9th CWRF

ESRF/ Grenoble, 20th – 24th June 2016

RF System Upgrade for the New Extremely Brilliant Light Source at the ESRF, Operation Experience with Klystrons and Solid State Amplifiers

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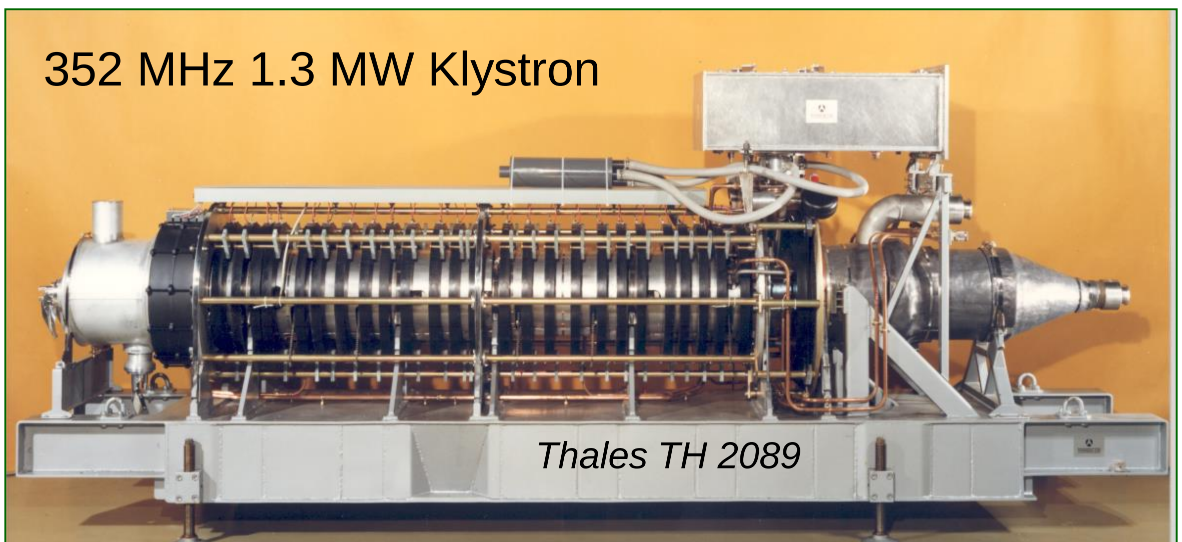
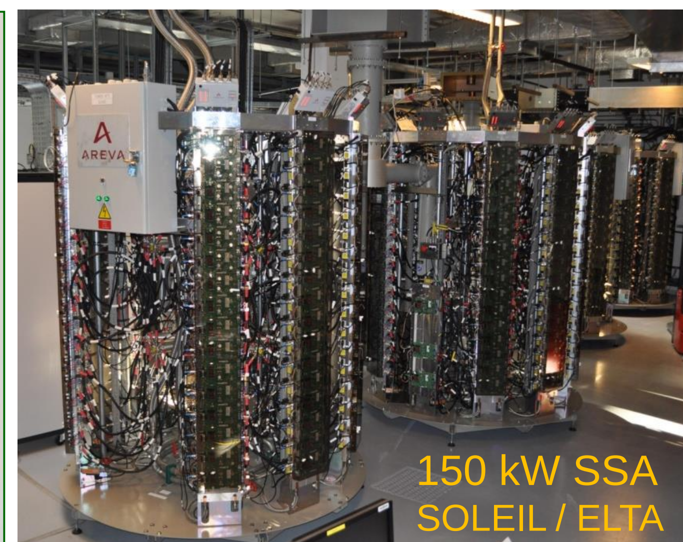
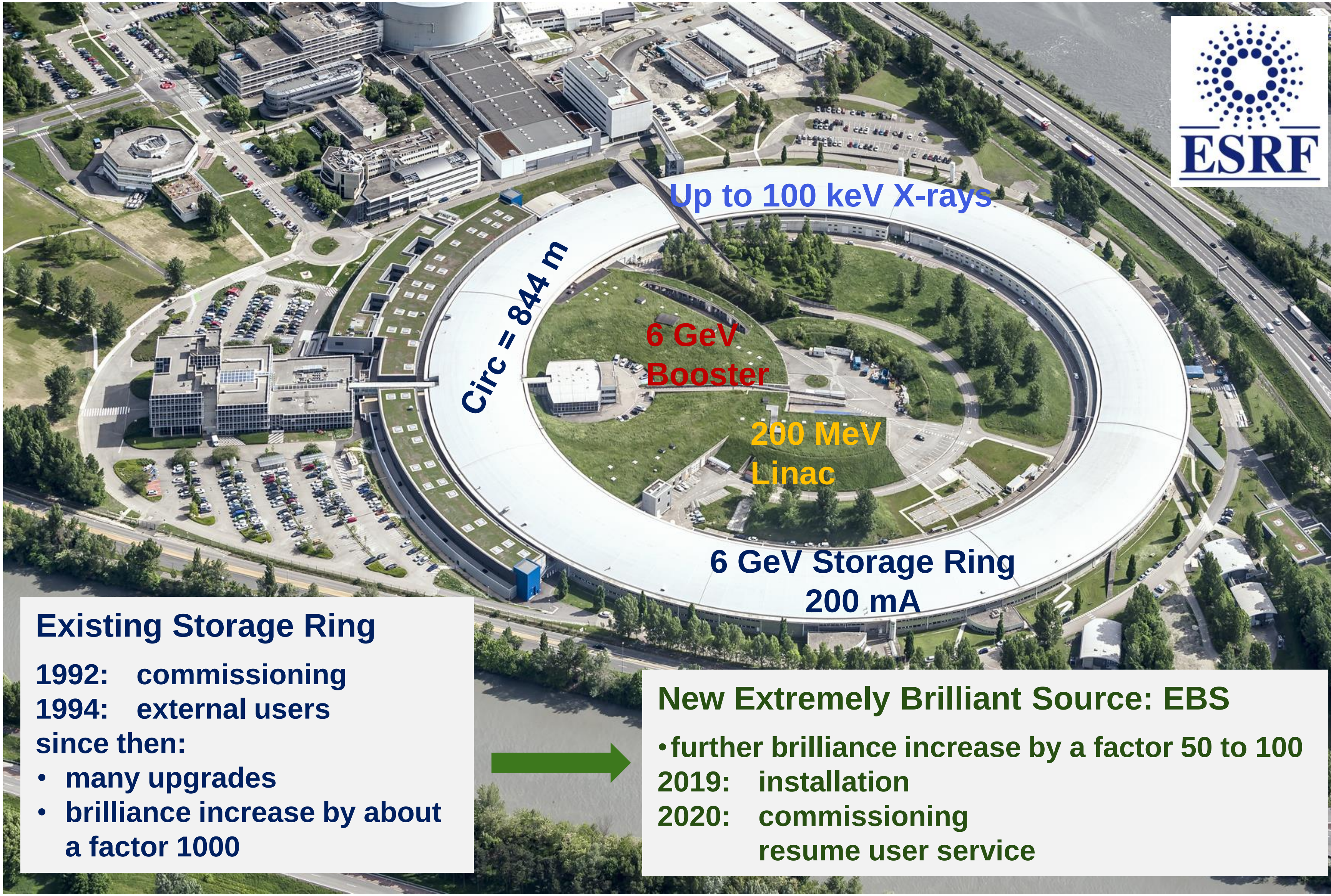
M. Langlois, G. Gautier, A. D'Elia

