Advanced Summer School on
Laser-driven Sources of High Energy Particles and Radiation
2017-07-14, CNR Conference Centre, Anacapri, Capri

Bernhard Hidding

Plasma-based space radiation mimicking for space radiobiology and electronics testing

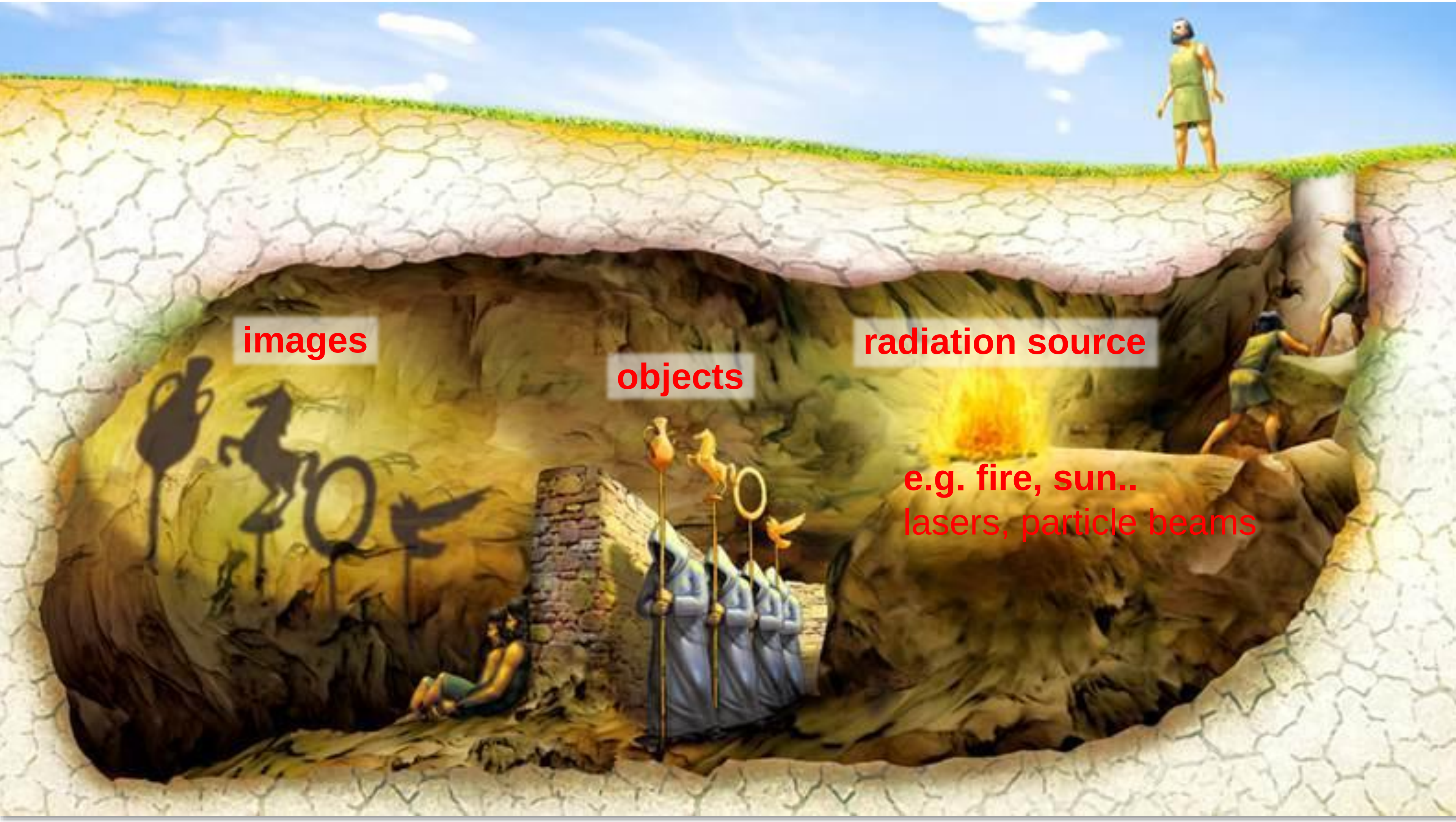
Scottish Centre for the Application of Plasma-Based Accelerators SCAPA,
Department of Physics, University of Strathclyde,
Scottish Universities Physics Alliance SUPA, UK

Strathclyde Centre for Doctoral Training P-PALS
Plasma-based Particle and Light Sources

Strathclyde Space Institute

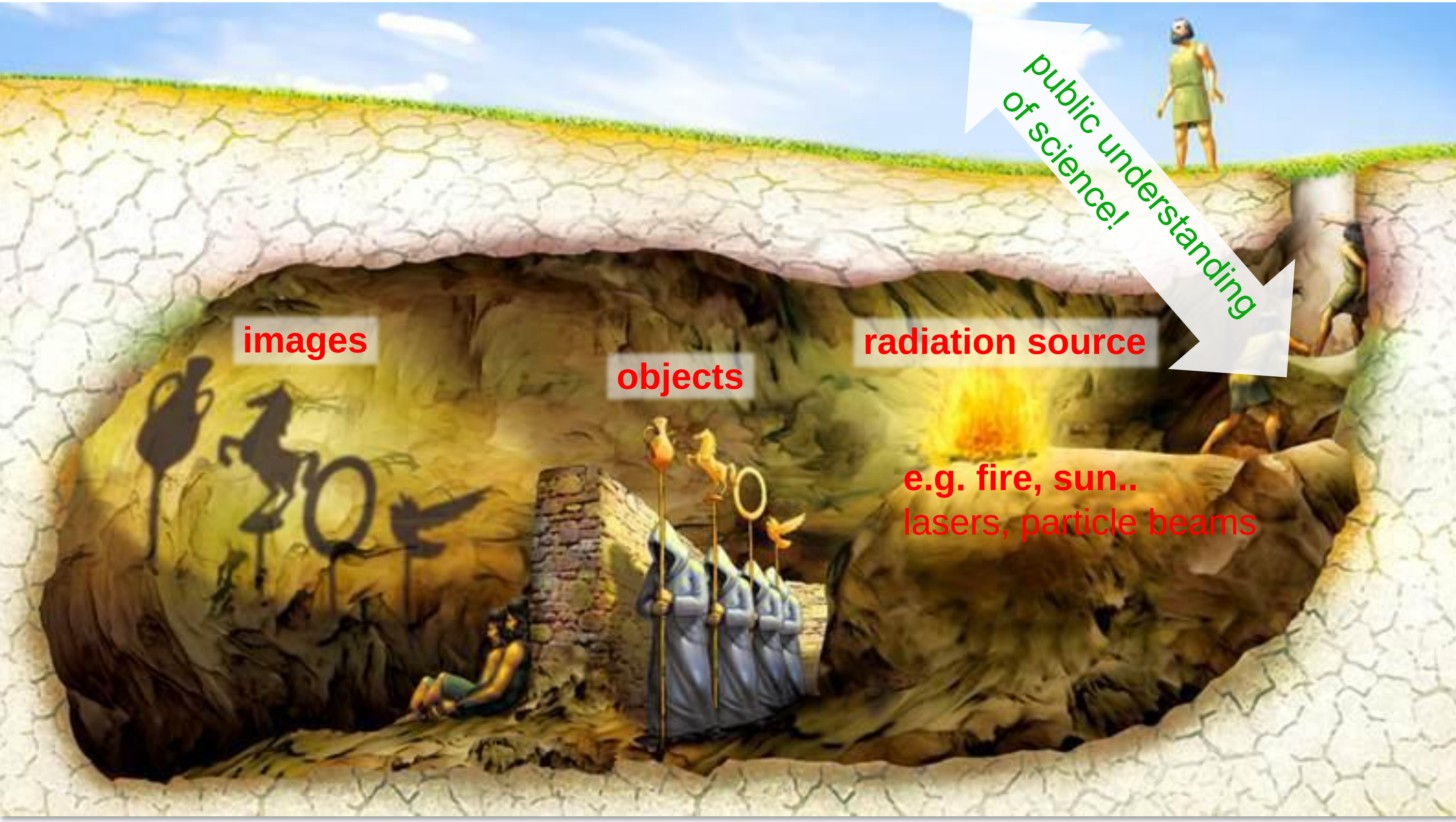
& The Cockcroft Institute

Radiation is a fundamental driver of knowledge.



Greek Philosophy: Allegory of the cave; Analogy of the sun
Plato, Politeia, 380 BC

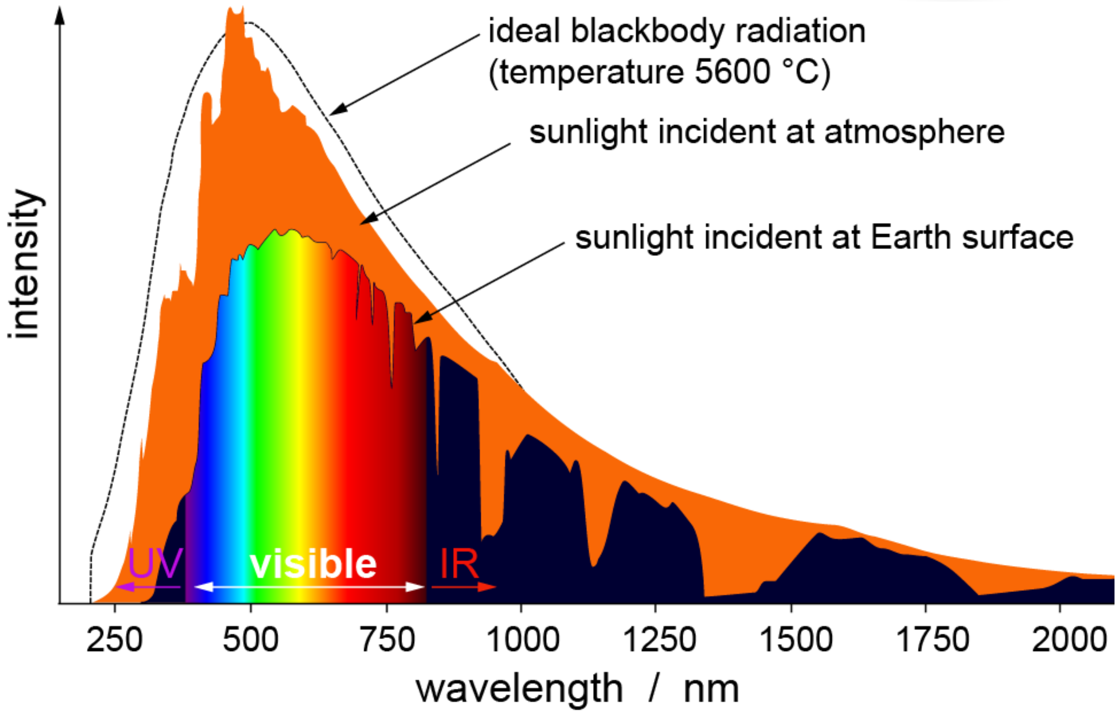
Radiation is a fundamental driver of knowledge.



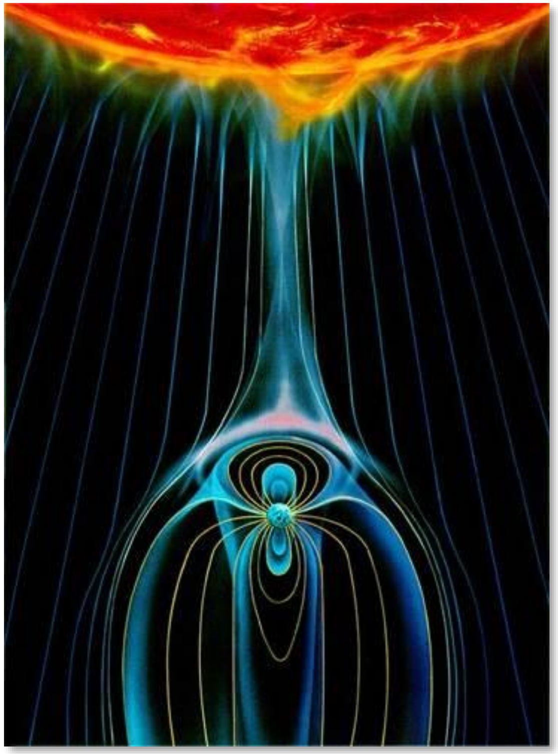
Greek Philosophy: Allegory of the cave; Analogy of the sun
Plato, Politeia, 380 BC

*The Sun: fusion and plasma processes send broadband **photon** and plasma **particle** radiation to Earth*

Earth provides the right amount of protection: too much photons or particles incident on Earth would prevent life to occur, but a little amount is required for genetic evolution

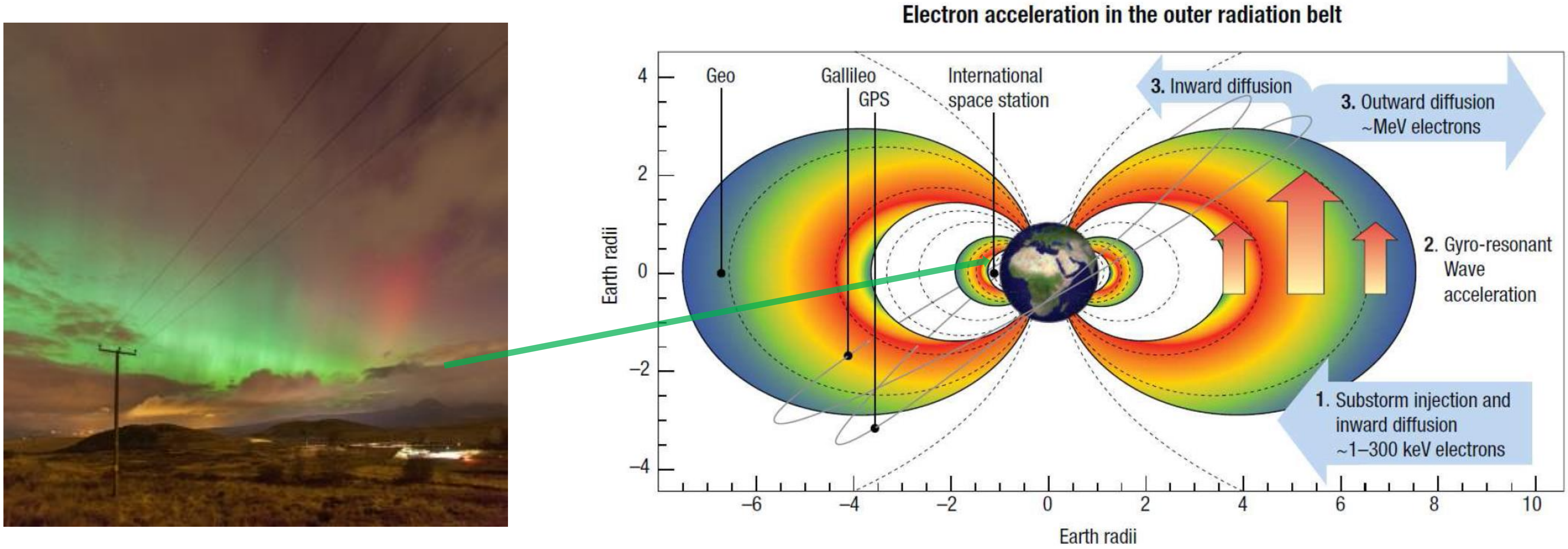


Atmosphere protects us from too intense and too hard **photon** flux



Magnetosphere protects us from too intense charged **particle** flux (electrons, protons, ions..)

Aurora Borealis – Northern lights (or for the Southerners Aurora Australis)



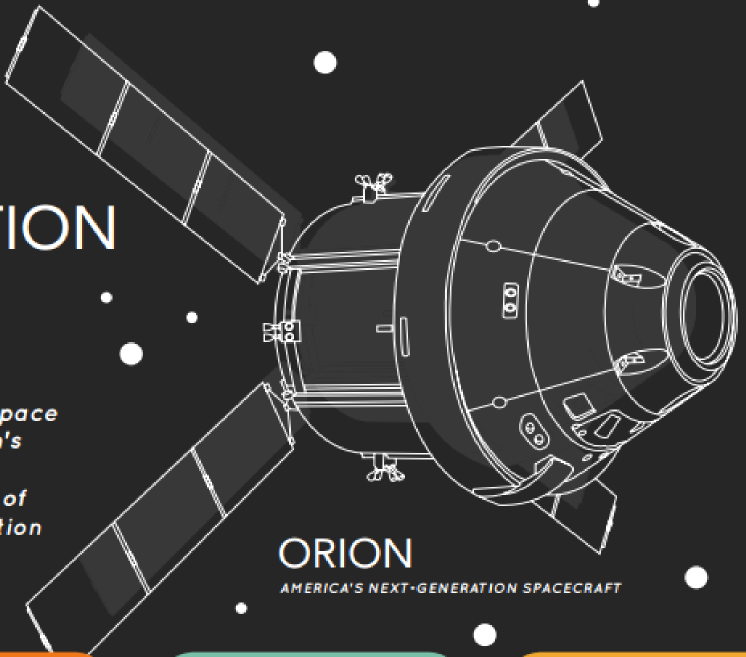
Ionization effects from electrons entering Earth at the magnetic poles

No protection in space – radiation major obstacle for space exploration

- In space, Earth’s protection via the magnetic field and atmosphere is lost
- Space radiation can be extremely versatile (electrons, protons, ions, neutrons, photons)
- Space radiation can kill satellites/missions/astronauts
- Testing & selection of space-grade electronics is one of the most money- and time-consuming factors in spacecraft design and operation. Up to 1/3 of total mission costs can be consumed by radiation hardness assurance (RHA)
- Each electronic component batch must be tested/certified via standardized method - major cost driver! ESA: satellite market 80 G€/a
- RHA of space electronics can be similarly complex as cancer radiotherapy. Multiple tests, with different types of beams at different facilities may be required
- Performance/size/weight of electronics used in space lags behind mass production COTS by several generations
- Space exploration is a vibrant and expanding field of interest with large governmental and industrial impact
- In the EU alone 12 billion euros are being invested between 2014 & 2020 to further Europe's presence in space

TYPES OF RADIATION *in Space*

The radiation environment of deep space is very different from that at Earth's surface or in low-Earth orbit. For people outside the protection of Earth's magnetic field, space radiation is a serious hazard.



