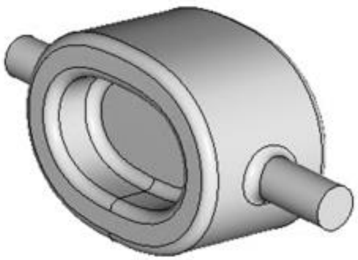
Crab Cavity Design Options

Double Quarter Wave (DQW)

Silvia Verdú-Andrés, Binping Xiao (BNL), Rama Calaga (CERN)

Update -- December 7, 2021

DQW Design Evolution



HL-LHC

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

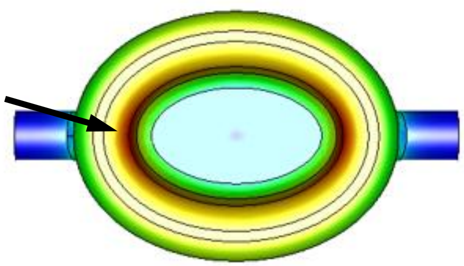
EIC

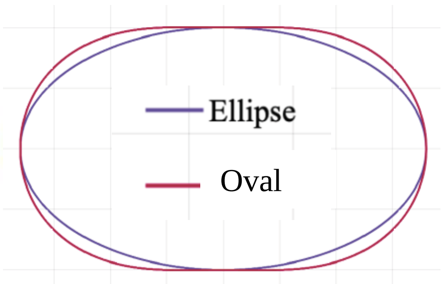
- 200, 400 MHz
- Horizontal kick
- Flat walls
- "Cassini" oval profile

… No clearance issues, ease fab, reduce cost →

…Further reduce peak fields →

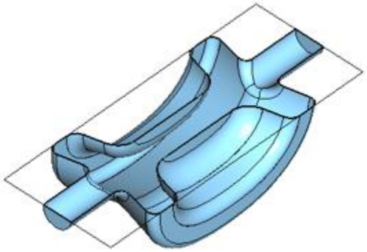
Max. peak surface H





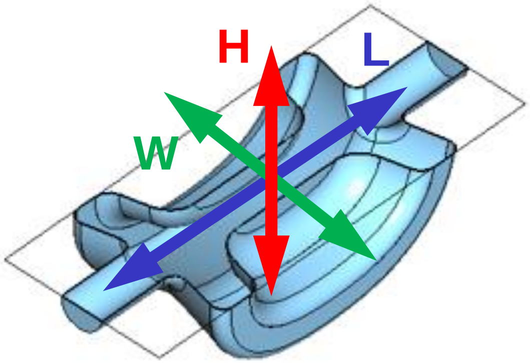
ILC = HL-LHC + EIC

- With waist, "Cassini" oval profile



ILC 1.3 GHz: DQW aperture study

	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)



* Peak fields may be further reduced with refined optimization

- Depending on beam scenario and adopted maximum peak fields and minimum aperture, one or two cavities needed to provide required crabbing kick with low peak fields.
  [Vt = 1.86 MV (for 125 GeV, with 1 cavity for 20 mm aperture or 2 for 30 mm) or 1.5 MV (for 500 GeV, with 5 cavities)]

- Next step : -- reiterate cavity optimization once aperture value is agreed upon

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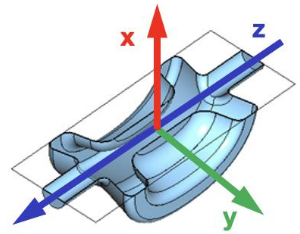
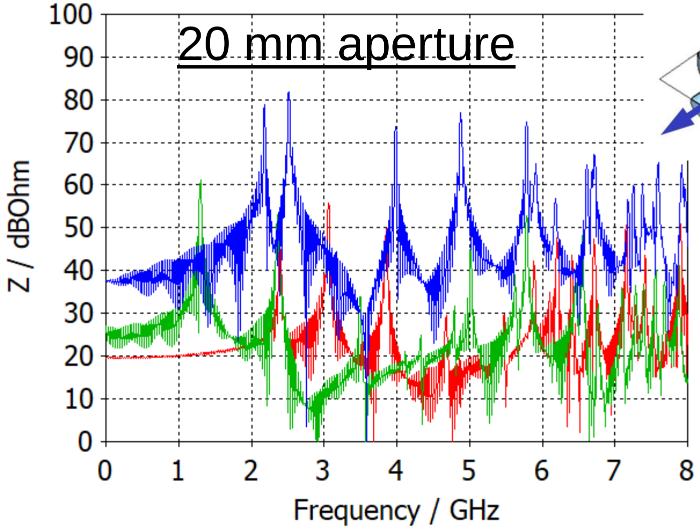
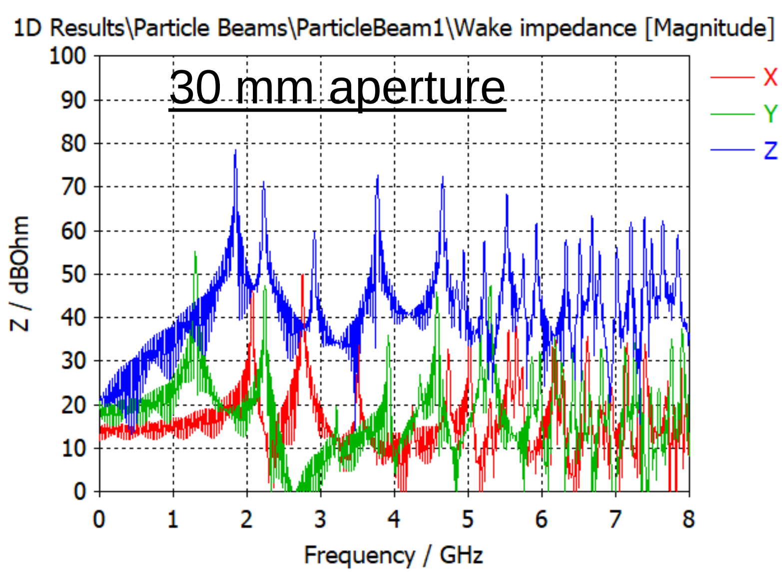
Mode spectrum w/o HOM Couplers

