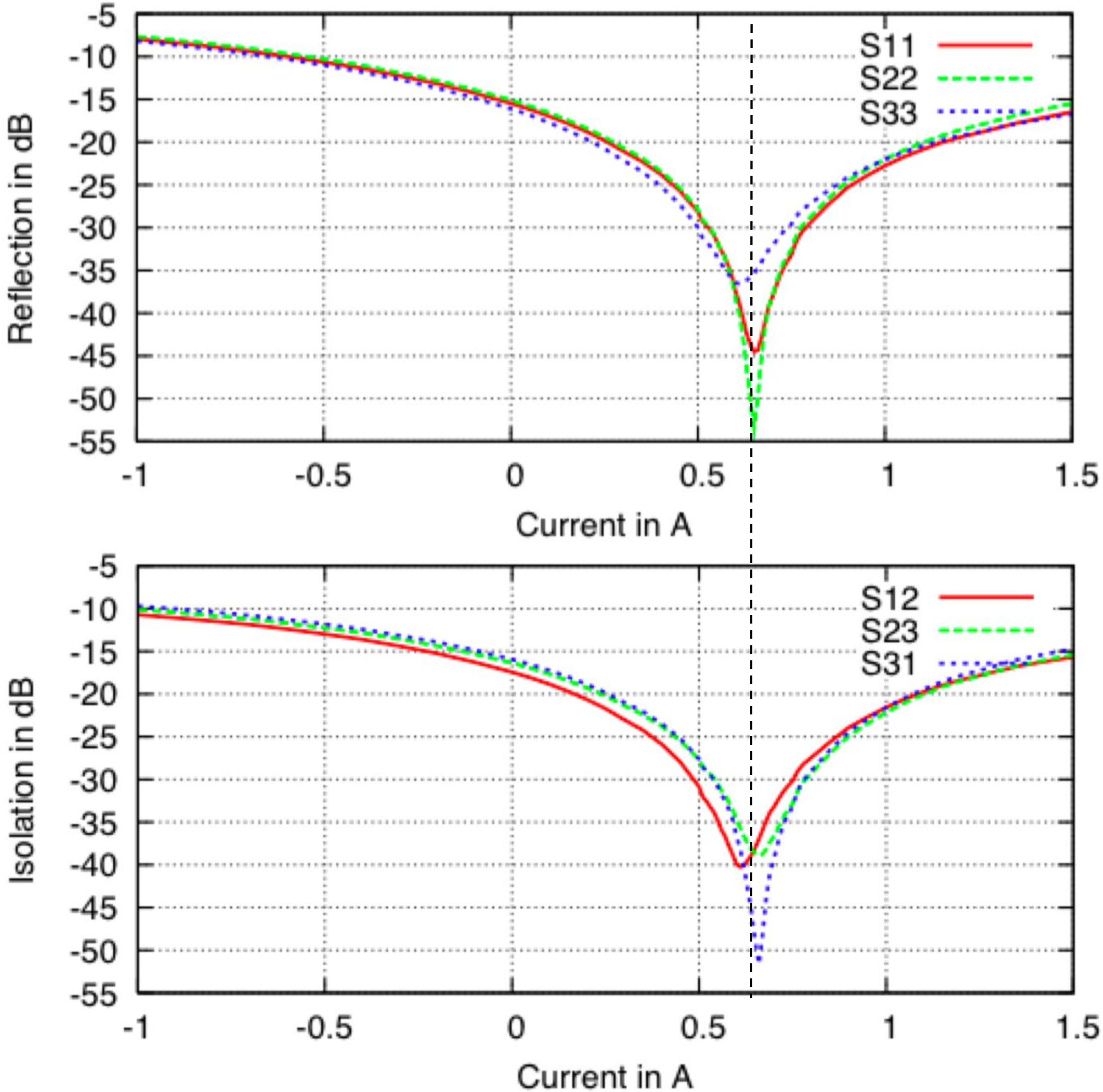
- Coax-2-waveguide transitions on all 3 circulator ports
- 4-Port Network Analyzer
  - Measurement of all S-Parameters in one go
- Simulation of High-Power by heating cooling water
  - heating device built by Pablo Martinez
  - 20 to 45 deg Celsius
- No control over ambient Temperature (assuming 20 to 23 deg Celsius)
- Current Source
  - -1 to +1.5 A
  - TCU not used

Ball park figure of all S-Parameters for different Temperatures and Currents Values

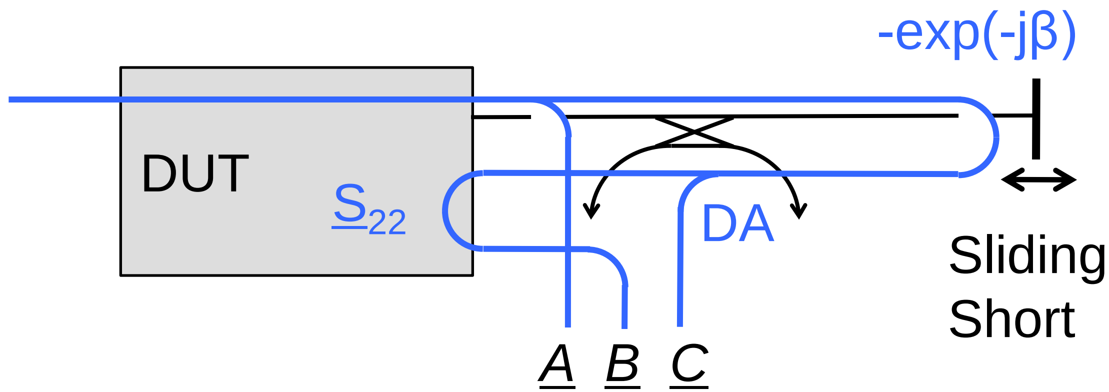


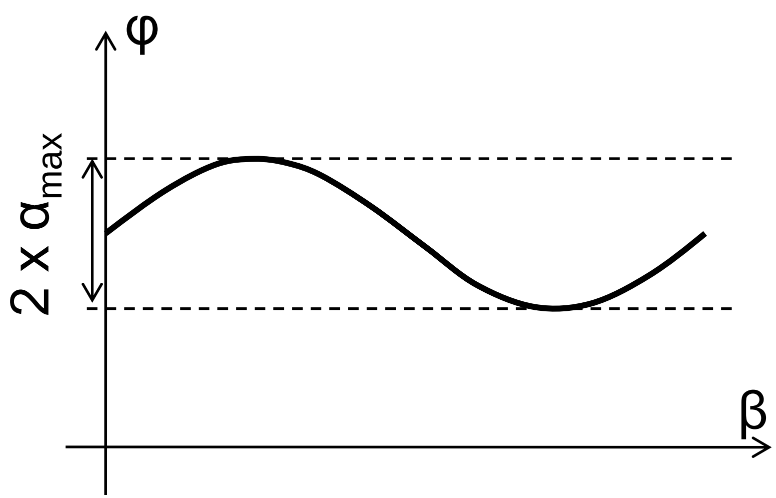
|S22| in dB
-5
-10
-15
-20
-25
-30
-35
-40
-45
-50
-55
|S22| in dB
0
-10
-20
-30
-40
-50
-60
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
Coil Current in A
20
25
30
35
40
45
Temperature in C

