Status and Results from CERN's High-Gradient (SPL) RF Testing Program

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on behalf of

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Acknowledgements:
Nuria Valverde Alonso, Antoine Benoit, Sauro Bizzaglia, Max Gourragne, Christophe Jarrige, Pablo Fernandez Lopez, Szabina Horvath-Mikulas, Gabriel Pechaud, Francois Pillon, Mathieu Therasse

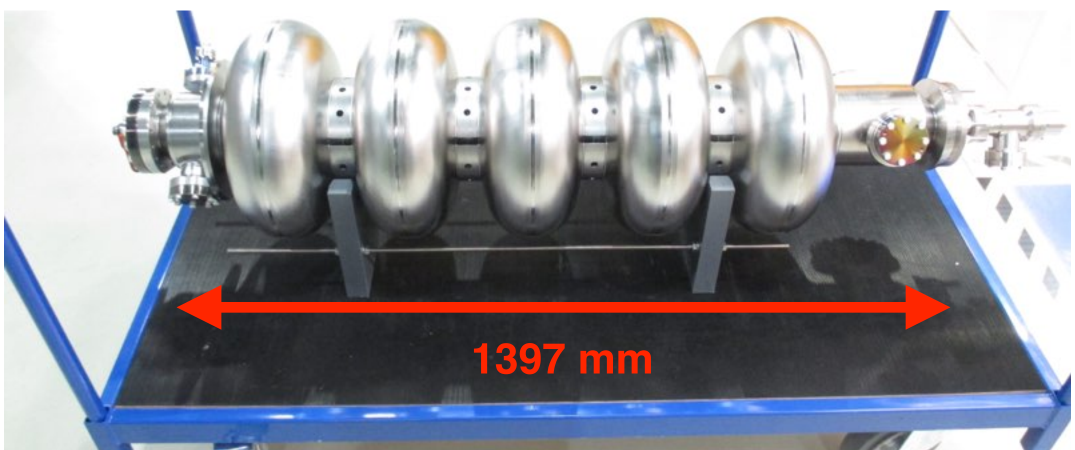
CERN's High Gradient (SPL) Program: Overview

- Four 5-cell Bulk Niobium β=1 cavities produced in industry
  - Test progam: mid 2014 till present

- Required cavity specifications

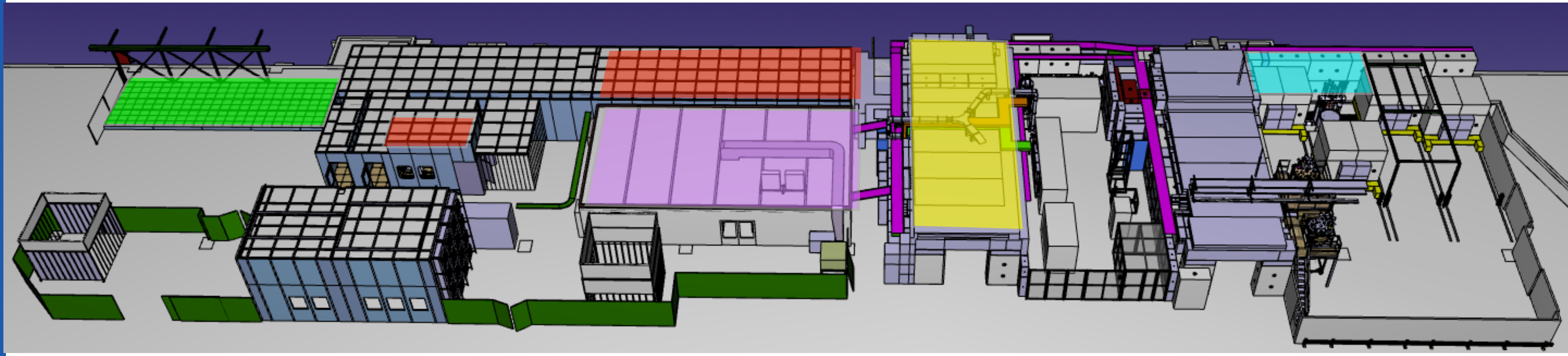
  E_{acc} =25 MV/m Q_0=1 x10^{10}

- Chemistry, preparation & testing:
  - Done entirely at CERN
  - Cold Tests at 2K in vertical cryostat
  - All measurements: **CW Operation**



SM18 Facilities: Identification of Working Space

- Cleanrooms: ISO4 for FPC & HOM Mounting and String Assembly
- External rail system: Cryostating of assembled string
- Horizontal Bunker: Test of Cryomodule - Power from adjacent zone
- Vertical cryostats: V3 & V4 for testing of bare and dressed cavities
- Control room: Faraday cage with measurement stands + LLRF



CERN's SM18 facility is becoming increasingly available in 2016

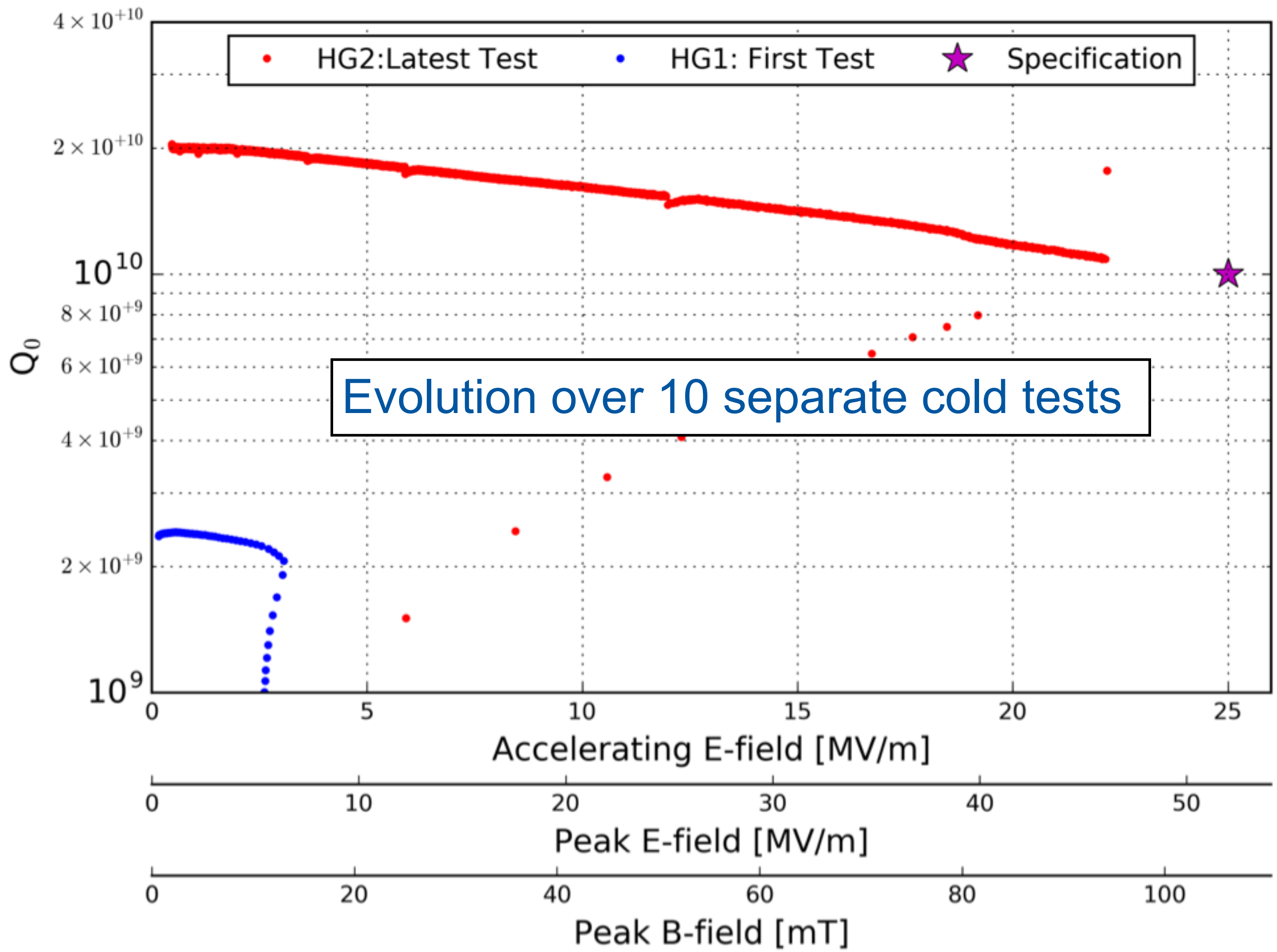
- progress in bare cavity testing
- upgrading of cryomodule testing infrastructure
- Acquisition and validation of cleanroom tooling for cavity handling

CERN's High Gradient (SPL) Program: Results Overview

- **Significant progress in achievable cavity performance**
  - Preparation & testing process now well understood
  - Opinion: Specification target is now attainable.

