PLASMA WAKEFIELD ACCELERATION FOR UHECR IN RELATIVISTIC JETS

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- Introduction – What makes a good accelerator
- A Brief History of Plasma Wakefields
- Plasma Wakefield Excitation by Alfven Shocks
- Simulations on Alfven Plasma Wakefields
- Summary

International Conference on Ultra Relativistic Jets in Astrophysics
Banff, Canada, July 10-15, 2005

Cosmic Acceleration Mechanisms

Addressing the Bottom–Up Scenario for Acceleration of Ordinary Particles:

- Conventional cosmic acceleration mechanisms encounter limitations:
  - Fermi acceleration (1949) (= stochastic accel. bouncing off B-fields)
  - Diffusive shock acceleration (1970's) (a variant of Fermi mechanism)

    Limitations for UHE: field strength, diffusive scattering inelastic
  - Eddington acceleration (= acceleration by photon pressure)

    Limitation: acceleration diminishes as $1/\gamma$
- Examples of new ideas:
  - Zevatron (= unipolar induction acceleration) (R. Blandford, astro-ph/9906026, June 1999)
  - Alfven-wave induced wakefield acceleration in relativistic plasma (Chen, Tajima, Takahashi, Phys. Rev. Lett. 89 , 161101 (2002).
  - Additional ideas by M. Barring, R. Rosner, etc.

WHAT MAKES AN IDEAL ACCELERATOR?

LESSONS FROM TERRISTRIAL ACCELERATORS

- Continuous interaction between the particle and the accelerating longitudinal EM field (Lorentz inv.)

  → Gain energy in macroscopic distance
- Particle-field interaction process non-collisional

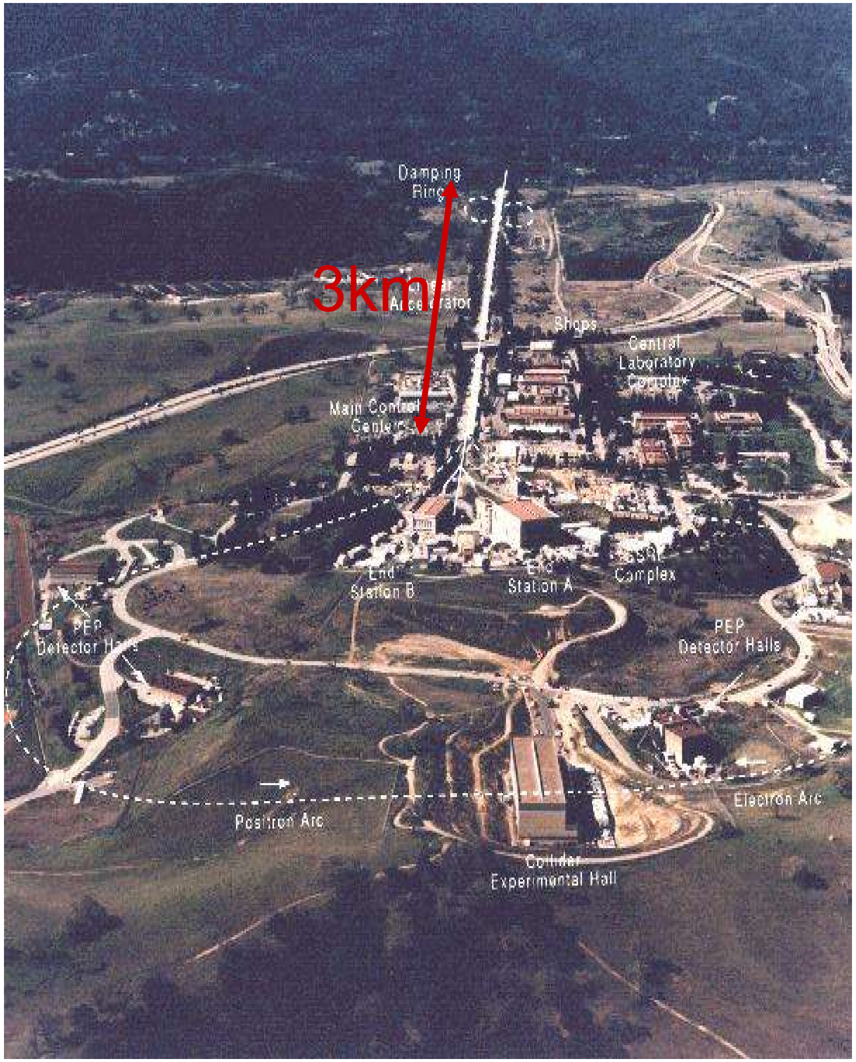
  → Avoid energy loss through inelastic scatterings
- To reach ultra high energy, linear acceleration (minimum bending) is the way to go

  → Avoid severe energy loss through synchrotron radiation

Are these criteria applicable to celestial accelerators?

LINEAR VS. CIRCULAR

SLAC



CERN

A Brief History of Plasma Wakefields

Motivated by the challenge of high energy physics

- Laser driven plasma acceleration
  T. Tajima and J. M. Dawson (1979)
- Particle-beam driven plasma wakefield acceleration
  PC, Dawson et al. (1984)
- Extremely efficient:

$$eE \geq \sqrt{n\,[\mathrm{cm}^{-3}]}\ \ \mathrm{eV/cm}$$

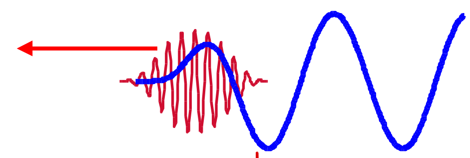
For $n=10^{18}\,\mathrm{cm}^{-3}$, $eE=100$ GeV/m → TeV collider in 10 m!

* Plasma wakefield acceleration principle experimentally verified. Actively studied worldwide

Concepts For Plasma-Based Accelerators

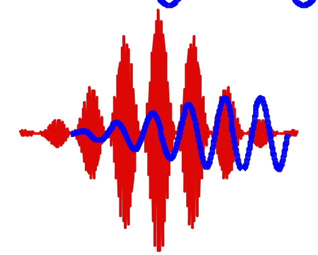
- Laser Wake Field Accelerator(LWFA)

  A single short-pulse of photons



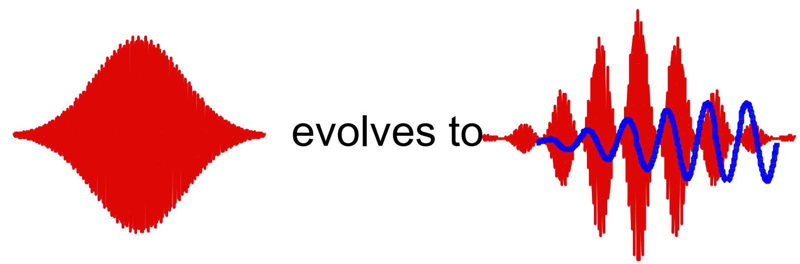
- Plasma Beat Wave Accelerator(PBWA)

  Two-frequencies, i.e., a train of pulses



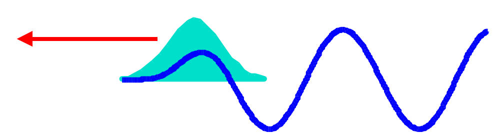
- Self Modulated Laser Wake Field Accelerator(SMLWFA)

  Raman forward scattering instability

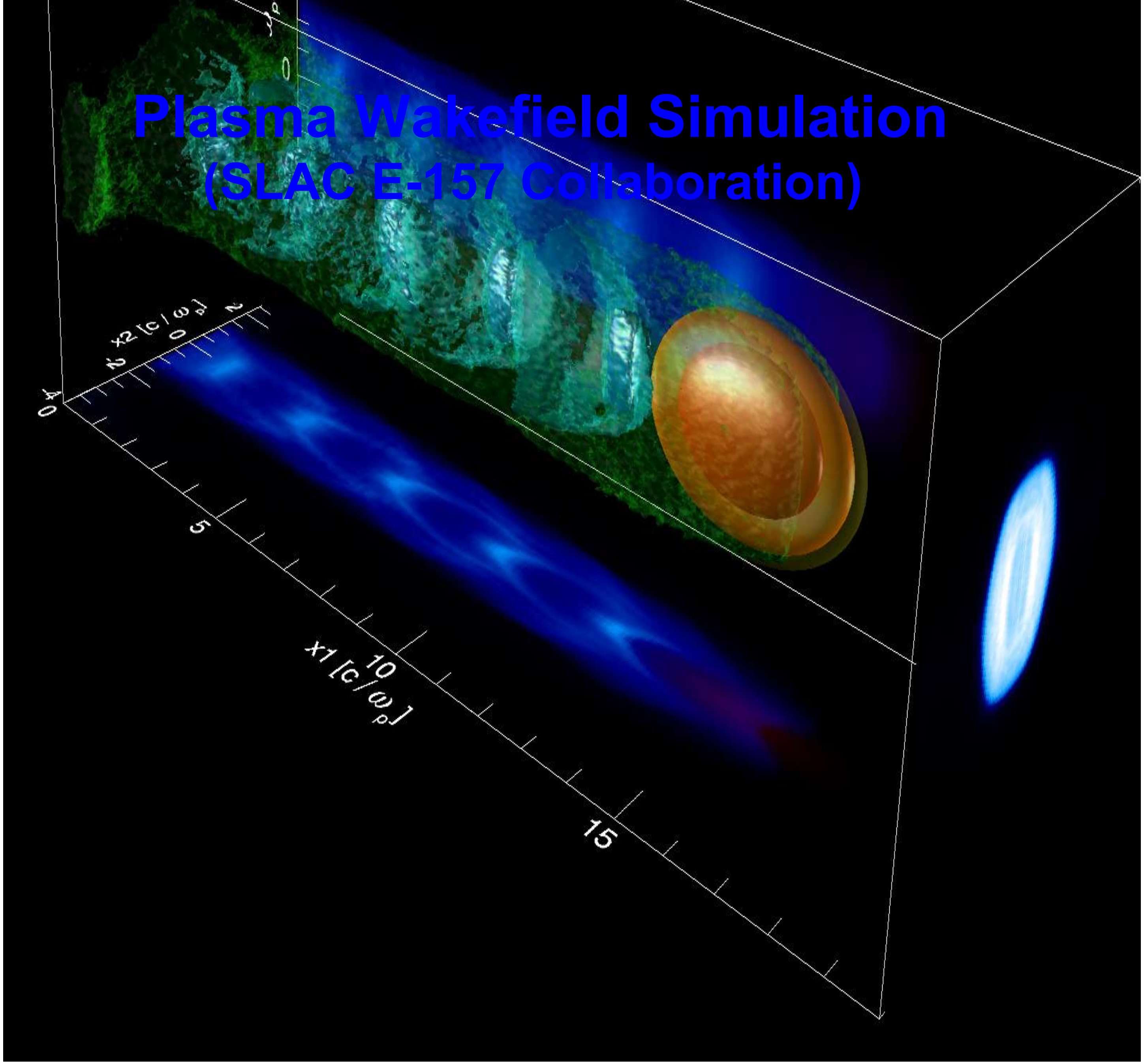


- Plasma Wake Field Accelerator(PWFA)

  A high energy electron (or positron) bunch

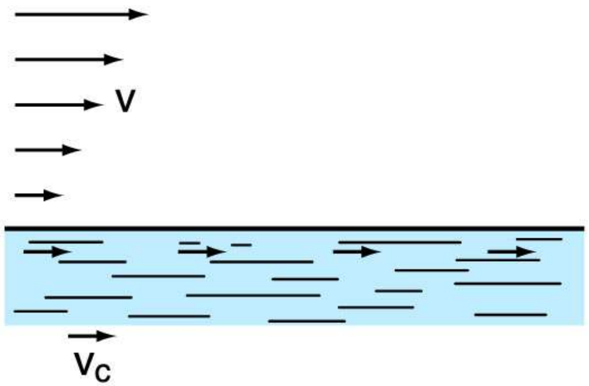


Plasma Wakefield Simulation
(SLAC E-157 Collaboration)



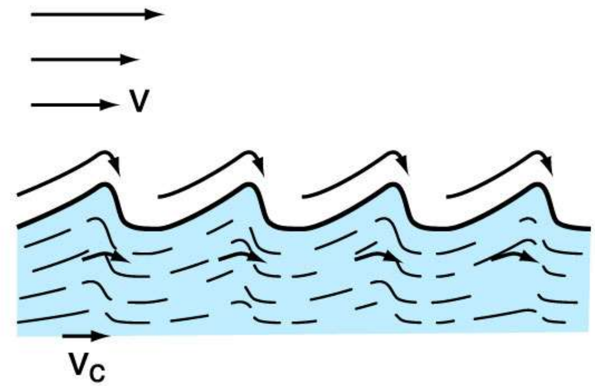
PLASMA WAKEFIELD ACCELERATION MECHANISM

$v < v_c$ (laminar flow)



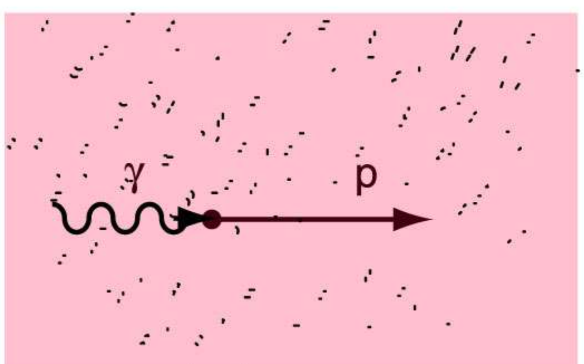
Viscosity of Molecules

$v > v_c$ (Kelvin-Helmholtz Instability)



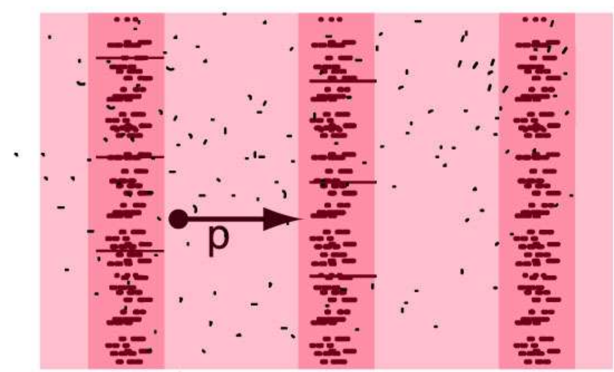
Anomalous Viscosity

Eddington Acceleration



"Pressure" Due to Individual Photons

Plasma Wakefield Acceleration



Acceleration Due to Collective Excitations

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Generation of Ponderomotive Force in Plasmas

- Ponderomotive force induced by the interaction of a localized EM energy density in a plasma is

$$F(r,t) = -\int dk/(2\pi)^3 H_{eff} \nabla f(k,r,t) ,$$

where $f(k,r,t)$ is the distribution function of the quasi-particles that represent the EM energy density.

- $H_{eff} = \hbar\omega$ and ω satisfies the dispersion relation

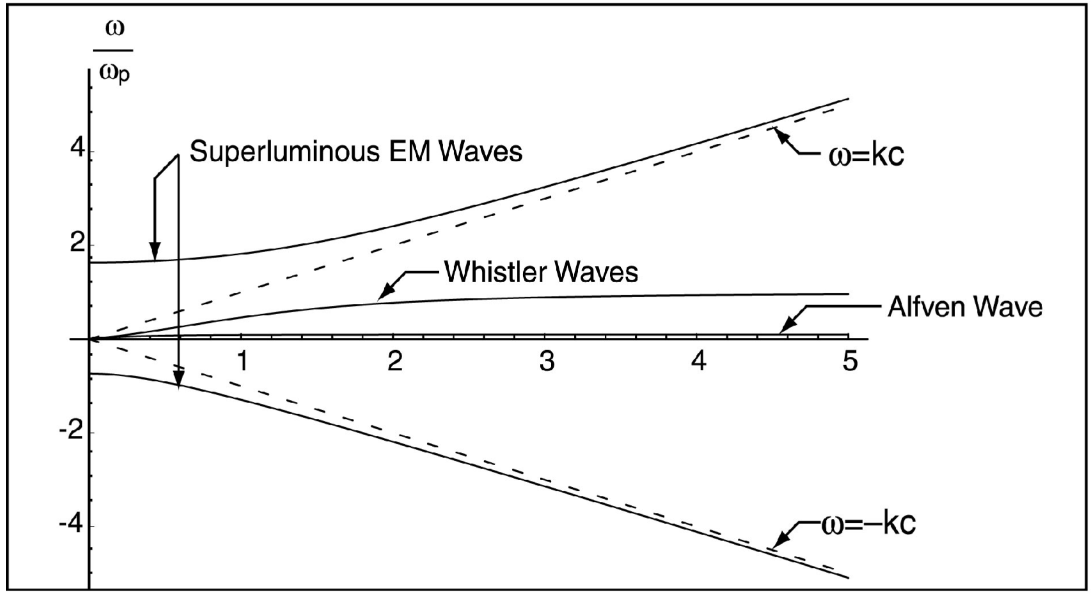
$$\omega^2 - c^2k^2 = \omega_{pe}^2/(1+ \Omega_e^2/\omega^2) + \omega_{pi}^2/(1+ \Omega_i^2/\omega^2) ,$$

where $\omega_{pe,pi}^2 = 4\pi e^2 n/m_{e,i}$ and $\Omega_{e,i} = eB/m_{e,i}c$.

