SPACE TRANSPORTATION

MEMS Radiation Testing Guidelines

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All the space you need

EADS astrium

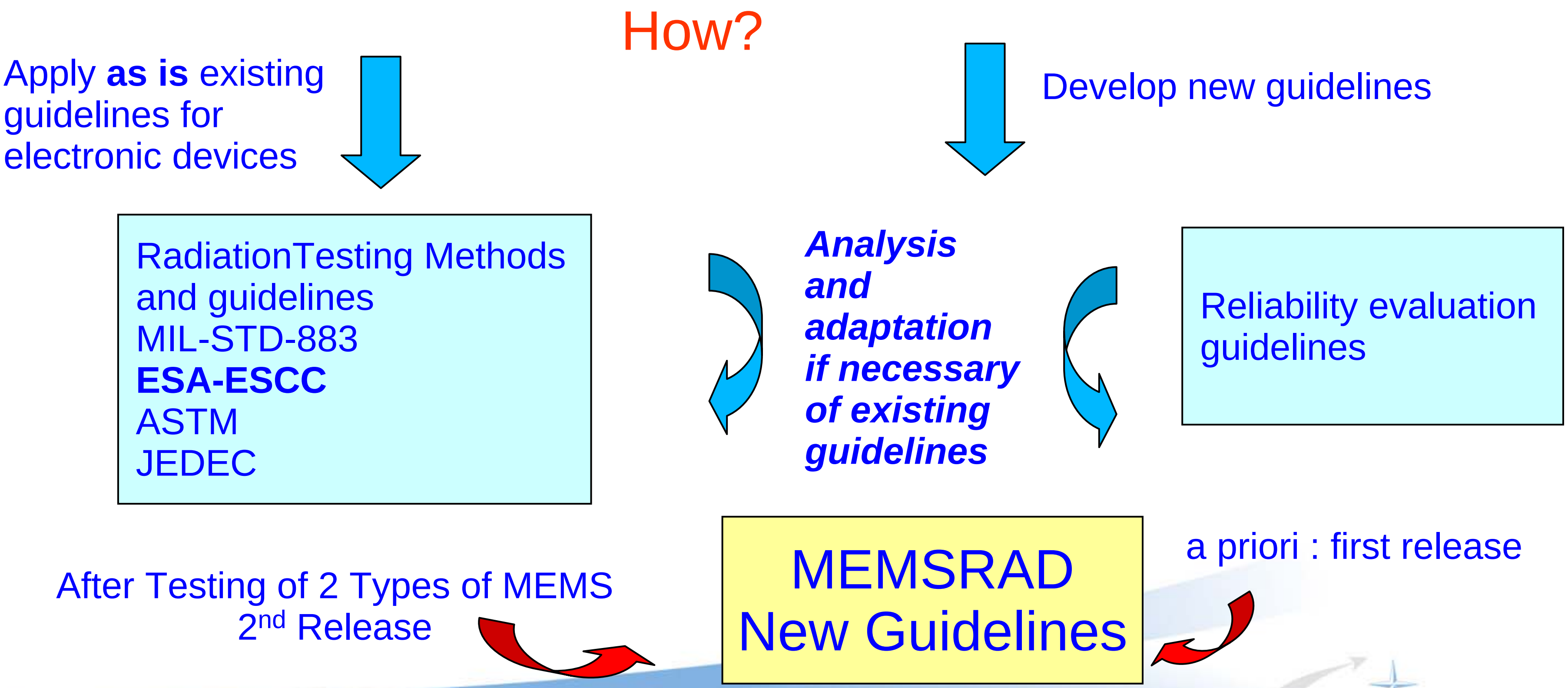
Radiation Testing Guidelines for MEMS

- Introduction:Purpose of this work and methodology
- From space environment to ground level testing
- Radiation Testing Standards
- Specificity of MEMS
- Discussion

General

- Purpose of this work
  - *Prepare guidelines for Radiation Testing of MEMS*
  - *Help to perform characterization of MEMS and obtain meaningful results.*
  - *Allow different labs to share and compare results obtained with a common testing procedure.*
- Methodology
  - Analysis of existing Radiation Testing Guidelines and Methods
  - Identification and Classification of MEMS
  - Identify important points to adapt or modify the guidelines
    - a priori
    - after performing tests on MEMS
  - Consider other Guidelines applied to MEMS:
    - Reliability evaluation
    - Specific testing methods related to the specific function

Statement:
To work correctly in space applications,
MEMS must be qualified
to Space Radiation Environment Specifications.



How?

