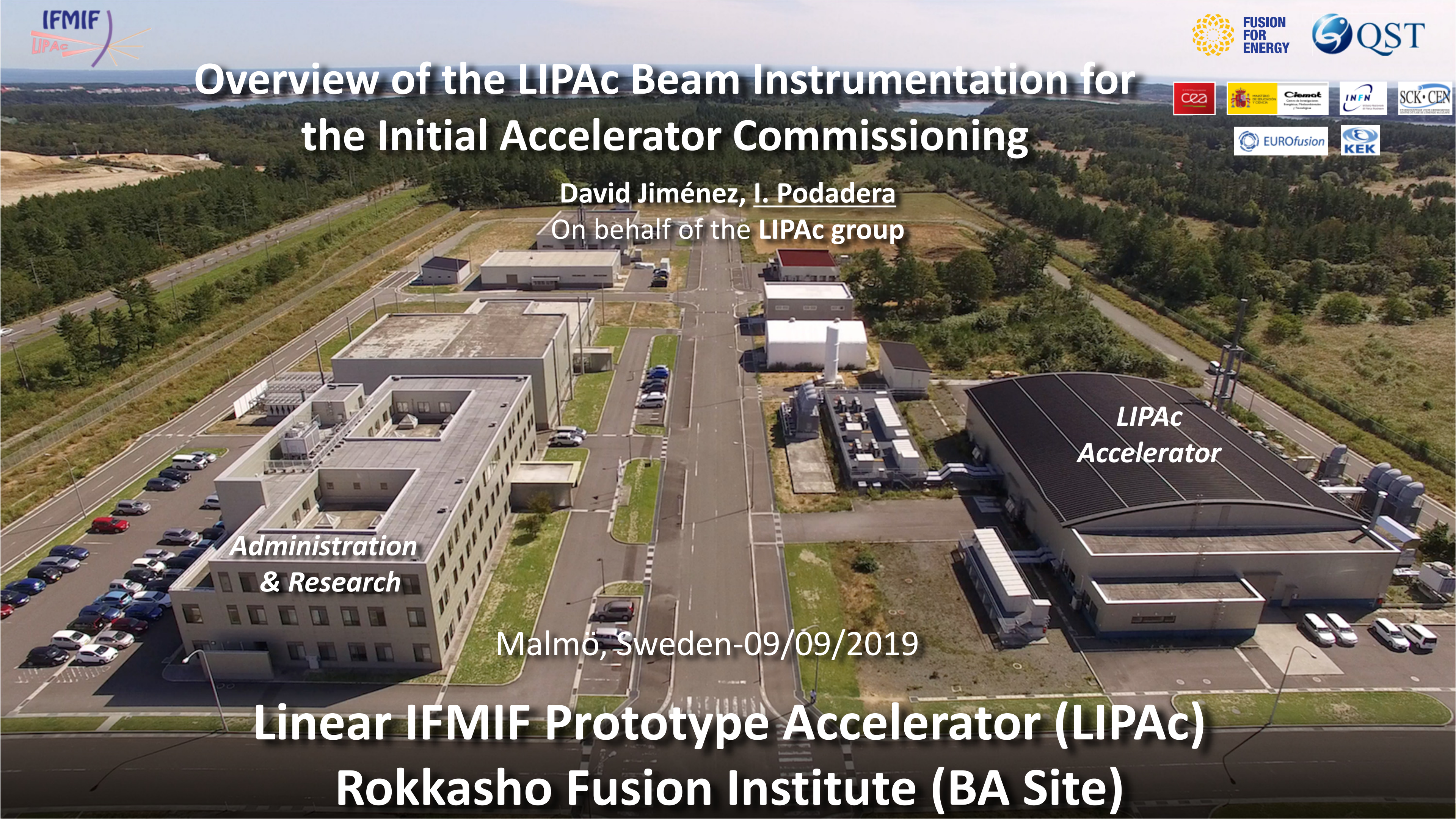
# Overview of the LIPAc Beam Instrumentation for the Initial Accelerator Commissioning

David Jiménez, I. Podadera
On behalf of the **LIPAc group**




Malmö, Sweden-09/09/2019

## Linear IFMIF Prototype Accelerator (LIPAc)
## Rokkasho Fusion Institute (BA Site)

# A collaboration work

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*ESS-Bilbao*: Ángel Rodríguez
*IREC*: Oriol Nomen

& the **LIPAc group**

# Summary

## IFMIF/EVEDA & LIPAc

## LIPAc Beam Instrumentation

## Feedback from different instruments

- Current measurements
- Beam position and phase measurements
- Interceptive profile measurements
- Transverse emittance measurements
- Non-interceptive profile measurements

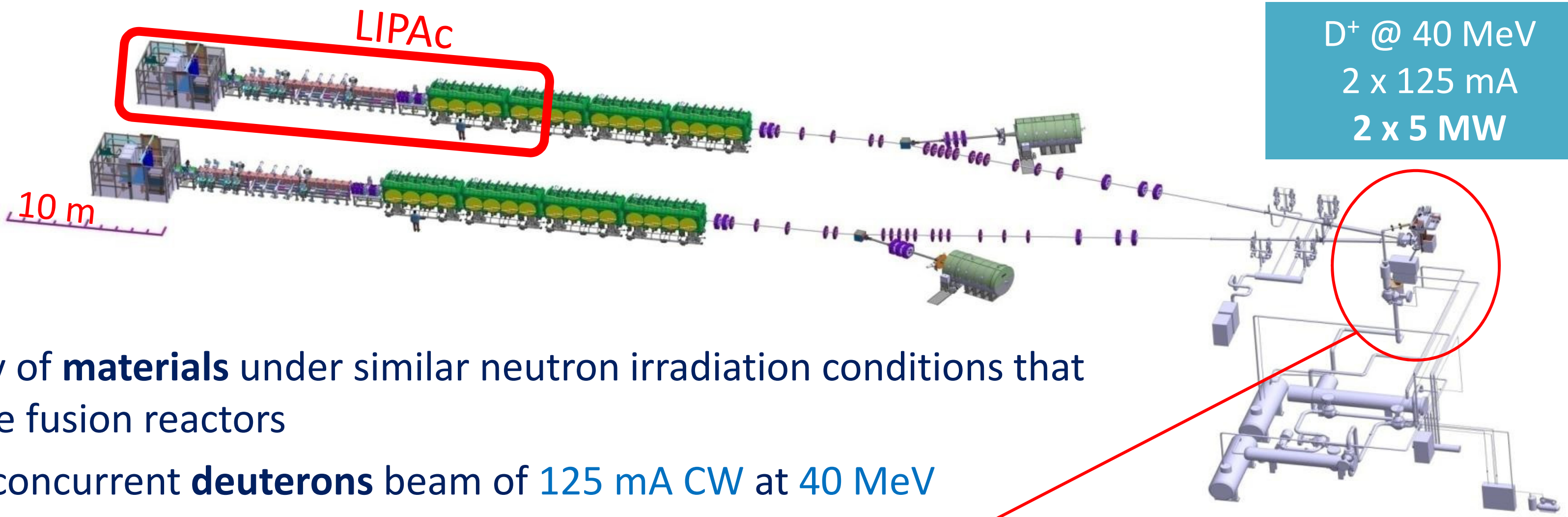
## Conclusions & outlook

# IFMIF-EVEDA & LIPAc

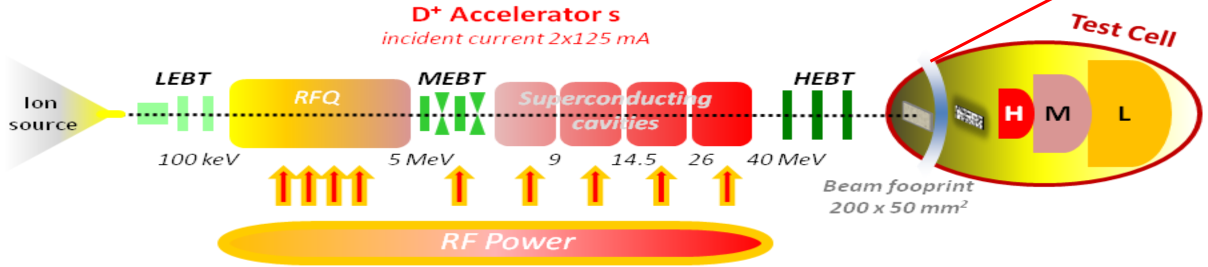
# IFMIF Concept

**IFMIF:** International Fusion Materials Irradiation Facility

D⁺ @ 40 MeV
2 x 125 mA
**2 x 5 MW**




- Study of **materials** under similar neutron irradiation conditions that future fusion reactors
- Two concurrent **deuterons** beam of 125 mA CW at 40 MeV
- Impact on a liquid **Li screen** flowing at 15 m/s




A flux of neutrons of ~**$10^{18}$ n/m²s** is generated in the forward direction with a broad peak at 14 MeV and irradiate three regions:

- >20 dpa/fpy in 0.5 liters (H)
- >1 dpa/fpy in 6 liters (M)
- <1 dpa/fpy in 8 liters (L)

