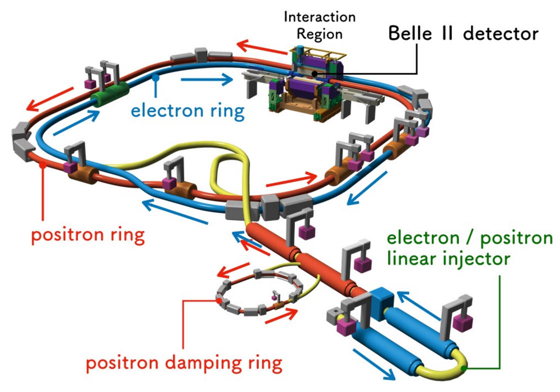
Observation of fireball-triggered RF breakdown in a 509-MHz normal-conducting cavity and its initial simulation study

Takaaki YAMAGUCHI, Tetsuo ABE, Tetsuya KOBAYASHI

High Energy Accelerator Research Organization (KEK)



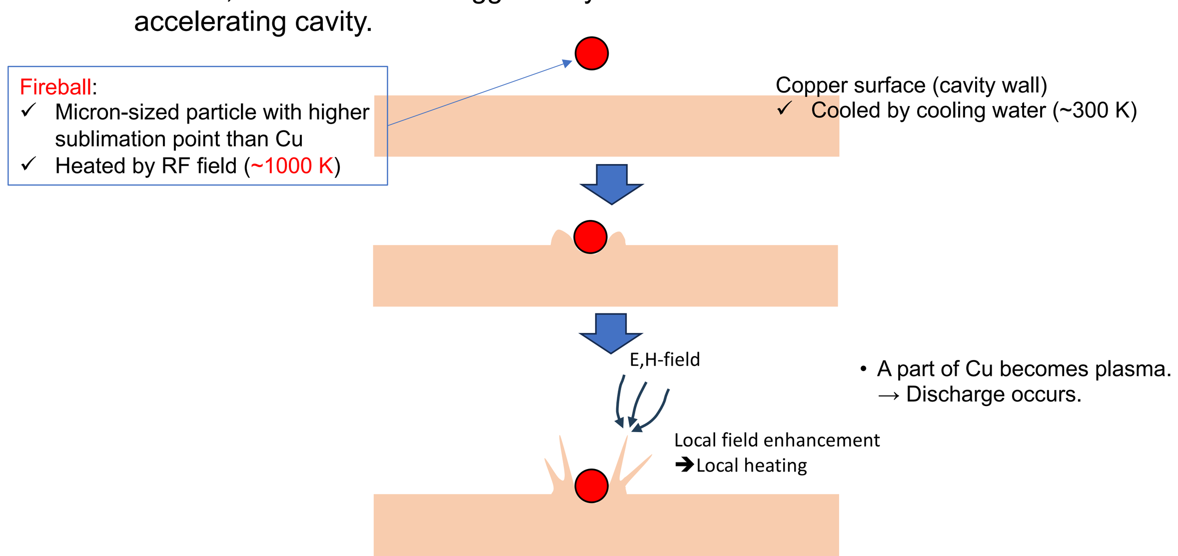
1. Introduction

Motivation

At KEK, fireball-triggered RF breakdowns [1] have been observed in a 509-MHz CW normal-conducting RF cavity. It has been found that the breakdown was caused by a high-temperature microparticle that we call "fireball" now. Recently, the fireball-triggered breakdowns attracts interests again in relation to the SuperKEKB accelerator that is suffering from sudden beam losses. A hypothesis is proposed that similar phenomena to the fireball breakdown could cause the sudden beam losses [2]. Because of such interests, we have started experimental study of the fireball-triggered breakdown in the accelerating cavity, again. In this study, we are trying to observe more detailed characteristics of the fireball-triggered breakdown, such as the emitted total current at the moment of breakdown. Furthermore, using the Particle-in-Cell simulation of CST Studio Suite, we are trying to reproduce the breakdown phenomena observed in the experiment. The results will be useful for better understanding the mechanism of the sudden beam loss in SuperKEKB. In this workshop, we report the initial experimental and simulation results.

Fireball-triggered breakdown[1]

- At KEK, RF breakdowns triggered by fireballs were observed in an RF accelerating cavity.



