WP3: ILC Crab Cavities

Down-selection Review – Design Specifications

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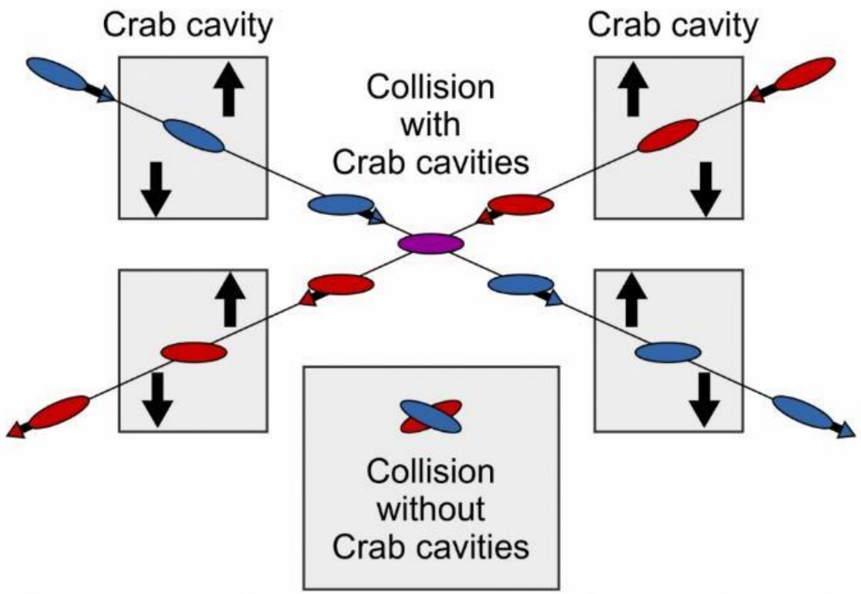
UKRI-STFC Daresbury Laboratory

4th – 6th April 2023



Science and Technology Facilities Council

Outline

- ILC CC Development Plans
- ILC Pre-Lab Time Critical Workpackages
- CC Specifications Development
- ILC BDS Beam Parameters
- CC Operational Requirements
- ILC IR Dimensional Constraints
- Proposed CC Specifications
- Other CC Expectations
- Summary

ILC Crab Cavity (CC) Development Plans

Activity	R&D Plan	Tmescale																When?
		2021				2022 (Yr 1)				2023 (Yr 2)				2024 (Yr 3)				
		Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	
Start of CC technology development	T0										Decision 1 (EM Design)						Decision 2 (Prototoye)	25-Mar-21
Set CC specifications	T0 + 3m																	24-Jun-21
Bare cavity EM design parameters																		
Hom damped cavity parameters																		
HOM coupler development																		
Mechanical design																		
1st Design Review (cavity, HOMs, couplers)	T0 + 9m																	07-Dec-21
Multipacting assessment																		
Tuning solution and pressure analysis																		
2nd Design Review (cavity, HOMs, couplers, multipacting, tuning)	T0 + 15m																	27-Jun-22
3rd Design Review (cavity, HOMs, couplers, multipacting, tuning)	T0 + 18m																	01-Nov-22
4th Design Review (cavity, HOMs, couplers, multipacting, tuning)	T0 + 21m																	27-Jan-23
Decision 1 - Down-selection (EM Design) (2 cavities chosen)	T0 + 23m																	06-Apr-23
Decision 2 - Down-selection (Prototype and Test) (1 cavity chosen)	T0 + 41m																	Oct-24

Critical (→ Set CC specifications)

Additional DR's (← 3rd and 4th Design Reviews)

Today (← Decision 1)

- CC development plans originally set in Mar21 (2-yrs ago):
  - Targeted a 1st (2-cavity) selection process in Oct22 (18-mo duration).
  - Ultimately to perform a 2nd selection of prototyped ILC CC technology in ~Apr24.
- At 2nd Design Review (Jun22), identified more development time needed:
  - Delayed today's 1st down-selection by ~6-mo), added 2 additional design reviews (Nov22 and Jan23).
- All IDT WP3 CC development processes captured at: https://agenda.linearcollider.org/category/256/

