Degradation and Recovery of Cavity Performance in SRILAC Cryomodules (Pulsed RF conditioning)

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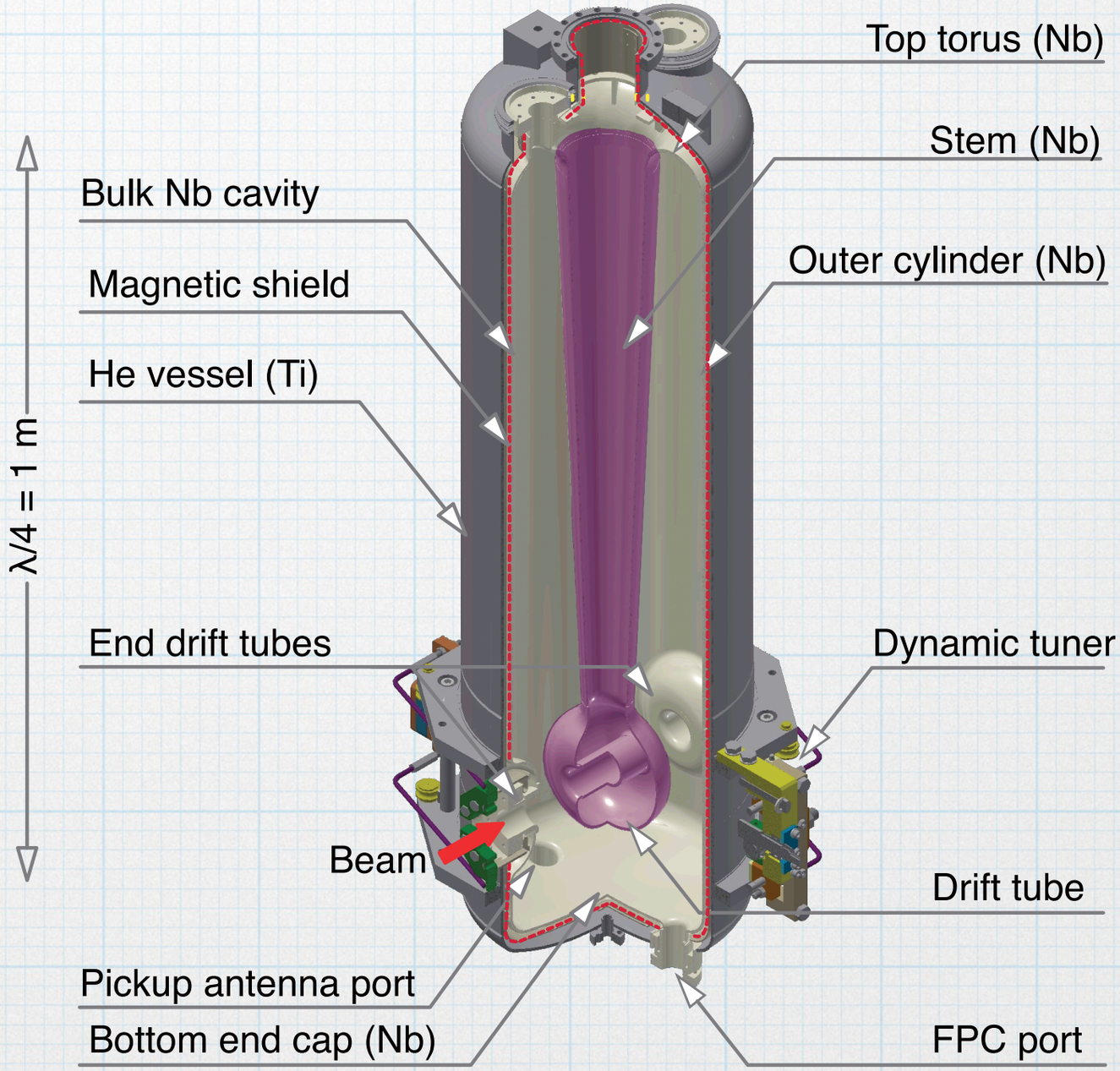
SCQWR for SRILAC

■ Bulk Nb (RRR 250) with BCP based Surface processing

BCP(100 μm)→Annealing(700° C, 3hr)→BCP(20 μm)→Baking(120° C, 48hr)

Parameters	
Frequency (MHz)	73.0 (c.w.)
Optimum β	0.08
R_{sh}/Q_0 (Ω)	579
G (=R_{sh}/Q_0)	22.4
V_{acc}(MV)	2.2
E_{acc} (MV/m)	6.8
E_{peak}/E_{acc}	6.2
B_{peak}/E_{acc}(mT/(MV/m))	9.6
Operating Temerature(K)	4
Target Q_0	1×10^9



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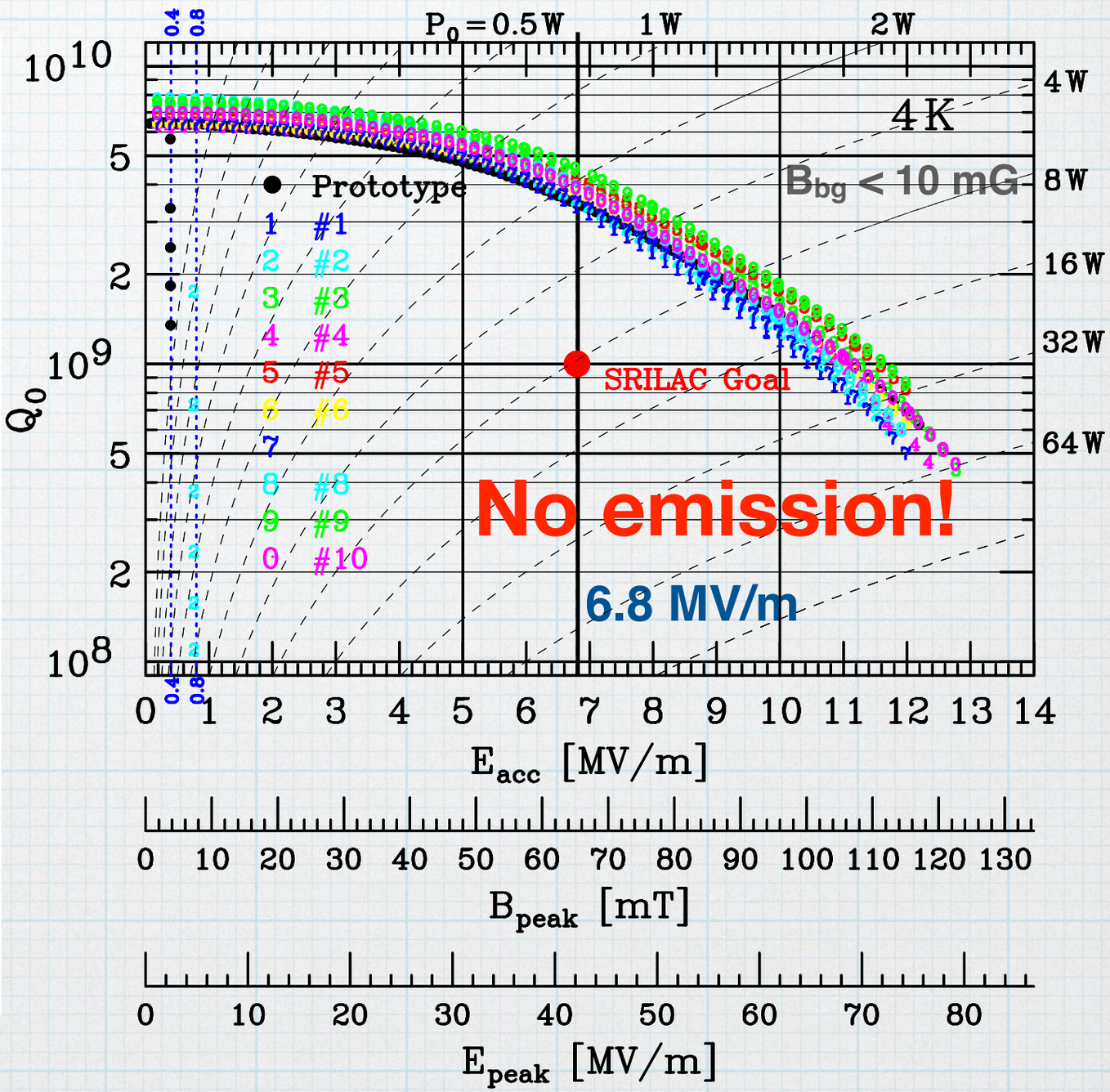


Cryomodule for SRILAC

- Operating temperature : **4.5 K**.
- 80 K Thermal shield with Liquid N_2
- He Ports:Pre-cooling port, Supply port, Return-port
- **Heat load estimation : 18 W/Cryomodule (not confirmed)**

