ISBN: 978-3-95450-261-5 ISSN: 2673-7000 doi: 10.18429/JACoW-NAPAC2025-TUP070

MULTIPLE INTERACTION POINTS IN GHOST COLLISIONS*

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Abstract

The Ghost Collider makes use of unique "ghost" bunches, which are electrically neutral combinations of electrons and positrons within the same RF bucket, eliminates the beam-beam effects typically present at the interaction point (IP) in conventional colliders. This allows for the novel possibility of placing multiple interaction regions in series, achieving additive luminosity without introducing significant disruption. However, to obtain higher luminosity, the beta functions at the IP reaches the millimeter scale, which in turn adds significant chromatic contribution to the collider. Correcting these chromatic effects is essential to maintain beam stability and ensure high luminosity during collider operation. By carefully adjusting the phase advance between two IRs that are placed in series, it becomes possible to cancel chromaticity globally, enabling stable collider operation while preserving high luminosity. In this paper, we discuss the design of such IR/IRs to be used in a ghost collider.

INTRODUCTION

A Linear Collider vision statement [1], published in March 2025, reaffirmed the commitment of the global scientific community to develop a high-energy, high-luminosity Higgs factory [2]. The Ghost Collider has emerged as an early contender for such a facility. Its unique use of *ghost* bunches, which are charged particle bunches composed of equal numbers of electrons and positrons, eliminates the beam-beam effects typically present at the interaction point (IP) in conventional colliders. Because the net charge of the ghost bunches is zero, they are electromagnetically neutral as seen from the outside, allowing them to co-propagate through the accelerator and collide without experiencing mutual disruption.

Ghost bunches, illustrated in Fig. 1 offer unique possibilities that are challenging or impossible in conventional two-beam linear colliders. Without beam-beam disruption, ghost bunches can traverse multiple interaction regions (IRs) in series, allowing the collider to achieve additive luminosity for each IP, without requiring independent beam delivery systems that usually accompany bending which in turn requires crabbing to obtain maximum luminosity.

INTERACTION REGION DESIGN

In the Ghost Collider, electrons and positrons travel toward the interaction point (IP) from opposite directions and are focused using the same set of final focus quadrupoles.

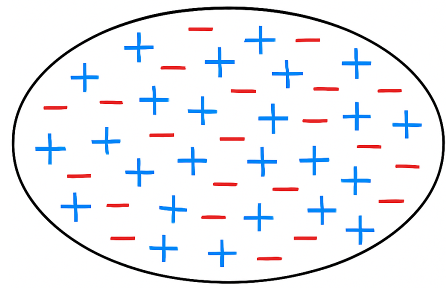

Figure 1: Conceptual illustration of a ghost bunch, composed of equal numbers of electrons and positrons occupying the same bunch.

This symmetric beam delivery scheme allows for a more compact and efficient optical design achieved by adopting equal horizontal and vertical beta functions at the IP: $\beta_x^* = \beta_x^* = 2\,\text{mm}$ [3]. Unlike traditional linear colliders such as the ILC, which require ultra-flat beams to mitigate beam-beam disruption ($\beta_x^* = 11\,\text{mm}$, $\beta_x^* = 0.48\,\text{mm}$), the Ghost Collider benefits from the absence of coherent beam-beam forces. As a result, round beams with equal transverse emittances can be used, significantly simplifying the interaction region optics.

Electrons and positrons arrive at the IR from both directions and are focused by a shared set of final focus quadrupoles (main triplet). And a secondary triplet adds the flexibility of having a symmetrical twiss parameter set at the starting end of the IR, which gives the possibility of having both positron and electrons to travel in both directions of the IR while maintaining the required spot size at the IP. This symmetric layout allows for compact interaction region designs and supports equal focusing conditions on both beams. Table 1 shows some chosen parameters for a linear ghost collider design currently in the design phase [3]. For a beam-pipe radius of 2 cm, the maximum field gradient

Table 1: A Parameters Set for a Linear Ghost Collider

Parameter	**Value**	**units**
Energy	275	GeV
Normalized emittance	6.5	mm−mrad
$\beta_{x,y}^*$	2	mm
Max $\beta_{x,y}$	64.9	km
Max $\sigma_{x,y}$	885	μm
Max quadrupole gradient	182	T−m

* This material is based upon work supported by Jefferson Science Associates, LLC under Contract No. DE-AC05-06OR23177 with the U.S. Department of Energy.
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used in the IR design is 183.5 T−m^{-1}. This is well within the range of conventional niobium titanium(NbTi) technology.

MULTIPLE INTERACTION REGIONS

Because ghost bunches are not disrupted by beam-beam interactions at the IP, it becomes feasible to place two interaction points in series along the same beamline, making luminosity from multiple IRs additive. However, ensuring high beam quality across multiple IRs requires careful control of chromatic aberrations introduced by strong focusing optics.

