National Synchrotron Radiation Research Center

Study of Multipacting in a Coaxial Coupler with Bias Voltage for the High Power Operation

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2018/06/29

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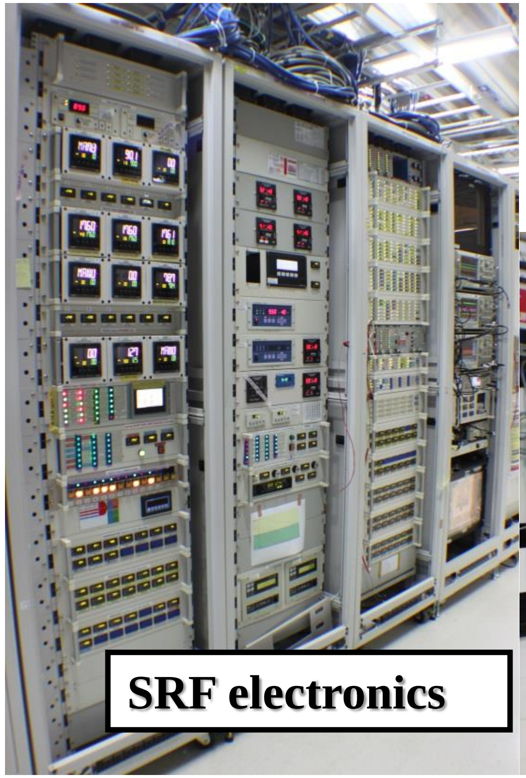
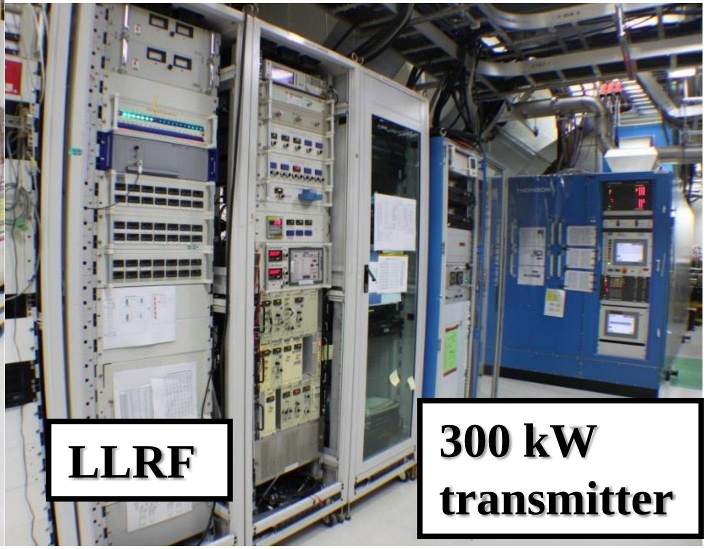
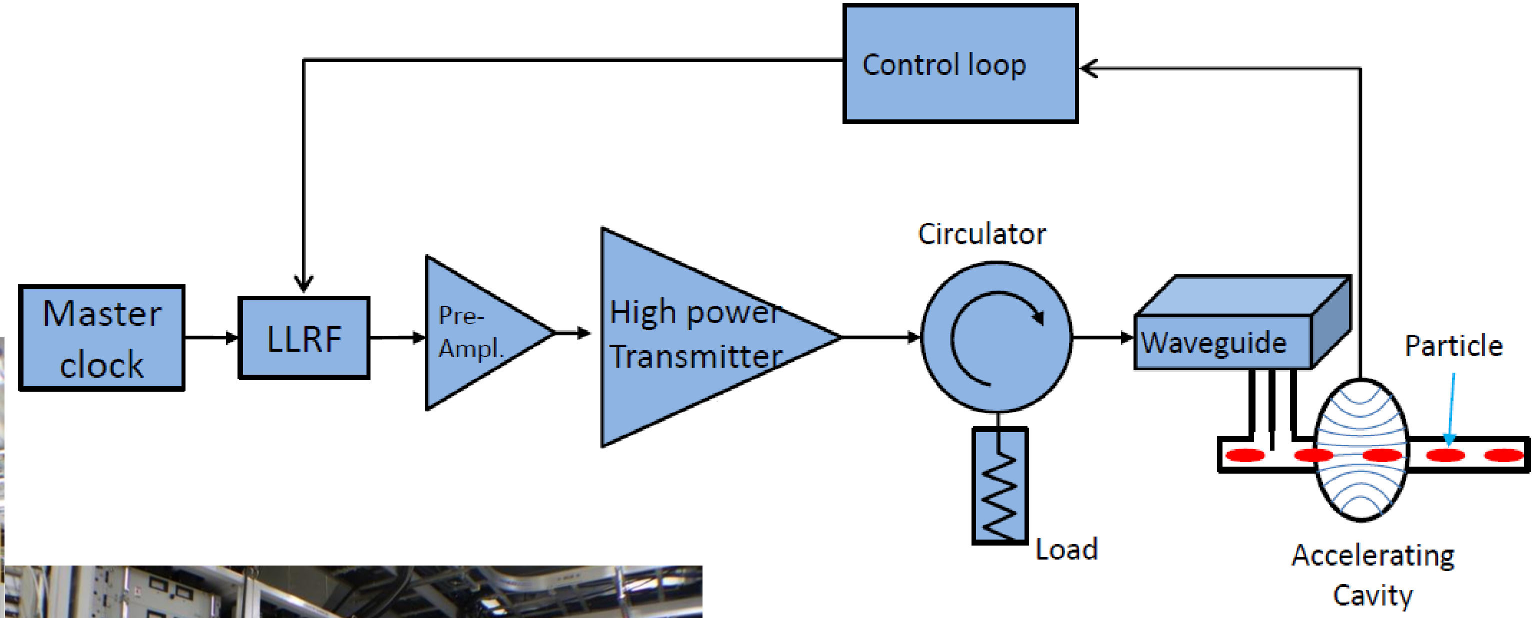
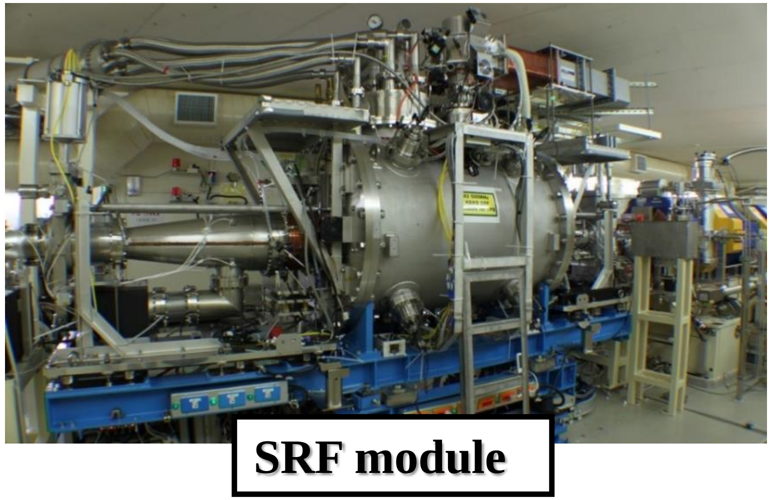
Outline

