800 MHz developments at CERN

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CERN, Rostock University
Jun 23, 2023

- A short history of (11+ yrs..)
- Present status for FCC

Traditio et Innovatio

Special thanks: U. Van-Rienen & E. Jensen

2012-15, LHeC Workshop

In the context of the LHeC studies, the frequency choice of 800 MHz was identified as best compromise (2012-15) with a proposal to build a **test facility** for ERL demonstration similar to LHeC

Which frequency? 700 MHz vs. 1300 MHz

Advantages 700 MHz

- Synergy SPL, ESS, JLAB, eRHIC
- Smaller BCS resistance
- Less trapped modes
- Smaller HOM power
- Beam stability
- Smaller cryo power
- Power couplers easier

Advantages 1300 MHz

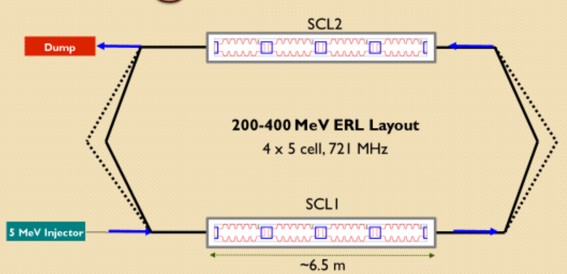
- Synergy ILC, X-FEL
- Cavity smaller
- Larger *R/Q*
- Smaller RF power (assuming same Q_{ext})
- Less Nb material needed

My main message is this:

721 MHz much larger stable beam current limit than 1323 MHz!

… but also:

ERL-TF @ CERN



	units	1-CM	2-CM
Energy	[MeV]	100	200-400
Frequency	[MHz]	721	721
Charge	[pC]	~500	~500
Rep. rate		CW	CW

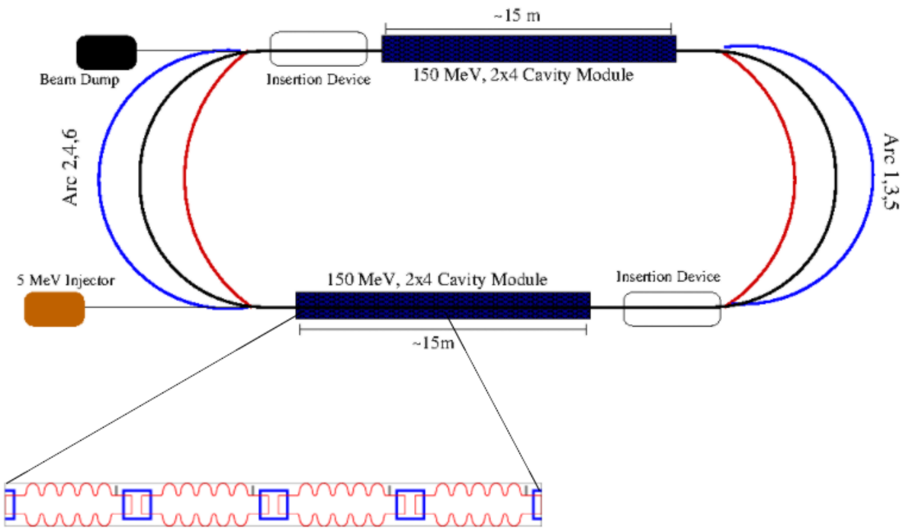
https://indico.cern.ch/event/183282/contributions/318618/attachments/249525/348968/ERL_and_Frequency_Choice1.pptx

2012-15, LHeC Workshops

ERL Facility Cavities

R. Calaga, CERN, Jun 25, 2015

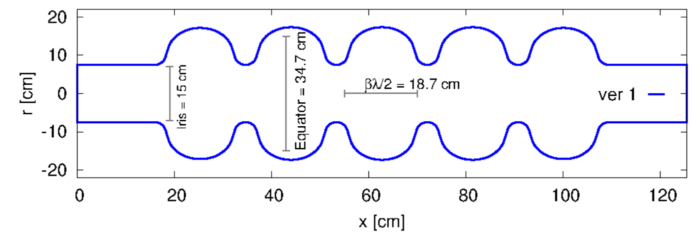
A quantum jump from zero to 60 GeV ERL is unlikely



Basic unit: 5-cell cavity into 4-cavity module

https://cds.cern.ch/record/1519112?ln=en
http://cds.cern.ch/record/2020926?ln=en

5-cell 801.58 MHz, v2



5-Cell RF Parameters

Parameter	Ver 1 (Scaled)	Ver 2
Frequency [MHz]	801.58	801.58
Number of cells	5	5
Active cavity length [mm]	935	935
Voltage [MV]	18.7	18.7
E_p [MV/m]	45.1	48.0
B_p [mT]	95.4	98.3
R/Q [Ω]	430	393
Cell-cell coupling (mid-cell)	4.47%	5.75%
Stored Energy [J]	154	141
Geometry Factor [Ω]	276	283
Field Flatness	97%	96%

For example, at 18.7 MV/cavity :

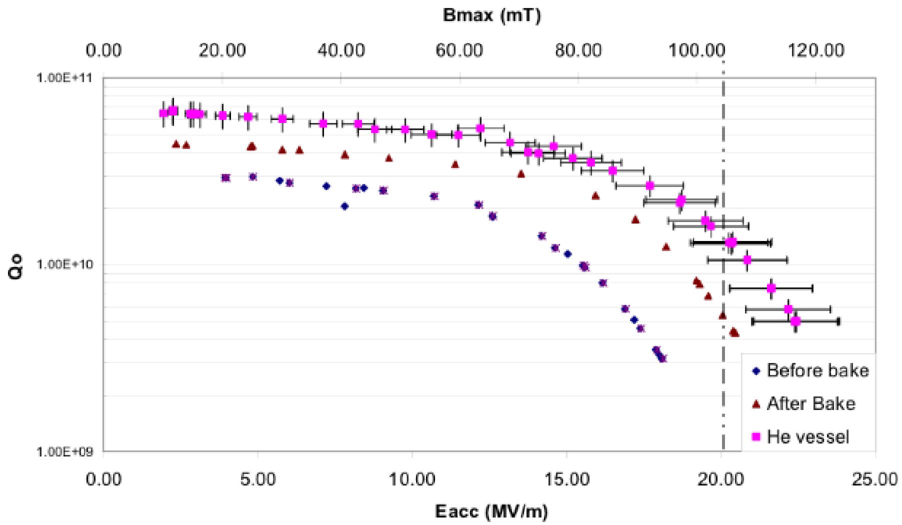
Cavity dynamic losses (assume Rs = 7-10 nΩ): ~22-31 W

Gradient reach limited by heat load & extraction (~ 1W/cm2 for piping)

Lots to be gained from high Q than small improvements in cavity geometry

2015, LHeC Workshop

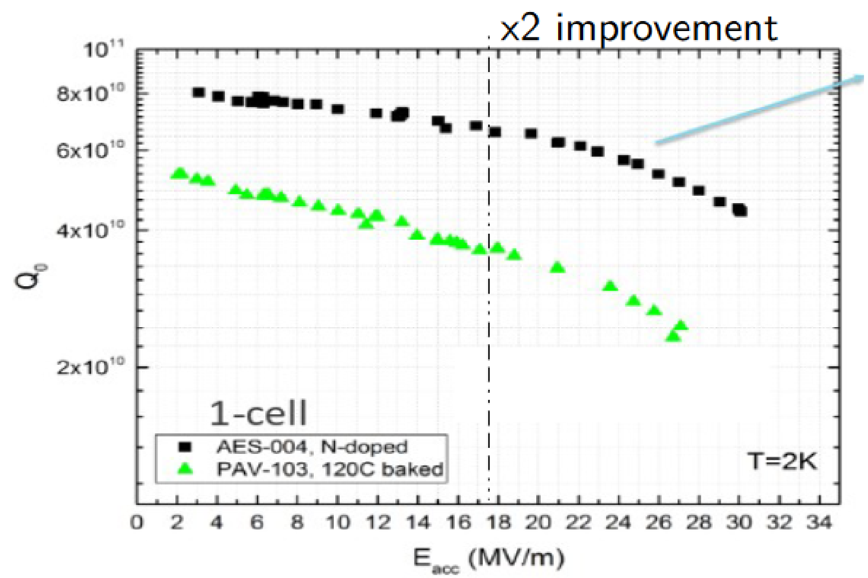
High Q0



BNL 704 MHz 5-Cell

A. Burill et al., AP Note 376

(translates to ~20 nΩ)



