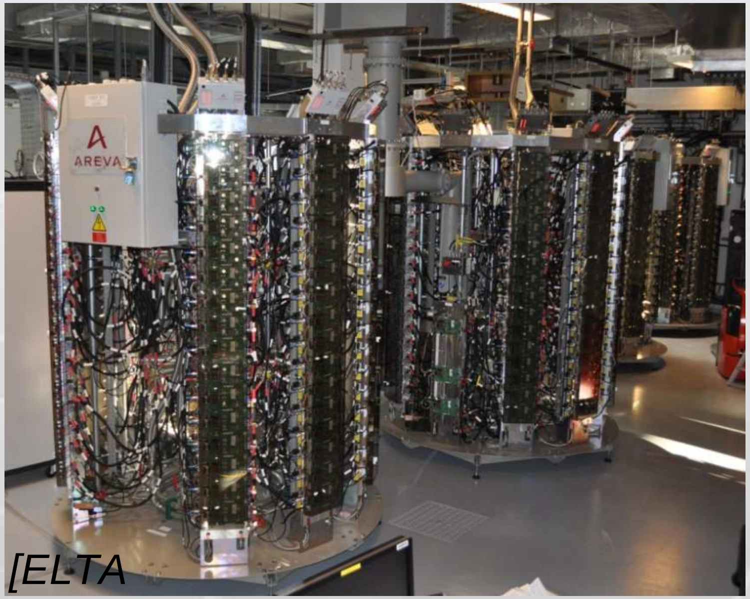
[ELTA]


[CINEL]

16th ESLS RF Meeting 2012
ALBA, 9th – 10th October

1st Experience with SSAs and New Cavities at the ESRF

Jörn Jacob
J.-M. Mercier
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M. Langlois
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European Synchrotron Radiation Facility

RF upgrade phase 1
well in progress

4 SSA from ELTA for the booster:

- In operation since March 2012
- Smooth and efficient commissioning
- Difficulty: Debugging of whole SYRF transmitter in limited time in March and April 2012, including common:
  - 400 kW power supply
  - LLRF with FPGA – IQ loop for the booster pulse
  - ESRF Control system

3 SSA from ELTA for SR:

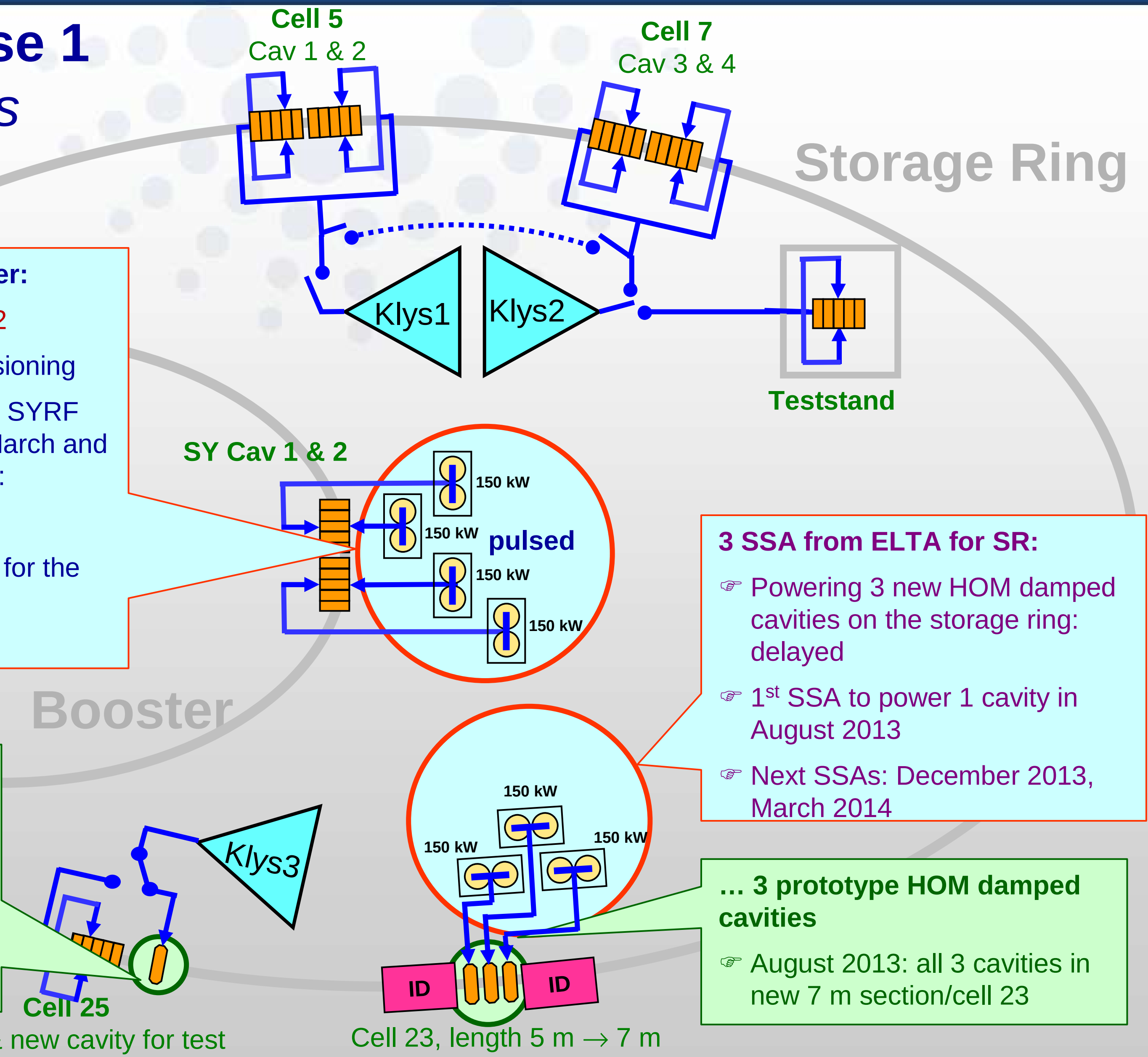
- Powering 3 new HOM damped cavities on the storage ring: delayed
- 1st SSA to power 1 cavity in August 2013
- Next SSAs: December 2013, March 2014

3 prototype HOM damped cavities …

- Test with beam one by one on cell 25 with klystron transmitter TRA3:
- **RI cavity on the ring since October 2011 !**

… 3 prototype HOM damped cavities

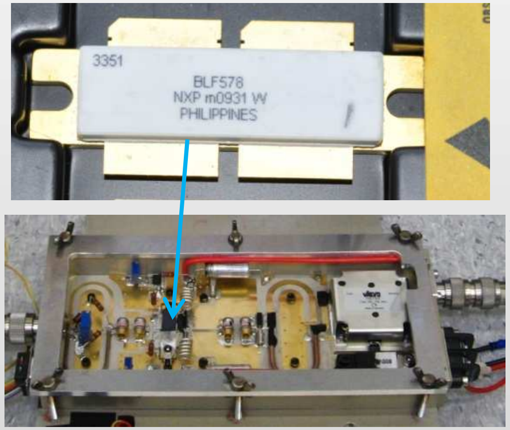
- August 2013: all 3 cavities in new 7 m section/cell 23



