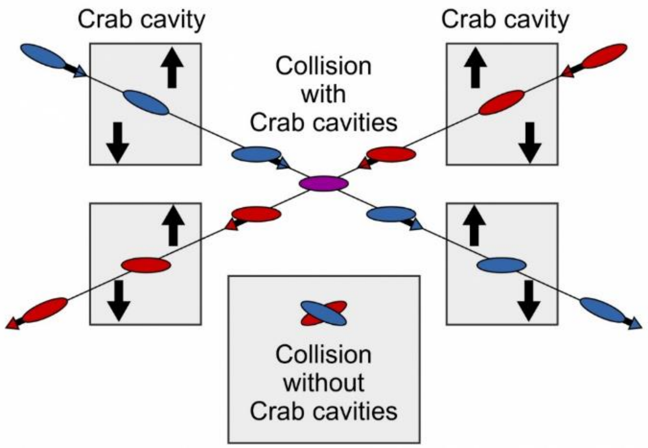
Crab Cavities (CC) for ILC

Peter McIntosh
UKRI-STFC Daresbury Laboratory
On behalf of the WP3 CC Design teams



SRF23, Grand Rapids, USA
25th – 30th June, 2023

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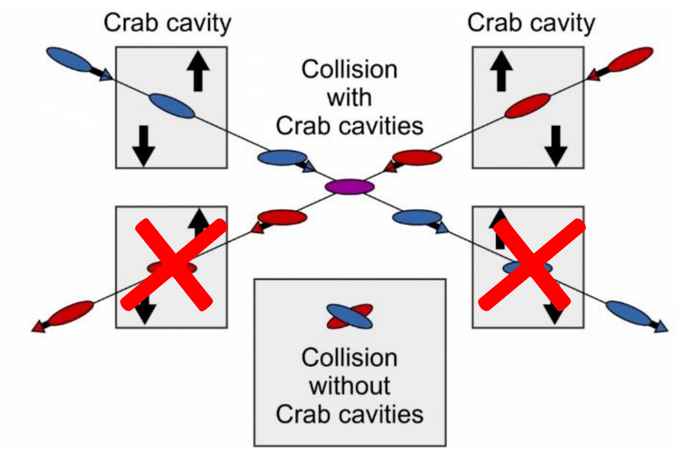
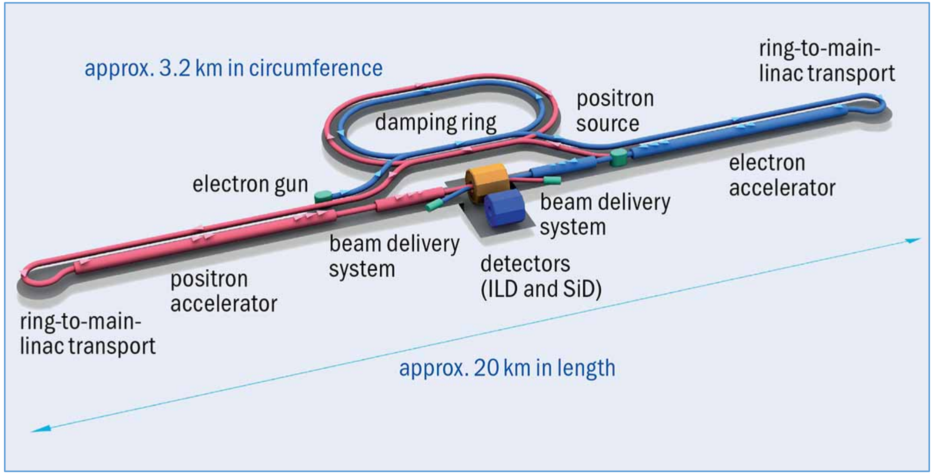


Science and Technology Facilities Council

Outline

- *ILC Pre-Lab Time Critical Workpackages*
- *CC Specifications Development*
- *CC Design Variants*
- *Down-selection Review*
- *Summary*



ILC Pre-Lab Time Critical Workpackages

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

WG2 Accelerator: Workpackages

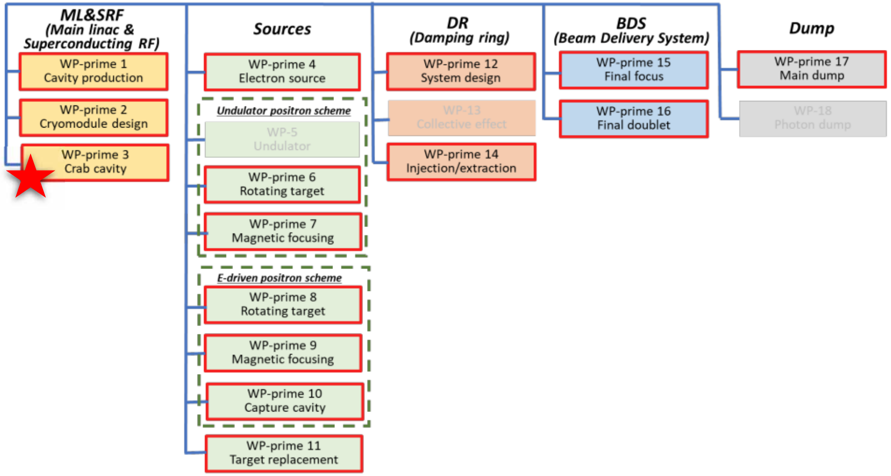


Figure 3: Time-critical WPs

CC design teams from Europe & USA.