March 2016

September 2014



Cavity Preparation

Cavity Preparation Process

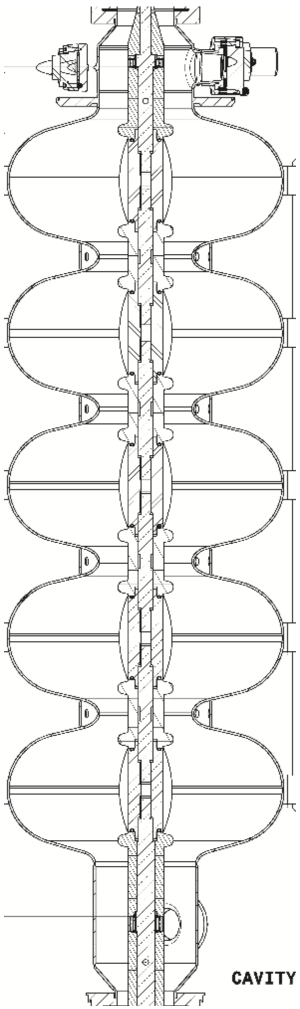
- **Chemistry**:
  - **Electro-polishing of 160 um (average)**
  - **Heat treatment:** 650 degree for 24hrs
  - Light Electro polishing of 20 um (average)
  - Degreasing & ultrasonic bath. Cavity double-bagged in N_2 for transport
- **HPR at 60 - 100 bar with ultra pure water**
  - Conductivity >18MΩ/cm TOC$_{in}$ < 10 ppb Water Temperature : 26°C
  - **Drying**: 48 hrs in laminar clean air flow (ISO4 cleanroom)
  - Optional: Drying in 100^{o}C nitrogen flush for 20 min
- **Cavity Assembly in clean room**
  - **Done in ISO-4 cleanroom.** Pump down within 8 hrs after of assembly
  - Optional: Bakeout at 120^{o}C for 48hrs
- **Mounting of cavity on cryostat insert**
  - Pumping line connection done in-situ but with in controlled laminar flow

Electro-polishing

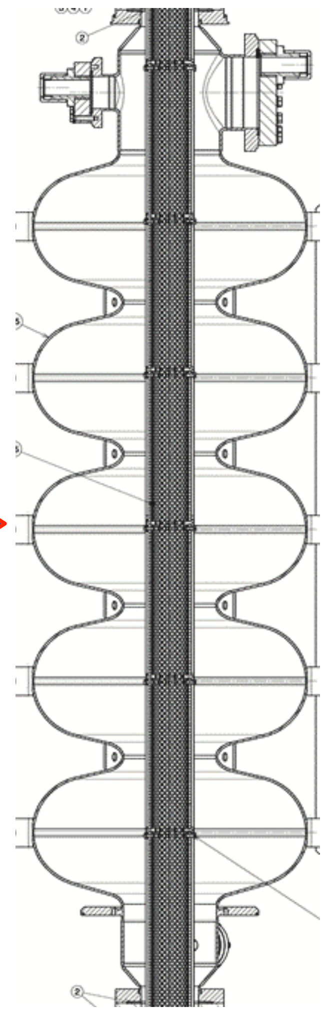
- **Observation**: Chemistry on first cavity was **unsatisfactory** and cavity performance was limited by high field emission
  - Triggered redesign of electro-polishing cathode
    - **Result: Much improved surface finish for HG2 & HG3**

Electro-polishing: Cathode Evolution

- Evolution of the electro-polishing Cathode



OLD

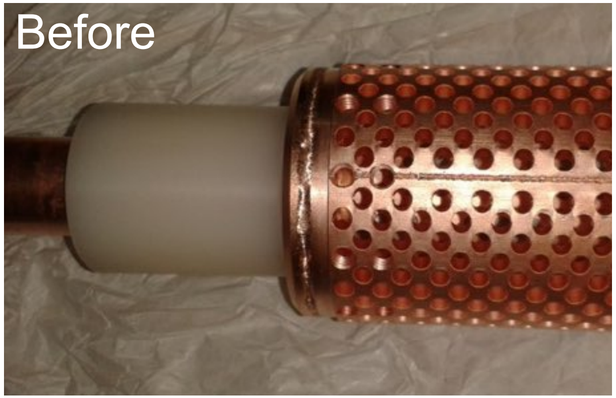


NEW

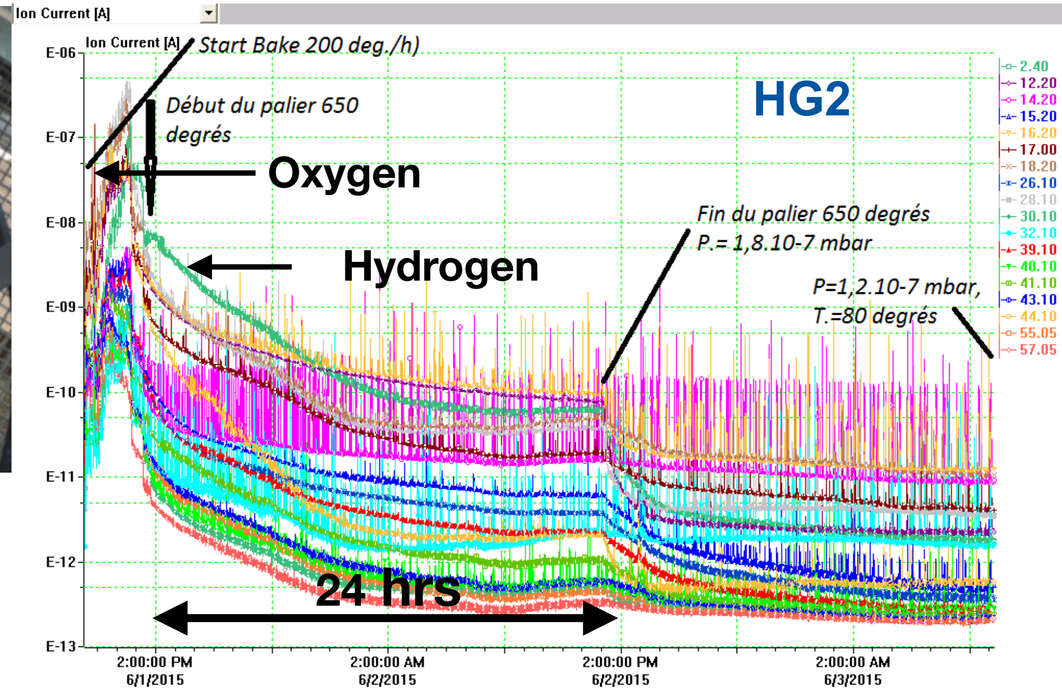
SLHiPP - 23 May 2016

Electro polishing: Experience with New Cathode

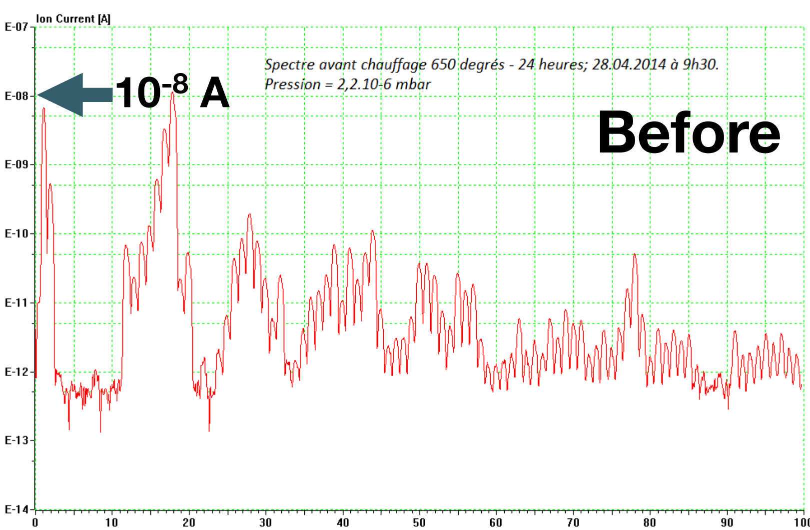
- **HG2: EP with copper mesh cathode.**
  - Good surface finish, but issue with clogging on cathode
  - flakes fall onto cavity => partial etching gives rougher surface
- **Move to Aluminium cathode => Clogging issue resolved**

