PIP-II Technical Workshop

PIP-II 2nd Technical Workshop, WG#2: cavity processing and testing

Prototypes experience (Processing, Facility, Tests…) @ INFN LASA

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Outline

- INFN LASA R&D activity on PIP-II LB650 prototypes:
  - EP optimization
  - Baseline treatment
  - High-Q treatments
- INFN LASA vertical test facility:
  - Diagnostics
  - Magnetic properties
  - Cryogenic capabilites
- Vertical test results:
  - B61S-EZ-002 (single cell)
  - B61-EZ-002 (multicell)

PIP-II prototypes strategy

A total of **7 PIP-II LB650 cavities produced** (single and multi cell), 3 of them shared with Fermilab for a joint development effort.

<u>INFN LB650 single-cells:</u>

- B61S-EZ-001: treated with high-Q recipe (N2 doping+900°C) and tested at FNAL
    - **Next:** re-test at LASA toward harmonization of testing infrastructure
- B61S-EZ-002 with baseline recipe (XFEL) qualified at LASA
    - **Next:** retreat with mid-T bake recipe, then VT at lasa
- B61S-EZ-003: foreseen to be treated with high-Q treatment (N2 doping-based), then VT at LASA

<u>INFN LB650 5-cell cavities:</u>

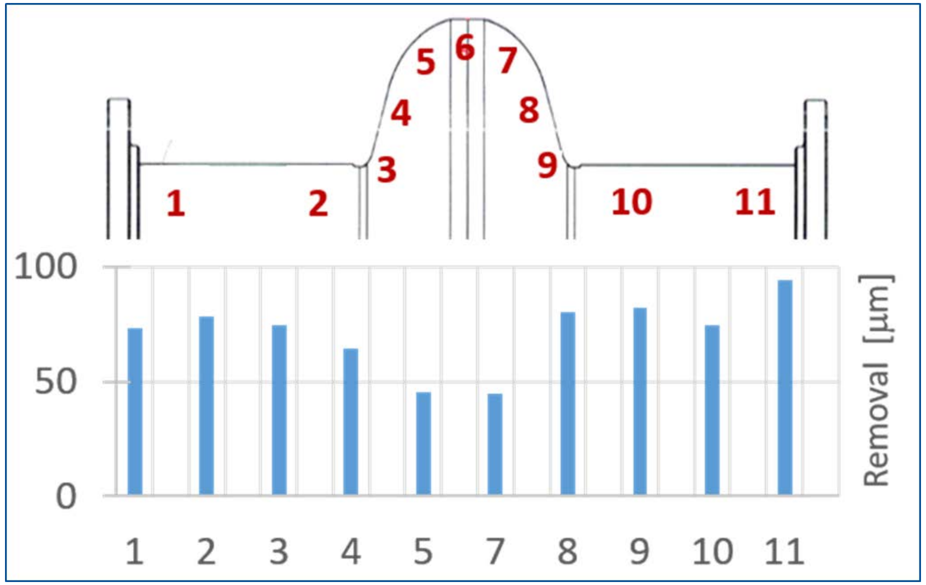
- B61-EZ-001 successfully qualified at Fermilab VTS both naked and jacketed
    - **Next**: targeted for dressed, horizontal cavity test in STC
- B61-EZ-002 treated with mid-T bake recipe, then VT at LASA

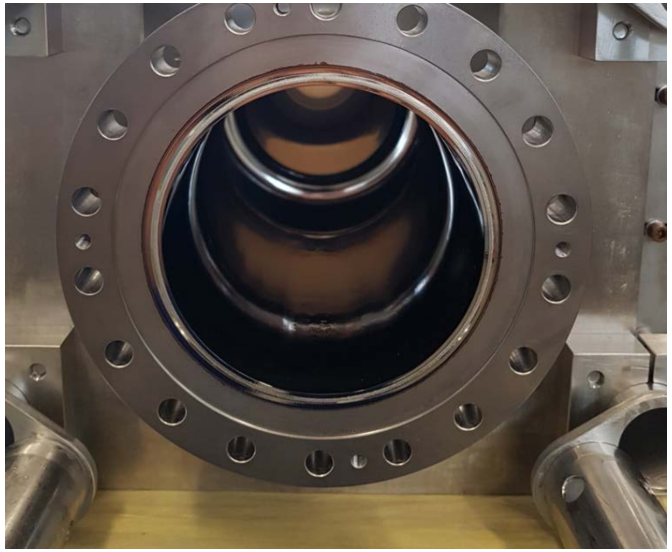
Surface treatments validation strategy

- **1° phase**: setup of Electropolishing parameters: on single cell cavity B61S-EZ-002
    - check: surface smoothness, iris/equator removal ratio, removal rate, frequency response
- **2° phase**: setup of the baseline (à la XFEL) recipe: on single cell cavity B61S-EZ-002
    - check: no fundamental limitation in performance (early quenches, field emission, Q-disease,…)
- **3° phase**: setup of a high-Q treatment: on single cell cavity B61S-EZ-002, B61S-EZ-003 and multicell cavity B61-EZ-002
    - check: project target values of Q_0 and E_{acc} w/o field emission, cavity mechanical stability

1° phase: setup of EP treatment

- First trials (40-60 um each) with ZRI plant, made with «plain» cathode
  - **63 mm** average removed thickness **[0.13 μm/min**]
  - **40 A** average current
  - **51 kHz** frequency shift. [**0.81 kHz/μm**]
  - Local thickness measured by US probe before and after the treatment. **40 μm** removed near equator vs **80 μm** removed on irises. Removal ratio is >2

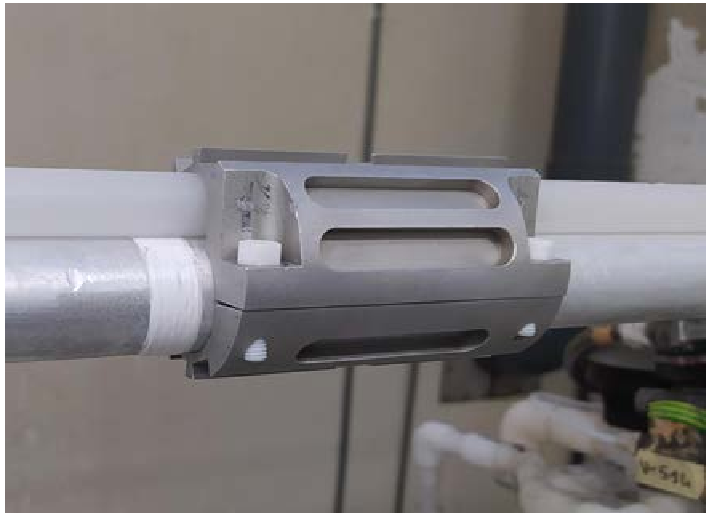




- Improved surface smoothness on beam tubes, irises and walls…
- …but modest gain in roughness at the equator

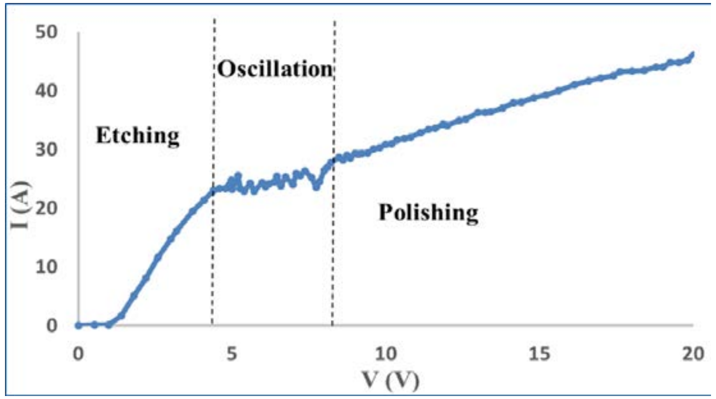
- **Removal at equator will be increased by:**
  - **Cathode enlargement**
  - **Temperature setpoint will be reduced so to stabilize the process**

