Proposta per l'uso di DAFNE come allungatore d'impulso per il fascio di positroni del Linac

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29 novembre 2017

The PADME experiment at BTF

- The **PADME** experiment proposes a search for the dark photon (A') in the $e^+e^- \rightarrow \gamma A'$ process in a positron-on-target experiment
- Positrons are produced by the high energy e^- beam impinging on the BTF target with gun in "long pulse" configuration
- The beam requirements for PADME are
  - Longest possible beam pulse, in order to keep the pile-up probability in the calorimeter as low as possible
  - Beam spot < 1mm, max angle < 1 mrad
  - Momentum spread < 1%
- The characteristics of the BTF beam are listed in the table

Energy (MeV)	550
Number of positrons per pulse	$2\ 10^4$ - 10^5
Pulse length (ns)	40 – 200
Repetition frequency (Hz)	49

M. Raggi et al., EPJ Web Conf. 96 (2015) 01025

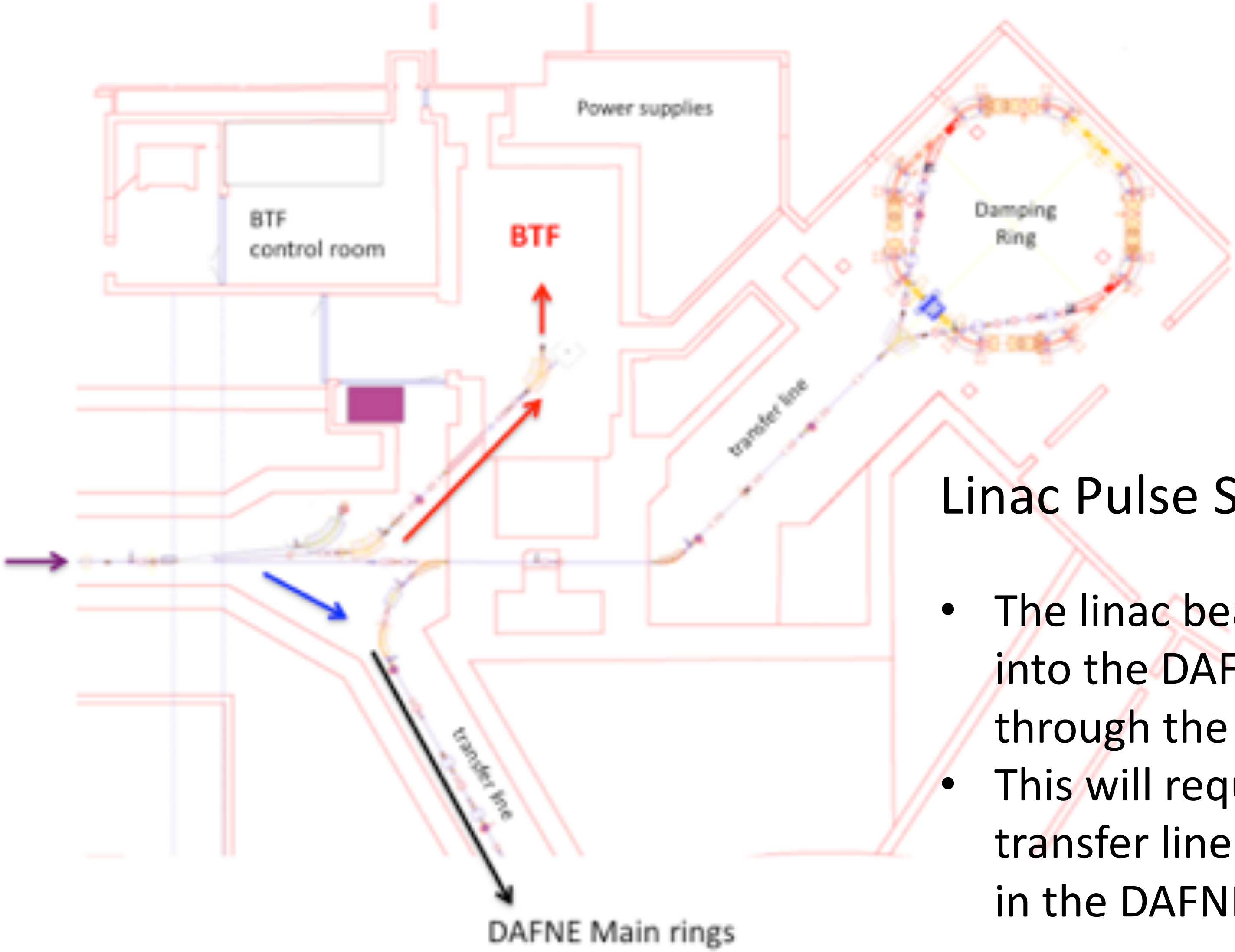
A positron beam for PADME

- Using the positron converter the linac could provide a number of positrons as high as 10^9/pulse in a 200 ns long pulse
- For PADME the number of positrons is limited below 10^5/pulse in order to keep the pile-up probability in the calorimeter low enough
- The low duty-factor (10e-5 = 200ns/20ms) is the major limitation for the PADME experiment at BTF
- By injecting the beam in the DAFNE positron ring and by spilling it with a slow resonant extraction a duty factor (~2% = 0.4/20 ms) nearly a factor 1000 larger can be achieved
- After the end of the Siddharta run it can be envisaged to use the DAFNE ring as a linac pulse stretcher to distribute the positrons of a single linac pulse in a much longer pulse
- All the following considerations are based on the work done at LNF for the ALFA proposal:

S. Guiducci, G. Martinelli, M. Preger, LNF-78/22(R), 22 maggio 1978

and IEEE Trans. On Nucl. Sci., Vol. NS-26, No.3, June 1979

Layout of the DAFNE injection system

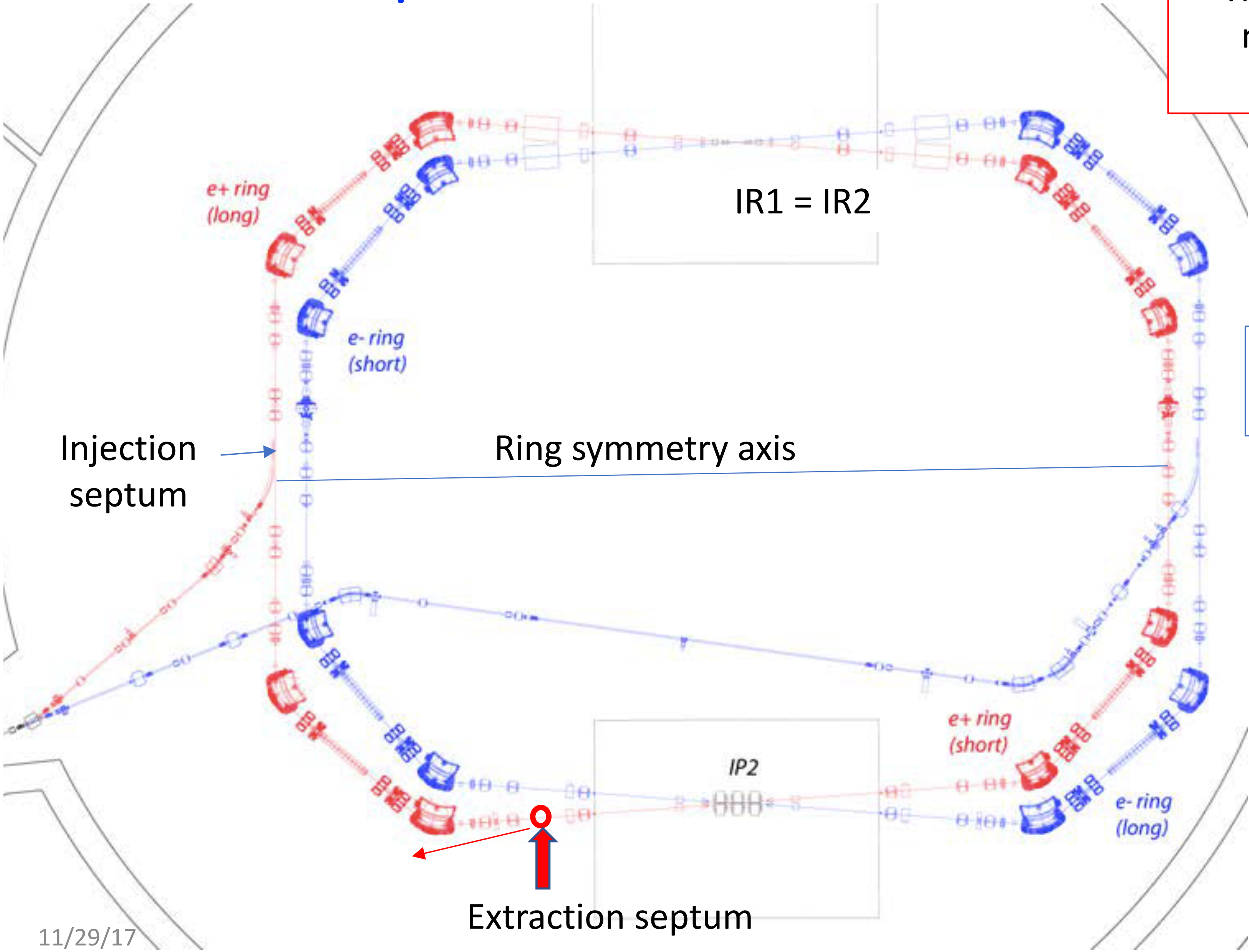


Linac Pulse Stretcher configuration

- The linac beam will be injected directly into the DAFNE ring without passing through the accumulator
- This will require a modification of the transfer line to bend the beam directly in the DAFNE hall (as it was for ADONE)

