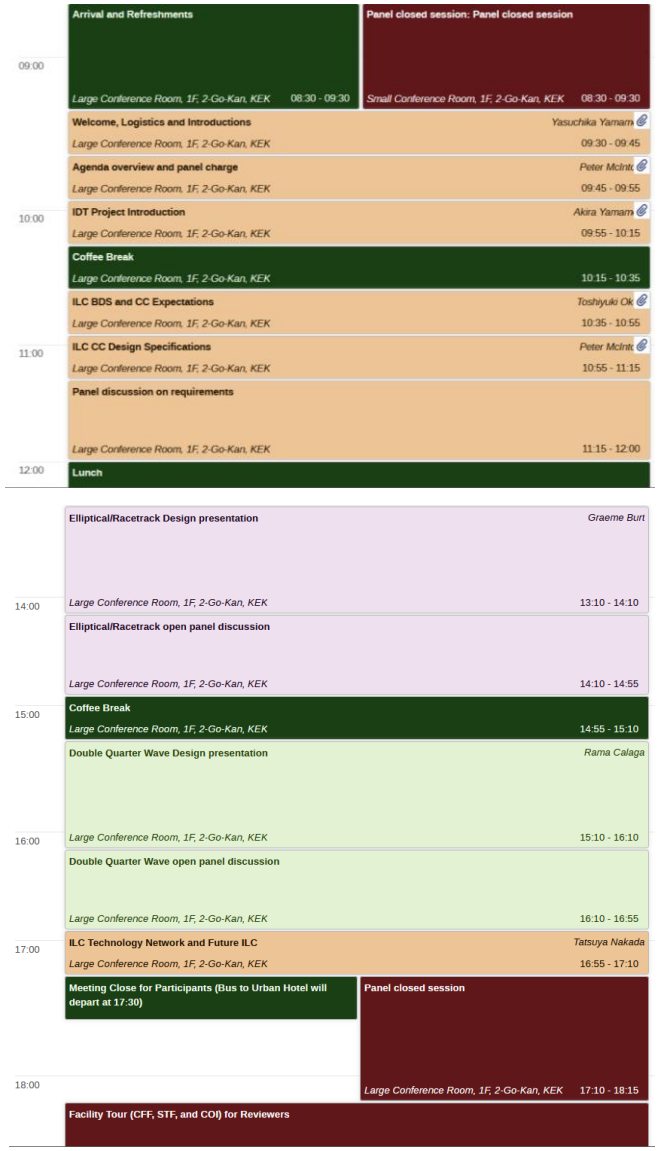
Down Selection Review on Crab cavity Design

