Development of Novel Detector Concepts for Nuclear Physics with Rare Isotope Beams at FRIB

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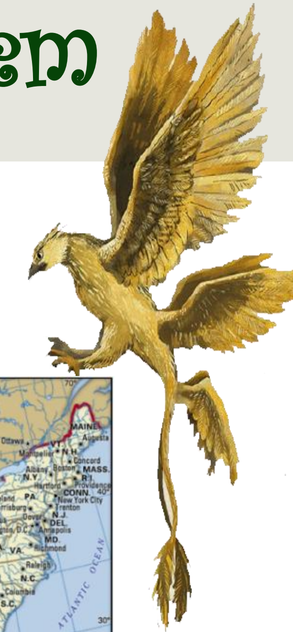
This material is based upon work supported by the U.S. Department of Energy Office of Science under Cooperative Agreement DE-SC0000661, the State of Michigan and Michigan State University. Michigan State University designs and establishes FRIB as a DOE Office of Science National User Facility in support of the mission of the Office of Nuclear Physics.

Fantastic Nuclei and where to find them

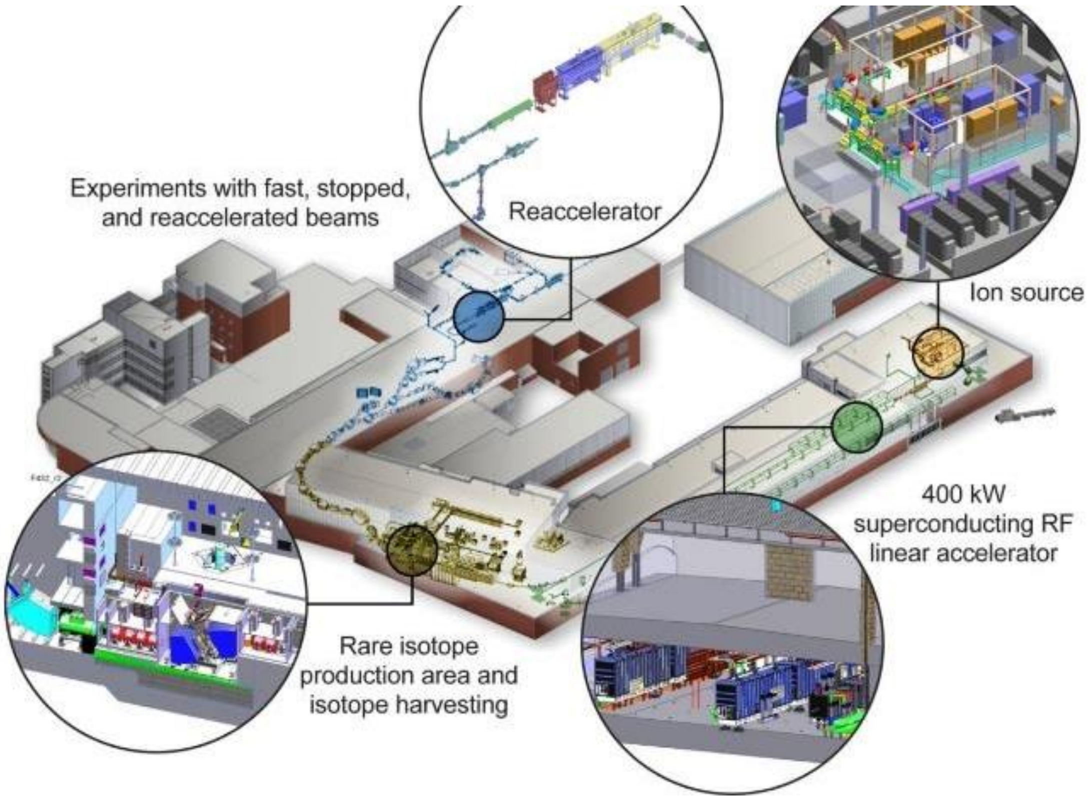


Facility For Rare Isotope Beams (FRIB)

- FRIB is a US DOE Office of Science scientific user facility (one of 28) intended to provide beams of rare isotopes – located on MSU campus
- FRIB started in 2008 and reached the last project milestone in January 2022, five months ahead of schedule and on budget
- Experiments began in May 2022. The first (three) experiments have all completed successfully
- FRIB is open to researchers from around the world based on scientific merit – Program committee approximately once per year

Key FRIB Features that Enable Discovery

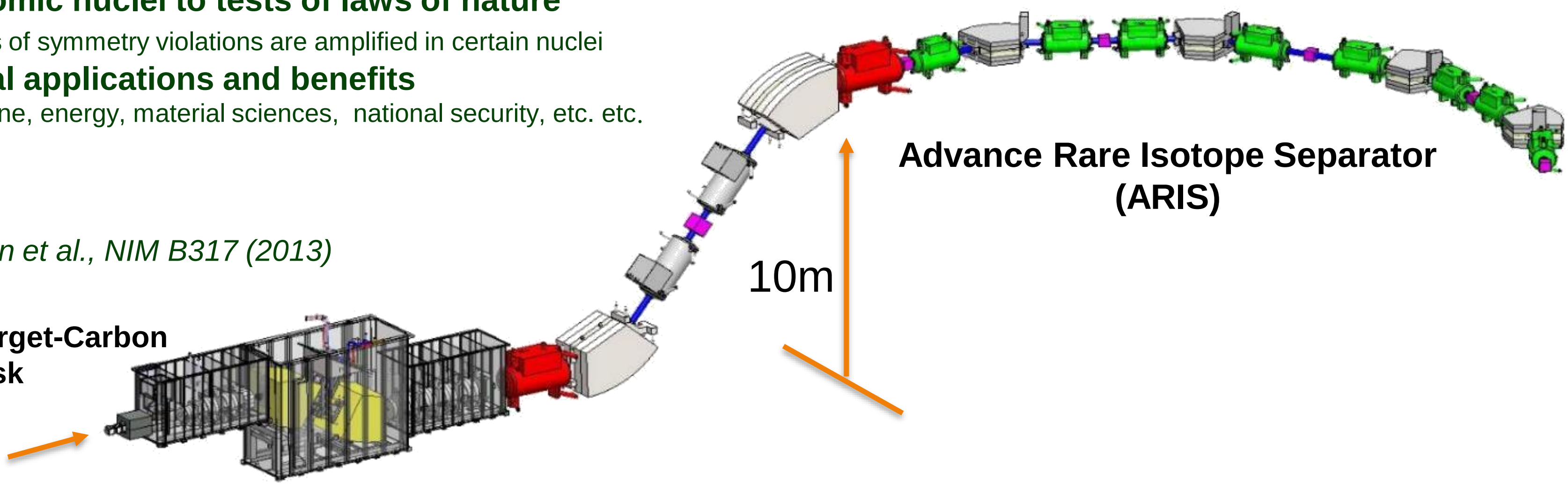
- FRIB's key feature is 400 kW beam power
  - 8 pμA or 5 x 10^{13} ^{238}U /s
  - 42 pμA or 2.6 x 10^{14} ^{48}Ca /s
- Experiments with fast (200 MeV/u), stopped (trapped), and reaccelerated beams (0.6 to 10 MeV/u)
- Separation of isotopes in-flight provides
  - Fast development time for any isotope
  - Beams of all elements and short half-lives
- Isotope harvesting capability from beam dump water



Thomas Glasmacher, FRIB Laboratory Director

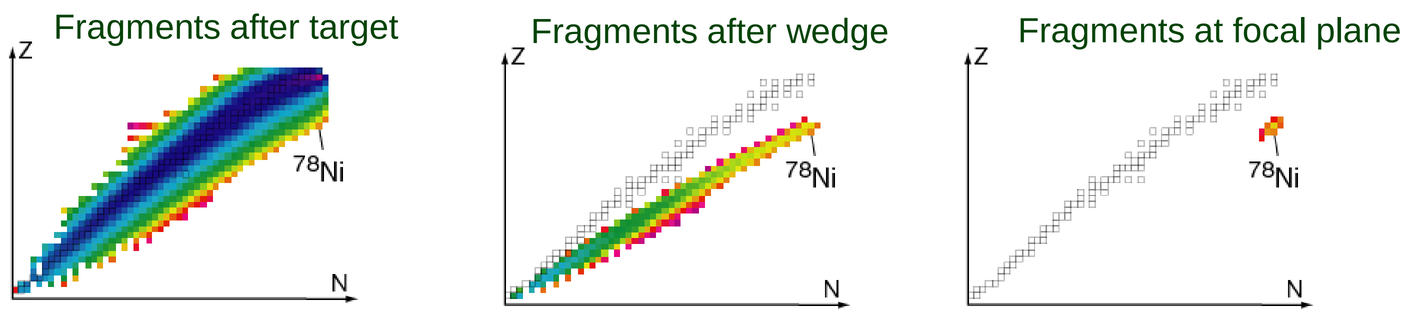
FRIB Enables Scientists to Make Discoveries in Four Areas

- **Properties of atomic nuclei**
  Study of predictive model of nuclei & their interactions, Many-body problem & physics of complex system
- **Astrophysics: Nuclear Processes in the Cosmos**
  Origin of the elements, energy generation in stars, stellar evolution & the resulting compact objects
- **Use atomic nuclei to tests of laws of nature**
  Effects of symmetry violations are amplified in certain nuclei
- **Societal applications and benefits**
  Medicine, energy, material sciences, national security, etc. etc.

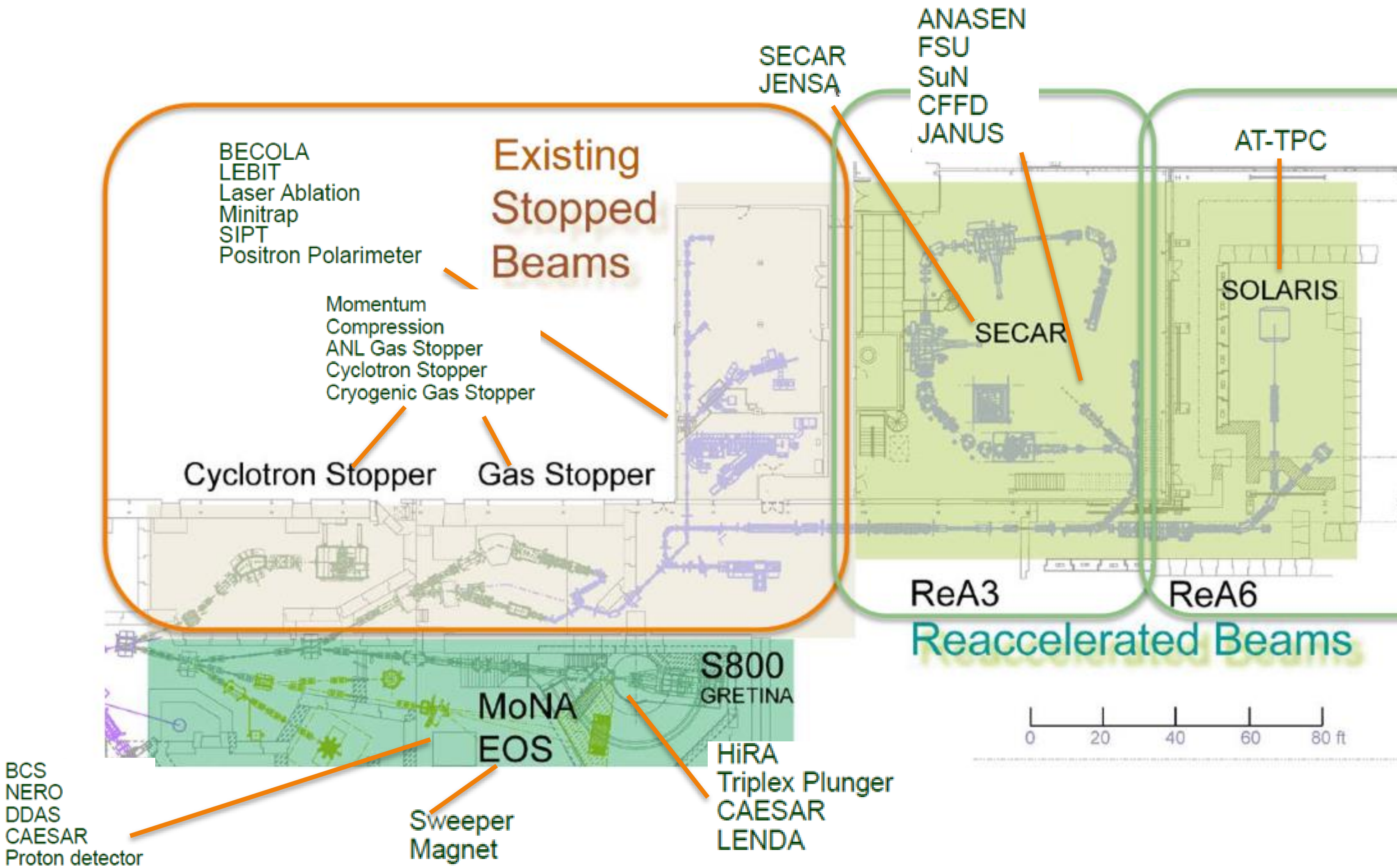


Hausmann et al., NIM B317 (2013)

