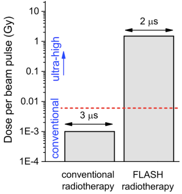
Beam monitoring for electron FLASH beams

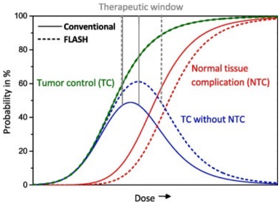
Medina E., Abujami M., Bersani D., Cirio R., Data E., Galeone C., Giordanengo S., Mart`i Villareal O., Mas Milian F., Montalvan Olivares D., Monti V., Sacchi R., Vignati A.

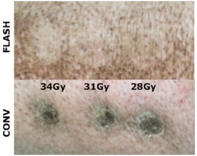
FLASH effect

- FLASH RT promising cancer treatment
- Single Irradiation with UHDR **> 40 Gy/s**
  Total delivery time **<100 ms**: much higher DR (up to 10^9 Gy/s) during each pulse
- Potential for widening the **therapeutic window**
- The most of the pre-clinical studies using **electron** beams (by LINACs with E<20 MeV)

More than 3 orders of magnitude! (Pulse duration comparable)







Mini-pig skin 36 weeks post RT

Beam Characteristics	CONV	FLASH
Dose Per Pulse D_p	~0.4 mGy	~1 Gy
Dose Rate: Single Pulse $\dot{D}_p$	~100 Gy/s	~10^5 Gy/s
Mean Dose Rate: Single Fraction $\dot{D}_m$	~0.1 Gy/s	~ 100 Gy/s
Total Treatment Time T	~days/minutes	< 500 ms

FRIDA project

FLASH **R**adiotherapy with h**I**gh **D**ose-rate particle be**A**ms

- Observed but not understood: experimental evidence **needs research** to be consolidated
- **Several questions** need to be answered
  - What is the root source of such sparing?
  - ‘in-vitro’ studies can help explaining the effect
  - what are the parameters that trigger the effect?

FRIDA project

- Several challenges posed by this potential revolution
- Mechanistic understanding and modeling of the effect
- New technologies development:
  Delivery,
  Dosimetry,
  Beam monitoring

University of Turin and INFN

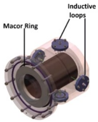
- **Beam Monitoring systems**: Silicon and Diamond detectors (TO)
- **Delivery system**: Upgrade of LINAC ELEKTA (TO)

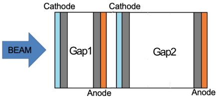
UNIVERSITÀ DI TORINO

INFN Istituto Nazionale di Fisica Nucleare

Beam monitoring of UHDR beams

- In CONV RT ICs are used.
- **But not for UHDR beams:** high rate of **recombination** and ICs **too slow** (tens of μs to collect ions)
- Ideal **beam monitor requirements**
  1. Temporal resolution at ms level
  2. Spatial resolution
  3. Beam Transparency
  4. Radiation hardness
- Possible solutions:
  BCT (electrons) or **Adapted IC** (protons)



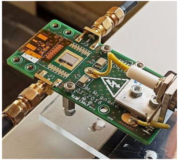


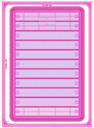
- **FRIDA** will explore new beam monitoring technologies
  - Air-fluorescence based
  - ICT
  - Multi-gaps ion chamber
  - SED
  - Solid-state detector:
    Thin silicon (TO),
    Diamonds (TO),
    SiC membranes (CT)

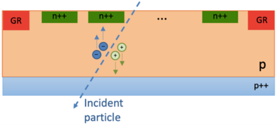
Silicon detectors and Readout

Silicon devices in Turin: used so far for *single particle counting* → With **TERA08** signal can be integrated

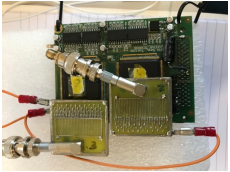
- **Silicon sensor** (strip area 2.2 mm^2, active thickness 45 μm, total thickness 615 μm)







- Readout with **TERA08** (chip based on *recycling integrator* principle)

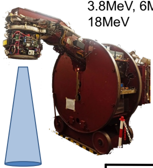


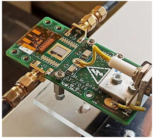
DAQ Period (μs)	Q_c(fC)	Max conversion freq per chn	Max conversion (total)	Max current (for 64 CHNs)
1e4 (0.01 s)	200 fC	20 MHz	1280 MHz	± 256 μA