Chromaticity

Linear colliders face significant constraints when implementing chromaticity correction using sextupoles due to the inherently compact and single-pass nature of their beamlines. Unlike storage rings, which offer multiple turns and abundant locations with natural dispersion, linear machines must correct chromatic aberrations within a limited section near the final focus.

The Montague chromatic amplitude function, or W-function [4], is a useful method for quantifying chromatic effects in beam optics. It characterizes the amplitude of betatron oscillations induced by an energy deviation δ and is defined as:

$$W \equiv \sqrt{\left(\frac{\partial \alpha}{\partial \delta} - \frac{\alpha}{\beta}\frac{\partial \beta}{\partial \delta}\right)^2 + \left(\frac{1}{\beta}\frac{\partial \beta}{\partial \delta}\right)^2} \qquad (1)$$

where $D(s)$ is the dispersion, $D'(s)$ its derivative, and $\beta(s)$, $\beta'(s)$ are the Twiss beta function and its derivative, respectively. A higher value of $W(s)$ indicates stronger chromatic distortion at that location.

The chromatic betatron oscillation, often referred to as the chromatic wave, oscillates at twice the frequency of the regular betatron motion. This property can be exploited to cancel chromatic effects introduced at one interaction region (IR) by placing a second IR downstream with a phase advance of exactly 90 degrees ($\pi/2$). At this specific phase relationship, the chromatic distortions from the two IRs interfere destructively, effectively canceling each other and minimizing the overall chromatic aberration in the system.

Two Interaction Regions

The absence of disruption at the interaction point presents a unique opportunity to place multiple collision points in sequence along the same beamline. Because the beams remain intact after each collision, the luminosity contribution from each interaction point is cumulative rather than divided. To preserve beam quality across multiple IPs, the optical phase advance between successive collision points must correspond to a $-J$ transformation. This condition is satisfied when the betatron phase advance is $(n \pm \frac{1}{2})\pi$, where n is an integer, in both transverse planes, effectively canceling the chromatic aberrations introduced at each IP. This cancellation minimizes the need for additional correction elements between IPs. By placing two interaction regions, as shown in Fig. 2 separated by a FODO like matching section that acts as a phase trombone, it is possible to cancel the chromaticity to more than 99%. Figure 2 shows such a layout and the resulting W function propagation through the interaction region.

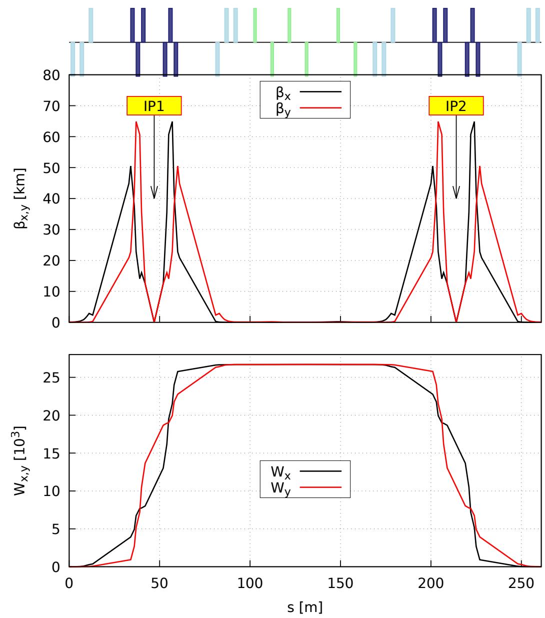

Figure 2: Two interaction regions for ghost collisions. Twiss functions are shown in the top figure for two IR's placed sequentially and separated by matching section to adjust phase advance. Bottom figure shows the montague function over the length of the section. Dark blue color quads are the primary triplet, light blue representst the secondary triplet while the light green quads are used to match the two IRs to each other while acting as a phase trombone for the correct phase advance.

Four Interaction Regions

The symmetric layout of the collider allows four interaction regions (IRs) to be placed in series while still canceling the chromaticity contributions from each IR. As shown in Fig. 3, the phase advances between the interaction points are chosen to match those of a standard two-IR system, ensuring that the chromatic effects cancel coherently. This configuration makes it possible to include multiple high-luminosity regions without degrading the overall beam optics.

