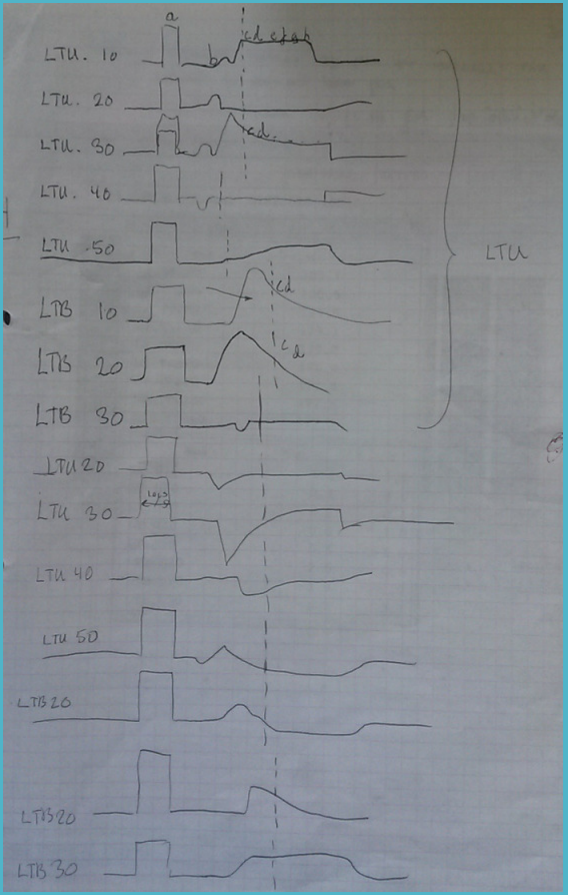
LINAC BEAM AND TRANSFER LINE REVISITED

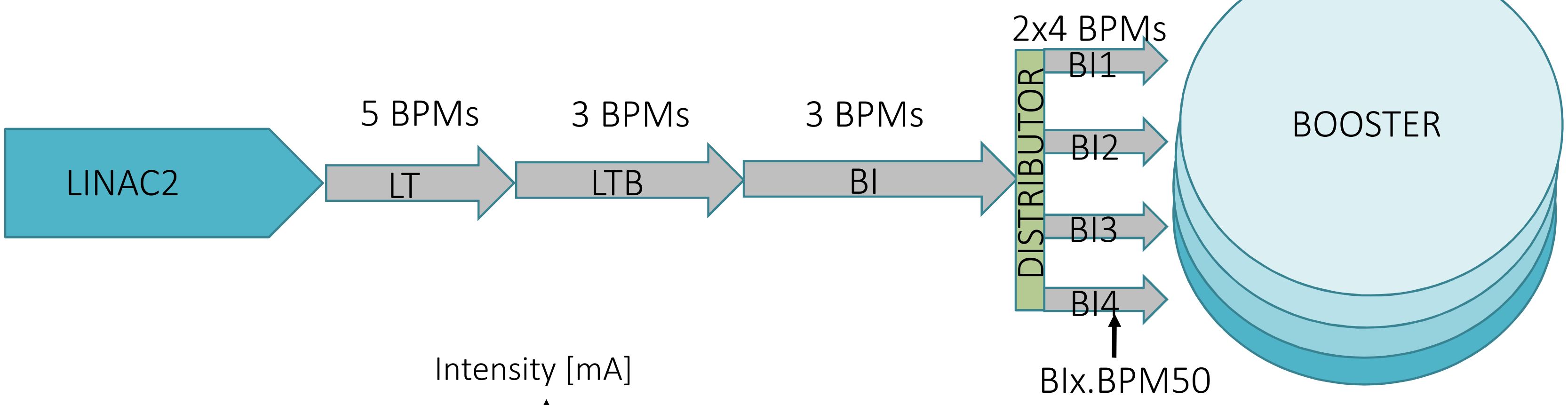


VINTAGE LT BEAM POSITION
Courtesy of L.Soby

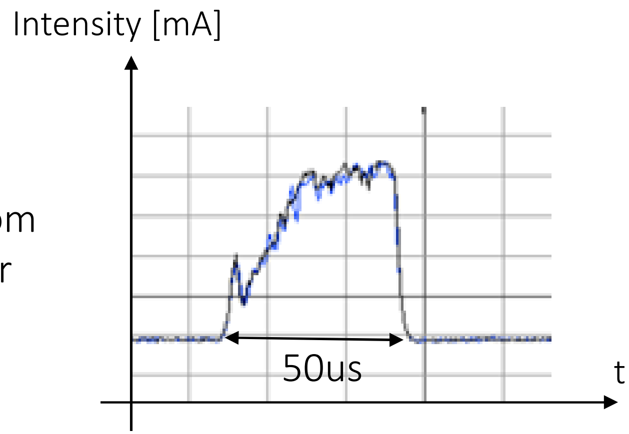
Michele Bozzolan (BE/BI)
CERN, 9 September 2015

Machine overview

Presentation is about shorted stripline BPMs installed in the transfer line connecting the LINAC2 with the booster.
LINAC2 produce pulses of bunched protons spaced by 4.95ns
BPMs are shorted stripline



