Space Research and Radiobiology at FAIR

Radek Pleskac (BIOMAT Project at APPA)
Introduction

Space Research
- Motivation
- Radiation in Space
- Experiments at GSI
- Some Examples: SOHO, ACE, AMS, ALTEA, cave A

Radiobiology and Therapy
- Nuclear Fragmentation
- Microbeam
- Heart Arrhythmia

BIOMAT at FAIR
- Future Experimental Facility
- Proton Thranostics
- Material Science

Summary
ROLIS descent image and –
- Welcome to a comet

C67/P Churyumov - Gerasimenko
Philae landing module

- low temperature
- almost vacuum
- radiation environment
Space Research at GSI

- Radiation environment in space has severely adverse aspects on human, electronics and materials
- Effects of highly charged highly energetic (HZE) heavy ions in the space are the most challenging

Simulation of cosmic particle radiation using high-energy accelerators

- Radiobiological effects on human beings (*risk assessment for manned space missions*)
- Electronic components (*radiation hardness tests*)
- Shielding materials
- Test and calibration of space flight instruments
- STS and ISS programs will be dropped, in favour of Moon and Mars manned exploration
- Radiation risk is a big problem for human planet exploration
A 501-day “free-return” Mars flyby passing within a hundred miles of the surface
- Only small correction maneuvers are needed during transit
- Simple mission architecture lowers risk
  - No entry into Mars atmosphere
- An exceptionally quick free return occurs twice every 15 years
  - 1.4 years duration vs. 2 to 3.5 years typical
  - Launch Jan 5, 2018, (or 2031)
  - Mars on 20 Aug 2018 (227 days)
  - Earth on 20 May 2019 (274 days)
  - At Mars, Earth is 38,000,000 miles away
- Video
  - http://www.youtube.com/watch?v=18Q1YNd2ImA

Data Point to Radiation Risk for Travelers to Mars

Dose = 1.8 mSv/day x 501 x 2 = 1.8 Sv
Galactic Cosmic Radiation (GCR)

- 2% electrons / positrons
- 98% particles
  - 87% protons
  - 12% helium
  - 1% heavier particles
Irradiation Facilities at GSI
High-Energy Irradiation Facility Cave A

Basic Specifications

• All ions from H to U
• Energies 50 – 2000 MeV/u
• Particle fluence $10^2$ – $10^{12}$ ions/cm$^2$
• Max. Fieldsize 20 x 20 cm$^2$

Beam delivery system
• Rasterscan-System intensity-controlled
• Excellent Homogeneity for large-area irradiations
• On-line beam monitoring

Sample handling devices
• Robot System
• Linear tables
• Positioning-Lasers
• TV-System remote-controlled
<table>
<thead>
<tr>
<th>Institution</th>
<th>Year(s)</th>
<th>Project/Instrument</th>
</tr>
</thead>
<tbody>
<tr>
<td>AMS-Kollaboration</td>
<td>2000-2005</td>
<td>Alpha Magnetic Spectrometer (ISS)</td>
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<tr>
<td></td>
<td></td>
<td>Hardware Data acquisition system</td>
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<tr>
<td>INFN Frascati</td>
<td>2000</td>
<td>VLSI-Chips</td>
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<tr>
<td>ALTEA Kollaboration</td>
<td>1997/2001 &amp; 2002-2005</td>
<td>RESURS-Satellit (Russ.)</td>
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<td>Univ. of California</td>
<td>1999</td>
<td>Detector Telescope NINA</td>
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<tr>
<td>CALTECH Pasadena &amp; Goddard Space Flight Center</td>
<td>1997</td>
<td>ALTEA (ISS) &quot;Phosphenes&quot;</td>
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<tr>
<td>Space Res. Lab Turku</td>
<td>1992/94</td>
<td>Glass Detectors (flown in MIR)</td>
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<tr>
<td>Univ. Salt Lake City</td>
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<td>Advanced Composition Explorer</td>
</tr>
<tr>
<td>IBM Manassas USA</td>
<td></td>
<td>ACE (in orbit)</td>
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<tr>
<td>Dublin Institute of Physics</td>
<td></td>
<td>ERNE-Detector</td>
</tr>
<tr>
<td></td>
<td></td>
<td>SOHO (in orbit 1995)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Nuclear track detectors</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Microprocessors</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Nuclear track det. (airplanes)</td>
</tr>
</tbody>
</table>
Example 1 (SOHO/ERNE)

