Wakefield mitigation in the High-Energy EuPRAXIA@SPARC_LAB X-Band Linac

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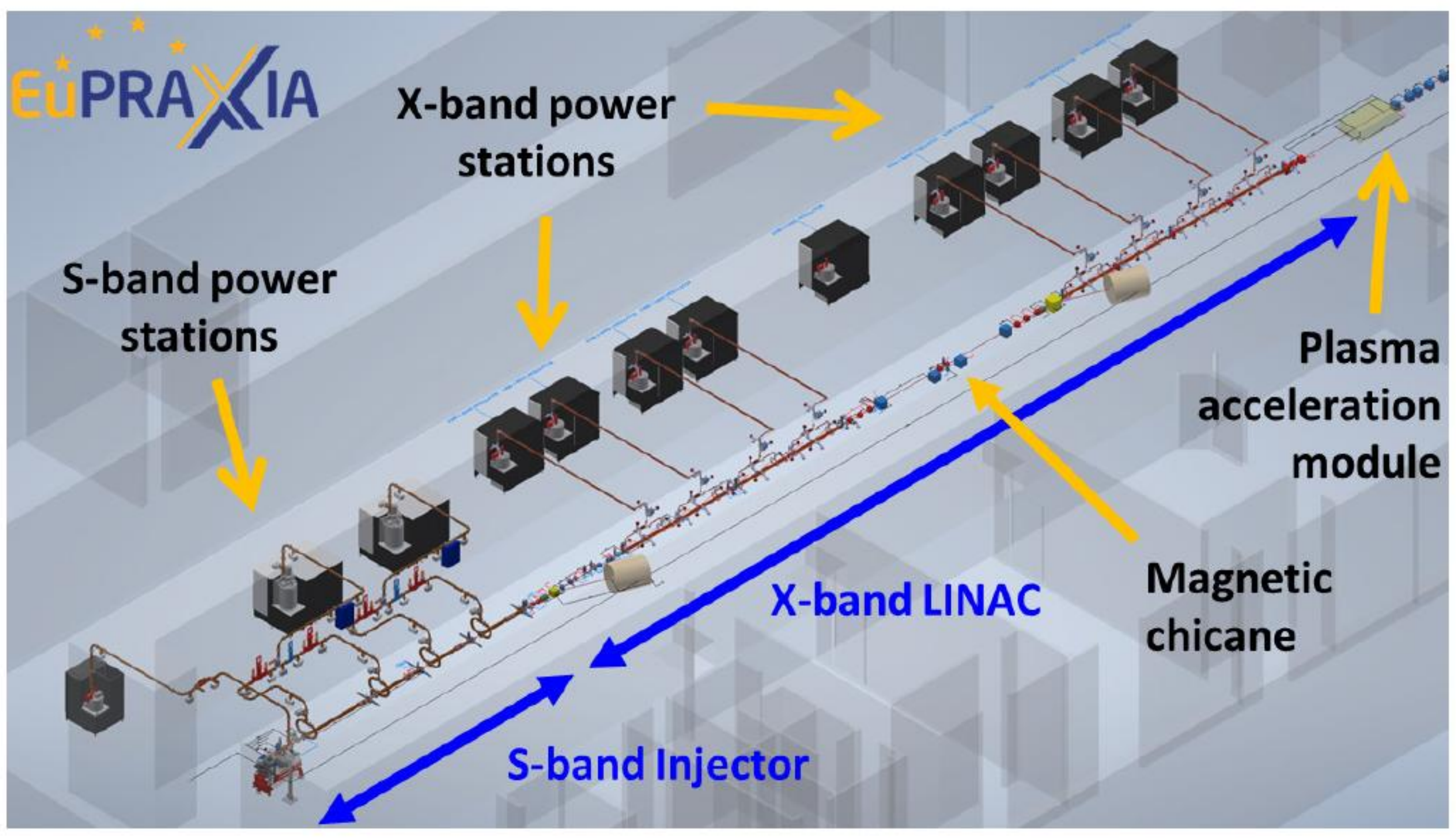
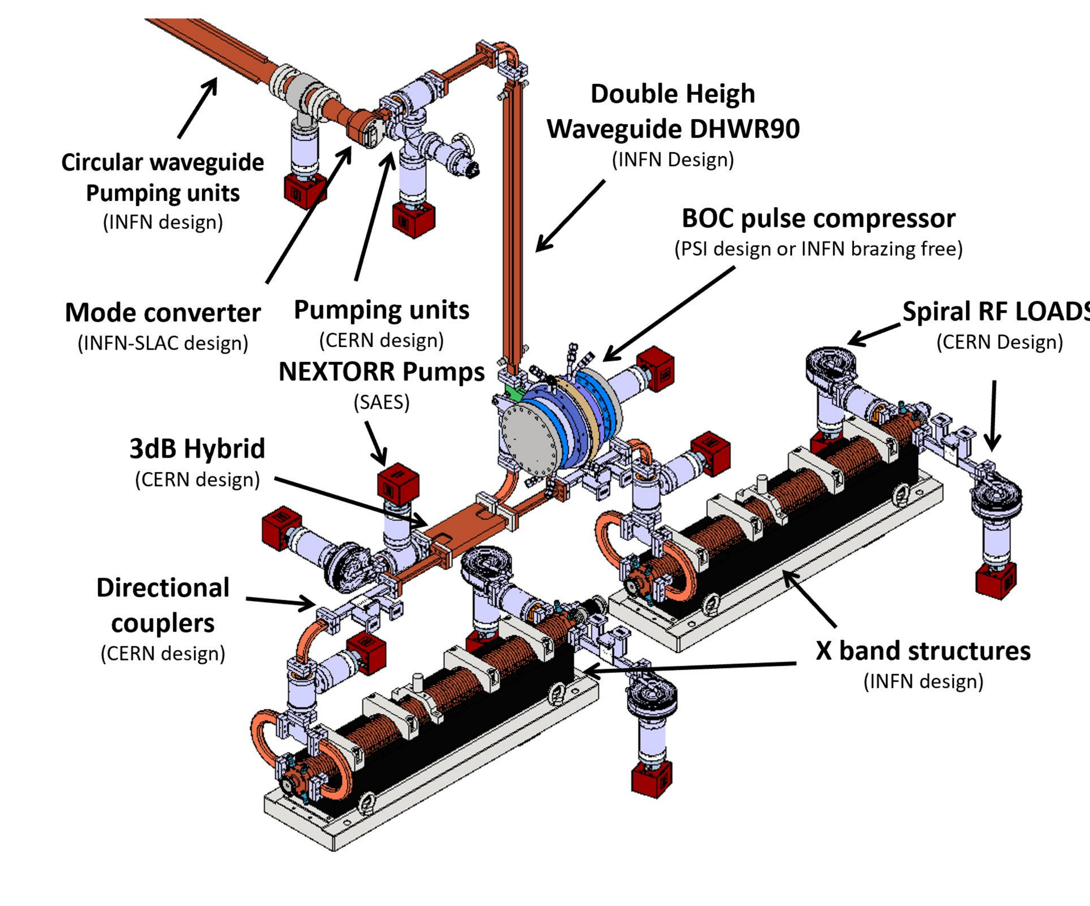
Abstract:

EuPRAXIA@SPARC_LAB aims to be the first European research infrastructure to demonstrate the application of a plasma accelerator. The project is currently in the technical design report preparation phase. This facility combines a high-brightness electron beam in the GeV range, produced by an X-band linac, with a powerful 0.5 PW-class laser system, by utilizing a sophisticated "particle-driven configuration" to achieve highly efficient particle acceleration. This method involves an RF injector system consisting of an S-band photoinjector and an X-band linac. In the typical operating scenario, the system is designed to handle a witness beam with a charge of 30 pC and a driver beam with a charge of 200 pC. These beams are longitudinally compressed within the photoinjector and boosted in energy in the X-band linac. This work reports on beam dynamics studies devoted to investigating and comparing several methods to mitigate wake fields contributions in the X-band linac due to residual machine misalignments regarding beam quality preservation. Dedicated simulations will be performed implementing Dispersion-Free Steering (DFS) and Wakefield-Free Steering (WFS) correction algorithms with the RF track code, aimed at minimizing trajectory deviations and mitigating transverse emittance dilution, thus ensuring the beam quality required for efficient plasma injection.

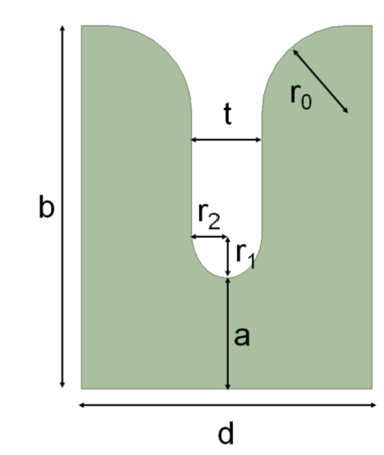
EuPRAXIA@SPARC_LAB



EuPRAXIA@SPARC_LAB High energy X-band Linac



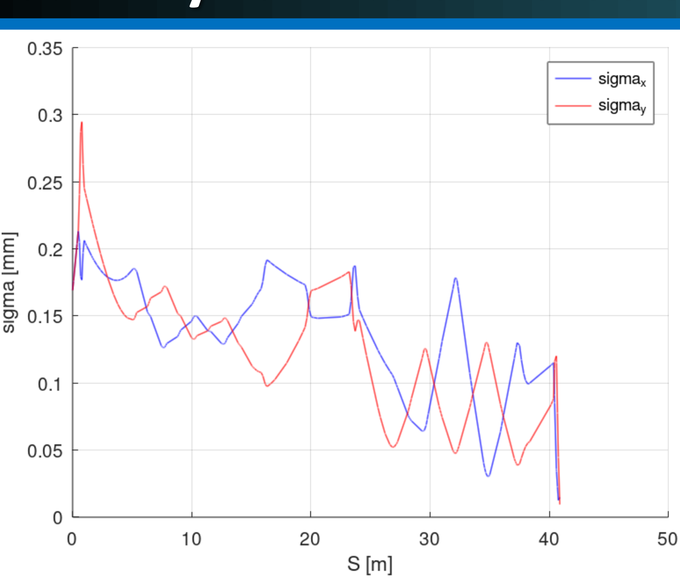
Accelerating structures parameter	Symbol	Unit	Value
Frequency	f_{RF}	GHz	11.9942
Average accelerating field	E_{acc}	MV/m	60
Iris radius (linear tapered)	a	mm	3.85-3.15 (3.5)
Structure active length	L_s	m	0.94
Number of cells	N_{cell}		112
Shunt impedance per unit length	R	MΩ/m	93-107 (100)
Effective shunt impedance per unit length	R_s	MΩ/m	350 (347)
Peak input power per structure	P_{peak}	MW	70
Input power per structure averaged over the pulse	P_{in}	MW	51
P_{out}/P_{in}		%	25
Filling time	τ_F	ns	130
Peak mod. Poynting Vector	S_c	W/μm²	3.6 (4.3)
Peak Surf. E field	E_P	MV/m	160 (190)
Quality factor	Q		6400
Phase advance per cell	ϕ		$2\pi/3$
Repetition rate	f_{rep}	Hz	100

