Advancements in Beam Delivery Systems: CLIC Innovations and Plasma Collider Applications

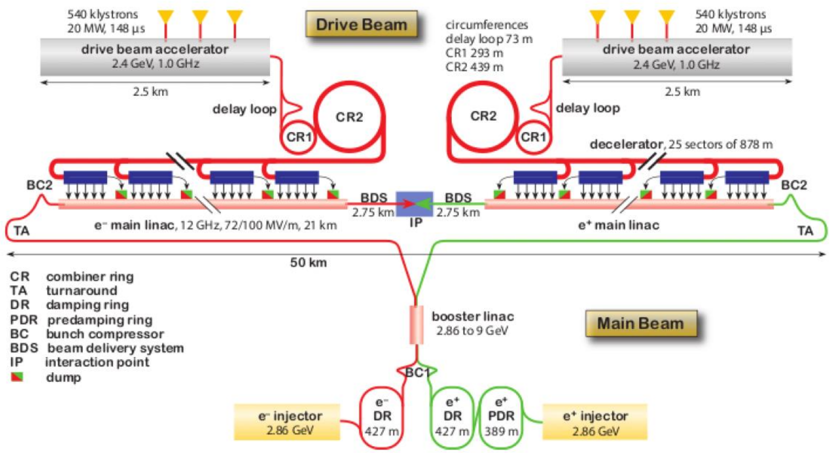
Vera Cilento, Enrico Manosperti and Rogelio Tomás

Outline

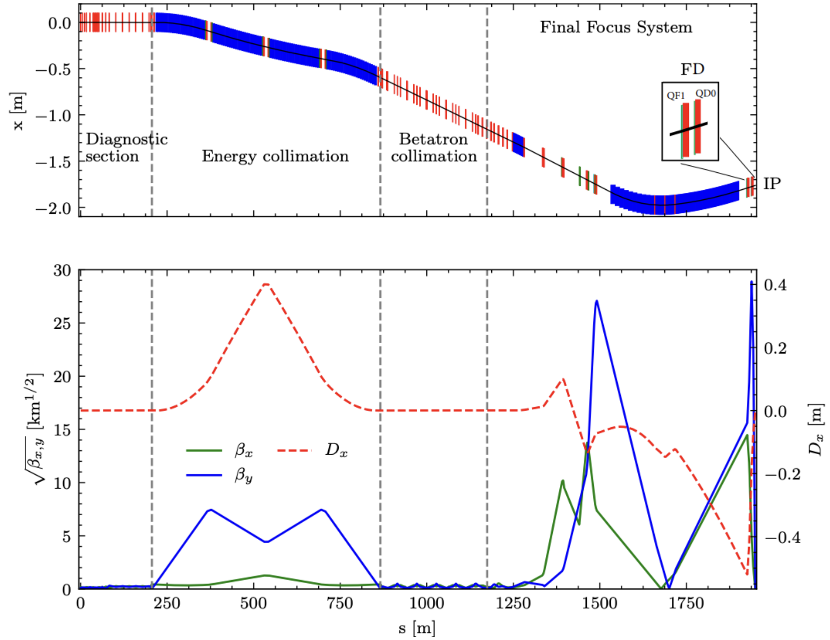
- Introduction to CLIC BDS
- BDS in CLIC: Objectives and Challenges
  - Update of the CLIC BDS 3 TeV performance
  - The Dual BDS Concept for CLIC
- BDS Requirements for Plasma Colliders
- BDS Synergies
  - CLIC & LPA
  - CLIC & HALHF
  - CLIC & PDPWA
- The Future of BDS: Scaling with Energies
  - CLIC BDS Design at 7 TeV
- Conclusions

Introduction to CLIC BDS

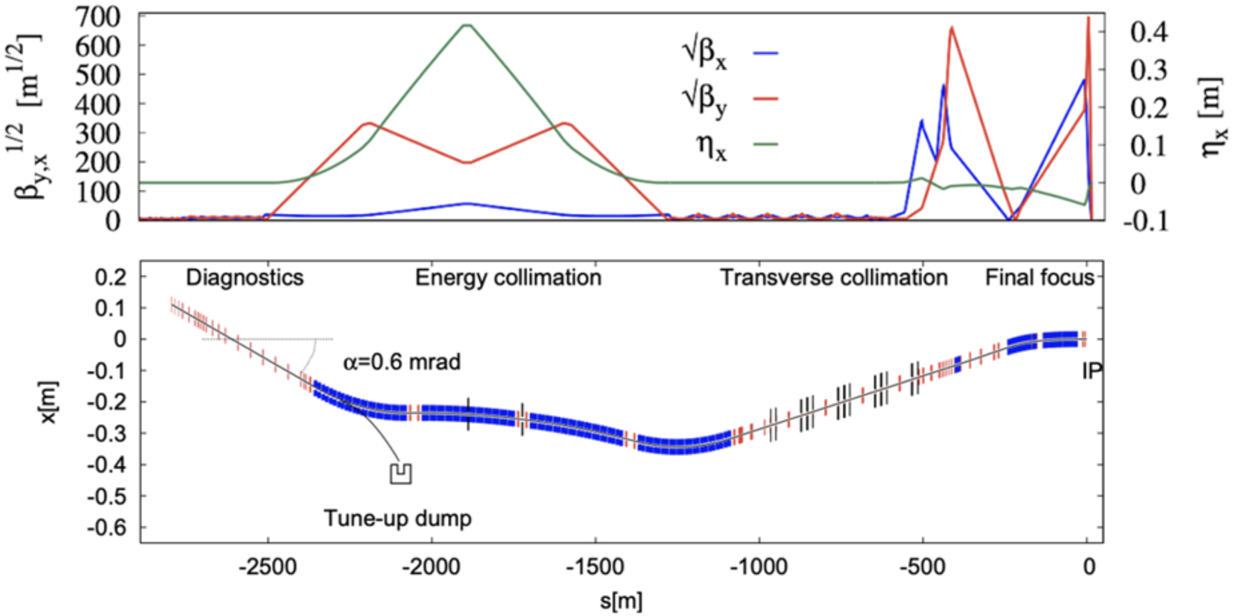
- The BDS is composed by:
  - Diagnostic Section (end of ML to collimation section)
  - Collimation Section (protects the downstream beamline and detector against mis-steered beams from ML and removes beam halo)
  - Final Focus System (focus the beam to nanometer level and correct the chromaticity)