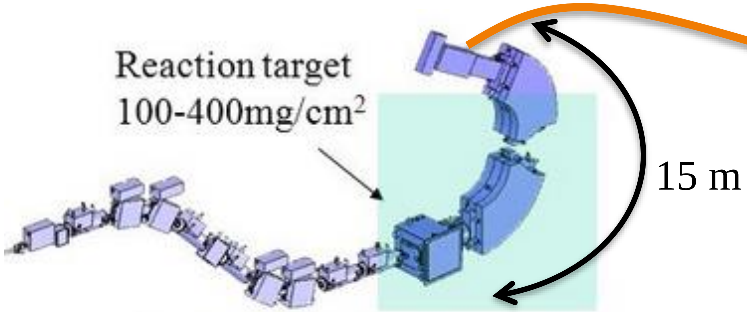
Example:
^{78}Ni from ^{86}Kr at 200 MeV/u



Science Opportunities at FRIB
with Fast, Stopped, Reaccelerated Beams

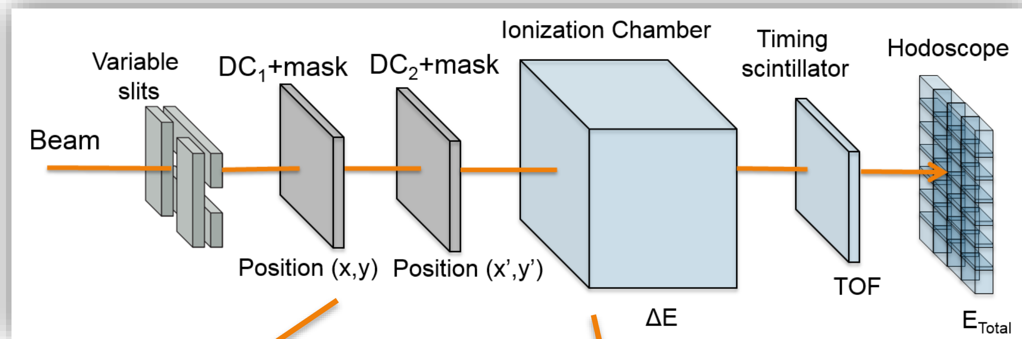


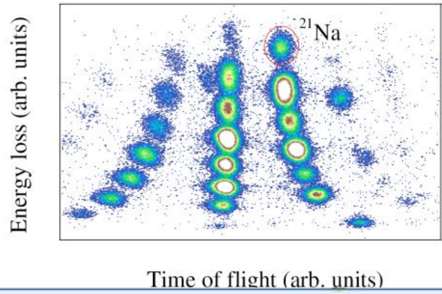
Fast-beam experiment with the S800



Reaction product identification
S800 spectrograph

Focal Plane detector system for heavy-ion PID





PID: Bρ-dE-ToF

Cathode Readout Drift Chamber (CRDC):

Position and angles

Two CRDCs, 1 m apart, with 30x60 cm^2 effective area filled with $CF4/(20\%)iC_4H_{10}$

- -) *Slow detector → low rate (<5KHz)*
- -) *Position resolution → <1 mm FWHM*
- -) *Aging problems*

Ionization Chamber (IC):

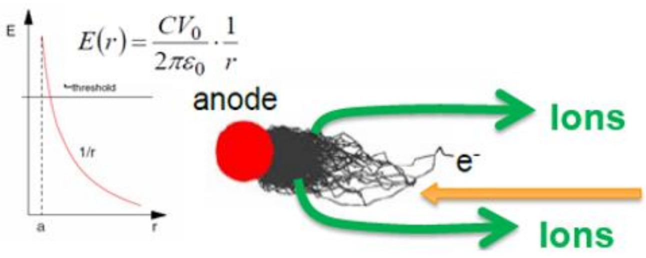
Z number identification

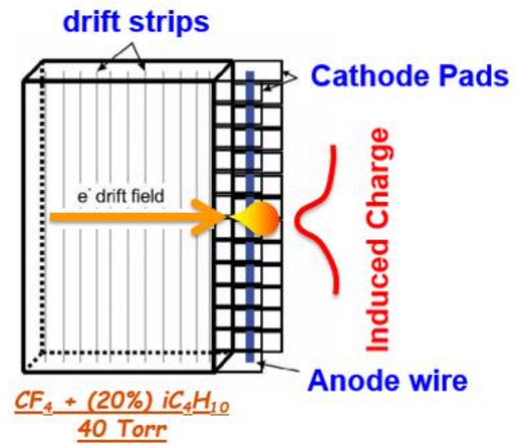
16 stacked-parallel plate ion chambers (each 1" long). filled with P10 (300-600 Torr)

- -) *Slow detector → low rate (<5KHz)*
- -) *Low SNR*
- -) *Good resolution only up to Z=50*

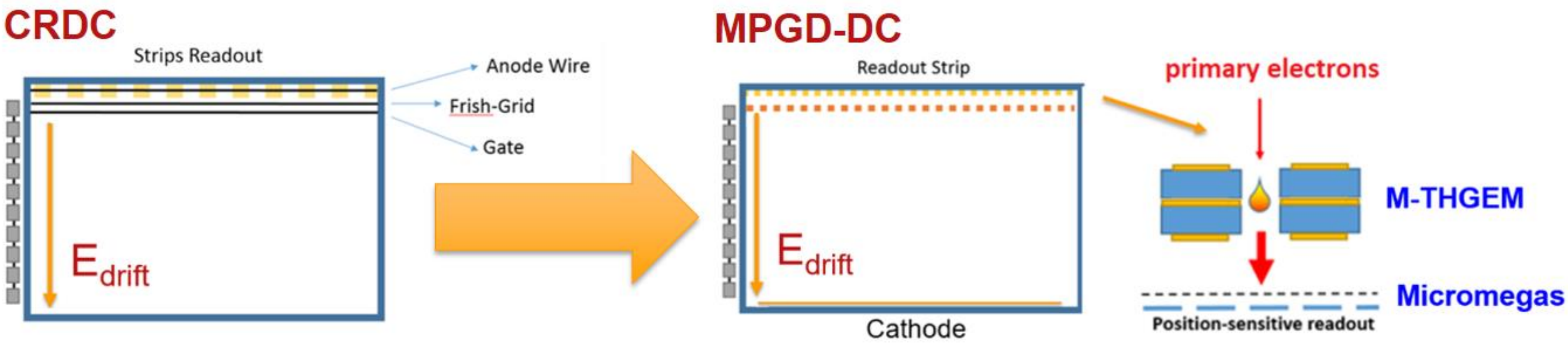
Tracking Readout: from wires to MPGD

Wire-Based Detector:
"Mechanics", Economic but
Secondary effects ➔ Gain limits
Space charge ➔ Counting-rate limits
Aging ➔ Damage after long-term operation





Goal → development of a new readout based on a hybrid MPGD structure, for the upgrade of the Cathode-Readout Drift-Chamber (CRDC) based tracking system



Position-Sensitive Micromegas Board

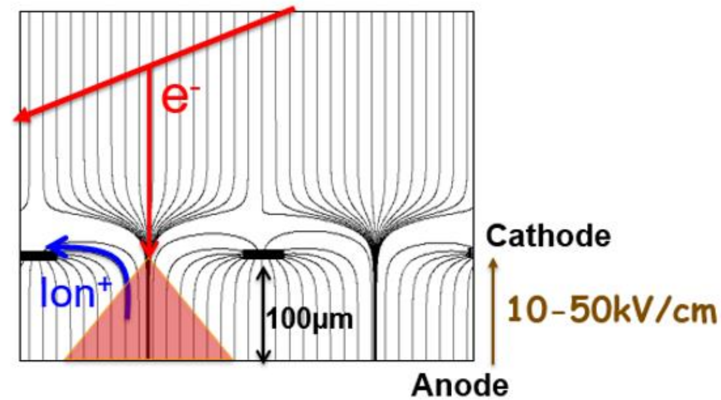
Giomataris et al. NIM A 376 (1996) 29

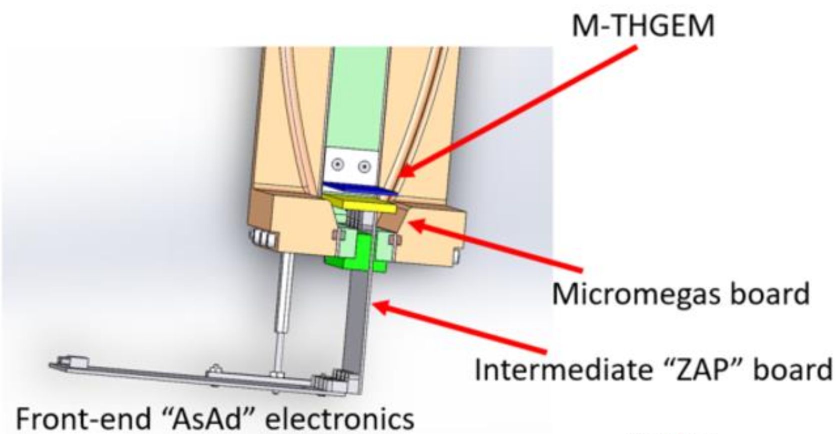
Micromesh Gaseous Chamber:

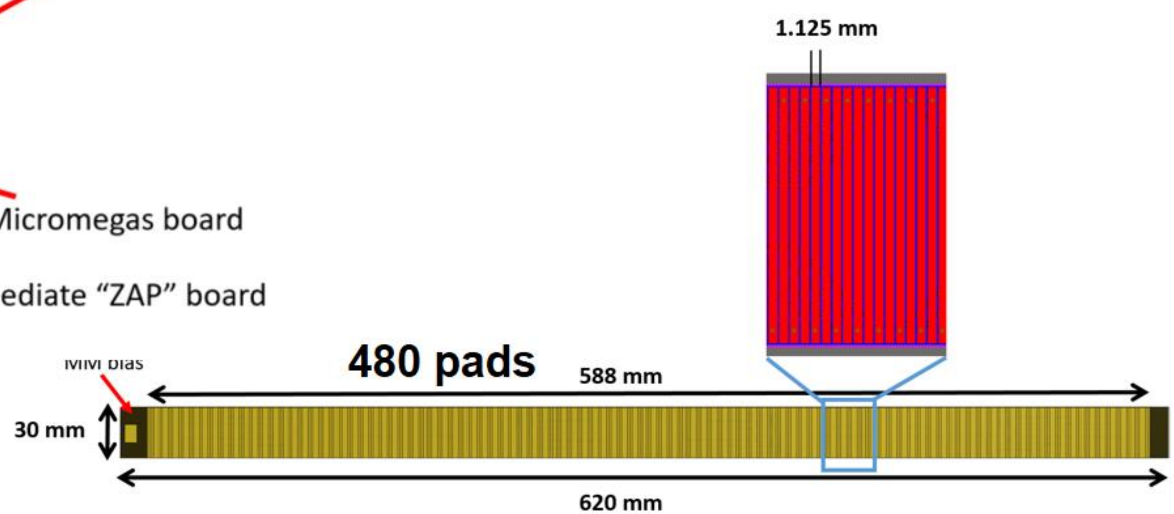
-) a thin mesh supported by 50-100 μm insulating pillars, mounted above readout structure

-) E field similar to parallel plate detector.

