Power RF systems for low emittance rings

Erk Jensen/CERN SY-RF

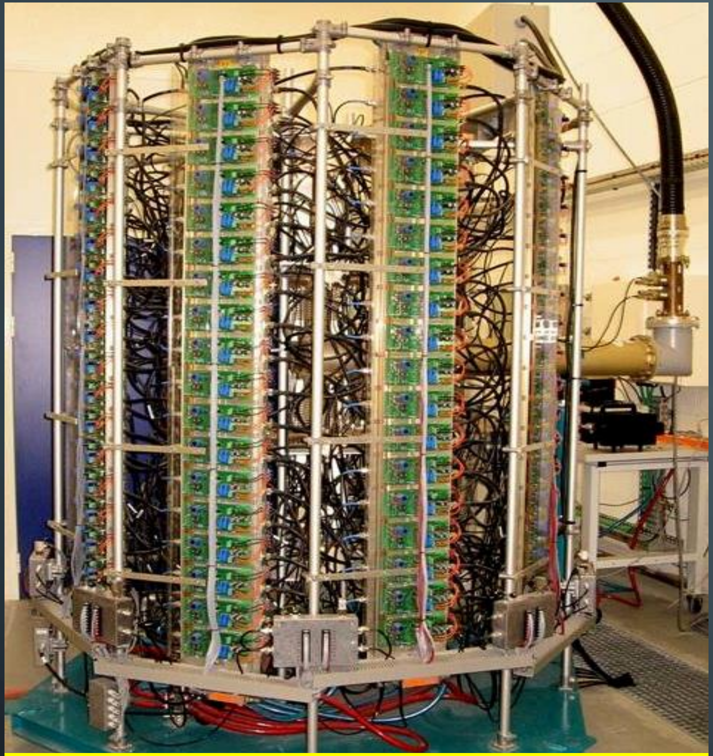
What Power RF system characteristics are needed?

- Low emittance rings:
  - Light source synchrotrons
  - Damping rings for LCs
  - Large colliders (FCC, CEPC)
- Synchrotron radiation dominated rings require large power (***high efficiency***)
- Light sources need ***high availability*** (MTBF $\rightarrow \infty$)
- Large currents: systems need to deal with heavy ***transient beam loading*** (not covered here)
- Power RF system characteristics are not given by the low emittance, but by the purpose of the low emittance facilities.

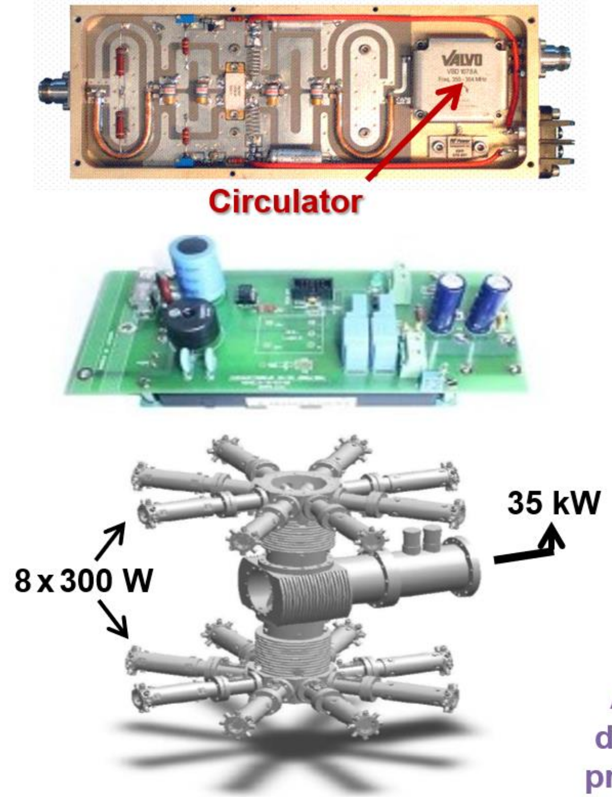
Light source synchrotrons: trend towards SSPAs

- Triggered initially by P. Marchand (SOLEIL), SSPA systems now dominate Synchrotron Radiation facilities worldwide.
- Distinct advantages compared to klystrons/vacuum tubes:
  - Possibility to design systems with inherent redundancy/fault tolerance
  - Vacuum tubes have limited lifetime
  - No need for high voltage systems
  - Conceptually possible to allow upgrade to advancing SS technology (LDMOS generation, e.g.)

SOLEIL Booster original 35 kW SSPA (2005)



Original 35 kW SSPA tower, 2005 – world record!