  FPC: 6 W, Helium pipes: 4.5 W, Tuner: 2.5 W,

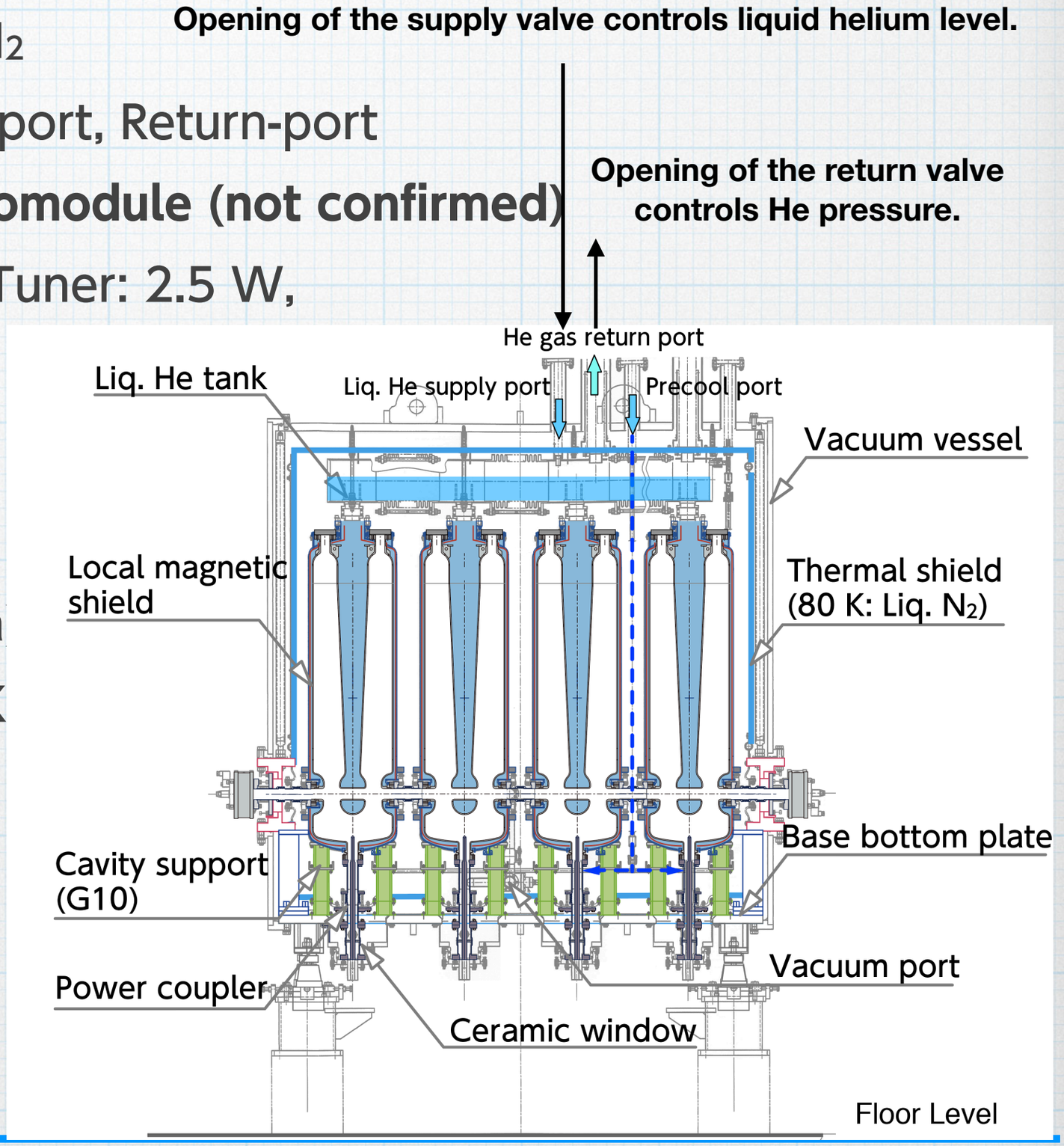
  Cavity support: 2 W
- Liquid helium cryogenic system

  HELIAL MF (Air Liquide)

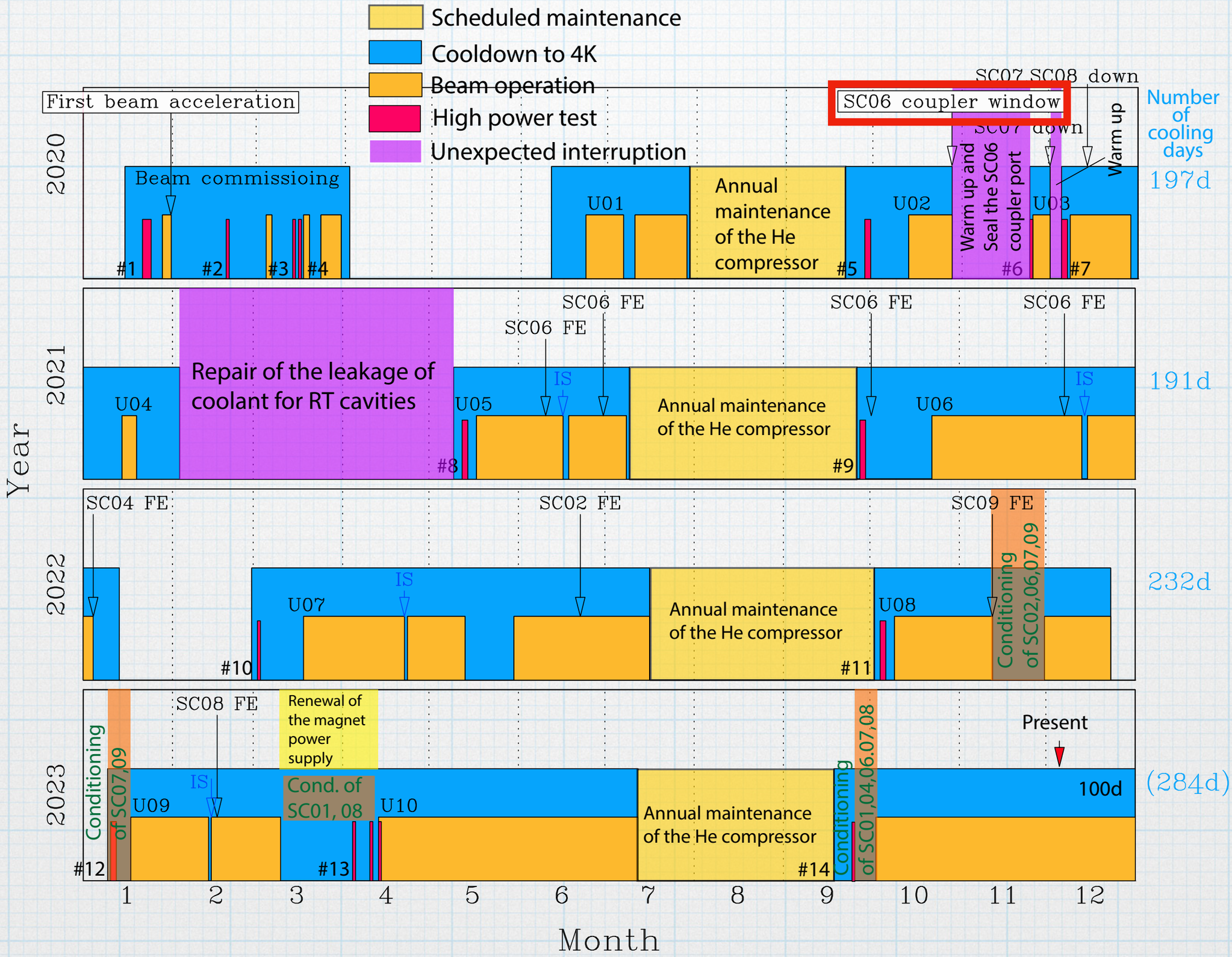
  +MYCOM Compressor(Maekawa

  Cooling capacity : **700 W@4.5 K**

  *Electric power consumption of the compressor is 300 kW Cavity vacuum is separated from isolation vacuum.
- Cavities are mounted on the bottom base plate
- Single RF window FPC



SRILAC Operation history



Mile stones of SRILAC

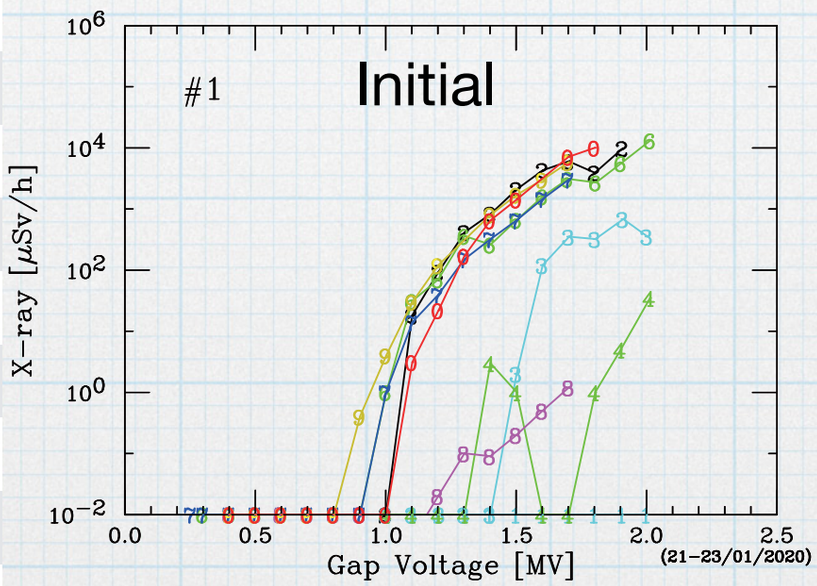
- First cooling : **2019/10/18**
- First beam : **2020/1/28**
- Vacuum leak from coupler windows

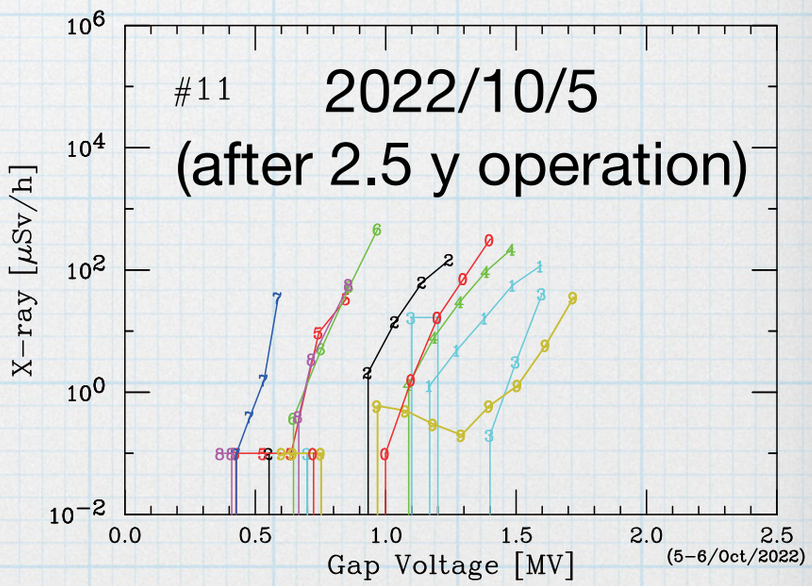
  SC05: 2019/11/18, SC06:2020/11/27
- Degradation of cavity performance caused decrease of acceleration voltages

  Multipacting(MP) : Cavities could not hold acceleration voltages.

  Field emission(FE) : FE increase occurred during beam operation repeatedly.

