The SIRAD irradiation facility

at the INFN - Legnaro National Laboratory

I. Introduction

The INFN - Legnaro National Laboratory (LNL)

http://www.lnl.infn.it

What is SIRAD?

SIRAD is the acronym for SIlicon and RADiation.

The SIRAD irradiation facility is dedicated:

"to investigate radiation effects
on silicon detectors, electronic devices and systems
in radiation hostile environments".

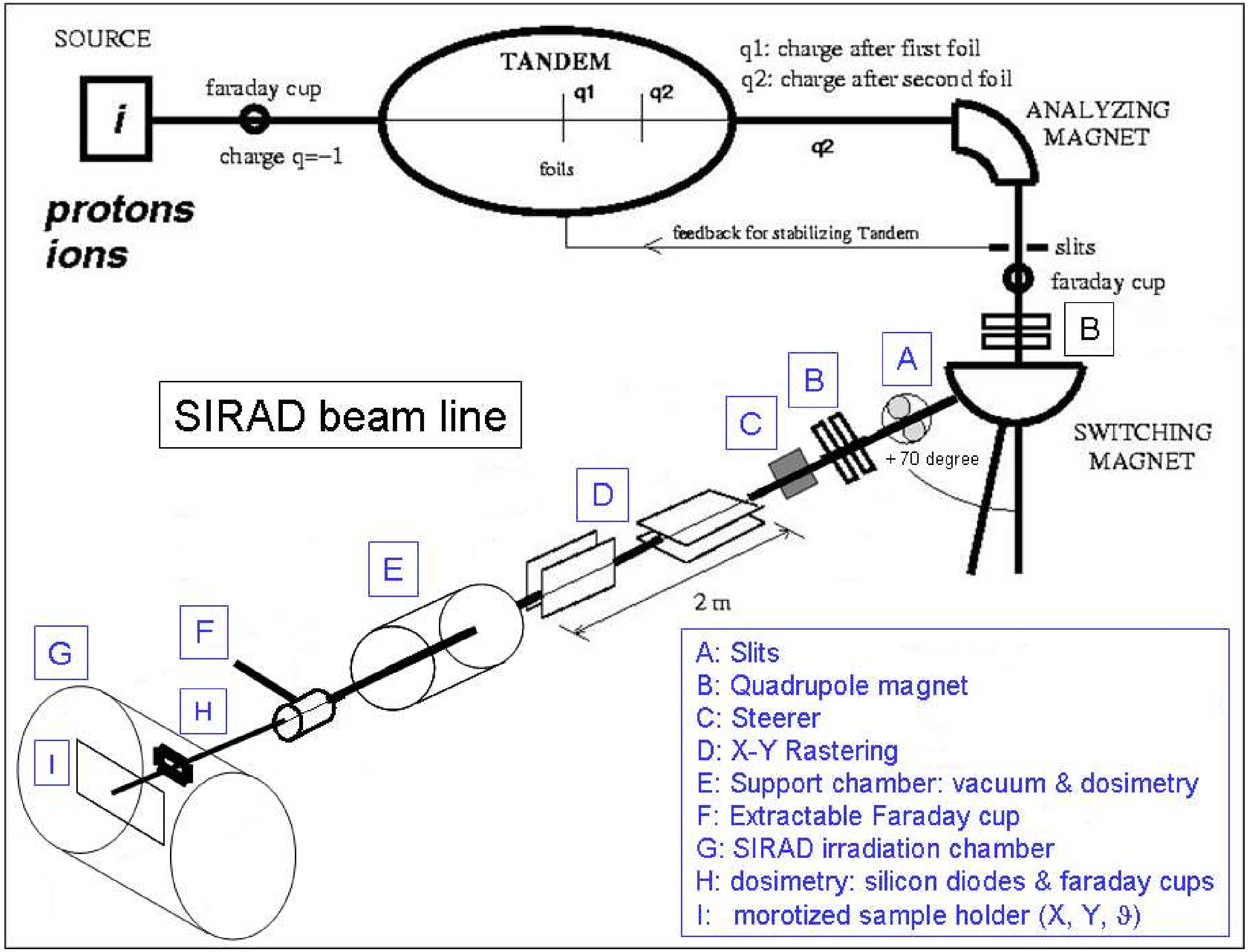
-Total dose effects as a result of ionization damage.
-Bulk effects as a result of displacement damage.
-Single event effects (SEE) as a result of an energetic particle strike and micromapping of the ion impacts for SEE studies by an Ion Electron Emission Microscope (IEEM): http://sirad.pd.infn.it/IEEM_IF/index.html

-High energy physics experiments.
-Space missions of scientific and commercial satellites.

The SIRAD Irradiation Facility

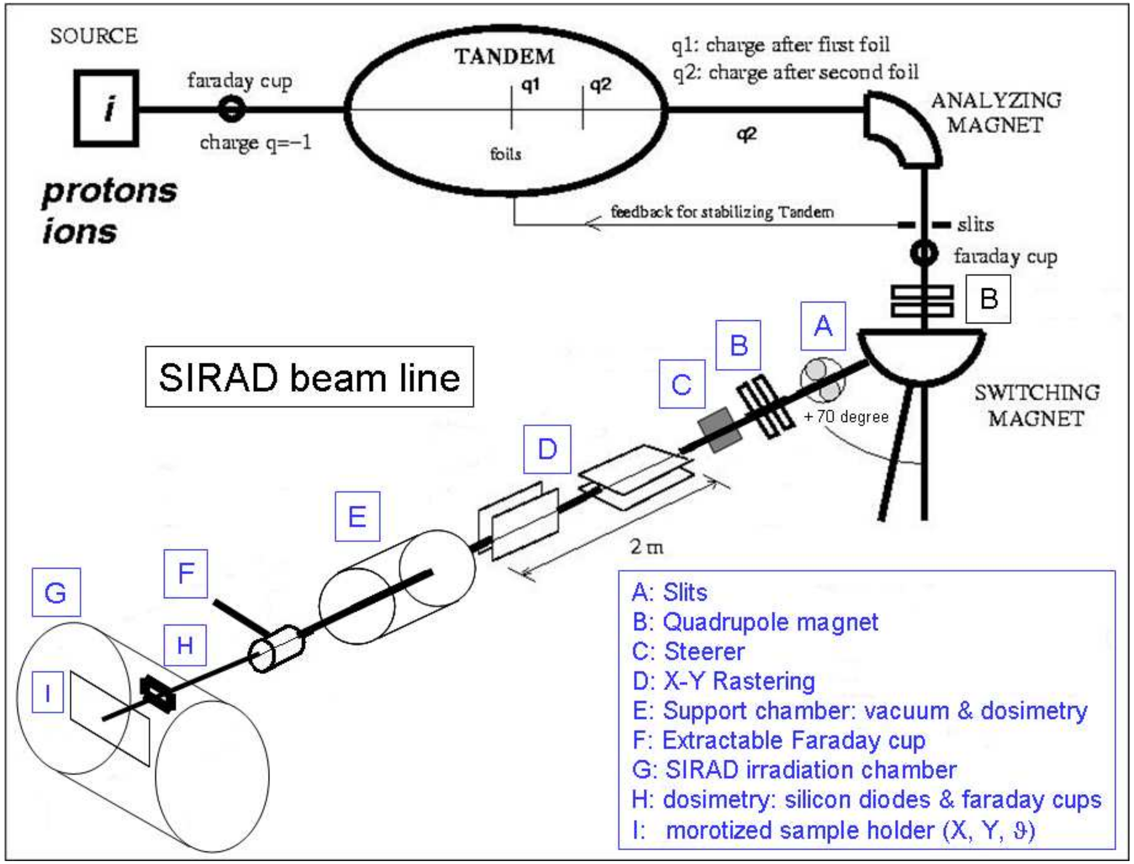
The SIRAD irradiation facility is located at the Tandem accelerator of the INFN National Laboratory of Legnaro (Padova, Italy).

Tandem accelerator: -Van de Graaff type; 15 MV maximum voltage; two strippers;
-servicing 3 experimental halls for nuclear and interdisciplinary Physics;

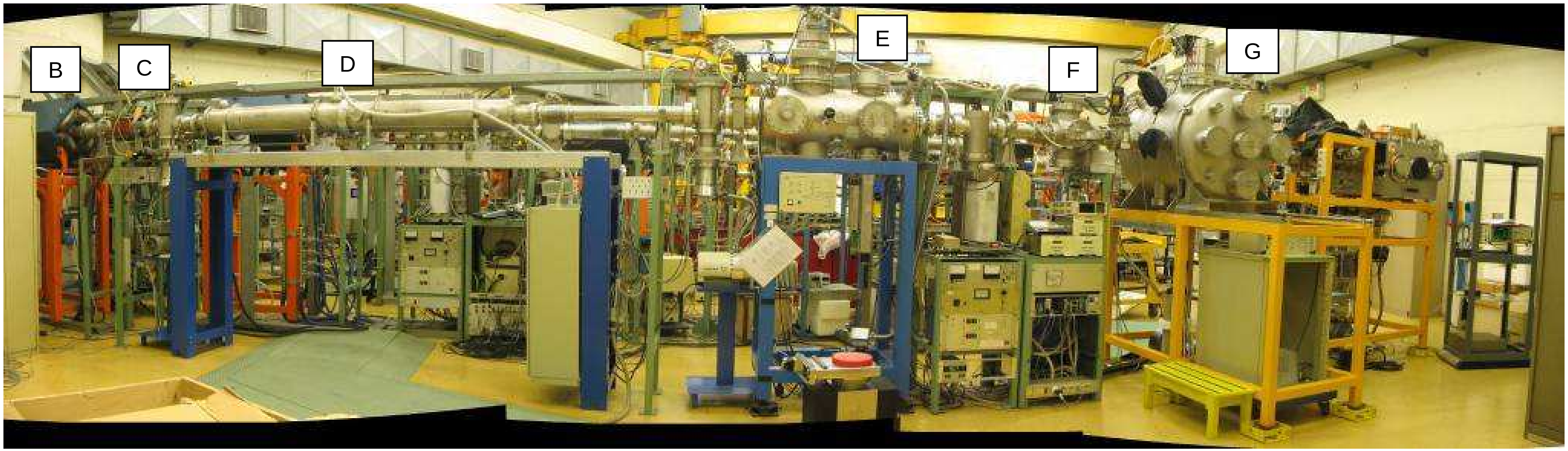


Schematics of the 15 MV **Tandem** Van de Graaff **accelerator** and of the **SIRAD irradiation facility** at the +70° beam line.

The SIRAD Irradiation Facility



SIRAD beamline



Typical ion species available at SIRAD

- Ion species from ^{1}H (22-30 MeV) up to ^{197}Au (1.4 MeV/a.m.u.)
- LET from 0.02 MeV×cm^2/mg (^{1}H) up to 81.7 MeV×cm^2/mg (^{197}Au)

The energy values refer to the most probable q_1 and q_2 charge state, with two stripper stations, and the Tandem operating at 14 MV.

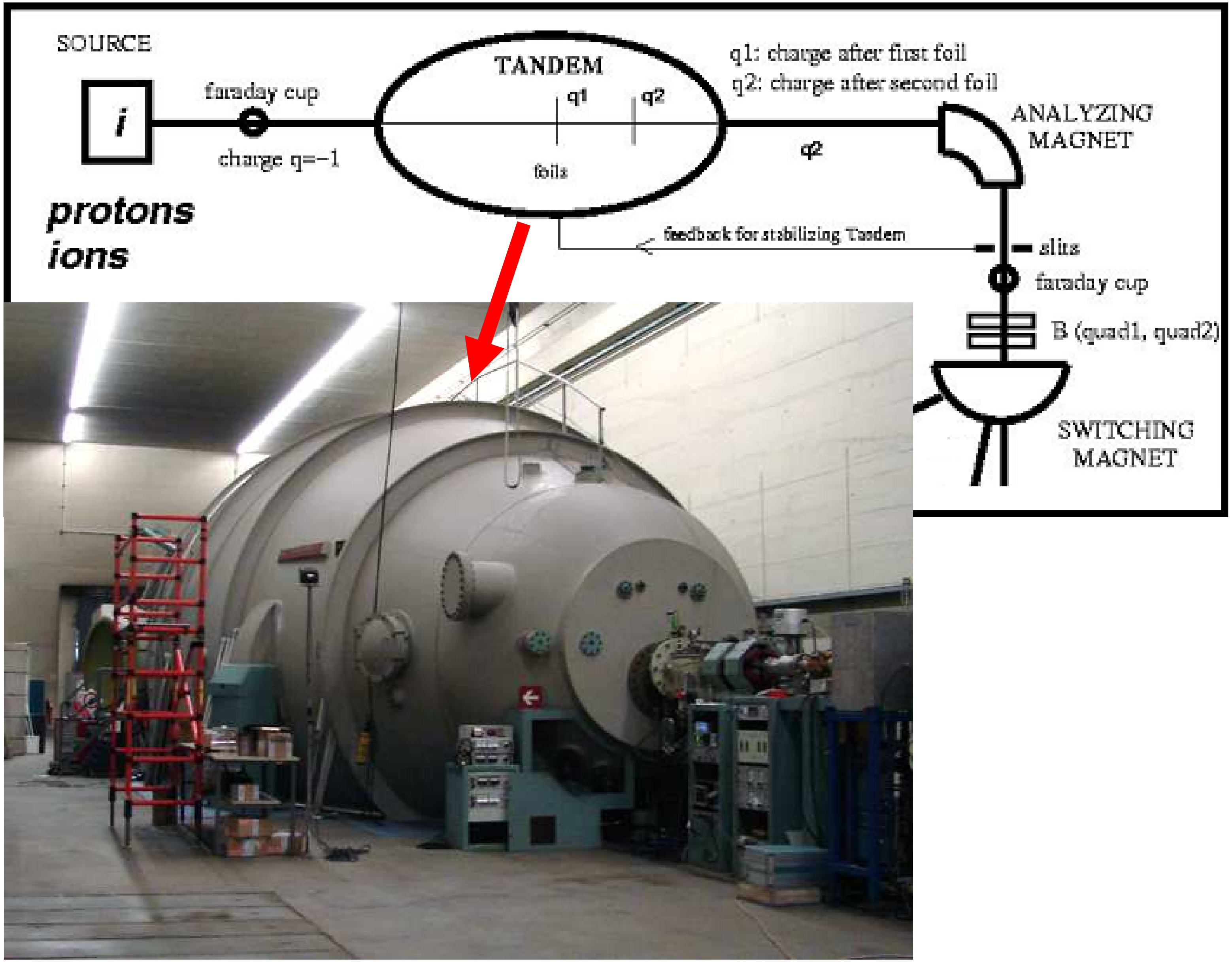
Ion Species	Energy (MeV)	q_1	q_2	Range in Si (µm)	Surface LET in Si (MeV×cm^2/mg)
^{1}H	28	1	1	4390	0.02
^{7}Li	56	3	3	378	0.37
^{11}B	80	4	5	195	1.01
^{12}C	94	5	6	171	1.49
^{16}O	108	6	7	109	2.85
^{19}F	122	7	8	99.3	3.67
^{28}Si	157	8	11	61.5	8.59
^{32}S	171	9	12	54.4	10.1
^{35}Cl	171	9	12	49.1	12.5
^{48}Ti	196	10	14	39.3	19.8
^{51}V	196	10	14	37.1	21.4
^{58}Ni	220	11	16	33.7	28.4
^{63}Cu	220	11	16	33.0	30.5
^{74}Ge	231	11	17	31.8	35.1
^{79}Br	241	11	18	31.3	38.6
^{107}Ag	266	12	20	27.6	54.7
^{127}I	276	12	21	27.9	61.8
^{197}Au	275	13	26	23.4	81.7