300 W CW - 352 MHz amplifier module VDMOS D1029UK05 from SEMELAB (G = 11 dB, η = 62 %)

600 W - 280 / 28 V dc power converter

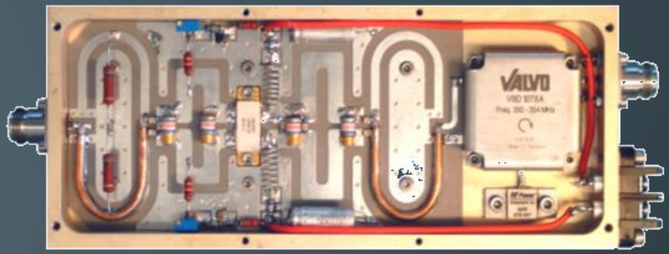
Power combiner (8 x 8 x 2)
8 dissipaters of 16 + 2* modules
*** Pre-amplifiers**

All amplifier components were designed in house and the mass production contracted to industry

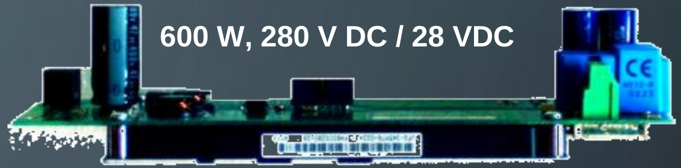
~ 80 000 running hours over 15 years and only one single trip from the SSPA, in August 2016, due to a loose connection on a monitoring cable (down time ~ 2.10^{-5} and MTBF ~ 38 000 hours)
~ 1 module failure / year, without impact on the operation, thanks to the modularity and redundancy

SOLEIL Main ring 180 kW system

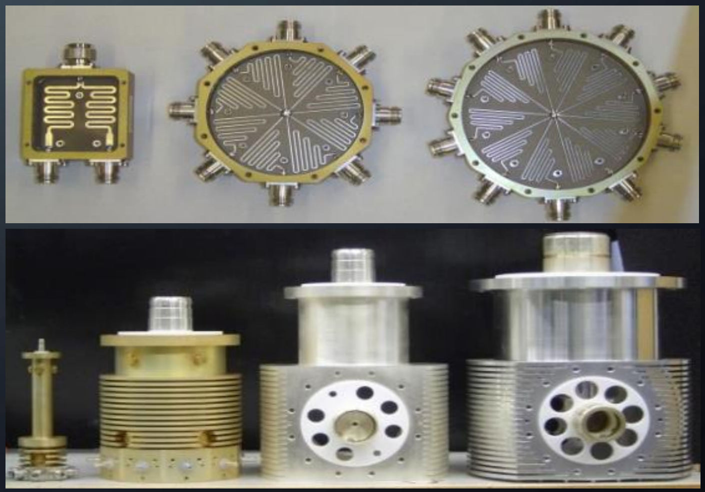
Amplifiers 1 & 2 (2 x 4 towers à 45 kW)
powering the 2 cavities of CM 1



600 W, 280 V DC / 28 VDC



Combiners



SOLEIL Main ring SSPA operational results

MTBF & beam downtime, cumulated by the 4 SR SSPA's over ~ 70 000 running hours in ~ 13 years

Equipment	MTBF	Downtime	Comments
a) 4 x RF amplifiers	~ 12 500 h	~ 1 10^{-4}	Failures from preamplifiers and 1st stage combiners
b) 4 x 500 kVA thyristor-based 230 Vac / 270 Vdc rectifiers	~ 8 000 h	~ 4 10^{-4}	Single rectifier per amplifier
a) + b) 4 x RF transmitters	~ 5 000 h	~ 5 10^{-4}	

Already **excellent MTBF and operational availability**!

Possible improvements:

- Provide some more redundancy:
  - In the DC-DC power conversion, which originally consists in a single 500 kW rectifier per SSPA,
  - In the preamplifier stage, where a failure of one switches the RF off.
- Improve the power capability of the 1st stage combiners

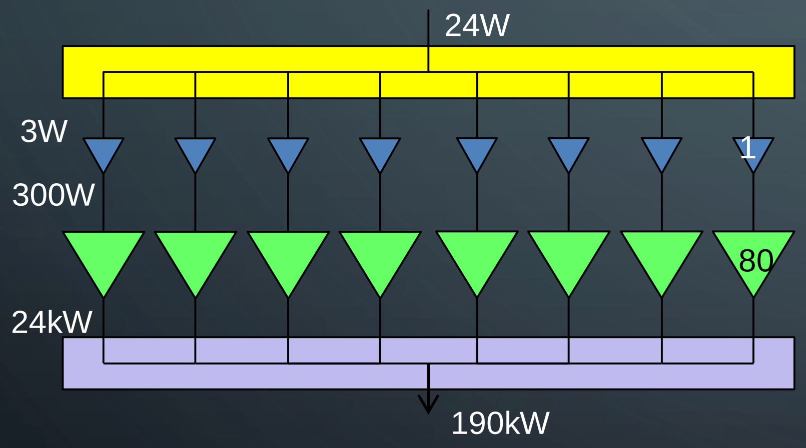
The SOLEIL team is working on these improvements.

