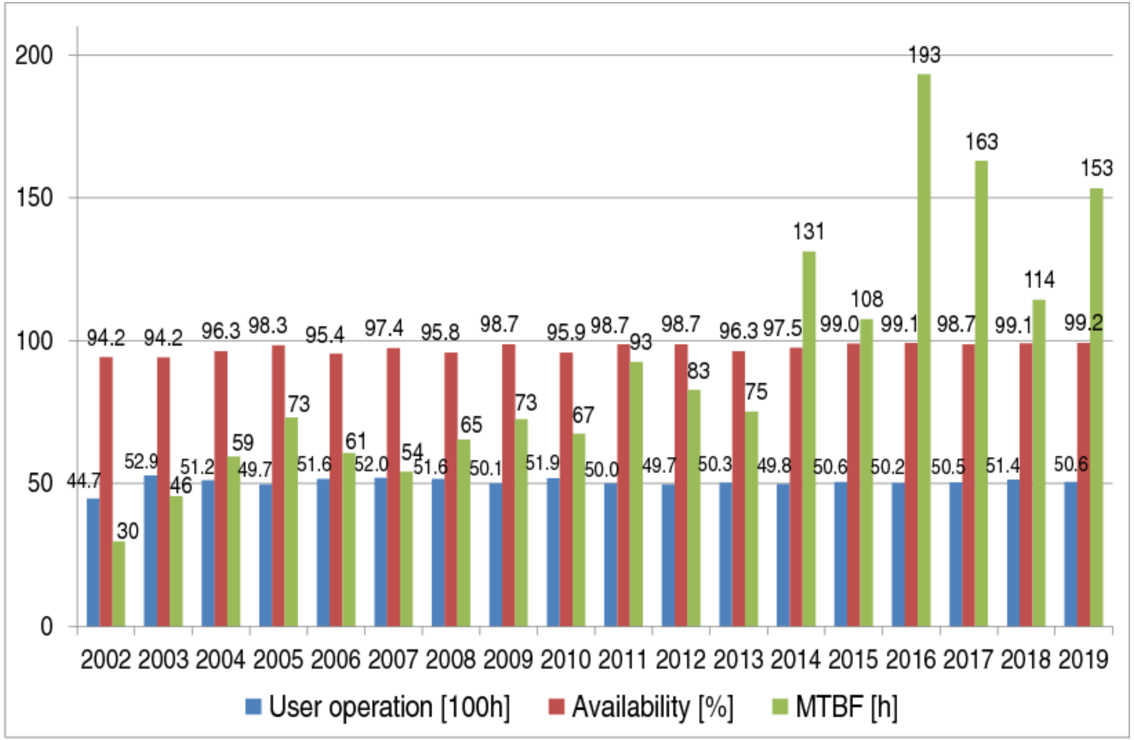
Lukas Stingelin :: RF-Systems 1 :: Paul Scherrer Institute

Operation and Upgrade of the SLS RF Systems and SwissFEL

24th European Synchrotron Light Source RF (ESLS-RF) workshop organized by KIT
November 2020

SLS-Operation Statistics until 2019

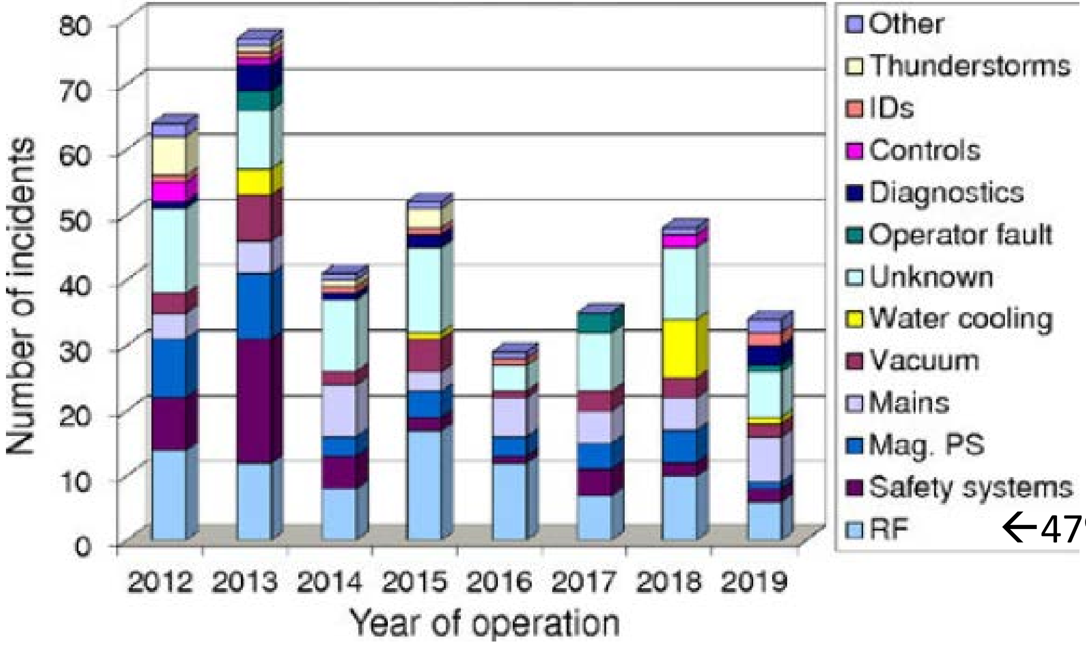


2019: Best beam availability since SLS-history!

Outages more than 5h:

- PS of personnel safety system
- Arcing at Klystron modulation anode cable

2019 SLS Failures by Category

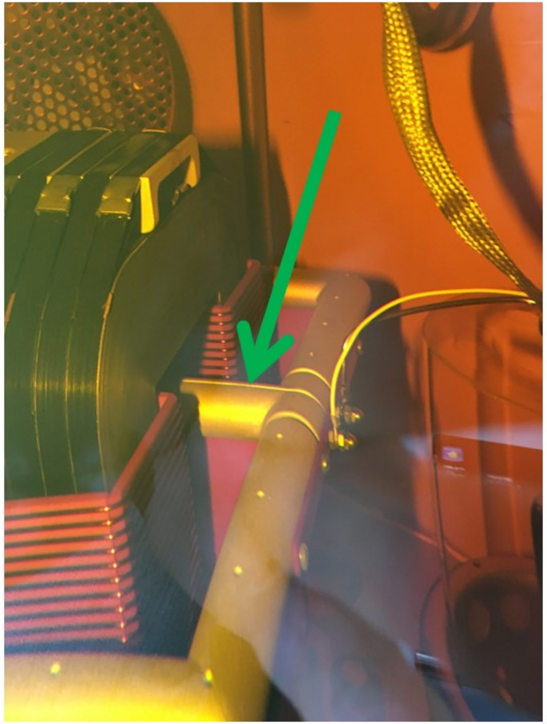


←47% of down-time attributed to RF

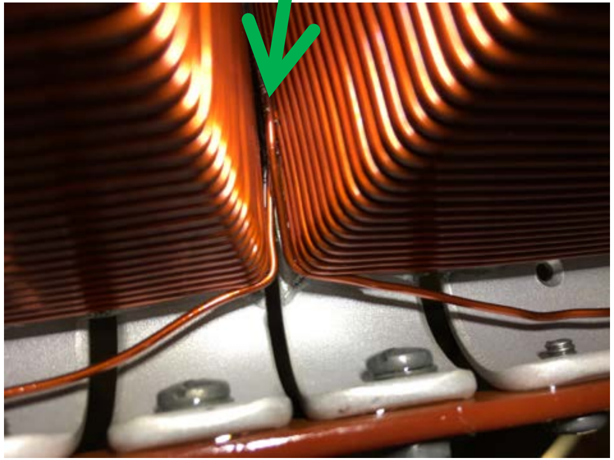
Major RF-issues in 2019:

- LINAC Klystron-Tank: arcing HV transformer.
- Bad contact in 50Ω Match at Klystron dir.-coupler caused refl. power interlocks
- Arcing at Klystron Modulation Anode cable.
- Phase-Jumps caused by phase controller.

