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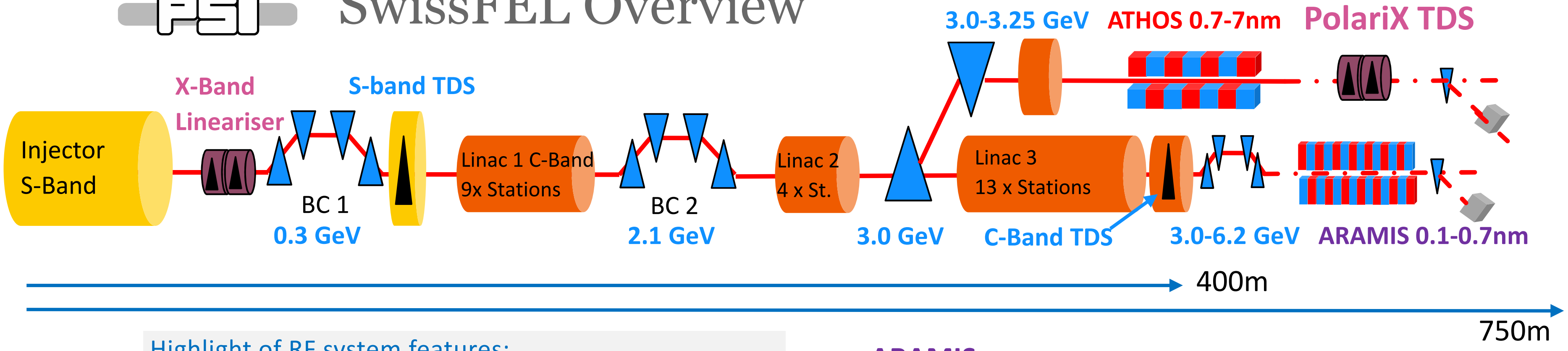
RF system performance in SwissFEL

LINAC2022 Liverpool, UK

Outline

- SwissFEL
  - Brief overview (Machine + RF Systems)
- RF system reliability
  - Main source of failure (Injector & Linac)
- RF system performance
  - Overall operational performance
  - Amplitude and phase stability
  - Key RF stations
- Summary / Trade-offs – performance versus reliability
- List of contributers

SwissFEL Overview



Highlight of RF system features:

- Technology: Normal conducting TW
- RF repetition rate: 100 Hz
- RF pulse length: 0.1 ~ 3.0 µs
- Charge per bunch: 10 to 200pC
- # bunch/pulse: 2 simultaneously @100Hz

Aramis (& Athos) beam stability requirements (RMS):

- Peak current (& bunch length): < 5 % *
- Beam arrival time: < 20 fs*
- Beam energy: < 5e-4 *

*Constraints largely determined by the RF system

ARAMIS

Beam Energy 6.2 GeV (~6 Nominal)

Hard X-ray FEL, λ=0.1 - 0.7 nm (12-2 keV)

First users 2018

ATHOS

Beam Energy 3.0 – 3.25 GeV

Soft X-ray FEL, λ=0.65 - 5.0 nm (2-0.2 keV)

