The magnetron is dead – long live Solid State RF Technology

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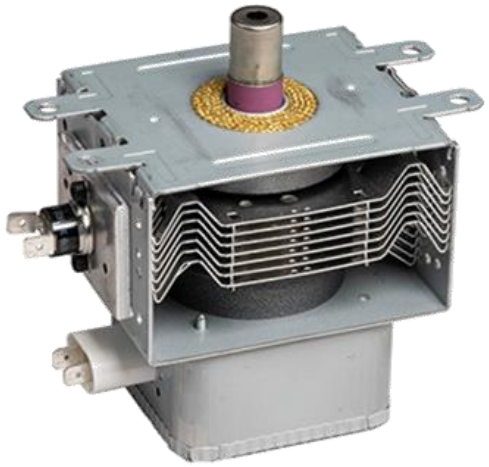
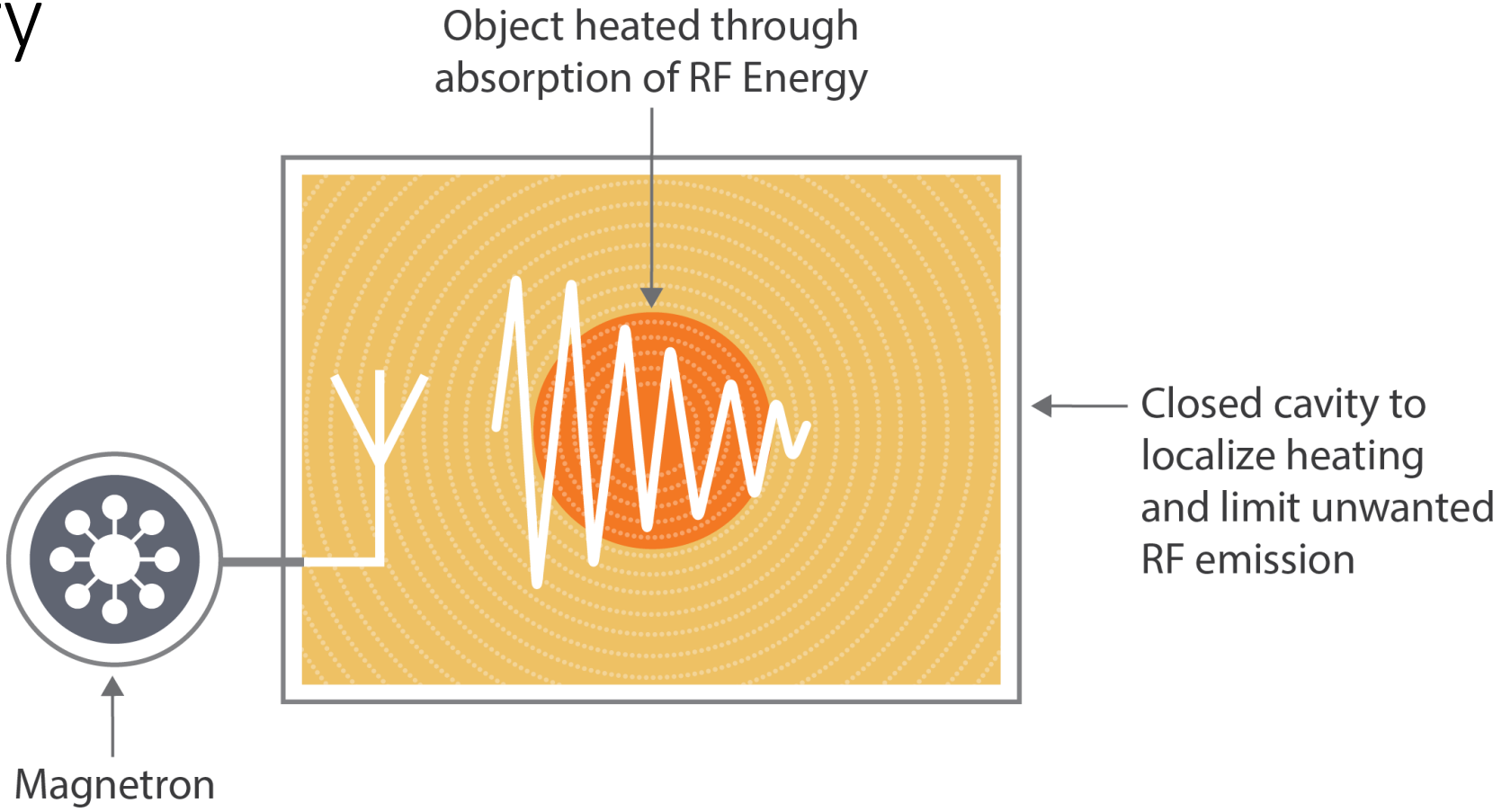
Introduction SSRF technology

- Technology basics
- Differences to magnetrons
- Control:
  - right amount of power,
  - At the right time
  - At the right place

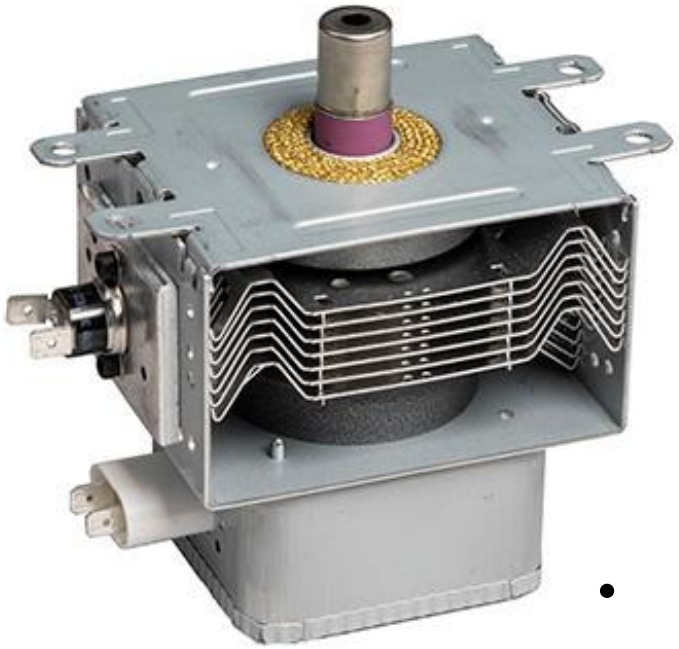
- E.g. leading e.g. to a homogeneously heated specimen

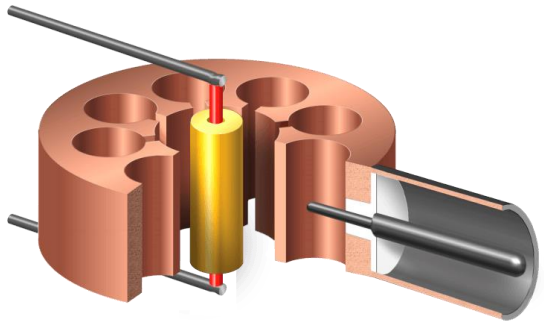
A classic: Magnetron as energy source in microwave oven or industry