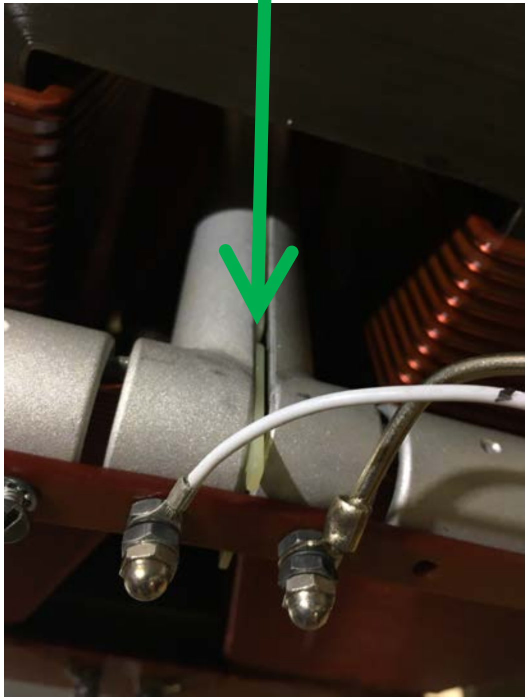
Arcing at LINAC Tank HV transformer



Arcing visible between the filament windings of the HV-Transformer



→Installed isolation plate:

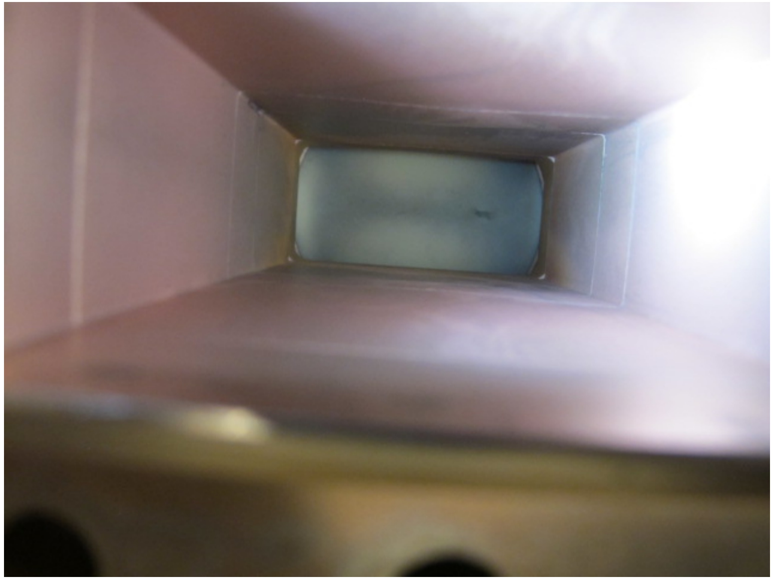


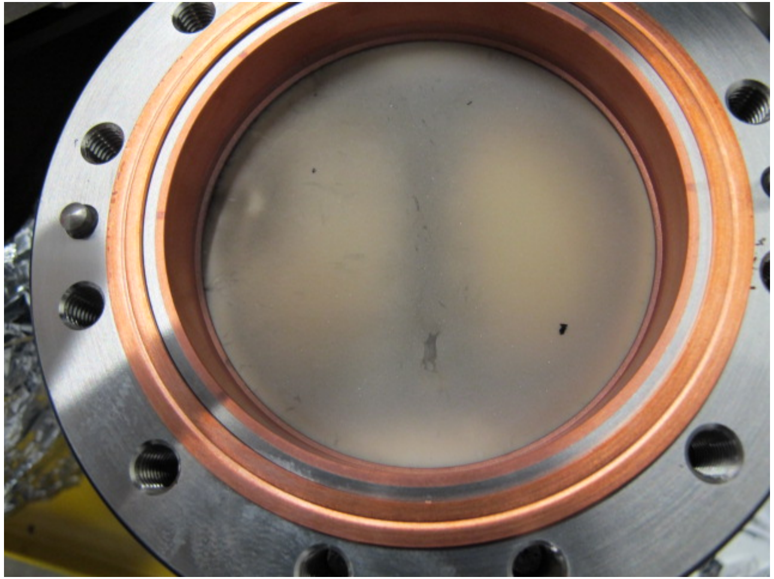
LINAC: Broken S-band windows at 50MeV structure

After 20 years of operation: 2 Failures within a few weeks

1) replaced only the ceramic disk of the window

2) Replaced full window assembly and reduced pulse width to 1µs





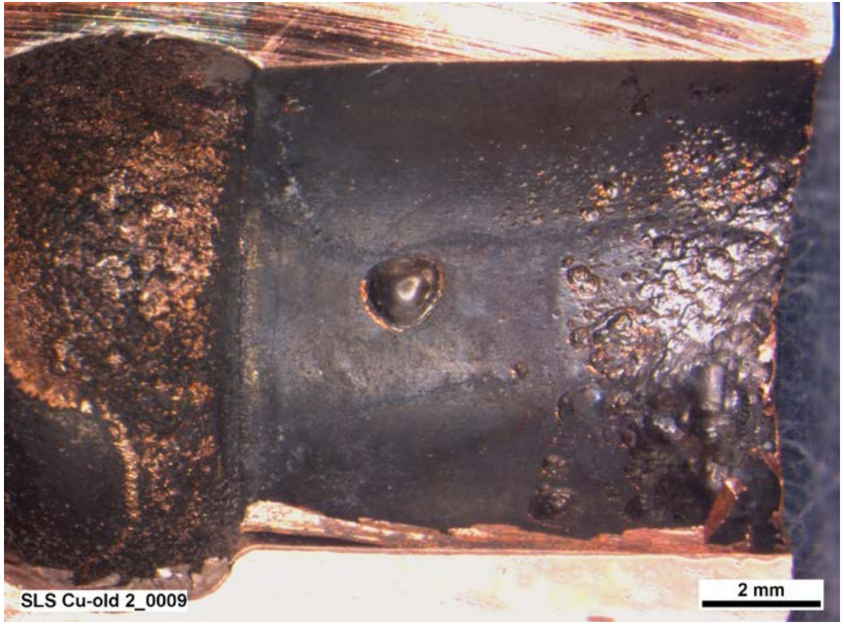
Water Leaks in the SR ELETTRA cavities

3 water leaks in the cavity wall-cooling circuit in 2020

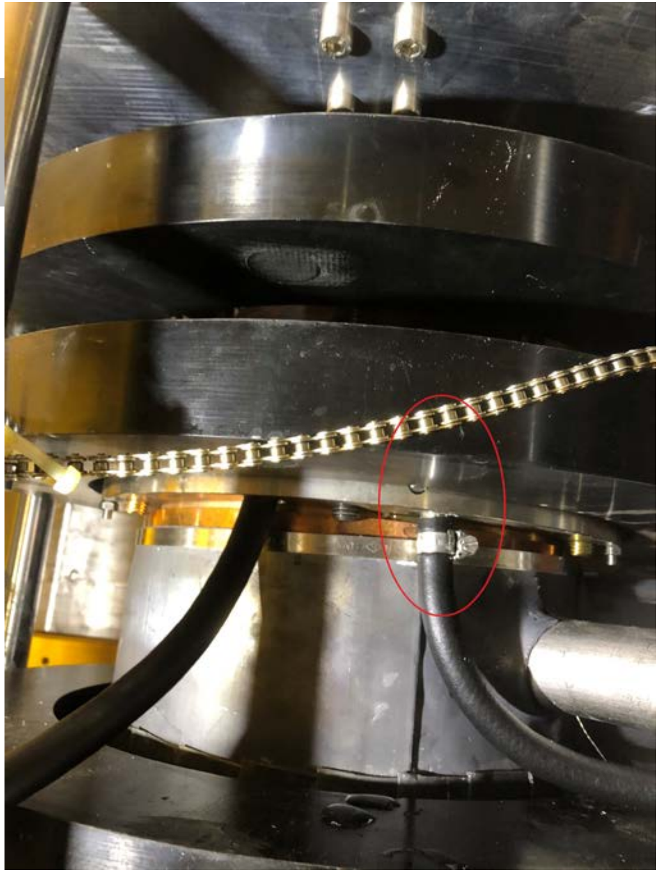
(old cavities had problems with the flange cooling circuit, improved in the new cavities)

Picture of the copper-tube of an old cavity (operation 2000-2014) → Flow Accelerated Corrosion

Picture from S. Ritter, water chemistry investigation by SvoBaTech

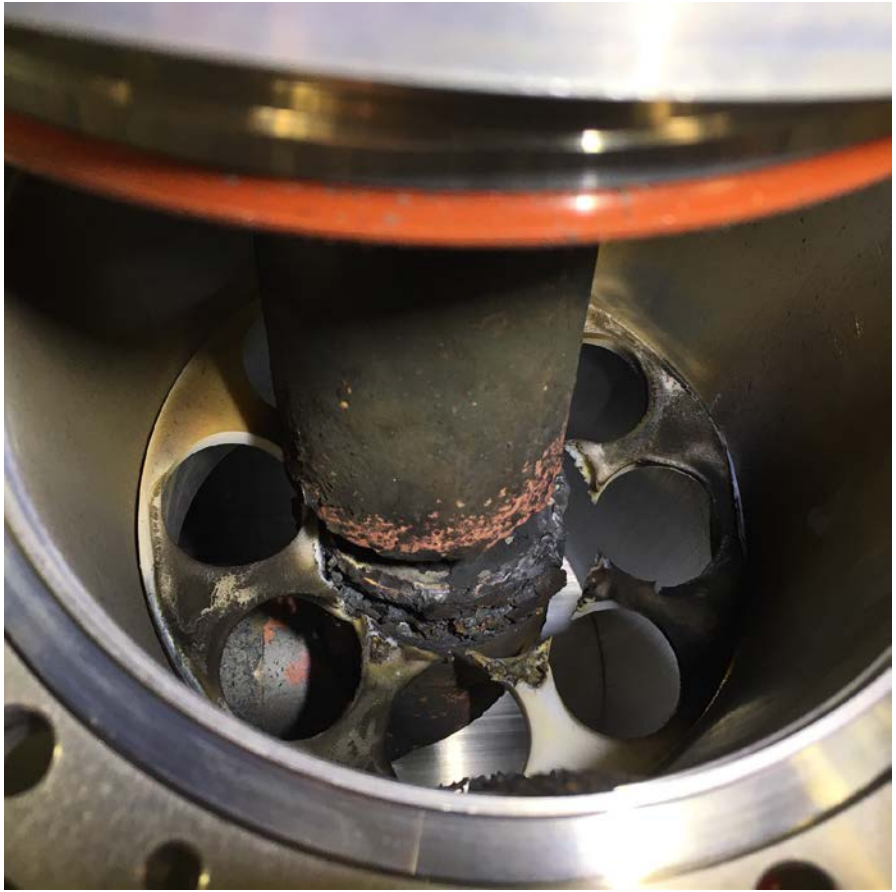


Water Leaks at 500MHz Thales Klystrons



Leak was repaired by flame-brazing, unfortunately, several other leaks were found and had to be brazed