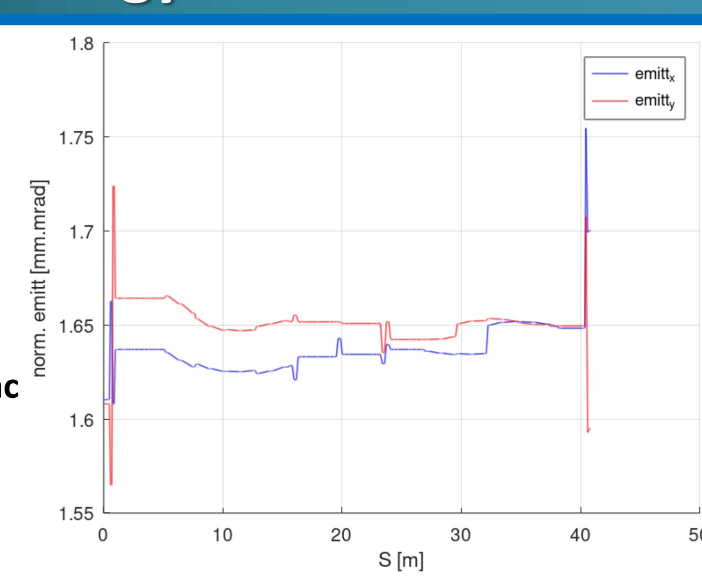


a = 3.5 mm
b = 10.555 mm
t = 2 mm
d = 8.332 mm
r0 = 2.5 mm

Beam dynamics simulations of the High energy X-band linac

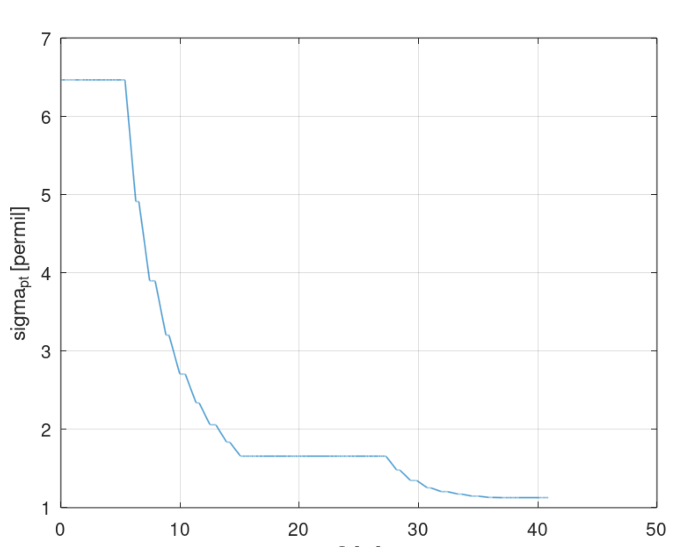
Driver 200pC

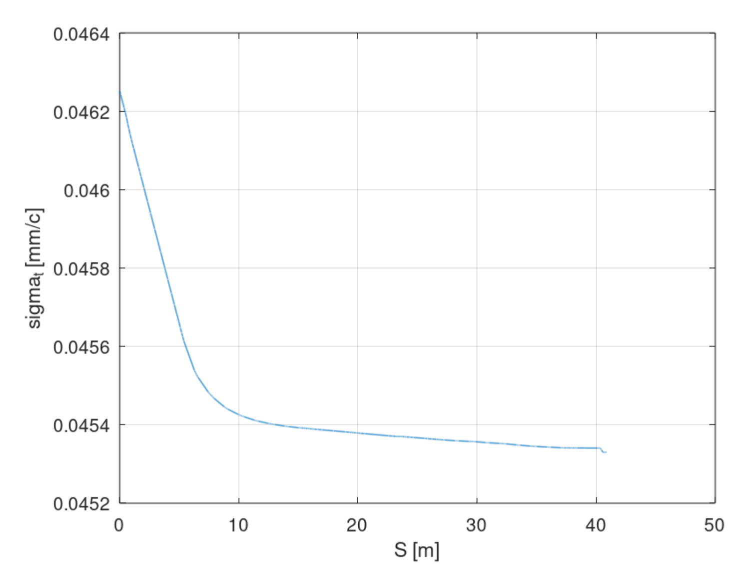