ILC Pre-Lab Time Critical Workpackages

Ref: ‘Time-critical WPs for the ILC construction’, IDT-WG2, v8.0 Jun 2022)

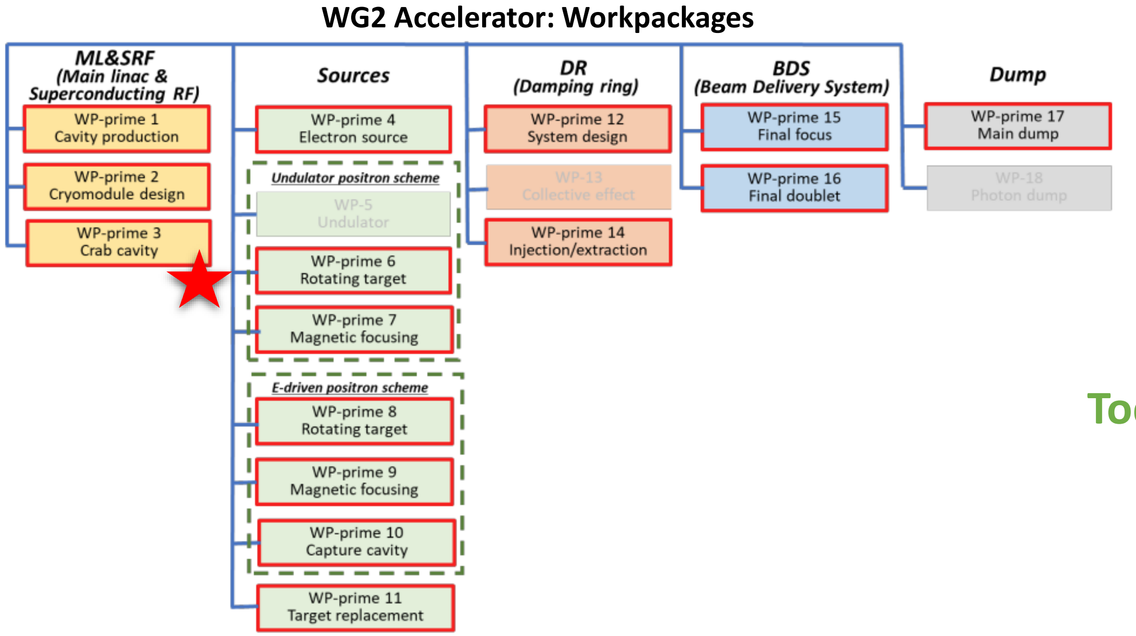


Figure 3: Time-critical WPs

- CC design teams from Europe & America.
- Strong organisational support from KEK:
  - Kirk Yamamoto – WP1/2 Coordinator
  - Akira Yamamoto – IDT WG2
  - Shin Michizono – IDT WG2 Chair

List of items:

Priority	*Items*	Y1 (2023)	Y2 (2024)	Y3 (2025)	Y4 (2026)
A	Decision of installation location with cryogenics/RF location accelerator tunnel	All			
A	Confirm the complete CC system specifications	All			
A	Development of CC cavity/coupler/tuner integrated design (ahead of Preliminary CC technology Down-selection)	EU, AM			
A	Preliminary CC technology down-selection (2 cavity options)	All			
A/B	CC Model-work and Prototype production and high-power validation of CC cavity/coupler/tuner integrated system (incl HPGS provision) for two primary candidates (ahead of Final CC technology Down-selection)	EU, AM	EU, AM		
B	Perform harmonized operation of the two prototype cavities in a vertical test to verify ILC synchronization performance (cryo insert development and commercial optical RF synchronization system).		EU, AM	EU, AM	
A/B	Final CC technology down-selection			All	
B	Preliminary Crab Prototype CM (pCM) design – confirming dressed cavity integration and compliance with beam-line specification (incl HPGS provision)			EU, AM	EU, AM
B	Final pCM engineering design prior to production			EU, AM	EU, AM
Note: Production of pCM is assumed after Y5 (P3)					