ESRF | The European Synchrotron







Existing Storage Ring

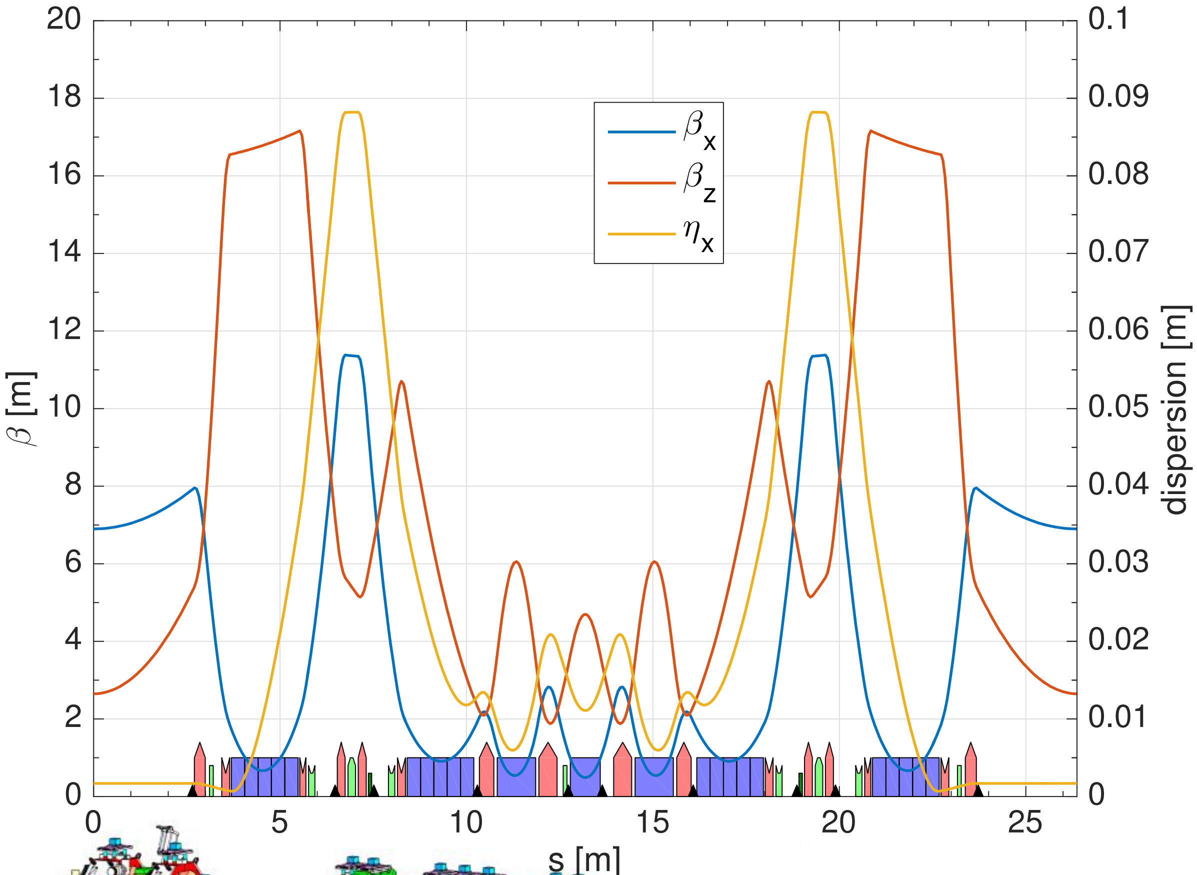
1992: commissioning
1994: external users
since then:

- many upgrades
- brilliance increase by about a factor 1000

New Extremely Brilliant Source: EBS

- further brilliance increase by a factor 50 to 100

2019: installation
2020: commissioning
resume user service



Main features:

- 2 regions with large dispersion for efficient chromaticity correction
- Rough sextupole compensation by having a ≈π phase advance between the 2 sections

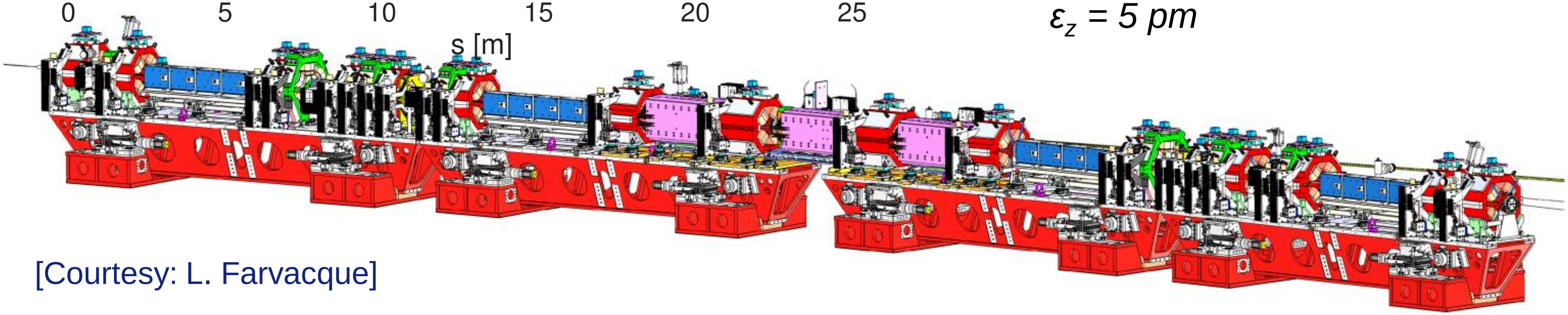
Performance:

- Natural equilibrium emittance:

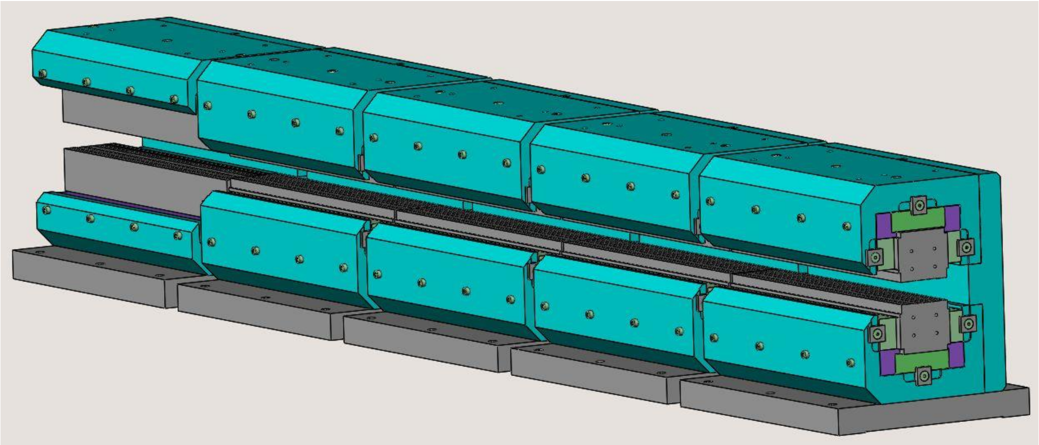
  ε_{x0} = *134 pm*
- Emittances with 5 pm coupled into the vertical plane and 0.5 MV radiation losses from ID's:

  ε_x = *107 pm*

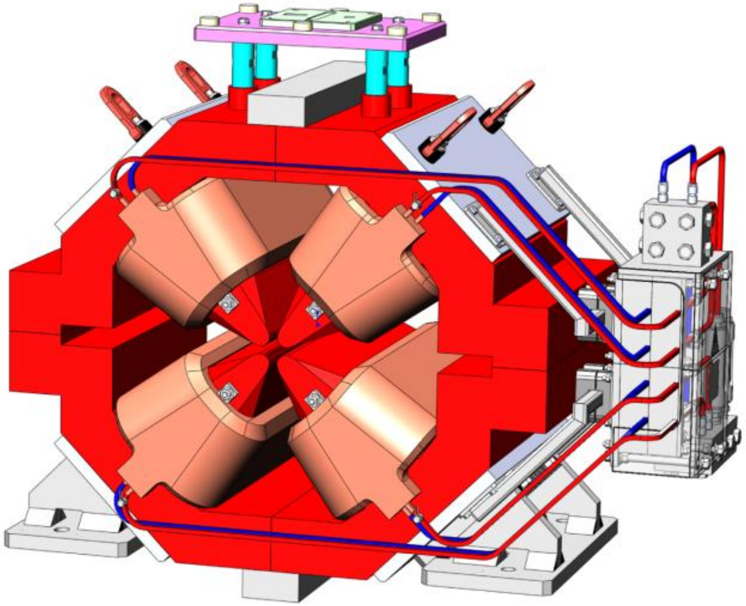
  ε_z = *5 pm*



[Courtesy: L. Farvacque]



DL
0.17 ➠ 0.67 T
permanent magnets,
5 modules

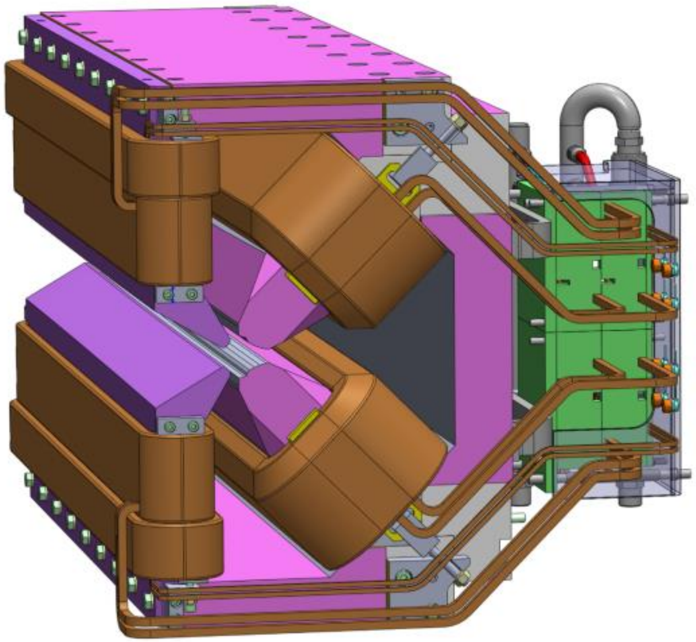


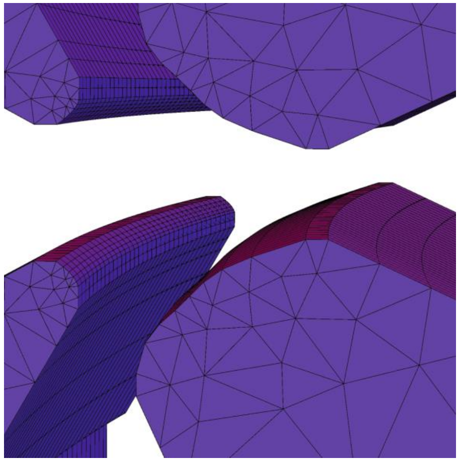
Quadrupole
91 T/m, ⌀25.4 mm

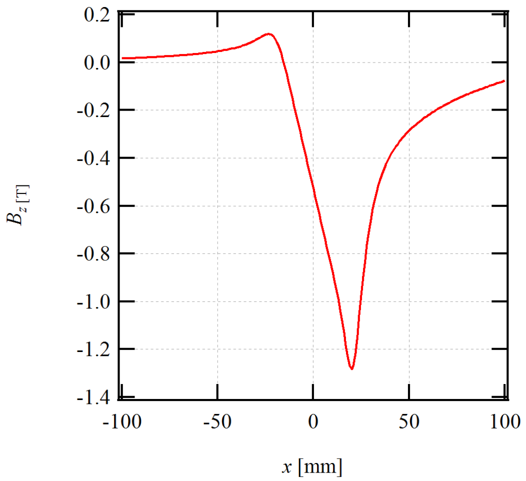
[Courtesy: Gael Le Bec]

ESRF-EBS MAGNETS

DQ
0.55 T, 37 T/m







[Courtesy: Gael Le Bec]

MAIN MACHINE PARAMETERS

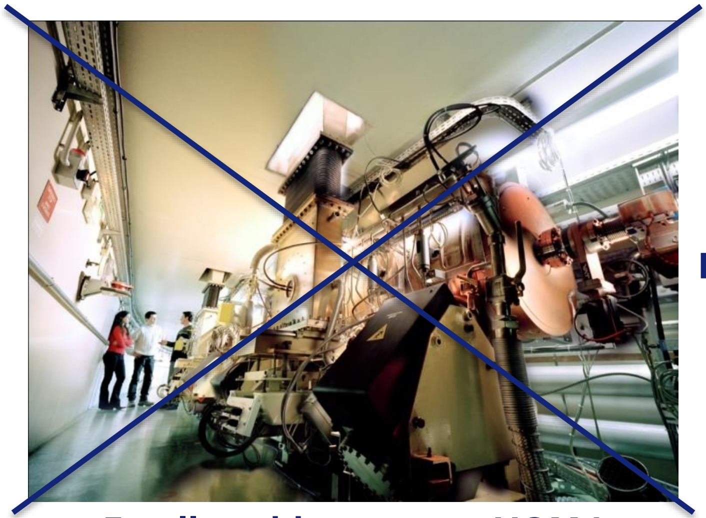
		Existing ESRF	ESRF-EBS
Same energy, current and filling patterns	E, Ibeam	6 GeV, 200 mA	6 GeV, 200 mA
Emittance	ε_x / ε_z	4000 pm / 5 pm	≈ 110 pm / 5 pm
Energy loss (incl. 0.5 MeV for ID's)	U	5.4 MeV/turn	3.1 MeV/turn
Same ID position ⇒ Δf_{rf} = + 170 kHz	f_{rf}	352.20 MHz	352.37 MHz
Longitudinal damping time	τ_s	3.5 ms	8.6 ms
Momentum compaction factor	α	$17.8\ 10^{-5}$	$8.4\ 10^{-5}$
Energy spread	σ_E/E	$1.06\ 10^{-3}$	$0.948\ 10^{-3}$
Nominal RF voltage	V_{acc}	8 MV (max 12 MV)	6 MV (max 6.6 MV)
⇒ 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) *[for a given HOM]*	ratio	1.9 to 1 ⇒ HOM damped cavities MANDATORY EBS	
Number of cavities	N_{cav}	5 (five-cell cav's ⇒ 25 cells)	13 to 14 (mono-cells, HOM free)
Cavity Coupling	β	4.4	3
Total RF power at 200 mA	$P_{tot-200mA}$	≈ 1400 kW	≈ 1000 kW