X-Band Deflector station recently commissioned

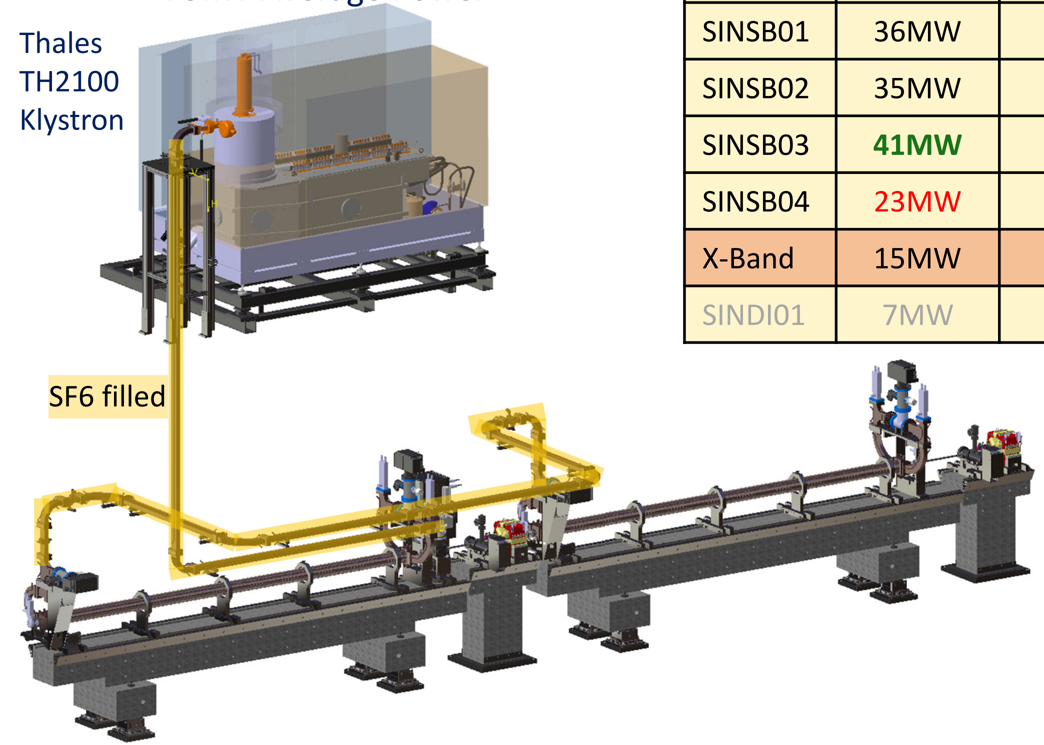
First users 2021

SwissFEL Injector Station

Scandinova K2-2 Modulator
100 Hz, 320 kV, 360 A
75kW Average Power

Injector station	RF Power	Structures	Energy Gain MeV	Working Phase	Voltage Stability
Gun	15MW	2.6 Cell SW gun	7.1	90°	19ppm
SINSB01	36MW	1x4m TW	70.5	90°	15 ppm
SINSB02	35MW	--	62.4	90°	45 ppm
SINSB03	**41MW**	2x4m TW	100	70°	19 ppm
SINSB04	23MW	--	79.5	70°	60 ppm*
X-Band	15MW	2x0.8m	-19.6	270°	27 ppm
SINDI01	7MW	5-Cell SW	Deflection	180°	

