

[CINEL]

European Synchrotron Radiation Facility

**8<sup>h</sup> CWRP**  
***Elettra / Trieste***  
**13<sup>th</sup> – 16<sup>th</sup> May 2014**

**RF Operation, HOM Damped  
 Cavities and 150 kW Solid State  
 Amplifiers at the ESRF**

J. Jacob  
 J.-M. Mercier  
 V. Serrière  
 M. Langlois  
 G. Gautier  
 A. D'Elia

## Recent ESRF RF upgrade

Replacement of Booster Klystron by:  
4 X 150 kW RF Solid State Amplifiers (SSA)  
from ELTA / AREVA:

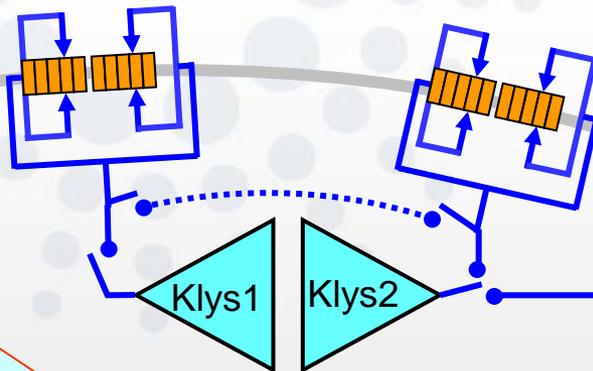
- In operation since March 2012
- 10 Hz pulses / 30 % average/peak power



5-cell cavities: strong HOM !

Booster

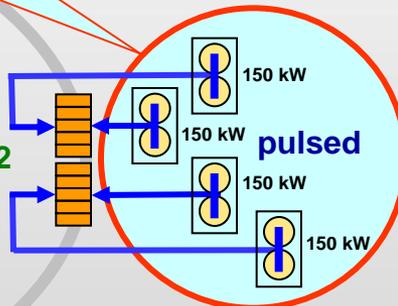
Cell 5  
Cav 1 & 2



Storage Ring

Teststand

SY Cav 1 & 2

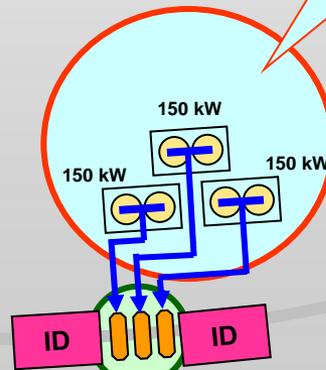


3 X 150 kW SSA from ELTA for  
the Storage Ring:

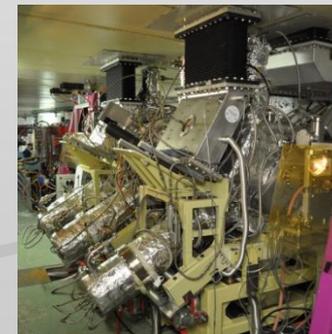
- Powering 3 new HOM damped cavities on the storage ring
- SSAs #1 & #3 in operation since October 2013
- SSA #2 operational since Jan. 2014 (but probl. with cav-tuner)

Klys3

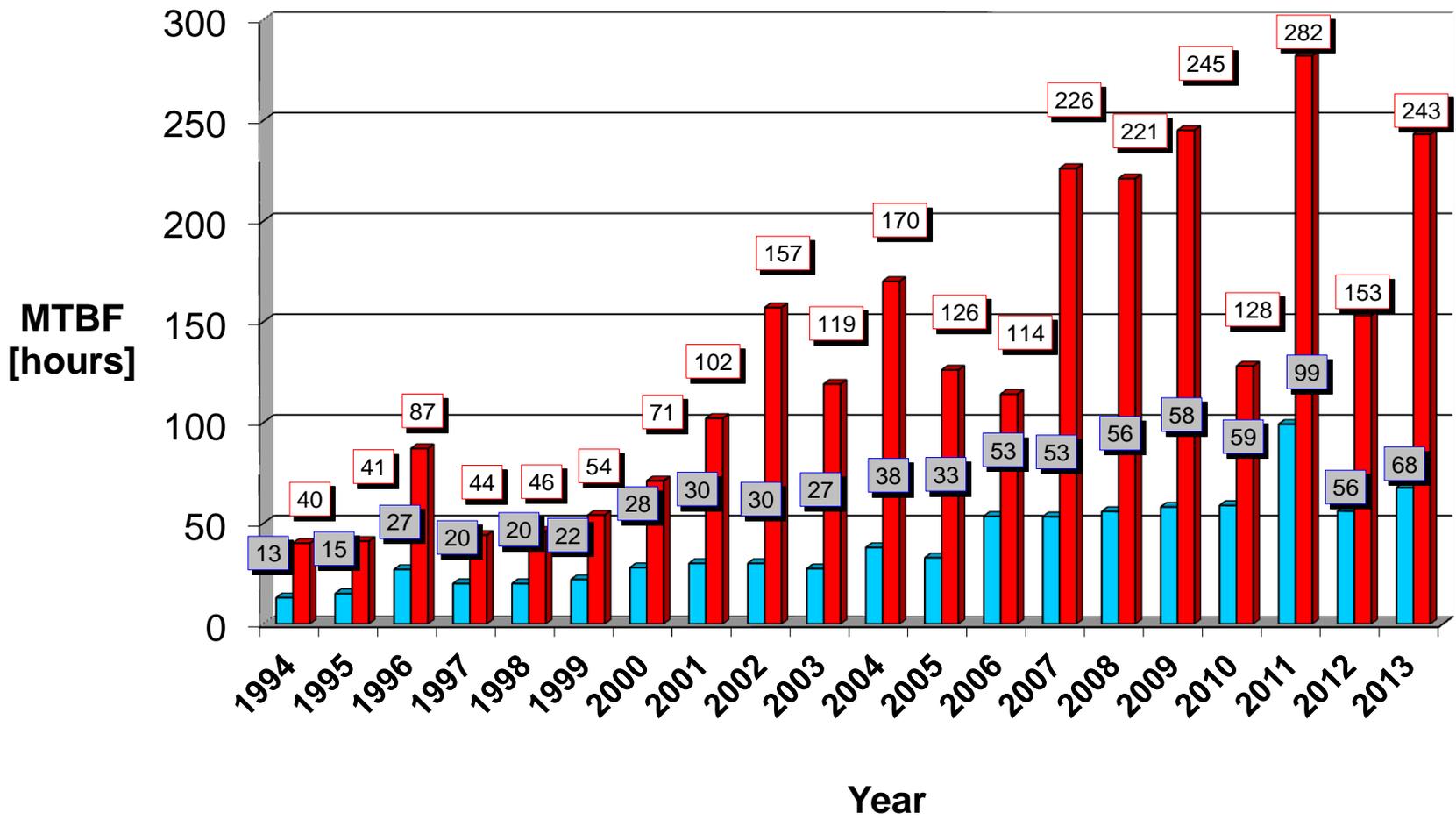
Cell 25: Cav 6 (Cav 5 removed)