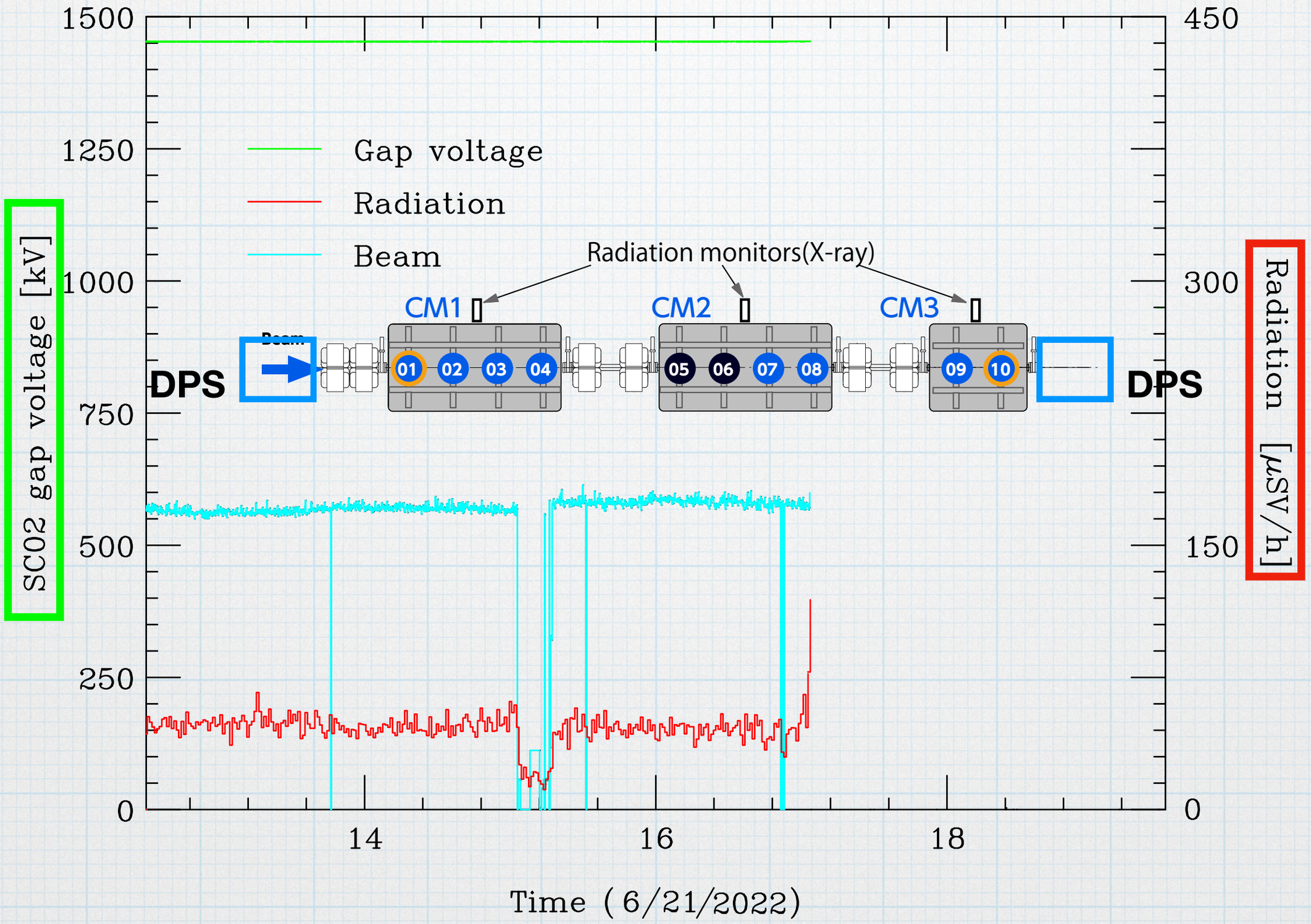
2020/12/1	SC07	MP
2020/12/7	SC08	FE
2021/6/9	SC06	FE
2021/6/29	SC08	FE
2021/9/30	SC06	FE
2021/12/6	SC06	FE
2022/1/3	SC08	FE
2022/6/21	SC02	FE
20221/11/144	SC09	FE
2022/11/14	SC08	FE





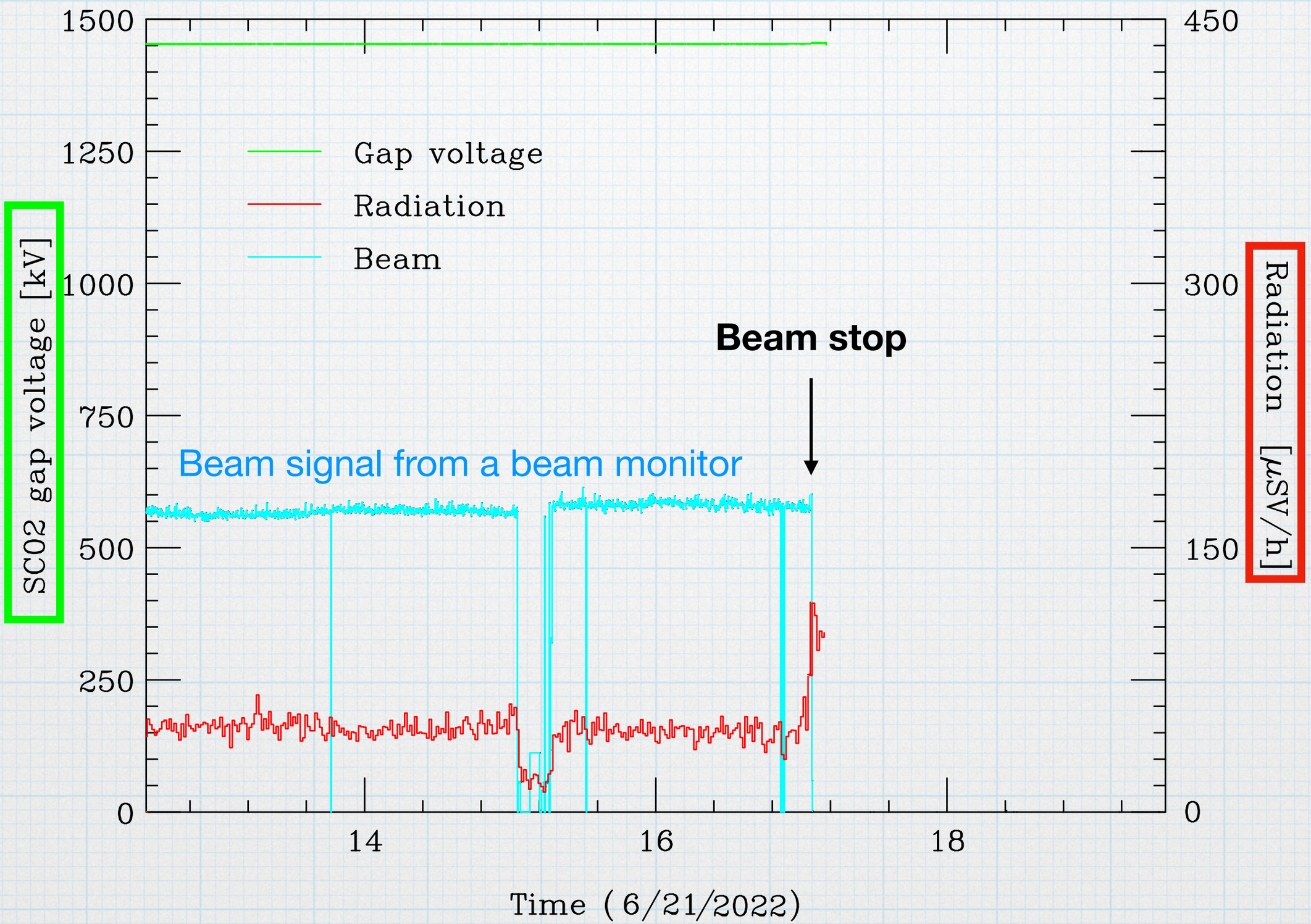
Field emission

- During a beam operation X-ray level of CM1 monitor was suddenly increased.



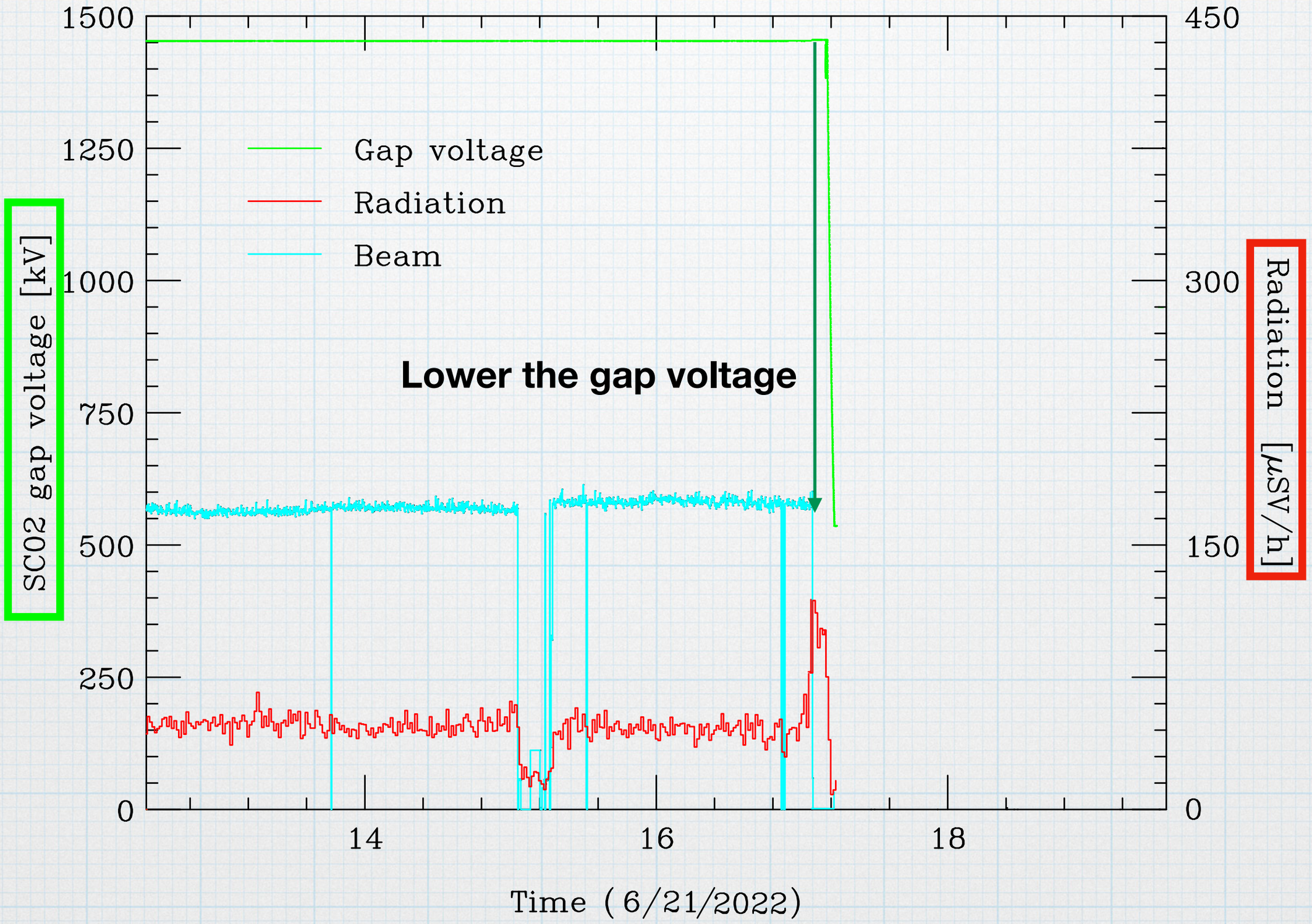
Field emission increase

- Even though an operator stopped the beam X-ray level remained.