Apply **as is** existing guidelines for electronic devices

Develop new guidelines

RadiationTesting Methods and guidelines
MIL-STD-883
ESA-ESCC
ASTM
JEDEC

Analysis and adaptation if necessary of existing guidelines

Reliability evaluation guidelines

After Testing of 2 Types of MEMS
2nd Release

MEMSRAD
New Guidelines

a priori : first release

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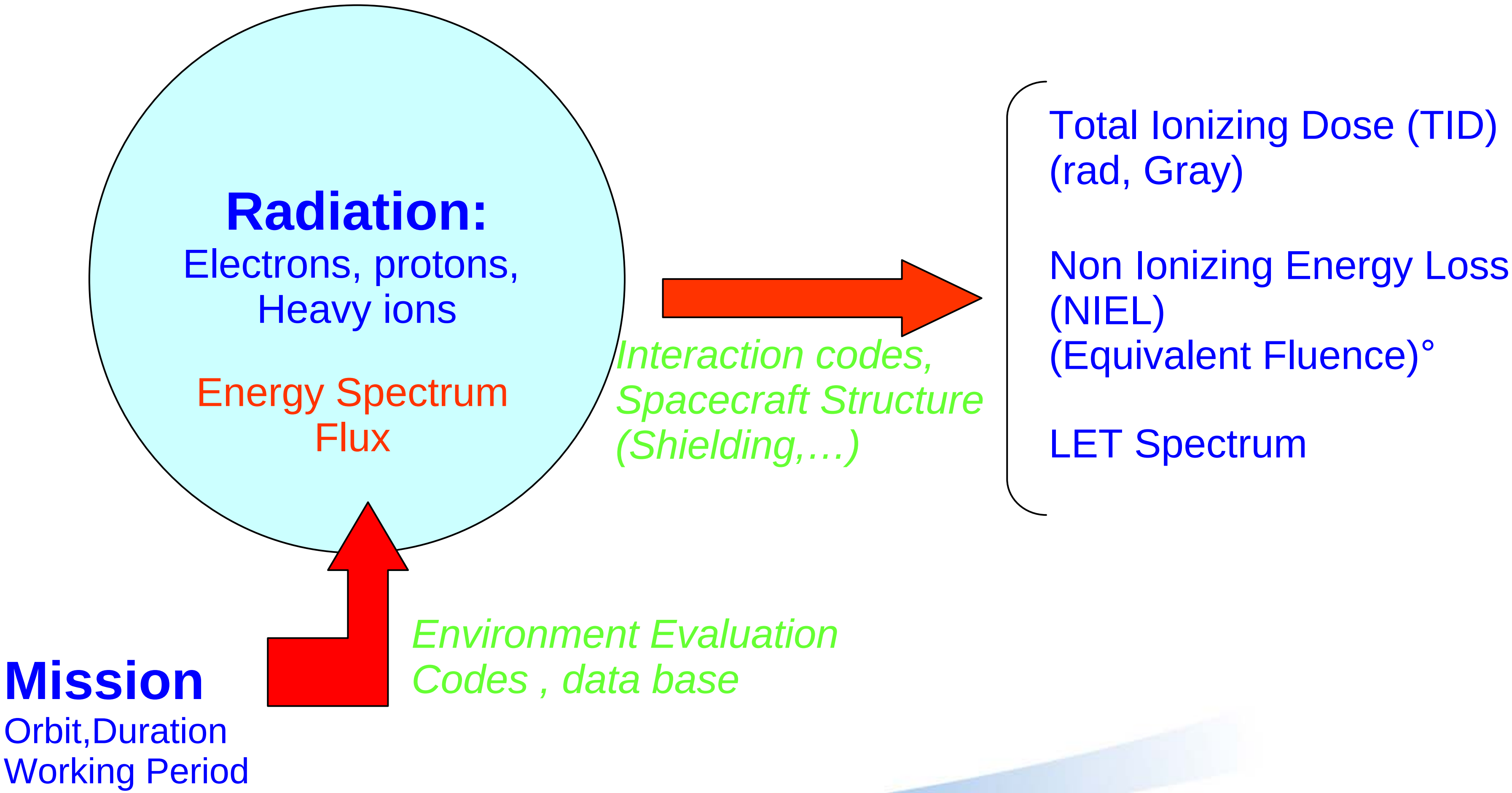
Space Environment and Ground Level Simulation (1)



Radiation:
Electrons, protons,
Heavy ions

Energy Spectrum
Flux

Interaction codes,
Spacecraft Structure
(Shielding,…)

Total Ionizing Dose (TID)
(rad, Gray)

Non Ionizing Energy Loss
(NIEL)
(Equivalent Fluence)°

LET Spectrum

Environment Evaluation
Codes , data base

Mission
Orbit,Duration
Working Period

Space Environment and Ground Level Simulation (2)

Specifications

Radiation Facilities?

Availability, Cost, Test Validity

Specifications		Radiation Facilities
Total Ionizing Dose (TID) (rad, Gray)	⇨	**Co^{60} γ Rays**, electrons, protons
Non Ionizing Energy Loss (NIEL) (Equivalent Fluence)°	⇨	**Protons**, neutrons
LET Spectrum	⇨	**Heavy Ions,** pulsed and focused Laser

How to Proceed?

Radiation Testing Standards and Guidelines

Standards and Guidelines

- Content
  - Facilities:
    - Simulation of effects, not environment
    - Dosimetry
  - Test Plan: « What we want to do »
    - Number of devices, parameters, irradiation level (dose, fluence, ….),
    - Configuration under irradiation,
    - On line or remote measurements…
  - Test Procedures: How to realise the Test Plan
    - Establish **good engineering methods** (cabling, measurement,
    - Selection of components to be tested
  - Test report: Allow to compare and reproduce experiment
    - What was tested?
    - How it was tested
    - What was obtained

Radiation Testing Guidelines: Facilities

TID

Co60

Dose rate available
Dose uniformity
Dosimetry and calibration
Volume available for irradiation
Connectors, cabling,..

Protons

Energy
Beam current,
temporal structure
Beam area,
beam uniformity
Dosimetry
Collimators
……..

Heavy ions

LET values
HI Ranges*,
Energy (MeV/amu)
Flux range (minimum-maximum)
Vacuum chamber
(volume, orientation, connectors)
Time to change ion species

ESA Sponsored Facilities

ESTEC Co60 source

UCL
PSI

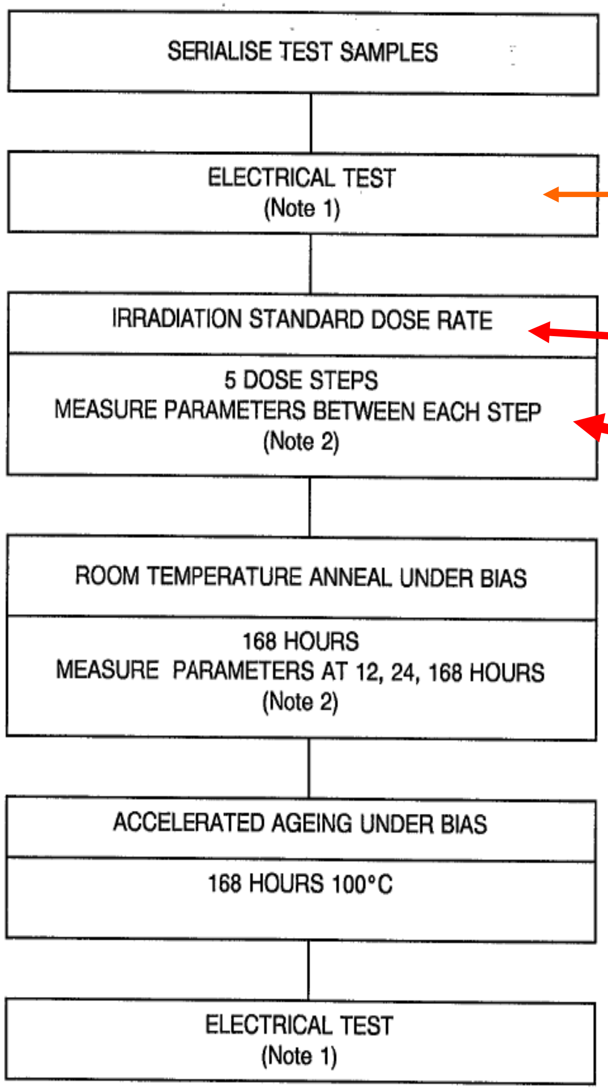
UCL
Jyvaskyla

Radiation Testing Standards: TID

Standard	MIL-STD 883E **Method 1019**	ESA-ESCC 22900
Release date	1019.6 03/2003 1019.7 02/2006	Issue 2 08/ 2003
Radiation source	Co60	Co60
Uniformity	+-10%	+-5%
Intensity	+-5%	+-5%
Dose rate (rad/s)		Window1: 1-10 Window2: 1 E-2 -1 E-1 Total irradiation time <96h
Dosimetry	ASTM Standards or other appropriate standards	ESCC21500, traceability to national standards

