PAN
(Penetrating particle ANalyzer)

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Instruments for its Distributed Space Weather Sensor System (D3S)
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Introduction

- PAN is a scientific instrument for deep space and interplanetary missions
  - Precisely measure and monitor in real time the flux, composition, and direction of **penetrating particles (> ~100 MeV/nucleon) in deep space**.
- Science goals: multidisciplinary
  - *Cosmic ray physics*: fill an in situ observation gap of **galactic cosmic rays** (GCRs) in the GeV region in deep space, crucial for the understanding of the origin of the GCRs and their interplay with solar activities, as well as antimatter searches
  - *Solar physics*: provide precise information on solar energetic particles for studying the physical process of solar events, in particular those producing intensive flux of energetic particles.
  - Space weather: improve **space weather models** from the energetic particle perspective.
  - *Planetary science*: measure and monitor energetic particles to develop a full picture of the **radiation environment of a planet**, in particular as a **potential habitat.**
  - *Deep space travel*: Penetrating particles are difficult to shield. PAN can **monitor the flux and composition of penetrating particles during a space voyage**. PAN can become a standard on-board instrument for deep space travel.

Introduction

- Presented at the ESA Deep Space Gateway Workshop, Dec. 5-6, 2017
- Presented at the NASA Lunar Orbital Platform-Gateway (LOP-G) Workshop, Feb. 27 – Mar. 1, 2018
- Included in the white paper on Jupiter’s radiation belts for the ESA's Voyage 2050 Call (Aug. 2019, https://arxiv.org/abs/1908.02339)
- Published in *Wu X., et al., Penetrating particle ANalyzer (PAN), Advances in Space Research, V63, 2672-2682 (2019)*

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Penetrating particle ANalyzer (PAN)

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Introduction

GRANT AGREEMENT

NUMBER 862044 — PAN

Horizon 2020
European Union Funding
for Research & Innovation

- Funded by the EU H2020 FETOPEN program to develop a demonstrator (Mini.PAN) in 3 years (2020-2023)
  - Consortium: University of Geneva (coordinator), INFN Perugia, Czech Technical University in Prague
  - Collaborating also with CERN for the magnet design
- Mini.PAN is suitable for space weather and planetary applications (5-8 kg)
- Also suitable for the PPE (Power and Propulsion Element) of the Gateway
- For astrophysics applications (GCR, antimatter) PAN is better (5x larger acceptance, ~20 kg)
  - Suitable for Gateway habitat modules or large missions

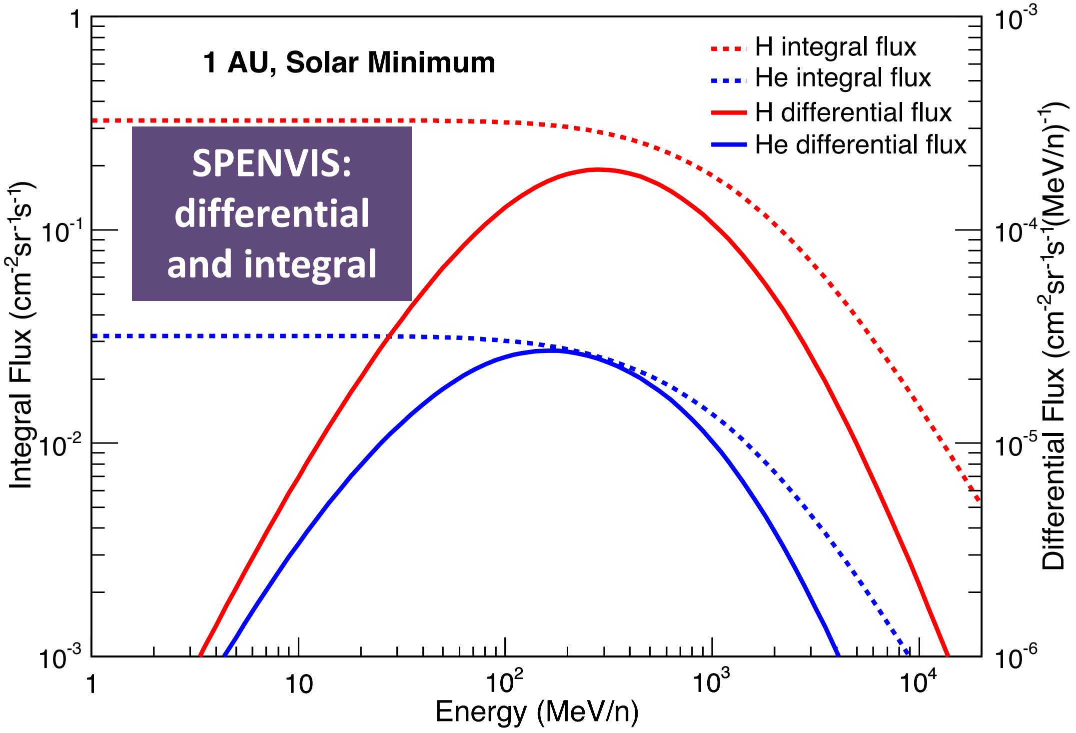
Radiation environment in deep space

- Plasma environment
  - Mainly low energy protons and electrons from solar wind
    - Unperturbed solar wind plasma (<10 keV)
  - Effectively stopped by multiplayer insulation (MLI) sheets (up to 100 keV)
- Particle radiation sources
  - Particles trapped in the Geomagnetic field
    - Negligible in deep space
  - Transient flux: Solar Energetic Particle (SEP)
    - Particles from solar eruptions (flare and Corona Mass Ejection)
    - Dominant at low energy (< 100 MeV)
      - "GeV" Solar Particle Events rare but potentially damaging/dangerous
  - Steady flux: Galactic Cosmic Rays (GCR)
    - Dominant at high energy (> 100 MeV), peak at ~1 GeV/n
    - Modulated by solar activities
    - Important contributor to shielded TID for long missions