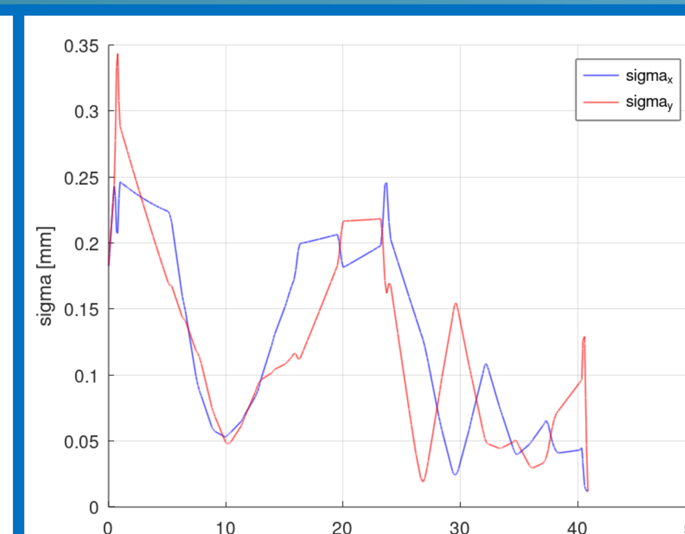
Beam parameter from linac

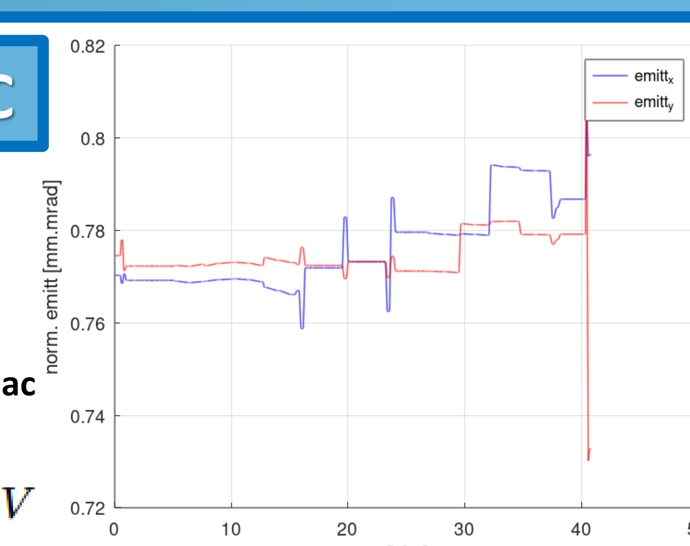
N	200000
$\langle E \rangle$	$563.827\,MeV$
σ_x	$0.009\,mm$
β_x	$0.054\,m$
α_x	0.663
σ_y	$0.009\,mm$
β_y	$0.056\,m$
α_y	0.707