- *Strong support from KEK:*
  - *Kirk Yamamoto – WP1/2 Coordinator*
  - *Akira Yamamoto – IDT WG2*
  - *Toshiyuki Oguki – ILC BDS*
  - *Shin Michizono – IDT WG2 Chair*

ILC Pre-Lab Time Critical Workpackages

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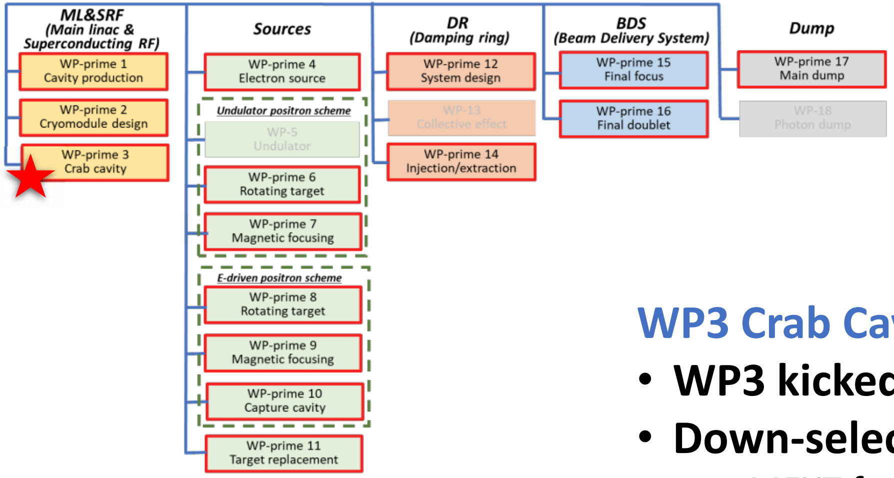

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WP3 Crab Cavities

- **WP3 kicked off**: *Mar21 – 5 CC variants (resource limited).*
- **Down-select 1**: *Apr23 – Select 2 CC variants to prototype:*
  - *MEXT funding to supply material for prototyping.*
- **Down-select 2**: *Oct24 – Select 1 CC variant for prototype cryomodule development.*
- *Fully dressed horizontal test and prototype CM (pCM) design finalized - 2026*

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ILC Pre-Lab Time Critical Workpackages

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WG2 Accelerator: Workpackages

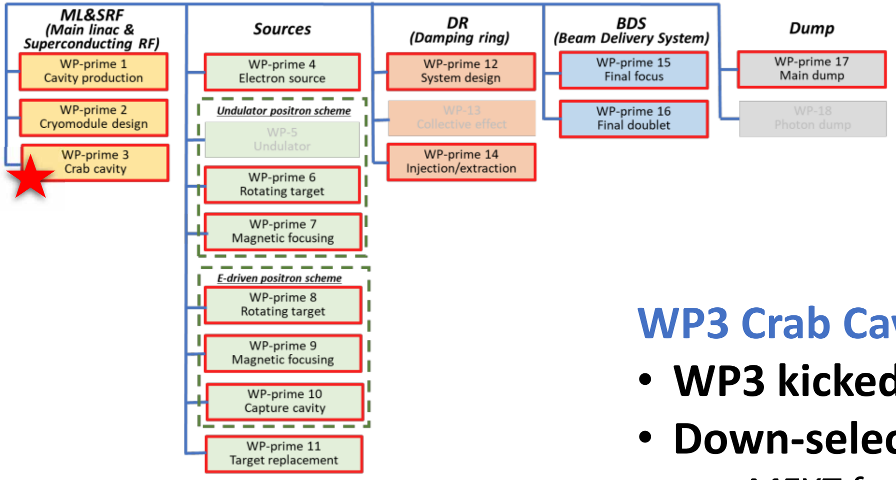

Figure 3: Time-critical WPs

All IDT WP3 CC progress captured: *https://agenda.linearcollider.org/category/256/*

