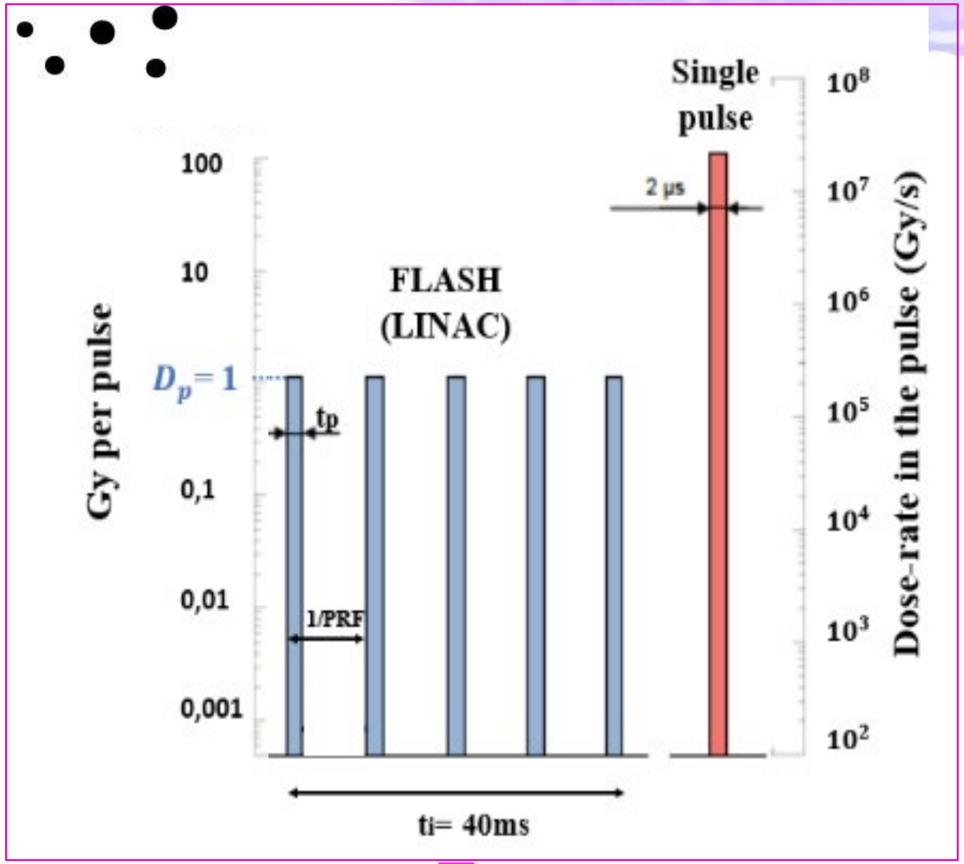
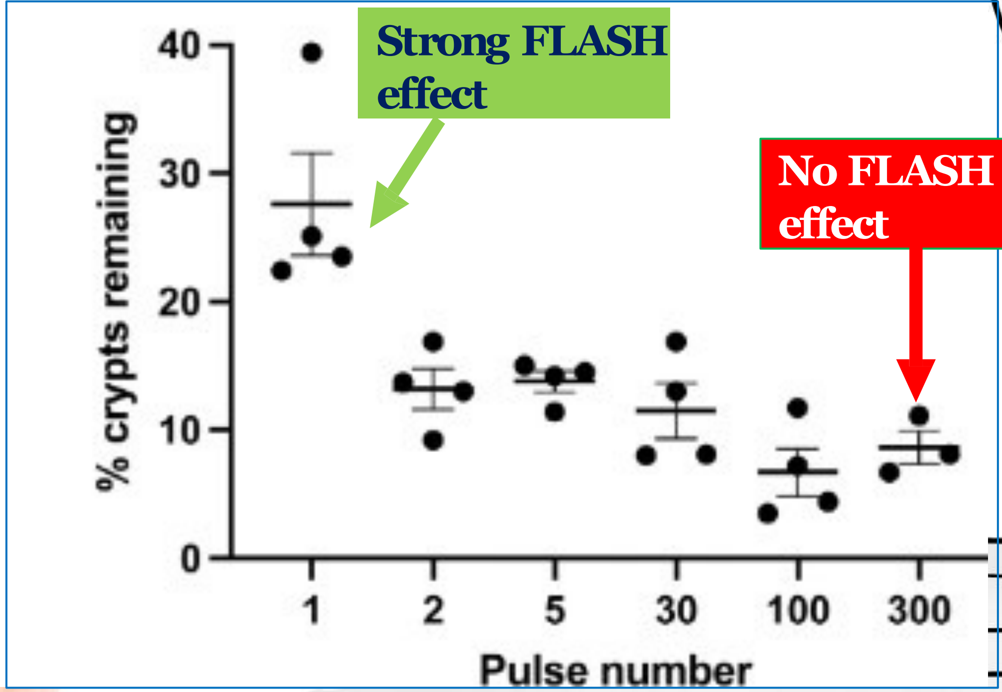
WP2 & WP3 round table

Conveners: **Lucia Giuliano** (Sapienza University of Rome – INFN Roma) , Anna Vignati (INFN) , Pablo Cirrone (NFN) , Maria Giuseppina Bisogni (INFN)

Single or multiple pulses for the same total dose?