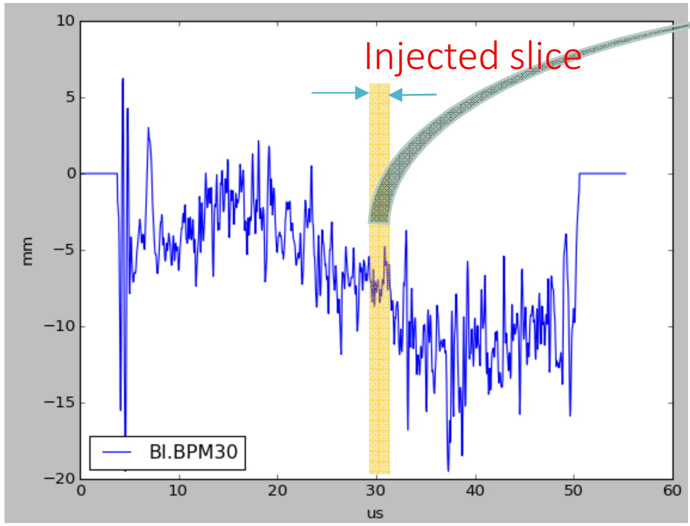
LINAC 2 PULSE seen from the current transformer



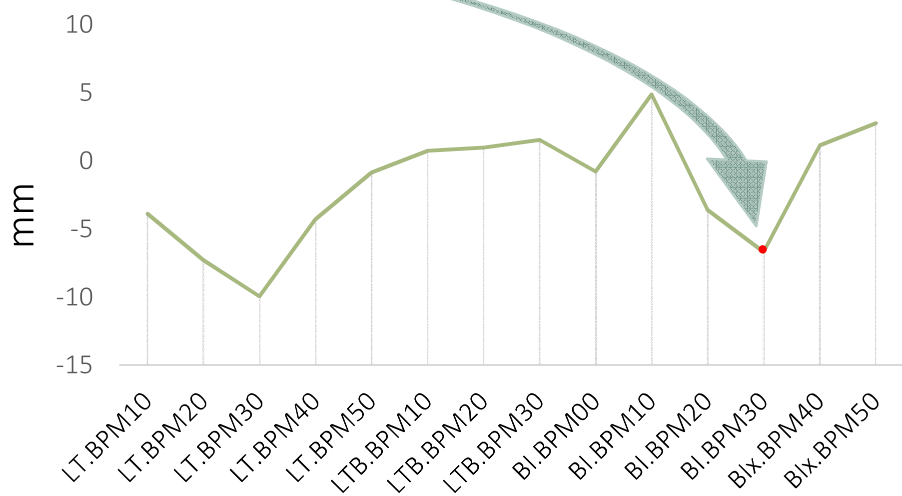
Beam position scalar value

The acquisition system records the instantaneous beam position with a sampling period of 40ns (25MHz)
Only **slices** of the linac pulse are **injected into the booster**
Beam trajectory at the BPM position is defined as the **mean position over the injected slice**

