AMICI ETIAM Workshop on SRF Cavity Testing

INFN LASA Vertical Test Infrastructure

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INFN Milano – LASA

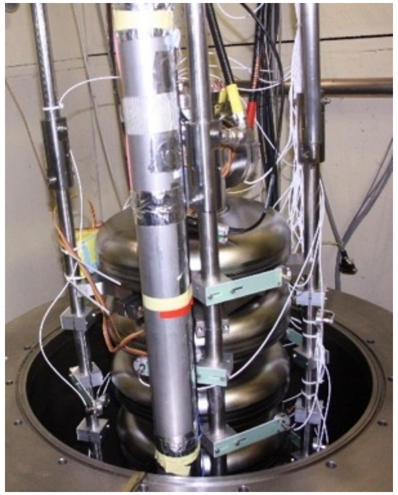
SRF cavity experience at LASA, short list

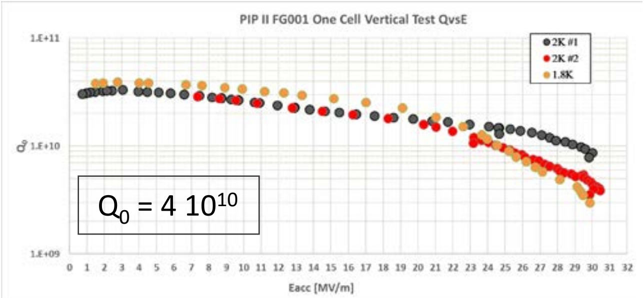
INFN LASA has a long experience on cavity design and, in collaboration with industry, in fabrication of SRF cavities. Among others:

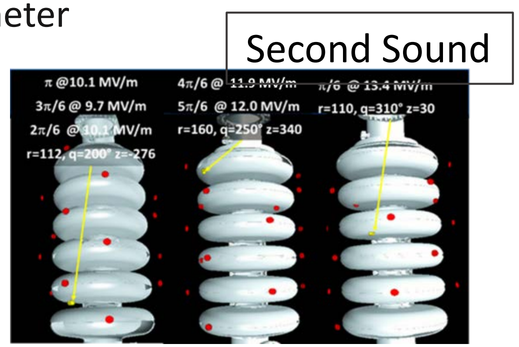
- Copper cavities for **CS** (Superconducting Cyclotron) at **LNF**
- Collaboration with **CERN** for Nb sputtering of **352.2 MHz LEP** copper cavities
- Construction and test of four cell SC Niobium prototype cavity for **ARES/LISA** at 500 MHz (~ 1990)
- Collaboration with **DESY** for the first **TTF** cavities
- Collaboration with **LANL** (Advanced Accelerator Applications, **350 MHz**) and **FNAL** (HINS, **325 MHz**) for the construction of SC Spoke cavities
- We have significantly contributed to the design of the **SNS cavities at 805 MHz**
- **TRASCO cavities** were designed at LASA and fabricated at **704.4 MHz**
- LASA was deeply involved in the mass production of the **800 cavities for XFEL at 1.3 GHz**
- **20 3.9 GHz** cavities for the third harmonic module of **XFEL** designed at LASA, fabricated and tested
- **38 704.4 MHz** cavities for the Medium Beta Section of the **European Spallation Source**
- **2 multi and 5 single-cells 650 MHz** prototype cavities for the Low Beta Section of **PIP-II** in preparation for the 38 cavities in-kind contribution

VT infrastructure at a glance

- **“Small” numbers:**
  - 61 SRF cavities cold tested in the last 10 years
  - About one half for R&D
- **Clean Room and UPW**
  - Ultra Pure Water plant
  - ISO4/7 clean room, HPR system, Qualified SPSV system
- **Main cryostat**: ϕ 700 mm, 4.5 m length, losses < 1 W @ 2 K
- **Residual magnetic field**: < 8 mGauss (outer + inner shields)
- **RF capability:** 500 to 3900 MHz
- **Sub-cooling system**:
  - Cooling power: up to 60 W at 2.0 K
  - Direct filling at 2 K
- **2 dedicated inserts with several diagnostics**:
  - OST detectors for quench localization
  - cryogenic photodiodes
  - Thermometry (standard and fast)
  - flux gate
  - X-ray counter and X-ray NaI spectrometer

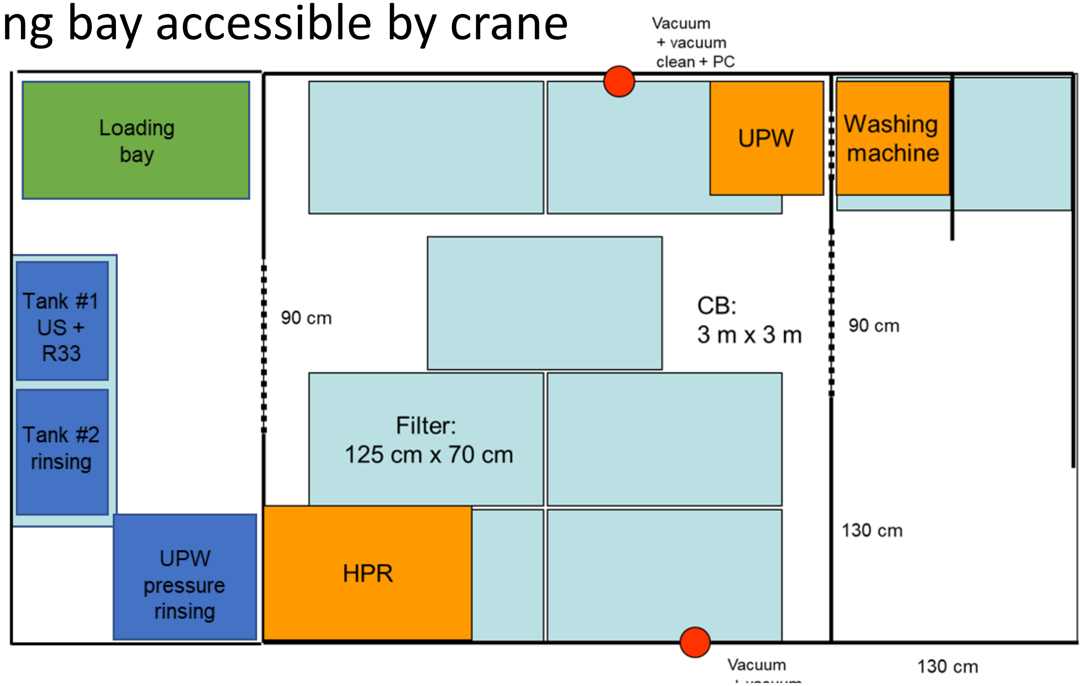


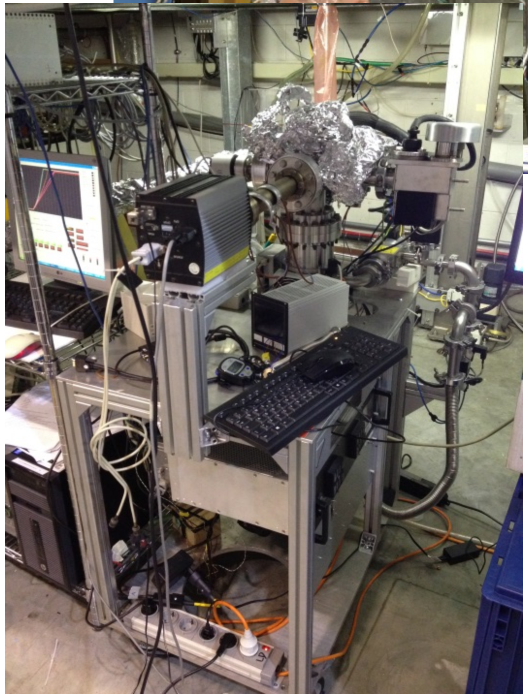




LASA Clean Room with SPSV

- 8800 m3/h air supply to a total of 9 HEPA ceiling filters
- 9 m2 ISO 4 area hosting cavity HPR
  - Lighthouse APEX P3 particle counter
  - SIMCO Ionizing Air Gun with clean N2 for particle cleaning and counting
  - SMC VMG1 Blow Gun for leak-check He gas flow
- ISO 7 Dressing room and pluri-tank area
- Slow Pumping / Slow Venting
  - Scroll pump, Agilent Triscroll 600
  - LD: LDS 1000 Oerlikon Inficon sensing head
  - 5 and 100 sl/min MKS flow controllers, differential MKS gauge for venting
- loading bay accessible by crane



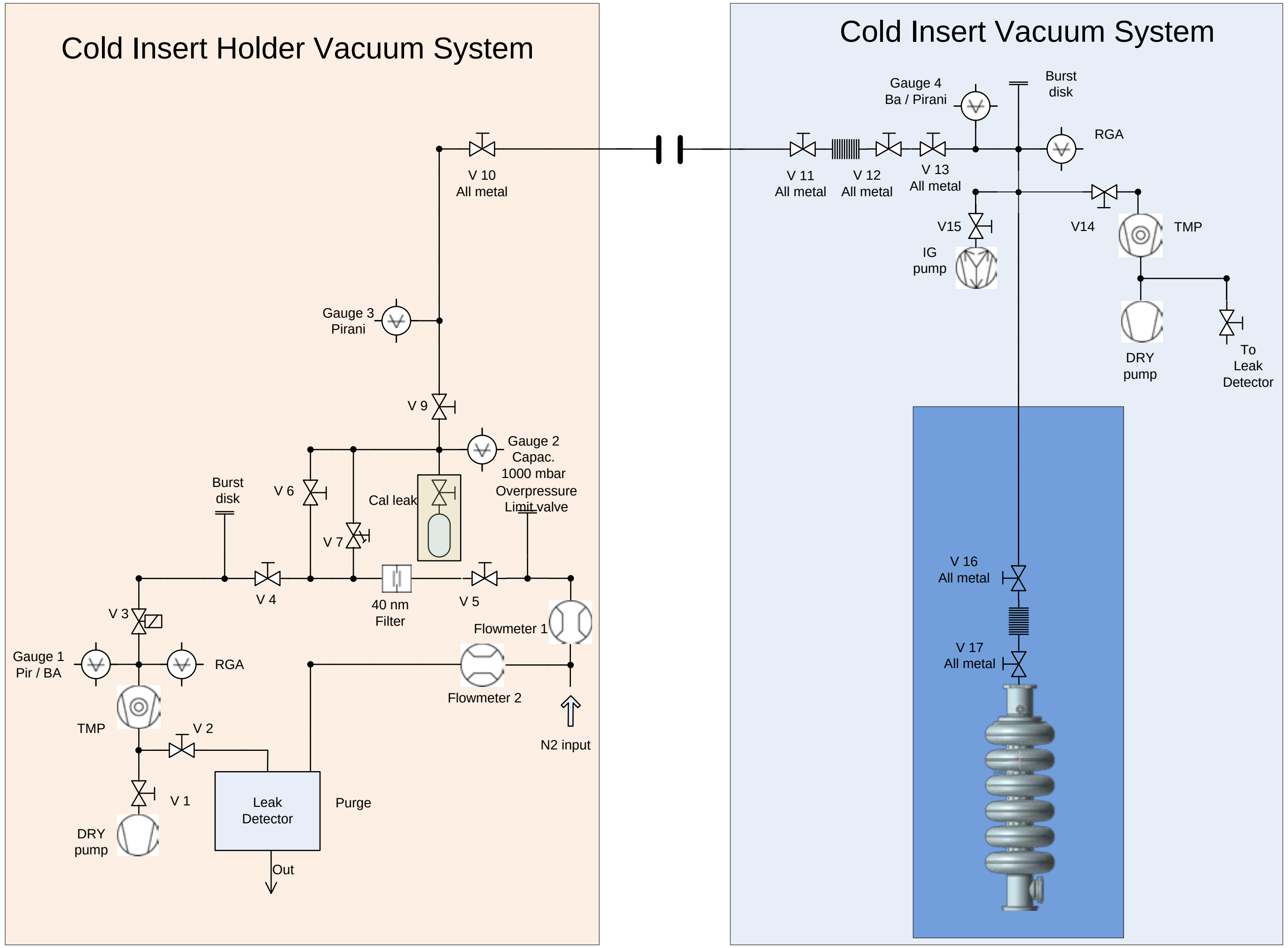


Inserts, preparation and clean assembly

- **Insert #1**: multi-purpose, 2 active pumping cavity lines
- **Insert #2**: specific for large multicell cavities, HX with JT for 2 K refilling

Both with active pumping for insert, either by SIG (on insert) or mechanical pumps (on insert + ext. scroll)

Inserts stand equipped with controlled, clean pumping/venting system



Inserts, preparation and clean assembly

Two transportable, clean venting, **air-flow systems with HEPA** filter for particle-free insert-to-cavity connection

- Clean-room tunnel setup with insert at its stand

Few **more cryostats** and inserts available:

- The largest of which are:
  - A 3 m deep and 500 mm diameter, originally designed for 1.5 GHz cavities
  - A 1.2 m deep and 200 mm diameter, currently used for sample testing and thermal cycling of components

Magnetic Hygene

Typical value of residual magnetic field of the main cryostat in the cavity area and in cavity axis direction is **about 8 mG.**

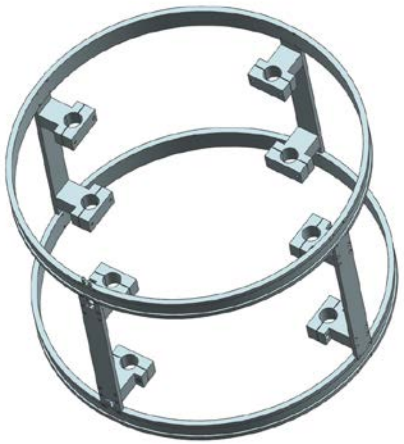
Passive counteractions:

✓Outer warm magnetic shield

✓**Cryo-perm inner shield** in order to lower the actual value in the cavity axis direction and reduce orthogonal components.