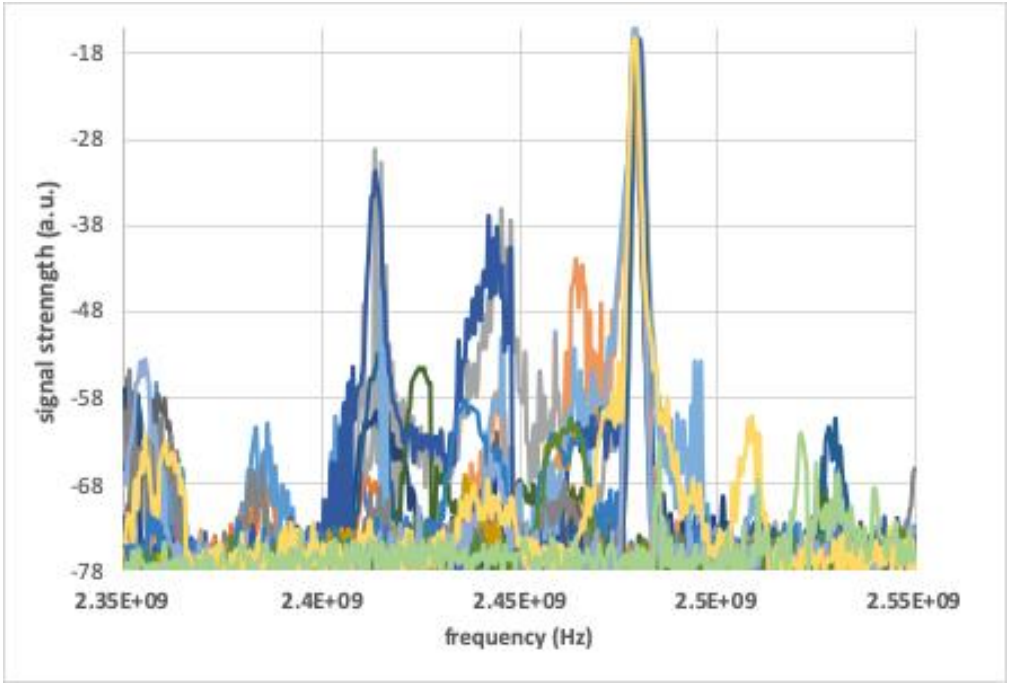




Magnetron + its spectrum



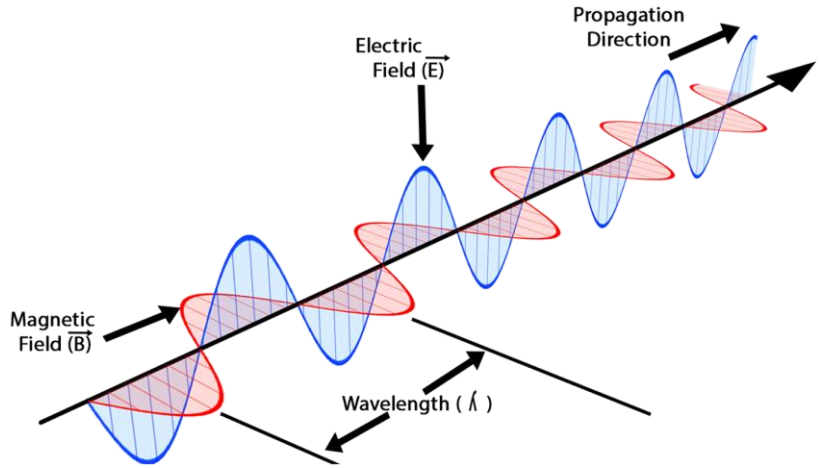


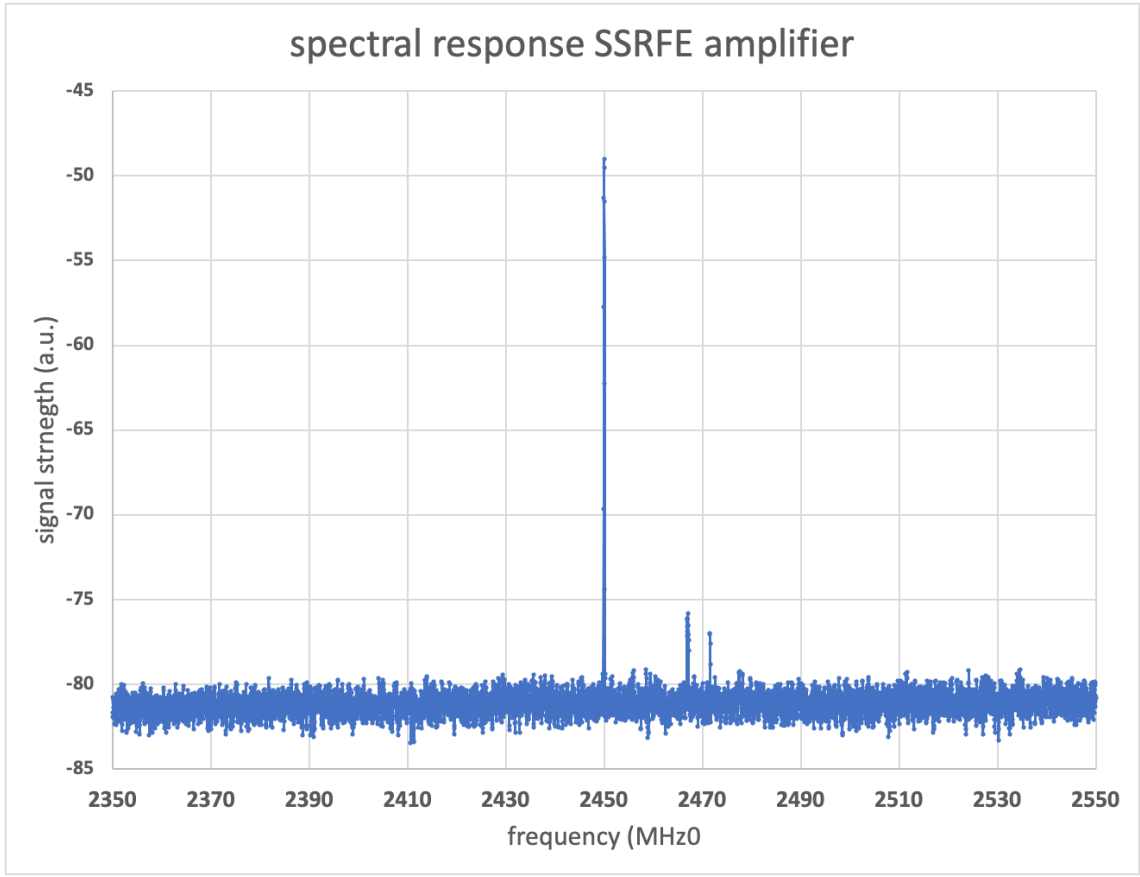


- Mechano-electrical oscillator
- None to poor spectral control
- Slow power control
- Industrial-grade magnetron systems can be “clean”

Solid state generated RF

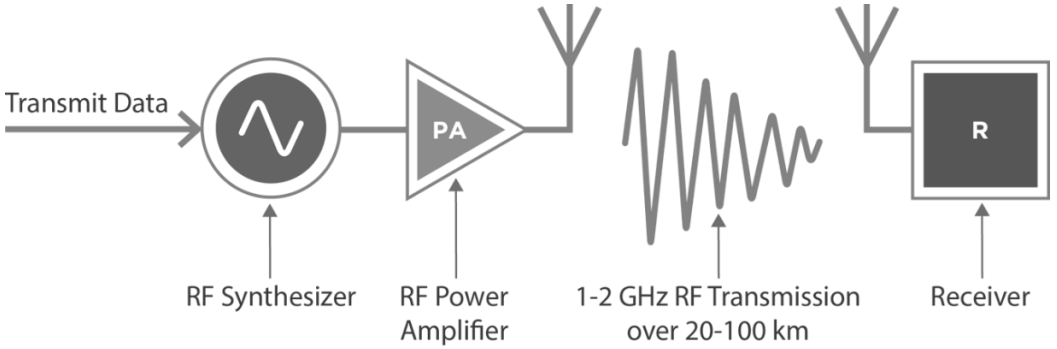
- Control: just one RF vector at a time
  - Precision frequency, amplitude and phase
  - -> Very clean spectral source
  - reproducible



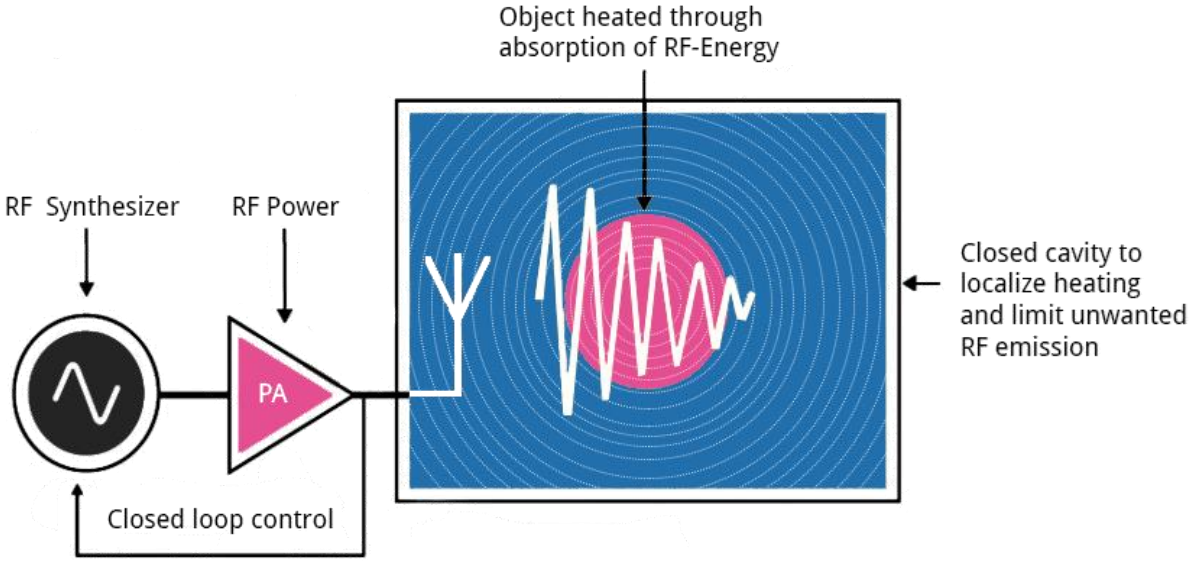


Semiconductor-based RF energy -> SSRFE

- Common use solid state RF:

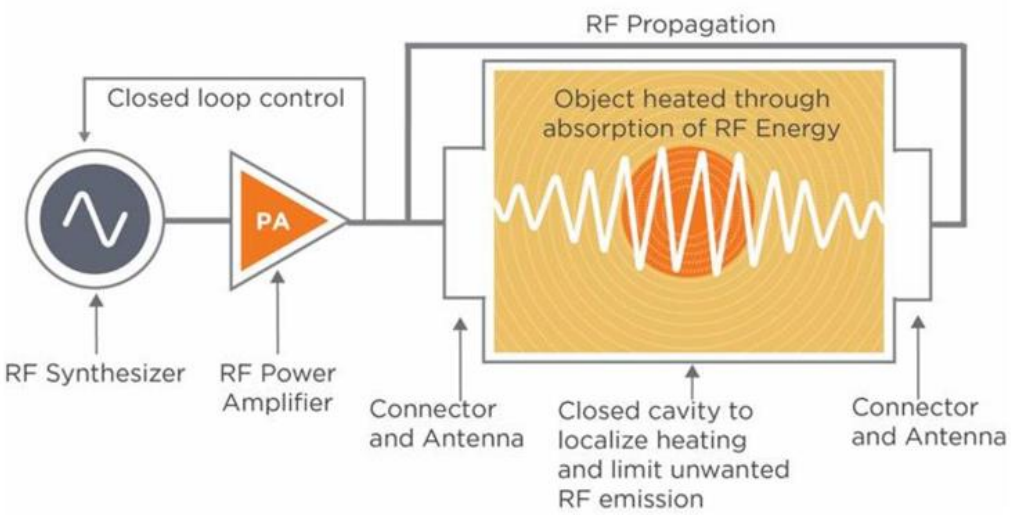


- We'll talk about heating dielectrics with non-ionizing, RF energy!



SSRFE & feedback

- Generators measure forward and reflected RF power (and phase)
  - Calorimetric process control & quality
  - ”Network analyzer” functionality
    - ”talk to your load”
- Large dynamic energy range (µJ -> MJ)
  - µs * W -> ks * kW
- Agile!
  - µs timescale
  - Swift response to arcing
  - Electronics and process protection

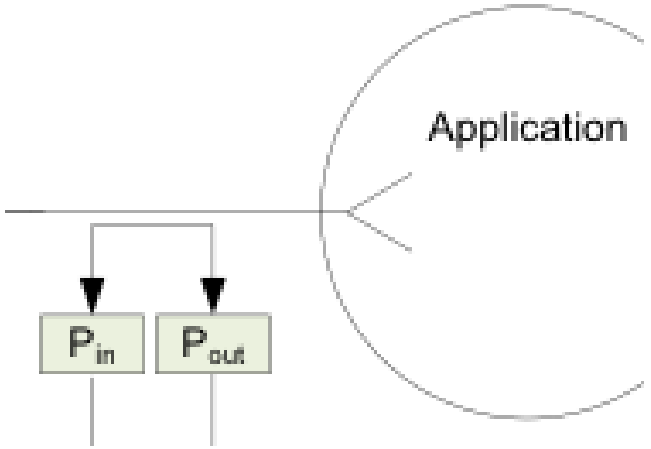


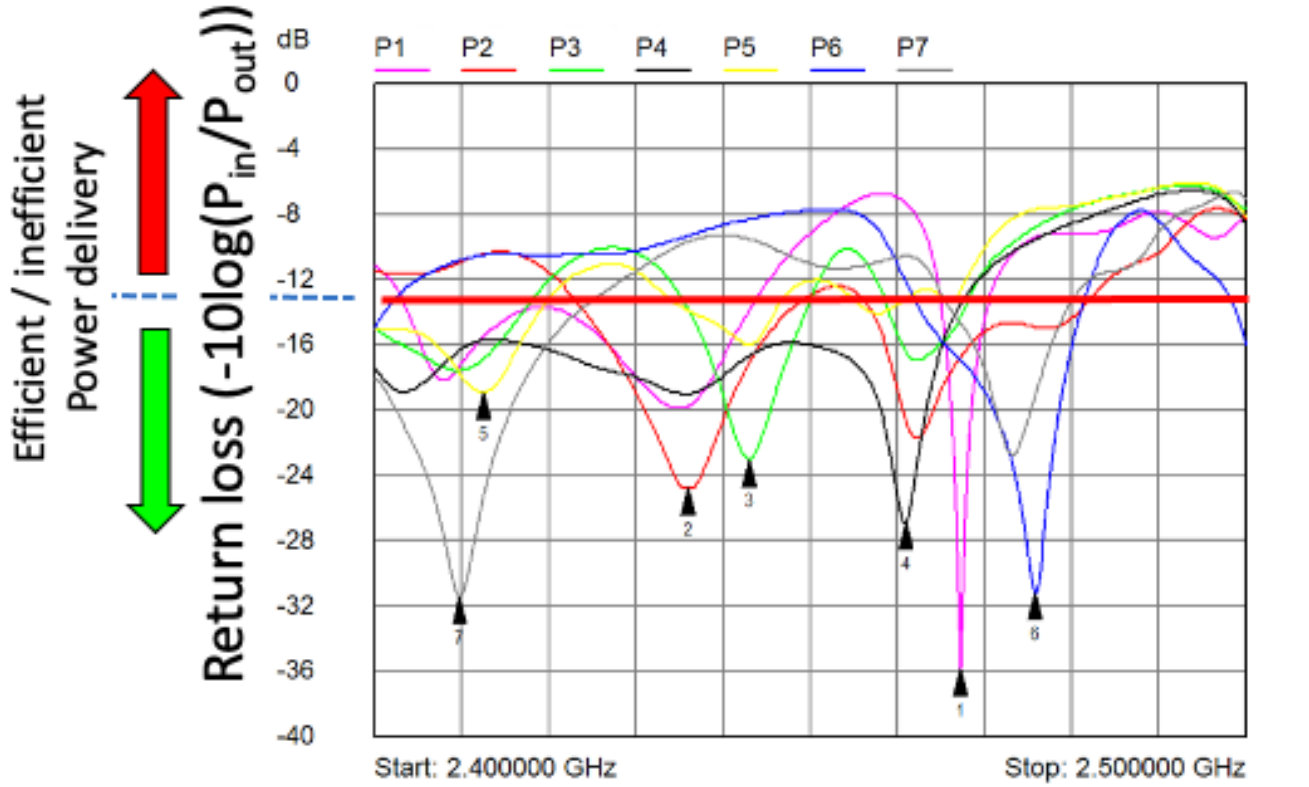
Solid-State RF Energy Sources – Characteristics Overview

- **Unprecedented control** over RF signal
  - Power, phase, frequency
  - Reproducibility -> “Precision”
    - Can be modeled/simulated
- Feedback
- Effective, and fast reaction to (changing) load conditions
  - Efficient energy delivery, fast shutdown, …
- Low-voltage electronics
- Small form factor; flexible hardware partitioning
- Solid state semiconductor-based reliability
- Electronics cost base enabled
- System efficiency on par with magnetrons

Precision energy delivered – into the applicator

- EM Energy into the applicator (the active volume with load)
- $P_{delivered} = P_{out} – P_{in}$
- Frequency to tune adaptively -> efficient process
  - situation will change during process
  - -> S11 tracker / “DLL”

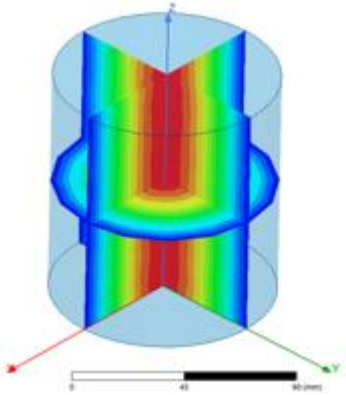


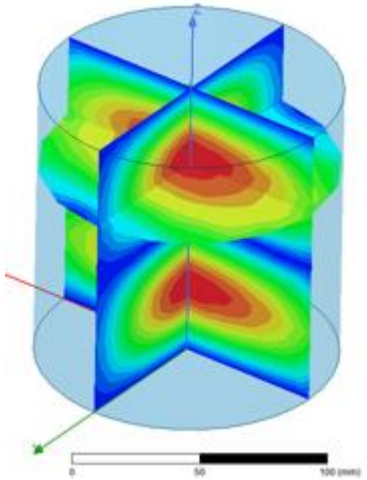


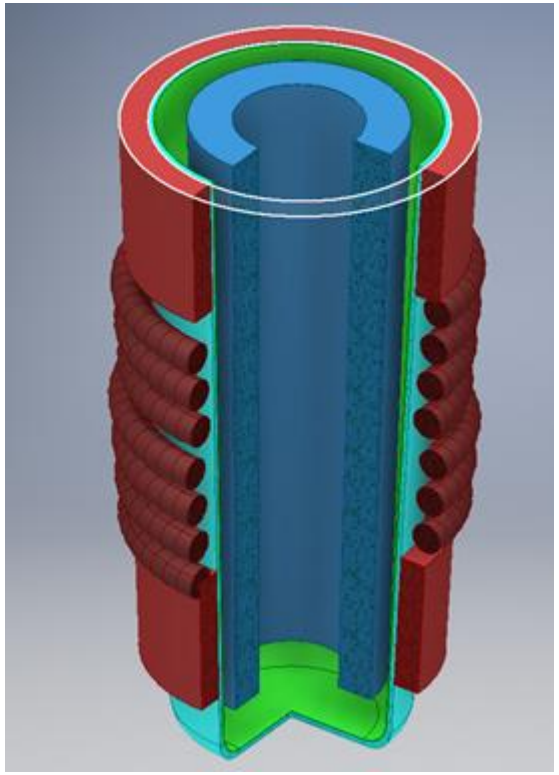
“Focusing or containing” RF energy -> applicators

- ”process”- size related to wavelength of radiation

- Irradiate smaller locations / objects of interest through:
  - frequency choice
  - Antenna design
  - Dielectric properties and modifications thereof
  - ...