Vertical beam position vs time of one LINAC 2 pulse

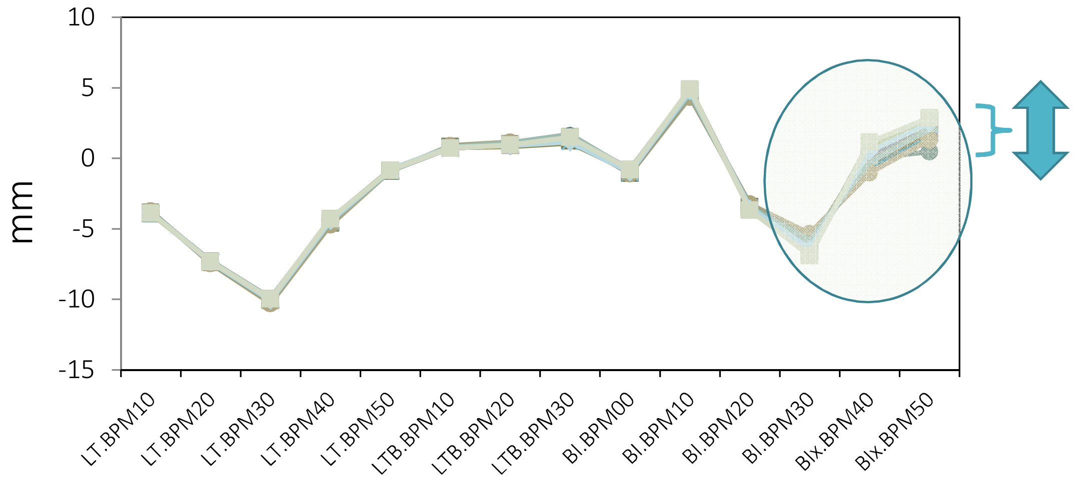


TRANSFER LINE V-TRAJECTORY (OP OUTLOOK) FOR ONE PULSE

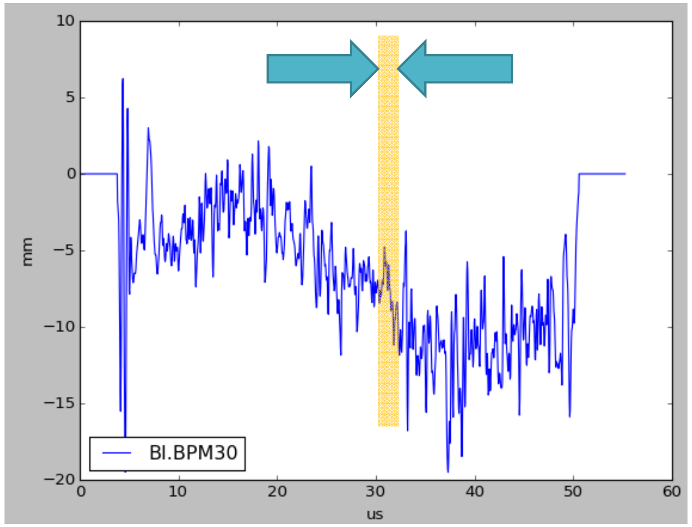


OP ISSUE: vertical position fluctuations

VERTICAL TRAJECTORY OF 20 PULSES



SINGLE PULSE POSITION vs TIME @ BI.BPM30



- Uncorrelated fluctuations on the instantaneous position lead to increasing fluctuation on the scalar values with decreasing injection duration
- OP states the beam CANNOT move as BPMs show since 2014 start-up
- ABP had the same opinion

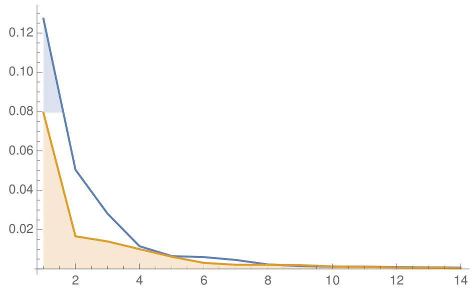
In BPMs we(BI) trust

- **Extensive measurements** excluded EMI, ELECTRONICS AND SIGNAL PROCESSING issues, see https://indico.cern.ch/event/407984/contribution/2/attachments/1127836/1610900/2015-07-17-BI_TechBoard.pdf

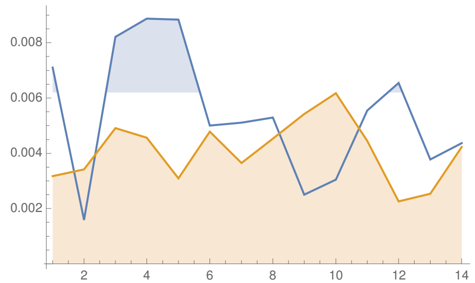
- **Literature, simulations and lab measurements** confirm stripline BPMs works fine

- Preliminary **SVD analysis from M.Wendt** on all BPM for ~900 pulses show **typical BPMs behavior** with 6 main eigenmodes and a resolution on the order of 10um

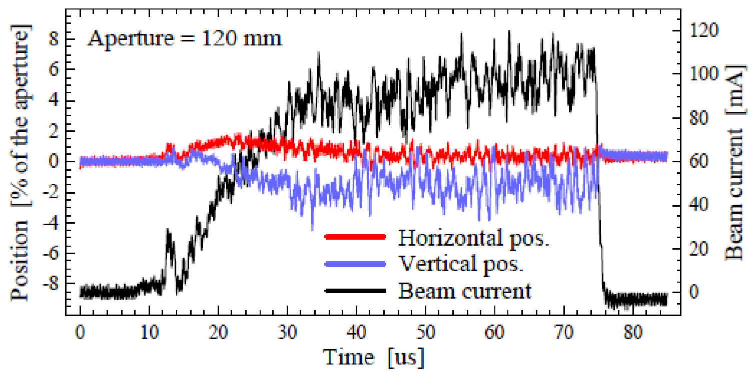
EIGENMODES AMPLITUDE



BPM RESOLUTION



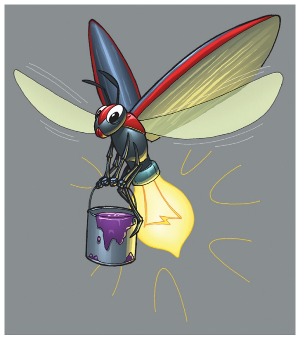
- One **inductive pickup by M.Gasior** installed at the LT.BPM20 position in 2005 already showed **high vertical fluctuations**



Changing point of view

BI and OP were seeing the problem from two different point of view.
Changing the perspective was the key to solve the impasse.