Experimental setup

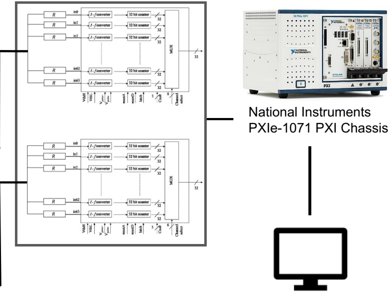
- **Silicon sensor**
- **TERA08**
- National Instruments PXIe-1071 PXI Chassis
- HV module

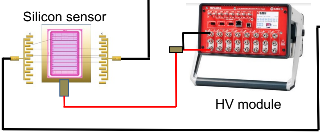
LINAC ELEKTA
e⁻ beams with energy:
3.8MeV, 6MeV, 10MeV or 18MeV





TERA08

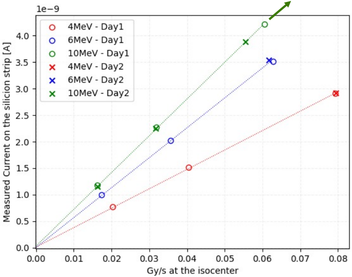


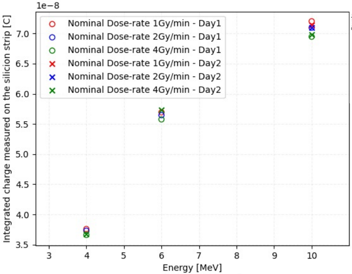


First tests with electrons beams

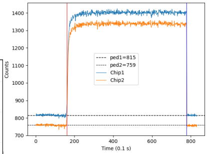
- Conventional beams at **LINAC Elekta SL18**
  - Linearity and reproducibility

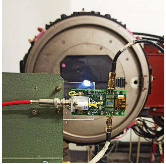
0.0016% TERA08 saturation





Example of data acquisition



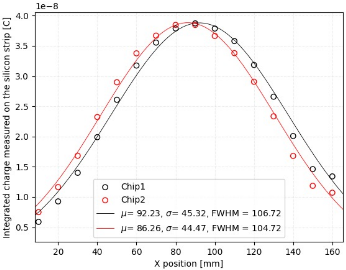


We expect to be able to measure up to **few kGy/s** (10MeV, present sensor + readout configuration)

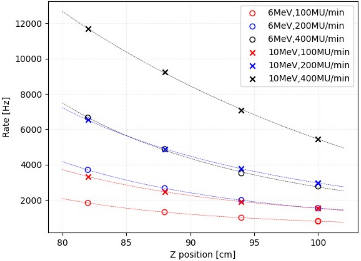
Elekta

First tests with electrons beams

- Conventional beams at **LINAC Elekta SL18**
  - Beam shape and relation with distance

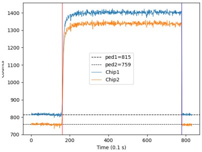


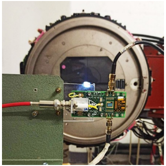
6MeV, 200 MU/min, 50 MU tot, FS 10X10cm^2
FWHM compatible with field size



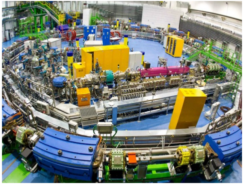
Rate measured as a function of the distance. The data were fitted with the function **y=a+b/(x-c)^2**

Example of data acquisition

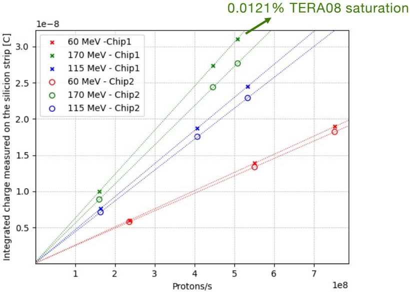




First tests with protons beams



- **CNAO**, National Center of Oncology Adrotherapy
- Same experimental setup
- Different fluxes: 1e9, 1e8 ,5e8 protons/spill
- Different energies: 60, 115, 170 MeV
- Tests at **TIFPA** (Trento, Italy) soon: UHDR proton beams will be available



