AFT microwave

Twelfth Continuous Wave and
High Average Power RF Workshop

+50 V/61538 A
1 mW
2 MW

12.-14.9.2022
CERN
Geneva, Switzerland
http://cern.ch/CWRF22

Overview of High-Power Ferrite Devices and Key Considerations for the Design, Operation and High-Power Testing of Ferrite Circulators

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CWRF 2022, CERN, Geneva

From Milliwatt to Megawatt

Outline

1. Introduction of AFT
2. Basics of microwave ferrites
3. Circulators & other ferrite devices and their use in high-power RF
4. About the term "Isolation" in an RF distribution system
5. High-power design aspects and power handling requirements
6. High-power test set-up, test procedure, safety interlocks, arc detection
7. Summary

AFT microwave

Who we are

AFT is a leading manufacturer of high-performance passive microwave components and subsystems based on own ferrite ceramics and thin-film technology.

Protection & reliability for MW systems „from milliWatt to MegaWatt“

Where we come from

1950:	AEG Telefunken: ferrite & circulator activities started
1993:	Advanced Ferrite Technology (AFT) established as spin-off from Bosch ANT
2001:	Take-over of thin-film technology from Bosch/Marconi & Siemens
2005:	AFT microwave GmbH, move to new factory building
Today:	About 55 employees in Backnang, Germany We have developed from prototyping to serial production.

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High-Power Products

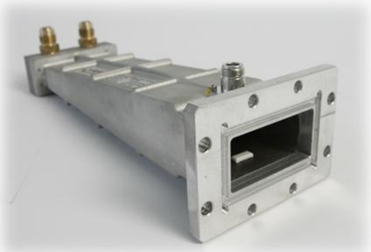
TCUs

Arc Detectors

Circulators

3-port and 4-port

Loads

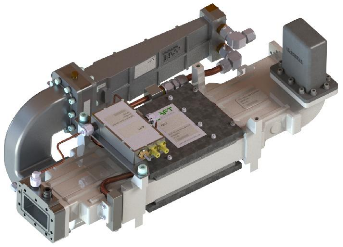


Ferrite, Water, SiC

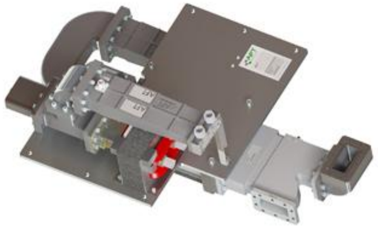
Directional Couplers

AFC Modules

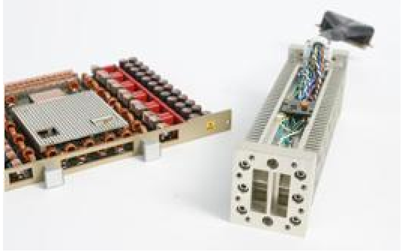
Isolator Assemblies



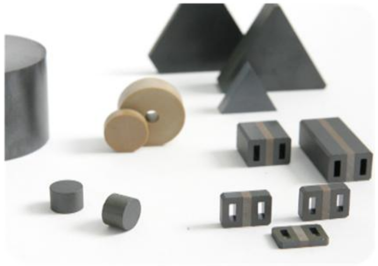
FFT- Power Variators



Ferrite Phase Shifters



Microwave Ferrites



Our Markets

Science

Particle Accelerators

Med-Tec

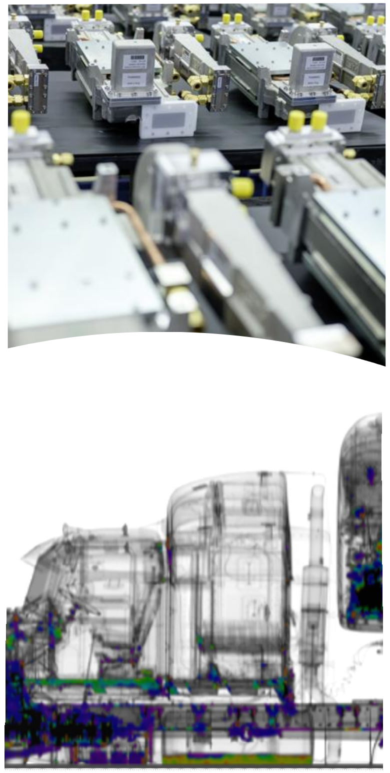
Radiation Therapy

Radar/SatCom

Commercial & Defense

Industry

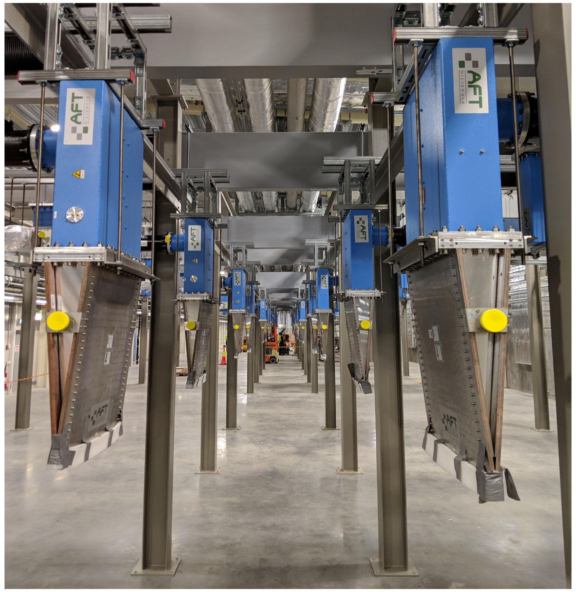
Cargo scan, NDT, sterilization, drying, plasma



AFT microwave

Large Scale Projects 2010 ff.

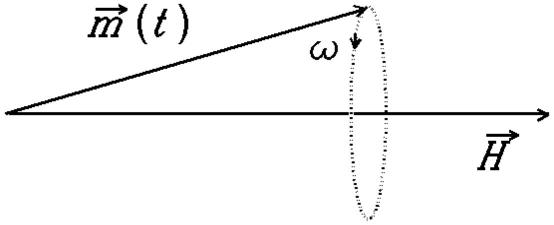
Our circulators & loads have supported the reliable operation of particle accelerators in major research facilities - all over the world & from the very first beginning.



Year	Quantity	Product	Customer, Country
2021	28	Circulator 805MHz 1MWp 90kW Wr1150	ORNL SNS, USA
2021	4	Circulator 352MHz 600kWcw WR2300	CEA, FRA
2021	4	Ferrite Load 352MHz 600kWcw WR2300	CEA, FRA
2020	5	Circulator 500MHz 140kWcw WR1800	Elettra, ITA
2020	10	Ferrite Load 500MHz 140kWcw WR1800	Elettra, ITA
2019/2020	5	Circulator 352MHz 3MWp 150kW WR2300	ESS Bilbao
2019/2020	6	Ferrite Load 352MHz 3MWp 150kW WR2300	ESS Bilbao
2019/2020	6	Ferrite Load 352MHz 1.5MWp 75kW WR2300HH	ESS Bilbao
2019	2	Circulator 352MHz 3MWp 150kW WR2300	ESS ERIC, SWE
2019	2	Ferrite Load 352MHz 1.5MWp 150kW WR2300HH	ESS ERIC, SWE
2019	2	Ferrite Load 352MHz 3MWp 150kW WR2300	ESS ERIC, SWE
2018/2019	80	Circulator 704MHz 1.5MWp 74kW WR1150	ESS ERIC, SWE
2018	82	Ferrite Load 704MHz 1.5MWp 74kW WR1150	ESS ERIC, SWE
2017/2018	26	Circulator 352MHz 400kWp 20kW 6 1/8" EIA	ESS ERIC, SWE
2017/2018	28	Ferrite Load 352MHz 400kWp 20kW 6 1/8" EIA	ESS ERIC, SWE
2015	8	Isolator 100MHz 120kWcw 6 1/8" EIA	MAX IV, SWE
201344	6	Circulator 350MHz 1300kWcw WR2300	KAERI, Korea
201443	6	Ferrite Load 704MHz 1.5MWp 100kW WR1150	CERN, SUI
2010	40	Ferrite Load 352MHz 2.8MWp 10kW WR2300	CERN LINAC4, SUI

2. Basics of Microwave Ferrites (biased)

Precessions of
electron spins

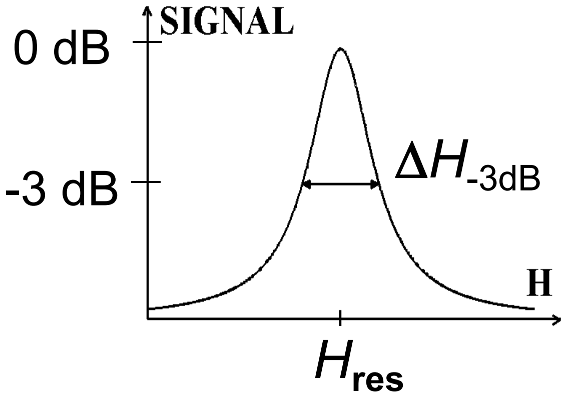


static magnet field

Gyromagnetic
resonance

$$f_{res} = \gamma \cdot H_i$$

γ = 2.8 MHz/Oe



Polder Tensor

Anisotropic
permeability

$$\overleftrightarrow{\mu} = \frac{\vec{B}}{\vec{H}} = \begin{pmatrix} \mu_+ - 1 & 0 & 0 \\ 0 & \mu_- - 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