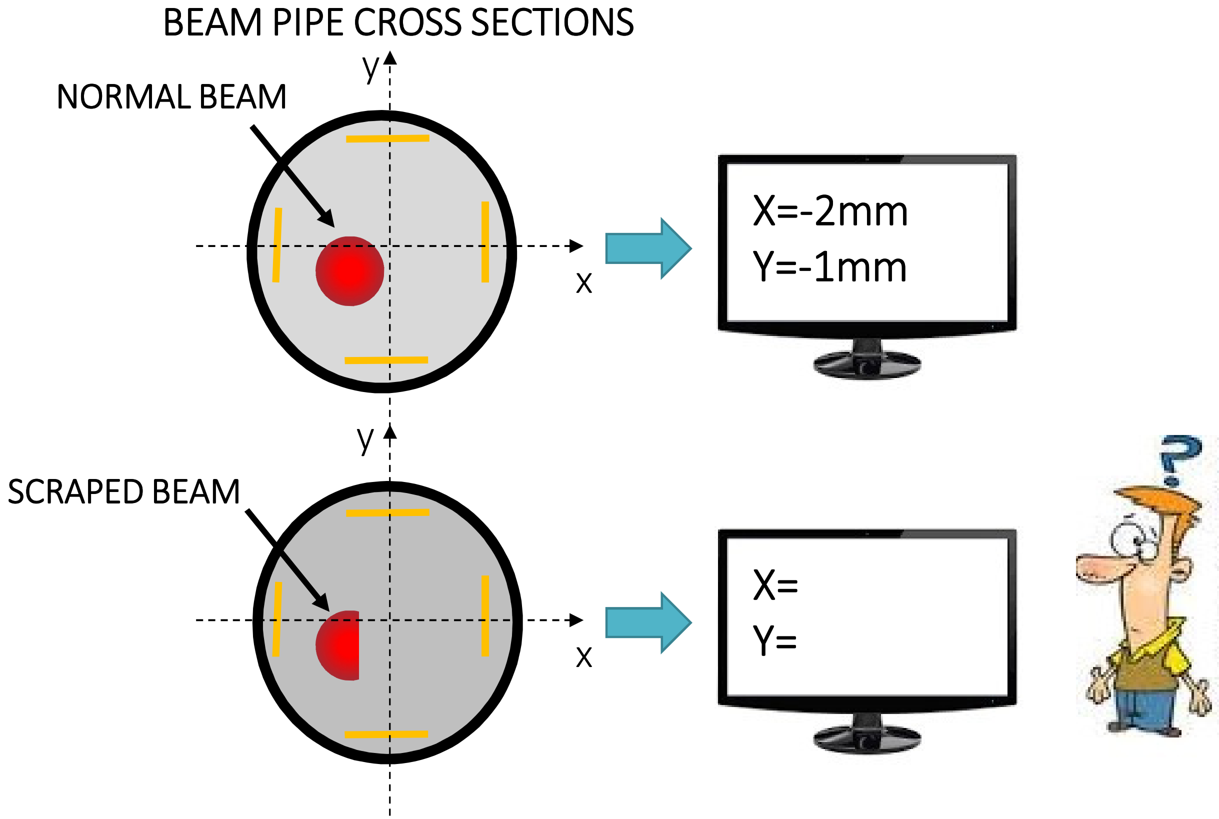
PHYSICISTS SIDE



ENGINEERS SIDE

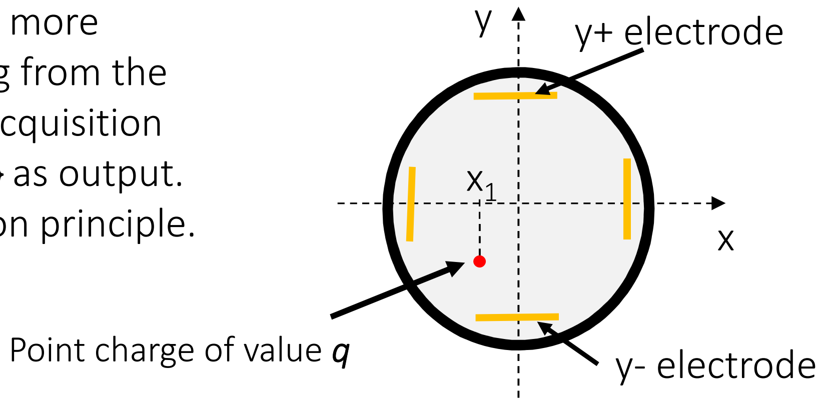
What is beam position?

Beam is a cloud of charges and we define the position of the cloud by mean of two numbers, but what is the relation between those numbers and the beam?
Imagine for example we have a evenly distributed beam and we scrape part of it. Do you think beam has moved or not?



What's the BPM measuring?

If we have only a point charge, position is no more ambiguous: we have a set of 4 values coming from the electrods $\{V_{x+}; V_{x-}; V_{y+}; V_{y-}\}$ as input of our acquisition system and the position of the charge $\{x_1, y_1\}$ as output. For more particles we can apply superposition principle.



Δ / Σ algorithm for point charge

$$\frac{\Delta V_x}{\Sigma V_x} = \frac{1}{S_X}\frac{q * x_1}{q} \longrightarrow X = Sx\frac{\Delta V_x}{\Sigma V_x} = x_1$$