1° phase: setup of EP treatment

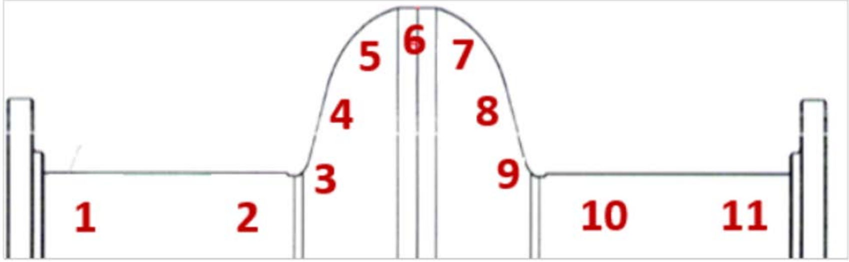


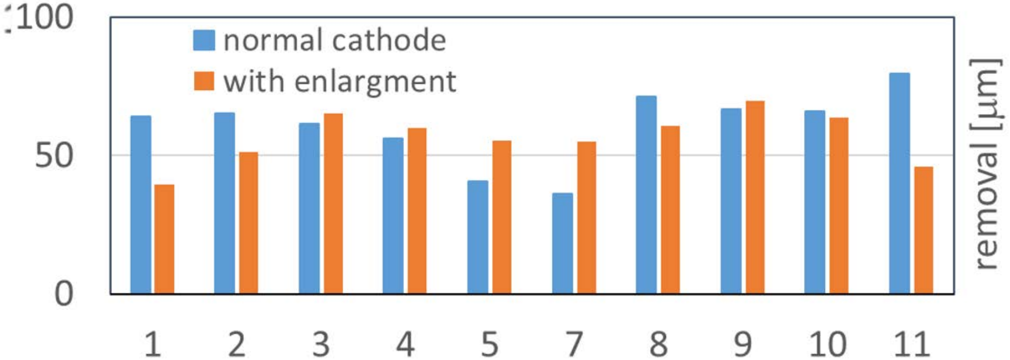
After cathode enlargement installation:

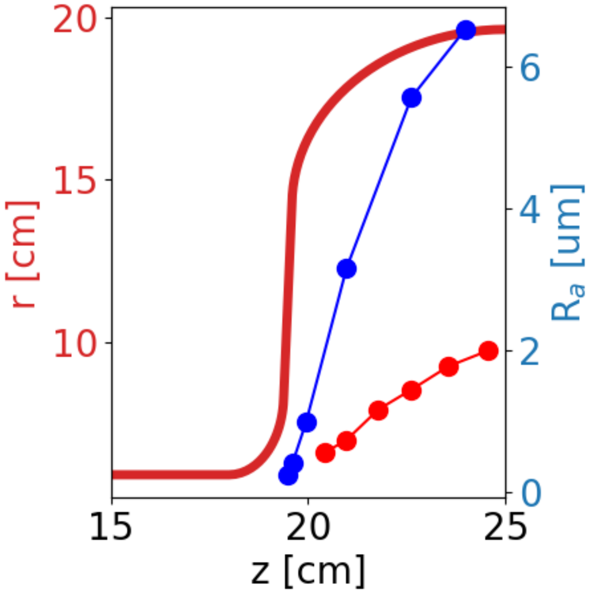
- Average current increases to >45-50 A
- Enhanced removal at equator as measured by US after treatment
- Equator roughness goes from 6 μm to 2 μm after 40 μm EP removal
- Plateau regime at V=17 V

