TEST DE COMPOSANTS ET SYSTEMES POUR L'ENVIRONNEMENT RADIATIF SPATIAL

COMPONENTS AND SYSTEMS RADIATION TESTING FOR RADIATION SPACE ENVIRONMENT

JOURNÉES THÉMATIQUES DU RÉSEAU IN2P3-IRFU SUR LES DÉTECTEURS SEMI-CONDUCTEURS

04/07/2023 – Subatech IMT Atlantique Bretagne-Pays de la Loire

Françoise Bezerra – Expert Radiations – CNES Toulouse

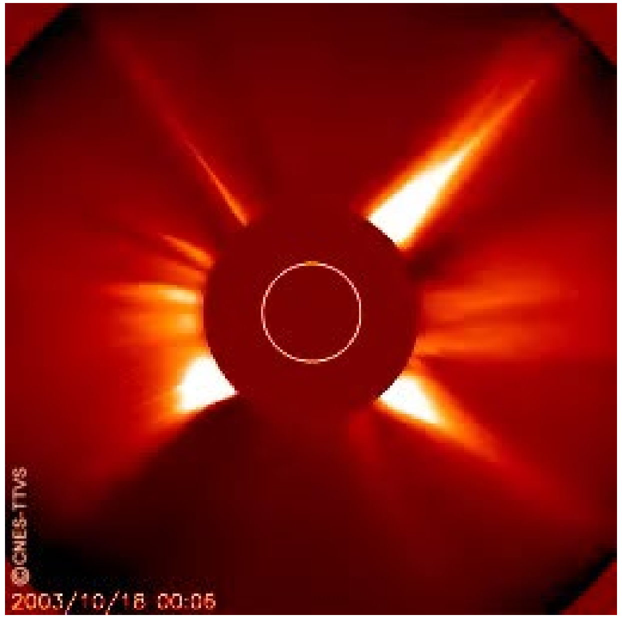
SPACE RADIATION SOURCES

Cosmic rays

Protons | Ions

max around 300 MeV/n
Energy up to 10 GeV/n

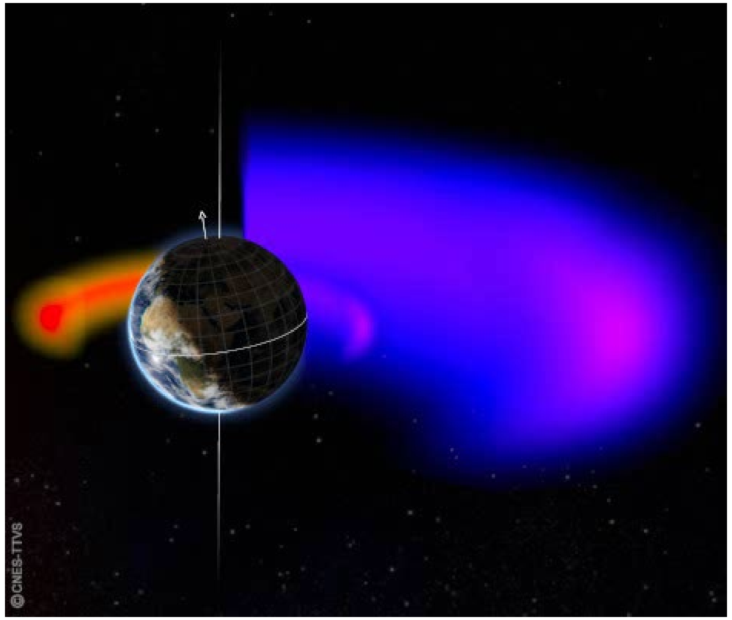
Sun & Solar events



Protons | Ions

keV- 500 MeV | a few 1-10 MeV/n

Radiation belts



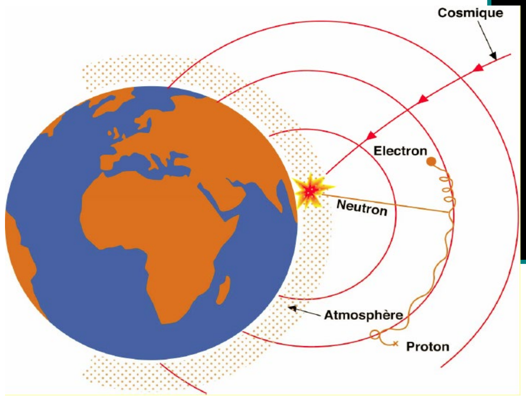
Protons | Electrons

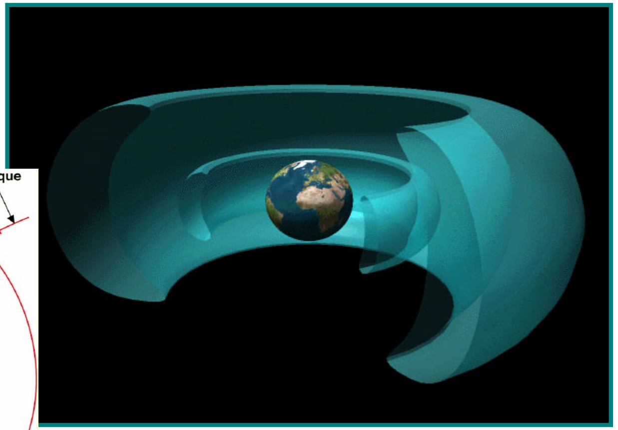
keV- 500 MeV | eV - ~ 10 MeV

Ions = charged nuclei from atoms with Z ≥ 2

ENVIRONMENT CHANGES WITH LOCATION AND TIME

- Altitude/latitude

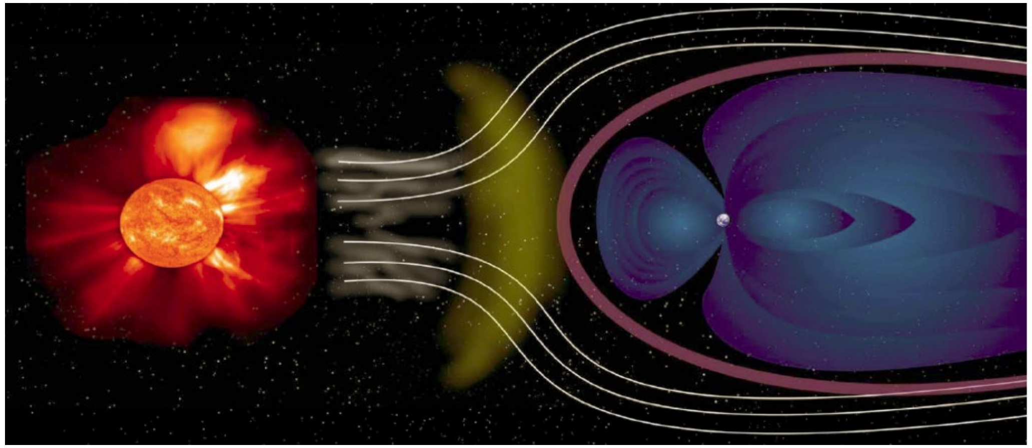




ICARE/SAC-C 15 March – 15 April 2001 1 image/day

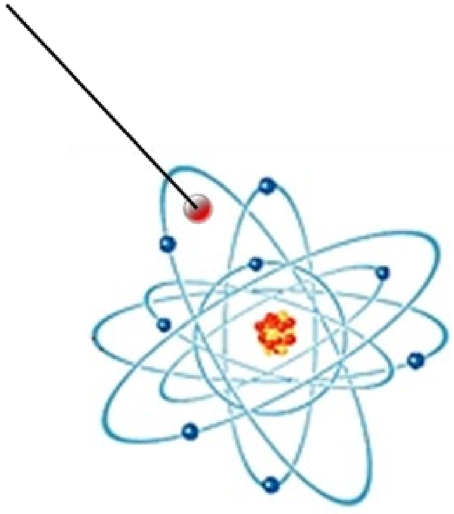
Low Earth Orbit (705km, 98°)

- Solar activity



EFFECTS IN ELECTRONICS

Charged particles interact either with electrons or nucleus of the target material.



Effects of radiation on electronic devices:

- Cumulative
  - Due to the collective contribution of multiple particles
  - Total dose = Ionizing dose (electrons) + Non Ionizing dose (Nucleus)

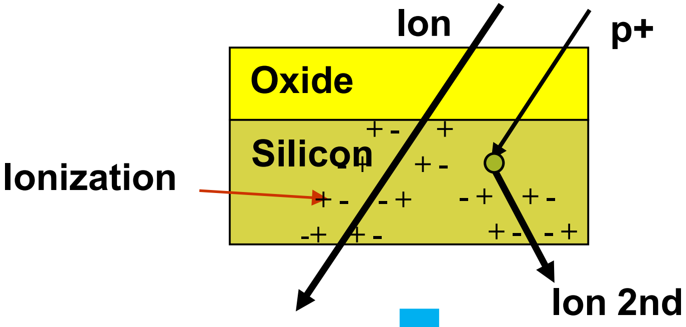
TID: Total Ionizing Dose **TNID or DDD: Displacement Damage Dose**

- Single
  - A unique particle is responsible of a change of state in the device.

Ionization => charge collection => SEE: Single Event Effect

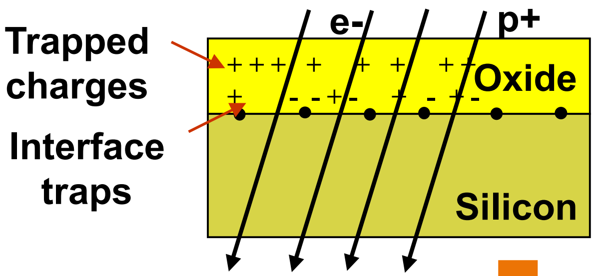
MAIN RADIATION EFFECTS IN ELECTRONICS COMPONENTS

Single event effects

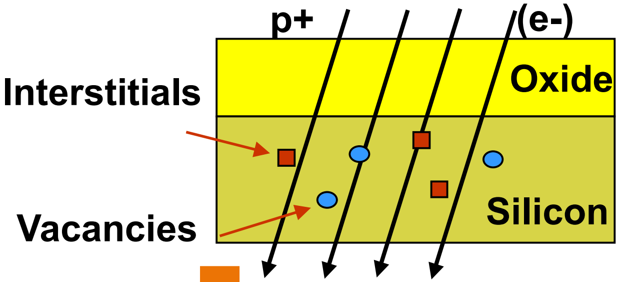


SET : transient
SEU : upset
SEL : latch-up
SEB : burn-out
SEGR : rupture

Ionizing dose



Atomic displacement



Parametric drift
Function loss

Lifetime

Hot pixels
RTS
Stuck bits
Weakened Cells

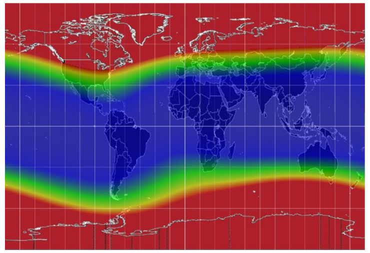
Operating safety
Dependability
Performances