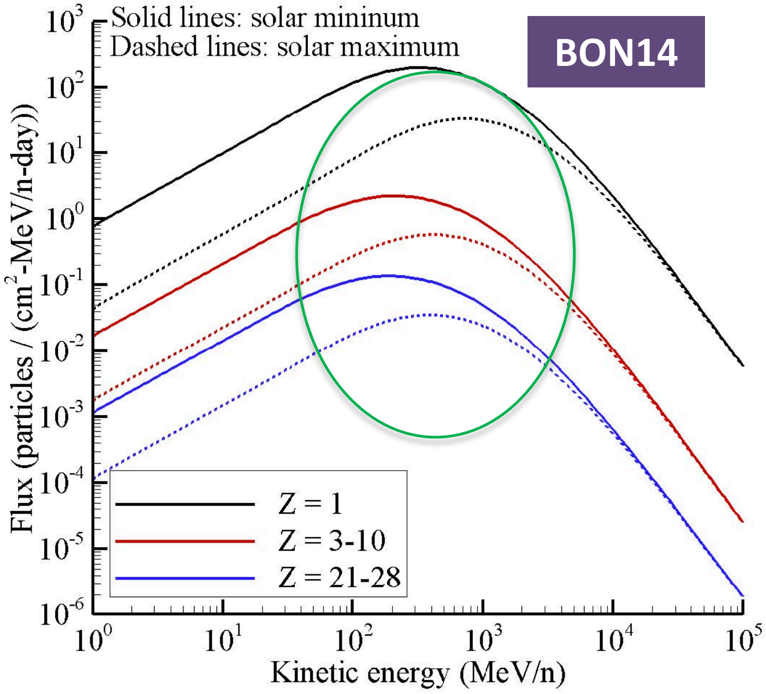
~GeV particle flux have not been precisely measured in situ in deep space

Galactic Cosmic Ray Flux at 1 AU

- Cosmic ray flux can be calculated with ESA's SPENVIS tool kit (**or NASA's BON14**)
  - Use ISO-15390 (Nymmik) standard model, at Solar Minimum (May 1996)



SPENVIS: differential and integral



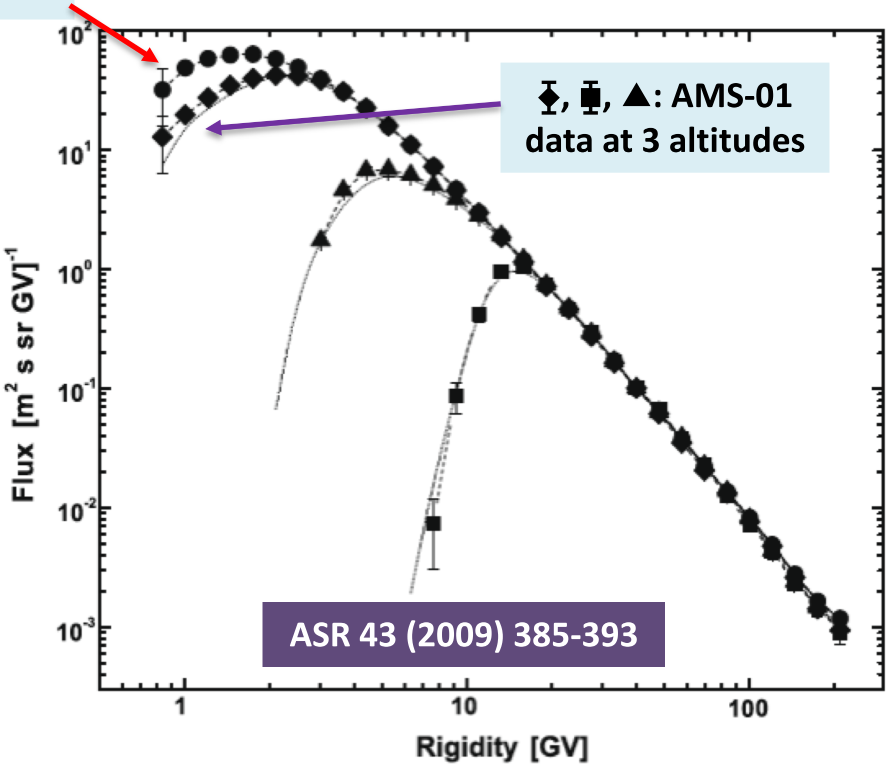
BON14

O'Neill, Golge, Slaba, NASA TP 218569, 2015

- Galactic cosmic ray flux in deep space modulated by solar activity
  - A few Hz/cm² (~0.3 pfu) at solar minimum, solar modulation ~x10 at 100 MeV
- Would be very useful to measure the solar modulation in the ~GeV region directly with the same instrument for a full solar cycle

Model and Data Comparison at 1 AU

- Many missions measure low energy cosmic ray flux up to ~100 MeV/n in deep space
  - IMP-8 (1973-2006), GEOS (since 1975), SOHO (since 1995), ACE (since 1997), …
  - ~GeV flux only measured by LEO/balloon missions using data near Earth at high altitude regions, not direct in deep space (close but not the same)



1 AU

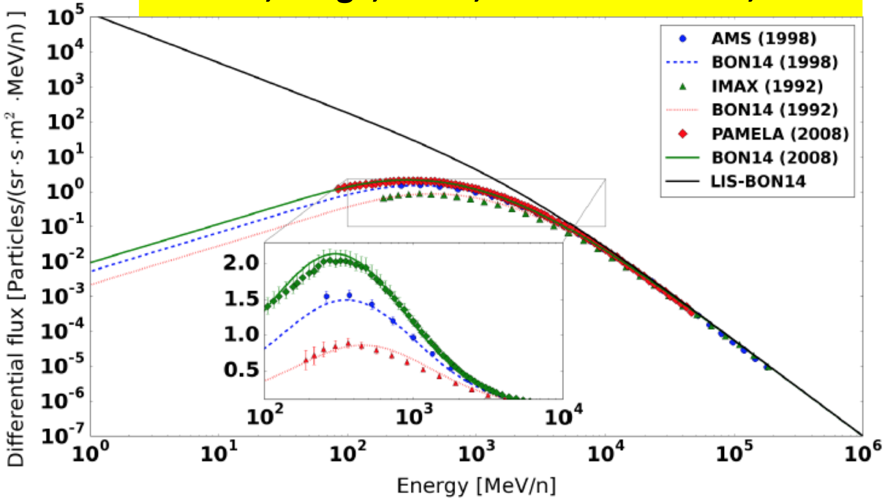
⧫, ■, ▲: AMS-01 data at 3 altitudes

ASR 43 (2009) 385-393

Fig. 3. Fluxes of He nuclei inside the magnetosphere. Values obtained using Eq. (4) (short-dots lines) are compared with AMS-01 data (symbols) for the three super-regions: SMa (squares), SMb (triangles) and SMc (diamonds). The full-circle data are those at 1 AU outside the magnetosphere.