Introduction (1) TPS RF System



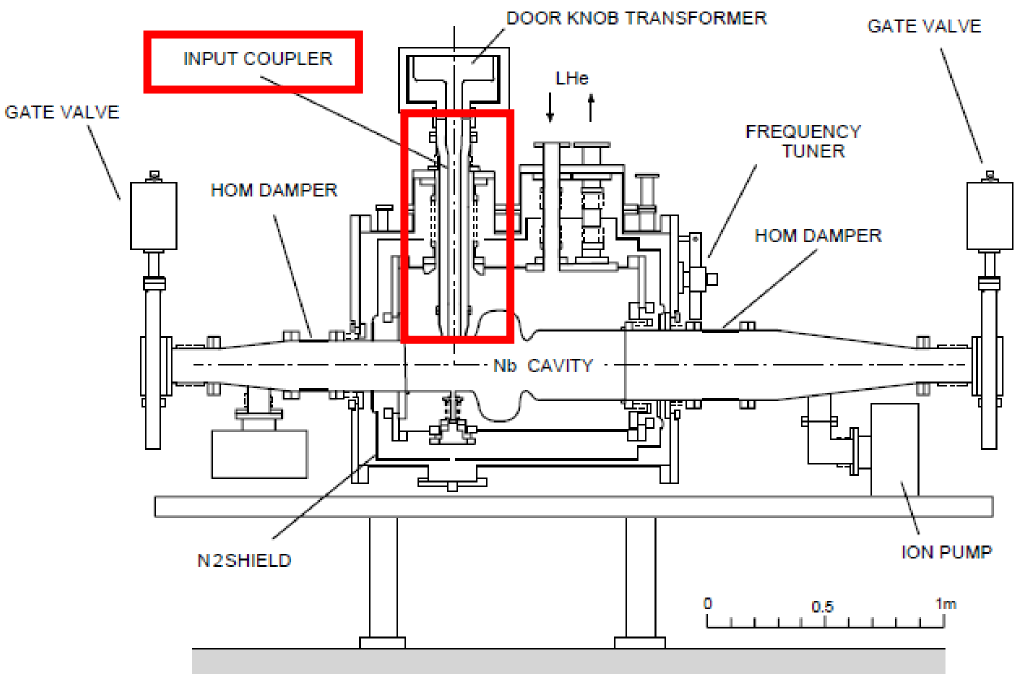






Introduction (2) SRF Module at TPS

Layout of KEKB SRF, and parameters for TPS RF system

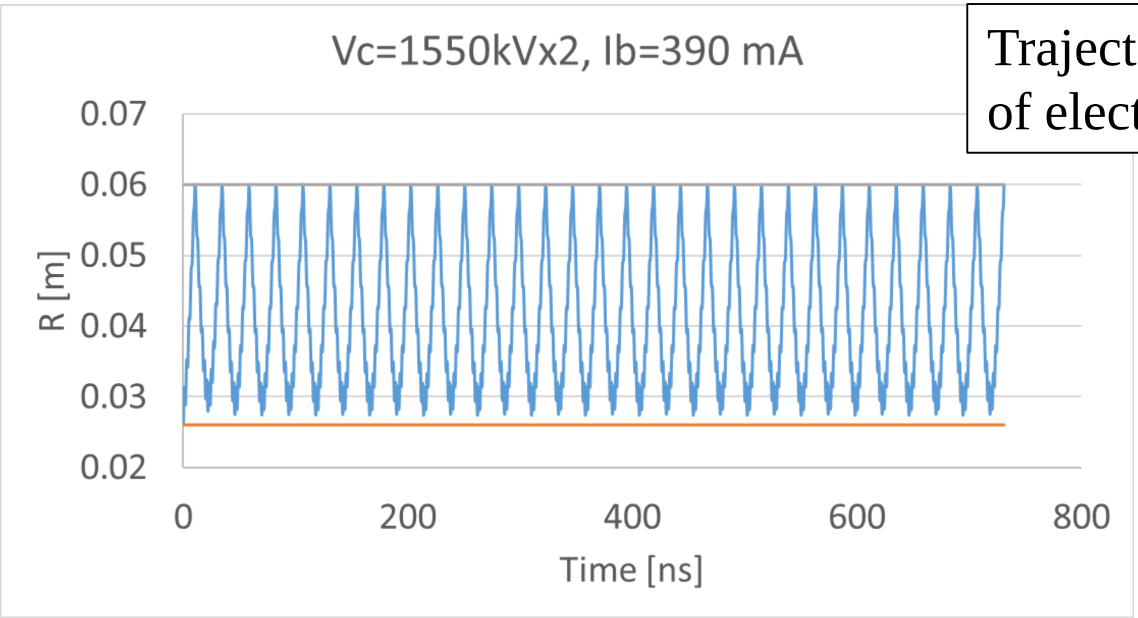


Beam Energy	3 GeV
RF frequency	499.65 MHz
Design Beam current	500 mA
Harmonic number	864
Energy loss per turn (w/o ID)	853 keV
Number of Cavity	2
Coupling Factor	~2.72 x 10^4
Q_L of cavity	~6.6 x 10^4
Max. RF power / cav	~300 kW

The inner conductor is water-cooled and maintained at room temperature. The outer conductor has a transition of surface temperature from room temperature to liquid-helium temperature.

Introduction (3) Multipacting (MP)

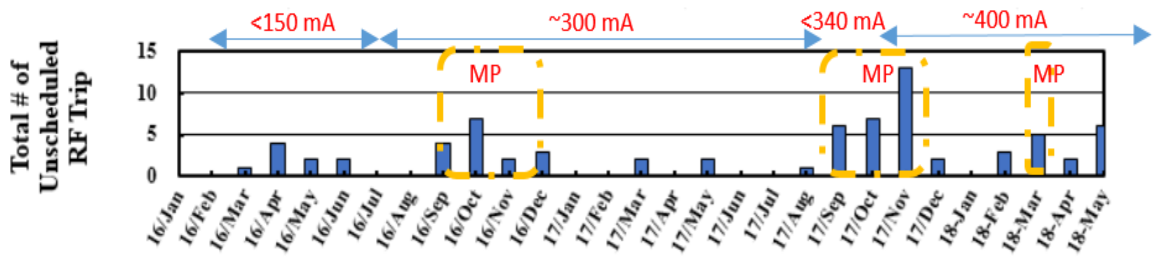
- Multipacting is a resonance phenomenon due to re-emission of secondary electrons：
  - ✓ The initial electrons are emitted from the surface of one side of the coupler, accelerated by the RF field and strike the surface of the coupler after some period.
  - ✓ Secondary electrons might be generated and accelerated again by the RF field.
- Two criteria for MP：
  1. Electrons synchronizes with the RF fields.
  2. Secondary emission yield > 1