here: for circular polarization
perpendicular to *H*

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Permeability Tensor

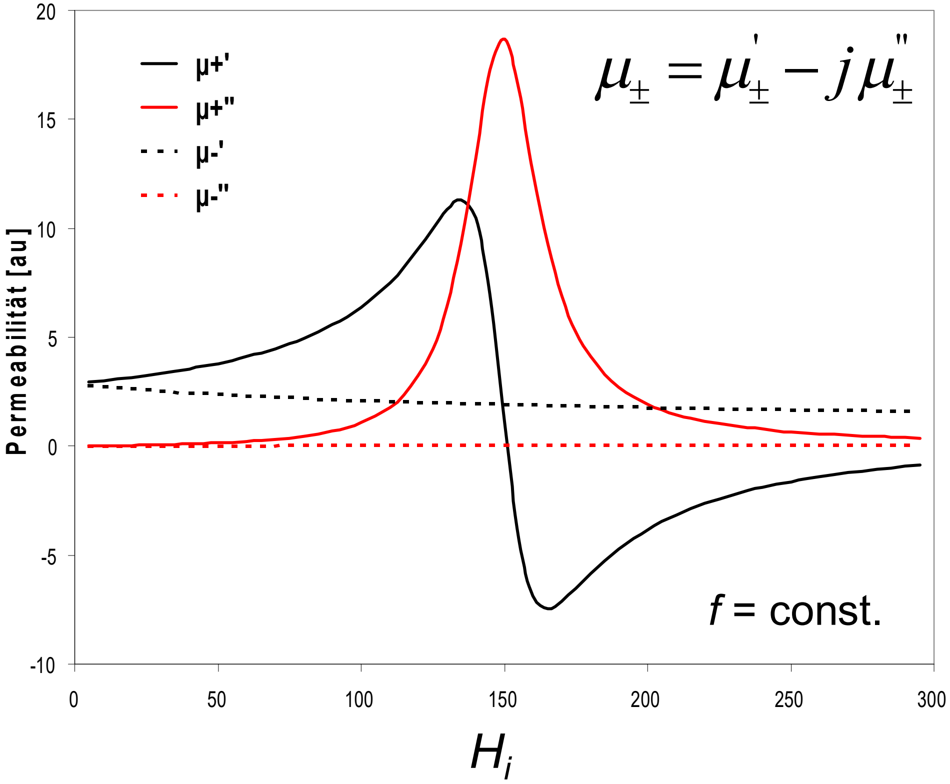
$$\overset{\leftrightarrow}{\mu} = \frac{\vec{B}}{\vec{H}} = \begin{pmatrix} \mu_+ - 1 & 0 & 0 \\ 0 & \mu_- - 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

here: for <u>circular polarization</u> perpendicular to H_0

$$k_\pm = \frac{\omega}{c} \cdot \sqrt{\varepsilon \mu_\pm} \,,$$

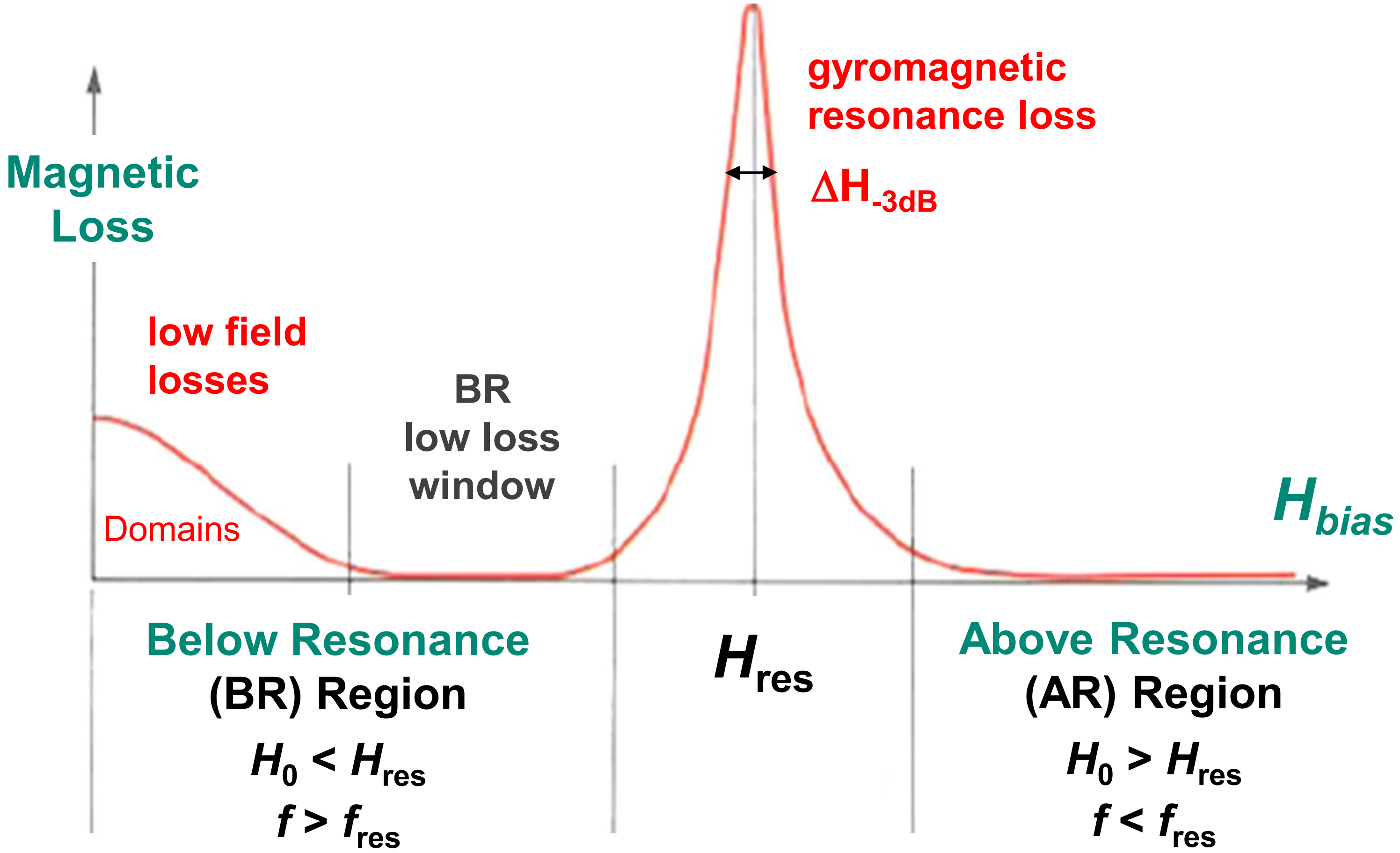
$$\beta_\pm = \frac{\omega}{c} \cdot \sqrt{\varepsilon \mu_\pm^{'}}$$

Complex Permeability



The difference in μ_+ and μ_- is the basis for non-reciprocal devices, the higher the more efficient. Permeability is set by ferrite saturation magnetization M_s, H_i and frequency.

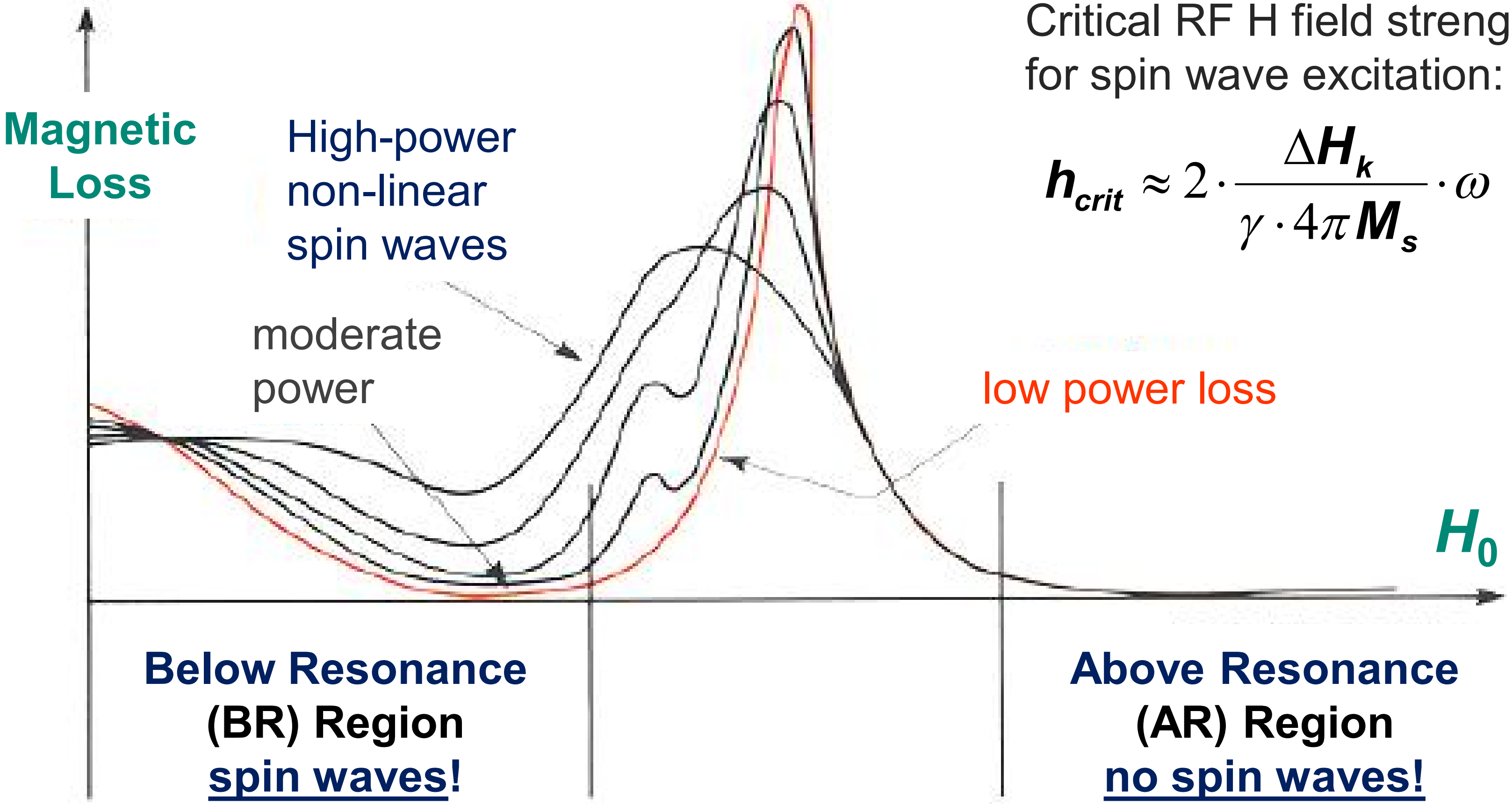
Magnetic Losses in Ferrite (Low Power), f = const.



