

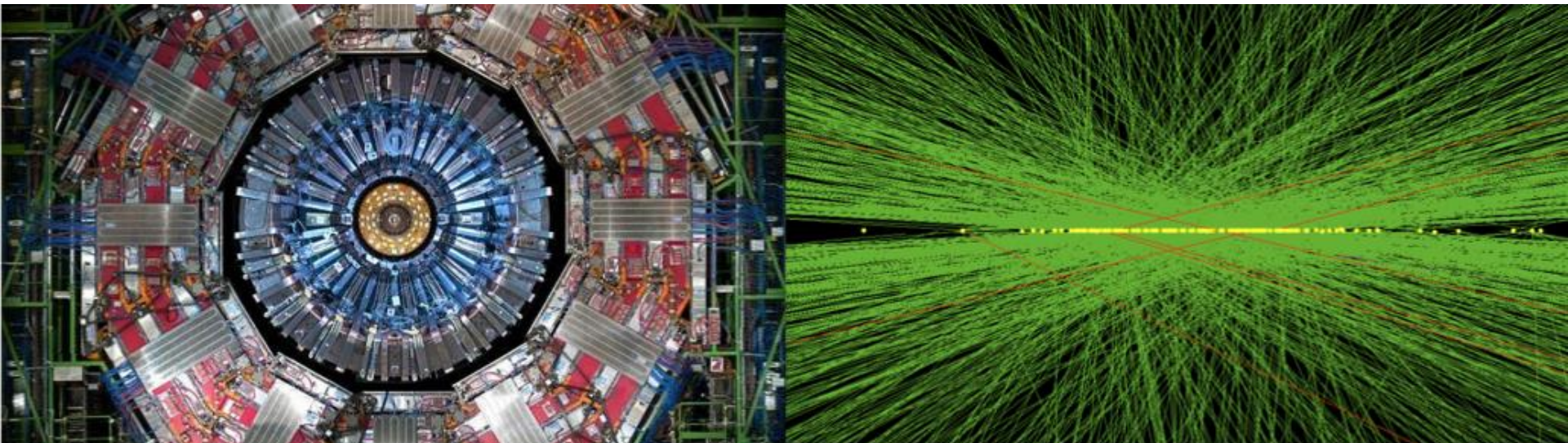


Vendor Qualification and Readiness: GEM Foils

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GE2/1 Engineering Design Review

May 22, 2019

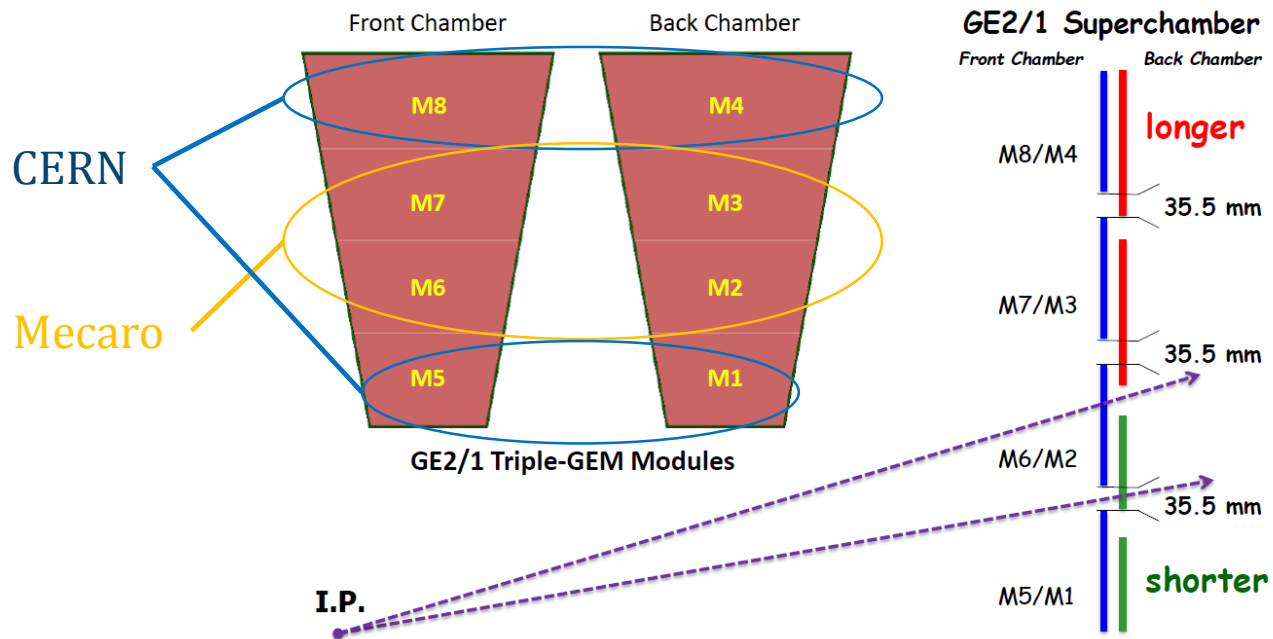


Outline

- GEM foil production planning
- Manufacturing technologies
- GEM foil production at CERN
 - CERN QA/QC procedures
 - Production rate and schedule
- GEM foil production at Mecaro
 - Mecaro Large-Size GEM Foil Validation
 - First Mecaro GE2/1 Size Foils
 - Mecaro QA/QC procedures
 - Production rate and logistics
- Summary

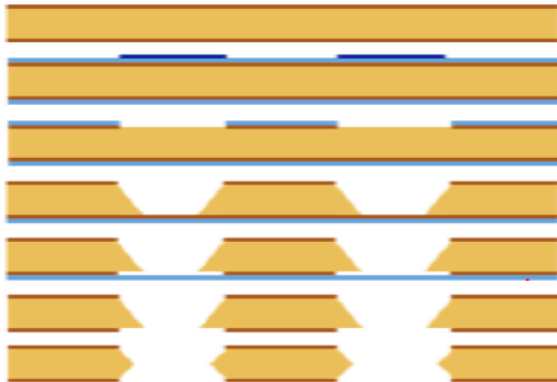

GEM Foil Production Planning

- GE2/1 project GEM foils:
 - 8 module types: M1-M8
 - 114 (108=18*2*3+6 spares) GEM foils for each module type
- Foil production is split between two vendors:
 - CERN: M1, M4, M5 and M8.
 - Mecaro: M2, M3, M6 and M7.



