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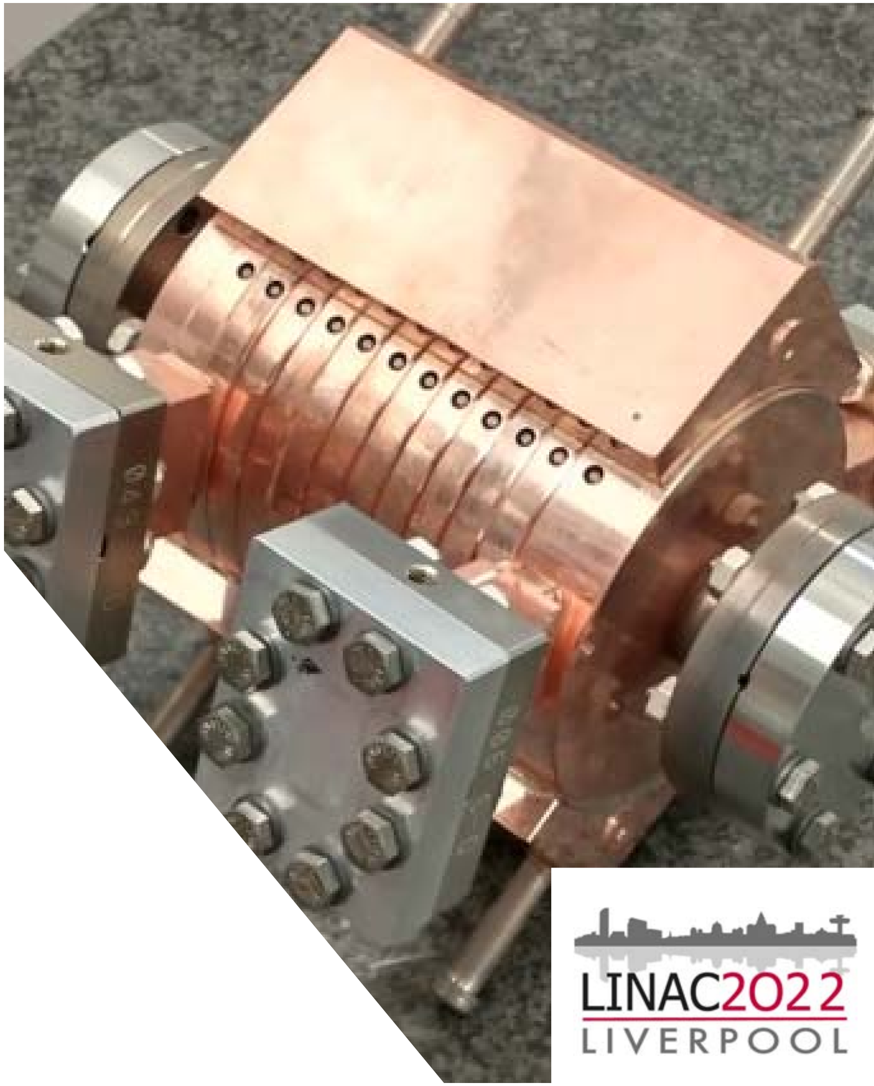
Crab and Deflecting Cavity Development for Linear Accelerators



Peter McIntosh STFC Daresbury Laboratory

31st Linear Accelerator Conference,
28th Aug – 2nd Sept, Liverpool, 2022

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Outline

- **Crab/Deflecting Cavities and Applications**
- **Beam Diagnostics:**
  - VELA/CLARA - STFC
  - PolariX – CERN/DESY/PSI
- **Beam Separation:**
  - ARIEL - TRIUMF
- **Colliders:**
  - CLIC – CERN
  - HL-LHC – CERN (Not Linear ☹)
  - EIC – BNL (Not Linear ☹)
- **Innovative Crab Technologies**
  - ILC - Global
- **Summary**

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Acknowledgements

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- Andrei Lunin (**FNAL**)
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- Toshiyuki Okugi (**KEK**)
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- Silvia Andres Verdu (**BNL/CERN**)
- Ben Wooley (**CERN**)
- Binping Xiao (**BNL**)
- Slava Yakovlev (**FNAL**)
- Akira Yamamoto (**KEK**)
- Kirk Yamamoto (**KEK**)

THANK YOU!

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Crab and Deflecting Modes

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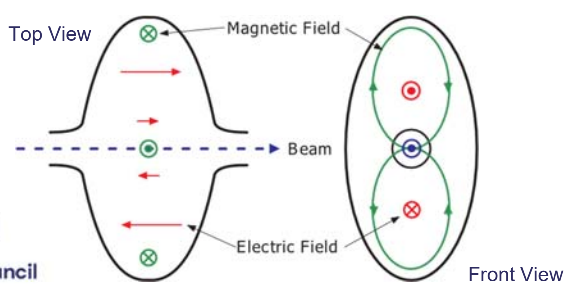
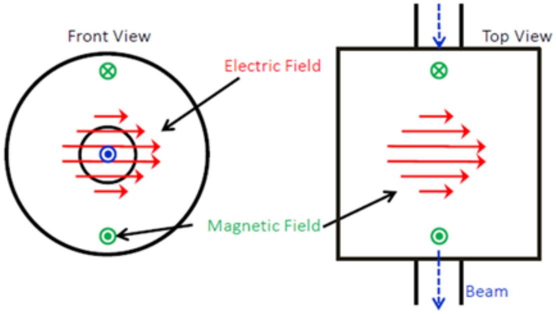
TM$_{110}$ type dipole mode:

- Net deflection is mainly from transverse Magnetic field contribution.
- **Has Lower Order Mode (TM$_{010}$ mode).**
- Squashed elliptical geometry:
    - Separates the two polarizations of same dipole mode frequency.
    - Cavity is typically large wrt wavelength.
- Able to accommodate large apertures.
- **Good for high frequency applications.**



TEM/TE$_{111}$ type dipole mode:

- Net deflection mainly from transverse Electric field contribution.
- **No LOM to extract/suppress.**
- Strong asymmetric geometries.
- Can't be a pure TE$_{111}$ mode where the contribution from electric and magnetic fields cancel each other.
- **Good for low frequency applications.**



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Crab and Deflecting Cavity Applications

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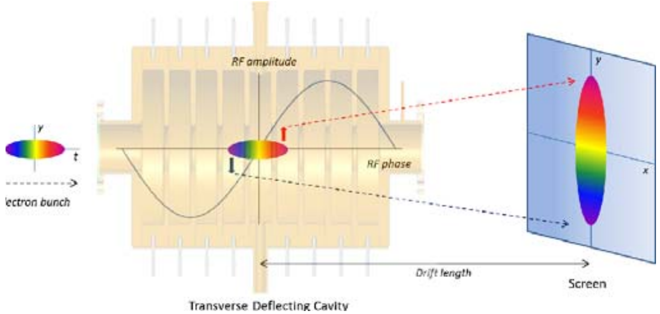
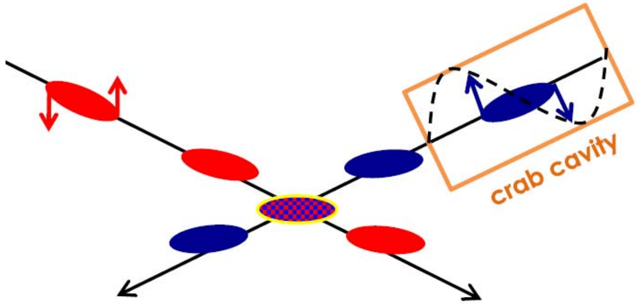
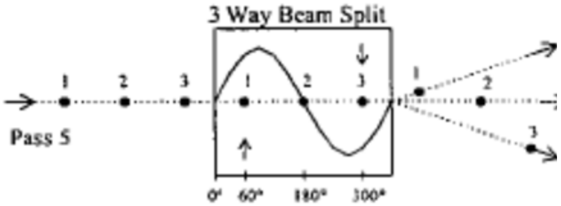
Beam Diagnostics – Bunch Length



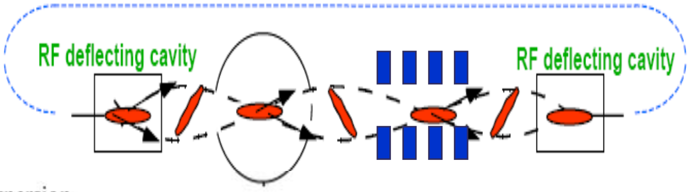
Colliders – Maximise Luminosity

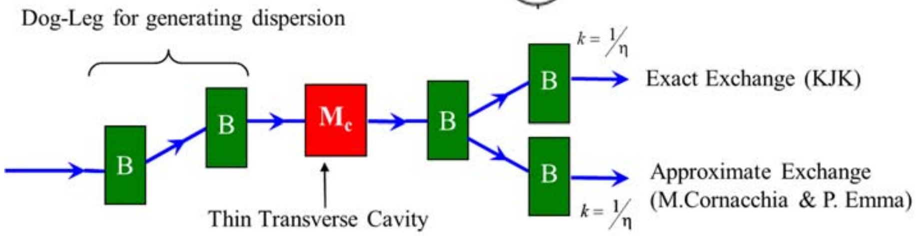


Beam Separation – Experiment Delivery



X-Ray Pulse Compression/Beam Emittance Exchange (not covering)





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VELA – Transverse Deflecting Cavity (TDC) @ Daresbury

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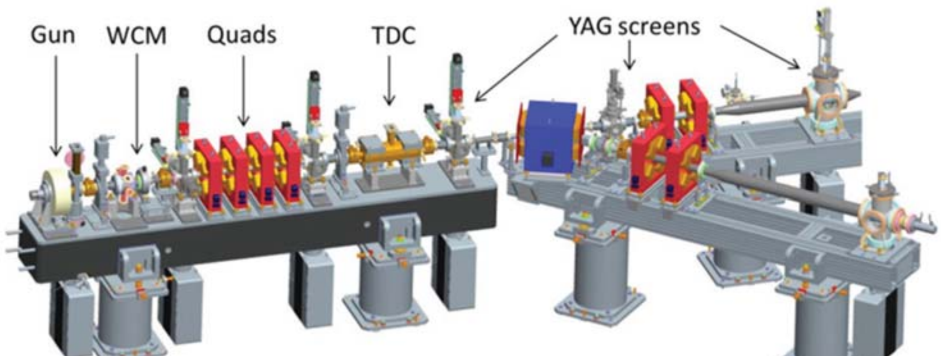
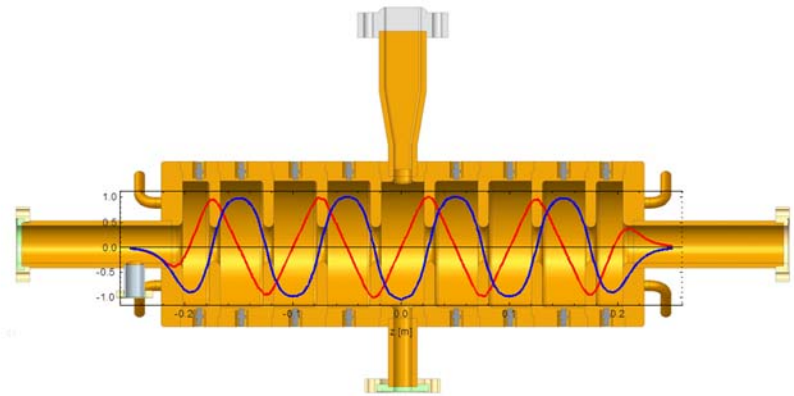
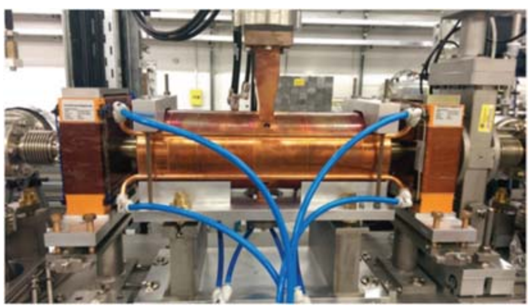