Facility	**Modified linac** Elekta SL75
Nominal energy	6 MeV
Dose	**11,2 Gy**
Temporal width of pulse	3,4 µs
PRF	100 Hz
Number of pulses	**Variable**



Ruan JL et al. Int J Radiat Oncol Biol Phys. 2021 Dec 1;111(5):1250-1261

One shot: **high charge** per pulse to obtain high dose

Multiple shot: possibility to have **less charge** in one pulse

Pencil beam or wide range?

FLASH effect has been seen essentially :

In **small volumes** of normal tissues (a few cc) on WIDE RANGE @LOW ENERGY

We design machine for WIDE RANGE @ HIGH ENERGY

Large field : **high charge** per pulse to obtain high dose

Pencil beam: **less charge** in one pulse to irradiate less volume with same dose

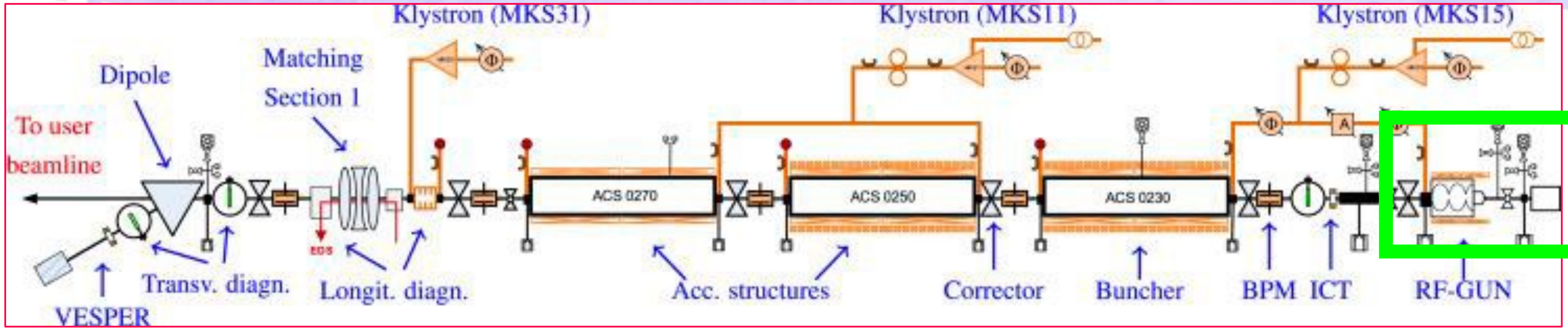
Different approaches are under discussion: **PENCIL BEAM**

- Premise to use normal conductive photoinjector based accelerators (CLEAR-CERN)
  - The DEFT linac (CERN-CHUV) want expand beam to target cross section >10 cm
- Premise to use super conductive photoinjector based accelerators (ELBE)
- Premise to use LASER based accelerators
- Work recently started within WP4 (SBAI)

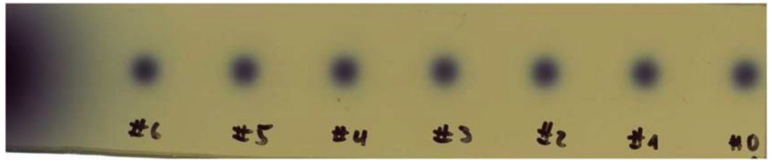
No evidence of FLASH effect with pencil beams @LOW energy

Can FRIDA prove it?

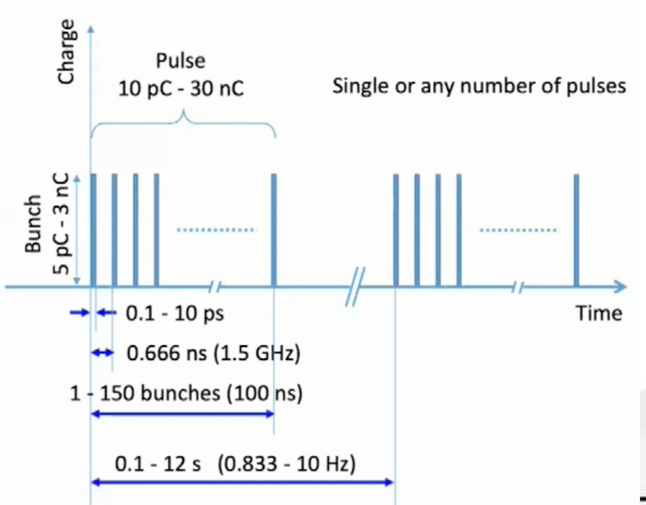
CLEAR for FLASH Radiotherapy Research



- Photoinjector : electrons are generated by a laser on the photocathode
- 3 accelerating structures followed by diagnostics sections
- Normal conductive structure
- Pencil beam (3,23 mm or 6,88 mm)

