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APPLICATIONS

EuPRAXIA
Preparatory Phase

Towards a Plasma Undulator Experiment at SPARC_LAB

Carlos Buitrago (INFN-LNF)
On behalf of the SPARC_LAB collaboration

EuPRAXIA_PP Final Meeting and EuPRAXIA_DN Conference, September 2026

Funded by the European Union

This project has received funding from the European Union´s Horizon Europe research and innovation programme under grant agreement No. 101079773. It is supported by in-kind contributions by its partners and by additional funding from UK and Switzerland.

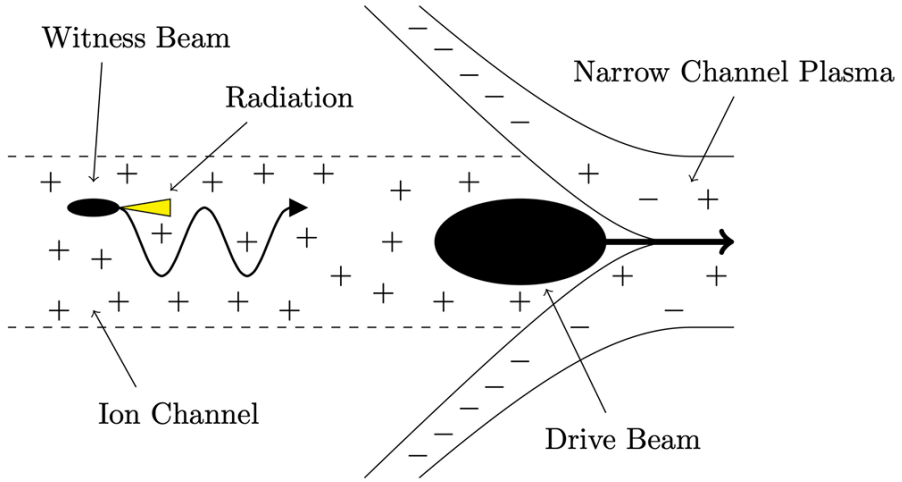
Outline

- Ion channel-based undulator
- Feasibility of experiment at SPARC_LAB
- Quasi start-to-end simulations
  - (ASTRA, FBPIC, GIOTTO, Radyno)
- Conclusions

Plasma ion channel as an undulator

- An ion column produces an approximately linear transverse focusing force

  → Betatron oscillations with ω_β



Litos, M., "Free Electron Lasers Driven by Plasma Accelerators: Status and Near-Term Perspectives," EAAC 2023, La Biodola, Isola d'Elba, Italy, 17–23 Sept. 2023

Analogous to magnetic undulator (small oscillations regime):

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

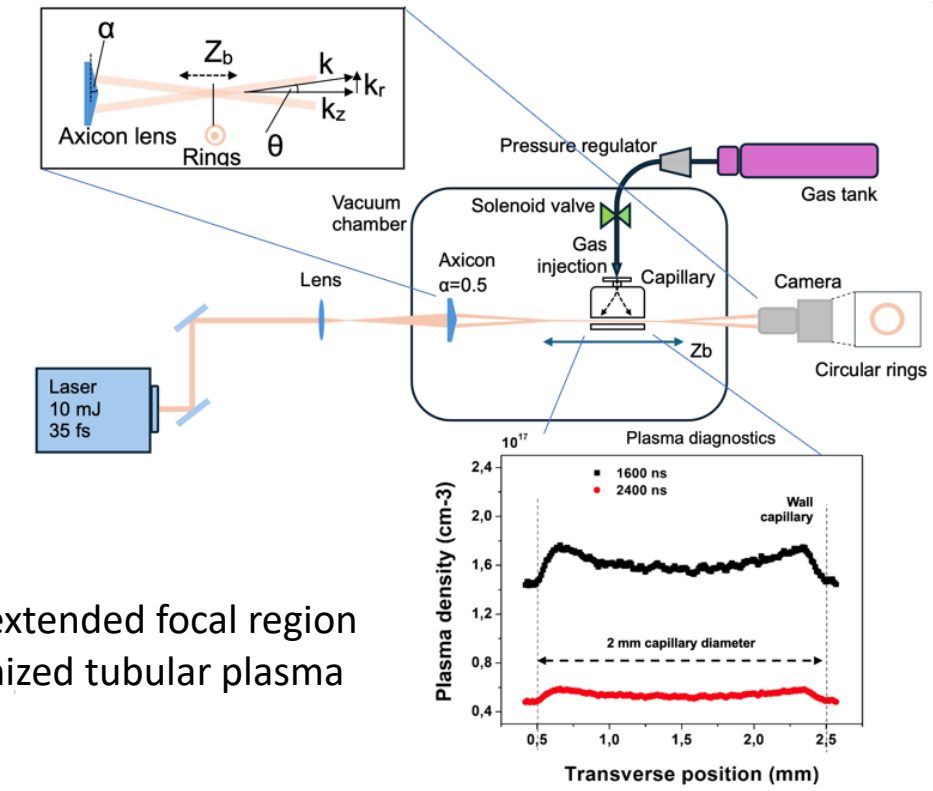
$$K_\beta = \gamma k_\beta r_\beta$$

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

But undulator parameters are **determined by particles dynamics**

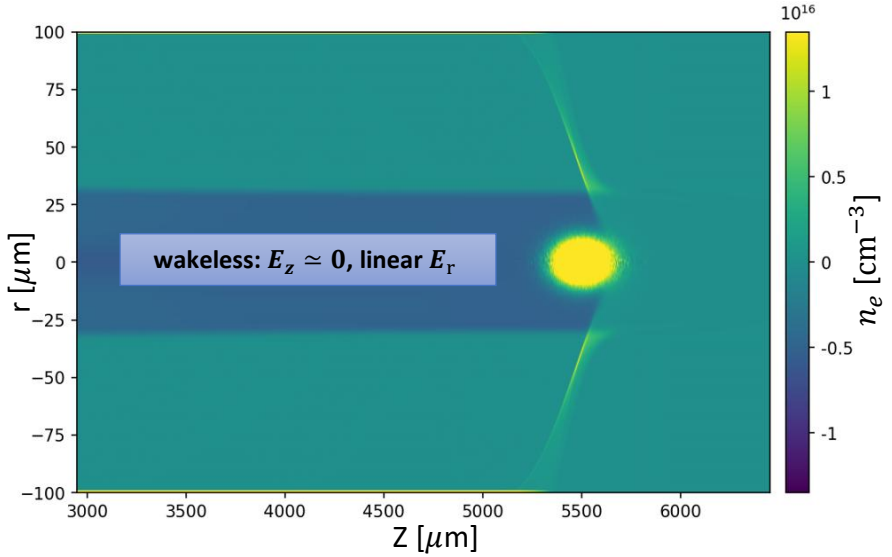
Scheme of the experiment at SPARC_LAB

Plasma source:



- ✓ Axicon lens → extended focal region
- ✓ Laser → pre-ionized tubular plasma

- **Driver:** high I_b → channel formation
- **Witness:** low ϵ_n, matched → radiation



Chiadroni E. et al., Proc. 17th Int. Particle Accelerator Conf. (IPAC'26), Deauville, France, 2026, pp. 1747–1749, doi: 10.18429/JACoW-IPAC2026-TUP3019

Ion channel formation

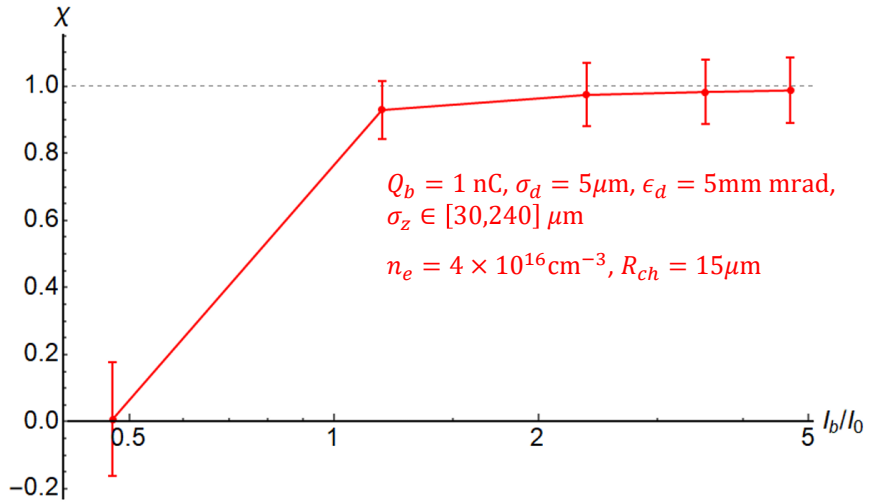
Simple scaling from imposing that the *maximum blowout radius produced by the driver exceeds the channel radius:*