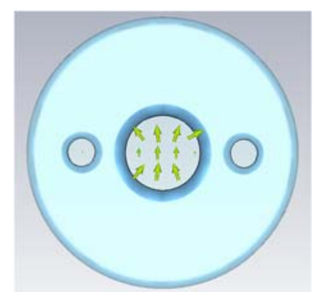
5 MeV Versatile Electron Linear Accelerator



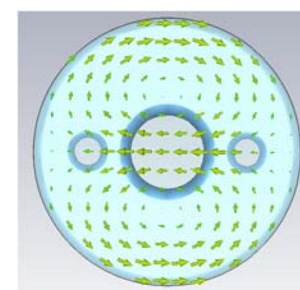
Normalised on-axis fields through the cavity of the components which contribute to the beam deflection Re{Ey} (red) and Im{Hx} (blue).



Parameter	Value	Unit
RF frequency	2998.5	MHz
Repetition rate	10	Hz
Time resolution	10	fs
Operating mode	TM110-like	
Nearest mode separation	> 5	MHz
Available RF power	5	MW
Maximum transverse voltage	5	MV
RF pulse length	< 3	µs
Average RF power loss	< 150	W
Phase stability	0.1	°
Number of cells	9	
Cell iris radius	16	mm
Outer cell beampipe radius	17.5	mm



Ey at iris



Hx in the cell

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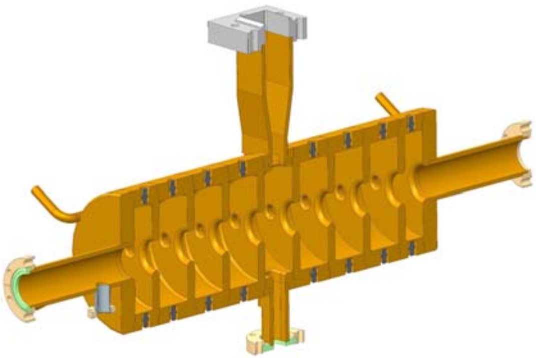
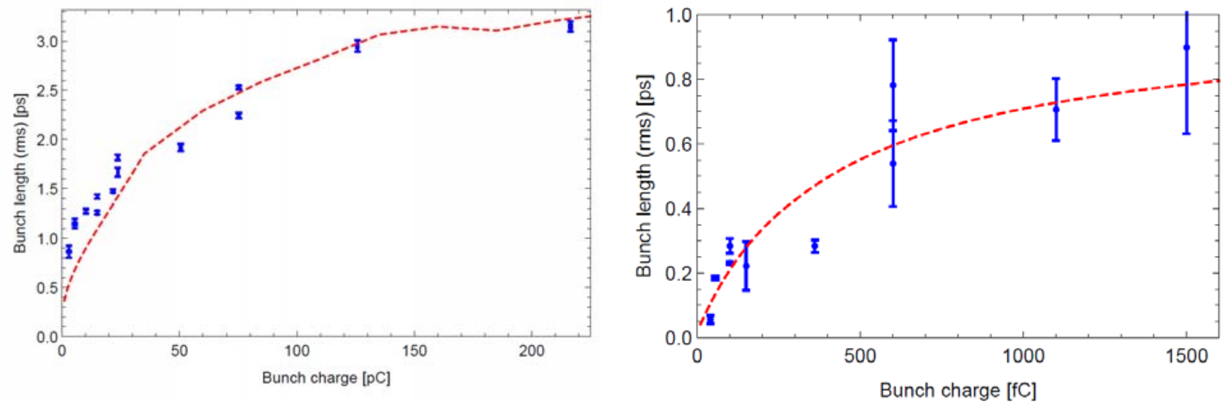
VELA – TDC Operation



Cross-section of prototype cell

Bunch Length vs Bunch Charge



Beam measurements performed on VELA – could measure as low as 50 fs bunch length at lowest measurable bunch charge (50 fC), therefore believe 10 fs measurements would be possible.

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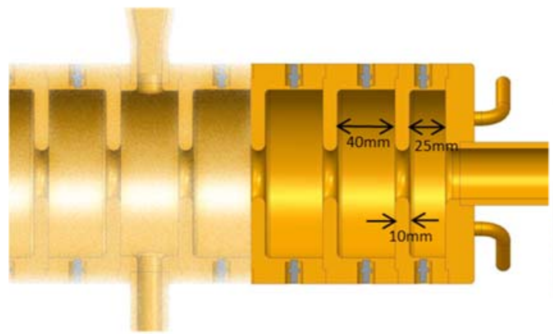
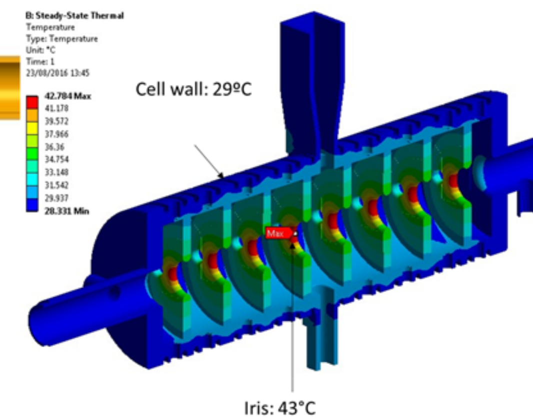
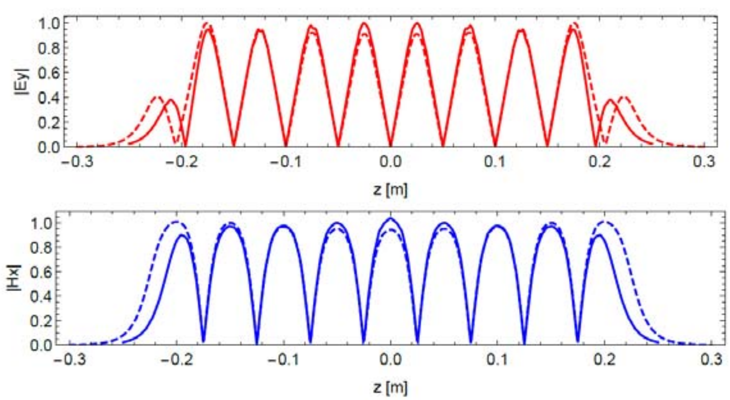
CLARA – TDC Preparations @ Daresbury

On VELA at 5 MeV, TDC gives an unwanted vertical displacement, a change in beam energy and energy spread when off-axis, as Ez scales with radius (Panofsky-Wenzel).

Can correct for this error by altering the end-cell design and utilising corrector magnets at entrance & exit of the TDC.







Dashed = original cavity design
Solid = final cavity design

CLARA TDC design same as VELA, but 10 MV voltage, for 10 fs rms resolution at 250 MeV:

- E_p 80 MV/m (limit 250 MV/m)
- H_p 284 kA/m (limit 350 kA/m)
- Doesn't require coupler or cavity redesign.

Increased repetition rate from 10 – 100 Hz.
New cell cooling system – improved field alignment.
Expected to be installed on CLARA in 2023/24.

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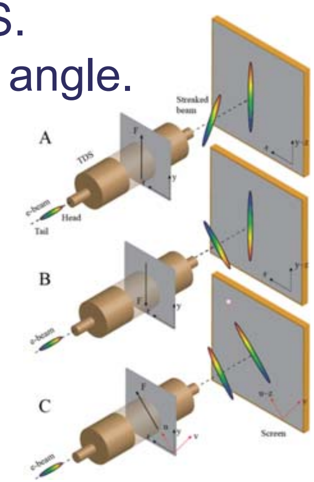
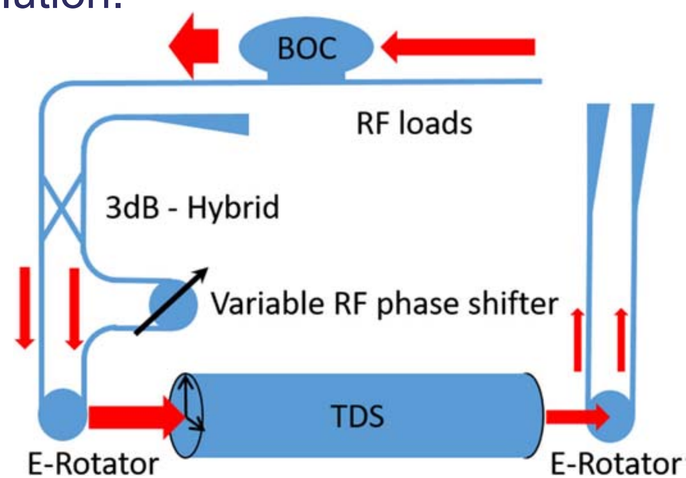
PolariX – Polarisable Transverse Deflecting System (TDS)

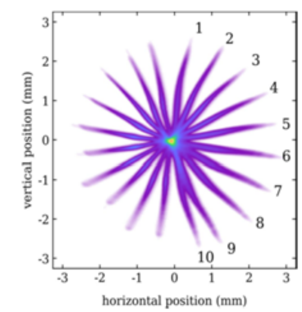
- DESY-CERN-PSI collaboration formed in 2018 to develop full X-Band TDS.
- Change the orientation of the TDS streaking field to an arbitrary azimuthal angle.
- With experimental verification to be performed at:
  - SwissFEL (ATHOS) – PSI (sub-fs and polarised)
  - FLASHForward (polarised 2020), FLASH-2 and SINBAD-ARES - DESY
- Longitudinal bunch profile and slice beam properties (energy spread, emittance etc.) with sub-fs resolution.