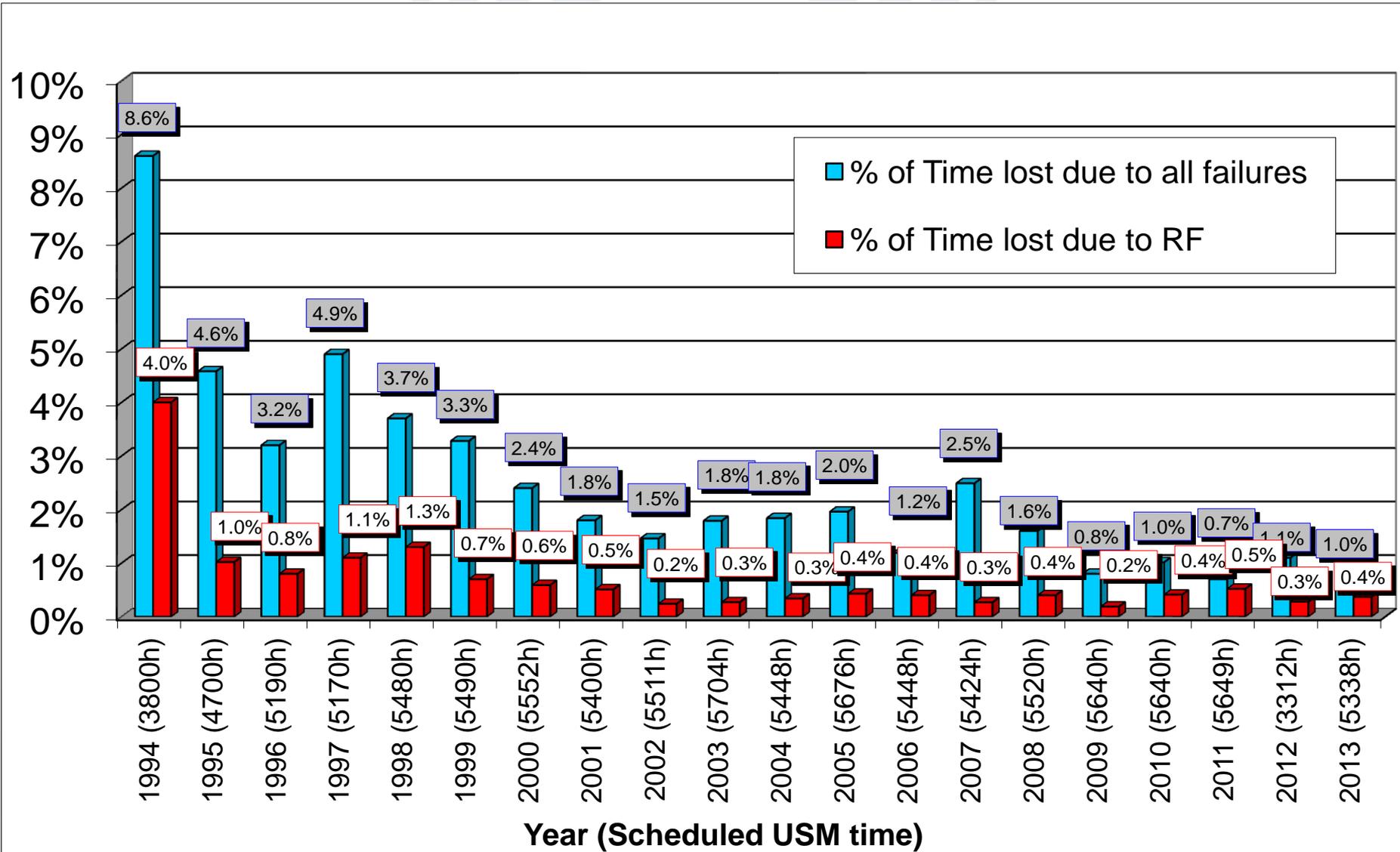


Cell 23: 3 HOM damped mono cell prototype cavities



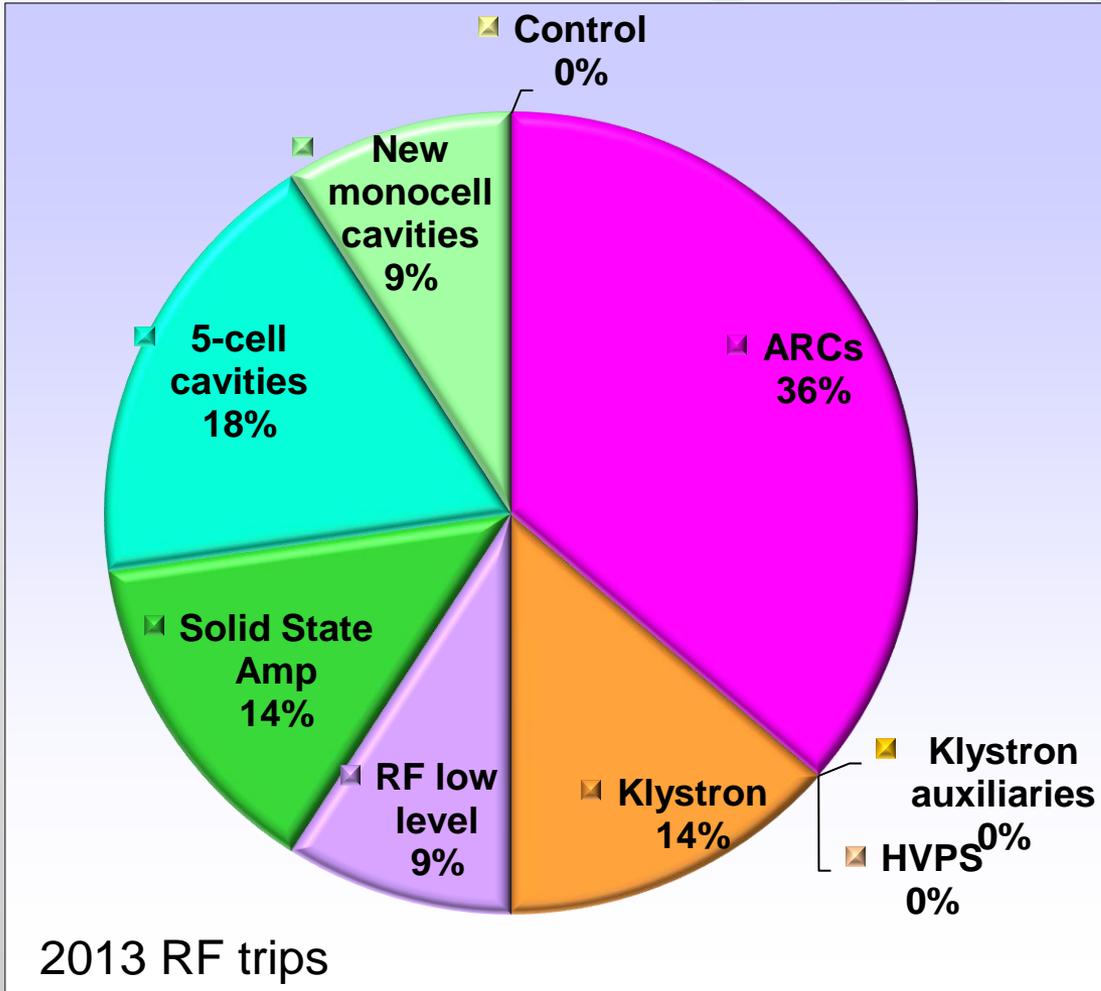
## ESRF operation statistics





**2013 : one of the best years for RF with “only” 22 RF trips / MTBF 243 hours**

*(the best was 2011 with 20 RF trips)*



## Still 8 false arc detections

- ➔ Improvement expected from multi-sensor arc detectors recently developed at CERN to get rid of false positives.
- ➔ We expect to test them as soon as they are made available.