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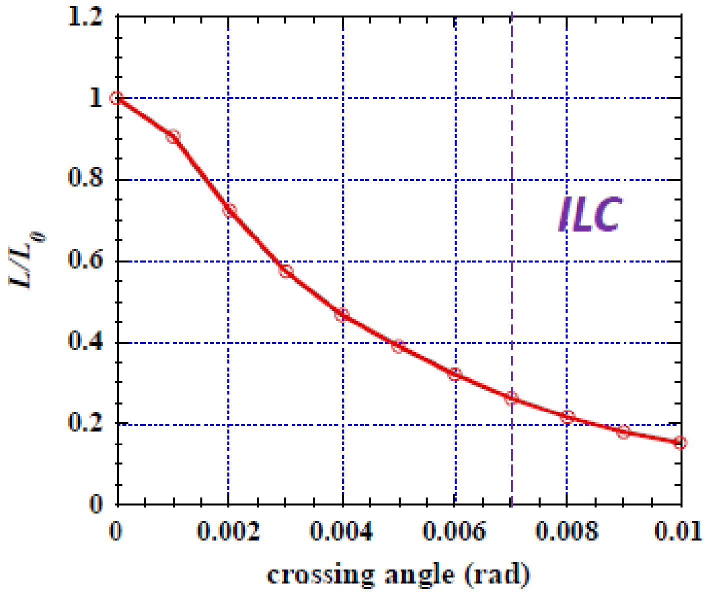
Crossing Angle - Crabbing is Essential!!!

ILC RDR parameter, by CAIN simulation



Ref: Shin Michizono (KEK), The ILC250 Accelerator, Sept 2020.

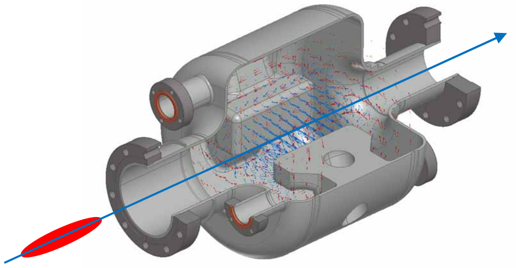
- *Large IR crossing angle preferred to separate the injection/extraction beams:*
  - *ILC requires 14 mrad crossing angle.*
- *Luminosity is reduced as crossing angle increases.*

Crab Cavities are fundamental to regain luminosity for ILC.

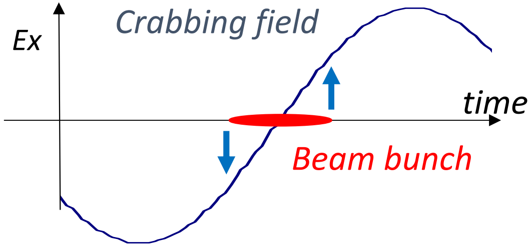
Small but Mighty!

CC Operational Requirements

- *The ILC Crab Cavity system must:*
  - *Provide the required* **deflecting voltage** *to optimally rotate the intersecting beam bunches at the Interaction Point.*
  - *Ensure its* **robust operation**, *within acceptable* **limits for stability.**



- *But also:*
  - *Suppress all* **unwanted HOM power** *(longitudinal and transverse) to an acceptable level.*
  - *Provide an ability to* **de-tune frequency**, *such that it can be safely 'parked' when not required.*
  - **Physically fit** *within the constraints of the ILC BDS Interaction Region location.*

