Developments of High CW RF Power Solid State Amplifiers at SOLEIL

R. Lopes P. Marchand F. Ribero T. Ruan

CWRF2012 BNL
07-11 May 2012

SOLEIL Amplifier

Summary

At SOLEIL, SSA are providing the required 352 MHz CW power: 1 X 35 kW into the Booster (BO) cavity and 4 X 180 kW into the 4 superconducting cavities of the Storage Ring (SR). Based on a design fully developed in house, they consist in a combination of a large number of 320 W elementary modules (147 in the BO and 4 X 724 in the SR) with MOSFET, integrated circulators and individual power supplies (DC/DC converter).

After 6 years of operation, this innovative design has proved itself and demonstrated that it is an attractive alternative to the vacuum tube amplifiers, featuring an outstanding reliability and a MTBF > 1 year.

Advantages of SOLEIL SSA: low noise, good linearity, high reliability, long life time, easy maintenance, simple spare parts, no HV, no X ray.

New developments

In the meantime, thanks to the acquired expertise and the arrival of the 6th generation LDMOS, SOLEIL has carried out developments which led to doubling the power of the elementary module (650 W) while improving the performance in terms of gain, linearity, efficiency and thermal stress.

3 years ago, 352 MHz 150 kW CW SSA with 6th generation MOSFET has been developed for the ESRF upgrade project.

Now 500 MHz amplifier based on this technology are being built for ThomX (50 kW) and SESAME (140 kW) projects. All key parts have been validated.

352 MHz SSA of SOLEIL Design

	Transistor type	Power supply per module	Module Parameters at nominal conditions	Amplifier design & nominal power	VSWR limitation *	Comments
SOLEIL Booster	D1029UK05 ◊ SEMELAB	1 x 600 W 280/28 Vdc	P_{1dB} = 330 W, G = 11 dB η = 60 % , T_{max} = 130°C	1 tower of 8 dis P_{nom} = 35 kW modulated	No limit with SOLEIL Booster duty cycle	1 trip over 7 years due to a human mistake
SOLEIL SR (actual)	LR301 Polyfet	1 x 600 W 280/28 Vdc	P_{1dB} = 315 W, G = 13 dB η = 62 % , T_{max} = 130°C	4 towers of 10 dis P_{nom} = 180 kW cw	70 kW full reflection Pr = 35 kW @ 180 kW	MTBF > 1 year
SOLEIL SR (upgrade)	BLF574XR NXP	1 x 600 W ♯ 280/48 Vdc	P_{1dB} = 350 W, G = 22 dB η = 69 % , T_{max} = 90°C	4 towers of 10 dis P_{nom} = 200 kW cw	70 kW full reflection Pr = 32 kW @ 200 kW	Much more robust than LR301
ESRF Booster (800W load)	BLF578 NXP	2 x 600 W 280/48 Vdc	P_{1dB} = 650 W, G = 20 dB η = 71 % , T_{max} << 75°C	2 towers of 8 dis P_{nom} =150 kW modulated	No limit with ESRF Booter duty cycle	In CW Pr limited at 5 kW for Pi = 150 kW
ESRF SR V1 (800W load)	=	=	P_{1dB} = 650 W, G = 20 dB η = 71 % , T_{max} = 75°C	2 towers of 8 dis P_{nom} = 150 kW cw	60 kW full reflection Pr = 30 kW @ 150 kW	→ minor modification on power combination
ESRF SR V2 (1.2kW load)	=	=	=	2 towers of 8 dis P_{nom} = 150 kW cw	85 kW full reflection Pr = 50 kW @ 150 kW	→ modified combination → + 1.2 kW load
ESRF SR V3 (power circul)	=	=	=	→ P_{nom} = 140 kW	140 kW CW full reflection	+ 5% power loss - 3% on efficiency Extra costs

- * VSWR limitation: when operating the amplifier at high CW incident power, Pi, with a high VSWR and the worst phase condition, **an unpowered module** (ie, both of its power supplies, or both sides of its push-pull broken) can see a power on its circulator load, Pload > Pi
- ***Rem***: full reflection for a short time (~10 ms) is not a problem (→ Pr interlock)
- ♯ 2 PS in series on 2 modules in //
- ◊ VDMOS ; all the other cases are LDMOS

Gain of MOSFET

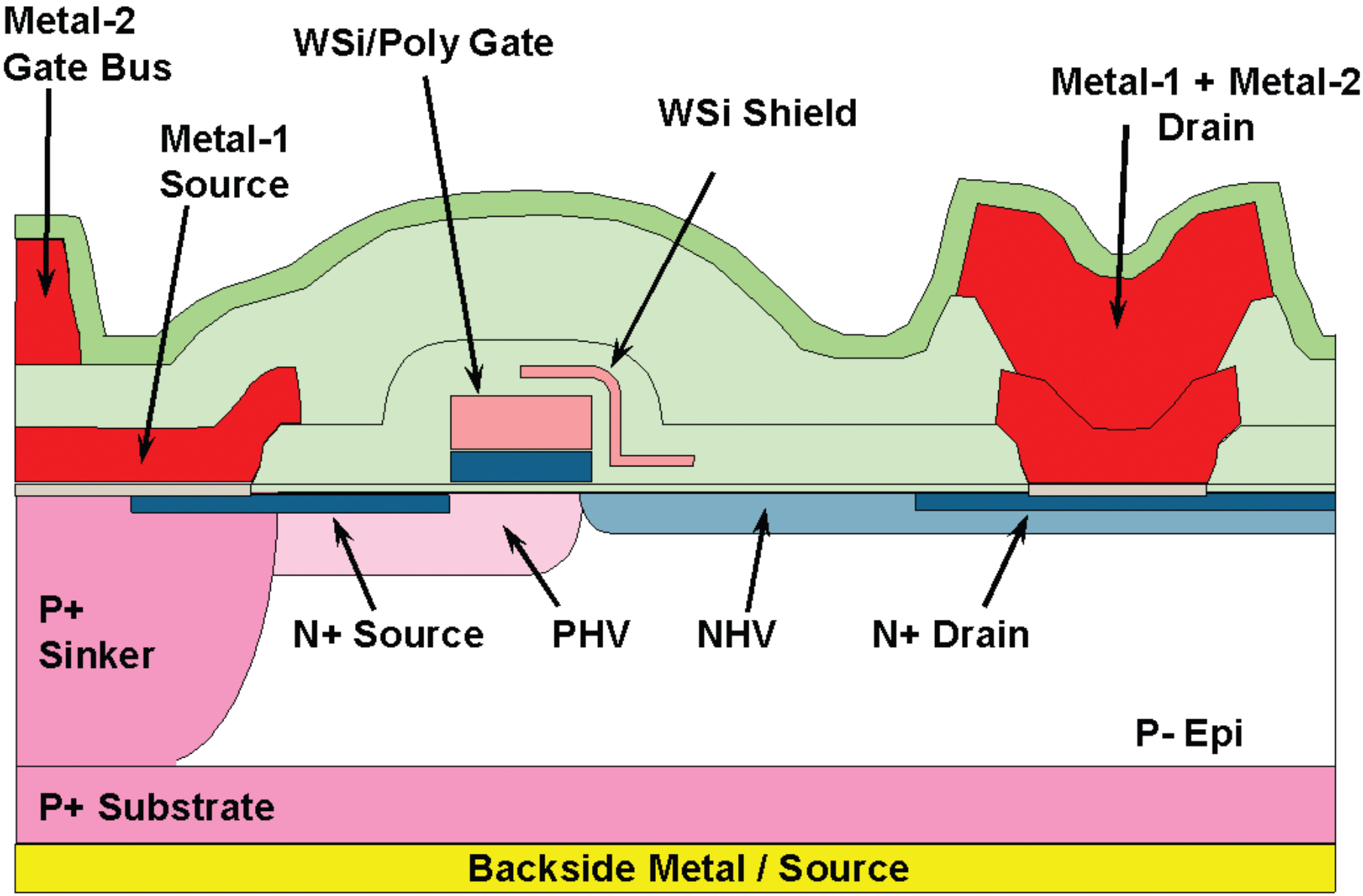
The Gain and Stability of a MOSFET depends on capacitance Crss between Gate and Drain