RF DESIGN ELEMENTS FOR ESRF-EBS

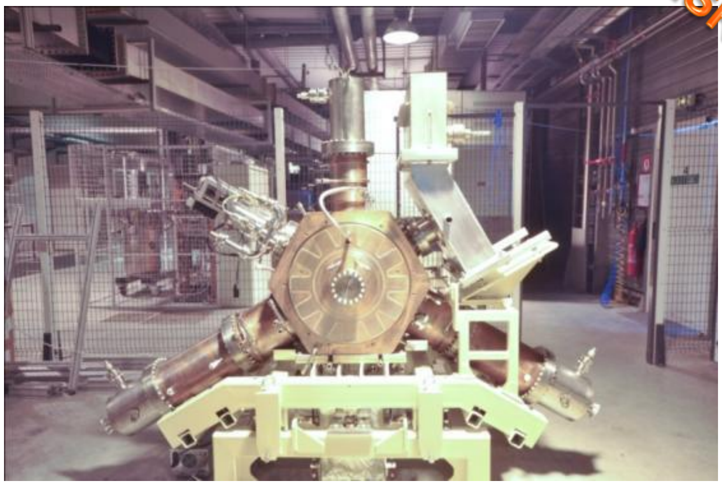
Total energy loss including ID radiation:	**3.1 MeV/turn**
Maximum RF Voltage:	**6.6 MV**
RF transmission losses:	**15 %**
☞ including RF losses, spurious mismatches	
Stored current with operational margin:	**220 mA**
RF frequency:	**352.371 MHz**

15 HOM damped cavities: **3 prototypes validated for 0.6 MV / 150 kW**

12 cavities in fabrication



5-cell cavities: strong HOM !



ESRF visit

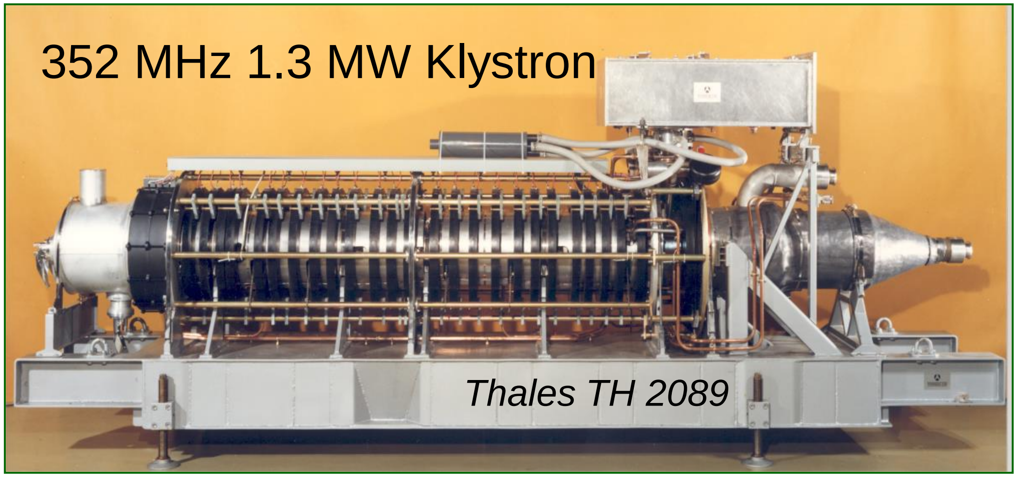
HOM damped mono-cell cavities developed at ESRF, based on BESSY/ALBA design

RE-USE OF EXISTING RF POWER SOURCES FOR ESRF-EBS

3 x 150 kW SSAs feeding prototype cavities in existing storage ring: re-used for EBS

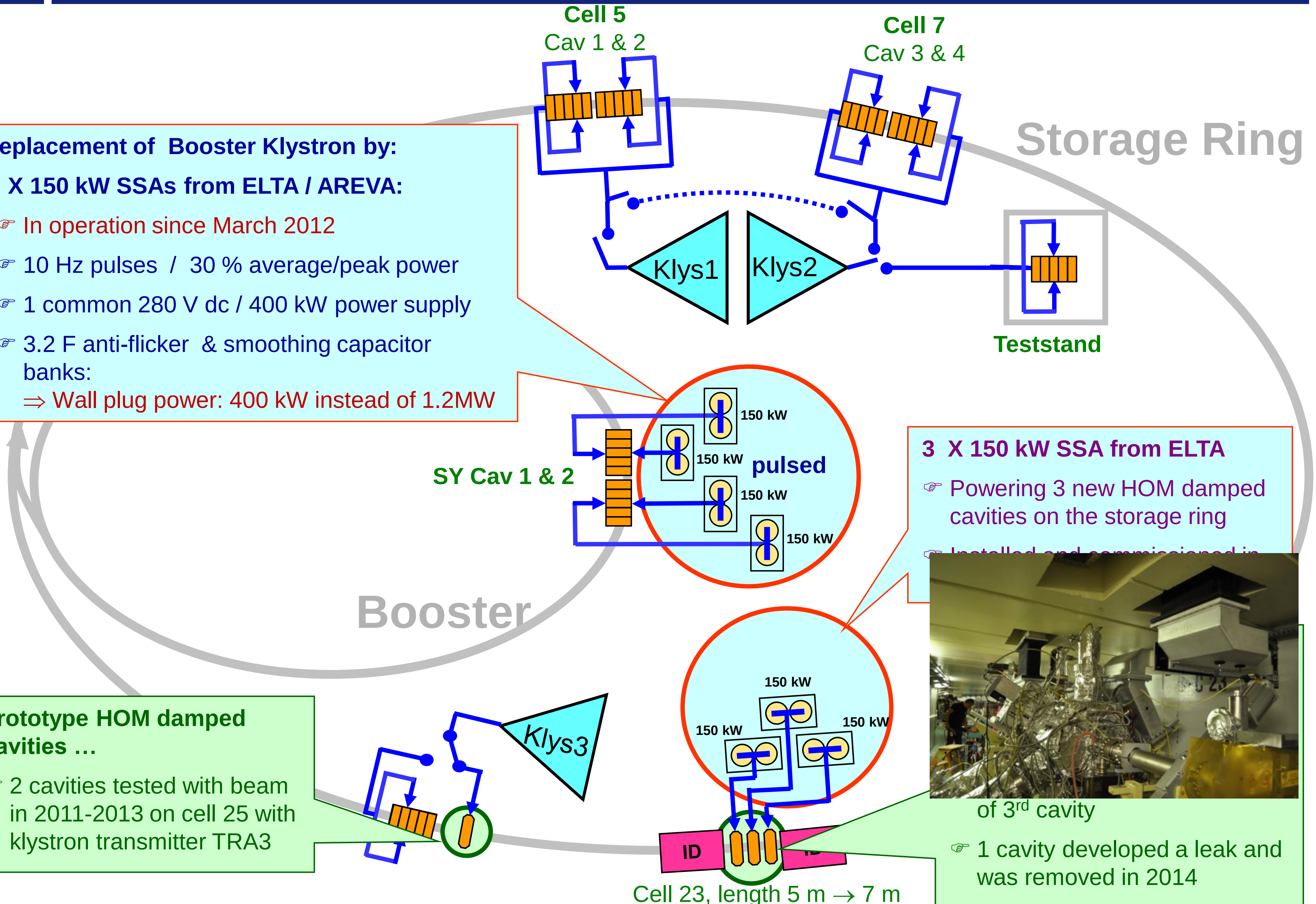
ESRF visit

85 kW SSA with cavity combiner, developed at ESRF [M. Langlois' talk]



2 of 3 existing klystron transmitters: re-used for EBS

REMINDER: 2009-2013 RF UPGRADE



Replacement of Booster Klystron by:

4 X 150 kW SSAs from ELTA / AREVA:

- In operation since March 2012
- 10 Hz pulses / 30 % average/peak power
- 1 common 280 V dc / 400 kW power supply
- 3.2 F anti-flicker & smoothing capacitor banks:
  ⇒ Wall plug power: 400 kW instead of 1.2MW