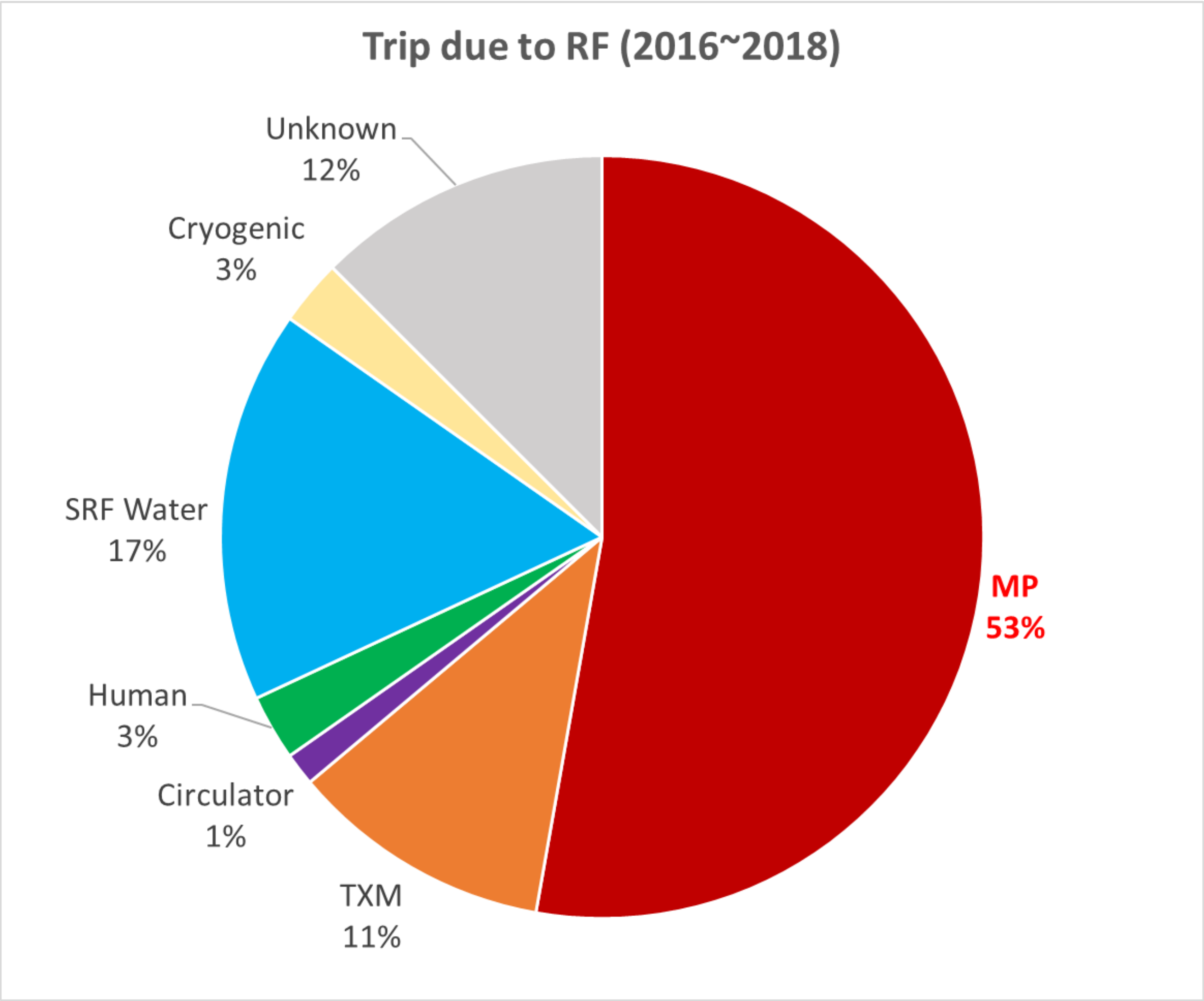


Trajectory of electron

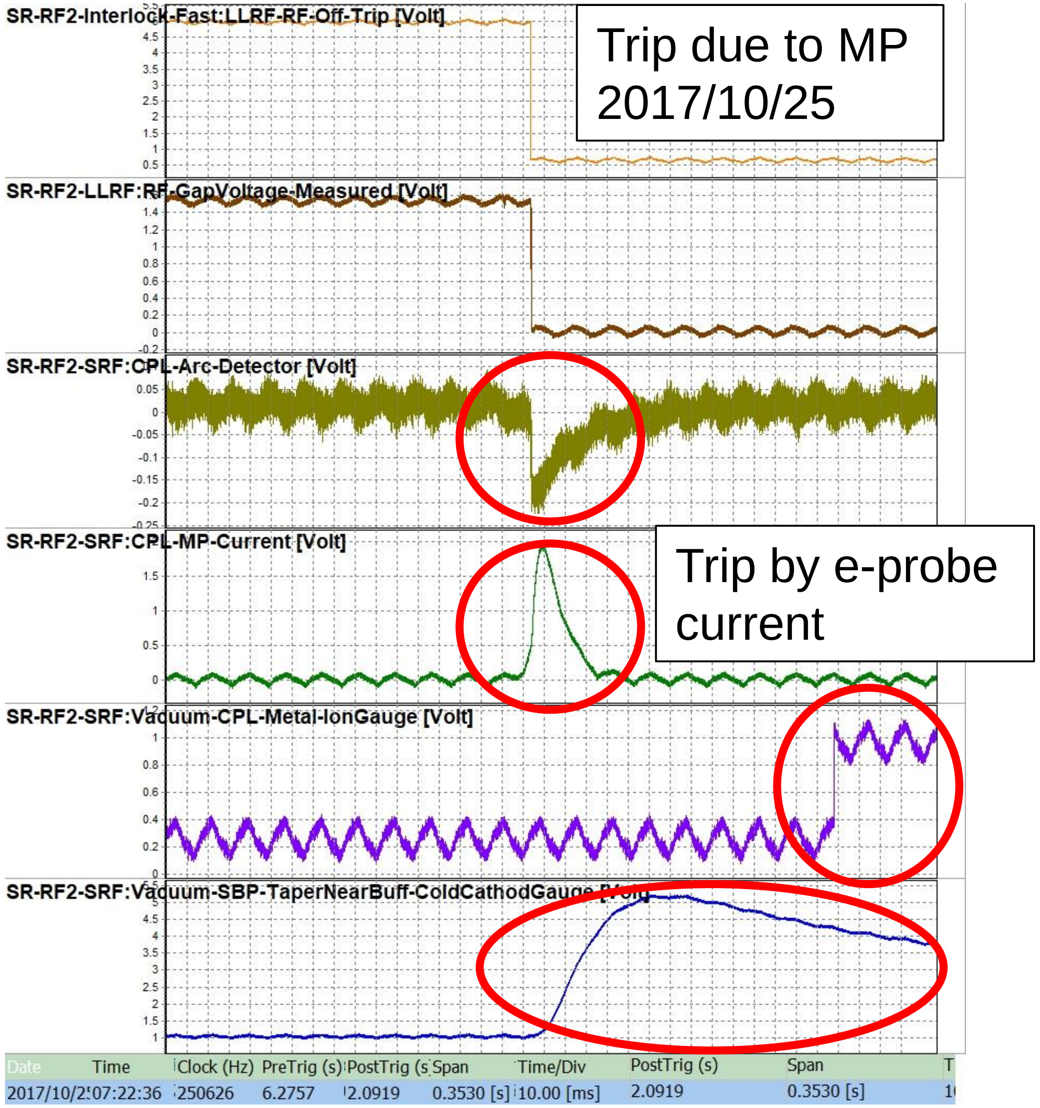
Introduction (4) MP in the TPS Routine Operation－1

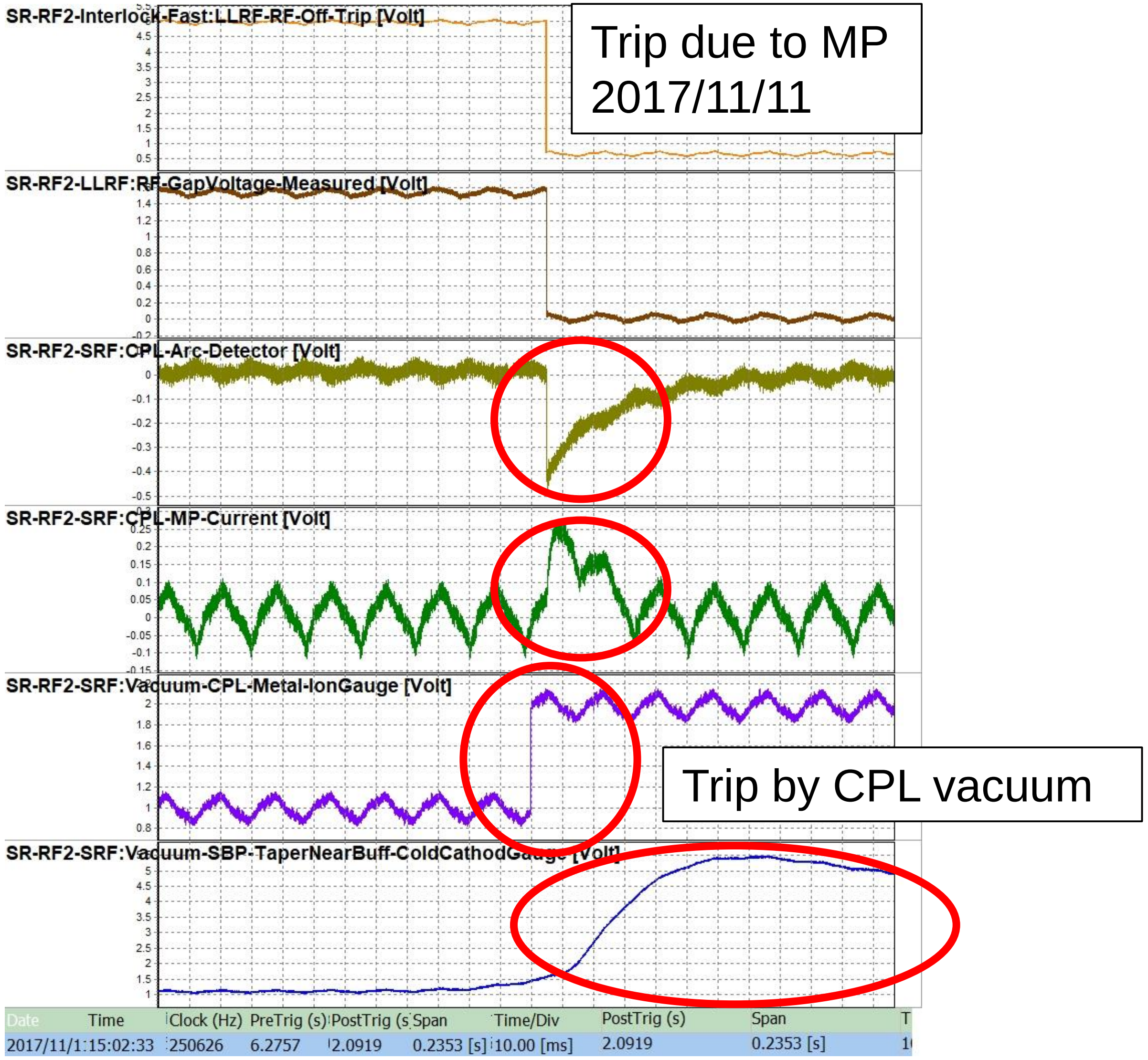
- 53% of RF trip events are due to excitation of MP during user time.
- Most of them are operated at high beam current.





