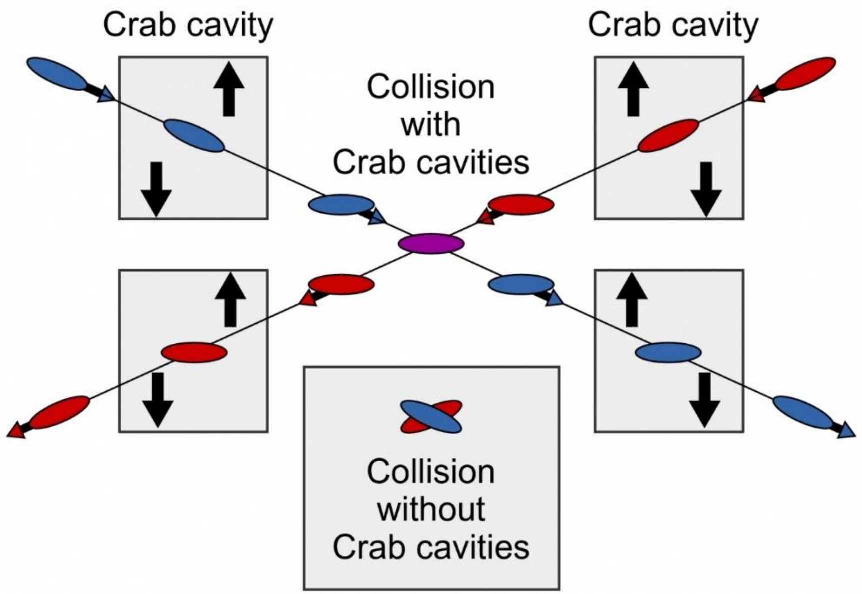
WP-3: Summary of Crab Cavity Workshop

Peter McIntosh,

UKRI-STFC Daresbury Laboratory

LCWS2021

15th -18th March 2021



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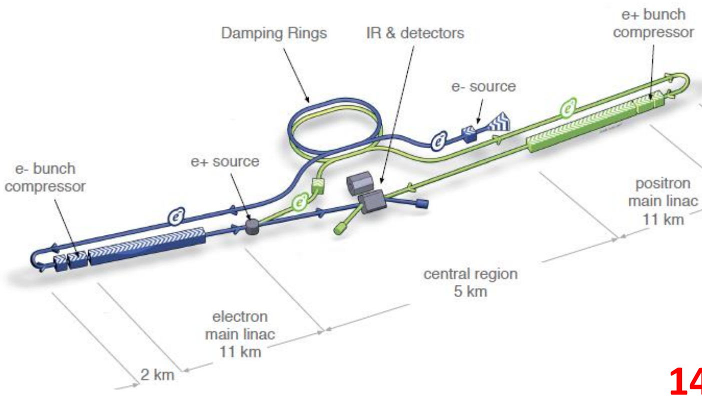
Overview

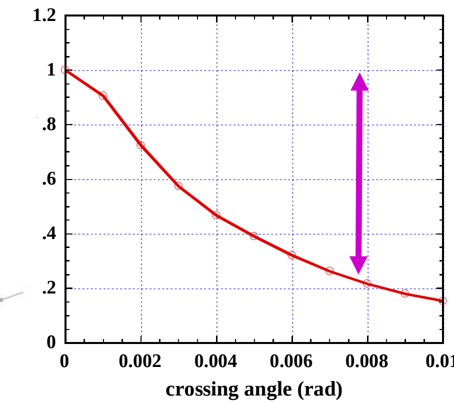
- ILC Crab Cavity (CC) Requirements
- ILC Technical Preparation (Pre-Lab)
- Crab Cavity Workshop
- Workshop Discussion/Questions
- Conclusions

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 (Nomura Research Institute, Ltd. considered CC as **not-matured technology**):
  - **During the technical preparation period (Pre-Lab), prototype CM should be constructed and tested.**
- IDT has provisionally restarted the ILC-CC activity:
  - 5th Meeting of SRF subgroup including crab kick-off meeting – 24th Nov 2020
  - 2nd Crab Cavity Meeting as joint meeting of BDS and SRF subgroups – 30th Nov 2020
  - Workshop for crab cavity – 18th Feb 2021

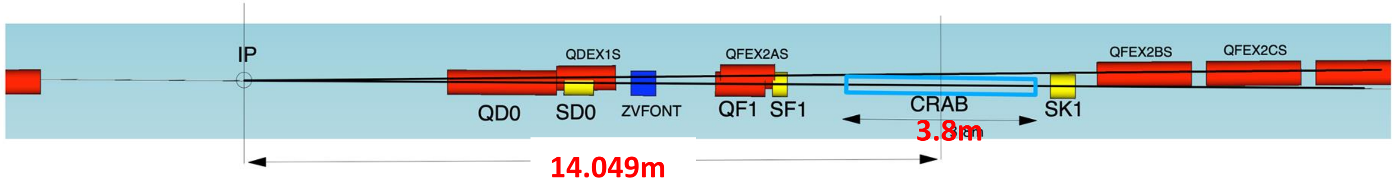


ILC RDR parameter, by CAIN simulation

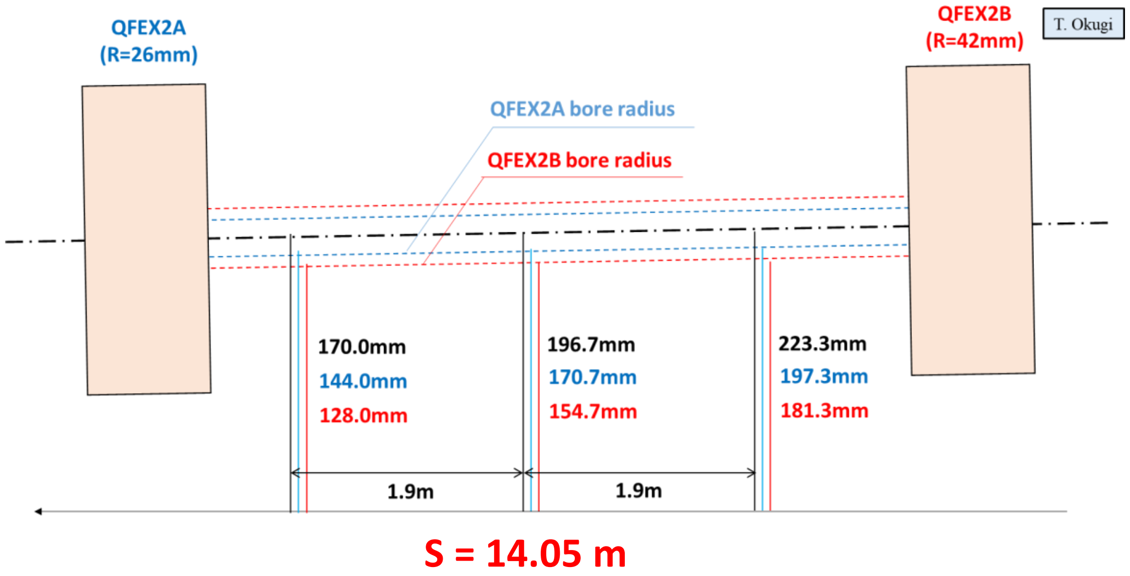


Two beamline separation
14.049m x 0.014rad = 197mm

H. Hayano



T. Okugi



ILC Technical Preparation (Pre-Lab)

WP3 Crab Cavity System

- ILC Pre-Lab phase aims to **produce and test a prototype CM** (pCM) system containing two cavities.
- Necessary to **demonstrate synchronized operation** with two sets of cavities in one pCM.
- If installed **14 m from the IP**, the **beam-pipe** for counter-beam extraction will **need to pass through the pCM**.
- The cavity, power coupler, tuner and pCM will be **designed and developed**.
- The pCM containing the two cavities will be **assembled**.
- In final year, a synchronized operation with two CC's to be performed to complete the **technical demonstration of the CC system**.
- **A collaboration is expected to be formed and the preparation to be advanced mainly abroad (i.e. not based in Japan).**