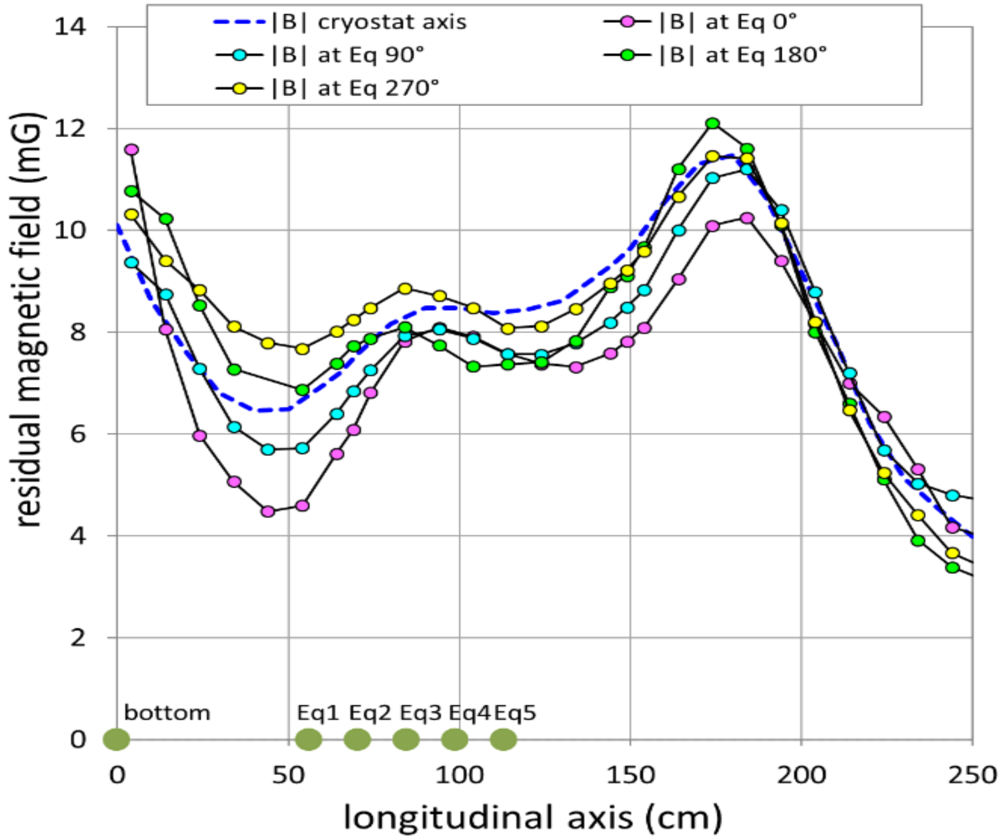
Active counteractions:

→Residual field local cancellation through **Helmholtz's coils** (on-going)



Coils frame for LASA insert

CryoPerm inner magnetic shield

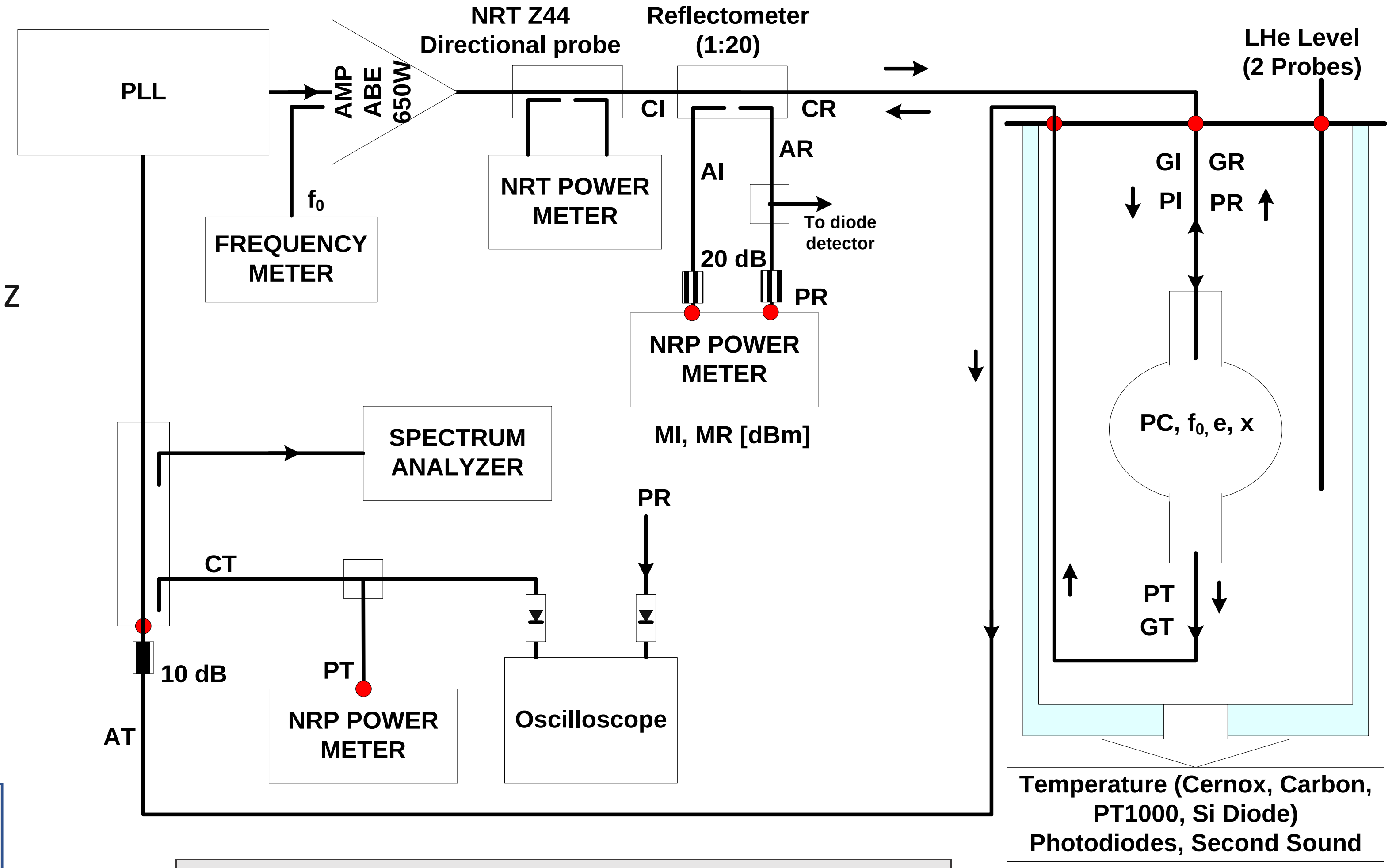


RF Systems

Currently, test capability for SC cavities with frequency > 500 MHz

Control Electronics (PLL) and **Power Amplifiers** available for:

- **500 < freq. < 900 MHz, 500 W**
- **1.2 < freq. < 1.4 GHz, 500 W**
- **3.5 < freq. < 3.95 GHz, 200 W**



General **Test Protocol for RF** measurements during vertical tests:

System Calibration (VNA + PM)

- ❑ A_I, A_R, A_T (S_{21}, RT)
- ❑ G_I, G_R, G_T (S_{11}, 4.2K and 2K)
- ❑ C_I, C_R, C_T (S_{21}, RT)
- ❑ Superfish: G, R/Q, L

Cavity Qualification: Q_0 vs E_{acc}

- ❑ **Calibration** @ 1 MV/m < E_{acc} < 2 MV/m
  - Acquired : P_I, P_R, P_T, f_π, τ_{VT}
  - Computed: P_C, Q_0, E_{acc}, $K_E = \frac{E_{acc}}{\sqrt{P_T}}$
- ❑ **Power Rise** → P_I raised via digital step attenuator
  - Acquired: P_I, P_R, P_T, f_π, τ_{VT}
  - Computed: P_C, Q_0, $E_{acc} = K_E\sqrt{P_T}$

Subcooling

- ❑ **Acquired**
  - T, P_I, P_R, P_T, f_π, τ_{VT}
- ❑ **Computed**
  - P_C, Q_0, R_S

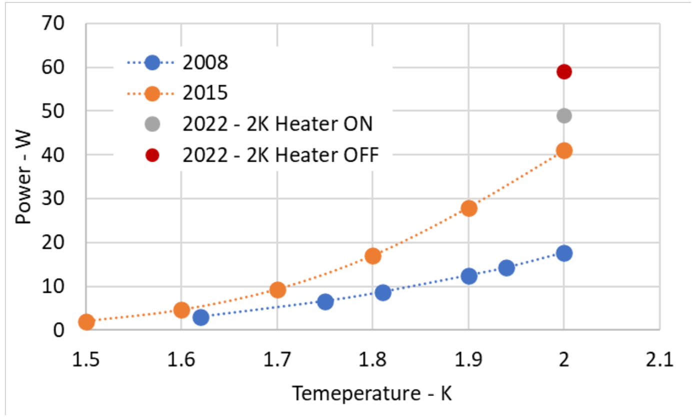
Vertical Test cryogenic plant

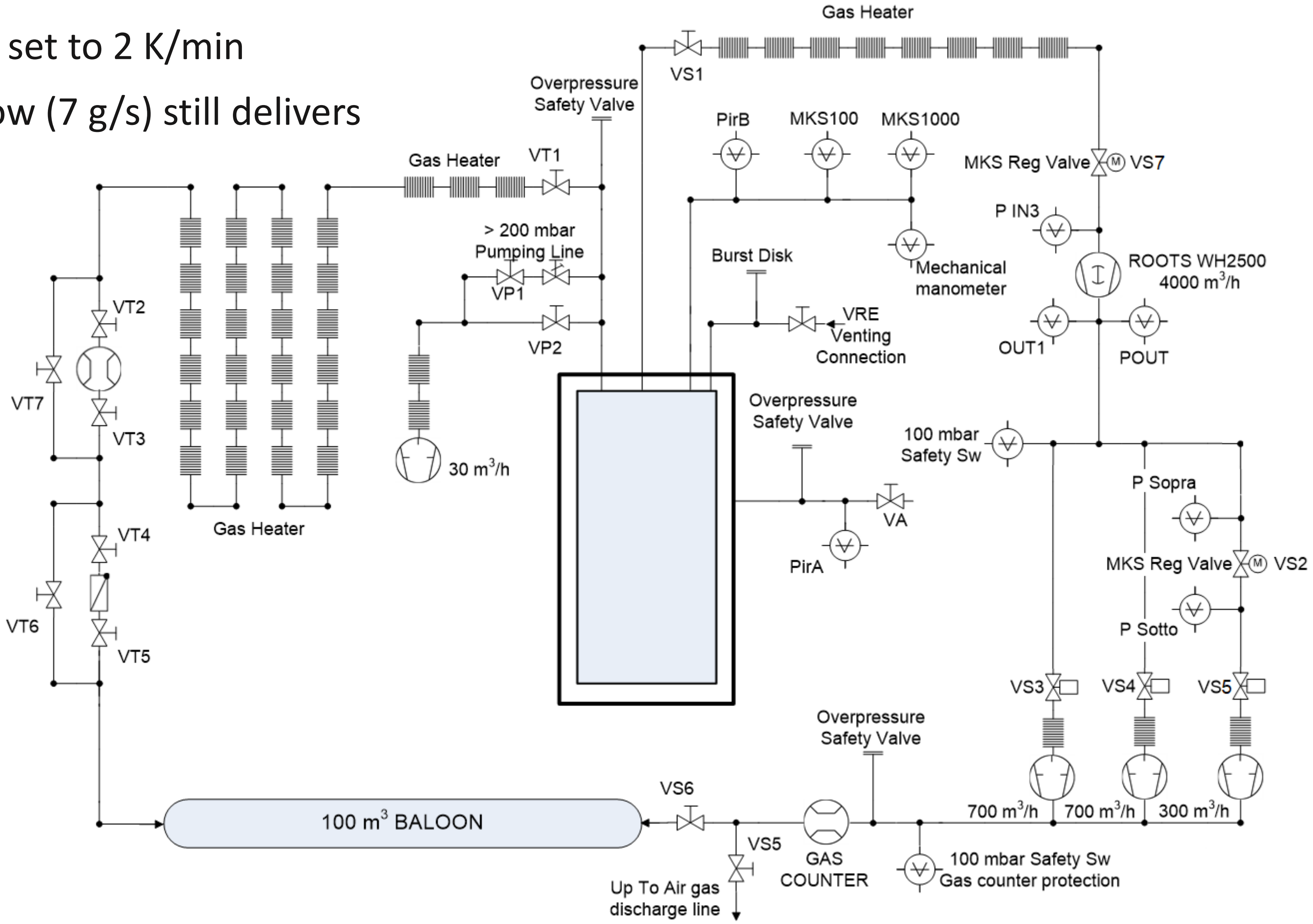
300 to 70 K: safety limit on rate set to 2 K/min

Below 40 K: highest He mass flow (7 g/s) still delivers only 0.5-0.7 K/min

- Need better LHe transfer geometry?