Manufacturing Technologies

- Two technology types: similar performance

	Single mask	Double mask
Production method		
Mask alignment	No need (film)	Crucial (glass)
Cost of necessary machines	Inexpensive	Expensive
Producible foil size Max.	Limited by raw material	Limited by machine
Production process	Complex	Simple
Production rate	Slow	Fast
	CERN, Micropack, Techtra	Mecaro

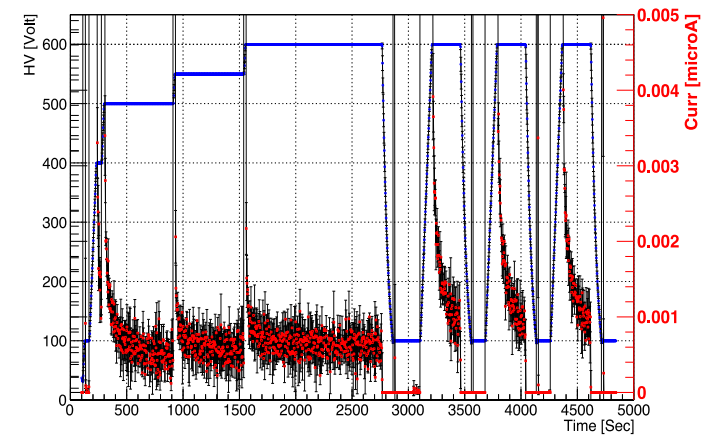
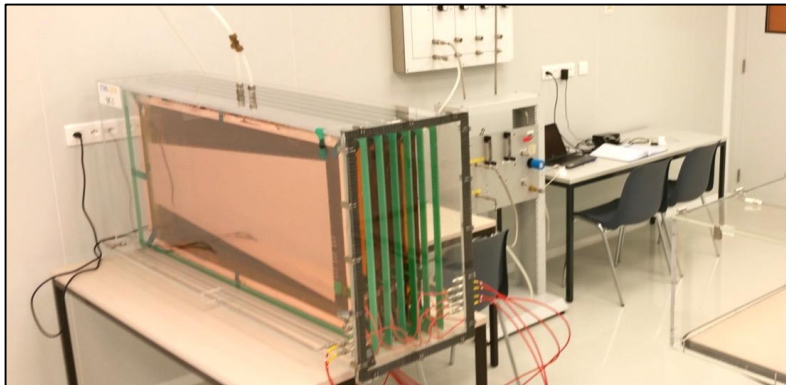
Foil Production at CERN

- Single-mask technology to produce large size foils
 - Asymmetric holes
 - The impacts of asymmetry on detector properties are well understood. <https://doi.org/10.1016/j.nima.2018.11.017>
 - No fundamental limitation on size of GEM foils
- Capacity and manufacturing rate are well understood and validated:
 - Experience of GE1/1 illustrates its capability for mass production
- Production testing and quality assurances are well understood:
 - All 144+17 CMS GE1/1 chambers that are now complete use CERN foils <https://doi.org/10.1016/j.nima.2018.11.035>
 - Of the 483 GEM foils have been produced at CERN for the GE1/1 project, only one foil over the full mass production rejected.
 - Cleaning protocol is effective, only about 7-8% of the foils needed second round of cleaning
- Full GE2/1 chamber prototype testing and validation:
 - 8 complete prototype chambers have been assembled and tested
 - The chambers successfully passed testing and meet all the requirements (TDR)



CERN QA/QC Procedures

- QC1: diameters, uniformity of diameters
 - Performed by CERN MPGD Lab.
- QC2: foil cleanliness, long term stability
 - Fast: with a HV of 500V connected, leakage current and the number of discharges are measured for 10 min.
 - Long: stress test + with a HV of 600V connected, leakage current and the number of discharges are measured for 6 h in dry condition
 - A foil passes if the leakage current < 5 nA, and the number of discharges < 2

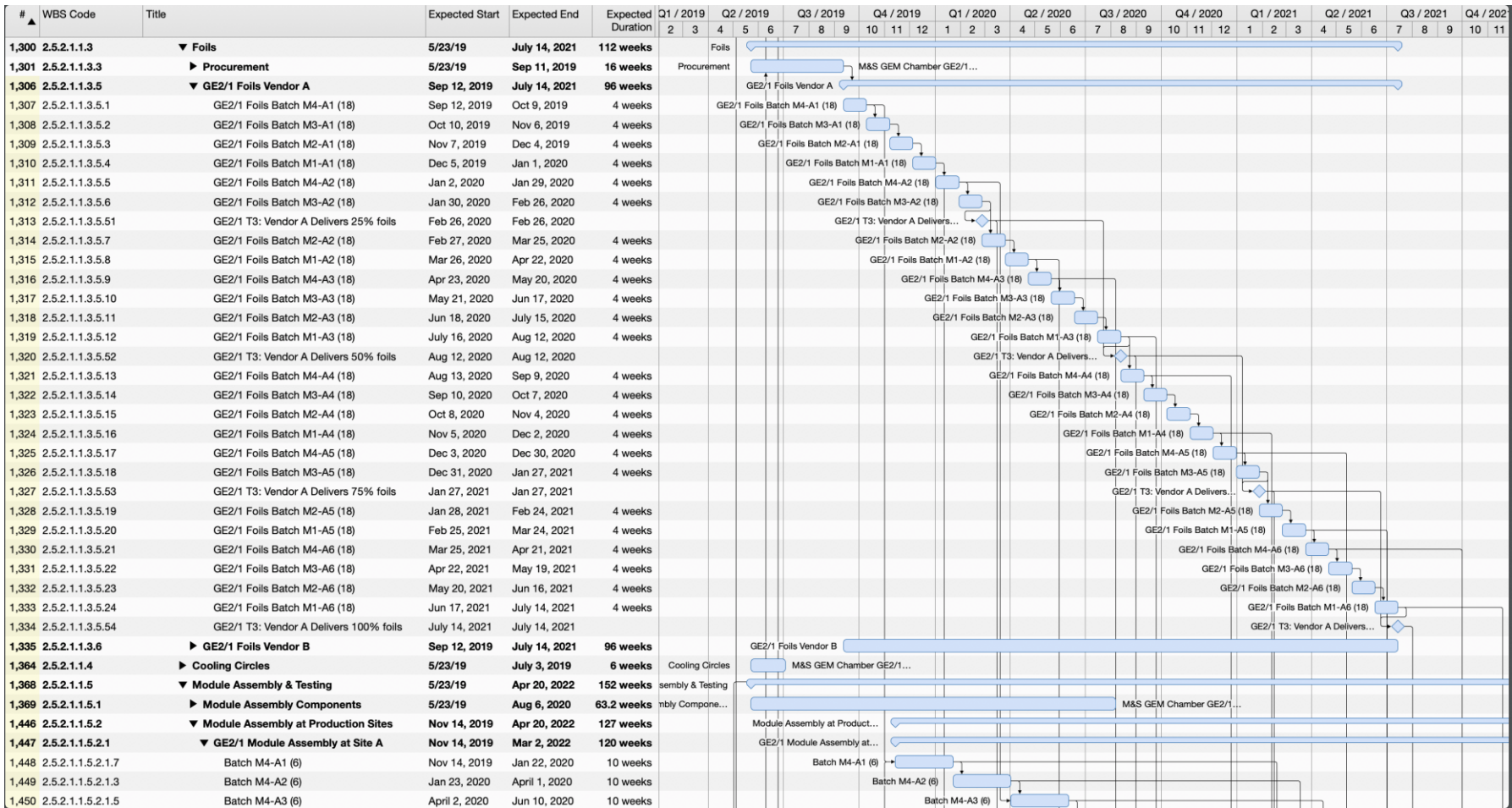


GE2/1 CERN Foil Production

- GE2/1 production rate in terms of frames/month:
 - Production rate of 12 frames/month per technician based on GE1/1 experience
 - Two technicians fully devoted to GE2/1 foil production
- Convert into the foils/month rate:
 - Smaller M1 and M5 type foils: fit two foils per frame: 48 foils per month
 - M4 and M8 type foils: 24 foils per month
- Average rate: 32 foils per month
 - GE2/1 production schedule uses the rate of 18 foils/month per vendor
- Additional capacity is achievable if a need arises
 - CERN site has the ability to allocate additional technicians to increase the production rate
 - Requires 2-3 months to deploy additional resources, up to a factor of two in production yield
 - Scenario studied as part of the developing risk response strategies