Item	Recent specification (after TDR)	
Beam energy	125 GeV (e^-)	
Crossing angle	**14 mrad**	
Installation site	**14 m from IP**	
RF repetition rate	5 Hz	
Bunch train length	727 μsec	
Bunch spacing	554 nsec	
Operational temperature	2.0 K (?)	
Cavity frequency	**3.9 GHz**	**1.3 GHz**
# of cell	3-cell	3-cell/9-cell (?)
Total kick voltage	**0.615 MV**	**1.845 MV**
Relative RF phase jitter	0.069 deg rms (49 fs rms)	0.023 deg rms (49 fs rms)

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CC Scope for Pre-Lab

	Work package	Items	Quantity
WP-3	Crab Cavity (CC) for BDS # CC production: 4 # CC-CM production: 1	Decision of installation location with cryogenics/RF location accelerator tunnel	–
		Design and development of prototype cavity/coupler/tune/CM including beam extraction line	–
		Cavity production, including cavities w/ He tank + mag. shield for CM, high-pressure gas regulation, EP/HT/Clean work, including VT	4
		Coupler production including preparation/RF processing readiness (excluding klystron, baking furnace, clean room)	4
		Tuner production readiness	4
		CM production including High-pressure gas, vacuum vessel, cold-mass, and assembly (cavity-string, coupler/tuner, SCM, etc.)	1
		CM test including harmonized operation with two cavities	1
		CC-CM transport cage and shock damper	1
		CC-CM transport tests	1
		Infrastructure for CC and CM development and test (with each regional responsibility.)	–

Note: Above assumes preferred CC solution defined for Pre-Lab.

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WP-3: Crab Cavity Workshop: 18th February 2021

Title	Speaker	Lab
Crab Cavity Workshop for ILC - Introduction	Kirk Yamamoto	KEK
UK ILC Crab Design	Graeme Burt	Lancaster University
ILC Crab Cavities, First Thoughts	Rama Calaga	CERN
Crab Cavity R&D Activities at Old Dominion University and Jefferson Lab	Jean Delayen	ODU/JLab
QMIR Deflecting cavity for ILC	Vyacheslav Yakovlev	FNAL
Crab Cavity Effort at BNL	Binping Xiao	BNL
Discussions and Preparation for International Review	ALL	

Attendees:

S. Belomestnykh, P. Burrows, G. Burt, R. Calaga, J. Delayen, S. De Silva, D. Delikaris, A. Faus-Golfe, M. Harrison, A. Lankford, N.C. Lasheras, R. Laxdal, T. Luo, T. Markiewicz, P. McIntosh, S. Michizono, T. Nakada, S. Posen, B. Rimmer, K. Umemori, B. Xiao, V. Yakovlev, A. Yamamoto, K. Yamamoto.

Development Groups:

BNL, CERN, FNAL, Jlab, Lancaster University, ODU, SLAC, TRIUMF, UKRI-STFC

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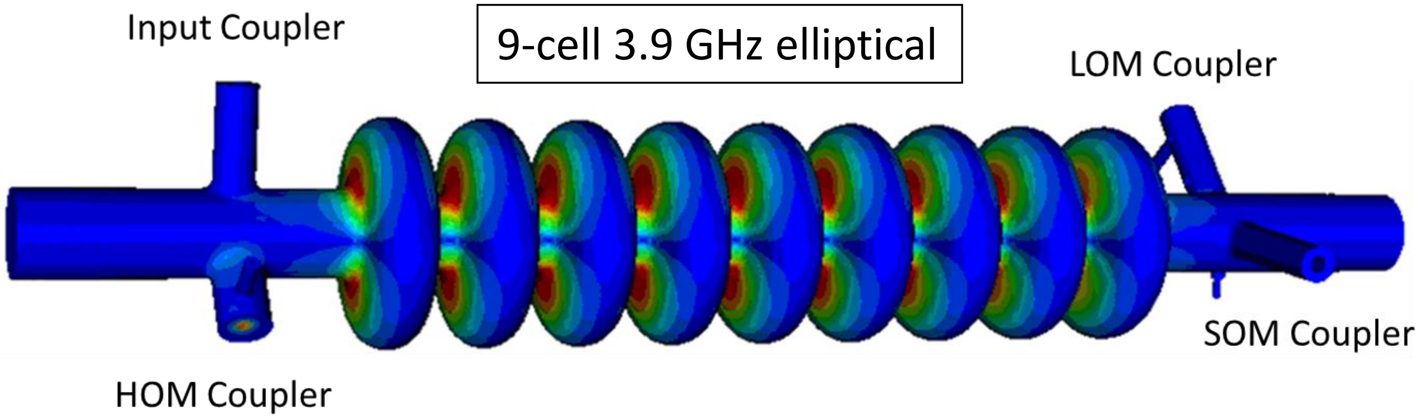
https://agenda.linearcollider.org/event/9090/

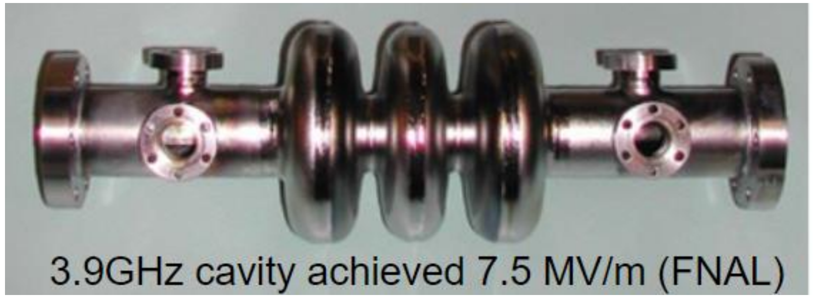
ILC-CC Design (RDR 2008: TDR 2013)

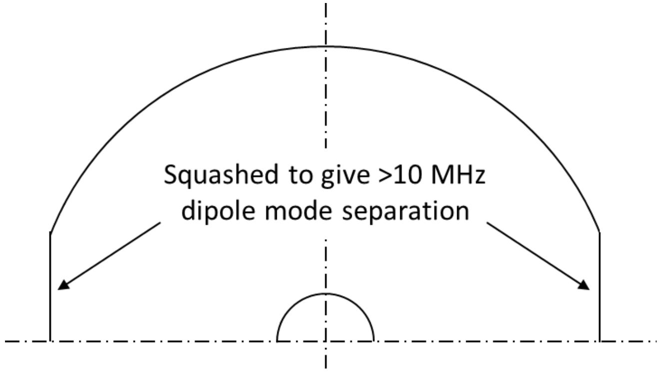
G Burt (Lancaster University)



At 5MV/m $P_\perp$:	
B_{MAX}	73 mT
E_{MAX} U	16.6 MV/m 0.25 J
Q (Nb, room temp)	4780
$\left(R/Q\right)' = \frac{1}{2}\frac{\lvert V_L(r)\rvert^2}{\omega U}\left(\frac{c}{\omega r}\right)^2$	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

Beam-pipe radius = 18mm
Cavity iris radius = 15mm
Equator Radius = 47.37mm





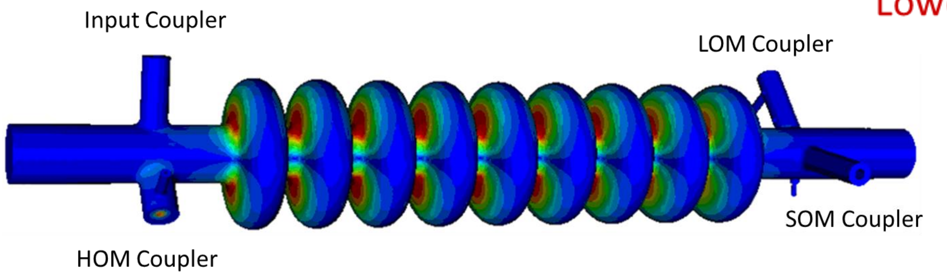
Crossing angle	14 mrad
Cavity frequency, GHz	3.9
Amplitude at 1TeV CoM, MV	2.6
Max amplitude with operational margin, MV	4.1
RMS relative phase stability for 2% rms Luminosity drop	0.094°
RMS amplitude stability for 2% rms Luminosity drop	6.6%
Horizontal beam clearance, mm	15
Vertical beam clearance, mm	10
Allowable X beam jitter at crab cavity, µm	500
Allowable Y beam jitter at crab cavity, µm	35

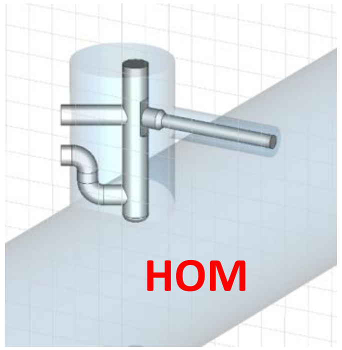
Lancaster University
UKRI Science and Technology Facilities Council
Fermilab
SLAC

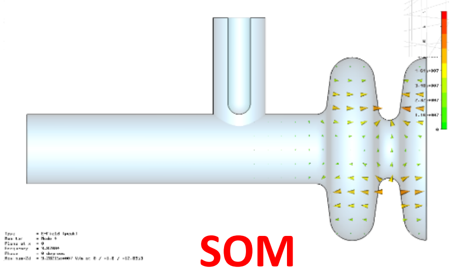
Nb: Larger polarisation separation feasible with racetrack solution.