Introduction (5) MP in the TPS Routine Operation – 2

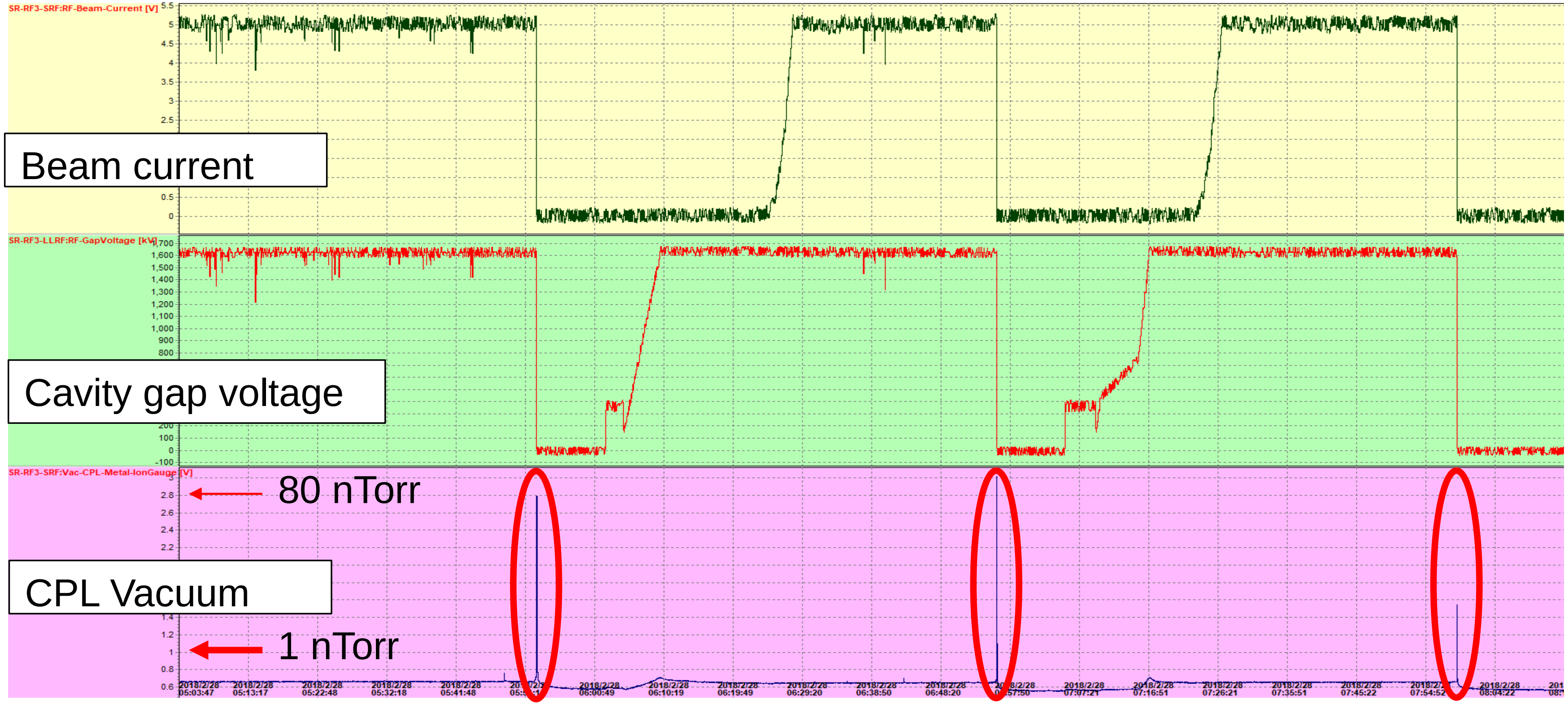




Introduction (6) MP in the TPS Routine Operation－3

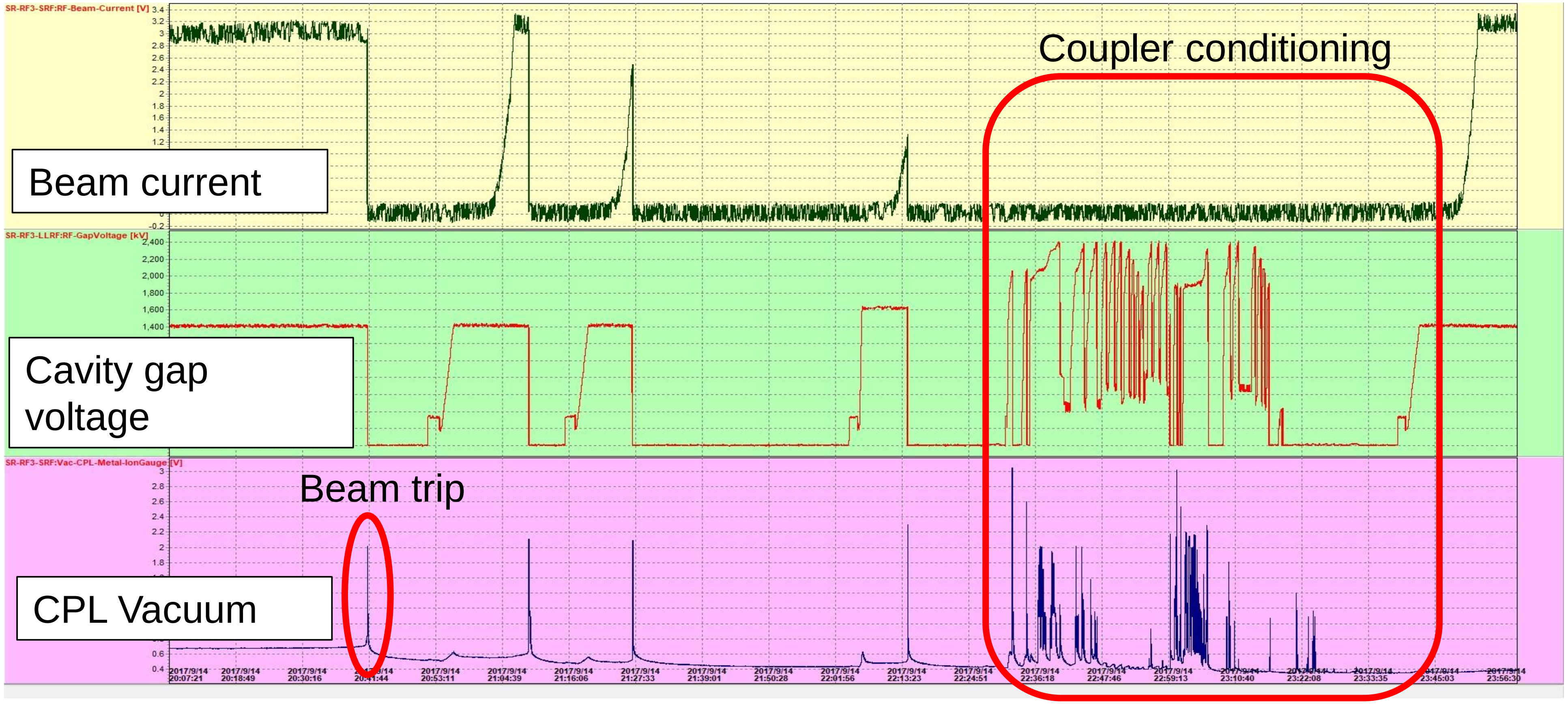
- It may occur many times in a short period. Increase the number of trips.

2018 2/28
SRF #3
Vacuum Trip x3 at 300 mA



Introduction (7) MP in the TPS Routine Operation－4

- It may take long time to recovery. It may need to do the coupler conditioning during user beam time. Increase the downtime.



Introduction (8) Motivation of this study

1. To solve the MP issue during the routine operation.

2. Applying a bias voltage between inner and outer conductors of the coaxial coupler might increase or decrease the strength of the multipacting effect.

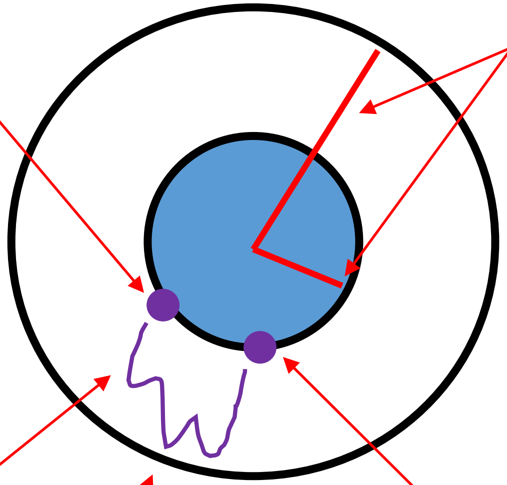
3. For the coupler of KEK-B type, the outer conductor is grounded; the inner conductor is connected to a high voltage, up to $\pm$2000 V.

4. We studied the effect of a bias voltage on multipacting using numerical simulation to track the motion of the electrons. The simulation results and an application for SRF operation with a large beam current are presented here.

Simulation Model (1)

1. Set the geometry.
   R_{out}=60.0 mm
   R_{in}=26.05 mm

2. Put initial electron.
   z, θ and initial phase set randomly, v_0=0.

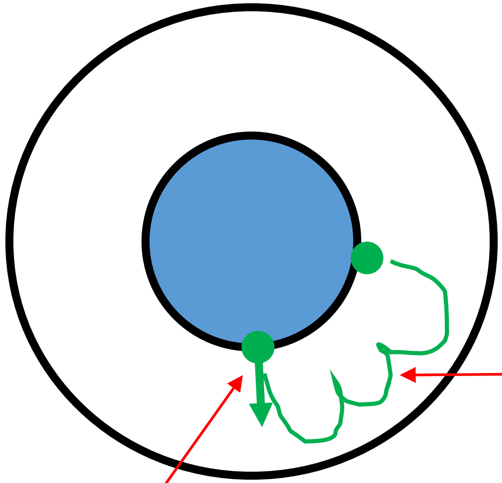


3. Using numerical method to calculate the position and velocity for each time step Δt ($1/f_{RF}/200$).

4. Check if the electron hit the boundary in **r** direction：$R_{in} < \mathbf{r} < R_{out}$.

5. If the electron hit the boundary, then calculate the impact energy and SEY.

Simulation Model (2)



7. Repeat 3~6 until:
   (1) Hit the boundary of **r** at first time step.
   (2) SEY < 1.0
   (3) $-\lambda < z < 0$
   (4) Number of impact >= 30

6. Replaced a new electron. the v_0 of new electron is 1.8 eV and perpendicular to the surface.

8. Counting the total generated electrons：

$$N_{30} = \Pi(SEY)$$

9. Repeat N_0 time，calculate the average N_{30}：

$$\bar{N}_{30} = M = \frac{\Pi(N_{30})}{N_0}$$

Simulation Model (3)

$$\Gamma_R = \frac{(1-\frac{I_b R_L}{V_C}\cos\phi_s) \Big/ (1+\frac{I_b R_L}{V_C}\cos\phi_s) - \tan^2\theta_L}{(1+\tan^2\theta_L)}$$

$$\Gamma_I = \frac{2\tan\theta_L}{(1+\frac{I_b R_L}{V_C}\cos\phi_s)(1+\tan^2\theta_L)}$$