1st multi-source

2nd multi-source

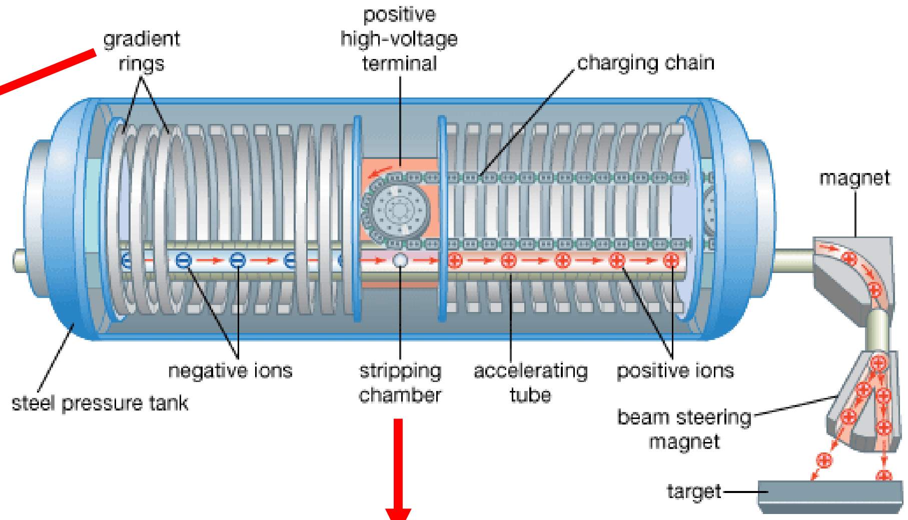
II. The Tandem accelerator

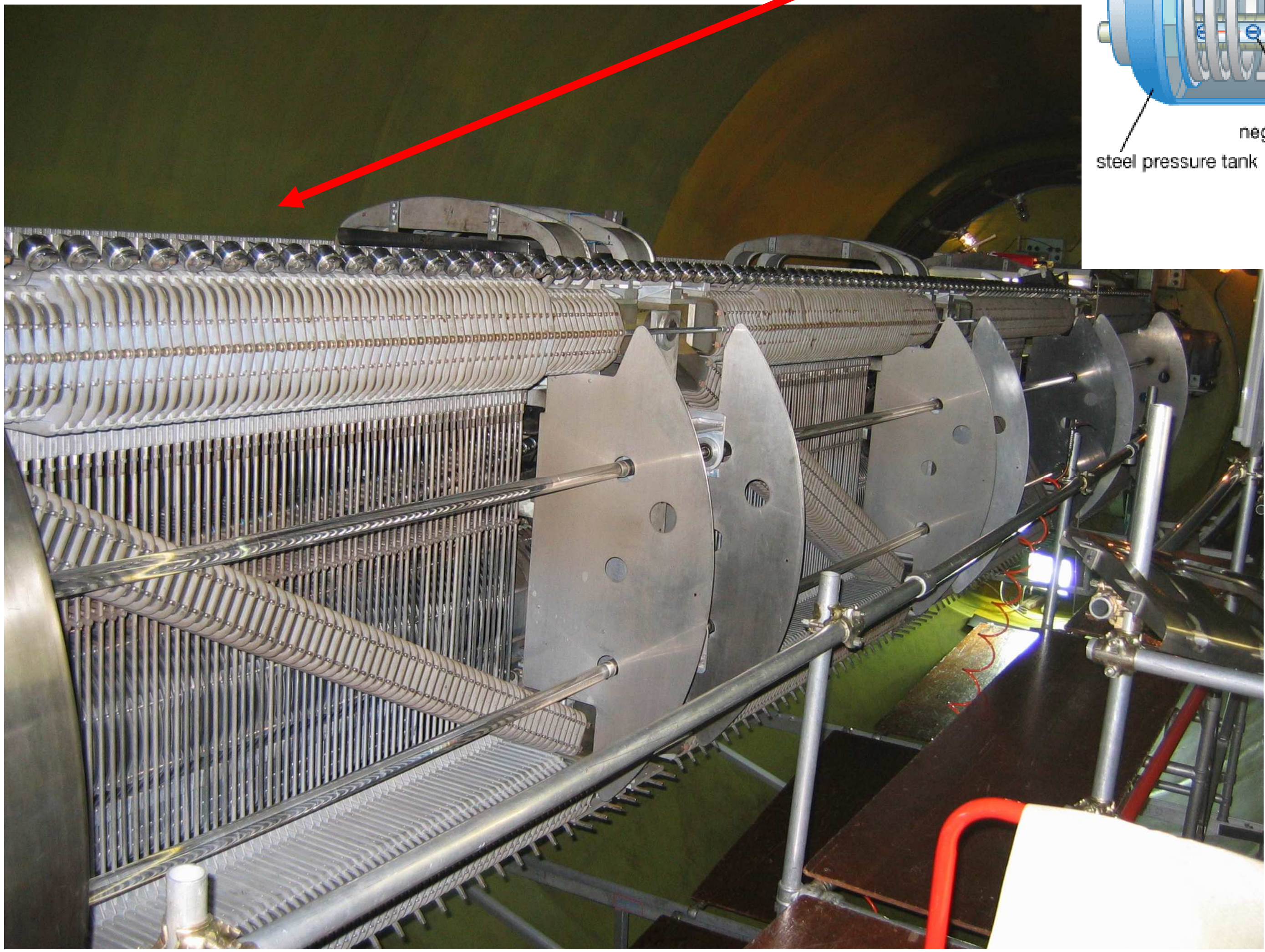
The Tandem accelerator: outside

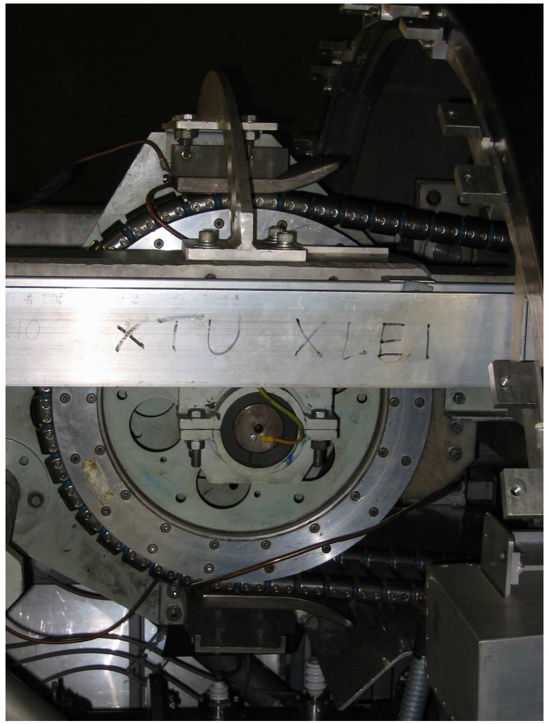


The tank of the Tandem accelerator called "Moby Dick"

The Tandem accelerator: inside

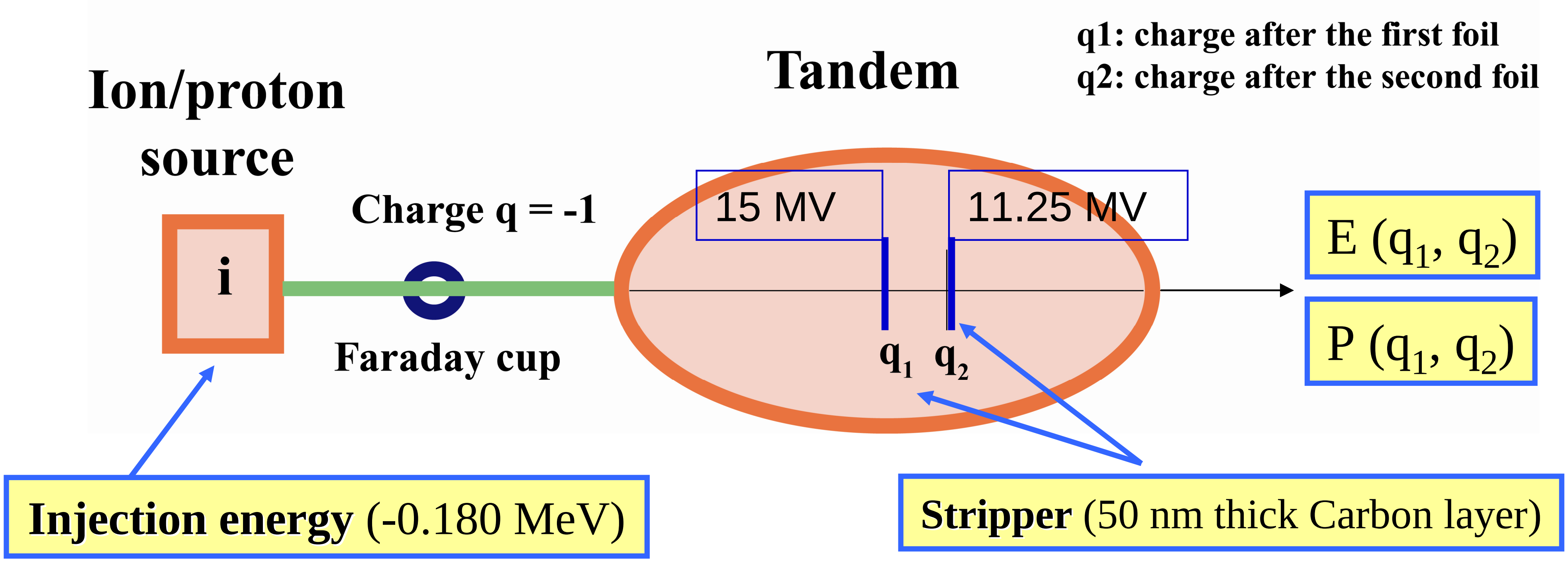






The Tandem accelerating column

The Tandem accelerator: ion energies



E(q_1,q_2): energy of an ion exiting the Tandem accelerator with charge q1 after the first stripper and q2 after the second stripper

$$E(q_1, q_2) = E_{inj} + V_0 \times (1 + 0.25 \cdot q_1 + 0.75 \cdot q_2)$$

P(q_1,q_2): probability that the charge state of an ion is q_1 after the first strippe and q_2 after the second stripper

$$\sum_{(q_1, q_2)} P(q_1, q_2) = 1$$

The analyzing magnet: to obtain a monochromatic beam

Each ion exiting the Tandem accelerator has a probability $P(q_1,q_2)$ to be ionized with a charge state q_1 after the first stripper foil and with a charge state q_2 after the second stripper foil. The energy of the ions exiting from the Tandem accelerator depends on the ion charge state after the first (q_1) and after the second stripper foil (q_2)

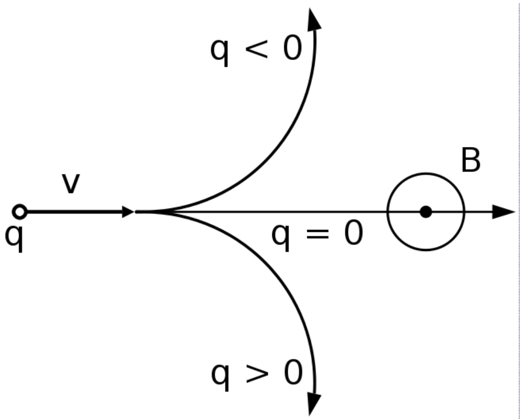
$$\boxed{P(q_1,q_2)}$$

$$\boxed{E(q_1,q_2) = E_{inj} + V_0 \times (1 + 0.25 \cdot q_1 + 0.75 \cdot q_2)}$$

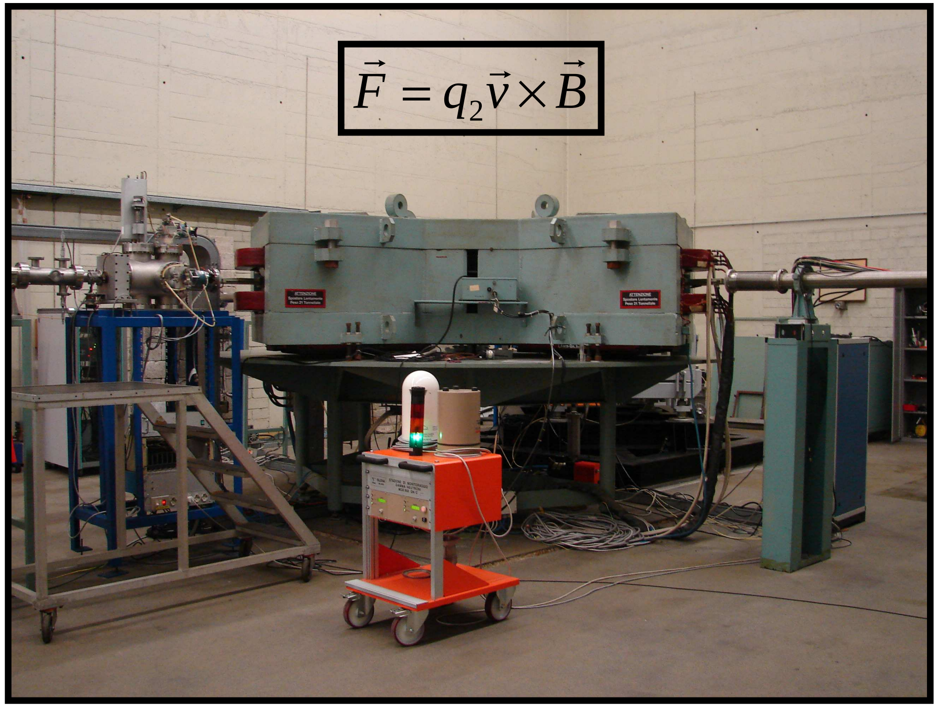
The analyzing magnet, which allows to deflect by an angle of 90 degree the ions of mass m having a charge state q_2 and a velocity v by the Lorentz force, allows to select an ion specie with a fixed energy, i.e. it allows to obtain a monochromatic beam:

$$F_r = q_2 vB = m\frac{v^2}{r}$$

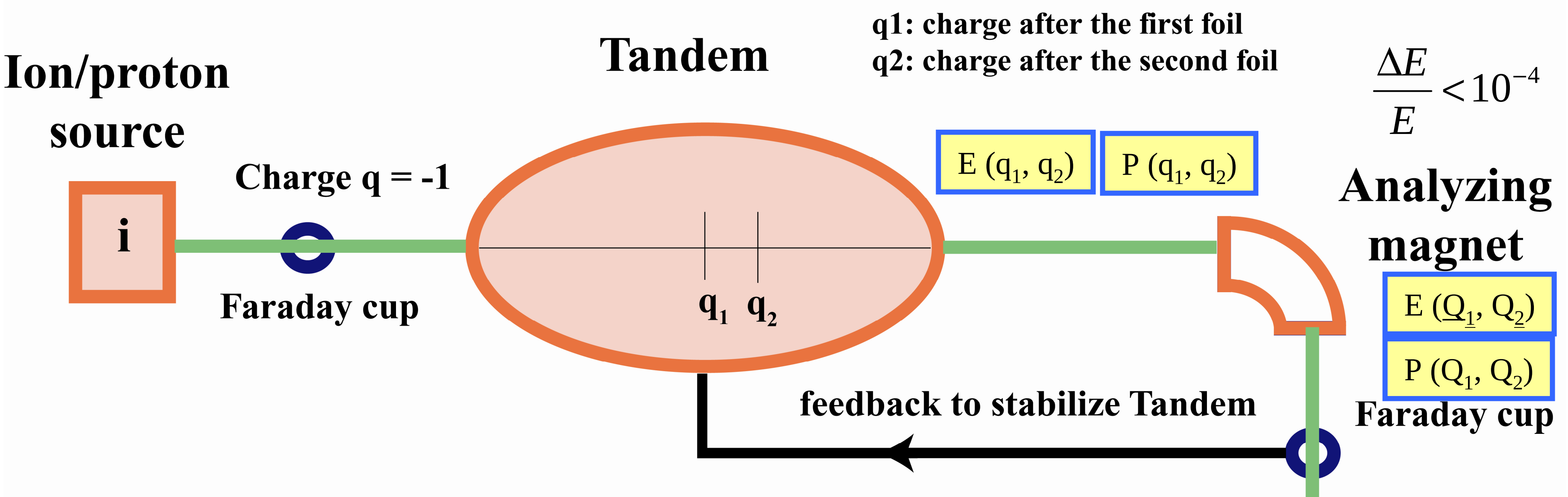
$$r = \frac{mv}{q_2 B}$$

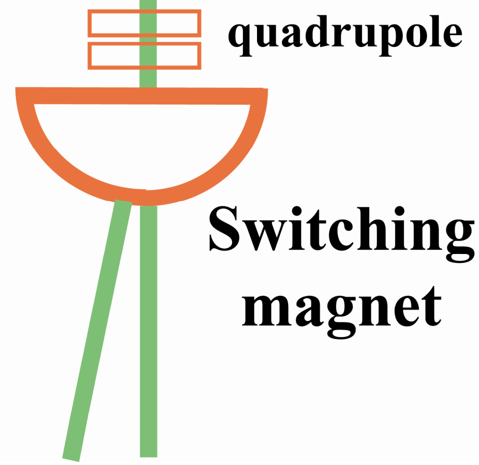


$$r = \frac{\sqrt{2mE_C}}{q_2 B}$$



The switching magnet: to deviate the beam to the experimental lines



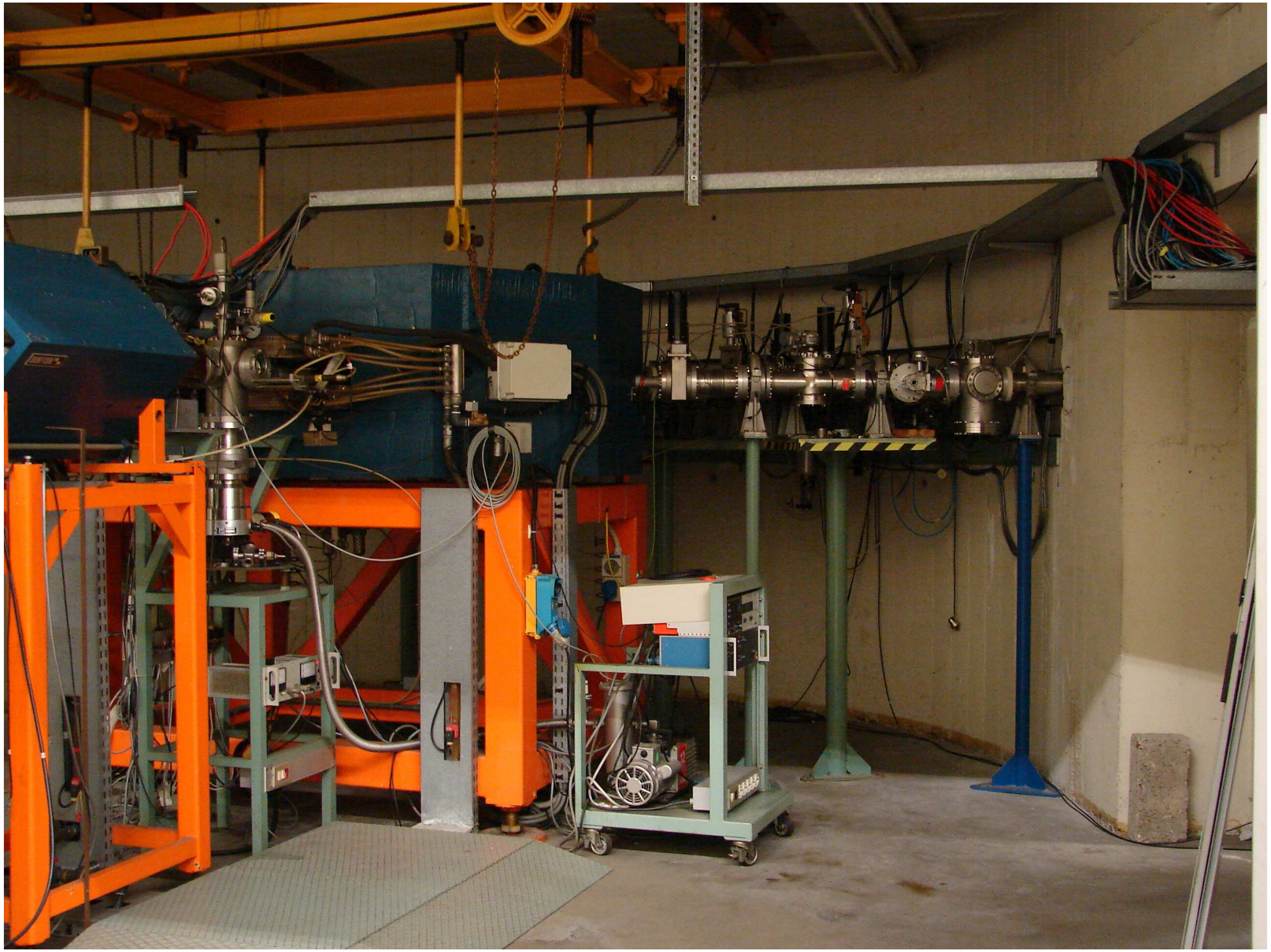


1) The ion current entering the Tandem accelerator is divided, at the exit of the Tandem accelerator, in ions with different energies $E(q_1,q_2)$, each with its own probability $P(q_1,q_2)$.

2) The analyzing magnet allows to select ions with only one energy $E(q_1,q_2)$.

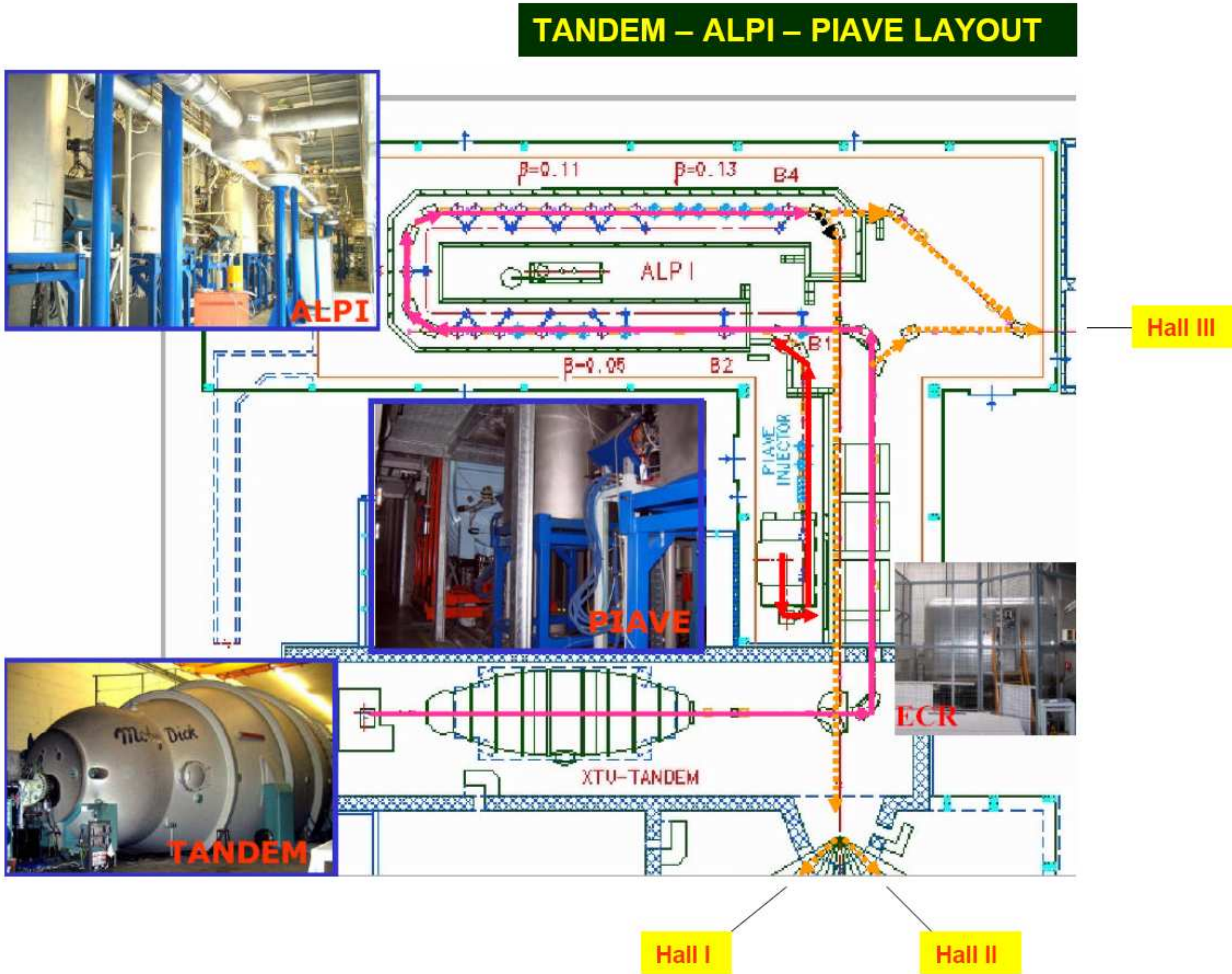
3) The switching magnet allows to deviate the monochromatic ions to the experimental beam lines.

The switching magnet: to deviate the beam to the experimental lines



The switching magnet from the side of the +70º experimental beam line

Tandem-ALPI complex



$$E_{\text{Tandem-ALPI}} = E_{\text{Tandem}} + E_{\text{ALPI}} = E_{\text{Tandem}} + Q_{\text{Tandem}} \times 35\ \text{MeV}$$

Comparison: Tandem accelerator and Tandem-ALPI complex

			Tandem			Tandem-ALPI		
Ion Species	q_1	q_2	Energy (MeV)	Range in Si (µm)	Surface LET in Si (MeV×cm^2/mg)	Energy (MeV)	Range in Si (µm)	Surface LET in Si (MeV×cm^2/mg)
^{1}H	1	1	28	4340	0.02	-----	-----	-----
^{7}Li	3	3	56	376	0.37	-----	-----	-----
^{11}B	4	5	80	185	1.13	-----	-----	-----
^{12}C	5	6	94	164	1.53	-----	-----	-----
^{16}O	6	7	108	107	2.95	-----	-----	-----
^{19}F	7	8	122	95	3.90	-----	-----	-----
^{28}Si	8	11	157	61	8.58	542	373	3.9
^{32}S	9	12	171	54	11.1	591	311	5.2
^{35}Cl	9	12	171	50	12.7	591	268	6.2
^{48}Ti	10	14	196	40	20.9	686	188	10.9
^{51}V	10	14	196	38	22.6	686	171	12.2
^{58}Ni	11	16	220	37	29.4	780	147	17.3
^{63}Cu	11	16	220	34	31.9	780	135	19.1
^{74}Ge	11	17	231	33	36.9	826	121	23.8
^{79}Br	11	18	241	33	41.8	871	112	28.1
^{107}Ag	12	20	266	29	58.4	966	83	49.4
^{127}I	12	21	276	30	65.4	1011	77	61.8
^{197}Au	13	26	275	26	79.1	1185	69	92.4