Schematic view of fireball-triggered breakdown

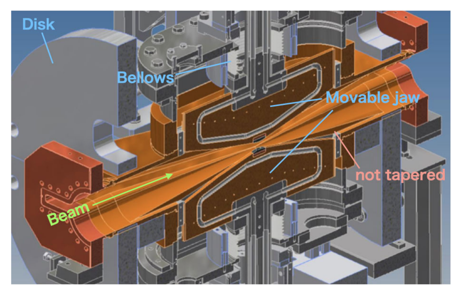
Sudden beam loss at SuperKEKB

- A phenomenon that stored beam is suddenly lost without any precursor.
- This phenomenon can seriously damge hardwares, and then limits beam current in recent SuperKEKB operation.

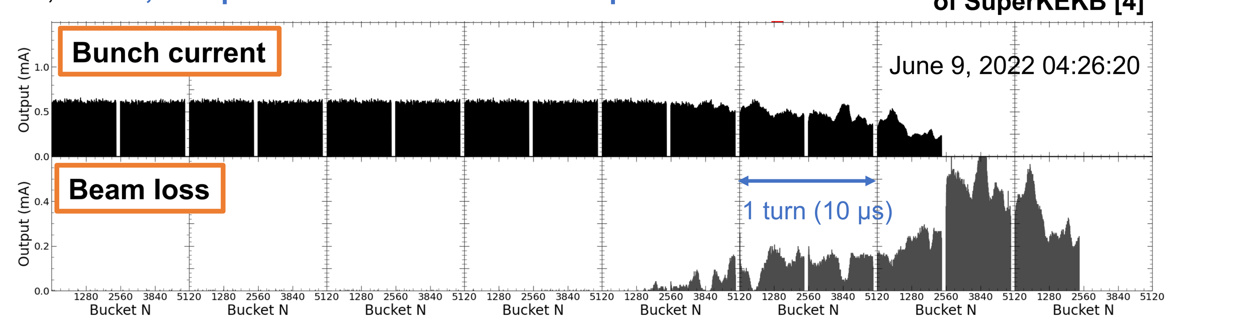
Fireball hypothesis

- If a similar phenomenon to the fireball breakdown happens at the beam collimators of SuperKEKB, it will cause large beam loss.

→ In detail, T. Abe, oral presentation of this workshop on Mar. 6



Vertical beam collimator of SuperKEKB [4]



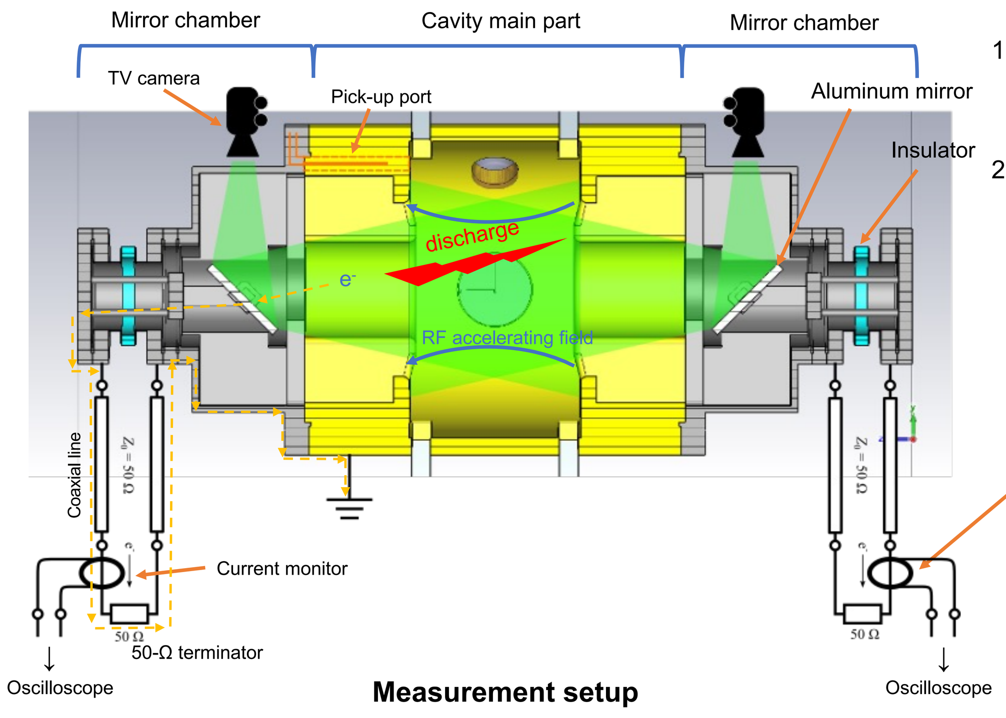
Bunch current monitor when sudden beam loss occurred [3]

2. Measurement

- To verify the fireball hypothesis, we have to confirm that the total emission current induced by a fireball is large enough to kick the stored beam to a large angle (the emission current of 100 A or larger is required to kick the stored beam).
- We restarted the experimental study of the fireball breakdown using a 509-MHz CW normal-conducting cavity for the positron damping ring at KEK.
- Our goal is to obtain the total emission current arising from the fireball breakdown.