LDMOS has much lower Crss than VDMOS

The 6th Generation LDMOS has only about 20 - 30% of Crss than normal LDMOS due to the shield between the Gate and Drain

6th Generation RF LDMOS

(Laterally Diffused MOS)



Advantages of New Module
with 6th Generation LDMOS

- Anti-Thermal Fatigue (Special PCB Laminate, Super High Q Capacitors etc. Temperature < 80°C)
- Higher Reliability, LDMOS MTBF > 2000 years (Transistor nominal power 1 kW)
- Excellent Ruggedness
- Higher Efficiency
- Better Linearity
- Lower tolerance of gain and phase
- More Compact (Double density of RF Power)

BLF578 Module Characteristics

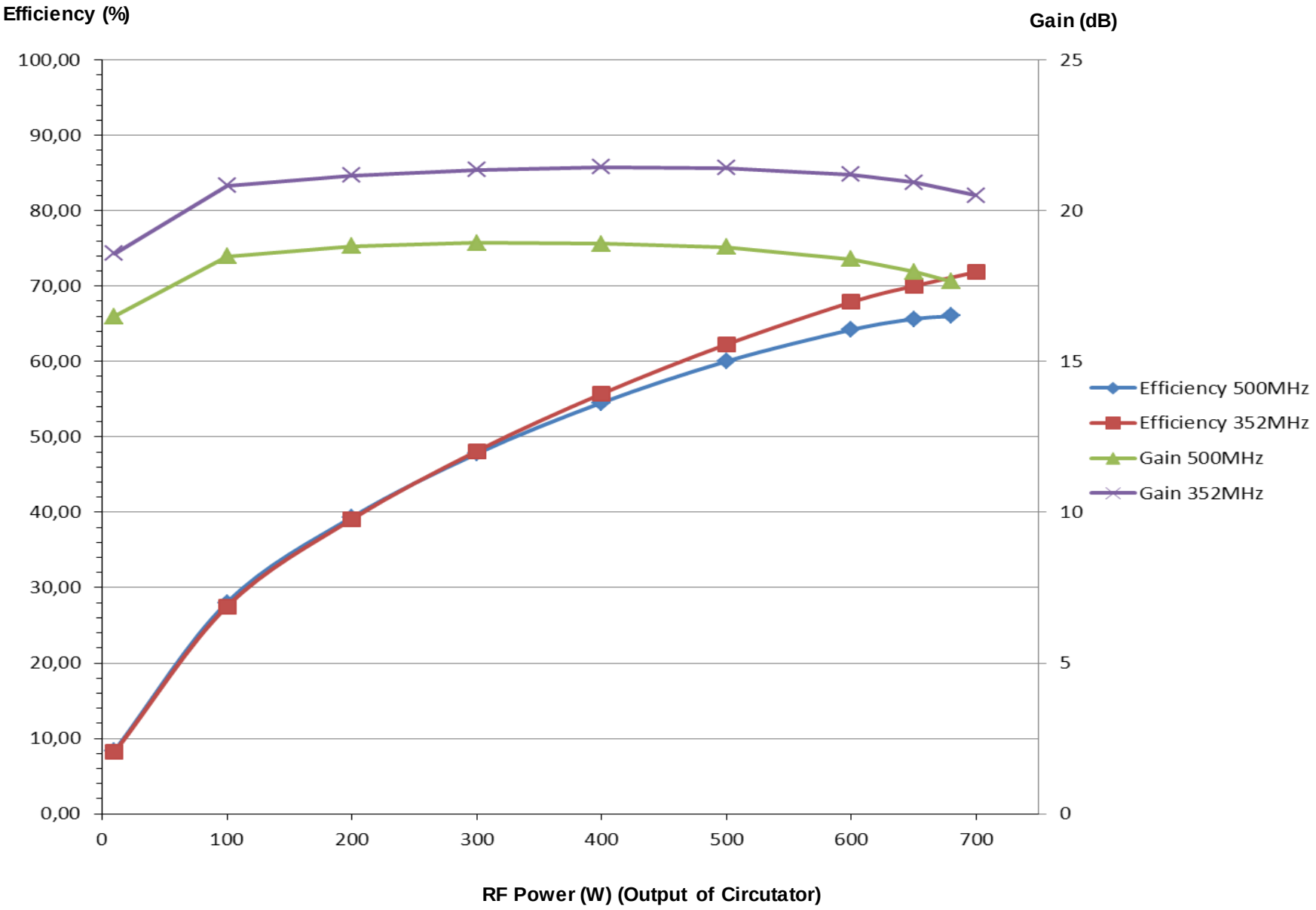
Module 500MHz

Pout (W)	Gain (dB)	Phase(deg)	I1 (A)	I2 (A)	S11 (dB)	Eff (%)
680	17,65	22,9	10,1	10,5	-52,6	66,02
650	17,98	23,3	9,73	10,08	-49,7	65,62
600	18,39	23,5	9,27	9,42	-41,9	64,21
500	18,8	23,5	8,38	8,28	-36,8	60,02
400	18,9	23,3	7,42	7,25	-35,4	54,53
300	18,93	23,1	6,37	6,19	-34,8	47,77
200	18,82	22,6	5,17	5	-34,1	39,33
100	18,48	22	3,64	3,5	-31,4	28,01
10	16,5	20,7	1,22	1,17	-23,1	8,37

Module 352MHz

Pout (W)	Gain (dB)	Phase(deg)	I1 (A)	I2 (A)	S11 (dB)	Eff (%)
700	20,5	-71,5	9,73	9,75	-56,3	71,87
650	20,93	-70,5	9,3	9,27	-47	70,01
600	21,2	-69,6	8,86	8,82	-43,1	67,87
500	21,41	-70	8,06	8	-38,5	62,27
400	21,44	-70,9	7,22	7,14	-35,6	55,71
300	21,36	-72,5	6,27	6,2	-33,8	48,12
200	21,17	-74,3	5,15	5,09	-31,6	39,06
100	20,83	-78,4	3,65	3,62	-28,4	27,51
10	18,58	-80,3	1,22	1,22	-21,4	8,20