For 60-230 MeV and the present sensor + readout configuration we expect to be able to measure up to **10^{12} – 10^{13} p/s.**

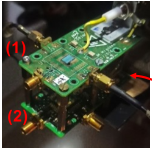
LINAC upgrade in Turin

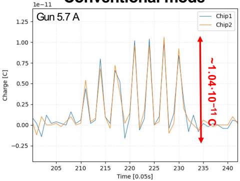
WORK IN PROGRESS

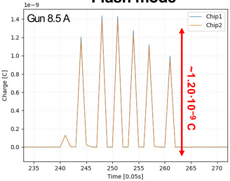
Elekta

Lempart et al. *2019*

- LINAC **for UHDR irradiation** (DR >40Gy/s) → test for devices (dosimetry/beam monitor)
- **Quick, reversible** change to flash mode
- Parameters adjusted for **10MeV**

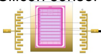






$$\frac{Q_{/pulse(Flash)}}{Q_{/pulse(Normal)}} = \frac{1.20e{-}9\ C}{1.04e{-}11C} = 115.4 \sim \mathbf{100}$$

Silicon sensor (2)

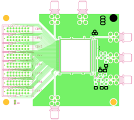


IN → Transimpedance amplifier+OP Amp → Schmitt-Trigger → ARDUINO UNO (As pulse counter) → Optocoupler circuit → **Thyratron**

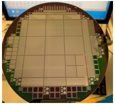
Next steps

- **Tests in new facilities**
  - ElectronFlash (Pisa)
  - Proton UHDR beams TIFPA (Trento)

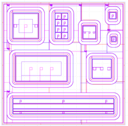
- Characterization on beam the **TERA09** front-end board (can handle higher input current compared to TERA08)



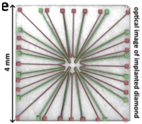
- Strip **segmentation** (strip area~3mm^2). Area 2.7×2.7 cm^2 and 146 strips (144 with gain, 2 no gain)

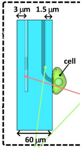


- **New production** of silicon sensors
  - 4 substrate thicknesses: 15, 20, 30, and 45 μm
  - Small active areas: from 2 mm^2 up to 0.03 mm^2



- **Diamond** detectors





Results

Silicon sensors for other experiments + readout electronics currently in use for ionisation chambers → verifying the performance for UHDR beams monitoting

- ✓ **Linearity and reproducibility** for conventional electron beams
- ✓ Possibility of studying the **shape** of the beam
- ✓ **Promising** readout performance **for future UHDR beams**
- ✓ **Gain of 100** obtained for charge per pulse after LINAC upgrade


THANK
YOU!

References

[1] Vignati, Anna, et al. "Beam monitors for tomorrow: the challenges of electron and photon FLASH RT." *Frontiers in Physics* (2020): 375.

[2] Cirio, Roberto, et al. "A simple method to increase the current range of the TERA chip in charged particle therapy applications." *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 798 (2015): 107-110.

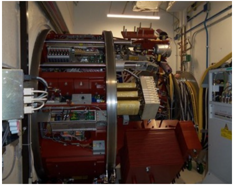
[3] Ashraf, Muhammad Ramish, et al. "Dosimetry for FLASH radiotherapy: a review of tools and the role of radioluminescence and Cherenkov emission." *Frontiers in Physics* 8 (2020): 328.

[4] Schüller, Andreas, et al. "The European Joint Research Project UHDpulse–Metrology for advanced radiotherapy using particle beams with ultra-high pulse dose rates." *Physica Medica* 80 (2020): 134-150.

[5] Lempart, Michael, et al. "Modifying a clinical linear accelerator for delivery of ultra-high dose rate irradiation." *Radiotherapy and Oncology* 139 (2019): 40-45.


