WG2 SRF: WP3 Crab Cavities

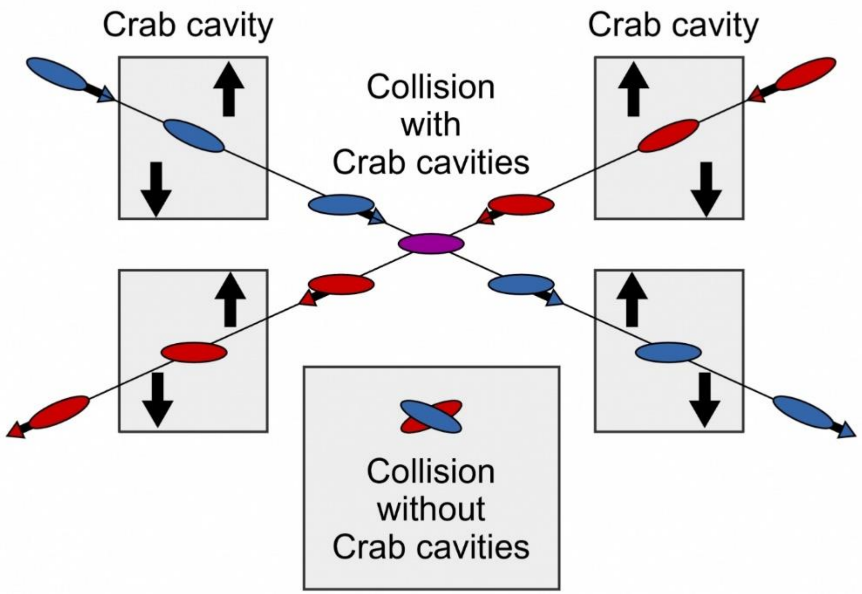
Summary of ILCX21 CC Session

Peter McIntosh

UKRI-STFC Daresbury Laboratory

WG2 SRF Meeting

9th November 2021



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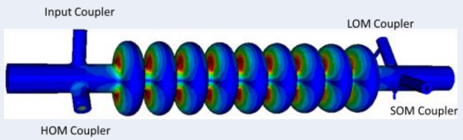
ILCX2021 SRF Machine: Crab Cavity session (27th Nov)

<table>
<tr><td>21:30</td><td>Crab Cavity Introduction, Specifications and Development Update</td><td>Peter McIntosh (STFC)</td><td></td></tr>
<tr><td>21:45</td><td>Elliptical/Racetrack</td><td>Graeme Burt (Lancaster University)</td><td>
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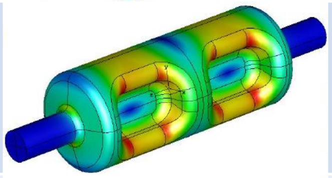
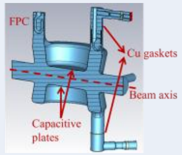
<tr><td>22:05</td><td>RF Dipole (RFD)</td><td>Jean Delayen (ODU/Jlab)</td><td></td></tr>
<tr><td>22:25</td><td>Double Quarter Wave (DQW)</td><td>Silvia Verdu Andres (CERN)</td><td>
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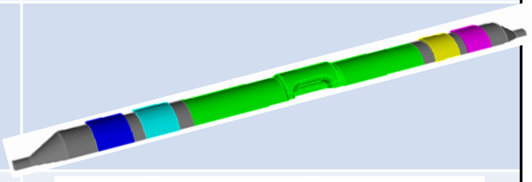
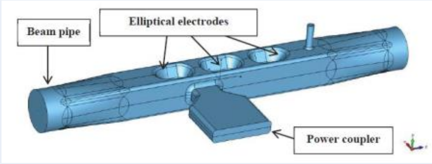
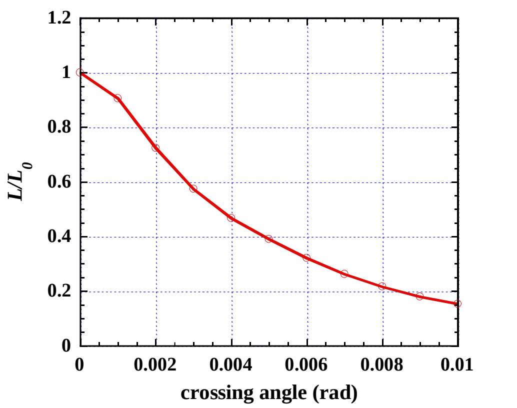
<tr><td>22:45</td><td>Wide Open Waveguide (WOW)</td><td>Binping Xiao (BNL)</td><td></td></tr>
<tr><td>23:05</td><td>Quasi-waveguide Multicell Resonator (QMiR)</td><td>Andrei Lunin (FNAL)</td><td>
</td></tr>
<tr><td>23:25</td><td>Nest Steps and Plans</td><td colspan="2">Peter McIntosh (STFC)</td></tr>
<tr><td>23:35</td><td>Discussion (25 mins)</td><td colspan="2">Specifications, Design options, Plans … etc</td></tr>
</table>

