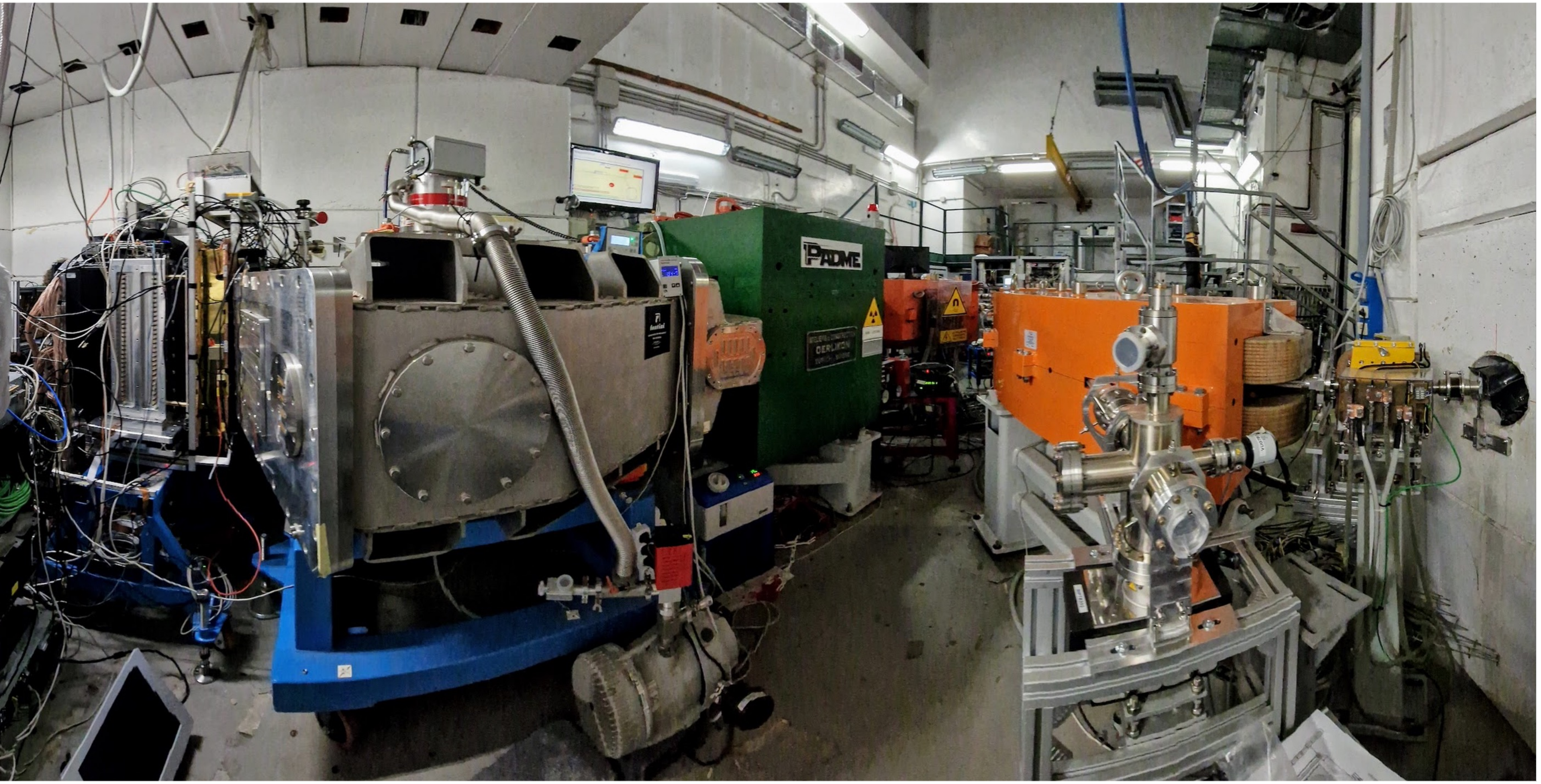
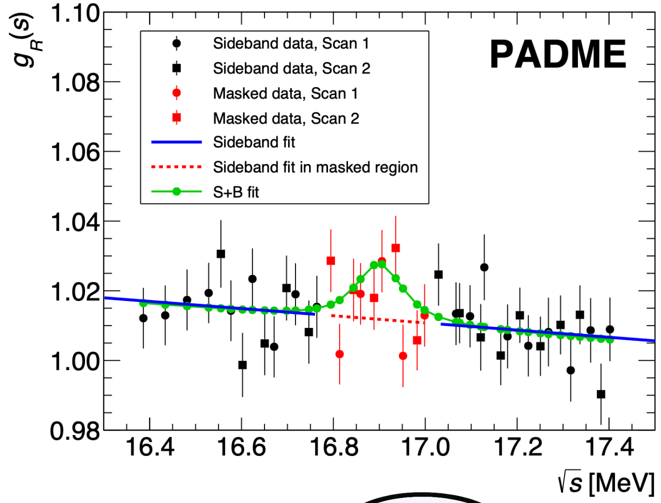
PADME future and prospects

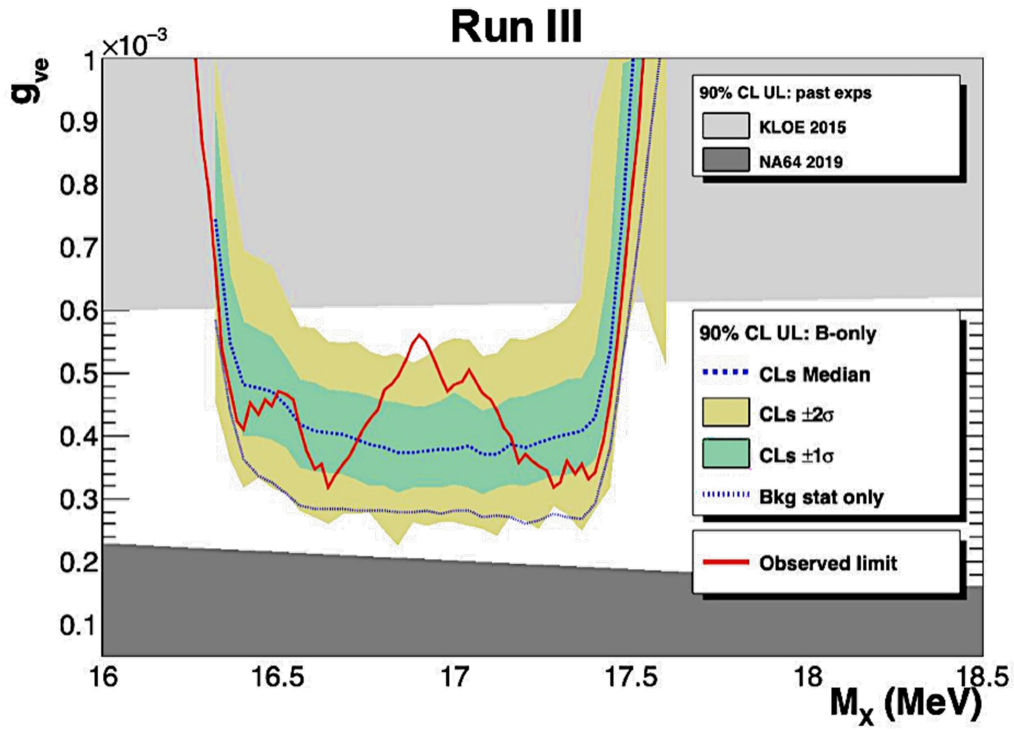
Paolo Valente

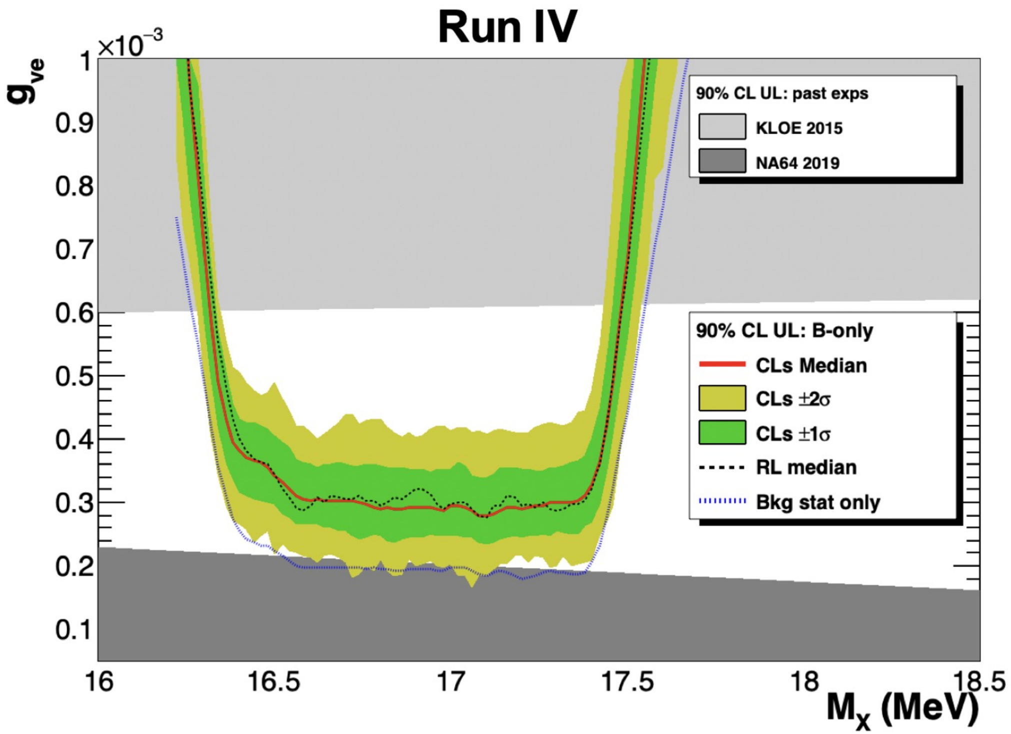




Frascati, March 19th 2026

Where we are





Run III: $0.75 \cdot 10^{10}$ pot/point [total $2.2 \cdot 10^{11}$ pot]

Run IV: $2 \cdot 10^{10}$ pot/point [total 10^{12} pot]

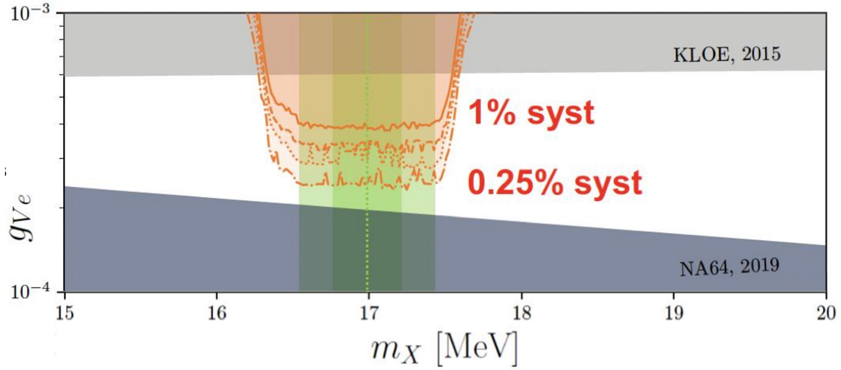
Paolo Valente

How to improve

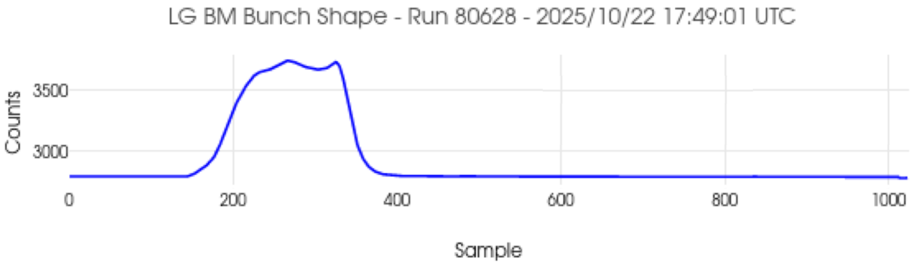
Of course, we can increase the **statistics, but quite soon limited by systematics**