Broken Coaxial Line at the Booster

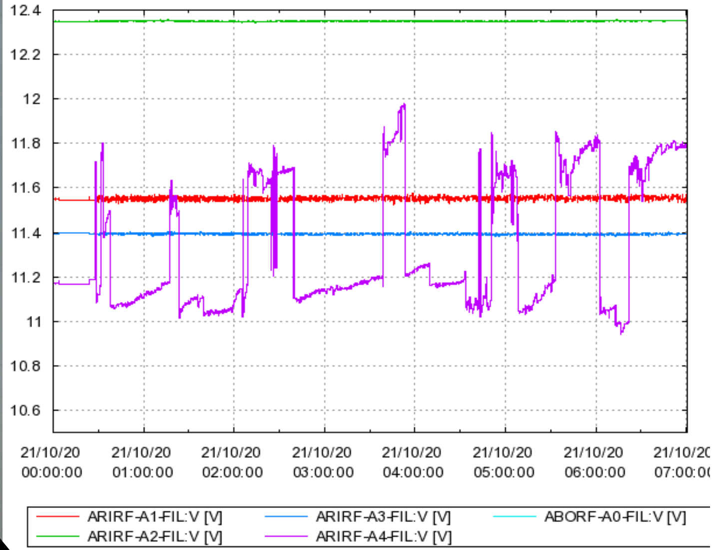


Burned coaxial line connecting solid-state amplifier to Booster cavity and teststand.

→ Switched to Klystron operation
→ Replaced the inner ellbows, soldered their joints
→ Added temperature sensors to the coaxial line and output air

Problems with «Pantak» Connector of 500MHz Klystrons

→Filament overvoltage interlocks:



No contact at the «shield»
→ Added copper disks

Bad contact at the tip
→re-soldered

SLS RF works

Done:

✓ LINAC 3GHz LLRF-upgrade → «SwissFEL»
✓ EEV-Klystron from Daresbury refurbished
✓ Storage-Ring: 2 HOMFS upgraded
✓ New water chemistry for the cavity cooling racks

In Progress:

□ Improvements on «Pantak» connectors?
□ Installation of filters to the cavity cooling rack
□ LINAC pulser board upgrade to shorter bunches
□ Storage-Ring+Booster cavities: HOMFS upgrade
□ Storage-Ring: LLRF upgrade

□ SLS2 RF Upgrade, TDR → See next slides

Progress on the SLS Upgrade: Project SLS 2.0

	Lattice B062	SLS
E [GeV]	2.7	2.4
Lattice: U_0 [MeV] (energy loss/turn)	0.690	0.532
$\delta E/E$ (natural energy spread)	$1.145\ 10^{-3}$	$8.585\ 10^{-4}$
α_c (momentum compaction)	$1.041\ 10^{-4}$	$6.049\ 10^{-4}$
τ_l [ms] (long. damping time)	6.380	4.340
τ_x / τ_y [ms] (transv. damping times)	4.128 / 7.519	8.651 / 8.670
ν_x / ν_y (betatron tunes)	39.35 / 15.25	20.43 / 8.73
Chromaticity x / y	< 2 / < 2	5 / 5
Beta function at Cavity x / y	9.0 / 6.6	1.5 / 1.1

New:
Higher energy
→ 4 RF stations

Lower $E \bullet f_s/\alpha_c/\tau_l$

→ lower LCBMI-threshold

New cavity position in long straight and lower chromas:
→ lower TCBMI-threshold

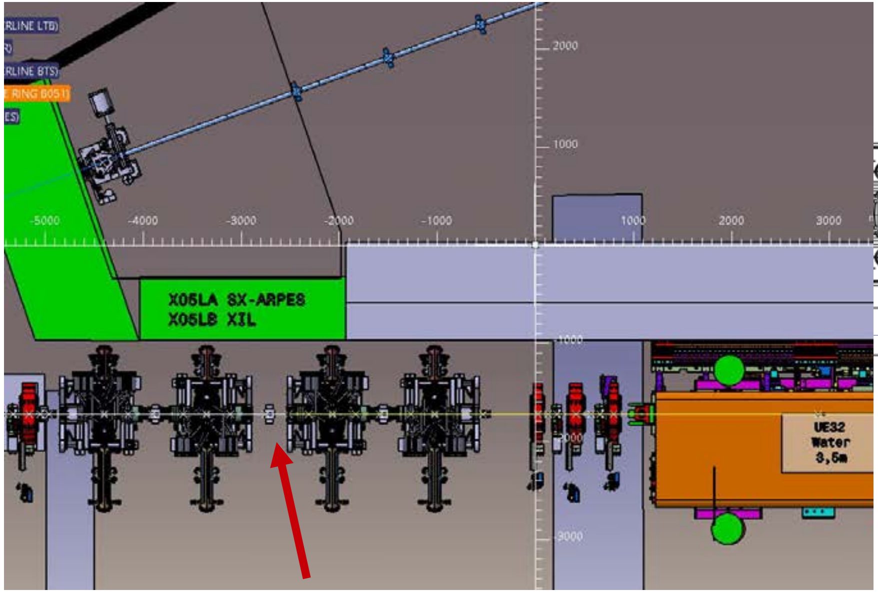
(court. of A. Citterio)

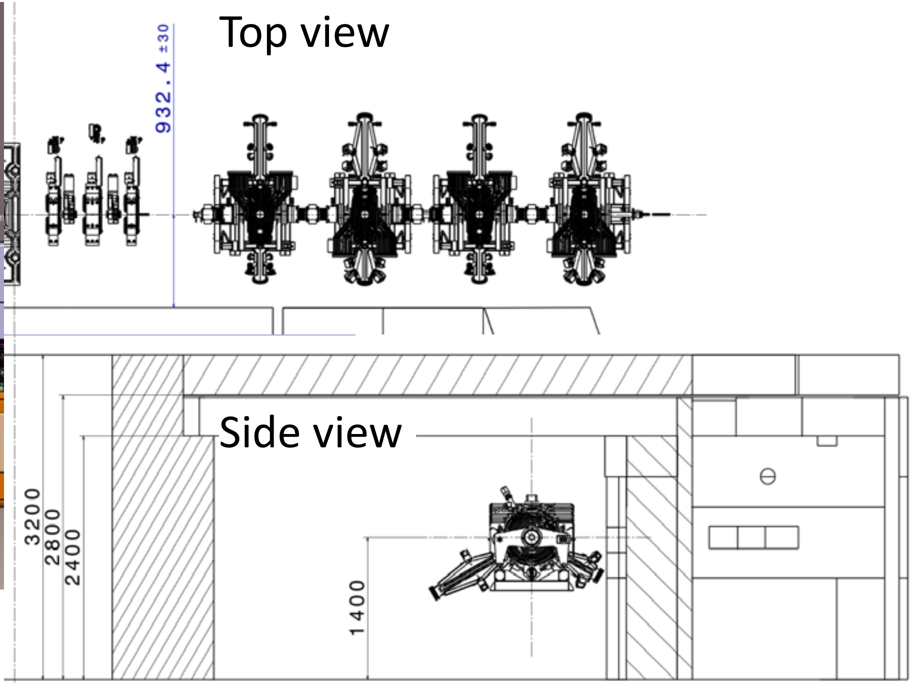
PAUL SCHERRER INSTITUT PSI

RF parameters (Example with parameters for ELETTRA cavity)

	SLS 2 @ 2.7GeV Lattice 062 (case for 400mA)	
SR-Losses in lattice	276kW	
Minimum power for IDs	44kW	
Average power for IDs	68kW	
Maximum power for IDs	85kW	
Total voltage in main RF cavities	1.78MV (445kV/cavity)	**3 Cavity operation:**
Wall-loss per cavity (ELETTRA)	~29.1kW	52kW
→RF-power range per station	**109.1kW … 119.4kW (Amp. Spec.: 150kW)**	**…172kW (150kW→Ib<320mA)**
→Coupling factor	**3.7 … 4.1**	…3.3 (or refl. power)
→Detuning for matching	**-32.9kHz … -34.1kHz**	
Ideal voltage for Super-3HC	**500kV … 522kV**	

Location of the 4 Main Cavities: In long straight 05: Here the case with old ELETTRA cavities upgraded with axial and radial dampers





Needs additional synchrotron radiation absorber in the middle of the cavities.