LHC+EIC-type DQW

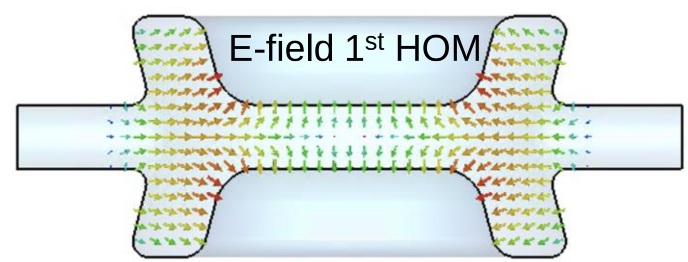




HOM Freq (GHz)	Type
2.18	Long. (z)
2.35	Horiz. (y)
2.39	Vertical (x)



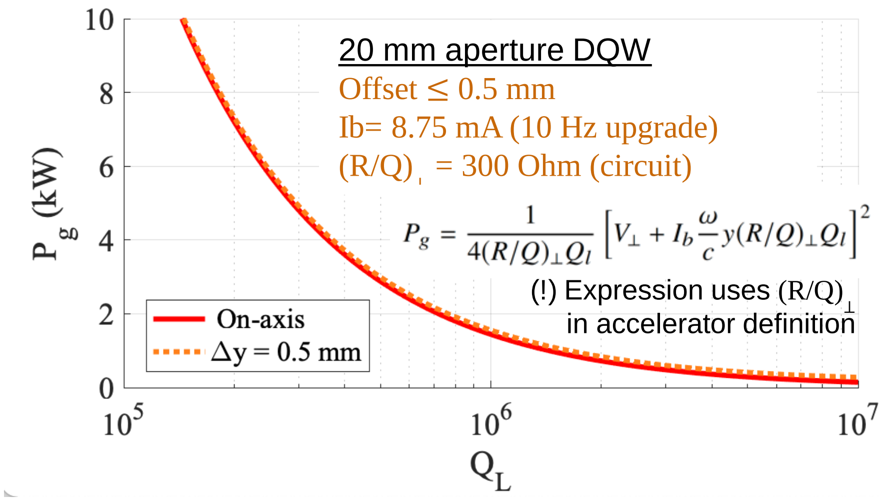
HOM Freq (GHz)	Type
1.84	Long. (z)



Couplers

INPUT POWER COUPLER

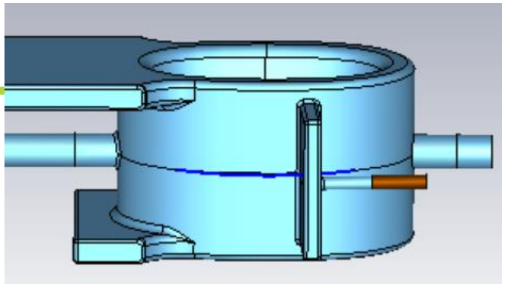
- Selecting a **loaded Q ~ 10^6** leads to **input power below 2 kW** with cavity **bandwidth of 1.3 kHz**.



HOM COUPLER

- Depending on the impedance requirements, either **coaxial or waveguide or a combination** can be used to damp the HOMs.
- Due to **high frequency of the 1st HOM**, a waveguide or a waveguide stub coupled to an antenna can be an efficient and simple solution.

[Rectangular WG with a ~ 83 mm has $f_{c,TE10}$ = 1.8 GHz.]



