10th CWRF

NSRRC, Hsinchu, Taiwan, 25-29 June 2018

Recent RF operation experience
&
RF upgrade for the new ESRF-EBS storage ring

Jörn Jacob, Alessandro D'Elia, Georges Gautier, Michel Langlois,
Jean-Maurice Mercier, Vincent Serrière

ESRF | The European Synchrotron

ESRF: FIRST 3rd GENERATION SYNCHROTRON LIGHT SOURCE

Existing Storage Ring

1992: commissioning
1994: external users
since then:

- many upgrades
- brilliance increase by about a factor 1000

New Extremely Brilliant Source: EBS

- further brilliance increase by a factor 40

2019: installation
2020: commissioning and resume user service

OUTLINE

Existing 352 MHz RF system

RF Operation figures – Klystron / SSPA

Examples of CWRF hardware issues

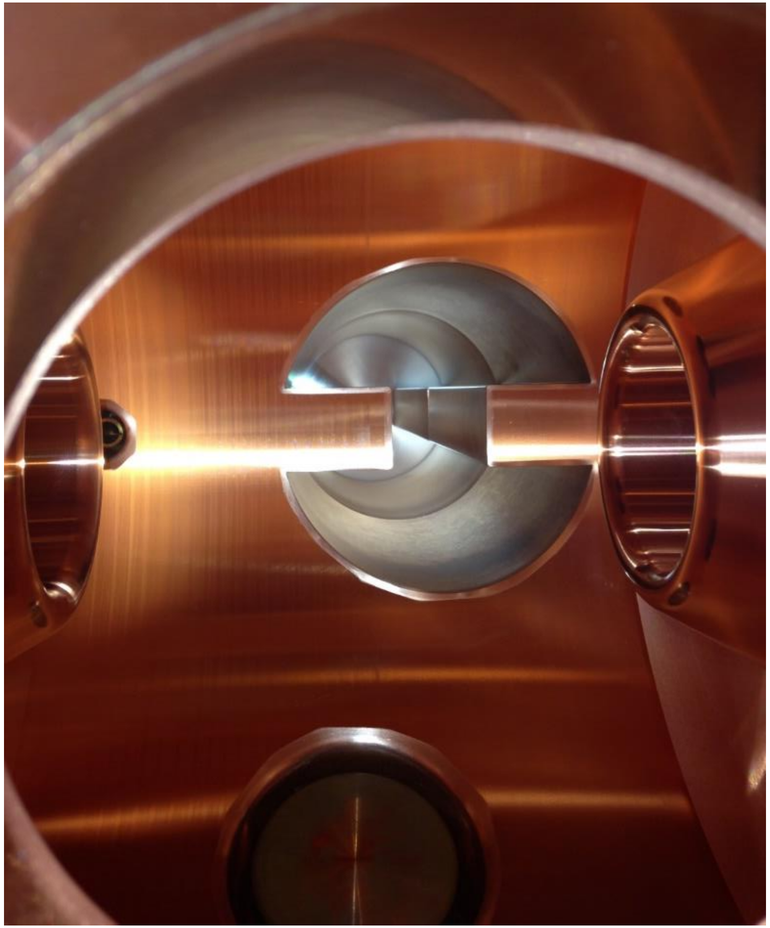
- ☞ EEV 4 reconditioning
- ☞ Why arc detectors at high power ?
- ☞ Repair of a cavity power coupler

RF upgrade for EBS

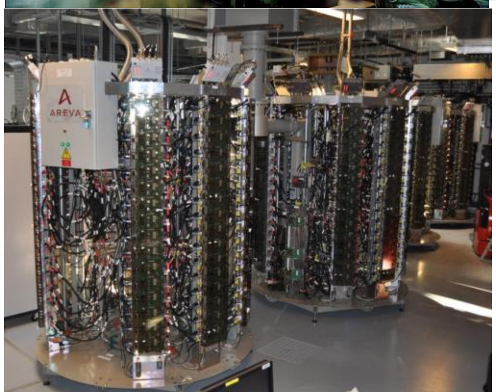
HOM damped single cell cavities

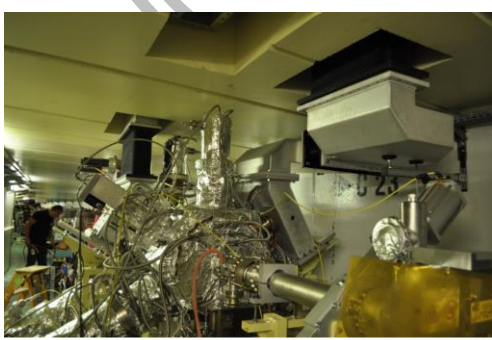
- ☞ Cavities, RF conditioning
- ☞ Movable tuners
- ☞ HOM absorbers

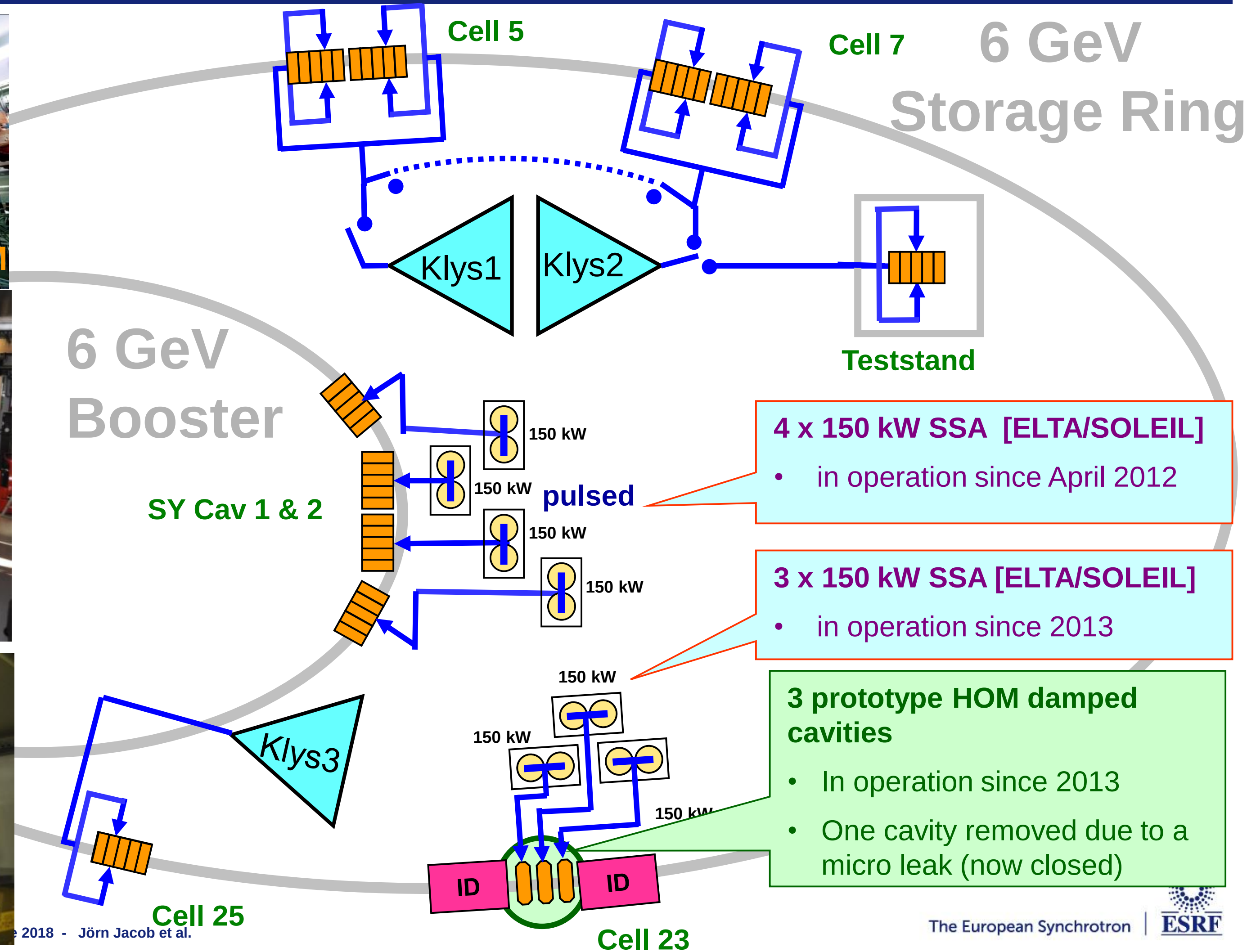
Transmitter & cavity control upgrade for EBS



RF LAYOUT – EXISTING MACHINE







4 x 150 kW SSA [ELTA/SOLEIL]

- in operation since April 2012

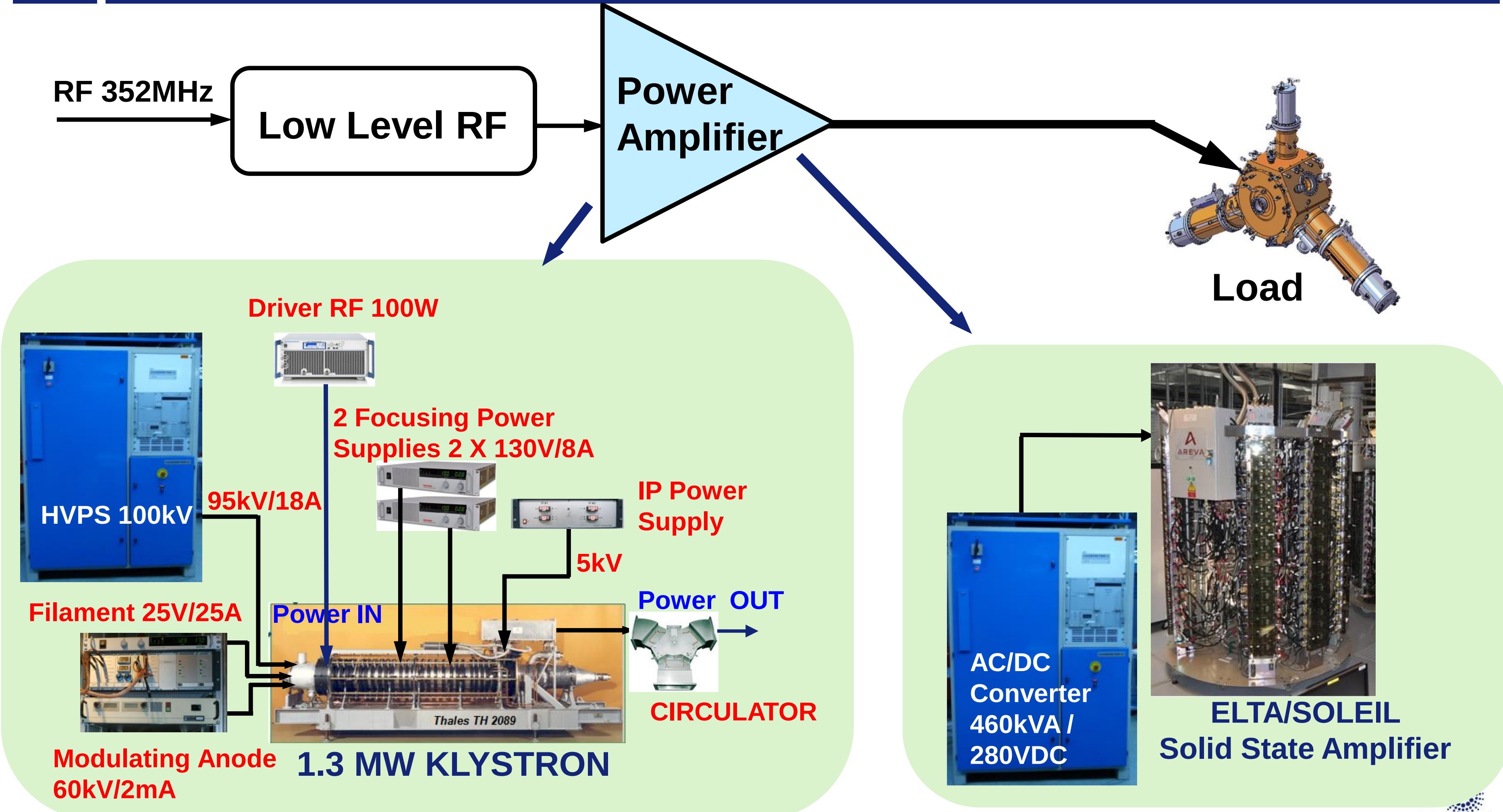
3 x 150 kW SSA [ELTA/SOLEIL]