6 x

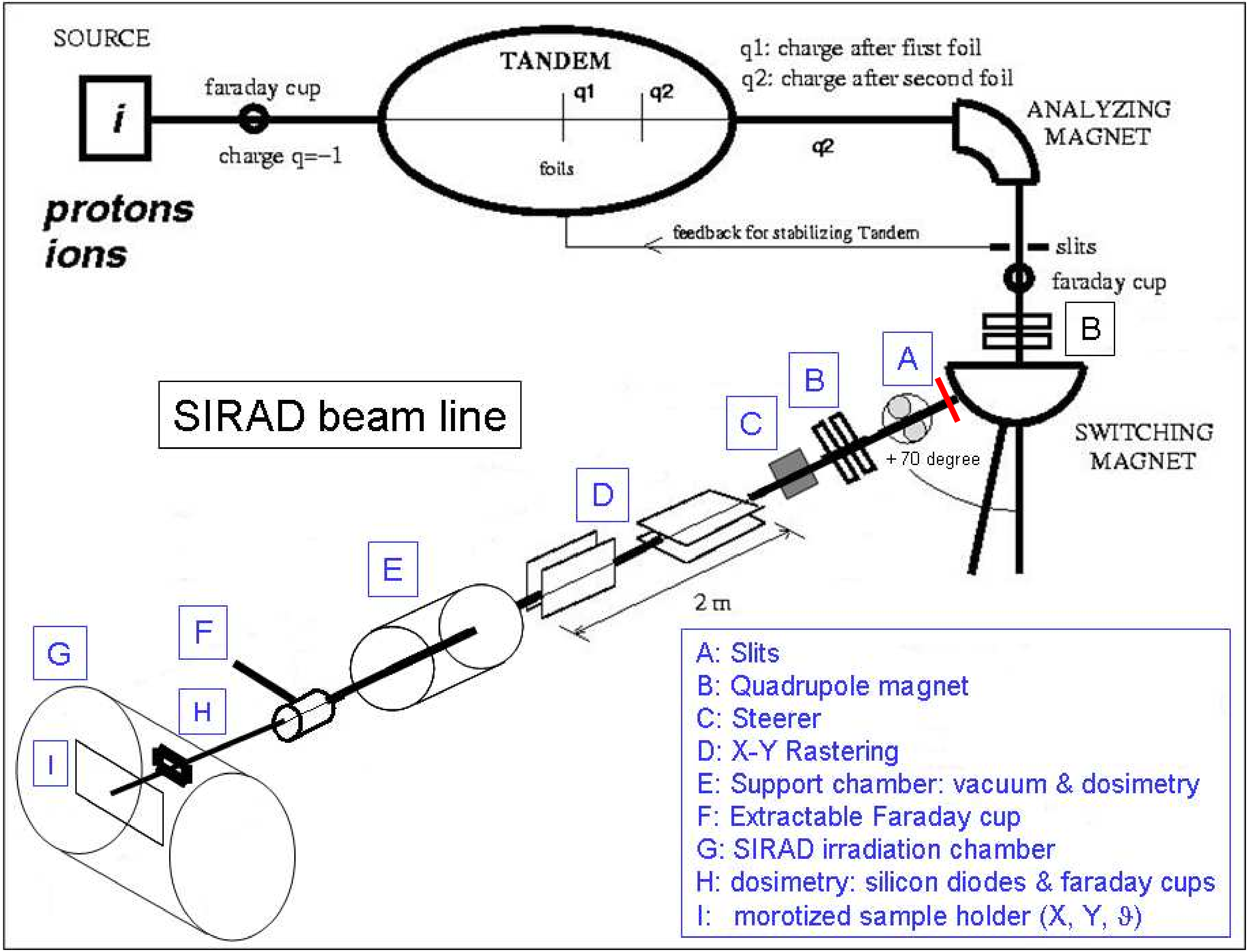
$\frac{1}{2}$ x

2.9 x

0.8 x

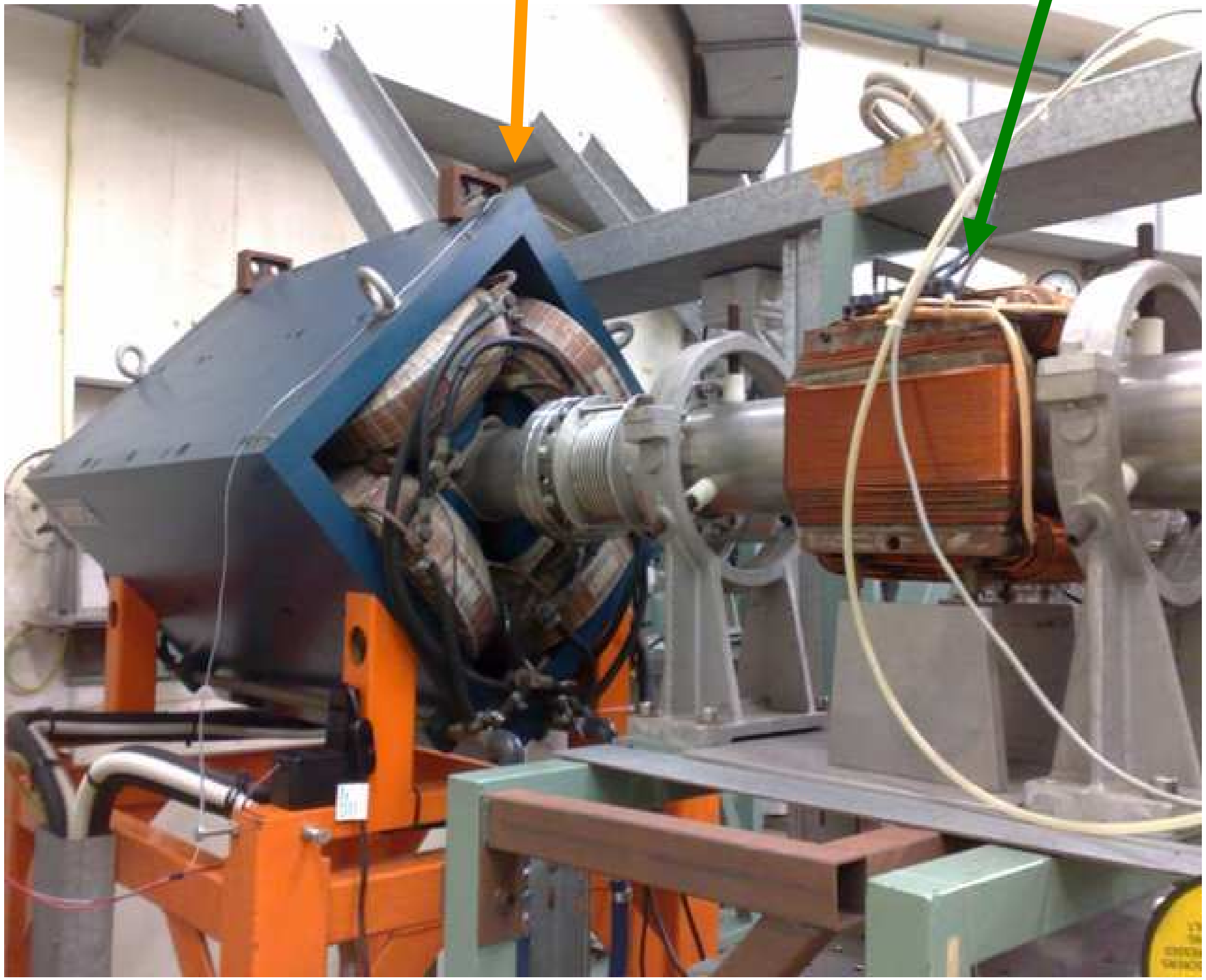
III. The SIRAD irradiation facility

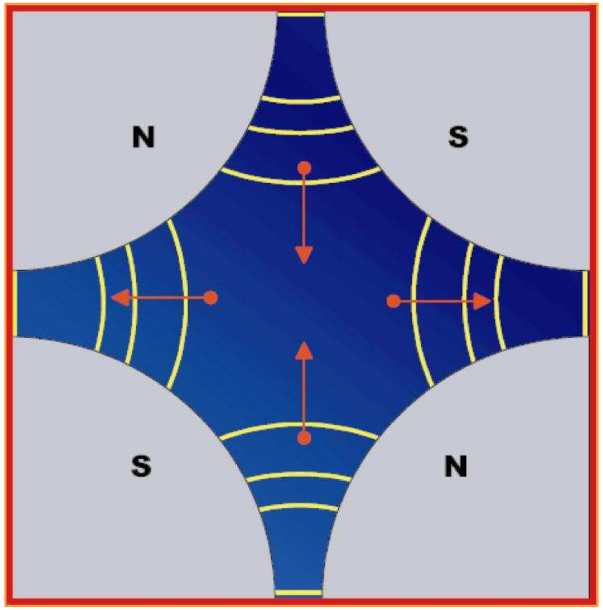
The SIRAD irradiation facility



SIRAD technical characteristics

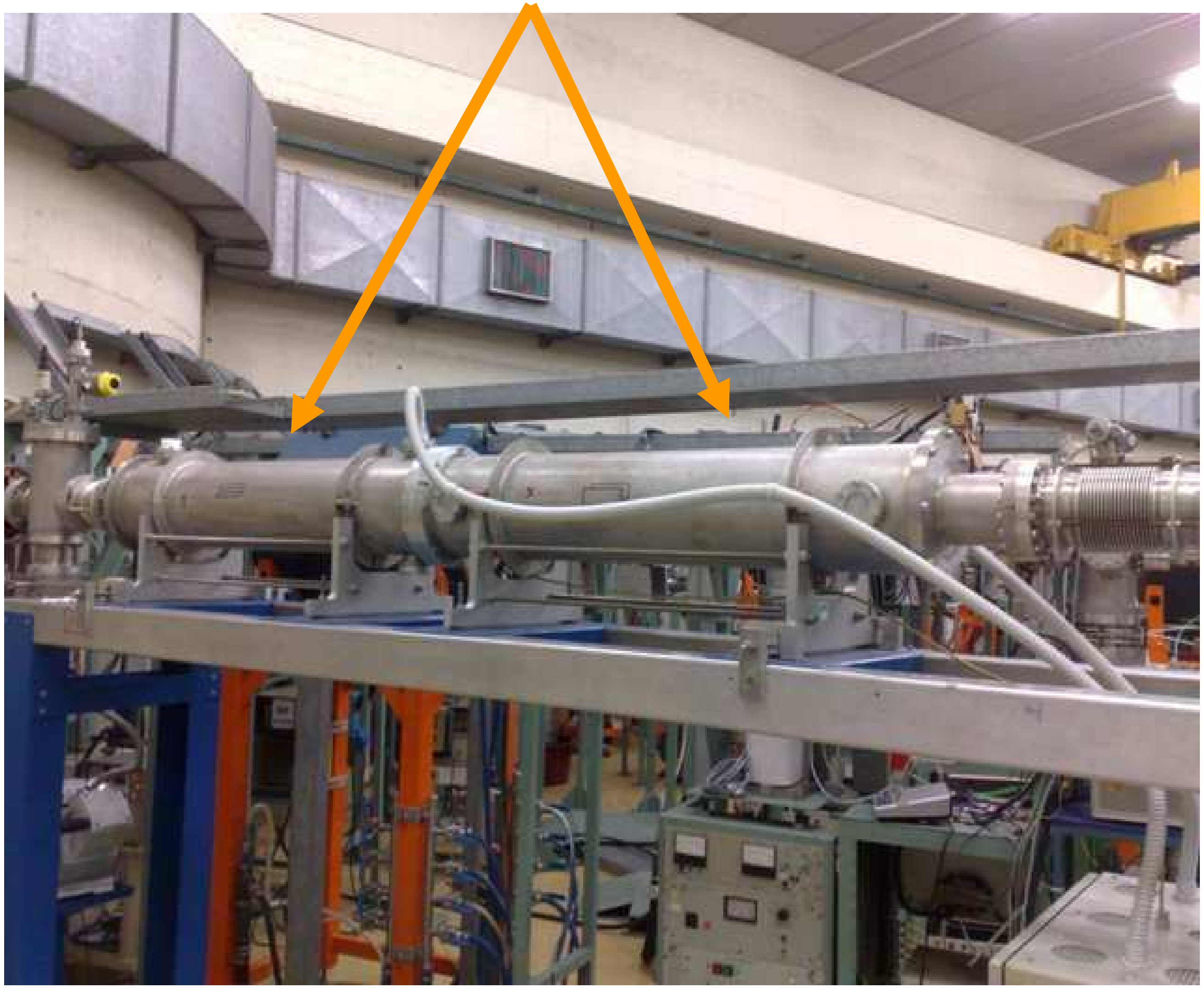
The magnetic quadrupole and the steerer





SIRAD technical characteristics

The rastering system

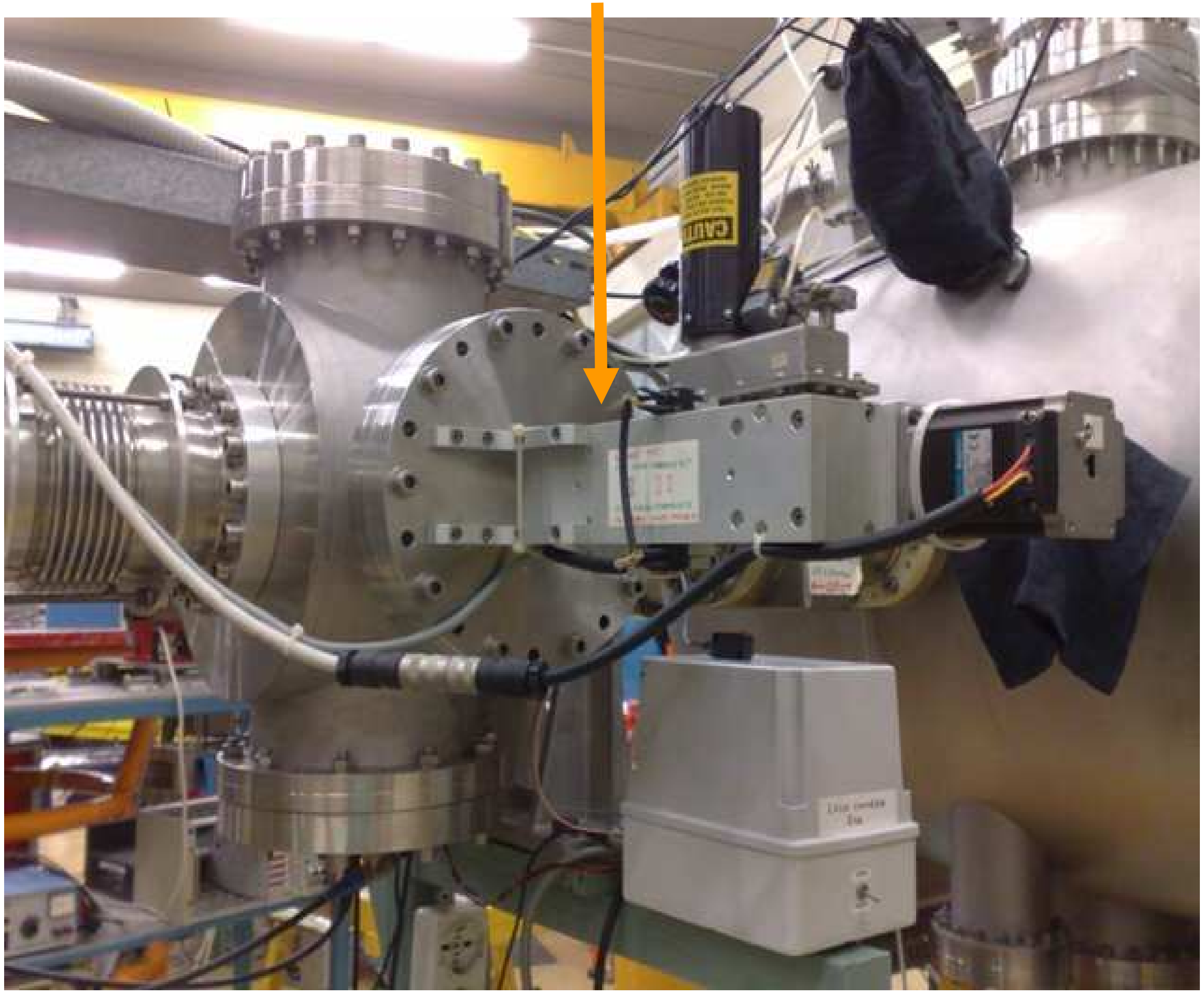


SIRAD technical characteristics

The support chamber: vacuum & dosimetry
(This is the "old" irradiation chamber (2001-2006) now used to increase the vacuum impedance and for measurements on the beam)