BON14: includes LEO/balloon data (AMS 1998, PAMELA, …)

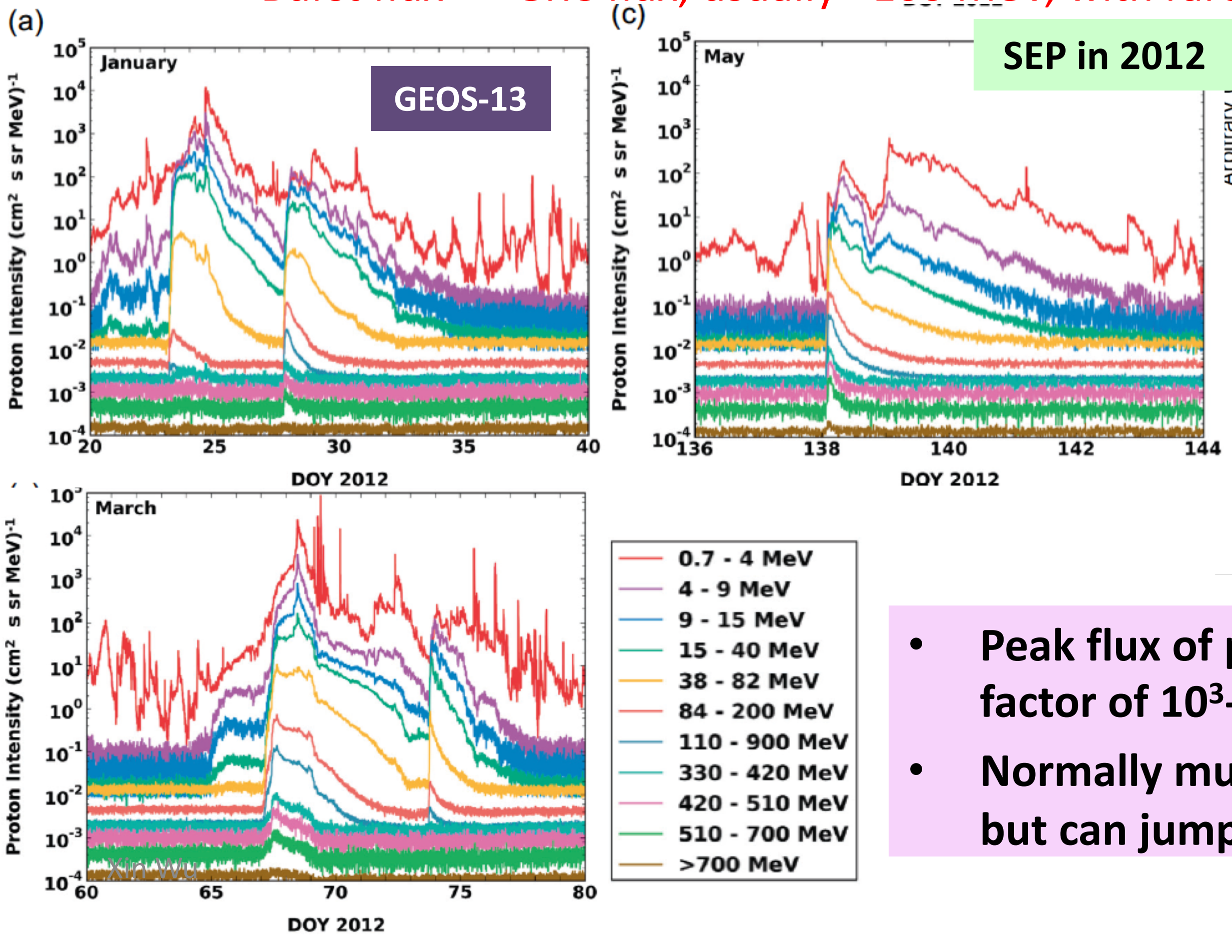
O'Neill, Golge, Slaba, NASA TP 218569, 2015

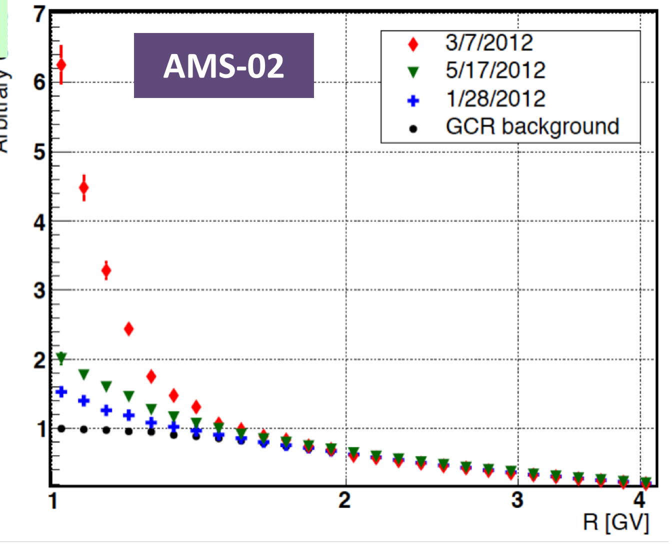


Direct measurements at 0.1-20 GeV will help to further improve the GCR interstellar, interplanetary and solar modulation models

Solar Particle Events (SPE)