Parameters	SINBAD	FLASH II	FLASHForward	ATHOS SwissFEL	Unit
Charge	0.5-30	20-1000	20-500 (driver) 10-250 (witness)	10-200	pC
Norm. emit. (rms)	0.1-1	0.4-3	2.0-5.0 (driver) 0.1-1.0 (witness)	0.3	mm
Bunch length (rms)	0.2-10	<3-200	50-500 (driver) 1-10 (witness)	2-30	fs
β function @TDS	10-50	7-20	50-200	50	m
Beam energy	80-200	400-1400	500-2500	3000	MeV
Rep. rate	10-50	10	10	100	Hz
TDS voltage	25-40	30-45	25-30	30-60	MV
# TDS	2	2	1	2	
Max. length	3	<1.91(8)	<2	4	m
TDS iris	4	4	4	4	mm
TDS frequency	11991.6	11988.8	11988.8	11995.2	MHz
Temperature	48	62	62	25-35	°C



Ref: B. Marchetti *et al*. Scientific Reports (2021) 11:3560



Streaked beams at multiple RF phases on FLASHForward

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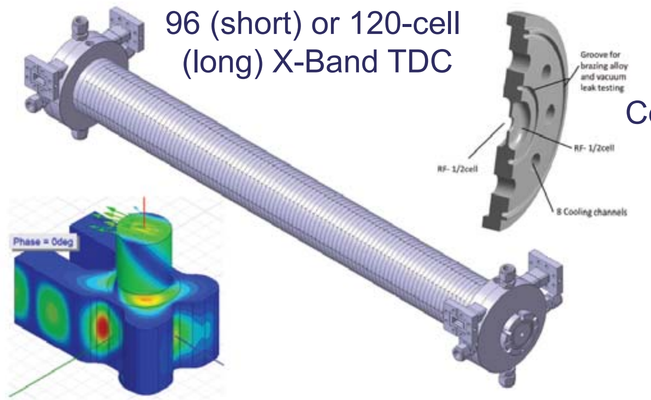
PolariX – TDS Testing at CERN

96 (short) or 120-cell (long) X-Band TDC

Cell disc

TE$_{11}$ Mode Launcher



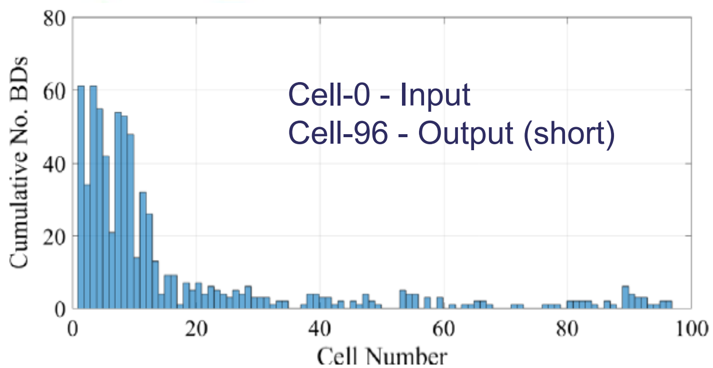
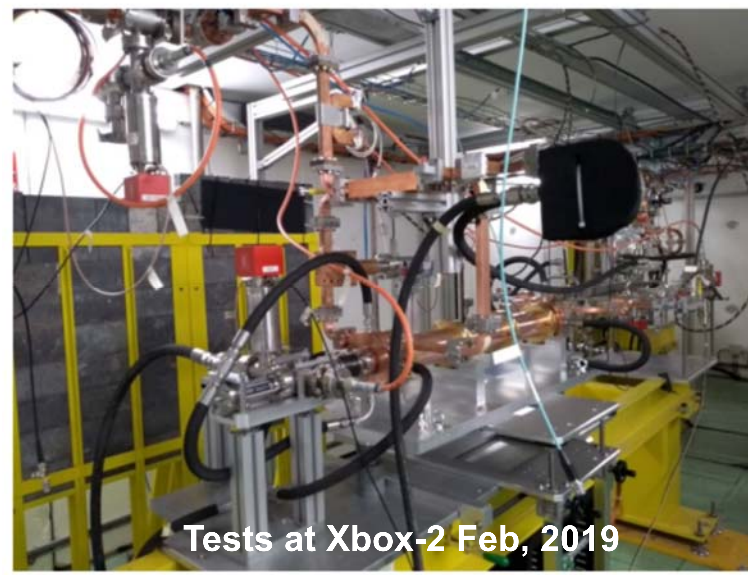
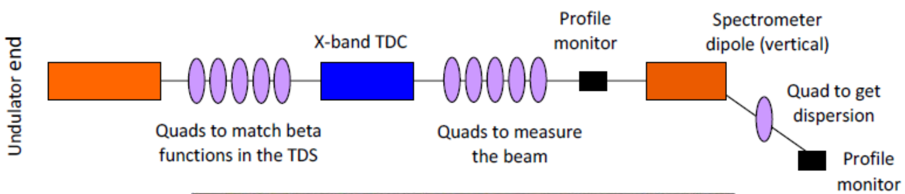
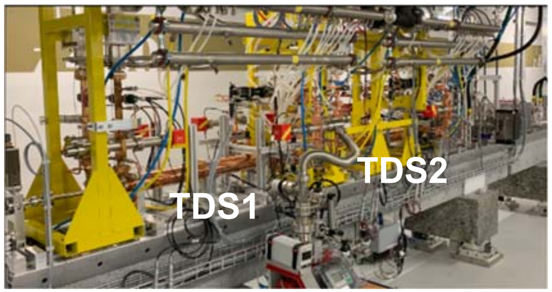


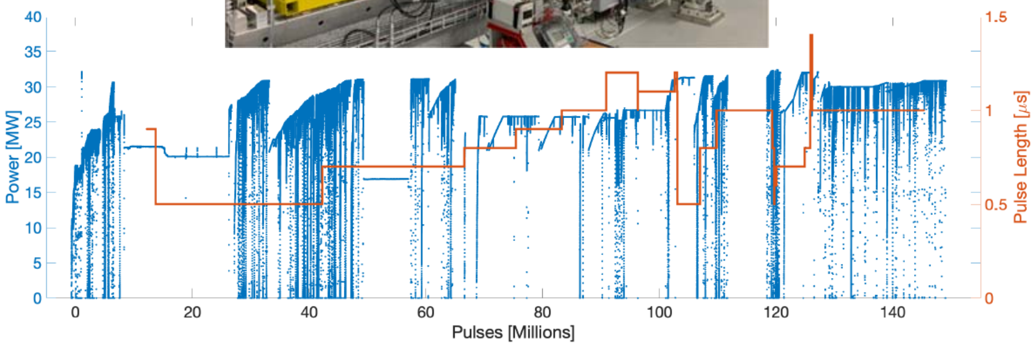
FIG. 32. Spatial distribution of breakdowns along the structure showing the number of breakdowns accumulated by each cell.



PolariX – Operation on ATHOS @ SwissFEL

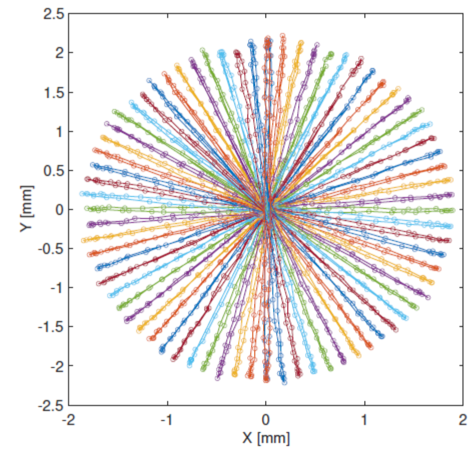




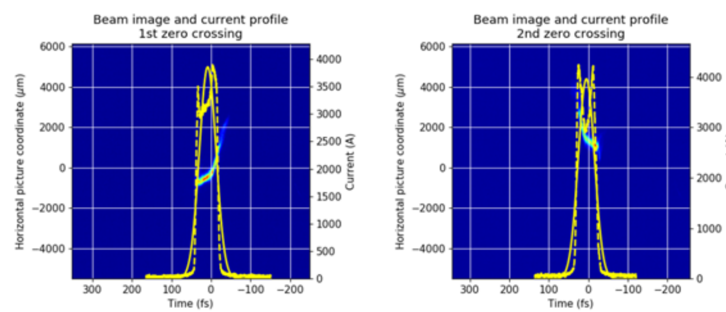


Providing 135 MW peak power at TDS and 80 MV integrated deflecting voltage.

- Bunch centroid on BPM downstream of the TDSs as global RF phase varied – 5°/scan.
- Measurements after few days conditioning (10 MW, short RF pulses) - targeting sub-fs resolution.

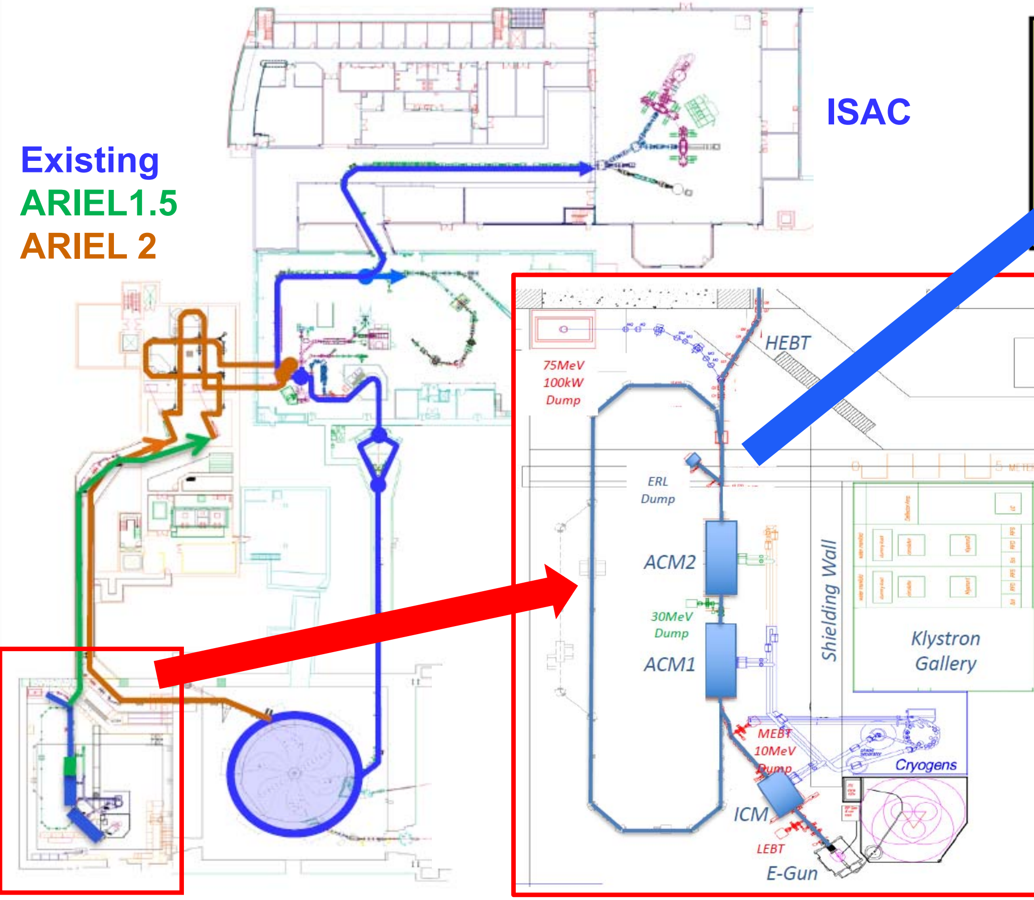


- 21 fs (rms) pulse duration, 2.36 fs resolution and calibration factor 33.89 μm/fs measured.