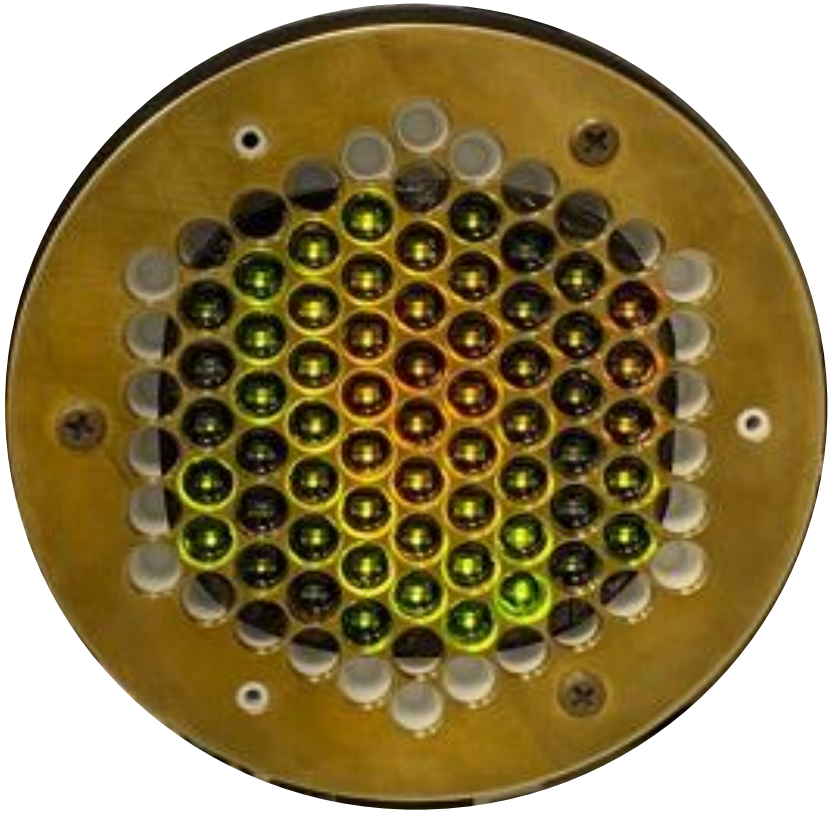


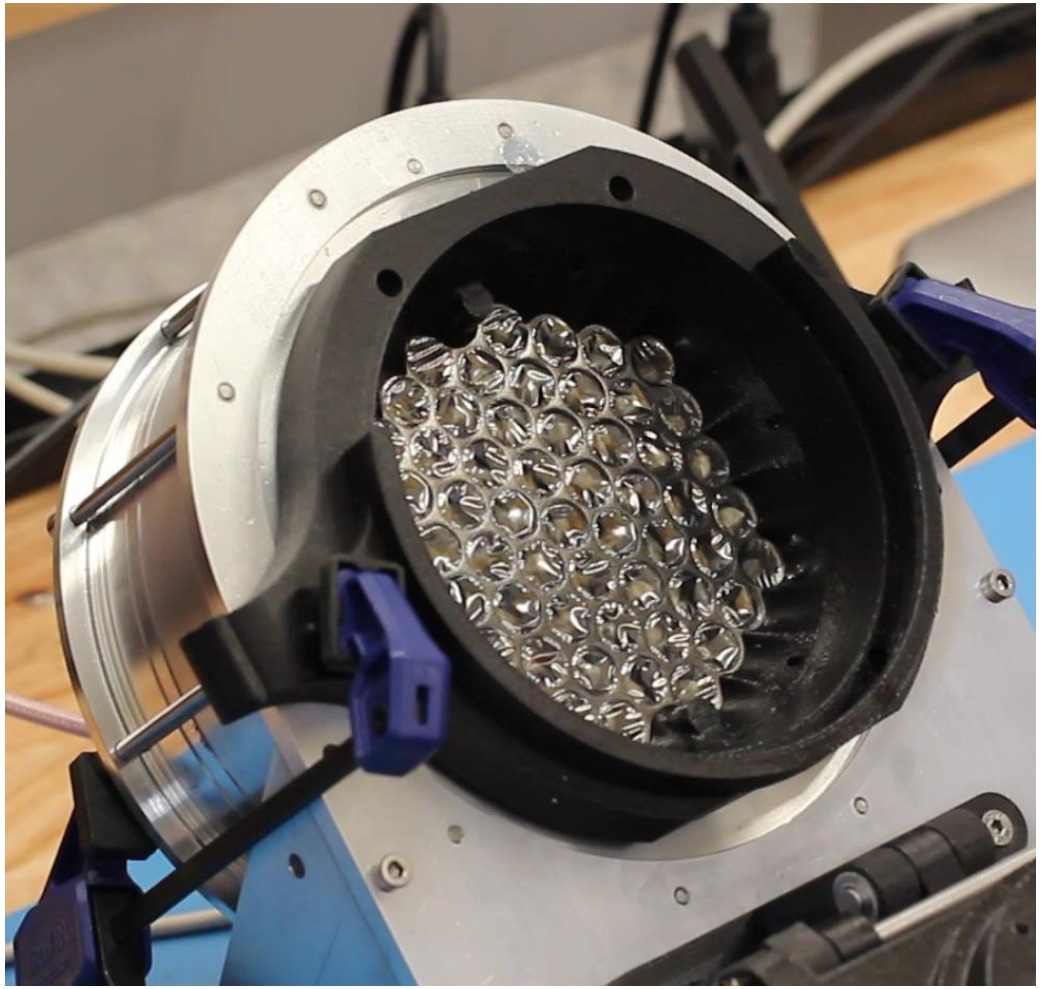




Plasma applications – musical torch

Popcorn popper





solid state feeding architecture -> power!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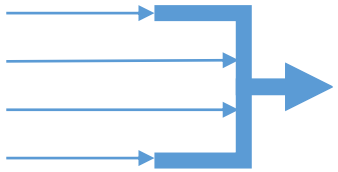
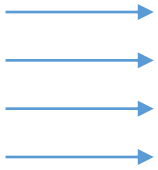
- ”magnetron” style
  - “single” point source – high to very high power levels
    - combine PA modules “outside”
    - ➔ magnetron replacement scenario for existing systems
    - Coherence required!