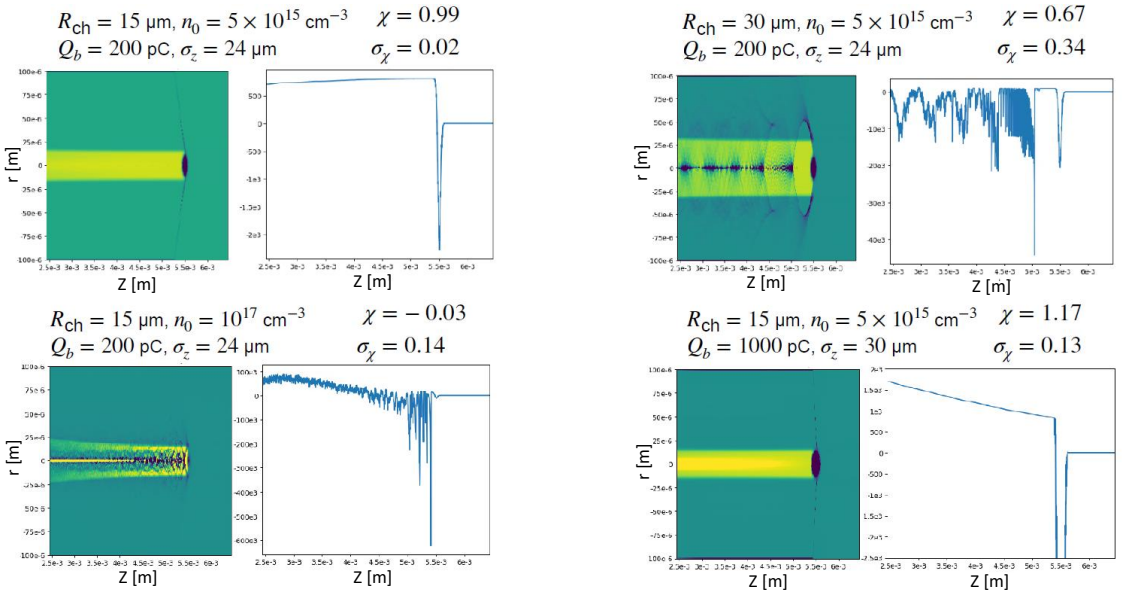
$$r_{\max} > R_{\mathrm{ch}} \longrightarrow \boxed{\frac{I_b}{I_0} > \frac{1}{2}}$$

(Approximate threshold)

$$\chi = \frac{\langle \rho \rangle}{\rho_i^{(0)}} \qquad \chi \to 1 : \text{Fully depleted IC}$$

$\sigma_\chi \approx 0 \rightarrow$ channel *uniformity*



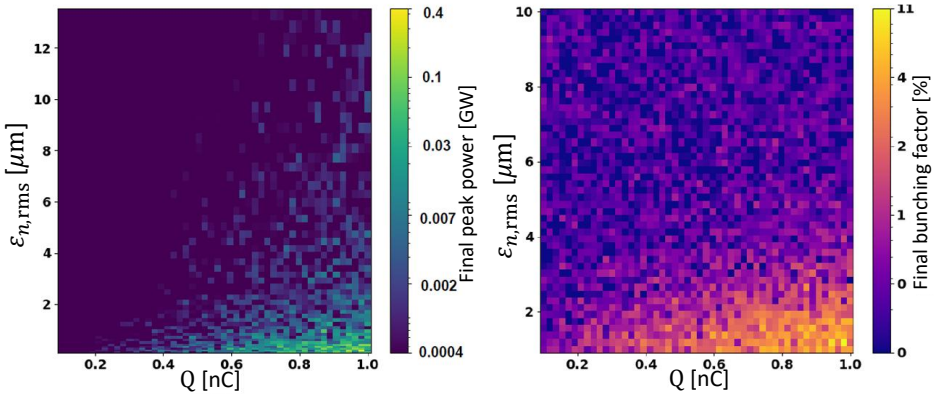


robust ion-channel formation for $I_b/I_0 \sim 1$or larger

Rossi, A.R. et al., "Ion channel formation for advanced betatron emission," 7th European Advanced Accelerator Conference (EAAC 2025), La Biodola, Isola d'Elba, Italy, 21–27 Sept. 2025.

Radiation and FEL-like amplification

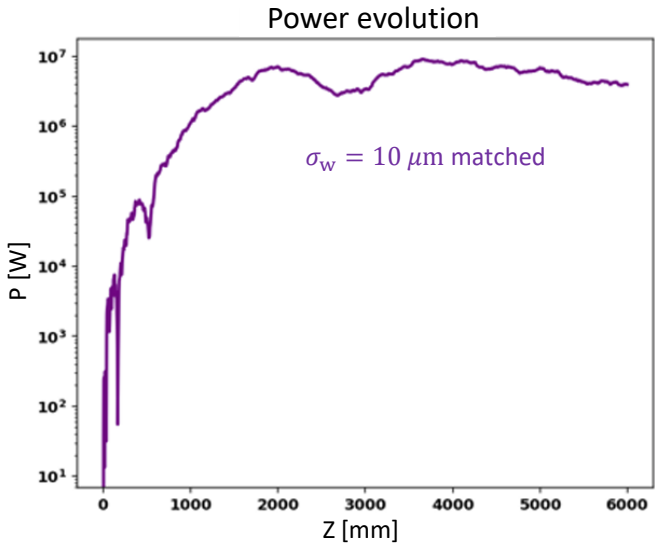
Parametric scan:
pre-formed IC + matched witness beam



$$\downarrow \varepsilon_n \,, \downarrow \sigma_m \;\Rightarrow\; \uparrow \text{coupling/gain}$$

$$\uparrow Q \;\Rightarrow \uparrow P$$

➢ Power evolution along a meter-scale plasma channel



Witness beam parameter	Symbol	Unit	Value
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}	$5 \cdot 10^{15}$

Radiation parameter	Symbol	Unit	Value
Radiation wavelength	λ_r	nm	223
Radiation peak power	P	MW	80
Number of photons	N_{ph}		$1.3 \cdot 10^7$

Exponential growth and saturation achievable in less than 2m

Main requirement: high transverse beam quality + proper plasma matching

Curcio, A. et al., “Betatron Radiation as a Path to Plasma Undulators: A Case Study at SPARC_LAB,” Appl. Sci. 2026,16, 4950, doi: 10.3390/app16104950.

From feasibility to an experiment

Start-to-end simulation of SPARC_LAB in order to generate and transport the required driver-witness pair

How close can we actually get to the matched (ideal) beams?

and

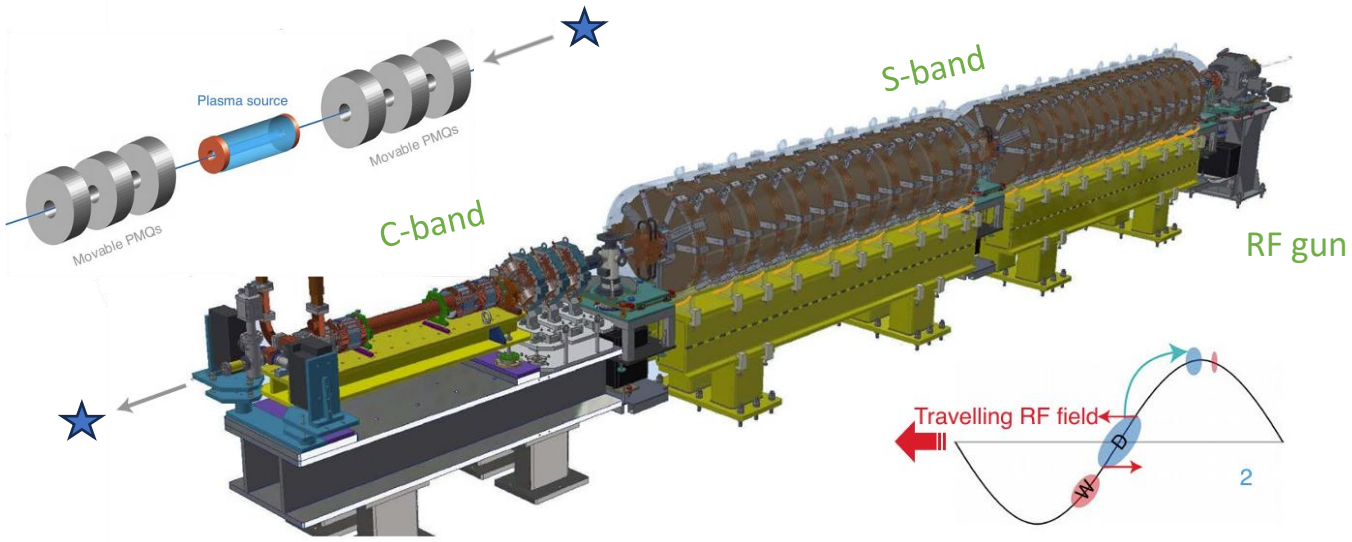
What radiation do we predict when we use the actual start-to-end electron distribution?

