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Heavy ions micro-beam study

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RADECS Thematic Workshop on European Accelerators – JYVASKYLA – 26th of May, 2005

OUTLINE

- Interest for a heavy ion micro beam.
  - Limitations of existing tools (heavy ions large beams and laser sources),
  - SEE characterizations,
  - Comprehension of basic phenomena,
  - Others.
- Specifications.
  - LET, range, spot size, beam flux…
- Available quasi-equivalent facilities.
- UCL proposal and perspectives.

Why an heavy ion micro beam?

- Could be a **complementary tool for SEE characterization** of electronic components and/or the study of specific phenomena.
- Compared to laser source, heavy ions micro beam offers the possibility to test the electronic devices **without any problem of metal shadowing** and with a more realistic charge collection mechanism (calibration not necessary).
- Compared to heavy ion beam, a micro beam allows the **identification of sensitive areas** and the **study of rare phenomena**.
- It gives the space community a chance to **increase the comprehension of basic phenomena.**
- It could also be used in a near future for the characterization of nanotechnologies such as carbon nanotubes…

Micro beam versus large heavy ion beam and laser source:

	Heavy ions beam	Laser	Heavy ions microbeam
Particle	Ion	Photon	Ion
Beam diameter at DUT level	A few cm	Down to 1µm	Down to 1µm
Limitations	Range ~ several tenth of µm in Si	Shadowing of metal layers	Range ~ several tenth of µm in Si
Localization of sensitive areas	No	Yes	Yes
Study of rare phenomena	No (problems of dose)	Yes	Yes
Event rate calculation	Yes	No	Yes

Opportunities for electronic devices studies.

- Support to design hardening. (identification of sensitive structures, comparison between various design options,…).

- SEE Expertise and Research tool: determination of sensitive structures (area and depth), investigation of physical phenomena (SEL, SET, SEB, SHE,…) in order to reach a better comprehension of basic phenomena.

- Rare phenomena characterization: µSEL, SEFI, MBU,…

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Study of rare phenomena

- **Large heavy ion beams** are optimized for **homogeneous distribution** of particles over the whole DUT surface.
- For a DUT area of 1cm², a maximum total fluence of 10^7 ions/cm² corresponds to 1 ion per 10µm².
- In recent VLSI (e.g. 256Mbit DRAM in a 2cm² die), the elementary cell area is lower than 1µm².
- This will increase with the integration of technologies.

=> SEE characterization performed with a large heavy ion beam cannot guarantee the immunity to rare phenomena such as $SEFI_1$ or $Burst_2$ in dense processors and/or memories.

- Example: *Bursts into SPOT5 mass memory. Some rare events were observed during the ground testing while in-flight anomalies are mainly due to these bursts (SEU are corrected by EDACs). In addition, in flight data revealed unpredicted signatures for these bursts.*

1: SEFI = Single Event Functional Interrupt

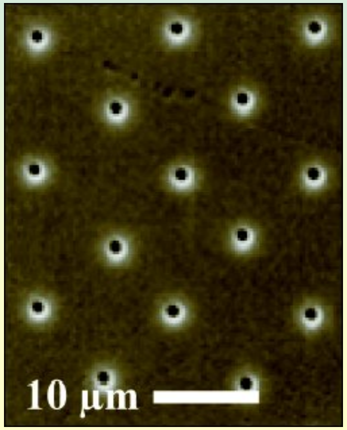
2: Burst = large amount of bits corrupted due to a single upset in a particular bit (selection line for example)

Study of rare phenomena

- **Various solutions:**
  - Increase the total fluence leads to high dose levels: not acceptable for all DUTs (pb for COTS).
  - The use of laser source has limitations in terms of charge collection mechanism and metal shadowing.
  - CEU: Computer Emulated Upset requires a complete characterization of all registers (same pb) and a very good description of functional description.
  - Use heavy ions micro beam seems to be the most confident technique.

Other opportunities

- Materials and Nanotechnologies: ion tracks can be used for nano structuring (diameter~10nm, variable length by choosing appropriated sample thickness.



Regularly spaced (10 µm apart) single ion tracks in a polymer matrix (picture from GSI Darmstadt). The close and regular spacing is achieved by using a focused ion beam (microbeam) and single ion detection.
(From Europhysics news n°5 Sept/Oct 2004).

