Operation Experience at CAFe

Institute of Modern Physics, CAS

Yuan HE, Teng TAN, Andong WU, Feng QIU, Shenghu ZHANG, Tiancai JIANG, Shichun HUANG, Ziqin YANG, Zheng GAO, Huan JIA, etc.

Supported by SPRP CAS and NSF

Outlines

Introduction

1. Evolution of CAFe
2. Machine Upgrade since SRF'19
3. Recent 100^2 beam commission: 100 kW for 100 h and nominal testing

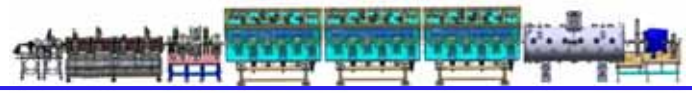
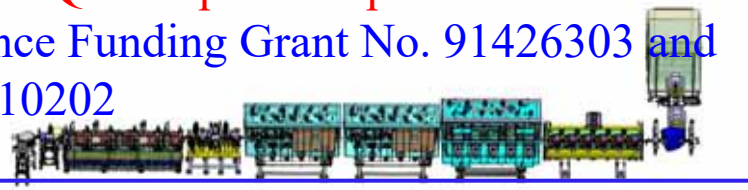
Technical Advances

1. SRF trips and mitigation during high power beam
2. Dirty operation and Surface processing history
3. High power beam dump experience

Towards CiADS

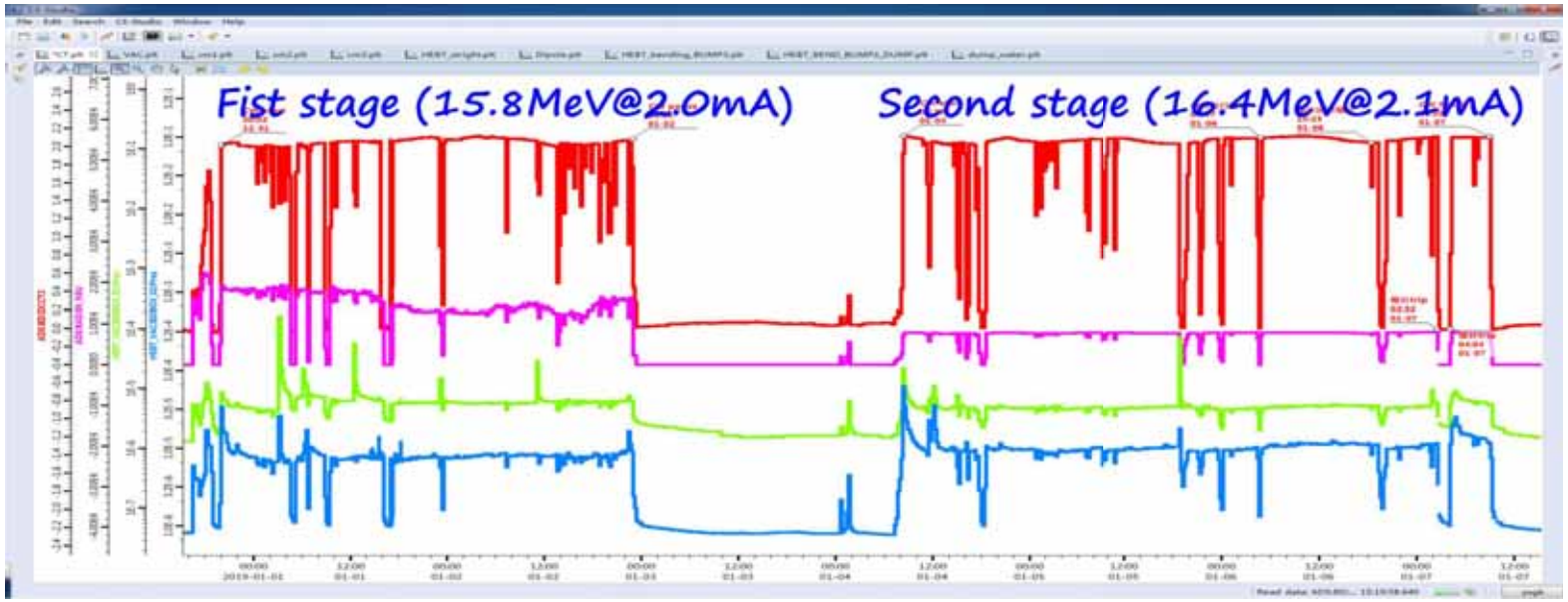
1. CiADS timeline and new challenge.
2. New cavity structures and materials.
3. Conclusion and outlook.

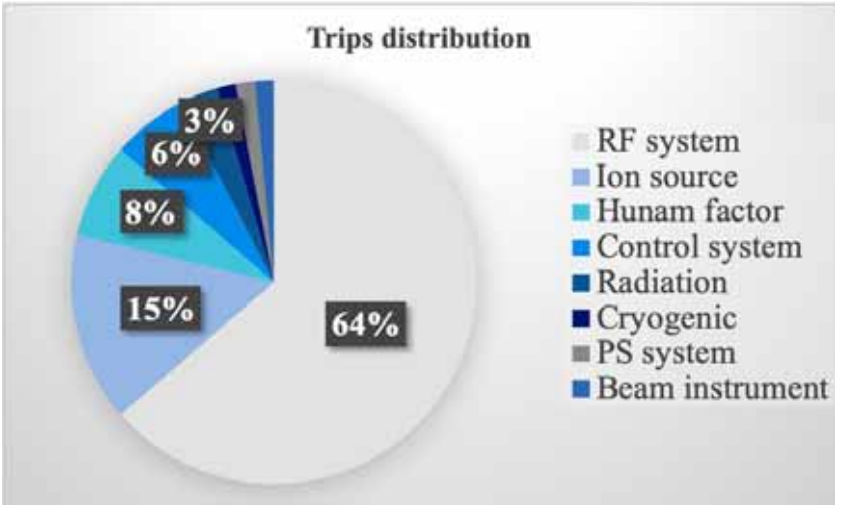
Evolution of CAFe to CAFE2

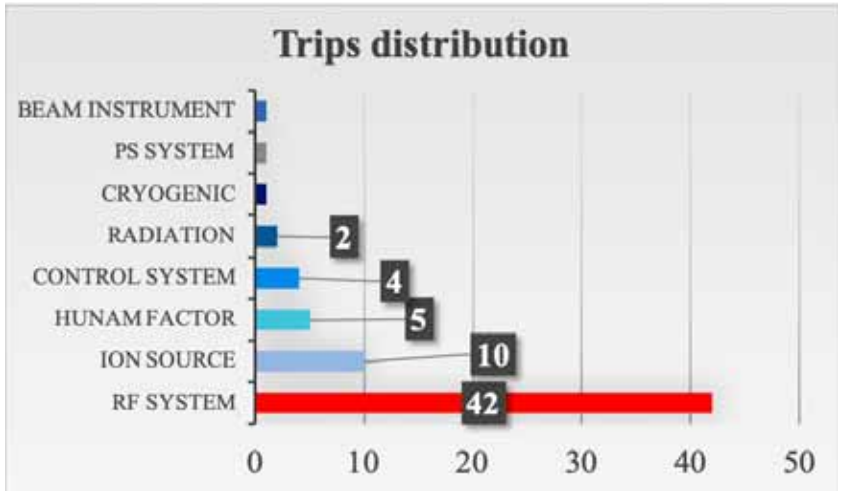
1	2011~2017, CAFe: China ADS Front-end Supported by Strategic Priority Research Program of CAS(SPRP) Grant No. XDA03020000 	June 6-7 2017, completed. 25 MeV, 0.17mA, around 10 min, CW, P; collaborated with IHEP
2	2017~2019, install a new RFQ for alpha to replace the old for P Supported by Nature Science Funding Grant No. 91426303 and SPRP Grant No. XDA21010202 	Dec. 31 2018 – Jan. 7 2019, achieved 16.1 MeV, 2.1 mA, 100 hours, CW, Proton
3	2019~2021, replace the spoke CM with a HWR CM Supported by Nature Science Funding Grant No. 11525523, SPRP Grant No. XDA21010202 and IMP 	Mar. , 2021, achieved nominal specification, CW 20 MeV, 10 mA, 200kW, Proton; 17.3 MeV, 7.2 mA, 127kW, 108 hrs; and 10 mA, 174 kW, 12 hrs.
4	2021~future, CAFE2: China Accelerator Facility for nEw Elements Replace the front-end and MEBT, install a recoil spectrum Supported by SPRP Grant No. XDB34010000 and IMP 	Facility for SHE and material irradiation Complete construction. Ca ~ Zn, A/q < 3, 5~15 puA , 4.5~7 MeV/u First experiment in September 2021

High Power Test in 2019

- Operation time 129.2 hours, downtime 12.3 hours, availability ~89%
- Trips is 66 and 64% due to RF system, mostly LLRF.
- Max power is 45 kW with 2.55 mA @17.5 MeV







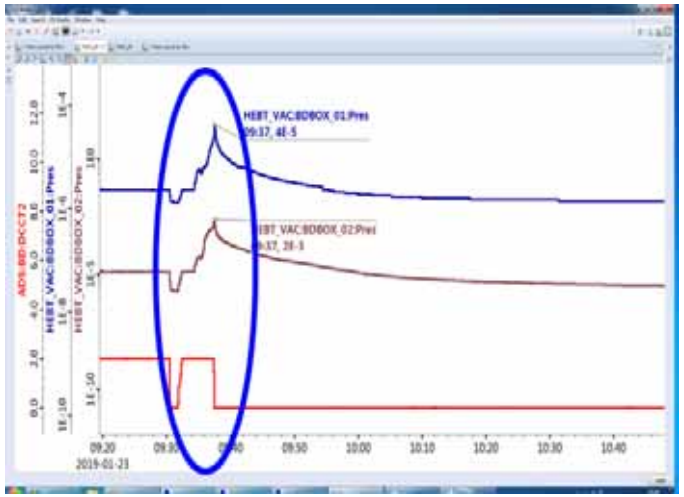
- 1st stage: 2018/12/31 18:44 - 2019/01/02 23:42

Availability	MTBF	MTTR
0.89	90.7 min	11.1 min

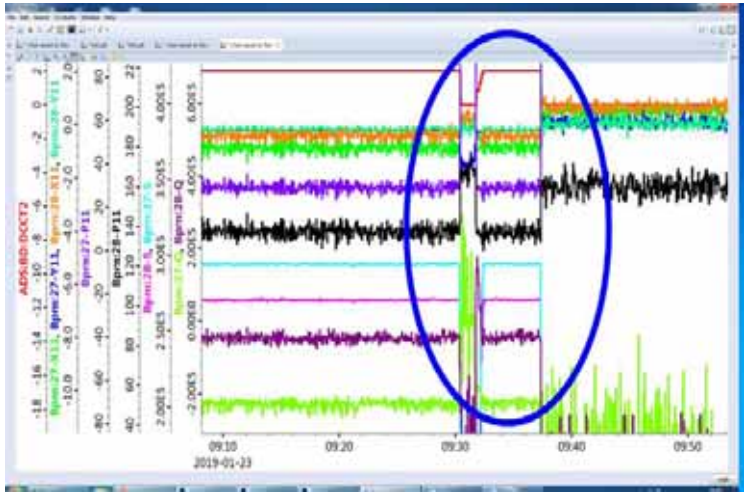
- 2nd stage: 2019/01/04 08:08 - 01/07 09:03

Availability	MTBF	MTTR
0.89	113.7 min	14.6 min

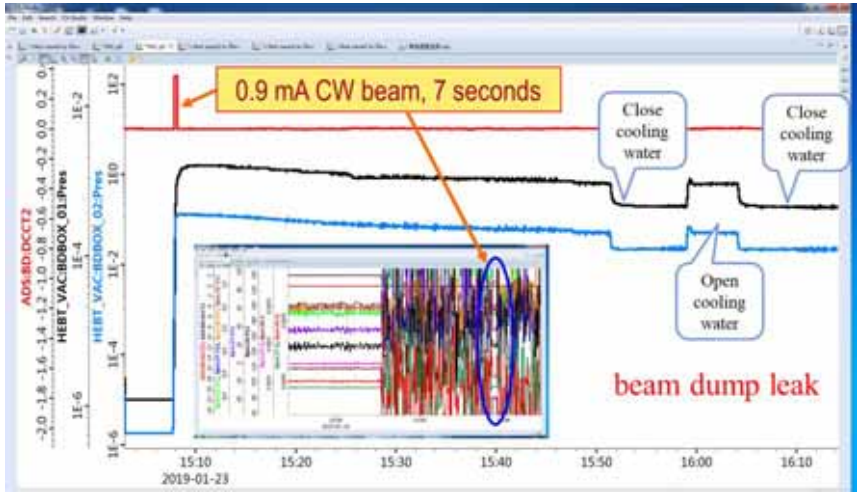
Accident of Dump Damage



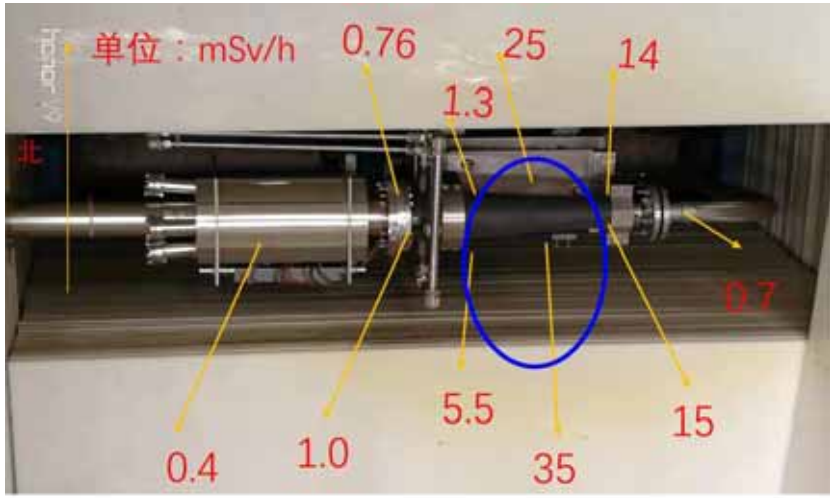
First VAC rising at HEBT stops the beam at 9:30