Driver and witness beam generation

Funded by the European Union

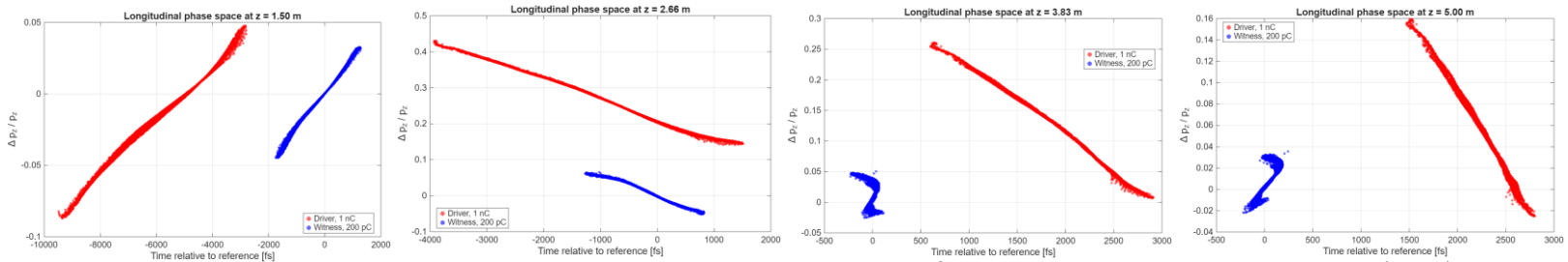
SPARC_LAB injector layout:

- Compression via **velocity bunching** at first S-band
- **Emittance compensation** using the solenoids around the S-band sections
- Permanent quadrupole triplet upstream of plasma module used for **final focusing**



Target beams:

Parameter	Symbol	Unit	Driver target	Witness target
Charge	Q	pC	1000	200
Transverse normalized emittance	ϵ_n	mm mrad	5	1
RMS bunch length	σ_z	μm	60	30
RMS spot size	$\sigma_{x,y}$	μm	6	3



Both beams must be optimized simultaneously

(Space-charge interaction couples the two bunches)

Pompili R. et al., *Energy spread minimization in a beam-driven plasma wakefield accelerator*, Nat. Phys. 17, 499–503 (2021), doi: 10.1038/s41567-020-01116-9.

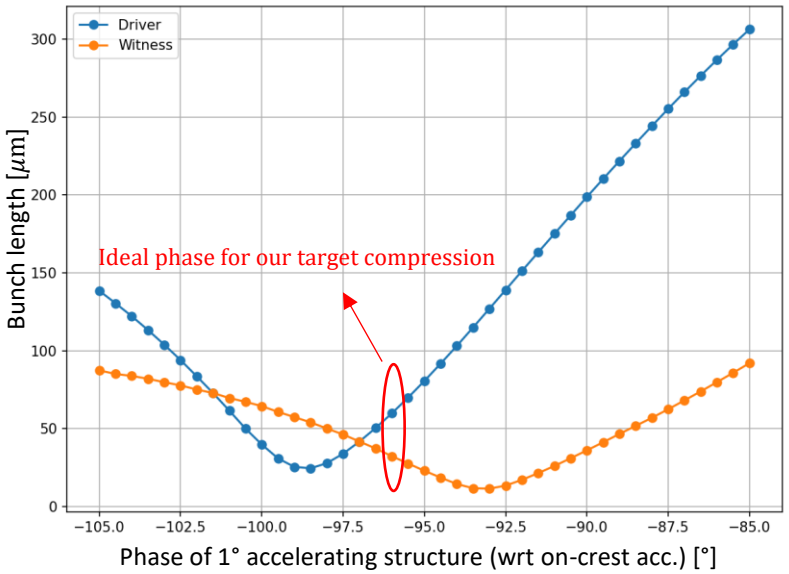
Serafini L. and Ferrario M., *Velocity bunching in photo-injectors*, AIP Conf. Proc. 581, 87–106 (2001), doi: 10.1063/1.1401564.

Driver and witness beam generation

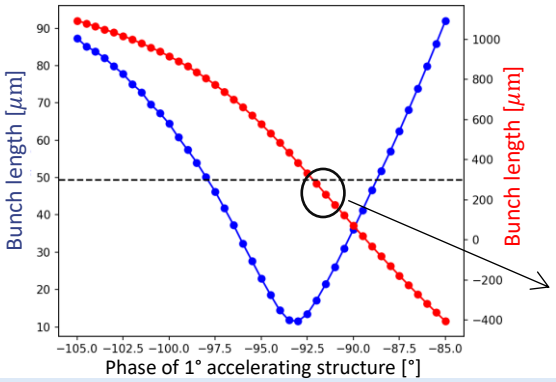
Funded by the European Union

Velocity bunching:

Compression curves of witness and driver beams



Compression vs. bunch separation

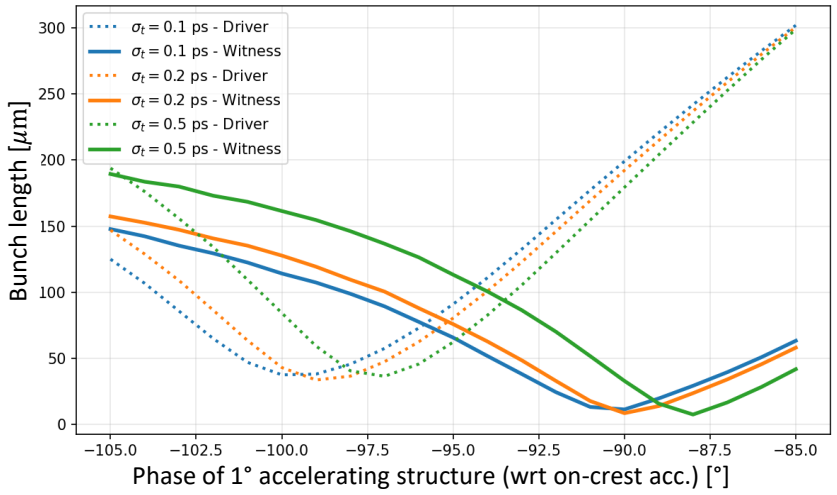


Minimum phase in order to have a separation of at least 1 ps

Cathode control:

Displacement of the compression curves due to variation of parameters at cathode:

Compression curves for different impulse lengths @ cathode



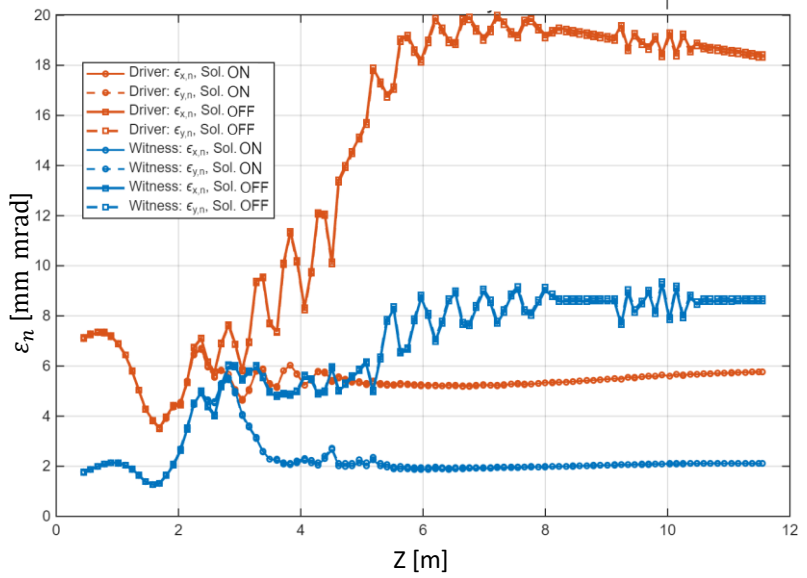
Allows us to find a configuration for which the target length for both bunches can be achieved simultaneously