- Next steps: -- HOM coupler integration, FPC

Crab Cavity Design Options

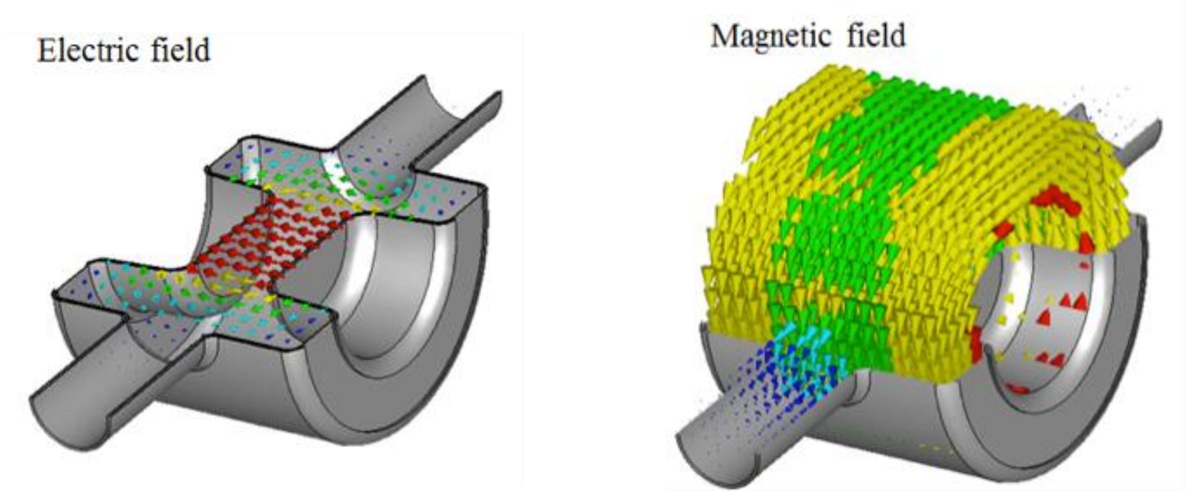
Double Quarter Wave (DQW)

Silvia Verdú-Andrés, Binping Xiao (BNL), Rama Calaga (CERN)

October 27, 2021

A compact crab cavity: the DQW

The **Double-Quarter Wave** (DQW) is an **SRF single-cell deflecting (crab) cavity** first proposed for the HL-LHC crabbing system.



The **fundamental mode** of a DQW cavity **provides a deflecting (crabbing) kick**, with **first Higher-Order Mode (HOM) well separated** from fundamental mode: *e.g.*, $f^{(1)}$=580 MHz for 400 MHz SPS DQW

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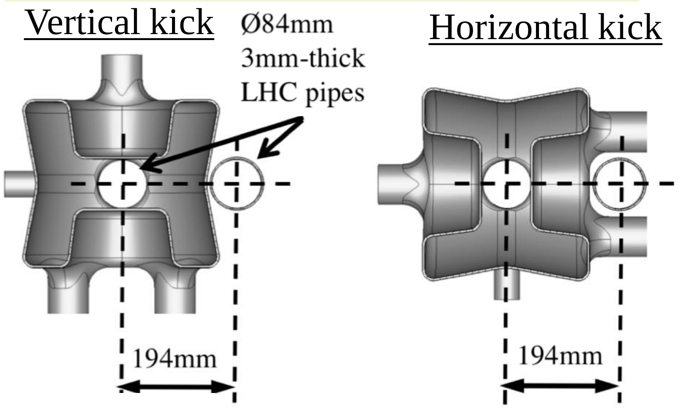
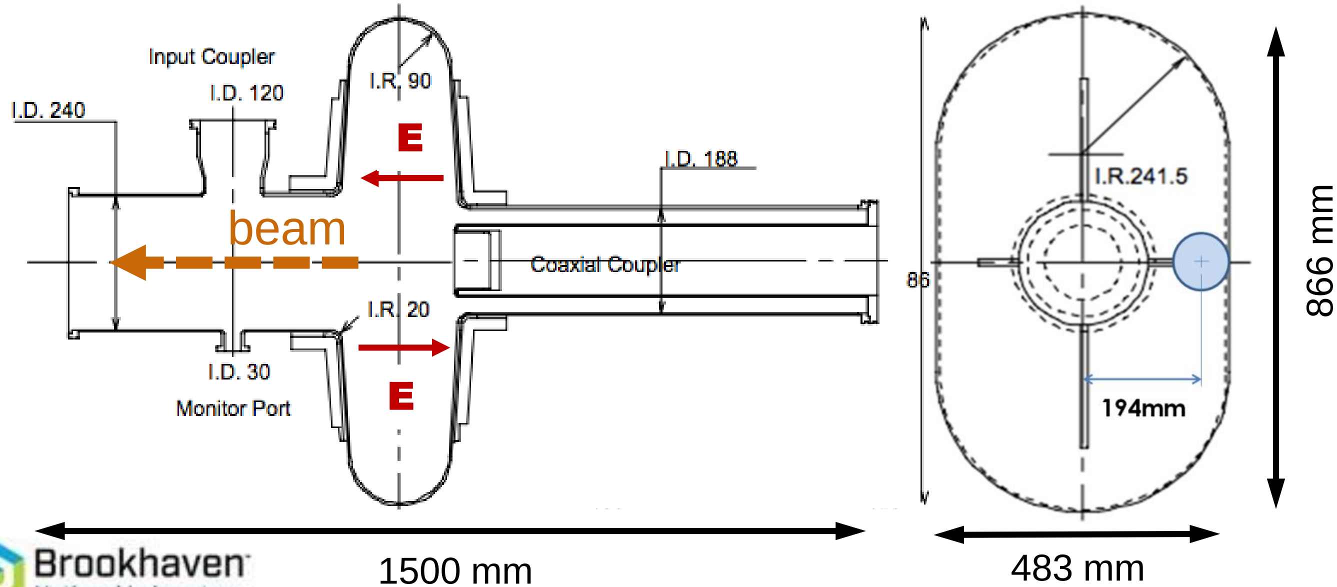
A compact crab cavity: the DQW

