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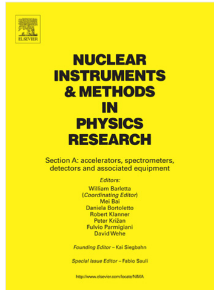

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Abstract

Passive plasma lenses in the underdense regime have been shown to give extremely strong linear focusing, with strength proportional to the local plasma ion density. This technique has been proposed as the basis of a scheme for future linear colliders that mitigates the Oide effect through adiabatic focusing. In this scenario the plasma density in the lens is ramped slowly on the scale of betatron motion, to funnel the beam to its final focus while forgiving chromatic aberrations. We present to the physics design of an adiabatic plasma lens experiment to be performed at SPARC Lab. We illustrate the self-consistent plasma response and associated beam optics for symmetric beams in plasma, simulated by QuickPIC using exponentially rising density profiles. We discuss experimental plans including plasma source development and betatron-radiation-based beam diagnostics.

I. Introduction

Accelerators are flagship instruments that have enabled a large swath of scientific progress for most of the last century. In enabling high-energy colliding beam experiments, they have provided discovery potential up to the TeV energy scale [1], most recently yielding the first observation of the Higgs' boson [2]. They have also brought rapidly growing capabilities in imaging based on X-ray light sources, a field that in the last decade has produced the first X-ray laser, based on the free-electron laser (FEL) concept [3]. This innovation has opened the door to the resolution of atomic and molecular structure at the time (femtosecond and below) and length (Angstrom) scale, using the burgeoning techniques of coherent imaging [4].

The march of scientific progress permitted by accelerators is, however, threatened by the enormous costs associated with the enterprise: many X-ray FELs are currently under construction, with a price tag on the order of $1B, while future colliders are presently estimated to cost over $10B. This situation has been acknowledged in the particle physics community, with increasing urgency, for the last 30 years. As such, new acceleration paradigms have been demanded, based on new physical mechanisms and technologies, such as lasers, plasmas, and beam-driven wakefields.

Out of this effort, plasma-based acceleration schemes are emerging as an exciting new approach to creation of compact new accelerators. Due to plasmas already being in an ionized state, they overcome the problem of breakdown, and acceleration gradients of up to 50 GeV/m have been demonstrated, with TeV/m foreseen [5]. The development of a linear collider (LC) out of a new acceleration method is a long and scientifically challenging process, with many issues in fundamental beam physics that need to be resolved in a greater than decade-long program embraced by researchers worldwide.

One unique aspect of plasma accelerators is the existence of ultra-strong plasma-based transverse focusing, which possesses unprecedented linear gradients This strong, linear focusing is essential to the evasion of phase space dilution inside of the plasma accelerator *per se*. It is also highly flexible, with strength proportional to the plasma density as it varies along the beam propagation direction, $n_0(z)$. As such it may also be exploited in a unique way, to have a profound effect on LC design. This scenario is termed the *adiabatic plasma lens* [6], and it has been proposed to resolve a serious problem, the limit on final focusing schemes due to synchrotron radiation in the final focus elements, a phenomenon termed the Oide effect [7]. This innovative scheme permits "funneling" of beam to the LC interaction point, thus mitigating the effects of the radiation-induced chromatic aberrations.

In the PWFA blowout regime of the [8], where the beam density $n_b >> n_0$, the beam channel is totally rarefied of plasma electrons. Under these conditions, the plasma response is very nonlinear, with relativistic electron velocities achieved, an amplitude-dependent period, and a large wave-breaking spike at the end of the first oscillation [9]. Inside of this electron-free "bubble", beam electrons experience linear focusing fields arising from the pure ion column, with force $F_r = -2\pi e^2 n_0 r$. Note that for a commonly encountered plasma density near $n_0 \simeq 10^{17}\text{cm}^{-3}$, that the linear force gradient is 900 TeV/m^2, equivalent to a 3 MT/m magnetic gradient. As laboratory quadrupoles do not reach more than ~600 T/m in practice, this is four orders of magnitude beyond the current state of the art. Further, the pure EM acceleration in the plasma bubble is independent of r. Thus the e-beam transport and acceleration dynamics are similar to those of an RF linac with quadrupole focusing, a dramatic improvement over the linear PWFA. These traits have made the blowout regime a dominant scenario for development of the PWFA in the last 25 years.