SOHO / ERNE

Joint project ESA and NASA

12 Instruments on Board
ERNE (Energetic and Relativistic Nuclei and Electrons)

Under test at GSI 1992-94

Start: Dec. 1995
ATLAS IAS

Juli 98: Satellite control lost!

since Nov. 98 all instruments active
Mission prolonged until 2007

Univ. of Turku, Finland, E. Valtonen

25/08/2015, R. Pleskac, ICNFP 2015, Kolimbari
Advanced Composition Explorer ACE

9 high-resolution spectrometers exploring the solar and cosmic particle radiation

CRIS and SIS were tested and calibrated at GSI

Since Aug. 1997 in space

Particle identification

\[ \Delta E, E, \text{ angle } \theta \]

GSI Test with Fe-ions

CRIS

Element abundance in GCR
Example 3 (AMS)

Alpha Magnetic Spectrometer AMS

Particle detector to be mounted at the International Space Station ISS

> 500 Scientists / 56 Institutions in 15 countries

Search for Antimatter and Dark matter
Origin of cosmic radiation

Tests of electronic components of the
Data acquisition system at GSI
Kr/Xe/Au/U Ions 2000/01/02/05

Launch 2009/2010?
Assembly at CERN
Tests at ESA-ESTEC
3 years on ISS

AMS-Test at GSI

Test conditions
- Ion source – Au⁷⁹;
- Energies: 120, 150, 200, 400 and 800 MeV/nucl;
- LETs: 12, 16, 23, 28, 33 MeV/(mg/cm²);
- Intensities: up to 10⁵ ions/spill;

GSI Test, June 2005

ACOP components
- DP83316 (NS), Ethernet Controller, SEL rate on ISS ~ 10⁻⁶ day⁻¹, accepted;
- AM79C973 (AMD), Ethernet Controller, SEL rate on ISS ~ 10⁻⁶ day⁻¹, accepted;
- 82551IT (Intel), Ethernet Controller, SEL rate on ISS ~ 10⁻⁴ day⁻¹, rejected;
- PDC2032 (Promise), SATA Controller, SEL rate on ISS ~ 2·10⁻⁵ day⁻¹, not recommended;
- SiI3114 (SI), SATA Controller, SEL rate on ISS ~ 10⁻⁵ day⁻¹, accepted w/reserv – test lower LETs.
Example 3 (AMS)
Example 3 (AMS)
Example 4 (ALTEA)

ALTEA - space

SDS
6 SDUs
1 SDU: 3 silicon planes with double detectors, view X & Area: 2 x (8 x 8) cm²
Maximum error of angular reconstruction: ±1.8°
Geometric factor: 160 cm² sr

VSU

Two color LCD-TFT oculars
XGA, 1024 x 768 pixels at 60 Hz
Field of view: 35° diagonal (21° V, 28° H)
Luminance 5-50 FL Contrast 40:1
256 colors out of a 16 million colors palette
Video memory: 2 MB

PushB.
Three independent pushbuttons

EEG
32 channels
128 - 16384 Hz per channel

Calibration at GSI
- November 2003 (SDU-PM1)
  C @100, 150, 400, 600 MeV/n
- April 2004 (all SDUs)
  C @ 100, 600, 1000 MeV/n
  Ti @ 200, 600 MeV/n

Astronauts Sunita Williams and Michael Lopez-Alegría

25/08/2015, R. Pleskac, ICNFP 2015, Kolimbari
Example 5 – Phoshenes in Radiation Therapy with C-Ions

39 patient studied at GSI (O. Kavatsyuk, D. Schardt, M. Krämer)
Radiation Damage in Electronic Components

Single energetic particles may cause malfunctioning of microelectronic devices
SEU = Single Event Upset
  e.g. Bit-Flip in Storage-Chips
http://ams.cern.ch/AMS/Beamtest/

Results of GSI beam times (AMS-Collaboration)

Table 2: Estimate of SEE rates per component on ISS.

