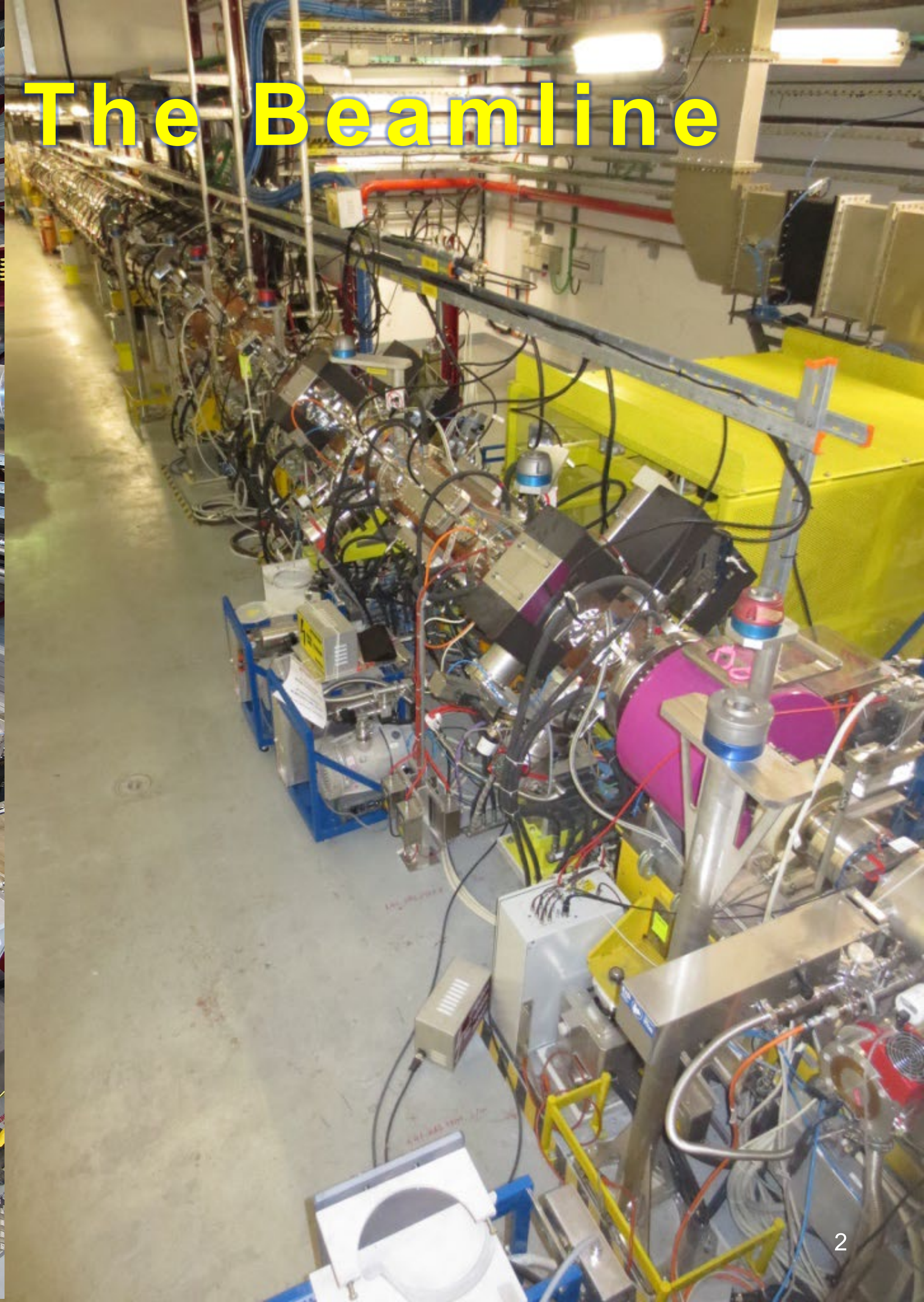
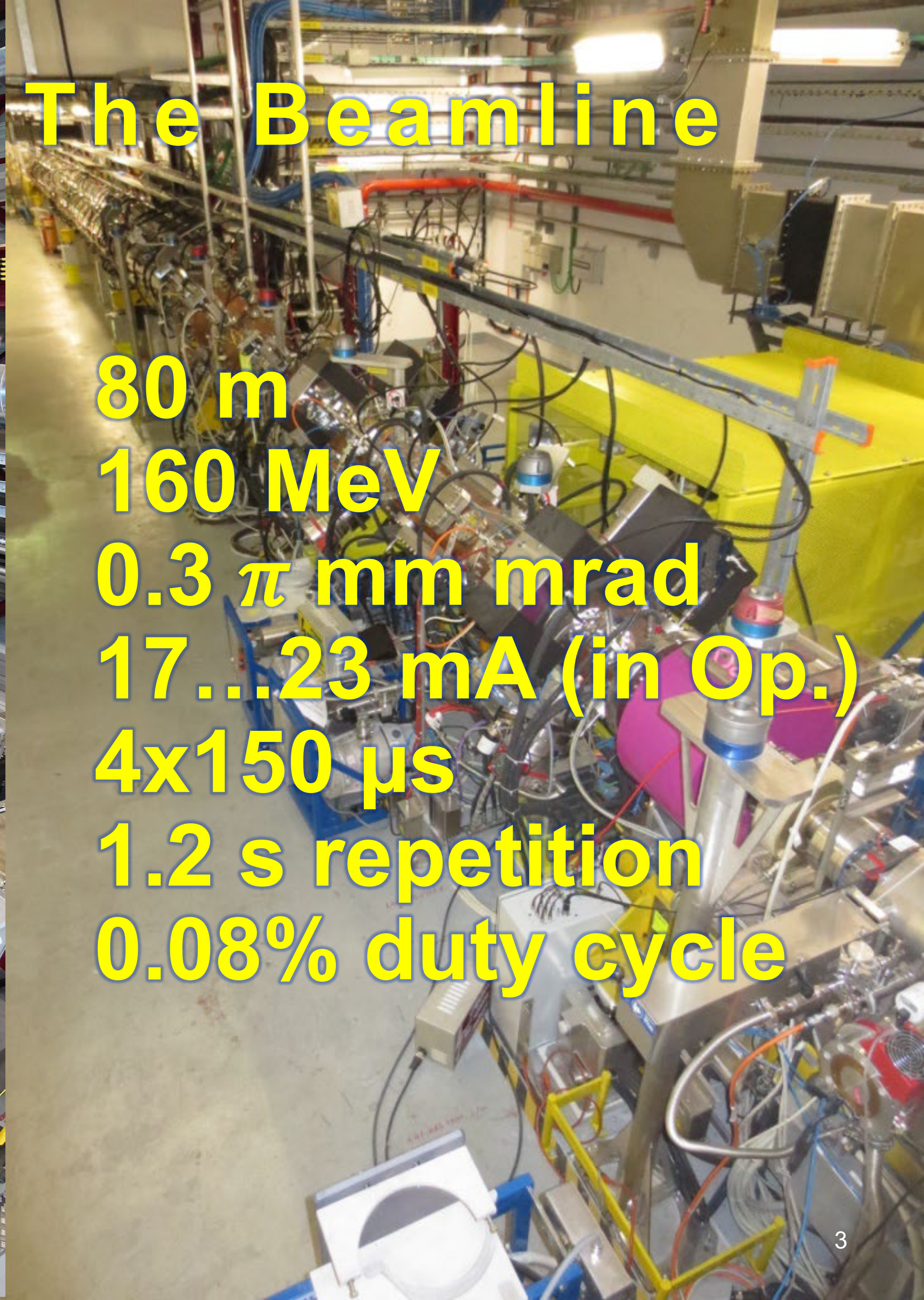
First Years of Linac4 RF Operation

Suitbert Ramberger on behalf of the CERN RF group, and with the support of Rolf Wegner