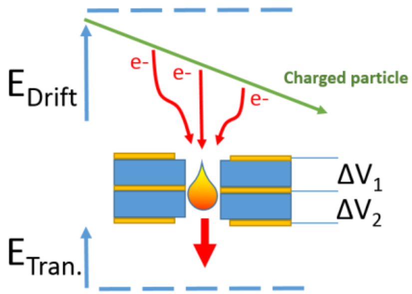
-) $E_{ampl}/E_{drift} > 100$ ➔ high e^- transparency & ion back-flow suppression

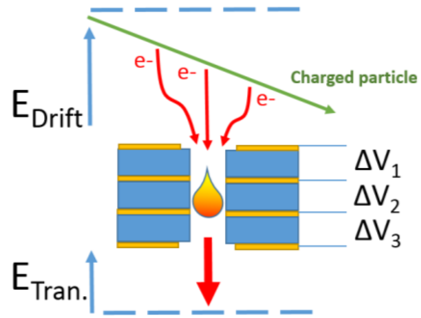






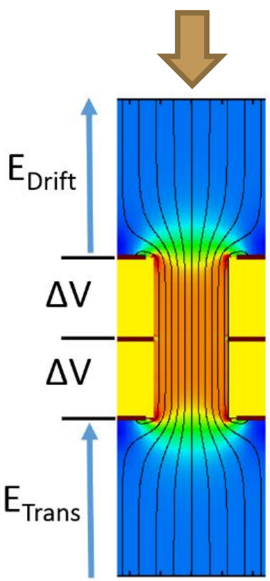
Pre-Amplification Stage: Multi-Layer THGEM





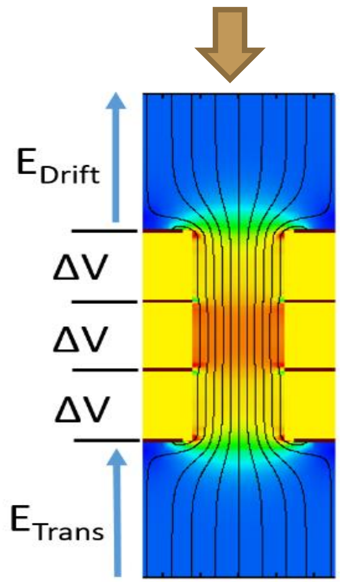
- -) No loss of charge ➔ high gain @ low voltage
- -) Robust avalanche confinement
  ➔ lower secondary effects
- -) Long avalanche region
  ➔ high gain @ low pressure
- -) Field geometry stabilized by inner electrodes
  ➔ reduced charging-up

2-Layer M-THGEM



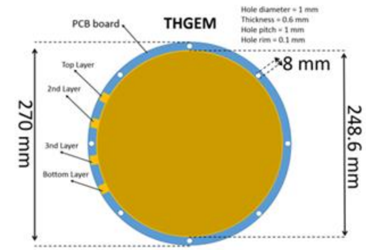
Low pressure

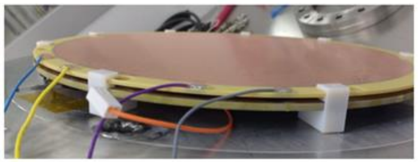
3-Layer M-THGEM



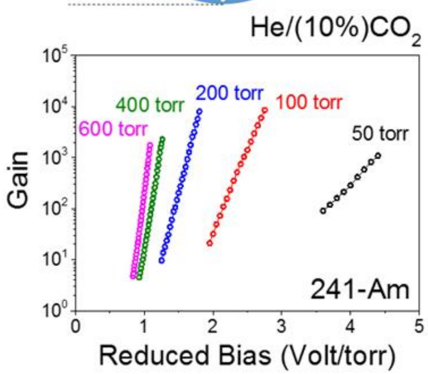
AT-TPC & pure gases

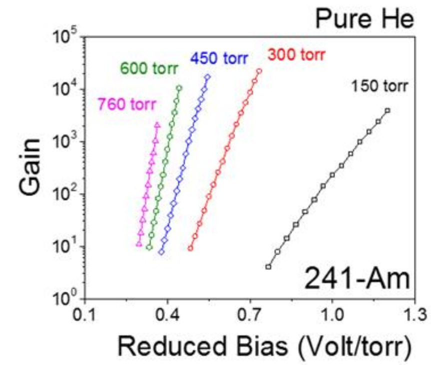
Cortesi et al., Rev. Sci. Ins. 88, 013303 (2017)



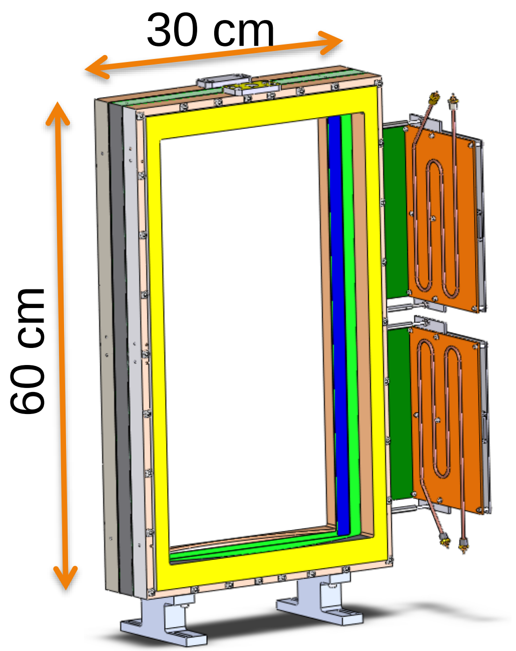


Single 3-layer M-THGEM

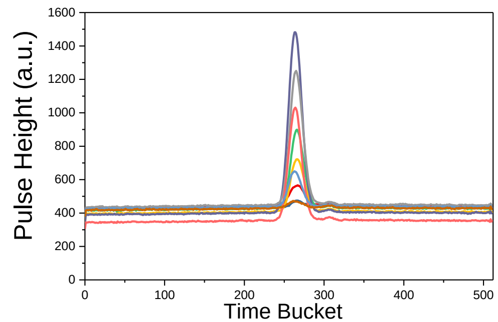




New Tracking System Performance



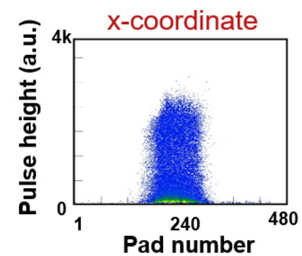
$^{78}Kr^{36+}$ (150 MeV/u)

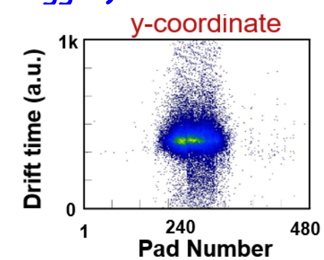


HITMAKER:
baseline + parabolic fit

-) Pulse Height
-) Peak location (time)

X → charge distribution (center of the gravity)
Y → Arrival time (external trigger)

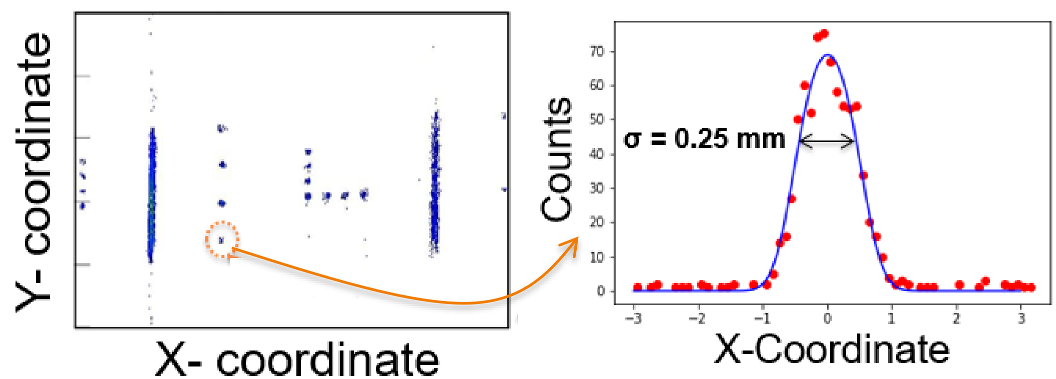




DAQ Based on the GET electronics fully integrated into the FRIBDAQ

- Number of samples (up to 512 time "buckets")
- Clock "sampling" frequency (time/sample)
- Peaking time; gain

-) Simple & robust Assembly
→ No aging problems expected
-) Better ions-backflow suppression
-) High detector gain @ low pressure (MM+THGEM)
→ large dynamic range
-) High counting rate (up to 20 kHz)
→ faster electronics + Multi-hit capability
→ expected up to 3 time lower dead time
-) High granularity (all pad are readout individually)
→ better position resolution (0.25 mm σ)



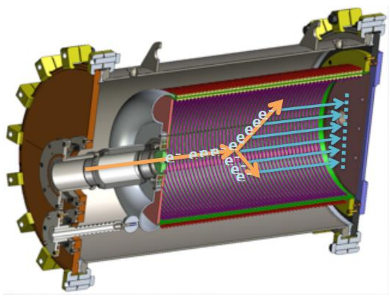
M-THGEM for AT-TPC readout

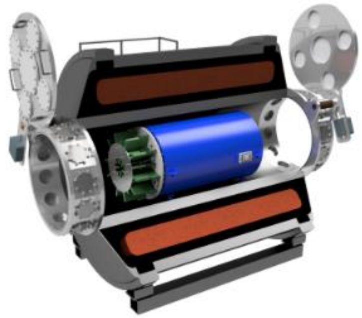
pAT-TPC

- Active volume 25 liters (L = 50 cm, Ø = 25 cm)
- Cylindrical pad plane (1,000 pads)

Full scale AT-TPC

- Active volume 200 liters (L = 100 cm, Ø = 50 cm)
- 10,240 triangular pads
- Placed inside SOLARIS solenoid





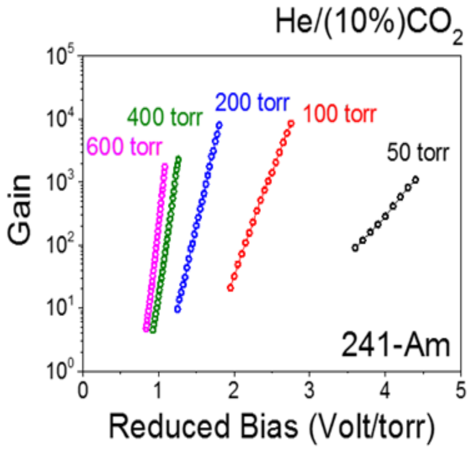
Filling Gas/Target

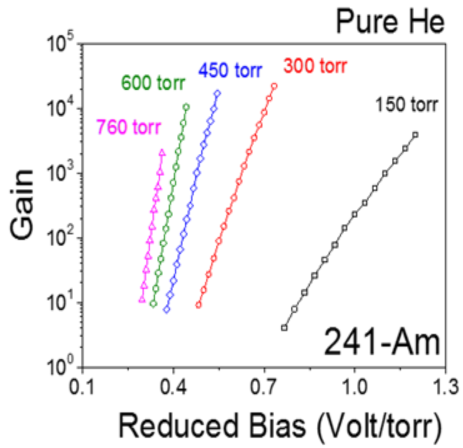
- H_2 as proton target
- D_2 as deuteron target
- ^3He as helion target
- ^4He as alpha-particle target
- Others: CF_4, CO_2, etc.

-) Purity (no quencher)
→ High Reaction Yield
-) Low-Pressure Operation
→ Large Dynamic Range

Gas Gain, Energy Resolution, Spatial Resolution, Counting Rate Capability, Stability etc...