DAFNE Layout with the positron injection and extraction septa

The positron ring is made symmetric
With IR1 = IR2

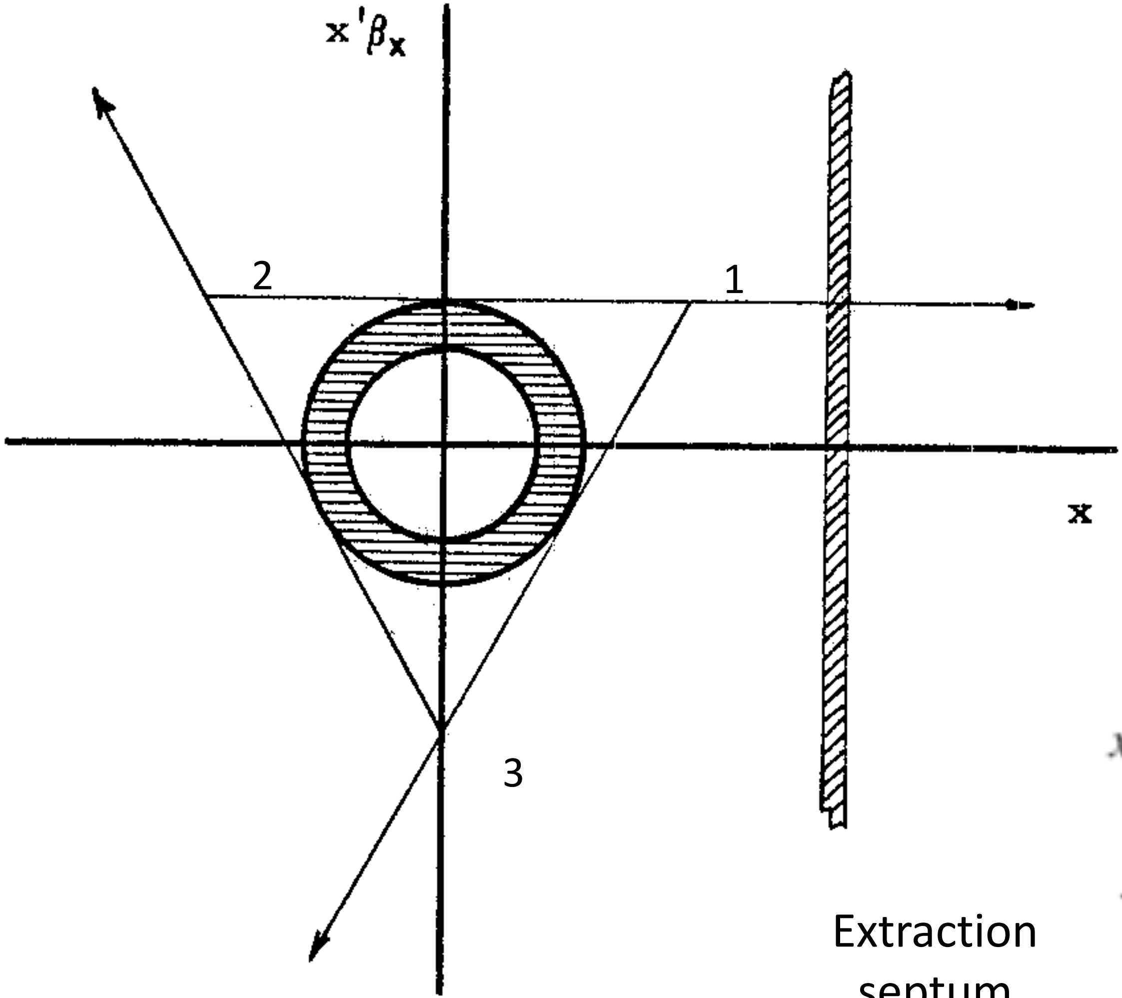


The extraction septum is in IR2

Resonant Extraction

- With a value of the betatron tune near to the 1/3rd resonance and a proper setup of sextupoles the stability region in the horizontal phase space (x, x’) is delimited by a triangle
- The particles outside the borders of the triangle become unstable and move outward along three lines, which are the continuation of the triangle’s sides.
- After injecting the beam inside the triangle it is possible to extract all the particles in a given time by reducing the size of the triangle by moving the betatron tune toward the resonance
- we will adopt a monochromatic extraction: the chromaticity will be adjusted in such a way that as far as the particles lose energy by synchrotron radiation their tune gets closer to the resonance and they are extracted

Schematic layout of the beam horizontal phase space at the extraction septum



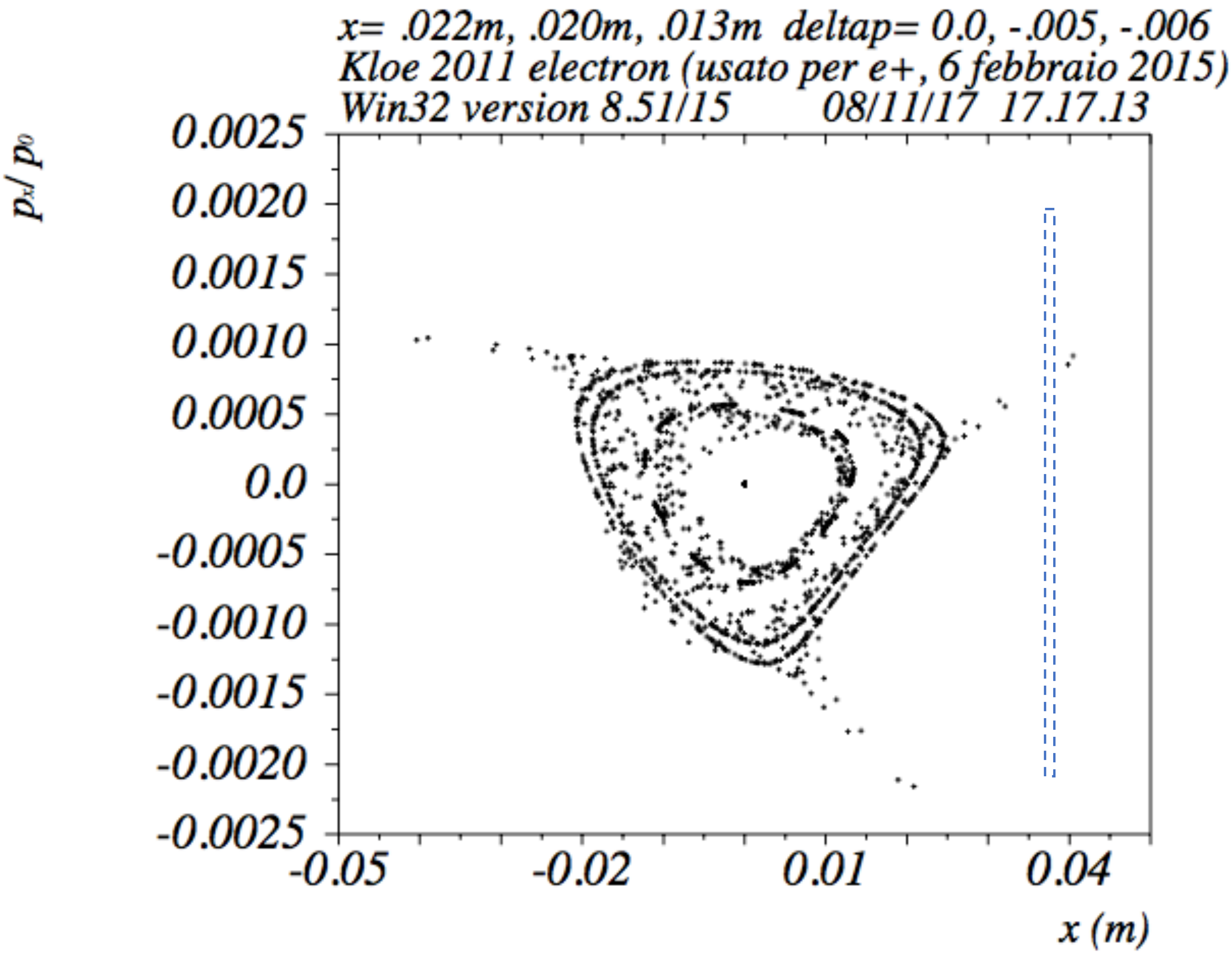
Extraction septum

- The injected beam has a hollow shape
- Particles outside the stability triangle start moving on the extraction directions and the jump Dx between two successive passages increases going outward
- The coordinates of the triangle's vertices are:

$$x_{o1,2} = \pm\rho\sqrt{\frac{\beta_x^{ext}}{R}}\frac{\Delta\nu}{2\sqrt{3}H_{33}} \qquad x_{o3} = 0$$

$$x'_{o1,2} = \pm\rho\sqrt{\frac{1}{\beta_x^{ext}R}}\frac{\Delta\nu}{6H_{33}} \qquad x'_{o3} = \pm\rho\sqrt{\frac{1}{\beta_x^{ext}R}}\frac{\Delta\nu}{3H_{33}}$$

Phase space plot from tracking



Some Comments

- Analytic expressions to evaluate the extraction time and the extracted beam parameters (emittance and energy spread) are reported in LNF-78/22(R)
- These formulae assume that the m/3 is the only resonant term driving the particle trajectories and are valid for a symmetric lattice with the extraction septum placed in the symmetry point
- They have been used to give a preliminary estimate of the extraction parameters
- To achieve a more precise estimate of the extracted beam parameters a study based on particle tracking is needed

- K. R. Symon, Extraction at a third integral resonance, Reports FN 130, FN 134, FN 140, FN 144, Fermilab (1968).
- G. Gendreau, J. L. Laclare and G. Leleux, Dynamics of chromatic particles in the resonant extraction, SOC/ALIS 22, Saclay (1969).

Extracted beam area in the horizontal phase space W_r

$$W_r = \frac{\Delta x \cdot \Delta x'}{4}$$

$$\Delta x = \frac{X_s^2 - X_o^2}{X_o / \tanh(3\sqrt{3}\pi\Delta\nu) - X_s} \qquad \Delta x' = \frac{\sqrt{W_M} - \sqrt{W_m}}{\sqrt{\beta_x^{ext}}}$$

- Where X_0 is the vertex nearest to the septum
- X_s is the position of the extraction septum
- $\Delta\nu$ is the distance from the resonance
- W_M and W_m are the maximum and minimum Courant-Snyder invariants of the injected beam
- β_x^{ext} is the betatron function at the extraction septum

Extraction parameters

$$x_{o1,2} = \pm\rho\sqrt{\frac{\beta_x^{ext}}{R}}\frac{\Delta\nu}{2\sqrt{3}H_{33}}$$

- Dv/H33 is calculated from W_M to have the triangle tangent to the external contour of the injected beam

$$\Delta\nu/H_{33} = 6\sqrt{R}/\rho\sqrt{W_M}$$

- $\Delta\nu$ gives the value of the jump Δx
- The choice of the "jump" Δx is a compromise between the extraction efficiency and the extracted beam Emittance
- The extraction loss is nearly the ratio between the extraction septum thickness and the jump
- Using an electrostatic septum with a thickness of 100 microns and a jump of 5 mm an efficiency of about 98% can be achieved.

