Working Group 2:
Performance Degradation, Cure, Beamline Quality

Hiroshi Sakai (KEK/DESY), Bob Laxdal (TRIUMF), Axel Matheisen (DESY)

The general aim of WG2 to gather and analyze the recorded degradations (or improvements) between vertical cavity tests and cryomodule performance for major accelerator projects. Both high and low beta types should be covered.

Fundamental questions

- What are the dominant limiting aspects - field emission, quench, Q-degradation, administrative limits, something else?
- What measures have been tried to cure the degradations, and how successful are these attempts?
- What efforts are underway or recommended to minimize contamination during cryomodule assembly and during connection to the beam line, such as particle-free vacuum components next to cold linac sections, especially in segmented linac designs with a large number of warm beam lines between modules?

24 pages

Session 1 – Chair: Bob Laxdal

Main topic: Degradation after VTA

VTA vs installed performance

14:00	**Summary of previous meeting about VTA vs cryomodule (E-XFEL(mainly), C100, FRIB, STF2)**	*Dr. Hiroshi SAKAI*		
	Field emission statistics for first production LCLS2 cavities and comparison (including setups) to XFEL	*Dr. Sebastian ADERHOLD*		
	STF2 Cryomodule degradation	*Dr. Yasuchika YAMAMOTO*	*Kellogg Center- 103AB*	14:30 - 14:45
	IMP results about VTA vs cryomodule	*Yongming LI*	*Kellogg Center- 103AB*	14:45 - 15:00
15:00	**ANL Experience -- VTA vs cryomodule --**	*Zachary CONWAY*		
	Short discussion about results of VTA vs cryomodule		*Kellogg Center- 103AB*	15:15 - 15:30

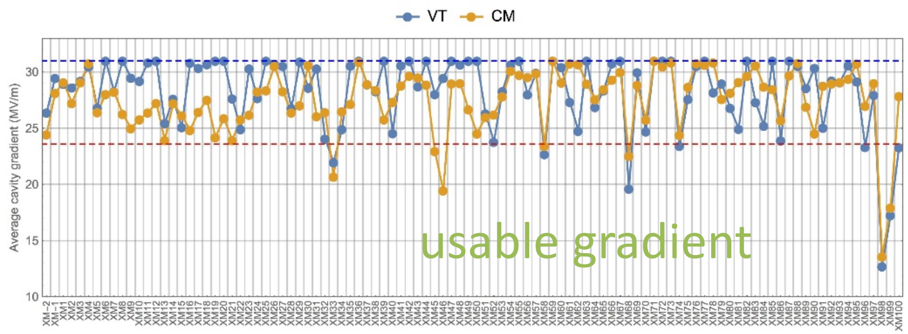
Degradation by magnetization

16:00	**First result of LCLS2 CM, Q0 studies as function of cooldown**	*Dr. Genfa WU*	*Kellogg Center- 103AB*	
	Experience with magnetic hygiene and in situ demagnetization to achieve < 2mGauss in CM		*Kellogg Center- 103AB*	
	Measurement of the magnetization of each component in KEK	*Prof. Eiji KAKO*	*Kellogg Center- 103AB*	
17:00	**Long discussion about degradation after VTA**		*Kellogg Center- 103AB*	16:45 - 17:30

Summary of VT vs cryomodule on previous TTC meeting (@CEA-Saclay), Hiroshi Sakai (KEK/DESY)

Two big data were presented again to discuss about VTA vs cryomodule test

Euro-XFEL (DESY/CEA-Saclay)



Nick Walker et al, DESY LINAC16 Conference (2016/Sep/28)

	N_{cavs}	Average	RMS
VT	815	28.3 MV/m	3.5
CM	815	27.5 MV/m	4.8

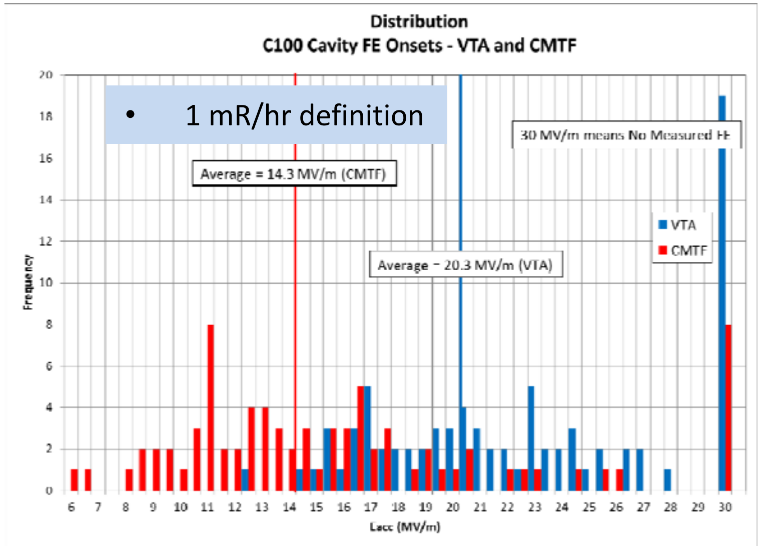
VT capped at 31 MV/m for fair comparison

97 module was installed in XFEL-tunnel.

~3% difference measured this way

We have small difference with each other.

C100 cryomodule (Jlab)



Compare the performance between VTA and CMTF by using radiation detector.

Average Onset drops by 6 MV/m from VTA to CMTF. Number of Cavities with no Field Emission drops by more than half

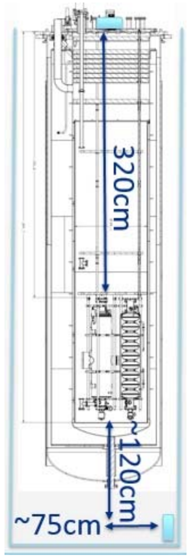
Possible reasons for degradation after VTA

- Many leaks detected in the C100 strings.
- "Slow pumpdown" 8X higher than VTA.
- Most string assemblies in old clean room (class 1000)

Field emission statistics for first production LCLS-II cavities and comparison (including setups) to XFEL, Sebastian Aderhold (FNAL)

LCLS-II FE specification

- Originates from < 10 nA per CM @16 MV/m in linac
- Conservative approach, including 10% gradient uncertainty
  < 1nA @ 17.5 MV/m in VTS
- Based on simulation and previous measurements
  Measure: <10mR/hr @17.5 MV/m
- No FE onset below 16 MV/m



FNAL

- Top sensor centered on dewar lid
- Bottom sensor off to the side
- Signal above background
  ~0.003 mR/hr

38 dressed production cavities total received at Fermilab

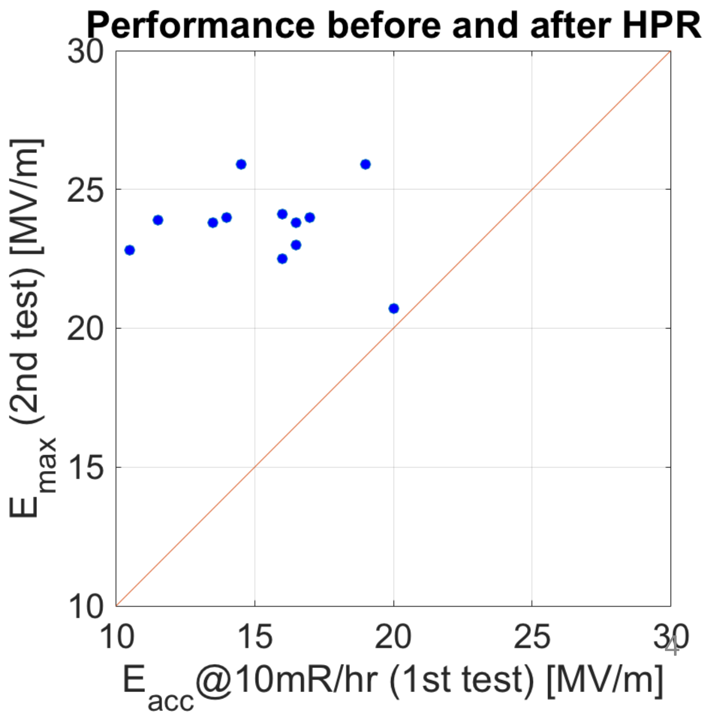
12 vendor A

26 vendor B

2 cavities without successful 1st test so far because of cold leak

Consider only re-processing by HPR due to FE

14 tests



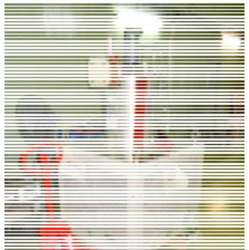
Summary

- Different vertical test and radiation sensor geometries
- No clear difference between top and bottom sensor
- No apparent relation between shocks during transport and FE onset
- HPR recovered 100% of FE limited cavities so far
- Re-rinse rates dropping but still too high