SUPERPOSITION PRINCIPLE

TWO CHARGES

$$X = \frac{q_1 * x_1 + q_2 * x_2}{q_1 + q_2}$$

$$X' = \frac{dX}{ds} = \frac{q_1 * x'_1 + q_2 * x'_2}{q_1 + q_2}$$

N EQUAL CHARGES

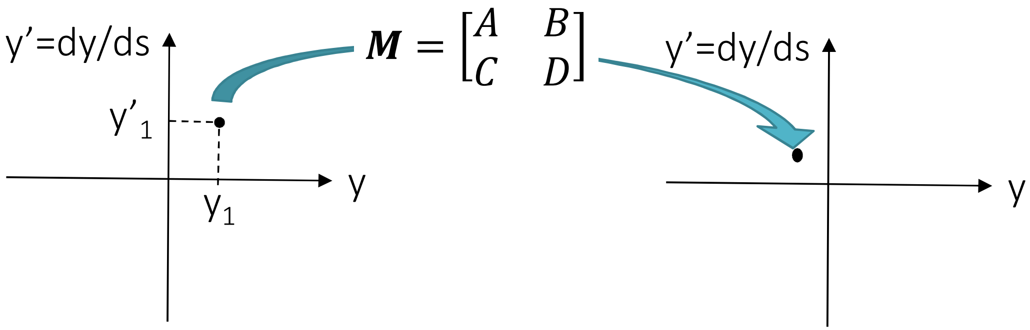
$$X = \frac{\Sigma_N x_n}{N}$$

$$X' = \frac{\Sigma_N x'_n}{N}$$

BPMs MEASURE ONLY the mean positions of the beam (CENTER OF GRAVITY)
BEAM IS EQUIVALENT TO A SINGLE PARTICLE of charge N located in X,Y
For the BPM the scraped beam has moved!!

Transverse beam optics

Transverse properties of a single particle in a specific point along the line (s axes) are defined by the phase space coordinates (x,x') and (y,y')
If only linear magnetic elements are present (dipole and quadrupole), transport of the particle between two longitudinal positions S1 and S2 is defined by a linear transformation with matrix ***M*** that depends only on the optics of the line



VERTICAL PHASE SPACE FOR s=S1

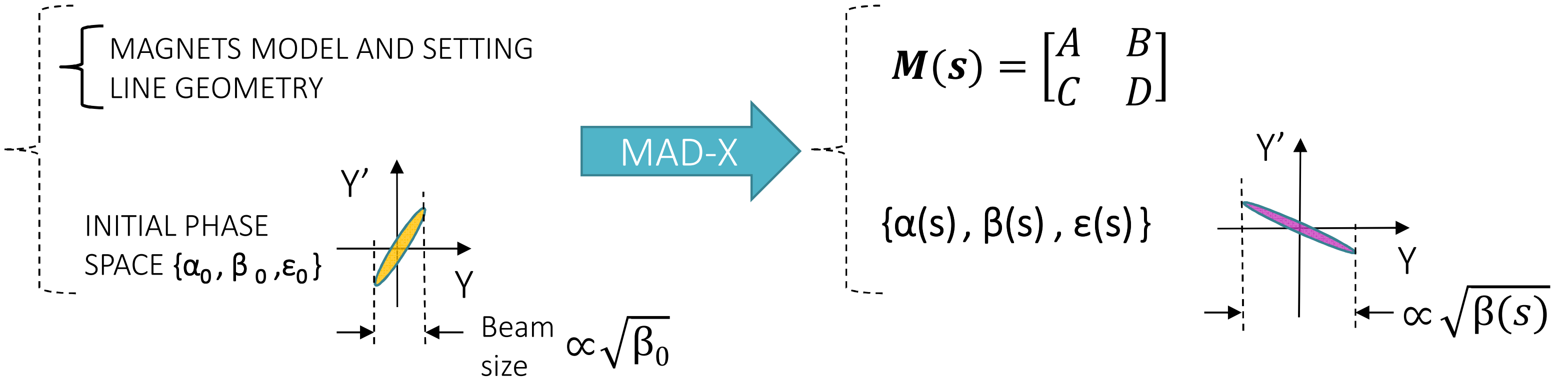
VERTICAL PHASE SPACE FOR s=S2

$$\begin{bmatrix} y_2 \\ y_2' \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} y_1 \\ y_1' \end{bmatrix}$$

all is linear → SAME MATRIX APPLY TO BEAM CENTER → BPM measure is TRANSPORTED BY THE SAME MATRIX **M**

Transverse beam dynamics

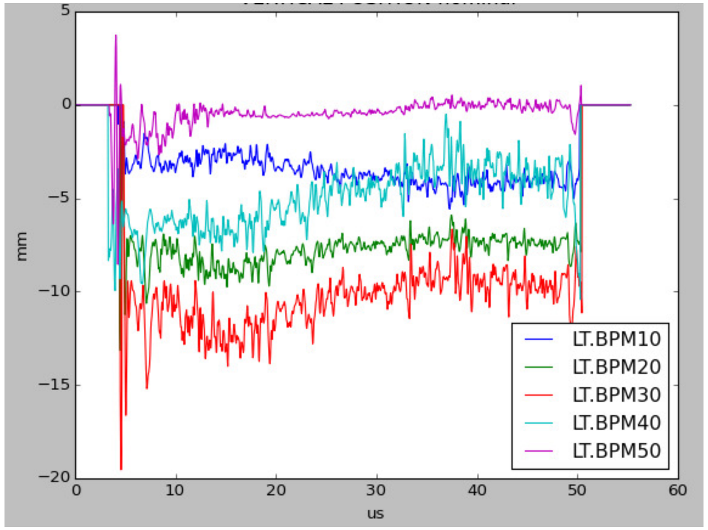
Beam dynamics is simulated and optimized by MAD-X
From the settings of the line, the software calculate transfer matrix of the line
In order to calculate phase space along the line, the initial elliptical phase space has to be defined by the triplet (α_0, β_0, ε_0)



Beam size is **proportional to the beta's square root** for a beam with a stationary distribution since charges are presents simultaneously over all the ellipse area (emittance)
For BPMs (measuring only the center of gravity) **the beam size turn to position fluctuation over time** as BPMs «see» only a point charge.
Beta function depends on the initial conditions so different initial conditions lead to different fluctuations along the line