Extraction parameters

- Due to chromaticity the betatron tune varies with the energy and as long as the particles lose energy by synchrotron radiation their distance from the resonance Δν decreases, the triangle shrinks and they are extracted
- When the energy loss is equal to $(DE/E)_L$ all the particles on the external ellipse are extracted
- To extract the particles with smaller emittances it is needed to loose more energy, which gives the energy spread of the extracted beam $(DE/E)_{ex}$ and the extraction time T_e

$$(DE/E)_{ex} = 12\frac{\sqrt{R}}{\rho}H_{33}\frac{\sqrt{W_x}}{C_x}$$

$$T_e = \frac{2\pi R\rho}{KE^3}\left((DE/E)_L + (DE/E)_{ex}\right)$$

Injection and Extraction parameters

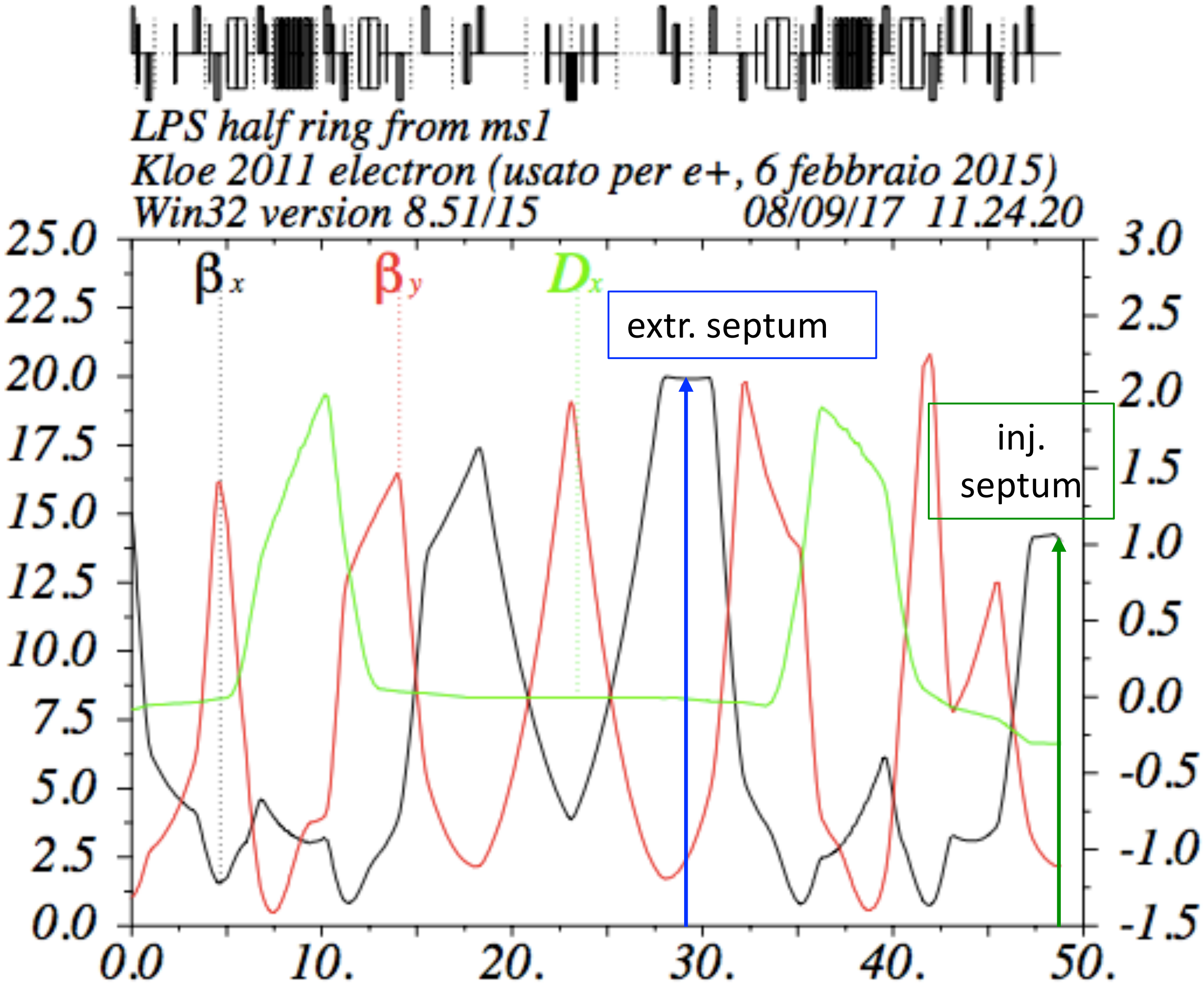
Table 2 - Linac beam parameters	
N^+/pulse	5.00E+07
Repetition frequency (Hz)	50
Pulse duration (ns)	150
E (GeV)	0.5
$(DE/E)_L$	0.01
Emittance W_x (m)	1.00E-06

Table 4 - Extraction parameters	
W_M (m)	4.00E-05
R (m)	15.5
ρ (m) wiggler OFF	1.4
$\Delta\nu/H_{33}(W_M)$	0.11
Xo (m)	4.90E-02
Xs (m)	6.00E-02
Δx (m)	5.00E-03
$\Delta\nu(W_M)$	0.010
C_x	-3
H_{33}	0.094
W_r (m)	**3.44E-06**
$(DE/E)_{ex}$	**1.06E-03**
T_e (s)	**4.56E-04**
W_m (m)	1.87E-05

DAFNE Lattice modifications

- The machine is symmetric with respect to the centers of the LONG and SHORT straight sections: the 2 IRs are both equal to IR2, with non intersecting beams
- For the moment the wigglers are on but a lattice with wigglers off will be designed soon
- Sextupoles are in the present position
- The injection septum is in the present position
- The extraction septum is in the IR2 straight section, between quadrupoles QUAPL201 and QUAPL202, in the external ring, in order to have space for the extraction line
- β_x at the extraction septum has to be the ring maximum, the function α_x and the dispersion function D_x need to be zero to minimize the emittance of the extracted beam.
- The horizontal tune has to be near the 1/3 resonance

Optical functions in half ring



TUNES OK
Qx = 4.30 , Qy = 4.27
Cx = -6.7 , Cy = -10.5

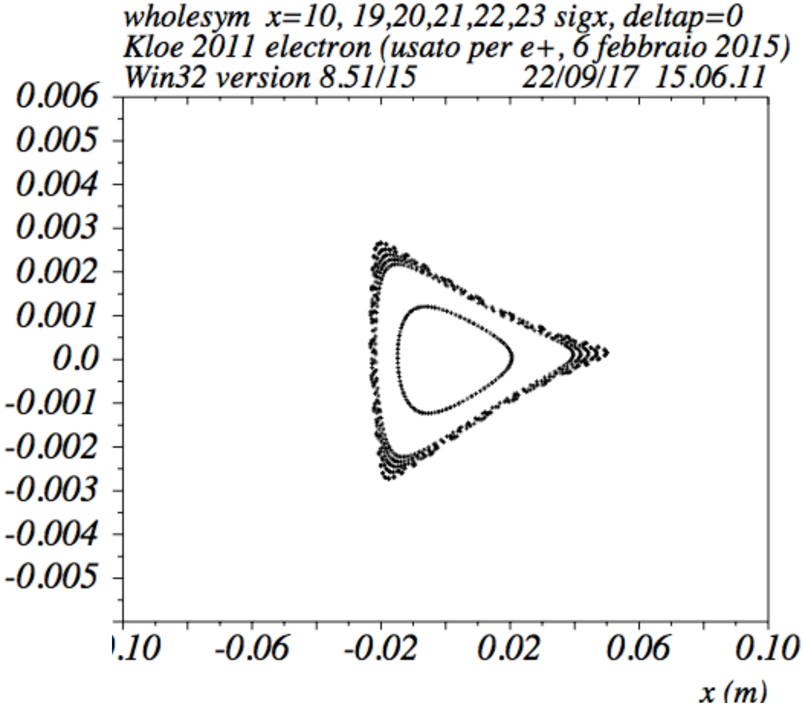
Al At extraction septum
betx = 20 m
alfx = 0.0
Dx = 0.0

