Beam dynamics of SPL: issues and solutions

P. A. POSOCCO
CERN – BE/ABP

46th ICFA Advanced Beam Dynamics Workshop on
High-Intensity and High-Brightness Hadron Beams

Summary

- What is SPL?
- SPL main parameters
- SPL architecture
  - Lattice choice
  - Magnetic stripping issue
  - Beam steering
- The branching issue
  - A novel approach
  - Results of Beam Dynamics
- Cavity jitter specifications
- The intra beam stripping phenomenon: an outstanding issue

What is SPL?

- SPL, Superconducting Proton LINAC, accelerates H- ions from 160 MeV to 5 GeV.
- The SPL can be the proton driver for a radioactive ion beam facility, or a neutrino factory.
- The SPL *could* replace the low-energy part of the CERN proton accelerator complex.

SPL main parameters

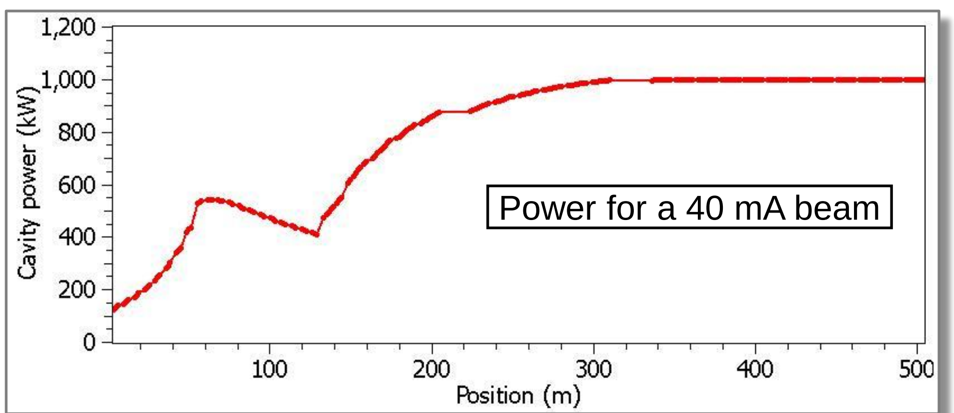
Parameter	Unit	Low Current	High Current
Energy	[GeV]	5	
Beam power	[MW]	4	
Rep. rate	[Hz]	50	
Av. pulse current	[mA]	20	40
Peak pulse current	[mA]	32	64
Source current	[mA]	40	80
Chopping ratio	[%]	62	
Beam pulse length	[ms]	0.8	0.4
Protons per pulse		10^{14}	
Beam duty cycle	[%]	4	2
Length	[m]	~550	

Cavities of SPL

- SPL extends to 5 GeV and uses two families of 5-cell elliptical cavities optimized for its current & range of energy.

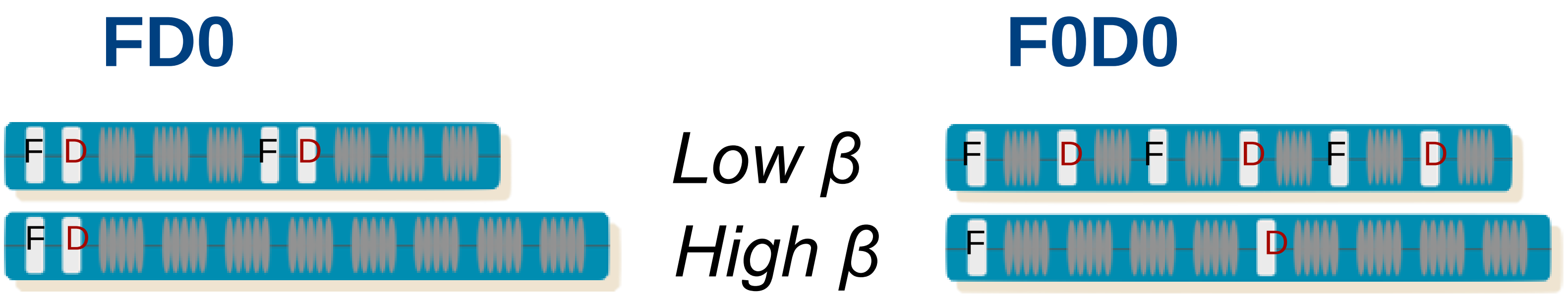
LINAC4 → $\beta = 0.6x$ → $\beta = 0.9x$ ($0 \leq x \leq 10$)

- Low beta region uses cavities with $\beta_{Geo} = 0.65$ and high beta region uses $\beta_{Geo} = 1$ cavities