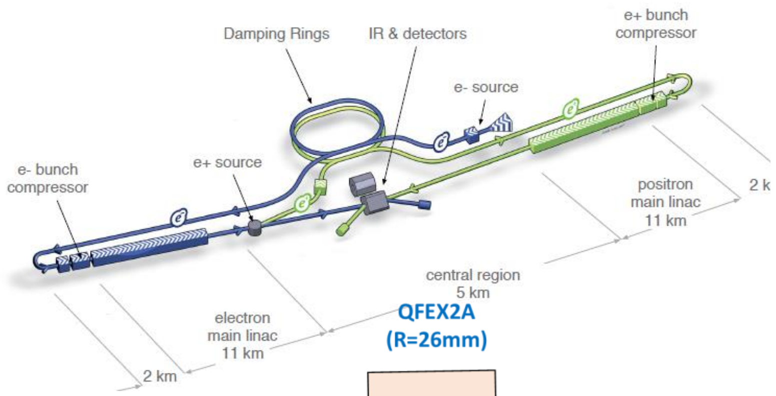
ILC Crab Cavity (CC) Requirements

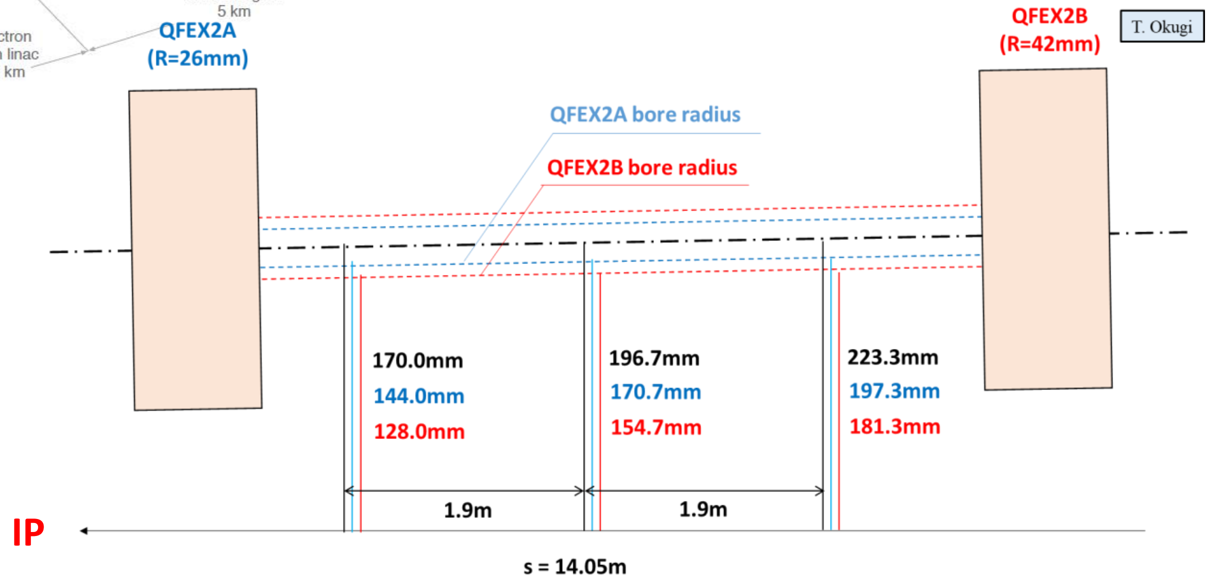
CC system is indispensable for ILC!

