Betatron radiation as emittance diagnostics for plasma acceleration experiments

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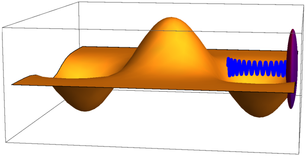
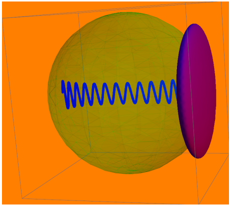
Summary

Plasma acceleration

Linear/Quasi linear regime



Bubble regime



Plasma Wakefields:

$$E_z(r,\zeta) = \frac{\sqrt{\pi}}{4} a_0^2 k_p c\tau_0 E_0 \exp\left[\frac{2r^2}{w_0^2} - \frac{k_p^2 c^2 \tau_0^2}{4}\right] \cos k_p\zeta$$

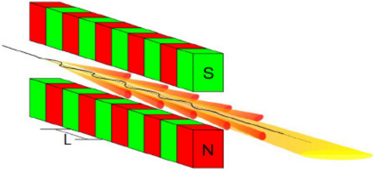
$$E_r(r,\zeta) = -\sqrt{\pi} a_0^2 \frac{c\tau_0 r}{w_0^2} E_0 \exp\left[\frac{2r^2}{w_0^2} - \frac{k_p^2 c^2 \tau_0^2}{4}\right] \sin k_p\zeta$$

Plasma Wakefields:

$$E_z(r,\zeta) = \frac{m}{3e}\omega_p^2 \zeta \cos k_p\zeta$$

$$E_r(r,\zeta) = \frac{m}{3e}\omega_p^2 r \sin k_p\zeta$$

Characteristics of the Betatron Radiation: wiggler analogy



The difference between a wiggler and an undulator resides in the anharmonic motion of the oscillating particles, due to high transverse velocities, which mirrors in a broadband spectrum, while the spectrum of an undulator is narrowband.

Wiggler parameters:

$$\lambda_W = \frac{L}{2\gamma_0^2}(1 + \frac{K_W^2}{2} + \gamma_0^2\theta^2)$$

$$K_W = 0.934B[T]L[cm]$$

$$E_c = 3\gamma_0^2 K_W \hbar\omega_W$$

Plasma wiggler parameters:

$$\lambda_b = \frac{\lambda_\beta}{2\gamma^2}(1 + \frac{K^2}{2} + \gamma^2\theta^2)$$

$$K = \gamma k_\beta r_0$$

$$E_c = 3\gamma_0^2 K \hbar\omega_b$$

A method to measure the transverse emittance: Definitions/1

$$\sqrt{\langle \Delta r^2 \rangle \langle \Delta \theta_d^2 \rangle - \langle \Delta r \Delta \theta_d \rangle^2}$$

Def. geometric emittance

$P(r)$

Transverse beam profile

$\Theta(\theta_d)$

Distribution of the angles with respect to the acceleration axis

$$\theta_d = \sqrt{\frac{\sqrt{1+\frac{1}{2}\gamma_0^2 r_\beta^2 k_{\beta 0}^2}}{4\gamma_0}}\, r_\beta k_p$$

$\rightarrow \mathrm{r}_\beta(\theta_d)$, $r = r_\beta/\sqrt{2}$

Correlation function

$R(r) = rP(r)$

Distribution of the oscillation amplitudes

A method to measure the transverse emittance: Definitions/2

$S_{\gamma,r_\beta}(E,\Omega)$ Single particle spectrum

$S(E) = \int dr_\beta d\gamma R(r_\beta)\Gamma(\gamma)d\Omega S_{\gamma,r_\beta}(E,\Omega)$ Electron bunch spectrum

$\int dr_\beta R(r_\beta) \sim \sum_i R_i$ Trick

$S(E_j) \equiv S_j = \sum_i R_i S_{ij}$ Spectrum discretization

$S_{ij} = \int\int d\Omega d\gamma \Gamma(\gamma) S_{\gamma,r_{\beta,i}}(E_j,\Omega)$ Def. of the S matrix

$$S_j - \Sigma_j = \sum_{ij} R_i S_{ij} - \Sigma_j = 0$$

From the profile to the divergence

$\omega_\beta = \omega_p/\sqrt{2\gamma}$

Betatron frequency

$\theta_d = \sqrt{\left\langle \left(\frac{dr}{dz}\right)^2 \right\rangle - \left\langle \left(\frac{dr}{dz}\right) \right\rangle^2} = \frac{\sqrt{2}}{2} r_\beta k_\beta$