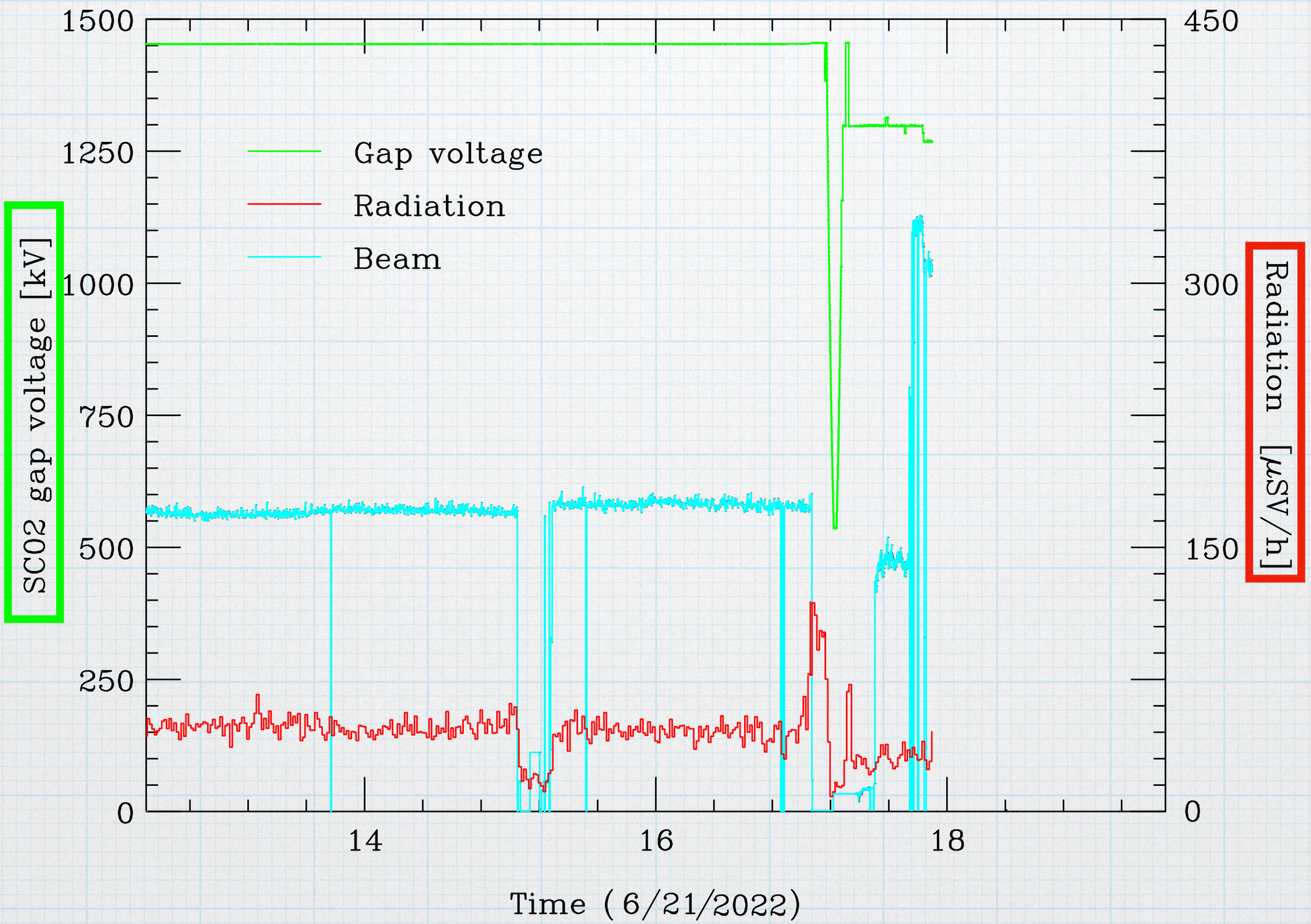
Field emission increase

- X-ray became low when the gap voltage was lowered to 500 kV.



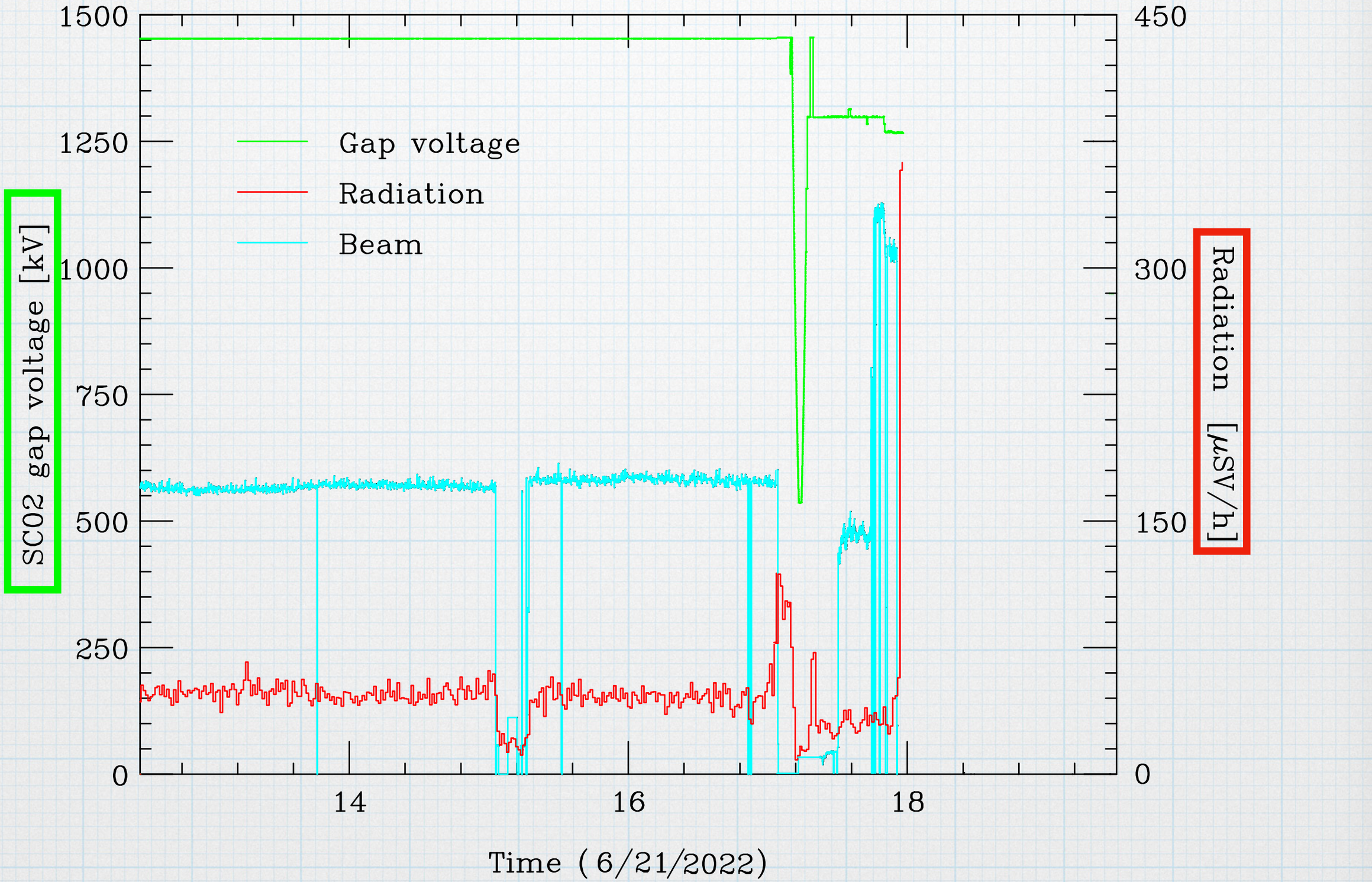
Field emission increase

- Accelerator tuning was started with a lower voltage of 1250 kV.