650 MHz, 1-cell: N-Doping

A. Romenenko et al., FCC Workshop

Washington, 2015

(translates to ~4 nΩ)

2015, LHeC Workshop

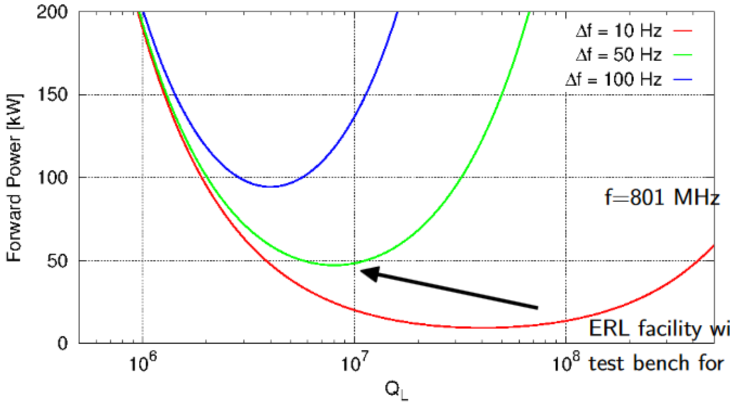
ERL, RF Power

"Zero" Beam Loading

Peak detuning

$$P_g = \frac{V^2}{R/Q} \cdot \frac{\Delta f}{f} \qquad \{ Q_{opt} = \frac{1}{2} \cdot \frac{\omega}{\Delta \omega} \}$$

Recall: static detuning w/o ER ~50 Hz, highest R/Q not essentially best



ERL facility will be excellent test bench for stable operation

RF powering, proper dimensioning & appropriate bandwidth is key for a robust ERL

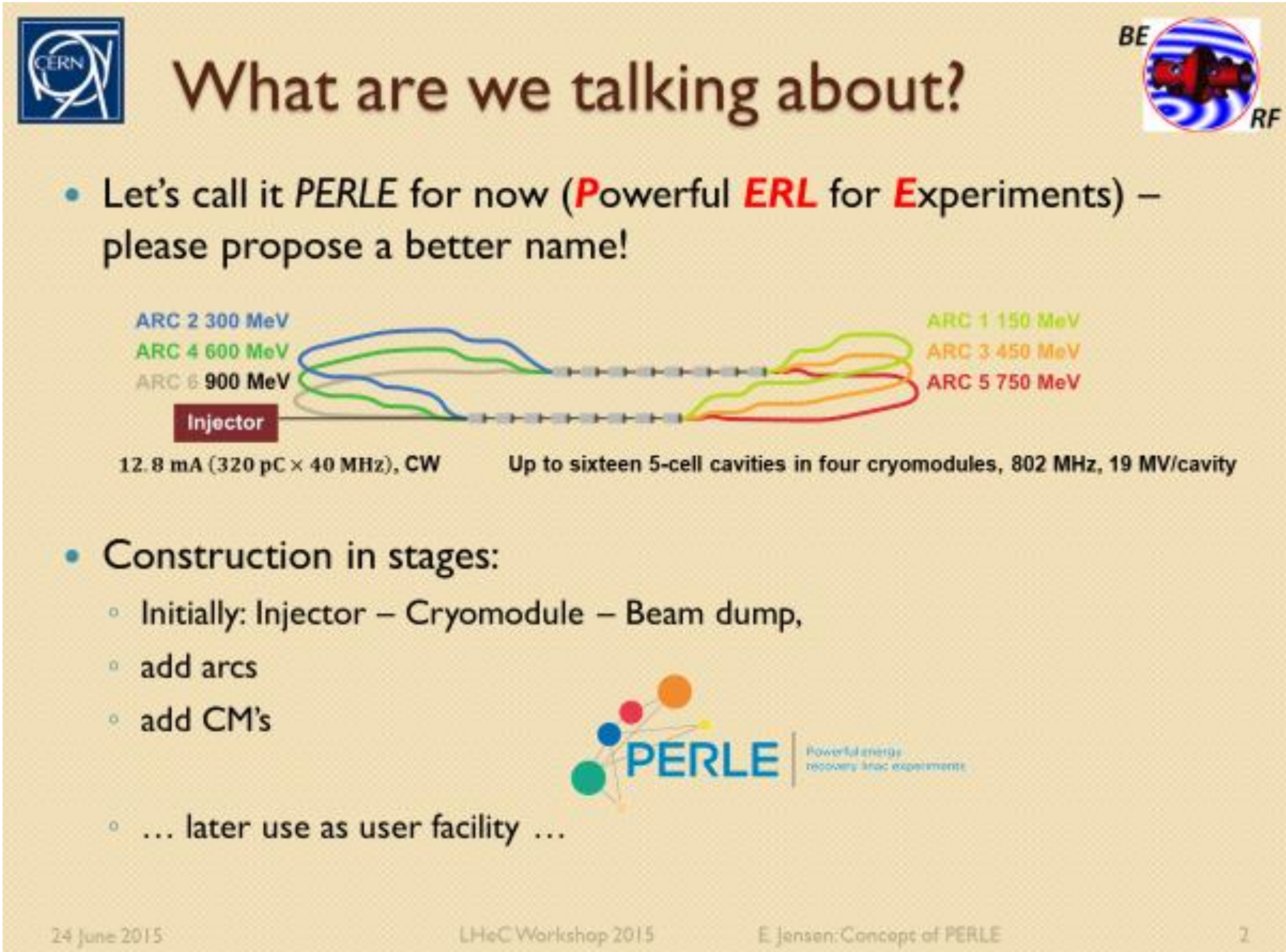
SPS 800 MHz IOTs

800 MHz IOTs (~60 kW) for the SPS 3rd harmonic system

Chain of 8 IOTs installed powering two cavities in the SPS

2016, LHeC/PERLE Workshop

2016, LHeC Workshop



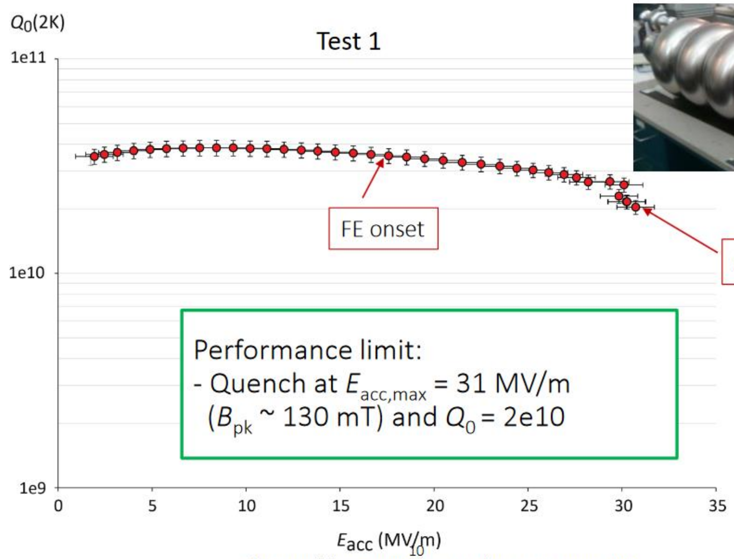
2017-18

A new Jlab design built under FCC-collaboration

Parameter Table for LHeC Cavity Candidates

Parameter	Unit	Value	Value	Value
Cavity type		JLab	CERN Ver. 1 from CERN-ACC-NOTE-2015 R Calaga, 5/28/15	CERN Ver. 2 from CERN-ACC-NOTE-2015 R. Calaga, 5/28/15
Frequency	MHz		801.58	
Number of cells			5	
L_{active}	mm	917.9	935	935
Long. loss factor (2 mm rms bunch length)	V/pC	2.742	2.894	2.626
$R/Q = V_{eff}^2/(\omega^* W)$	Ω	523.9	430	393
R/Q/cell	Ω	104.7	86.0	78.6
G	Ω	274.6	276	283
$R/Q \cdot G$/cell		28788	23736	22244
Eq. Diameter	mm	328.0	350.2	350.2
Iris Diameter	mm	130	150	160
Tube Diameter	mm	**130**	**150**	**160**
Eq./Iris ratio		2.52	2.19	2.19
Wall angle (mid-cell)	degree	0	12.5	12.5
E_{pk}/E_{acc} (mid-cell)		2.26	2.26	2.40
B_{pk}/E_{acc} (mid-cell)	mT/(MV/m)	4.20	4.77	4.92
k_{cc}	%	3.21	4.47	5.75
N^2/k_{cc}		7.78	5.59	4.35
cutoff TE_{11}	GHz	1.35	1.17	1.10
cutoff TM_{01}	GHz	1.77	1.53	1.43