Foil Production Schedule



- The schedule above is updated for the shift in the EDR and foil PRR dates only
 - E.g. does not take into account potential changes to the LHC schedule

Foil Production at Mecaro

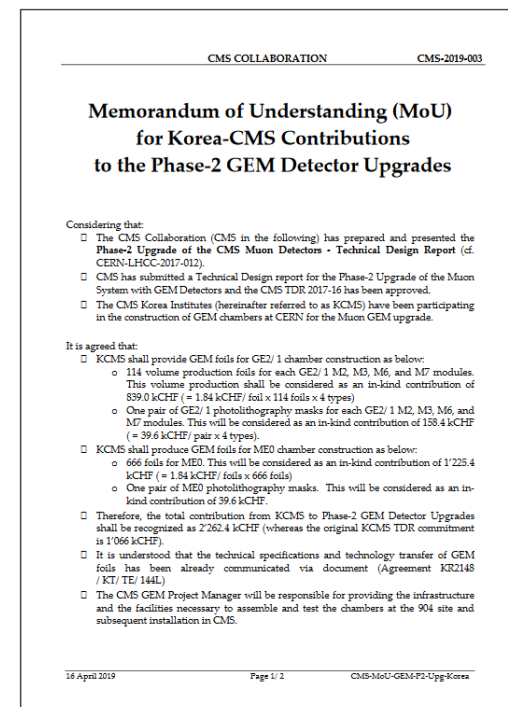
- KCMS and Mecaro have formed a consortium to allow for a second supplier of GEM foils
 - Mecaro is a Korean semiconductor manufacturing company
 - A close partnership and good collaboration with CERN to transfer the expertise and technology
- Double-mask technology:
 - Automatization allows a substantial increase in the production rate
 - Residual misalignment of the masks under $3\mu m$
 - Foil size up to $1300 \times 610 \text{ mm}$
 - Limited by the machine size $1379\text{mm} \times 813\text{mm}$
- Geometry
 - diameter of Cu (PI) hole = $70 \text{ (} 50 \text{)} \mu m$, pitch = $140 \mu m$.
 - Symmetrically biconical holes



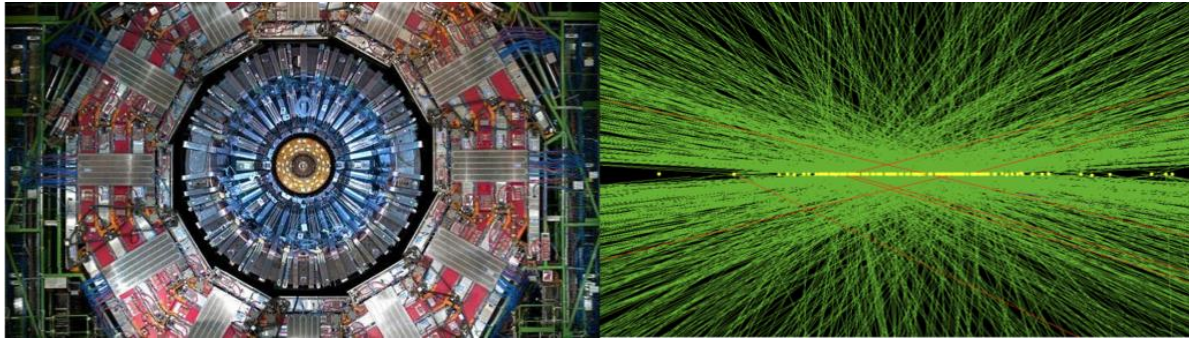
Large size bipolar UV exposure

Mecaro Foil Production Planning

- MoU between Korean government and CMS has been signed.
 - “KCMS shall provide 114 foils for each GE21 M2, M3, M6, M7 modules. This volume production shall be considered as an in-kind contribution of 839.0 kCHF(=1.84 kCHF/foil*114 foils *4 types)”
- Mecaro preparations for mass production:
 - GEM facility is being moved to a new building
 - Not a concern as Mecaro has experience of successfully moving similar facilities in the past
 - Governmental inspection for the environmental safety is scheduled for Aug. 1, 2019
 - Sep. 2019 is a realistic start date for mass production
 - Compatible with the current schedule