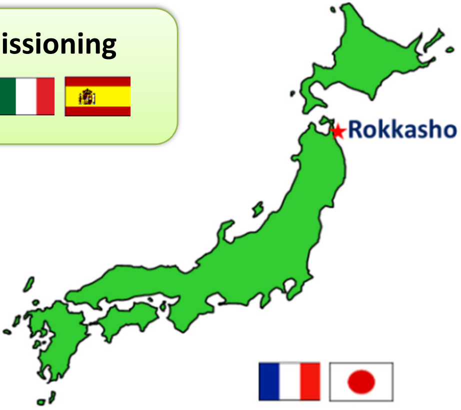
# Japan-Europe scientific collaboration

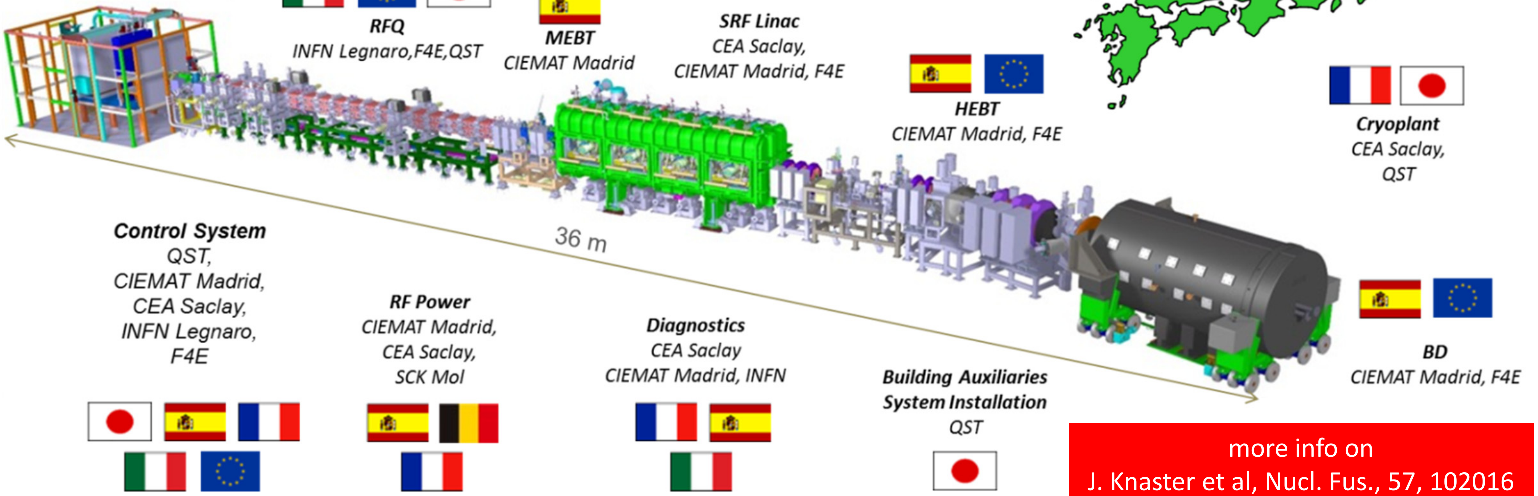
**EVEDA:** Engineering Validation & Engineering Design Activities

**System Installation, Checkout, Start-up, Commissioning**

~50 people

LIPAc (Accelerator Facility)
$D^+$,9MeV, 125mA CW, 1.125 MW




Broader Approach

**JA-EU Collaboration**

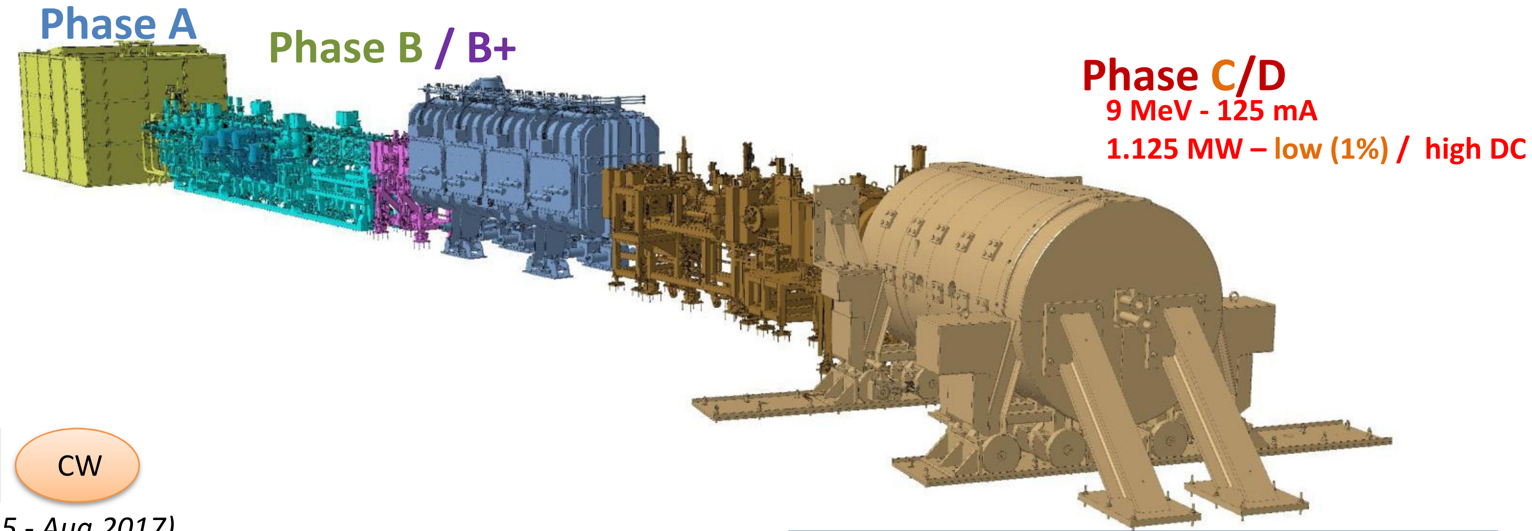
**In Japan**

more info on
J. Knaster et al, Nucl. Fus., 57, 102016

**Equipment designed and constructed in Europe, Installed and commissioned in Rokkasho**

# LIPAc commissioning

## 4 configurations tested in 5 main phases to validate the LIPAc performances




**A** | Injector | CW

*(TESTED Apr.2015 - Aug.2017)*

**B** | Injector | RFQ + MEBT | D-Plate+LPBD | 0.1-1ms

*(TESTED June 2018 – July 2019)*

**Status**
- ✓ **1st $H^+$** @2.5 MeV on June 2018
- ✓ **125 mA $D^+$** @5 MeV on July 2019 (1 ms / 1 s / 625 W)
- ✓ Installation of beam for restart with Phase B+ next spring

**B+** | Injector | RFQ + MEBT | Drift line + HEBT/D-Plate | 1ms-CW | Final Beam Dump

**C/D** | Injector | RFQ + MEBT | SRFL + HEBT/D-Plate | 1 ms/CW | Final Beam Dump

P. Cara, MOPOY057, IPAC'16

M. Sugimoto, TU2A04, LINAC'18

# LIPAc Beam Instrumentation

# LIPAc Beam Instrumentation

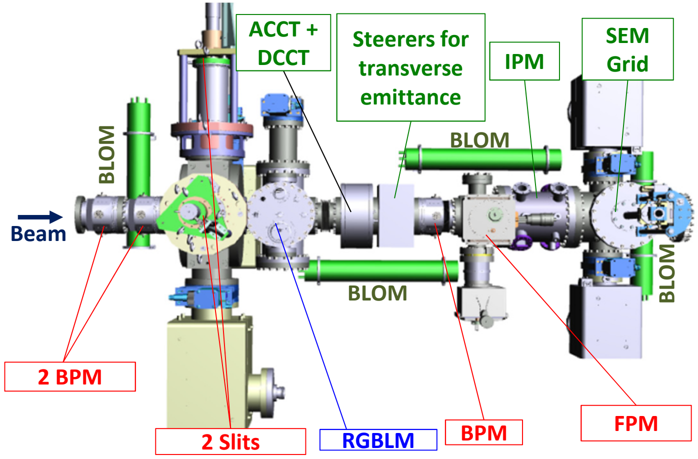
## Challenges

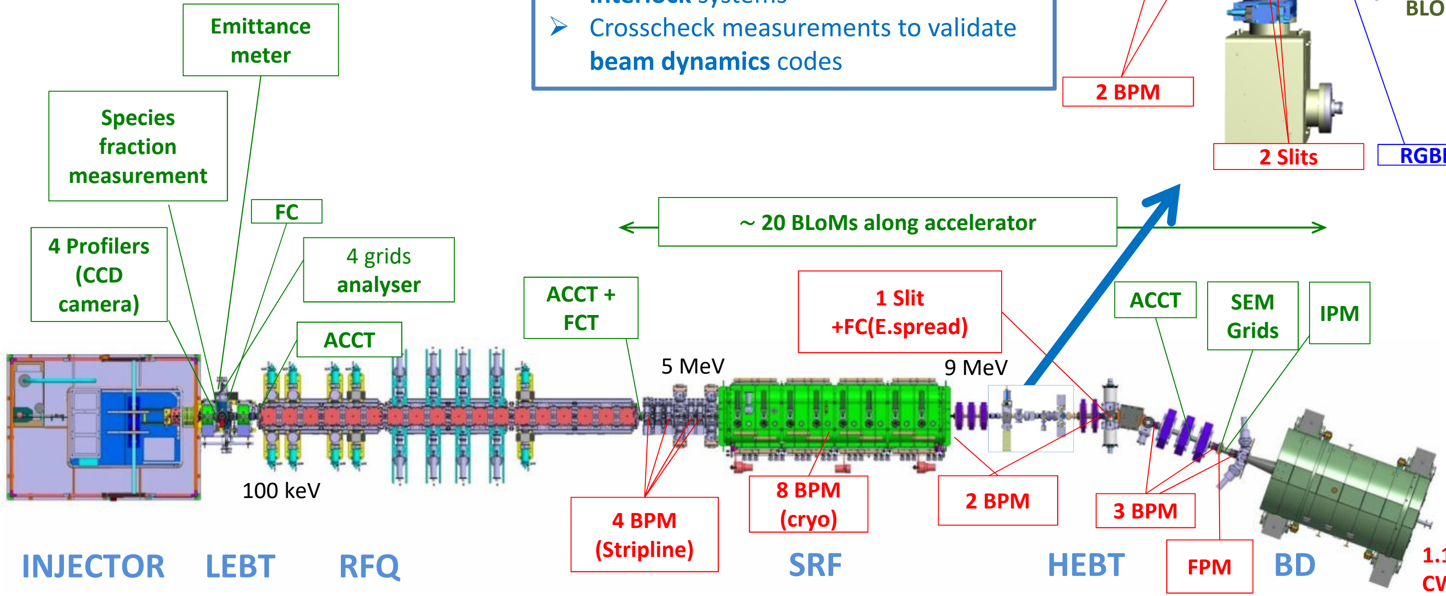
- **High** beam current in CW **(D$^+$ 125 mA)**
- **Low** beam energy **(5-9 MeV)**
- **High** beam power **(up to 1.12 MW)**

## Goals

- **Checkout** of the BI operation along all beam commissioning
- **Matching and tuning** of RFQ and MEBT parameters
- Provide information about machine parameters and **beam quality**
- Validate the operation as beam **interlock** systems
- Crosscheck measurements to validate **beam dynamics** codes