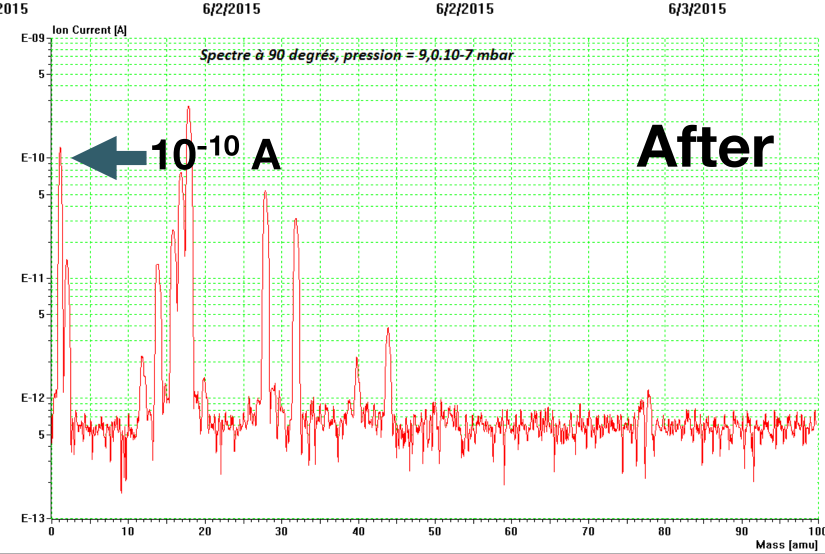


Thermal Treatment: 650 °C for 24hrs



Same thermal treatment as SACLAY cavity





HPR and Contamination Sources

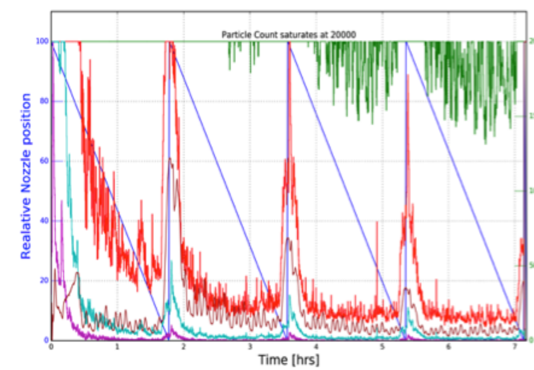
High Pressure Rinsing

- HPR system has now been optimised for performance

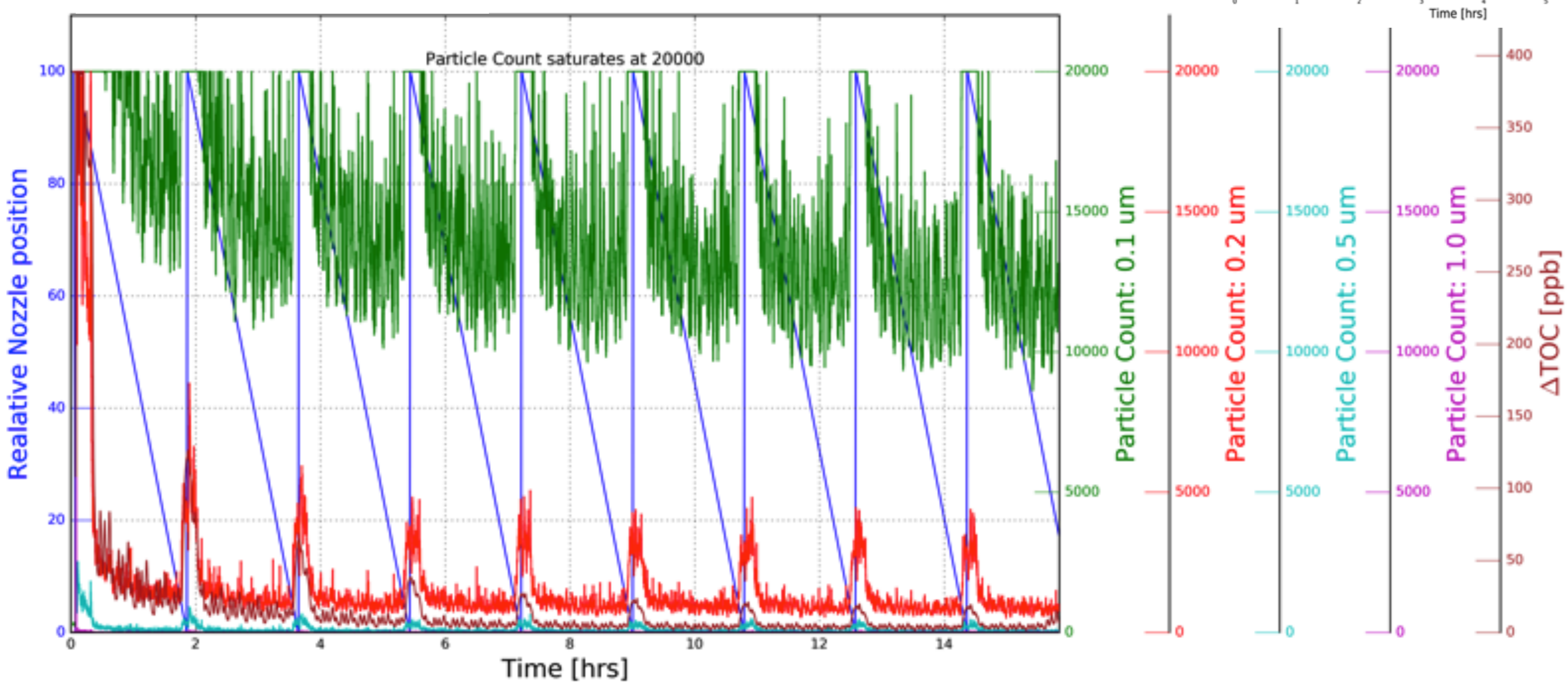
High Pressure Water Rinse

- **Rinsing procedure extended**
  - For HG1 -> **8hrs** while for HG2 -> **~60 hrs**
- **Water quality carefully monitored**
  - Particle count, TOC, Resistivity, pH

HG2: 1st 7hr HPR



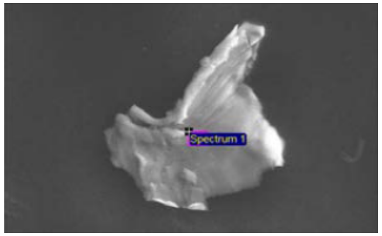
HG2: Last 14hr HPR



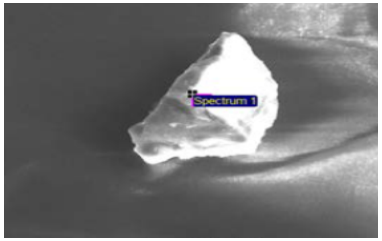
Contamination: Observed Debris Scale

Contamination Feature Size

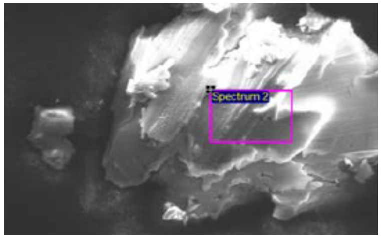
~10 um — Stainless steel chips dislodged during HPR



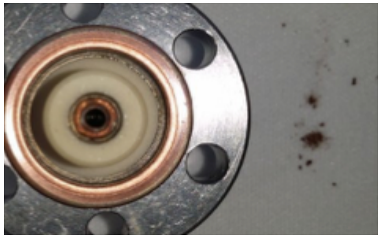
10 - 50 um — Thermal grease used on instrumentation : Silicon Oxide



100 - 200 um — Flakes from silver coated screws released during assembly



0.1-1 mm — Corrosion from incorrect material on antenna feedthrough screw

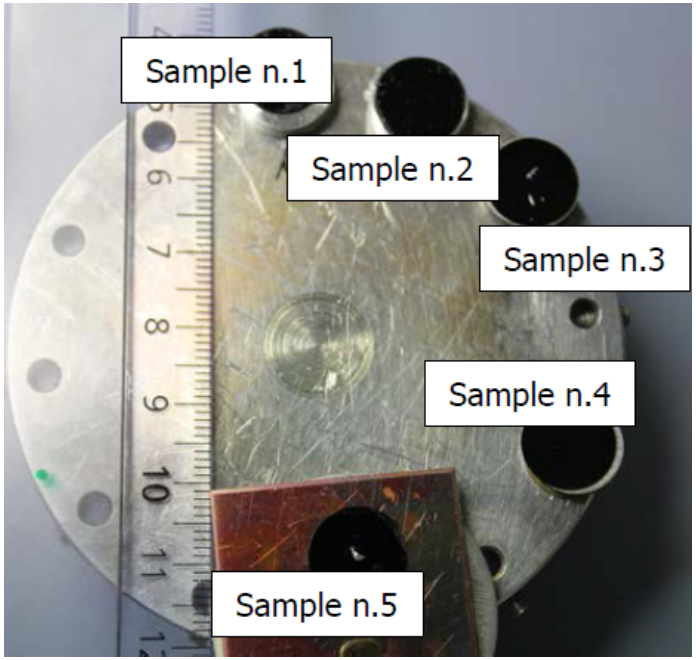


1 - 5 mm — Macro-contamination during preparation and assembly

Chemical analysis of contamination before/after HPR

- Analysis of particulates by energy dispersive X-ray spectroscopy
- Samples taken from cavity interior, exterior and HPR cabinet
  - Samples taken both before and after HPR

Courtesy: A.T Perez Fontenla



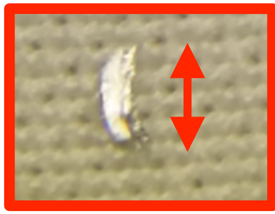
carbon sticker:

C(84,6%), O (14,6%), Na (0,4%) &S (0,4%)

Chemical Analysis after poor RF performance of HG2

- **Significant impurities inside & outside cavity**
  - Dominated by metallic particulate of various sizes
  - Silicon trace detected in HPR cabinet & cavity
- **Metallic contamination due to electrostatic pickup**
  - Handling process outside HPR/cleanroom not adequate