ORION

AMERICA'S NEXT-GENERATION SPACECRAFT

IONIZING

GALACTIC COSMIC RADIATION

This type of radiation is emitted as immense clouds of high-energy charged particles thought to originate from supernovas.

CAN NOT BE PROTECTED AGAINST

TRAPPED RADIATION

This type of radiation occurs when charged particles become trapped in Earth's magnetic field and spiral around inside the field.

ONLY INSIDE EARTH'S MAGNETIC FIELD

SOLAR ENERGETIC PARTICLES

Solar energetic particles are released by the Sun in solar particle events. This can result in sudden, intense storms.

EASIEST TO PROTECT FROM

NON-IONIZING

ULTRAVIOLET RADIATION

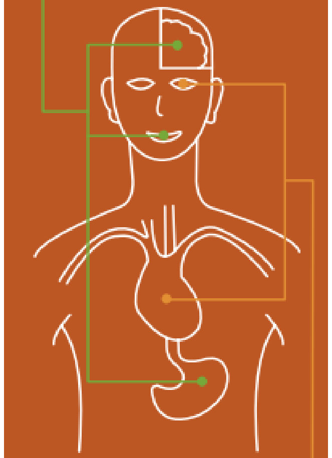
Ultraviolet radiation is less energetic. Particles impart energy on to the atoms and molecules with which they interact, but do not strip off electrons.

LIGHT FROM THE SUN

RADIATION EFFECTS ON HUMANS

ACUTE

- Felt almost immediately when a large dose of radiation is accumulated in a short amount of time
- Causes nausea, vomiting fatigue, and central nervous system diseases, which can lead to changes in motor function and behavior



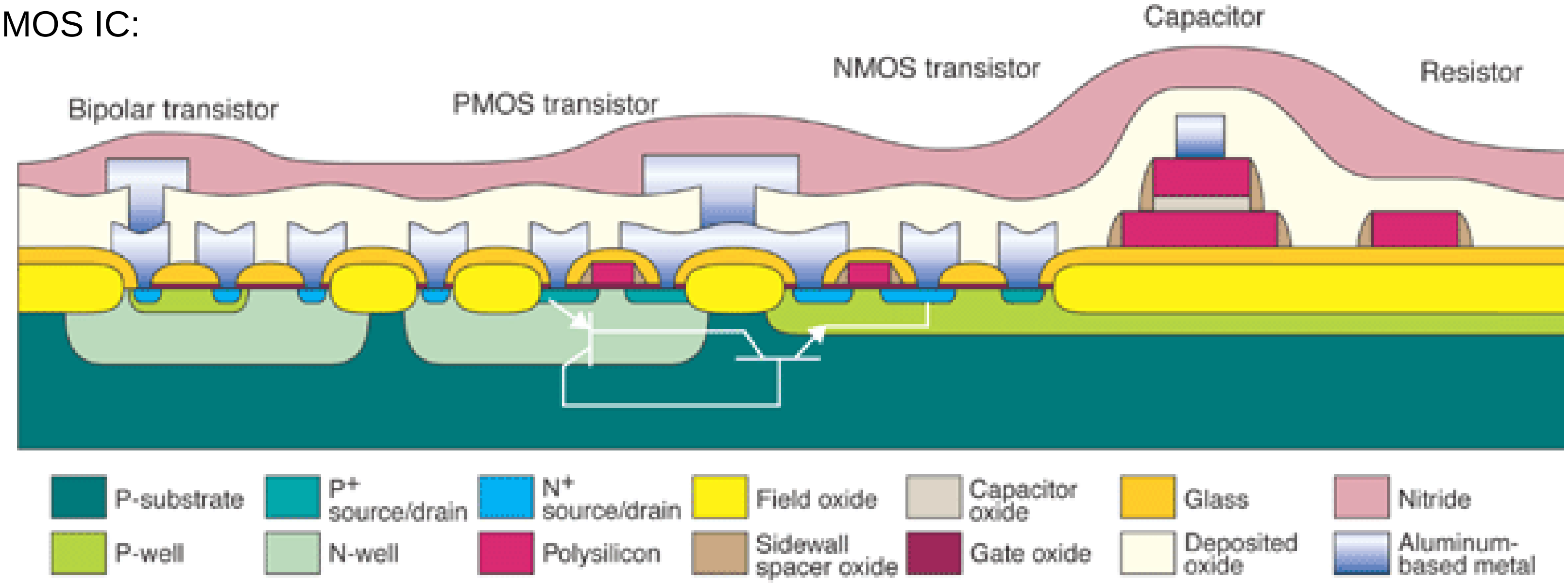
CHRONIC

- Effects can be experienced decades after exposure
- Results from an accumulated dose of radiation over a long period of time
- Causes increased risk of cancer, cataracts and vision impairment, degenerative cardiac disease

Various damage effects e.g. on electronics

- Total ionizing dose (TID), cumulative damage
- Single Event Effects (SEE)
- Surface charging (low energy electrons/protons)
- Deep Dielectric Discharge (DDD)
- ...

Typical CMOS IC:

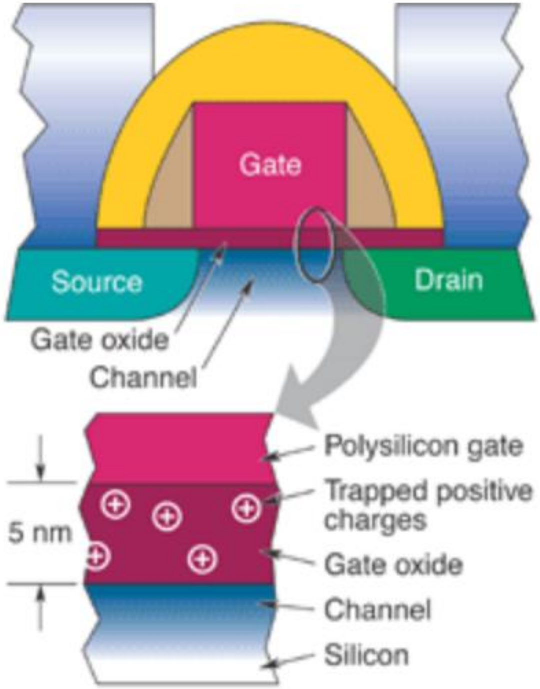


Figures from Aerospace Corporation Magazine

Components separated by dielectrics, protective layers of passivating insulators and glass.

Space radiation can bridge isolation between components, or generate fields/charge within components.

Total ionizing dose

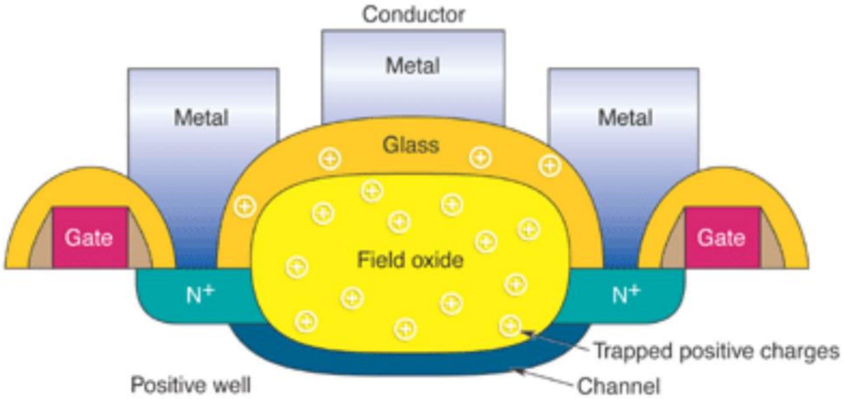


NMOS: gate allows current to flow above threshold voltage
SiO2 gate oxide should be ideal insulator, BUT is ionized by received dose
Electron/hole pairs are created in SiO2, electrons drift away, but fraction of holes are trapped and accumulate.
Large positive charge has same effect as positive voltage applied to gate: NMOS spuriously turns on, remains on.

PMOS analogoulsy: When radiation has produced enough positive charge in gate oxide, device stays off permanently.

In CMOS logical circuit: output will be frozen at “0“ or “1“

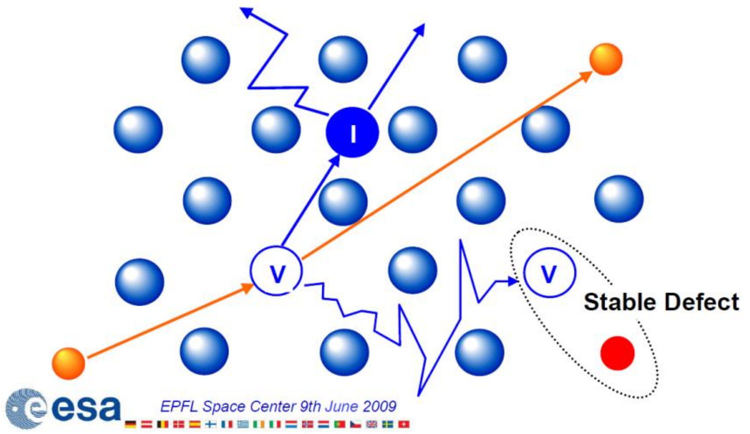
Hardened gate oxides trap much less holes than commercial mass products (material sciences)



Adjacent transistors are separated by thick field oxide layers, where enough positive charge can be trapped to connect both transistors etc.

This “edge leakage“ is today often the dominant, and limiting total-dose effect:
transistors collectively leak too much for power supply

Displacement damage



PKA: Primary Knock on Atom

Displacement damage energy thresholds in Si:
E_d ~ 25 eV (single lattice atom, Frenkel pair)

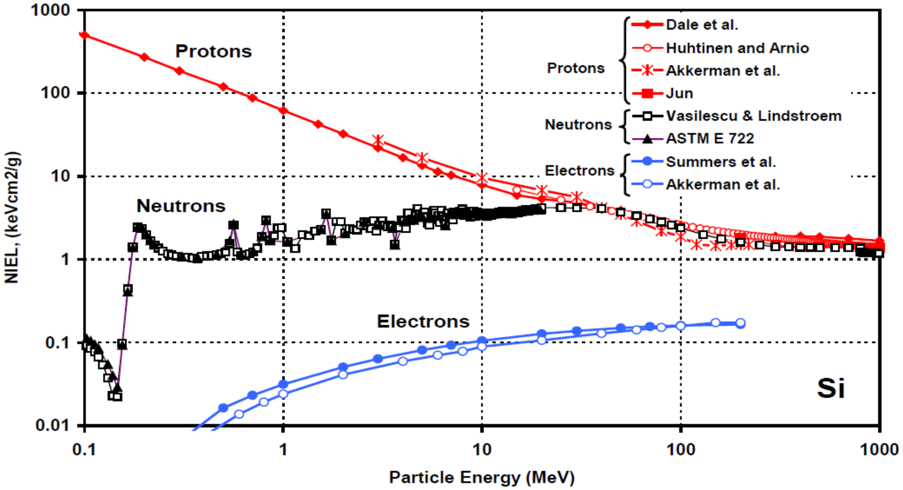
Neutrons: $E_n > 185$ eV
Electrons: $E_e > 255$ keV

Energy transfer in binary collision:

$$T_{\max} = \frac{2ME(E+2mc^2)}{(m+M)^2c^2+2ME}$$ (relativistic)

$$T_{\max} = E\frac{4Mm}{(m+M)^2}$$ (nonrelativistic)

Disruption of crystalline semiconductor lattice structure leads to degradation of electric performance
NIEL: non-ionizing energy loss
(about 0.1% of total energy loss)
DDD: displacement damage dose



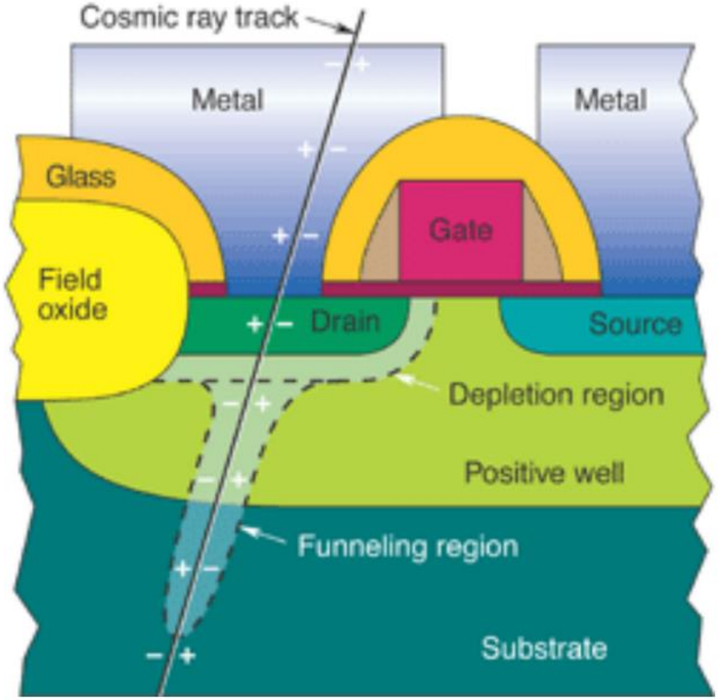
D. Poivey, G. Hopkinson, Displacement Damage and Effects, EPFL 2009

Single Event Effects

High energetic proton or ion generates ionization track

Number of charge pairs propotional to
LET: linear energy transfer (in MEV-cm^2/mg)
Stopping power, Bragg peak

e.g., in NMOS: short is generated between substrate (grounded) and drain: above critical charge, spike current may generate single-event upset (SEU)



ESA Herschel, 2009:

-SEU in RAM of the Local Oscillator Control Unit (LCU) of HIFI telescope activated an emergency switch off.
-This switch was designed to protect the local oscillators against damage from a drop in spacecraft power supply (28 V).
- But now the switch was activated while power supply was still up, resulting in an overvoltage spike.
- overload in one of the power converters, leading to permanent failure of a diode.

=> months downtime

Example: killer electrons


P-ANIK!

High-tech chaos as satellites spin out of control

Plug pulled on phones, TV, radio, pagers

The New York Times

2 Canadian Space Satellites Are Knocked Out by Storm

Developing Service Promises Accurate Space Weather Forecasts in the Future

Science & Medicine

Weathering the storm in space

REPORT ON BUSINESS

Sun gets blame for zapped Aniks

Telesat still trying to fix $300-million satellite, but chance of revival

Image Credit: L. J. Lanzerotti,
Bell Laboratories, Lucent Terchnologies, Inc.

- Early example: “Anik Panic“ 1994:
- Control over Canadian Anik Satellites lost after
- Bombardment with radiation (electrons)

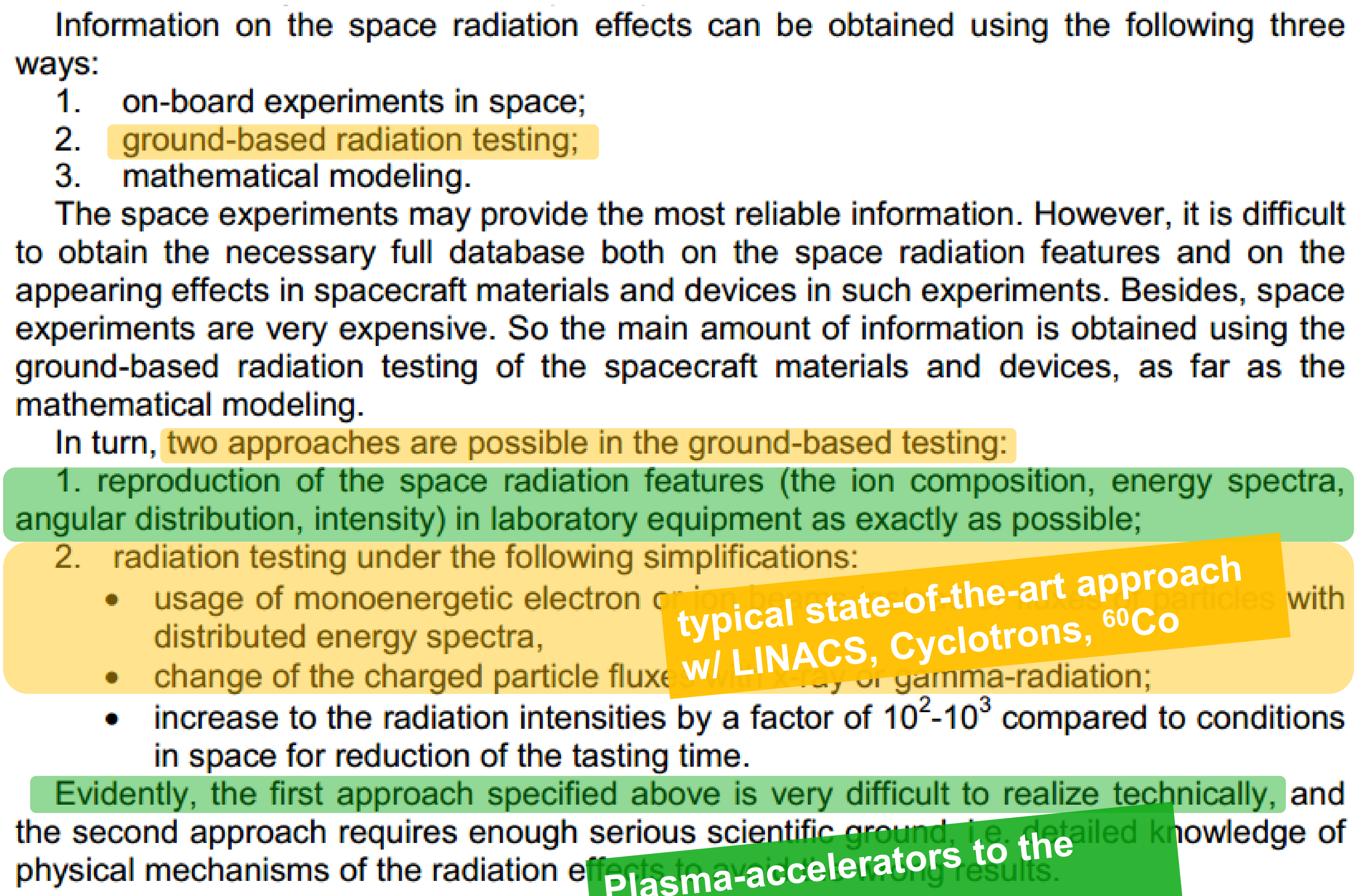
- Killer electrons usually occur most strongly in outer van Allen Belt, distance to Earth 3-9 Earth radii
- E.g., GPS /Galileo satellites at approx. 22000 km, MEO (Medium Earth Orbit) is passed by every spacecraft (manned or unmanned) going beyond LEO

- Telephone/cell phone/radio/television/navigation can be heavily affected, killer electrons can knock out computers, degrade solar arrays, pierce spacesuits, damage tissues of astronauts, endanger Mars missions etc.