PLASMA DISPERSION RELATIONS

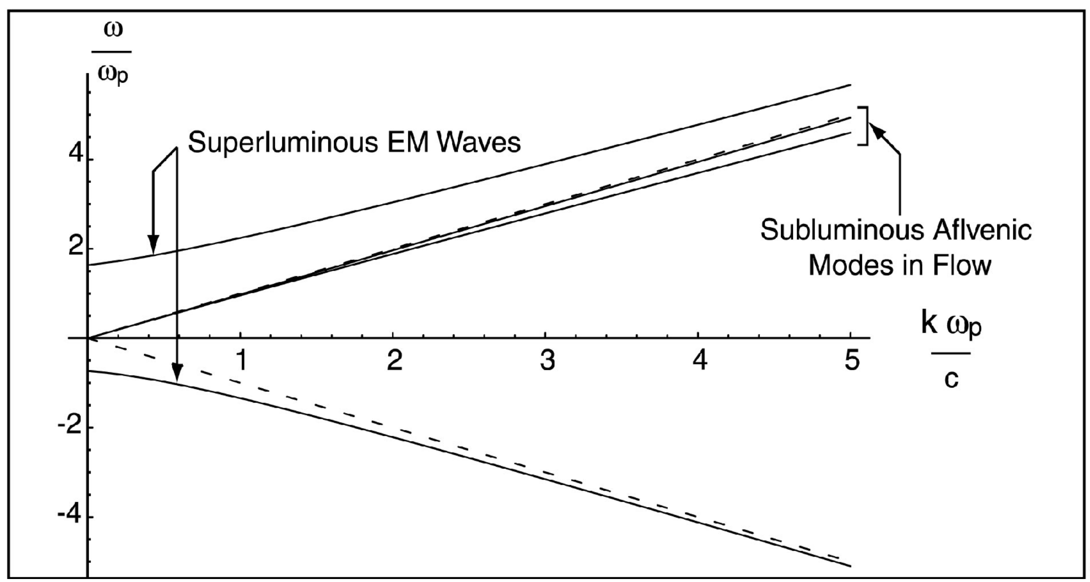
For non-relativistic plasmas, Alfven waves are typically slow:
$E_A/B_A = v_A/c << 1.$

$\omega(k)$ $[v_0=0]$



In an ultra relativistic plasma flow,
$E_A/B_A = v_A/c \leq 1.$
Indistinguishable from subluminous EM waves

$\omega(k)$ $[v_0=0.9c]$



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Alfven Wave Induced Ponderomotive Force

- The distribution function is related to the Alfven wave/shock energy density of the propagating "driver" is

$$f(k,r,t)=(E_A^2+B_A^2)/(8\pi\hbar\omega_A)=(v_A^2+1)B_A^2/(8\pi\hbar\omega_A).$$

- Inserting into the formula, we find

$$F(r,t) = -(1/16\pi)[(\omega_{pe}^2/\Omega_e^2)/(1+\Omega_e^2/\omega^2) + (\omega_{pi}^2/\Omega_i^2)/(1+\Omega_i^2/\omega^2)] \cdot \nabla \int dk/(2\pi)^3 (c^2k^2/\omega\omega_A)(E_A^2+B_A^2) .$$

Ponderomotive force depends on the *gradient* of the Alfven shock intensity.

Plasma Waves Driven by Different Sources

Equations for electron density perturbation driven by electron beam, photon beam, neutrino beam, and Alfven shocks are similar:

Electron beam

$$\left(\partial_t^2+\omega_{pe0}^2\right)\delta n_e=-\omega_{pe0}^2 n_{e-beam}$$

Photons

$$\left(\partial_t^2+\omega_{pe0}^2\right)\delta n_e=\frac{\omega_{pe0}^2}{2m_e}\nabla^2\int\frac{d\mathbf{k}}{(2\pi)^3}\ \frac{N_\gamma}{\omega_{\mathbf{k}}}$$

Neutrinos

$$(\partial_t^2+\omega_{pe0}^2)\delta n_e=\frac{\sqrt{2}\,n_{e0}G_F}{m_e}\nabla^2 n_\nu$$

where δn_e is the perturbed electron plasma density

Bingham, Dawson, Bethe (1993): Application to NS explosion

Alfven Shocks

$$\left(\partial_t^2+\omega_{pe0}^2\right)\delta n_e=\frac{A}{2m_e}\nabla^2\int\frac{d\mathbf{k}}{(2\pi)^3}\ \frac{c^2k^2}{\omega_{\mathbf{k}}\quad A}(E_A{}^2+B_A{}^2)$$

All these processes can in principle occur in astro jets.

Plasma Wakefield Potential

- In the nonlinear regime, the maximum field amplitude that the plasma can support is

$$E_{max} \approx a_0 E_{wb} = a_0 (mc\omega_p/e).$$

E_{wb} is the cold wave breaking limit in the linear regime.

$a_0 = eE_A/mc\omega_A$ for Alfven shocks.

- For relativistic plasma flow with Lorentz factor Γ_p , the maximum "acceleration gradient" mcexperienced by a single charge riding on the this PWF is

$$G = e\,E_{max}/\,\Gamma_p^{1/2} \approx a_0 mc^2\,(4\pi r_e\,n/\,\Gamma_p\,)^{1/2}\ .$$

CONNECTION TO ULTRA RELATIVISTIC JETS

- Assume GRB is the site of acceleration, with energy release ~ 10^{50} erg/sec. Assume 10^{-4} goes into Alfven shocks. Then the Alfven shock amplitude is $B_A \sim 10^{10}$ G at $R \sim 10^9$ cm.
- Assume that at $R \sim 10^9$ cm, the relativistic jet has a density $n \sim 10^{20}$ cm^{-3} and balk flow of $\Gamma \sim 10^2$.
- Taking these and $\omega_A \sim 10^4$ sec^{-1} as references, we find the acceleration gradient

$$G = 10^{15}\,[(eB_A/mc\omega_A)/10^9][10^2/\Gamma]^{1/2}\,[10^9/R]^{1/2}\ \text{eV/cm}.$$

- For the sake of discussion, let's take all [...] to be 1. Then we obtain $\varepsilon = 10^{20}$ eV in a distance $L \sim 10^5$ cm !!

ENERGY SPECTRUM

- Stochastic encounters of accelerating and decelerating phase of plasma wakefields results in energy distribution that follows the Fokker-Planck equation:

$$\partial f/\partial t = \partial/\partial\varepsilon \int d(\Delta\varepsilon)\Delta\varepsilon W(\varepsilon,\Delta\varepsilon) f(\varepsilon,t) + \partial^2/\partial\varepsilon^2 \int d(\Delta\varepsilon)(\Delta\varepsilon^2/2) W(\varepsilon,\Delta\varepsilon) f(\varepsilon,t)$$

- Assumptions on the transition rate $W(\varepsilon,\Delta\varepsilon)$ in plasma wakefield:

  a. $W(\varepsilon,\Delta\varepsilon)$ is an even function of $\Delta\varepsilon$

  b. $W(\varepsilon,\Delta\varepsilon)$ is independent of

  c. $W(\varepsilon,\Delta\varepsilon)$ is independent of $\Delta\varepsilon$

  → $W(\varepsilon,\Delta\varepsilon)$= const.

ENERGY SPECTRUM

- Steady state ($\partial f/\partial t = 0$) solution:

$$f(\varepsilon) = \varepsilon_0 / \varepsilon^2$$

* Power-law spectrum results from random encounters of accelerating-decelerating phases; Particle momentum direction unchanged.

- When "phase slippage" and other dissipative energy loss mechanisms are included, the power-law may be modified:

$$f(\varepsilon) = \varepsilon_0 / \varepsilon^{2+\alpha}$$

Alfven Wave Induced Wake Field Simulations

K. Reil (SLAC), PC and R. Sydora (U of Alberta)

Dispersion relation for EM waves in magnetized plasma:

$$\frac{k^2c^2}{\omega^2} = 1 - \frac{2\omega_{pe}^2}{\omega^2 - \Omega_e^2}$$

$\omega_{pe}{}^2 = 4\pi e^2 n/m$

$\Omega_c = eB/mc$

E.M. waves propagate when

(i) $\omega > \sqrt{2\omega_{pe}^2 + \Omega_e^2}$, the high frequency branch

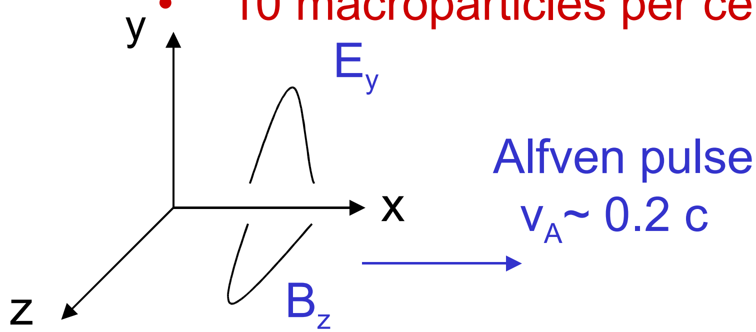
(ii) $\omega < \Omega_e$, the low frequency (or Alfven) branch

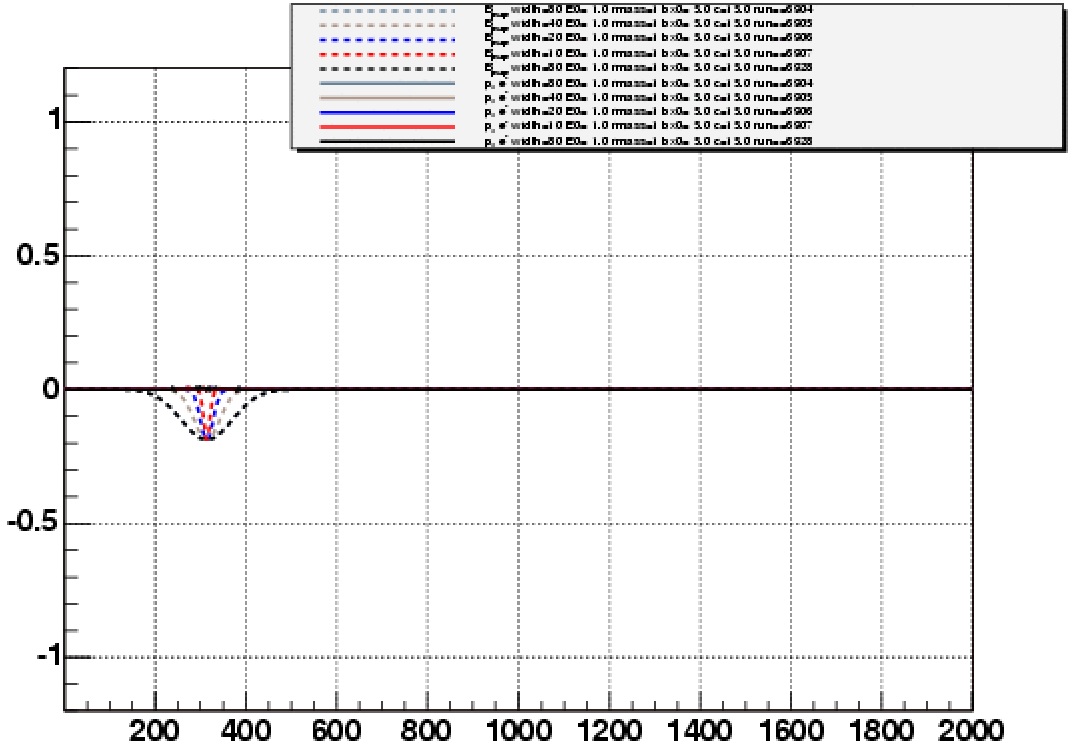
$$\omega \simeq kV_A\left(1 - \frac{k^2\omega_{pe}^2 V_A^2}{\Omega_e^4 c^2}\right), \text{ where } V_A = \frac{c}{\sqrt{\left(1 + 2\frac{\omega_{pe}^2}{\Omega_e^2}\right)}}$$

Simulation parameters for plots:

- e+ e- plasma (mi=me)
- Zero temperature (Ti=Te=0)
- Ω_{ce}/ω_{pe} = 1 (normalized magnetic field in the x-direction)
- Normalized electron skin depth c/ω_{pe} is 15 cells long
- Total system length is 273 c/ω_{pe}
- dt=0.1 $\omega_{pe}{}^{-1}$ and total simulation time is 300 $\omega_{pe}{}^{-1}$
- Aflven pulse width is about 11 c/ω_{pe}
- 10 macroparticles per cell

Simulation geometry:





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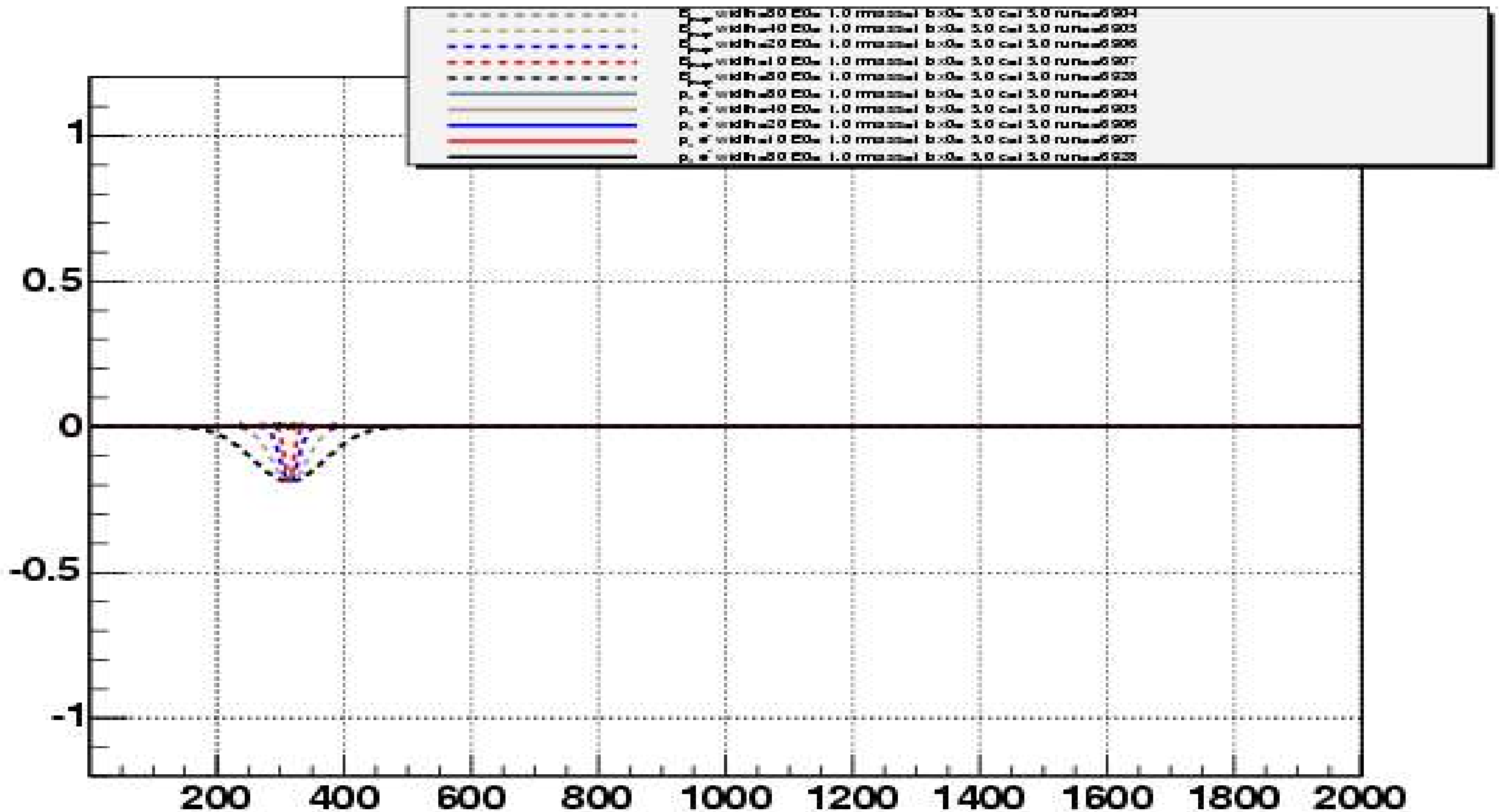
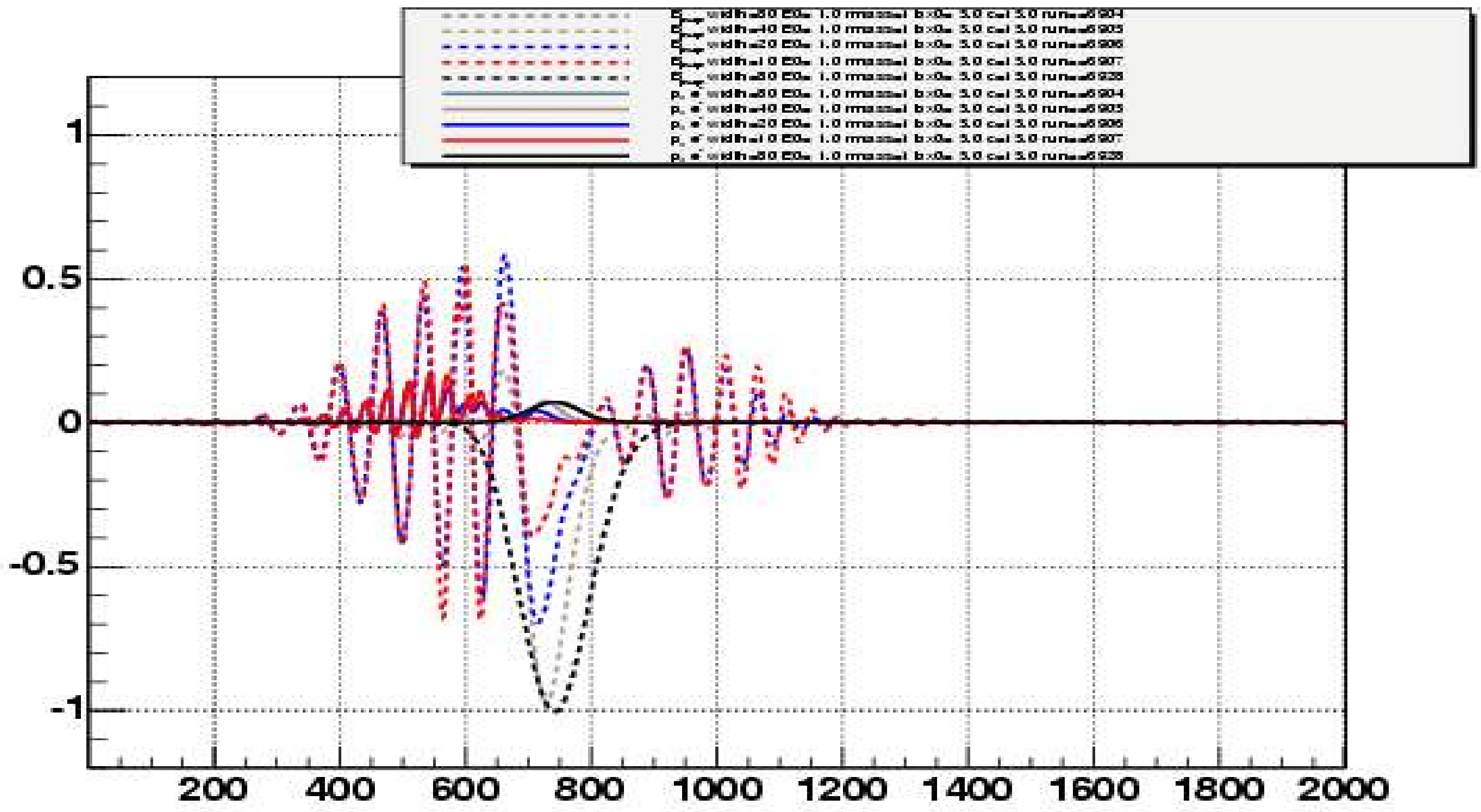
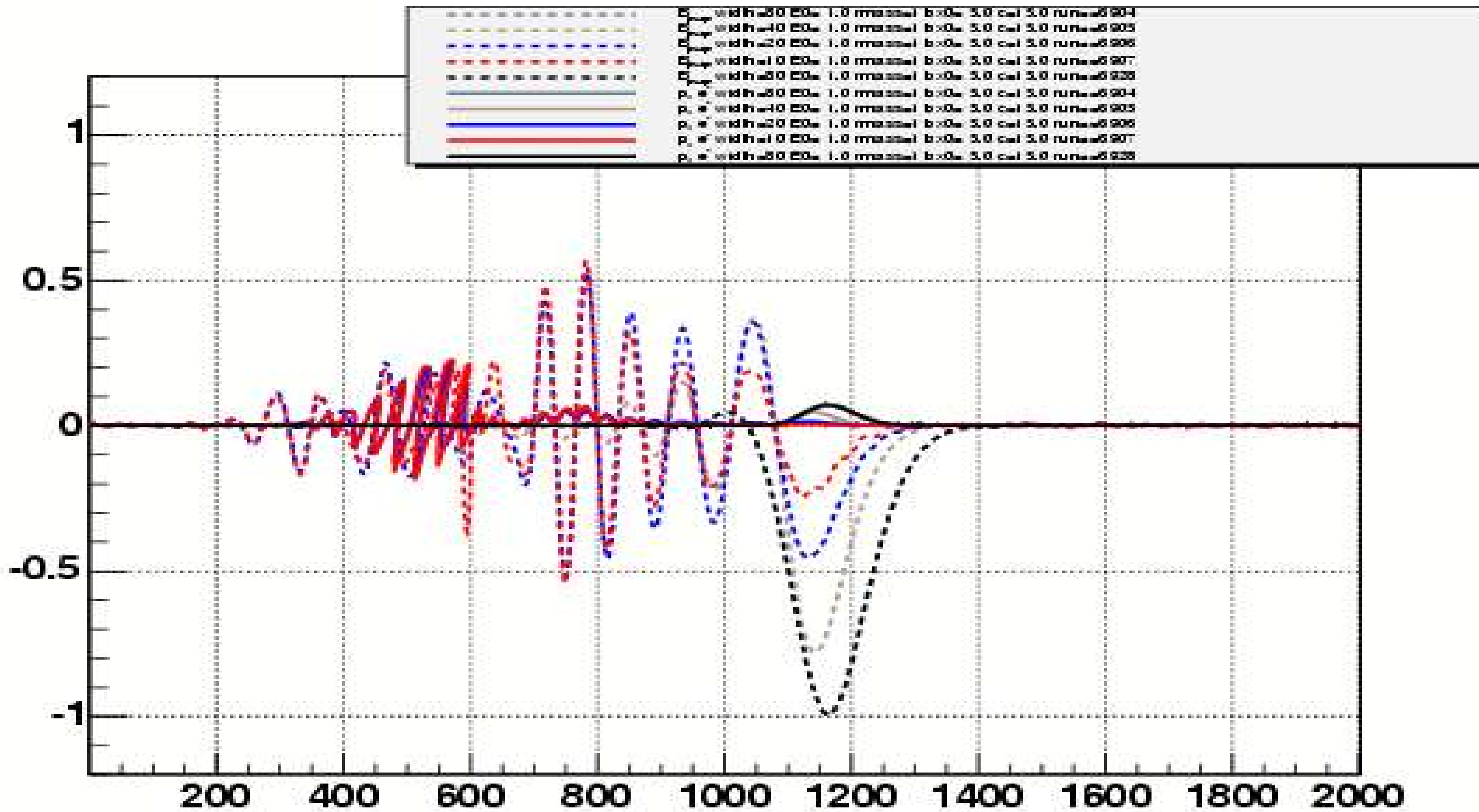
R_{mass}=1 T=25 ω_p^{-1}



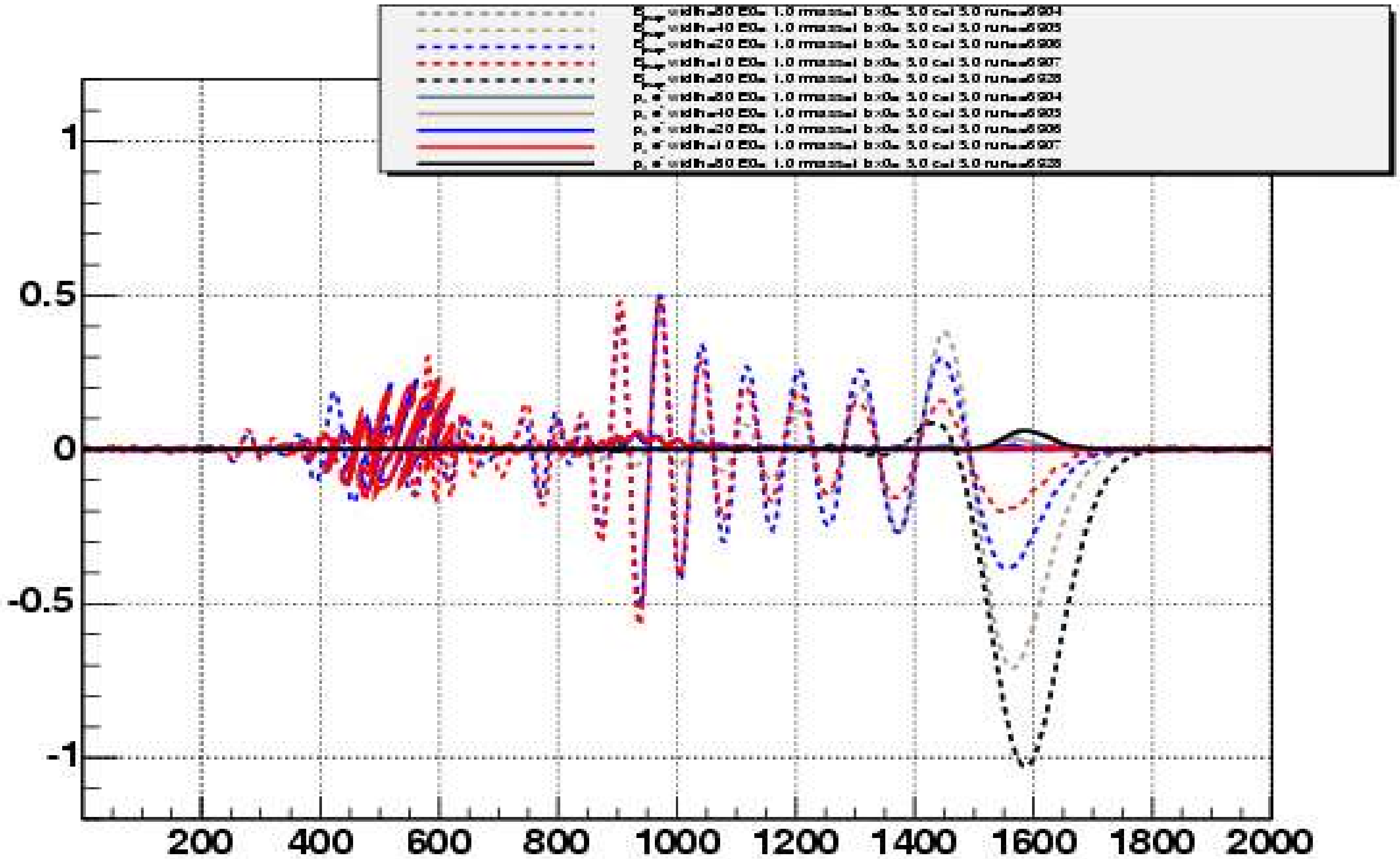
R_{mass}=1 T=150 ω_p^{-1}

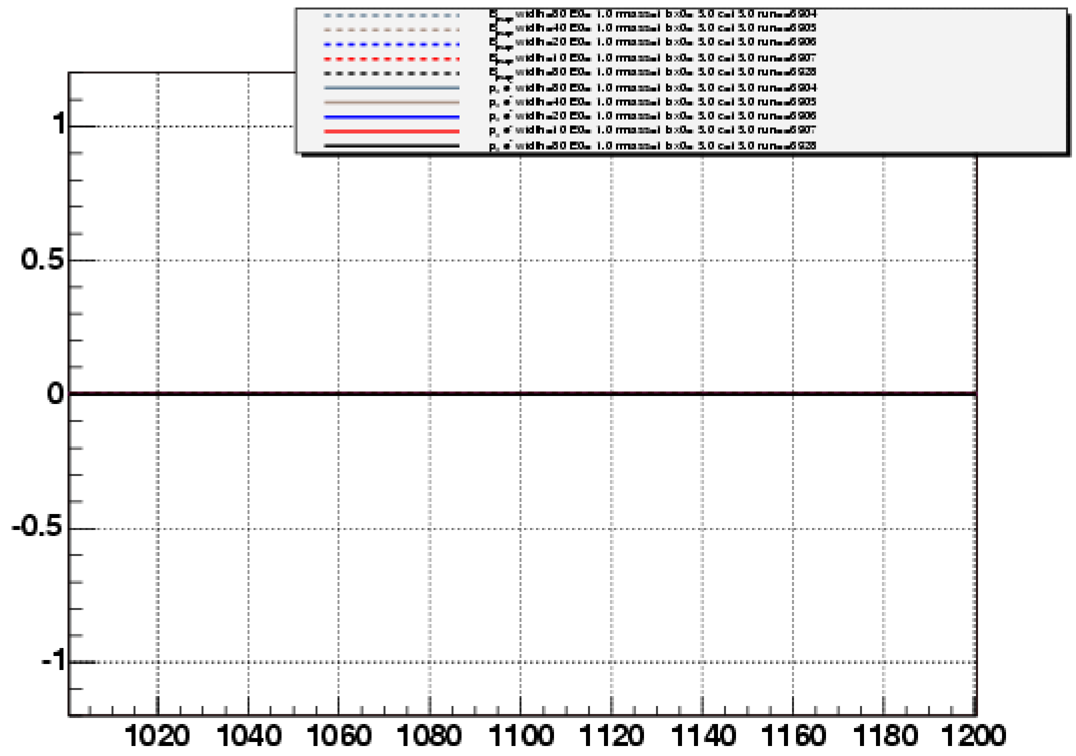


R_{mass}=1 T=275 ω_p^{-1}



R_{mass}=1 T=400 ω_p^{-1}

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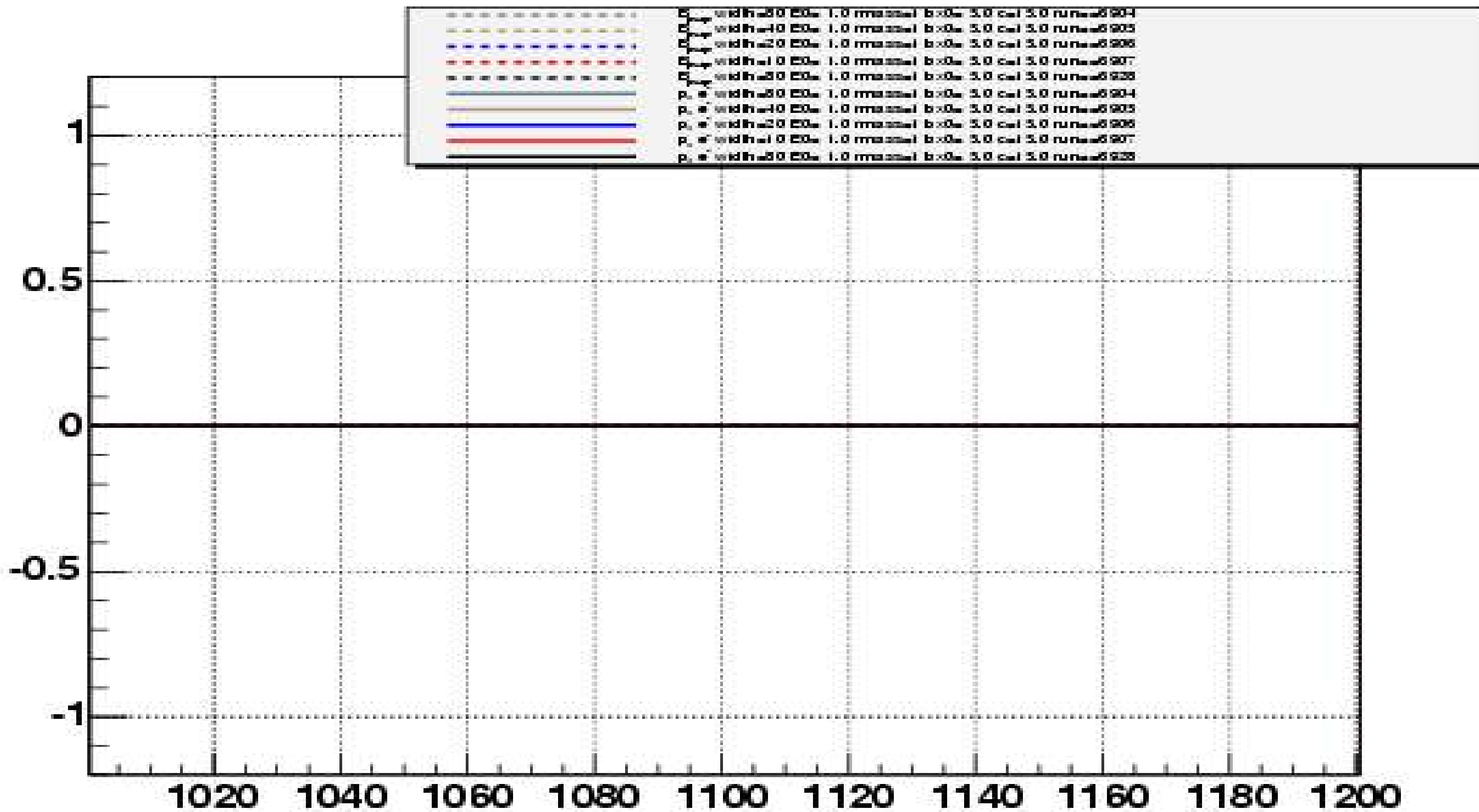
R_{mass}=1 T=25 ω_p^{-1} (Zoomed)



