Microbunching Instability Studies: A Semi-Analytical Insight for EuPRAXIA@SPARC_LAB

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G. Campri[1,2,3], S. Di Mitri[3], A. Giribono[4], C. Vaccarezza[4], M. Ferrario[4]

[1]La Sapienza University of Rome, 00185 Roma, Italy
[2]INFN-Sez. Bologna, 40127 Bologna, Italy
[3]Elettra Sincrotrone Trieste, 34149 Basovizza (TS), Italy
[4]Frascati National Laboratories INFN-LNF, 00044 Frascati (RM), Italy

1. EuPRAXIA@SPARC_LAB

- First user-oriented FEL facility driven by plasma wakefield acceleration (PWFA) [1]
- Driving a SASE FEL featuring ultra-shorts (~fs) high-brilliance pulses, in the water window spectral region (AQUA beamline)

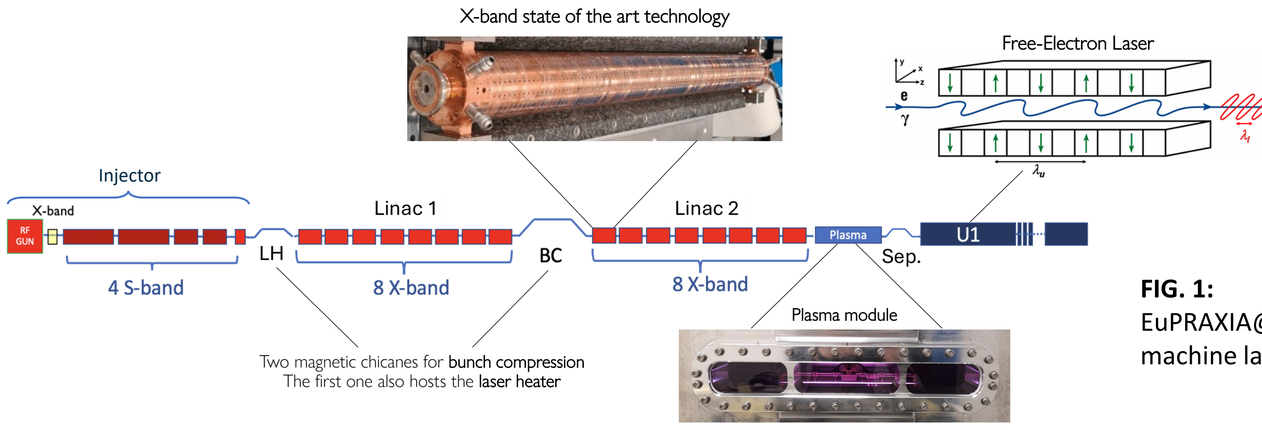


FIG. 1: EuPRAXIA@SPARC_LAB machine layout

2. Microbunching Instability

- Initial current inhomogeneities b_0 (shot noise) drive formation of energy modulations along the bunch, through impedences (LSC, CSR)
- Energy modulations are transformed into amplified current modulations through non-isochronous dispersive sections ($R_{56} \neq 0$)
- The new-formed current modulations drive new amplified energy modulations, and a positive feedback loop is established

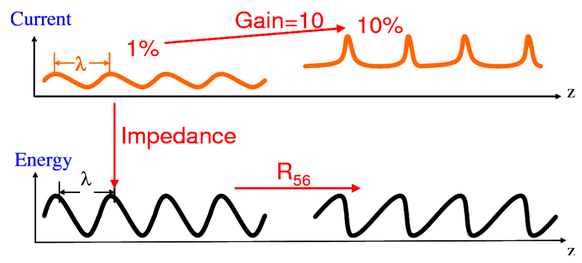


FIG. 2: Mechanism of microbunching instability buildup

3. Analytical Model

- The analytical study of the microbunching instability (MBI) is carried out in Fourier space (the bunching is the Fourier transform of the relative current modulation)

$$b(k) = \frac{1}{\Delta z_b}\int_{-\infty}^{+\infty}\frac{\Delta I(z)}{I_0}e^{-ikz}dz$$

- The Huang-Kim formalism is grounded on the linearization of the Vlasov-Maxwell equation for electron beam distribution passing through a four-dipole symmetric chicane [2]
- The impedances effects are modeled as an integral equation containing the physics of collective effects, including Landau damping

$$b_f(k;s) \approx \frac{CkR_{56}}{\gamma}\overbrace{\frac{4\pi\, I_0}{Z_0 I_A}\int_0^s b_0(k)Z_{LSC}(k;s')ds'}^{\Delta\gamma} LD_{\parallel} \qquad LD_{\parallel} = \exp\left[-\tfrac{1}{2}(CkR_{56}\sigma_\delta)^2\right]$$

- The equivalent instability-induced energy spread is computed as the integral of the energy modulations over all frequencies [3]

$$\sigma_{MBI} = mc^2\sqrt{2\int_0^\infty \frac{|\Delta\gamma(\lambda)|^2}{\lambda}d\lambda}$$

- Values are to be taken as an indication, since smaller intrinsic energy spread σ_{int} and larger initial bunching b_0 can lead to greater instabilities