- In addition: Solar activity can push radiation belts much closer to Earth!
- E.g., “Halloween Storm“ 2003: SAMPEX (Solar Anomalous and Magnetospheric Particle Explorer) detected: center of outer van Allen belt as close as 6 miles to Earth!

- $\Rightarrow$ 30 satellites reported malfunctions, one was a total loss (avg. total satellite costs ~500 M€)

L.S. Novikov, Space Radiation Effects Simulation Methods. SINP MSU 2003 9/722:



Information on the space radiation effects can be obtained using the following three ways:

1. on-board experiments in space;
2. ground-based radiation testing;
3. mathematical modeling.

The space experiments may provide the most reliable information. However, it is difficult to obtain the necessary full database both on the space radiation features and on the appearing effects in spacecraft materials and devices in such experiments. Besides, space experiments are very expensive. So the main amount of information is obtained using the ground-based radiation testing of the spacecraft materials and devices, as far as the mathematical modeling.

In turn, two approaches are possible in the ground-based testing:

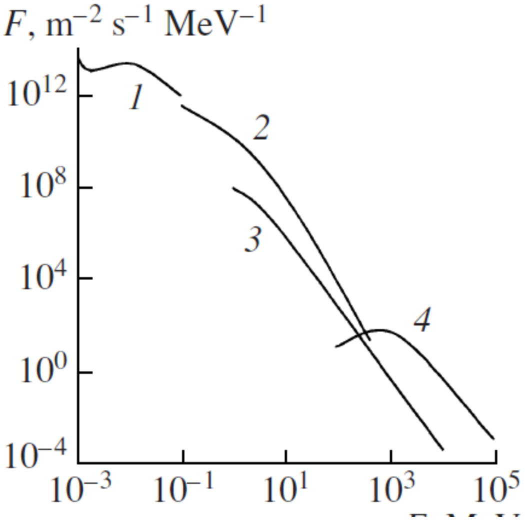
1. reproduction of the space radiation features (the ion composition, energy spectra, angular distribution, intensity) in laboratory equipment as exactly as possible;
2. radiation testing under the following simplifications:
   - usage of monoenergetic electron or ion beams instead of fluxes of particles with distributed energy spectra,
   - change of the charged particle fluxes with x-ray or gamma-radiation;
   - increase to the radiation intensities by a factor of 10^2-10^3 compared to conditions in space for reduction of the tasting time.

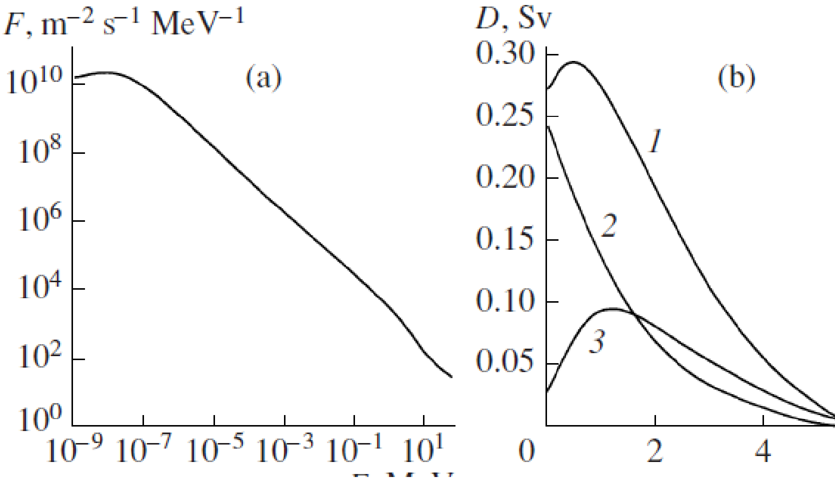
Evidently, the first approach specified above is very difficult to realize technically, and the second approach requires enough serious scientific ground, i.e. detailed knowledge of physical mechanisms of the radiation effects to avoid the wrong results.

typical state-of-the-art approach w/ LINACS, Cyclotrons, ^{60}Co

Plasma-accelerators to the rescue!

Space Radiation is a complex mix of electrons, protons/ions, neutrons and ***broadband,*** *typically with exponential / power–law reduction of flux towards higher particle energies:*





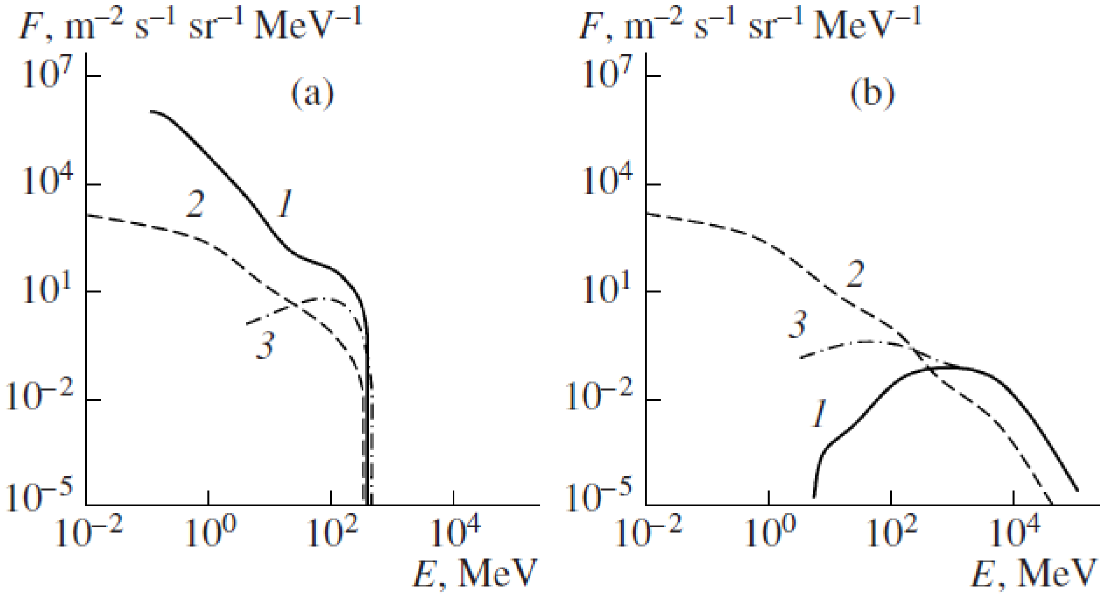
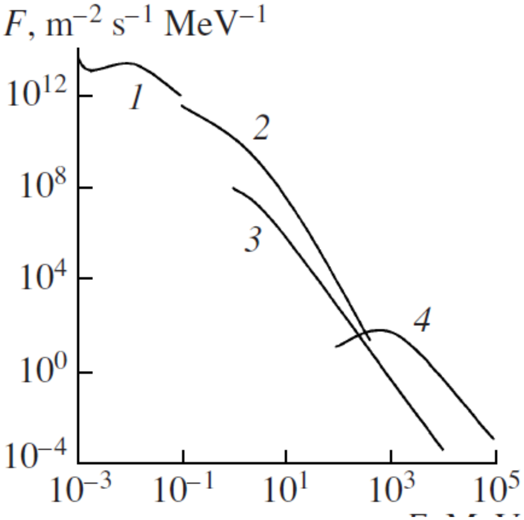
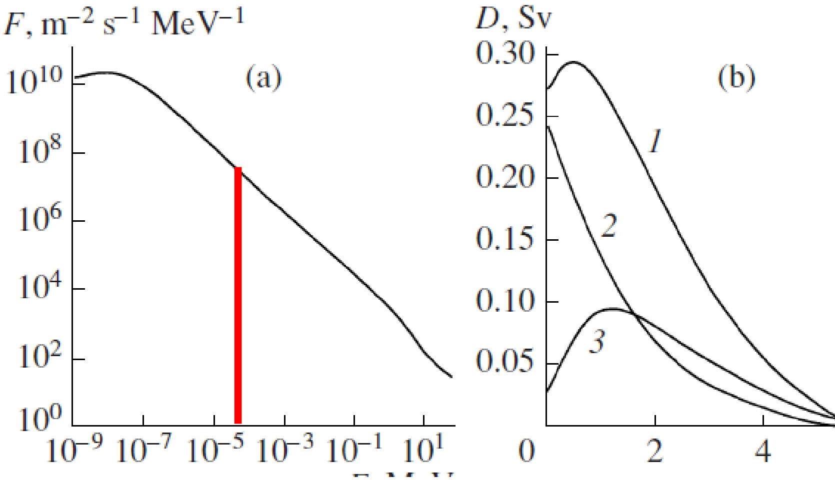


Fig. 5. Energy spectra of particles inside the module “Columbus” formed by (a) ERB and (b) GCR protons: (*1*) primary particles and (*2*) and (*3*) neutrons and protons inside the module.

Linacs and cyclotrons inherently produce ***monoenergetic****, “unnatural” beams.*
Reproduction of the exponential/power-law shaped spectral flux would be desirable





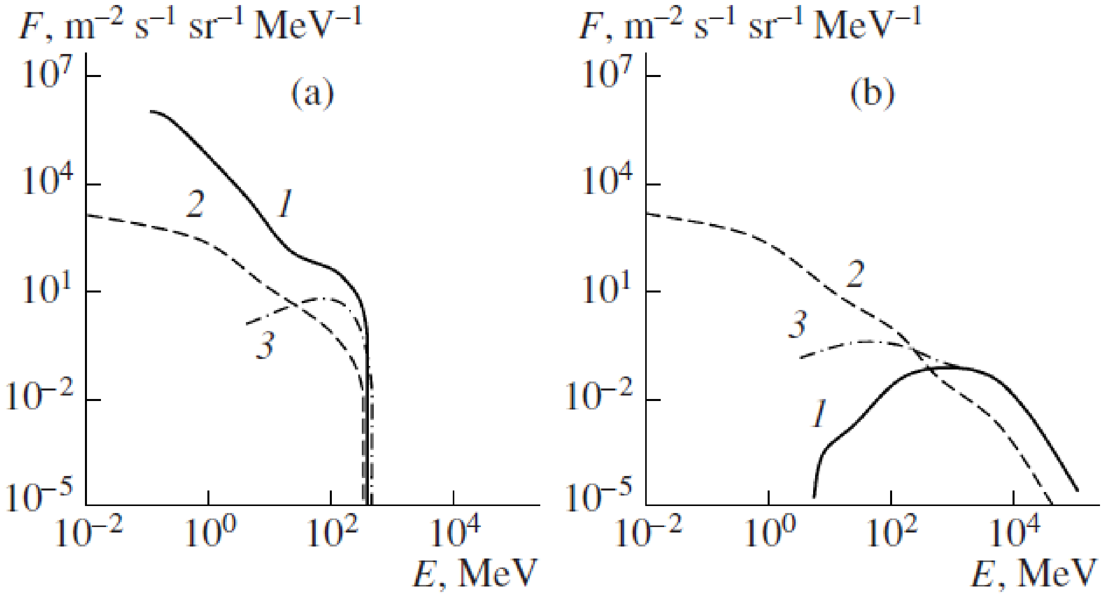
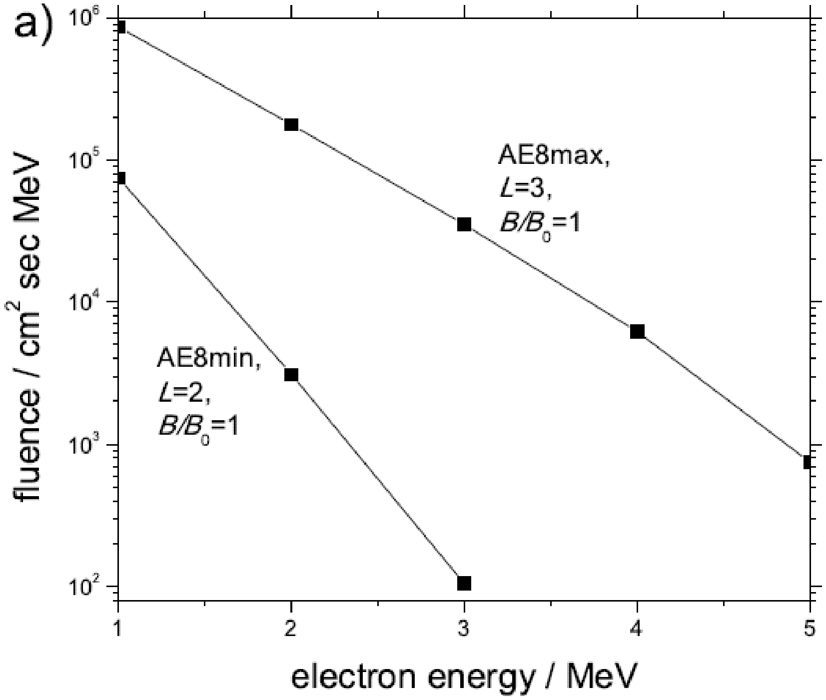


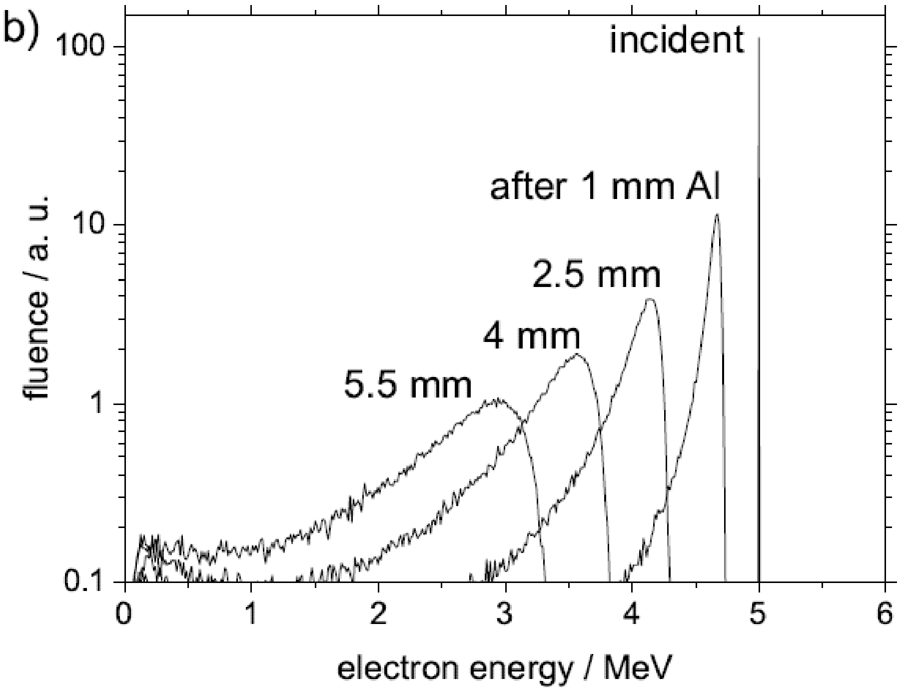
Fig. 5. Energy spectra of particles inside the module “Columbus” formed by (a) ERB and (b) GCR protons: (*1*) primary particles and (*2*) and (*3*) neutrons and protons inside the module.

Spectral flux in space vs. linac/cyclotron output

Occurring in space:



From rf cavity-based accelerator:

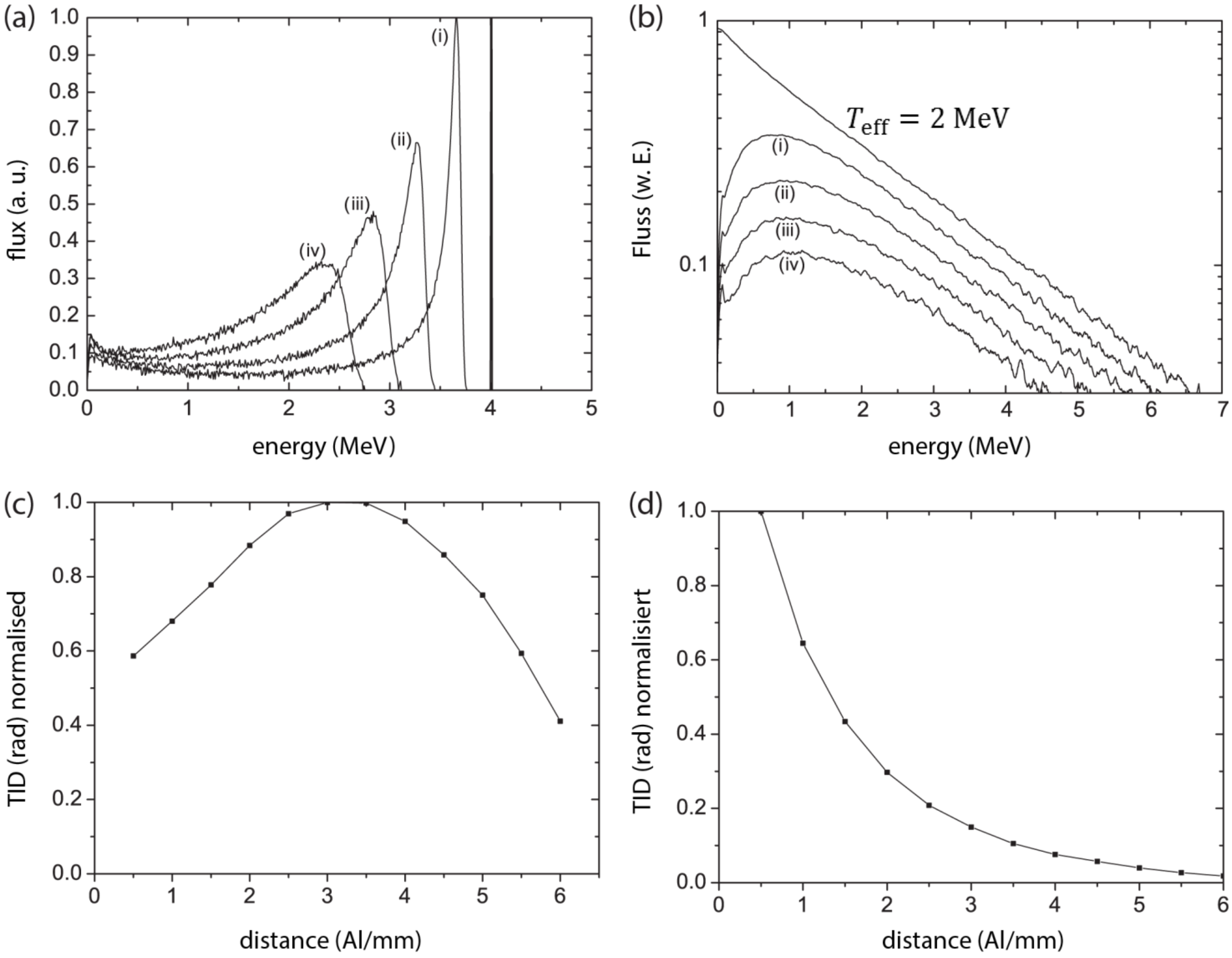


- Spectra are substantially different, even diametrally opposed.
- Since charge/dose deposition and resulting damaging is fundamentally different, conventional approaches are insufficient