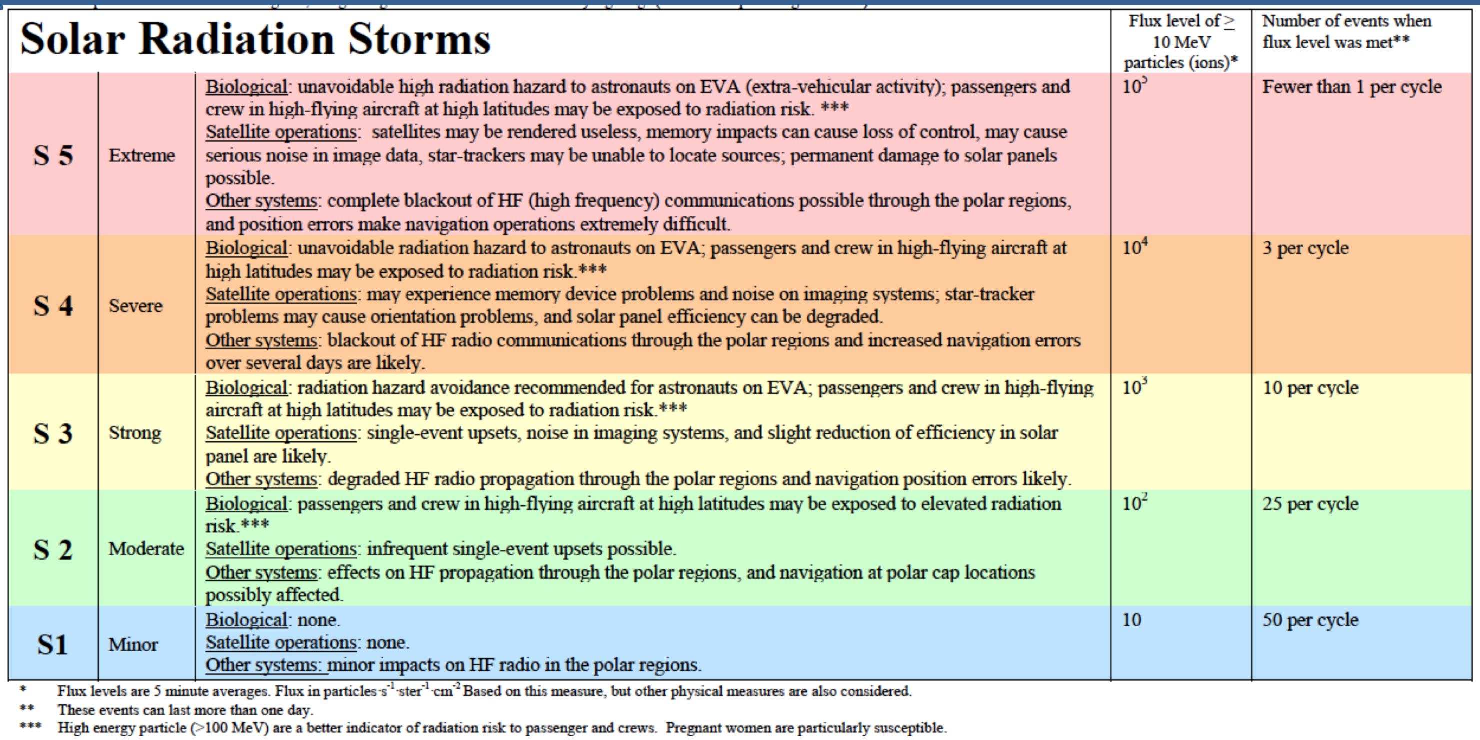
- SPE: solar events that produce SCR, or Solar Radiation Storms
  - A few days at a time, a few per year on average (correlated to solar activity)
  - Definition: flux of protons at energies ≥ 10 MeV equals or exceeds 10 proton flux units (1 pfu = 1 particle $cm^{-2}s^{-1}sr^{-1}$)
  - Burst flux >> GRC flux, usually <100 MeV, with rare "GeV storms"





- **Peak flux of proton >10 MeV can jump by a factor of 10^3-10^5, up to 10^5 pfu**
- **Normally much less for proton >100 MeV, but can jump to 1- 1000 pfu**

NOAA SPE Scale



Solar Radiation Storms			Flux level of ≥ 10 MeV particles (ions)*	Number of events when flux level was met**
S 5	Extreme	Biological: unavoidable high radiation hazard to astronauts on EVA (extra-vehicular activity); passengers and crew in high-flying aircraft at high latitudes may be exposed to radiation risk. *** Satellite operations: satellites may be rendered useless, memory impacts can cause loss of control, may cause serious noise in image data, star-trackers may be unable to locate sources; permanent damage to solar panels possible. Other systems: complete blackout of HF (high frequency) communications possible through the polar regions, and position errors make navigation operations extremely difficult.	10^5	Fewer than 1 per cycle
S 4	Severe	Biological: unavoidable radiation hazard to astronauts on EVA; passengers and crew in high-flying aircraft at high latitudes may be exposed to radiation risk.*** Satellite operations: may experience memory device problems and noise on imaging systems; star-tracker problems may cause orientation problems, and solar panel efficiency can be degraded. Other systems: blackout of HF radio communications through the polar regions and increased navigation errors over several days are likely.	10^4	3 per cycle
S 3	Strong	Biological: radiation hazard avoidance recommended for astronauts on EVA; passengers and crew in high-flying aircraft at high latitudes may be exposed to radiation risk.*** Satellite operations: single-event upsets, noise in imaging systems, and slight reduction of efficiency in solar panel are likely. Other systems: degraded HF radio propagation through the polar regions and navigation position errors likely.	10^3	10 per cycle
S 2	Moderate	Biological: passengers and crew in high-flying aircraft at high latitudes may be exposed to elevated radiation risk.*** Satellite operations: infrequent single-event upsets possible. Other systems: effects on HF propagation through the polar regions, and navigation at polar cap locations possibly affected.	10^2	25 per cycle
S1	Minor	Biological: none. Satellite operations: none. Other systems: minor impacts on HF radio in the polar regions.	10	50 per cycle

* Flux levels are 5 minute averages. Flux in particles·s^{-1}·$ster^{-1}$·cm^{-2} Based on this measure, but other physical measures are also considered.

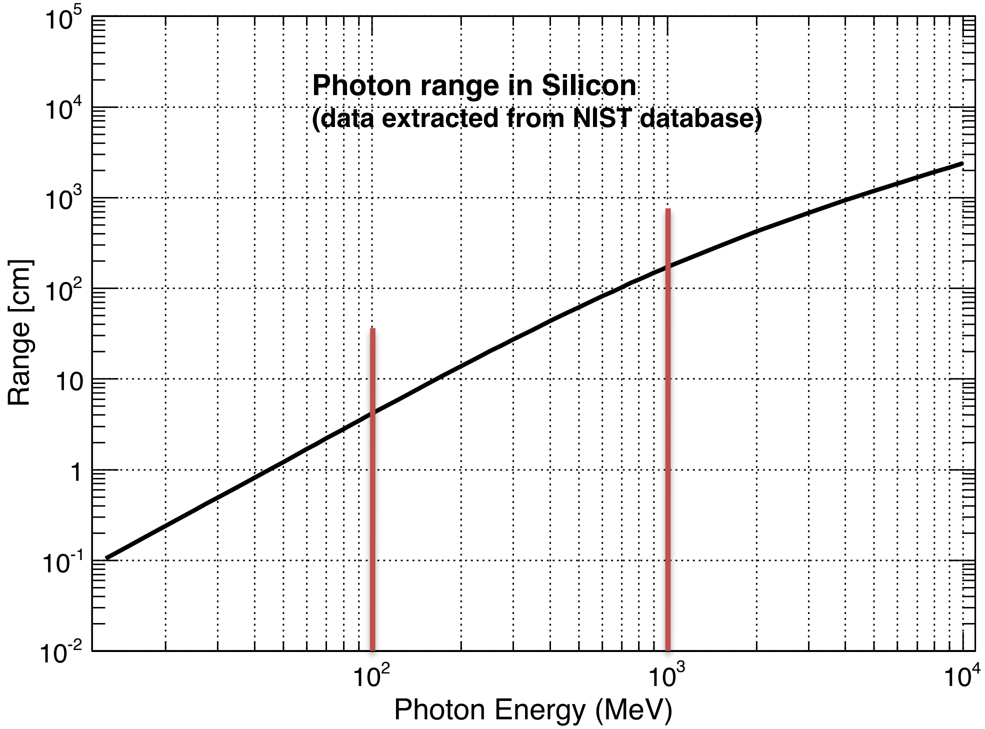
** These events can last more than one day.