29 August 2022

The Klystron Hall & The Beamline



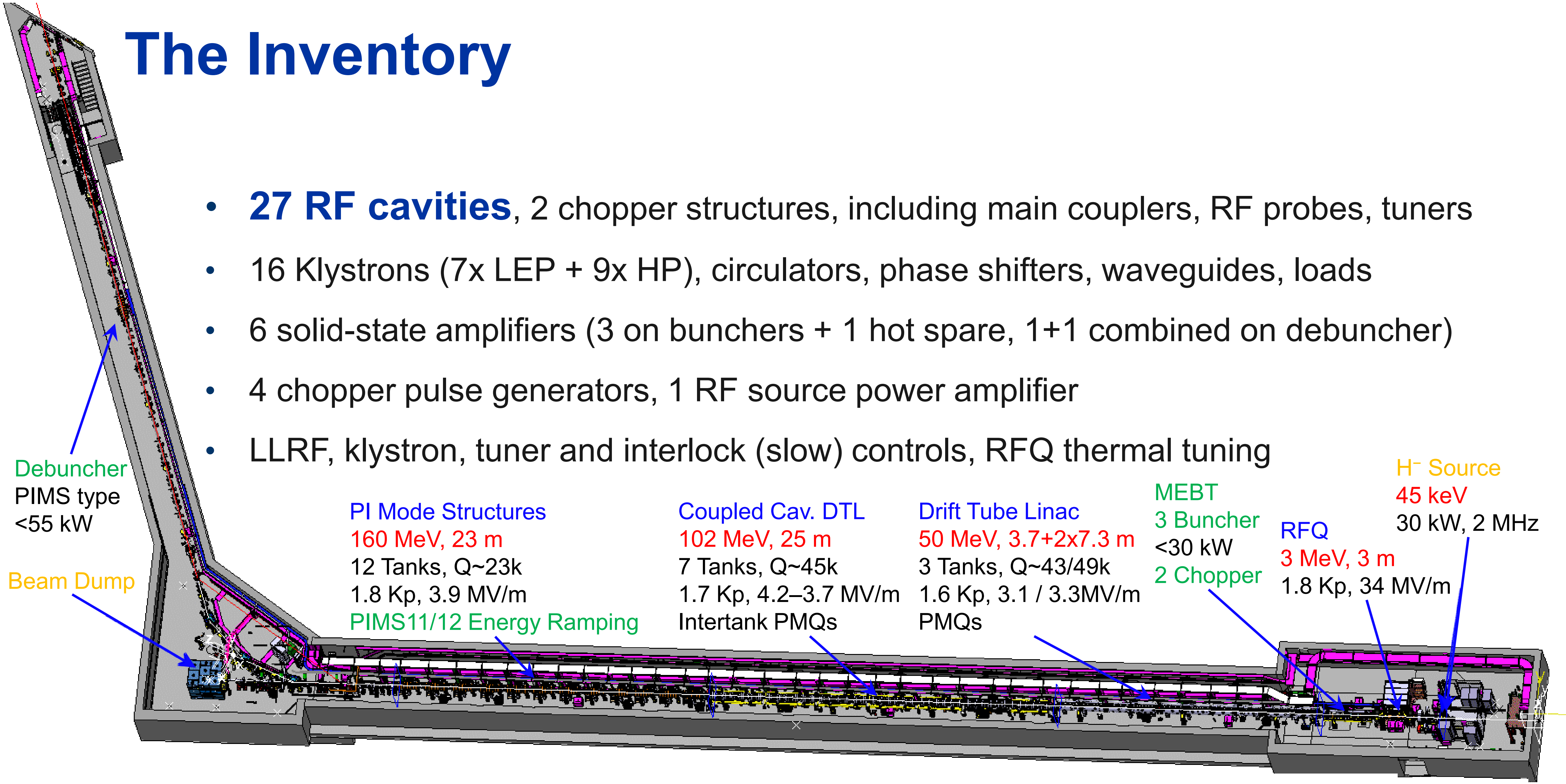


The Klystron Hall & The Beamline

The Klystron Hall	The Beamline
100 m x 12 m	80 m
12 m above tunnel	160 MeV
352.2 MHz	0.3 π mm mrad
7x 1.3 MW LEP Klystrons	17…23 mA (in Op.)
9x 2.8 MW HP Klystrons	4x150 µs
110 kV Modulators	1.2 s repetition
Faraday cage for LLRF	0.08% duty cycle

The Inventory

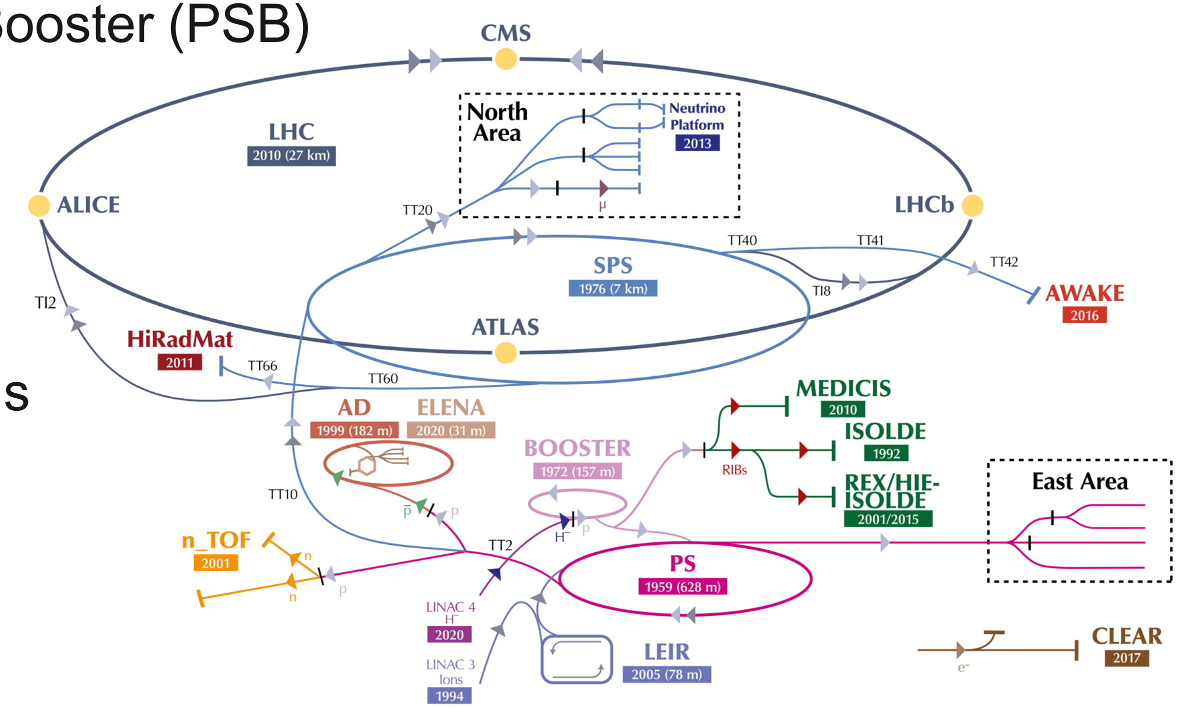
- **27 RF cavities**, 2 chopper structures, including main couplers, RF probes, tuners
- 16 Klystrons (7x LEP + 9x HP), circulators, phase shifters, waveguides, loads
- 6 solid-state amplifiers (3 on bunchers + 1 hot spare, 1+1 combined on debuncher)
- 4 chopper pulse generators, 1 RF source power amplifier
- LLRF, klystron, tuner and interlock (slow) controls, RFQ thermal tuning



The Clients

- Linac4 is at the start of the proton injector chain
- Linac4 delivers H⁻-ions to the Proton Synchrotron Booster (PSB)
- The PSB is the master for the injection

- Charge exchange injection into the PSB (4 rings)
- Energy painting to fill PSB buckets in up to 150 turns
  - Last two PIMS cavities for energy ramping
  - Debuncher for energy spread variation
  - Synchronisation with the chopper unit