- Equation of Motion

$$m_e\gamma \cdot \frac{d^2\vec{x}}{dt^2} = e\cdot\left[\vec{E} + \frac{d\vec{x}}{dt}\times\vec{B} - \frac{1}{c^2}\left(\frac{d\vec{x}}{dt}\cdot\vec{E}\right)\frac{d\vec{x}}{dt}\right]$$

- The electromagnetic fields of the input TEM mode with a complex reflection coefficient

$$E_r = \frac{V_a}{r}\{\cos[\omega(t-\frac{z}{c})+\phi_0] + \Gamma_R\cos[\omega(t+\frac{z}{c})+\phi_0] - \Gamma_I\sin[\omega(t+\frac{z}{c})+\phi_0]\} + E_{DC}$$

$$B_\theta = \frac{V_a}{rc}\{\cos[\omega(t-\frac{z}{c})+\phi_0] - \Gamma_R\cos[\omega(t+\frac{z}{c})+\phi_0] + \Gamma_I\sin[\omega(t+\frac{z}{c})+\phi_0]\}$$

$$E_\theta = E_z = B_r = Bz = 0$$

Simulation Model (4)

- Calculation of SEY (Functions and parameters are from the fitting measurements in the literature)

$$\delta = \delta_{ts} + 0.3 \cdot \delta_{el}$$

$$\delta_{ts} = \delta_m \frac{s \cdot u}{s - 1 + u^s} \quad , \quad s = 1.54$$

Consider the reflected electrons

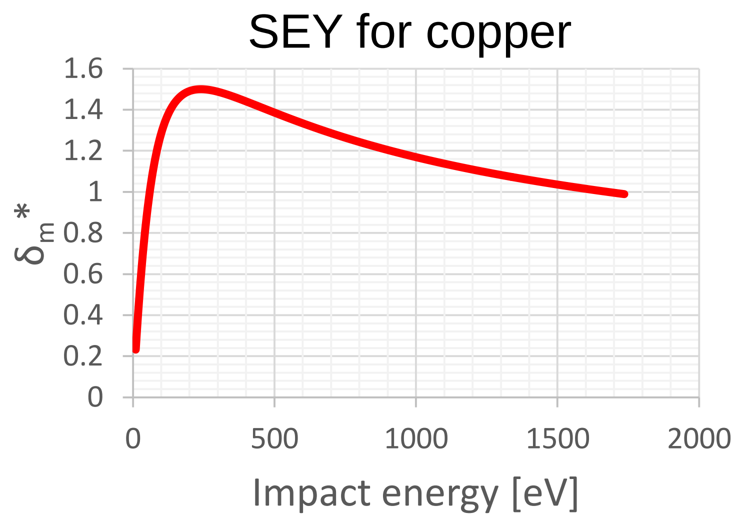
$$\delta_{el} = \left(\frac{\sqrt{E_{imp}} - \sqrt{E_{imp} + E_0}}{\sqrt{E_{imp}} + \sqrt{E_{imp} + E_0}} \right)^2 \quad , \quad E_0 = 150eV$$

Consider the incident angle

$$u = \frac{E_{imp}}{E_m}$$

$$\delta_m = \delta_m^* \cdot e^{0.5 \cdot (1 - \cos\theta)} \quad , \quad \delta_m^* = 1.5$$

$$E_m = E_m^* \cdot (1 + 0.7(1 - \cos\theta)) \quad , \quad E_m^* = 278.4eV$$



Reference: Fritz Caspers et. al, "Beam-Induced Multipactoring and Electron-Cloud Effects in Particle Accelerators"

Results and Vacuum Data (1)

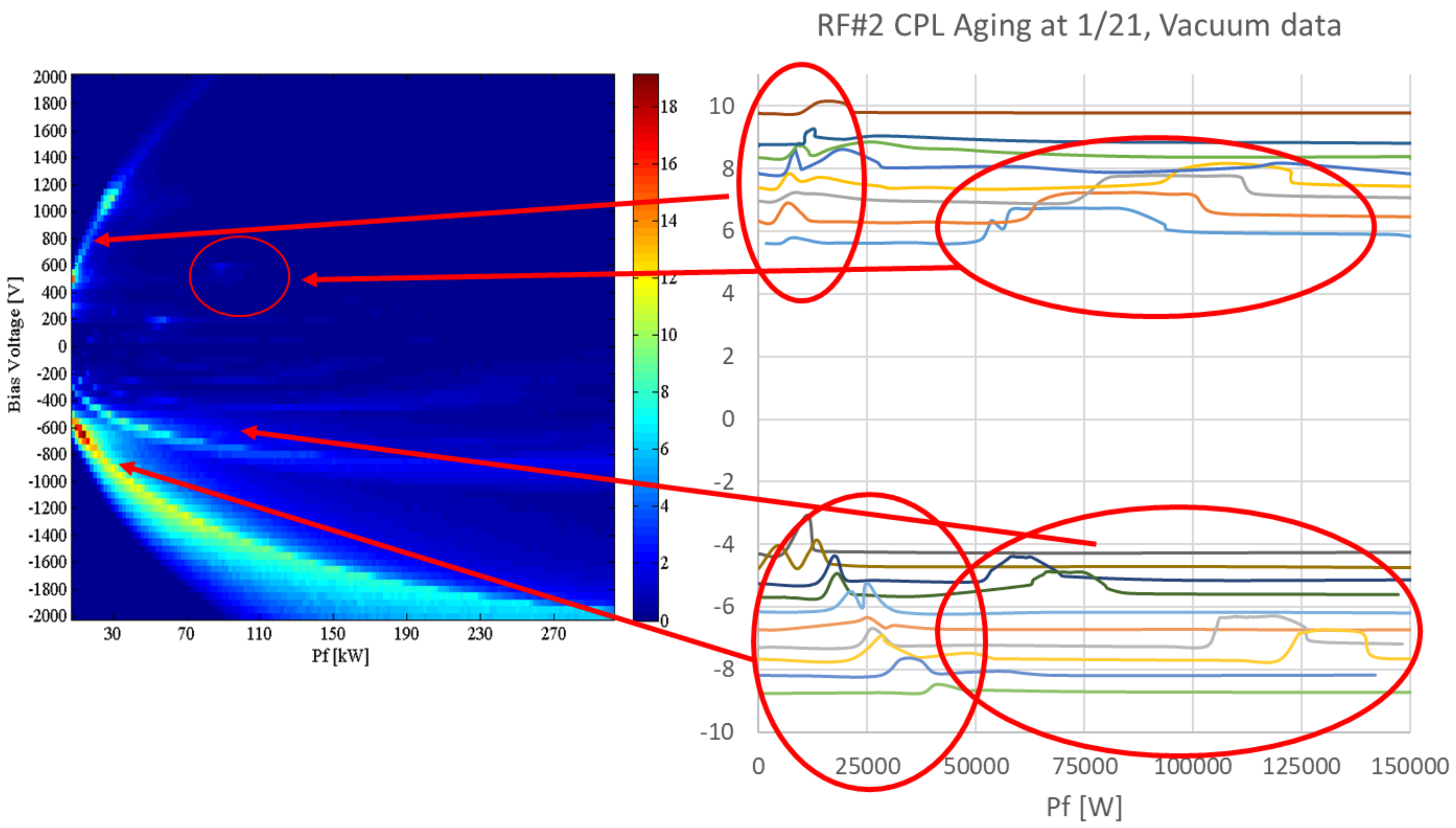
1. To validate this model, we compare the simulation results with following vacuum data.

- During Coupler Conditioning:
  - ✓ At warm.
    a. Apply before cool down.
    b. Increase forward power to 300 kW with & without bias voltage.

  - ✓ At cold.
    a. Apply bi-weekly during maintenance.
    b. Off resonance: increase Pf to 300kW.