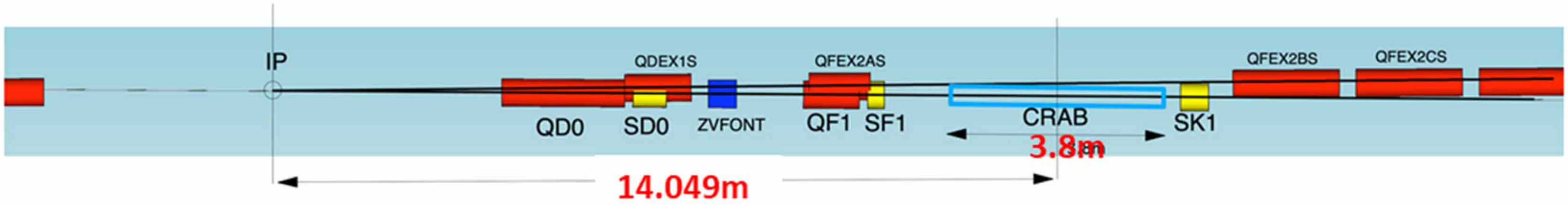


ILC Interaction Region Constraints

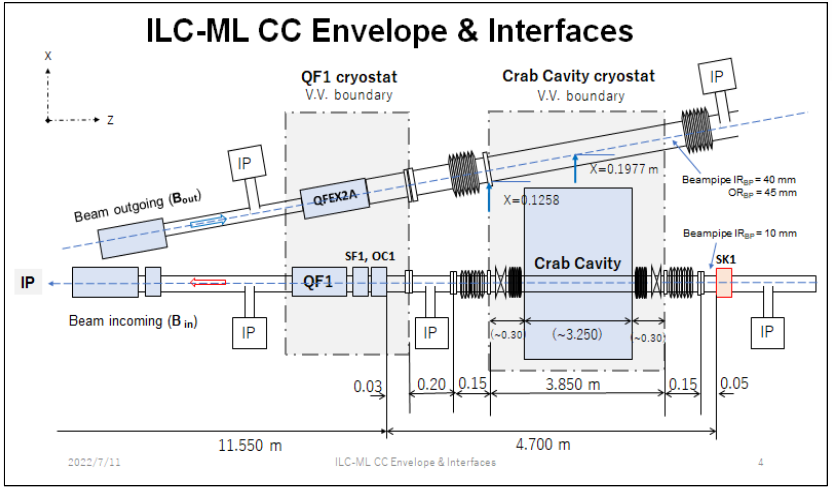
Two beamline separation

14.049m x 0.014rad = 197mm

H. Hayano



- **3.85 m longitudinal space** *in the IR, for CC cryomodule (incl. gate-valves).*
- **197 mm beam-line separation** *at centre of 3.85 m location, which varies across its length (for* **14 mrad crossing angle***).*



Proposed CC Specifications

Parameter	ILC250		10Hz Upgrade	ILC1000		
Beam Energy (GeV) e+/e-	**125/125**			**500/500**		
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)	*3.85 (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)*					
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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**					

Proposed CC Specifications

2 beam energy options
(plus ILC500 - 250/250)

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Frequency (x3)
Kick Voltage (x3)

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Kick Voltage (x3)

CW operation required (Avoid LFD effects)

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(plus ILC500 - 250/250)

Conservative pk Fields
(Improve reliability)

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CC System operation	**assume CW-mode operation**					

2 beam energy options (plus ILC500 - 250/250)

Conservative pk Fields (Improve reliability)

Min CC beam-pipe size (Collimation constraints)

CW operation required (Avoid LFD effects)

Frequency (x3)
Kick Voltage (x3)

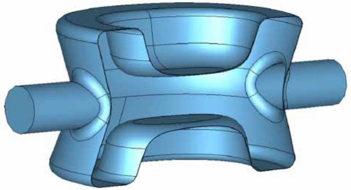
CC Variants in Conceptual Design Stage

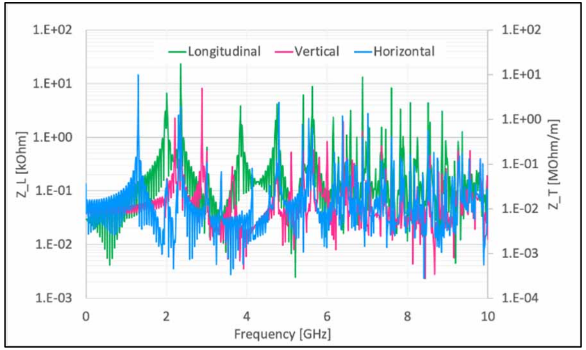
Variant	AKA	Institute	Mode	RF Frequency
Double Quarter Wave	*DQW*	*CERN/BNL*	*TEM*	*1.3 GHz*
RF Dipole	*RFD*	*ODU/JLab*	*TEM*	*1.3 GHz*
Wide Open Waveguide	*WOW*	*BNL*	*TEM*	*1.3 GHz*
Quasi-waveguide multicell	*QMiR*	*FNAL*	*TEM*	*2.6 GHz*
Elliptical Racetrack	*Racetrack*	*Lancaster U*	*TM*	*3.9 GHz*

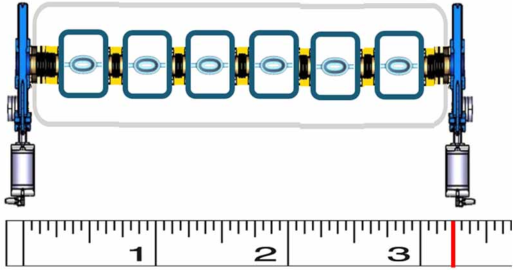
1.3 GHz Double Quarter Wave

(S Verdu-Andres/R Calaga – BNL/CERN)

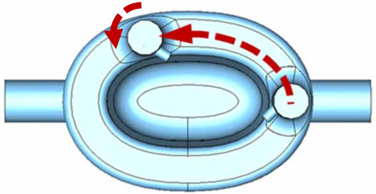
- *Design takes advantage of considerable experience gained with 400 MHz DQW cavity* **built and tested for HL-LHC**.
- *A 1.3 GHz variant for DQW modelled after the HL-LHC cavity with small modifications and operation at 90 degrees to provide a* **horizontal kick**.
- *Based on the Bpk and Epk specification* **two single-cell** *DQW cavities per beam would give 54% margin for the 125/125 GeV beams (***or 6 for 1 TeV***).*
- *Cavity compactness lends itself to a* **machined cavity ingot** *(at least the main body and interfaces).*