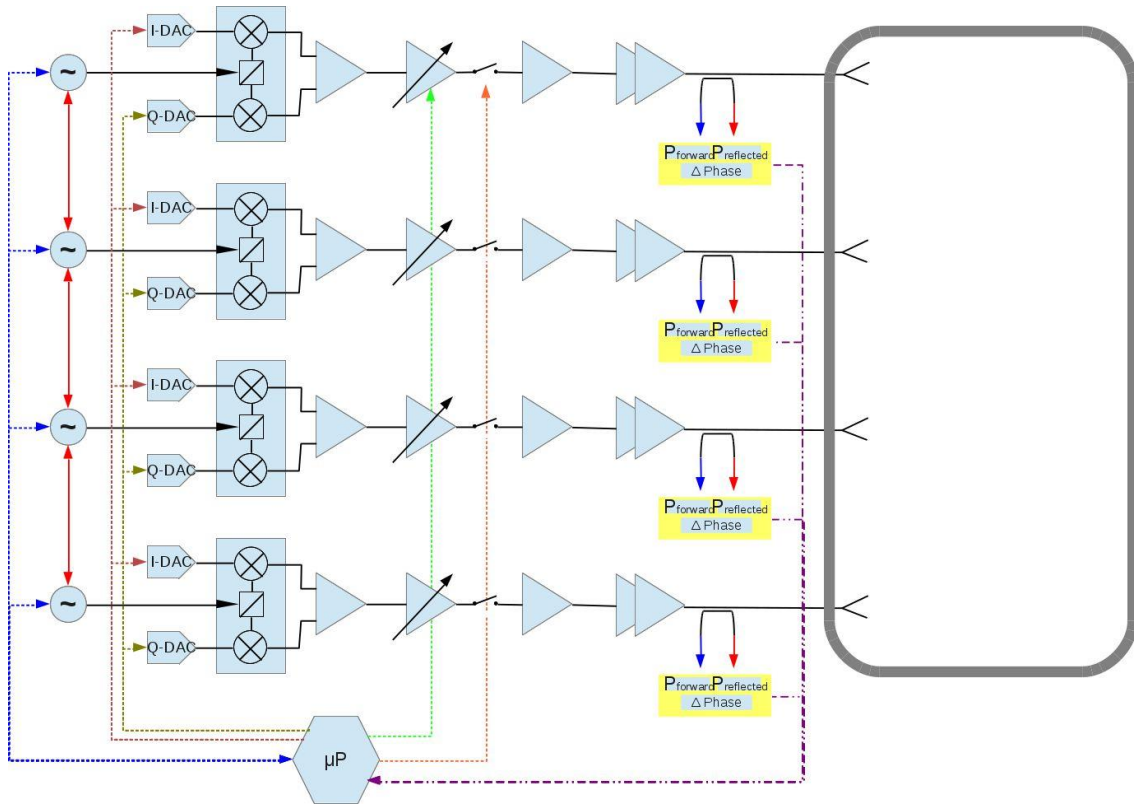


- “distributed” style
  - multiple feed points, limited power per feed line/PA
  - flexible, distributed, redundant, “optimal” control
  - integration/control issue for large number of generators



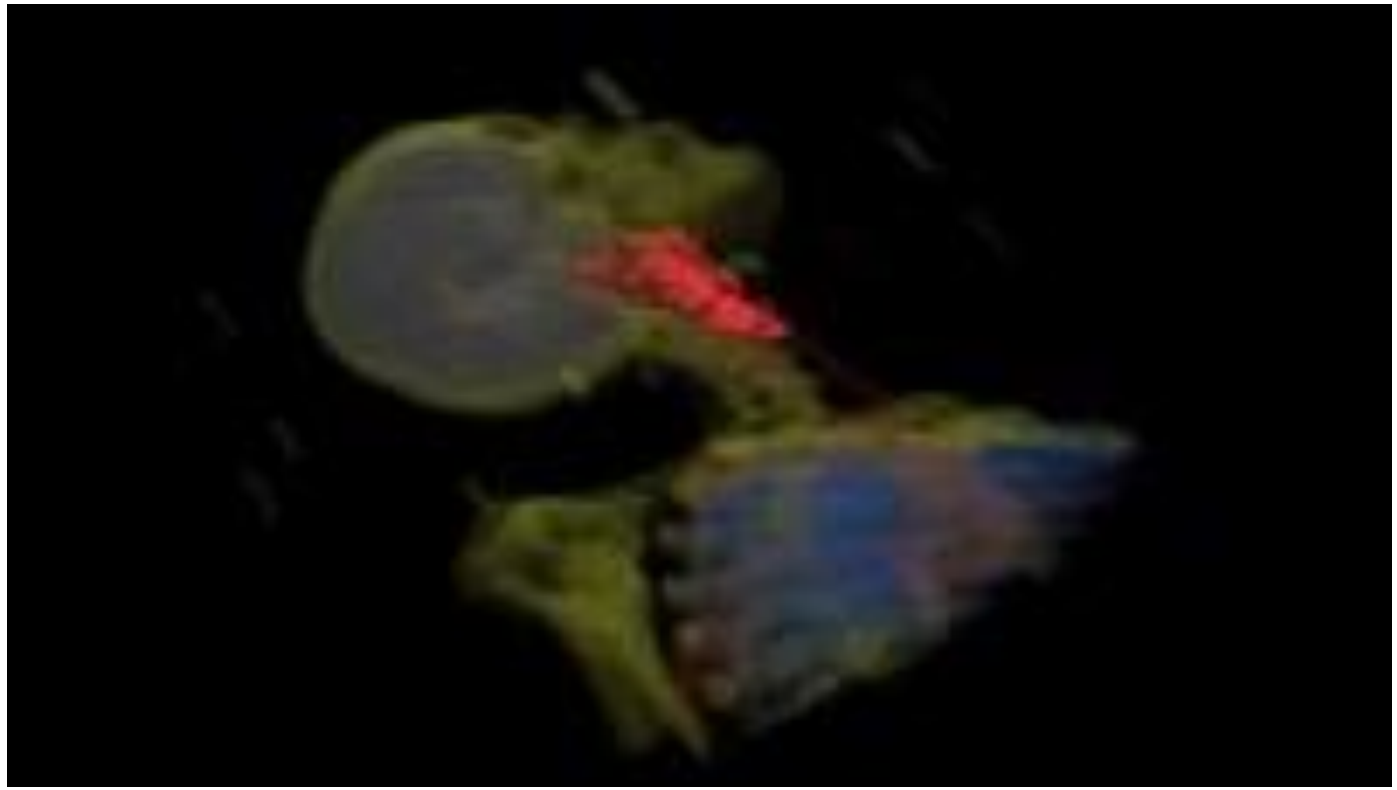
Coherence – maintain phase

- Distributed local oscillator
  - Mind phase offsets
  - Mind AM2PM
    - Common mode delta
    - Differential delta
- Possible issues:
  - Power combining problems
  - Agreement simulation with reality
- Application:
  - Hyperthermia treatment



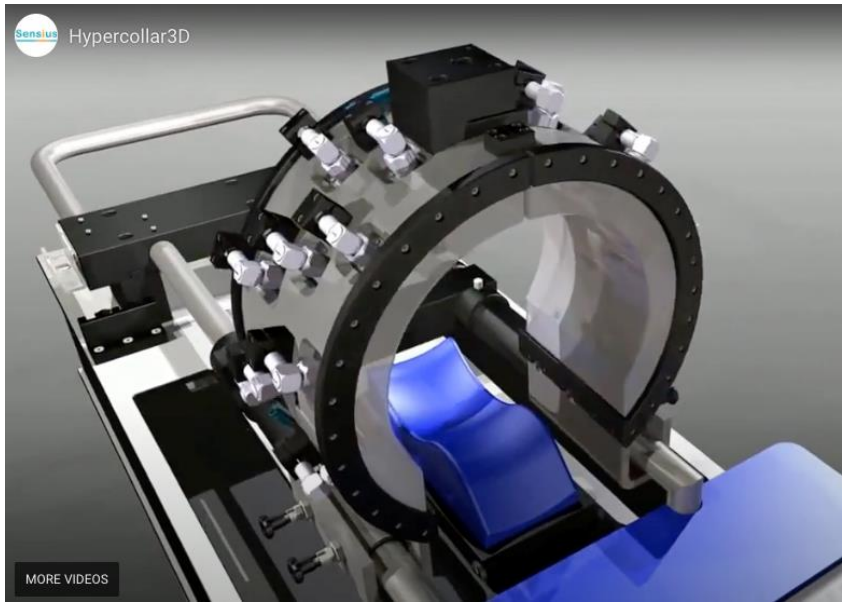
Hyperthermia treatment

- Superposition of multi-channel wavefronts permit the exact “focus” of maximum energy deposition at the location of the tumor
- Lot of modeling required