Improving availability: SOLEIL combiner/divider

Goal: cure the lack of redundancy in the preamplifier stage

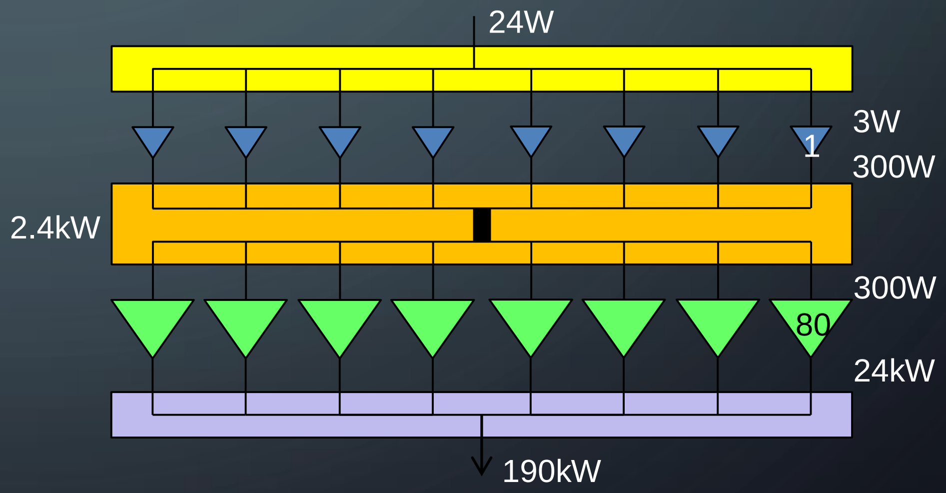
Former configuration

- Each pre-ampli drives 80 modules; if one of them fails, the amplifier is stopped.



Upgrade with combiner/divider

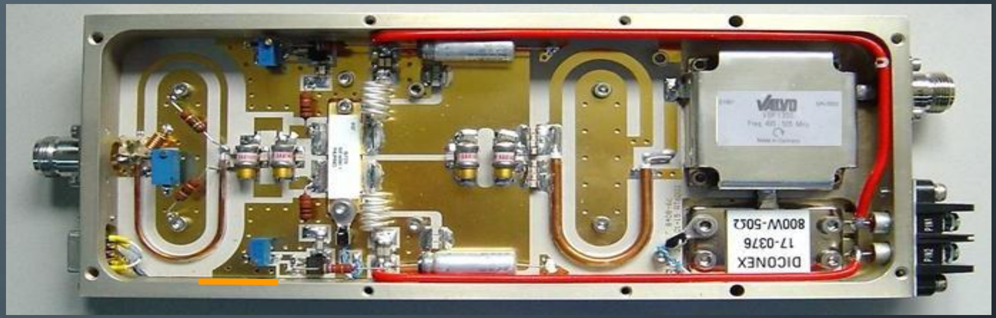
- Thanks to the combiner-divider, the failure of a pre-ampli does not affect the functioning anymore.



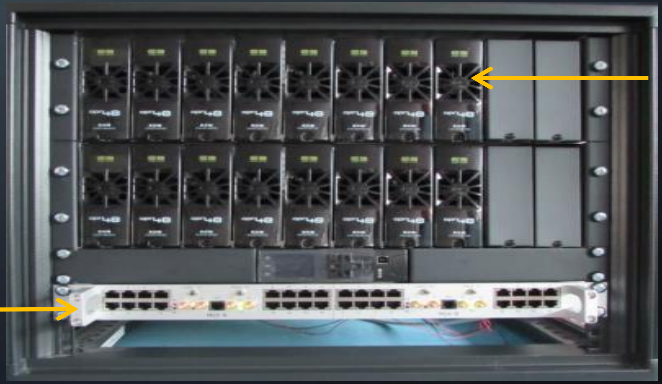
Mid 2019: 12 of the 16 towers already refurbished (~ 2400 modules)

SSPA R&D @ SOLEIL

- New 650 W/500 MHz modules using 6th generation ($V_D = 50$ V) LDMOS BLF578:
  - RF output power $P_n = 650$ W CW
  - Return loss -40 dB @ P_n
  - Unconditional stability ($K > 10$ dB)
  - Gain: 17 dB @ P_n
  - Efficiency: 62% @ P_n
  - Gain dispersion $\pm 0.2\ dB$ @ P_n / phase dispersion $\pm 5°$ @ P_n (required for good combining efficiency!)