Available cryogenic power now limited to about **60 W at 2.0 K**





Diagnostics – Temperature, Pressure

Sensors, gauges

DT-670-SD-1.4L Silicon Diodes
- Main Use to monitor cooldown to 4.2 K
- Installed on the insert bottom plate
- T range 1K < T < 325 K
- From calibration curve 1<T<20K δT < 10 mK

Cernox thin film resistance cryogenic temperature sensors
- Placed on cavity cells, up to 6
- Used for Fast Thermometry, on-line calibration

CCS Carbon Ceramic Sensors
- Installed on cavity cells for Fast Thermometry, up to 6
- Installed along the insert for Standard Thermometry

PT1000
- Installed along the insert for Standard Thermometry

Vapor Pressure T < 4.2 K
- Redundancy with Pirani and capacitive gauges
- MKS 100 torr used as reference pressure and T

Readout and control electronics

Diode & Standard Thermometry
- Lakeshore 224 Temperature Monitors
- Persistent error between Si Diode readout and pressure, about 40 mK at 2.0 K

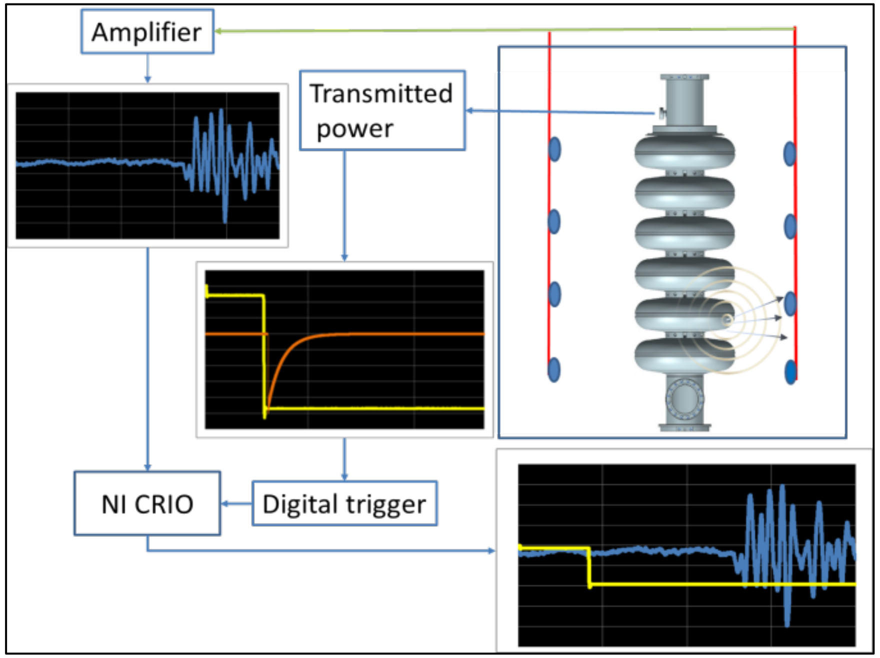
Fast Thermometry for thermal breakdown
- Home-made driver electronics: with 10 – 100 μA FET Current Generator and Instrumentation Amplifier
- NI cRIO DAQ system
- Time resolution about 1 ms

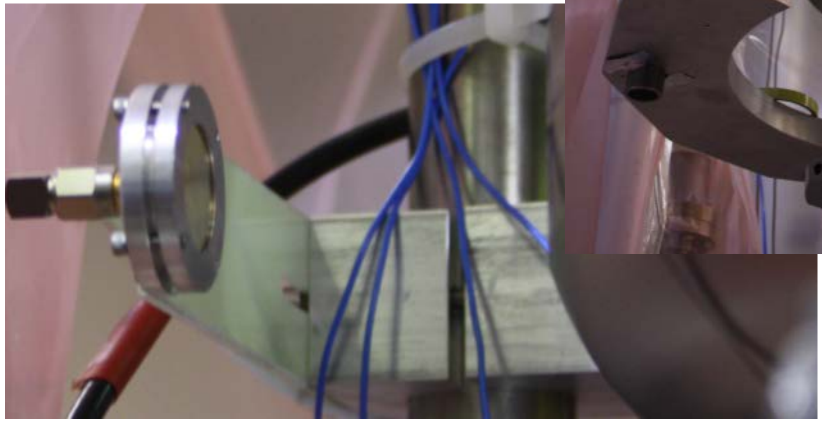
Pressure Control System
- Double MKS 600 series pressure controller (ISO-NW100 and ISO-KF40)
- Typical pressure regulation precision of +/- 0.1 mbar or +/- 1 mK

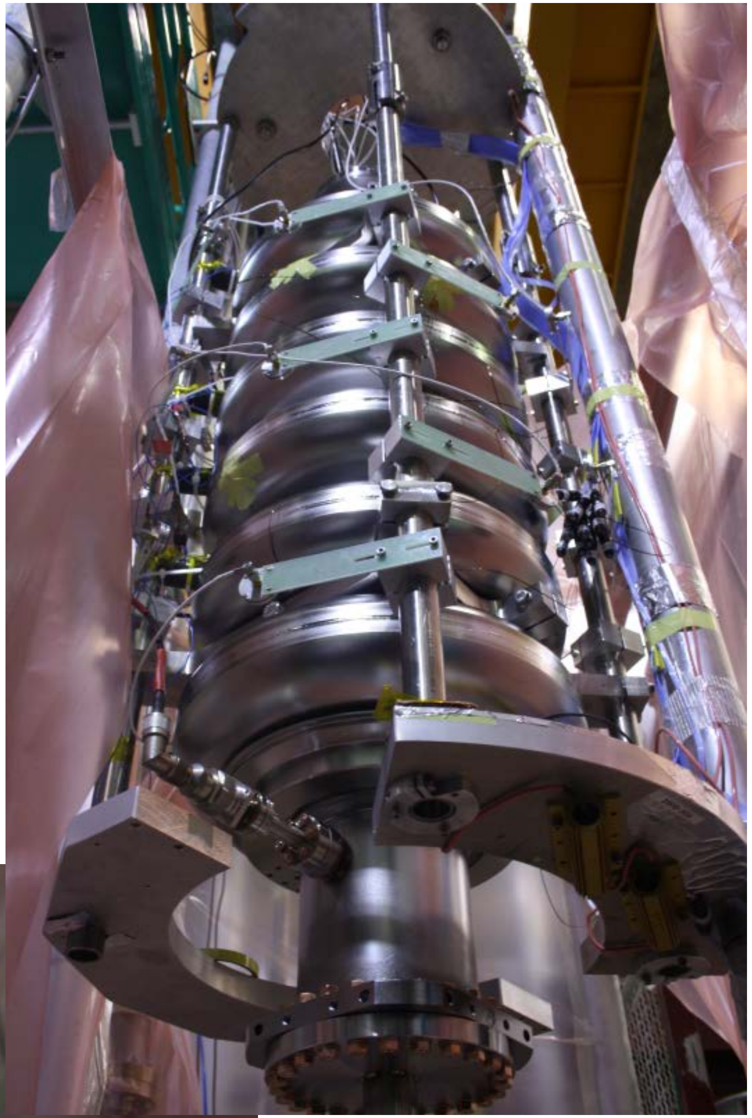
Diagnostics – Cavity Diagnostics

Second Sound detectors for quench source detection:

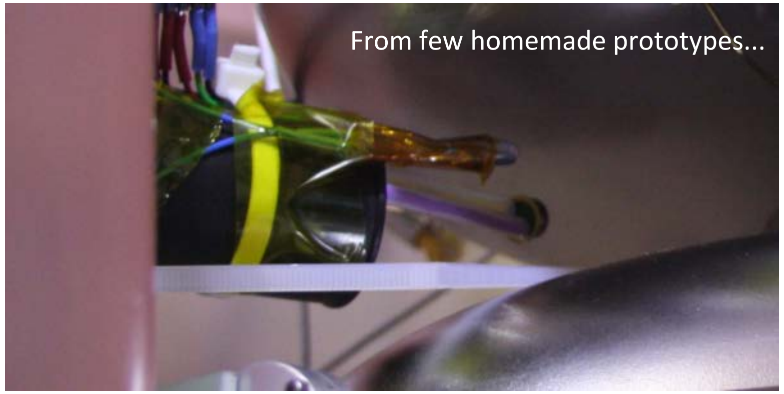
- More than 20 **OST** (Oscillating Superleak Detectors) in house developed can be installed inside cryostat
- 20 channels external amplifier provides 90V polarization to sensors and 27 dB gain to sensors signal with a 100 kHz bandwidth.
- Signals are acquired by NI CRio unit, triggered with a digital signal generated from the drop of transmitted power
- Quench position can be calculated by choosing several algorithms of trilateration. Final spatial resolution is limited to 5-10 mm.







Diagnostics – Radiation



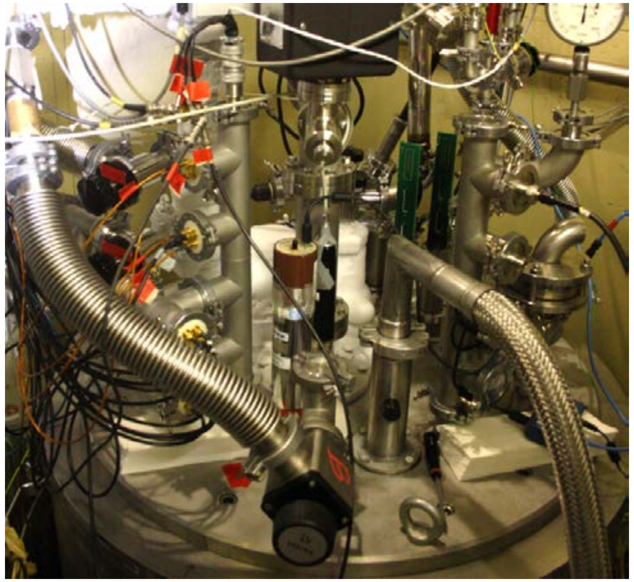
Cavity Field Emission diagnostics

Cryogenic Photodiode detectors

- Allow to localize the FE origin and a direct evaluation of real radiation yield
- S6775 Pin diode (replacing Hamamatsu S1223-01 with magnetic packaging)
- Amplifier boards are placed nearby the diode so that pick-up noise from cables is minimized. All the electronics is suitable in the cryogenic context (CMOS based op-amps, metal film capacitors,…).
- Sensors signals are extracted from cryostat and collected by a NI DAQ unit. Now a maximum of 28 sensors can be installed in the cavity frame.

External radiation detectors on top cryostat cover only, close to cavity axis

- **Gas-filled (Xe) proportional counter** (Thermo Electron FH 40-G) for dose measurement:
  - Measurement range from 100 nSv/h to 1 Sv/h
  - Continuous acquisition every 1 sec.
  - Energy range from 45 keV to 1 MeV→ poor sensitivity for higher energies
- **NaI(Tl) scintillator** (Ortec 905-3) for measuring X-ray spectrum
  - Maximum count rate 10^6 counts/sec
  - Energy range from few keV to 10 MeV
  - Due to its high sensitivity to radiation, for high doses detector saturates producing counts pile-up: screening with high Z material is needed!



LASA VTS summary table

LASA SRF Main Cryostat and related plants				
No	Property name	Value	Unit	Comment
1	LHe volume	1200	L	
2	Operating temperature	> 1.5	K	Up to 60 W cryogenic power at 2.0 K
3	Diameter / size	0.7 diameter / 4.5 depth	m	8 mGauss peak residual B field, inner + outer shielding
4	Number of inserts	2		• Insert #1: multi-purpose, 2 active pumping cavity lines • Insert #2: specific for multicell cavities, HX with JT for 2 K refilling
5	RF Frequency	500-900 1200-1400 3500-3950	MHz	In-house designed analog PLLs
6	Maximum Incident power	500 500 200	W	For each frequency band respectively
7	Additional instrumentation	• OST detectors • Cryogenic photodiodes • Thermometry (standard and fast) • Flux gate • X-ray counter, NaI spectrometer		
8	Typical testing rate (Vts / year)	6		Average from 2012, peak at 10 cavities tested in 2015
9	Possibility to test naked cavities	YES	YES / NO	
10	Infrastructure for small intervention	YES	YES / NO	ISO4 Clean-Room with SPSV, UPW plant with HPR, movable CR tunnels

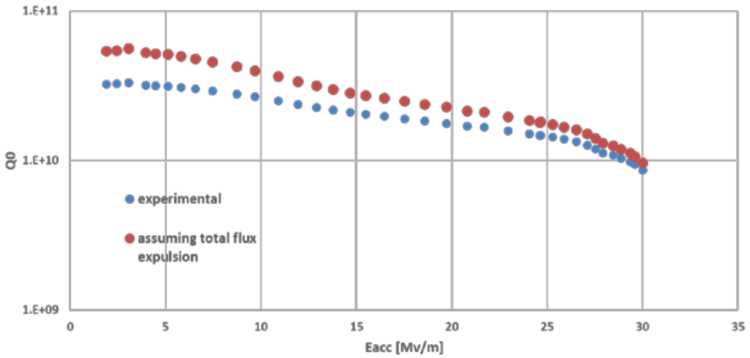
Closing remarks

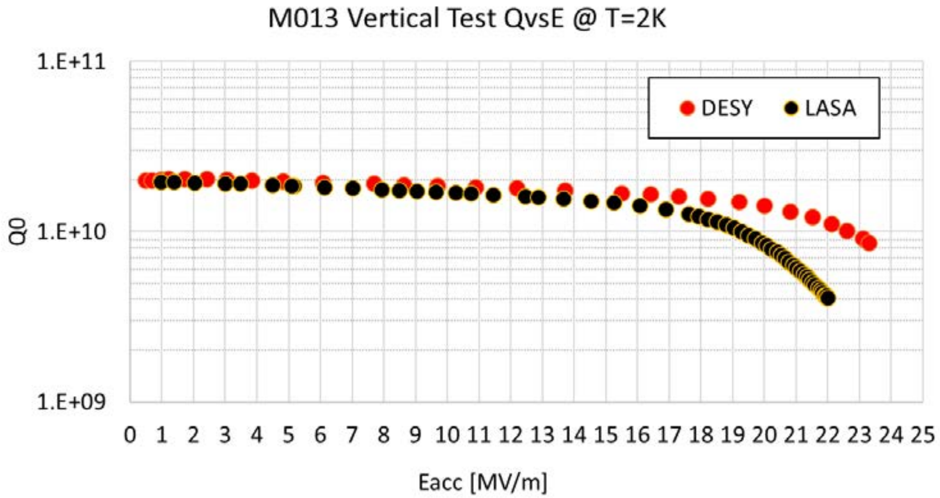
Vertical Test results **harmonization** within different infrastructures in the N-doping and mag-hygiene times

- Temperature time rate
- Temperature delta across the cavity
- Residual B field
- Helium mass flow

… Which fundamentals?
Which analytical approach?