Limiting factor: **positron density**

$\sim$**12 POT/ns** $\times$ **250 ns = 3·10³ pot/pulse**



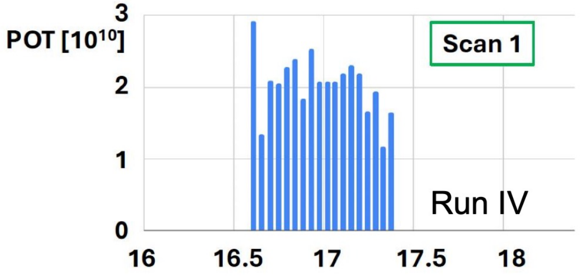
Decrease positron density

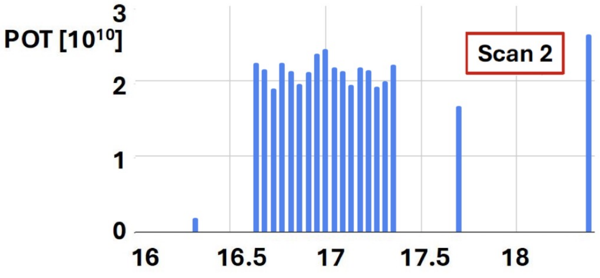


and **increase the pulse length**

Limiting factor: **repetition rate**

$\times$ **49 Hz** $\times$ 0.86·10⁵ s = 1.3·10¹⁰ pot/day





250 ns/20 ms $\sim 10^{-5}$

... and/or improve the **duty cycle**

Paolo Valente

How to improve

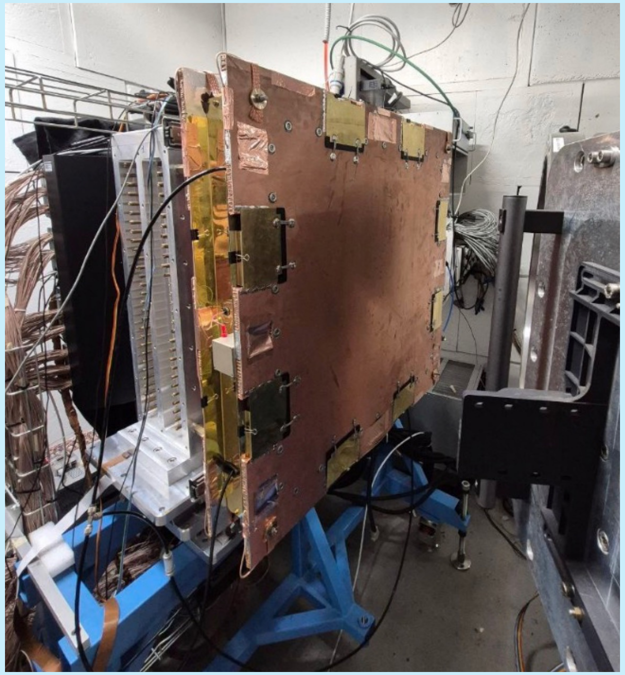
Reducing the positron **beam density** would:

- 😊 Allow reconstructig individual events with **tracking** detectors
- 😊 Dramatically **reduce background** in the calorimeter

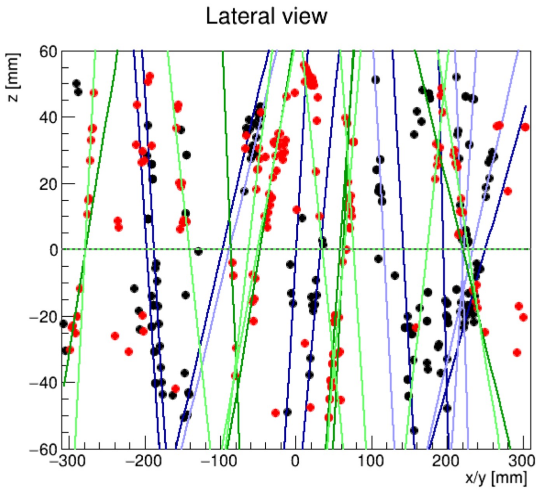
- 😟 But **also** require a **trigger** for opening the acquisition window at the right time

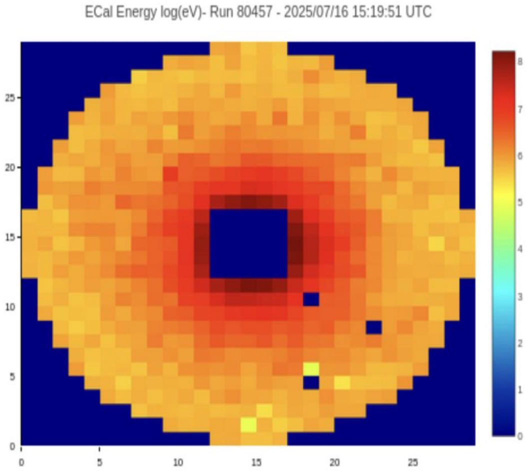
AND/OR

Drastically **reduce the material budget** in front of the tracking detectors and calorimeter



PADMME Micromegas tracker



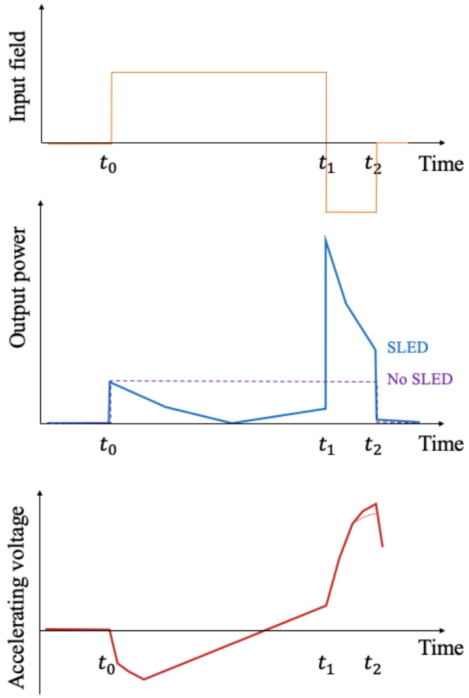


How to improve: increase the beam pulse length

Working on the LINAC only

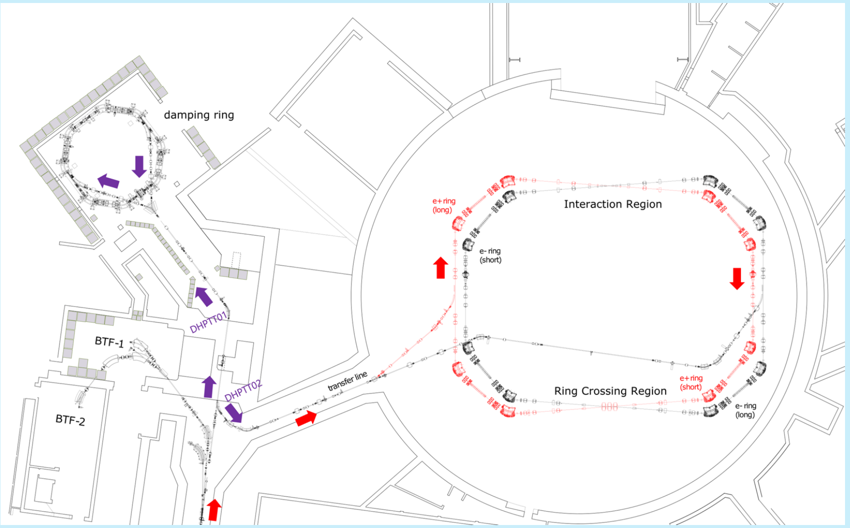
Two main **limitations**:

- **SLED compression**, used to increase the RF power, largely reduces the «flat top» of the accelerating voltage
    - Working “off-crest” allowed us to extend the pulse duration from 10 ns to **250 ns** [*J.Phys.Conf.Ser.* 874 (2017) 1, 012017]
    - Some **ideas** for further extending the beam pulse put forward in [arXiv:2001.10258]
- **Modulator** pulse length limited to 5 μs
    - Considering the time needed for **filling** the accelerating cavities
    - Reduction of RF power if detuning/bypassing the SLED’s



OR

Using a ring in the DAFNE complex as pulse stretcher



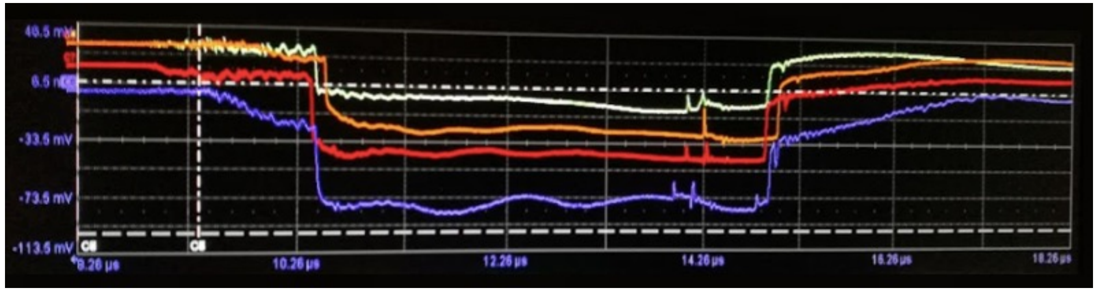
Increase the LINAC beam pulse length

- Considering a filling time of approximately 800 ns, expect up to **2-3 μs** pulses
- Without SLED compression expect a factor 1.6 reduction in RF power, i.e. **maximum energy** down to **320 MeV**

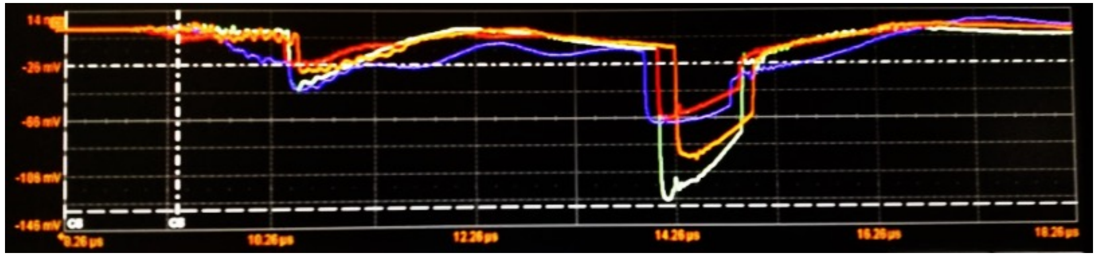
😁 Still up to **one order of magnitude** improvement

😕 **Hardware modifications** needed: de-tuning or bypassing the SLED cavities

5 μs



SLED-in

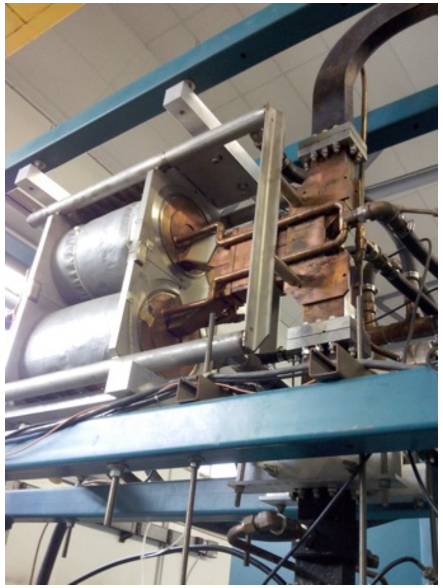


SLED-out

800 ns

to accelerating sections

SLED cavities



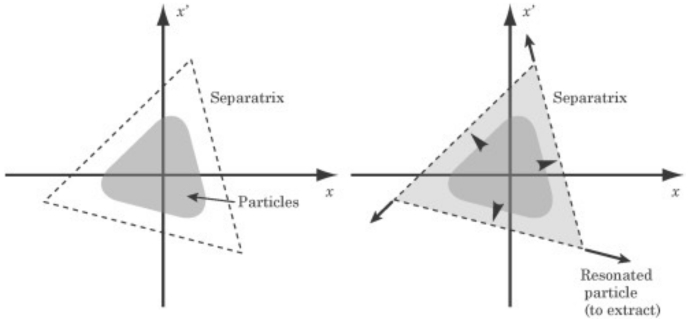
from klystron

Paolo Valente

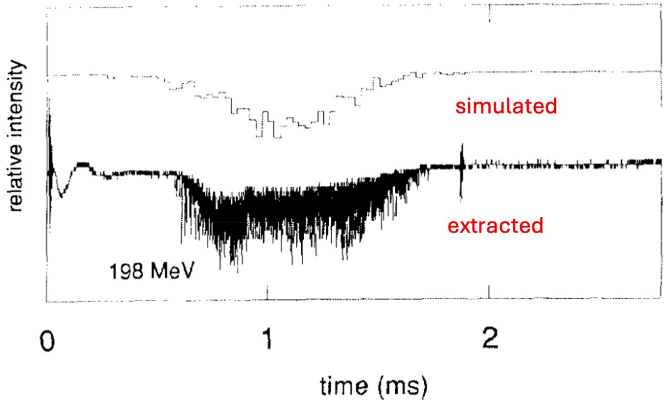
DAFNE as pulse stretcher ring

- POSEYDON, P. Valente [arXiv:1711.06877]: extend the positron beam pulses using **slow extraction** from DAFNE, used as "stretcher" ring [like ELSA at Bonn]
  - Typically, third integer resonant extraction $Q = n + \frac{1}{3}$; need to drive particles close to the resonance condition
  - S. Guiducci, use "**monochromatic**" extraction: bring the betatron tune close to a $\frac{1}{3}$ resonance and use **synchrotron energy loss** – keeping the **RF off** – to drive the beam slowly out of the stable triangular region along one separatrix
  - Requires chromaticity ≠0 to transfer momentum changes to tune changes, $\frac{\Delta\nu}{\nu} = \xi \frac{\Delta p}{p}$
  - ALFA at ADONE LINAC proposal, S. Guiducci *et al.*, [LNF-78/22(R), 1978]
  - Realized at Saskatchewan synchrotron [EROS], 360 Hz, 50-300 MeV electrons, up to 30% duty cycle: L.O. Dallin *et al.*, [Proc. 13th IEEE PAC (1989) 22]