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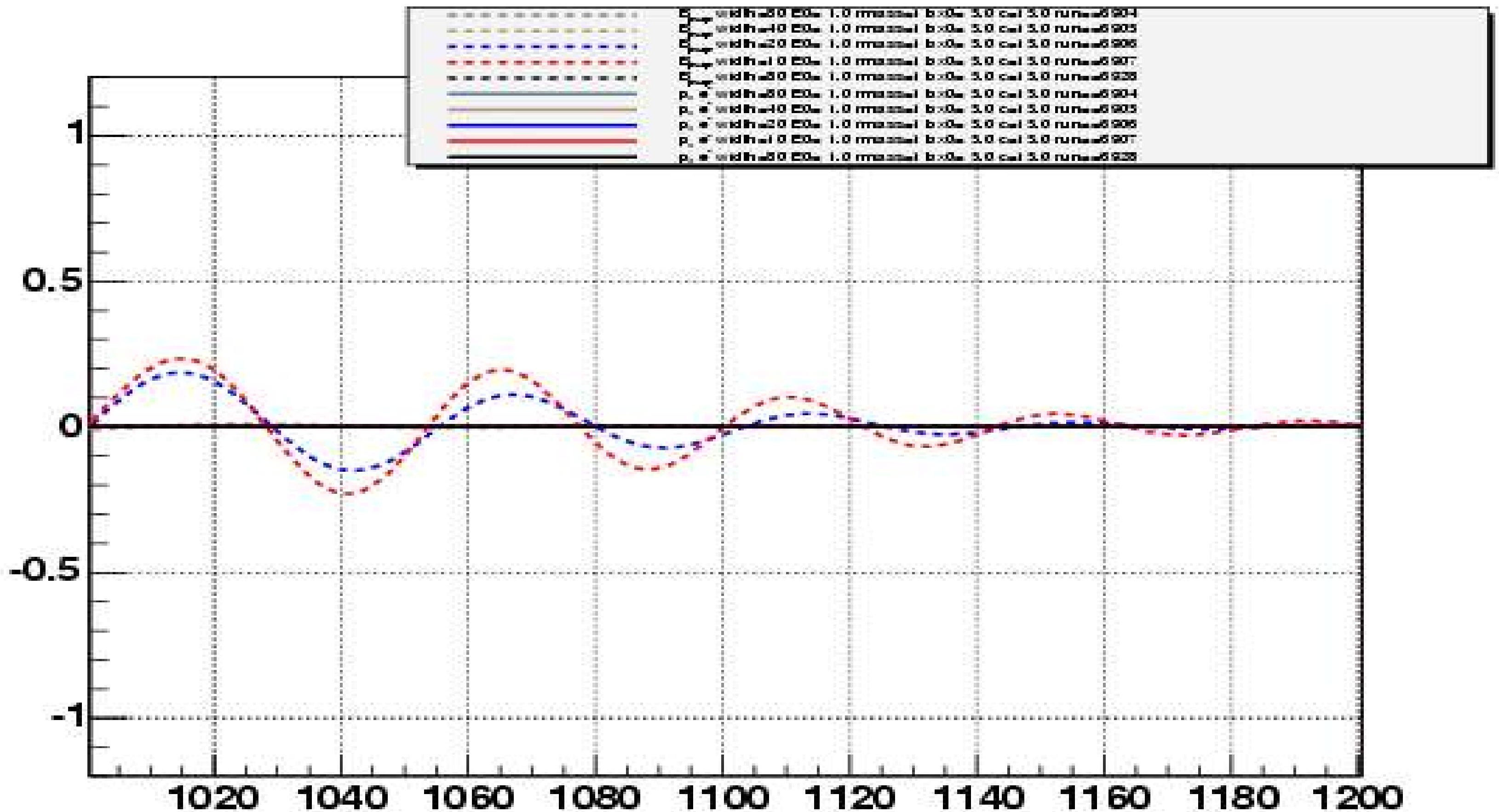

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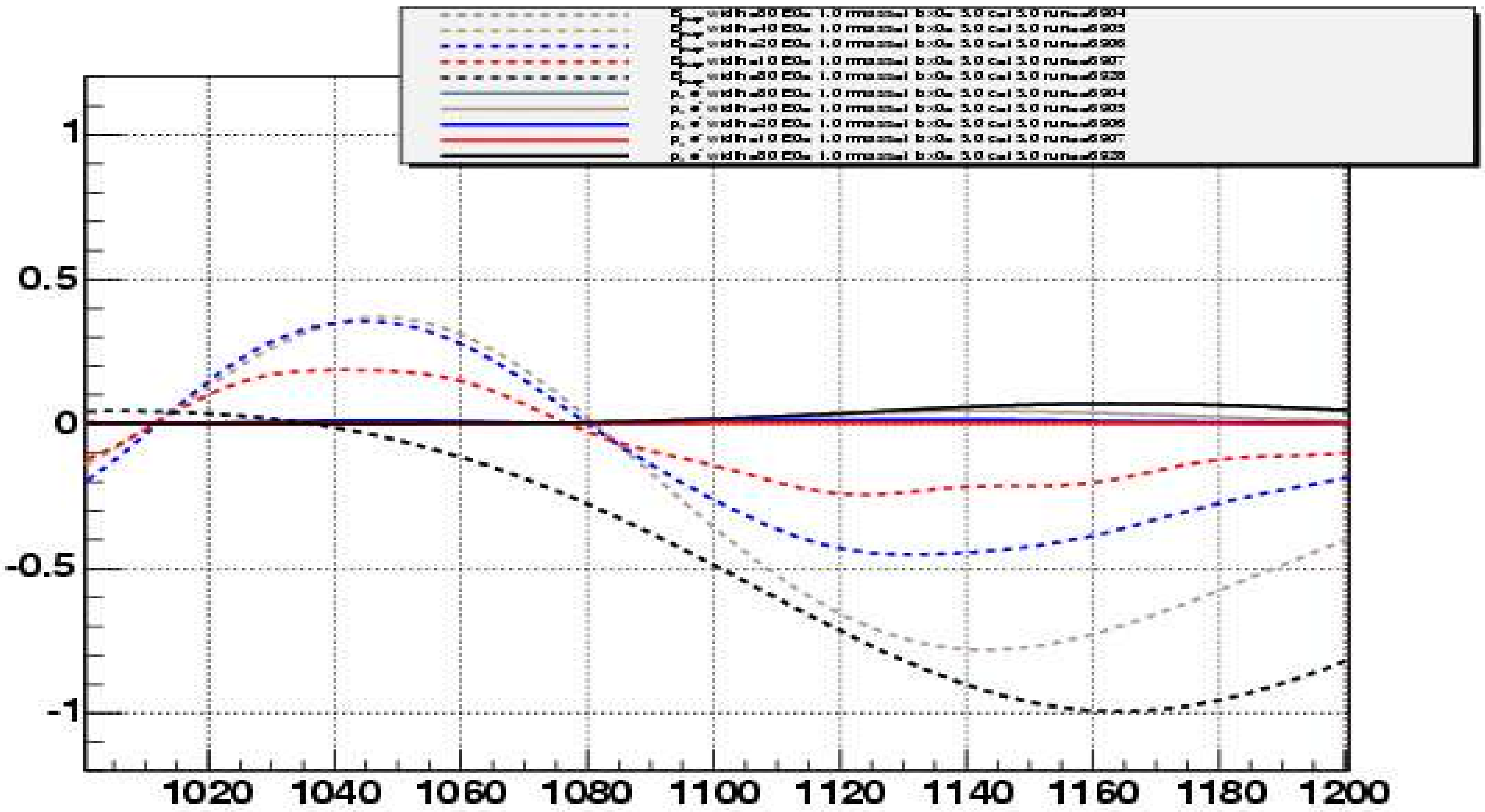

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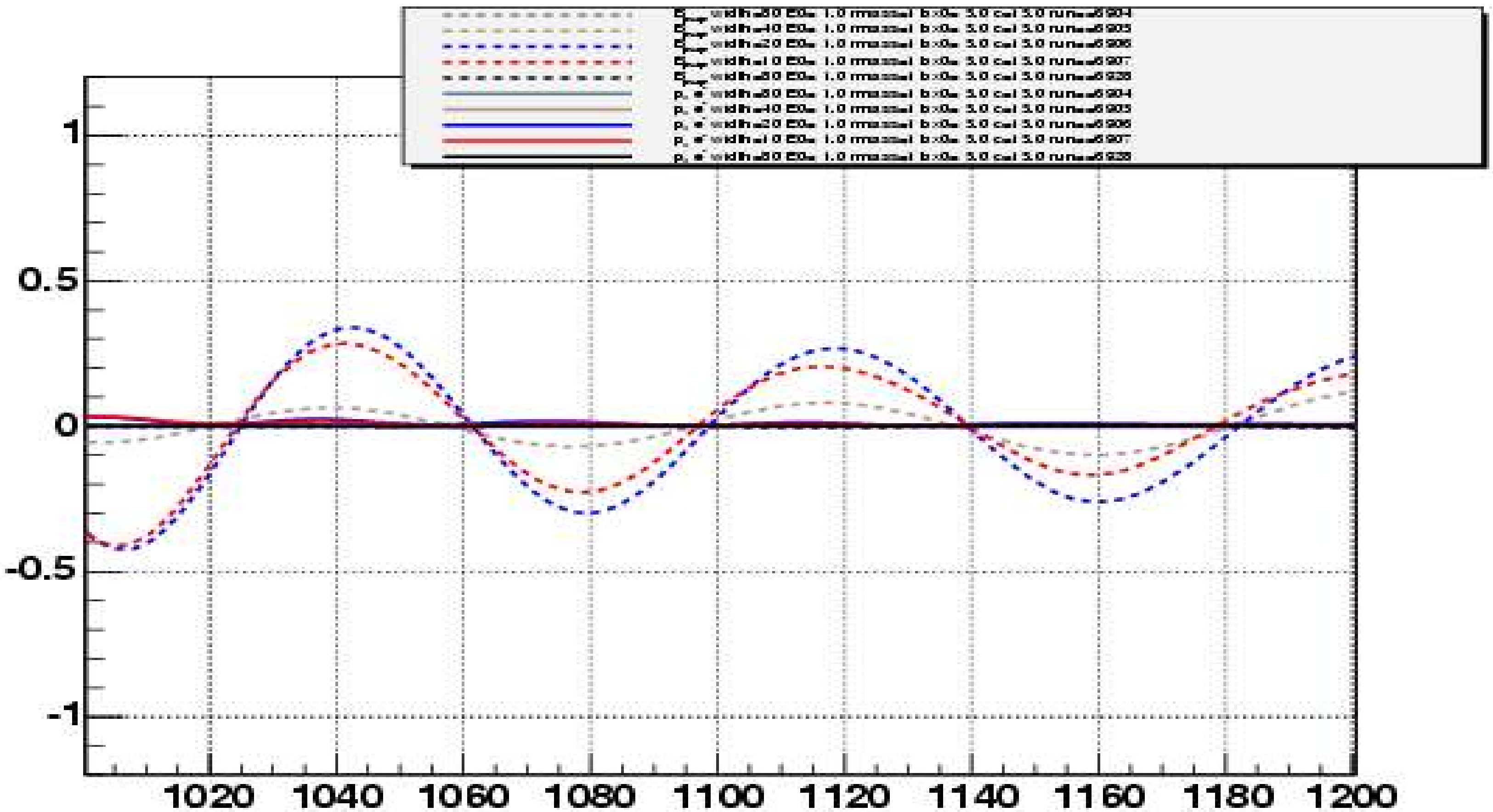