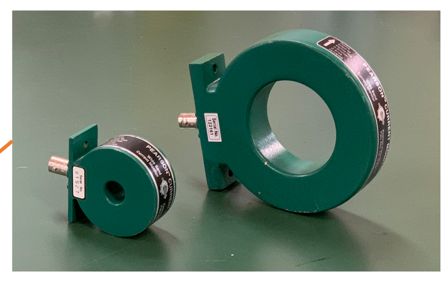
Measurement setup

- Aluminum mirrors are attached on the beam port to observe the inside of the cavity using TV cameras.
- The mirrors are insulated from the cavity main part.
- Current monitors are installed to measure the emission current colliding with the mirrors.
- We input CW power of up to 200 kW corresponding to RF accelerating voltage of 700 – 900 kV (accelerating gradient: 2.7 – 3.5 MV/m).



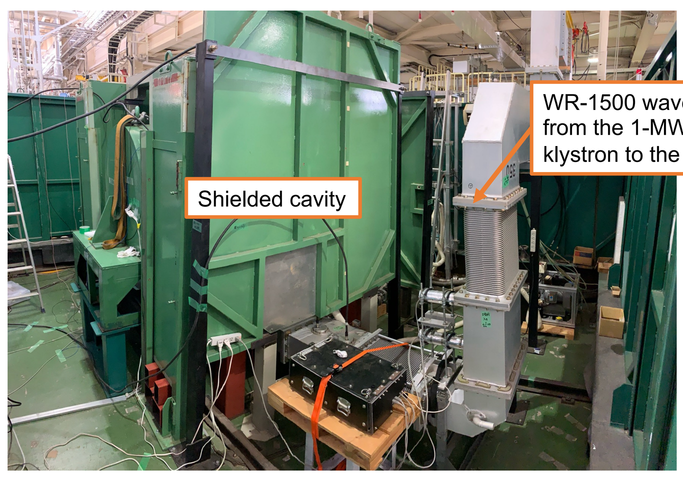
Measurement setup

1. At the moment the breakdown occurs, one of the cameras captures a bright spot that corresponds to the emission point.
2. The ratio of electrons reaching the mirrors to the total emitted electrons were deduced by PIC simulation.

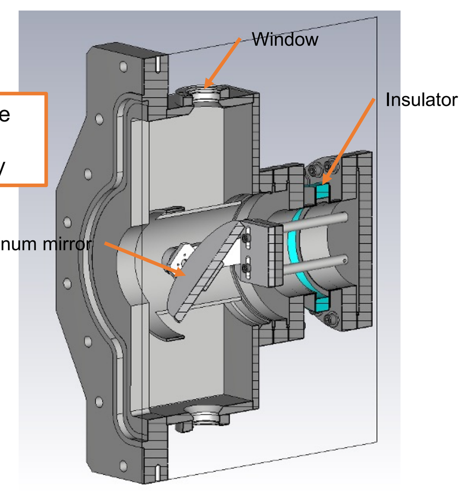


Current monitor (Pearson Electronics, Model 411 and 110, Bandwidth: 1 Hz – 20 MHz)