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

400 MHz DQW
(TEM-like, Vt=3.4 MV at 2K)



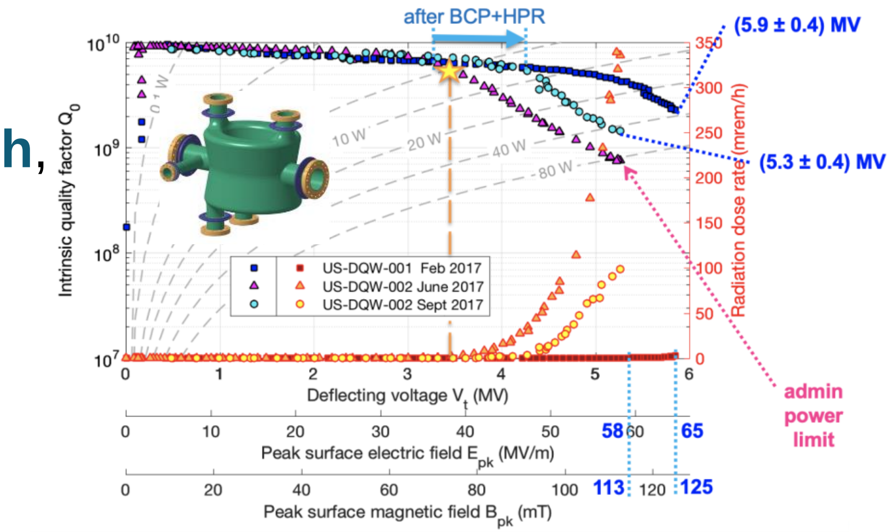
509 MHz KEK-B
(TM110h, Vt=2.8 MV at 2.8K)



SAME SCALE

400 MHz DQW Performance

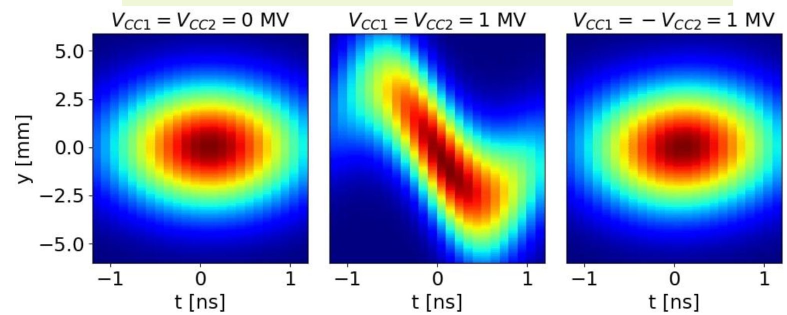
- Bare DQW cavity SPS-series reached **Vt = 5.9 MV before quench**, corresponding to **Bpk = 125 mT**.



- 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

Crabbing reconstruction from head-tail monitor signal



Phys. Rev. Accel. Beams 24, 062001

- KEK, CERN and BNL exploring **DQW performance after electropolishing**.

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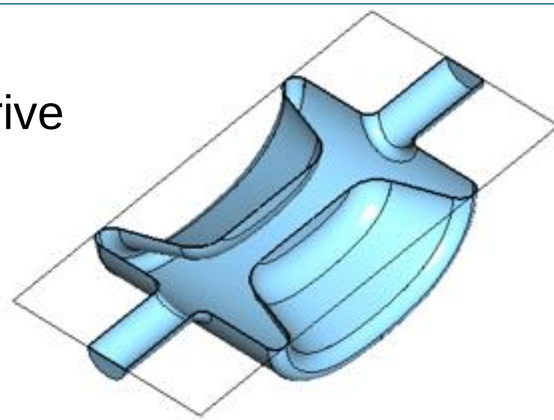
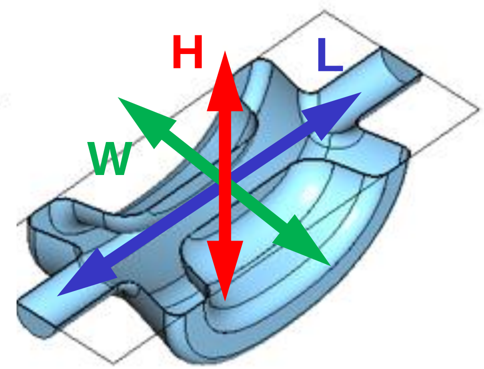
ILC 1.3 GHz: Two DQW designs

	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)