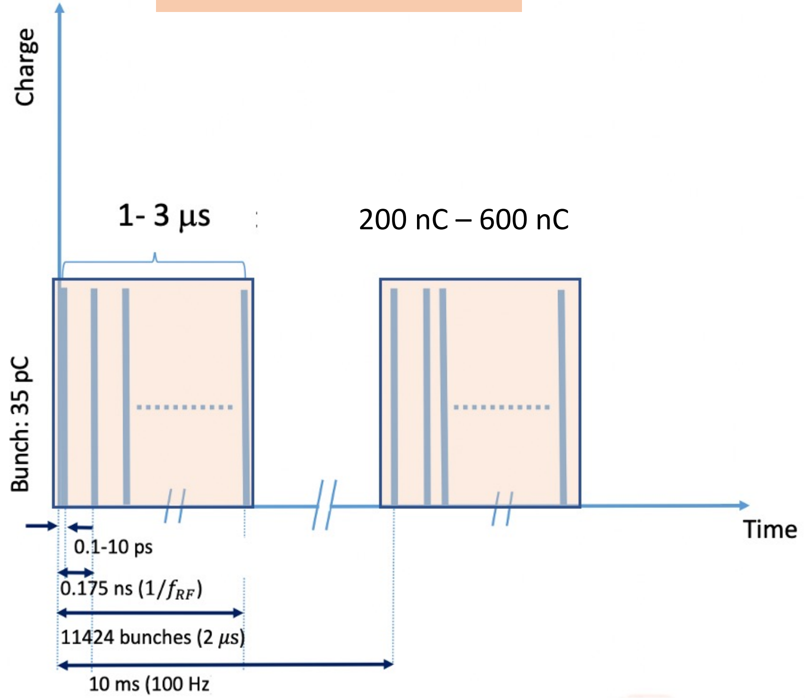


Symbol	Description	Value
E	Beam energy	60 - 220 MeV
t_p	Pulse width	0.1 - 10 ps
PRF	Pulse repetition frequency	0.8333 - 10 Hz
Q_p	Pulse charge	0.001 - 3.0 nC
	Max. pulse charge	30 nC
	bunch per pulse	1-150
D_p	Dose in a single pulse	0.2 - 12 Gy in ⌀3.5 mm
$\dot{D}_p$	Instantaneous Dose-rate	10^{10} Gy/s
$\bar{\dot{D}}$	Mean dose rate	>100 Gy/s



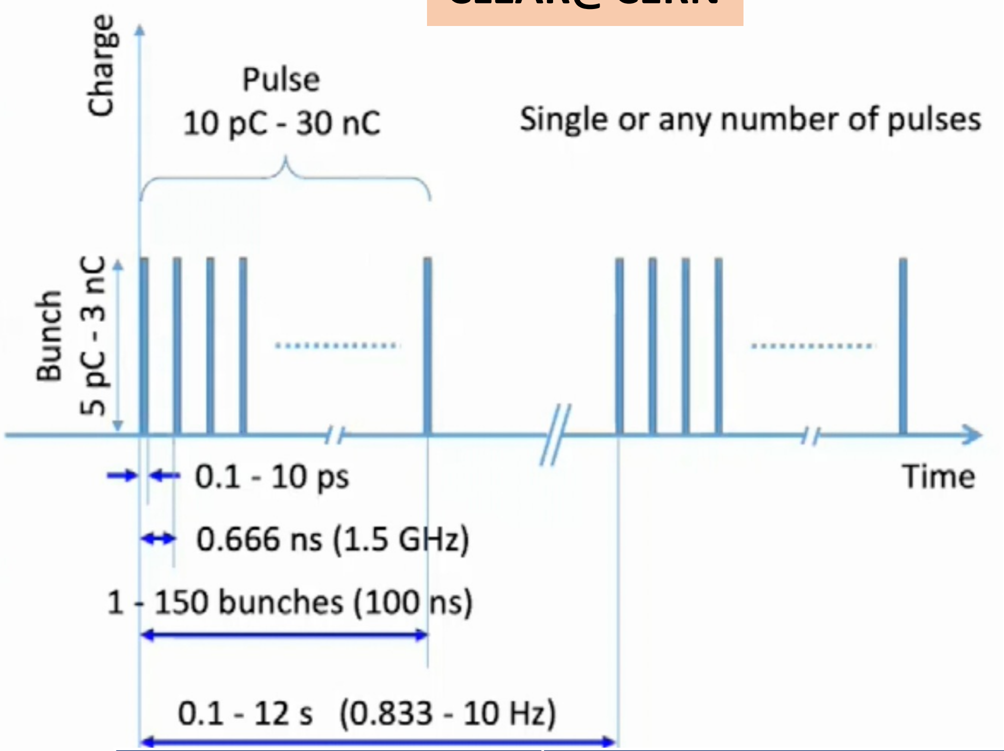
Temporal structure of the pulse for different VHEE LINACs