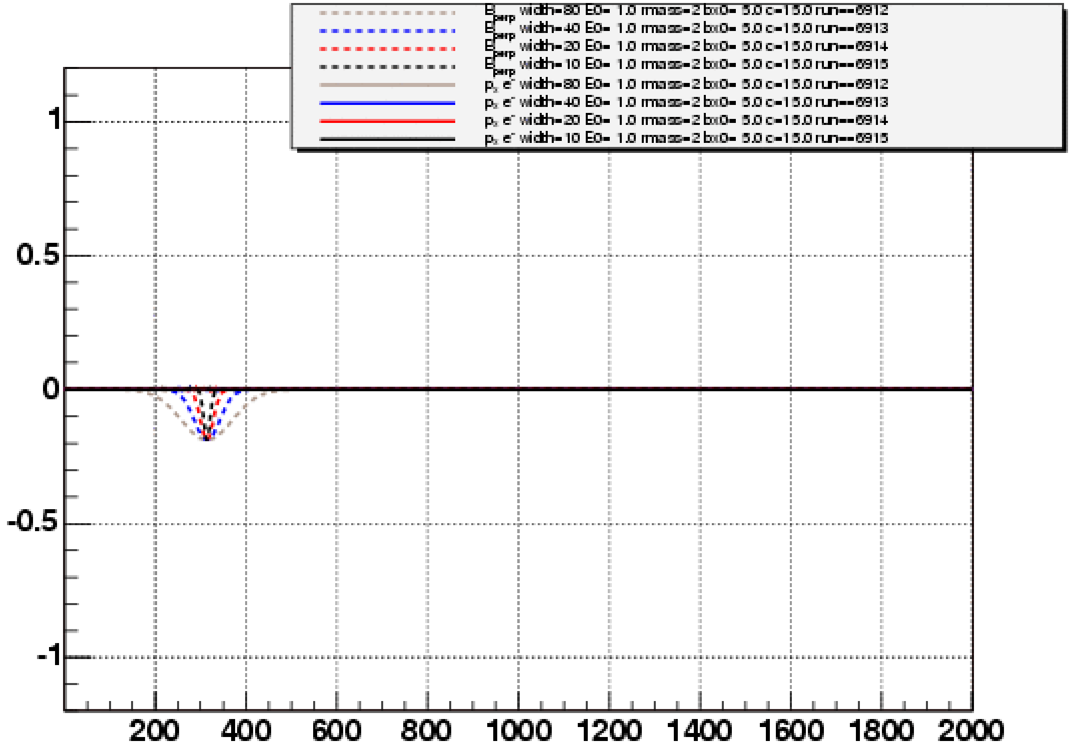

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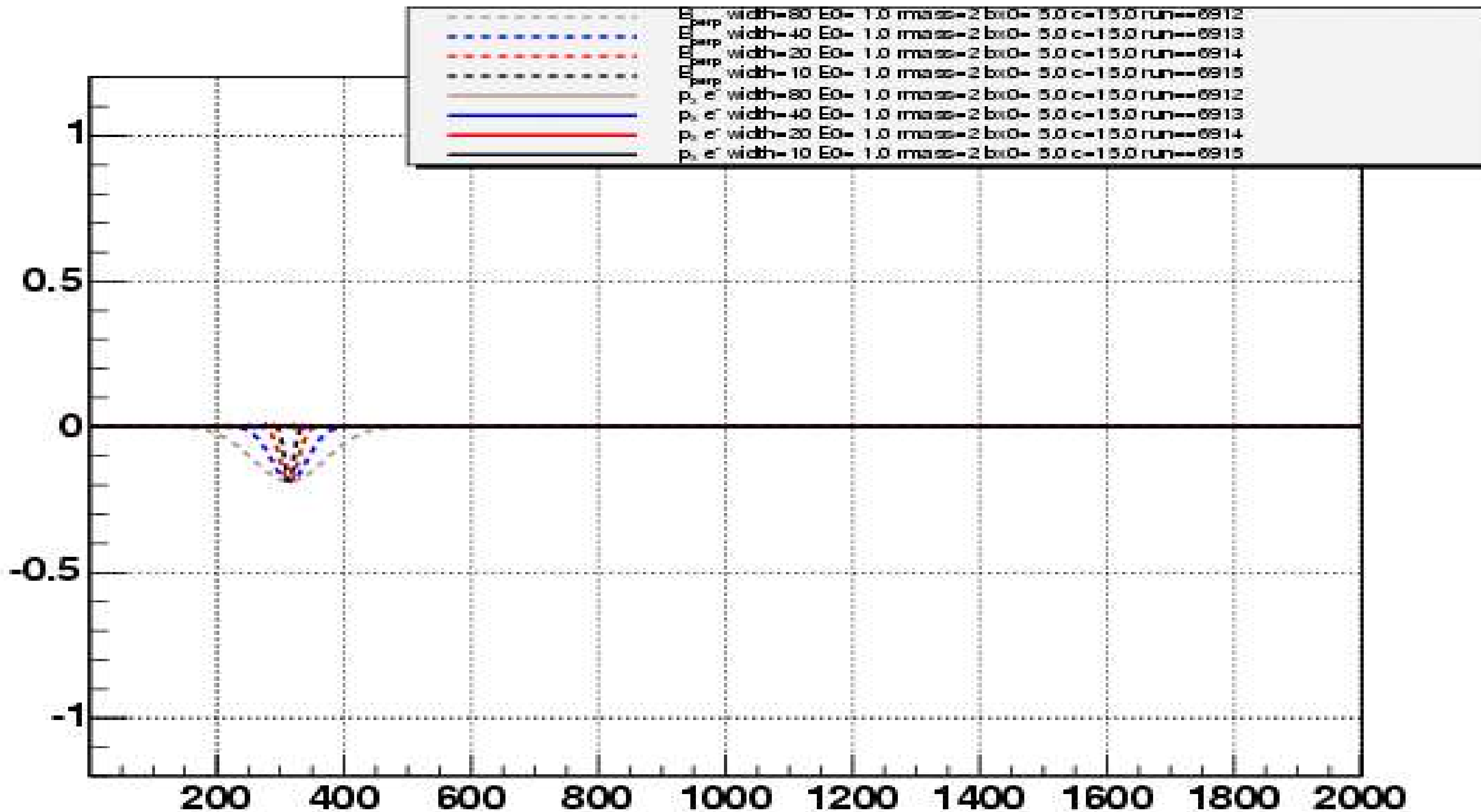
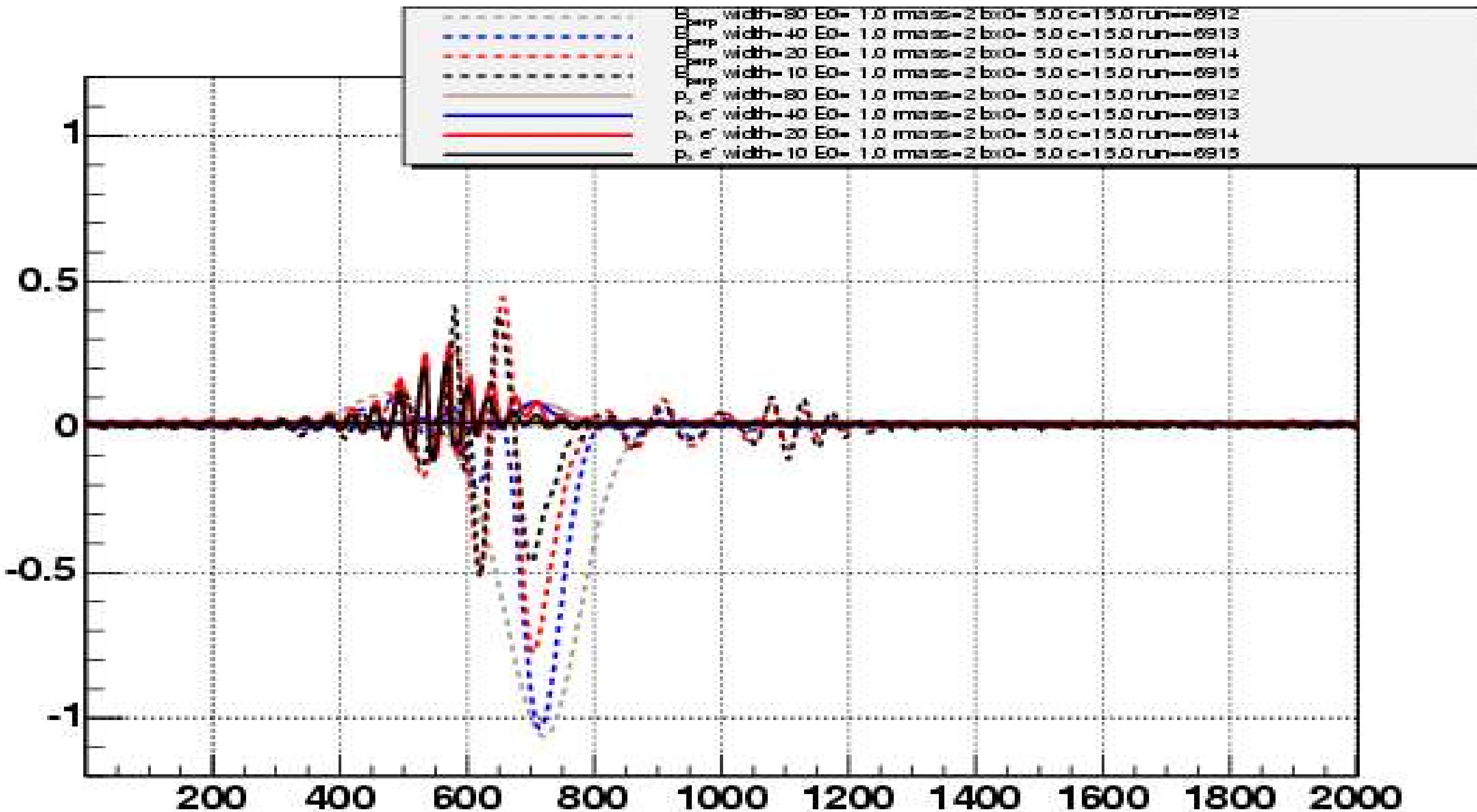
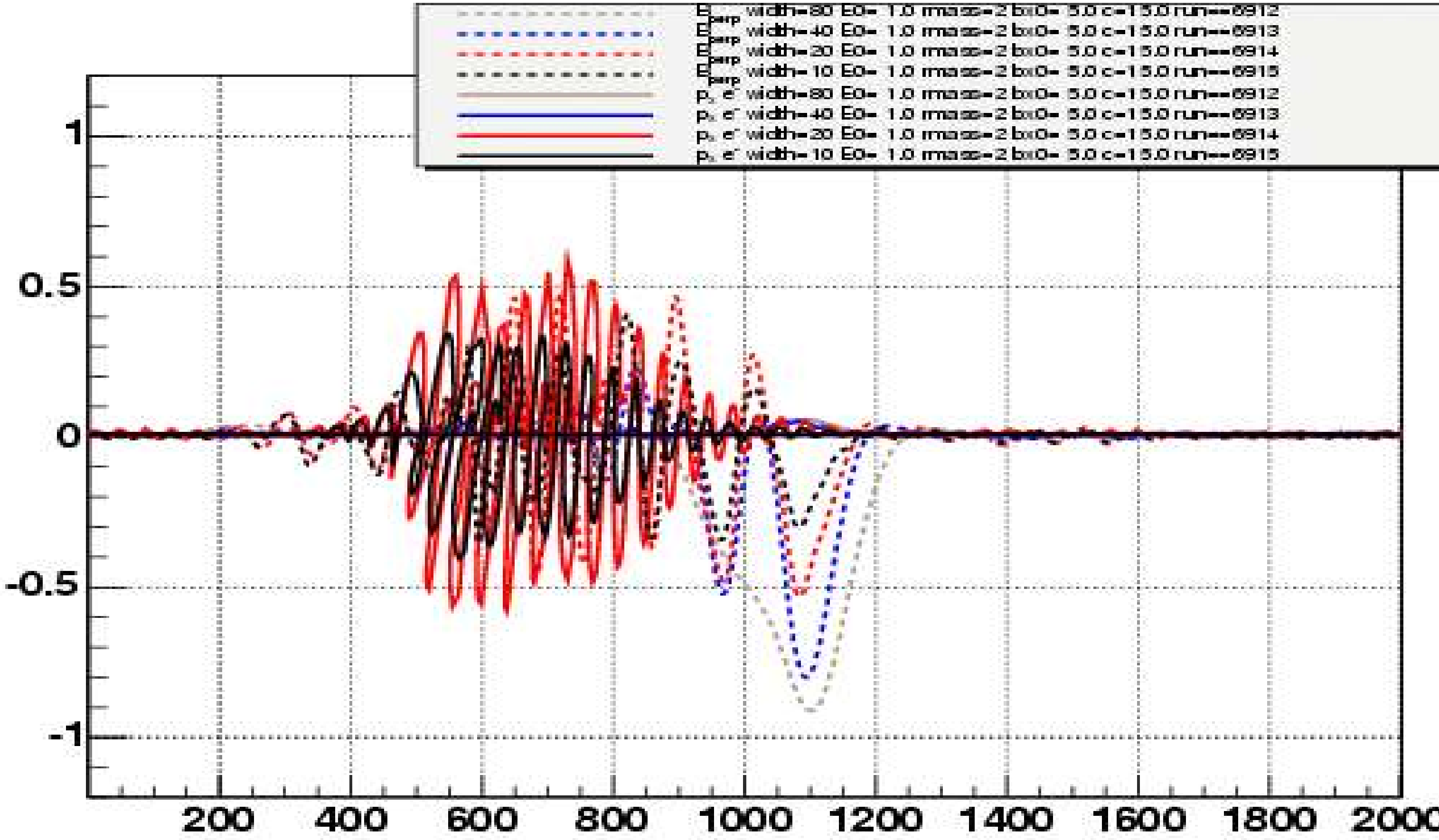
R_{mass}=2 T=25 ω_p^{-1}



R_{mass}=2 T=150 ω_p^{-1}



R_{mass}=2 T=275 ω_p^{-1}



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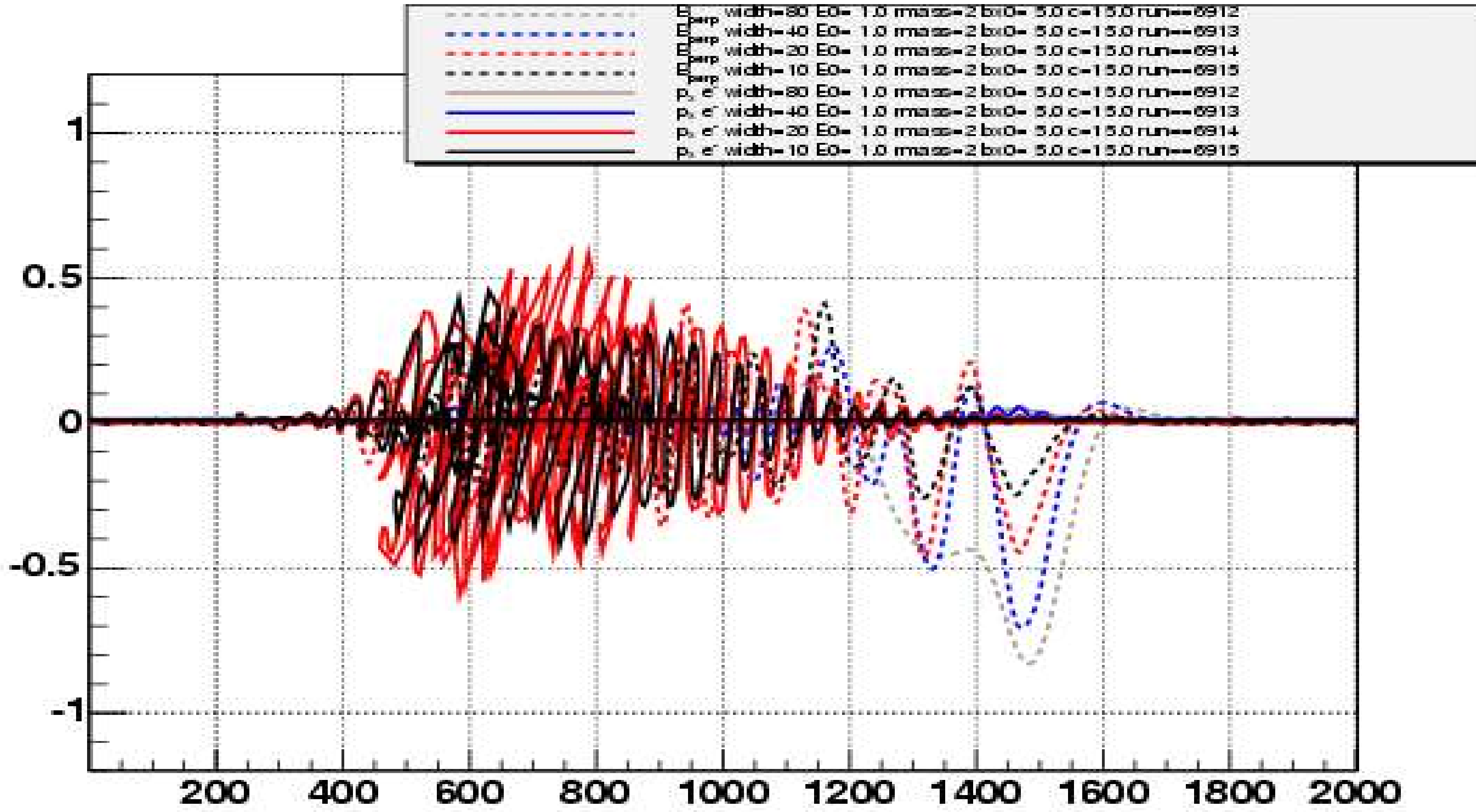