High-Power Ferrite Losses, f = const.

There is a <u>power limit in BR</u>!
Critical RF H field strength
for spin wave excitation:

$$\boldsymbol{h}_{crit} \approx 2 \cdot \frac{\Delta \boldsymbol{H}_k}{\gamma \cdot 4\pi \boldsymbol{M}_s} \cdot \omega$$



Below Resonance
(BR) Region
<u>spin waves!</u>

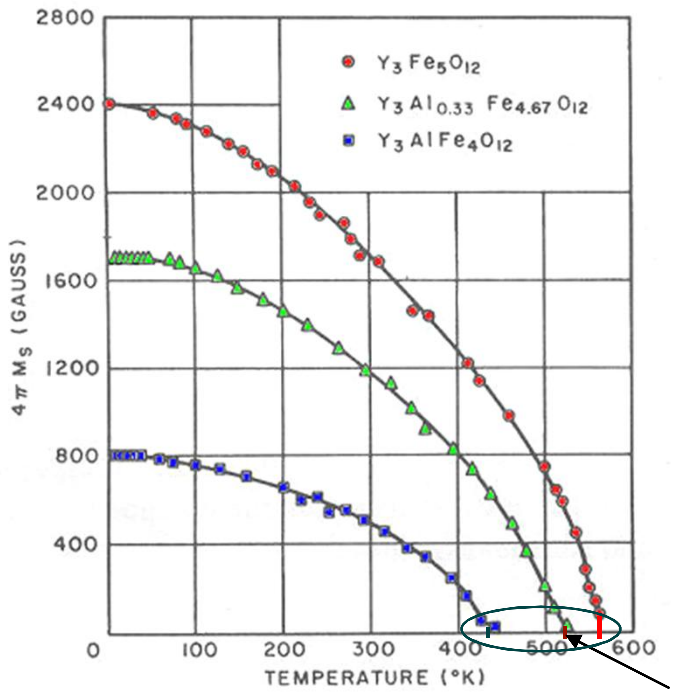
Above Resonance
(AR) Region
<u>no spin waves!</u>

Below Resonance vs. Above Resonance

	Below Resonance	Above Resonance
Definition	$H_{bias} < H_{res}$ $f > f_{res}$	$H_{bias} > H_{res}$ $f < f_{res}$
Criterion for Ms	upper limit to avoid low field loss: $4\pi \boldsymbol{M_s} < \frac{\omega}{\gamma} - \boldsymbol{H_a}$	no limits
Frequency Range	1 GHz to 100 GHz	10 MHz to 10 GHz
Bandwidth	broadband (up to 50%)	narrowband (1 to 20%)
Losses	limits due to low field losses and spin waves over power → ΔH_k !	Very low, since no domains and no spin waves, fully saturated ferrite
Magnet System	low bias → compact, light weight	high bias → bulky, heavy weight
Use	high frequencies, broadband application, low to moderate loss, moderate power, latching	low frequencies, lowest loss, highest power

Ferrite Saturation Magnetization

Al-doped YIG



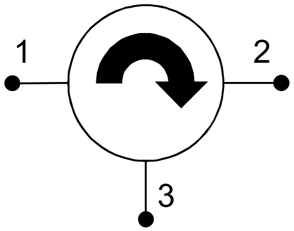
T_{Curie}
$(M_S=0)$

Saturation magnetization M_S decreases with temperature.

→ thermal drift of permeability and circulator performance

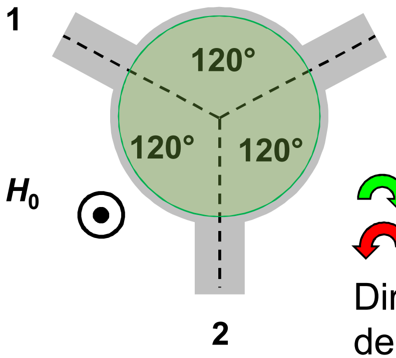
Thermal stabilization by:

1) ferrite doping, e.g. Gadolinium, however with higher losses.
2) Active temperature compensation with magnetic bias control → TCU



3. 3-Port Junction Circulator

Ferrite-loaded junction



$$R \approx \frac{1.84}{2\pi}\cdot\frac{\lambda_0}{\sqrt{\mu_{eff}\,\varepsilon_{r,eff}}}$$

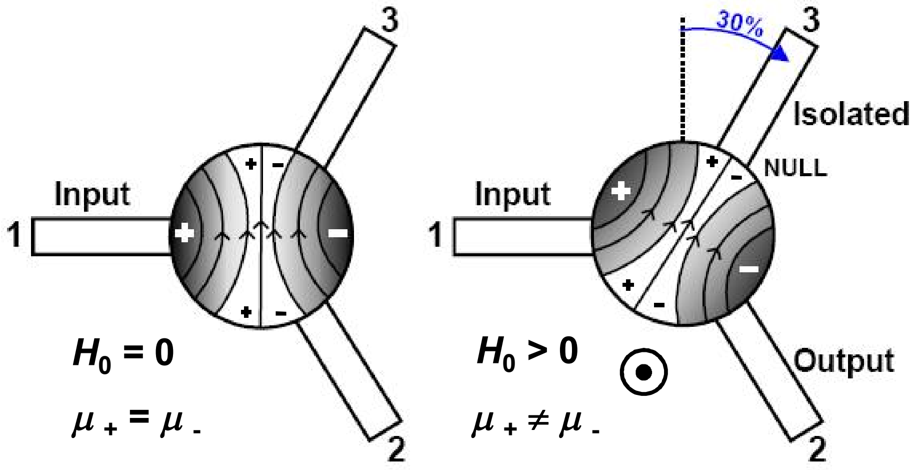
↻ k_+, μ_+

↺ k_-, μ_-

Direction of rotation depends on H_0

$$k_\pm = \frac{\omega}{c}\cdot\sqrt{\varepsilon\,\mu_\pm}\,, \quad \beta_\pm = \frac{\omega}{c}\cdot\sqrt{\varepsilon\,\mu_\pm'}$$

Resonant E field pattern



Transmission 1 → 2, if $2\beta_+\ell - \beta_-\ell = \pm 2N\pi$

Isolation at Port 3, if $\beta_+\ell - 2\beta_-\ell = \pm(2M-1)\pi$ $N, M = 0, 1, 2 \ldots$

Circulator Characteristic Parameters

S-Matrix of an ideal 3-port circulator (lossless)

$$\begin{pmatrix} S_{11} & S_{12} & S_{13} \\ S_{21} & S_{22} & S_{23} \\ S_{31} & S_{32} & S_{33} \end{pmatrix} = \begin{pmatrix} 0 & 0 & 1 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \end{pmatrix}$$

S_{11}, S_{22}, S_{33}: Reflection Coefficients

S_{12}, S_{23}, S_{31}: Isolation Coefficients

S_{21}, S_{32}, S_{13}: Transmission Coefficients

Return Loss Measure for reflected/reverse power

$10 \cdot \log (P_{out\_i} / P_{in\_i})$ [dB] = $10 \cdot \log (P_{refl\_i} / P_{Fwd\_i})$ [dB] for port i

Insertion Loss: Measure for loss due to reflection, dissipation, radiation

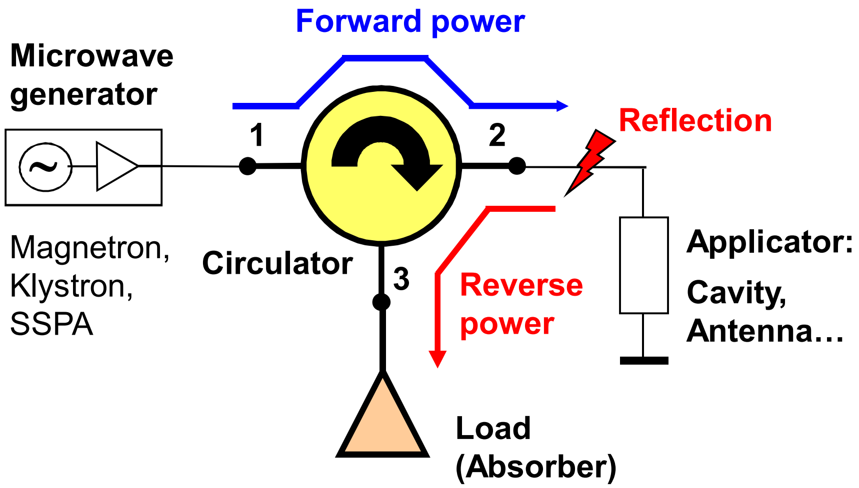
$10 \cdot \log (P_{out\_ii} / P_{in\_i})$ [dB] from port i to port ii

Isolation: Measure for suppression of reflected/reverse power

$10 \cdot \log (P_{out\_i} / P_{in\_ii})$ [dB] from port ii to port i

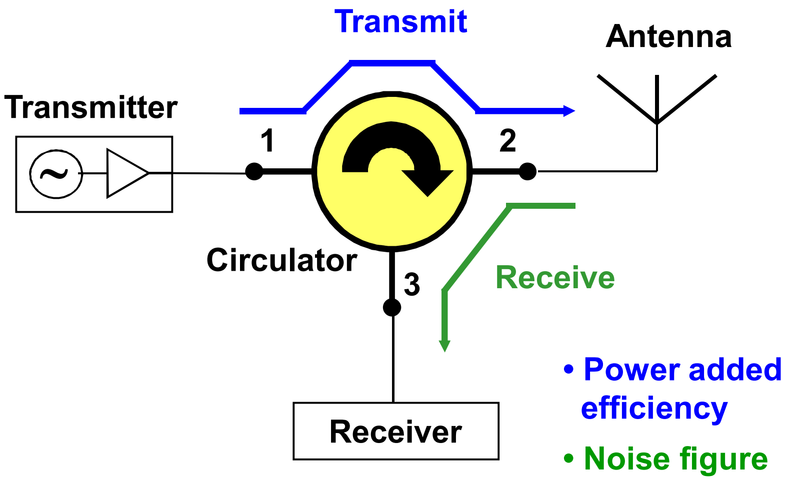
Two Main Circulator Applications

Isolator := Circulator + Load



Reliable protection & stabilization of high-power RF tubes and SSPAs, improve life-time of tube & system, allow continuous failure-free operation.

