Evolution of a Compact TOF Mass Spectrometer from Space Exploration to the Internet of Things

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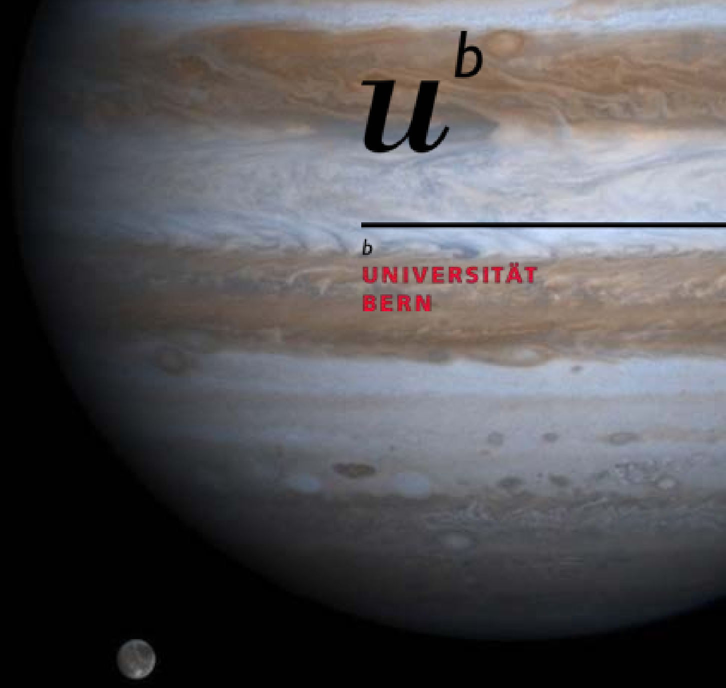
Spacetek technology

2019 HEMS Workshop



Part 1: Neutral and Ion Mass Spectrometer (NIM)

D. Lasi, M. Tulej, S. Meyer, M. Fohn, R. Fausch, D. Piazza, M. Gerber, S. Brungger, G. Bruno, M. Rieder. M. Lüthi, A. Nentwig, S. Oeschger, P. Fahrer, M. Althaus, P. Gubler., M. Gruber, H. Munz, and P. Wurz

University of Bern, Physics Institute, Sidlerstrasse 5, 3012 Bern (Switzerland)

4 Generations of TOF Space Mass Spectrometers

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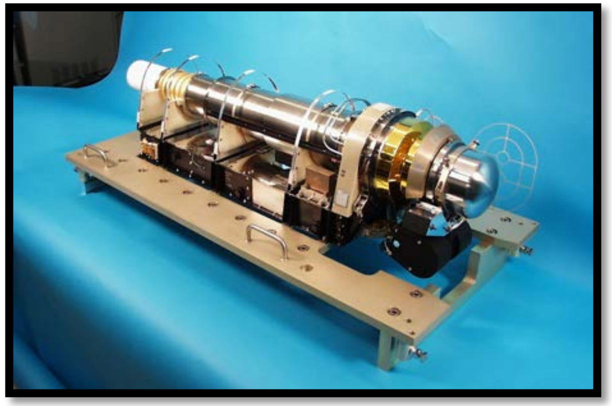
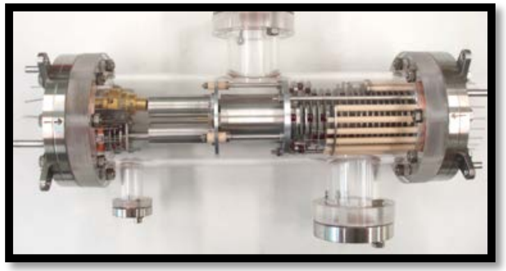
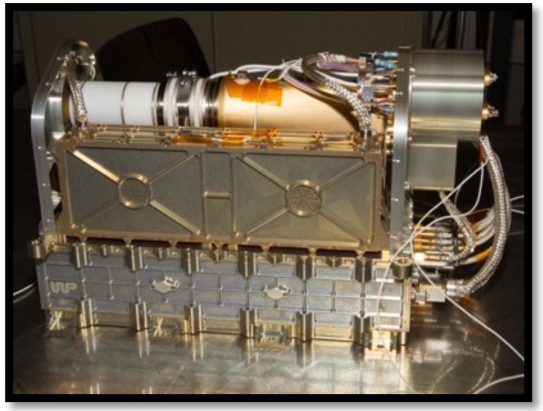
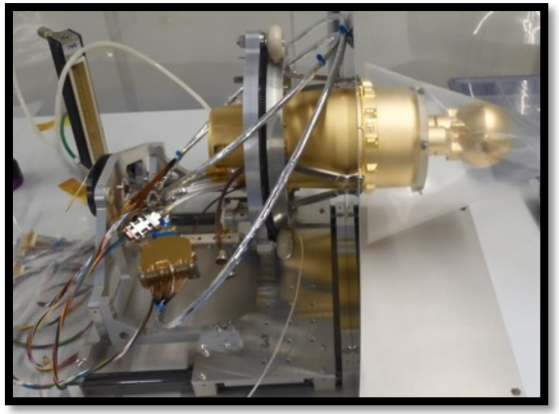


~1m







~30 cm

1998-2002	RTOF	Rosetta (European Space Agency)
2015	EGT	P-BACE (Balloon mission)
2011-2018	NGMS	Luna-Resurs (Roscosmos)
2012-Now	NIM (PEP)	JUICE (European Space Agency)

The Neutral and Ion Mass spectrometer (NIM)

Mission profile of JUICE (2022)

- Flybys Europa, Ganymede, Callisto
- Orbit around Ganymede

Key goals of the mass spectrometer

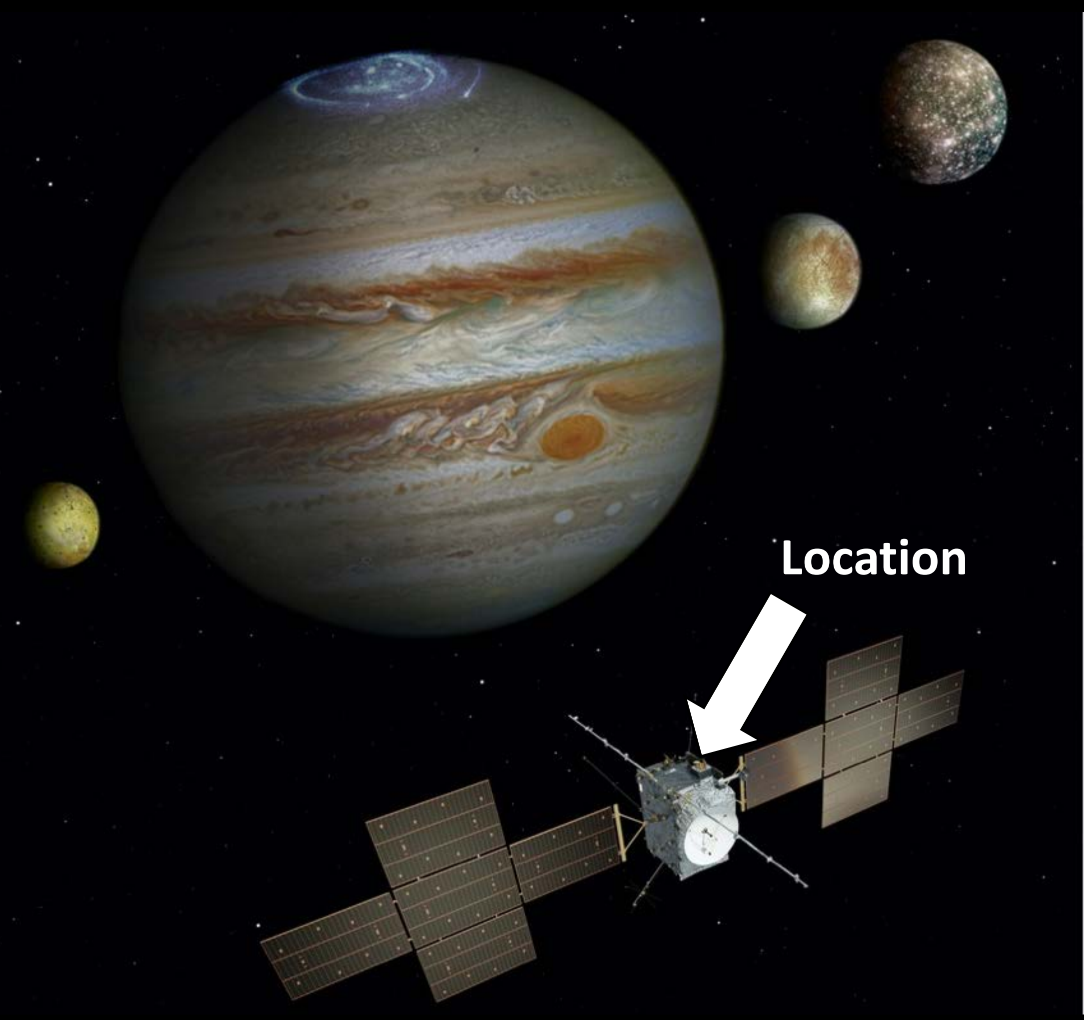
- Characterize exosphere of icy moons (neutral, ions)
- Achieve a spatial resolution of ~25–50 km

Key instrument requirements

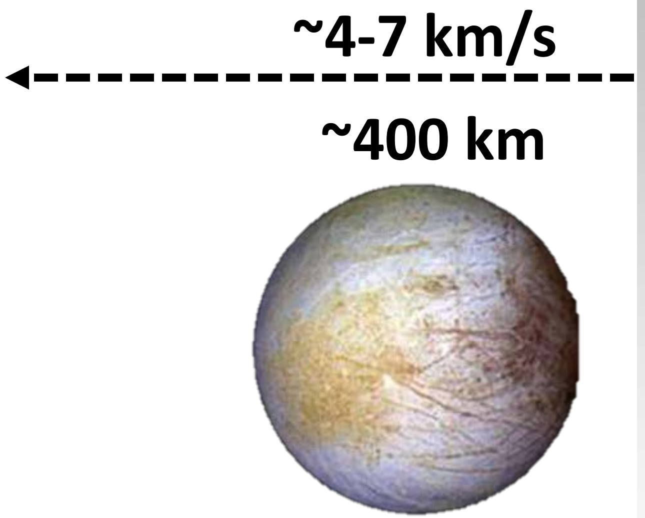
Mass range	up to 300 u
Mass resolution	> 500 M/ΔM
Dynamic range	> 10^5 (5s integration)
Measurement cadence	5s (flyby), 1s (plume)

Constraints

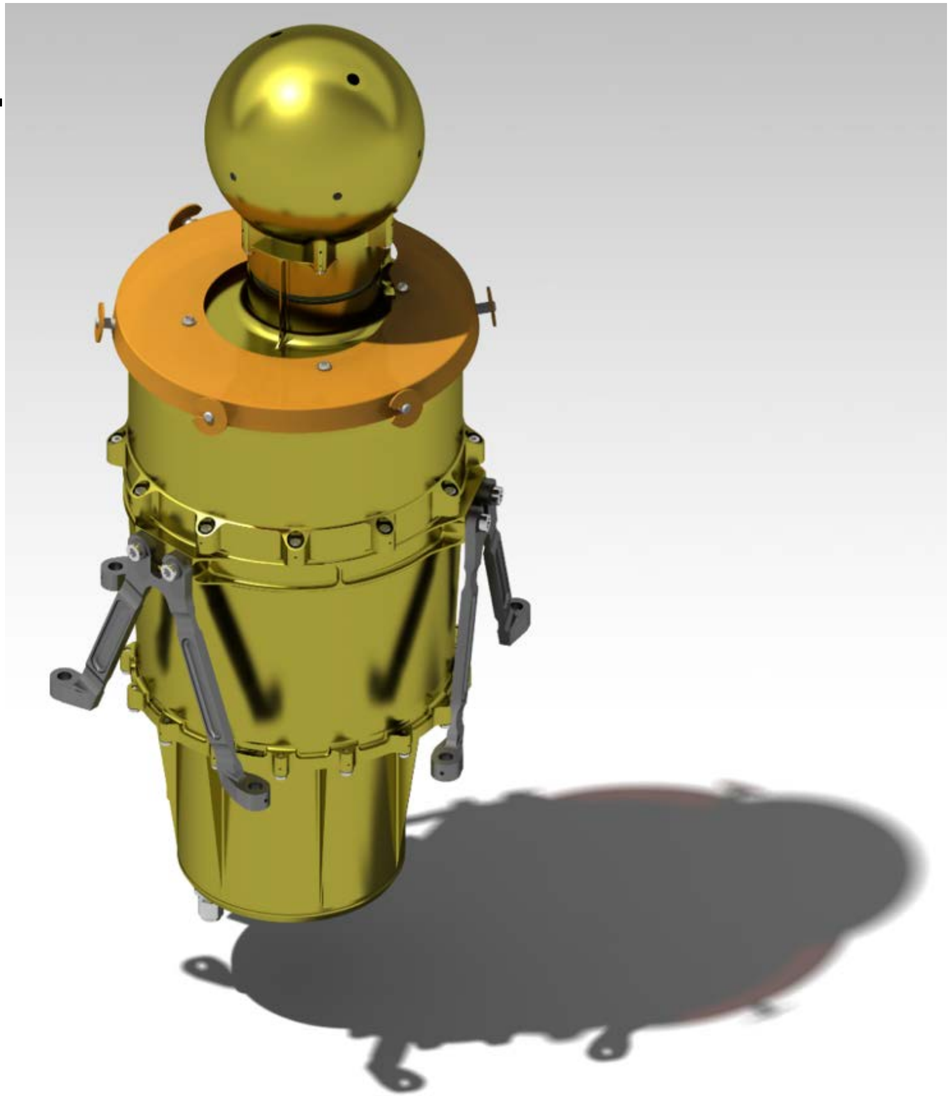
- Survive <u>and measure</u> in the radiation environment (@Europa)
- Mass: 3 kg (excluding radiation shielding)
- Power: 12 W (before common DCC)