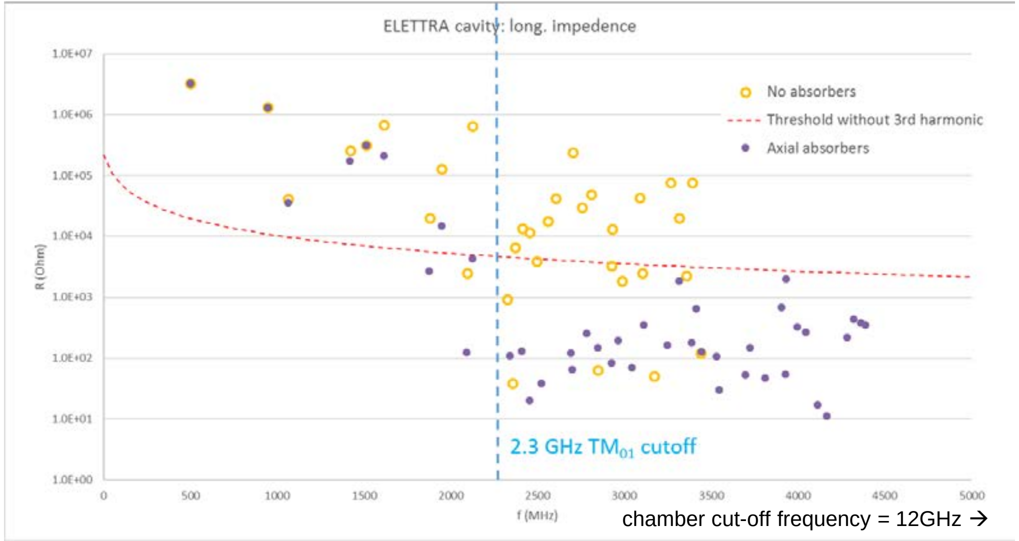
Reserved space for main cavities: 4.5m

Old Cavity Option 1: «ELETTRA axial damper only»

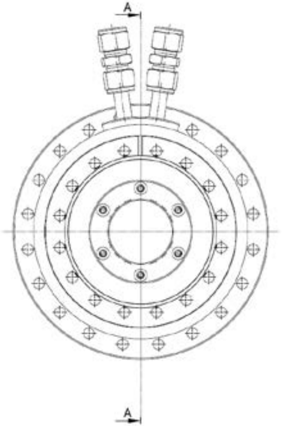
(Upgrade of the existing Elettra cavities with axial absorbers)

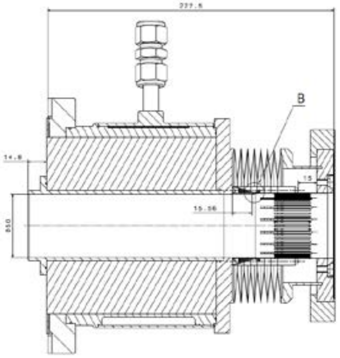
Only axial dampers (see CDR)

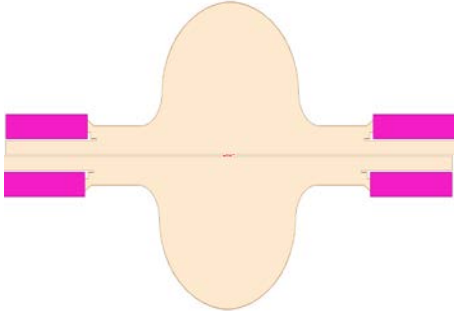
- Advanced design
- Good damping for all modes modes ≥ L9
- Extra length seems not to create problems
- **Partial reduction of the Q for few modes below L9, this could create problems to find a stable region.**



(court. of R. Zennaro)



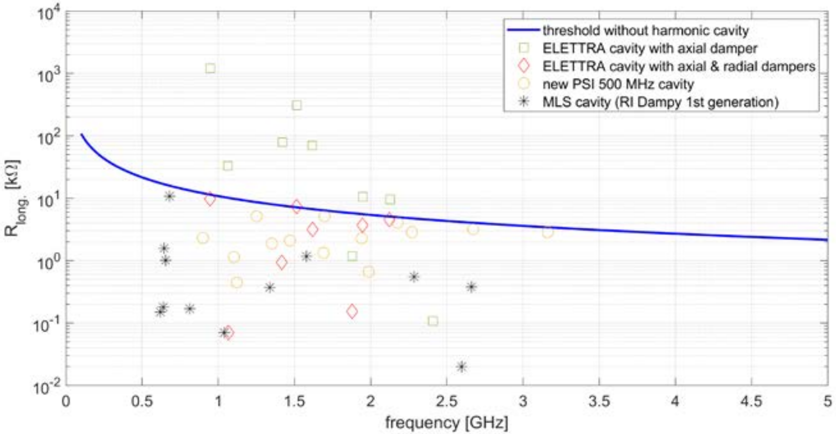


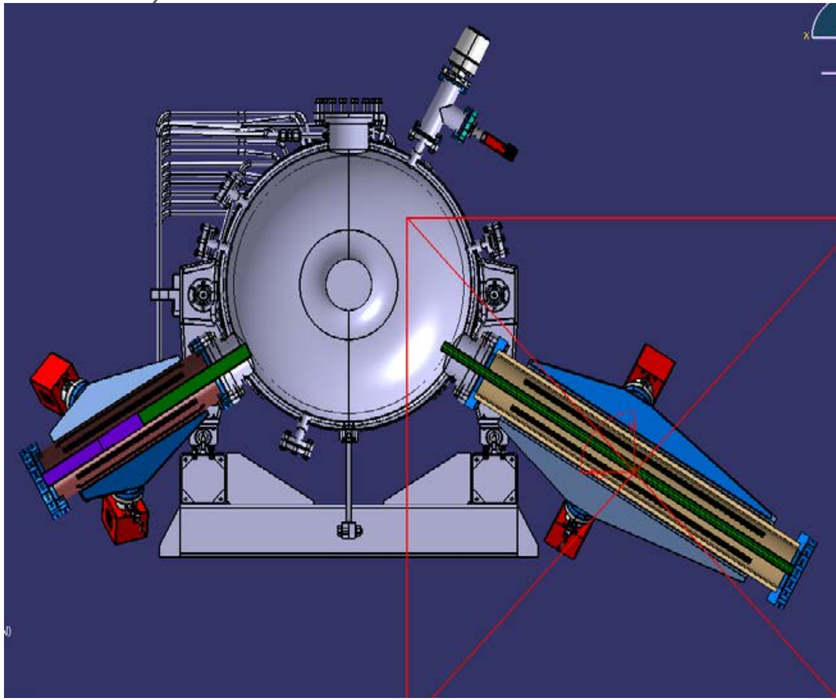


Old Cavity Option 2: «ELETTRA damped»
(Axial and radial absorbers in ELETTRA cavities)

Axial and radial dampers:

- Advanced design
- Enough damping for all longitudinal HOM modes, no need anymore of fine tuning to avoid instable regions
- Plunger for HOM-detuning not available anymore
- Vacuum pumping probably ok but not ideal
- **Very poor results for the transverse modes + issues with water-leaks!**





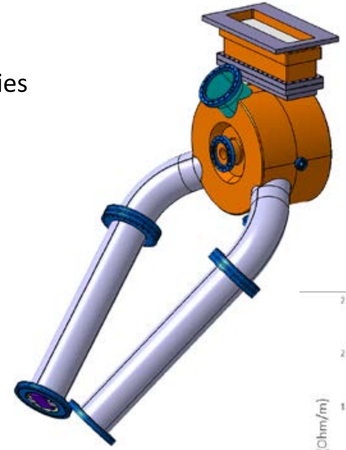
(court. of R. Zennaro, J. Buchmann)

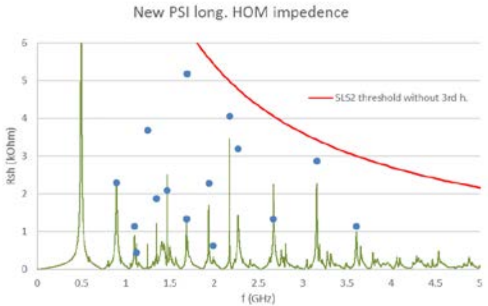
Design of new cavities, the «PSI-Cavity»

(court. of R. Zennaro)

Design of a new cavity:

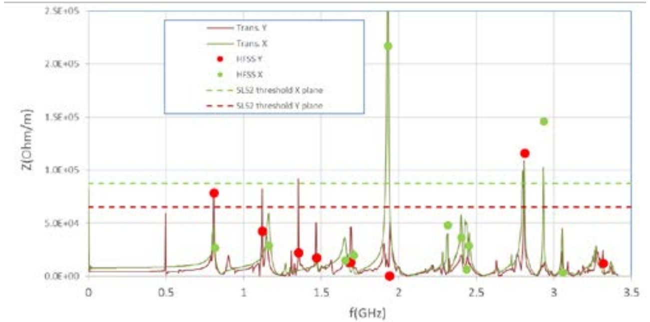
- ✓ Freedom in the design and positioning of the damping waveguides to reach the required damping for longitudinal and transverse modes
- ✓ The design can be done for proper installation in SLS2 tunnel
- ✓ Design that allows the complete production at PSI using the existing facilities of the workshop
- ✓ A new design could solve the problems with the RF power couplers
- ✓ A new design could solve the water leaks problems of ELETTRA cavities
- ✓ Preliminary conceptual design



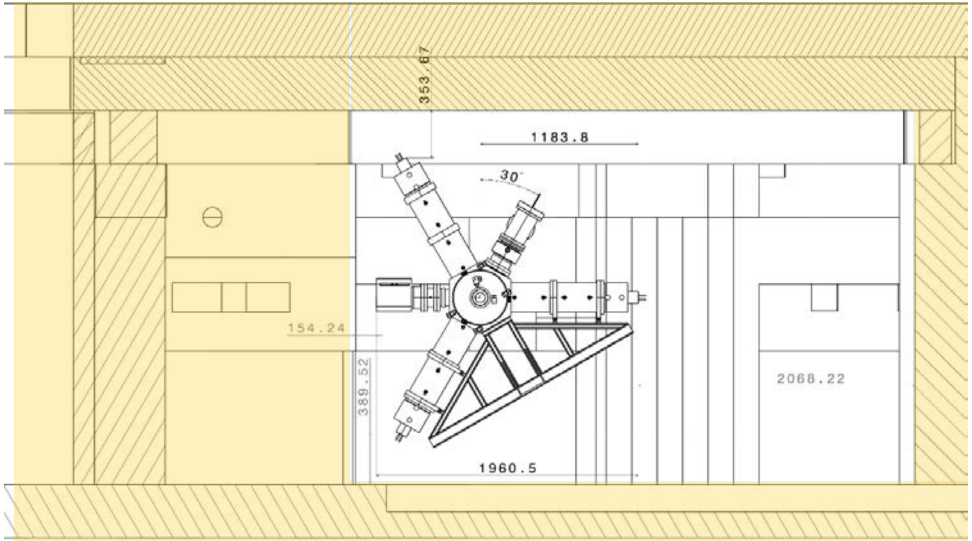


New cavity main features:

- Direct waveguide to cavity adjustable coupling
- Ceramic window in waveguide
- Damping of longitudinal and transverse HOMs
- Removable silicone carbide loads, no brazing, no ferrite absorbers
- Small vacuum impedance, direct large vacuum port in the cavity



Other cavity option are envisgeable: example with the EU damped cavity



- The RI Dampy cavity fits to the long straight 05, if it is rotated by 30°.
- No cooling rack required: The water cooling can be connected directly to the cooling of the storage ring (no hole in tunnel required).
- Installation, supports etc. to be checked in detail.

Transverse CBI growth rates & thresholds

(court. of M. Dehler)

- Assuming beta constant everywhere:
- Growth rate, smeared out, full fill

$$\tau^{-1} = \frac{I_{tot} c}{4\pi Q E_0/e} Re\{Z_T(n\,\omega_{rev} + \omega_\beta)\}$$

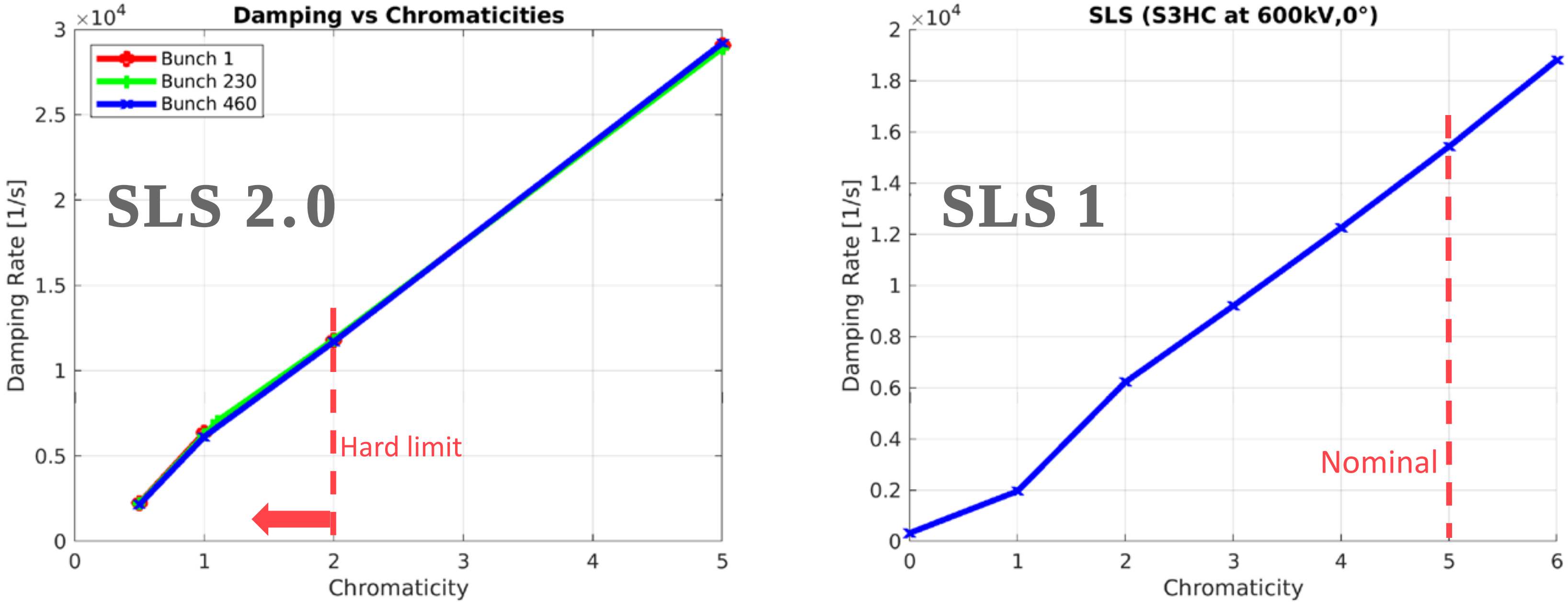
localized impedance

$$\tau^{-1} = \frac{I_{tot} c \beta_{cav}}{\frac{2E_0}{e} C} Re\{Z_T(n\,\omega_{rev} + \omega_\beta)\}$$

⇒ In SLS 2: $\beta_{x,y}$= 9.0/6.6 m ⇒ $\tau_{x,y}$ = 4.1/7.5 ms,
⇒ In SLS 1: $\beta_{x,y}$= 1.5/1.1 m ⇒ $\tau_{x,y}$ = 8.6 ms

- Effective damping due to three components
  - Natural damping rate $\alpha_n = 1/\tau_{x,y}$
  - Damping due to the tune spread caused by chromaticity and energy spread
  - Optionally the bunch by bunch feedback

Vertical Damping vs Chromaticity - SLS 2.0 vs SLS 1.0

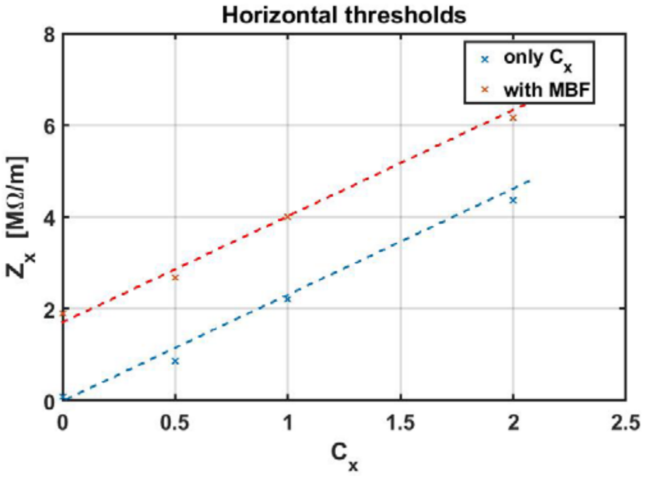


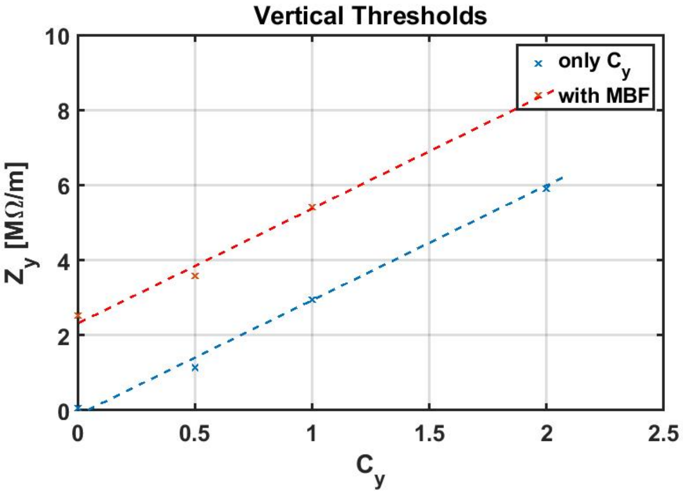
Two counter effects: Lower betas in SLS 1 increasing threshold, but smaller effect of chromaticity