- in operation since 2013

3 prototype HOM damped cavities

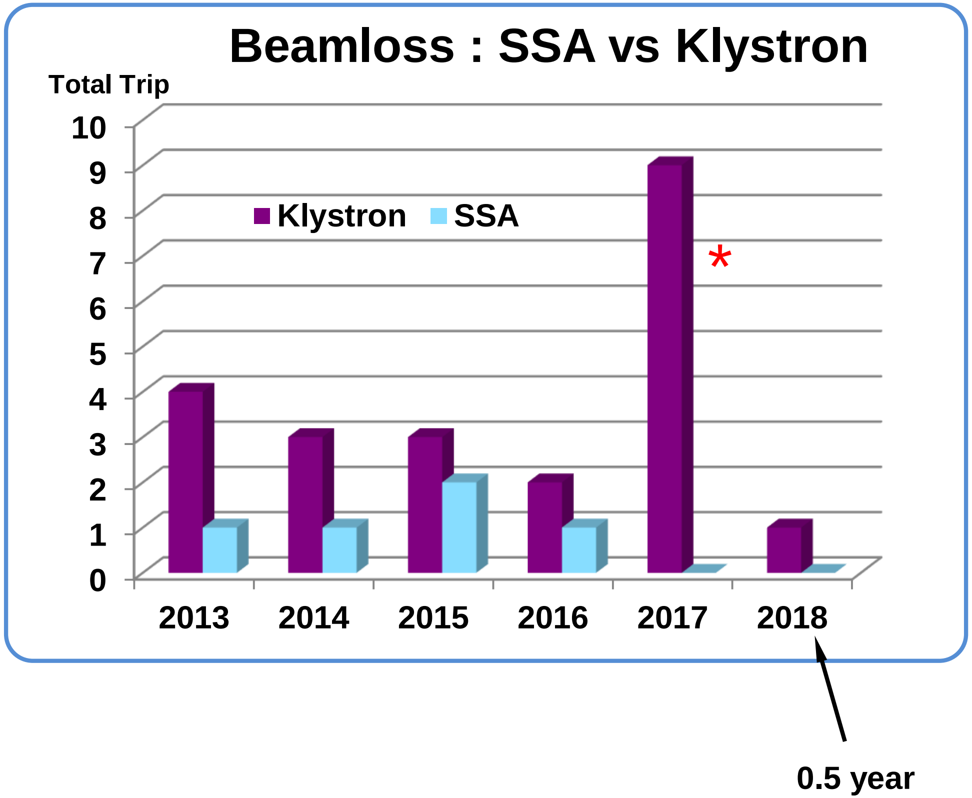
- In operation since 2013
- One cavity removed due to a micro leak (now closed)

SSPA versus KLYSTRON – Setup comparison



[Jean-Maurice Mercier]

SSPA versus KLYSTRON – TRIP RATE



Including auxiliaries and Power supplies

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

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

* When a klystron begins to be sick it can generate several beam interruptions in a short time lapse

[Jean-Maurice Mercier]

OPERATION EXPERIENCE WITH 7 x 150 kW SSA

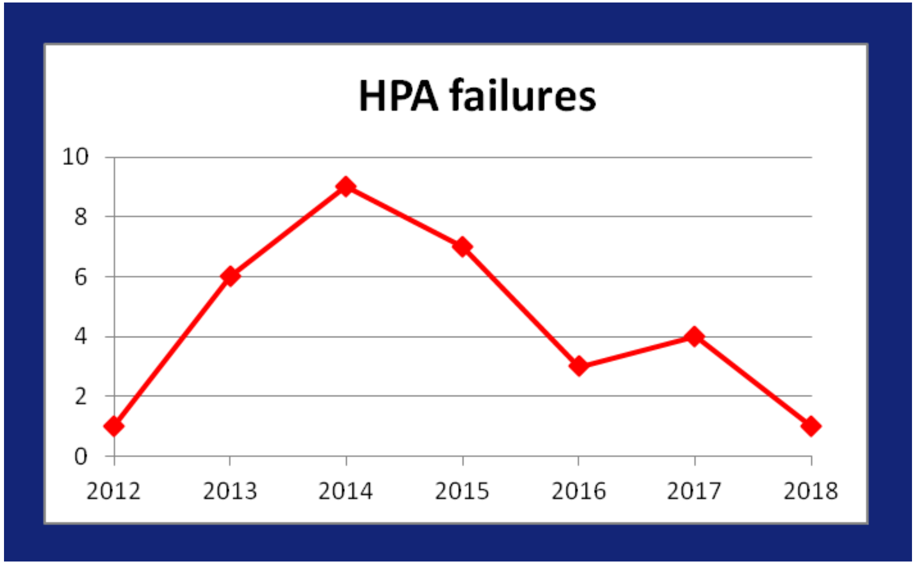
- Booster → **4 x 150 kW SSA**, since January 2012 (**6,400 hr**), Top-up since April 2016
- SR → **3 x 150 kW SSA**, since October 2013 (**32,000 hr**), 1 is out of operation because of cavity failure
- So far **no transistor failure** (BLF578 from NXP, now produced by Ampleon)
- Nominal Power Efficiency 58% Gain 63.3 dB – No variation in time (last control March 2018)

Component	Event count	Disturb Operation ?	Comment
HPA 650W (filter)	SR 22 SY 9	No No	CMS filters stressed when soldering on the PCB. Youth problem, now fixed with time. Last failure: February 2018.
DC/DC Converter 280V/50V	SR 12 SY 3	No No	Primary filter capacitors (C12 & C24).
Pre-Driver	SR 0 SY 5	 Yes 1	Conception problems, which have been fixed: Gain loss, bad soldering, bad logic circuitry …
MUXBOX Control Interface	SR 3 SY 4	Yes 3 No	The SSA trips when the fuse blows because the relays for cooling interlocks are fed by this interface. *This is a weakness of the system, which can be improved.*
Water Cooling	SR 1 SY 2	No Yes 1	Fortunately it happened outside of machine operation
TOTAL	**SR 38** **SY 23**	**3** **2**	**1 in 2014 + 1 in 2015 + 1 in 2016 → Beam loss** **2 in 2012 → Refill postponed**

[Jean-Maurice Mercier]

SSA : 650 W - HPA Failures

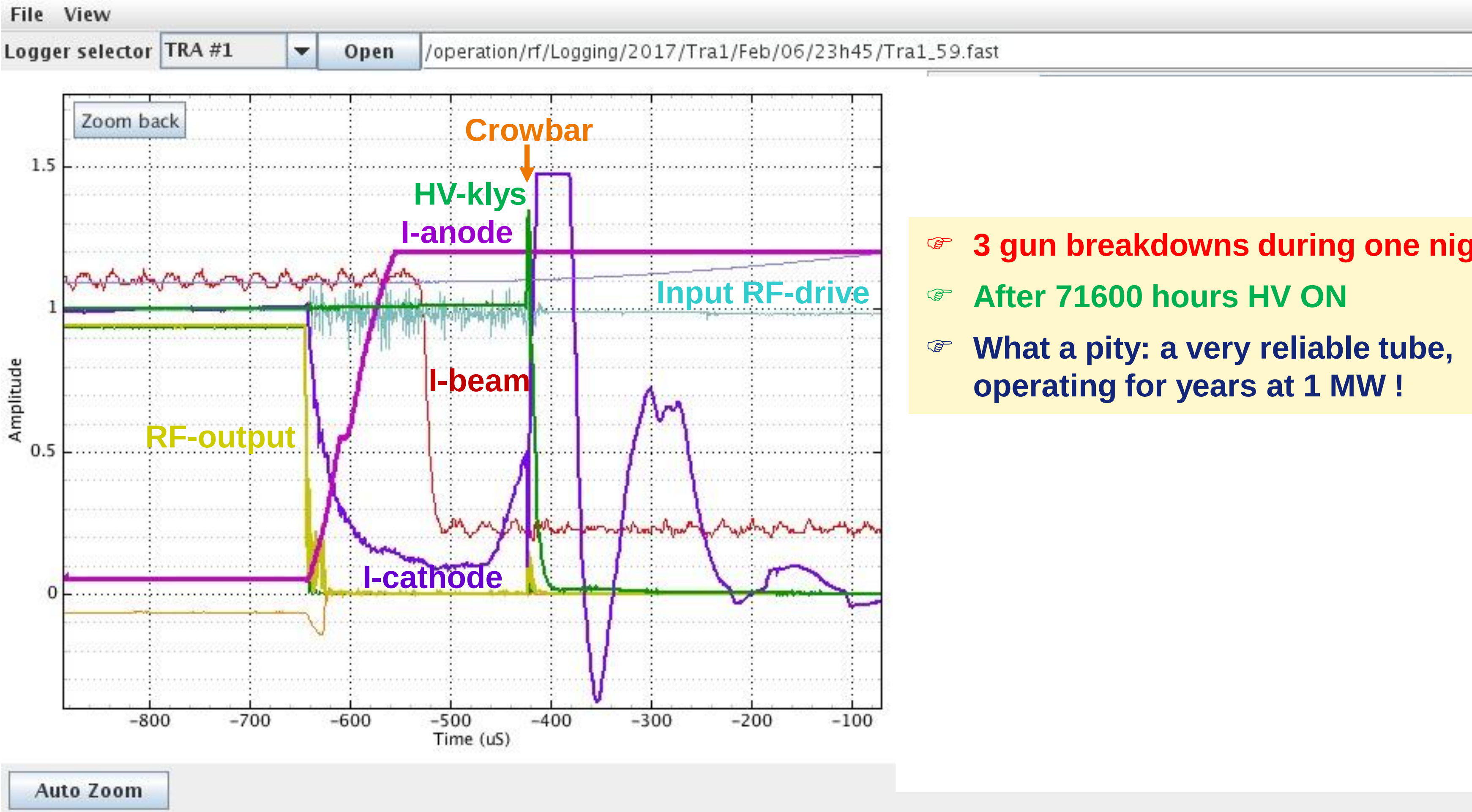
Year	SY	SR	Total
2012	1		1
2013	3	3	6
2014	2	7	9
2015	3	4	7
2016	0	3	3
2017	0	4	4
2018	0	1	1



Average 5 HPA failures per year for a total of 1820 HPA (128+2 / tower)

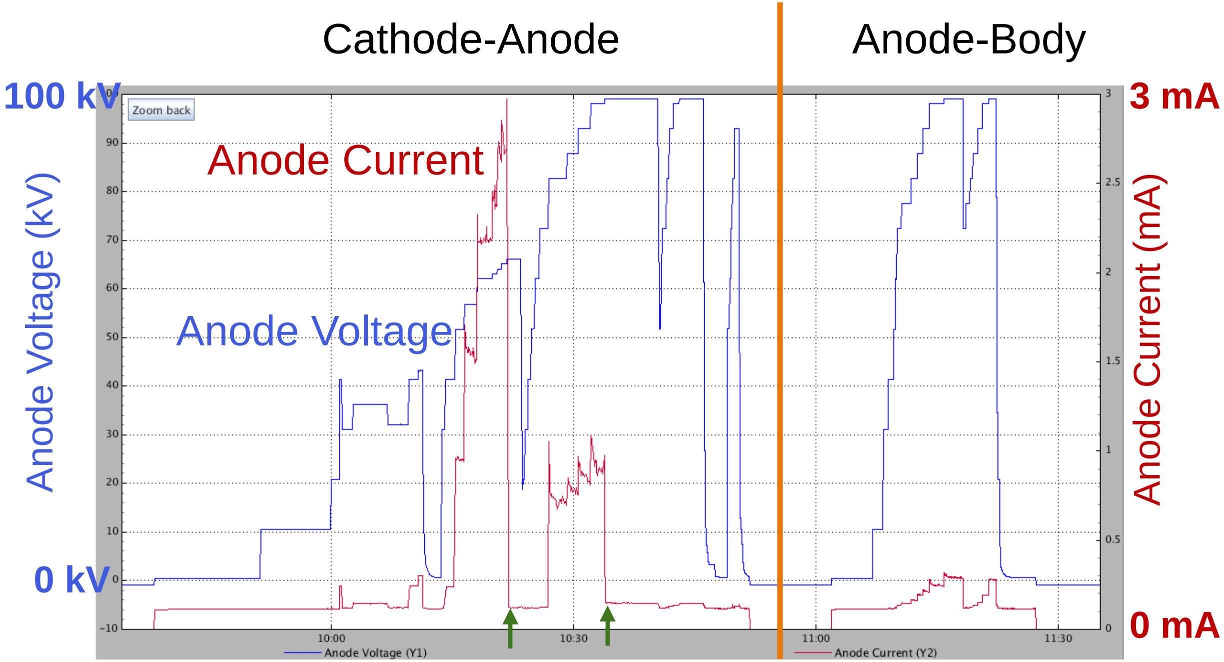
[Jean-Maurice Mercier]

7TH FEBRUARY 2017: EEV-4 KLYSTRON - HV Gun breakdowns



- 3 gun breakdowns during one night
- After 71600 hours HV ON
- What a pity: a very reliable tube, operating for years at 1 MW !