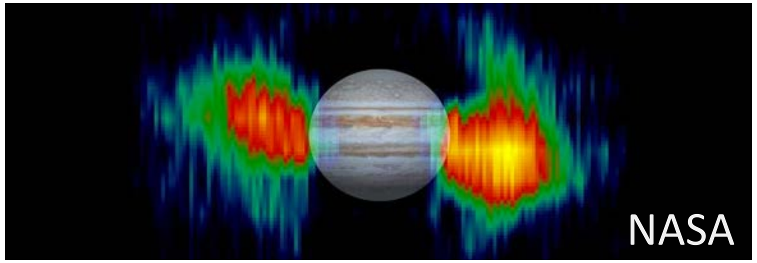
Instrument Overview

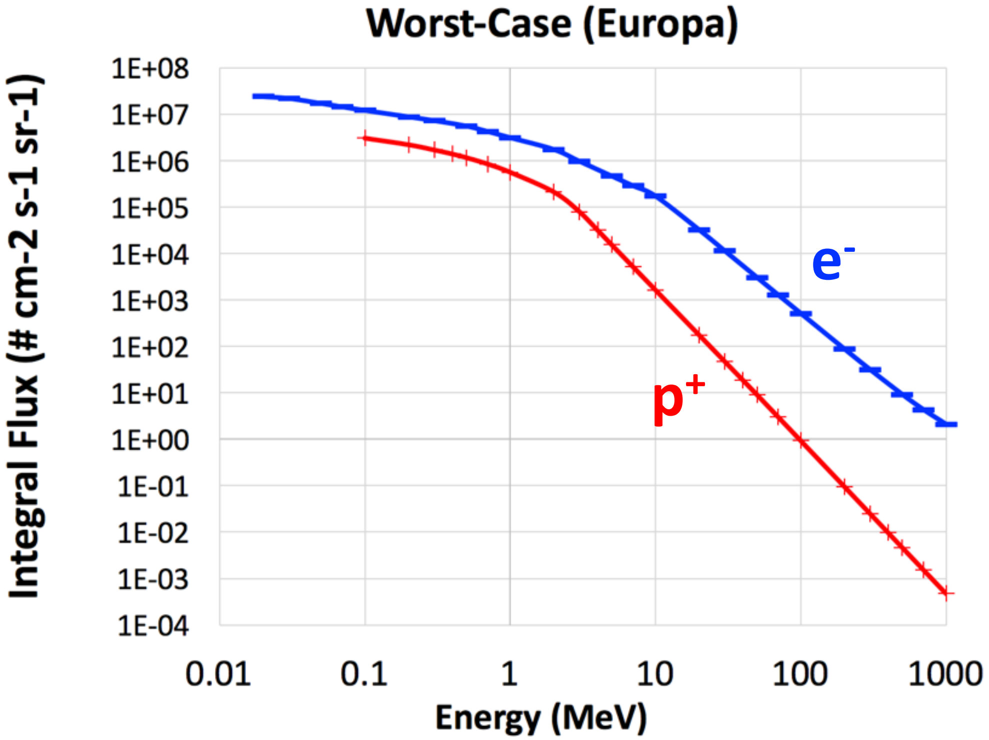


- **Architecture:**
  - Reflectron TOF MS
  - Electron impact ionization
  - MCP detector
  - ~10 kHz repetition rate
- **Three different operation modes**
  - **Neutral**: direct FoV + ionization
  - **Ion**: direct FoV (no ionization)
  - **Thermal**: antechamber + ionization (2pi FoV + extended energy range)
- **Switching mechanism (shutter)**



A Very Harsh Radiation Environment!





→ Strategy: shield differently against fluence and flux

Shield **electronics** against **fluence (TID)**

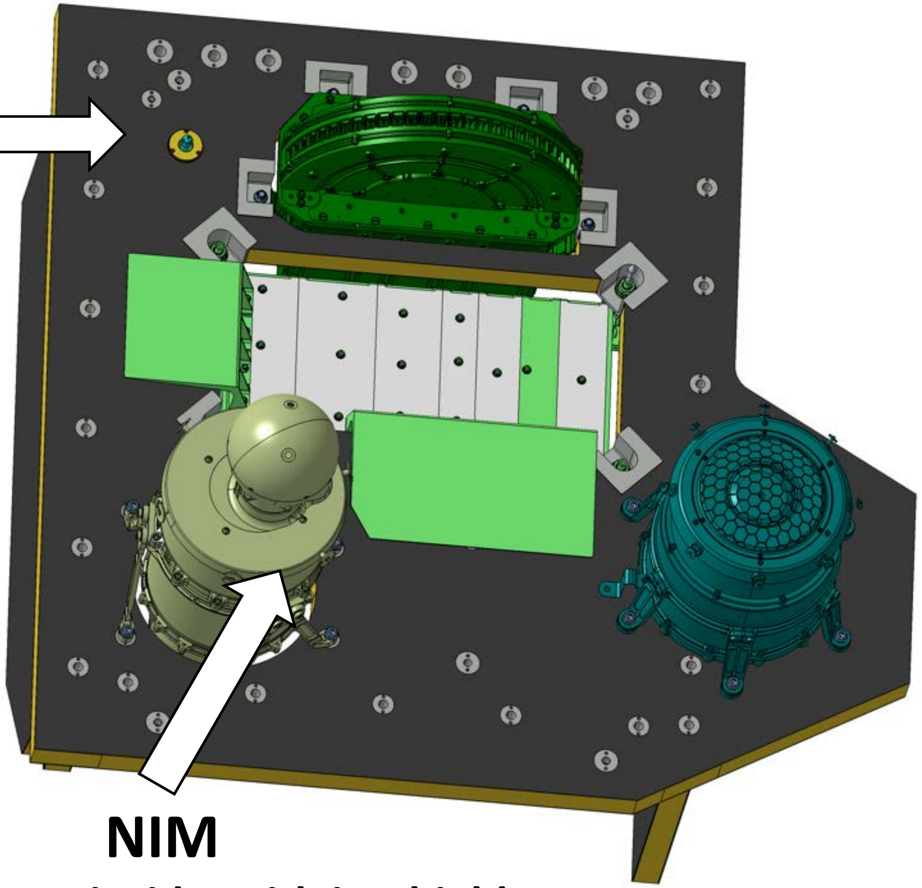
- Driver — end of life
- Goal — <50 krad Si
- Need — ~2 mm Ta
- How? — PEP vault

Shield **detector** against **flux**

- Driver — worst case
- Goal — <~10^5 #/s
- Need — ~10 mm Ta
- How? — Dedicated shield

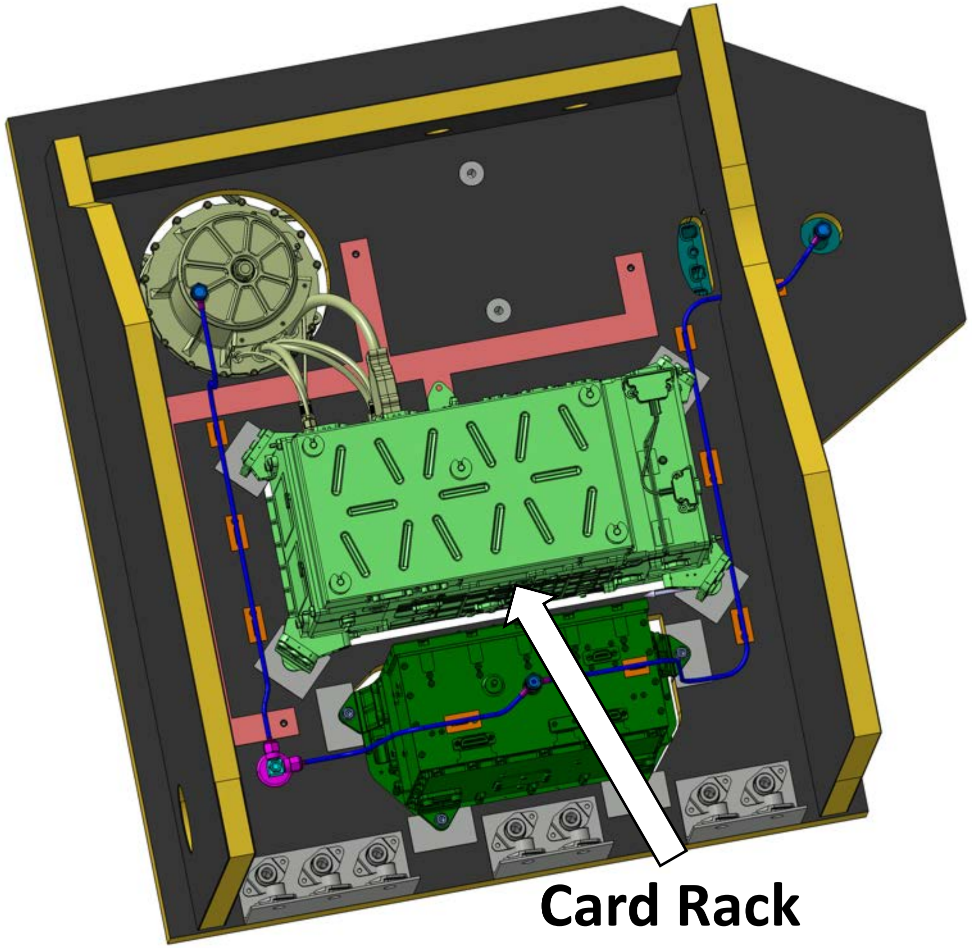
Total dose (unshielded: ~0.05 mm Al) → ~160 Mrad

Particle Environment Package (PEP) Nadir Unit (NU)



NIM

Tiny detector inside, with its shield
Everything else unshielded



Card Rack

'Common Vault' of PEP NU Electronics

2 mm WCu

Coming Next → selected design insights 'following the ions'

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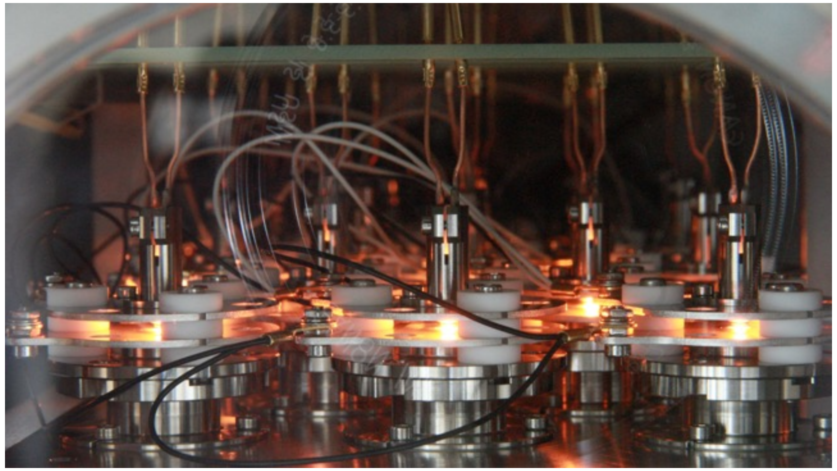
Electron Emitters

- Considered **cold cathodes** (FEA, CNT)
  - Interesting because low power, but
  - low TRL and heritage, uncertain reliability, limited availability
- Decided for **thermionic emitters** from Kimball Physics
  - Enhanced yttria oxide (baseline)
  - Barium oxide (backup)
- **AC instead of DC to save power**!

Property	Y_2O_3 (enhanced)
Lifetime	**>10’000 cycles**
Power at 300 µA emission	**1.2 W**



10,000 hours goal
~2,000 hours run so far without issues

Extraction with Fast High Voltage Pulser

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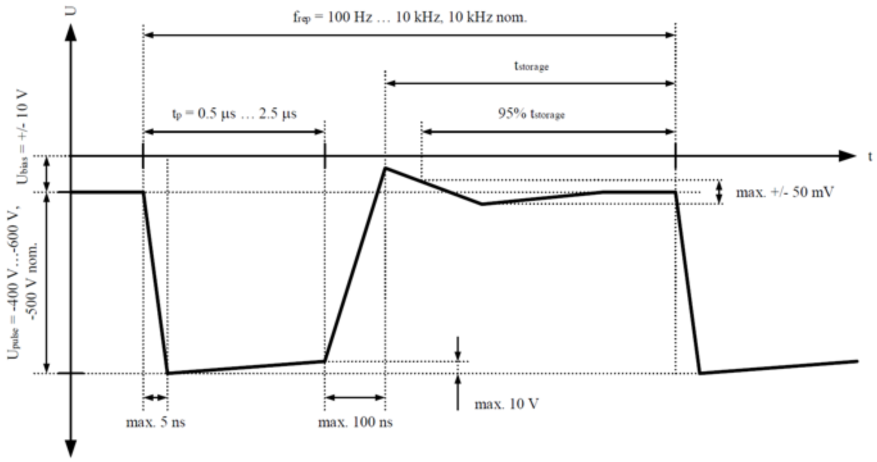
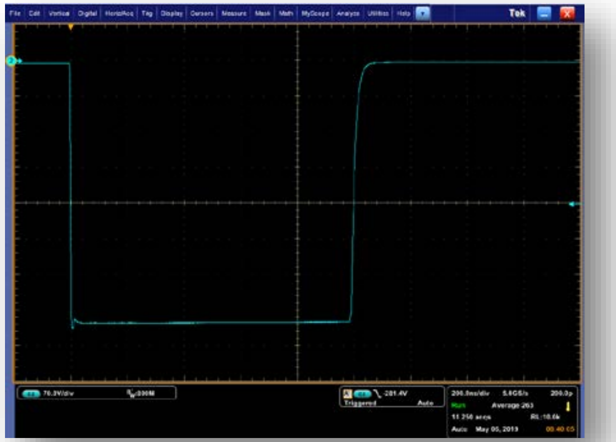
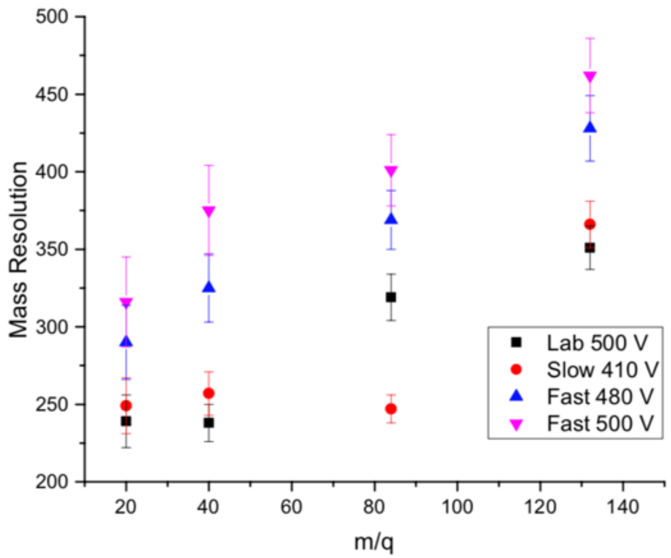
- **Critical requirements →**
  - Mass resolution ~ S/N
- **Limited choice of radhard MOSFETs**
- **Prototyped two pulser designs:**
  - 2 MOSFETs in cascade
    - Can go up to 600V (derating)
    - 'Slower' (~6.5ns)
  - 1 MOSFET
    - Can go up to 480V (derating)
    - 'Faster' (4.5 ns)
- **Selected:** faster pulser
  - Takeaway: leading edge steepness more important than pulse height!
- **Optimized shape at point of application** with optimized ceramic electrode