Today ➡ (Preliminary CC technology down-selection (2 cavity options))

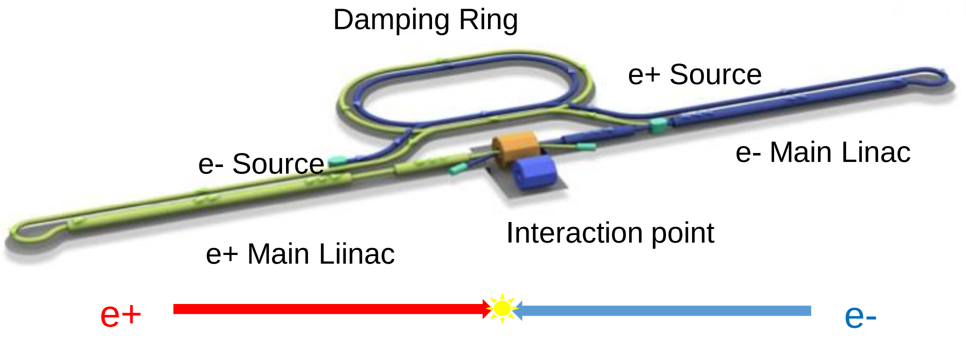
CC Specifications Development

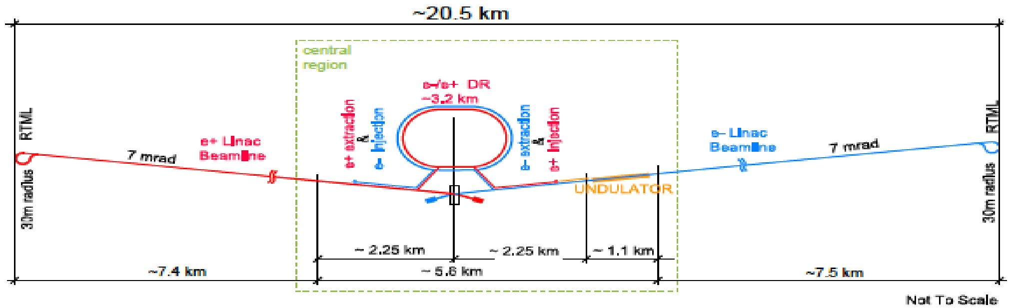
- Beam parameters to comply with:
  - BDS driven specifications for; beam current, bunch spacing, beam size, number of bunches, repetition rate, train length and bunch spacing etc.
- Cavity operational requirements:
  - Kick voltage, RF frequency, HOM impedance thresholds, amplitude/phase stability, frequency tuning, peak fields etc.
- Dimensional constraints:
  - Beam crossing angle, beam separation, beam-pipe aperture, alignment tolerances and length restriction etc.

- Worked closely with the ILC BDS team (Toshiyuki Okugi in particular) to identify many of the proposed specifications (identified in the v19) document as uploaded.