Transverse thresholds for SLS 2.0

- Total damping rate: $\alpha_{total} = \alpha_{natural} + \alpha_{chroma}\ \{....+\alpha_{MBF}\}$
- Derive chromatic damping from multi particle simulations
- Optionally add effect of MBF: α_{MBF} =1/200 turns = 5000 sec^{-1}
- Compute thresholds (both with/without MBF) from analytical formula

(court. of M. Dehler)



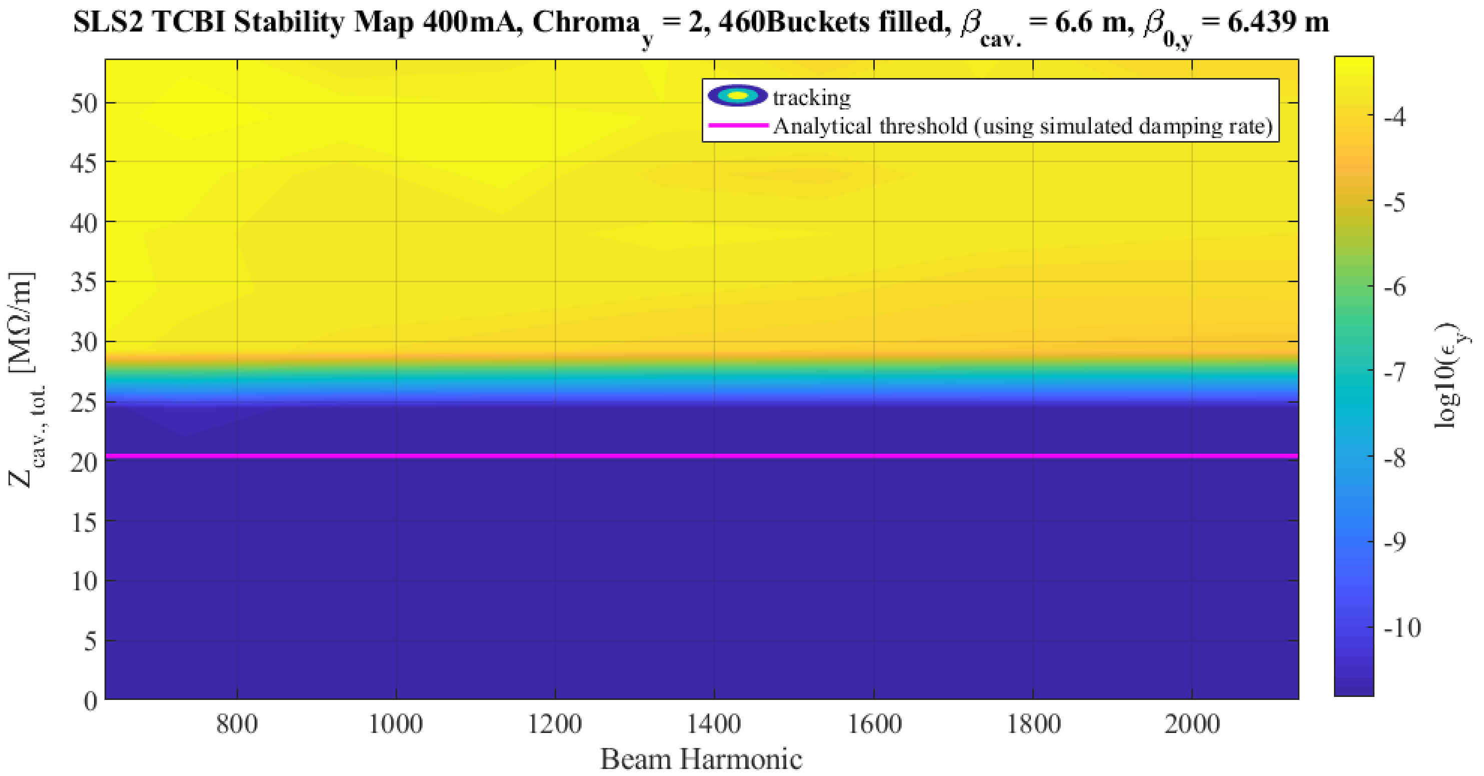


- The hard limit of chromaticity given by acceptance is at 2, we assume a value of 1.5
- Without MBF, thresholds are Z_x = 3.3 MΩ/m, Z_y = 4.4 MΩ/m per cavity
- With MBF, thresholds are Z_x = 5.1 MΩ/m, Z_y = 6.9 MΩ/m per cavity

Validation with Elegant

(court. of A. Citterio)

Total threshold (4 cavities)

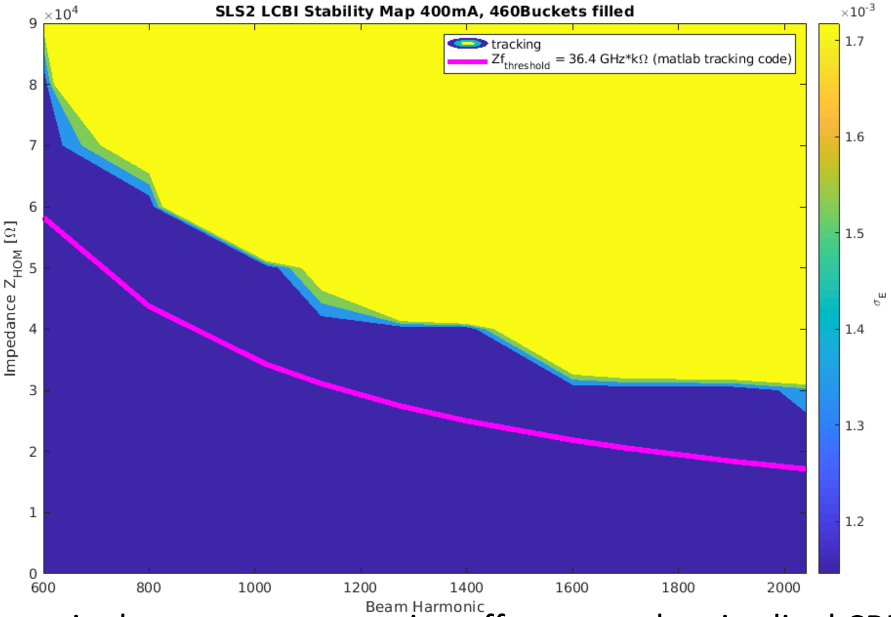


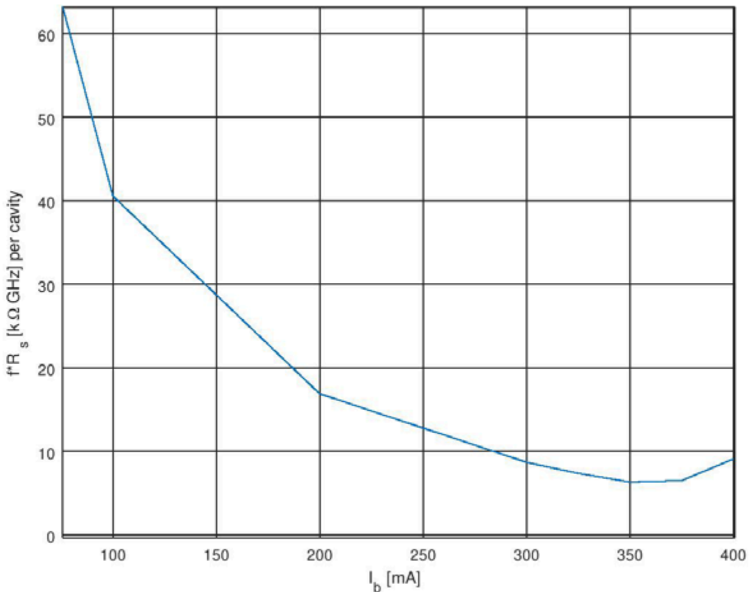
- **We tested the semianalytical model against a multi bunch/multi particle model in Elegant using the lattice and impedances of SLS 2.0**
- **Result: Semianalytical model predicts a safe (=pessimistic) threshold**

LCBI: Syncrotron frequency and Landau damping

(court. of A. Citterio)

Total threshold
(4 cavities)





Third harmonic cavity has two counteracting effects w.r.t. longitudinal CBI thresholds