Integrated ceramic pull grid

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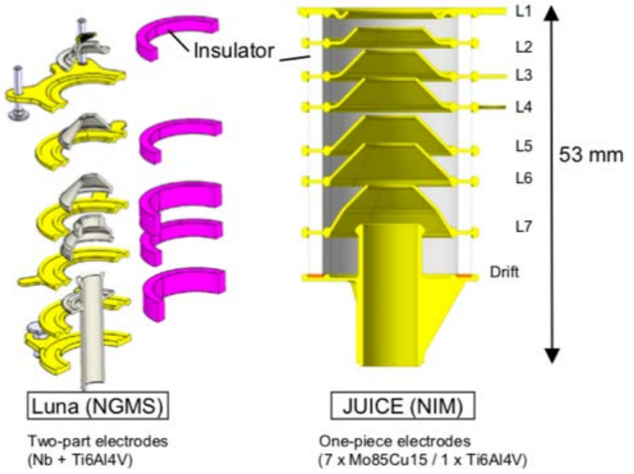
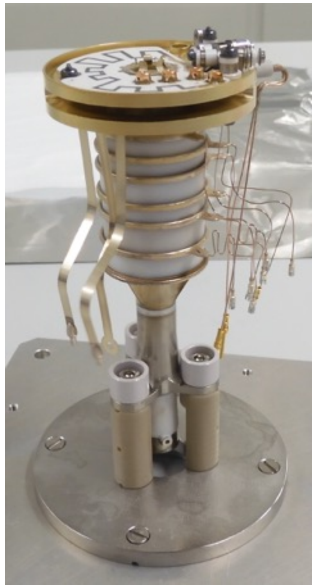
Brazed Metal Ceramics Ion Optics

- **Heritage:** RTOF (Rosetta), NGMS (Luna-Resurs)
- **Ion source**
  - New one-piece electrode design
  - From Nb + Mo to MoCu (85:15)
  - Better manufacturability
  - Same CTE than alumina
  - See Elsener et al., 2019





- **Reflectron**
  - Screen-printed electrodes (DuPont Series 2000)
  - Excellent mechanical properties
  - Min. field corrugation→ Efficient use of volume
  - Verified with 18 MeV p +up to 85 Mrad
  - See Scherer et al., 2006; Lasi et al., 2017

Image credits: EMPA Dübendorf (Switzerland)

Micro-Channel Plate (MCP) Detector and Shielding

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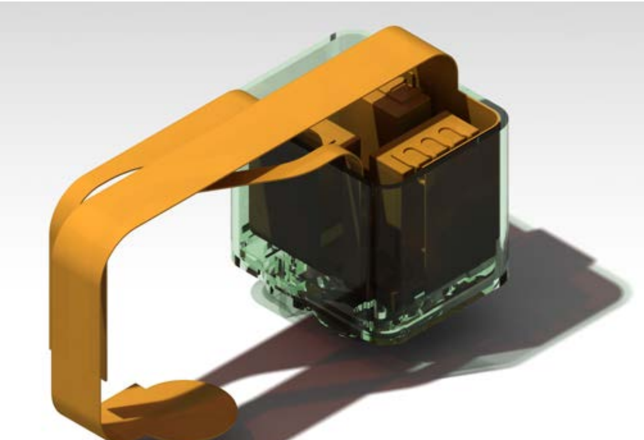
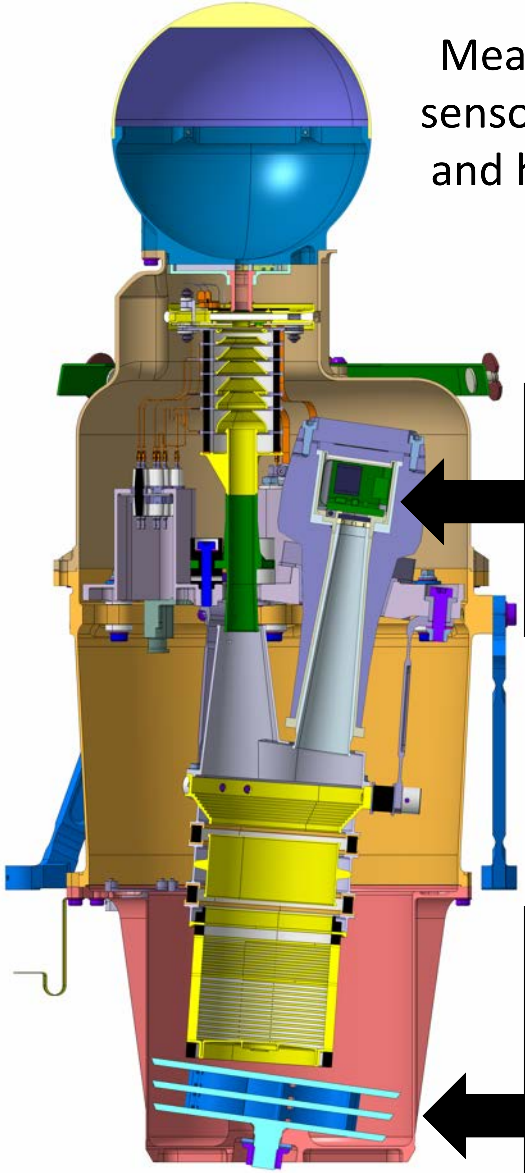
- **10 mm MCPs**
- **Design drivers**
  - Minimum volume
  - Availability of EEE parts
  - Signal quality
  - Routing through shield
- ➢ **Rigid-flex PCB**
- ➢ **Folding process**