BACKUP
SLIDES

LINEAR ACCELERATOR ELEKTA SL18



Linear Accelerator

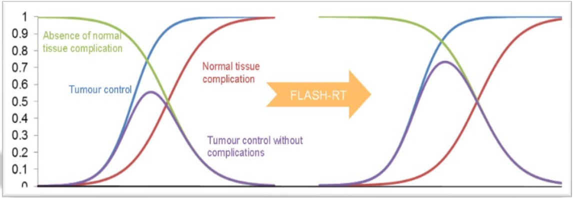
The Linac consists of a cylindrical copper waveguide with copper irises inserted along its length at defined intervals to form a series of cavities, each iris having a circular aperture through which the electrons can pass. The RF power generated by the magnetron is launched into the linac waveguide by the input mode transformer and is propagated as a travelling wave through the accelerating structure. The pulses of electrons emitted from the gun are injected through a hole in the centre of the input mode transformer and are accelerated by the axial electric field component of the waves. The wave velocity and the amount of energy transferred to the electrons are governed principally by the accelerating guide radius and the radius of the iris apertures, although the iris pitch and thickness also contribute.

In the first part of the accelerator waveguide (injector section) the phase velocity of the travelling waves is slowed down initially to match the velocity of the electrons injected by the gun. Electrons captured by the travelling waves are formed into bunches, one bunch per wave, and the electron velocity rapidly increases to nearly the velocity of light. In the rest of the accelerator waveguide (relativistic section) the electron velocity increases only slightly and the electron energy gain results mainly in a relativistic increase in mass.

The RF power losses in the linac are due to energy transfer to the electron beam and resistive losses in the accelerator waveguide structure (copper loss). The residual RF power at the end of the linac is extracted via the output mode transformer and fed back to the directional coupler for recirculation, while the electron beam passes straight-on into a flight tube. The linac waveguide is water-cooled and is maintained at a high vacuum (less than 10^{-5} torr) by the two ion pumps connected to the input and output ends of the linac.

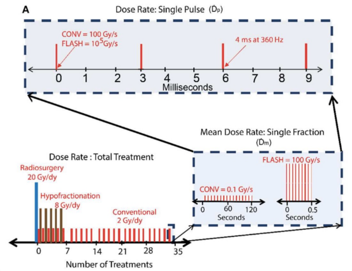
Flash effect

- Interest from the international community
- Single Irradiation with ultra-high dose rate **> 40 Gy/s** for a total delivery time <100 ms
- Much higher dose rates (up to 10^9 Gy/s) during each pulse
- Potential for widening the therapeutic window (balance efficacy on diseased tissues and toxicity on healthy tissues)



Dose delivery time structure

- A crucial role: **dose delivery time structure** (parameters need to be kept under control)
- FLASH effect can be triggered using **electrons, x-rays, protons**
- LINAC typically have a pulse duration of 3-5us, with repetition rate of ~200-400Hz
- Cyclotron based protons beams quasi-continuous (short pulse and rr)
- **A)** DR scheme in RT. **B)** Typical temporal beam characteristics for CONV and FLASH using electrons.



B

Beam Characteristics	CONV	FLASH
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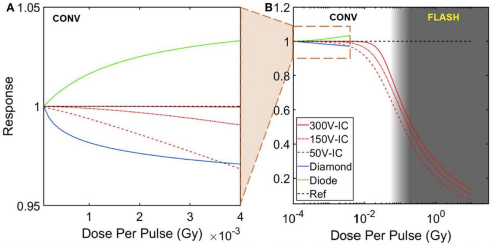
Dose Rate: Single Pulse D_p	~100 Gy/s	~10^5 Gy/s
Mean Dose Rate: Single Fraction $\dot{D}_m$	~0.1 Gy/s	~ 100 Gy/s
Total Treatment Time T	~days/minutes	< 500 ms

Orders of magnitude higher! Problems of saturation and non-linear response

Charge based detector

- Based on principle of creation e-h pair, collected, correlated to dose
- **IC** with high DPP, ions **pairs can recombine**: decrease in sensitivity with increasing DPP

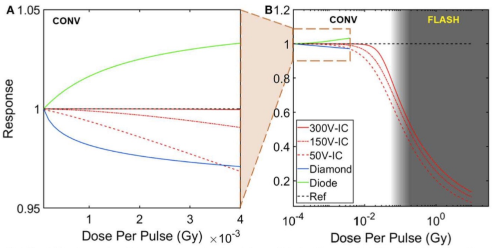


Solid state detector (diamonds, diodes)

- Used in dosimetry for their high sensitivity and small size
- Charge recombination more complex process: dominated by indirect recombination
- RG (**recombination-generation**) centers and impurities that can act as trap center