Emittance compensation:

Transverse emittance growth due to off-crest acceleration

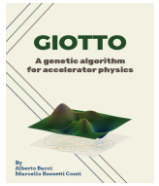
Corrected using accelerating cavities' solenoids (4 triplets in each S-band)

Normalized transverse emittance: Solenoids OFF vs ON



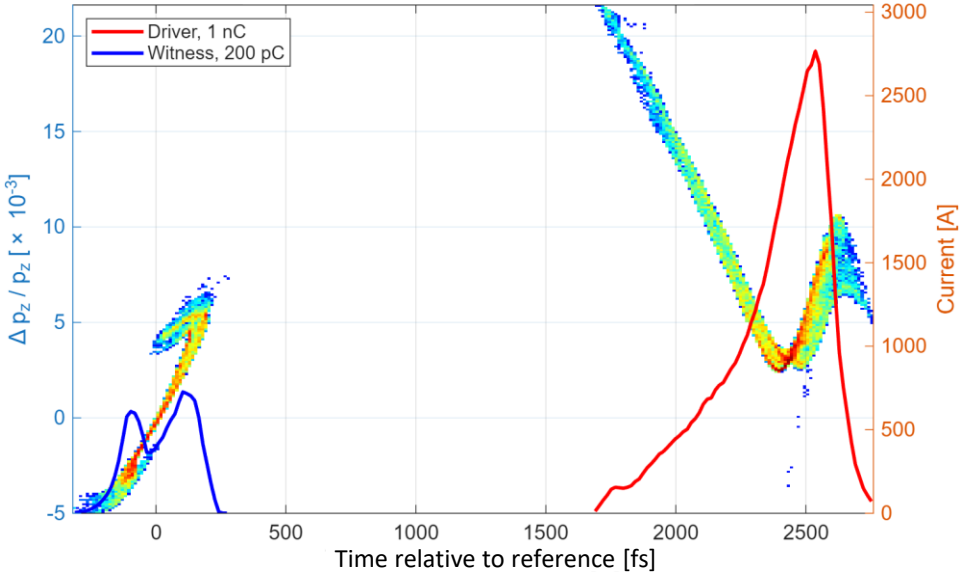
Experimental working points

Final optimization (before final focusing) carried out with the genetic algorithm GIOTTO

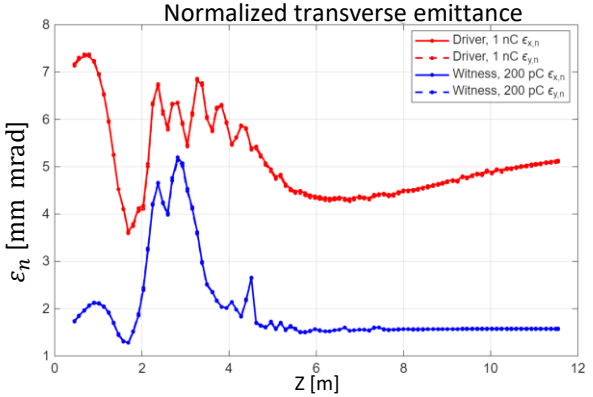


Parameter	Reference	Optimized WP
Driver		
Charge Q_d	1 nC	1 nC
RMS bunch length $\sigma_{z,d}$	60 μm	62 μm
Norm. transverse emittance $\varepsilon_{n,d}$	5 mm mrad	5.4 mm mrad
Witness		
Charge Q_w	200 pC	200 pC
RMS bunch length $\sigma_{z,w}$	30 μm	33 μm
Norm. transverse emittance $\varepsilon_{n,w}$	1 mm mrad	1.5 mm mrad
Beam energy E	$\sim$ 100 MeV	103 MeV

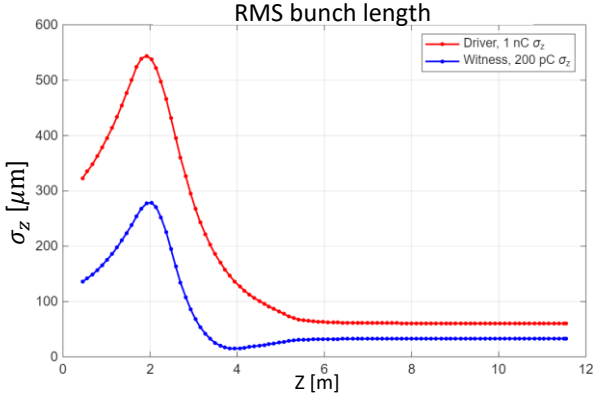
Longitudinal phase space at plasma entrance



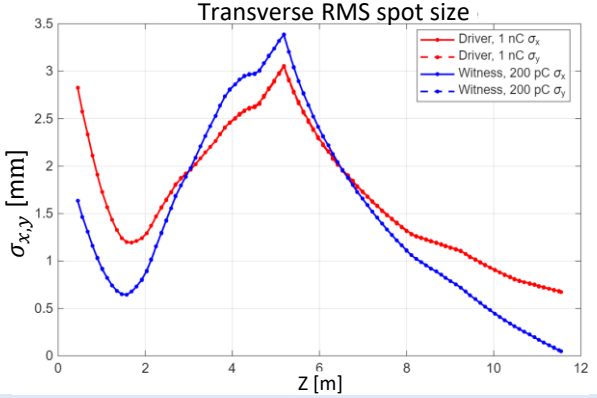
Normalized transverse emittance



RMS bunch length



Transverse RMS spot size



Alternative WP with $Q_d = 600pC$ and $Q_w = 120pC$ is also being studied → IC formation still feasible (similar I_b/I_0 for lower n_e)

A. Bacci, A.; Petrillo, V.; Rossetti Conti, M., "GIOTTO: A Genetic Code for Demanding Beam-dynamics Optimizations," Proc. 7th Int. Particle Accelerator Conf. (IPAC'16), Busan, Korea, 2016, pp. 3073–3076, doi: 10.18429/JACoW-IPAC2016-WEPOY039.

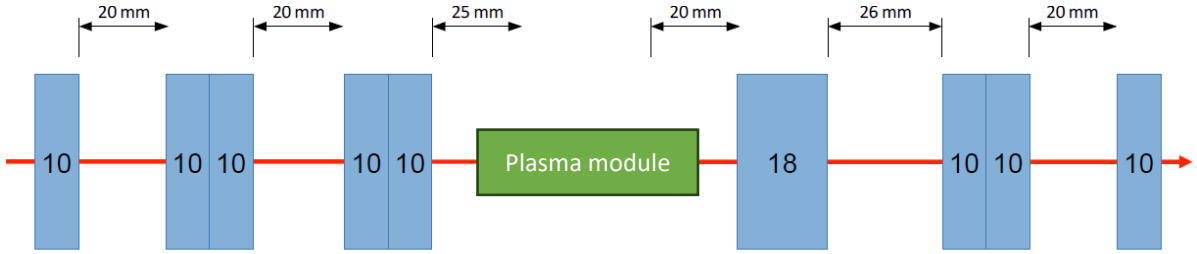
Final focusing and plasma matching

Matching condition: $\epsilon_n = \gamma \sigma_m^2 k_\beta$

→ For the nominal $n_e = 5 \times 10^{15}\mathrm{cm}^{-3}$, the matched spot sizes :

$\sigma_{\mathrm{m,w}} \approx 3.48\ \mu\mathrm{m}$ $\sigma_{\mathrm{m,d}} \approx 6.33\ \mu\mathrm{m}$

PMQs layout (only the triplet before the plasma is used for final focusing):