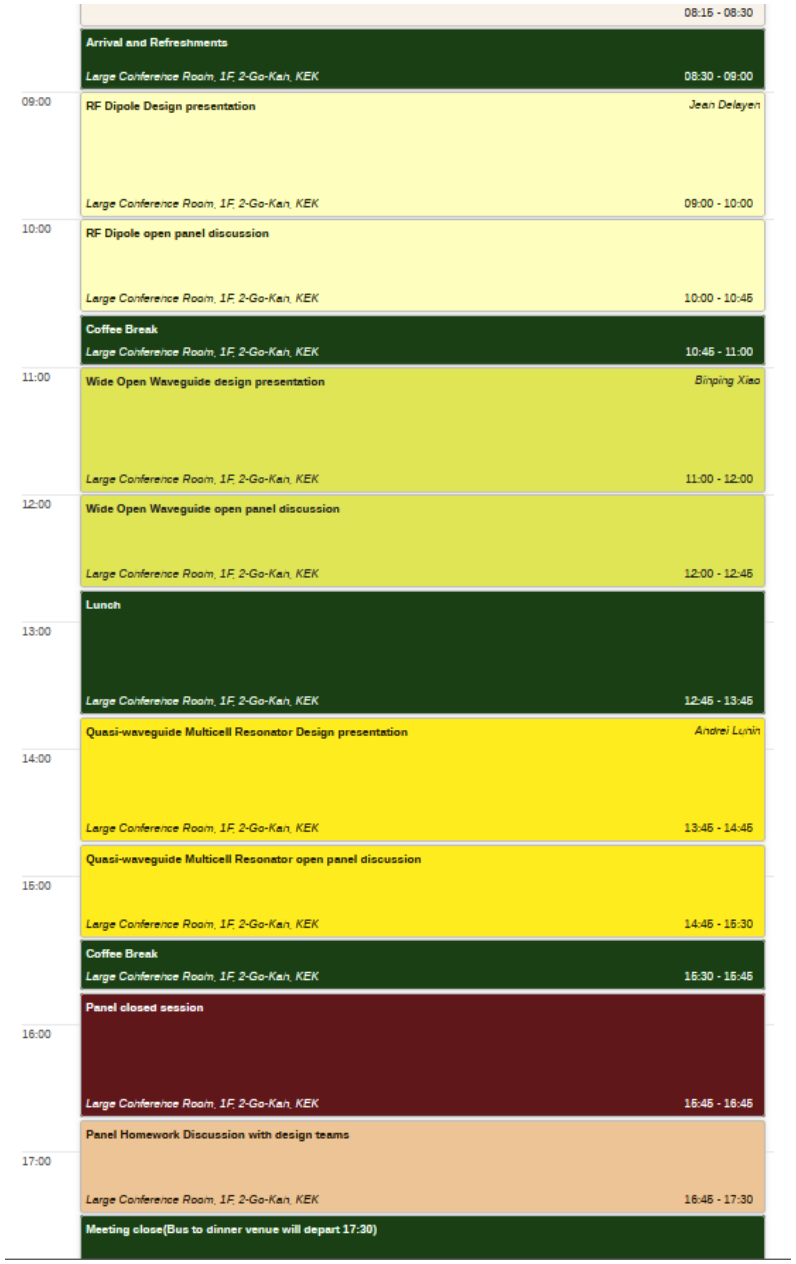
April 4-6, 2023

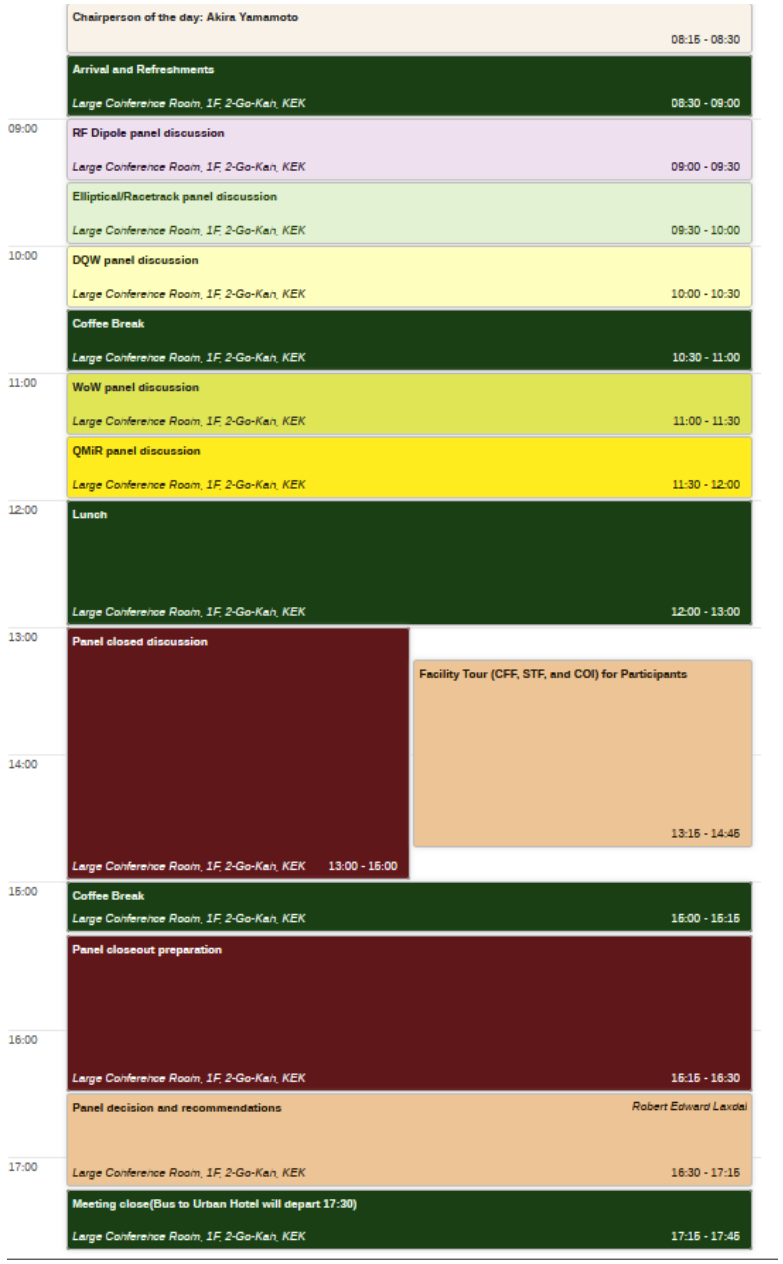
Opening remarks

- The committee thanks our KEK hosts and international ILC crab cavity coordination team for their organization of this event and hospitality during our stay.
- A very important aspect of the review was the extended periods offered for question and answer – the committee never felt rushed and this is rare in a review
- The Committee also thanks all teams for presenting a clear and comprehensive overview of their design and for providing helpful feedback to our questions and requests for follow-up material. This project has managed to collect the best crab cavity experts in the world.
- We note that it has been a challenge for some teams to get priority due to competing funded projects and that there was a variation in the maturity of the designs. However, we were very impressed with the quality of the work and the collective knowledge in the room. We acknowledge that the contributions represent a significant investment on a best effort basis and thank all of them for their engagement. Regardless of our recommended outcome the study of all variants will make the final product better.
- The global crab cavity community is small and many variants have similar features and so it is strongly recommended that the two successful variants reach out for support as they move through the design and prototyping phase.

Timetable

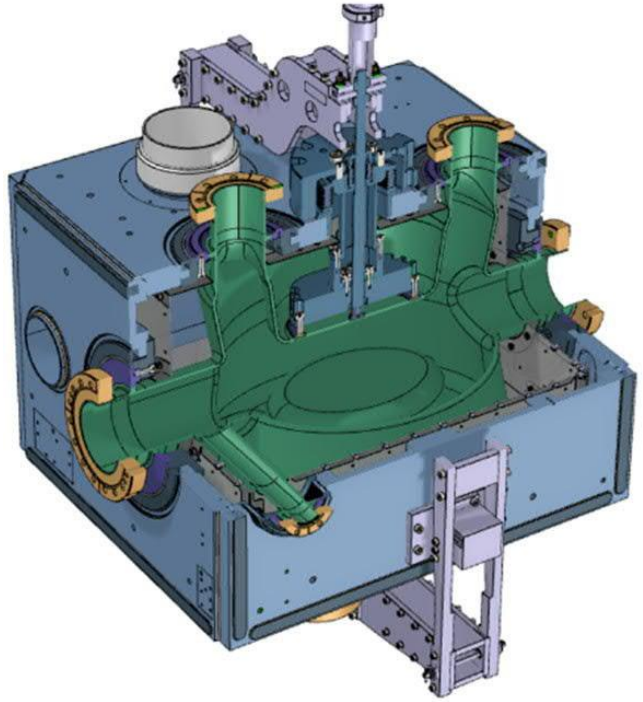

09:00
Arrival and Refreshments
Large Conference Room, 1F, 2-Go-Kan, KEK 08:30 - 09:30