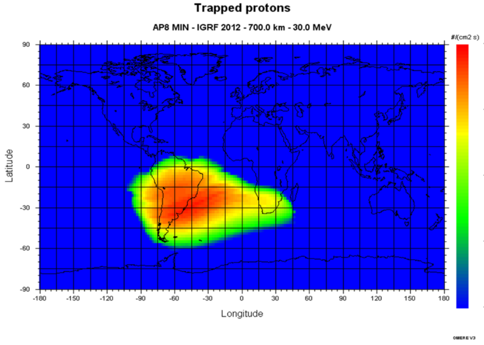
Selection of components compatible with the environment of the mission:

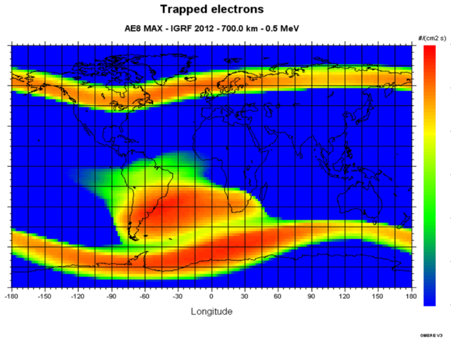
1. Determination of the mission environment

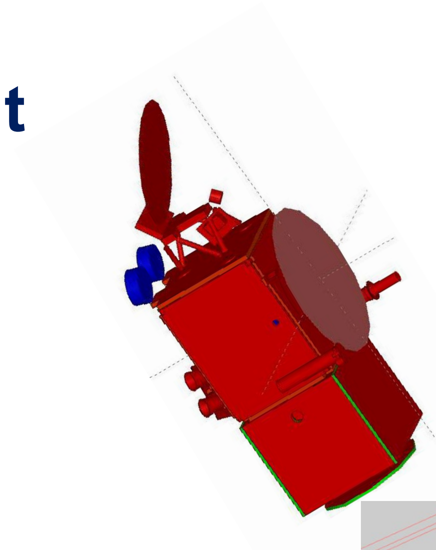
➡ Modelling

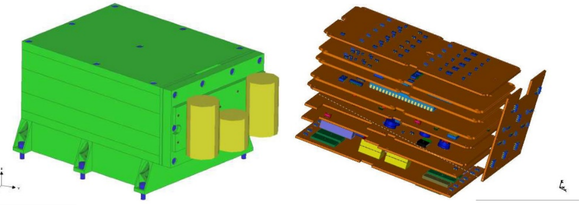
Heavy ions density at LEO orbite (800km)



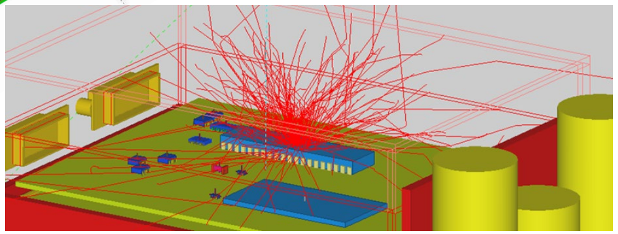








CARMEN2 on board of JASON2



2. Determination of the device response

➡ Test under radiation emulation facility

WHICH FACILITY FOR WHICH EFFECT

Facility\Effect	SEE	TID	TNID
Ion accelerator	X		
Proton accelerator	X	x	X
Neutron beam	X		X
Co60 source		X	
X-Rays		x	
Cf252 source	x		
Laser	x		
Pulsed X-rays	x		

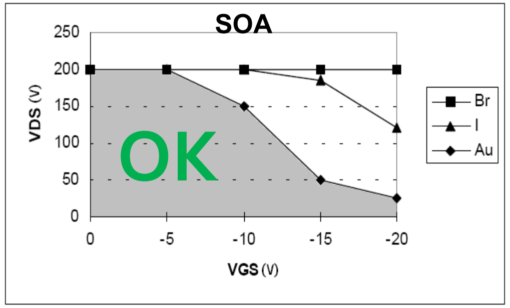
X : Compatible with the standards requirements

x: Alternative and/or complimentary techniques

SEE test principle: 3 types of SEE

- **Destructive SEE with no possible protection:**
  - Single Event Gate Rupture in Power devices
  - Some very harsh Single Event Latch-up

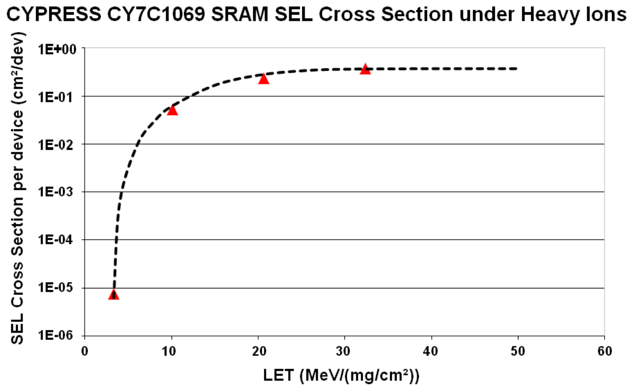
Determination of the Safe Operating area



Device is accepted if biasing is inside the SOA whatever the mission is.

- **Potentially destructive SEE (with protection)**
  - Single Event Burnout in Power devices
  - Single Event Latchup
- **Non destructive SEE**
  - Single Event Transient
  - Single Event Upset
  - Multiple Bit Upset
  - Single Event Functional Failure

Statistical approach:
Determination of the SEE cross section



In-flight error rate prediction for a given mission

SEE test principle:

- **Input data for in flight rate calculation**

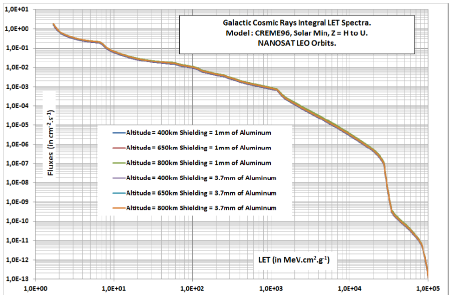
GCR

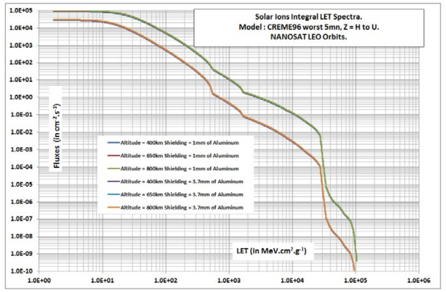
Solar

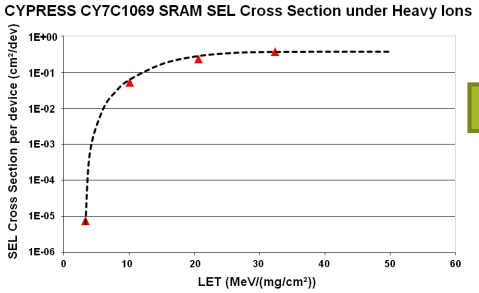
VA belts

X section SEE

Ions



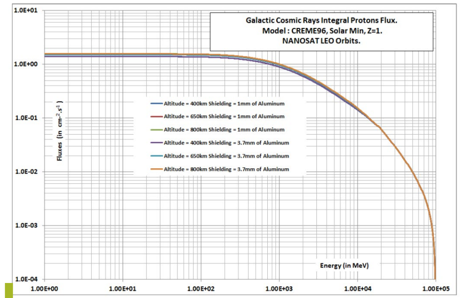


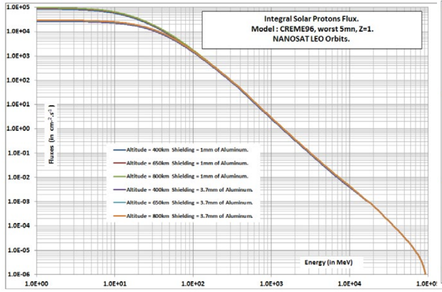


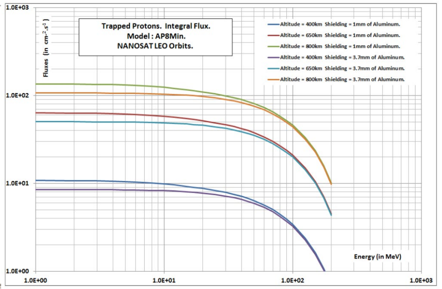
Heavy ions SEE rate

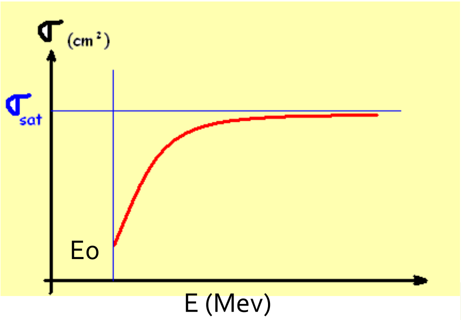
+

Protons









Proton SEE rate

Global SEE rate

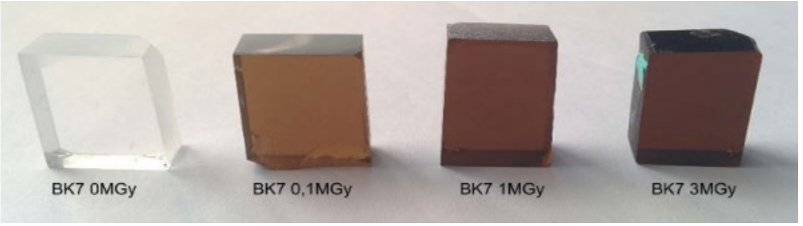
Mission environment

DUT Sensitivity

Device is accepted <u>if the rate is compatible with constraints of the mission</u>

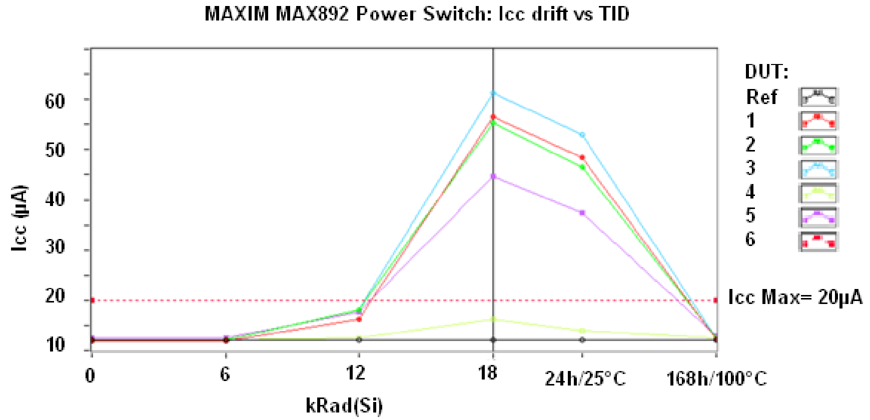
TID test principle:

- **Irradiation with significant source**
  - Cobalt 60 (Gamma rays) for devices or systems inside satellites (electronic components)
  - Electrons for those outside (some materials, coatings, solar cells, …)
- **Parametric and functional test**
  - Continuous measurement
  - Step by step remote testing



Glass samples darkening with increasing dose

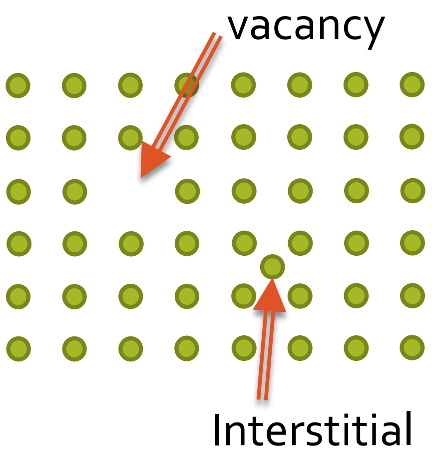
- **Gradual deposition of dose**
- **Accelerated test vs space dose rate**
  - Potential dose rate effect
- **Temperature and bias effects**



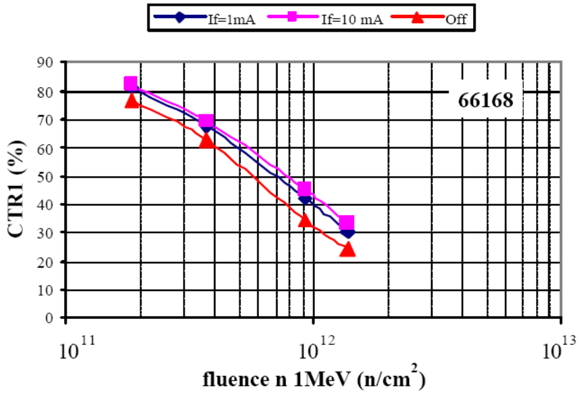
Parametric drift during and after irradiation under Co60

TNID test principle: similar to TID

- **Irradiation with significant source**
  - Protons
  - Neutrons
- **Parametric and functional test**
- **No significant dose rate, temperature or bias effects**
- **Sample activation may lead to long cooling delays**

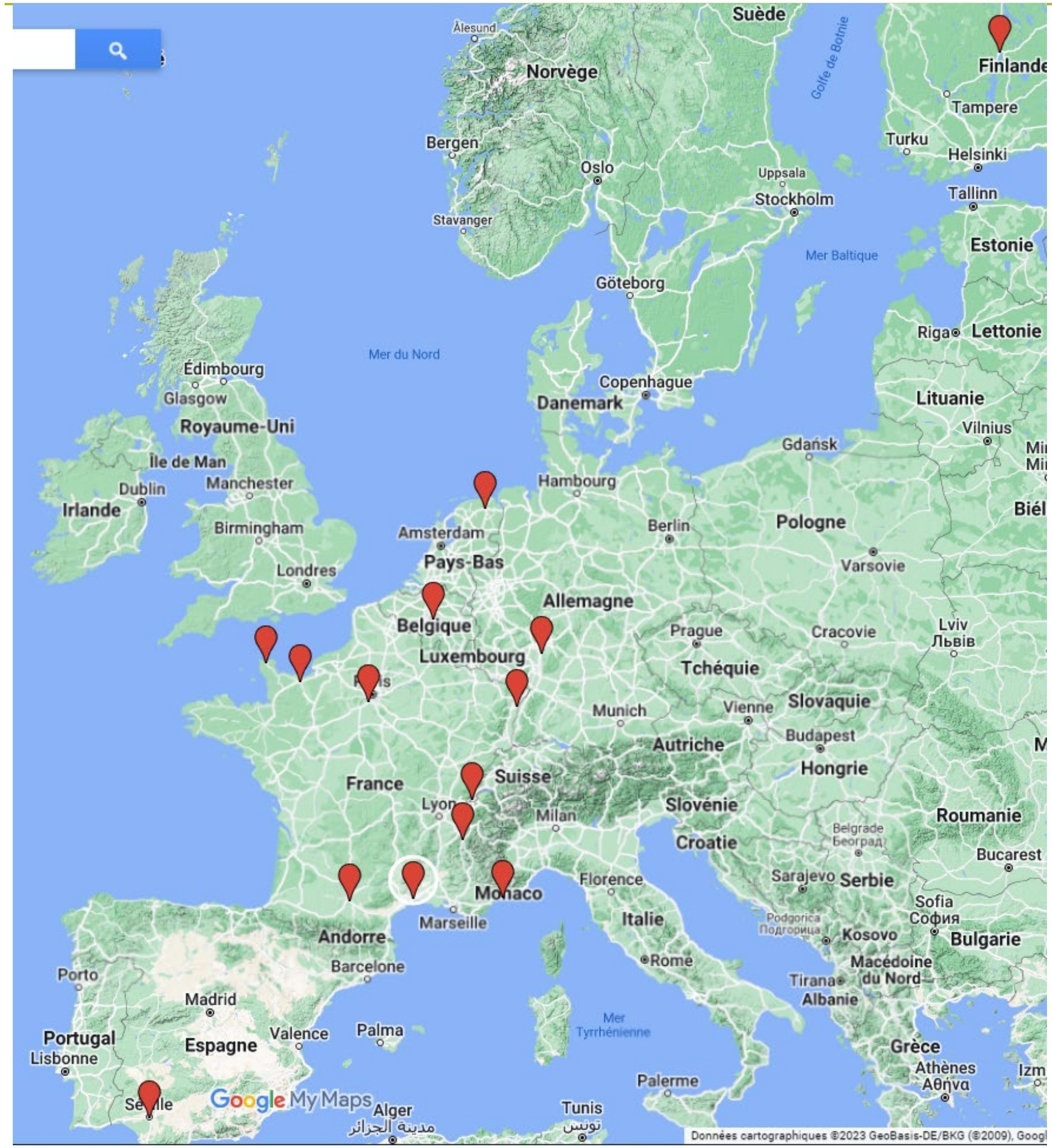


Bias effects on MICROPAC 66168
CTR drift under 1MeV neutrons



R. Mangeret et al RADECS 2001

FACILITIES USED BY CNES



Finland (Jyvaskyla): RADEF-JYFL
The Nederlands (Groningen): UMCG-PARTREC
Belgium (Louvain la Neuve): UCLouvain
Germany (Darmstadt): GSI
Switzerland (Villigen): PSI
Spain (Sevilla): CNA

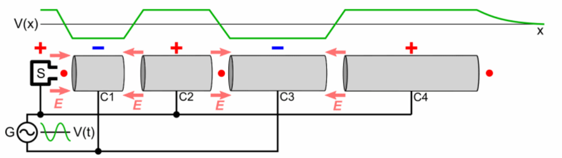
France:
ATRON-FELIX (Cherbourg en Cotentin)
GANIL et CYCLHAD (Caen)
ICPO (Orsay)
IPHC-Cyrcé (Strasbourg)
ESRF et Arc Nucleart (Grenoble)
CAL (Nice)
TRAD/GAMRAY, ONERA/MEGA (Toulouse)
TRAD-MPT (Montpellier)

Sources for TID — Under investigation

PARTICLE ACCELERATORS

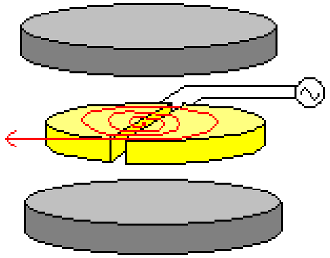
Type of accelerators used for space radiation tests

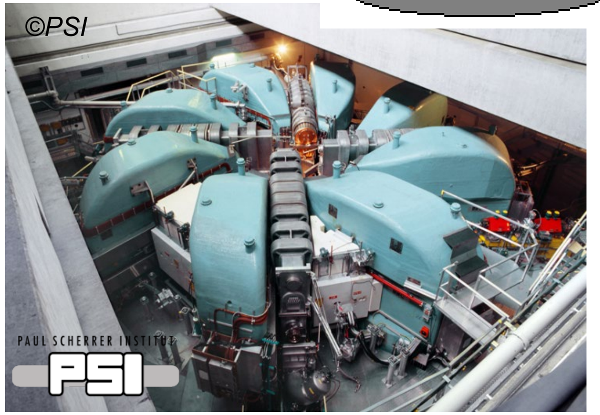
- Linear:



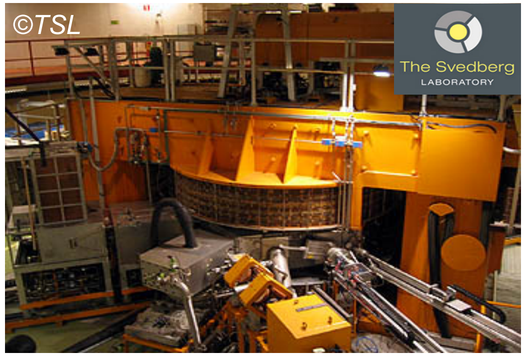
UNIversal Linear ACcelerator

- Cyclotrons

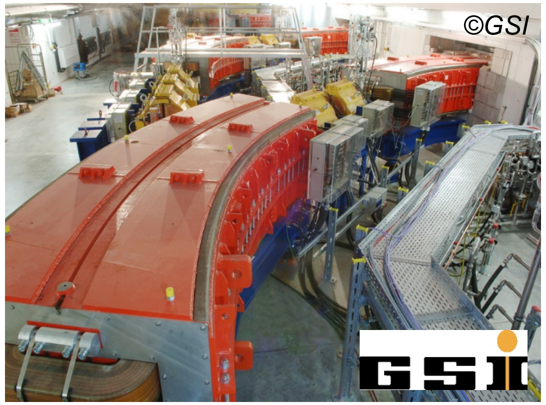


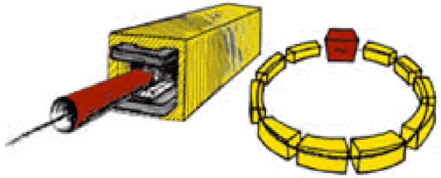


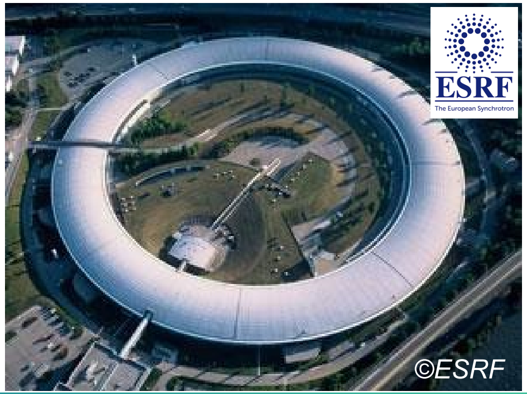
- Synchro-Cyclotrons



- Synchrotrons







PARTICLE ACCELERATORS

Facilities used by CNES for SEE testing:

- Heavy ions:
  - High energy heavy Ions (>10MeV/n)
    - GANIL, Caen, France
    - RADEF, Jyvaskyla, Finland
  - Medium energy heavy ions (<10MeV/n)
    - UCL, Louvain-la-Neuve, Belgium
- Protons:
  - PARTREC, Groningen, The Netherlands
  - IPNO, Orsay France

Facilities used by CNES for TNID testing and calibration of detectors:

- Protons:
  - PARTREC, Groningen, The Netherlands
  - UCL, Louvain-la-Neuve, Belgium
  - CAL, Nice, France

Alternative and complementary facilities (Currently under test)

- ESRF, Grenoble, France (SEE with Pulsed XRays=)
- CHARM, CERN, Geneva (Mixed field=
- ATRON-FELIX, Cherbourg, France (calibration with e-)
- …

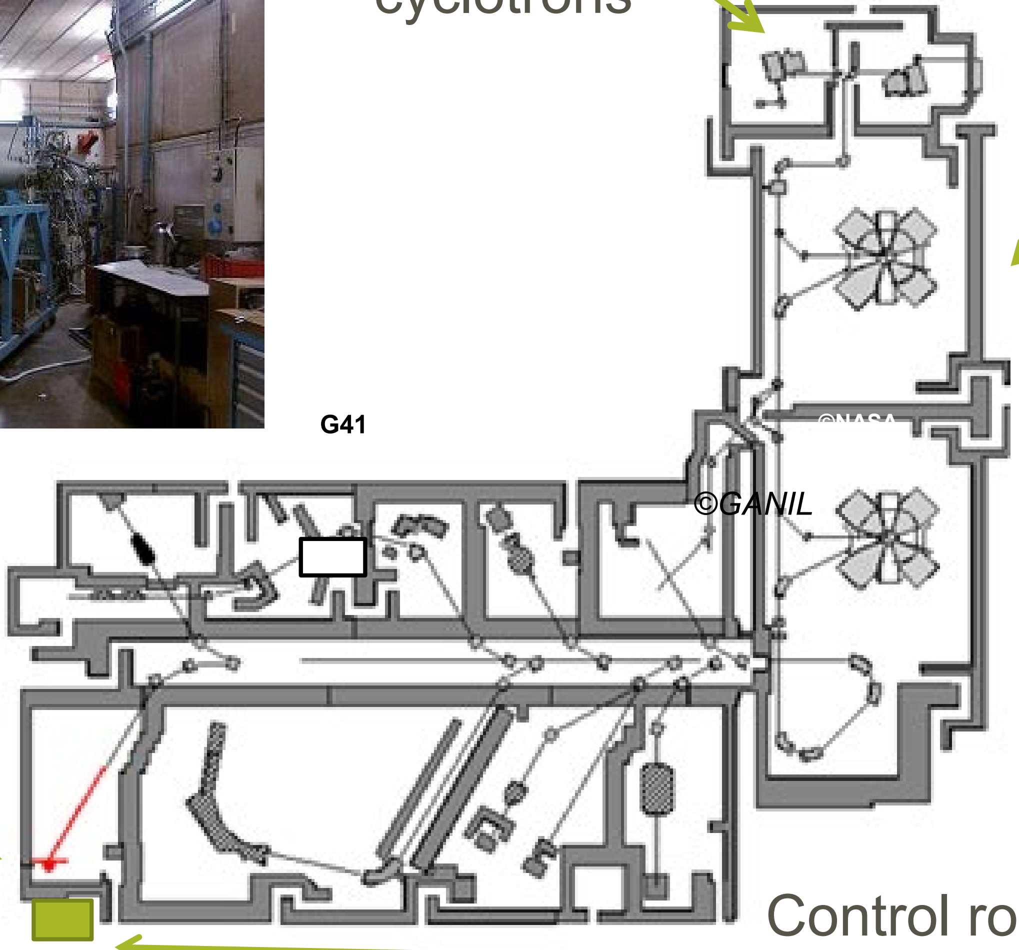
GANIL (heavy ions)

Grand Accelerateur National d'Ions Lourds, Caen, France.

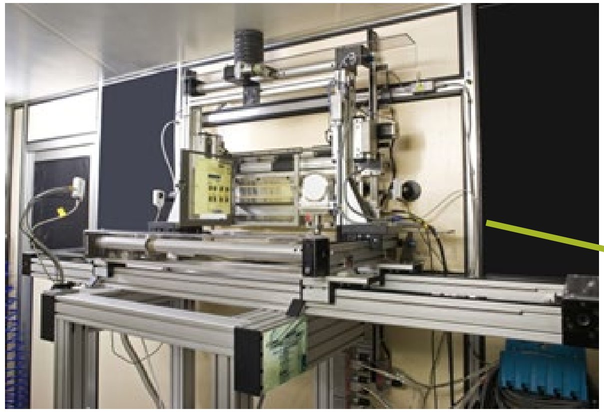
Beam Transport

2x compact cyclotrons

2x 4 sectors cyclotrons



DUT Holder



Control room

GANIL (heavy ions)

One ion available per campaign

- Example: $^{136}Xe^{48+}$, E = 49.6 MeV/u = 6745.6 MeV, Flux: 10^2 -10^5 ions/cm²/s
  - Characteristics in Si:

Air (mm)	Al (µm)	E (MeV/n)	LET (MeV/(mg/cm²))	Range (µm)
53	0	46.89	26.63	707.65
100	100	40.25	29.17	568.16
100	400	20.69	41.54	233.44
100	500	11.93	51.95	122.53
150	500	9.27	55.35	93.58

After J.C. Foy, GANIL

  - Only a few weeks/year for industry

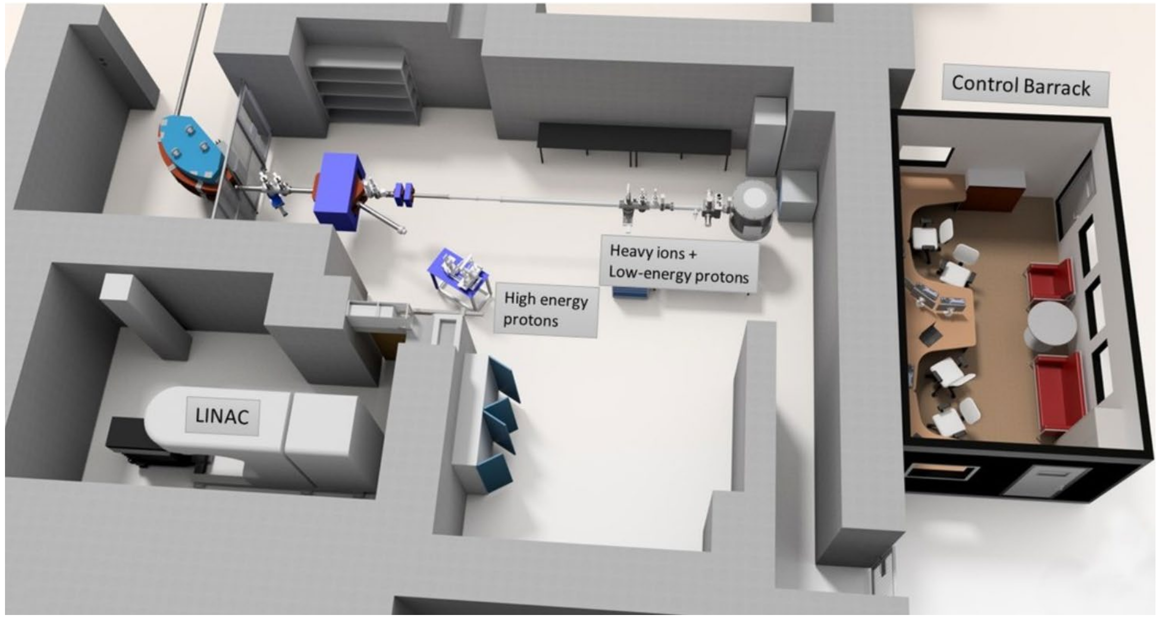
RADEF (Heavy ions)

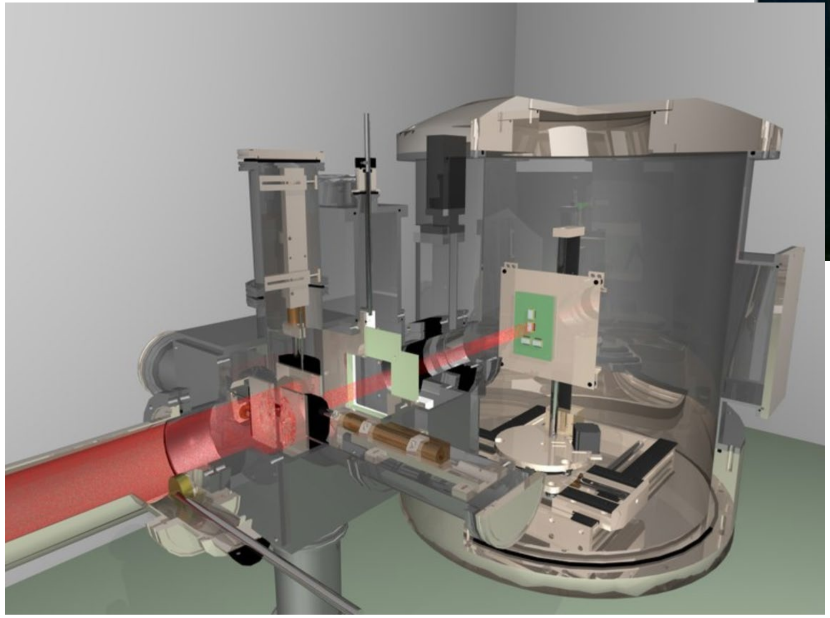
4 ion cocktails

- **9.3MeV/n, 10MeV/n, 16.3 MeV/n ; 22 MeV/n ion beams:**
  - Ion specie change in 15 minutes
  - Intensity $5*10^5$ ions/cm^2/sec
  - Beam delivered in air or Vacuum
  - Beam area 2x2cm and up to 10cm diameter.

University of Jyväskylä

Also available: protons





RADEF (Heavy ions)

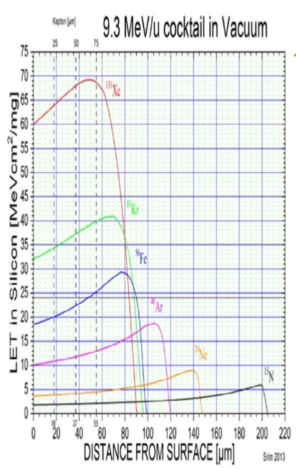
University of Jyväskylä

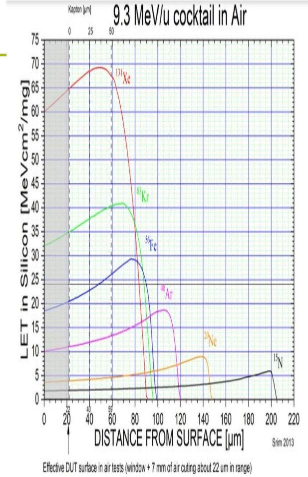
cnes

Radiation Effects Facility, Jyvaskyla, Finland.