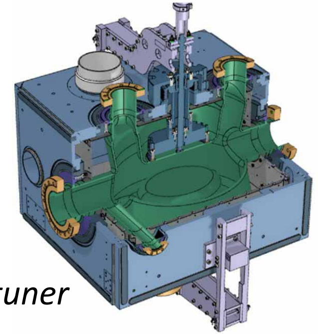






TESLA type





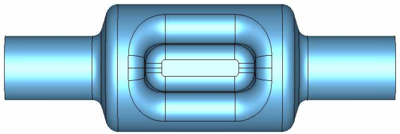
HL-LHC tuner

Science and Technology Facilities Council

1.3 GHz RF Dipole (RFD)

(S De Silva/J Delayen – ODU/JLab, USA)

- *RFD takes advantage of several cavity variants ranging from 400 MHz to 952 MHz that have reached prototyping stage, with* **400 MHz cavities applied for HL-LHC***.*
- **No LOM** *to extract, 2 - 3 TESLA type HOM couplers on one side of cavity good mitigation to HOMs with the FPC/HOM couplers located outside helium vessel.*
- **Two single-cell** *RFDs to meet the 125/125 GeV requirement with 47% margin (***or 6 for 1 TeV***).*
- *Fabrication proposed employ hybrid machining or forming from* **medium grain ingot***.*



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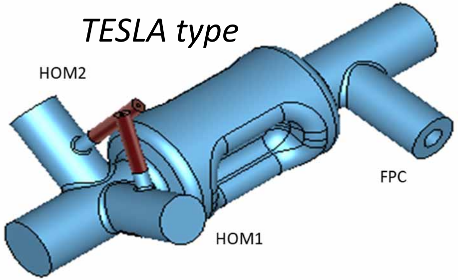
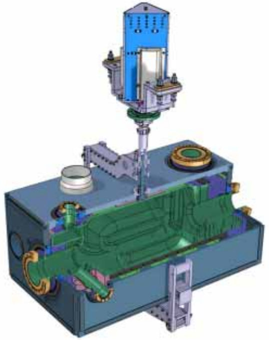
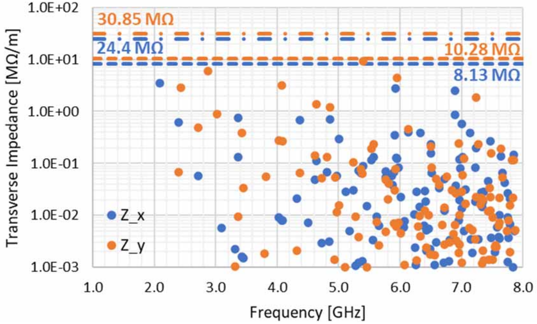
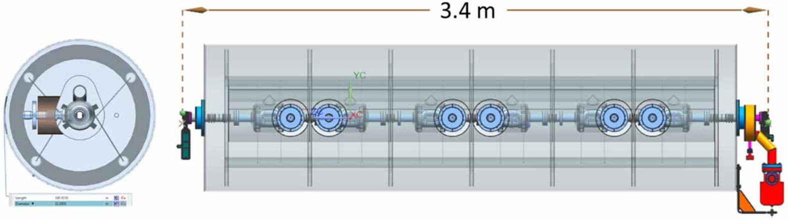




HL-LHC tuner

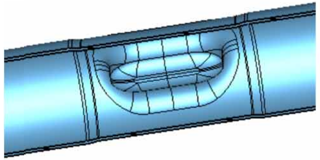


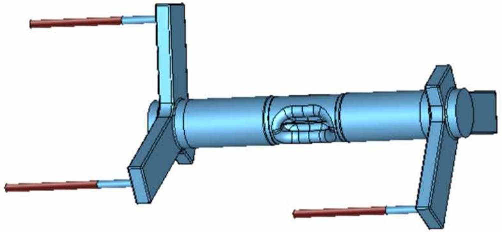


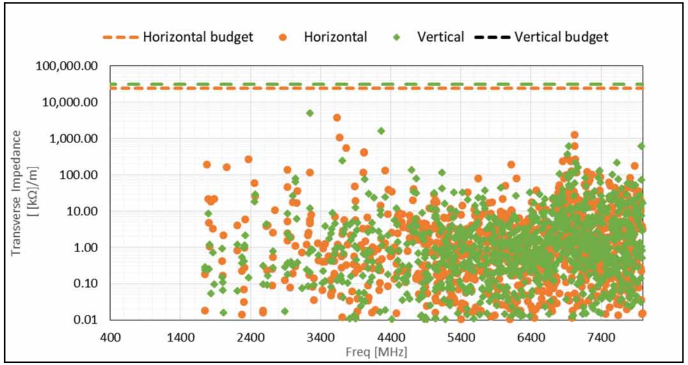
1.3 GHz Wide Open Waveguide

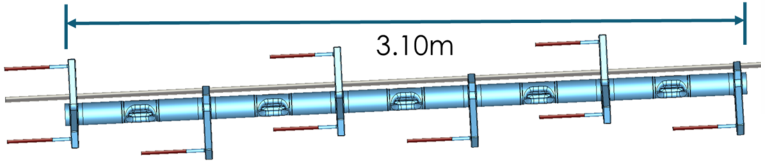
(B Xiao – BNL, USA)