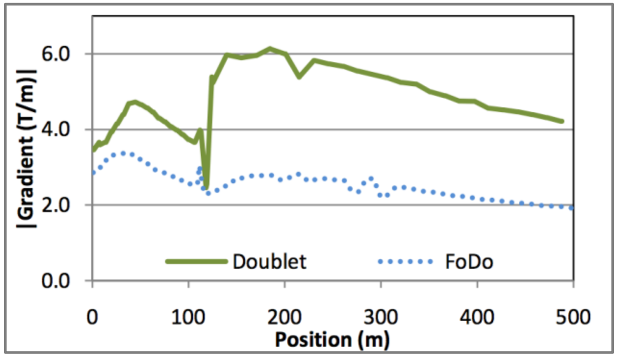
Architectures

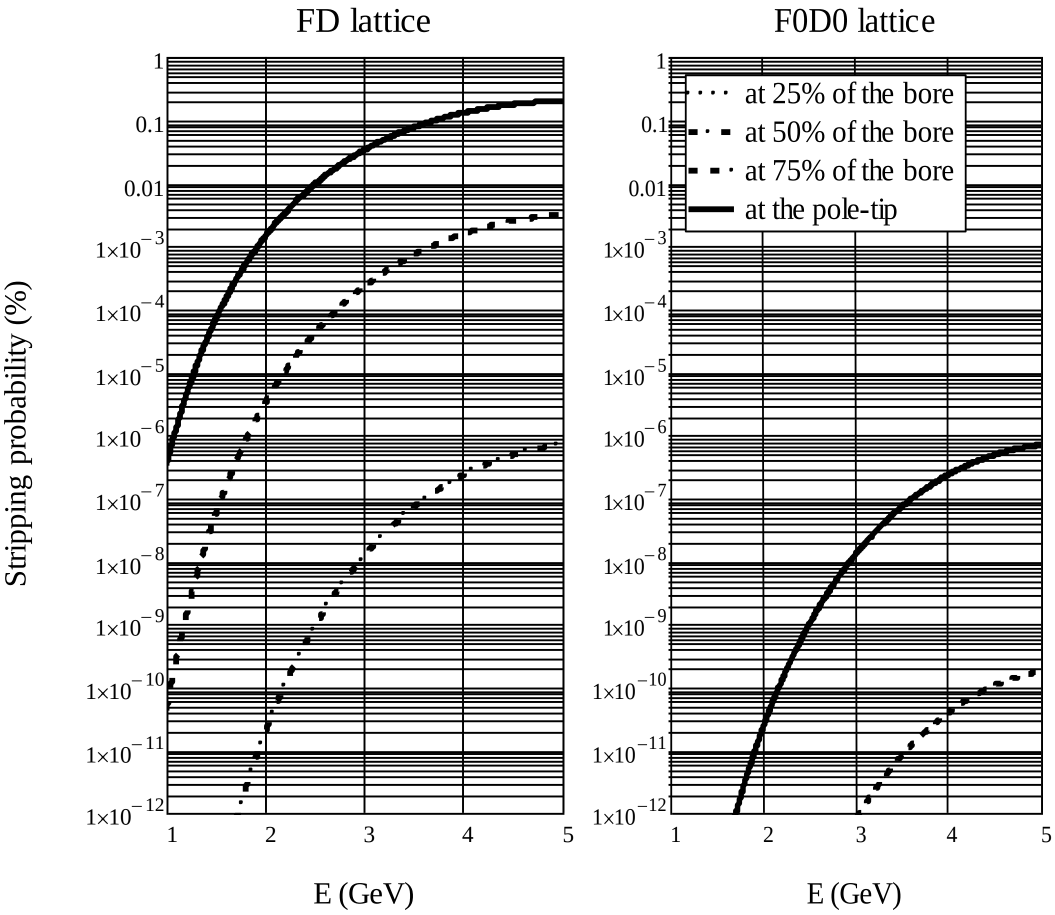
- The baseline solution for SPL uses a quadrupole doublet (FD0) focusing:
  - Pro: more flexible for cryo-sectioning (warm or cold magnets)
  - Contra: alignment sensitivity
- An alternative solution is based on F0D0 lattice:
  - Pro: weaker quadrupoles to achieve the same focusing
  - Contra: longer period, more quadrupoles per period at low β



Magnetic stripping (1/2)

Stripping probability for the nominal SPL quadrupole (50 mm bore radius, 450 mm long) as function of the beam energy.