BPMs along the acc, w/o jump before and after the trip



BPMs along the acc were normal during 7 seconds; VAC shows the leak



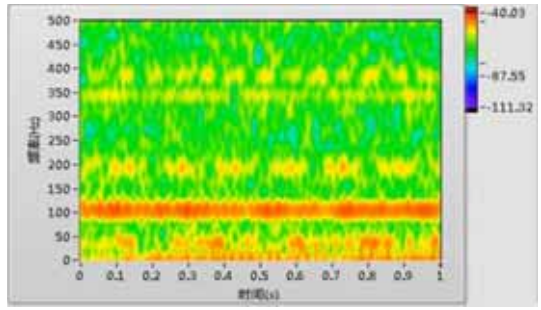
One year after accident, Dose near the dump

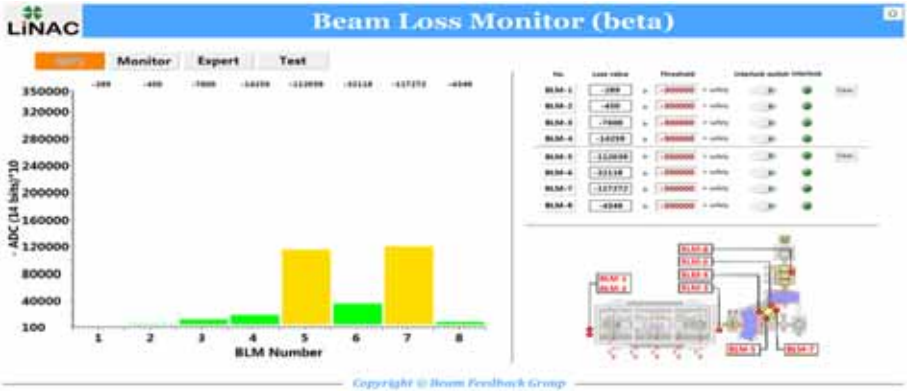
inside of the dump facing beam

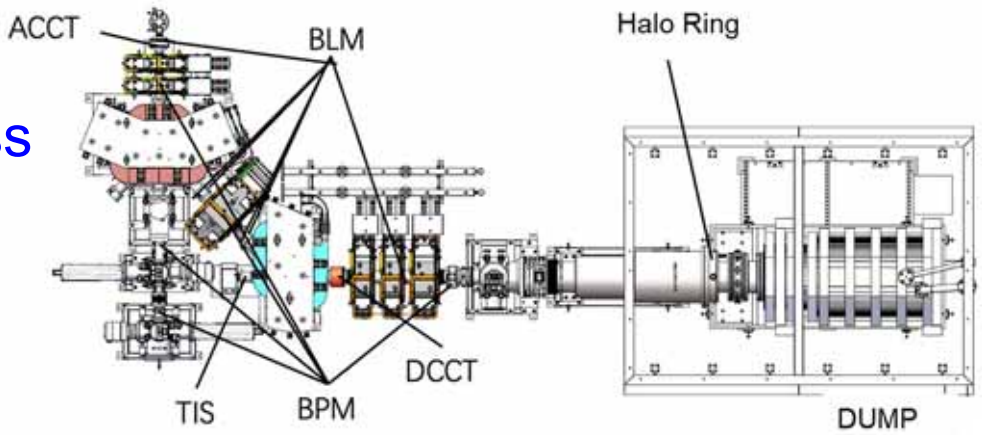
damaged inner suface

Upgrade since 2019

- Improve the Stability of SRF cavities
  - New digital low-level RF system with adaptive learning FF and FB
  - Independent monitor system for phase and amplitude
  - Mitigating Microphonics and pondermotive
  - Flashover trip
- Construct a New HEBT and a New Dump
  - Enlarge the aperture of HEBT
  - New aluminum dump for nominal 120 kW
  - Beam loss detector and Image system
- Improve MPS and RRS
  - Machine Protection System base on beam loss
  - Rapid Recovery System base on Timing
- Replace the Spoke CM with a HWR CM
  - Prepare for the acceleration of heavy ion



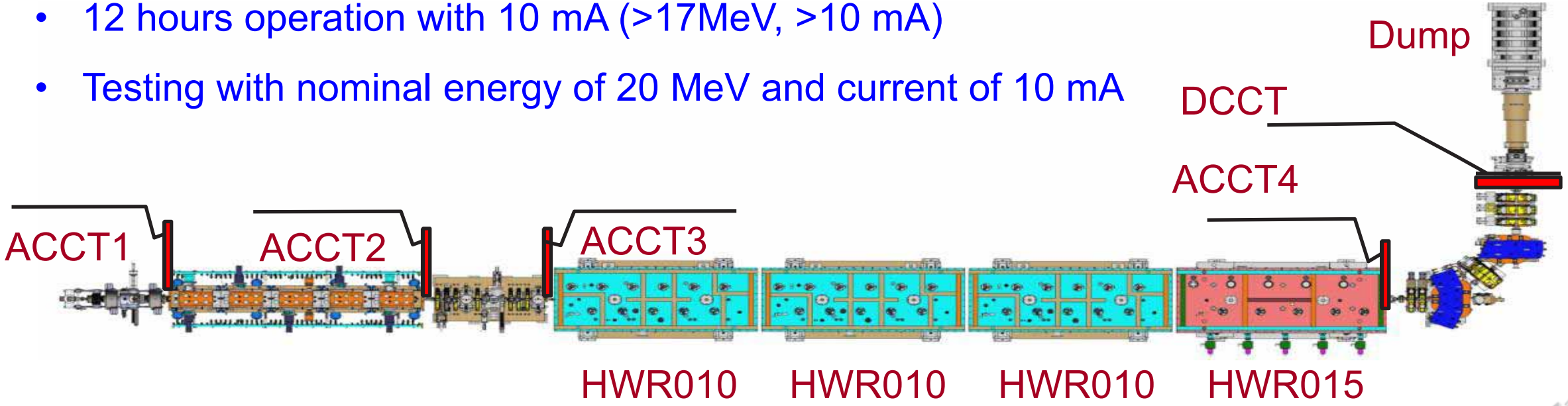




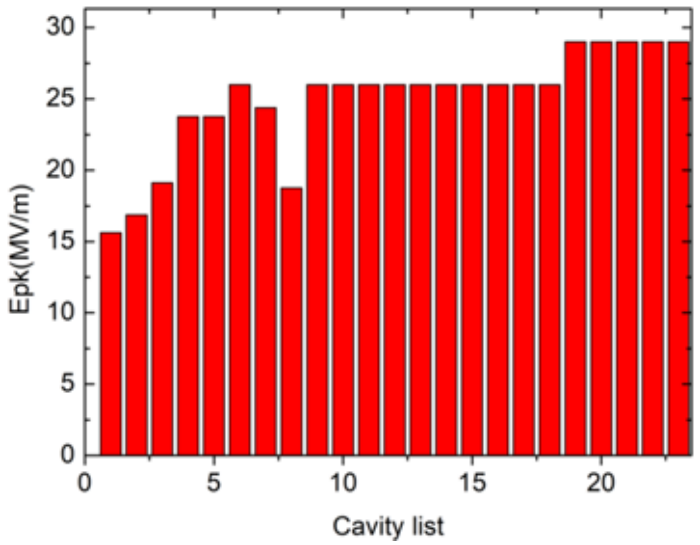
High Power Test Campaign in 2021

Goal of Commissioning Campaign

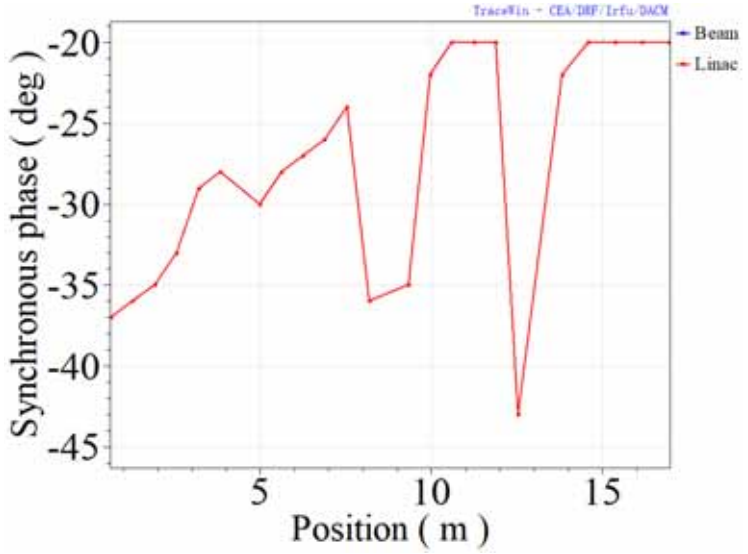
- 100 hours operation with more than 100 kW (>17MeV, >5mA) beam power
- 12 hours operation with 10 mA (>17MeV, >10 mA)
- Testing with nominal energy of 20 MeV and current of 10 mA