Diplexer



Diplexer in T/R modules of radar systems with phased array antennas

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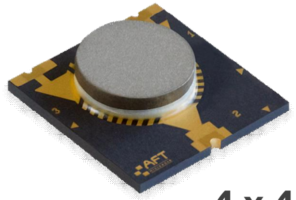
3-Port Circulators

From milliWatt to MegaWatt

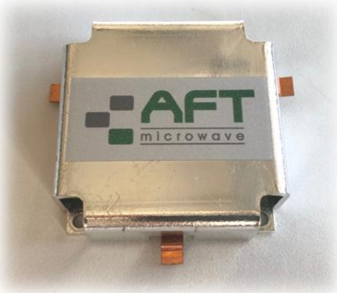
From 27 MHz to 31 MHz

Thin film
Microstrip, SMD



4 x 4 mm²

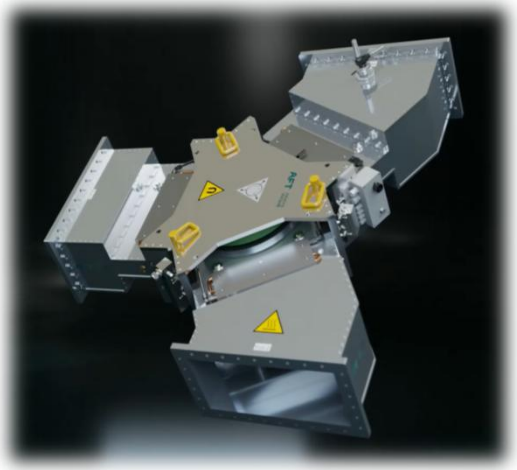
Drop-In
Stripline for SSPA



Coaxial

Power ↑, Frequency ↓

Waveguide



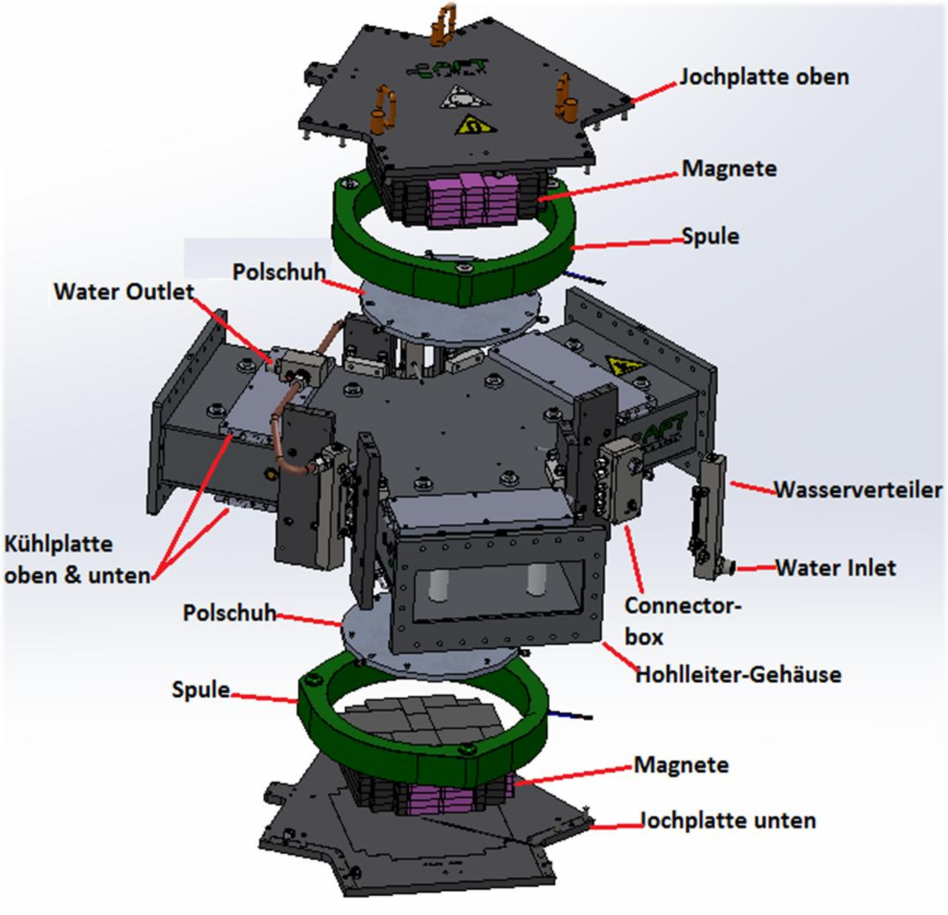
2 x 2 m²

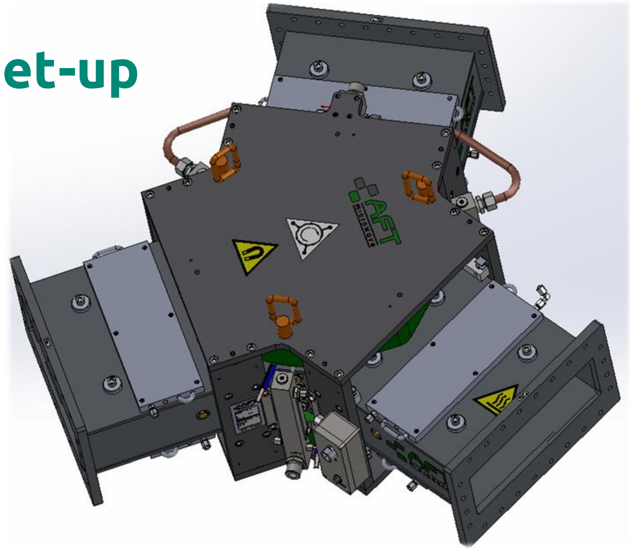
up to

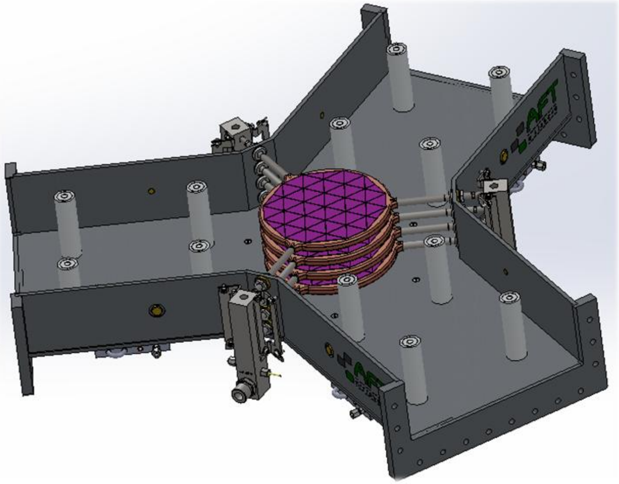
1.3 MW cw

3 MW peak
unpressurized

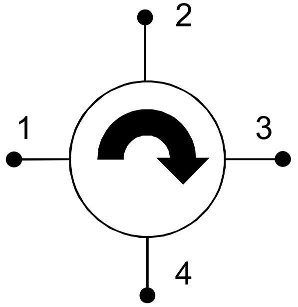
High-Power 3-Port Circulator – Principle Set-up

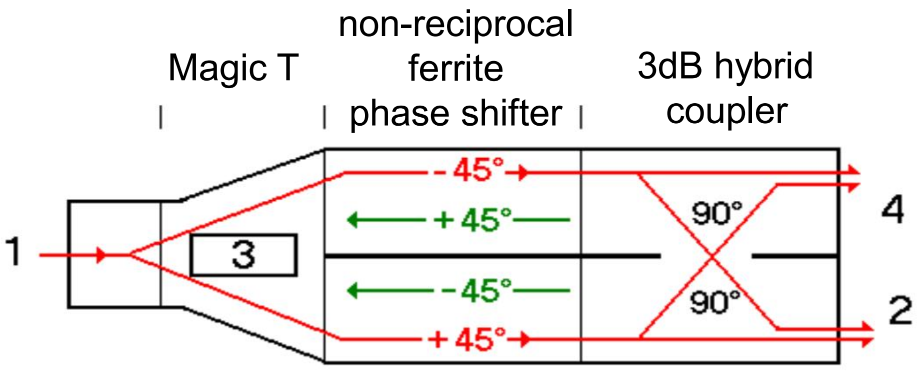




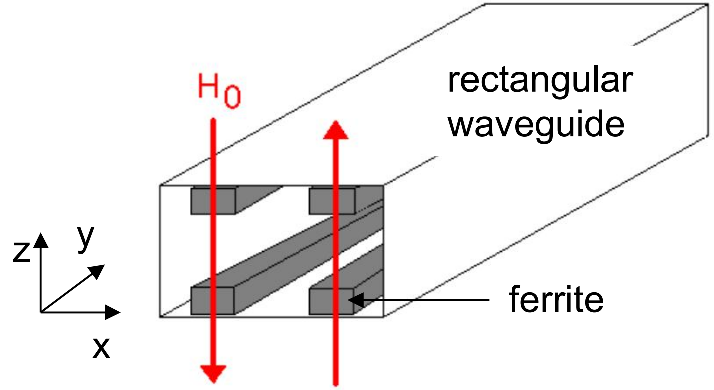


4-Port Phase Shift Circulator

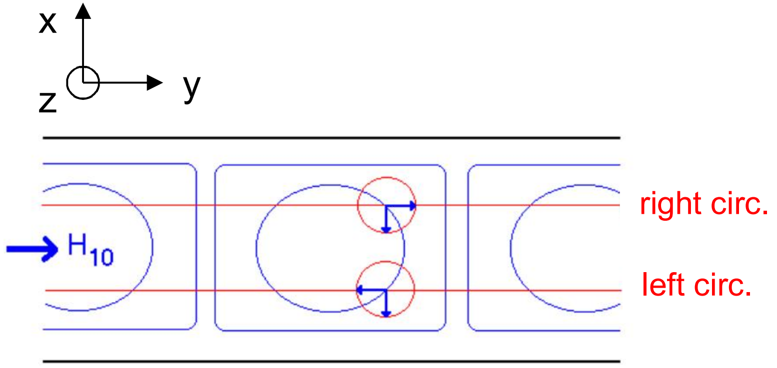




$$\Delta\Phi = \Phi(\mu_+) - \Phi(\mu_-) = 90$$

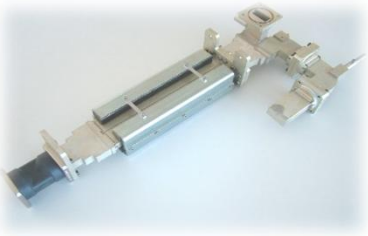


- higher power capability than a 3-port
  - no resonant ferrite structure,
  - lower E fields,
  - larger ferrite area for cooling
- more bulky than a 3-port
- two load terminations required