SIRAD technical characteristics

The **extractable Faraday cup**

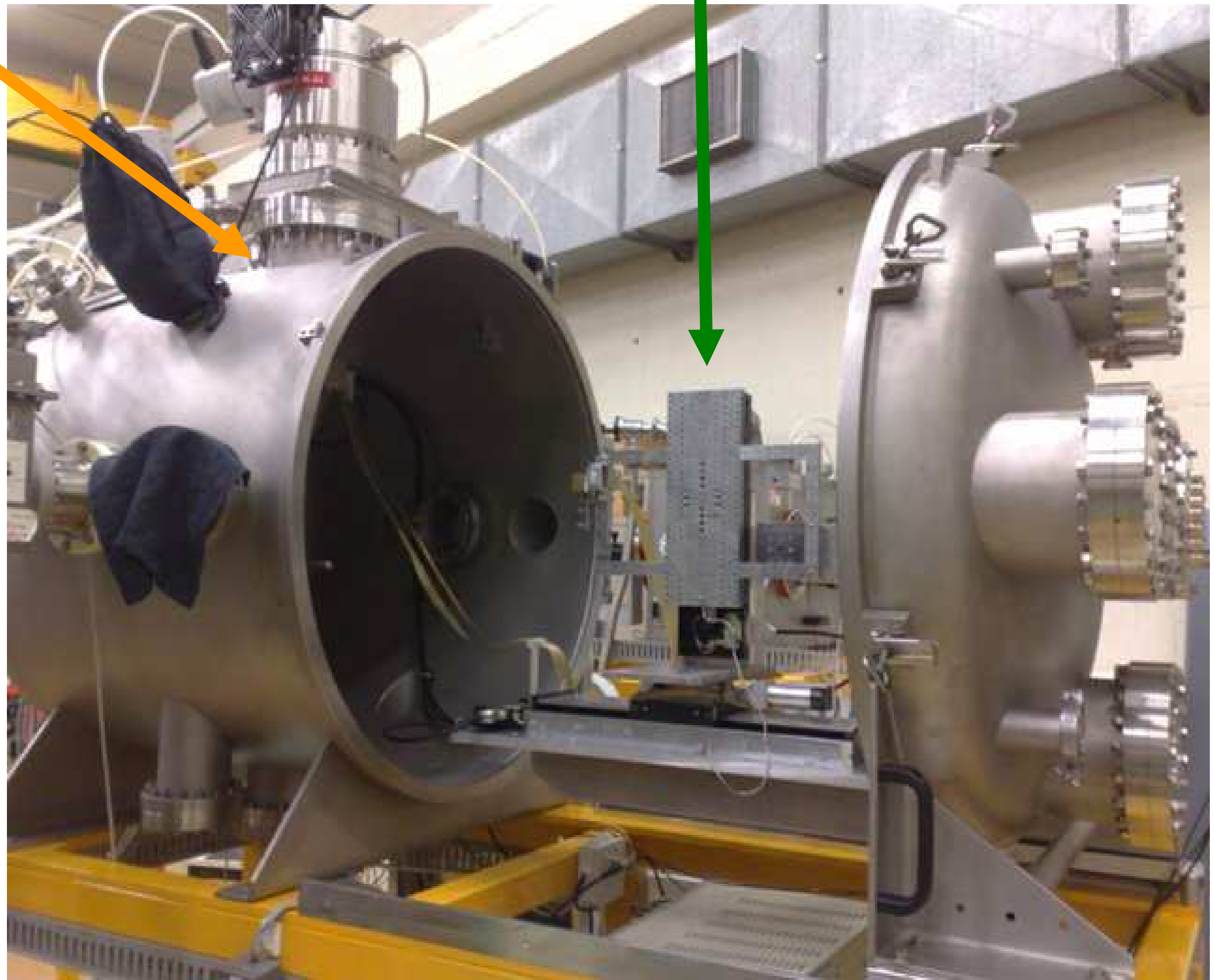


SIRAD technical characteristics

The **SIRAD irradiation chamber**

Open with the **motorized sample holder (X, Y, ϑ)**

Closed



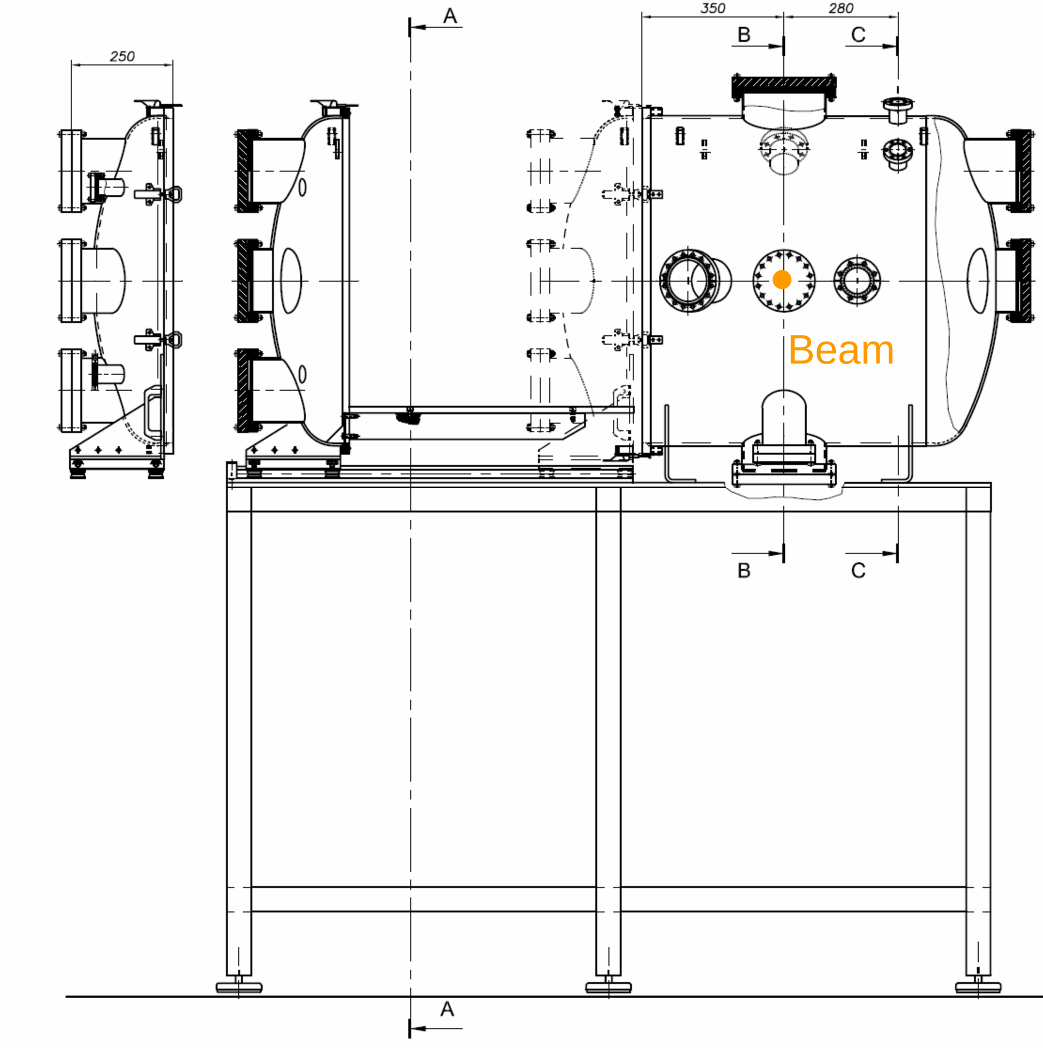
SIRAD technical characteristics

Shape: cylinder

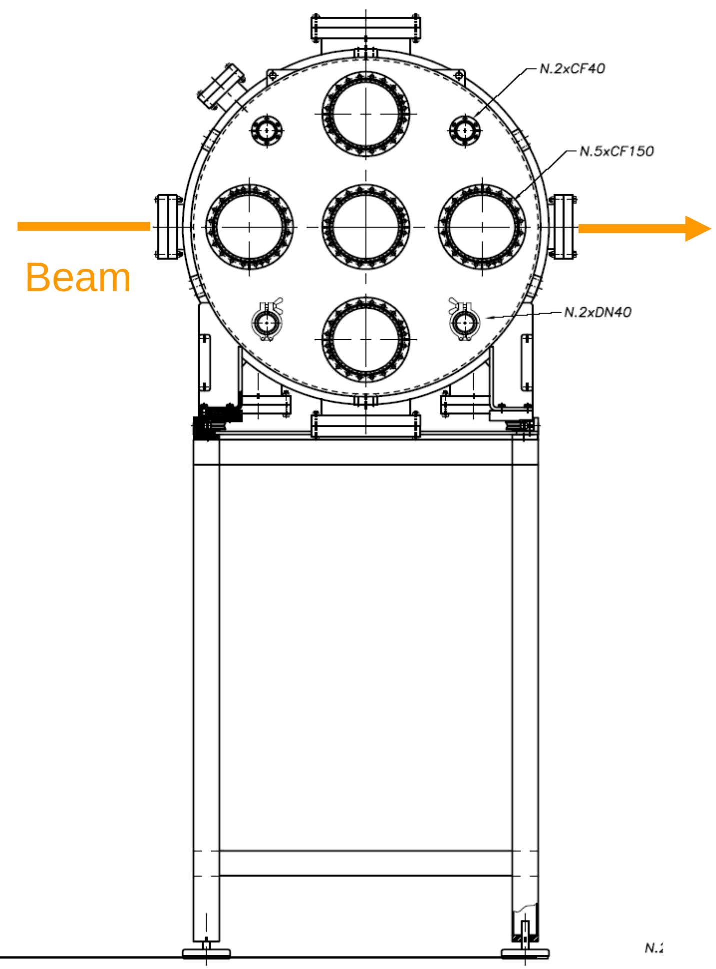
Dimensions: L=80 cm, D=80 cm

Manufacturer: RIAL Vacuum

Frontal view

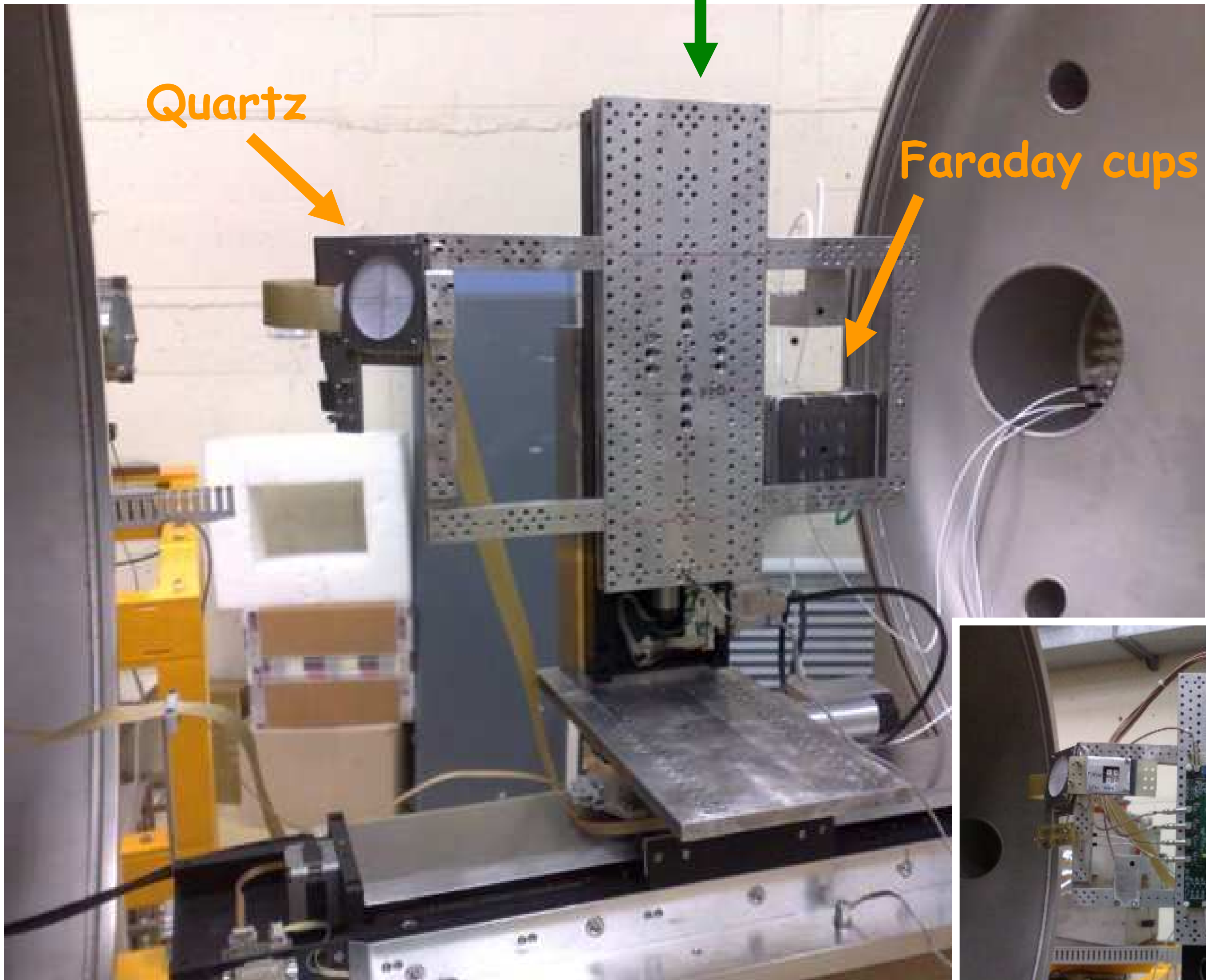


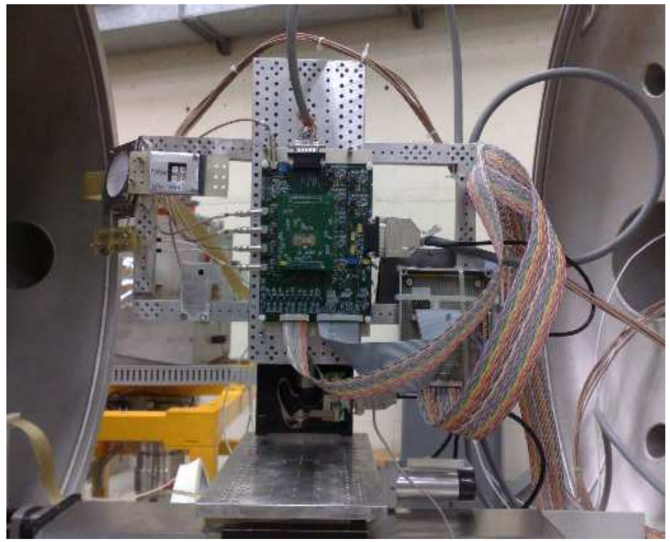
Lateral view



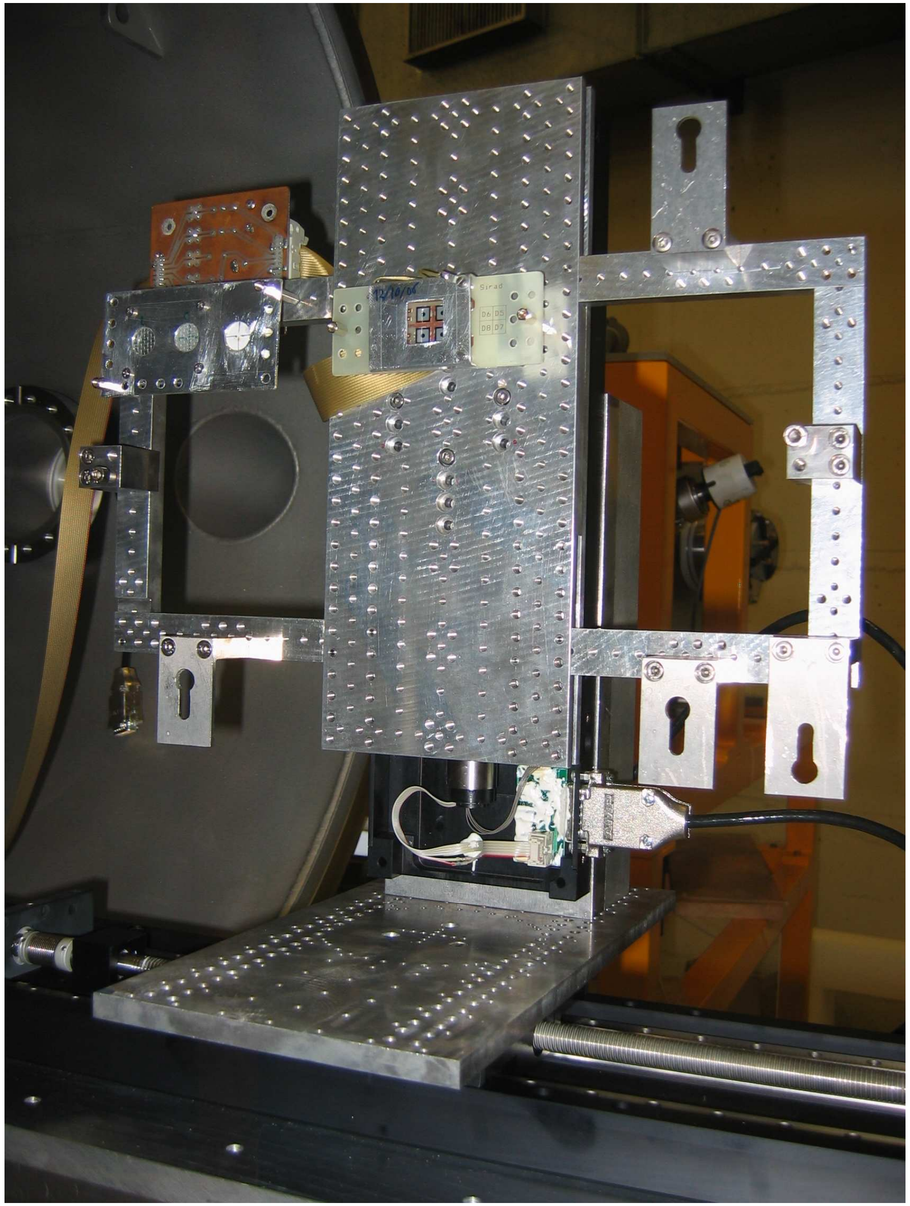
SIRAD technical characteristics

The **motorized sample holder (X, Y, ϑ)**

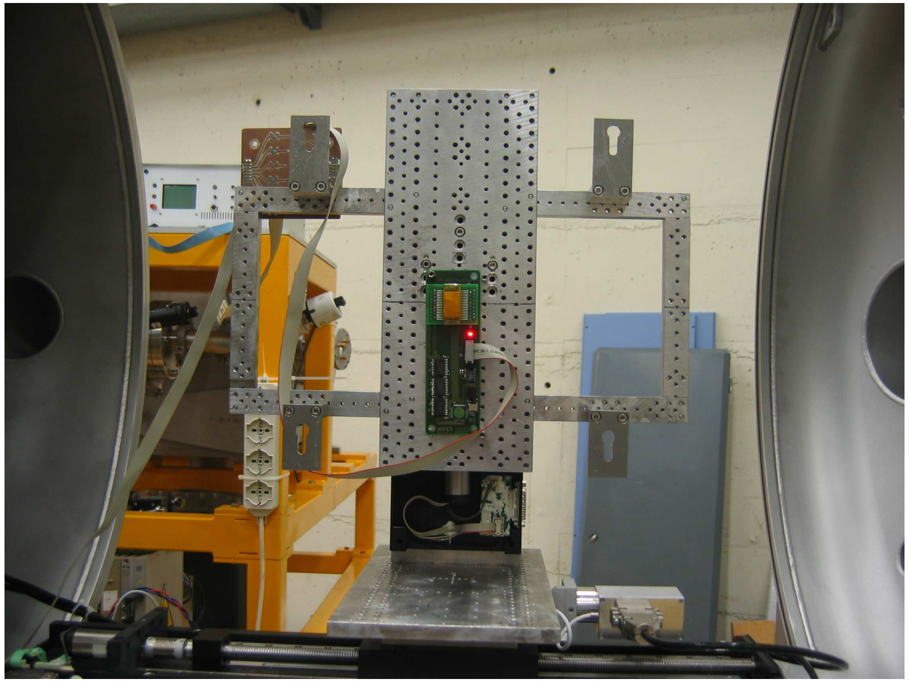




SIRAD technical characteristics



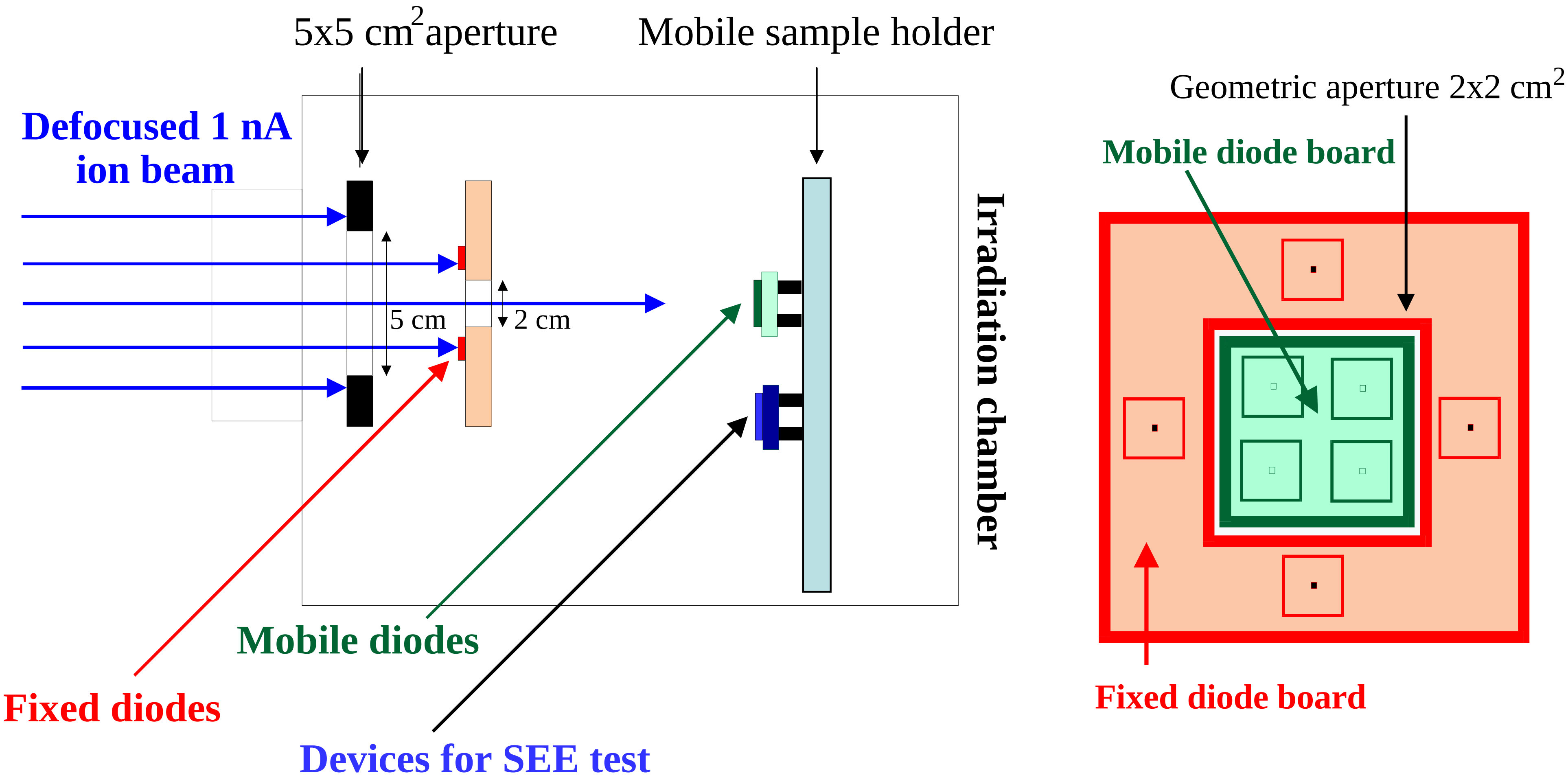
The motorized sample holder



Laser for the sample holder positioning

SIRAD technical characteristics

Low flux ($\approx 10^2$-10^5 ions/cm$^2\times$s) irradiation on a 2×2 cm^2 area



The **on-line beam monitoring system for defocused beams** by the fixed and mobile diodes:
-left: side view of the experimental set-up;
-right: front view (transverse to the beam) of the fixed and mobile diode boards.
The mobile diodes are mounted on the sample holder with the DUT. The figure is not drawn to scale.

Low flux (≈10^2-10^5 ions/cm^2×s) irradiation on a 2×2 cm^2 area