Sep. Low Power Measurements – Behavior @ 28 C



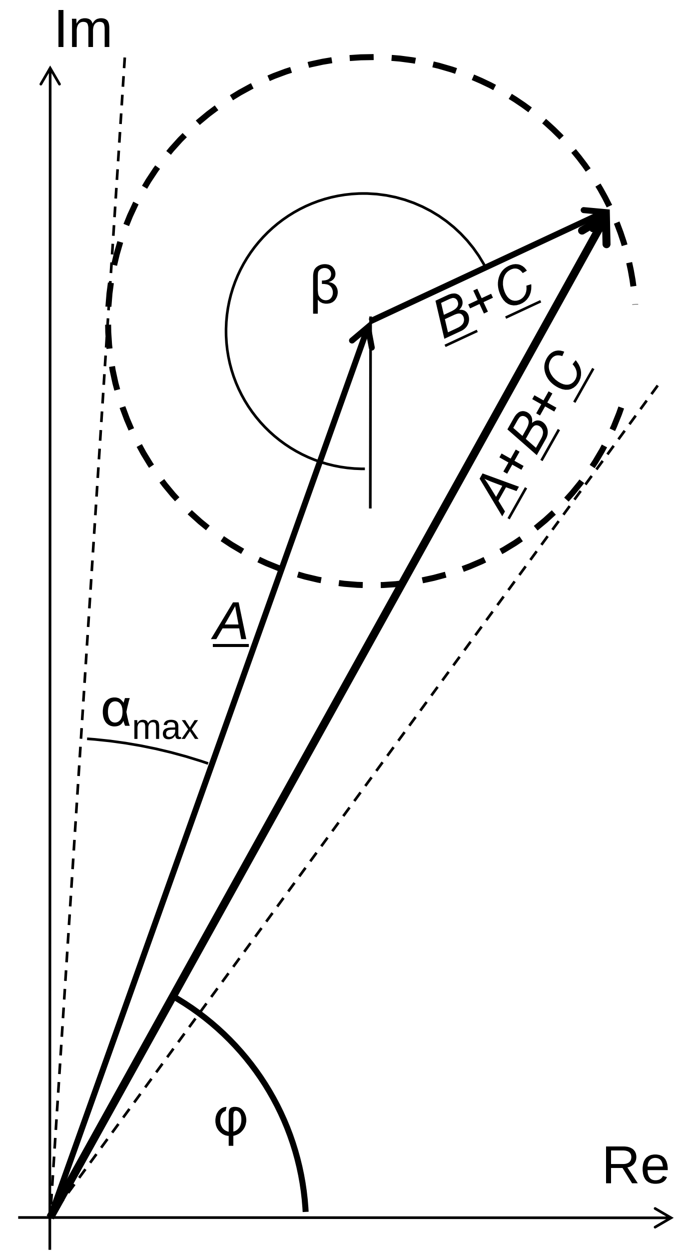
“Hot” S_{22} - Measurement Principle





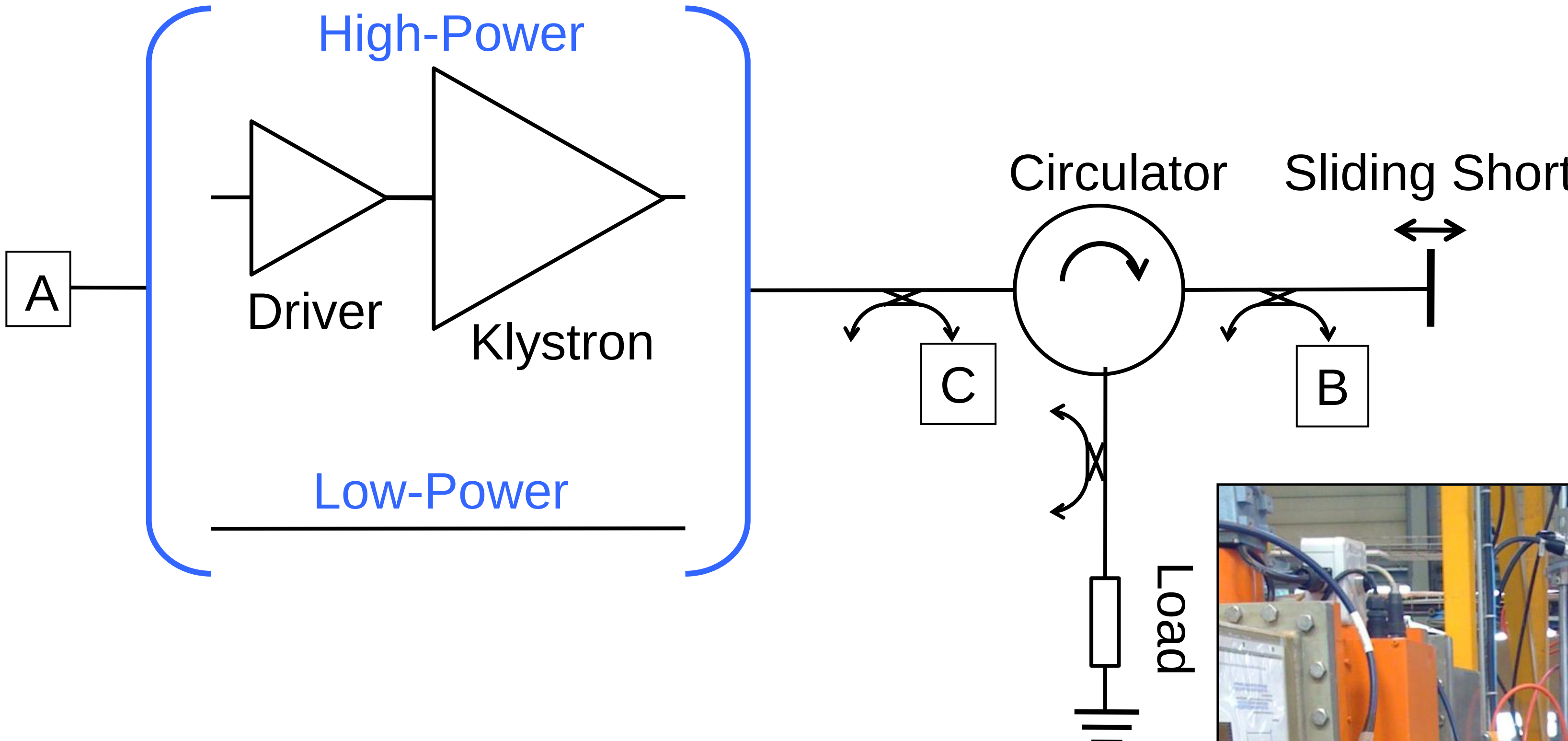
With |B| >> |C|,

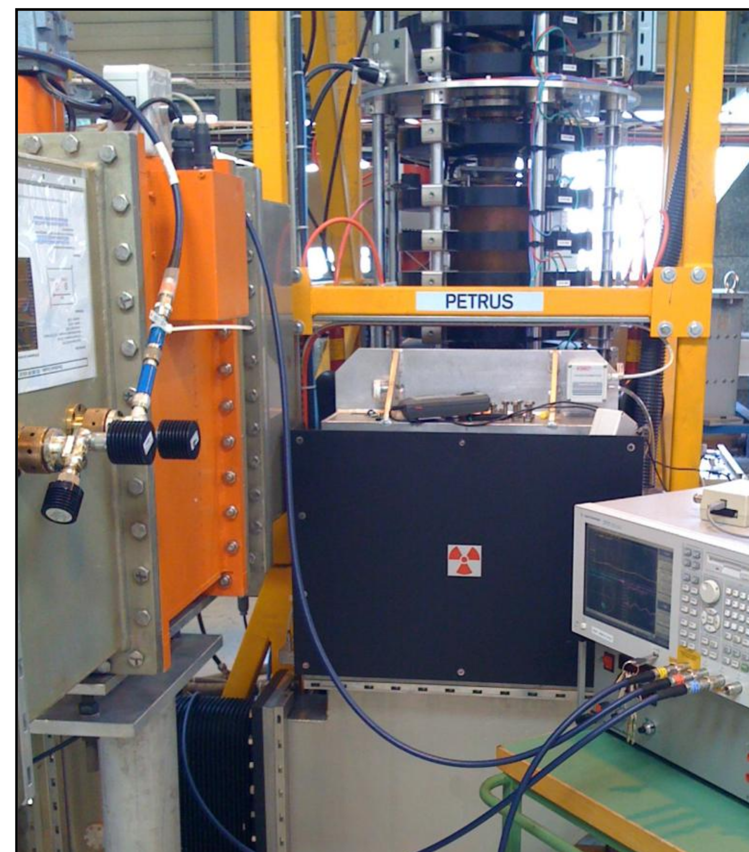
$|S_{22}| = |B/A|$
$= \sin(\alpha_{max})$



[NM09] Patrick Naraine and Chandra Mohan. Theory and proposed method for determining large signal return loss or ”hot S22 ” for power amplifiers. Microwave Journal, 52(6):92, June 2009.