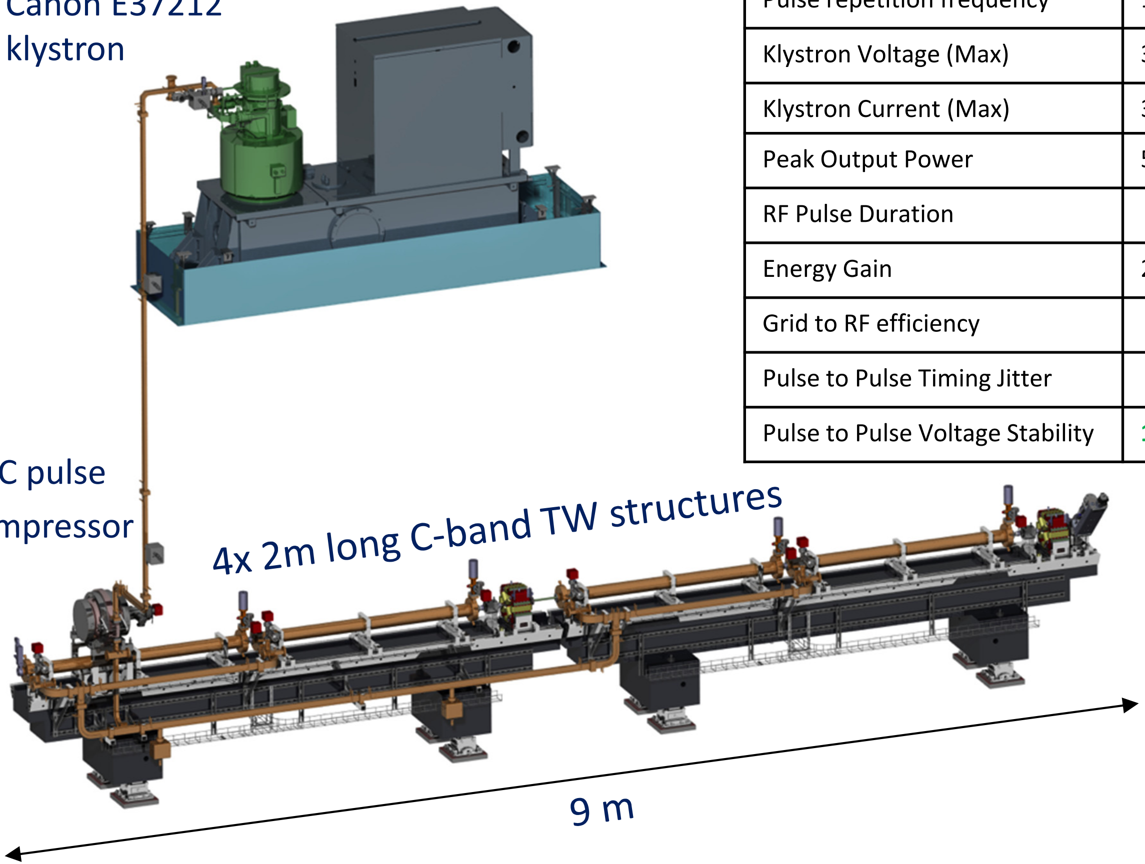
*Discussed later



Comments

- Injector relocated from SwissFEL Test Facility
- Modulator improvements Stability (improved from ~200ppm)
- First Canon E37327A tube – SINSB03
- **SINSB03 & 4 Off-crest to produce energy chirp in BC1**
- SINSB04 – limited by Klystron Arcing (No spare)
- X-Band Stability dominates machine performance **BC2 Peak current stability**
- **Injector has ZERO redundancy**

C-Band Station (27 stations)



Parameter	Max	**Typical**	Comments
Pulse repetition frequency	100 Hz	**100Hz**	
Klystron Voltage (Max)	370 kV	**310-340kV**	Reduced for improved MTBF
Klystron Current (Max)	344 A	**260-300A**	
Peak Output Power	50MW	**33-42MW**	BOC MP ↑ Arcing/Breakdown↓
RF Pulse Duration		**3us**	Φ-inversion 2.6us
Energy Gain	250 MeV	**~240 MeV**	~30MV/m
Grid to RF efficiency		**~20%**	Klystron 43%
Pulse to Pulse Timing Jitter		**70 to 650 ps**	
Pulse to Pulse Voltage Stability	**11ppm**	**<15ppm**	Low Amplitude jitter

Comments

- Common Vacuum (from Klystron Window – Structure)
- RF Conditioning (8 weeks to nominal power)
- All Structures and BOC produced at PSI
- 14 Ampegon, 13 Scandinova Modulators
- Canon E37212 Klystrons ~34k Hours no Failures

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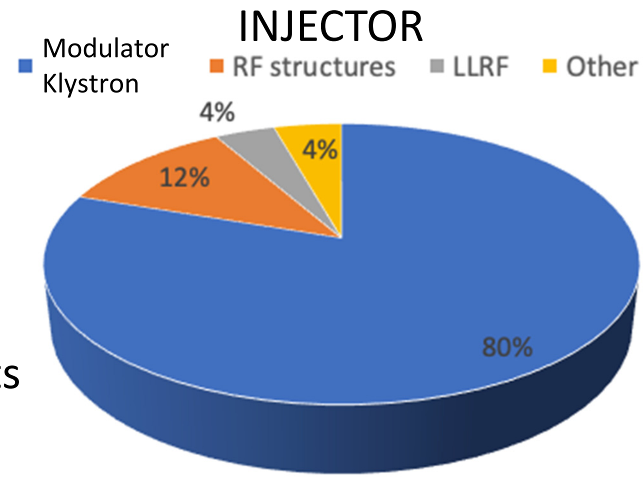
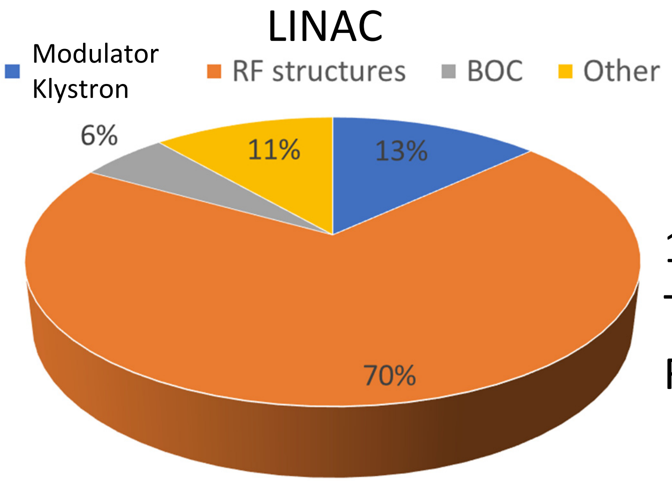
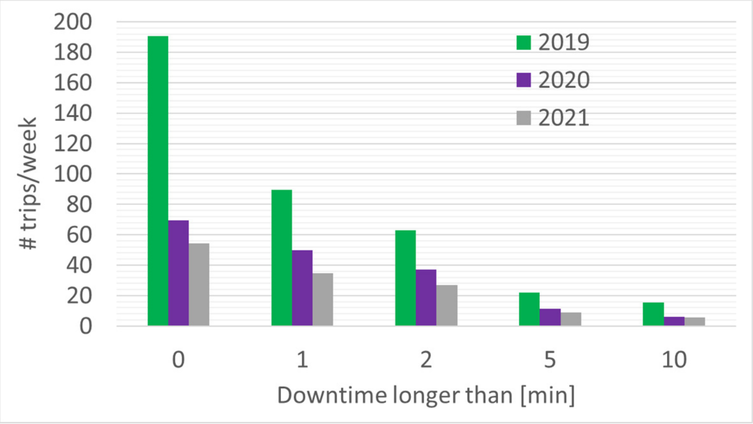
RF Faults Analysis – 2021