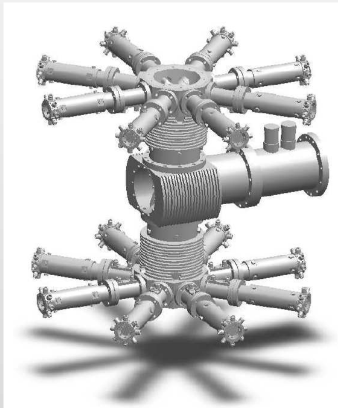
150 kW RF SSA at 352.2 MHz

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

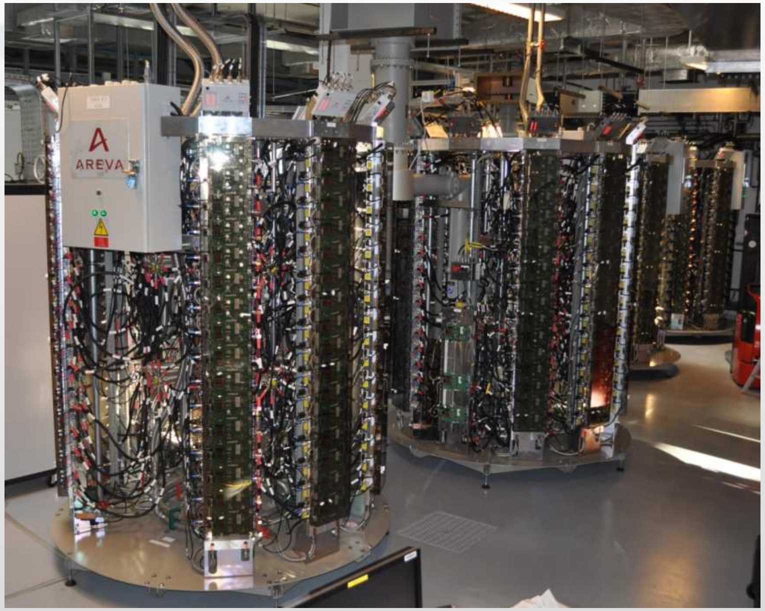
Pair of push-pull transistors



x 128



x 2



650 W RF module

➢ 6^{th} generation LDMOSFET (BLF 578 / NXP), V_{ds} = 50 V

➢ Efficiency: 68 to 70 %

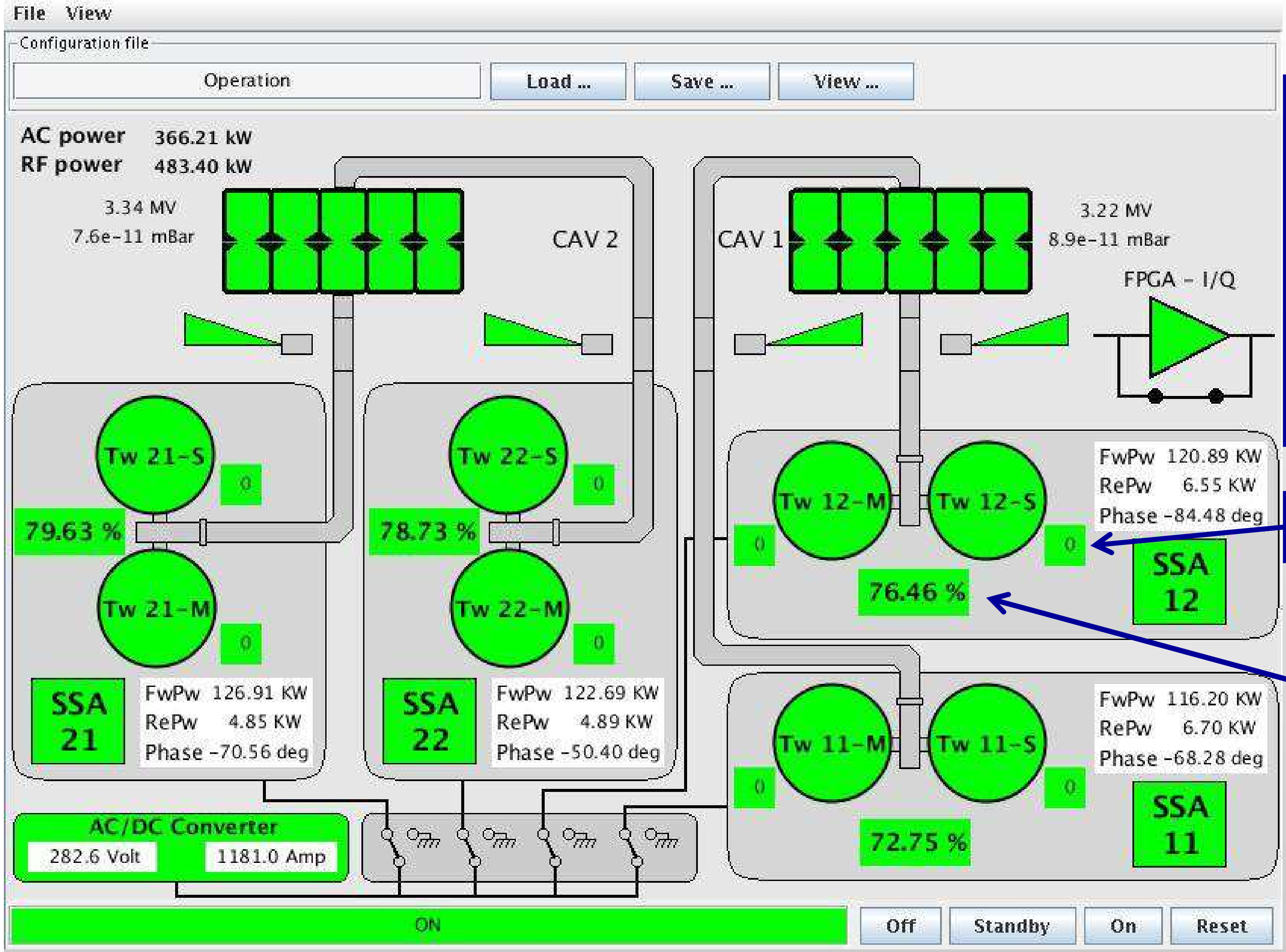
75 kW Coaxial combiner tree

with $\lambda/4$ transformers

150 kW - 352.2 MHz Solid State Amplifiers for the ESRF booster

Efficiency: > 55 % at nominal power

Main application of the booster transmitter



Average electrical power:
366 kW ac
334 kW dc

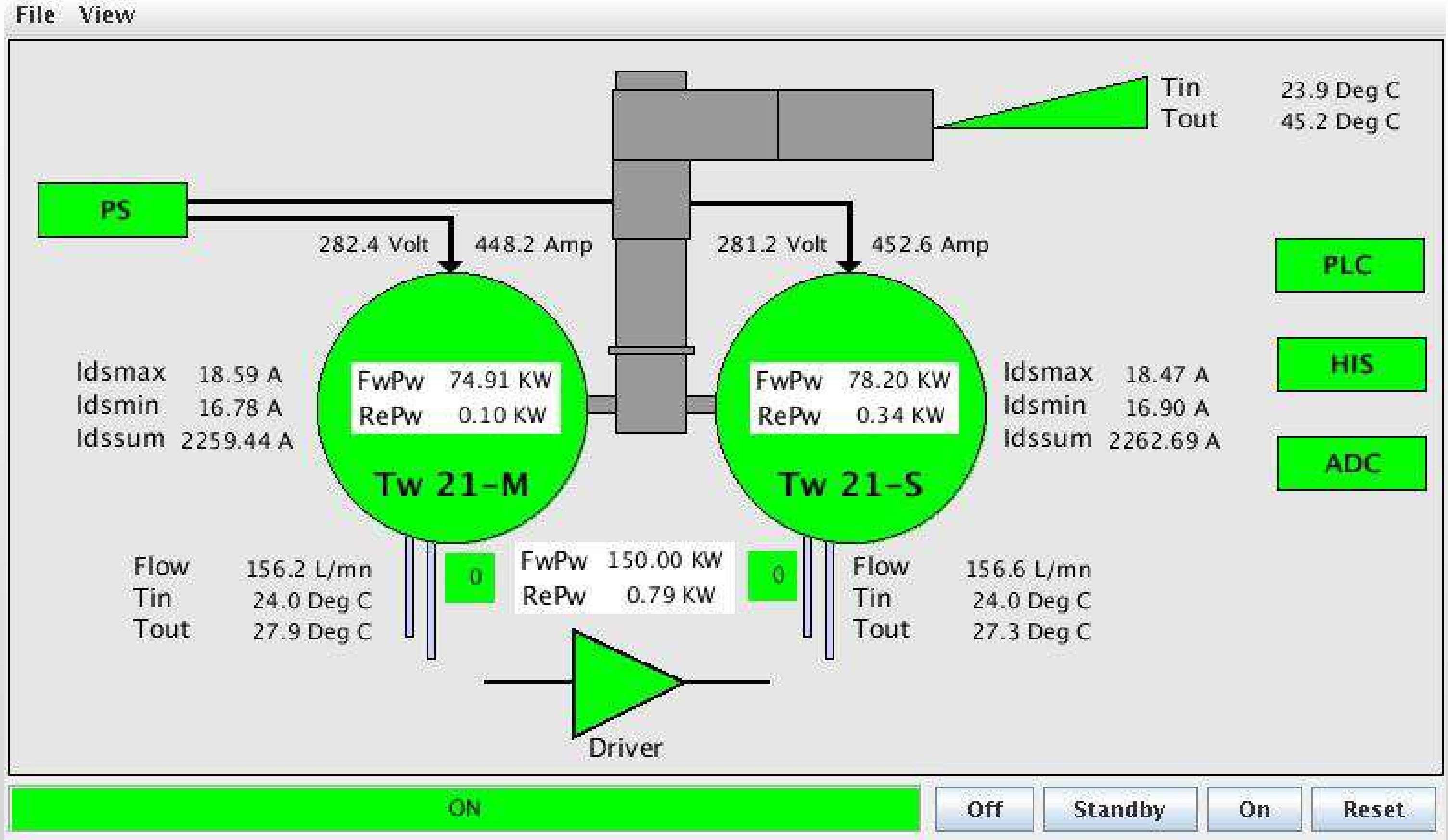
Peak RF power:
483 kW

$n_{missing}$ modules

Overload factor:

$$\frac{FwPw}{150kW}\frac{[256-12]}{[256-2\times n_{\text{missing}}]}$$

Application of SSA-21



Here in CW operation on dummy load at the last summer restart to check:

	SSA1-1	SSA1-2	SSA2-1	SSA2-1
$\eta_{RF/DC-280V}$ =	57.2 %	57.0 %	57.8 %	57.0 %

Example: monitoring transistor and load temperatures

Failures after first 500 hours of operation – from RF logbook

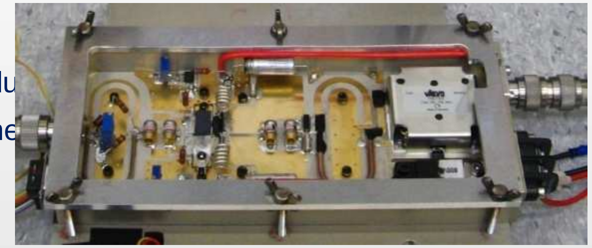
Date	Run hour	Machine Stop ?	SSA #	Position	Domain	Failure Description	Corrective Action
25-Mar-12	156	no	1-1	TM7	Cooling	Flowmeter remains interlocked despite the water flow is correct	Shaking the flow meter allows to reset
23-Apr-12	172	**yes**	1-1	TM7	Cooling	Flowmeter remains interlocked despite the water flow is correct	The flowmeter is swapped with the one of TM3 (wait and see)
23-Apr-12	172	no	1-2	TS5	Combiner 8	Power unbalance between both half PADA (Youth problem)	Replacement of combiner 8
26-Apr-12	173	no	2-1	TS2/12	DC/DC Converter	Fuse F1 (10A) blown without any apparent reason	Replacement of the fuse
26-Apr-12	173	**yes**	2-1	TM	Pre-driver	Impossible to reset pre-driver interlock (Youth problem)	Disconnect and reconnect J1 (PS)
22-May-12	180	no	1-1	TM7/10	MUXBOX	HPA detected OFF when the current was correct (Youth problem)	Bad connection of the I2C connector (DB9)
5-Jul-12	306	no	2-2	TS4/14	**HPA Transistor**	HPA failure detected by RF control application - Low current (HPA 11.0909)	Replacement of the HPA (report SYRF/2012-001)
17-Jul-12	330	no	1-1	TM3	Cooling	Flowmeter remains interlocked despite the water flow is correct	Strap (Report SYRF/2012-002)
30-Aug-12	374	no	2-2	TM6/14	**DC/DC Converter**	HPA failure detected by RF control application - Bias current always at 2.5A	Replacement of the DC/DC converter (Report SYRF/2012-003)
22-Sep-12	467	no	1-1	TM3	**MUXBOX**	Fuse 4A blown - Blows again when replacing it	Replacement of the MUXBOX
23-Sep-12	468	no	1-1	TS9	**MUXBOX**	Fuse 4A blown	Replacement of the fuse OK

Bad surprise at acceptance test of 1st SSA

- ESRF Specification:
  - a) 50 kW reflection all phases for 150 kW: OK
  - b) Up to 6 RF modules OFF without performance degradation: OK

But:

- a) and b) at the same time → Arcing at output of passive modules!
- Up to 1500 W to 1700 W measured on the circulator loads of passive modu
- Destruction of load circuit, arcing propagating along cable towards combine



Solutions for batch 1 on the booster:

- Booster in pulsed operation → no overheating OK

Solutions for batch 2 for the storage ring:

1. 150 kW power circulator at SSA output not retained by ELTA
2. Replace 800 W loads by 1200 W loads (also for booster spares) retained by ELTA
   (Power tests of Circulator and 1200 W loads are scheduled by ELTA very soon)
1. Optimum phase between 6kW and 50 kW Combiners retained by ELTA
   (proposed by P. Marchand's team at SOLEIL and simulated by ELTA with AWR & CST for electrical length optimization)
4. Additional interlock: $P_{reverse}$ < 3.5 kW at output of 1st x8-combiner retained by ELTA

⇒ Delivery of batch 2 delayed by 1 to 1.5 years

Mismatch of unpowered modules: over-load of individual circulator loads

$$\begin{bmatrix} b_1 \\ b_2 \\ b_3 \\ \dots \\ b_N \\ b_{N+1} \end{bmatrix} = \begin{bmatrix} (1-N)/N & 1/N & 1/N & \dots & 1/N & 1/\sqrt{N} \\ 1/N & (1-N)/N & 1/N & \dots & 1/N & 1/\sqrt{N} \\ 1/N & 1/N & (1-N)/N & \dots & 1/N & 1/\sqrt{N} \\ \dots & \dots & \dots & \dots & \dots & \dots \\ 1/N & 1/N & 1/N & \dots & (1-N)/N & 1/\sqrt{N} \\ 1/\sqrt{N} & 1/\sqrt{N} & 1/\sqrt{N} & \dots & 1/\sqrt{N} & 0 \end{bmatrix} \times \begin{bmatrix} a_1 \\ a_2 \\ a_3 \\ \dots \\ a_N \\ a_{N+1} \end{bmatrix}$$

input arms: $a_1 \dots a_N$, $b_1 \dots b_N$,
output arm: a_{N+1}, b_{N+1}

Simplified S-matrix of an ideal “ x N” combiner

☞ *λ/4 coaxial combiner: some phase factors and different S_{ij}, $i \neq j \in [1 \dots N]$*

☞ *however, similar conclusions as sketched here below*

Example 1: x8 combiner,
$|a_i|^2$ = 650 W, no losses

Input arms: strongly mismatched but,

$$\forall i, j \leq N, a_i = a_j \quad \Rightarrow \quad b_i = b_j = 0 \text{ and } b_{N+1} = \sqrt{N} \times a_i$$

b_i = 0: difference of large numbers
$|b_{N+1}|^2$ = 8 x 650 W = 5.2 kW

If one input arm i is unpowered:

$$a_i = 0 \quad \Rightarrow \quad b_i = \frac{N-1}{N} \times a_j \quad , \quad j \neq i$$

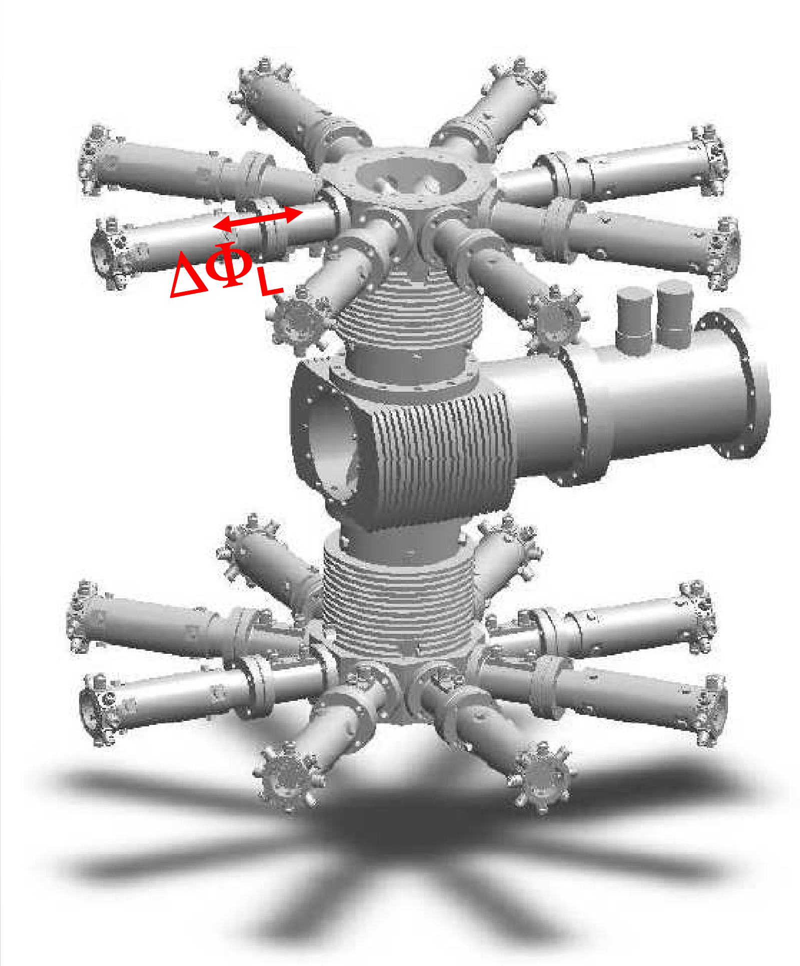
$|b_i|^2 = (7/8)^2$ x 650 W = 498 W
☞ *645 W for SSA = x256 combiner*

