Positron and electron beams for FFF

Subtitle: "More or less feasible projects, a very personal point of view"

January 13th 2021

Preliminary considerations

Due to time constraints [and often preliminary ideas] everything will be described **without many details**. Even so, there are **too many and too dense slides**, mainly intended for further reflection

I've tried pursue **two** equally important objectives in [what I think is] the spirit of this workshop:

1. Make an **inventory of the opportunities** for increasing the physics potential of PADME [as it is now, or with some modification not discussed here], with [at least rough] estimates of the **achievable statistics**
2. Make a first **estimate of the effort** needed to reach the quoted target

FFF should [in my opinion] add at least one **F** in the title for "**Feasible**" and another for "**Fast**":

- In order to exploit the window of opportunity for performing interesting physics in the transition from the DAΦNE/SPARC to the EUPRAXIA era, the beam should be available **and** the experiment(s) performed **in the short-medium term**, not only for coping with international competition, but also for avoiding conflicts with the main activities in the Lab
- Needed **resources** should be balanced to a **next-to-leading** priority

Of course I've selected ideas which **have come to my mind** or **I was aware of**

In many cases, the main limitation is a lack of knowledge of **technical details**: that's why I have solicited the Accelerator Division and DAΦNE team for **input from the experts**

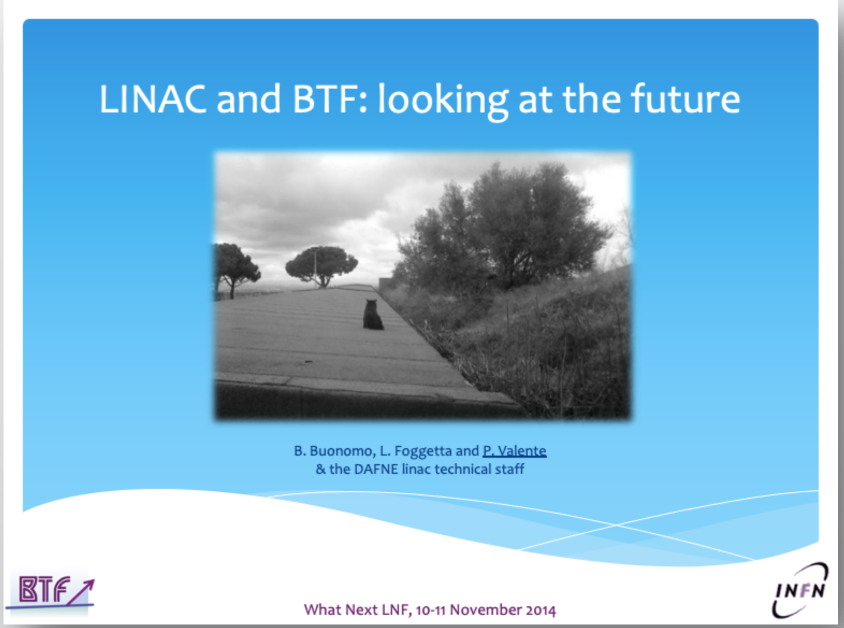
- The slides of the informal discussion of last October (containing most of the information) were exactly intended for **stimulating qualified contribution**
- I have indeed included the [**not abundant**] inputs I have received

Needless to say, should an idea be considered interesting, it will need to be **more deeply studied**

In many cases I share ideas with other colleagues: I've always tried to give the **appropriate credit**

However, **I take full responsibility** for all considerations made here

Preamble: “Where do we come from”



Many of the ideas (actually, almost all) briefly reported here **are not brand new**

On the contrary, (mainly) I have been proposing them in the last ≈**6 years**, in different contexts.

At least two similar workshops on Frascati future took place during this period:

- LNF What Next, Nov. 2014, https://agenda.infn.it/event/8563/timetable/#all

[Long pulse ideas, de-tuned SLED’s, alternative locations for dump-experiment, re-use of accumulator hall]

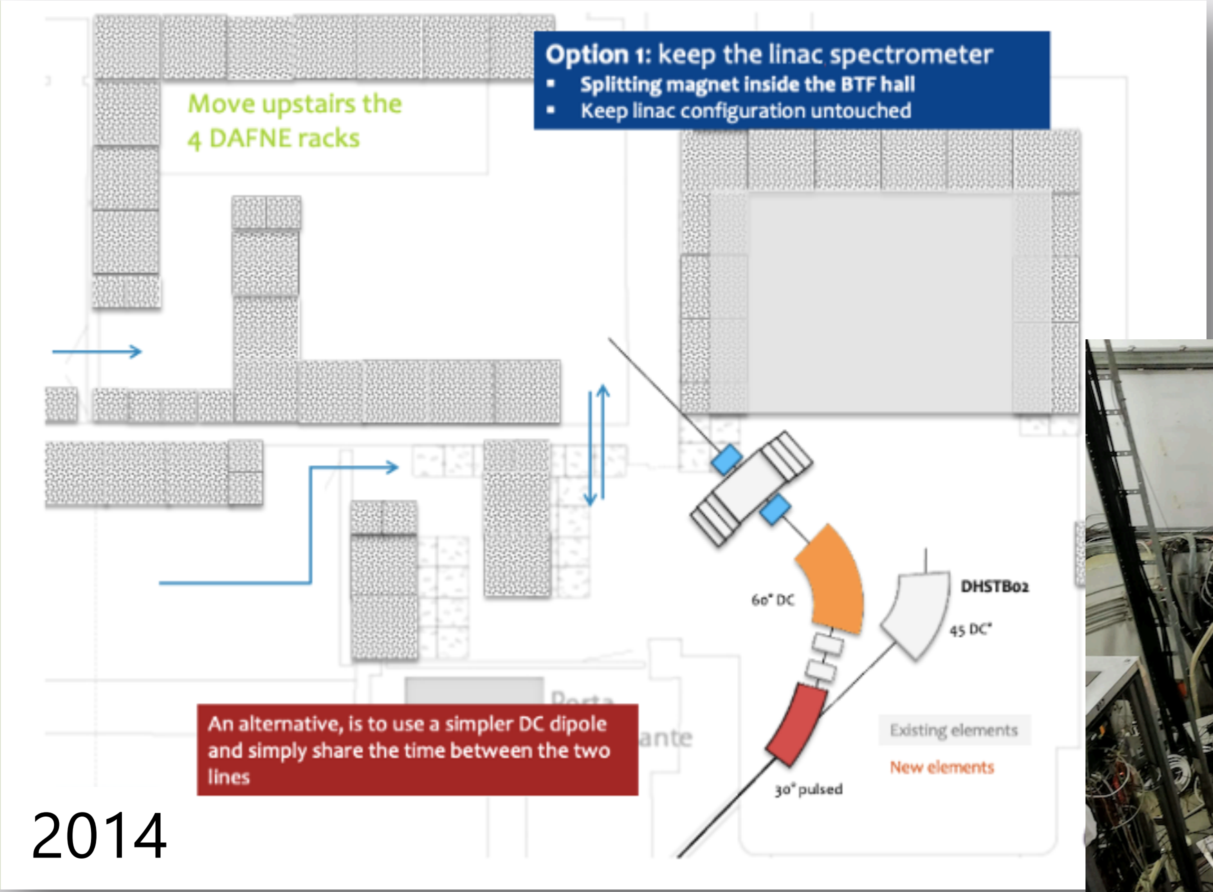
- DAFNE TF Workshop, Dec. 2018, https://agenda.infn.it/event/16334/page/2177-program-timetable

[Resonant extraction and crystal extraction from DAFNE ring]

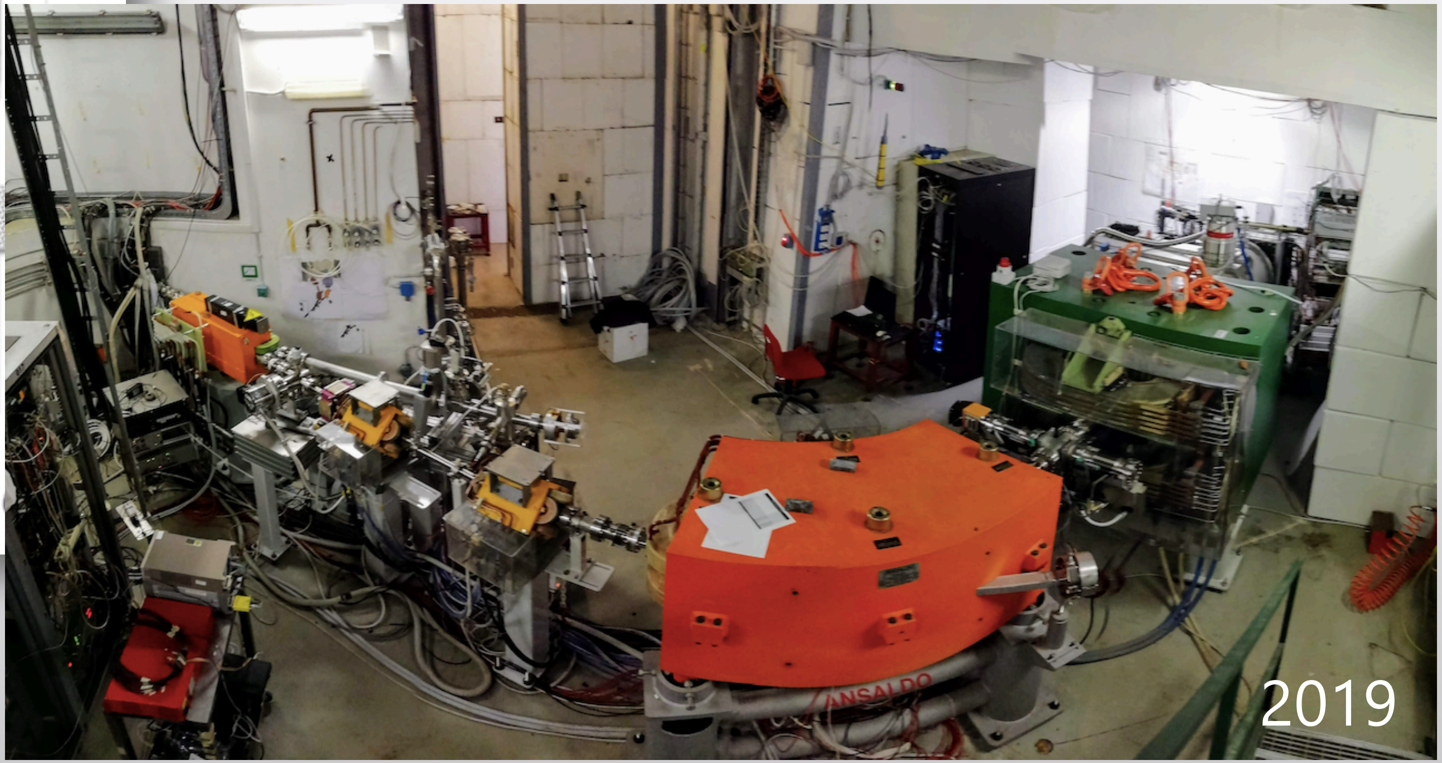
- The exploitation or the upgrade of the existing accelerator infrastructure at an “affordable price” was already the main rationale

On the other side: something **has happened** in these 6 years

Preamble: “Where we are now”



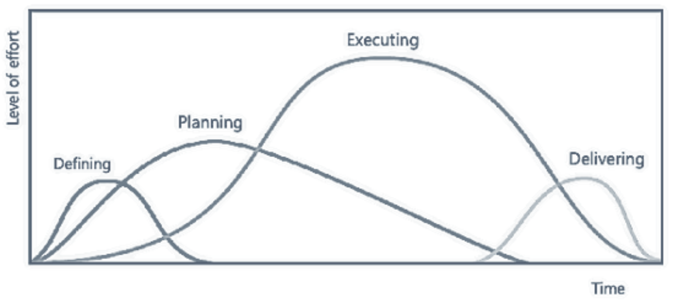
- BTF beam-line doubling **and** LINAC consolidation (≈2.6 M€), started in 2016
- PADME (≈1.5 M€) has been constructed, installed and commissioned; **two physics runs were performed in the last 2 years**



Preamble: "Where do we go from here"

How is this relevant in the present context?

- The investment on the LINAC was finalized to allow its operation, **not necessarily as DAΦNE injector**, for at least **5-10 more years**, in connection with the doubling of the BTF line
- The BTF upgrade was aimed at having a **experiment-oriented** line and experimental hall, i.e. dedicated to medium-long term installations, **in addition** (and whenever possible, **in parallel**) to the infrastructure dedicated to the test-beam activities



Gray & Larson, McGraw-Hill (2006)

Maintaining an user facility is [or at least **used to be** and in my opinion still **should be**] a **strategic asset** in the Lab portfolio

- This in the larger meaning of "user", **including** medium-term experimental programs, in addition to activities, like beam-tests, with a very fast cycle
- This is important to keep a working life-cycle of projects

This can [and in my view should] apply to the entire complex [not only LINAC+BTF]

- Many of the ideas in the following **imply the use of LINAC** plus one of the **BTF lines** or one of the **DAΦNE rings** (the positron Main Ring or the Accumulator)
- Since these are important facilities of the Lab, any idea has to **sustainable** in the context of the **general planning**

Why positrons?

To cut a long story short:

- Bogdan Wojtsekhowsky proposed fixed-target positron annihilations and missing mass dark photon searches: **arXiv:1207.5089**: first at VEPP-3 ring by-pass (internal target) and then at the (**never approved**) resonantly-extracted positron beam at Cornell (MMAPS)
- The idea of performing such an experiment using DAΦNE positrons at the BTF was born shortly after [end of 2013]
- Recently it has been pointed out that using a positron beam **also** brings two additional bonuses: direct annihilation and resonant production:
    - *Phys.Rev.Lett.* 121 (2018) 4, 041802; *Phys.Rev.D* 97 (2018) 9, 095004
- **The physics potential will be addressed by PADME experiment and theory talks**

The downside: there are very few **extracted** positron beams (of useful energy) in the world

I. Rachek, B. Wojtsekhowsky, M. Raggi, V. Kozhuharov, P.V. (Oct. 2016)

PADME-like experiment requirements

At the Frascati LINAC, the main limitation to the **luminosity** is the **duty-cycle**, i.e. the combination of two factors:

- The limited **repetition rate** of the LINAC (50 Hz, actually 49 usable pulses/s)
- The limited **macro-bunch length**
  - The **pile-up** in the calorimeters and **over-veto** probability (in the calorimeters and in the scintillating bars charged particle veto) limit the maximum tolerable particle density
  - **Assuming the performance of the present PADME detector** this can be expressed by the following rule-of-thumb: $\boldsymbol{n_{e^+}} = \mathbf{100} \times$ **pulse length[ns]**

The "**dream beam**" would be a **continuous**, low intensity positron beam, making possible to reconstruct each individual interaction in the [thin] target; this would allow a **zero-background** experiment.