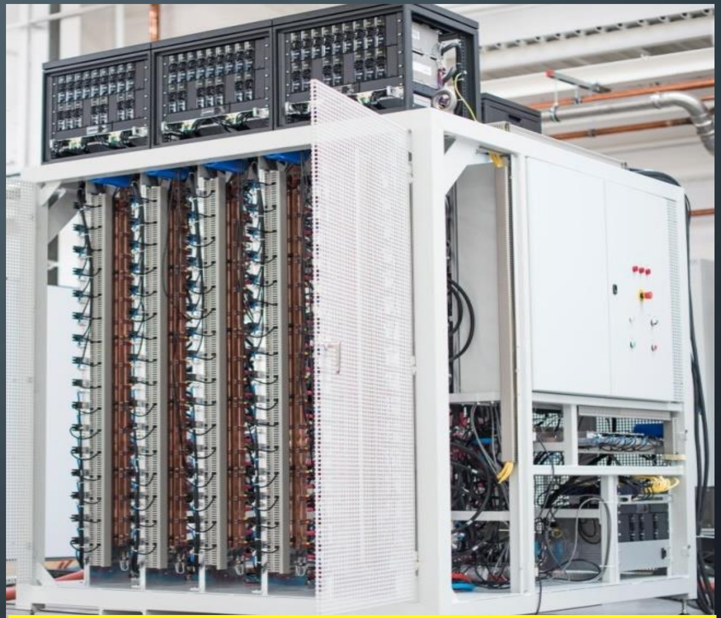
- Modular (2 kW) power converters 230 V AC to 50 V DC
  - Optimized efficiency for all operating power levels



500 MHz SSPA for ThomX & SESAME

- New SSPAs developed & prototyped @ SOLEIL:

ThomX 50 kW SSPA
(6 x 16 RF modules + 3 x 15 PS)

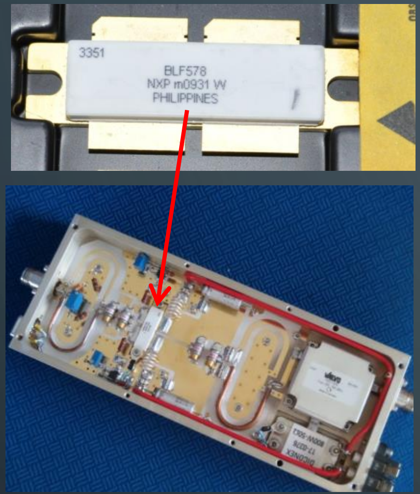


SESAME 80 kW SSPA
(10 x 16 RF modules + 5 x 16 PS)

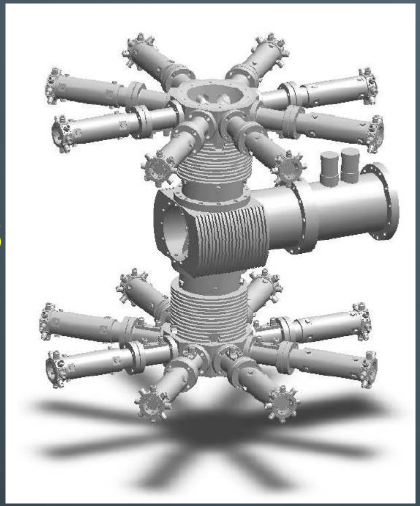
ThomX: Compton X-ray source under construction in Orsay, France
SESAME: Jordan Synchrotron light source