Measurements on the Test-Stand

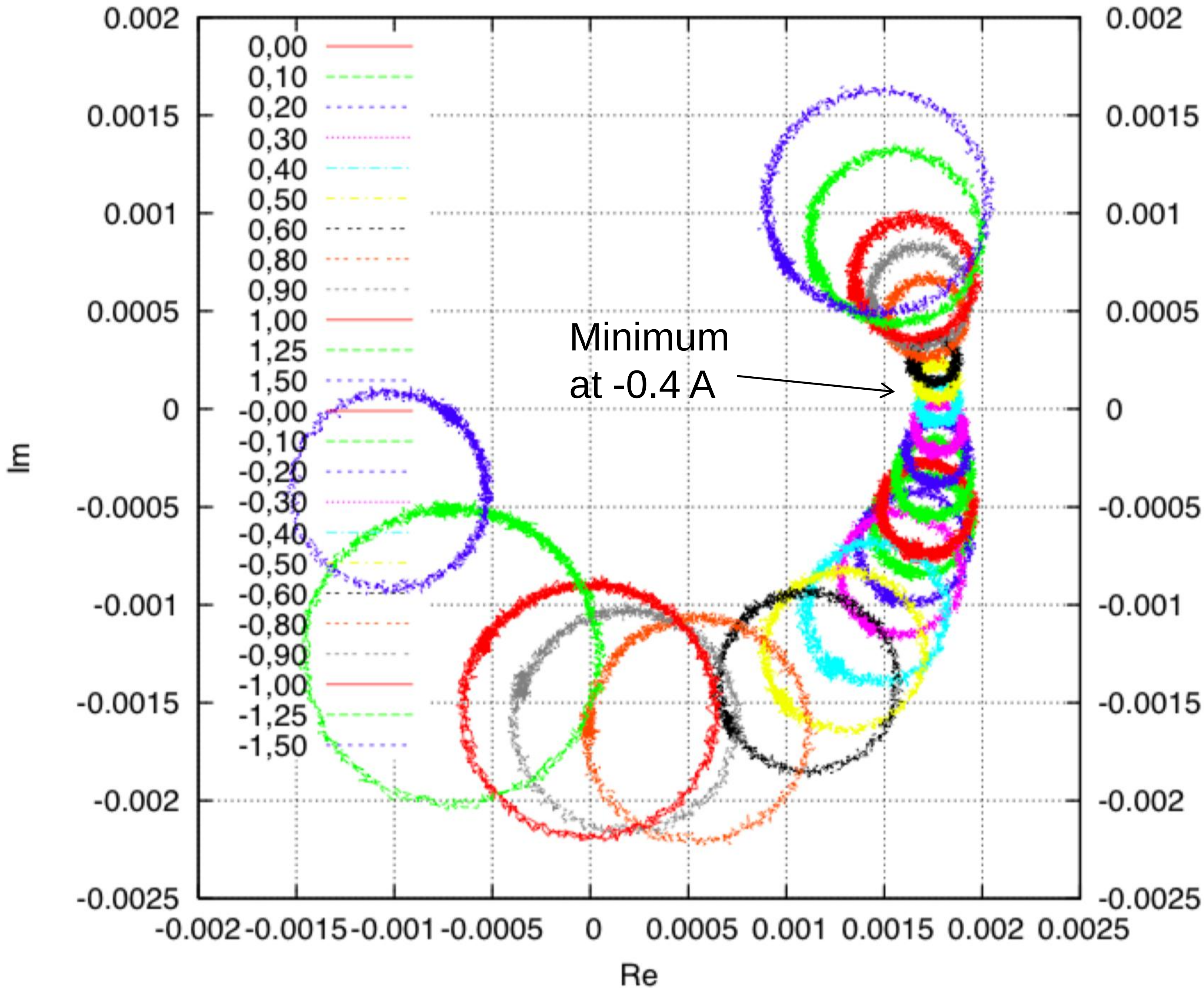




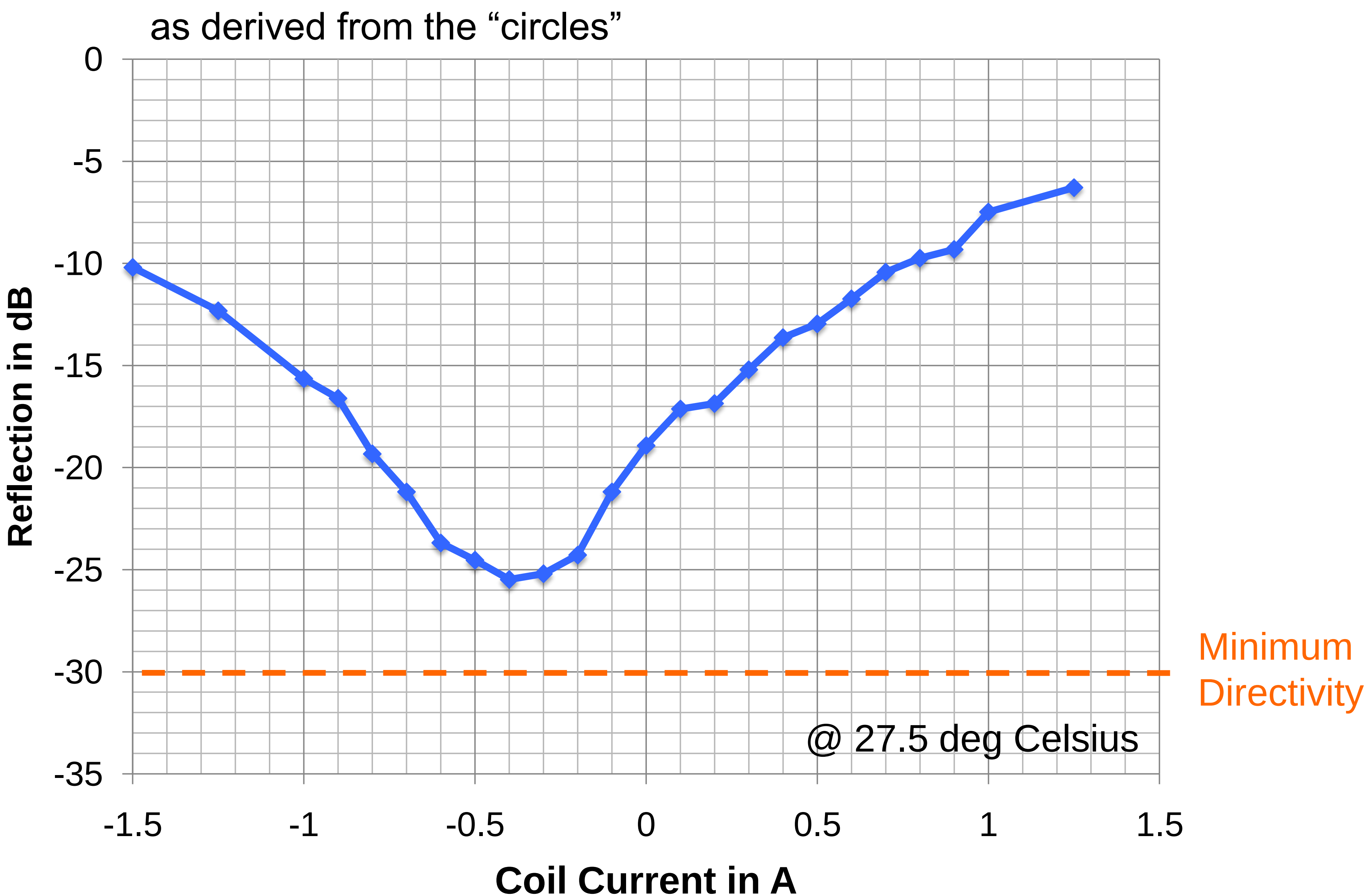
Low-Power Measurements:
S_{AA} = Input Reflection
S_{BA} = Transmission through Circulator

High-Power Measurements
S_{CA} = Forward Power
S_{BA} = Transmission through Circulator

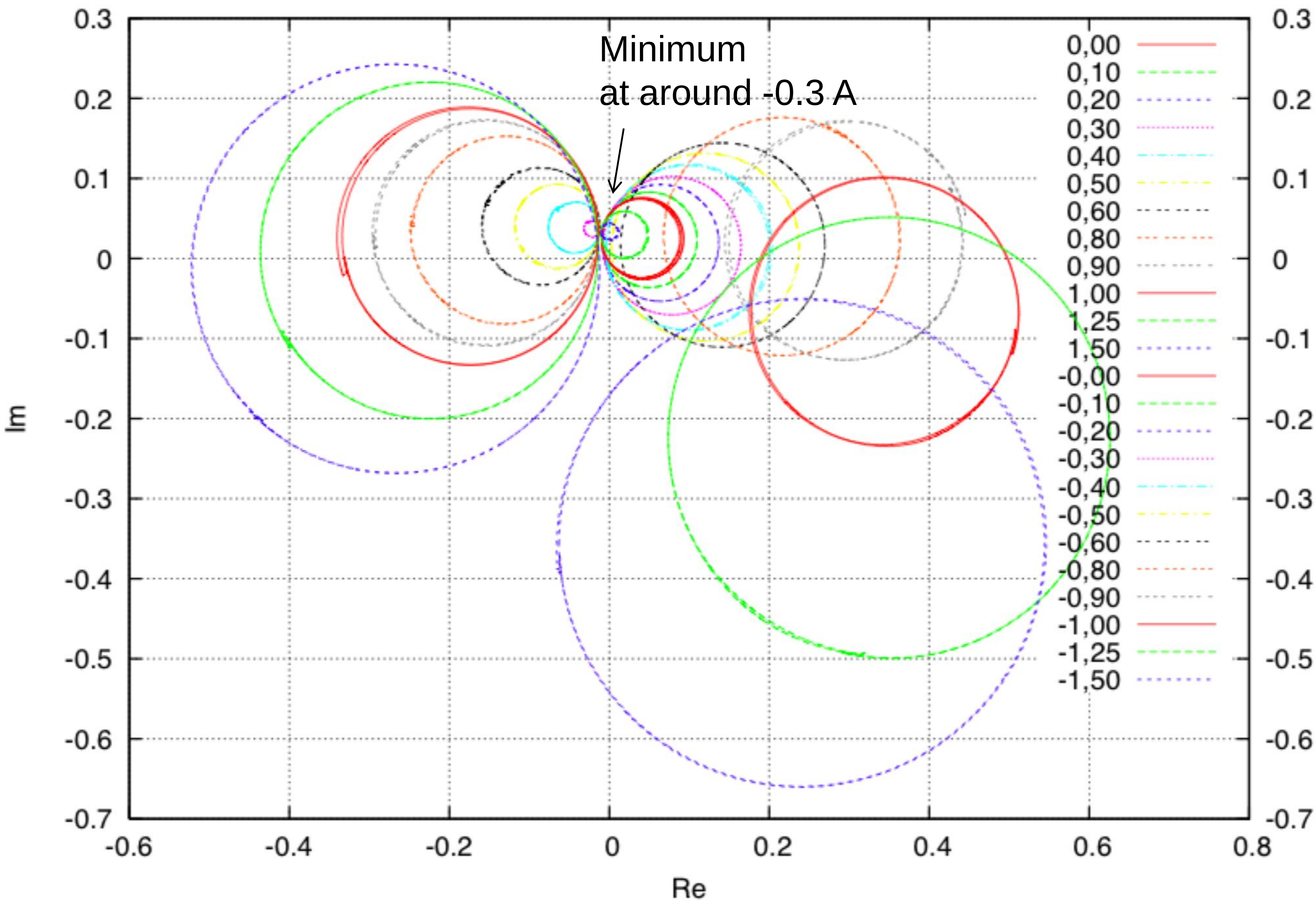
Low Power Measurements – Circles for S_{BA}