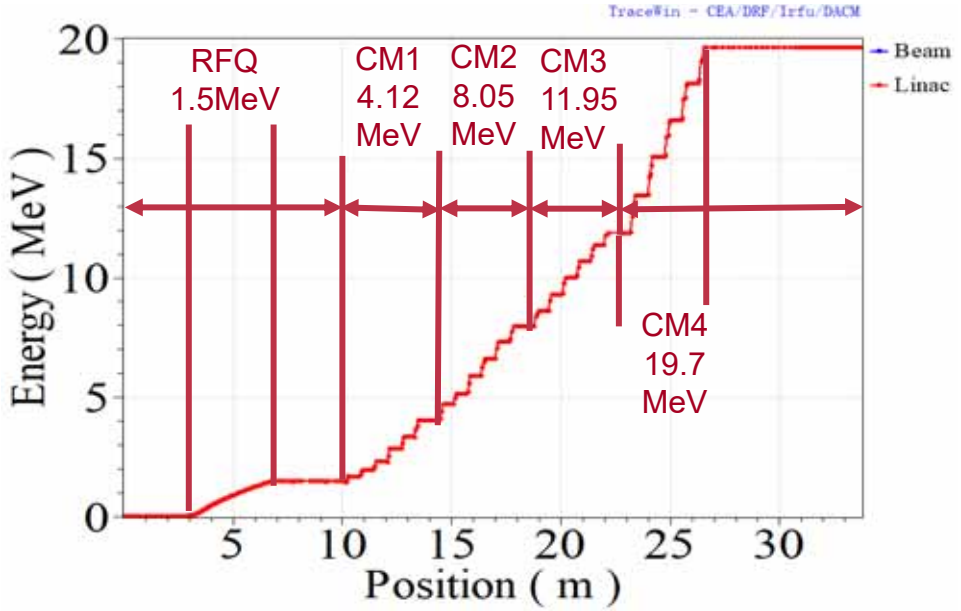
Nominal Design of new CAFE



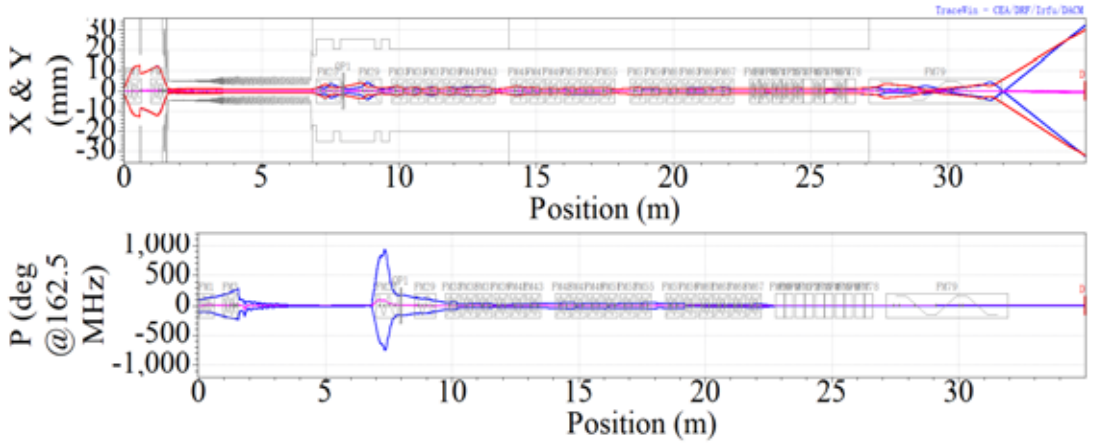
Nominal Epk of the 23 HWR resonators



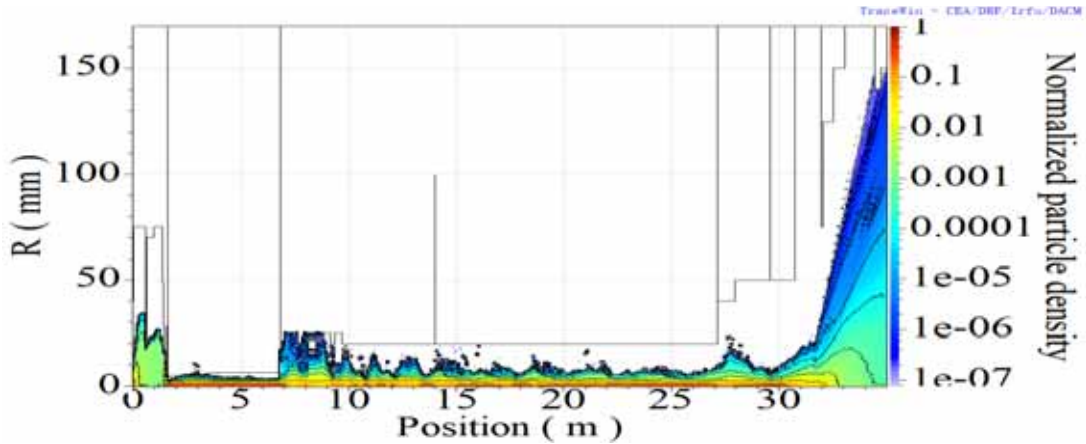
The synchronous phase



The energy along the linac



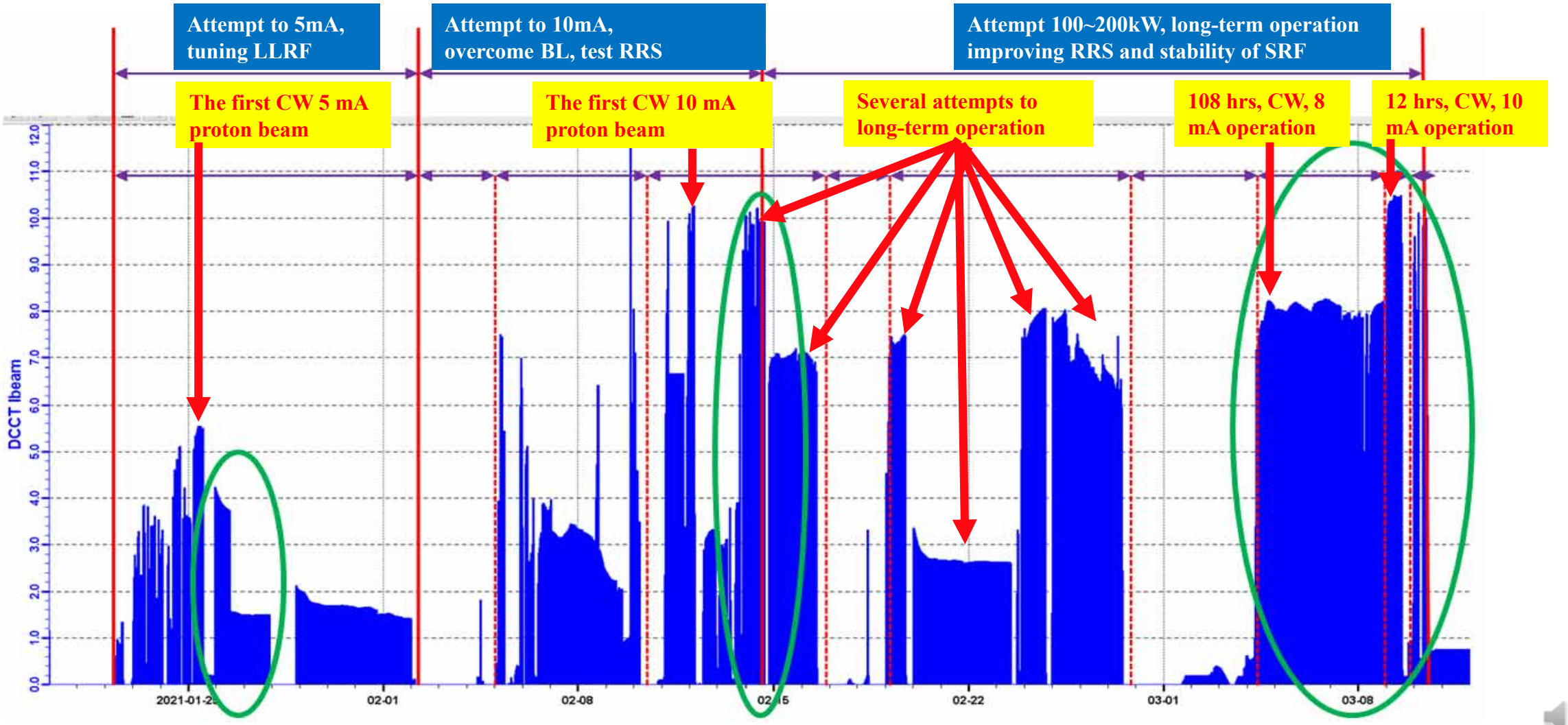
envelope along the linac



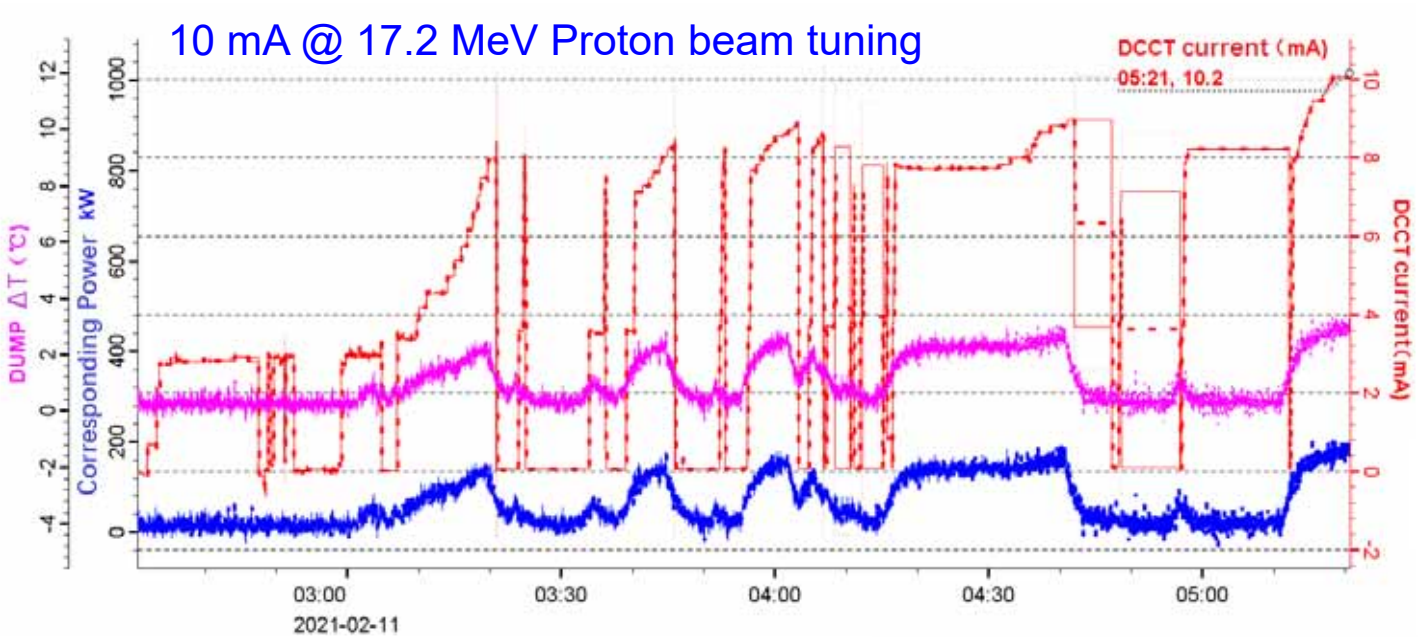
transversal beam density

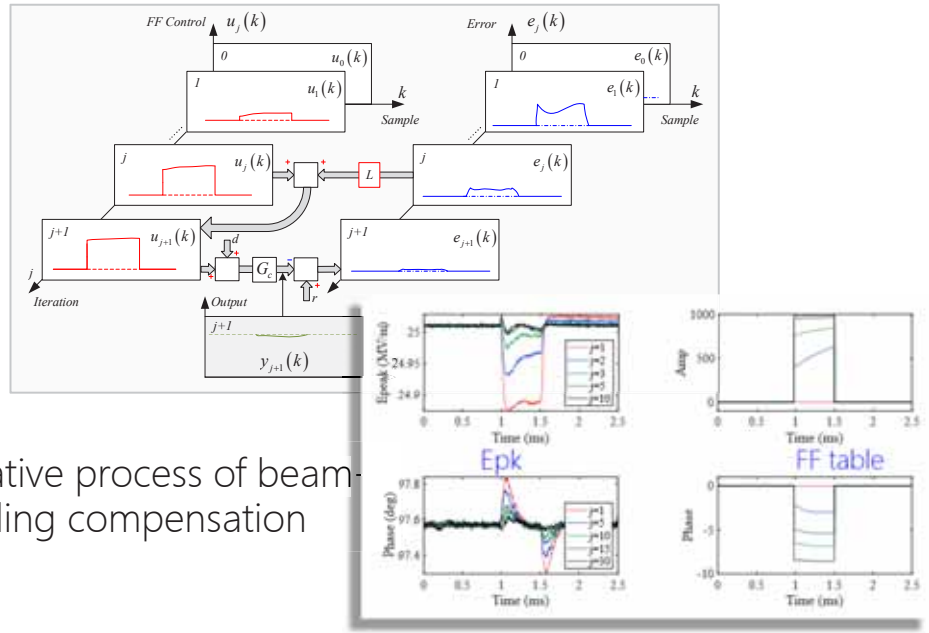
High Power Test Campaign in 2021

- **Operation from Jan. 20 to Mar. 10, 2021**

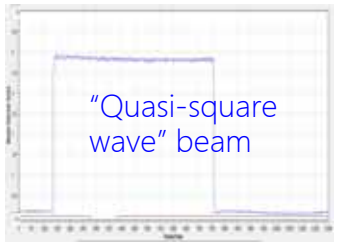


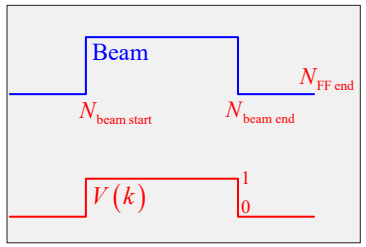
First attempt to CW 10 mA



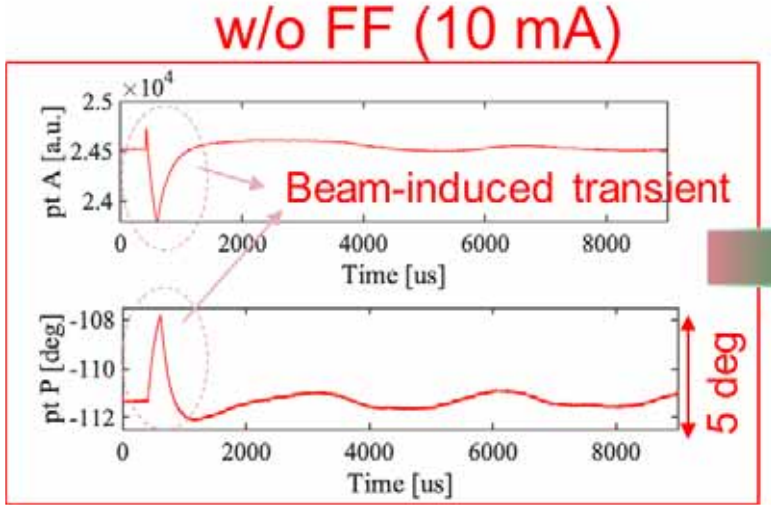


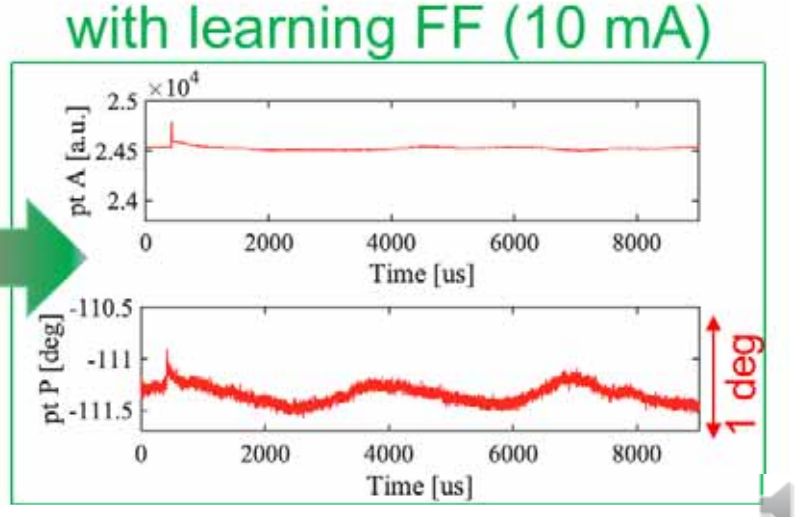
Iterative process of beam-loading compensation





- High Beam-loading issue is one of the main challenge
- A simplified iterative learning control method (with square shape FF) was successfully applied to compensate for the beam-loading effects.





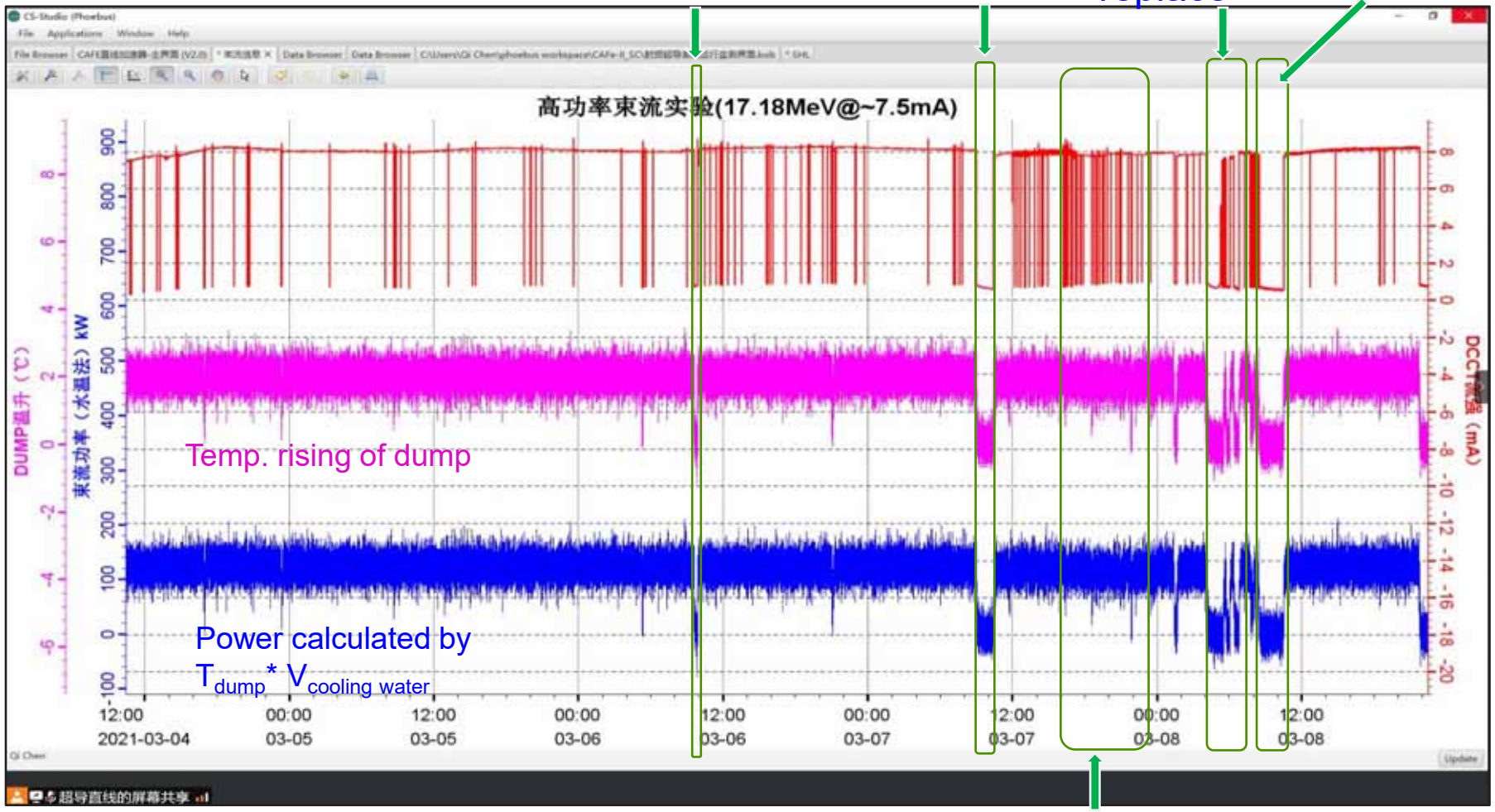
Historical Data of 108 hours @ 120 kW

PS failure
EMC

LLRF failure
Chassis PS

Pump failure
Near dump
replace

Timing system PC
failure, unknown reason



IS arcs, maybe mistake of MPS and RRS Logic

Energy	17.27±0.03MeV
Current	7.30±0.02mA
Beam power	126.0kW
Pre-set operation time	108 hours
Availability	93.5%
Availability of SRF	98.0%