$\frac{1}{3}$ resonance



EROS ring



DAFNE as pulse stretcher ring

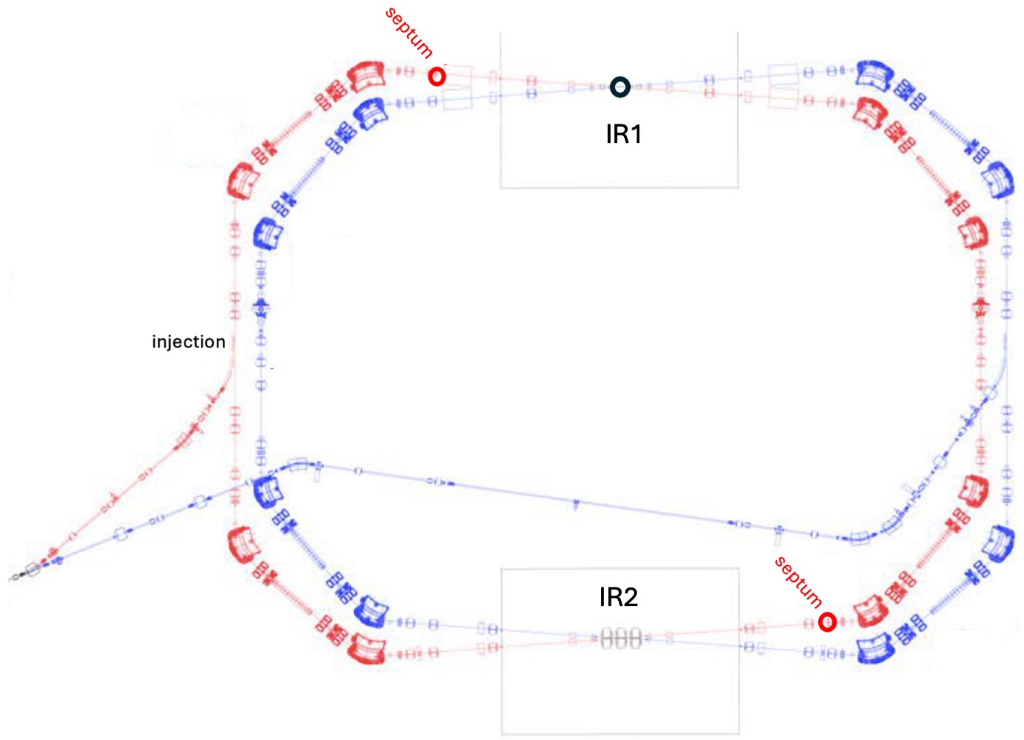
First calculations with DAFNE positron main ring [*J.Phys.Conf.Ser.* 1067 (2018) 6, 062006]

- Tune: $\boldsymbol{Q_x}$ =**4.37** and $\boldsymbol{Q_y}$ =**4.27**
- Cromaticity: $\xi_x = -$**3.3** and $\xi_y = -$**6.3**
- Inject **off-axis** with $\Delta p/p$ =+0.45%
- **Direct injection** from LINAC + collimation system, for emittance and energy spread control

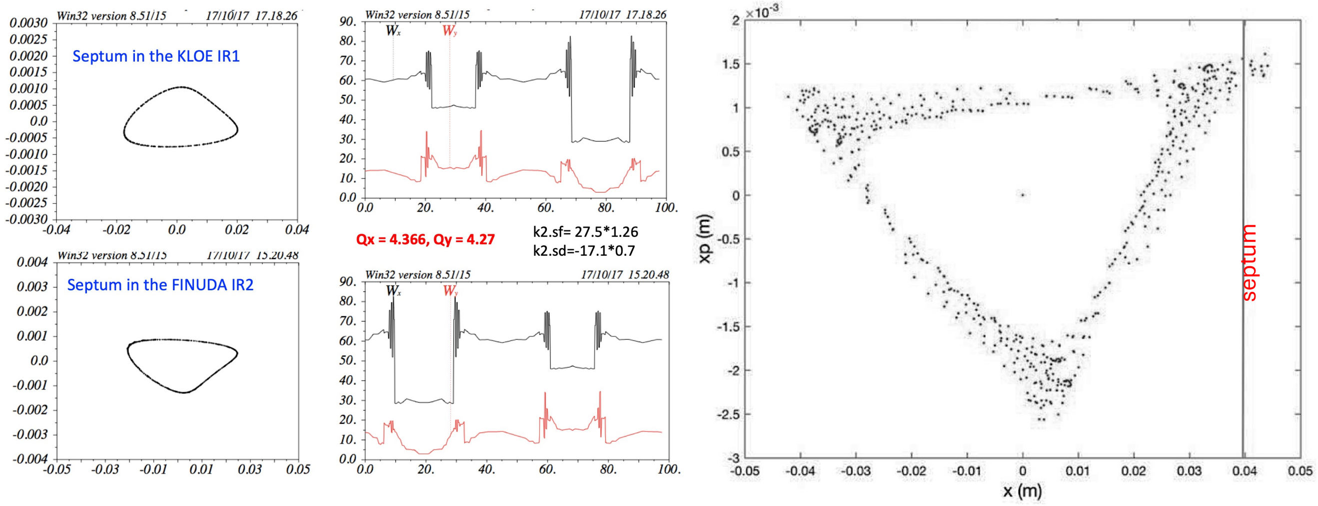
- **Remove low-beta** insertion from IR1 and make it equal to IR2
- Magnetic extraction septum (e.g. equal to the injection one)
- **Electrostatic septum**: ~ 50KV/cm, L~1m, x=40 mm, thickness~100 μm
- Reach $\Delta p/p$ = -0.45% in **660 turns** with **RF** and **wigglers off**

Extraction time totally determined by the energy loss = **0.21 ms**

😁 Gain of 3 orders of magnitude



[S. Guiducci]



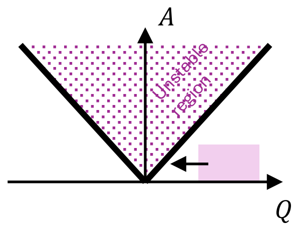
Extraction from DAFNE

Requires:

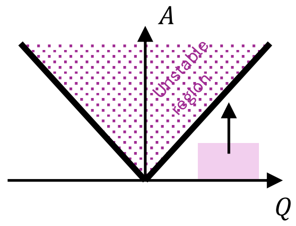
- **Direct injection** of positrons from the LINAC to get the maximum repetition rate
- Place the **extraction** in a suitable spot: **high $\boldsymbol{\beta}$** function and **zero dispersion**, e.g. one of the straight sections
- Modify the ring **optics** to have the correct betatron **tune** and **chromaticity** values
- An **electrostatic septum**, plus a **magnetic septum** and extraction line
- Most importantly, even without wigglers and RF, requires to **operate one complete main ring** plus the transfer-lines

Alternative to the "monochromatic" extraction:

- **RF knock-out** can be used: increase the amplitude of betatron oscillations using a **kicker** at a **frequency** close to a harmonic of the revolution frequency: $f = \left(n \pm \frac{1}{3}\right) f_R$
- [Much] **longer spills** can be achieved



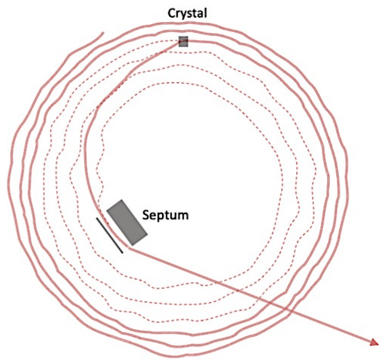
Energy loss



Increase amplitude

Alternative to the electrostatic septum:

- **Channeling** effect in a bent crystal can be used to **kick** the beam towards a magnetic septum
- **Not local scheme**: kick imparted at previous phase advance



Alternative to the main ring:

- Use DAFNE **damping ring**:
  - **Shorter**, 1/3 of the length, and **simpler**
  - Large **acceptance**

SHERPA project

Crystal extraction from main ring

SHERPA main result:

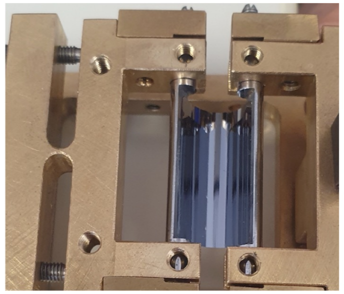
- Experimental evidence that a thin, **15 microns**, Silicon crystal can be bent to achieve **1.2 mrad** deflection of **450 MeV positrons**

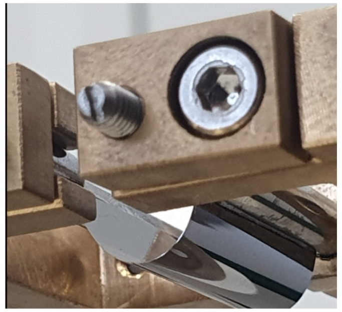
M. Garattini *et al*. [Phys. Rev. Accel. Beams 28 (2025) 2, 023501]

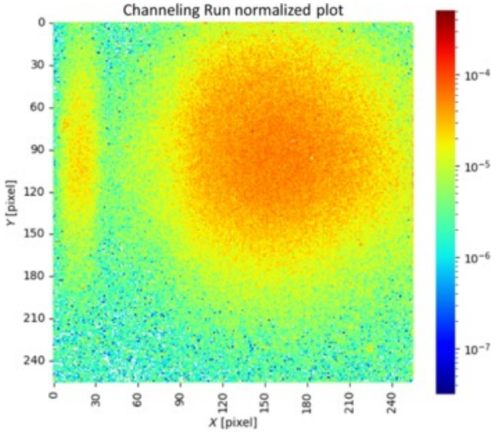
Main e+ ring, SIDDHARTA 2019 optics, **not optimized**

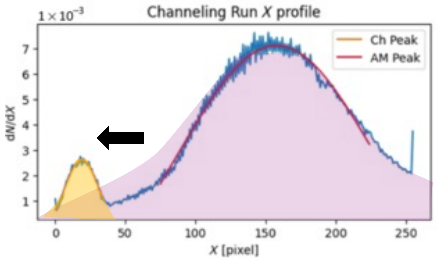
- **Crystal** at **x=8 mm**, **1 mrad** kick, **20 mm offset**
- ~**0.4 ms** extraction time at 510 MeV

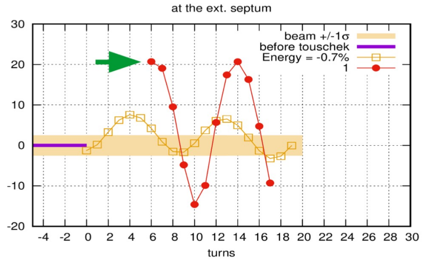
M. Garattini *et al*. [Phys. Rev. Accel. Beams 25, 033501 (2022)]