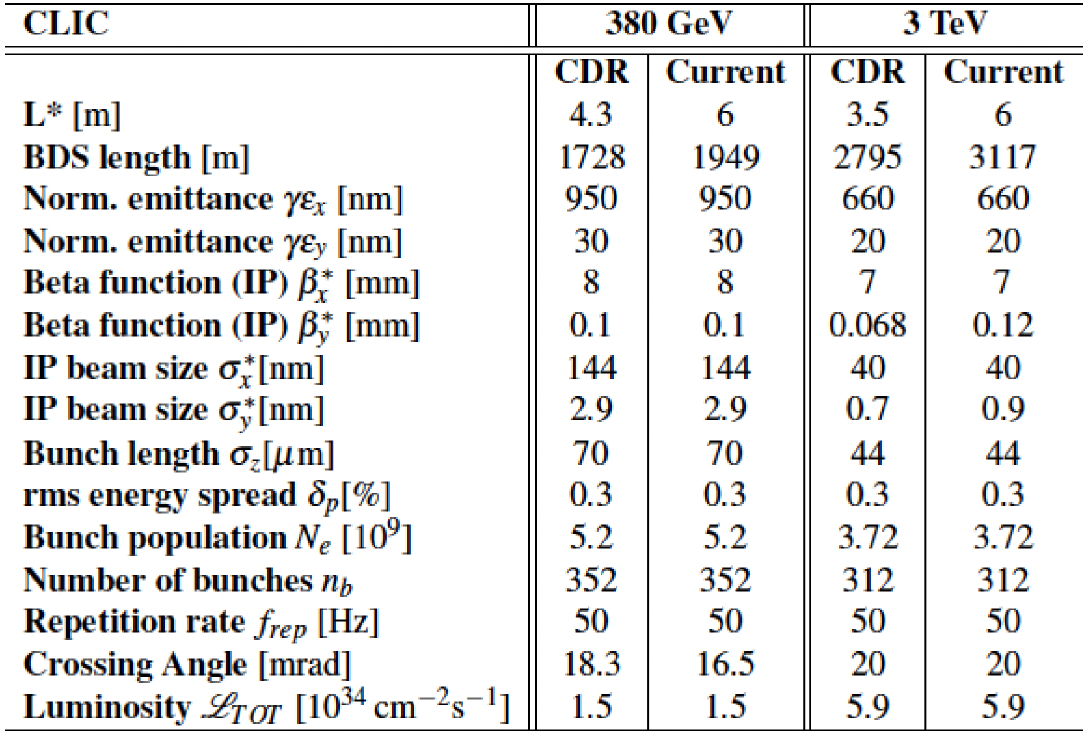
- 380 GeV



- 3 TeV

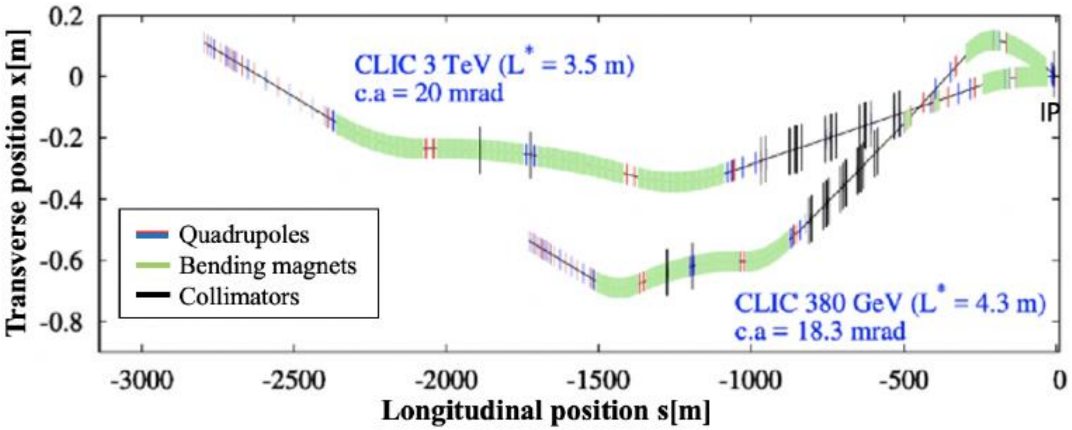


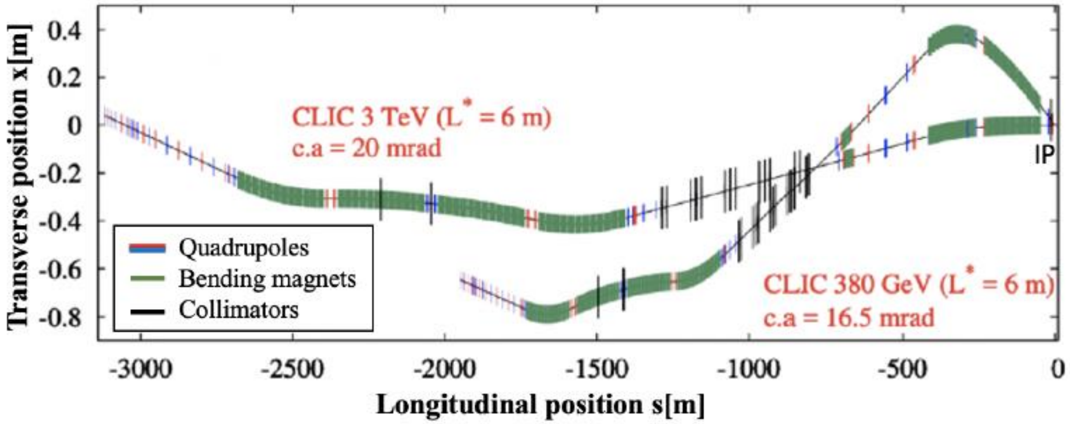
BDS in CLIC: Objectives and Challenges



CLIC	380 GeV		3 TeV	
	CDR	Current	CDR	Current
L^* [m]	4.3	6	3.5	6
BDS length [m]	1728	1949	2795	3117
Norm. emittance $\gamma\epsilon_x$ [nm]	950	950	660	660
Norm. emittance $\gamma\epsilon_y$ [nm]	30	30	20	20
Beta function (IP) β_x^* [mm]	8	8	7	7
Beta function (IP) β_y^* [mm]	0.1	0.1	0.068	0.12
IP beam size σ_x^*[nm]	144	144	40	40
IP beam size σ_y^*[nm]	2.9	2.9	0.7	0.9
Bunch length σ_z[μm]	70	70	44	44
rms energy spread δ_p[%]	0.3	0.3	0.3	0.3
Bunch population N_e [10^9]	5.2	5.2	3.72	3.72
Number of bunches n_b	352	352	312	312
Repetition rate f_{rep} [Hz]	50	50	50	50
Crossing Angle [mrad]	18.3	16.5	20	20
Luminosity $\mathscr{L}_{TOT}$ [10^{34} cm^{-2}s^{-1}]	1.5	1.5	5.9	5.9

- Main challenges: minimizing beam size, correcting chromatic aberrations, and maintaining beam stability





*Cilento, Vera. *Optics Design of a novel Beam Delivery System for CLIC: the case of two Interaction Regions. First experiments for the validation of the ultra-low betay* nanometer beam size at ATF2*. Diss. Université Paris-Saclay, 2021

*Pastushenko, Andrii. *Optimization of CLIC Final Focus System at 380 GeV and implementation studies for Ultra-low β* at ATF2*. Diss. Université Paris-Saclay, 2022.

Update of the CLIC 3 TeV performance

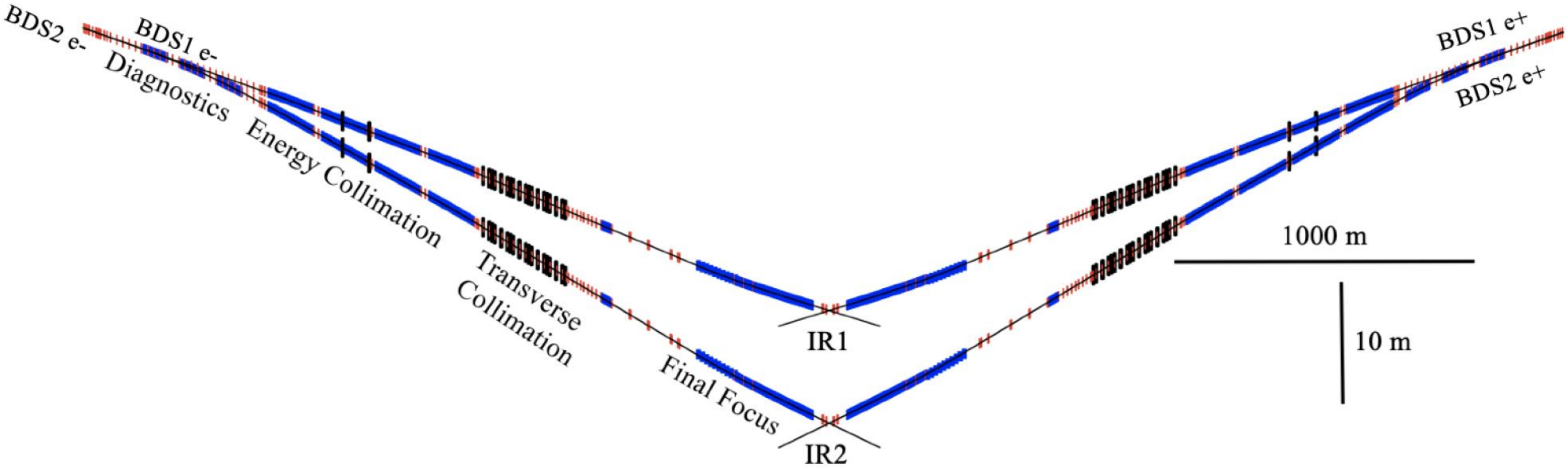
σ_x^* [nm]	**ideal**	**w/ SR**
baseline	41.4	50.3
σ_y^* [nm]	**ideal**	**w/ SR**
baseline	1.06	1.69

Luminosity [10^{34} cm^{-2} s^{-1}]	**ideal**	**w/ solenoid**	**w/ SR**	**w/ sol+ SR**
baseline	9.40	8.65	6.50	6.22

- The update involves the integration of the detector solenoid effects in the performance evaluation
- The detector solenoid effect was never evaluated for the CLIC with L*= 6 m, while for the L*= 3.5 m was ~ 4%
- The evaluation of the luminosity including the detector solenoid effects has been done with PLACET tracking procedure (ideal, w/ sol, w/ sol+ SR) and GUINEA-PIG
- **The luminosity loss from the solenoid field for the the current design with L*= 6 m is about 4%**