Panel closed session: Panel closed session
Small Conference Room, 1F, 2-Go-Kan, KEK 08:30 - 09:30
Welcome, Logistics and Introductions
Yasuchika Yamam
Large Conference Room, 1F, 2-Go-Kan, KEK 09:30 - 09:45
Agenda overview and panel charge
Peter McIntc
Large Conference Room, 1F, 2-Go-Kan, KEK 09:45 - 09:55
10:00
IDT Project Introduction
Akira Yamam
Large Conference Room, 1F, 2-Go-Kan, KEK 09:55 - 10:15
Coffee Break
Large Conference Room, 1F, 2-Go-Kan, KEK 10:15 - 10:35
ILC BDS and CC Expectations
Toshiyuki Ok
Large Conference Room, 1F, 2-Go-Kan, KEK 10:35 - 10:55
11:00
ILC CC Design Specifications
Peter McIntc
Large Conference Room, 1F, 2-Go-Kan, KEK 10:55 - 11:15
Panel discussion on requirements
Large Conference Room, 1F, 2-Go-Kan, KEK 11:15 - 12:00
12:00
Lunch
Elliptical/Racetrack Design presentation
Graeme Burt
Large Conference Room, 1F, 2-Go-Kan, KEK 13:10 - 14:10
14:00
Elliptical/Racetrack open panel discussion
Large Conference Room, 1F, 2-Go-Kan, KEK 14:10 - 14:55
15:00
Coffee Break
Large Conference Room, 1F, 2-Go-Kan, KEK 14:55 - 15:10
Double Quarter Wave Design presentation
Rama Calaga
Large Conference Room, 1F, 2-Go-Kan, KEK 15:10 - 16:10
16:00
Double Quarter Wave open panel discussion
Large Conference Room, 1F, 2-Go-Kan, KEK 16:10 - 16:55
17:00
ILC Technology Network and Future ILC
Tatsuya Nakada
Large Conference Room, 1F, 2-Go-Kan, KEK 16:55 - 17:10
Meeting Close for Participants (Bus to Urban Hotel will depart at 17:30)
Panel closed session
Large Conference Room, 1F, 2-Go-Kan, KEK 17:10 - 18:15
18:00
Facility Tour (CFF, STF, and COI) for Reviewers