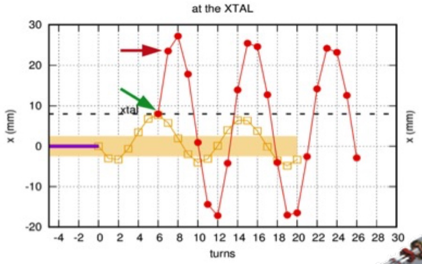


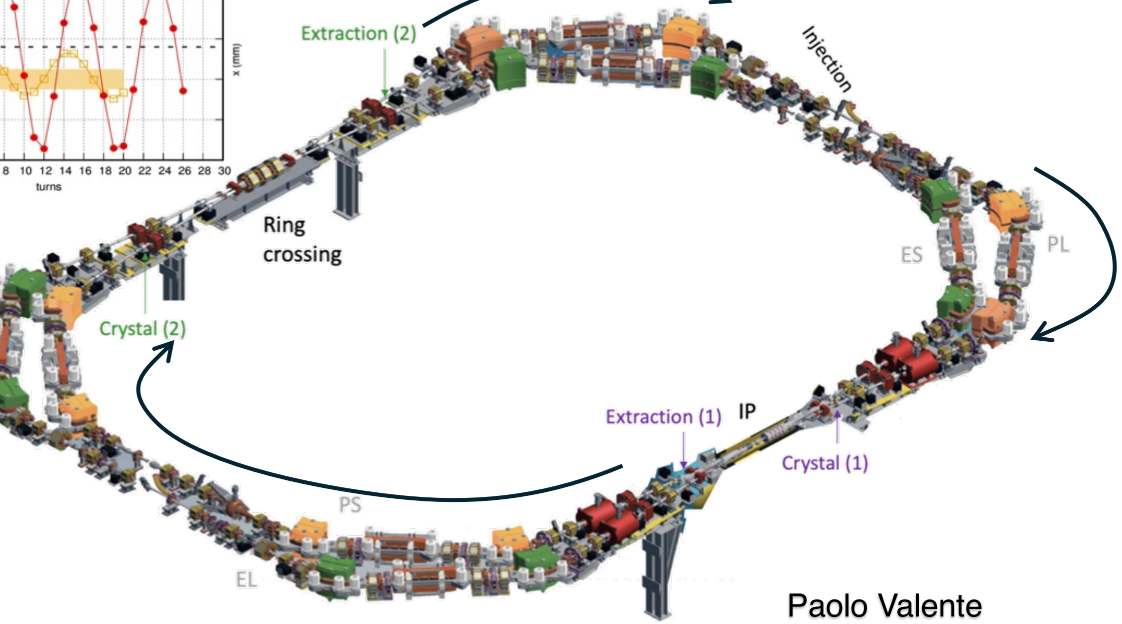






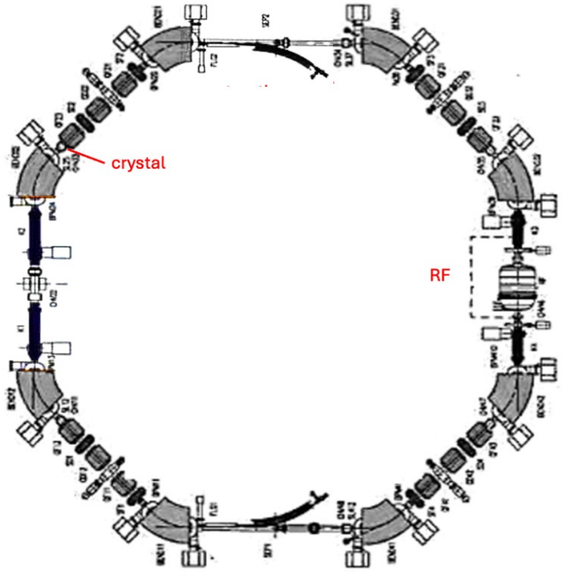






Paolo Valente

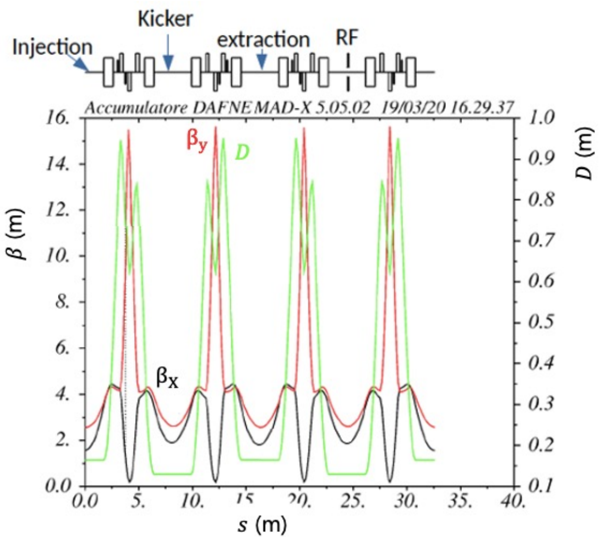
Extraction from damping ring



- 32 m long, 108 ns revolution period
- 4 arcs: 2 **dipoles**, 3 **quadrupoles** and 1 **sextupole** each
- 2 couples of **magnetic septa**: 2° + 34°
- Energy acceptance **1.5%**, but with **low $\boldsymbol{\beta}$** and **chromaticity $\sim$0**

Monochromatic extraction at E = **300 MeV, RF off**
- $Q_x = 0.325$
- $\xi_x = -6.0$
- ΔE = 1 keV/turn
- $\delta E = \pm 1\%$

Extraction time ~ **0.6 ms**



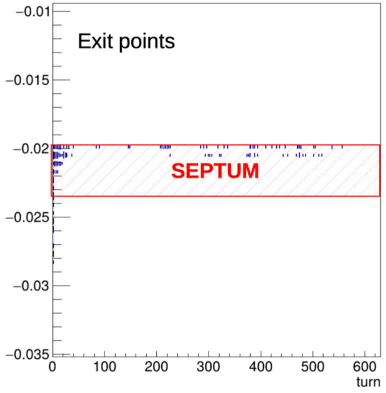
BUT

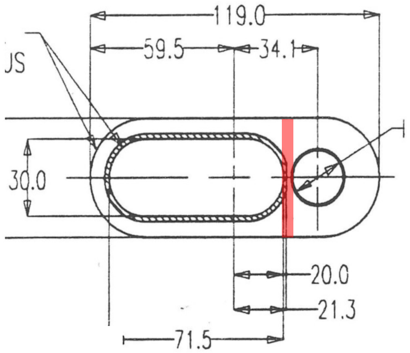
😟 **Thickness** of 2° septum: **4 mm**

😫 **Very few particles** go directly beyond the magnetic septum **without** a very thin **electrostatic septum**

Further studies needed

[**A. De Santis**, DA.StorageRing group]





Paolo Valente

Crystal extraction from damping ring

SHERPA studies of **crystal-assisted** extraction in the damping ring:

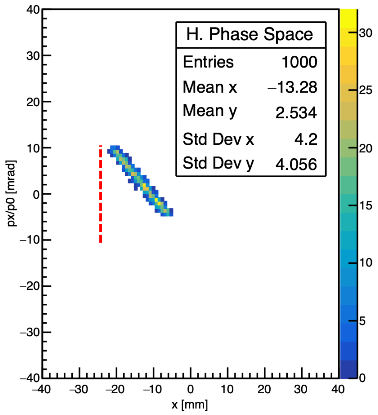
- Inject **off-axis** by **+10 mm** from beam-pipe center
- Optics optimized to have larger β, reducing the acceptance: $\boldsymbol{\delta E = -0.6\%}$ in 600 turns [5.2 keV/turn at **510 MeV**]
- Betatron oscillations: $x = \frac{\Delta p}{p}\left(|D| + \sqrt{H\beta}\right)$
- Crystal at $-$**30 mm** from center providing a kick of **1 mrad**
- At septum: $\Delta x_2 = \sqrt{\beta_1 \beta_2}\,\sin(2\pi\Delta\mu)\Delta x_1'$
- Plugging 1 mrad, $\Delta\mu \sim 1/4$ and $\beta \sim 17$ m: displacement should be **sufficient** to go beyond the septum wall

😌 Promising results, but study should be **updated**, optics and injection can be further optimized, etc.

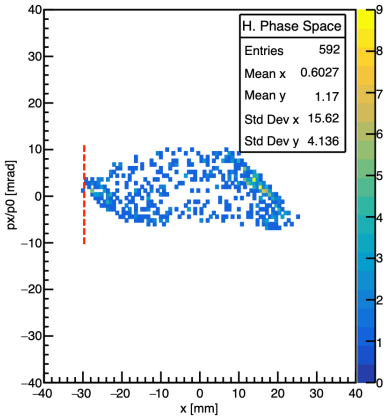
😌 600 turns × 108 ns ≈ **60 μs spills** at **510 MeV**

😁 Expect a factor **2×** (**4×**) at **400 (320) MeV**

At crystal, turn 1

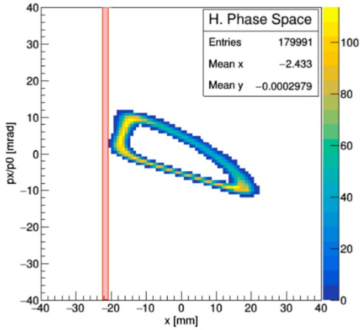


At crystal, turn 500

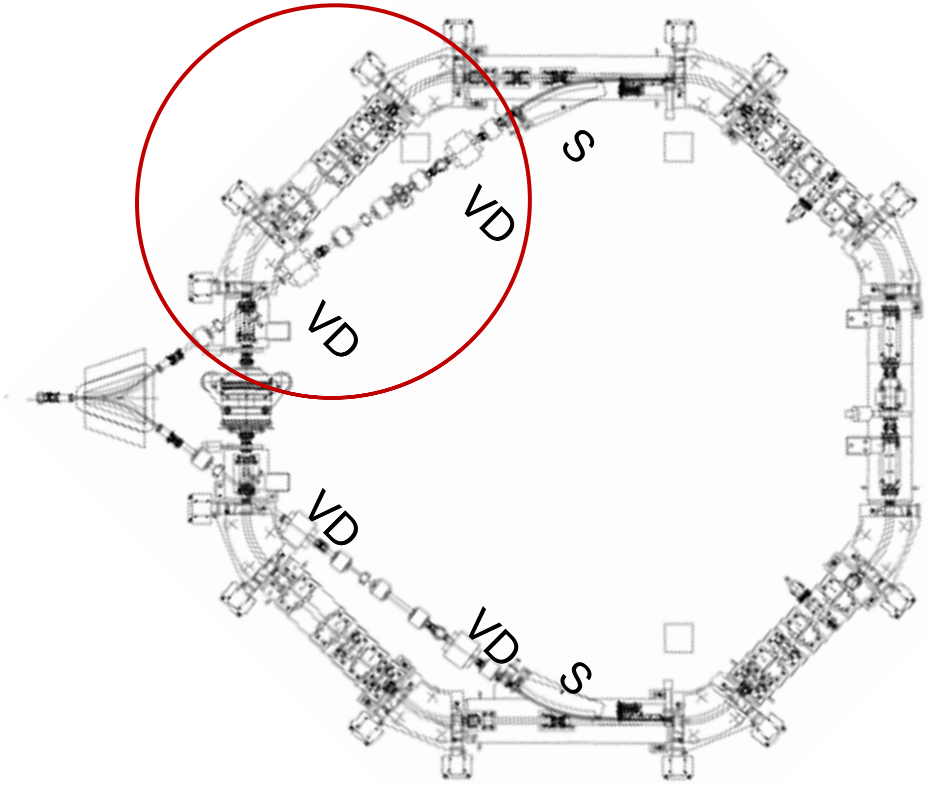


M. Garattini *et al.*
[Phys. Rev. Accel. Beams 25, 033501 (2022)]

At septum



Extraction from damping ring



- 😌 Not enough room in the damping ring hall
- 😌 Damping ring at a different height wrt transfer line to/from the LINAC