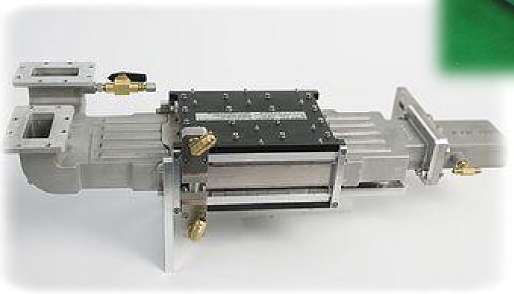
4-Port Circulators
High Power WG

X-Band
9300 MHz WR112



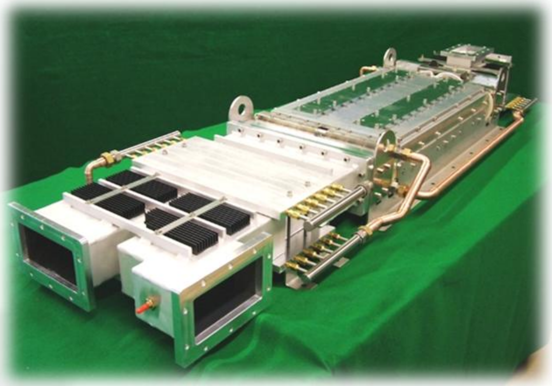
0.35 m

S-Band
2998 MHz WR284



0.65 m

L-Band 1300 MHz WR650



1.5 m

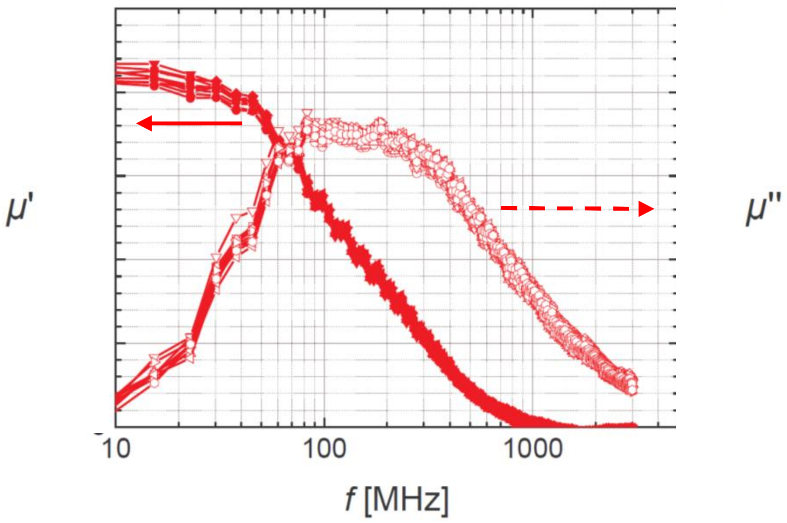
352 MHz WR2300

5.4 m

Frequency ↓
Power ↑

Ferrite RF Loads

Complex permeability of an unbiased ferrite

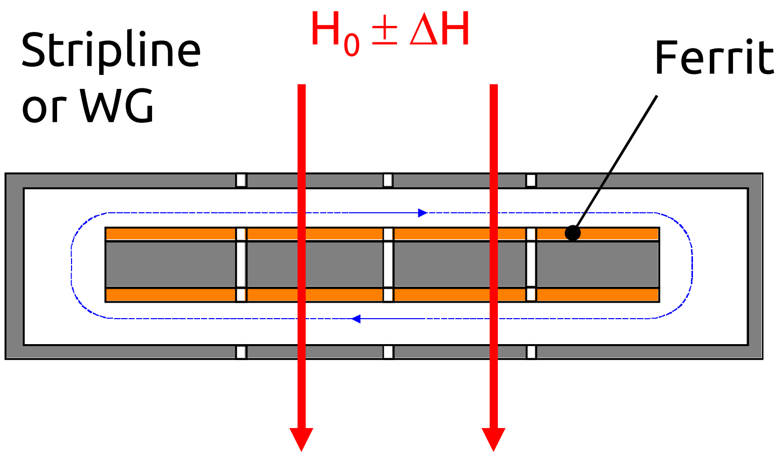


- broadband absorption covering lower frequencies
- temperature stable absorption
- excellent stability over power

800 kW cw in WR1500

- ferrite tiles bonded to WG walls
- effective cooling structure (brazed)
- water is clearly separated from RF
- robust & reliable design, no wear parts
- from VHF to X-Band, WR2300 to WR112
- modular set-up, up to 800 kW cw

Fast Ferrite Tuner (FFT) – A reciprocal ferrite phase shifter



Ferrites in a shorted transmission line. Permeability is controlled by variable bias $H_0 \pm \Delta H$.

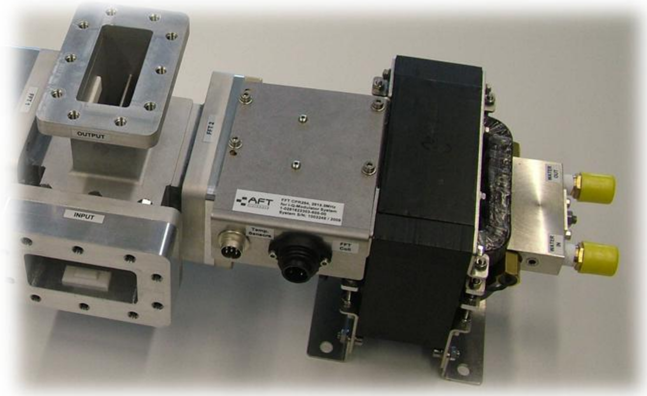
using a permanent-magnet (H_0) and a fast-switching current driven electromagnet ($\Delta I \rightarrow \Delta H$)

Tuning speed limited to ms-range by eddy currents in RF conductors

→ Continuously tunable phase shift:

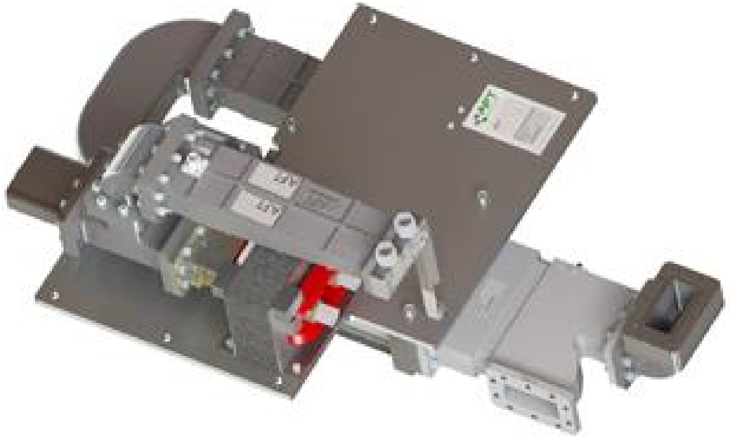
$$\Delta\Phi(\Delta H) = \frac{2\pi}{\lambda_0} \cdot L \cdot \sqrt{\varepsilon_{r,eff}} \cdot \left[\sqrt{\mu_{r,eff}(H_0 - \Delta H)} - \sqrt{\mu_{r,eff}(H_0 + \Delta H)} \right]$$

FFTs in Power Variators (PV) and I-Q-Modulators



FFT acts as a tunable reflection-type phase shifter (90°/180°) or phase switch.

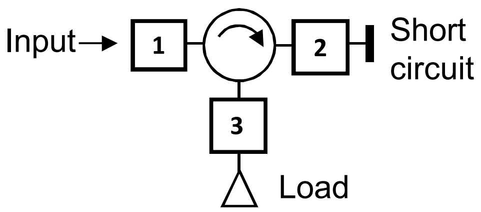
- low loss (above resonance)
- high peak and avg. power capability
- low switching time (1ms)



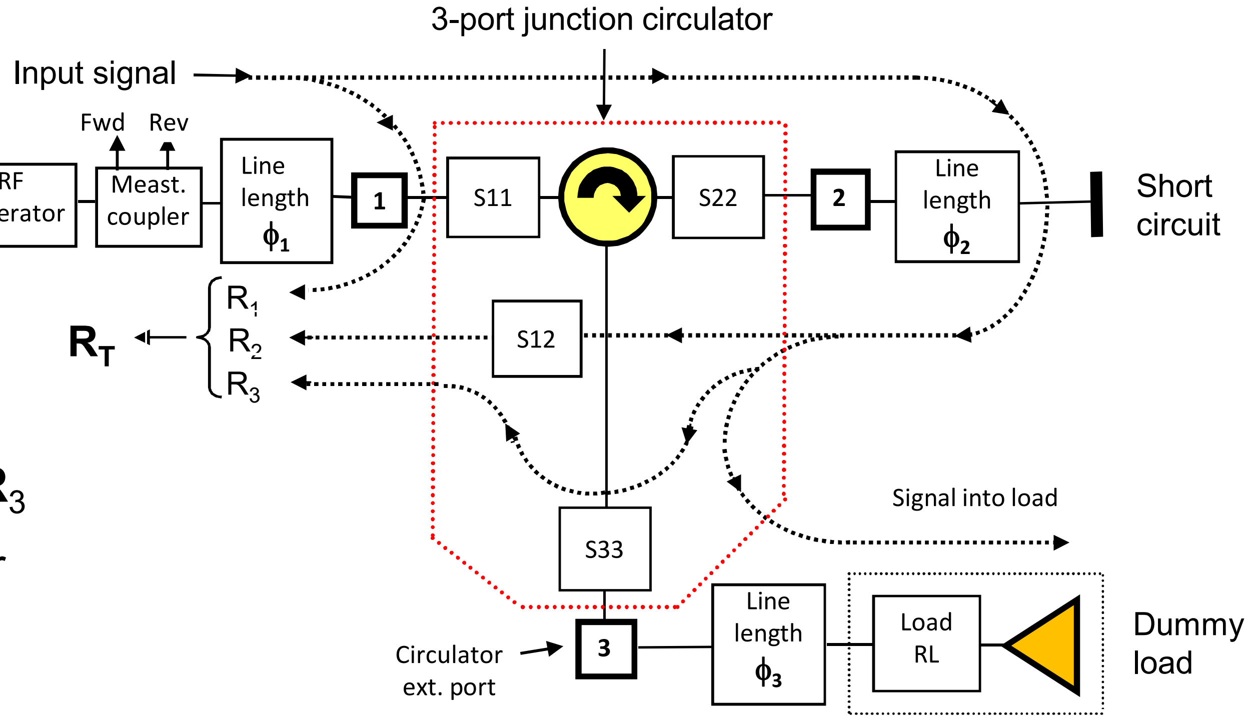
Application example:

S-Band 4-port isolator incl. an FFT PV

- PV and energy switching in dual-energy X-ray sources for cargo scanning & NDT
- With pulse-to-pulse PV up to 1kHz



4. About the Term “Isolation” in an RF System



ϕ_3 can be adjusted to minimize RT

Input reflection as seen by generator

$$\mathbf{R_T} = \mathbf{R_1} + \mathbf{R_2} + \mathbf{R_3}$$

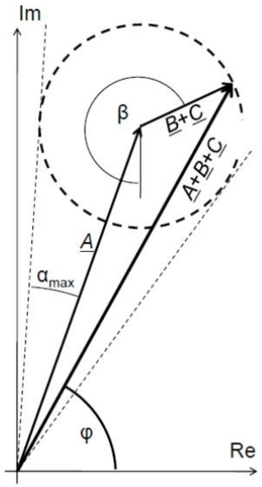
is a sum of 3 major reflection signals:

$$\mathbf{R_1} = S_{11}\, e^{j\phi 1}$$

$$\mathbf{R_2} = S_{21}\, S_{12}\, e^{j\phi 1 + j\phi 2}$$

$$\mathbf{R_3} = S_{21}\, S_{23}\, S_{13}\, R_L\, e^{j\phi 1 + j\phi 2 + j\phi 3}$$

4. About the Term “Isolation” in a System



$$\mathbf{R_T} = \mathbf{R_1} + \mathbf{R_2} + \mathbf{R_3}$$

For a lossless circulator ($S_{21}, S_{32}, S_{13} = 0$) we get:

$$\begin{array}{l} \mathbf{R_1} = S_{11} \; e^{\,j\phi 1} \\ \mathbf{R_2} = S_{12} \; e^{\,j\phi 1 + j\phi 2} \\ \mathbf{R_3} = R_L \; e^{\,j\phi 1 + j\phi 2 + j\phi 3} \end{array}$$

$\mathbf{R_T}$ depends on magnitudes & phases !

max. magnitude
if all are in phase: $|R_{T,max}| = |S_{11}| + |S_{12}| + |R_L|$

Good system isolation (low R_T) under arbitrary phase conditions or varying phases does not only require a good circulator (low $|S_{11}|$ and $|S_{12}|$) but also a high quality and power-stable load (low R_L), which is often disregarded!

Adjusting the phase lengths ϕ_2 and ϕ_3 is an option to improve the achievable R_T in an RF distribution system.

4. About the Term “Isolation” in a System

Example:

If all 3 signal contributions are of same magnitude $|S_{11}| = |S_{12}| = |R_L| = |R_x|$

$$|R_{T,max}| = |S_{11}| + |S_{12}| + |R_L| = |R_x| \cdot \mathbf{3}$$

$$20 \cdot \log R_{T,max} = 20 \cdot \log (R_x \cdot 3) = 20 \cdot \log R_x + \mathbf{9.54\ dB}\ !$$

Assuming a minimum RL_T of 20 dB (VSWR < 1.2:1) is required for the RF source, we ask for: $|20 \log R_x| = 20\text{dB} + 9.54\text{ dB} = 29.54\text{ dB} \approx \mathbf{30\ dB}$.

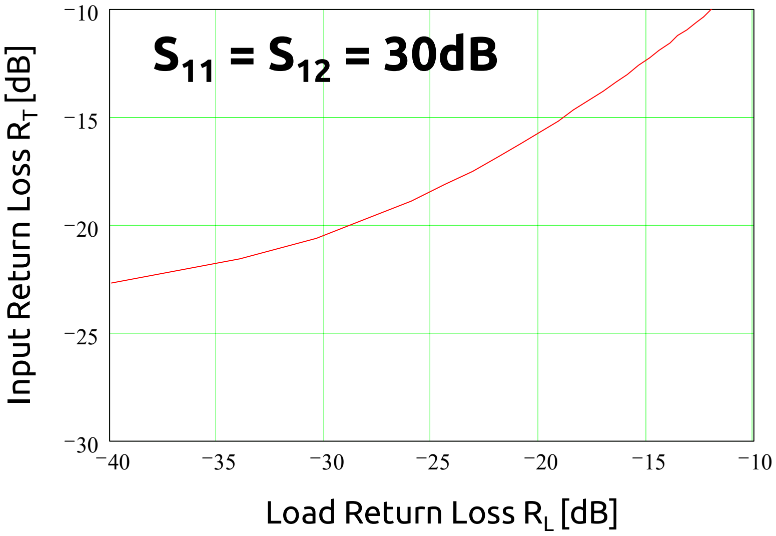
With other words we need a circulator with $|S_{11}| = |S_{12}| \geq 30$ dB and a dummy load with a min. return loss of 30 dB, to achieve $|R_T| \geq 20$dB and to safely protect the RF generator under all possible phase conditions.

Worst Case Input Return Loss R_T vs. Load Return Loss R_L

Input return loss R_T

	Case 1	Case 2	Case 3
S_{11} [dB]	30	30	26
S_{21} [dB]	30	30	26
R_L [dB]	30	26	20
R_T [dB] worst	20.46	18.91	13.97

Input return loss R_T vs. R_L



Even if in practice we usually won´t find all three reflection signals in phase, it is good practice to use the worst case scenario for specifying circulator and load requirements.

5. High-Power Handling Requirements

Basically, a circulator shall provide low loss, high isolation and low reflection.

But what are the crucial high-power requirements for a circulator?

1) Handle full peak and average power.

2) Handle forward power and reverse power up to 100% reflection and at any phase.

3) Consider worst case operating conditions.

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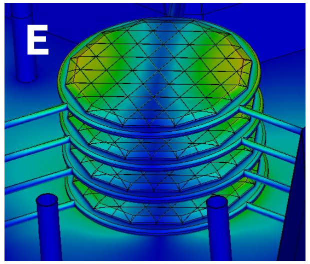
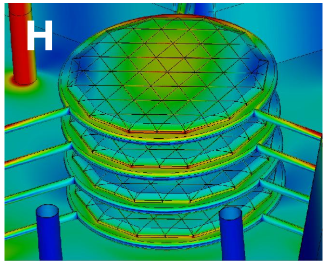
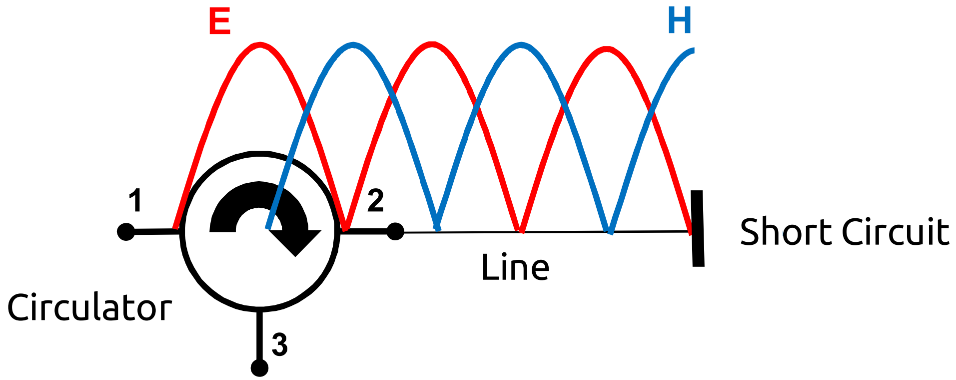
High-Power Design Aspects





	Peak Power	Average Power
Characteristic	1) high voltage & E field 2) high current & H field	losses in ferrites, dielectrics & conductors → power dissipation → heating
Risk	1) electrical breakdown (arcing) in air gaps between ferrites and at edges & corners 2) burning at poor electrical contacts	• overheating & burning of materials • reduced el. breakdown capability at overheated surfaces • thermo-mechanical stress • thermal drift of ferrite properties
Solution	• elaborated design by 3D EM sim., covering detailed E field analysis • proper design margins • avoid sharp edges • well defined electrical contacts • gas pressurization, if required	• careful 3D thermal modeling based on the simulated EM power loss • low ferrite loss by material and bias • good el. conductors, low loss dielectrics • good thermal bonding of ferrites • adequate cooling of hot spots/areas • thermal compensation (TCU)

Standing Waves between Circulator and Short Circuit



E and H are displaced by 90°

Standing wave pattern
repeats at 180° (λ/2) intervals

The superposition of forward and reverse wave results in a standing wave between the short circuit and the circulator (also inside!).
The standing wave moves with the phase of the short circuit (line length).

Thus, the magnitudes of E- and H-field in the circ. vary significantly with phase.
Same is true for the circulator power loss.