- Biotechnology: investigation of cellular response to low doses of radiation (mono ion beam)

Specification of a new european heavy ion micro beam dedicated to SEE investigations:

- Spot size: down to 1µm.
- Range in silicon: >40µm.
- LET in silicon: 0 to 60 MeV/(mg/cm²).
- Beam flux: Screening a DUT shall require less than 1 hour per ion (beam time).

Heavy ions micro beams available for SEE tests.

- USA: (SANDIA) Albuquerque, New-Mexico
  Tandem => limited energy => LET and range too low.
- Europe: (GSI) Darmstadt, Germany.
  Linear accelerator => high energies available.
  Little or none access for industrial needs, mainly dedicated to high energy physics and research on material and biology.
- Japan: (JAXA/JAERI TIARA facility) Takasaki.
  Cyclotron with Flat Top Acceleration System => Only a few ions compatible with the FTAS => $(LET_{max})_{Si}$~28MeV/(mg/cm²).

Specifications versus UCL cyclotron

- LET/range specification are compatible with UCL 88inch Cyclotron and M/Q=3.3 cocktail.
- An additional ion with a LET in Si around 60MeV/(mg/cm²) shall be added (already under development for HIF).
- PPAC detector and diffusion foil used on HIF line are no more necessary.
- The beam monitoring system shall be replaced due to specific beam intensity needs.

UCL proposal

Current M/Q=3.3 ion cocktail + Xe (under development)

Ion	Charge	M/Q	Ecyclo	LET(Si)	Range(Si)	Mass
C - 13	4	3.25	133	1.2	276	13.00115
Ne - 22	7	3.14	241	3.2	207	21.98754
Si - 28	8	3.50	248	6.6	115	27.97253
Ar - 40	12	3.33	390	9.9	125	39.95578
Ni - 58	18	3.22	603	19.9	106	57.92545
Kr - 83	25	3.32	813	31	100	82.90039
Xe - ??	TBD	TBD	TBD	TBD	TBD	TBD

Remark:
Ion change will take more time than for HIF because more complicated (optical parameters of the line shall be adjusted for each ion).

UCL proposal

- Spot size:
  - Screening of sensitive area could be done in several steps using 4 sizes of beam spot:
    - 1 X 1 mm^2
    - 100 X 100 μm^2
    - 10 X 10 μm^2
    - 1 X 1 μm^2
- 2 cases when performing SEE characterization on electronic devices:
  - VLSI: sensitive volumes may be very small => requires the 4 spot sizes.
  - Others: bigger sensitive volume => 10µm x10µm is enough.

UCL proposal

- Worst case: screening of the whole surface of a DUT (~1cm²) in 400 steps when searching for a unique very small sensitive node:
  - 100 pass with 1mm² spot size
  - 100 pass with 10000 µm² spot size
  - 100 pass with 100 µm² spot size
  - 100 pass with 1 µm² spot size
- How long does it takes?
  - Depends on the beam flux.

UCL proposal

- Beam flux: up to 10^8 ions/s.cm²
  - If a tested area is considered sensitive after 10 events detected, for a nominal Xsection=10^{-4} cm²/device and a unique sensitive volume:

Step	Beam spot	Tested area	Flux for 10 SEE	Run duration (10 SEE)
1	1 X 1 mm	10^{-6} m²	10^5 ions / s cm² [*]	1s (fast screening)
2	100 X 100 µm	10^{-8} m²	10^4 ions / s cm² [**]	10s
3	10 X 10 µm	10^{-10} m²	10^6 ions / s cm² [**]	10s
4	1 X 1 µm	10^{-12} m²	10^8 ions / s cm² [**]	10s