EEV-4 KLYSTRON: COLD RECONDITIONING



Depollution of the Cathode-Anode ceramic: sudden drop to 0.2 mA

Result:

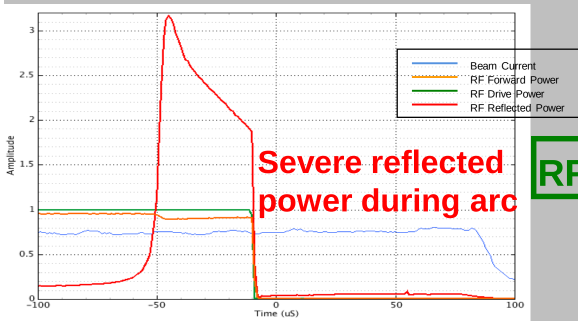
- ✓ Klystron successfully reconditioned
- ✓ June 2018 → 80 000 hours HV ON
- ✓ Still in operation on SR transmitter 1 at 1 MW without any problem

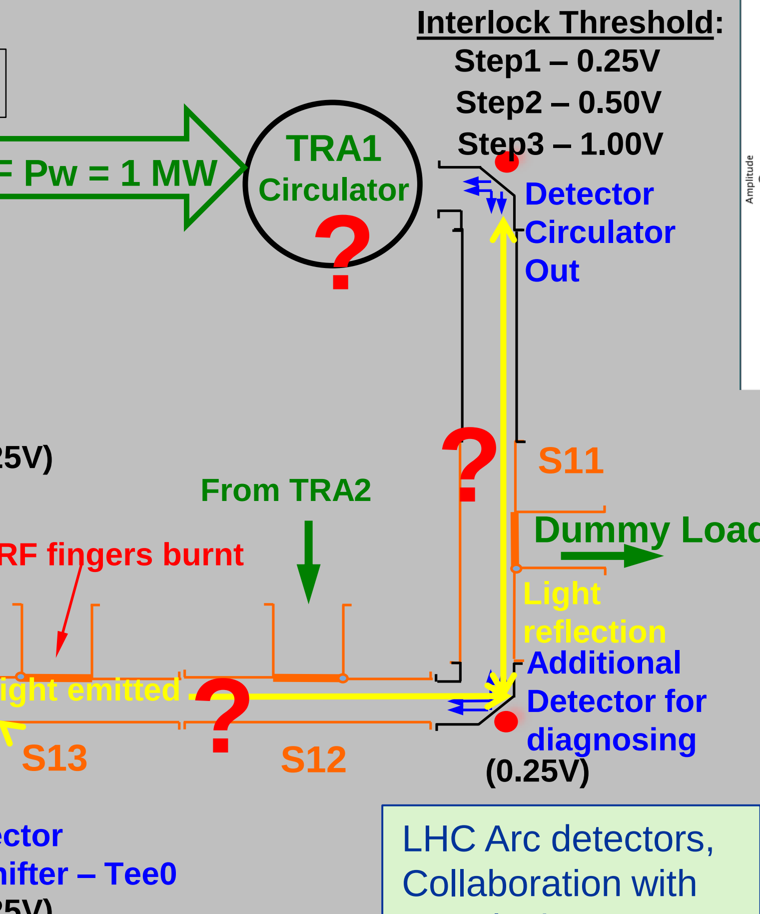
[Michel Langlois]

AVAILABLE KLYSTRONS - STATUS JUNE 2018

RF Station	Klystron Id	HV time	Extrapolation
#1	EEV4	**80,140**	Potential time of 94,000 hours assuming a life time of 40,000 hours / klystron **EBS:** Normally only 1 klystron in operation for 8000 hours per year $\Rightarrow$ more than **10 years of operation on EBS**
#2	EEV5	12,800	
#3	PHILIPS	33,740	
Spare Klystrons	EEV3	8,374	
	TH89022-2	18,428	
	TH89018-2	36,340	
	EEV1	36,410	

WHY ARC DETECTORS AT HIGH POWER ?





LHC Arc detectors, Collaboration with D. Valuch CERN

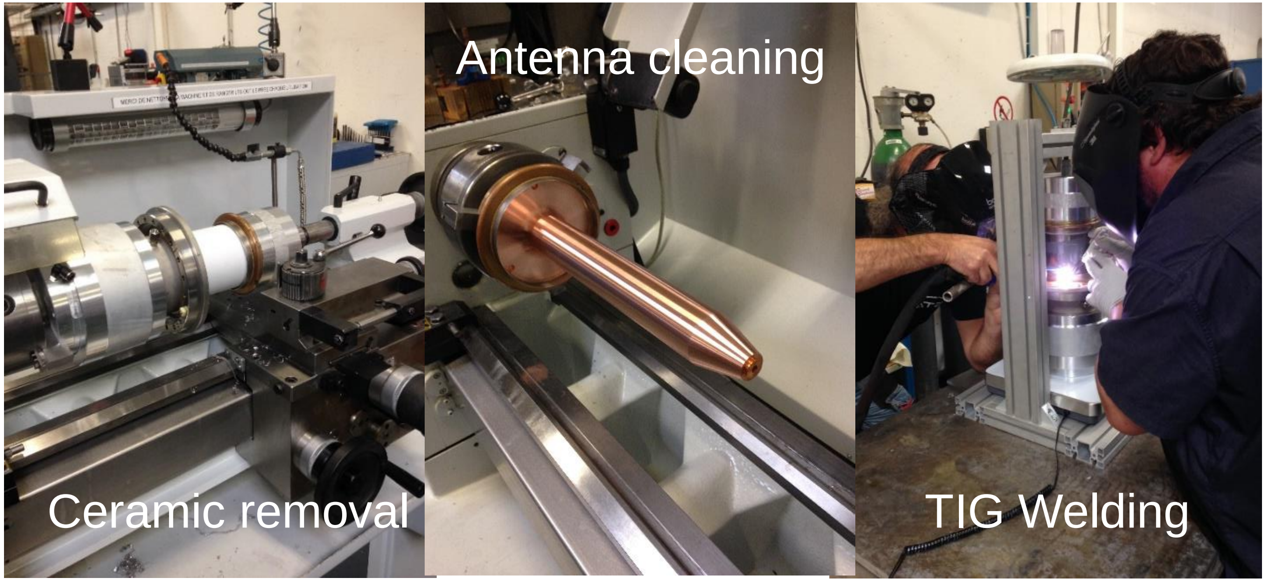
Actions:

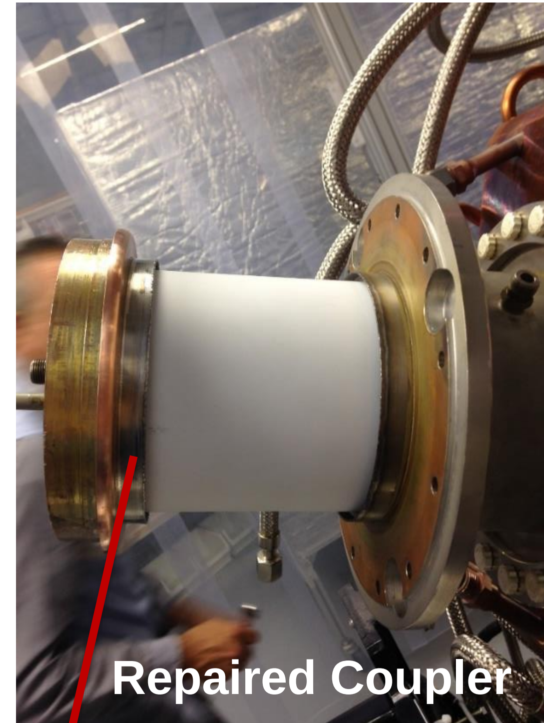
1. Interlock Threshold back to 250 mV
2. Additional detector to be connected with TRA1 fast interlock system
3. When the first arc detection occurs, the entire high power waveguide run must be conscientiously inspected
4. A detector upgrade to better identify which photodiode trigged (and not only how many)

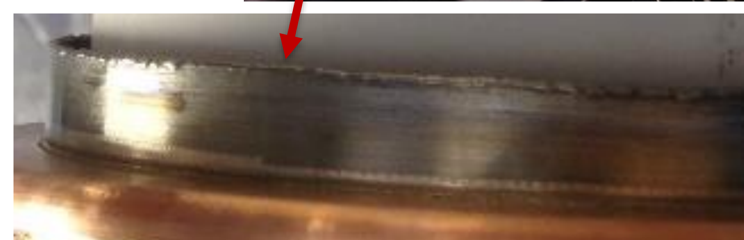
[Jean-Maurice Mercier]

DAMAGED WAVEGUIDE SWITCHES

IN HOUSE REPAIR OF POWER COUPLER: CERAMIC WINDOW REPLACEMENT



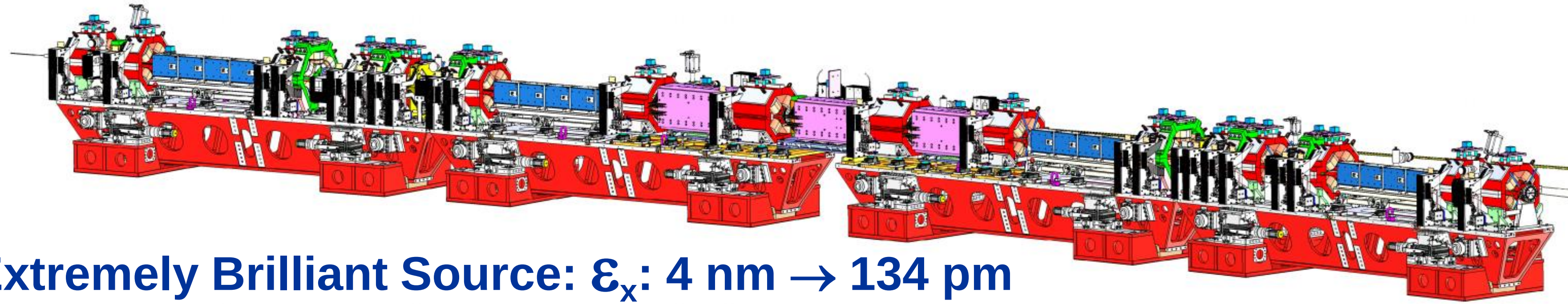




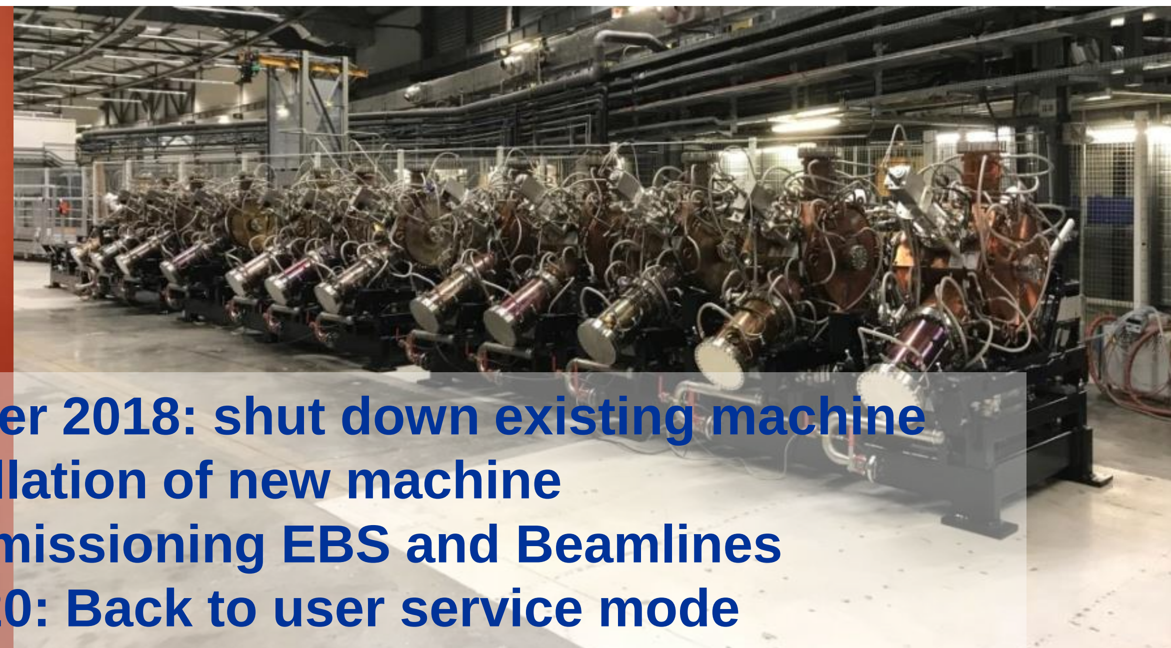
- Disassembly revealed bad initial assembly with uncomplete contact between window face and body
- Repaired coupler installed on new EBS Cavity#12
- Successful power test during RF conditioning to 750 kV