Performance Degradation in Testing STF-2 Cryomodule,

Yasuchika yamamoto (KEK)

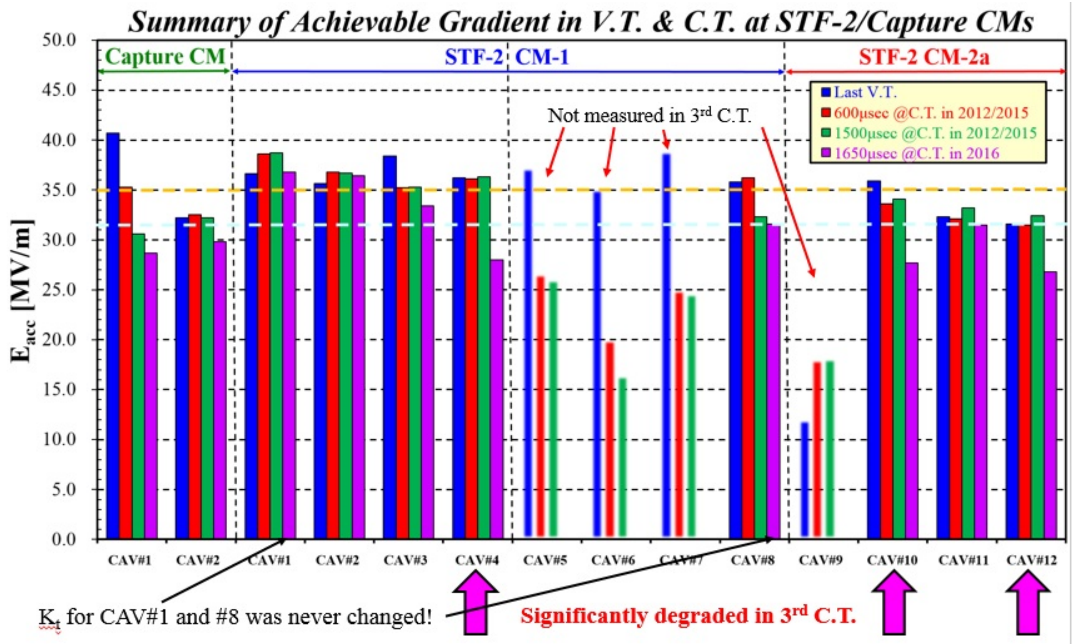
Single Cavity Operation in 2015



800kW Klystron
(Distributed RF System)

8 Cavities Operation in 2016

10MW Multi-beam Klystron

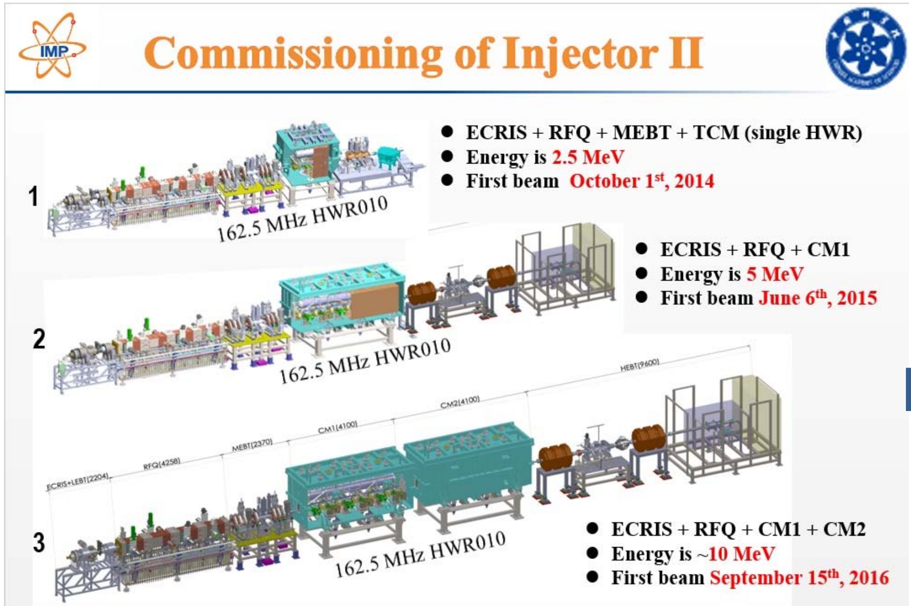


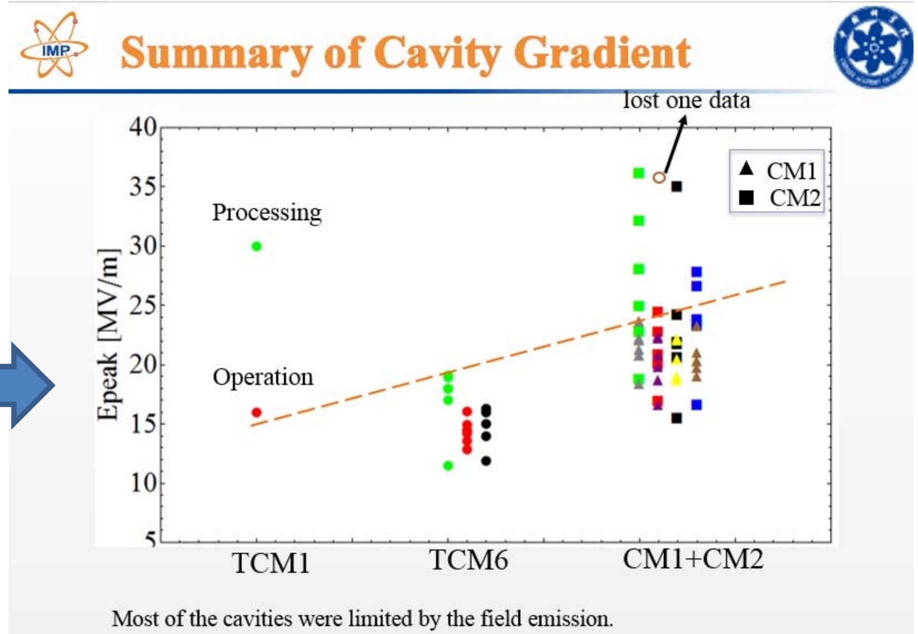
We met degradation in 2016 systematically.

Possible reasons of degradations of cryomodule tests after 2015

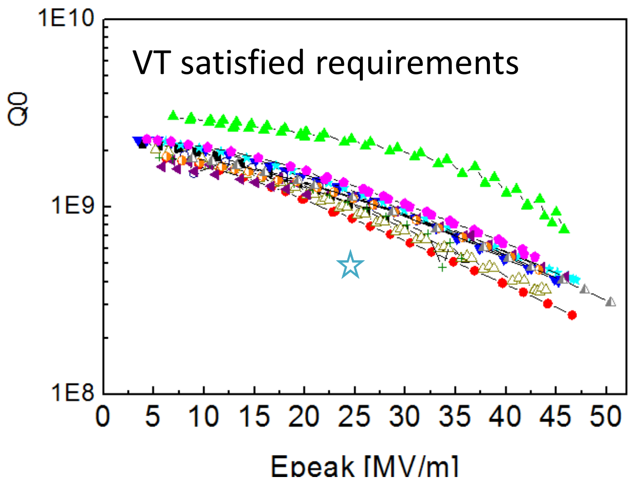
- Change of RF System. Generally, some systematic errors exist between different RF systems
- Too High Forward Power distributed to Power Coupler
  After power adjustment, distributed power changed from 400kW to 260kW
- We have experienced by Level 4 earthquakes many times in these years

HWR Cavity VTA VS Cryomodule Test ,Yongming Li (IMP)





10 MeV HWR Module (case)



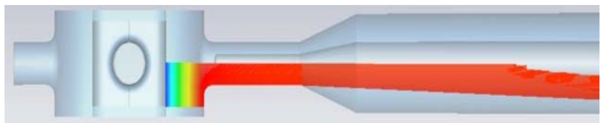
But, 10 MeV operation for 2 months, ceramic windows of 4 couplers were leaking. The vacuum is drop from 10^{-7}Pa to 1E-5 and 1E-6 Pa.