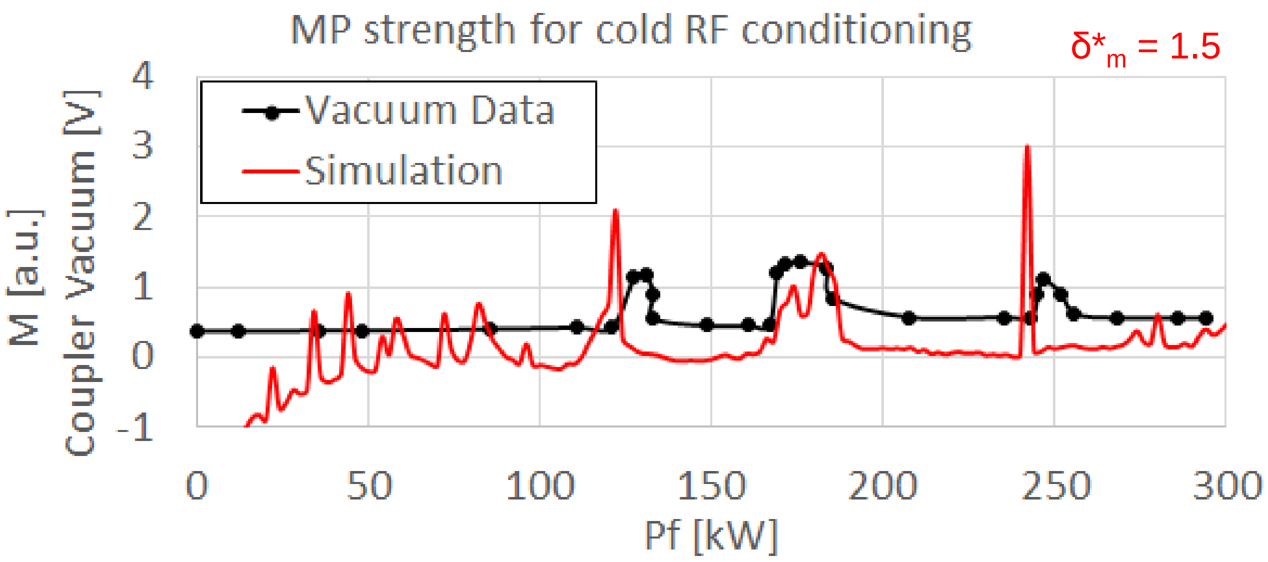
- During routine machine time for high beam current test.
  - ✓ 431 mA at ~1550 kV x2 (ex. 2016/06/16 09:18 SRF#2)

Results and Vacuum Data (2)
Coupler warm conditioning with bias voltage



Results and Vacuum Data (3)
RF conditioning at cold (detuned)

1. During the weekly RF conditioning at TPS, the forward RF power is up to 300 kW or 2400 kV depending on whether the cavity is detuned or at resonance.



2. Vacuum burst events are observed during RF conditioning for the detuned cavity.

3. Three MP zones are predicted, consistent with the vacuum data.

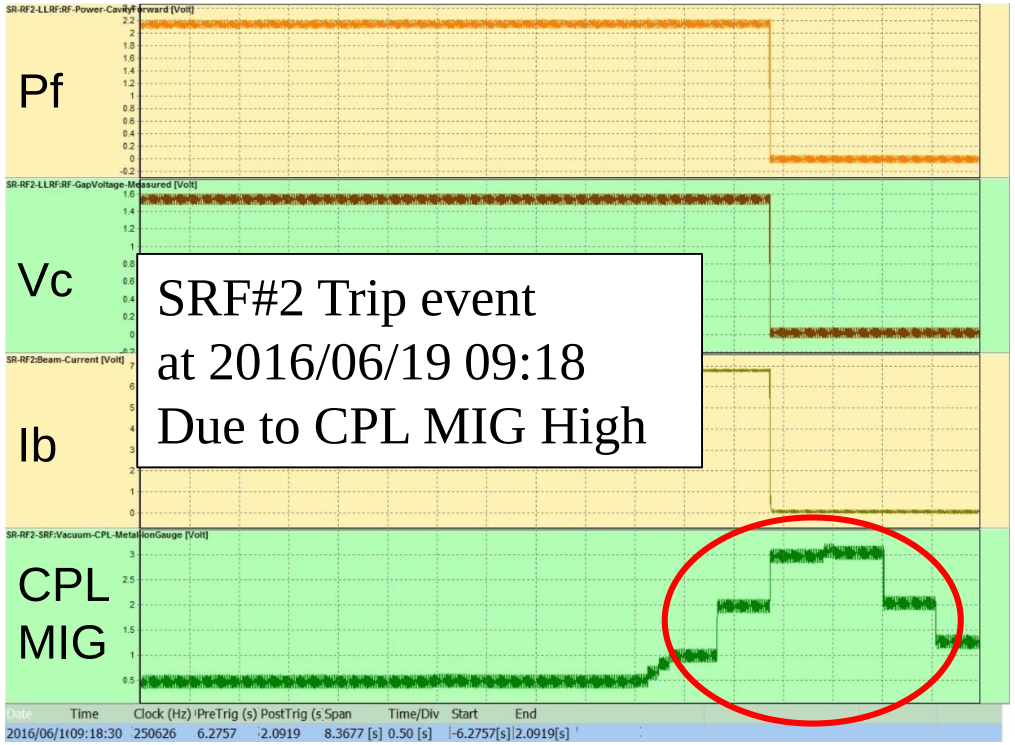
4. 1 V corresponds to 1 nTorr and 2 V corresponds to 10 nTorr.

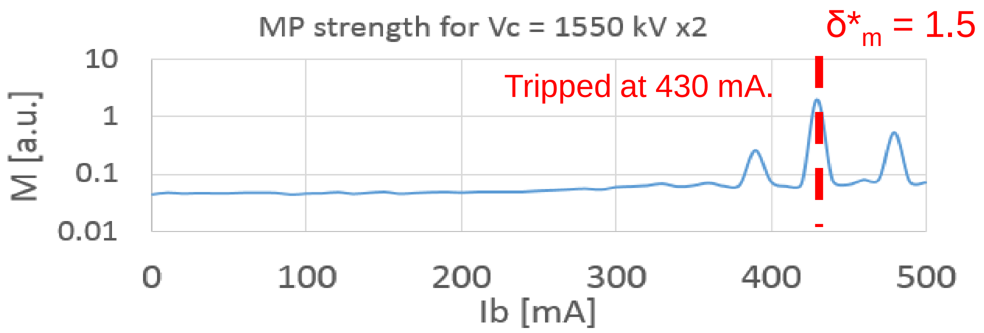
Results and Vacuum Data (4)
Operation with High Beam Current

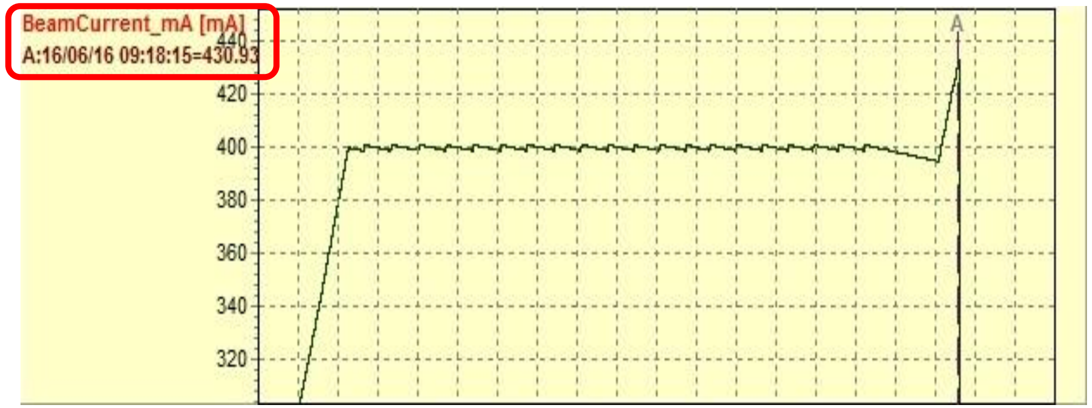
During the high current test, the vacuum trip events occurred:

Cavity gap voltage: 1550 kVx2

Beam current: 430 mA 。



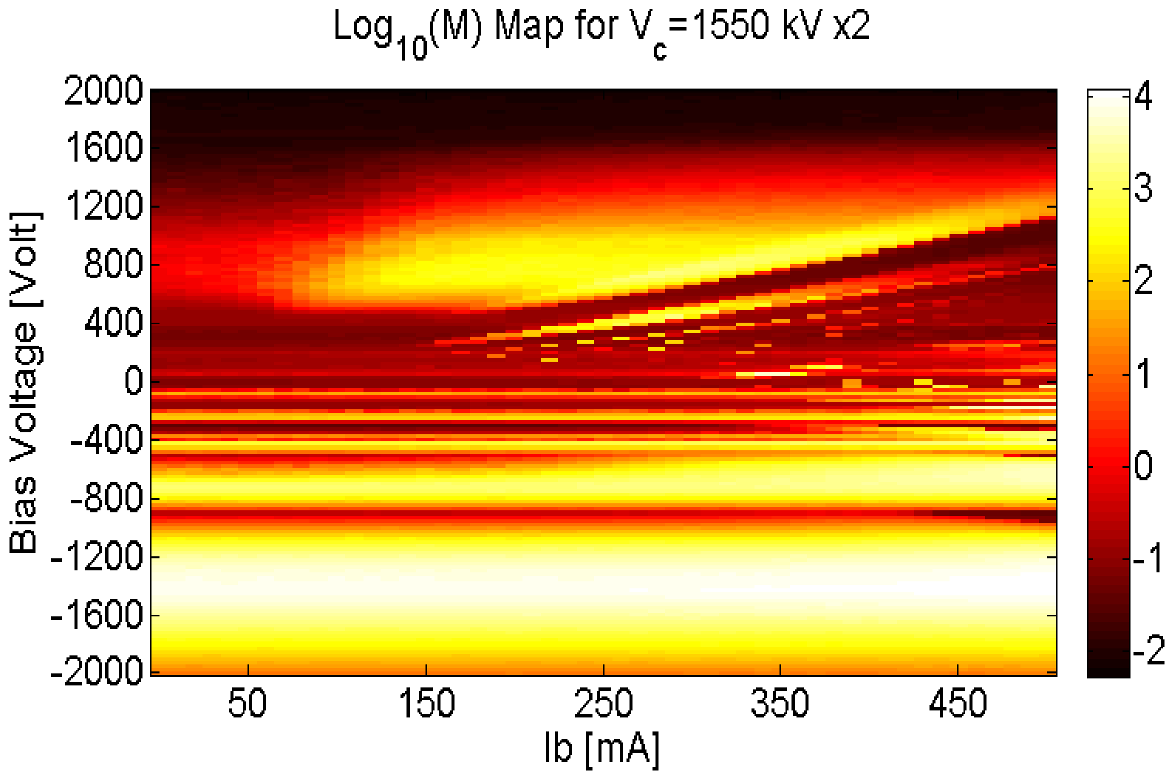




Effect of Bias Voltage for High Power Operation

1. Right plot shows a map of the MP zone for a beam current from 0 to 500 mA and bias voltage from -2000 V to 2000 V with total RF voltage 3100 kV.