TID Flow Chart
(from ESCC22900)

FIGURE I - FLOW CHART FOR EVALUATION TESTING



SERIALISE TEST SAMPLES

ELECTRICAL TEST
(Note 1)

IRRADIATION STANDARD DOSE RATE

5 DOSE STEPS
MEASURE PARAMETERS BETWEEN EACH STEP
(Note 2)

ROOM TEMPERATURE ANNEAL UNDER BIAS

168 HOURS
MEASURE PARAMETERS AT 12, 24, 168 HOURS
(Note 2)

ACCELERATED AGEING UNDER BIAS

168 HOURS 100°C

ELECTRICAL TEST
(Note 1)

And mechanical

Try different dose rates

Electrical and Mechanical
Conditions under irradiation

TID: On Line and Off-Line measurements

ON LINE

Advantages

Follow the degradation

Check correct bias, functionality

Drawback:

Restricted conditions

Limited parameters

Complexity of experiment

REMOTE or OFF LINE

Advantages

Detailed characterization

Different bias and input conditions

Drawback:

Need removal from facility

Timing (annealing, rebound)

Discrete dose values

Mix ON-LINE and Remote measurements

Parameters to be measured and how to measure them

- Closely related to the function
  - (IMU, accelerometers, RF Mems, pressure sensors)
- In accordance to data sheet
- In accordance to standards
- MEMS are systems:
  - electrical and mechanical variables
  - Feedback
  - Global testing
- MEMS are **micro**-systems
  - Special apparatus and techniques (microscopy, interferometry,….)

Application: Accelerometers

- Zero offset
- Linearity
- Maximum range
- Dynamic response as a function of frequency
- Out of axis sensitivity
- Apparatus needed:
  - Obtain the acceleration (rotating table ,..)
  - Vibration
  - Electronic apparatus (power supply, scopes, …..)

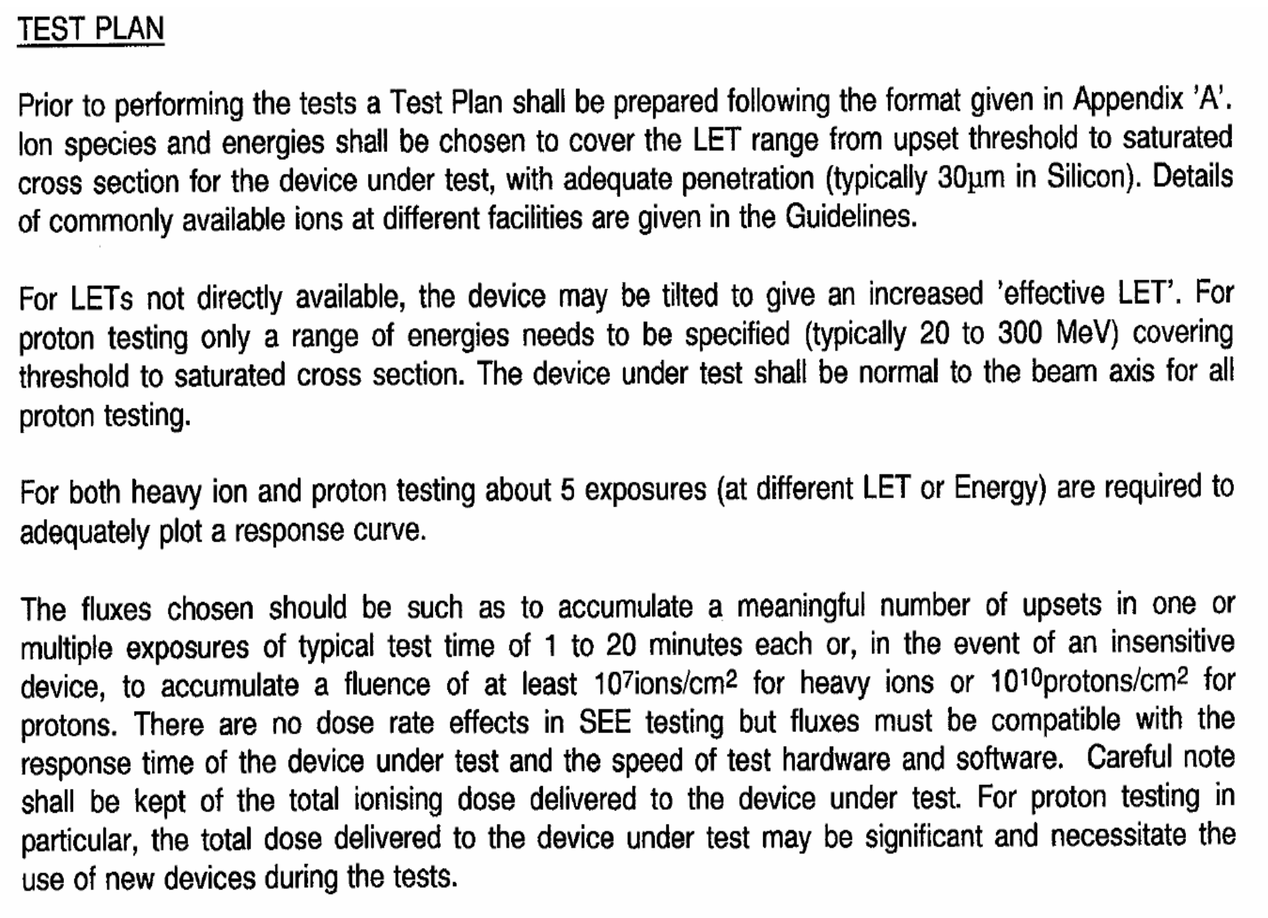
Application: RF MEMS

- Activation levels, Hysteresis curve
- S parameters: On and Off
- Switching speed
- Apparatus:
    - Signal generators,
    - Network analysers
    - Microscopes, Interferometry

Single event EffectsTesting

- Only electronic parts in the system are concerned?.
    - Accelerometers, IMU, sensors,
    - RF MEMS: probably not!
    - Dielectrics: breakdown?,
- Test of a system
    - Influence of the system state: (output voltage, temperature, feedback constant)
- ESCC25100 is used as a guide to establish guidelines on SEE testing on MEMS.