The whole picture: all positions are correlated

V POSITIONS ON LT LINE FOR THE SAME PULSE



Positions of **ALL** BPMs show A COMMON PATTERN
By SCALING and SHIFTING all traces can be OVERLAPPED
Translating in mathematical language:

$$\boxed{y(s_2) = K_1(s_2, s_1) * y(s_1) + K_2(s_2, s_1)}$$

K_1 measures the RELATIVE FLUCTUATIONS

K_2 is the OFFSET between the measure and the optical center and it is not relevant for the rest of the discussion

K_1 and K_2 are INDEPENDENT ON THE PULSE and DEPENDS ONLY ON THE USER (settings of the line)
FLUCTUATIONS are a BEAM PROPERTY not due to EMI or other source

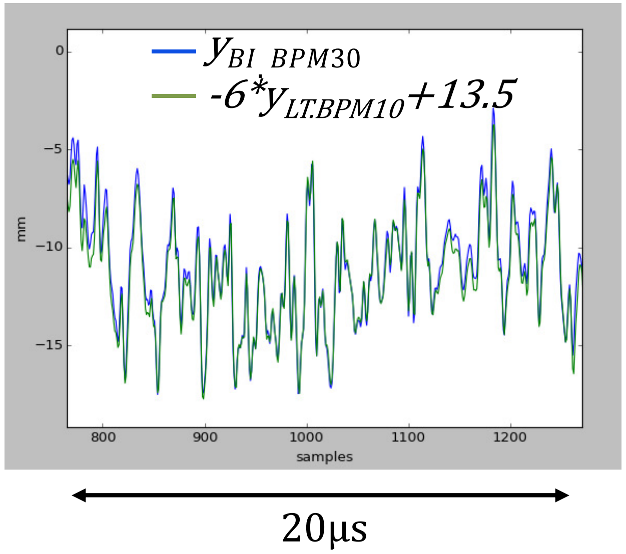
MAYBE FLUCTUATIONS ARE TRANSPORTED BY THE OPTICS OF THE LINE?

How linear relation hold along the line

We take LT.BPM10 as reference and we verify how the linear relation behave along the line

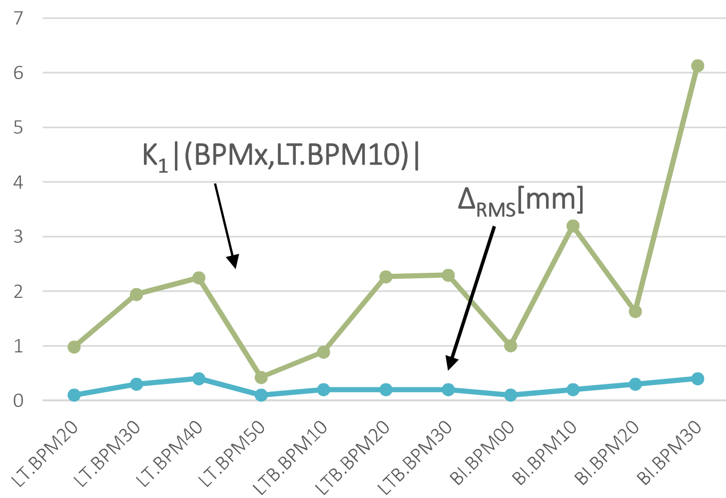
$$y^*_{BPMX} = K_1 * y_{LT.BPM10} + K_2$$
$$\Delta_{RMS} = RMS\{y^* - y\}$$

Example of fitting in time domain:
VERTICAL POS. Vs TIME ZOOM



	K_1	K_2	Δ_{RMS}[mm]
LT.BPM10	1	0	0
LT.BPM20	-1	-11.5	0.1
LT.BPM30	-2	-18	0.3
LT.BPM40	-2.2	-12.5	0.4
LT.BPM50	-0.45	-1.8	0.1
LTB.BPM10	1	4.5	0.2
LTB.BPM20	2.2	9	0.2
LTB.BPM30	2.2	9	0.2
BI.BPM00	-1	-4.5	0.1
BI.BPM10	-3	-5.5	0.2
BI.BPM20	1.6	2	0.3
BI.BPM30	6	13.5	0.4
BIx.BPM40	-5	-18	
BIx.BPM50	-3	-14	

Graphs of fluctuation (K_1) and rms error between measures and linear fitting



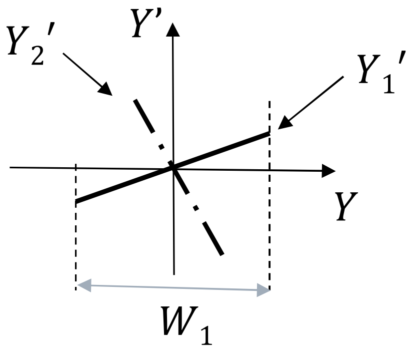
Position measurement in one point of the line predict position in the rest of the line

BI line has the higher *K*

Transport matrix check

To verify the A and B of the simulated matrix we look for an initial condition that fit the empirical formula for the position.