Charge based detector

- Based on principle of creation e-h pair, collected, correlated to dose
- **IC** with high doses per pulse, ions **pairs can recombine**: decrease in sensitivity with increasing DPP



Solid state detector (diamonds, diodes)

- **Diamonds**: increased/decreased sensitivity depending on construction (microDiamond detector type 60019 PTW in blue)
- **Diodes**: over-respond at high DPP (opposite of ICs)
- Kinetic model of recomb process in solid state detector is needed

Research activity with diamonds

Ref: Marinelli, Marco, et al. "Design, realization, and characterization of a novel diamond detector prototype for FLASH radiotherapy dosimetry." *Medical Physics* 49.3 (2022): 1902-1910.

- FLASH radiotherapy **dosimetry**
- PTW 60019 microDiamond (mD)
- Schottlky diode
- Sensitivity ~1nC/Gy
- Active volume instrinsic diam layer deposited on top of a conductive p-type boron-doped diam layer (used as back contact)
- Built-in voltage ~1V
- Active area few mm2

INFN-TO and University of Turin

- The project started in January and for the moment we have been using silicon devices (from September diamonds)
- Very different principle of use
- We will deposit electrodes at different depths (create different thicknesses on the same sensor)
- Diamond by Rinati and Marinelli is a dosimeter: very small by definition
- We work on beam monitors: we would like to cover a few cmxcm (ok for irradiating cells)

Solid State Devices for Beam Monitoring

Conv solid state detector + UHDR beams: saturation of both sensor and readout (thin sensor to overcome this issue)

SILICON (Ultra-thin ~10μm, segmented, high polarized)

- high sensitivity, spatial res, developed technology
- Unkown factor: linearity with DR, recombination effect, radiation resistance

DIAMOND

- Radiation hardness, h resistivity of intrinsic diamond, large saturated carrier velocity
- Challenging issues: DR linearity, possibility of straddle areas several cm^2

SIC

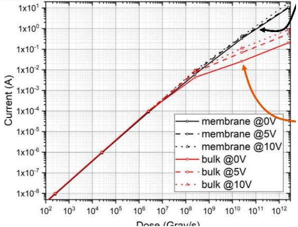
- Ideal compromise: h electrical stiffness, speed of charges, melting T, thermal diffusivity, industrual maturity
- Preliminary simu: DR linearity up to 10^{11} Gy/s on X-ray beams for SiC membrames (2 μm thick)

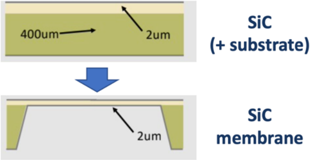
	Energy Gap [eV]	W e-h pair energy [eV]	Density [g/cm^3]
Silicon	1.12	3.62	2.33
SiC	3.26	7.78	3.21
Diamond	5.45	13	3.52

Diamond and SiC are expected to be **less sensitive than Si** → Advantage for UHDR application (reduce tot charge released in the sensor chn)

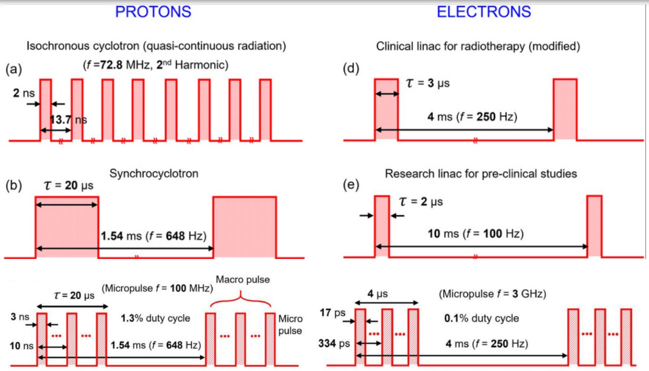
SiC membranes

- SiC membranes promising as hard X-ray beam position monitors → Preliminary simulations: a **DR linearity up to 10^{11} Gy/s** on X-ray beams for SiC membrane (2 μm thickness)
- Substrate removal improves the detector linearity in X-rays (12.5 keV) high dose-rates.
- Thinning procedure **unique expertise of STLab**.