Single Event Effects: Test Plan from ESCC25100



TEST PLAN

Prior to performing the tests a Test Plan shall be prepared following the format given in Appendix 'A'. Ion species and energies shall be chosen to cover the LET range from upset threshold to saturated cross section for the device under test, with adequate penetration (typically 30µm in Silicon). Details of commonly available ions at different facilities are given in the Guidelines.

For LETs not directly available, the device may be tilted to give an increased 'effective LET'. For proton testing only a range of energies needs to be specified (typically 20 to 300 MeV) covering threshold to saturated cross section. The device under test shall be normal to the beam axis for all proton testing.

For both heavy ion and proton testing about 5 exposures (at different LET or Energy) are required to adequately plot a response curve.

The fluxes chosen should be such as to accumulate a meaningful number of upsets in one or multiple exposures of typical test time of 1 to 20 minutes each or, in the event of an insensitive device, to accumulate a fluence of at least 10^7ions/cm^2 for heavy ions or 10^{10}protons/cm^2 for protons. There are no dose rate effects in SEE testing but fluxes must be compatible with the response time of the device under test and the speed of test hardware and software. Careful note shall be kept of the total ionising dose delivered to the device under test. For proton testing in particular, the total dose delivered to the device under test may be significant and necessitate the use of new devices during the tests.

Conclusion

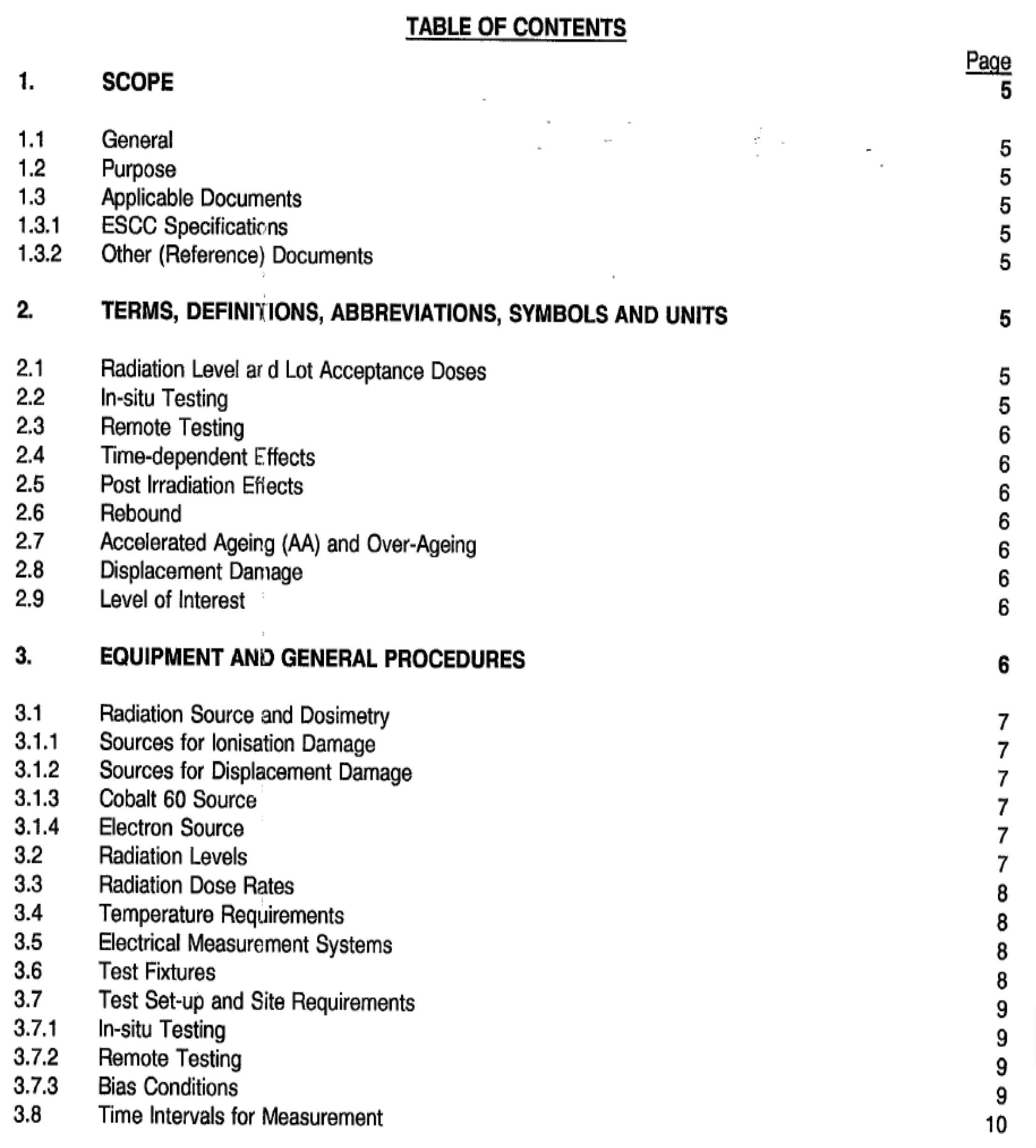
- Most of existing radiation testing guidelines for microelectronics can be applied « as is »
    - Facilities,
    - Test plan, Test reports

*MEMS designers and users (**MDU**) should contact Radiation Effects Testing Community (**RETC**)*

- Adaptations are necessary to take into account specificity of MEMS: mixed system of mechanical,(optical), electronic parameters
    - Measurement methods
    - Packaging limitations
    - Simulations of inputs to sensors
    - Worst case: Dose rate, bias, inputs, temperature
    - Heavy ions range