- Serves the LHC, the AD, the ISOLDE complex, and fixed target experiments

The Challenge: 95% Availability at Start-Up

Availability

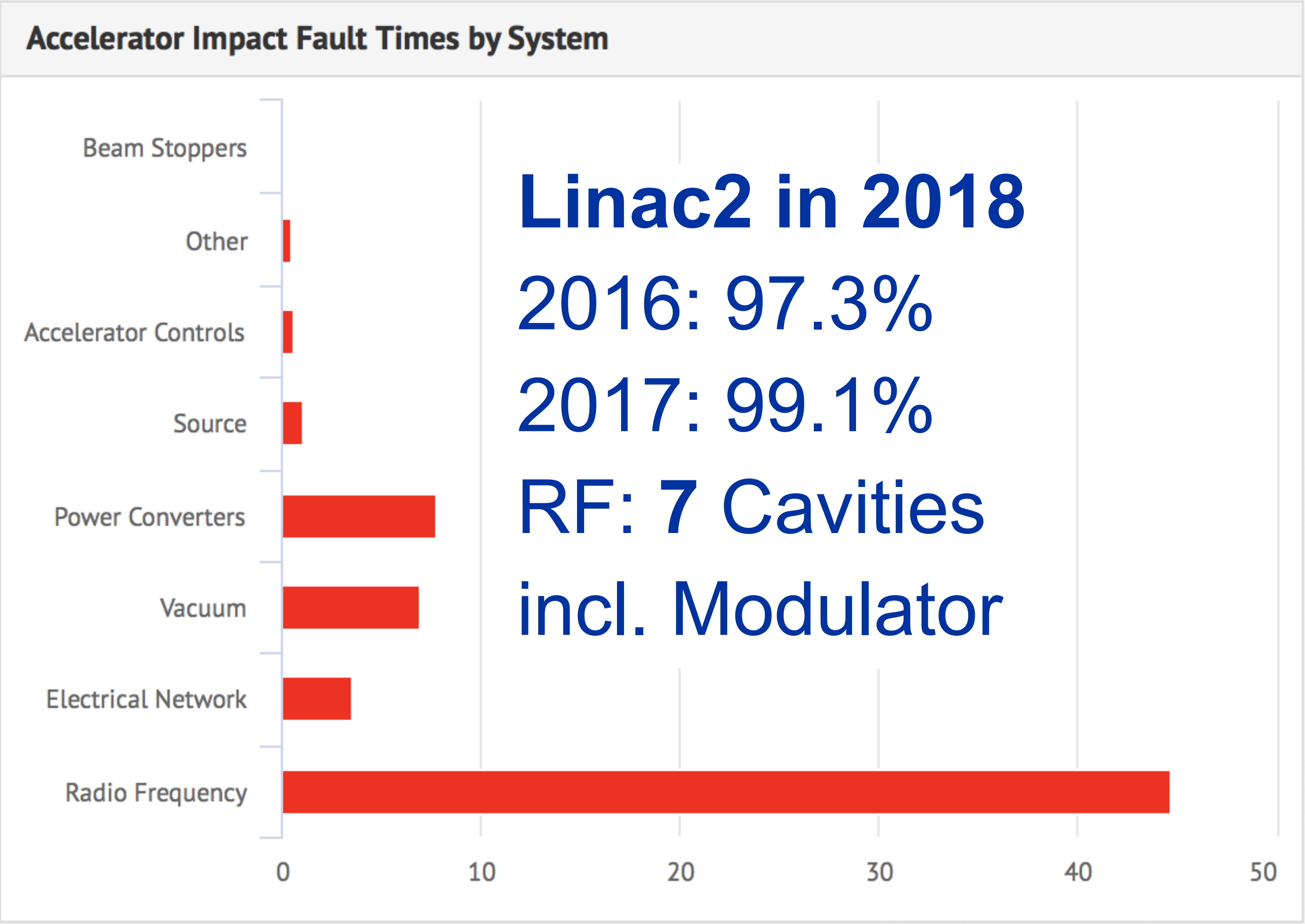
99.0%

Fault count

65

Fault Labels for LINAC2

- AWG Notable Fault
- TIOC



Linac2 in 2018

2016: 97.3%

2017: 99.1%

RF: **7** Cavities

incl. Modulator

The Organisation

- Key to the success of Linac4 is the dedication of all contributors
- 4 (earlier 6) sections of the RF group working together (klystrons, controls, feedback, linacs)
- Tight collaboration with other contributors: cooling, mains electricity, power converters, vacuum, general controls, beam physics, operation, and many more
- 24/7 piquet teams: three in RF for klystrons, HLRF & LLRF, lists of experts

- An RF coordinator in the RF group
- A team of 9 Linac4 machine coordinators – 3 OP, 3 ABP group, 3 equipment groups (1 from RF)

- Daily and weekly coordination meetings
- A tight follow-up of issues
- Regular yearly maintenance (Klystrons, RF Amplifiers, Water Sensors)
- Software tools to support this: e-Logbook, Accelerator Fault Tracking, Impact, etc.

The Timeline

First Beam Milestones (Beam Physics Group)				
3 MeV	12 MeV	50 MeV	107 MeV	160 MeV
RFQ at test-stand	1 DTL	3 DTL	7 CCDTL + 1 PIMS	12 PIMS
13 March 2013	5 August 2014	26 November 2015	1 July 2016	25 October 2016

Linac4 Beam Commissioning Runs (Beam Physics Group)				
Half Sector Test		Reliability Run		
Oct. – Dec. 2016	Feb. – Mar. 2017	July – Sep. 2017	Oct. – Dec. 2017	April – May 2018
	During EYETS	Debuncher Inst.	⇒ YETS	

Linac4 Beam Commissioning Runs (Operation Group)			
Towards Operation Run	LBE Meas. Line Tests	Run3 Beam Commiss.	Run3 (LHC from 2022)
Sep. – Dec. 2018	Oct. – Dec. 2019	Aug. – Dec. 2020	Jan. 2021 – Dec. 2025
⇒ LS2			

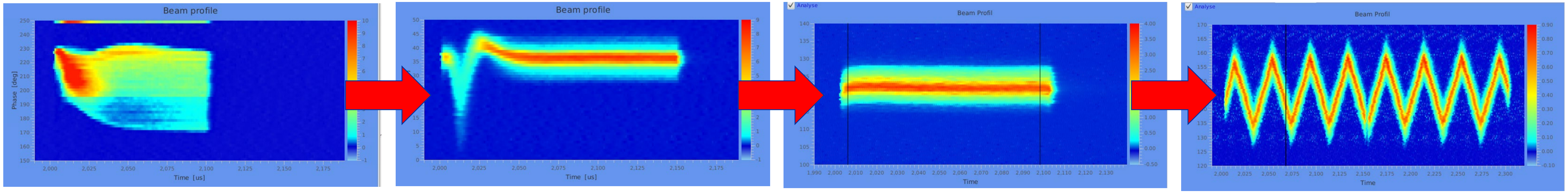
Linac4 Tunnel ⇒ Transferline ⇒ Beyond towards PS Booster Injection

Hardware Availability ⇒ Beam Availability ⇒ Beam Quality

The LLRF System

P. Baudrenghien, B. Bielawski and R. Borner, "Low-Level RF Control Algorithms for the CERN Proton Linac4", TH1AA06, this conference, 2022.

- Complex system: Long loop distances (100..150m), and up to ~30% beam loading
- Beam loading compensation: Kalman Predictor and Adaptive Feed-forward (AFF)
- Pulse-to-pulse modulation (PPM)
- Completely new hardware and firmware (existing libraries), required debugging a few versions
- Critically perceived: parameter persistence and phase variations, required rephasing
- Debugging of controls interfaces, hardware upgrades, RF probe exchanges, etc.