## DIAGNOSTICS PLATE




**CT**: Current Transformer (ACCT, DCCT, FCT)
**BLoM**: Beam Loss Monitor
**RGBLM**: Residual Gas Bunch Length Monitor
**BPM**: Beam Position Monitor
**IPM**: Ionization Profile Monitor
**FPM**: Fluorescence Profile Monitor
**Interceptive:** Slits & Faraday Cup (FC)
**SEM**: Secondary Emission Monitor

# LIPAc BI- Phase B



## BI during initial beam commissioning

**Injector preparation**
- FC measurement
- EMU measurement

**RFQ acceleration**
- CT's measurement
- CT's for optimization

**Characterization**
- BPM
- Profile measuements
- BLoM
- Radiation monitors
- Transverse emittance

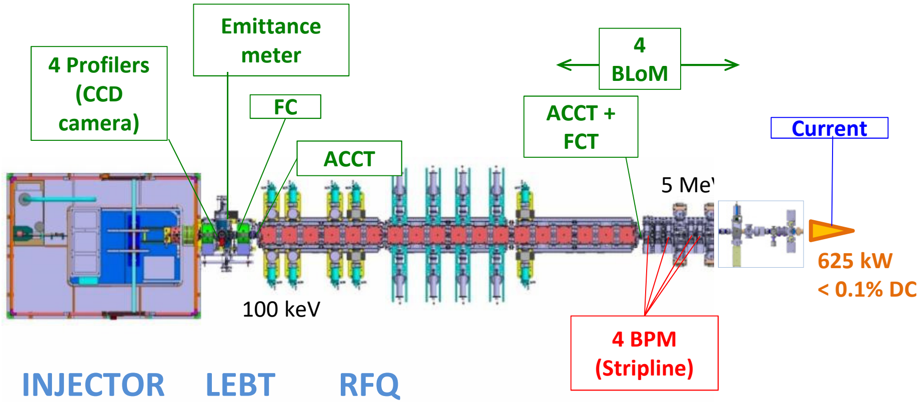
**General status BI**

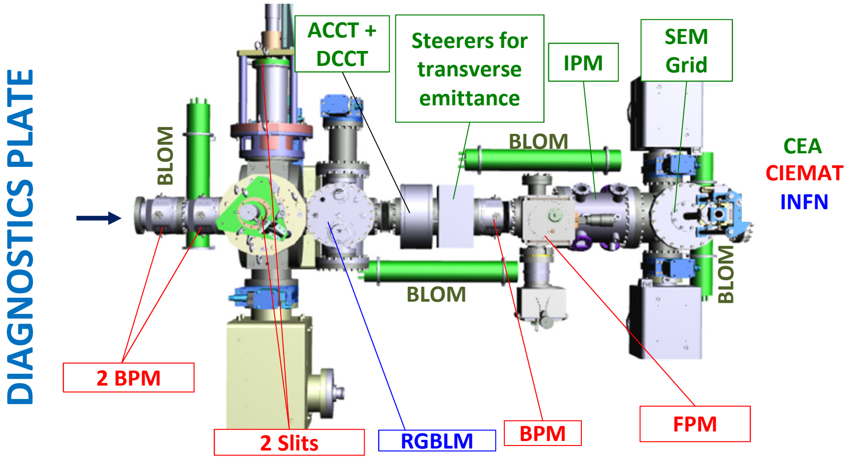
✓ All instrumentation **tested** with proton and deuteron

✓ A lot of data and **knowledge** has been learned from all the systems

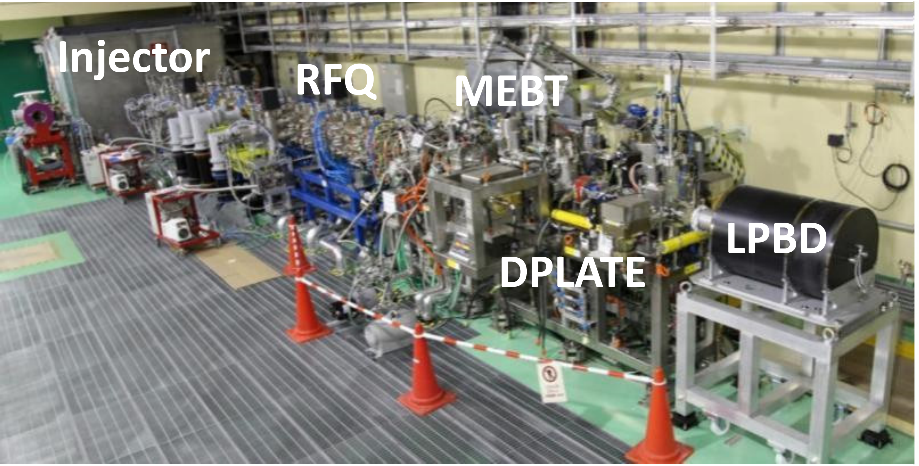
✓ **Postprocessing** and crosschecking with Bdyn of recent data still under way

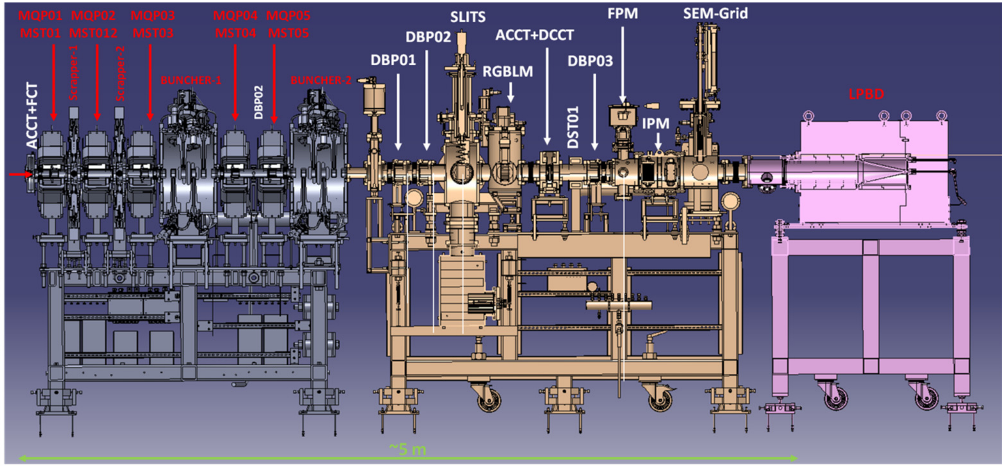
✓ **Upgrade** the instruments with the lessons learned from operation during this maintenance period to be ready for CW operation



# Status Phase B Beam Instrumentation



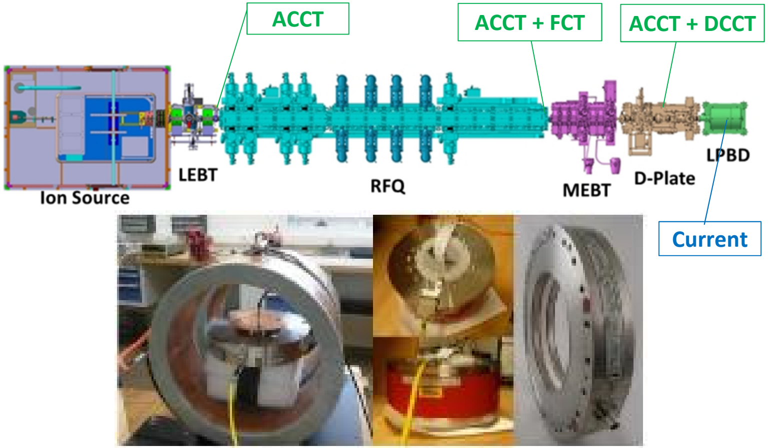



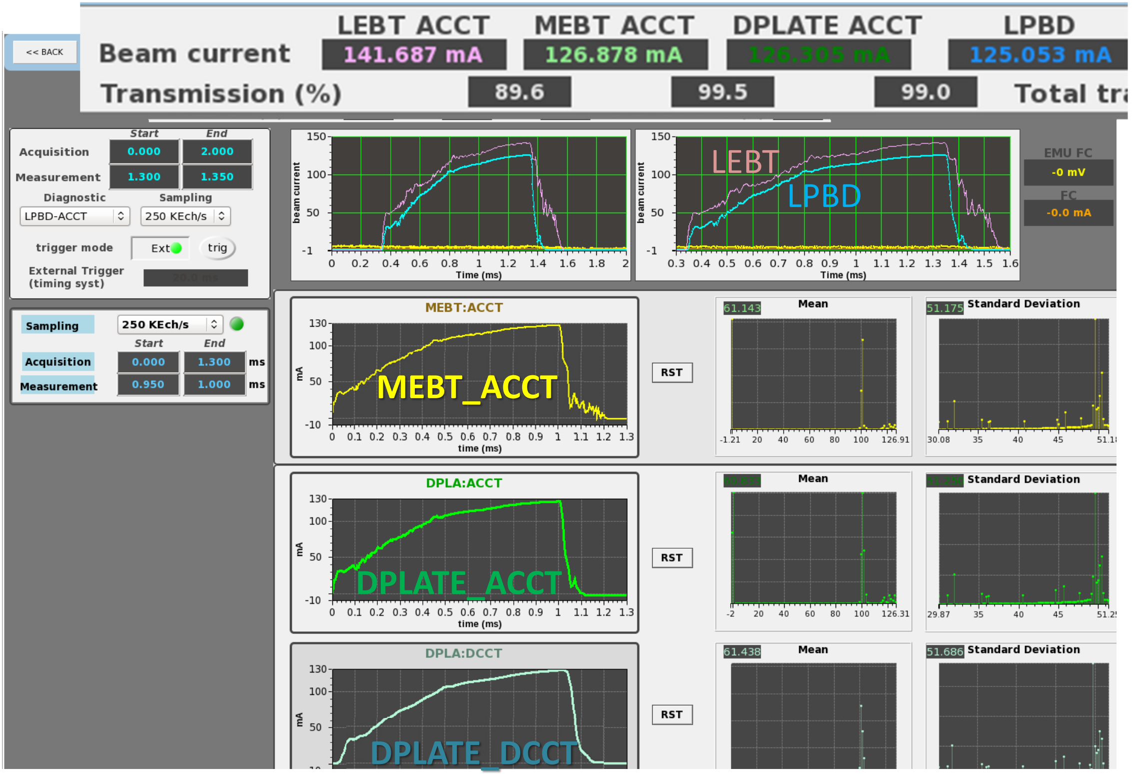

| Requirement | Target | Status |
|---|---|---|
| ACCT-DCCT and FCT | Current, Transmission, and Phase | Ok |
| BPM | Position, Phase & Energy | Ok |
| DP Interceptive (Slit+Steerer+Grid) | Transverse Profile | Ok |
| | Emittance | |
| FPM | Position and beam shape | Ok but only @ low beam current |
| IPM | Position and beam shape | Under study |
| BLOM & Radiation sensors | Beam losses and transmission | Ok |
| RGBLM | Longitudinal emission | Under study |