20 x 23 x 23 mm

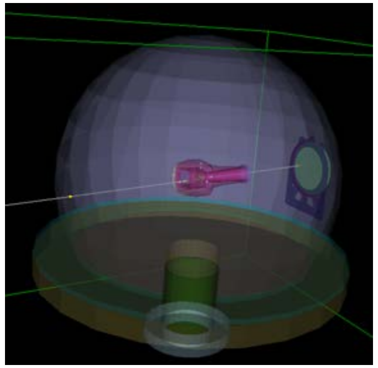


Measured total PFM sensor mass, shielding and harness included

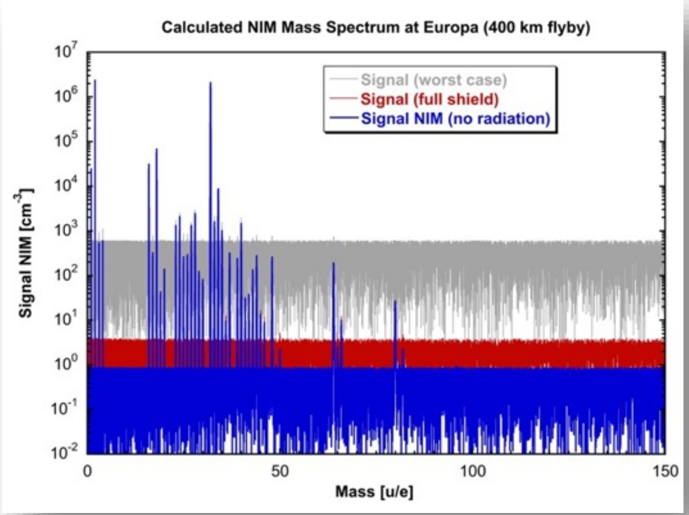
3035 g

1159 g
1-10-1 mm
Al-WCu-Al

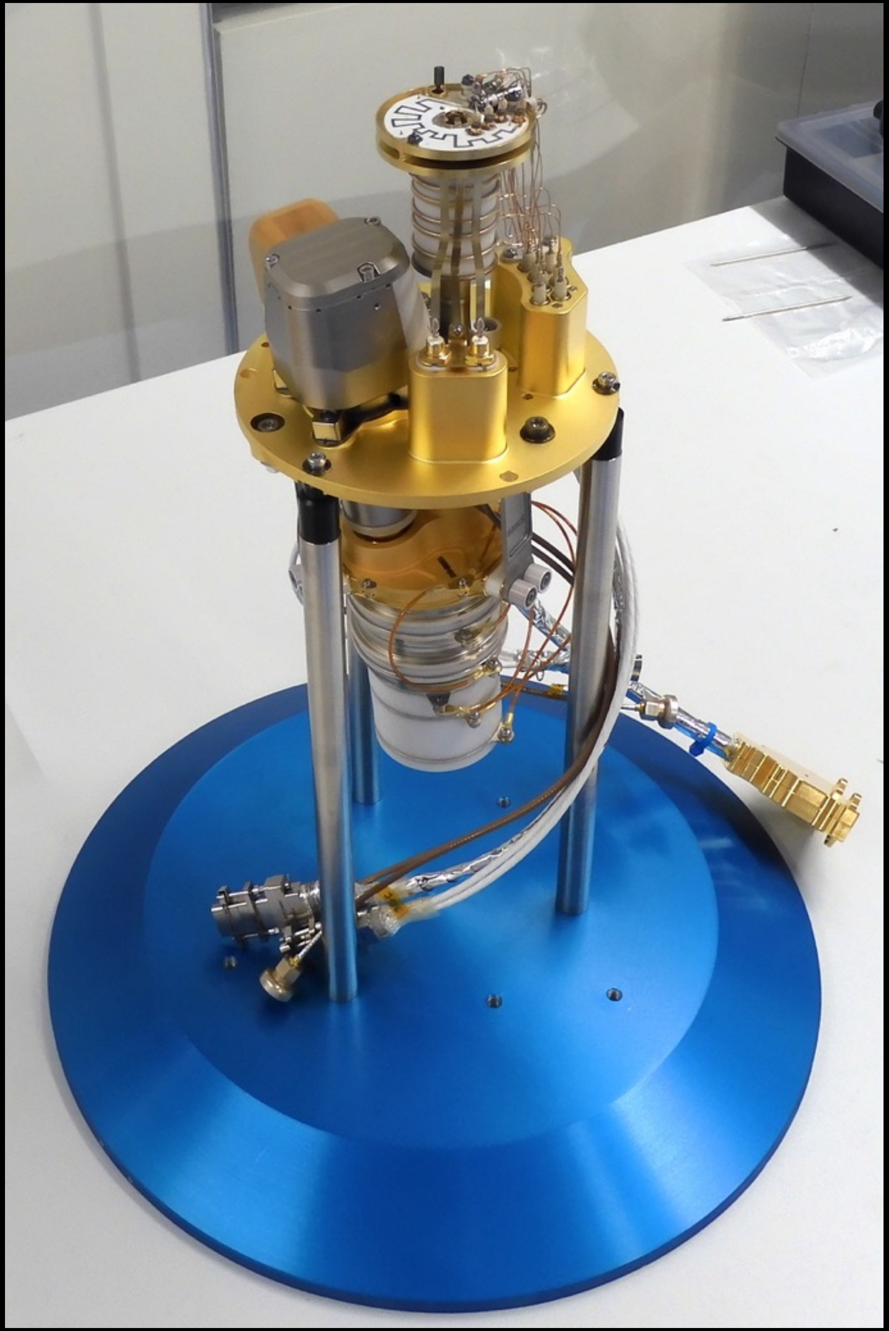
478 g
3 x 2mm
Ta



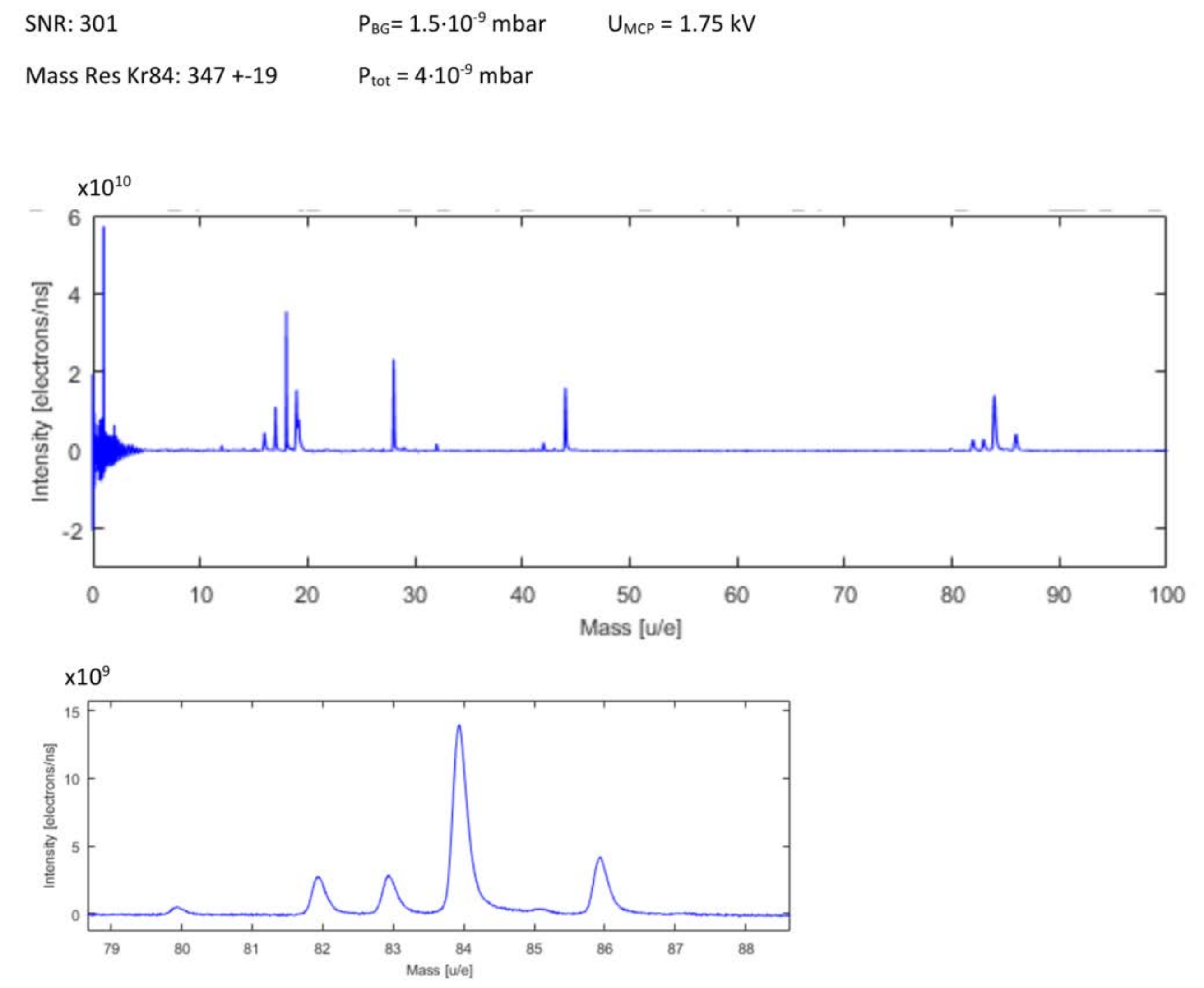
- **Geant4 sim.** (PSI, IRF, Aberystwyth)
- **Tests with 11-345 MeV e^-** (PSI)
- See Tulej et al., 2015, 2017 and Lasi et al., 2019



NIM Sensor
PFM (2019)



First Result



- ✓ Very 1st spectrum!
- ✓ September 9th, 2019
- ✓ With initial manual settings
- ✓ With lab electronics (but our own pulser)
- ❑ Now optimizing using Particle Swarm Algorithm
- ❑ Connecting to flight electronics in Jan 2020

References

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Part 2: From Space to IoT

D. Lasi[1,2], L. Hofer[2], J. Jost[1], A. Péteut[1], M. Gruber[1], S. Gasc[1]

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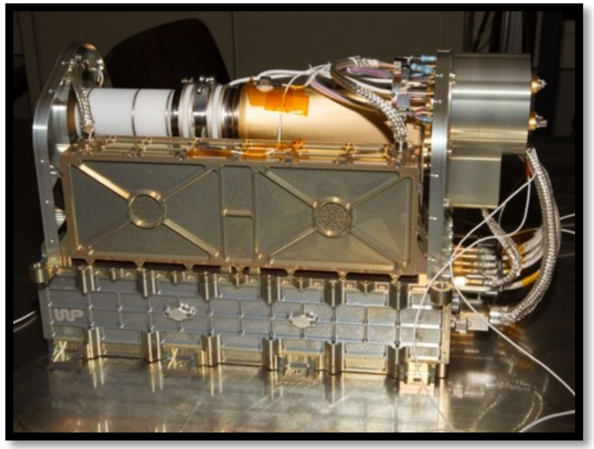
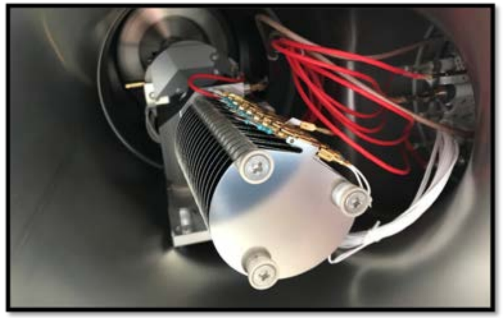
From Space to Earth

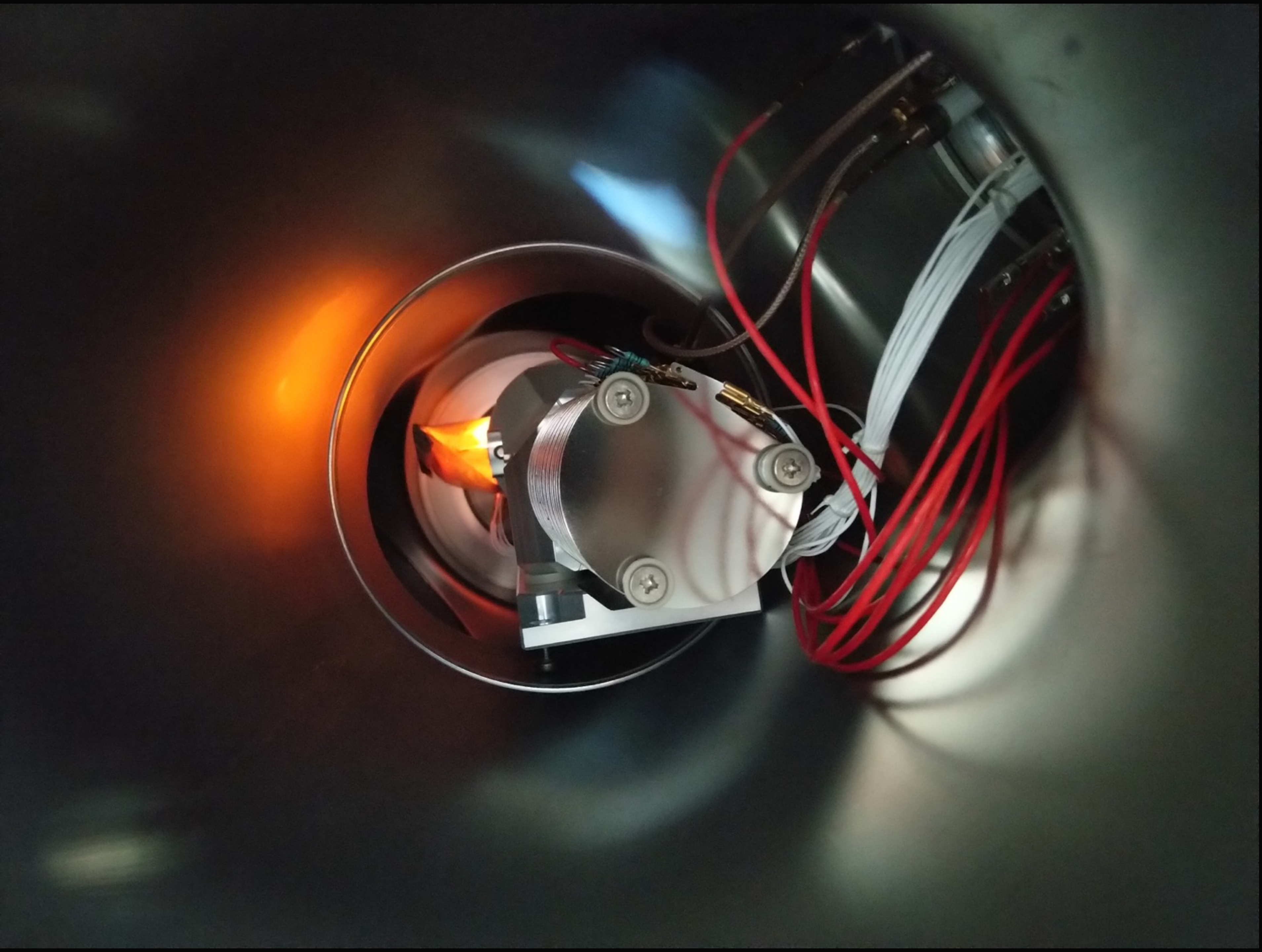
NGMS PFM (UBe, 2018)



Spacetek TOF and Electronics (2019)



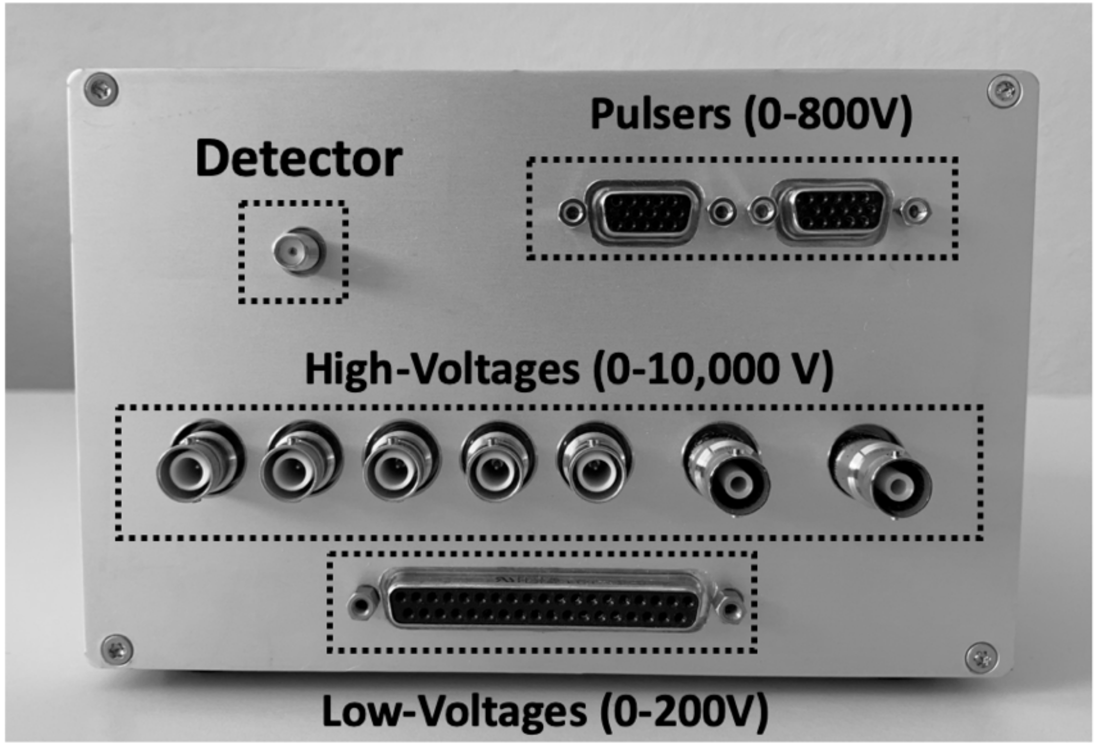
- **100% redesign from the ground up...**
- **What's IN?**
  - Most architectural decisions
  - Remote control and diagnostic
  - Automated particle swarm optimization
- **What's OUT? (for the time being)**
  - Metal-ceramic ion optics
  - MCP detectors (→CEM)
  - Vacuum electronics
  - Radhard design
    (EEE, scrubbing, TMR, materials, shielding, ...)
- **What's NEW?**
  - Use of ARM System-on-Chip (SoC)
  - HTTP API (→ Internet of Things device)

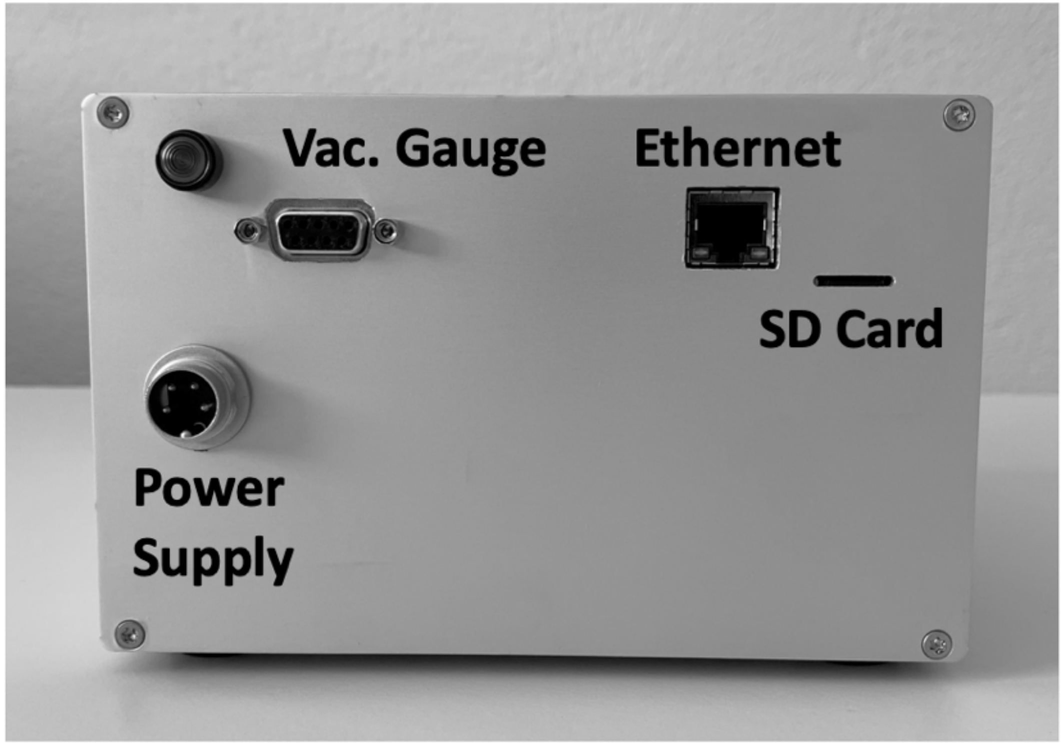


Sensor length:
~300 mm

Optimized for manufacturability (assembly < ½ day)