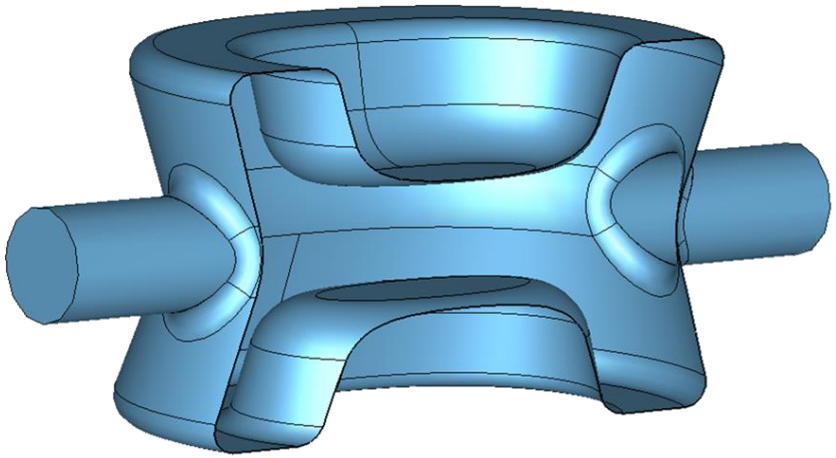

08:15 - 08:30
Arrival and Refreshments
Large Conference Room, 1F, 2-Go-Kan, KEK 08:30 - 09:00
09:00
RF Dipole Design presentation
Jean Delayen
Large Conference Room, 1F, 2-Go-Kan, KEK 09:00 - 10:00
10:00
RF Dipole open panel discussion
Large Conference Room, 1F, 2-Go-Kan, KEK 10:00 - 10:45
Coffee Break
Large Conference Room, 1F, 2-Go-Kan, KEK 10:45 - 11:00
11:00
Wide Open Waveguide design presentation
Binping Xiao
Large Conference Room, 1F, 2-Go-Kan, KEK 11:00 - 12:00
12:00
Wide Open Waveguide open panel discussion
Large Conference Room, 1F, 2-Go-Kan, KEK 12:00 - 12:45
Lunch
Large Conference Room, 1F, 2-Go-Kan, KEK 12:45 - 13:45
13:00
Quasi-waveguide Multicell Resonator Design presentation
Andrei Lunin
Large Conference Room, 1F, 2-Go-Kan, KEK 13:45 - 14:45
14:00
Quasi-waveguide Multicell Resonator open panel discussion
Large Conference Room, 1F, 2-Go-Kan, KEK 14:45 - 15:30
15:00
Coffee Break
Large Conference Room, 1F, 2-Go-Kan, KEK 15:30 - 15:45
Panel closed session
Large Conference Room, 1F, 2-Go-Kan, KEK 15:45 - 16:45
16:00
Panel Homework Discussion with design teams
Large Conference Room, 1F, 2-Go-Kan, KEK 16:45 - 17:30
17:00
Meeting close(Bus to dinner venue will depart 17:30)


Chairperson of the day: Akira Yamamoto
08:15 - 08:30
Arrival and Refreshments
Large Conference Room, 1F, 2-Go-Kan, KEK 08:30 - 09:00
09:00
RF Dipole panel discussion
Large Conference Room, 1F, 2-Go-Kan, KEK 09:00 - 09:30
Elliptical/Racetrack panel discussion
Large Conference Room, 1F, 2-Go-Kan, KEK 09:30 - 10:00
10:00
DQW panel discussion
Large Conference Room, 1F, 2-Go-Kan, KEK 10:00 - 10:30
Coffee Break
Large Conference Room, 1F, 2-Go-Kan, KEK 10:30 - 11:00
11:00
WoW panel discussion
Large Conference Room, 1F, 2-Go-Kan, KEK 11:00 - 11:30
QMiR panel discussion
Large Conference Room, 1F, 2-Go-Kan, KEK 11:30 - 12:00
12:00
Lunch
Large Conference Room, 1F, 2-Go-Kan, KEK 12:00 - 13:00
13:00
Panel closed discussion
Large Conference Room, 1F, 2-Go-Kan, KEK 13:00 - 15:00
Facility Tour (CFF, STF, and COI) for Participants
13:15 - 14:45
14:00
15:00
Coffee Break
Large Conference Room, 1F, 2-Go-Kan, KEK 15:00 - 15:15
Panel closeout preparation
Large Conference Room, 1F, 2-Go-Kan, KEK 15:15 - 16:30
16:00
Panel decision and recommendations
Robert Edward Laxdal
Large Conference Room, 1F, 2-Go-Kan, KEK 16:30 - 17:15
17:00
Meeting close(Bus to Urban Hotel will depart 17:30)
Large Conference Room, 1F, 2-Go-Kan, KEK 17:15 - 17:45