BLF578 Module Characteristics

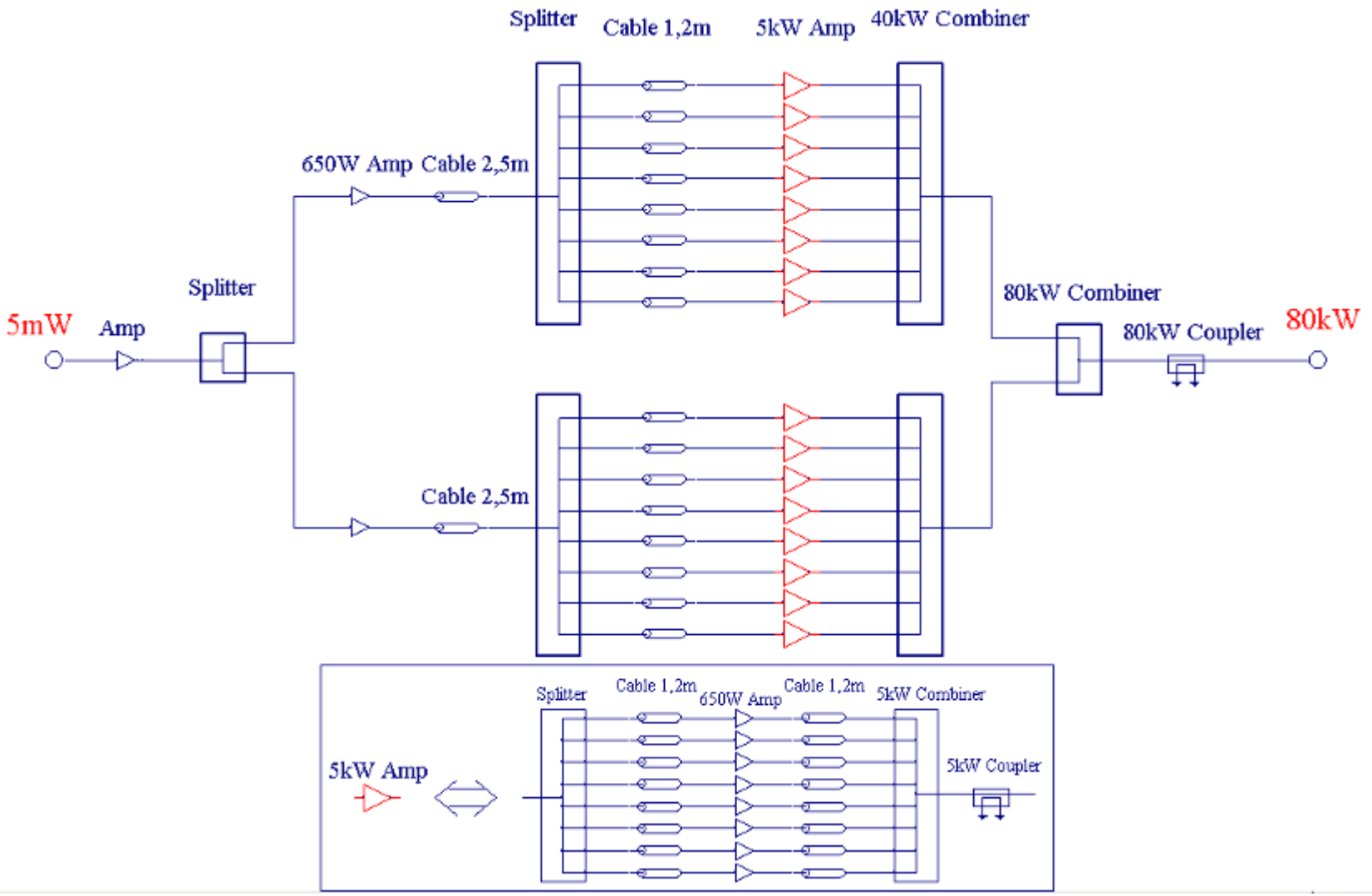


Combination of Modules

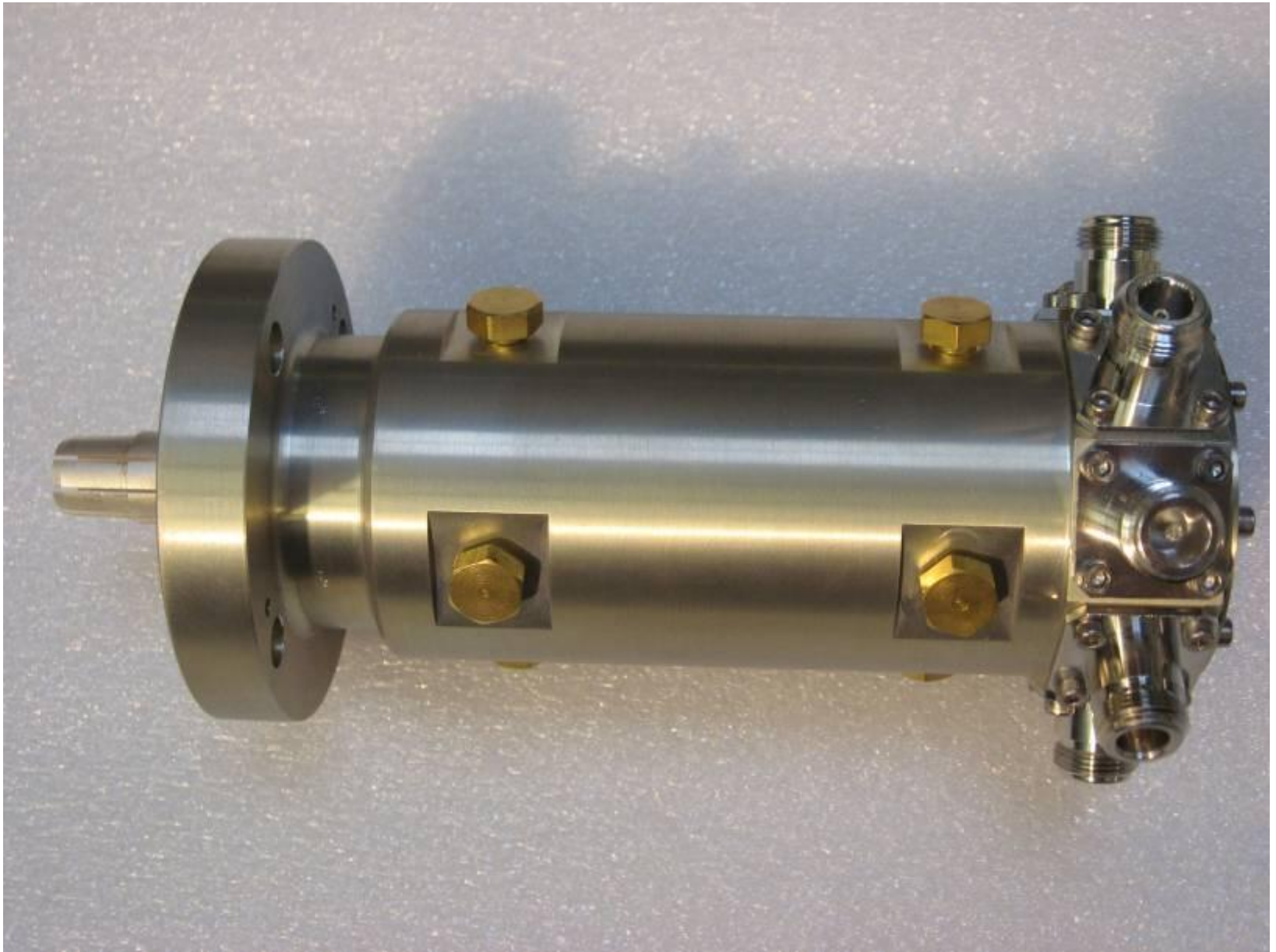
- How to combine 650 W modules to a 80 kW Tower
- For a high power, coaxial system the traditional design: 90° 3 dB Hybrid.
- For RF high power amplifier, Wilkinson Hybrid has bad performance due to the parasitic capacitance of floating power termination.
- SOLEIL Design:

  Each amplifier module is integrated with one circulator, the combiners become very simple.