Mecaro Large-Size GEM Foil Validation

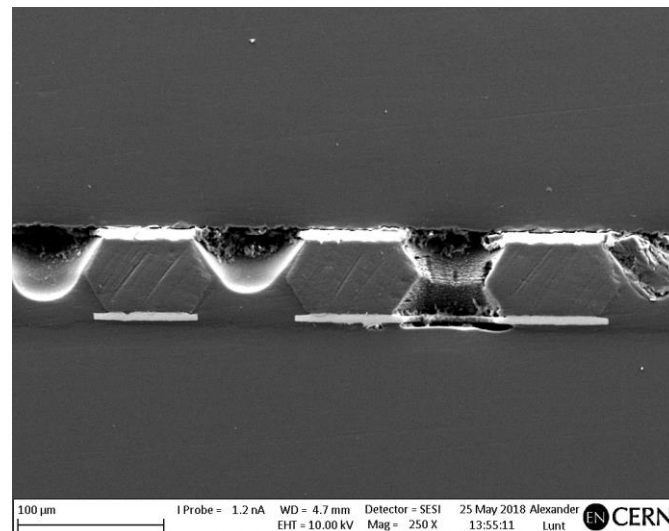


Large-Size Foil Production R&D

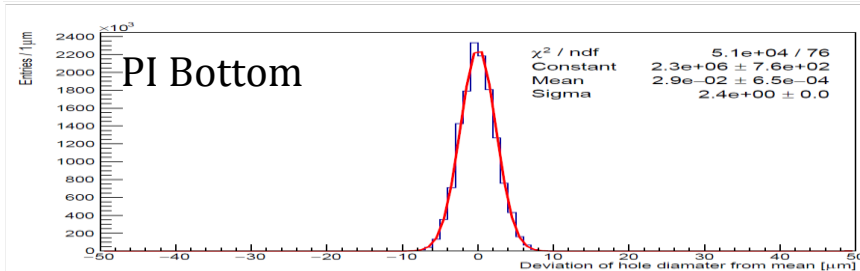
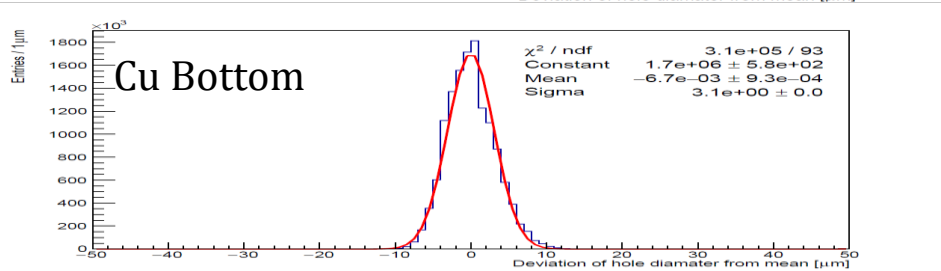
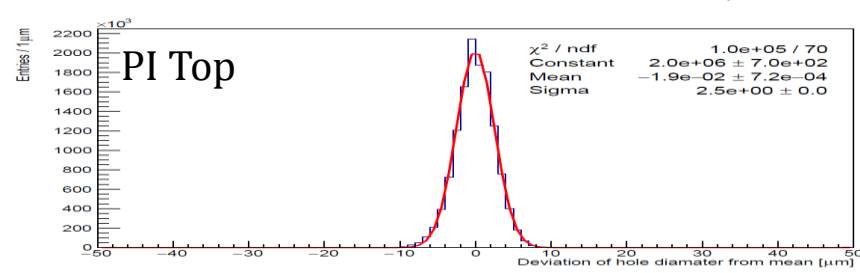
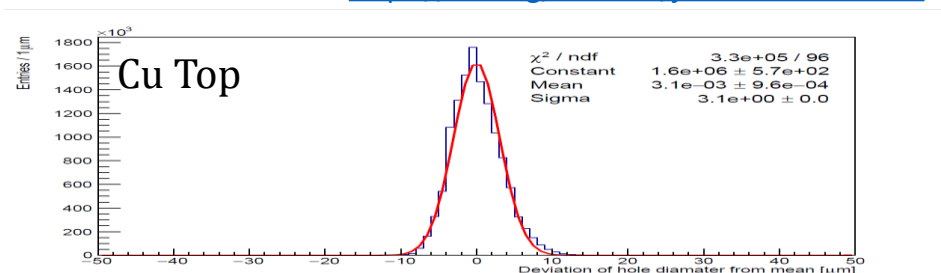
- Extensive early work to establish generic GEM foil production capabilities using double mask technology
 - 10x10 cm and 30x30 cm foils since 2012
- Since 2017, shift focus to working out the manufacturing flow for large-size foil production and establishing QA/QC procedures
 - **Batch 1: Dec 2017:**
 - Aim to qualify Mecaro's ability to produce large-size foils of the required geometry
 - Goal achieved, but validation revealed that a pasting Ag epoxy has been missed at Mecaro. The missing step has been performed at CERN following foil re-cleaning.
 - **Batch 2: Jan. 2018:**
 - Aim to exercise the full production cycle for the first time including updated QA/QC procedures and assess the production rate capabilities
 - Achieved, but the QC2 discovered that the foils short or spark at lower voltages than expected. Traced to insufficient foil cleaning. Cleaning protocol and packaging methods have been revised, including the use of a different solution. Introduce additional QC stages to be performed at the production site at Mecaro
 - **Batch 3: Jun. 2018:**
 - Aim to iterate on the improvements established following batch 2
 - Goal achieved: foils have successfully passed all standard CMS GEM QC tests
- Valuable technical experience as well as establishing efficient communication lines and technical collaboration with Mecaro
 - Mecaro and Korean physicists working together on identifying and correcting issues, training of the personnel at Mecaro, a much improved understanding of the process

Mecaro Foil Validation: Geometry

- Double mask technology became well understood yielding desirable mechanical parameters
- Measured hole diameter using a microscope (sampled over 450 holes):
 - Cu: $70.24 \pm 0.91 \mu\text{m}$
 - PI: $49.04 \pm 0.79 \mu\text{m}$
- Hole uniformity measured using the automatic CCD
 - Hole uniformity exceeds requirements
 - Thanks to M. Posik (Temple Univ.)
 - <https://doi.org/10.1016/j.nima.2015.08.048>