DQW proposal

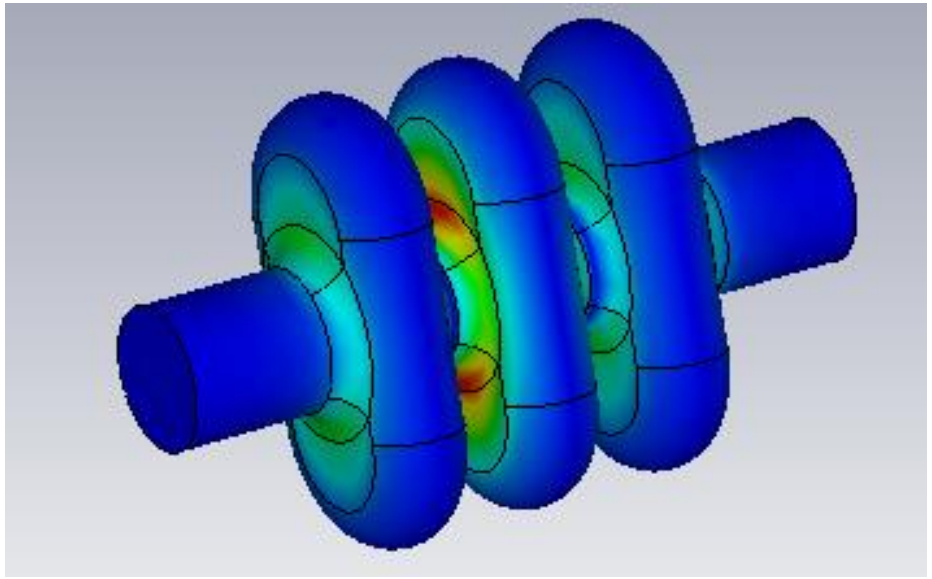
- The design takes advantage of the considerable experience that has been gained with the 400MHz DQW cavity that has been built and tested for Hi-Lumi
- A 1.3GHz variant of the DQW is proposed by the ILC and is modeled after the Hi-Lumi cavity with small modifications and operation at 90 degrees to the Hi-Lumi application to provide a horizontal kick
- Based on the Bpeak and Epeak specification two DQW cavities per beam would give 54% margin in deflecting the 125/125 GeV beams
- Cavity compactness lends itself to a machined cavity ingot (at least the main body and interfaces).