Single particle divergence

$\gamma \sim \gamma_0$

Linear correlation $\rightarrow$ zero emittance

$\gamma^* \sim \gamma_0/\sqrt{1 + K_{\beta 0}^2/2}$

Non linear correlation $\rightarrow$ non-zero emittance

$\Theta(\theta_d) \propto P(r(\theta_d))$

Distribution of the correlated divergences

Experimental Results: Setup

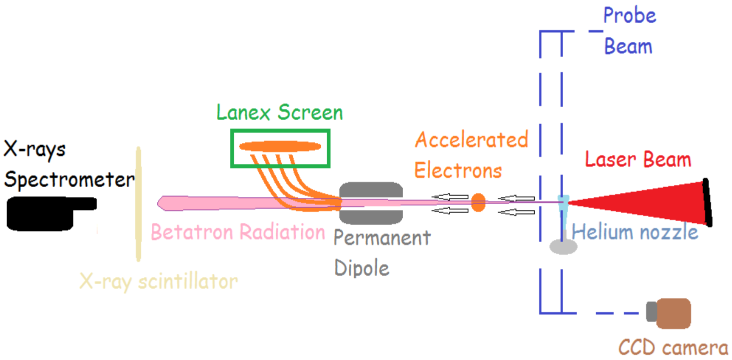


Figure: The main laser beam impinges on the supersonic helium jet, ionizing, channeling and generating plasma wakefields. The electrons, while accelerating, emit X-ray betatron radiation in the forward direction, detected by a CCD-X camera. The plasma channel is probed with interferometry. The electrons are damped out on the screen of the magnetic spectrometer.

Experimental Results: Plasma channel

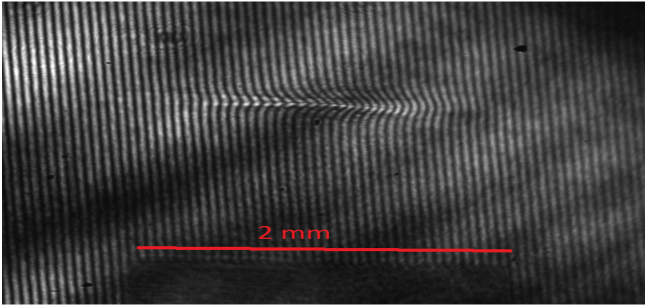


Figure: The Rayleigh length of the laser is evaluated $z_R \sim 100\ \mu m$, while the detected high-intensity/high-density ($8 \times 10^{18} cm^{-3}$) region, where the acceleration occurs, is longer than one millimeter.

Index of refraction $\eta \sim 1 - \frac{\omega_p^2}{2\omega_0^2}\left(1 + \frac{\delta n_e}{n_0} - \frac{a^2}{4}\right)$

$a^2(x, y, z, t) \propto I(x, y, z, t)$ (Laser Intensity)

Experimental Results: Betatron Spectrum

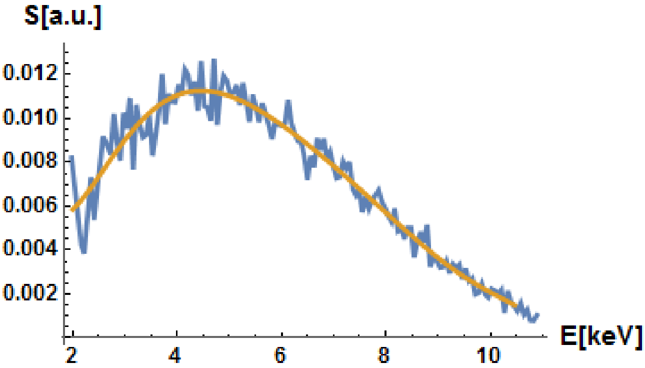


Figure: Betatron spectrum detected with a CCD-X camera working in single photon counting mode together with a polynomial fit.

Experimental Results: Electron Spectrum

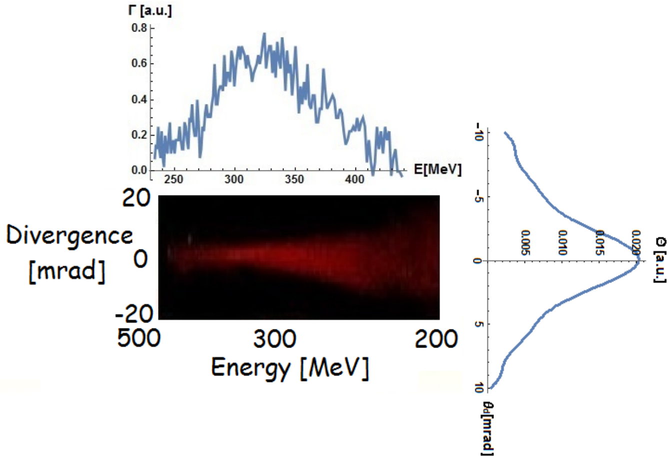


Figure: Electron energy spectrum relative to the electron bunch accelerated in the bubble regime. Central energy $\gamma_0 = 320\ MeV$, energy spread $2\sigma_\gamma/\gamma_0 \sim 20$ %. The outlines of the energy spectrum (up) and of the beam divergence (right) are reported.