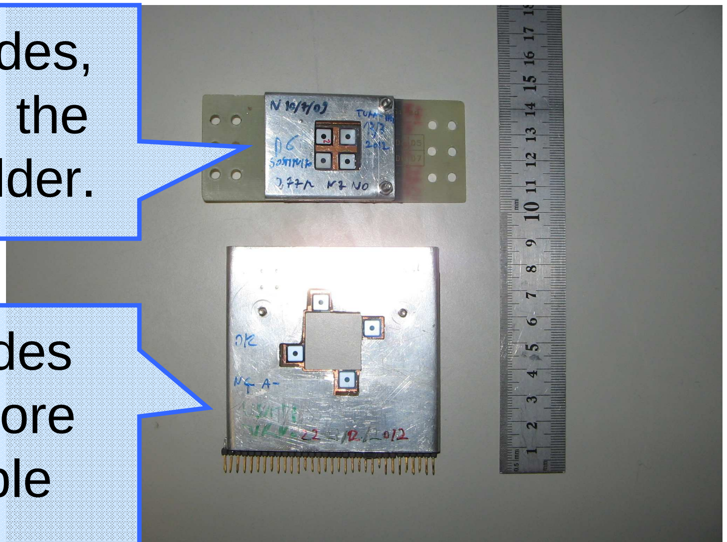
The SIRAD dosimetry system for low flux (10^2-10^5 ions/cm^2×s) irradiations is performed by 2 boards hosting 4 silicon diodes each:

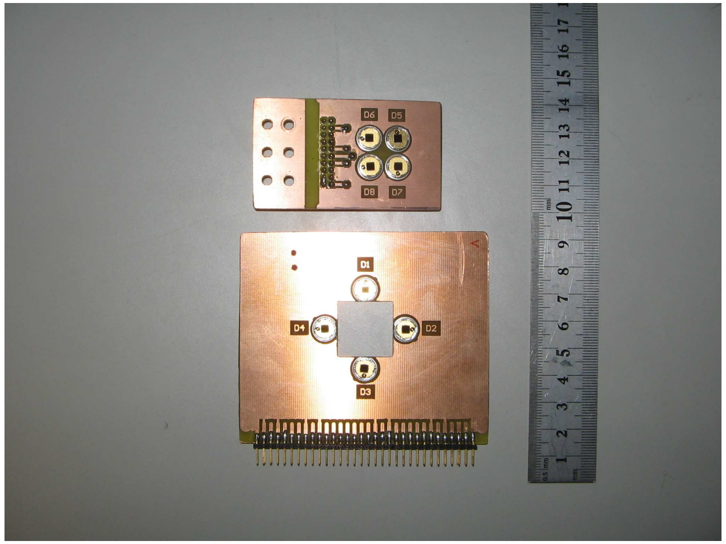
1) the first board (called **fixed diode board**) is located before the sample holder: it has 4 silicon diodes to monitor the beam during the irradiation, the silicon diodes are located around a 2x2 cm^2 square aperture, which allows the beam to hit the Device Under Test (DUT).

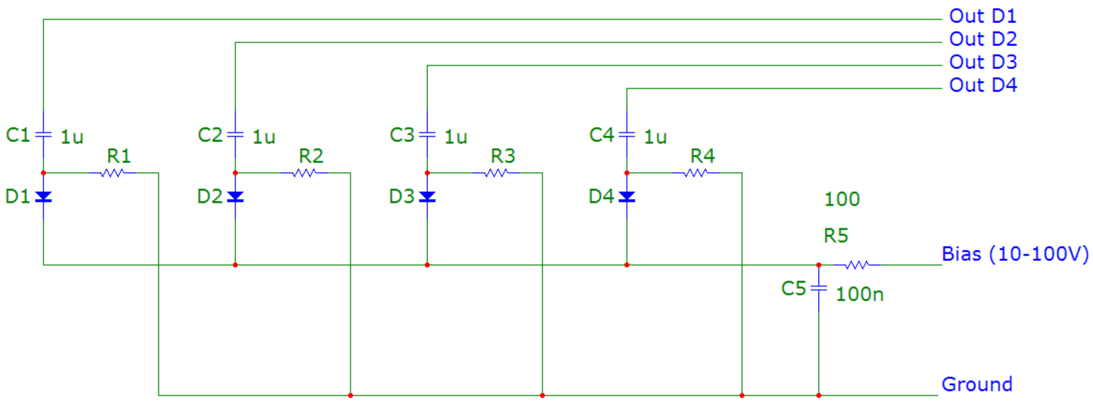
2) the second board (called **mobile diode board**) is mounted on the sample holder and allows to monitor the beam in the irradiation area of the Device Under Test (DUT) during the calibration phase.

Mobile diodes, located on the sample holder.

Fixed diodes locate before the sample holder.







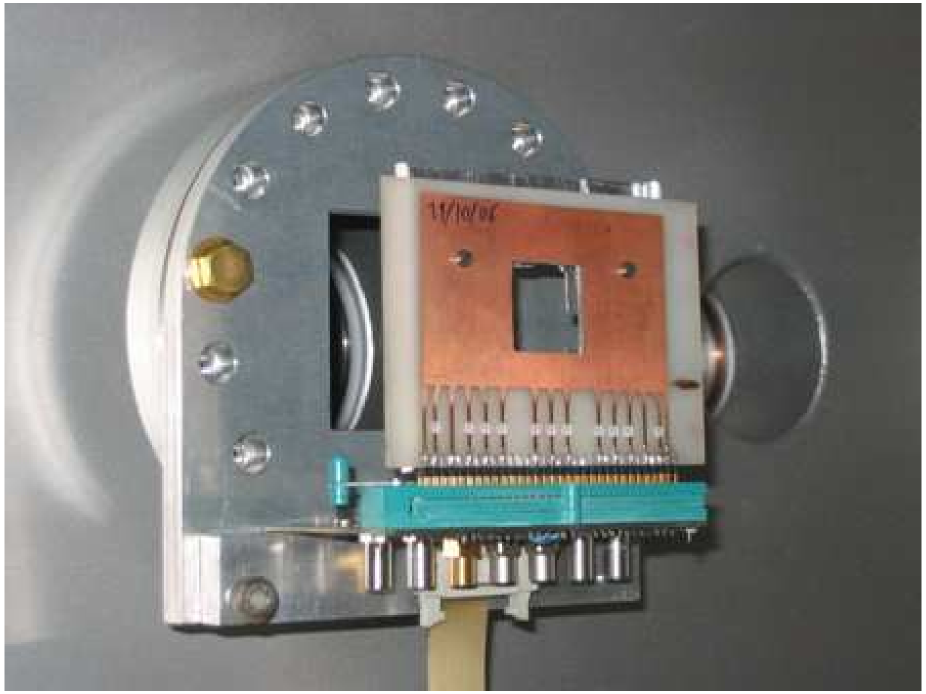
The dosimetry system boards use:

-8 commercial silicon diodes (ITC-IRST) with 5×5 mm^2 active area;

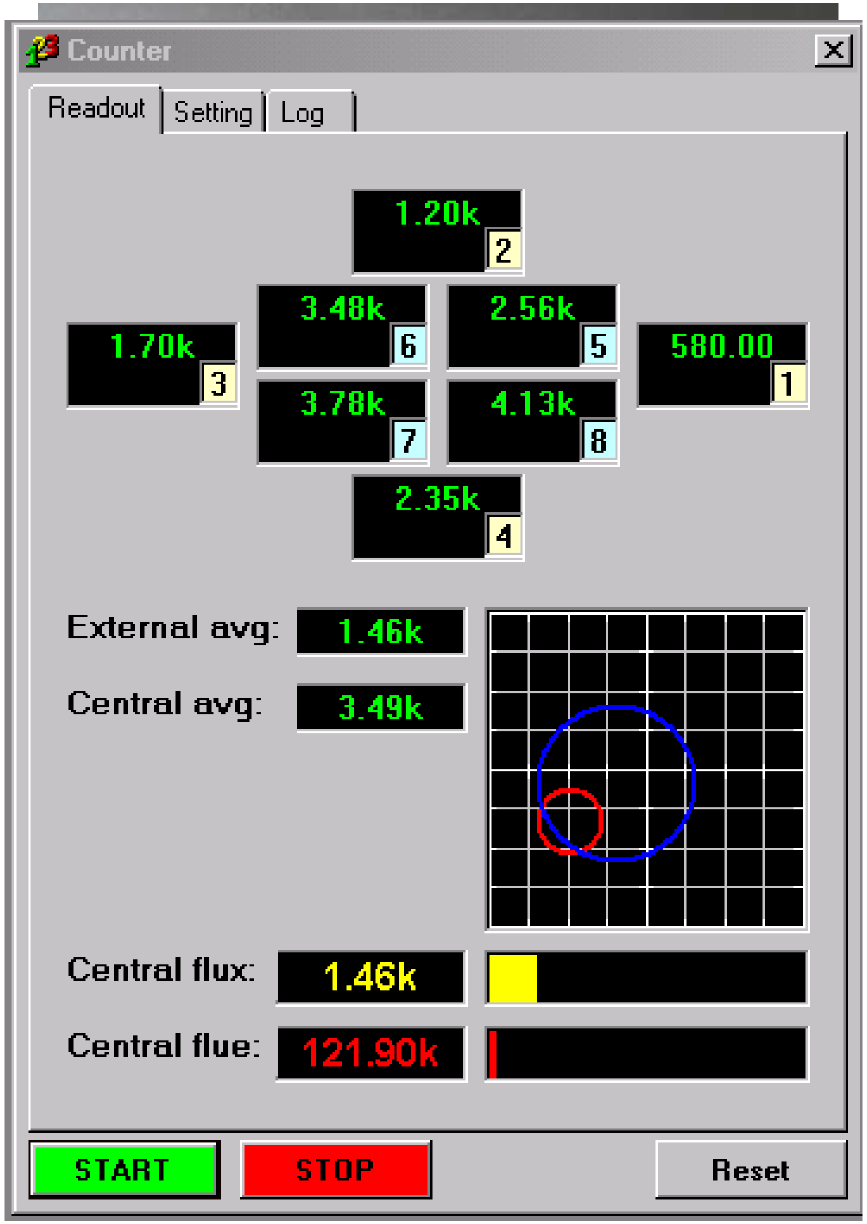
or

-8 commercial silicon diodes (Siemens BPW 21) with 2.73×2.73 mm^2 active area.

Low flux ($\approx 10^2$-10^5 ions/cm$^2\times$s) irradiation on a 2×2 cm^2 area



The "**fixed diode board**" from backside



Software for dosimetry

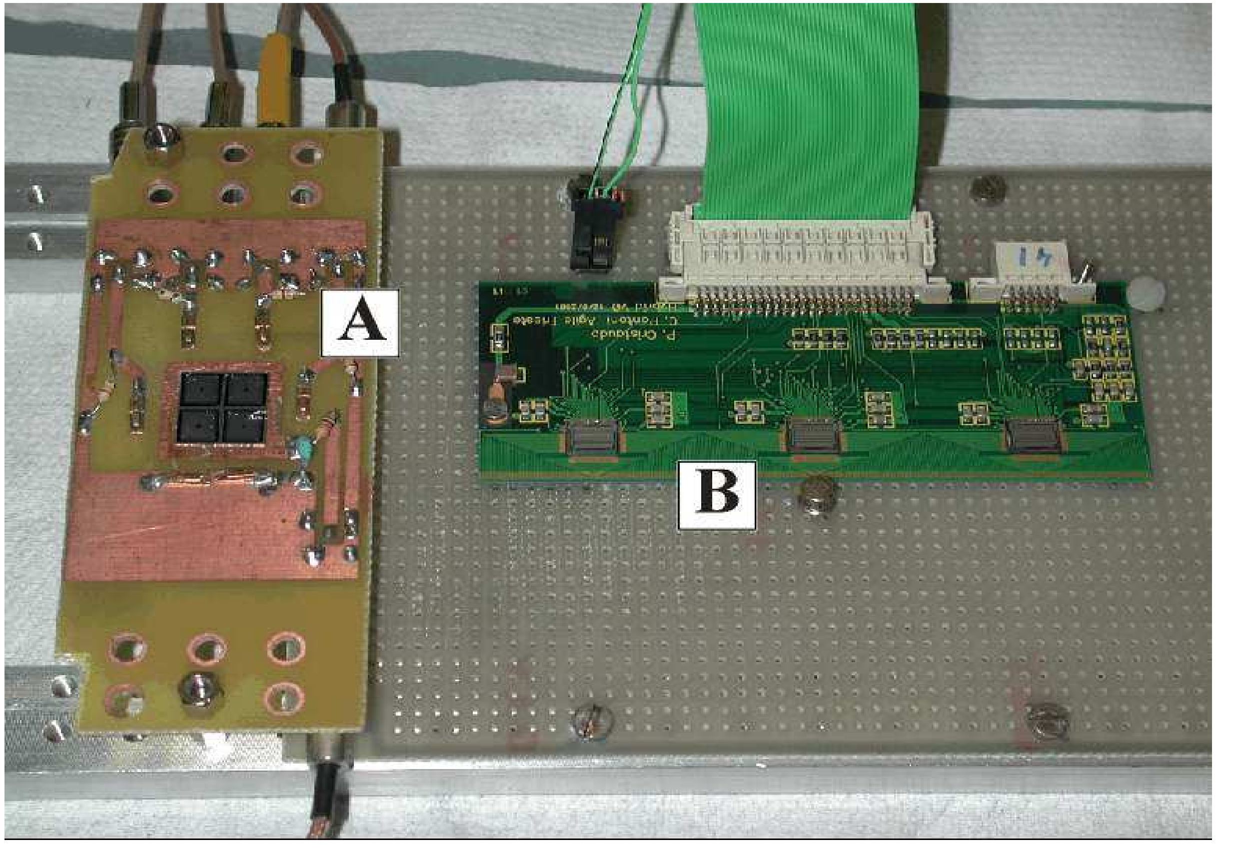
Low flux (≈10^2-10^5 ions/cm^2×s) irradiation on a 2×2 cm^2 area