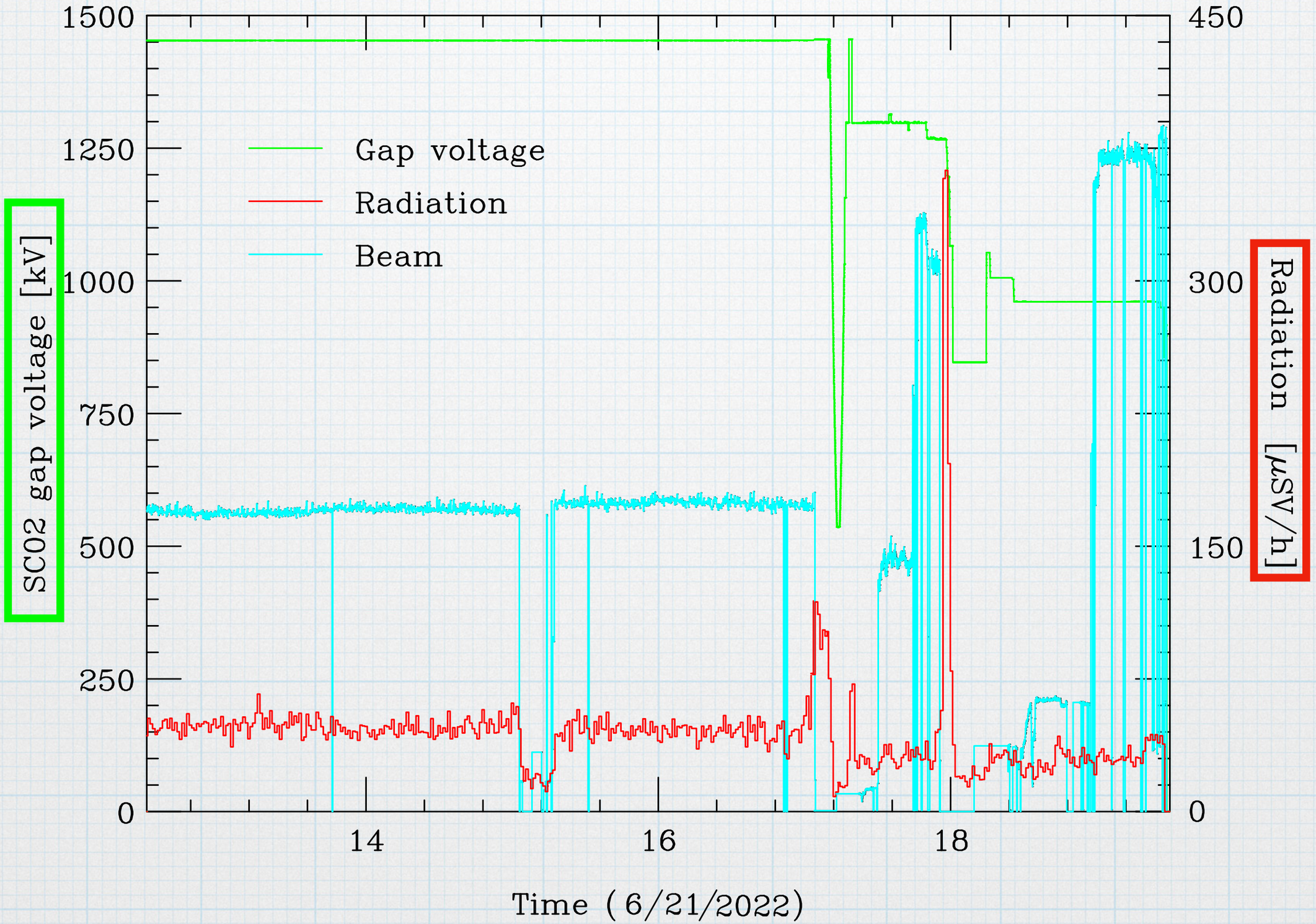
Field emission increase

- Again X-ray level of CM1 monitor was significantly increased.



Field emission increase

- Beam operation was continued with a voltage of 950 kV.



Acceleration Volgages

RUN	Date	SC01	SC02	SC03	SC04	SC05	SC06	SC07	SC08	SC09	SC10	Total (kV)
#2	2020/7/17	1447.6	1300.6	1341.1	1317.7	0.0	1406.3	1413.7	1353.2	1448.7	752.0	11780.9
	2020/7/26	1445.7	1299.1	1339.2	1316.7	0.0	1404.1	1411.8	1351.0	1447.1	1972.1	12986.8
#3	2020/10/19	1398.8	1438.3	1355.3	1448.4	0.0	1469.6	1417.6	1404.5	1394.8	425.1	11752.4
#4	2020/11/27	1565.8	1573.1	1565.3	1561.7	0.0	0.0	1474.7	1241.7	1490.8	1505.9	11979.2
	2020/12/9	1583.3	1582.3	1581.5	1581.3	0.0	0.0	854.4	1024.5	1494.1	865.0	10566.4
	2020/12/13	1579.3	1581.2	1576.3	1574.7	0.0	0.0	373.5	1075.7	1583.7	1263.7	10608.3
#5	2021/5/19	1446.6	1447.1	1444.1	1446.4	692.9	1090.3	375.1	1030.6	1453.6	1201.9	11628.7
	2021/6/9	1446.6	1447.1	1444.1	1446.4	692.9	1090.3	375.1	1030.6	1453.6	1201.9	11628.7
	2021/6/30	1443.3	1445.4	1449.1	1448.2	692.2	1089.8	374.7	928.6	1554.1	1048.5	11473.8
#6	2021/10/22	1443.0	1443.5	1439.5	1443.2	542.5	922.1	480.7	716.8	1451.9	1016.1	10899.3
	2021/11/6	1450.6	1452.6	1447.3	1452.9	545.4	927.0	482.5	720.9	1460.4	815.1	10754.8
	2021/12/6	1535.0	1441.8	1437.8	1442.6	548.0	821.8	513.8	716.3	1450.2	741.0	10648.3
	2022/1/3	1543.6	1449.7	1446.6	1297.1	563.2	678.6	522.1	720.3	1506.4	783.4	10511.2
#7	2022/3/14	1563.1	1444.4	1435.2	1140.5	556.9	671.3	523.3	730.5	1537.2	1038.5	10640.6
	2022/4/6	1510.7	1482.8	1434.5	1163.8	553.5	653.6	520.5	627.8	1536.4	1068.2	10551.8
	2022/6/21	1523.4	897.9	1477.6	1221.1	671.5	809.8	562.0	636.0	1552.4	769.0	10120.8
	2022/7/15	1345.8	1043.0	1476.5	1222.4	670.9	809.5	561.8	635.4	1551.8	769.7	10086.8
#8	2022/10/7	1346.2	1041.7	1478.6	1219.5	669.9	808.8	561.4	632.7	1547.2	759.5	10065.4
	2022/11/4	1364.2	1037.6	1469.6	1215.9	666.0	804.6	558.5	631.0	1150.5	1118.7	10016.7
	2022/11/14	1367.8	1040.3	1472.7	1216.8	668.2	807.1	560.4	631.7	1021.6	1293.5	10080.2
	2022/11/30	1370.5	1042.3	1475.3	1218.3	669.3	809.0	561.4	632.8	1156.1	1125.9	10060.9
#9	2023/1/17	1368.1	1308.1	1273.2	1136.3	667.4	1074.6	856.2	632.0	992.9	1019.0	10327.9
#10	2023/4/13	1365.5	1332.0	1279.5	1145.3	668.6	1098.0	883.1	852.8	1292.0	812.5	10729.4

Available total acceleration voltage was decreased significantly.

Cure for degraded cavity at KEK

- KEK has succeeded to cure the degraded cavity performance by a pulsed RF conditioning with high power. (E. Kako et al., SRF17, MOPB097, pp. 289–293.)
- In2015, increase of the x-ray radiation level reached to 100 mSv/h in No.3 cavity, 10 mSv/h in No.2 cavity and 1 mSvh/ in No.1 cavity for cERL.

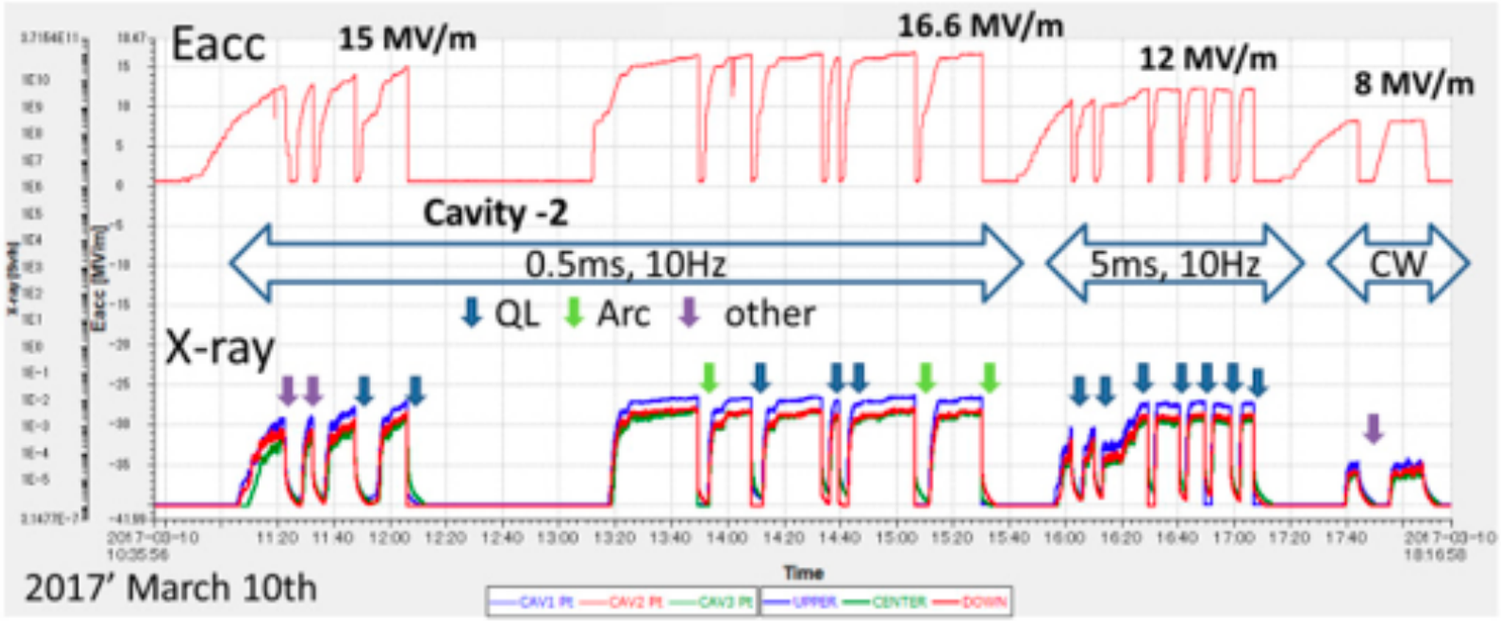
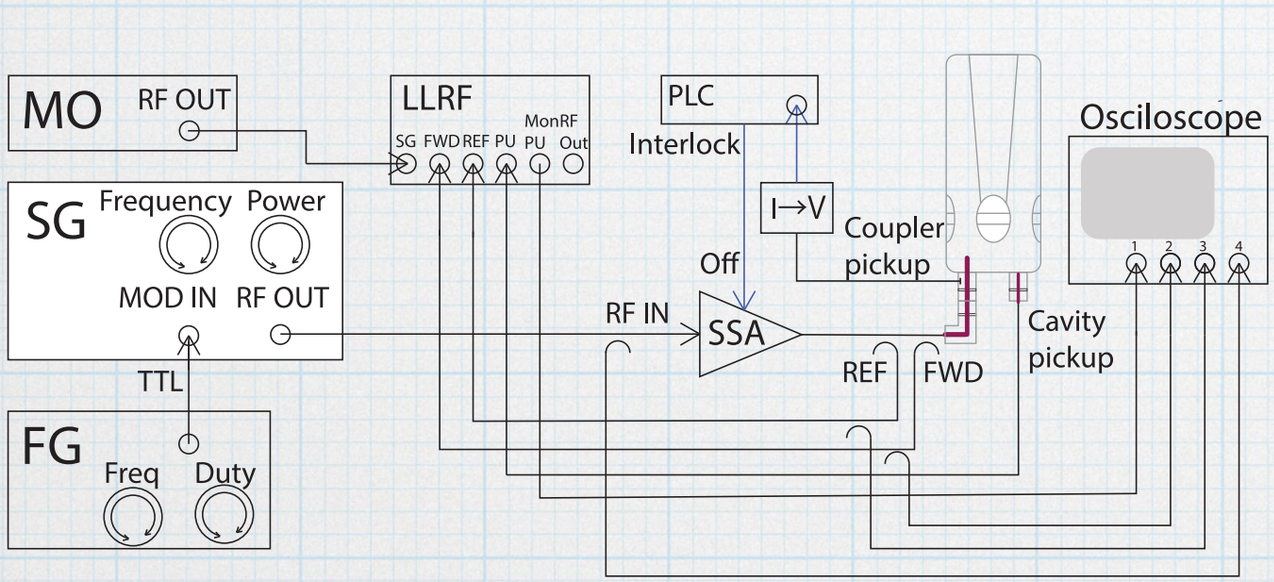