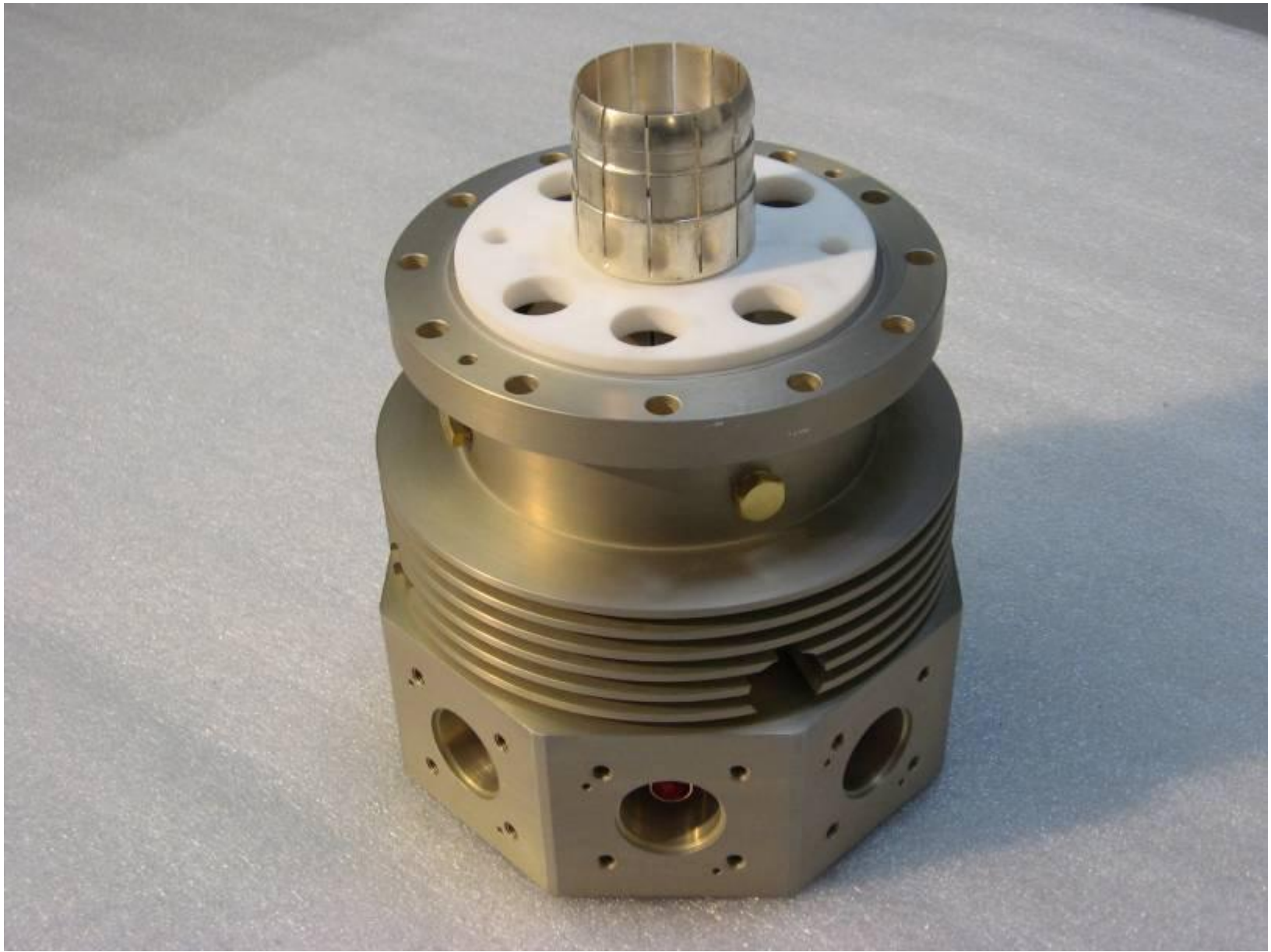
500 MHz 80 kW Tower



8-Way 500 MHz 5 kW Power Combiner



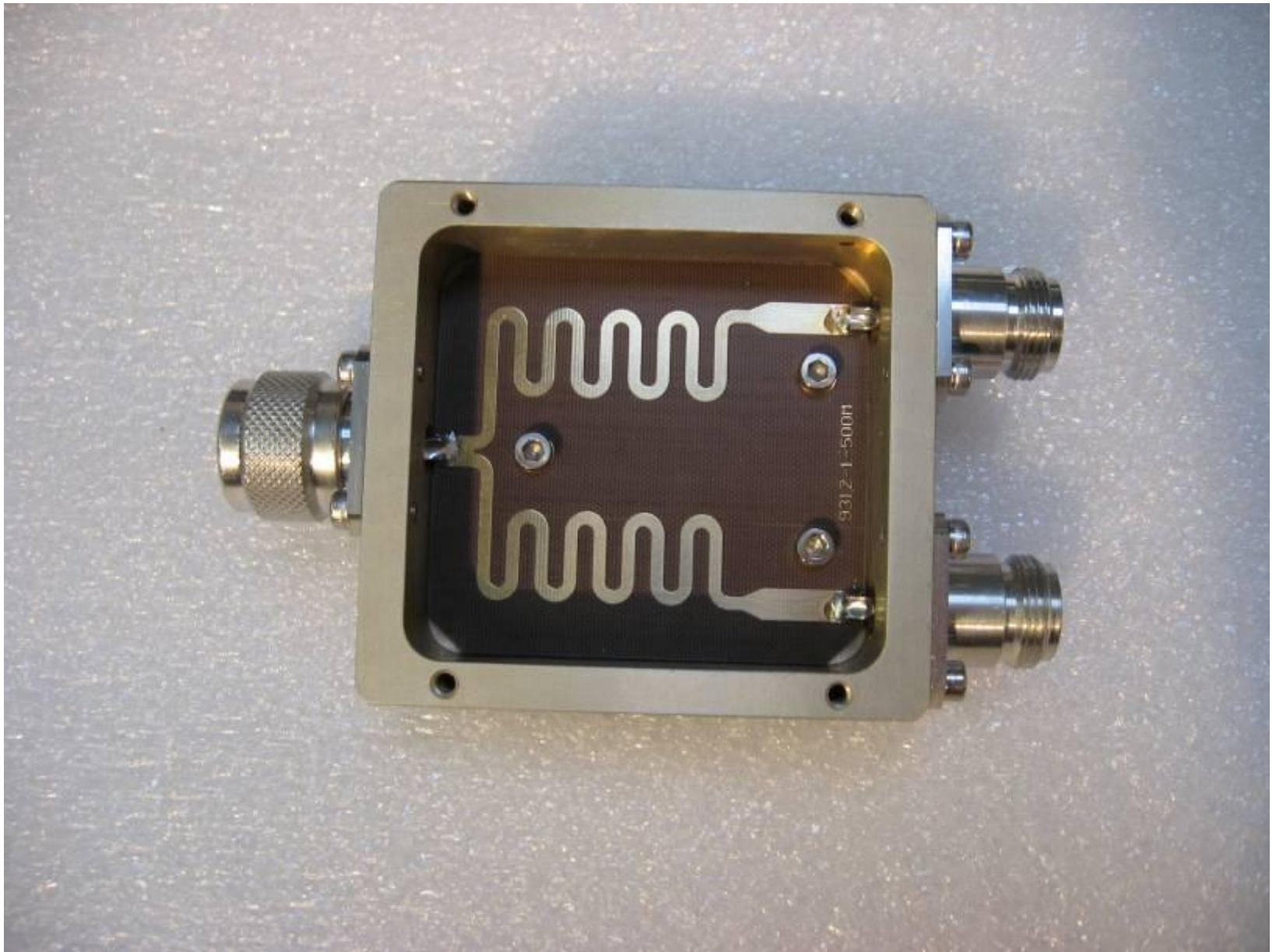
8-Way 500 MHz 40 kW Power Combiner



2-Way 500 MHz 80 kW Power Combiner

5 kW Double Directional Coupler

2-Way 500 MHz Power Splitter



8-Way 500 MHz Power Splitter

Upper Frequency Limits

For a coaxial line the frequency of operation is determined by the cut-off frequency fc of high order mode of propagation