# Feedback from different instruments

# Current Measurements: macropulse





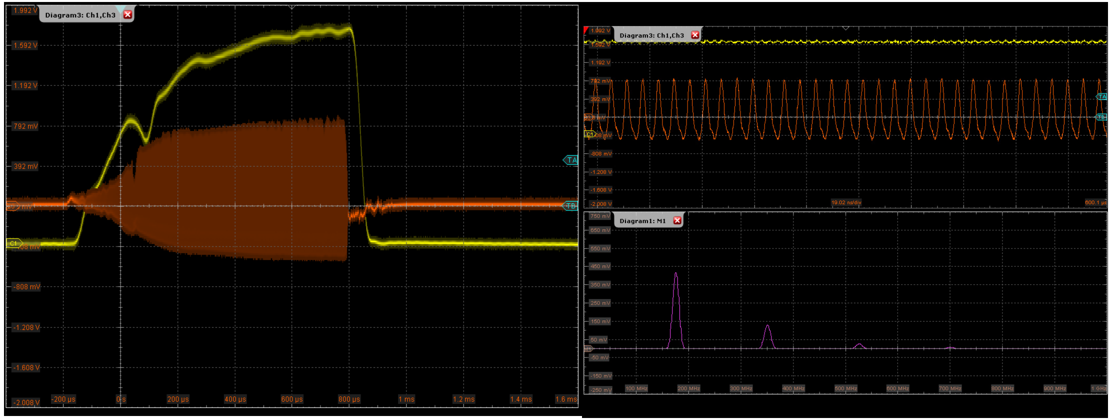

Current measurements during
**first 125 mA deuteron beam acceleration** (1 ms / 1 Hz)

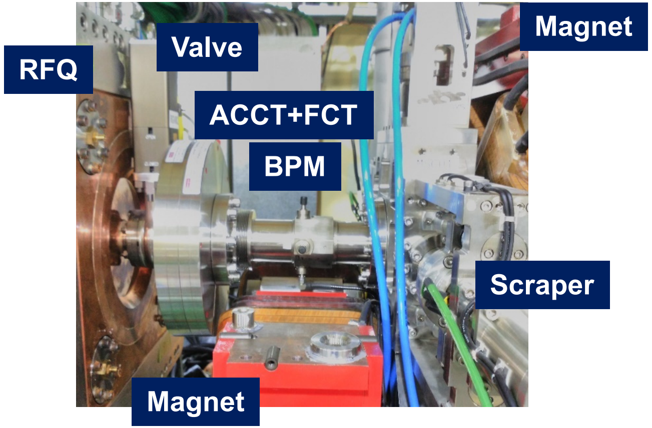
- Macropulse was measured with:
  - One comercial **ACCT** upstream the RFQ
  - One ACCT combined with FCT downstream the RFQ
  - One ACCT in DPlate.
- They have been **key devices** for the beam commissioning from the beginning both with proton / deuteron at pulsed mode
- Used during:
  - First checkout
  - RFQ transmission optimization
  - High energy transport line optimization
- Method to compensate ACCT long droops →

Y. Hirata, MOPP009 (Monday)

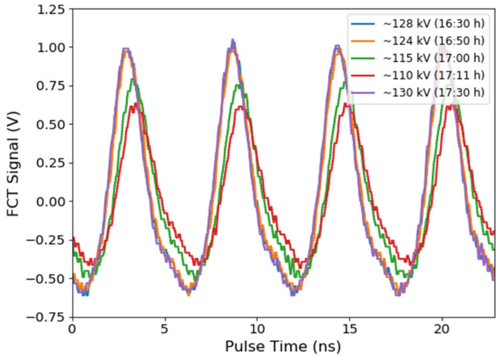
# Current measurements: bunch

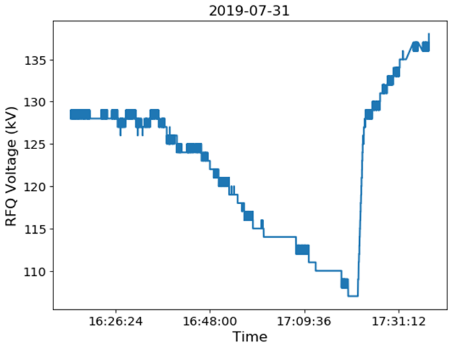
- A Fast Current Transformer is installed together with the ACCT just downstream the **RFQ**
- **Very complex installation in this area**
- However, the **bandwidth** is limited to 14.2 kHZ – 266.2 MHz, meaning 175 MHz bunch shape is **filtered**
- Monitor has been used during RFQ scans → Postprocessing of the data is still under way with this device






RFQ VOLTAGE SCAN $D^+$ @5MeV /125 mA / 1ms/1Hz

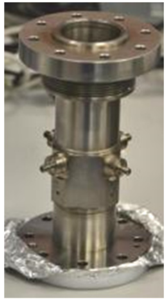


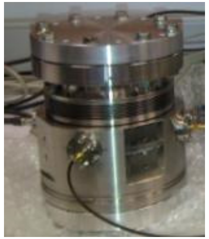



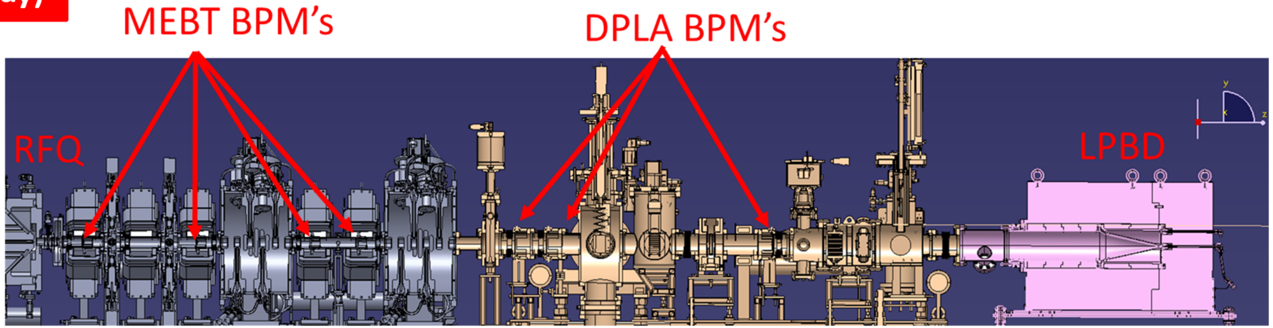
# Position and phase measurements

I. Podadera, WEPP013 (Wednesday)

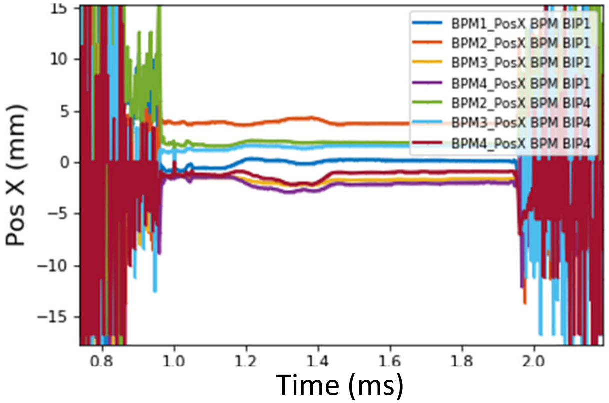
4 x MBPM 3 x DBPM





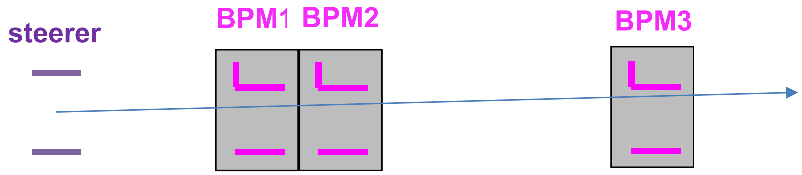



- Measurement of the position of the **centroid (transverse position and phase)**,
- **Digital acquisition** based on IQ demodulation of the 1st or 2nd harmonic after RF downmixing in analog frontend
- Matching of the long RF cables during installation
- **Automatic calibration** directly from AFE to minimize phase and amplitude errors introduced by the cable length
- **Installation** inside magnets aperture in MEBT due to lack of space (complex) → aligned to less than 150 µm
- From July, integration **new digitizers** from Seven Solutions adding new features to the system (intrapulse measurement, White Rabbit synchronization, direct energy measurement...)