<table>
<thead>
<tr>
<th>Component</th>
<th>Part Number</th>
<th>SEL rate (day$^{-1}$)</th>
<th>SEU rate (day$^{-1}$)</th>
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<tbody>
<tr>
<td>DSP</td>
<td>ADSP2187L</td>
<td>8·10$^{-8}$</td>
<td>1·10$^{-4}$</td>
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<tr>
<td>DSP</td>
<td>ADSP2189M</td>
<td>2·10$^{-7}$</td>
<td>2·10$^{-4}$</td>
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<tr>
<td>DALLAS controller</td>
<td>DS80C390</td>
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<tr>
<td>CPU</td>
<td>PPC750</td>
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<tr>
<td>Host/PCI bridge</td>
<td>CPC700</td>
<td>1·10$^{-10}$</td>
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<tr>
<td>PCI Adaptor</td>
<td>PLX PCI9080</td>
<td>1·10$^{-3}$</td>
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<tr>
<td>Watchdog Timer</td>
<td>AMD679</td>
<td>5·10$^{-9}$</td>
<td>4·10$^{-8}$</td>
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<td>CPLD</td>
<td>CY3700</td>
<td>2·10$^{-12}$</td>
<td>3·10$^{-5}$</td>
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<td>SDRAM 128 Mbit</td>
<td>MT48LC8M16A2</td>
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<td>FLASH memory</td>
<td>MBM29DL324TE</td>
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<td>3·10$^{-7}$</td>
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<td>HV controller</td>
<td>HMV100</td>
<td>2·10$^{-6}$</td>
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<td>PGA</td>
<td>QL12X16BL</td>
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<td>PGA</td>
<td>Actel 548X32</td>
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<td>RICH FE chip</td>
<td>AMS</td>
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<td>8·10$^{-8}$</td>
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<td>ECAL FE chip</td>
<td>AMS</td>
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<tr>
<td>HCC</td>
<td>AMS</td>
<td>2·10$^{-7}$</td>
<td>negl</td>
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<tr>
<td>Digital Coupler</td>
<td>ISO150</td>
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<td>5·10$^{-4}$</td>
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<tr>
<td>Digital Coupler</td>
<td>ADM</td>
<td>6·10$^{-9}$</td>
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<td>ADC</td>
<td>ADS803U</td>
<td>3·10$^{-9}$</td>
<td>2·10$^{-7}$</td>
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<td>VA32 old</td>
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<td>1·10$^{-8}$</td>
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<tr>
<td>VA32 new</td>
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<td>2·10$^{-8}$</td>
<td></td>
</tr>
</tbody>
</table>
Significance of nuclear fragmentation in RT

Nuclear fragmentation

➔ Loss of primary ions ➔ depth-dose, RBE

➔ Buildup of secondary fragments ➔ dose-tail, lateral dose
Angular distribution setup

→ Beam energy of 120 MeV/u
→ Cylindrical water target (diameter of 150 mm)
→ Telescope positionned at 0°, 20°, 30°, 60°, 90° and 120°
FIRST – experimental setup in cave C

→ Beam diagnostics
→ New detectors in interaction region (IR)
→ ALADIN dipole
→ MUSIC + ToF Wall
→ LAND

Measurable
→ Double-differential cross-section for Z particles

Experiment in August 2011
(carbon beam fragmented on thick targets)

→ C + C (5 mm) at 400 MeV/u
→ C + Au (0.5 mm) at 400 MeV/u

→ coincidence measurement
→ on event-by-event basis

IR – START scintillator
IR – Beam Monitor
IR – Target
IR – Si Pixel Vertex Detector
IR- KENTROS
ALADIN Magnet
TP-MUSIC IV
TOF wall
LAND

25/08/2015, R. Pleskac, ICNFP 2015, Kolimbari
Microbeam – Irradiation of single cells

Nucleus of a human fibroblast cell

Biological response visualized by immuno-staining;