Hyperthermia treatment system

- ≤ 20 channels



- Antennae in water boluses; boluses in contact with skin

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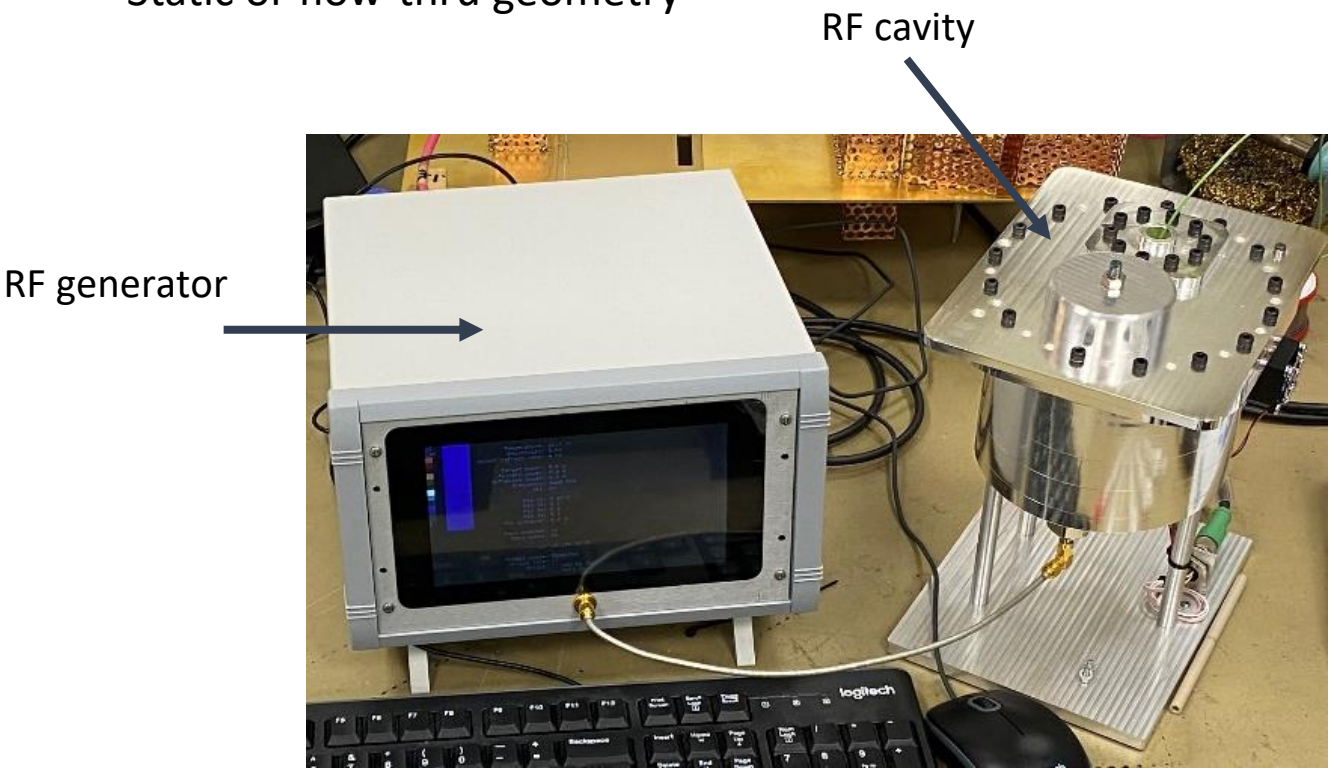
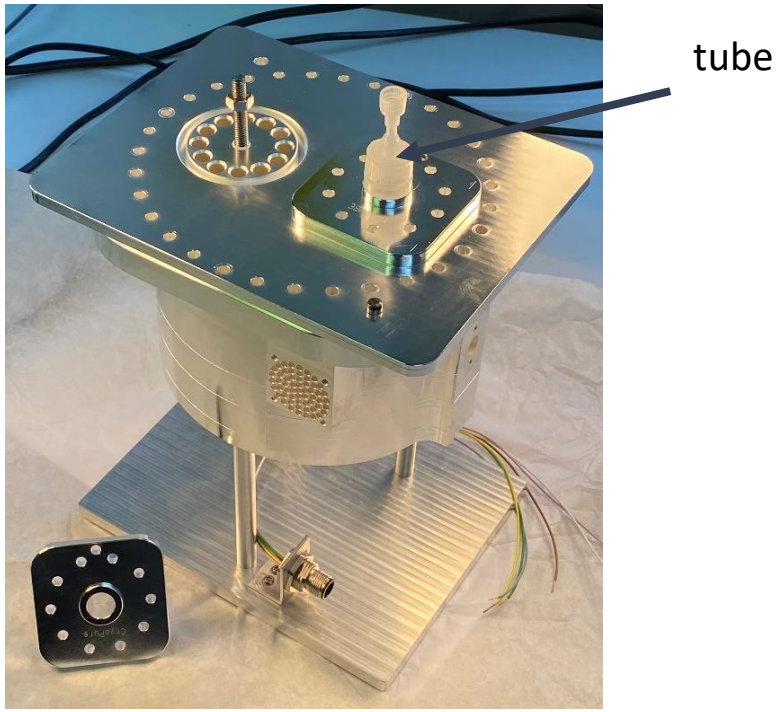
Sub-ml heater for micro-chemistry

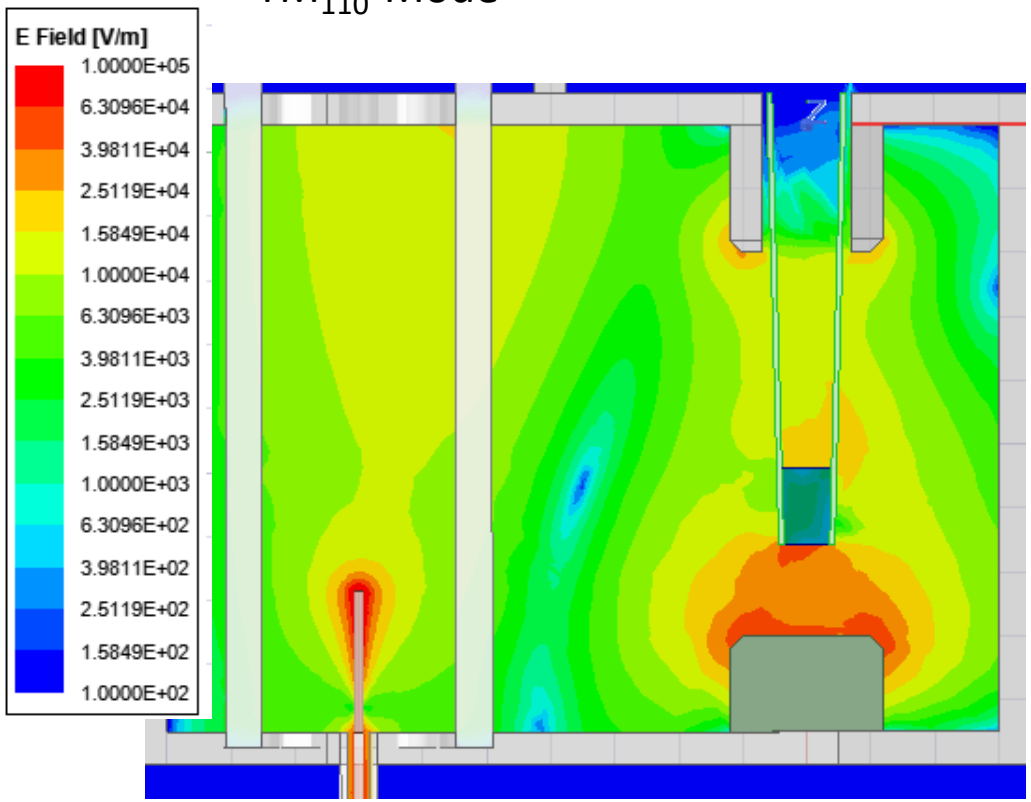
- 20 W, 2.45 GHz RF Generator including signal generator, power amplifier and control unit + Screen
- Static or flow-thru geometry