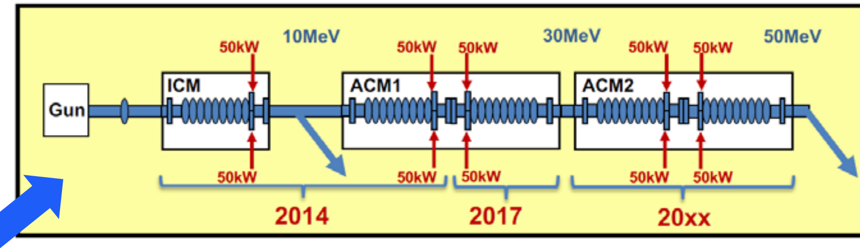


Ref: P. Craievich *et al*. RF Conditioning and First Experiences with the PolariX TDS at PSI, FEL22

ARIEL E-Linac at TRIUMF



ARIEL E-Linac



Provision for RLA and/or ERL.

Recirculating Linac (RLA):

- Increase energy for RIB production.
- **Single user mode.**

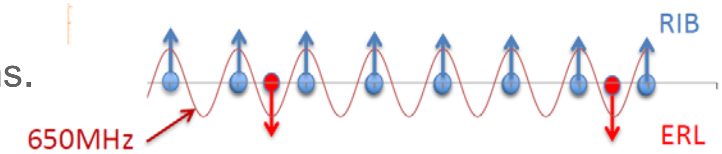
Energy Recovery Linac (ERL):

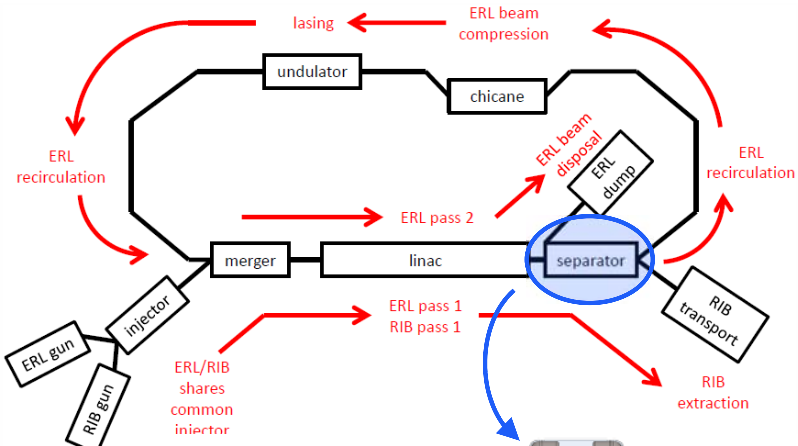
- IR and UV FELs.
- Intense THz source (FEL/CSR).
- X-ray CBS.
- **Dual user mode with interleaved bunches.**

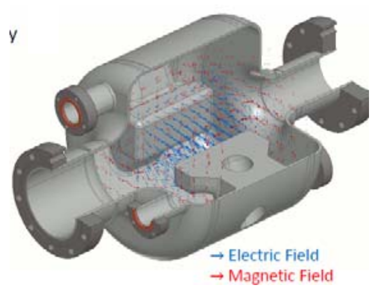
E-Linac ERL Beam Separation

Dual-use possible with two interleaved bunch trains into 1.3GHz buckets:

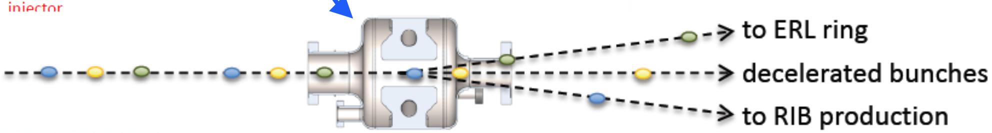
- 650MHz pulse train - single pass acceleration for RIB production – low brightness.
- 650MHz/n pulse train for ERL – high brightness.
- 2 electron guns required to provide RIB and ERL beams.
- **650MHz RF separator used to separate the beams.**







Parameter	Value	Unit
Resonant frequency	650	MHz
Inner Diameter	204	mm
Inner Length	175	mm
Aperture	50	mm
Deflecting voltage	0.3 – 0.6	MV
Shunt impedance, $R_{\perp}/Q$	625	Ω
Geometry Factor	99	Ω
Peak electric field	9.5 – 19	MV/m
Peak magnetic field	12 – 24	mT
RF power dissipation at 4.2 K	0.35 – 1.4	W



‘Post and Ridge’ Deflecting Cavity

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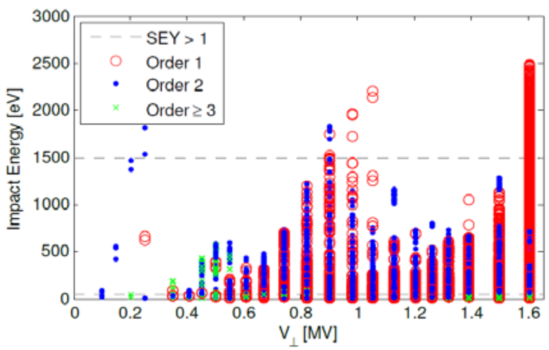
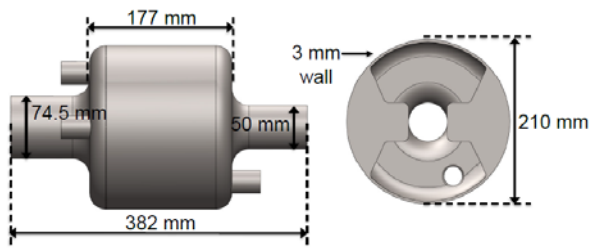
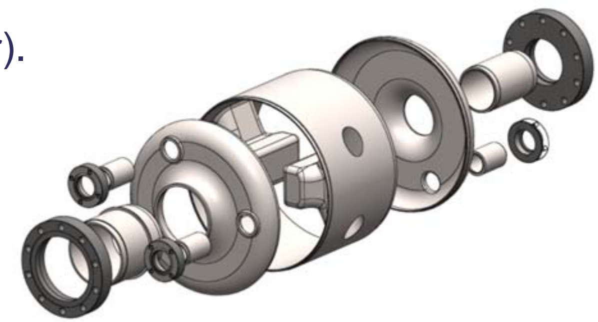
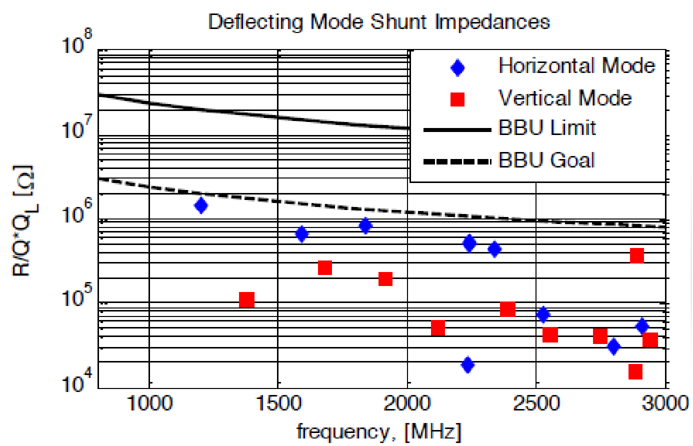
To provide more opportunities for simplified manufacture:

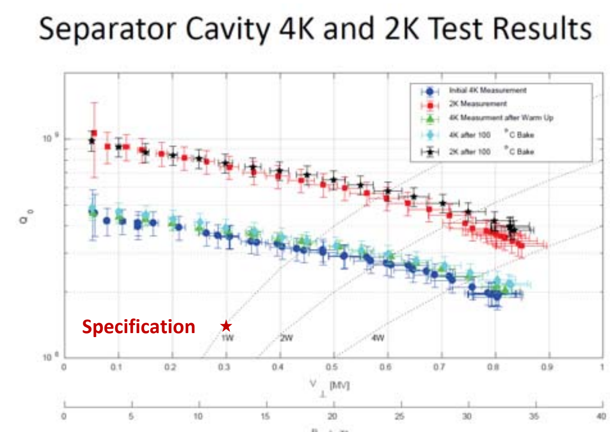
- Use of reactor-grade Nb material (RRR = 45).
- Central-ridge section machined from single Nb billet (<10 Hz/mbar).
- TIG-welding of all Nb-Nb welds.











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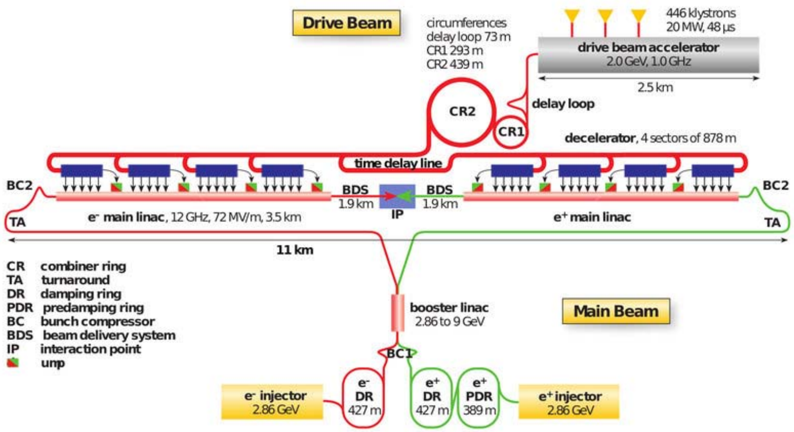
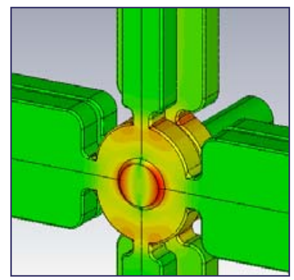
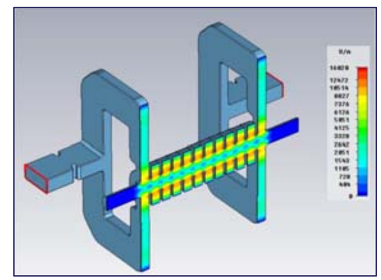
CLIC Crab Cavity (Lancaster U/CERN)

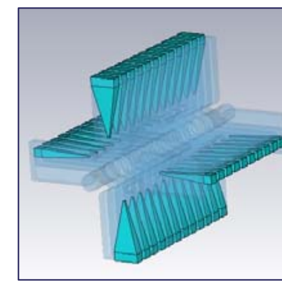


CLIC CC Design

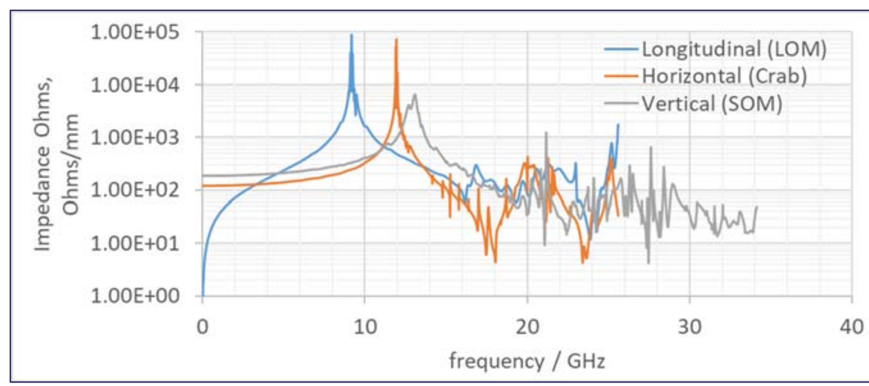
- Waveguide on-cell damping with SiC loads for damping.
- Wide waveguides needed to damp the opposite-plane crabbing LOM mode.