At injection septum
betx = 15 m
alfx = 0.0
Dx = 0.25 m

The triangle at the symmetry points

The triangle at the extraction septum on IR2

SHORT



Cx = 0

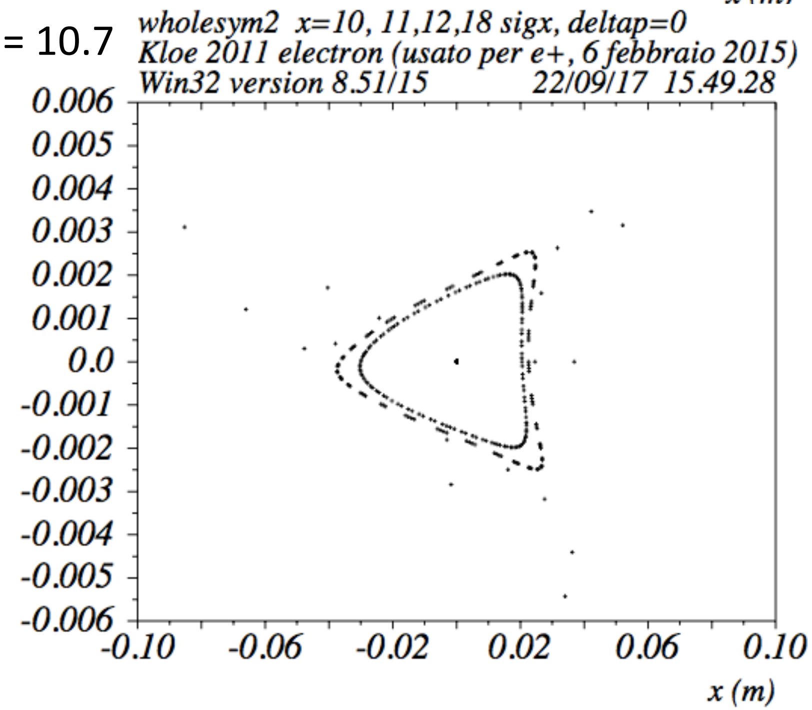
Cy = =-1.8

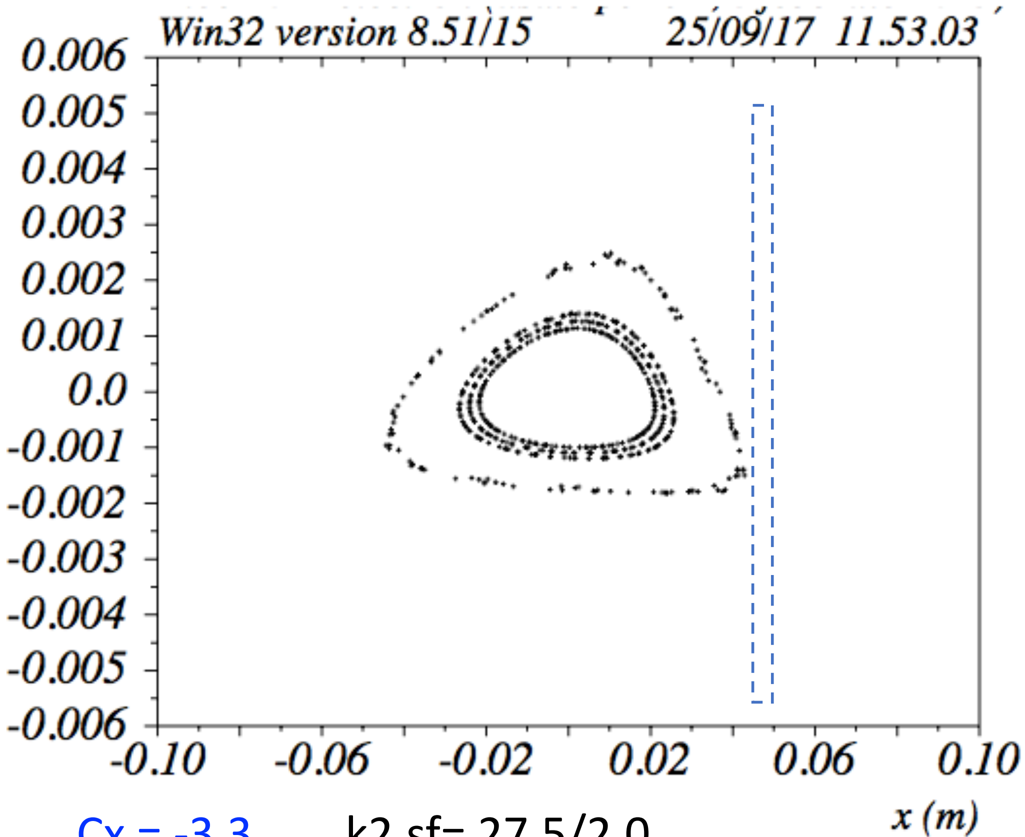
k2.sf= 27.5

k2.sd=-17.1

k2.SXTL204 = 10.7

LONG





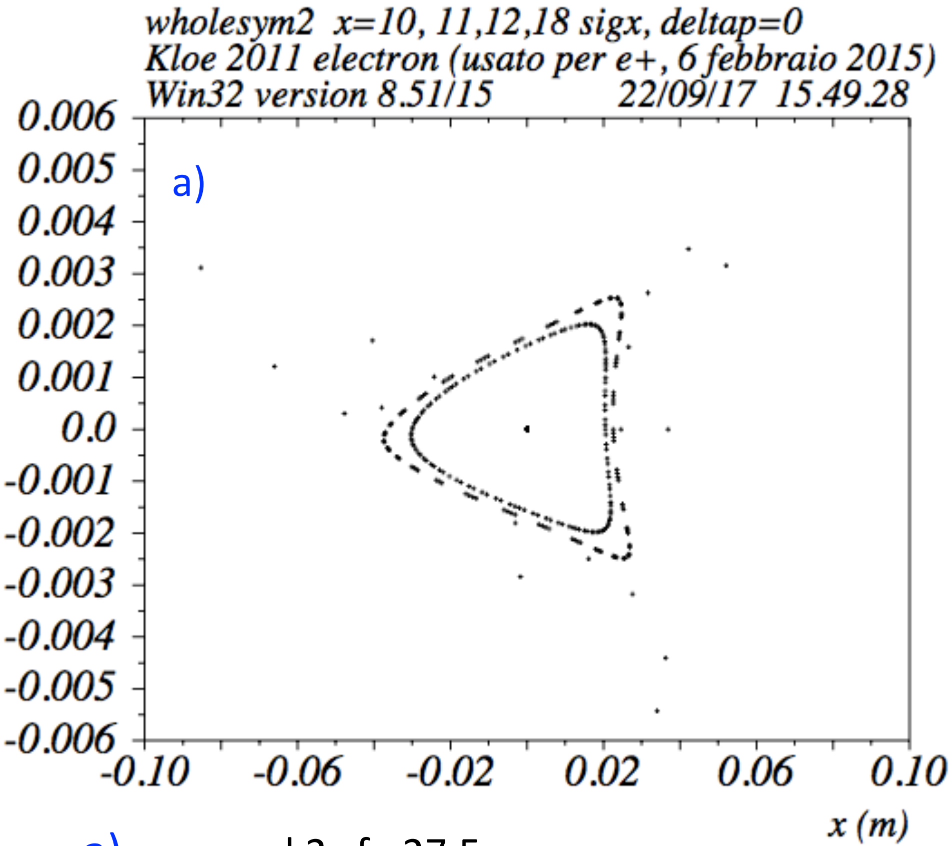
Cx = -3.3 k2.sf= 27.5/2.0

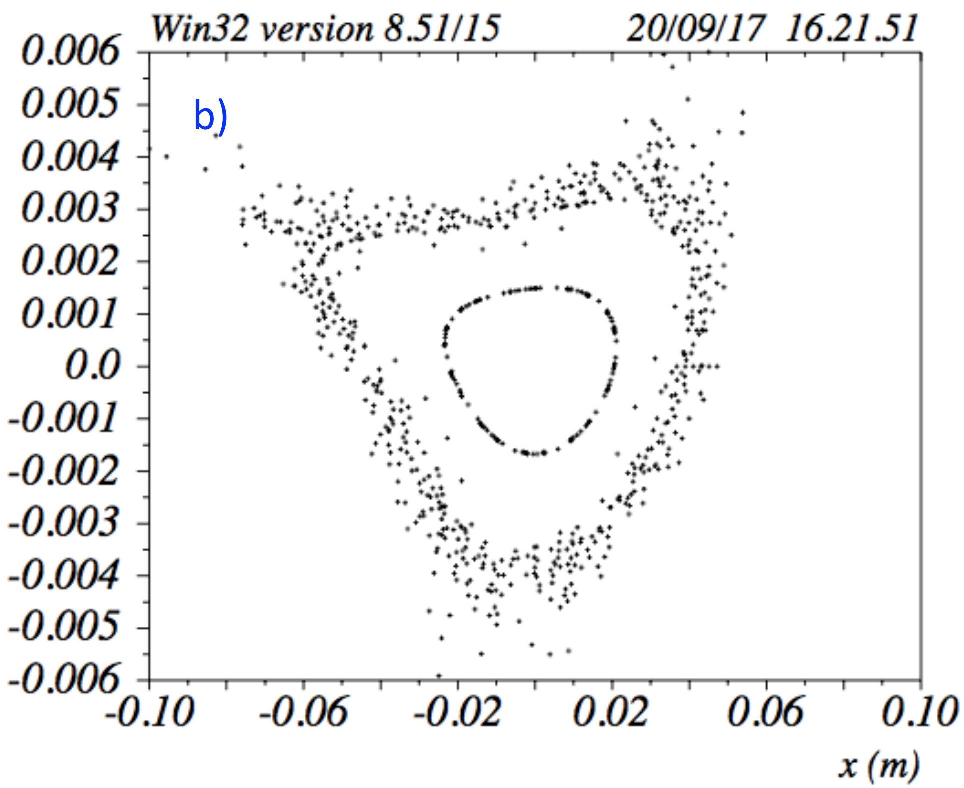
Cy = -6.3 k2.sd=-17.1/2.0

The vertex nearest to the septum has x'< 0

The triangle at the extraction septum has to be rotated

At the symmetry point





a)

k2.sf= 27.5
k2.sd=-17.1
k2.SXTL204 = 10.7

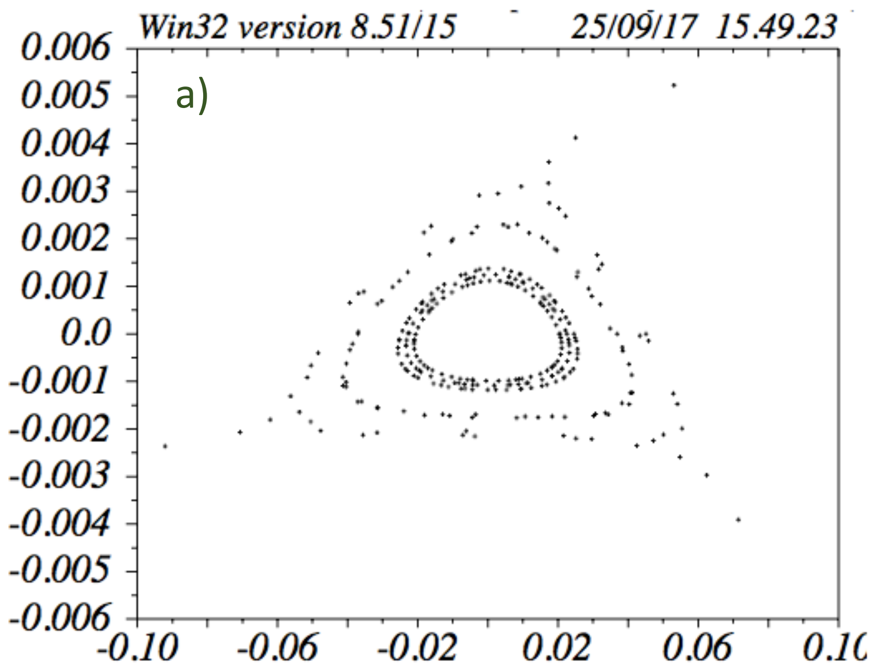
b)

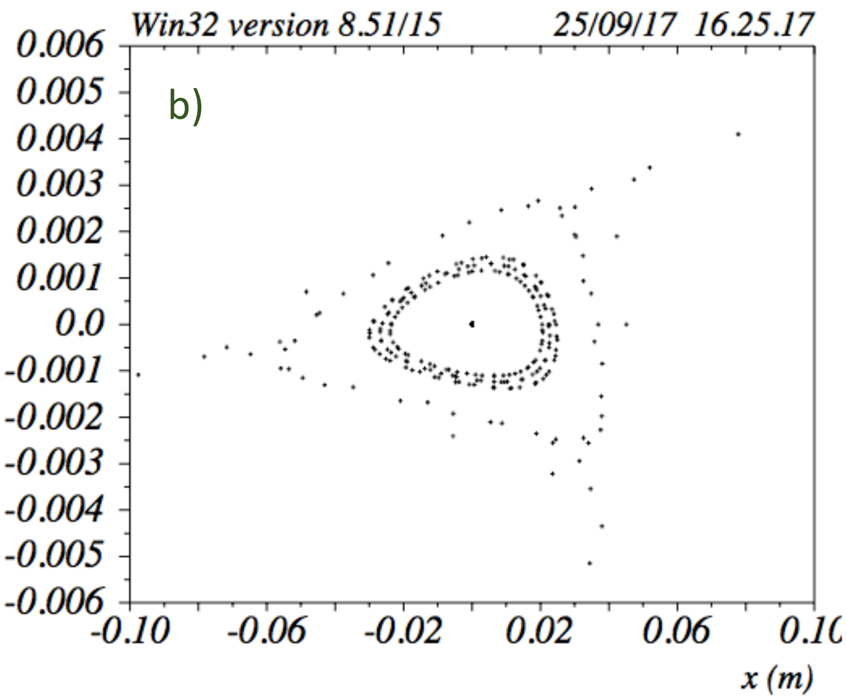
k2.sf= 27.5/2.0
k2.sd=-17.1/2.0
k2.SXTS101 = 55.1
k2.SXTS201 = 11.02
k2.SXTL101 = 55.1
k2.SXTL204 = 11.02