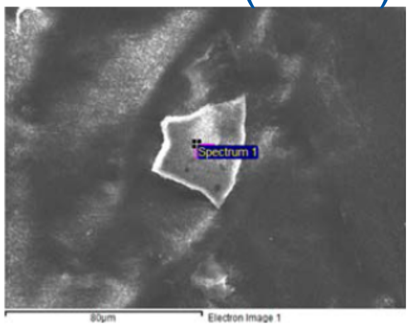
Main elements detected	Control after poor Cold test performance			
	Cavity interior	Cavity beam port	Cavity exterior	HPR Cabinet
Fe, Cr, Mn Ni		8	3	
Ca, C, O	1	1		
Si, O		2		
Zr		1		
Ag		3	8	
Al	**2**	1	3	
Cu			1	
Nb			1	
Pb, Sn	1			
C,O	1			
Ti				2
Si,Mg,C,O				2



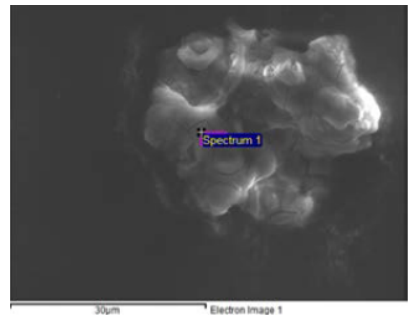
O(3mm)

Examples of foreign particulate observed

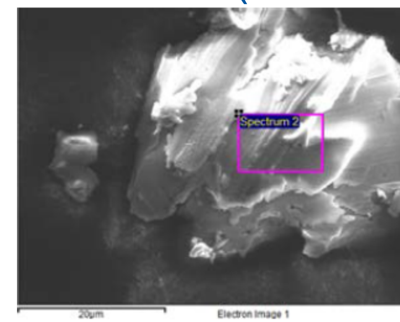
Ti chip
Size: O(30um)



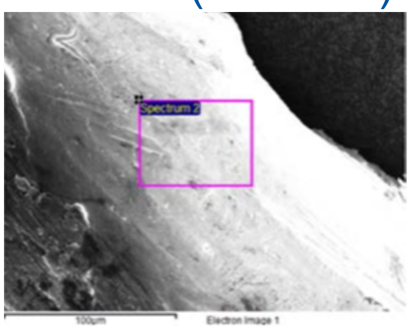
Oxidised Iron
Size: O(30 um)



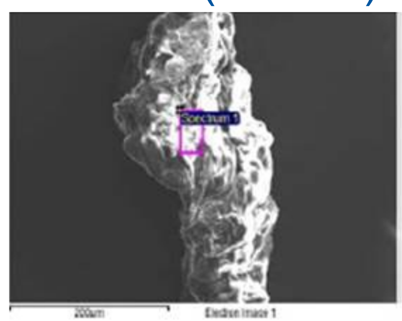
Ag chip
Size: O(100 um)



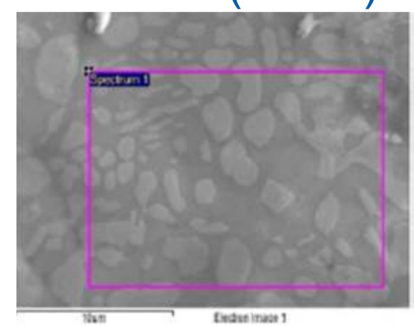
Al Flake
Size: O(3000um)



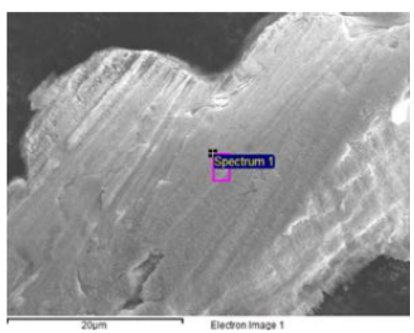
Carbon Flake
Size: O(400um)

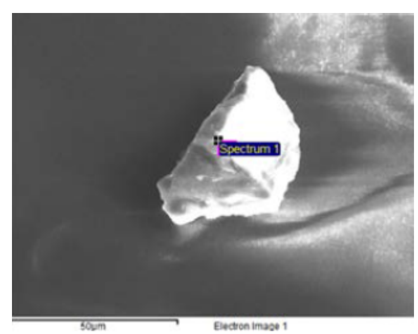


Pb and Sn
Size: O(50um)



Cu chip
Size: O(200 um)





Silicon Oxide
Size: O(50 um)

Chemical analysis after revised cavity handling

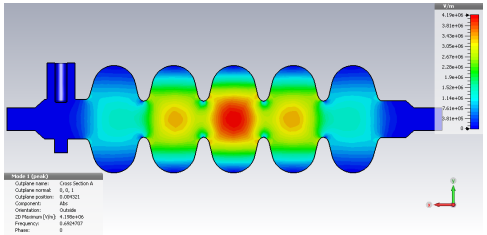
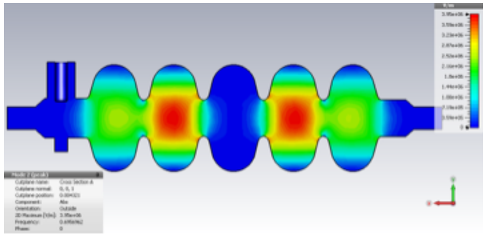
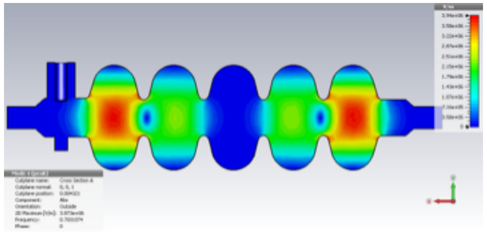
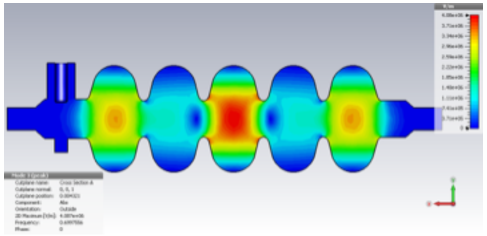
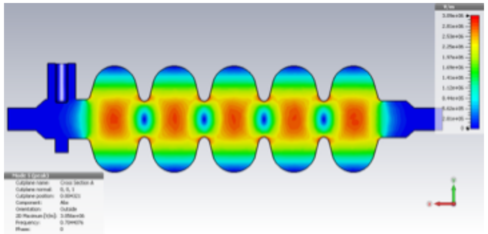
- **Tighter control of cavity & environment prior to HPR**
  - Minimised electrostatic pickup of metallic debris
- **Prior to rinsing: Much reduced contamination observed**
  - Cavity interior: Foreign metallic debris suppressed
- **After rinsing: RF surface is cleaner**
  - Residual particulate on entire cavity surface & HPR cabinet

Main elements detected	Before HPR		After HPR	
	Cavity	HPR	Cavity	HPR
C, Cl, Ca, S, O	2	1	2	2
Fe, Cr, Mn, Ni, S, C	5	-	2	6
Cu,Zn,O	1	-	-	-
Ca,S,O,C	-	6	-	-
Si,O	1	-	-	-
Si, Al, Na, Ca, K	-	4	1	2
Ag	-	-	3	3
Al	1	-	-	-
Fe,O	-	-	-	2
Nb	1	-	-	-
S,C	-	-	-	1