Before leak, cavity gradient > 22MV/m.

After leak, cavity gradient < 20MV/m.

In cryomodule operation

Field emission e from the cavity hitting on the ceramic window



Helium Processing was used to improve the performance of the cavity

Before Helium Processing: 7 MeV

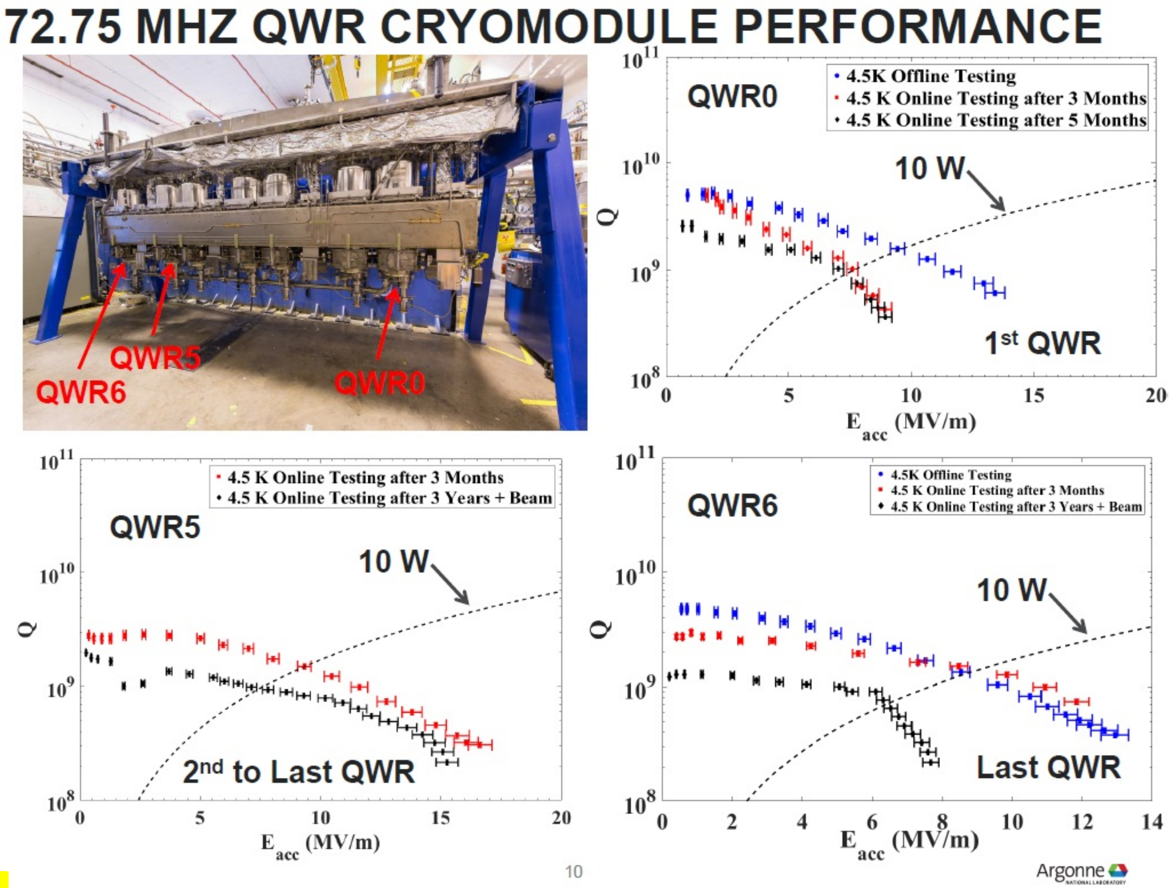
After Helium Processing:10.06MeV

Argonnne's 72 MHz QWR Cryomodule performance, Zachary Conway (ANL)

& **ARGONNE'S CLEAN ROOM TECHNIQUES FOR CRYOMODULE ASSEMBLY (Session 3)**

ATLAS' intensity and efficiency upgrade. QWR were installed.

ANL Low-β Cavity HPR



Employ hardware to make sure the clean assembly stays clean:

–Vacuum pumping/venting system to control and filter the flow.

–Beam line cold traps to help reduce contamination from adjacent, dirty, accelerator components.

Liq.N2
Beam line

Initial performance is OK due to the clean assembly work. But after 5 month operation. Performance degradation were shown. Until now, I did not find the reasons.

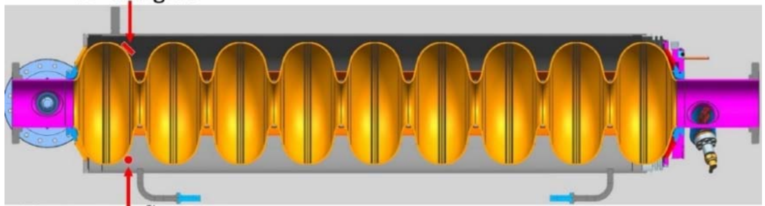
Experience with magnetic hygiene & in-situ demagnetization to achieve <2 mGin CM ,Saravan K Chandrasekanran (FNAL)

LCLS-II 1.3 GHz CM ambient mag. field spec. <5 mG

Fluxgates in pCM cavities

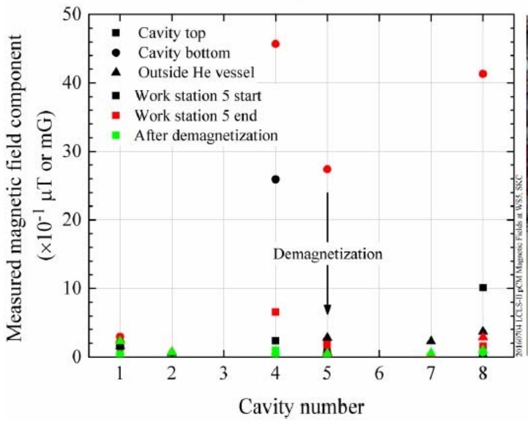
- 4 cavities instrumented with fluxgates inside helium vessel
  - Cavities 1, 4, 5, 8
- 2 fluxgates per cavity
- These fluxgates were instrumental in obtaining <2 mG in CM

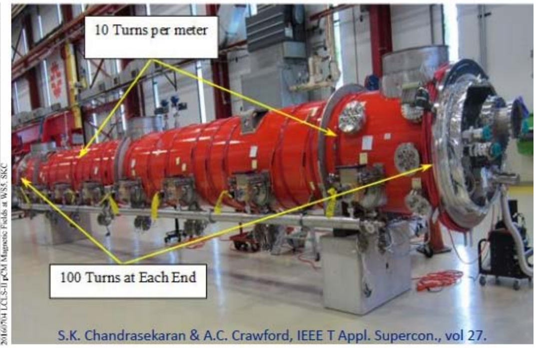
45° fluxgate



Transverse fluxgate

In-situ demagnetization





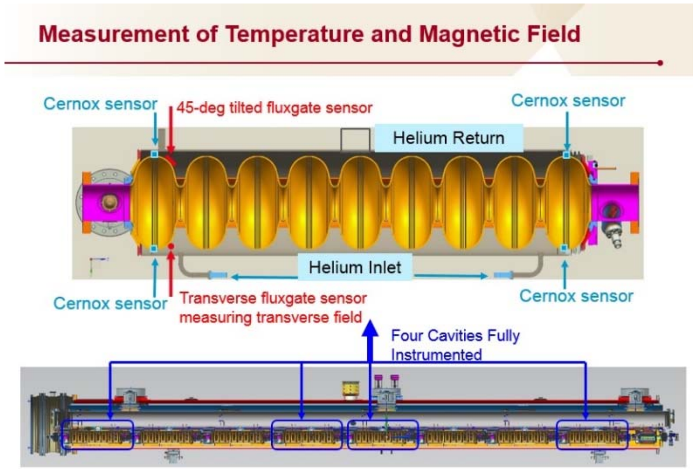
Less than 2mG

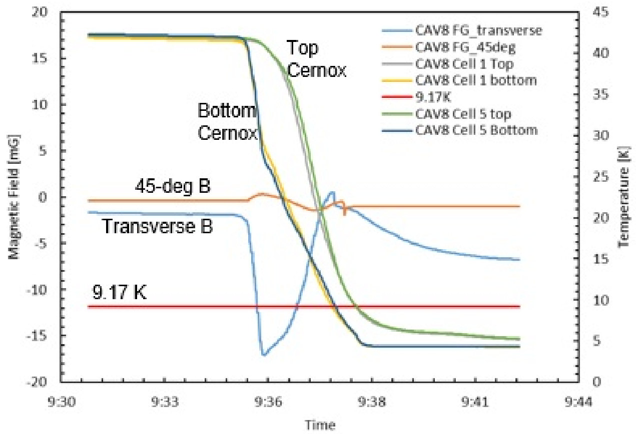
- Fields up to 46 mG discovered after assembly & installation
  - Attributed to cryo-piping welds within CM
  - Most likely due to re-magnetization of the vacuum vessel & magnetic shields
    - Vacuum vessel permeability ~300, shield permeability ~40,000
- Fields up to 10 mG after cryo-plant piping maintenance welding above CMTS
- Cryomodule successfully demagnetized using in-place coils