[V. Serrière & B. Cocat]

RF UPGRADE FOR THE ESRF-EBS STORAGE RING



Extremely Brilliant Source: ε_x: 4 nm → 134 pm



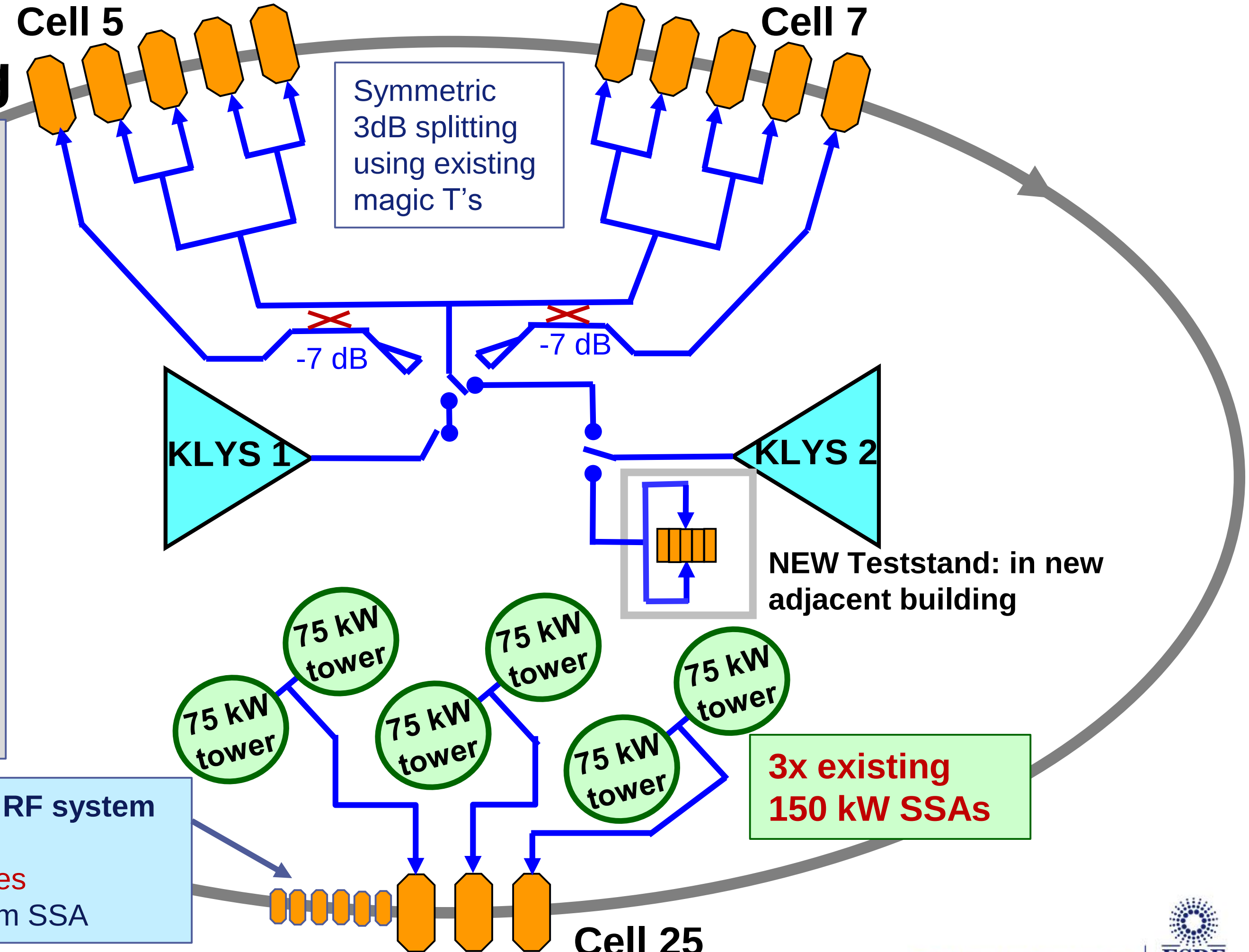
10 December 2018: shut down existing machine
2019: Installation of new machine
2020: Commissioning EBS and Beamlines
August 2020: Back to user service mode

EBS RF SYSTEM LAYOUT

EBS Storage Ring

EBS upgrade:

- Remove 5 five-cell cavities
- Remove 2 prototype HOM damped cavities from cell 23
- Install 13 single cell HOM damped cavities in cells 5, 7, 25
- Suppress existing 3rd Klystron transmitter in cell 25
- Move 3 x 150 kW SSAs from cell 23 to cell 25
- Rebuild waveguide distribution system
- Rebuild control system for klystron transmitters and cavities



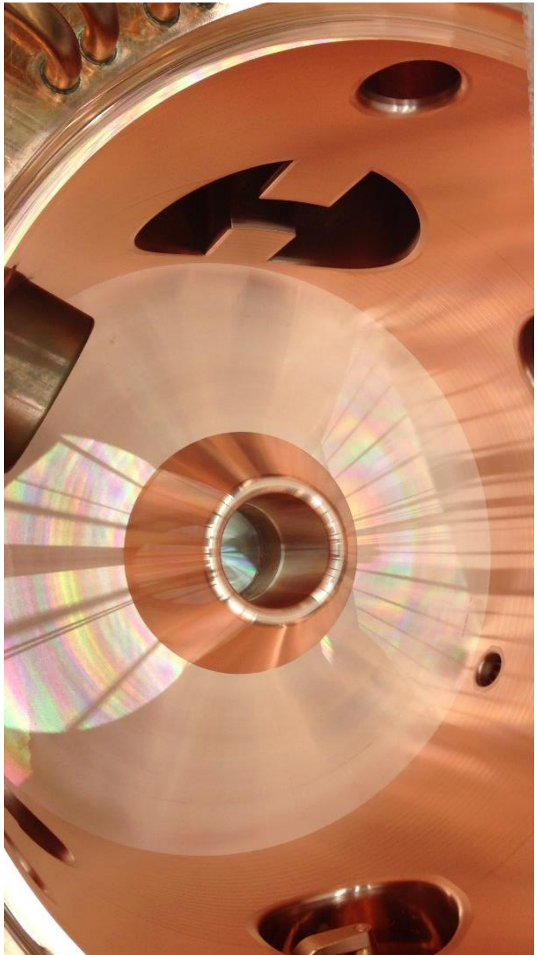
Space for 3rd harmonic RF system

- Still under study: 5 to 6 active NC cavities
- ≈ 40 kW per cavity from SSA

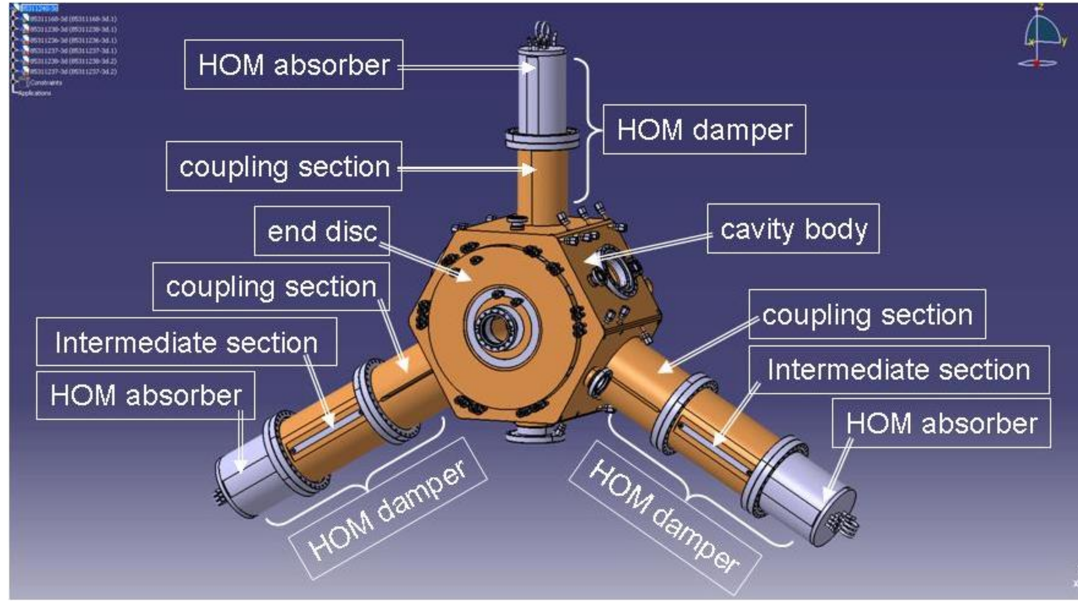
MAIN RF PARAMETERS FOR ESRF-EBS UPGRADE

Total energy loss:	**3.1 MeV/turn**
☞ Energy loss from dipole radiation:	2.6 MeV/turn
☞ Energy loss from ID radiation:	0.5 MeV/turn
Maximum RF Voltage:	**6.6 MV**
Stored current with operational margin:	**220 mA**
HOM damped cavities:	
☞ 2 of 3 prototypes on SR since 2013:	0.5 MV / 90 kW *(standard operation)*
☞ Prototypes validated with beam up to:	0.6 MV / 150 kW *(phased for max beam loading)*
☞ All 12 series cavities conditioned to:	0.75 MV
EBS 30 % less total RF power than now:	**≈ 1 MW at nominal 200 mA**

HOM DAMPED SINGLE CELL CAVITIES



[ESRF design by V. Serrière]



f_{res}	352.372	MHz
Q_0	35700	(measured)
R/Q	145	Ω
R_s	≈ 5	MΩ
Tuning range	-350 / +900	kHz
V_{acc} nominal / max	500 / 750	kV

STATUS: CAVITIES WITHOUT HOM ABSORBERS

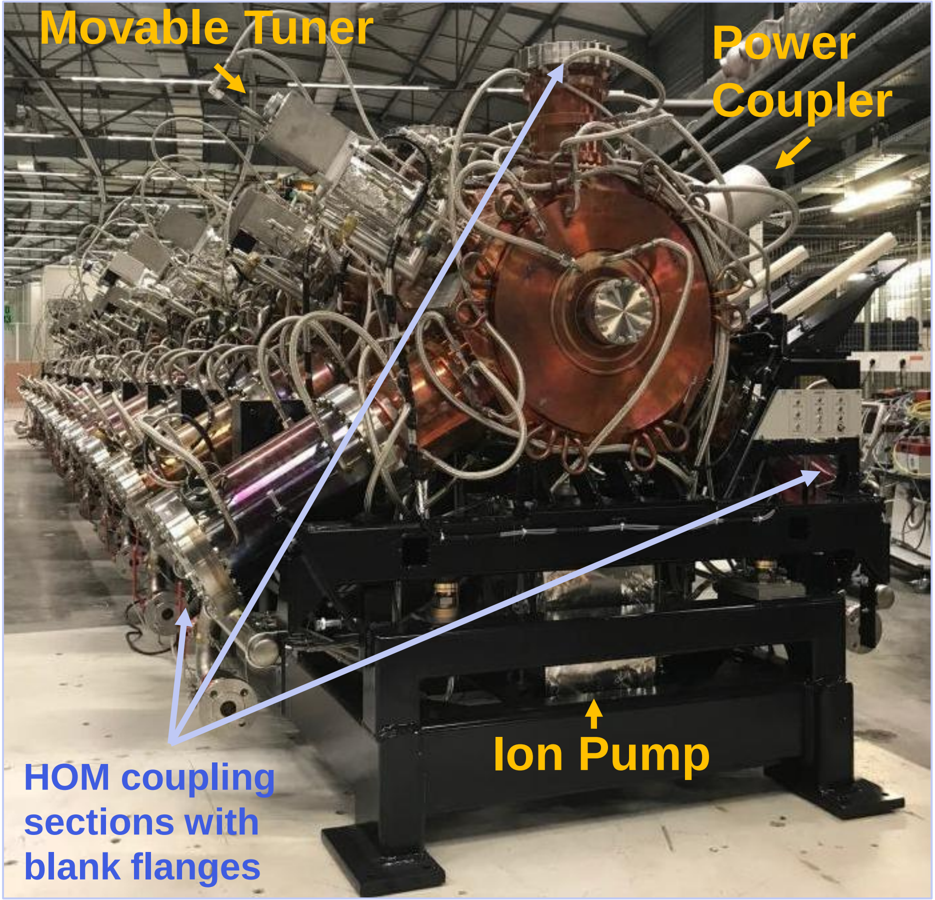
12 series cavities from RI - Research Instruments:

- All delivered
- All conditioned to 750 kV
- All fully equipped and ready for installation, except for:
- Installation of HOM absorbers and sector vacuum valves

☞ *Delay on 1st cavity due to problem with 3 consecutive brazing steps:*

- ➢ *Brazing sequence from BESSY cavity didn't work due to higher copper mass*
- ➢ *Thanks to their brazing expertise, RI successfully applied modified brazing sequence (which took a few months)*

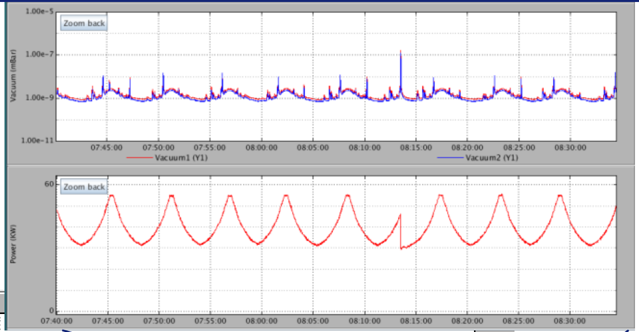
⇒ *Extremely good vacuum (10^{-11} mbar range) and fast RF conditioning*



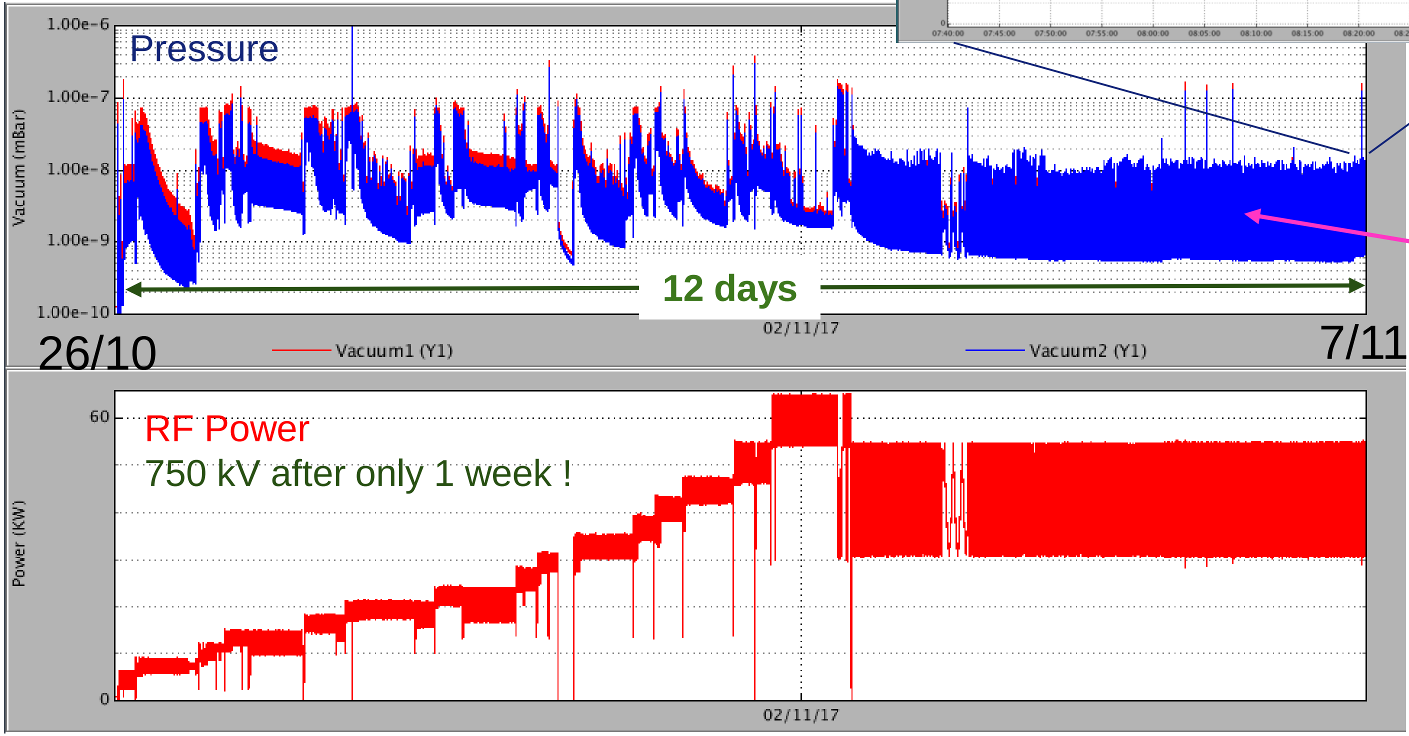
[A. D'Elia, V. Serrière, J.-M. Mercier, D. Boilot, B. Cocat, P. Chatain, P. Chappelet]

CAVITY RF CONDITIONING – EXAMPLE RI #11

RF conditioning [à la Eric Montesinos / CERN]**:**
- Power range increased in steps
- 20 µs, 40 µs, … 10 ms RF pulses then CW



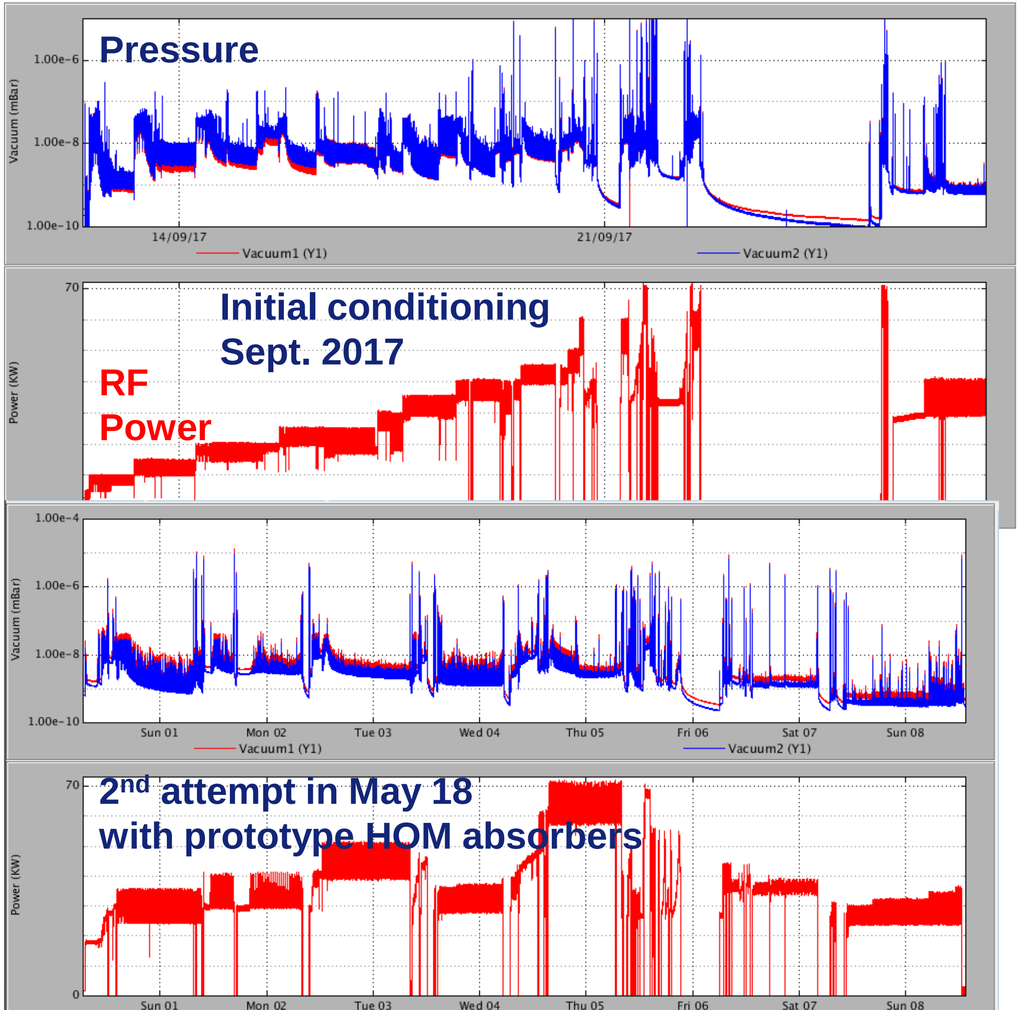
At the end, power cycling in CW without problem, @ a few 10^{-9} mbar



Very few pressure bursts after having conditioned multipactor zones

[A. D'Elia, N. Michel]

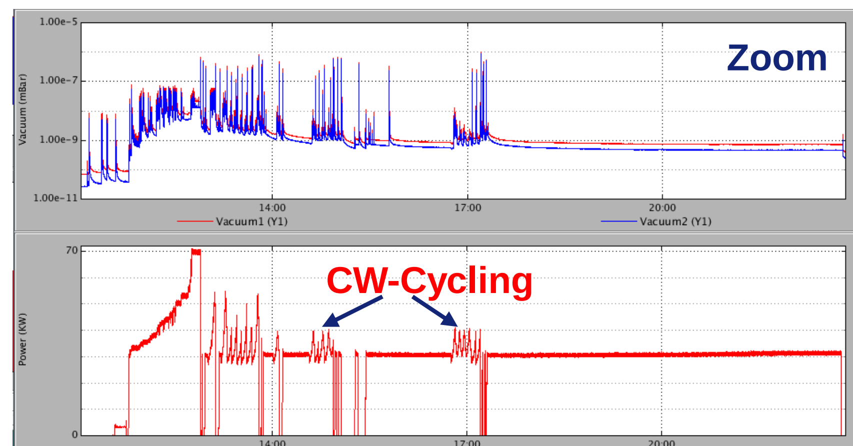
ONLY 1 PROBLEMATIC CAVITY: RI #9



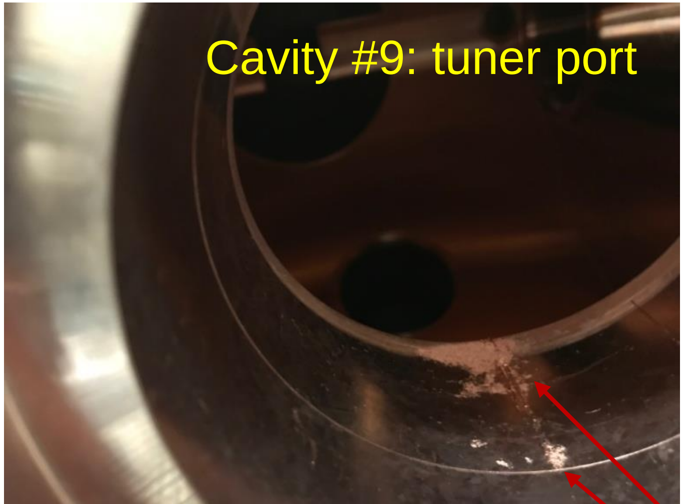
Even after conditioning up to 750 kV:

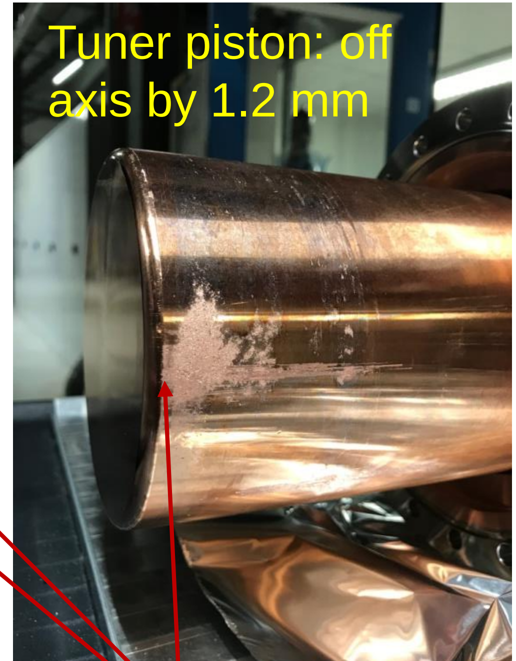
- Many remaining pressure bursts
- No improvement by conditioning
- Slow ramping: we easily reach 750 kV
- Pressure spikes mainly when cycling in CW
- ….. ?