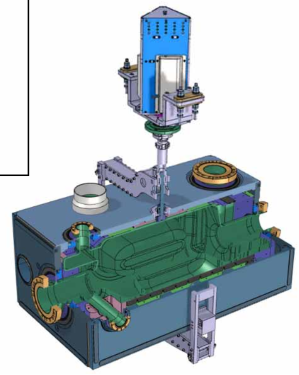
- *Design* **extends from EIC** *design work (197/394 MHz) - contend with a large beam current and considerable HOM power.*
- **Large beam pipe** *utilized with fc above the fundamental, sufficient to allow HOMs to transmit to waveguide and coax absorbers.*
- *Design allows the FPC, PU and HOM damper all outside the helium vessel.*
- *Uses* **two single-cell** *WOW cavity for operation per beam in 125/125 GeV ILC design (***or 5 for 1 TeV***).*
- *Alternative* **beam-pipe absorbers** *also considered to simplify the design.*
- *Expect* **manufacture from Nb sheets***.*











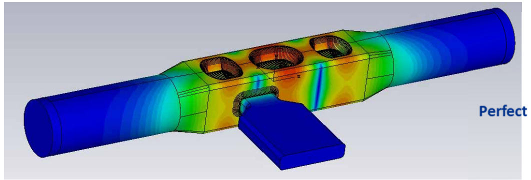
HL-LHC tuner

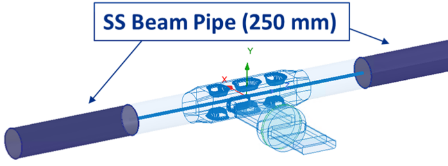
Science and Technology Facilities Council

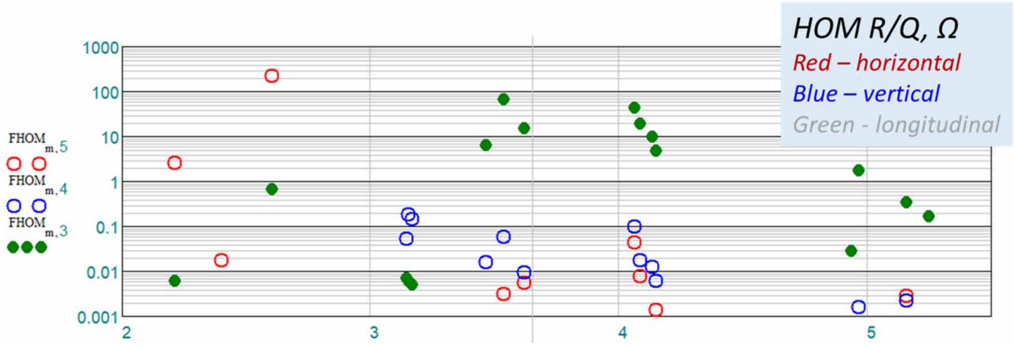
2.6 GHz Quasi-waveguide Multicell Resonator

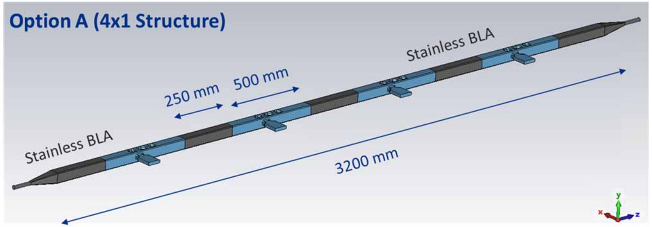
(A Lunin/Y Yakovlev– FNAL, USA)

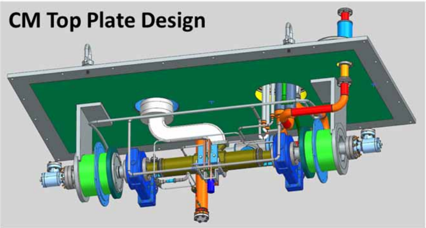
- *Design initially developed for an application at* **2.8 GHz for APS SPX** *project.*
- *Proposal for 2.6 GHz with a* **3-cell cavity, no LOM, no HOM couplers** *with sparse low Q SOM/HOMs and a WG coupler.*
- *The HOMs propagate down the beam-pipe and absorbed in* **SS beam-pipe** *sections.*
- *At operating voltage,* **a single 3-cell** *cavity provides 14% margin (***or 4 for 1 TeV***).*
- *Cavity to be produced by machining in* **two halves from fine grain Nb ingot***, as done for APS SPX.*