509-MHz accelerating cavity for the positron damping ring at SuperKEKB



High-power teststand

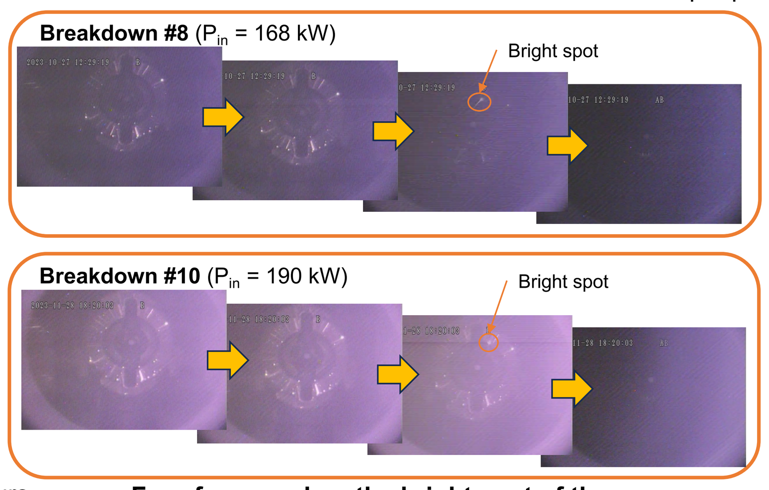


3D drawing of the mirror chamber

Measurement results

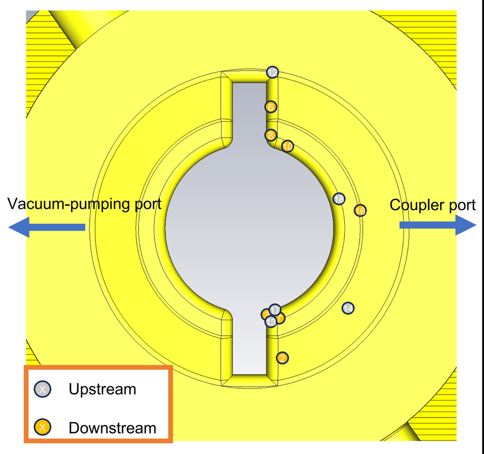
- We observed totally 18 breakdown phenomena.
  - ✓ Events that the input power was turned off by coupler arc or reflection interlocks and the pick-up signal decreased much faster than the filling time (~8 μs) of the cavity
- Some examples of measurement results are shown below.
- The input power at the moment of observing breakdowns were 100 – 200 kW (corresponding to the RF voltage of 680 – 920 kV).

❑ TV camera • The frame rate was 30 Hz.



Four frames when the bright spot of the breakdown appeared.

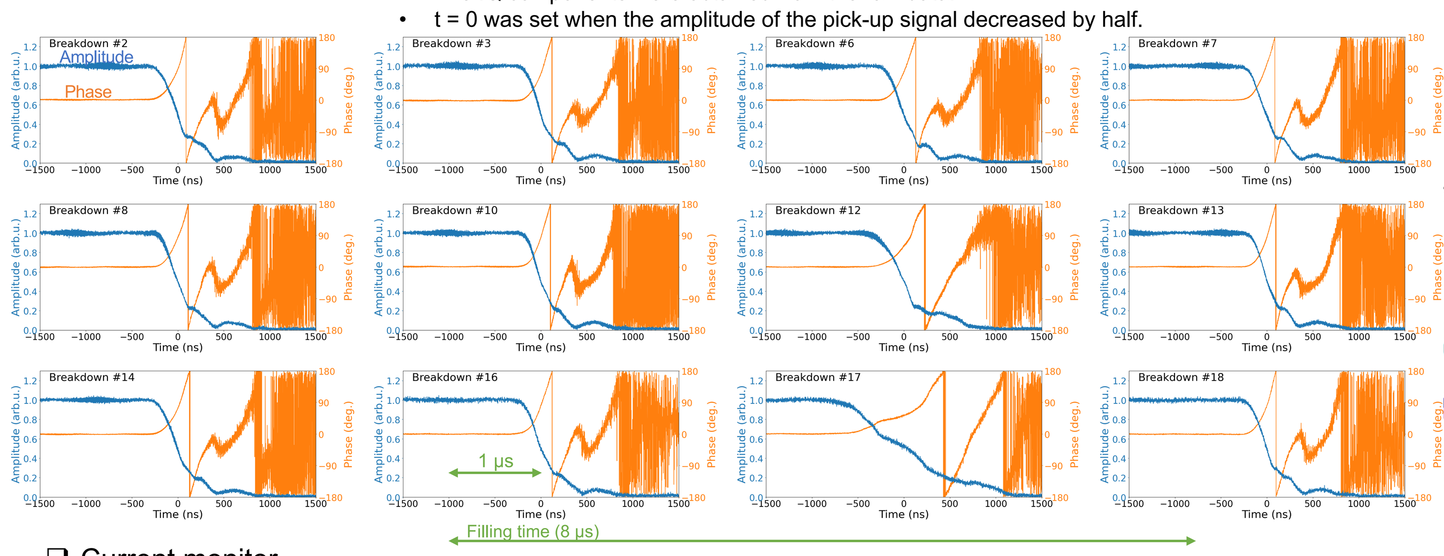
Snapshot of the movie when the breakdown occurred