The Dual BDS Concept for CLIC

- 380 GeV

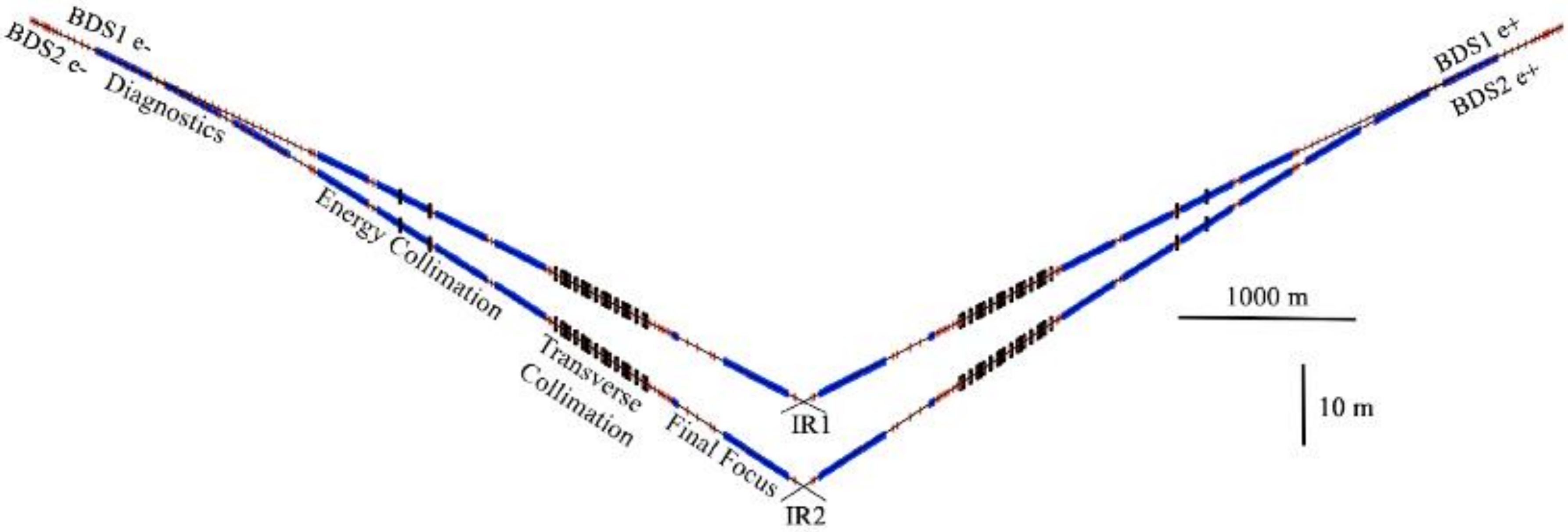


- ➢ Four different beam lines have been constructed to provide:
  - Longitudinal separation of ∼ 40 m at IP.
  - Transverse separation of 10 m at IP.
- ➢ The θ in the DS of the BDS2 is 4.83 mrad.
- ➢ **The crossing angles at IR1 and IR2 are respectively 16.5 mrad and 26 mrad**.

The Dual BDS Concept for CLIC

- 3 TeV

Cilento, Vera, et al. "Dual beam delivery system serving two interaction regions for the Compact Linear Collider." *Physical Review Accelerators and Beams* 24.7 (2021): 071001.



- ➢ In order to have the IRs at the exact same locations as in the CLIC 380 GeV case:
  - The θ in the DS of the BDS2 is 2.75 mrad
  - **The crossing angles at IR1 and IR2 are respectively 20 mrad and 25.5 mrad**
  - Additional length of 1.2 km → total length of the DS is ~ 1.5 km

The Dual BDS Concept for CLIC

- Beam Size and Luminosity with PLACET and GUINEA-PIG for CLIC 380 GeV including detector solenoid effects

σ_x^* [nm]	ideal	w/ SR
IR1	141	144
IR2	141	144

σ_y^* [nm]	ideal	w/ SR
IR1	3.07	3.08
IR2	3.06	3.07

Luminosity [10^{34} cm^{-2} s^{-1}]	ideal	w/ solenoid	w/ SR	w/ sol+ SR
IR1	1.515	1.512	1.492	1.412
IR2	1.491	1.475	1.466	1.392

- The beam size simulations with the different codes (MAPCLASS and PLACET) show consistency of the results
- **The luminosity loss can be considered negligible for the CLIC 380 GeV case**

The Dual BDS Concept for CLIC

- Beam Size and Luminosity with PLACET and GUINEA-PIG for CLIC 3 TeV including detector solenoid effects

σ_x^* [nm]	ideal	w/ SR
IR1	43.5	51.5
IR2	44.9	64.8

σ_y^* [nm]	ideal	w/ SR
IR1	1.02	1.71
IR2	1.02	1.92

Luminosity [10^{34} cm^{-2} s^{-1}]	ideal	w/ solenoid	w/ SR	w/ sol+ SR
IR1	9.0	8.21	6.30	6.09
IR2	8.33	7.59	5.14	4.17

- The beam size simulations with the different codes (MAPCLASS and PLACET) show consistency of the results
- **The impact on the luminosity performance of CLIC 3 TeV for the solenoid field is ~ 4% for the IR1 and ~ 19% for IR2**

BDS Requirements for Plasma Colliders

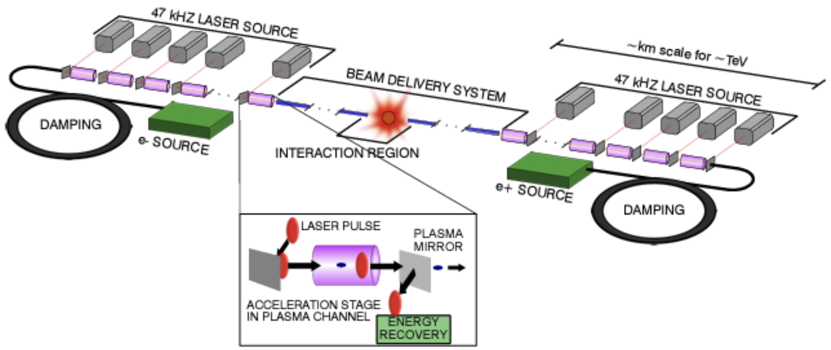
- The BDS challenges are mostly common to both traditional accelerator complex and plasma colliders

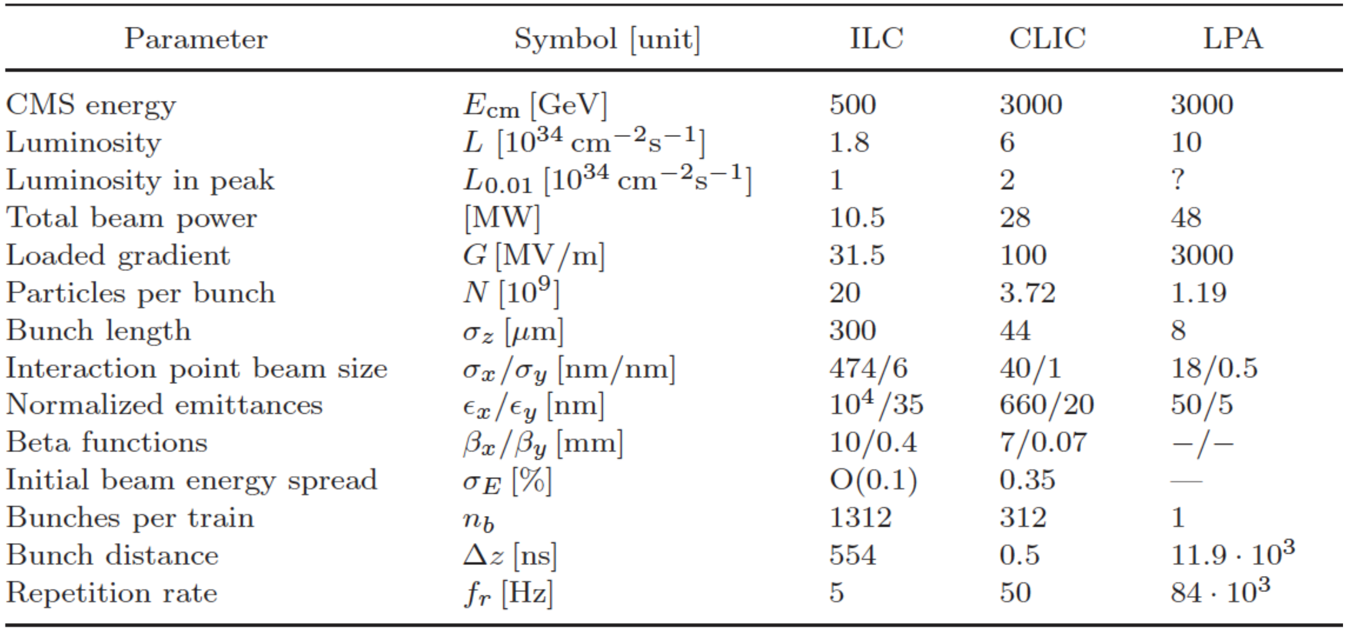
- Addressing these challenges is vital for realizing the full potential of plasma-based acceleration, opening new frontiers in high-energy physics research

  - Main challenges:
    - **Focusing and Emittance Control →** Achieving and maintaining tight beam focus while controlling emittance growth in plasma is crucial
    - **Chromaticity and Dispersion Correction →** Chromatic effects are larger in plasma colliders as relative energy spread of the beam could be larger
    - **The ratio of the BDS length to the total size of the complex** presents a unique design challenge specific to plasma colliders

BDS Synergies: CLIC & LPA

- Both CLIC and LPA aim for collisions at 3 TeV, facing overlapping challenges in their BDS
- Achieving nanometer beam sizes at the IP is critical for both CLIC and LPA → LPA beam size at the IP is compatible with the use of CLIC BDS (with unknown energy spread and if the target emittance is reached)
- Main challanges: transverse emittance preservation and ground motion effect