*** High energy particle (>100 MeV) are a better indicator of radiation risk to passenger and crews. Pregnant women are particularly susceptible.

- SPE scale defined with level of >10 MeV ion flux
  - 10^5 pfu: Extreme, fewer than 1 per cycle
  - 10^4 pfu: Severe, 3 per cycle
  - 10^3 pfu: Strong, 10 per cycle
  - 10^2 pfu: Moderate, 25 per cycle
  - 10^1 pfu: Minor, 50 per cycle (correlated with solar activity, 14 in 2012)

Challenge of measuring GeV protons

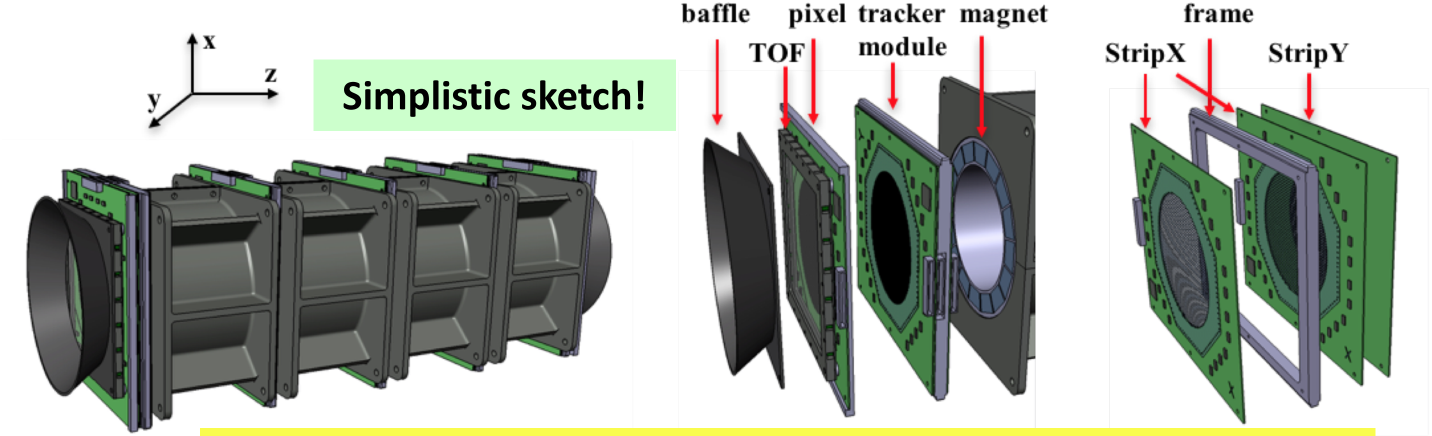
- Energy of GeV protons cannot be measured by the ΔE – E method used for low E
  - Only ~4 cm Si to stop 100 MeV protons, but 170 cm Si to stop 1 GeV protons
  - Nuclear interaction length of Si = 46.52 cm ⇒ even with 170 cm of Si, more likely to produce a hadronic shower before losing all the energy by dE/dx
    - If use a calorimeter ⇒ too thick, bad resolution (best ~30-40%)



Solution: use magnetic spectrometer to measure rigidity, then infer the momentum and energy with independently measured Z

PAN Instrument proposal (LOP-G or satellite)

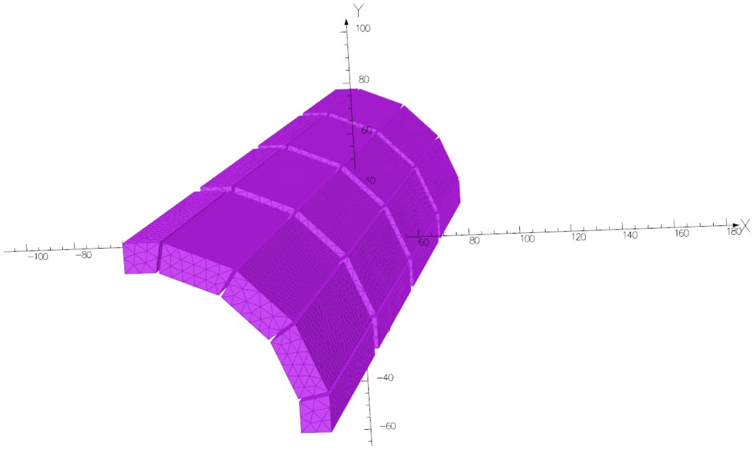
- Light weight (20 kg) low power (20 W) spectrometer with permanent magnet

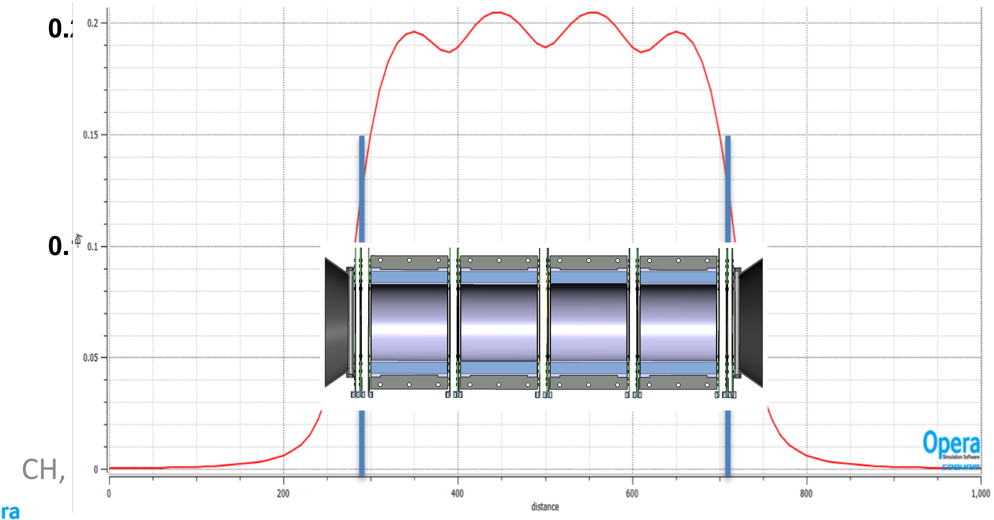


Simplistic sketch!