However, a significantly long beam pulse structure [i.e. **comparable** to the inter-bunch of 20 ms] would be **very interestingly close** to the ideal beam

Existing high-energy positron beams

Electron-positron colliders

- SuperKEKB and BEPC-II
  - **No extracted beam**
- DAΦNE
  - **Primary** (<550 MeV) and **secondary** (<700 MeV, strongly depending on intensity) positrons at **BTF**

- VEPP
  - Not an extracted beam, but a **by-pass** in the VEPP-3 ring (510 MeV)

Secondary positrons

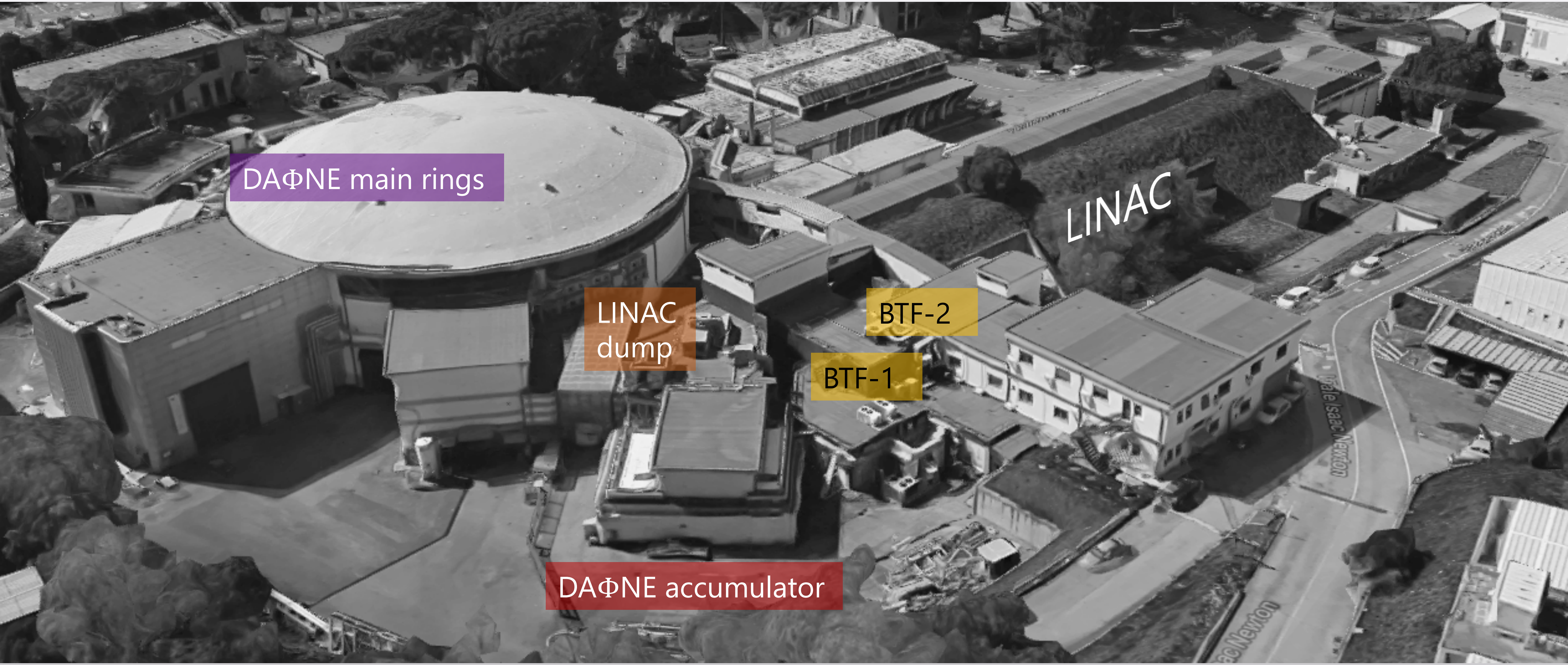
- DESY-II
  - 0.5 to 6 GeV/c secondary positrons
- CERN SPS north area
  - H4 "dedicated" beam-line, but production also possible in H2 and maybe H6-H8
  - Up to 200 GeV with variable purity

Proposed high-energy positron beams

- **Electron-positron colliders**
  - DAΦNE
    - Proposal for resonant and not-resonant extraction of **primary positrons** at **510 MeV**
    - Proposal for LINAC modifications for bunch extension <**300 MeV**
  - CESR
    - Proposal for $n + \frac{1}{3}$ resonant extraction of primary positrons at 6 GeV **not approved**
- **LINAC-based**
  - CEBAF at Jefferson Lab
    - Proposal for **11 GeV primary positron** source (**JPOS**), not yet approved, ≈5 years of construction
    - Possibility of **secondary positron beams**, ???
  - FACET-II at SLAC
    - Proposal for **10 GeV primary positrons** (produced from extracted electrons, damped and re-accelerated)
    - Approved but staged to Phase-2, >2022

LNF

Options at Frascati



Options at Frascati

1. DAΦNE LINAC only

1.1 Extracting to the BTF

1.1.1 Stretching the **positron** pulse length **beyond 300 ns** for increasing the PADME luminosity

1.1.2 As it is **now**, but at the maximum allowed intensity of $3 \cdot 10^{12}\ s^{-1}$ in the BTF-1 hall for **electron** beam-dump experiment

1.1.3 Increasing the authorized limit (by improving the shielding) and thus increasing the **electron** beam charge

1.2 Dumping the beam «somewhere» else

Use the full power of the beam in a different place to be identified, adapted and **authorized**

2. Using one of the two DAΦNE rings as pulse stretcher of the LINAC

2.1 Using the "standard" $n + \frac{1}{3}$ resonant extraction

2.2 Using crystal channeling

- Possibly can be used as an upgrade of the "standard" extraction

Options at Frascati

3. Using the DAΦNE damping ring (accumulator) as pulse stretcher of the LINAC

3.1 Using the "standard" $n+\frac{1}{3}$ resonant extraction

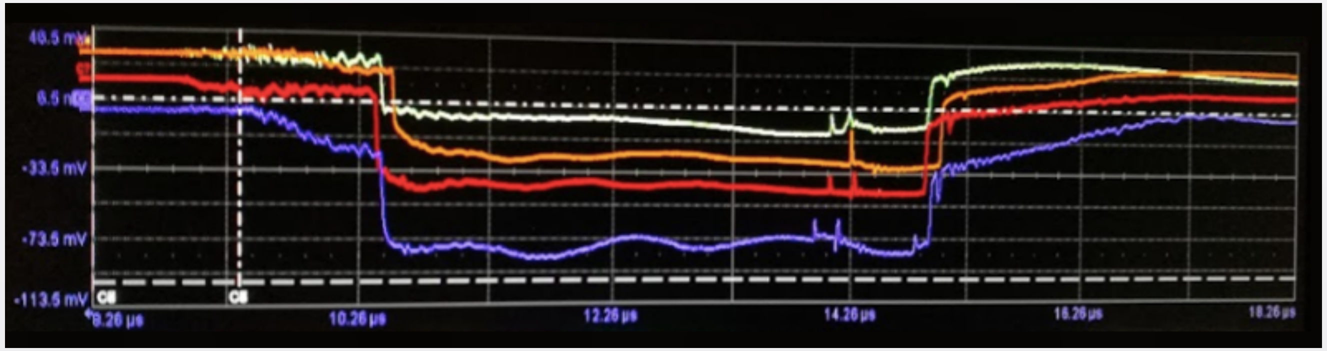
- Different ring length, dipole strength and radius, energy spread → different extraction time
- Different optics, different septum configuration

3.2 Using crystal channeling

4. Other extraction ideas

RF power in and out of the SLED

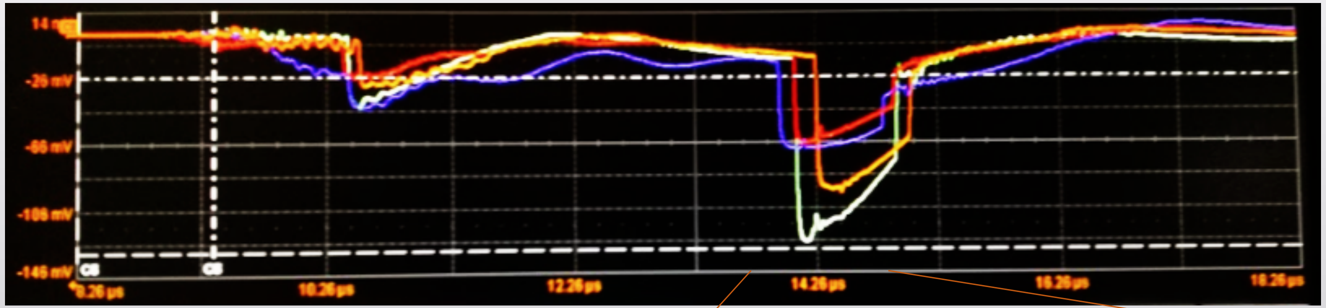
Phase inversion



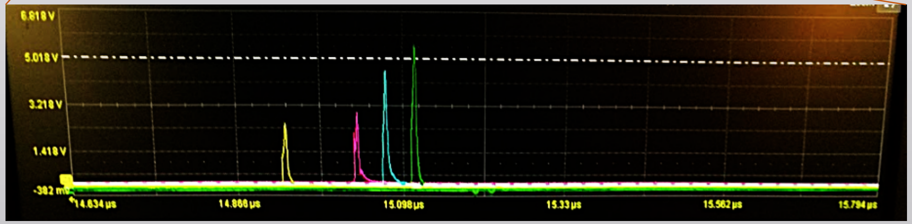
SLED input power

- In order to reach the required 510 MeV energy and high-current (100 mA) for injecting both electron and positron beams into DAFNE, with a S-band, 60 m long LINAC, the RF pulse is compressed by a dedicated device (SLED)
- This is not an issue, since short bunches are needed for injection into the damping ring (accumulator), and from there to the main rings

800 ns



SLED output power



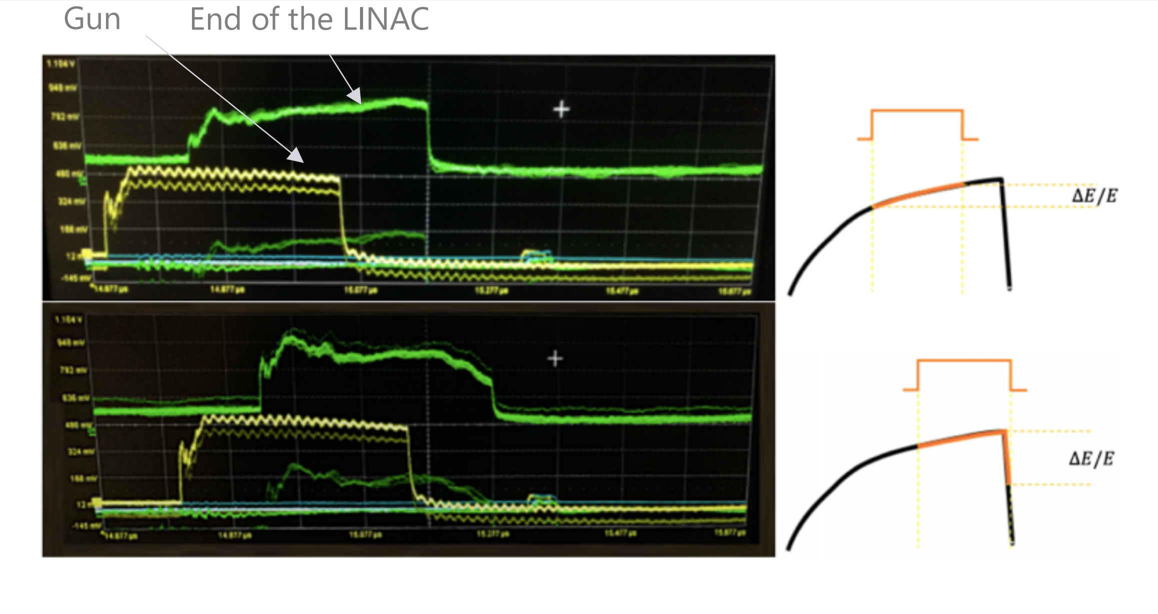
Current monitors along the LINAC (≈10 ns pulses)

Extended LINAC beam [present]

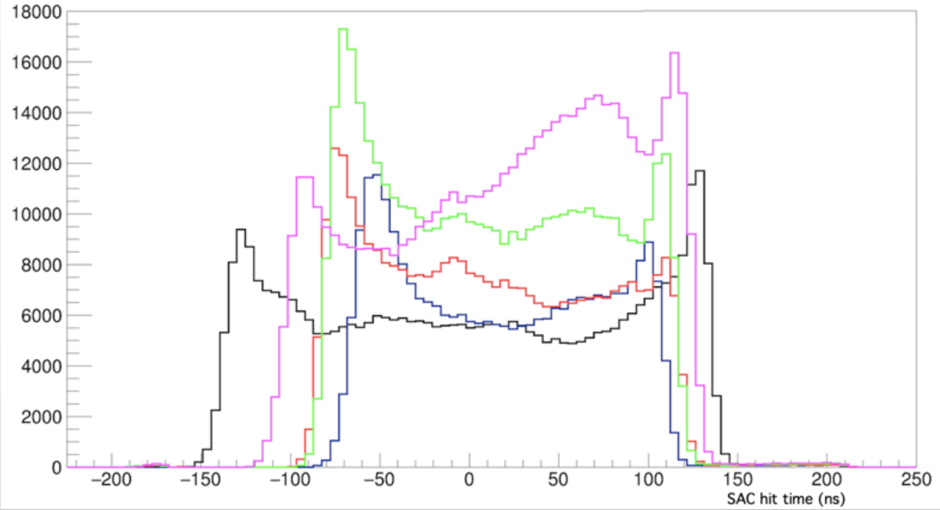
LINAC primary beam pulse has been extended from ≈10 ns up to **300 ns**, at the price of (slightly) reducing the maximum energy (from 550 MeV down to **490 MeV**) and (significantly) increasing the energy spread (from 0.3% to **few %**):

- The primary electron pulse produced from the gun has been extended (HV pulser up to 5 μs installed since 2016)
- Relative delays and phases of the 4 modulators tuned to obtain an (almost) flat accelerating voltage
- Limited to **300-350 ns** due to the maximum momentum spread accepted by the BTF transfer-line

*P. Valente et al., Journal of Physics: Conf. Series **874** (2017) 012017*



C. Taruggi, PADME preliminary



1.1.1 Stretching the positron beam

- *P. Valente, **arXiv:2001.10258***

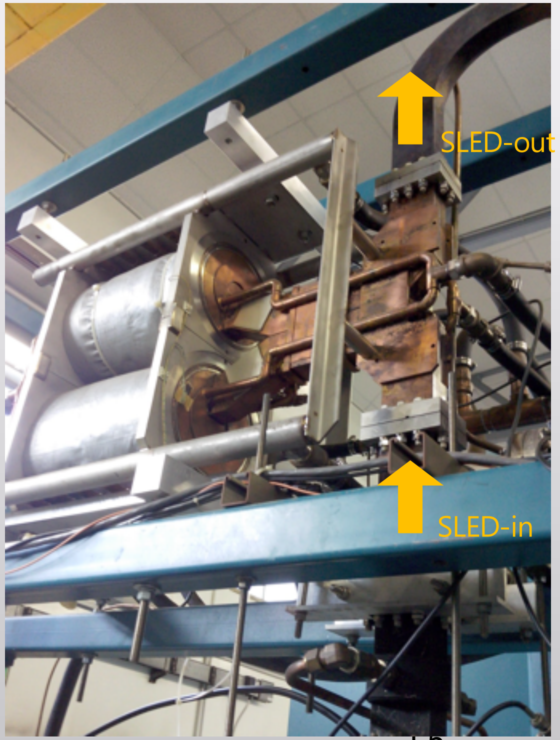
Two main ways for **extending beyond 300 ns** the positron pulse:

- **1.1.1.1 Flatten the pulse** after the phase-inversion, modulating the LLRF, like at the ELETTRA linac (simple ramp), using a FPGA-based board. The modulated (practically costant) accelerating field will be lower

Expect **400 MeV** for **positrons** (**550 MeV** for **electrons**), ≈**800 ns**

- **1.1.1.2 Remove the SLED** compression, in order to get a flat RF pulse
  - This should produce a **flat and long pulse** once the accelerating cavities are filled
  - At the price of a **reduced energy**, by a factor ≈**1.6**

  How to **by-pass**:
    - Standard method: use the appropriate W **de-tuning needle** but in one of the four SLED's it has fallen inside
    - More radical method: connect the klystron output directly to the waveguide network (**SLED-in to SLED-out**)
    - Other methods: multiple phase inversions, partial de-tuning, cooling the cavities, etc.