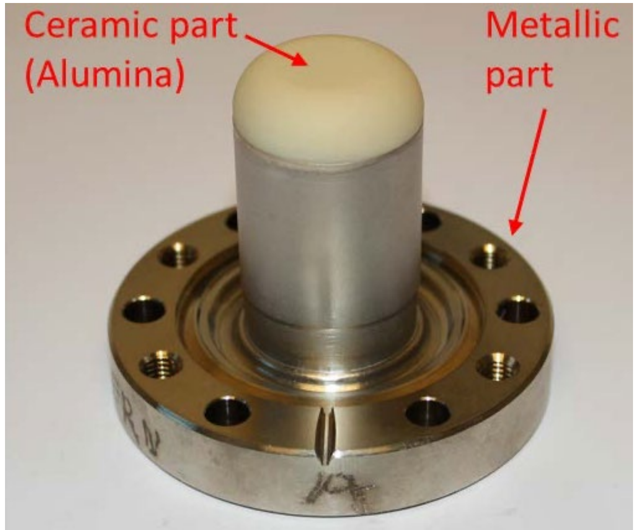
RF probe windows damaged by breakdowns

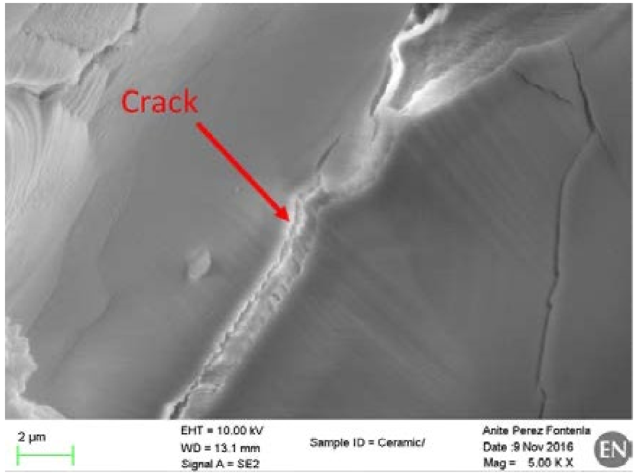
30 November 2015 – 2 August 2018

- Sporadic failures with vacuum leaks during conditioning
- Became more and more regular with operation
- Breakdown activity damages the ceramic vacuum window
- Pattern: Big cavities showed more issues than smaller ones
- Correlated with cavity stored energy (24J on DTL Tank3)
- Material tests before and after confirmed breakage of ceramic.

Solution:

- Redesign of RF probes with retracted commercial coaxial feedthrough
- Some RF probes are calibrated. Required coordinated exchange
- Since then no vacuum leak





Arc detector control logic with R2E issues

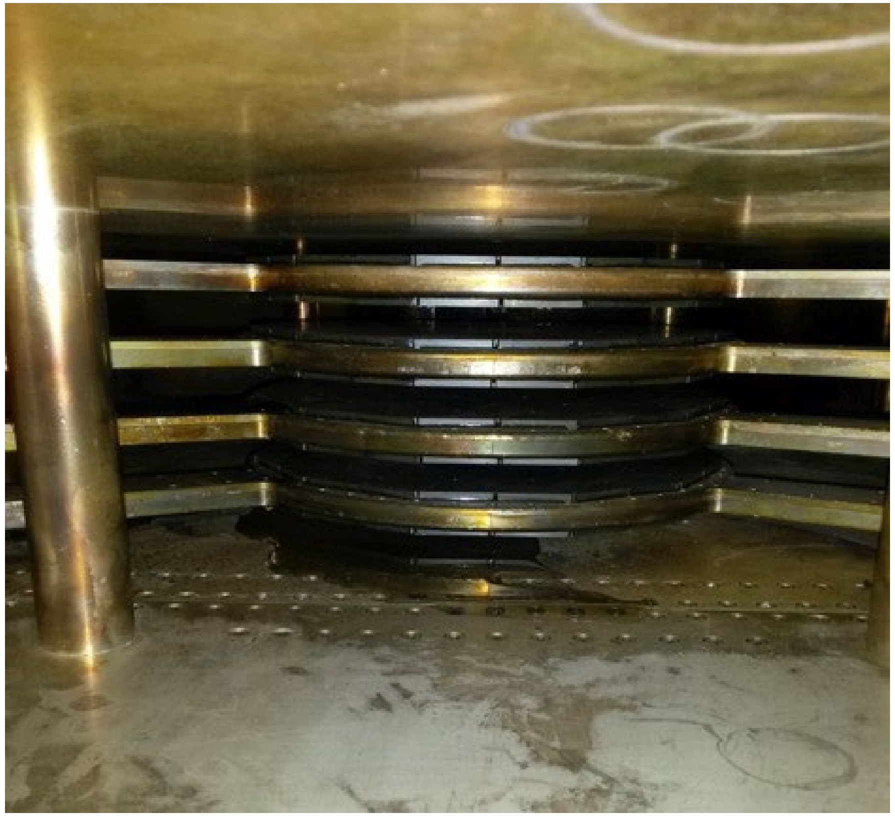
17 July 2017 – Summer 2018

- Light detectors installed in corners of hollow waveguides, interlocking the operation.
- Two-part systems. Detector unit built radiation hard, control logic not, but long cables are ok.
- Rearming required access to the tunnel.
- Correlation with beam energy and beam intensity. Only issues above 50 MeV.
- Two options:
  - a) Move and shield control logic locally in the tunnel, and if required redevelop radiation hard version.
    - Modifications can be introduced stepwise as required at different energy levels.
  - b) Move control logic away from the tunnel to the klystron hall
    - This is easy to do but laying cables and moving electronics comes at upfront costs.
- Bold decision to get rid of the issue reliably going for option b). The issue was quickly resolved.

Circulator Cooling

29 October 2020 – 16 November 2020

- Phase drift on PIMS02
- Water leak developed on circulator of PIMS01
- Both cavities powered by the same klystron
- Phase and amplitude only of PIMS01 stabilized
- Small and inside, only discovered few weeks later
- The water cooling was removed (low duty cycle!)
- Phase stopped drifting but remained unstable



Solution:

- Cool circulator by temperature controlled air-flow
- Stabilize cavities on vector sum of cavity voltages

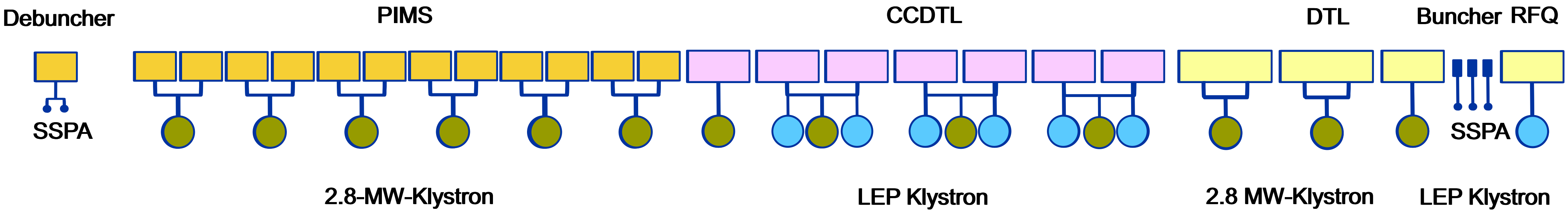
The Spares

The spares policy has direct repercussions on the Mean Time To Repair (MTTR)

RF redundancy in linacs is limited as all **cavities** are **unique** and need to be **always operational**

- Spare Buncher Amplifier and RF Patch Panel – make the most of spare material
- Debuncher Amplifiers – coupling of amplifier 2 racks, can be run as single units, degraded beam
- Spare Chopper Structure – 2 structures installed. – What is the minimum number of spares?
- Various Spare Ancillaries
- **Klystron Spares** – a strategy reviewed a few times to fit the available beam currents
- **Spare RFQ Project** – RFQ2 currently being built in CERN workshops

