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Towards a Plasma Undulator Experiment at SPARC_LAB

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ABSTRACT

Plasma-based undulators offer a promising route towards compact radiation sources by exploiting the betatron motion of relativistic electrons in an ion channel [1,2]. A proof-of-principle experiment is being developed at SPARC_LAB [3], within the EuPRAXIA@SPARC_LAB project [4], to investigate this concept under experimentally realistic conditions. Previous studies assessed ion-channel formation and the radiation emitted by a matched witness bunch, identifying beam quality and transverse matching as key requirements for the observation of enhanced betatron radiation and FEL-like amplification [5]. Building on these results, we present ongoing studies toward the experimental implementation of the scheme. Particular attention is devoted to identifying suitable accelerator working points for the generation and transport of the required driver-witness beam configuration and to evaluating the radiation expected from realistic electron beam distributions.

THEORETICAL BACKGROUND

Ion channel undulator:

An ion channel (IC) provides an approximately linear transverse focusing force, inducing betatron oscillations that emulate the periodic motion of a magnetic undulator. In the proposed scheme, a high-current **driver** expels the electrons from a narrow pre-ionized plasma channel, leaving a nearly pure, wakeless ion column. A trailing **witness** bunch propagates in this focusing field and emits betatron radiation. For the IC:

$$\lambda_\beta = \frac{2\pi c}{\omega_\beta} \qquad \omega_\beta = \frac{\omega_p}{\sqrt{2\gamma}} \qquad K_\beta = \gamma k_\beta r_\beta$$

$$\lambda_r = \frac{\lambda_\beta}{2\gamma^2}\left(1 + \frac{K_\beta^2}{2}\right)$$

Unlike a magnetic undulator, the effective undulator parameters are intrinsically linked to the beam dynamics and transverse matching.

FEL formalism:

A 1D time-dependent FEL model describes the self-consistent evolution of the radiation field E, the ponderomotive phase ψ_j, and the relative energy deviation δ_j:

$$\frac{dE}{dz} = -\frac{n_e e}{4\varepsilon_0\gamma_0}\left\langle \frac{K_{\beta j}}{1+\delta_j}\left[J_0\left(\frac{K_{\beta j}^2}{4+2K_{\beta j}^2}\right) - J_1\left(\frac{K_{\beta j}^2}{4+2K_{\beta j}^2}\right)\right]e^{-i\psi_j}\right\rangle,$$

$$\frac{d\psi_j}{dz} = \frac{4\pi}{\lambda_\beta}\left[\delta_j + \frac{\delta_j K_{\beta j}^2}{2} - \frac{K_{\beta j}^2}{4}\right],$$

$$\frac{d\delta_j}{dz} = -\frac{eK_{\beta j}}{4\gamma_0^2 mc^2(1+\delta_j)}\left(Ee^{i\psi_j} + E^* e^{-i\psi_j}\right),$$

The bunching factor b quantifies microbunching and the onset of coherent FEL-like amplification:

$$b = \left\langle e^{-i\psi_j}\right\rangle$$

Plasma matching condition:

Matching minimizes envelope oscillations and fixes the transverse beam size, directly affecting the beam–radiation coupling and FEL gain.

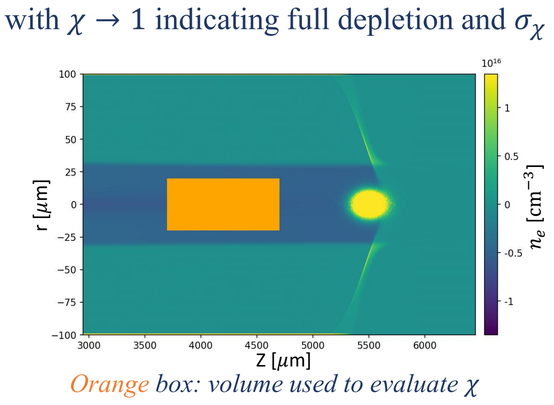
$$\varepsilon_{n,\mathrm{rms}} = \gamma\,\sigma_w^2\,k_\beta$$

FEASIBILITY STUDIES

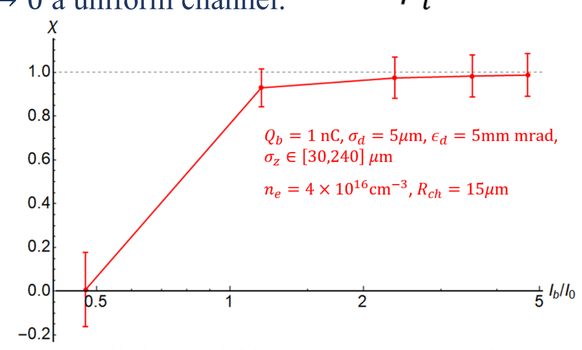
Ion channel formation:

FBPIC simulations quantify ion-channel depletion through χ, with $\chi \to 1$ indicating full depletion and $\sigma_\chi \to 0$ a uniform channel.

$$\chi = \frac{\langle\rho\rangle}{\rho_i^{(0)}}$$



Orange box: volume used to evaluate χ

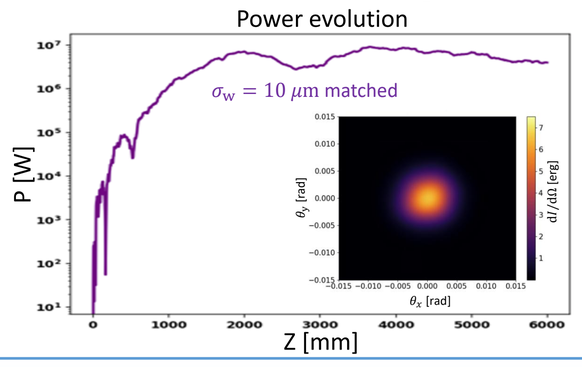


A well defined IC is obtained as $I_b/I_0 \sim 1$

FEL-like amplification:

For a transversely matched witness with SPARC_LAB-compatible parameters, the 1D FEL model predicts exponential power growth and saturation within a meter-scale plasma channel.

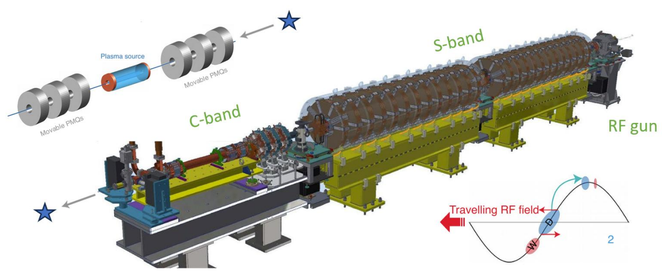
Parameter	Symbol	Unit	Value
Beam and plasma parameters			
Beam energy	E_{beam}	MeV	100
Beam charge	Q	pC	200
Norm. slice emittance	$\varepsilon_{n,\mathrm{rms}}$	mm mrad	1
RMS longitudinal size	σ_z	μm	< 30
Ion-channel radius	R_{ch}	μm	15
Plasma density	n_0	cm^{-3}	5×10^{15}
Radiation parameters			
Radiation wavelength	λ_r	nm	223
Peak power	P	MW	80
Number of photons	N_{ph}	–	1.3×10^{7}



SPARC_LAB WORKING POINT

Start-to-end comb generation:

- SPARC_LAB injector layout:

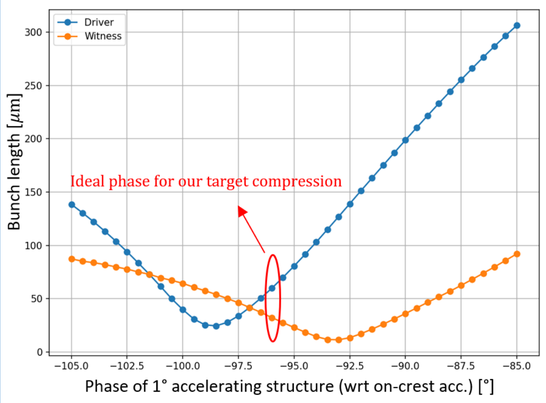


Nominal target beams:

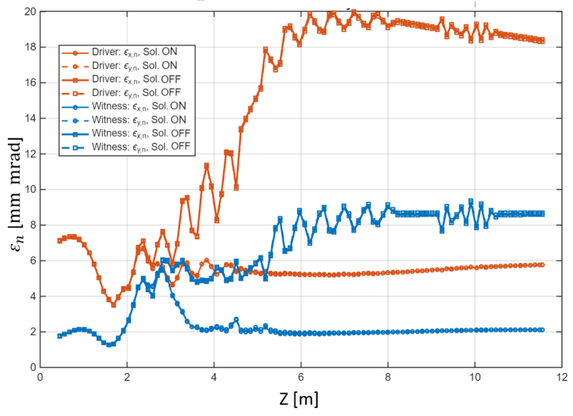
	Driver	Witness
Charge	1 nC	200 pC
σ_z	$\sim 60\,\mu$m	$\sim 30\,\mu$m
ε_n	~ 5 mm mrad	~ 1 mm mrad
Role	IC formation	Radiation