Cavity Test Results

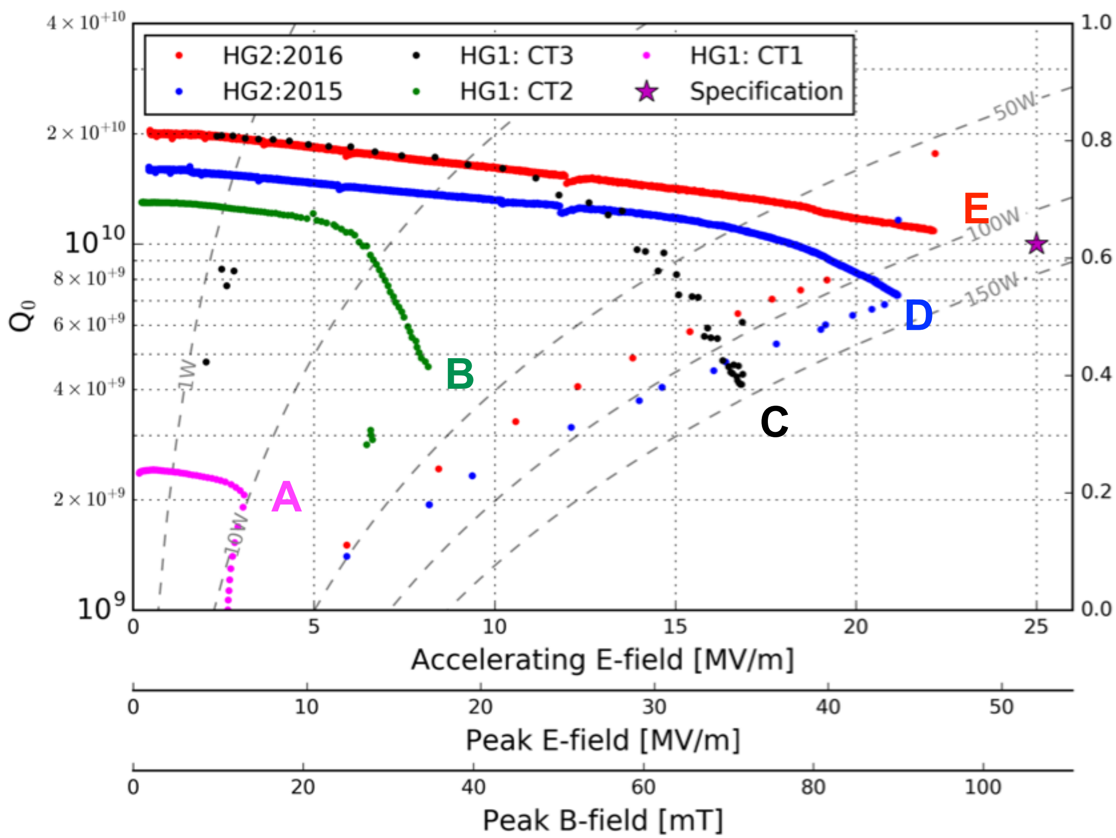
Passband Frequencies

	HG1	HG2
1/5 π mode		
Simulated (2K)	692.470 MHz	692.470 MHz
Measured (4.5K)	692.062 MHz	
Measured (1.8K)	692.293 MHz	
Measured (300K +vacuum)	691.235 MHz	691.164 MHz
Measured (300K + 1 Bar)	691.109 MHz	691.083MHz
2/5 π mode		
Simulated (2K)	695.696 MHz	695.696 MHz
Measured (4.5K)	695.277 MHz	
Measured (1.8K)	695.500 MHz	
Measured (300K +vacuum)	694.454 MHz	694.439 MHz
Measured (300K + 1 Bar)	694.325 MHz	694.351 MHz
3/5 π mode		
Simulated (2K)	699.756 MHz	699.756 MHz
Measured (4.5K)	699.464 MHz	
Measured (1.8K)	699.382 MHz	699.734 MHz
Measured (300K +vacuum)	698.627 MHz	698.567 MHz
Measured (300K + 1 Bar)	698.505 MHz	698.490 MHz
4/5 π mode		
Simulated (2K)	703.107 MHz	703.107 MHz
Measured (4.5K)	702.773 MHz	-
Measured (1.8K)	702.992 MHz	703.169 MHz
Measured (300K +vacuum)	701.391 MHz	701.995 MHz
Measured (300K + 1 Bar)	701.797 MHz	701.917 MHz
π mode		
Simulated (2K)	704.408 MHz	704.408 MHz
Measured (4.5K)	704.219 MHz	704.358 MHz
Measured (1.8K)	704.432 MHz	704.508 MHz
Measured (300K +vacuum)	703.359 MHz	703.321 MHz
Measured (300K + 1 Bar)	703.215 MHz	703.249 MHz

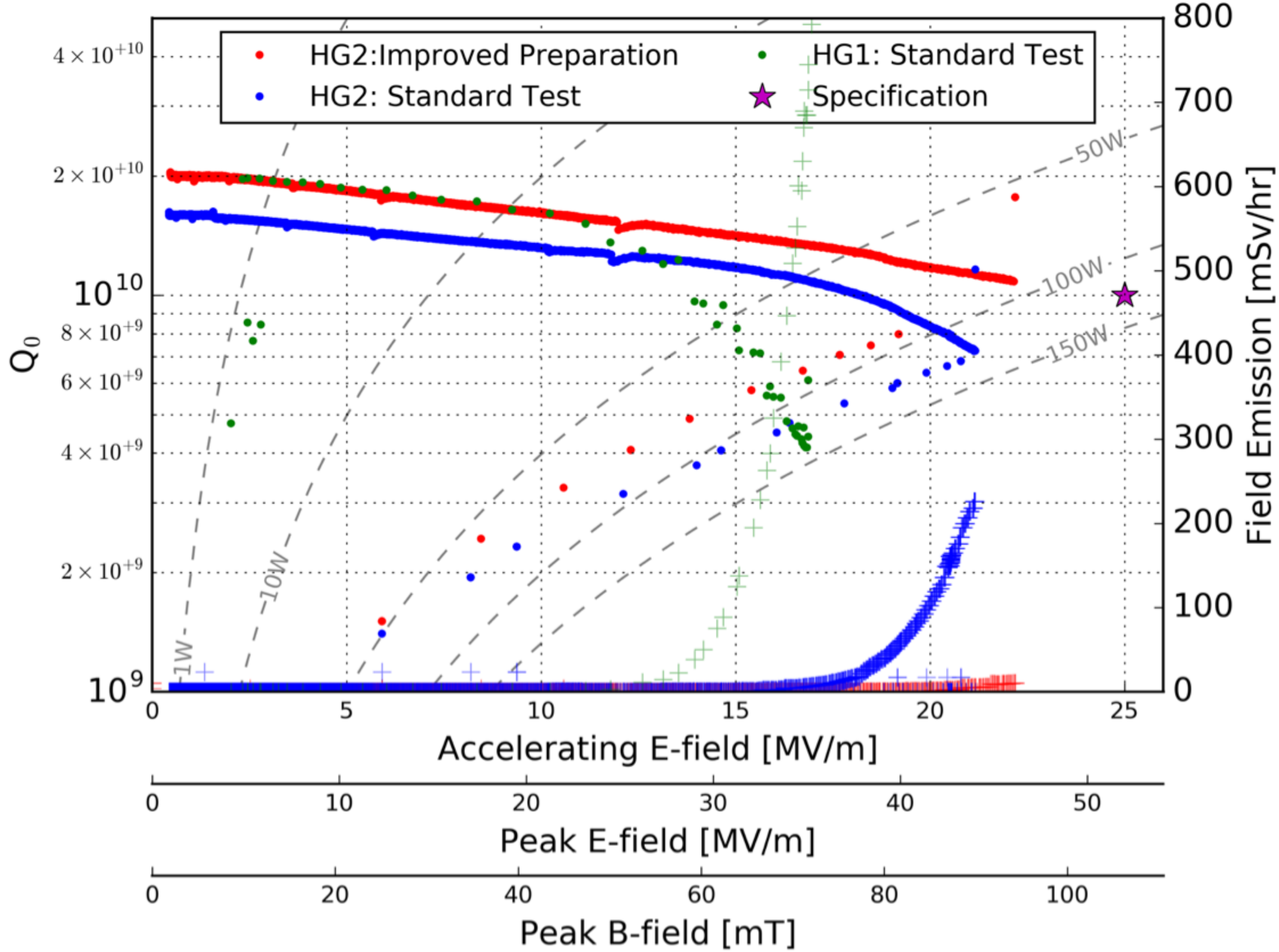
Evolution of Cavity Performance

Cold Test	A	B	C	D	E
Cavity	HG1	HG1	HG1	HG2	HG2
Standard HPR	✗	✗	✓	✓	✓
120°C Bakeout	✓	✓	✗	✗	✗
Thermal Gradient Control at T_c	✓	✓	✓	✓	✓
Ambient B-field (<30nT)	✗	✓	✓	✓	✓
Improved Pre-HPR Preparation	✗	✗	✗	✗	✓