Exchanges between MDU and RETC and Brain Storming is a must

Back-up



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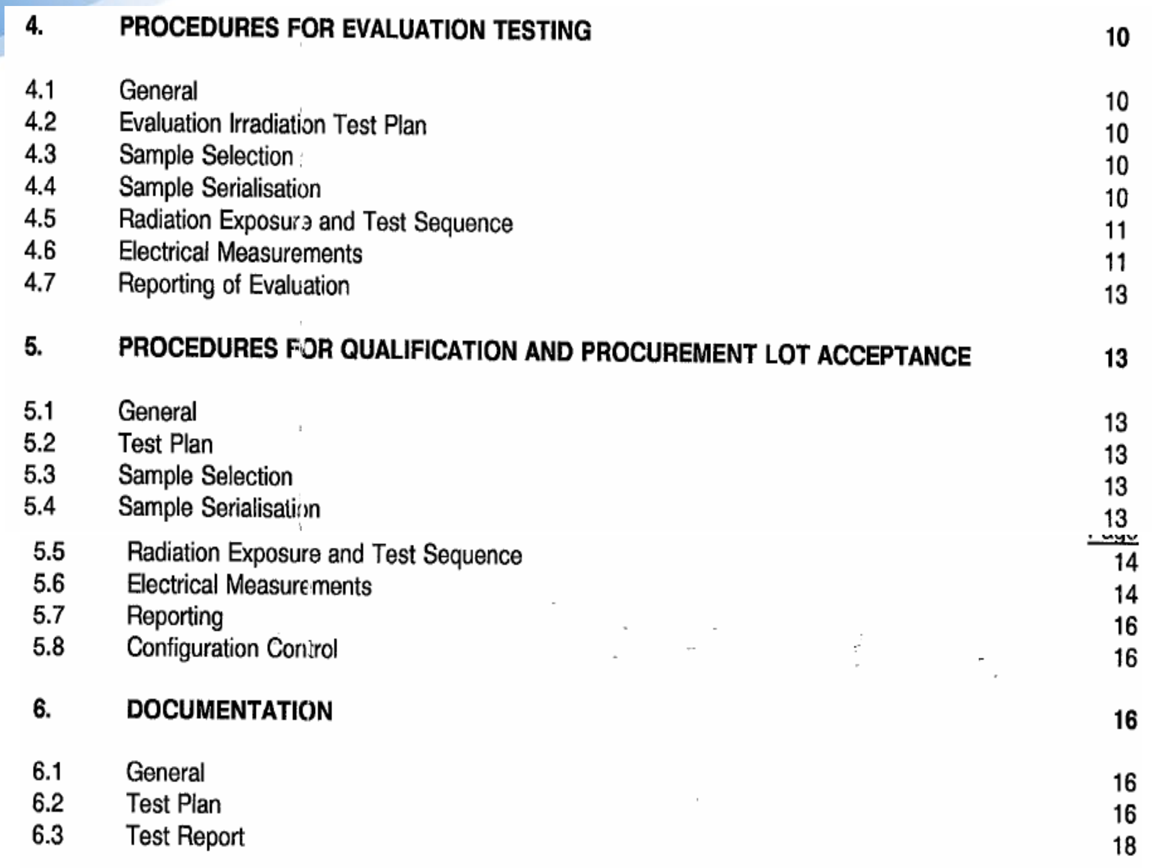

Testing Procedure

- 3. PROCEDURE. The test devices shall be irradiated and subjected to accelerated annealing testing (if required for time-dependent effects testing) as specified by a test plan. This plan shall specify the device description, irradiation conditions, device bias conditions, dosimetry system, operating conditions, measurement parameters and conditions, and accelerated annealing test conditions (if required).
- 3.1 Sample selection and handling. Only devices which have passed the electrical specifications as defined in the test plan shall be submitted to radiation testing. Unless otherwise specified, the test samples shall be randomly selected from the parent population and identically packaged. Each part shall be individually identifiable to enable pre- and post-irradiation comparison. For device types which are ESD-sensitive, proper handling techniques shall be used to prevent damage to the devices.

Burn-in prior to irradiation

- 3.2 Burn-in. For some devices, there are differences in the total dose radiation response before and after burn-in. Unless it has been shown by prior characterization or by design that burn-in has negligible effect (parameters remain within post-irradiation specified electrical limits) on the total dose radiation response, then one of the following must be done:
- 3.2.1 The manufacturer shall subject the radiation samples to the specified burn-in conditions prior to conducting total dose radiation testing or
- 3.2.2 The manufacturer shall develop a correction factor, (which is acceptable to the parties to the test) taking into account the changes in total dose response resulting from subjecting product to burn-in. The correction factor shall then be used to accept product for total dose response without subjecting the test samples to burn-in.

Test conditions

- 3.9 Test conditions. The use of in-flux or not in-flux testing shall be specified in the test plan. (This may depend on the intended application for which the data are being obtained.) The use of in-flux testing may help to avoid variations introduced by post-irradiation time dependent effects. However, errors may be incurred for the situation where a device is irradiated in-flux with static bias, but where the electrical testing conditions require the use of dynamic bias for a significant fraction of the total irradiation period. Not-in-flux testing generally allows for more comprehensive electrical testing, but can be misleading if significant post-irradiation time dependent effects occur.
- 3.9.1 In-flux testing. Each test device shall be checked for operation within specifications prior to being irradiated. After the entire system is in place for the in-flux radiation test, it shall be checked for proper interconnections, leakage (see 2.4), and noise level. To assure the proper operation and stability of the test setup, a control device with known parameter values shall be measured at all operational conditions called for in the test plan. This measurement shall be done either before the insertion of test devices or upon completion of the irradiation after removal of the test devices or both.
- 3.9.2 Remote testing. Unless otherwise specified, the bias shall be removed and the device leads placed in conductive foam (or similarly shorted) during transfer from the irradiation source to a remote tester and back again for further irradiation. This minimizes post-irradiation time dependent effects.
- 3.9.3 Bias and loading conditions. Bias conditions for test devices during irradiation or accelerated annealing shall be within ±10 percent of those specified by the test plan. The bias applied to the test devices shall be selected to produce the greatest radiation induced damage or the worst-case damage for the intended application, if known. While maximum voltage is often worst case some bipolar linear device parameters (e.g. input bias current or maximum output load current) exhibit more degradation with 0 V bias. The specified bias shall be maintained on each device in accordance with the test plan. Bias shall be checked immediately before and after irradiation. Care shall be taken in selecting the loading such that the rise in the junction temperature is minimized.