798 Total Faults



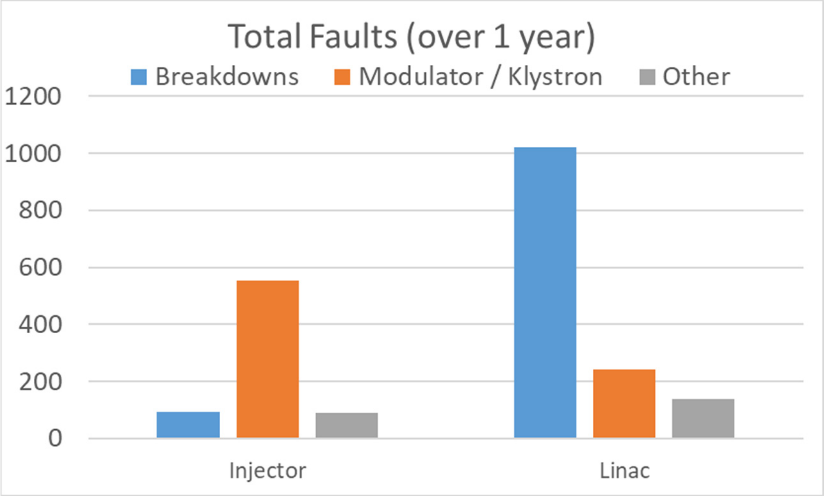
1381 Total Faults

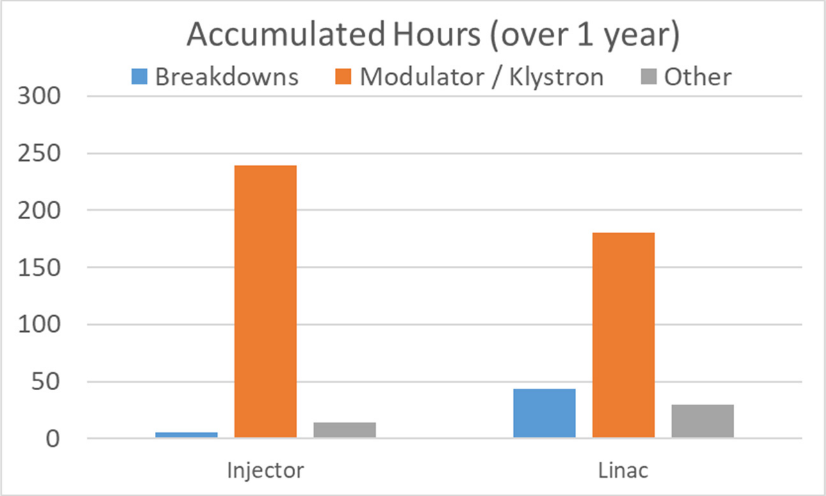


- Injector RF faults are dominated by klystron arcing.
- Injector – 3.3 trips/Station/week (6 stations)
- Linac Faults are dominated by breakdowns
- Linac - 1.3 trips/station/week (27 stations)
- Large Improvement in reliability each year
- Conditioning of C-Band Structures evident

SwissFEL RF Failures 06/2021- 05/2022

- Injector faults resulted in several days downtime each
  - Transformer Repair / Klystron Recovery
- Failures in the Linac are less severe, due to operational redundancy – Set-up required
- Breakdowns, cause many albeit short interruptions (few minutes).
- SwissFEL is operational ~6500 hours per year