The first studies of blowout regime plasma *focusing* was performed at the Argonne Wakefield Accelerator (AWA) facility [10], where equilibrium beam propagation was demonstrated with low brightness beams at low plasma density. This led to the initial observation of beam deceleration and acceleration, including use of witness beams, in the PWFA blowout regime [11]. Later, short underdense ($n_b >> n_0$) plasma lenses were first examined in a UCLA-FNAL experiment [12]. Notably, these measurements also showed focusing of strongly asymmetric ("flat", as encountered in LCs) beams. Plasma focusing in the blowout regime has produced many novel effects, such as the collective beam refraction at a plasma boundary [13]. The experiments initiated at the AWA as well as subsequent investigations at SLAC FFTB [14], demonstrated long range guiding of beam in the underdense blowout regime [1,15] of the beam-plasma interaction.

II. Adiabatic plasma lens

Plasma focusing strength has led to the proposal to use the *underdense plasma lens* as an element of a linear collider final focus [16]; this is a strong advantage, as it permits very short focal length final focus lenses. Indeed, with the possibility of producing TeV beams in ~100 m plasma accelerators, the prospect of a km-scale final focusing system [17] is jarringly unpromising. Plasma lenses may potentially shrink the LC beam delivery system to the <10-metre length scale.

As the strength of the plasma focusing gradient is proportional to $n_0(z)$ which may be easily tailored. The adiabatic plasma lens, takes advantage of this feature, relying on an adiabatic increase in focusing strength to funnel the beam size to very small spots. As the beam is in a slowly varying equilibrium in this scheme, one may strongly mitigate the chromatic aberrations introduced by the Oide effect.

The adiabatic plasma lens is a physical system in which the strength associated with the beam-plasma focusing interaction wake in the limit $n_b > n_0$, and where $k_p\sigma_z$ >>1, where $k_p = \sqrt{4\pi r_e n_0}$ is the wavenumber of the plasma wake, i.e. $k_p = \frac{\omega_p}{c}$, and thus there is small longitudinal wake, ramps upward slowly in z. In this case the associated local betatron frequency k_β ramps upward in a similar manner, as one may write $k_\beta^2(z) = 2\pi r_e n_0(z)/\gamma = k_p^2(z)2/2\gamma$. Without ramping, one may define an equilibrium β-function, $\beta_{eq} = k_\beta^{-1}$. If the upward ramping of the plasma density is *adiabatic*, then β has a slowly changing quasi-equilibrium, simply written as $\beta_{q-eq}(z) \cong k_\beta^{-1}(z)$. The $n_0(z)$ profile defines a scale length, which should to preserve adiabaticity be much longer than the β-function, giving $L_s \equiv n_0(z)/n_0'(z)$ >> $\beta_{q-eq}(z)$. The increase in $n_0(z)$ serves to increase the beam density as well, as the spot area is simply $A(z) = 2\pi\varepsilon_n\beta_{q-eq}(z)/\gamma$. Thus n_b increases as $n_0^{1/2}$, and the underdense condition, $n_b/n_0 \propto n_0^{-1/2}$>1, is easiest to satisfy at the beginning of ramp. Indeed, the end of the ramp may be related to the limit n_b/n_0 ~1, as we shall see in simulations below. On the other hand, the starting point for the ramp is defined by the condition on the beam distribution that avoids a strong longitudinal wake response that has an onset when $k_p\sigma_z$~2. Fortunately, during this phase of the interaction n_0 is low and the longitudinal wake is concomitantly weak.

For the requirements given above, a high brightness beam with significant peak current and low emittance is needed. At the SPARC Lab at INFN-LNF, such a system exists, as well as relevant plasma source technology, due to the current emphasis on plasma acceleration research at SPARC. Further, many relevant beam diagnostic systems are available that may be used to perform an adiabatic plasma lens experiment. To introduce the planned experiments, we begin by discussing PIC simulations of a likely scenario.

III. Simulations of Beam Dynamics

The beam plasma interaction and subsequent focusing is simulated by a particle-in-cell code, QuickPIC, which utilizes a frozen-plasma field scheme optimized to permit fast simulation of long interactions in plasma. The plasma density profile is taken to be exponentially rising over a six cm ramp, followed by a flat-top, as shown in Figure 1. The plasma density is initiated at a density of $n_0 = 5\times10^{15}$ cm^{-3}, and is increased by a factor of 400 to $n_0 = 2\times10^{18}$ cm^{-3}. The parameters for simulations of the beam-plasma interaction are given in Table 1, with beam parameters obtained from experimentally benchmarked simulations of the beam as produced, accelerated, and compressed, in the RF photoinjector at SPARC. The beam-plasma system initially obeys $k_p\sigma_z$=2.