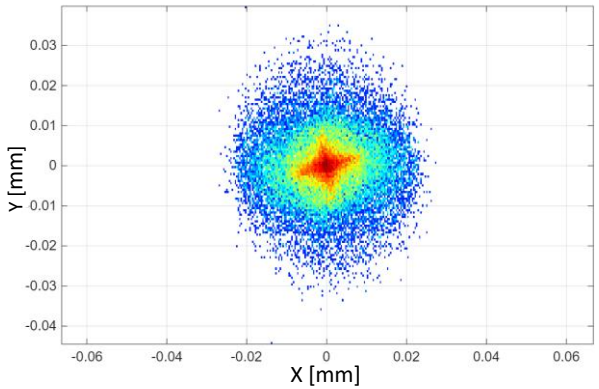


PMQs can move by ± 7mm between them

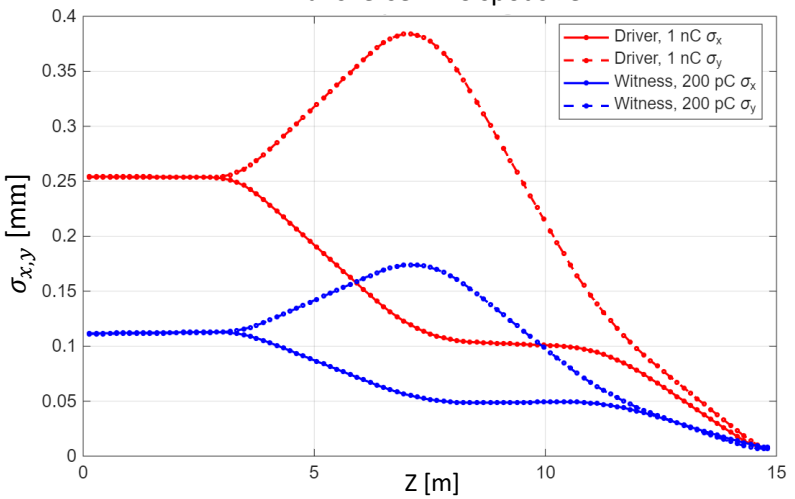
➢ PMQs position optimization + fine tuning of upstream machine parameters (via GIOTTO)

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

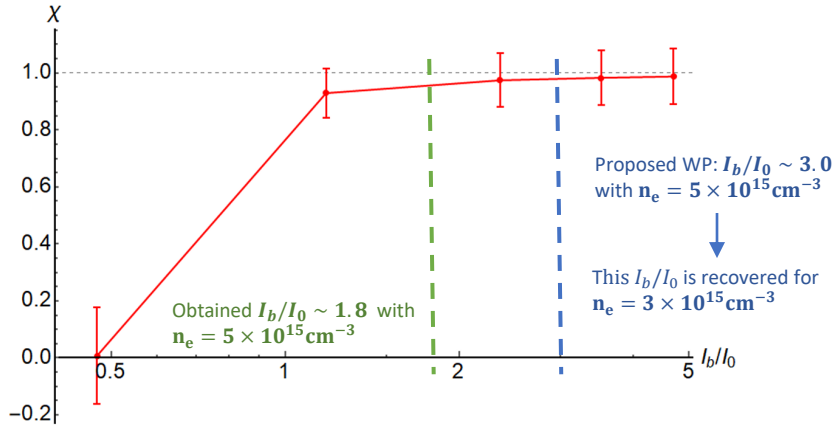
Transverse beam profile



Transverse RMS spot size



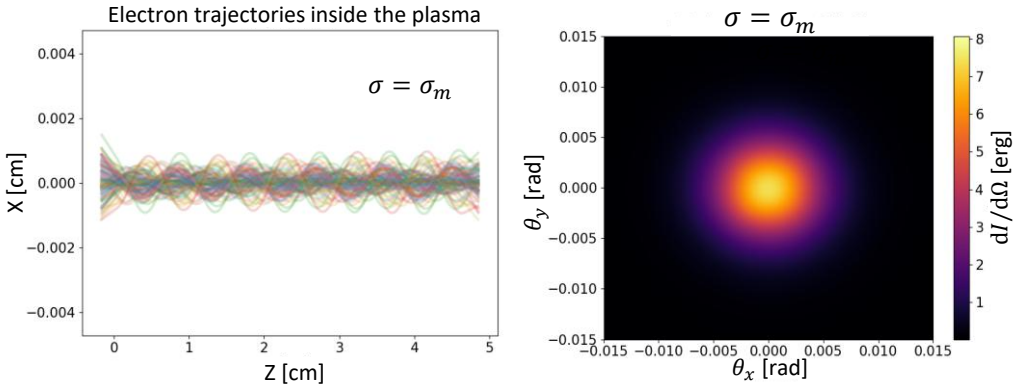
In this configuration the driver's bunch length increases 62 μm → 98 μm. however IC formation is still feasible:

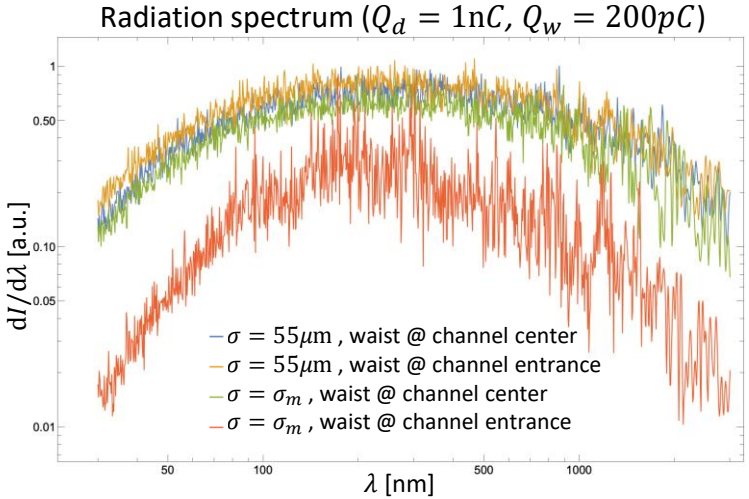


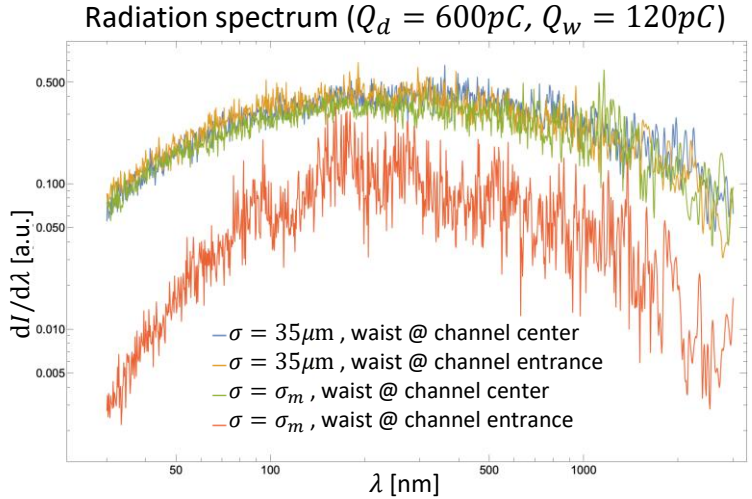
Pompili R. *SPARC_LAB recent results and activities*, 61st LNF Scientific Committee, Frascati, 6 May 2021.