De-tuning or by-passing the SLED: **2 μs** positron pulses at **300 MeV**
- Just above the X17 production threshold (282 MeV)
- As in previous case, +150 MeV for electron beam

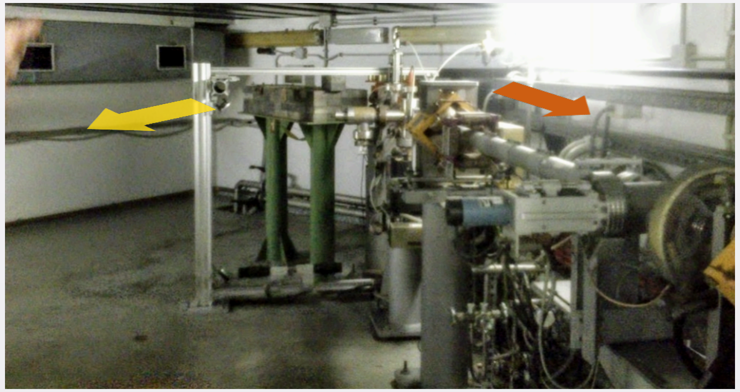
1.1.2 Electron beam-dump with present configuration

- Just by multiplying the maximum allowed **average** flux for the BTF-1 bunker (at the maximum design energy of 800 MeV) of 3.125 10^{10} particles/s $\times$ $3{\cdot}10^{7}$ seconds, one gets **10^{18} eot**
- This is possible since the average is defined on a year basis, so a [reasonably] higher charge can be dumped in the BTF-1 hall, while staying within the allowed limit thanks to the usually $\ll$100% duty-cycle
- **650 MeV** should be easily achievable (**electron beam**)

1.1.3 Increasing the charge dumped in BTF hall

- In order to be competitive with other dump experiments in the same dark mediator mass range, it is necessary to aim at **10^{20} eot/year** or more
- This is achievable by the DAΦNE LINAC in **electron mode** extending the pulse length, as shown at the price of a (slight) reduction of the maximum energy
- The BTF-1 bunker has to be reinforced, according to detailed calculations of the additional shielding required
- Aiming at **10^{20} eot/year** we have to assume a realistic efficiency for estimating the required instantaneous intensity
  - Using the standard **10^{7} s/year** still translates in a quite demanding 150 days at 80% efficiency
  - This requires delivering pulses of **32 nC** charge at 49 Hz
- However, the main issue is the modification of the existing bunker, and the need for authorization update: this requires **at least 1.5 years after the request is filed** (meaning that the project has been defined in all details)

1.2 Dumping the high-charge beam "somewhere else"



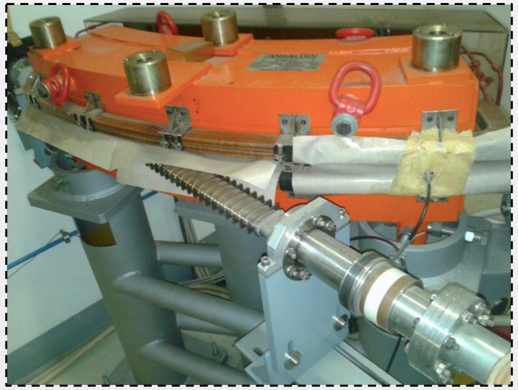
1.2.1 Exploit the existing beam-dump of the LINAC

- The transfer-line towards the damping ring is at 45° wrt to the LINAC direction
- If the bending fails, the beam is dumped straight ahead, onto a 4.5 m thick concrete with a cavity filled with Pb bricks
- Directly behind this wall there is a technical building with water pumps and heat-exchangers for the DR cooling (magnets, RF) **that can be adapted for hosting a sufficiently large experimental setup**.

Dumping a high-intensity beam on a target systematically could require additional shielding, as well as an **update of radio-protection authorization**

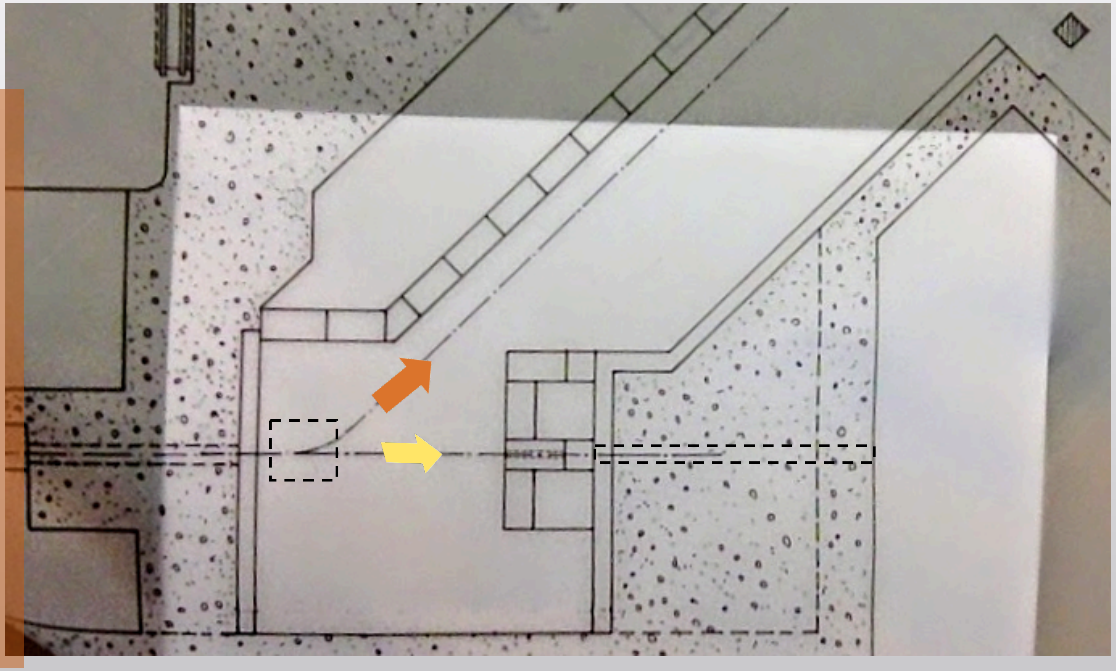
1.2.1 Using the LINAC dump and “sala pompe”

- Need a two-way vacuum pipe for the straight exit of the beam, with pulsed 45° dipole DHPTT01 off:: can be copy-pasted from DHPTT02
- What is the optimal depth of the target/absorber?
  - It depends on the experimental requirements
  - Digging a hole in the 4.5 m concrete wall all the way to the hall behind would give maximum flexibility
  - **This** would **definitively** need a radio-protection evaluation



No significant advance since I put forward this idea **6 years ago** :

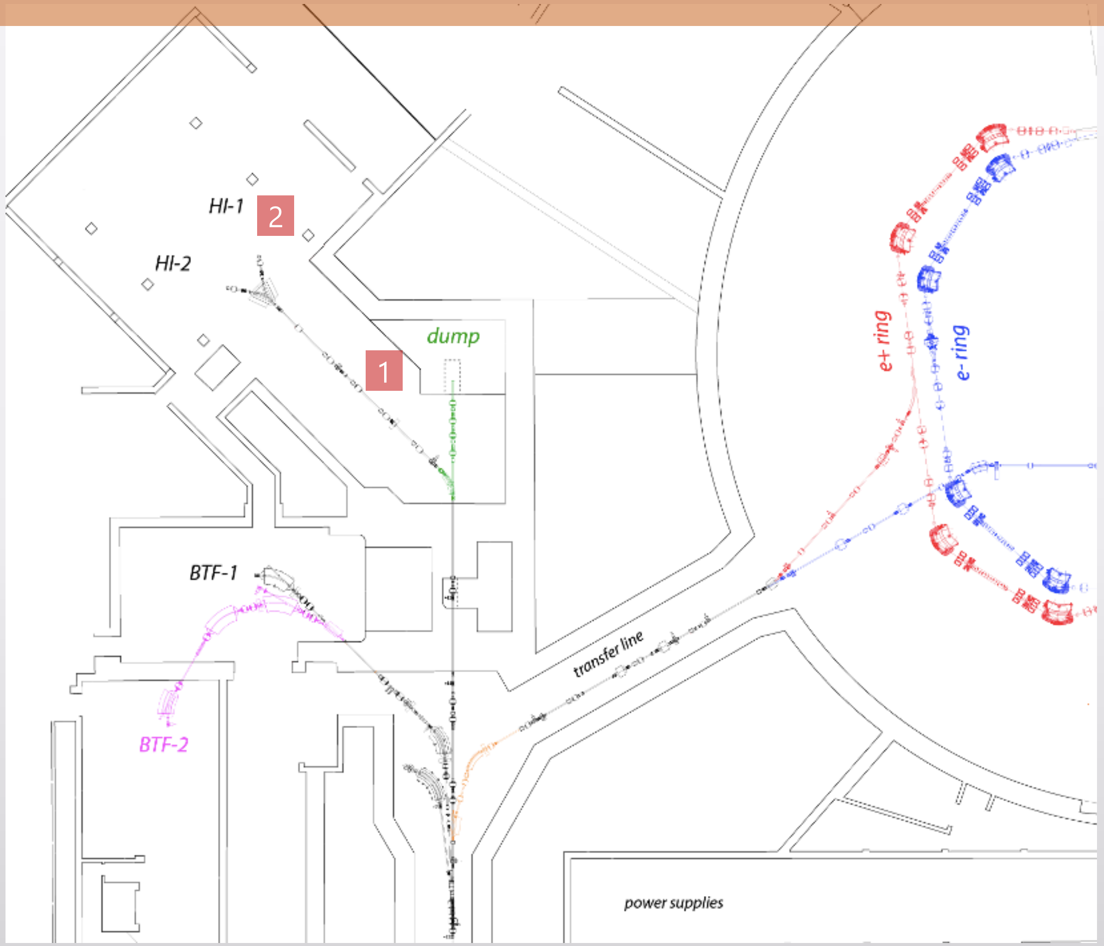
- **No detailed technical drawing** of the area seems to exist, only an old map of the building shows something close to the present configuration of the dump
- **No calculation of the dump** seems to exist, and not even its exact dimensions are known (concrete wall and lead thickness, etc.)
- It has been **impossible to inspect the inside of the dump** (supervised area), the basic questions being:
  - How deep is the cavity in the concrete wall?
  - How thick is the lead layer?



1.2.2 Dumping into "sala accumulatore"

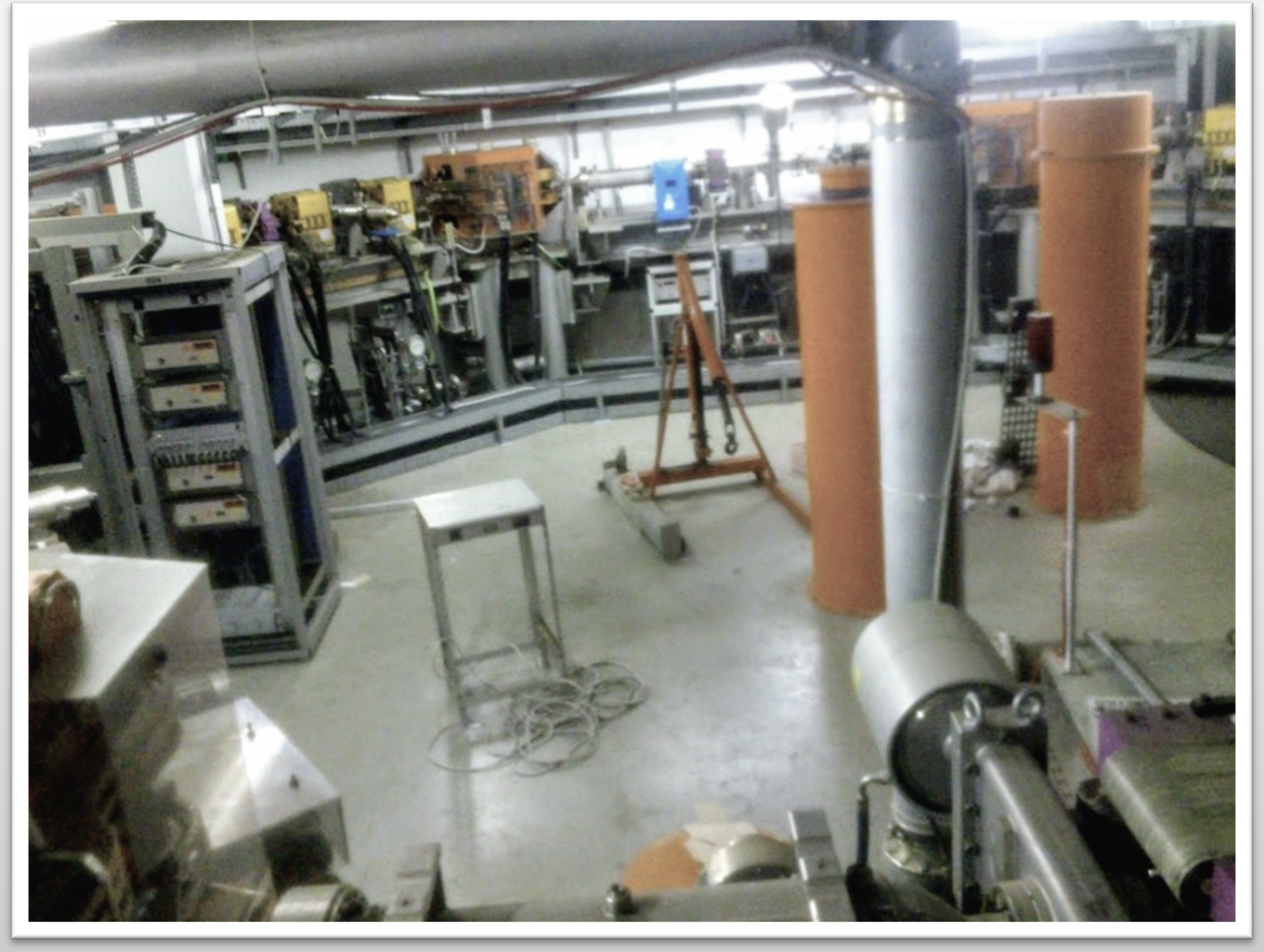
A technically much easier option, but feasible only at the end of the DAΦNE collider life: use the **damping ring hall** ("sala accumulatore")

- Several mSv/h during injections tolerated, due to additional external concrete shielding and supervised area kept free outside
- **No need of authorization update**
- Space available once the damping ring will be – at least partially – dismantled: in principle separate electron and positrons line can be used
- "Natural" beam-sharing with BTF operations, using the existing timing system and pulsed magnets used for ring injections
- In principle, injecting electrons into the e^- ring of DAFNE for synchrotron-lines operations **does not require** the damping ring



1.2.2 Dumping into “sala accumulatore”

2 Damping ring



1 Transfer-line to damping ring

Recoil/directional detectors

BDX @LNF

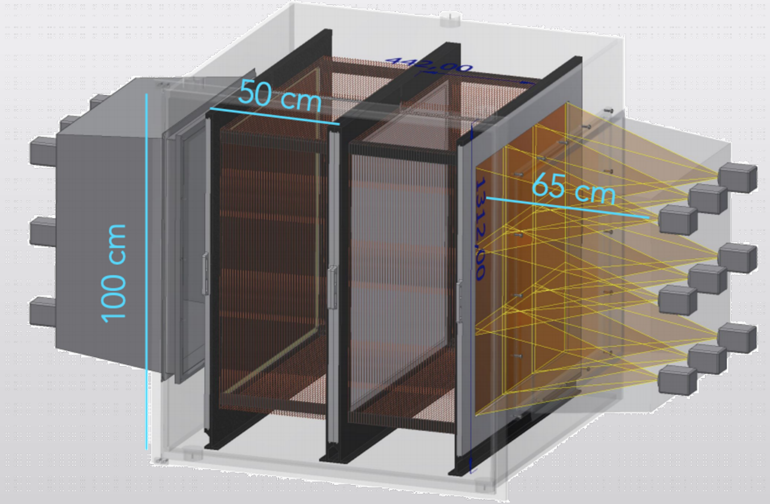
Preliminary study for 1.5 GeV electron beam, $7\cdot10^{19}$ eot

- $\approx$20 events in 1 m^3 scintillating detector (1 MeV_{ee} threshold)
- $\approx$50 mrad average opening angle
- Few MeV proton recoil energy
- Great advantage of the pulsed beam with respect to BDX@JLAB, due to the beam timing, strongly suppressing backgrounds

CYGNO @LNF

Use a recoil detector with directional capabilities

- Add the knowledge of the beam tri-momentum to the timing
- Issue: a gas detector pays a huge factor due to low density in the sensitive mass



- *E. Bracchini et al.*, ***INFN-19-06/ROMA1***
- **https://agenda.infn.it/event/17980/contributions/84115/**

1.2.3 Dumping at the accumulator switchyard

At least in the CYGNO case, the setup can be significantly shorter than PADME or BDX or a similar experiment