9,3MeV/n ion cocktail:

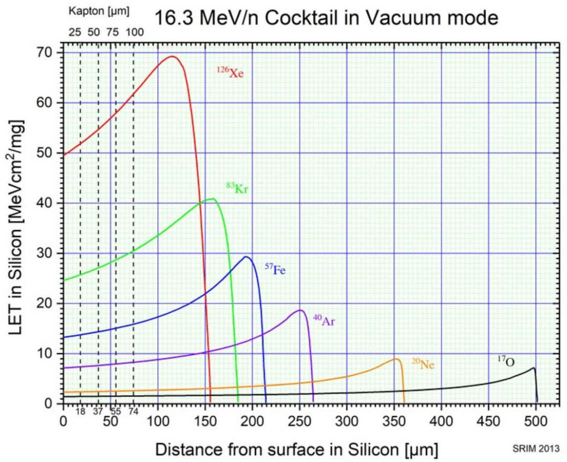
Ion	Δm/q (%)	Energy [MeV]	LET at Surface [MeV·cm²/mg]	LET at Bragg peak [MeV·cm²/mg]	Range [μm]
$^{15}N^{4+}$	0	139	1.87	6.0(@198)	202
$^{20}Ne^{6+}$ *	0	186	3.63	8.9(@138)	146
$^{40}Ar^{12+}$ *	-0.06	372	10.1	18.6(@105)	118
$^{56}Fe^{15+}$	-0.56	523	18.6	29.3(@76)	97
$^{83}Kr^{22+}$	-0.71	768	32.2	40.9(@68)	94
$^{131}Xe^{35+}$	-0.26	1217	60.0	69.3(@50)	89

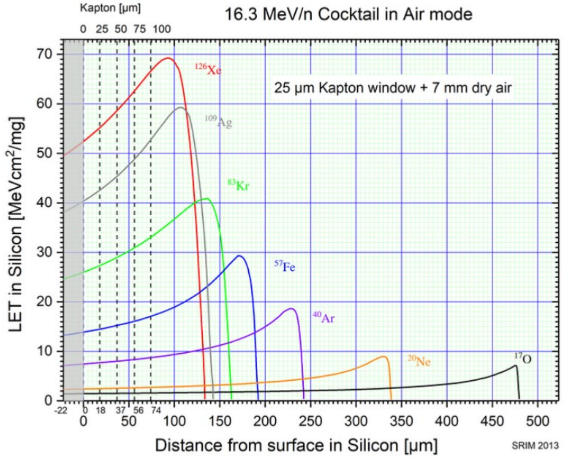




16,3 MeV/n ion cocktail:

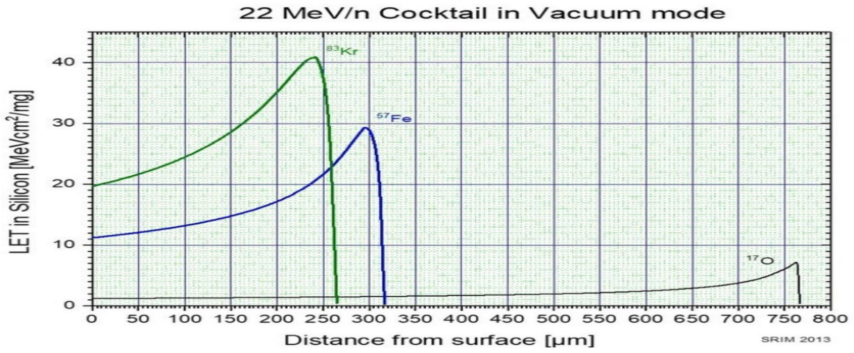
Ion	Δm/q (%)	Energy [MeV]	LET at Surface [MeV·cm²/mg]	LET at Bragg peak [MeV·cm²/mg]	Range [μm]
$^{17}O^{6+}$	-0.75	284	1.52	7.17(@477)	481
$^{20}Ne^{7+}$	0.06	328	2.3	8.95(@352)	360
$^{40}Ar^{14+}$	0	657	7.2	18.6(@251)	264
$^{57}Fe^{20+}$	-0.27	941	13.3	29.3(@192)	214
$^{83}Kr^{29+}$	0.16	1358	24.5	40.9(@159)	185
$^{126}Xe^{44+}$	0.25	2059	48.5	69.3(@119)	157





22 MeV/n ion cocktail:

Ion	Δm/q (%)	Energy [MeV]	LET at Surface [MeV·cm²/mg]	LET at Bragg peak [MeV·cm²/mg]	Range [μm]
$^{40}Ar^{11+}$	4.02	400	9.7	18.6(@117)	130
$^{84}Kr^{23+}$	-0.22	840	31.3	40.9(@78)	104
$^{197}Au^{54+}$	0	1973	85.6	94.2(@56)	107



PARTREC (protons)

cnes

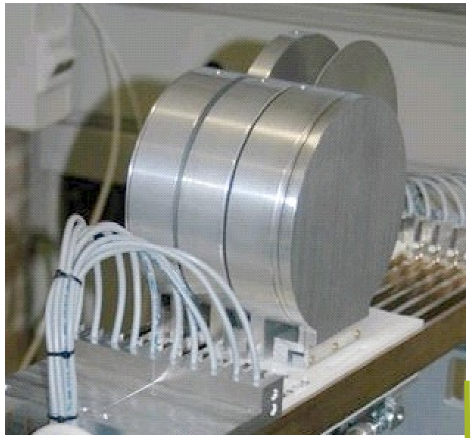
Kernfysisch Versneller Instituut – Center for Advanced Radiation Technology

umcg

university of groningen


AGOR cyclotron

Beam energy degrader



DUT holder

Possible close-to-DUT test system location

PARTREC (protons)

Proton Beam characteristics:

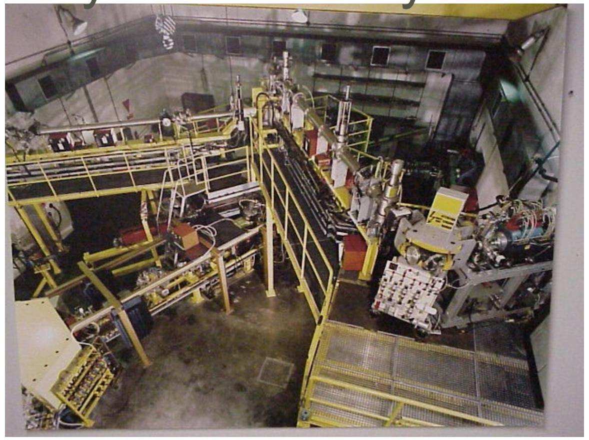
- Energy at DUT level (using degraders): 10-184MeV
- Flux: 10^8 to 10^9 p/cm²/s
- Flux diameter at DUT level versus homogeneity:
  - Standard: 70 mm , 3%
  - Wider: 110mm, 10%
- Distance between DUT and Test system placed at:
  - Control room: 40 m
  - B-Lab: 15m
  - Close-to DUT location: 1m

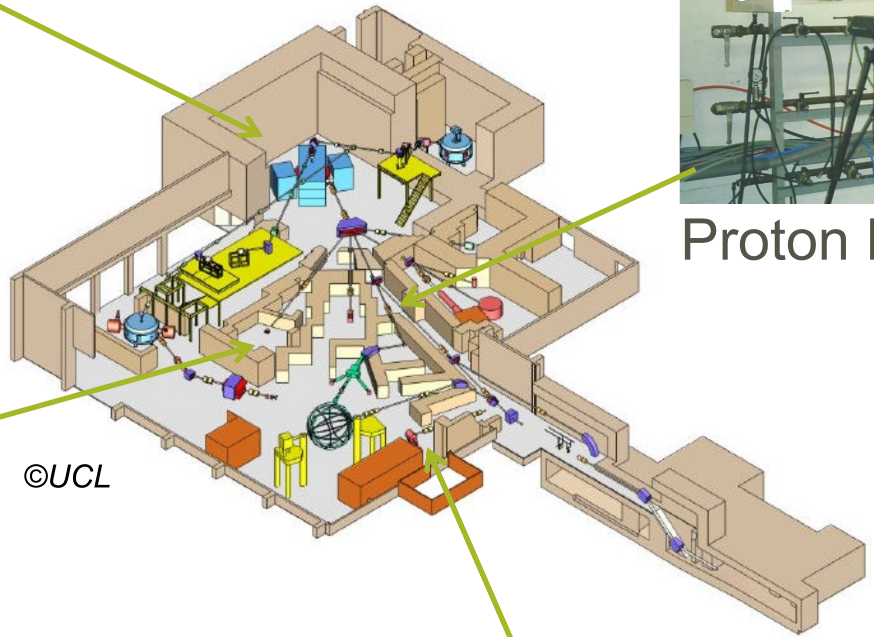
  - **Also available:** Heavy ions (not used by CNES yet)

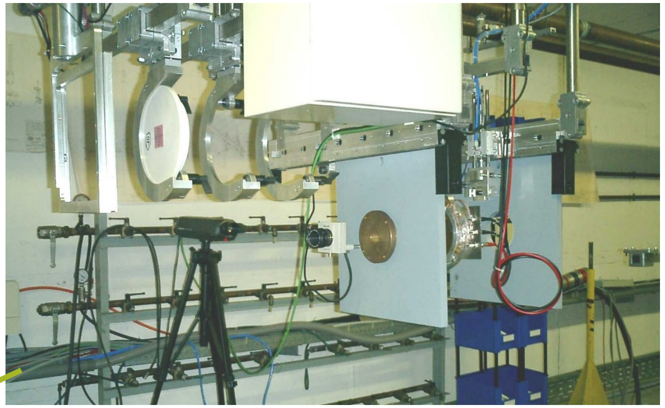
UCL (Heavy ions & protons)

Université Catholique de Louvain-la-Neuve, Belgium

Cyclone 110 cyclotron







Proton Line (LIF)

Mono Energetic
Neutron line (NIF)

Heavy ions line (HIF)