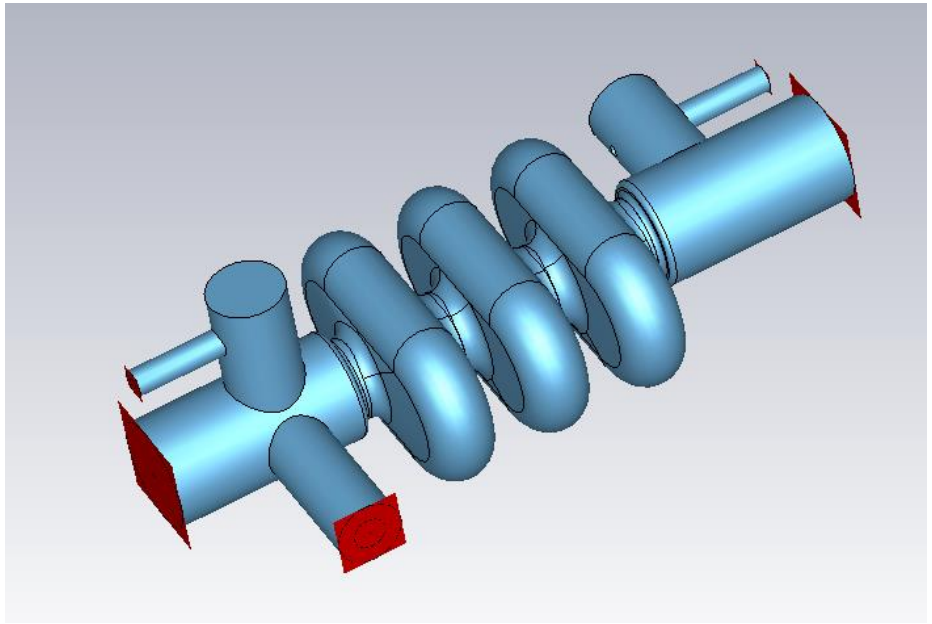




Elliptical proposal

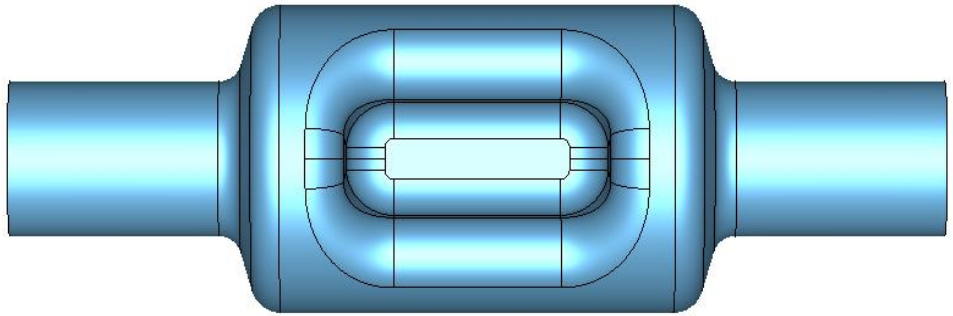
- The proposal re-optimized the original ILC crab cavity design evolving to a 3.9 GHz 3-cell cavity design.
- Using a racetrack geometry gives improved separation to the same-order mode and minimizes the peak magnetic fields
- The frequency choice of 3.9 GHz allows a lower required kick voltage, providing comfortable operational margins. One cavity per beam would deliver the specified kick of 0.615MV for the 125/125 GeV beams with 20% margin in peak magnetic field.
- A two-cell variant was shown in the homework session – two of these cavities per beam would provide 80% margin on the 125/125 GeV kick requirement

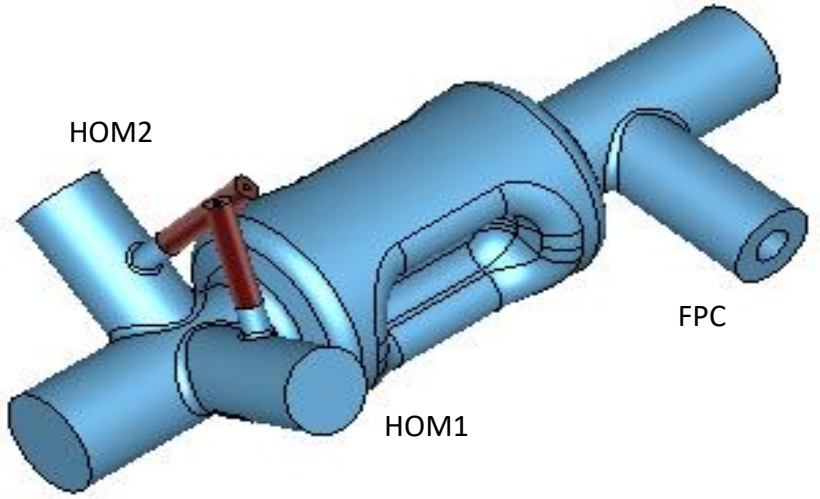




RFD proposal

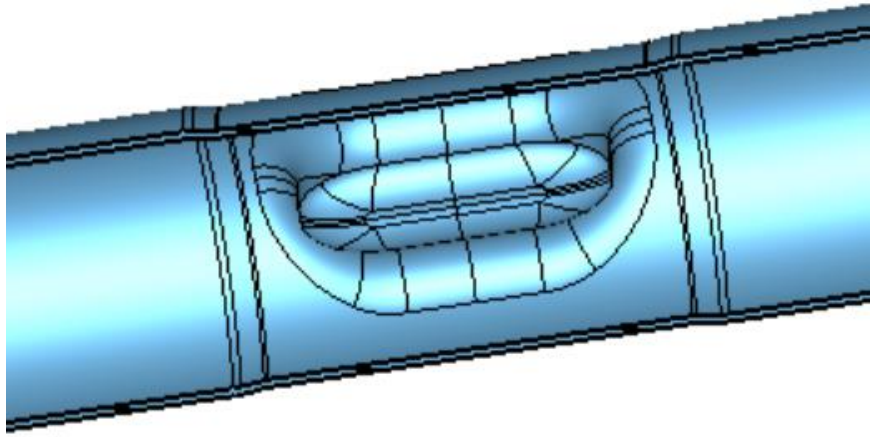
- The RF Dipole takes advantage of several cavity variants ranging from 400MHz to 952MHz that have reached the prototyping stage
- The RFD 400MHz is now in production for HL-LHC
- Two single cell RFDs per beam meet the 125/125 GeV requirement with 47% margin
- HOM analysis shows that 2-3 TESLA type HOM hooks on one side of the cavity give good mitigation to HOMS with the FPC and HOM hooks located outside the helium vessel
- A fabrication scheme could employ a hybrid machining/forming scheme from medium grain ingot