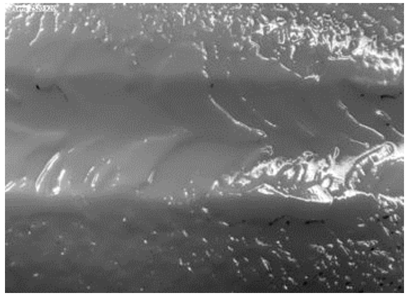


US measurement before and after Al doughnut installation





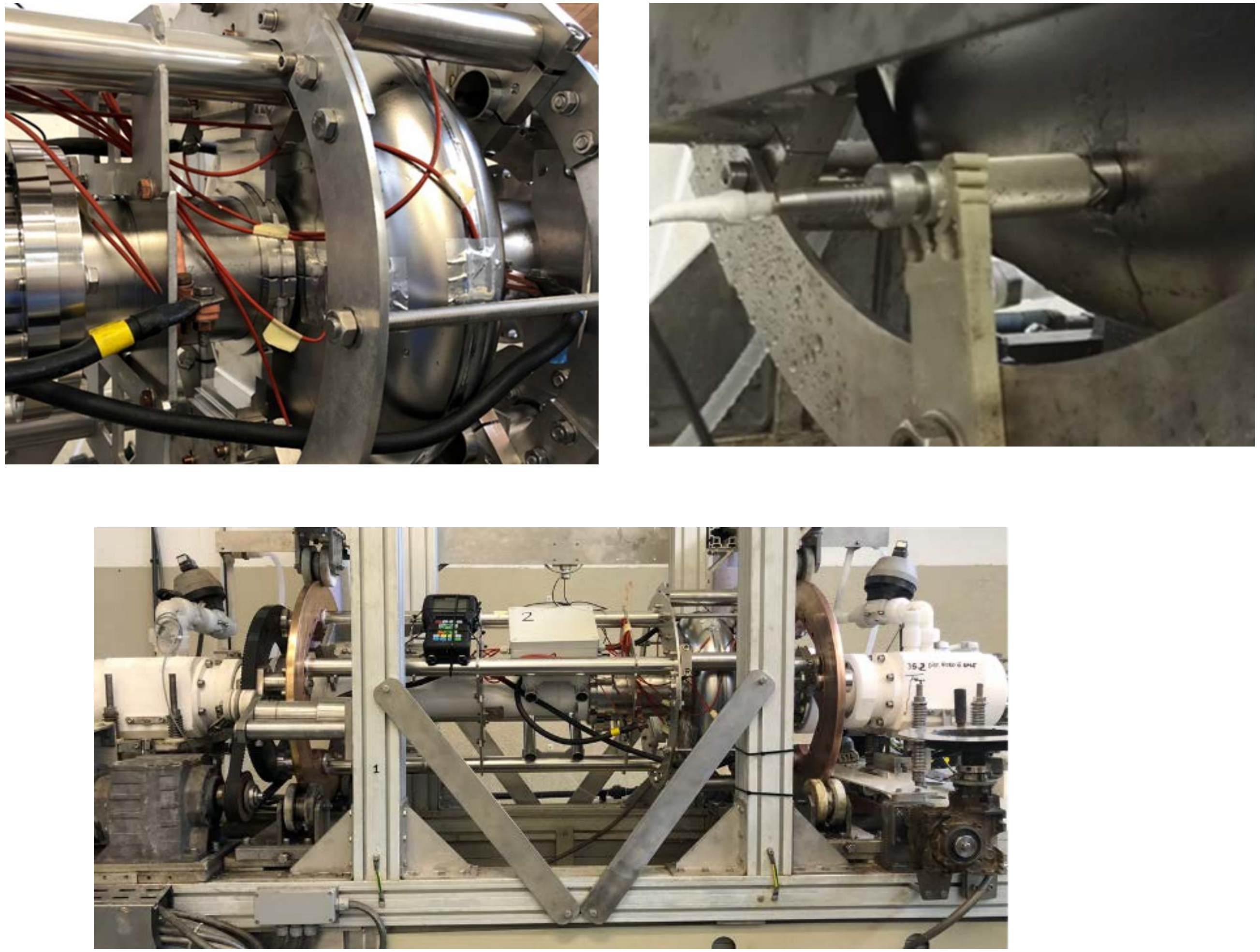




Roughness measurement on replicas by 3D microscope before and after 40 um EP

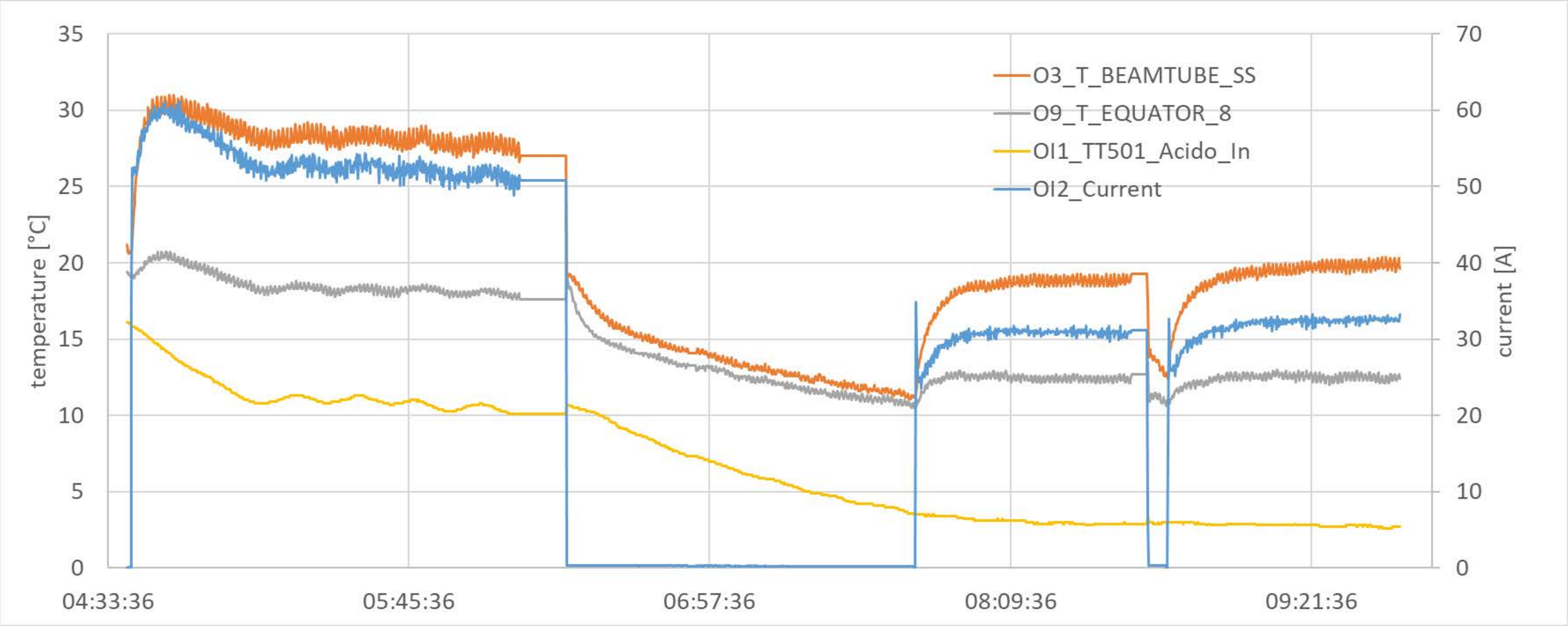
Single cell bulk EP: the warm regime

- The already existing EP plant at ZRI is now optimized for the single cell cavity.



- Target removal: 150 μm avg.
- Voltage=17 V
- Nb initial dilution in electrolyte: 4.5 g/L
- 50% cathode coverage at beam tubes
- Acid overall throughput: >6L/min
- Acid inlet temperature (at beginning of process): 15°C
- Temperature setpoint for chiller: 20-21°C avg
- External water cooling on beamtubes (if T>25°C)
- US continuous reading on iris, wall and equator

Single cell final EP: The «cold» regime



First 15 um (300 kC) warm
V=17V, 19-20°C acid chilling setpoint
Max 20-21°C on cell, 28°C on BT

Acid chilling
Treatment stopped (V=0).
Acid cooled down to 7-8°C

Last 10 um (200 kC) cold
V=17V, 7-8°C acid chilling setpoint
Max 13°C on cell, 18°C on beamtubes

2° and 3° step: the recipe book

- The «baseline» recipe (à la XFEL)

  200 μm bulk EP + 800 °C 2h heat treatment+25 μm final EP (15 μm warm+10 μm cold)+ 120°C 48h bake

  Performed on cavity B61S-EZ-002

- The «mid-T bake» recipe:
  - 150 mm bulk EP + 800˚C HT + final EP (5 μm cold)+ 300˚C 3h bake

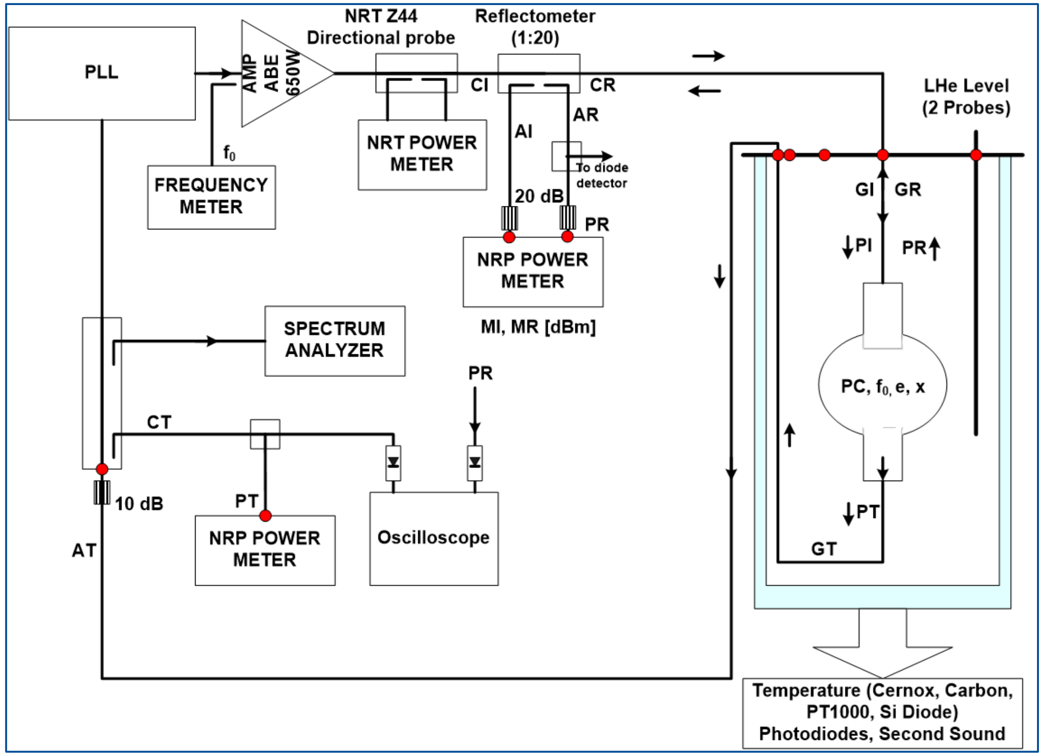
  Performed on cavity B61-EZ-002, to be used on B61S-EZ-002 after surface reset

- The «nitrogen doping» recipe:
  - 150 μm bulk EP+ 900 ◦C 2h heat treatment+ 2/0 N2 doping (25 mTorr) @ 800 ◦C +7 μm cold EP
  - To be performed on B61S-EZ-003

The INFN LASA vertical test facility

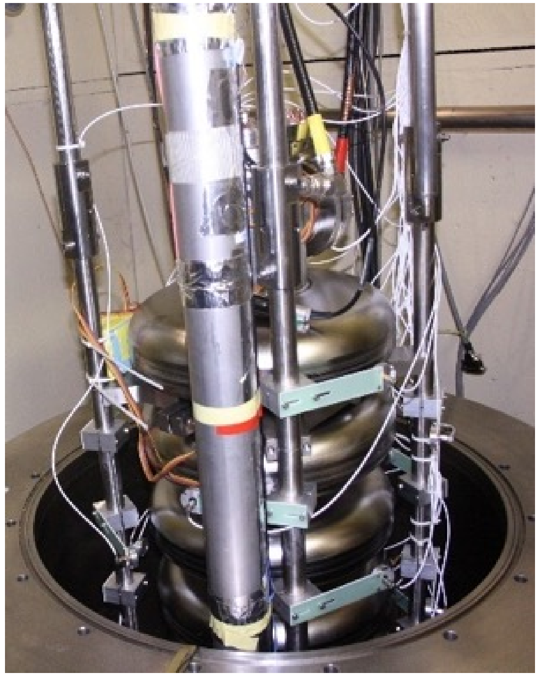
RF system:

- **650 W** UHF power amplifier
- Input power coupled by high-Q antenna ($\mathbf{Q_I = 10^{10}}$)
- Transmitted power measured by pickup antenna with $\mathbf{Q_{ext} = 3 \cdot 10^{11}}$
- PLL to lock cavity frequency (due to high-Q, cavity bandwidth is <0.1 Hz)



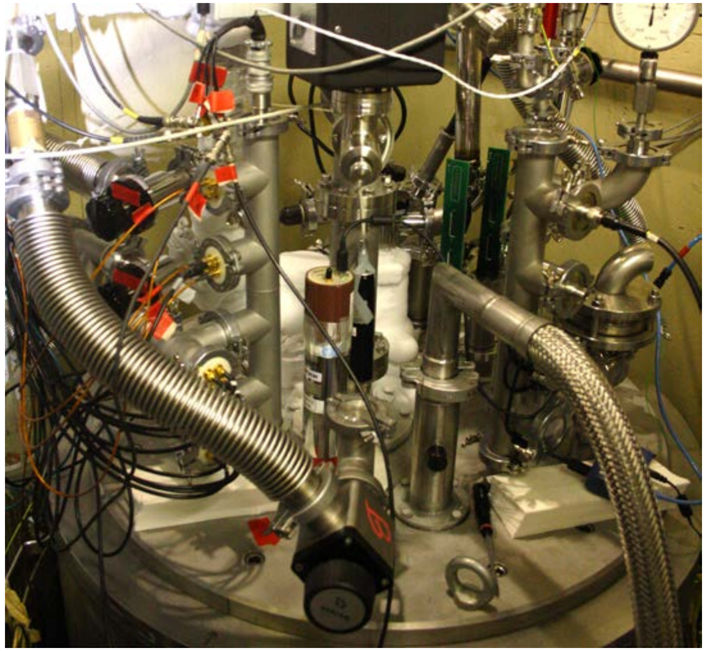
Cryostat: ϕ 700 mm, 4.5 m length, **losses < 1 W @ 4 K**