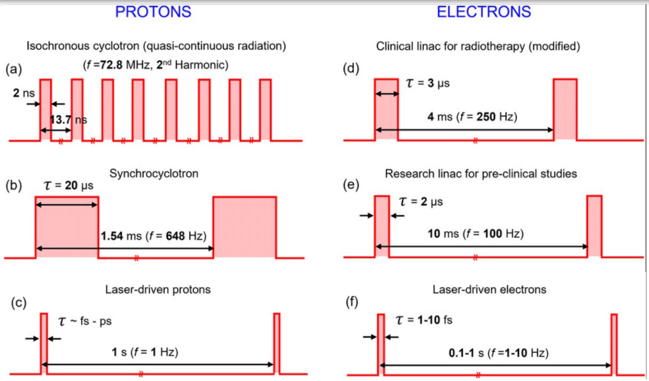


Time characteristics of pulses



F Romano, C Bailat, P Gonçalves Jorge, M L F Lerch, A Darafsheh. Ultra-high dose rate dosimetry: Challenges and opportunities for FLASH radiation therapy. Medical Physics, 2022

Time characteristics of pulses



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Beam monitors technologies FRIDA

BM type	Status	Description	Possible advantages	Main challenges	Sect.
Air fluorescence based	To be developed within the project Very preliminary tests with a raw prototype showed encouraging results	The incoming beam interacts with the air inside a PVC 'empty' container. Fluorescent light is produced and readout by PMT/SiPM at the side of the container.	- Minimize the detector impact on the beam - Preserve the best irradiation conditions for the patient - Perform pulse by pulse measurements - Negligible saturation - Reduced energy dependency	- Pressure and temperature dependence (possible need of calibrations) - First application in this medical application field	RM1
Integrating current transformers	To be developed within the project	Current induced in a coil from the magnetic field generated by an intense ion beam will be registered and characterized.	Avoid destructive interference on the beam current and energy.	- Linearity with the fluence of pulsed beams must be verified - Dose rate independence must be verified, as well	LNS

Beam monitors technologies FRIDA

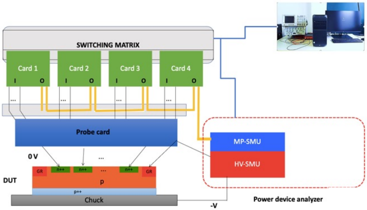
BM type		Status	Description	Possible advantages	Main challenges	Sect.
Solid-state detectors	Thin silicon	First prototypes available / improved devices to be developed	Polarized thin silicon (<20 um)	- Performing fluence measurements pulse per pulse (or even within the pulse) - High spatial resolution - Minimal impact of the detector on the beam line	- Linearity with dose-rate - Radiation resistance	TO
	Diamond		CVD diamond with buried electrodes			TO
	SiC membranes		"Free-standing membranes" of thickness ranging between 0.2 and 10 um (no substrate)			CT

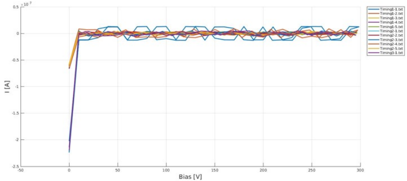
Beam monitors technologies FRIDA

BM type	*Status*	*Description*	*Possible advantages*	*Main challenges*	*Sect.*
Multi-gaps ion chamber	Available. The system has been already tested under 400 Gy/sec pulsed proton beams	Two/three ionization chambers of different gaps, calibrated against the Faraday Cup, will be adopted to estimate the ions recombination at high rates	Correction of the ion-recombination effects at high dose rate pulse-per-pulse, up to FLASH (> 40/Gy/sec) and ultra FLASH (>10^9 Gy/min) regimes	- On-line monitoring of the released absolute dose - Linearity with the released dose	LNS
Secondary Emission Monitor Detector (SED)	Available	The electrons extracted by the beam interaction with a metallic thin foils, are measured and integrated	Real-time, pulse per pulse, non destructive measure of the absolute dose (after calibration) up to flash and ultra flash (>10^9 Gy/min) regimes.	Linearity over an extremely wide range of dose rate (from 1 Gy/min up to 10^9 Gy/min)	LNS

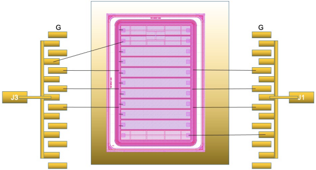
Thin Silicon sensors

- Switching Matrix and a dedicated probe card (current-voltage) → **Completed depleted for Bias > 20V**





Strip area: 2.2 mm^2
Active thickness: 45 μm
Total thickness: 615 μm



Simulation of FLASH e⁻ UHDR in Si

Vignati, Anna, et al. "Beam monitors for tomorrow: the challenges of electron and photon FLASH RT." *Frontiers in Physics* (2020): 375.

