Utilizing Cherenkov Radiation From a Correspondingly Altered Dielectric Medium for Non-Invasive Plasma Diagnostics at CERN's Proton Synchrotron

CERN Beamline for Schools (BL4S) Proposal
From Team Cherenk-off the Charts

Anahita Joshi
Ansh Lalwani
Anwita Belambe
Hemang Keswani
Vineet Jade

1. Introduction and Motivation

Plasma underlies numerous phenomena in nature and technology. Precise characterization of plasma properties is crucial for advancing these fields, yet existing diagnostic techniques often introduce perturbations that potentially alter the plasma's intrinsic behavior.

The main challenge in plasma diagnostics is obtaining accurate measurements without disturbing the plasma, as probe-based methods physically interact with it and optical techniques often require high-intensity lasers that can alter its properties, leading to inaccurate results.

Our proposed approach utilizes Cherenkov radiation—electromagnetic radiation emitted when charged particles traverse a medium at speeds exceeding the local phase velocity of light. The key innovation lies in our indirect approach: rather than passing particles through the plasma itself, we direct electron beams near dielectric materials adjacent to the plasma.

The plasma's properties influence the refractive index distribution in these materials, consequently affecting the Cherenkov radiation characteristics. A critical consideration for this technique at CERN is accounting for magnetic fields from both the plasma confinement system and the nearby proton synchrotron, which can significantly affect Cherenkov radiation patterns.

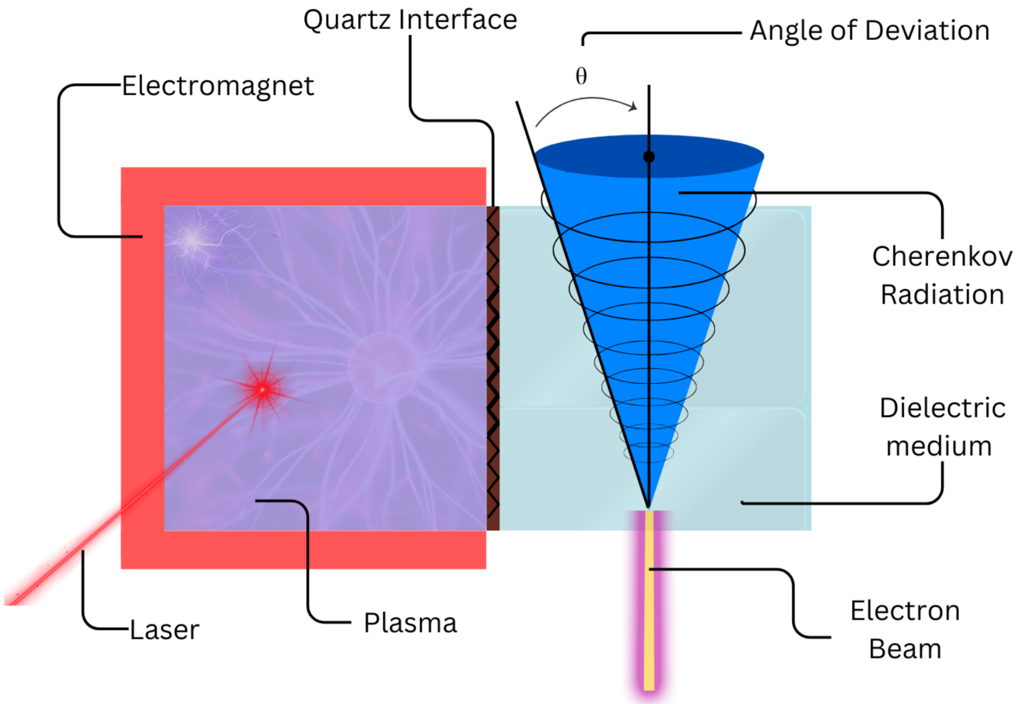

Figure 1: Conceptual illustration of Cherenkov radiation generation at plasma-dielectric interface.

2. Methodology

The PS provides electron beams with precisely controlled energy, emittance, and temporal structure—parameters critical for generating well-characterized Cherenkov radiation.

The beam stability (position jitter $< 30\,\mu\text{m}$, energy stability $< 0.1\%$) enables high-precision measurements required for detecting subtle plasma-induced effects. CERN's existing technical infrastructure, including vacuum systems, radiation shielding, and synchronized timing systems (precision $< 10\,\text{ps}$), eliminates the need for custom development.