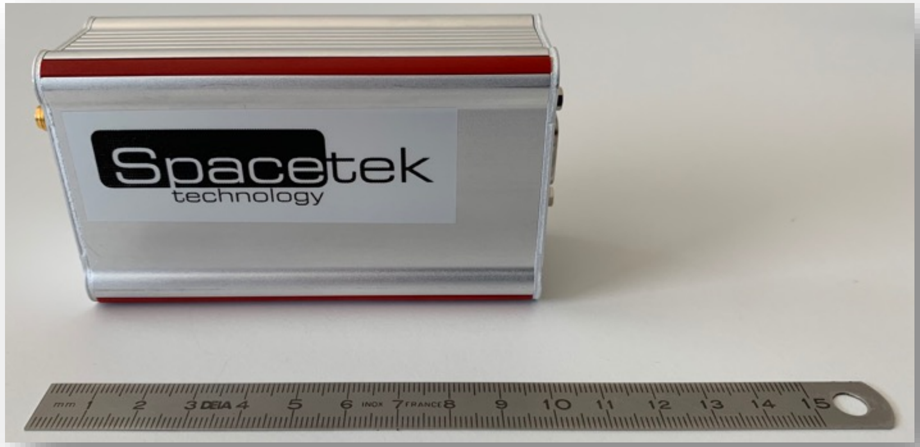
Instrument Electronic Box

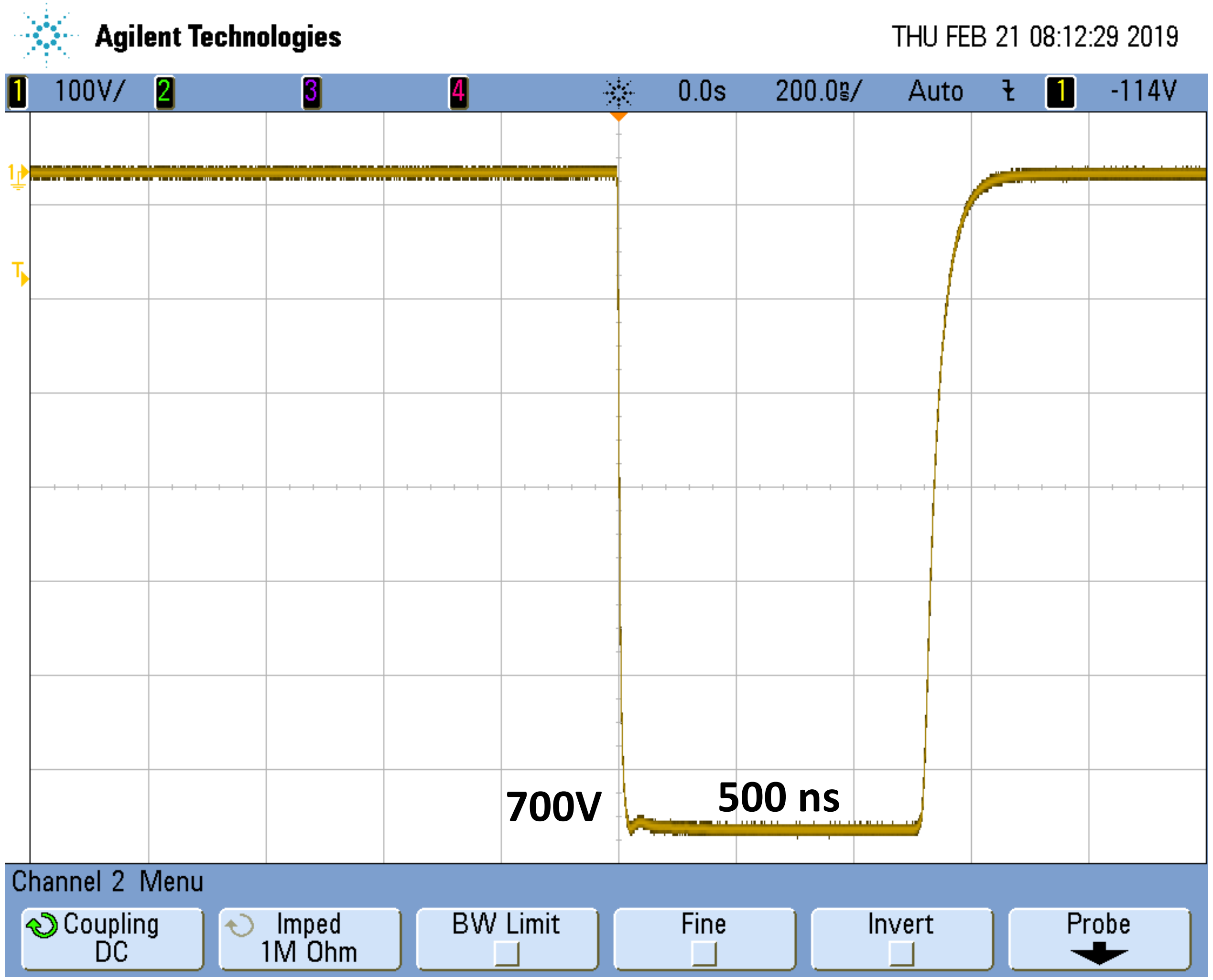




- **100% developed in-house**
- **Box size:** 238 x 165 x 105 mm
- **50% volume reduction possible with layout optimization**
- **Power consumption:** ~25 W (excl. vacuum pump)

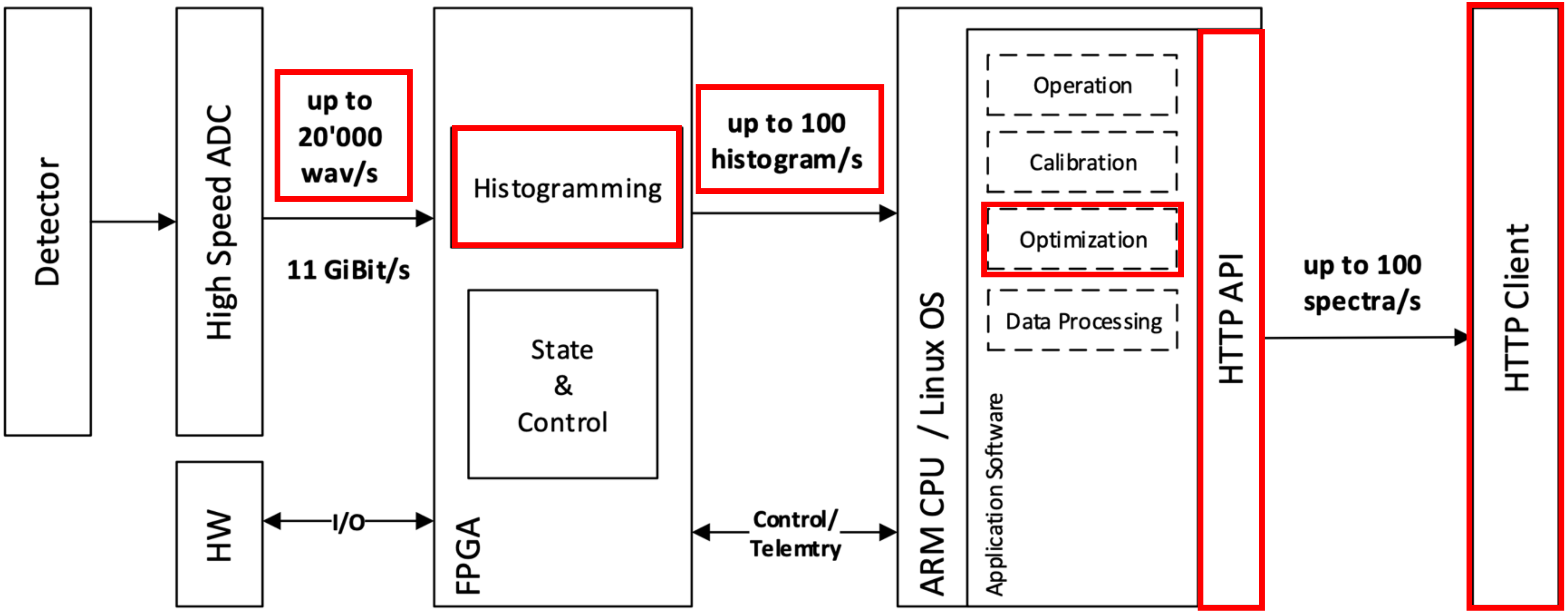
Fast High-Voltage Pulser





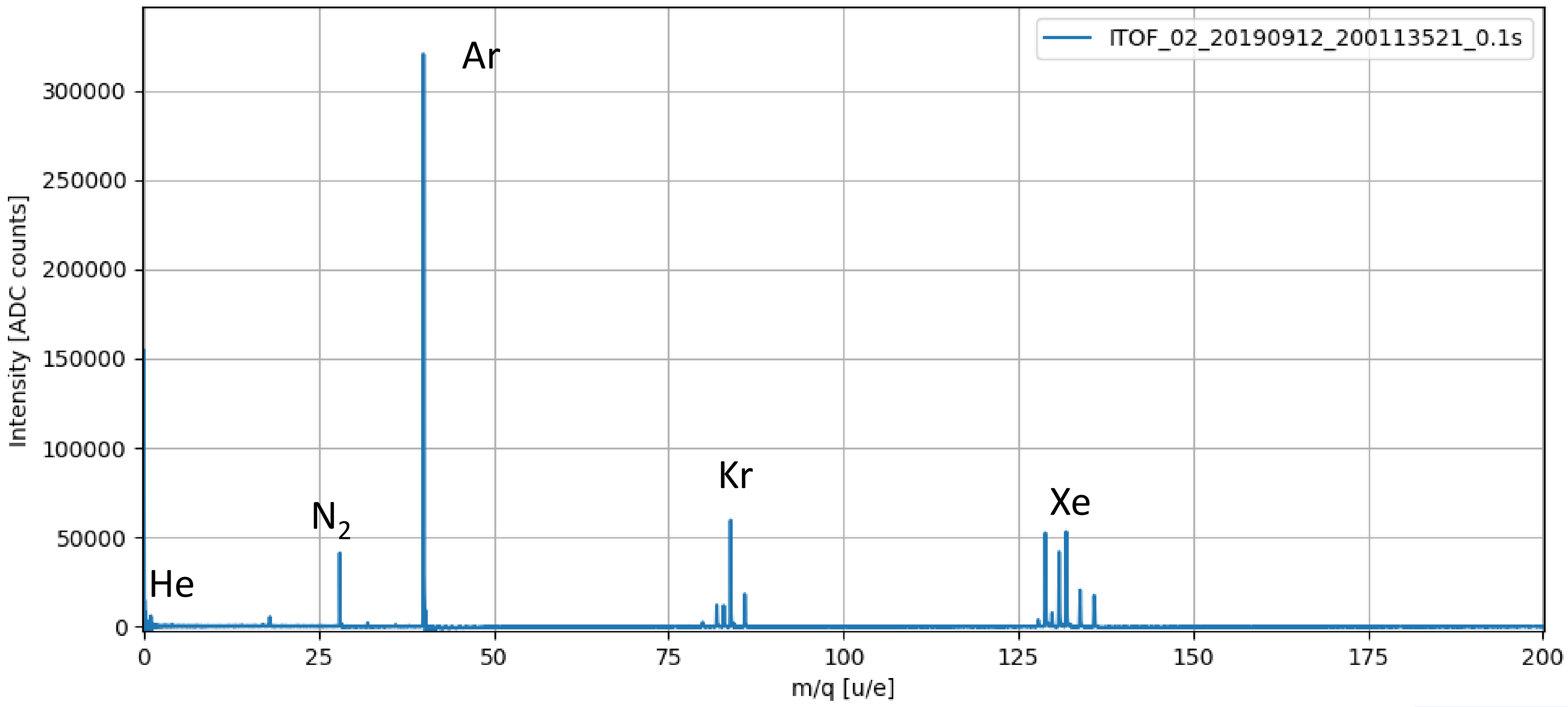
- **100% developed in-house**
- **External box:** flexibility, short cables
- **Pulse height:** up to ~800V (+ or -)
- **Adjustable duration**
- **Rise time:** ~2-3 ns

Electronics Design and Capabilities



First Results

Kr	**10%**	**N2**	**10%**
Xe	**10%**	**Ar**	**60%**
He	**10%**		



September 12th, 2019!