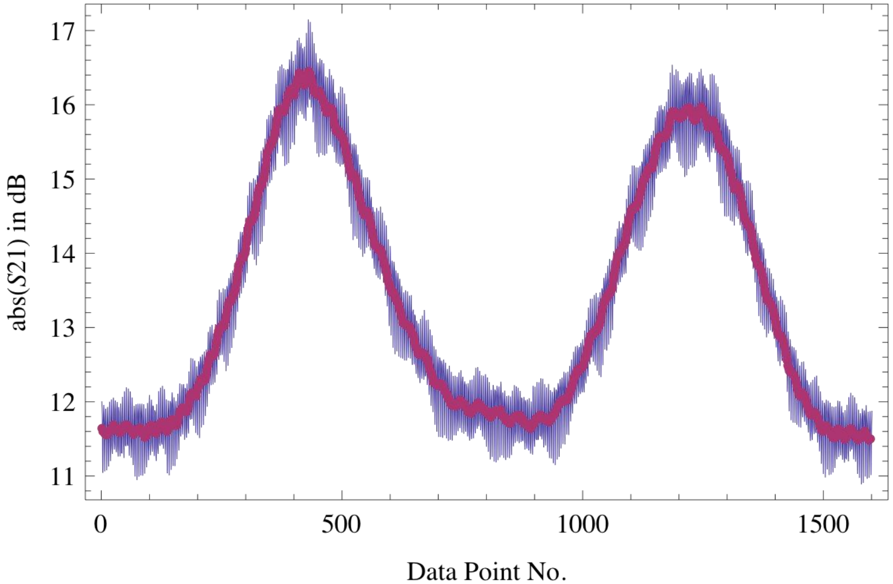
Low Power Measurements – S_{22} versus Current

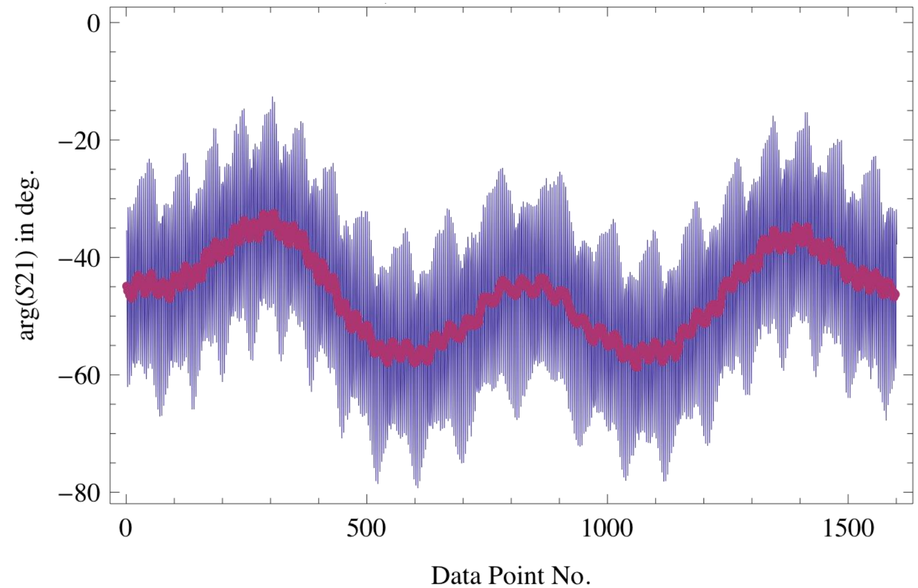


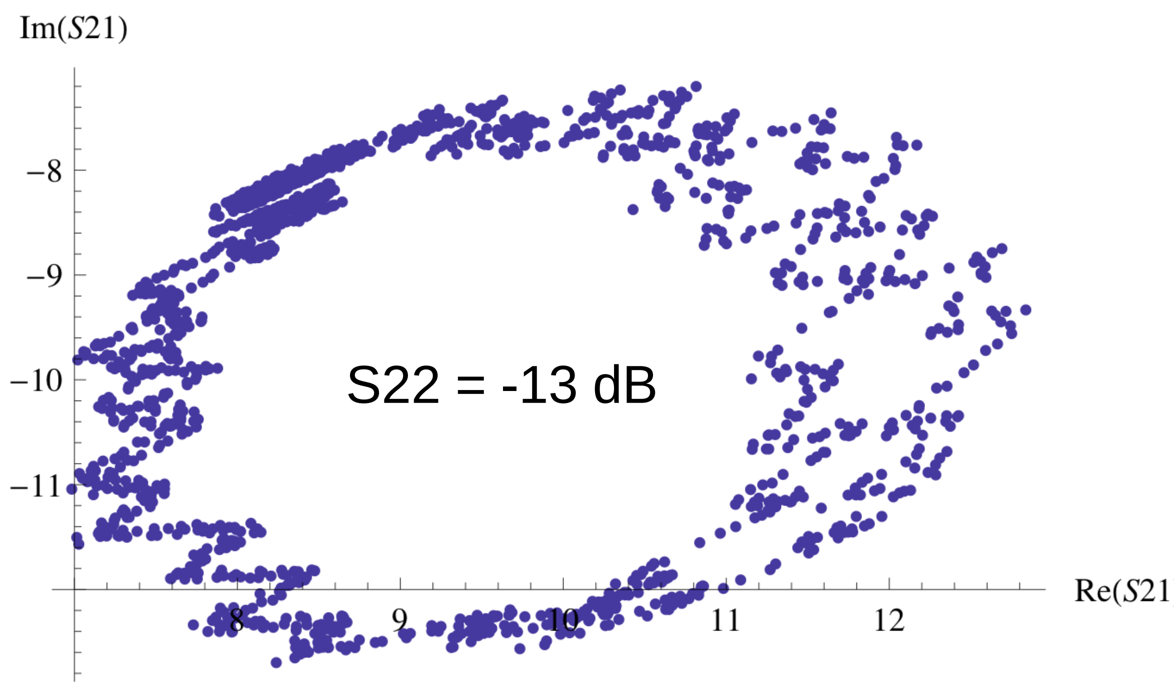
Low Power Measurements – Circles for S_{AA}