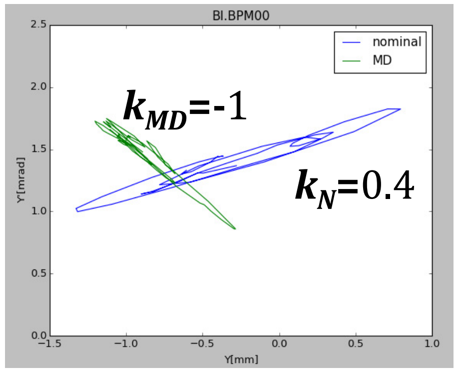
$$\begin{cases} Y_2(t) = K_1 * Y_1(t) + \cancel{K_2(s_2, s_1)} \\ Y_2(t) = A * Y_1(t) + B * Y_1'(t) \end{cases} \longrightarrow \quad Y'_1(t) = \underbrace{\frac{K_1 - A}{B}}_{k} Y_1(\mathrm{t})$$



The solution is a beam center of gravity moving in a straight line in it's phase space along the pulse.
A linear transformation can shrink, expand and rotate but it always maintains a straight line where *W* is the fluctuation.
With two different optics, calculated *k* matches the measured one.

OPTICS	SIMULATED *M*(BI.BPM50→BPM00)	K_1	$k=(K_1-A)/B$
MD	$\begin{bmatrix} 2.36 & 8.47 \\ -0.49 & -1.32 \end{bmatrix}$	-6	-1
NOMINAL	$\begin{bmatrix} 1.59 & 3.18 \\ -0.35 & -0.079 \end{bmatrix}$	3	0.44

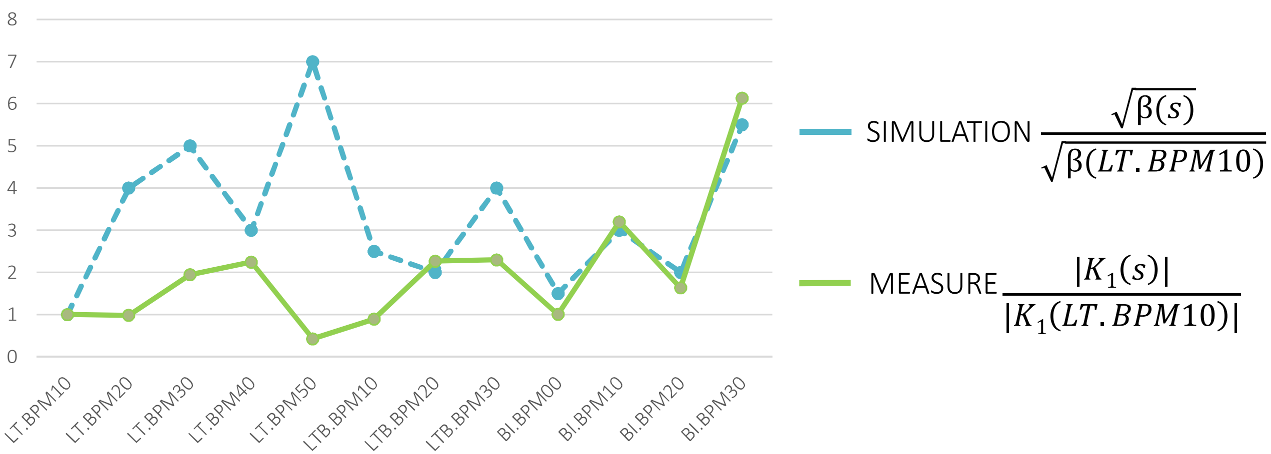
MEASURED BPM PHASE SPACE @ BI.BPM00



VERY GOOD, SIMULATED MATRIX MATCHES THE MEASURES FOR TWO DIFFERENT OPTICS, BUT ...

What about the fluctuations?

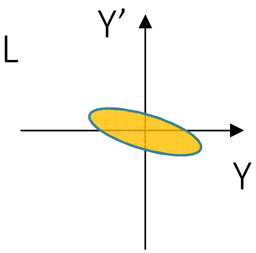
Now we can try to check if the measured fluctuations match the square root of the simulated beta functions. Initially the didn’t.



But matrix was ok, so we can try to change the initial conditions ...