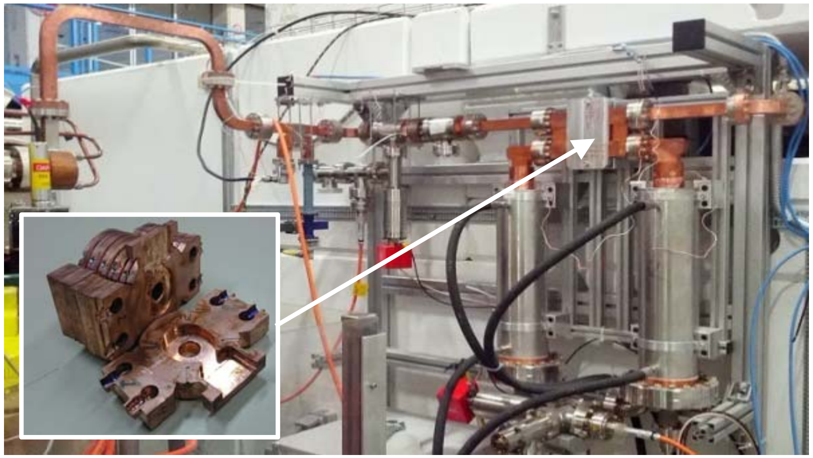


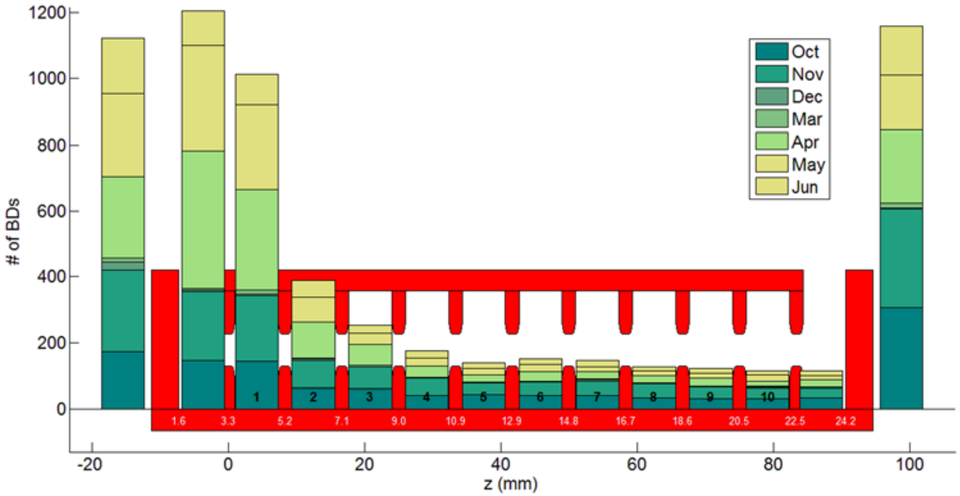


Crab Cavity Specification	Value
Frequency (GHz)	11.9942 – 12-cell
Mode	$2\pi/3$, TM_{110} BW TW
Bunch Rotation (mrad)	10
Deflecting Voltage (MV)	2.55/cavity
RF Power (MW)	14
Max surface peak field (MV/m)	250
Timing Tolerance for 2% Luminosity loss (fs)	4.4



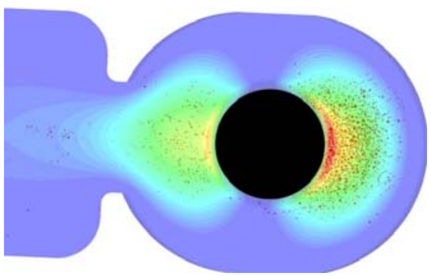
Undamped CLIC CC Tests @ CERN

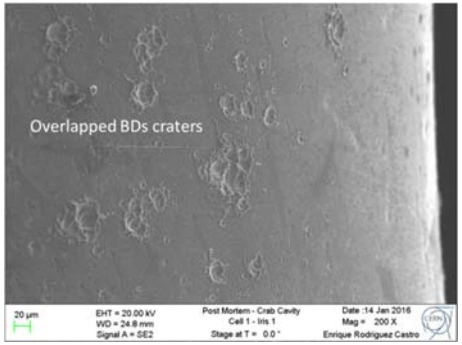




- Undamped CC tested at Xbox-2 in 2017.
- **CC conditioned to 43 MW power, 200 ns pulses, BDR 3e-6 – 2x design gradient!**
- Breakdown analysis shows breakdown at high E-field regions of coupling and C1 cells.

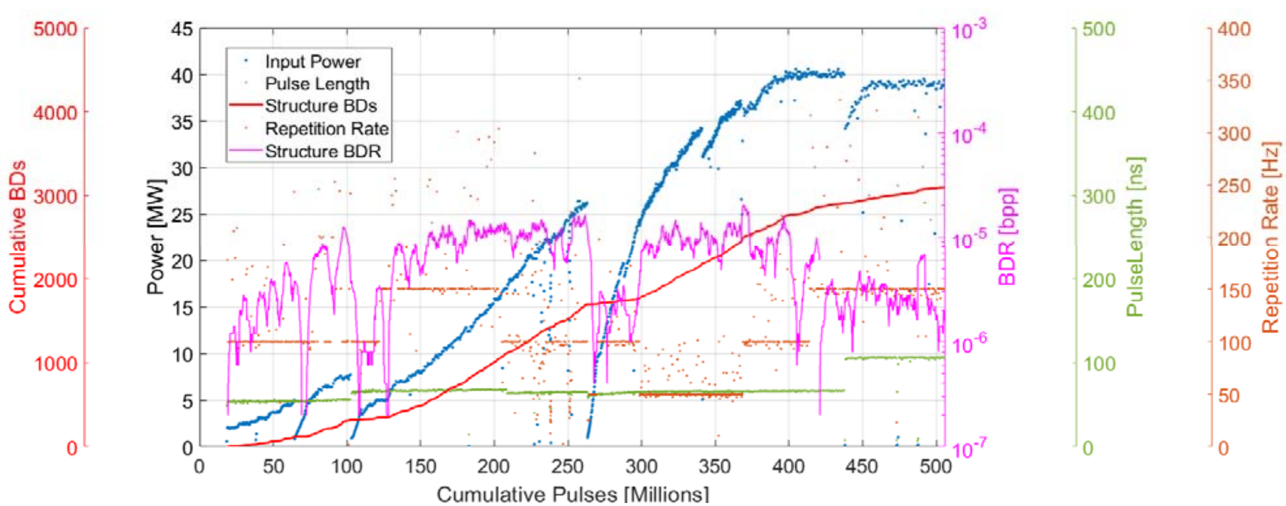
Cell 1 – Iris 1

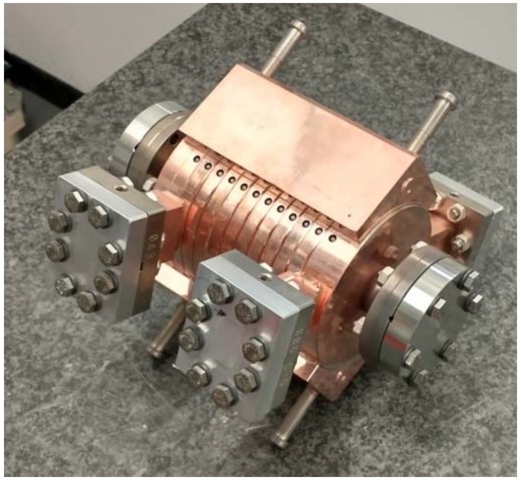




Damped CLIC CC Tests @ CERN

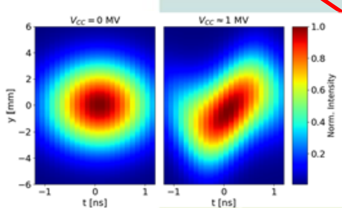
- Damped CC tested at Xbox-3 in early 2022.
- Power at BDR of 10^{-6} with 120 ns pulses at up to 200 Hz repetition rate:
  - Undamped structure >40 MW.
  - Damped structure 38 MW.
- No significant difference in performance re: damped & undamped CC structures.



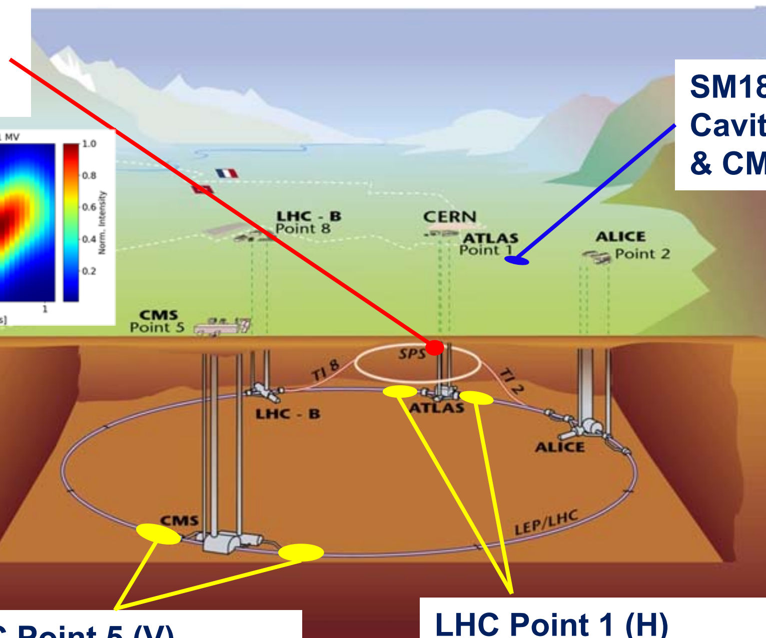


HL-LHC Crab Cavities – Circular Collider

SPS BA6
Prototype CM test with proton beam
1 DQW CM + 1 RFD CM



DQW CM SPS test in 2018

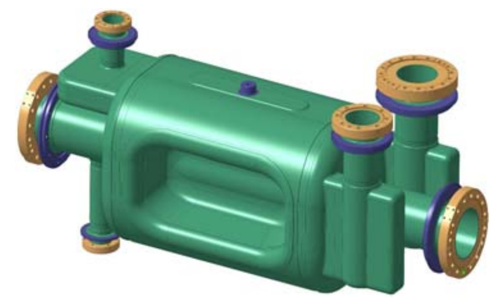


SM18
Cavity cold testing, clean room facilities & CM qualification

Double Quarter Wave (DQW) Cavity (BNL)