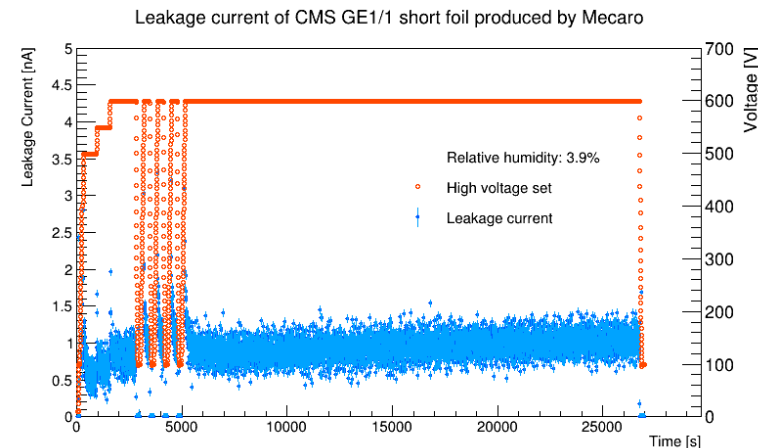


Cross section of Mecaro GE1/1 foil



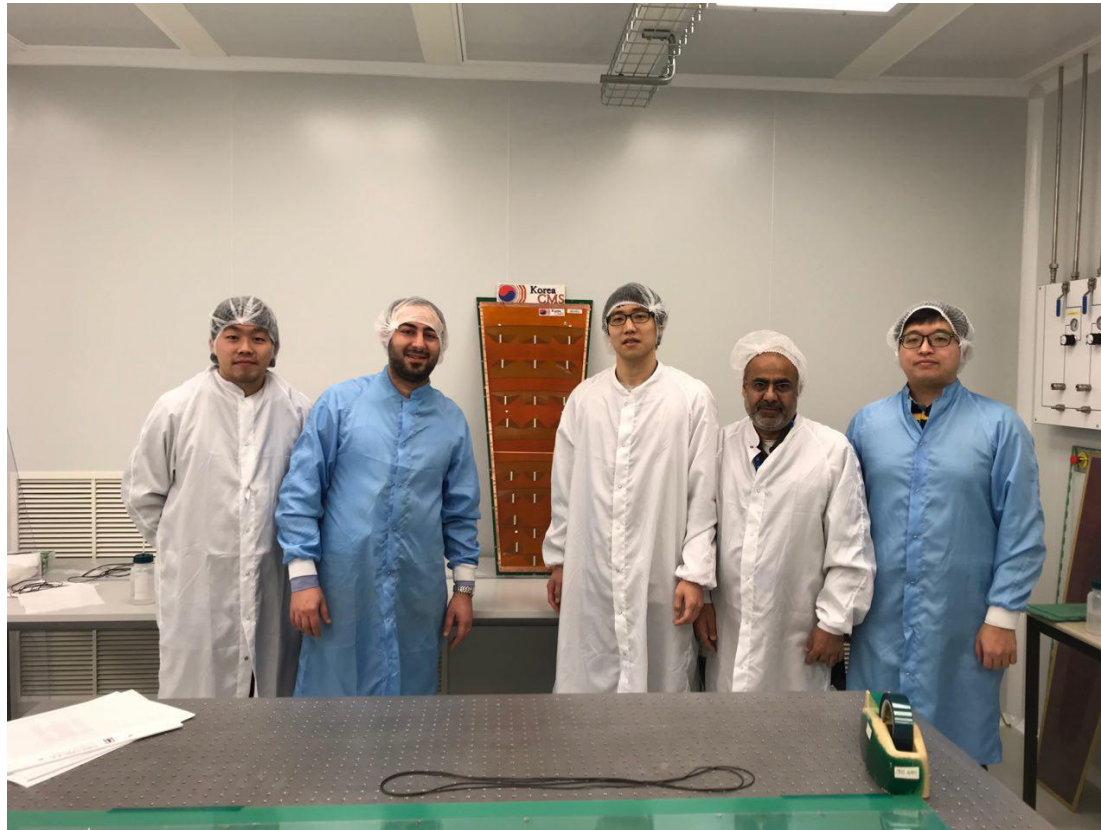
Mecaro Foil Validation: Electrical

- Foil cleanliness is a critical parameter affecting foils performance
 - Evaluated using the standard CMS GEM QC2 protocol
- Early problems with the first large size foils have been understood, including full understanding of the causes, and corrected
 - See page 12



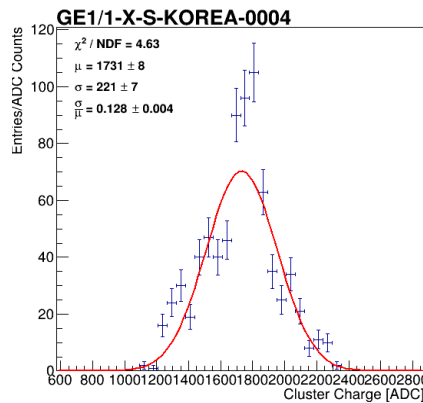
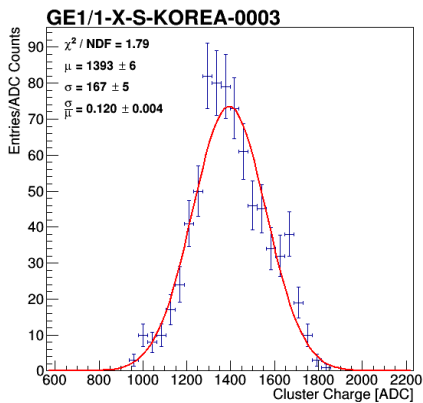
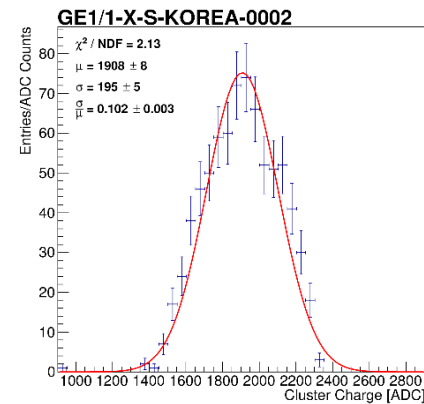
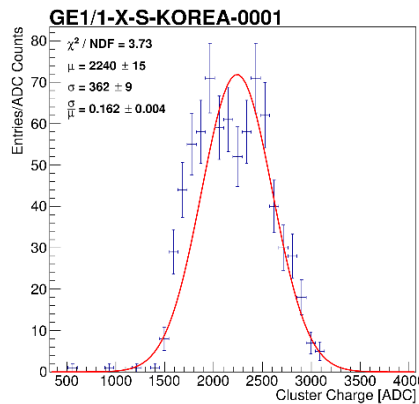
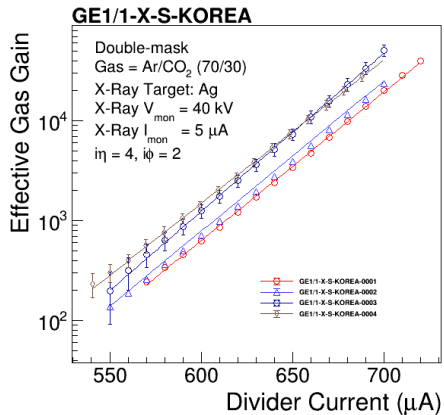
Mecaro Foil Validation: Assembly

- Four GE1/1 chambers with Mecaro foils assembled at CERN
 - Full standard QC testing
 - Gas tightness, I-V curve, spurious signal rate, gain, gain uniformity etc.
 - Additional measurements: rate capability, aging, discharge probability
- Meets and exceeds the requirements for HL-LHC operations