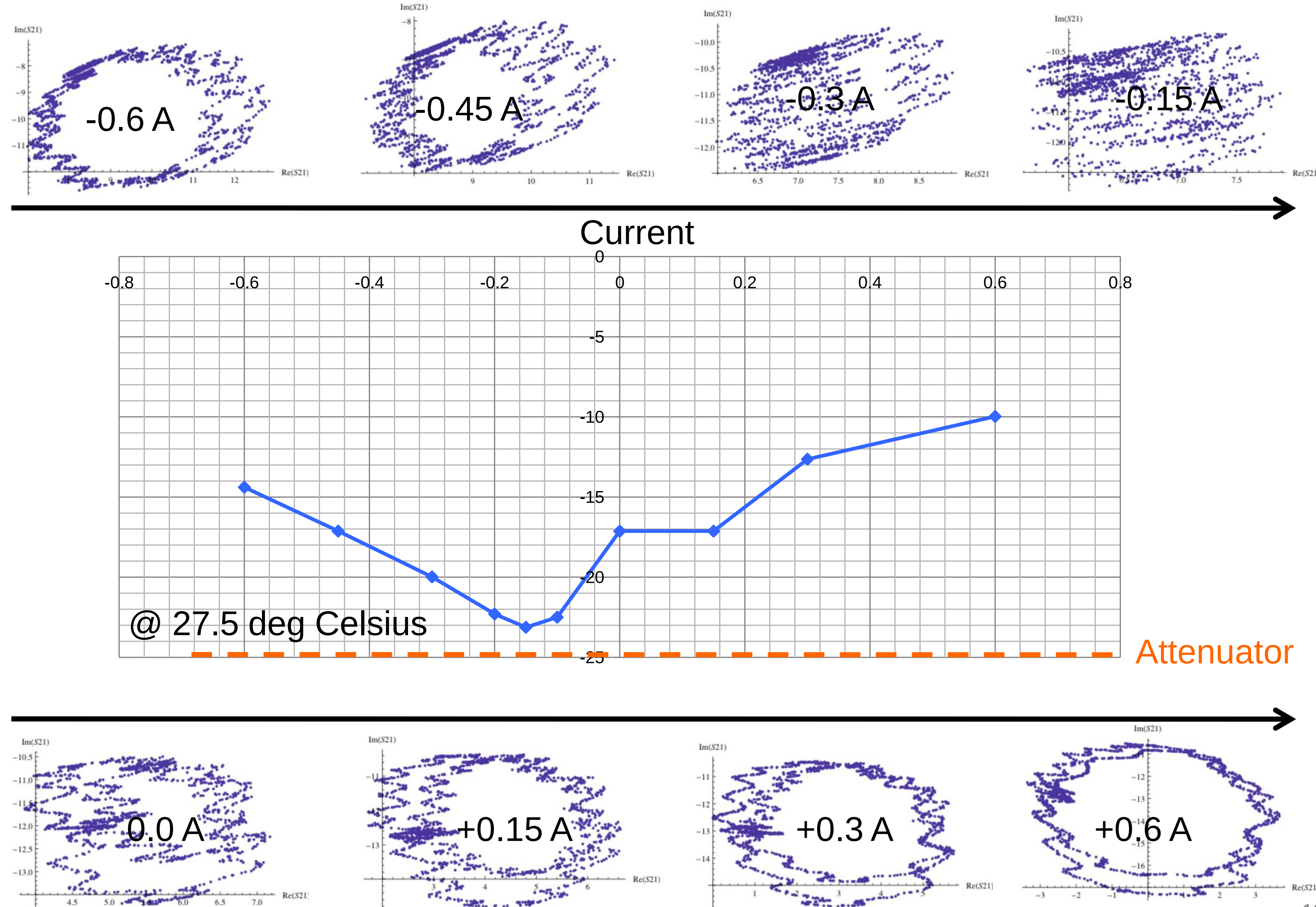
High-Power Measurements – 50 kW - Current +0.6 A



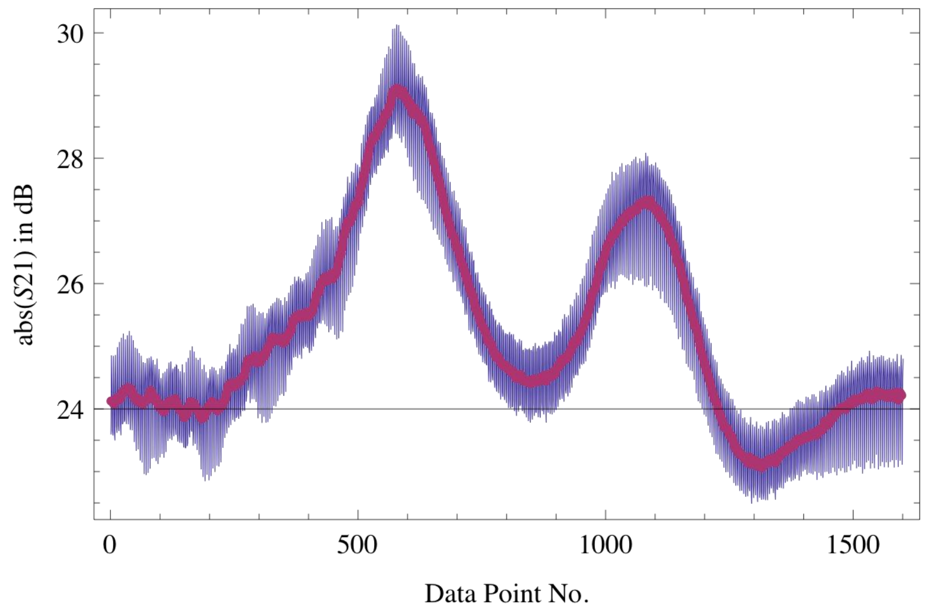


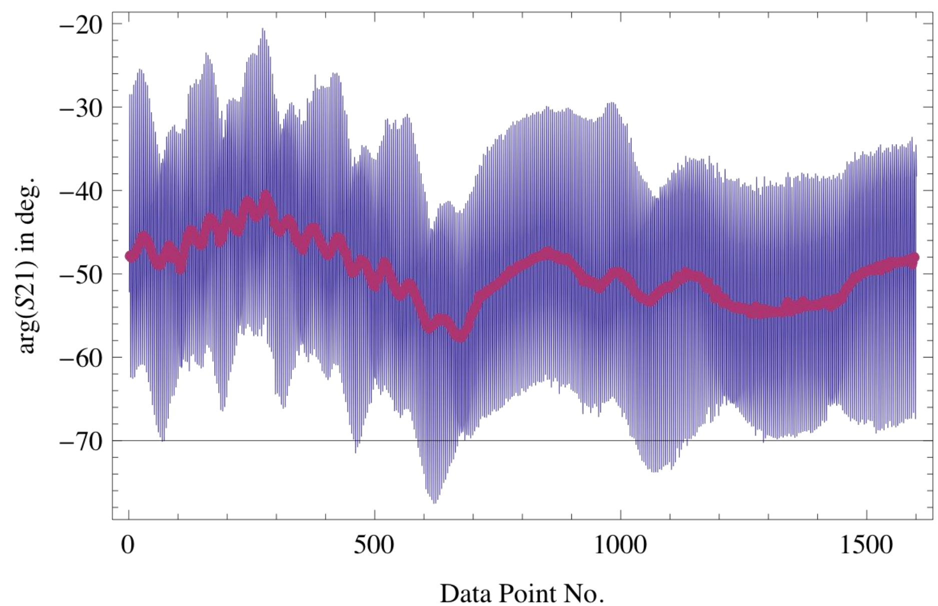


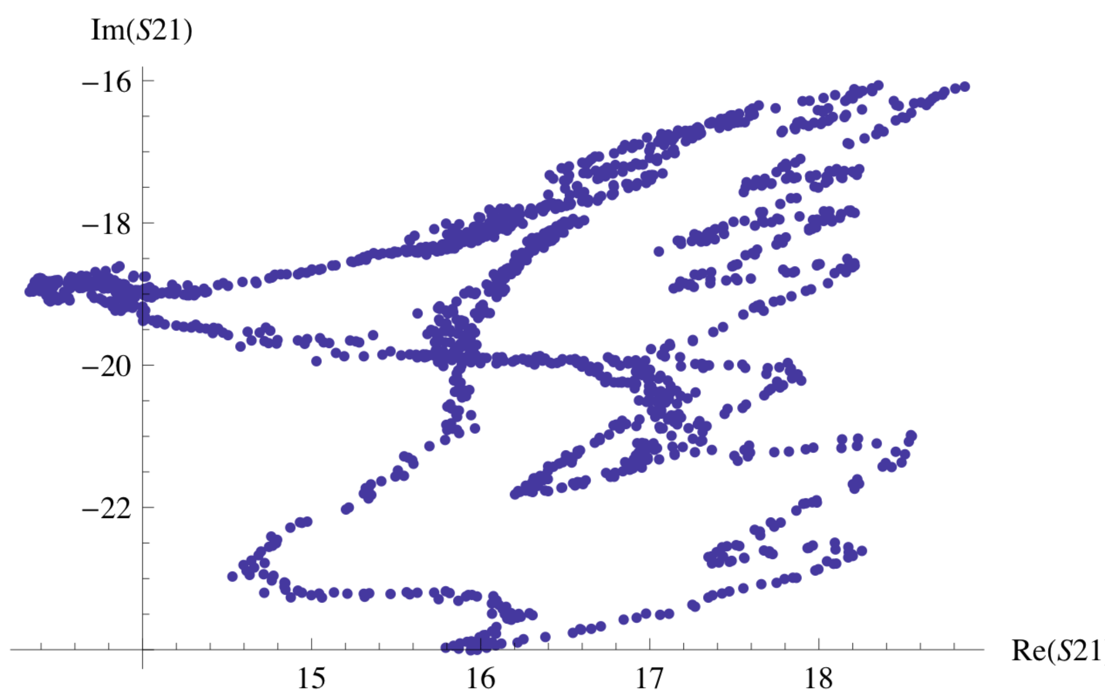
High-Power Measurements – 50 kW - S_{22} versus Current