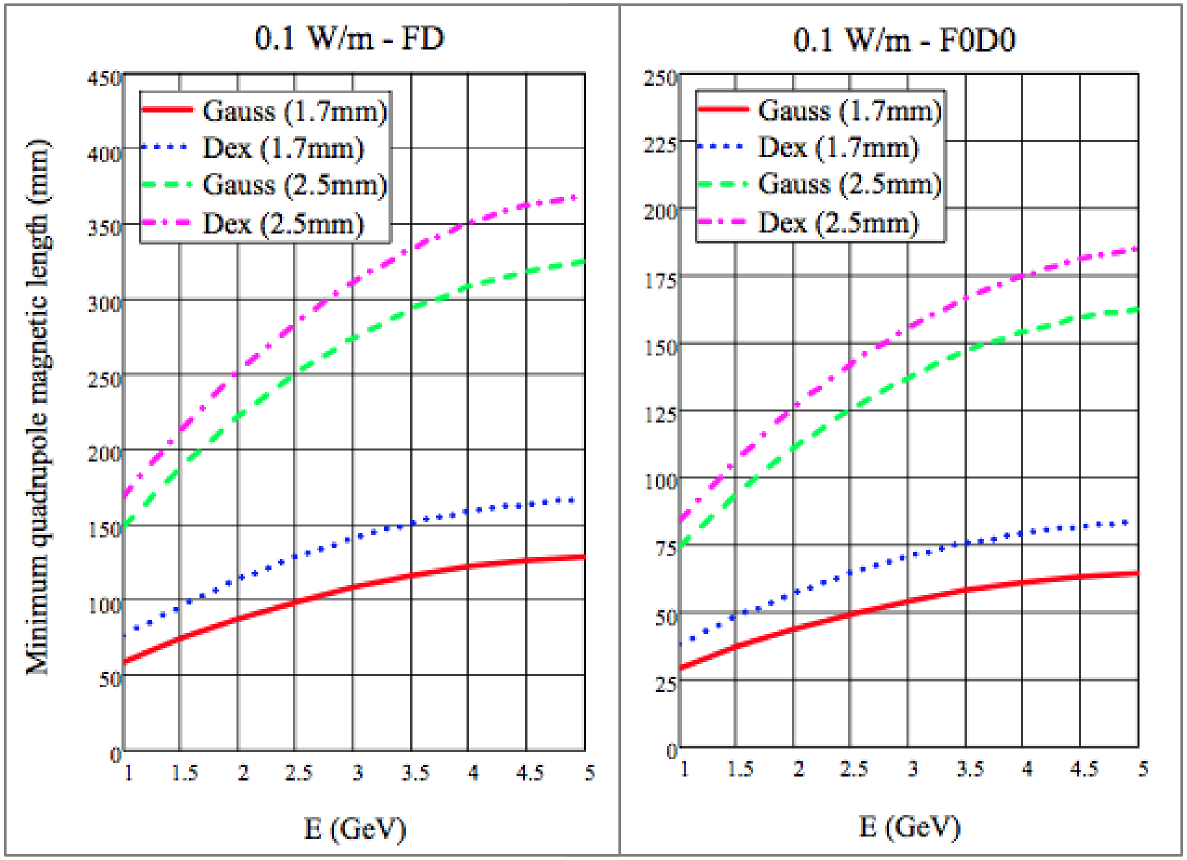


Magnetic stripping (2/2)

These values are calculated using either a Gaussian or a Double Exponential distribution with the max. displacement:

1 mm for
σ = 1.7 mm

10 mm for
σ = 2.5 mm



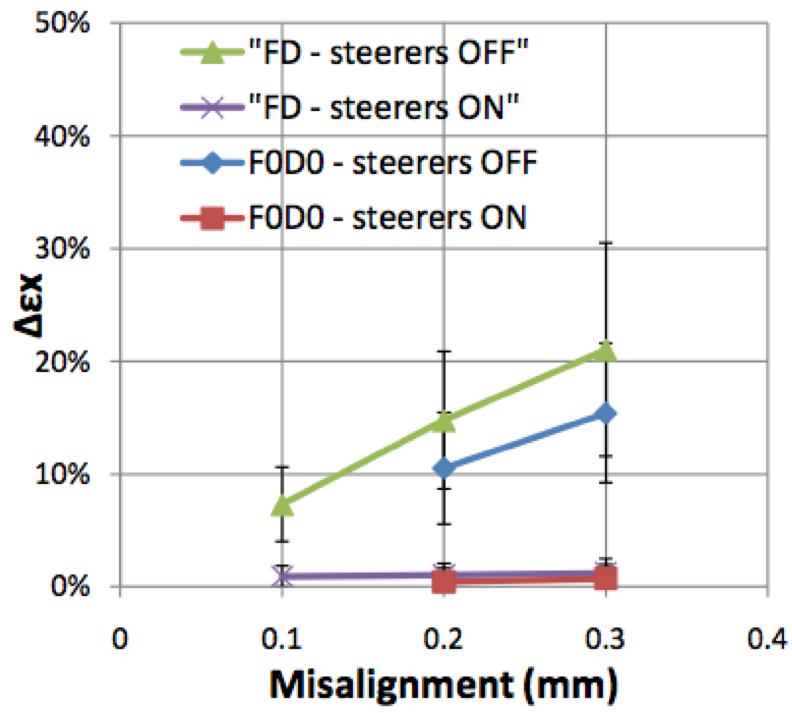
Transverse correction

Quadrupoles equipped with steerers can correct the beam center and maintain the emittance.

X steerer F quad

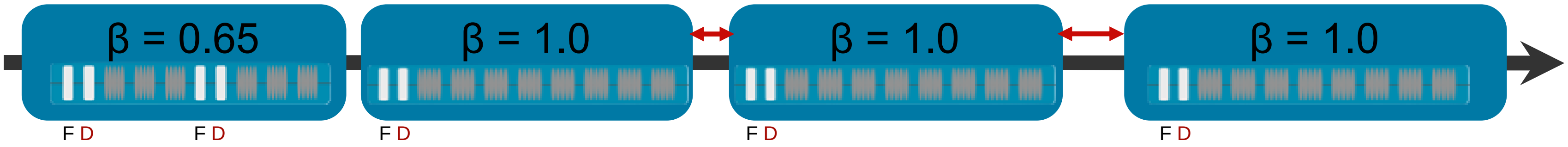
Y steerer D quad

BPM every two quads



The branching issue

- A branch-off is needed twice, at 1.4 and 2.5 GeV, each requiring, due to the magnetic stripping issue, a minimum drift space of 13.6 and 21 m respectively in the periodic structure of LINAC.



- Each time the focusing structure changes, the beam settles to a new equilibrium and this process is always accompanied by emittance growth and halo formation.

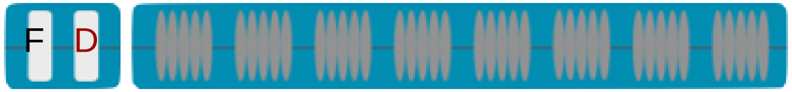
BUT

- If there has to be a 21m drift, why not change the focusing?

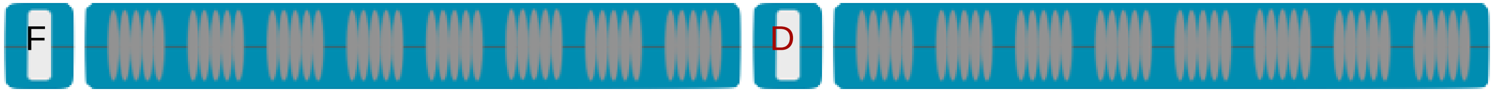
A novel approach

- Low beta cavities / doublets are used from 160 to 750 MeV

- From 750 to 2500 MeV high beta cavities are used. One period in the middle is skipped to house one period length (15.1 m) branch-off. 1.5 period length at the end leaves enough space for 2.5 GeV bends.