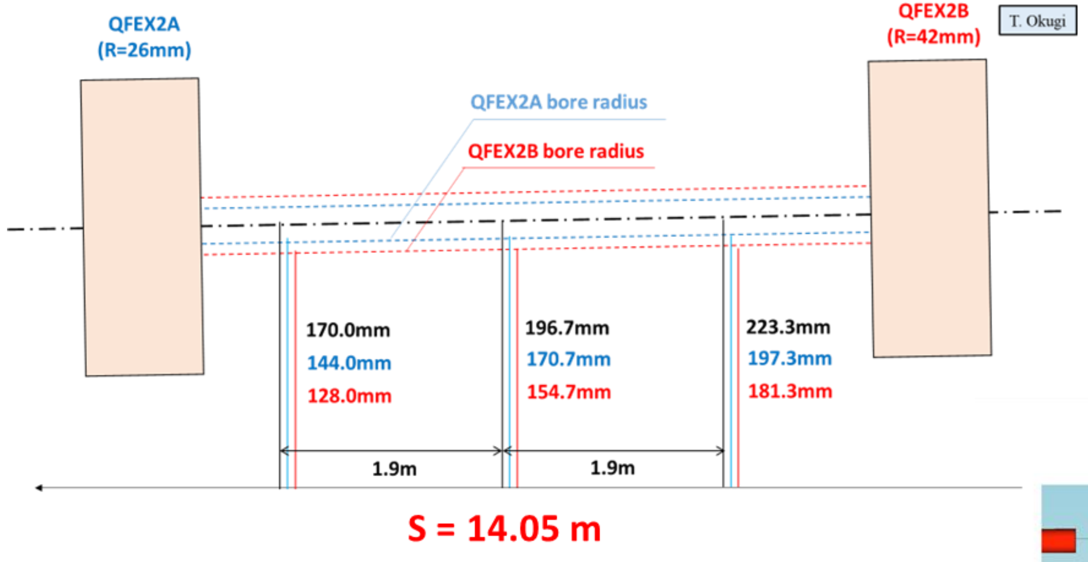
ILC BDS Beam Parameters

- Driving BDS constraints:
  - CC wakefields – transverse primarily
  - Alignment tolerances (x, y and roll)
  - Beam offset
  - Beam-pipe aperture - collimation



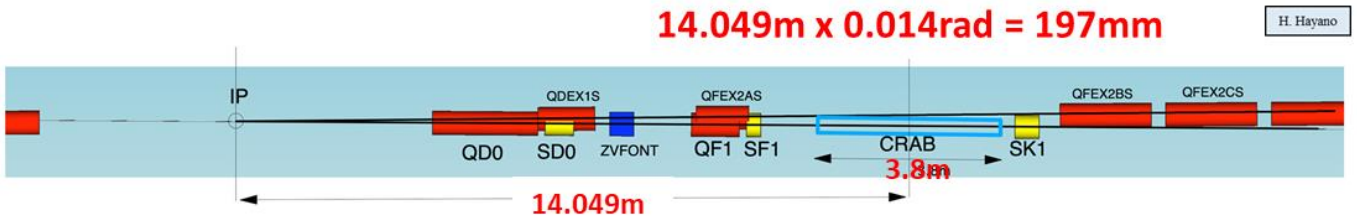


ILC-250 (e+, e-swapped)



Two beamline separation

14.049m x 0.014rad = 197mm



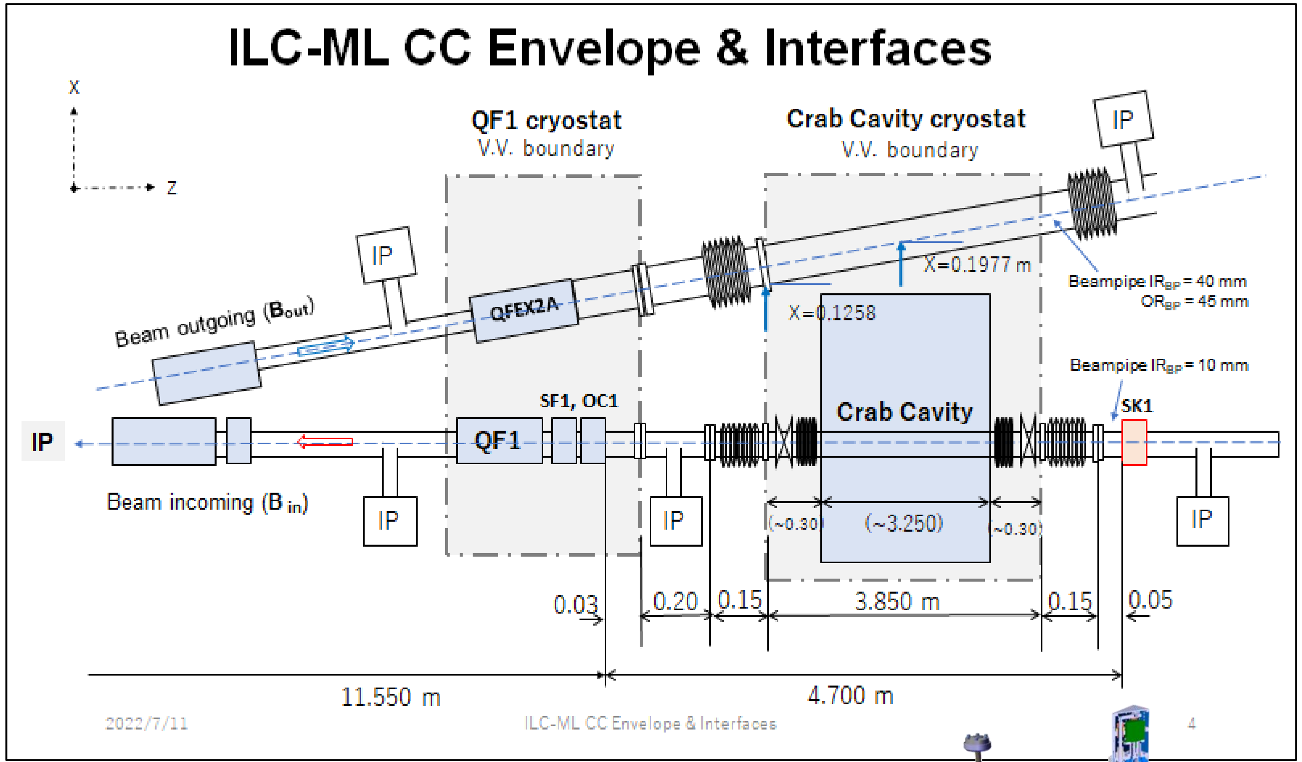
See Okugi-san's talk earlier.