Intrapulse measurements with new acquisition upgrade

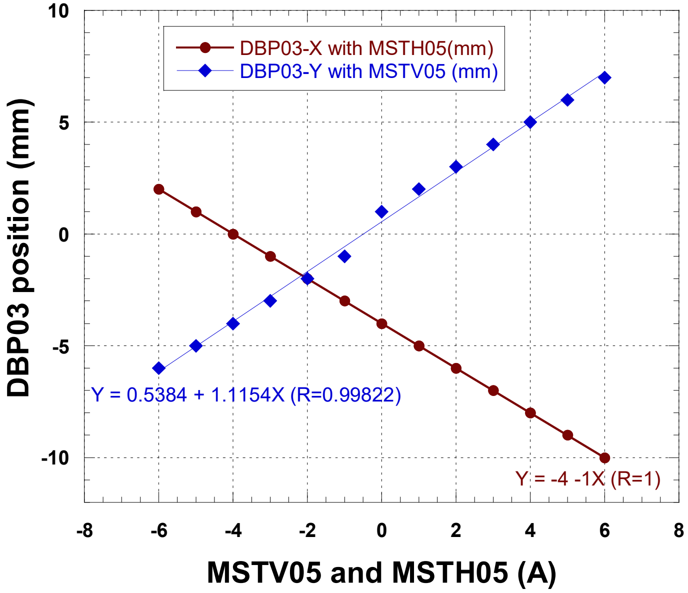
# Position measurements




- Used for the **transport** down to the LPBD
- A lot of tests for the **absolute calibration** of the channels and measurement (under work)
- **Characterization** tests of the system (linearity, resolution, sensitivity...) → under analysis

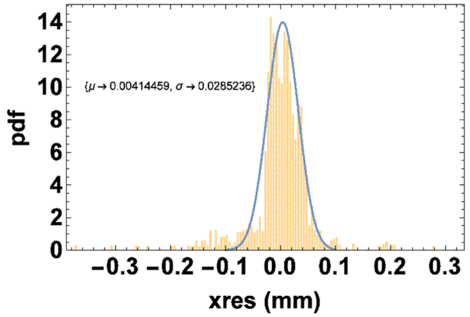
## Preliminary BPM steering analysis

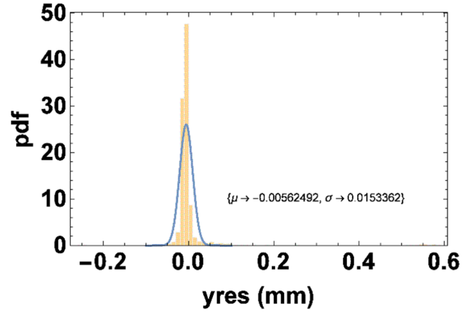
$H^+$ / 2.5 MeV / 6.5 mA / 300 µs / 1 s




## Preliminary BPM resolution analysis

Using 3 BPM method



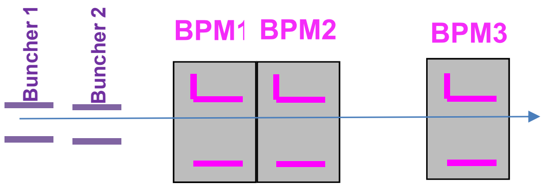

$D^+$ / 100 mA / 1 ms / 1s

Average = 400 µs

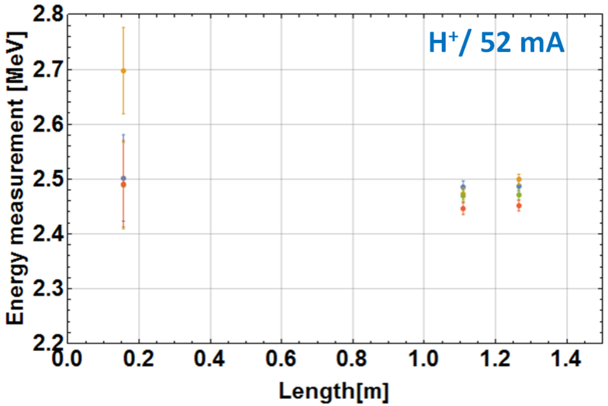
**BPM resolution**

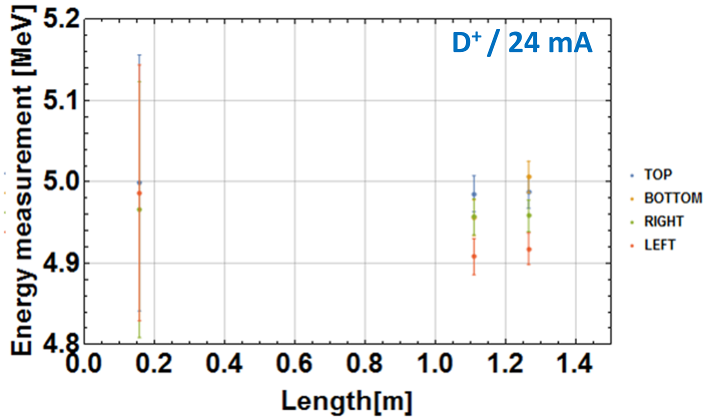
hor < 30 µm / ver < 12 µm

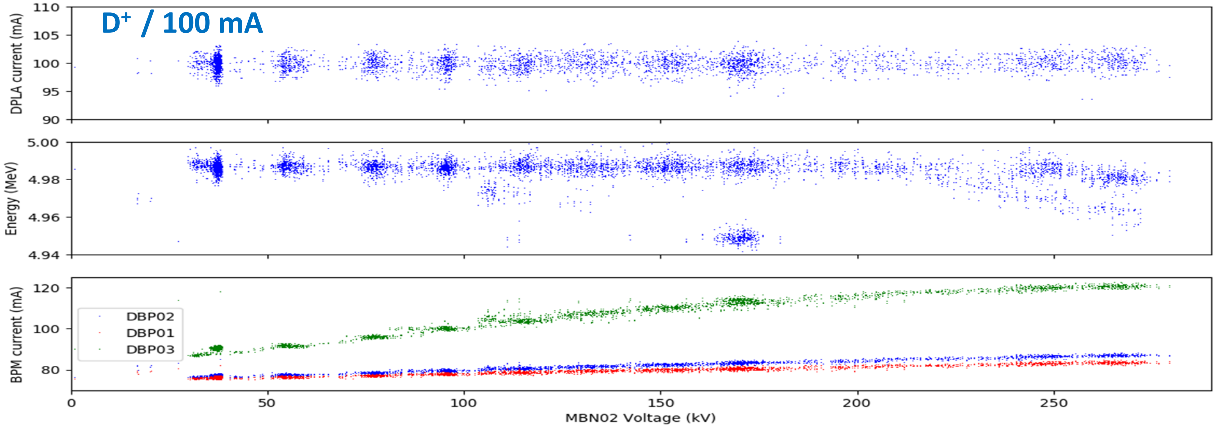
# Phase measurements



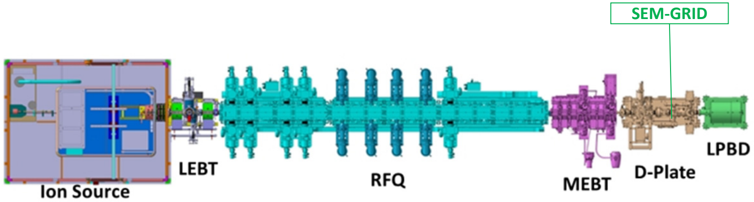

- Used for the **energy measurements, RFQ voltage scans** and **re-buncher cavities tuning**
- A lot of tests for the **absolute calibration** of the channels and measurement (under work)



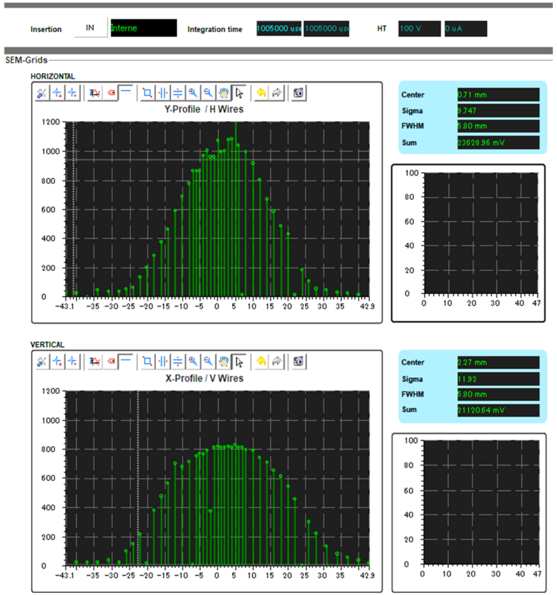



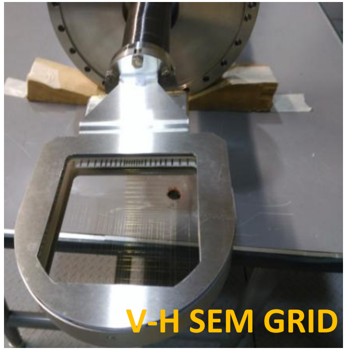



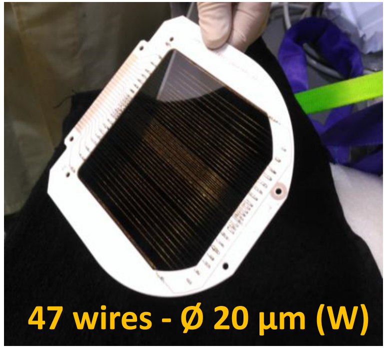
# Interceptive profile measurements




**J. Marroncle et al., TUPP006 (Tuesday)**




## SEM Grid by GANIL

**2 squared wire grids:**

- **Tungsten golden plated wires**
- **47 wires H & V → Ø = 20 µm**
- **Frames: Rogers 4350B**
- **Aperture = 100 mm**
- **Repeller (+100 V)**

**1 actuator**

**1 CF DN200**

**Integration time: 40 µs to 16 s**

**Integrating capacitors = 68 nF**

**Monitoring: PLC**

**Pulse length is limited well below the thermionic threshold, using a thermal software for each beam conditions**

→ Depends on $\sigma_{beam}$, $E_{beam}$ and $I_{beam}$

**Secondary Emission Current**

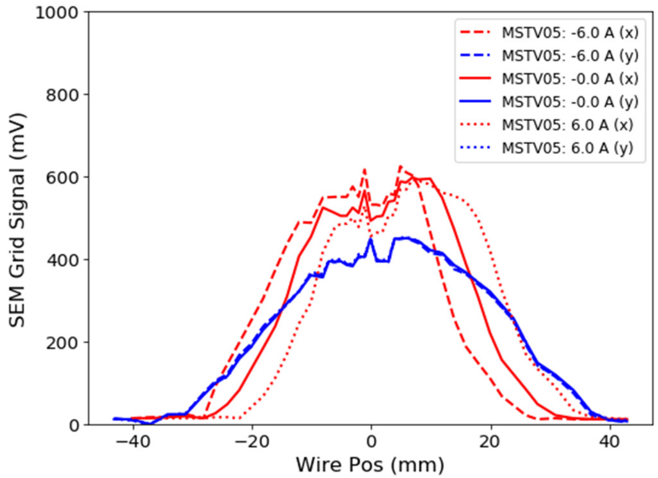
→ Measurement is in agreement with estimation following the rule of thumb (electron emission occurring in the 1 nm outer layer)