Luminosity reduced by >80% without CCs!

- No development progress since TDR (2013).
- Further development required as CC considered **not-matured technology** (Nomura Research Institute, Ltd):
  - **During the technical preparation period (Pre-Lab), prototype CM should be constructed and tested.**

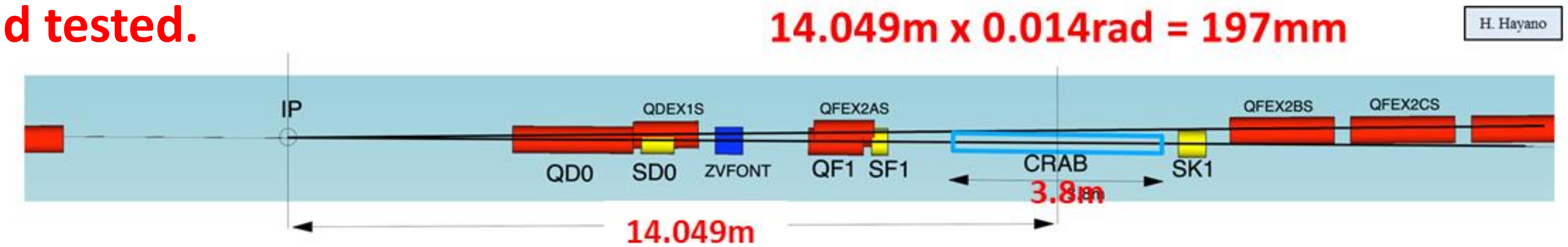






Two beamline separation

14.049m x 0.014rad = 197mm



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ILC CC Specifications

Parameter	250 GeV CoM (Post-TDR)		10Hz Upgrade[1,2]	1 TeV CoM[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		
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					
Cryomodule installation length (m)	3.8					
Horizontal beam-pipe separation (m)	0.197 (centre) ±0.0266 (each end of installation length)					
Operating Temperature (K)	2					
Crab Cavity Specifications						
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
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)					
Longitudinal impedance threshold (Ohm)	CC wake-potential input to BDS wakefield simulations					
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)	20 (same as FD magnets)					
Minimum Extraction beam-pipe aperture size (mm)	20					

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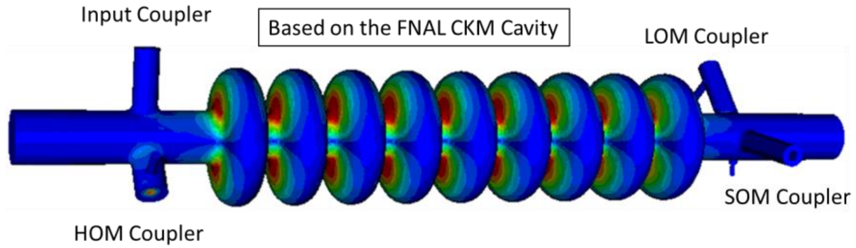
Elliptical/Racetrack – G Burt (Lancaster U, UK)