Integration time (full spectrum):

100 ms

(sum 1,000 single shots @ 10 kHz)

Mass resolution:

900 M/ΔM (CO_2)

1,250 M/ΔM (Xe)

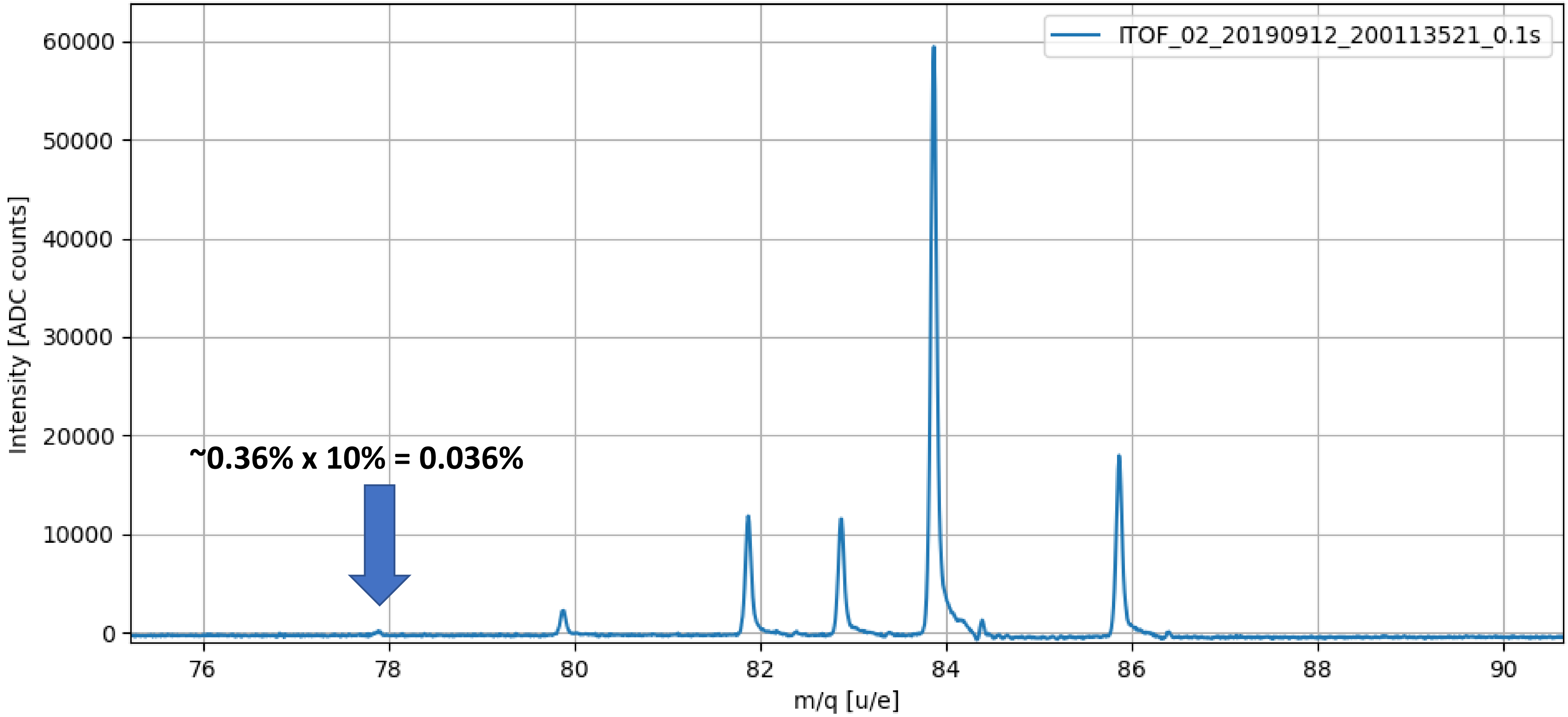
Dynamic range

~10^5

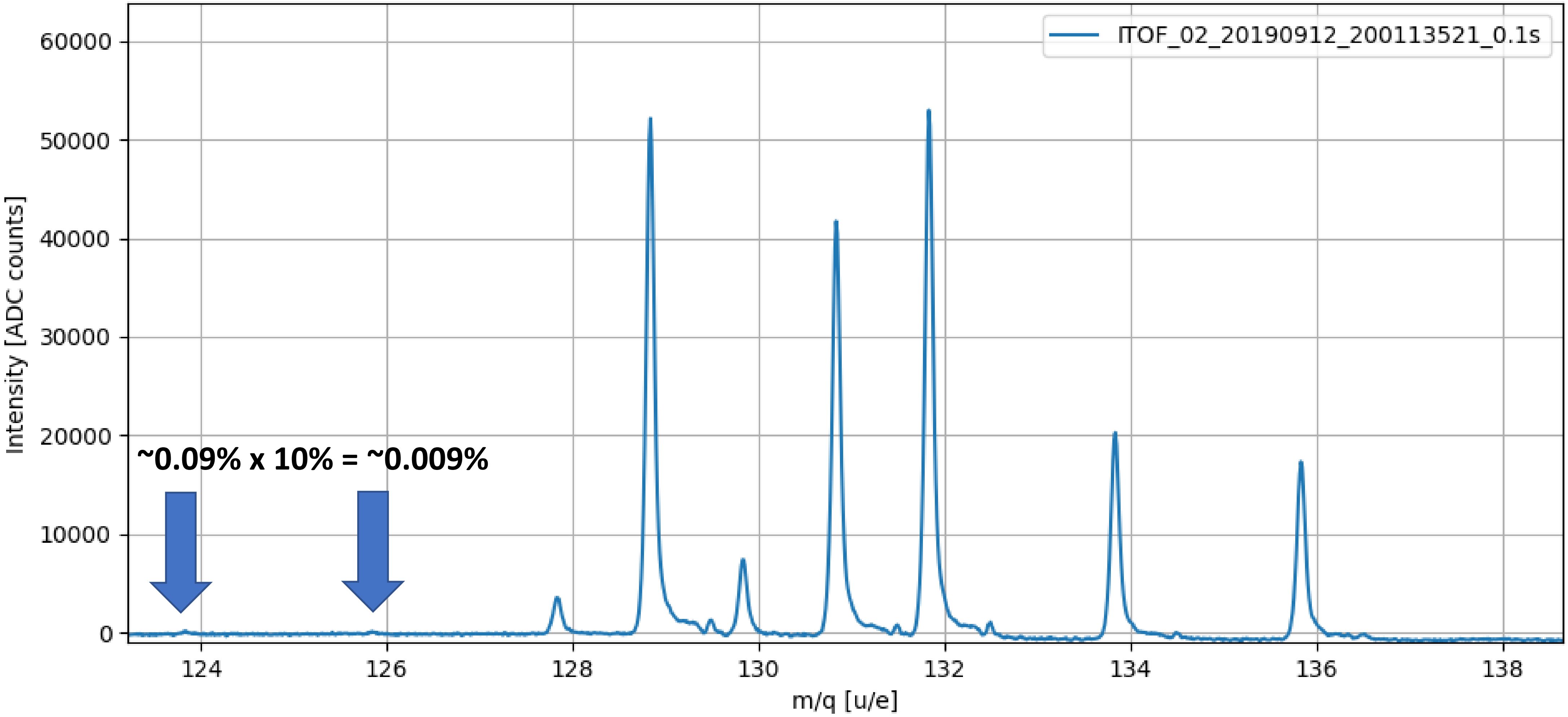
(six decades: achievable goal)

All the way up to 720 u

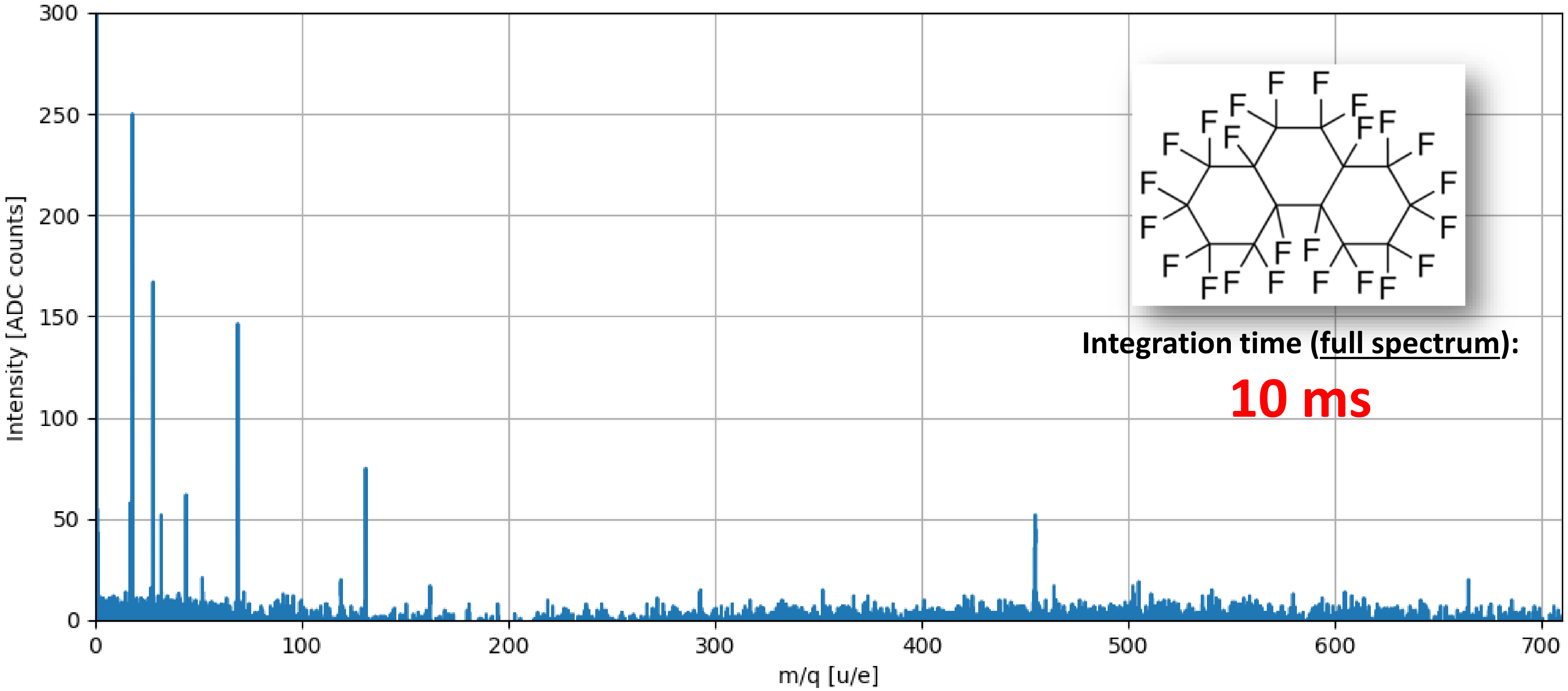
Zooming-in on the isotopes of Kr



Zooming-in on the isotopes of Xe



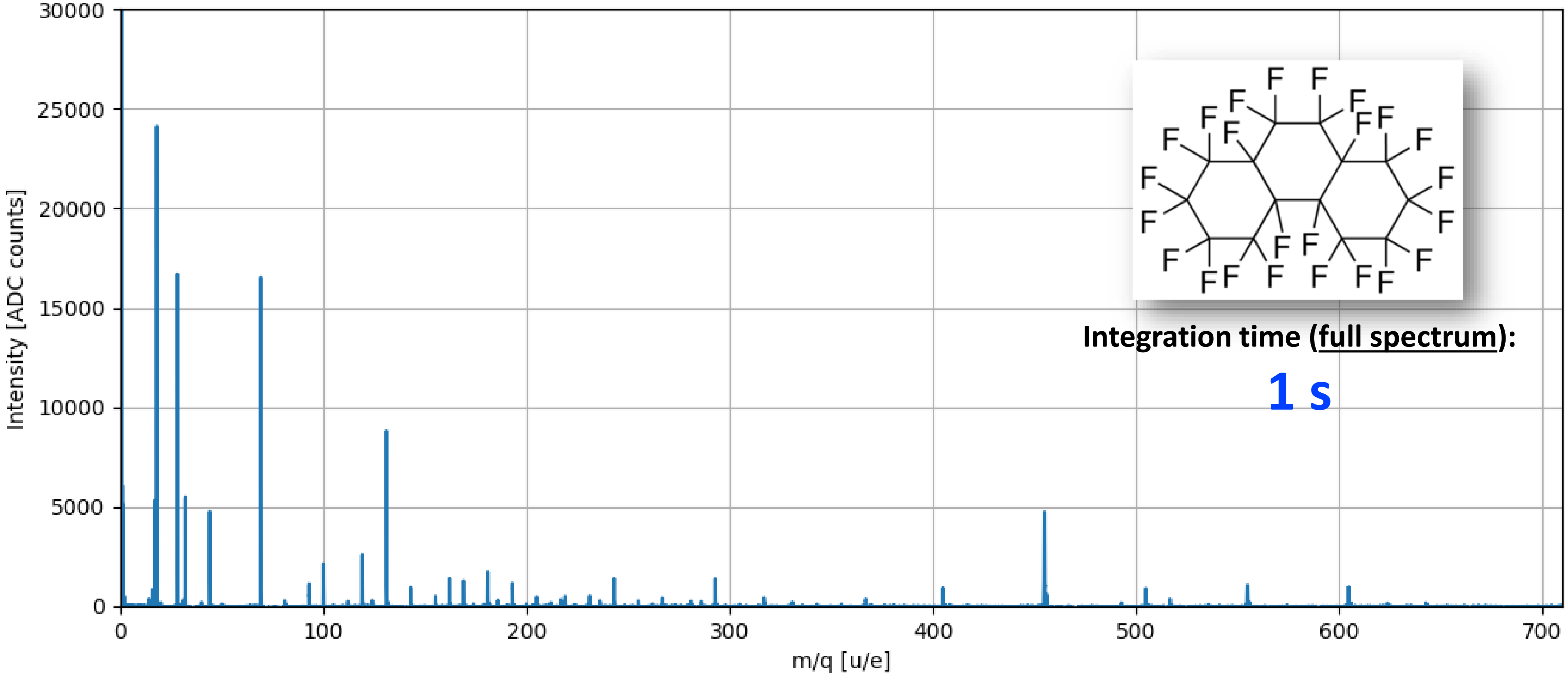
A Heavier Calibration Compound



Integration time (full spectrum):