The Klystron Strategy

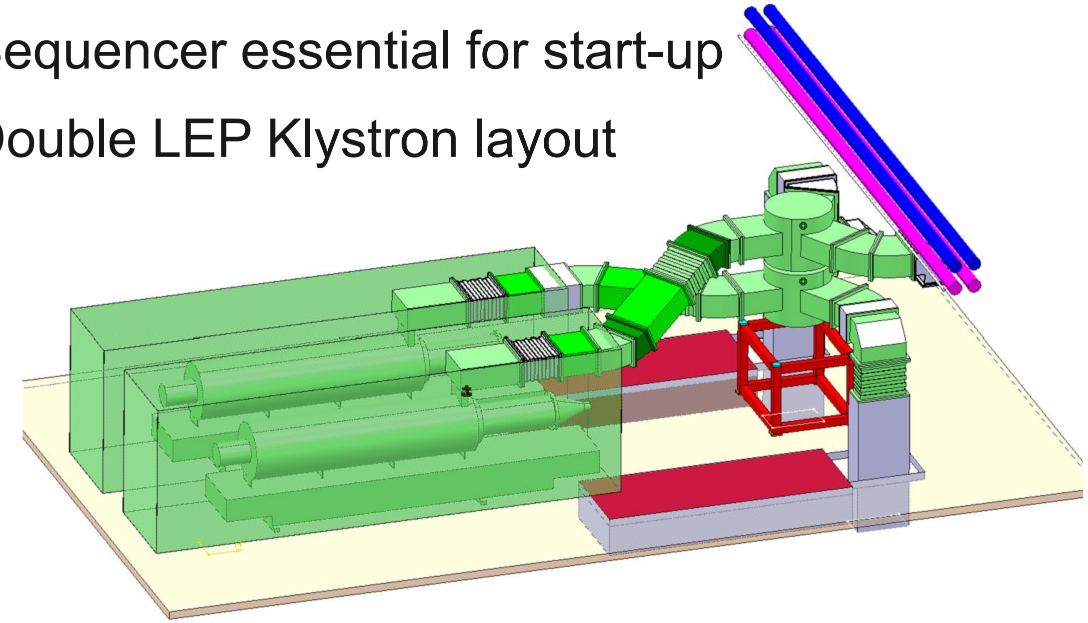


In 2019, change 4x100µs ⇒ 4x150µs beam. Going from 25mA to 40mA of average beam.

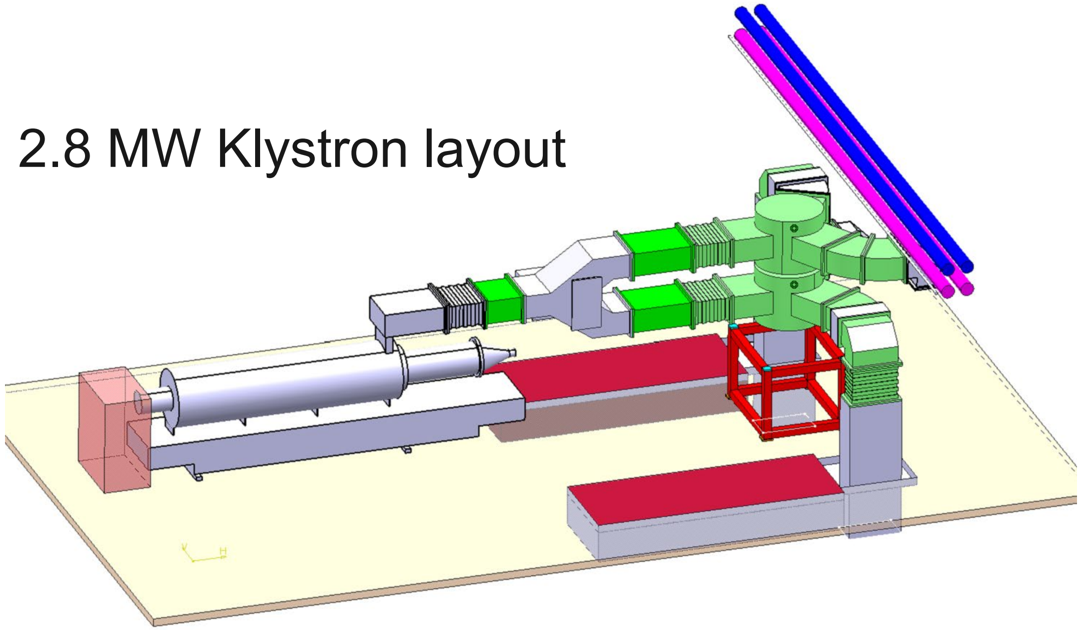
2 klystrons broke and were sent for repair, one 2-to-1 exchange

Sequencer essential for start-up

Double LEP Klystron layout

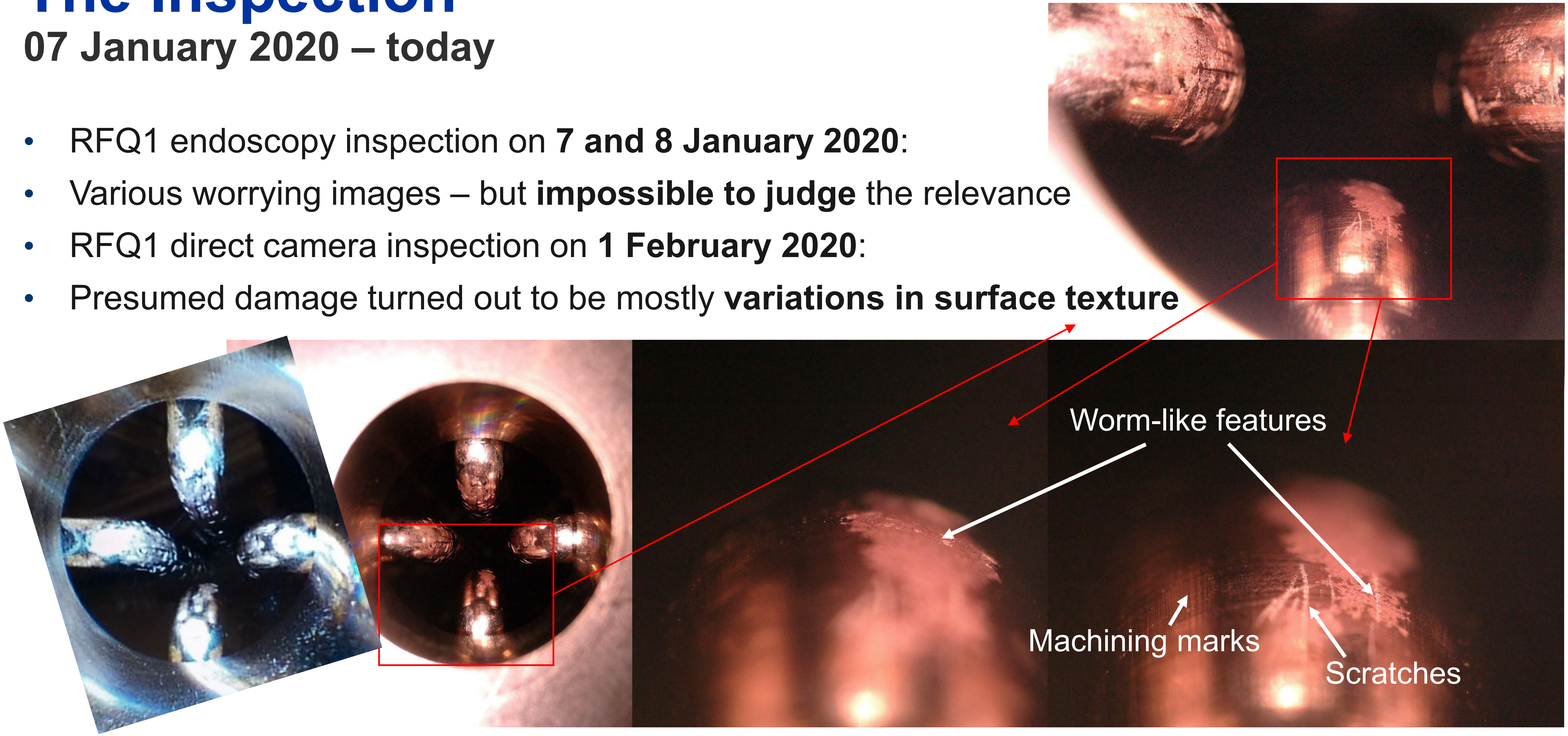


2.8 MW Klystron layout



The Inspection
07 January 2020 – today

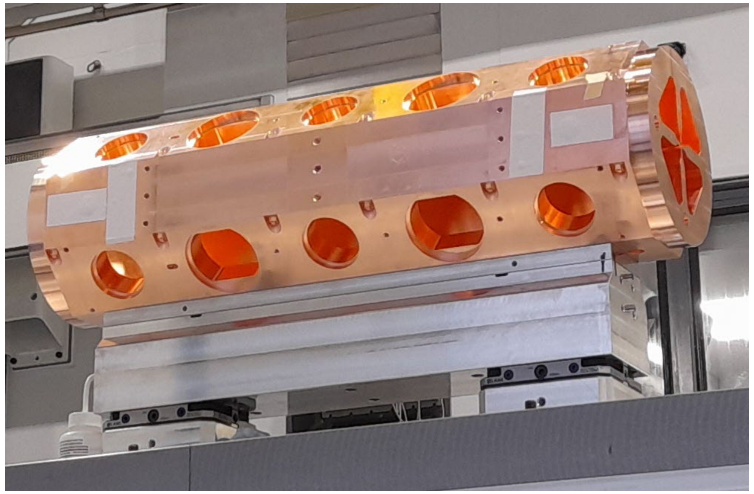
- RFQ1 endoscopy inspection on **7 and 8 January 2020**:
- Various worrying images – but **impossible to judge** the relevance
- RFQ1 direct camera inspection on **1 February 2020**:
- Presumed damage turned out to be mostly **variations in surface texture**