VHEE@Sapienza



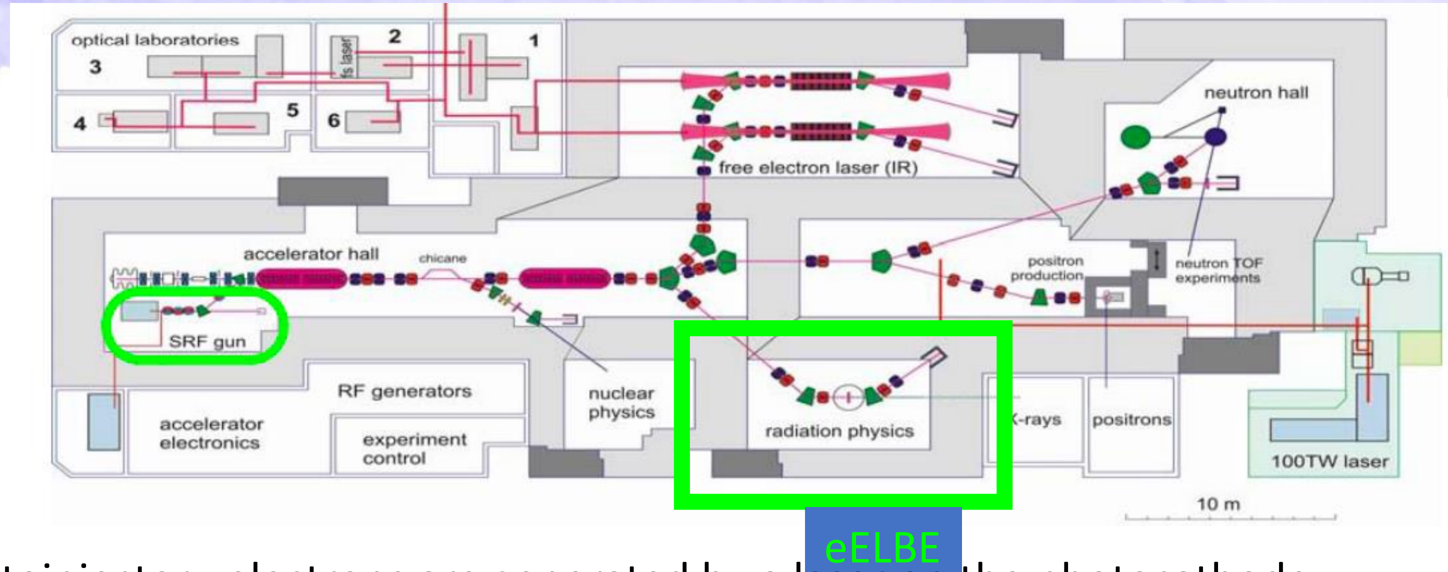
Beam parameters VHEE@Sapienza	Range
Energy	60 – 130 MeV
Bunch Length	12 ps (rms)
Bunch Charge	35 pC (for 400 nC total charge)
Number of bunches per pulse	11424
Repetition rate	100 Hz
Bunch spacing	0.175 ns

CLEAR@CERN



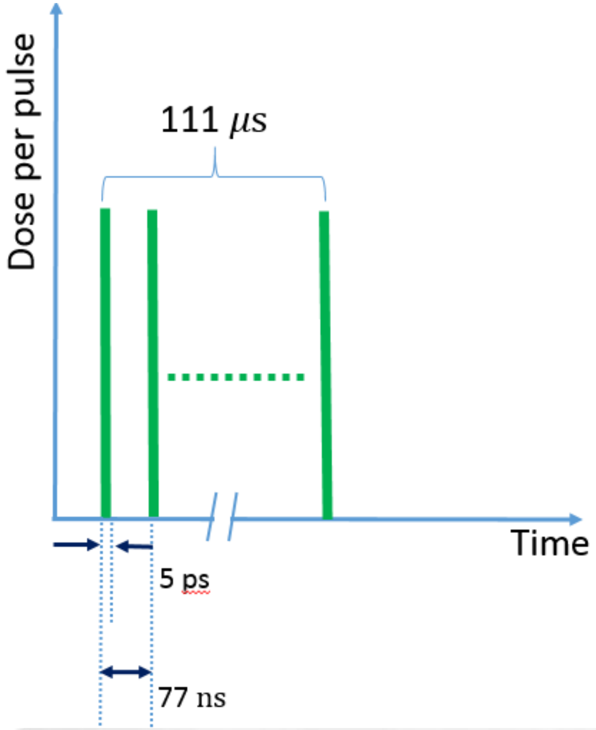
Beam parameters CLEAR@CERN	Range
Energy	60 – 220 MeV
Bunch Length	0.1-10 ps (rms)
Bunch Charge	5 pC – 3nC (max 30 nC)
Number of bunches per pulse	1 to 150
Repetition rate	0.8 - 10 Hz
Bunch spacing	1.5 GHz (from the laser)