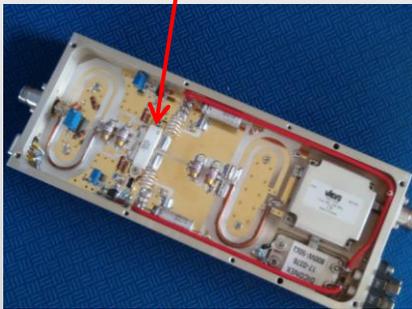
## Klystrons:

- No klystron died after some early deaths in the 1990's
- Our oldest klystron is an EEV operating on TRA1. It took 6386 hours in 2013 to reach 50553 hours.

## Reminder: 150 kW RF SSA for ESRF upgrade

- Initially developed by SOLEIL
- Transfer of technology to ELTA / AREVA

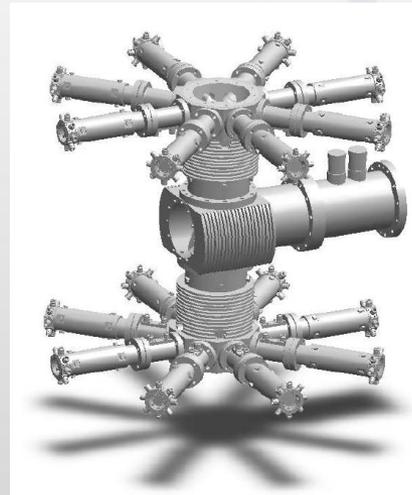
Pair of push-pull transistors



x 128

**650 W RF module**

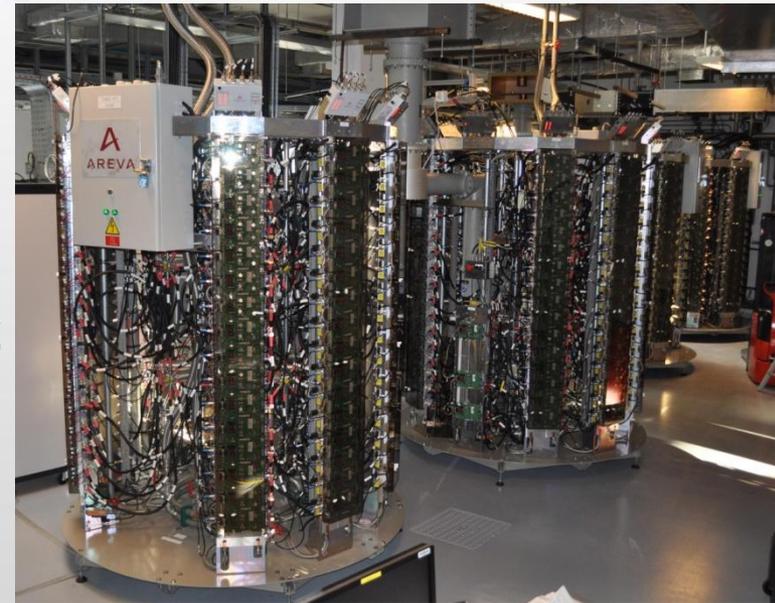
- 6<sup>th</sup> generation LDMOSFET (BLF 578 / NXP),  $V_{ds} = 50 \text{ V}$
- DC to RF:  $\eta = 68 \text{ to } 70 \%$



x 2

**75 kW coaxial power combiner tree**

with  $\lambda/4$  transformers



**150 kW - 352.2 MHz Solid State Amplifier**

DC to RF:  $\eta > 57 \%$  at nominal power

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

## Events on 4 x 150 kW Booster SSA's

Year	SSA	Domain	Description - Cause	Intervention	Impact w/ operation
2012	1-1	ELTA	Flowmeter	Immediate	Refill postponed
	1-1	ELTA	Control interface - Fuse blown	Hot swapping	No
	1-1	ELTA	Control interface - Bad connection I2C	Hot swapping	No
	1-1	ELTA	Control interface - Fuse blown (Capacitor short-circuit)	Hot swapping	No
	1-2	ELTA	Combiner 8 - Unbalance	Delayed	No
	2-1	ELTA	DC/DC converter - Fuse blown	Delayed	No
	2-1	ELTA	Pre-driver - Reset impossible (hardware bug)	Immediate	Refill postponed
	2-1	ELTA	Control interface - Fuse blown	Hot swapping	No
	2-2	ELTA	HPA module - Low bias current (Filter badly mounted)	Delayed	No
	2013	2-1	ESRF	LLRF Driver - Gain loss	Delayed
2014	1-1	ELTA	DC/DC converter - Resistor badly soldered	Delayed	No
	1-2	ELTA	Pre-dirver - Bad soldering of a component	Immediate	Refill postponed
	1-2	ESRF	Voltage Interlock - Differential probe failure	Immediate	Refill postponed
	2-1	ELTA	HPA module - Low bias current (Filter badly mounted)	Delayed	No

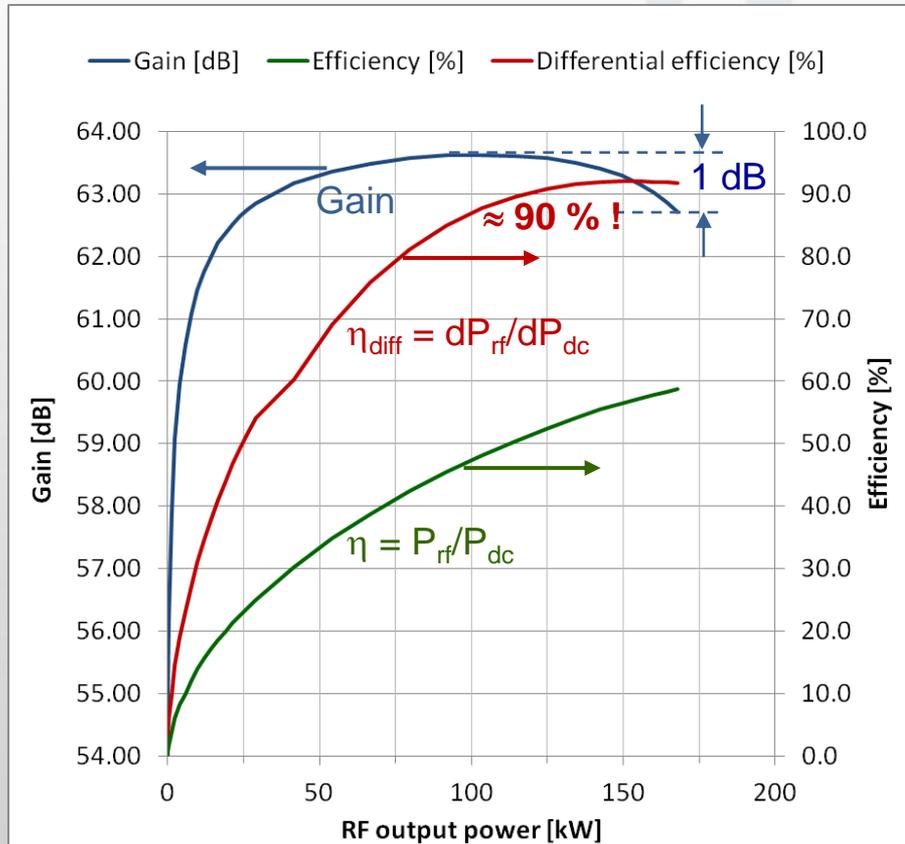
- **1040** RF HPA modules – 1600 h runtime since 2012
- No major HPA component failure (transistor, circulator ...)
- Only **youthful problems**
- **Maintenance at low price** per year
- **Efficiency:** No degradation → 58% at 150kW
- **Very High MTBF** must be stabilized for **Top-up operation mode**