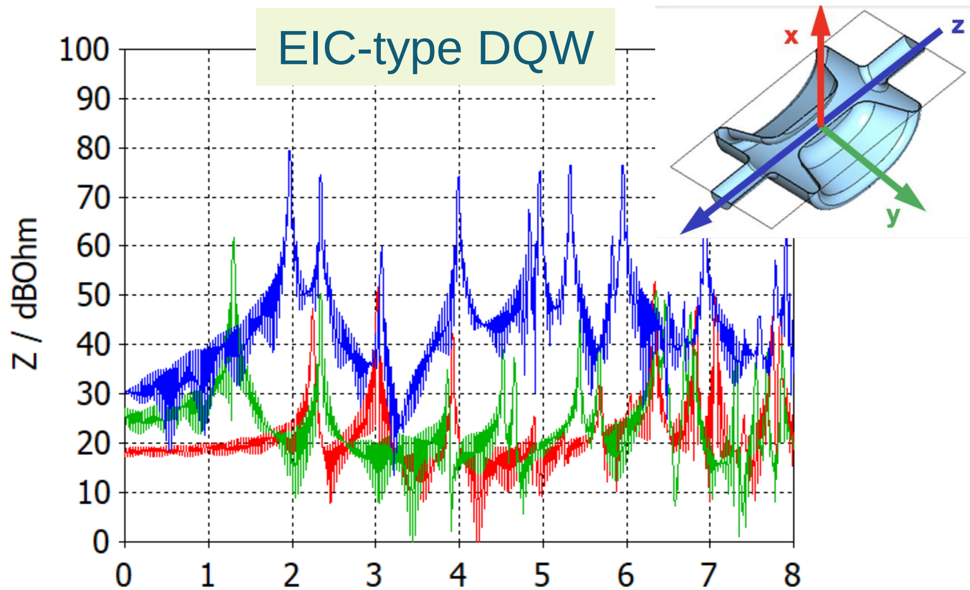
* *Also studied 40 mm aperture*

Coupler integration may drive the choice between the two.

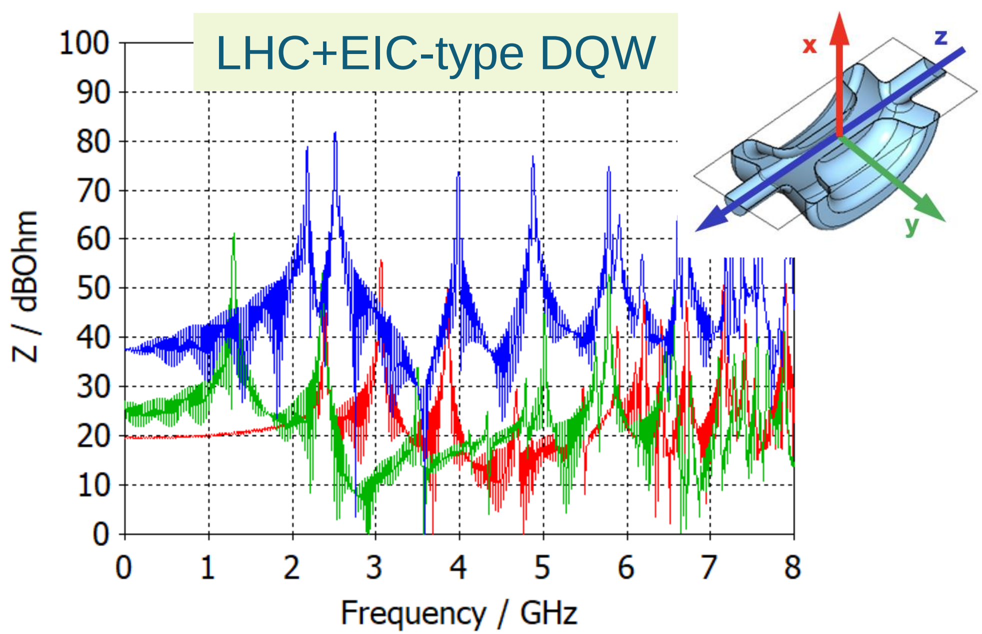




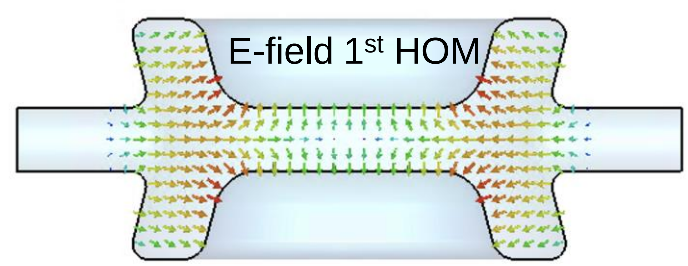
Mode spectrum w/o HOM Couplers



HOM Freq (GHz)	Type
1.98	Long. (z)
2.26	Vertical (x)
2.34	Hybrid (y,z)