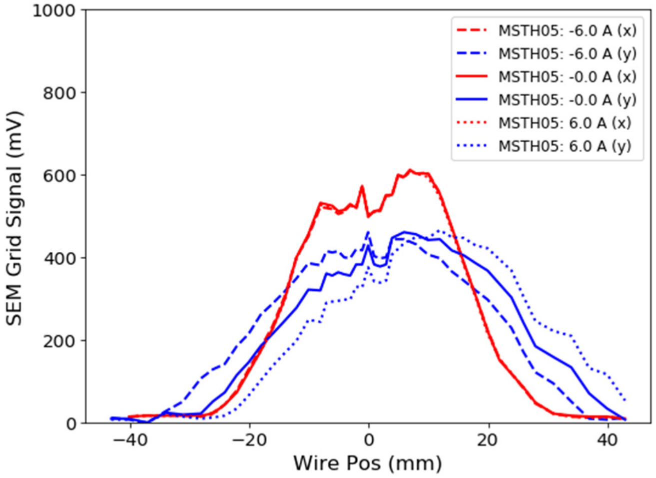
# Interceptive profile measurements



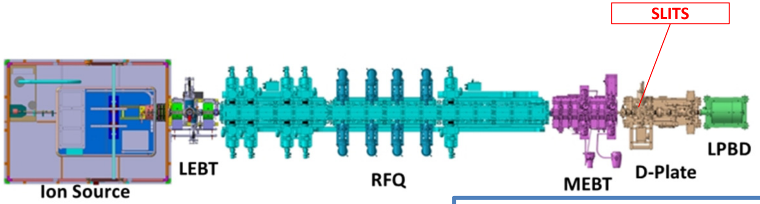
Used for **optimization** of the profile & losses to the LPBD

Example of last MEBT vertical (*top*) and horizontal (*bottom*) magnetic field steering scan



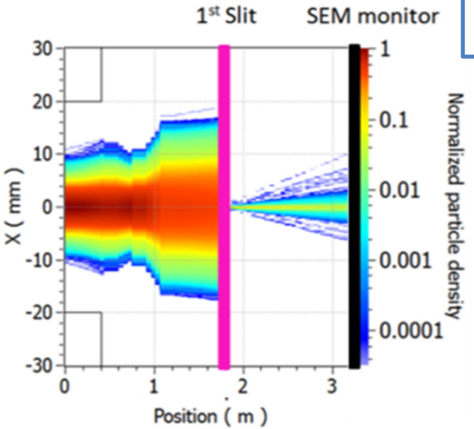
# Transverse emittance measurements



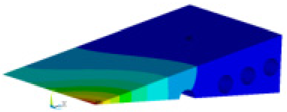

**Slits** are used in combination with **SEM grids** for the **emittance measurement** in each direction, by moving it along the beam distribution

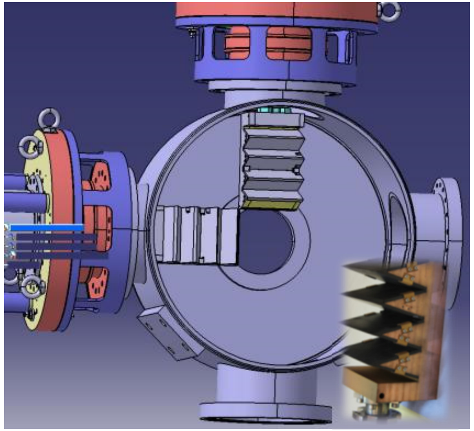
**Difficulties:**
- Slits alignment and perpendicularity with beam
- High motion accuracy and bidirectional repeatability
- Slits size **200 µm** (high flatness and aperture parallelism)
- Long measurements time (~30')
- Shot to shot variation
- Required a control system for motion and acquisition very precise

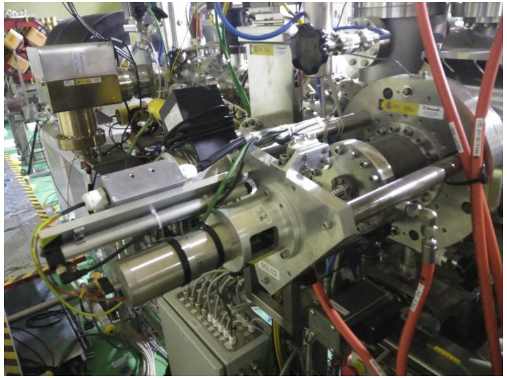
**Uncertanties**
- Material dynamic properties
- Thermal shock
- Fatigue assessment:
  - Plastic follow-up or ratcheting
  - Post failure behaviour: crack propagation or stability
- Thermal interaction between surfaces: conduction by pressure




thermo-mechanical simulations



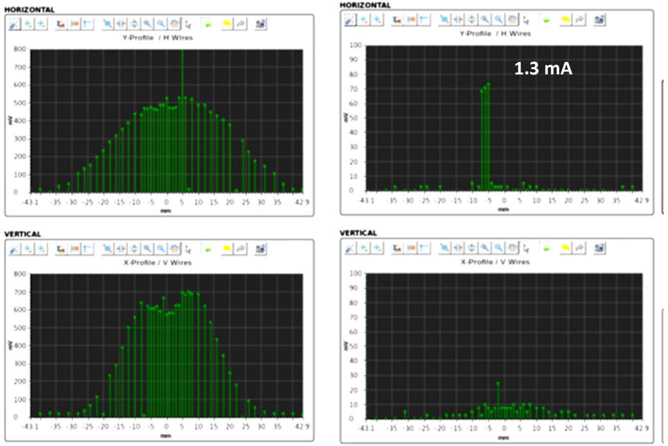




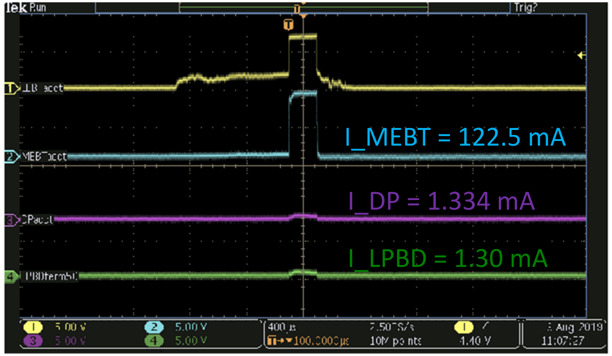
Low Duty Cycle (Maximum up to 1 Hz, 100 us, 0.1% DCycle)

# Transverse emittance measurements

Slit OUT    Slit IN




Slit IN



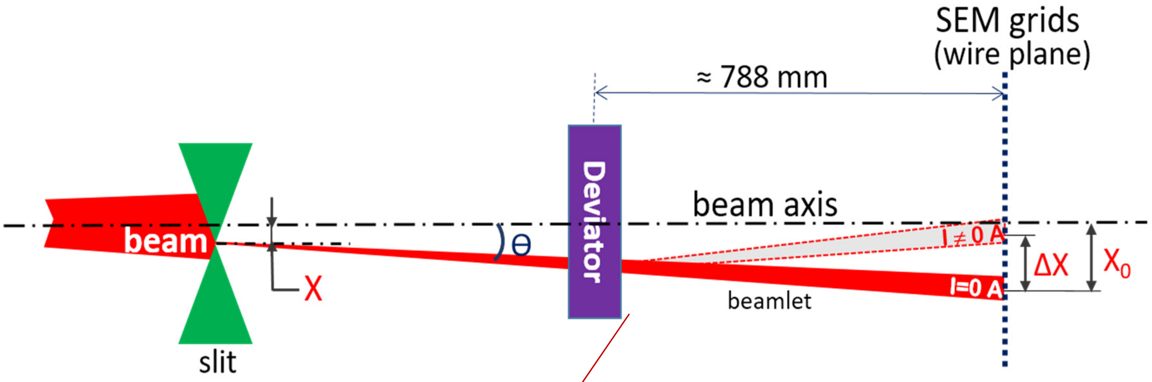

**D$^+$ @5 MeV, 120 mA (200us/single-shot)**

**Thermomechanical validation** of slits and SEM-grid @ 125 mA (low DC / Single beam pulse)

# Transverse emittance measurements

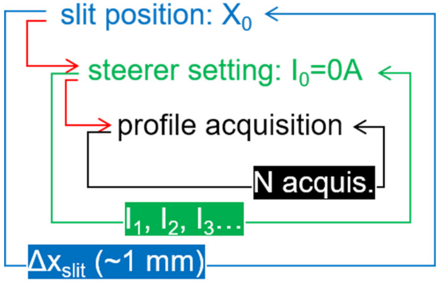
**J. Marroncle et al., TUPP006 (Tuesday)**

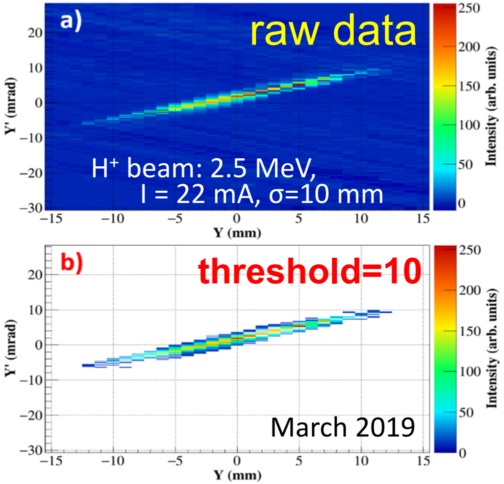
As Read-Out is a SEM-Grid, large wire gaps (1, 2, 3 mm) avoid measuring accurately beamlets
→ Steerers allow for sweeping the beamlet on few wires




$\int \vec{B}\cdot\vec{dl} < 23.3$ G.m
→ Δ=3 mm for 9 MeV $D^+$
Aperture 105 mm
Power Supply: ±11A/±15V