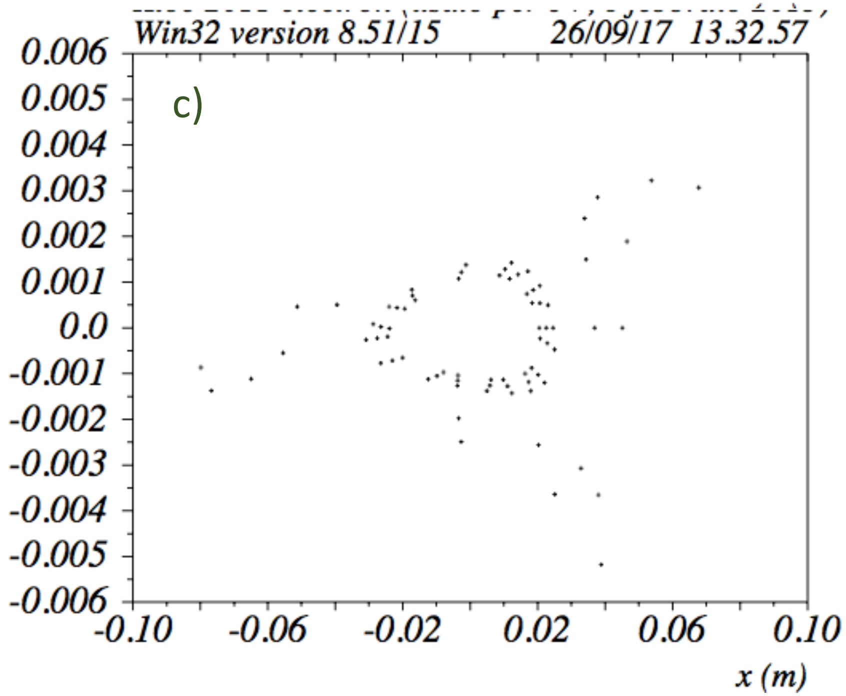
The sextupoles in the zero dispersion region are used to rotate the triangle
To get a ~30 gradi rotation strong sextupoles are needed and the stability region is deformated

At the septum the triangle can be rotated by only a few degrees

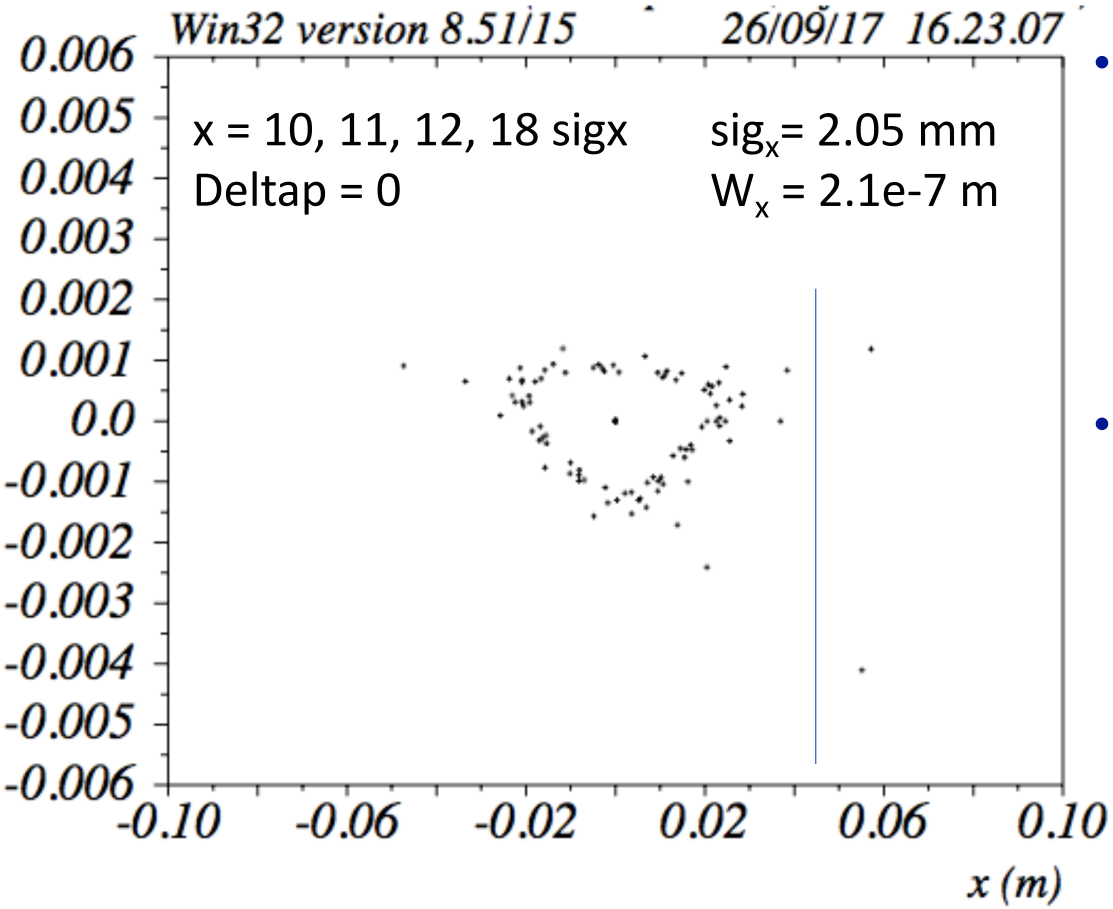
	a)	b)	c)
k2.sf	27.5/2	27.5/2	27.5/2
k2.sd	-17.1/2	-17.1/2	-17.1/2
k2.SXTS101	0	29.1	30.1
k2.SXTS201	36.1	29.1	44.6
k2.SXTL101	0	29.1	30.1
k2.SXTL204	0	29.1	-44.6







For Qx above 4.33 the triangle has the correct orientation at the extraction septum