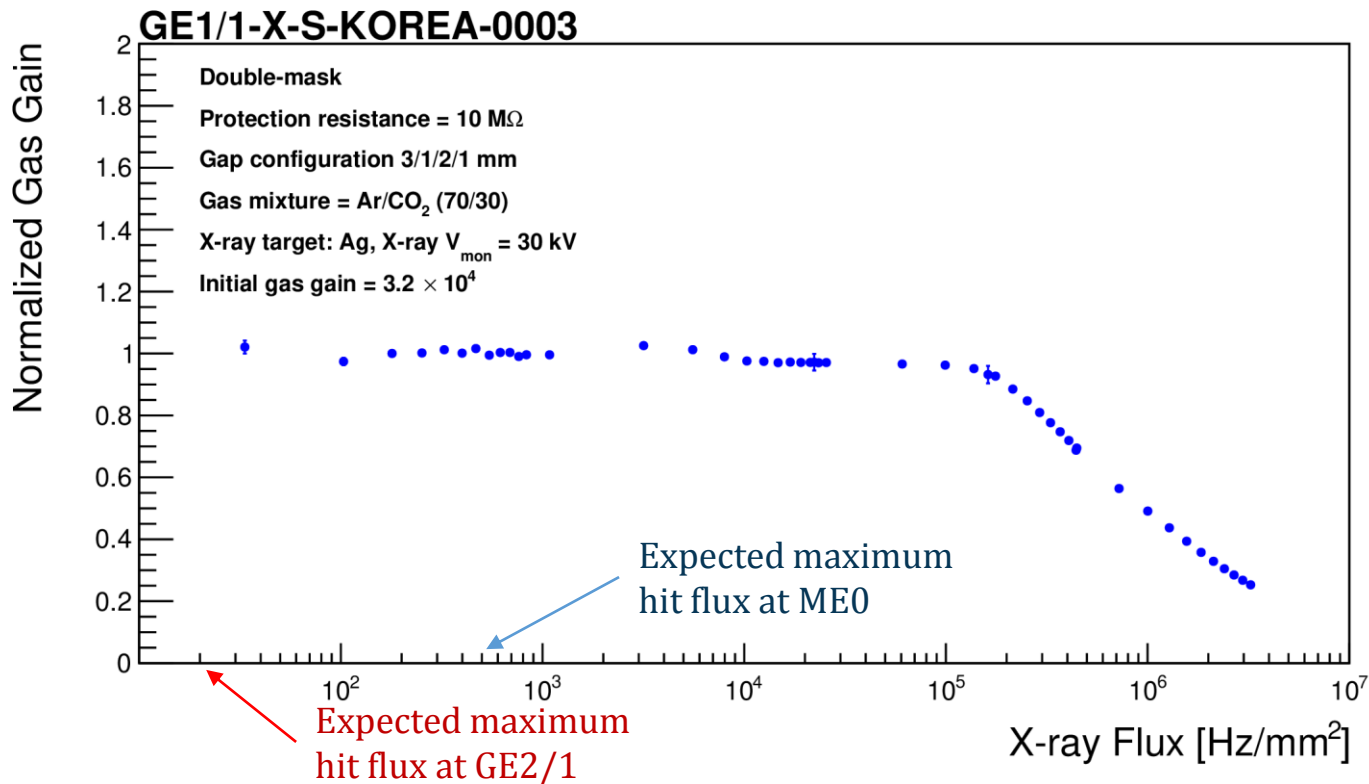
Mecaro Foil Validation: Gain

- Gain measurements consistent with the detectors built with CERN foils
 - Gain: $0.5 - 1.1 \times 10^4$ at $660 \mu\text{A}$ (operating voltage)
 - Gain variance: 10-16%
- Meets and exceeds the requirements for HL-LHC operations



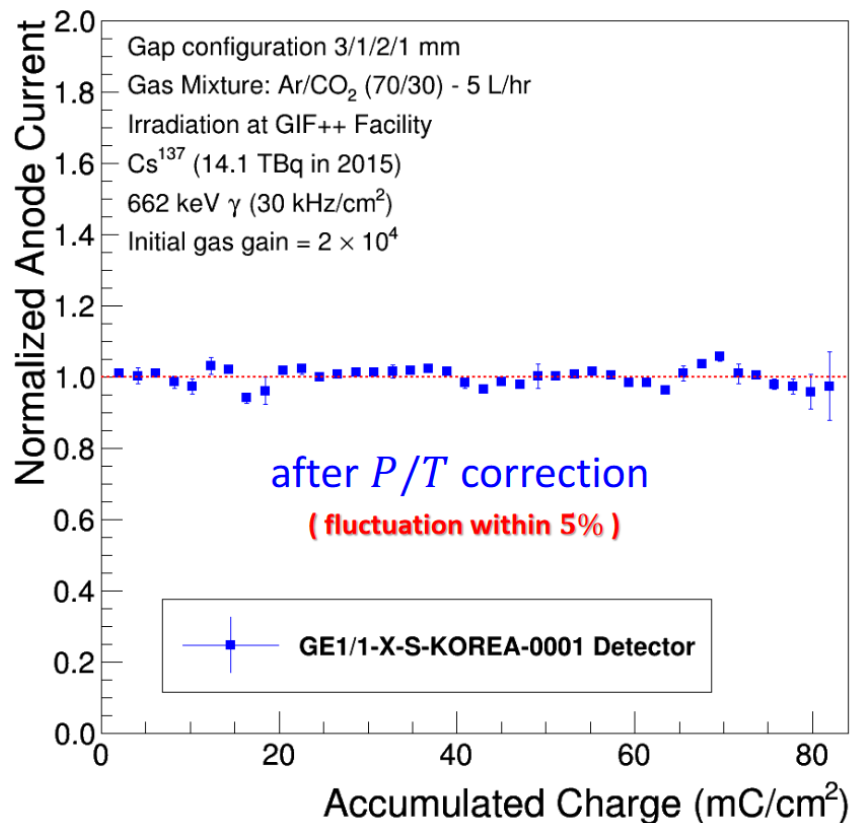
Mecaro Foil Validation: Rate Capability

- Gain remains stable x-ray flux up to $1 \times 10^5 \text{ Hz/mm}^2$
 - Gain drops at very high flux because of voltage drop at the protection resistor
- Meets and exceeds the requirements for HL-LHC operations



Mecaro Foil Validation: Aging Properties

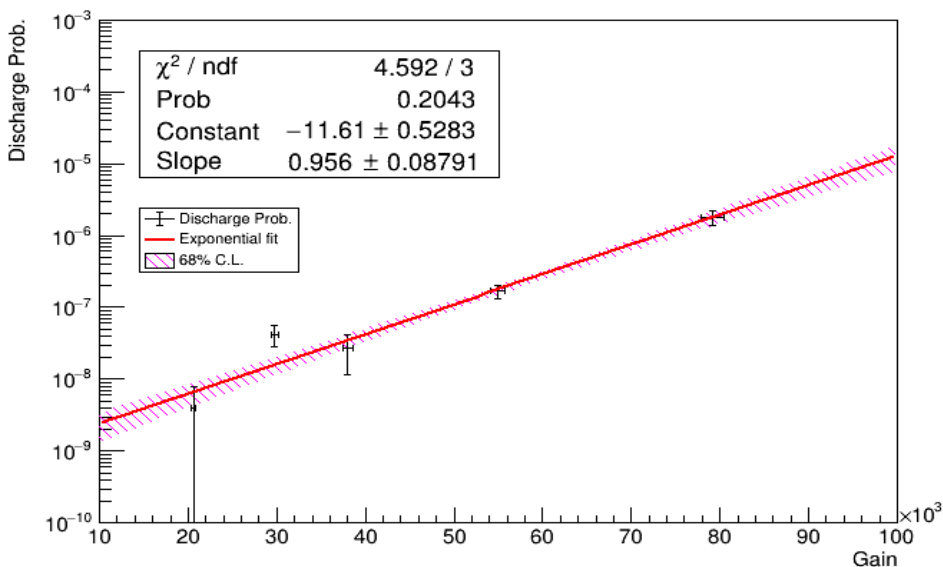
- No gain degradation due to aging is observed up to 82 mC/cm²
 - Corresponds to 273 years of GE2/1 operations at HL-LHC
- Meets and exceeds the requirements for HL-LHC operations