Measure particles coming in from both ends (symmetric)

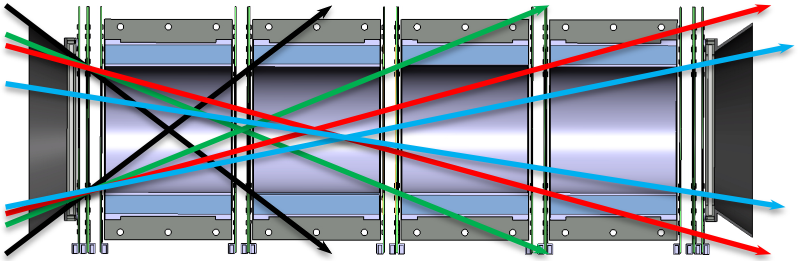
- 4 Halbach permanent magnet sectors, each ϕ = 10 cm, L = 10 cm, provide a dipole magnetic field of ~0.2 Tesla, total weight ~11 kg

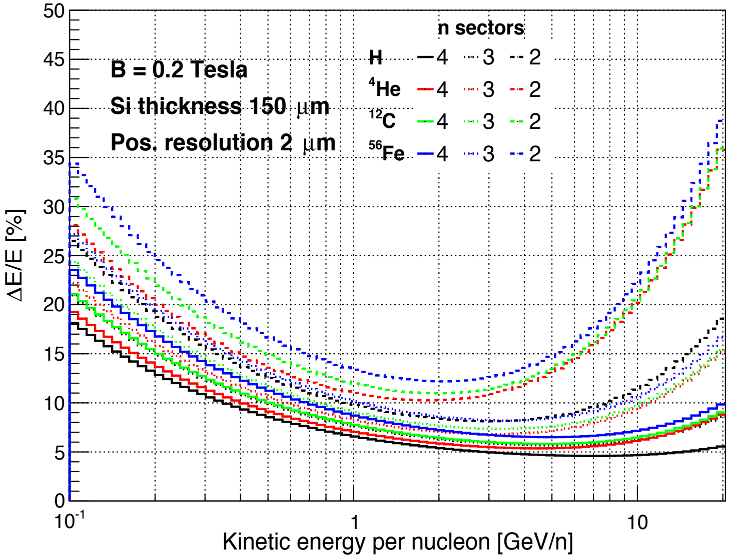


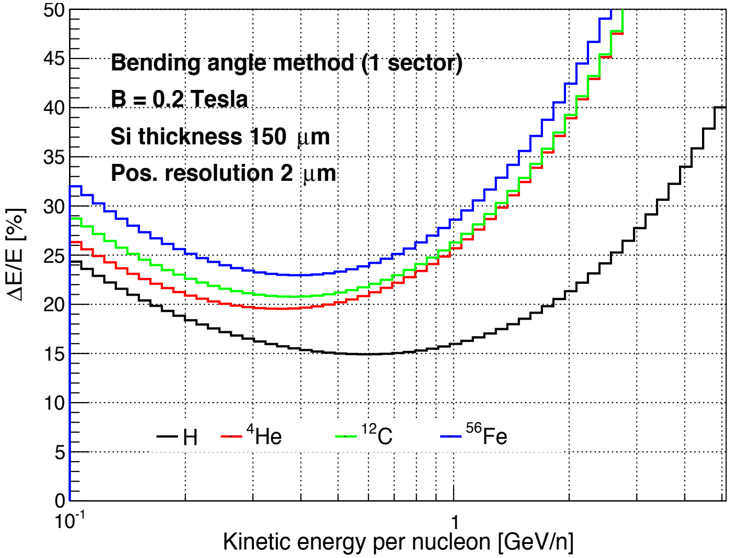


PAN measurement principle

- Measure momentum by both radius and bending angle, to have large acceptance
  - GF: ~32, 10, 5, 3 cm^{2}sr (x2 for isotropic sources), for crossing 1, 2, 3, 4 sectors
  - Open angle 25, 33, 47, 80°



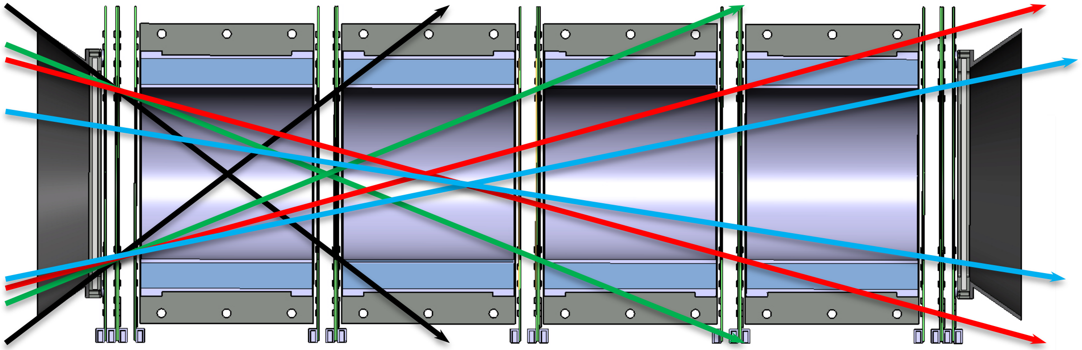


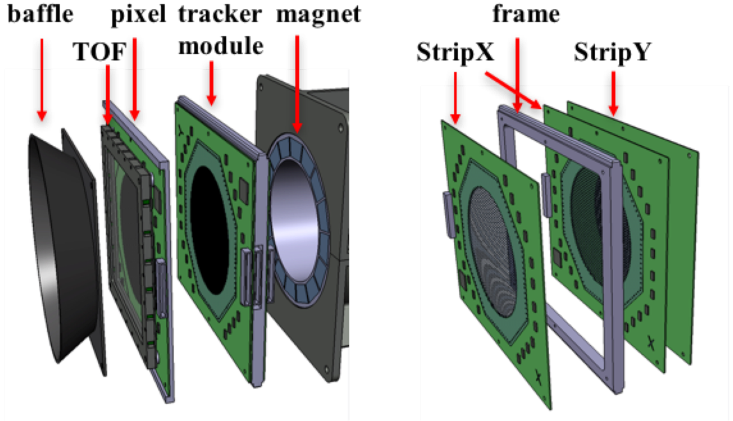


- Energy resolution <10% for protons of 0.4 – 20 GeV for 4-sector acceptance
  - <20% for protons of 0.2 – 2 GeV for 1-sector acceptance