Under worst phase conditions, for any output reflection of, say, 1/3 in power, the unpowered input arm i will receive

$$|b_i| = \left\{ \frac{N-1}{N} + \frac{1}{\sqrt{3}} \right\} |a_i|$$

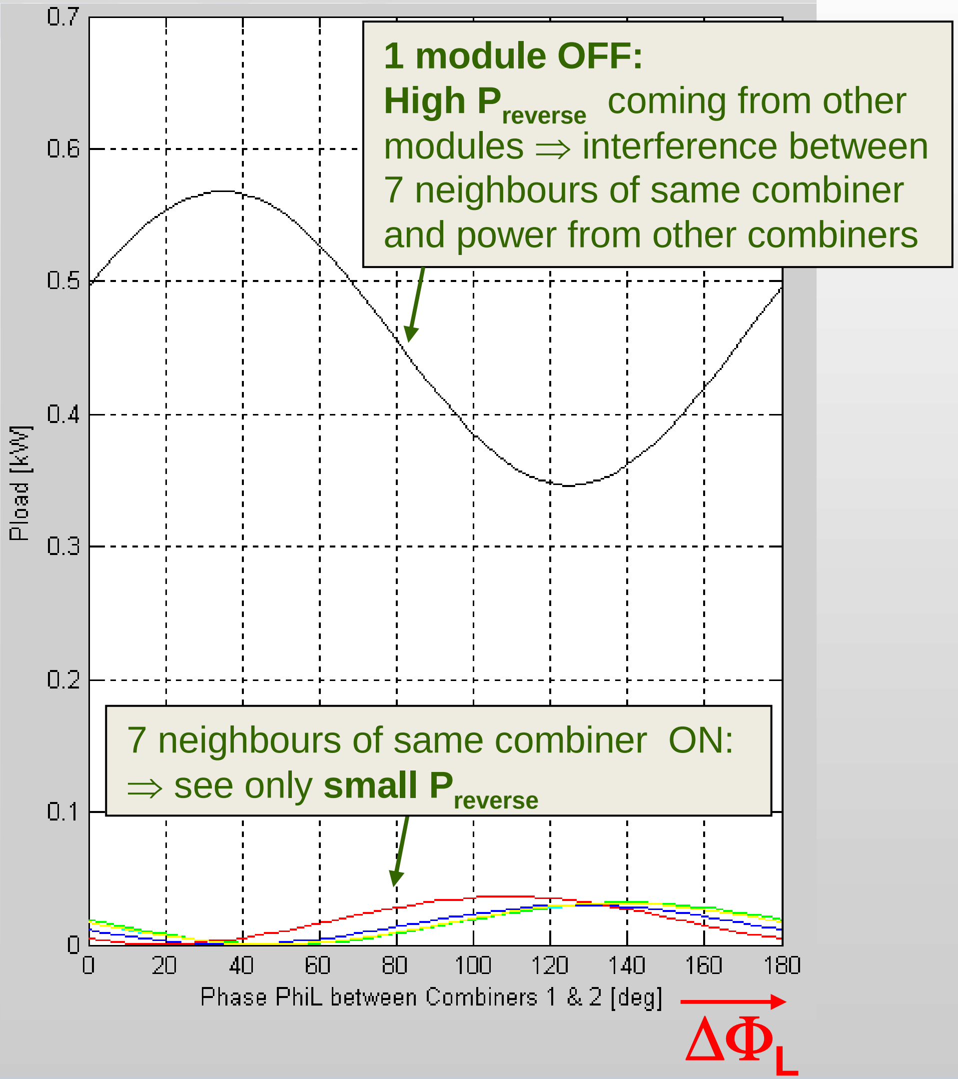
$|b_i|^2 = (1.45)^2$ x 650 W = 1371 W
☞ *1609 W for SSA = x256 combiner*

Adjustment of phase between 1st and 2nd 8x-Combiner stages



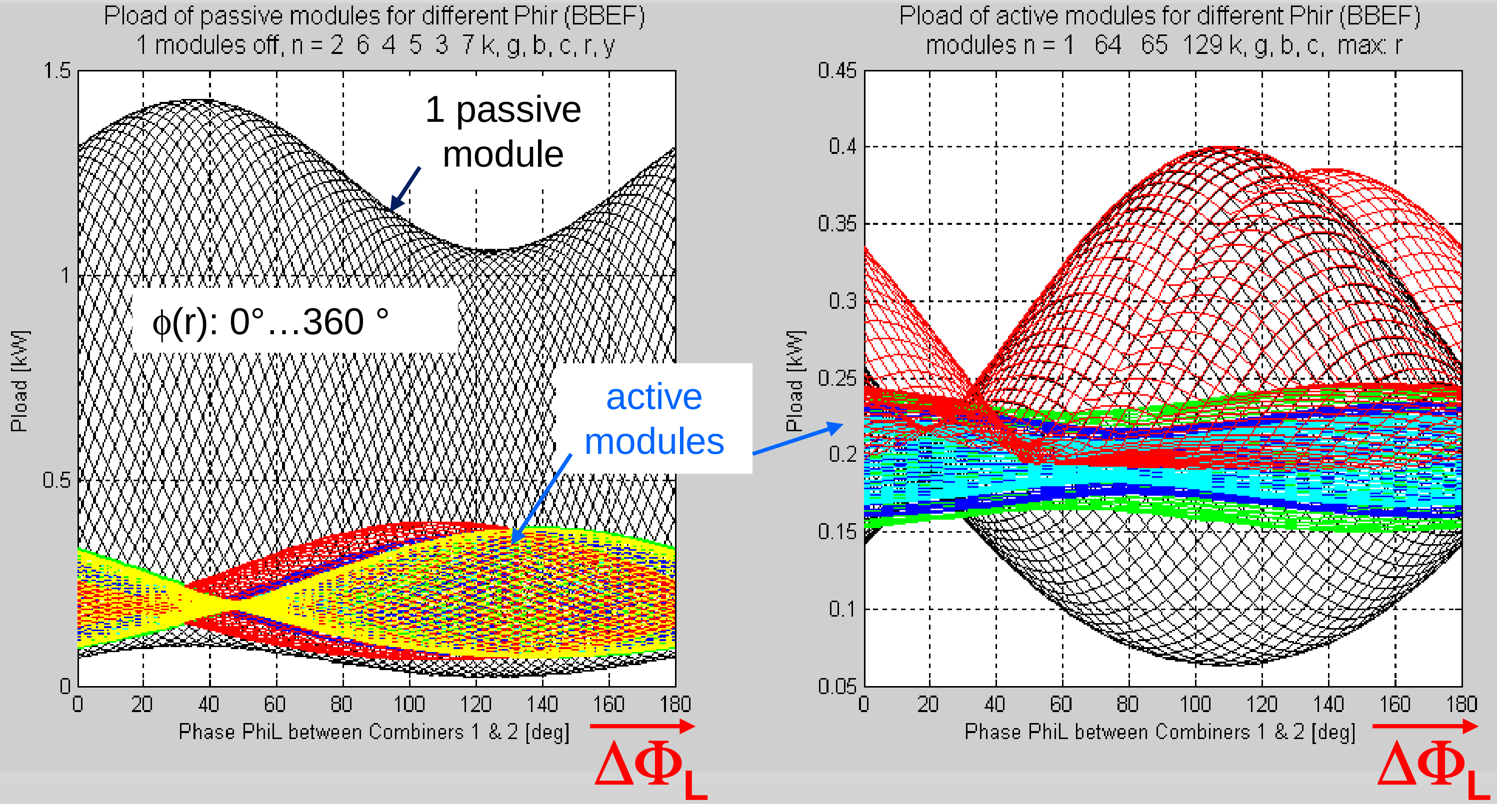
☞ Idea from P. Marchand's team

SSA matched: r = 0



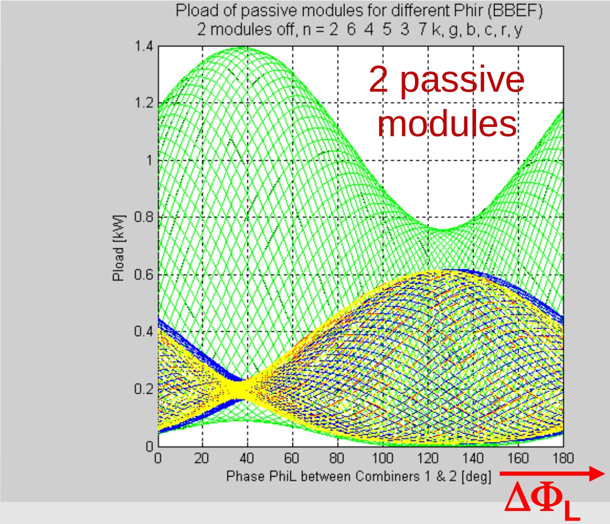
Adjustment of phase between 1st and 2nd 8x-Combiner stages