ILC RDR/TDR Crab Cavity Solution

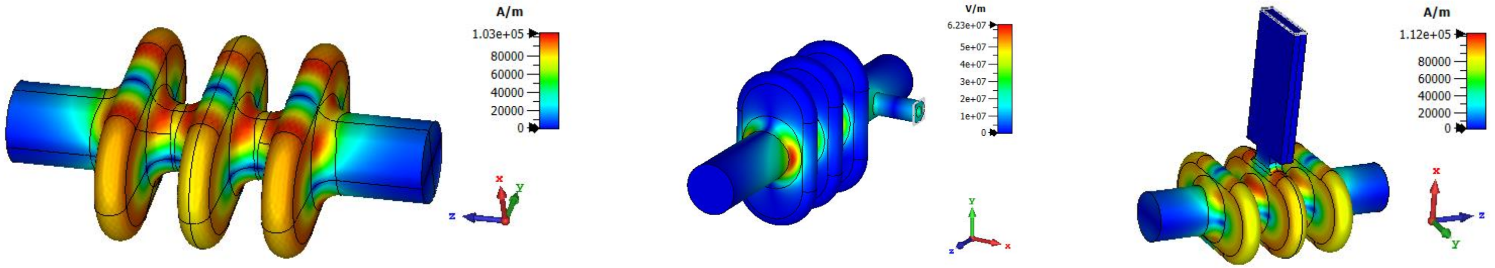


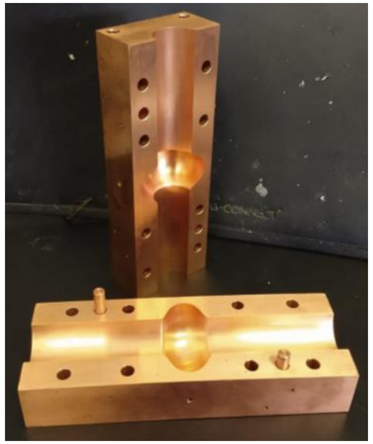
The Cockcroft Institute of Accelerator Science and Technology — Fermilab — SLAC NATIONAL ACCELERATOR LABORATORY

Original design

At 5MV/m $P_\perp$:	
B_{MAX}	73 mT
E_{MAX}	16.6 MV/m
U	0.25 J
Q (Nb, room temp)	4780
$\left(\frac{R}{Q}\right)' = \frac{1}{2}\frac{\lvert V_L(r)\rvert^2}{\omega U}\left(\frac{c}{\omega r}\right)^2$	235 Ω
$G = Q \times R_{SURF}$	225Ω
R_{BCS}(best measurement) @ 1.8K	30nΩ
R_0(best measurement)	40nΩ
Q @ 70nΩ1.8K	3.2 x10^9
Surface power @ 70nΩ	1.9 W

- Decided to re-optimise the ILC crab cavity to increase the gradient and further separate the SOM, now achieves 9 MV/m @ 80 mT.
- At 3.9 GHz for 250 GeV, requires a 3-cell cavity @ 5 MV/m, or 2 cells at @8 MV/m.
- Coax and waveguide solutions being investigated but original coax HOM damper designs already prototyped in copper (mature)





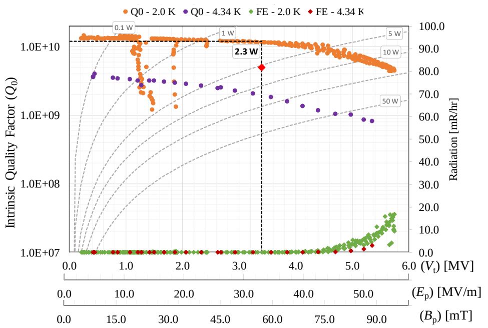
- CERN and Lancaster separately developed split cavities (SWELL) for thin film coated cavities.

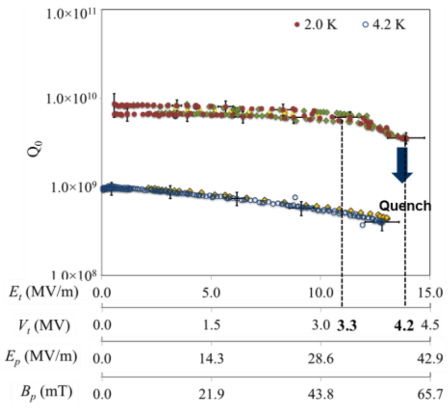
Summary

- 3.9 GHz elliptical still optimal - can achieve same gradient as a 1.3 GHz cavity, needs only 1/3 of the length.
- Can use a single cavity per IP at 1 TeV so simpler than several single cells and mature technology.

RF Dipole – J Delayen (ODU/Jlab, USA)