Sources for high dose rate electron irradiation @ELBE center



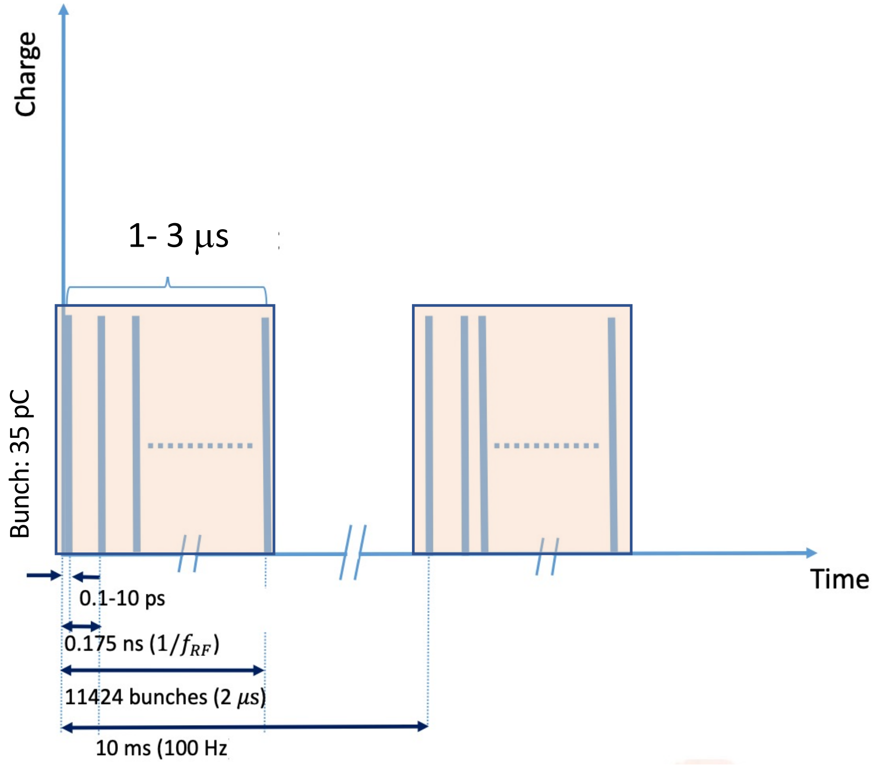
- Photoinjector : electrons are generated by a laser on the photocathode
- Superconductive structure
- Pencil beam (1.5 mm – 3 mm)

Symbol	Description	Value
E	Beam energy	20 MeV
t_p	Pulse width	5 ps
PRF	Pulse repetition frequency	2.5 - 1000 Hz
Q_p	Pulse charge	77 pC
	bunches per pulse	1441
D_p	Dose in a single pulse	26 Gy in Ø3 mm
$\dot{D}_p$	Instantaneous Dose-rate	10^9 Gy/s
$\bar{\dot{D}}$	Mean dose rate	2.6×10^5 Gy/s

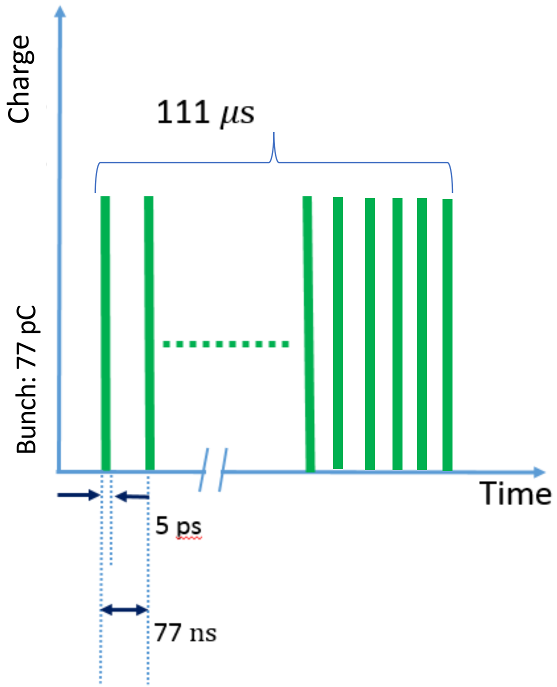


Temporal structure of the pulse for different VHEE LINACs

Normal conductive



Superconductive



VHEE@SAPIENZA

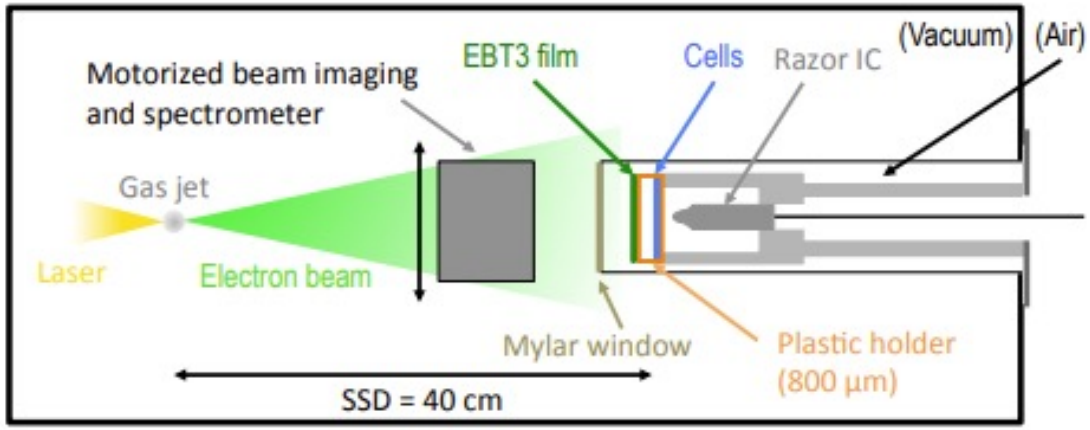
- One pulse of 11424 bunches
- Mean dose rate: >100 Gy/s
- Pulse dose rate: ~ 10^6 Gy/s
- Dose per pulse (2 µs) **200 Gy Ø 50 mm**