PAN detector modules

- 5 tracker modules, 2 TOF modules, 2 pixel modules





- **Tracker module**
  - 2 StripX: 25 μm readout pitch, 150 μm thick, **2 μm resolution**, to measure both bending radius and bending angle, 40k channels, total power budget 8W
  - 1 stripY: 500 μm readout pitch, 150 μm thick, high dynamic range ASIC for Z = 1 – 26, trigger signal, time stamp (<100 ps resolution), 1k channels, total ~1 W
- **TOF module**
  - 3 mm thick scintillator, read out on all sides by SiPM: trigger, particle counter (max. ~10 MHz), charge measurement (Z = 1 -26), time (<100 ps), total ~1 W
- **Pixel module**
  - Avoid measurement degradation for high rate solar events
  - Issue to be resolved: total (static) power consumption ~2-4 W, for ~190 cm^2

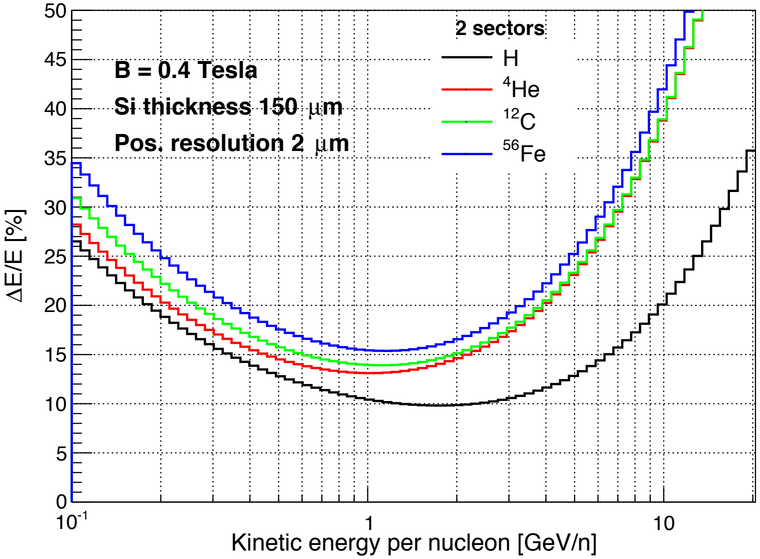
Role of the pixel detector

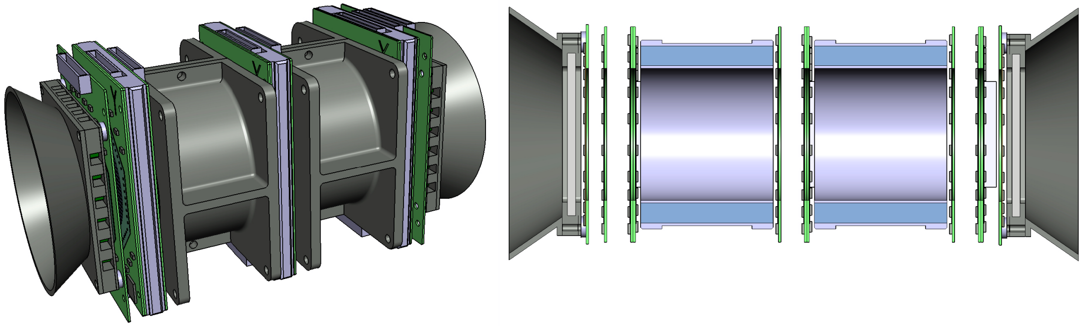
The key of the PAN design is to optimize resource utilization for both long term low rate (GCR) and short term high rate (SEP) operation

- At high rate (S5 SEP events)
  - Improve measurement of triggered events: TOF pileup and Si layer multi-hits
    - Pixel, no pileup: provide unambiguous charge and 3d points
  - Non-triggered pixel hits, ~2.4 MHz
    - Pixel is working ”standalone”, so energy information limited, but at least can provide an integrate flux measurement for >20 MeV
  - Requirement: up to 5-10 MHz (~95 cm^2) → ~1.5-3 Hz/pixel
- At lower rate (up to S4 SEP events)
  - 1 extra 3d point
    - With 4-10 μm position resolution, improve energy resolution
    - With ~100 μm position resolution, help pattern recognition
  - 1 extra charge measurement
    - At least for lower Z, effective limit to be investigated

Mini.PAN for space weather/planetary missions

- Smaller device for in-situ radiation measurement and monitoring
  - 2 Halbach permanent magnet sectors, each ϕ = 5 cm, L = 5 cm, provide a dipole magnetic field of ~0.4 Tesla, magnet weight ~2 kg, total < 5 kg
  - GF: ~6.3 or 2.1 cm^{2}sr (x2 for isotropic sources, for crossing 1 or 2 sectors