Spectral flux & TID when passing through (Al) shielding:

monoenergetic electron flux

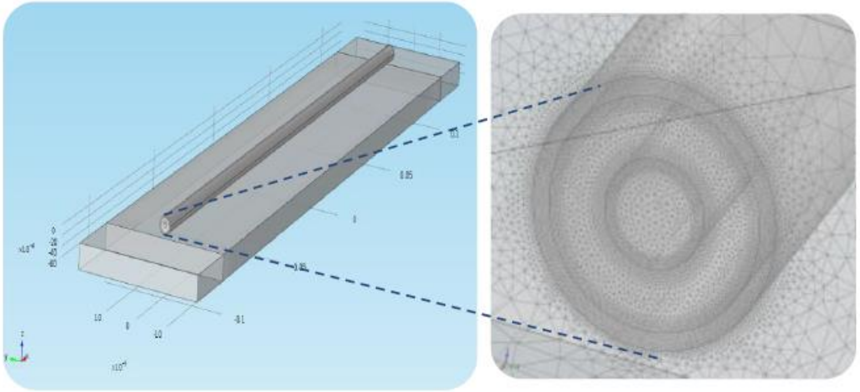
exponential electron flux



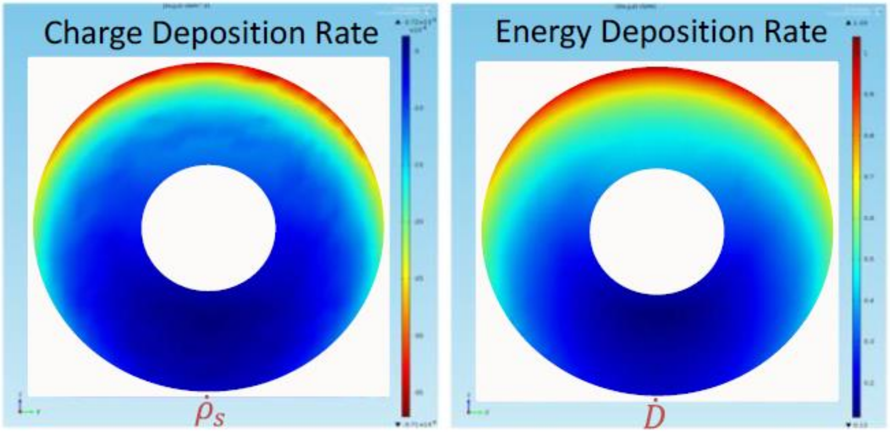
Königstein, Karger et al., Journal of Plasma Physics, 2012

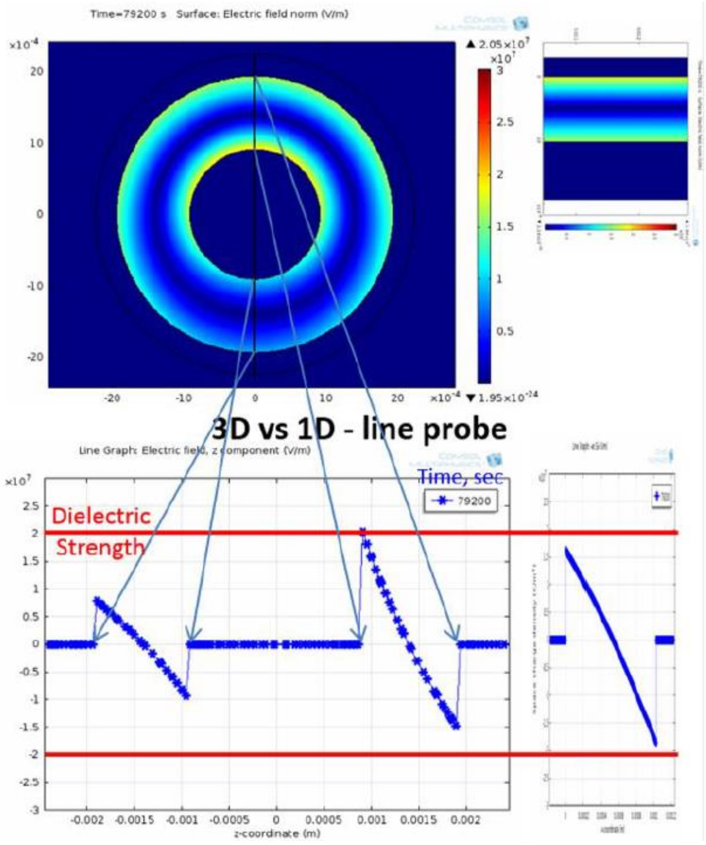
Various kinds of damage (SEU, DDD, IESD..)

For example, internal electrostatic discharge (IESD): space “killer“ electrons are accumulated in dielectrics due to low conductivity. E-field builds up and if it exceeds breakdown threshold of the dielectric ⇒ discharge ⇒ damages of surrounding electronics ⇒ spacecraft failure



e.g. a cable



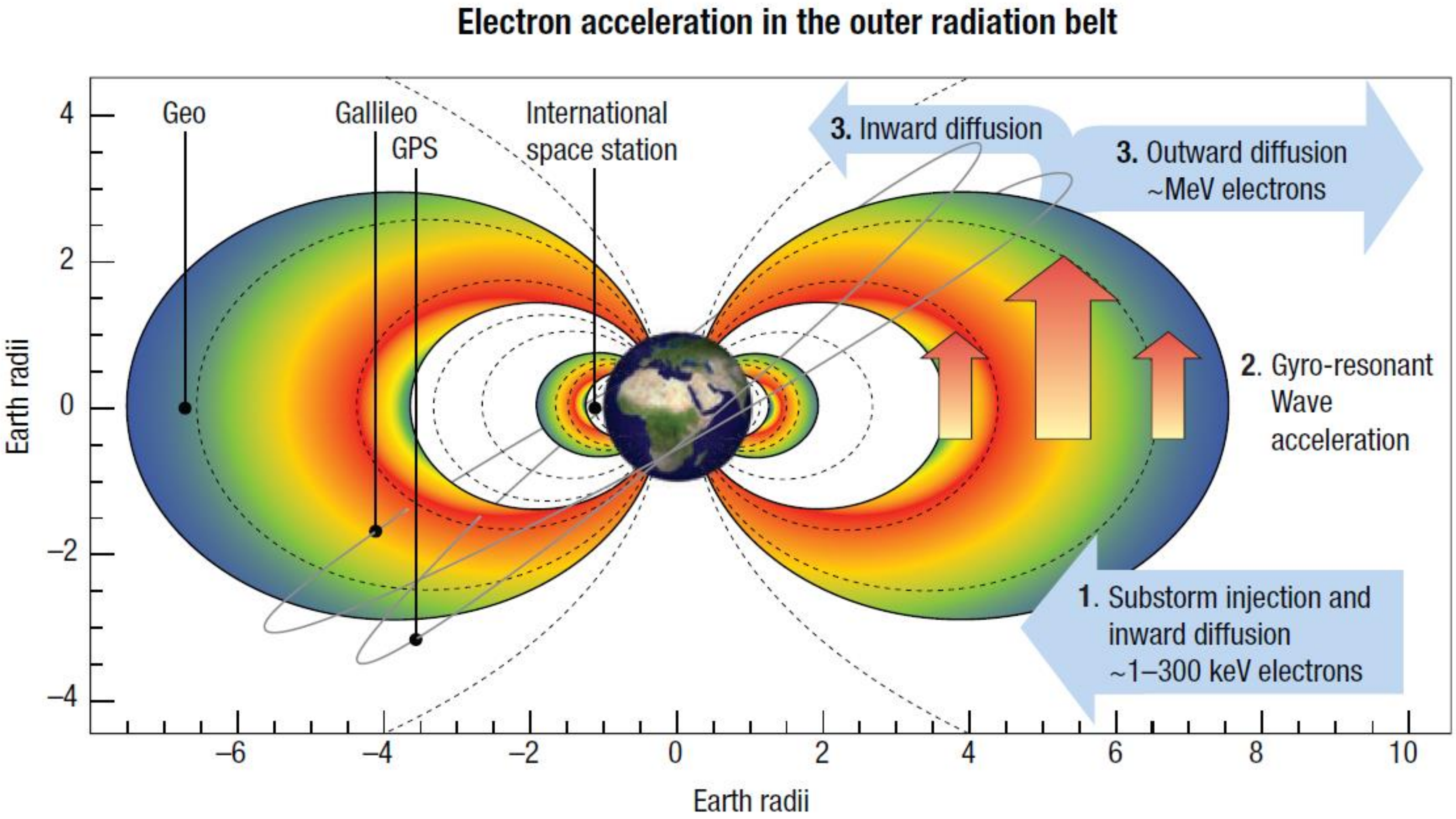


3D NUMIT results,
courtesy W. Kim, NASA JPL

Directionality and energy distribution of electron flux matters

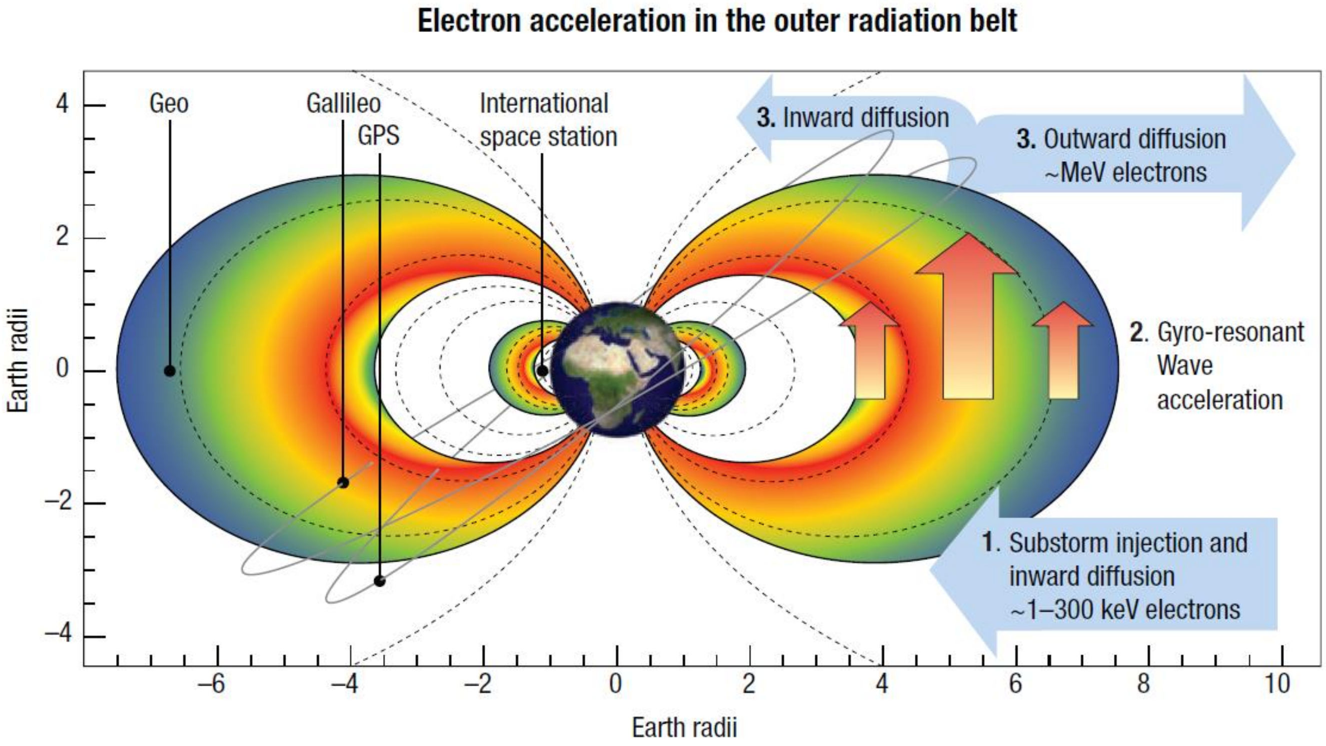
Van Allen belt acceleration mechanisms and killer electrons

Acceleration mechanisms in space are an own vibrant field of research



Horne et al., "Wave acceleration of electrons in the van Allen radiation belts", Nature 437, 2005
Chen et al., "The energization of relativistic electrons in the outer van Allen radiation belt", Nature Physics 3, 2007
Horne et al., "Plasma astrophysics: Acceleration of ***killer electrons****", Nature Phys. 3, 2007*
Horne et al., "Gyro-resonant electron acceleration at Jupiter", Nature Physics 4, 2008

Van Allen belt acceleration mechanisms and killer electrons



Inner Belt: 1,000-6,000 km
Lower boundary can extend down to 200 km (ISS at 400 km) depending on solar activity and the South Atlantic Anomaly (SAA)

Dominated by protons

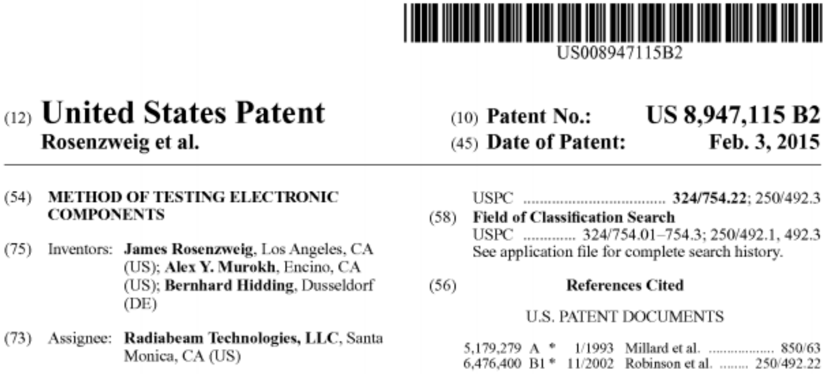
Outer Belt: 13,000-60,000 km

Dominated by electrons

Use plasma accelerators to reproduce space radiation for RHA

- DE Patent (2010) and US/PCT patents (2011/12) (RadiaBeam & UCLA US United States Patent 8947115, 2015)

- ESA-funded seed activities: ESA NPI “*Study of Space Radiation Effects with Laser-Plasma-Accelerators*”, 2011-2013, ESA GSP “*Laser-Plasma-Accelerator’s Potential to Radically Transform Space Radiation Testing*”, 2012-2014



US008947115B2

(12) **United States Patent**
Rosenzweig et al.

(10) **Patent No.:** **US 8,947,115 B2**
(45) **Date of Patent:** **Feb. 3, 2015**

(54) **METHOD OF TESTING ELECTRONIC COMPONENTS**

(75) Inventors: **James Rosenzweig**, Los Angeles, CA (US); **Alex Y. Murokh**, Encino, CA (US); **Bernhard Hidding**, Dusseldorf (DE)

(73) Assignee: **Radiabeam Technologies, LLC**, Santa Monica, CA (US)

USPC **324/754.22**; 250/492.3

(58) **Field of Classification Search**
USPC 324/754.01–754.3; 250/492.1, 492.3
See application file for complete search history.

(56) **References Cited**

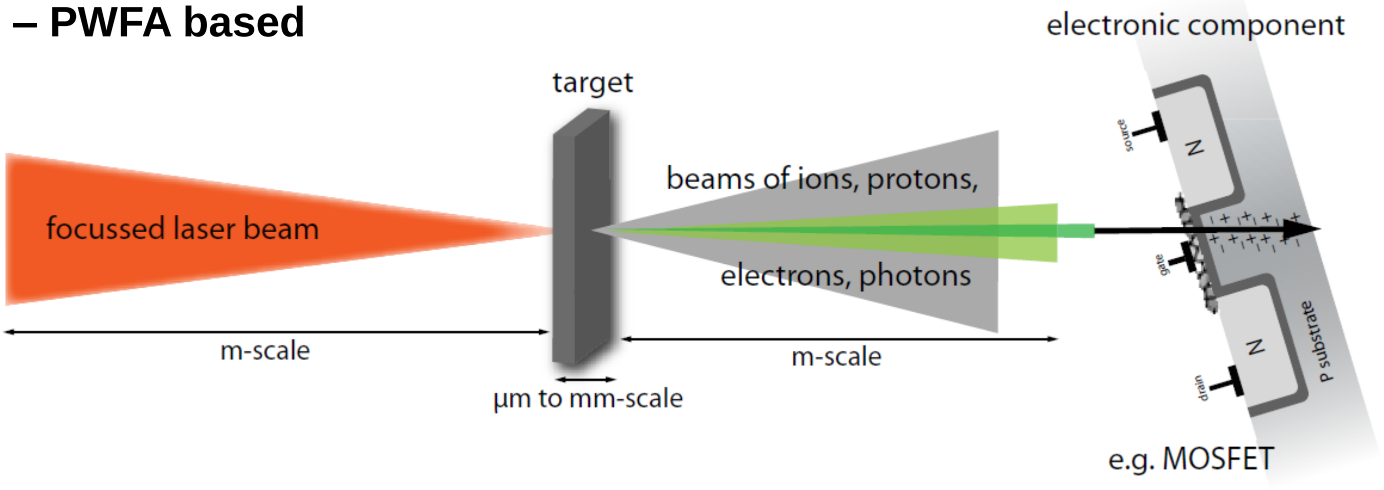
U.S. PATENT DOCUMENTS

5,179,279 A * 1/1993 Millard et al. 850/63
6,476,400 B1 * 11/2002 Robinson et al. 250/492.22

How to reproduce exponential/power law space radiation flux mit plasma accelerators?