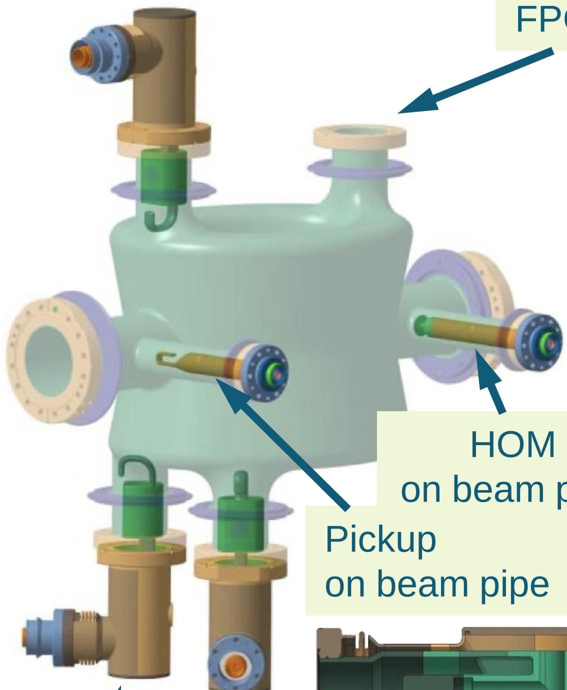


HOM Freq (GHz)	Type
2.18	Long. (z)
2.35	Horiz. (y)
2.39	Vertical (x)



Coupler possibilities (FPC, HOM)

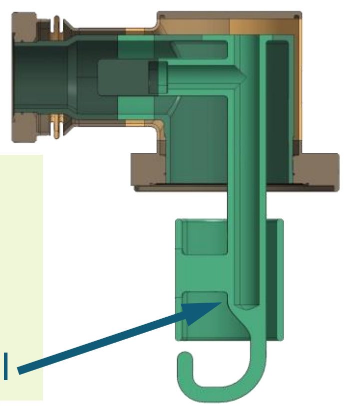
HL-LHC



FPC

HOM
on beam pipe

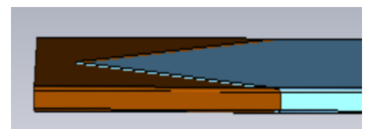
Pickup
on beam pipe

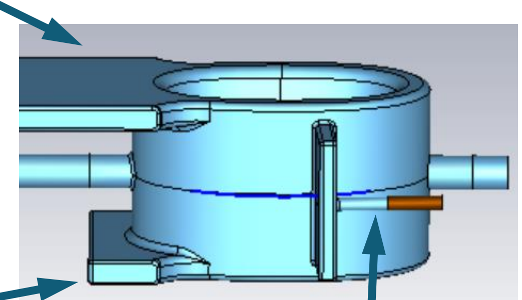


3 x HOM
Nb H-probe with
high-pass filter;
He jacket and
He cooling channel

EIC

WG with absorber

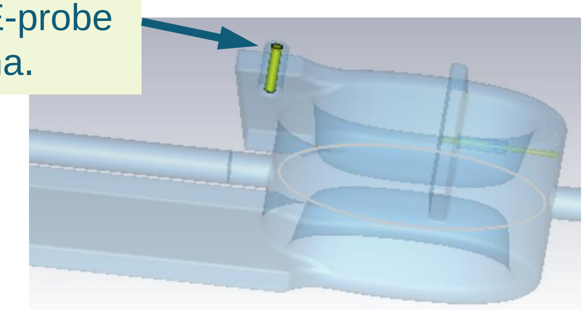




Short WG to preserve field symmetry, hosts FPC.

WG to Cu E-probe coax absorber

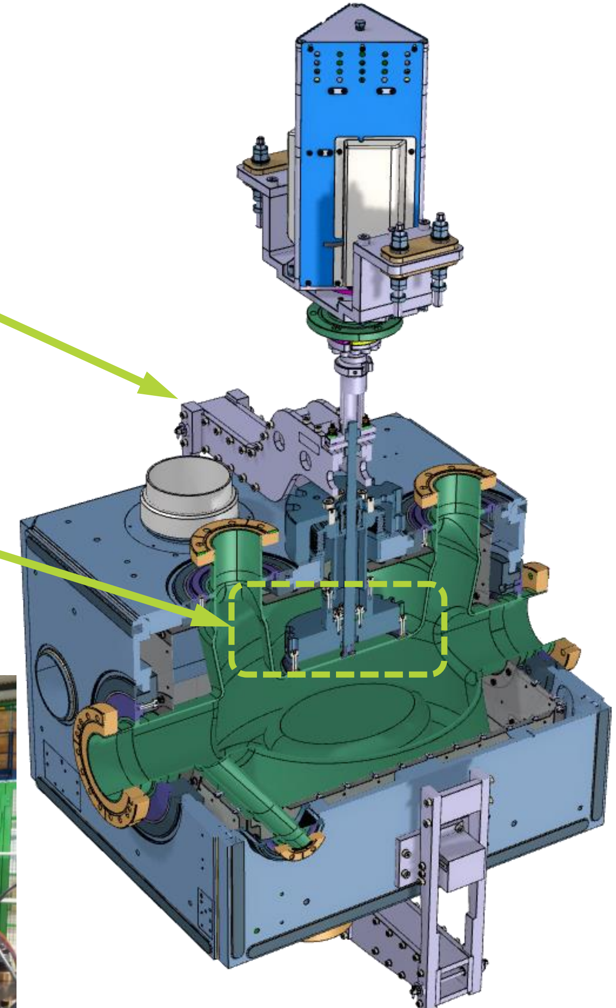
FPC is Cu E-probe coax antenna.



Tuning System

- **Active tuning** realized by scissor-jack frame connected to the push-pull tuning systems of both capacitive plates.