- Long F0D0 periods, have the advantage of requiring weaker quadrupole as well as simple and flexible cryo-modules.

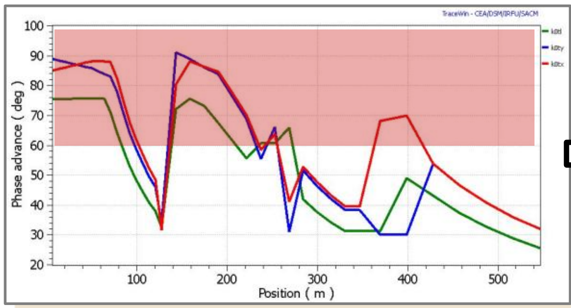


Design Criteria

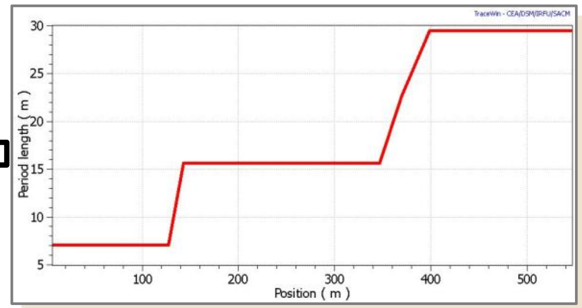
- When the space charge is not negligible, i.e. $\sigma/\sigma_0 < 1$, the zero current phase advance σ_0 should be smaller than 90°.
- The external force on the beam, $(\sigma_0/Lp)^2$, has to be smooth and continuous.
- Special care has to be taken to avoid the parametric as well as the space charge resonances.

Implementation of the criteria

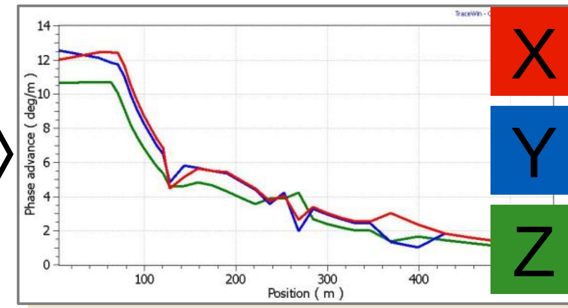
Phase Adv. (Deg)

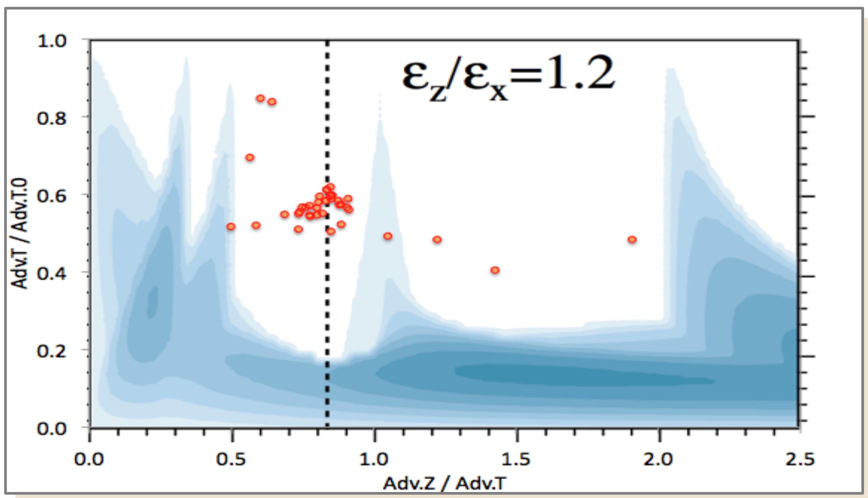


L. period (m)



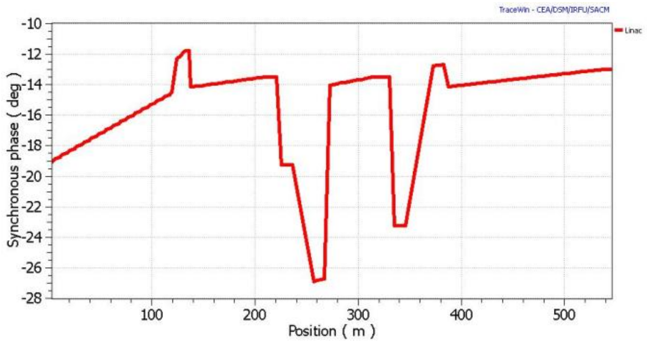
Phase Adv/m (deg/m)



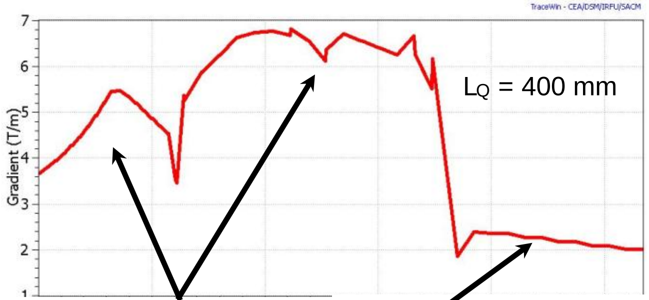


Phase, Grad and Power

Sync Phase (Deg)

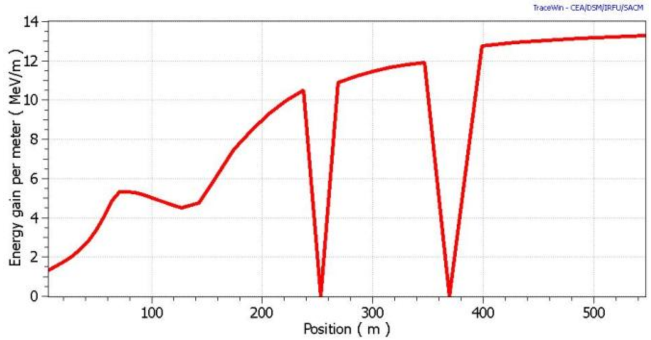


Quad. Grad (T/m)