Magnetic hygiene → lessen learned

- Demagnetization of fully assembled CM a must for low fields
  Must be done after the final weld is performed.
  Weld could be part of assembly or installation.
- Welding currents easily magnetize vacuum vessel (VV) and
- SST 316LN displayed no signs of residual magnetic fields
- SST 316L can get magnetized, but readily demagnetize
- SST 304 requires greater magnetic force to demagnetize
- Carbon steel easily magnetized & demagnetized

First Results of LCLS-II Cryomodule, Q_0 Studies as Function of Cooldown, Geng Wu (FNAL)





After demagnetization of cryomodule, do the cryomodule test of LCLS-II

Cavity	Usable Gradient [MV/m]	Q_0 @16MV/m* Fast Cool Down	Q_0 @16MV/m* Slow Cool Down
TB9AES021	18.2	2.6E+10	1.8E+10
TB9AES019	18.8	3.1E+10	1.5E+10
TB9AES026	19.8	3.6E+10	3.3E+10
TB9AES024	20.5	3.1E+10	2.1E+10
TB9AES028	14.2	2.6E+10	1.9E+10
TB9AES016	16.9	3.3E+10	2.0E+10
TB9AES022	19.4	3.3E+10	2.1E+10
TB9AES027	17.5	2.3E+10	1.8E+10
Average	**18.2**	**3.0E+10**	**2.1E+10**
Total Voltage	**148.1 MV**		

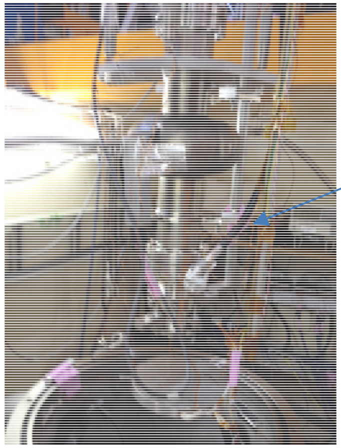
No degradation from VT

- Q_0 performance maintained from vertical tests to cryomodule
- Thermal current induced fields are present in cryomodule
- Slow cool down avoids the dynamic thermal magnetic field, but cannot avoid the static thermal currents in current cryomodule design from outer magnetic field.
- Fast cool down is needed to ensure minimal magnetic field trapping
- Quench will degrade cavity Q_0 in the presence of static thermal magnetic field

Measurement of magnetization of each components in KEK-STF vertical test , Eiji Kako (KEK)

Degradation of R_res?
Strange magnetic flux behavior? → Check magnetization for most of all the components of vertical test

No.	name	Magnetic field [mG]
14	Φ034 metal valve ①	430
15	Φ034 metal valve (which observed vacuum leak)	80
19	Φ034 metal valve ②	59
25	Volts and washers for support of input coupler shaft	140
28	Nuts and washers for hanging cavity	110
29	Stat-volts, nuts and washers for hanging cavity	300

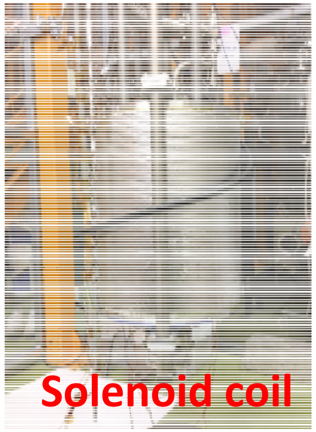


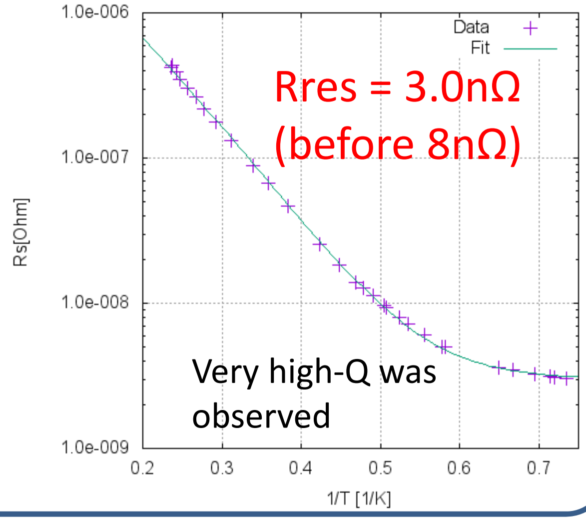
SUS shafts for variable coupler were highly magnetized. More than 1 G!!

remove

VT started in 2006.

- FG single-cell cavity (Tokyo-Denkai)
- Nominal recipe (Not N-doping)
- With cancelling coil
- With thermal gradient by heater





- Magnetization was investigated for each components of vertical tests.
- Some components were highly magnetized. One of highest was shaft for variable coupler.
- Magnetized components were removed or exchanged. Also solenoid coil was prepared.
- After these effort, high-Q could be measured and clear flux expulsion signal was observed.

WG 2 (2nd session Chair: Hiroshi Sakai)

Main topic : maintain for a long time

Can we keep the cavity performance during long term cryomodule operation
- at different Lab ?
- for High or Low beta structures?

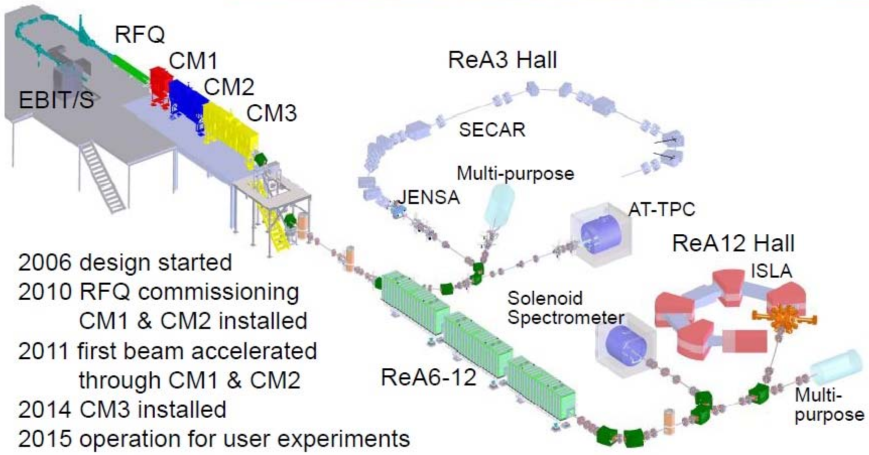
Processing was effectively worked to recover the cavity performance in cryomodule operation ?