4 on Meeting, Daresbury 15-16 January 2018 Jefferson Lab



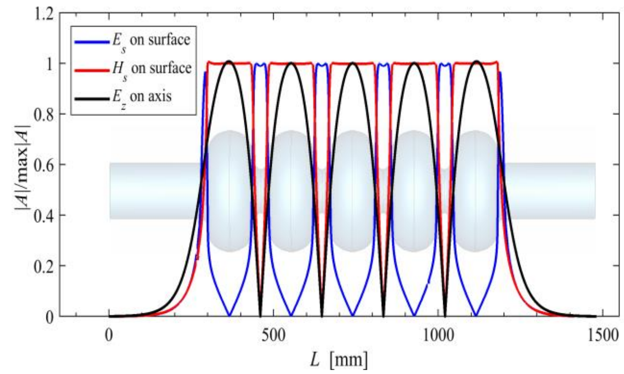
3rd PERLE Collaboration Meeting, Daresbury 15-16 January 2018 Jefferson Lab

and adopted for PERLE

$t\bar{t}$ of FCC-ee studies, 2017-19

- Minimize intrinsic surface losses (peak fields) & field flatness
- Separation between first two HOMs (TE_{111}, TM_{110}) minimized
- The end-cell aperture increased to reduce Q_{ext} for the first monopole/dipole pass band

UROS, 5-cell 801.58 MHz



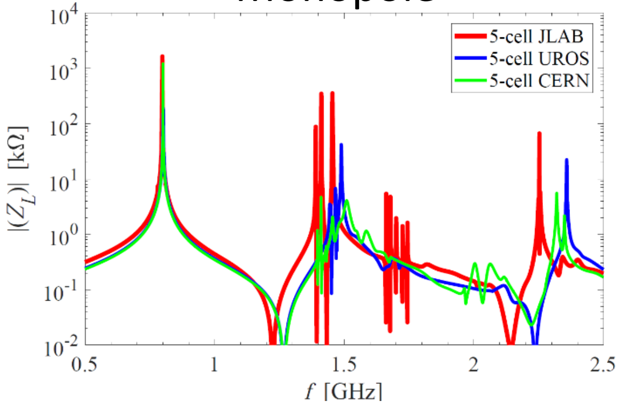
https://cds.cern.ch/record/2776785
(S. G. Zadeh thesis)

	PERLE	FCC-$t\bar{t}$
Injection energy [MeV]	5-10	Top-up
Maximum beam energy [GeV]	1	182.5
Bunch charge [pC]	320	36850
RMS Bunch Length (SR/BS) [mm]	3	1.97/2.54
Beam Current [mA]	15	5.4
Bunch spacing [ns]	25	3396
RF frequency [MHz]	801.58	400.79 / 801.58
RF Voltage	300 MV/pass	10.93 GV
Duty factor	CW	CW

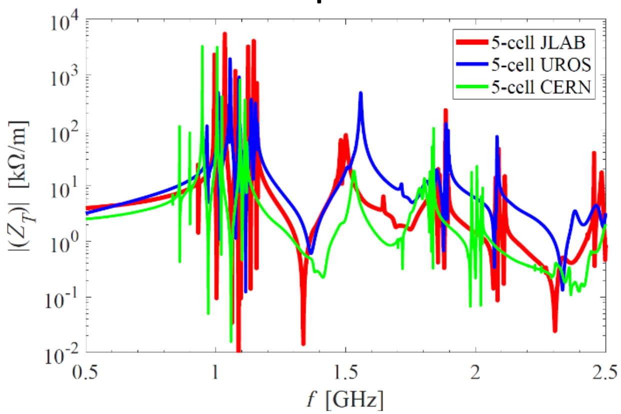
Cavity Comparisons (2018-19)

Parameters	UROS. FCC-ee	CERN LHeC v2	Jlab v2
Frequency [MHz]	801.58	801.58	801.58
Number of Cells	5	5	5
Material	Bulk Nb.	Bulk Nb.	Bulk Nb.
Temperature [K]	2.0	2.0	2.0
R/Q [Ω] *	521	393	523.9
Geometry Factor [Ω]	273.7	283	274.7
G.R/Q [Ω]	142597	111219	143915
B_{pk}/E_{acc} (mid-cell) [$\mathrm{mT/(MV/m)}$]	4.2	4.92	4.2
E_{pk}/E_{acc} (mid-cell)	2.0	2.4	2.26
Cavity Active Length [mm]	919.5	935	917.9
Iris radius [mm]	60	80	65
Beam Pipe radius [mm]	78	80	65
Wall angle (mid-cell) [degree]	100	102.5	90
Cell to cell coupling of mid cells [%]	2.25	5.75	3.21
Field Flatness [%]	99	96	-
$k_{\|\|}(\sigma_z = 2\mathrm{mm})$ [V/pC]	3.37	2.63	2.74
Cutoff TE_{11} [GHz]	1.126	1.10	1.35
Cutoff TM_{01} [GHz]	1.471	1.43	1.77
Cryo dynamic losses / cavity (E_{acc}=18.7 MV & $Q_0=10^{10}$) [W]	67.1	89	66.7
Wall plug power / cavity (COP=800 W/W) [kW]	53.7	71.2	53.4

Monopole



Dipole

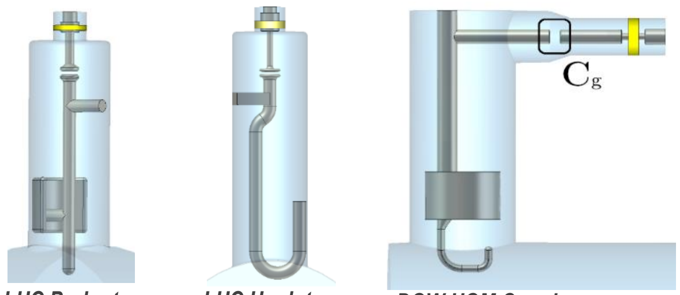


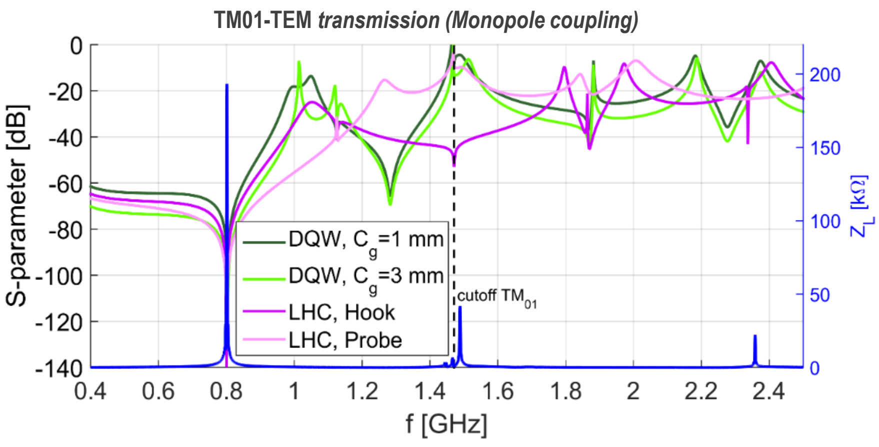
Note: Impedances are for bare cavity and the peaks are not fully resolved.