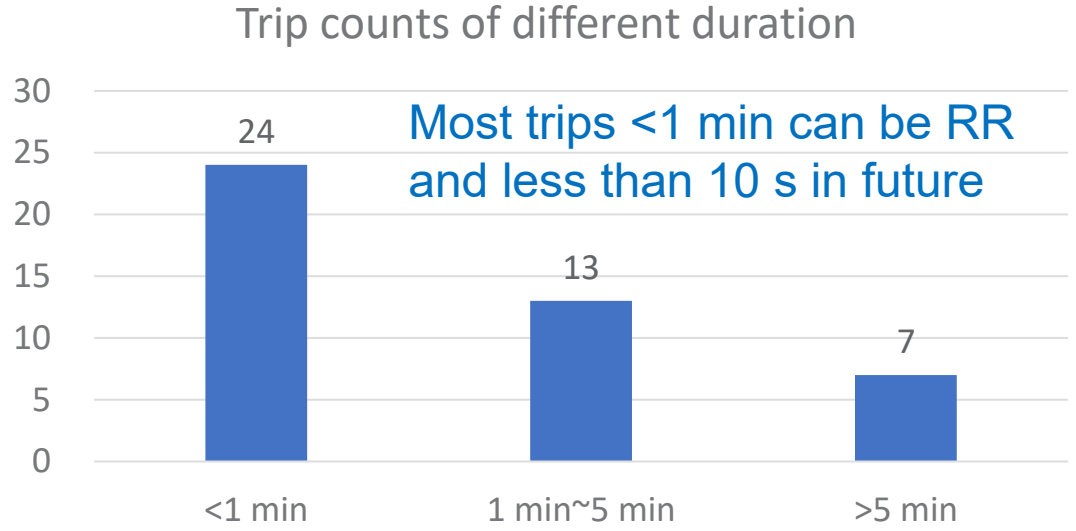
RAMI Analysis

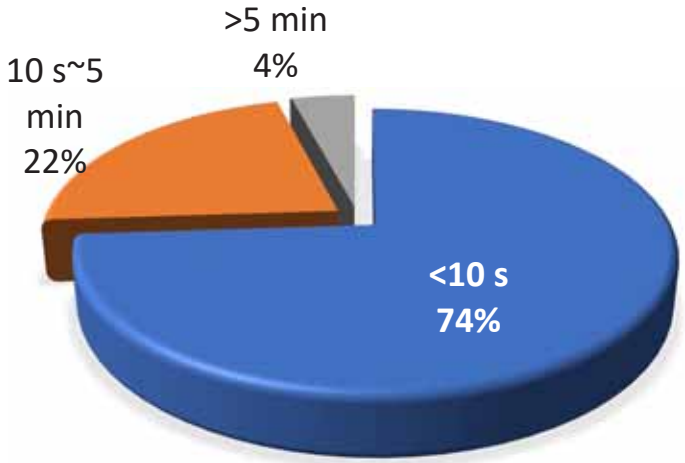
Operation Period：

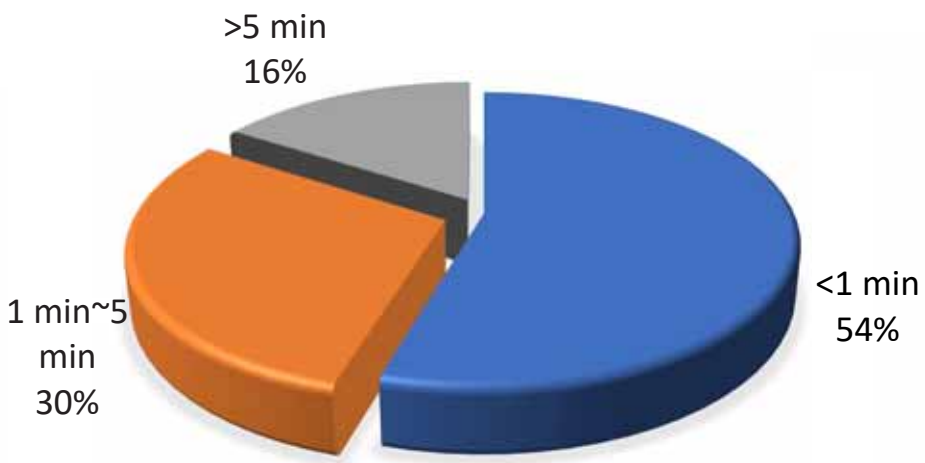
9:42, Mar. 4, 2021 ~21:43, Mar. 8, 2021;

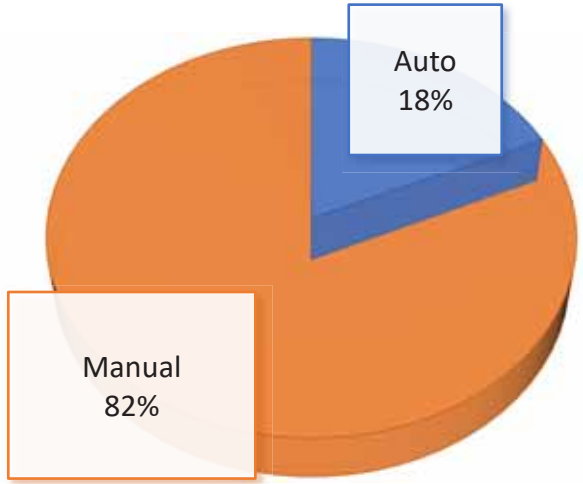
Data：

Operation time:	108 hrs (pre-set by the reviewers)
Downtime：	6.85 hrs
Availability：	93.6%
MTTF:	9.3 min (12.1 at the first 72 hrs)
MTBF:	135 min (382 at the first 72 hrs)







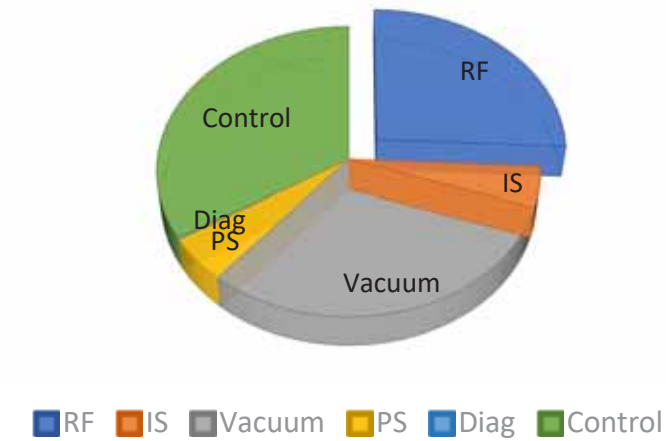


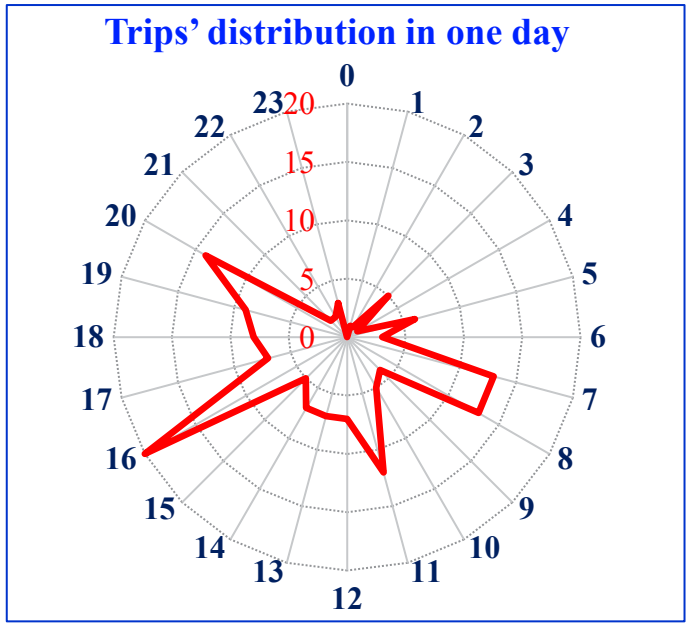
All trips <10s are Rapid recovered, not court.

Trips' Distributions

TRIP COUNTS RATIO OF DIFFERENT SYSTEMS

TRIP TIME RATIO OF DIFFERENT SYSTEMS





- RF, IS and Ctrl are the main trips' sources
- But the Vac. and ctrl. took max downtime
- Almost all trips occurred from 7 am to 8 pm

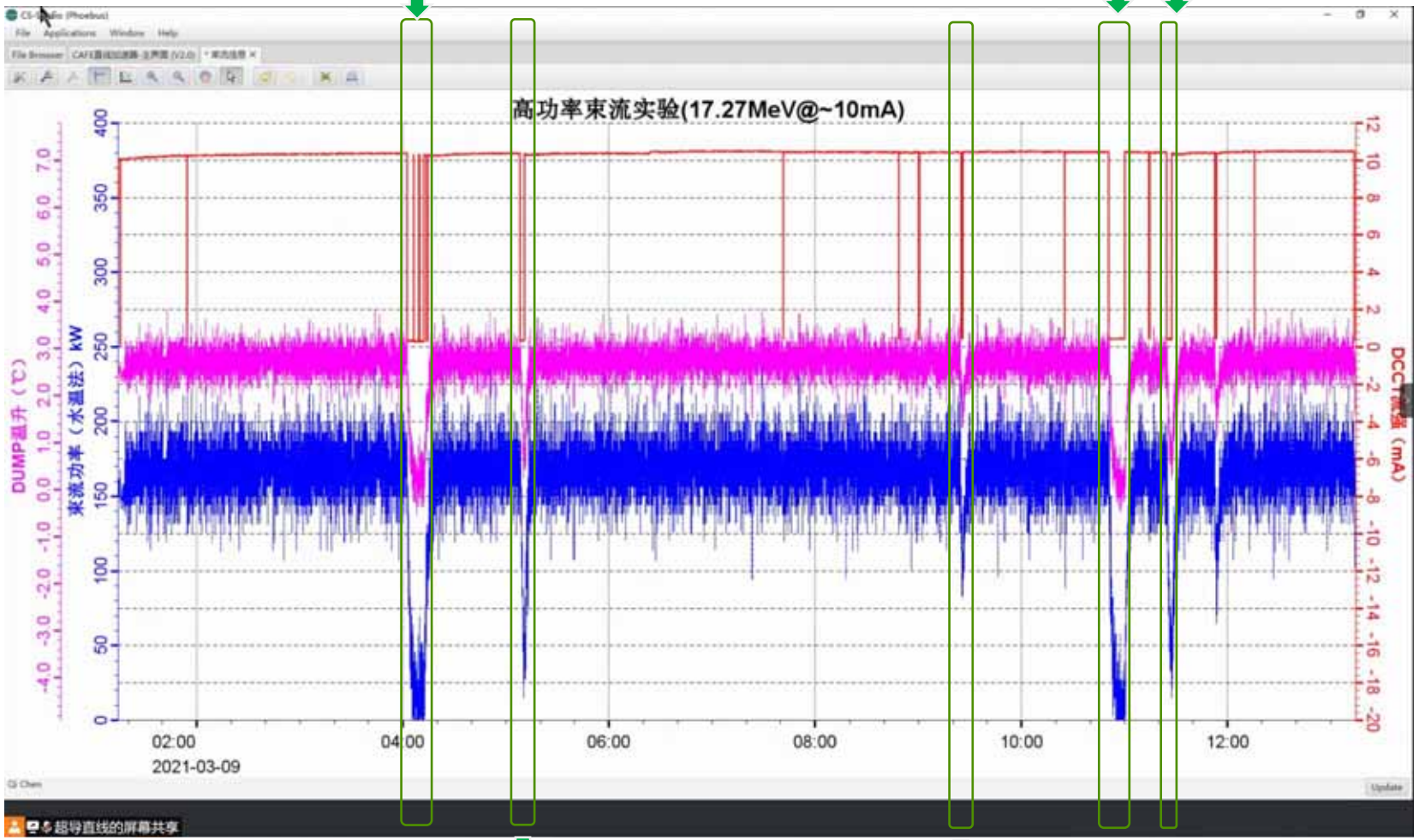
Trip sources	Downtime (s)		Trips		Avg time (s)
RF	6360	26%	18	41%	353
Cryo.	0	0%	0	0%	0
IS	1103	4%	8	18%	138
Vac.	7598	31%	3	7%	2533
Mag.	0	0%	0	0%	0
PS	1244	5%	2	5%	622
Diag.	35	0%	1	2%	35
Ctrl.	8317	34%	12	27%	693