For the nominal $n_e = 5\times10^{15}$cm^{-3}

- Velocity bunching at 1st S-band:

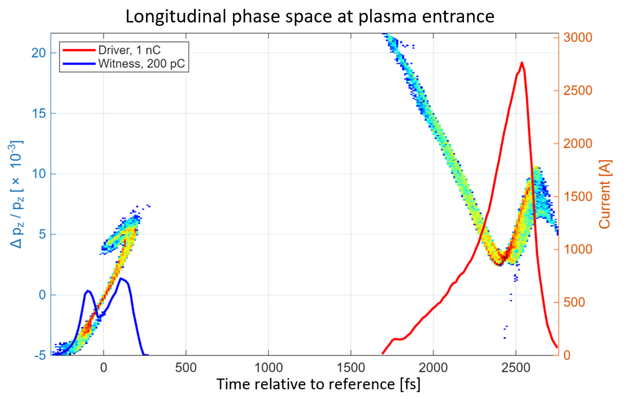


- Emittance compensation with solenoids:



The final optimization stage before the PMQs is carried out with GIOTTO [6]:

Parameter	Optimized WP
Driver	
Charge Q_d	1 nC
RMS bunch length $\sigma_{z,d}$	62 μm
Norm. transverse emittance $\varepsilon_{n,d}$	5.4 mm mrad
Witness	
Charge Q_w	200 pC
RMS bunch length $\sigma_{z,w}$	33 μm
Norm. transverse emittance $\varepsilon_{n,w}$	1.5 mm mrad
Beam energy E	103 MeV

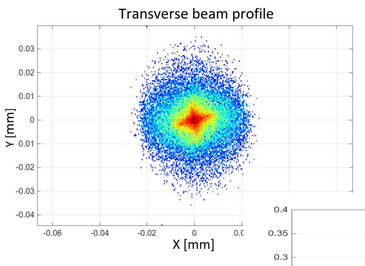


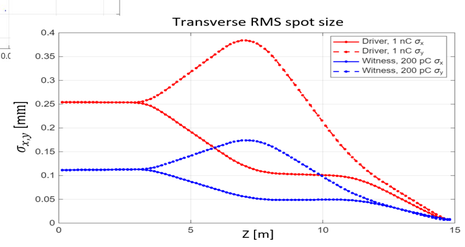
An alternative WP with $Q_d = 600pC$ and $Q_w = 120pC$ is also investigated, since it reduces space-charge-induced degradation of the beam quality. Lower driver charge reduces the peak current available for ion-channel formation, the plasma density must be adjusted accordingly.

Final focusing and plasma matching:

For the nominal WP at $n_p = 5\times10^{15}$cm^{-3}, the corresponding matched rms sizes are shown in the table. Final focusing is done using a triplet of PMQs upstream of the plasma entrance.

	Driver	Witness
Target	6.33 μm	3.48 μm
Current best	~ 7 μm	~ 7 μm

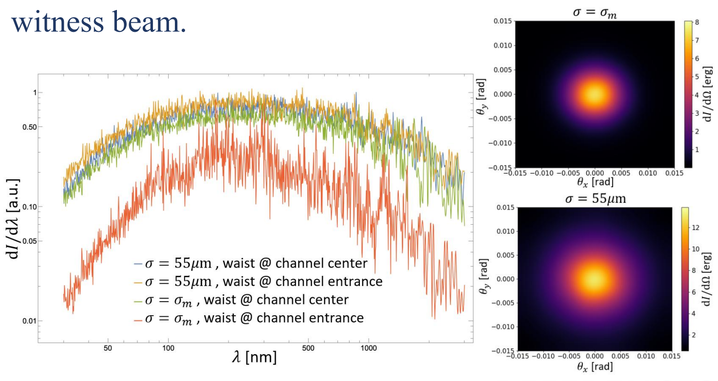




In this configuration the driver's bunch length increases 62 μm → 98 μm, however IC formation is still feasible by using a lower n_e

Preliminary radiation studies:

Radiation emitted at both WPs: Unmatched and matched (shrinked via transfer matrices) witness beam.



- Matched beam → narrower spectrum and angular distribution
- Waist at plasma entrance → narrower spectrum
- Larger unmatched spot → stronger emission, but broader spectrum

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