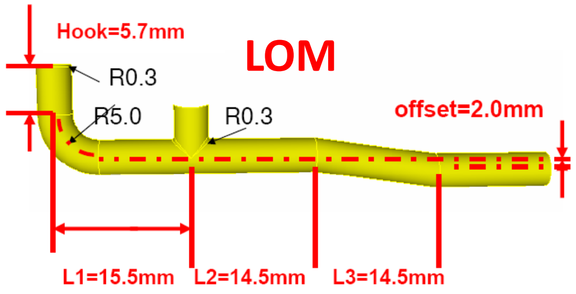
Modal Calculations in MAFIA

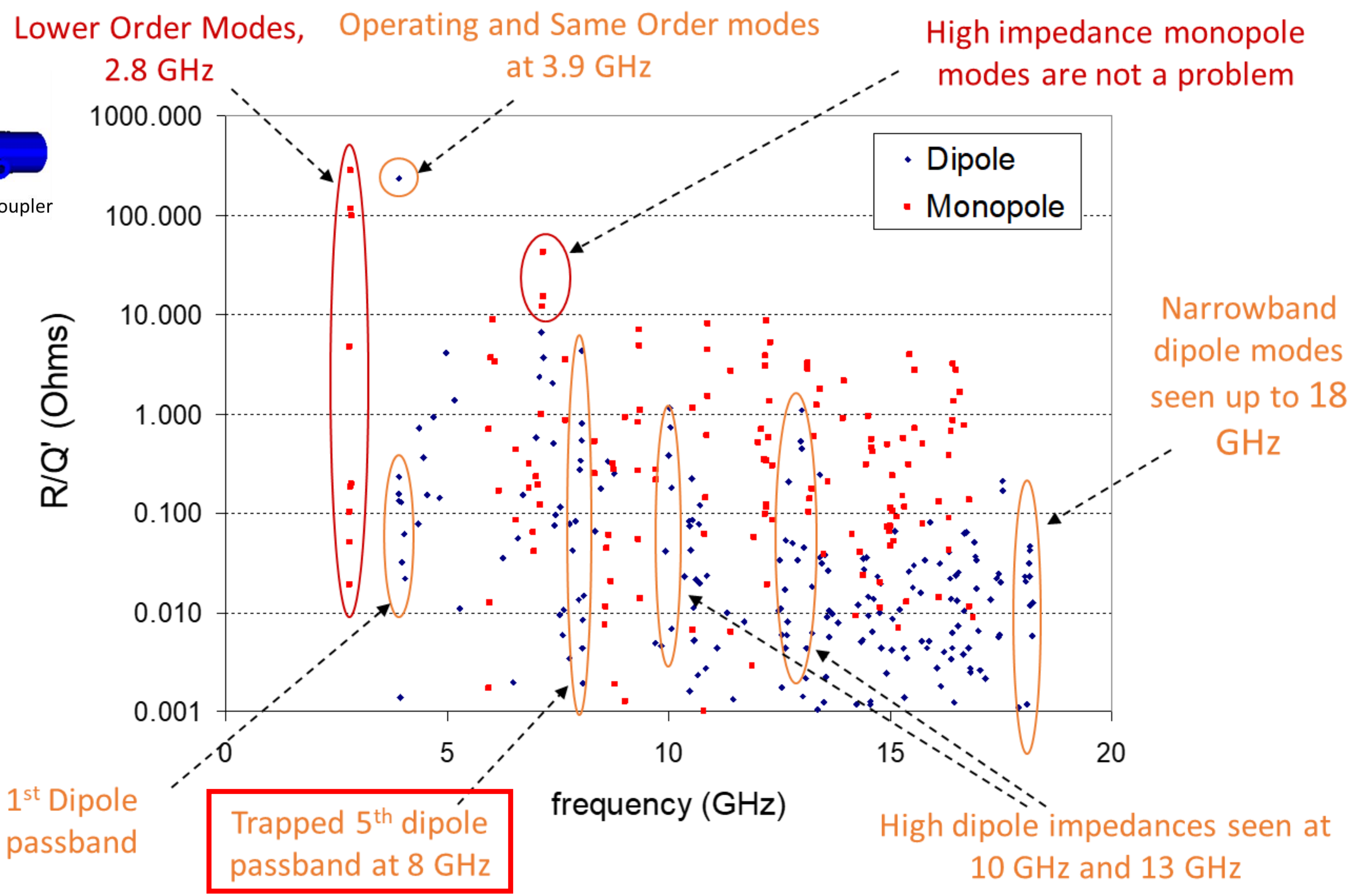
G Burt (Lancaster University)





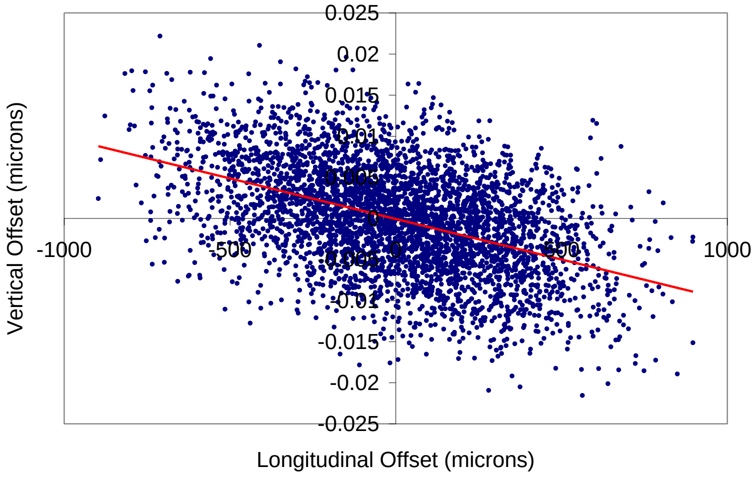




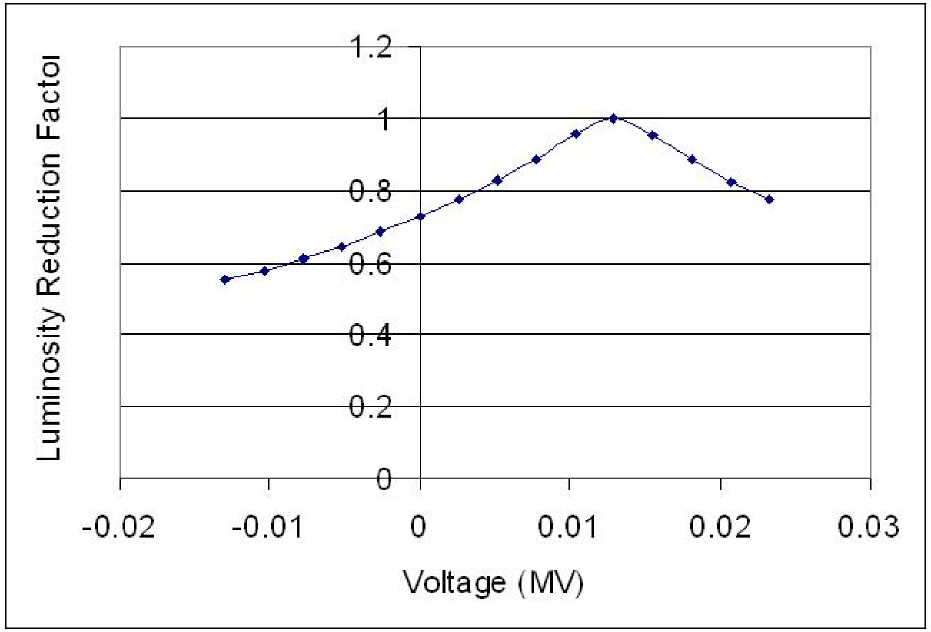


Cavity Alignment (Anti-crabbing)