## Events on 2 x 150 kW Storage Ring SSA's

Year	SSA	Domain	Description - Cause	Intervention	Impact w/ operation
2013	C23-1	ELTA	HPA module - Low bias current (Filter badly mounted)	Delayed	No
	C23-1	ELTA	HPA module - Low bias current (Filter badly mounted)	Delayed	No
	C23-3	ELTA	HPA module - Low bias current (Filter badly mounted)	Delayed	No
2014	C23-1	ELTA	HPA module - Low bias current (Filter badly mounted)	Delayed	No
	C23-1	ELTA	HPA module - Low bias current (Filter badly mounted)	Delayed	No
	C23-1	ELTA	HPA module - Low bias current (Filter badly mounted)	Immediate	Yes
	C23-2	ELTA	Control interface - Fuse blown (Capacitor broken)	Hot swapping	No
	C23-3	ELTA	HPA module - Low bias current (Filter badly mounted)	Delayed	No
	C23-3	ELTA	HPA module - Low bias current (ELTA for expertise)	Delayed	No
	C23-3	ELTA	DC/DC converter -ELTA for expertise	Delayed	No
	C23-3	ELTA	Flowmeter	Immediate	No (Restart)

- **2 SSAs (#1 and #3) in operation on the machine since October 2013**  
(Problem with cavity #2 tuner ⇒ SSA #2 not yet used in ESRF user operation)
- Run time = 3600 h / SSA
- Only youthful problems
- **8 RF HPA modules and 1 DC/DC converter failed within the 6 first months**
- **1 of the faulty HPA was a driver, which produced glitches on the cavity voltage, then induced RF trip**

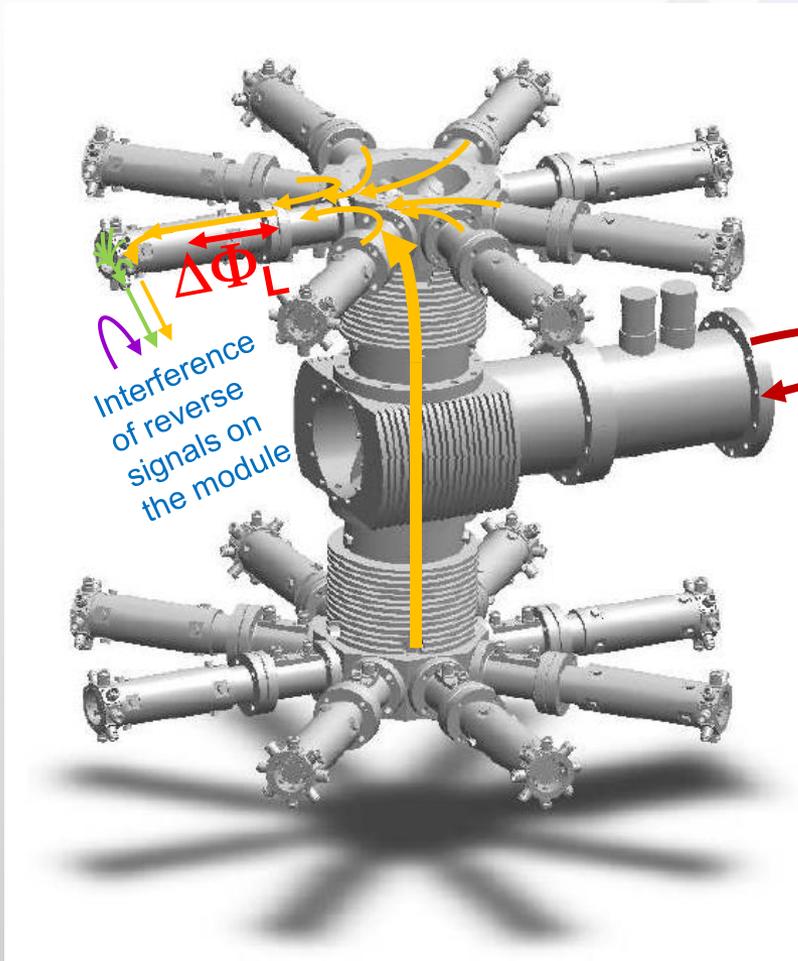
## SSA gain/power, harmonics – CW & pulsed operation



Efficiency / gain curve of 150 kW ELTA SSA at ESRF

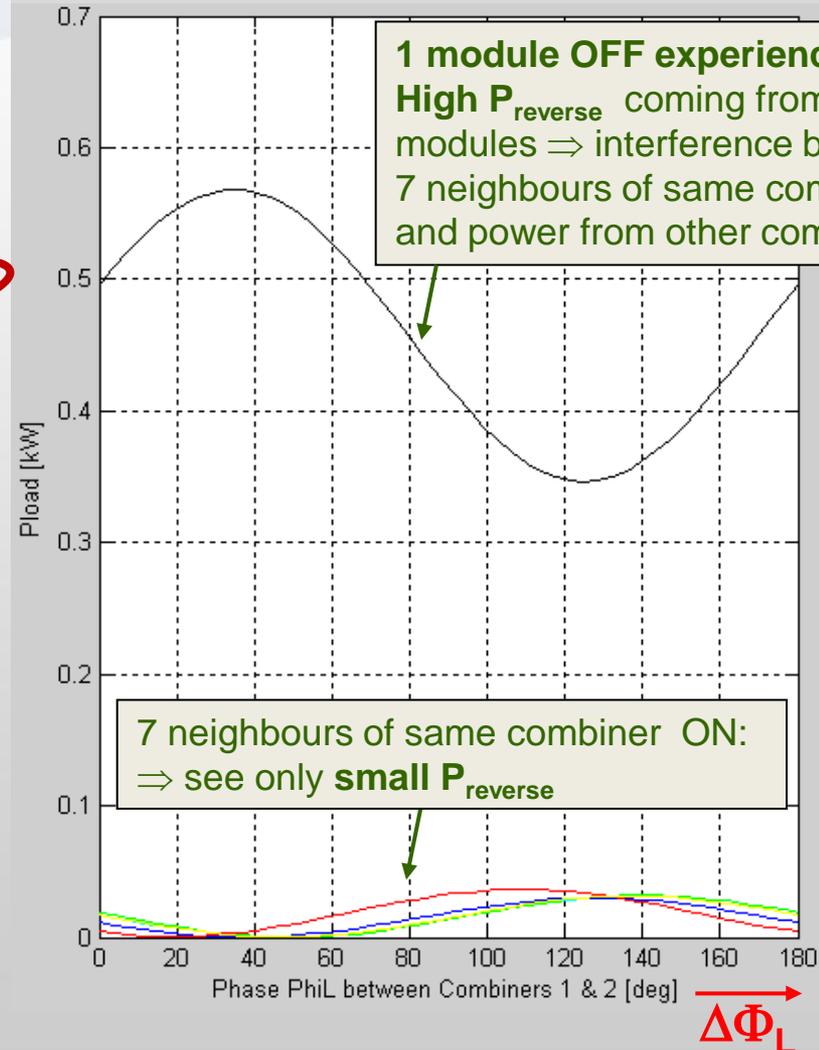
- Specified efficiency easily met:
  - ✓  $\eta > 57\%$  at  $150\text{ kW} = P_{nom}$  (spec: 55%)
  - ✓  $\eta > 47\%$  at  $100\text{ kW} = 2/3 P_{nom}$  (spec: 45%)
- Gain compression  $< 1\text{ dB}$  at  $P_{nom} = 150\text{ kW}$ 
  - ☞ Gain curve and  $P_{nom}$  adjusted by means of load impedance on RF module
- Avoid overdrive conditions
  - High peak drain voltage can damage the transistor
  - ⇒ Overdrive protection interlock
- Short pulses (20  $\mu\text{s}$ )
  - Transient gain increase up to  $\approx 1.3\text{ dB}$
  - Risk of overdrive
  - ⇒ Overdrive protection needs to be adjusted carefully
- Requested redundancy → operation reliability:
  - ✓ all specifications met with up to 2.5% i.e. 6 RF modules OFF (becoming faulty during operation)
- Power margin paid with efficiency: must be dimensioned carefully
- Harmonics:  $H2 < -36\text{ dBc}$ ,  $H3 < -50\text{ dBc}$
- Spurious sidebands / phasenoise:
  - $< 68\text{ dBc}$  at 400 kHz (from DC/DC PS's, harmless)
  - compare klystron  $-50\text{ dBc}$  from HVPS ripples at 600 Hz, 900 Hz, 1200 Hz, ... moreover close to  $f_{synchrotron}$