Preliminary radiation studies

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

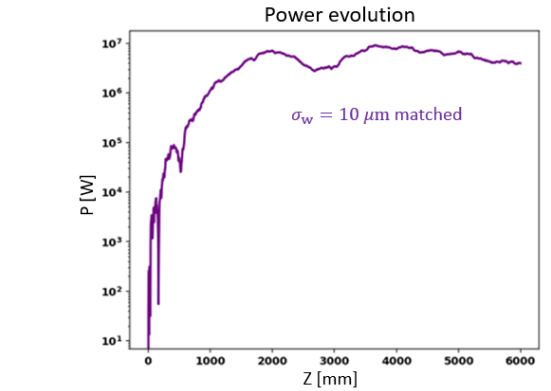


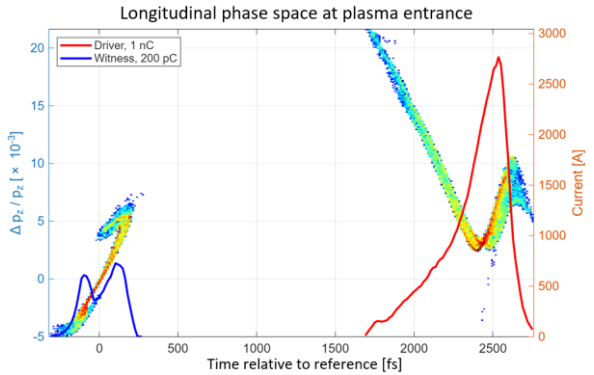


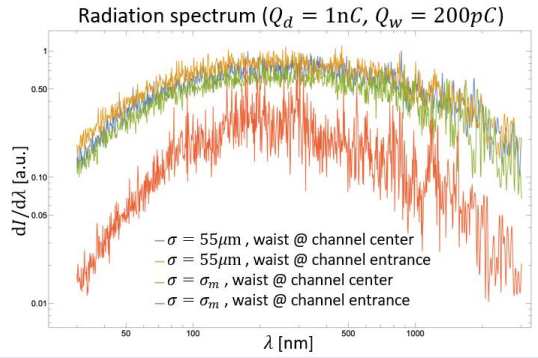


Conclusions

- Previous studies showed that a suitable driver can form the ion channel and that a properly matched witness can produce undulator-like betatron radiation with potential FEL-like amplification.
- Quasi start-to-end optimization of the SPARC_LAB injector provides candidate high- and lower-charge configurations approaching the required bunch length and emittance targets. A lower charge working point is also under study.
- Preliminary simulations with realistic beam distributions show that radiation is very sensitive to transverse beam quality. The central wavelength of the obtained radiation is in line with the value we expected.
- **Next step:** complete the PMQ optimization and simulate the radiation using the actual final-focused beam distributions.







Thank you for your attention

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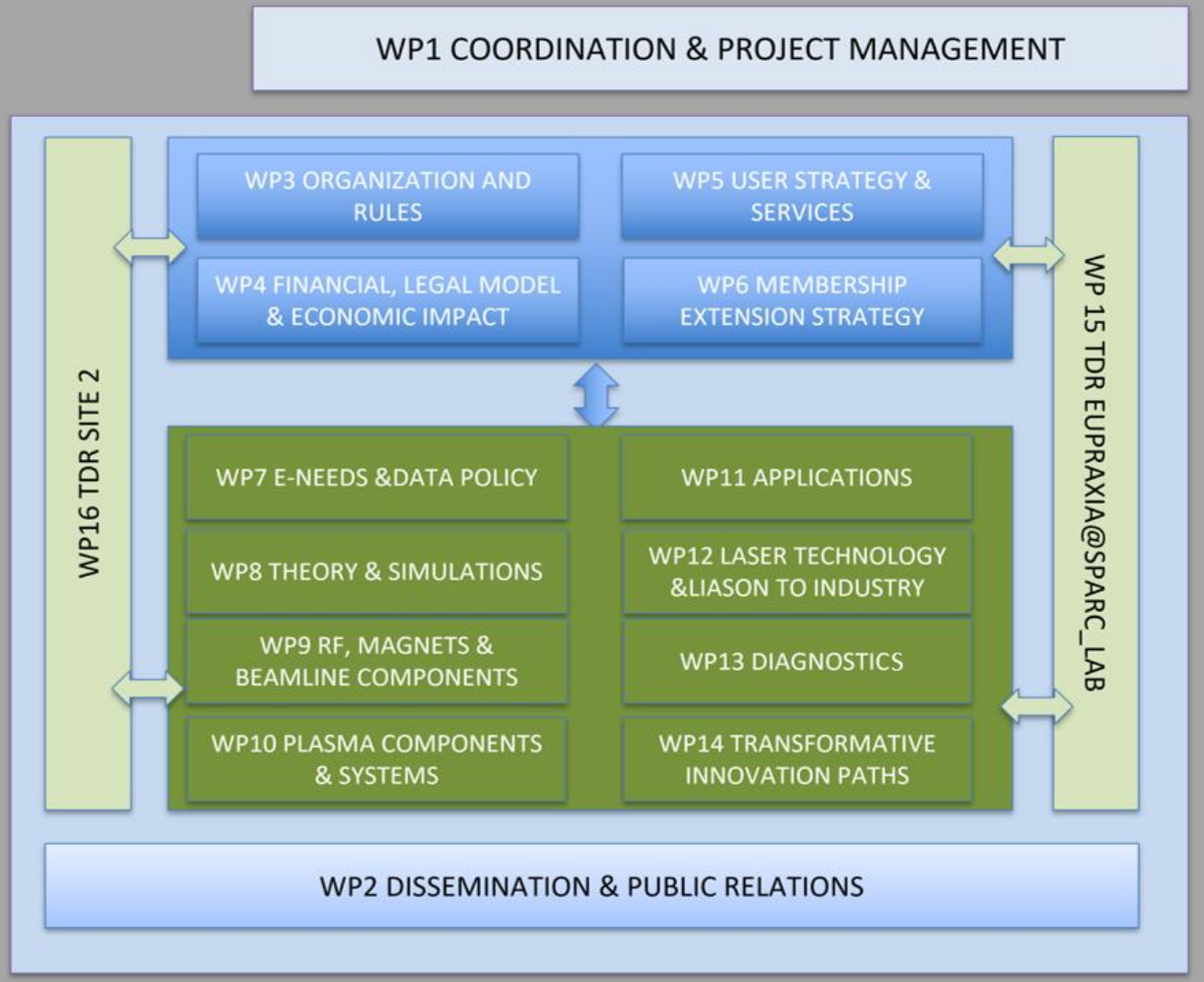

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Acknowledgements

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EuPRAXIA Doctoral Network

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EuAPS

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Backup slides

FEL formalism in plasma wave undulators

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

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

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

- $\psi_j = (k_\beta + k)z_j(t) - \omega t + \phi_j$ is the ponderomotive phase, which represents the longitudinal position of an electron within a radiation wavelength $\lambda_r \simeq \lambda_\beta / 2\gamma_r^2$. The initial phase ϕ_j accounts for the electron's position at injection.
- $\delta_j = (\gamma_j - \gamma_0)/\gamma_0$ is the relative energy deviation of particle j, describing how much its energy differs from the reference Lorentz factor γ_0. This deviation is important because it governs the electron's phase slippage relative to the radiation.
- n_e is the electron density of the bunch.
- $K_{\beta j} = \gamma_0(1+\delta_j) r_{\beta j}\omega_\beta / c$ is the betatron strength parameter, analogous to the undulator parameter K in conventional FELs. It quantifies the amplitude of the transverse oscillation in units relevant to radiation emission.

Bunching factor:

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

Its modulus $|b|$ quantifies the strength of the coherent emission, since the radiated power scales as $|b|^2$

Radiation bandwith:

$$\left(\frac{\Delta\lambda}{\lambda}\right)^2 \simeq \left(\frac{2\,\Delta\gamma}{\gamma}\right)^2 + \left(\frac{1}{N_\beta}\right)^2 + \left[\frac{K_\beta^2}{2+K_\beta^2}\frac{\Delta K_\beta}{K_\beta}\right]^2.$$

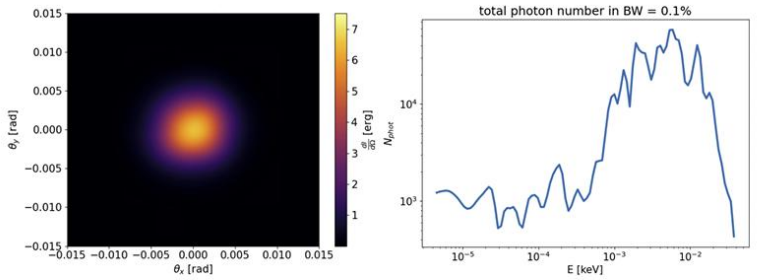


Figure 8. Radiation emitted by the witness bunch in a 10 cm long IC. **Left**: Radiation intensity on a virtual screen. **Right**: Photons yield in a 0.1% bandwidth as a function of energy.