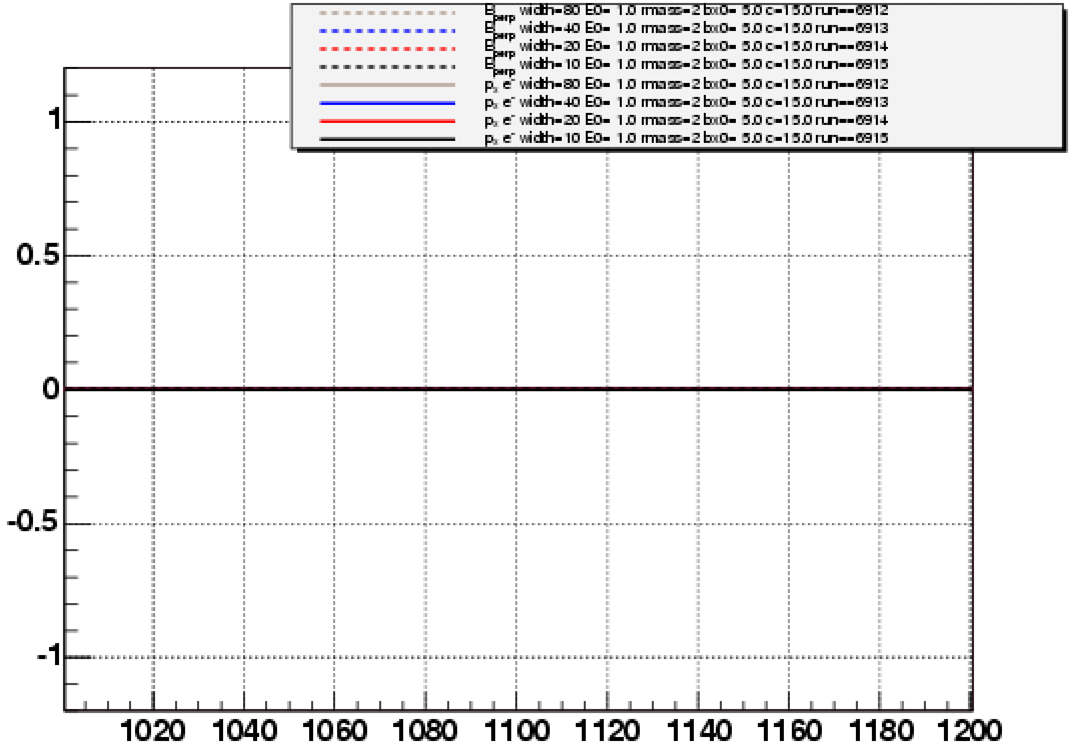

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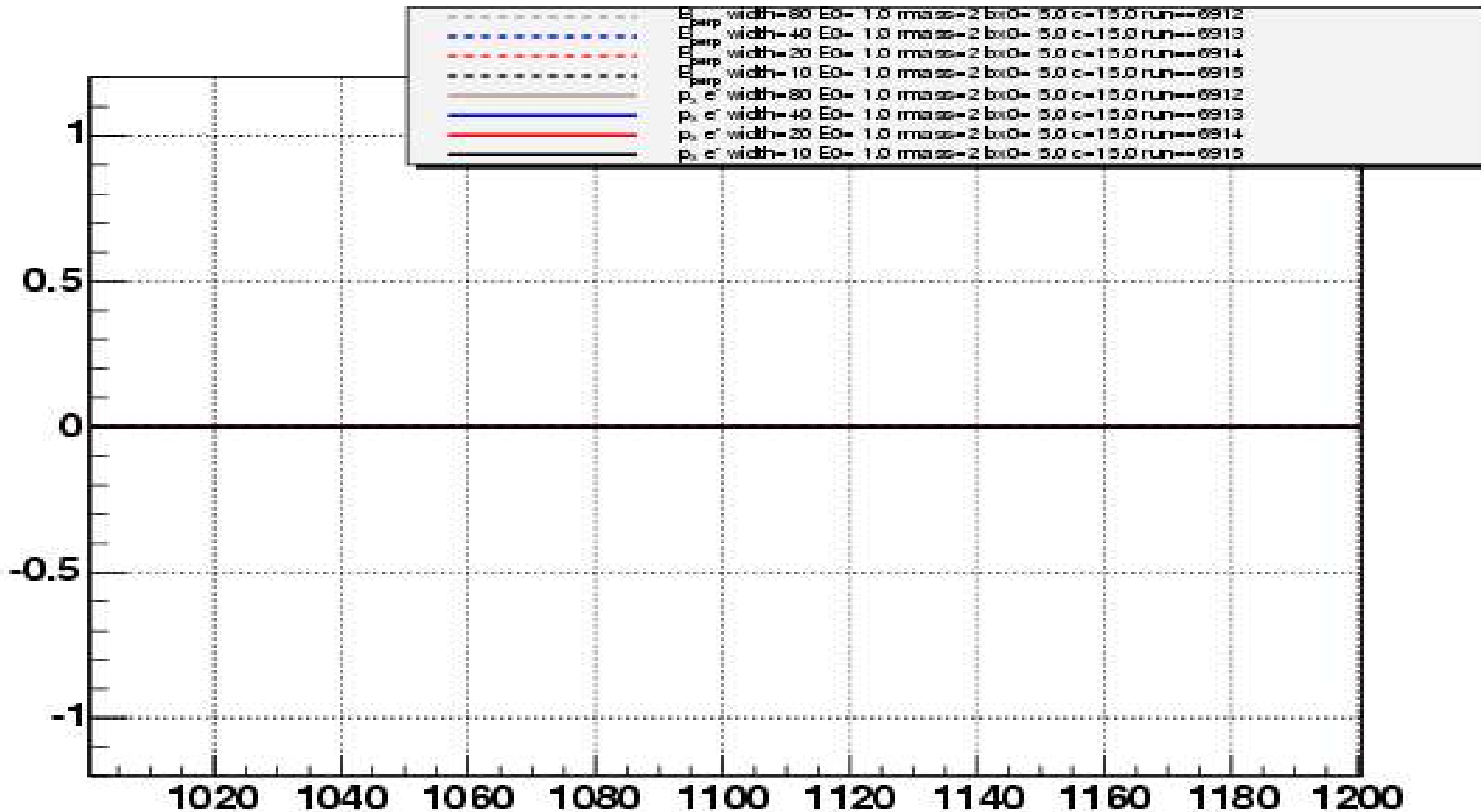
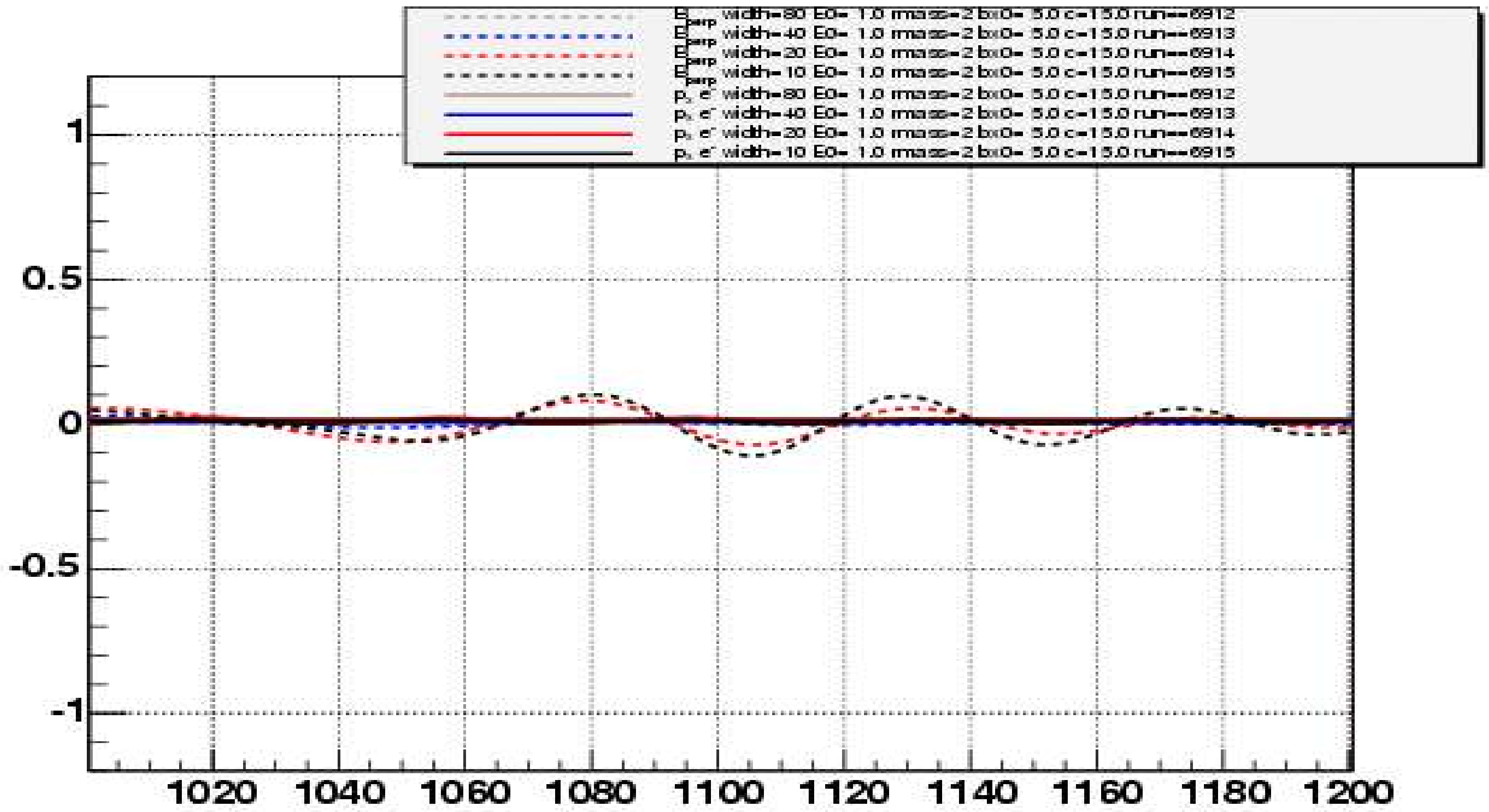
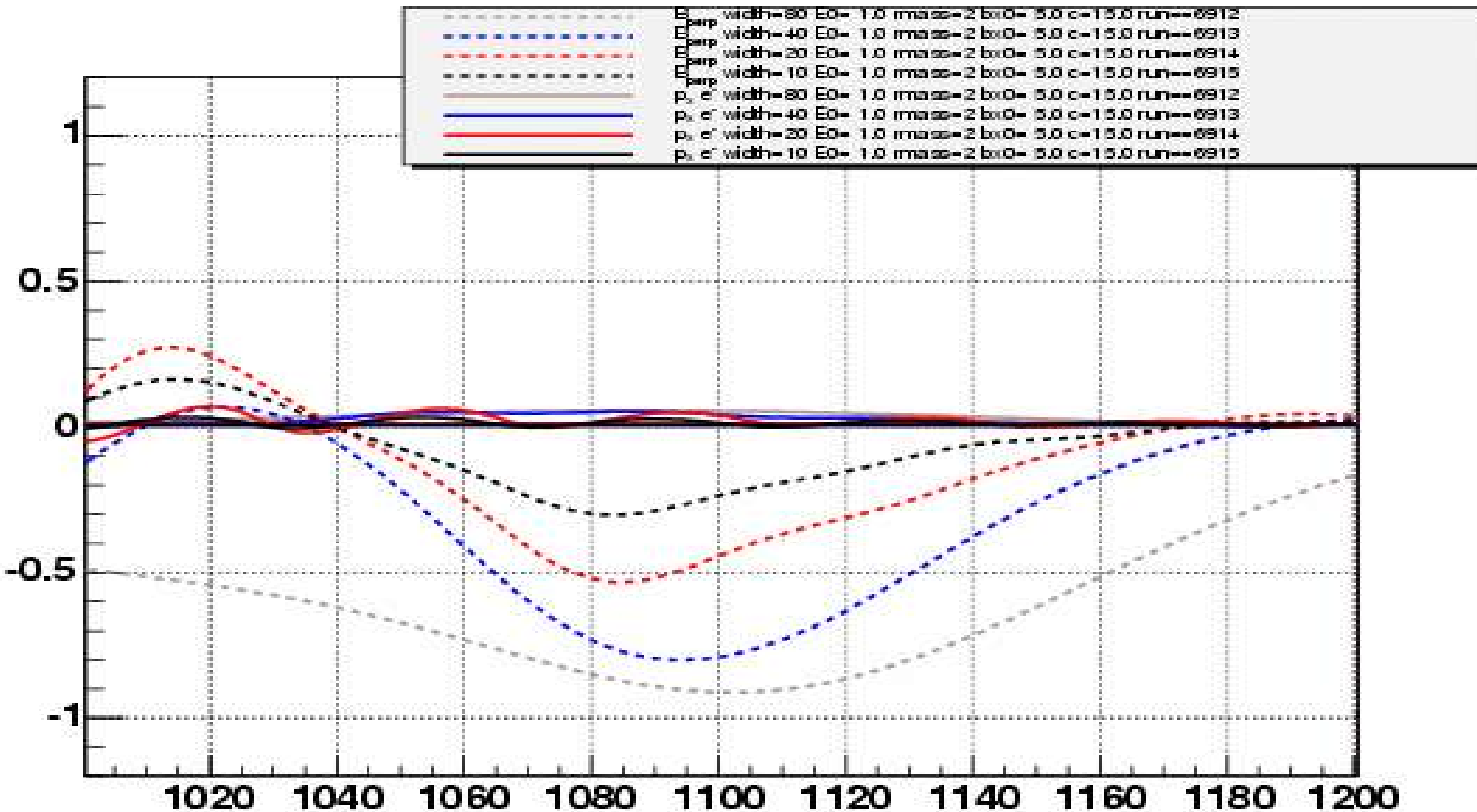
R_{mass}=2 T=25 ω_p^{-1} (Zoomed)



R_{mass}=2 T=150 ω_p^{-1} (Zoomed)



R_{mass}=2 T=275 ω_p^{-1} (Zoomed)



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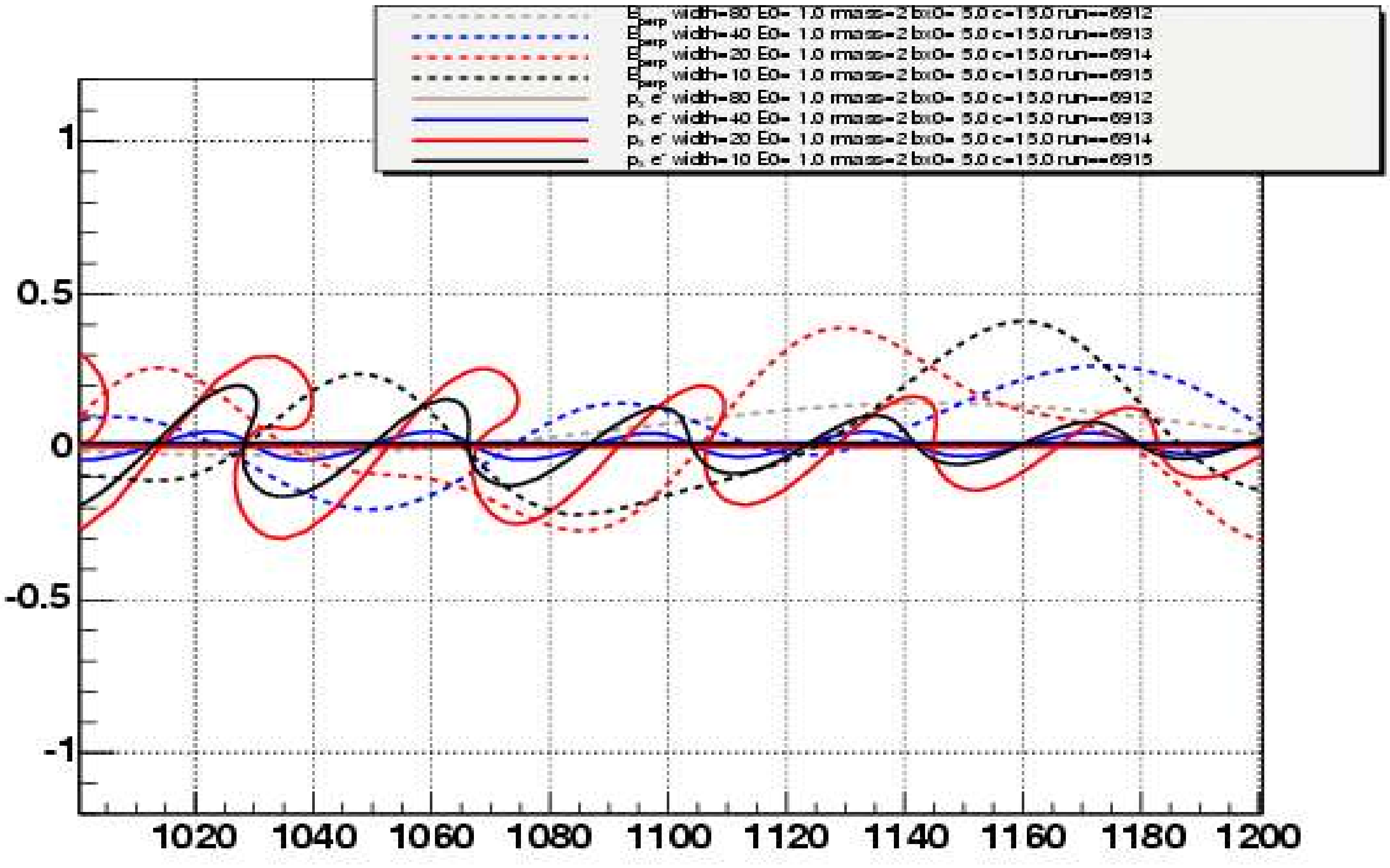