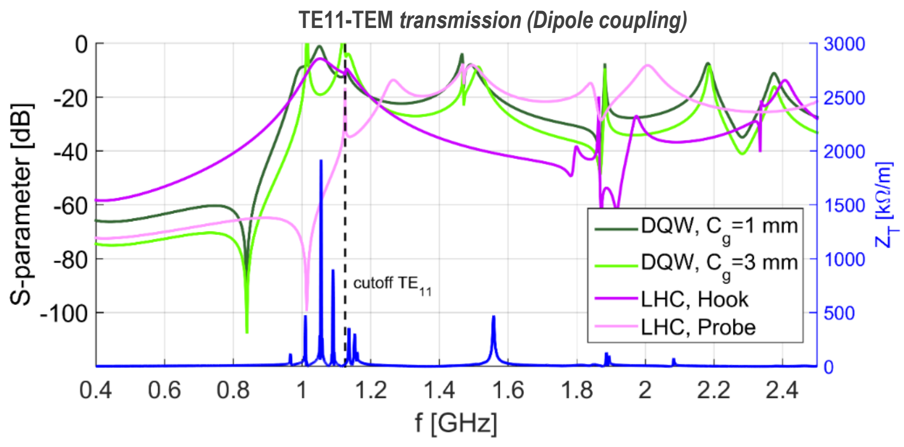
*Note: Input power not to be forgotten ($Qe \sim 8 \times 10^6$ → 40-60 kW, detuning ~50 Hz)

Coaxial HOM Couplers

- The notch effect of all couplers is tuned to 801.58 MHz for the monopole coupling.
- The DQW HOM coupler can deliver a high value of transmission at both first higher order dipole and monopole band.





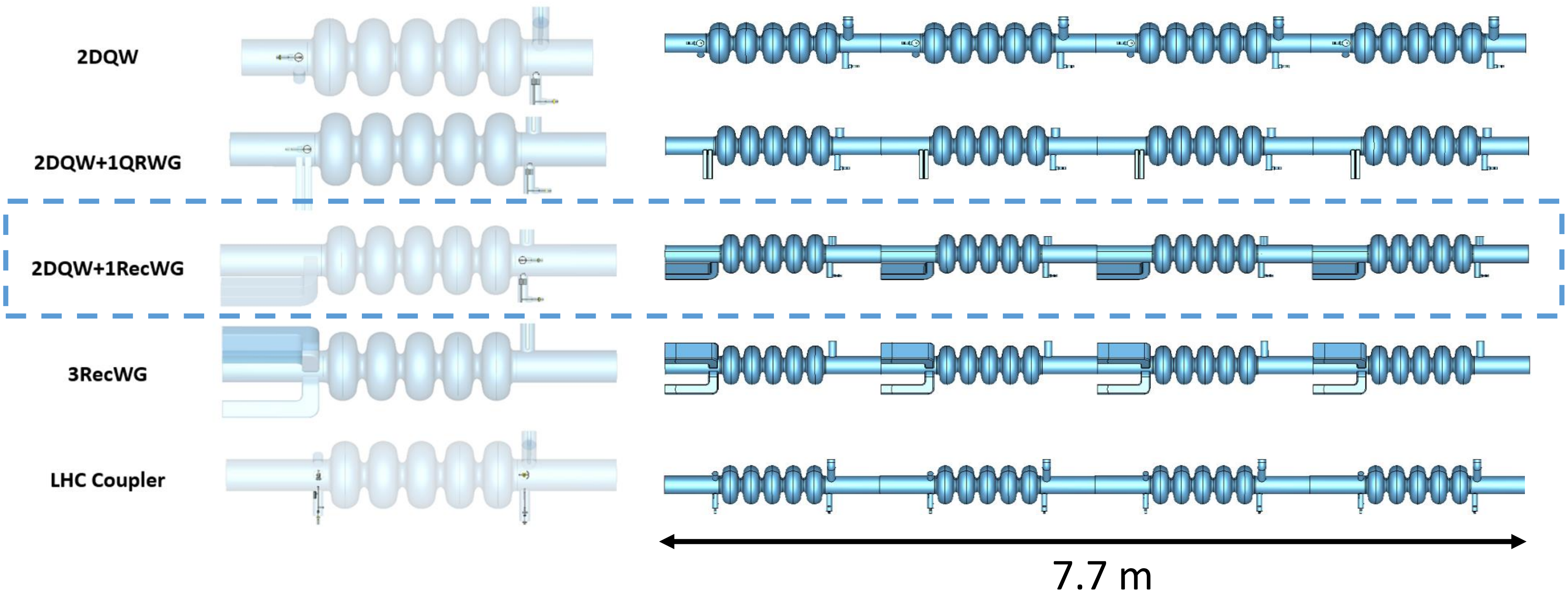


Impedances are for bare cavity and the peaks are not fully resolved.

https://cds.cern.ch/record/2776785 (S. G. Zadeh thesis)

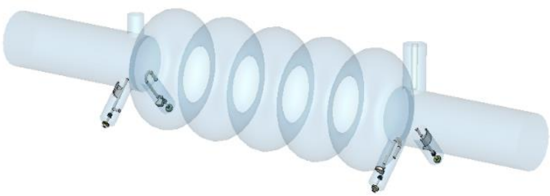
Damping schemes for the $t\bar{t}$ running

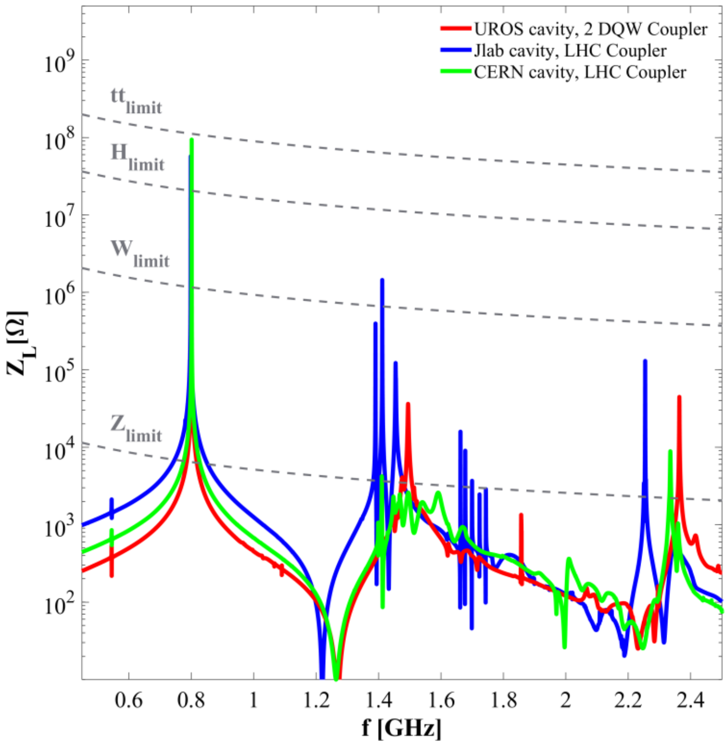
Five damping schemes are compared in the following slides. An extra “high freq” waveguide in addition to co-axial couplers is very effective for high power extraction with short bunches

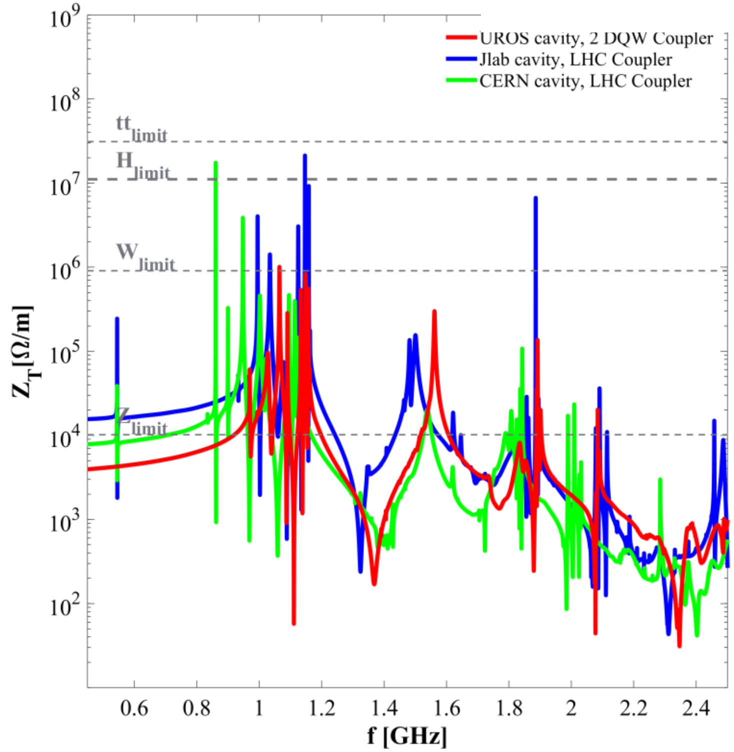


https://cds.cern.ch/record/2776785 (S. G. Zadeh thesis)