Test reports

- 3.14 Test report. As a minimum, the report shall include the device type number, serial number, the manufacturer, package type, controlling specification, date code, and any other identifying numbers given by the manufacturer.
- The bias circuit, parameter measurement circuits, the layout of the test apparatus with details of distances and materials used, and electrical noise and current leakage of the electrical measurement system for in-flux testing shall be reported using drawings or diagrams as appropriate.
- Each data sheet shall include the test date, the radiation source used, the bias conditions during irradiation, the ambient temperature around the devices during irradiation and electrical testing, the duration of each irradiation, the time between irradiation and the start of the electrical measurements, the duration of the electrical measurements and the time to the next irradiation when step irradiations are used, the irradiation dose rate, electrical test conditions, dosimetry system and procedures and the radiation test levels.
- The pre- and post-irradiation data shall be recorded for each part and retained with the parent population data in accordance with the requirements of MIL-PRF-38535 or MIL-PRF-38534. Any anomalous incidents during the test shall be fully documented and reported. The accelerated aging annealing procedure, if used, shall be described. Any other radiation test procedures or test data required for the delivery shall be specified in the device specification, drawing or purchase order.

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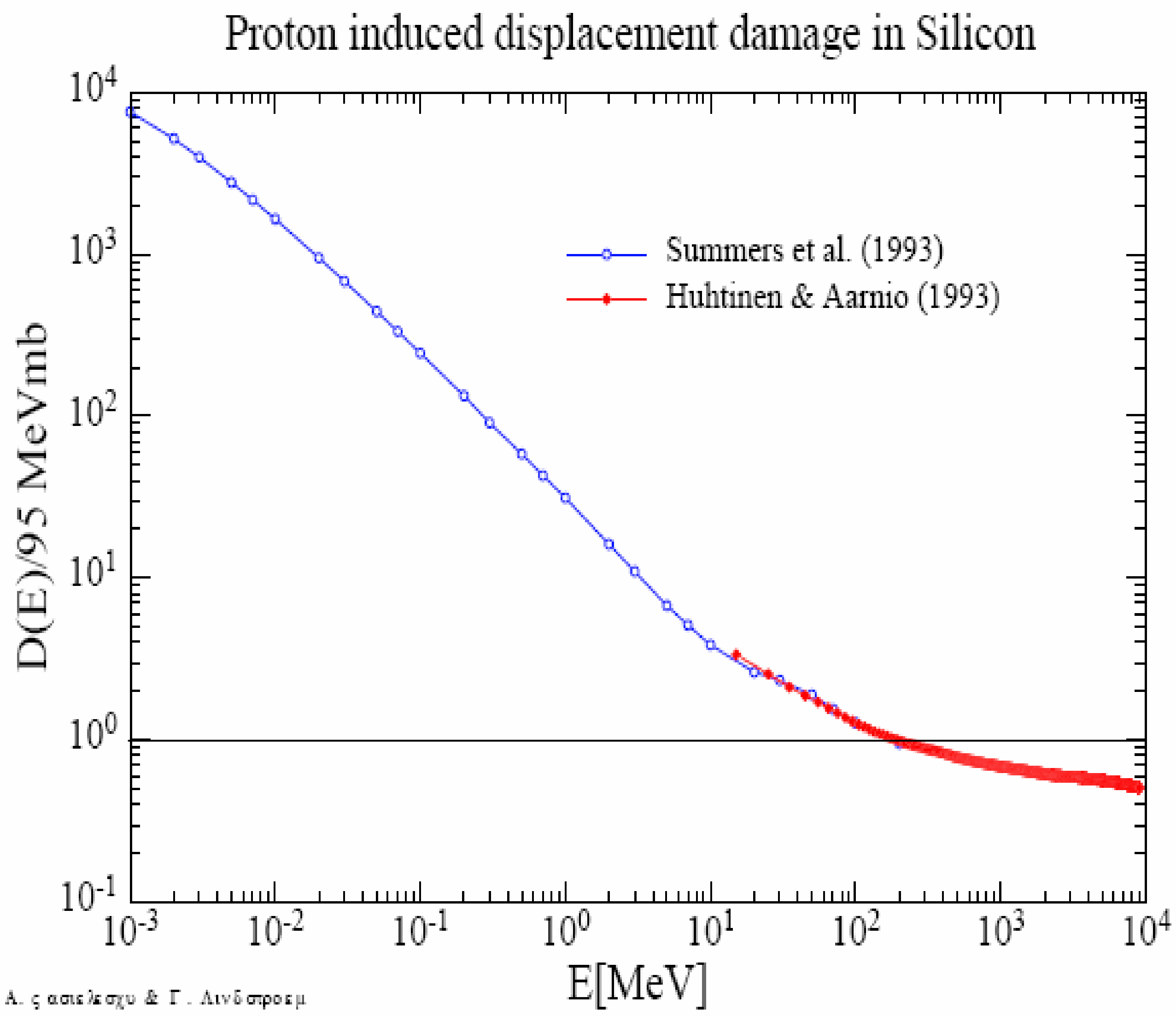
Displacement Damage

- Space : protons
  - To simulate Effects: NIEL Coefficient
  - NIEL is related to a material
- Ground Level: Protons or neutrons (1MeV damage equivalent)
- Microelectronics: Independant of electrical state
- MEMS: mechanical part? influence of strain, stress? Propagation of microcracks?
- Only remote testing?



Α. ς ασιελεσχυ & Γ. Λινδστροεμ

PSI PIF High Energy:Main Features

- Initial proton energies: 254, 102 and 60 MeV
- Energies available using the PIF degrader:
  quasi continuously from 35 (6) MeV up to 254 (60) MeV
- Energy straggling for the 300 MeV initial beam beam:
  e.g. FWHM=7.2 MeV at 200.0 MeV, FWHM=15.4 MeV at 50.0 MeV.
- The maximum beam intensity at 254 MeV: 1 nA
- The maximum flux at 254 MeV with 10 mA split beam (focused beam):

  $2.5*10^8$ protons/sec/cm2
- Beam profiles are either flat or Gaussian-form with minimum FWHM=6 cm
- Irradiations take place in air
- The maximum diameter of the irradiated area: diameter 9 cm
- The accuracy of the flux/dose determination: 5%
- Neutron background: less than 10-4 neutrons/proton/cm2
- Irradiations, devices and sample positioning are supervised by the computer
- Sample mounting frame 25 x 25 cm2 (SEU and HIF facilities compatible)
  is attached to the XY table
- Data acquisition system allows automatic runs with user pre-defined irradiation criteria

PSI Low Energy Main features

- Energy range: 6 to 63 MeV
- Proton flux: <5· 10^8 p/cm2/sec
- Beam spot: circle, up to 9 cm diameter
- Beam uniformity: > 90% over 5 cm diameter
- Flux/Dosimetry: about 5% absolute accuracy
- Irradiation take places in air
- Sample frame Brookhaven and HIF compatible is fixed on the XY table