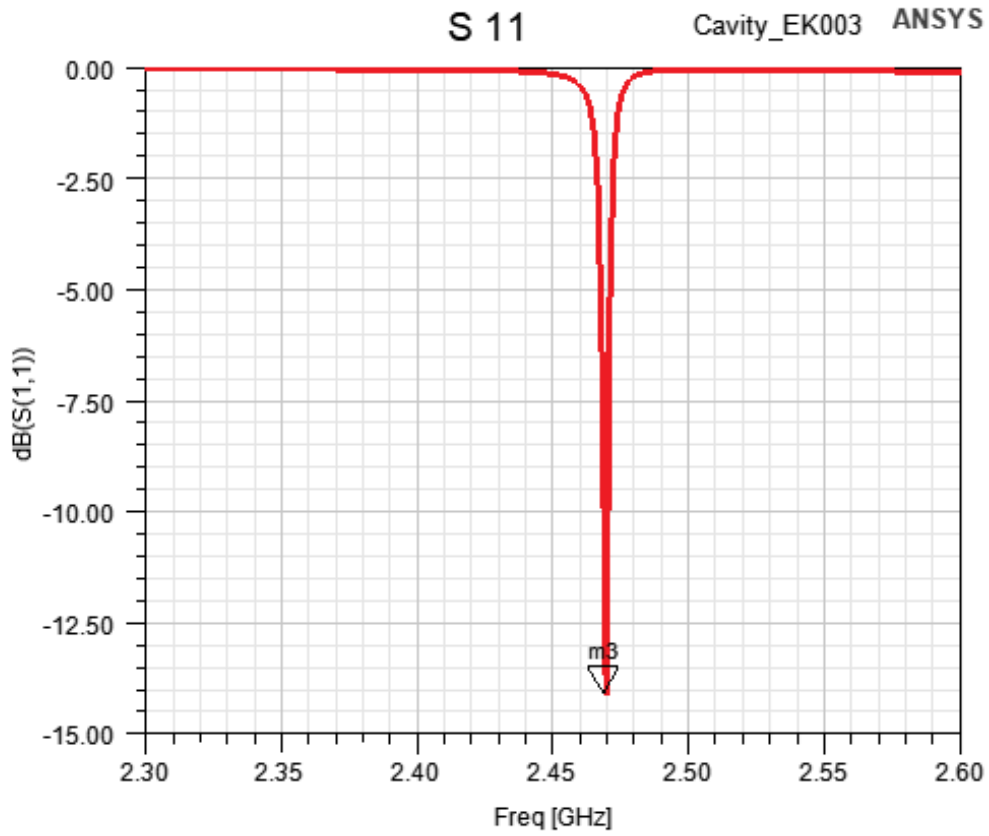




3D-EM Simulation of the Applicator incl. sample tube

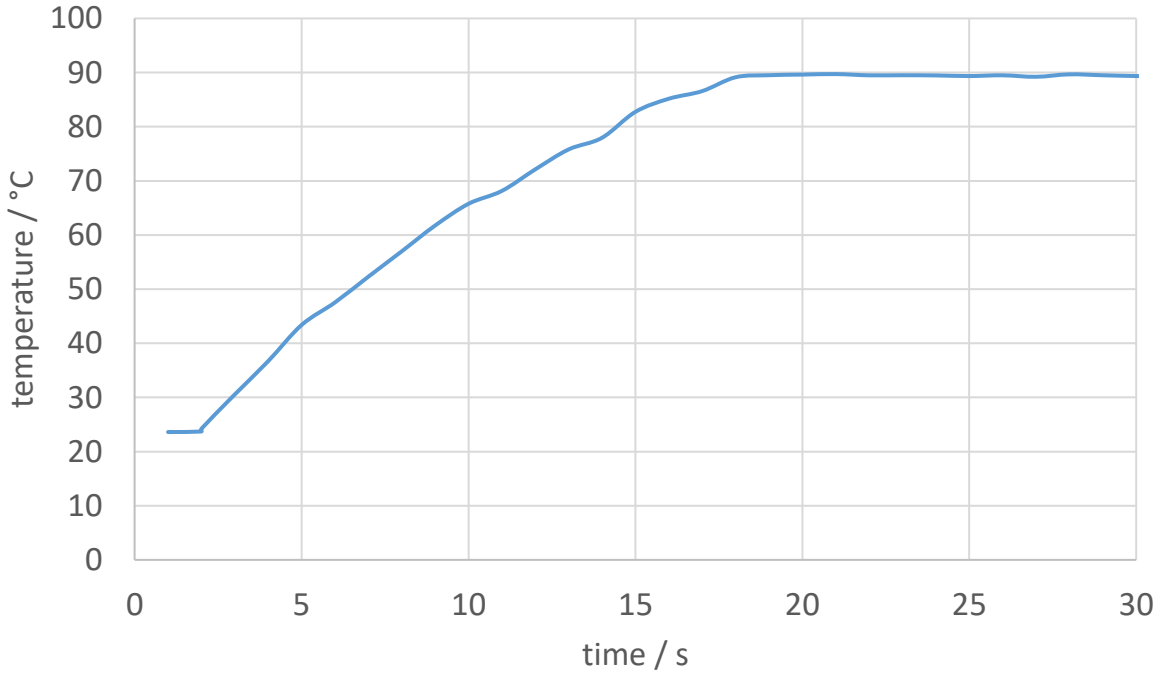
- Simulation outcome (with tube)
- TM_{110}-Mode





RF testing with 20 W

- Heating test up to 90 °C
- Heating rate: 3.9 K/s from 24°C to 90°C



Conclusions

- Solid State RF:

Predictable energy, timely delivered with laser precision

pinkRF

The RF Energy Company

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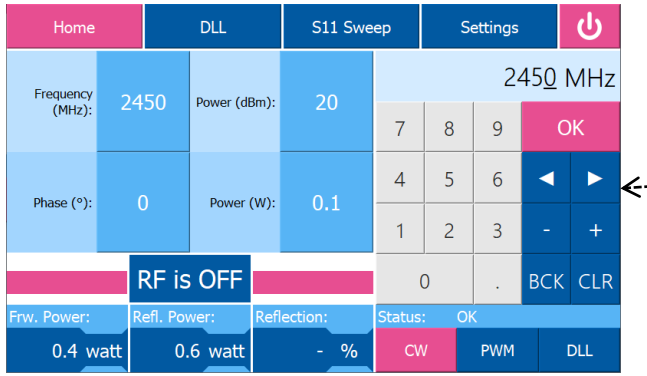
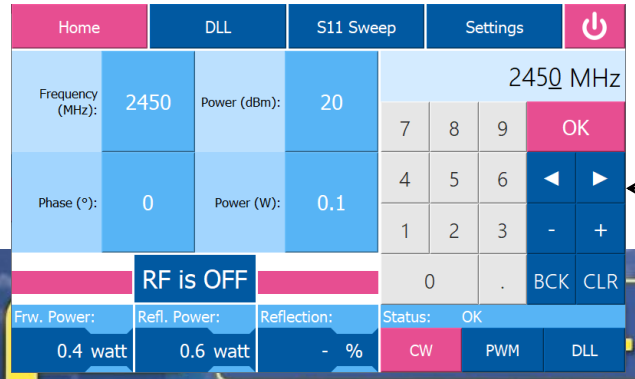
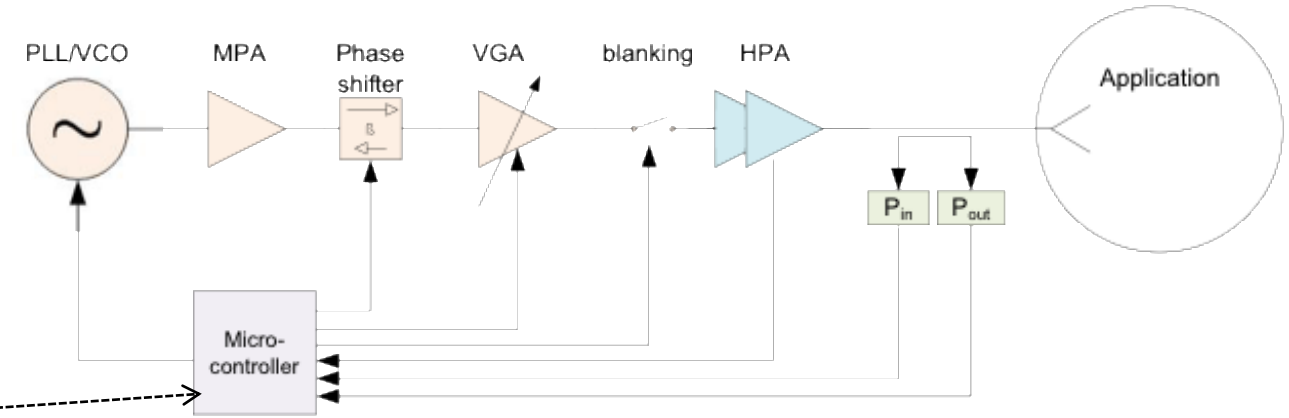
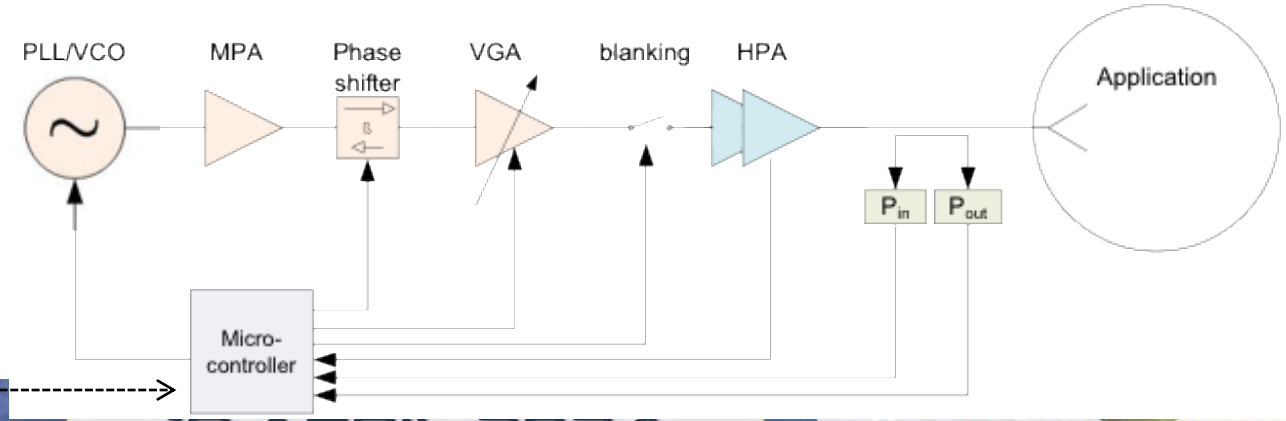
SSRFE generator hardware schematic – 2 x 250W, 2.4 – 2.5GHz