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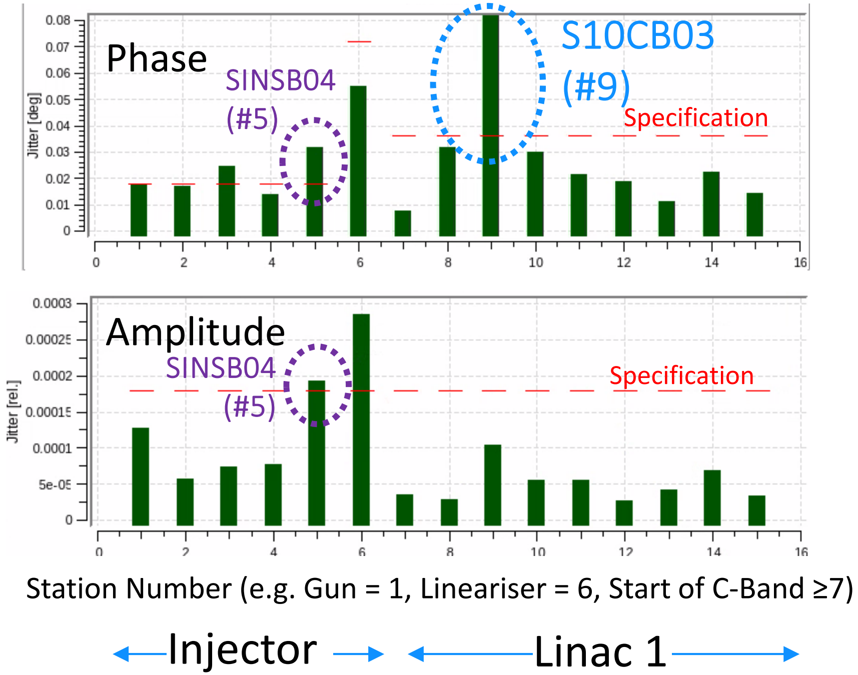
SwissFEL Overall RF Performance

p-2-p relative amplitude and phase jitter (rms)				
	Amplitude Meas.	*Amplitude Spec.*	**Phase Meas.**	*Phase Spec.*
S-band	**0.01-0.2%**	*0.018%*	**0.025°**	*0.018°*
X-band	**0.05%**	*0.018%*	**0.058°**	*0.072°*
C-band	**0.01-0.02%**	*0.018%*	**0.035°**	*0.036°*

- Low baseline in Linac Amplitude and Phase, More tolerant on other instabilities such as…
- S10CB03 (#9) displays High Phase jitter (BOC Multipacting)
  - Compression Jitter affected. Mitigated at higher operating power.
- SINSB04 (#5) Dominates Longitudinal Beam Jitter
  - Higher Amplitude and Phase jitter (Next Slide)



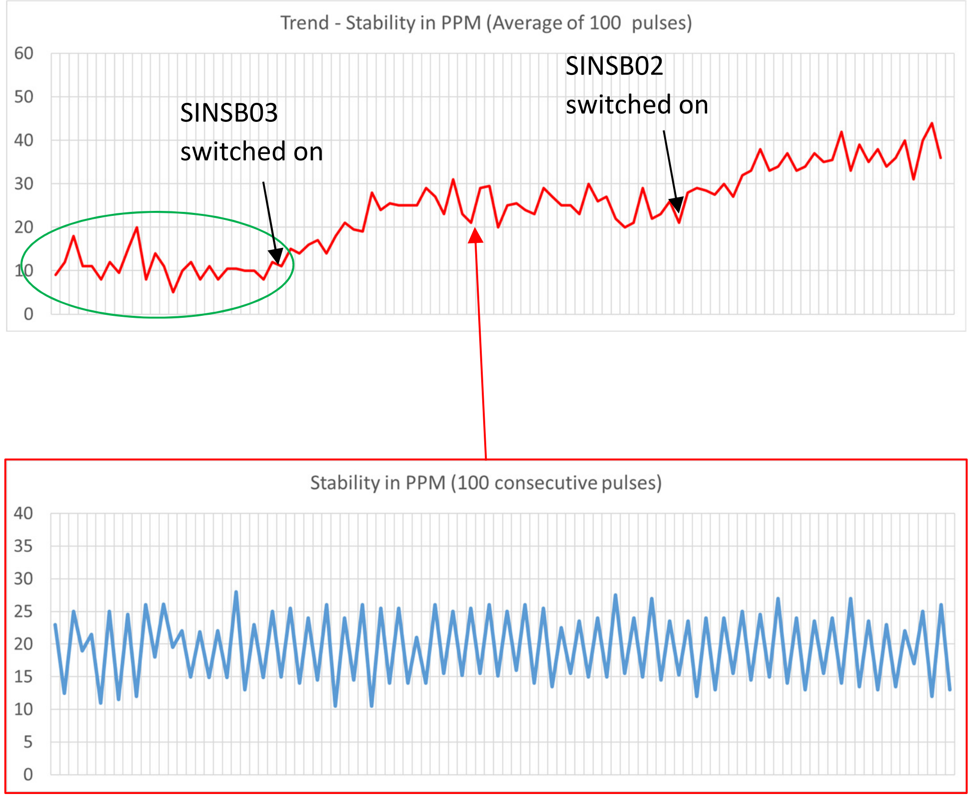
Aramis beam stability Measurements (RMS):

- Peak current (& bunch length): < 5 % ~6.4 %
- Beam arrival time: < 20 fs <10fs
- Beam energy: < 5e-4 ~2e-4