☞ **Finally movable tuner suspected ...**



INDEED: PROBLEM WITH TUNER ON CAVITY RI #9





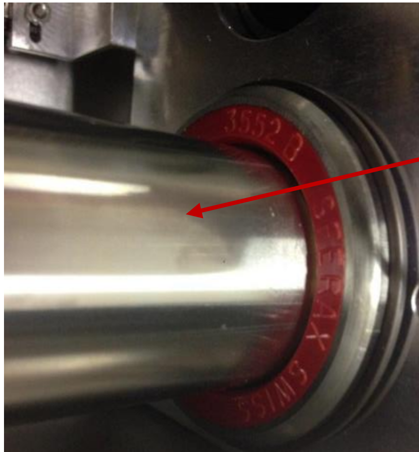
Tuner **scratched** the cavity port

Special tool to repair the port:
- 3D printed in house
- Holds rag wetted with alcohol
- Avoids Cu particles falling into the cavity

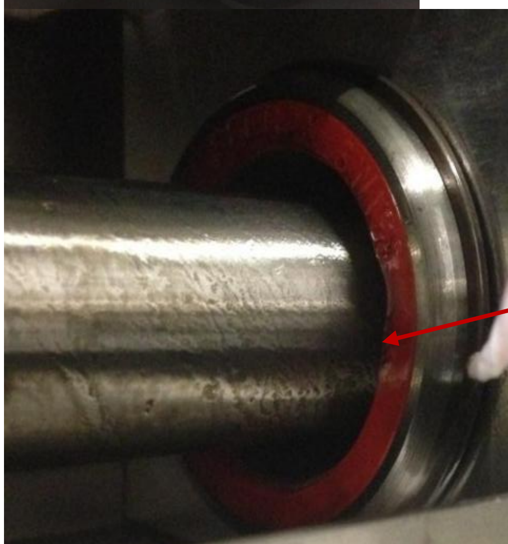
← Some **RF fingers broken**
Fortunately not fallen into cavity !

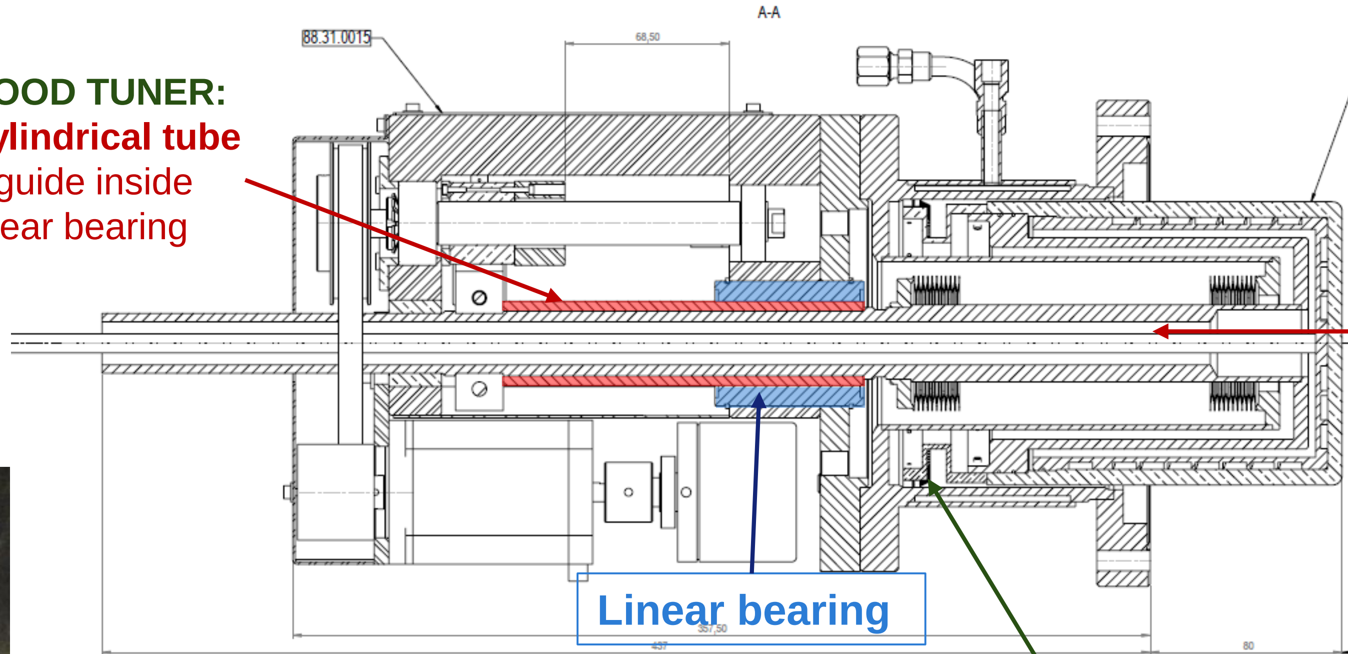
[A. D'Elia, V. Serrière, D. Boilot, B. Cocat]

IN FACT: BAD TUNER ON CAVITY RI #9



GOOD TUNER:
Cylindrical tube
= guide inside linear bearing





BAD TUNER: fabrication mistake

- **Cylindrical tube is missing !**

⇒ Piston is not well guided

☞ 2 first series tuners concerned (on Cavities #9 and #8)

☞ Moreover: systematic alignment tolerances of all tuners being checked !

RF fingers: have probably maintained the piston in the absence of the cylindrical guide

COMPLETE CHECK UP OF ALL NEW TUNERS

All Tuners produced for the EBS have been re-machined:

Cavity ports: Diam = 120 mm

Tuner pistons: Diam = 118 mm → re- machined to 116 mm

Dimensional control, all tuners within;

Concentricity: a few 0.01 mm

Sag: 0.1 to 0.25 mm

⇒ We are sure that piston can no longer hit cavity port

Pressure control of water cooling circuits:

Nominal: 10 bar

Test pressure: 15 bar

⇒ 1 piston face bulged out: tuner was badly brazed !
(production prototype, not repairable)

Cavity #9 after repair, with re-machined tuner on RF teststand:

Check re-conditioning time and vacuum up to 750 kV, start these days

HOM ABSORBERS

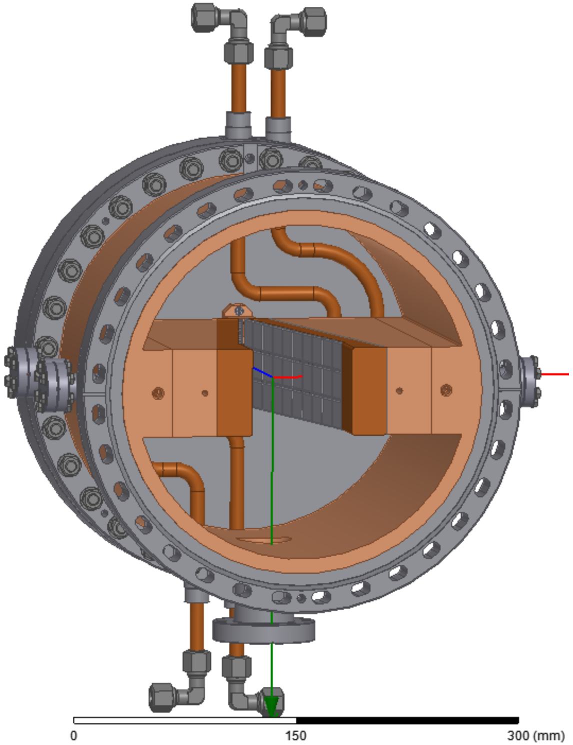
Contract for 14 batches of 3 HOM absorbers:

- Initial contract
  - December 2013: signature of the contract
  - January 2016: the ESRF has evidence that the contractor doesn't master the brazing process for the ferrite tiles!
  - February 2017: Closure of the contract
- New contract with RI – Research Instruments
  - December 2016: signature of the contract
  - RI has experience with similar devices for many other projects and proposed their own design, which was adapted to EBS cavities in collaboration with ESRF experts
  - Specification was amended by **improved qualification procedure** for ferrite brazing:
    - RF power tests with IR detection performed by RI
    - Ultrasonic test by French "Institut de Soudure" (IS)
    - Calibration by metallographic cuts and microscopic evaluation of brazing joints by IS

Ferrite tiles brazed on stainless steal wedges to form an absorbing taper for all Higher Order Modes.

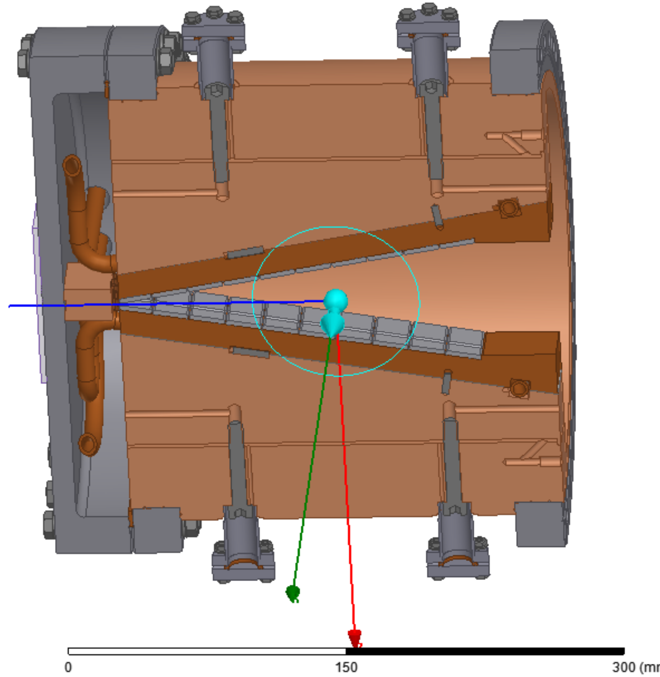
[V. Serrière, A. D'Elia]

HOM ABSORBERS - RI DESIGN



RI design features

- Made of copper
- Wedges built separately
- Ferrite tiles are brazed on the separate copper wedges
- Wedges are then screwed into the absorber bodies



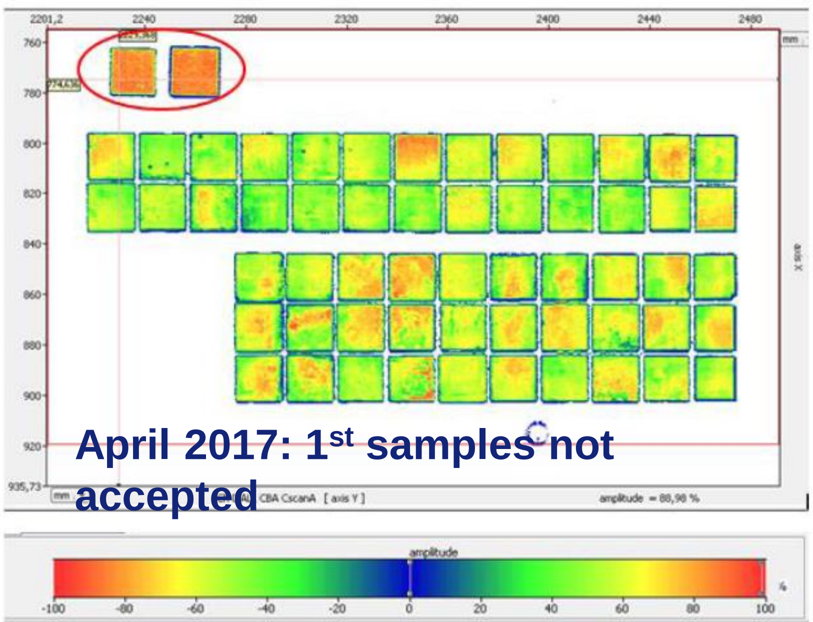
[RI, V. Serrière, A. D'Elia]