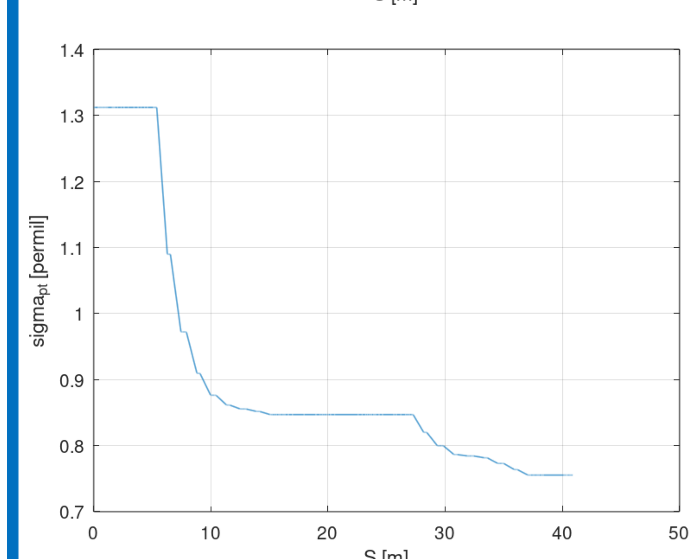
Witness 30pC

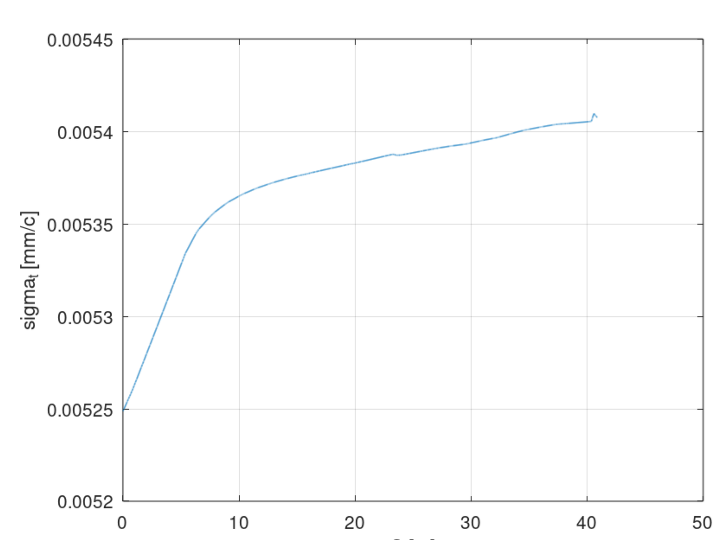




Beam parameter from linac

N	29999
$\langle E \rangle$	$562.506\,MeV$
σ_x	$0.004\,mm$
β_x	$0.025\,m$
α_x	1.016
σ_y	$0.004\,mm$
β_y	$0.026\,m$
α_y	0.964





DFS and WFS analysis

Orbit Correction

We can correct the orbit computing the correctors strength required in order to center the bunch through all BPMs.

If $\mathbf{R}$ is the "response matrix" of our accelerator, that is, the matrix containing the response of each bpm to each corrector,

$$R_{ij} = \frac{\partial b_i}{\partial \theta_j},$$

then, one can anticipate -in linear approximation- the vector of BPM readings, $\mathbf{b}$, corresponding to any arbitrary set of corrector strengths, $\boldsymbol{\theta}$:

$$\mathbf{b} = \mathbf{R} \cdot \boldsymbol{\theta}.$$

Inverting this equation, given a measured orbit, $\mathbf{b}$, one can find the set of correcting correctors settings, $\Delta\boldsymbol{\theta}$:

$$\Delta\boldsymbol{\theta} = -\mathbf{R}^{-1} \cdot \mathbf{b}$$

that provide a counteractin beam excitation. In this equation, $(\mathbf{R})^{-1}$ denotes the pseudo-inverse of the matrix $\mathbf{R}$.

Dispersion-Free Steering

We change the RF phase to send a test beam with an energy different from the nominal. Dispersion-free steering aims to have nominal and test beams pass through the same BPM positions.

$$\begin{pmatrix} & \mathbf{b} \\ \omega_d & (\mathbf{b}_1 - \mathbf{b}) \end{pmatrix} = \begin{pmatrix} & \mathbf{R_0} \\ \omega_d & (\mathbf{R}_1 - \mathbf{R_0}) \end{pmatrix} \boldsymbol{\theta}.$$

Given a measured orbit and dispersive trajectory, the system of equations provides the correcting correctors' settings:

$$\Delta\boldsymbol{\theta} = -\begin{pmatrix} & \mathbf{R_0} \\ \omega_d & (\mathbf{R}_1 - \mathbf{R_0}), \end{pmatrix}^{-1} \begin{pmatrix} & \mathbf{b} \\ \omega_d & (\mathbf{b}_1 - \mathbf{b}) \end{pmatrix},$$

where $(\cdots)^{-1}$ denotes the pseudo-inverse of the matrix.