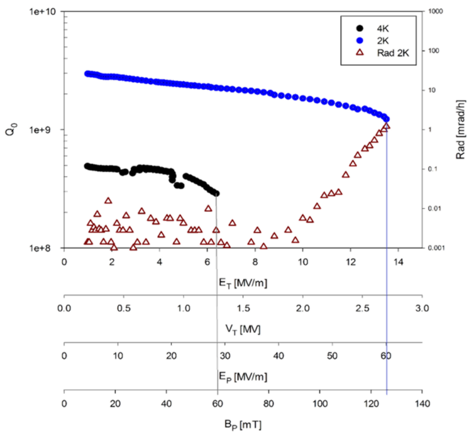
HL-LHC 400MHz RFD



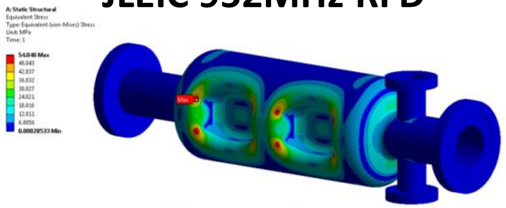


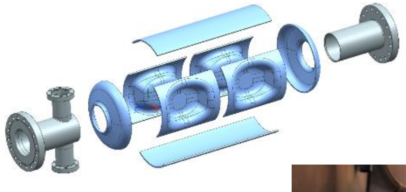
JLab 499MHz RFD Deflector

JLAb/MEIC 750MHz RFD



Crab Cavity Manufacture JLEIC 952MHz RFD

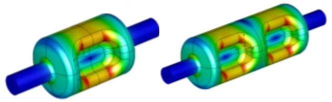




Summary:

- Design looks reasonable, with further possibilities to optimize.
- Long-range wakefield analysis needs more work:
  - Shorter bunch, short range.
- Number of cells is still an open question.

ILC 1.3 GHz RFD

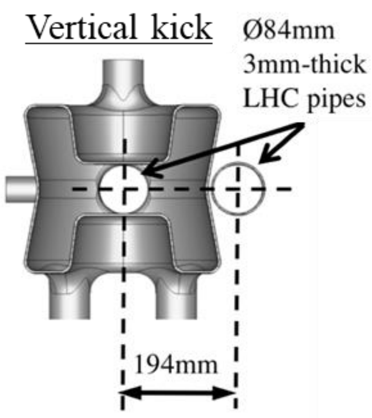


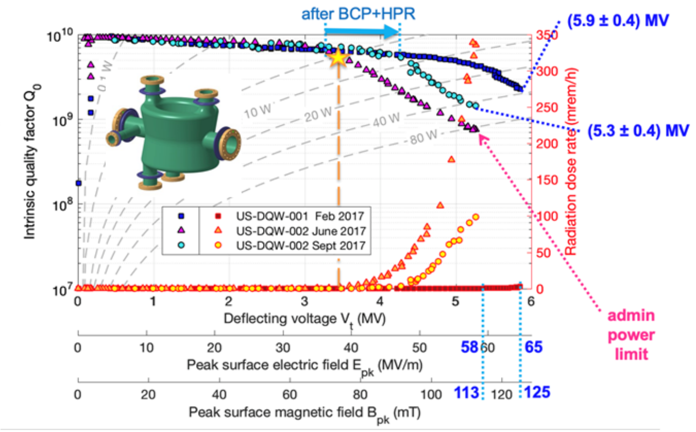
Property	1-cell	2-cell
Operating frequency [GHz]	1.3	1.3
SOM [GHz]	–	1.188
1st HOM [GHz]	2.085	1.932
E_p/E_t^*	3.84	3.98
B_p/E_t^* [mT/(MV/m)]	8.04	7.94
B_p/E_p [mT/(MV/m)]	2.10	1.99
G [Ω]	133.0	137.2
R/Q [Ω]	280.2	556.7
R_tR_s [Ω²]	3.7×10⁴	7.6×10⁴
V_t [MV]	1.0	2.0
E_p [MV/m]	33.3	34.54
B_p [mT]	69.7	68.82
Total V_t [MV]	1.845	1.845
No. of cavities	2	1
Pole separation, beam aperture (mm)	30	30
Cavity Length [mm]	172.32	297.4
Cavity Diameter [mm]	107.4	109.4
Pole Length [mm]	85	85

Double Quarter Wave – S Verdu Andres (CERN, Switzerland)

HL-LHC 400 MHz DQW

- “Born” to satisfy **tight spatial constraints** imposed by the 2nd beam pipe **of LHC**, the **DQW is remarkably compact**.





- DQW used for **first crabbing of proton bunches at SPS**; test campaign will continue over 2022.