This opens the possibility of using the switchyard area **in front of the LINAC dump** (instead of the room behind it), of course sending the beam straight (45° pulsed dipole off)

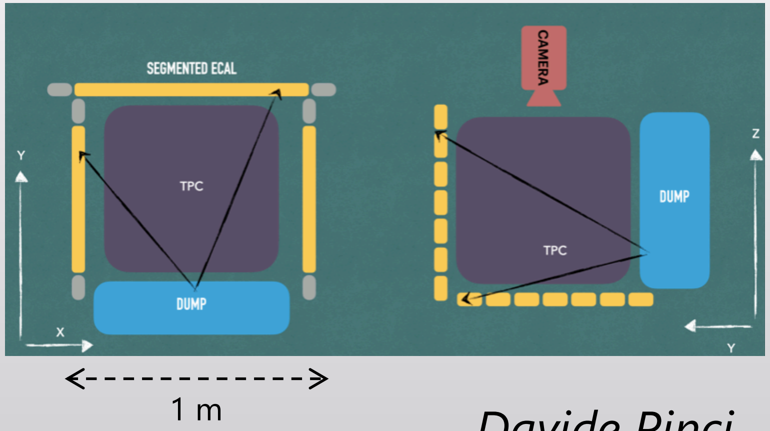
This certainly would have a much smaller impact from the point of view of radio-protection

45° pulsed dipole to DR

LINAC dump

Lead shielding

Reduced size CYGNO setup [LIME], placed behind a 20 cm tungsten dump [not discussed here]



Davide Pinci

2. DAΦNE ring as pulse stretcher

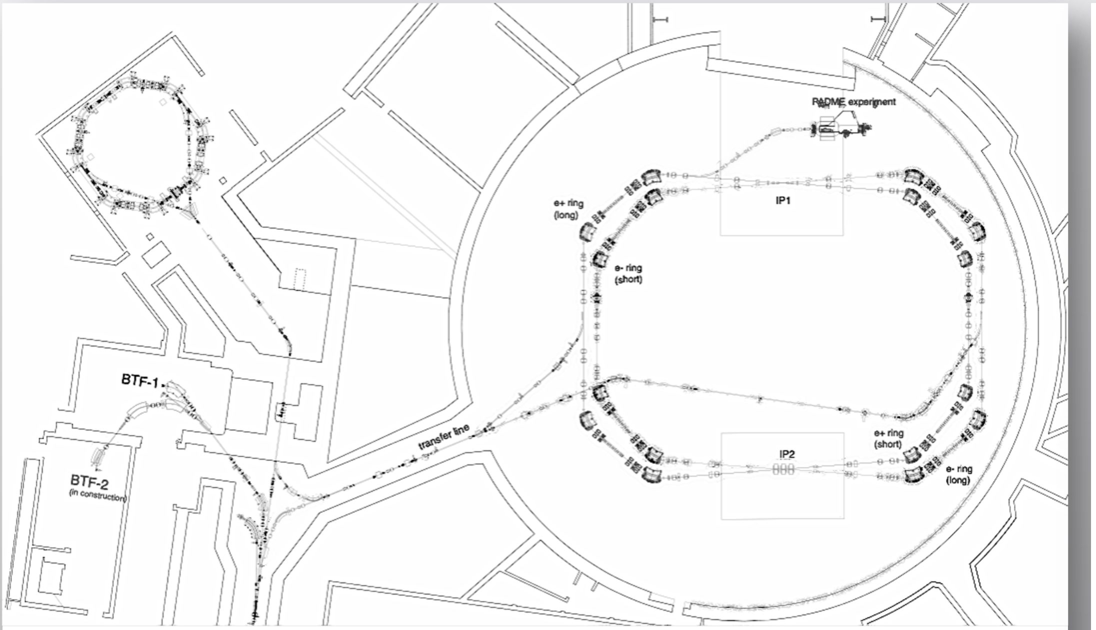
POSEYDON *proposal:*

P. Valente, arXiv:1711.06877, S. Guiducci et al., J. Phys. Conf. Ser. 1067 (2018) 6, 062006

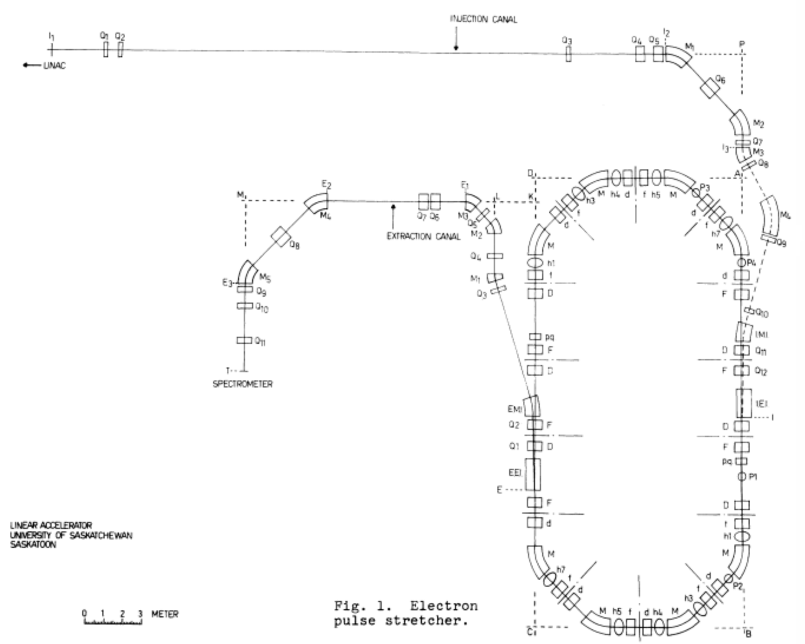
*Inspired by **EROS** ring in Saskatchewan [50-300 MeV], L.O. Dallin et al., Proc. 13th IEEE PAC (1989) 22*

Same principle proposed for:

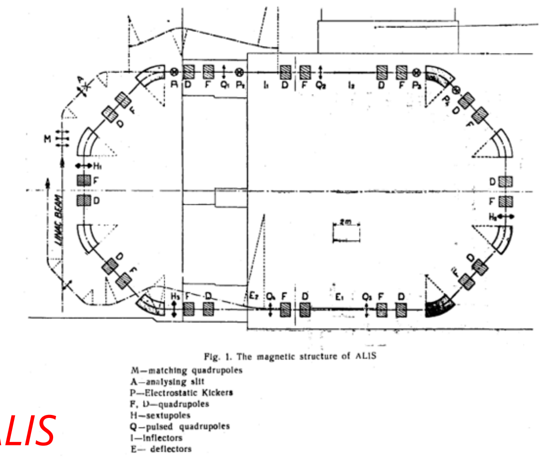
- ***ALFA*** *at ADONE LINAC [200-500 MeV]: S. Guiducci, G. Martinelli, M. Preger, LNF-78/22(R), 1978*
- ***ALIS*** *at Saclay [1.7 GeV]: R. A. Beck et al., Conf. Proc. C690827 (1969) 94-102*



DAΦNE/POSEYDON



EROS



ALIS

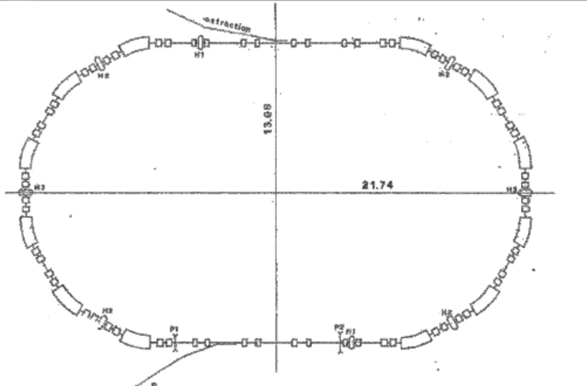


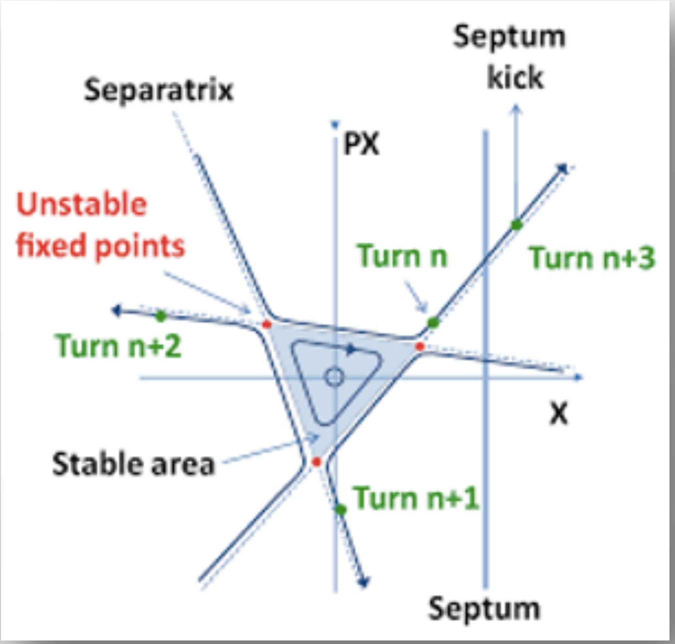
FIG. 4 - Ring layout. The positions of injection and extraction septa, sextupoles and injection orbit perturbators are shown.

ALFA

Resonant extraction

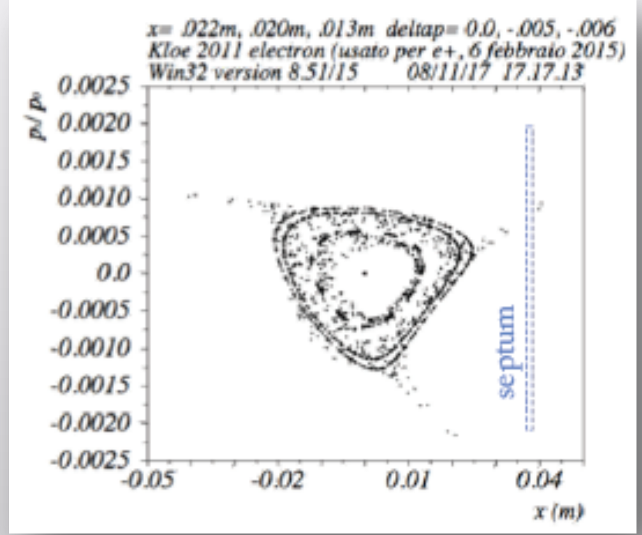
The basic principle is the $n + \frac{1}{3}$ **resonant extraction** from a synchrotron, a well-known technique, widely used for proton and ion machines

- When the betatron tune is close to a 1/3 of integer, **an unstable region of the phase space** is created, outside the area delimited by a triangle
- The line extending each side of the triangle is called a “separatrix”
- When some particles reach the unstable region, they’ll start moving along a separatrix
- If a septum is placed at a given distance, it will **extract** those particles, i.e. it will drive them out of the ring
- In order to go on and extract **more particles**, the stable triangle has to be **shrunk**, moving the tune **closer** to the resonance



2.1 "Monochromatic" extraction from DAΦNE

- If the ring **chromaticity** is $\boldsymbol{\xi \neq 0}$, the energy spread is transferred to the tune: $\Delta\boldsymbol{\nu}/\boldsymbol{\nu} = \boldsymbol{\xi}\Delta\boldsymbol{p}/\boldsymbol{p}$
- Electrons and positrons naturally lose their energy in a ring, due to the synchrotron radiation emission: with **RF off**, particles will thus move from the stable to the unstable region **just by losing energy**
  - The required tune is reached when particles reach a given energy, hence the name "monochromatic" extraction
  - The **full beam** can be extracted
  - **Extraction time** is given by the **synchrotron loss** and the energy spread: **4.5** (9) **keV/turn** with wigglers **off** (on)
- First calculations in *S. Guiducci, DAΦNE note G-73 (2017)*:
  - Some modifications to the DAΦNE optics for optimal chromaticity, $\boldsymbol{\xi_x = -3}$
  - Inject off-axis with $\Delta\boldsymbol{E}/\boldsymbol{E}$ =**+0.5%** and reach **-0.6%** in **1400 turns** with **wigglers off**
  - Electrostatic **septum**, 0.1 mm thick, at x=40 mm
  - **Step at septum 5 mm**, extraction losses ≈2%
- To be evaluated the possibility of using an existing **magnetic septum**
  - e.g. thin septum from **CTF-3** combiner ring (2 mm thick, 0.048 Tm) would give, with the same step, 40% extraction losses (which could even be OK)



With **0.5% spread** at injection, wigglers **off**, expected pulse length of **0.42 ms**

DAΦNE modifications

- Setting the optimal chromaticity can be done with the **present ring components** (required fields in the sextupoles in particular should be well in the operative range)
- Some modification for the installation of the **extraction septum** (either electrostatic or magnetic) has to be done
  - The optimal place would be a low-dispersion point, e.g. one of the straight sections
- Beam has to be driven to the experiment preserving its emittance: a (relatively simple) **extraction line** is also needed
- Some modification to the injection is needed in order to **fill the ring** with the longest possible bunch (324 ns) from the LINAC:
  - Kickers pulse length should be increased.
  - Collimators for controlling the intensity, beam-spread and emittance will be also needed
  - **Direct injection** (no accumulator) requires modifying the transfer-line to the main rings
- Operations:
  - Energy loss is decreased by switching **off the wigglers** which implies a **significant reduction of power requirements**
  - **RF off** also implies a reduction of cost and complexity

Power requirements

System	Power (kW)			
	KLOE-2	**POSEYDON only** (1 ring, no wigglers)	DAΦNE-Light only (1 ring, 1 wiggler)	**POSEYDON + DAΦNE-Light** (2 rings, 1 wiggler)
Magnets PS	1850	550	640	1190
RF MR	320	-	160	160
LINAC	230	230	230	230
Cooling	300	300	300	300
Cryogenics	250	-	-	-
HVAC	260	200	200	260
KLOE	120	-	-	-
Total	3330	1240 ≅ **40%**	1530 ≅ **45%**	2140 ≅ **60%**

From data provided by R. Ricci

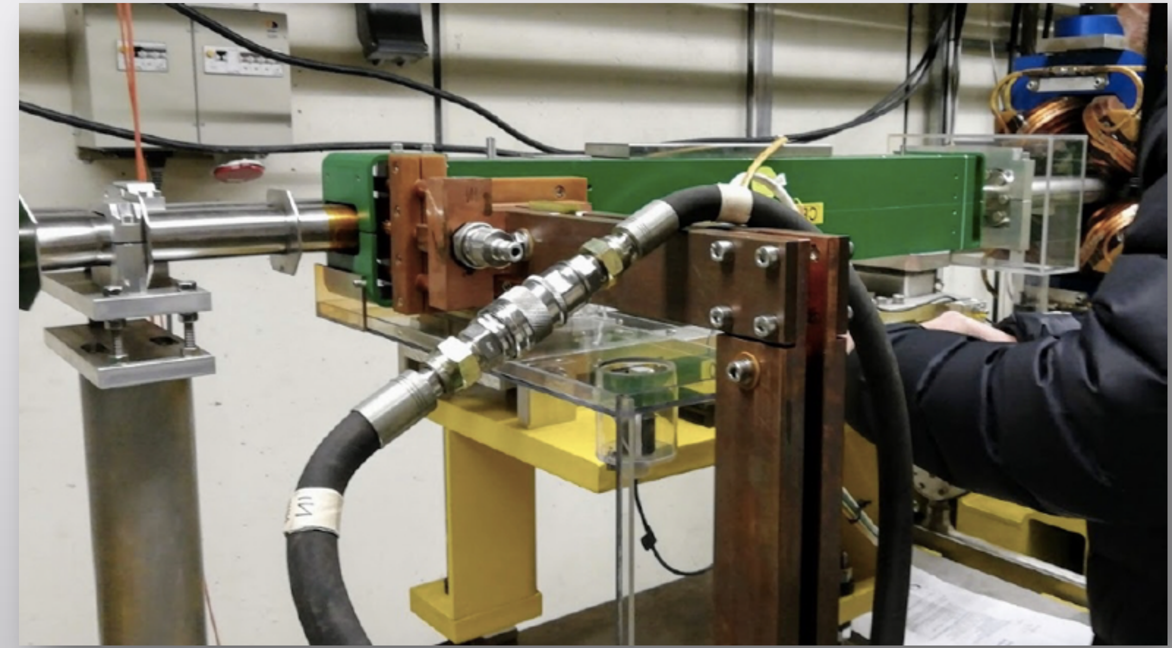
-60%

-40%

Possible magnets for extraction line

- Components from the discontinued CTF-3 facility at CERN have been made available for re-use in Frascati
- I have prepared a list, including the **thin septum** of the combiner ring, **quadrupoles**, **correctors**, EPA **dipoles** from the chicane
- Formal claim was submitted and reportedly accepted by the CTF-3 collaboration
- I have personally **reviewed** and **tagged** the material on site