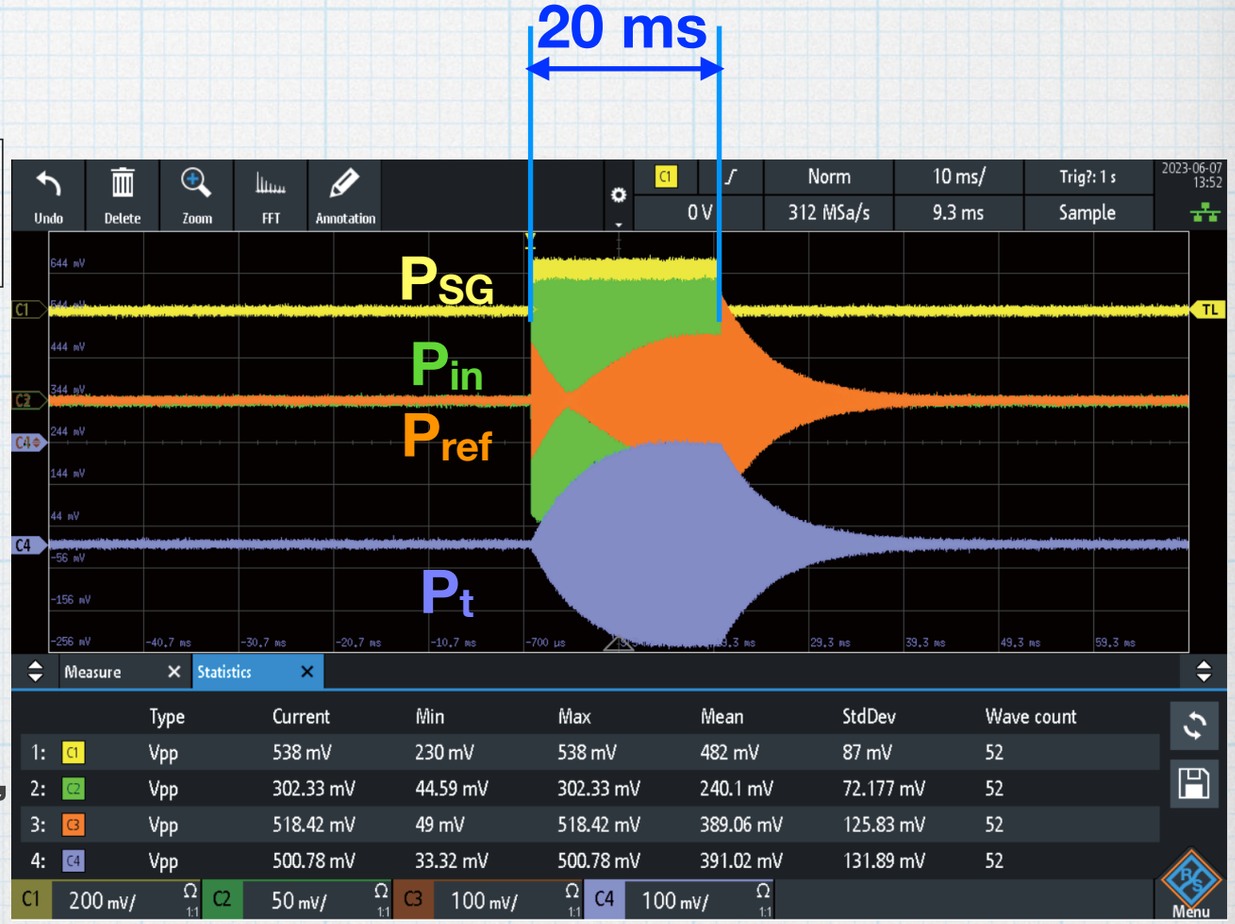
Figure 10: Time evolutions of accelerating gradients, Eacc, (top) and x-ray radiation levels (bottom) during high power pulsed RF conditioning for 8 hours.

- The x-ray radiation levels in each cavity dramatically decreased by high power pulsed RF conditioning .

Setup for Conditioning

- First attempt on recovery of SC07 was performed at 4.5 K with a conditioning method using high-voltage pulsed RF power, which is relatively simple and imposes a low load on the cavity and its coupler window.
- The amplitude modulation set to 0.5 Hz and a 1% duty RF pulse with a width of 20 ms was adopted which was sufficient ot raise the cavity voltage (P_t) up to 90% with a detuning of 50 Hz.





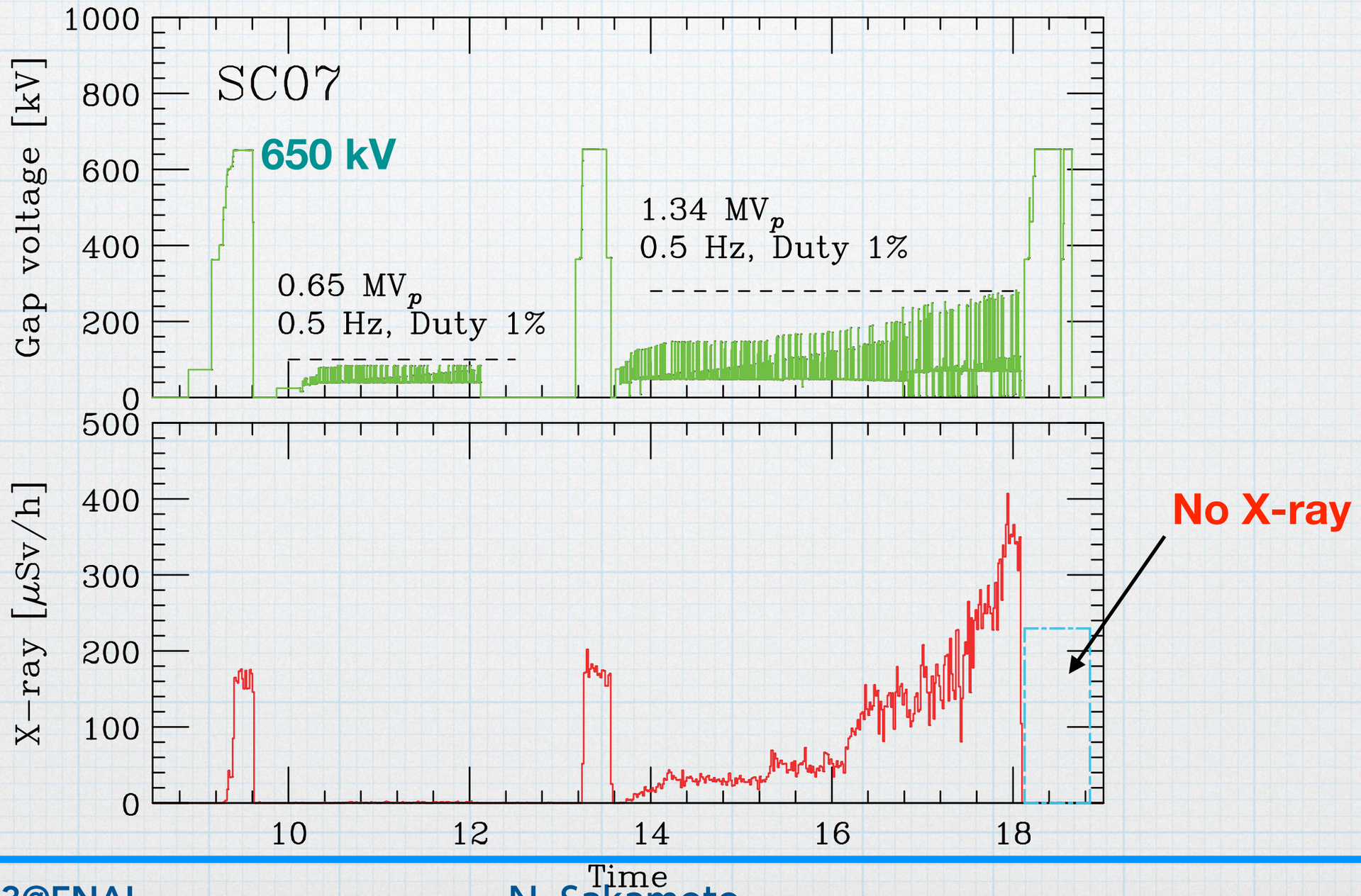
P_{SG} : input pulse,

P_{in}, P_{ref} : signals from DC,

P_t : cavity pickup signal

First Attempt on Recovery (SC07)