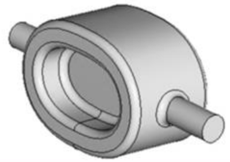

Cryomodule for SPS tests of 2 fully-equipped DQWs

For ILC at 1.3GHz

- 2 DQW designs being explored (HL-LHC and EIC variants):

HL-LHC

- 400 MHz
- Vertical kick
- With waist
- Elliptical profile



EIC

- 200, 400 MHz
- Horizontal kick
- Flat walls
- “Cassini” oval profile

… No clearance issues, ease fab, reduce cost →

…Further reduce peak fields →

	EIC-type DQW	LHC+EIC-type
Aperture, capacitive plate distance (mm)	20	20
Profile	Oval, straight walls	Oval, with waist
Dimensions: L x W x H (mm)	115 x 98 x 82	117 x 76 x 97
Circuit Rt/Q (Ohm)	333	311
Geometric factor (Ohm)	82	97
Epk (MV/m) at 1.86 MV	56	55
Bpk (mT) at 1.86 MV	81	84
First HOM (GHz)	1.98 (z)	2.18 (z)

Coupler integration may drive the choice between the two.

Input Coupler

- **loaded Q ~ 10^6** needs **input power <2 kW** for cavity **BW of 1.3 kHz**.

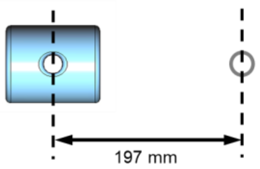
HOM Couplers

- **coaxial or waveguide or combination** can be used to damp the HOMs.
- Due to **high frequency of the 1st HOM**, a waveguide/stub coupled to an antenna is efficient and simple solution. (Rectangular WG with a ~ 7.5 cm has $f_{c,TE10}$ = 2 GHz.)

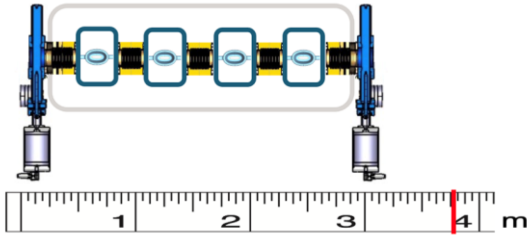
Summary

- **DQW** cavity is **compact solution for ILC crabbing system**. One **single-cell cavity** provides **1.86 MV with safe max. peak fields**.
- Tuner/coupler integration can be borrowed from HL-LHC & EIC.
- DQW c**ompactness opens manufacture out of ingot.**

Front view, distance to 2nd beam pipe

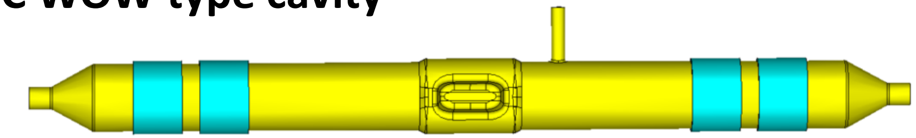


Side view, 4 DQW in cryomodule



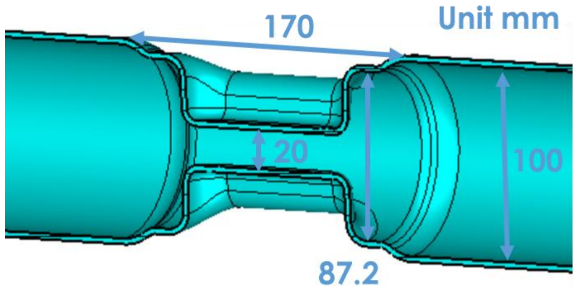
Wide Open Waveguide – B Xiao (BNL, USA)

EIC WOW type cavity



Property	Value
Operating frequency [GHz]	1.300
1^{st} longitudinal HOM [GHz]	2.318
1^{st} transverse HOM [GHz]	1.878
E_p/E_t with $E_t=V_t/(\lambda/2)$	3.37
B_p/E_t [mT/(MV/m)]	5.77
B_p/E_p [mT/(MV/m)]	1.71
G [Ω]	112.0
R/Q [Ω]	732.2
R_tR_s [Ω^2]	80470

Scaled to ILC at 1.3 GHz



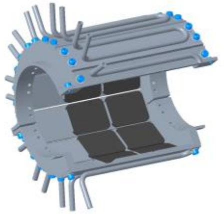
- Needs 1.845 MV for 125 GeV case and 7.4 MV for 500 GeV case.
- If we use 2 cavities for 125 GeV and 5 cavities for 500 GeV, and 1.48 MV per cavity, peak fields drop to 43.3 MV/m Epk and 74.1 mT Bpk.