In principle ready to be shipped to Frascati [but nothing has happened since Jan. 2019]

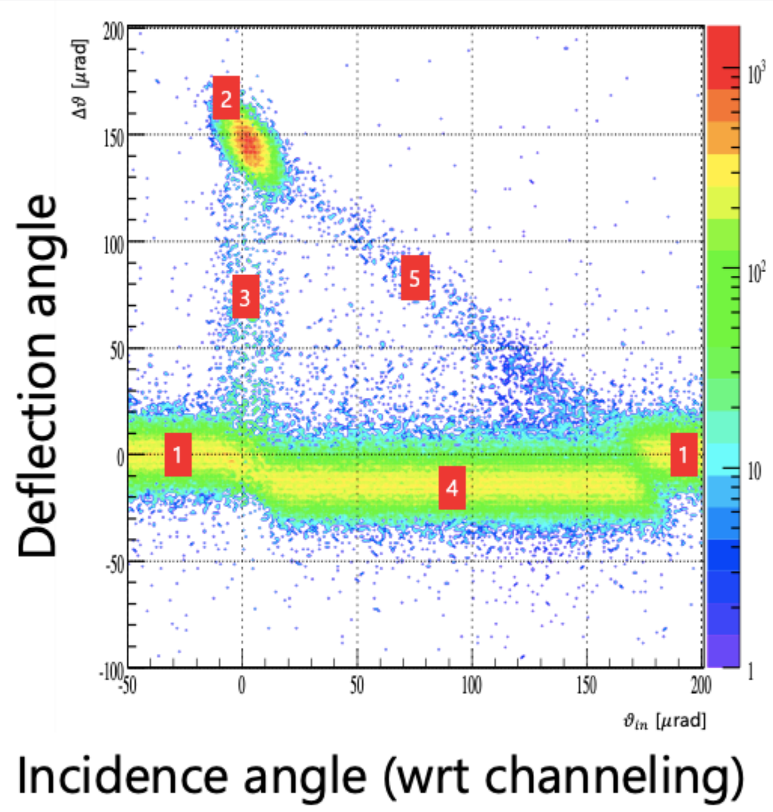


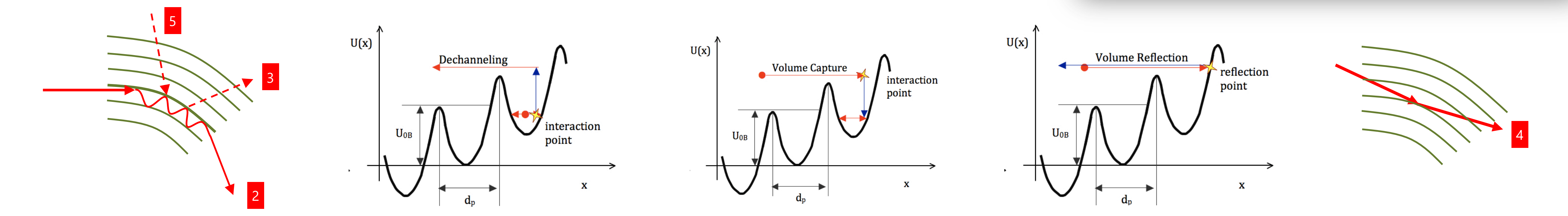
Beam energy vs. extraction time

- Considering an energy spread at injection of 1.1%, the synchrotron energy loss gives an extraction time of **0.42 ms** for **510 MeV**
- Lowering the energy of the ring (and of course of the injected and extracted beam as well), the same spread will correspond to a lower total amount of energy *linearly*, while the synchrotron energy loss will decrease with E^4, thus **increasing the extraction time**
- Assuming the same energy spread:
  - **0.88 ms** at **400 MeV**
  - **2 ms** at **300 MeV** [Interesting for X17 resonant searches]

2.2 Positrons from DAΦNE ring through crystal channeling

- Alternative approach for displacing positrons: use **coherent processes in bent crystals**. When a charged particle hits the periodic potential of a regular crystal lattice with a given curvature, it can:
  - Interact just by random scattering (1) AMORFOUS
  - Perform multiple reflections in the potential well, following the curvature of the crystal (2) CHANNELING, in case at some point escaping the channel (3) DECHANNELING, or entering it at a given depth (5) VOLUME CAPTURE
  - Be mirrored [in the opposite direction and at a well defined angle] (4) VOLUME REFLECTION





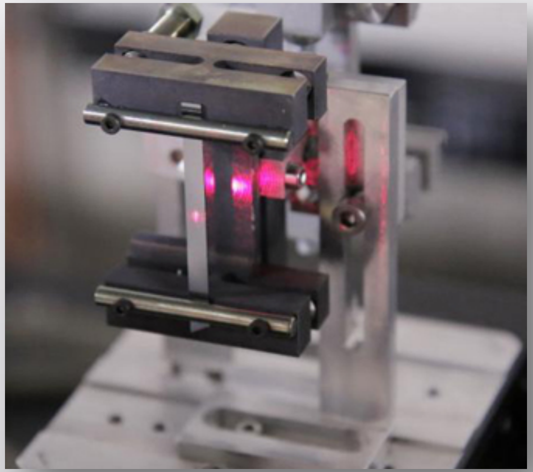
2.2 Positrons from DAΦNE ring through crystal channeling

Idea: kick the positrons at the edge of the circulating beam and drive them to an extraction line

- Many results with **hadrons** mainly from UA9, very few on leptons mainly from MAMI (855 MeV electrons); even less on **positrons**, practically only from BTF (100-500 MeV)

- The main limitation is the typically **small deflection angle**, which is directly related to the critical angle, in turn depending on the beam energy and lattice parameters

UA9 holder and bent crystal (CERN & INFN)



- **SHERPA** project – CSN5 young researchers grant, PI Marco Garattini – will investigate (Mar. 2020-Mar. 2022) the basic parameters of this idea tailored to DAΦNE:
  - At **510 MeV**, critical angle for Si(110) ϑ_c= **210 μrad**
  - To be compared with multiple scattering = **16 μrad/μm**
  - De-channeling length of 510 MeV positrons: **400 μm**

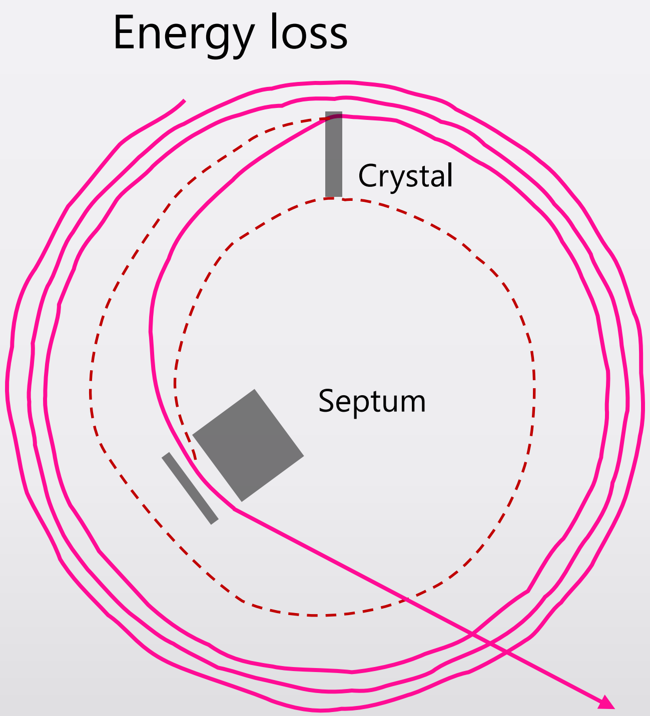
Main questions [in addition to technical "details" like holder, goniometer, vacuum, …]

- Which process? [**channeling** vs. **volume reflection** vs. **mirroring**]
- Is it possible to build a crystal with required parameters? [e.g. **thickness=30 μm**, width=10 mm, **angle=1 mrad**]
- What channeling efficiency can be reached?
- How to drive positrons [possibly all the beam] to the crystal?
- Which modification to **the machine optics**? Where to **place the crystal** and where the extraction **septum**?

Crystal extraction

- The betatron oscillation is adjusted in order to hit the crystal at a given location:

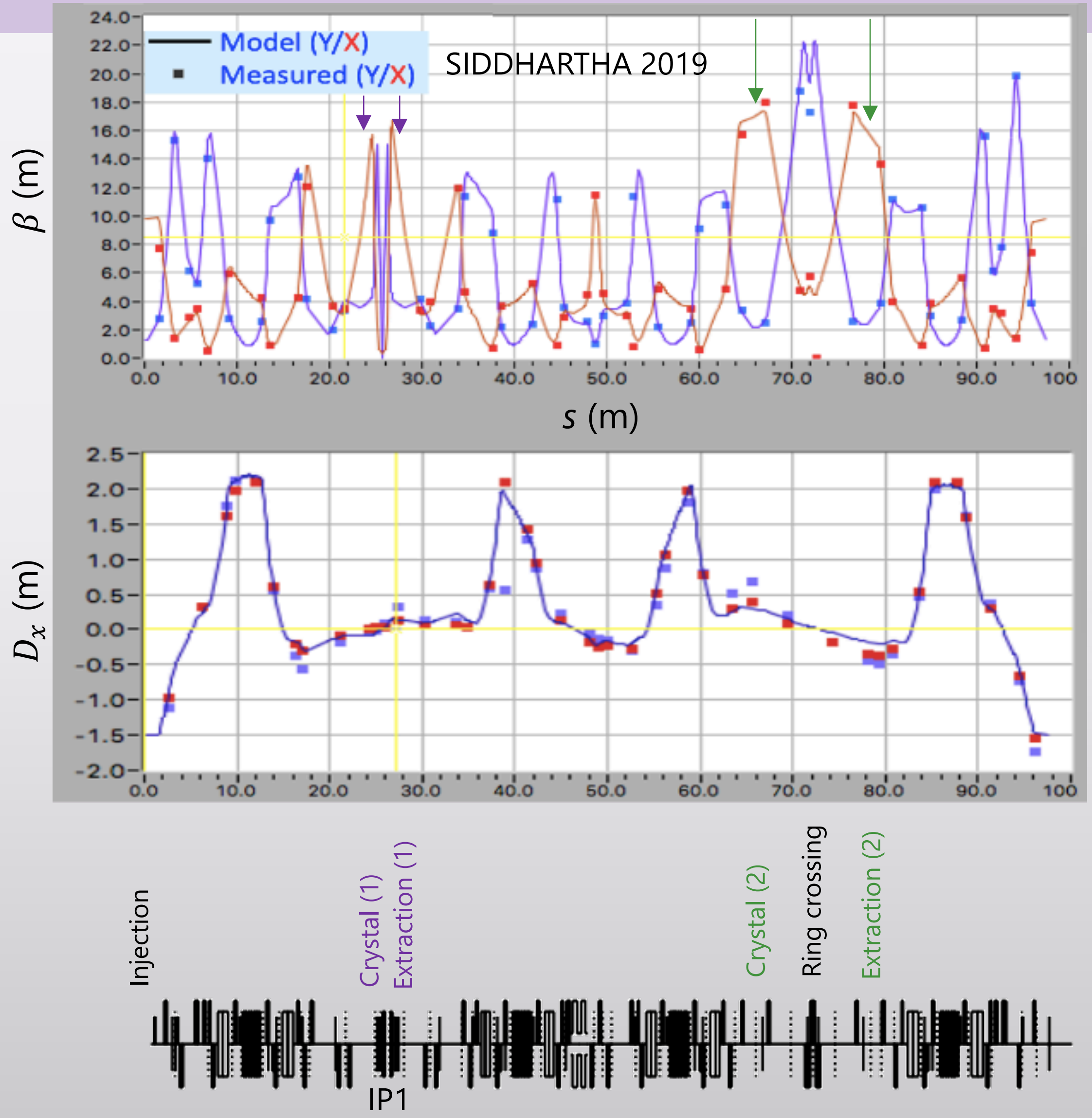
$$x = \frac{\Delta p}{p}\left(|D| + \sqrt{H\beta}\right)$$

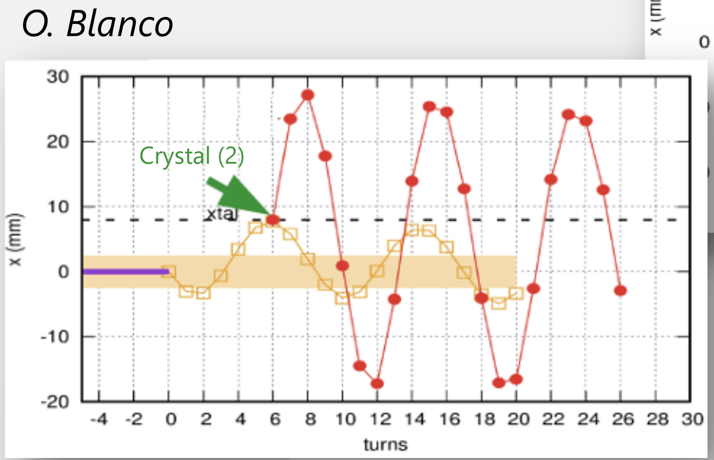


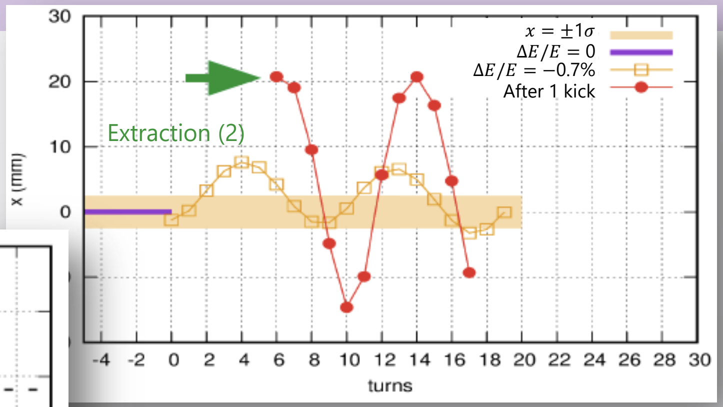
- In principle the extraction can be "**local**", i.e. the beam gets kicked out from the beam-pipe by the crystal if the deflection given is large enough to get enough separation with the available space:
  - 1 mrad kick offsets by 2 cm at 20 m distance, which is definitively not enough
- A "**non-local**" extraction could be used instead:
  - Kick is imparted in one point by a crystal and particles reach a septum for a further deflection **after a given phase advance** or even **some turns**
  - Positrons can encounter the crystal multiple times and get further kicks or got lost