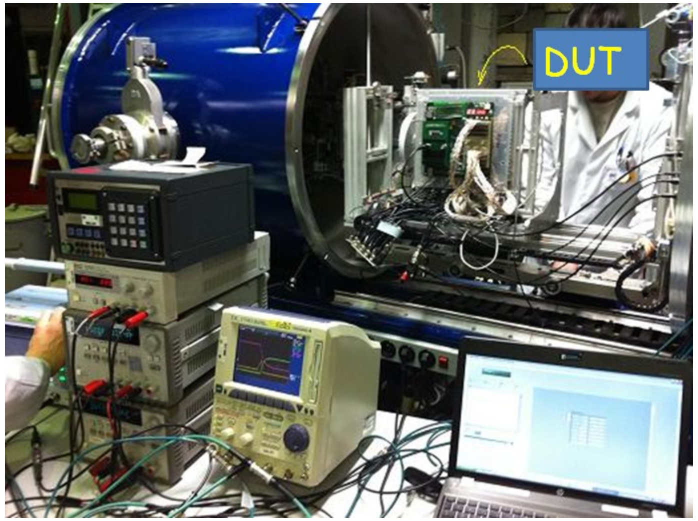
UCLouvain (Heavy ions)

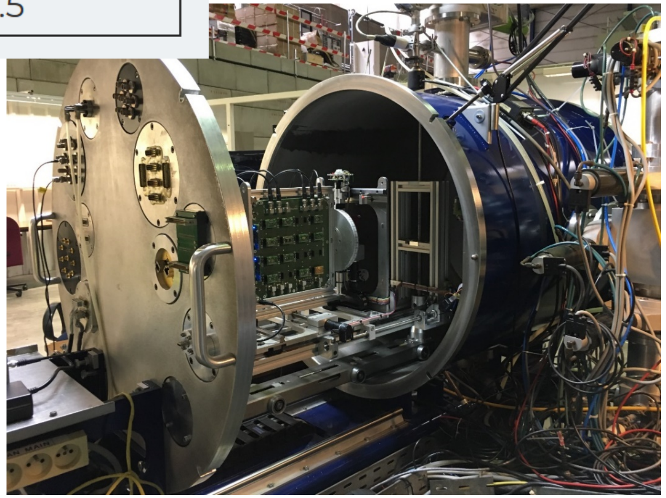
Heavy Ion Facility (HIF)

- HIF ion cocktail:

Available particles inside the cocktail:

M/Q	Ion	DUT energy [MeV]	Range [µm Si]	LET [MeV/(mg/cm²)]
3.25	$^{13}C^{4+}$	131	269.3	1.3
3.14	$^{22}Ne^{7+}$	238	202.0	3.3
3.37	$^{27}Al^{8+}$	250	131.2	5.7
3.27	$^{36}Ar^{11+}$	353	114.0	9.9
3.31	$^{53}Cr^{16+}$	505	105.5	16.1
3.22	$^{58}Ni^{18+}$	582	100.5	20.4
3.35	$^{84}Kr^{25+}$	769	94.2	32.4
3.32	$^{103}Rh^{31+}$	957	87.3	46.1
3.54	$^{124}Xe^{35+}$	995	73.1	62.5

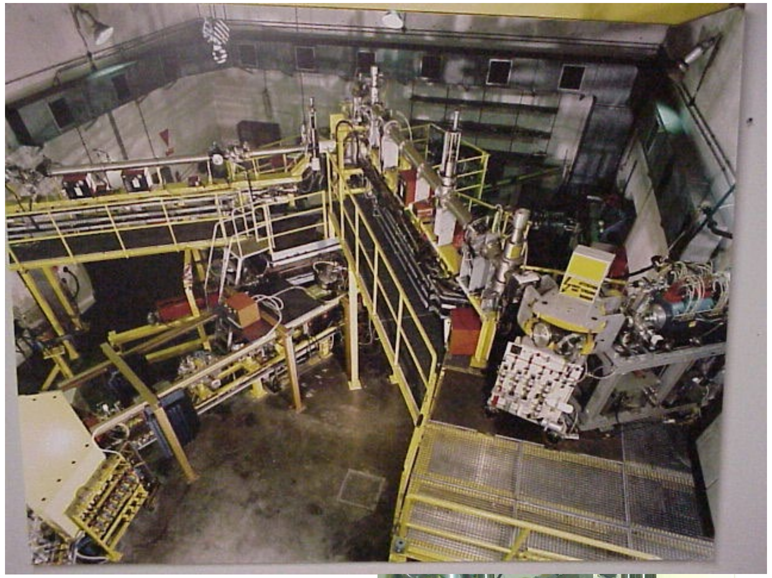


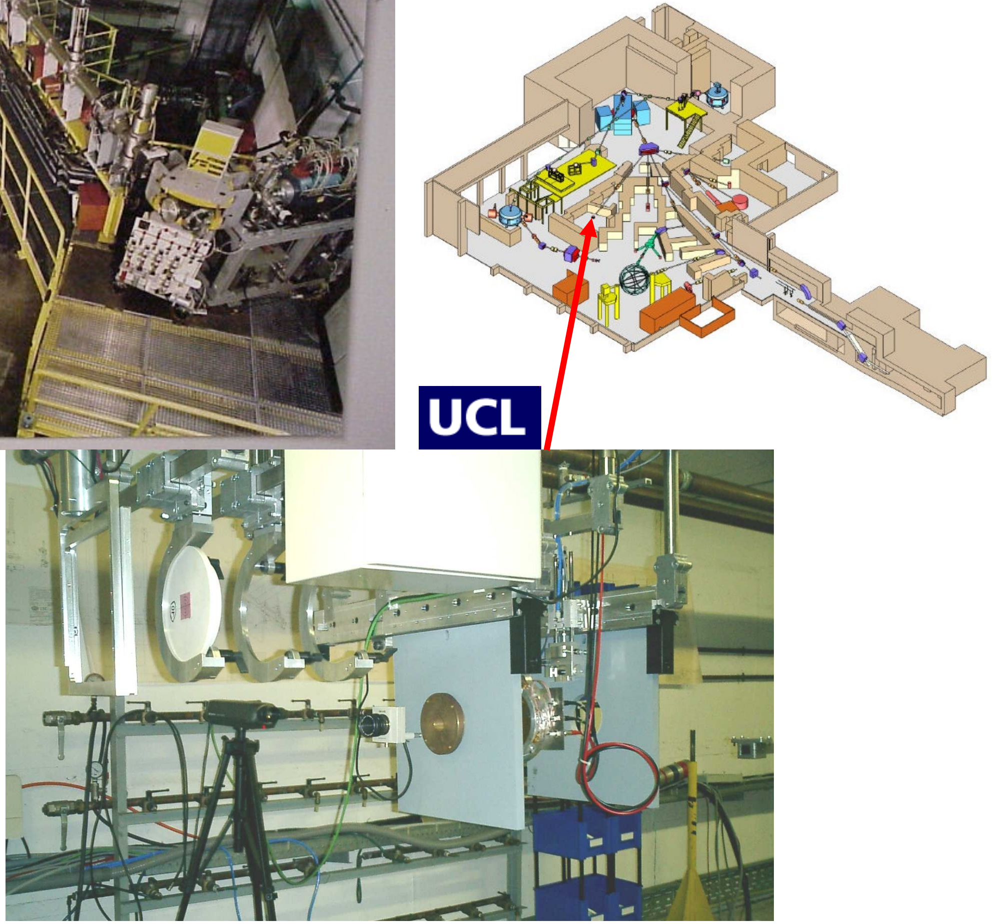


- Typical fluxes few particles/cm²/s to 1,5 10^4 ions/cm²/s
- Beam diameter: 2.5 cm (10% homogeneity)

UCLouvain (protons)

Light Ion Facility (LIF)





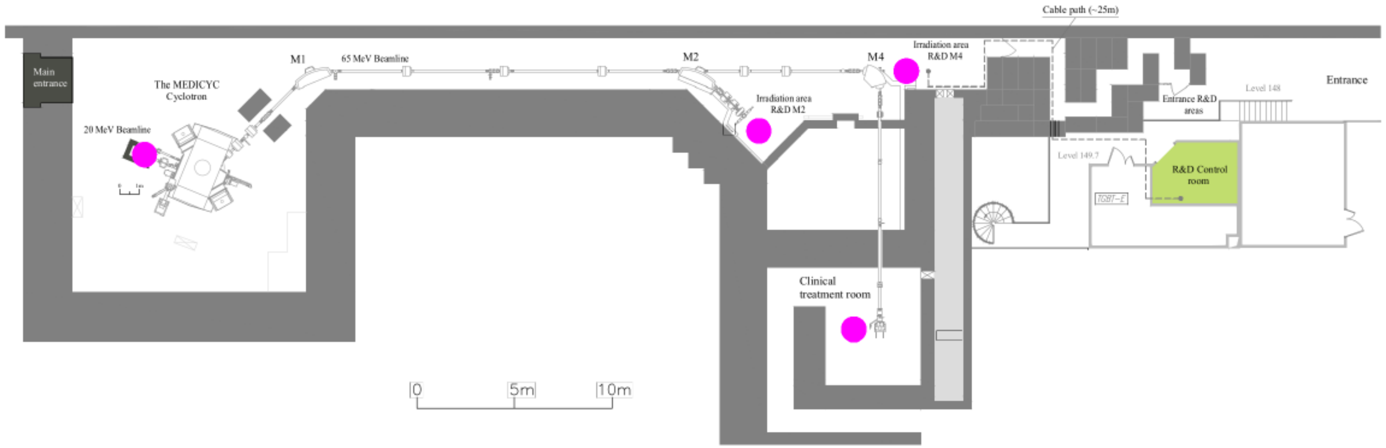
Proton line

- E 10-62MeV
- DUT in original package
- Control room 10m
- Flux : 1000 – 2E8 p/cm²/s
- Beam: 8x8cm (10% homogeneity)
- DUT and irradiation room activation
  - Limited effect compared to KVI
  - Quarantine for irradiated samples

Centre Antoine Lacassagne (Nice):

The Medicyc Facility

- Isochronous cyclotron, 65 MeV proton
- In 2020, a collaboration project started between CAL and CNES
- Radiation hardness tests
- 1E4 → 1E11 p/cm2/s
- Possibility to use in the near future 230 MeV protons



Antoine Lacassagne
CENTRE DE LUTTE CONTRE LE CANCER DE NICE

cnes

Radiation sources: Example of a Co60 source for TID testing

cnes

GAMRAY (TRAD, Toulouse) based on a panoramic irradiator.