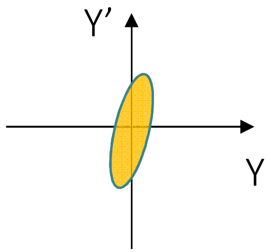
ORIGINAL INITIAL CONDITIONS

α_0=0.1 β_0=2.5



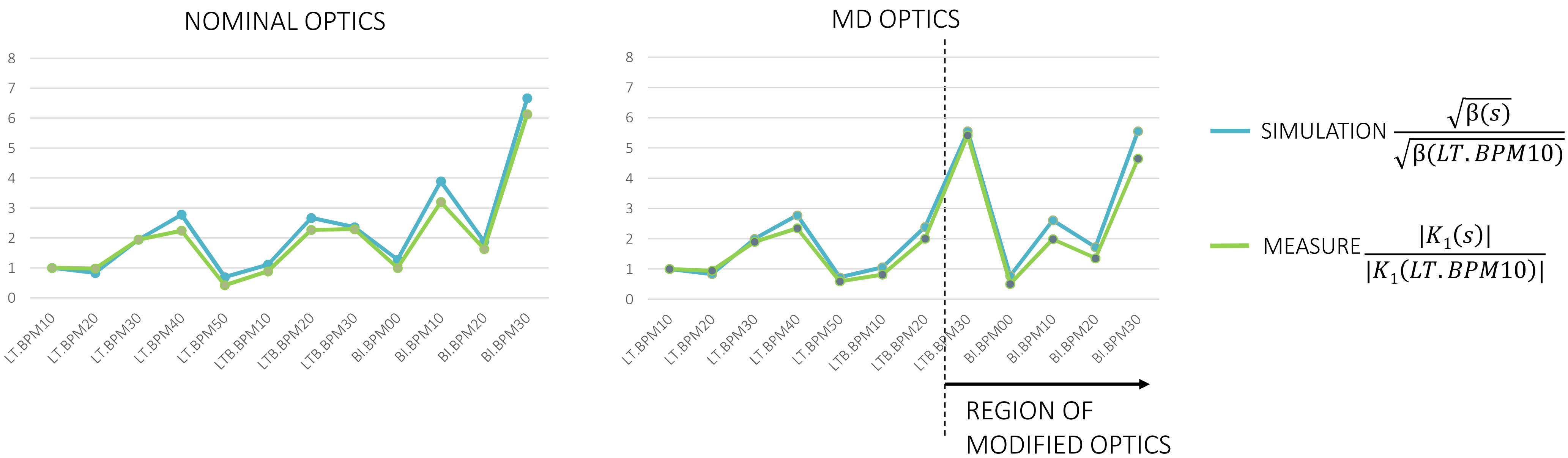
NEW INITIAL CONDITIONS

α'_0=-1 β'_0=0.4



Results with the new initial values

With the same new initial conditions both nominal and MD optics fits.
As it must be only fluctuation in the region of modified optics changes.

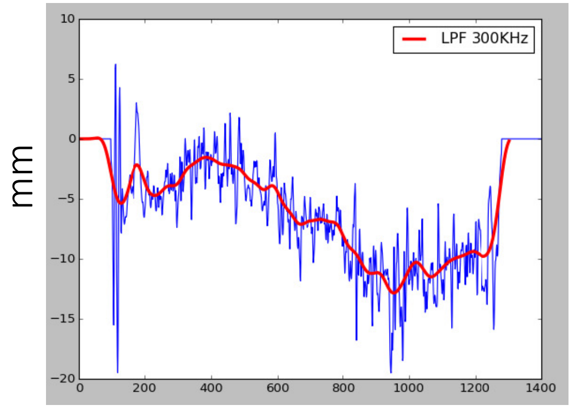


Now we have full agreement between simulation and measures!

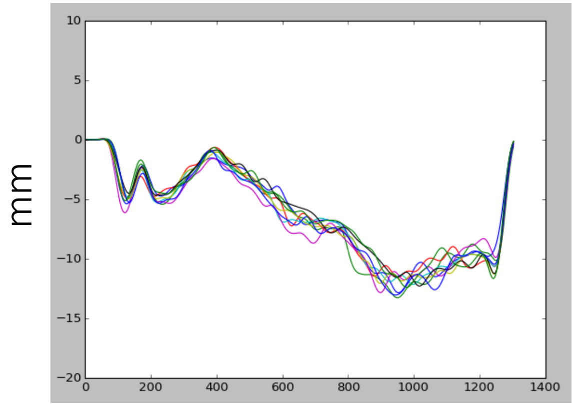
Position components and the «OP filter»

Instantaneous position is composed by a relative stable (pulse to pulse) low frequency (<300KHz) component and an uncorrelated (pulse to pulse and intra-pulse) high frequency component.

V POSITION BI.BPM30 vs TIME



10 PULSES LP-FILTERED V POSITION BI.BPM30 vs TIME



Low pass filtering reduce about 5 times the scalar position fluctuation but cannot be applied directly on Bix.BPM40 and Bix.BPM50 where signal is present only for the injection slice (~1us).
However the linear relation between vertical positions can be applied to obtain the same goal:

$$V_{BPMx}=LPF(V_{BPMx})+HPF(V_{BPMx}) \longrightarrow \mathbf{LPF(V_{BPMx})}=V_{BPMx}-HPF(V_{BPMx})\mathbf{=V_{BPMx}-K_1*HPF(V_{BPMy})}$$

Conclusions and outlook

- BPMs works well: vertical fluctuations are a beam property
- High beta → High fluctuations
- Two differents behaviour in frequency domain

- «OP FILTER» smooths fluctuations
- Simulations match measures and fluctuations can be exploited as a verifying tool
- A new dipole will be installed to improve optics on the BI line

- MD using SEM grids
- MD with different debuncher phase

Acknowledgments

- OP G.Di Giovanni, B.Mikulec, PSB operators
- ABP O.Berrig, A.Lombardi, R.Scrivens
- BI M.Ludwig, L.Soby, J.Tan, U.Raich, M.Wendt

Appendix A: What about H plane?

H plane is much more stable than V line. Peak-peak fluctuation in the injected region of the pulse is on the order of 1mm, more than 10 time less than in V plane for BI.BPM30

Simulation has good agreement with the measures already with the initials settings

Comparison of the pulse position vs time in H & V plane for two different BPMs.