Hybrid readout: Micromegas + (3 layers) M-THGEM

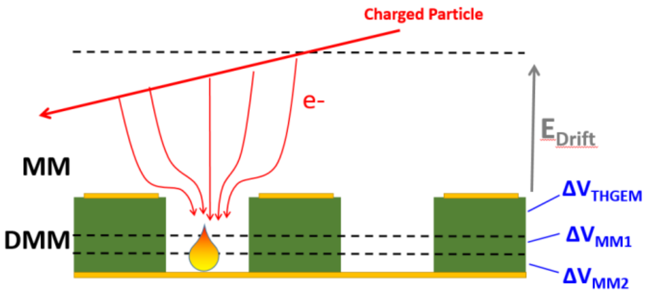


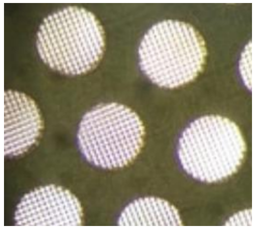


Ayyad et al. Eur. Phys. J. A (2018) 54: 181
Cortesi et. al. EPJ Web of Conferences 174, 01007 (2018)

Structures derived from the M-THGEM

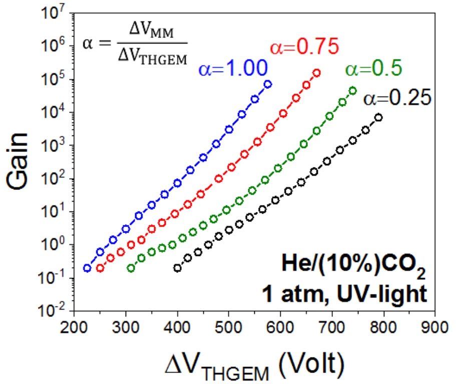
Multi-Mesh THGEM (MM-THGEM)

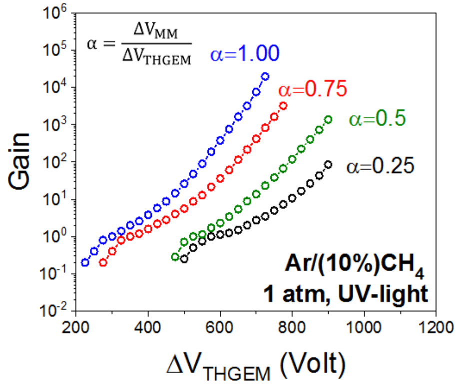




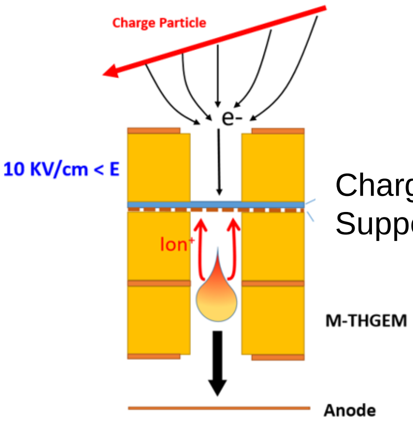
De Olivera & Cortesi 2018 JINST P06019

Advantages:
-) Uniform avalanche field
-) Lower Ion backflow
-) Double/Replaceable MM over large area



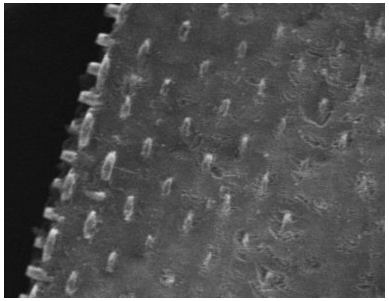


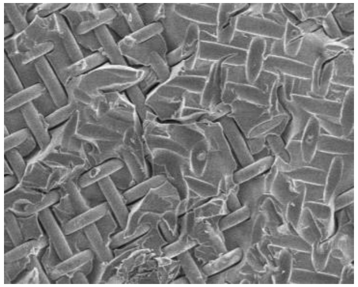
MM-THGEM with inner e-/ion filter



Charge filter (Graphene/aerogel)
Supported by a fine mesh

-) First stage → e- collection
-) Filter → High e- transmission, neutralize ions
-) Second stage → gas avalanche multiplication
➔ *Lower ion back flow*

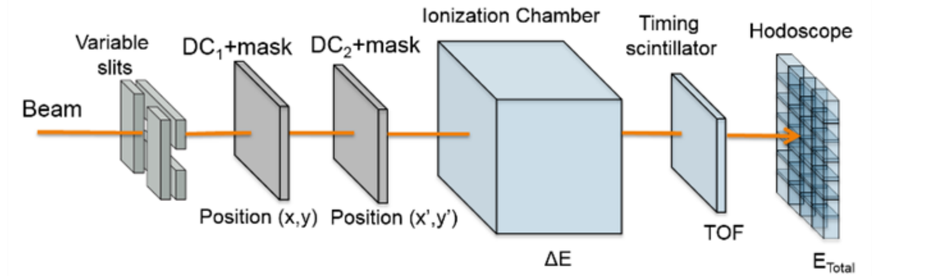


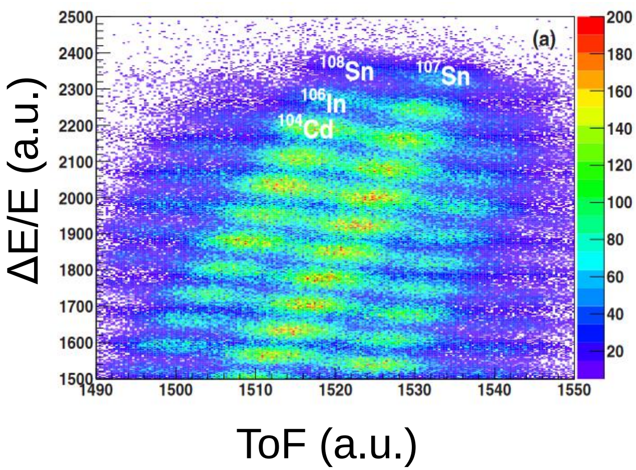


First prototype: 200 um thick aerogel – 40 nm C evaporated on both side

Limit of the current S800 PID System

-) Time resolution (plastic scintillator) ≈ 450 ps (FWHM)
-) Energy resolution IC ΔE/E ≈ 1.2% (A≈100)
-) Good PID resolution up to A < 100
-) Rate capability < 5 kHz

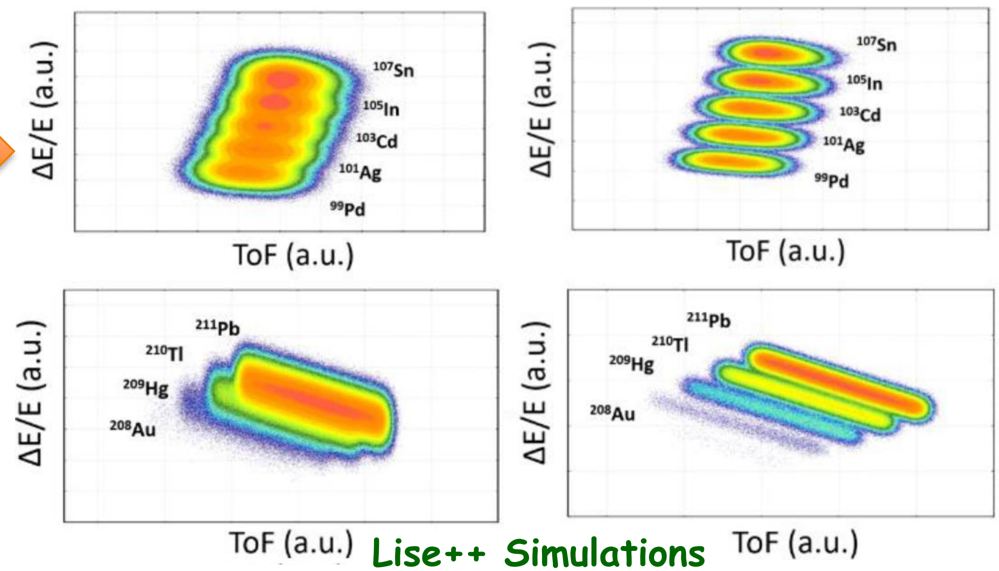




Cerizza,et al, Phys. Rev. C 93, 021601 (2016)

(1.2%) Present Ion Chamber

Proposed ELOSS **(0.4%)**

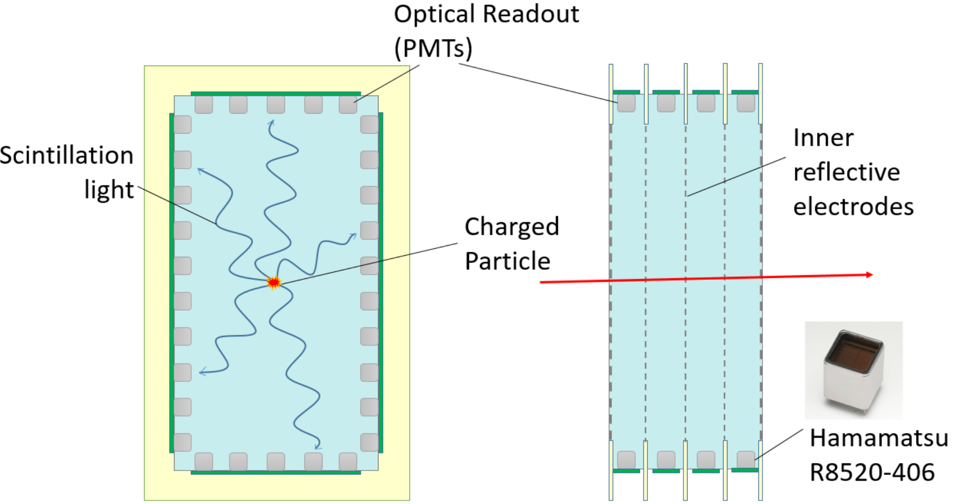


Lise++ Simulations

Improve ΔE/E to explore new regions of the nuclear chart for nuclear structure and nuclear astrophysical studies ➔ heavier beams expected from FRIB!

ELOSS operational principle

Energy-Loss Optical Scintillation System
ELOSS



Xenon (300-800 Torr)

Operational principle:

-) Large volume filled with high-scintillation yield gas (Xe)
-) Excitation created along the track of a charged particle that crosses the volume
-) De-excitation with emission of intense, prompt scintillation light
  **) Optionally: stimulated emission of electro-luminesce light*
-) The light readout by array of photodetectors that surround the detector effective volume

-) dE/E based on Xe scintillation light detection
- -) High scintillation yield ➔ 28 photons/keV - 70% of NaI(Tl)
- -) Fast process ➔ scintillation photons emitted within a few ten nsec
- -) Homogeneous medium, no radiation damage
- -) Compact and flexible geometry
- -) Increase resolution ➔ stimulated electroluminescence
- -) Scintillation light detection based on well-developed technology
  - ➔ single-electron sensitivity with 30% quantum efficiency
  - ➔ time resolution < 100 ps
- -) Easy purification and high efficiency gas recovery technique
- -) Readout decoupled from the sensitive medium ➔ high SNR

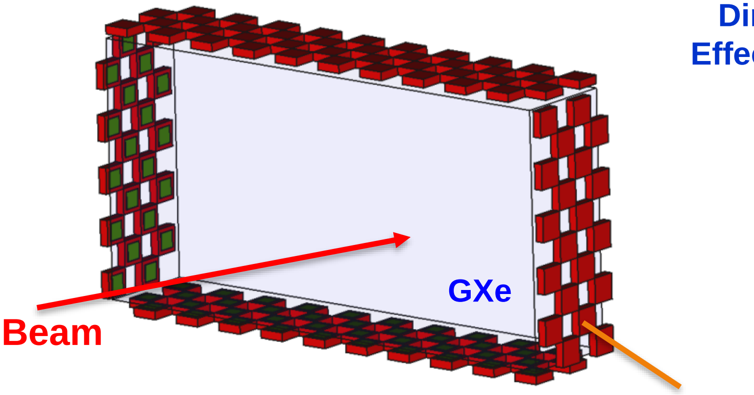
-) Thee optical readout configurations evaluated
- -) Array of Hamamatsu PMTs (120 units) model R8520