2. With zero bias voltage, three hot spots of MP, exist, located at 390, 430 and 480 mA.



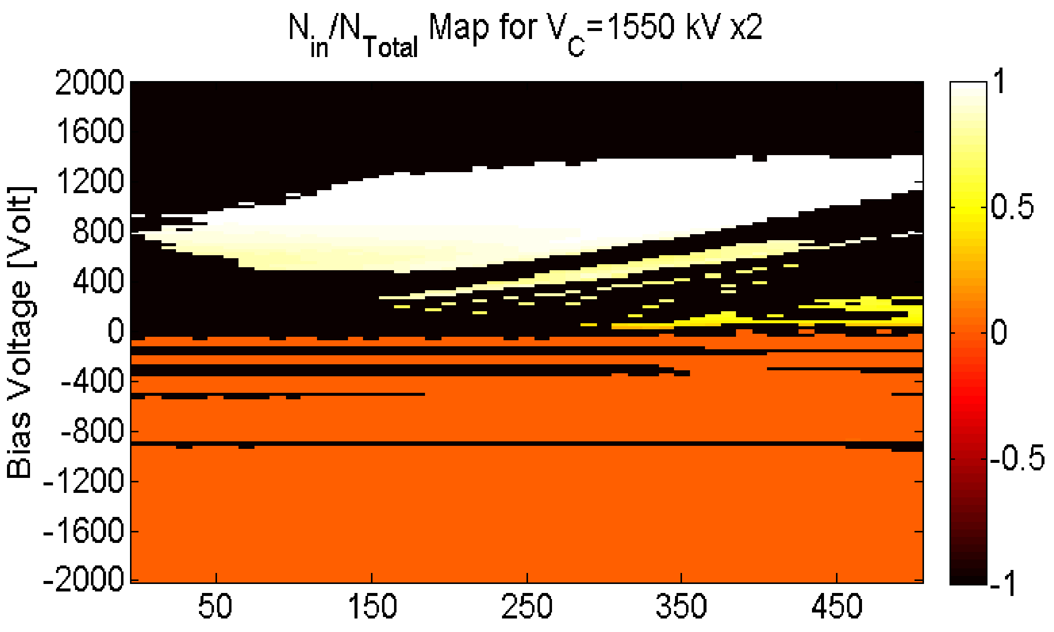
3. With a larger positive bias voltage the strength of MP can be decreased whereas a negative bias voltage enhanced the strength of MP.

Effect of Bias Voltage for High Power Operation

1. R can be used to determine where the MP occurred：

$$R = \frac{N_{inner}}{N_{inner} + N_{outer}}$$

2. If MP occurred at inner conductor (1-side), R~1；if it occurred at outer conductor (1-side), R~0；For the 2-sides MP, R~0.5；R is set to -1 for M<1.



3. The MP are indicated all to occur at the outer conductor with a negative bias voltage and the MP are from two-sided MP or one-sided MP from the inner conductor with a positive bias voltage. (<~ 800 V)

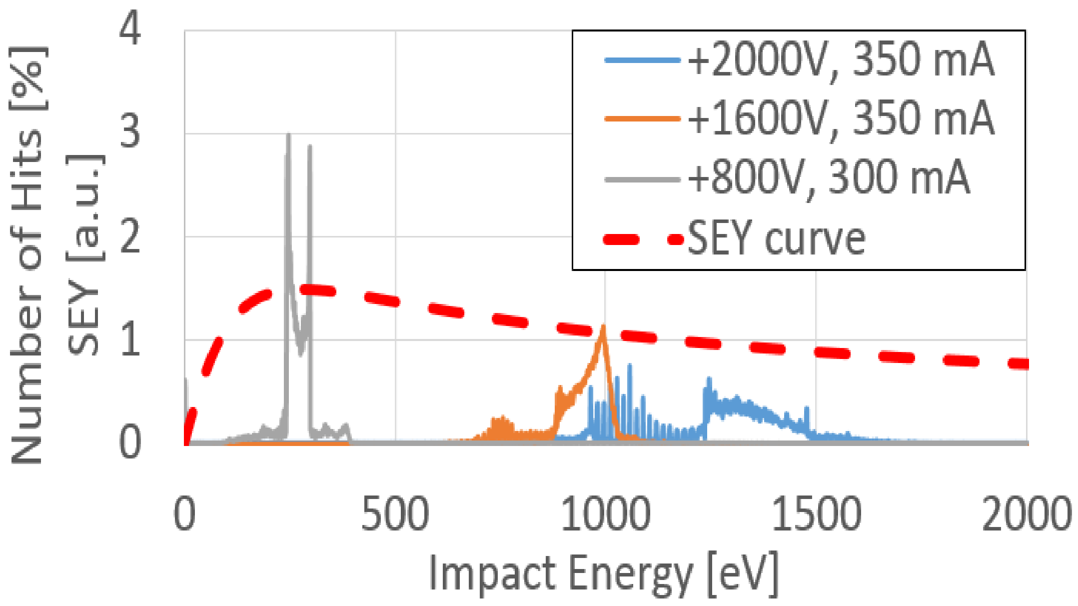
4. With a bias voltage greater than 1600 V, the strength of MP is all smaller than 1 (black region in the plot).

Study for Operation with High Beam Current

1. The outer conductor for a KEK-B designed coupler is the cold surface. The gas loading is thus heavier on the outer conductor than on the inner conductor.

2. Applying a positive bias voltage can change the location of the MP to the inner conductor, which can avoid a heavy gas loading on the cold surface.

3. Applying a greater positive bias voltage also decreases the strength of MP, typically larger than about 1500 V, because the greater positive bias voltage results in a larger impact energy of the primary electrons.

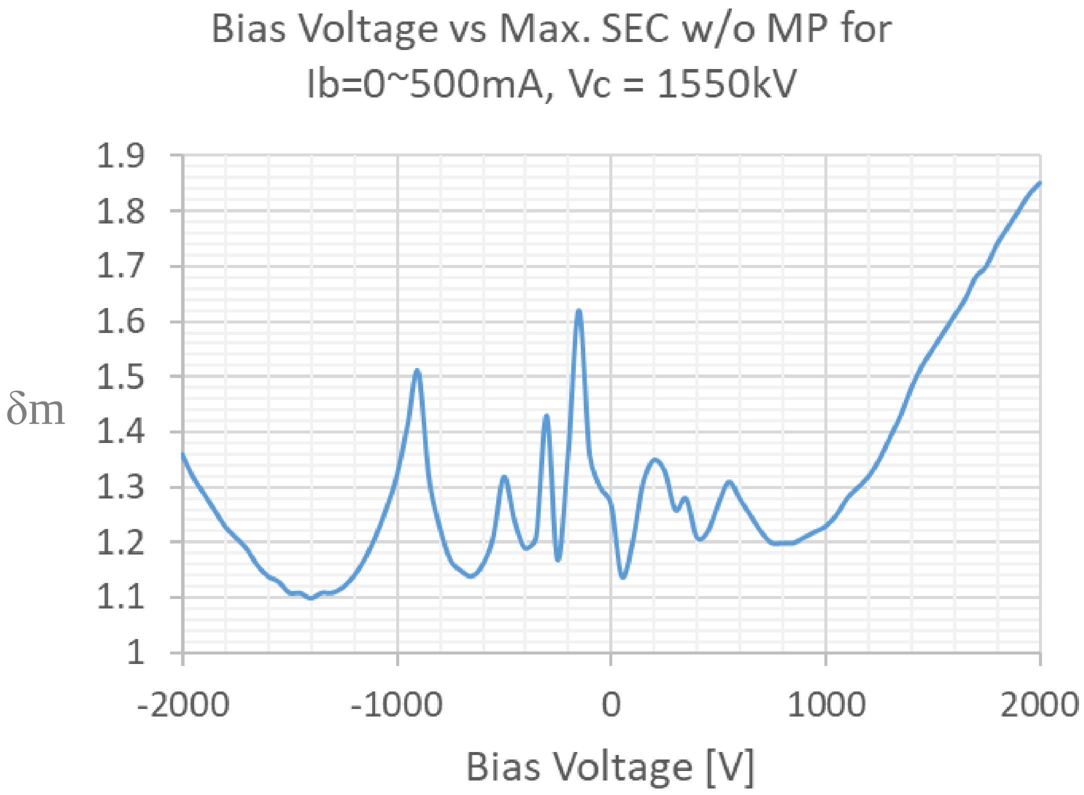


Study for Operation with High Beam Current

1. Change the δm* to find the maximum δm* with M < 1 for all current. For example, Vb = 0, δm* = 1.27, it means that at δm*=1.27 and Vc=1550 kV, the M are all smaller than 1 for Ib = 0~500mA.