G Burt (Lancaster University)

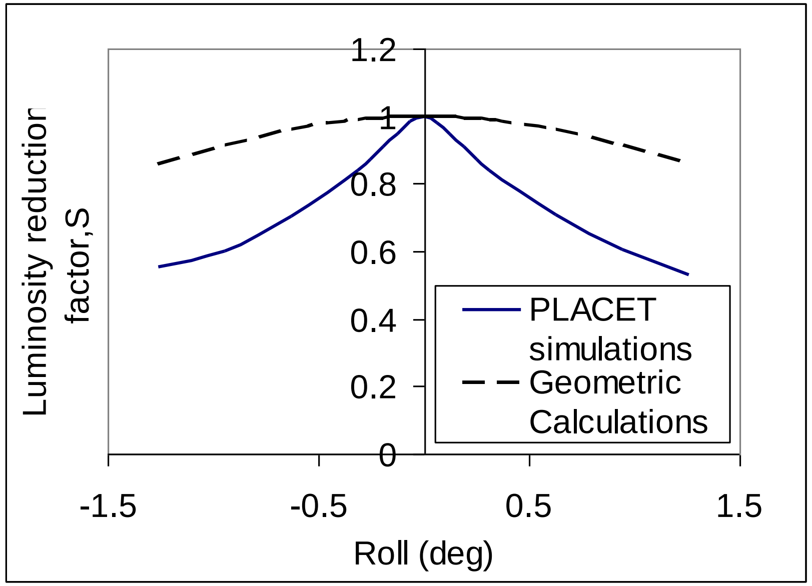


As we vary the anti-crab cavity voltage we can see the luminosity increasing back to the optimum value. 100% of the luminosity can be recovered in this way.



If the cavity has a roll misalignment it will cause a small crossing angle in the vertical plane.

This will significantly reduce the luminosity.



As we only require 10’s kV this can be performed with a normal conducting cavity.

ODU/Jlab RF Dipole (RFD) Developments

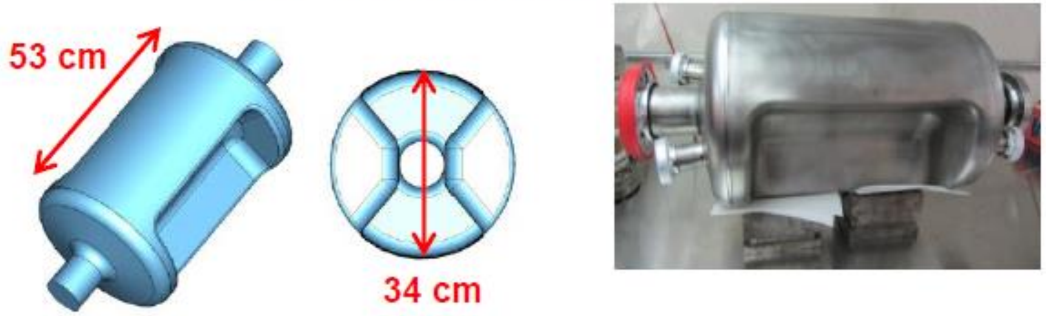
J Delayen (ODU/Jlab)

Proof-of-principle cavities

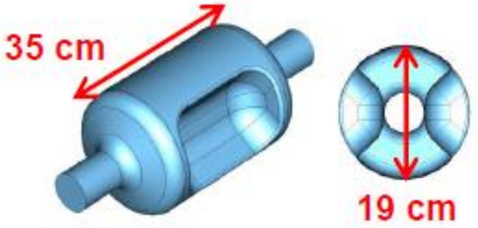
Frequency	499.0	400.0	750.0	MHz
Aperture Diameter (d)	40.0	84.0	60.0	mm
d/(λ/2)	0.133	0.224	0.3	
LOM	None	None	None	MHz
Nearest HOM	777.0	589.5	1062.5	MHz
E_p^*	2.86	3.9	4.29	MV/m
B_p^*	4.38	7.13	9.3	mT
B_p^*/E_p^*	1.53	1.83	2.16	mT/ (MV/m)
$[R/Q]_T$	982.5	287.2	125.0	Ω
Geometrical Factor (G)	105.9	138.7	136.0	Ω
$R_T R_S$	1.0×10^5	4.0×10^4	1.7×10^4	Ω^2
At $E_T^* = 1$ MV/m				

499 MHz Deflecting Cavity for Jefferson Lab 12 GeV Upgrade

400 MHz Crabbing Cavity for LHC High Luminosity Upgrade



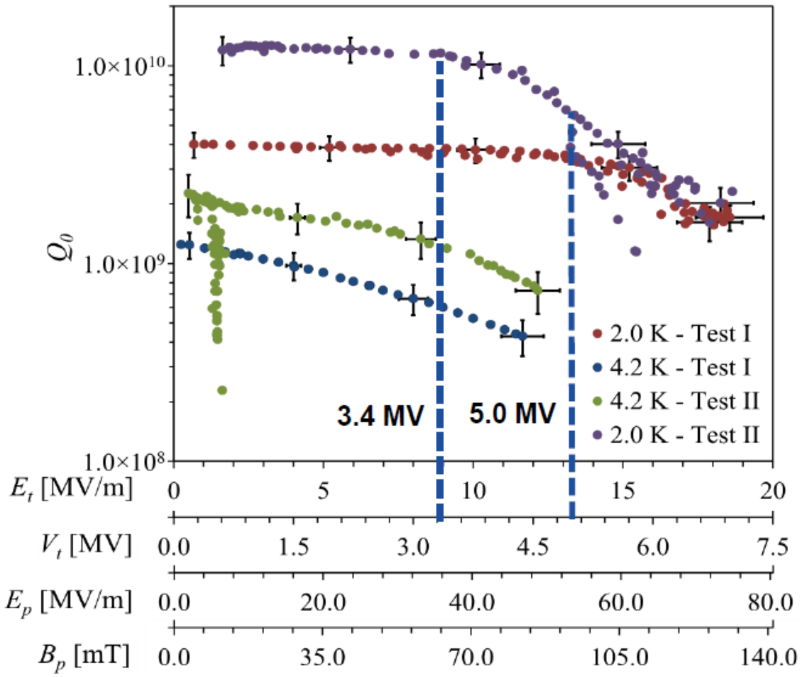
750 MHz Crabbing Cavity for MEIC at Jefferson Lab



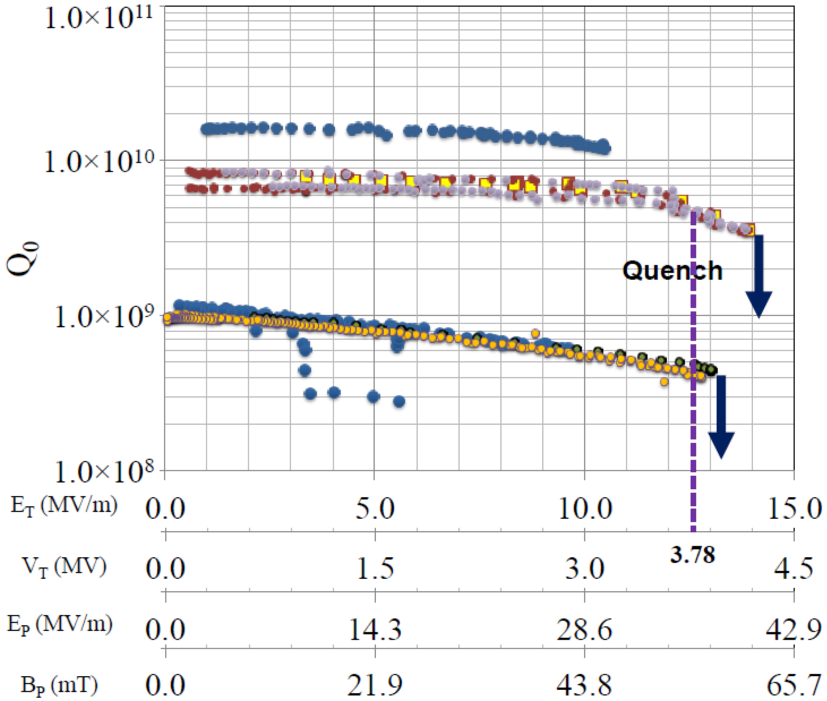
RFD Cavity Tests

J Delayen (ODU/Jlab)