12-hrs 10-mA Operation Test

RFQ waveguide temp. alarm

PS

Arc, R manually

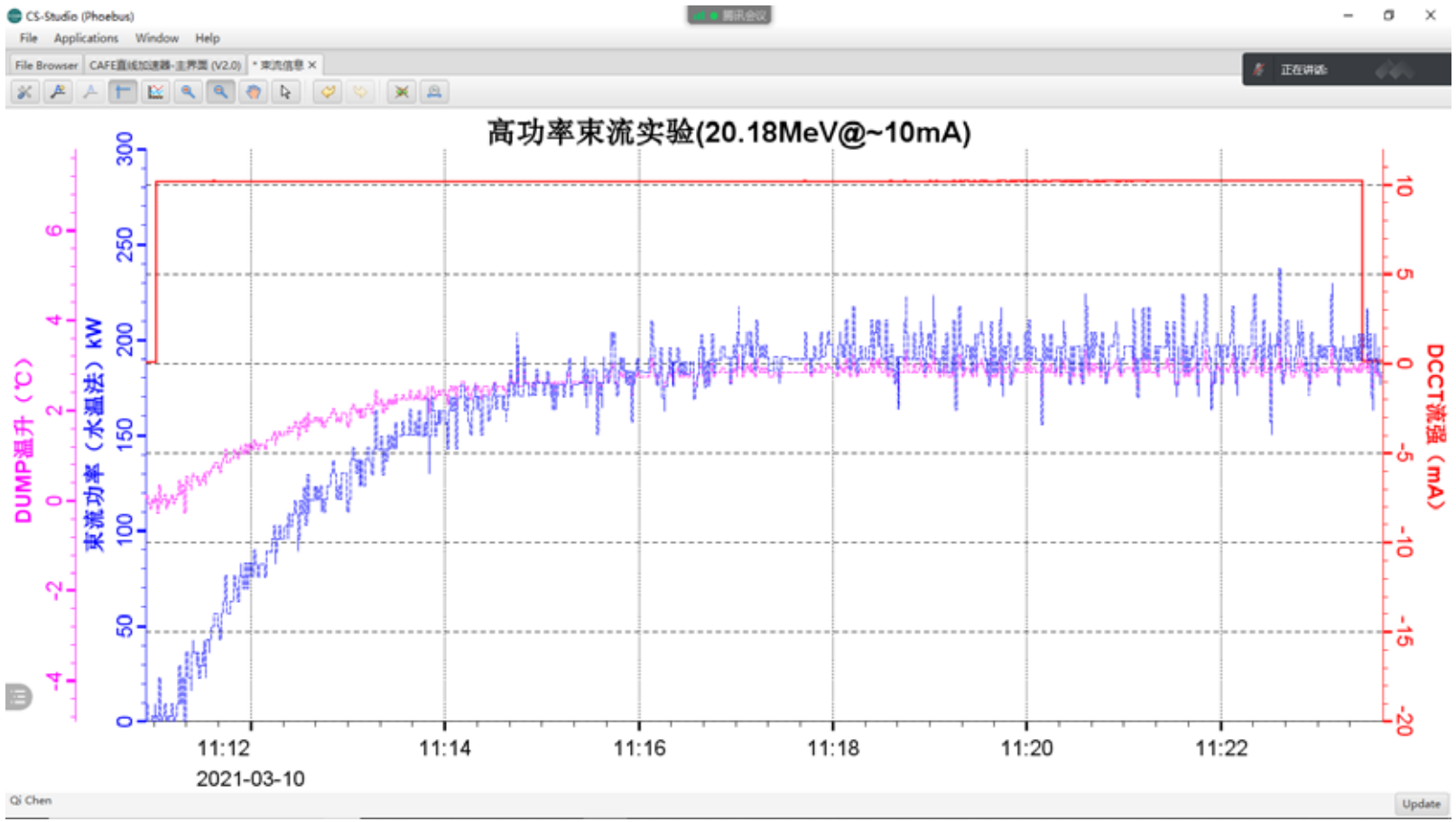


CM2-1 coupler Vac.

IS arc, R manually.

Energy	17.27±0.03 MeV
Current	10.08±0.00 mA
Beam power	174.0 kW
Pre-set operation time	12 hours
Availability of SRF	99.6%
Availability of whole system	96.2%

Nominal Current & Energy Test



Item	Parameter
Beam E	20.18 MeV
Ave. Beam	10.2mA
Max. Beam Power	205.5kW
Total Time	12 mins

Outlines

Introduction

1. Evolution of CAFe
2. Machine Upgrade since SRF'19
3. Recent 100^2 beam commission: 100 kW for 100 h and nominal testing

Technical Advances

1. SRF trips and mitigation during high power beam
2. Dirty operation and Surface processing history
3. High power beam dump experience

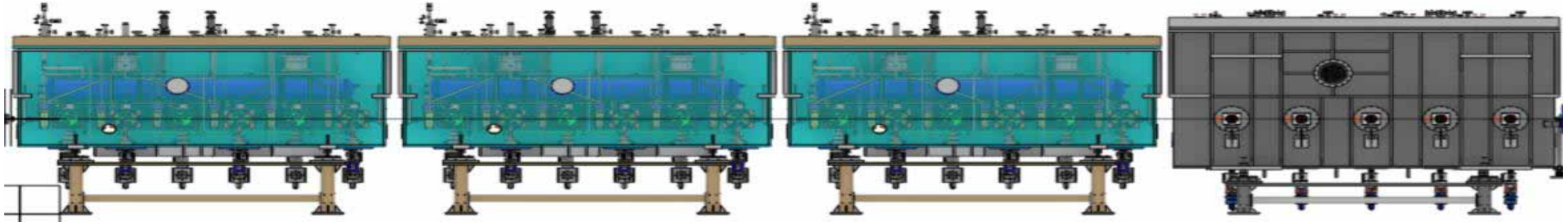
Towards CiADS

1. CiADS timeline and new challenge.
2. New cavity structures and materials.
3. Conclusion and outlook.

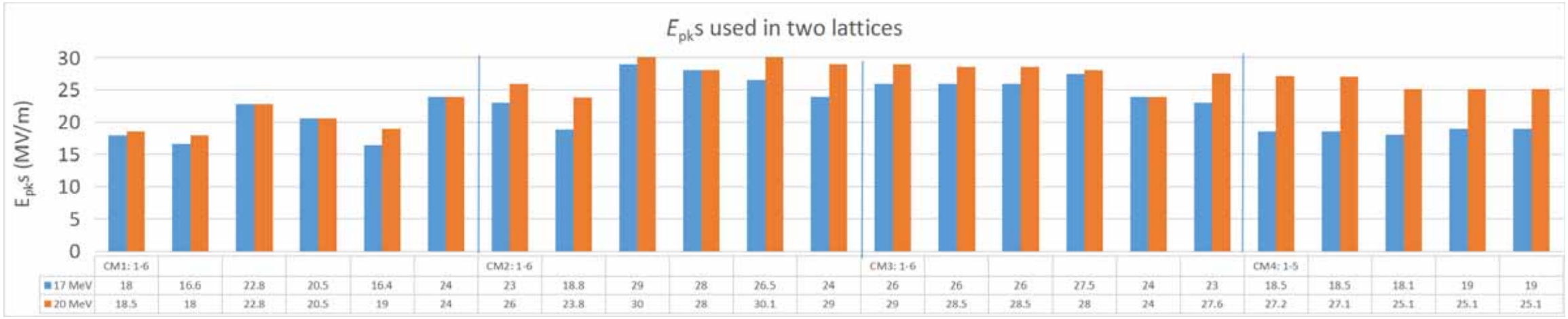
The Reliable Operation

The history of the CMs for the operation

MEBT



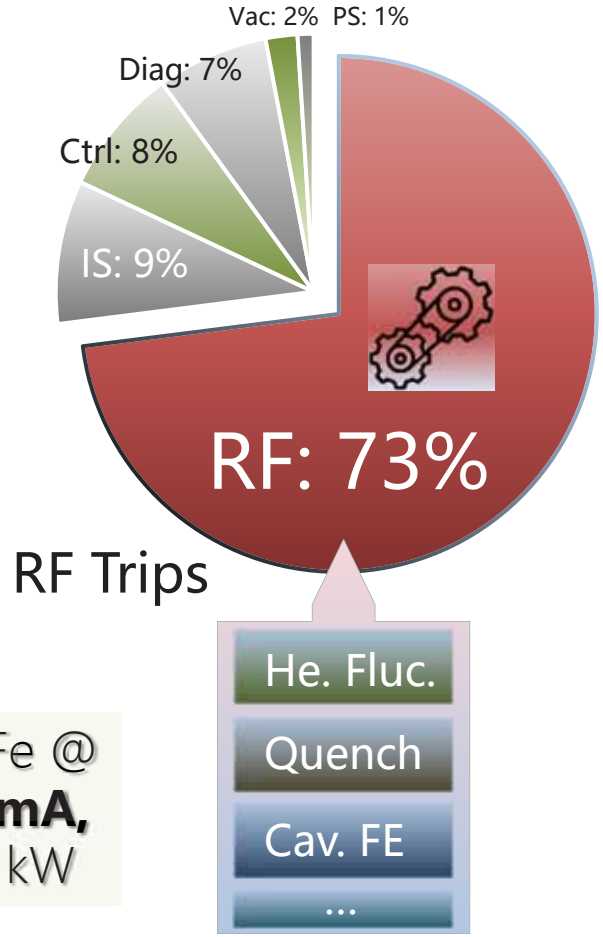
HEBT



	CM1	CM2	CM3	CM4
Cleanroom	2015.3	2018.12	2019.8	2019.10
Online	2015.4 (17.1-18.9 offline)	2019.2	2019.10	2019.11
comments	Online FPC replaced			Vac. leak