The lowest fc occurs with the TE11 mode

Recommended Standard

50 Ohms 6-1/8’’ Coaxial Line Connector

TE11 Mode fc	Straight	Right Angle
880 MHz	830 MHz	580 MHz

CW Power Rating

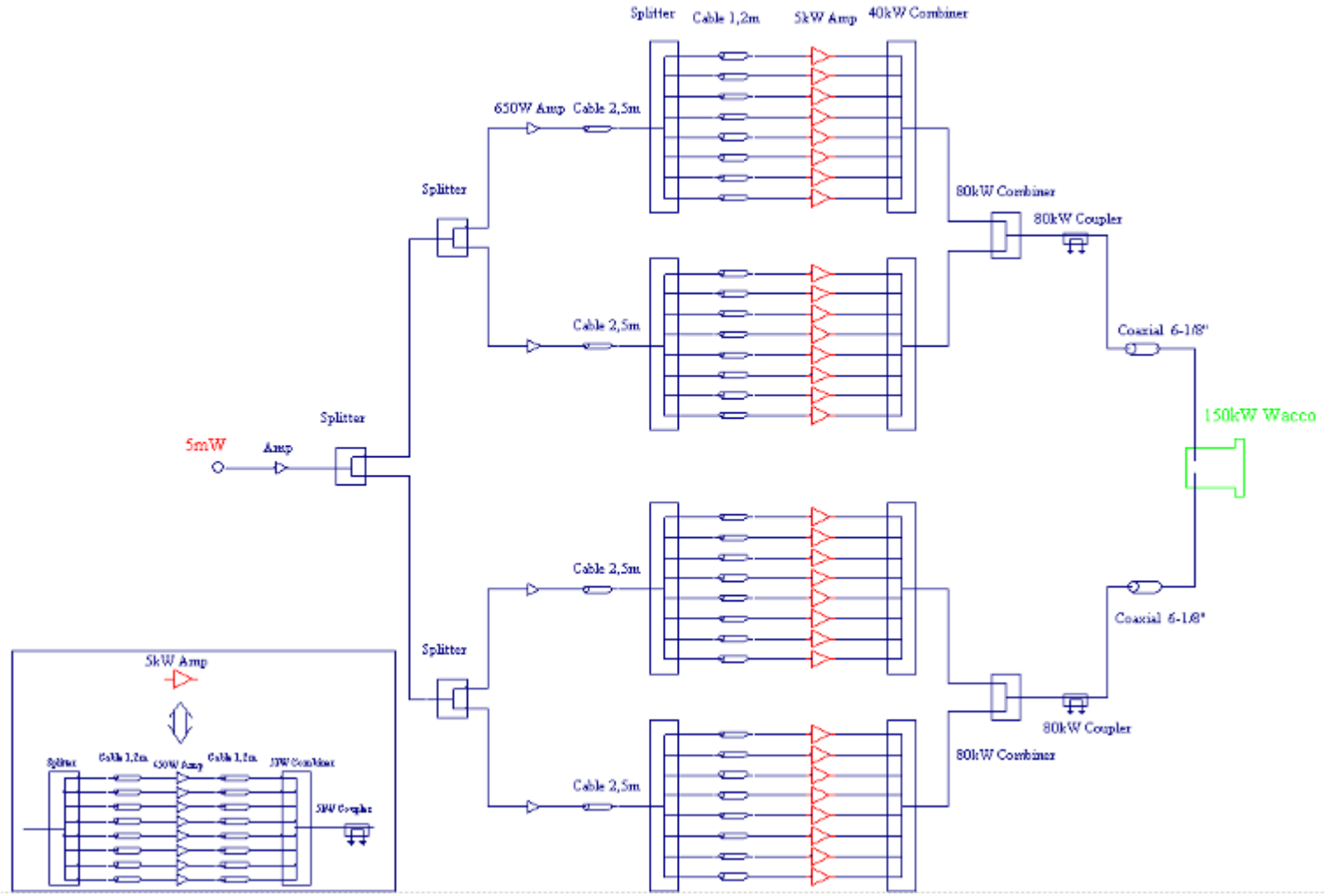
At 500 MHz the CW power rating of 6-1/8” coaxial line is **77 kW**
Based on VSWR = 1 with an ambient temperature 40°C and a maximum inner conductor temperature of 102°C.

At 500 MHz **> 77 kW** CW power the waveguide WR1800 should be used.

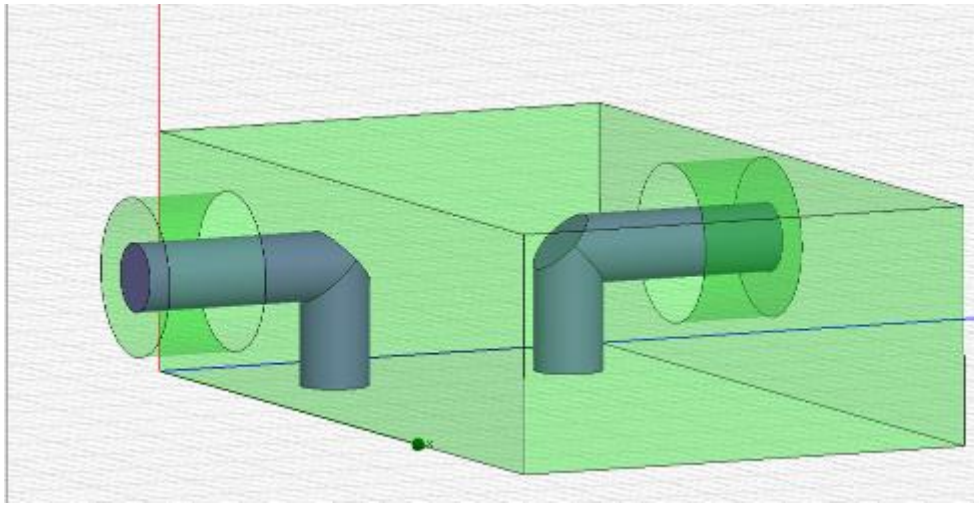
The traditional design:
2 pieces of waveguide to coaxial transition + waveguide Magic Tee or 90° 3 dB Hybrid + high power waveguide dummy load.