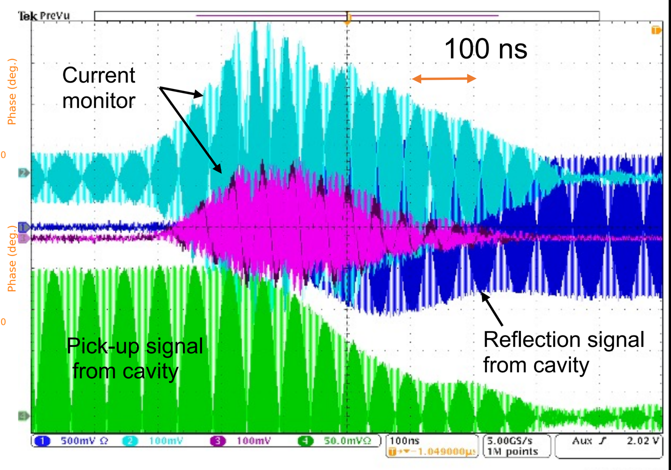
Positions of the breakdowns

❑ Pick-up signal from cavity

- Pick-up signals (509 MHz) were sampled by an oscilloscope with the sampling rate of 2.5 or 5.0 GHz.
- The IQ components were obtained from the raw data.
- t = 0 was set when the amplitude of the pick-up signal decreased by half.

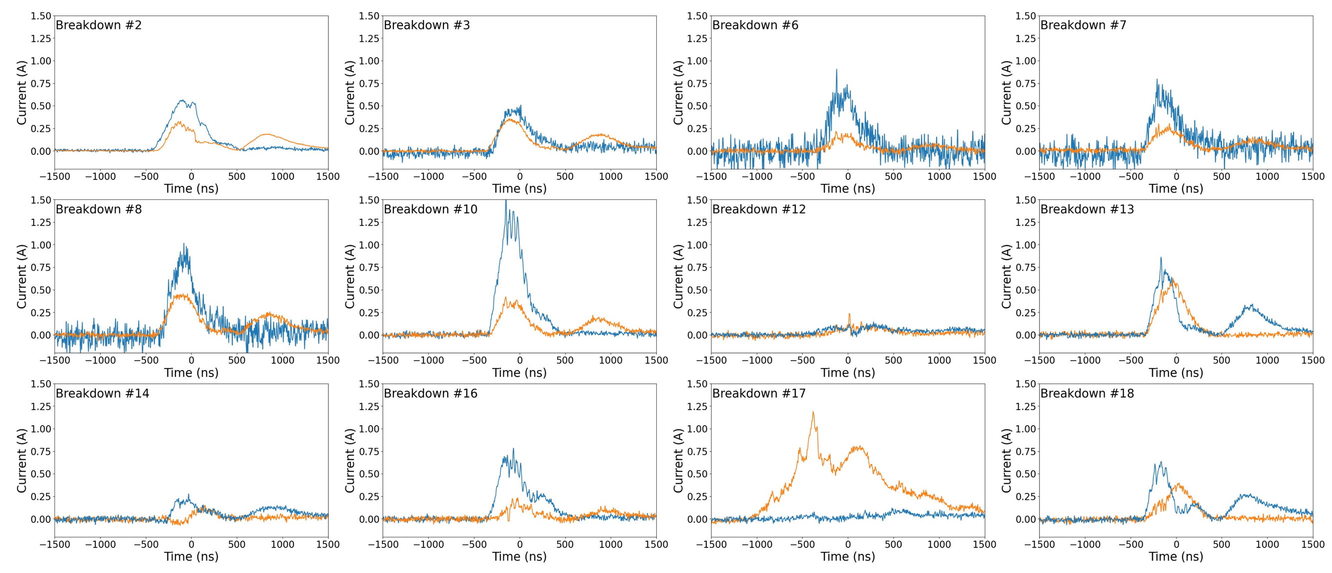


✓ The amplitude of the pick-up signal fell in ~1 μs that is much faster than the cavity filling time (8 μs).



Oscilloscope snapshot (breakdown #13)