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Dosimetry

- 3.3 Dosimetry measurements. The radiation field intensity at the location of the device under test shall be determined prior to testing by dosimetry or by source decay correction calculations, as appropriate, to assure conformance to test level and uniformity requirements. The dose to the device under test shall be determined one of two ways:
- (1) by measurement during the irradiation with an appropriate dosimeter, or (2) by correcting a previous dosimetry value for the decay of the 60Co source intensity in the intervening time. Appropriate correction shall be made to convert from the measured or calculated dose in the dosimeter material to the dose in the device under test.
- 3.4 Lead/Aluminum (Pb/Al) container. Test specimens shall be enclosed in a Pb/Al container to minimize dose enhancement effects caused by low-energy, scattered radiation. A minimum of 1.5 mm Pb, surrounding an inner shield of at least 0.7 mm Al, is required. This Pb/Al container produces approximate charged particle equilibrium for Si and for TLDs such as CaF2. The radiation field intensity shall be measured inside the Pb/Al container (1) initially, (2) when the source is changed, or (3) when the orientation or configuration of the source, container, or test-fixture is changed. This measurement shall be performed by placing a dosimeter (e.g., a TLD) in the device-irradiation container at the approximate test-device position. If it can be demonstrated that low energy scattered radiation is small enough that it will not cause dosimetry errors due to dose enhancement, the Pb/Al container may be omitted.

Accelerometer testing

- The basic building blocks for each axis are thus identical to that of a conventional single-axis, digital, pendulous torque balanced accelerometer. It is on this basis that the accelerometer was tested using a procedure and data reduction method similar to the procedures specified in IEEE STD 337-1972 and IEEE STD 530-1978.
    - IEEE STD 337-1972, *IEEE Standard Specification Format Guide and Test Procedure for Linear, Single Axis, Pendulous, Analog, Torque Balance Accelerometer*
    - IEEE STD 530-1978, *IEEE Standard Specification Format Guide and Test Procedure for Linear, Single-Axis, Digital, Torque-Balance Accelerometer*
- These documents describe in detail a model for the accelerometer that defines an input/output function with associated error terms.
    - The test procedure consist of observing the output of the test device to input accelerations using the Earth’s gravitation field as the excitation source.
    - Data is collected for different orientations of the devices input axis relative to the local gravity vector.
    - The coefficients of the model terms are determined by regression analysis (least squares fit) of the test data. The magnitude of the coeftlcients provides insight into the error sources present in the design. Stability of the coefficients overtime and temperature provides a measure of device stability.
- The objectives of this first series of tests were to characterize the accelerometer under static conditions for
    - stability of bias (zero offset) and scale factor over temperature and time
    - linearity over the range of* one g acceleration

Update by R. Harboe-Sørensen (ESA)

2nd RADECS Thematic Workshop – January 25th 2007.
“LET-Requirements and Testing for Space Applications”

- **Main European Heavy Ion Test Facilities:**

HIF	Ion Range Medium
RADEF	Ion Range Medium
GANIL	Ion Range High
SIRAD	Ion Range Low

- **Main USA Heavy Ion Test Facilities:**

BNL	Ion Range Low
LBL	Ion Range Medium
Texas A&M	Ion Range High

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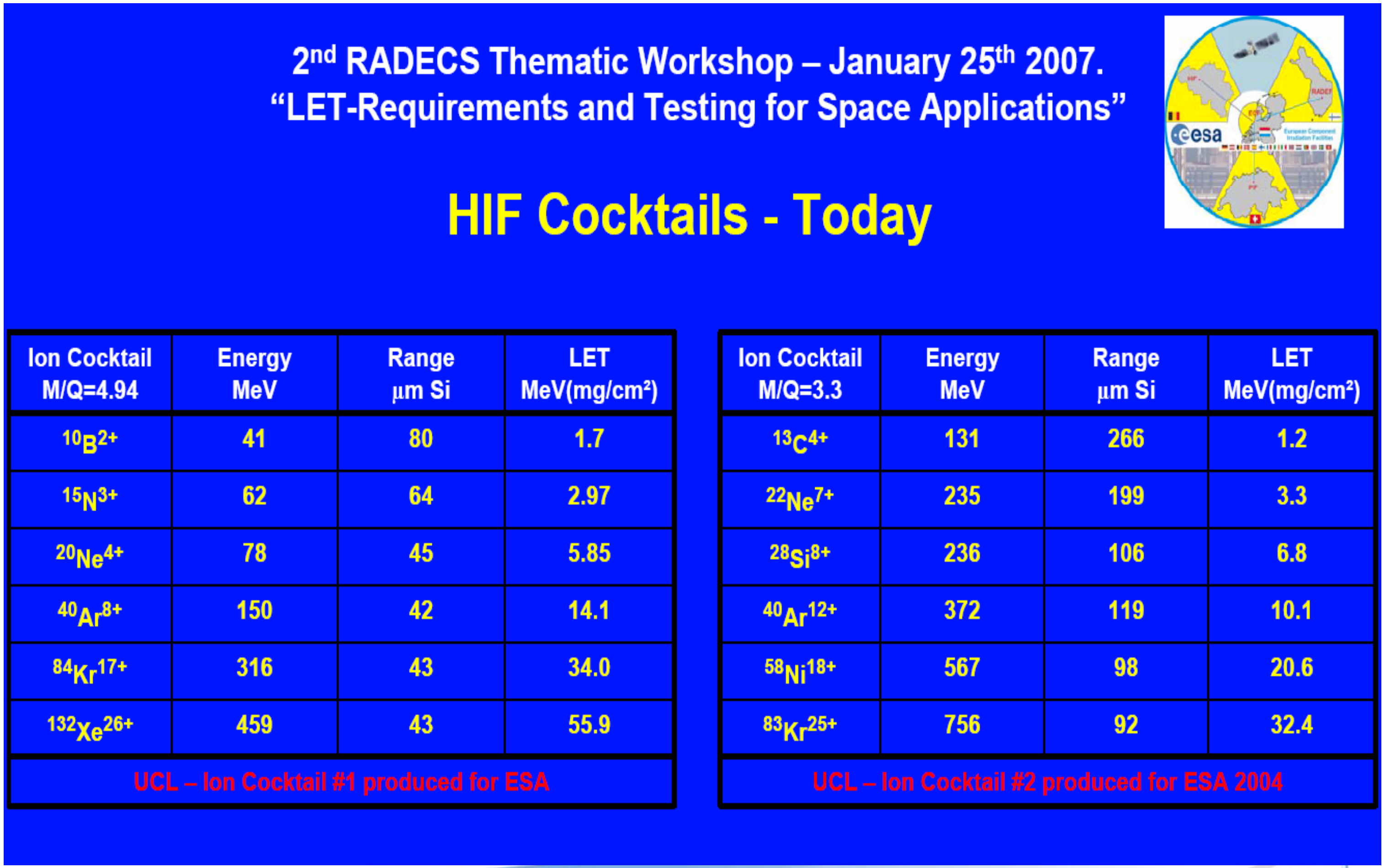