Various options, e.g.

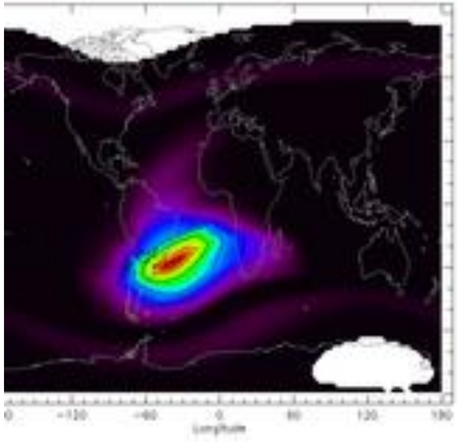
- **Ti:Sapphire plasma acceleration (with solids or with underdense targets)**
- **CO2 laser plasma acceleration**
- **Linac – PWFA based**



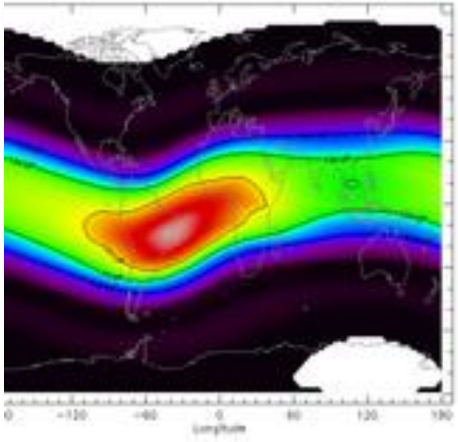
Space radiation from laser-solid interaction (TNSA-style)

Radiation belt spectral flux calculations

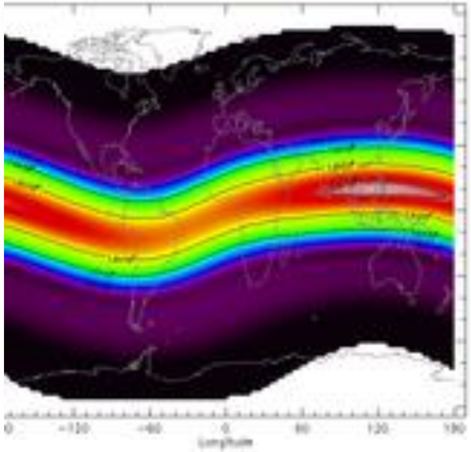
Using NASA AE8/AE9 & AP9 models: Electrons > 100 keV



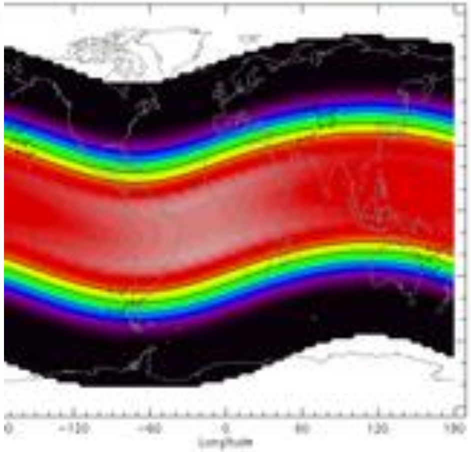
Inner Belt, 1200km
(SAA)



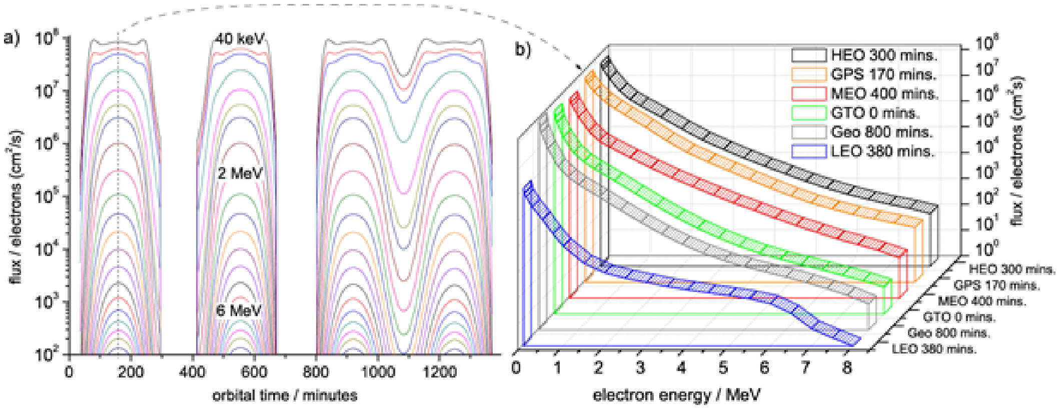
Inner Belt, 3000km



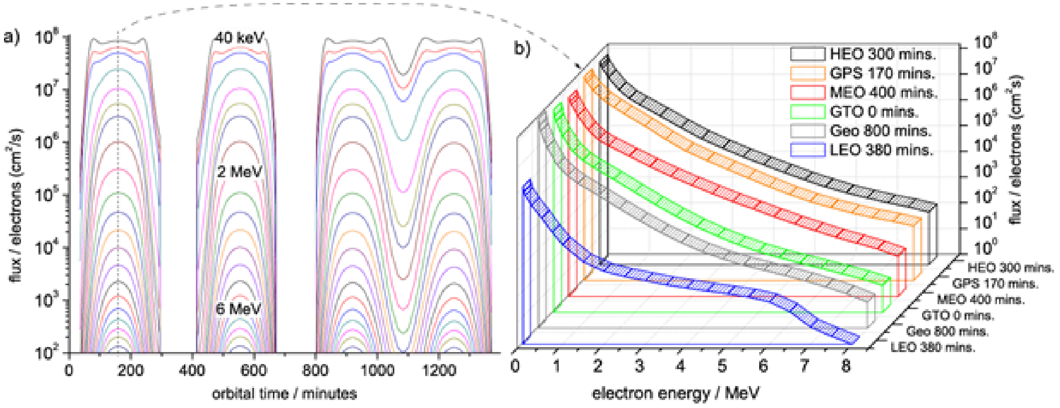
8000km



Outer belt, 20,000 km



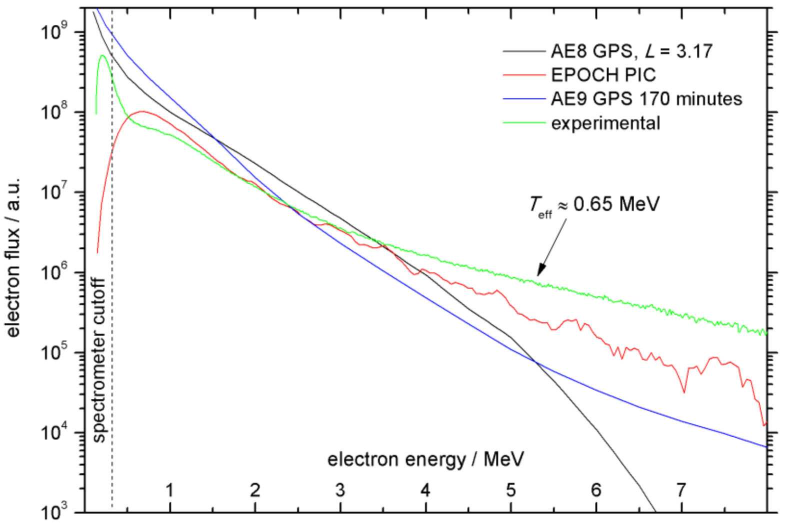
1. Use NASA AE9/AP9 to calculate spectral flux in space:



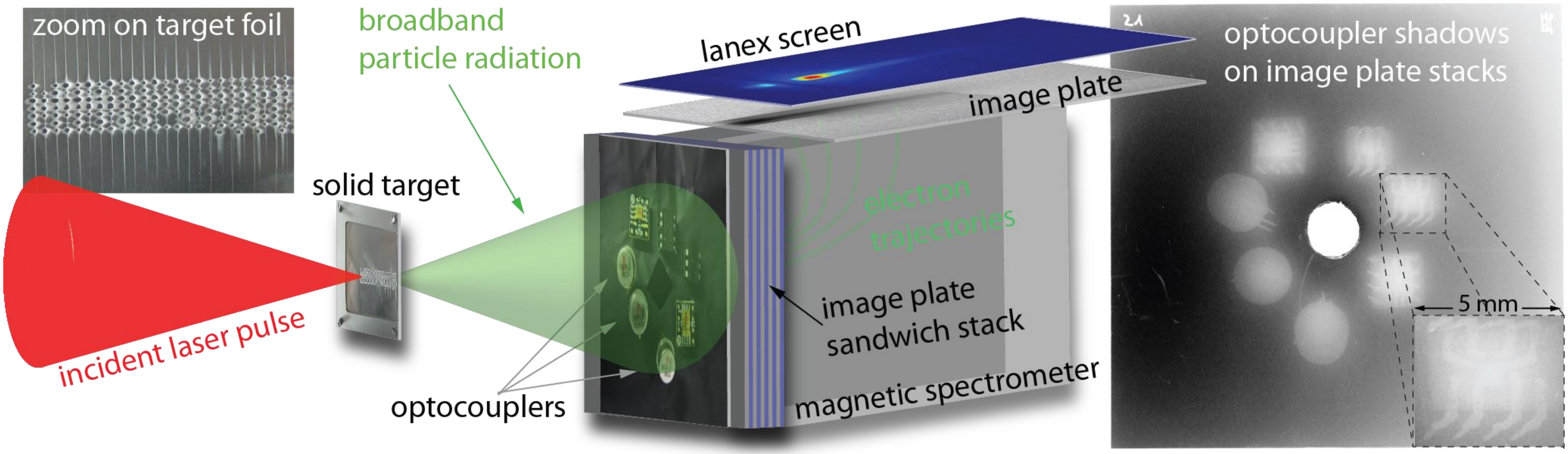
$$N(E) = N_0 e^{-E/k_B T}$$

Use well-known scalings by Wilks, Beg, Kluge et al.

2. Tune laser-plasma-output to match the spectral flux as in space:

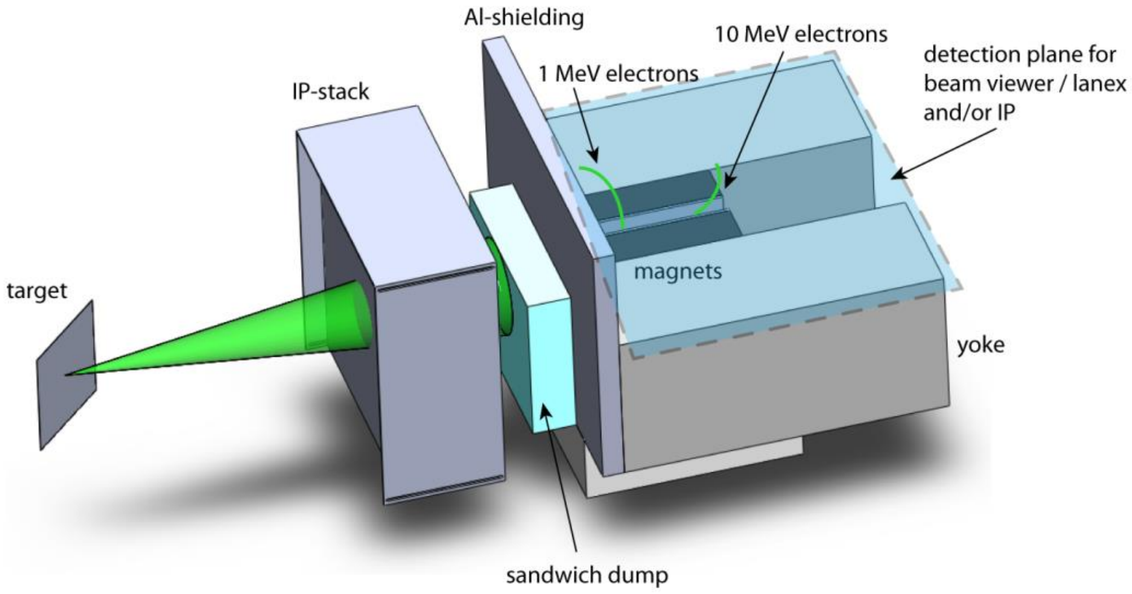


3. Setup, adapt testing techniques, monitor flux and irradiate devices

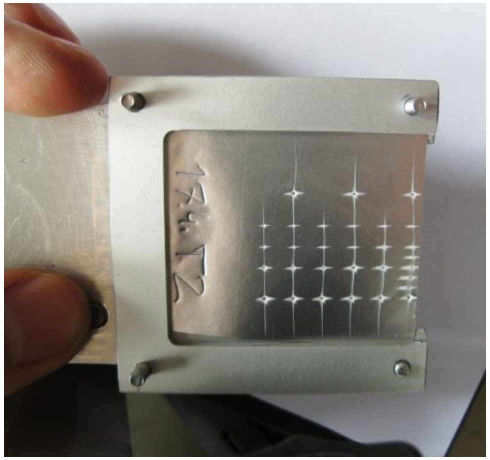


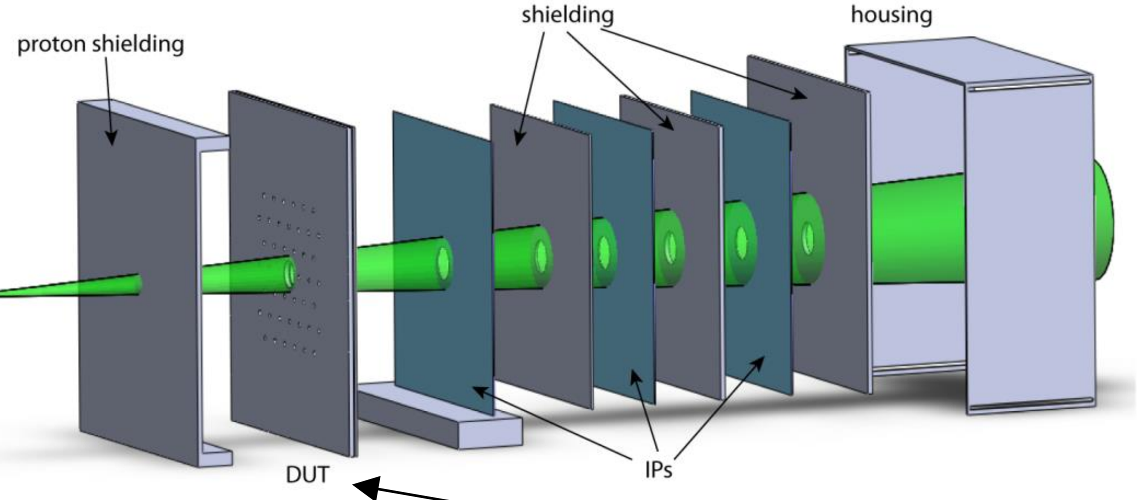
Results: first accurate reproduction of space radiation, also production of broadband protons, significant degradation of optocoupler performance

Main diagnostics: Image plate stack for dose monitoring + magnet spectrometer on axis