Worst Case Standing Wave Conditions into a Short

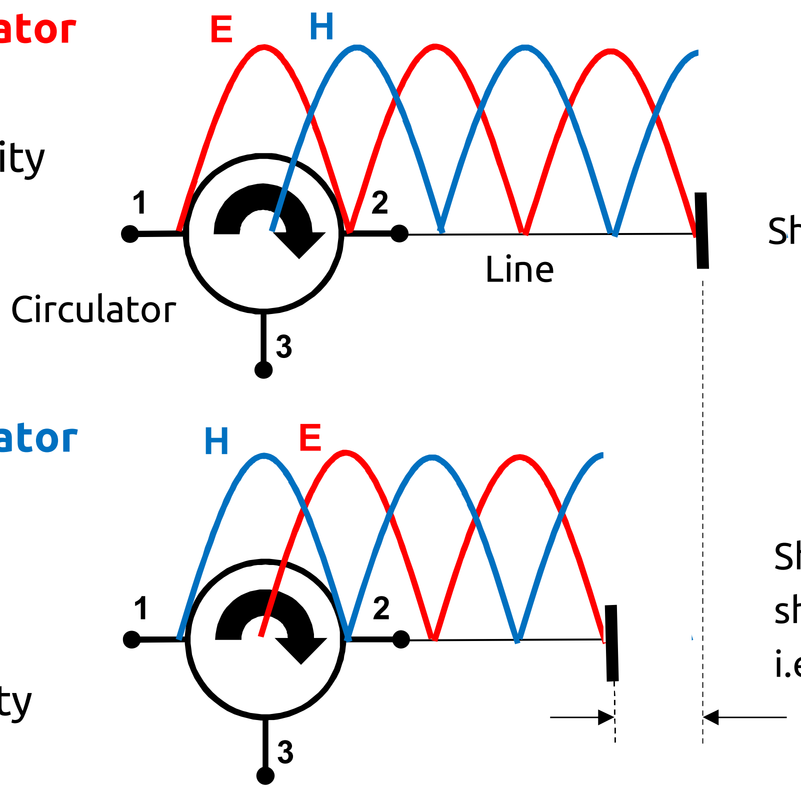
Max. E field in circulator

→ critical for voltage breakdown capability

Max. H field in circulator

→ max. power loss in ferrites

→ critical for thermal dissipation capability



Short circuit

Short circuit
shifted by 90° 1-way
i.e. 180° 2-way

A relative phase shift of 180° (2-way) is required to cover the worst cases in the circ.

High-Power Handling Requirements for the Worst Cases

	Characteristic Peak Power max. E field	**Maximum Power Loss** max. H field
Design criterion for power capability	$P_C = \left(\sqrt{P_{FWD1}} + \sqrt{P_{REV2}} + \sqrt{P_{REV3}}\right)^2$ $\approx \mathbf{4 \cdot P_{FWD}}$ for $P_{REV2} = P_{FWD1}$, $P_{REV3} \approx 0$ (R_L > 30 dB)	≈ **3 * Insertion loss** (1-way) for a 3-port circulator operated into a short
Notes	In the simulation of a circulator with matched terminations, we have to consider **4 times** the forward power to calculate max. E field strength. A bad dummy load would increase P_c significantly: factor 4.4 for R_L = 20dB factor 9 for R_L = 0dB The circulator is usually not designed to withstand these conditions!	The max. ferrite power loss is more than 2 times the insertion loss as expected for the FWD and REV wave, due to the resonant pattern in the 3-port junction. Ferrite power loss varies between 1 and 3 times insertion loss as the short phase is shifted by 180° (2-way).

How to Test Full Power Capability into a Short Circuit?

We need a short circuit of variable phase at circulator port 2:

(1) sliding short or

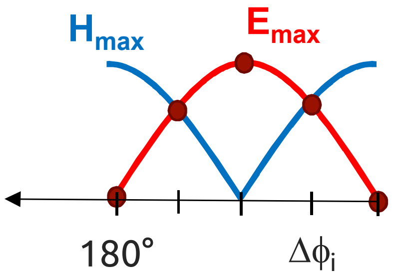
(2) fixed short plus additional offset line length.

A total phase shift of 180° (2-way) is sufficient as the standing wave pattern repeats every $\lambda/2$.

What is a reasonable number a phase samples/ increments to adequately cover max. E and H field in the circulator?

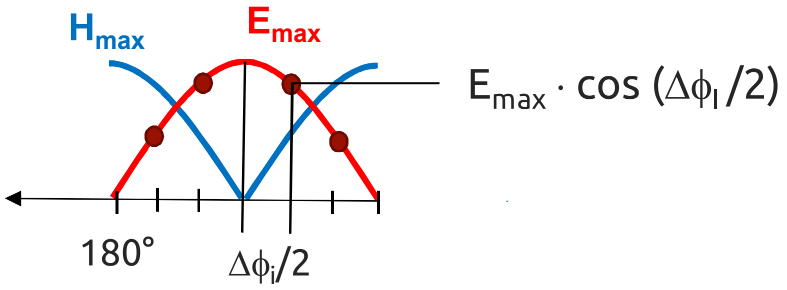
Standing Wave Sampling with Phase increment $\Delta\phi_l$ (1-way)

Best case: samples align with max. field



field exposure 100%

Worst case: samples displaced by $\Delta\phi_l$ /2

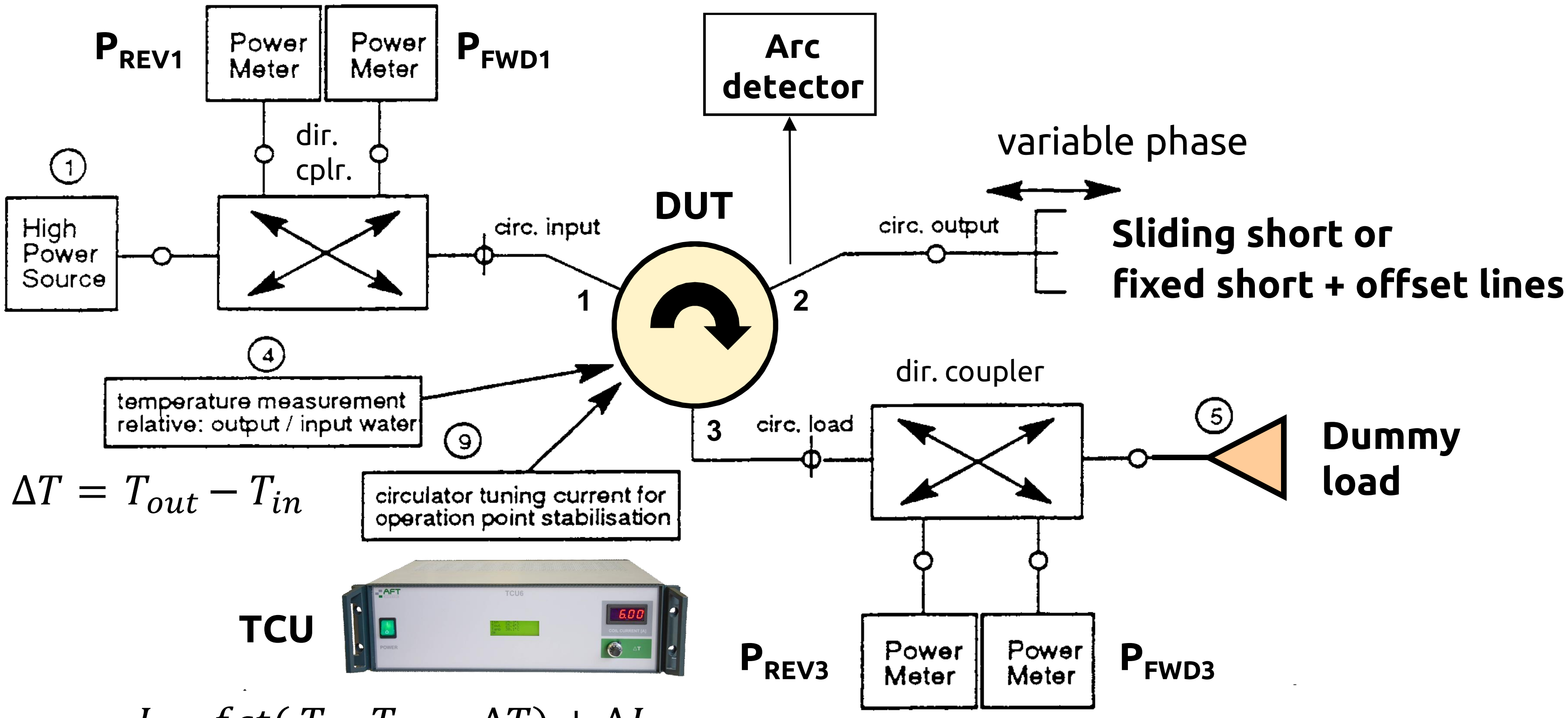


min. field exposure [%] := $\cos(\Delta\phi_l/2) \cdot 100\%$

Min. field exposure [%]	**70.7**	**86.6**	**92.4**	**95.1**	**96.6**	**98.5**	**99.2**	**99.6**
Phase increment $\Delta\phi_i$ [°]	90	60	45	36	30	20	15	10
No. of line sections for 180°	1	2	3	4	5	8	11	17

→ A 30° phase increment is a reasonable practical trade-off for high exposure (96.6%) and reduced efforts in testing with only 5 line sections.

6. High-Power Test Set-up for Circulators



$$\Delta T = T_{out} - T_{in}$$

$$I = fct(T_{in}, T_{amb}, \Delta T) + \Delta I_{RF}$$

High-Power Measurement Categories for Circulators

Category	Definition	Unit	Remark
Reverse power seen by the RF source	$\boldsymbol{P_{REV1}}$	W	
Input return loss of circulator at port 1	$\boldsymbol{RL_1} = 10 \cdot \log \frac{P_{REV1}}{P_{FWD1}}$	[dB]	same as R_T before
Return loss **of dummy load** at port 3	$\boldsymbol{RL_3} = 10 \cdot \log \frac{P_{REV3}}{P_{FWD3}}$	[dB]	monitor load and its stability over power
Water temperatures	$\boldsymbol{\Delta T} = T_{out} - T_{in}$	[°C]	measured by TCU
Calorimetric power loss of the ferrites	$\boldsymbol{PL} = \boldsymbol{\Delta T} \cdot c_w \cdot waterflow$	[W]	more precise than coupler+power meter
Body temperature at circulator port 2	$\boldsymbol{T_{body}}$	[°C]	hottest at output port due to standing wave

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Important Notes on Test Equipment

- **Verify DUT in a cold test** prior to high-power test
- Use **calibrated test equipment** only, verify before use at high power
- **Directional couplers**:
  - High directivity ($D >> R_L$) is required for a precise measurement of low reflected power otherwise high errors due to FWD power leakage.
  - Verify directivity and coupling coefficient before installation.
  - Install low-pass filters between couplers and power detectors to suppress power contribution by harmonics.
  - Install directional couplers close to the DUT but use safety distance of at least $\lambda/4$.