Any use of the extracted beam must be outside the DR hall

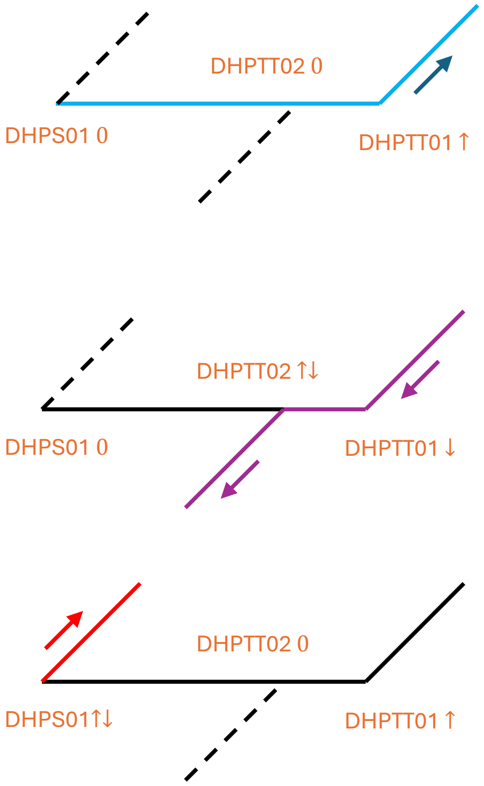
Paolo Valente

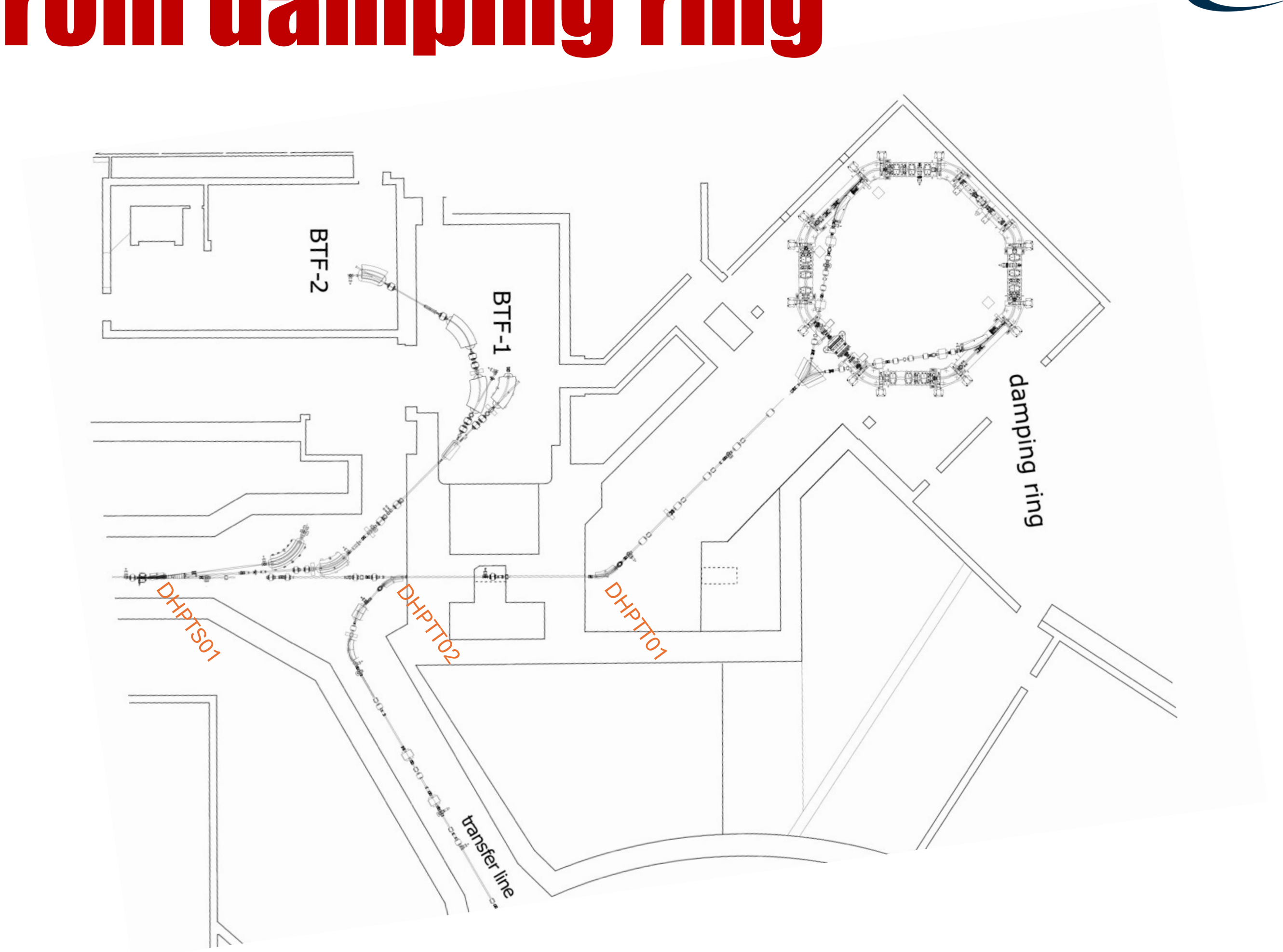
Extraction from damping ring

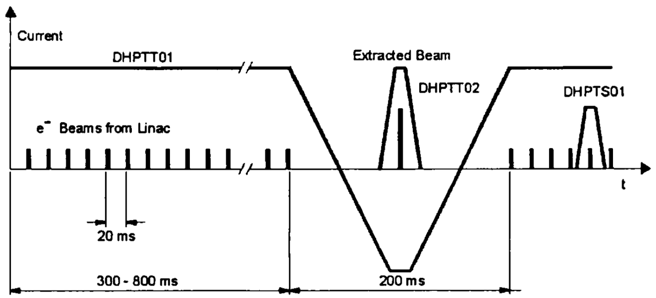
injection

extraction

spectrometer







C. Sanelli *et al.*, CERN/PS 98-024 (PO)

- 🙁 Common injection and extraction line to the damping ring
- 🙁 Maximum repetition rate of the **current pulsed dipoles** is **2 Hz**
- 🙁 This implies a **reduction** factor of **25** wrt BTF configuration at 49 Hz

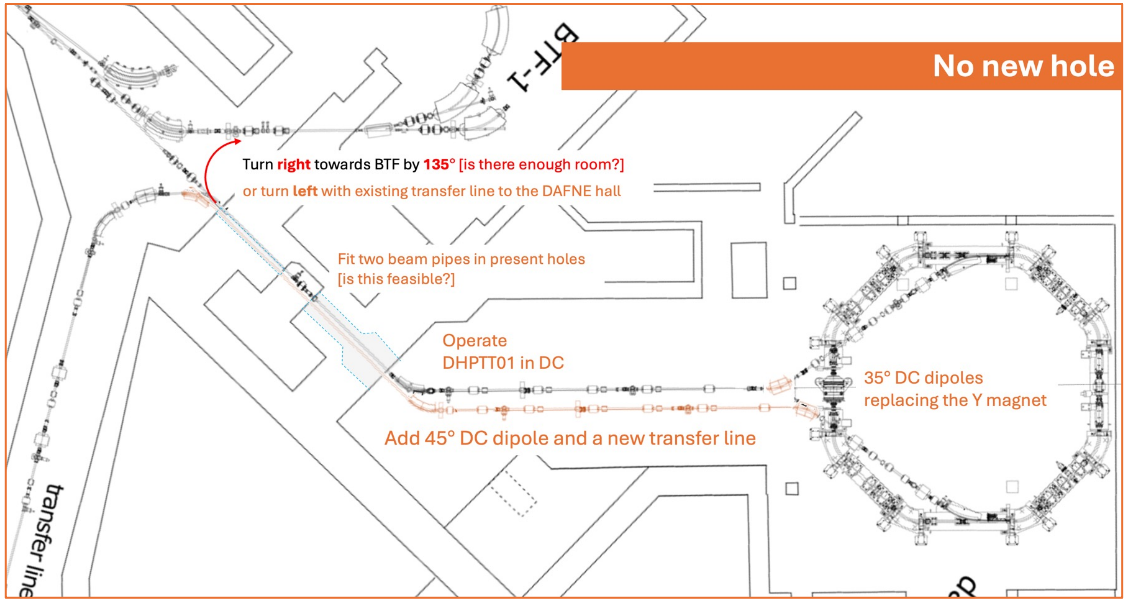
Paolo Valente

Doubling the transfer line?

😁 No need to move PADME setup in most of the cases

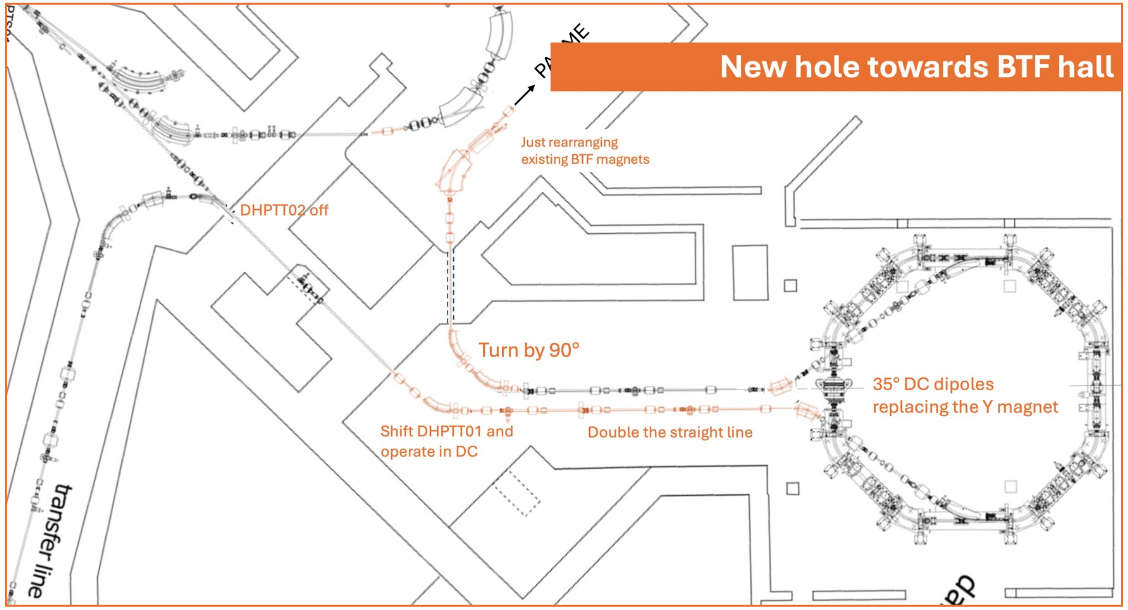
If **no new hole** in the walls is drilled:

- 🙁 A second beam-pipe has to fit in the [relatively small] hole connecting LINAC tunnel with “hot-cell”
- 🙁 Bending dipoles turning towards BTF-1 are needed:
  - 🙂 Elements of the transfer-line towards the main rings can be reused
  - 🤔 **Alternatively: move PADME setup in DAFNE hall**



If a **new hole** is drilled connecting DR and BTF-1 halls:

- 🙁 Radioprotection approval will be needed
- 😁 No modification to BTF/spectrometer/damping ring switchyard



Expected performance vs. impact

	BTF	Extend LINAC RF flat-top	Extraction from main ring		Extraction from damping ring	
			Resonant, RF off	RF knock-out	Resonant, RF off	RF knock-out
Beam max. E	500 MeV	320 MeV	400 MeV		400 MeV	
Pulse length	250 ns	2-3 μs	0.25→1 ms	O(10 ms)	100→300 μs	O(ms)
Repetition rate	49 Hz	49 Hz	2 Hz 49 Hz		2 Hz 49 Hz	
				Crystal		Crystal
Infrastructure		De-tune or by-pass SLED's	Direct injection line to DAFNE hall Electrostatic septum	Vacuum goniometer	Separated injection, extraction lines and new hole to BTF-1 Electrostatic septum	Vacuum goniometer
Gain factor	1	10	40→160 $10^3 \to 4 \cdot 10^3$	$10^3 \to 10^4$	16→50 $400 \to 1.2 \cdot 10^3$	$10^2 \to 10^3$
Comments		Small hardware modifications No need to run a ring No new beam-lines Marginal on maximum energy Use BTF target or directly adjust LINAC energy	Need to run large infrastructure Even for 1 ring only, no wiggler, no RF, several 100 kW Electrostatic septum or cystal require vacuum installation on the ring		RF knock-out can be implemented with kickers Crystal requires simpler vacuum installation than electrostatic septum	
			RF knock-out gives good performance even at 2 Hz Adjusting extracted beam energy requires target + spectrometer			