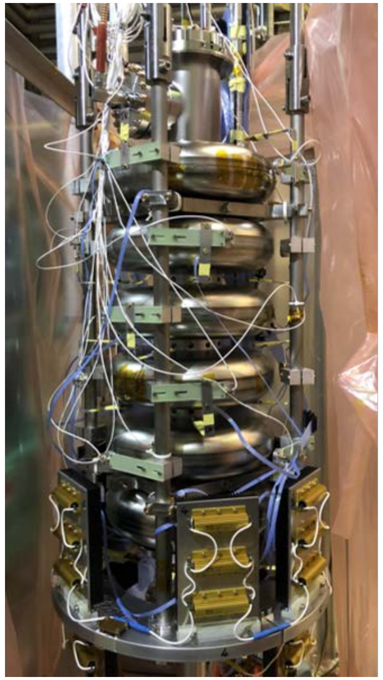
- Can host f>500 MHz cavities
- temperature sensors, He vapor pressure reading to control He-bath temperature, LHe level probes so to monitor LHe transfer
- Approximately 2500 liters of LHe @1Atm needed to cover PIP-II cavity@2K (32 mbar)

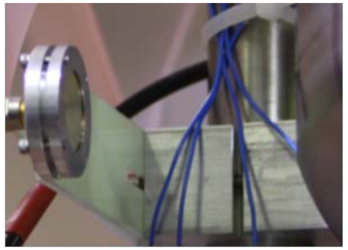


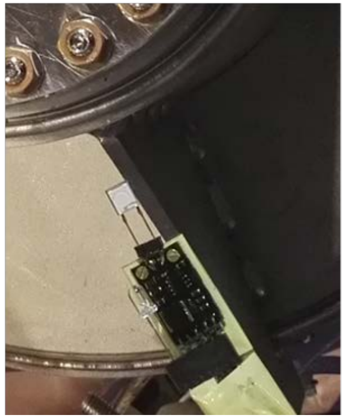
LASA INFN VTS diagnostics

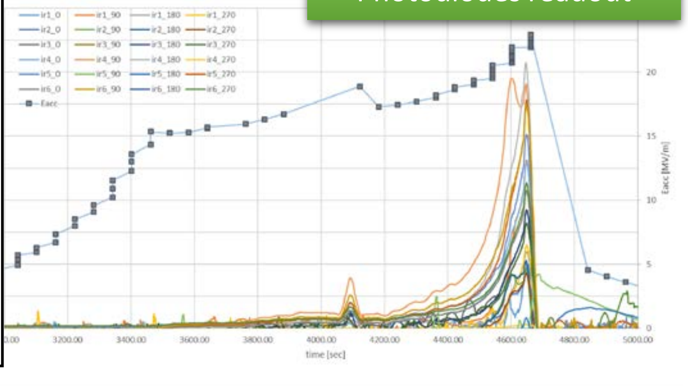
- Quench diagnostics:
  - 11 fast thermometry sensors (CCS\Cernox©)
  - 20 second sound sensors (OST)
- Field emission diagnostics:
  - 28 cryogenic photodiodes inside cryostat
  - Proportional counter for dose rate
  - NaI scintillator for X-ray sectrum (both on cryostat top)
- Magnetic field diagnostics:
  - 1 Cryogenic fluxgate
  - Soon: AMR sensors



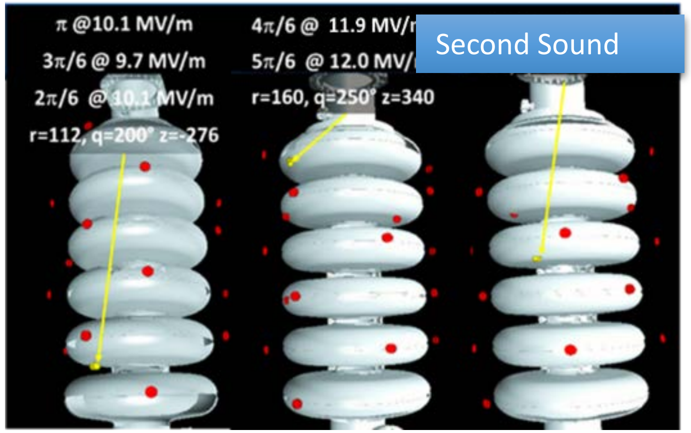








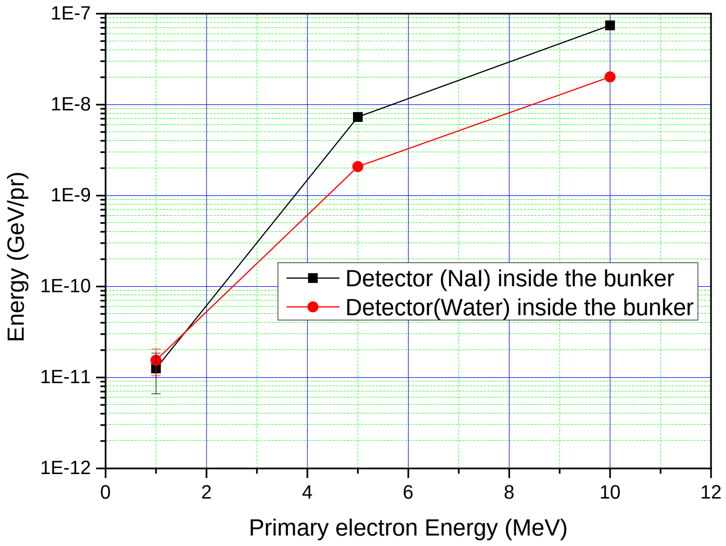
Photodiodes readout



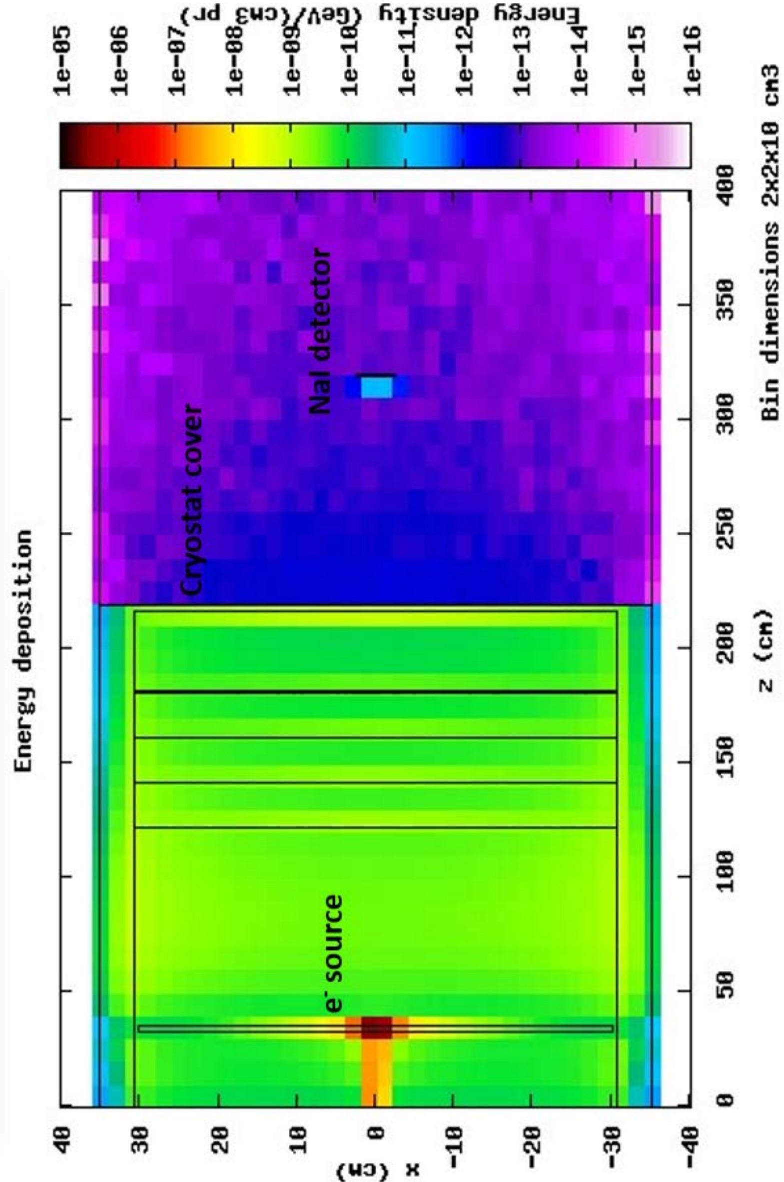
Second Sound

LASA VTS radiation scenario

- FLUKA model: 10^7 electrons at 10 MeV hitting the cavity beam tube flange, then generating Bremsstrahlung X-rays, which are then attenuated by thermal shields, the cryostat cover, etc,…
- External detectors (NaI and tissue-equivalent (H_2O)) to collect counts and dose rate
- Total counts in detector: $N_{det.}/N_{tot} \sim 10^{-4}$
- energy deposited on detector: $E_{det.}/E_{tot} \sim 10^{-6}$