## Adjustment of phase between 1<sup>st</sup> and 2<sup>nd</sup> 8x-Combiner stages



$\Delta\Phi_L$ : proposed by SOLEIL

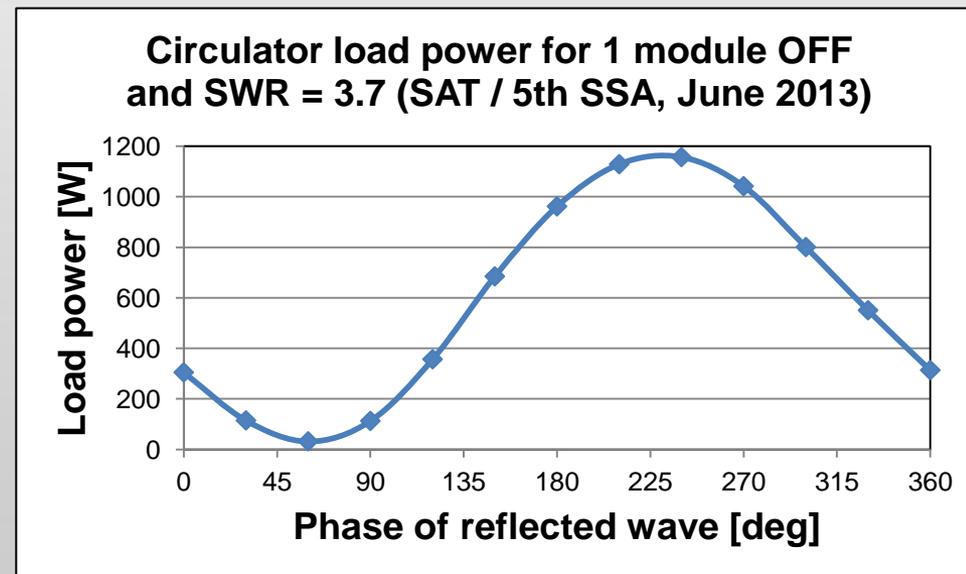
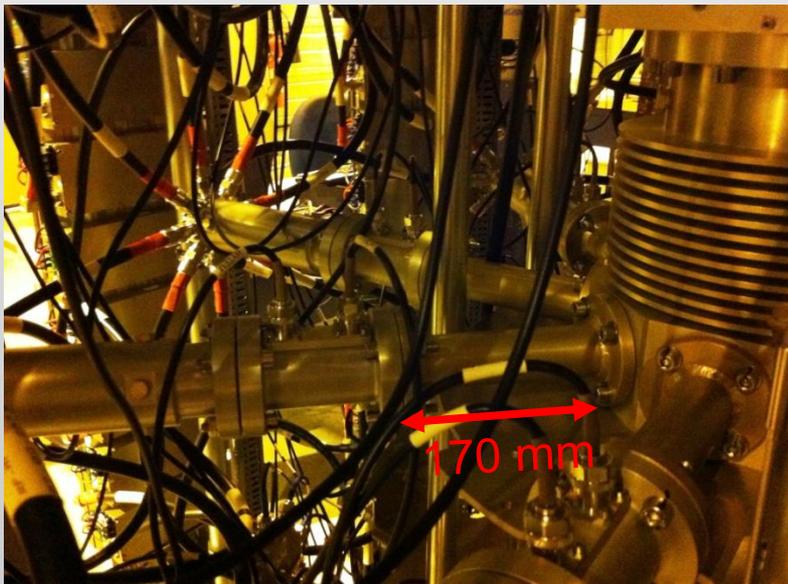
when SSA matched:  $r = 0$