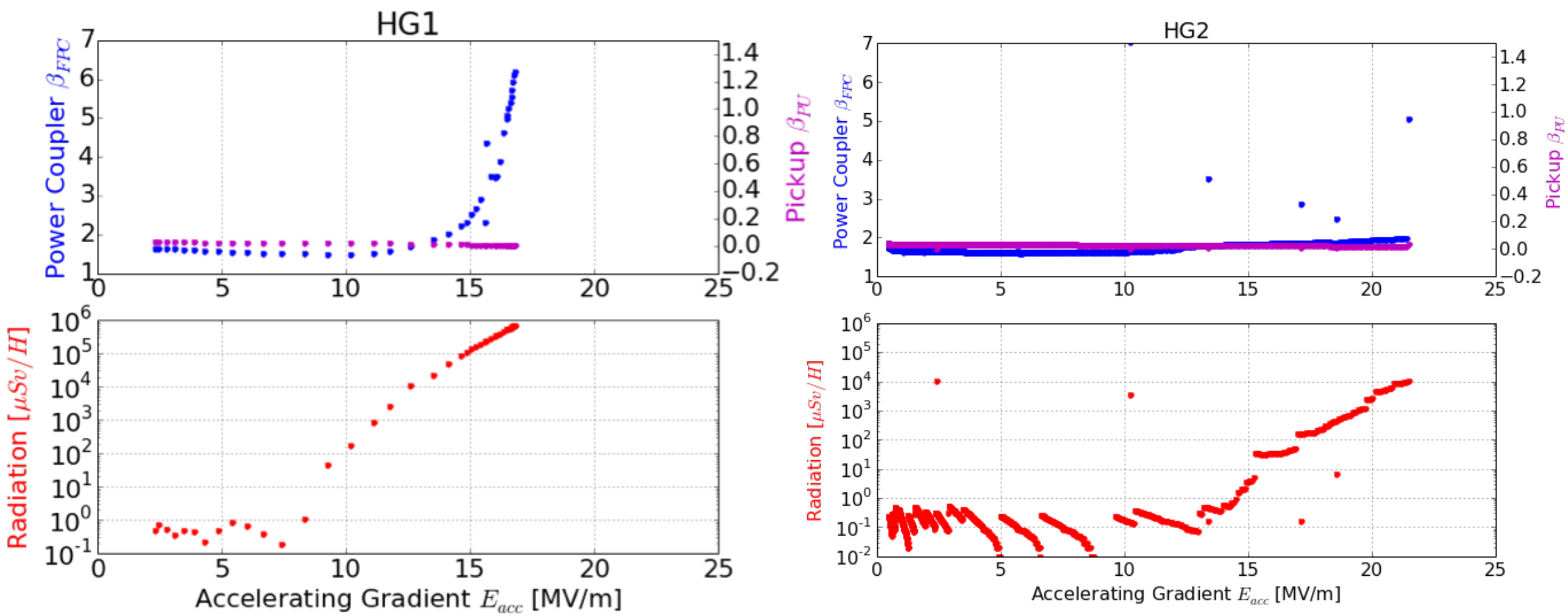
Comparison of HG 1 & HG2

- Improved performance correlated with reduced field emission



Comparison of HG1 and HG2

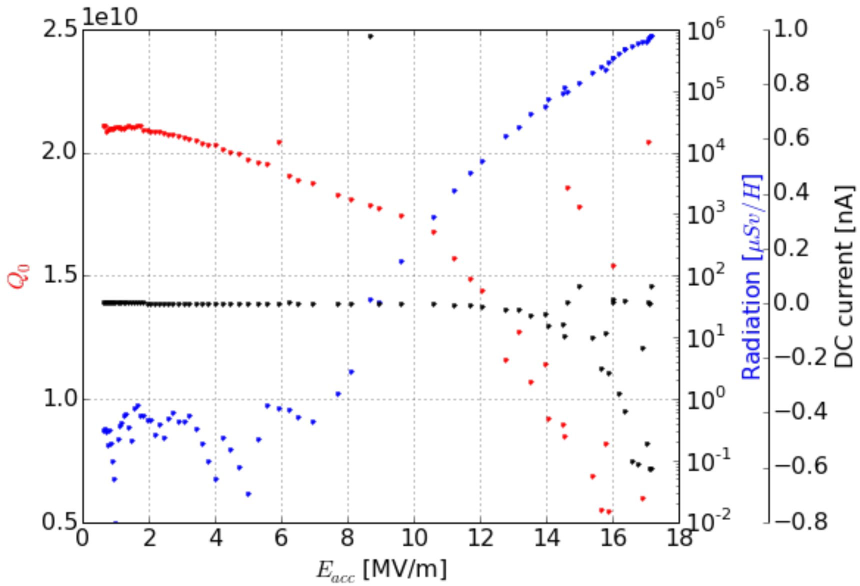
- **Field emission dominated HG1 but was reduced for HG2**
  - Onset clearly seen in coupling of input power
- **HG2 field emission starts at ~14 MV/m**
- **Objective: push field omission onset above 18MV/m**
  - reduce surface contamination with cleanroom tooling
  - Systematic inspection of RF surface to assess chemistry

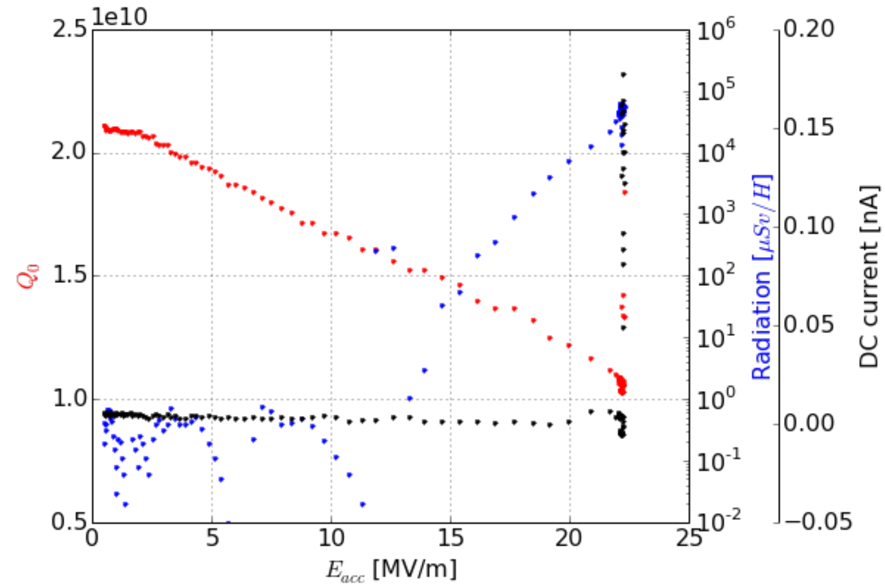


Performance Comparison of HG1 & HG2

- **Cavity 'Dark Current' = DC current on pickup antenna**
- **HG1: Dark current correlated with field emission**
  - Observed beam port flange heating from accelerated electrons
- **HG2: No dark current correlation with field emission**

=> either HG2 antenna not exposed to accelerated electrons or HG1 & HG2 have different high field quench mechanisms

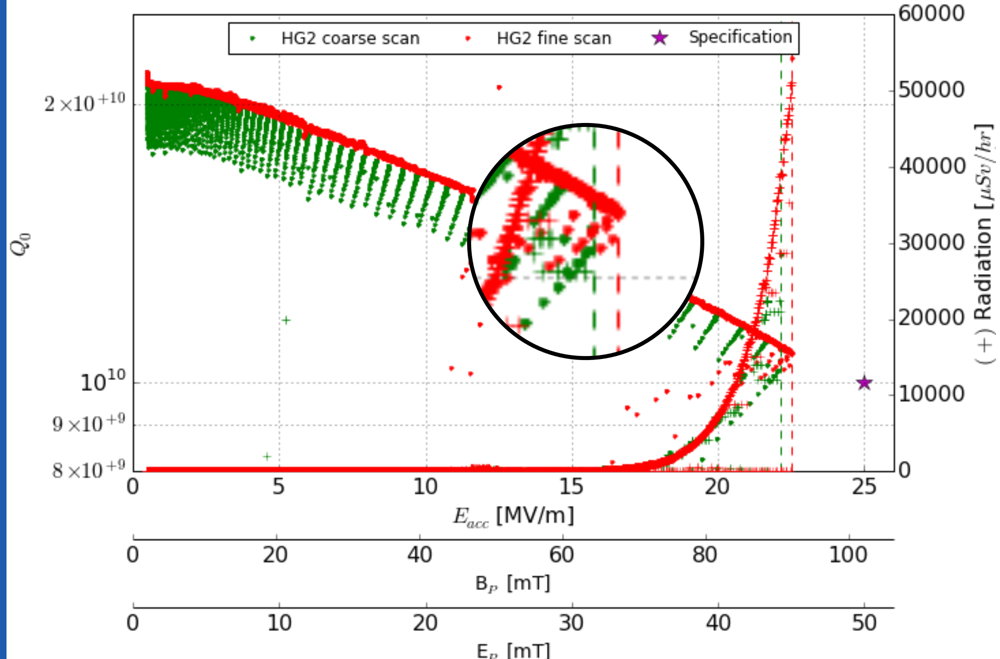




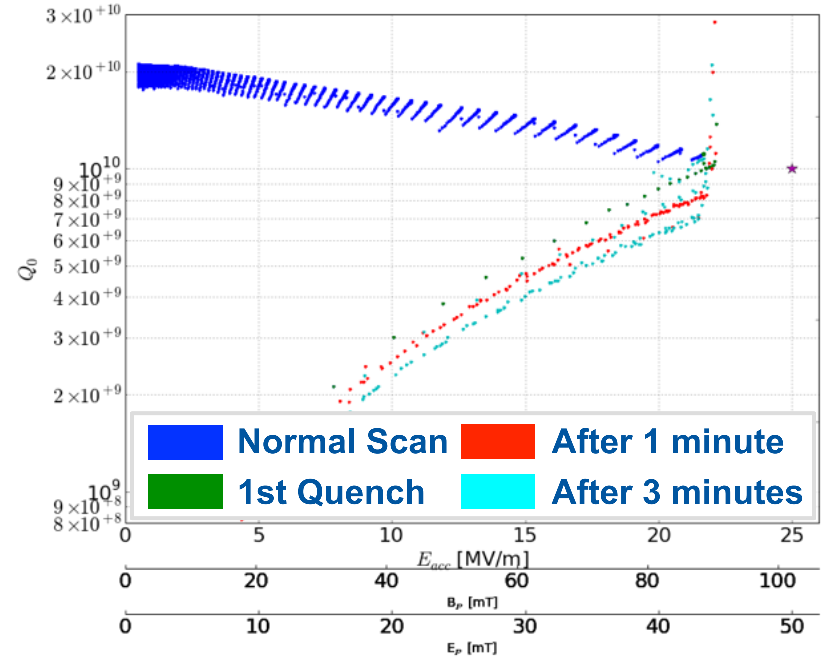
Present Performance Limitations: HG2

- **TESLA cavity design: Risks multipactor @E_{pk} ~45 MV/m**

- **Observation**:
  - Processing with amplitude modulation is slow but possible
- **Processing difficult due to thermal runaway/quenching**
  - Cause for optimism to process through the barrier