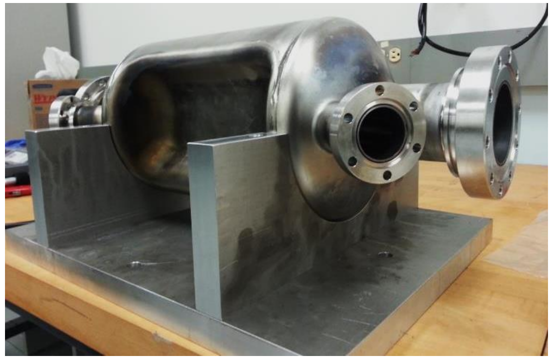
400 MHz HL-LHC

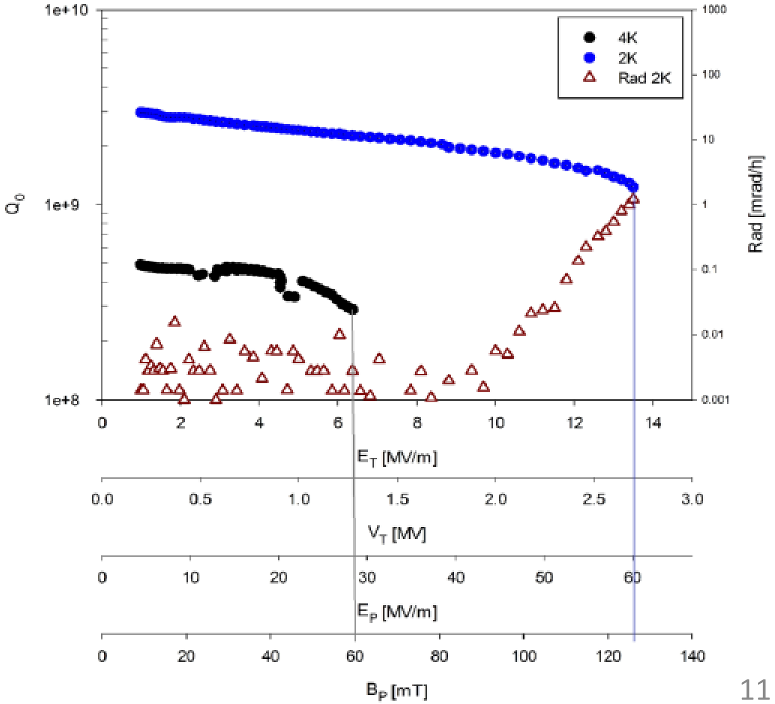


499 MHz Jlab Upgrade

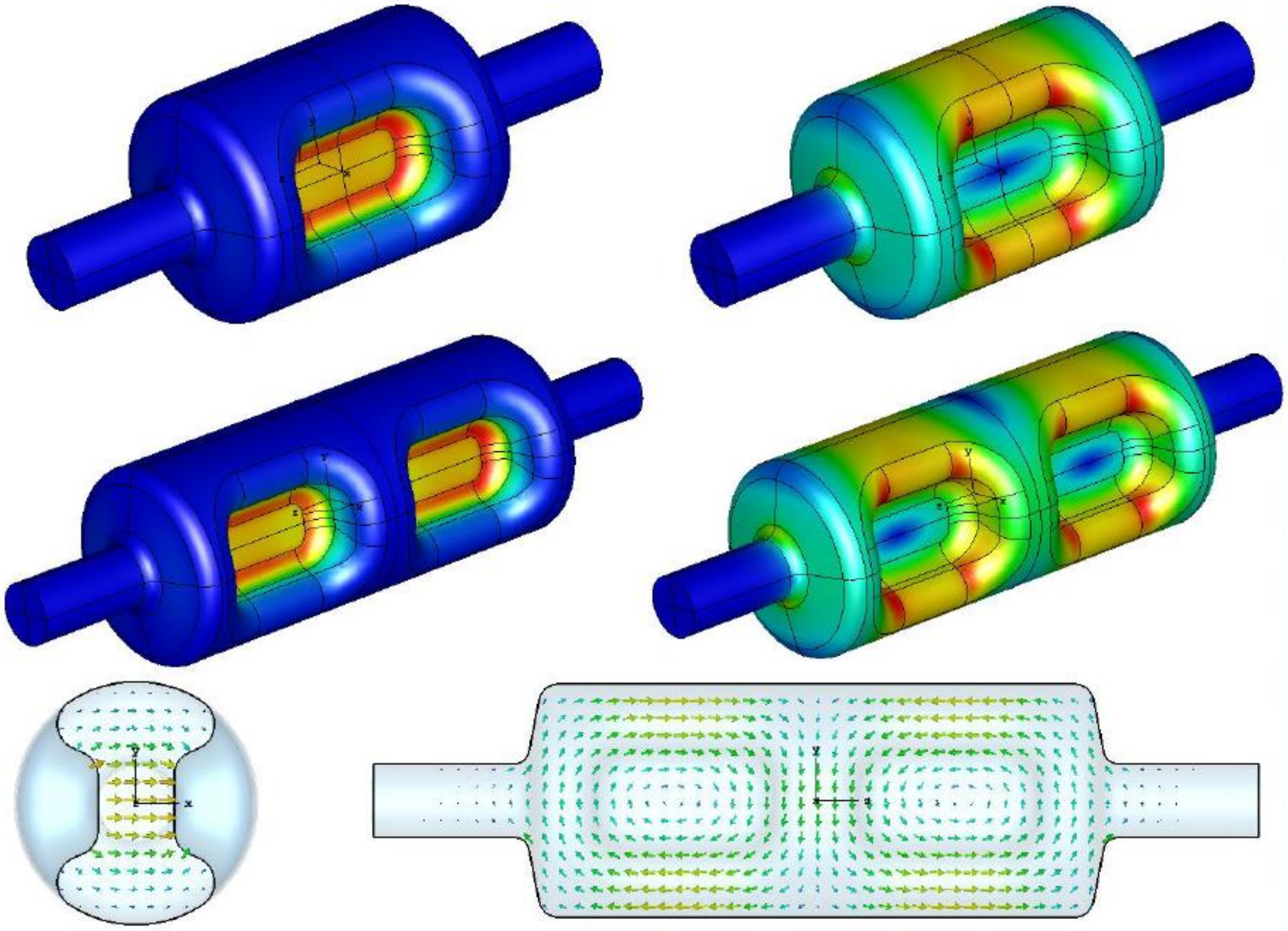


750 MHz Jlab MEIC





1.3 GHz RFD Cavity



Property	1-cell	2-cell
Operating frequency [GHz]	1.3	1.3
SOM [GHz]	–	1.188
1st HOM [GHz]	2.069	1.932
E_p/E_t^*	4.45	4.57
B_p/E_t^* [mT/(MV/m)]	9.09	8.92
B_p/E_p [mT/(MV/m)]	2.04	1.95
G [Ω]	142.5	147.3
R/Q [Ω] (V^2/P)	182.2	370.7
R_tR_s [Ω^2] (V^2/P)	2.6×10^4	5.5×10^4
Reference length $V/E_t = \lambda/2$ (mm)	11.54	11.54
V_t [MV]	1.0	2.0
E_p [MV/m]	38.58	39.66
B_p [mT]	78.85	77.36
Pole separation, beam aperture (mm)	36	36
Cavity Length [mm]	172.32	297.4
Cavity Diameter [mm]	128.6	114.5
Pole Length [mm]	85	85