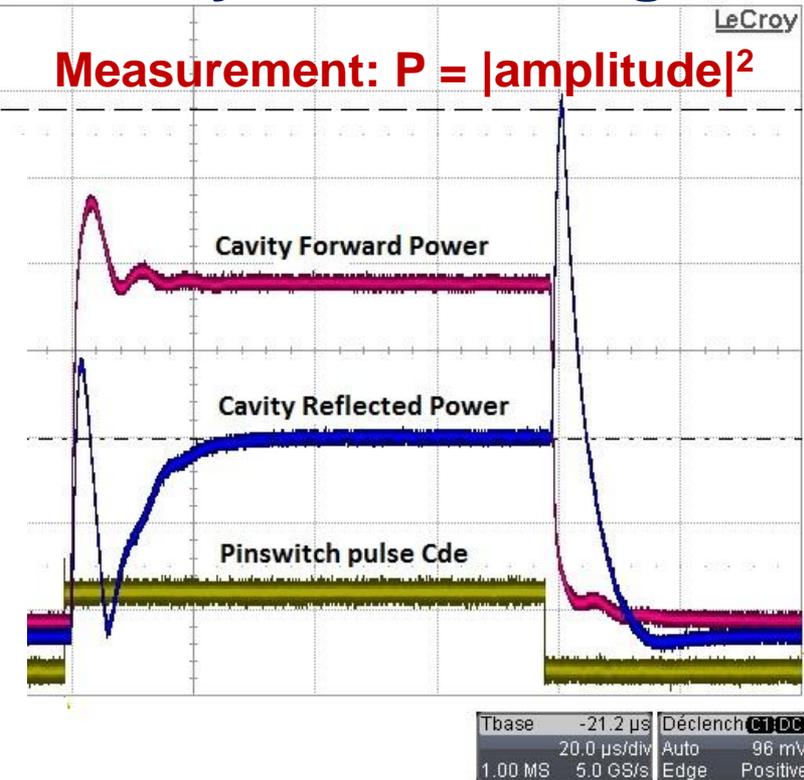
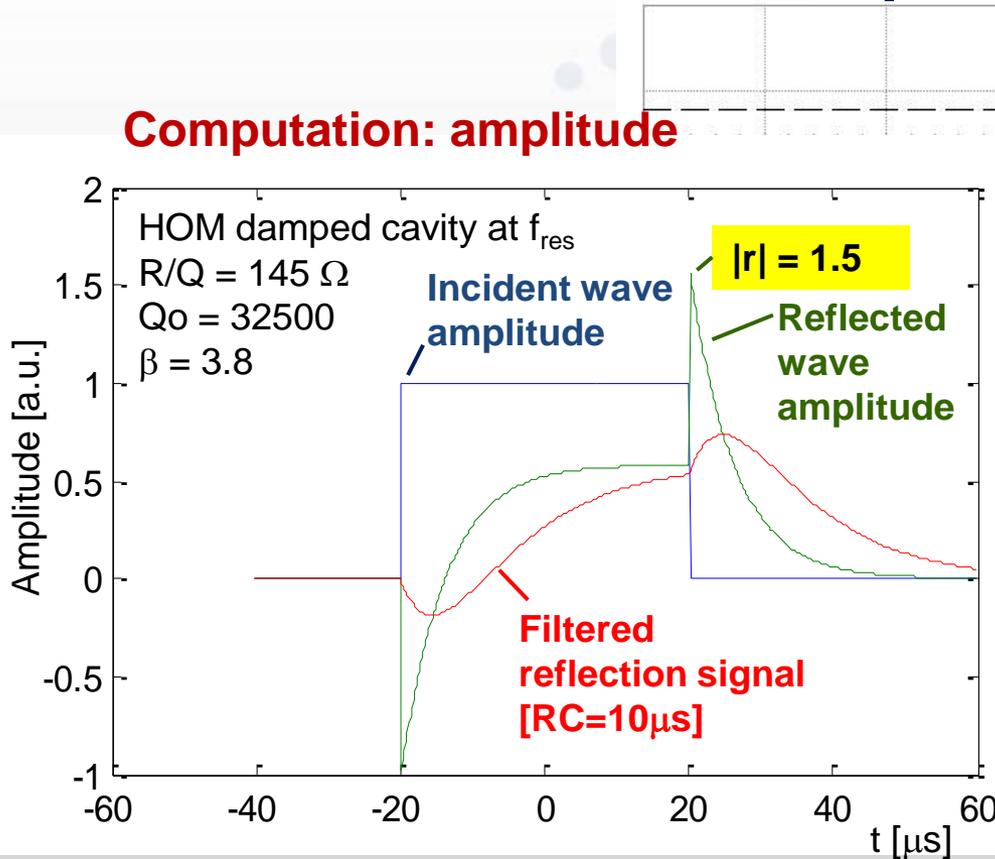
## Adjustment of phase between 1<sup>st</sup> and 2<sup>nd</sup> 8x-Combiner stages

**Additional interference with reflection for mismatched operation:  $|r| = 1/\sqrt{3}$  (ESRF spec)**

- 1 module OFF: depending on  $\Delta\Phi_L$  (and on reflection phase) the circulator load receives up to
    - $P_{\text{rev}}^{\text{max}} = 1500 \text{ W}$  to  $1700 \text{ W}$  for worst  $\Delta\Phi_L$
    - $P_{\text{rev}}^{\text{max}} = 1100 \text{ W}$  for best  $\Delta\Phi_L$
  - Active modules receive the remaining power: maximum of  $400 \text{ W}$  for best  $\Delta\Phi_L$
- ⇒ Successful implementation of **best  $\Delta\Phi_L$**  and **1200 W loads** on the SSA for the SR, which are operated in CW
- ☞ NB: not necessary on booster, operated in pulsed mode (800 W loads tested above 2000 W pulsed RF)

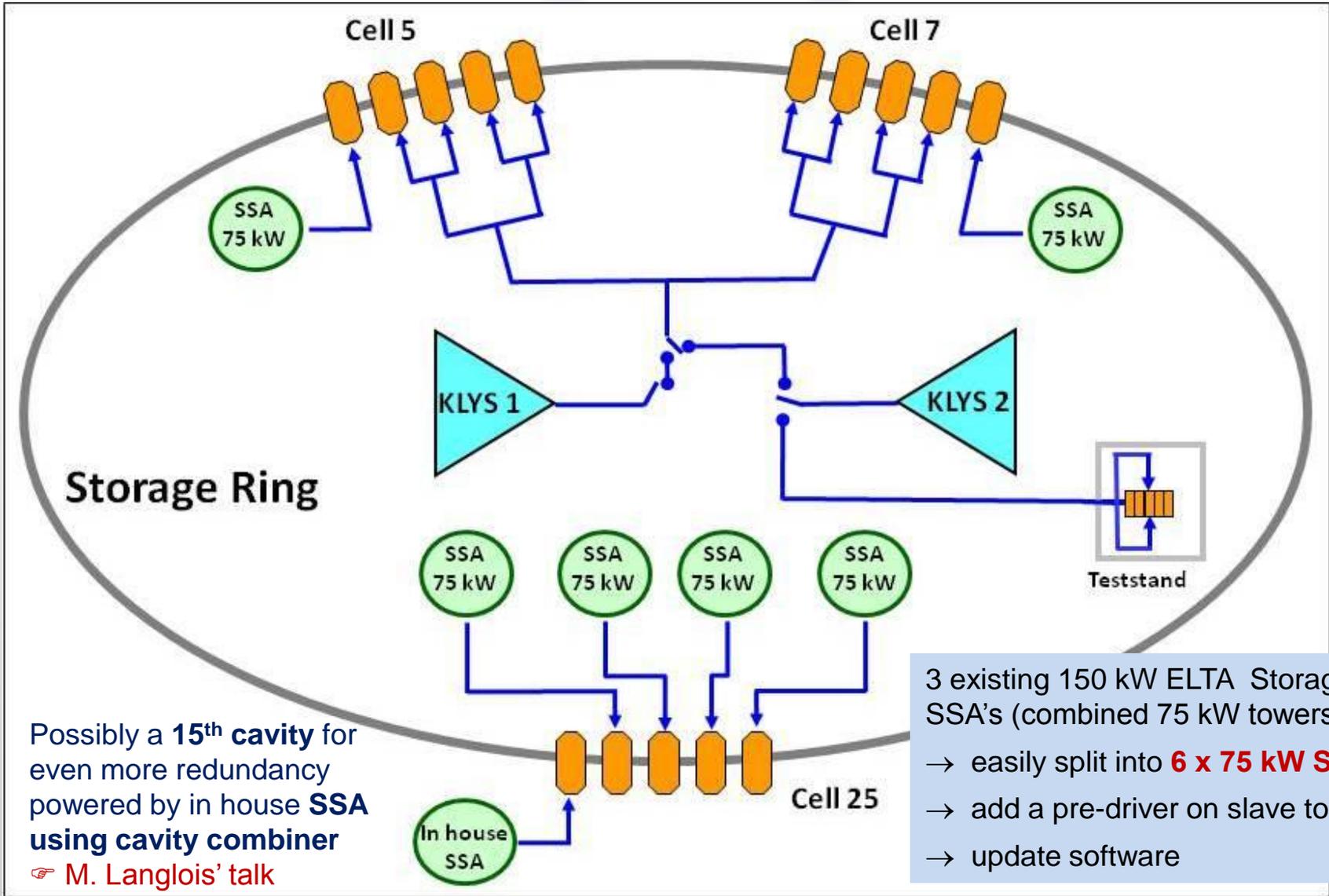


## Transient reflections for pulsed cavity conditioning



- SSA tested with 20  $\mu$ s /150 kW pulses at full reflection
- ⇒ Fast interlock for  $P_{refl} > 150$  kW
- ⇒ Interlock on low pass filtered signal for  $P_{refl} > 50$  kW