The Cherenkov radiation angle (θ_C) is given by:

$$\cos\theta_C = \frac{1}{\beta n} \tag{1}$$

where $\beta = v/c$ and n is the refractive index. For a plasma,

$$n^2 = 1 - \frac{\omega_p^2}{\omega^2} = 1 - \frac{n_e e^2}{\varepsilon_0 m_e \omega^2} \tag{2}$$

The presence of plasma near a dielectric medium creates a refractive index gradient at the interface. When an electron beam passes through this region, the Cherenkov radiation pattern becomes asymmetric, with characteristics directly corresponding to the plasma density distribution.

Analyzing these patterns enables reconstruction of the plasma density profile with high spatial resolution.

In magnetic fields, the electron trajectory and Cherenkov cone are altered: the beam is deflected by the Lorentz force, and the cone develops asymmetry perpendicular to the field. These effects are compensated via:

Active Compensation

Three orthogonal Helmholtz coil pairs generate counter-fields controlled at $1\,\text{kHz}$, neutralizing both Earth's field ($\sim 47\,\mu\text{T}$) and synchrotron fluctuations ($0.8\,\mu\text{T} - 2.3\,\mu\text{T}$).

Passive Shielding

Mu-metal enclosures ($2\,\text{mm}$ thick) provide $40\,\text{dB}$ attenuation, redirecting magnetic lines away from the experiment.

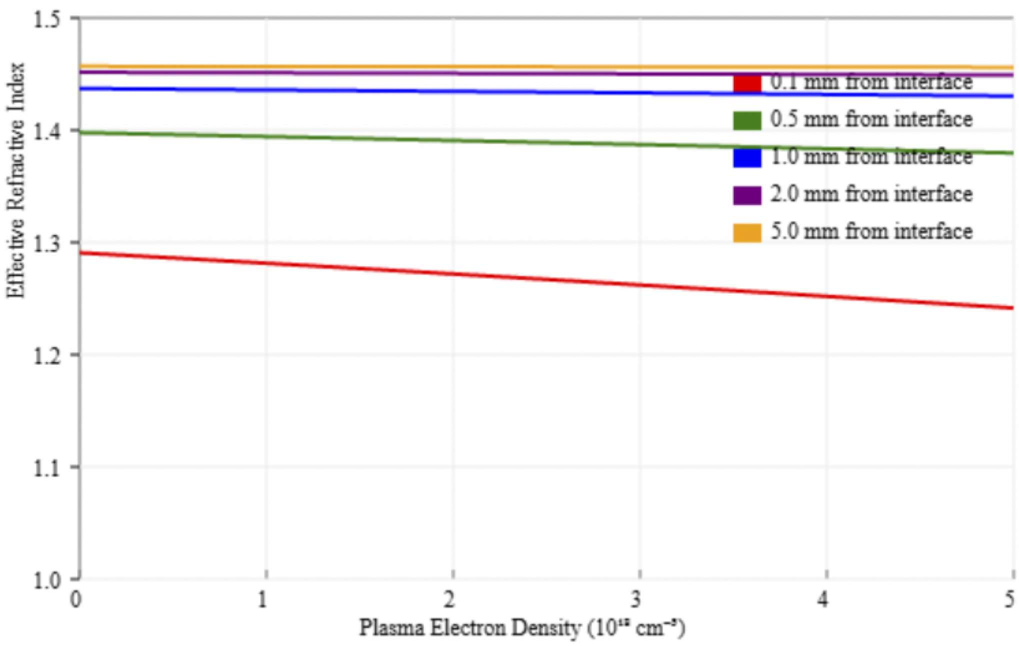

Figure 2: Plasma density vs. effective refractive index at various distances from the interface.

3. Experimental Setup

Component	**Parameter**	**Specification/Working**
Electron Beam	Energy	3.5 GeV
Plasma System	Gas Species	H_2, He, purity 99.9999 %
	Pressure Range	10^{-3}–10 Torr, MKS flow controlled
	Electron Density	10^{16}–10^{19} cm^{-3}
	Temperature	1–10 eV, laser-controlled
	Plasma Length	1–30 cm, aperture adjusted
Laser System	Wavelength	800 nm, Ti:Sapphire
	Pulse Energy	10–100 mJ
	Pulse Duration	100 fs
Detection System	Screen	ZnS, Ag screens for light conversion
	Spectrometer	200–800 nm, Princeton Instruments
	PMT Array	Hamamatsu H12700, 64 channels
	Beam Splitter	Optical routing