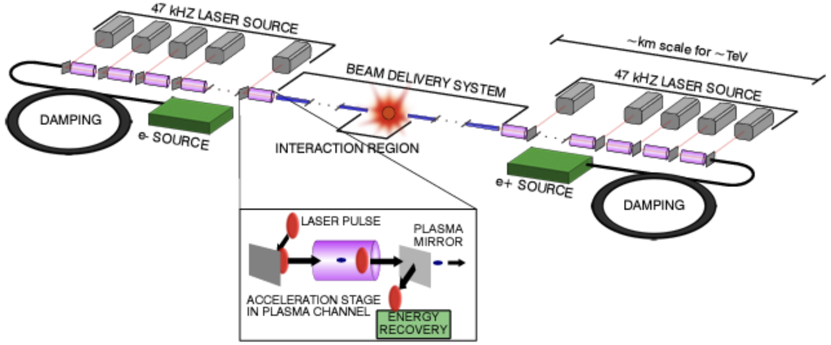
Parameter	Symbol [unit]	ILC	CLIC	LPA
CMS energy	E_{cm} [GeV]	500	3000	3000
Luminosity	L $[10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}]$	1.8	6	10
Luminosity in peak	$L_{0.01}$ $[10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}]$	1	2	?
Total beam power	[MW]	10.5	28	48
Loaded gradient	G [MV/m]	31.5	100	3000
Particles per bunch	N $[10^9]$	20	3.72	1.19
Bunch length	σ_z [μm]	300	44	8
Interaction point beam size	σ_x/σ_y [nm/nm]	474/6	40/1	18/0.5
Normalized emittances	ϵ_x/ϵ_y [nm]	10^4/35	660/20	50/5
Beta functions	β_x/β_y [mm]	10/0.4	7/0.07	–/–
Initial beam energy spread	σ_E [%]	O(0.1)	0.35	—
Bunches per train	n_b	1312	312	1
Bunch distance	Δz [ns]	554	0.5	$11.9 \cdot 10^3$
Repetition rate	f_r [Hz]	5	50	$84 \cdot 10^3$

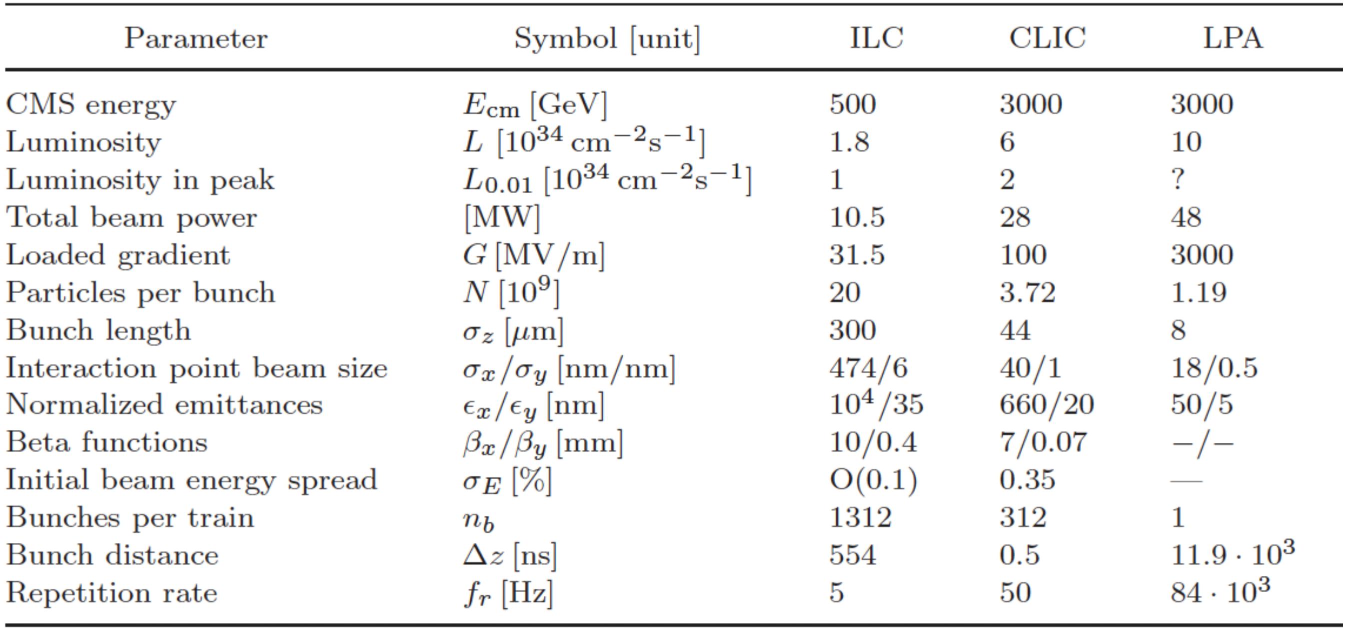
*Schulte, Daniel. "Application of advanced accelerator concepts for colliders." *Reviews of Accelerator Science and Technology* 9 (2016): 209-233.
*Schroeder, C. B., et al. "Linear colliders based on laser-plasma accelerators." *Journal of Instrumentation* 18.06 (2023): T06001.

BDS Synergies: CLIC & LPA

- Preliminary simulation for a LPA 3 TeV BDS
  - Using the parameters shown in the Table we get from PLACET Tracking and GUINEA-PIG:
    - w/SR
    - Energy spread of CLIC (0.1%)
    - CLIC betas at the IP (7 mm and 0.12 mm)

σ_x^* [nm]	σ_y^* [nm]	Luminosity [10^{34} cm^{-2} s^{-1}]
27	0.6	12.7



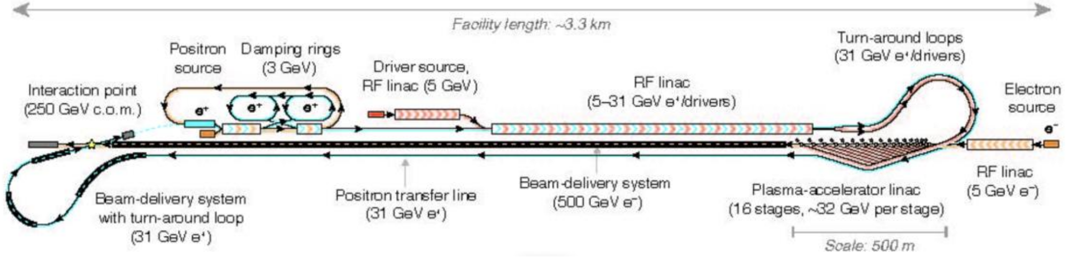


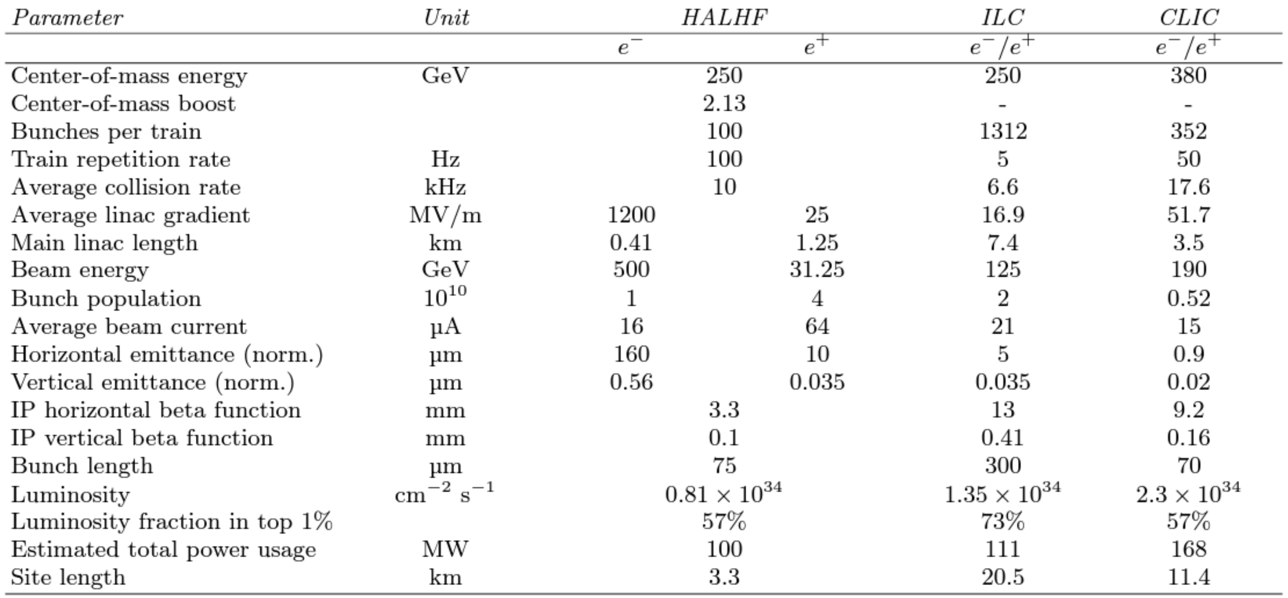
Parameter	Symbol [unit]	ILC	CLIC	LPA
CMS energy	E_{cm} [GeV]	500	3000	3000
Luminosity	L [10^{34} cm^{-2}s^{-1}]	1.8	6	10
Luminosity in peak	$L_{0.01}$ [10^{34} cm^{-2}s^{-1}]	1	2	?
Total beam power	[MW]	10.5	28	48
Loaded gradient	G [MV/m]	31.5	100	3000
Particles per bunch	N [10^9]	20	3.72	1.19
Bunch length	σ_z [μm]	300	44	8
Interaction point beam size	σ_x/σ_y [nm/nm]	474/6	40/1	18/0.5
Normalized emittances	ϵ_x/ϵ_y [nm]	10^4/35	660/20	50/5
Beta functions	β_x/β_y [mm]	10/0.4	7/0.07	–/–
Initial beam energy spread	σ_E [%]	O(0.1)	0.35	—
Bunches per train	n_b	1312	312	1
Bunch distance	Δz [ns]	554	0.5	$11.9 \cdot 10^3$
Repetition rate	f_r [Hz]	5	50	$84 \cdot 10^3$