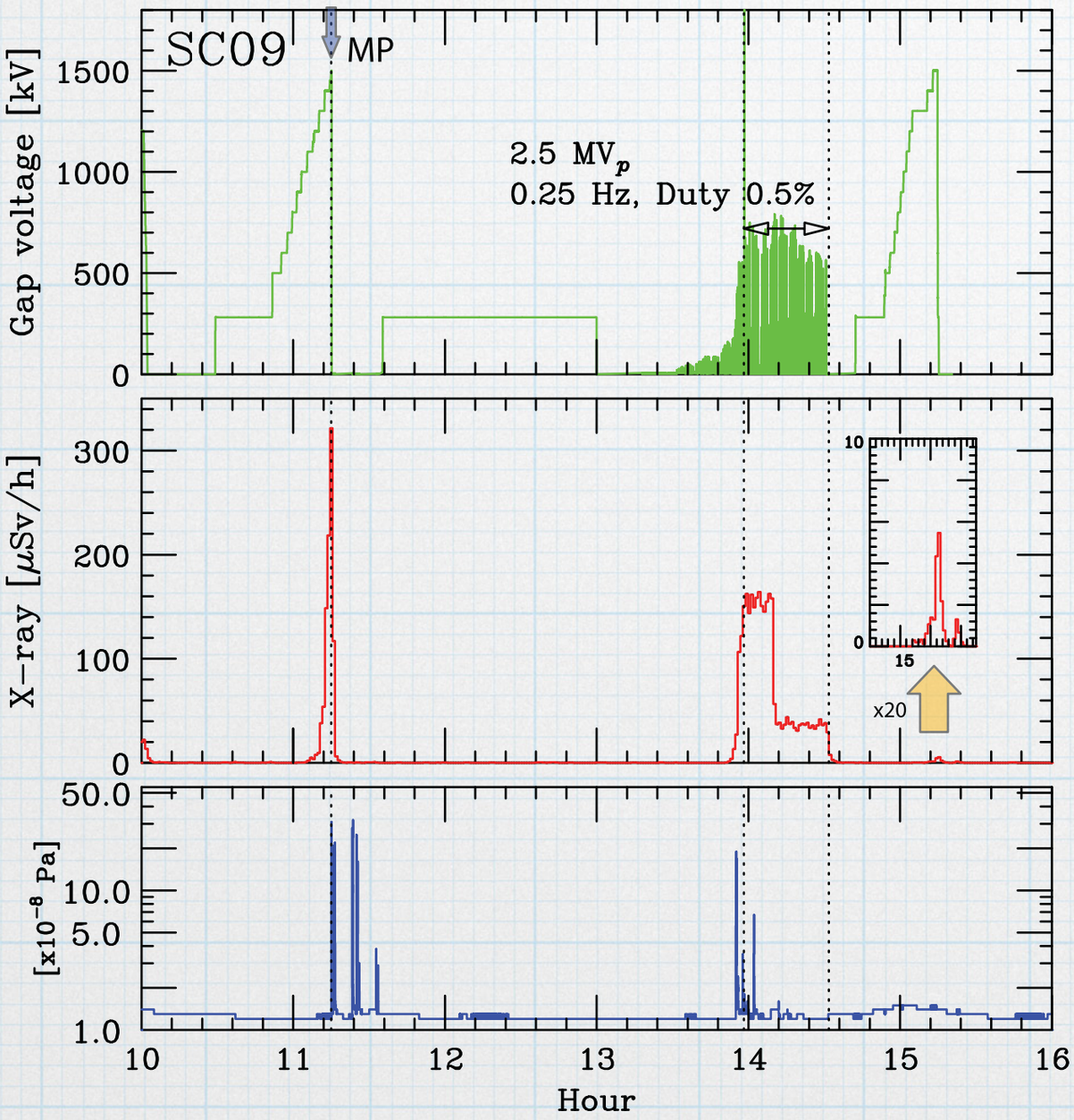
- Peak cavity voltage was kept 0.65 MV for 2h but there found no effect on x-ray reduction.
- Peak voltage was further increased step wise to 1.34 MV. Then x-ray level was successfully reduced.



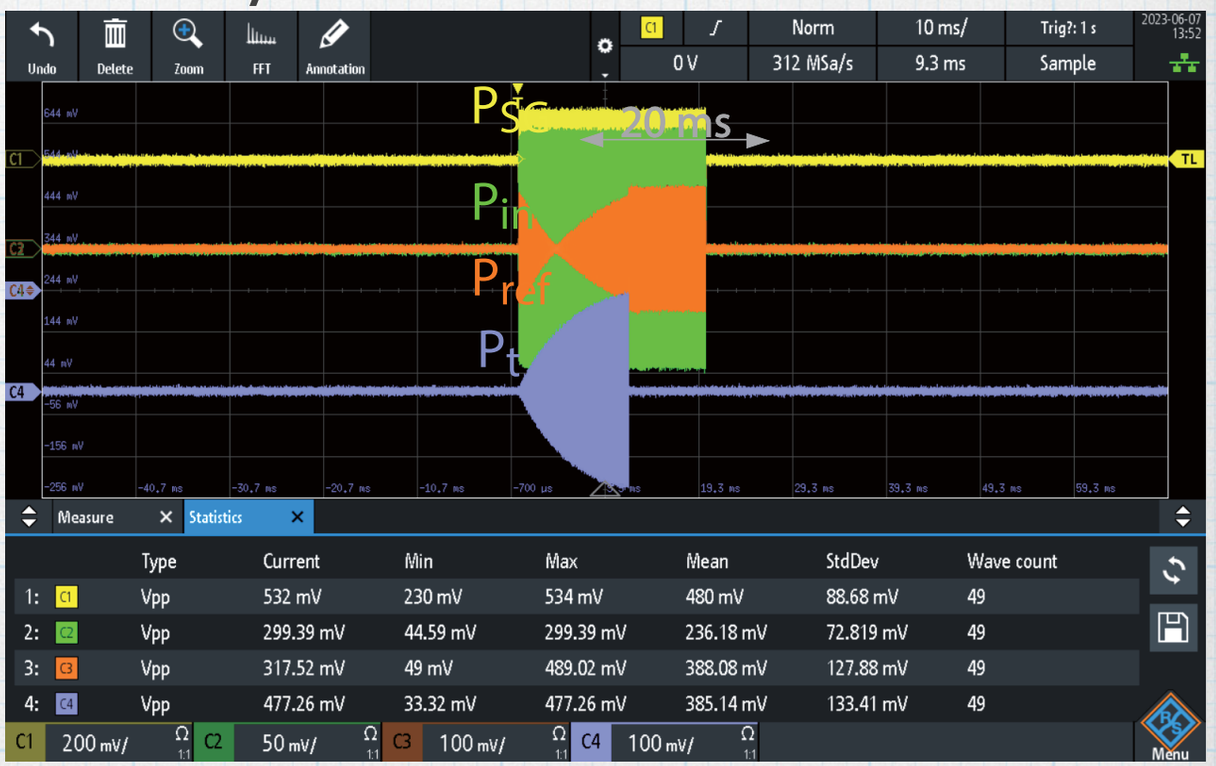
Conditioning of SC09

- Multipacting (MP) was another issue in cavity operation.

- Sudden voltage drop was also observed during RF pulse conditioning, accomplished by variation in the vacuum pressure.



- P_{in} between pulses must be zero to extinguish MP.
- After completing the conditioning, x-ray level was successfully suppressed and MP occurred scarcely.



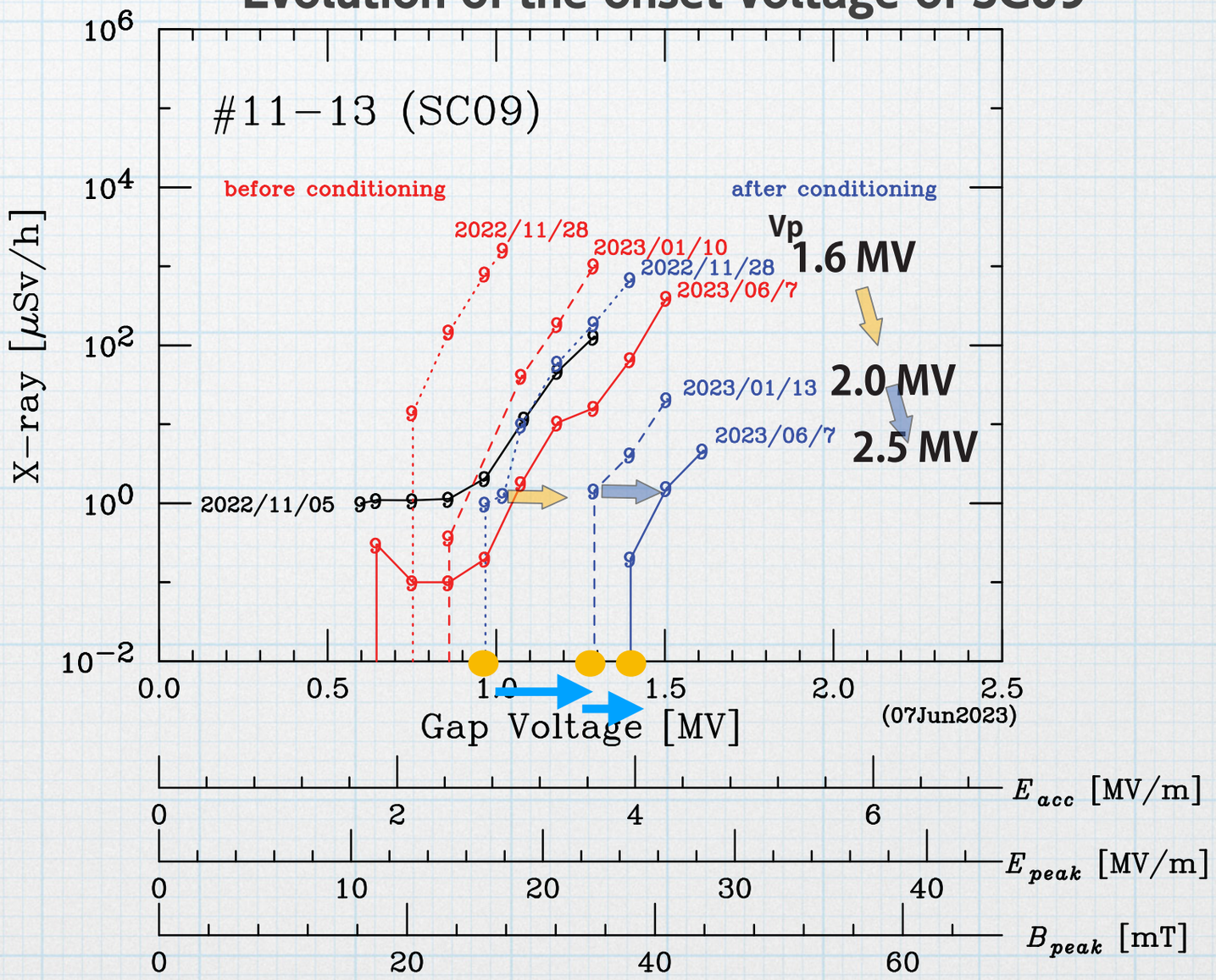
Pulsed RF power and onset voltage

- The SC09 cavity was repeatedly conditioned by gradually raising the maximum pulsed voltage.
- The onset voltage became increasingly high reaching 1.4 MV higher than that of the initial measurement.