- Pulse high power processing
  - Helium processing
  - Plasma processing

09:00	ReA SRF peration experience over several years	*Qiang ZHAO*	*Kellogg Center- 103AB*	09:00 - 09:14
	Performance degradation and recovery of ISAC-II quarter wave cavities during operation	*Tobi JUNGINGER*		
	Longterm operation and its care to keep performance in CEBAF (including Helium processing)	*Mike DRURY*		
	Plasma processing for SNS cryomodule	*Dr. SANG-HO KIM*	*Kellogg Center- 103AB*	
10:00	Plasma Processing setup for LCLS2 at FNAL	*Mr. Paolo BERRUTTI*	*Kellogg Center- 103AB*	09:56 - 10:10
	Discussion about effort to maintain and improve cryomodule performance		*Kellogg Center- 103AB*	10:10 - 10:30

ReA Operational Experience over Several Years, Qiang Zhao (FRIB)

ReAccelerator (ReA)



2006 design started
2010 RFQ commissioning
CM1 & CM2 installed
2011 first beam accelerated
through CM1 & CM2
2014 CM3 installed
2015 operation for user experiments
ReA6 under construction
ReA12 under design

ReA3 β=0.041 Cryomodules

CM1:
one β=0.041 QWR
two solenoids

CM2:
six β=0.041 QWRs
three solenoids

A total of 7 β=0.041 QWRs

ReA3 β=0.085 Cryomodule

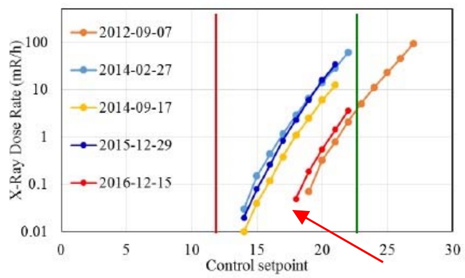
CM3:
eight β=0.085 QWRs
three solenoids

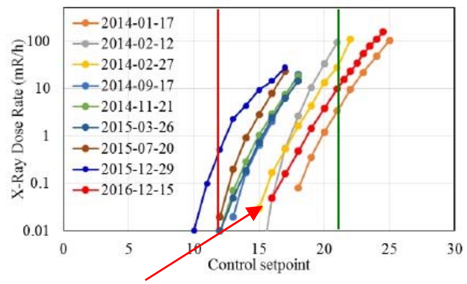
A total of 8 β=0.085 QWRs

ReA has been successfully serving users for two years ReA3 performance was improved. Most resonators have been operating stably and reliably. β=0.041 resonators over 5 years, β=0.085 ones for 2 years

X-ray Measurements

- Two outer resonators in CM2
- X-ray less than 10 mRem/hour for operation





After Pulse process (red line)

First resonator in CM2 — Last resonator in CM2

Field emission degradate the cavity performance.
Pulse processing recover the cavity performance

Operational issues

Field emission increased in some β=0.041 resonators
-- Especially the first and the last in the second cryomodule
-- RF condition is quite effective to recover the degradation
Severe multipacting appeared in a few resonators
— Recovered after warm-up

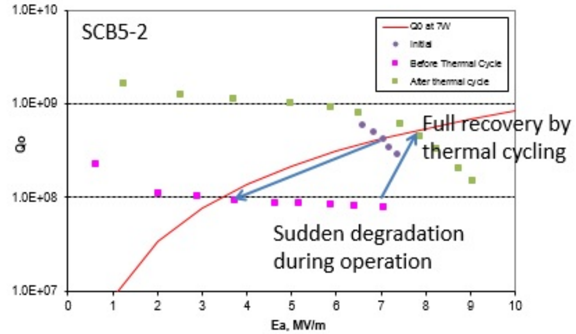
Degradation and recovery of ISAC-II cavities ,Tobi Junginger (TRIUMF)

ISAC-II accelerator magnetic environment

- 5 low beta cryomodules with 4 QWRs each
- 3 high beta cryomodules with 2x6 and 1x8 QWRs
- Each module contains a solenoid for focusing

- During operation cavities sometimes trip
- In a few cases the cavity will have a largely reduced Q_0, multipacting or lower quench level afterwards
- Our assumption is that the cavity has quenched and flux from the solenoid has been trapped

Turn off solenoid and warm cavity up



Quench with solenoid off did not recover Q_0

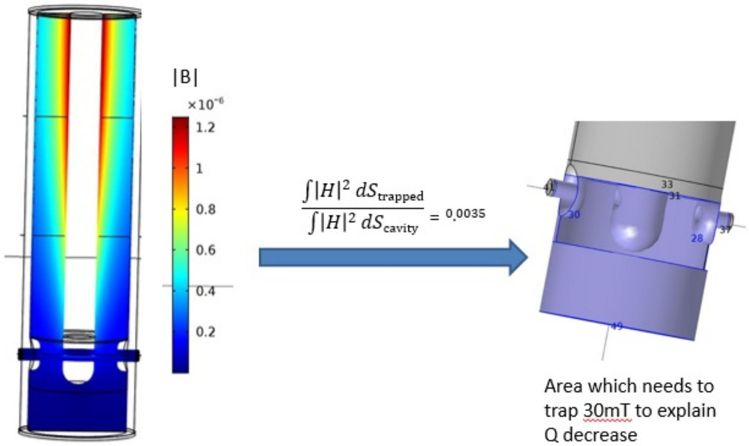
Warm up above Tc with solenoid off recovers Q_0

Why do cavities degrade during operation ?

Assumption: Cavity quenches and traps flux from solenoid while the Meissner shield remains effective

- Three possible points of flux entry
  - Top plate → Field from solenoid below 1µT
  - Beam port → Field from solenoid below 1µT
  - Bottom plate

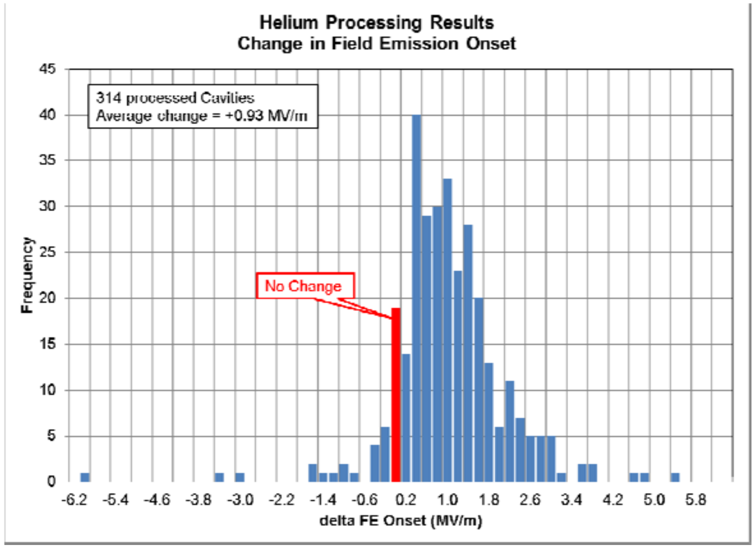
RF simulation



Substantial amounts of flux can only enter through the bottom plate, where the RF magnetic field is small and a large area would need to quench to explain the observed Q degradation

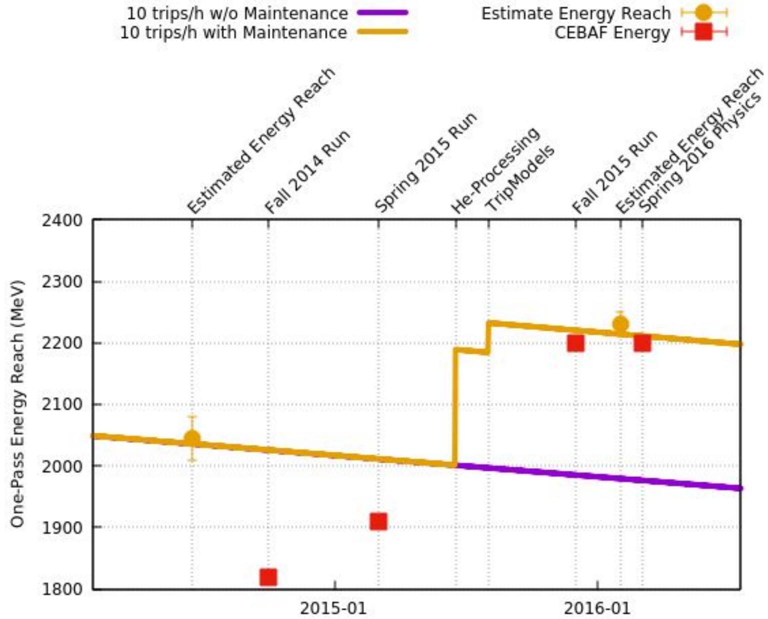
Long Term Operation and Performance Maintenance in CEBAF, Mike Drury (Jlab)

- Factors that may limit gradient in operational setting in CEBAF
  - Other cavity metrics:
    - Field Emission
    - Microphonics, etc. (see Tom Powers)
  - Cryomodule vacuum integrity
  - Other hardware issues
  - Gradient management→ **Currently 13 C50 cryomodules installed with a goal of one per year**



- Before helium processing (3/29/2015) and after (11/17/2015)
- Average change = +0.87 MV/m

~ 201 MeV gain in energy per pass at 10 trips / hour



- The CEBAF machine has been in operation since 1995
  – C50 program slowly replacing aging cryomodules while improving techniques.
  – Helium processing program in place to reduce field emission and associated problems.