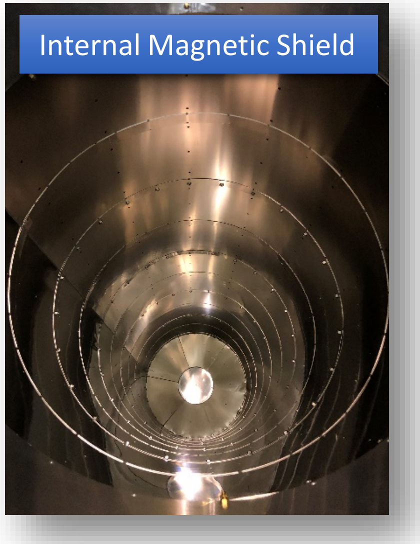


- $E_{det.}/E_{tot}$ depends upon the electron impact energy
- FE-power can be assessed by measuring X-ray energy



LASA INFN VTS flux expulsion scenario

- **Sub-cooling system**:
  - Cooling power: ~ **70 W @ 2 K**
  - Lowest temperature **1.5 K**.
  - Cooldown rate now limited to about **1 K/min**…but **10^2 K/m** of T-gradient at the transition across cavity
  - Soon capability of **direct filling at 2 K,** and faster cooldown rate (by different distribution of LHe flow around cavity
- **Residual field**:
  - With mu-metal external shield: 10 mG in correspondance of equators.
  - After cryoperm inner shield installation: 5 mG max expected
  - Soon: field active cancellation by means of Helmoltz coils



$$S = \frac{B_{trap}}{B_{NC}} = \left(1 - \frac{\frac{B_{SC,eq}}{B_{NC,eq}} - 1}{R_{PD} - 1}\right)$$

- R_{PD}=1.9 for tesla-shaped cavities→ S=0.87

87% of external field is trapped
13% is expelled

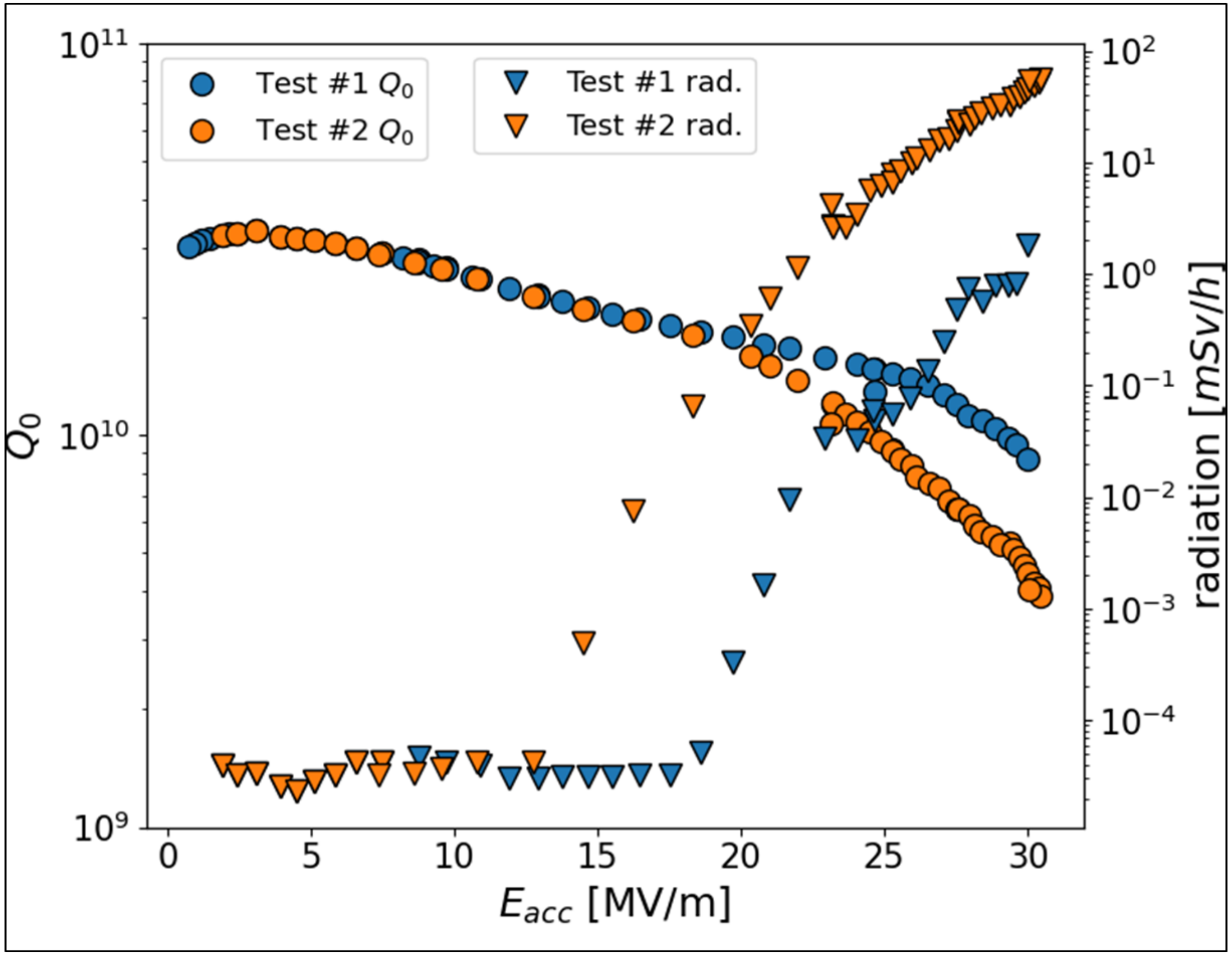
assuming 0.3 nΩ/mG for baked niobium at 650 MHz:
→R_{fl}=0.87*0.3*10=2.6 nΩ of contribution due to trapped flux

Cavity test: B61S-EZ-002 (baseline recipe)

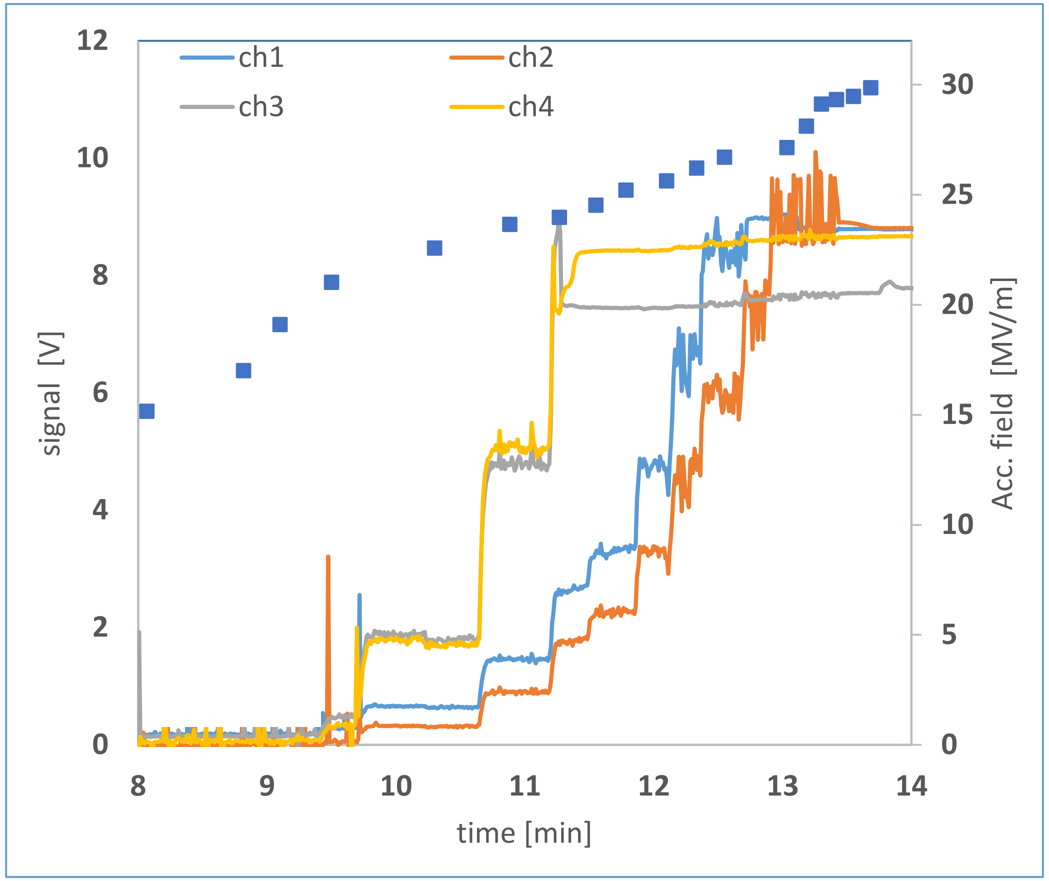
- Slow cooldown (1K/min) across critical temperature (9.2K)