- Typical FLASH DR: fluence rate of electron/photons on the silicon sensor surface as a function of the geometry and particle energy
- Unkown factor (recombination effect, saturation and sensor linearity with dose)

Beam	Dose rate (Gy/s)	Rate of charge produced (µC/s) (pC of charge produced in 5 µs pulses)			
		Sensor thickness 100 µm		Sensor thickness 20 µm	
		Pixel area		Pixel area	
		1 × 1 mm²	50 × 50 µm²	1 × 1 mm²	50 × 50 µm²
Monoenergetic 1 MeV photons	10^3	5.0	$1.3 \cdot 10^{-2}$	$4.0 \cdot 10^{-1}$	$1.0 \cdot 10^{-3}$
		(25)	(0.063)	(2.0)	(0.0051)
	10^6	$5.0 \cdot 10^3$	$1.3 \cdot 10^1$	$4.0 \cdot 10^2$	1.0
		(25,000)	(63)	(2,000)	(5.1)
6 MV LINAC photons	10^3	2.3	$5.8 \cdot 10^{-3}$	$1.9 \cdot 10^{-1}$	$4.8 \cdot 10^{-4}$
		(12)	(0.029)	(0.96)	(0.0024)
	10^6	$2.3 \cdot 10^3$	5.8	$1.9 \cdot 10^2$	$4.8 \cdot 10^1$
		(12,000)	(29)	(960)	(2.4)
6 MeV electrons	10^3	$4.3 \cdot 10^1$	$1.1 \cdot 10^{-1}$	8.6	$2.2 \cdot 10^{-2}$
		(220)	(0.54)	(43)	(0.11)
	10^7	$4.3 \cdot 10^5$	$1.1 \cdot 10^3$	$8.6 \cdot 10^4$	$2.2 \cdot 10^2$
		(2,200,000)	(5,400)	(430,000)	(1,100)

Simulation of FLASH e^- UHDR in Si

Vignati, Anna, et al. "Beam monitors for tomorrow: the challenges of electron and photon FLASH RT." *Frontiers in Physics* (2020): 375.

- **Thin sensor**: limit charge build-up effect, reduce recombination probability ($100\mu m \rightarrow 20\mu m$ en released lowers by over a factor 10)
- **Small pixel areas:** cuts down the en released, but increases # readout chns

Beam	Dose rate (Gy/s)	Rate of charge produced (μC/s) (pC of charge produced in 5 μs pulses)			
		Sensor thickness 100 μm		Sensor thickness 20 μm	
		Pixel area		Pixel area	
		1×1 mm^2	50×50 μm^2	1×1 mm^2	50×50 μm^2
Monoenergetic 1 MeV photons	10^3	5.0	$1.3 \cdot 10^{-2}$	$4.0 \cdot 10^{-1}$	$1.0 \cdot 10^{-3}$
		(25)	(0.063)	(2.0)	(0.0051)
	10^6	$5.0 \cdot 10^3$	$1.3 \cdot 10^1$	$4.0 \cdot 10^2$	1.0
		(25,000)	(63)	(2,000)	(5.1)
6 MV LINAC photons	10^3	2.3	$5.8 \cdot 10^{-3}$	$1.9 \cdot 10^{-1}$	$4.8 \cdot 10^{-4}$
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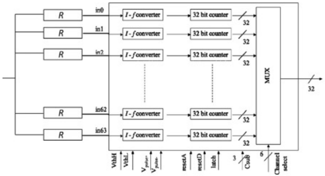
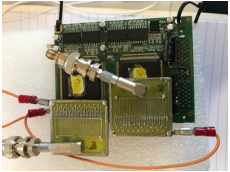
		(2,200,000)	(5,400)	(430,000)	(1,100)