BDS Synergies: CLIC & HALHF

- BDS specification for the hybrid, asymmetric, linear Higgs Factory (HALHF), in which electrons are accelerated to higher energy in PWFAs and positrons are accelerated to lower energy in conventional RF cavities is proposed

- Due to the asymmetry of the BDS, the HALHF positron BDS will be much shorter (320–740 m), simulations could be done starting from the CLIC 380 GeV design





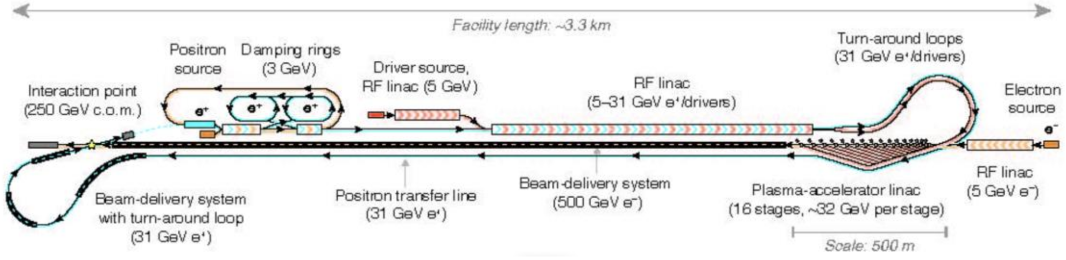
Parameter	*Unit*	*HALHF*		*ILC*	*CLIC*
		e^-	e^+	e^-/e^+	e^-/e^+
Center-of-mass energy	GeV	250		250	380
Center-of-mass boost		2.13		-	-
Bunches per train		100		1312	352
Train repetition rate	Hz	100		5	50
Average collision rate	kHz	10		6.6	17.6
Average linac gradient	MV/m	1200	25	16.9	51.7
Main linac length	km	0.41	1.25	7.4	3.5
Beam energy	GeV	500	31.25	125	190
Bunch population	10^{10}	1	4	2	0.52
Average beam current	µA	16	64	21	15
Horizontal emittance (norm.)	µm	160	10	5	0.9
Vertical emittance (norm.)	µm	0.56	0.035	0.035	0.02
IP horizontal beta function	mm	3.3		13	9.2
IP vertical beta function	mm	0.1		0.41	0.16
Bunch length	µm	75		300	70
Luminosity	$\mathrm{cm}^{-2}\ \mathrm{s}^{-1}$	0.81×10^{34}		1.35×10^{34}	2.3×10^{34}
Luminosity fraction in top 1%		57%		73%	57%
Estimated total power usage	MW	100		111	168
Site length	km	3.3		20.5	11.4

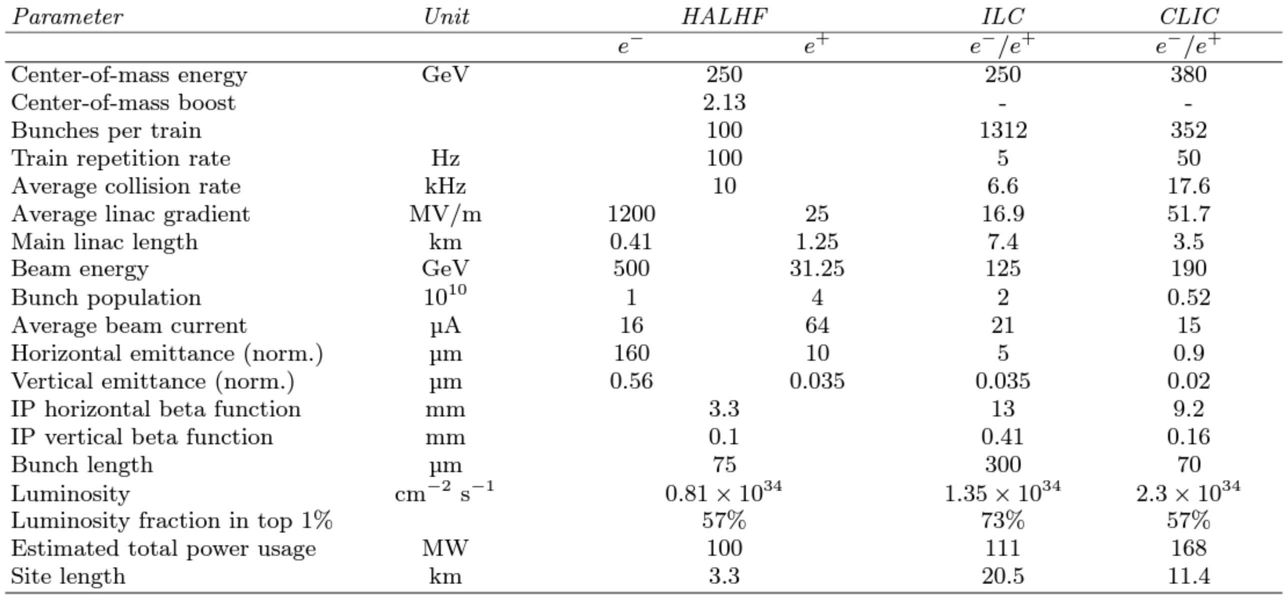
*Foster, B., D'Arcy, R., & Lindstrøm, C. A. (2023). A hybrid, asymmetric, linear Higgs factory based on plasma-wakefield and radio-frequency acceleration. *New Journal of Physics*, *25*(9), 093037.

BDS Synergies: CLIC & HALHF

- Preliminary simulation for a HALHF 250 GeV BDS
  - A simulation with GUINEA-PIG has been done in order to asses the luminosity of the facility considering the values in the Table and:
    - w/ SR
    - Energy spread 0.15%
    - Betas at the IP (3.3 mm and 0.1 mm)

σ_x^* [nm]	σ_y^* [nm]	Luminosity [10^{34} cm^{-2} s^{-1}]
734.5	7.6	1.1





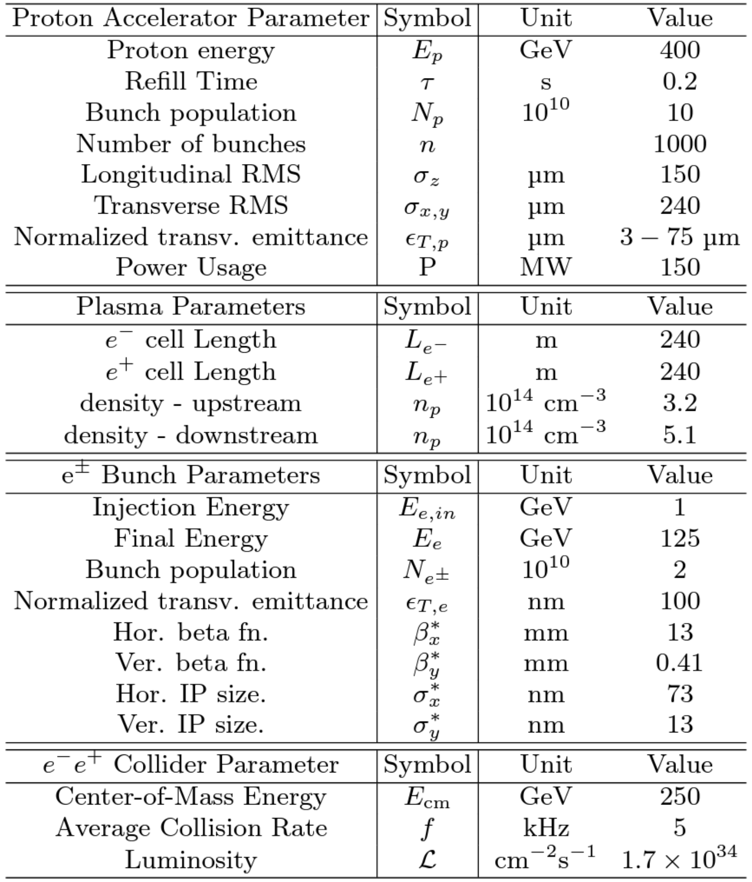
Parameter	*Unit*	*HALHF*		*ILC*	*CLIC*
		e^-	e^+	e^-/e^+	e^-/e^+
Center-of-mass energy	GeV	250		250	380
Center-of-mass boost		2.13		-	-
Bunches per train		100		1312	352
Train repetition rate	Hz	100		5	50
Average collision rate	kHz	10		6.6	17.6
Average linac gradient	MV/m	1200	25	16.9	51.7
Main linac length	km	0.41	1.25	7.4	3.5
Beam energy	GeV	500	31.25	125	190
Bunch population	10^{10}	1	4	2	0.52
Average beam current	µA	16	64	21	15
Horizontal emittance (norm.)	µm	160	10	5	0.9
Vertical emittance (norm.)	µm	0.56	0.035	0.035	0.02
IP horizontal beta function	mm	3.3		13	9.2
IP vertical beta function	mm	0.1		0.41	0.16
Bunch length	µm	75		300	70
Luminosity	cm^{-2} s^{-1}	0.81×10^{34}		1.35×10^{34}	2.3×10^{34}
Luminosity fraction in top 1%		57%		73%	57%
Estimated total power usage	MW	100		111	168
Site length	km	3.3		20.5	11.4