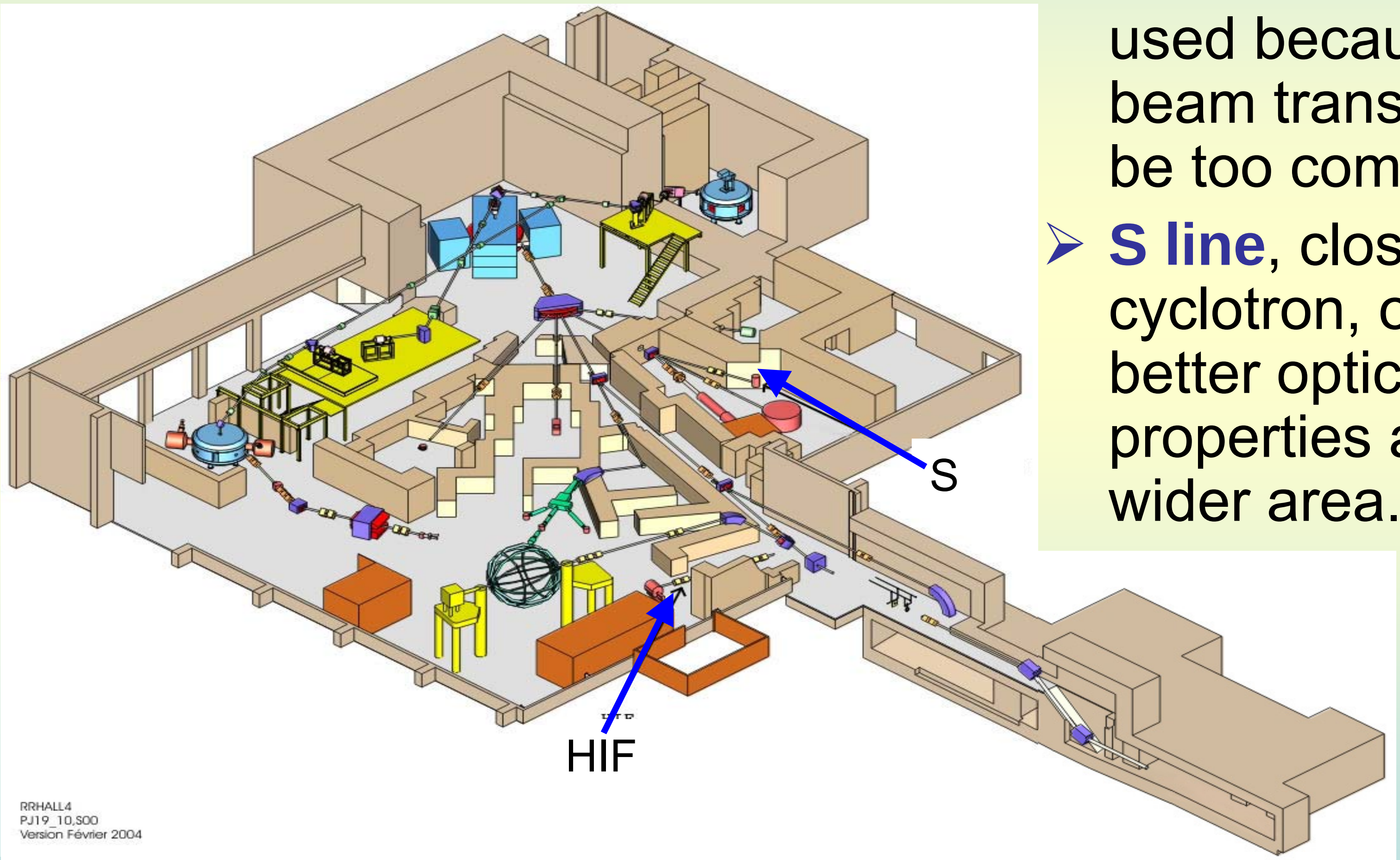
** If the test system is able to record 10 events/s*

*** for 1 ion/s in the tested surface and 10 events recorded.*

=> 3100s

  - In the case of rare SEE (Xsect~10^{-6}cm²/device), fluxes at steps 1 to 3 can be enhanced by a factor 100. Last step (1µmx1µm) duration will be 100 times longer.