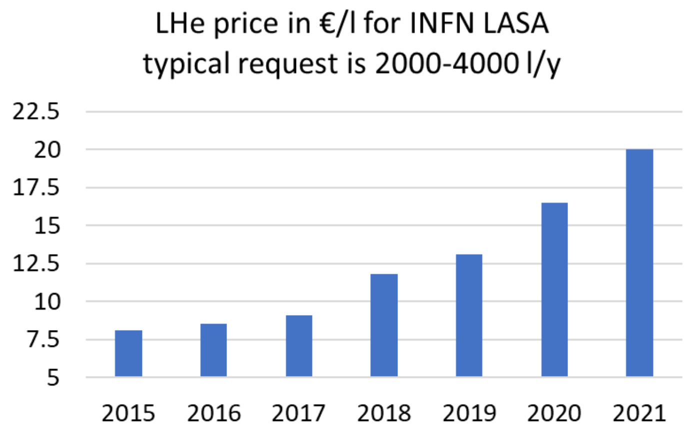
- ….we have Perfect flux expulsion? trapped field residual resistance set to 0
- $R_s(T)=R_{BCS}(T)+R_0+R_{fl}$ where $R_{fl}=\eta*S*B=2.4$ nΩ in our experimental case
- New $R_s=R_{BCS}(T)+R_0=5.9-2.4=3.5$ nΩ→ Q_0@low field=G/R_s =5.4E10





Liquid Helium availability, and cost

- 3 months total shortage in summer 2021, then OK so far
- Price going way up

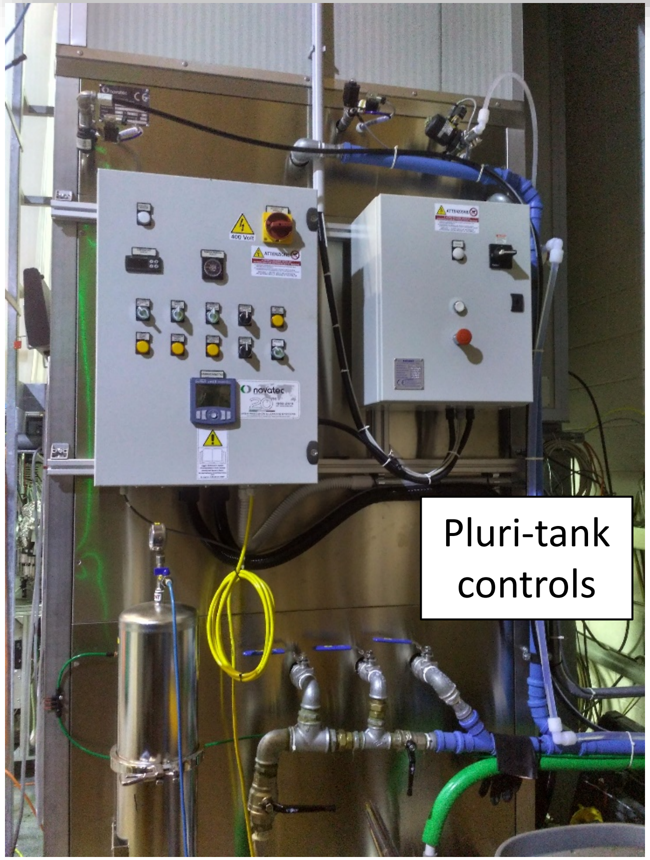


Thank you!

E. Del Core (INFN) up next to report about FE and dark current simulations and case study

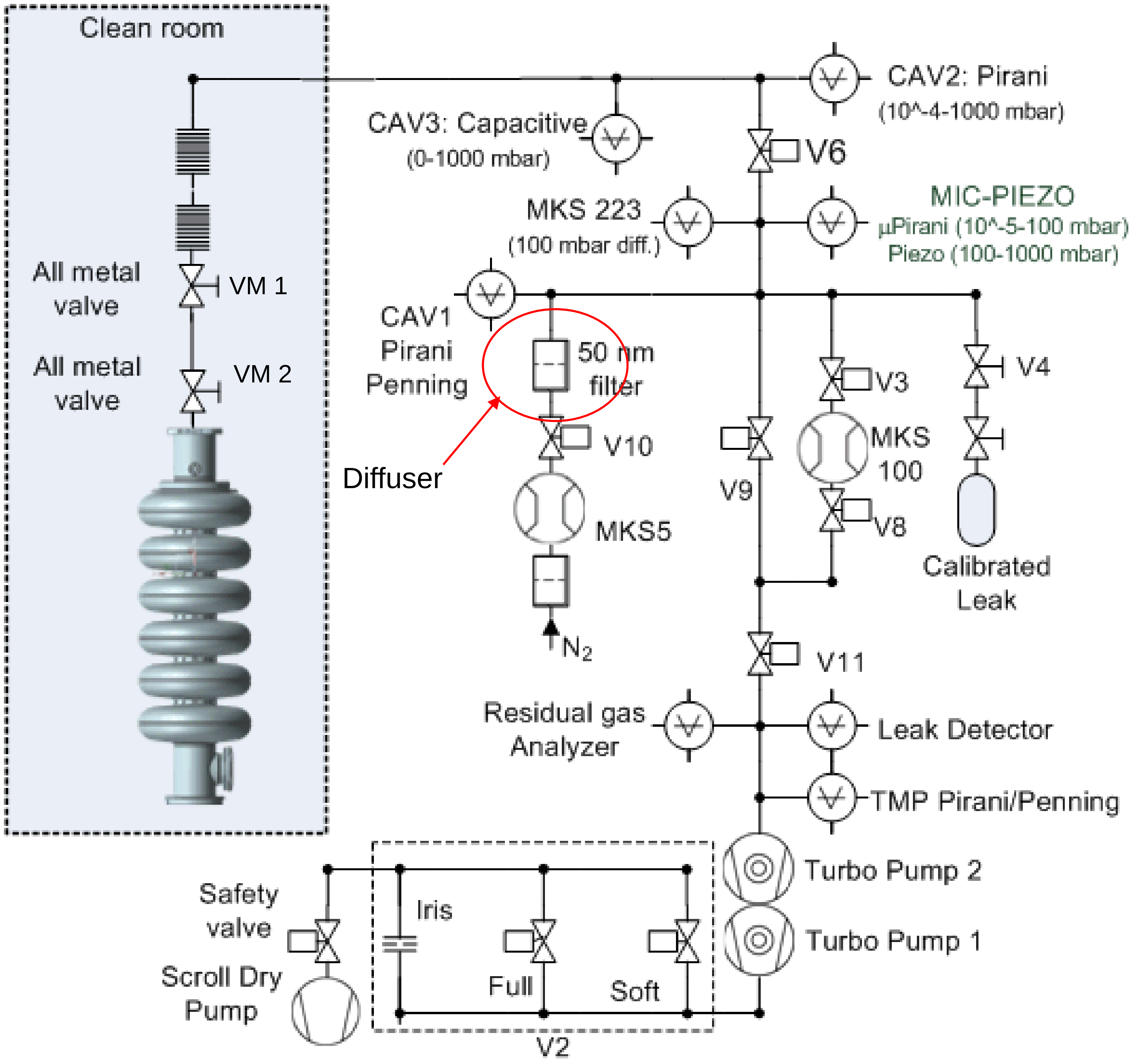
Extra slides

LASA Clean Room



LASA SPSV

- Scroll pump, Agilent Triscroll 600
- TMP1: LDS1000 TMP
- TMP2: Pfeiffer MP
- LD: LDS 1000 Oerlikon Inficon sensing head
- V2: VAT double valve
- V6, V8, V9, V10, V3, V11: Varian Viton seal on the bonnet, **metal seal on the body**
- MFC1: MKS, 5 sl/min flow controller
- MFC2: MKS, 100 slm flow controller
- VM1, VM2: all metal valve
- MKS223: differential capacitive MKS gauge for venting (+ 5 mbar)



HPR: High pressure rinsing with UPW

Cavity inner surface rinsing with high pressure water jets

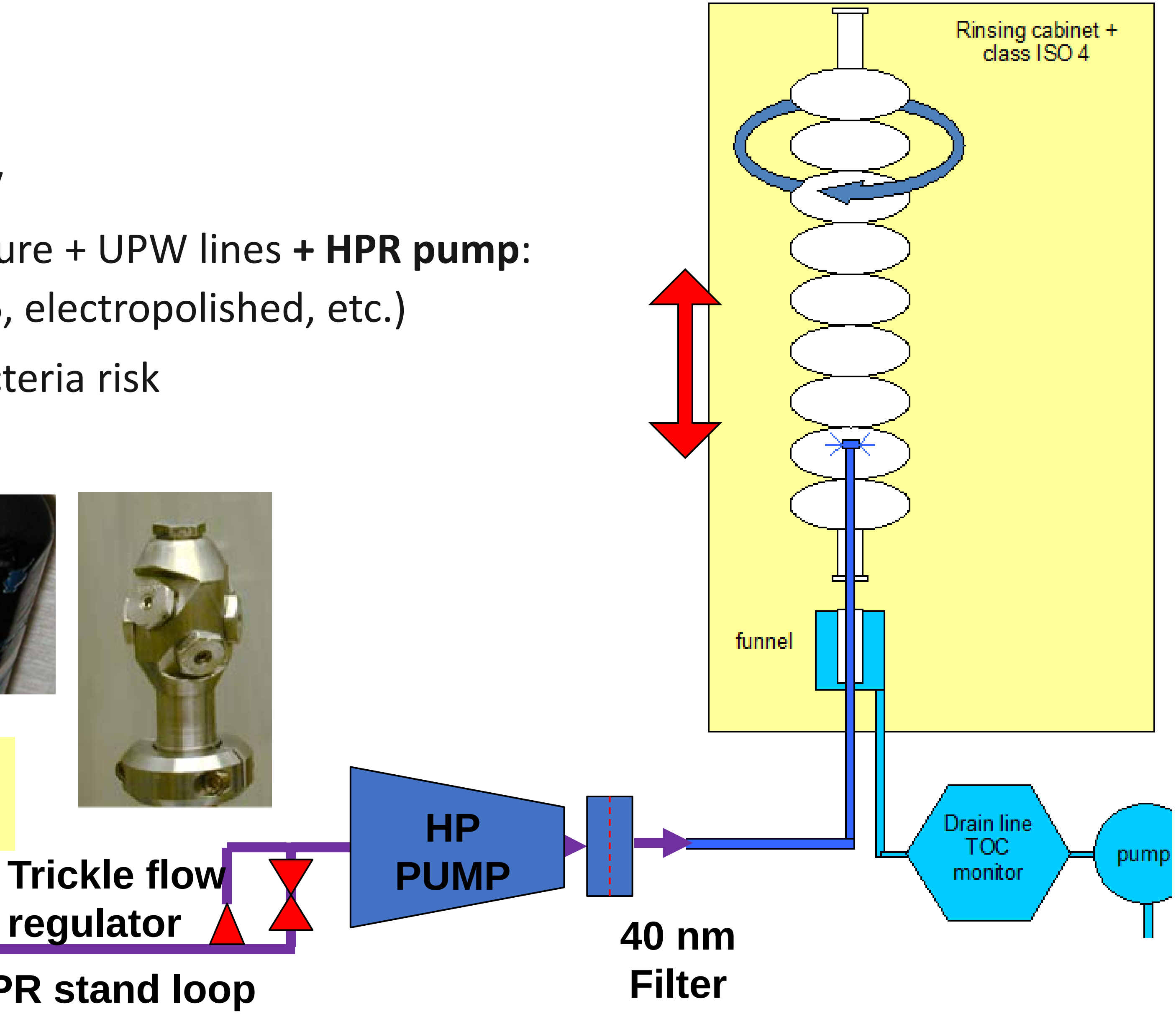
- HPR is the **final cleaning** step of the cavity preparation process
- Removal of **last treatment residuals**, **dust**, particles, etc.
- **Water jet must be moved continuously**: if jet impacts stably in one point Nb **surface can be damaged.**
- **Continuous motion of the cavity respect jets** (drawing a **spiral behavior** that covers completely the Nb surface)
- Typical pressure: **100 bar**
- **Water quality: E-1.2** (ASTM), **40 nm** filter **after HP pump!** No flex line should be used after the filter, to reduce particle generation.
- **Ultra pure (6.0) filtered (40 nm) nitrogen** protection gas injection coaxial with water to reduce risk of particles entering
- **Cavity must be grounded** otherwise it will be electrically charged.