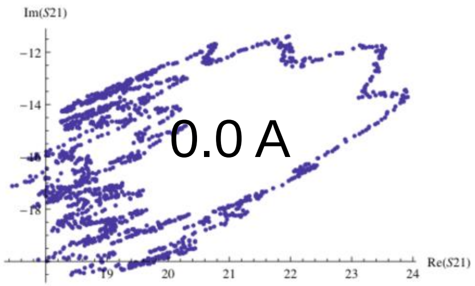
High-Power Measurements – 200 kW - Current +0.3 A

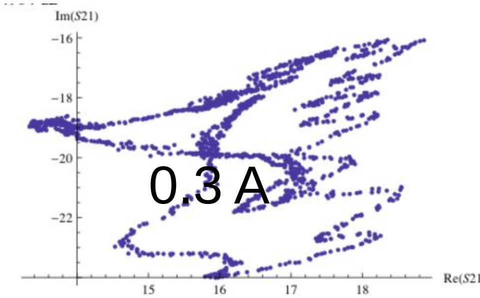


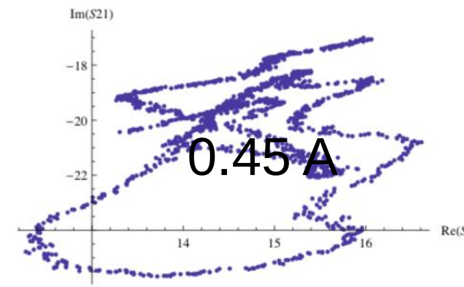




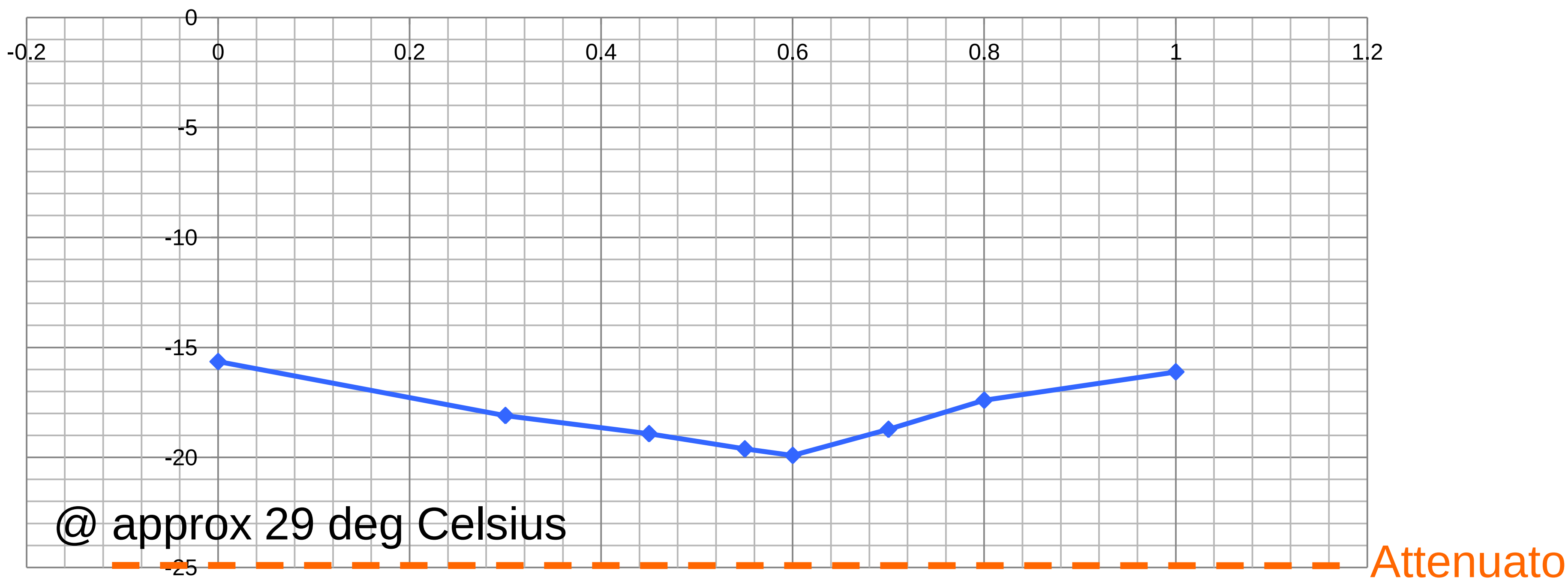
High-Power Measurements – 200 kW - S_{22} versus Current