ITC-IRST silicon diode

-Area:	5×5 mm^2
-Thickness:	300 μm
-Operating voltage:	100-200 V
-Guard-ring:	Yes

Siemens BPW21 silicon diode

-Area:	2.73×2.73 cm^2
-Thickness:	>100 μm
-Operating voltage:	50-100 V
-Guard-ring:	Yes

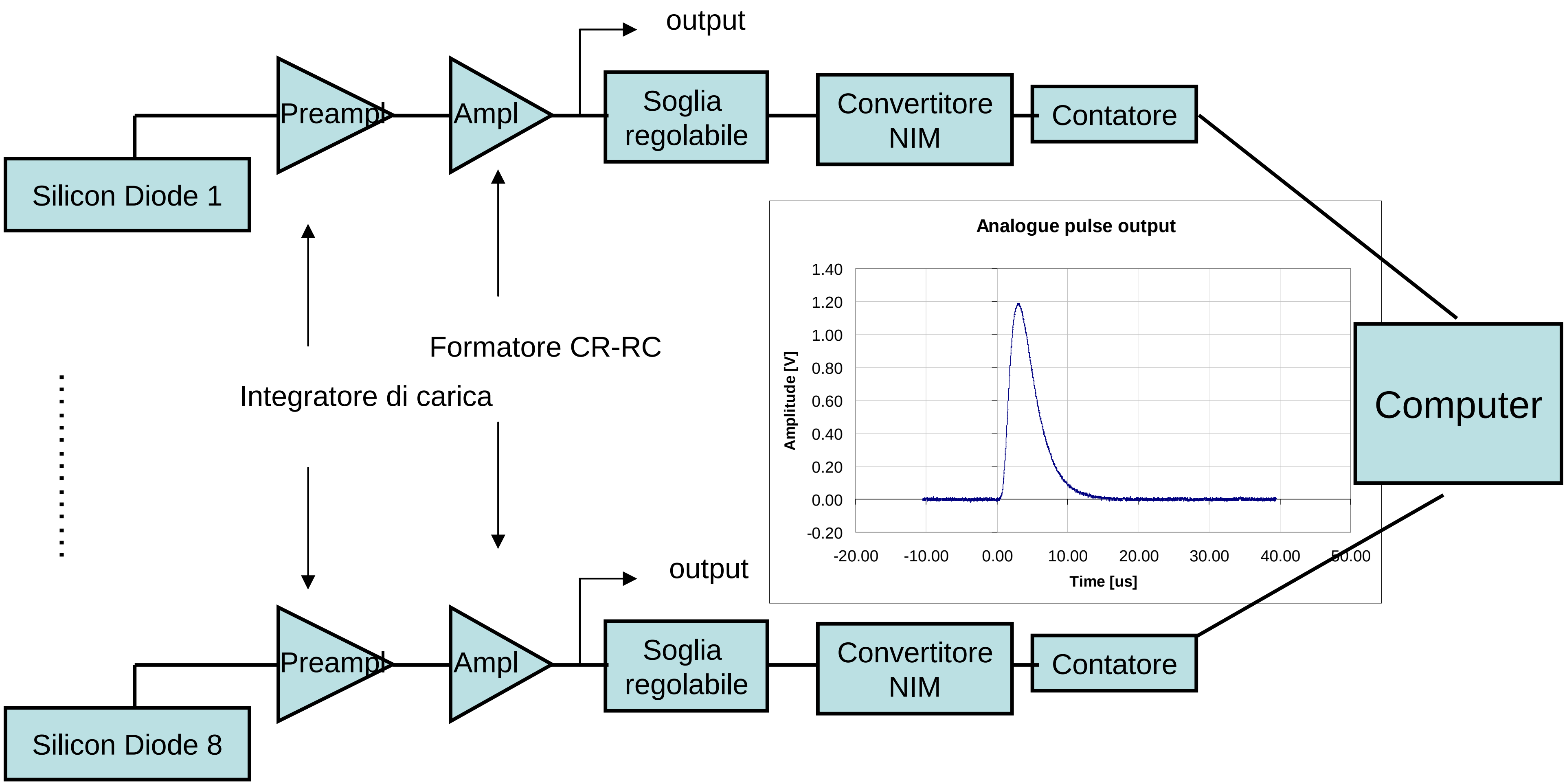


Advantage:
The use of 4 mobile and 4 fixed diodes allows an accurate ion flux measurement on the DUT irradiation area.

Ion range, energy deposition and induced degradation in ITC-IRST silicon diodes:

- ^{7}Li ions: range larger than the diode thickness, ≈30 MeV deposited in 300 μm silicon.
- Ion from ^{11}B to ^{197}Au: range smaller than the diode thickness, all the ion energy (80 MeV - 275 MeV) deposited inside the active volume.
- Radiation induced degradation: leakage current (shot noise) increase, charge collection efficiency decrease. The maximum delivered fluence range is 10^9-10^{11} ions/cm^2, i.e. suitable for Single Event Effect tests.

Low flux ($\approx 10^2$-10^5 ions/cm$^2\times$s) irradiation on a 2$\times$2 cm^2 area



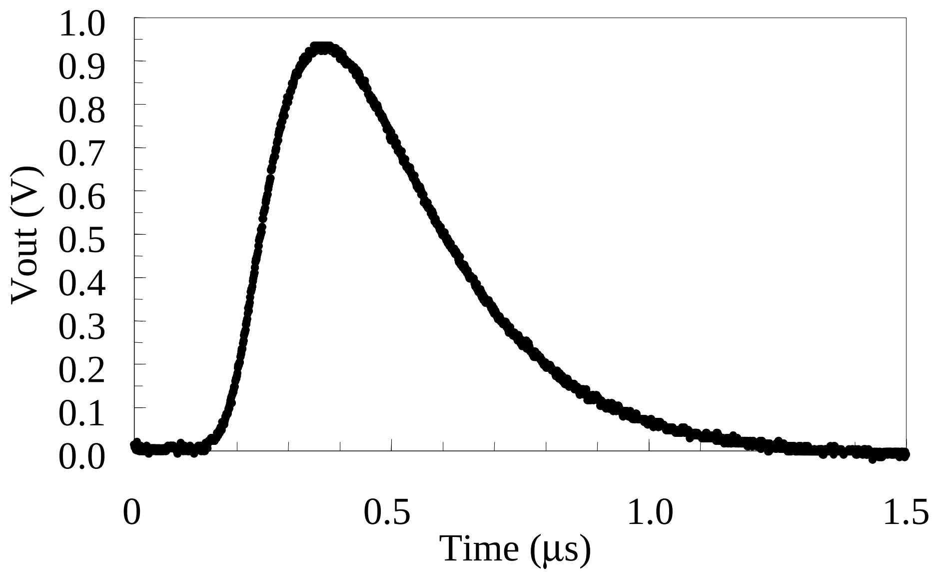
Block diagram of the read-out electronics for low flux measurements by the fixed (1,2,3,4) and mobile (5,6,7,8) diodes. The read-out electronic channels of the diodes 2-7 are not shown for brevity. The signal at the output of the shaper is connected to a multi-channel analyzer and to an oscilloscope for energy spectroscopy measurements.

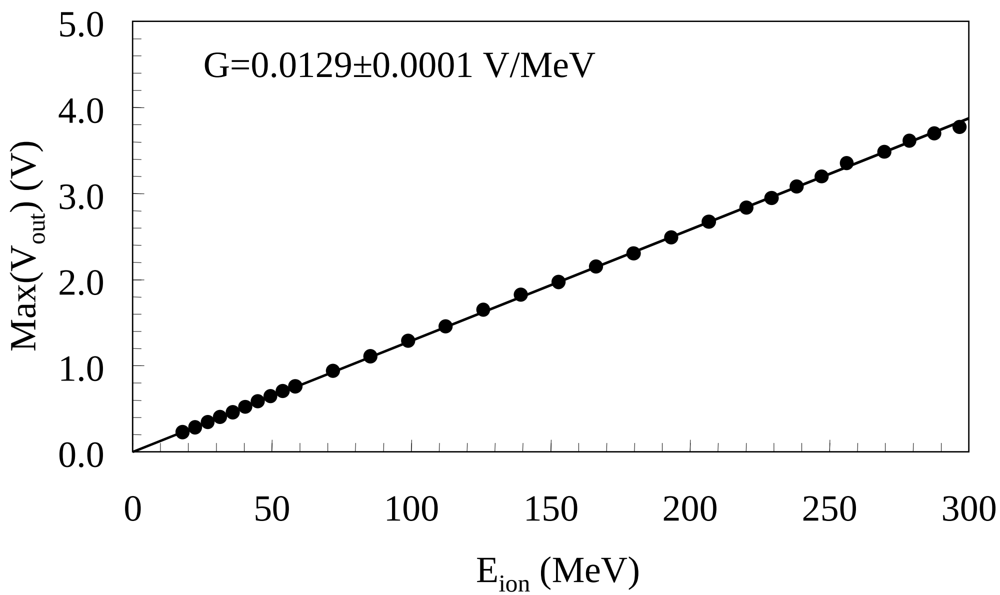
Low flux ($\approx 10^2$-10^5 ions/cm$^2\times$s) irradiation on a 2×2 cm^2 area

- Preamplifier and shaper with low noise commercial operational amplifiers.

- Signal time duration ≈1 μs. Maximum ion flux for single ion impact counts (Poisson statistics): ≈10^5 ions/(cm$^2\times$s) for 0.25 cm^2 diode area.

- Gain and linearity assure SEE dosimetry from Li (0.37 MeV×cm^2/mg) up to Gold (81.7 MeV×cm^2/mg).

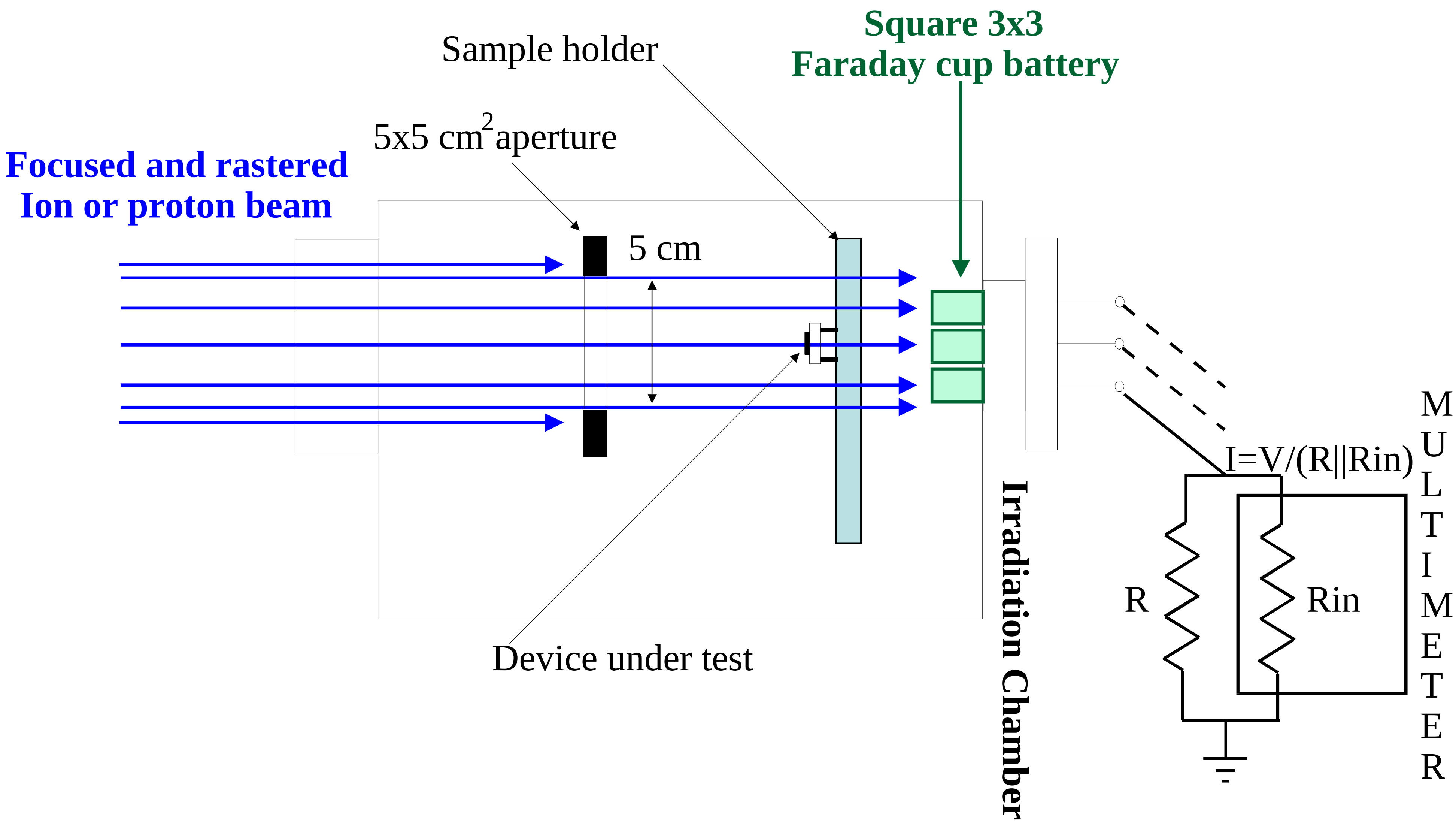




Voltage signal at the shaper output for a 3.2 pC injected charge at the preamplifier input, corresponding to 71.9 MeV energy deposited in silicon in form of ionization ($E_{e\text{-}h}$=3.6 eV) and full charge collection.

Maximum of the signal at the shaper output as a function of the ionization energy deposited in Si assuming full charge collection.

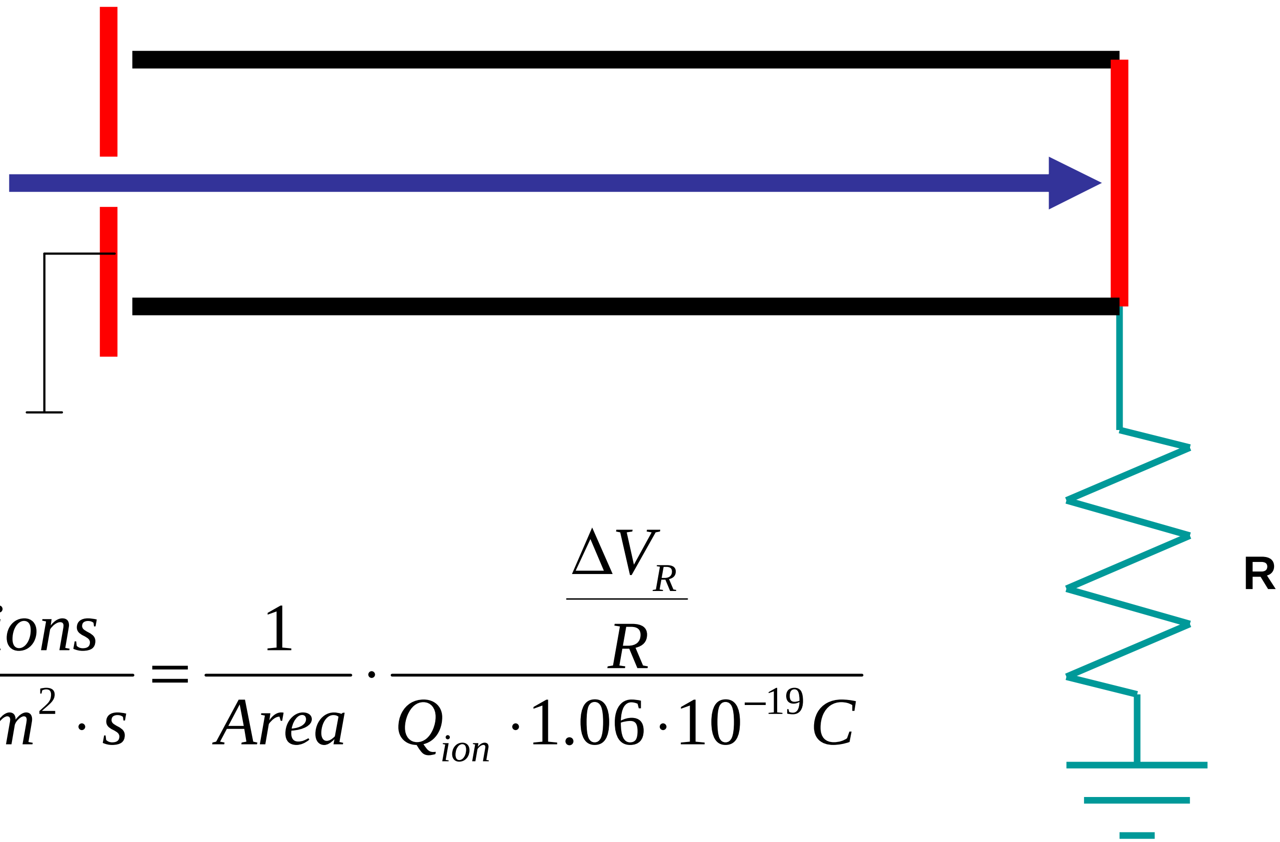
High flux (>10^8-10^9 ions/cm^2×s) irradiation on 5×5 cm^2 area



The **on-line beam monitoring for rastered proton and ion beams** by the 3×3 battery of Faraday cups positioned behind the DUT: side view of the experimental setup. The aperture of each Faraday cup is 0.6×0.6 cm^2. The figure is not drawn to scale.