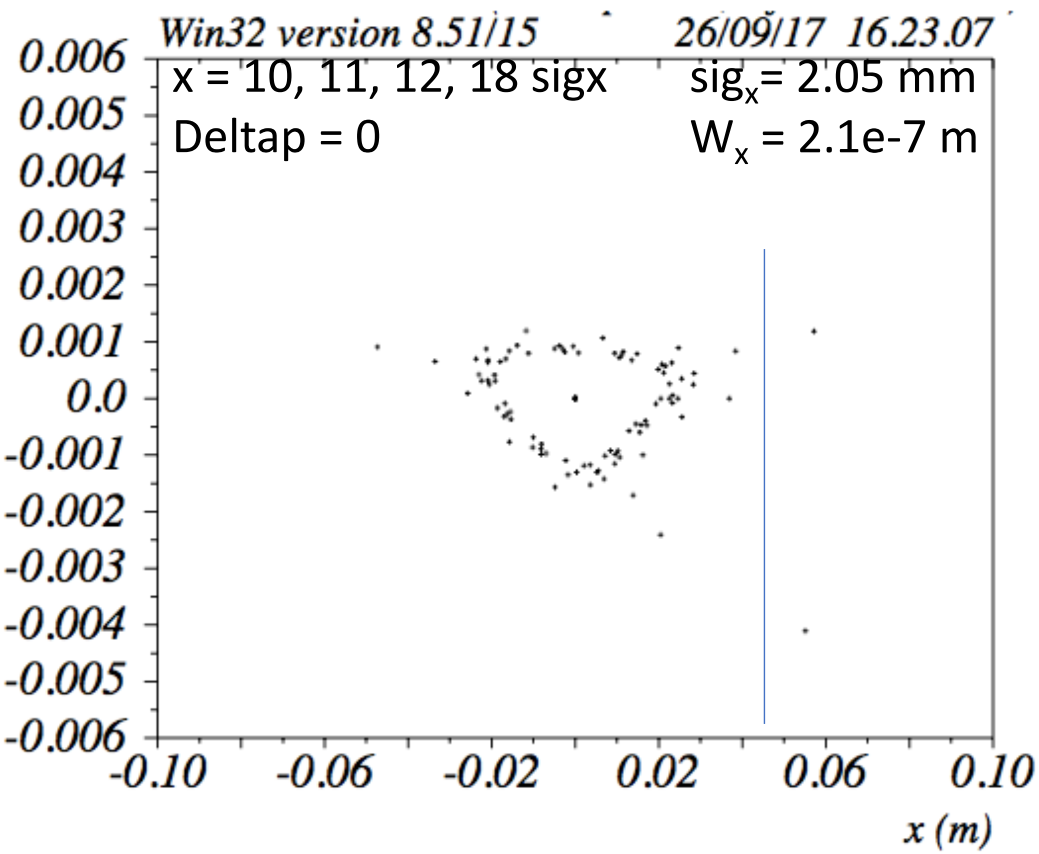


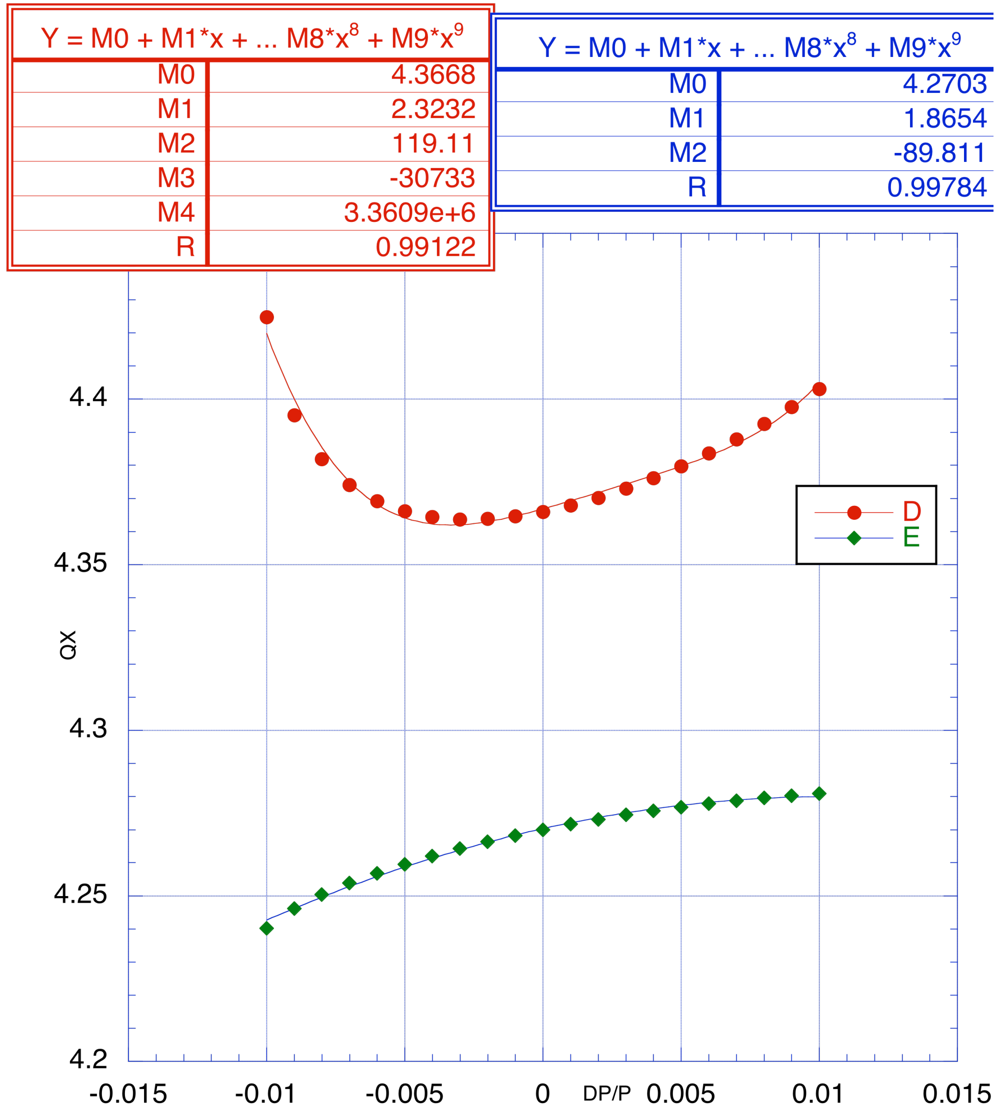
- To evaluate the extracted emittance, the percentage of particles lost on the extraction septum and the extraction time it is necessary to perform tracking along the ring, the analytical formulae are not accurate enough
- **Extraction Parameters**
  - tune distance from the resonance
  - chromaticity
  - strengths of the non chromatic sextupoles
  - size of the injected beam

But the chromaticity has to be positive and the sextupoles are higher

Tunes		Chromaticity		Chromaticity with chromatic sextupoles		
Qx =	4.366	Cx =	-6.7	Cx =	+3.42	k2.sf= 27.5*1.3
Qy =	4.270	Cy =	-9.8	Cy =	-0.58	k2.sf= 27.5*1.3

For Qx above 4.33 the triangle has the correct orientation at the extraction septum

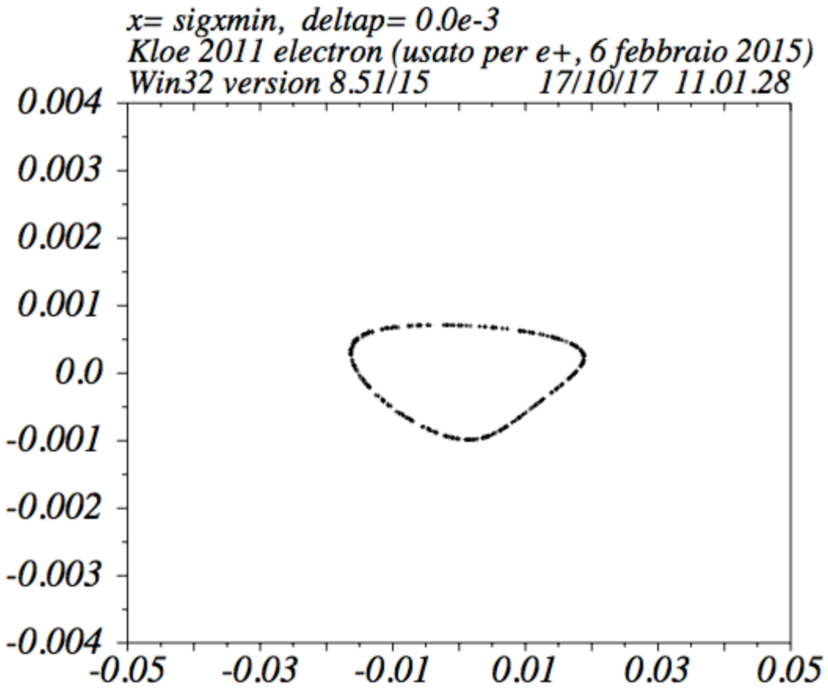


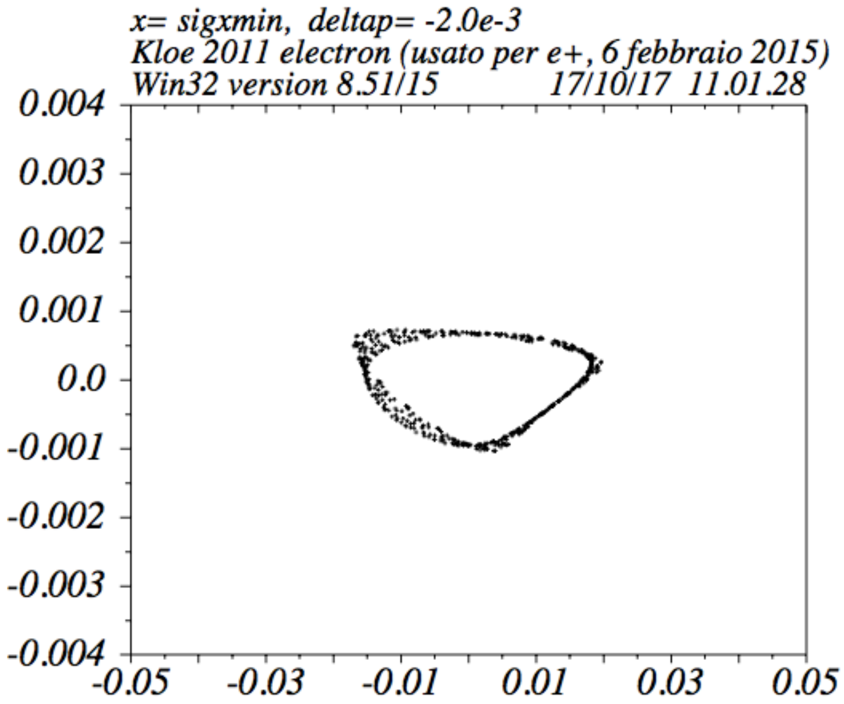


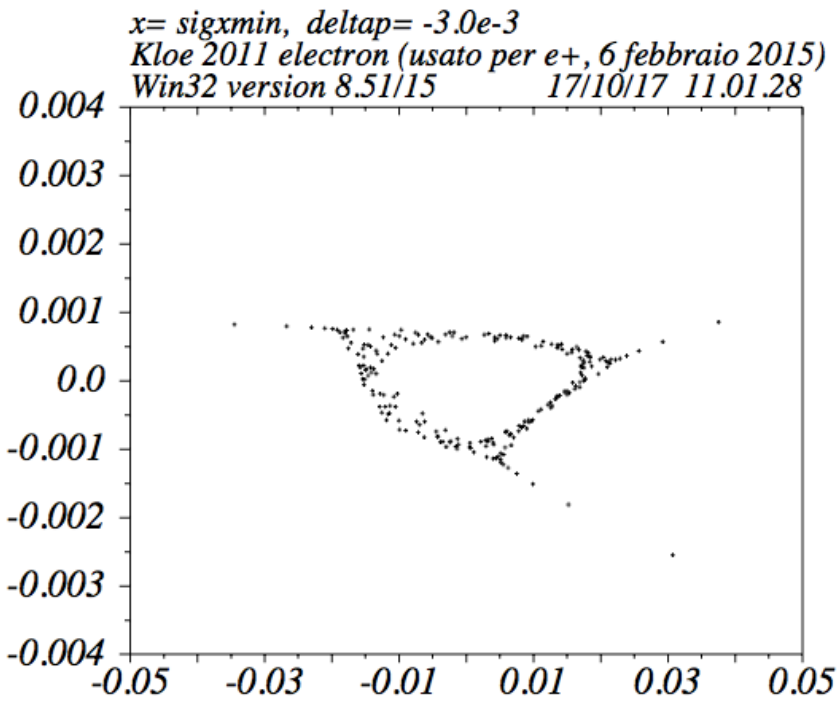
But the chromaticity has to be positive and the sextupoles are higher

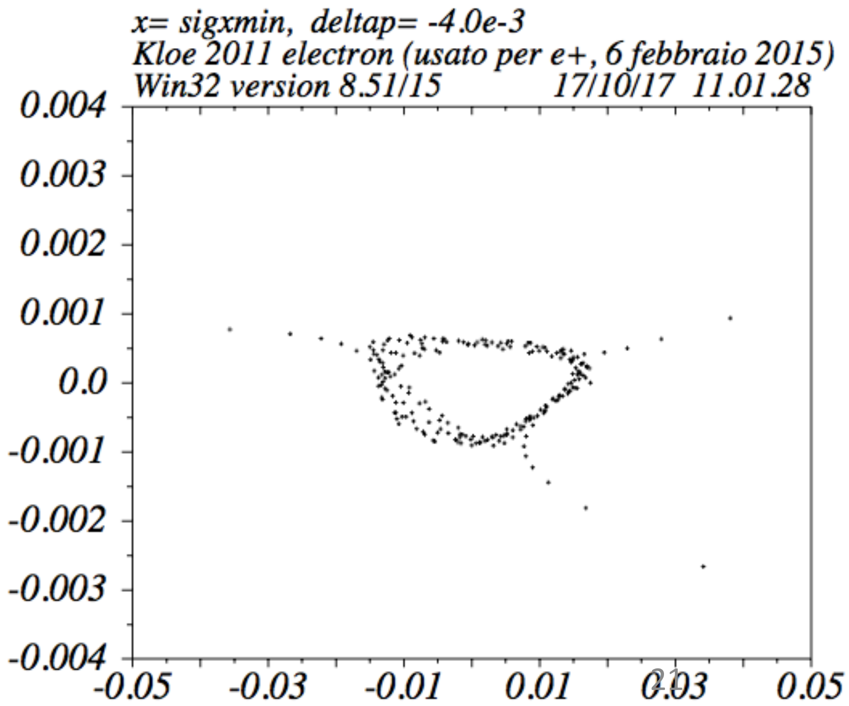
- The size of the stability region is smaller
- The chromaticity has a parabolic behaviuor