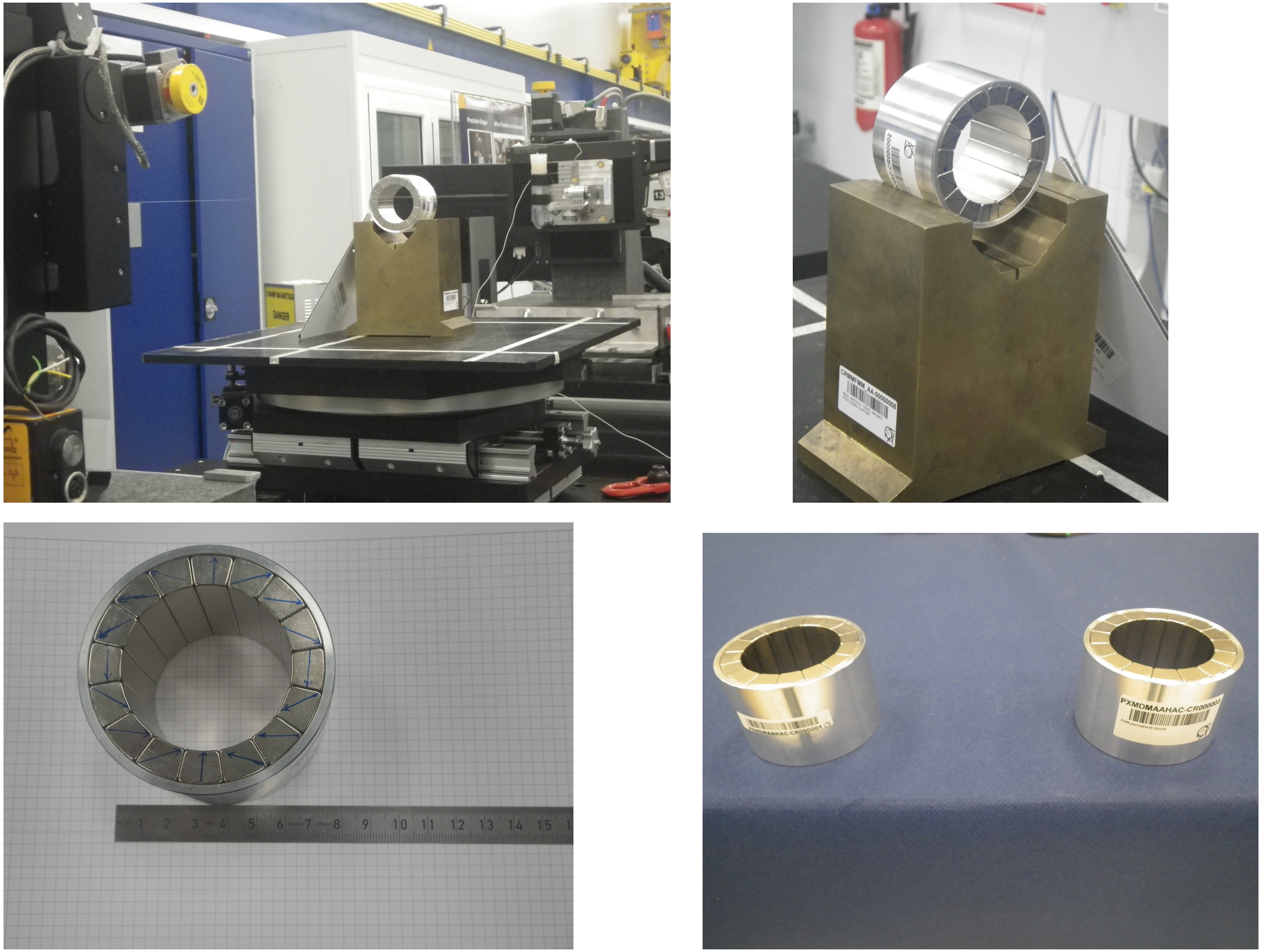
Can be simplified further with only one-side sensitive

- Energy resolution <20% for p of 0.2 – 10 GeV for 2-sector acceptance
- Energy resolution for 1-sector acceptance same as PAN (<20% for protons of 0.2 – 2 GeV)
  - Shorter sector length compensated by stronger B field

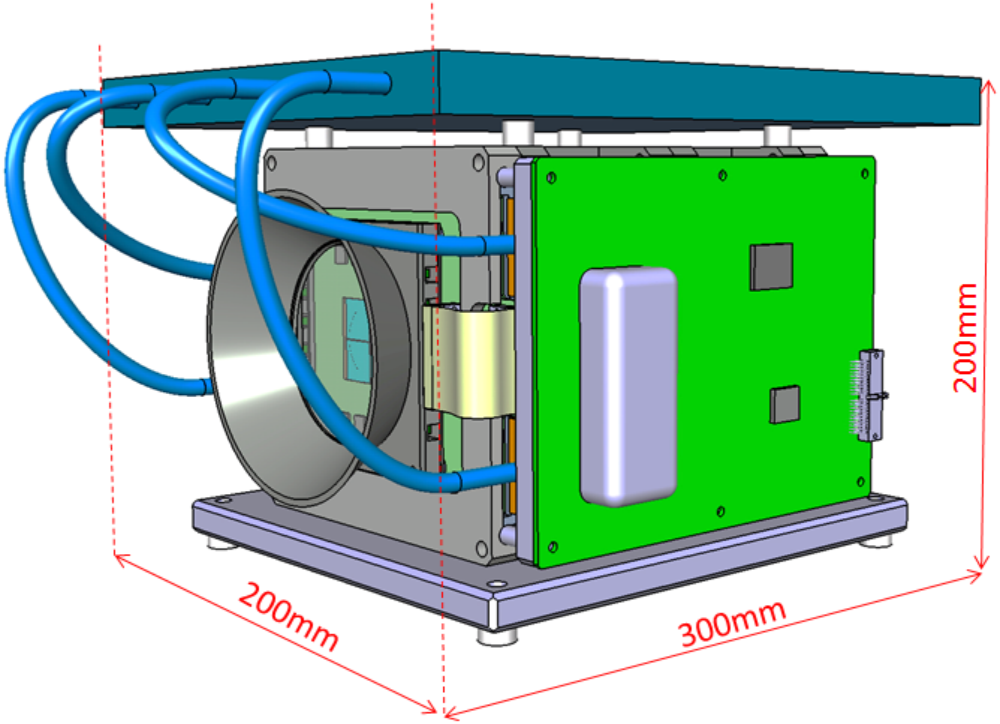
Can add a few layers of Si detectors to measure 10 MeV – 20 MeV with the classical ΔE –E method (~2.4 mm of Si) ⇒ full range energetic particle monitor

Conclusion

- Direct measurements of penetrating particles (100 MeV/n – 20 GeV/n) in deep space are important
  - Fill a gap in cosmic ray observation
  - Open a new window for solar physics
  - **Unique input to space weather modeling and forecasting**
  - Indispensable for human deep space missions
  - Important for planetary exploration
- Magnetic spectrometer is the most suitable measurement technique in this range
  - Basic principle and technologies demonstrated by PAMELA and AMS-02
  - High precision strip detector and high rate low power active pixel detectors are becoming available
- PAN is suitable for LOP-G or medium to large solar missions, while mini.PAN is suitable for space weather and planetary exploration missions
- **Instrument development is starting**



- A few Mini.PAN magnet prototypes have been designed (P. Thonet of CERN) and produced
  - Each magnet is ~0.8 kg
  - Currently under test and measurement



Thanks you for your attention!