- Tested with inner cryoperm shield, 8mG measured by fluxgate at the transition
- assuming 0.3 nΩ/mG for baked niobium @650 MHz and 87% trapped flux: R_{fl}=2.6 nΩ

- Q0 @17 MV/m=2E10
- Max field=30.5 MV/M, limited by FE
- 30 min RF processing session at the end of 1° test
- Radiation level increased when the Cold test was repeated, with a slight degradation of Q0
- Radiation onset moved from 20 mV/m to 12 MV/m
- Dose rate of 10 mSv/h at the target gradient



Cavity test: B61S-EZ-002 diagnostics

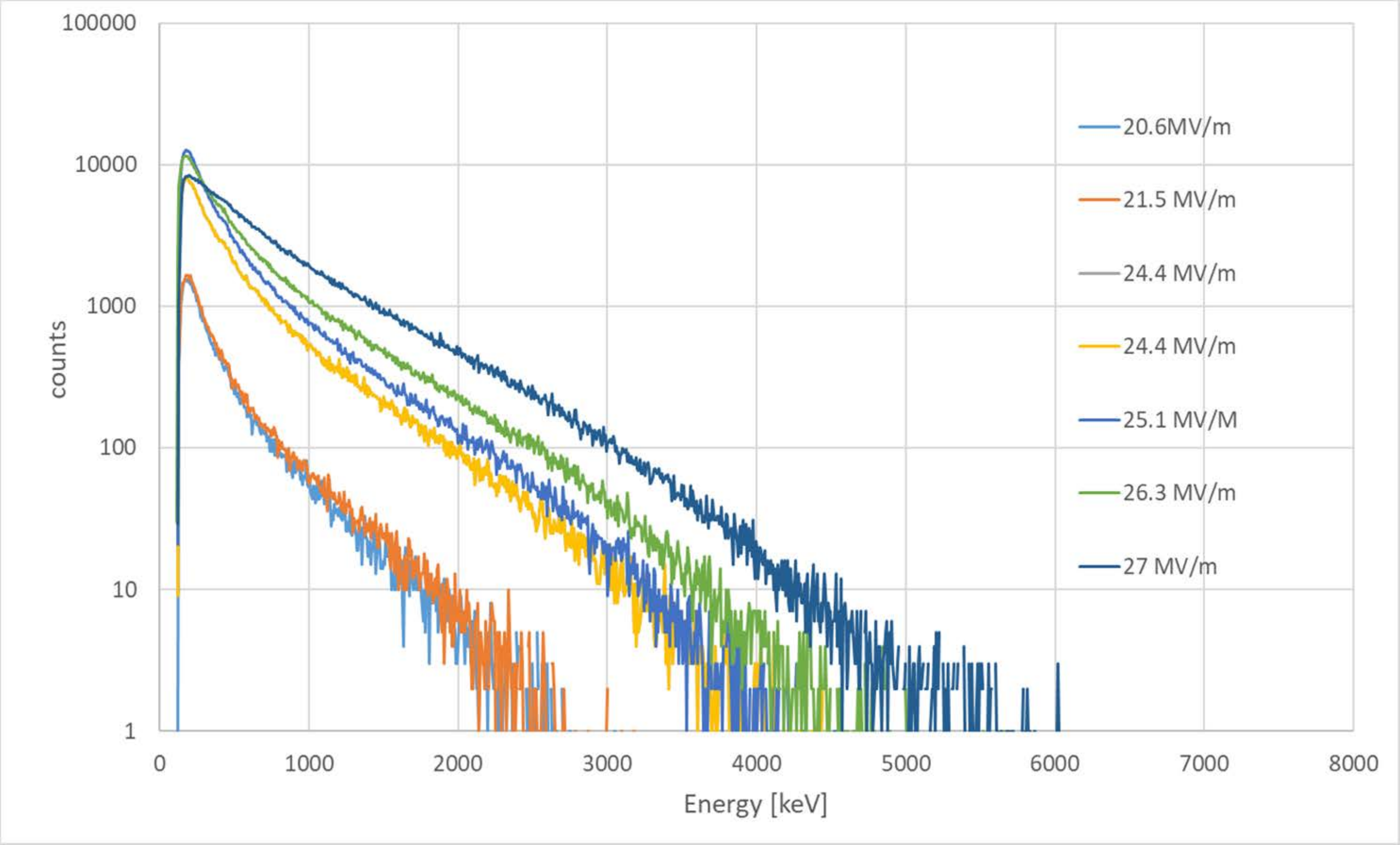


Photodiode readout for first rise:

- radiation onset at 20 MV/m.
- Ununiform angular distribution of X-rays
- Signal saturates at 8V

Scintillator spectra at some gradient levels

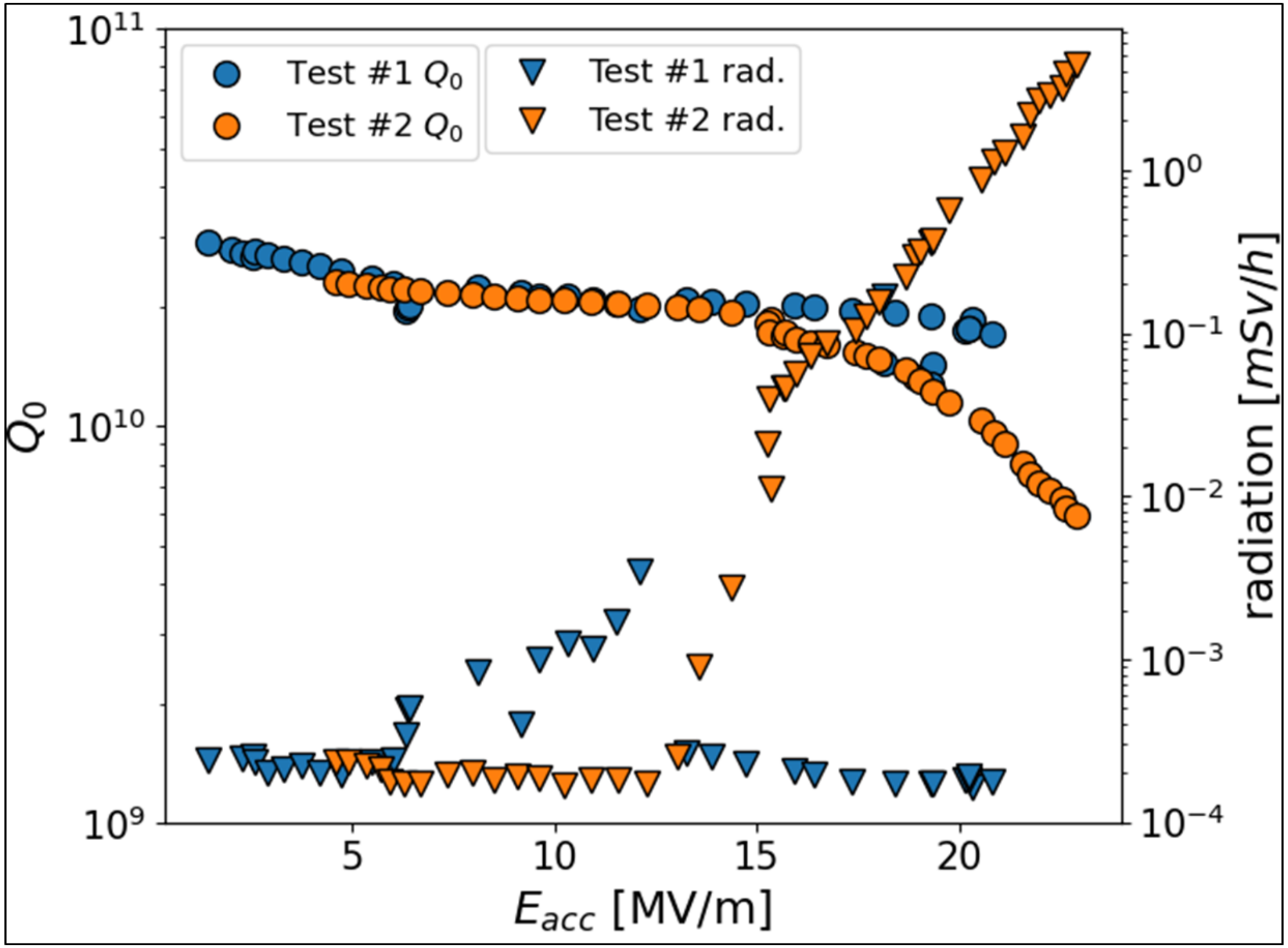
- X-ray onset jumps from 2.5 MeV@20MV/m to 4 MeV@24.4MV/m
- Detector saturates at 27 MV/m due to pile-up