LPS_chrom4
k2.sf= 27.5*1.4
k2.sd=-17.1*0.7
k2.SXTS101 = 0.0









Dp/p	stab	extr			
0.004	0	1		WM =	2.88E-05
0.002	1	0		x0 =	0.024
0	1	0		fact*SF=	1.26
-0.002	0	1			

Dp/p	stab	extr			
0.005	0	1		WM =	2.45E-05
0.004	0	1		x0 =	0.022
0.002	1	0		fact*SF=	1.26
0	1	0			
-0.002	1	0		LPS_chrom1	
-0.004	1	0		mad 2.ps	
-0.005	0	1			

Dp/p	stab	extr			
0.005	0	1		WM =	1.96E-05
0.004	1	0		x0 =	0.020
0.002	1	0		fact*SF=	1.26
0	1	0			
-0.002	1	0		LPS_chrom1	
-0.004	1	0		mad 2.ps	
-0.005	1	0			
-0.006	0	1			
-0.007	1	0			

Dp/p	stab	extr			
0.005	1	0		WM =	1.75E-05
0.004	1	0		x0 =	0.019
0.002	1	0		fact*SF=	1.26
0	1	0			
-0.002	1	0		LPS_chrom1	
-0.004	1	0		mad 2.ps	
-0.005	1	0			
-0.006	1	0			
-0.007	1	0			
-0.008	1	0			
-0.009	1	0			

Sempre stabile!

Extraction energy for different oscillation amplitudes

Given an injected emittance W_x = 1e-6 m
The Maximum and minimum oscillation amplitudes at the extraction septum are

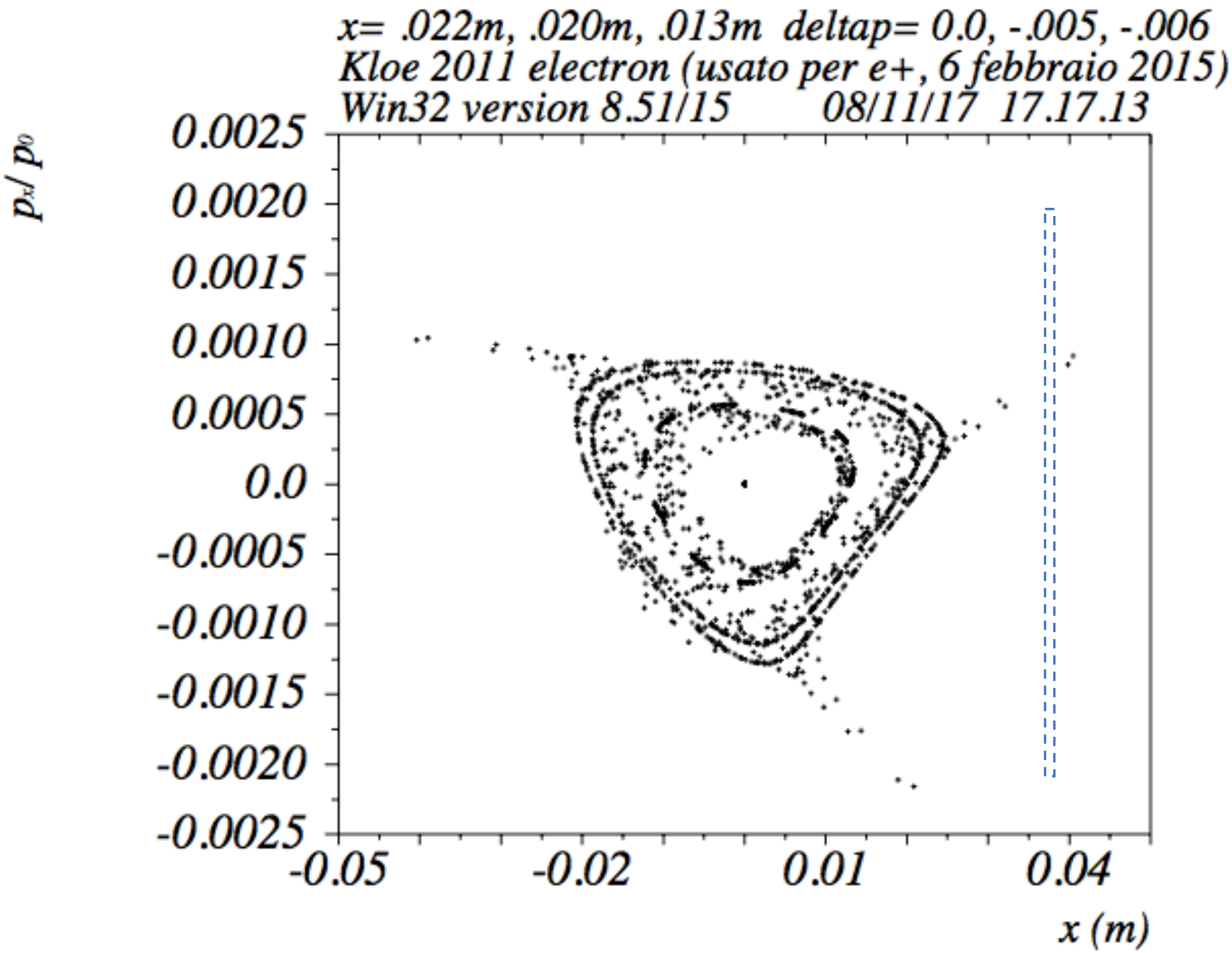
$$x_{0M} = .024 \text{ m}$$
$$X_{0m} = .015 \text{ m}$$

The range of amplitude and energies, which are extracted, is too small with respect to the extracted beam parameters

Possible solutions:

- Moving the extraction septum in the symmetric position in the ring, where it is possible to extract below resonance using a negative chromaticity and lower sextupoles
- Using the “RF knock-out” method

Phase space plot from tracking

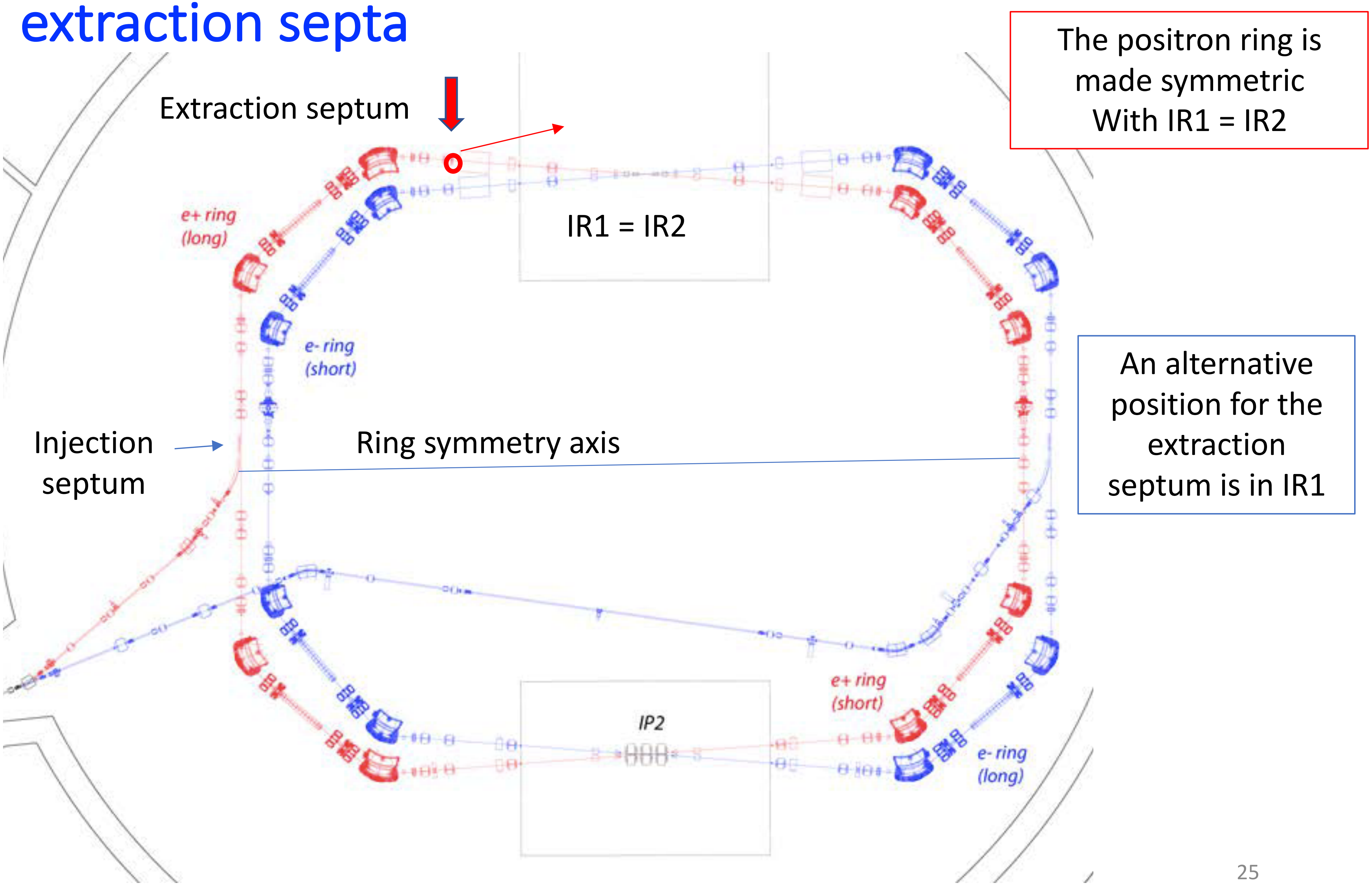


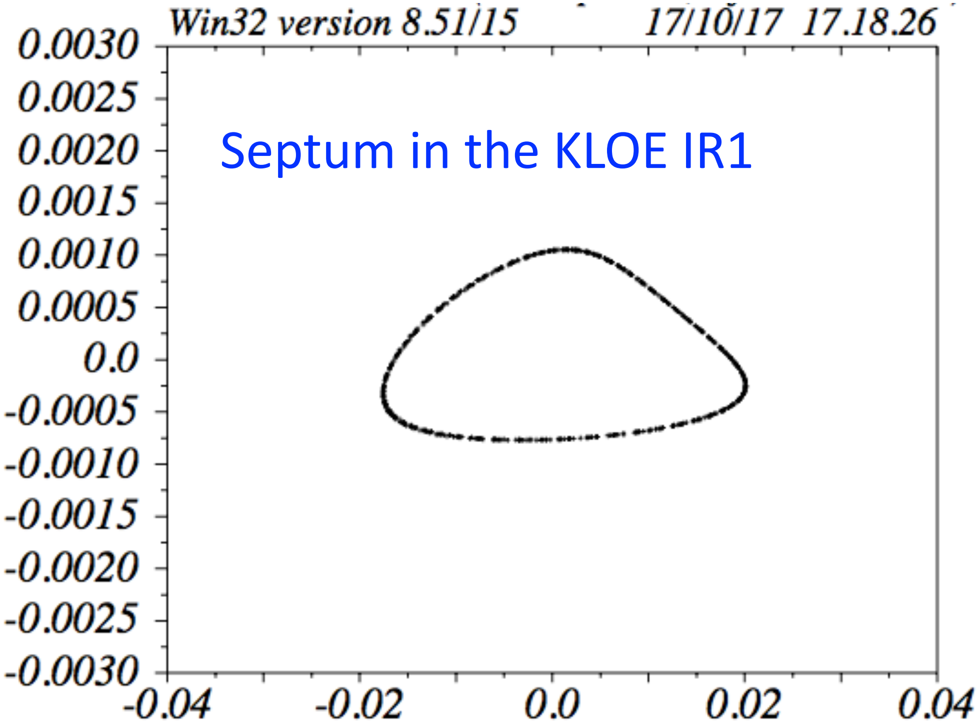
Extraction energy for different oscillation amplitudes