BDS Synergies: CLIC & PDPWA

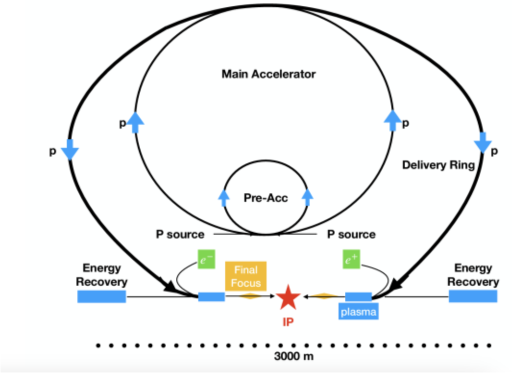
- A proton-driven plasma wakefield acceleration scheme is proposed as a novel approach for a Higgs Factory, offering a simpler and more compact alternative to existing RF-based collider designs

- The BDS would need to accommodate beam dynamics resulting from ultra-high acceleration gradients, including energy spread and emittance preservation

- Design considerations must ensure precise beam focusing and collimation to meet luminosity goals while mitigating beam-induced plasma effects



Proton Accelerator Parameter	Symbol	Unit	Value
Proton energy	E_p	GeV	400
Refill Time	τ	s	0.2
Bunch population	N_p	10^{10}	10
Number of bunches	n		1000
Longitudinal RMS	σ_z	µm	150
Transverse RMS	$\sigma_{x,y}$	µm	240
Normalized transv. emittance	$\epsilon_{T,p}$	µm	3 – 75 µm
Power Usage	P	MW	150
Plasma Parameters	Symbol	Unit	Value
e^- cell Length	L_{e-}	m	240
e^+ cell Length	L_{e+}	m	240
density - upstream	n_p	10^{14} cm^{-3}	3.2
density - downstream	n_p	10^{14} cm^{-3}	5.1
$e^\pm$ Bunch Parameters	Symbol	Unit	Value
Injection Energy	$E_{e,in}$	GeV	1
Final Energy	E_e	GeV	125
Bunch population	$N_{e\pm}$	10^{10}	2
Normalized transv. emittance	$\epsilon_{T,e}$	nm	100
Hor. beta fn.	β_x^*	mm	13
Ver. beta fn.	β_y^*	mm	0.41
Hor. IP size.	σ_x^*	nm	73
Ver. IP size.	σ_y^*	nm	13
e^-e^+ Collider Parameter	Symbol	Unit	Value
Center-of-Mass Energy	E_{cm}	GeV	250
Average Collision Rate	f	kHz	5
Luminosity	$\mathcal{L}$	cm^{-2}s^{-1}	1.7×10^{34}

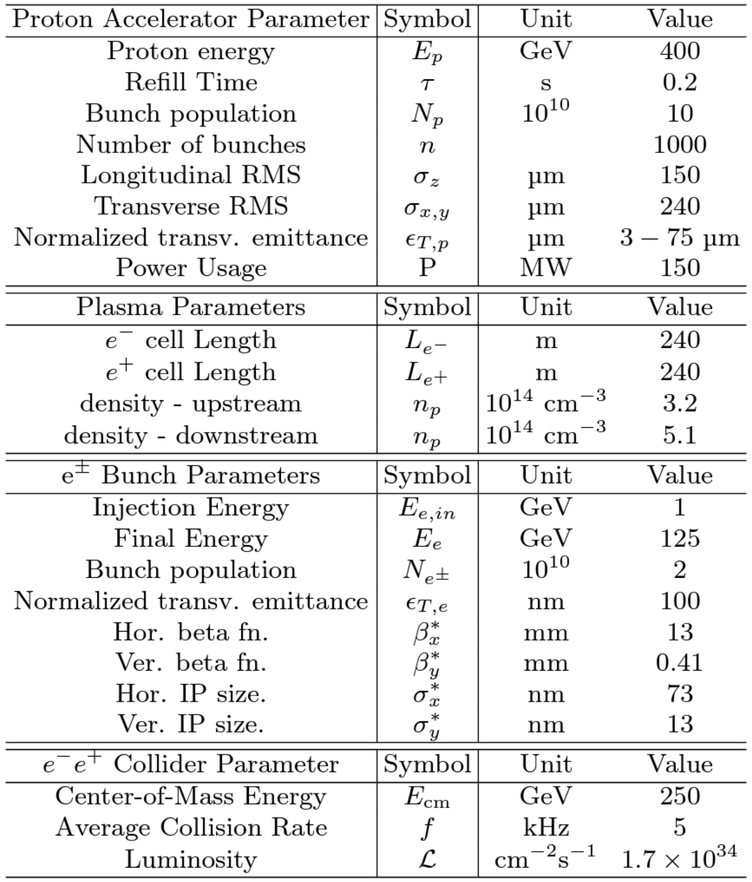


*J. Farmer, A. Caldwell, and A. Pukhov, *Preliminary Investigation of a Higgs Factory based on Proton-Driven Plasma Wakefield Acceleration*, arXiv:2401.14765

BDS Synergies: CLIC & PDPWA

- Preliminary simulation for a PDPWA 250 GeV BDS
  - A simulation with GUINEA-PIG has been done in order to asses the luminosity of the facility considering the values in the Table and:
    - w/ SR
    - Energy spread of CLIC (0.1%)
    - Betas at the IP (13 mm and 0.41 mm)

σ_x^* [nm]	σ_y^* [nm]	Luminosity [10^{34} cm^{-2} s^{-1}]
73	13	4.3

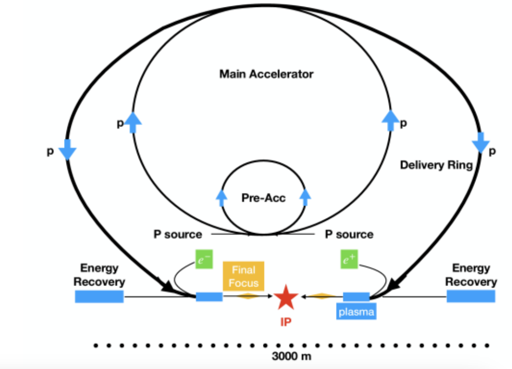


Proton Accelerator Parameter	Symbol	Unit	Value
Proton energy	E_p	GeV	400
Refill Time	τ	s	0.2
Bunch population	N_p	10^{10}	10
Number of bunches	n		1000
Longitudinal RMS	σ_z	µm	150
Transverse RMS	$\sigma_{x,y}$	µm	240
Normalized transv. emittance	$\epsilon_{T,p}$	µm	$3-75$ µm
Power Usage	P	MW	150

Plasma Parameters	Symbol	Unit	Value
e^- cell Length	L_{e^-}	m	240
e^+ cell Length	L_{e^+}	m	240
density - upstream	n_p	10^{14} cm^{-3}	3.2
density - downstream	n_p	10^{14} cm^{-3}	5.1

$e^\pm$ Bunch Parameters	Symbol	Unit	Value
Injection Energy	$E_{e,in}$	GeV	1
Final Energy	E_e	GeV	125
Bunch population	$N_{e\pm}$	10^{10}	2
Normalized transv. emittance	$\epsilon_{T,e}$	nm	100
Hor. beta fn.	β_x^*	mm	13
Ver. beta fn.	β_y^*	mm	0.41
Hor. IP size.	σ_x^*	nm	73
Ver. IP size.	σ_y^*	nm	13

e^-e^+ Collider Parameter	Symbol	Unit	Value
Center-of-Mass Energy	$E_{\rm cm}$	GeV	250
Average Collision Rate	f	kHz	5
Luminosity	$\mathcal{L}$	cm^{-2}s^{-1}	1.7×10^{34}