3 X 150 kW SSA from ELTA

- Powering 3 new HOM damped cavities on the storage ring

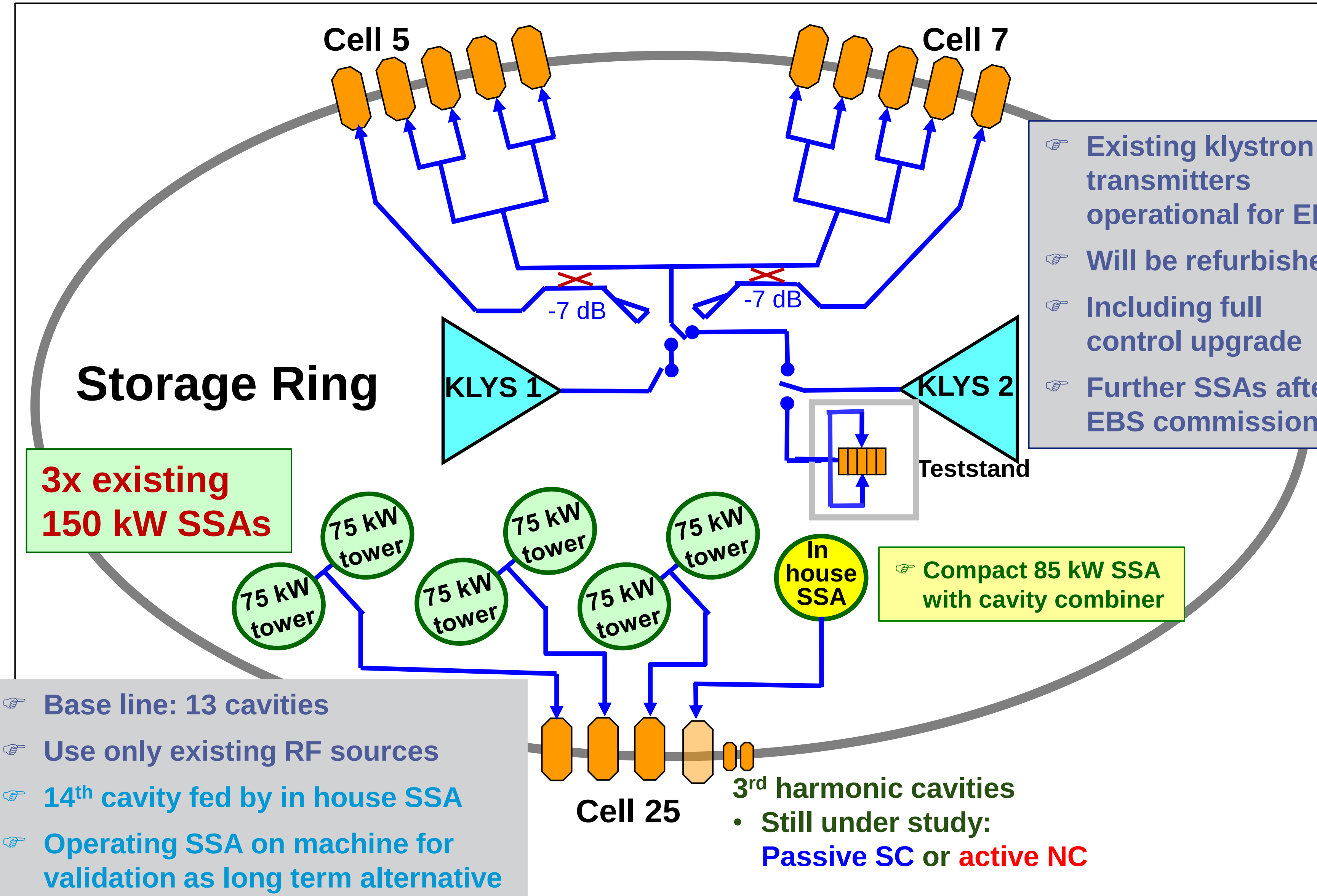
of 3rd cavity

- 1 cavity developed a leak and was removed in 2014

prototype HOM damped cavities …

- 2 cavities tested with beam in 2011-2013 on cell 25 with klystron transmitter TRA3

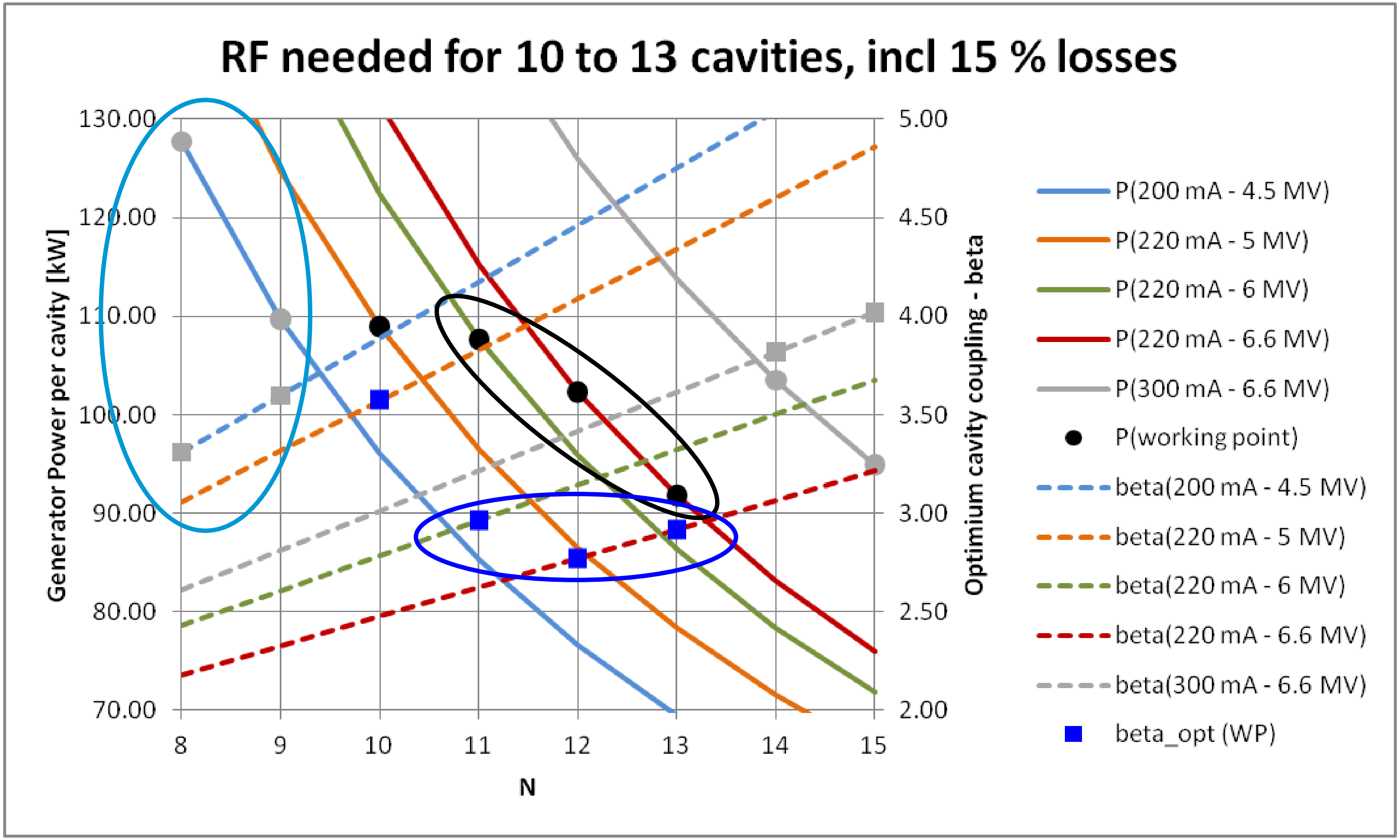
UPGRADE FOR ESRF-EBS IN 2019



- Existing klystron transmitters operational for EBS
- Will be refurbished
- Including full control upgrade
- Further SSAs after EBS commissioning