10 ms

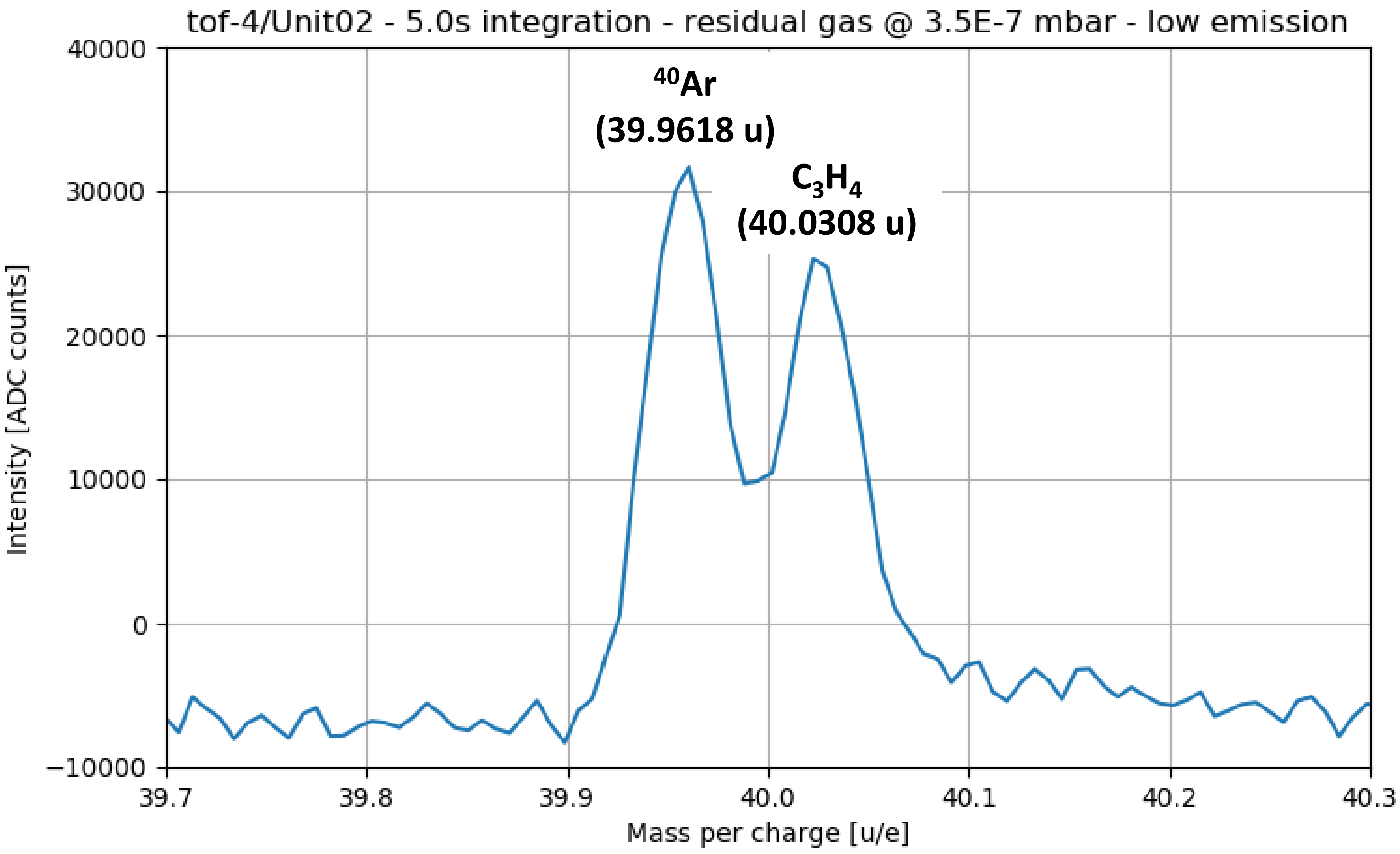
A Heavier Calibration Compound



Integration time (full spectrum):

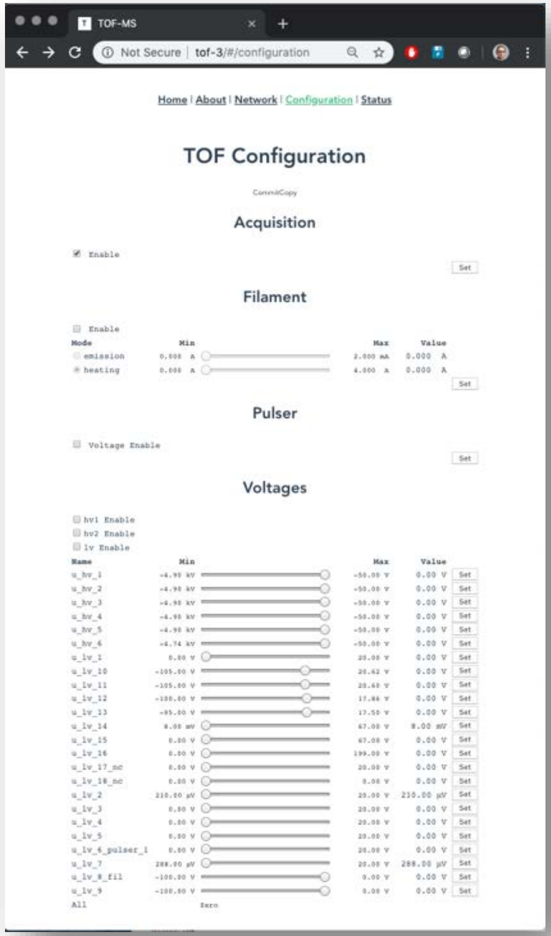
1 s

On Mass Resolution...

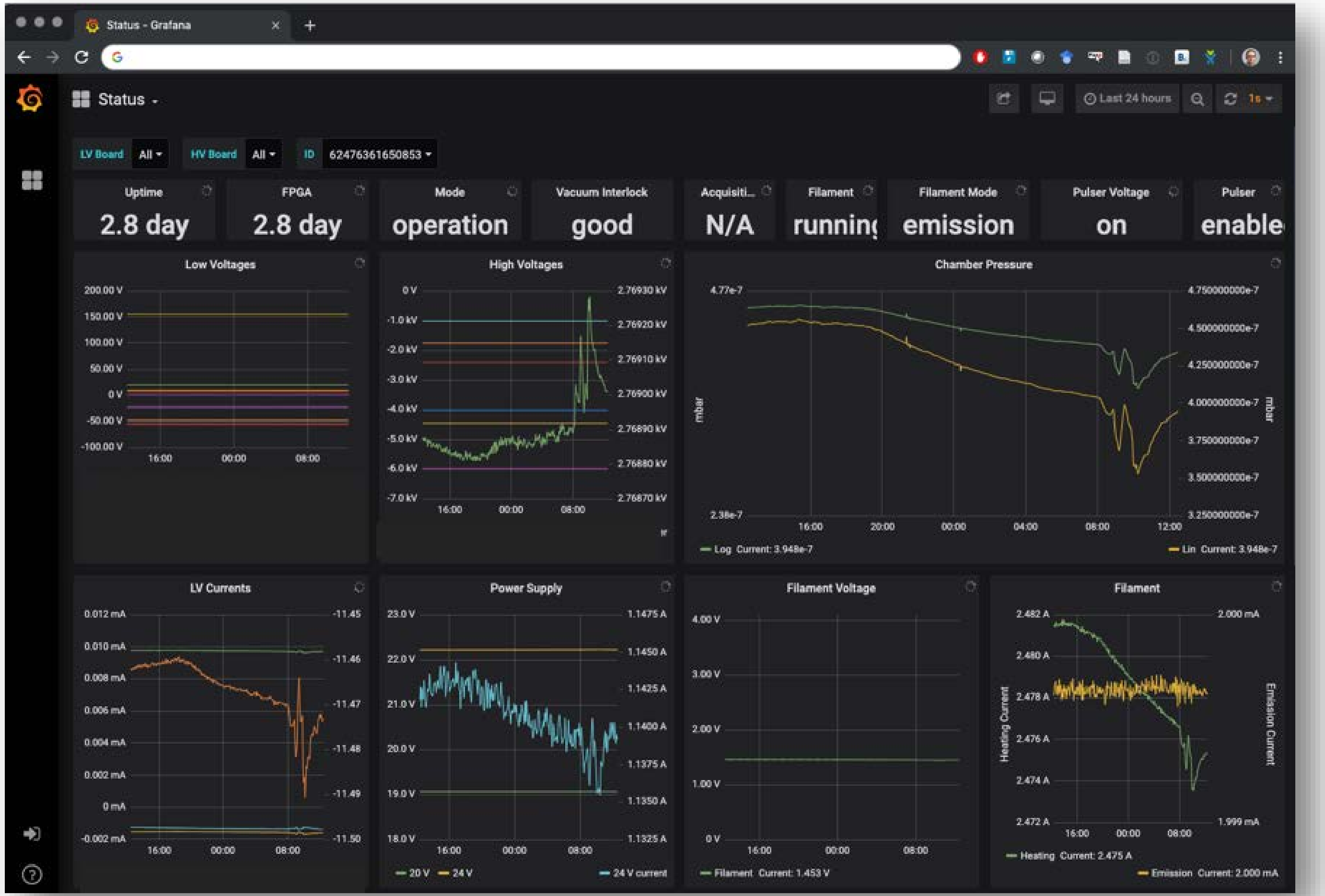


Software and IoT Concept

Full Remote Control

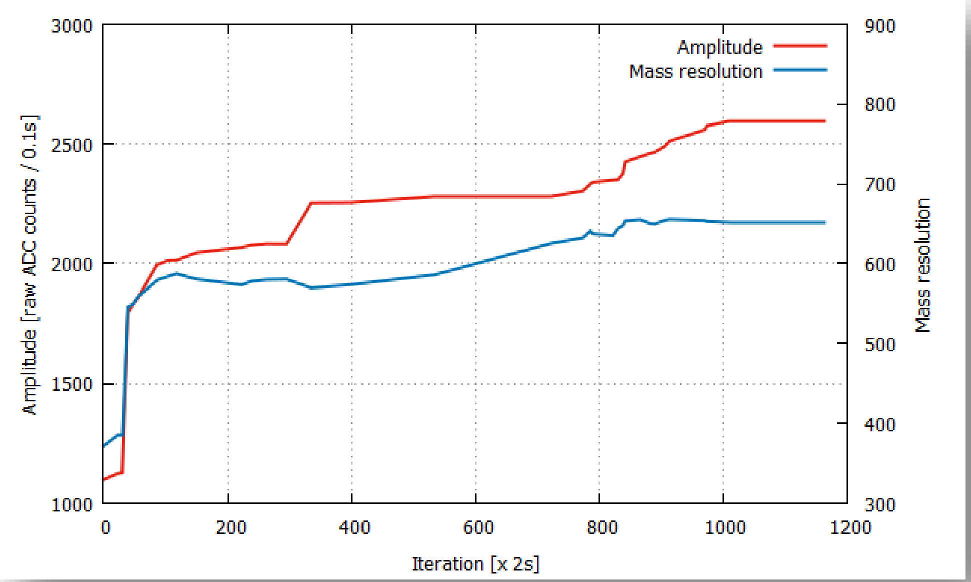


Real-Time Data Recording to Time Series Database (housekeeping and measurement results)

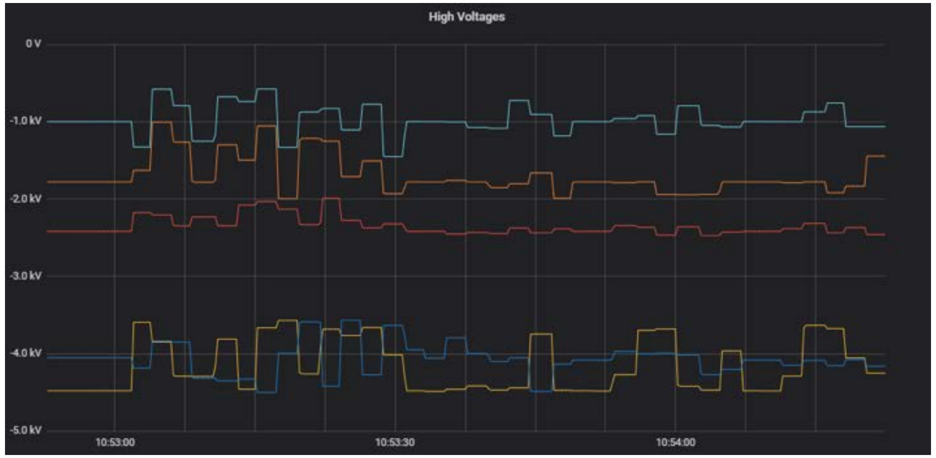


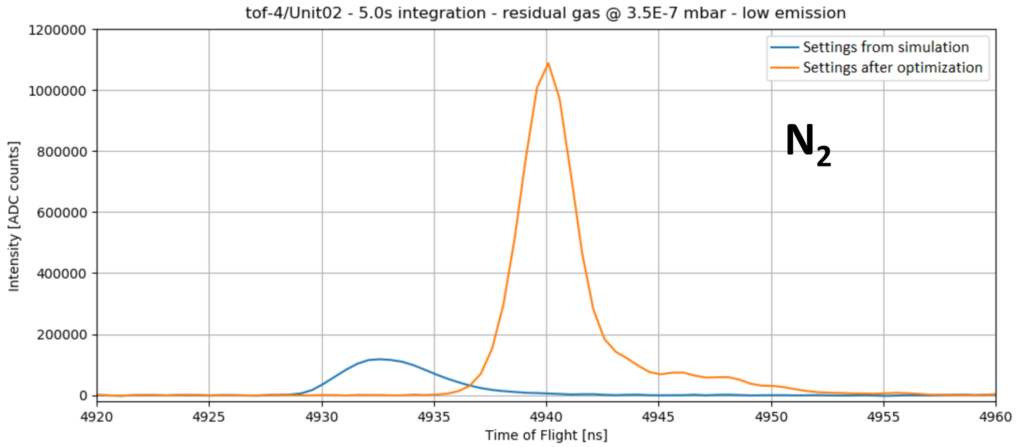
Automated Optimization

- Particle Swarm Algorithm (used on RTOF/Rosetta), which aim at finding the global optimum of ion optics settings (emitters, ion source, pulser, reflectron, etc.)
- Different score functions can be implemented: Area, Area/FWHM, Area/FWHM^2, Area^2/FWHM, ...
- Uses residual gas peaks (e.g., CO_2, H_2O, ...), >10^{-7} mbar
- Performance: 1 optimization step every 2s