-) Commercially available DAQ
- -) Based on MDPP-32 for PMT-based readout

Work supported by the NSF-MRI grant: PHY-2017986

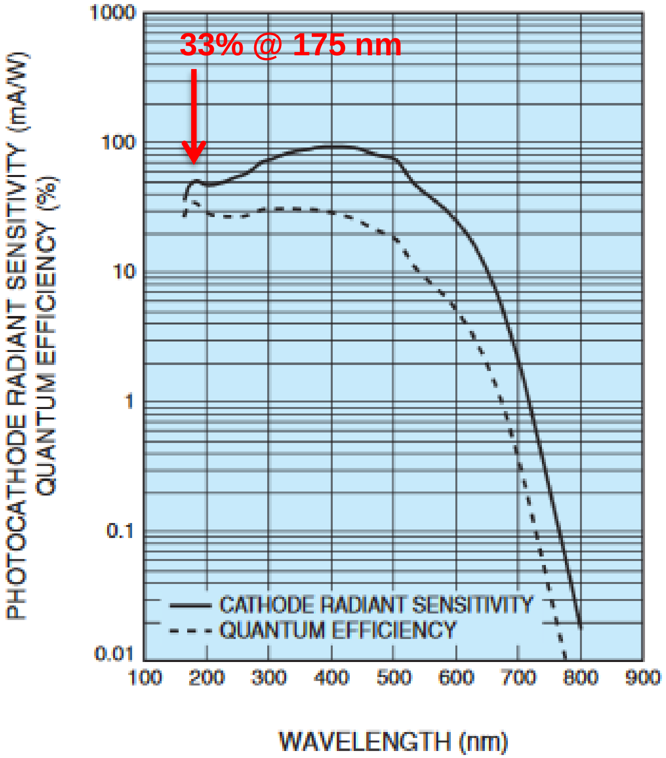
Optical Readout: R8520-406 PMTs

- Geometry: arrays of Hamamatsu PMTs (model R8520-406)



120 PMTs R8520

Dimension 30mm x 30mm
Effec. Area 20.5mm x 20.5mm

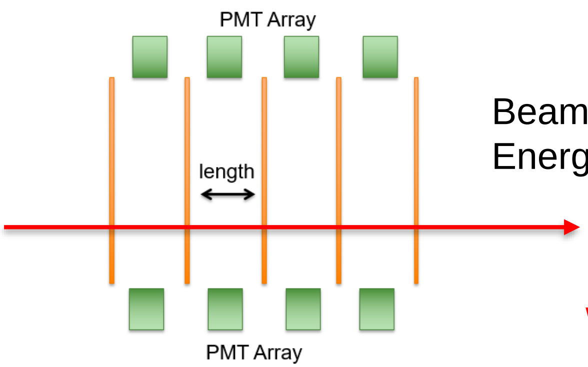


Flexible geometry: the distance between arrays can be adjusted!
GEANT4 studies to optimize geometry

Parameter		R8520-406			R8520-506			Unit
		Min.	Typ.	Max.	Min.	Typ.	Max.	
Cathode sensitivity	Luminous (2856 K)	80	100	—	80	100	—	µA/lm
	Blue sensitivity index (CS 5-58)	—	11.0	—	—	9.5	—	—
	Radiant at 420 nm	—	100	—	—	80	—	mA/W
	Quantum efficiency at 175 nm	—	30	—	—	3	—	%
	Quantum efficiency at 420 nm	—	25	—	—	25	—	%
Anode sensitivity	Luminous (2856 K)	40	100	—	40	100	—	A/lm
	Gain	—	1×10^6	—	—	1×10^6	—	—
Anode dark current (After 30 minute storage in darkness)		—	2	20	—	2	20	nA
Time response	Anode pulse rise time	—	1.8	—	—	1.8	—	ns
	Electron transit time	—	12.4	—	—	12.4	—	ns
	Transit time spread (FWHM)	—	0.8	—	—	0.8	—	ns
Pulse linearity (2 % deviation)		—	30	—	—	30	—	mA

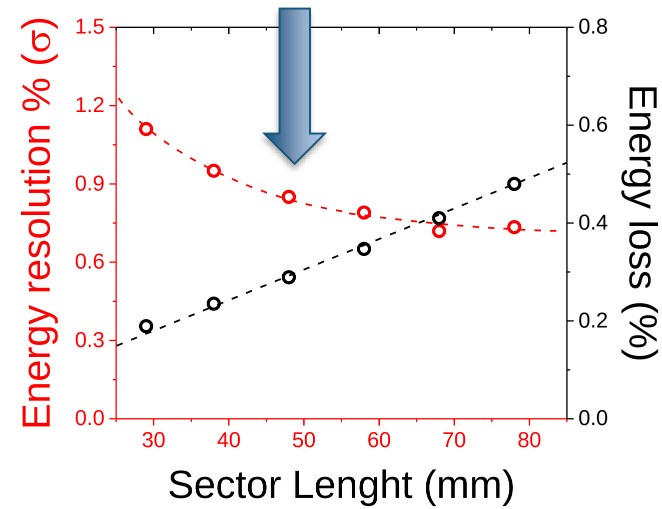
Geometry optimization: GEANT4 simulation

Optimal gap (sector length) ➔ 50 mm (PMT dimension = 25.7 mm)



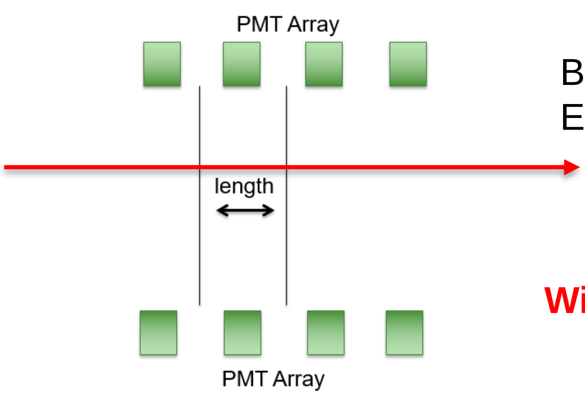
Beam: $^{108}Sn^{+50}$
Energy : 80 MeV/u

With reflectors/electrodes



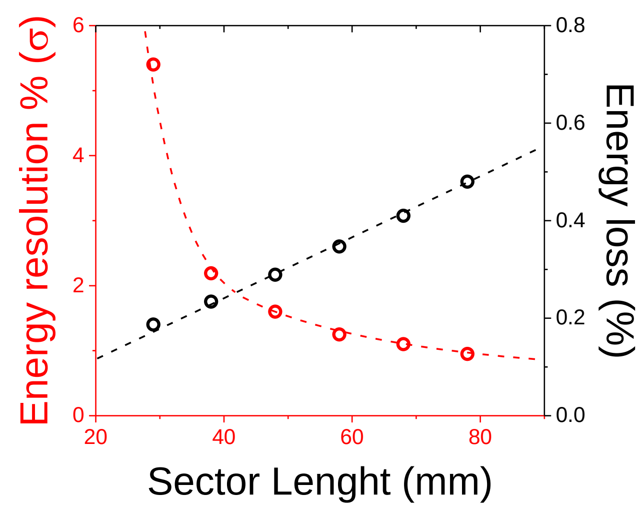
Advantages of using reflectors:

1)Higher photon collection efficiency → better energy resolution
2)Possibility to increase photon yield by secondary emission

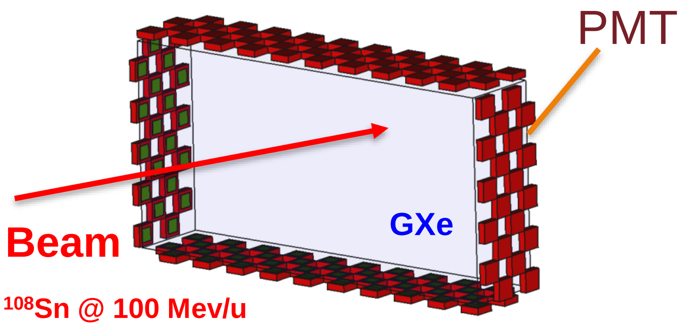


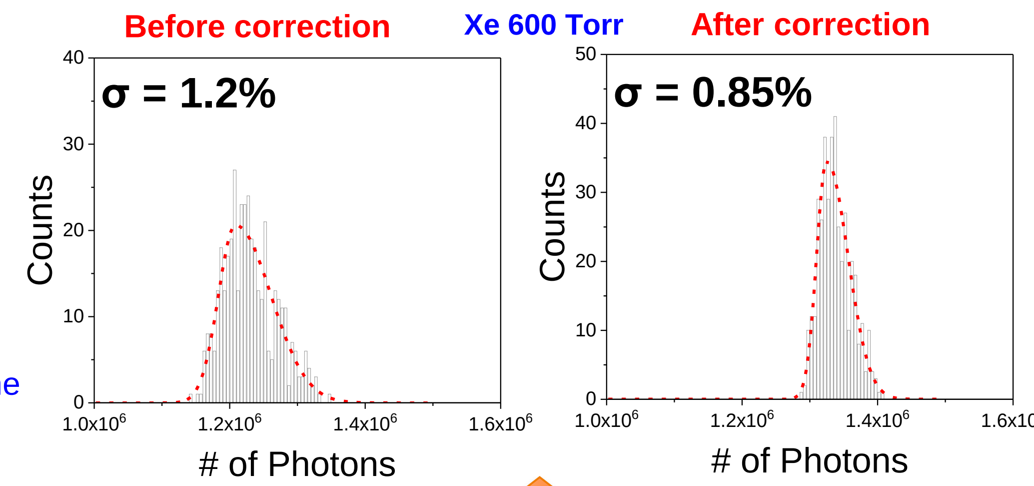
Beam: $^{108}Sn^{+50}$
Energy : 80 MeV/u

Without reflectors/electrodes



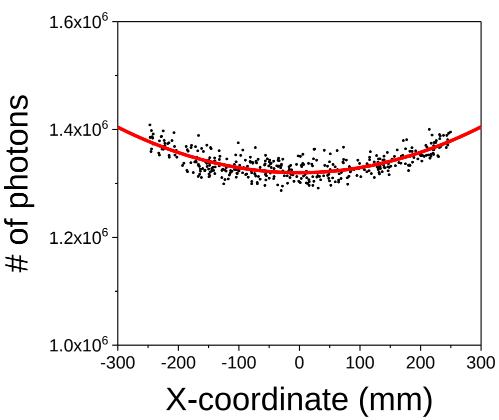
Resolution vs Position



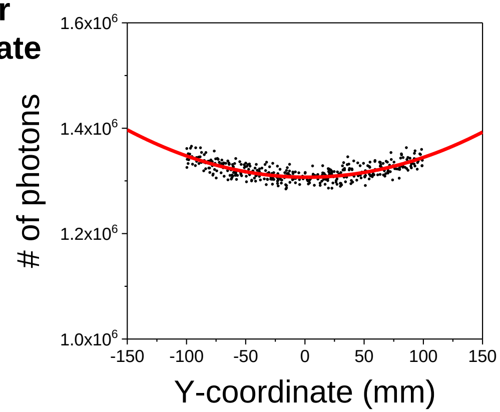


The photon collection efficiency depends on the position of the impinging particle

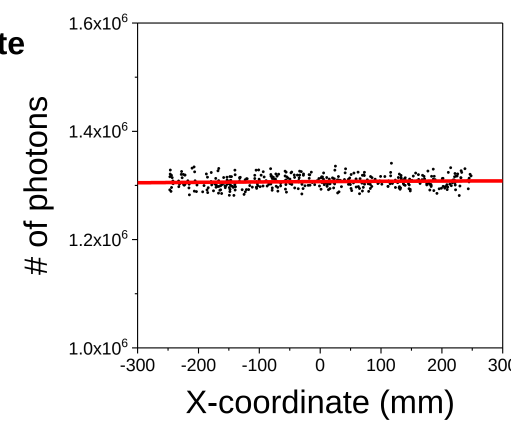
- ➔ Need position correction!
- ➔ Localization is extracted from the distribution of light detected by the array