VHEE@ELBE

- One pulse of 1441 bunches
- Mean dose rate: 2.6 x 10^5 Gy/s Ø 3 mm
- Pulse dose rate: 10^9 Gy/s
- Dose per pulse (111 µs) **26 Gy Ø 3 mm**

Laser plasma technology

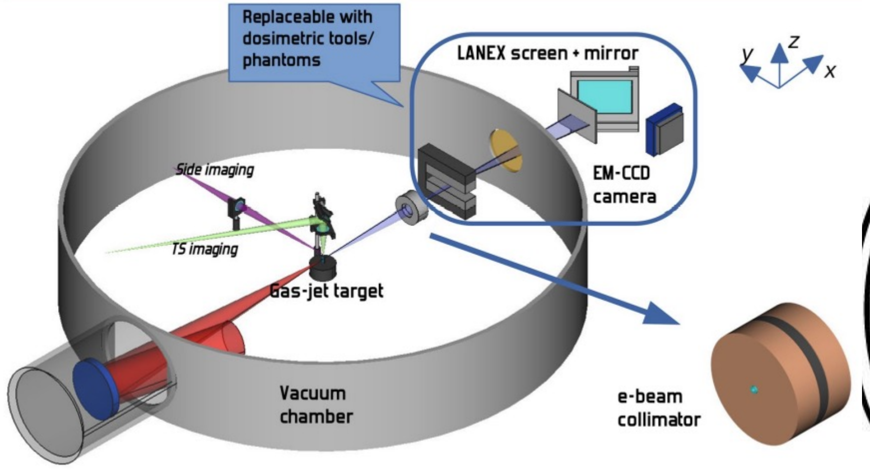
kHz, mJ laser-plasma @LOA



Symbol	Description	Value
E	Beam energy	0.5 - 1 MeV
t_p	Pulse width	few ps
PRF	Pulse repetition frequency	1 KHz
Q_p	Pulse charge	1 – 10 pC
D_p	Dose in a single pulse	1 mGy in ⌀1 cm^2
$\dot{D}_p$	Instantaneous Dose-rate	> 10^7 Gy/s
$\overline{\dot{D}}$	Mean dose rate	1 Gy/s

M. Cavallone, et al.Appl.Phys.B, 127 (4), 2021.

1 Hz, J laser plasma @CNR-Pisa



Symbol	Description	Value
E	Beam energy	50 - 250 MeV
t_p	Pulse width	30 fs
PRF	Pulse repetition frequency	1 Hz
Q_p	Pulse charge	120 pC
D_p	Dose in a single pulse	0.02 Gy in few mm
$\dot{D}_p$	Instantaneous Dose-rate	10^{11} Gy/s
$\overline{\dot{D}}$	Mean dose rate	1 Gy/min

L.Labate, et al. Scientifc Reports 10:17307, 2020.

Compact source for VHEE but (still) limits in average dose rate

What we know

We design accelerator by knowing the **CHARGES**

We use accelerator to deliver **DOSE**

FRIDA

10 nC ~ 1 Gy in ⌀3 cm
with applicators

L. Giuliano measurements @Curie Institut **(7 MeV)**

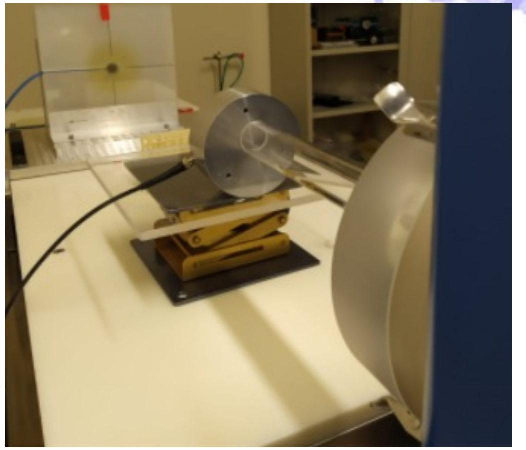
2nC ~ 1 Gy in ⌀1 cm

A. Schiavi et al. using by FRED code **(100 MeV)**

CLEAR - CERN investigation **(200 MeV)**

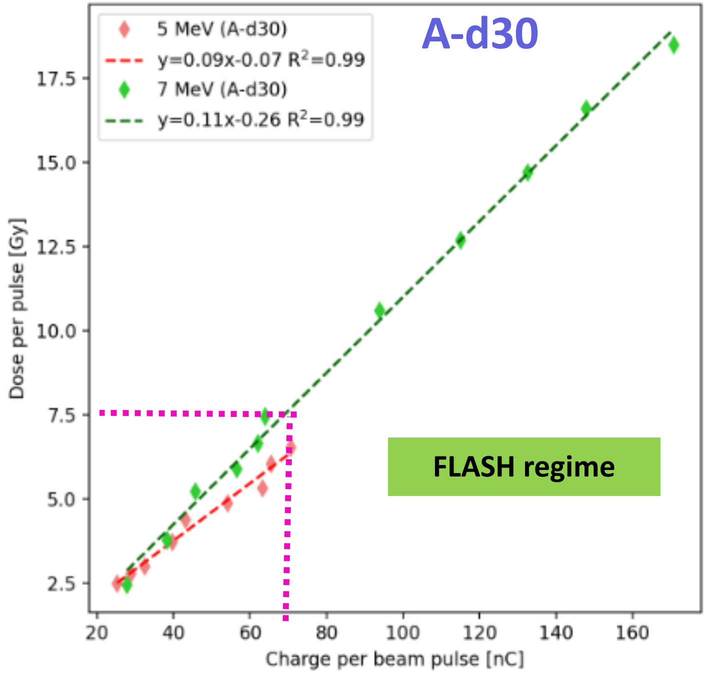
Daniela Poppinga et al 2021 Biomed. Phys. Eng. Express 7 015012