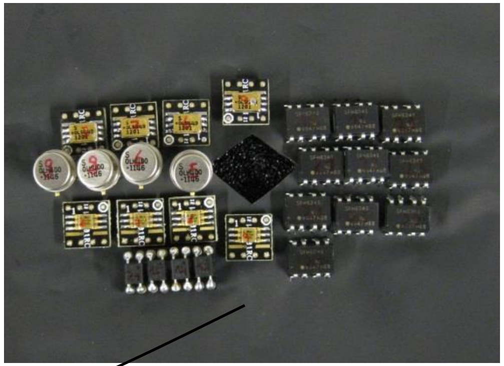


Metallic target foil
after laser shots



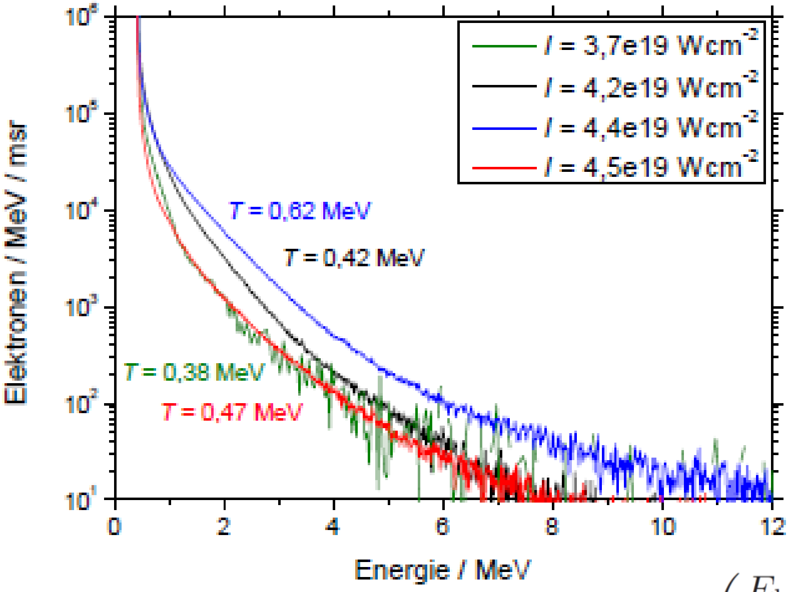


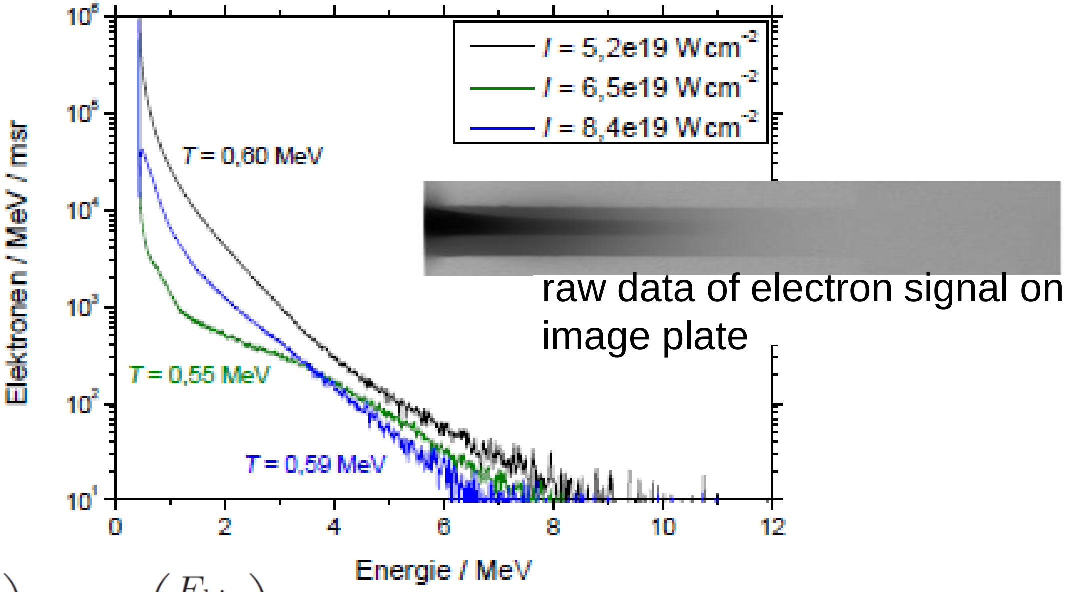
DUT's: Optocouplers
on Al foil



Measured electron spectra: Tuning of spectrum via laser intensity to GEO levels

$$T_{\mathrm{eff}} \propto (I\lambda^2)^{\zeta}$$



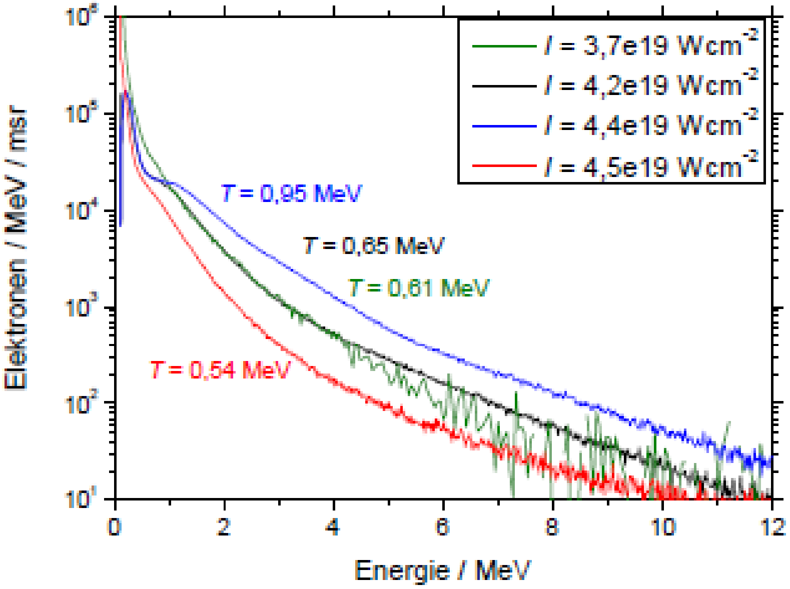


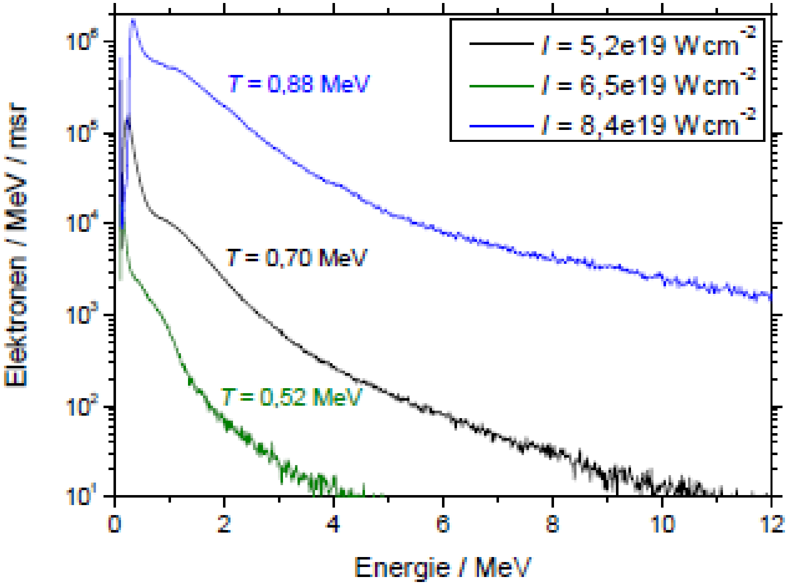
raw data of electron signal on image plate

(a)

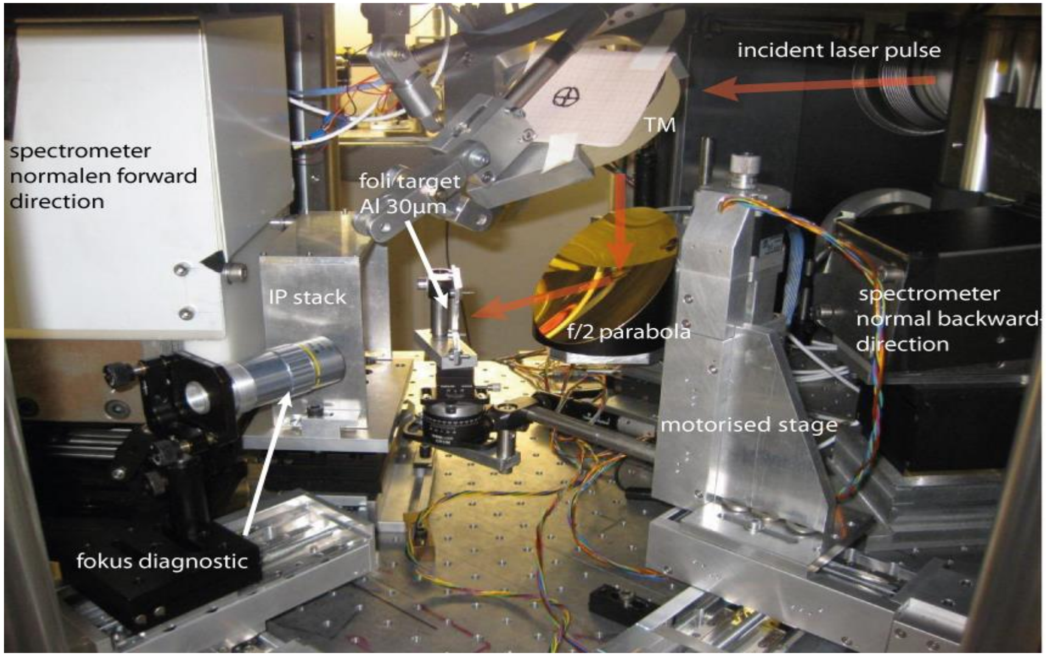
$$N \propto \exp\left(\frac{E_{\mathrm{kin}}}{k_B T}\right) = \exp\left(\frac{E_{\mathrm{kin}}}{T_{\mathrm{eff}}}\right)$$

(b)





Ti:Sapphire: *Proof-of-concept runs w/ 150 TW Arcturus laser at University Düsseldorf (electrons mainly, via laser-solid interaction) and at VULCAN PW (protons)*



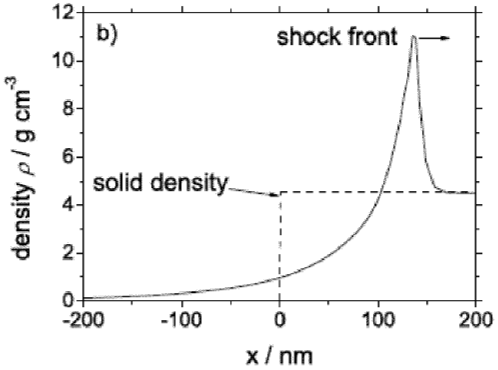
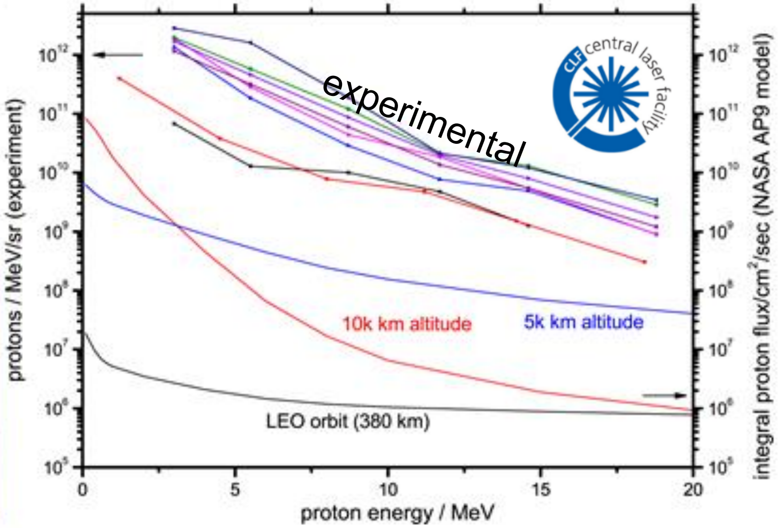
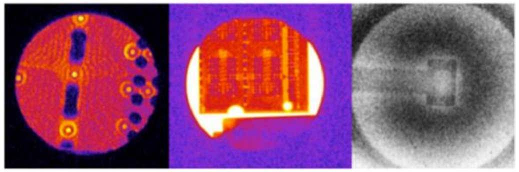


FIG. 4B



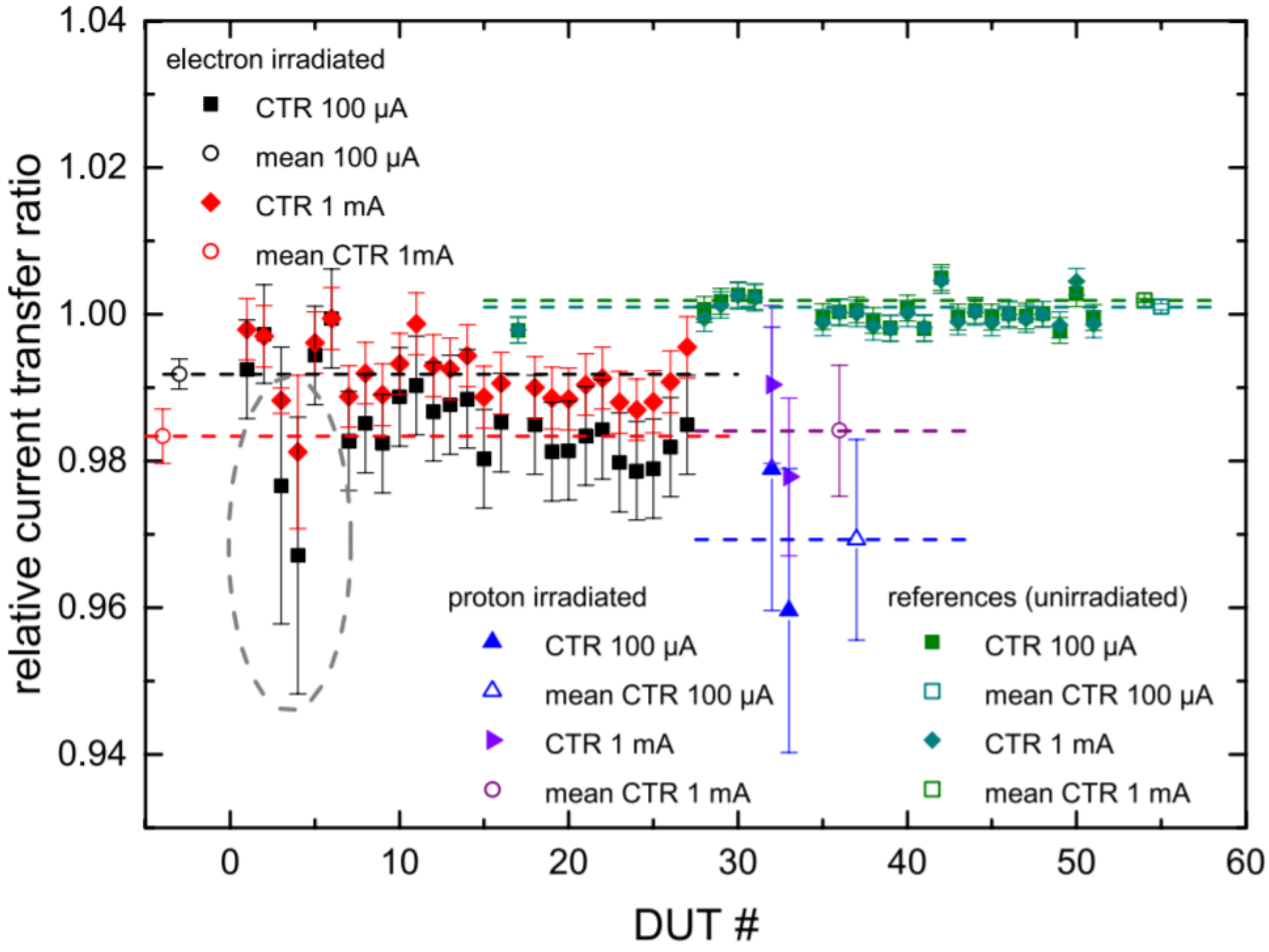


other electronics with Strathclyde per gamma rays

SCAPA

Proof-of-concept studies and experimental results

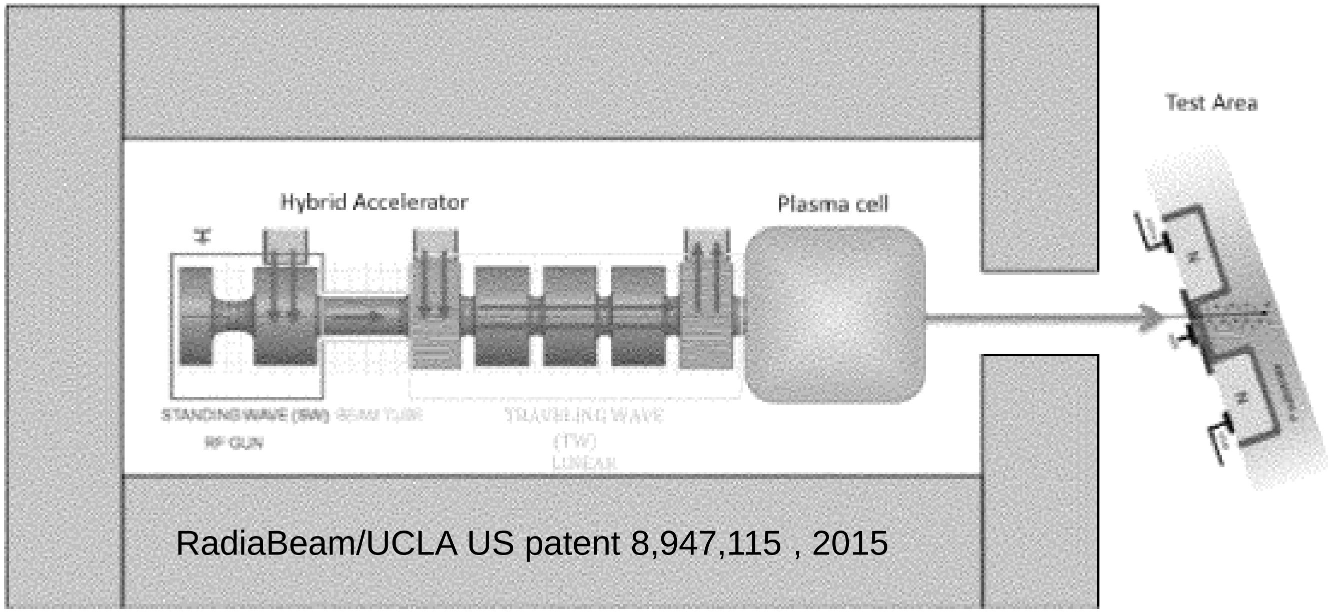
Degradation of optocoupler performance: Current Transfer Ratio (CTR)



Laser-plasma-based Space Radiation Reproduction in the Laboratory, Sci. Reports 7: 42354 (2017)

Space radiation from PWFA-style systems

Linac – PWFA driven: Earth radiation belt



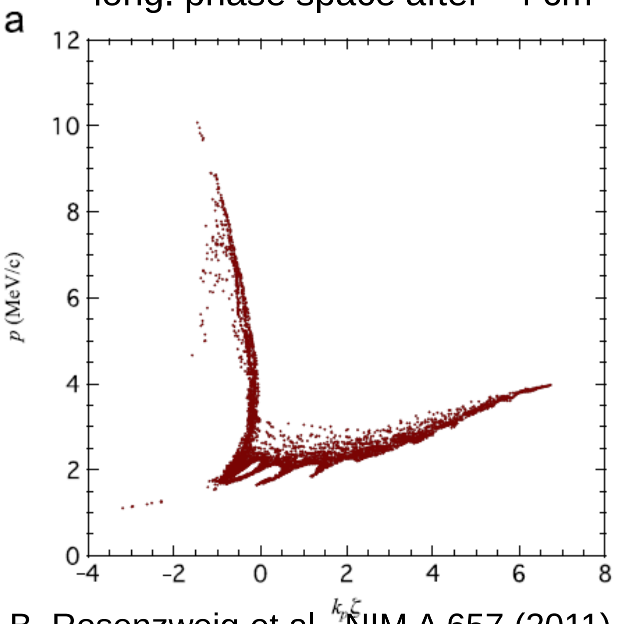
RadiaBeam/UCLA US patent 8,947,115 , 2015