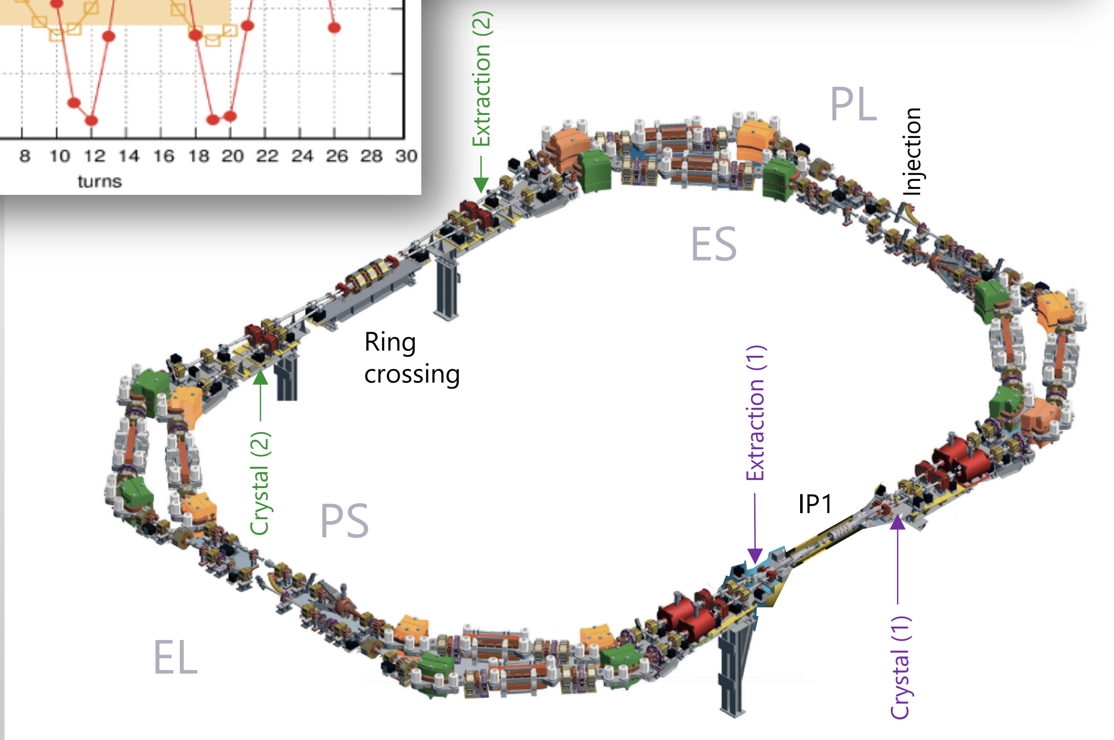
- The displacement x_2 at **location 2** due to a kick x_1' given at **location 1** can be calculated from R_{12}: $x_2 = \sqrt{\beta_1\beta_2} \cdot \sin(2\pi\Delta\mu) \cdot x_1'$; where $\Delta\mu$ is the phase advance
- In order to have **maximum displacement**, the $\boldsymbol{\beta}$ **functions** should be as **large** as possible and **$\Delta\boldsymbol{\mu}$=1/4**

Present positron ring optics





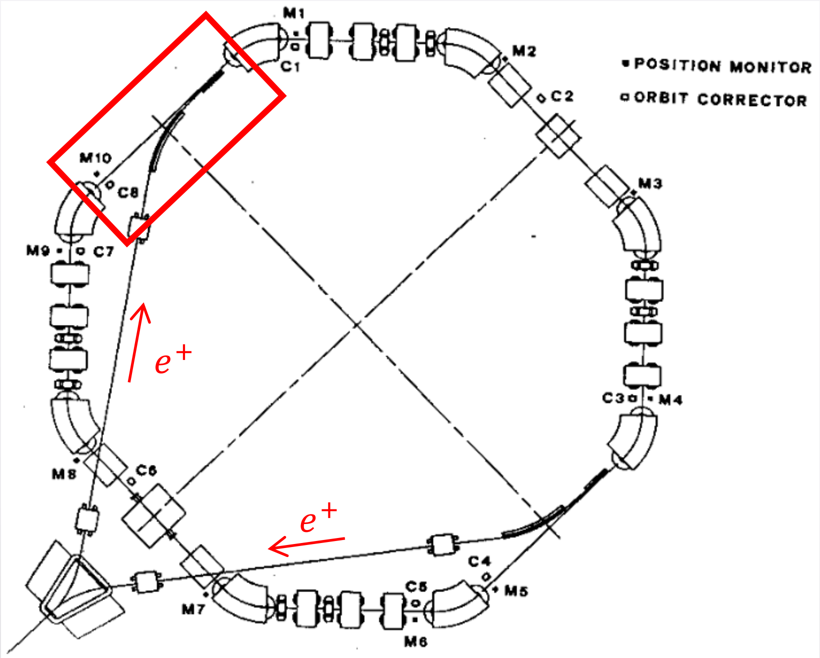




2.2 Positrons from DAΦNE ring through crystal channeling

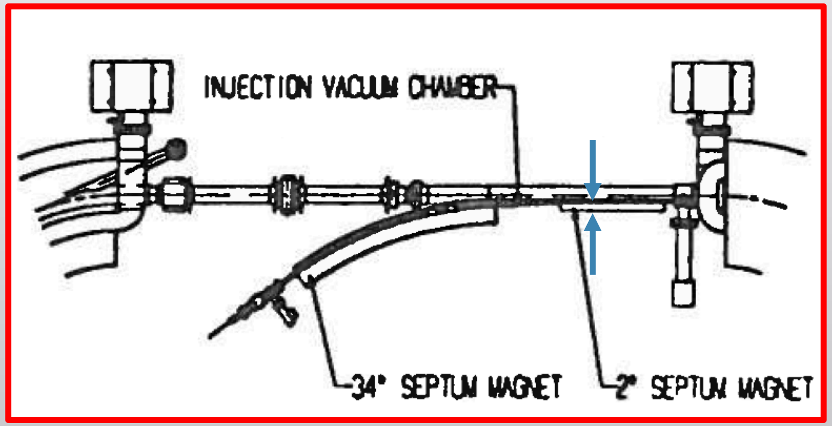
- Expected positron beam
  - What kind of time structure? The same considerations as in the case of the resonant extraction can be done, computing the number of turns needed to reach the crystal, **given the energy loss and spread**
  - Difficult to make an estimate of the achievable rate, but even with very low efficiency intensity should be sufficient starting from $\approx 10^{10}$ circulating positrons (1.5 nC single bunch over 324 ns)
- Status
  - SHERPA should produce, in 2 years, a crystal with required parameters [it can be done! Now **being produced** by Ferrara], its holder [**drawings available**] and goniometer [**available**]
  - The setup will be tested at the BTF with a positron beam
  - The following step would be the **detailed design** for the implementation of the system in the machine
  - **A septum and a basic extraction line would be in any case needed**
  - Can be **complementary** or an upgrade of the resonant extraction project
- Input for more studies (*S. Guiducci*)
  - Crystal at x =8 mm from beam orbit is too close: need to be at $\approx 10\ \sigma$ at injection
  - Optics modifications to have more space for septum, larger β, optimize phase advance, move close to the resonance, etc.

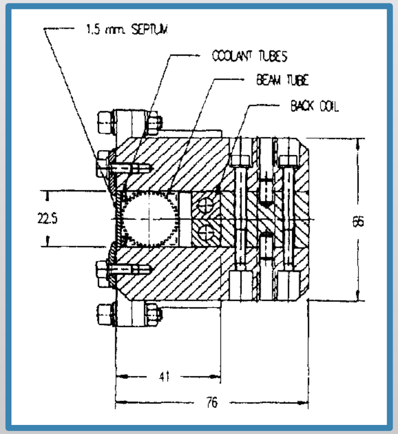
3.1 Resonant extraction from accumulator



Main parameters of the accumulator:

- **1/3 of the length of the main rings**: 32 m (**108 ns**)
- 1/5 of the main radio-frequency: 74 MHz
- 3× energy acceptance: **1.5%**
- 2° septum: **1.5 mm** thick, at **-20 mm** (inwards) from nominal orbit
- Same number of dipoles (8) but smaller radius:
  - **1.1 m** wrt **1.4 m**
  - Similar synchrotron energy loss: **5.2 keV/turn** wrt to the main ring 9 keV (**4.5 keV**)**/turn** with wiggler on (**off**)





To be studied:

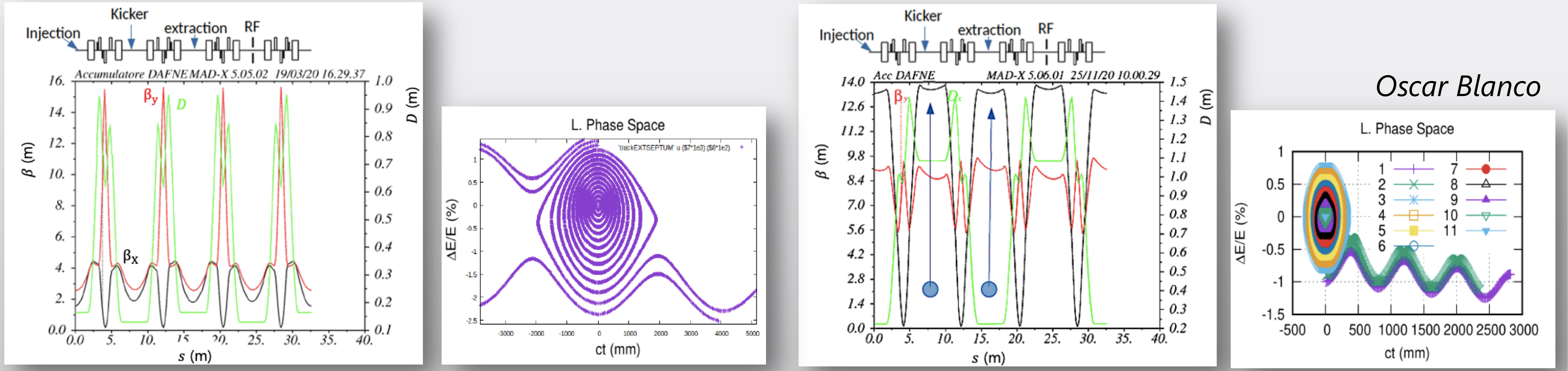
- Optimal optics: standard has ξ_x, ξ_y ≈0 and small β, vs. for instance the aperture
- Is it possible to use the **existing magnetic septa**?

The clear advantage of the accumulator is the presence of injection **and** extraction septa

3.1 Resonant extraction from accumulator

- The standard accumulator optics has ≈**0 chromaticity** and **small $\boldsymbol{\beta}$**
  - This at advantage of a large momentum acceptance

- Optics modified in order to have **largest possible $\boldsymbol{\beta}$** in the straight sections (**initially for crystal extraction**) and have a chromaticity $\xi \neq \mathbf{0}$
  - The momentum acceptance is reduced: [−0.5%; +0.1%]



- 0.6% of energy lost by synchrotron radiation in 600 turns
- The extraction time is thus ≈**60 $\boldsymbol{\mu}$s**

3.2 Crystal extraction from accumulator

- With an energy loss of 0.6% offset is $x = -5$ mm at crystal position (-3 mm at septum)
- The crystal will give a kick to the positrons hitting it, we assume $\boldsymbol{x}' = \mathbf{1}$ **mrad**
- In the first attempt $\boldsymbol{\beta_x}$ =**10 m**, approximately $\boldsymbol{x} = -\mathbf{11}$ **mm** at the septum

Is this the optimal configuration? Most likely not

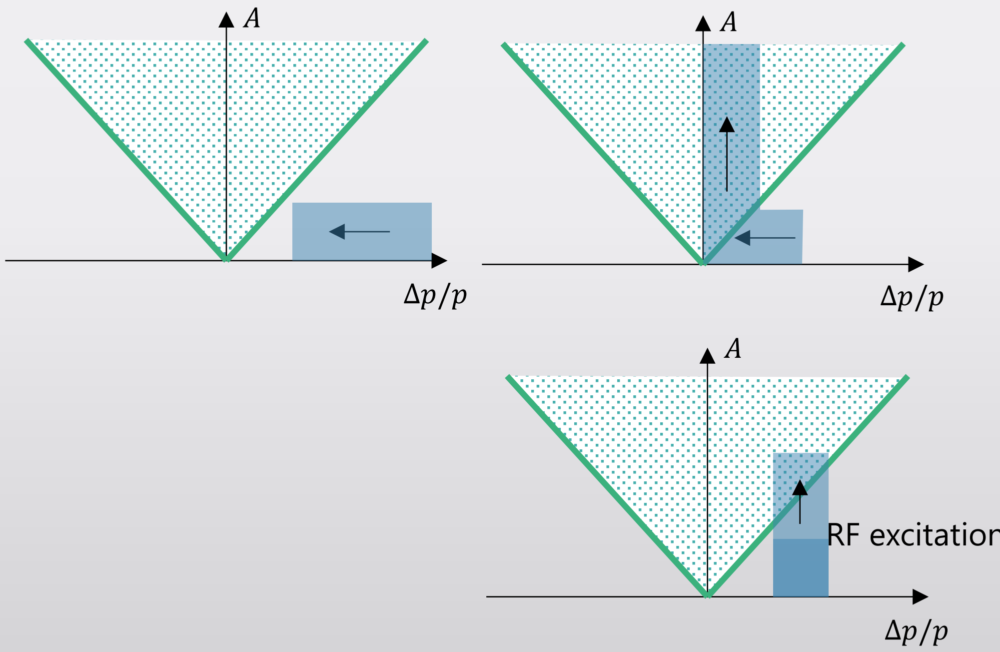
- Optimizing chromaticity for working **closer to the 1/3rd resonance** should increase both the energy acceptance and dynamic aperture, enough to inject at out of energy / out of axis.
- e.g. starting from $\Delta\boldsymbol{E}/\boldsymbol{E} = +0.5\%$ should ≈**double the pulse length**

More studies are needed

Controlling the extraction rate

- The **uniformity of the extracted beam** is very important: can be controlled modulating the betatron oscillations
- In the so-called "RF knock out" the amplitude is increased for injecting into the separatrix particles with smaller $\Delta p/p$
  - This is done applying an external, transverse electric field [for instance with a kicker] matching the betatron frequency.
  - Due to the tune spread given by not vanishing chromaticity, either modulate the frequency or inject a white noise

- Also in crystal extraction, a RF excitation could be used to populate the periphery of the beam
- In this way particles with **smaller displacement** could be extracted
- **If a sufficient portion of the beam could be driven to the crystal this could yield a longer beam spill**
  - This deserves a careful experimental study
  - All estimates for crystal extraction use the central orbit
  - For this reason the **same length** as in the **resonant option** is quoted



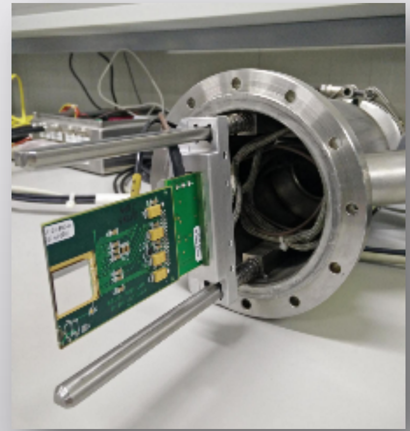
- In the **SPS crystal extraction studies** the population of the beam halo has been steadily sustained by injecting a properly tuned transverse random noise using a ADT ("Adiabatic Transverse Dumper", a sort of electrostatic capacitor)

M. Garattini

Further studies

- Studying linear and not linear effects in the rings (both the main ring **and** the accumulator) would be of paramount importance for all proposed solutions

- Not so much interest by beam dynamics experts **and** in the DAΦNE team
  - Latest development in Spring 2018 (*S. Guiducci, IPAC '18*)
  - More recently interesting contributions from O. Blanco in the context of SHERPA
  - On the contrary, a coordinated effort would be very important
- Also more interest would give a positive push to hardware-related activities, e.g. performing tests and measurements on the machine