- 2 channel, 2x250W, 2.45GHz
- Independent operation



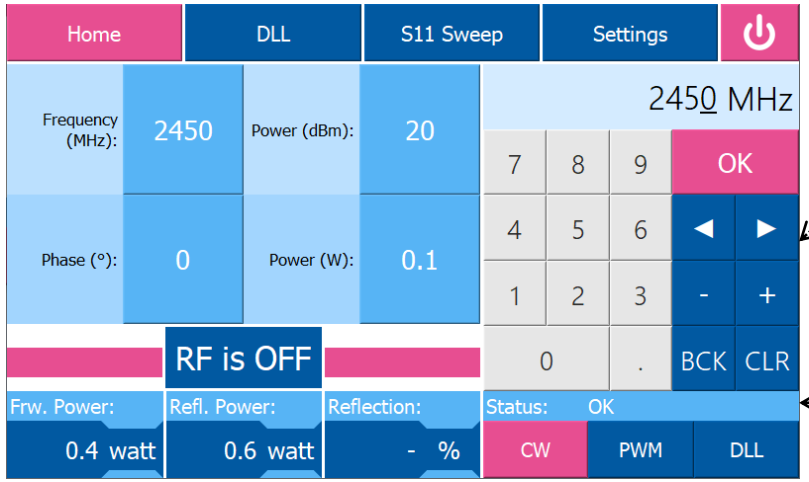


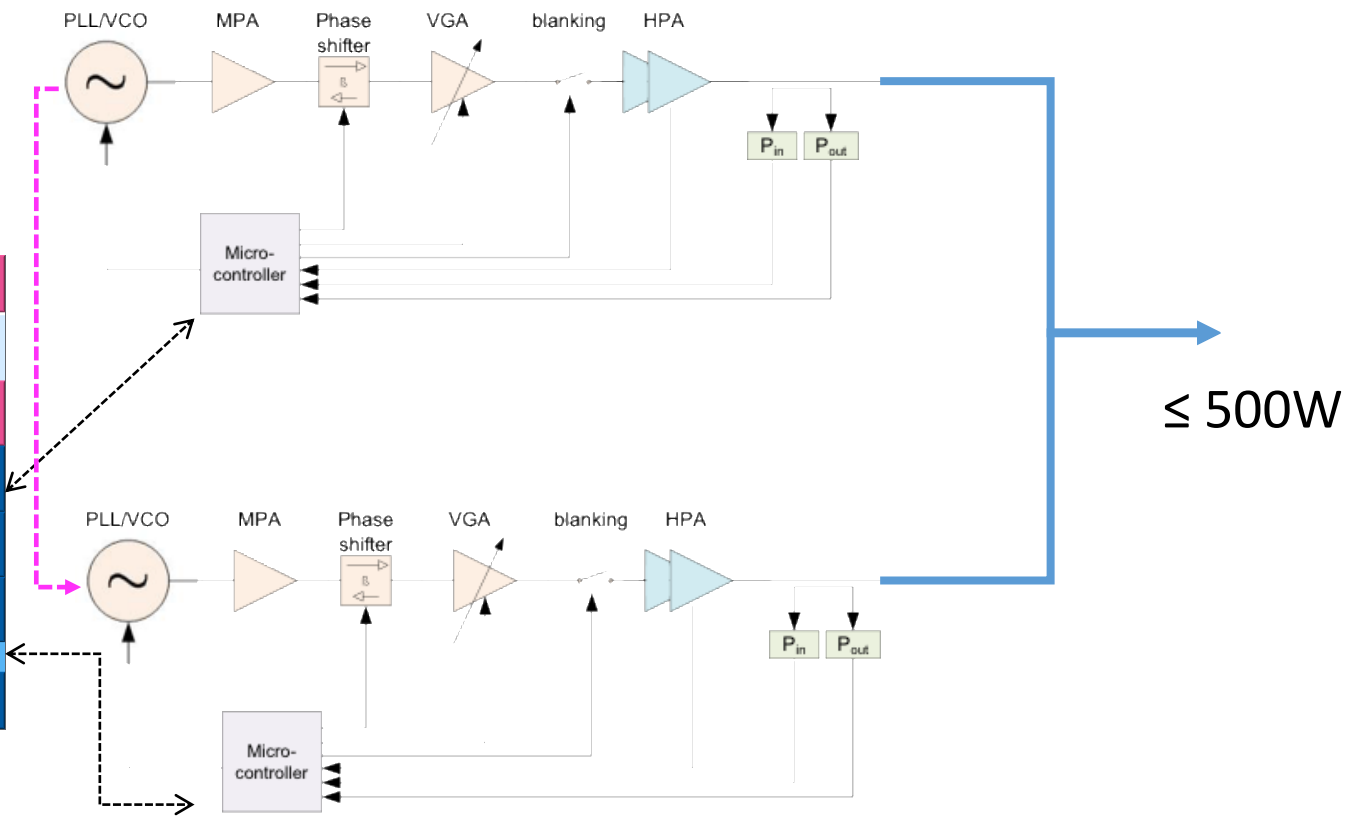




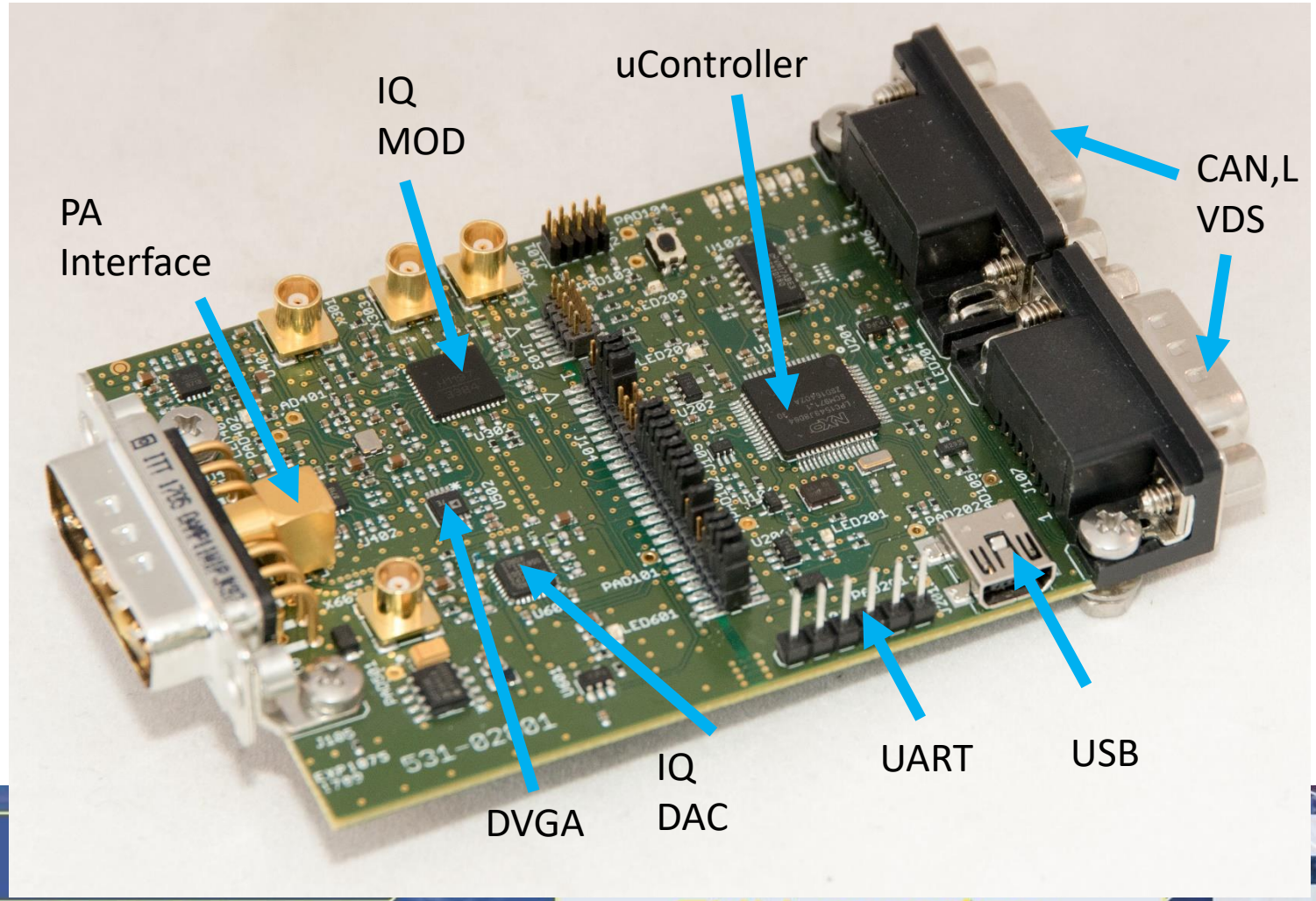
SSRFE generator hardware schematic – 500W configuration

- 1 channel, 2x250W = 500W
  2.45GHz
  - coherent operation





Building Blocks – a typical small signal generator



Building Blocks – Power amplifier