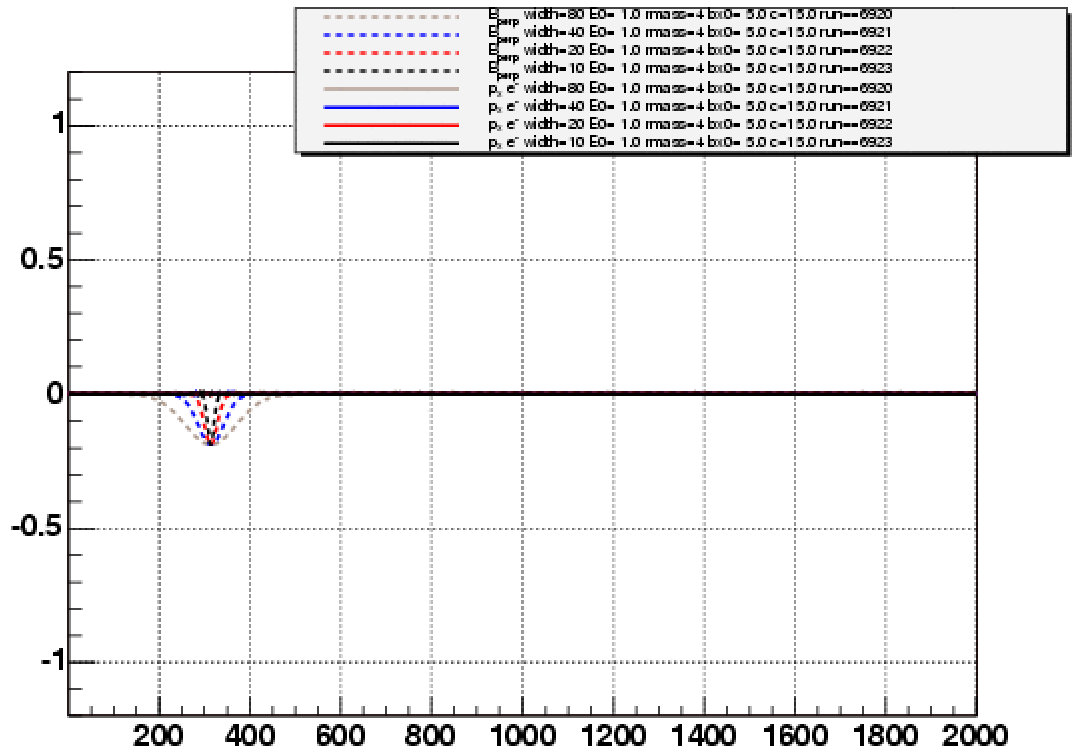
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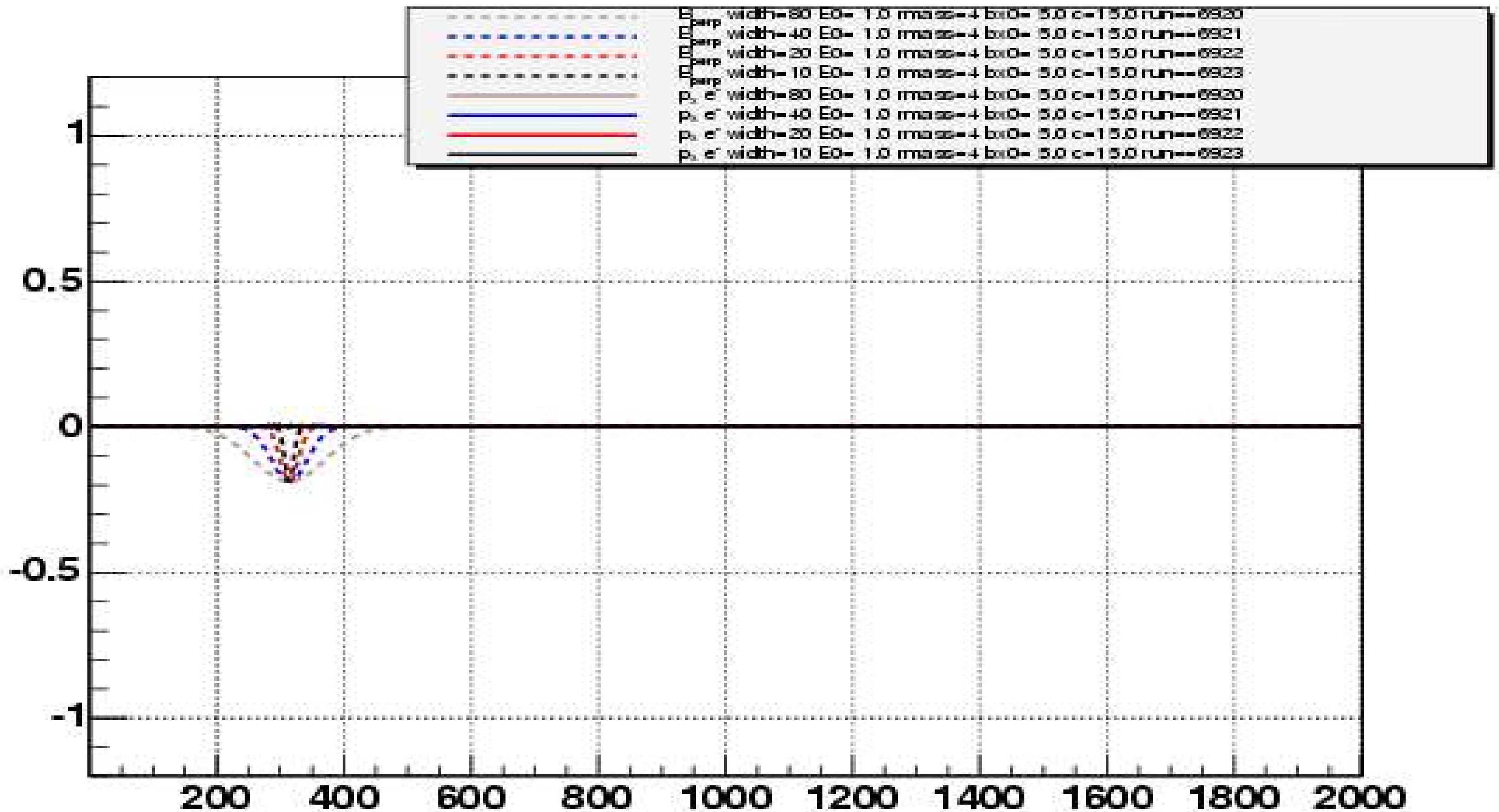
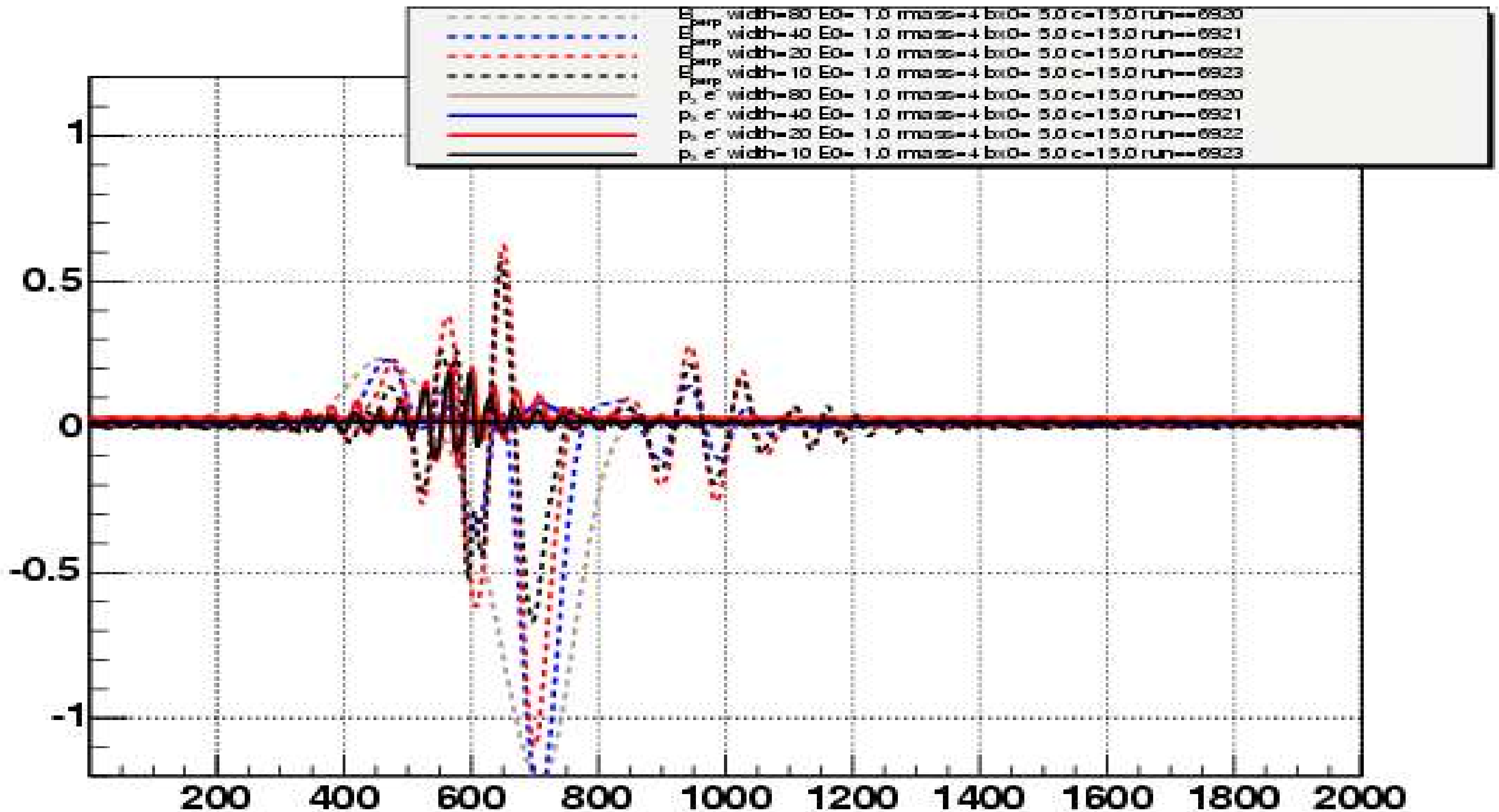
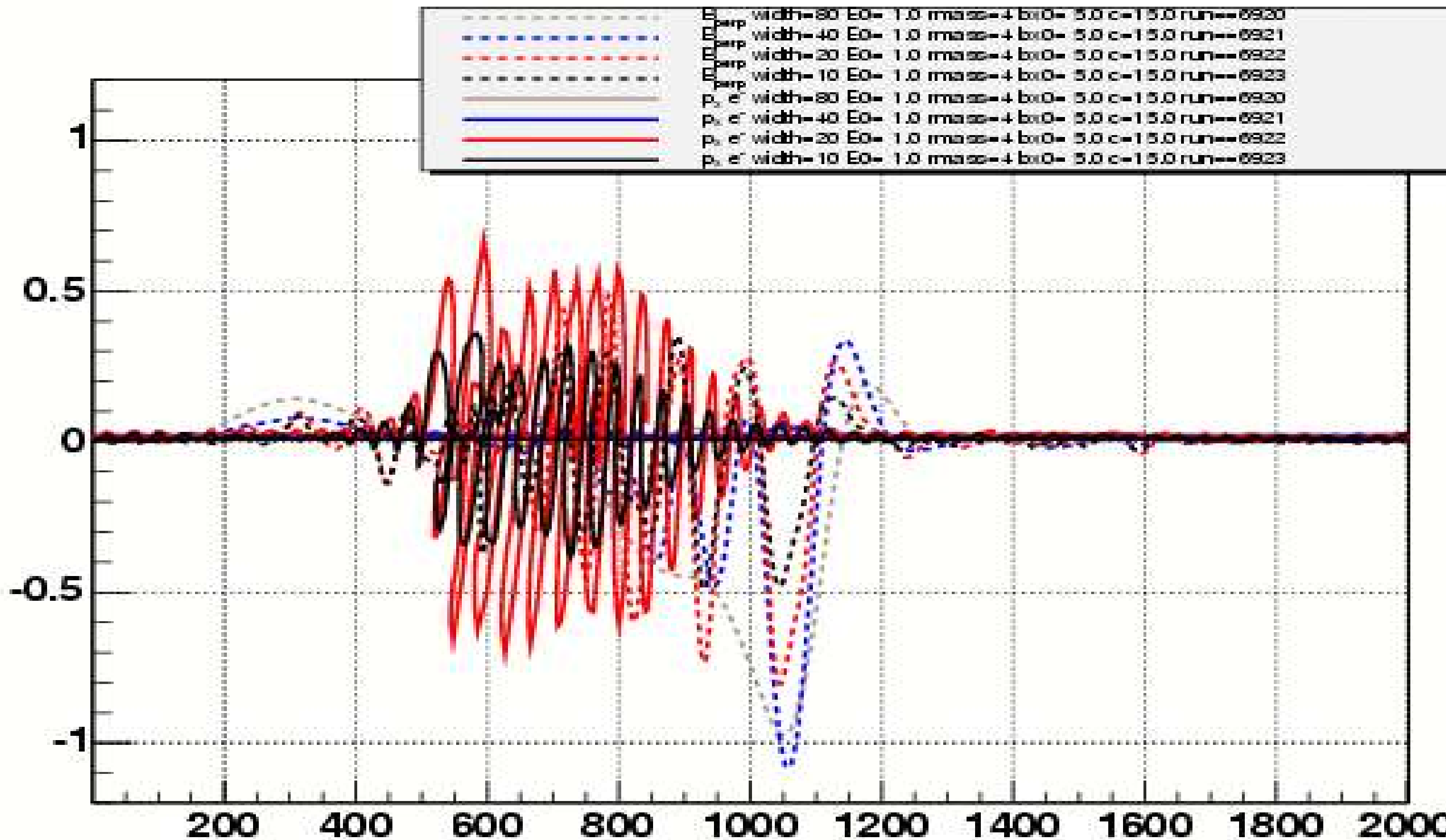