Technical solution:



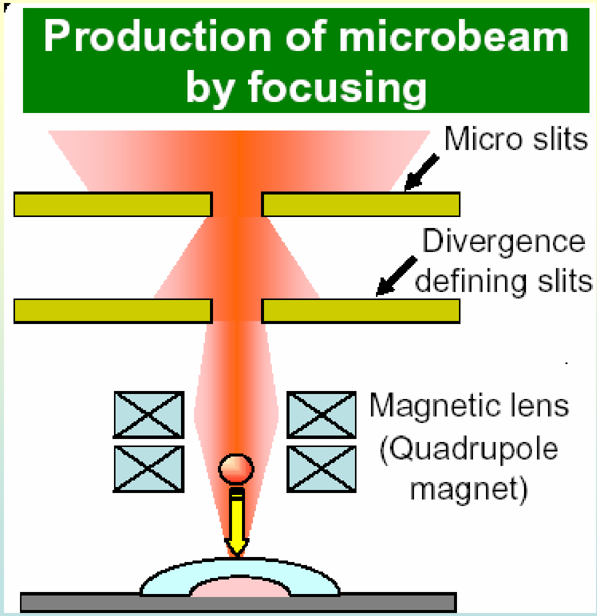
- **HIF line** cannot be used because optical beam transport would be too complex.
- **S line**, closer from the cyclotron, offers better optical properties and also a wider area.

Technical solution:

- The major difficulty with a cyclotron is the chromatic aberration ($\Delta E/E \approx 10^{-3}$) that determine the spot size at DUT level.
- TIARA facility uses a "Flat-Top" Acceleration System in order to reduce this energy spread: A cavity has been added that combines the 5th harmonic. It is then possible to focus the beam down to 1mm² using magnetic lenses (quadrupole magnet). The final spot is resized using two micro slits.
- The geometry of UCL cyclotron cavities doesn't allow this solution.

=> best solution:

slits coupled to a focusing system.



Technical solution:

- Transport:
  - Several tests have been performed on line S1 with Argon beam (390MeV) in order to find the best possible beam geometry (smaller spot) at the last quartz level:

    ⇒Final size: 0,93cm x 0,39cm.

    ⇒ transport yield >62°/oo.
- Modifications on the line configuration:
  - A 4m long transport tube has been added after the 2 lasts quadrupoles with at its end a quartz, 2 pairs of manual slits and a precision Faraday coupled to a x1000 amplifier.

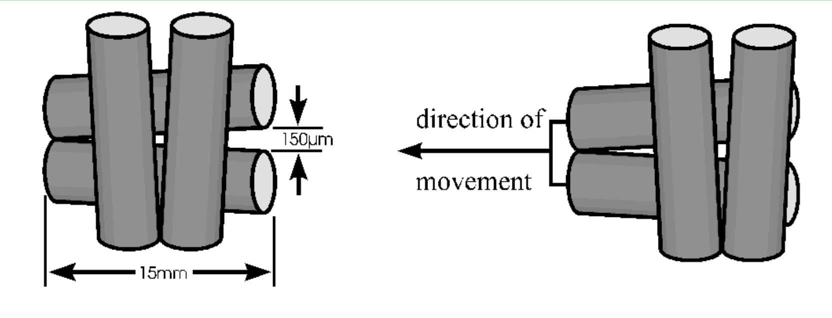
Technical solution:

- Beam intensity:
  - Worst case is for a maximum flux at the output of the line (10^8 ions/s.cm²) and the weaker transport yield (62°/oo).
  - 10^8 (ions/cm²)/s correspond to a beam intensity at cyclotron output: 16 pA particules / cm².

Ion	Charge	I S1.3 [elec pA]	I output cyclo [elec nA]
C - 13	4	64	1.0
Ne - 22	7	112	1.8
Si - 28	8	128	2.0
Ar - 40	12	192	3.1
Ni - 58	18	288	4.6
Kr - 83	25	400	6.5

Technical solution:

- Beam focusing:
  - First idea:
    reduce beam diameter using 2 sets of cylindrical micro slits (diameter 4mm): one at the beginning of the S1 line, the other at its end, close to the DUT.



  - Interaction of Argon 390MeV beam and the surface of the slits has been calculated using SRIM. This has shown problems of beam scattering and energy straggling => Solution abandoned
  - A new focusing system, based on magnetic quadrupoles is under study.

Perspectives

- Technical needs for a new European heavy ions micro beam have been identified.
- Technical definition is in progress. Some solutions have been abandoned (Flat Top Acceleration System and micro-slits focusing system).
- Beam generation and transport line have been calibrated and tested with a reference beam ($^{40}Ar^{12+}$ 390 MeV),
- A new focusing system based on magnetic lenses is under study.
- Next step will consist in a complete calibration with the whole ion cocktail.