Expected performance vs. impact

	BTF	Extend LINAC RF flat-top	Extraction from damping ring	
			Resonant, RF off	RF knock-out
Beam max. E	500 MeV	320 MeV	400 MeV	
Pulse length	250 ns	2-3 μs	100→300 μs	O(ms)
Repetition rate	49 Hz	49 Hz	2 Hz 49 Hz	
				Crystal
Infrastructure		De-tune or by-pass SLED's	Separated injection, extraction lines and new hole to BTF-1 Electrostatic septum	Vacuum goniometer
Gain factor	1	10	16→50 400→1.2·10^3	10^2→10^3

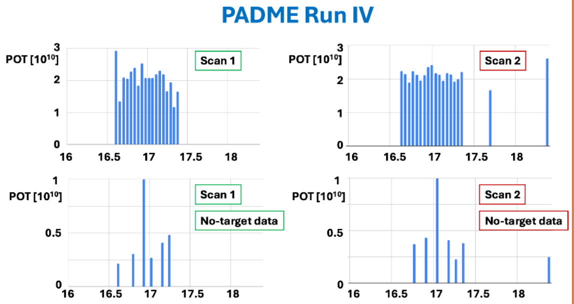
- Running the entire DAFNE complex requires a lot of resources + modifications to the ring and transfer lines: let's consider the extraction **from the damping ring only**
- Gaining **2 or 3 orders of magnitude** requires <u>either</u> running at **49 Hz** <u>or</u> **RF knock-out**
- **Crystal** kick substitute the **electrostatic septum**
- However, very long beam pulses from **RF knock-out** put more stringent requirements on PADME TDAQ, even though there is plenty of time for pre-processing/storing data in between spills

Paolo Valente

Extracted beam: scanning around 17 MeV

Changing the beam energy

- PADME-X17 requires to acquire a **large number of points** at different beam energies, scanning around the invariant mass of 17 MeV, i.e. between 250 and 310 MeV of E_{e+}
- Acquiring some data also **out of the resonance** region, both slightly above and below the interesting range is also important
- Tuning the resonance extraction **from the damping ring at many different energy values can be difficult and/or time consuming**

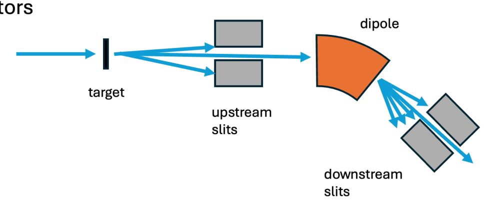


Extract at fixed energy, e.g. 400 MeV, and then **degrade**, **select the momentum,** and **collimate** the positron beam

Tuning the positron beam energy

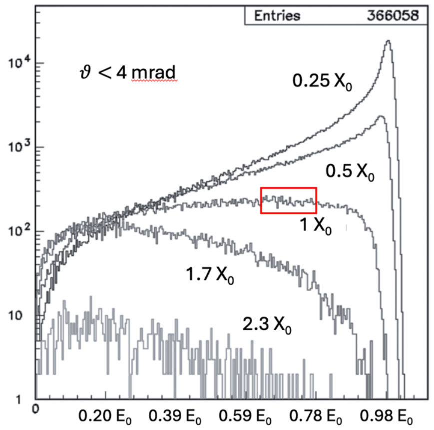
Basic idea:

- Extract from the ring at a fixed energy, [slightly] **higher** than the required range
- And then use a momentum selection system "**BTF-like**": target + slits + dipole + slits
- It is possible to **optimize** the distribution of the **variable energy** out of the selector aiming to have a **constant yield** in the useful **range** by choosing:
  - The target thickness in terms of X_0
  - The extraction energy, in input to the selector
  - The angular cut of the collimators



Tuning the positron beam energy

- For $\vartheta < 4$ mrad and t=1 X_0 it is possible to get a practically **flat** distribution in a wide energy range
- Assuming, for instance, to stay in the range 0.6-0.8 E_0, gives a fixed extraction energy $E_0 \approx 400$ MeV
  - To be optimized with the optics studies and with spill length, since $\Delta t \sim E^{-3}$
- The **intensity reduction** due to the energy selection depends on the chosen **momentum band**, defined by the slits' aperture: assume from $\mathbf{10^{-3}}$ to few $\mathbf{10^{-4}}$ for a spread of **few per mil**
  - To be checked with a more detailed Monte Carlo
- In the hypothesis of requiring $\mathbf{3 \cdot 10^4}$ selected positrons, need to extract $\mathbf{3 \cdot 10^7}$-$\mathbf{10^8}$ **positrons/spill**



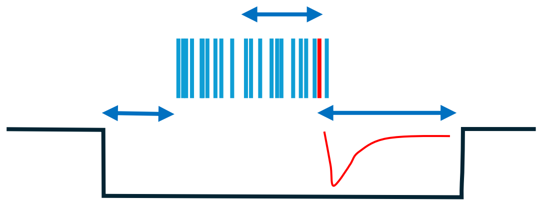
Acquiring longer beam pulses

We would like to reduce the positron density while keeping [or even increasing] the statistics by **increasing the positron pulse length**

BUT

Already close to the limit of due to the **1 μs** PADME TDAQ **window**:

- a few tens of ns are needed **before** the signal
- detector signal starting with a spread = **beam pulse duration**
- add a sufficient number of digitized points to **measure the charge**



DAQ window = 1 μs

Going **beyond 500-600 ns** will require upgrading the **PADME readout**

- Need sufficient **memory** to buffer the events in a spill
- Also need the **bandwidth** to **transfer** the samples and **record** data on disk

Acquiring longer beam pulses

CAEN Tools for Discovery

MODEL[1]	Form Factor	# channels	Sampling Frequency (MS/s)	# Bits	Input Dynamic Range (Vpp)	Bandwidth (MHz)	Memory (Msample/ch) *Record Lenght* small	big	DPP firmware[4]
x724	VME	8	100	14	0.5 - 2.25 - 10	40	0.5 *500µs*	4 *4ms*	PHA
	Desktop/NIM	4							
x720	VME	8	250	12	2	125	1.25 *5ms*	10 *40ms*	CI, PSD
	Desktop/NIM	4							
x730	VME	16	500	14	0.5 and 2 [5]	250	1.25 *250µs*	10 *2ms*	PHA, PSD[6]
	Desktop/NIM	8							
x725	VME	16	250	14	0.5 and 2 [5]	125	1.25 *500µs*	10 *4ms*	PHA, PSD[6]
	Desktop/NIM	8							
x731	VME	8/4	500/1000	8	2	250/500	2/4 *2ms*		-
	Desktop/NIM	4/2							
x751	VME	8	1000/2000	10	1	500	1.8/3.6 *1.8ms*	14.4/28.8 *14.4ms*	PSD, ZLE
	Desktop/NIM	4							
x761	VME	2	4000	10	1	1000	7.2 *1.8ms*	57.6 *14.4ms*	-
	Desktop/NIM	1							
x740	VME	64	62.5	12	2 - 10	30	0.19 *3ms*	1.5 *24ms*	QDC
	Desktop/NIM	32							
x742	VME	32+2	5000[2]	12	1	600	0.128[3] *200ns*		-
	Desktop/NIM	16+1							
x743	VME	16	3200[2]	12	2.5	500	0.003[7] *640ns*		CM
	Desktop/NIM	8							

- Model **x720**: sampling **250 MS/s** at 12 bits
- Buffer from 0.128 to 10 MS/ch: **×80**
- **0.32 ms buffer**
- 9 GB **per spill** for 600 ch [not zero suppressed]!

- Charge integration available in the FPGA, very simple trigger based on total energy can be implemented

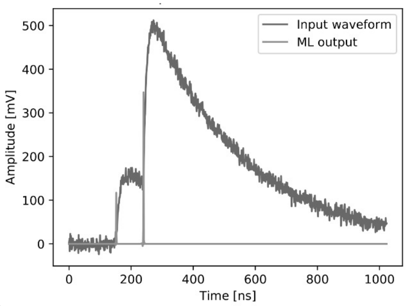
- Reduce **resolution** from 12 bits to **10 bits**?

Model **x751**: **1000 MS/s** but 3× larger buffer

Current PADME digitizer: **V1742**

- Running at 1000 MS/s, 1000 ns memory length ×128 records buffer

- Sampling rate can be lower if much lower pile-up probability
- Further **downsampling** possible? **Performance**?
- 8 ch/board: ~80 boards, 4× VME crates
- **Cost**?



CONET2 1.25 Gb/s optical link

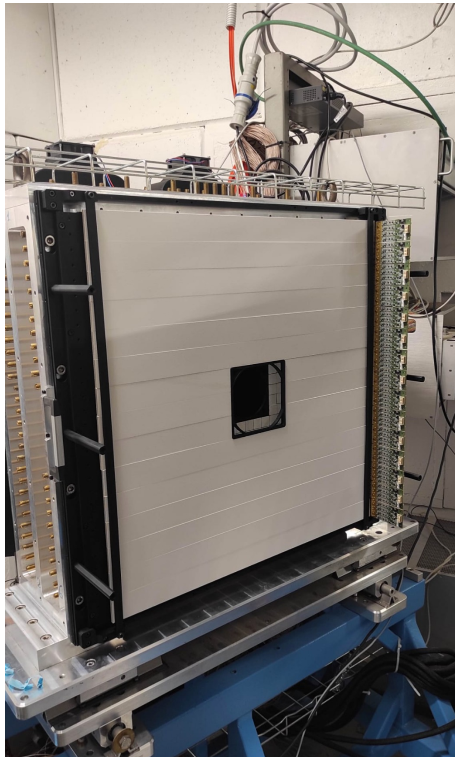
- Up to 100 MB/s per link, up to 4 links [card A3818 PCIe] **can be the real bottleneck**

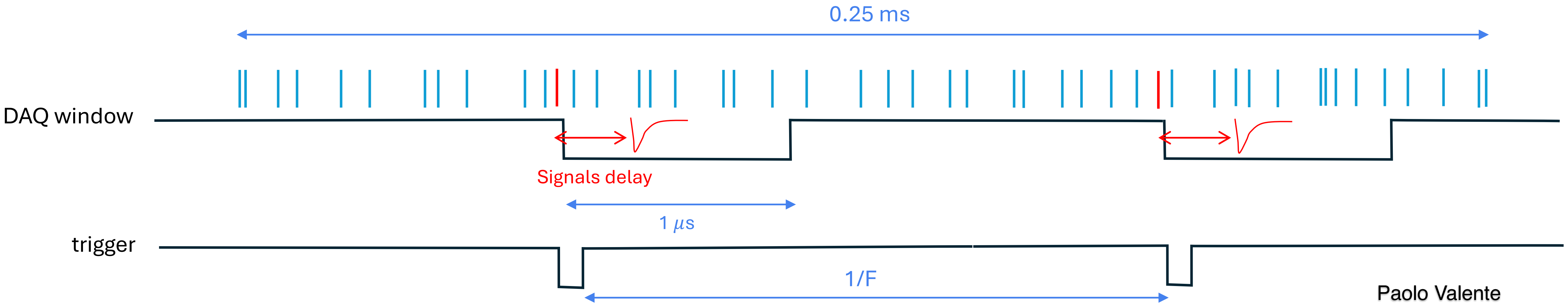
Paolo Valente

Acquiring longer beam pulses

Alternative to upgrading the PADME readout:

- Implement a **trigger** capable of reducing the rate at a level manageable by present readout and DAQ
  - **Dead time** of V1742 boards ~**200 μs**
  - Equivalent maximum trigger rate: **5 kHz**
- Adding a segmented scintillating hodoscope á la NA62 implementing a sector logic
- Assuming **same number** of positrons diluted in **1000**× pulses: $3 \cdot 10^3$ pot in a 0.2-0.3 ms spill, average distance between two positrons ~100 ns
- Depending on trigger topology [mainly ϑ] expect 10^{-3} probability: $\langle \Delta t_{\mathrm{trig}} \rangle \sim O(100 \mu s)$ close to maximum DAQ rate
- Requires to form digital signals to be sent to a trigger logic + **delaying all analog signals** in order to stay inside the DAQ window





A staged plan

Phase 1

Machine:

- Study the **optics** for resonant extraction from the DR with crystal + existing magnetic septa
- Build the **vacuum goniometer** + **holder** + **crystal** for ~1 mrad kick

PADME:

- Test **new readout** or **trigger** system for O(ms) pulses

Phase 2

Machine:

- **Remove** part of the transfer-line towards the main rings
- **Test** the extraction:
  - RF off: up to 300 μs at **2 Hz**
  - RF knock-out: try to further extend beam pulses

PADME :