The Measures Taken

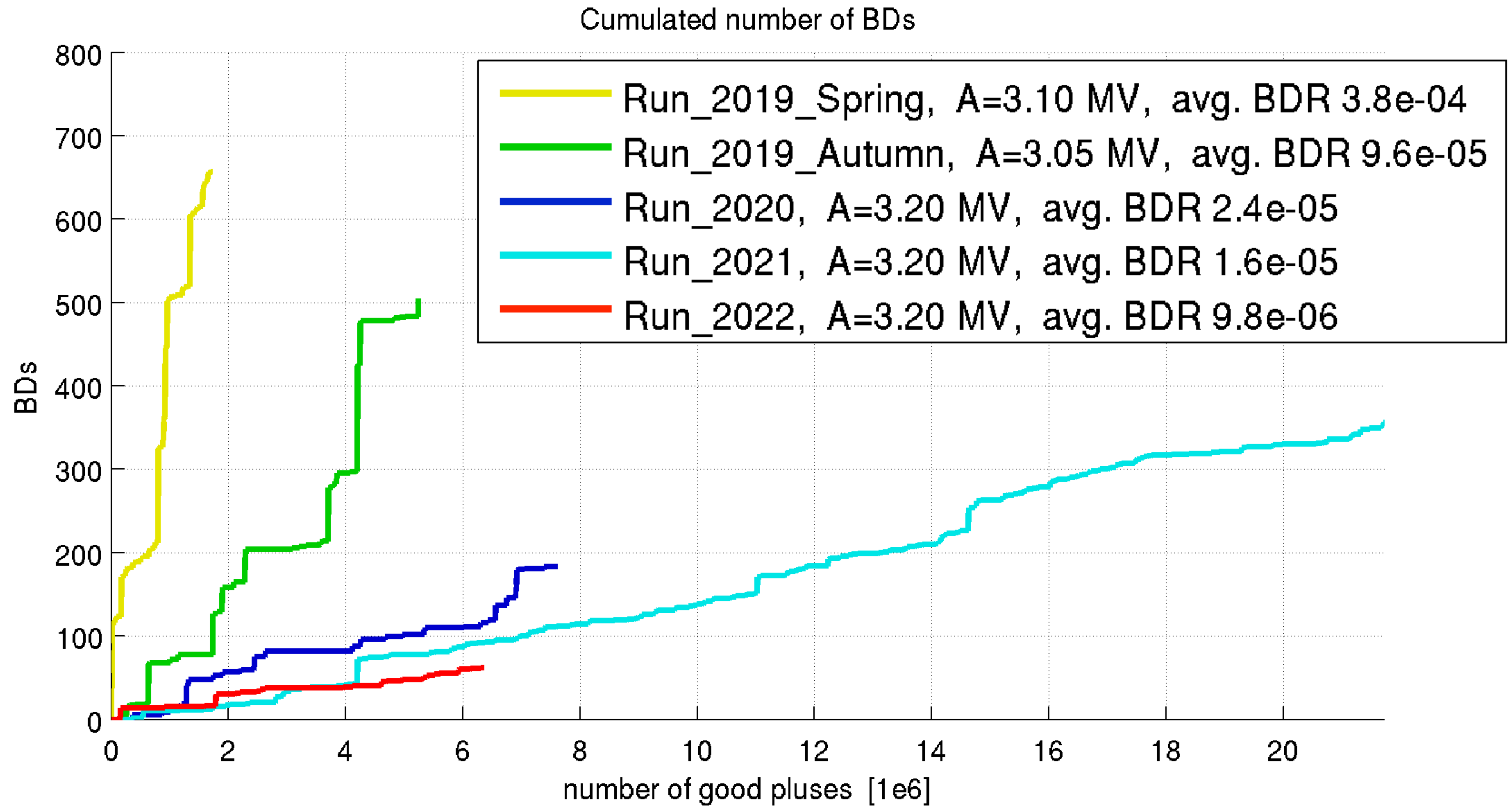
H. W. Pommerenke et al., “Beam Dynamics and RF Design of the New RFQ for CERN Linac4 Upgrade”, TUPOPA10, this conference, 2022.

- Improvement in beam steering: Steering magnet settings were restricted
- Collimation – was found not to be effective
- Decision to **build a spare RFQ**: RFQ2
  - 4-vane RFQ is built “monolithically” – there are no individual spare parts
  - A detailed risk analysis had been established early in the Linac4 project
  - RFQ1 is reasonably close to operationally acceptable BD limits
  - RFQ2 is being built as a near carbon copy of RFQ1



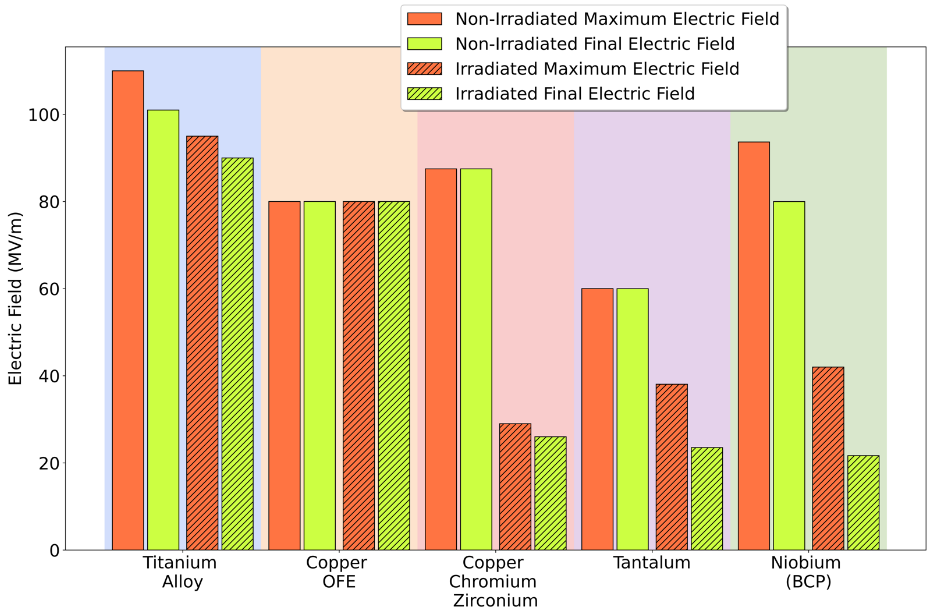
- Implementation of a **breakdown protection**:
  - Pulse to pulse inhibit in case of breakdowns and power ramping
  - Level dependent reconditioning according to number of breakdowns
- Started a **material study** to better understand surface changes and for any future RFQ (RFQ3)