Cernv2, Jlab and UROS cavity impedance with coaxial HOM coupler







There are different versions of Jlab cavity. For further information see "Next Generation HOM damping" by F. Marhauser

https://indico.in2p3.fr/event/19904/ (PERLE HOM meeting)

HOM power, UROS Cavity (2019)

- The HOM power in a non-resonant excitation case, is approximated by $P_{HOM} = k_{||} q_b I$
- If beam spectral line falls on the HOM resonance of the cavity then the voltage builds up in the cavity and the HOM power can rise significantly. In such a case, the HOM power can be estimated from $P_{res} = \frac{R}{Q} Q_L \, {I_0}^2$

	PERLE	tt
5-cell cavity at 800 MHz		
Bunch Length [mm]	3	1.97/2.54
P [kW]	0.01	1.09/0.89

Non-resonant HOM power calculated from $P_{HOM} = k_{||} q_b I$

	PERLE	tt
5-cell cavity at 800 MHz		
f* [GHz]	P_{res} [W]	
1.49	16	8
2.36	20	10

* Resonance excitation power of two monopole modes with the highest longitudinal impedance

https://indico.in2p3.fr/event/19904/ (PERLE HOM meeting)

Joachim-Jungius-Förderpreis 2022 (01.07.2022)

v.l.: Tom Streicher (GFUR Vorsitzender), Preisträgerin Dr. Victoria Aladin (MNF), Preisträger Dr. Shahnam Gorgi Zadeh (IEF), Prof. Udo Kragl (Prorektor für Forschung und Wissenstransfer)
Foto: Thomas Rahr / ITMZ

Dr.-Ing. Shahnam Gorgi Zadeh (Institut für Allgemeine Elektrotechnik, Betreuerin Prof. Dr. rer. nat. habil. Ursula van Rienen) wird am 1. Juli 2022 mit dem Joachim-Jungius-Förderpreis 2022 der Gesellschaft der Förderer der Universität Rostock e.V. (GFUR) für seine Dissertation „Accelerating cavity and higher order mode coupler design for the Future Circular Collider" ausgezeichnet. Die weiteren Preisträger sind Dr. Victoria Aladin und Dr. Lukas Kölsch (beide Mathematisch-Naturwissenschaftliche Fakultät).

Thesis completed with a special mention of **summa cum laude**!

FCC-ee $t\bar{t}$ studies, 2021-23

Can we improve further the UROS 5-cell design for ttbar and full energy booster ? (Thesis subject of S. Udongwo)

Objective function

$$\min_{\mathbf{x}_i,\mathbf{x}_e\in\mathbf{X}} \left(\frac{E_{\mathrm{pk}}}{E_{\mathrm{acc}}}, \frac{B_{\mathrm{pk}}}{E_{\mathrm{acc}}}, -R/Q, |Z_{\parallel,p}|, |Z_{\perp,q}|\right)$$

s.t.

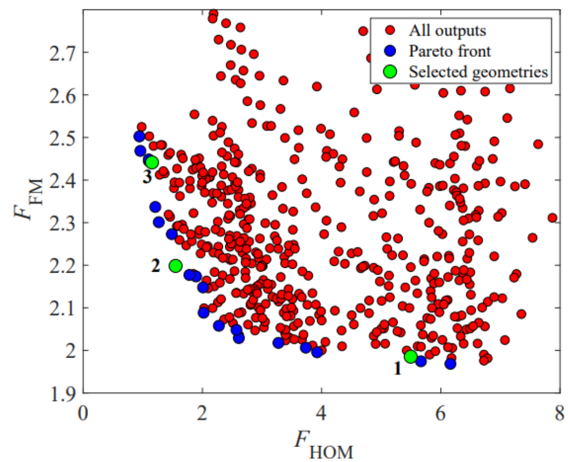
$$R_{\mathrm{eq}}/\mathrm{mm} = \underset{R_{\mathrm{eq}}}{\arg\min} \quad f(R_{\mathrm{eq}}) - f_{\mathrm{FM}},$$
$$L_{\mathrm{e}}/\mathrm{mm} = \underset{L_{\mathrm{e}}}{\arg\min} \quad f(L_{\mathrm{e}}) - f_{\mathrm{FM}},$$
$$A_{\mathrm{i,e}}, B_{\mathrm{i,e}}/\mathrm{mm} \in [20, 80],$$
$$a_{\mathrm{i,e}}, b_{\mathrm{i,e}}/\mathrm{mm} \in [10, 60],$$
$$R_{\mathrm{i,i,e}}/\mathrm{mm} \in [60, 85],$$
$$L_{\mathrm{i}}/\mathrm{mm} = 93.5,$$
$$\alpha_{\mathrm{i}} \geq 90^\circ,$$
$$\frac{E_{\mathrm{pk}}}{E_{\mathrm{acc}}} \leq 3,$$
$$\frac{B_{\mathrm{pk}}}{E_{\mathrm{acc}}} / \frac{\mathrm{mT}}{\mathrm{MV/m}} \leq 5,$$

Multi-objective optimisation algorithm

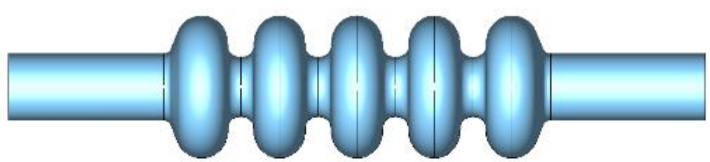
Algorithm 1 Pareto-based Genetic Algorithm

Initialisation: $\mathbf{X} = (\mathbf{x}_1, \dots, \mathbf{x}_Q)$, $n = 0$, v_t;
  ▷ First generation, v_t : hypervolume threshold value.
while $n < N$ **do** ▷ Generation loop
  for $\mathbf{x} = \mathbf{x}_1 \dots, \mathbf{x}_Q$ **do** ▷ Half-cell geometry loop
    run SLANS, ABCI
    ▷ for $\frac{E_{\mathrm{pk}}}{E_{\mathrm{acc}}}, \frac{B_{\mathrm{pk}}}{E_{\mathrm{acc}}}, R/Q, |Z_{\parallel,p}|, |Z_{\perp,q}|$
  $\mathbf{P}_n \leftarrow$ Evaluate and interpolate Pareto hypersurface
  if $n > 0$ **then**
    Evaluate hypervolume v between $\mathbf{P}_n$ and $\mathbf{P}_{n-1}$
    if $v < v_t$ **then**
      break
  do Ranking and Selection, Crossover, Mutation
  do Introduce random half-cell geometries
  $\mathbf{X} \leftarrow$ newly created geometries
return $\mathbf{P}_n$

Cavity Designs



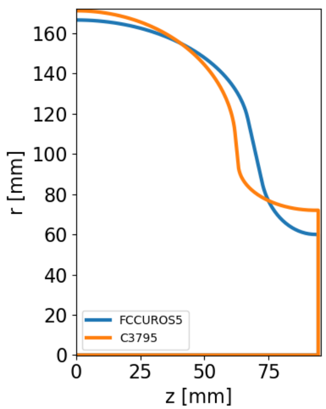
C3795



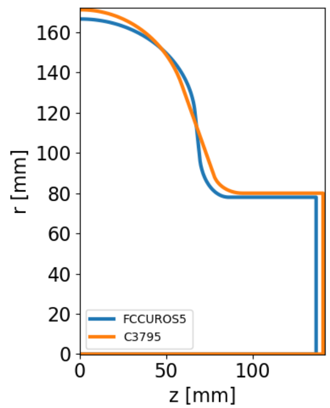
https://zenodo.org/record/7661145

FCC-ee $t\bar{t}$ studies, 2021-23

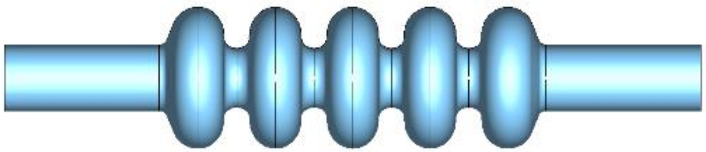
Variable	C3795	FCC_{UROS5}
R_i, R_{ie} [mm]	**72**/80	**60**/78