History of conditioning

Date	SC#	Duration	Vpeak(MV)
2022/11/22	SC07	7h37m	1.34
2022/11/24	SC06	4h5m	1.52
2022/11/28	SC09	1h14m	1.57
2022/11/29	SC02	37m	1.98
2023/1/12	SC07	54m	1.55
2023/1/13	SC09	1h44m	1.99
2023/3/29	SC08	2h35m	1.80
2023/4/13	SC01	40m	2.23
2023/6/7	SC09	1h13m	2.54
2023/7/3	SC02	1h53m	2.98
2023/9/28	SC08	7h40m	2.53
2023/9/29	SC07	22m	1.43
2023/9/29	SC06	1h17m	1.63
2023/10/2	SC01	1h18m	2.90
2023/10/3	SC04	1h04	2.60

Evolution of the onset voltage of SC09



Conclusions

- The SRILAC has been in operation for the past four years.
- However, the degree of performance degradation hs become a significant issue, jeopardizing the continuity of operations.
- Therefore, high-power pulsed RF conditioning was tested to restore the performance.
- The conditioning worked well (so far) to successfully suppress the x-ray levels and MP.
- Currently , minimal conditioning is being performed to sustain beam operation.
- It is planned to further high-power pulsed RF conditioning with higher voltages.

Questions:

Why the pulsed RF conditioning is so effective to SRILAC?

Is FE harmful for the cavity performance?

How long will the conditioning be effective?

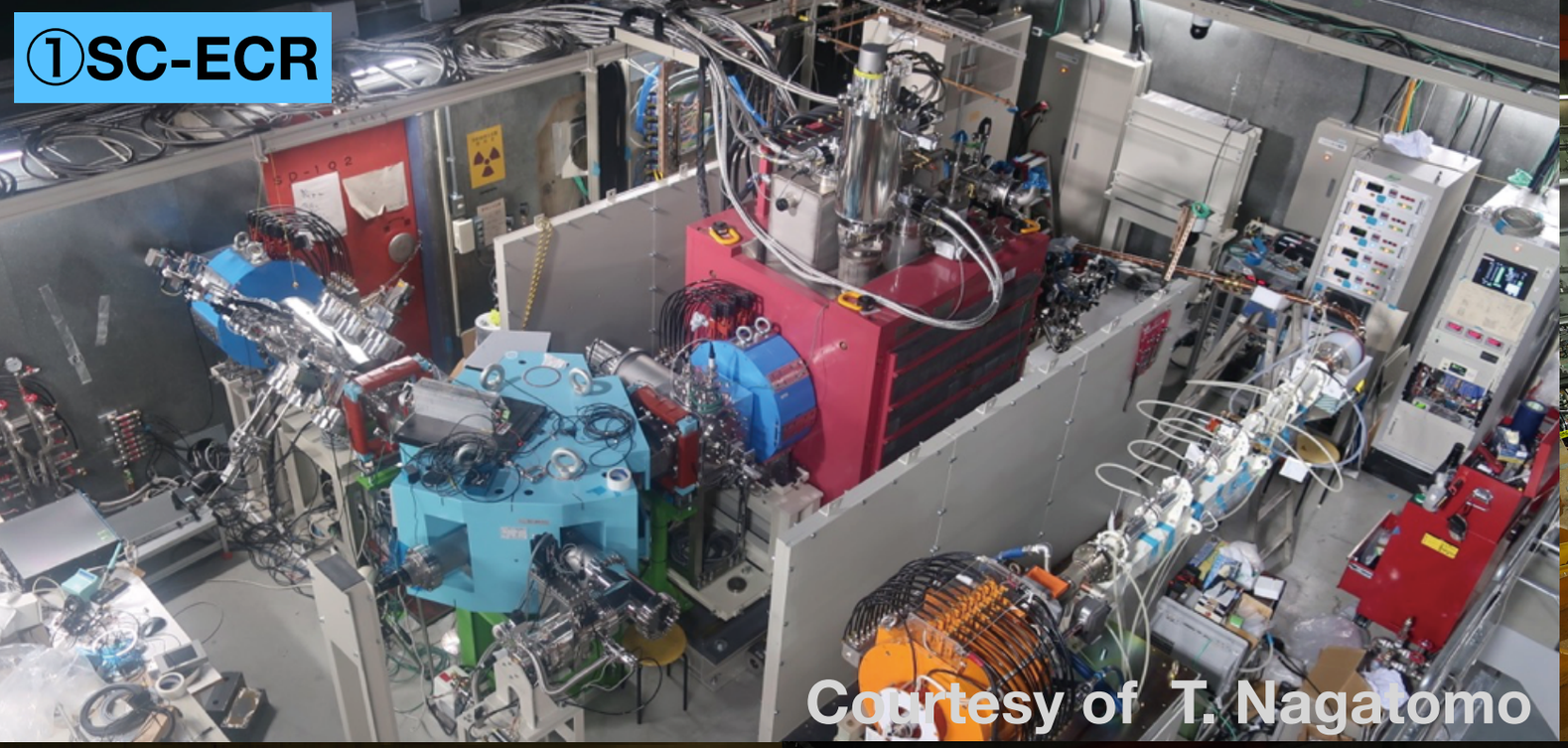
Is helium processing effective to SRILAC?

Acknowledgement

- The authors are grateful to Prof. H. Sakai from KEK for sharing his valuable experience on the pulsed power conditioning of cERL.
- They also thank Prof. K. Saito for joining our discussion on how to mitigate the degraded cavities.
- We sincerely thank all the operating staff of the SHI Accelerator Service Ltd. for their effort to ensure the continuous opera- tion of the SRILAC.

Thank you.

①SC-ECR



Courtesy of T. Nagatomo

③Joint Box and Cold Box

②RILAC

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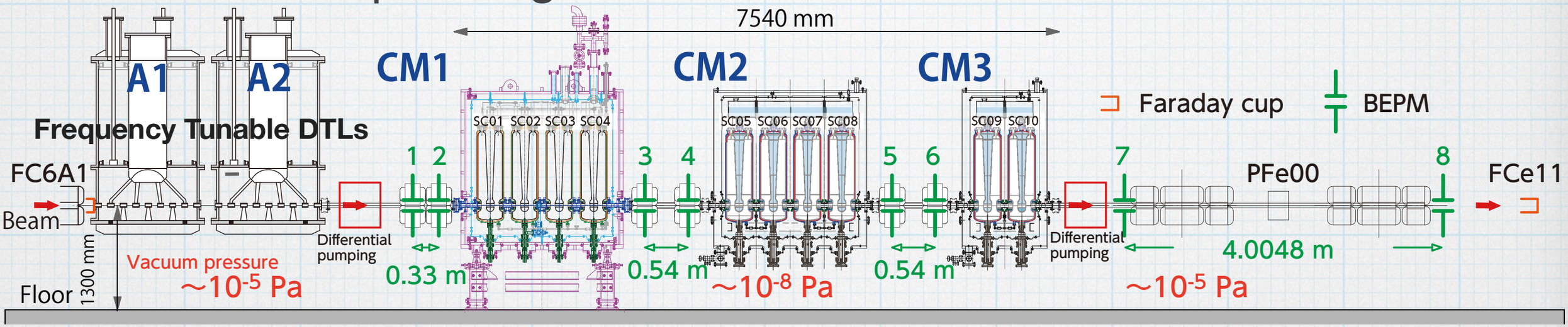
④Transfer Line

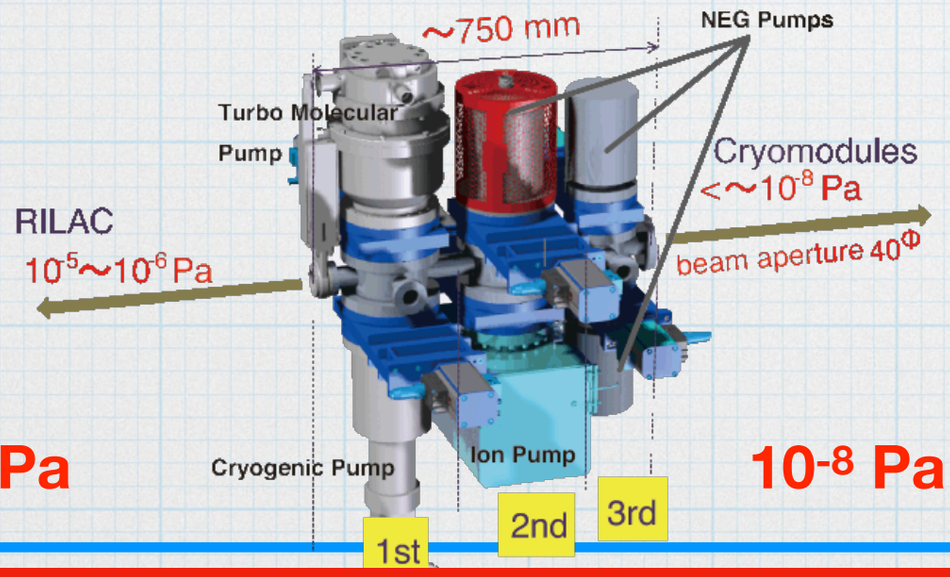
⑤Cryomodules

Overview of SRILAC

- **Three Cryomodules host 10 SC-QWRs (CW, 73 MHz) at 4.5 K.**
- RT Quadrupole magnets are located in the MEBT.
- Vacuum pressure of MEBT line is about 1x10^{-8} Pa with IP and NEG pumps.
- At the both end of the SRILAC three-stage differential pumping systems (DPS) are introduced to prevent gas flow from RT section where several x10^{-5} Pa.



Design view of the differential pumping system



- 1st stage: **TMP**(HiPAce700:Pfeifer) w/ dry roughing pump(NeoDry60E;Kashimaya) +**Cryogenic pump**(CRYOU6H;ULVAC)
- 2nd stage: **ZAO**(Capacitor HV1600;SAES) +**IP**(Valcon Plus 200:Agilent)
- 3rd stage: **UHV ZAO**(Capacitor Z400:SAES)

2) **H. Imao et al., SRF2019, TUP013**