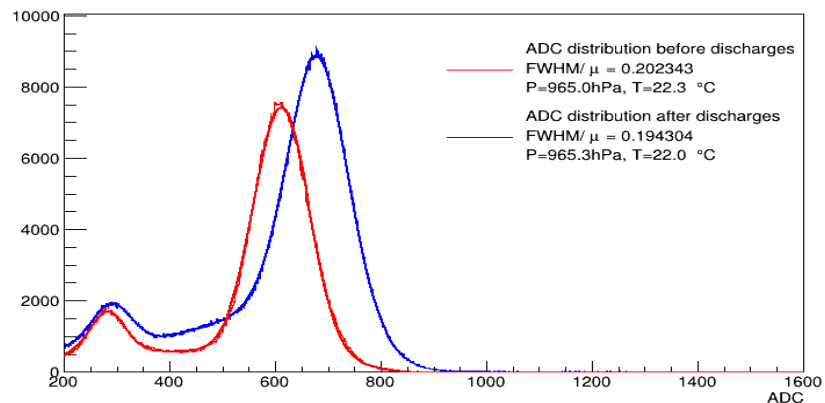
Mecaro Foil Validation: Discharges

- Probability of discharge induced by α from ^{241}Am .
 - Discharge Prob. (at gain= 1×10^4) = $2.4 \times 10^{-9} \pm 1.0 \times 10^{-9}$.
 - No degradation on detector performances after 229 discharges
- Meets and exceeds the requirements for HL-LHC operations

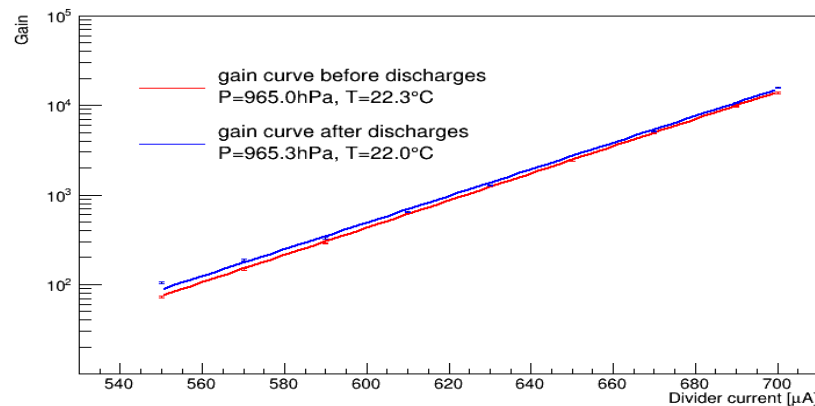
Discharge Prob. Vs. Gain, 5.5 MeV α



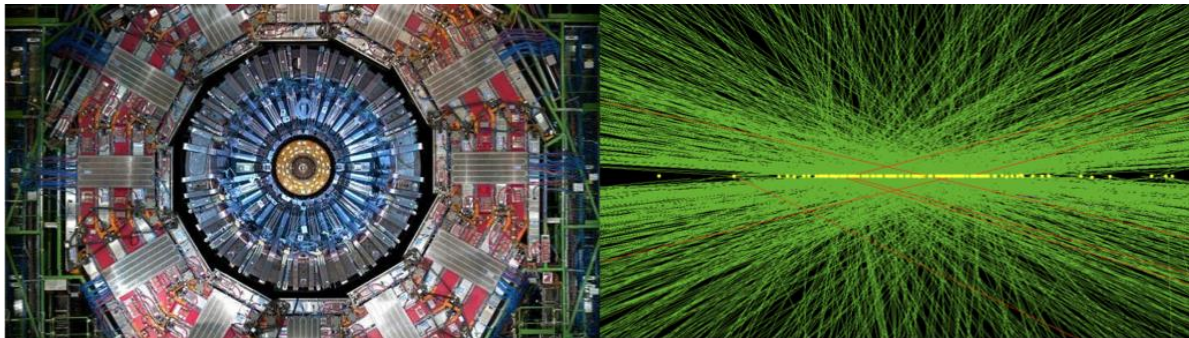
ADC distribution before/after discharge Prob. measurement