Channel formation condition derivation

$$r_{max} > R_{ch}$$

$$r_{max} \approx 2n_b^{1/2}\sigma_d \qquad n_b = Q_b / e(2\pi)^{3/2}\sigma_z\sigma_d^2 n_e$$

plasma line number densities

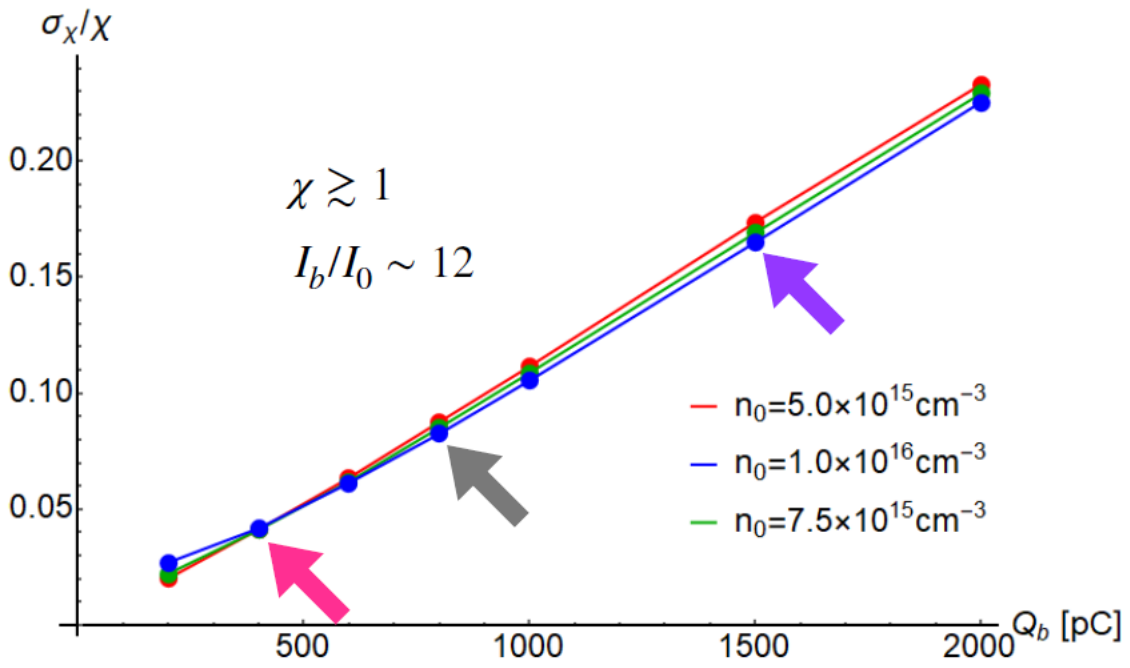
$$2n_b^{1/2}\sigma_d < R_{ch} \qquad \Lambda_b = Q_b/(e\sqrt{2\pi}\sigma_z) \quad \Lambda_0 = \pi R_{ch}^2 n_e$$

$$\left(\frac{\Lambda_b}{\Lambda_0}\right)^{\frac{1}{2}} > 2^{-\frac{1}{2}}$$

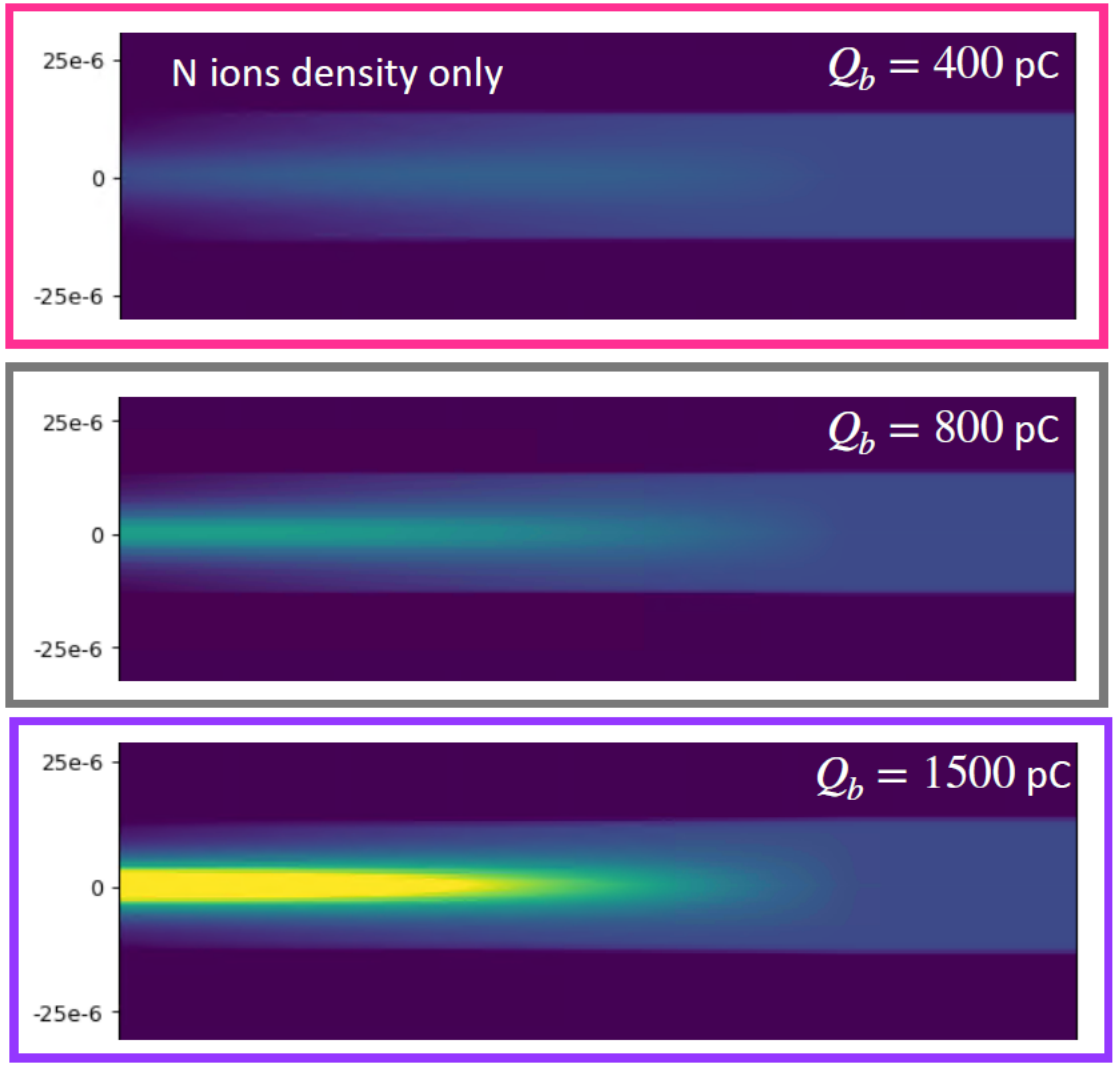
Squaring Equation (1) and multiplying numerator and denominator by *ec*

$$\frac{I_b}{I_0} > \frac{1}{2}$$

Channel uniformity



- For fixed $I_b/I_0 \gg 1$, σ_χ/χ grows linearly $\Longrightarrow$ **ION MOTION!**



Machine parameters for the experimental WPs

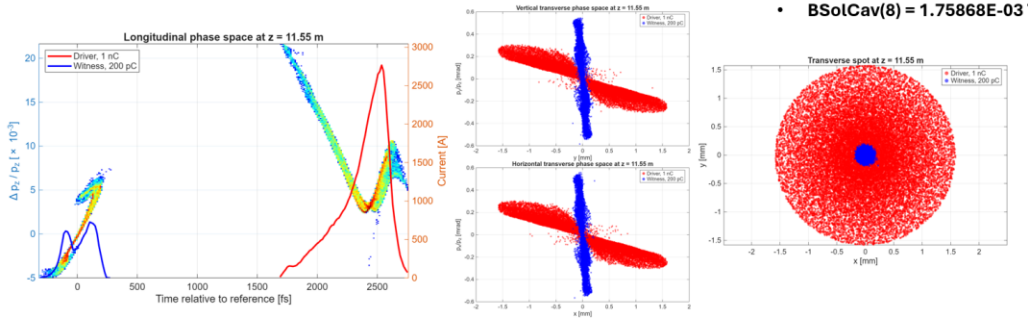
Funded by the European Union

1 nC + 200 pC

- sigXWitness = 5.00250E-01 mm
- sigXDriver = 5.99789E-01 mm
- sigTWitness = 1.07063E-04 ns
- sigTDriver = 9.63834E-05 ns
- deltaT = -5.29573E-03 ns

- BSolGun = 2.78261E-01 T
- PhaseGun = 8.99703E-02°
- PhaseCav1 = -9.61098E+01°
- PhaseCBand = 3.51845E-02°

- BSolCav(1) = 2.00871E-02 T
- BSolCav(2) = 3.32811E-02 T
- BSolCav(3) = 1.09347E-02 T
- BSolCav(4) = 3.16699E-02 T
- BSolCav(5) = 2.68315E-02 T
- BSolCav(6) = 2.62470E-02 T
- BSolCav(7) = 4.72756E-02 T
- BSolCav(8) = 1.75868E-03 T