Correct for X-coordinate

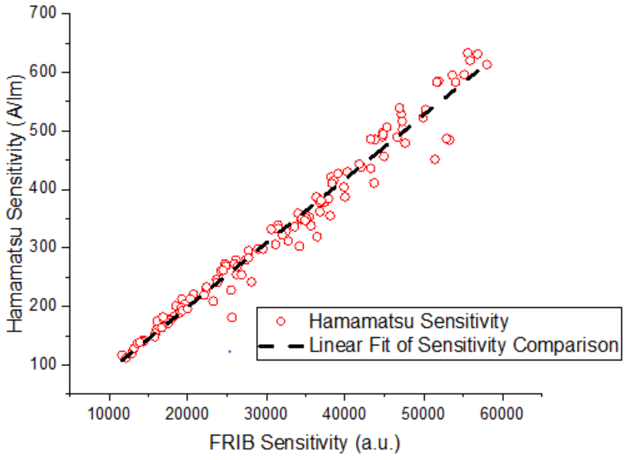


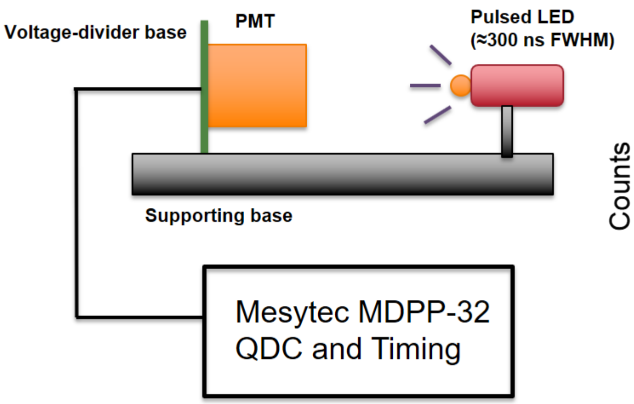
Correct for Y-coordinate

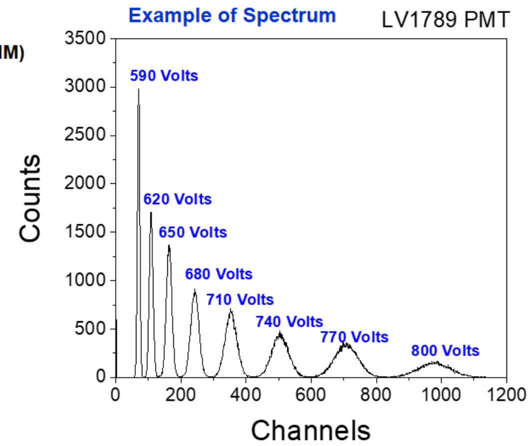


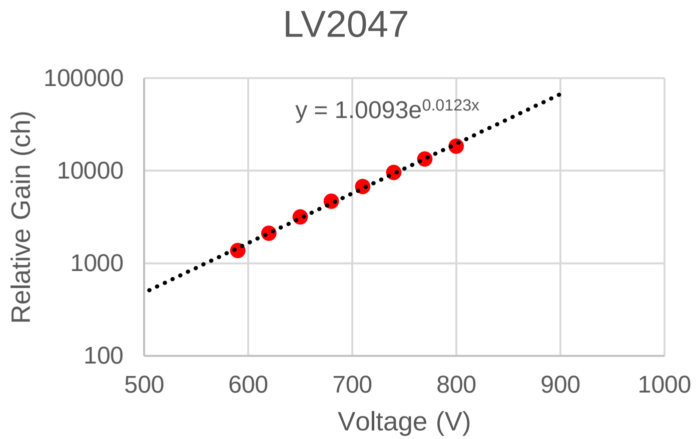
PMT's calibration

- Goal: uniform gain across all PMTs
- Method:
  - Calibrate each PMT to the same relative gain by decreasing the voltage bias and the potential across two inner dynodes
  - Use a dedicated test stand with known/fixed experimental setup
  - Compare FRIB sensitivity to Hamamatsu sensitivity for confirmation of successful calibration procedure



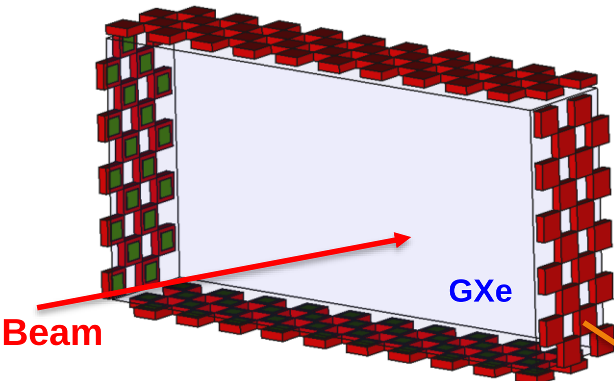






ELOSS Expected Performance

- Geometry: array of Hamamatsu PMTs (model R8520-406)

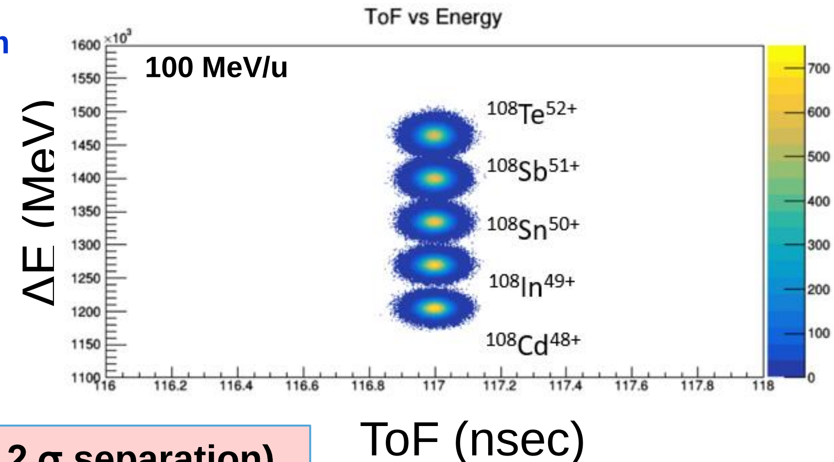


120 PMTs R8520

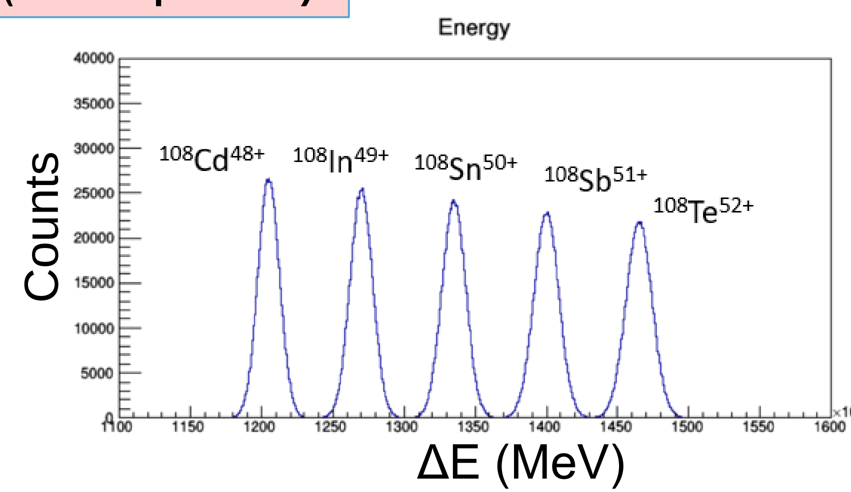
Total PC area = 504 cm^2
PC area * QE = 151 cm^2

Dimension 30mm x 30mm
Effec. Area 20.5mm x 20.5mm

R8520



ΔZ ≈ 0.31 (3.2 σ separation)



$$\frac{\text{Det. Ph}}{\Delta E} \approx 0.29 \text{ ph/MeV}$$

Coll. Effic. ≈ 3.3%

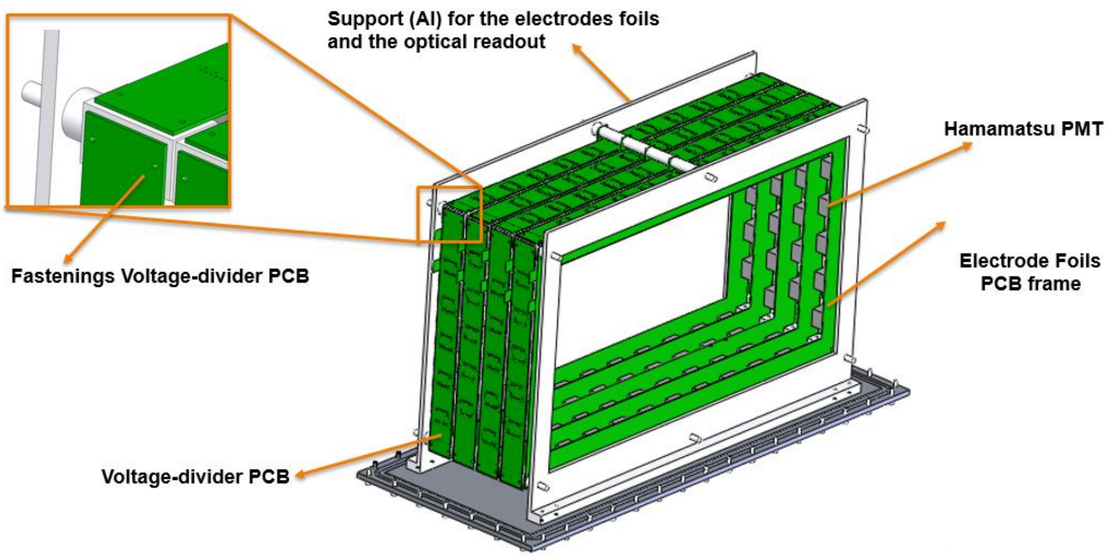
ToF < 100 psec (σ)

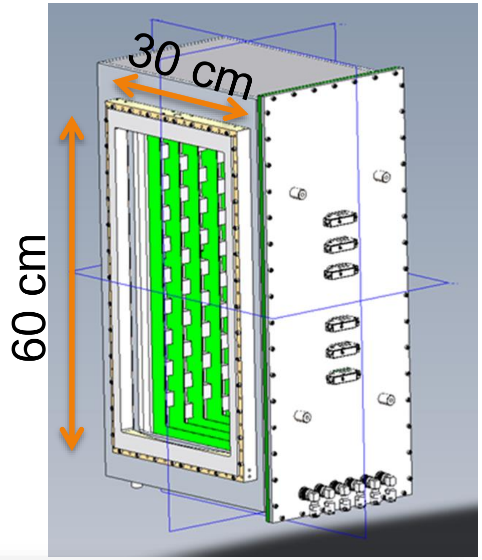
rate up to 50 KHz

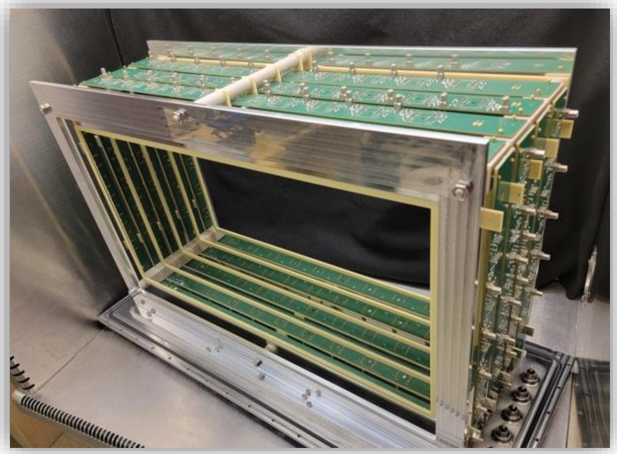
ELOSS Vessel

Detector vessel

- 30 cm x 60 cm effective area (30 cm depth)
- Xe volume = 120 Liter (operational pressure 300-800 Torr)
- Aluminized polypropylene foils separate 4 equally spaced segments
- Kevlar reinforced PPTA pressure windows (up to 1.3 Atm)
- Aluminum and PEEK support pieces to minimize outgassing



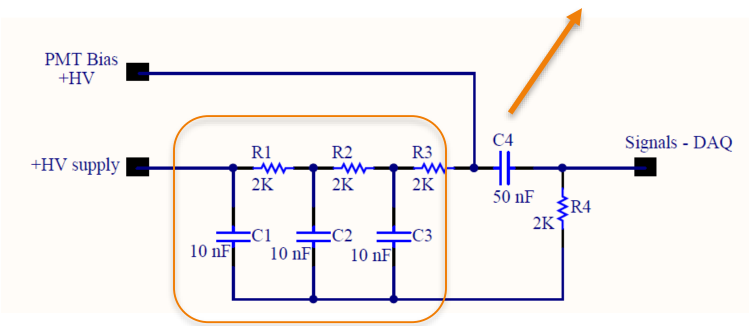




The mechanical support structure hold the ELOSS inner electrode frames as well as the PMT voltage-divider PCB.