PWFA in blowout regime, $n_b>n_0$

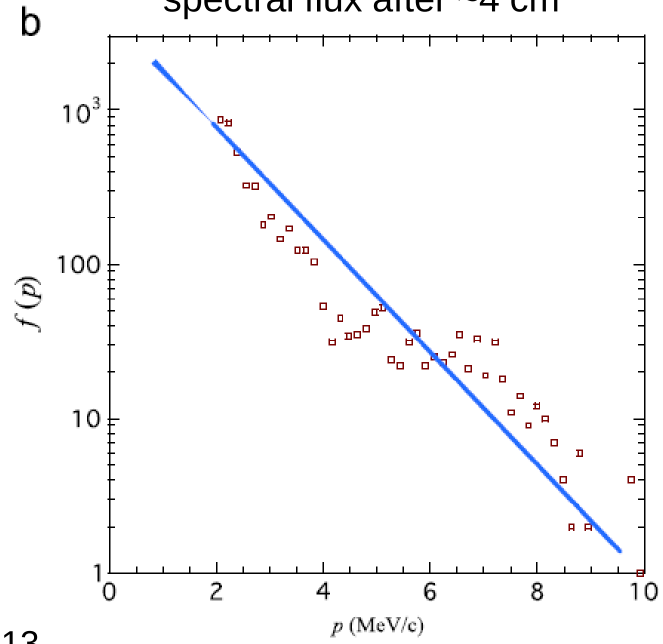
σ_z ~ 2 ps, n_0~ 10^{14} cm^{-3}

Tail decelerates

long. phase space after ~4 cm



spectral flux after ~4 cm

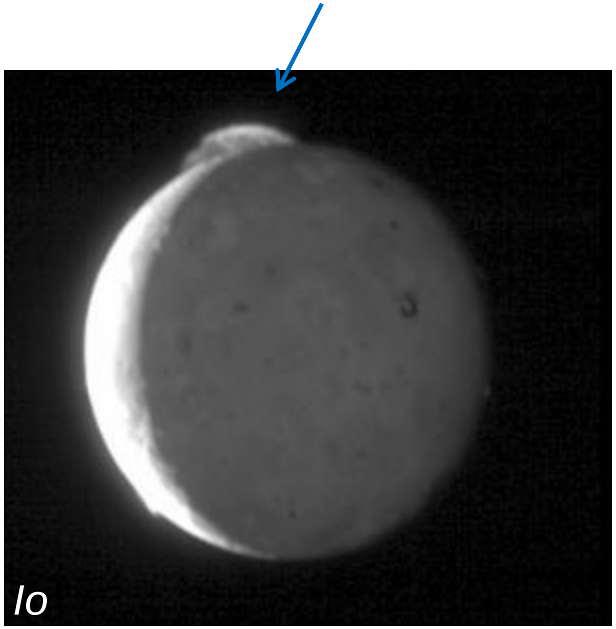


- Good fit for killer electrons in radiation belts of Earth
- E.g. linacs such as CLARA/UK, SPARC/Italy, CTF3/CERN…

J. B. Rosenzweig et al., NIM A 657 (2011), 107-113

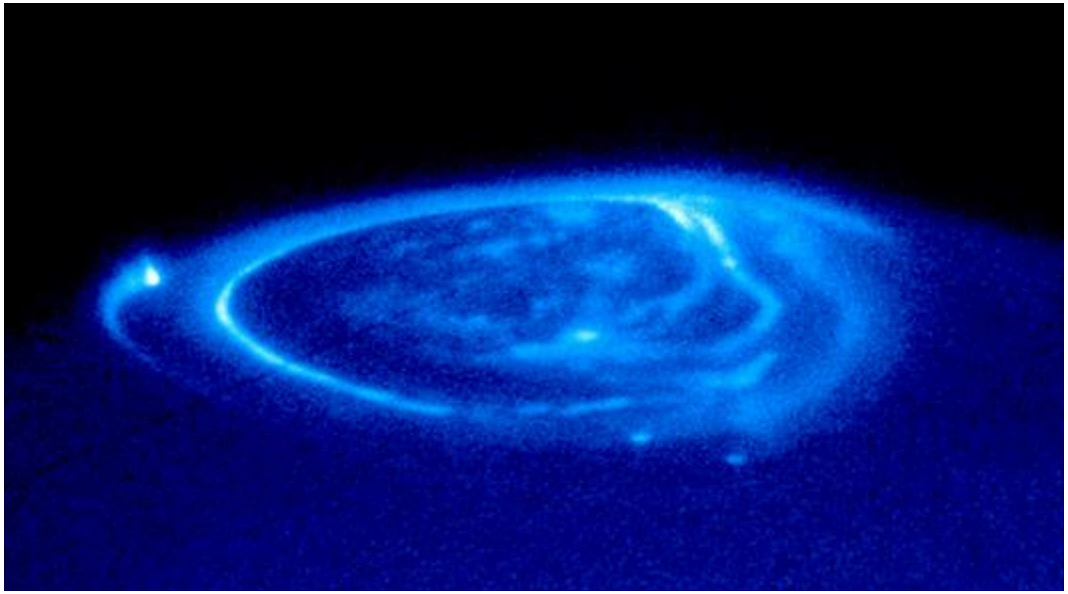
Nature is producing the exponential flux similar as we do in the lab!

volcanic mass ejection



"the gas jet"

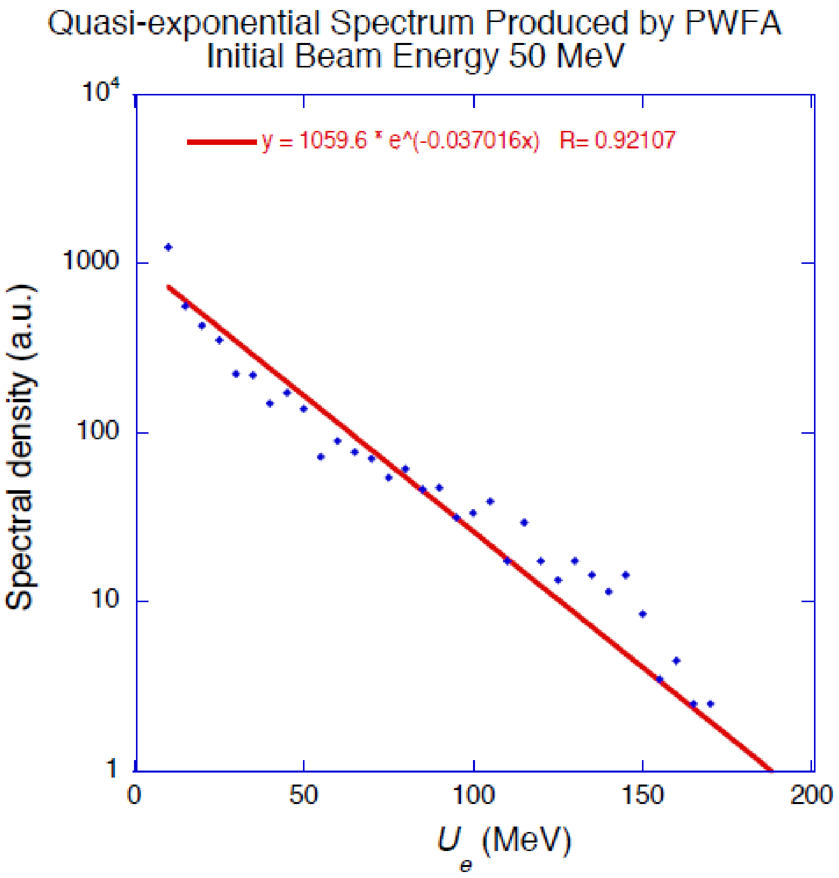
sunlight and impact ionization produces Jovian aurora

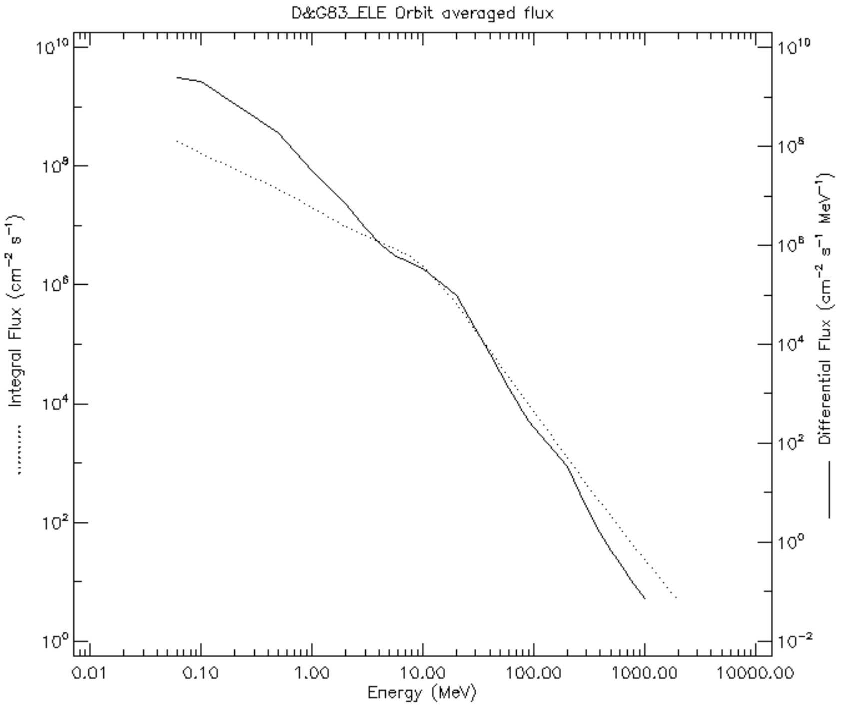


"the laser/linac plasma source"

then the gyromagnetic interaction in the Jovian magnetic fields accelerates the electrons..

Linac – PWFA driven; Jovian missions (ESA JUICE, NASA)





Integral and differential **electron** flux calculated with SPENVIS based on JOSE, avgd. 10 circ. orbits at a dístance of 14 Rj.

- Jovian electron flux is orders of magnitude more intense than in Earth radiation belts
- Jovian proton flux ~ 2 orders of magnitude less than electrons

Space rad designer flux: combine different exponential spectra

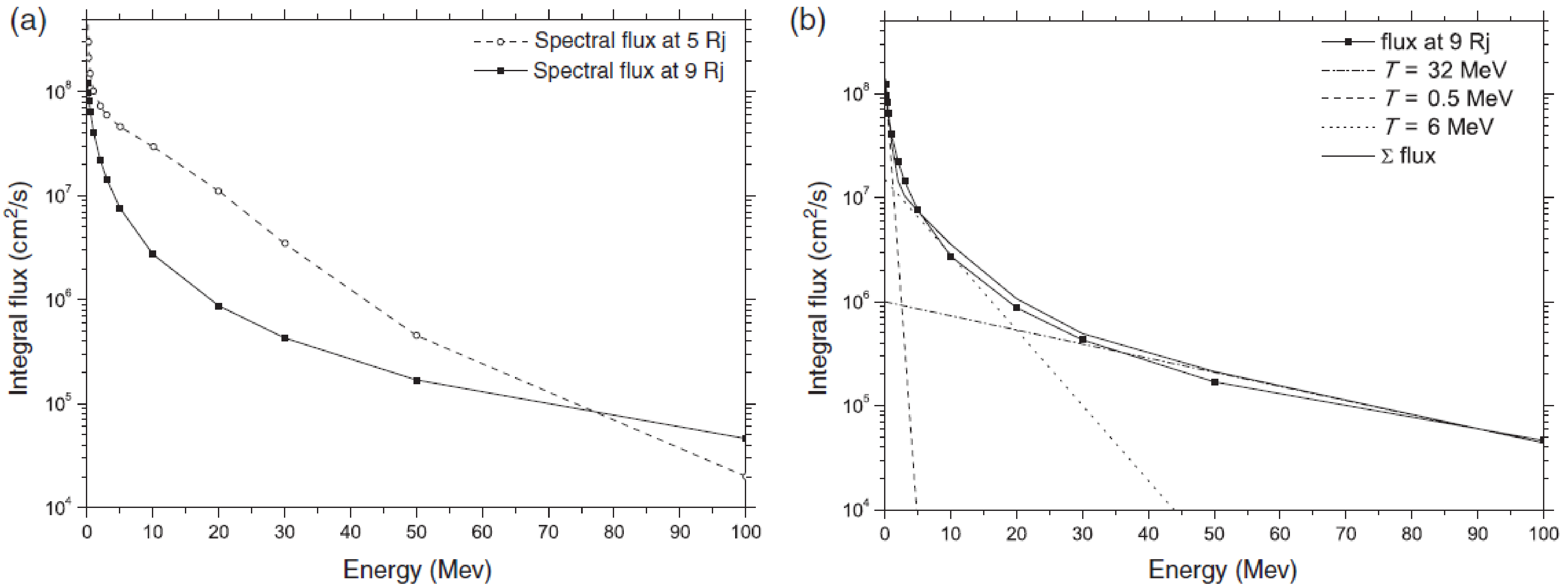
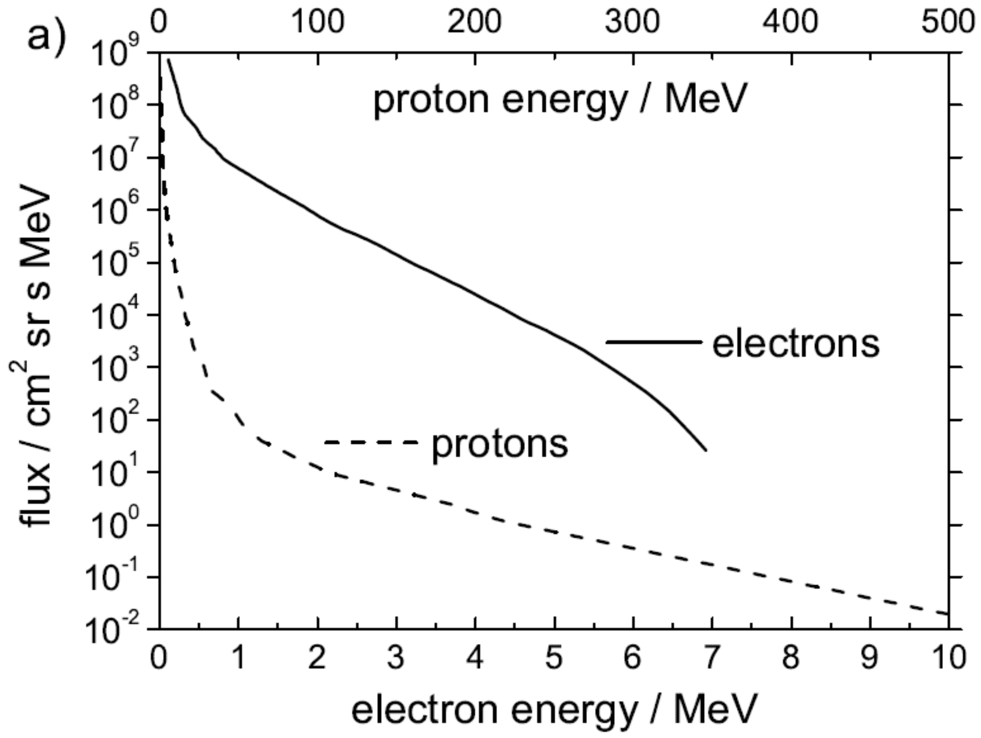


Figure 6. Spectral flux in Jupiter's radiation belt. (a) Flux at a distance of 5 R_J and 9 R_J, (b) overlaying three exponential spectra can reproduce with high accuracy the flux expected at 9 R_J.

General considerations:

- electron energies ~order of magnitude lower than proton energies e.g. in Earth rad belts
- electron flux e.g. in Earth rad belts exceeds proton flux by orders of magnitude
- rad. damage by protons/ions much higher than by electrons;



← electron and proton flux on KuaFu-B satellite orbit per NASA AE8/AP8 model

Protons of few MeV energies are getting increasingly important especially for sub-45 nm technology (secondaries)

Extremely high flux on target surface, when close to the target

Then massive flux reduction because of a) divergence of beam, b) time-of-flight differences

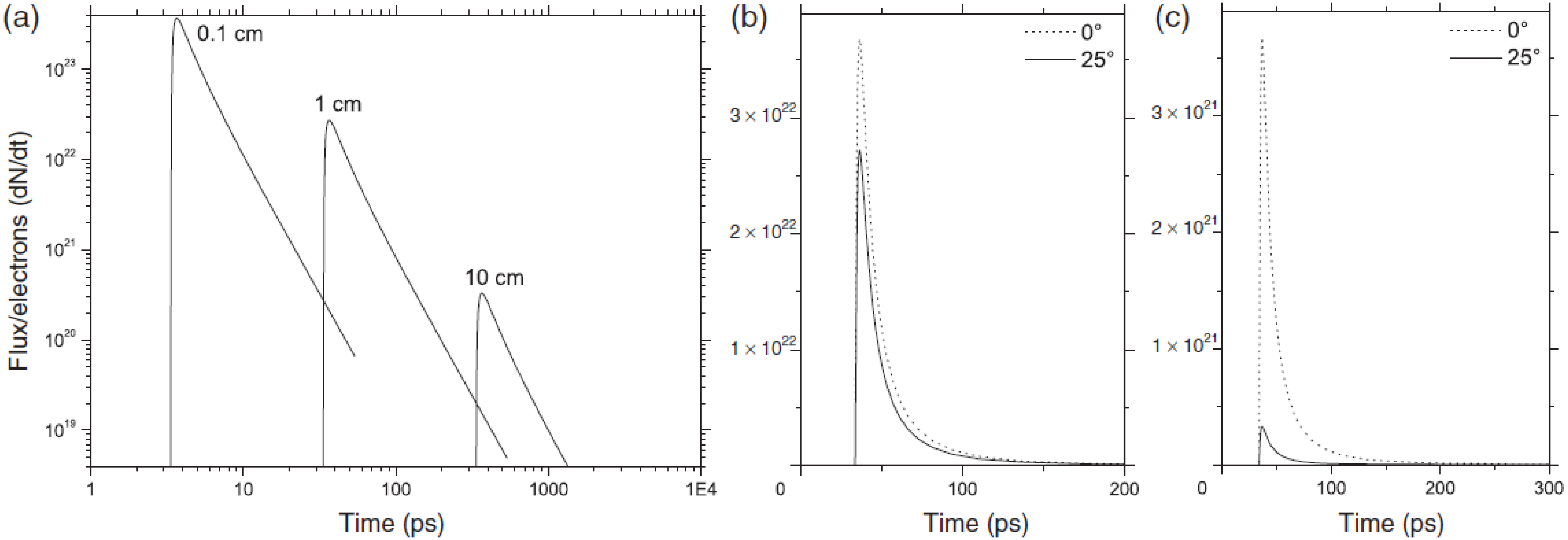
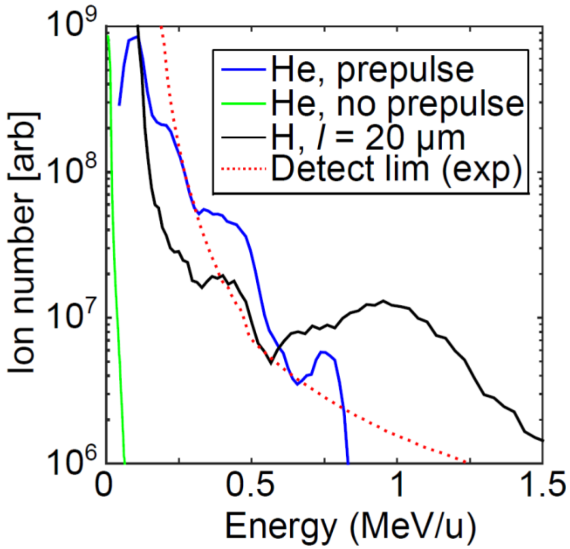


Figure 5. Reduction of exponential-energy electron flux due to energy-dependent velocities and divergence. In (a), the flux of a beam with $T_{\text{eff}} = 0.35\,\text{MeV}$, $Q = 100\,\text{nC}$, and a divergence $\theta = 25^\circ$ through a DUT area of $1\,\text{cm}^2$ is calculated at distances 0.1, 1, and 10 cm behind target (note the logarithmic scaling). Next, the influence of the divergence is visualized by plotting the flux through $1\,\text{cm}^2$ after a distance 1 cm (b) and 10 cm (c) for the beam with parameters as in (a), but for a hypothetical divergence of $\theta = 0^\circ$ and 25°.