Three Interaction Regions

Placing three IRs in series is somewhat different from the previous even numbered IR layouts in that the phase advance between interaction regions is now $\frac{\pi}{3}$ radians. Because of the chromatic wave behavior, a $(n \pm \frac{1}{3})\pi$ phase advance provides a near total cancellation (< 90 %) of the total chromaticity introduced by the IR system. The twiss parameters and the W-function of this configuration is shown in Fig. 4. It is worth noting that, in comparison to the two-IR configuration, the four-IR arrangement exhibits approximately

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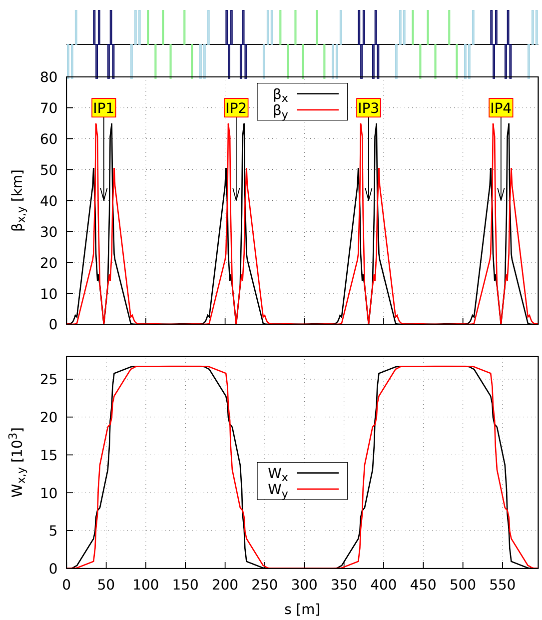

Figure 3: Two interaction regions for ghost collisions. Twiss functions are shown in the top figure for two IR's placed sequentially and separated by matching section to adjust phase advance. Bottom figure shows the montague function over the length of the section.

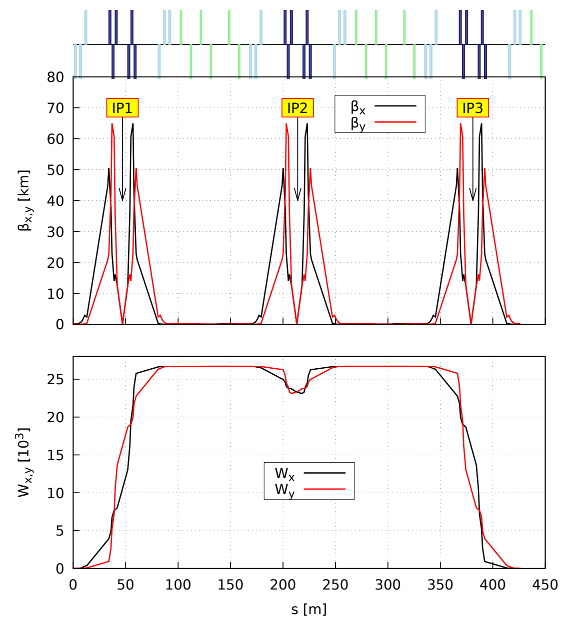

Figure 4: Three interaction regions placed in series. Twiss functions are shown in the top figure for two IR's placed sequentially and separated by matching section to adjust phase advance. Bottom figure shows the montague function over the length of the section.

twice the chromaticity at the central interaction point. This increase arises from the relative phase separation of the W-function vectors, which are offset by $\frac{2\pi}{3}$. This should be accounted for when estimating the achievable total luminosity.

FUTURE WORK

Although the unique nature of ghost bunches eliminates the beam-beam effects resulting from chromatic effects in typical colliders, the chromaticity still has a direct impact on the beam size, specifically the interaction point. These effects must be studied further to estimate the impact they have on luminosity. On-going simulation work involves investigating the increase in beam size and the resulting impact of that on the luminosity.

In a typical circular collider, the remaining chromaticity can be corrected using a dedicated chromaticity compensation section, where sextupoles are strategically placed in regions of high dispersion and large beta functions, while maintaining phase advance conditions consistent with the IR design. However, as noted earlier, linear colliders inherently lack regions with natural dispersion, which is an important requirement for sextupoles to function effectively, making conventional chromatic correction schemes more difficult to implement. In this case a correction scheme where special regions with high β functions that replicate one half of the IR, places each side of the IR section (2 or 4) of the line should be able to effectively cancel most of the chromatic effects at each IP. One thing to note here is that the phase advances between the IP's will remain the same, but the design (β function propagation) of the IR itself should be symmetrical.

SUMMARY

The Ghost Collider presents a novel approach to linear collider design by making use of ghost bunches, which are electron and positron cohabiting bunches that open the door for more flexible and compact interaction region (IR) layouts. Various multi-IR configurations were investigated, including designs with two, three, and four IRs. The analysis shows that with careful control of the phase advance between IRs, chromaticity contributions can be effectively canceled. Overall, ghost bunch operation presents a promising path toward simplified, high-performance, and high-luminosity linear collider design.

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