❑ Current monitor



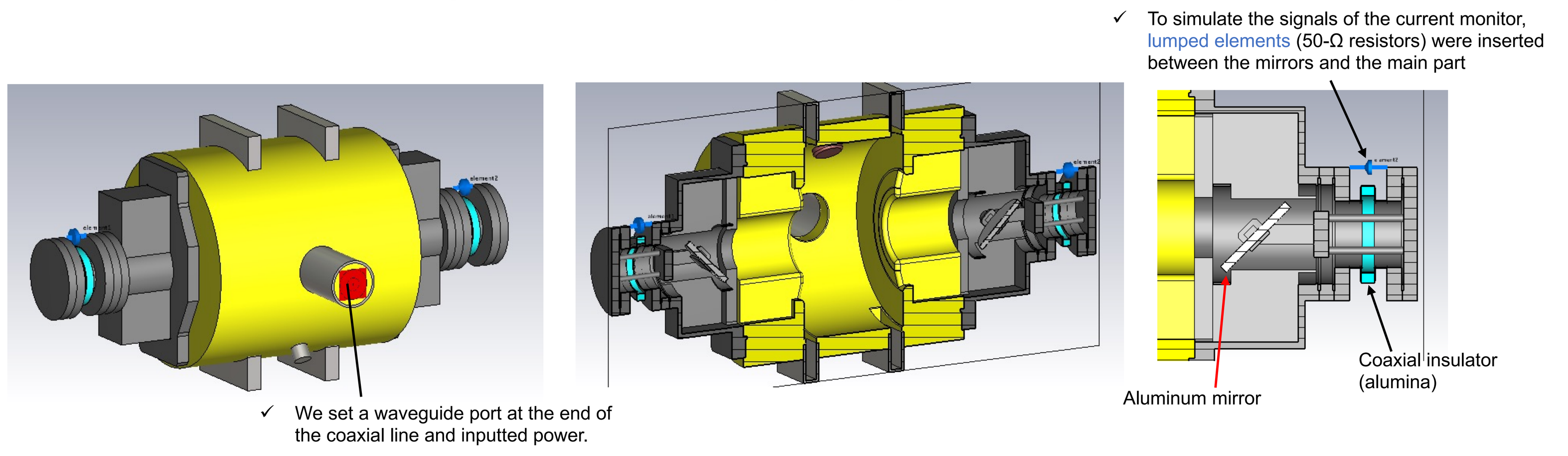
- The output voltages from the current monitors were converted to currents using the sensitivity of 0.05 V/A (for 50-Ω termination).
- The raw data with sampling rate of 5 GHz were filtered by a digital low pass filter (fc = 100 MHz).

3. PIC Simulation

- We tried to reproduce the measurement results with the Particle-in-Cell (PIC) simulation (CST Particle Studio was used).

Simulation setup

1. We input CW RF power (509 MHz) into the cavity through the coupler to excite the accelerating field.
2. After waiting for the accelerating field to become in a steady state, we emitted electrons and copper ions (Cu^+) from an end plate.
   - ✓ The emitted current is assumed to have a Gaussian form in time.
   - ✓ The initial energy distribution of emitted particles is assumed to obey the Maxwell-Boltzmann distribution.
3. The currents of electrons colliding with the mirrors and the pick-up signals are simulated.



Simulation model of the cavity

Power consumed by plasma creation

- The process of plasma creation by a fireball is not known clearly.
- The energy of the RF field would be used by plasma creation.
- To take into account the power consumed by plasma creation, we added a signal for damping the RF voltage (damping signal) to the input signal for the coupler.

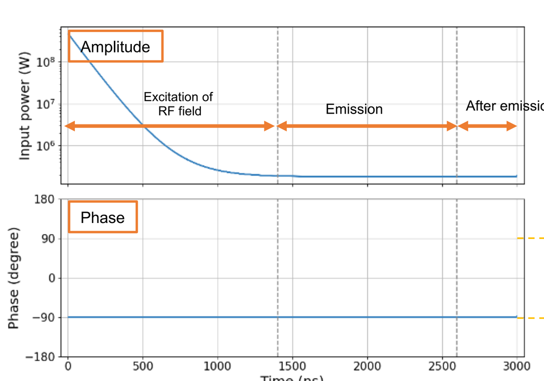
In the steady state,

- Input power: 182 kW
- RF voltage: 1.0 MV
- Stored energy in the EM field: 2.1 J

- To rapidly damp RF field, we fed an additional RF power with a reversed phase.

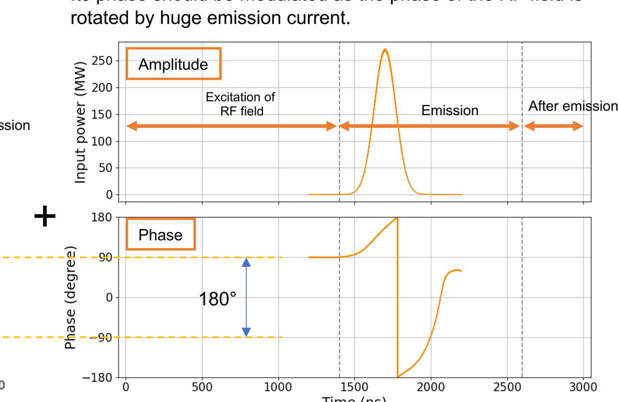
→ The energy consumed by plasma creation was removed from the RF field.

- Its phase should be modulated as the phase of the RF field is rotated by huge emission current.