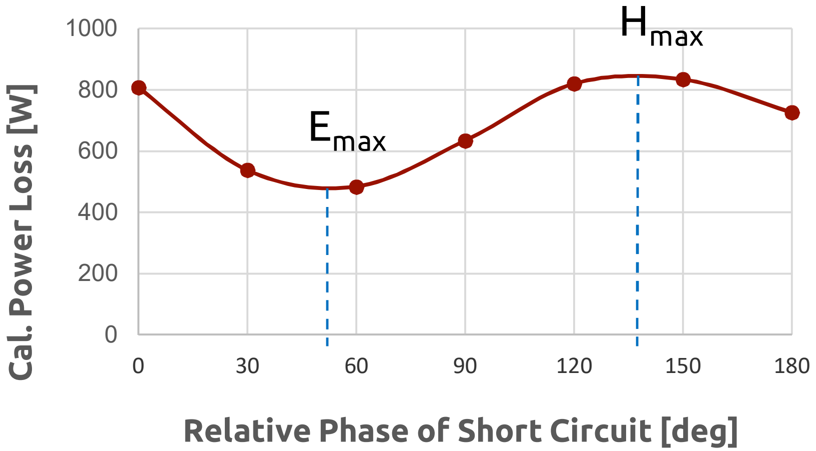
High-Power Test Procedure

Potentiometer to set
ΔT gain factor

1. Set/install first short circuit phase
2. Start with a lower power setting ~ $P_{max}/10$
3. Record measurements at thermal stabilization (ΔT stable) after ~5 minutes
4. If reflected power becomes too large due to a thermal drift of the circulator, adjust the TCU ΔT gain factor with potentiometer, also bias control with GUI.
5. Carefully increase power stepwise and repeat 3. and 4.

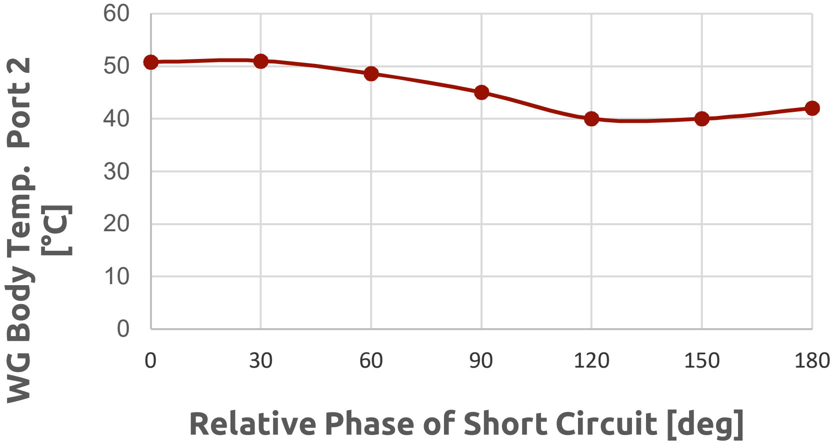
   Pulsed power: start with peak at low average before increasing duty, so to separate peak (breakdown) and average (thermal) power effects.
6. Set/install next short phase and repeat 2. to 6.
7. Evaluate test results. Figure out phase for max. power loss & max. E field.
8. If required, repeat the test and fine adjust ΔT to achieve compromise setting.

Test Results 3-Port Circulator WR1150 805MHz at 1MWp 76kWavg



Calorimetric power loss vs. 180° phase range sampled with a $\Delta\phi_i$=30° increment

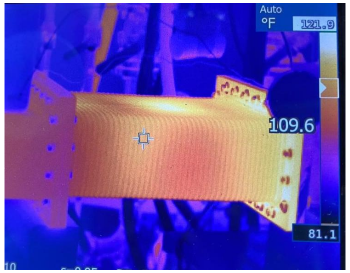
- shows expected standing wave pattern
- max. loss of 1.1% only at max. H field
- min./max. loss vs. phase ratio is about 1.7



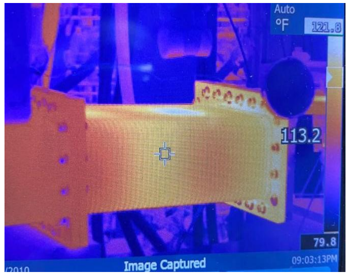
Body temperature at circulator output port varies with phase due to moving H field pattern.

Test Results 3-Port Circulator WR1150 805MHz at 1MWp 76kWavg

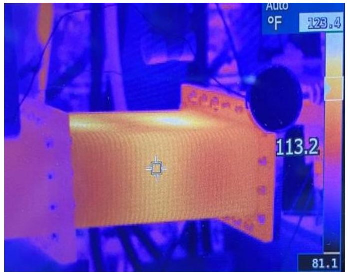
Visualize the H-field (current) standing wave pattern vs. phase
by heat mapping with an IR camera
on a black-painted waveguide section (l ~ λ) connected to circ. output port.



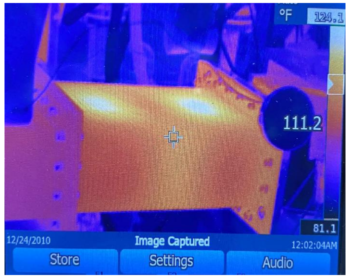
60°



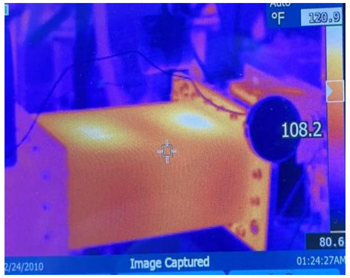
90°



120°



150°



180°

An extrapolation of the visualized H field pattern to the center of the ferrite section allows to predict the phases for max. and min. H field in the circulator: 150° & 60° respectively → very good agreement with power loss measurement!

Useful Safety Notes for Installation & Operation

- Keep clean: avoid dust, dirt and particles in the waveguide.
  Check and clean if required before installation. Risk of arcing!
- Keep dry: avoid moisture and condensation in the waveguide.
  Condensation, if water temp. is below dew point and at high humidity.
  Stay well above dew point and protect interior from entering humidity.
  A wet circulator will result in severe arcing!
- Check Flanges: avoid contamination, deep scratches, burrs, uneven and misaligned flanges, ensure stress-free flange connections.
  Risk of burning, arcing and RF leakage (check with RF sniffer).
- Check for water leakage at all installed pipes and connections.

Crucial Safety Interlocks for High-Power Operation

- **Cooling**
  - max. outlet temperature T_{out}
  - min. coolant flow rate
  - max. coolant inlet pressure
- **Arc Detector**: crucial at very high power and at first test
- **TCU** power failure interlock (if applicable)
- **Minimum gas pressure** (if applicable)
- **Max. reverse power** for RF generator (optional)

Install and <u>check</u> all selected interlocks for final GO condition!

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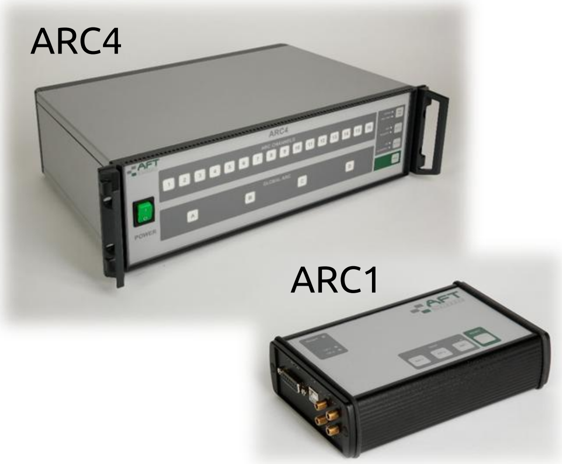
About the Importance of Arc Detection

- Circulators are thoughtfully designed to handle full RF power under the specified operating conditions, while containing regions of high RF field strength, especially in air gaps between ferrites.
- However, they are <u>not</u> able to withstand arcing as a consequence of voltage breakdown due to moisture, dirt or abnormal operating conditions.
- Arcs of high energy will result in <u>permanent damage</u> by bursting and melting of metals and ceramics (hot plasma >> 1000°C).
- Under CW RF arcs <u>travel back</u> to the RF generator at high velocity!
- Goal of arc detection: quench the arc by removing RF power fast before the arc energy reaches critical values (> 5 Joule) → prevent damage.

Best Solution: Optical Arc Detectors



- Key features of an optical arc detector:
  - high optical sensitivity, usually < 1 Lux
  - very low response time < 2 μs
  - hard-wiring to RF generator interlock within ~10 μs shut-off time
- An arc viewport monitors light or heat flashes in the WG interior.
- AFT arc detectors use low loss optical fibers to connect the viewport and so allow separation of detector electronics from radiation areas.
- “Coincidental” arc detection effectively helps to reduce spurious arc detection under radiation influence or scintillation:

  2 viewports for 1 observation point, both output signals AND-combined.

Summary

- Ferrites are unique, partly unrivaled materials for high-power RF: distinctly functional (non-reciprocity, tunable μ) and very low loss.
- Ferrite circulators and loads provide key contributions to the reliable operation of high-power RF generators (tubes & SSPA): Protection from reflected power, stable operating conditions, improve life time of tubes, high system availability and long system operating life.
- They are usually designed to safely operate under 100% reflection any phase, thus under all possible and worst case operating conditions.
- Sophisticated design, low loss ferrites, proper bias, effective cooling and a solid temp. compensation are the keys to high-performance and reliability.
- High-power testing into a short circuit with variable phase is required to verify the full power capability. Protection by interlocks is essential.

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Many thanks for your attention & interest!

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From Milliwatt to Megawatt