2nd RADECS Thematic Workshop – January 25th 2007.
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HIF Cocktails - Today

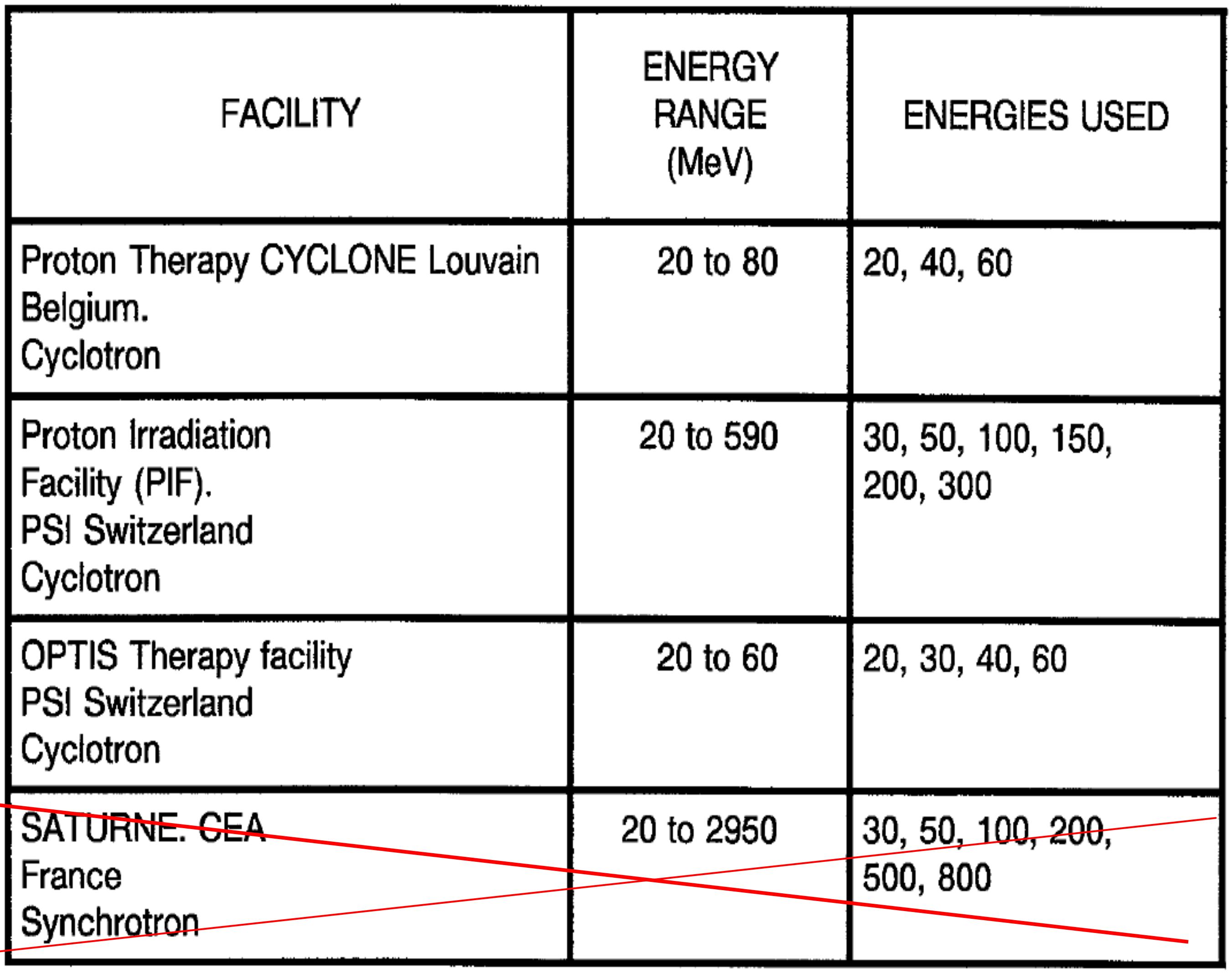
Ion Cocktail M/Q=4.94	Energy MeV	Range µm Si	LET MeV(mg/cm²)
$^{10}\mathrm{B}^{2+}$	41	80	1.7
$^{15}\mathrm{N}^{3+}$	62	64	2.97
$^{20}\mathrm{Ne}^{4+}$	78	45	5.85
$^{40}\mathrm{Ar}^{8+}$	150	42	14.1
$^{84}\mathrm{Kr}^{17+}$	316	43	34.0
$^{132}\mathrm{Xe}^{26+}$	459	43	55.9

UCL – Ion Cocktail #1 produced for ESA

Ion Cocktail M/Q=3.3	Energy MeV	Range µm Si	LET MeV(mg/cm²)
$^{13}\mathrm{C}^{4+}$	131	266	1.2
$^{22}\mathrm{Ne}^{7+}$	235	199	3.3
$^{28}\mathrm{Si}^{8+}$	236	106	6.8
$^{40}\mathrm{Ar}^{12+}$	372	119	10.1
$^{58}\mathrm{Ni}^{18+}$	567	98	20.6
$^{83}\mathrm{Kr}^{25+}$	756	92	32.4

UCL – Ion Cocktail #2 produced for ESA 2004

TABLE II - PROTON FACILITIES



FACILITY	ENERGY RANGE (MeV)	ENERGIES USED
Proton Therapy CYCLONE Louvain Belgium. Cyclotron	20 to 80	20, 40, 60
Proton Irradiation Facility (PIF). PSI Switzerland Cyclotron	20 to 590	30, 50, 100, 150, 200, 300
OPTIS Therapy facility PSI Switzerland Cyclotron	20 to 60	20, 30, 40, 60
~~SATURNE. CEA~~ ~~France~~ ~~Synchrotron~~	~~20 to 2950~~	~~30, 50, 100, 200, 500, 800~~