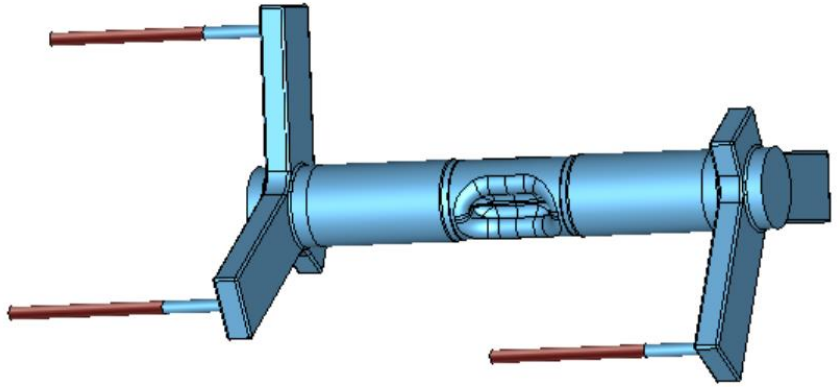




WOW proposal

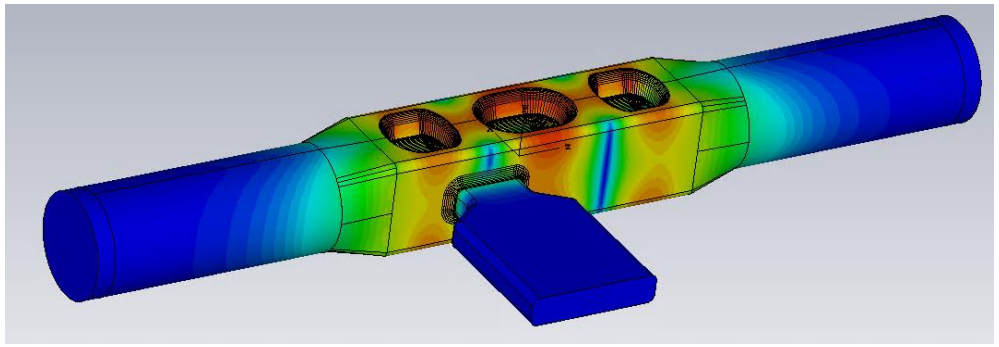
- The proposal extends from EIC design work (197/394MHz) and can take further profit from that work as it evolves
- EIC has to contend with a large circulating current with considerable HOM power
- A large beam pipe is utilized with cut-off frequency above the fundamental but sufficient to allow HOMs to transmit to waveguide and coax absorbers
- The 1.3GHz ILC proposal uses the single cell RFD cavity providing 70% margin for operation with two cavities per beam in 125/125 GeV ILC design
- The design allows the FPC, PU and HOM damper all outside the helium vessel.
- During discussions other variants using in-line dampers were also considered to simplify the design

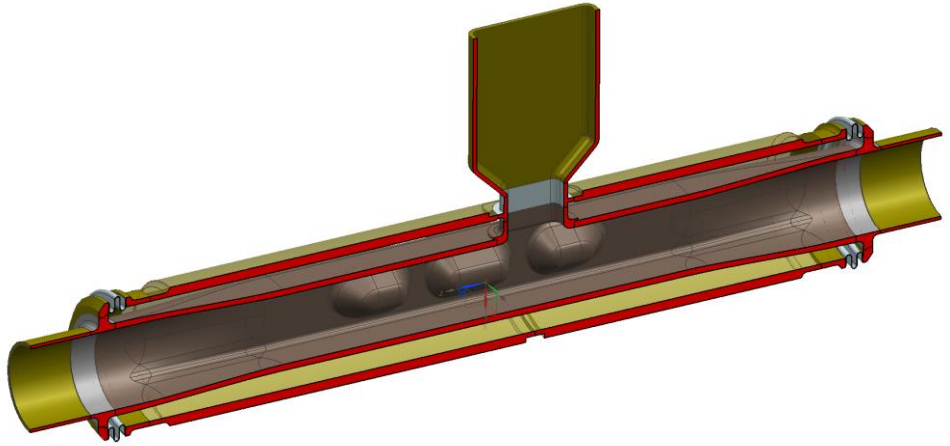




QMiR proposal

- The proposal was initially developed for an application at 2.8GHz for APS SPX project
- The ILC proposal calls for 2.6GHz with a 3-cell cavity, no HOM coupler with sparse low Q HOMs, low Q SOMs, and a WG coupler.
- The HOMs propagate down the beampipe and can be absorbed in SS sections. SOMs couple to the waveguide port
- At the operating voltage for the ILC the three cell variant provides 14% head room compared to the peak field limits in the specification
- The cavity could be produced with machining in two halves as for APS