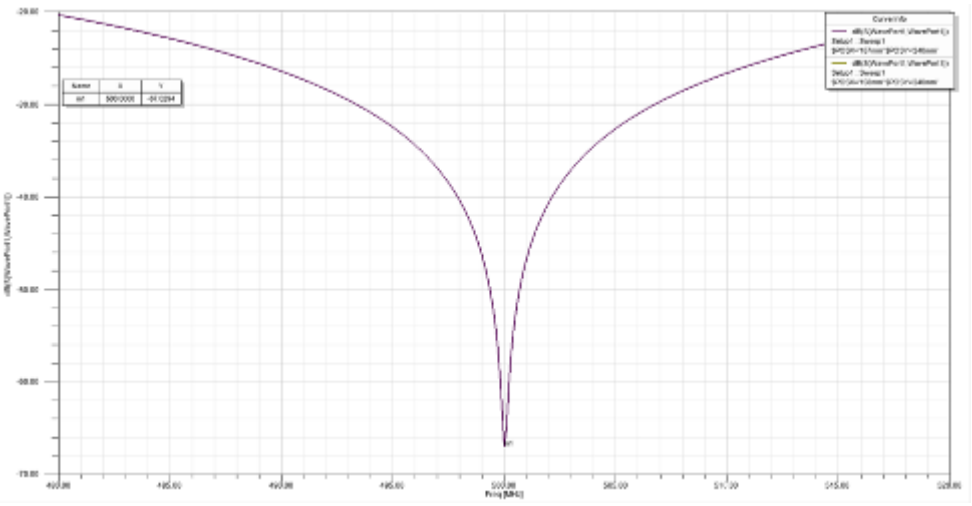
SOLEIL Design is much more simple

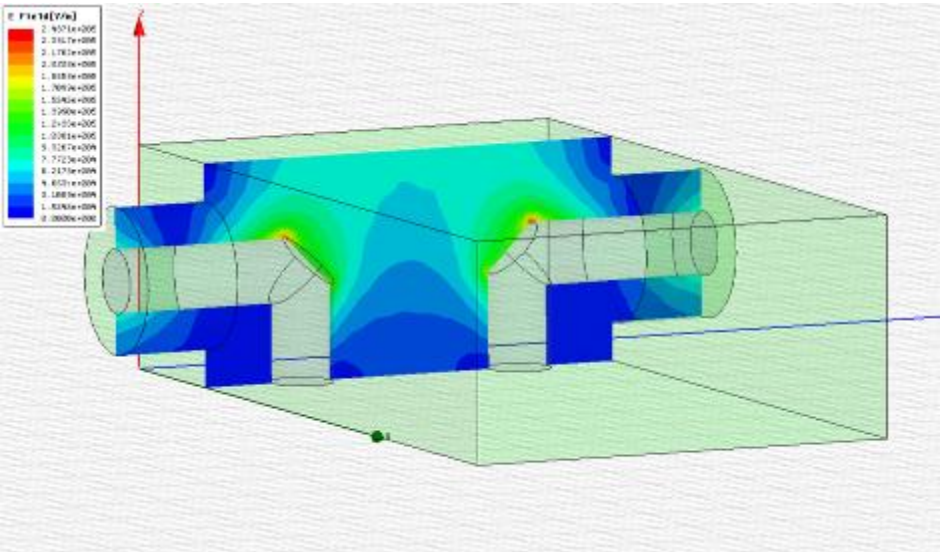
500 MHz 150 kW Amplifier

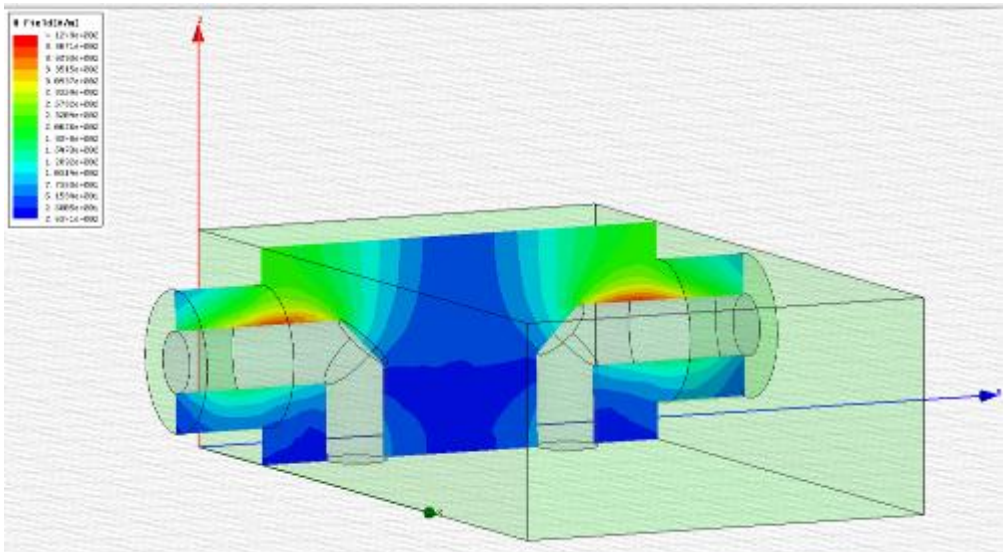


2-Way Loop Waco

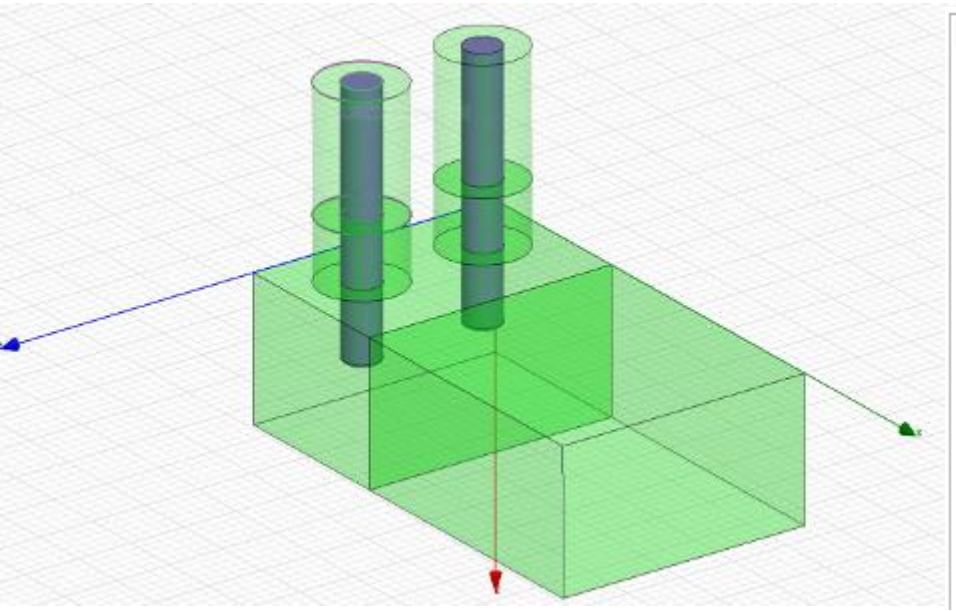


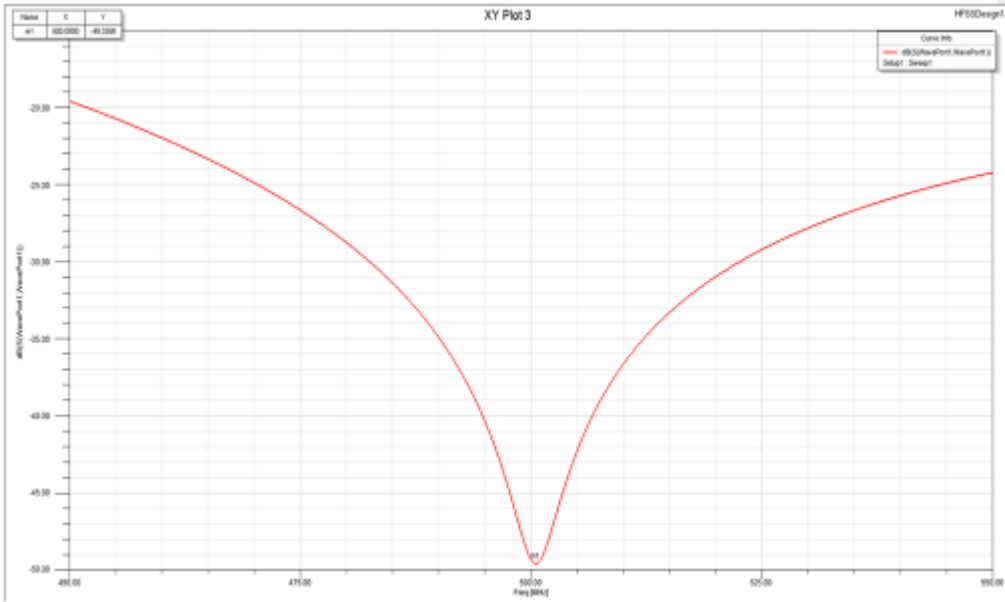


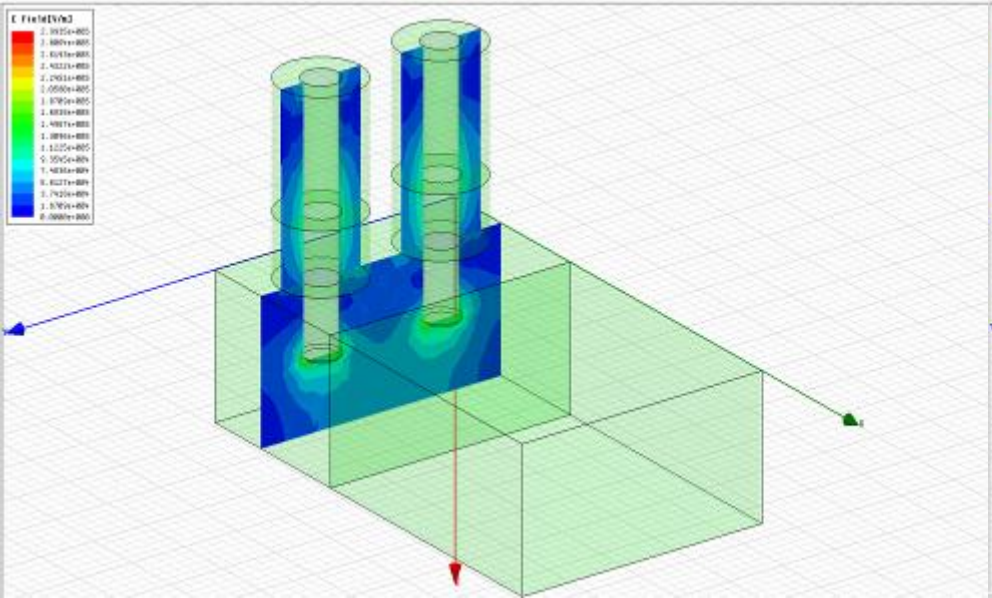


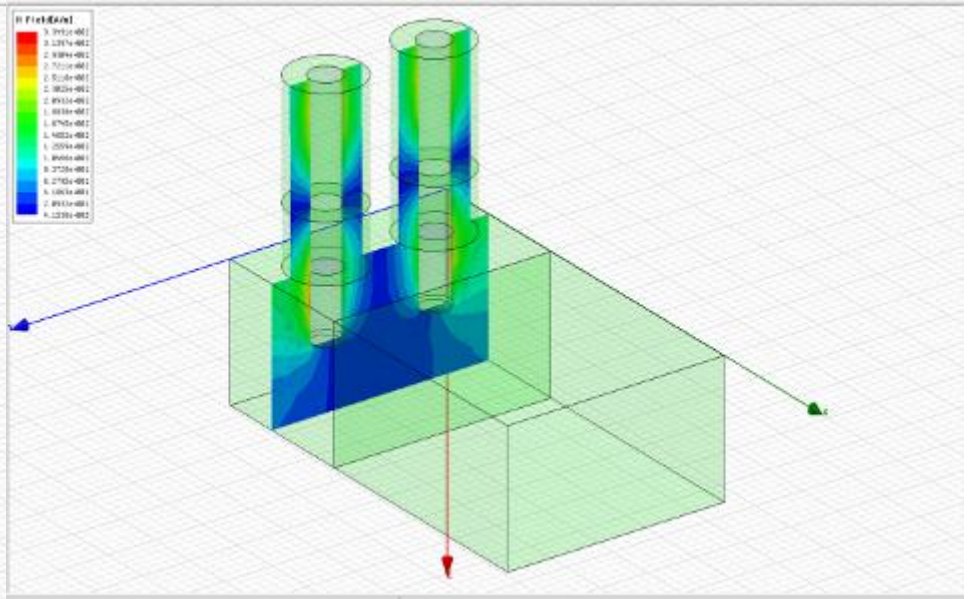