ESRF SSPA system

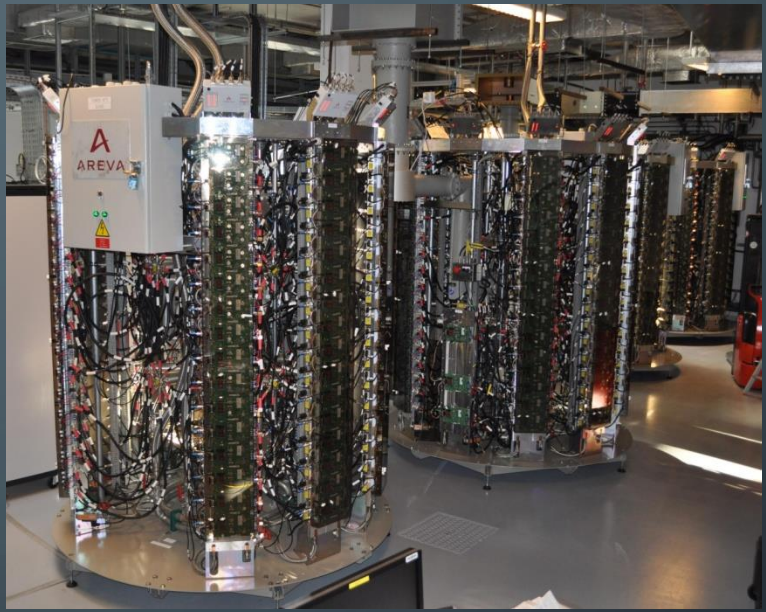
Pair of transistors BLF578 in push-pull



x 128



x 2



650 W RF module

- DC to RF: η = 68 to 70 %

75 kW coaxial power combiner tree

- Fault tolerant: no trip even at maximum power with up to 6 faulty modules

$\Rightarrow$ High redundancy

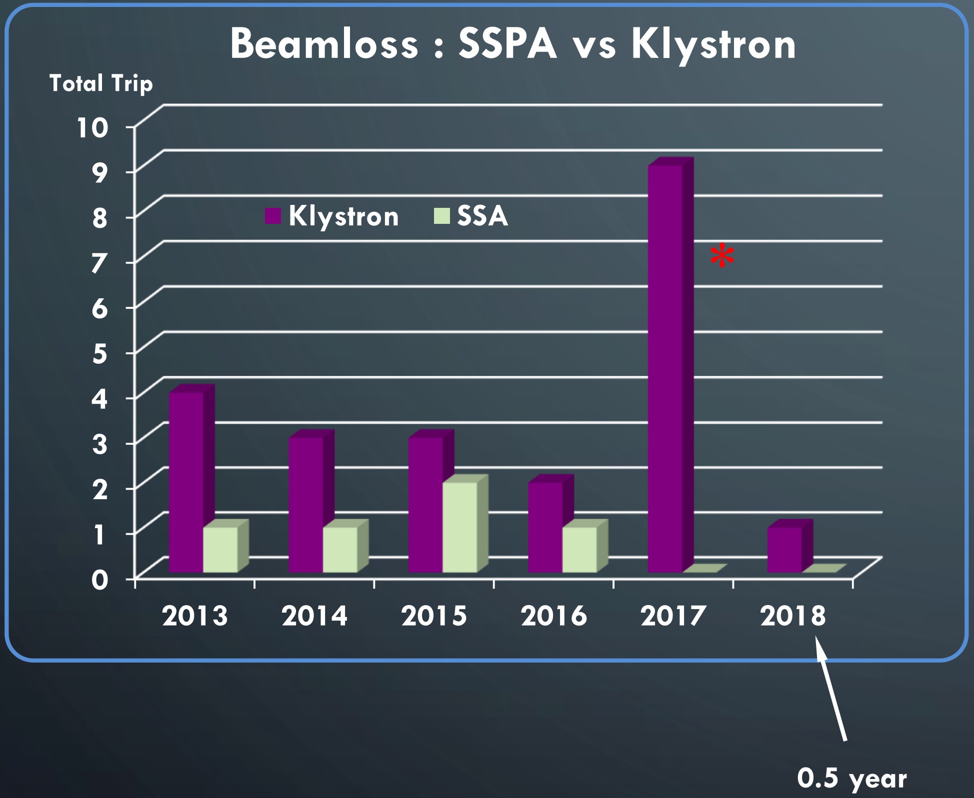
150 kW - 352.2 MHz SSA

DC to RF: η = 58 %, G = 63.3 dB at P_{nom}

☞ **7 such SSAs in operation at the ESRF!**

- Initially developed by SOLEIL
- Transfer of technology to ELTA / AREVA
- RF modules & coaxial lines built by BBEF (PRC)

ESRF operational experience



Including auxiliaries and Power supplies

KLYSTRON average failure: **4** trips / year

SSA average failure: **0.9** trips/ year

CERN 200 MHz SSPAs for SPS

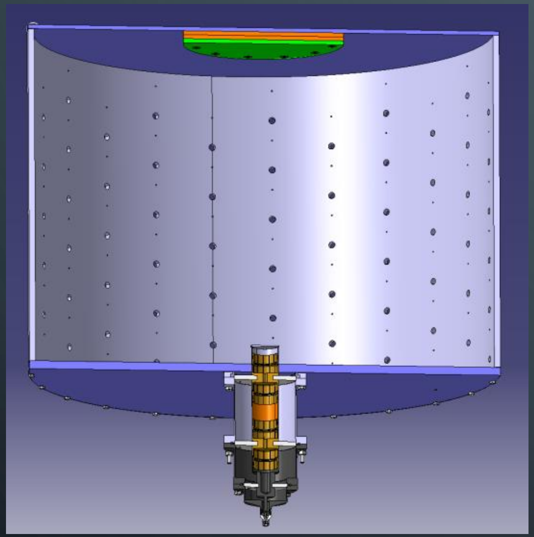
- Started within the need for the LHC Injector upgrade in 2011, for which more power is needed in the SPS (additional 2×1.6 MW needed).
- The original tender did not specify the technology (possible: SSPA, tetrodes, diacrodes, IOTs …), but the SSPA solution came out as best compliant offer. The concept for the SSPA solution also came from SOLEIL.
- SPS existing systems: “Philips” and “Siemens”, both tetrode-based.