HPR system: set up

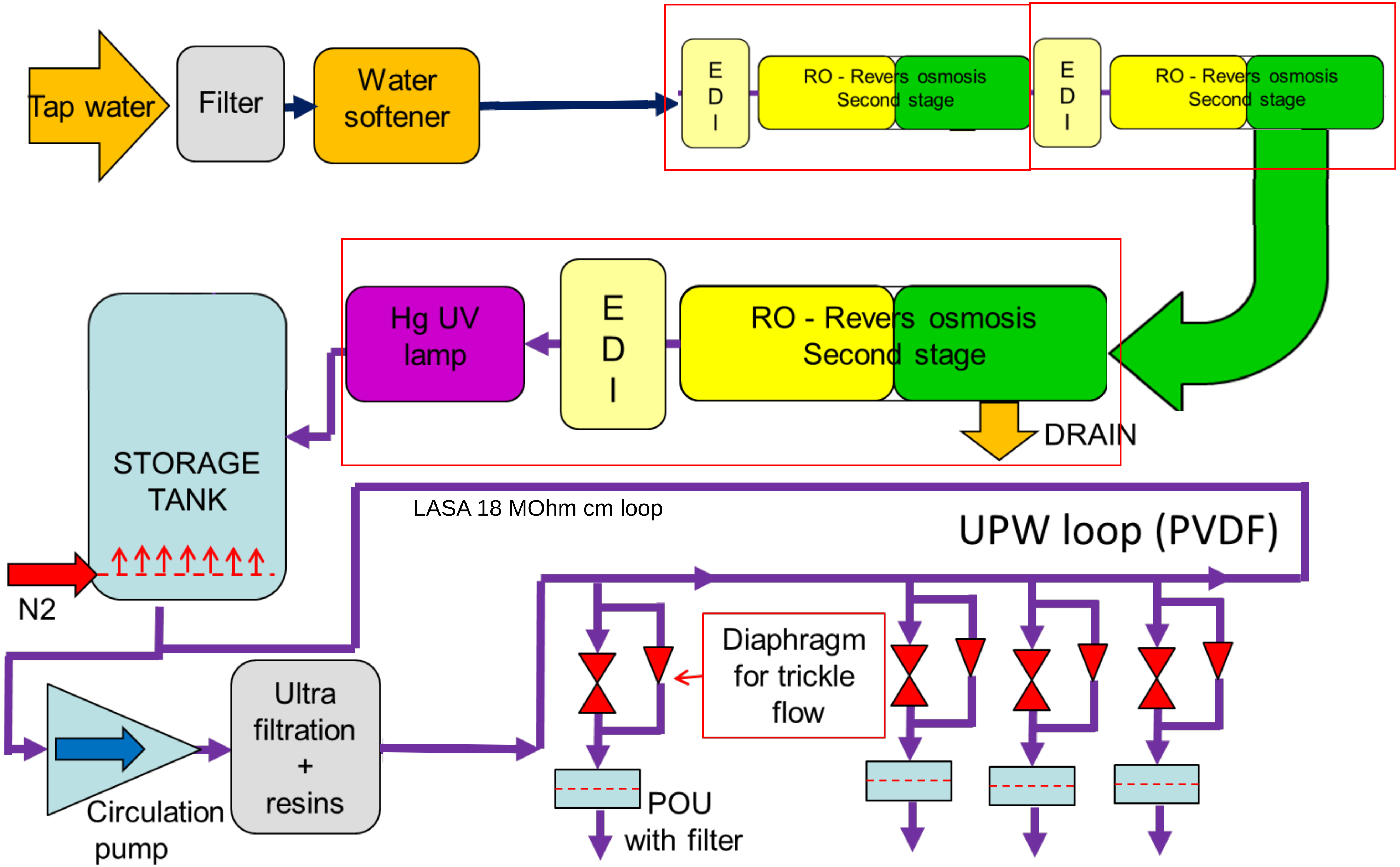
- **HPR stand in ISO 4 / 5**
- Nozzles: **sapphire nozzles**
- **No moving parts inside the cavity**
- adequate materials for high pressure + UPW lines **+ HPR pump**: not all stainless steels are OK (316, electropolished, etc.)
- **Trickle flow** all time to reduce bacteria risk

Sapphire nozzles

Nozzle head with sapphire nozzles

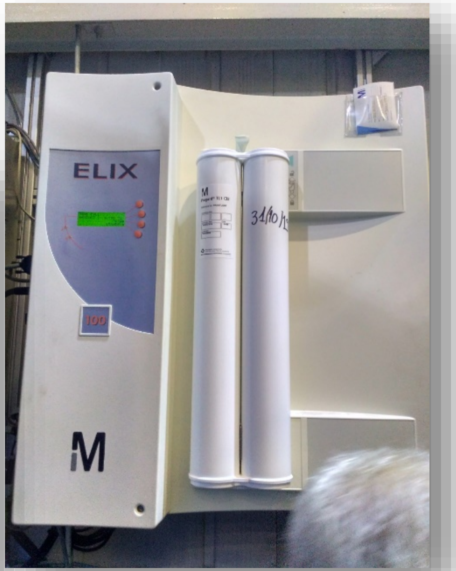


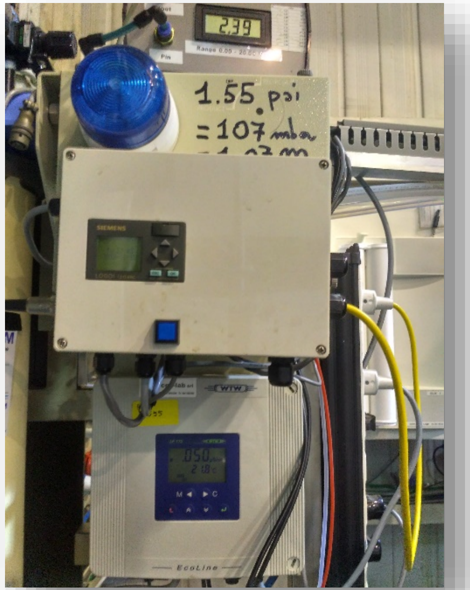
UPW LASA production scheme



LASA UPW plant

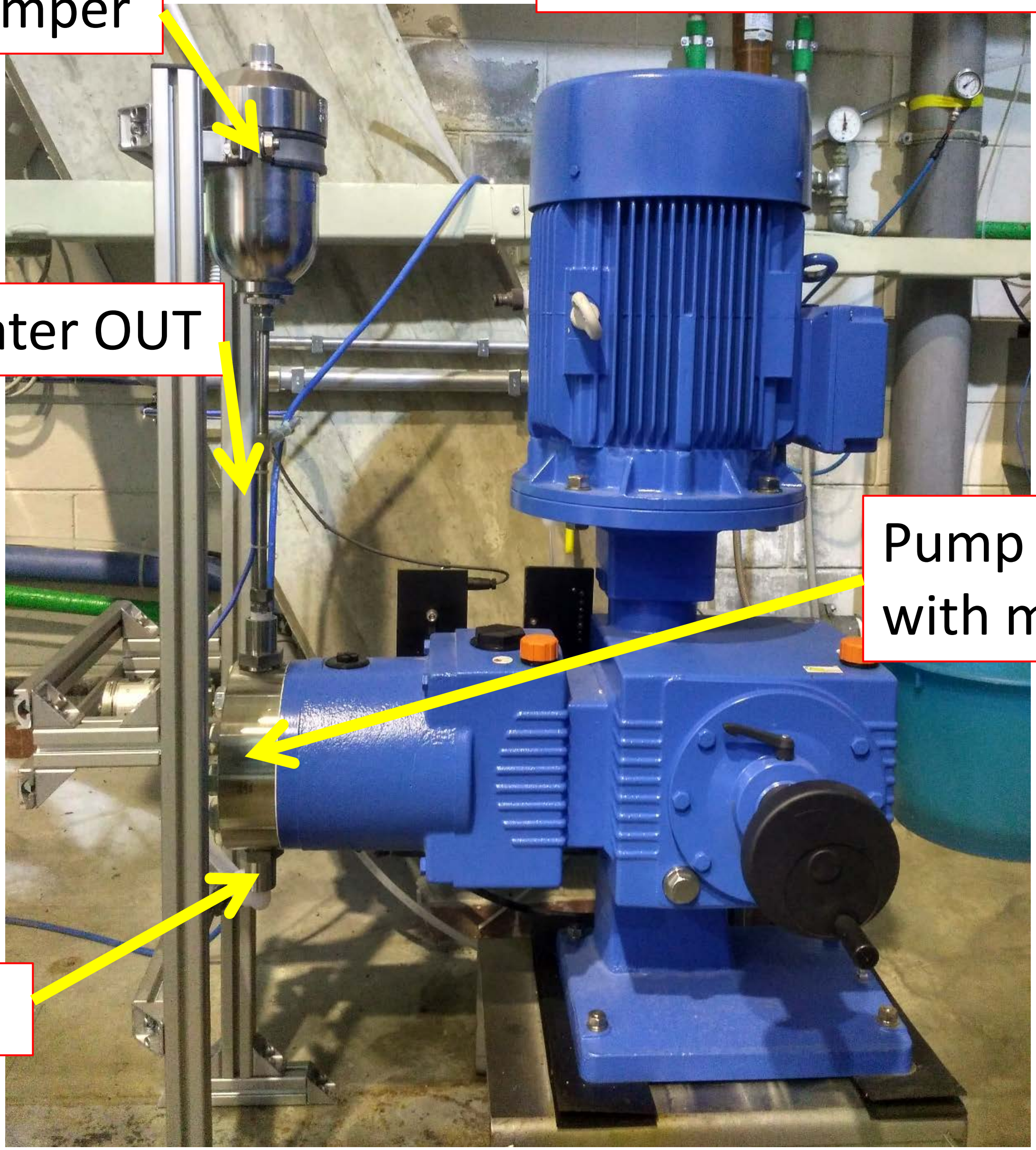
- Production: 170 l/h
  - 100 + 35 + 35 l/h Millipore ELIX RO
- Millipore Super-Q Plus system (Ion-Ex, Organex, Durapore)
- Storage: 6000 l of > 1 MOhm cm water
- Online TOC and Conductibility measures
  - MP A10 TOC Monitor, typical value 1-3 ppb
- Inner Loop at 18-20 MOhm cm
  - Serving the clean room