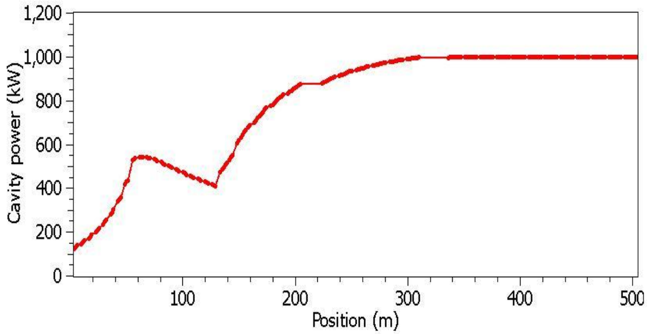


$$G = \frac{\gamma\, m\, v\, \sigma}{q\, l\, \sqrt{L\, D}} \qquad G = \frac{\gamma\, m\, v\, \sigma}{q\, l\, L}$$

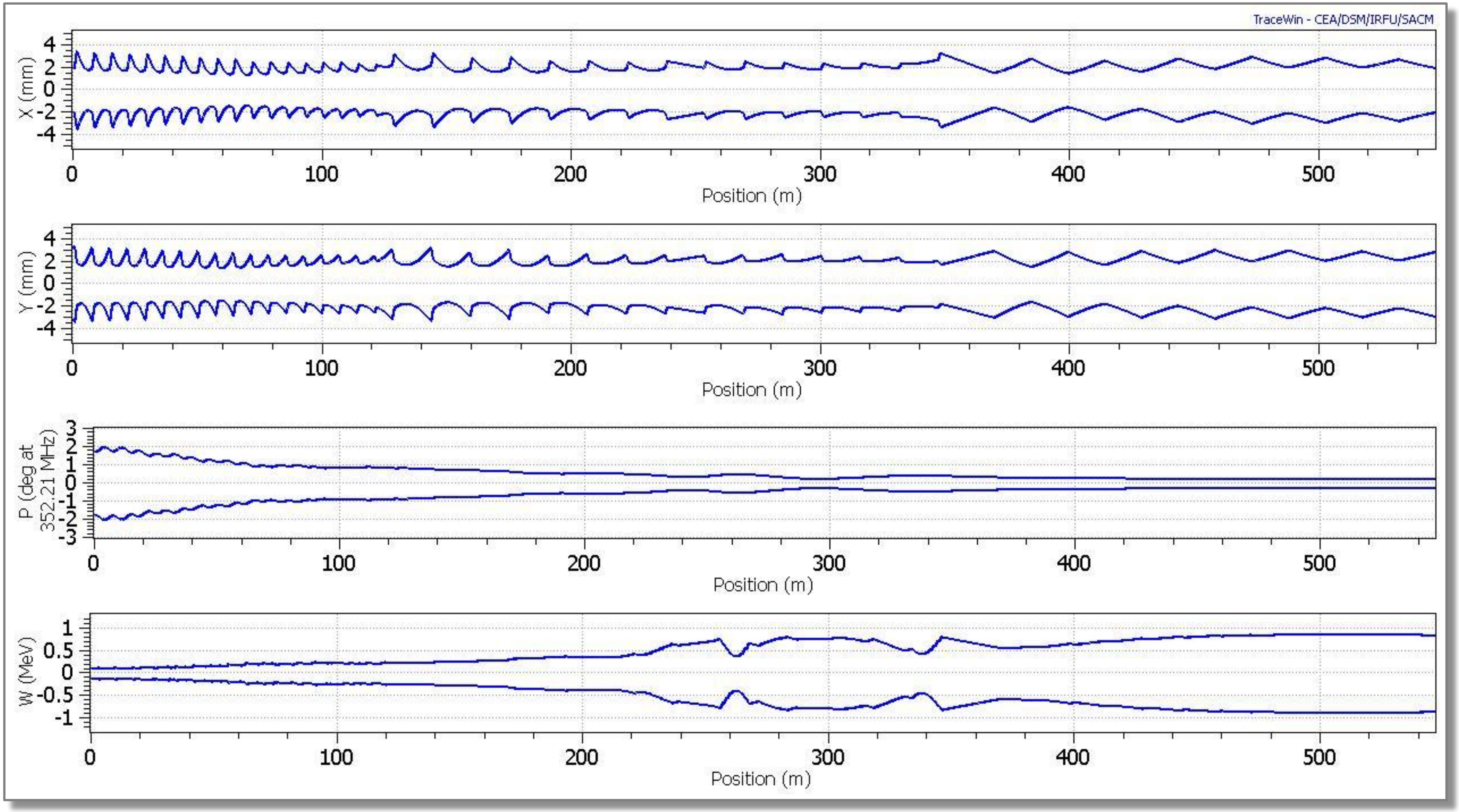
REG (MeV / m)



Power/Cavity (kW)