The RFQ Breakdown Protection

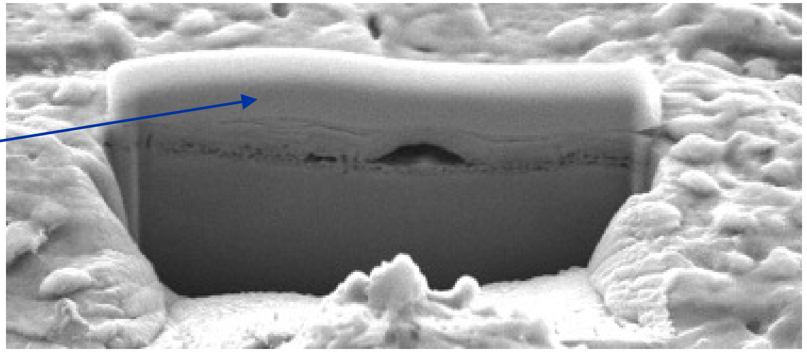


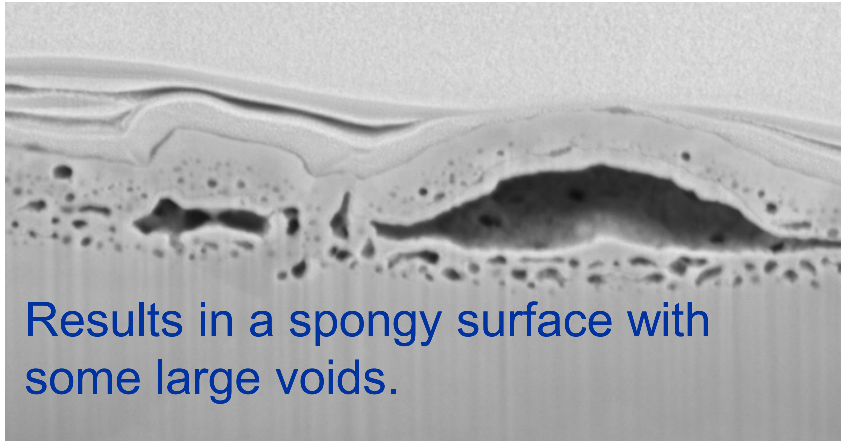
The Material Studies

- Hydrogen implantation into copper
- In OFE-Cu samples accumulates in bubbles
- Process of blistering as reported in literature
- Seen as change of surface texture
- Material irradiation/breakdown test programme
- Effect on breakdown statistics studied



Pt deposit to protect the surface during ion milling





Results in a spongy surface with some large voids.

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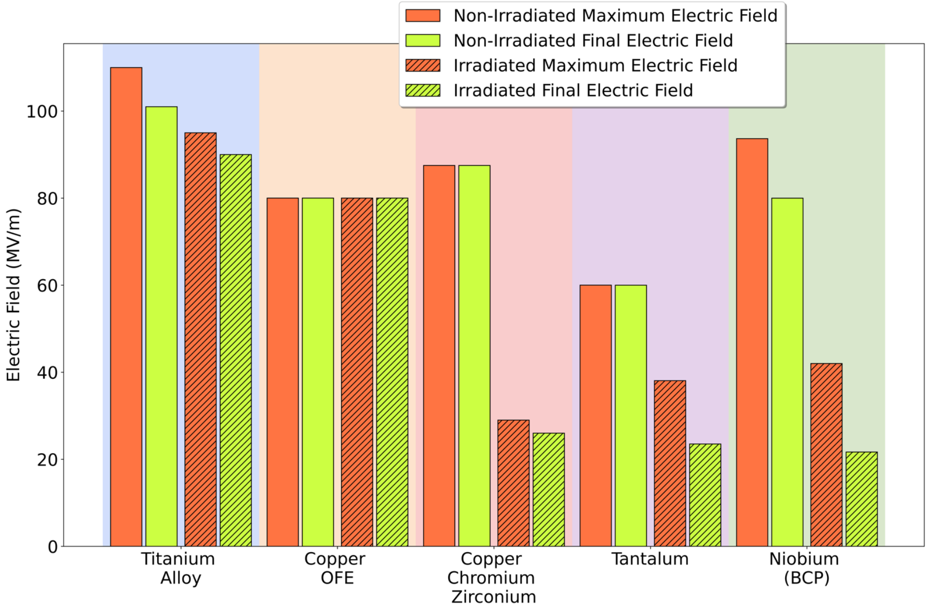
R. Peacock et al., "Pulsed DC High-Field Measurements of Irradiated and Non-Irradiated Electrodes of Different Materials", TUPOPA13, this conference, 2022.



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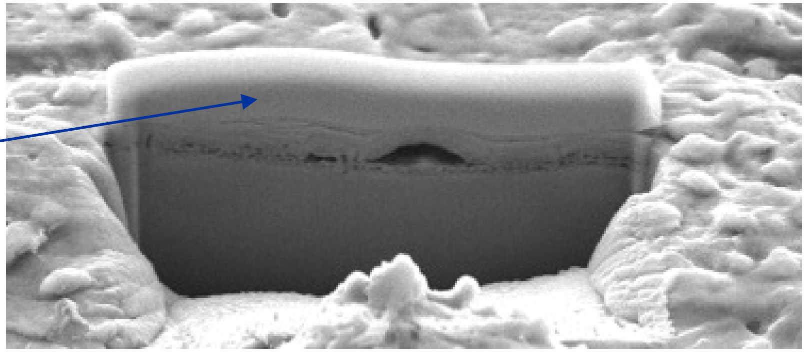

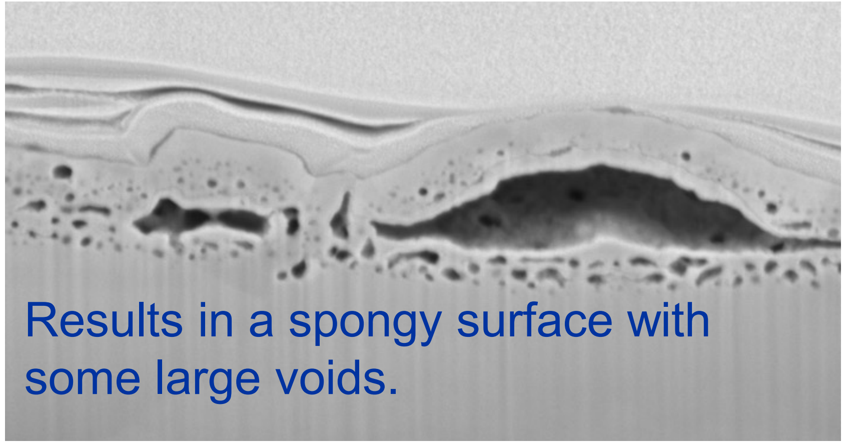

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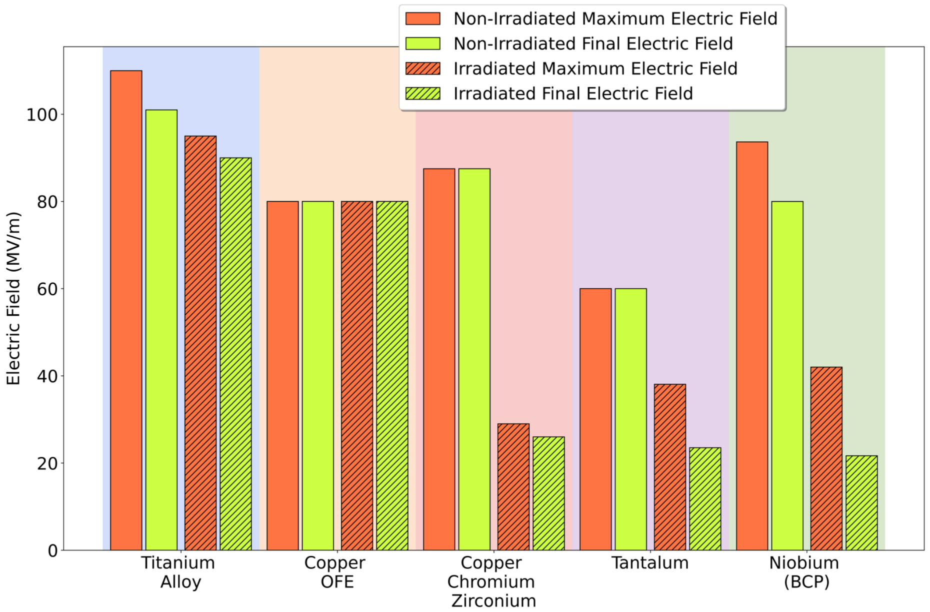
C. Serafim et al., "Microscopy Investigation on Different Materials after Pulsed High-Field Conditioning and Low Energy H-", TUPOPA06, this conference, 2022.