Experimental Results: Beam Profile Reconstruction

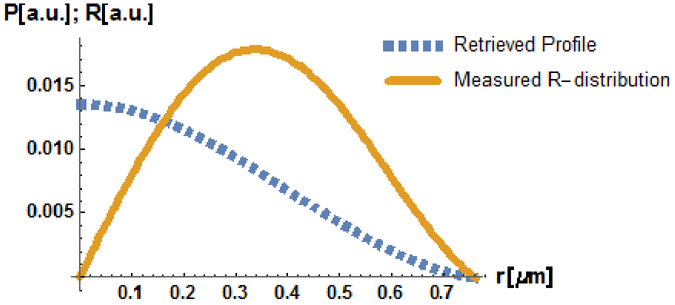


Figure: The beam profile $P(r)$ derived directly from the measured function $R(r_\beta)$. The rms betatron radius is found $\sigma_r \sim 0.42 \pm 0.04\ \mu m$.

Experimental Results: Radiation Beam Distribution

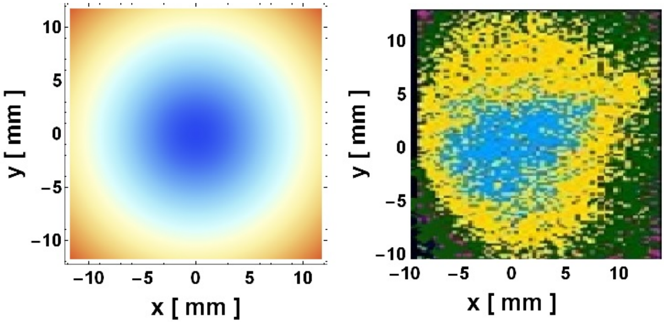


Figure: Betatron radiation spatial distribution: simulation (left) and measurement (right). Measured divergence of the radiation beam $\theta_\beta^{meas} = 8.2 \pm 0.3\ mrad$, simulation value $\theta_\beta^{sim} = 8.5\ mrad$.

Experimental Results: Distribution of the correlated divergences

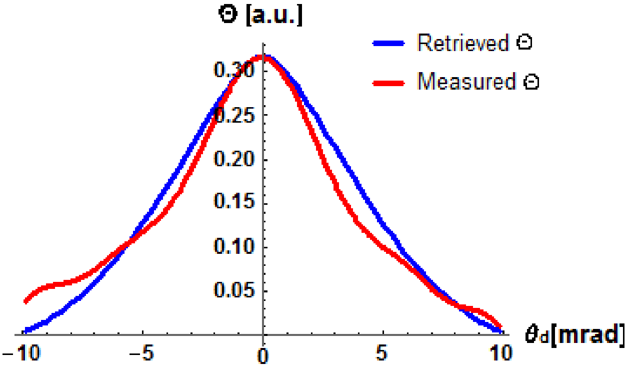


Figure: Comparison betweeen the measured and the retrieved $\Theta(\theta_d)$ function. Corresponding values of beam divergence $\sigma_\theta^{meas} = 5.9 \pm 0.6$ *mrad* and $\sigma_\theta^{retr} = 5.2 \pm 0.6$ *mrad*.

Experimental Results: Emittance Measurement

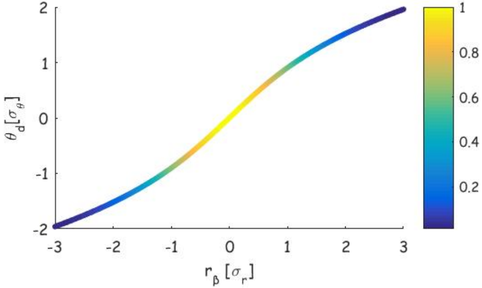


Figure: Reconstructed trace space density.

$$\epsilon_{r_\beta N} = \gamma_0 \sqrt{(\sigma_\gamma/\gamma_0)^2 \sigma_r^2 \sigma_\theta^2 + \epsilon_{r_\beta}^2} = (0.6 \pm 0.1)\ mm\ mrad$$

Upper Limit: $\gamma_0 \sigma_r \sigma_\theta^{meas} = (1.5 \pm 0.3)\ mm\ mrad$

Conclusions

⋆ We summarized typical features of betatron radiation

⋆ We presented a methodology able to reconstruct the transverse trace space of low emittance electron beams accelerated in the bubble regime. The single-shot measurement of both the betatron radiation spectrum and the electron energy spectrum can allow a complete measurement of the transverse emittance, including the correlation term.

⋆ We reported experimental results obtained at the SPARC-LAB test facility through the interaction of the ultra-short ultra intense $Ti : Sa$ laser FLAME with a He gas-jet target.

Thanks for your attention