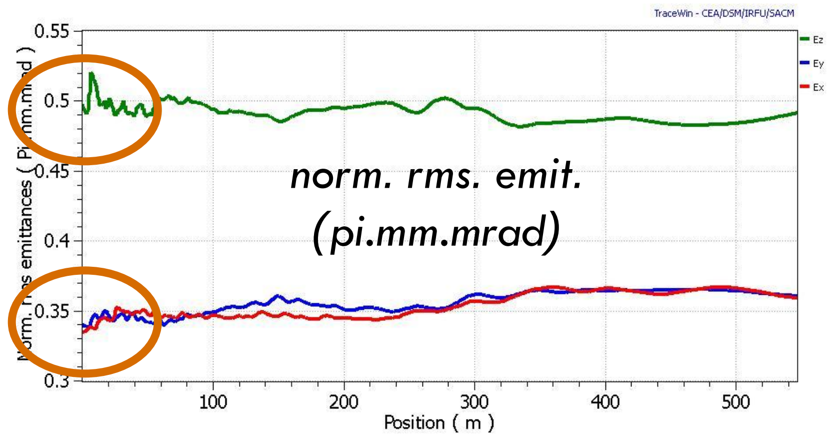


Envelopes

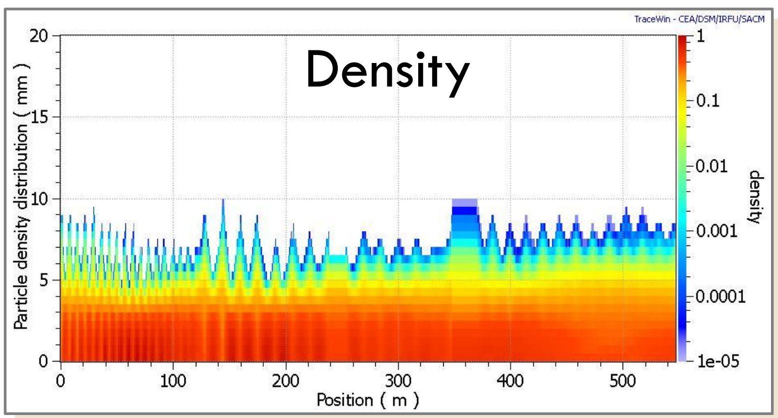

TraceWin - CEA/DSM/IRFU/SACM
X (mm)
Position (m)
Y (mm)
Position (m)
P (deg at 352.21 MHz)
Position (m)
W (MeV)
Position (m)