22.2 MV/m → 22.5 MV/m
12 hrs of amplitude modulation



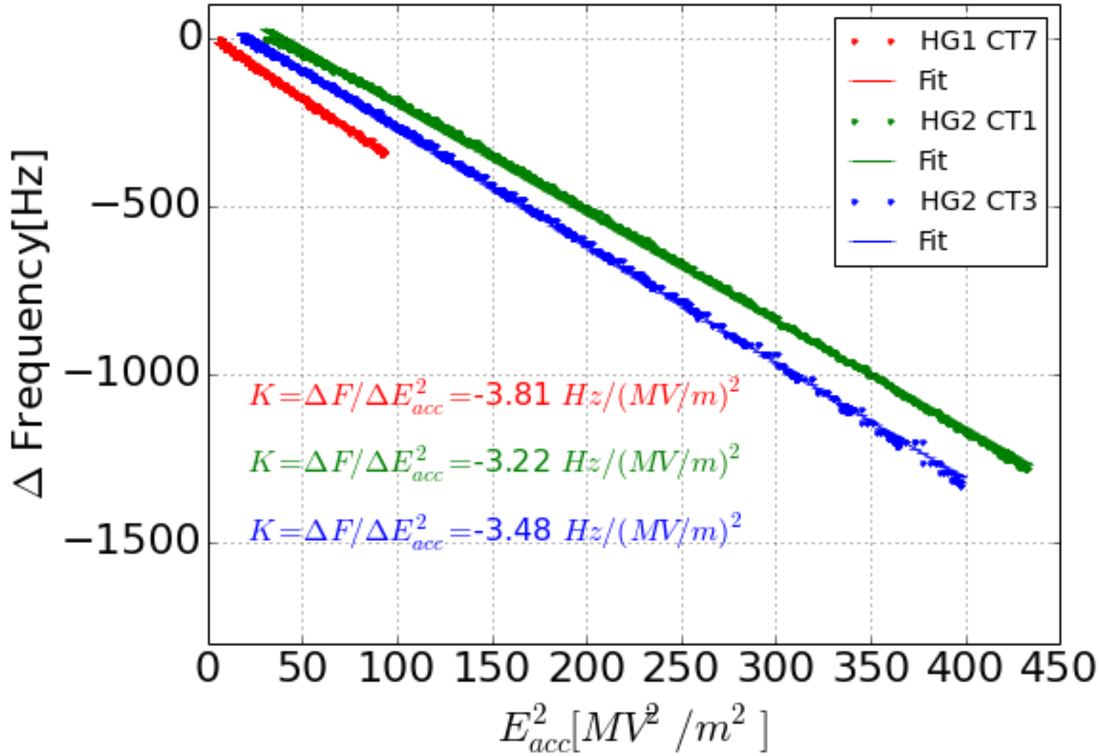
Processing limited by thermal issues & quenching

Lorentz Force detuning

- Cavity deformation from radiation pressure

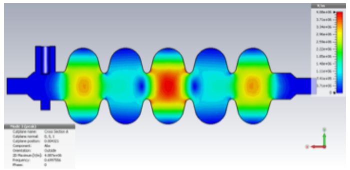
$$\Rightarrow \Delta f \propto E^2_{acc}$$

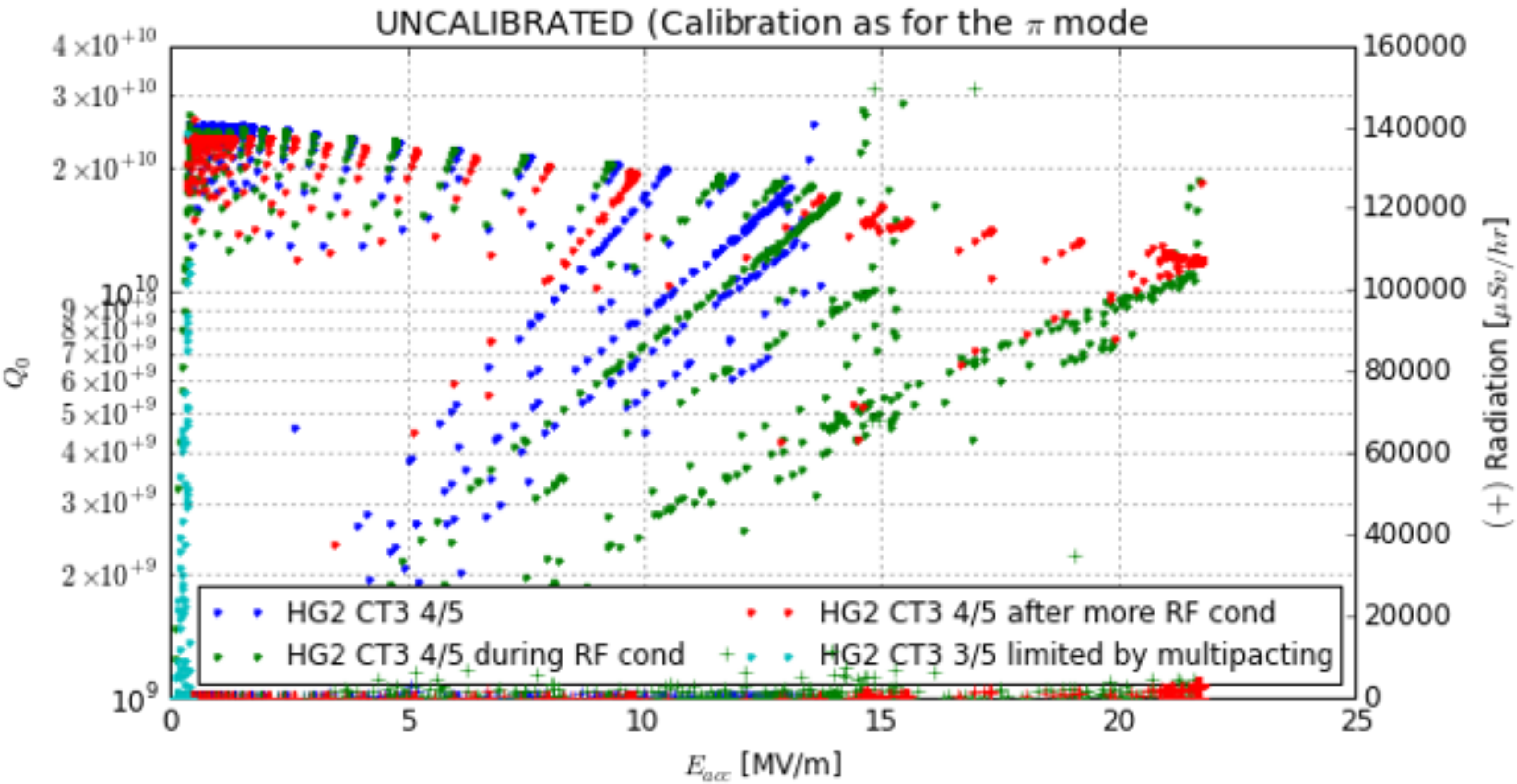
- Measured value ~ 1/2 expected value
  - Need to reconsider cavity support and anti-collapse system



Processing in the 4/5 π Mode

- **Use different passband modes for cavity processing**
  - Difficult to couple in power
  - Gives coarse localisation of field emitters

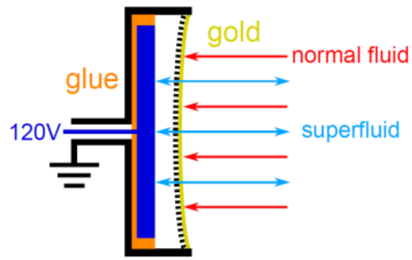


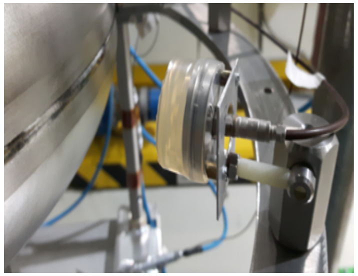


Planning and things to address

Quench Studies

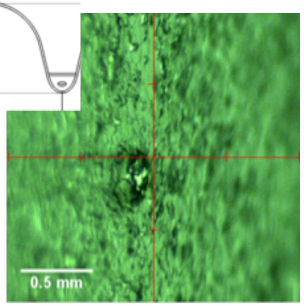
- Detection & analysis of 2nd sound waves in superfluid Helium