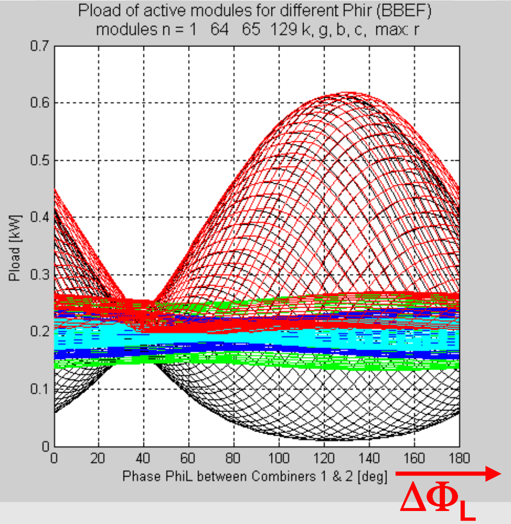
SSA mismatched: $|r| = 1/\sqrt{3}$ *(ESRF spec)*

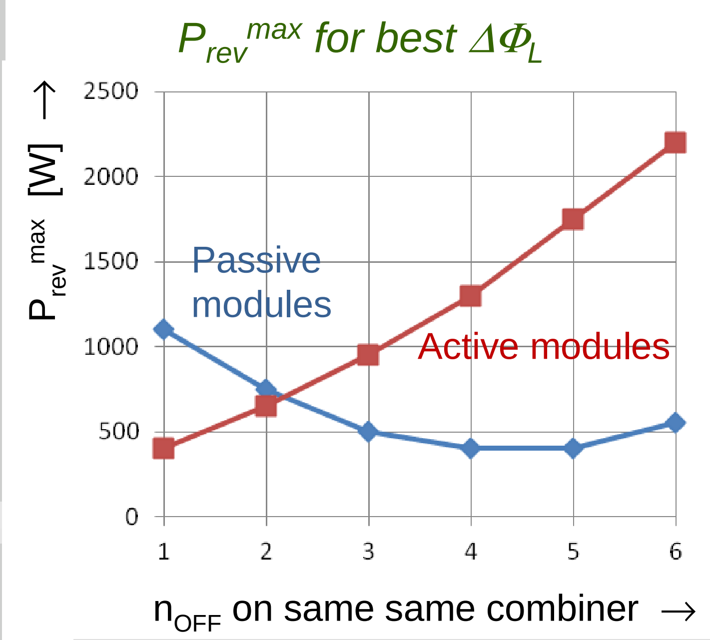


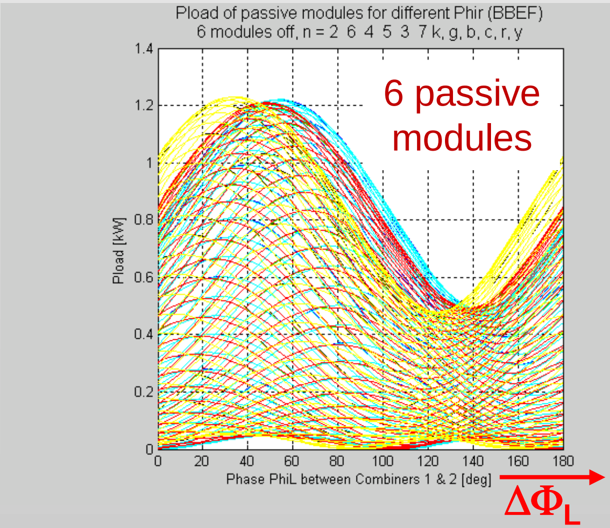
- 1 module OFF: depending on $\Delta\Phi_L$ the circulator load receives
  - P_{rev}^{max} = 1400 W for worst $\Delta\Phi_L$
  - P_{rev}^{max} = 1100 W for best $\Delta\Phi_L$
- Active modules receive the remaining power: maximum of 400 W for best $\Delta\Phi_L$

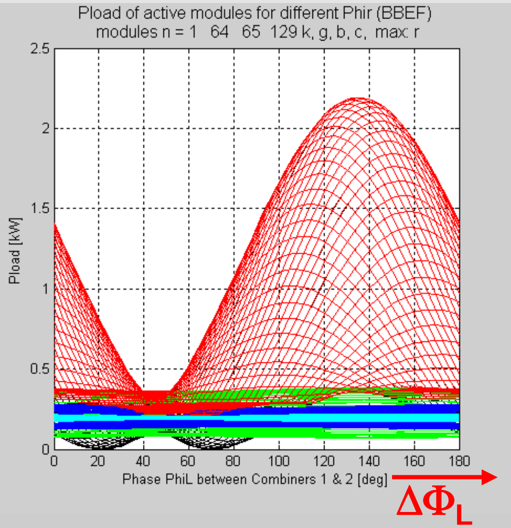
Adjustment of phase between 1st and 2nd 8x-Combiner stages