TERA08

- **A**pplication **S**pecific **I**ntegrated **C**ircuit designed by our group and used in several laboratories: **TERA**
- 64 equal CHNs
- In each CHN **Current-to-frequency converter** (each digital pulse = fixed input charge quantum)
- Max conv frequency=20MHz
- Converter accepts both polarities + 32-bit counter (up/down counting capability)
- Converter based on **Recycling integrator architecture**

CHIP1



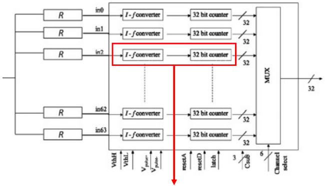


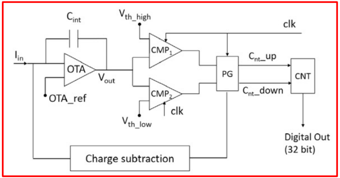
TERA08

- I_{in} integrated over 600fF capacitor $\mathbf{C_{int}}$ (via Operational Transcoddutance Amplifier **OTA**)
- $\mathbf{V_{out}}$ compared to +/-thr (by 2 synchronous comparators $\mathbf{CMP_1}$ $\mathbf{CMP_2}$)
- Pulse Generator **PG**: pulse to increment/decrement counte **CNT**
- In parallel PG: pulse to **Charge Subtraction Circuit** (subtract +/- charge quantum to C_{int})

DAQ Period (µs)	Q_c(fC)	Max conversion freq per chn	Max conversion (total)	Max current (for 64 CHNs)
1e4 (0.01 s)	200 fC	20 MHz	1280 MHz	± 256 μA

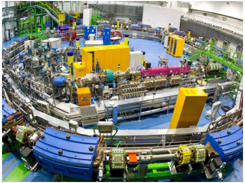
CHIP1

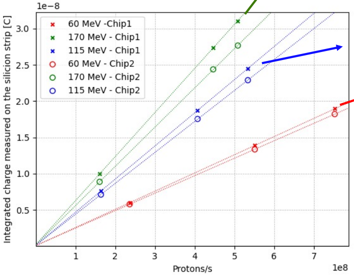




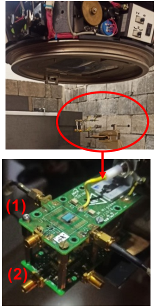
First tests with protons beams

CNAO
Centro Nazionale di Adroterapia Oncologica



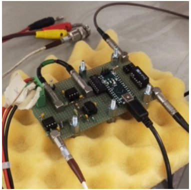


LINAC upgrade



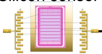
Silicon sensor **(2)** as a beam pulse radiation detector

1. Signal to a **in-house built electrical circuit**: transimpedance amplifier converts photocurrent into small V with subsequent amplification
2. Gain chosen to have suitable input to a Schmitt-Trigger
3. Signal of ~5V as input to ARDUINO to count pulses
4. When amount of pulses reached: logical signal to Optocoupler circuit → **Strigger to Thyratron**



In-house built electrical circuit

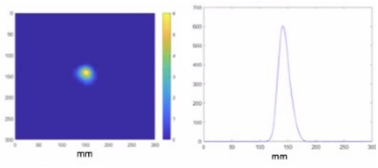
Silicon sensor (2)



IIN → Transimpedance amplifier+OP Amp → Schmitt-Trigger → ARDUINO UNO (As pulse counter) → Optocoupler circuit → **Thyratron**

TIFPA

- FLASH beam in course of upgrade at **TIFPA** (cyclotron)
- Reached **140Gy/s in 1cm^2** (Shoot Through mode)
- Current **1.42e12 p/s**
  Efficiency at isocenter 76%
- For nominal current of extraction from the cyclotron: **300nA**



2D and 1D profile of a beam realized in TIFPA

CPFR

- ElectronFlash

	CONV	UHDR
Pulse Lenght	1us	0.5-4us
Pulse Rate freq	1-245Hz	1-245 Hz (to4us) or 350Hx (to 2us)
FS	10-120mm diam	10-120mm diam
Distance from source	50-220 cm	50-220 cm
Beam energy	7 and 9 MeV	7 and 9 MeV
DPP	From 6cGy	Up to 13 Gy
DR	From 3cGy/s	Up to 4Gy/s