2-Way Antenna Waco









Conclusion of Waco Design

Design	Emax (kV/m)	Hmax (A/m)	BW (MHz) S11 = -30 dB
Antenna Waco	299,4	334,5	45
Loop Waco	248,7	412,5	13

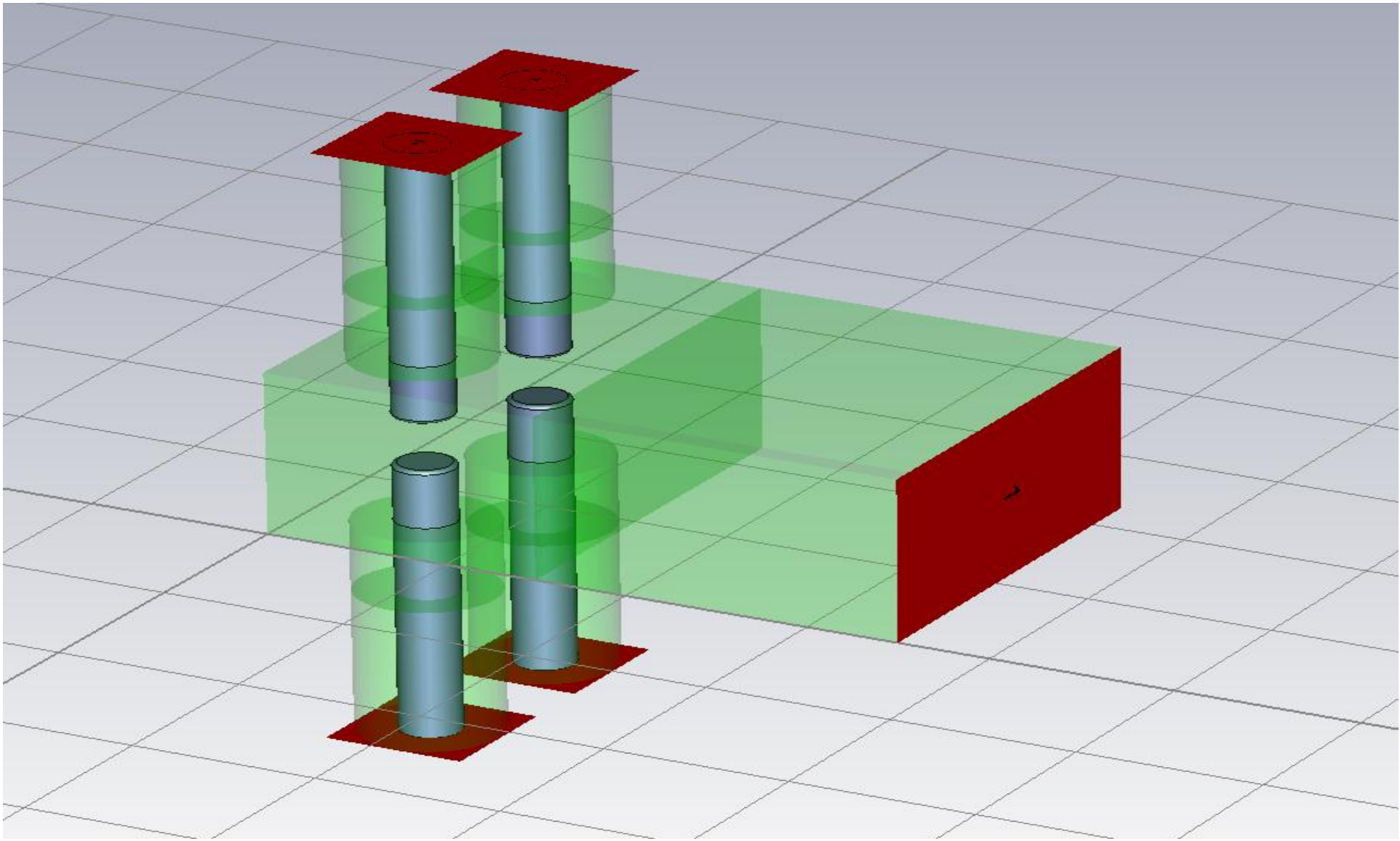
Advantages of Antenna Waco

1) Easy to be manufactured
2) Wider bandwidth
3) Low RF current density and Higher efficiency
4) Easy to be adjustable