Main figures of merit

Spectral Gain

$$G(\lambda) = \left|\frac{b_f}{b_0}\right|$$

Relative energy spread

$$\sigma_\delta = \frac{1}{E}\sqrt{\sigma_{int}^2 + \sigma_{IBS}^2 + \sigma_{LH}^2 + \sigma_{MBI}^2}$$

Intrisic energy spread (initial ~2 keV) | Intrabeam scattering | Laser heater

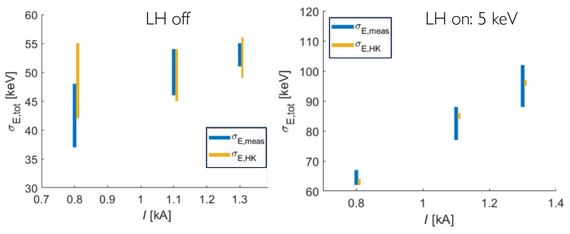
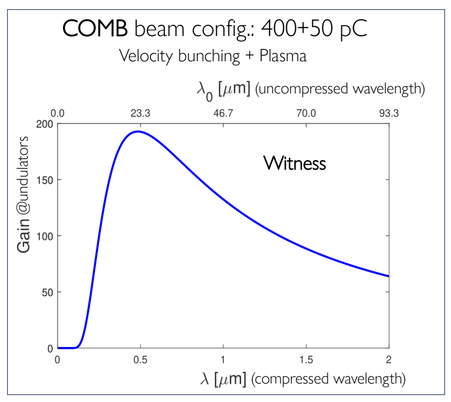


FIG. 3: Benchamark of measurements @FERMI for three bunch compression factors, with laser heater off (left) and at 5 keV (right)

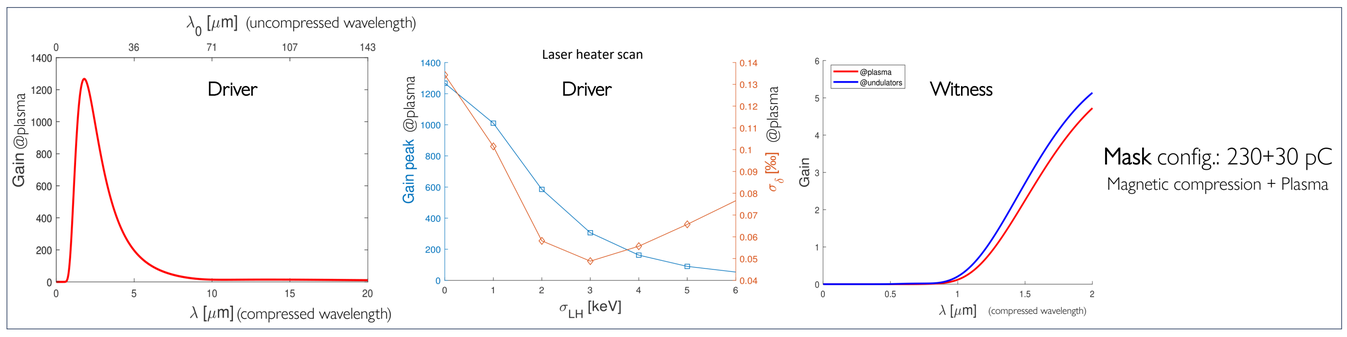
4. Results



Tab. 1: Machine parameters for the configurations tested and corresponding analytical model results

Parameter		COMB		Mask		Full-RF
Beam energy @LH (MeV)		100		270		250
Beam energy @BC (MeV)		330		400		670
Beam energy @Plasma (MeV)		560		600		-
Beam final energy (GeV)		1.0		1.0		1.1
LC chicane R_{56}, T_{566}	(mm)	-		-60.0, 59.0		-60.5, 59.7
BC chicane R_{56}, T_{566}	(mm)	-		-25.0, 24.0		-25.0, 24.0
Sep. chicane R_{56}, T_{566}	(mm)	-1.0, 1.5		-1.0, 1.5		-
		witness	driver	witness	driver	-
Q (pC)		50	400	30	230	250
σ_δ @Plasma (‰)		0.1	0.1	0.3	0.1	-
σ_δ @Undulator (‰)		0.1	-	0.3	-	< 0.1