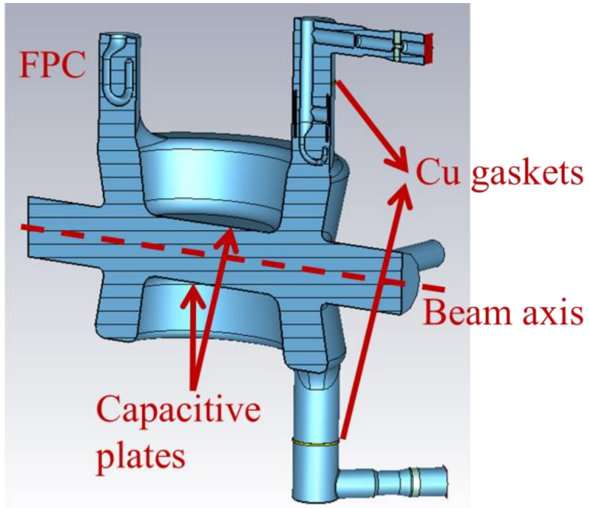
BNL CCs Scaled for ILC at 1.3 GHz

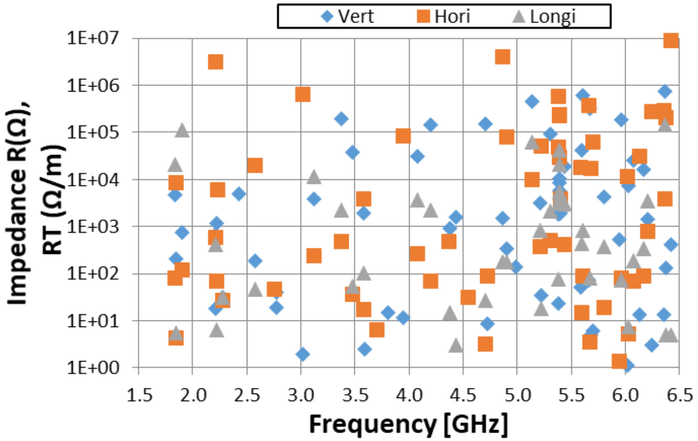
B Xiao (BNL)

Double Quarter Wave (DQW)
Wide Open Waveguide (WOW)

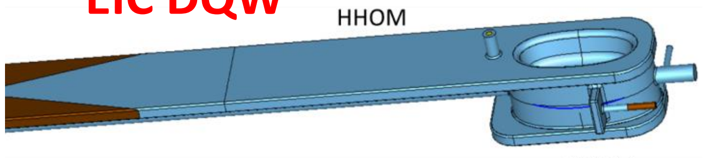
	LHC DQW	EIC DQW	EIC WOW
Couplers	3 x coax (with filter)	1 x waveguide 1 x rect/coax	2 x SiC beampipe
ID Beam Pipe (mm)	25.8	15.2 (too small)	30.3
V_t (MV)	1.15	2	1.27
E_p (MV/m)	41.3	51.6	50.4
B_p (mT)	80	80	80
Max Long Imp (MΩ)	0.12	0.0016	0.0015
Max Trans Imp (MΩ/m)	8.8	1.5	0.029

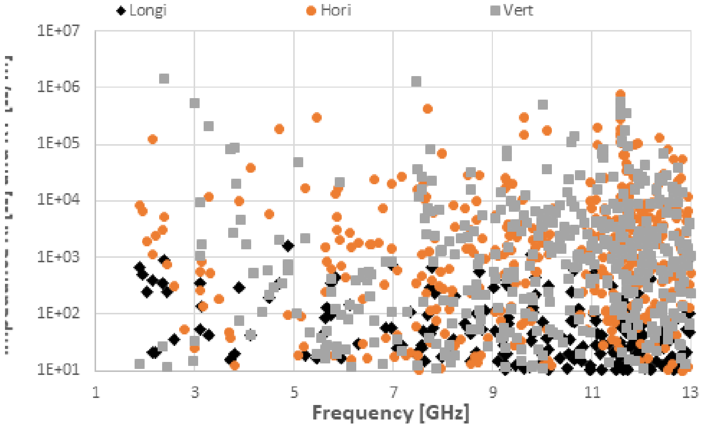
LHC DQW



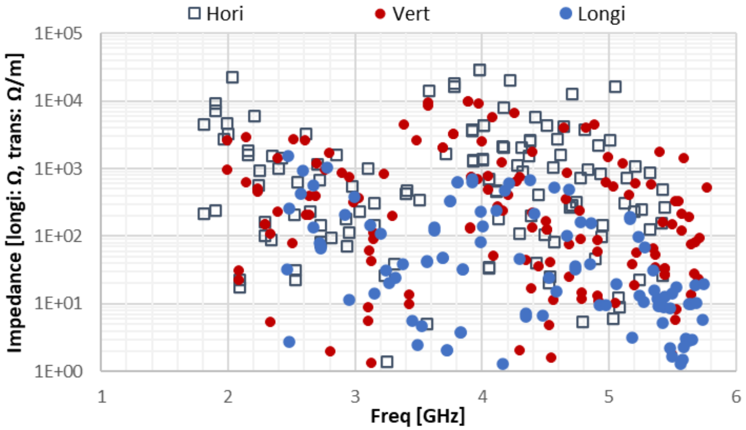


EIC DQW





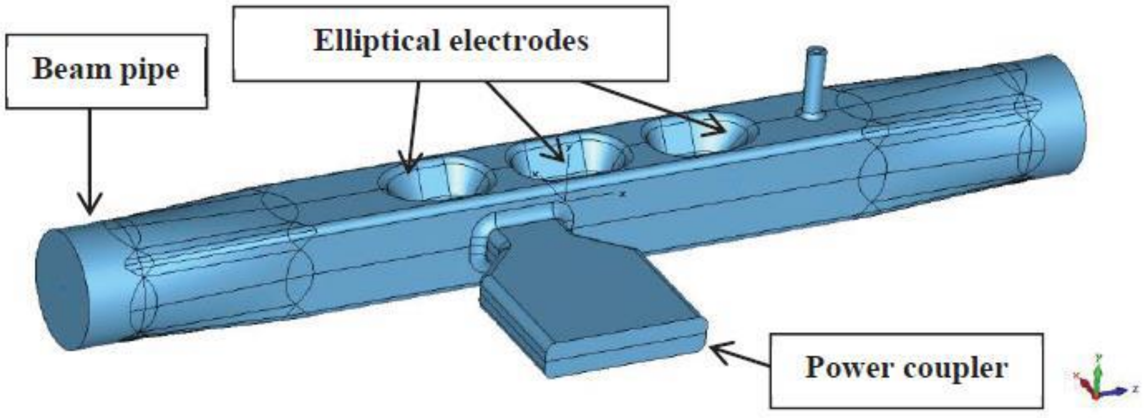
EIC WOW (BNL/SLAC)



Quasi-Waveguide Multicell Deflecting Resonator (QMiR)

V Yakovlev (FNAL)

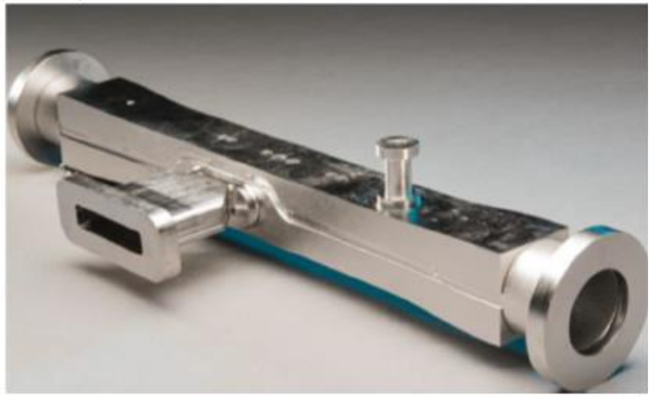
ANL/SPX:



Freq	2815 MHz
V_{kick}	2 MV
E_{max}	54 MV/m
B_{max}	75 mT
$(R/Q)_Y$	521 Ω
G	130
Q_{ext}	5.3E5
P_{out}	7.2 kW
Length (excl SiC absorbers)	0.45 m

Note that "circuit" impedance definitions are used.