Interfaces

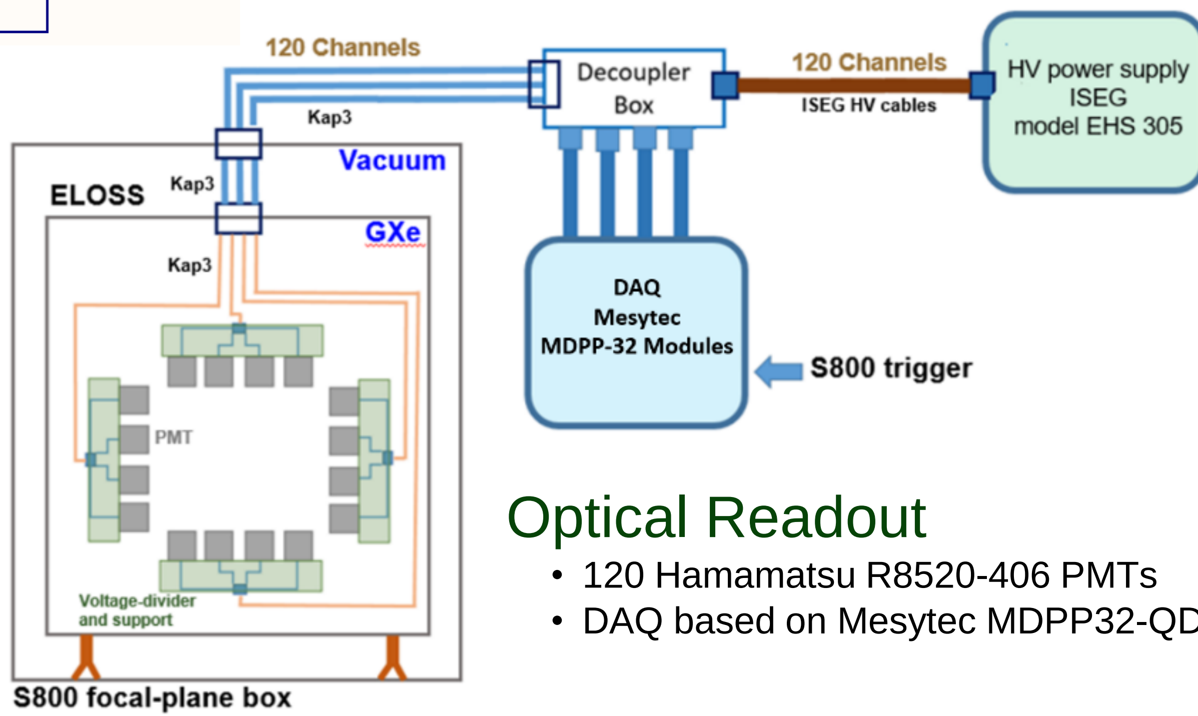
Decoupling capacitor



Low-pass filter
Cut noise induced by the HV power supply

Reduced number of cables using same technical solution developed for the PANDAX experiment (same PMTs), by make use of an external HV/signal de-coupler circuit

X. Chao et al., *Scien. China Phys., Mech. & Astron.* **57**, 1476 (2014).



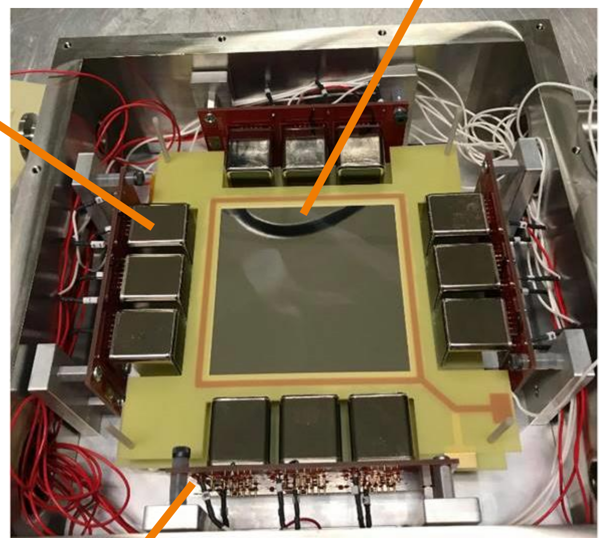
Optical Readout

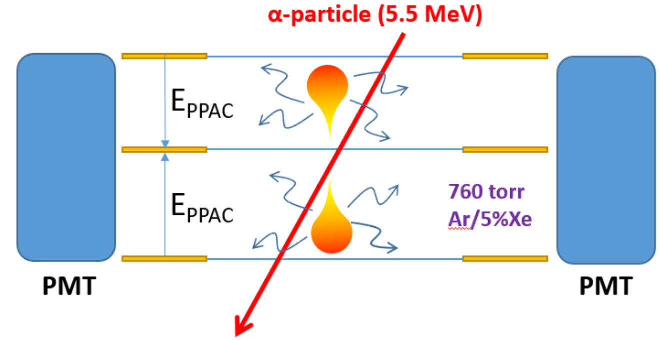
- 120 Hamamatsu R8520-406 PMTs
- DAQ based on Mesytec MDPP32-QDC

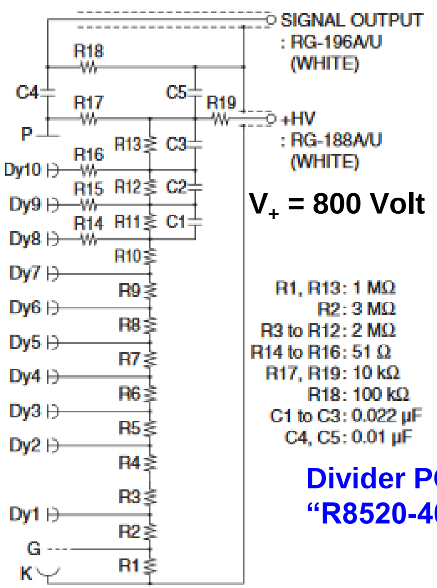
ELOSS Prototype

Hamamatsu PMT
Model R8520-406

PPAC cathode electrode used as mirror &
electron-stimulated electroluminescence emission



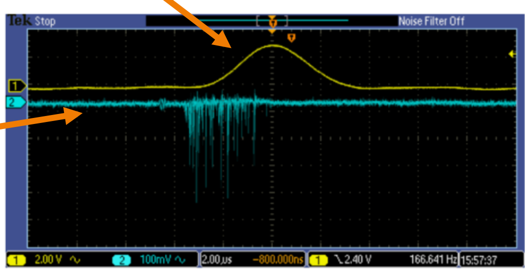




V_+ = 800 Volt

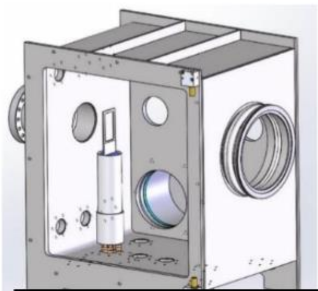
Divider PCB with pick-up signal
"R8520-406 Datasheet"

PPAC Anode
Charge-Premp

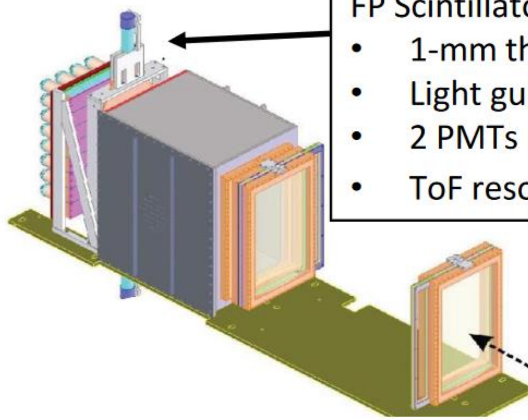


PMT-Light
Fast-Premp
(Electroluminescence)

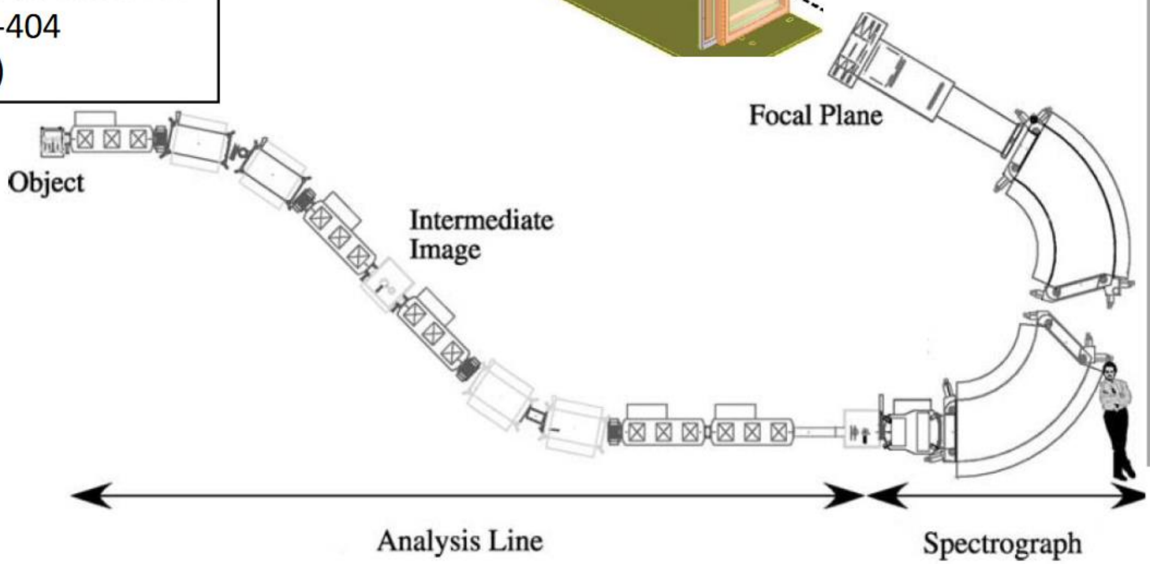
The current S800 ToF detector System

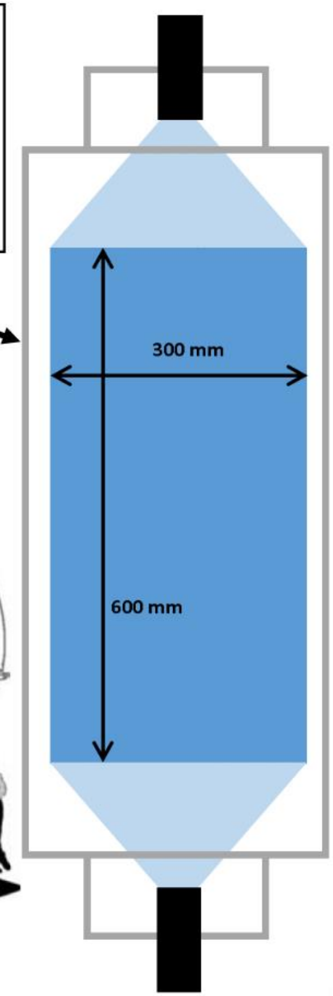


Object Scintillator: **Start TOF**
- 130-um BC-404
- PMT (R329)



FP Scintillator: **Stop TOF**
- 1-mm thick, BC-404
- Light guide
- 2 PMTs (R329)
- ToF resolution **~170 ps** (σ)