The initial and final beam spots are shown in Figure 2. The scaling of the beam density as $n_0^{1/2}$ is clearly displayed, with the line-out showing a factor of 20 times increase in beam density, validating the simple quasi-equilibrium model. In the final state at the flat-top, the ratio of the beam-to-plasma density is n_b/n_0=1.15, and blowout is just enforced. Nevertheless, the focusing is robust.

This is found not to be the case when then beam accesses the underdense regime, as is shown in Figure 3. The simulation of this case, where the same physical parameters are used as in Figure 2, with the exception of a pulse length longer by a factor of two (and thus a final beam density that would not exceed n_0) displays a radial oscillation of the plasma density at the end of the ramp, indicative of the onset of a modulational instability. This is the type of instability that is employed by the AWAKE proton-driven PWFA [18] experiment, and is sought after in that case to resonantly excite longitudinal wakes through the introduction of a beam current structure periodic with λ_p. It can be seen that this occurs in the final stage of the adiabatic focusing process, and is clearly not a desirable effect for adiabatic plasma lens focusing.

Table 1. Beam and plasma simulations for example adiabatic plasma lens experiment at SPARC.

Beam energy	110 MeV
RMS bunch length (σ_z)	75 μm
Normalized emittance ε_n	2 mm-mrad
Bunch charge	600 pC
Initial plasma density, n_0	5 x 10^{15} cm^{-3}
Initial matched β_{q-eq}	1.6 mm
Plasma scale length L_s	τ_l=1 cm
Total ramp length, L	6 cm

IV. Plasma Source

The type of plasma source needed for this experiment, an ablative capillary discharge, has been at use by UCLA for BNL ATF PWFA experiments, and also at SPARC, where it is employed in the PWFA program. The development and use of this discharge source was pioneered for accelerator and laser applications [19] at Hebrew Univ. This capillary discharge produces, confines, and shapes hydrogen-dominated plasmas. The nominal peak density of the plasma is tuned by the time delay between the discharge and the experimental application, *i.e.* the beam passage in our case. The plasma is formed by removal of material of the capillary walls, and is initiated by a laser pulse that ablates a small amount of surface near the cathode, where a voltage of a few tens of kV is applied. In the case, the capillary is made of plastic, and hydrogen is an abundant component of the plasma, a situation that can be reinforced by injection of hydrogen gas. This permits spectral analysis of hydrogen lines to obtain the plasma electron density and temperature [20], including the region interior to the capillary, which is optically accessible through the plastic. Initiated measurements at LNF have been performed on both standard and tapered capillaries, and are reported in a companion paper [21]. The tapering may be changed simply by addition of new tapered transition regions (fabricated by 3D printing) having a variety of tapering angles and lengths. These shapes are pre-optimized by use of an analytical guide derived from previous measurements and analysis [22] that indicate the electron density should depend approximately on the radius of the capillary as ~ $R^{-3/2}$. The design is further informed by magneto-hydrodynamic code simulations. Preliminary measurements indicate that scale lengths of nearly a cm may be achieved with this approach.

V. Beam Diagnosis with Betatron Radiation

The oscillatory motion of an electron propagating under the influence of ion focusing in the blowout regime gives rise to *betatron radiation* [23,24,25,26]. This is a type of synchrotron or undulator radiation that has spectral characteristics that depend on the betatron amplitude of the electron in the ion-focusing channel. This amplitude dependence may permit determination, through a frequency spectrum measurement, of the beam emittance. This is because the undulator parameter is dependent on the betatron amplitude x_0 *0* as $K_u = k_\beta \gamma x_0$, where the betatron wavenumber $k_\beta = k_\beta/\sqrt{2\gamma}$.