- No HOMs above cut off (5.2 GHz for monopoles and 4.2 GHz for dipoles).
- High $(R/Q)_t$
- Small loss factor, $k_{//}$ = 0.7 V/pC for σ_z = 10 mm.
- No MP up to 3 MV.
- No issues with thermal breakdown.

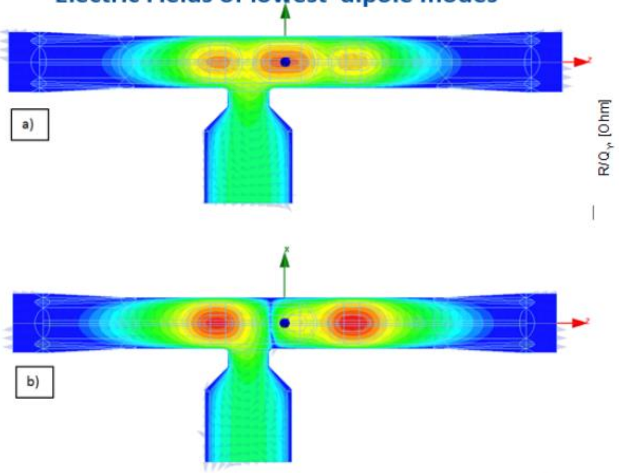


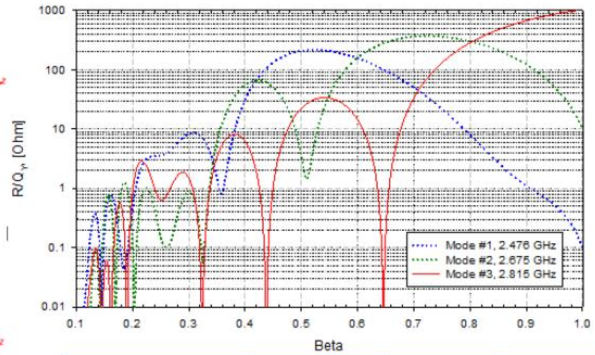
A. Lunin, I. Gonin, M. Awida, t. Khabiboulline, V. Yakovlev, A. Zholents, Physics Procedia 79 (2015) 54 –62

QMiR SOM/HOM Management

Same Order Mode (SOM)

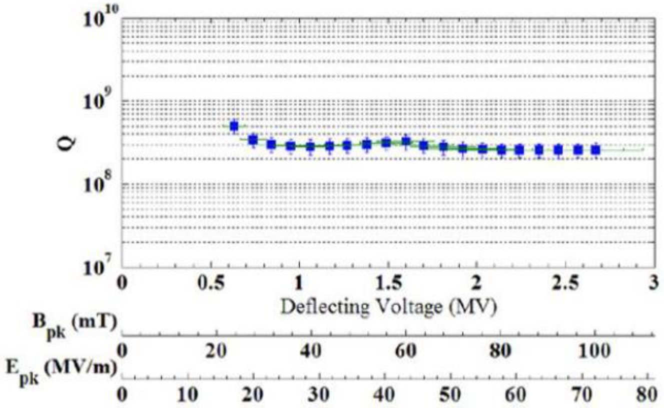
Electric Fields of lowest dipole modes





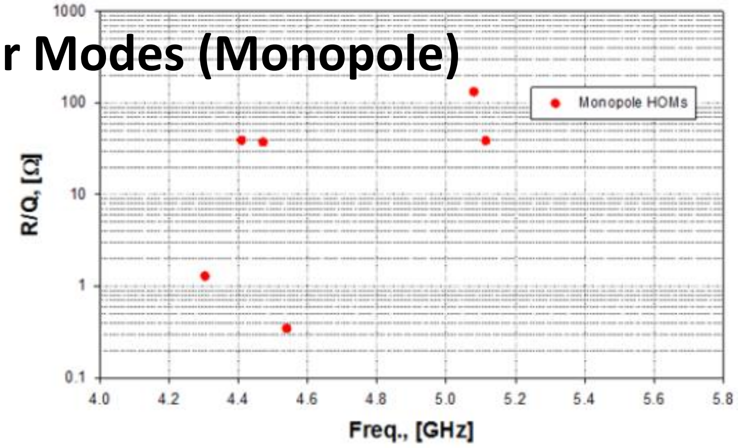
Freq., [GHz]	$(R/Q)_t$, [Ω]	Q_{ext}	R_t [MΩ/m]
2.476	0.03	2400	3e-3
2.675	5.0	6800	1.9

(Operation mode: f=2.815 GHz, $(R/Q)_t$=523 Ohm, Q_{ext}=5.3e5)



In the preliminary 2K cold tests of QMiR the measured deflecting voltage (2.7 MV) exceeded the design goal of 2.0 MV !

Higher Order Modes (Monopole)



Freq., [GHz]	R/Q, [Ω]	Q	Rs, [MΩ x GHz]
4.304	1.3	55	3E-4
4.409	39	530	0.09
4.471	37	400	0.07
4.530	0.35	4900	8E-3
5.080	132	390	0.26
5.114	39	108	0.02

Cavity is HOM-free above at f > 5.2 GHz

QMiR Scaled for ILC

V Yakovlev (FNAL)

Loss Factor:

- $k_{//} \sim 1/\sigma$ and for $\sigma = 0.3$mm, $k_{//} = 45$ V/pC or ~3 W radiated power
- Dissipated in beam channel, not in the cavity itself (50% each direction) – Not an issue!

Cryo Losses:

- At 2K for N2-doped cavity would expect:
  - 2.6 GHz @ 0.135 MV: $R_s = 30$ nΩ, $P_c = 0.6$ mW
  - 3.9 GHz @ 0.9 MV: $R_s = 68$ n Ω, $P_c = 0.6$ mW

  } Not an issue!

Surface Fields:

- For 2.8 GHz @ 0.9 MV, $E_p = 25$ MV/m and $B_p = 35$ mT
- Expect 3.9 GHz to be similar; as V~1/f and gap ~f (expect to be wider gap).
- Poles to be profiled for optimum EM-field parameters (known procedure)

Kick Factor:

- For ANL/SPX QMIR $k_t = 0.5$ V/pC/m; so for a 1 mm displacement, vertical kick ~ 1.6 V – Negligible

RF Power:

- For ILC: I_b of 5.8 mA and offset x = 1 mm, deflecting voltage (V) power $P_g = 2(kx)VI_b = 300$ W

HL-LHC CC Global Collaboration

Cavities

Old Dominion University

Fermilab

Brookhaven National Laboratory

SLAC National Accelerator Laboratory

CERN

Lancaster University

Cryomodules

TRIUMF

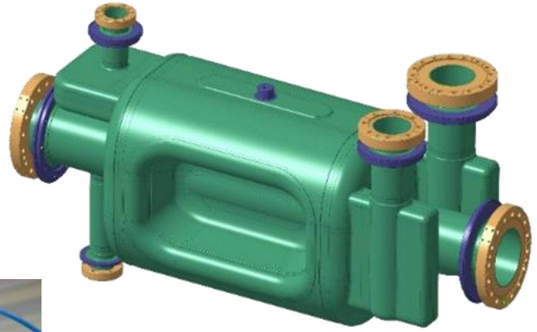
UKRI Science and Technology Facilities Council

HL-LHC Crab Cavities (DQW and RFD)

R Calaga (CERN)

DQW (V-ATLAS)
(up to to 6 MV)

RFD (H-CMS)
(up to 7 MV)