Plasma processing for SNS cryomodules, Sang-ho Kim (SNS)

Motivation

To achieve 1-GeV operation, we need to IMPROVE the cavity performance to a new higher operating gradients

Hydrocarbon was observed in SNS and will make field eission

Plasma processing:

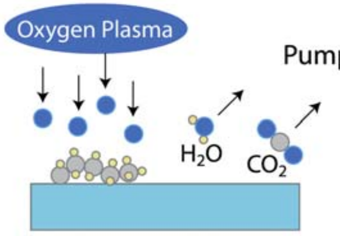
Reducing FE by increasing work function of cavity RF surface

10-20 % increase in ϕ leads to 20-30% increase

Process gas optimization Ne (background) for stability of plasma and O2 as a reactive gas

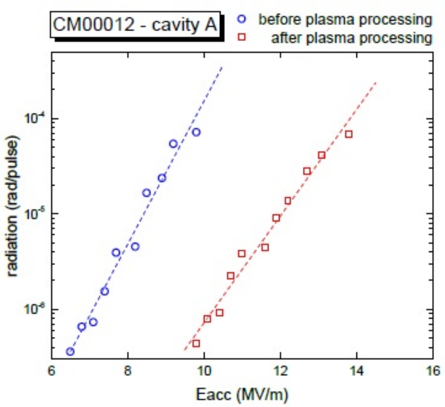
$$J = a\frac{(\beta E)^2}{\phi} e^{-b\frac{\phi^{3/2}}{\beta E}+\frac{c}{\phi^{1/2}}}$$

$$dJ = 0 \quad \Rightarrow \quad \frac{dE_{acc}}{E_{acc}} \approx \frac{3}{2}\frac{d\phi}{\phi}$$

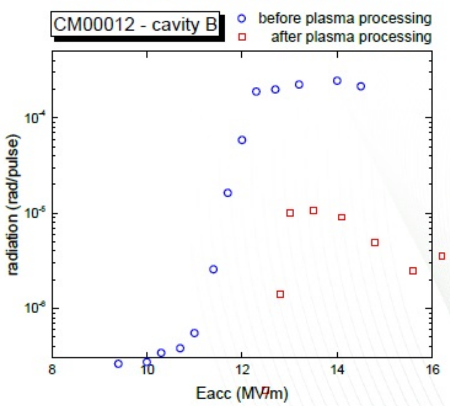


- Examples of radiation signals from two cavities
- Plasma processing has been observed to reduce radiation related to both field emission and multipacting
- Reduction varies between cavities

Field emission regime



Multipacting regime



Summary and present status

1 offline cryomodule
2 cryomodules in tunnel
Improvements of Eacc
10 MV/m per cryomodule increase on average (20%)
No cavity performance degradation from plasma processing observed so far.

Plasma Processing setup for LCLS-II at FNAL, Paolo Berrutti (FNAL)

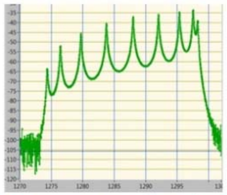
Plasma ignition: forward power needed

- Compared to SNS cavity geometry LCLS-II will require more power to ignite the plasma:
  - lower coupling → nominal Q_{ext} 4E7 (LCLS-II) compared to 7E5 (SNS)
  - 9-cell (LCLS-II) versus 6-cell (SNS) cavity design

CELL #		1	2	3	4	5	6	7	8	9
MODE1	MODE#	8/9pi	8/9pi	5/9pi	7/9pi	7/9pi	7/9pi	5/9pi	8/9pi	8/9pi
	AMP	0.67	0.75	0.75	0.58	0.75	0.5	0.75	0.71	0.67
	dF HBW	0	-1.5	0	1.5	0	-1.5	0	1.5	-1.5
MODE2	MODE#	pi	3/9pi	8/9pi	4/9pi	5/9pi	4/9pi	8/9pi	3/9pi	pi
	AMP	0.33	0.25	0.25	0.42	0.25	0.5	0.25	0.29	0.33
	dF HBW	1.5	0	-1.5	1.5	0	-1.5	1.5	0	-1.5
Total Pf at FPC		160 W	200 W	130 W	280 W	80 W	310 W	130 W	200 W	160 W

- LCLS-II coupler is adjustable: Q_{ext} can be lowered to 3-4E6
- Max forward power needed is very high due to mismatch Q_0=1E4 at room temperature.
- Possibility of igniting plasma in the FPC.
- For π-mode through FPC:

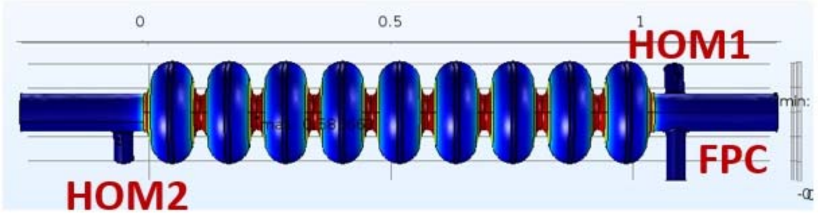
$$\beta = \frac{Q_0}{Q_{ext}} \approx 0.003 \rightarrow |\Gamma|^2 \approx 0.99$$



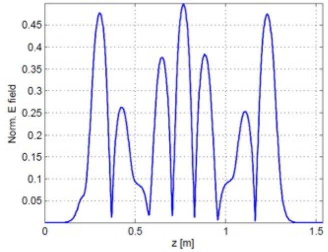
S21 measurement 1st pass-band LCLS-II cavity

Find other method ?

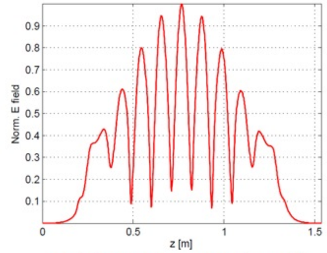
Ignite the plasma on each cell by **FPC + HOM coupler**



- Ignition in cell #5 assuming needed E_{pk}=12 kV/m.

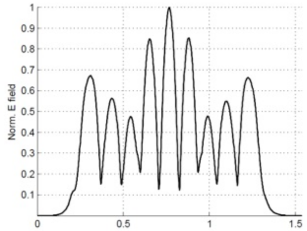


1st pass-band: 7/9pi mode



2nd dipole band: 1st mode

β	0.0046
P_f W	30
P_c W	<1
E_{pk} kV/m	6
$\|\Gamma\|^2$	0.982



β	0.97
P_f W	<5
P_c W	<5
E_{pk} kV/m	6
$\|\Gamma\|^2$	0.0003

- SNS dual tone excitation technique shows good results also for 9-cell cavities.
- The combination of 1st pass-band modes and HOMs looks promising and it will be used to overcome possible FPC ignition due to low coupling at room temperature.
- HOMs plasma ignition requires low power: safe for cables in cryomodule.

WG 2 (final session Chair: Axel Matheisen)

Main topic : Keep clean !!

Goal of all doing cavity integration to modules is
-----Keep gradients and FE onset level of cavities as handed over from VT---

Are there different approaches
- at different Lab ?
- for High or Low beta structures? (this time more focused on low beta structure assembly)

Do different approaches give same statistics?

Lessons learned and improvements found where all can gain from?