If the oscillations are small $K_u \ll 1$, then one may easily relate this measurement to the emittance. In terms of normalized amplitude (single particle normalized phase space area ε_{n1}), one may write $K_u = \sqrt{k_\beta \varepsilon_{n1}}$. The amplitude dependence of $K_u$then produces a redshift in the wavelength of the on-axis undulator radiation, as $\lambda_r \cong (\lambda_\beta/2\gamma^2)[1 + K_u^2/2]$, where $\lambda_\beta = \frac{2\pi}{k_\beta}$ is the betatron wavelength. Assuming a Gaussian phase space distribution, summation over amplitudes produces a simple expression for the rms normalized emittance in terms of the rms spectral width, as $\Delta\lambda_{rms} = 2\varepsilon_n/\gamma$. If $K_u \geq 0.5$, then the analysis is a bit more complex [27], but more information is available, in the form of radiation harmonics, as discussed below. When one measures this spectral width, the radiation emitted should be collected at constant γ. This requires a significant length of beam-plasma interaction where ion focusing is present while acceleration is not, which is the case in our final state (with the adiabatic ramp in density finished and flat $n_0(z)$ is utilized), with the lensing condition $k_p \sigma_z$ >2.

For SPARC experiments, we analyze a scenario where the final plasma density is chosen to optimize this type of measurement, again choosing $n_0 = 1.5 \times 10^{18}$ cm^{-3}. In this case, even with a relatively small emittance of SPARC, the rms value of K_u =1.6. With the betatron period of the fundamental photon wavelength is 12 nm (photon energy ~100 eV), and is thus in the EUV spectral range. The expected spectrum for this experiment has been simulated using the code SPECTRA, with the result given in that the spectrum has the expected fundamental energy, but with spectral spreading due to off-axis red shifting, the inherent spread in K_u due to the betatron amplitude distribution. This spectrum also shows evidence for harmonics up to n=4 due to the large K_u. It should be noted that the large K_u can be exploited to give enhanced information on the angles of the electron betatron trajectories in the plasma.

In implementing this revealing this measurement, we look to approaches used in previous experiments at both the BNL ATF in context of UCLA nonlinear inverse Compton scattering (ICS) experiments [28,29] and at LBNL BELLA laser plasma accelerator betatron radiation experiments [26]. As these previous measurements were in different spectral region, we must change the dispersive element in the spectrometer, while keeping much of the method intact. The system for ICS measurements at the ATF gives a single shot, double differential spectral (DDS) measurement in the 5-25 keV range, employing a bent, multi-layer, Si-Mo crystal for dispersing the spectrum. The bent multi-layer disperses the wavelengths in the crystal bend plane, while leaving the angular information in the vertical direction (along that of a collimating slit) of the image at the micro-channel plate detector.

The spectrum of nonlinear ICS is quite similar to that of the betatron radiation, as both are effectively large K_u undulators with a systematic variation in strength. In Ref. 45, an analysis of near-axis radiation collected in this spectrometer is given and is in analogy to the betatron amplitude analysis described above, yielding information about the beam-laser interaction.

The geometry employed in the BNL ICS experiments will be merged with that used in the BELLA betatron radiation measurements, with a collimating slit introduced. In this case we will substitute the bent multi-layer crystal with an EUV capable grating [30]. This system can utilize an MCP employed at UCLA EUV ICS experiments [31]. As an alternative approach, one may consider employing a CCD array as was used in single-photon-per-pixel mode to give the soft-X-ray spectrum in BELLA measurement system.

VI. Conclusions

The rationale and physics goals underpinning the adiabatic plasma lens experiment at the SPARC Lab has been presented. A robust scenario for testing the concepts involved, in which the beam is adiabatically focused to a density 20 times that of the initial value is outlined, with the aid of scaling laws and detailed PIC simulations. The major consequences of failing to obey the blowout conditions on the adiabatic plasma lens performance are identified.

We have reviewed briefly the progress made on developing adequate plasma source for this experiment based on existing discharge-based approaches but with tailored entrance boundaries to control the hydrodynamic expansion of the gas and the expansion dynamics plasma after formation. The details of such experimental development are discussed in Ref. 20. The physics that can be revealed through betatron radiation spectral measurements have been analyzed, and a spectrometer system designed to obtain the relevant experimental signals has been identified.

With the initiation of the experimental program on plasma acceleration and lensing at SPARC now underway, the adiabatic plasma lens measurements may begin within the next year. This experiment should provide an invaluable demonstration of the unique utility of plasma lensing in the context of advanced collider physics applications. In this regard, future work in simulations and experiments will concentrate on the focusing of asymmetric (transversely elliptic-shaped) beams, due to their complex beam-plasma interaction physics and the high relevance to collider scenarios.