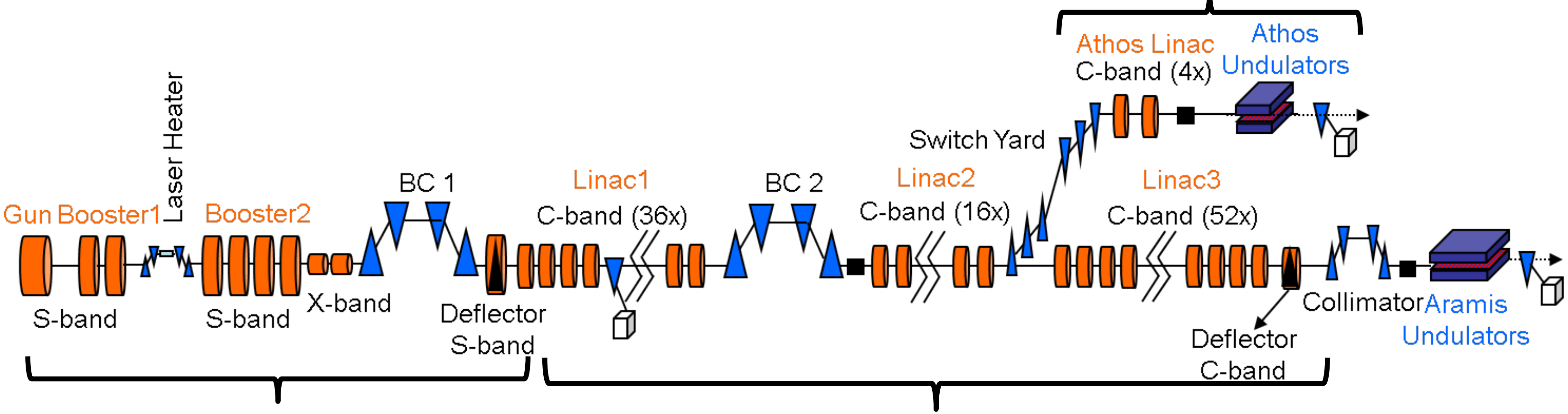
- Synchronous frequency decreases, lowering thresholds
- As potential well flattens, Landau damping kicks in increasing thresholds

Impedance threshold per cavity:

- Minimum threshold is not a nominal current but during filling at ca 350 mA: 6.2 kΩ GHz (SLS exhibits a similar effect with the most unstable point/lowest threshold at roughly 200 mA)

SwissFEL: RF Systems Overview

ATHOS: 1x C-band RF station under commissioning, 1x X-band PolariX-TDS installation.



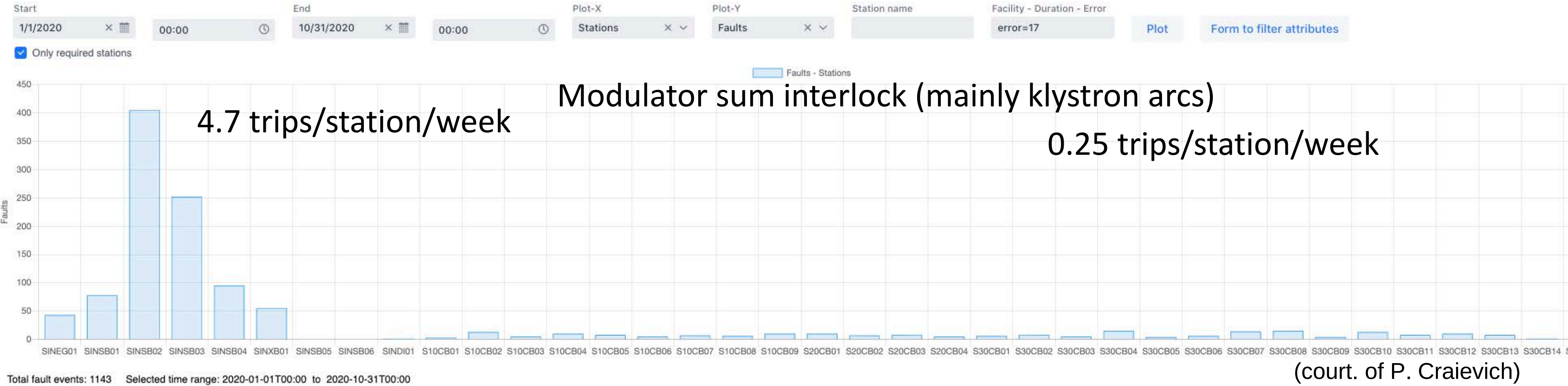
Injector: 7 RF stations routinely in operation
1x S-band RF gun, 4x S-Band TW structures, 1x X-band structures and 1x TDS

Linac 1, 2 and 3: 26x C-band RF stations routinely in operation (with a TDS systems shared in S30CB13/14)

- ✓ ARAMIS mainly in user operation, ATHOS is under beam and photon commissioning
- ✓ All RF stations ran at 100 Hz in 2019 (the low energy TDS system runs at 1 Hz)
- ✓ Linac 1 and Linac 3 can provide 1 spare RF station in hot-standby
- ✓ A beam energy of 6.3 GeV was achieved with compressed beam (300 MeV at the injector)
- ✓ New LLRF high level application installed

(court. of P. Craievich)

SwissFEL: Faults Analysis – January to October

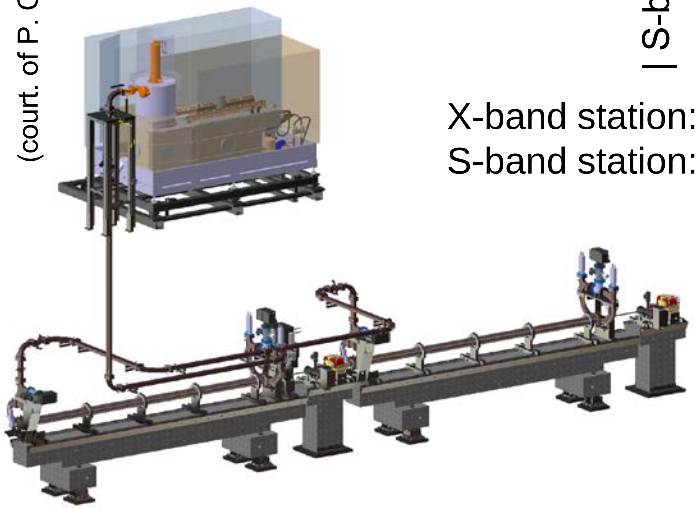


(court. of P. Craievich)

SwissFEL: High Power RF Systems – Injector

	Injector station	Structures	Energy Gain [MeV]	RF Power (maximum) [MW]	Klystron Voltage [kV]	issues/limitation
	SINEG01	2.6 Cell SW	7.1	15	230kV	Low perveance (SLS)
| S-band stations |	SINSB01	1x4m TW	70.5	36 (45)	267kV	Klystron arcing
	SINSB02	1x4m TW	62.4	26 (45)	260kV	Klystron arcing
	SINSB03	2x4m TW	96.4	35 (45)	239kV	Klystron arcing, water leak at collector
	SINSB04	2x4m TW	96.4	35 (45)	283kV	Klystron arcing, water leak at collector
X-band station:	SINXB01	2x0.8m	-19	7	320kV	Solenoid water leaks
S-band station:	SINDI01	5 Cell SW	TDS	5	137kV	Operation 1 Hz

(court. of P. Craievich)



Comments on the High Voltage stability:

- stability of all S-Band stations are between 10 and 15ppm at our operating voltage (measurements done in Nov. shutdown);
- SINXB01 seems to be at best 21ppm, this needs additional power supplies or replacement with new X-band modulator under development for ATHOS;

SwissFEL: High Power RF Systems – Injector Upgrade

(court. of P. Craievich)

Short term: <5 years

TH2100 Klystrons (or compatible)

2 x TH2100 Klystron repairs per year. Goal up to 45 MW 1μs RF Stable operation.
First is installed and performs well!

Medium term: 5 to 10 years

Progressively replacing Modulators (Priority X-Band)

Up to 45MW SINSB01 to SINSB04 as required

Long term: >10 years

Replacing of Injector Modulators Completed

Gradual replacement of all S-Band Klystrons for >45MW

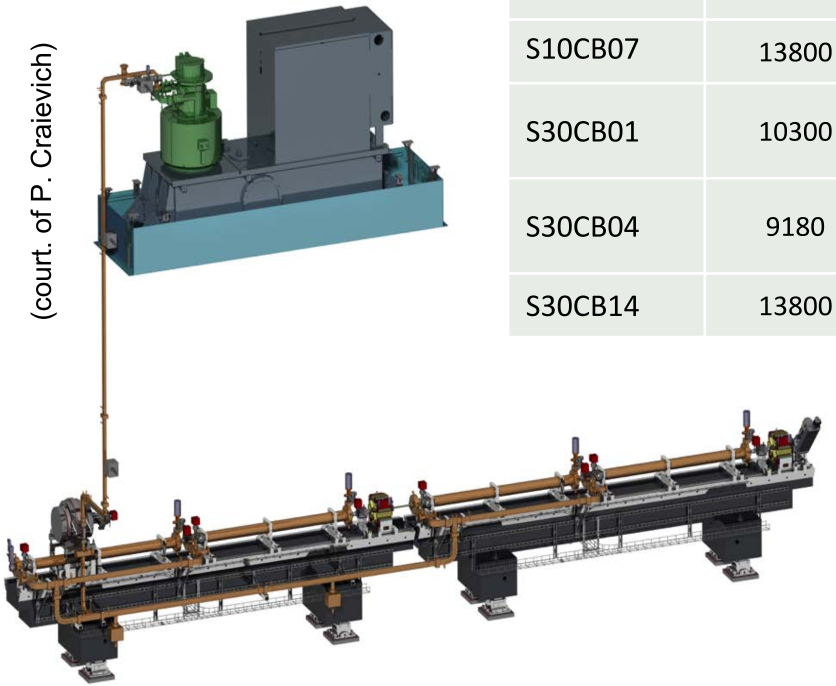
SINSB05 (Spare Station)/pulse compressor