LHC Point 5 (V)
4 DQW CM + 1 spare

LHC Point 1 (H)
4 RFD CM + 1 spare



RF Dipole (RFD) Cavity (ODU/Jlab)

- Measured growth x4 smaller than predicted (2018 & 2022)
- Suppression of emittance growth due SPS machine impedance confirmed!
- **Predictions for HL-LHC realistic.**

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HL-LHC CC's (CERN/UK/US)

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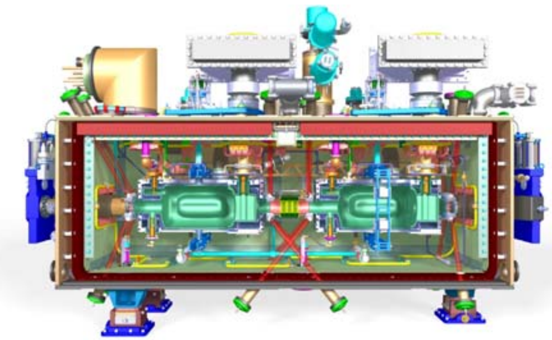
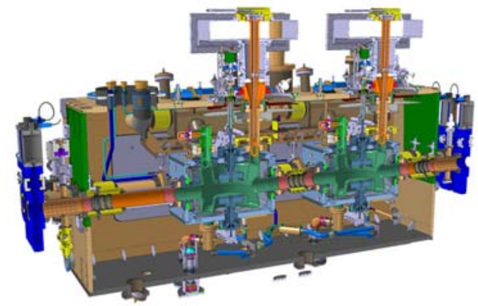
CERN/STFC/ULAN – UK (Daresbury)

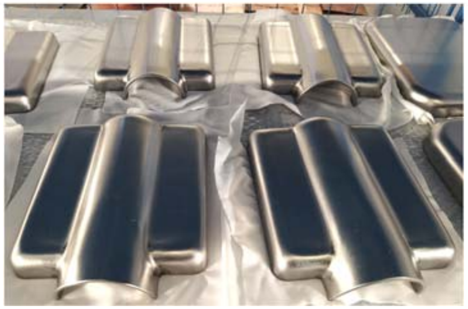
- Pre-Series RFD CM

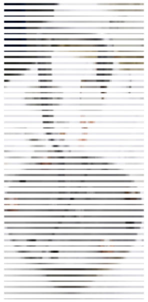


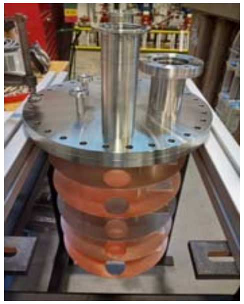
CERN/BNL/Jlab/TRIUMF - AUP

- Series DQW CM Components









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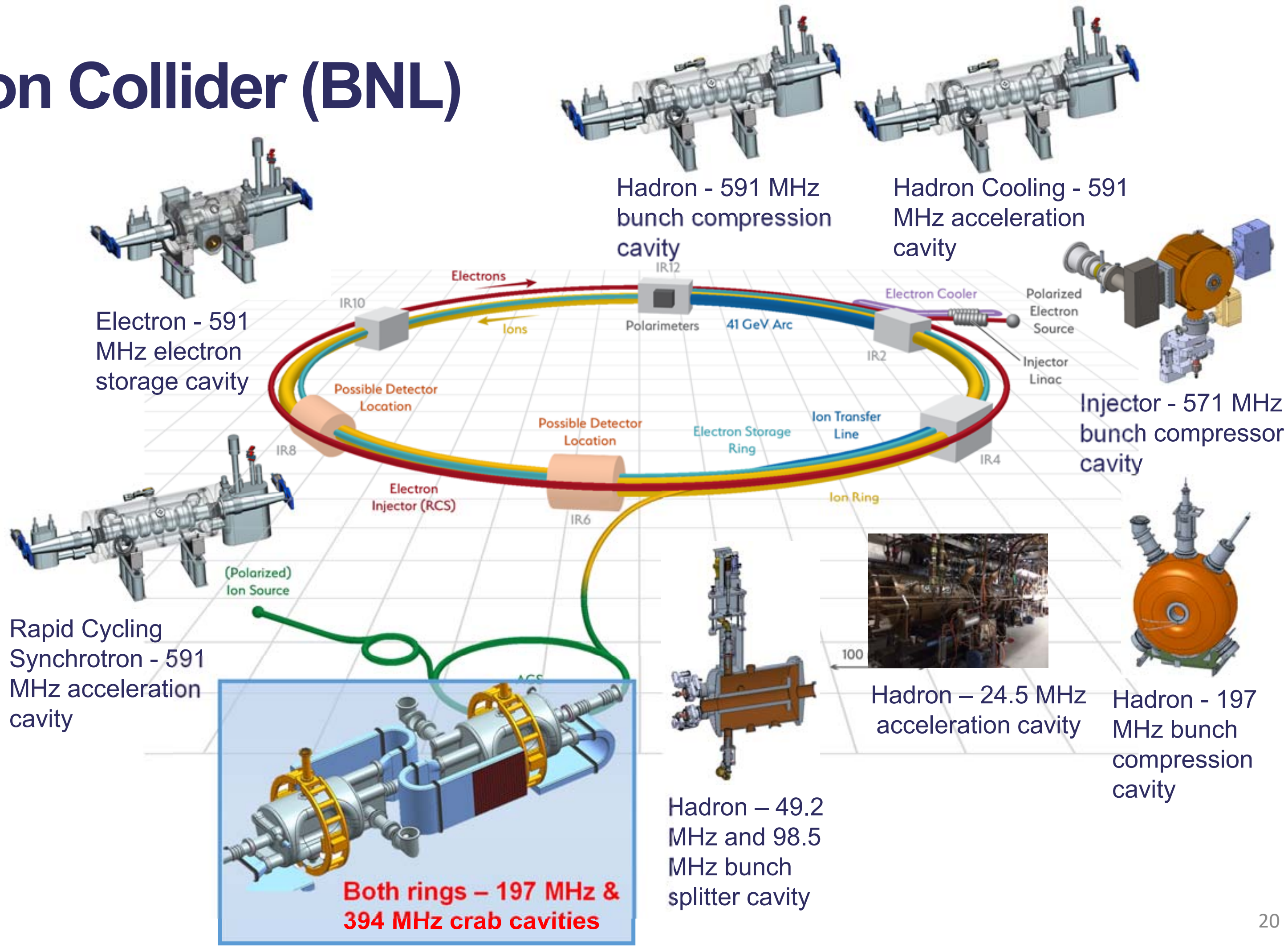
UK provides: 1 x Pre-Series RFD CM
4 x Series DQW CMs

AUP provides: 4 x Series RFD CMs

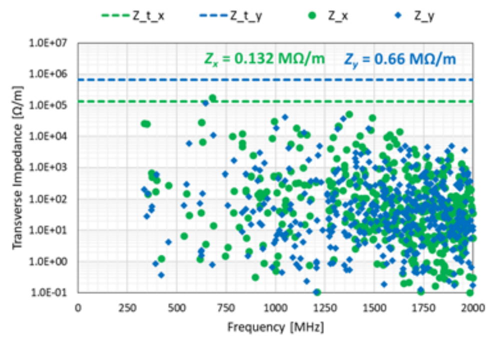
Electron Ion Collider (BNL)

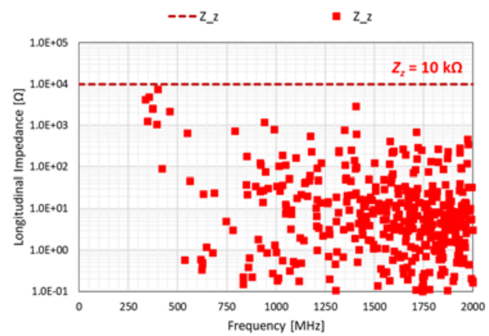
- EIC includes two storage rings:
  - Electron storage ring (ESR).
  - Hadrons storage ring (HSR).
- EIC supports 2 IRs with one on project (2nd is possible future upgrade).
- EIC RF systems are developed by JLab with BNL.



EIC Crab Cavities

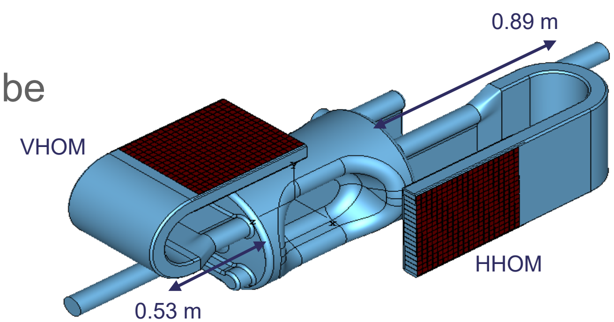
- RFD EM design complete.
- Mechanical analysis ongoing.
- A 197 MHz CC to be prototyped:
  - Fabrication development underway.
- Prototype cavity timeline:
  - Nb sheets procured.
  - Mechanical Design and Engineering Analysis – to be completed 09/2022.
  - Cavity Fabrication – to be completed 06/2024.

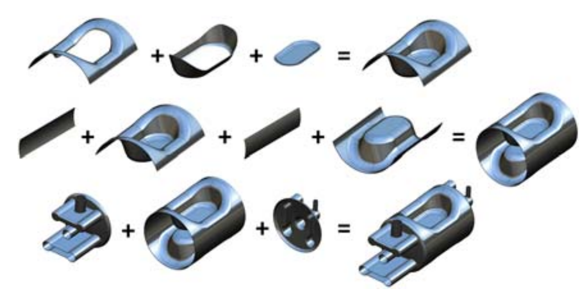




* Includes 50% safety margin!