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

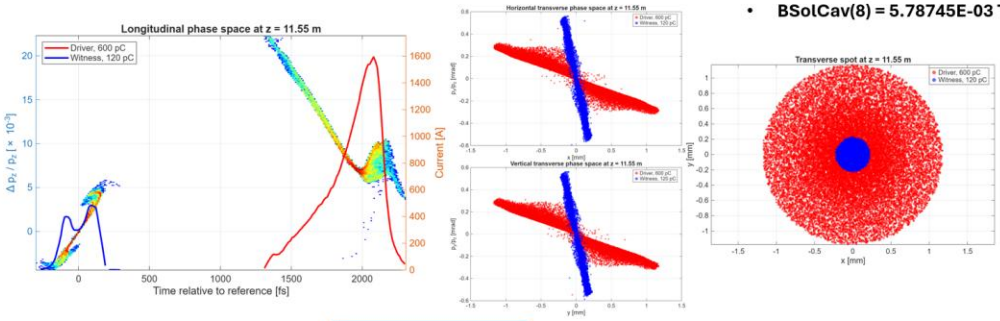
Target spot size for plasma matching: $\sigma_{\mathrm{x,w}} = 3.48$ µm, $\sigma_{\mathrm{x,d}} = 6.33$ µm → For $n_e = 5 \times 10^{15}$ cm^{-3}

600 pC + 120 pC

- sigXWitness = 3.57307E-01 mm
- sigXDriver = 4.85607E-01 mm
- sigTWitness = 1.59174E-04 ns
- sigTDriver = 1.87049E-04 ns
- deltaT =-5.56266E-03 ns

- BSolGun = 2.77277E-01 T
- PhaseGun = -1.35695E+00°
- PhaseCav1 = -9.45857E+01°
- PhaseCBand = 1.51311E-01°

- BSolCav(1) = 2.54316E-02 T
- BSolCav(2) = 2.75350E-02 T
- BSolCav(3) = 1.55868E-02 T
- BSolCav(4) = 2.89181E-02 T
- BSolCav(5) = 1.97234E-02 T
- BSolCav(6) = 4.65771E-02 T
- BSolCav(7) = 5.34627E-02 T
- BSolCav(8) = 5.78745E-03 T



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

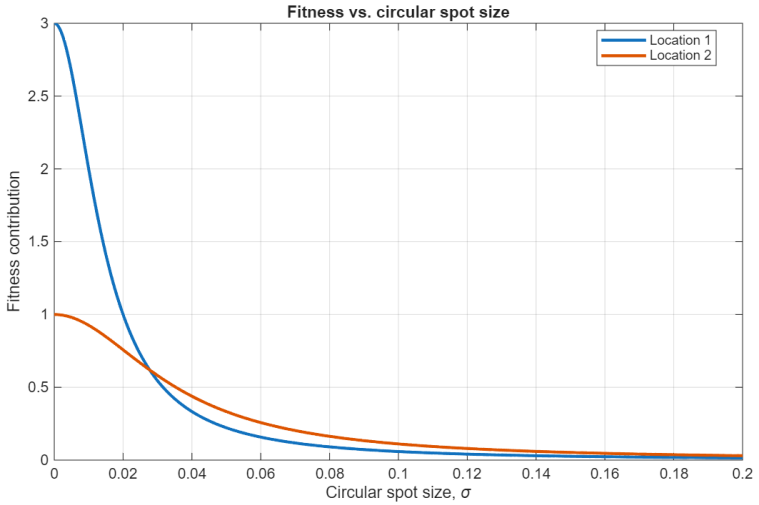
Target spot size for plasma matching: $\sigma_{\mathrm{x,w}} = 3.22$ µm, $\sigma_{\mathrm{x,d}} = 5.81$ µm → For $n_e = 3.1 \times 10^{15}$ cm^{-3}

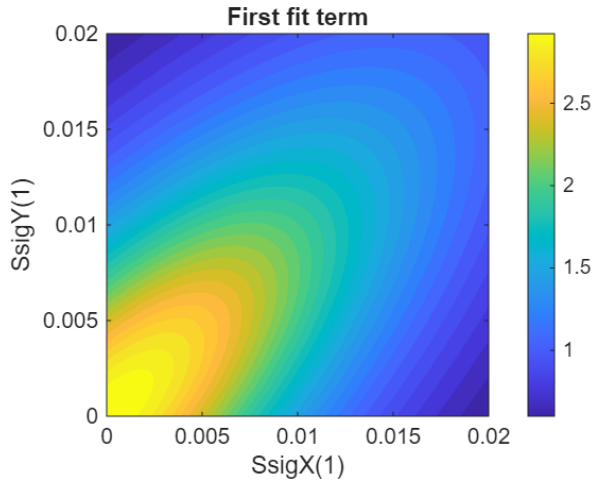
PMQ optimizer fitness function

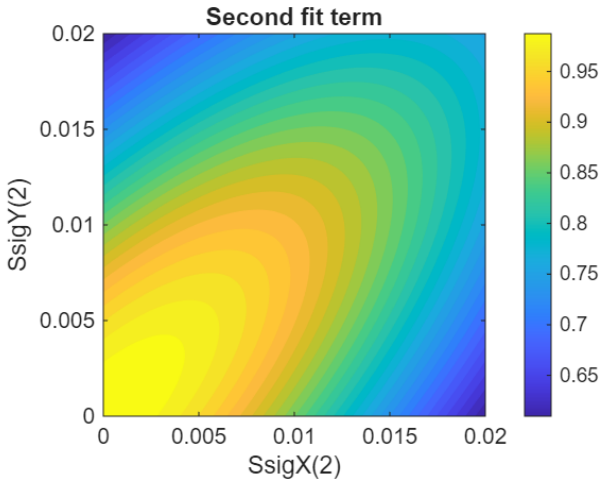
$$F(\sigma) = \frac{w^2}{(\sigma - \sigma_0)^2 + w^2},$$

$$F_i = \frac{W_i^2}{\sigma_{x,i}^2 + \sigma_{y,i}^2 + \lambda(\sigma_{x,i} - \sigma_{y,i})^2 + W_i^2}$$

```
[idoneity]
0.020 sqr SsigX(1) sqr SsigY(1) sqr + SsigX(1) SsigY(1) - sqr 3 * + 0.020 sqr + / 3 *
0.050 sqr SsigX(2) sqr SsigY(2) sqr + SsigX(2) SsigY(2) - sqr 3 * + 0.050 sqr + / 1 * +
```







Beam parameters after final focusing

```
Approximate charge bunch 1: 1.000000 nC
Approximate charge bunch 2: 199.920000 pC

RMS bunch length:

Driver, 1 nC
  sigma_t  = 328.495192 fs
  sigma_z  = 98.480381 um

Witness, 200 pC
  sigma_t  = 75.997702 fs
  sigma_z  = 22.783538 um

Centroid separation:
  Delta t = 1774.292292 fs
  Delta z = 531.919448 um

Normalized transverse emittance:

Driver, 1 nC
  eps_x,n = 4.392284 pi mm mrad
  eps_y,n = 5.010730 pi mm mrad

Witness, 200 pC
  eps_x,n = 1.955274 pi mm mrad
  eps_y,n = 2.126758 pi mm mrad

Transverse rms spot sizes:

Driver, 1 nC
  sigma_x = 7.961648 um
  sigma_y = 7.289591 um

Witness, 200 pC
  sigma_x = 7.942950 um
  sigma_y = 6.955544 um
```

```
Twiss parameters:

Driver, 1 nC
  Horizontal:
    alpha_x = -0.325748
    beta_x  = 0.002900 m
    gamma_x = 381.372124 1/m
    eps_x,g = 2.182987e-08 m rad
  Vertical:
    alpha_y = -0.011878
    beta_y  = 0.002129 m
    gamma_y = 469.779950 1/m
    eps_y,g = 2.492537e-08 m rad

Witness, 200 pC
  Horizontal:
    alpha_x = 0.419508
    beta_x  = 0.006380 m
    gamma_x = 184.332320 1/m
    eps_x,g = 9.894326e-09 m rad
  Vertical:
    alpha_y = -0.192712
    beta_y  = 0.004480 m
    gamma_y = 231.528672 1/m
    eps_y,g = 1.077673e-08 m rad
```