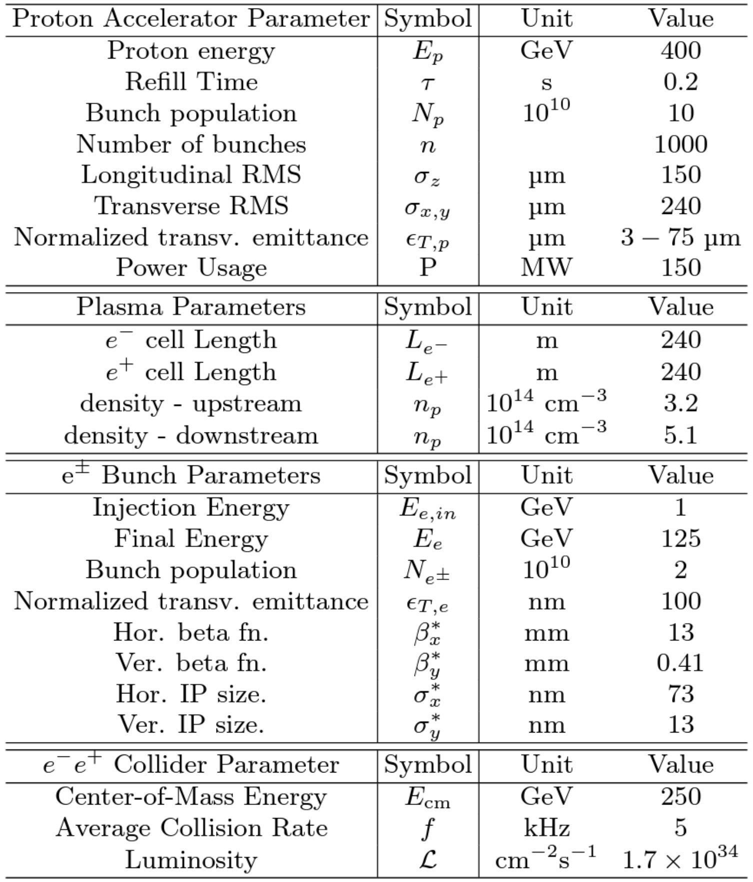


BDS Synergies: CLIC & PDPWA

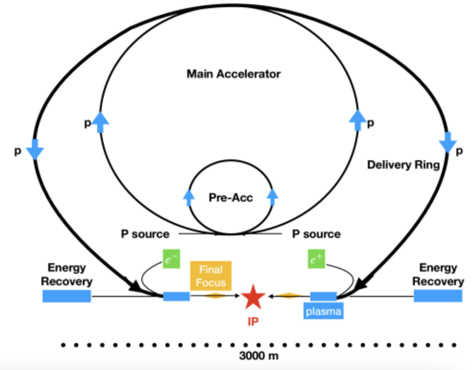
- Preliminary simulation for a PDPWA 250 GeV BDS
  - Simulation for normalized transverse emittance scaling $\epsilon_{T,e}$

$\epsilon_{T,e}$ [nm]	σ_x^* [nm]	σ_y^* [nm]	Luminosity [10^{34} cm^{-2} s^{-1}]
100	73	13	4.3
150	90	16	4.1
200	103	18	3.7

  - small impact on lumi but it could be thanks to lower beamstrahalung ?? → short bunch length (maybe try larger one to confirm simulations)



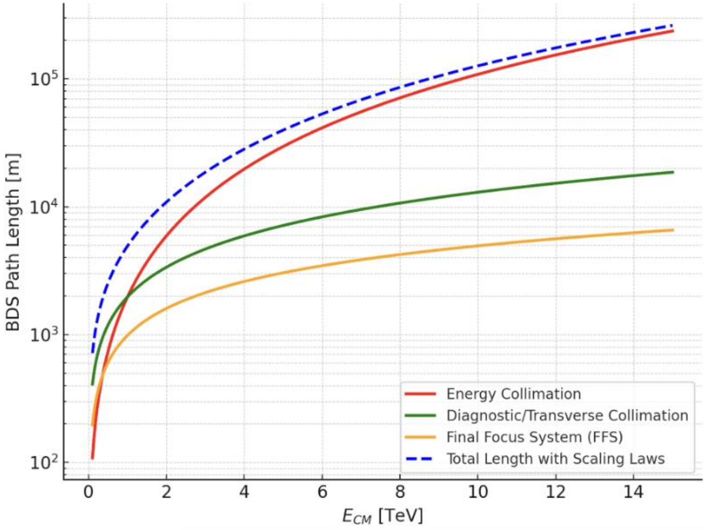
Proton Accelerator Parameter	Symbol	Unit	Value
Proton energy	E_p	GeV	400
Refill Time	τ	s	0.2
Bunch population	N_p	10^{10}	10
Number of bunches	n		1000
Longitudinal RMS	σ_z	µm	150
Transverse RMS	$\sigma_{x,y}$	µm	240
Normalized transv. emittance	$\epsilon_{T,p}$	µm	3 – 75 µm
Power Usage	P	MW	150
Plasma Parameters	Symbol	Unit	Value
e^- cell Length	L_{e^-}	m	240
e^+ cell Length	L_{e^+}	m	240
density - upstream	n_p	10^{14} cm^{-3}	3.2
density - downstream	n_p	10^{14} cm^{-3}	5.1
e$^\pm$ Bunch Parameters	Symbol	Unit	Value
Injection Energy	$E_{e,in}$	GeV	1
Final Energy	E_e	GeV	125
Bunch population	$N_{e\pm}$	10^{10}	2
Normalized transv. emittance	$\epsilon_{T,e}$	nm	100
Hor. beta fn.	β_x^*	mm	13
Ver. beta fn.	β_y^*	mm	0.41
Hor. IP size.	σ_x^*	nm	73
Ver. IP size.	σ_y^*	nm	13
e^-e^+ Collider Parameter	Symbol	Unit	Value
Center-of-Mass Energy	E_{cm}	GeV	250
Average Collision Rate	f	kHz	5
Luminosity	$\mathcal{L}$	cm^{-2}s^{-1}	1.7×10^{34}

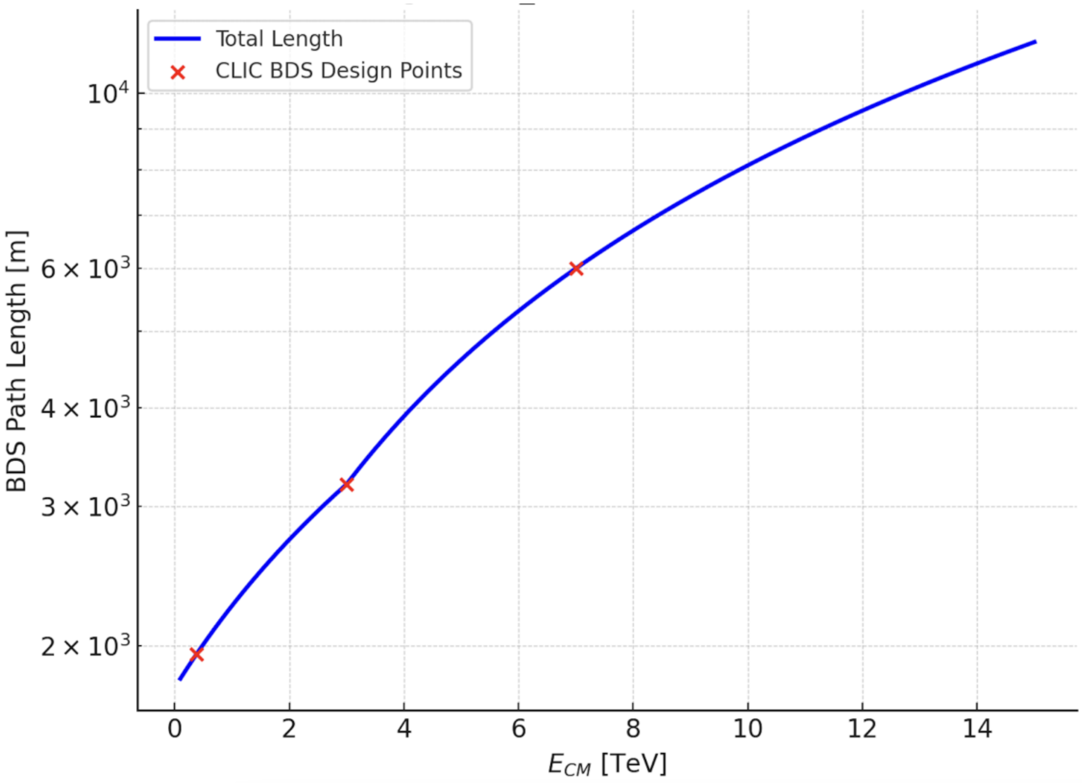


The Future of BDS: Scaling with Energies

- As we venture into higher energy frontiers, the role of BDS becomes increasingly critical