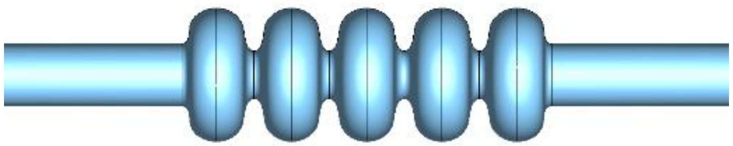
Mid half-cell contour



End half-cell contour



C3795

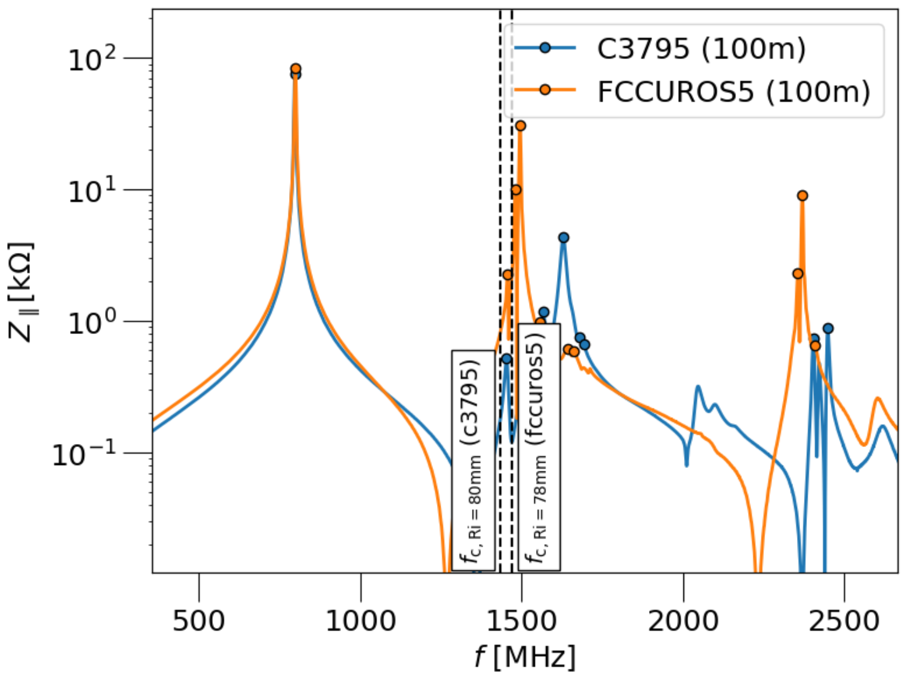


FCCUROS5

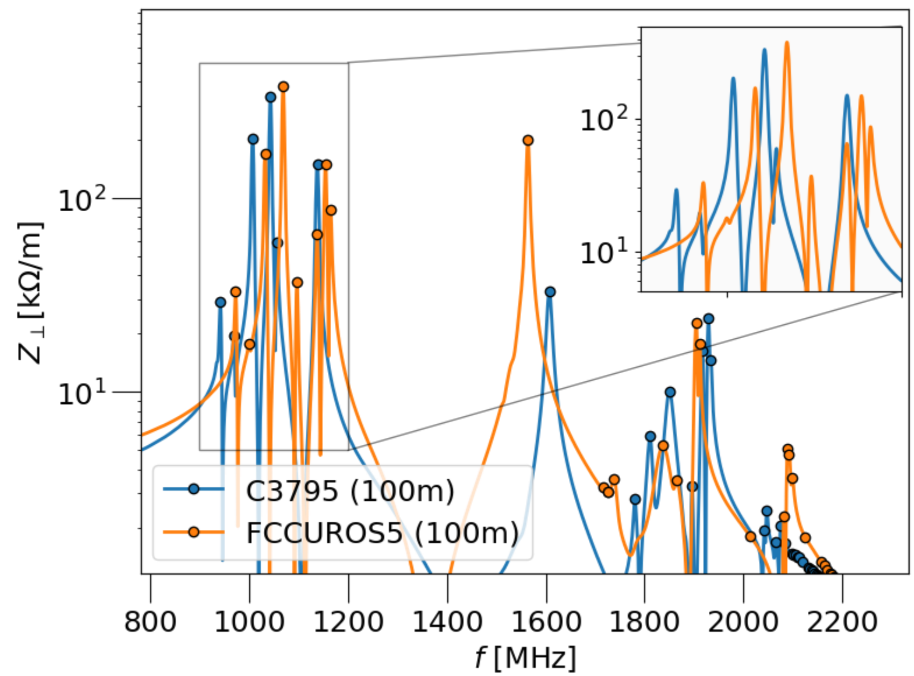
Variable	FCCUROS5 (2019)	C3795 (2023)
R/Q [Ω]	521.06	448.1244
G [Ω]	272.93	261.63
k_{cc} [%]	2.04	2.64
E_{pk}/E_{acc} [-]	2.05	2.43
B_{pk}/E_{acc} [mT/MV/m]	4.33	4.88

FCC-ee $t\bar{t}$ studies, 2021-23

Compromise the fundamental mode performance for HOM improvement. The goal is longitudinal "HOM free" multi-cell cavity which should also reduce the overall HOM power for short e-bunches



Longitudinal impedance



Transverse impedance

FCC-ee $t\bar{t}$ studies, 2021-23

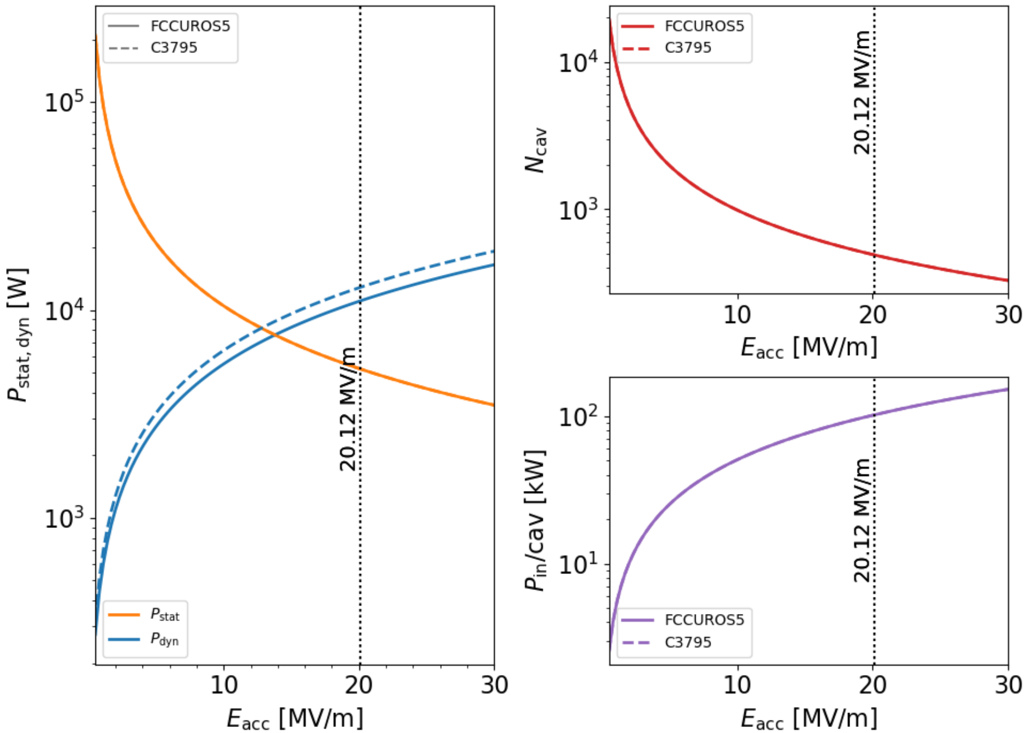
HOM Figures of Merit Comparison

Variable	FCCUROS5 (2019)	C3795 (2023)
$k_{\parallel}$ [V/pC] (SR, σ_z=1.67 mm)	3.784	2.632
$k_{\perp}$ [V/pC/m] (SR, σ_z=1.67 mm)	3.539	2.017
P_{HOM} [W] (SR, σ_z=1.67 mm	1115	698