$< \rho_{FEL} \sim 10^{-3}$



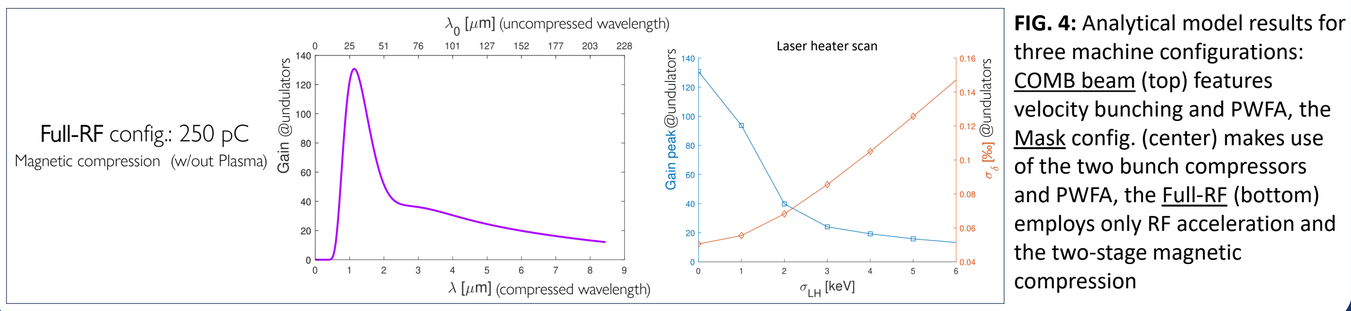


FIG. 4: Analytical model results for three machine configurations: COMB beam (top) features velocity bunching and PWFA, the Mask config. (center) makes use of the two bunch compressors and PWFA, the Full-RF (bottom) employs only RF acceleration and the two-stage magnetic compression

5. Laser Heater Design

- The laser heater (LH) is a device that can be used to increase the uncorrelated energy spread of the electron beam before the instability builds up, harnessing longitudinal Landau damping of the MBI [4]
- The design of EuPRAXIA@SPARC_LAB laser heater system has been studied to accomodate all possible machine configurations

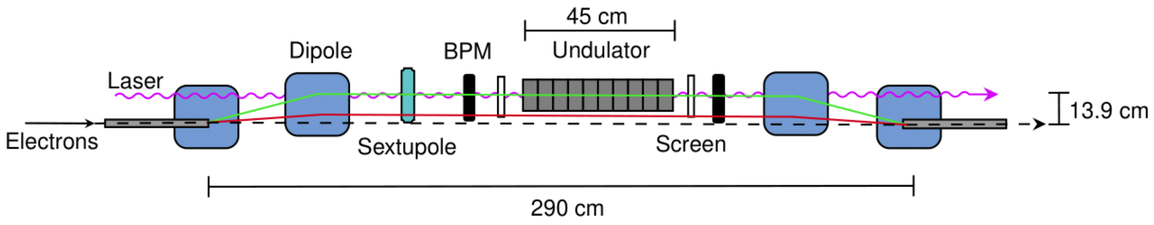


FIG. 5: Schematic layout of EuPRAXIA@SPARC_LAB laser heater system

Planar Undulator
- 45 mm period
- 10 periods
- Remanent field 1.2 T
- Full gap 15–35 mm
- Undulator parameter 0.8–3

Laser System
- Branch of the PIL system (Ti:Sapphire)
- Up to 50 μJ (~5 MW)
- Fundamental harmonic ($\lambda_l \approx 800$ nm)
- Second harmonic ($\lambda_l \approx 400$ nm)
- Independent vertical and horizontal focusing

Magnetic Chicane
- Adjustable angles $|\theta_B| = 4$–$14.5°$
- Beam horizontal excursion 39–139 mm
- Common transverse translation stage, movable in a range of ~110 mm

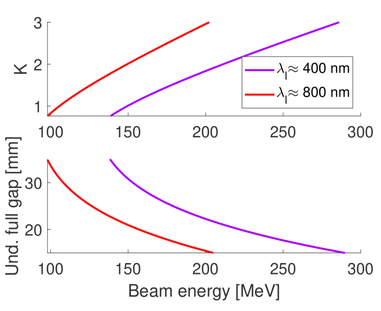


FIG. 5: Undulator parameter and full gap in the resonant condition (Analytical)

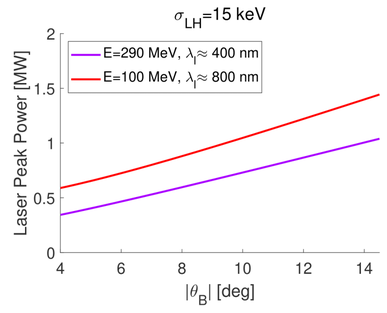


FIG. 6: Laser peak power vs. chicane bending angles for an induced energy spread of 15 keV (Analytical)

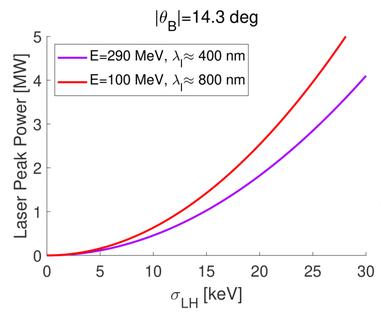


FIG. 7: Laser peak power vs. induced energy spread for low and high beam energy (Analytical)

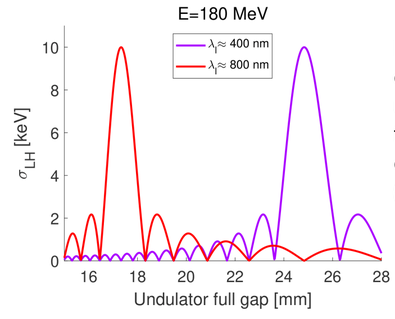


FIG. 8: Induced energy spread vs. undulator full gap for a beam energy of 180 MeV (Analytical)

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