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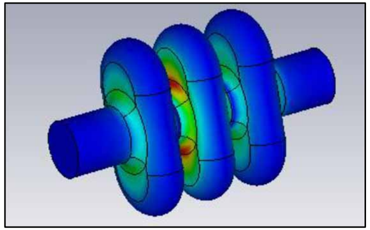
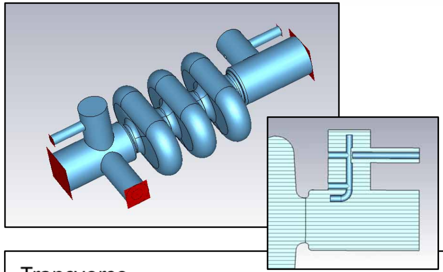
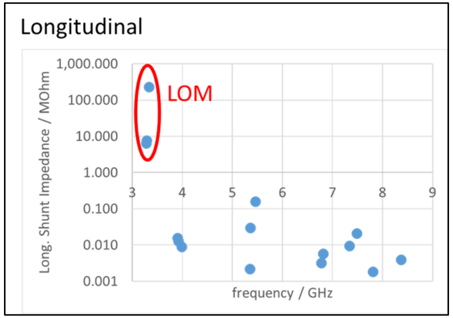
3.9 GHz Racetrack

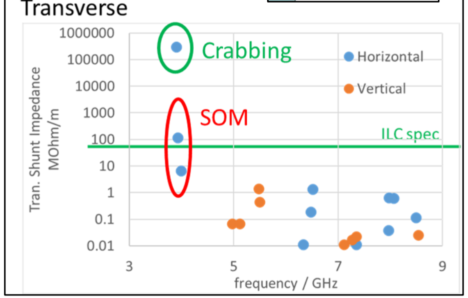
(G Burt – Lancaster U, UK)

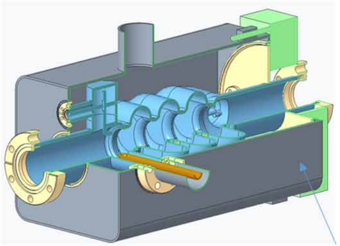
- *Re-optimized original ILC crab cavity design evolving to a 3.9 GHz 3-cell cavity design.*
- *Using a racetrack geometry gives* **improved separation to the same-order-mode** *(SOM) and minimizes the peak magnetic fields.*
- *Frequency choice of 3.9 GHz allows* **lower required kick voltage***.*
- **Single 3-cell cavity** *for specified kick of 0.615 MV for the 125/125 GeV beams with 20% margin in Bp (***or 4 for 1 TeV***).*
- *A* **2-cell variant** *(improves trapped modes) considered – 2 cavities per beam provide 80% margin for 125/125 GeV kick requirement (***design not so advanced***).*
- *Expect to manufacture from* **Nb sheet** *material.*



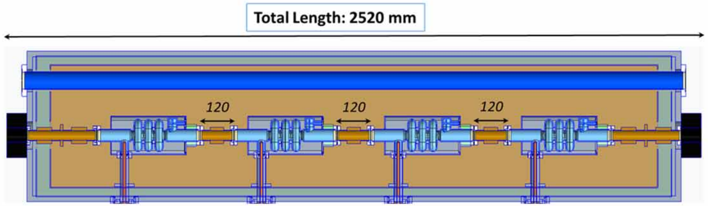








Helium Tank



Science and Technology Facilities Council

CC Down Selection #1 Review
4th to 6th April @ KEK

https://agenda.linearcollider.org/event/9958/

Bob Laxdal (TRIUMF) - Chair

Eiji Kako (KEK)

Enrico Cenni (CEA)

Michele Bertucci (INFN)

Hiroshi Sakai (KEK)

Rong-Li Geng (ORNL)

Toshiyuki Okugi (BDS)

Review Panel Charge

1. *Assess the* **predicted compliance** *against the functional* **specifications for the ILC-250**, *the* **upgrade capability** *to the ILC-500, and the feasibility for higher energy (1TeV).*
2. *To* **identify their risk in comparison to other comparable systems** *presently in operation or in development elsewhere in the world.*
3. *Review* **choices of materials, fabrication processes, tuning concepts, power couplers, HOM couplers, SRF performance**, *etc.*
4. *Review the* **plan for the prototype development** *including possible cooperation (or consortium) with other laboratories and industry.*
5. *Identify* **2 most appropriate crab cavity designs** *to meet the operational requirements for ILC, to be* **taken forward to prototype** *development and high-power validation.*
6. *Provide suggestions for* **how best to progress the collaborative crab cavity developments**, *after the down-selection decision is to be made.*
7. *Provide advice for* **criteria and further processes to be scoped for the final CC down-selection (post-prototype)**, *towards unifying system design for cryomodule integration.*