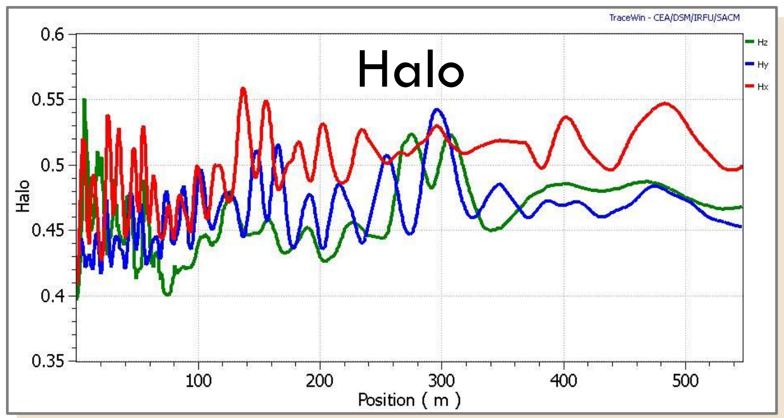
Density, Halo & Emittance

Redistribution



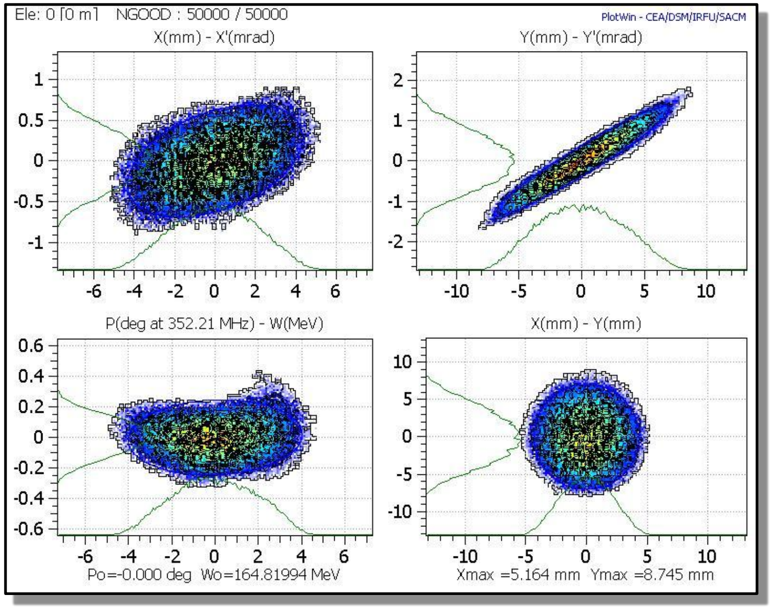
X	7.4%
Y	6.2%
Z	-1.0%



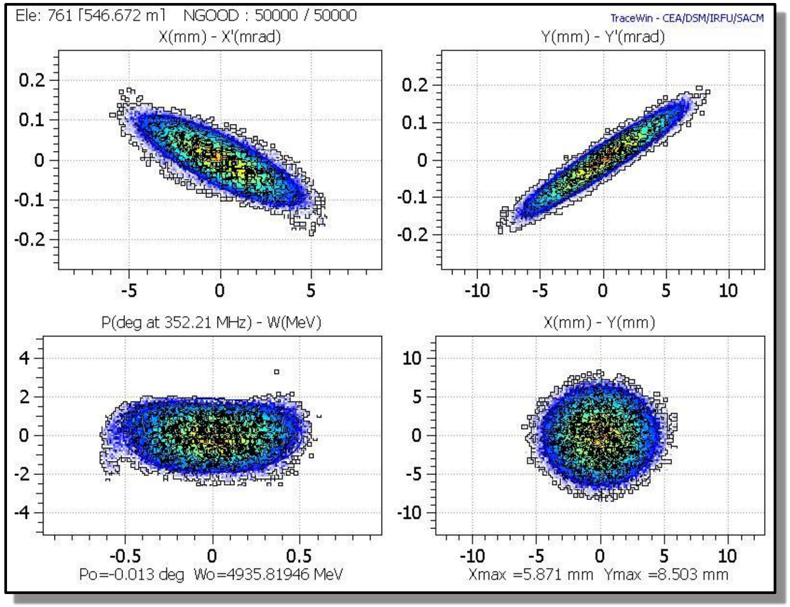


Beam In / Beam Out

Input beam, 165 MeV



Output beam, 4.93 GeV

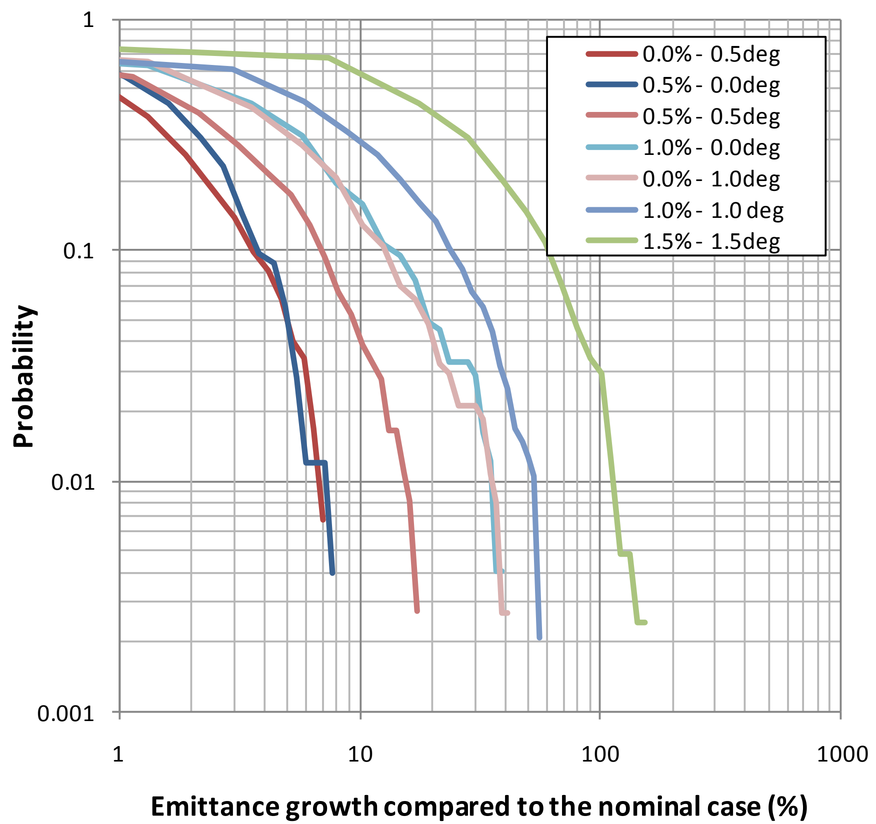


Cavity jitter specifications

Cumulative probability in log – log scale over 500 linacs generated with uniform random errors in voltage and synchronous phase.

Since the max. tolerable emittance increase is set at about 10%, the resulting specification is:

0.5% - 0.5deg



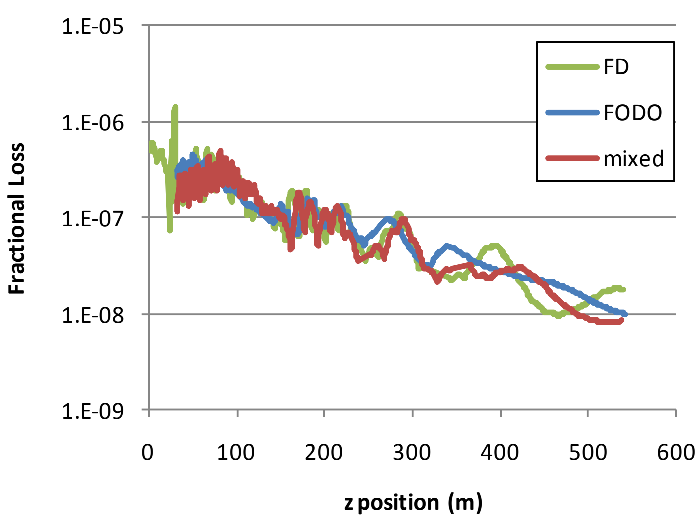
Intra-beam stripping: an outstanding issue

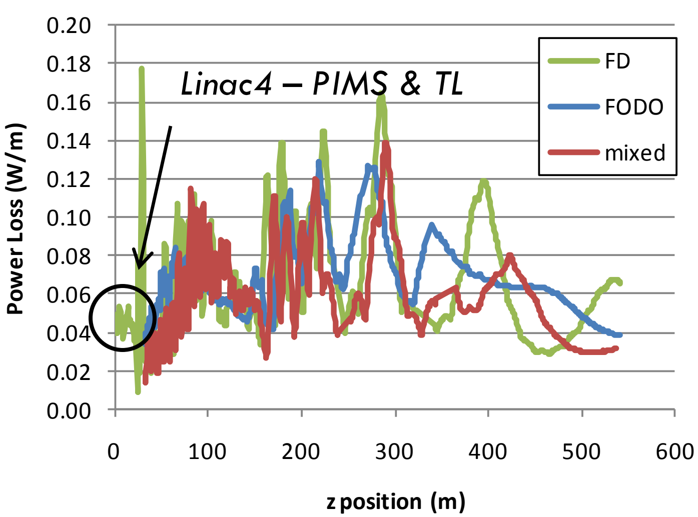
Fractional Loss* (developed by V. Lebedev and F. Ostiguy):

$$-\frac{1}{N}\frac{dN}{ds} \simeq \frac{N\sigma_{\text{stripping}}}{8\pi^2\sigma_x\sigma_y\sigma_s\gamma^2\beta c}\sqrt{\sigma_{v_x}^2+\sigma_{v_y}^2+\sigma_{v_z}^2}\cdot F(\theta_x,\theta_y,\theta_z)$$

F is a form factor which is =2/√3 (max) when all 3 velocity spreads are equal.