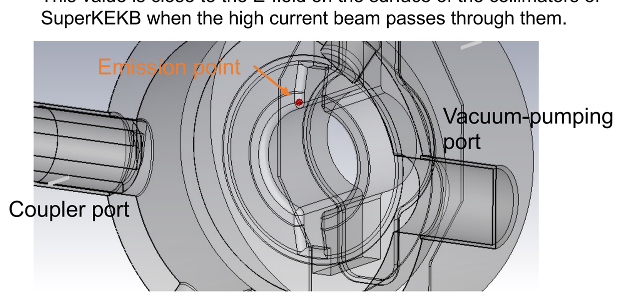
RF power into the input coupler

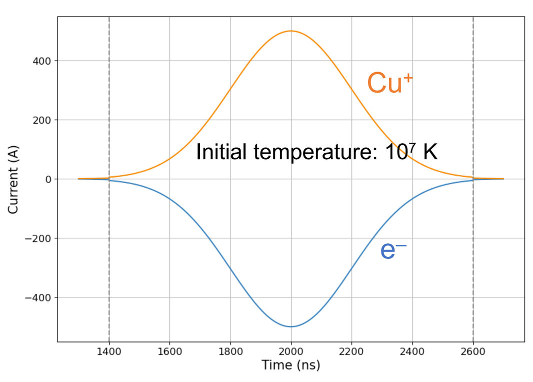
+



Damping signal input to the cavity with a reversed phase

- The E-field at the emission point is ~10 MV/m before the emission.
- This value is close to the E-field on the surface of the collimators of SuperKEKB when the high current beam passes through them.



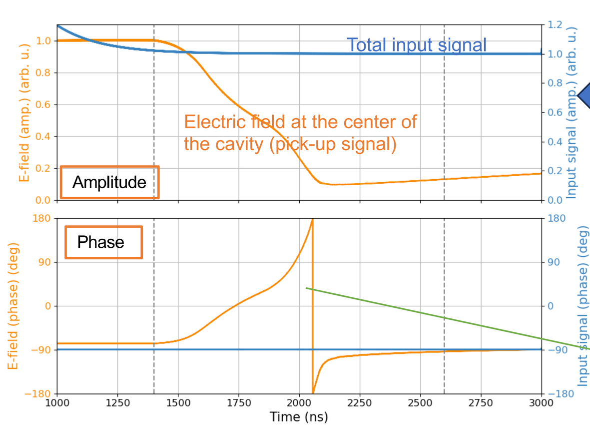


Setting of the emitted current

Simulation results

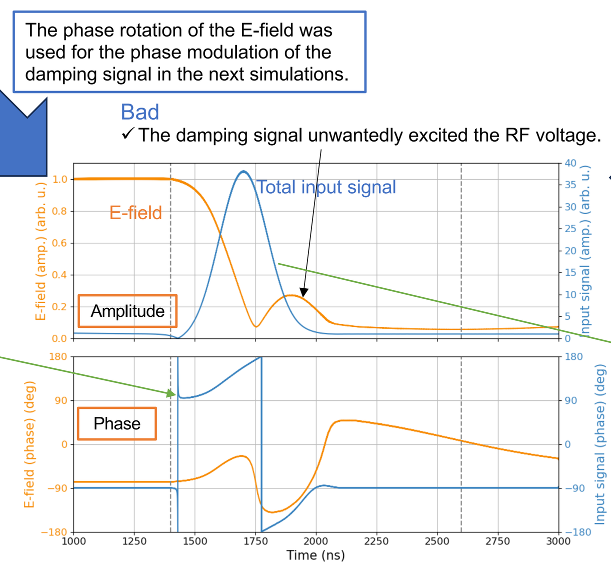
❑ Iterations for the optimization of the damping signal

- To damp the RF field effectively by the damping signal, we have to modulate its phase as the phase of the RF field is rotated by the emission of the particles.
- We need several iterations of simulations for optimizing the damping signal.



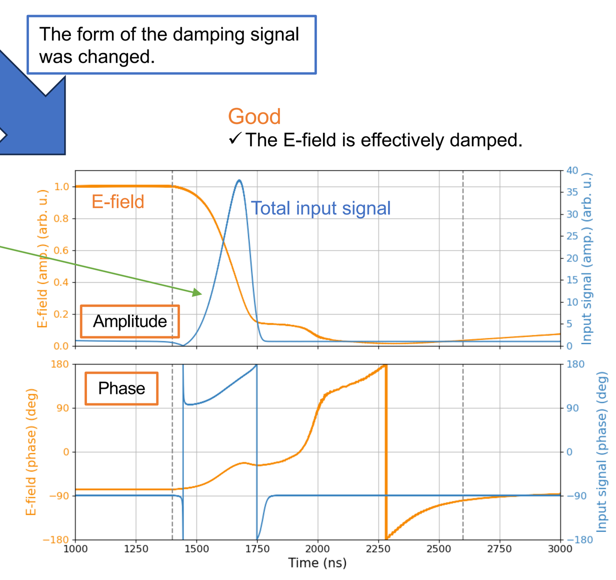
First simulation (without damping signal)

The phase rotation of the E-field was used for the phase modulation of the damping signal in the next simulations.