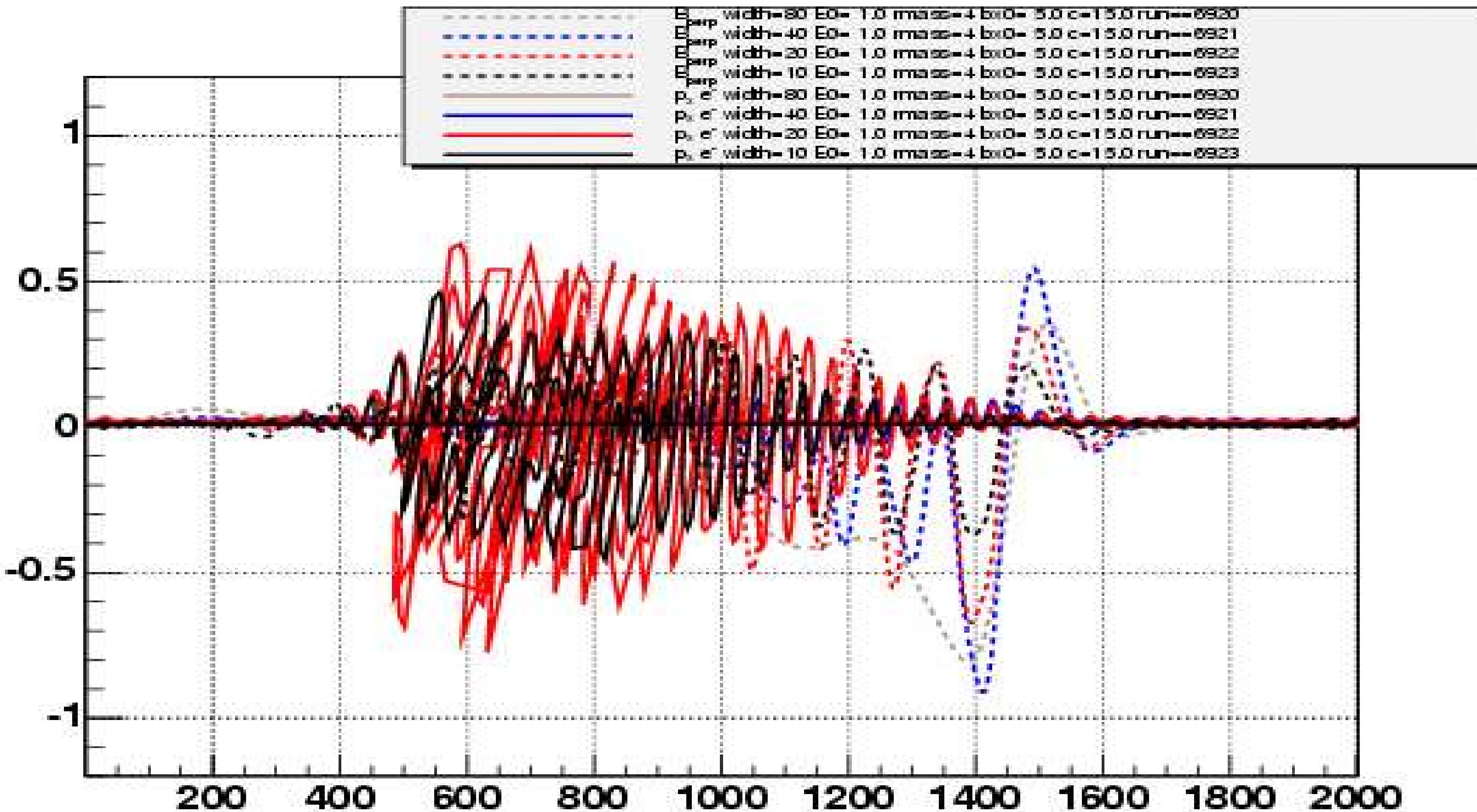
R_{mass}=4 T=150 ω_p^{-1}

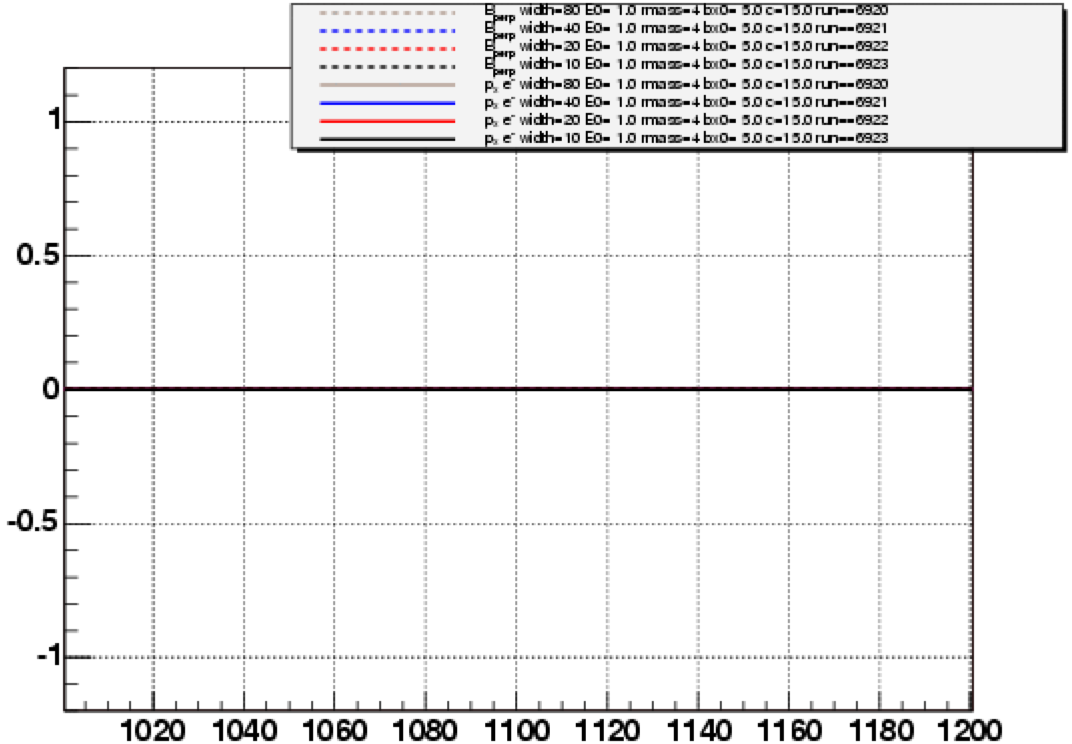


R_{mass}=4 T=275 ω_p^{-1}



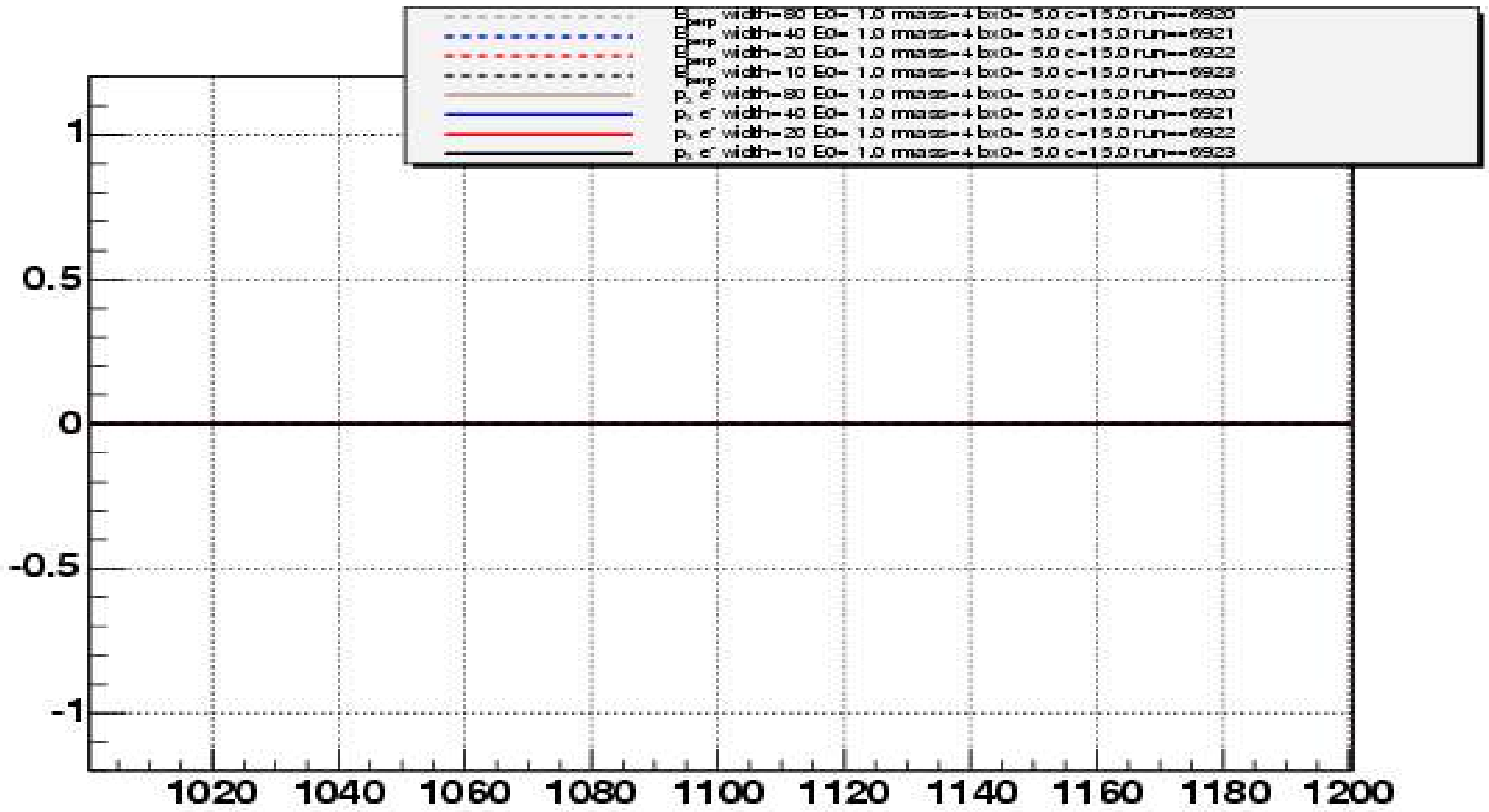
R_{mass}=4 T=400 ω_p^{-1}



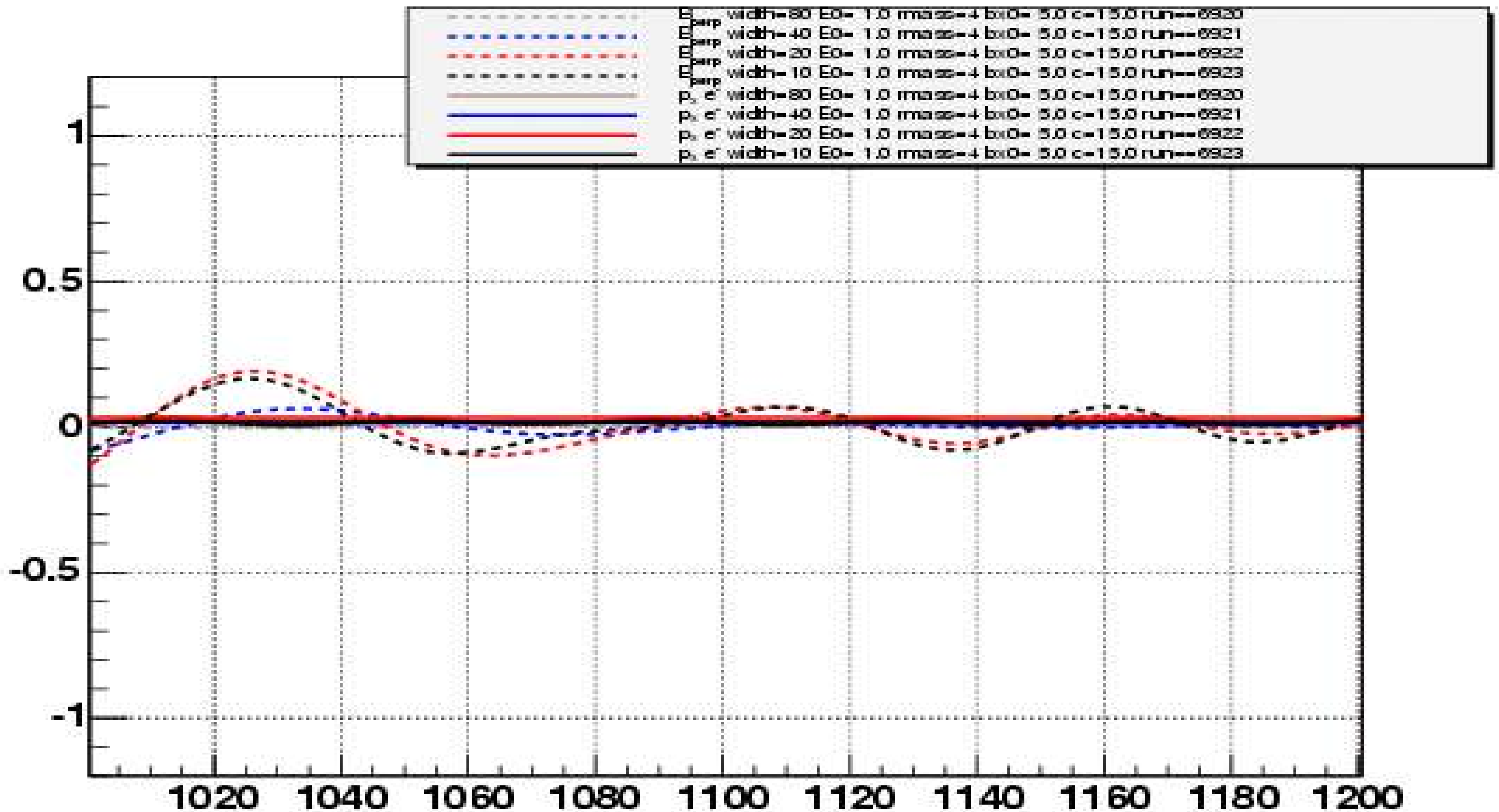


B perp width=80 E0= 1.0 rmass=4 bx0= 5.0 c=15.0 run==6920
B perp width=40 E0= 1.0 rmass=4 bx0= 5.0 c=15.0 run==6921
B perp width=20 E0= 1.0 rmass=4 bx0= 5.0 c=15.0 run==6922
B perp width=10 E0= 1.0 rmass=4 bx0= 5.0 c=15.0 run==6923
p_s e^- width=80 E0= 1.0 rmass=4 bx0= 5.0 c=15.0 run==6920
p_s e^- width=40 E0= 1.0 rmass=4 bx0= 5.0 c=15.0 run==6921
p_s e^- width=20 E0= 1.0 rmass=4 bx0= 5.0 c=15.0 run==6922
p_s e^- width=10 E0= 1.0 rmass=4 bx0= 5.0 c=15.0 run==6923
1
0.5
0
-0.5
-1
1020
1040
1060
1080
1100
1120
1140
1160
1180
1200

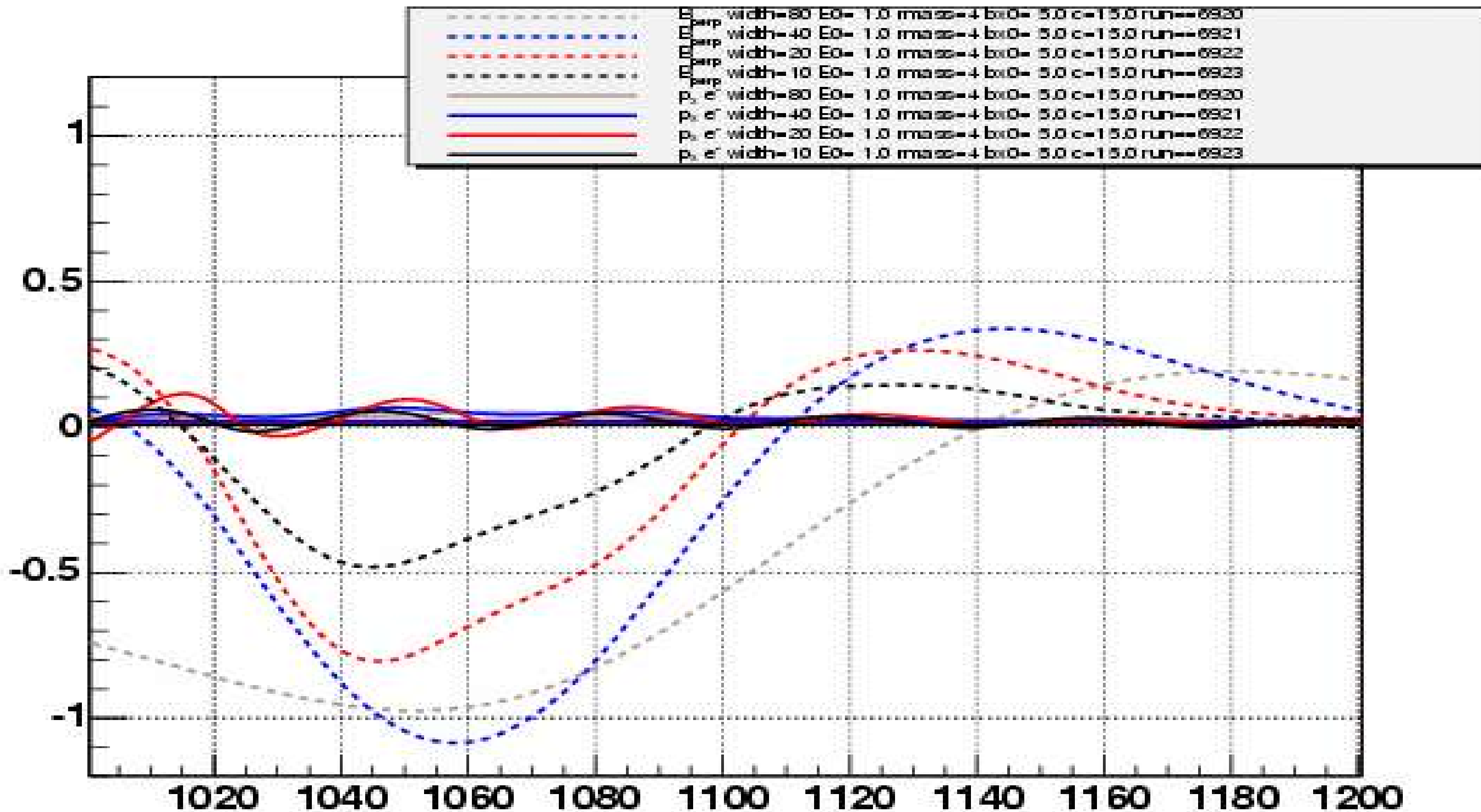
R_{mass}=4 T=25 ω_p^{-1} (Zoomed)



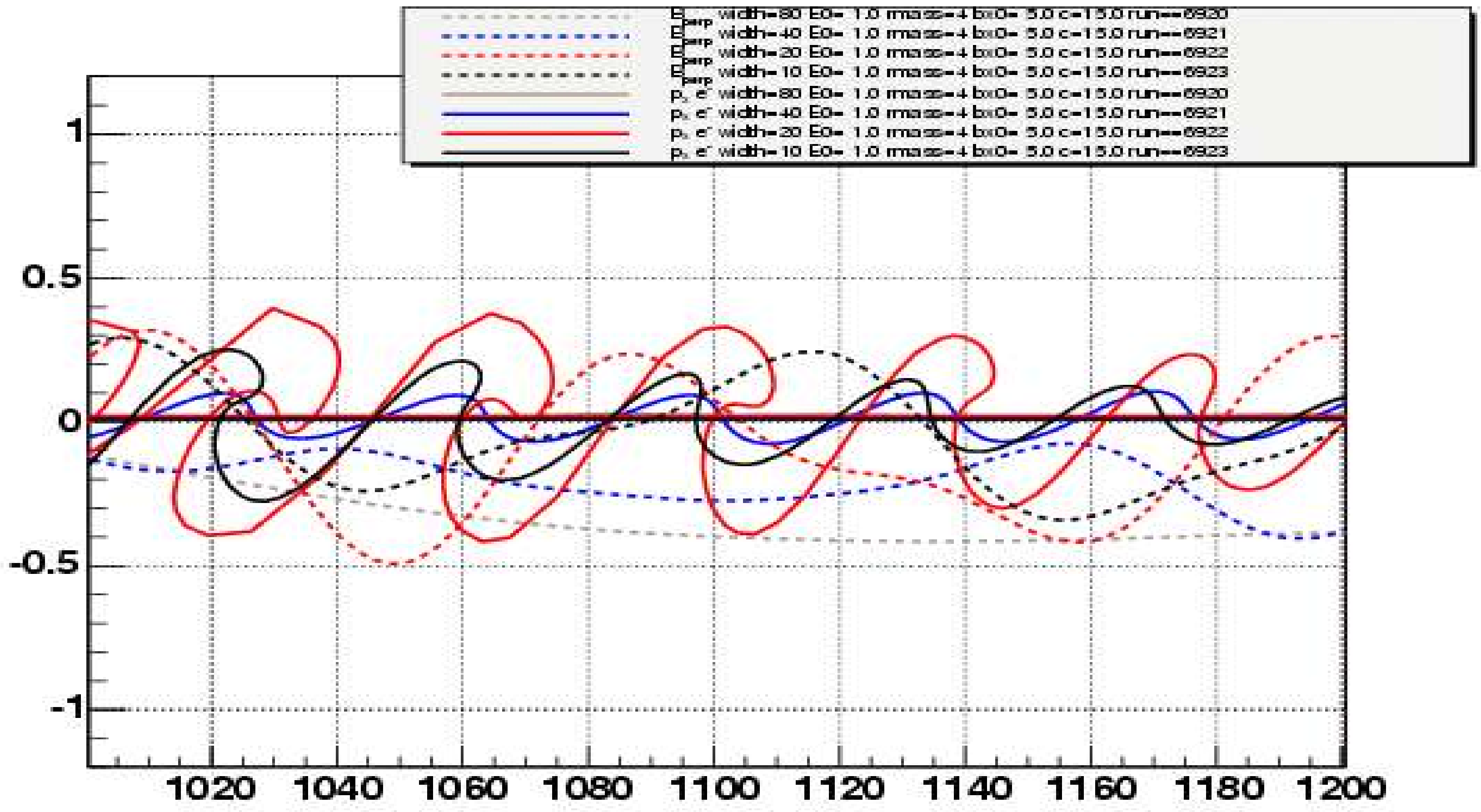
R_{mass}=4 T=150 ω_p^{-1} (Zoomed)



R_{mass}=4 T=275 ω_p^{-1} (Zoomed)



R_{mass}=4 T=400 ω_p^{-1} (Zoomed)



Summary

- Plasma wakefields induced by Alfven shocks can in pirnciple efficiently accelerate UHECR particles.
- Preliminary simulation results support the existence of this mechanism, but more investigation needed.
- In addition to GRB, there exist abundant astrophysical sources that carry relativistic plasma outflows/jets.
- Other electromagnetic sources, for example GRB prompt signals, filamentation of e^+e^- jets, intense neutrino outburst, etc., can also excite plasma wakefields.

So let's surf and wave!