Contribution details

11:00 E-XFEL clean room procedure and QC steps

Presenter(s): Dr. Stéphane BERRY *(CEA/Irfu)*
Room: Kellogg Center- 103AB

11:20 Clean room procedures and QC steps that FRIB adopts for assembly of low beta CMs

Presenter(s): Mrs. Laura POPIELARSKI *(Michigan State University)*
Room: Kellogg Center- 103AB

11:40 Study on the choice of isolation valves for the FRIB cryomodules

Presenter(s): Byron OJA *(FRIB)*
Room: Kellogg Center- 103AB

11:55 Presentation describing the clean room procedures and QC steps that ANL adopts for assembly of low beta CMs

Presenter(s): Zachary CONWAY *(Argonne National Laboratory)*
Room: Kellogg Center- 103AB

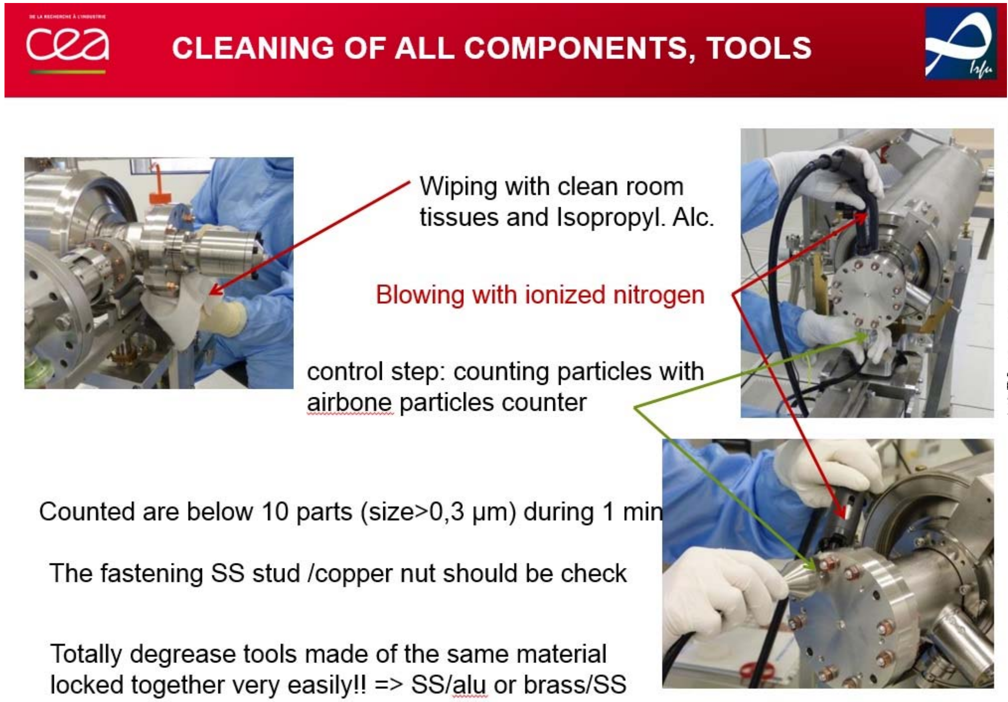
12:10 Discussion on clean works procedure including instrumentation preperation

Room: Kellogg Center- 103AB

E-XFEL clean room procedure and QC steps, Stéphane BERRY (CEA)

Clean Room PROCEDUREs

- Written procedures
- DESY Particules free flanges assembly (PFFA)
- Change Procedure in a controlled way (based on data) example solution 3 on cav008 then XM27 then XM54-
- Audits: XM26 mitigate the performance deviation,
  XM54 implement new procedure external auditor,
  XM84 maintain quality at the end



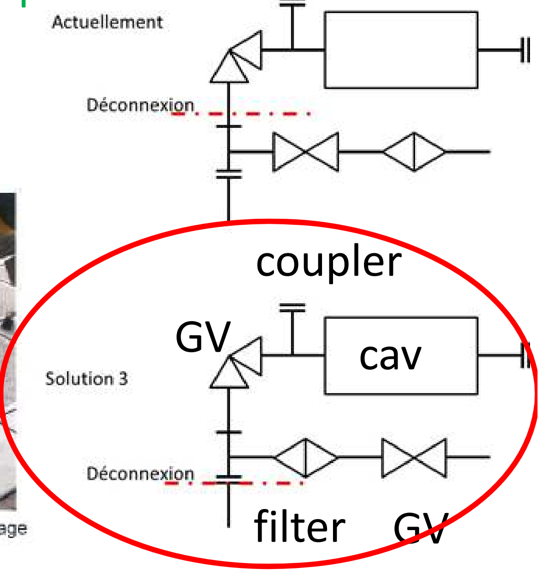
- Vacuum management is critical due to particulate contamination risk
- Problems: as cleaning takes time One-week throughput on SA WS was difficult

Goal: compensate for human factor

reduction of operator time:8H

Only one time open to coupler assembly

2. Raccorder le tuyau d'azote au "T" de balayage Fig. 2)



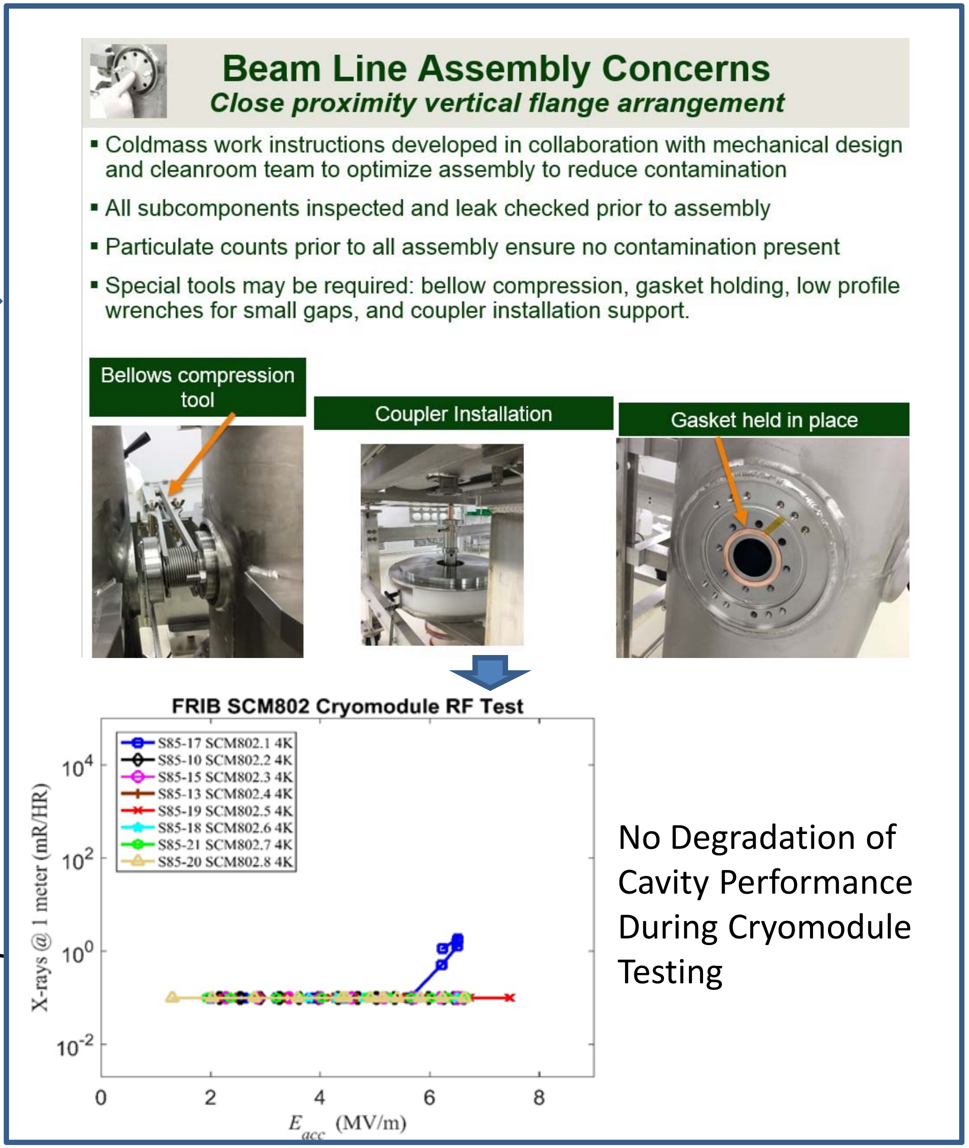
One-week throughput at String Assembly achievable while increasing the quality

A simplification of the clean room procedures was introduced at XM54: **no degradation after**

Clean Room Procedures and QC Steps That FRIB Adopts for Assembly of Low Beta CMs, Laura L. Popielarski (FRIB)

Many QC steps in clean works of low-beta cavity was carried out for Vertical Test Assembly Procedure

- After HPR cavity is dried overnight in an ISO 5 cleanroom
- ports are covered with clean plastic caps to prevent particles from entering
- assembly method starts on the bottom of the cavity and goes up to reduce the contamination from handling hardware above ports.
- cavity is mounted on test insert with a long flexible coupling to make the vacuum connection.
- slow pump and purge processes to pump out and purge at 1 torr/s. A helium mass spectrometer is used to verify the seals
- After testing diligence is done on cleaning the flange and bolt holes prior to disassembly.
- A cleanroom HEPA vacuum cleaner is used to remove loose contaminate and a saturated polyester wipe with isopropyl alcohol is used to clean further.
- This procedure has been validated during vertical testing of cavities and cryomodule tests.