Wakefield-Free Steering

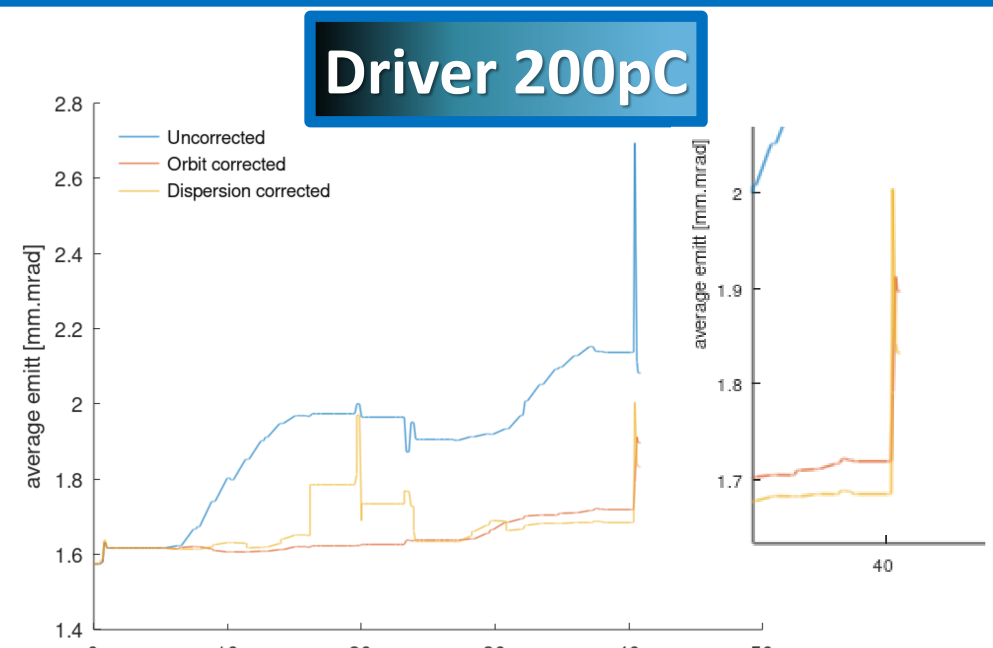
We can apply the same principle to suppress the effect of wakefields on the trajectory. Wakefield-free steering uses a test beam with a different bunch charge to assess the impact of wakefields on the trajectory.

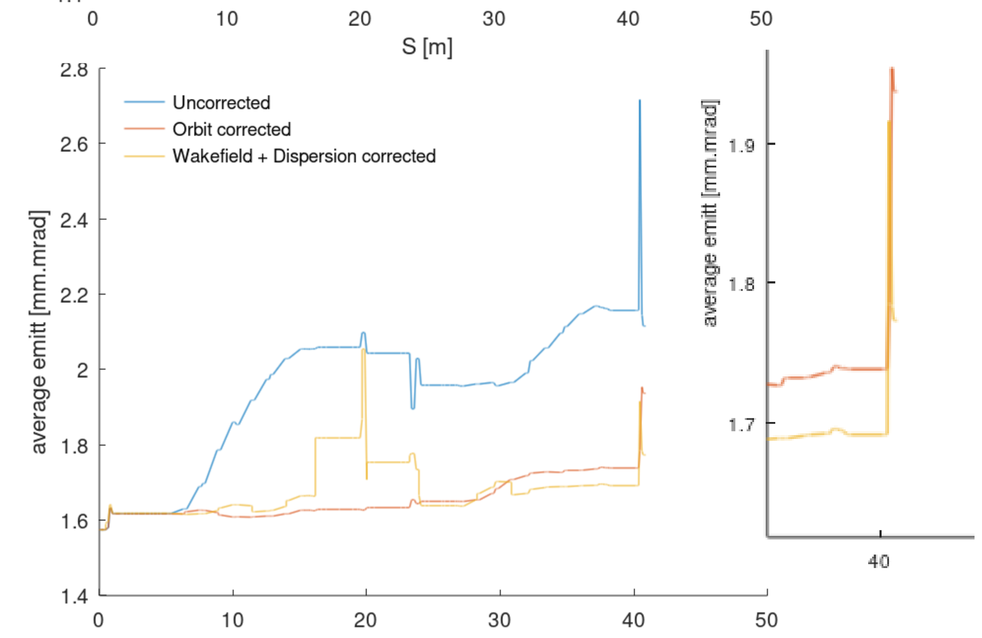
$$\begin{pmatrix} & \mathbf{b} \\ \omega_d & (\mathbf{b} - \mathbf{b}_1) \\ \omega_w & (\mathbf{b} - \mathbf{b}_w) \end{pmatrix} = \begin{pmatrix} & \mathbf{R_0} \\ \omega_d & (\mathbf{R}_1 - \mathbf{R_0}) \\ \omega_w & (\mathbf{R}_w - \mathbf{R_0}) \end{pmatrix} \cdot \boldsymbol{\theta}.$$

Effectively, the trajectory proposed by this algorithm will be minimally subject to the impact of wakefields, that is, the trajectory passing close to each structure's electromagnetic axis. More information about Wakefield-free steering can be found at this reference [1].