Table 1: Experimental Parameters and Components

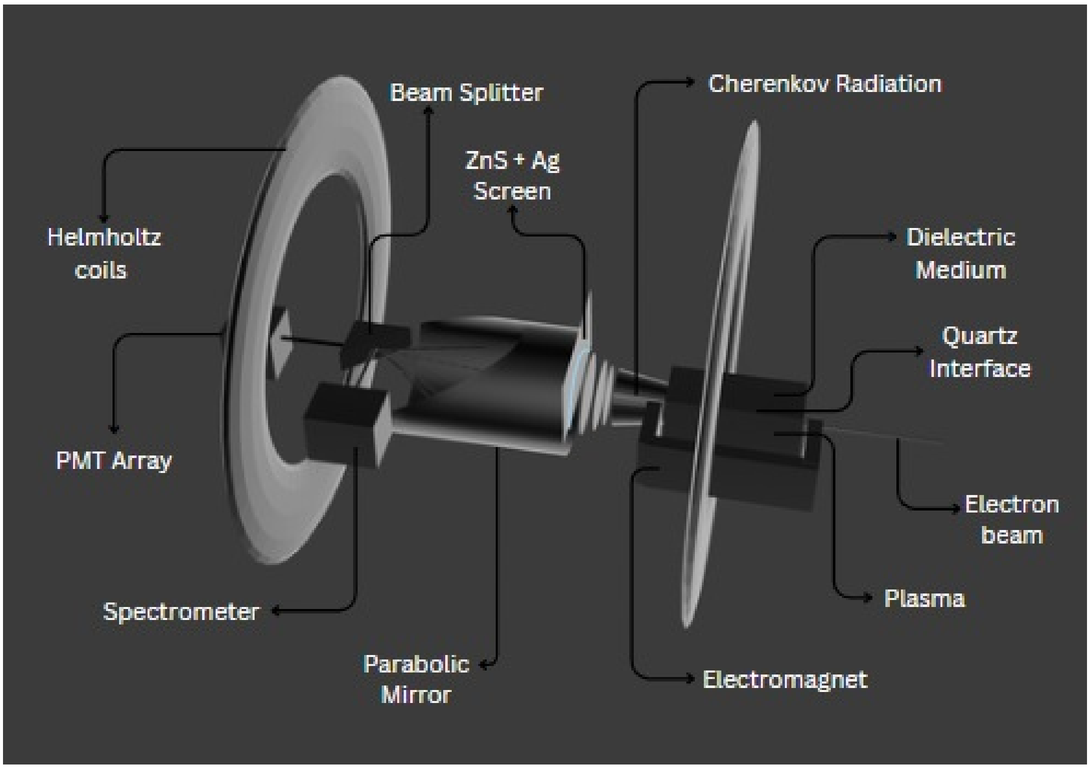

Figure 3: Schematic of experimental setup at CERN PS

4. The Experiment

Phase 1: Baseline Establishment
Characterization without plasma for calibration.

Phase 2: Controlled Plasma Studies
Parameter scan across density, temperature, and gradients.

Phase 3: Dynamic Plasma Evolution
Synchronization of beam with plasma events for ultrafast dynamics.

Phase 4: Validation and Cross-calibration
Comparison with interferometry and Thomson scattering.