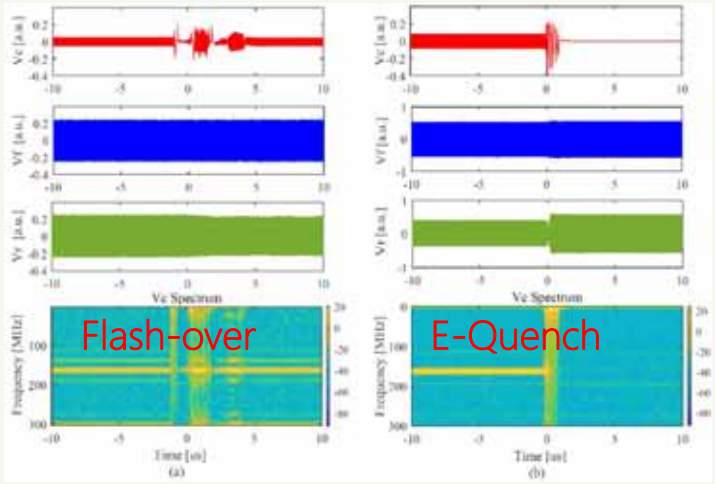
RF trips in CAFe

- RF contributes the main parts of the total trips including <10s

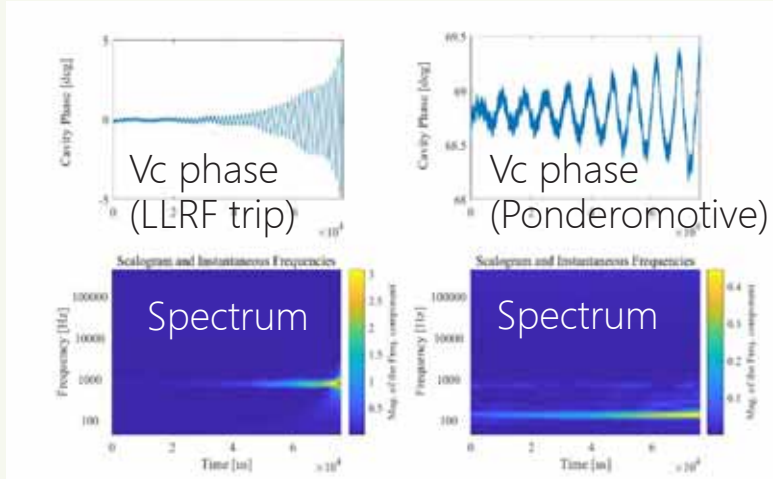


CAFe @ **10 mA,** 174 kW

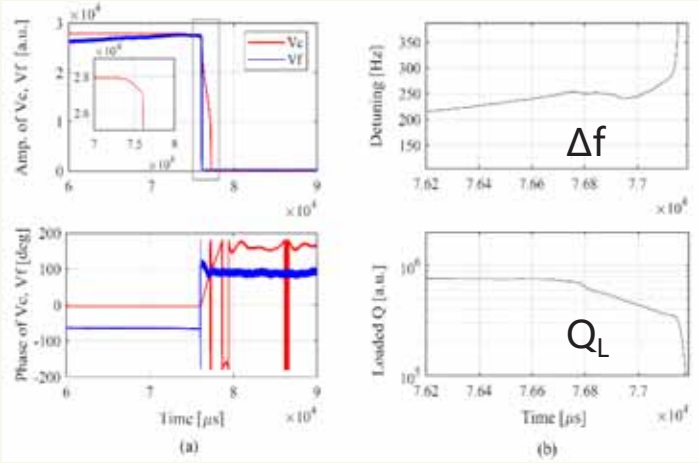
Flash-over & E-Quench



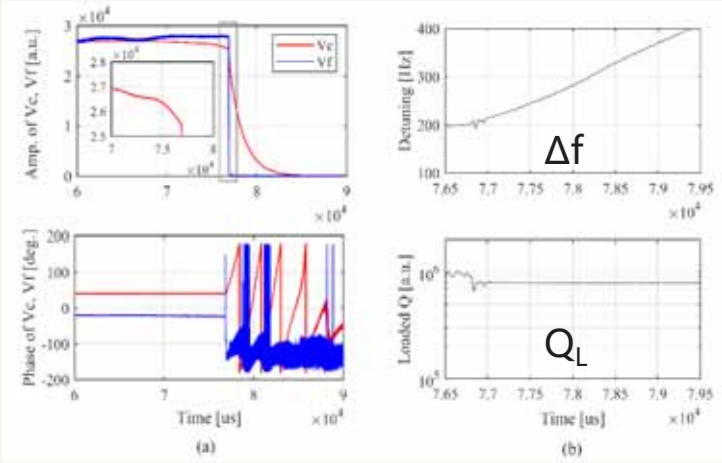
LLRF trip & Ponderomotive



Thermal-Quench

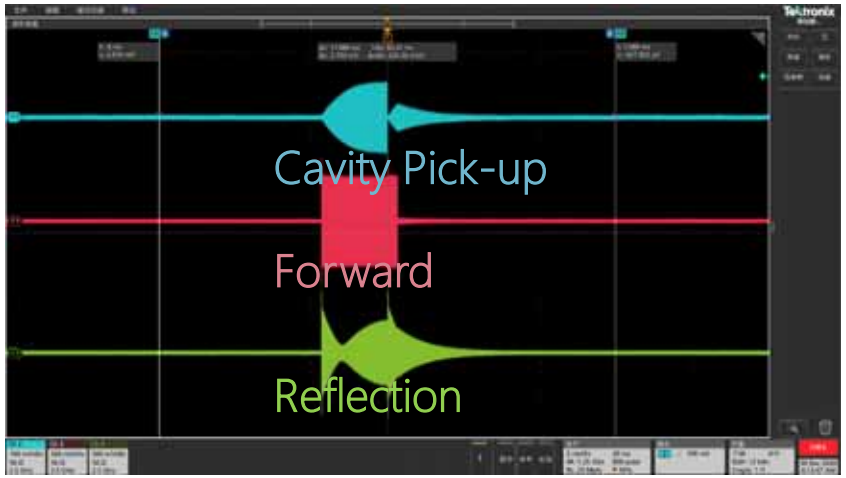


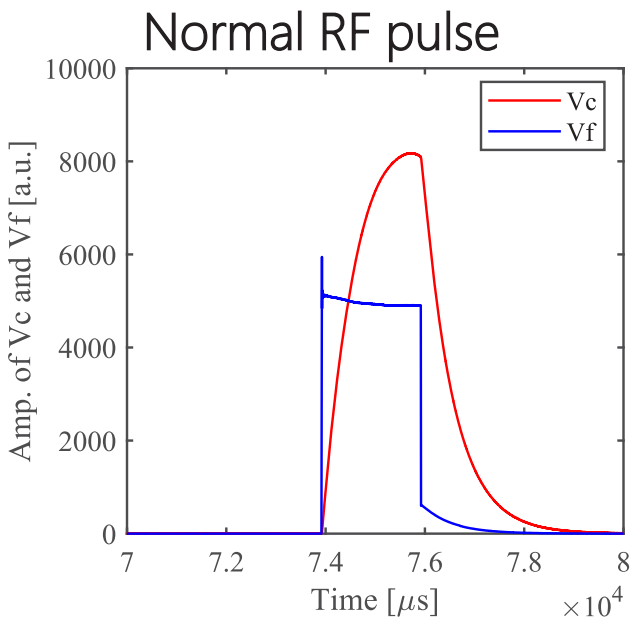
He. Fluc.

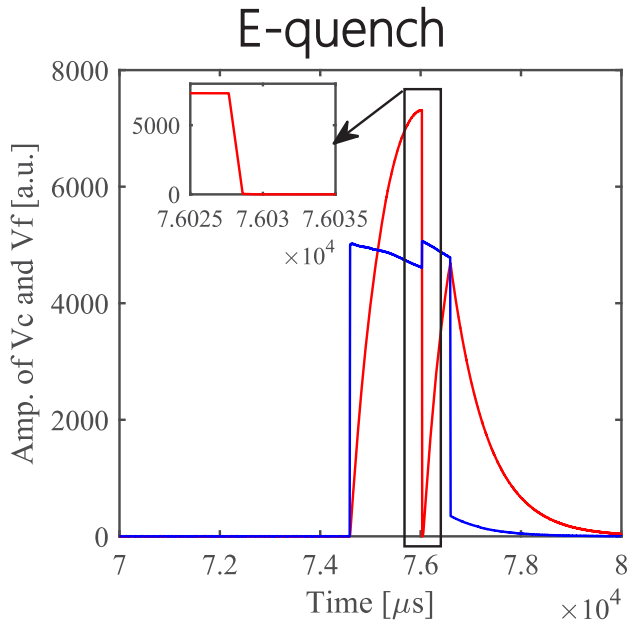


E-Quench phenomena

- We observed the " **E-quench**" phenomena.
- Energy stored in the cavity is completed absorbed by dark current within 1 μs.







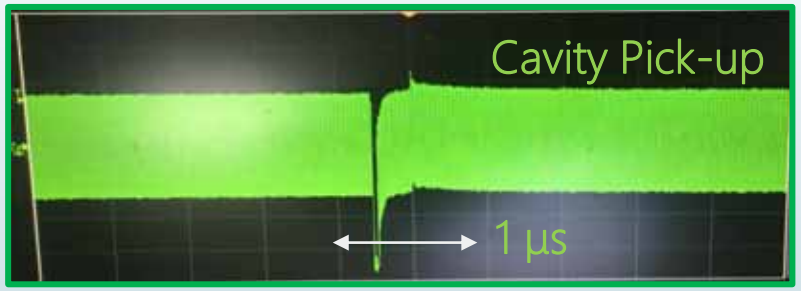
Energy stored in the cavity lost within 1 μs

E-Quench (J-Lab): The accepted theory is that electrons are stripped off of gas molecules and accelerated by cavity fields. The initiating mechanism has been, and continues to be, an area of investigation, **PRAB, 23, 114601 (2020)**

Flash-over Phenomena

- Two types of “ **Flash-over**” Phenomena（probably with different physical mechanisms）

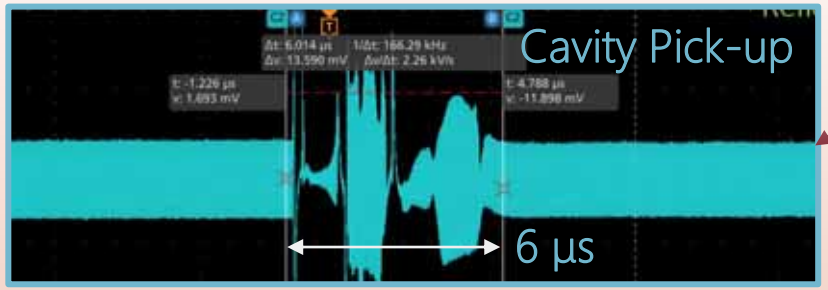
Type I



Phenomena: the actual cavity field is **not** affected. An undesired response may occur under LLRF feedback.

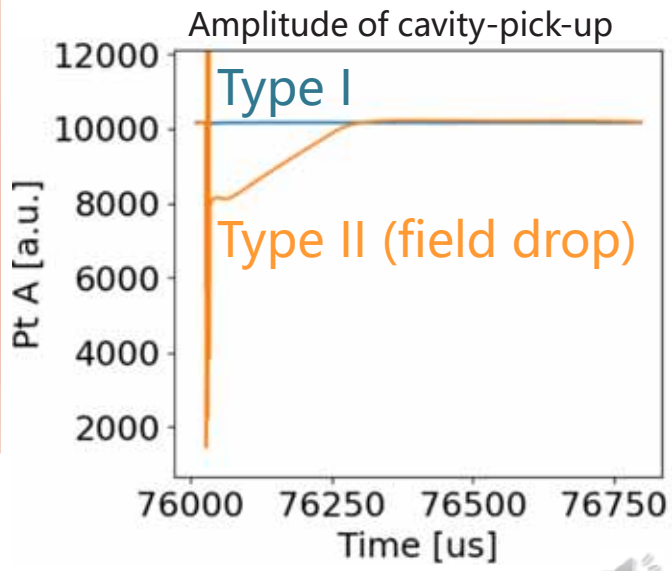
Mechanisms: discharge of pick-up coupler (probably).

Type II



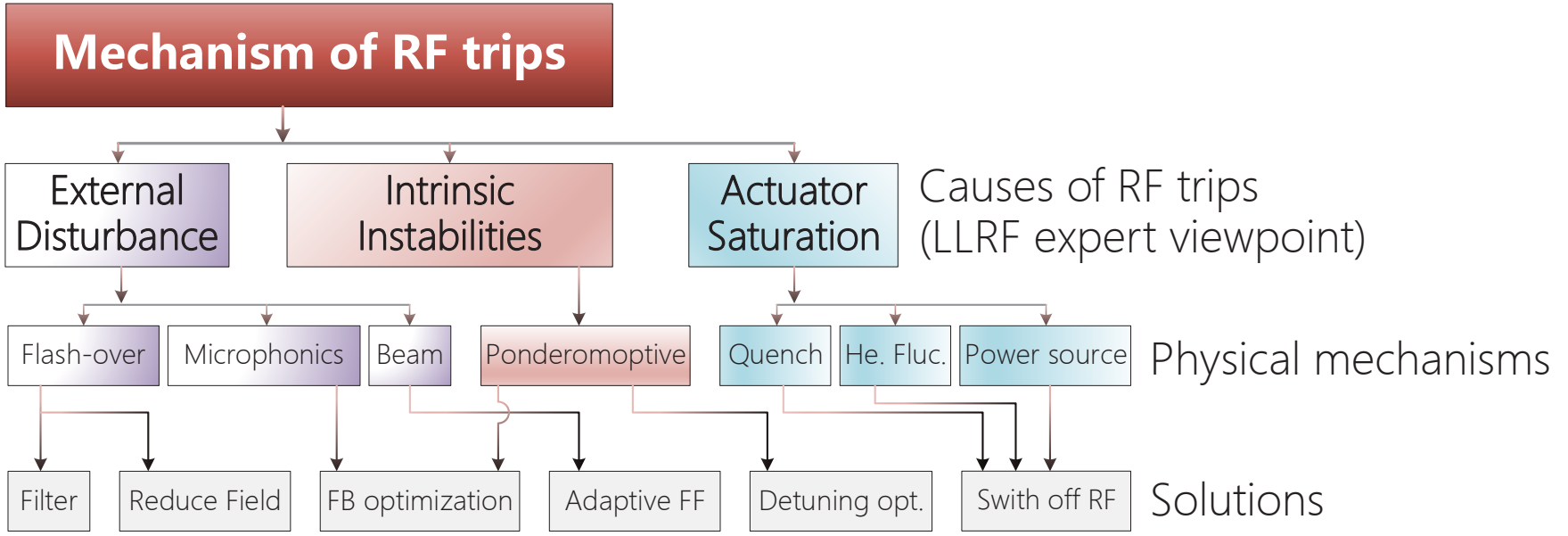
Phenomena: A real “**cavity field drop**” is observed (part of the energy stored in cavity is absorbed).

Mechanisms: still a mystery, probably related with FE triggered break-down



Mechanisms of RF trips

- The RF trips can be classified into three categories (LLRF expert viewpoint):
  - External perturbation
  - Intrinsic instabilities
  - Actuator saturation

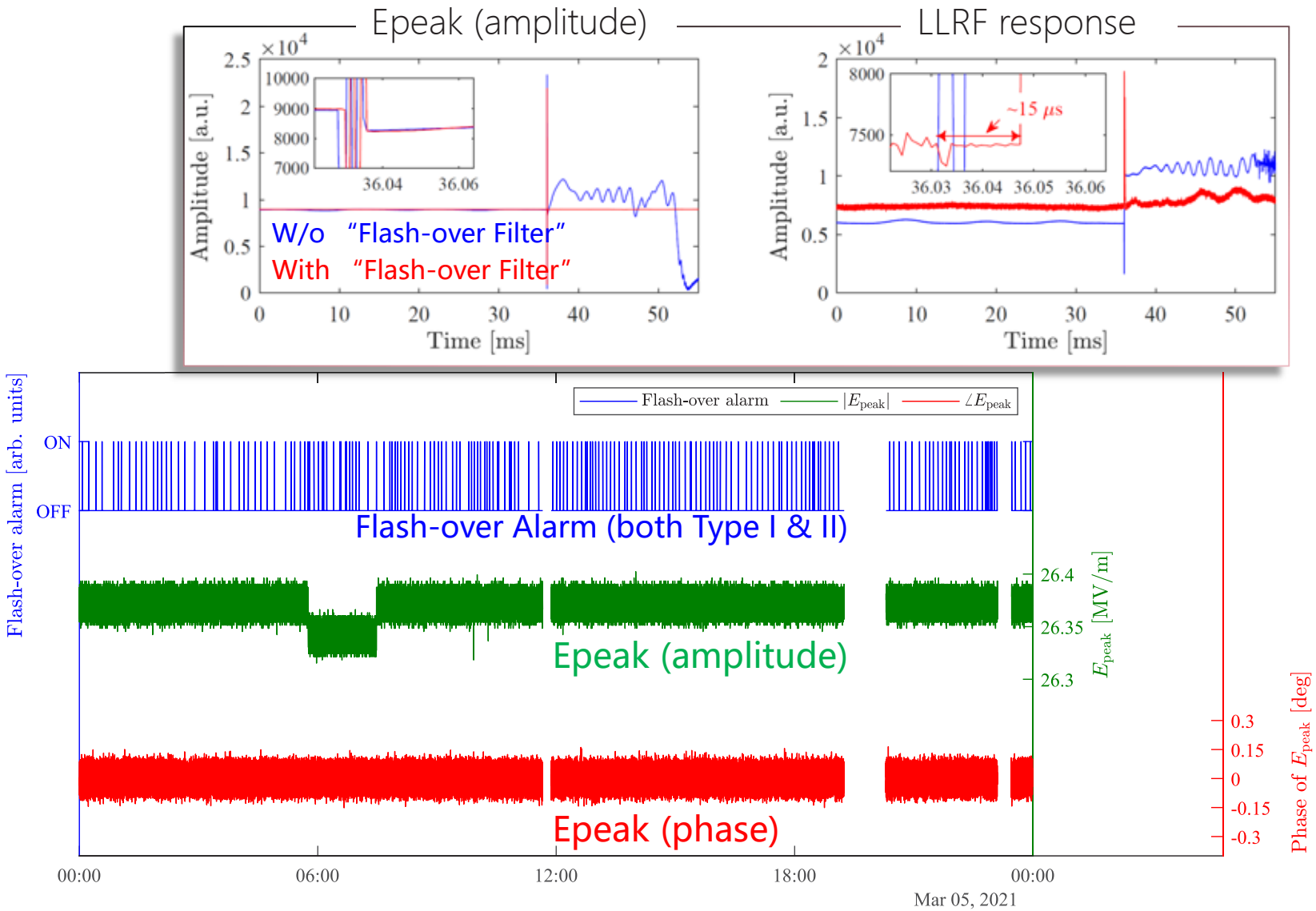


Part of RF trips during the beam (RF)-commissioning

RF & Cavity Trips	2-3	2-4	2-5	2-6	3-1	3-2	3-3	3-4	3-5	3-6	4-1	4-2	4-3	4-4	4-5
He. fluctuation			√		√	√	√		√	√		√			
Ponderomotive	√	√	√√	√	√	√√		√√	√	√	√√	√√		√√	√
LLRF trip			√		√	√			√	√	√	√		√	√
Flash-over		√			√√		√		√√	√√					
E-Quench									√	√					
Thermal Quench						√			√			√			
RF power source			√						√√		√√	√√	√√	√√	

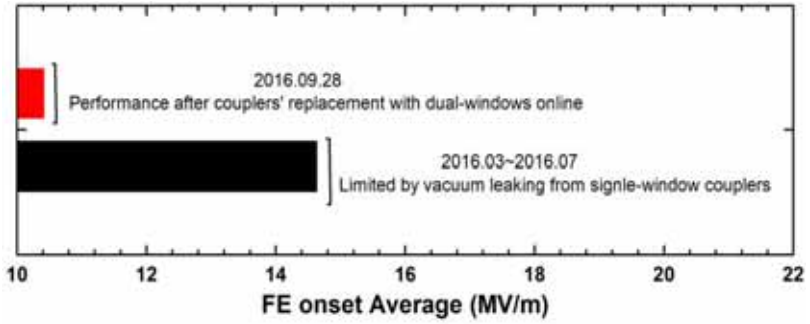
Flash-over Mitigation

- To solve this problem, we added a filter to prevent the LLRF loop response.
- Validity of this method was demonstrated during the 10-mA beam commissioning.