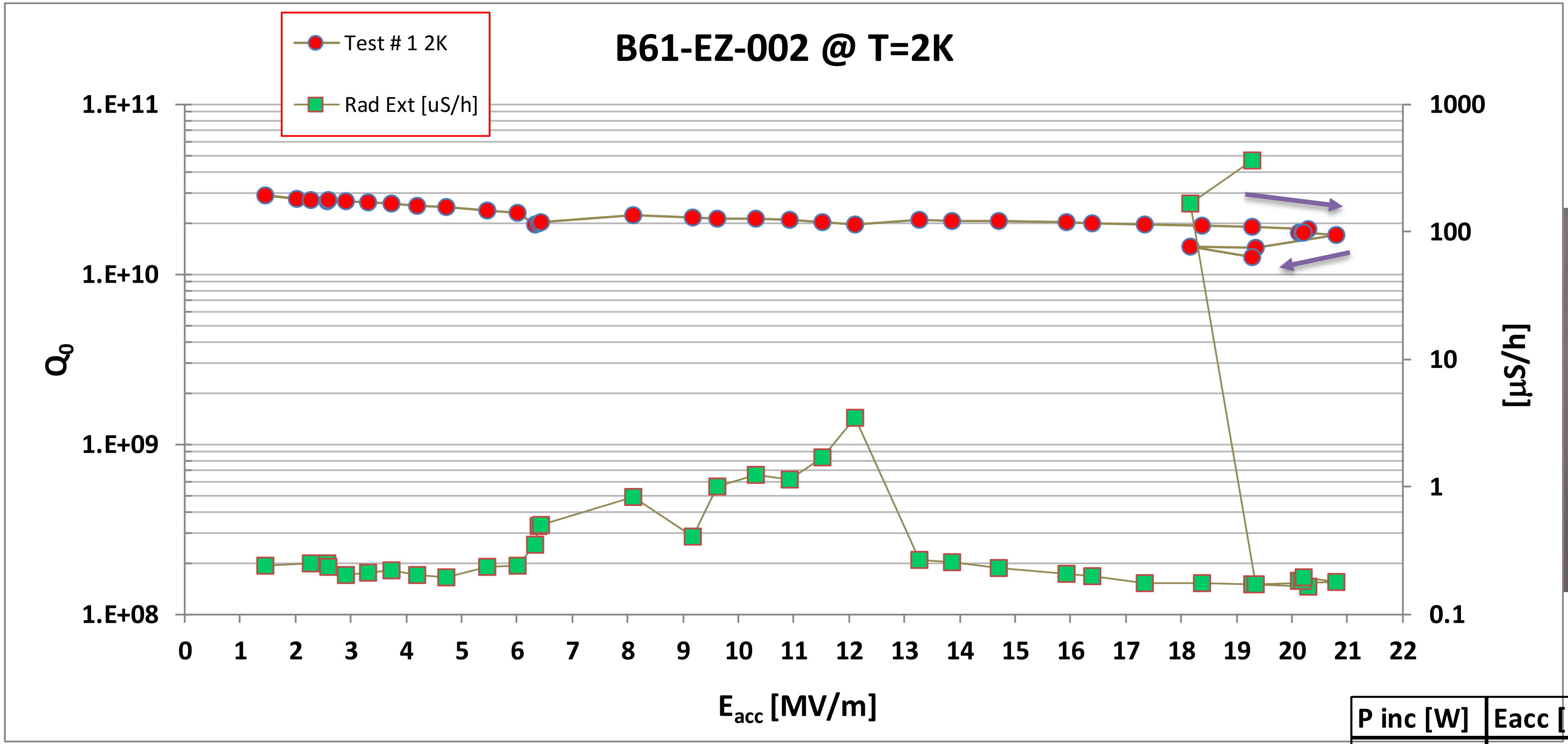
Cavity test: B61-EZ-002 (mid-T bake recipe)

- Slow cooldown (1K/min) across critical temperature (9.2K)
- 5 mG of residual field at cavity equator
- assuming 0.3 nΩ/mG for baked niobium @650 MHz: R_{fl}=2.4 nΩ

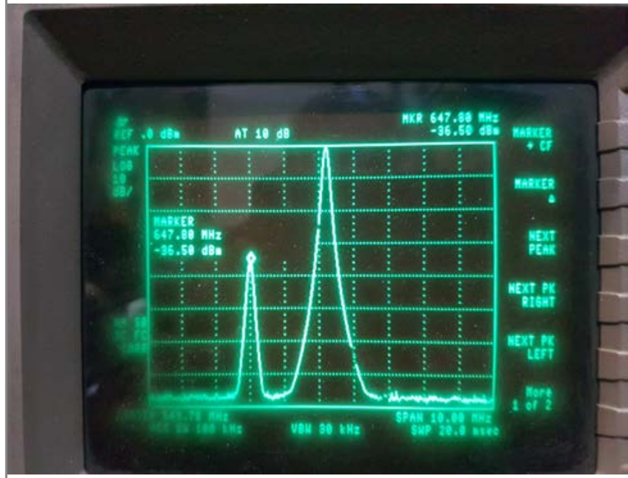
- 1° test: some MP with radiation, then sudden rise of radiation at 20.8 MV/m and Q degradation
- Test repeated from low fields
- 2° test: same behavior as the 1° test up until 14 MV/m….
- …then, sudden rise of radiation and drop of Q_0
- Cavity quench at 23 MV/m with **FE**
- **Irreversible activation of a field emitter!**



B61-EZ-002 VT @ LASA Run # 1 instabilities



Parasitic mode excitation

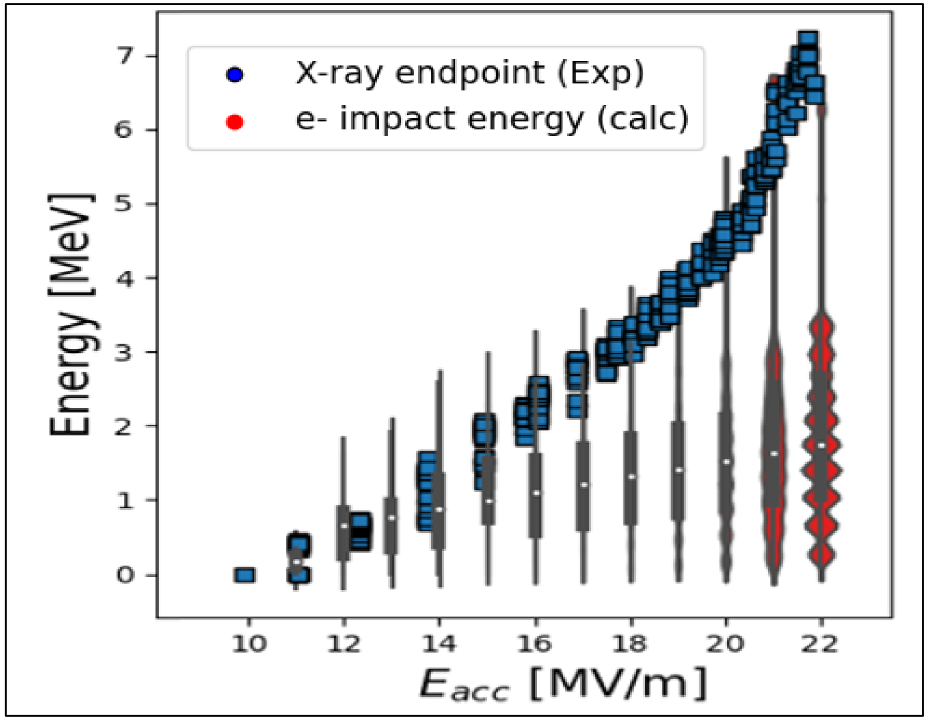


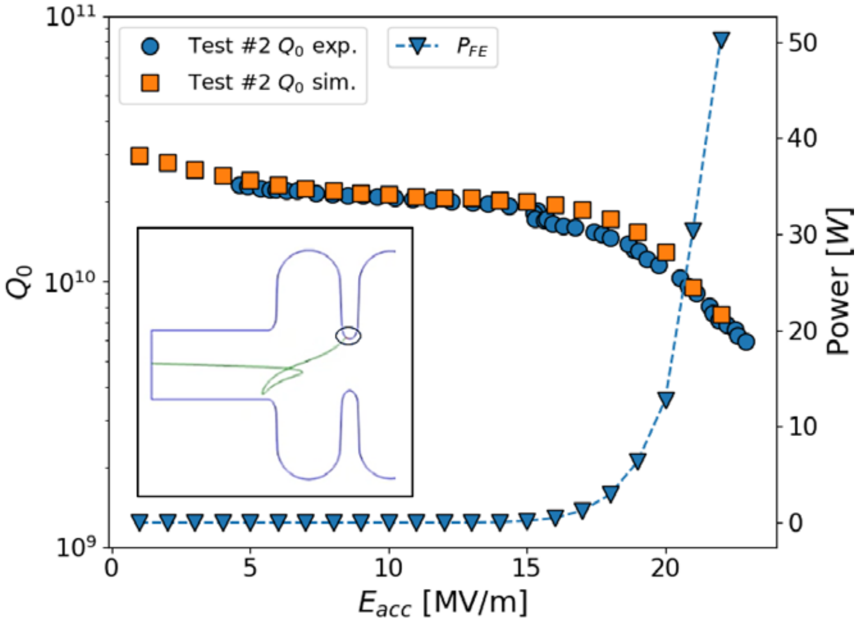
P inc [W]	Eacc [MV/m]	Q0	Rad Ext [uS/h]
35.58	20.20	1.75E+10	0.183
35.59	20.21	1.75E+10	0.193
38.62	20.79	1.71E+10	0.18
39.96	19.35	1.43E+10	0.172
34.81	18.16	1.44E+10	167.6
44.67	19.28	1.27E+10	358.9