- Procure **new boards** and crates or implement **trigger**

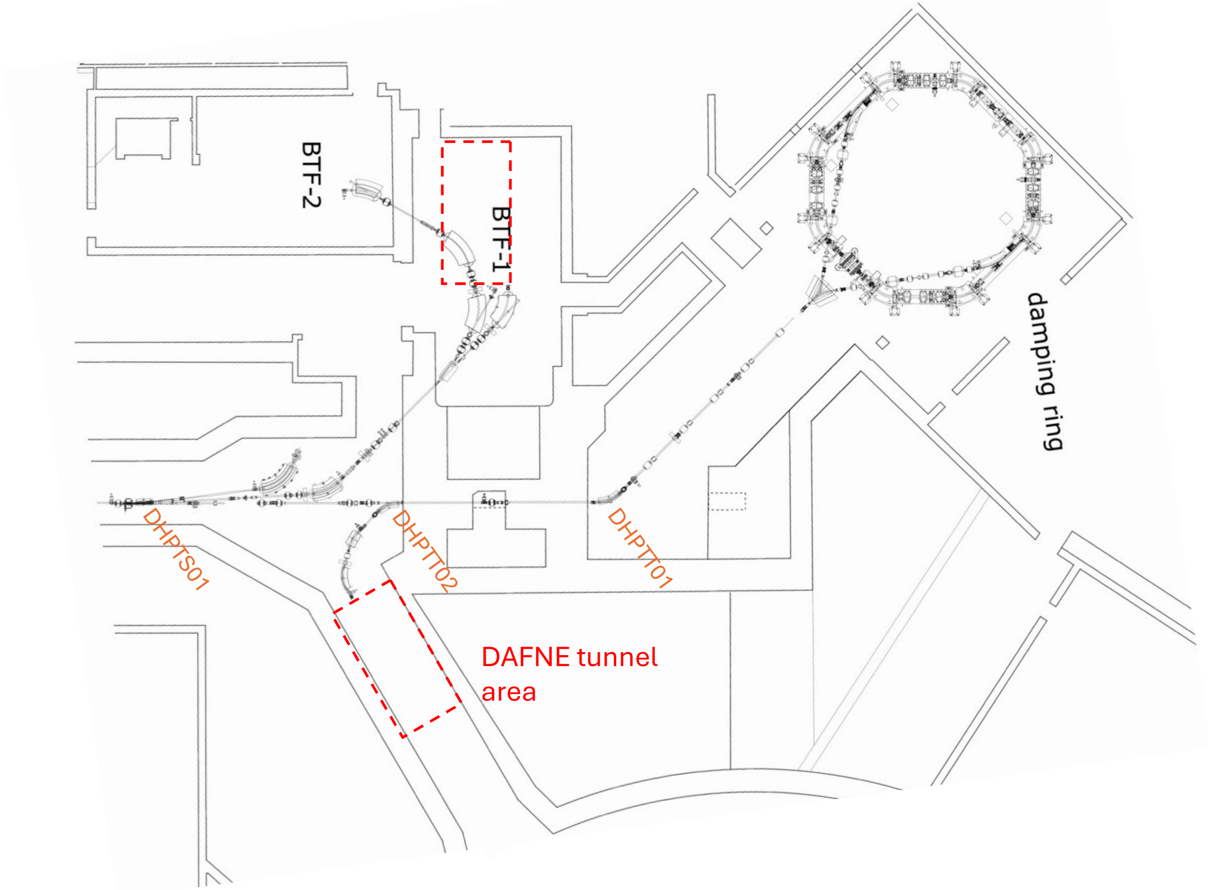
Phase 3

- Move PADME setup to the “DAFNE tunnel” area
- Commission detectors and TDAQ
- **Take data**

General rationale:

👎 Give up civil engineering, new transfer lines, installing new magnets

👍 Use as much as possible existing infrastructure



Moreover:

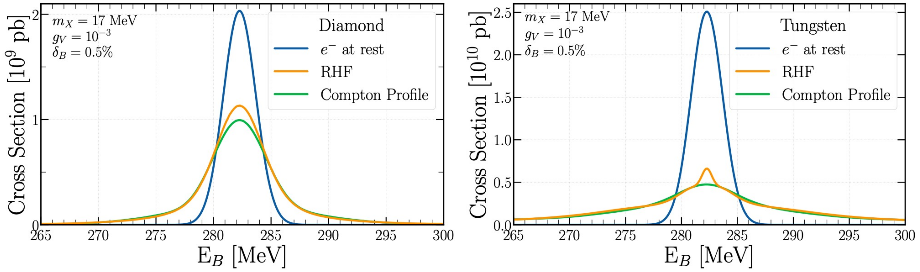
😁 Completely decouple from BTF-1 and BTF-2 operations

😁 Do not occupy DAFNE main hall

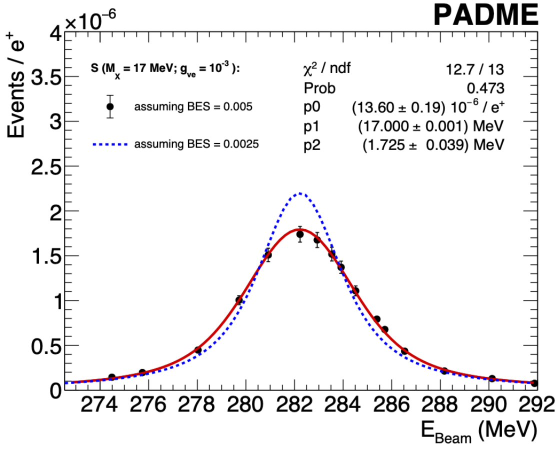
How to improve signal shape

Limiting factor:
electrons motion spread $\otimes$ positron beam **momentum spread**

Change **target material** to reduce electron motion <u>**and**</u> **decrease** beam **energy spread**



[Phys. Rev. Lett. 132 (2024) 261801]



⇢ Be, Li, ... target

- 👎 Metallic target in general imply giving up having an active target
- 👎 Safety problems with low Z materials: Beryllium toxicity and Lithium high reactivity

<u>However</u>:

- 👍 A Beryllium foil can be used at the same time as **vacuum separation window** and **target**
- 👍 Many **Lithium compounds** exist, but with different issues: LiH high flammability, LiOH corrosivity, LiF toxicity, Lithium deposit on metallic substrate, etc.

Paolo Valente

Run III and Run IV setup

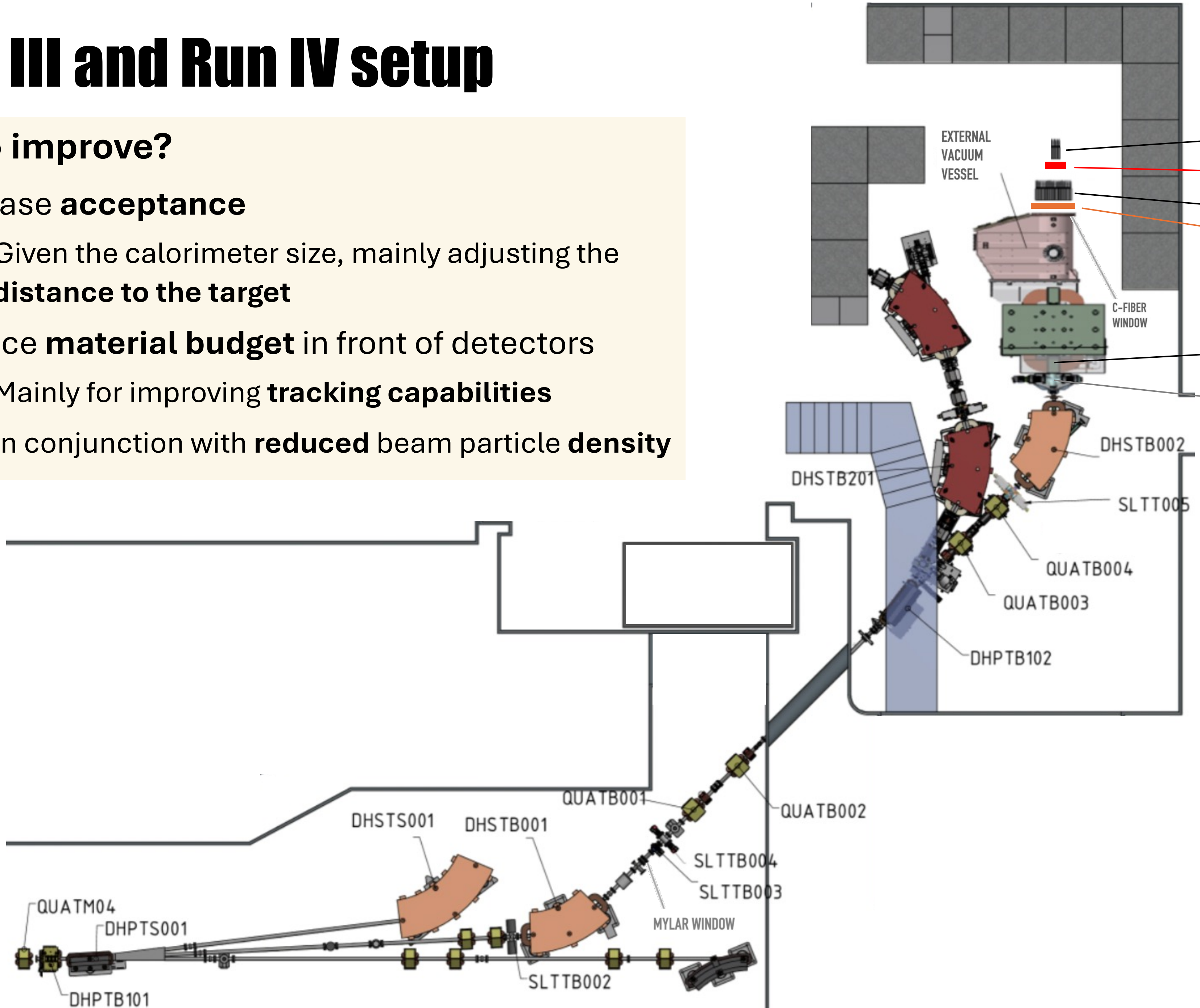
How to improve?

↑ Increase **acceptance**

- Given the calorimeter size, mainly adjusting the **distance to the target**

↓ Reduce **material budget** in front of detectors

- Mainly for improving **tracking capabilities**
- In conjunction with **reduced** beam particle **density**



Run III:
Leadglass
Timepix
Calorimeter
ETag

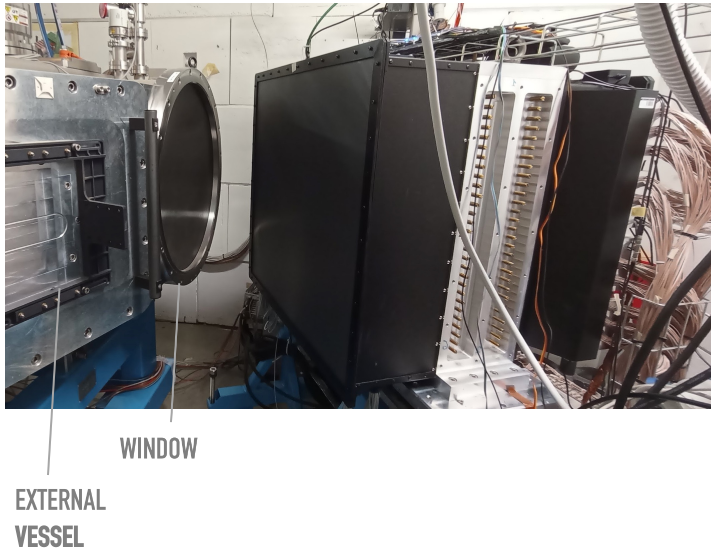
Run IV:
Leadglass
TMM
Calorimeter
Micromega