**F. Ostiguy: "Intrabeam Stripping Loss Estimates For Project-X"*





Acknowledgements

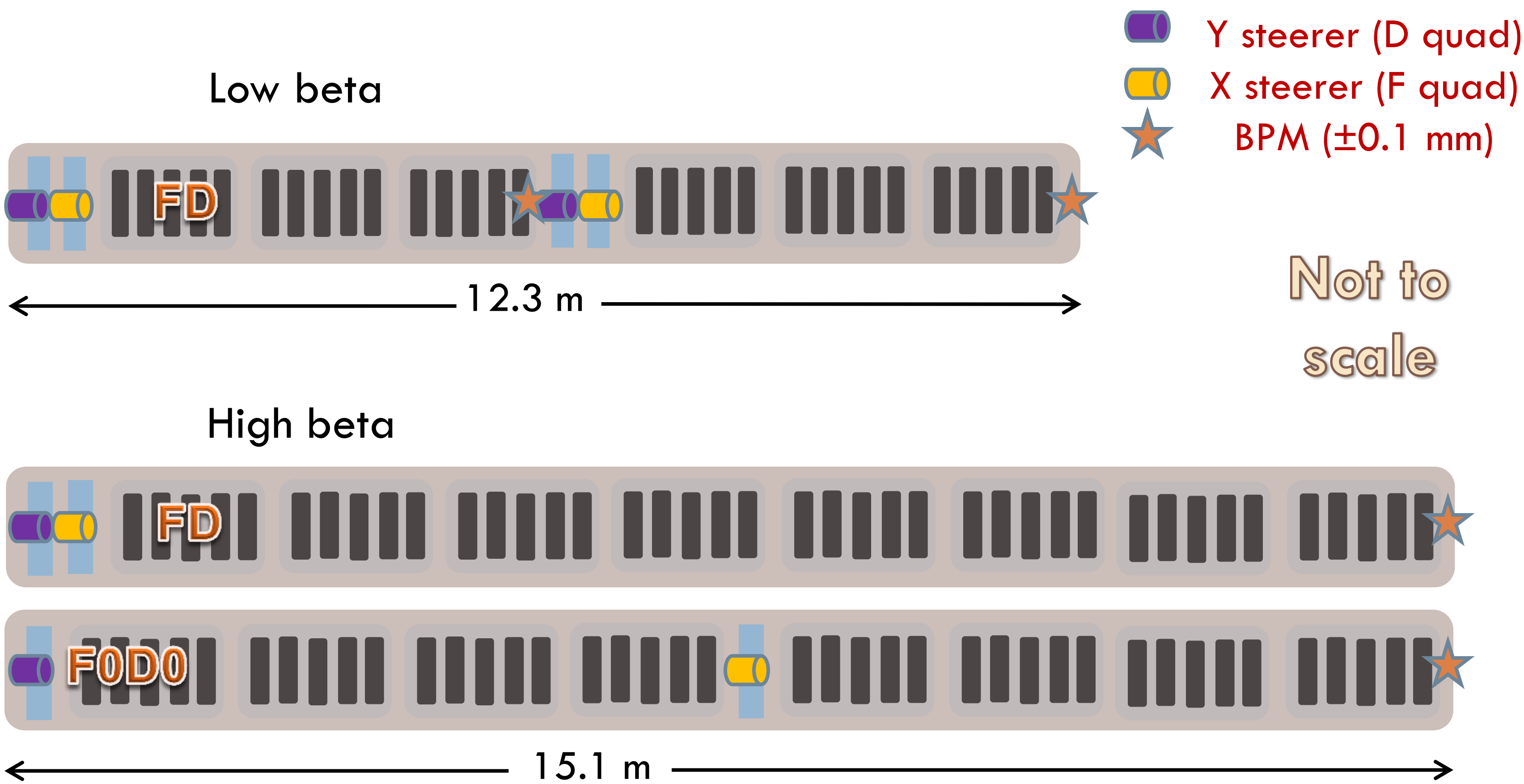
To the co-authors, M. Eshraqi and A. Lombardi (CERN)

To the simulation-aholic, M. Garcia Tudela (CERN)

To F. Ostiguy (Fermilab) for the fruitful discussion about intra-beam stripping

Back-up slides

Required Correction (1/2)



Mixed vs. Doublet

Inventory comparison

	L (m)	E (MeV)	No. Period	Cav. / per	No. Quads	No. Cav.
Doublet	550	786 / 4989	20 / 23	3 / 8	90	244
Mixed	546	654 / 4936	18 / 15 / 6	3 / 8 / 16	78	254*

* Power limited to 1 MW/cavity and gradients are 19 and 25 MV/m

Performance comparison

	Єx n.rms	Єy n.rms	Єz n.rms	ΔЄx %	ΔЄy %	ΔЄz %
Doublet	0.369	0.356	0.517	11.2	5.0	4.2
Mixed	0.359	0.361	0.492	7.4	6.2	-1