- Designed to ensure symmetric displacement of the plates and hence **preserve the electric field center location**.



Elastic tuning range at 2 K:
± 509 kHz
±1.6 mm

Max. force: ± 3.8 kN

Sensitivity: 318 kHz/mm
2.2-2.4 kN/mm

"Status of the HL-LHC Crab Cavity Tuner", SRF'19, TUP081

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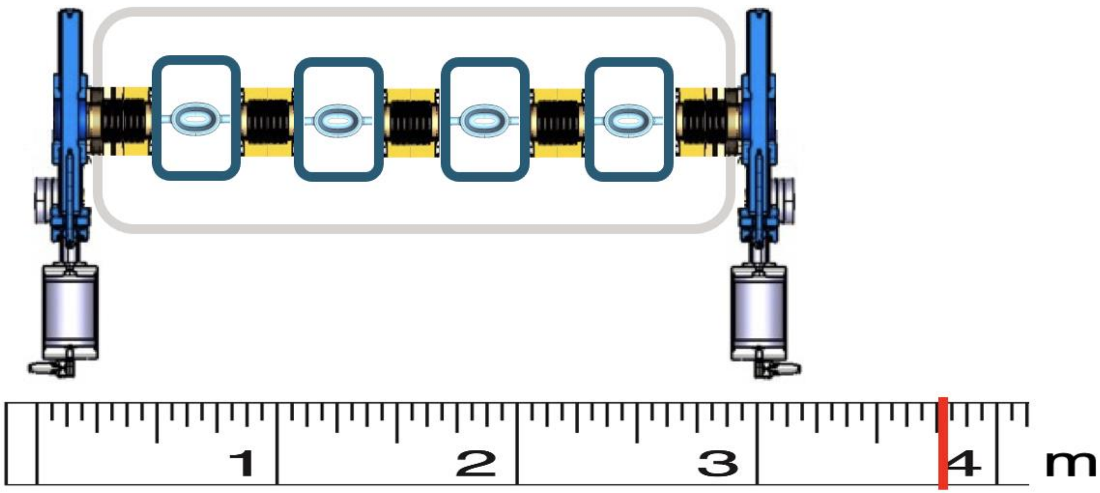
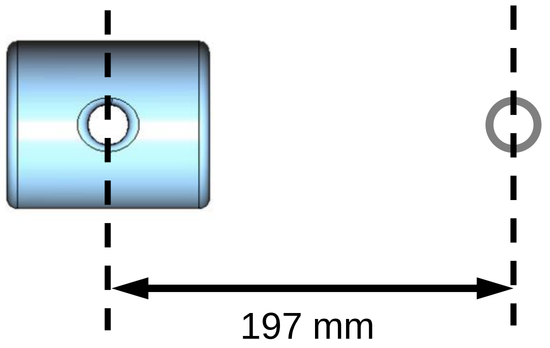
Integration: cryomodule, 2nd beam pipe

- For 1 TeV CoM beam scenario, **4 or 5 DQW cavities** are sufficient to **provide a 7.4 MV crabbing kick at 1.3 GHz**. Adding a 5th cavity could reduce the V_t/cavity to 1.5 MV.
- Length available of **3.8 m enough for crab cavities and other necessary components** (cold-warm transitions, gate valves, etc.).
- Sufficient **clearance to 2nd beam pipe for coupler integration**.

Side view, 4 DQW in cryomodule



Front view, distance to 2nd beam pipe



Summary and Overview

- The **DQW** cavity is a **compact solution for the ILC crabbing system**. One **single-cell cavity** provides **1.86 MV with safe max. peak fields**.

- Tuner and coupler integration can be borrowed from HL-LHC and EIC.

- Cavity **compactness opens the possibility of manufacturing the cavity out of ingot**, which in turn makes the port fabrication much easier and enables the implementation of port interfaces with smooth surfaces for peak field reduction. (The HOM coupler for the HL-LHC DQW was made from ingot and demonstrated good performance.)

- Fabrication and **testing of a prototype** will help the decision on how many cavities are needed to provide the required crabbing kick for ILC.

Backup

References

[1] S. Verdú-Andrés et al., "*Power requirement and preliminary coupler design for the eRHIC crab cavity system*", in Proc. of the 9th International Particle Accelerator Conference (IPAC18), Vancouver, British Columbia, Canada, April 29 - May 4, 2018: https://www.osti.gov/servlets/purl/1436274

[2] J. Tuckmantel, "*Cavity-beam-transmitter interaction formula collection with derivation*", CERN, Geneva, Switzerland, Rep. CERN-ATS-Note-2011-002-TECH, Jan. 2011.

[3] S. Belomestnykh, "*PHY554 - Lecture 7: Circuit model and RF power requirements*", presented at the Center for Acceler- ator Science and Education (CASE), Stony Brook, United States, Spring 2014: http://case.physics.stonybrook.edu/index.php/Courses:_P554_Fundamentals_of_ Accelerator_Physics, _Spring_2014

[4] S. Verdu-Andres et al., *"Pathways for a compact double-quarter wave cavity with low peak surface fields and large deflecting kick",* BNL Technical Note, Sep. 2021.