High flux (>10^8-10^9 ions/cm^2×s) irradiation on 5×5 cm^2 area

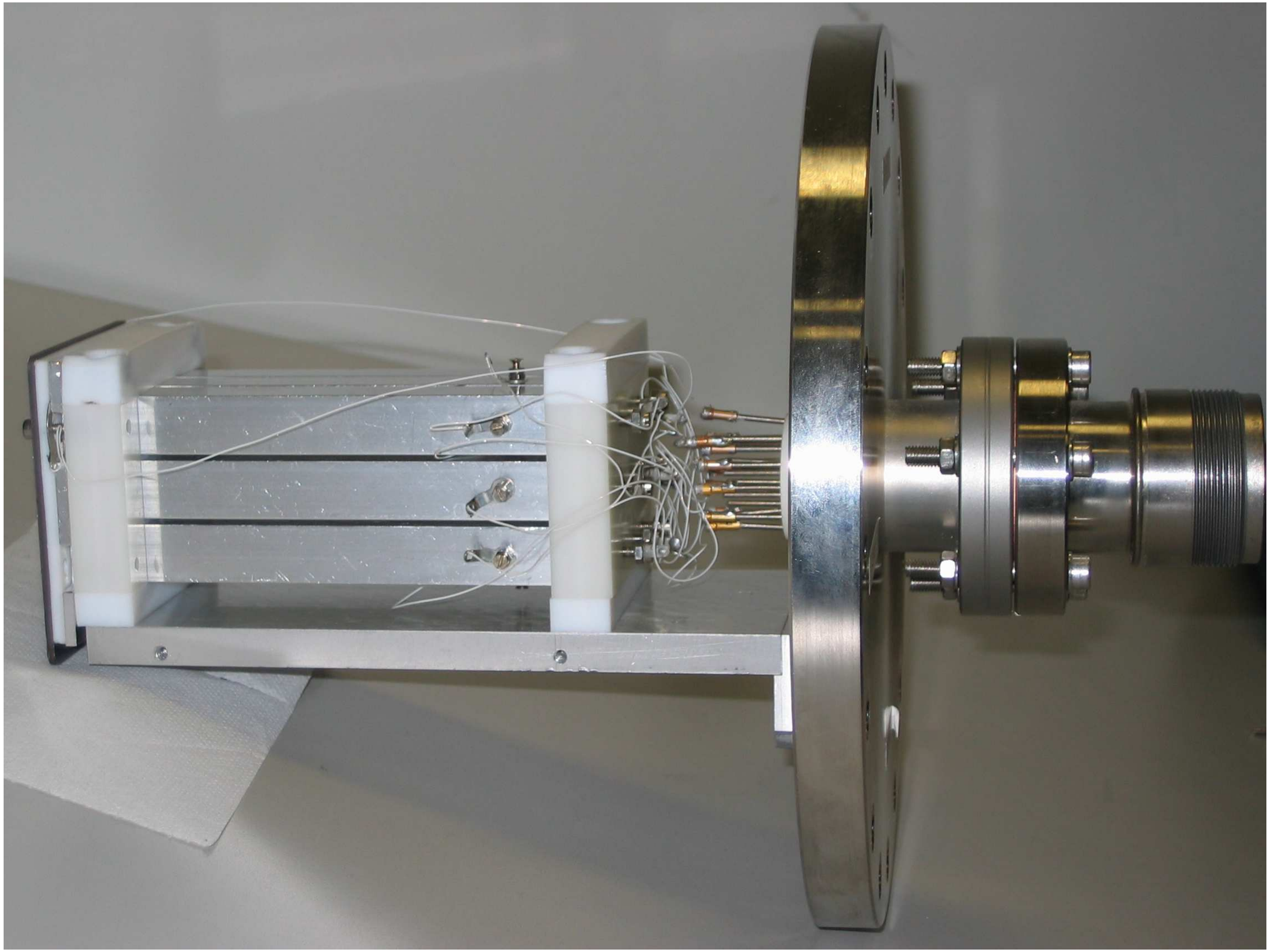
-A charged ion, entering the Faraday Cup and hitting its bottom part, charges the Faraday cup with its charge.
-If the Faraday cup would be electrically isolated its potential would increase rapidly.



The Faraday cup is connected to ground by a high value resistance (100MΩ): the measure of the potential drop on the resistance allow to determine the ions current entering the Faraday cup.

$$\frac{ions}{cm^2 \cdot s} = \frac{1}{Area} \cdot \frac{\frac{\Delta V_R}{R}}{Q_{ion} \cdot 1.06 \cdot 10^{-19} C}$$

High flux (>10^8-10^9 ions/cm^2×s) irradiation on 5×5 cm^2 area



The composite Faraday cup, made up of 9 independent elements

Beam time shift: details

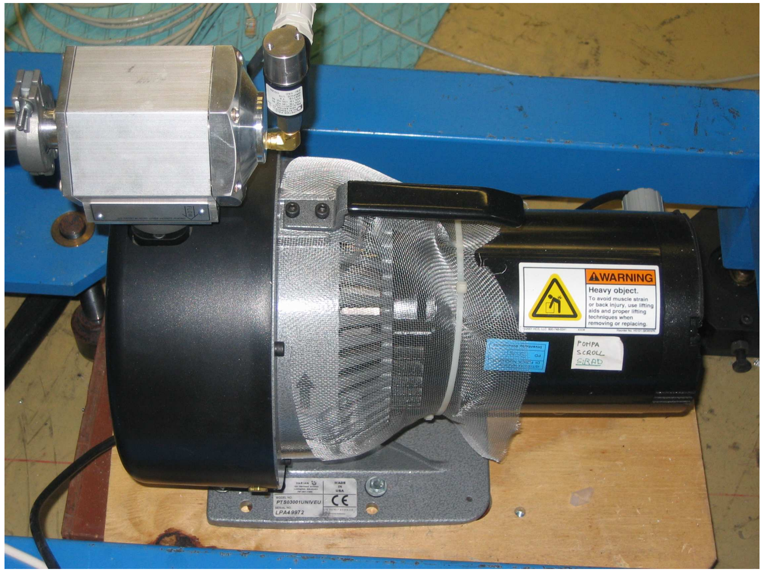
Irradiation beam time shift: 24-48 hours, eventually to be shared among more groups depending on the requirements.

Personal support: 2 operators for running the Tandem accelerator
1 person for running the SIRAD facility (if requested by users)

Time required for beam setting: 2 hours for each ion species (average value)
6 ion species are routinely considered in 24 hours

Required vacuum level: 8×10^{-6} mbar
Pumping system: scroll pump for pre-vacuum + turbo pump for high vacuum
Time required for vacuum: 30-45 minutes, depending on the material budget

Vacuum pumps



Scroll pump

Scroll pump schematics
(see -> Wikipedia “Scroll compressor”)

Turbomolecular pump

Electrical connections and set-up

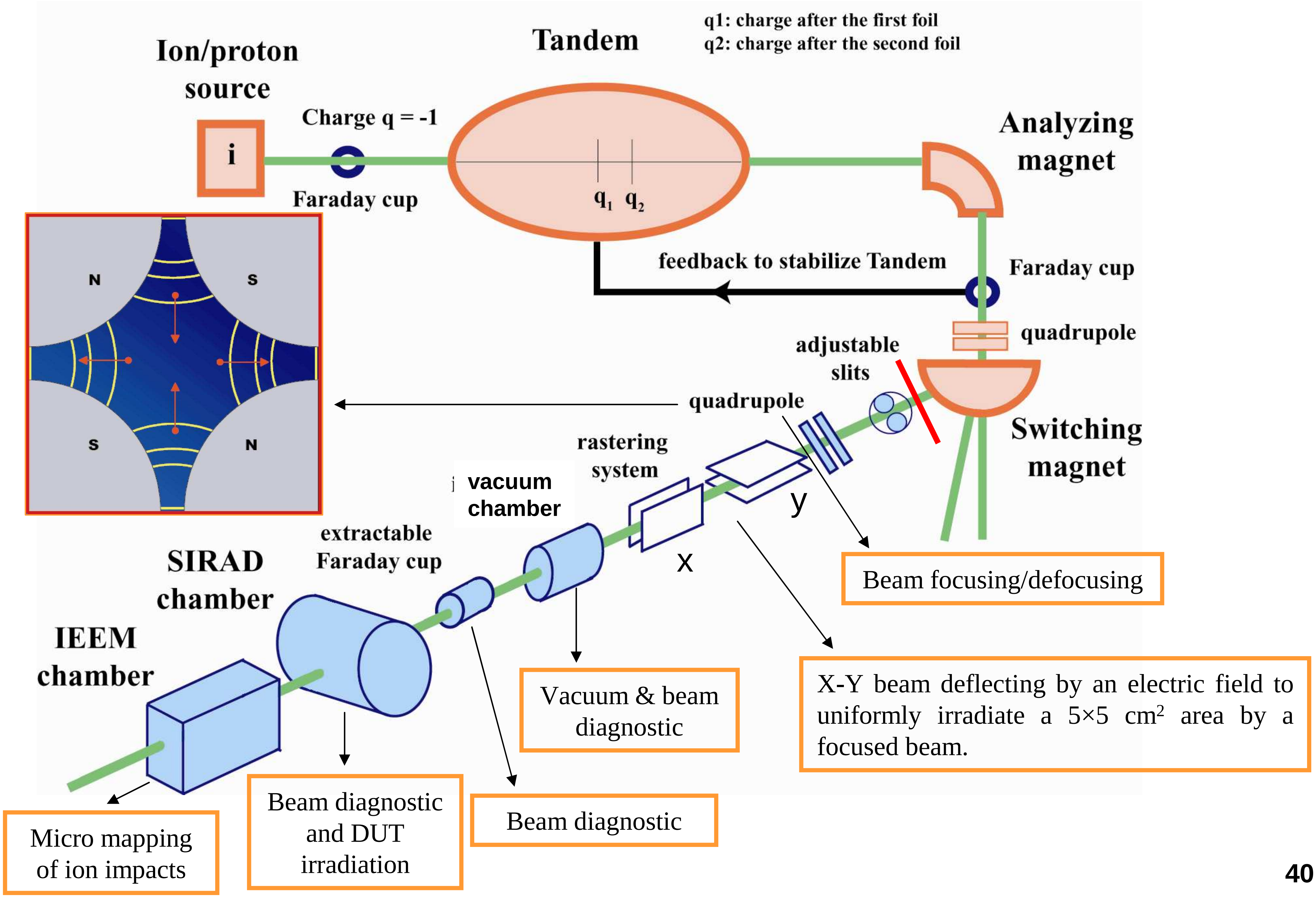
Possibility to see/illuminate the DUT: glass window

Electrical connectors on the chamber: 16 BNC + 8 High Voltage BNC (or 24 BNC)
2 connectors DSUB with 50 pin

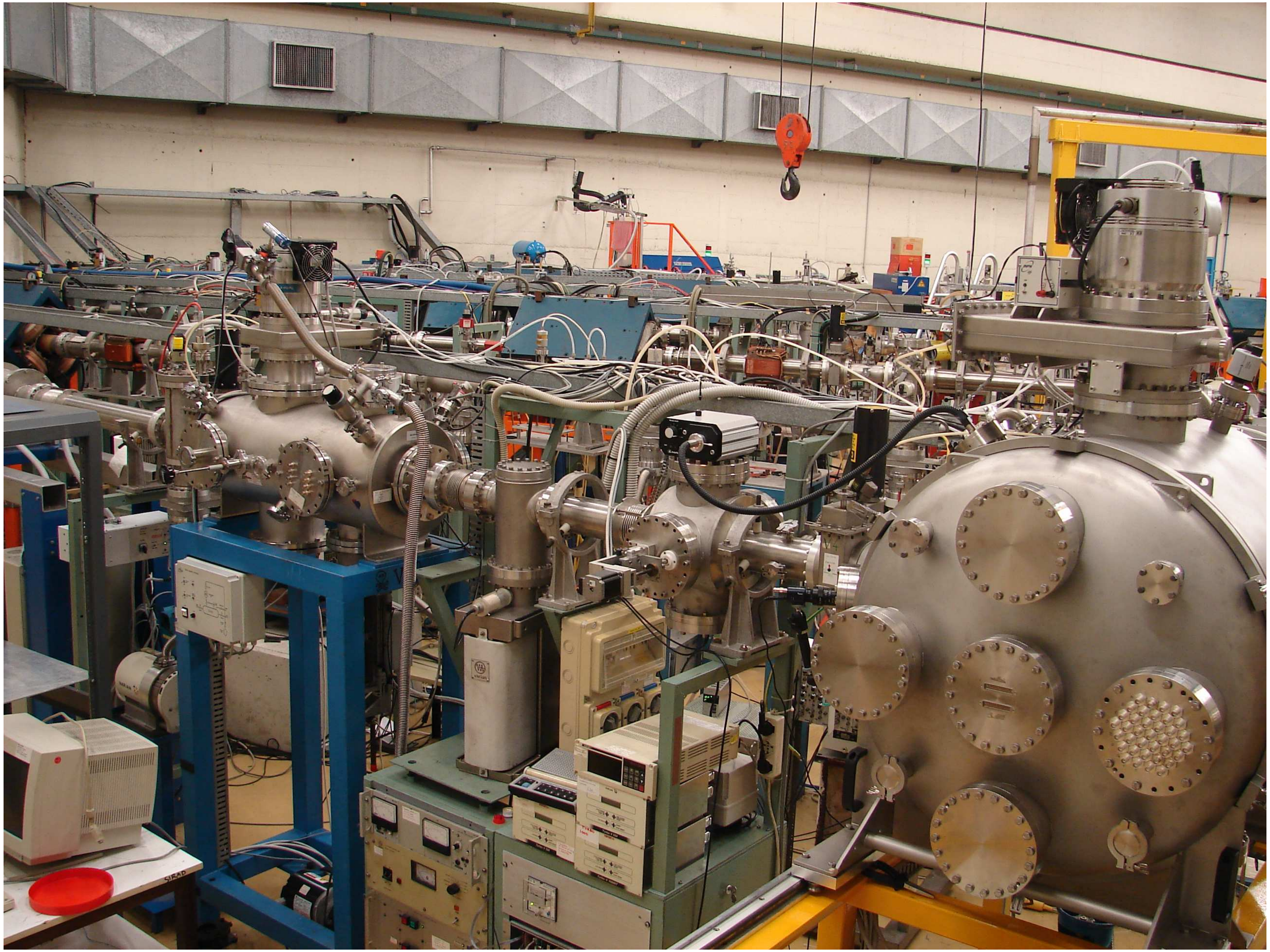
Experimental set-up: DAQ with remote PC close to the SIRAD beam line and control PC in the user box

Connections SIRAD beam line - user box: 3 network cables for computers
20 BNC connections 50 Ohm
1 video cable 75 Ohm

The SIRAD Irradiation Facility



The SIRAD Irradiation Facility



The vacuum chamber, the extractable Faraday cup and the irradiation chamber