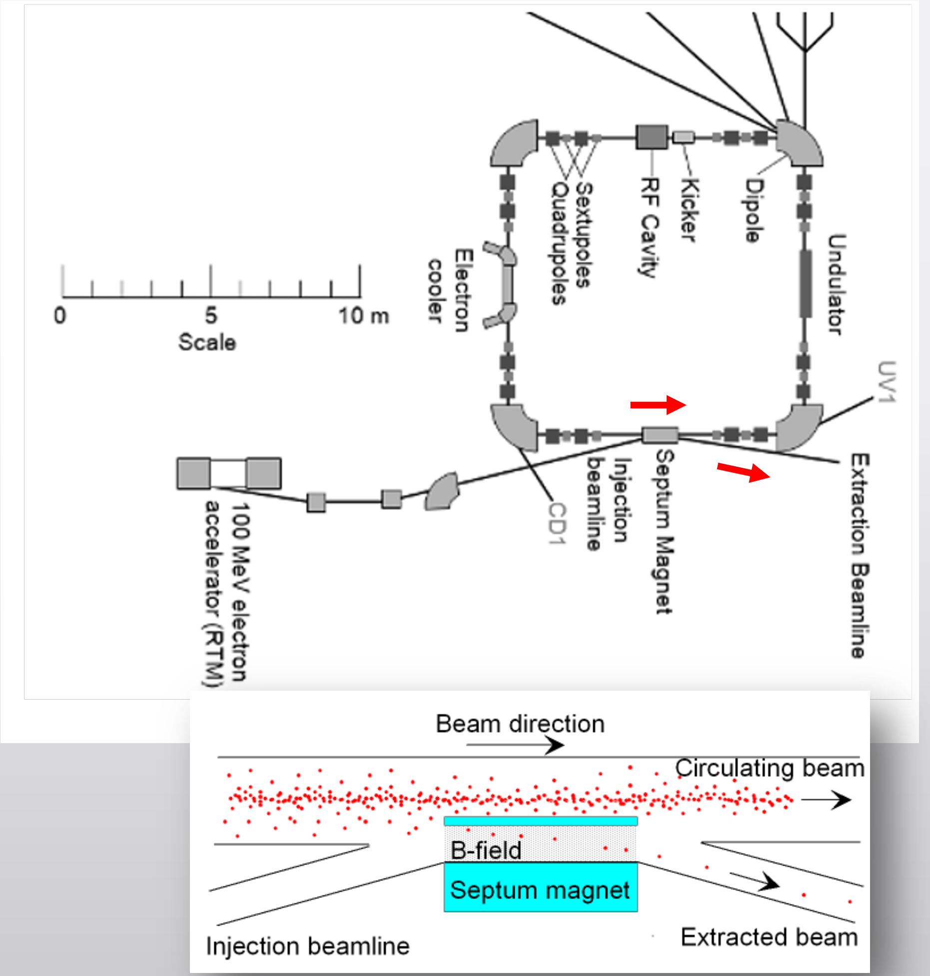


- For instance, studying **beam losses** in one of the DA*Φ*NE **main rings** and/or in the **accumulator** would be essential to cross-check with models and calculations
- This can be done with devices **outside** the beam pipe or with a suitably instrumented **Roman pot** [like for UA9 experiment studies in SPS and LHC]

- This was one of the synergies suggested for a new UA9 phase
- Unfortunately the new MoU is NOT YET approved, neither by CERN and INFN
  - Proposal of joining UA9 for studying crystal-assisted extraction in summer 2018 not successful
  - Still a very small team for the SHERPA project

Other ideas: Touschek extraction

- *Inspired by parasitic extraction from ASTRID, Aarhus (DK): S. P. Moeller, K. Kirsebom,* ***ISA Newsletter 6 (1995) 4***

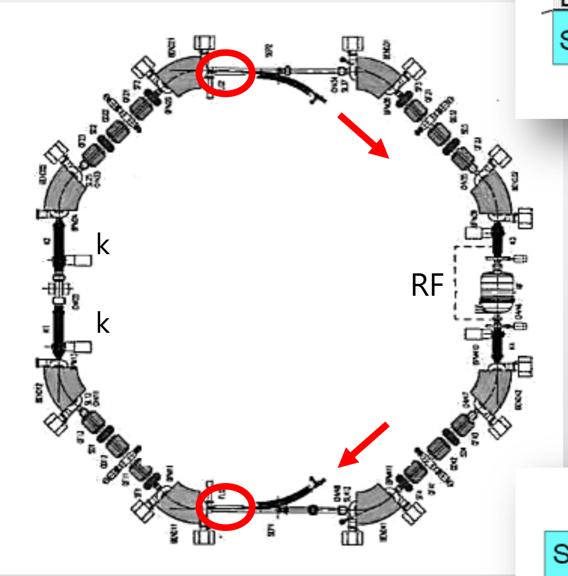


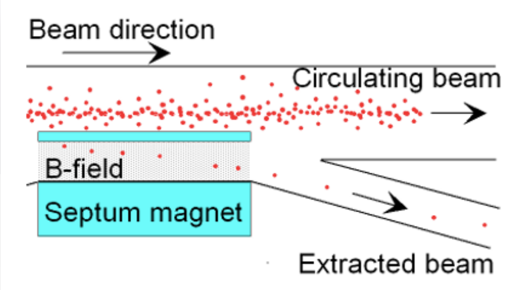
- ASTRID ring, 40 m length, RF 105 MHz, 140 nm emittance, 2.29/2.69 tunes, -4.0/-7.1 chromaticity, 6 m dispersion at septum
- With **200 mA** beam at 580 MeV, lifetime of **12 h**, about **$4 \cdot 10^6$ electrons/s** are **lost**, a fraction goes to the extraction line
- Electrons with **+0.88% energy** go to the septum
- Extracted beam proportional to circulating current and and $1/\tau$:
  - Intensity: **$3 \cdot 10^4$/s**
  - Increased reducing vertical beam size up to **$1.5 \cdot 10^5$/s**
- Beam size at septum: **15×0.5 mm^2** (H×V)

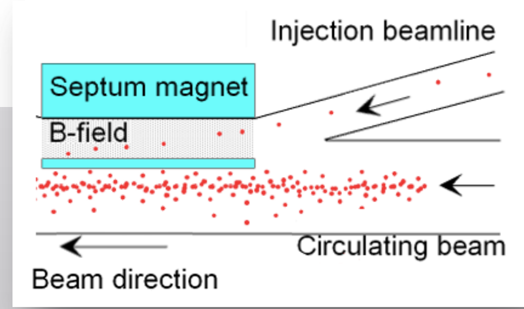
Main questions:

- Is it possible to get a useful positron rate out of DAΦNE?
- Main ring vs accumulator
- How to control the extraction rate

Parasitic extraction using accumulator septum







- DAΦNE accumulator, 32 m length, RF 73.65 MHz, 0.260 μm emittance, 3.12/1.14 tunes, ≈0 chromaticity,
- With **100 mA** beam ($6{\cdot}10^9$ positrons) at 510 MeV, assuming a loss rate of $5{\cdot}10^{-4}$ s^{-1} (τ~0.5 h*), **$3{\cdot}10^6$ positrons/s** are **lost**
  - Particles are lost when amplitude for a given energy spread ϵ is equal to the physical aperture: $A = \epsilon\left(\sqrt{H\beta} + D\right)$
  - This happens when $\Delta E = -2.2\%$ (modified optics with large β)
- Particles **losing** ≈**1.8% energy** are shifted inwards by **−11 mm** at the septum, which should be enough to be extracted
- Extracted beam proportional to the circulating current and $1/\tau$
- Contrary to the accumulator, no extraction septum is installed in the main rings

* M. E. Biagini *et al.*, Conf. Proc. C 980622, 415-417 (1998)

Main questions:

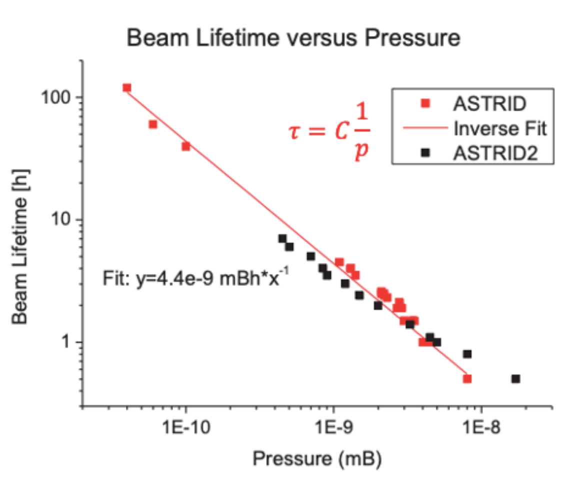
- Is it possible to get a useful positron rate out of DAΦNE?
- Main ring vs accumulator
- How to control the extraction rate

Parasitic extraction using accumulator septum

There are four mechanisms diminishing the number of particles in a stored beam:

1. Photon emission (quantum lifetime)
2. **Elastic scattering with residual gas (Coulomb scattering)**
3. **Inelastic scattering with residual gas (Bremsstrahlung)**
4. Scattering between beam particles (Intra-Beam Scattering aka Touschek effect), usually dominant in electron/positron machines

- Touschek lifetime can be reduced squeezing the beam: $\tau \sim \frac{1}{\epsilon} \cdot \frac{1}{\sigma_L \sigma_x \sigma_y} N$
- Particle loss due to the interaction with the residual gas is proportional to the pressure, could this give an handle on the rate by injecting gas in a controlled way? However elastic and inelastic interactions give different ΔE spectra



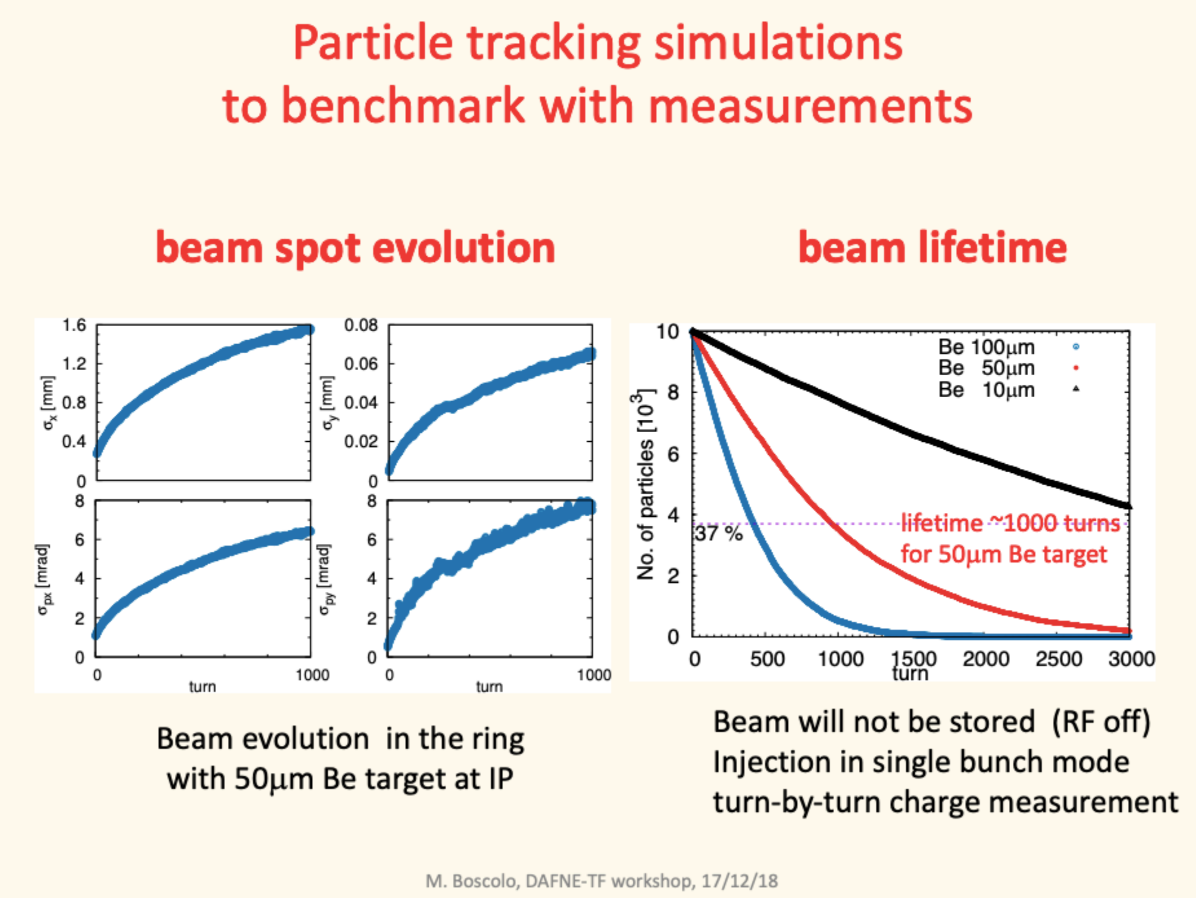
Main questions:

- Is it possible to get a useful positron rate out of DAΦNE?
- Main ring vs accumulator
- How to control the extraction rate

Other ideas: target in the ring

- *Inspired by **wire extraction** from ELSA ring, Bonn;*
- *Also suggested by G. Finocchiaro, M. Antonelli et al.*

M. Boscolo



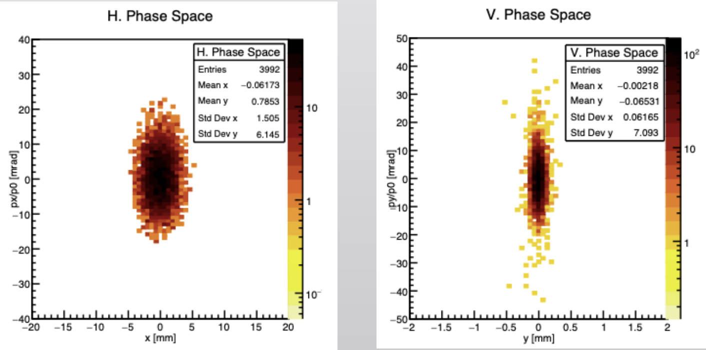
Internal target: lifetime heavily reduced already with L=10 μm Be

- $\tau \propto 1/L$, mainly due to energy losses [Bremsstrahlung]
- Located at IP (D =0) ≈3500 turns i.e. of the order of **1 ms**
- Lost particle rate reasonably flat in the first τ of the exponential

More than an extended target, better a strip or a wire, intercepting only a fraction of the stored beam

- But how many of the scattered positrons can be captured and driven to an experiment?
- An obvious advantage of the SHERPA implementation would be the possibility of performing tests with the crystal in amorphous condition (30 μm Si)

Transverse phase-space after 900 turns, 50 μm Be target

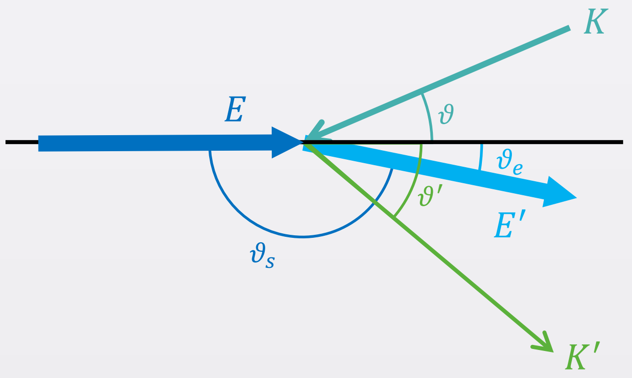


$\sigma_{x'} = 6$ mrad
$\sigma_x = 1.5$ mm

$\sigma_{y'} = 7$ mrad
$\sigma_y = 0.06$ mm

Other ideas: inverse Compton scattering

- *Suggested independently by B. Wojtsekhowsky and A. Variola*



$$K' = \frac{K\,(1+\beta\cos\vartheta)}{1-\beta\cos\vartheta' + \frac{K}{\gamma mc^2}(1-\cos\vartheta_s)}$$

For large γ and small ϑ': $K' = \frac{2\gamma^2 K(1+\beta\cos\vartheta)}{1+\gamma^2\vartheta'^2}$

For **head-on collisions**, $\vartheta \cong 0$: $K' \cong \frac{4\gamma^2 K}{1+\gamma^2\vartheta'^2} \approx K_{max}\left(1-\gamma^2\vartheta'^2\right)$