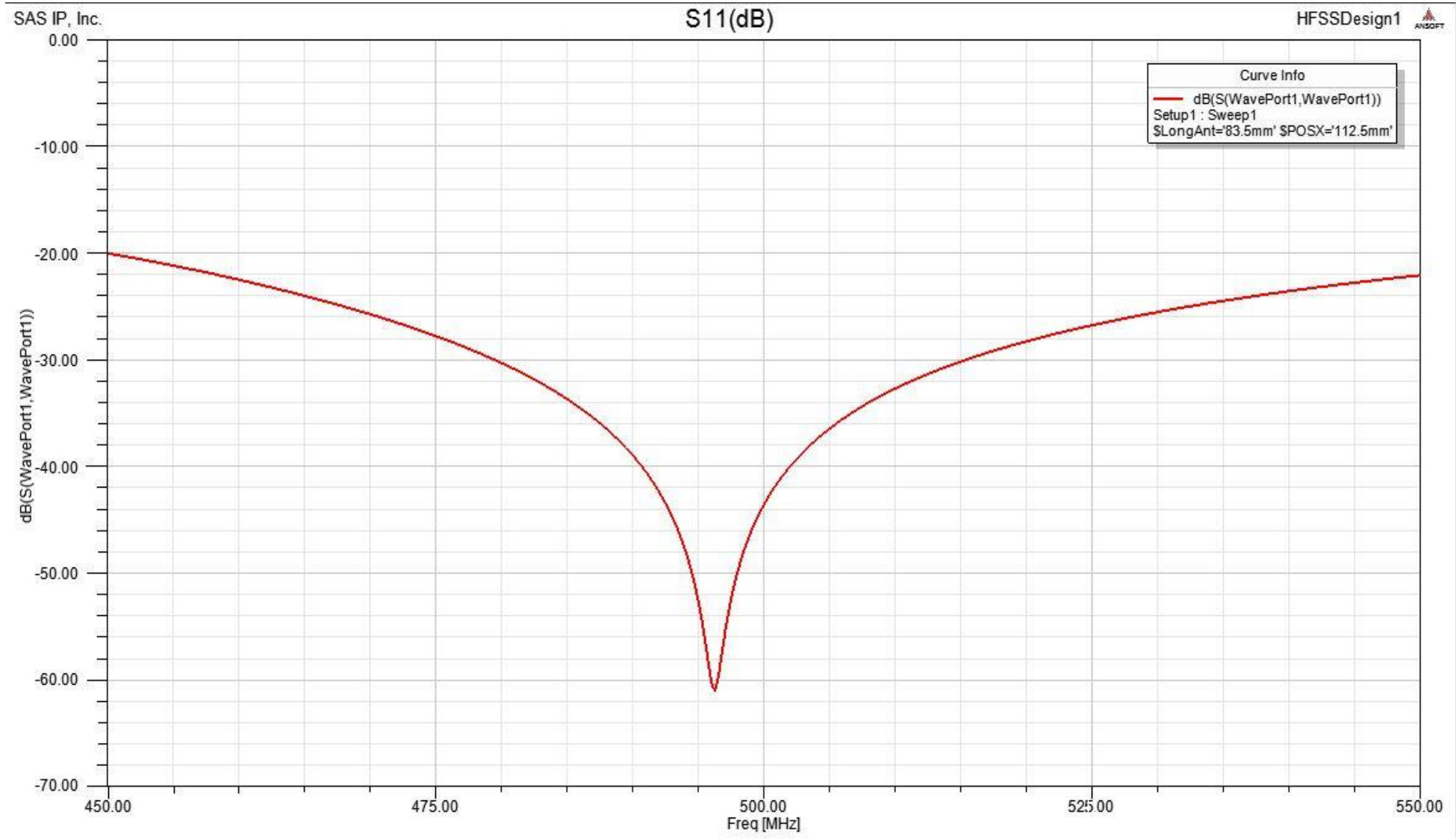
2-Way 500 MHz 150 kW Waco

500 MHz Power Combiners

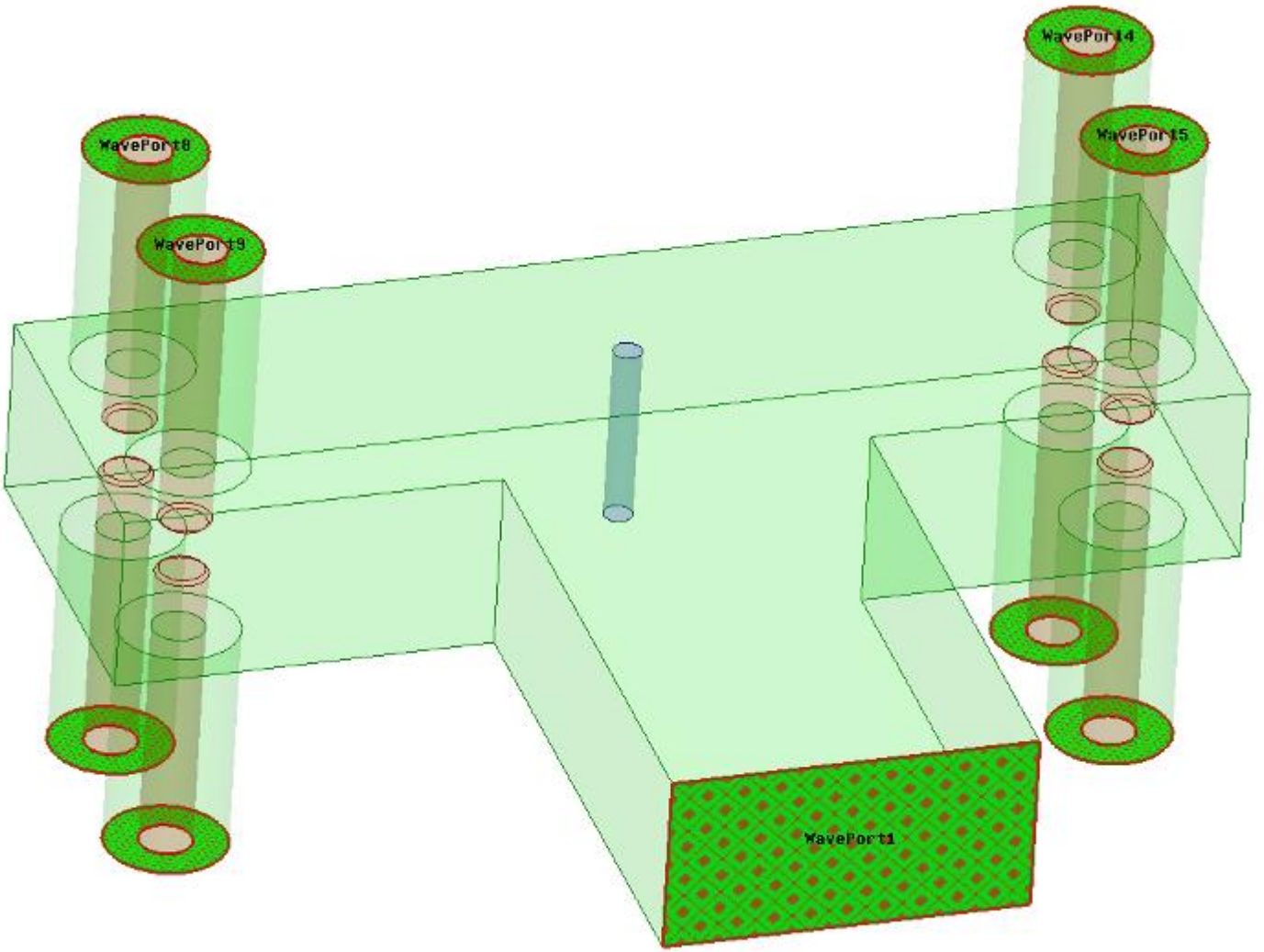
4-Way 500 MHz 300 kW Waco



4-Way 500 MHz Waco S11



8-Way 500 MHz 600 kW Combiner



N-Way Waco Applications

- N-Way Waco is not only able to be used for SSA of different frequency, but also for IOT and klystron amplifier as a power combiner
- It is able to be used as power splitter also
- Advantages

  Low cost

  Compact

  Wide bandwidth

Conclusion

SOLEIL Design Idea is able to be used for different frequency and different power SSA

It is low cost and compact design

Thanks for your attention