Gain curves before/after discharge Prob. measurement

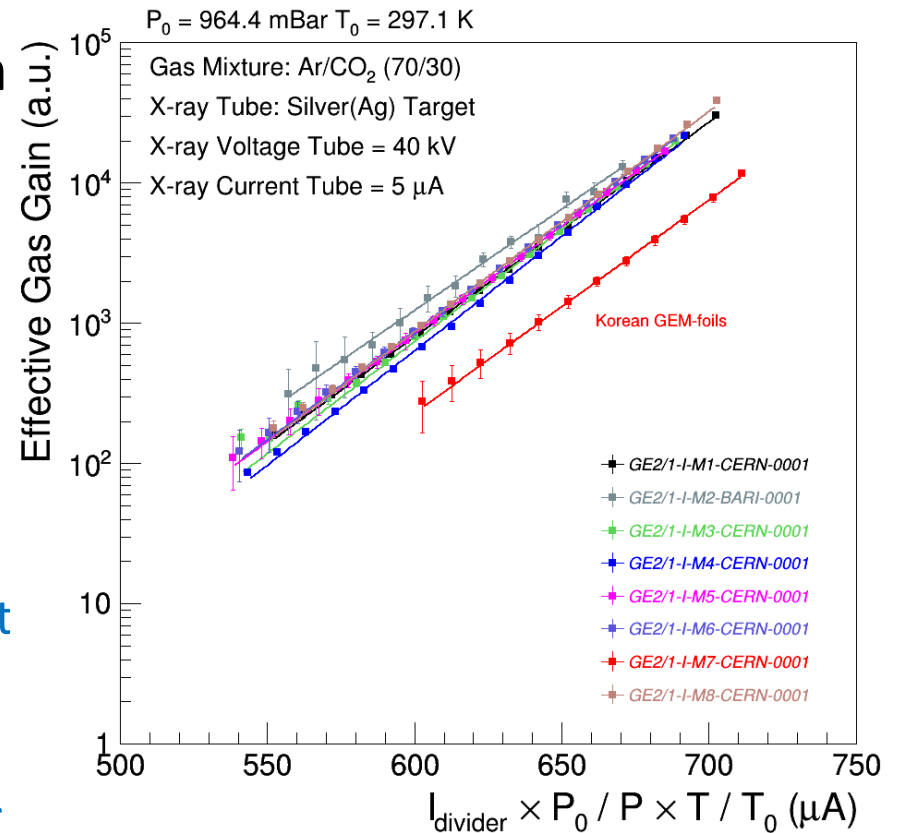


First Mecaro GE2/1 Size Foils



First GE2/1 Mecaro Foils Validation

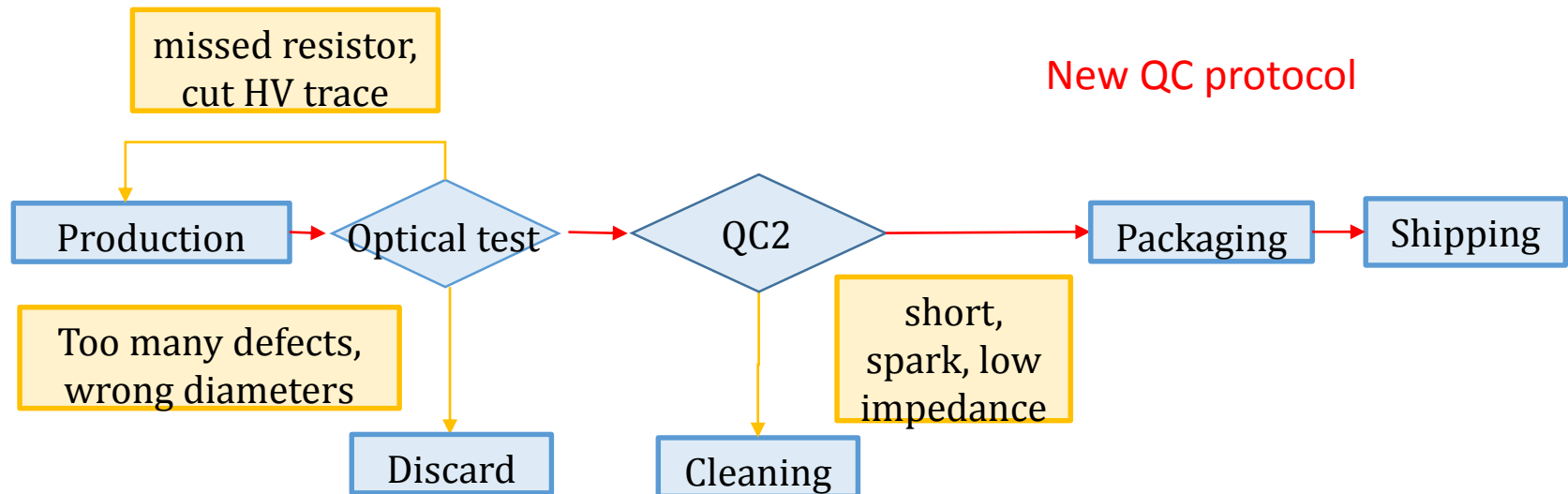
- First batch of GE2/1 M7 type foils produced and delivered in Dec. 2018
 - Aim to exercise to produce actual GE2/1 foils, perform the full chain of QA/QC flow and measure the production rate
- Production QC and Standard CERN QC acceptance tests:
 - No reported problems during production
 - Successfully passed then-current QC protocol at Mecaro site
 - Successfully passed acceptance tests
 - Assembled chambers passed QC tests up to and including QC5 gain uniformity measurement
 - Failed QC5 absolute gain measurement



GE2/1 M7 module with Mecaro foils shows 3-4 times lower gain than expected

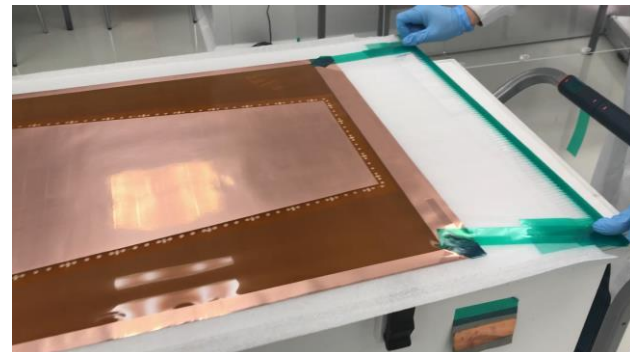
First GE2/1 Mecaro Foils Validation

- Investigation of the causes and a review:
 - Foil holes geometry not to spec: larger than required Cu holes and smaller PI holes
 - Traced to an incorrect setting of the machine's etching time parameter at Mecaro
 - Then-existing QC protocol has been followed appropriately, but failed to detect the problem
- Response:
 - Modified standard production QC procedures to include optical tests to perform explicit measurement of the foil mechanical properties in addition to QC2 testing will allow immediate identification of similar problems in the future
- Double-segmented GE2/1 foils with proper geometry will be delivered once Mecaro is back to online



Production Rate & Logistics

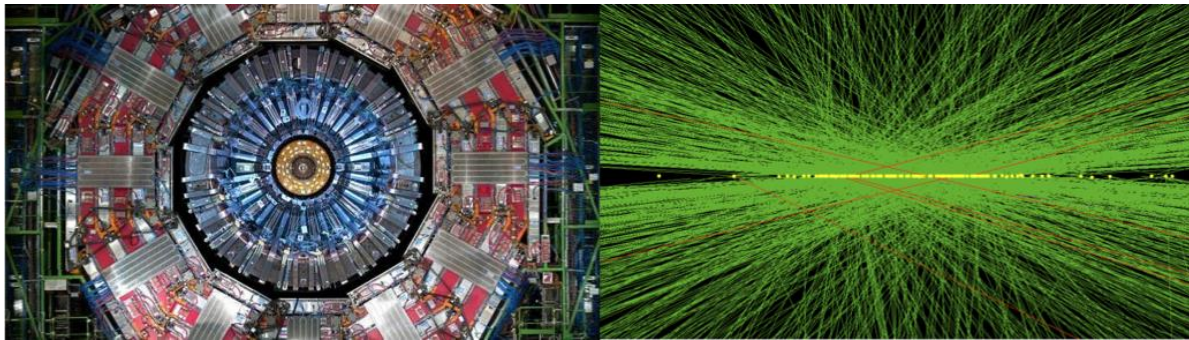
- Current production rate at Mecaro is 40 foils/month
 - Limited by the technicians time for soldering the resistors, not by the machine
 - Expect the rate can be increased by as much as ~50% with current manpower
 - If need arises, Mecaro will be able to allocate additional manpower
- Shipping logistics:
 - A custom built container: foils are protected by anti-static sheet, foam and poly-carbonate sheet
 - Shipping and export/import documentation handled by an experienced company that has been working with KCMS for many years (supplied RPC gaps for CMS)



Summary

- GEM foil manufacturing preparations for the CMS GE2/1 project is well on track
 - Two vendors: CERN and Mecaro (Korea)
- High confidence in the developed production plan:
 - CERN MPGD lab: extensive record and past experience; capacity and rate meet the requirements for the GE2/1 GEM foil needs:
 - Capability to increase the production rate studied as part of the project's risk management program
 - Mecaro: demonstrated ability to manufacture large-size GEM foils, high production yield capabilities, a well established QA/QC protocol

Backup



Large Foil Validation (Mecaro)

	Requirement	Measured	
Diameters	Cu: 65-75 μm PI: 50-55 μm	Cu: 70.24 \pm 0.91 μm PI: 49.04 \pm 0.79 μm	
Cleanliness	Pass QC2 fast and long	Pass since The 3 rd GE1/1	
Gain	$(1.0 \pm 0.5) \times 10^4$ @ 660 μA	$0.5 - 1.1 \times 10^4$ @ 660 μA	
Gain variance	Less than 36 %	10-16 %	
Rate capability	Larger than $2.1 \times$ $10^1 Hz/mm^2$	$1 \times 10^5 Hz/mm^2$	
Aging	Larger than $9mC/cm^2$	$82mC/cm^2$	Ongoing for ME0
Discharge Prob.	Does not impede performance or operation	$2.4 \times 10^{-9} \pm 1.0$ $\times 10^{-9}$	induced discharge by α from ^{241}Am