Acknowledgments

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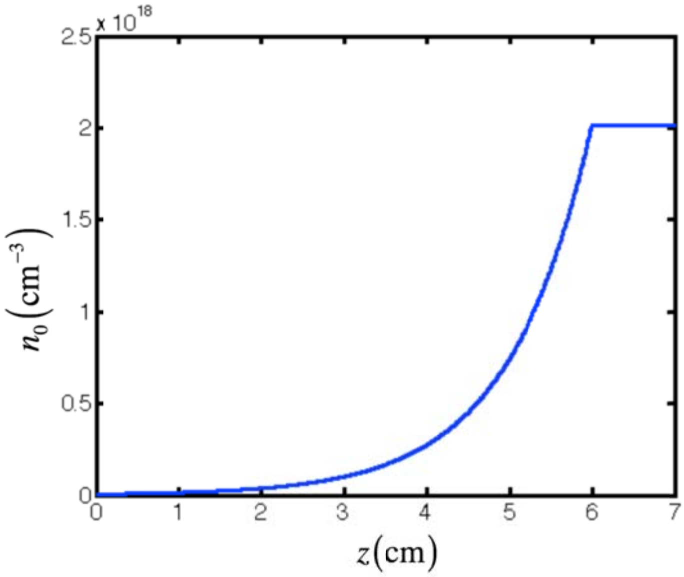

Figure 1. Plasma density profile used in adiabatic lens simulations.

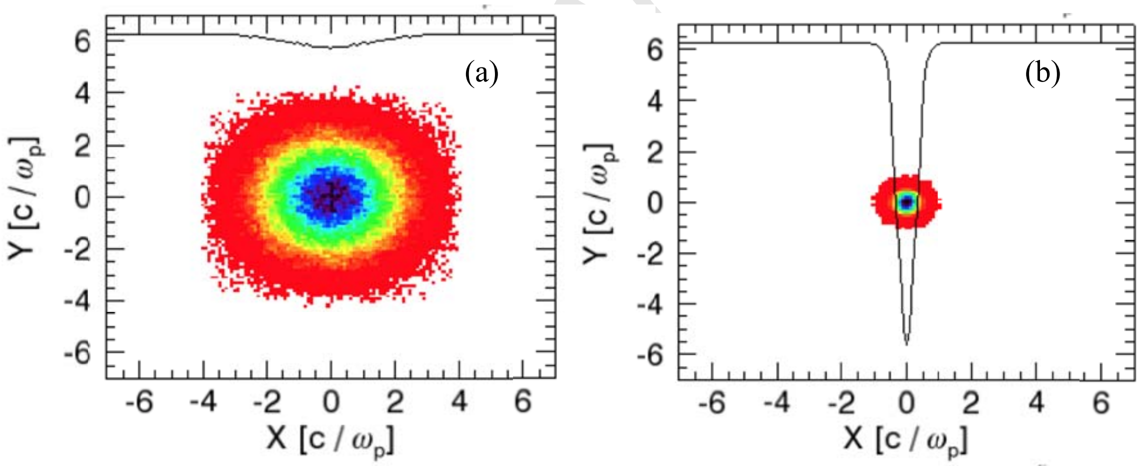

Figure 2(a) Initial and (b) final beam *x-y* distributions from PIC simulation of adiabatic plasma lens with parameters as described in Table 1, shown in linear red-blue color map and line-out.