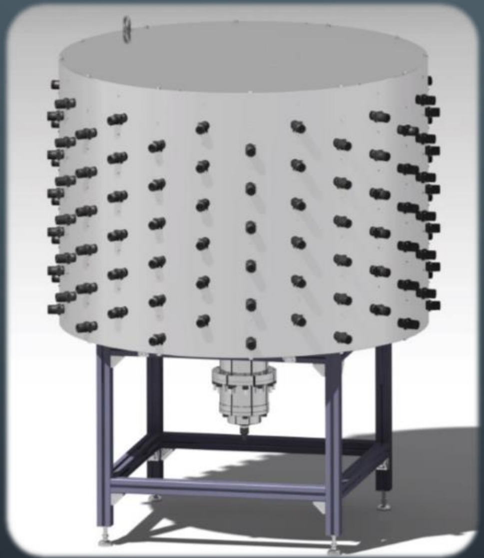
Siemens, 2×1.1 MW, 20 tetrodes

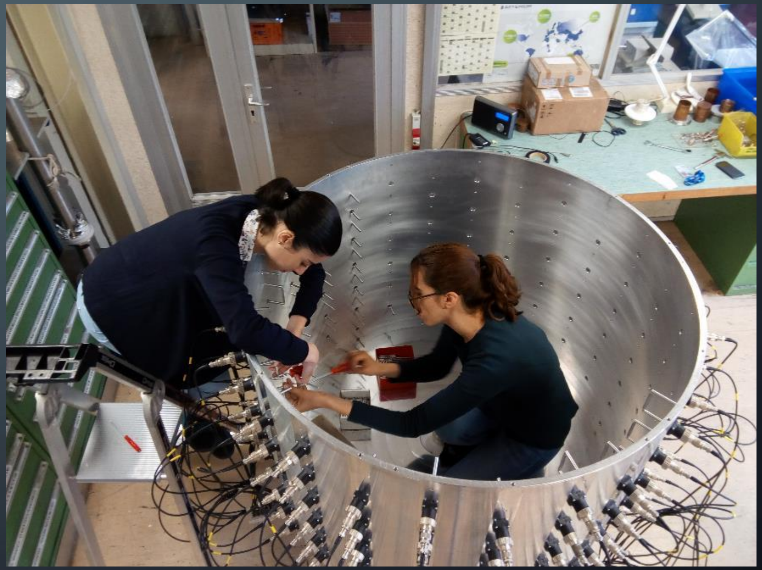
Philips: 2×1.1 MW 68 tetrodes

CERN SPS 200 MHy Cavity Combiner

- Every stage in a combination of binary combiners (3-dB) adds losses - need to combine many inputs in a single stage.
- Again triggered by colleagues from SOLEIL and ESRF (Thanks, Jörn Jacob and CRISP!)







- For future SSPA systems, the key will again be in the power combiner!

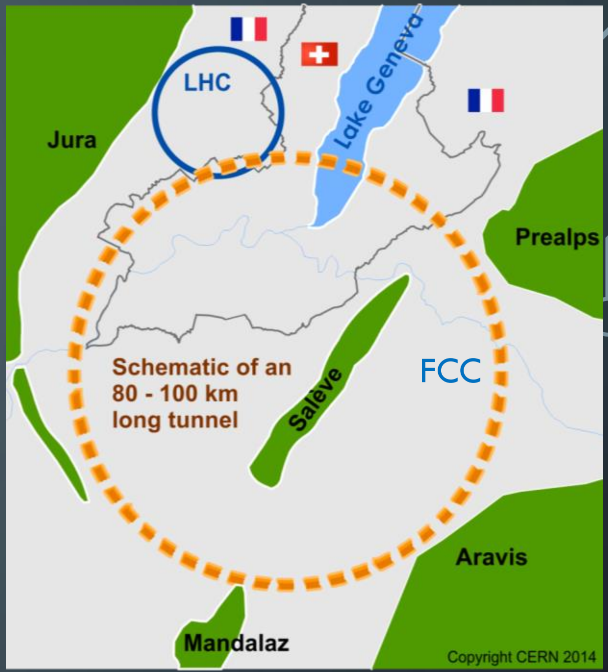
Today, all systems are fully validated and run reliably

Upstairs: 32 towers of 80 kW each

Downstairs: Final combiner stages (16 → 1)

… just waiting for the beam to return

FCC-ee RF system concept:



- FCC-ee is like LEP, just 3 times larger.
- It is dominated by synchrotron radiation losses of 2x50 MW (!)
- Of course it is a low-emittance ring (if you want some luminosity).
- Like light sources, it will be operated with top-up injection.
- The power RF system must supply 2x50 MW in CW (plus a pulsed booster)
- Again, efficiency and availability are the main issues to solve.
- But at this power level, SSPA's are not (yet) available.