Cavity Properties	Value	
Dipole Mode (MHz)	197	
1st HOM [MHz]	347	
E_p/E_t^*	2.87	
B_p/E_t^* [mT/(MV/m)]	5.19	
G [Ω]	97.2	
R/Q [Ω]	1161.4	
V_t [MV]	8.5	11.5
E_p [MV/m]	32.1	43.4
B_p [mT]	58.0	78.4
Cavity Length [m]	**1.5**	
Cavity Diameter [m]	**0.6**	





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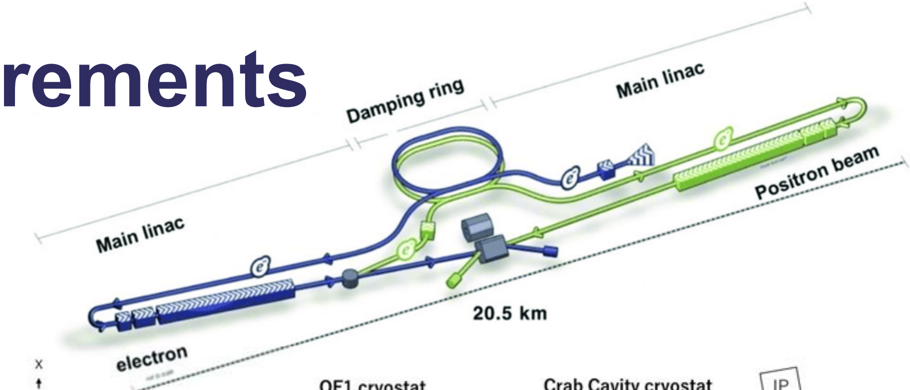
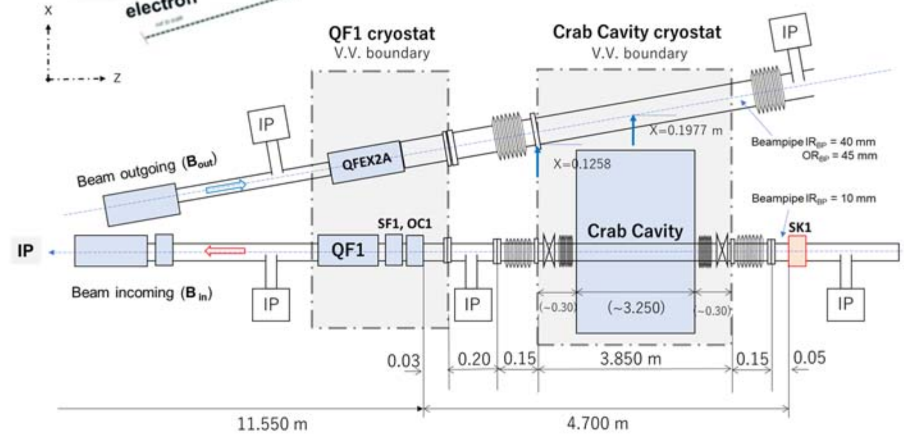
ILC Crab Cavity Requirements

CC system is indispensable for ILC!

Luminosity reduced by >80% without CCs!



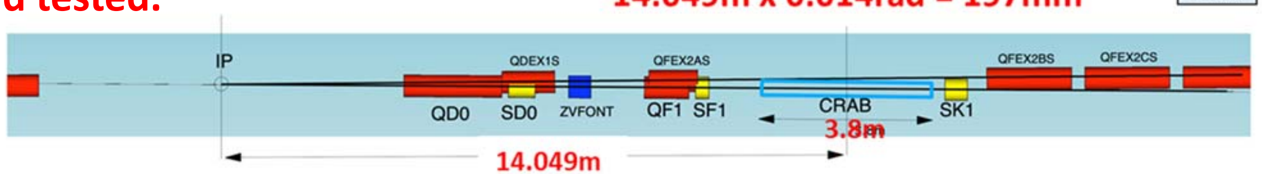
- In Aug 2020, ICFA approved formation of an International Design Team to prepare for the ILC Pre-Lab in Japan.
- No development progress since TDR (2013).
- ILC CC considered **not-matured technology** (Nomura Research Institute, Ltd):
  - **During the technical preparation period (Pre-Lab), prototype CM should be constructed and tested.**



Two beamline separation

14.049m x 0.014rad = 197mm

H. Hayano



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ILC Crab Cavity Specifications

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Parameter	250 GeV CoM Post-TDR	250 GeV CoM 10Hz Upgrade	1 TeV CoM
Beam Energy (GeV)	125		500
Crossing Angle (mrad)	14		
Installation site (m from IP)	14		
RF Repetition Rate (Hz)	5	10	[illegible]
Number of bunches	1312	2625	2450
Bunch Train Length (ms)	727	[illegible]	897
Bunch Spacing (ns)	554	366	
Beam current (mA)	5.8	8.75	7.6
Operating Temp (K)	2		
Cryomodule installation length (m)	[illegible] (incorporating [illegible]s)		
Horizontal beam-pipe separation (m)	[illegible] (centre) ±0.0266 ([illegible] end of installation [illegible])		

Parameter	250 GeV CoM			1 TeV CoM		
Cavity Frequency (GHz)	3.9	2.6	1.3	3.9	2.6	1.3
Total Kick Voltage (MV)	0.[illegible]	0.023	[illegible]	2.5	3.7	7.4
Max Ep (MV/m)	45			45		
Max Bp (mT)	80			80		
Amplitude regulation/[illegible] rms)	3.5 (for 2% luminosity drop)					
Relative RF Phase Jitter ([illegible] 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 – BDS Simulations to clarify					
Transverse impedance threshold (MOhm[illegible])	48.8, 61.7					
Cavity field rotation tolerance ([illegible] rms)	5.2 (for 2% luminosity drop)					
Beam tilt tolerance (H and V) ([illegible] and urad rms)	0.35, 7.4 (for 2% luminosity drop)					
Minimum CC beam pipe aperture size (mm)	>25 (same as FD magnets)					
Minimum F[illegible] 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					
CC System operation	CW-mode					

→ Beam Energy
→ Crossing Angle
→ CM installation length
→ Cavity Frequency
→ Kick Voltage
→ Peak Fields Ep and Bp
→ Timing tolerance
→ Field rotation tolerance
→ CC beam pipe aperture
→ CW mode operation

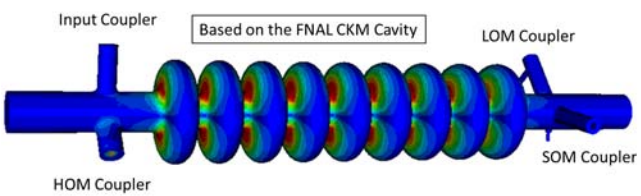
Very provisional CC studies underway!

Progress can be accessed here:

https://agenda.linearcollider.org/category/256/

Elliptical/Racetrack – (Lancaster U)

ILC RDR/TDR Crab Cavity Solution



The Cockcroft Institute of Accelerator Science and Technology

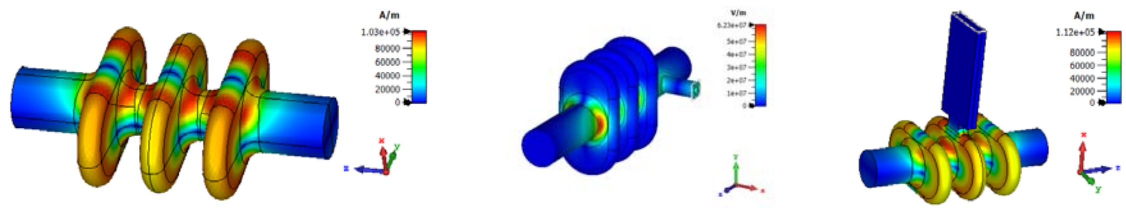
Fermilab

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

- Re-optimised to increase gradient and further separate the SOM, now achieves 1 MV @ 80 mT.
- At 3.9 GHz for 125 GeV, a single 3-cell cavity can provide 0.6 MV.
- Coax & waveguide HOM damping solutions being investigated.



- 3.9 GHz elliptical still viable - can achieve same gradient as a 1.3 GHz cavity, needs only 1/3 of the length.
- Can use 3 x 3-cell cavities (or single 9-cell cavity) per IP at 500 GeV to provide 2.5 MV – somewhat simpler to configure than several single cells.

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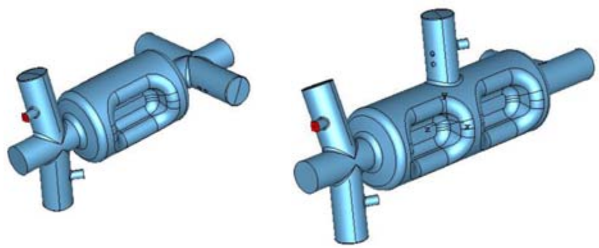
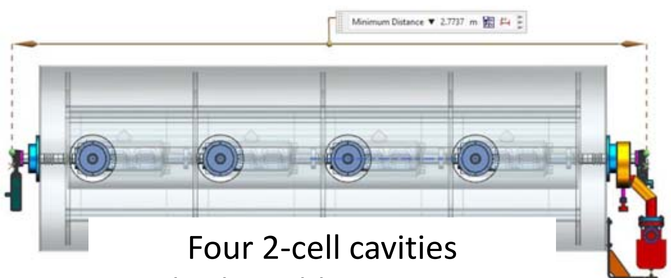
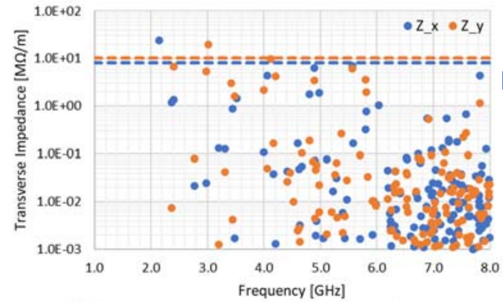
RF Dipole – (ODU/JLab)



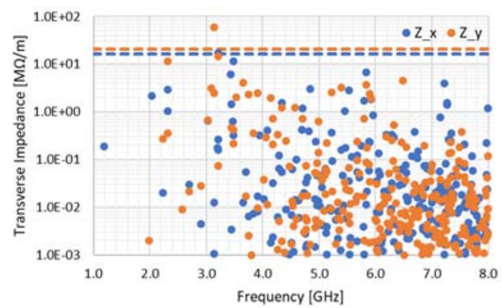


Four 2-cell cavities
Total achievable V_t = 10.8 MV

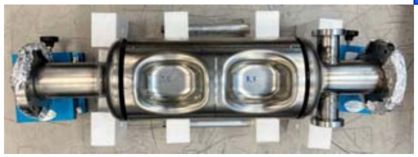
- Both 1-cell and 2-cell designs meet specifications:
  - Dimensions, peak fields with transverse voltage & HOM damping.
- Initial cavity designs are completed with FPC.
- Preliminary mechanical analysis completed.
- Options allow trade-off V_t vs CM size.



2-cell Transverse Impedances



952 MHz 2-cell Cavity



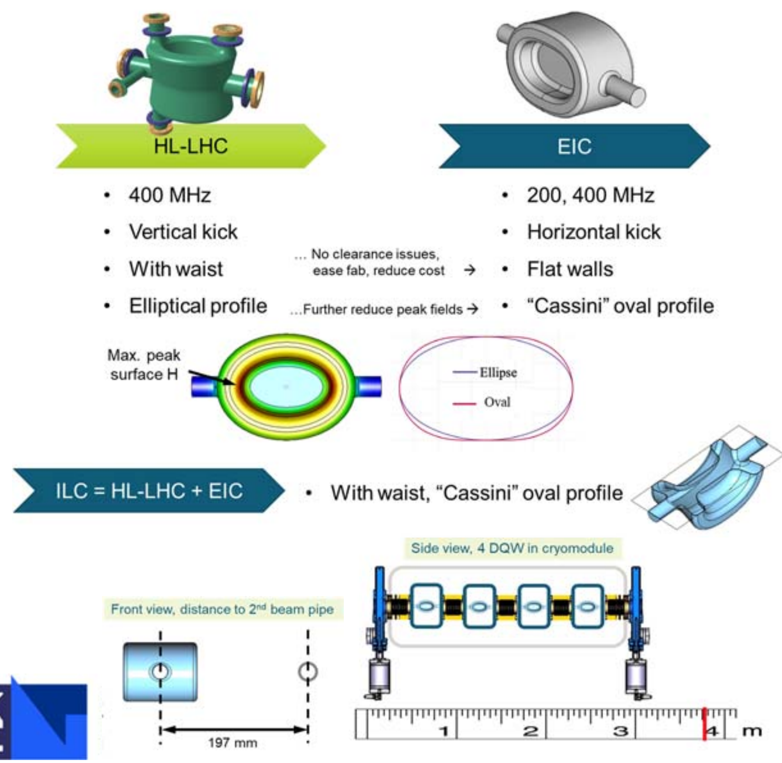
Crab cavity for JLEIC (H. Park, S. De Silva, J. Delayen)

Property	1-cell	2-cell
Operating frequency [GHz]	1.3	1.3
SOM [GHz]	–	1.198
1st HOM [GHz]	2.142	2.039
E_p/E_t^*	3.83	3.85
B_p/E_t^* [mT/(MV/m)]	6.84	6.84
B_p/E_p [mT/(MV/m)]	1.79	1.78
G [Ω]	129.9	132.2
R/Q [Ω] (V^2/P)	444.8	892.7
R_tR_s [Ω^2] (V^2/P)	5.78×10^4	1.18×10^4
Reference length $V/E_t = \lambda/2$ [mm]	115.3	115.3
V_t [MV]	1.35	2.70
E_p [MV/m]	44.8	45.0
B_p [mT]	80.1	80.0
Pole separation [mm]	25	
Beam aperture [mm]	30	
Cavity Length [mm] (flange-to-flange)	310	450
Cavity Diameter [mm]	100.3	103.4
Pole Length [mm]	80	80

Double Quarter Wave – (BNL)

For ILC at 1.3 GHz

- DQW design is evolution of HL-LHC and EIC variants.