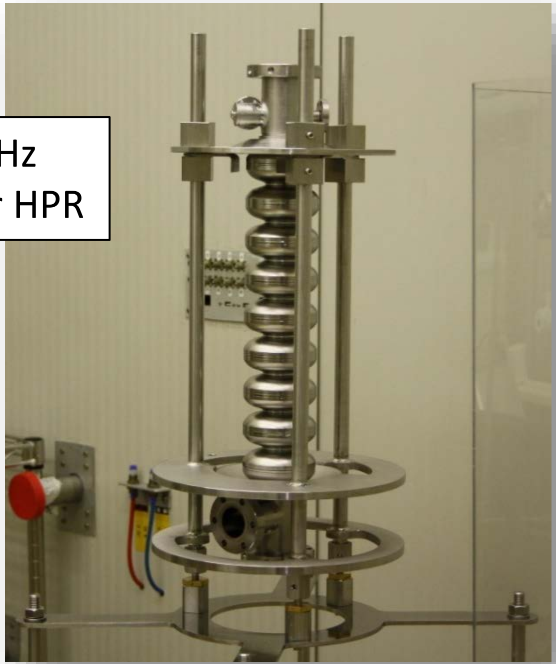
LASA HPR UPW pump

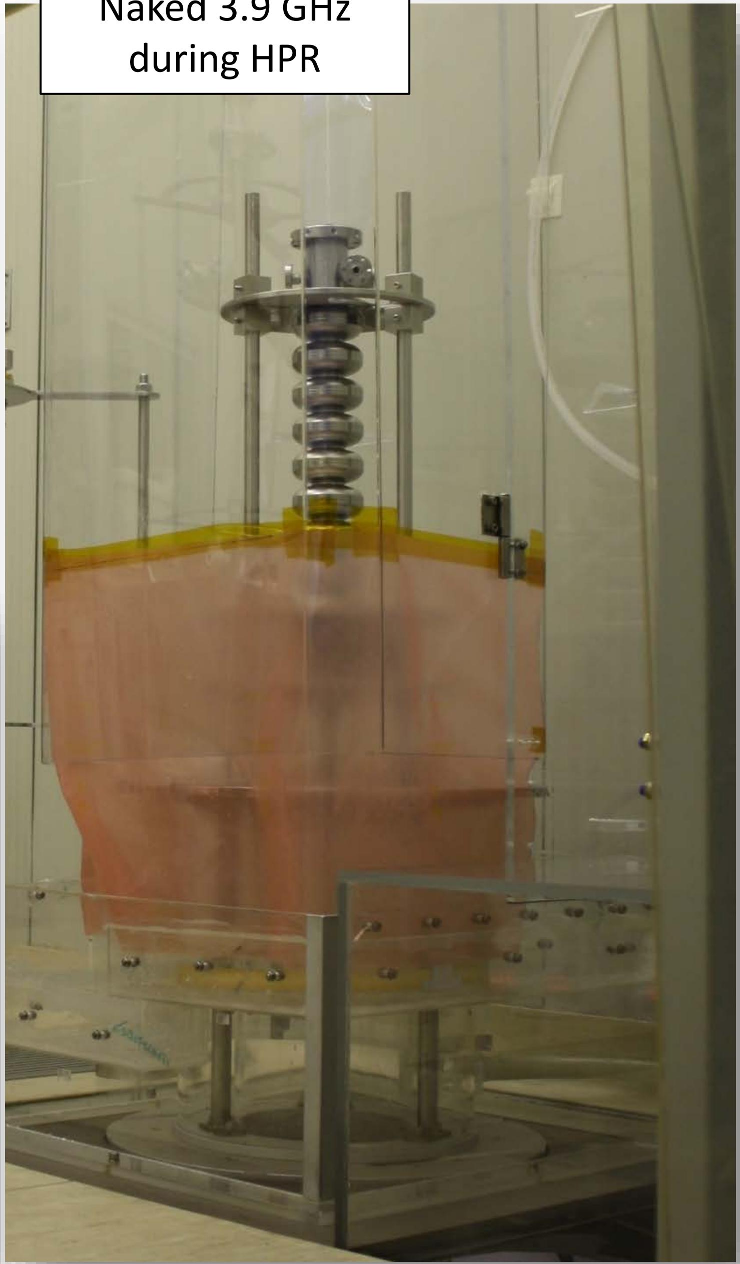
- Membrane pump from LEWA, FC Laboratory Pump
- **Physical separation** between oil lubricated part and UPW.
- Membrane maintained routinely



LASA HPR

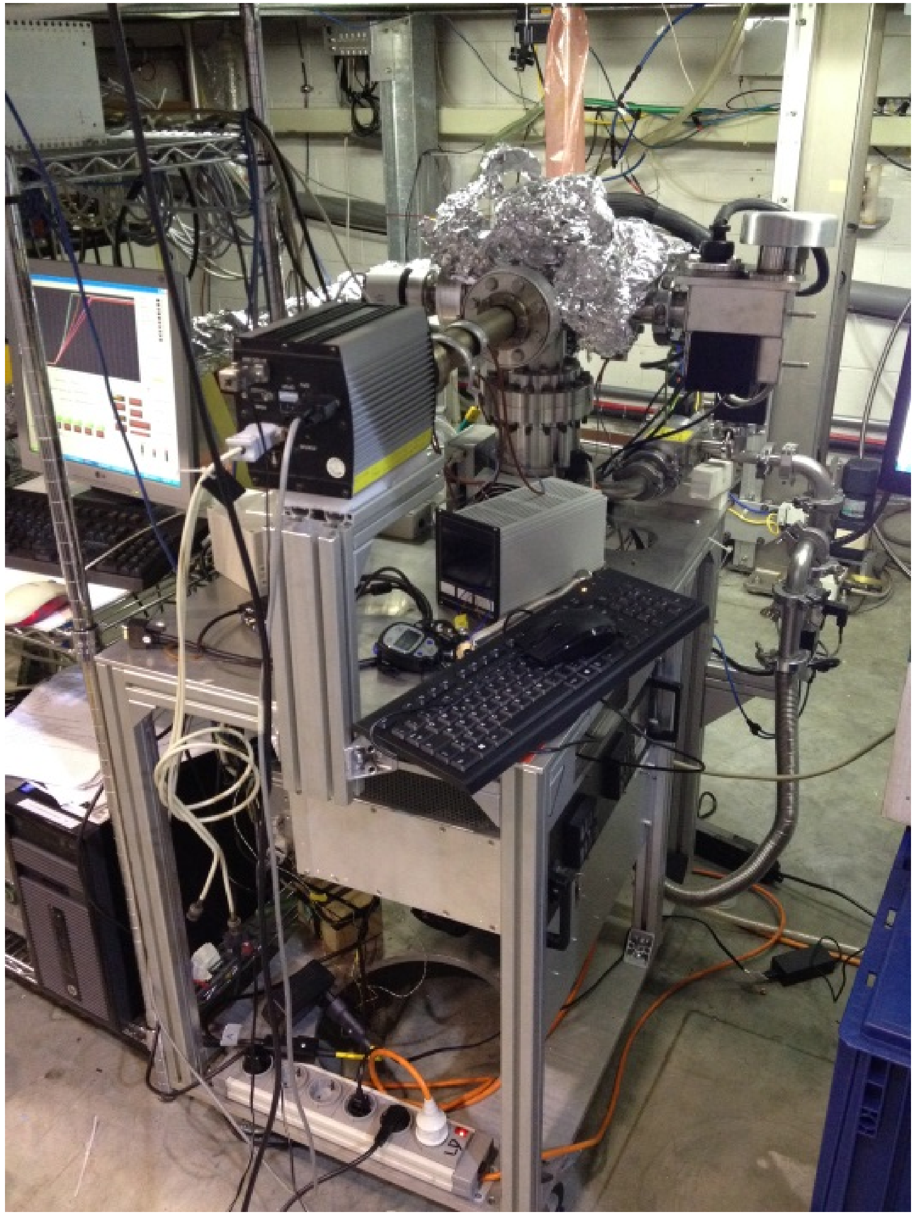
- EP stainless steel rod with FlowMeca connection with zero dead volume.
- 3 to 115 mm/min vertical speed.
- Rotational speed: 0.45 to 15 rpm
- Maximum excursion of about 1.1 m
- PALL T high pressure filter with stainless steel EP housing, 0.05 μm pore size
- Typical flow rate of 600 l/h

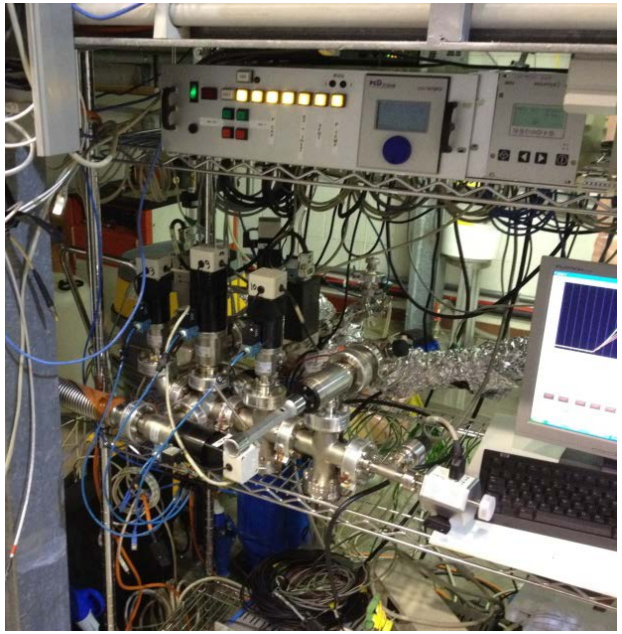

Naked 3.9 GHz cavity ready for HPR

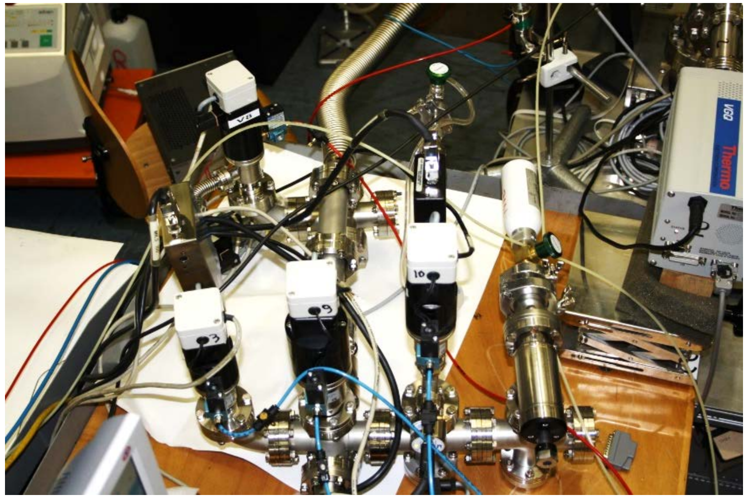

Naked 3.9 GHz during HPR

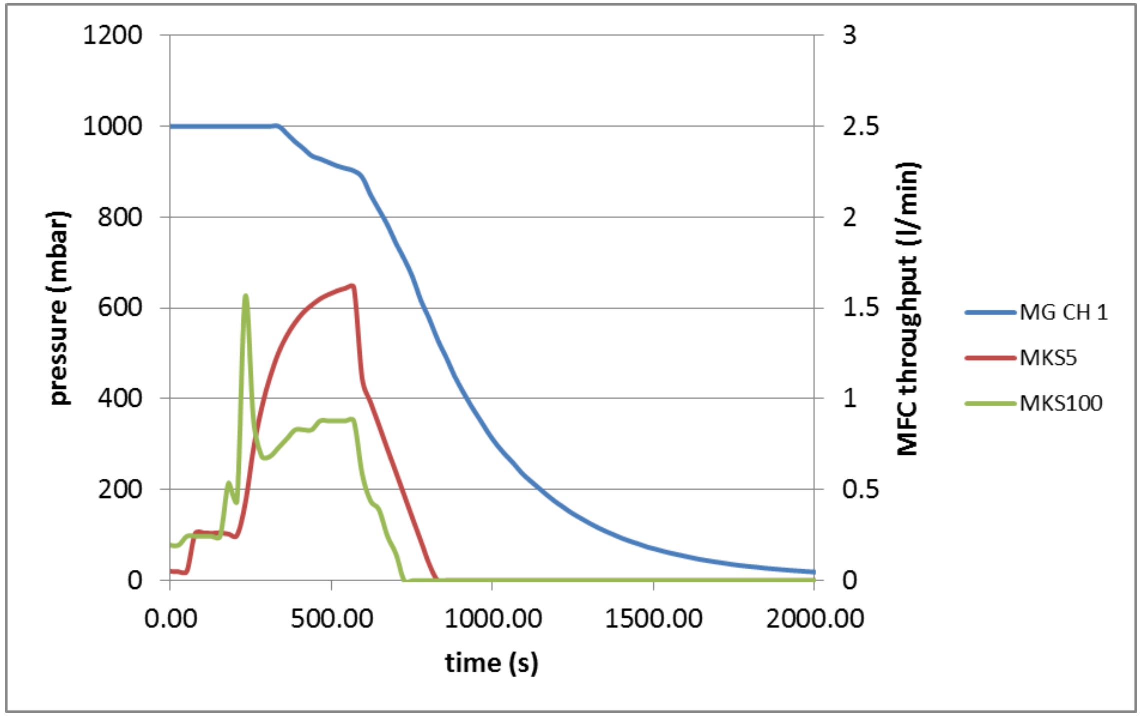

HPR rod and moving basement with high pressure filter

LASA SPSV

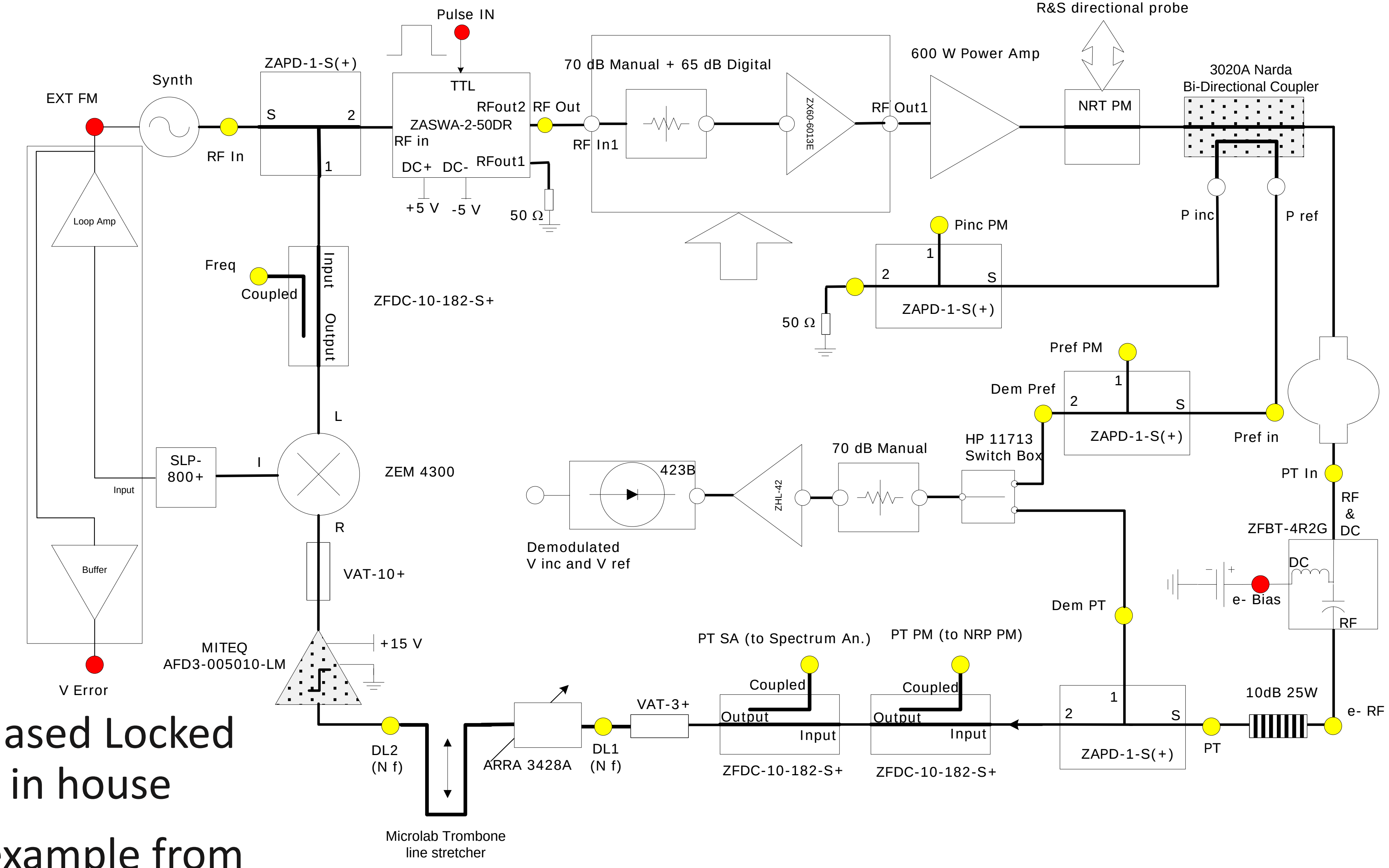







1200
1000
800
600
400
200
0
pressure (mbar)
3
2.5
2
1.5
1
0.5
0
MFC throughput (l/min)
0.00
500.00
1000.00
1500.00
2000.00
time (s)
MG CH 1
MKS5
MKS100