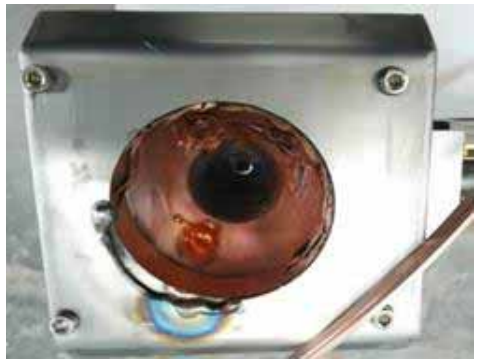


Performance degradation in CAFe

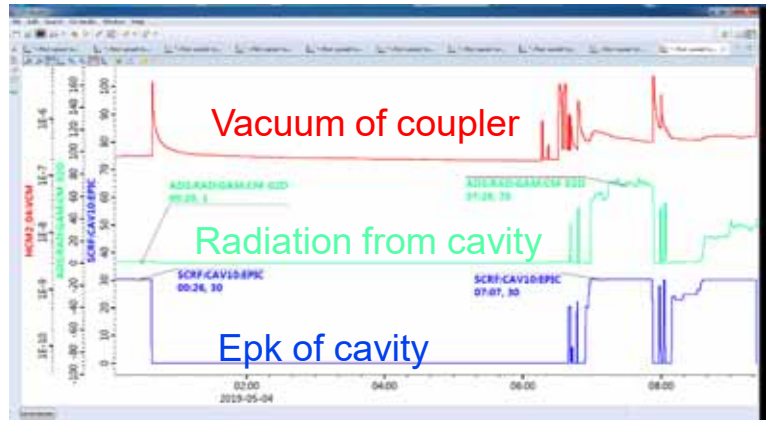
Degradation from single-window coupler leakage and replacement



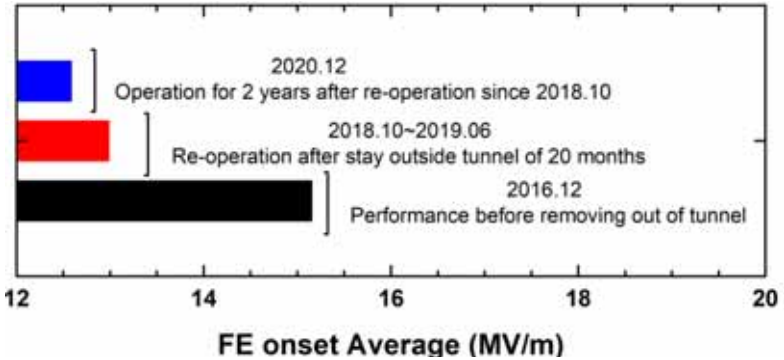
Degradation from particle migration from RT part



Degradation due to gas desorption from surface of coupler



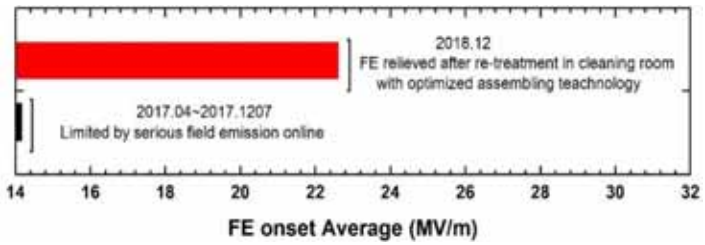
Unknown contamination during assembly



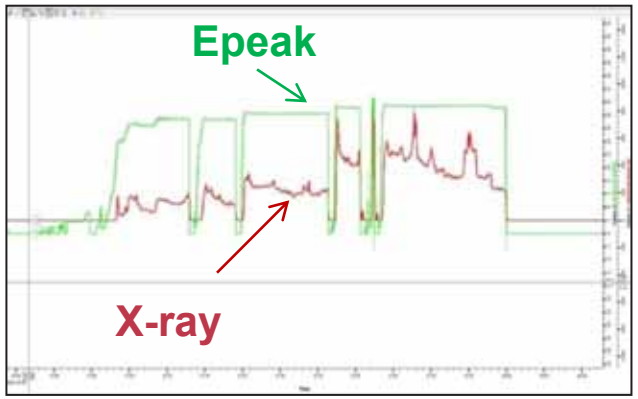
Operation means the contamination comes from anywhere.
The degradation is inevitable.

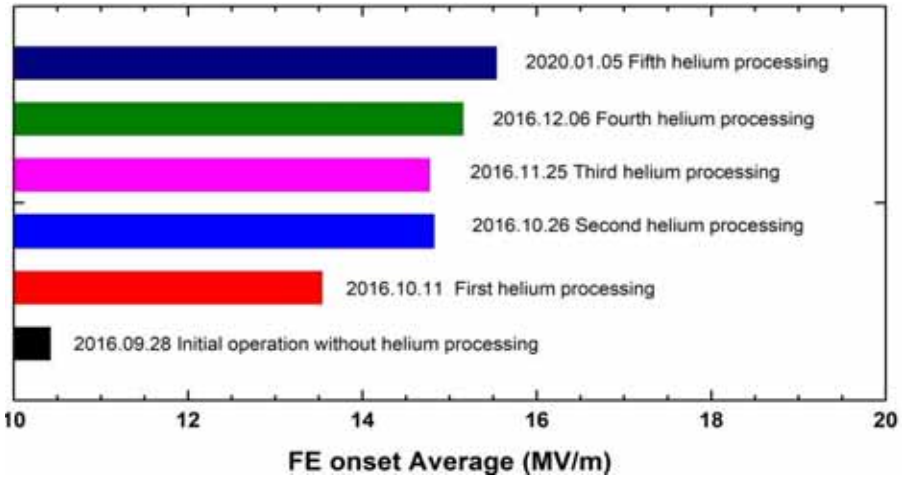
Recipes for the reliable operation

Treatment in clean room

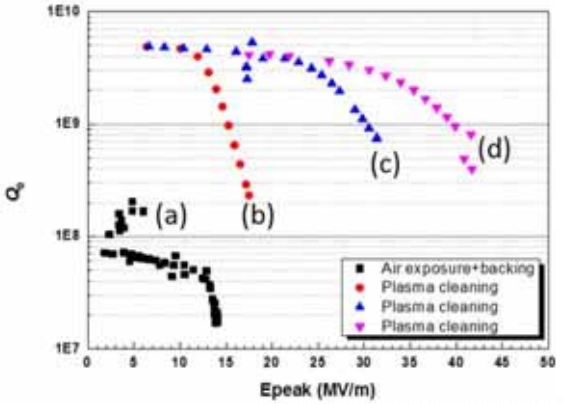


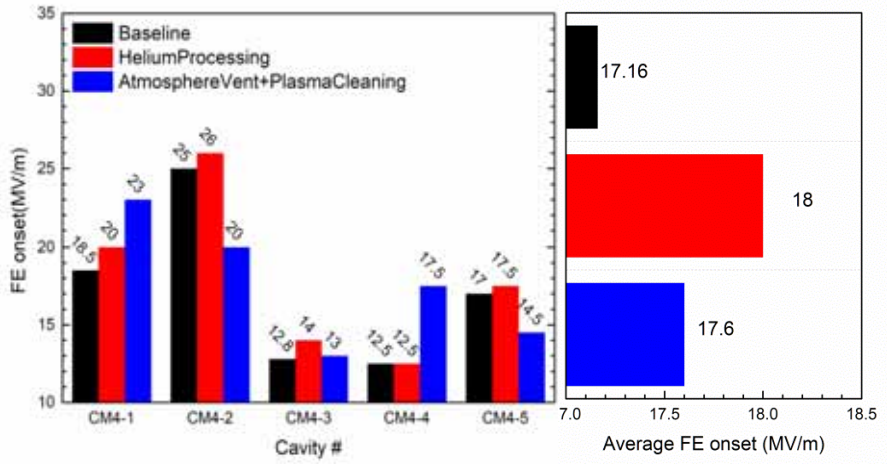
Helium & high power processing





Reactive O_2 plasma cleaning





Most effective but time cost of 2~3 months.

Time cost of hours but limited with saturation level.

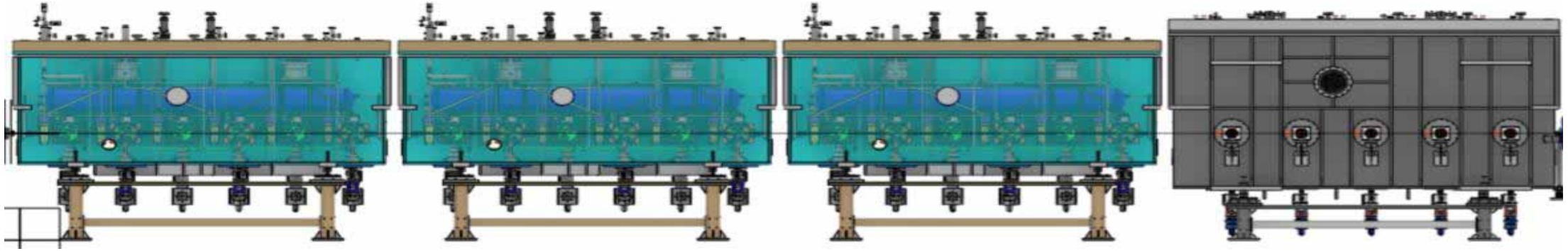
Effective for carbons with time cost of 10 days.

What is the types and components of contamination on the inner surface of SRF online? And how to choose proper recipes?

Surface Processing

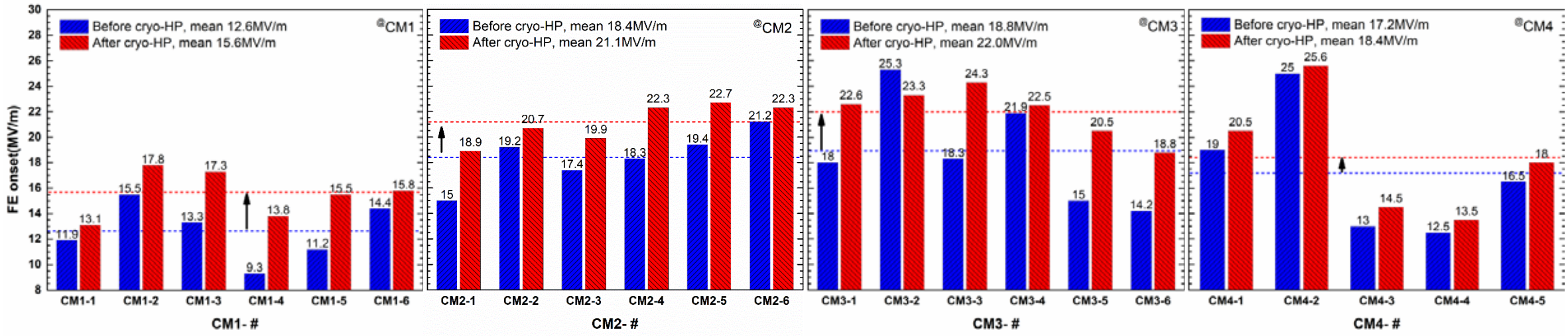
FE onset of each cavity on Jul. 2020 and Jan. 2021

MEBT



HEBT

FE onset point was marked at Gam=0.3~0.4uSv/hrs.



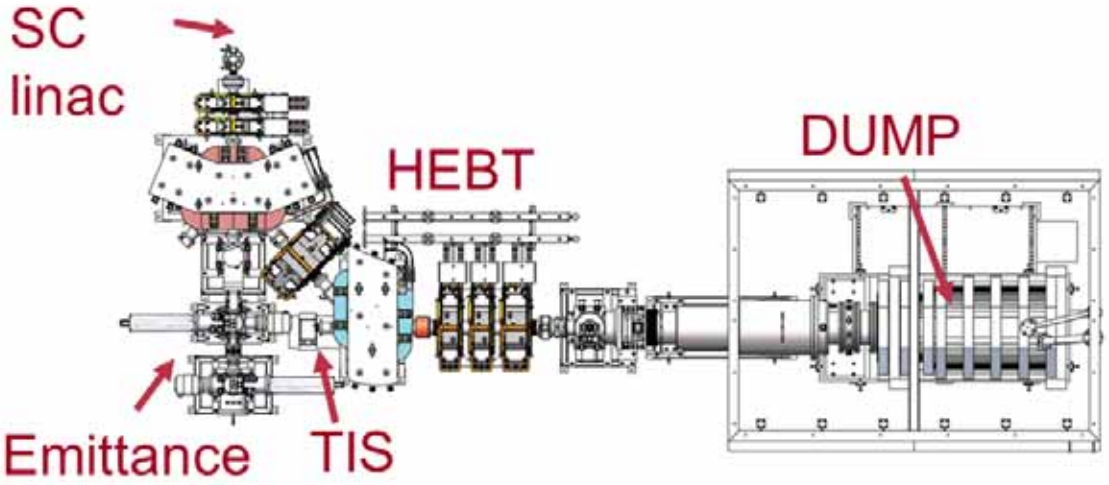
Average gradient of 4 Cryo-module increase 3.0、2.7、3.2、1.2 MV/m, respectively.