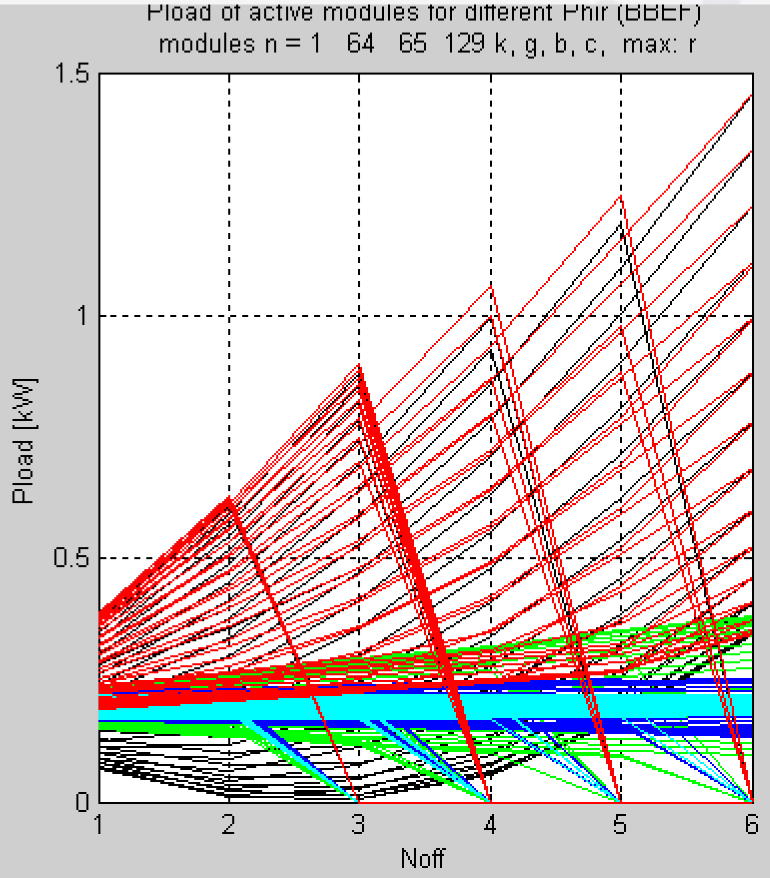


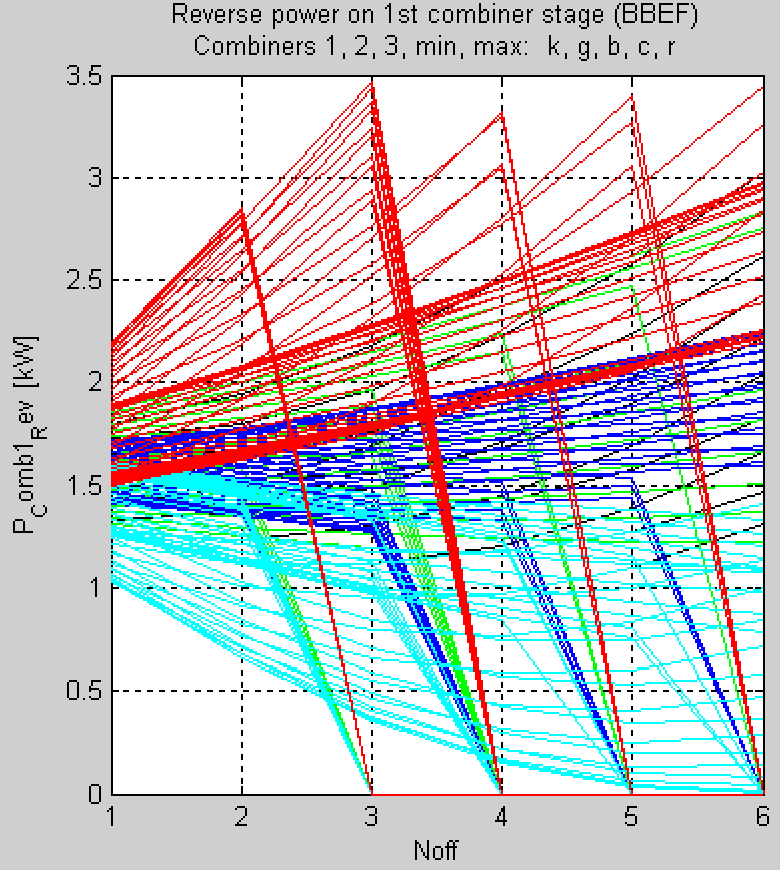
↑

☞ Not more than 3 modules OFF on the same combiner !

Interlock $P_{reverse}$ < 3.5 kW

- Protection against short circuits of Combiners
- Partial protection against operation at high reflection with many modules OFF



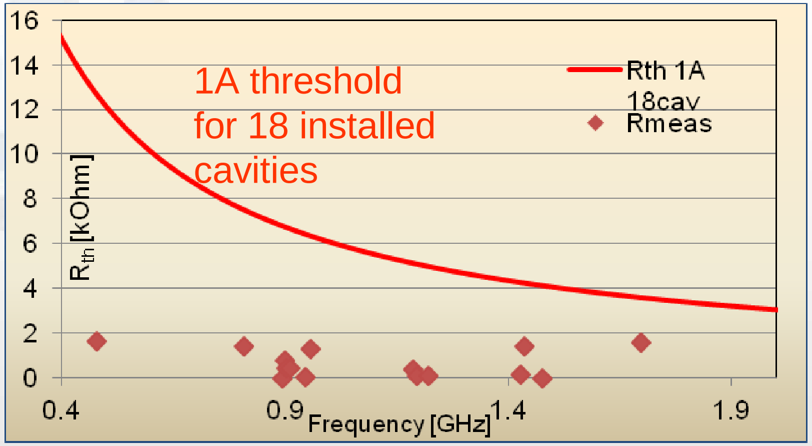


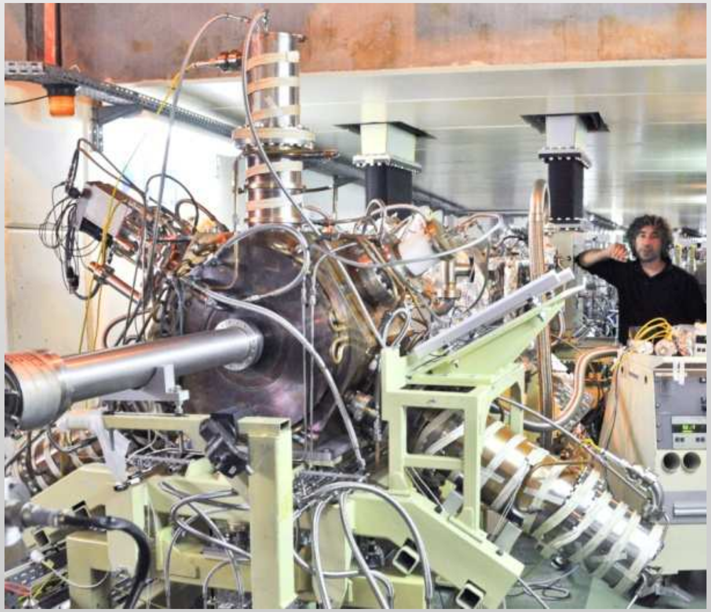
* This work, carried out within the framework of the ESRFUP project, has received research funding from the EU Seventh Framework Programme, FP7.

1st HOM damped cavity delivered by RI – Research Instruments

- ✓ Excellent fundamental mode impedance:

  R_s = 4.9 MΩ,
  Q_0 = 33800 (expected 30000 to 35000)
- ✓ HOM spectrum a factor two lower than design goal





October 2011: Installation on Storage Ring cell 25

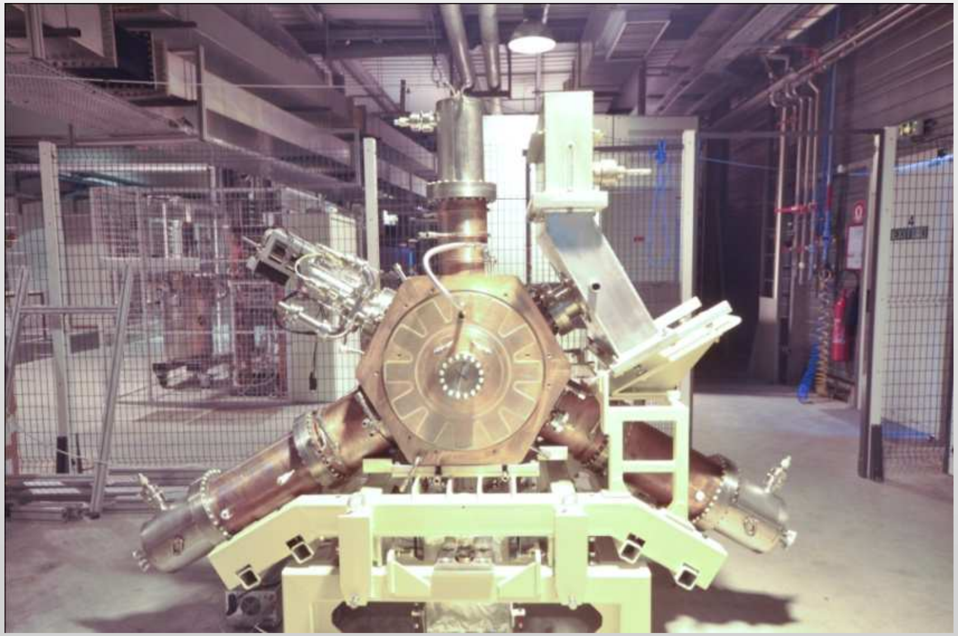
- Passive operation with **excellent vacuum behaviour** at
  - ✓ 200 mA in mutlibunch fillings (a few hours after machine restart)
  - ✓ 95 mA in 16 bunch filling (most demanding for HOM dampers)
- Active operation - **beam acceleration very satisfactory**
  - ✓ V_{acc} = 0.5 MV (conditioned to 0.6 MV)
  - ✓ I_{beam} = 200 mA in uniform fill pattern during MDT, with almost 150 kW of incident power (100 kW transferred to the beam)
  - ✓ I_{beam} = 4*10 mA during one week of USM without trip (however a few pressure bursts)
  - ✓ I_{beam} = 85 mA in 16 bunch after a few hours of conditioning

* This work, carried out within the framework of the ESRFUP project, has received research funding from the EU Seventh Framework Programme, FP7.