Preliminary RF parameters		Existing ESRF	New ESRF lattice
Emittance	$\varepsilon_x / \varepsilon_z$	4000 pm / 4 pm	$\approx 150$ pm / 3 pm
Energy loss (incl. 0.5 MeV for ID's)	U	5.4 MeV/turn	3.1 MeV/turn
Same ID position $\Rightarrow \Delta f_{rf} = + 170$ kHz	$f_{rf}$	352.20 MHz	352.37 MHz
Longitudinal damping time	$\tau_s$	3.5 ms	8.86 ms
Momentum compaction factor	$\alpha$	$17.8 \cdot 10^{-5}$	$8.72 \cdot 10^{-5}$
Energy spread	$\sigma_E/E$	$1.06 \cdot 10^{-3}$	$0.948 \cdot 10^{-3}$
Nominal RF voltage	$V_{acc}$	8 MV	6 MV
$\Rightarrow$ RF Energy acceptance (incl. ID's)	$\Delta E/E$	2.9 %	4.9 %
Synchrotron frequency	$f_s$	1.86 kHz	1.22 kHz
$I_{threshold}$ for HOM driven instabilities (LCBI) <i>[for a given HOM]</i>	ratio	1.9	to 1 $\Rightarrow$ HOM damped cavities MANDATORY for Phase 2
Number of cavities	$N_{cav}$	5 (five-cell cav's $\Rightarrow$ 25 cells)	14 (mono-cells, HOM free)
Cavity Coupling	$\beta$	4.4	3.2
Copper loss per cavity	$P_{copper} / N_{cav}$	47 kW	19 kW
RF power per cavity at $I_{nom} = 200$ mA (incl. 10% transmission losses)	$P_{tot-200mA} / N_{cav}$	292 kW	<b>70 kW</b> <b>(75kW @ 5.7 MV with 1 cavity off)</b>
Total RF power at <b>200 mA</b> (incl. 10% losses)	$P_{tot-200mA}$	1460 kW	980 kW



Possibly a 15<sup>th</sup> cavity for even more redundancy powered by in house SSA using cavity combiner

→ M. Langlois' talk

3 existing 150 kW ELTA Storage Ring SSA's (combined 75 kW towers):

- easily split into **6 x 75 kW SSA's**
- add a pre-driver on slave towers
- update software

➤ Gradual implementation of more SSA's is envisaged on longer term

## HOM damped cavities for ESRF upgrade

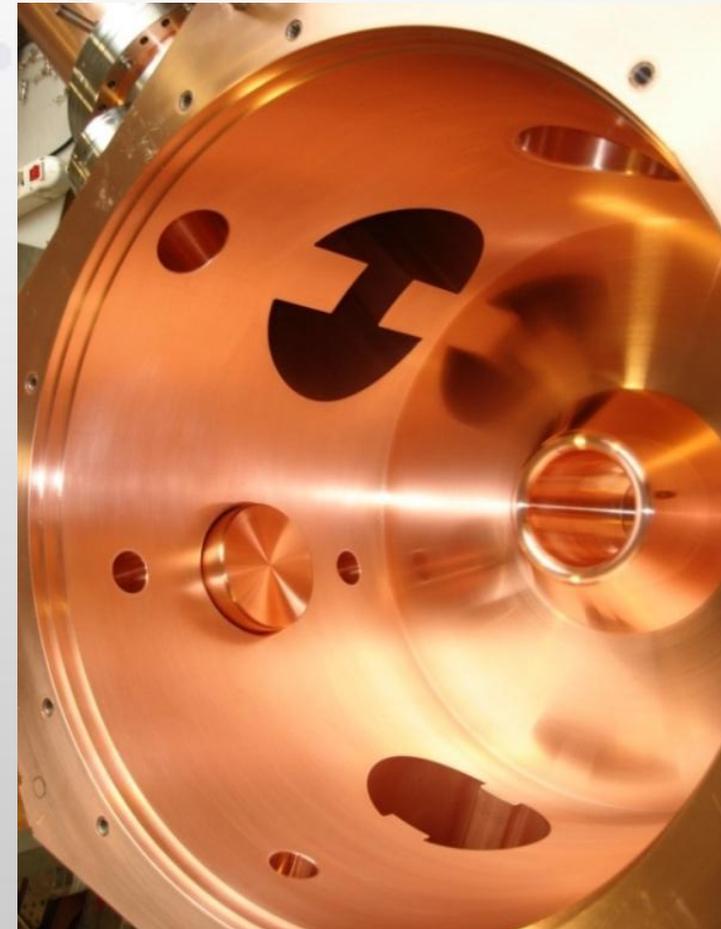
### 3 functional cavities on the ring from RI, CINEL and SDMS

- $V_{ACC}$  : 0.5 to 0.75 MV
- 150 kW with beam successfully tested
- 2 cavities in operation since October 2013
  - ☞ 0.5 MV, 80 kW at 200 mA
- 1 cavity qualified with beam but in standby for the moment due to a mechanical problem with tuner plunger (currently being solved)