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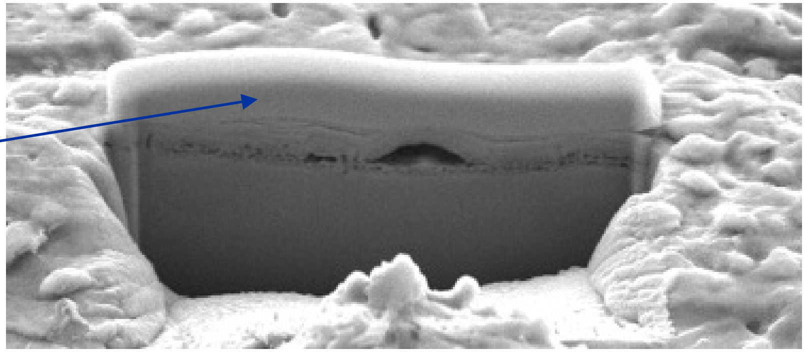
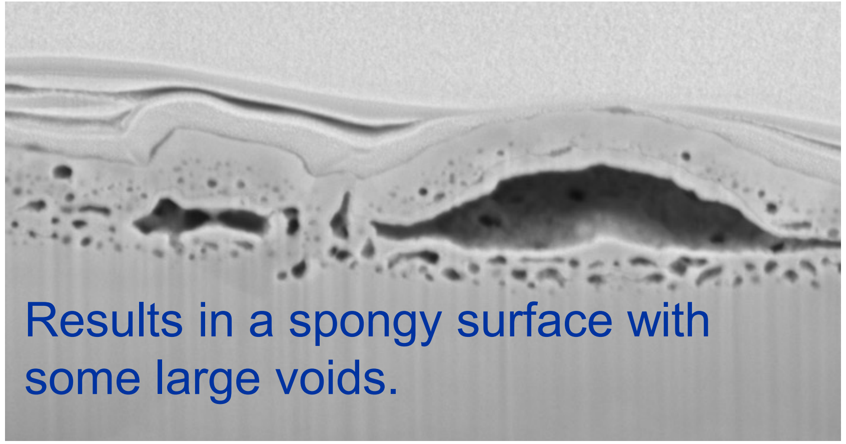
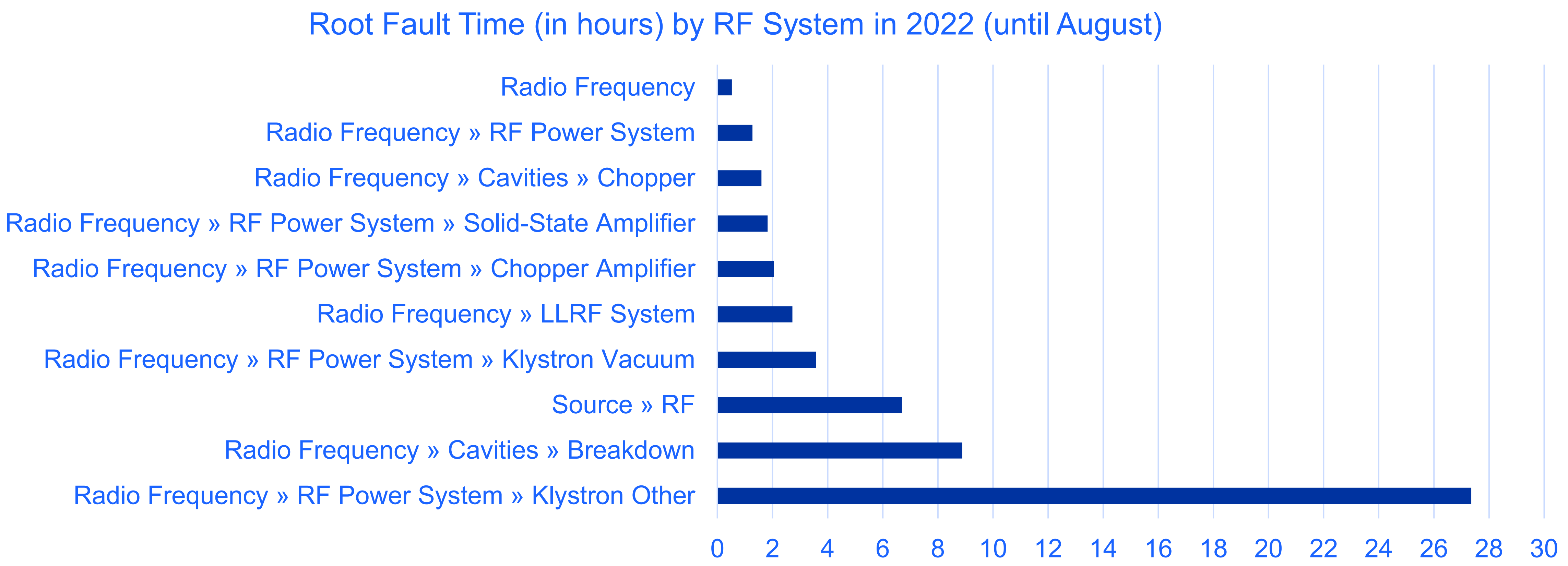




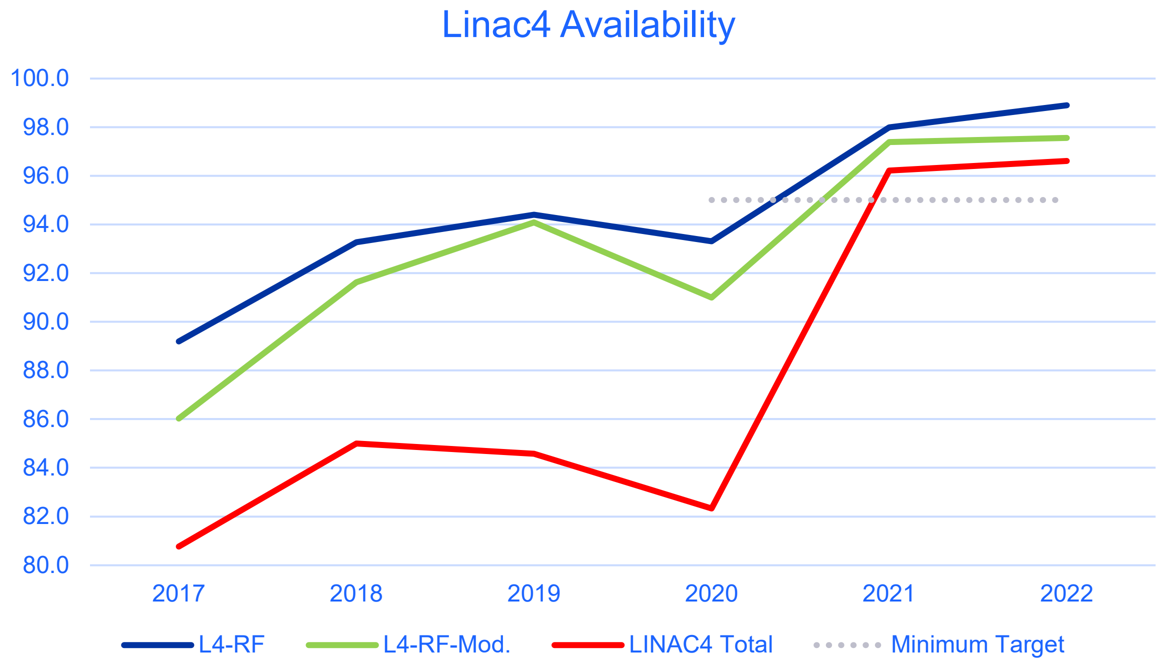
Fault Tracking in 2022



- Most faults are on HV systems and many of these are due to high field breakdown
- New chopper driver & source solid-state amplifier studied. LEP klystron replacements in due time.

The Summary

- Hardware Availability ⇒ Beam Availability ⇒ Beam Quality – Increasing requirements
- **95% target** with full beam quality **reached**, – we know, we can go beyond
- 2-3 months of runs with technical stops were essential for reaching the target
- Data persistence, phase stability
- Quick recovery & restart after stops
- Sorting out issues needs **time & persistence**
- With **dedicated teams** and **tight follow-up**



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