Evaluation process

Proposed CC Specifications

The proposals were judged against the specifications as well as other criteria including prototyping risk.

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)	$<< 1.6 \times 10^3$							
Vertical kick factor (ky) (V/pC/m)	$<< 1.2 \times 10^2$							
CC System operation	assume CW-mode operation							

Prototyping considerations

- Clearly some proposals were more advanced than others
- The timetable proposed by the WP3 conveners for prototyping and testing is aggressive and so favours more mature designs
- The timeline discussed with the conveners can be summarized as:
  - Phase I: 0-18 months
    - complete detailed design, fabrication of the bare cavity and qualify in a vertical test with HOM couplers
  - Phase 2: 18-36 months
    - complete jacketing, tuner and FPC and perform a fully dressed cold test in an HTS including FPC and tuner with a jacketed cavity, FPC and tuner
    - Complete an engineering concept for a CM

WP-prime 3: Crab Cavity Development with the design down-selection

List of items:

Priority	*Items*	Y1	Y2	Y3	Y4
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)					

← We are here

Selection process

- Two members of the committee, a lead and a second, were assigned to each variant and led the discussion for each proposal. One member of the committee was assigned to look at integration.
- The proposals were scored independently by all committee members based on several criteria as defined in our charge.
- The readiness of designs to advance to prototyping as opposed to the potential of a certain variant was an important aspect in our ranking
- A discussion point during the review was whether having two cavities per beam would be an advantage during operation.
    - Redundancy
    - Potential to cancel uncertainty in clocking angle between the two crabbing systems with vector sum
    - The committee did not take this into account but WPP-3 should consider the relevance of this specification

Criteria

Cavity design	Prototype development	HOM analysis/ mitigation	Rf ancillaries Tuners/FPC	MP analysis	df/dP
Expected performance, thoroughness of design, characteristic parameters	logic, cost, risk, timeline, can the suggested schedule be reached	thoroughness of analysis, appropriateness/complexity of mitigation	complexity, risk	thoroughness of analysis, issues related to design	evaluation and issues related to analysis
10	10	10	5	5	5

cavity tuning analysis	fabrication process	cryomodule implications	compliance with requirements	ILC500?	Overall risk
thoroughness of analysis, correctness of approach	appropriateness of suggested path - risk/chanllenge	risks, costs, complexity with integration,	margin and risks	Extendibility of design to ILC500	degree of confidence that the proposal will meet the specifications with reasonable cost and effort
5	10	10	10	10	10

Summary of Performance Analysis

- 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 1 TeV
  - Some were more advanced than others
  - Some had more margin than others
  - Some required only one cavity per beam and others two cavities per beam to meet the 125/125 GeV specification
  - All could meet the 250/250 GeV specification within the required space

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

Method: Sub-set of Committee members scored the proposals on the 12 criteria

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

Selection

- 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 be advanced

- Proposal A – RF Dipole ODU/JLab
- Proposal B – QMiR FNAL
- Proposal C – Elliptical racetrack - UK

Recommendations

- WPP-3 to advance to the next prototyping phase with RFD and QMiR
- WPP-3 to coordinate discussions on a fine tuner (nm resolution) for on-line tuning
- WPP-3 to consider whether there is an advantage to have multiple cavities on each side of the IP for
  - Redundancy
  - To mitigate clocking errors in the cavities via vector sum correction
- QMiR is encouraged to increase the operating margin – two cavities per beam for 125/125GeV would give redundancy and the potential for cancelation of clocking errors

The global crab cavity community is small and many variants have similar features and so it is strongly recommended that the two successful variants reach out for support as they move through the design and prototyping phase.

Good Luck

Acknowledgements

- Thanks to the committee for detailed and informed discussions and who always engaged positively in the process. Although the decision was not easy given the quality of the proposals we finally arrived after carefully and cooperatively considering all aspects.

- Thanks also to WPP-3 for the opportunity to participate in this review!