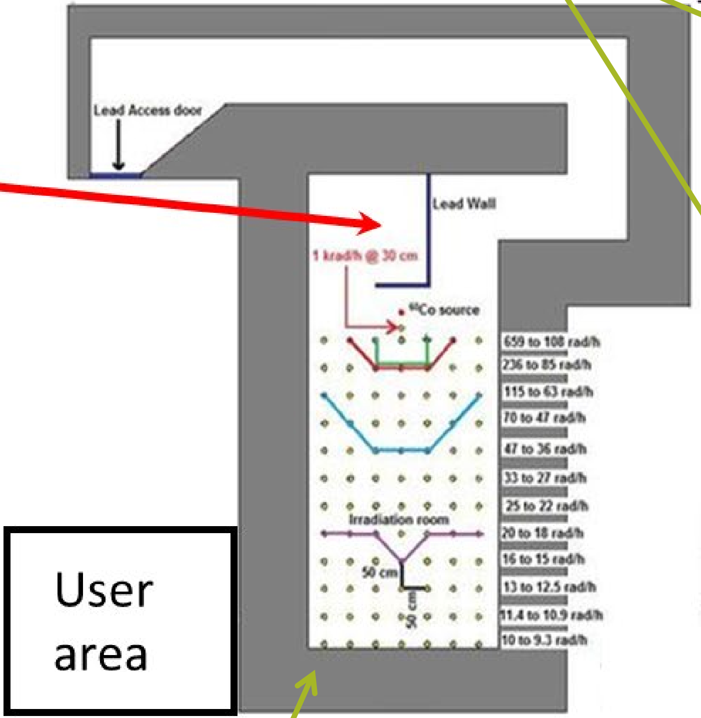
Source Activity: ~400Cu, Dose Rate: 10rad(Si)/h to 4krad(Si)/h without shielding.

TRAD Tests & radiations a HEICO company

Depleted U shielded storage chamber

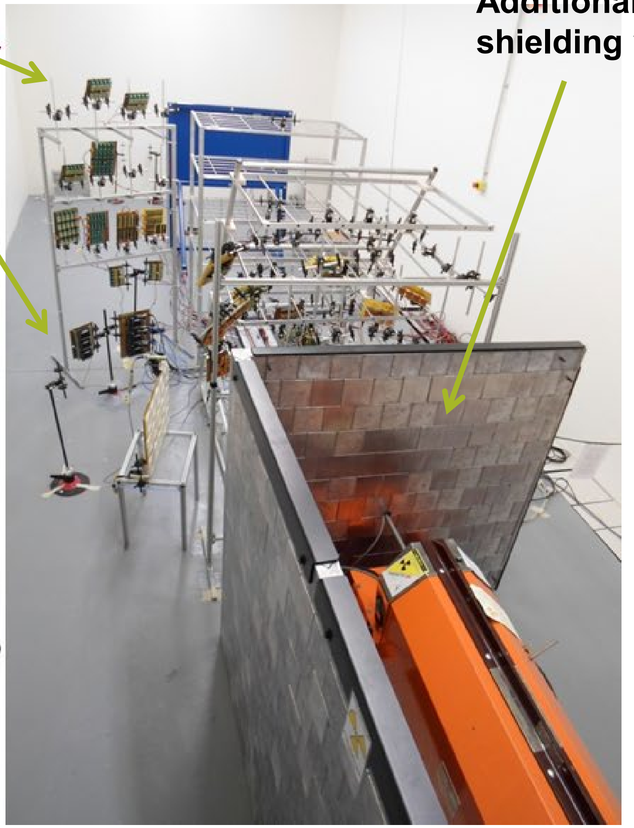
Source guide

Various samples under exposure



Concrete wall >1m

Additional Lead shielding wall

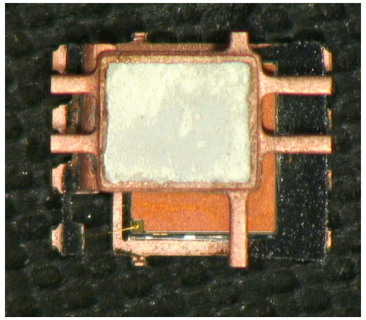


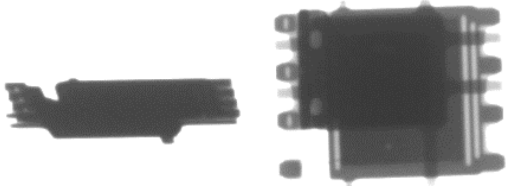
©TRAD

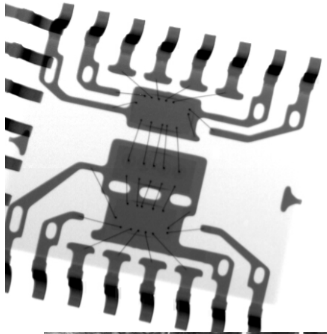
Alternative and complementary facilities:

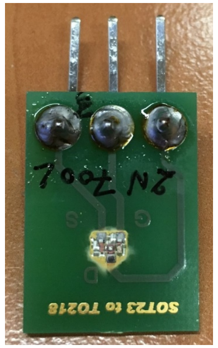
Heavy ion facilities are quite rare and there is not enough beam time.

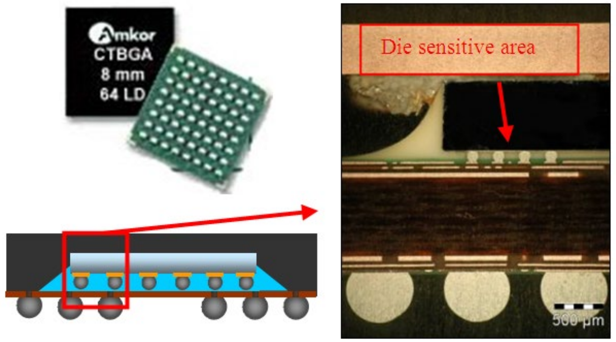
- We try to develop alternative testing techniques:
  - to limit conventional beam time when possible (R&D)
  - To solve issues when test with conventional beam is not possible

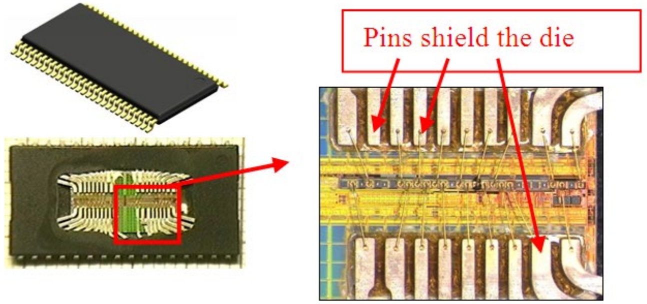












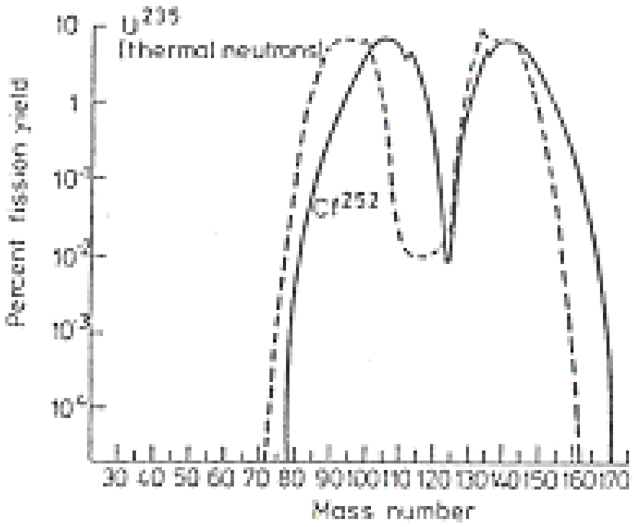
Complementary facility: Cf252 source

Cf252 source is not a standard facility.

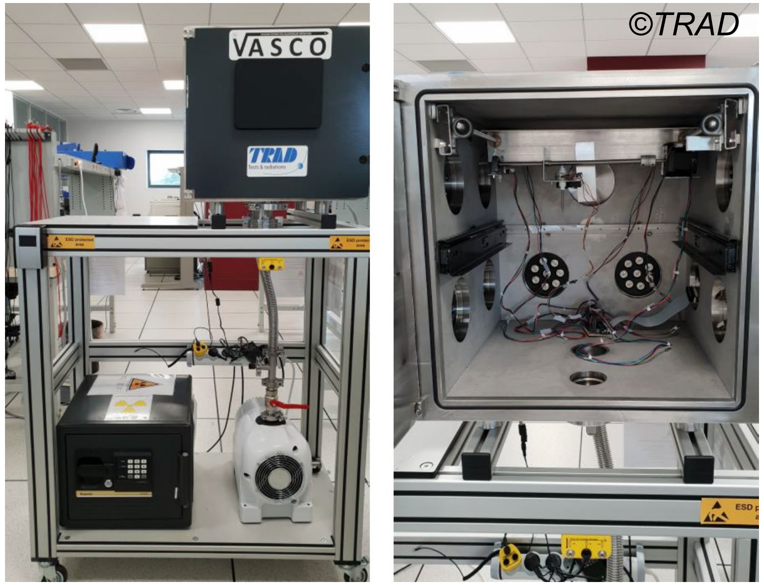
- Used by space community for SEE pre-test or hardware validation.

$$^{252}Cf \rightarrow {}^{95}Zr + {}^{95}Nb + {}^{103}Ru + {}^{106}Ru + {}^{106}Rh + {}^{134}Cs + {}^{137}Cs + {}^{141}Ce + {}^{144}Ce + {}^{144}\mathrm{Pr} + {}^{152}Eu + {}^{154}Eu + \alpha + n$$

Very low energy ions



- Small range in materials
  - Vacuum chamber mandatory
  - DUT package must be opened
- Quick LET decrease in DUT
  - Unknown LET at sensitive volume



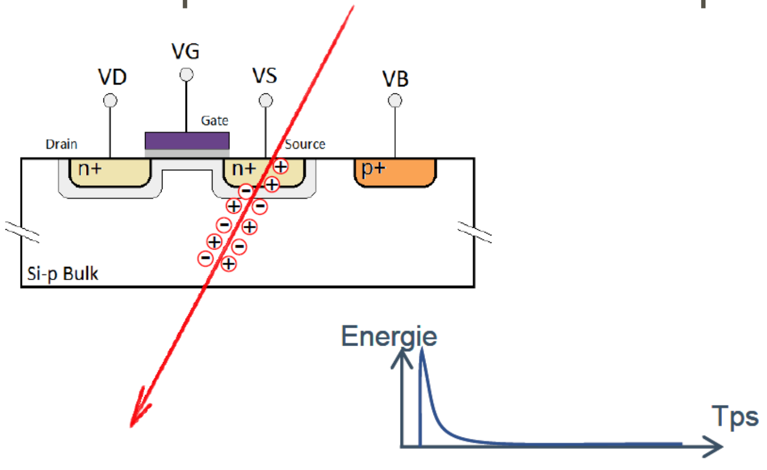
VASCO Cf252 facility at TRAD

- Test in vacuum => same constraints than heavy ion beams.