B61-EZ-002 scintillator X-ray spectrum : the movie

B61-EZ-002 Field emission model

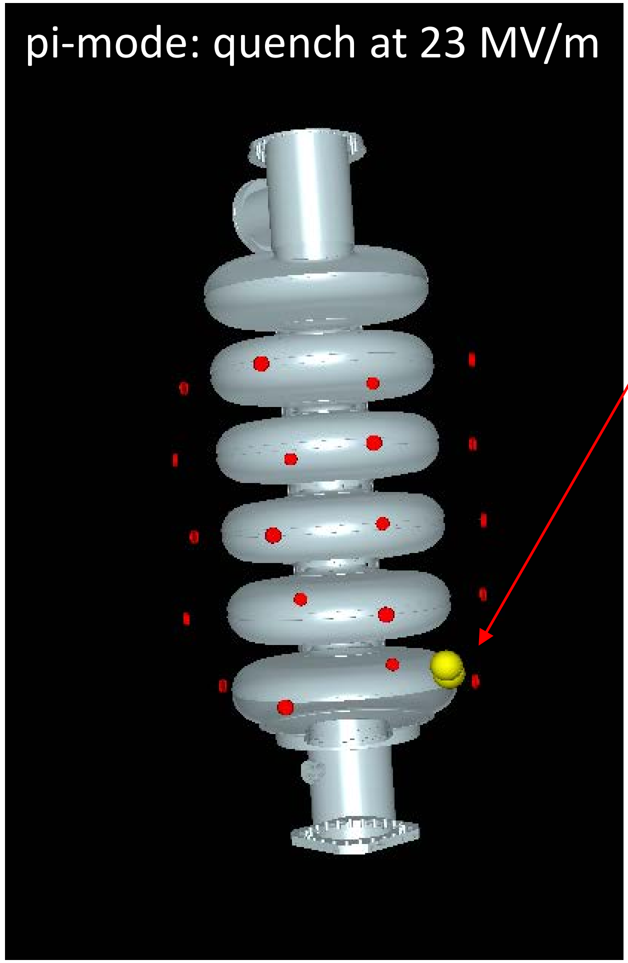
- The emitter is modeled by its position on cavity, emitter area S and field enhancement factor β_{FE}
- The Power adsorbed by FE-electrons with impact energy $E_{k,i}$: $P_{FE} = \frac{1}{T_{RF}} \sum_i E_{k,i}$ (sum all over RF-cycle)…..
- …causes a drop in the measured Q according to: $\frac{1}{Q_0{}'} = \frac{1}{Q_0} + \frac{R/_Q P_{FE}}{(E_{acc} l)^2}$

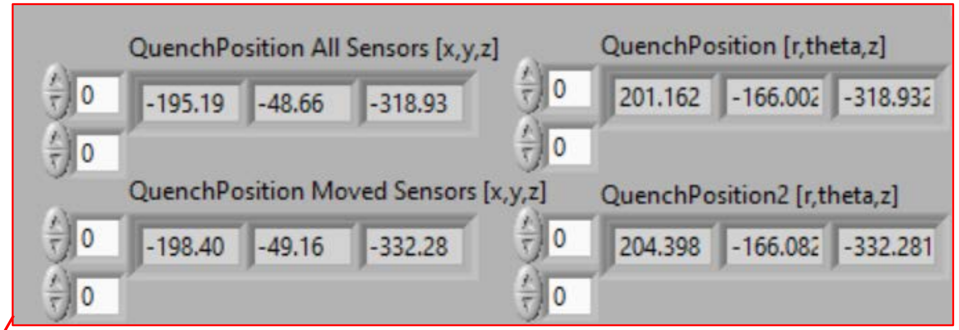




- β_{FE} is evaluated by Fowler-Nordheim fit
- FE-electron pattern is generated for every E_{acc} value, with a *Fishpact*-based code, by probing different emission sites
- Simulated e^- impact energies are matched with X-ray spectrum measured by scintillator
- Overall power P_{FE} is evaluated for the best match, and the Q-curve calculated
- **The resulting site is nearby iris 2, with $\boldsymbol{\beta_{FE} = 300}$ and $\boldsymbol{S = 1 \times 10^{-15} m^2}$**

B61-EZ-002 quench diagnostics


pi-mode: quench at 23 MV/m



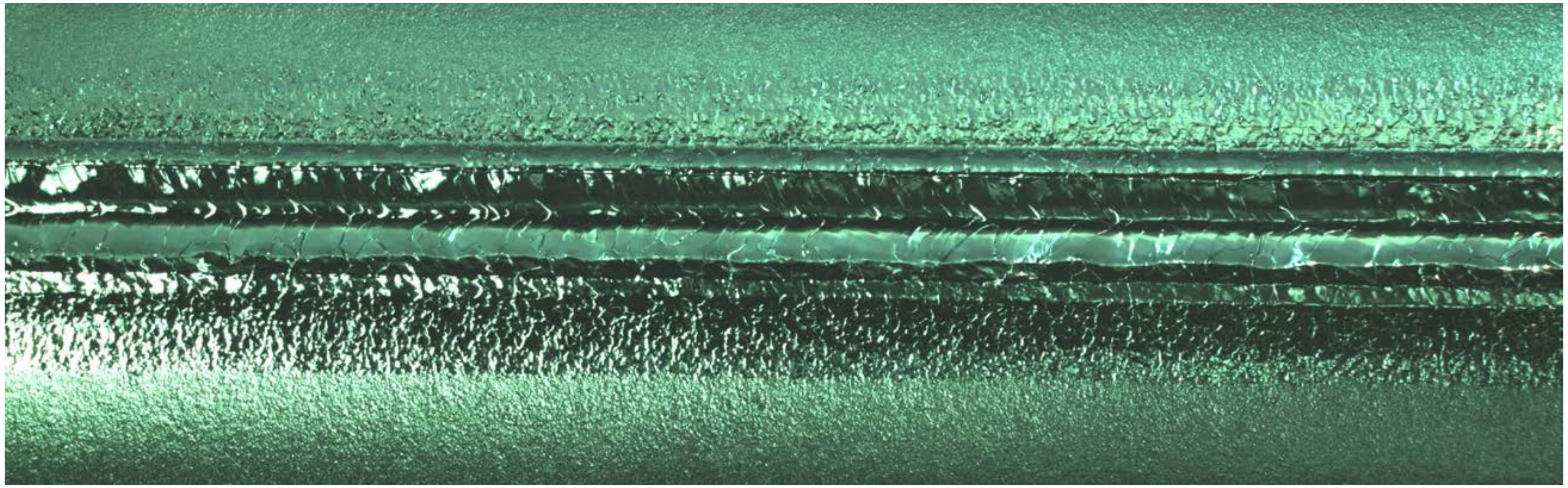
QuenchPosition All Sensors [x,y,z]			
0	-195.19	-48.66	-318.93
0			

QuenchPosition [r,theta,z]			
0	201.162	-166.002	-318.932
0			

QuenchPosition Moved Sensors [x,y,z]			
0	-198.40	-49.16	-332.28
0			

QuenchPosition2 [r,theta,z]			
0	204.398	-166.082	-332.281
0			

Second sound:
Quench position located in Cell 1 equator at angle 194°
No significant features can be noticed by visual inspection→ Quench induced by FE?



conclusions

- INFN LASA R&D activity on cavity treatments is ongoing: the goal is to establish a high-Q recipe suitable in the industrial context.

- LASA VTS is capable to cold-test PIP-II 650 MHz LB cavities. The facility is full equipped with cavity diagnostics. Upgrades are planned for the next future (faster cooldown rate, Helmoltz coils,….)

- First test results are encouraging. Performances are very close to project specs, even if residual field in cryostat is still high. Theoretically, both cavities would be above target if working in the fast-cooldown regime or with active field cancellation