Second simulation (with damping signal ver.1)

The form of the damping signal was changed.



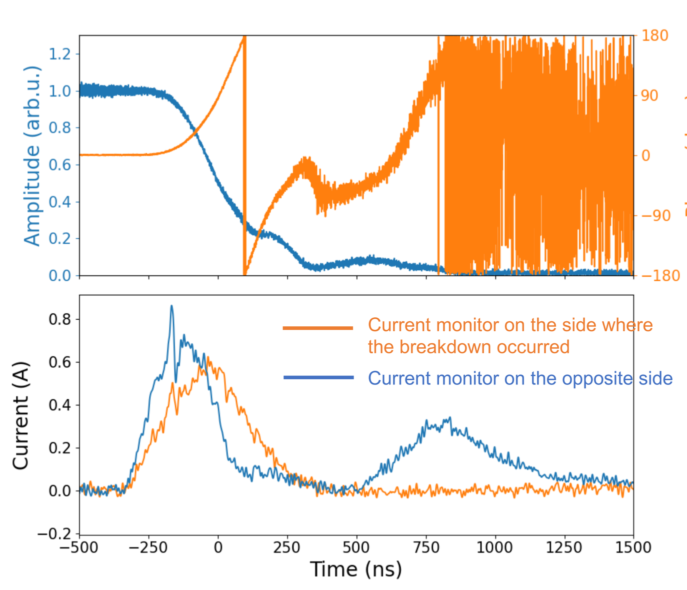
Third simulation (with damping signal ver.2)

Comparison with the measurement results

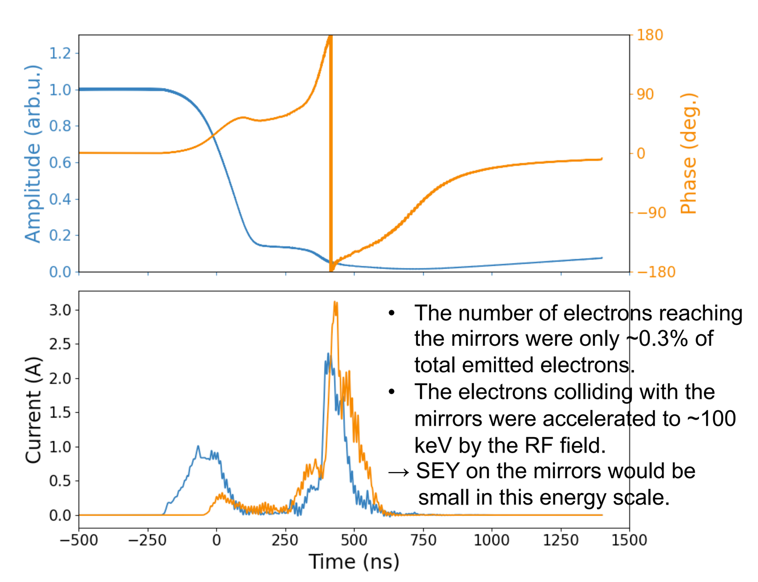
- ✓ The simulated waveforms of the pick-up signal and the current were similar to the experimental results.

Pick-up signal

Current monitor



Measurement (Breakdown #13)



Third simulation

- The number of electrons reaching the mirrors were only ~0.3% of total emitted electrons.
- The electrons colliding with the mirrors were accelerated to ~100 keV by the RF field.

→ SEY on the mirrors would be small in this energy scale.

4. Summary and future plan

- We have observed 18 breakdown phenamena and measured the emitted current of the discharges and the pick-up signals from the cavity at the moments of breakdowns.
- The initial PIC study showed similar results to the measurements.
  - ✓ Total emitted current will be deduced by further PIC simulations.
- More detailed simulations are essential:
  - ✓ Initial temperature of the emitted particles
  - ✓ Emission time span
  - ✓ Shape of the damping signal

Reference

[1] T. Abe, et al., Phys. Rev. Accel. Beams **21**, 122002 (2018).
[2] T. Abe, this workshop.
[3] M. Aversano, in Presentation of skb-itf-sbl meeting, June 30, 2023.
[4] T. Ishibashi, et al., Phys. Rev. Accel. Beams **23**, 053501 (2020).