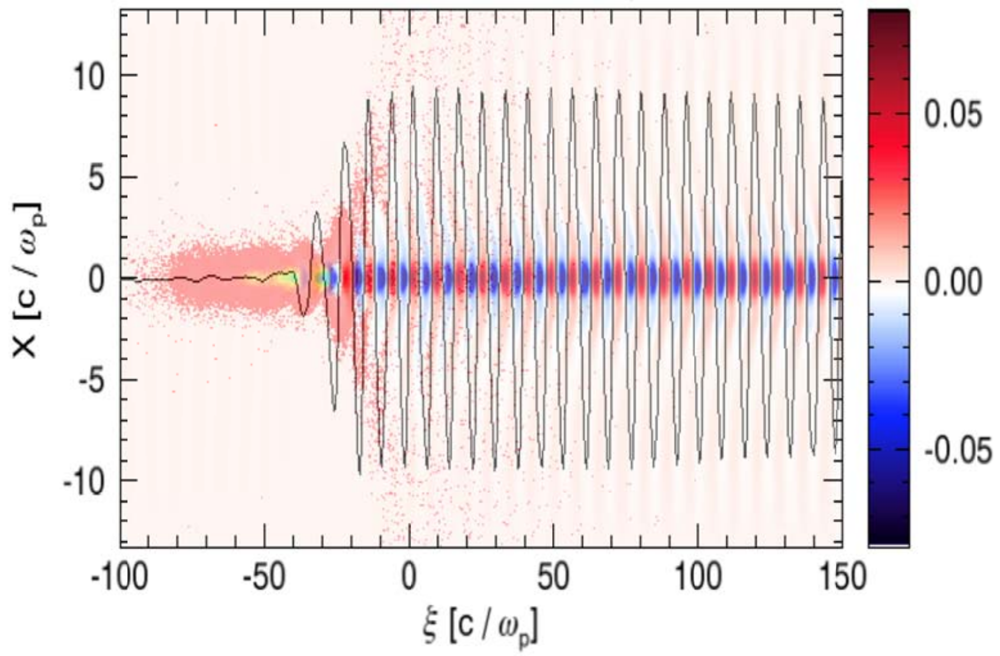

Figure 3. Final beam x-ξ distributions from PIC simulation of adiabatic plasma lens with same parameters as in Figure 2, but with double the bunch length, i.e. σ_z=150 μm. Also shown, longitudinal wakefield on-axis profile.

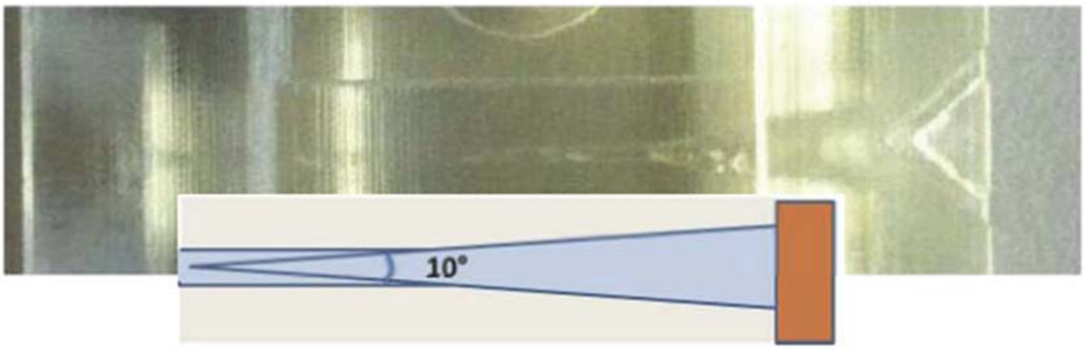

Figure 4. Photograph of the tapered plastic capillary for production of ramped plasma density profile needed for adiabatic lens experiments, with schematic of the tapering scheme.

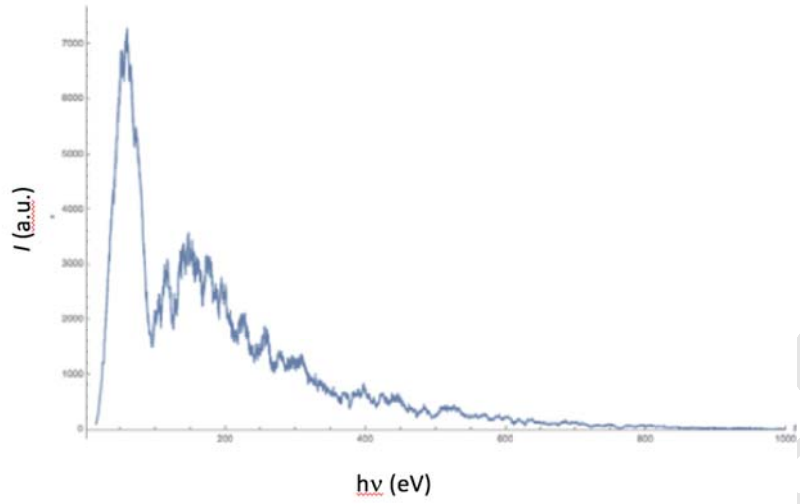

Figure 5. SPECTRA calculation of spectral content of betatron radiation for example experimental scenario.