HOM ABSORBERS – ULTRASONIC TESTS BY INSTITUT DE SOUDURE

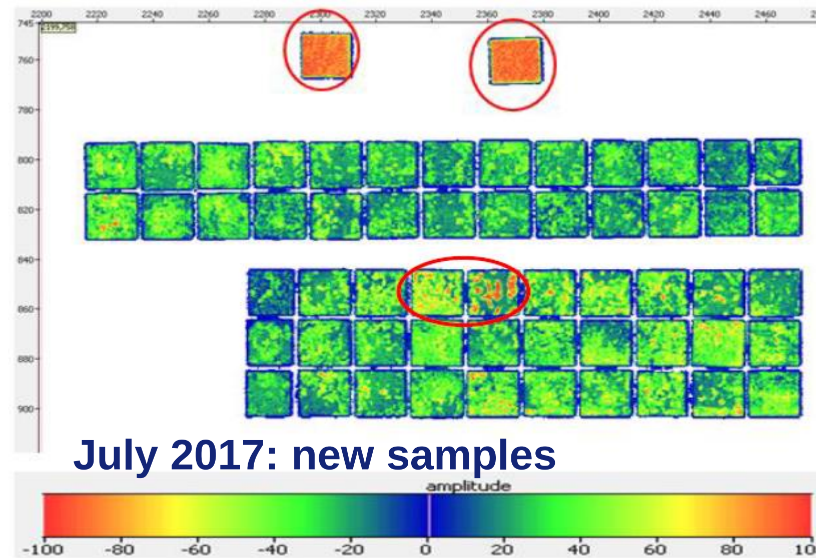
Brazing Samples

Brazing definitely improved, also looks mechanically very sound

☞ **But …**

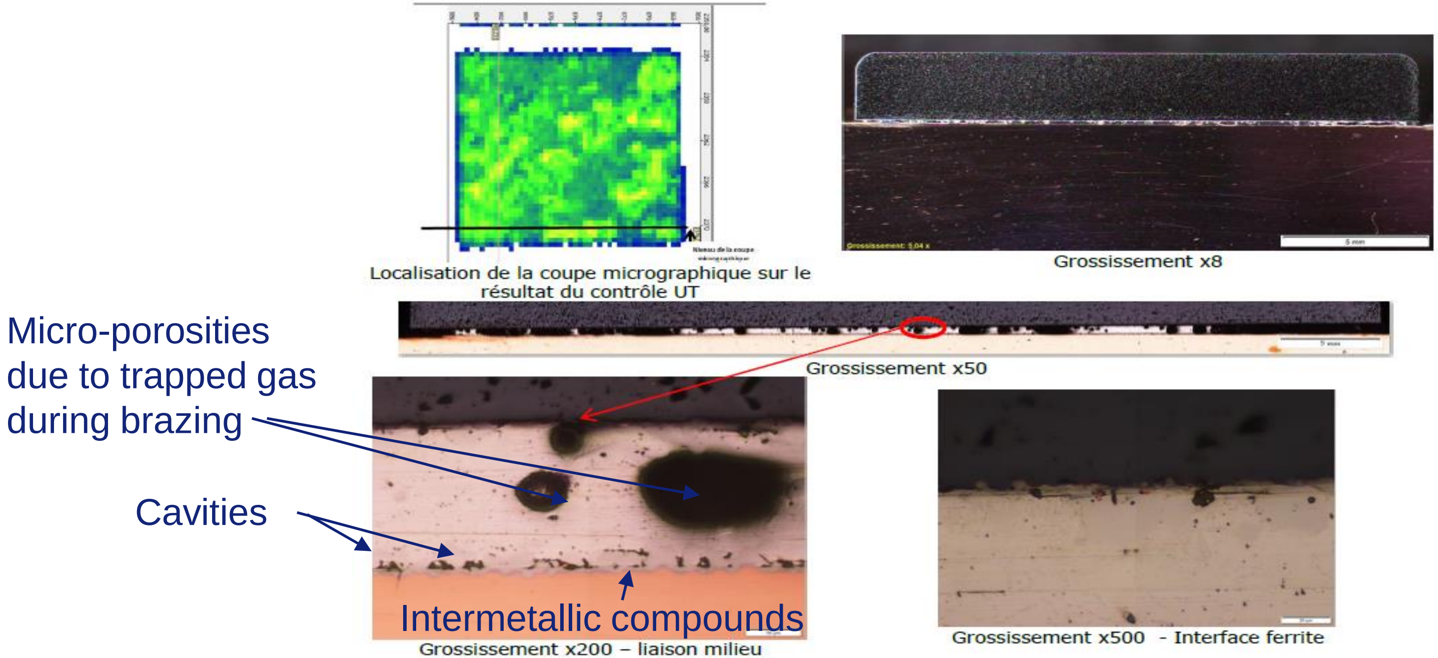


April 2017: 1st samples not accepted



July 2017: new samples

MICROSCOPIC CUT ANALYSIS



Still defects:

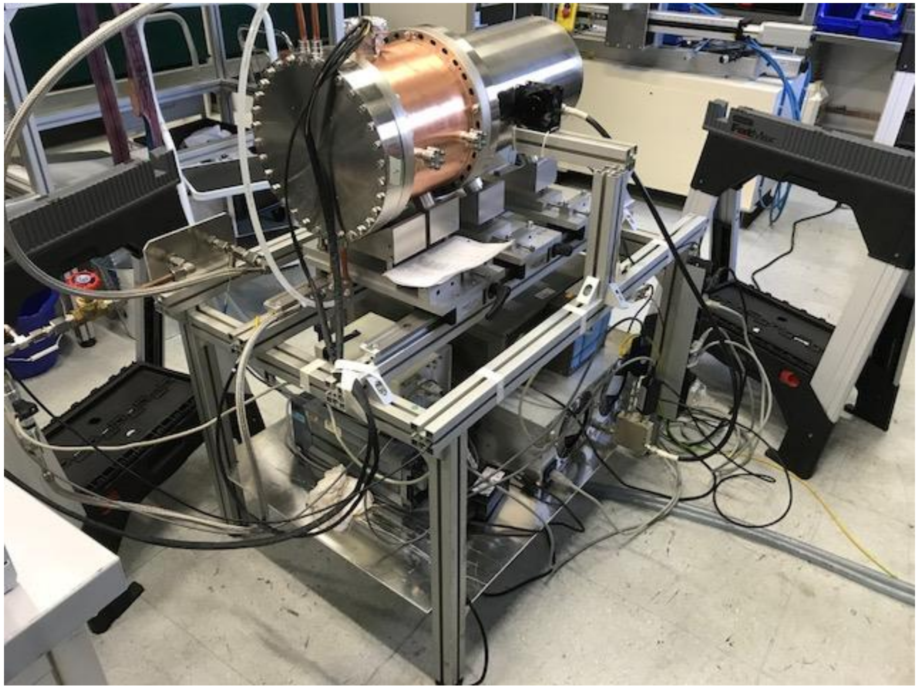
- Copper / brazing interface looks not very homogeneous
- Wetting of copper looks fine
- Ferrite / brazing interface looks better

⇒

- Deffects make brazed interface fragile
- In principle no guarantee for good adhesion in time

⇒ **Fatigue/ageing test required** [Y. Dabin, ESRF]

AGEING TEST



- 570 cycles RF power (15 min ON / 15 min OFF) ➔ at least 5 years of 16 bunches (with 1 beam loss/day)
- 1/3 of the cycles at 360W (max dissipated power measured in the dampers in cell 23), 2/3 at 500W
- Monitoring temperature on several ferrite tiles:
  - → No evolution of temperature profiles and thermal time constants observed
- No measurable difference of ultrasonic cartographies before and after RF cycles:

⇒ No degradation of the brazing junction

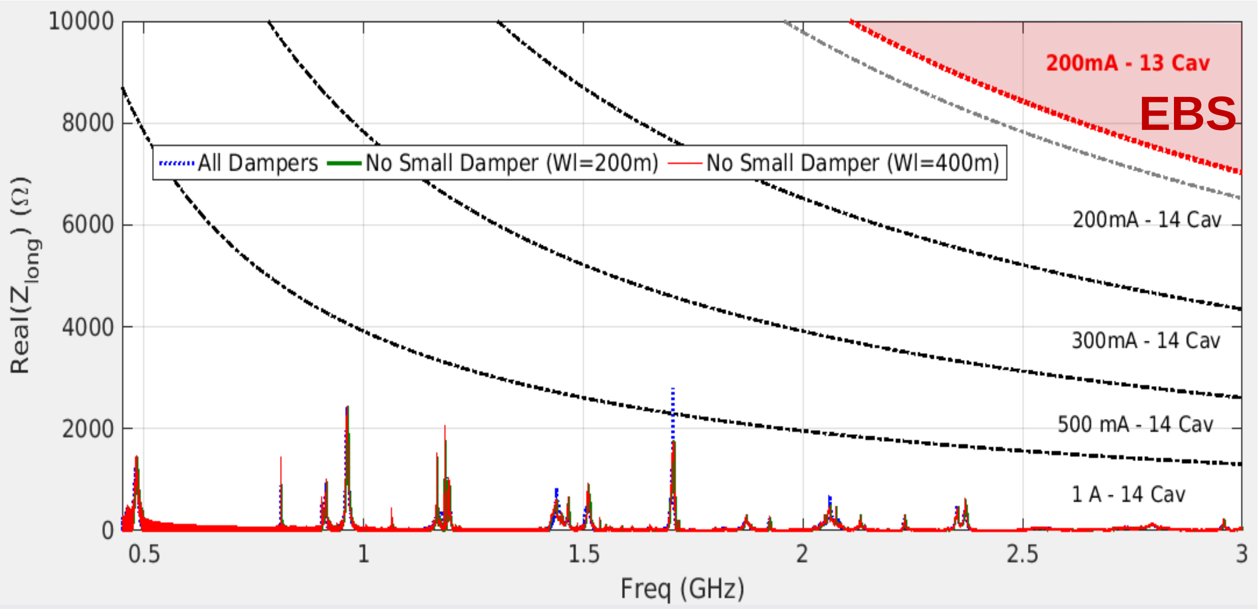
⇒ Brazing samples accepted and series fabrication of HOM absorbers launched

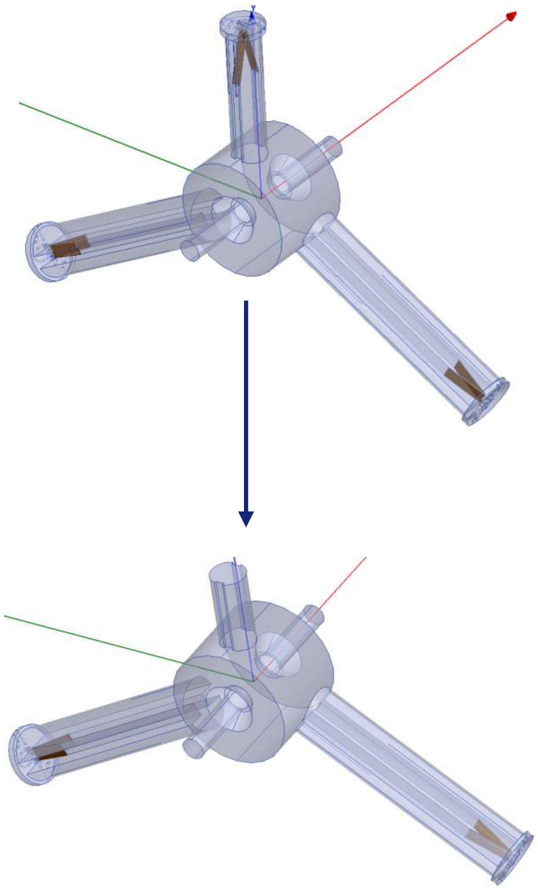
[V. Serrière, A. D'Elia, B. Cocat, D. Boilot]

FURTHER RISK REDUCTION: SUPPRESSION OF SMALL HOM ABSORBER ON TOP

- Uncertainty of simulation codes 10 years ago: safer with 3rd small HOM damper on top of the cavity against a few HOMs above 1 GHz
- Today's improved codes, confirmed by bead pull measurements: → no need for small HOM damper
- DECISION: small HOM absorber replaced by special flange for good electrical contact with HOM ridge waveguide in place

⇒ Avoids any residual risk of a ferrite tile falling into the cavity





[A. D'Elia, V. Serrière]

STATUS OF HOM ABSORBERS

- HOM absorbers:
  - ✓ 9 batches delivered
  - ✓ 5 batches expected early July 2018
- Excellent vacuum performance: in the 10^{-11} mbar range after bake out
- Installation on cavities together with sector valves and revised tuners starting now
- No time for reconditioning all cavities in RF teststand $\Rightarrow$ everything prepared to do it in situ on new machine

TRANSMITTER AND CAVITY CONTROL UPGRADE

Klystron transmitter control upgrade

- Objective 1: get rid of obsolete VME controllers
  - VME replaced by a PCI with RS232 and WAGO analog & digital I/O modules, interconnected via Ethernet
  - Klystron transmitter 2: upgraded in 2016
  - Klystron transmitter 1: upgraded in 2017
- Objective 2: New modern Hardwired Interlock System (HIS): done on both transmitters in 2017
  - Autonomous, status no longer read by the PLC, but given to PCI via RS232
- Objective 3: replace obsolete Simatic S5 by modern WAGO PLCs
  - Klystron transmitter 2: successfully tested ⇒ definitely installed for May 2018 restart
  - Klystron transmitter 1: will be done next, before long shut down
  - Waveguide PLC controllers: also foreseen before long shut down.
- Connection and adaptation to new cavity control
  - Planned for long shut down (after disconnection from existing cavities)

New cavity control

- Besides a few upgrades: essentially same as existing system of prototype cavities from cell 23

[G. Gautier, J.-M. Mercier, N. Michel, M. De Donno, P. Chappelet, J.-L. Pons et al.]