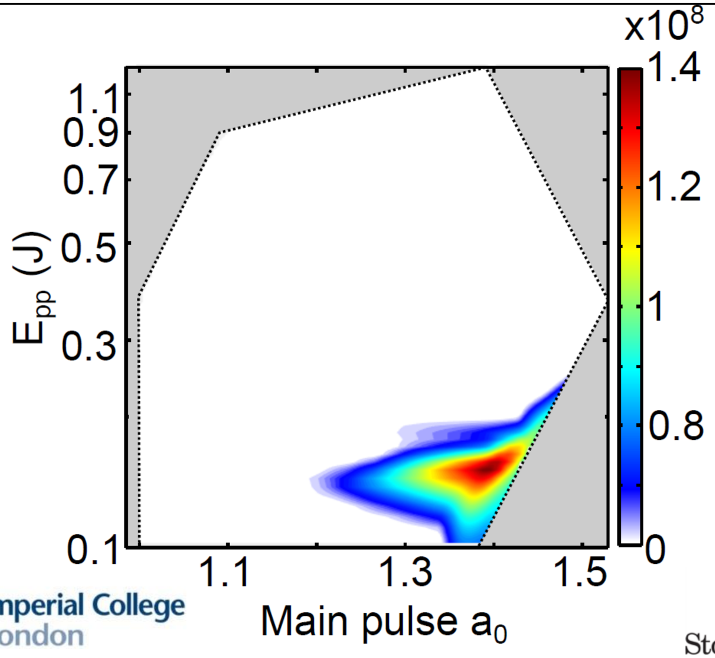
Space radiation from CO2-laser systems

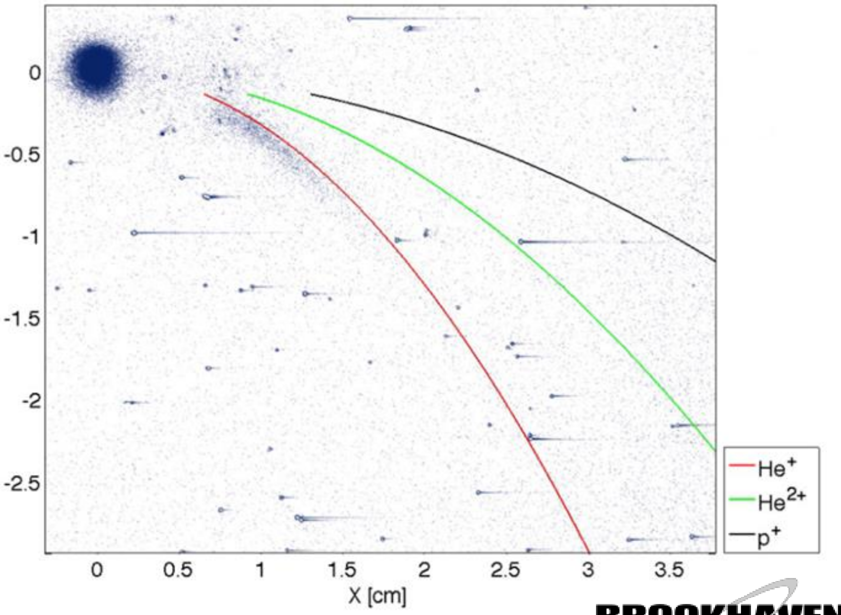
Reproducible ion acceleration with 10 μm CO_2

- At BNL ATF, observed production of MeV proton and helium beams via collisionless shock acceleration
- Optical shaping of targets using controlled pre-pulse provides means to reproducible ion beams



Recently Published: O. Tresca, N. P. Dover, N. Cook, C. Maharjan, M. N. Polyanskiy, Z. Najmudin, P. Shkolnikov, and I. Pogorelsky. Phys. Rev. Lett. **115**, 094802 (2015).





JAI John Adams Institute for Accelerator Science

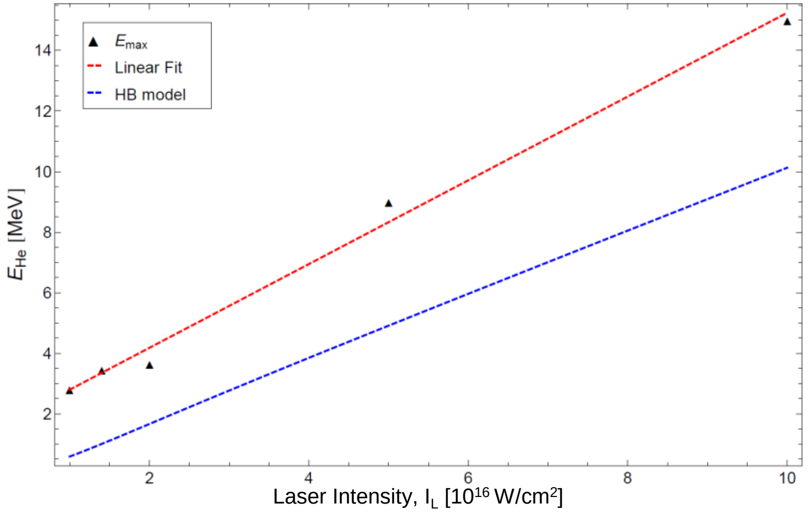
Imperial College London

Stony Brook University

BROOKHAVEN NATIONAL LABORATORY

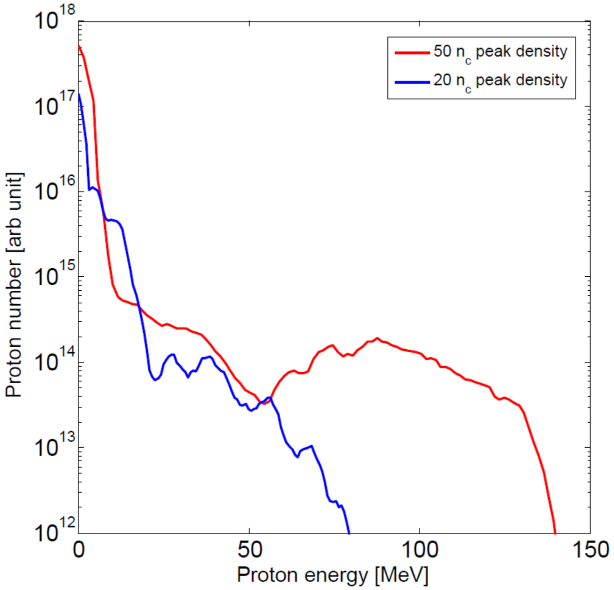
Efficient scaling of acceleration with laser intensity

- Collisionless shock acceleration exhibits strong scaling with laser energy, $E_{ion} \sim I_L/n_e$
  - Peak energies exceed those predicted by hole-boring RPA models



Simulations performed using EPOCH in 2D. Images courtesy N. Cook and O. Tresca.

- ATF-II projects 100 TW peak intensities, $a_0 \approx 10$ - **protons energies > 140 MeV at full power are possible!**
  - Variation with peak target density, thickness, and laser parameters requires further consideration



Work supported by U.S. DOE Contract No. DE-AC02-98CH10886, U.S. DOE Grant No. DE-FG02-07ER41488, UK EPSRC Grant No. EP/K022415/1, and BNL/LDRD Grant No. 12-032.

Potential and future development of the scheme

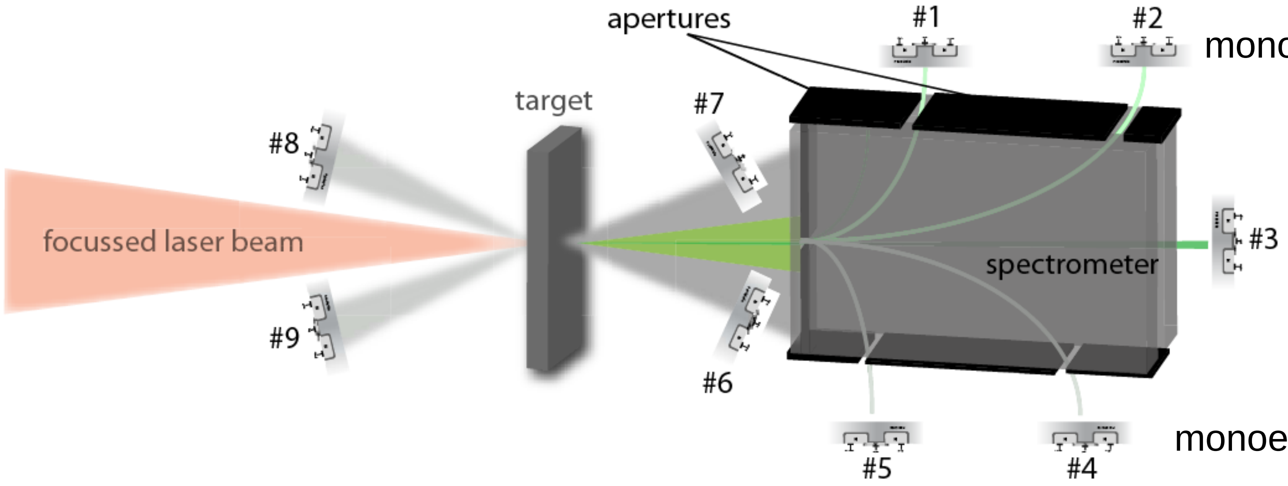
Potential and future development of the scheme

Irradiation times, assuming daily fluence on Nav-orbit: 3 x 10^{12} cm^{-2}:

6.5 hrs	w/ LINAC @ 1.3 x 10^{8} $cm^{-2}s^{-1}$
3.9 hrs	w/ laser-plasma-accelerator @ 2.1 x 10^{7} cm^{-2} per shot at 10 Hz rep rate (today's standard)
140 sec	w/ laser-plasma-accelerator @ 2.1 x 10^{7} cm^{-2} per shot at 1 kHz rep rate (avantgarde but existing and already used laser systems, e.g. Schmid et al., PRL 2009). Requires tape drive targets / droplets / gas jets.
1.4 sec	w/ laser-plasma-accelerator @ 2.1 x 10^{7} cm^{-2} per shot at 100 kHz rep rate (appearing on the horizon, especially efficient fiber and thin disc lasers. Remark: Theoretical value, limiting factors: vacuum system & too high peak flux)

Using the full solid angle of radiation for testing:

Laser development requirements synergistic with EuPRAXIA



monoenergetic electrons

monoenergetic protons, ions

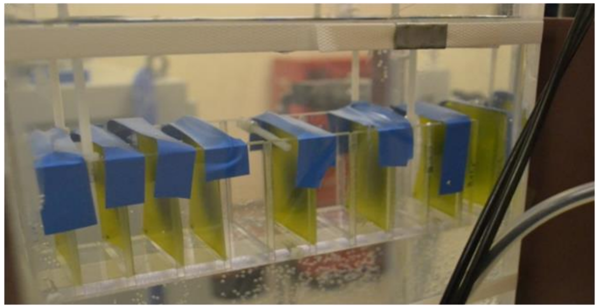
Options for (space) radiobiology

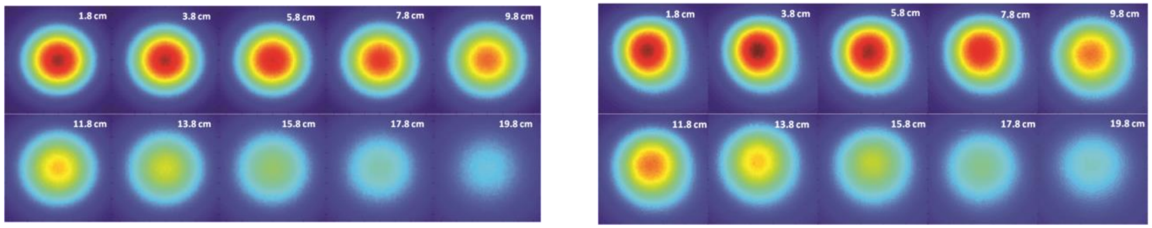
SUPA Physics Scotland

SCAPA

University of Strathclyde Glasgow

- Radiobiology: VHEE (very high energy electrons) dosimetry, D. *Jaroszynski et al Phys. Med. Biol.*



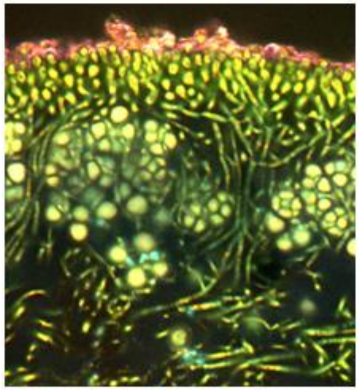


dose mapping measurement vs. calculation for 135 MeV
LWFA-generated electrons in water phantom

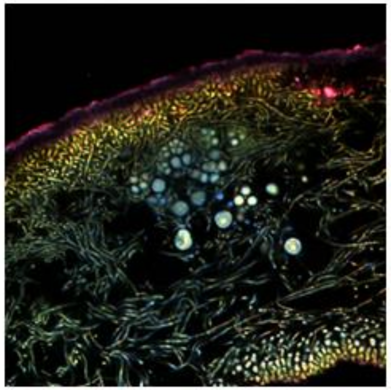
funded by
Science & Technology
Facilities Council

- Düsseldorf w/ kHz laser:

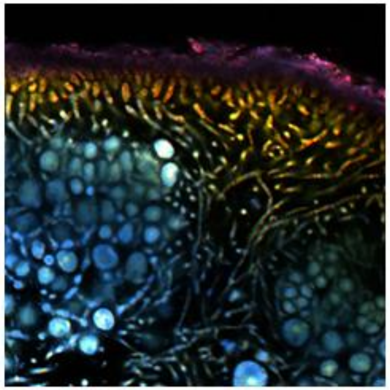
Xanthoria elegans (Flechte)



control sample
CLSM photos
(confocal laser scanning microscope)



sample after 360 sec.



sample after 480 sec.

I. Halezki, F. Gaußmann et al.

Potential for dedicated RHA beamline

Scottish Centre for the Application of Plasma-based Accelerators

- Collaborative research opportunity for Glasgow & Scotland, the UK and beyond
- ~£10M investment + additional infrastructure funds (SFC, SUPA, UoS..)
- Accelerator and Light Source R&D
- Strong engagement in European and other large projects
- In-depth programme of **applications, knowledge exchange & commercialization**

- 3 high-power laser systems, initially up to 350 TW
- 3 shielded radiation caves, fully vibration-isolated, w/ 2000 tons of concrete shielding
- up to 7 accelerator application beam lines
- ~1200 m^2 on two levels
- High-energy particle beams: electrons, protons, ions, positrons, neutrons
- High-energy photon beams: fs duration, (coherent) VUV, X-ray & gamma-rays

Summary & Outlook

- Plasma accelerators inherent ability to produce broadband, “exponential” beams is a highly desirable feature for space rad reproduction & testing
- Ti:Sapphire, CO2 and linac driven plasma acceleration useful
- High fluence is desirable (test over full life cycle of satellite)?
- Laser development (especially high rep rate) desirable
- Ti:Sapphire: over- and underdense interaction possible, both electrons and protons (e.g. TNSA). In laser-solid interaction, nC per shot possible, but rep rate limited. Near-future few-TW Ti:Sapphire lasers and underdense interaction may allow for kHz output at Earth radiation belt scale energies (up to 10 MeV). Jovian energy levels (up t0 150 MeV) accessible with 10-100 TW lasers.
- Linac: electrons (both Earth and Jovian). Longer term towards application: High rep rates possible, nC per shot & large fluence
- Develop test standard together with National Physical Laboratory, CLF and CI
- Further tests with active electronics
- Space radiobiology tests

- Develop European R&D programme jointly with ESA and other partners (e.g. H2020)

Literature

- B. Hidding, T. Königstein, O. Willi, G. Pretzler. Method for testing the radiation hardness of electronic devices with particle and photon beams generated by laser-plasma-interaction.German Patent AZ 10 2010 010 716.6, March 2010. Filed on March 8, 2011 as extended United States patent in collaboration with RadiaBeam Technologies, Santa Monica, Method for testing electronic components, Serial No. 13/042,738

- Laser-plasma-accelerators -- A novel, versatile tool for space radiation studies, B. Hidding, T. Königstein, O. Willi, J.B. Rosenzweig, K. Nakajima, and G. Pretzler. Nucl. Instr. Meth. A, Vol. 636, 1, 2011.

- Design and applications of an X-band hybrid photoinjector, J.B. Rosenzweig, A. Valloni, D. Alesini, G. Andonian, N. Bernard, L. Faillace, L. Ficcadenti, A. Fukusawa, B. Hidding, M. Migliorati, A. Mostacci, P. Musumeci, B. O'Shea, L. Palumbo, B. Spataro and A. Yakub, Nuclear Instruments and Methods in Physics A, 657, 1, pp. 107-113, 2011.

- Design considerations for the use of laser-plasma accelerators for advanced space radiation studies, T Königstein, O. Karger, G. Pretzler, J. B. Rosenzweig, B. Hidding, Journal of Plasma Physics, Volume 78 / Special Issue 04 / August 2012, pp 383-391

- ESA NPI project “Study of Space Radiation Effects with Laser-Plasma-Accelerators” final report, 2014

- ESA GSP project “Laser-Plasma-Accelerator’s Potential to Radically Transform Space Radiation Testing”, 2014

- Proof-of-concept Ti:Sapphire laser experiment, Sci. Reports 2017