**Measurement synopsis**

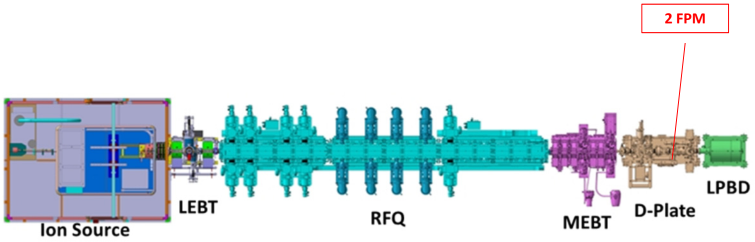


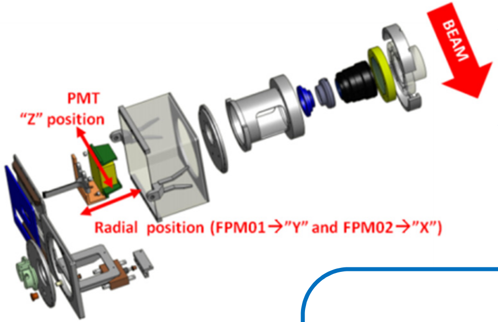




Experimental transverse Emittance and Twiss parameters are in good agreement with dynamics simulations

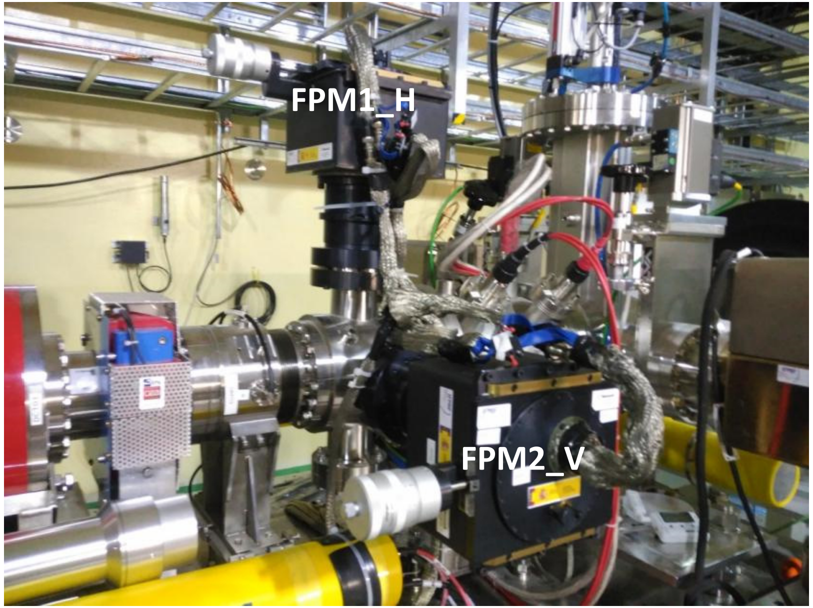
| Measurement | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| SOL1 [A] | 135 | 135 | 135 | 131 |
| SOL2 [A] | 160 | 160 | 162 | 162 |
| V [kV] | 66 | 62 | 70 | 70 |
| Norm. $\varepsilon_{exp}$ / $\varepsilon_{sim}$ [π mm mrad] | 0.24 / 0.24 | 0.24 / 0.24 | 0.22 / 0.23 | 0.24 / 0.28 |
| $\beta_{exp}$ / $\beta_{sim}$ [mm/π mrad] | 7.1 / 7.5 | 8.0 / 8.1 | 6.6 / 6.3 | 6.5 / 6.0 |
| $\alpha_{exp}$ / $\alpha_{sim}$ | -4.8 / -5.5 | -5.4 / -6.0 | -4.3 / -4.3 | -4.4 / -4.5 |

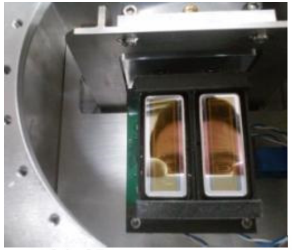
# Fluorescence profile monitors

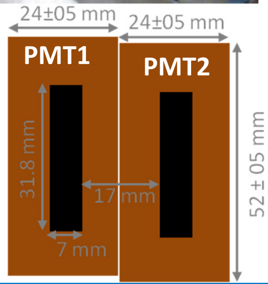


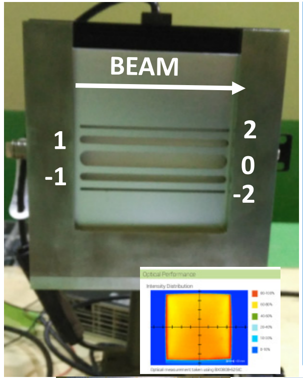

- 2 **PMT** arrays of 32 channels
- PMT1 & PMT2 shifted 500 μm to increase **spatial resolution**
- **Optical adjustment** of PMT (focal, radial and "Z") and lens

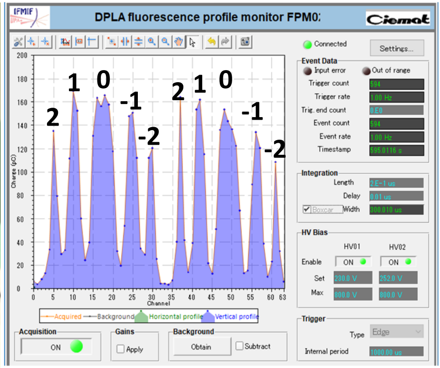





## Calibration



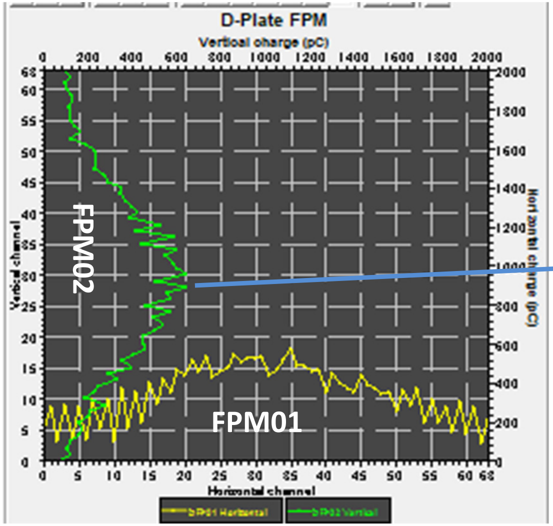

Channel calibration :

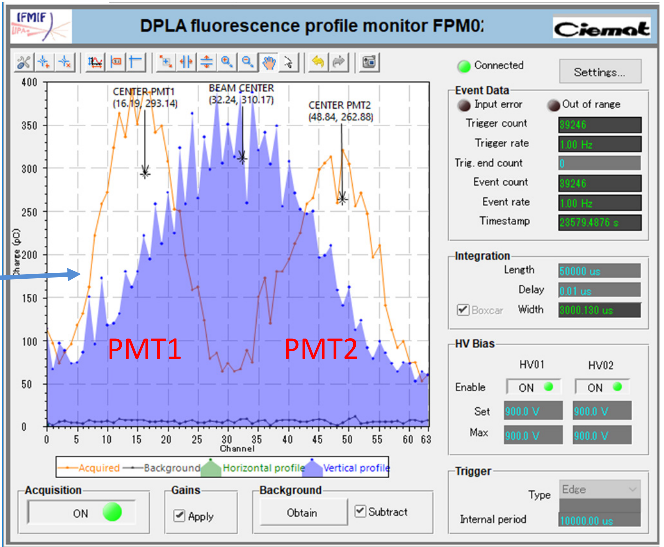
**PMT1 (1-32ch): 1ch = 2.65 mm (Peaks)**
**PMT2 (33-64ch): 1ch =2.65mm (Peaks)**
**FOV < 70 mm**