SINSB04 – Pulse-to-Pulse Stability

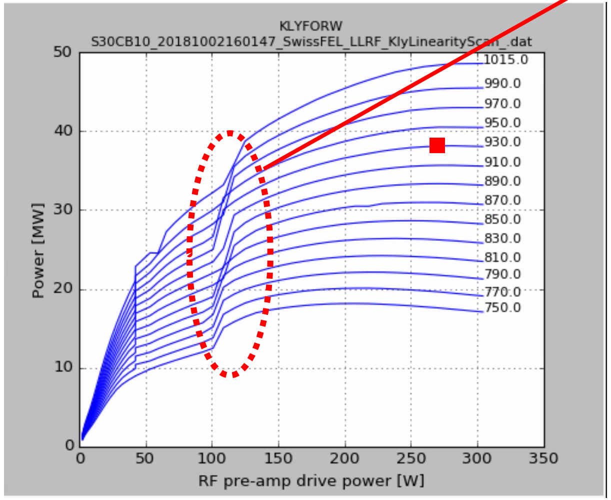
- High Amplitude and Phase Jitter
- Modulator p2p stability during operation was ~60ppm
- During the shutdown we measured 14 to 20ppm!!
  – As other stations were switched on, a clear jumps in the stability trend was seen.
  – Finally, by measuring 100 consecutive pulses, a 50Hz contribution through the mains is observed.

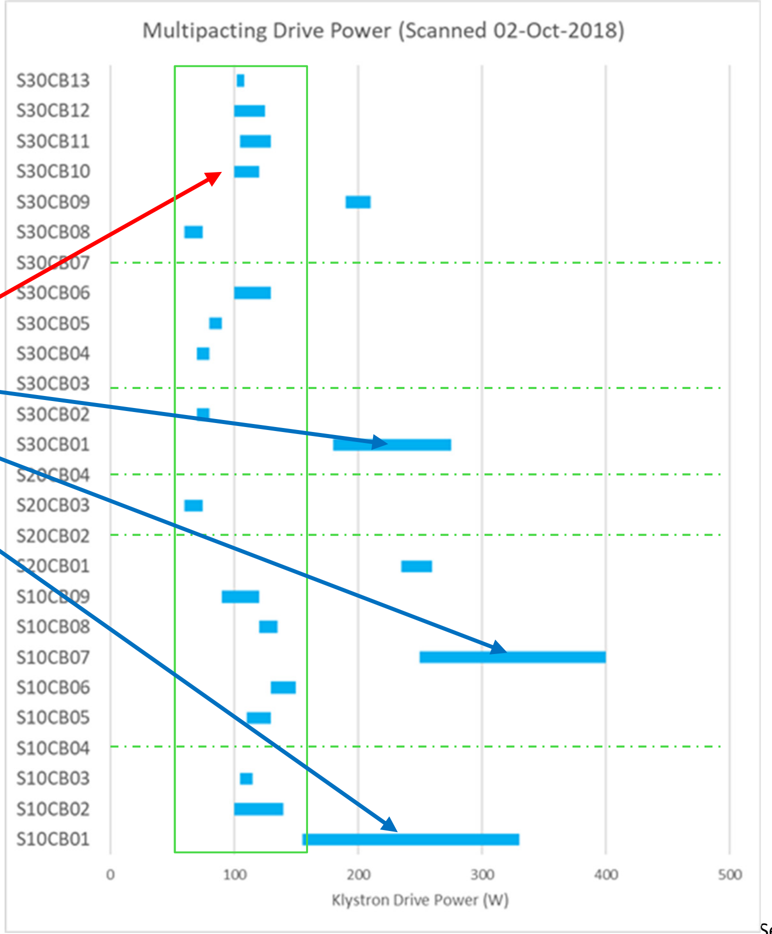
- Feed-forward system to be proposed



C-Band Klystron Instability (1)