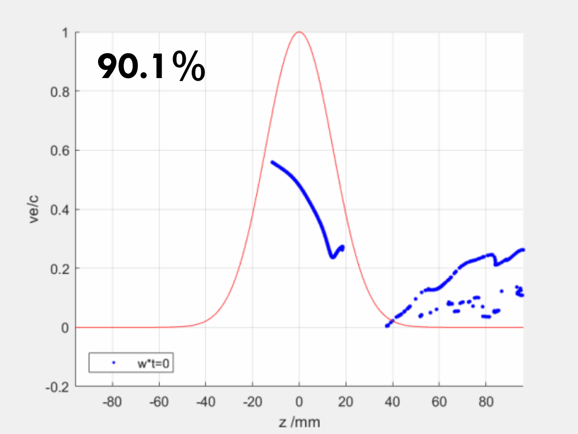
High efficiency klystron development

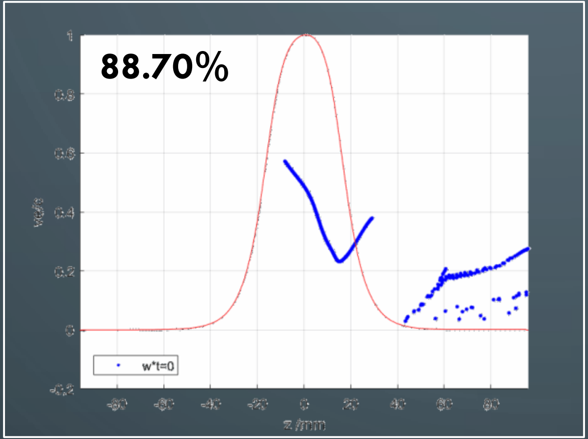
- Started in 2013, new ideas questioned the bunching mechanism in the good old klystron, promising to boost its power conversion efficiency significantly. Key player: I. Syratchev
- Some of these new ideas are:
  - "COM": core oscillation method (A. Baikov)
  - "BAC": bunch – align – collect (I. Guzilov)
  - "CSM" core stabilization method (C Marrelli, E. Jensen)
  - Keywords: "bunch congregation", "radial bunch stratification", "saturated bunch" … (Syratchev, Cai,…)
- CERN is presently building (with Thales) a high efficiency version of the LHC 400 MHz, 300 kW klystron, which will allow to run it at 350 kW with the same power consumption. It will be a PoP for the FCC-ee development.

Example: predicted performance of an FCC HE klystron

90% efficiency would be possible with the perfectly saturated and congregated bunch (not in “real life”)

Optimised congregation → **Linear** congregation (usually the case in real tubes)



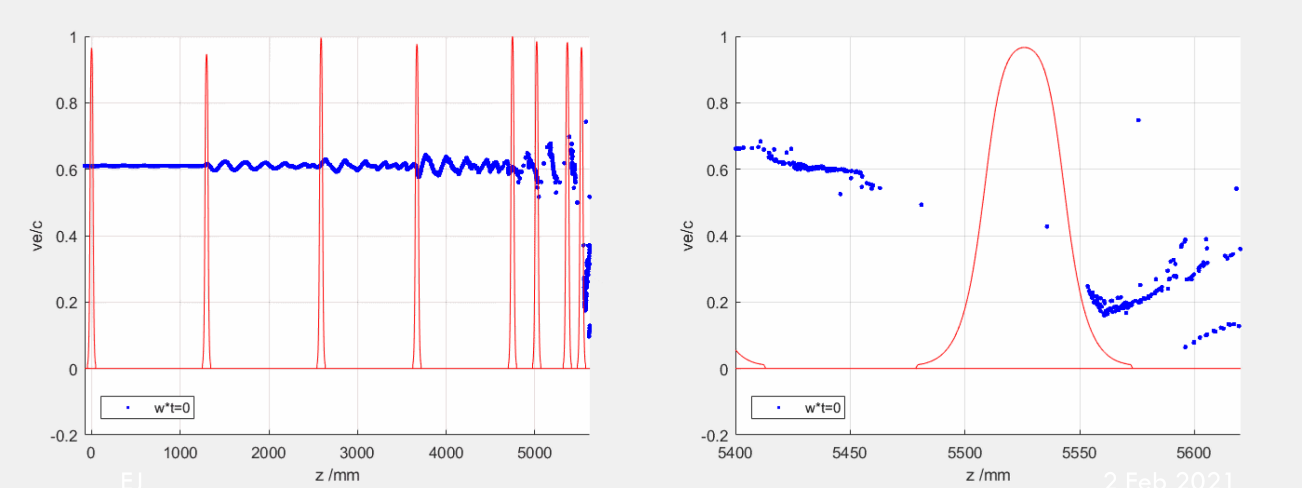


Reflected electrons as ultimate limiting factor

In “real life” obtaining such a perfect bunch is not always possible:

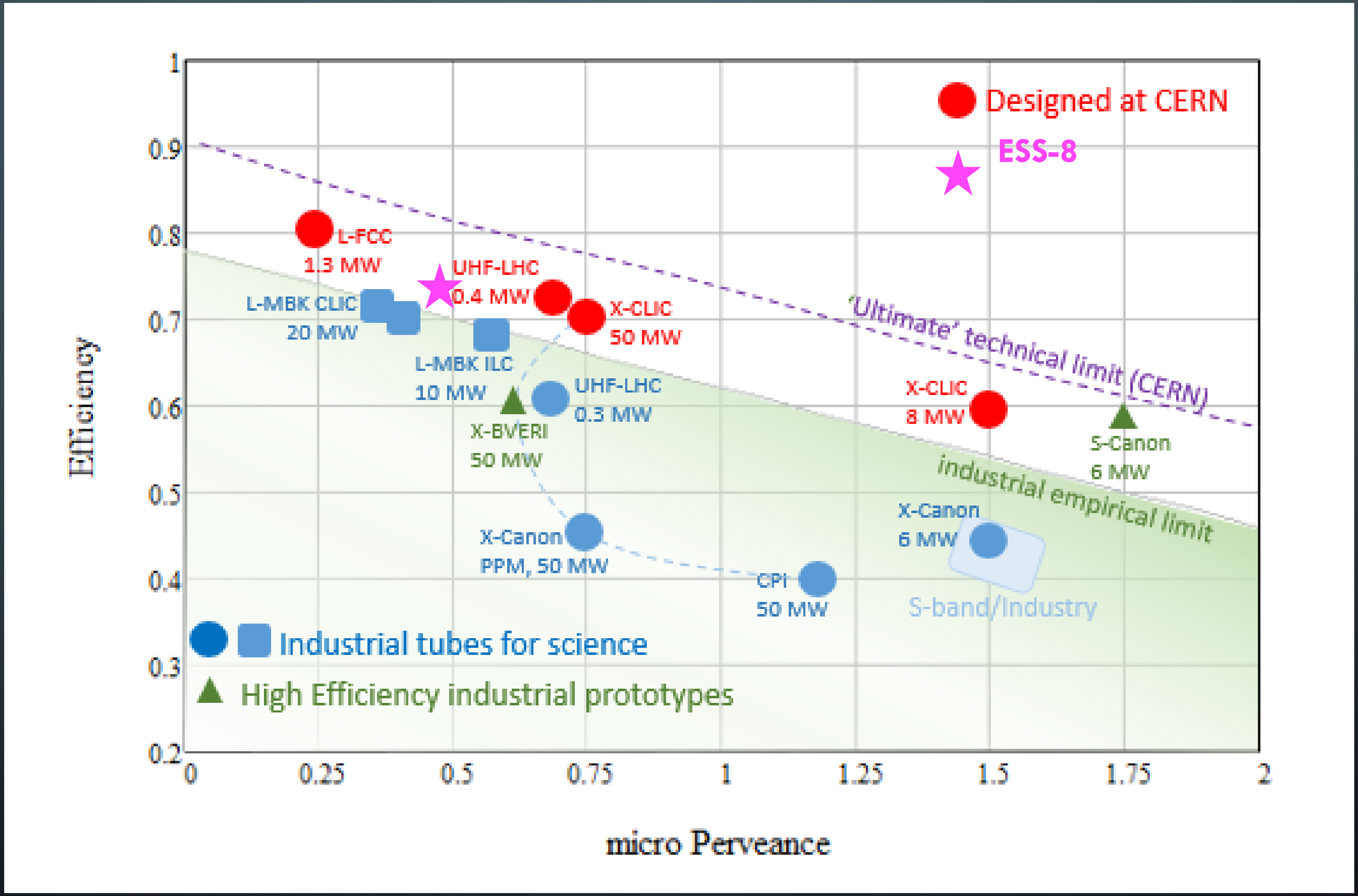
FCC COM tube example:

- bunch saturation (**-1%**)
- bunch congregation ‘as received’ (**-3.8%**)



I. Syratchev, 7th Low Emittance Rings Workshop, Jan 2018

Potential reach of novel high-efficiency klystrons



Summary

- Power RF systems for low emittance rings are challenging, they require high availability, high efficiency and good stability.
- The trend clearly goes to SSPAs, which can be fault tolerant and can can be upgraded, following progress in solid-state devices.

Sorry if I didn't cover your favourite power RF system – I threw this presentation together only last night!

Thank you very much for your attention!