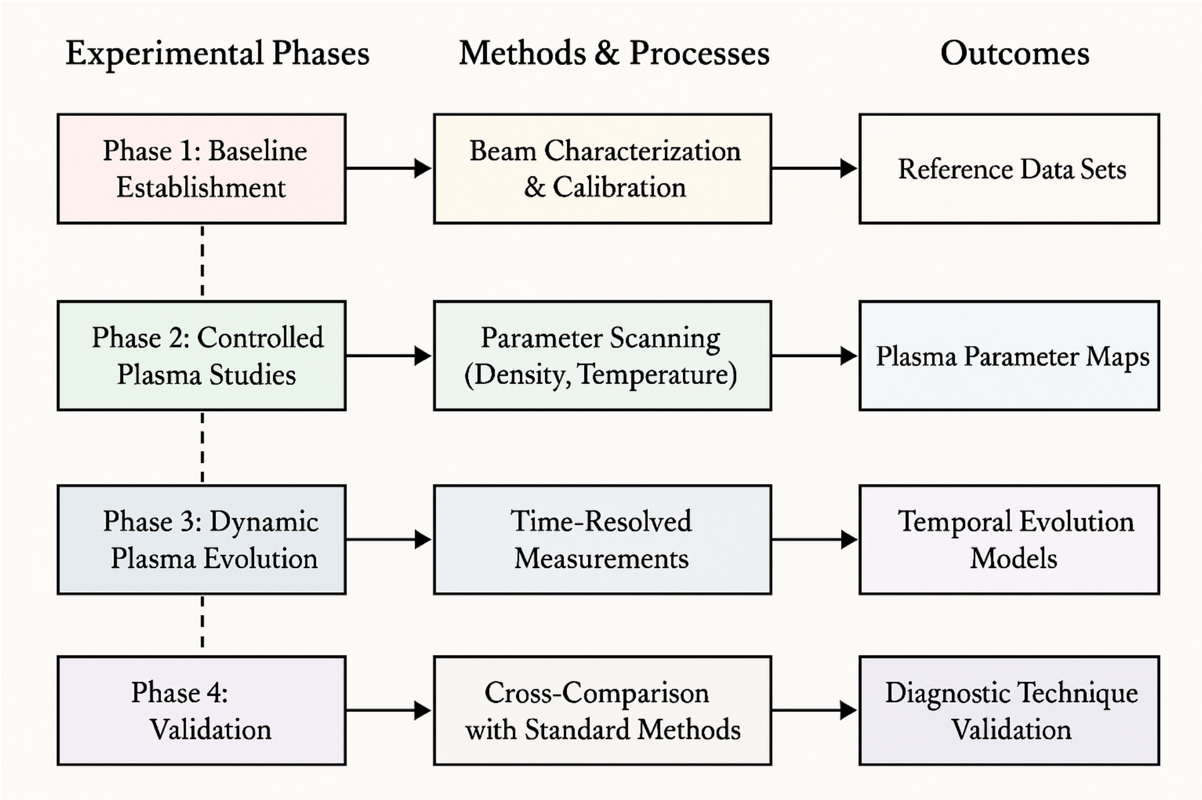

Figure 4: Experimental methodology and analysis pipeline

5. Expected Results and Implications

Diagnostic Precision: Anticipated density resolution $< 10^{15}$ cm^{-3}, spatial resolution $<$ 100 µm, and temporal resolution < 1 ps.

Technical Advancement: A novel calibration framework linking Cherenkov patterns to plasma properties applicable to other facilities.

Appendix A: Detailed Theoretical Analysis

A.1 Cherenkov Radiation in Plasma-Adjacent Media

$$\omega_p = \sqrt{\frac{n_e e^2}{\varepsilon_0 m_e}} \tag{3}$$

$$n_{\text{plasma}}(\omega) = \sqrt{1 - \frac{\omega_p^2}{\omega^2}} \tag{4}$$

$$n_{\text{eff}}(x, \omega) = n_d + (n_{\text{plasma}}(\omega) - n_d)e^{-x/\lambda_s} \tag{5}$$

$$\frac{d^2W}{d\omega d\Omega} = \frac{e^2}{4\pi^2 c}\omega \sin^2\theta_C \left| \int e^{i\omega(t - n(\vec{r})r\cos\theta/c)} dt \right|^2 \tag{6}$$

A.2 Plasma Density Reconstruction Algorithm

$$n_e(r) = -\frac{\varepsilon_0 m_e}{e^2}\omega^2 \frac{1}{\pi}\int_r^\infty \frac{d\theta_C(r')}{dr'} \frac{1}{\sqrt{r'^2 - r^2}} dr' \tag{7}$$

Iterative algorithm:

- Initial guess from Abel inversion
- Simulate forward Cherenkov pattern
- Compare with measured data
- Update estimate via maximum likelihood
- Repeat until convergence

Appendix B: References

1. Frank, I.M., & Tamm, I.E. (1937). *Doklady Akademii Nauk SSSR, 14, 109-114.*
2. Glinec, Y., et al. (2006). *Rev. Sci. Instrum., 77, 103301.*
3. Hutchinson, I.H. (2002). *Principles of Plasma Diagnostics.* Cambridge Univ. Press.
4. Maksimchuk, A., et al. (2008). *Plasma Phys. Controlled Fusion, 50, 124010.*
5. Cianchi, A., et al. (2018). *Nucl. Instrum. Methods A, 909, 350-354.*
6. Litos, M., et al. (2014). *Nature, 515, 92-95.*
7. Adli, E., et al. (2018). *Nature, 561, 363-367.*
8. Sävert, A., et al. (2015). *Phys. Rev. Lett., 115, 055002.*
9. Golovin, G., et al. (2016). *Phys. Rev. ST Accel. Beams, 19, 031301.*
10. Hooker, S.M. (2013). *Nature Photonics, 7, 775-782.*