Review Panel Criteria Utilised

Design Criteria	Specifics	Weighting
Cavity design	*Expected performance, thoroughness of design, characteristic parameters*	*10*
Compliance with requirements	*Margin and risks*	*10*
HOM analysis/mitigation	*Thoroughness of analysis, appropriateness/complexity of mitigation*	*10*
Prototype development	*Logic, cost, risk, timeline, can the suggested timeline be reached*	*10*
Fabrication process	*Appropriateness of suggested path – risk/challenge*	*10*
Cryomodule implications	*Risks, cost, complity for integration*	*10*
ILC500?	*Extendibility of design*	*10*
Overall risk	*Degree of confidence that the proposal will meet the specifications with reasonable cost and effort*	*10*
RF ancillaries: FPC, tuners	*Complexity, risk*	*5*
Multipactor analysis	*Thoroughness of analysis, issues related to design*	*5*
df/dP	*Evaluation and related issues*	*5*
Cavity tuning analysis	*Thoroughness of analysis, correctness of approach*	*5*

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Review Panel Feedback

- *The panel saw* **no show-stoppers** *in any of the proposals.*
- **All had the potential** *to meet the 125/125 and 250/250 GeV ILC variants with upgradeability to 500/500 GeV.*
- *Some were* **more advanced than others** *and some had* **more margin than others.**
- *Some required only 1 x cavity per beam and others 2 x cavities per beam to* **meet the 125/125 GeV baseline** *specification.*
- **All could meet the ILC500 (250/250) specification within the required space.**

Variant	Frequency (GHz)	Required Kick (MV)	125/125				250/250	500/500	Manufacture
			# Cavities	Operating Bp (mT)	Operating Ep (MV/m)	Margin	# Cavities	# Cavities	
DQW	*1.3*	*1.85*	*2*	*49.5*	*29*	*55%*	*4*	*6*	*Sheet & Ingot*
Elliptical	*3.9*	*0.615*	*1*	*67*	*23*	*20%*	*2*	*4*	*Sheet*
RFD	*1.3*	*1.85*	*2*	*54*	*30*	*47%*	*4*	*6*	*Sheet & Ingot*
WOW	*1.3*	*1.85*	*2*	*46*	*26*	*72%*	*4*	*5*	*Sheet*
QMiR	*2.6*	*0.923*	*1*	*70*	*35*	*14%*	*1 or 2*	*4*	*Ingot*
Elliptical (2-cell)	*3.9*	*0.615*	*2*	*44*	*14*	*82%*	*2*	*4*	*Sheet*

Review Panel Recommendations

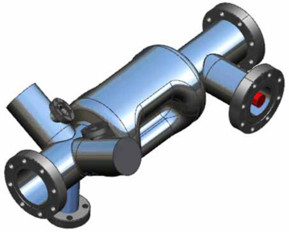
Proposal\Committee	C1	C2	C3	C4	C5	Average	Rank
A	76	83	80	87	86	82.4	1
B	70	87	75	84	66	76.4	2
C	83	62	74	82	71	74.4	3
D	42	77	56	80	53	61.6	4
E	61	61	62	70	54	61.6	4

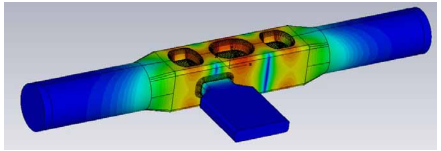
- *Based on the analysis the committee recommends Proposal A and Proposal B be given the opportunity to move to the prototyping phase.*
- *If for any reason one of these proposals has to drop out then we recommend Proposal C to be advanced.*

Review Panel Recommendations

Proposal\Committee	C1	C2	C3	C4	C5	Average	Rank
A	76	83	80	87	86	82.4	1
B	70	87	75	84	66	76.4	2
C	83	62	74	82	71	74.4	3
D	42	77	56	80	53	61.6	4
E	61	61	62	70	54	61.6	4

- *Based on the analysis the committee recommends Proposal A and Proposal B be given the opportunity to move to the prototyping phase.*
- *If for any reason one of these proposals has to drop out then we recommend Proposal C to be advanced.*
    - **Proposal A – RF Dipole - ODU/Jlab**
    - **Proposal B – QMiR - FNAL**
    - *Proposal C – Racetrack - Lancaster U*





Summary

Crab cavities critical for maintaining expected luminosity performance for ILC!

- *BDS requirements have been comprehensively integrated into the required CC specifications.*
- *All CC designs meet ILC250, ILC1000 (and ILC500) requirements –* **no show stoppers!**
- **All meet ILC Interaction Region dimensional constraints – even for highest energies!**
- *First down-selection review achieved an important milestone, for focussing next stage CC technology development.*

The RFD (ODU/JLab) and QMiR (FNAL) designs are now being taken forward to prototype – both machined from ingot material!

- *Early stage Nb procurement preparation underway – MG for RFD and FG for QMiR.*

Look forward to first test results and achieving final ILC CC down-selection ahead of SRF25!

MANY THANKS

Acknowledge: All CC design teams, KEK support and down-selection review panel!

UKRI Science and Technology Facilities Council