2nd cavity delivered by SDMS

May 2012: Installation on RF teststand

- ✓ V_{acc} = 0.5 MV after long (5 weeks) conditioning
- ✓ September: Straightforward conditioning from 0.5 to 0.75 MV
- ✓ 4 hours Run test at V_{acc} = 0.75 MV:
  - ➢ thermal degassing =f(power), 4.10^{-8} mbar at 0.75 MV
  - ➢ over heating of Ti-coated field probe housing
  - ➢ Also over coupling of RF field probe
  - ⇒ field probe & housing will be “shortened” in the coming days
- ✓ Installation in cell 25 in coming winter shutdown

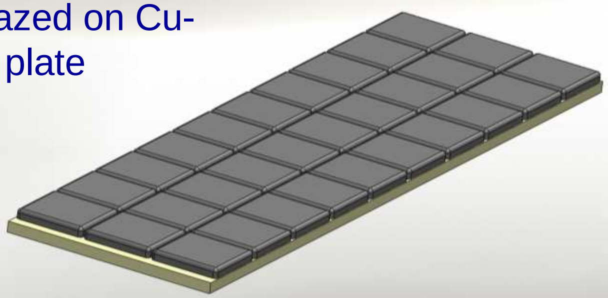


3rd cavity delivered by CINEL

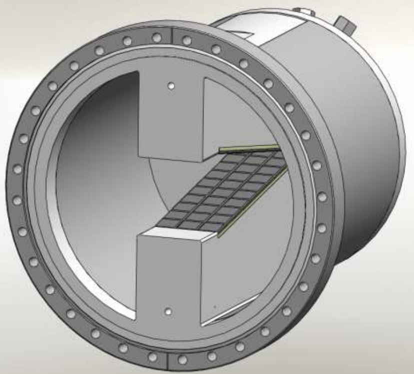
Delivered in June 2012

- ✓ Two HOM absorbers missing,
  - ☞ problem with brazing of Ferrite / Cu-W plate on stainless steel tapers
  - ☞ brazing should be re-done in the coming weeks and delivery expected mid November
- ✓ Vacuum test (SAT) OK for cavity, two intermediate sections & one HOM absorber
- ✓ Starting RF conditioning before the end of the year
- ✓ Test with beam directly on cell 23 (we skip cell 25 test)

☞



C48 ferrite tiles brazed on Cu-W plate



Ferrite/Cu plate brazed on tapered stainless steel absorber

3 cavities in cell 23

Summer 2013: Installation of all 3 cavities on cell 23 = first straight lengthened to 7 m

Preparation in progress:

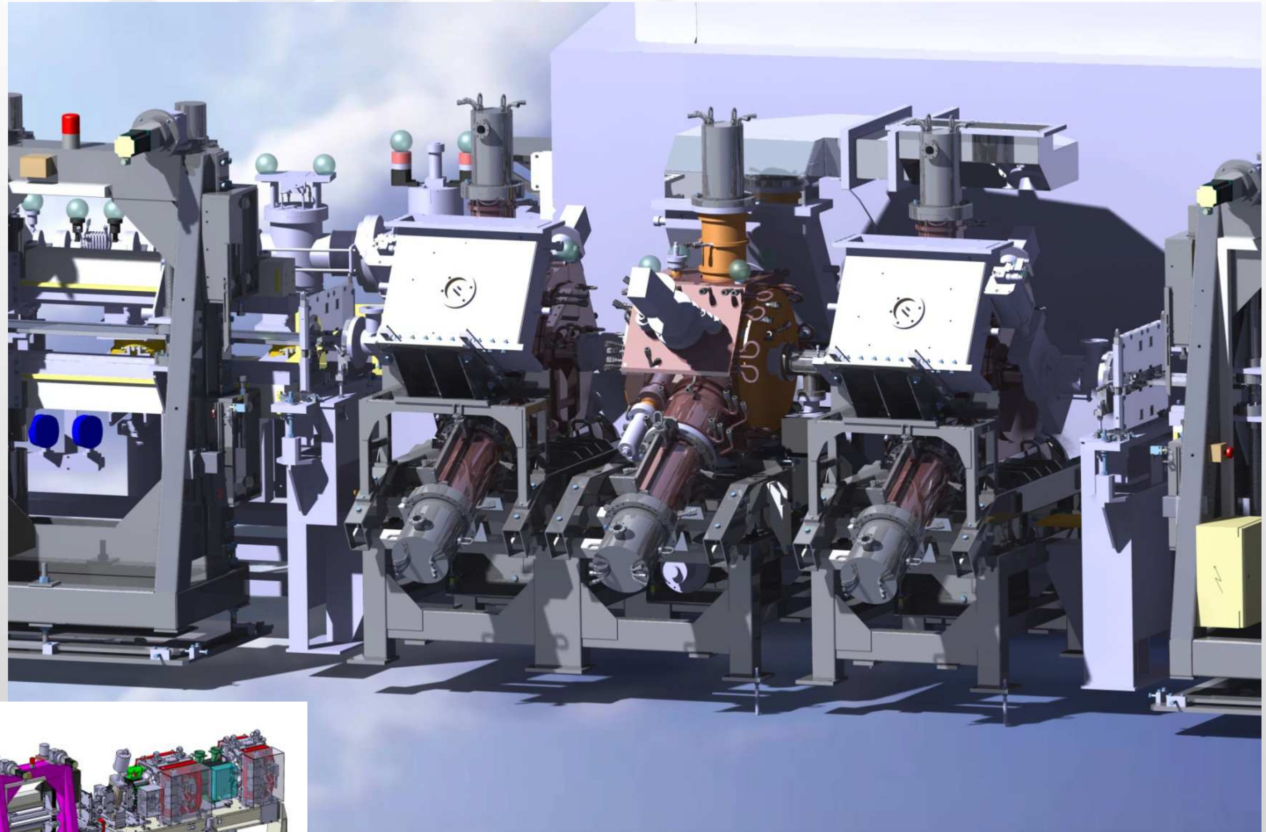
✓New magnets

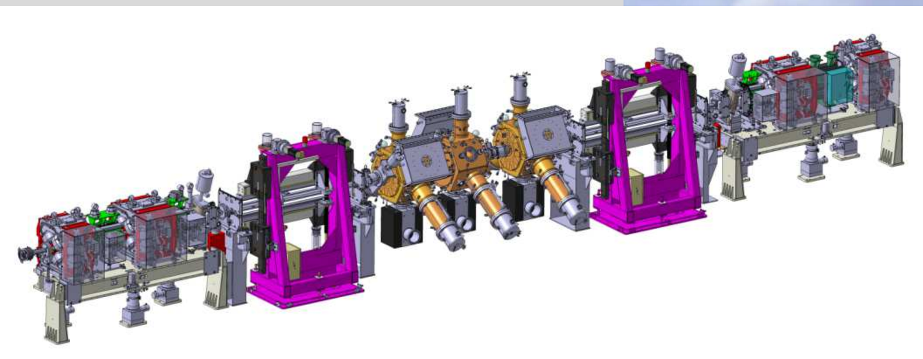
✓Dedicated PS's

✓New roof beams for RF waveguides in place

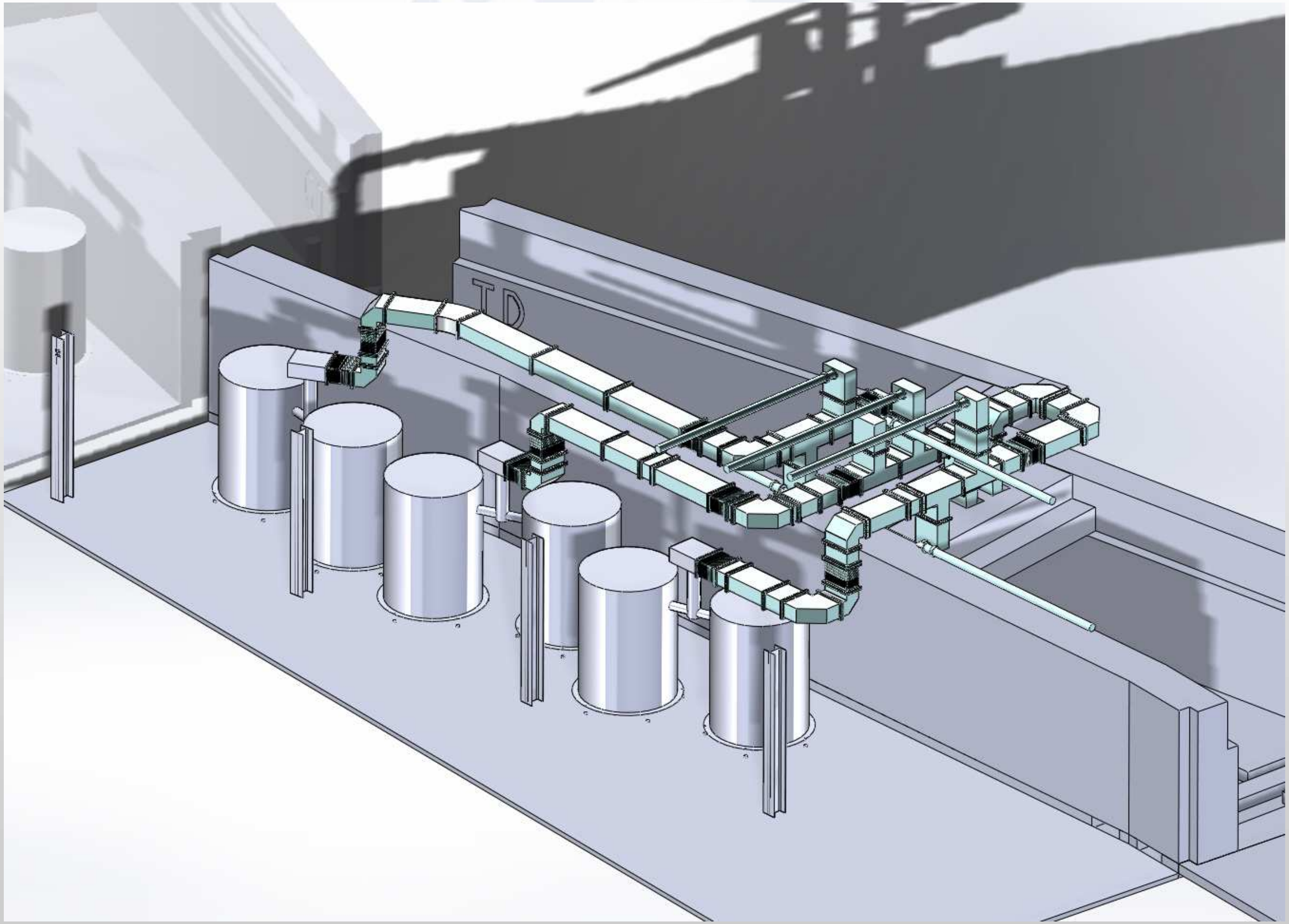
✓Physical Extension to 7m in Dec. 2012

✓Commissioning of new optics at Jan.' 2013 restart

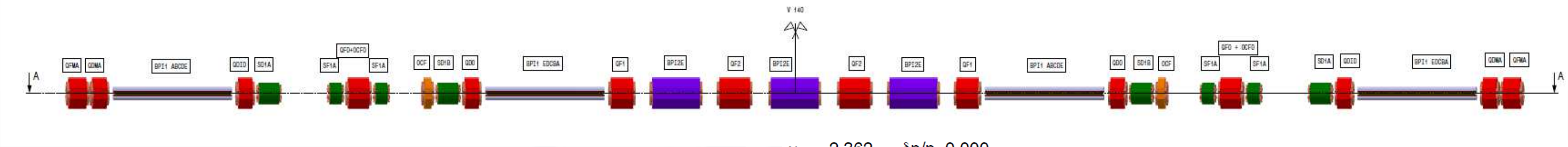




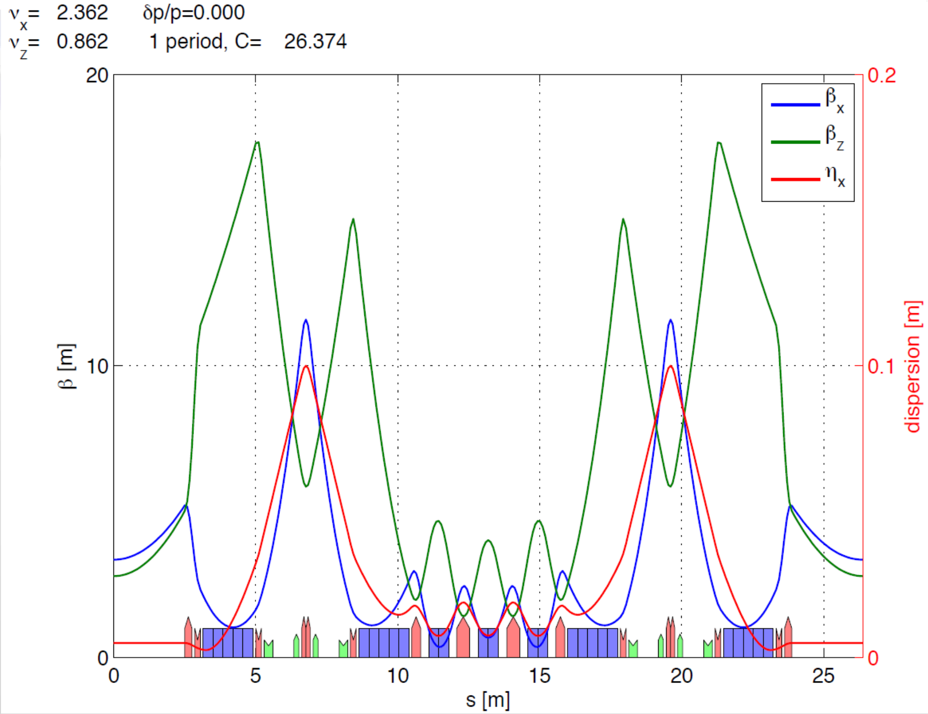
3 SSAs of batch 2 feeding new cavities on cell 23



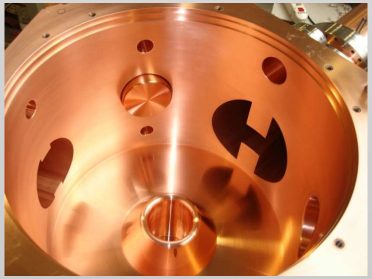
Outlook: new low emittance lattice for the ESRF



- Low horizontal emittance
  ε_x : today 4 nm → ≈ 150 pm
  - Keep Electron E = 6 GeV, nominal beam current I_{beam} = 200 mA
  - Project under study for phase 2 of ESRF upgrade (commissioning ≈ 2019)
  - 7 bend achromate
  - Dipoles: 4 with longitudinal field gradients, 3 horizontally shifted quadrupoles, overall reduced field
  - Keep existing SR tunnel and injector
  - Maintain existing 32 straight sections, as much as possible at same position



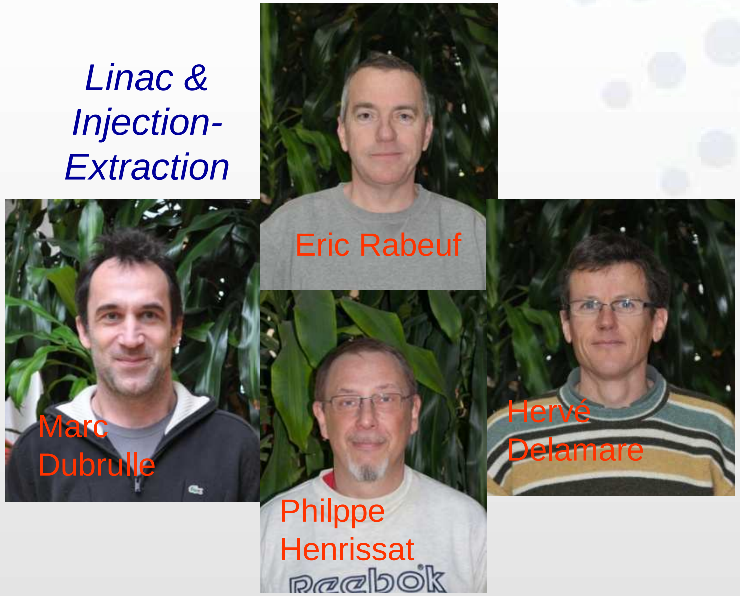
- Increased sensitivity to HOMs
  - ⇒ **HOM damped cavities mandatory !**



Preliminary RF parameters		Existing ESRF	New ESRF lattice
Horiz. emittance	ε_x	4 nm	≈ 150 pm
Energy loss (incl. 0.5 MeV for ID's)	U	5.41 MeV/turn	3.56 MeV/turn
Longitudinal damping time	τ_s	3.4 ms	7.9 ms
Momentum compaction factor	α	1.78 10^{-4}	8.66 10^{-5}
Energy spread	σ_E/E	1.06 10^{-3}	1.10 10^{-3}
Nominal RF voltage	V_{acc}	9 MV	6 MV
⇒ RF Energy acceptance	$\Delta E/E$	3.9 %	4.4 %
LCBI threshold for given HOM impedance	ratio	**2 : 1**	
Number of mono cell HOM damped cavities	N_{cav}	18 / 15 *	12 / 10 *
Cavity Coupling	β	3.5	3
Copper loss per cavity	P_{copper} / N_{cav}	26 kW for 0.5 MV – 38 kW for 0.6 MV	
RF power per cavity at I_{nom} = 200 mA	$P_{tot\text{-}200mA} / N_{cav}$	82 kW / 105 kW *	86 kW / 109 kW *
RF power per cavity at 300 mA	$P_{tot\text{-}300mA} / N_{cav}$	109 / 138 kW *	119 kW / 147 kW *

** degraded operation with reduced number of cavities*

Linac & Injection-Extraction



Thank you for your attention !

ESRF Linac / Injection-Extraction / RF Group

RF Oper., Systems & Support

Cavities

LLRF, Dig. Electron. & Timing

Transmitters & SSA