Beam monitoring with Faraday Cup at Institut Curie



- The peak current is always the same (> 100 mA) : Linear proportionality of the dose and the pulse width
- Linear proportionality of the nC with the dose per pulse

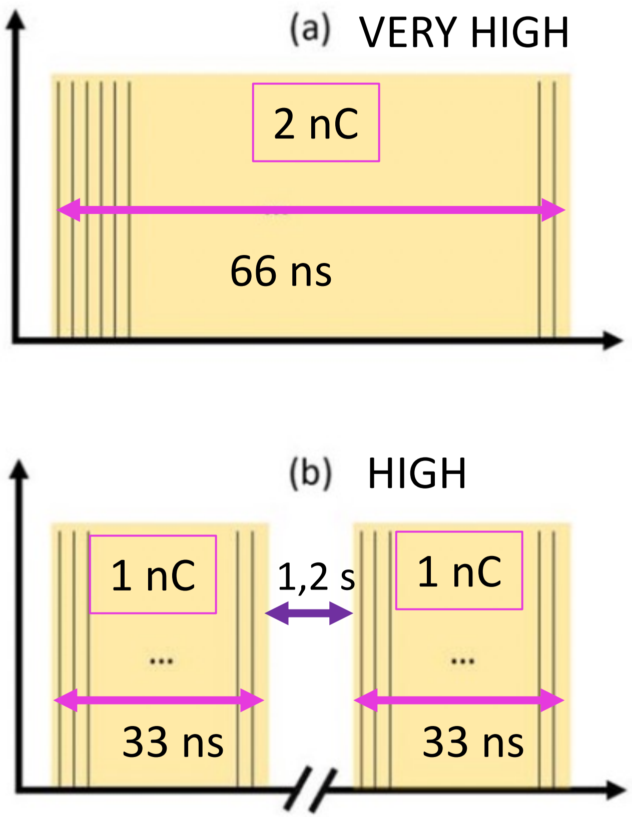
$$C = \frac{1}{R}\sum_{0}^{t} V\Delta t$$



10 nC ~ 1 Gy in ⌀3 cm with applicators (**7 MeV**)

Pulse duration [μs]	Gy/nC
0,3	10,12
0,6	8,74
0,8	9,56
1	9,33
1,2	8,57
2	8,85
2,5	9,05
3	9,02
3,5	8,90
4	9,22

CLEAR investigations



Gy/nC ~2 in ⌀1 cm
(200 MeV)

Beam size	Beam configuration	No of pulses	Dose per pulse	Film measurement front of probe holder [Gy/nC]	Film measurement back of probe holder [Gy/nC]	Chamber measurement [Gy/nC]	Error Dose Error [Gy]
3.5 mm	LOW	36	0.20	4.08	4.15	3.98	0.21
		37	0.20	4.10	4.07	3.85	0.21
		37	0.21	4.21	4.06	3.81	0.21
		39	0.19	3.80	4.26	3.94	0.21
		39	0.20	4.12	4.37	3.96	0.21
		41	0.17	4.18	4.00	3.76	0.19
		45	0.16	4.30	3.98	3.69	0.18
	MEDIUM	4	2.31	4.32	4.34	2.29	0.24
		4	2.17	4.42	4.30	2.37	0.23
	HIGH	2	4.76	4.25	4.41	1.80	0.25
		2	4.46	3.40	3.52	1.48	0.25
		2	4.99	4.54	4.17	1.71	0.25
		2	4.98	4.56	4.03	1.68	0.25
	VERY HIGH	1	7.82	4.53	4.50	1.62	0.33
		1	9.08	4.44	4.59	1.53	0.36
		1	9.17	4.60	4.61	1.54	0.36
		1	6.70	4.47	4.18	1.38	0.25
		1	10.15	4.57	4.34	1.42	0.38
7 mm	LOW	80	0.13	2.29	2.15	1.83	0.12
		85	0.12	2.25	2.12	1.81	0.13
	HIGH	2	5.03	2.11	1.89	0.85	0.16
		2	5.09	2.11	1.89	0.83	0.16
	VERY HIGH	1	9.60	2.23	2.02	0.66	0.18
		1	11.65	2.24	2.07	0.67	0.22