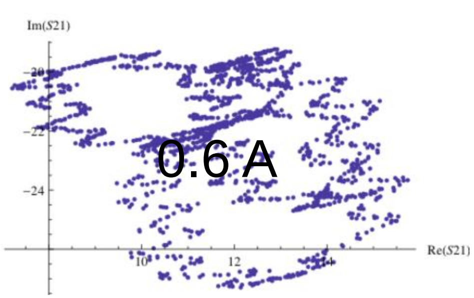


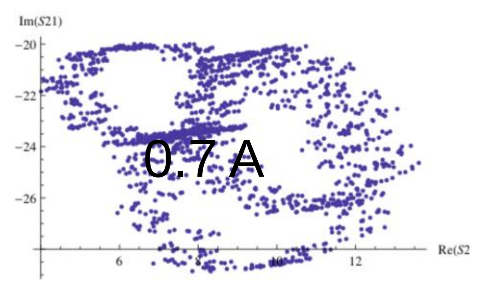


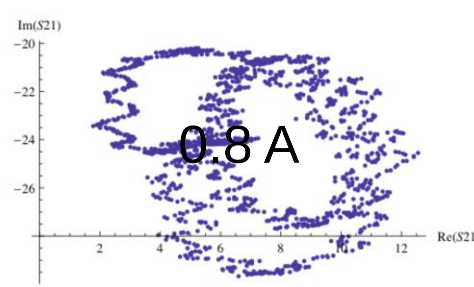


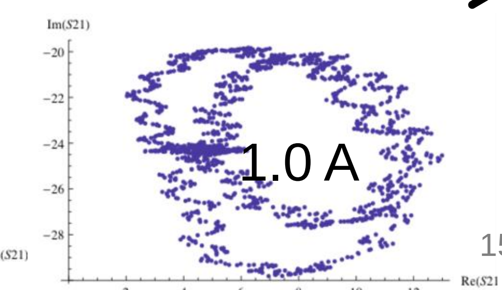
Current





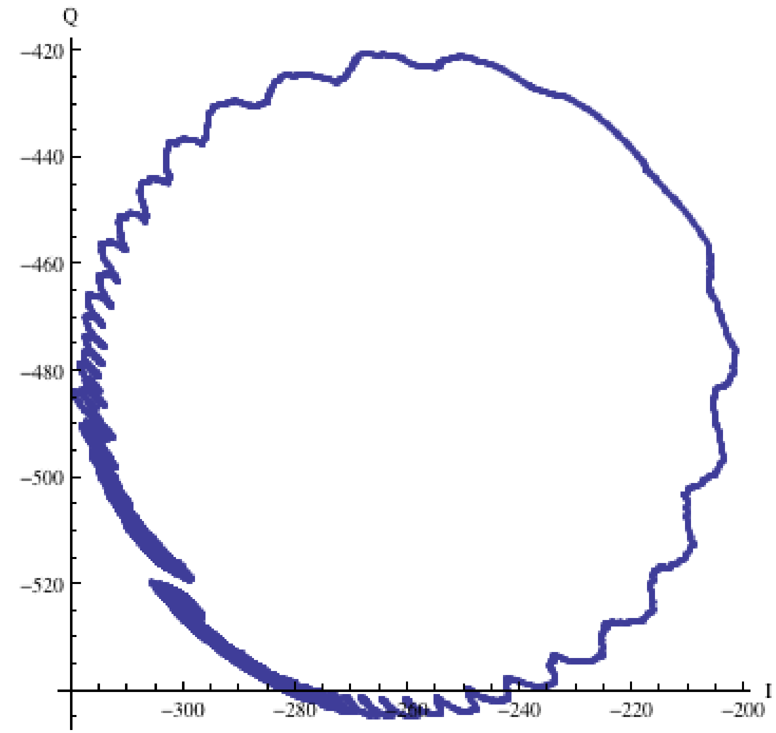


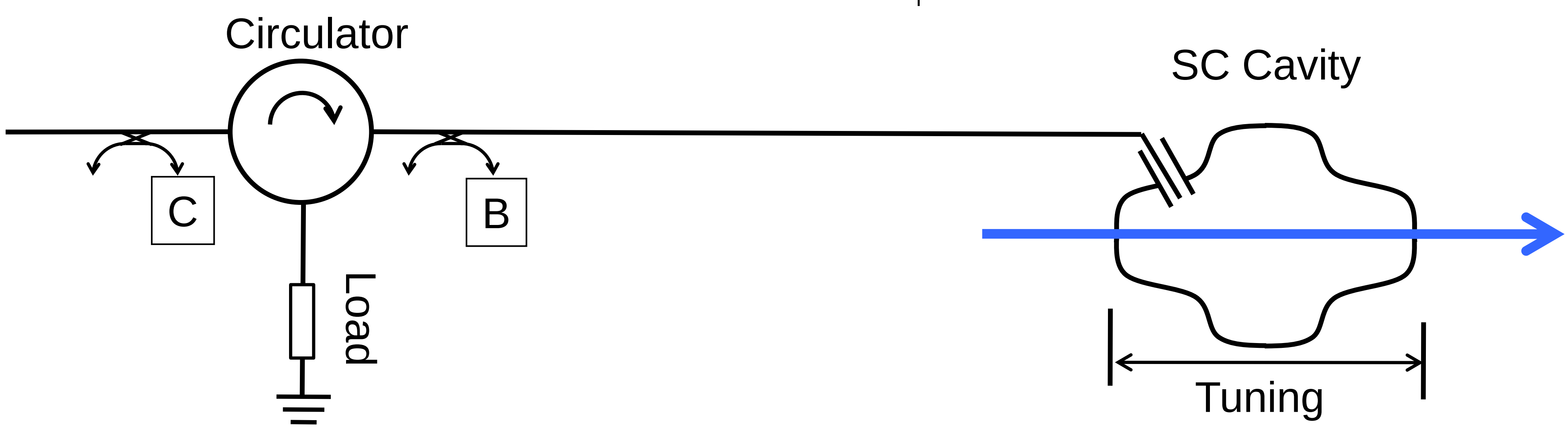




In-situ Measurements performed in LHC

- At start up 2009, LLRF Team performed S22 measurements using installed cavities
  - Phase shift by detuning cavity
- For 160 kW the measurements give an S22 of -22 dB
  - Current = -0.41 A (TCU)





Summary and Outlook

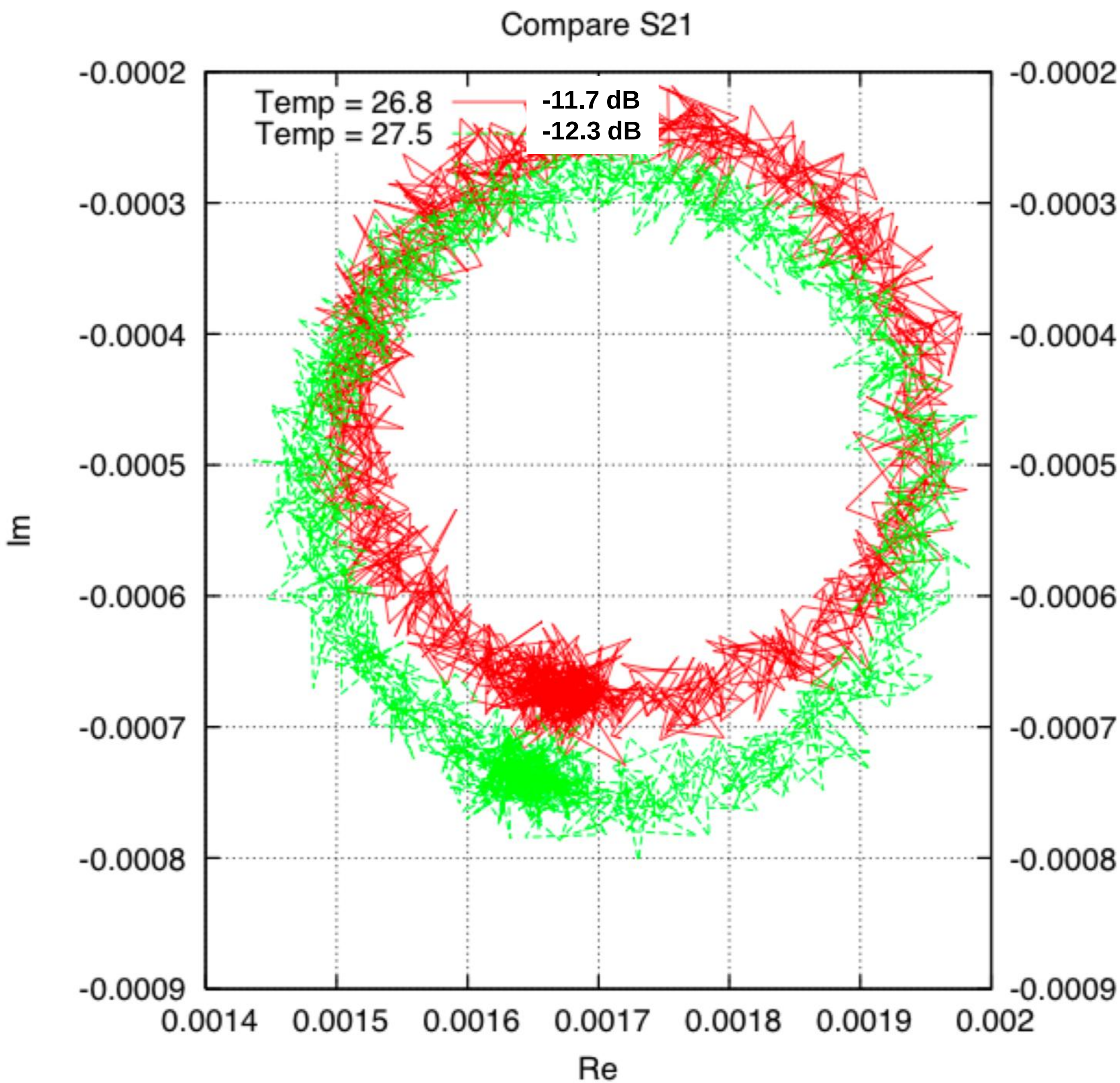
➔ The Method for “hot” S_{22} measurement works

➔ Improvements necessary at:
- Compensation of thermal drift during sliding short movement
- Reduction of phase noise
- Analysis and compensation of input power variations
- Reduction of the reflection of the Test-Stand and other used components

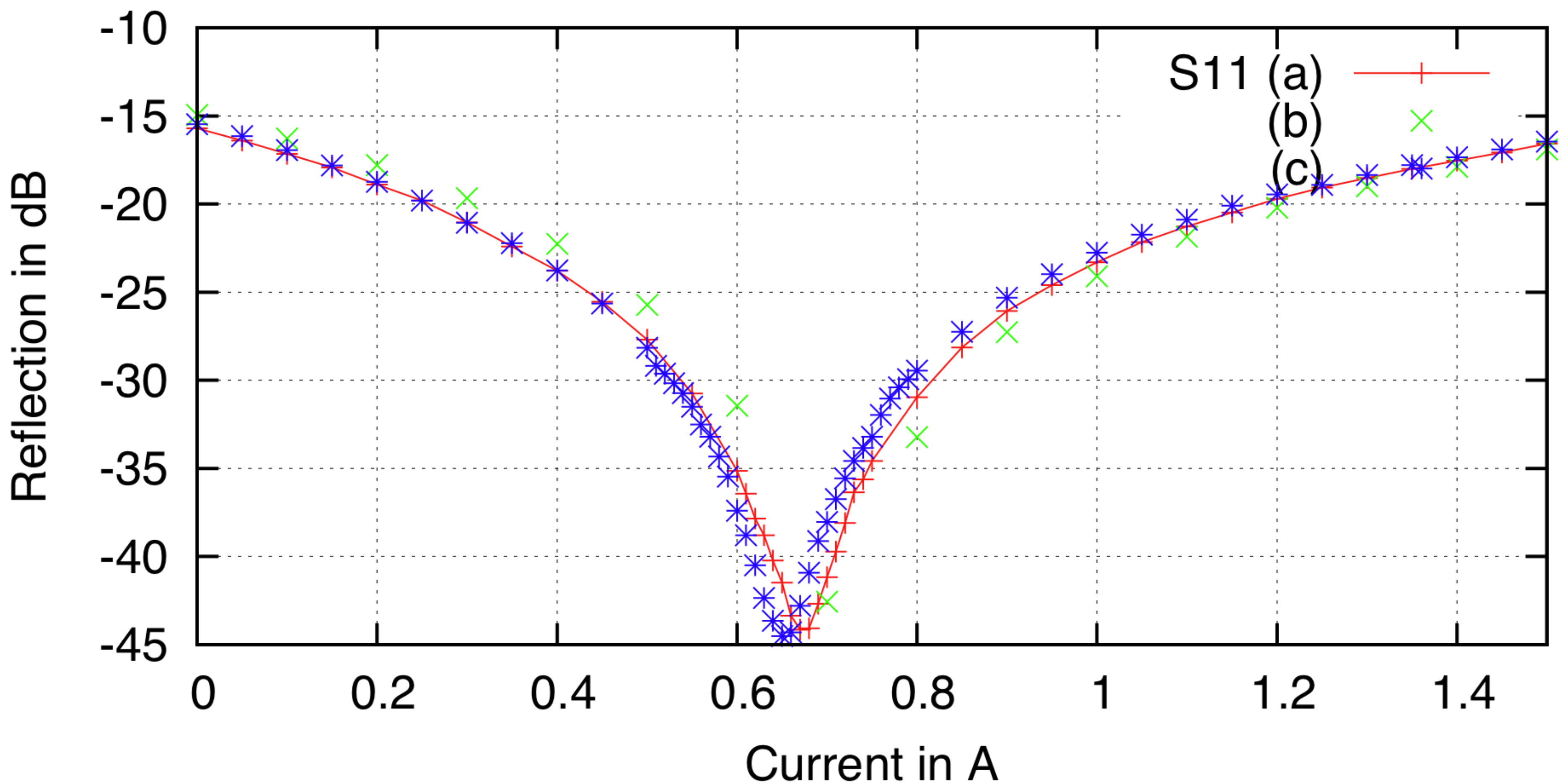
➔ **“While we are at it, what else would be worth investigating?”**