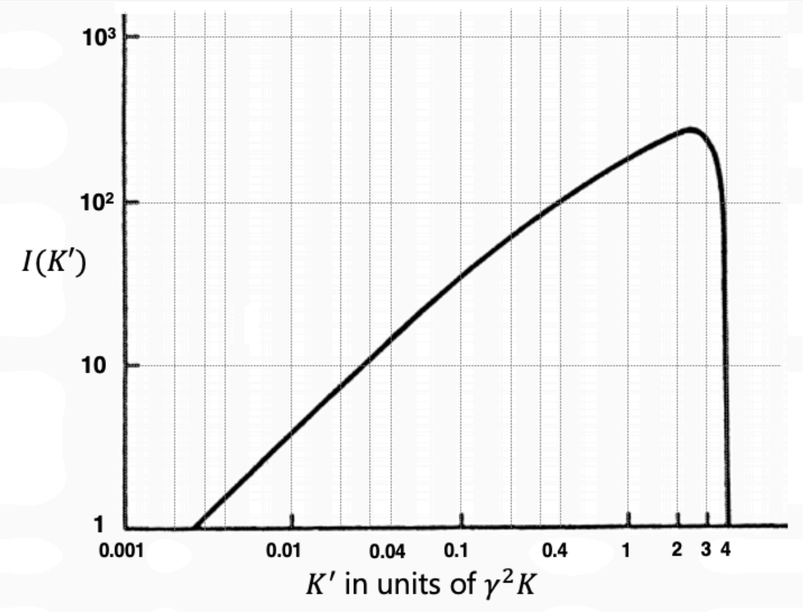
$$K'_{max} \approx 4\gamma^2 K$$

Electron energy difference: $E' - E \cong K - K'$

E =510 MeV, γ =10^3

Excluding very large angles: $K' \gg K$ and $E' - E \approx -K'$

- Green laser: λ = 532 nm, K = 2.33 eV, $K'_{max}/E \approx$ 9.28 MeV/510 MeV = 1.8%
  - At thermal equilibrium this translates into a spread of ≈**8%**
- With a fiber laser at λ = 1021 nm, the spread should still be ≈**5.7%**



A. Variola

Summary: extraction mechanisms

In general:

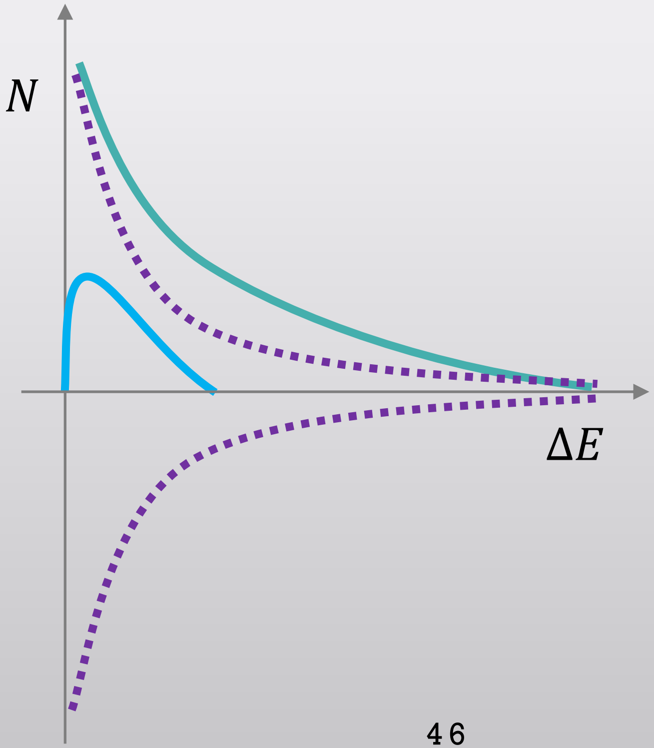
- Positrons **lose** (or even gain, in case of elastic collisions) **some energy**
  - Either due to the interaction with a “target” (residual gas, solid target, IBS)
  - Or continuously due to **radiation emission**
- Momentum change reflects in changing orbit **and** betatron oscillations amplitude: $x = \frac{\Delta p}{p}\left(|D| + \sqrt{H\beta}\right)$, as **RF** is kept **off**
- Horizontal offset is such to reach an extraction device providing an **angular kick** (crystal or electrostatic septum or magnetic septum)

Inverse Compton: $\Delta E \cong K'$

Bremsstrahlung: $\Delta E \cong \frac{1}{E}$

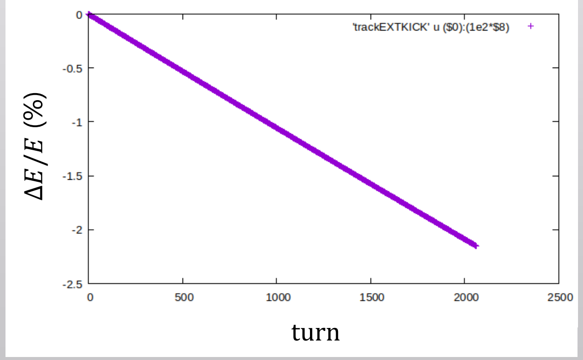
Touschek: $\Delta E \cong \pm E^{-a}$

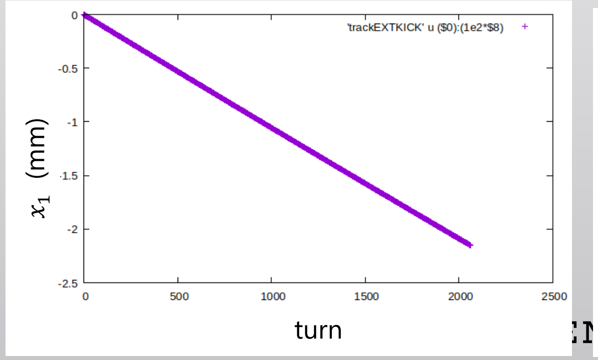
[Synchrotron: $\Delta E = c * t$]

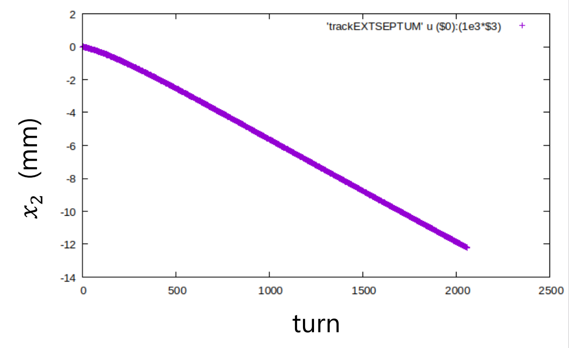


O. Blanco

Accumulator
large β optics







Summary: more interesting options

Too many options can be confusing, but **my personal bottom line** is:

- The **resonant extraction** from the positron **main ring** seems to yield the best parameters, using a practically standard technique (at least for hadrons)
- The system can be improved replacing the electrostatic septum with a **bent crystal**
- Being the “monochromatic” method (governed only by the synchrotron loss) the baseline, adding a white noise to the RF could provide a practical handle for **controlling the extraction time** in order to optimize **spill uniformity**. This is essential in order to go to “single particle” mode.
- Since not negligible changes to the machine layout are required (direct injection, adding the septa and the extraction line), **using the accumulator** could be considered a simpler solution that can be also considered a **preliminary stage**
  - <u>both</u> for **studying** the different options and possible variants to the basic scheme
  - <u>and</u> for **performing** a significant experiment in a **shorter time** (practically no layout modification is necessary) and in a much **simpler** and **cheaper** to run ring

  The performance will be worse wrt to the extraction from the main ring, **but still interesting** (not worse than 1 order of magnitude, most likely a factor 2-4 in terms of pulse length)
- Among other **completely different methods** I like the idea of Inverse Compton Scattering: this can be a viable option in case of a wider interest, for instance in synergy with the development of a ICS photon source

Summary table

As underlined many times: I've just put together estimates **at the present stage** of the studies, often very preliminary.

However – even with large uncertainties – this can already give an insight on what can be [reasonably] done at LNF

Accelerator	Beam-line	Upgrades	Time scale	Pulse length	Maximum energy	Positrons on target/year(1)	Electrons on target/year(2)
LINAC	BTF-1	None	Now	300 ns	490 MeV e+	$3{\cdot}10^4{\times}49{\times}10^7=\mathbf{1.5{\cdot}10^{13}}$	
					650 MeV e-		$3{\cdot}10^{10}{\times}3{\cdot}10^7=\mathbf{0.9{\cdot}10^{18}}$
		De-tuned SLED's	2 years	2 μs	300 MeV e+	$2{\cdot}10^5{\times}49{\times}10^7=\mathbf{10^{14}}$	
		LLRF modulation	2 years	800 ns	400 MeV e+	$8{\cdot}10^4{\times}49{\times}10^7=\mathbf{4{\cdot}10^{13}}$	
	LINAC dump	Biological shielding	4 years	300 ns	650 MeV e-		$10^{11}{\times}49{\times}10^7=\mathbf{0.5{\cdot}10^{20}}$
	"sala accumulatore"	Dismantle damping ring	4 years				
LINAC + main ring(3)	POSEYDON	ES septum [or crystal]+ M septum + extraction line	3 years [4 years]	0.42 ms	510 MeV e+	$4.2{\cdot}10^7{\times}49{\times}10^7=\mathbf{2{\cdot}10^{16}}$	
				2 ms	300 MeV e+	$2{\cdot}10^8{\times}49{\times}10^7=\mathbf{10^{17}}$	
LINAC + accumulator	tbd	extraction line? [+ crystal]	3 years [4 years]	60 (120) μs	510 MeV e+	$6{\cdot}10^6{\times}49{\times}10^7=\mathbf{3\ (6){\cdot}10^{15}}$	
				0.3 (0.6) ms	300 MeV e+	$3{\cdot}10^7{\times}49{\times}10^7=\mathbf{1.5\ (3){\cdot}10^{16}}$	

(1) Assuming $\mathbf{10^2}$ **particles/ns**.
Divide by 10^3 to get «single particle» or **1 particle/10 ns**

(2) Limited by radio-protection authorization

(3) Wigglers off

Summary: which way to go

There are [often] different ways to reach a given goal, but not necessarily an absolutely “best choice”, since each path can be:

- the easiest
- the quickest
- the cheaper
- the most enjoyable
- …

Which is the best option very much depends on the boundary conditions, like priorities and resources

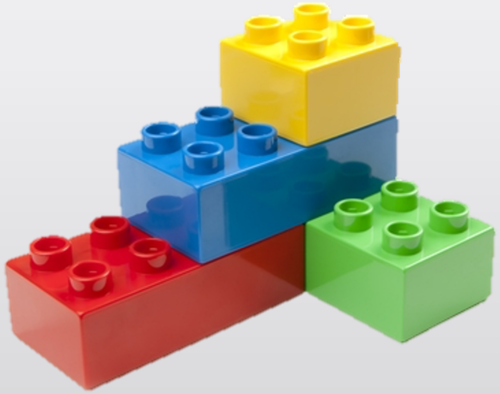
Closing remarks: size of the project and timing

I have followed a **general rationale**:

- **Re-use** and exploit the **existing infrastructure**, with limited modifications or upgrades only

Based on a few **simple but fundamental assumptions**:

- The DAΦNE complex – or a part of it – will **be operational** at least in the **next 5 years**
- There will be **access to the machine** for testing (before), installation and commissioning (after) and finally for performing the experiment
- A **medium-term time scale** for the design first, and then for the realization of the project, in parallel to the necessary adaptation of the PADME setup, will be foreseen in the **general planning** of Lab activities
- There will be **sufficient**, although **small-medium-sized** financial, human and operation **resources**
  [small-medium meaning: running only for a fraction of the year, using only part of the complex, keeping wigglers off, re-using existing components, avoiding big infrastructural work, etc.]



Closing remarks: accelerator availability

The PADME physics potential was originally estimated on the goal of **4×10^{13} pot** [positrons-on-target] in **2 years** with a 60% overall efficiency: 2* [2×10^{4} pot *50 Hz *2×10^{7} s]

- A **minimal** benchmark statistics was then agreed at **1×10^{13} pot**
- We have collected **5×10^{12} pot** with primary positrons i.e. $\approx$**1/2 of the minimal benchmark** and **1/8 of the original target**, accumulated in three different periods [commissioning and physics data-taking]
- Overall running with dedicated beam of $\approx$6 months from Nov. 2018 to Dec. 2020, corresponding to an **overall duty-cycle of $\approx$1/4**
- According to the present planning, **no dedicated period will be available in 2021**, bringing the dedicated beam availability (all-included) to $\approx$**1/6**

- This is due **not only** to the incompatibilities with other planned scientific activities [like SIDDHARTA-2, BTF users, irradiation, etc.], **but also** with the unavoidable down-time for maintenance, radio-protection checks [or improvements, like the BTF upgrade]
- In conclusion, a limited availability – well below 50% – of the accelerator complex [especially the common infrastructures like the LINAC] has to be considered, impacting **not only the operation** [data-taking], but also the time needed for **tests** and **machine modifications**

Closing remarks: scheduling

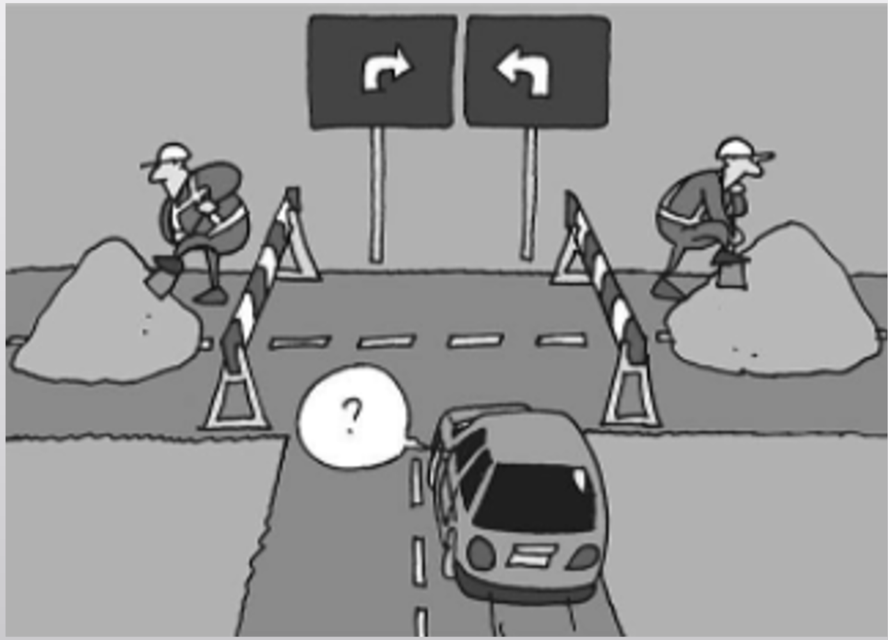
Some consideration on basis of the two projects [relevant in this context] which I had direct experience with:

- The **BTF upgrade** was originally planned on a 3 years schedule:
  - CDR Mar. 2016 [**arXiv:1603.05651**]; Cash flow started Apr. 2017; final installation currently planned in Spring 2021

  [all components constructed and delivered; Infrastructure (building, cooling, conditioning, shielding, etc.) almost complete]
- The **PADME construction and installation** was planned on a 2 years schedule:
  - Technical Proposal, Sep. 2015; Cash flow started Feb. 2016; Official inauguration Oct. 4th 2018

Even in a small-medium project **unavoidable issues** arise, especially when working on an accelerator infrastructure

- Strong interplay of **several** (if not **all**) technical services of the accelerator division as well as the technical [and sometimes research] one, and the other key-roles of the Lab like RP and the safety officers
  - Without a proper general planning there will be **conflict** with other activities
- Small and big **incidents do happen** (like the Be window failure)
  - Delays and conflicts can be produced even with a reasonable general plan **and** provided all necessary personnel and resources
- A not negligible role also played by the **overhead due to administrative issues**



Closing remarks: how to go on

It would be very important to bring preliminary studies **at least for the main options** at a **reasonably advanced level***
in a **reasonably short time****

*Detailed enough for 1. confirming the main beam parameters [the ones in the table: essentially, the achievable pulse length and intensity] and 2. having a more precise estimate of the needed time and resources

In my opinion PADME needs to know – before the end of 2021 – what are the perspectives, **if any, for making relevant physics in next few years

Practically, this requires to:

1. **Support existing efforts** like SHERPA and **start** [or resume] work on [some of] the other options
2. **Share existing knowledge** on the machine: past experience, ideas, tests, etc.
3. **Plan** a few but significant **tests on the machine** (LINAC, accumulator, main ring) in order to check calculations and simulations and validate solutions
4. **Provide** all necessary **technical details**, e.g. on radio-protection issues, services, machine components, etc.

Then, once (**if ever**) a positive decision has been taken:

5. **Execute the project** in an appropriate time, provided a proper planning and adequate resources