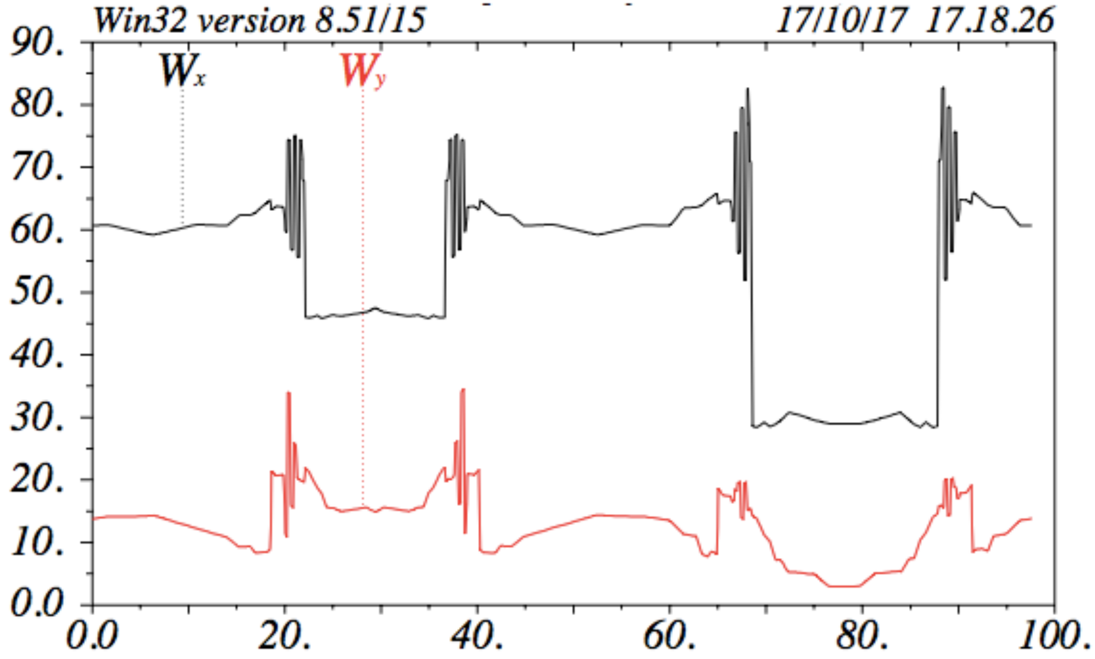
- The range of amplitude and energies, which are extracted, is too small with respect to the extracted beam parameters
- Possible solutions:

- Moving the extraction septum in the symmetric position in the ring (IR1)
  - The triangle has the correct orientation to extract below resonance
  - Extraction with negative chromaticity and lower sextupoles
  - Unfortunately in the IR1 there is little space available for the extraction line and the PADME detector
- Using different strengths for the SHORT and LONG chromatic sextupoles
  - We should get the correct triangle orientation in the IR2 section with betatron tune Q_x below resonance
  - The sextupole strengths could be larger with respect to the solution with septum in IR1
- Using the "**RF knock-out**" method

DAFNE Layout with the positron injection and extraction septa

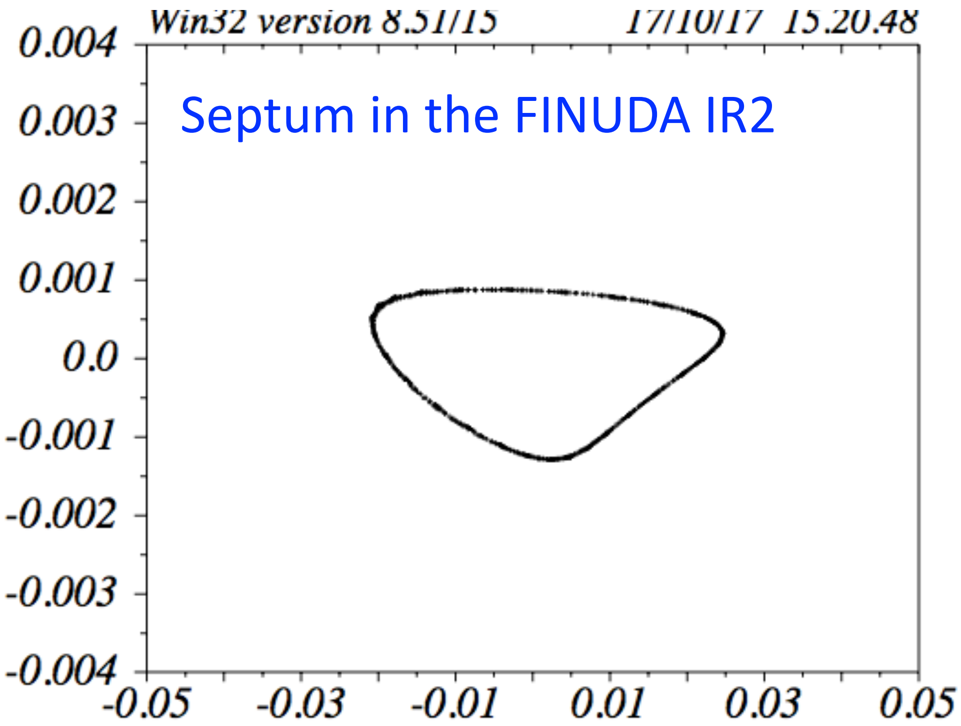


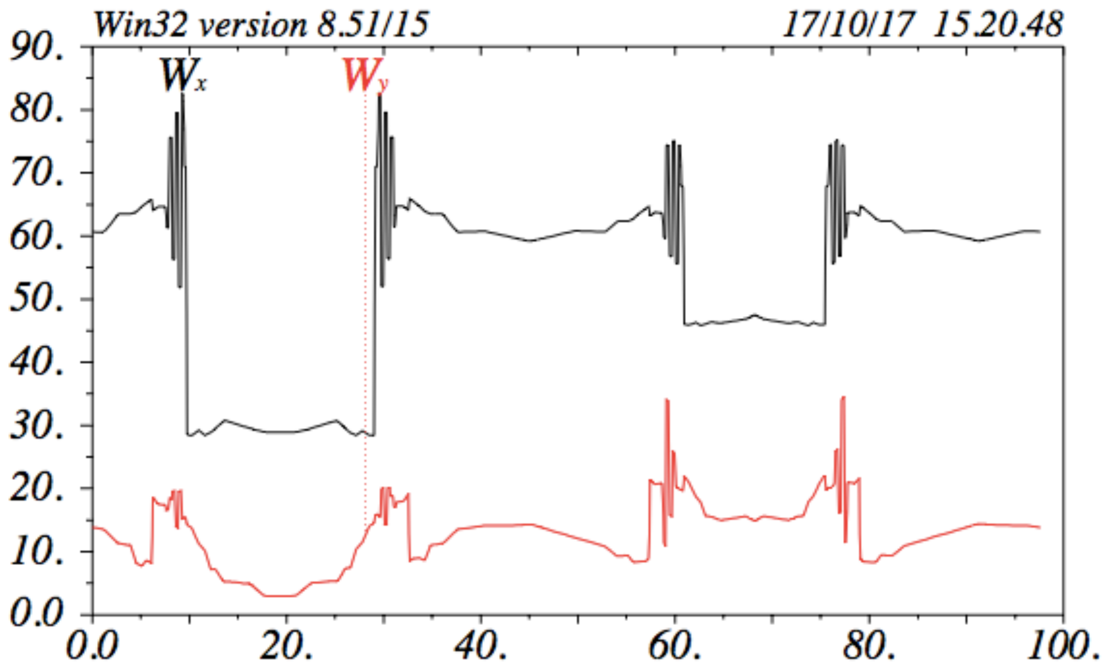




Qx = 4.366, Qy = 4.27

k2.sf= 27.5*1.26
k2.sd=-17.1*0.7





RF Knock-out system (used at CNAO)

- The RF-knockout extraction system involves the use of a kicker, which perturbs the beam horizontally
- The frequency of the signal given to the kicker f_0 is of the order of the revolution frequency f_{rev} modulated at an harmonic of the horizontal betatron frequency

$$f_0 = (n \pm q_x) \times f_{rev}$$

q_x is the fractional part of the horizontal tune and $n \in N$

- The RF signal increase the beam oscillation amplitude and drives the particles outside the stable region
- To have a constant rate of extracted beam, the amplitude of the RF signal is increased during the extraction

Hardware modifications

- Remove the low-beta insertion from IR1
  - The solution depends on the choice for the e- ring utilization
  - A possible solution is to have IR1 equal to IR2, as proposed here
- Magnetic extraction septum (can be made equal to the injection one)
- Electrostatic extraction septum
  - ~ 50KV/cm, thickness ~100 μm, length ~ 1m
- Wigglers and RF turned off
- Modification of the transfer line to go directly from the linac to the ring (as it was in Adone)
- Insert a collimation system on the transfer line to control emittance and energy spread of the injected beam
- Installation of additional shielding (to be evaluated)

Conclusions

- With this scheme it is possible to get at DAFNE an extracted positron beam with 5e7 e+/pulse, pulse length 0.5 ms and duty cycle ~2%
- The required hardware modifications are rather limited
- In order to get a detailed design still much work is necessary and your collaboration is very much appreciated