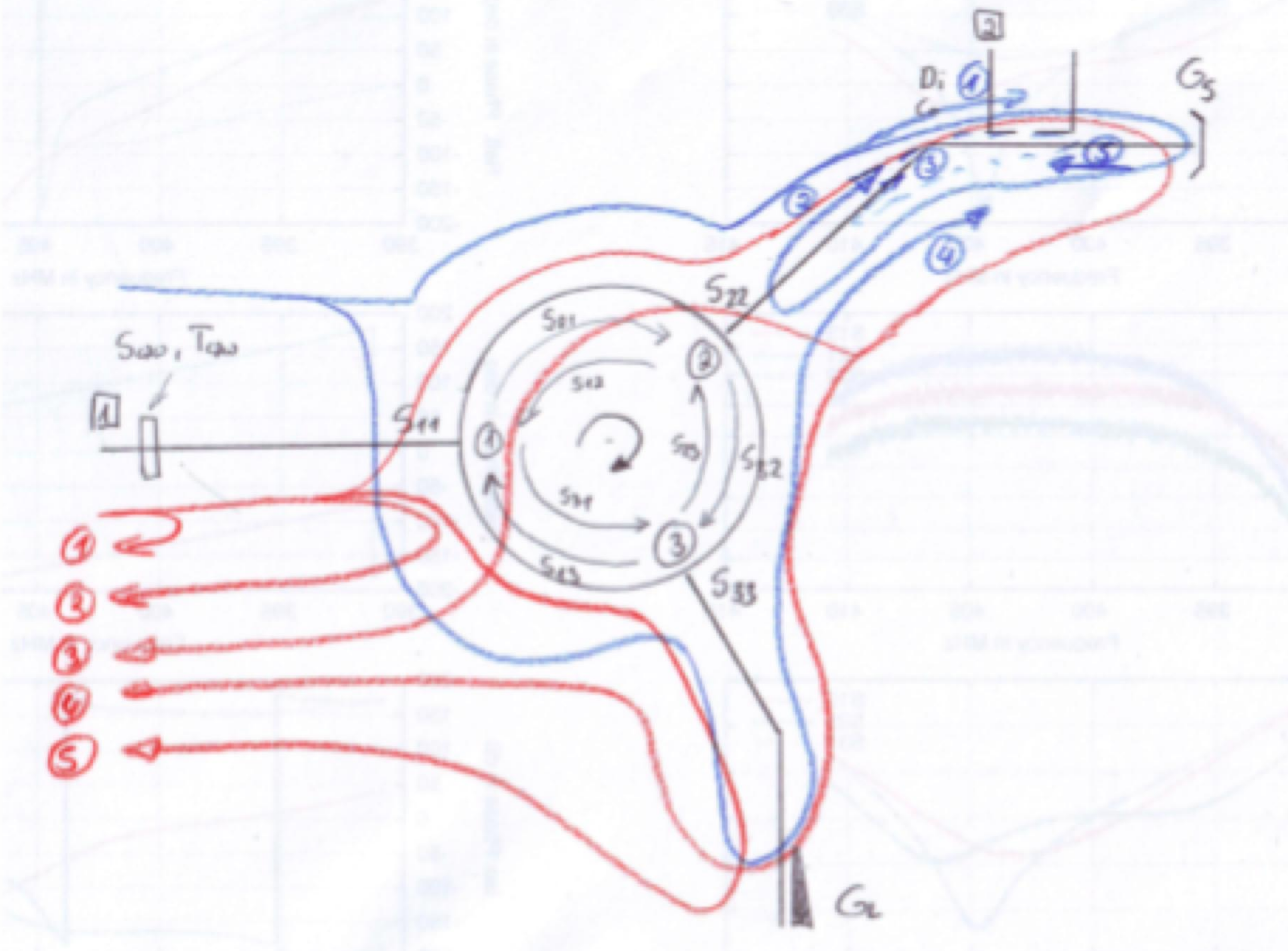
➔ Measurement results shall help:
- To improve the determination and adaptation of the loaded Q
- To provide a model of the circulator for different working conditions

Low-Power Measurements: Thermal Drift



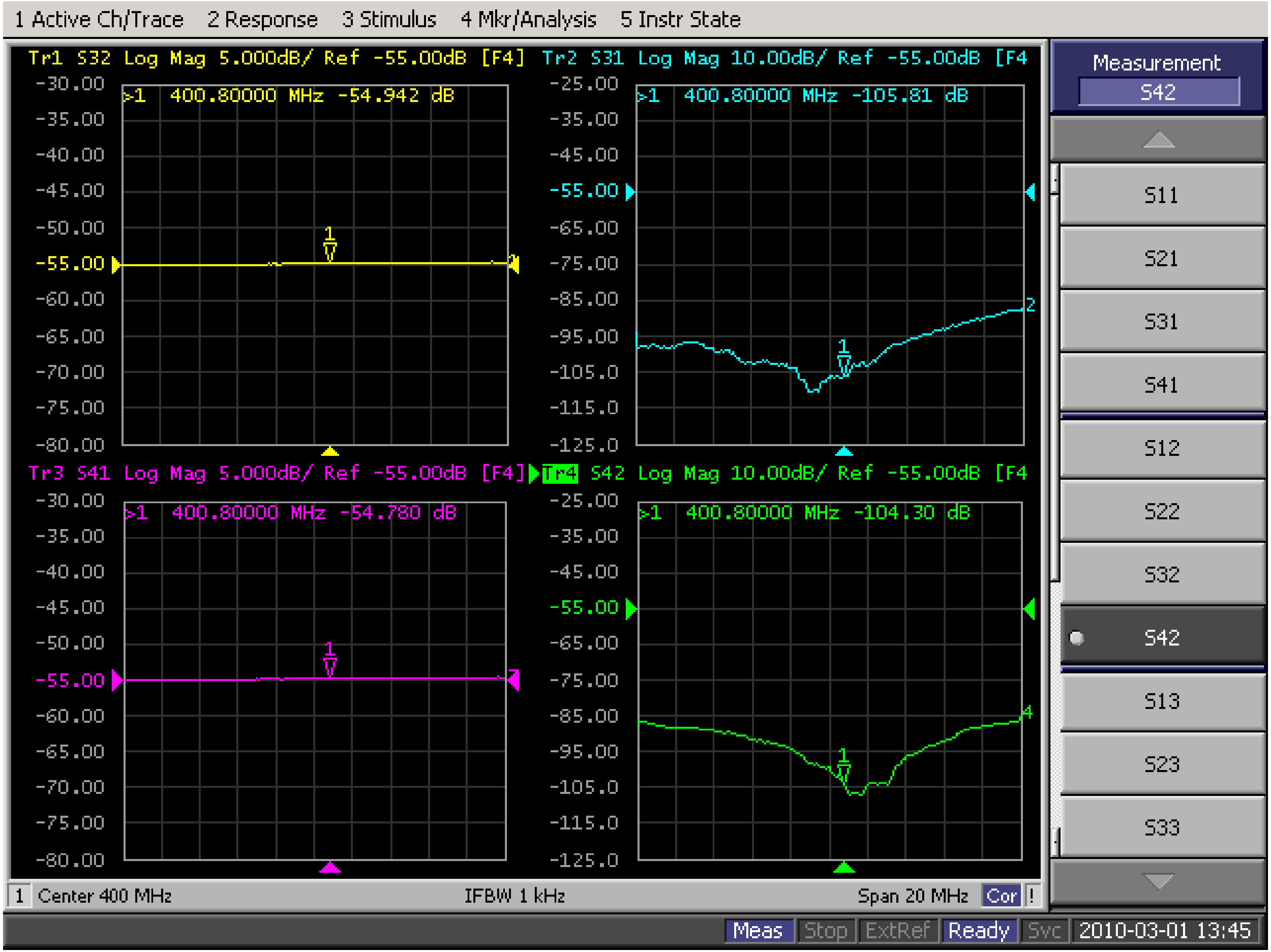
Measurement Stability





2
Di
1
Gs
3
5
2
4
S22
S21
2
S12
S11
1
S0a, T0a
1
S32
S23
S31
3
S13
S33
1
2
3
4
5
GL

Directional Coupler Values



Attenuator Values