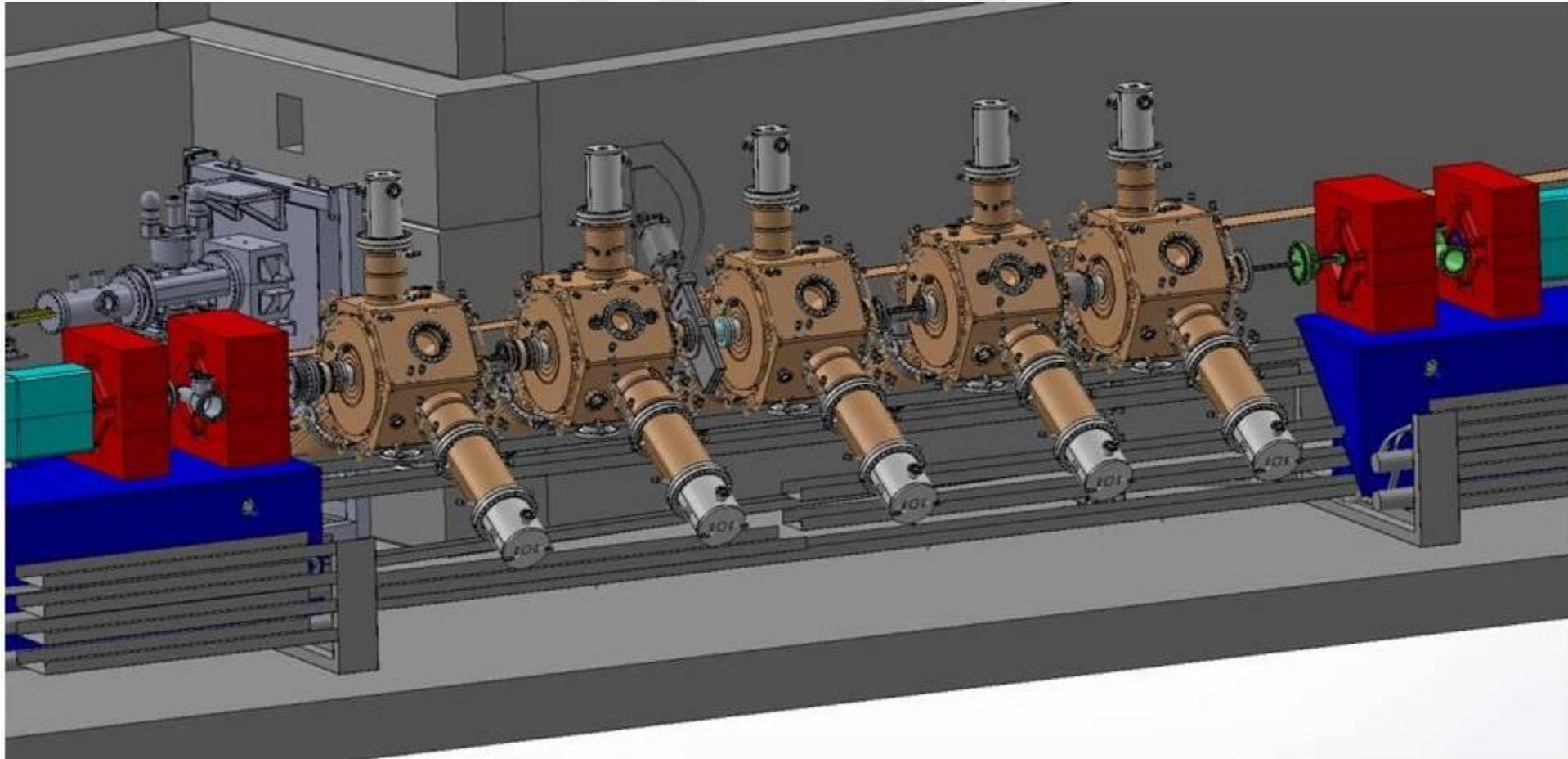
### 12 additional cavities in fabrication:

- Cavities from RI – Research Instrumentation
- 14 sets of HOM absorbers from SDMS
- delivery scheduled beginning 2016

### 15 cavities for the new machine



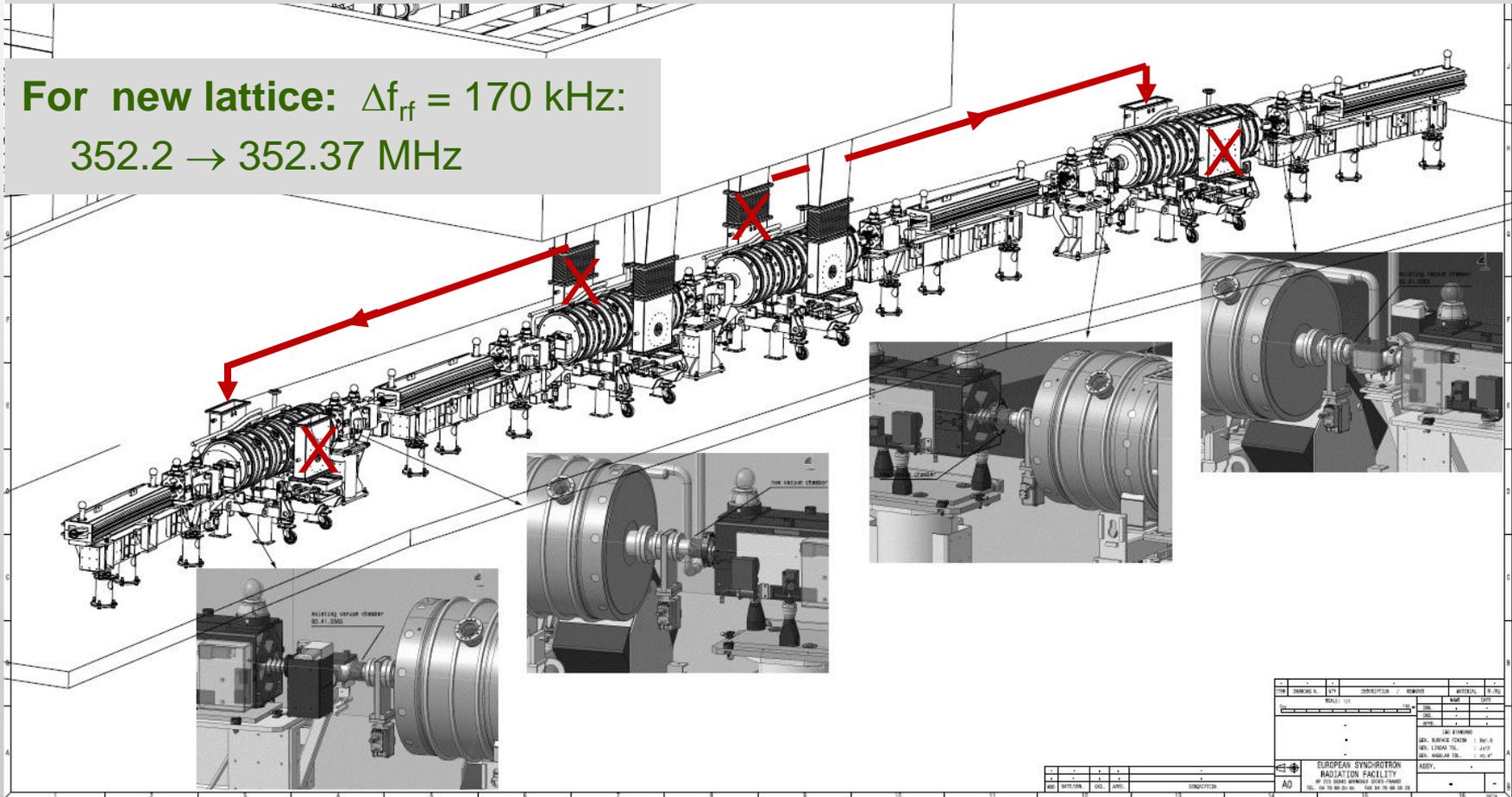
## 1 RF section of new machine with 5 HOM damped cavities



## Started booster RF upgrade for top up: “4 five-cell cavities”

- 2 cav x 2 SSA/cav → 4 cav x 1 SSA/cav
- Nominal operation → half the RF power
- 4 x 150 kW SSAs: 7...8 MV max → 10 ... 11 MV max
- 3 x 150 kW (1 missing SSA): still 7... 8 MV redundancy

For new lattice:  $\Delta f_{rf} = 170$  kHz:  
352.2 → 352.37 MHz



## Lifetime in the new machine

- New lattice: in principle same operation modes as existing machine:

(preliminary)	Multibunch	16-bunches	4-bunches
Total current [mA]	200	90	40
Nb. Bunches	868	16	4
Bunch length [ps]	23	64	77
<b>Lifetime [h]</b>	<b>7.5</b>	<b>2.4</b>	<b>1.8</b>

- ☞ Later implementation of harmonic cavities for bunch lengthening and increased Touschek lifetime is envisaged:
  - e.g. **Super3HC** type like at Elettra or SLS: at 1.057 GHz or 1.409 GHz (3<sup>rd</sup>, resp. 4<sup>th</sup> harmonic)
  - **Possible collaboration with other labs?**

# Thank you !!