Heart Arrhythmia Project

Description

- First worldwide experiment in July 2013 in swines for the treatment of heart arrhythmia with heavy ions
- Collaboration with Mayo Clinics, USA, and Heidelberg University Clinics
- First experiment at GSI (cave M) from July 17 - 23, 2014

Specification

- Update of the electronics for the beam scanner currently in Cave M
- Authorization by Hessian authorities for animal experiments at GSI/FAIR, including swines
Catheter ablation

drawbacks:
• invasive method
• long (several hours)
• severe complications
• about 30% of the procedures need to be repeated after 1 year

Video: Catheter Ablation for Atrial Fibrillation, Cleveland Clinic, 2011
Cappato R et al., Circulation 111(9), 2005 und Cappato R et al., Circ. Arrhythm. Electrophysiol 3(1), 2010; Jongbloed MR et al., Radiology, 234(3), 2005
Radiosurgery as arrhythmia treatment?

**Radiotherapy**
- Non-invasive
- Reduced treatment time

**Why scanned carbon ions?**
- High precision
- Good sparing of surrounding tissue
Feasibility study at GSI

Photo: Matthias Prall, GSI
Main physics goal: to construct a world-leading, unique facility for experiments in applied sciences (biology, medicine, material science)

Biophysics
Spokesperson: Marco Durante

Topics
• space radiation protection
• theranostics
• particle therapy

Materials research
Spokesperson: Christina Trautmann

Topics
• radiation hardness
• extreme conditions (p, T, irradiation)
• geophysics
• nanoscience

Collaboration/users
• 20 Countries
• 70 Institutes
BIOMAT Irradiation Facility in APPA Cave

**Projectiles**
- Protons: $E = 29$ GeV/u
- Light ions: $E = 14$ GeV/u ($^4\text{He}$, $^{12}\text{C}$, $^{20}\text{Ne}$, $^{40}\text{Ar}$)
- Medium mass ions: $E = 11$ GeV/u ($^{56}\text{Fe}$, $^{84}\text{Kr}$, $^{132}\text{Xe}$)
- Heavy ions: $E = 11$ GeV/u ($^{179}\text{Au}$, $^{238}\text{U}$)

**Options**
- SIS18 or SIS18+SIS100 option
- All intensities offered by the machine

25/08/2015, R. Pleskac, ICNFP 2015, Kolimbari
BIOMAT Beamline

- Beamline (ion optics, vacuum, beam diagnostics)
- Control room
- Beam scanning system
- Target station (target handling, multi-purpose UHV chamber, high-pressure equipment, X-ray machine)

Intensity-controlled raster scan technique allows high-quality irradiations of larger sample areas (max. irradiated area of 10 x 10 cm²)

High-pressure cells (PE type) and laser heating system

UHV target chamber for sample irradiation and in-situ analysis
Description
Preparations of biological samples before irradiation and analysis of the samples after irradiation

Specifications
Very close to the irradiation facility, equipped with incubators, laminar flow boxes, Coulter counters, microscopes, etc.

T- Reiter (ESA) visiting GSI in 2013
- Proton therapy and radiography
- Collaboration between biophysics and plasma physics
- to exploit the PRIOR setup for therapy
- Relativistic protons (4.5 GeV) for image-guided, high-resolution, real time, stereotactic radiosurgery at PRIOR setup
- First image of a biological target (zebra fish) with 800 MeV protons at ITEP in 2011
- Images of human-like phantom and mouse recorded at LANL using 800 MeV protons in 2013
Matter under extreme conditions

- Simulating geological processes in the inner Earth
- Ion-beam stabilized high pressure phases

During irradiation T and p like in the inner earth is applied to minerals. So, tracks induced by natural fission fragments in the minerals of the inner earth can be simulated.

Nanoscale manipulation of the properties of solids at high pressure with relativistic heavy ions
Summary / Outlook

- Broad scientific program
- Large International collaboration / user community
- Nuclear fragmentation important in space research and radiotherapy
- Future experiments at Cave A, M and APPA Cave
- Cooperation with European Space Agency