Beam Line Absorber (BLA)

- Optimization of BLA is still on-going.
- Possible solutions include one BLA with tapered thicknesses, two BLAs with different thicknesses (uniform thickness in each), and BLA with ferrite tiles.

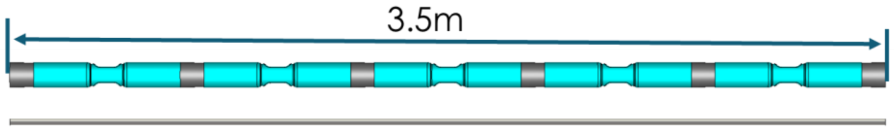
Shrink-fit SiC (W. Xu)

Tile SiC
(T. Schultheiss, SBIR)



Tile ferrite (TT2-111R)
for LEReC

Cavity String (estimation)



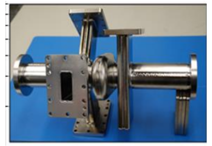
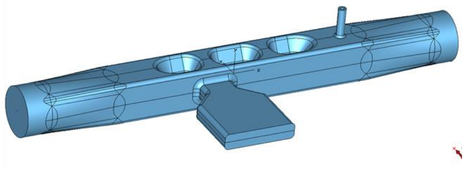
Gate valves, bellows and cryomodules not shown here.

Summary:

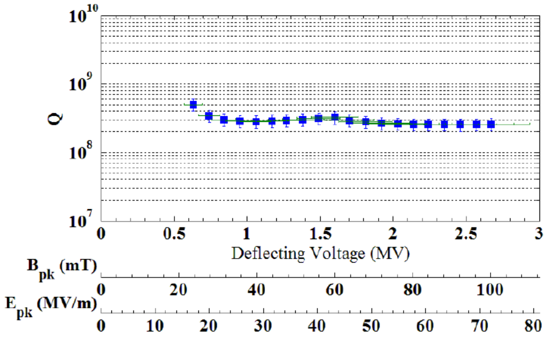
- WOW is good cavity solution for ILC, with FPC/PU/BLA all outside the helium vessel.
- Finished preliminary cavity design and optimization on cavity & BLA is on-going.
- More effort on ancillaries (FPC/PU, RF window, amplifier, tuner etc) is needed. Very tigh space requirements.

Quasi-waveguide Multicell Resonator – A Lunin (FNAL, USA)

- QMiR cavity proposed as replacement of Mark-II deflecting cavity for APS/SPX project.

4 x  → 1 x 

- Prototype built and tested at ANL in 2013.

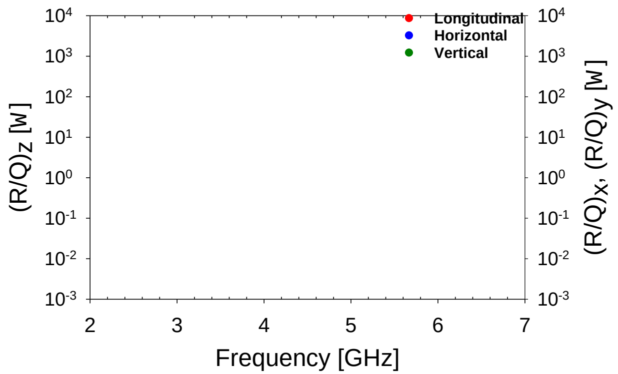


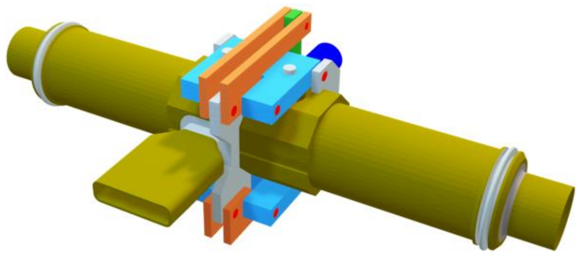
Freq	2815 MHz
V_{kick}	2 MV
E_{max}	55 MV/m
B_{max}	76 mT
$(R/Q)_Y$	1040 Ω
G	130
W_{STOR}	0.23 J