CONCLUSION

Excellent operation performance of existing RF power transmitters

- ✓ Existing klystron stock expected to provide 10 years of operation, powering 10 cavities on new EBS machine
- ✓ After 5 years of operation the seven 150 kW Solid State Amplifiers are extremely reliable and easy to maintain – not a single transistor failure so far !
- ✓ SSA will feed 3 cavities on EBS ring

Examples of CWRF issues

- ✓ After successful reconditioning, EEV klystron provides reliable 1 MW operation beyond 80,000 hours HV ON time
- ✓ Arc detectors positioned at strategic locations are required to protect the equipment at high RF power
- ✓ High power coupler performance depends on appropriate design **and** on correct assembly

RF upgrade for EBS

- ✓ Some issues with HOM absorbers, tuners: understood and mitigated
- ✓ 12 new cavities successfully conditioned to 750 kV and ready for EBS (except mounting of HOM absorbers and valves and revised tuners)
- ✓ Transmitter and cavity control: will be up to date and ready for EBS

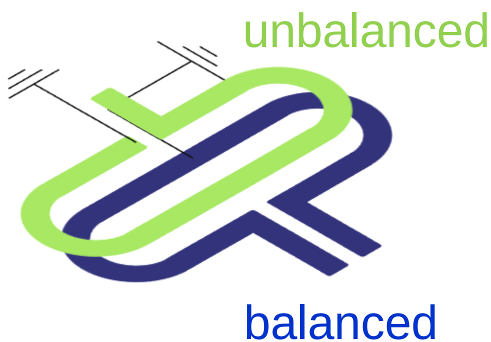
Next ambitious RF project in preparation

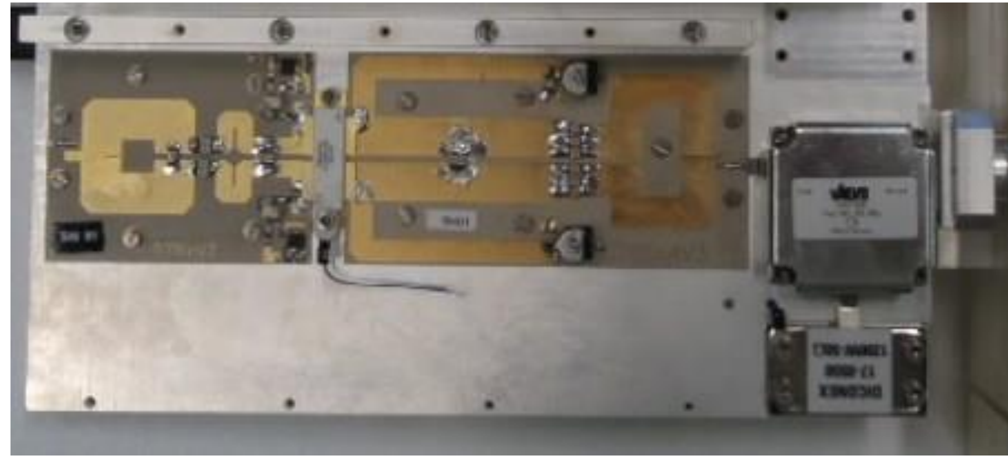
- ➢ Investigations for a harmonic RF system for EBS are starting now

Additional slides shown at the workshop on the development at the ESRF of a Compact 85 kW Solid State Amplifier using a Cavity Combiner

RF AMPLIFIER MODULE: ESRF IN HOUSE DEVELOPMENT

Motorola patent





ESRF fully planer design:

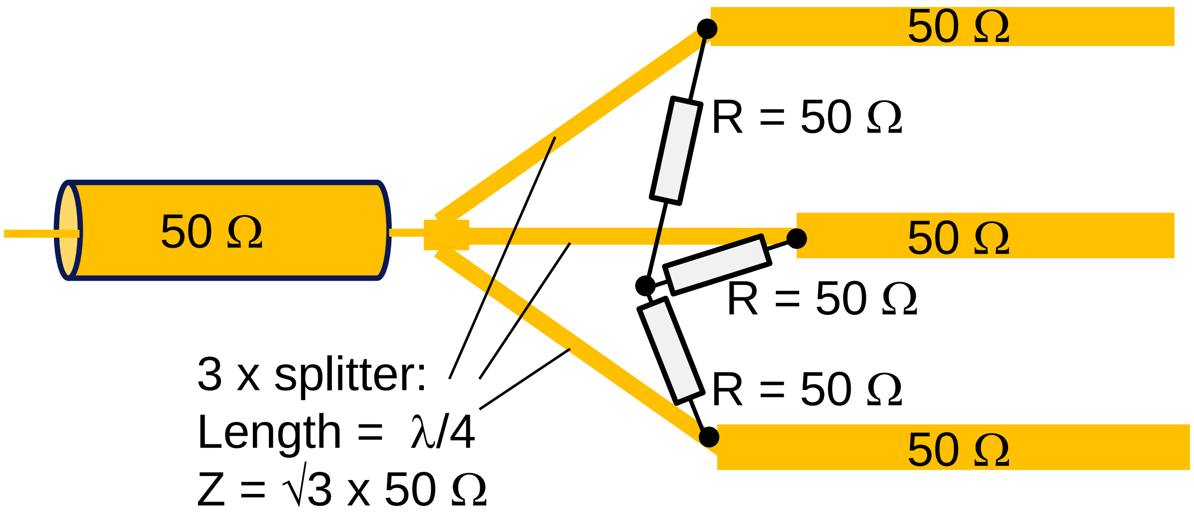
- Printed circuit baluns
- RF drain chokes replaced with “quarter wave” transmission lines.
- Very few components left, all of them SMD and prone to automated manufacturing

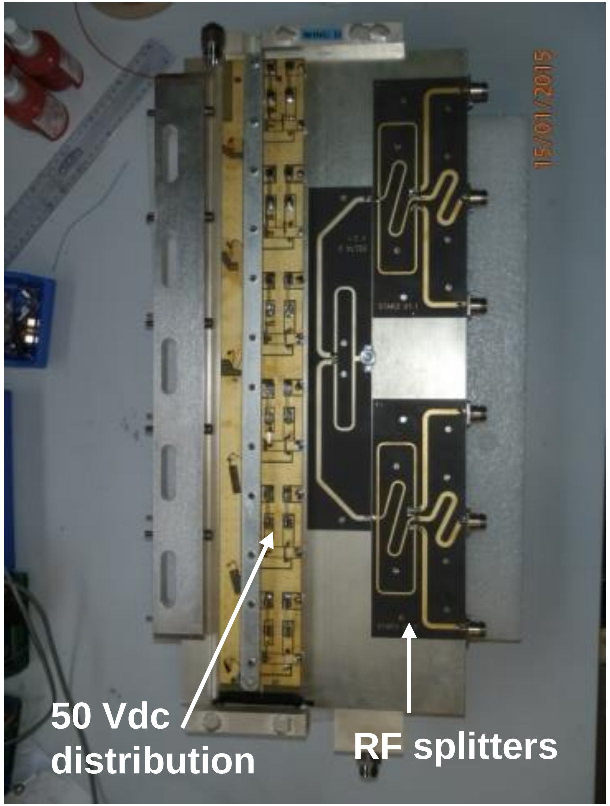
⇒ Reduced fabrication costs

18 modules incl. output circulator	Average Gain	Average Efficiency
at P_{RF}^{out} = 400 W	20.6 dB	50.8 %
at P_{RF}^{out} = 700 W	20.0 dB	64.1 %

[M. Langlois, ESRF]

WILKINSON SPLITTER FOR THE RF DRIVE DISTRIBUTION



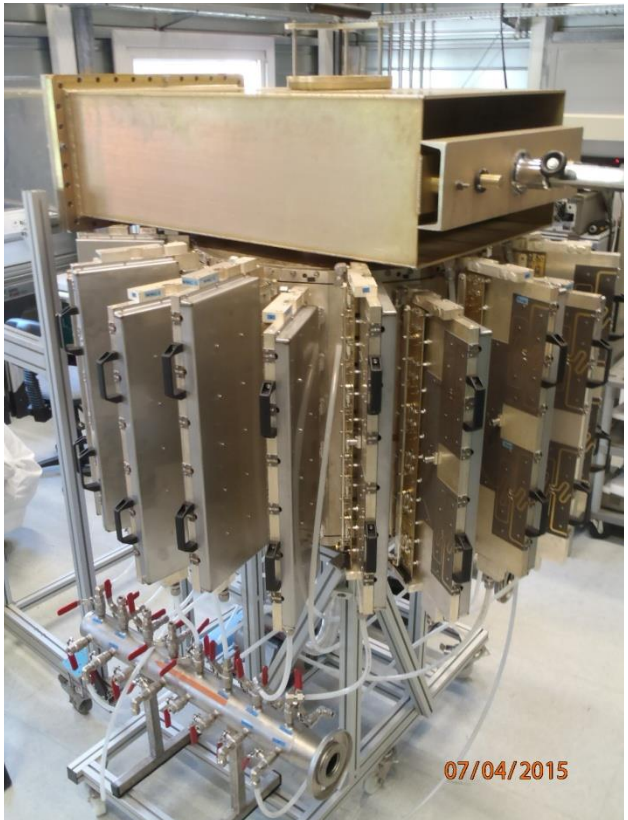


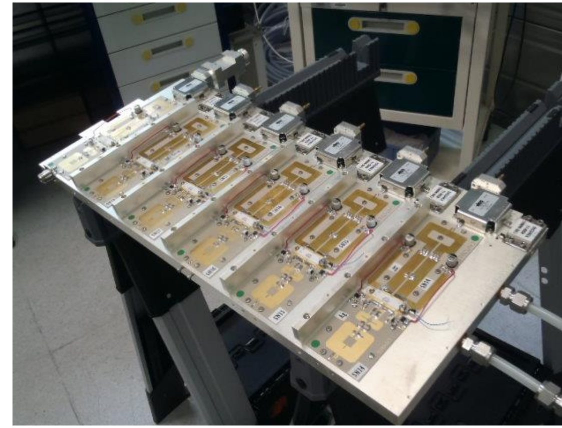
Water cooled wing with 6 RF modules, developed at ESRF

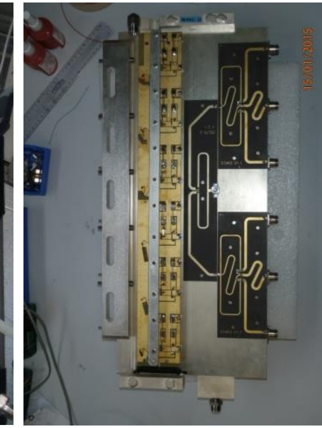
Addition of resistors to absorb differential signals without perturbing the common mode, thereby decoupling the connected outputs from each other

[M. Langlois, ESRF]

ESRF DESIGN USING A CAVITY COMBINER *







$\eta_{RF/DC}$ = 62 % at P_{nom} = 85 kW

P_{test} = 90 kW

P_{nom} obtained with 1 wing off

Direct coupling of RF modules to the cavity combiner:

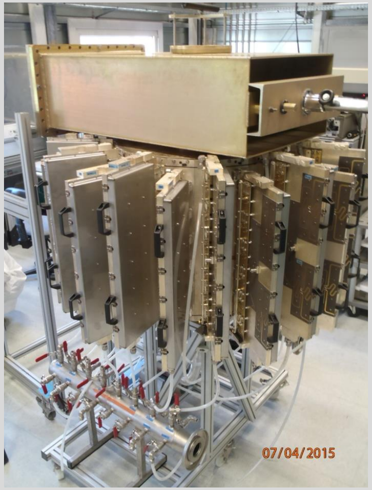
- No coaxial RF power line
- Very few, sound connections
- 6 RF modules are supported by a water cooled “wing”
- The end plate of the wing is part of the cavity wall with built on coupling loops
- One collective shielding per wing
- **Less than half the size of a 75 kW tower with coaxial combiner tree**

[M. Langlois, ESRF]

DC SUPPLIES WITH INCREASED EFFICIENCY, MODULARITY AND REDUNDANCY

ESRF 352 MHz - 85 kW SSPA:

- Direct 400 Vac / 50 Vdc converters from EEI
  - ⇒ Higher efficiency than 2 stages
  - ➢ OK for CW, but antiflicker capacitances for pulsed operation 6x higher at 50 Vdc
- One 160 A / 8 kW PS per wing = 6 RF modules
  - ⇒ Redundancy: can tolerate 1 PS failure at P_{nom} without tripping the SSPA



MANY THANKS FOR YOUR ATTENTION

We highly appreciated the contribution of so many of you to the CWRF 2016 in Grenoble

Let us now address our thanks to Ming-Chyuan Lin, the LOC and NSRRC for welcoming us and having so nicely organized the 10th CWRF 2018 here in Hsinchu !