Requirements

$$f_0 = 400\ \text{MHz}$$

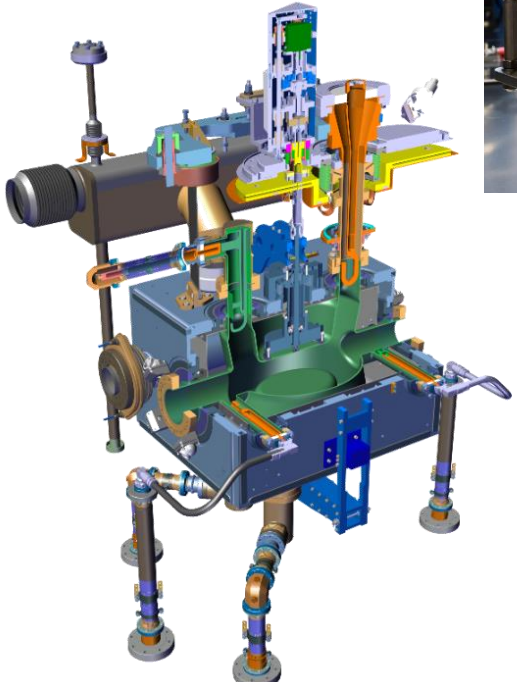
$$V_T = 3.4\ \text{MV/cavity*}$$

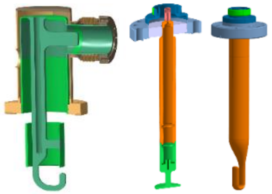
$$(E_p, B_p < 40\ \text{MV/m}, 70\ \text{mT})$$

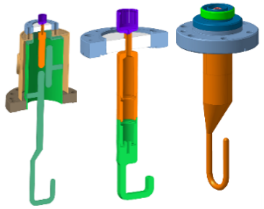
Beam aperture = 84 mm

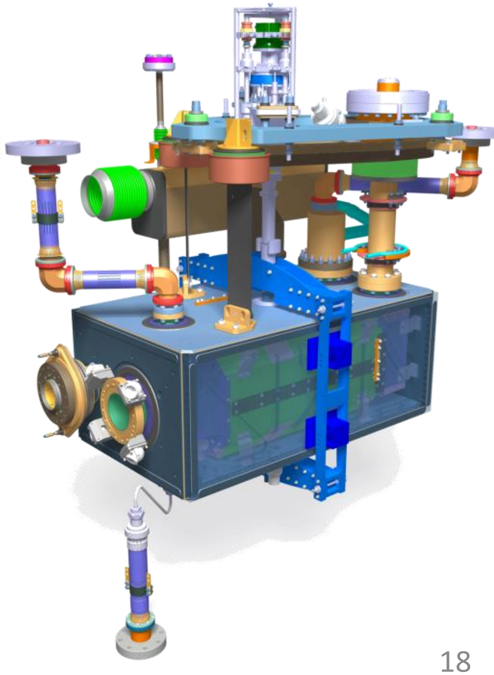
Common FPC = 40 kW-CW

Operating Temp = 2 K





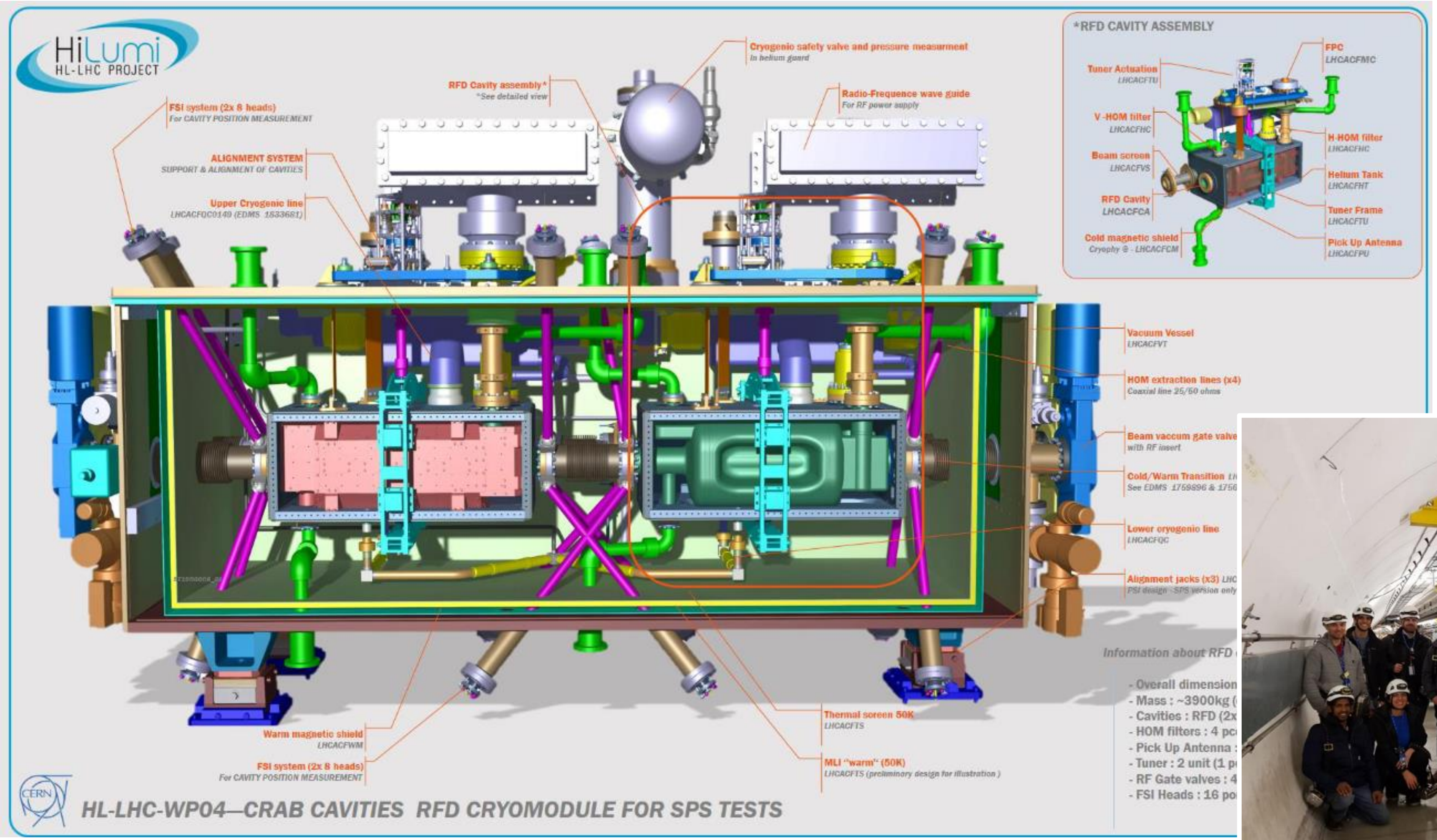




Both cavities use 2K cryperm magnetic shield inside helium jacket

HL-LHC Crab Cavity Cryomodule (RFD)

R Calaga (CERN)



HOM lines (green), alignment (magenta)

Length ~ 3m

DQW CM test in SPS (2018)

ILC CC Workshop Discussion/Questions

BDS Implications for the various CC technology and frequency options:

- Expected noise sources.
- IR optics configuration and impact on CC's.
- Beam dynamics impacts; bunch-by-bunch, bunch trains etc.

} Refined CC specifications?

- Luminosity performance and expected tolerances - cavity roll and appropriate mitigation.

CC Solution:

- HOM damping and impedance requirements.
- Manufacturing simplification by direct machining from Nb ingot.
- Cryomodule integration options – main linac compatible or top-loaded (i.e. HL-LHC).
- Energy upgrade provisions, impact on 250Gev CC solution – space, modularisation etc

Pre-Lab Planning:

- R&D, prototyping and CC down-selection process – how/when.
- Collective contributions and expectations for Pre-Lab activities.
- Realistic scope, timescales and responsibilities for the Pre-Lab phase.

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Discussion points for next session!

Conclusions

- Various CC technology solutions feasible for ILC:
  - Elliptical – ILC (RDR and TDR)
  - DQW – EIC, HL-LHC
  - RFD – EIC, HL-LHC, Jlab Upgrade, JLEIC and MEIC
  - QMiR – SPX
  - WOW – EIC
- Significant alternative CC developments since ILC TDR in 2013.
- Must note that the CC system is not as ‘mature’ as the Main Linac.
- A number of organisations identified as potential collaborators for ILC Pre-Lab phase for CC system developments.
- HL-LHC demonstrates highly effective collaborative approach for global CC technology development (SPS CC CM R&D and test 2018):
  - BNL, CERN, FNAL, Lancaster University, ODU/Jlab, SLAC, TRIUMF and UKRI-STFC.

ILC Pre-Lab has a strong possibility to follow this successful realisation!

MANY THANKS

Questions?

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