Daniela Poppinga et al 2021 Biomed. Phys. Eng. Express 7 015012

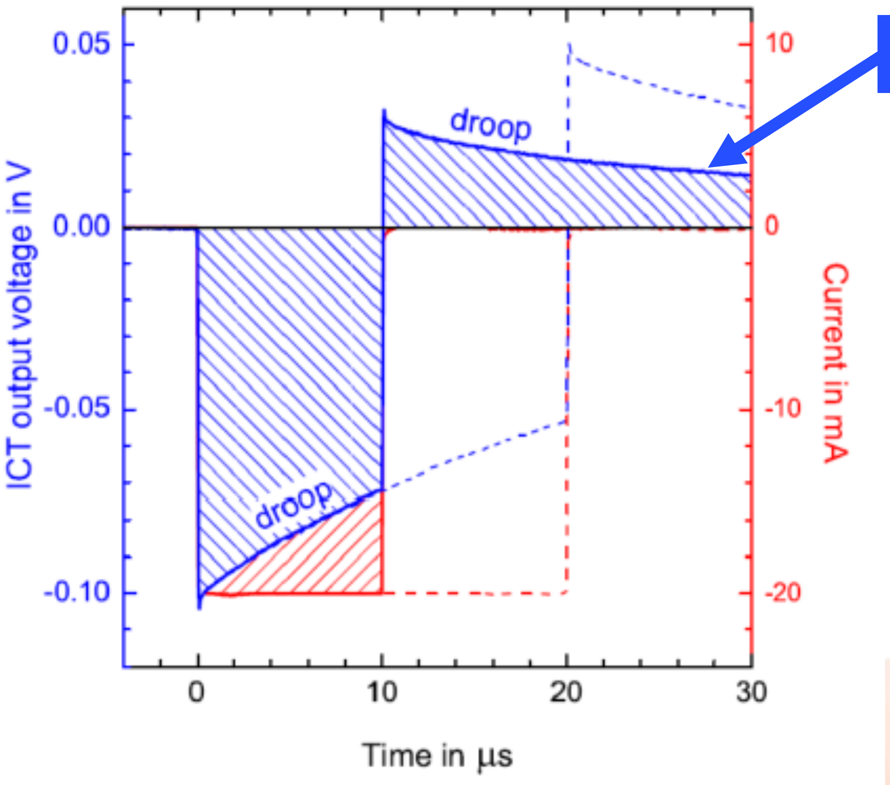
Beam monitoring

We need accurate determination of dose with precisions at 1 % . Is **toroid** the solution?

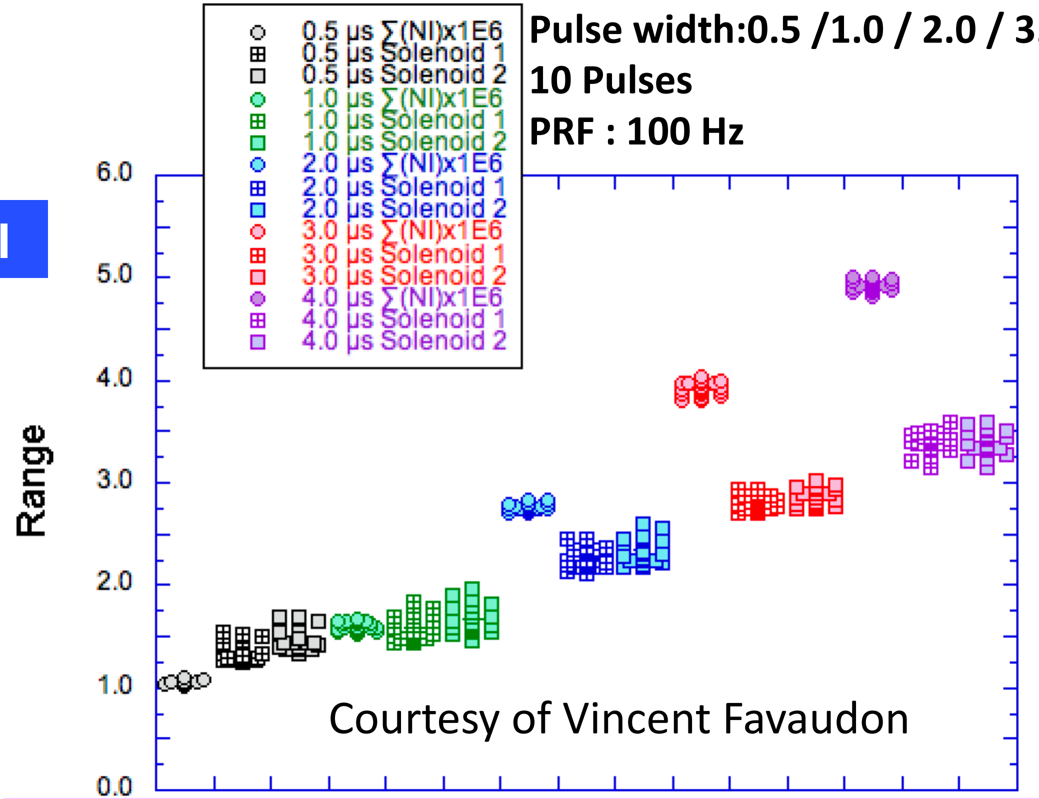
Curie experience with *Persol* toroids

droop rate = 35%/µs
limits the toroid good response

toroid's signal



Pulse width:0.5 /1.0 / 2.0 / 3.0 / 4.0 µs
10 Pulses
PRF : 100 Hz



Courtesy of Vincent Favaudon

Toroid's response is fluctuating and do not represent accurately the current of the beam.

Thank you