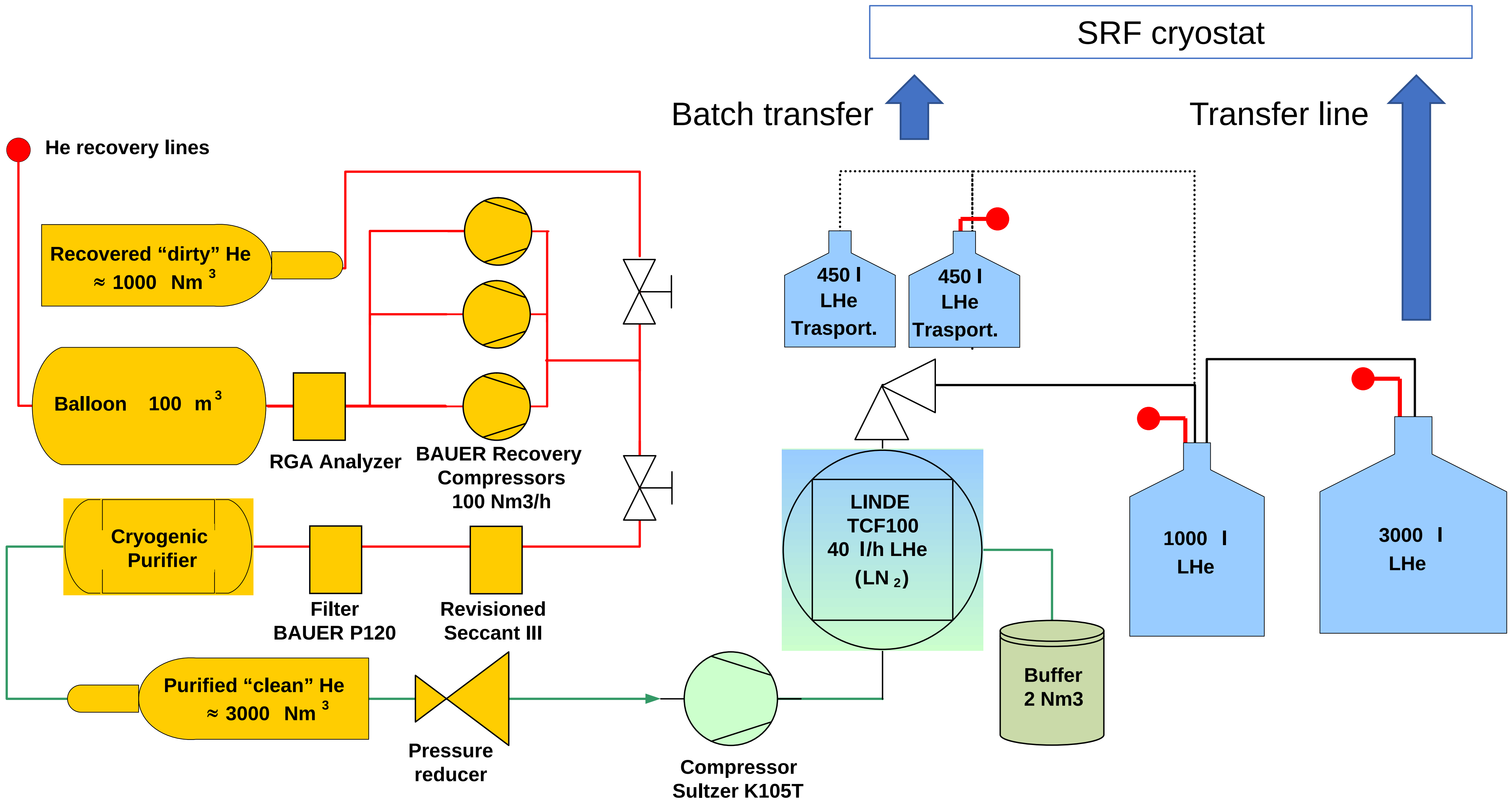
RF Systems – Phase Locked Loop



Fully analog, Phased Locked Loops made in house

Scheme is and example from ESS_MB and PIP2_LB cavities

LASA cryogenic infrastructure, 2022



LHe transfers, cool-down and 2 K filling

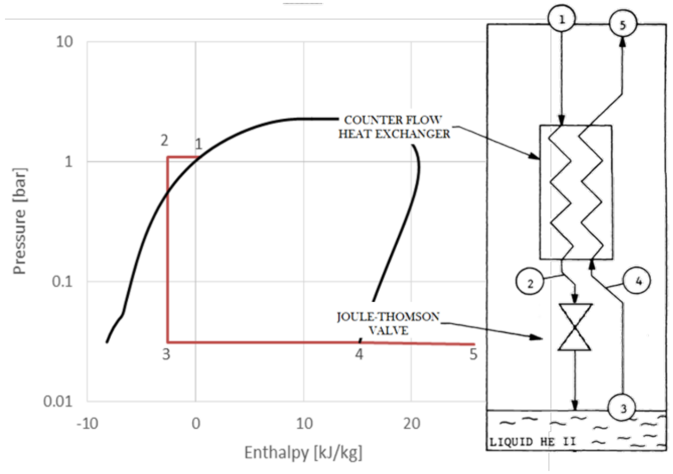
- Standard VT cryogenic procedure
  - Cool-down by gHe flow only (no LN2 pre-cool)
  - Fill up by transfer at atmospheric pressure
  - Pump-down to 32 mbar
  - Perform tests in boiling phase-II LHe
  - Additional tests at lower temp/pressure
  - LHe transfer back from cryostat to dewar
  - Final boil-off and warm-up
- 1800-2200 LHe liters are required in total
- Enabled alternatives for insert #2
  - Refilling at 2 K to extend testing time
  - Immediate pump-down after initial LHe accumulation followed by fill-up at 2.0 K

Cool-down

300 to 70 K: safety limit on rate set to 2 K/min

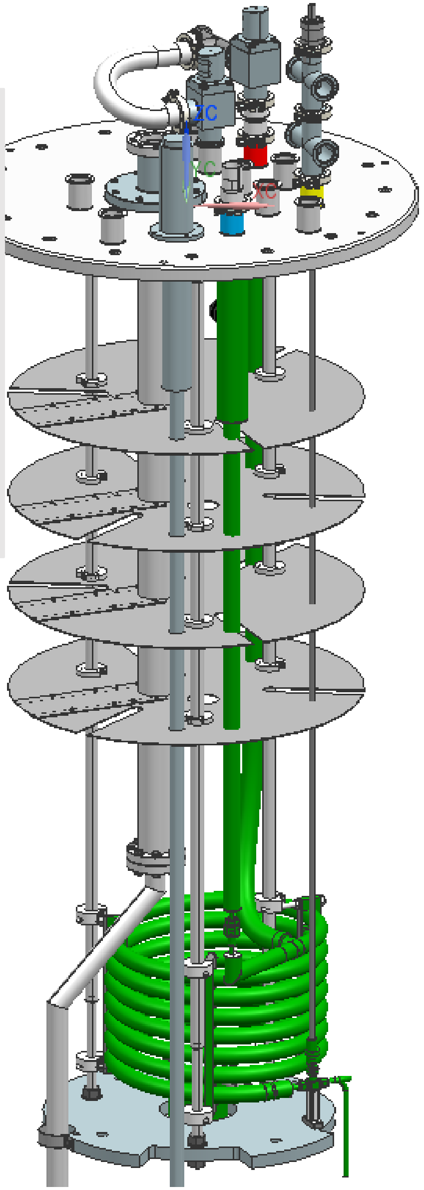
Below 40 K: highest He mass flow (7 g/s) still delivers only 0.5-0.7 K/min

- Need better LHe transfer geometry?



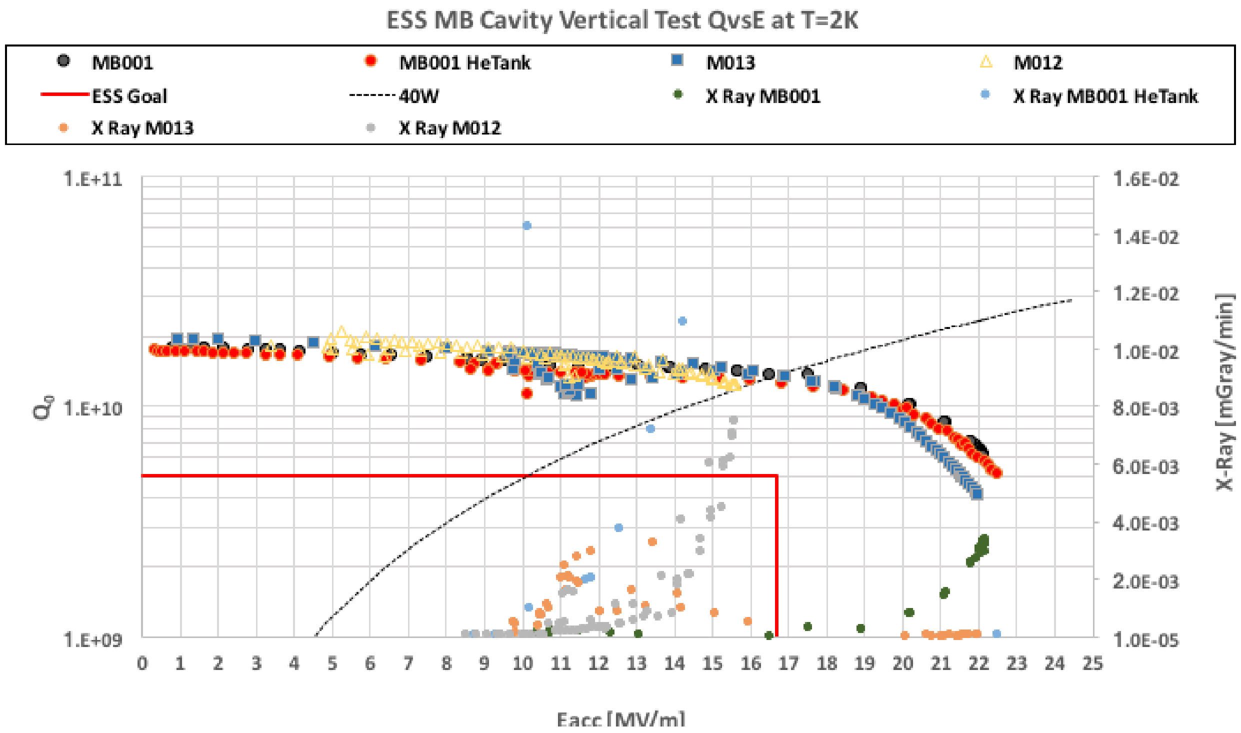
2 K refilling system:

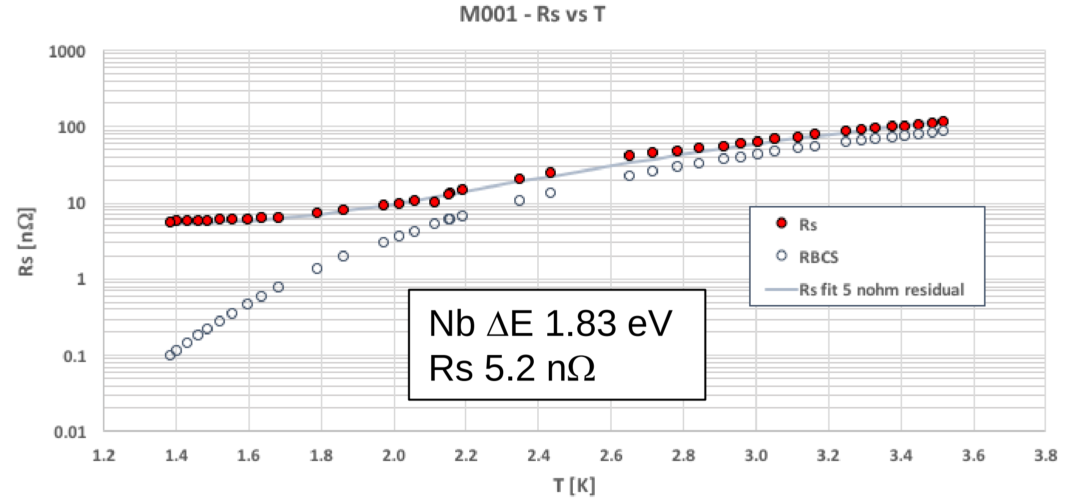
Counterflow, tube-in-tube heat exchanger serving manually actuated JT valve

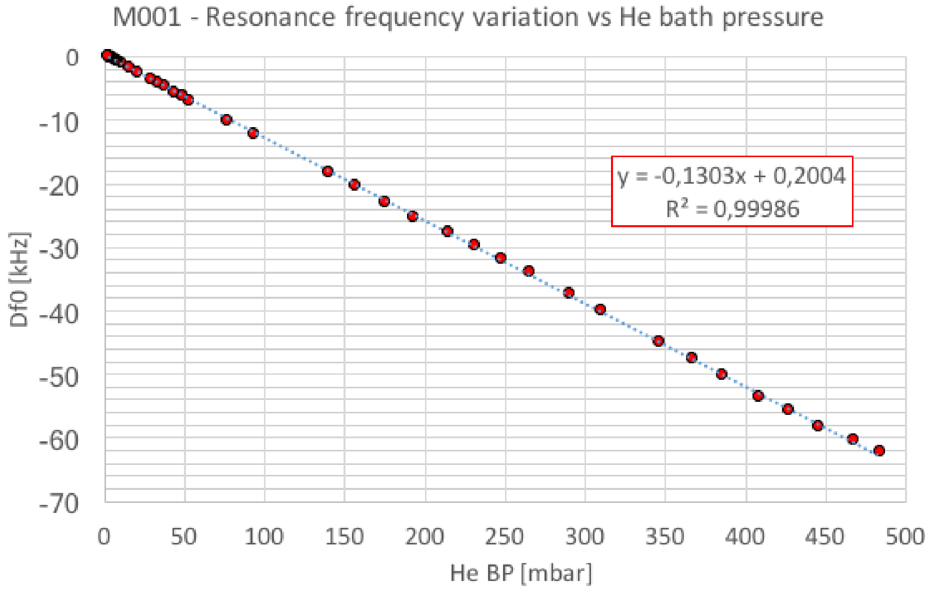


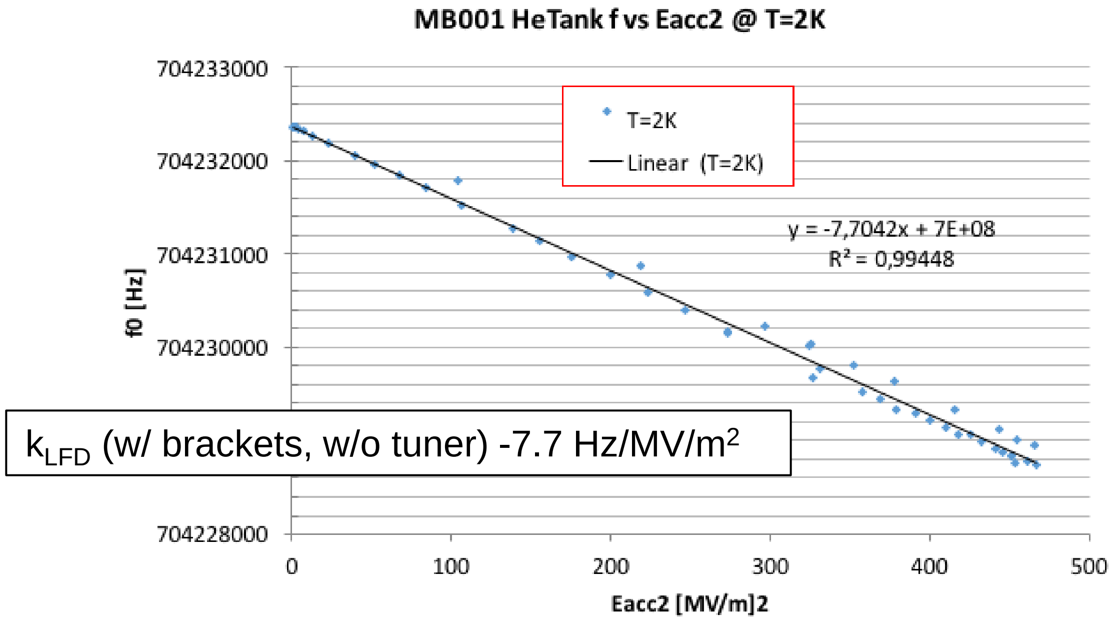
AMICI ETIAM Workshop on SRF Cavity Testing

Examples of RF Test Results



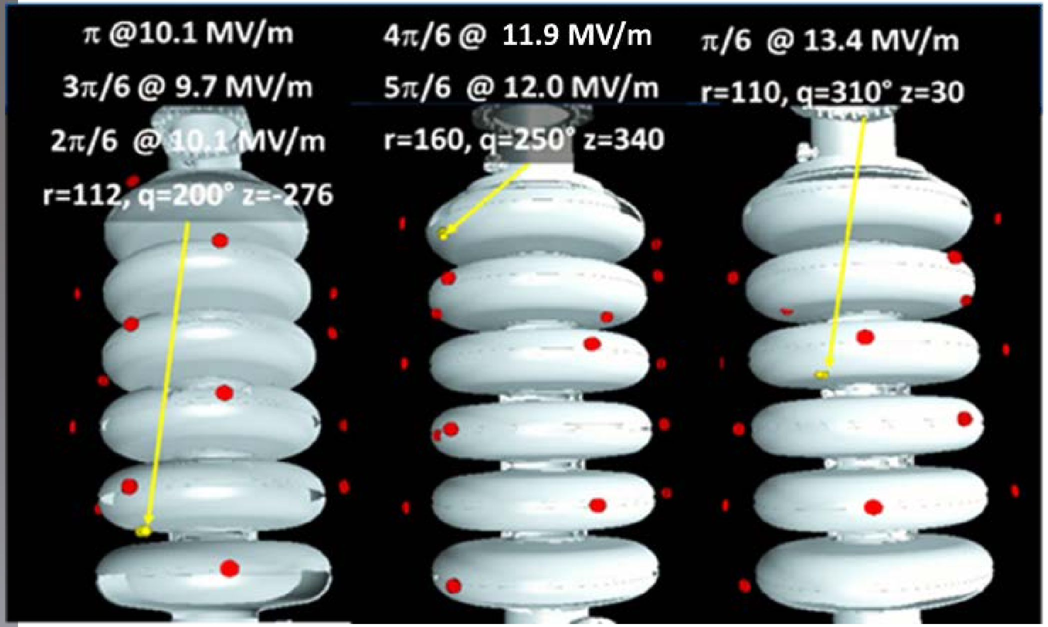




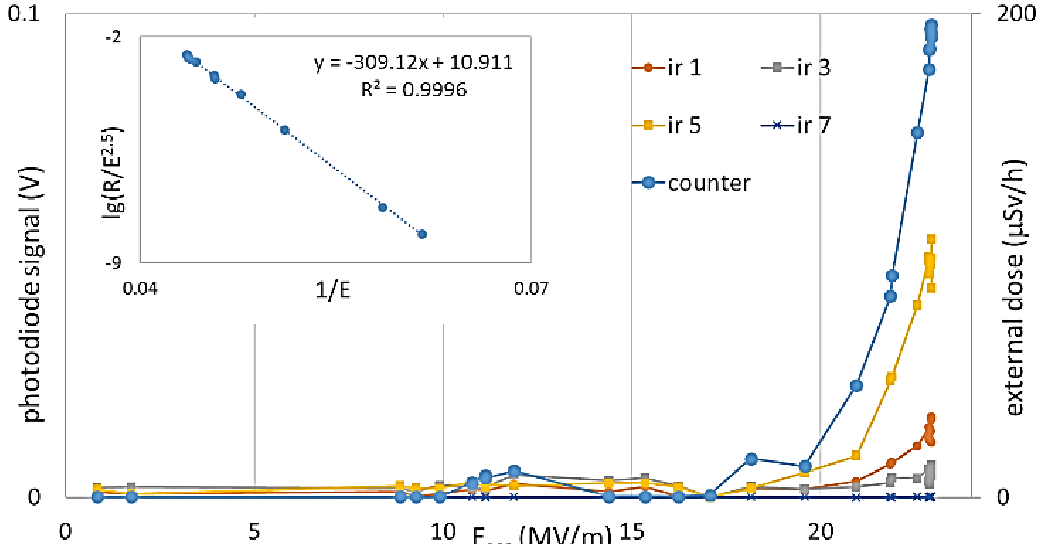


ACCELERATOR AND MAGNET INFRASTRUCTURE FOR COOPERATION AND INNOVATION

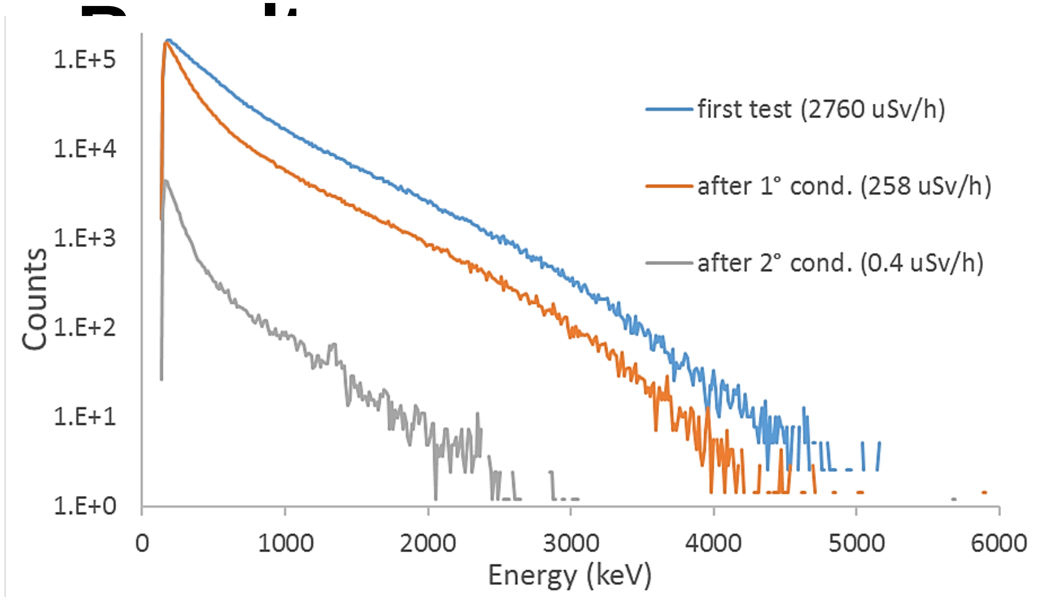
Examples of Diagnostic



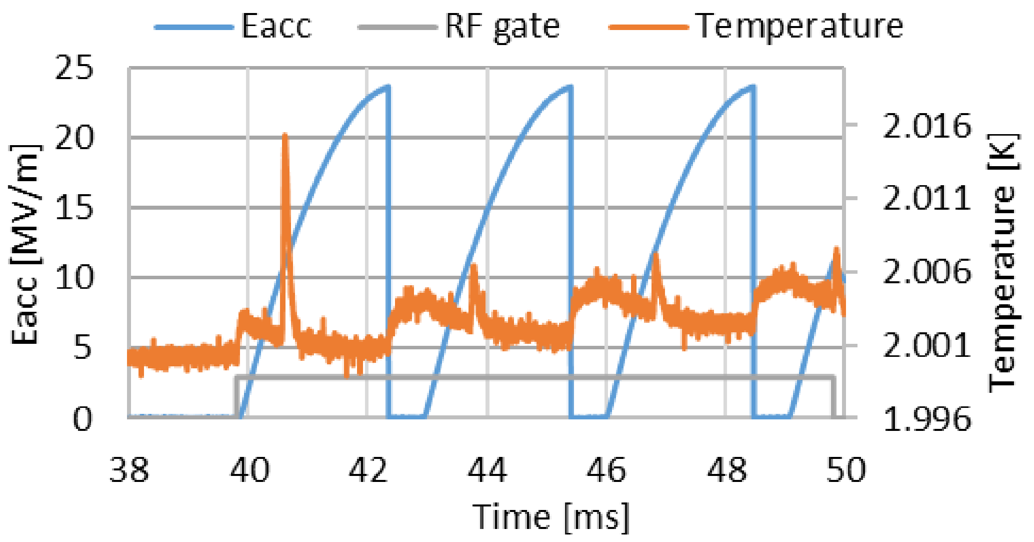
Second sound reconstruction of the 6 passband modes quench



Photodiode signals vs Eacc, labelled with corresponding cavity irises, and external radiation level



Scintillation spectra at quench field before and after conditioning



Cernox sensor during quench at 22 MV/m