Example of high-voltages variation during optimization run



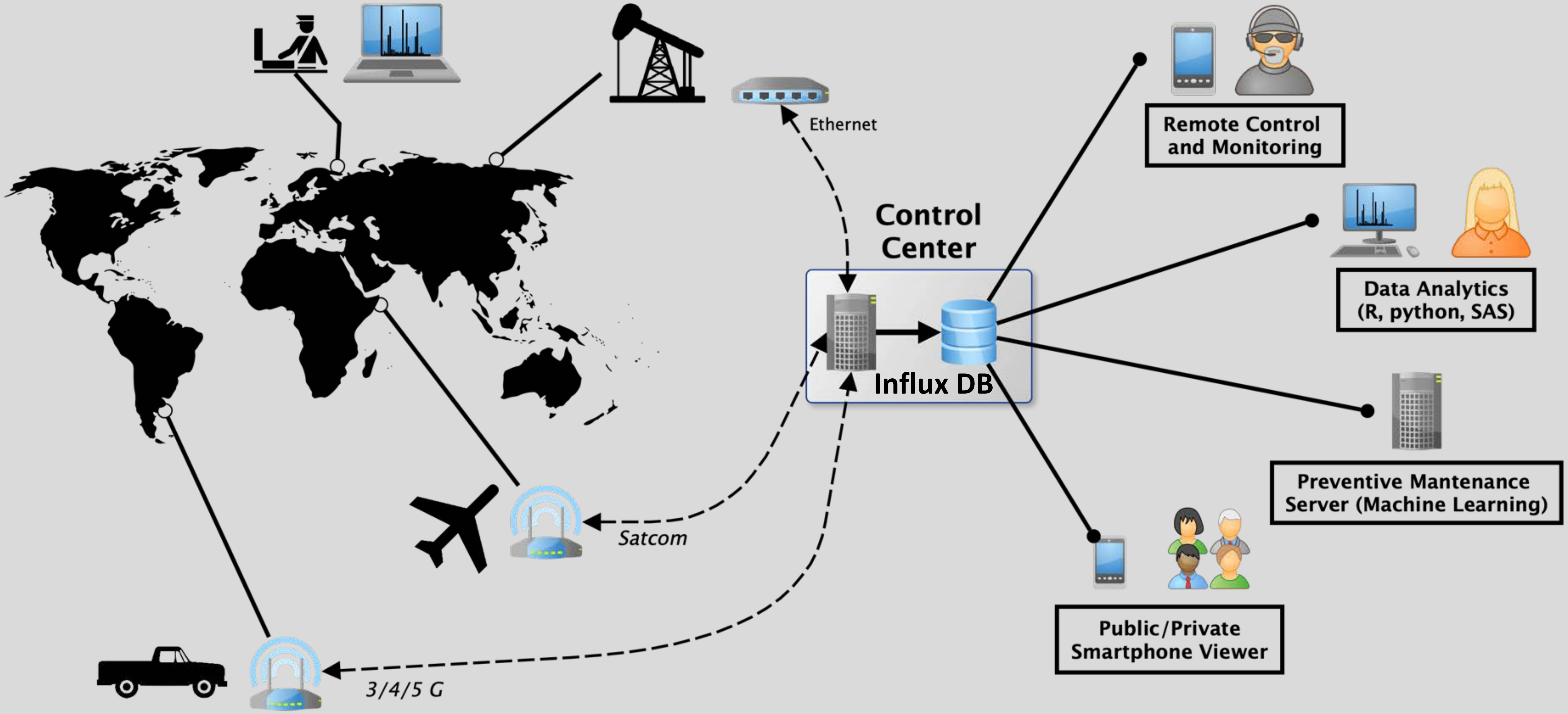


 Algorithm description: A. Bieler et al. " Jou. Mass Spectr. 46 (2011)

Vision

An IoT instrument enabling systems whose potential go beyond narrow definitions of capabilities of isolated ‘offline’ devices

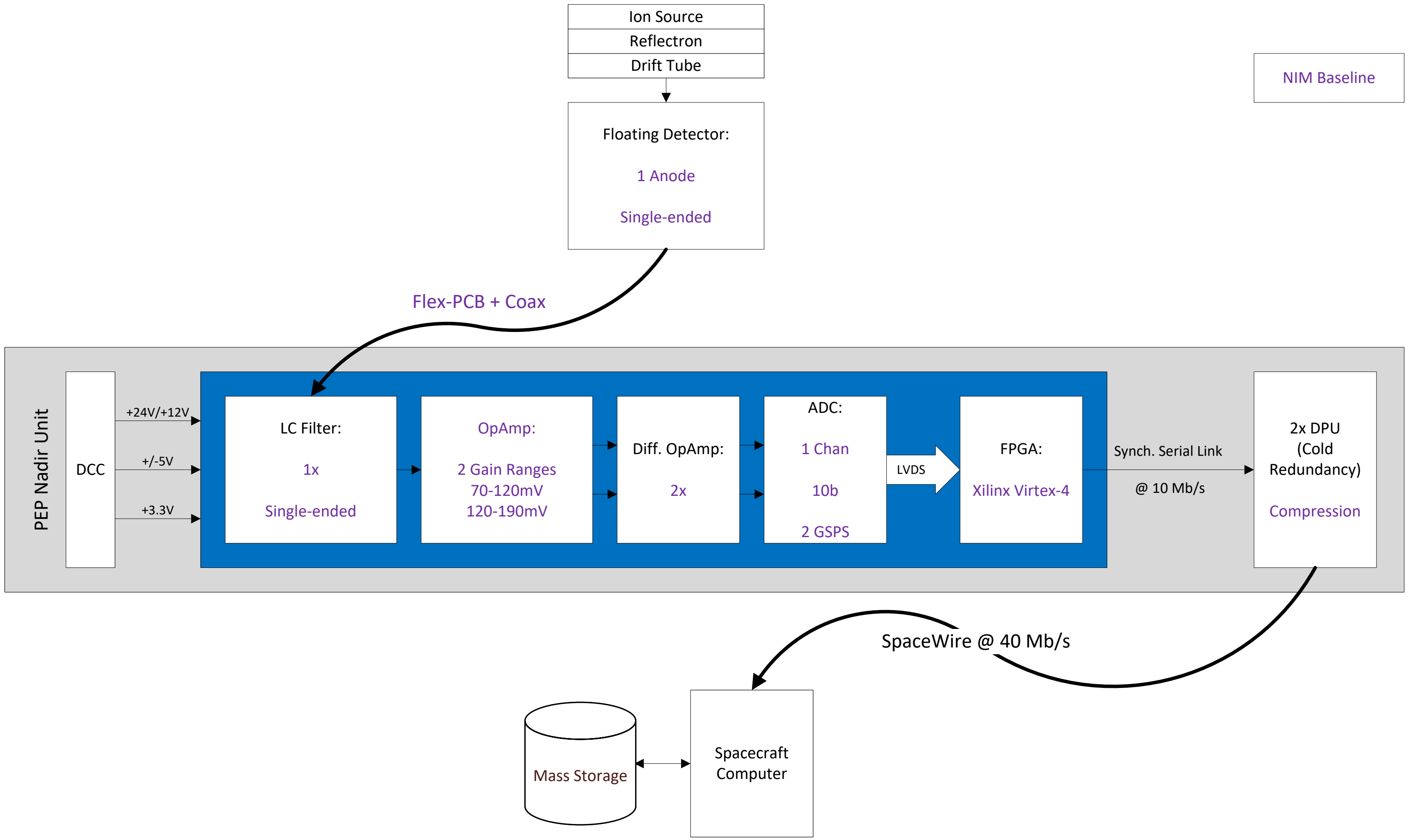
New ConOps


Ethernet
Control Center
Influx DB
Satcom
3/4/5 G
Remote Control and Monitoring
Data Analytics (R, python, SAS)
Preventive Mantenance Server (Machine Learning)
Public/Private Smartphone Viewer

Thank You!

Looking forward to your questions, feedback, ideas, ...

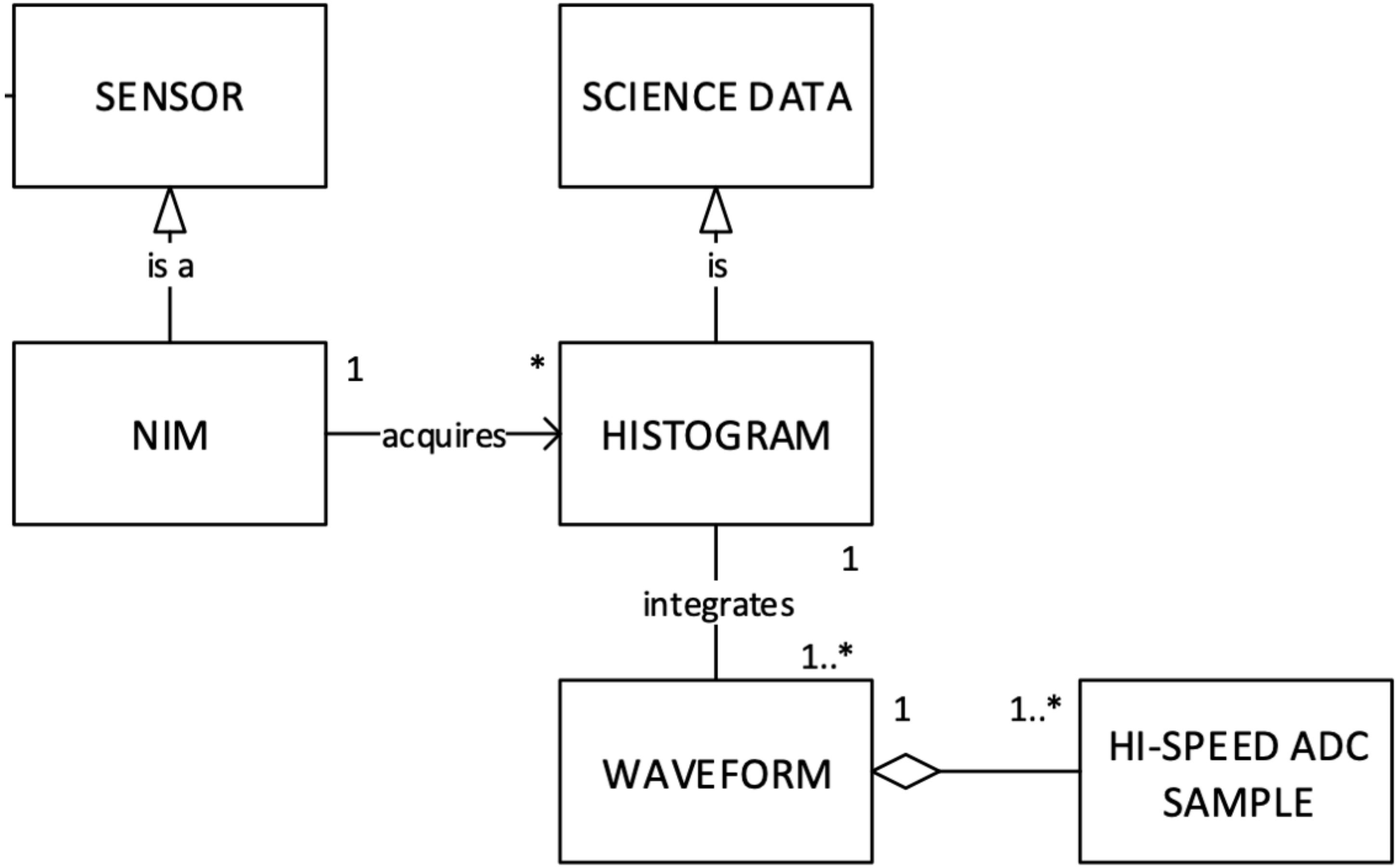
Signal Chain of NIM



Key features:

- Floating detector
- 10 bit ADC, 2 GSPS
- LVDS link to FGPA (Virtex-4)

Data Processing of NIM



MG, v0.5

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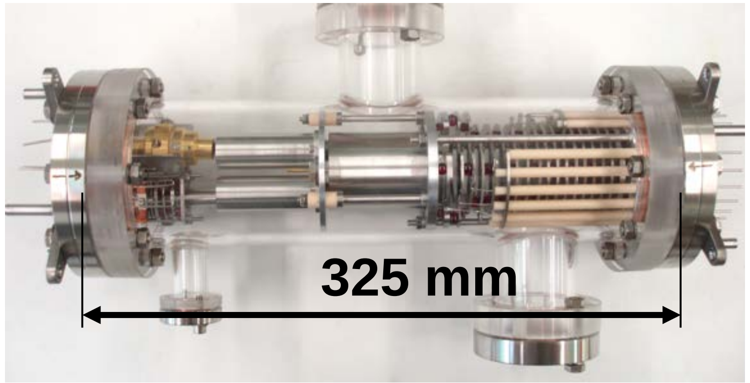
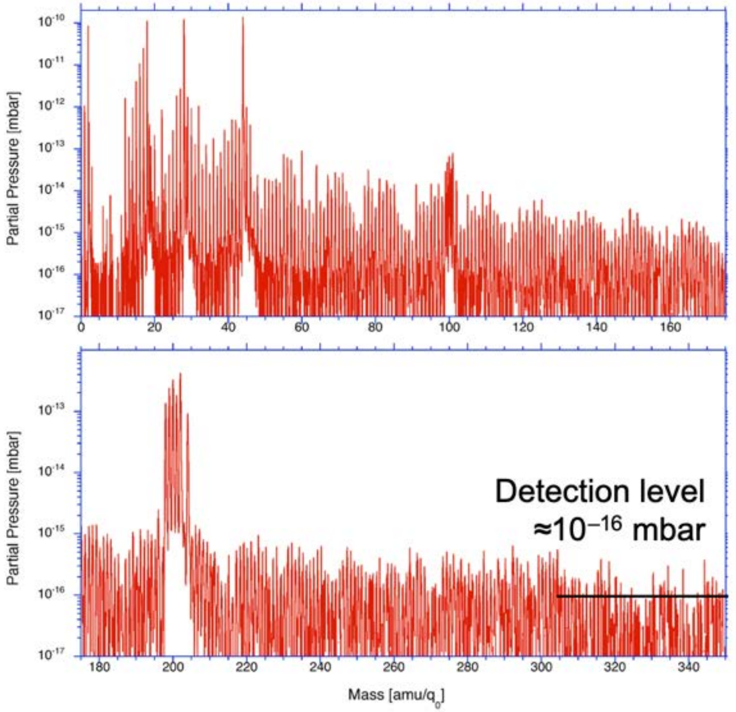
Expected Performance & Capabilities



From our space instrumentation experience:

- Speed: 0.1s (or longer, per spectrum)
- Mass resolution: ~900 M/ΔM
- Mass range: 1-1000 u
- Dynamic range: 10^6 (~10s @ 10 kHz, 1 mV rms white noise)
- Detection level: 10^{-16} mbar



D. Abplanalp, P. Wurz, et al., Adv. Space Res. 44 (2009) 870–878.