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251 **References**

1. I.Blumenfeld et al., *Nature* **445**, 741 (2007)
2 S. Chatrchyan, et al., Physics Letters B 716, 30 (2012)
3 C. Pellegrini, *Eur. Phys. J. H* **37,** 659-708 (2012)
4 T. Ekeberg, *et al. Phys. Rev. Lett*. **114,** 098102 (2015)
5 J.B. Rosenzweig, et al., *Nucl. Instr. and Methods A* doi:10.1016/j.nima.2011.01.073 (2011).
6 P. Chen, K. Oide, A.M. Sessler and S.S. Yu, *Phys. Rev. Lett.* **64,** 1232 (1990)
7 K. Oide. Phys. Rev. Lett. 61, 1713 (1988)
8 J. B. Rosenzweig, *et al.*, *Phys. Rev. A -- Rapid Comm* . **44**, R6189 (1991).
9 J. B. Rosenzweig, N. Barov, M. C. Thompson, and R. B. Yoder Phys. Rev. ST Accel. Beams **7**,061302 (2004); N. Barov, J. B. Rosenzweig, M. C. Thompson, and R. B. Yoder, *Phys. Rev. ST Accel. Beams* **7**, 061301 (2004)
10 N. Barov, M.E. Conde, W. Gai, and J.B. Rosenzweig, *Physical Review Letters.* **80**, 81 (1998)
11 N. Barov, et al., *Phys. Rev. ST Accel. Beams* **3** 011301 (2000).
12 M. C. Thompson, et al., *Phys. Plasmas*, **17**, 073105 (2010)
13 P. Muggli, et al., Phys. Rev. ST Accel. Beams 4 (2001)
14 C.E. Clayton, et al., Phys. Rev. Lett. 88, 154801 (2002)
15 M. Hogan, *et al. Phys. Rev. Lett.,* **95**, 054802 (2005)
16 P. Chen, S. Rajagopalan, and J. Rosenzweig, *Phys. Rev. D* **40**, 923 (1989).
17. P. Raimondi and A. Seryi, Phys. Rev. Lett. 86, 3779 (2001)
18 A. Caldwell, K. Lotov, A. Pukhov, F. Simon, *Nature Physics* 5, 363–367 (2009)
19 Y.Ehrlich, C.Cohen, A.Zigler, J.Krall, P.Sprangle, E.Esarey, *Phys. Rev. Lett.* 77 (1996)
20 H R Griem, *Plasma spectroscopy* McGraw-Hill, 1964.
21 F. Filippi, et al., these proceedings.
22 D. Kaganovich *et al., Appl. Phys. Lett.* 71, 2925 (1997).
23 S. Kneip, *et al.* Phys. Rev. Lett. **100**, 105006 (2008)
24 Kim Ta Phuoc, et al., Phys. Rev. Lett. **97**, 225002 (2006)
25 S. Corde, et al., Phys. Rev. Lett. **107**, 255003 (2011)
26 Aihua Deng, et al., Phys. Rev. ST Accel. Beams **15**, 081303 (2012)
27 G.R. Plateau, et al., *PRL* 109, 064802 (2012)
28 Y. Sakai, *et al., Phys. Rev. ST Accel. Beams*,**18**, 060702 (2015)
29. Y. Sakai *et al., Phys. Rev. ST Accel. Beams***, 20,** 060701 (2017)
30. D.L. Voronov, *et al. Journal of Physics: Conference Series* 425 (2013) 152006
31. G. A. Krafft, A. Doyuran, and Phys. Rev. E 72, 056502 (2005)

Highlights

- Passive plasma lenses can, by virtue of their extraordinary, locally tunable strength, can be used in a new type of focusing, where electron beams are adiabatically diminished in transverse size.
- This adiabatic plasma lens may provide an essential method for avoiding the Oide limit on focusing in TeV-class linear colliders.
- A first experimental test of adiabatic lensing is proposed to take place at the SPARC Lab at INFN-LNF in Frascati, Italy. Detailed simulations illustrate the feasibility of this experiment.
- Development of the unique ramped-density plasma source at INFN-LNF for this experiment is reported.
- Diagnosis of the beam focusing to few micron size by using betatron radiation is described.