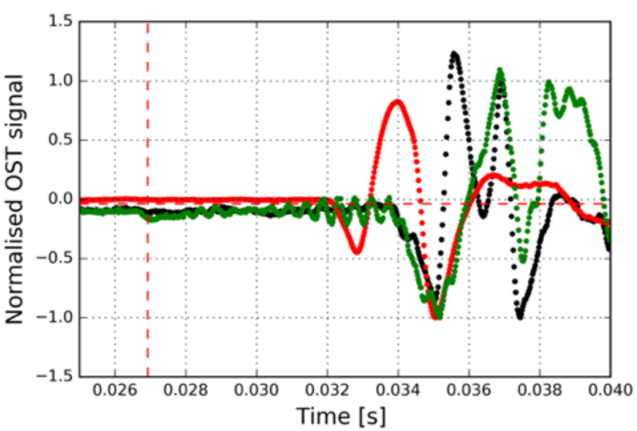




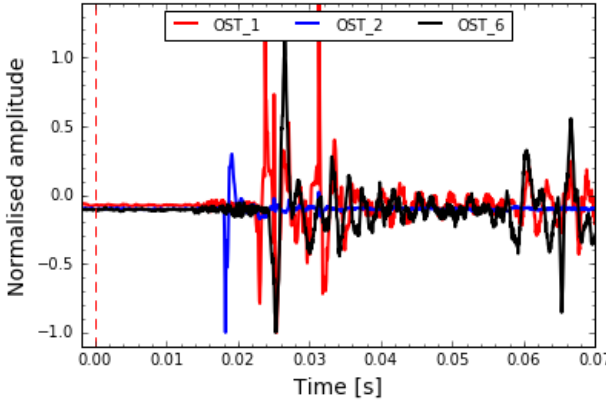
- Quench spot localisation by triangulation of at least 3 sensors

- **HG1: Mid-field Quench**
  - Localisation & identification of quench spot





- **HG2: High-field Quench**
  - No consistent localisation
    => Suggests global quench



Cleanroom Activities: Where we need to improve

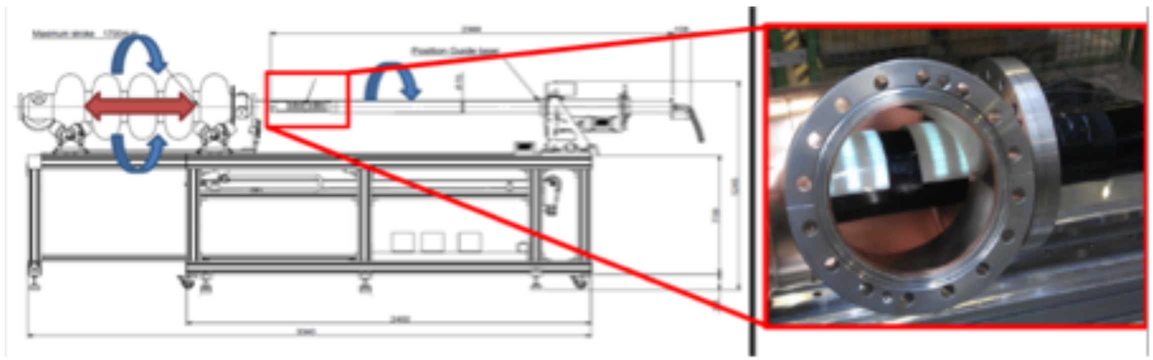
- **Full cavity handling tooling not yet in place**
  - Cavity handling robots being assessed/procured
  - Antenna mounting is 100% manual

- **Post HPR Drying is with ISO4 vertical laminar flow**
  - Possibility of adding drying step of 100^{o}C N_2 flush



Optical test bench

- **Present system - Developed at KEK:**
  - Manual Operation: Full HG inspection => 300000 pictures
  - System is specific to 704MHz elliptical cavities



- **Upgraded Optical Bench**
  - Dual high/low resolution system
  - Able to accommodate variety of cavities (LHC, Crab, HG)
  - Required resolution ~5μm
  - Automated image acquisition and image analysis

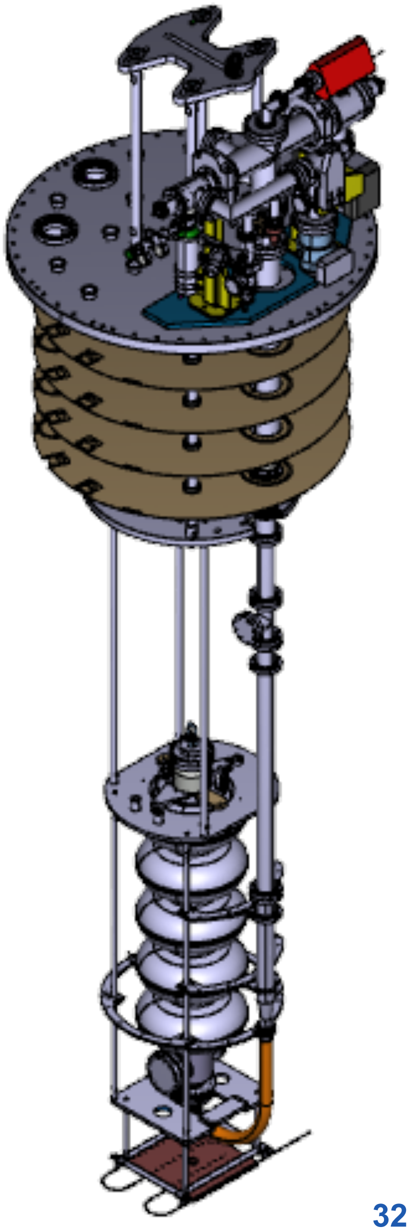
- **Two systems under consideration**
  - JLAB styled long distance microscope (www.questarcorporation.com)
  - Chromatic Confocal sensing for depth profile (www.stil.com)

Cryostat Insert upgrade

Upgrades being implemented

- New insert frame with possibility to electrically isolate cavity from cryostat

  => control/monitor thermal-electric currents
- Mobile coupler for operating in 2K LHe
- Ambient B-field compensation: below 30 nT
- Residual Gas analyser on cavity vacuum line

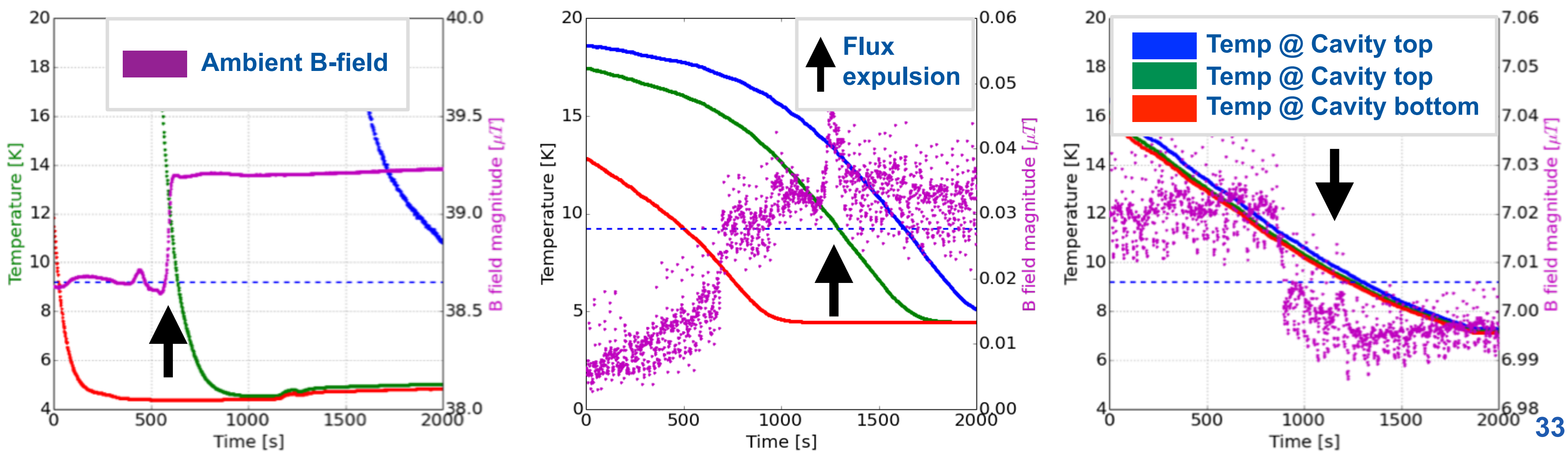


Ambient magnetic field & Cool down

- **Spatial thermal gradient**
  - Operationally: Can be controlled or eliminated
- **Ambient Magnetic Field**
  - Use compensation coils to control/set ambient B-field
    - Standard Operation: B-field set at 30nT
  - Flux expulsion observed at T_c transition

New insert + full control of thermal gradients & ambient B-fields

=> can study cavity performance factors due to cool down procedure & thermal electric currents



Planning: High Gradient Activities

- **High Gradient Cavity Cold tests: Push toward specifications**
  - Interleaved with other CERN SRF projects (eg HL-LHC Crabs)