2. The maximum δm* is happened at Vb = +2000V, the value is 1.85.

3. We may apply Vb = +2000V to overcome the MP if the gas load is a problem for high beam current operation.

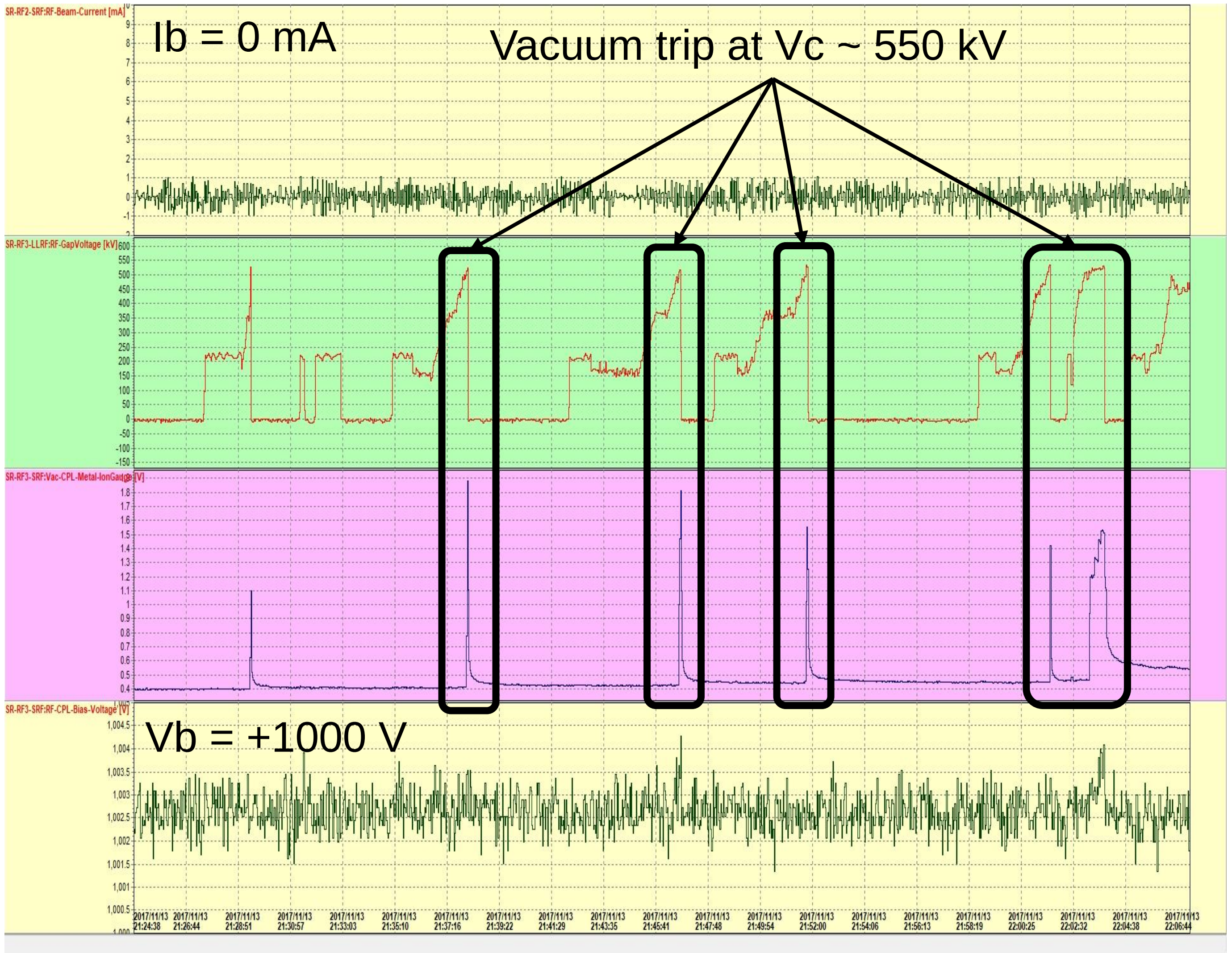


Experience for the operation with bias voltage

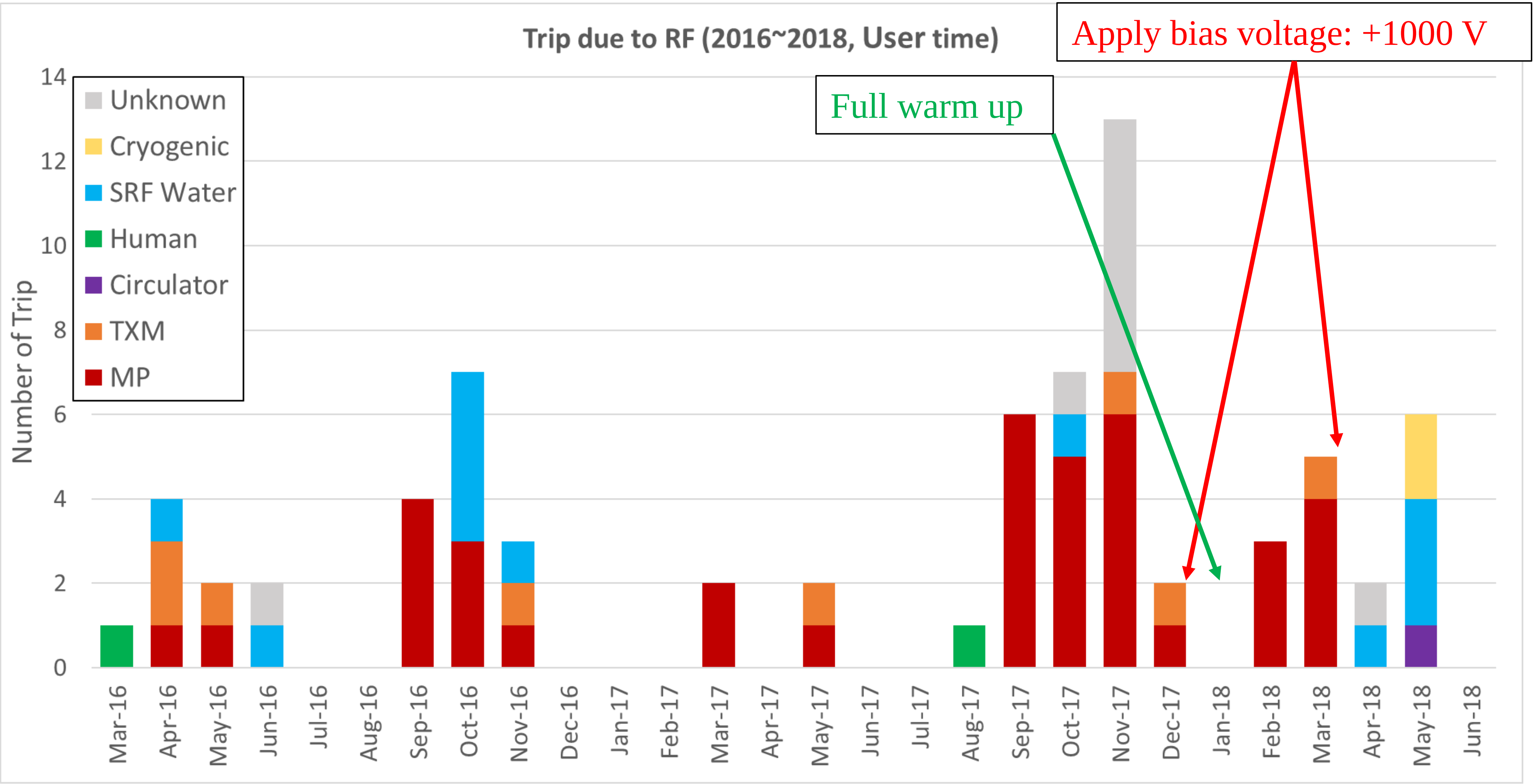
1. Because we don't know the effect for the ceramic window if the Vb is applied. We don't apply high bias voltage. We only apply **Vb = +1000 V** for the TPS routine operation.

2. Advantage of +1000 V of bias voltage: All MP occurred at inner conductor (avoid heavy gas loading on the cold surface).

3. Applying +1000V:
   - Difficulty: vacuum trips for the low Vc without beam current
   - Solution: Turn on bias voltage after Vc > 1400 kV.



Experience for the operation with bias voltage



Summary

1. The MP effect degrades the SRF operating performance, which is a major problem for high beam-current operation.

2. A numerical simulation was used to study the MP effect.

3. The results of simulation are consistent with the vacuum data for the weekly RF conditioning and the high beam-current test.

4. The simulation shows also that applying a large positive bias voltage can not only avoid a heavy gas load on the cold surface but also decrease the strength of MP.

5. Vb = +1000 V is applied for the TPS routine operation. After applying this bias voltage, it reduces the RF trips due to MP effects a lot.