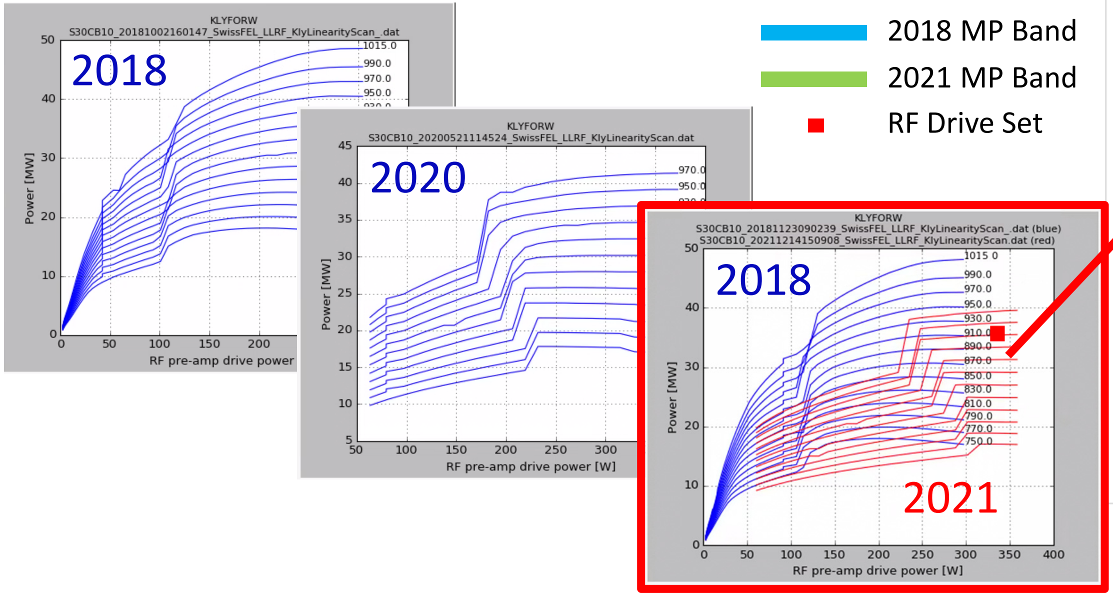
- All klystrons curves are scanned for operation.
- HV and RF Drive Setpoints are determined from the curves.
  - To minimise effect of amplitude jitter **Klystrons are operated in Saturation**
- We observed discontinuities, possibly multipacting (MP) during many klystron scans
  - MP only detected with automated scanning process (fine resolution)
  - Often occurs at fixed and Low drive
  - Few klystrons had MP in regions affecting operation
  - Several Klystrons were MP free. Only 3 had bands of concern