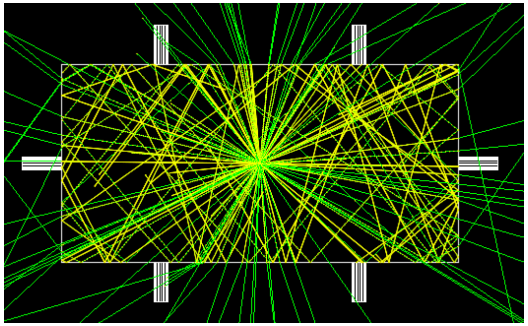


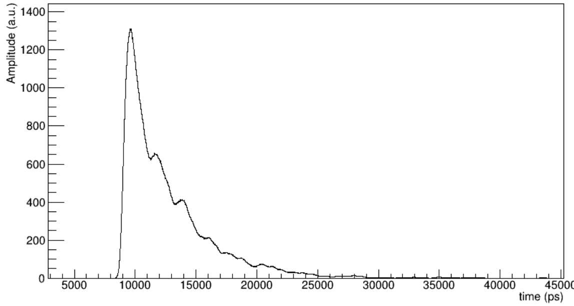


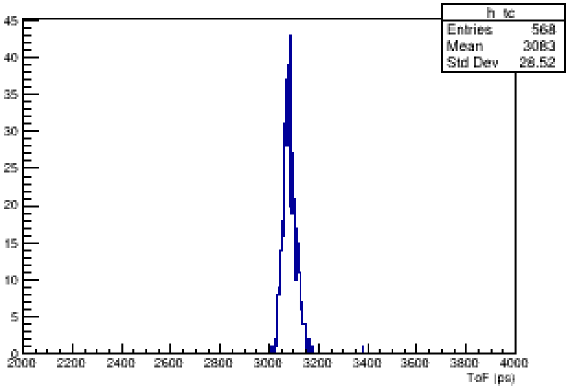
Existing system δ**ToF~450 ps (FWHM)** → Must be improved to **150 ps (FWHM)**

GEANT4 Simulations of Time Signals

- Scintillator response: light generated by nuclear beam, and photon transport
  - GEANT4: time distribution of photons reaching photocathodes ("photon arrival time")
  - Different plastic materials, wrapping, geometry, PMT configuration, light guides
- Photomultiplier response (novel technique)
  - Single-Electron-Response (SER): CR-RC4 filter function (Choong, Phys. Med. Biol. 2009)
  - Random Gaussian and Polya distributions used for photoelectron transient-time and PMT signal amplitude spreads, respectively
  - Single-Electron-Response (SER) was convoluted with simulated photon-arrival time to photocathode
- Time-of-Flight distribution for each PMT
  - Simulated PMT signals are "filtered" by CFD or LE to extract ToF
  - Gaussian fit to ToF distribution to extract resolutions

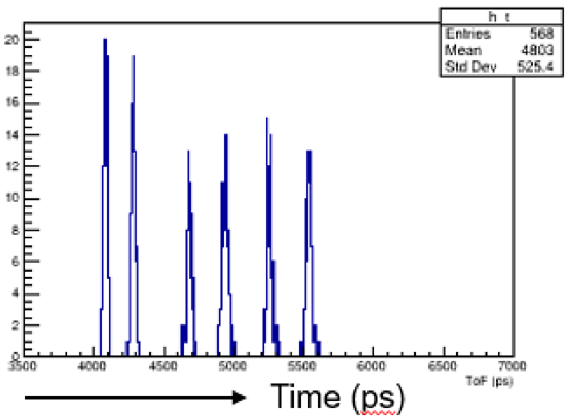


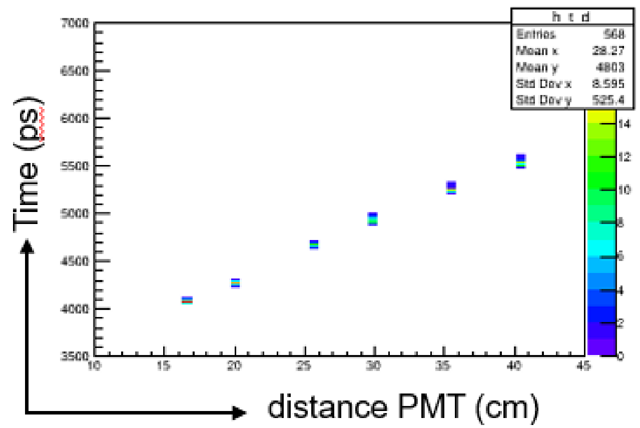


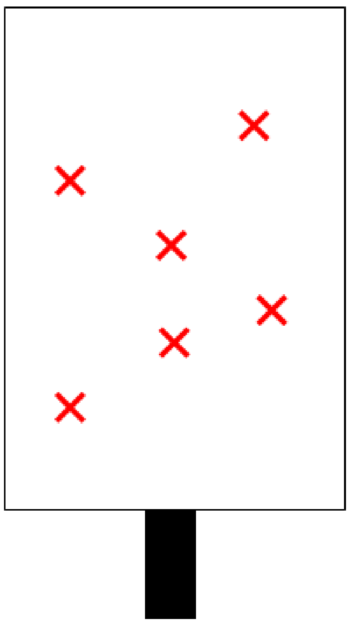


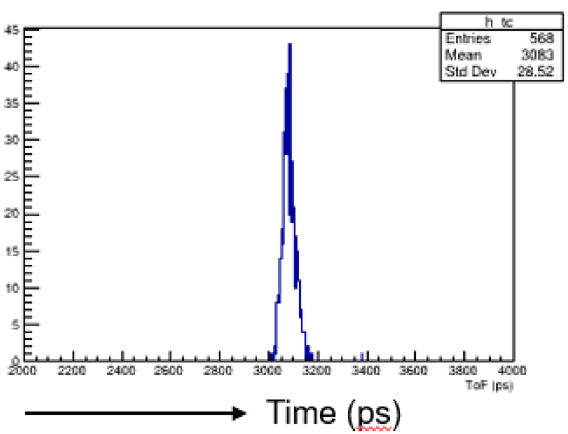
Resolution vs Position

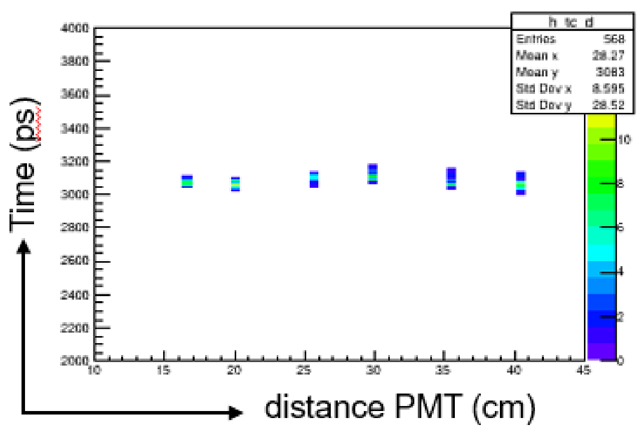
Large beam-spot size in focal plane introduces position-dependence





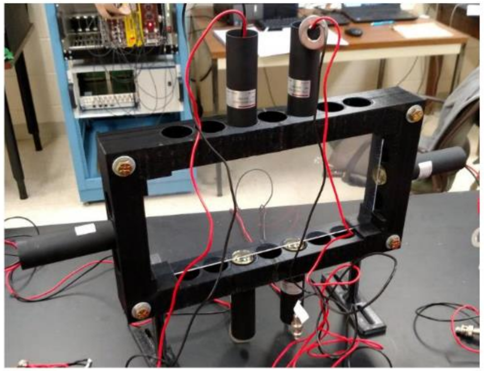






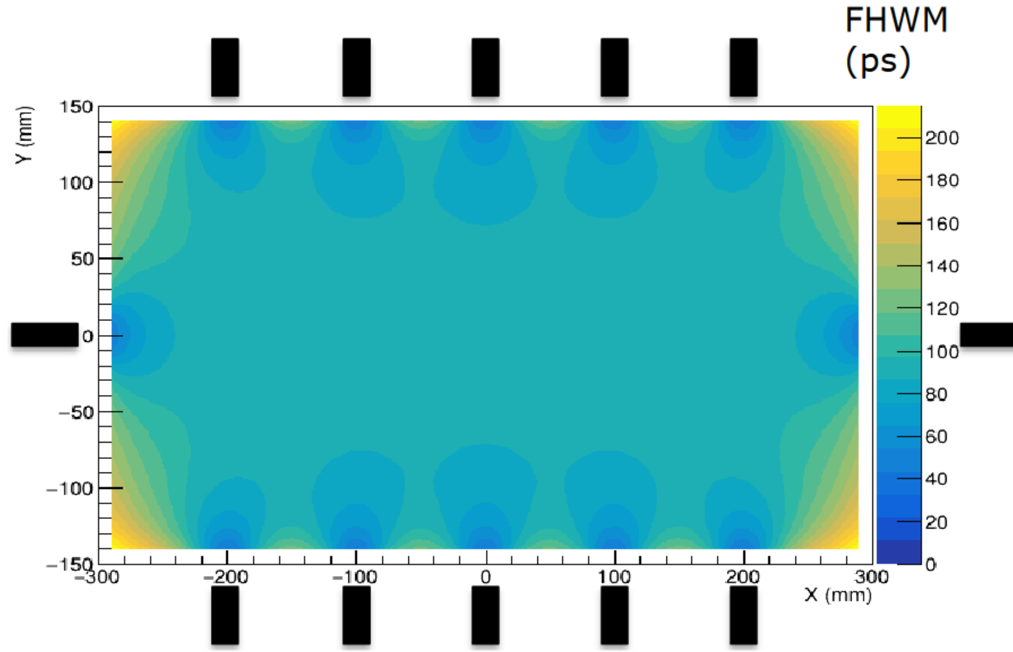
The new S800 Plastic Scintillator

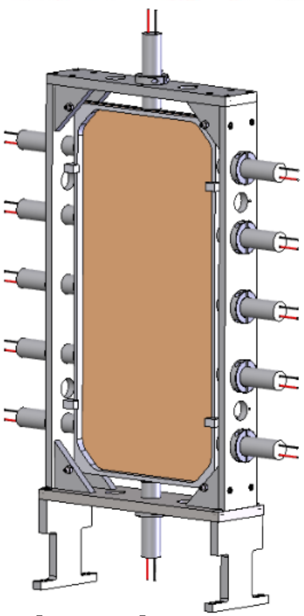
PI: Jorge Pereira



Projections S800

- EJ-230: **600 mm x 300 mm**
- 12 PMTs H6533
- Optimum resolutions: **~ 38 ps, sigma** (goal was 64 ps)





Approved Design

Conclusion

- FRIB is premiere facility for production of Rare Isotopes Beam, state of the art diagnostic/detector technologies is required
- A powerful, 400kW, Superconducting Linear Accelerator will produce nearly 4,500 rare isotopes, with experimental facilities for fast, stopped, and reaccelerated beams
- The S800 spectrometer was the most used equipment at NSCL and it is expected to be an important tool also for FRIB
- New upgrade of the S800 focal plane detector system will allow FRIB science program and serve as benchmark for the development of other similar infrastructure (High-Rigidity Spectrometer / Sweeper Magnet)

Summary

- Tracking System → from single wire to MPGD based readout
  -) Single-particle tracking of radioactive beam fragments
  -) 100% particle transmission with low induced straggling (low pressure operation)
  -) Position resolution ≈ 0.25 mm (σ) ➔ angle resolution < 2 mrad (3 times better compared to the CRDC)
  -) Trigger rate capability > 20 kHz (4 times faster compared to the CRDC)
  Commissioning planned for December 2022

- Z-number identification: from charge to optical based readout (ELOSS)
  -) Single-particle dE/E measurement of radioactive beam fragments
  -) 100% particle transmission (pressure range 300-800 Torr)
  -) Energy resolution <1% (σ), sensitive to Z>50
  -) Rate capability > 50 kHz (10 time faster than the conventional IC)
  -) Provide timing (< 150 ps σ) and moderate localization capability (a few mm resolution)
  Commissioning planned for September 2023

- Timing/Triggering by ToF measurement using a Plastic Scintillator readout by PMTs (provide also low-resolution dE/E measurement):
  -) Single-particle ToF measurement of radioactive beam fragments
  -) 100% particle transmission
  -) Time resolution <150 psec (FWHM)
  -) Rate capability > 1 MHz
  -) Thickness = 1 mm (3 mm for light fragments)
  Commissioning planned for December 2022