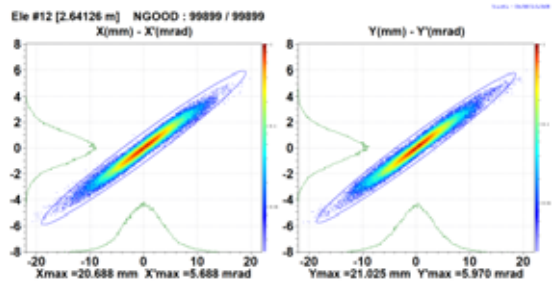
Cavities that are closer to room temperature part are inferior. This might relate to the migration of contaminants.

The New 120 kW Dump

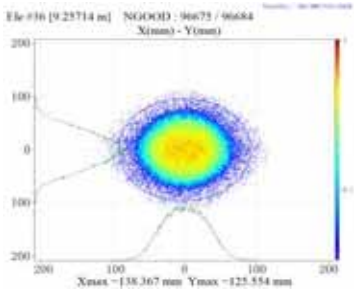
Design Principles:

- Larger beam spot and cone dimension to limit power density at ~200 W/cm^2.
- Al6063 and pre-shielding with Pb for lower residual dose.
- BLM,TIS, DCCT, Collimator for CW real-time monitoring and interlock protection.

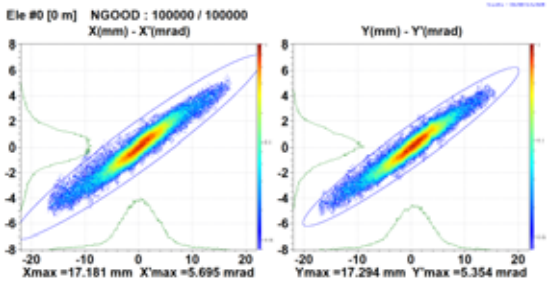




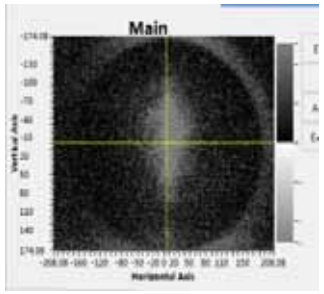
simulation



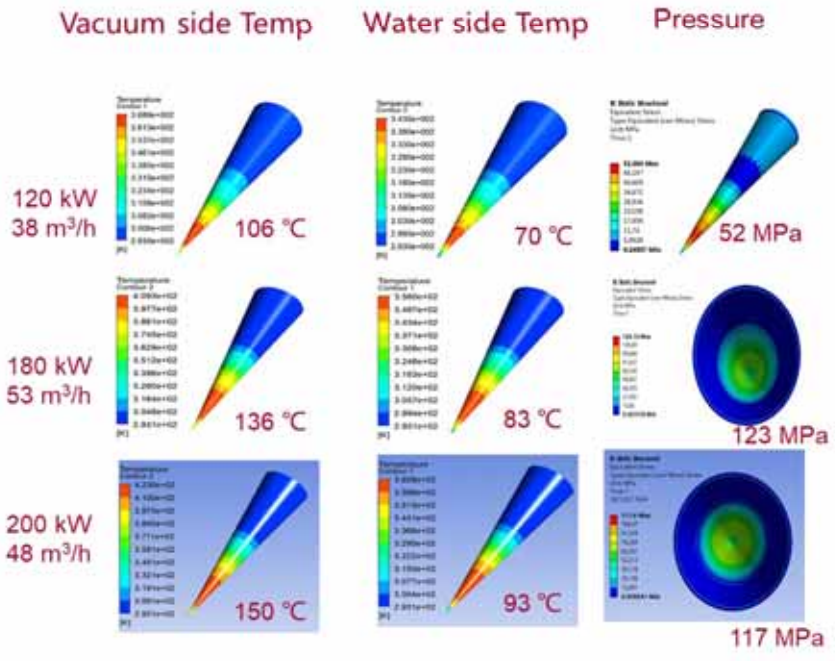
simulation

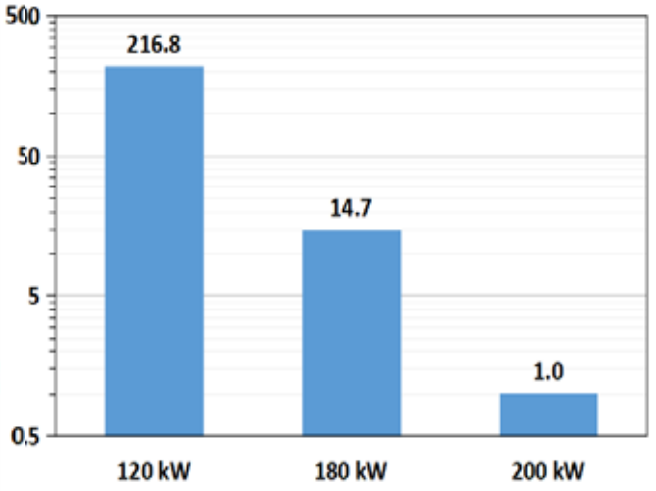


measurement



TIS





Total CW beam 2049 mAh

Outlines

Introduction

1. Evolution of CAFe
2. Machine Upgrade since SRF'19
3. Recent 100^2 beam commission: 100 kW for 100 h and nominal testing

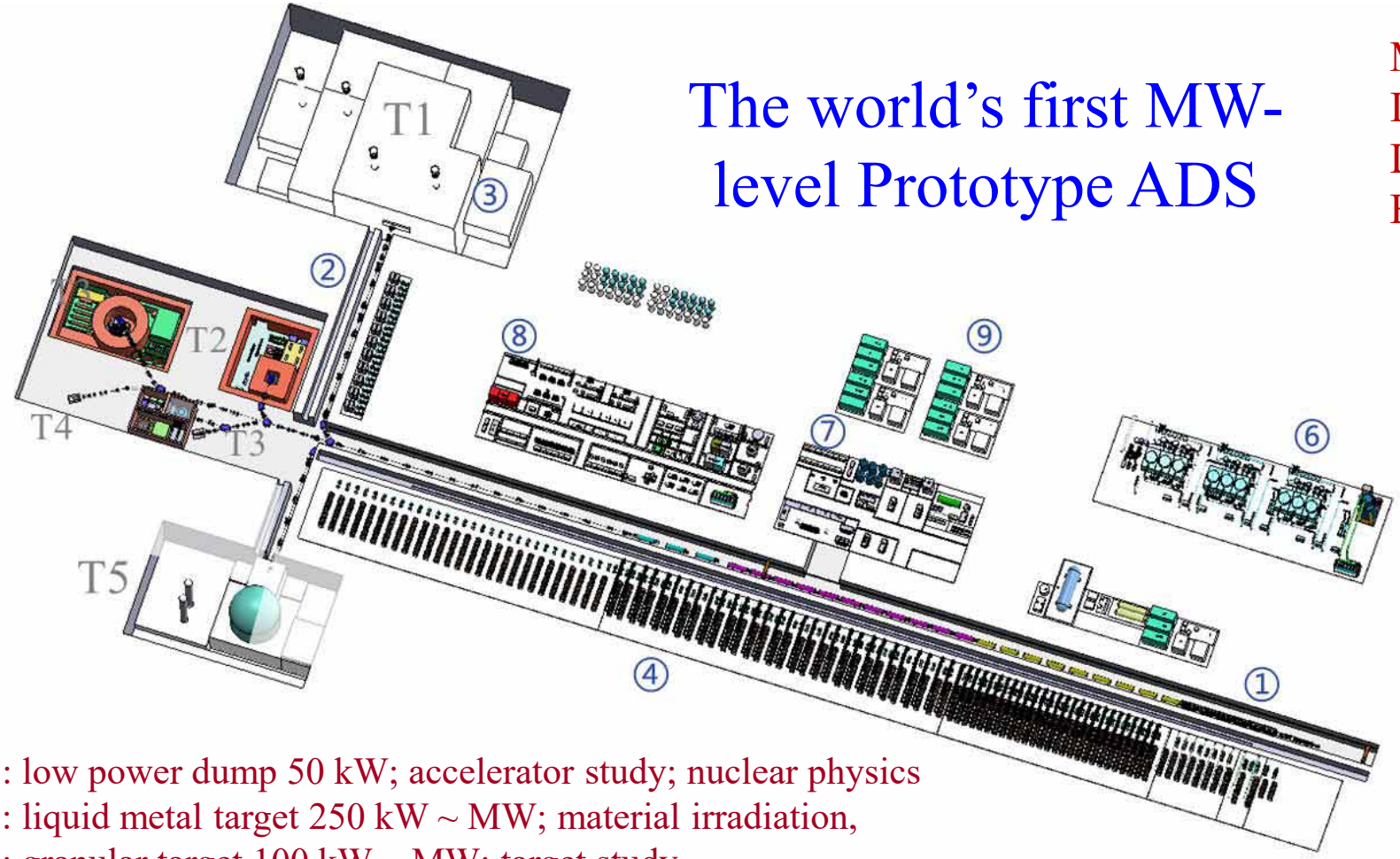
Technical Advances

1. SRF trips and mitigation during high power beam
2. Dirty operation and Surface processing history
3. High power beam dump experience

Towards CiADS

1. CiADS timeline and new challenge.
2. New cavity structures and materials.
3. Conclusion and outlook.

The Numbers of CiADS

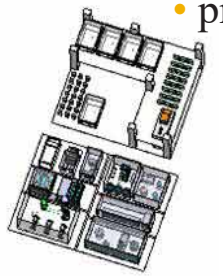


The world's first MW-level Prototype ADS

Managed by IMP;
Involved: IHEP, CIAE, CGN…
Location: Huizhou, Guangdong
Budget: 4 billion CNY (~620 million $)

- Energy: 500 MeV (to 1.5GeV)
- design current: 5 mA (to 10 mA)
- Reactor Power: 10 MW
- modes: pulse&CW（Hus gap for reactor）
- energy stability: ±1%@100ms
- current stability: ±2%@100ms
- position stability: ±1mm
- profile stability: vv±1mm

- T1: low power dump 50 kW; accelerator study; nuclear physics
- T2: liquid metal target 250 kW ~ MW; material irradiation,
- T3: granular target 100 kW ~ MW; target study
- T4: 10 MW fast reactor, LBE target, Keff ~0.97; demo of ADS
- T5: upgrade ISOL target: iLinac of HIAF is post-acc, to 100 MeV/u



CiADS:

- **Beam-trip-duration tolerance is 10 s.**
- **< 10 s, rapid recovery**
- **10 s ~ 5 min, <2500 /year**
- **> 5 min, < 50 /year**

Officially funded in July, the first beam of RFQ in Dec. and the first beam in reactor in 2026.


Power plant
Exp. Hall
Reactor plate
P-linac tunnel
CiADS
June 10, 2021

Nb/Cu Clad Cavity Activities

➢ Nb/Cu clad cavity technology: a robust technology for SRF accelerator with an improved operating stability

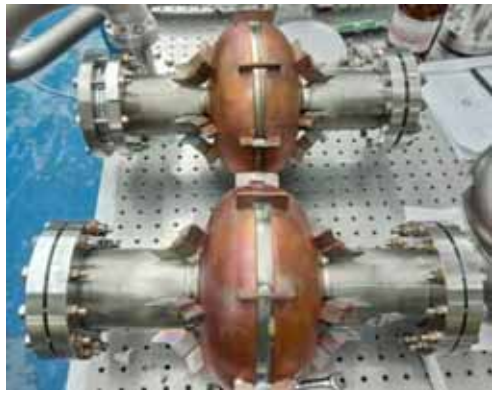
- High mechanical stability, thick Cu and thin Nb (e.g. Cu/Nb (8mm/1.5mm))
- High thermal stability, Cu with higher thermal conductivity;
- Performance of bulk Nb cavity;

➢ Two strategies are being pursued

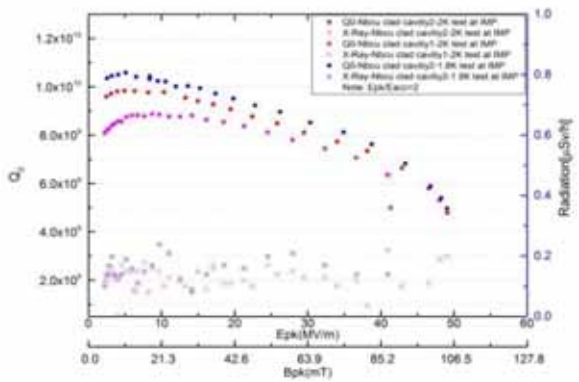
- Based on Nb/Cu composite sheets and traditional forming technology

- Back-coating copper on cavities made of Nb sheet

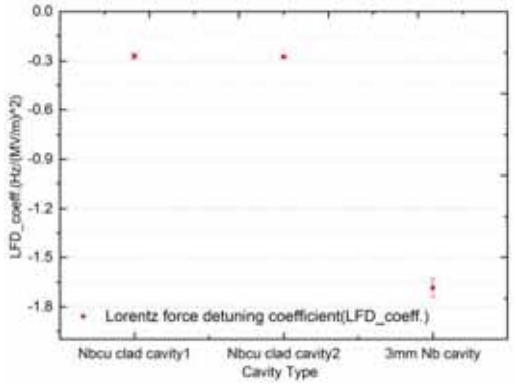
HWR010 cavity coating with copper



A photo of two single cell elliptical cavities



Test results of the single cell elliptical cavity



Mesured LFD_coeff. between 3mm Nb cavity and Nb/cu cavities

Spoke021 cavity coating with copper

- ✓ Epk~=50MV/m(processed by BCP), Q0=9.8E9, low field and at 2K;
- ✓ High sensitivity to cooling dynamics crossing Tc
- ✓ About 6 times improved of LFD. Coeff. And df/dp compared to 3mm Nb cavity

➢ Preparing for cryogenic tests to validate its RF performance and mechanical properties.

Conclusion

- 100 kW, 100 hours cw proton beam had been commissioned on CAFe, with only 23 SRF cavities. Nominal power of 204 kW beam was achieved with 12 mins duration. These showed the feasibility of commercial grade high power cw proton machine.
- New technologies including beam dynamics, surface processing, beam loading effect, LLRF control, and reliable dump contributed to this success.
- The ADS front-end demo linac CAFe started commissioning in 2017 and achieved nominal specifications at the beginning in 2021. It requires more the reach a MW-grade ADS demo facility, CiADS. More improvement including new materials, new structures, and new control methodologies are under development.

Thank you for your attention!