Beam Current [mA] = 10mA, Bunch Intensity N_b $[10^{11}]$ = 2.26

FCC-ee $t\bar{t}$ studies, 2023

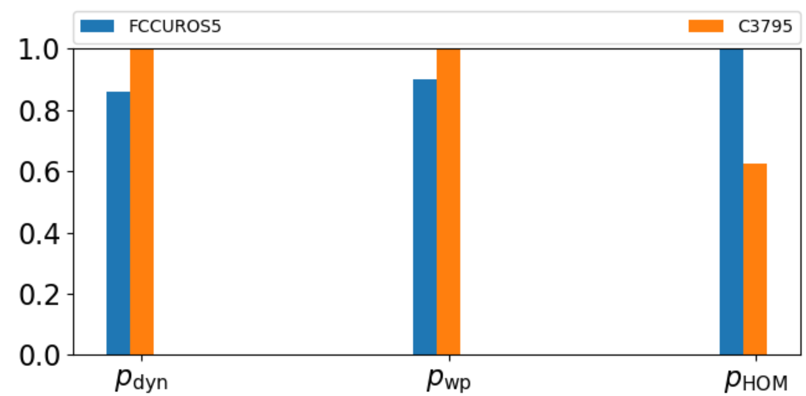
Power Comparison



Plot of static and dynamic power loss, no of cav and input power (P_{in}) vs E_{acc}

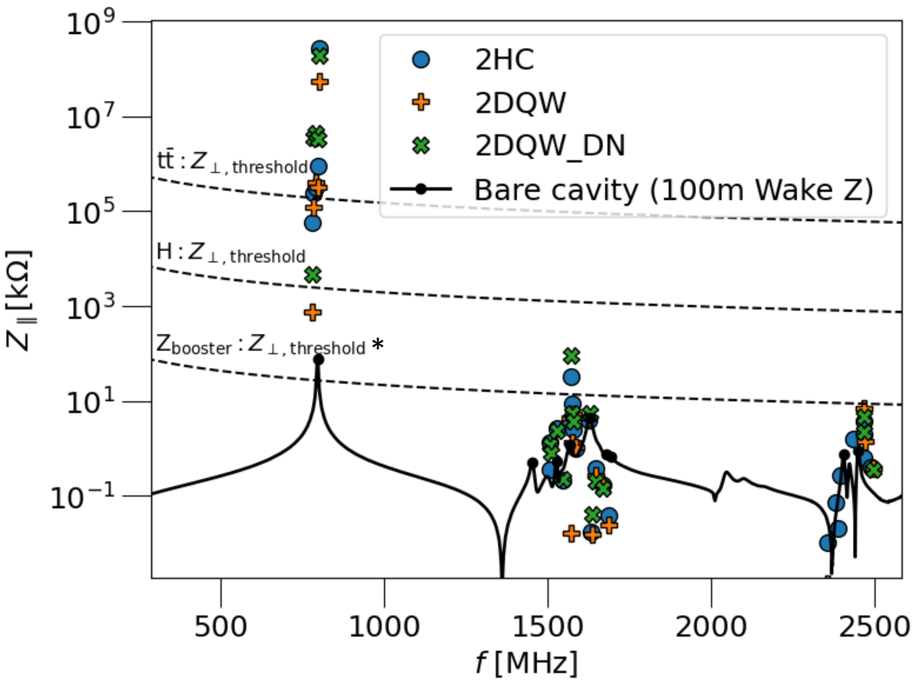
Assumed $Q_0 = 3.0E10$

Variable	C3795	FCUROS5
n_{cav}	488	488
P_{stat} (kW)	5.19	5.19
P_{dyn} (kW)	12.89	11.10
P_{wp} (MW)	12.1	13.47
$P_{HOM,tot}$ (kW)	340.44	543.94

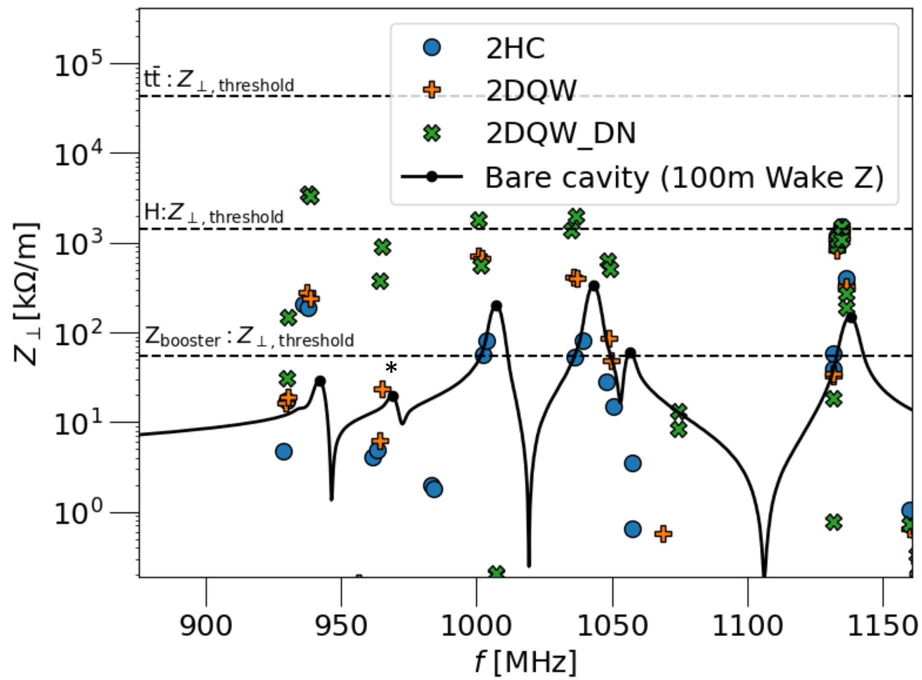


Bar plot summary dynamic, wall and HOM power comparison.

C3795 HOM performance, FCC-ee



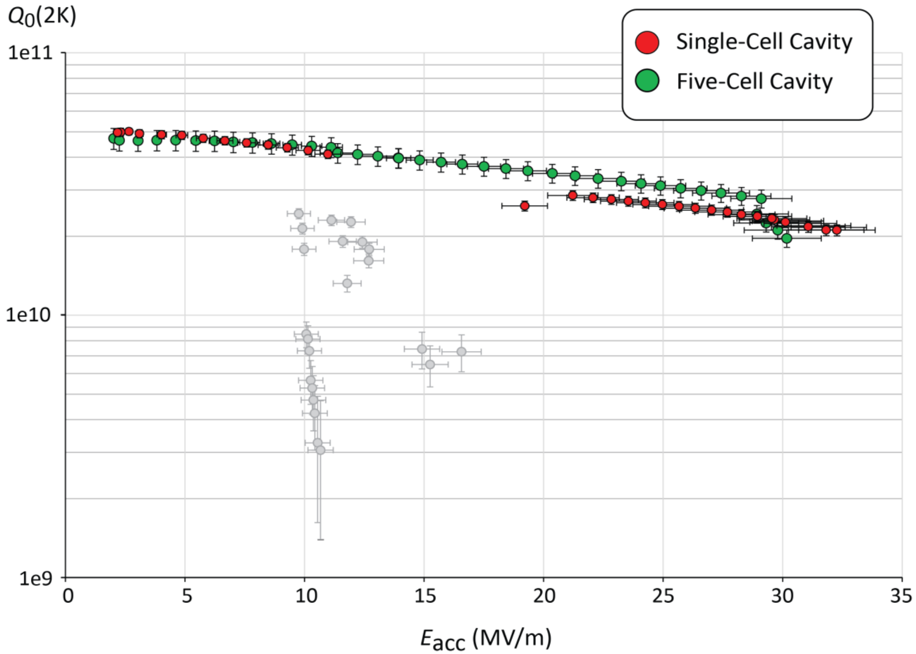
Cavity + HOM coupler assembly longitudinal impedance plot