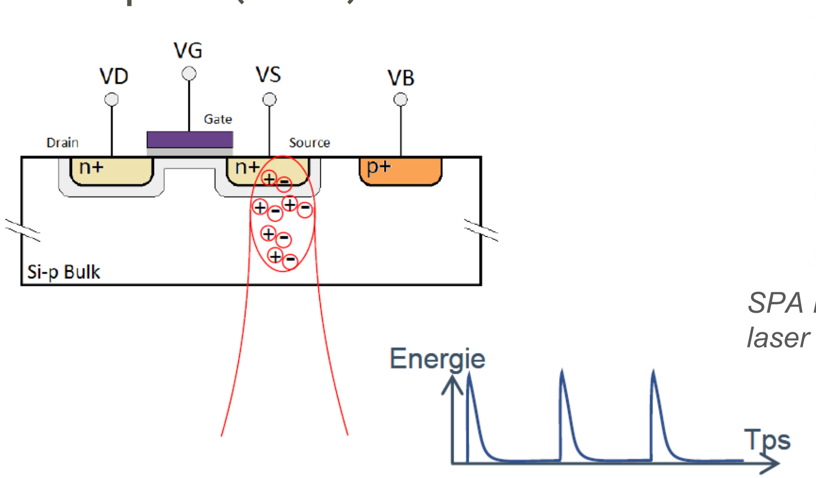
Complementary facility: Laser source

Pulsed laser beam is not a standard facility.

- Used by space community for SEE complementary investigations or hardware validation.
  - Localization of sensitive areas (spot size 1µm)
  - Fault injection "at home"
  - Optical transmission of photons: λ<1064nm (in Si)

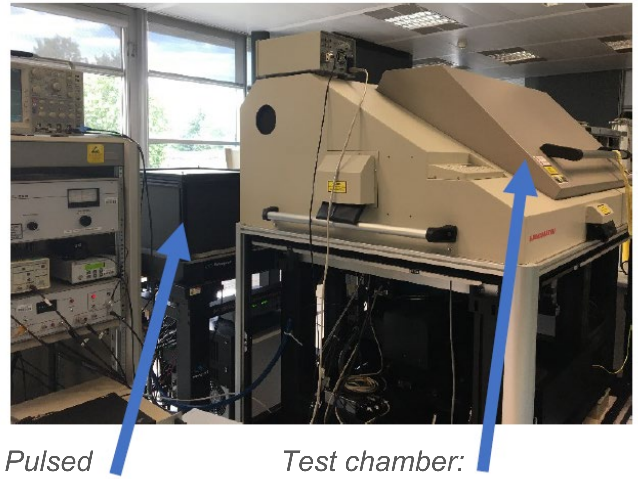


Ion charge deposition



SPA Pulsed laser charge deposition

CNES facility – ©G. BASCOUL



SPA Pulsed laser source

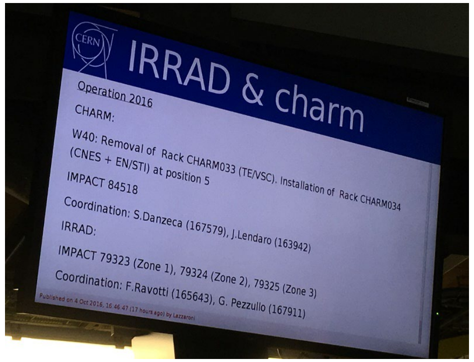
Test chamber: Dark room in air

- Backside irradiation: to avoid metal lines shadowing
- Sample preparation: thinning and polishing.
- Two Photo Absorption: better localization in z but much more complex than SPA

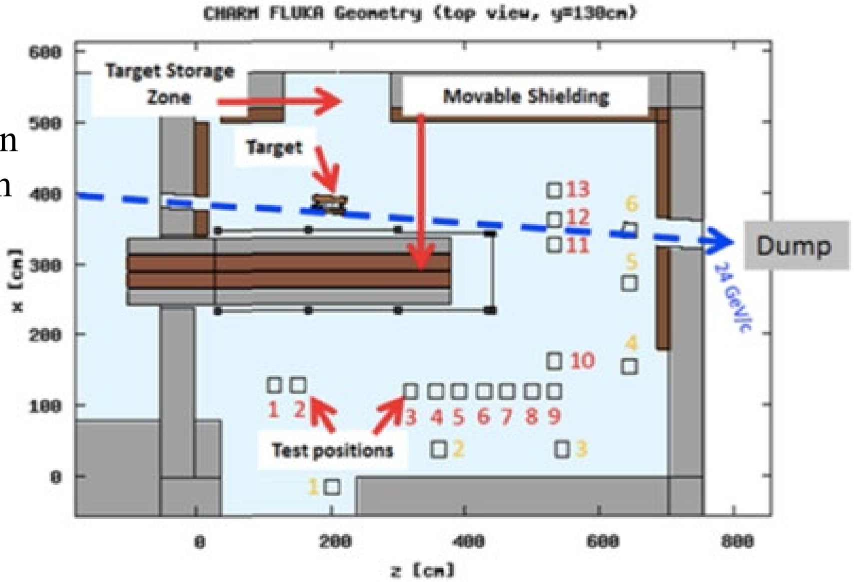
Complementary facility: Mixed- field

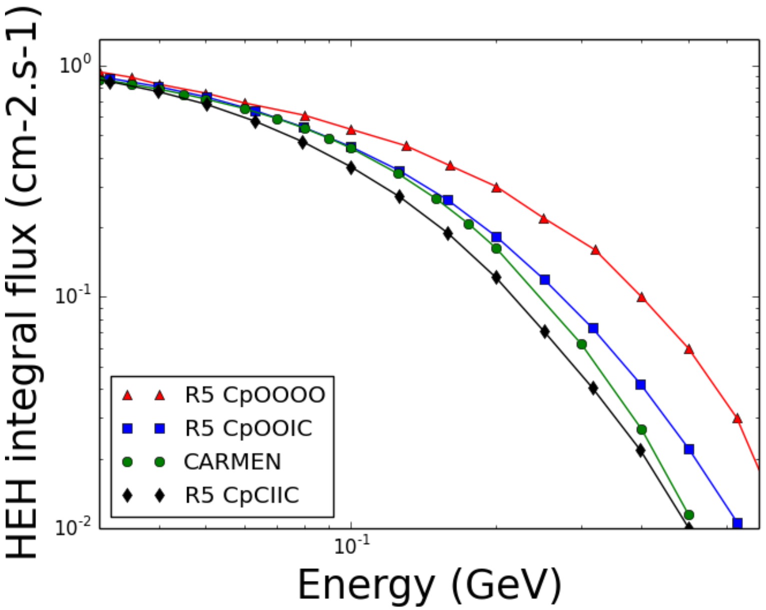
CERN High energy AcceleRator Mixed field facility (CHARM), Geneva, Switzerland

- Used for component/system level fault injection vs mission profile
  - Mixed (p+, n, …) spectrum 0-200MeV up to 24GeV.
  - Various irradiation conditions with DUT location and shielding combinations
  - Possibility to irradiate component, board, equipment



24GeV proton primary beam





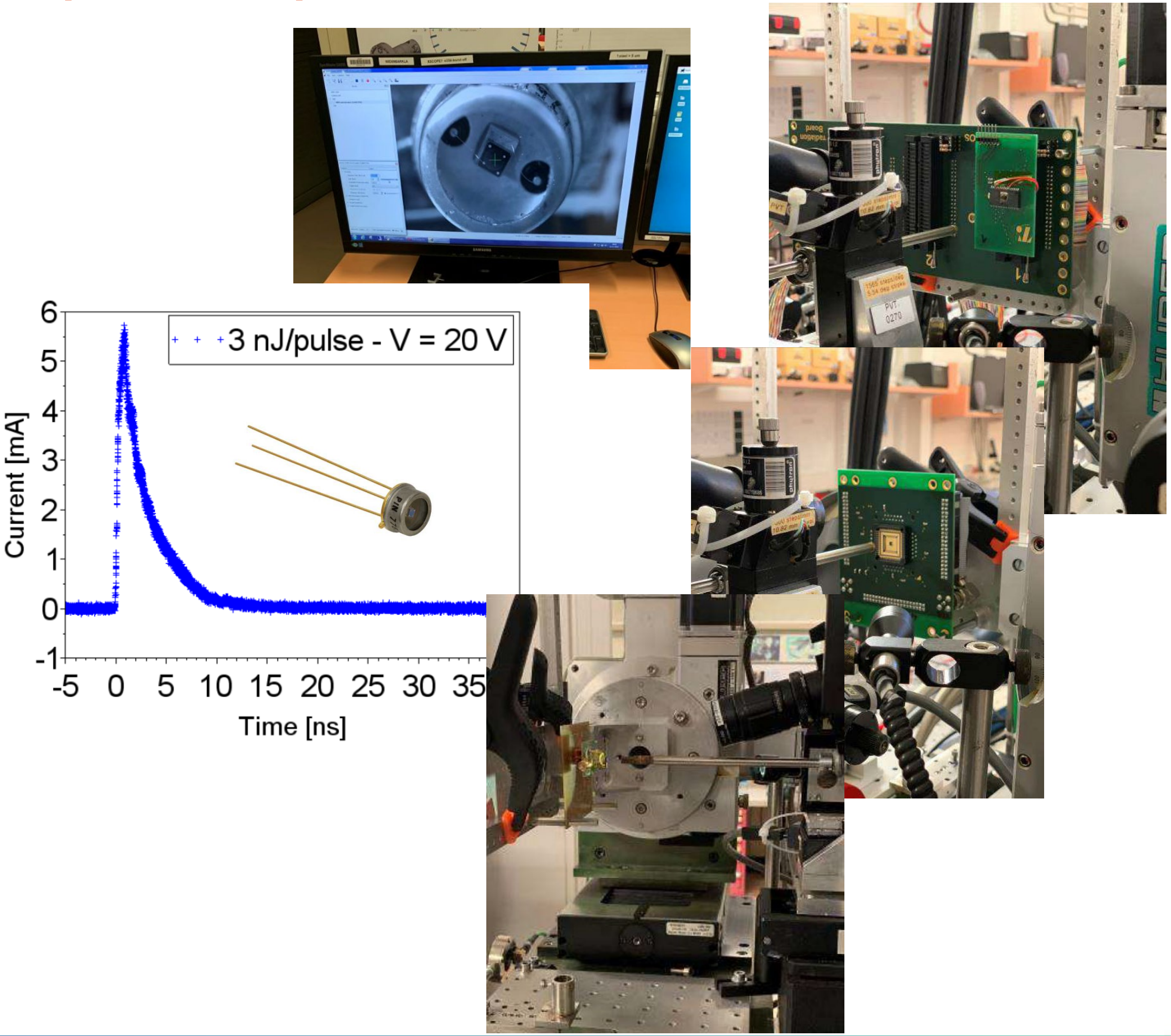
Comparison of integral flux for space (CARMEN) and different configuration in position 5 normalized to the HEH flux at 20MeV

Complementary facility: Pulsed X-Rays

European Synchrotron Radiation Facility (ESRF), Grenoble, France

- First validation test campaign end 2018
- Second campaign On-Going
  - Spot size diameter 5-25µm
  - Pulse duration <100ps
  - Photon energy 7-30keV
  - Pulse energy: 0,1-600nJ

- Energy deposition equivalence proven
- Continued in 2021
  - XY spot localization control
  - Energy selection vs thickness
  - Repeatability
  - SEL sensitive volume localization
  - Test of GaN power devices



QUESTIONS ?