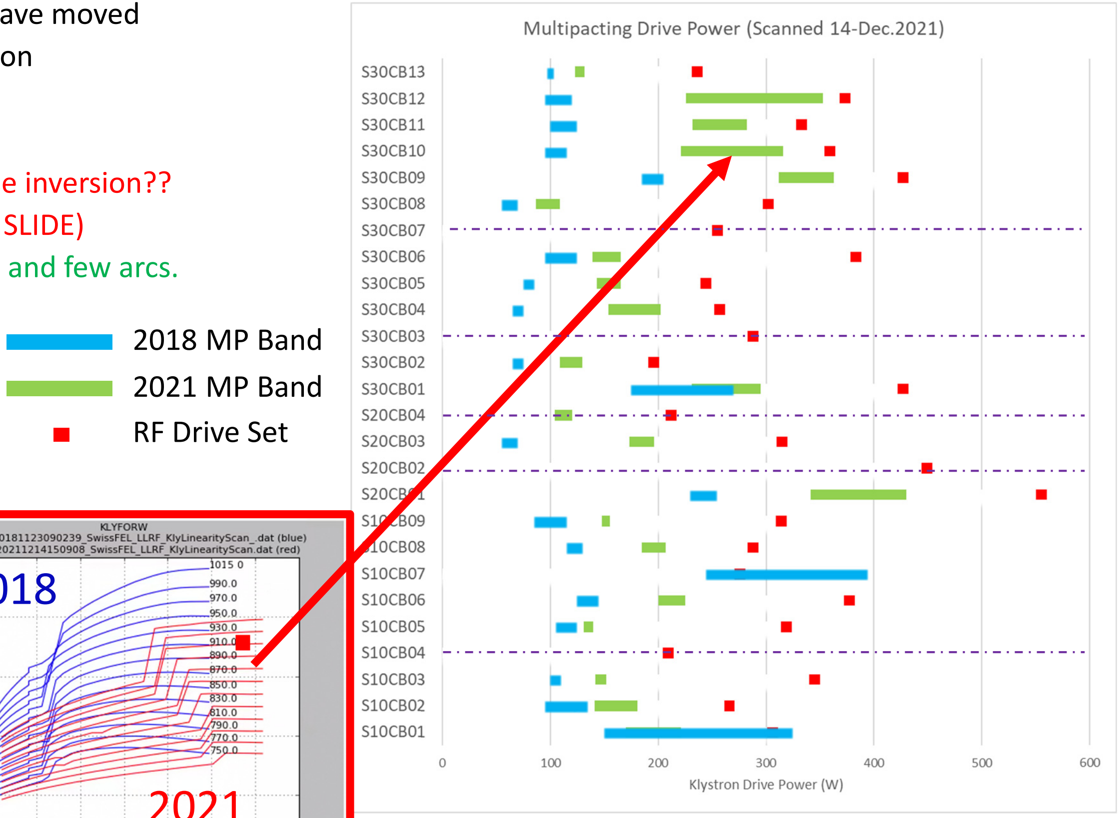




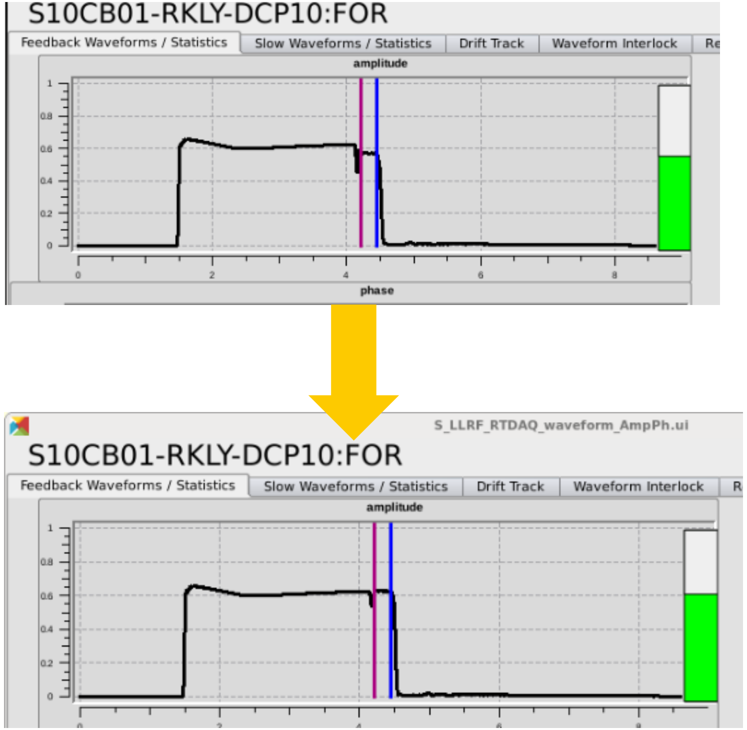
C-Band Klystron Instability (2)

- Over 3 years operation, many of the MP bands have moved
  - Degradation in beam stability the first indication
  - S30CB10 example below
- SACLA operate ~80 E37212 with only 5 issues.
  - Are we inducing the MP klystrons by our phase inversion??
  - Measurement taken at end of RF pulse (NEXT SLIDE)
- E37212’s Averaging 34000 hours with no failures and few arcs.





C-Band Klystron Instability (3)



Phase Inversion Settings

• RF pulse length	3us
• Phase Inversion start	2.6us
• Phase Inversion speed	50ns
• Phase change	180°
• Equivalent frequency shift	10 MHz

- Same klystron voltage, RF drive
- Example: Measured output power jumps sporadically between 28 and 34 MW.

- Not conclusive, but suggestive that the Phase Inversion is causing the long term degradation in the klystron.

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Summary and Next Steps

- **Despite some issues and instabilities, machine availability during user operation ~95.5%**
- Most faults occur during machine development shifts - stress the machine more
- Operation regime favours higher reliability whilst meeting the specified performance
  - All linac stations at nominal accelerating voltage
  - No hot spare, however large overhead available accelerating voltage (in event of Linac failures)
  - Susceptible to multipacting in klystrons and BOC, and klystron arcing.

Aramis beam stability Measurements (RMS):

- Peak current (& bunch length): < 5 % ~6.4 %
- Beam arrival time: < 20 fs <10fs
- Beam energy: < 5e-4 ~2e-4

- Reliability Outlook
  - Exchange S-Band Klystrons (2-3 Years)
  - Injector Redundancy & Eventual Exchange of Injector Modulators (4-7 Years)
  - Further Conditioning of C-Band stations (Improve breakdown rate)

- Performance Outlook
  - Feed Forward – 50Hz Compensation (Injector)
  - Investigation for the root cause of klystron instability (MP)
  - Avoid BOC mulitpacting

Thank you to Contributors

- Many Contributions from RF Section (More specifically)
  - Juergen Alex
  - Paolo Craievich
  - Zheqiao Geng
  - Roger Kalt
  - Tom Lucas
  - Marco Pedrozzi
  - Sven Reiche
  - Riccardo Zennaro

  SwissFEL Operations and Beam Dynamics Team

  Controls Section for the diagnostic tools

  Timing & Synchronisation Section

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- Many thanks to:
- the SPC for the invitation.
- LOC for the excellent organisation.
- (& Congratulations) to Peter, Graeme and Carsten on a great conference