Target **Run IV**

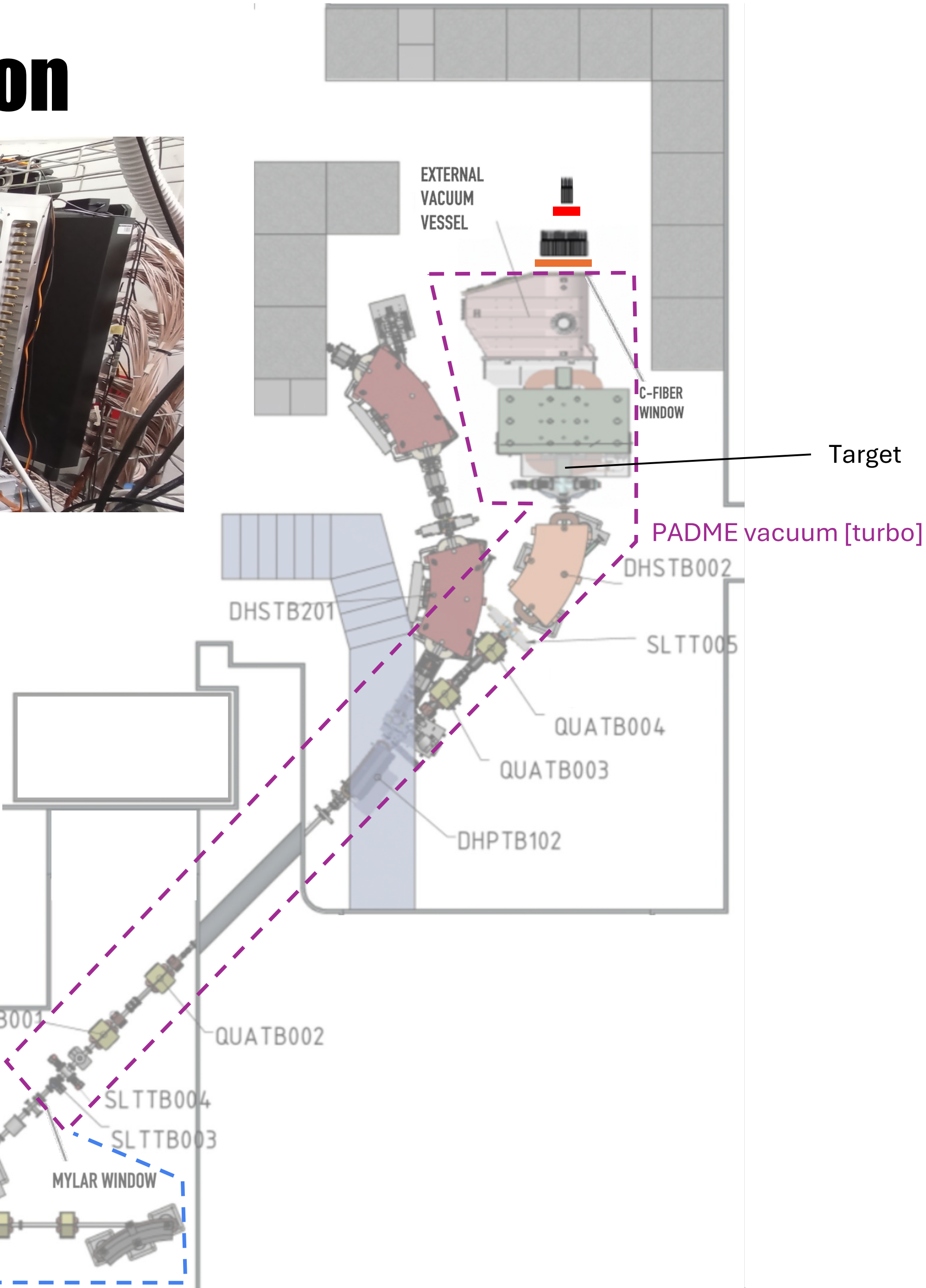
Target **Run III**

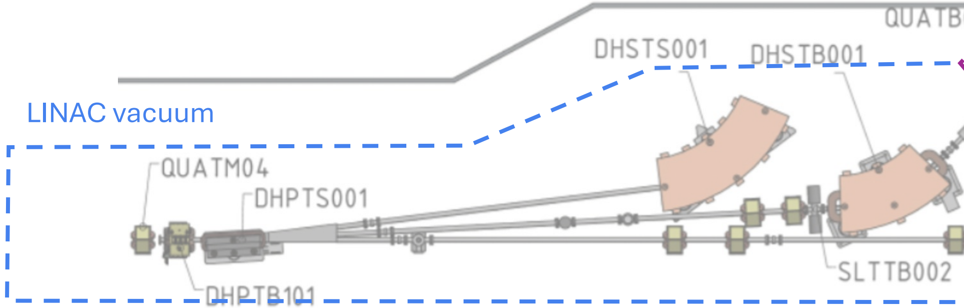
Paolo Valente

Present vacuum configuration



INTERNAL
VESSEL



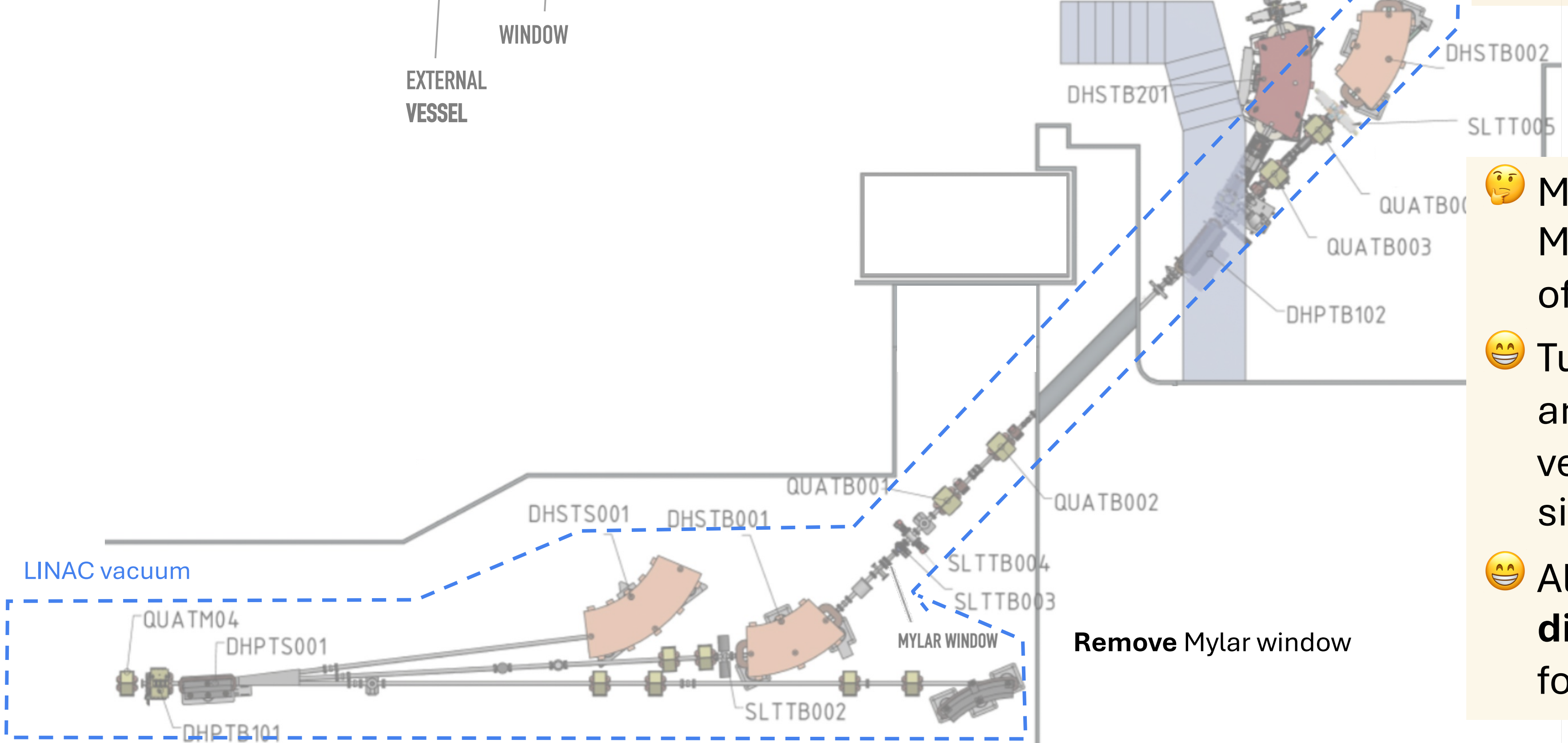


Paolo Valente

Proposed vacuum configuration

WINDOW

EXTERNAL
VESSEL

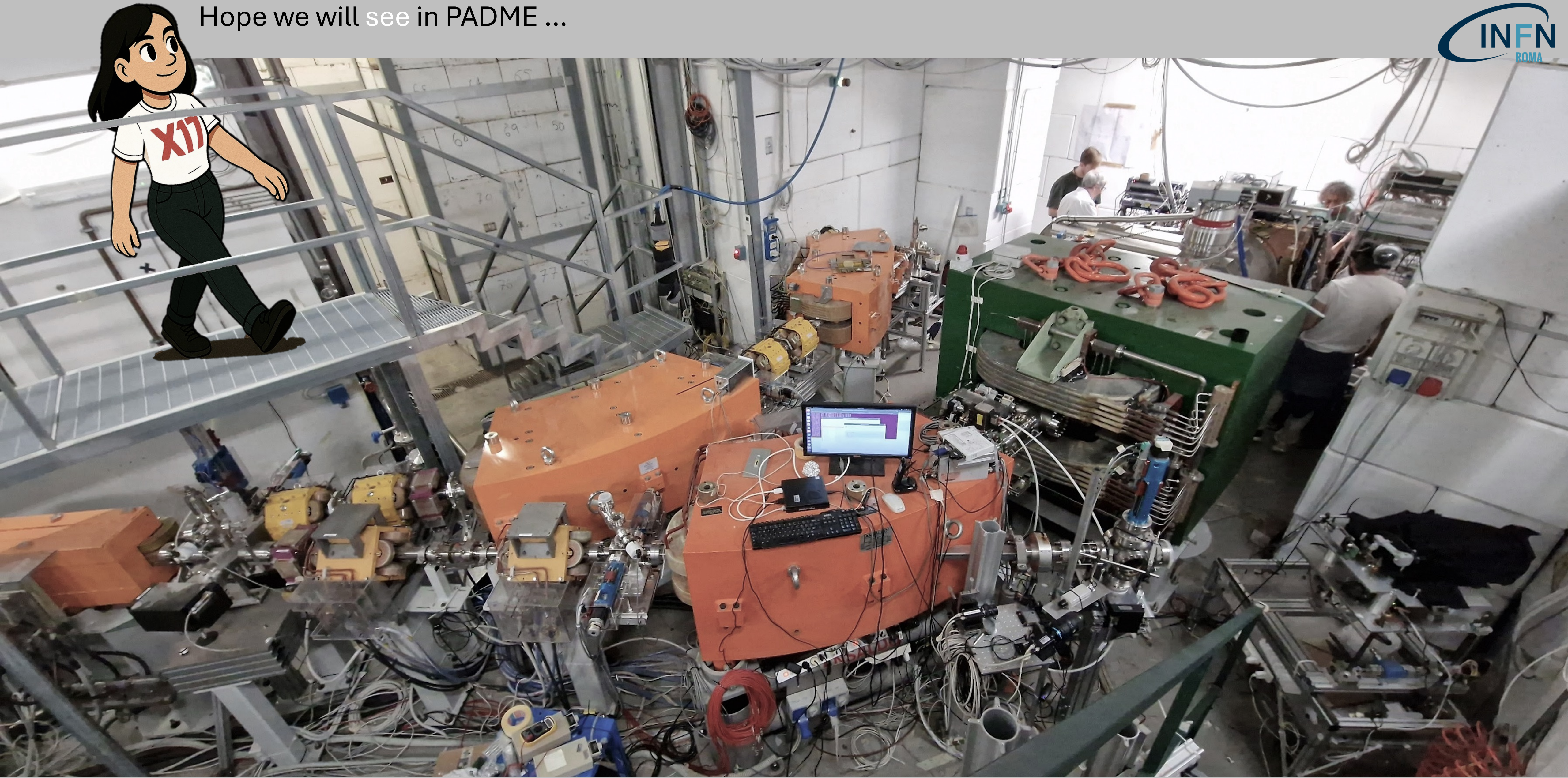


Replace C-fiber with thin Mylar

Beryllium window **as target**

- 🤔 Monte Carlo can help tune Mylar **thickness vs. pressure** of the "low vacuum" region
- 😁 Turbo-pump **not needed** anymore: the **external vacuum** vessel can be **replaced** with a simpler, lighter and **shorter** box
- 😁 Also allow to further **reduce** the **distance** target to calorimeter for larger acceptance

Hope we will see in PADME ...



Many thanks to S. Guiducci, M. Garattini, A. De Santis, storage ring, LINAC and BTF teams

Paolo Valente