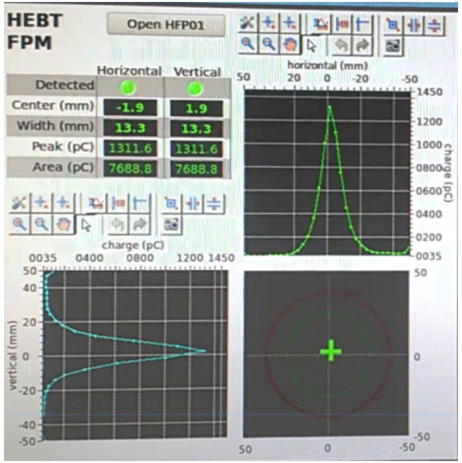
# Fluorescence profile monitors

$H^+$@2.5 MeV, I-LEBT= 22 mA (3.7 ms/1Hz), integration time 1 msec

SOL1/SOL2=142/150V_RFQ=70 kV

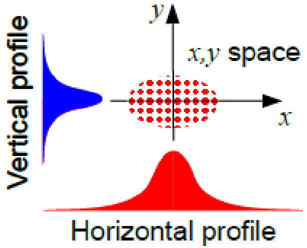


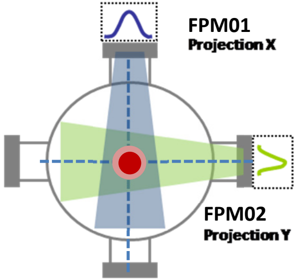




$$\varepsilon \sim \sigma^{eq} \cdot P_{gas} \cdot I_{beam} \cdot d_{path}$$

$$N \sim \varepsilon \cdot \Omega \cdot \tau \cdot \chi^{sist}$$

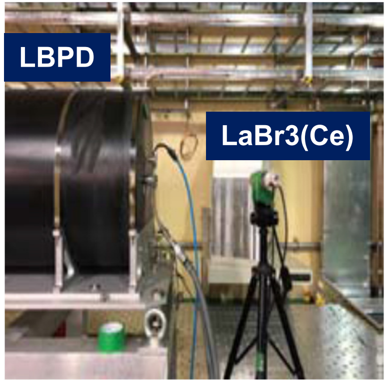


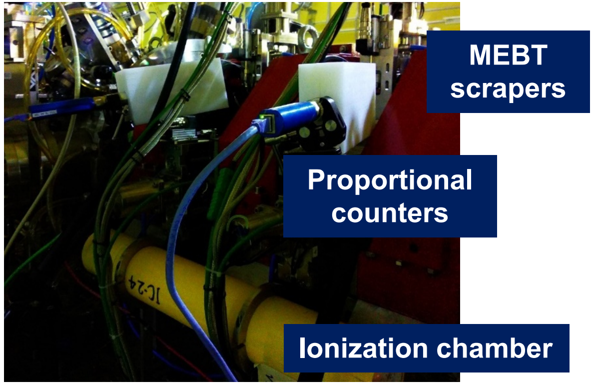



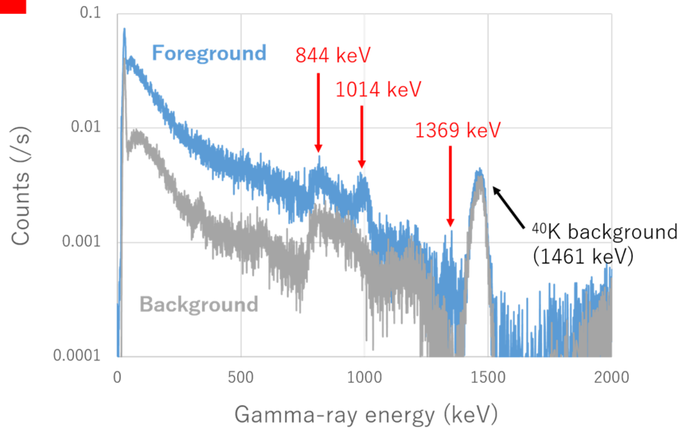

- **Used for studies of the profile to the LPBD**
- **Linearity** with $I_{beam}$ and with pressure
- **High efficiency** even at low current and vacuum pressure, $1e^{-7}$mbar or lower
- Beam shape spectrum with pulse length above 1 ms and $I_{beam}$ above 22 mA
- the approximation to the triple product of $\tau \cdot P_{gas} \cdot I_{Beam} \simeq 1E^{-7}$ (The light efficiency, N)
- At **high current** the radiation (in phase B) the increase of background level from beam dump is masking the beam signal → under investigation for Phase B+

# Beam loss measurements: $H^+$

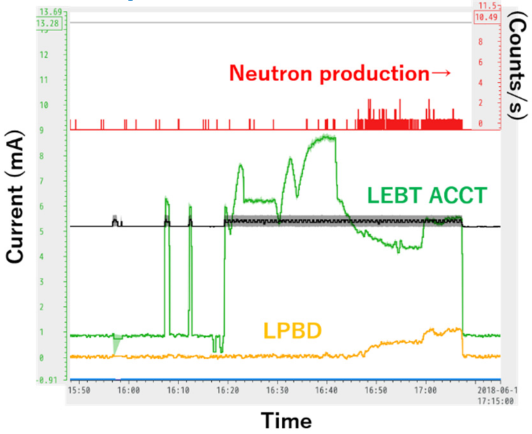
K. Kondo et al., MOPTS047, IPAC'19



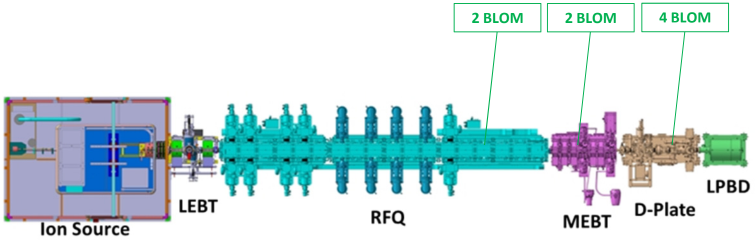



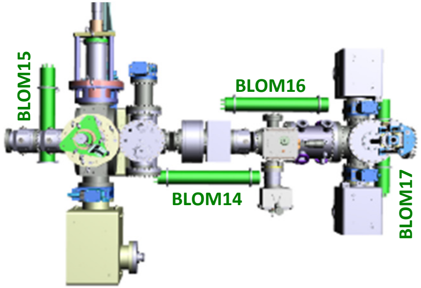

## 1st proton beam @ LBPD



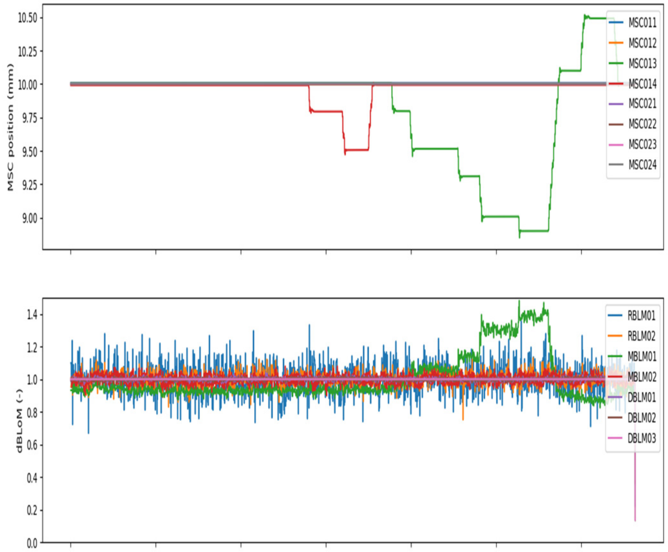

- Slow signal was obtained from:
  - LaBr3(Ce) **scintillation detectors** for gamma-ray detection downstream the LPBD
  - He-3 **proportional counters** for neutron detection surrounding the MEBT
- Used for beam checkout and energy measurement:
  - **Gamma-rays** corresponding to certain excited states of aluminium (LPBD) coming from inelastic scattering reactions: 844 keV /$^{27}$Al(p,p'$\gamma$1), 1014 keV / $^{27}$Al(p,p'$\gamma$2), 1369 keV/ $^{27}$Al(p, $\alpha\gamma$1) $^{27}$Mg (*Eth*> 1.7 MeV)
  - Also some **neutrons**, which would originate from the interaction of protons with copper -$^{65}$Cu(p,n)$^{65}$Zn, *Eth*> **2.17 MeV**- of **MEBT scrapers**, were observed.

# Beam loss measurements: D$^+$




## MEBT Scrapers scan



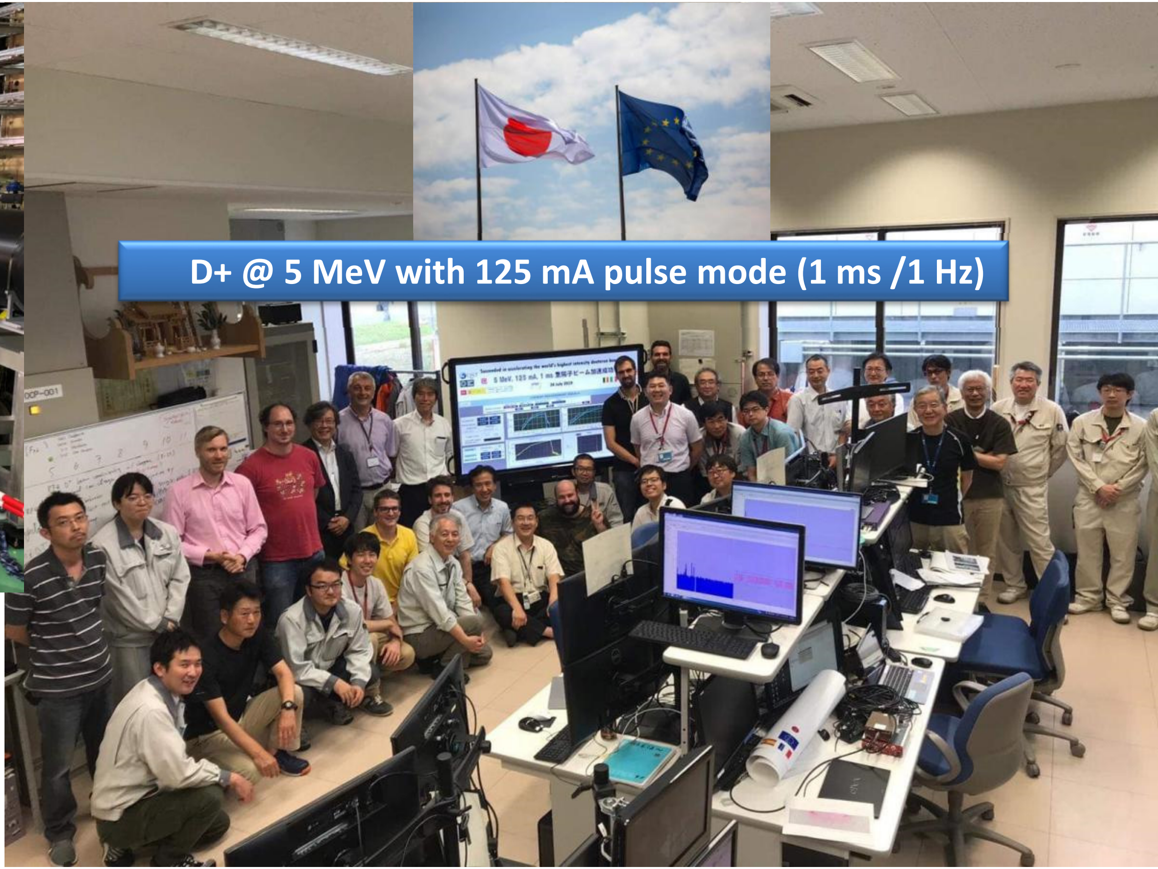

- Signal obtained from **ionization chambers**
- BLoMs signal proportional to beam current (LPBD irradiation) and sensitive to beam losses
- Useful for **MEBT scrapers scan** (signal only detected by nearest BLoM)
- **Alarm & MPS thresholds** still be defined after more machine time and simulations crosscheck

# Conclusions & outlook

- Beam Instrumentation has been key devices for LIPAc validation in pulsed mode:
  - **$H^+$@ 2.5 MeV with I_LPBD = 62 mA (800us / 1Hz)**
  - **$D^+$ @ 5 MeV with 125 mA pulse mode (1 ms /1 Hz)**

- **Main beam Instrumentation is operational**
- RFQ and MEBT operational parameters has been tested at high current, and transmission through MEBT has been optimized
- The information obtained in the present commissioning phase is vital for the operation in CW, and for SRF-linac operation:
  - Characterization of **current, position and energy** has been performed at all operation regimes
  - Characterization **transverse profile** with protons and deuterons (single pulse).
  - Characterization **transverse emittance** only at low current and low duty cycle protons
  - Characterization of **longitudinal profile** and **longitudinal emittance** planned to be measured during the next commissioning phase

- Using the data acquired to **upgrade** the instrumentation during **maintenance period** to be ready for a new phase bringing us to $D^+$ @ 125 mA_CW operation (Phase $B^+$)




# Thanks !!