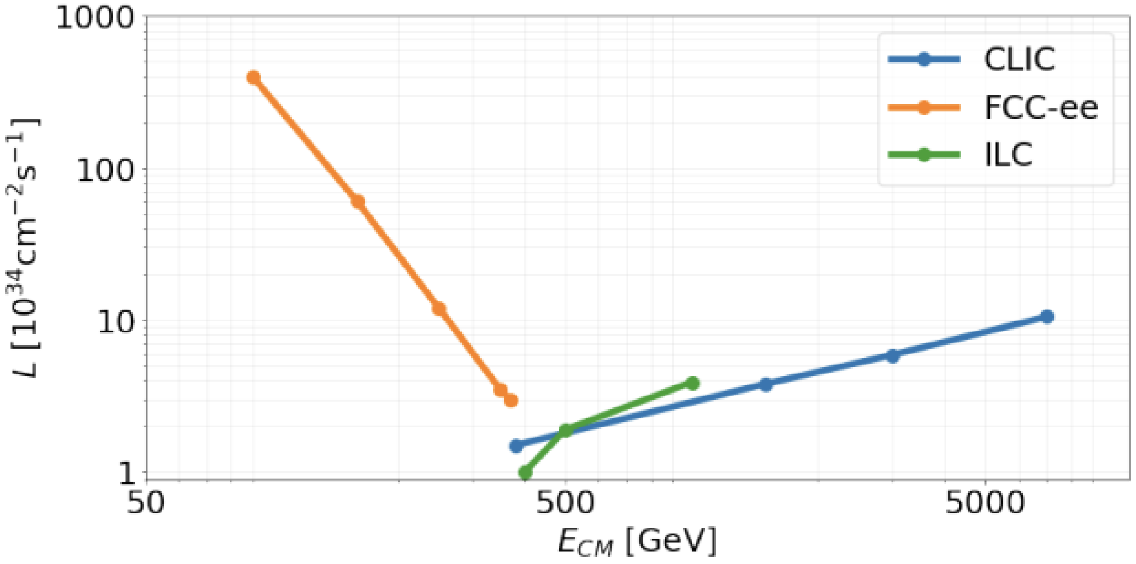
- Scaling laws of the different parts of the BDS*:
  - Energy Collimation scales between $L\sim E$ and $L\sim E^2$*
  - Diagnostic and Transverse Collimation scale between $L\sim\sqrt{E}$ and $L\sim E$*
  - FFS scales as $L\sim E^{7/10}$





*White, G., et al. "Beam delivery and final focus systems for multi-TeV advanced linear colliders." *Journal of Instrumentation* 17.05 (2022): P05042.

The Future of BDS: CLIC BDS Design at 7 TeV



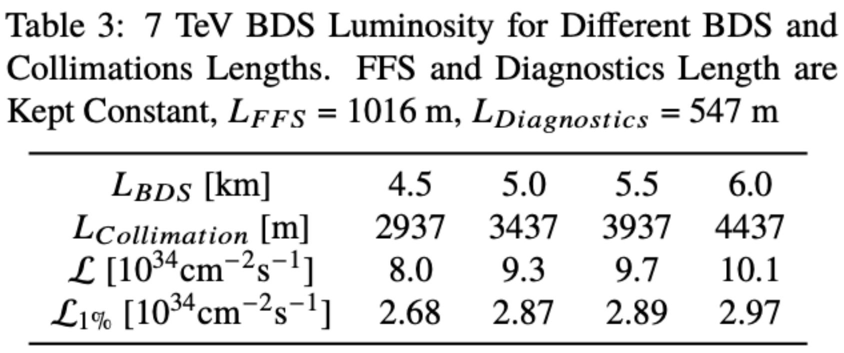
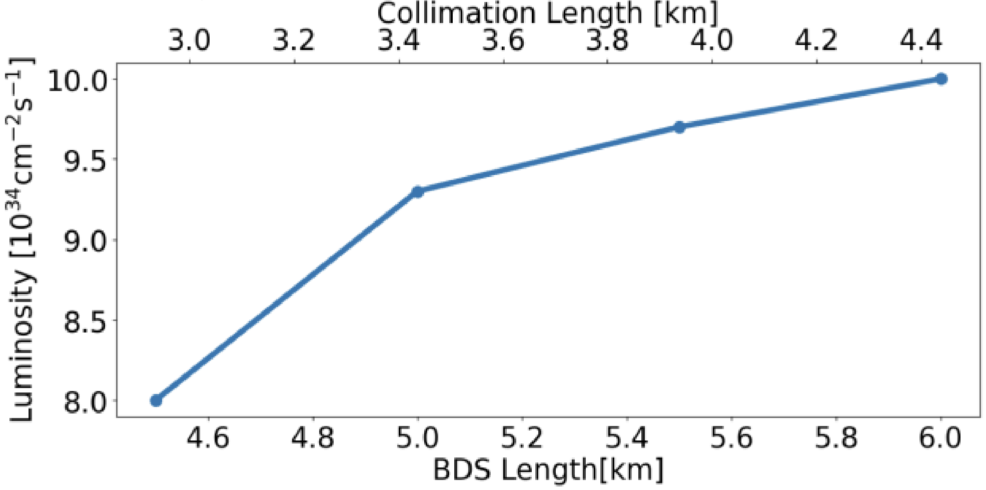


Table 3: 7 TeV BDS Luminosity for Different BDS and Collimations Lengths. FFS and Diagnostics Length are Kept Constant, L_{FFS} = 1016 m, $L_{Diagnostics}$ = 547 m

L_{BDS} [km]	4.5	5.0	5.5	6.0
$L_{Collimation}$ [m]	2937	3437	3937	4437
$\mathcal{L}$ [10^{34}cm^{-2}s^{-1}]	8.0	9.3	9.7	10.1
$\mathcal{L}_{1\%}$ [10^{34}cm^{-2}s^{-1}]	2.68	2.87	2.89	2.97

- The challenges of this new design are minimizing the extent of trajectory bending for collimation and chromaticity correction to reduce the effects from synchrotron radiation, ensuring a good transverse aberration control at the IP

- In Figure, four possible lengths of the BDS have been proposed to achieve a target luminosity of approximately 10^{35} cm^{-2} s^{-1} at 7 TeV (the Figures shown are not considering the solenoid losses)



Manosperti, E., R. Tomás, and A. Pastushenko. "JACOW: Design of CLIC beam delivery system at 7 TeV." *JACoW IPAC* 2023 (2023): MOPL113.

Conclusions

- **Innovations on CLIC BDS:**
  - **The dual BDS design is competitive up to 3 TeV** with a total luminosity loss of about 30% for the extra line with larger crossing angle
  - The impact on the luminosity performance of CLIC 3 TeV for the detector solenoid field is about 4% for the baseline and for IR1 and about 19% for IR2

- **Synergies between CLIC and Plasma Colliders:**
  - The collaboration between CLIC and plasma collider projects has highlighted shared solutions to common challenges
  - First simulations with CLIC BDS for LPA, HALHF and PDPWA show that the **luminosity goals are reached →** the largest challenge are the emittance preservation and possibly the missing energy spread (new possible simultions with different energy spread)

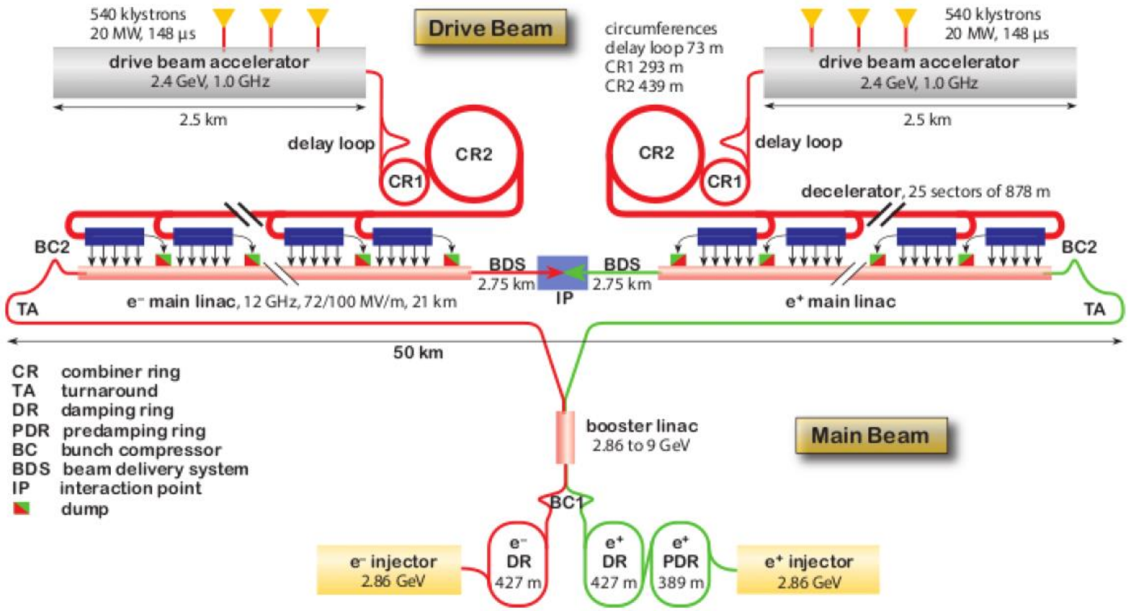
- **Exploring the scaling laws of BDS components has laid a foundation for future collider designs** to tackle the demands of higher energies

Thank you for the attention!

Back-up Slide

Beam Delivery System

- The BDS is composed by:
  - Diagnostic Section (end of ML to collimation section- skew correction, emittance diagnostic section-laser wires, beta matching section)
  - Collimation Section (protects the downstream beamline and detector against mis-steered beams from ML and removes beam halo)
  - Final Focus System (focus the beam to nanometer level and correct the chromaticity)



- Measure the linac beam and match it into the final focus
- Remove large amplitude particles (beam-halo) from the linac to minimize background in the detectors
- Measure and monitor key physics parameters (energy and polarization before and after collisions)
- Ensure that the extremely small beams collide optimally at the IP
- Protect the beamline and detector against mis-steered beams from the main linacs and safely extract them to beam dump