Establishing cleanroom quality control and clean assembly procedures are critical to SRF accelerator performance! → need to be learned more !

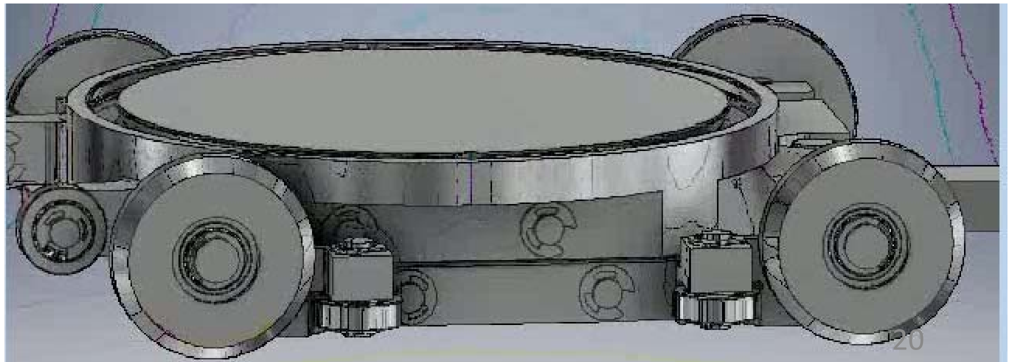
Study on the Choice of Isolation Valves for FRIB Cryomodules , Byron Oja (FRIB)

Gate Valve Use on 0.085 Coldmass

Arisen Issues

- Viton is standard O-ring material for gate valves. FRIB Required radiation resistance which was provided by EPDM
- Valves were evaluated, final 25/52 had very high particle counts
  - Attempted to clean valves, unsuccessful.
- After 2 weeks previously accepted valves were found to be over spec
  - Discovered IPA on a gasket acts as short term lubricant
- Second round particle checks averaged 34 times higher than original
  - Valves will not open after an extended storage period (>1 week)
- Found linkages to be too long and EPDM to be too ‘tacky’
- Replacing linkages enabled valves to open after extended periods in the closed position
  - EPDM remains too “tacky” and continues to cause high particle counts

Study the mechanism of this gate valve

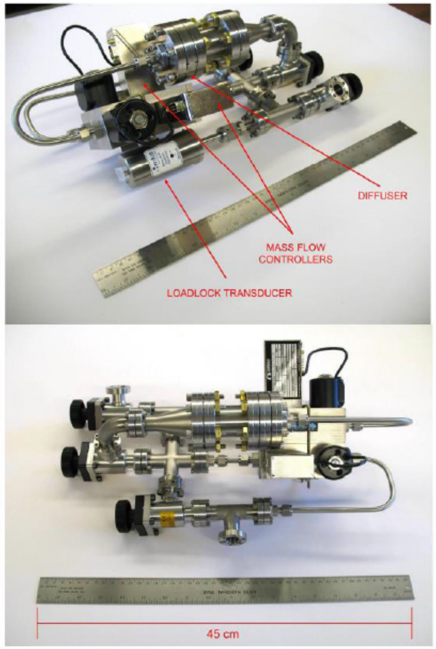


Additional Changes: Baking the O-rings

ARGONNE'S CLEAN ROOM TECHNIQUES FOR CRYOMODULE ASSEMBLY

VACUUM PUMPING/VENTING FLOW CONTROL SYSTEM

- At Argonne the cryomodule pumping and venting is controlled by a pair of mass flow controllers:
  - One for evacuating the volume.
  - One for venting the volume.
- The flow rate is set to 50 mbar l/s.
- The vent gas is filtered with a 0.003 μm diffuser.
- The cryomodule pressure is held ~4 torr above atmosphere prior to opening the clean assembly.
- This system was used to replace all 7 pick-up probes on the 72 MHz QWR cryomodule operating in ATLAS since 2014 with no additional low-particulate cleaning.



K. Zapfe, SRF'07
S. Gerbick, SRF'09

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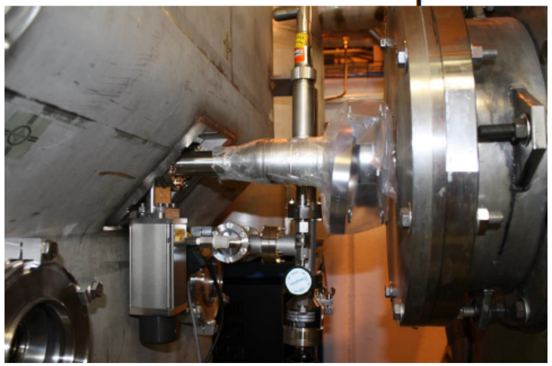
Argonne

HPR With Hand Held Nozzle

Beam Line Cold Trap



Summary of degradation after VTA

- **What are the dominant limiting aspects - field emission, quench, Q-degradation, administrative limits, something else?**

- Limitations are dependent on pulsed vs cw applications (high field vs high Q)
- Field emission - Most dominant or most easily monitored
  - how to monitor to compare VTA and on-line – not easy to do true comparison
    - this is only an issue at installation – should also monitor long-term installed cavity performance with active monitoring
  - Challenge: - more complicated assembly – multiple articles – larger volume to pump
  - Example: Euro-XFEL, C100, STF2, IMP, ANL
- Quality factor – high Q performance easily affected by installation environment (magnetic pollution), details of cooldown (fast vs slow) and cavity material (strong or weak pinning)
  - Since coupler is not typically near critical coupling the Q is inferred from cryogenic measurements with heaters used for calibration
  - Challenge – more cold mass harder to keep field free – may be hard to cool quick enough – fluxgate monitors inside jacket and degaussing coil very useful
  - Example : FNAL LCLS-II CM assembly, KEK VTA, TRIUMF
- Quench – can be associated with high field emission or thermal shorts – can trap flux
- Administrative limits – often applied after CM installation since a conditioning incident could cause an issue only recoverable with an extensive intervention

- **Issues impacting long term operation**

- FE gets worse over time
  - Some indication that first and last cavities are more vulnerable
- MP gets worse over time especially for cw low beta applications
  - Frozen gas changes SEC? – pulse conditioning used in the short term - or warm-up recovers performance
- Trapped flux during quench or during cooldown in a high background field (insufficiently degaussed environment (low beta))
  - Quench annealing may work in the short term – or warm-up after deguass
- Micro-phonics
  - Can cause out of lock trips
- Gradient management
  - OPS turns down cavity to achieve stable operation and lower gradient is accepted without trying mitigations

- **What measures have been tried to cure the degradations, and how successful are these attempts?**

- Helium processing
  - IMP, J-Lab - make effective use
  - 3 e-5 Torr helium added to cavity volume - cw or pulsed conditioning – typical improvement of 10-15% in field on-set but some reported reduction in performance
- High power pulse conditioning
  - Adjust coupling to allow short high gradient pulses at a duty factor to avoid quenches
- Plasma processing
  - Development at SNS moved from test bench to horizontal test cryostat, to CM in test bunker to vault installation
  - FNAL is starting a development with support from SNS and SLAC

What efforts are underway or recommended to minimize contamination during cryomodule assembly and during connection to the beam line, such as particle-free vacuum components next to cold linac sections, especially in segmented linac designs with a large number of warm beam lines between modules?

- Low beta and high beta techniques have converged
  - start with clean components and keep it clean during assembly
  - Any good QA program requires good records and procedures, inspection reports, training and cross checking
- Connection of the CM to the beamline
  - Local clean tents used
  - Slight overpressure of filtered N2
  - Clean parts
- When installing new module into an older system a cold trap has been used to stop migration of volatile pollution

That’s all . Thank you.