Cavity + HOM coupler assembly transverse impedance plot showing first dipole passband modes

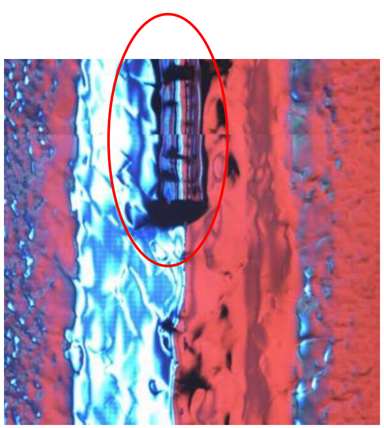
*Assumed current for Z-booster operating point is 128mA

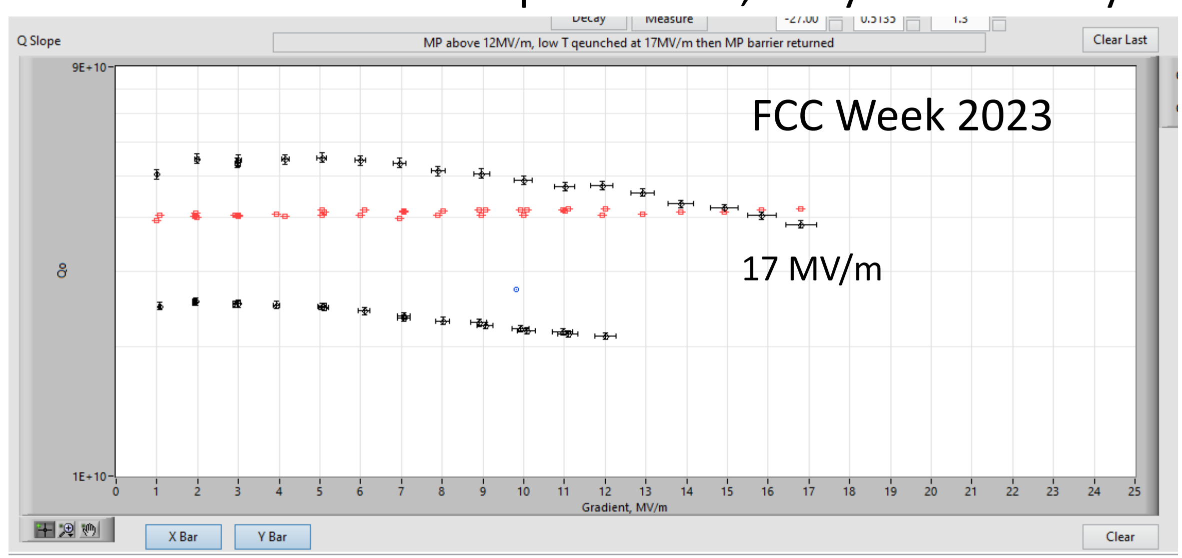
Jlab Cavity at FNAL (high Q_0)



FCC Week 2018

defect at equator weld, likely worsened by EP





S. Posen, FCC Week 2023

Next Steps, Prototype

5-cell cavity at FNAL for testing (S. Posen)

- Test cavity as received
- with mid-T bake, EP, mid-T bake → test
- Nb_3Sn coating trials (tbc)

Single cell copper cavities at CERN for Nb-Coating

- Nb coating on Cu single cell in preparation
- Recent studies on 1.3 GHz seamless cavities shows promising results & Q-slope mitigation with HIPIMS coating

Final Comments

It took more than a decade to convince the accelerator community that 800 MHz (and nearby frequencies) are optimum for high current machines CW machines

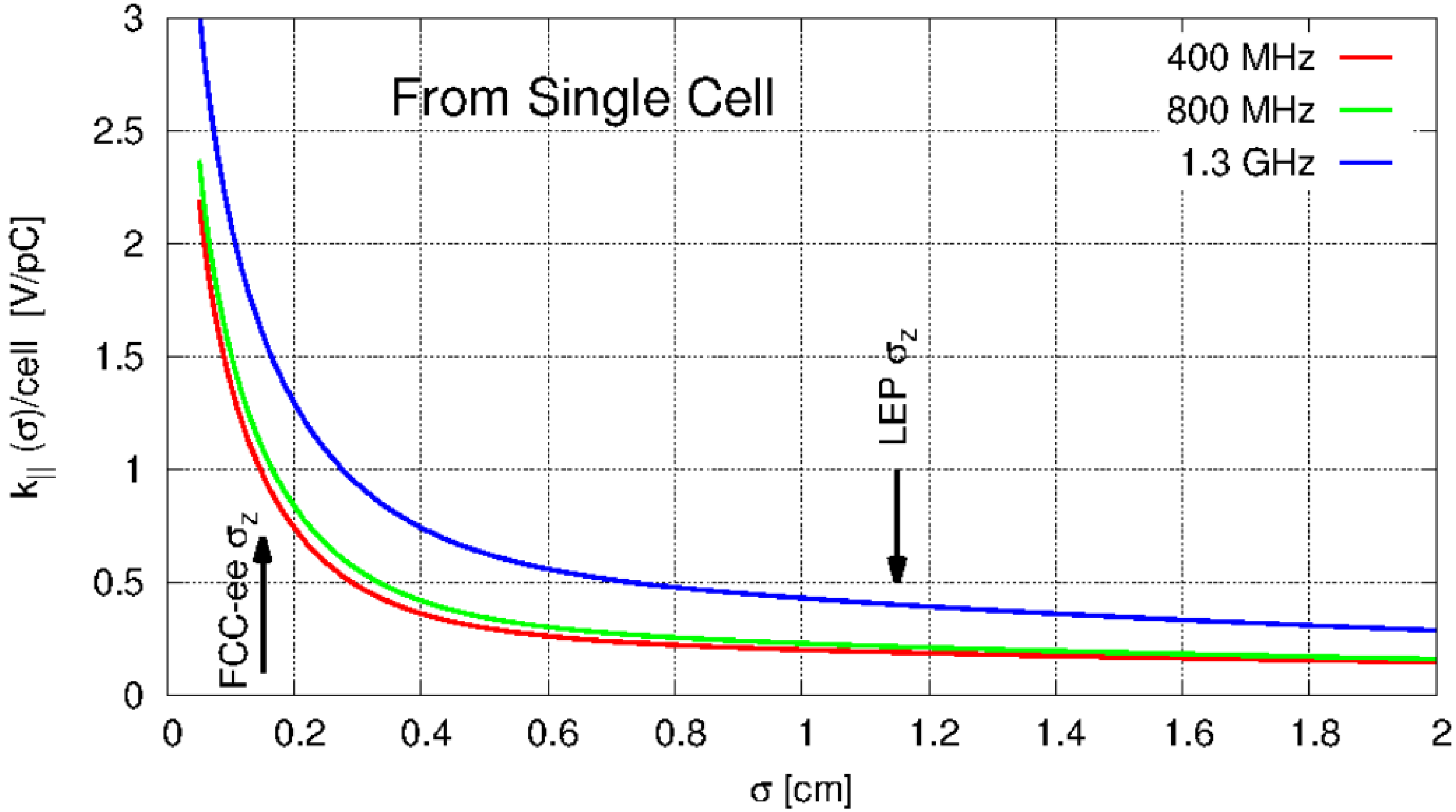
PERLE made the step forward to embark on this journey & will likely set the standard for such technology

In my personal opinion, this will be a necessary step to implement an eventual FCC-ee/eh with 800 MHz

Loss Factor vs Bunch Length

$$k_{(loss)} \propto \frac{1}{R_{(iris)}} \sqrt{\frac{gap}{\sigma_z}} \sqrt{(N_{cell})}$$

Longer bunch lengths to be considered also for transverse impedance



*Remember: 400 → 800 MHz: approx x1.5 increase in # of cells

https://accelconf.web.cern.ch/SRF2015/papers/frba04.pdf