SwissFEL: High Power RF Systems – C-Band Linacs

Klystron Issues

Linac station	Filament hours	HV Pulse length	Klystron Voltage	Output Power (Req’d> 40 MW)	Issues / limitations
S10CB01	12300	4.1 us	320 kV	34.4 MW	Multipacting
S10CB07	13800	4.0 us	335 kV	38.1 MW	Detuned
S30CB01	10300	4.5 us	303 kV	37.7 MW	Between Multipacting Regions
S30CB04	9180	5.0 us	333 kV	43.1 MW	Excessive Arcing, Switch Unit jitter
S30CB14	13800	4.7 us	240 kV	6.5 MW	Issues at low power

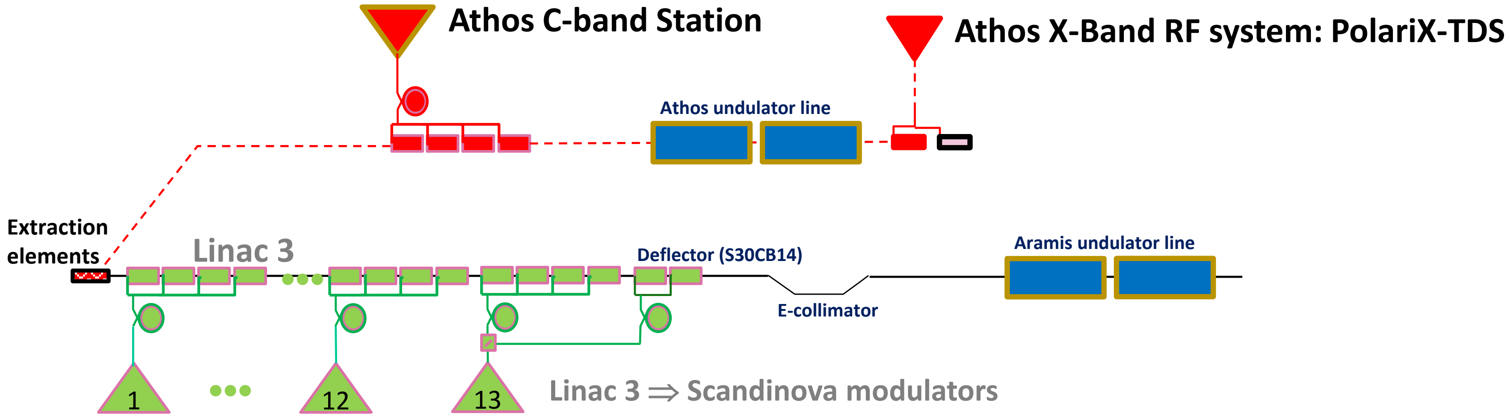
(court. of P. Craievich)



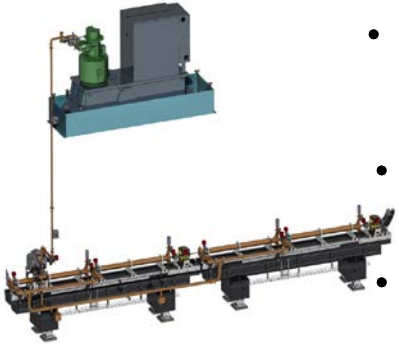
Common Issues

- Klystron Arcs occurs at High voltage (>300kV ~40MW setpoint)
- Multipacting occurs <40MW setpoint
- Large spread in Klystron Perveance, 1.44 to 1.6 (additionally large variation in heater power, 200 to 500 Watts)
- Detuning of Klystron (x3), all shifted 7, 10 & 14 MHz higher

SwissFEL Athos:

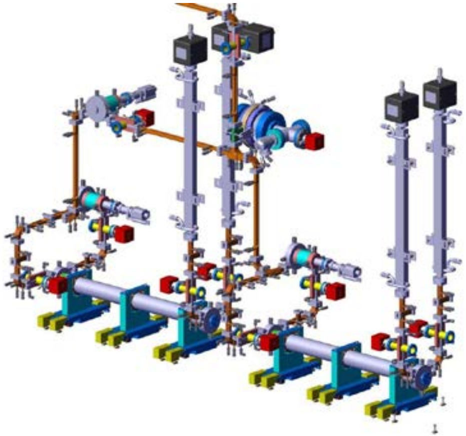


(court. of P. Craievich)



Athos C-band:

- Module installed in tunnel
- April 2021: available for acceleration
- Goal: Athos Users experiment start in September 2021



PolariX-TDS:

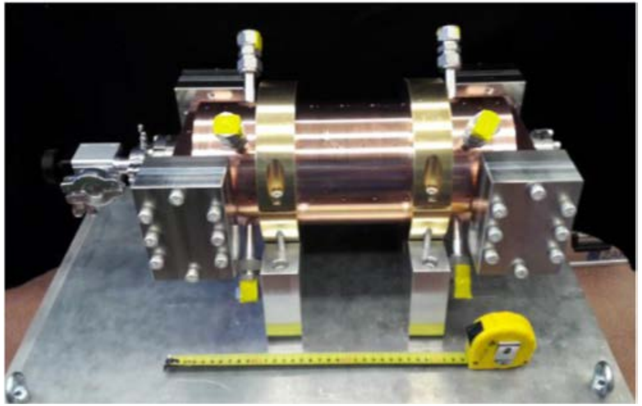
- Installation in Progress
- Tests of RF components ongoing
- PolariX-TDS already in operation at FlashForward (DESY)

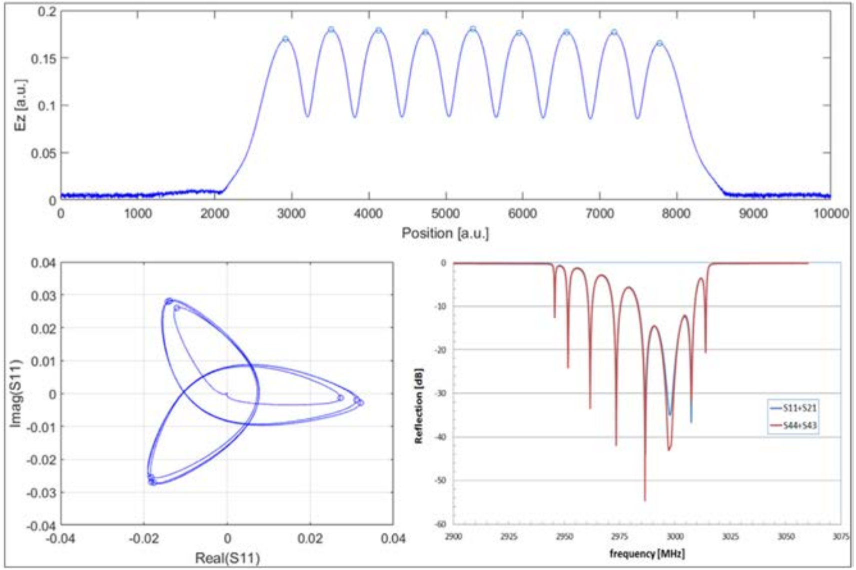
PAUL SCHERRER INSTITUT
PSI

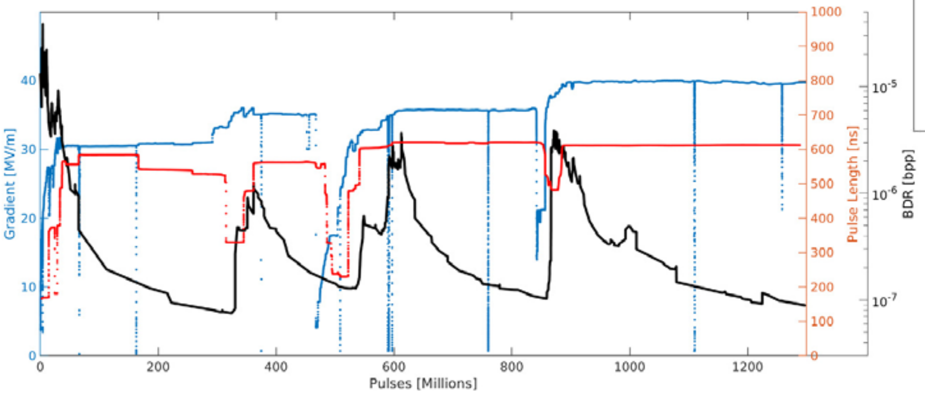
High Gradient S-Band Accelerating Structure

(Collaboration with FERMI: manufactured and measured at PSI)

(Ref: NIMA 979 (2020) 164473)







Wir schaffen Wissen – heute für morgen

Questions?