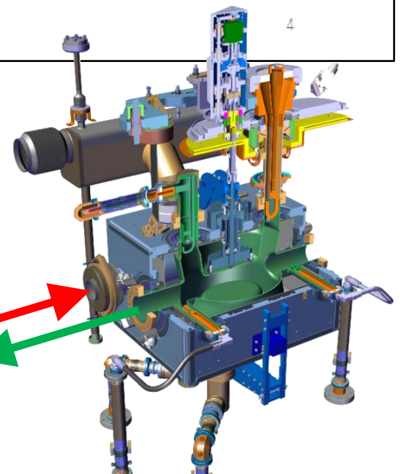
CC Operational Requirements

- The ILC Crab Cavity system must:
  - Provide the required CW deflecting voltage to optimally rotate the intersecting beam bunches at the IP.
  - Suppress all unwanted HOM power (longitudinal and transverse) to an acceptable level.
  - Ensure its robust operation, with acceptable limits for stability: peak fields, multipactor, alignment and RF control.
  - Provide an ability to de-tune its frequency, such that it can be safely 'parked' during beam operations.
  - Physically fit within the constraints of the ILC BDS Interaction Region location.

ILC BDS IR Dimensional Constraints

- 3.8 m longitudinal space in the IR, for CC cryomodule (incl. gate-valves).
- 197 mm beam-line separation at centre of 3.8 m location, which varies across its length (for 14 mrad crossing angle).
- Outgoing beam-pipe will likely be incorporated inside CC cryomodule, maybe even within CC helium tank (similar to HL-LHC).
- Incoming external beam-pipes are 20 mm diameter (beyond bellows), impacts cryomodule transition space required (wakefield effects).





Other CC Expectations

- Identify CC manufacturing provisions.
- Methodology:
  - Sheet forming, billet machining or hybrid.
  - How much Nb and NbTi material will be required, in what form (sheet or billet) and to what specification.
- Identification for cryomodule integration complexity.

- KEK expecting to utilise MEXT funding during 2023 to assist in procuring Nb/NbTi material for the 2 down-selected CC designs for prototyping.
- Re-affirming the importance for this down-selection review at this time.