- Base line: 13 cavities
- Use only existing RF sources
- 14th cavity fed by in house SSA
- Operating SSA on machine for validation as long term alternative to klystrons

RF POWER REQUIREMENTS



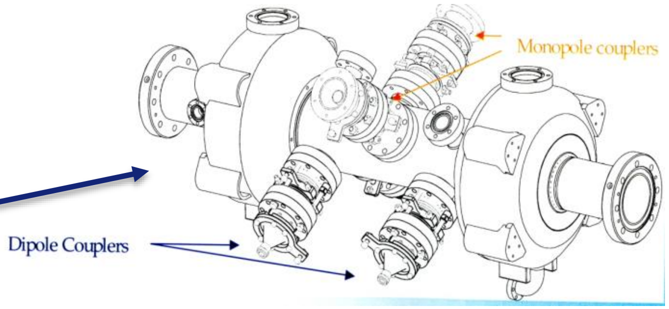
- **Even with 5 cavities in fault (1 complete cell) ☞ operation at 4.5 MV / 200 mA still possible**
- **Also room left for performance upgrade**

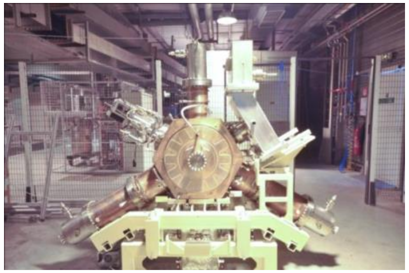
LIFETIME IN THE NEW MACHINE

New lattice: same operation modes as existing machine:

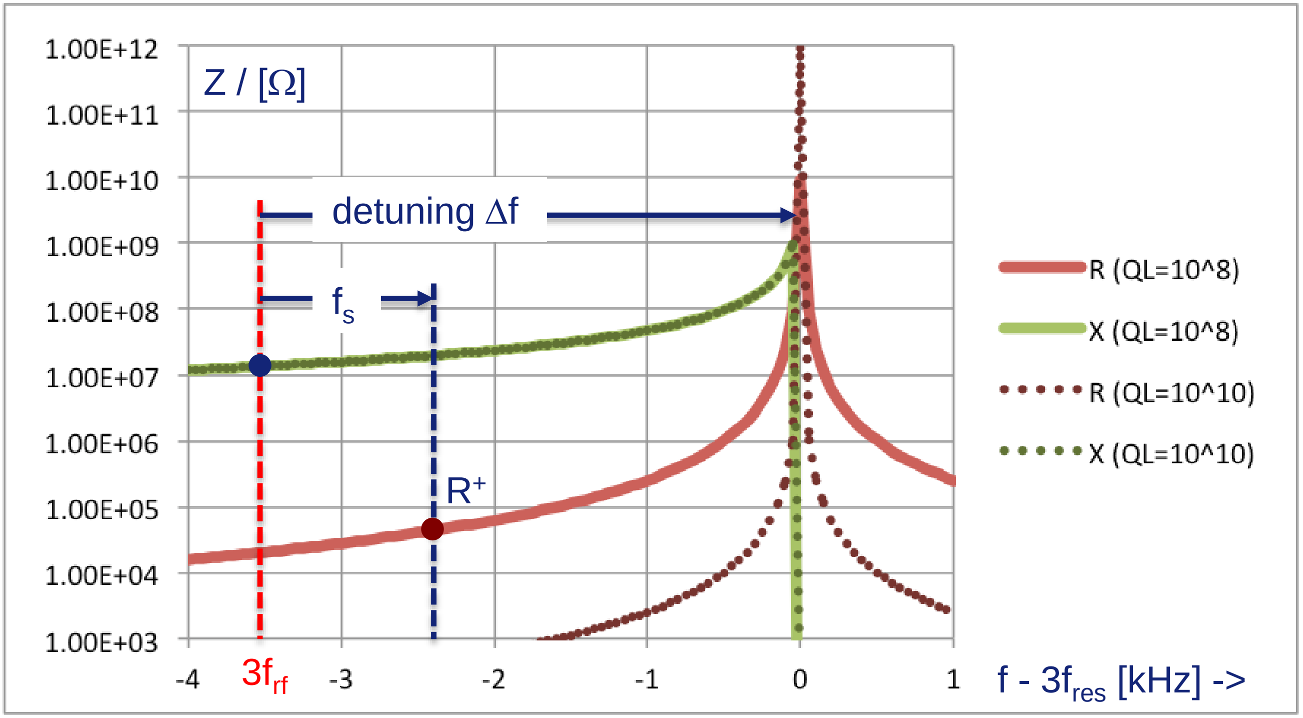
	Multibunch	16-bunches	4-bunches
Total current	200 mA	90 mA	4 x 10 mA
Nb. Bunches	868	16	4
Bunch length	23 ps	64 ps	77 ps
Lifetime for ε_{vert} = 5 pm	19 h	1.8 h	1.2 h

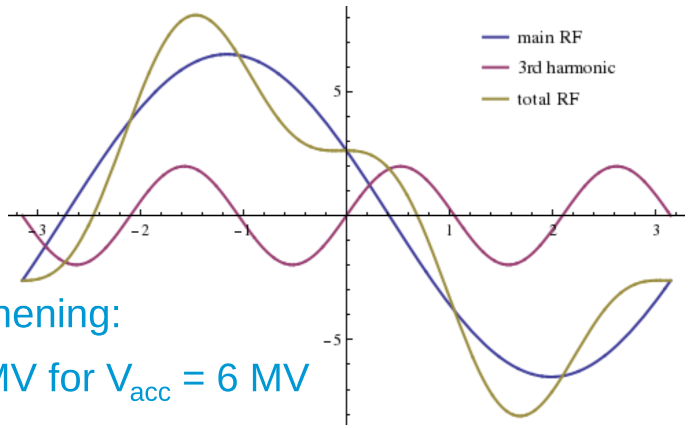
- Implementation of 3rd harmonic cavities at 1057.1 MHz for bunch lengthening and increased Touschek lifetime under study.
- Alternatives:
  1. Passive SC cavity, Super3HC type like at Elettra or SLS: collaboration with CEA / IRFU / SACM in Saclay, France
  2. Active NC cavities: scaling of ESRF HOM damped accelerating cavity





OPERATION OF PASSIVE SC HARMONIC CAVITY





Bunch lengthening:

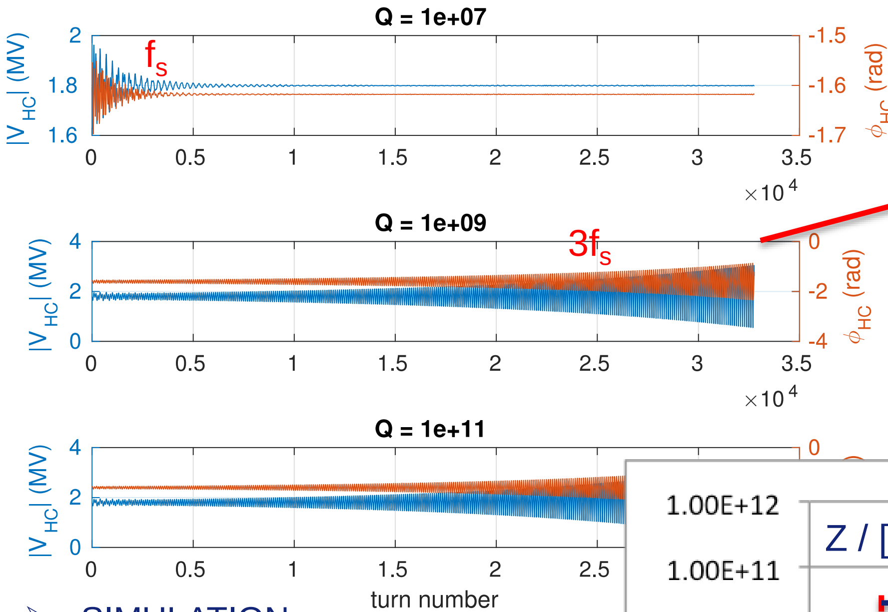
V_{harm} = 1.7 MV for V_{acc} = 6 MV

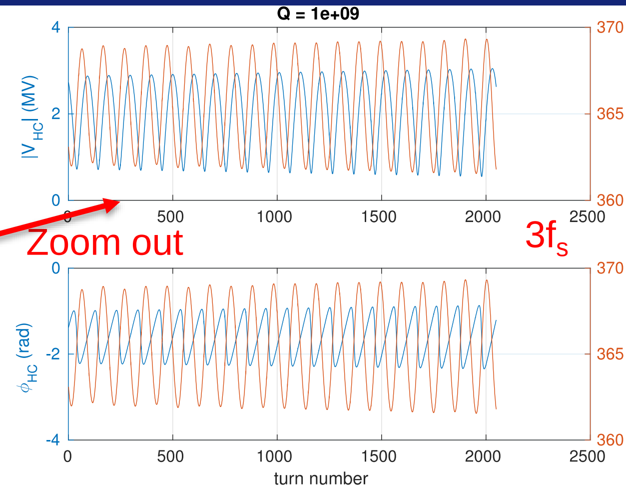
- Strong detuning Δf of Super3HC like cavity:
  - Zcav ≈ jX, with X >> R, X ≠ f(QL)
  - Δf such that: 2 I_{beam} X = V_{harm}
  - Δf ≈ 3.5 kHz for I_{beam} = 70 mA
- Smaller I_{beam} ➔ larger X ➔ smaller Δf ➔ larger R^+

  => Problem of AC Robinson instability for I_{beam} < 70 mA !

  (off resonance, Φ_{harm} follows rigid bunch motion at $f_s \neq 0$)

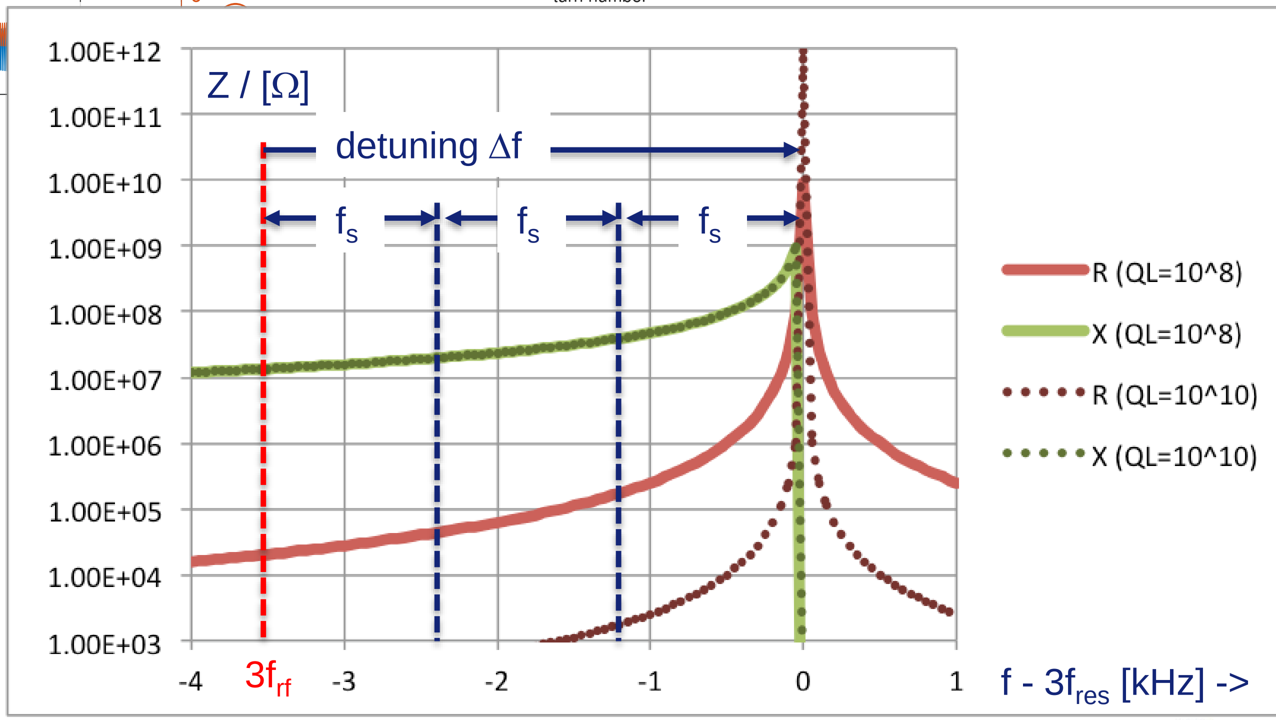
EXAMPLE OF AC ROBINSON INSTABILITY ON 3RD SYNCHROTRON SATELLITE





[Multiparticle tracking simulation using AT with beam loading effects in cavities by N. Carmignani in collabopration with B. Nash, ESRF]

- SIMULATION:
  - Bunch center of mass: unstable oscillation at $3f_s$ for large QL
  - Strong Amplitude & phase oscillation of V_{harm} at $3f_s$
- Tentative explanation: beating between
  - Nominal harmonic voltage driven by the beam at $3f_{rf}$
  - Strong voltage from tiny $3f_s$ synchrotron sideband close to SC-cavity resonance



BOOSTER RF ALREADY UPGRADED

Initially since 1991:

- 1 klystron powered 2 five-cell cavities
- via 2 couplers/cavity
- 600 kW in total
- Total V_{acc} up to **8 MV**

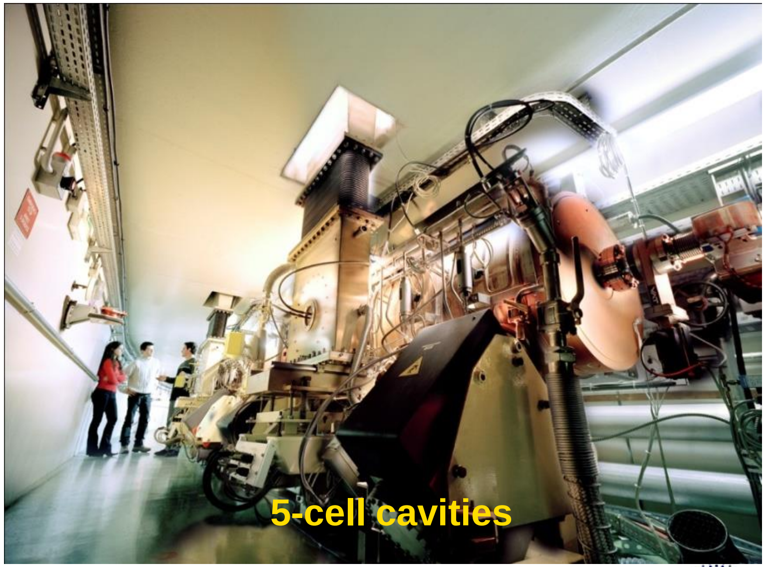
April 2012 upgrade:

- 4 x 150 kW SSAs powered 2 cavities
- Reminder: SSA $\rightarrow$ technology transfer from SOLEIL to ELTA / AREVA

January 2016 upgrade:

- 4 x 150 kW SSAs feed 4 cavities
- 1 SSA/cavity via 1 coupler/cavity
- Total V_{acc} uo to **11 MV**
- Redundancy: 8 MV operation with 3 systems (i.e. if one cavity or one SSA fails)

Ready for safe frequent top up operation started in 16 bunch in April 2016



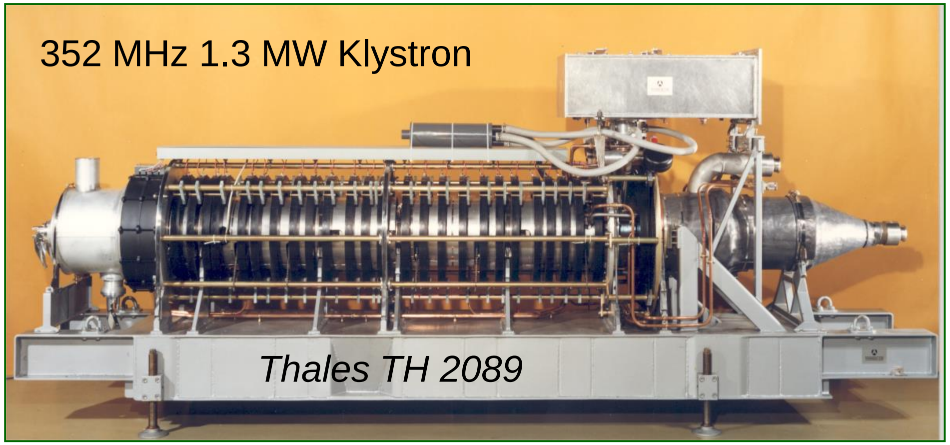
OPERATION EXPERIENCE WITH 7 X 150 KW SSA

- **Booster → 4 SSA 150 kW each. In operation since January 2012 (4500 hours)**
  - Top-up since April 2016
- **SR → 3 x SSA 150 kW each. In operation since October 2013 (17400 hours)**
  - One 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 2016)**

Component	Event count	Disturb Operation	Comment
HPA 650W (filter)	SR 10 SY 9	No No	CMS filters stressed when soldering on the PCB. Youth problem, now fixed with time. Last failure: April 27 2015.
DC/DC Converter 280V/50V	SR 4 SY 3	No No	Fuse blown. OK after replacing the fuse
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 2 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 18** **SY 23**	**2** **2**	**1 in 2014 + 1 in 2015 → Beam loss** **2 in 2012 → Refill postponed**

KLYSTRON TRANSMITTERS

- **STORAGE RING** - 3 RF stations with **1.1 MW and 1.3 MW klystrons**
  - RF station #1 feeding 4 five-cell cavities
  - RF station #2 as backup for #1 or for RF Power Test Stand
  - RF station #3 feeding 1 five-cell cavity (formerly 2 cavities)
- Stations #1 and #2 in operation since 1991, station #3 since 1997
- Stations #1 and #2: control refurbished year 2000 following the standard of station #3
- Obsolescence of VME / linux computers comprising measurement and digital I/O boards
  - ⇒ New control is under refurbishment using PCI and independent measurements and digital I/O
- Klystron EEV2-2 dead at 21770 hours in October 2015
- Station #3 will be dismantled end of 2018 for new ESRF-EBS machine



AVAILABLE KLYSTRONS - STATUS MARCH 2016

RF Station	Klystron Id	HV time	Average/year
#1	EEV4	**65,087**	6,100
#2	EEV1	34,121	5,000 (next 2 years: extensive cavity conditioning)
#3	PHILIPS	22,775	4,500
Spare Klystrons	EEV3	8,374	Potential time of 110,000 hours for pessimistic klystron lifetime expectation of 40,000 hours per tube: → corresponds to **11 years of operation** (9 years after EBS upgrade)
	TH89022-2	18,428	
	TH89018-2	36,340	
	EEV5	10,631	

KLYSTRON VERSUS SSA FAILURES

Year	Klystrons + ancillaries*		SSA	
	Beam losses	% of total RF failures	Beam losses	% of total RF failures
2012	2	8%	0	0%
2013	3	14%	0	0%
2014	3	9%	1	3%
2015	1	4%	1	4%

* Modulating Anode PS, Focusing PS, Filament PS, IP

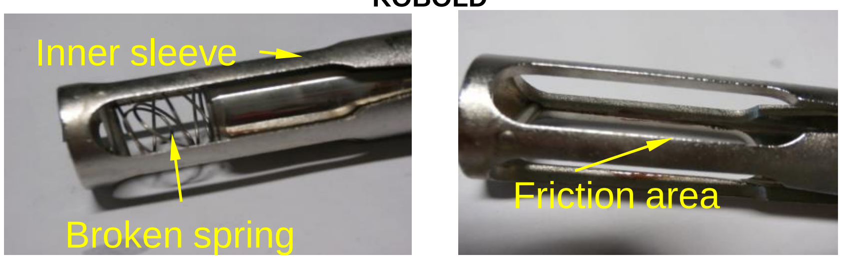
WHAT COULD BE IMPROVED ON 150 KW SSA

Interlocked cooling water flow controllers:

- 1 Kobold flow controller per cooling plate, supporting 16 HPA of 650 W or drivers
- 18 cooling plates per SSA

Erosion issue

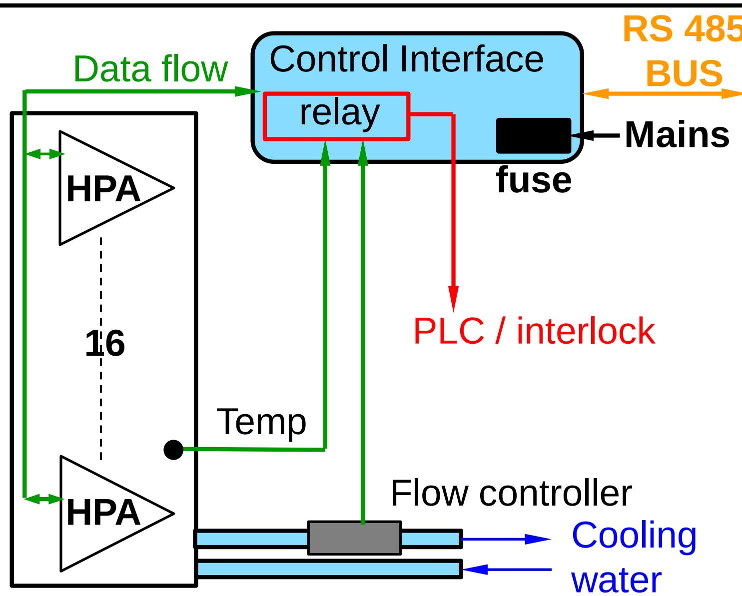
KOBOLD



Alternative to KOBOLD

7x18 = 126
to be replaced

Design issue



When the Control Interface fuse is blown the SSA is tripped only because the flow and temperature interlocks are conditioned by this interface (relay).
Interlock should be processes independently.


Thank you !!!