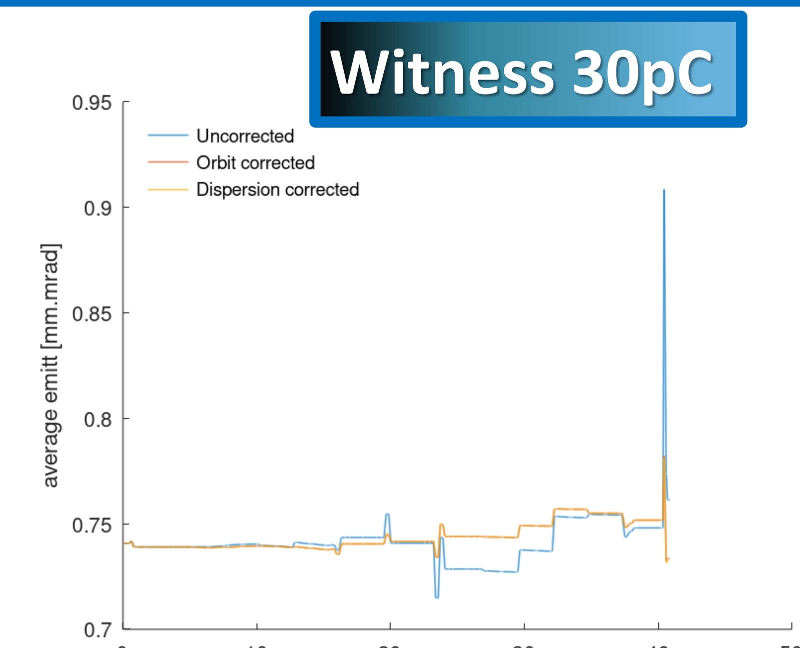
[1] A. Latina et al., "Tests of Beam-based Alignment at FACET", IPAC'14, Dresden, 2014.

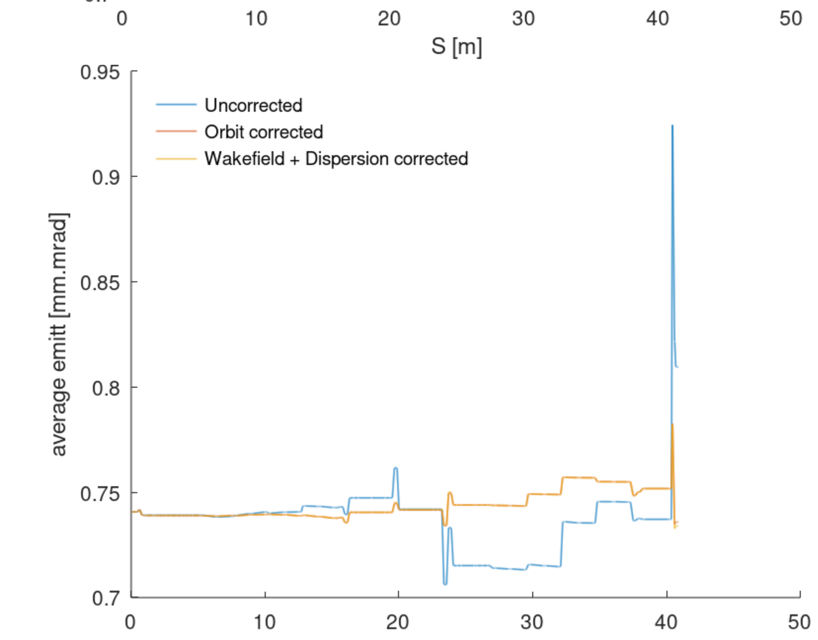
Driver 200pC





Witness 30pC





Conclusion

A beam steering technique aimed at simultaneously mitigating the effects of dispersion and wake fields on the emittance in a linac has been investigated. Further dedicated simulations are required to perform a comprehensive parametric scan of the entire linac, accounting for different misalignment scenarios, as well as to carry out an empirical optimization of the weighting factors (w_d and w_w) to achieve optimal machine performance.