Proposed CC Specifications (v19 file as posted)

2 beam energy options

Frequency
Kick Voltage

CW operation required

Parameter	Post-TDR Specification		10Hz Upgrade[1,2]	1 TeV CoM Spec [2]		
Beam Energy (GeV) e-	125			500		
Crossing Angle (mrad)	14					
Installation site (m from IP)	14					
RF Repetition Rate (Hz)	5		10	4		
Number of bunches	1312		2625	2450		
Bunch Train Length (ms)	727		961	897		
Bunch Spacing (ns)	554		366			
Beam current (mA)	5.8		8.75	7.6		
Operating Temp (K)	2					
Cryomodule installation length (m)	3.8 (incorporating gate valves)					
Horizontal beam-pipe separation (m)	0.1967 (centre) ±0.0266 (each end of installation length)					
Cavity Frequency (GHz)	3.9	2.6	1.3	3.9	2.6	1.3
Total Kick Voltage (MV)	0.615	0.923	1.845	2.5	3.7	7.4
Max Ep (MV/m)	45					
Max Bp (mT)	80					
Amplitude regulation/cavity (% rms)	3.5 (for 2% luminosity drop)					
Relative RF Phase Jitter (deg rms)	0.069					
Timing Jitter (fs rms)	49 (for 2% luminosity drop)					
Max Detuning (kHz)	240	170	100 - 180	240	170	100 - 180
Longitudinal impedance threshold (Ohm)	Cavity wakefield dependent					
Trasverse impedance threshold (MOhm/m) (X,Y)	48.8, 61.7					
Cavity field rotation tolerance/cavity (mrad rms)	5.2 (for 2% luminosity drop)					
Beam tilt tolerance (H and V) (mrad rms and urad rms)	0.35, 7.4 (for 2% luminosity drop)					
Minimum CC beam-pipe aperture size (mm)	>25 (same as FD magnets)					
Minimum Exraction beam-pipe aperture size (mm)	20					
Beam size at CC location (X, Y,Z) (mm,um,um)	0.97, 66, 300					
Beta function at CC location (X, Y) (m,m)	23200, 15400					
Horizonal kick factor (kx) (V/pC/m)	<< 1.6×10^3					
Vertical kick factor (ky) (V/pC/m)	<< 1.2×10^2					
CC System operation	assume CW-mode operation					

Consistent CC Design Parameters

Parameter	Elliptical/Racetrack	RFD	DQW	WOW	QMIR	Units
Operating frequency	**3.9**	**1.3**	**1.3**	**1.3**	**2.6**	GHz
SOM						GHz
1st Longitudinal HOM						GHz
1st Transverse HOM						GHz
E_p/E_t^*						
B_p/E_t^*						mT/(MV/m)
B_p/E_p (including ports)						mT/(MV/m)
G						Ω
R/Q (accelerator definition per cavity)						Ω
R_tR_s						Ω^2
V_t max per cavity						MV
V_t operational per cavity (125 GeV)						MV
E_p operational						MV/m
B_p operational						mT
Total No. of cavities (125 GeV beam)						
Extendability (500 GeV beam)						
Vt max/Vt operational						
Flange-flange Cavity Length						mm
Number of cells						
Cavity Diameter (RF model ID largest transverse horizontal dimension closest to 2nd beam-pipe)						mm
Minimum Aperture						mm
FPC Q_L						
Loaded Bandwidth						Hz
Cavity Input Power						kW
Longitudinal Loss Factor kz						V/pC
Horizontal Kick Factor k_x						V/pC/m
Vertical Kick Factor k_y						V/pC/m
Stored Energy W (at Vt operational)						J
HOM impedance (Longitudinal)						MΩ
HOM impedance (Transverse) H						MΩ/m
HOM impedance (Transverse) V						MΩ/m
First 3 multipole pararameters						
Nb material quantity (Kg) per cavity prototype						Kg
Nb material sheet/ingot						Sheet/Ingot
Maximum stresses, max pressure at RT (weakest)?						MPa

Summary

- ILC CC development plans have 'more-or-less' remained on-track over the past 2-years, to arrive at this week's review.
- ILC BDS requirements have been comprehensively integrated into the required operational CC specifications (as best we can).
- Have tried to remove any performance parameter inconsistency, by defining an agreed set of CC Design Parameters.

Important Note:

- Each of the 5 CC design solutions have developed at varying rates – their design maturity therefore will not be the same!

MANY THANKS

Questions?

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