- Measured max. deflecting voltage of 2.7 MV exceeds design goal of 2 MV @ 2K.
- Relatively low Qo (3E8) due to extra RF losses at covering flanges.
- QMiR has a record high (R/Q)t >1kΩ

QMiR Cavity for ILC (scaled to 2.6 GHz)

- There are 2 Same Order Modes (SOM) with low (R/Q)*Q.
- SOM/HOM external couplings Qext < 10^4.
- SOM/HOMs longitudinal and transverse impedances (@1mm):
  - $(R/Q)z <= 100\ \Omega$, $(R/Q)x <= 1\ \Omega$ and $(R/Q)y <= 10\ \Omega$
- SOM/HOM spectrum is sparse and strongly damped.

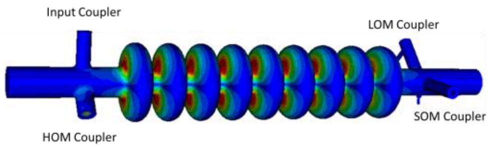




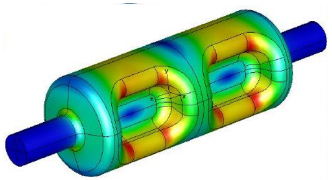
Summary:
- QMIR is good option for the ILC Crab Cavity.
- Very compact and simple - has acceptable loss/kick factors.
- Peak field presented were low but aperture was a factor of 2 smaller than requirements. Likely to increase peak fields.
- Required RF power (overhead 100%): Pgen < 1 kW but again with a much smaller aperture.
- No MP in operation voltage domain.

WP3 Crab Cavity Development Plan

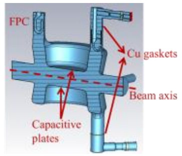
Options study (currently underway):



Elliptical/Racetrack

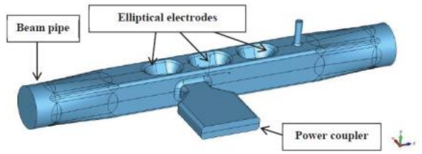


RFD



DQW

WOW



QMiR

- Cavity down-selection #1 (**Sept 22**):
  - EM design optimisation for cavity, couplers (input and HOM) and tuner.
  - Select 2 primary options to take forward to prototype stage.
- Cavity down-selection #2 (**Sept 23**):
  - Choose most optimum single CC technology solution from prototype tests.
- Propose to use both prototype CC's in VTS for synchronisation studies.
- Use final chosen design as basis for 2-cavity CM integration design and prototype
  - Targeted basis for **ILC Pre-Lab phase**.

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CC Session Discussion

- Beam aperture specification clarified as >20mm relating to beam halo expectation as result of collimation. Synchrotron radiation may require a larger aperture which needs more studies
  - Noting <20mm would make cavity cleaning more difficult in any case.
- High field multipacting for lower frequency (1.3 GHz) dipole cavities requires careful optimisation, due to resonances close to fundamental mode. MP free demonstrated for 3.9 GHz elliptical and 2.8 GHz QMiR.
- Smaller cavity geometries (either elliptical at 3.9 GHz or compact 2.6 GHz/1.3 GHz) could benefit from ingot machining manufacture, easier to control tuning sensitivity and cheaper.
- Pulsed operation introduces Lorentz Force Detuning challenges, preference therefore for CW mode of operation – no reason why not identified.
- CC system solution must be conservatively specified, not push extreme operation, as its robustness and reliability must be critically preserved:
  - Limit Epk to ~20 MV/m for example (however no design currently achieves this, would require 40% more cavities).
- The 1st CC technology down-selection in Sept 22 must include all expected cryomodule components, cavity, couplers, tuner, dampers, bellows, tapers etc.

Key Specification Issues to Resolve

- Beam aperture clarification re: photon flux impact?
  - Minimum 20mm aperture defined from collimation depth studies.
  - Is further aperture required for additional SR photon losses?
- Is a more conservative field voltage required to ensure operational robustness and if so, how best to specify?
  - Epk and Bpk
  - Integrated kick voltage
- CW or pulsed operation?
  - LFD issues removed if CW
  - System synchronisation simpler if CW

MANY THANKS

Questions?

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