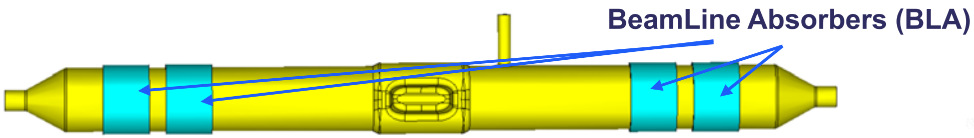
	LHC+EIC-type	LHC+EIC-type
Aperture, capacitive plate distance (mm)	30*	20
Profile	Oval, with waist	Oval, with waist
Dimensions: L x W x H (mm)	126 x 91 x 106	117 x 76 x 97
Circuit Rt/Q (Ohm)	153	311
Geometric factor (Ohm)	104	97
Epk (MV/m) at 1.86 MV	63	55
Bpk (mT) at 1.86 MV	109	84
First HOM (GHz)	1.84 (z)	2.18 (z)

Coupler integration may drive preference:

- $Q_L \sim 10^6$ has input power <2 kW for BW ~ 1.3 kHz.
- Coaxial, waveguide or both to damp HOMs.
- Single cavity gives 1.86 MV with safe peak fields.
- 4 x DQW cavities can give V_t = 7.4 MV at 1.3 GHz.
- Tuner/coupler solutions can be 'borrowed' from HL-LHC & EIC.

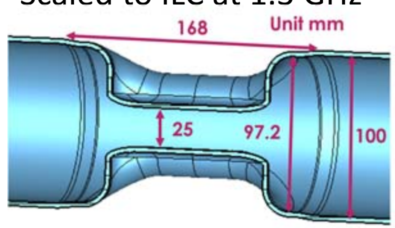
Wide Open Waveguide – (BNL)

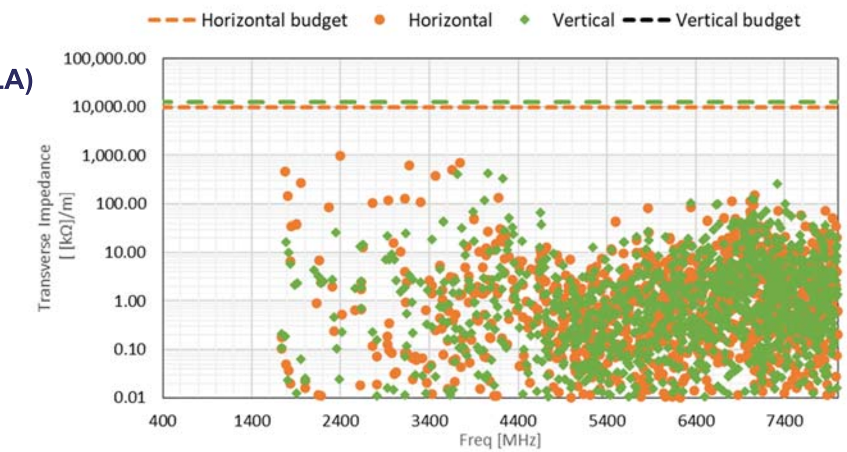
EIC WOW Cavity (RFD Type)

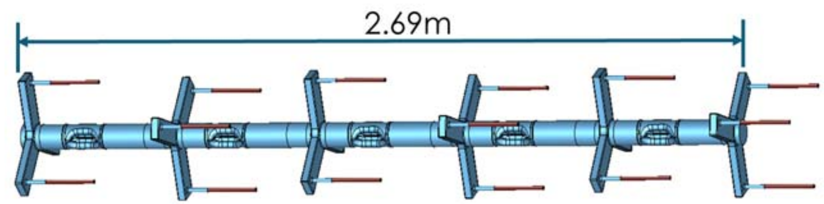


PropertyV	Value
Operating frequency [GHz]	1.300
1st longitudinal HOM [GHz]	2.299
1st transverse HOM [GHz]	1.765
E_p/E_t with $E_t=V_t/(\lambda/2)$	3.24
B_p/E_t [mT/(MV/m)]	5.75
B_p/E_p [mT/(MV/m)]	1.77
G [Ω]	130.9
R/Q [Ω]	454.3
R_tR_s [Ω^2]	59446

Scaled to ILC at 1.3 GHz





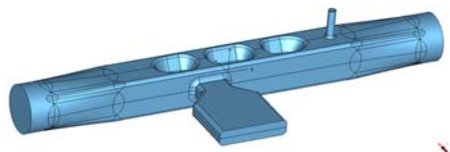


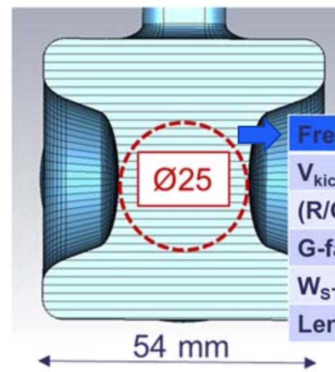
- Need 2 cavities for 125 GeV (V_t = 1.5 MV)
- 5 cavities for 500 GeV (V_t = 7.5 MV).

- Simple (robust) cavity design, with FPC/PU/BLA all outside the helium vessel.
- Excellent HOM damping performance using BLA's and waveguide dampers.

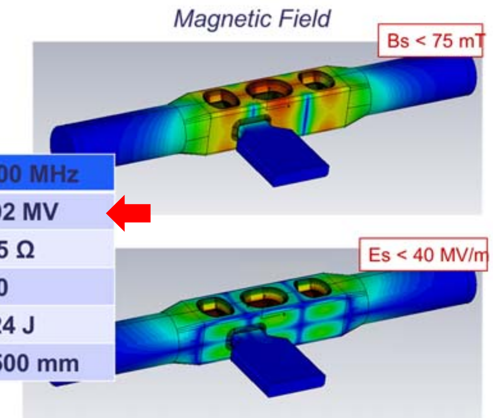
Quasi-waveguide Multicell Resonator – (FNAL)

- QMiR cavity designed as alternative deflecting cavity for APS/SPX project at ANL in 2013.



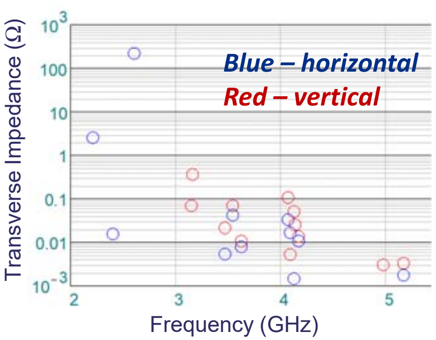


Freq	2600 MHz
V_{kick}	0.92 MV
$(R/Q)_t$	225 Ω
G-factor	130
W_{STORED}	0.24 J
Length	< 500 mm



QMiR Cavity for ILC (scaled to 2.6 GHz)

- Has 2 Same Order Modes (SOM) with low (R/Q)*Q.
- SOM/HOM external couplings $Q_{ext} < 5 \times 10^3$.
- HOM spectrum is sparse and loaded to beam-pipe.



- Compact (<0.5 m) and simple - acceptable loss/kick factors.
- No multipactor in operation voltage domain and HOM-free above 4 GHz.
- At V_t ~ 0.9 MV the cavity has acceptable surface fields, $E_p \approx 40$ MV/m, $B_p \approx 75$ mT – 2 cavities for 125 GeV.
- 4 QMiR cavities can provide V_t ~ 4 MV for 500 GeV option.

Crab/Deflecting Cavities at Linac2022

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ID	Title	Author	Day
MOPOPA21	RF Beam Sweeper for Purifying In-Flight Produced Rare Isotope Beams at ATLAS Facility	Martinez et al	Monday
MOPORI08	Improved Multi-Dimensional Bunch Shape Monitor	Martinez et al	Monday
MOPORI10	5D Phase-Space Tomography of Electron Beams at ARES	Jaster-Merz et al	Monday
MOPORI21	Development of a Transverse Deflecting Cavity as a Beam Separator for ELBE	Hallilingaiah et al	Monday
MOPORI20	Fabrication, Field Measurement, and Testing of a Compact RF Deflecting Cavity for ELBE	Hallilingaiah et al	Monday
TU1PA03	The Physics of Transverse Emittance Manipulations	Carlsten	Tuesday
TUPORI12	Beam Dynamics for the MAX IV Transverse Deflecting Cavity Beamline	Kraljevic et al	Tuesday
TUPOGE10	A Final Acceptance Test Kit for Superconducting RF Cryomodules	May et al	Tuesday
THPOGE18	Design of a 1.3 GHz RF-Dipole Crabbing Cavity for International Linear Collider	De Silva et al	**Thursday**
THPOJO02	Commissioning of a Movable Bunch Compressor for Sub-Fs Electron Bunches	Kuropka et al	**Thursday**

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Summary

Acknowledge all contributors once again!

- **Crab/Deflecting cavities provide wide variety of critical delivery capabilities:**
  - Bunch length diagnostic (single-plane and polarised)
  - Bunch rotation (collision/luminosity optimisation)
  - Beam separation (multi-user exploitation)
  - X-Ray pulse compression
  - Emittance exchange
- **Crab/Deflecting cavity development challenges:**
  - HOM/Wakefield management.
  - Amplitude, phase and rotation tolerances.
  - Complex geometries - fabrication complications.
  - Installation constraints (particularly for colliders) – drive compact technology solutions.
- **NC and SC technology solutions very well developed over large frequency range.**
- **Most recent HL-LHC and EIC CC (circular) developments for compact, innovative solutions are more broadly applicable – such as for ILC (linear)!**

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Thank you

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