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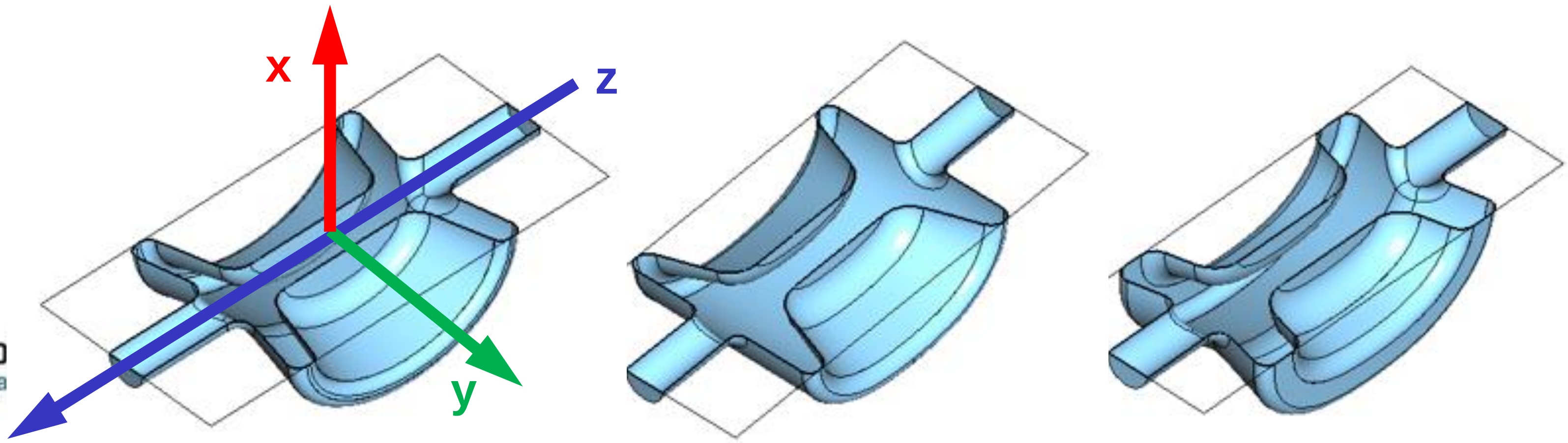
	LHC-type DQW	LHC+EIC-type	LHC+EIC-type
Aperture*, capacitive plate distance (mm)	40*	30*	20
Profile	Round, with waist	Oval, with waist	Oval, with waist
Dimensions: L x W x H (mm)	120 x 108 x 108	126 x 91 x 106	117 x 76 x 97
Circuit Rt/Q (Ohm)	95	153	311
Geometric factor (Ohm)	98	104	97
Epk (MV/m) at 1.86 MV	95*	63	55
Bpk (mT) at 1.86 MV	159*	109	84
First HOM (GHz)	--	1.84 (z)	2.18 (z)

** May reach lower peak fields with oval profile*

Comparison between cavity models

	LHC-type DQW (B05)	EIC-type DQW (A42)	LHC+EIC-type (C02)
Aperture, capacitive plate distance (mm)	20	20	20
Profile	Elliptical, with waist	Oval, straight walls	Oval, with waist
Dimensions: L x W x H (mm)	95 x 100 x 88	115 x 98 x 82	117 x 76 x 97
Circuit Rt/Q (Ohm)	309	333	311
Geometric factor (Ohm)	80	82	97
Epk (MV/m) at 1.86 MV	50	56	55 ←
Bpk (mT) at 1.86 MV	99	81	84 ←
First HOM (GHz)	1.74 (z)	1.98 (z)	2.18 (z) ←



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Backup

Evolution of EIC DQW Crab Cavity

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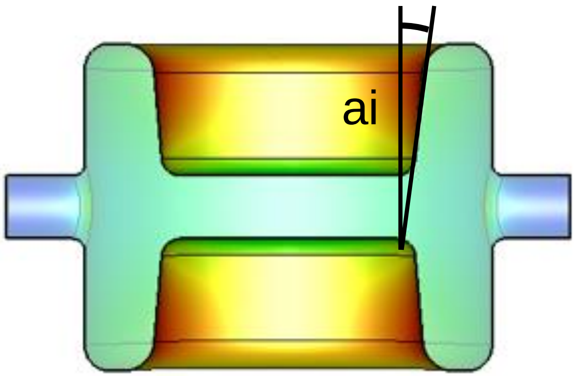
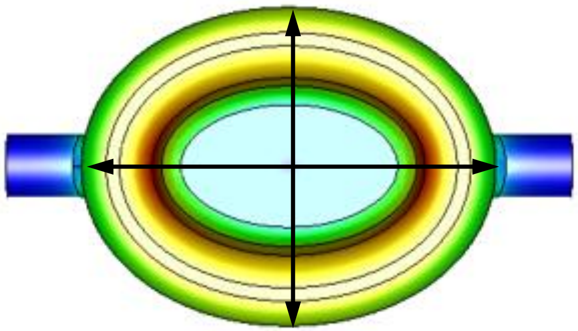
Pathway to low Bpk/Vt

- Low Bpk/Vt in the 197 MHz DQW thanks to:

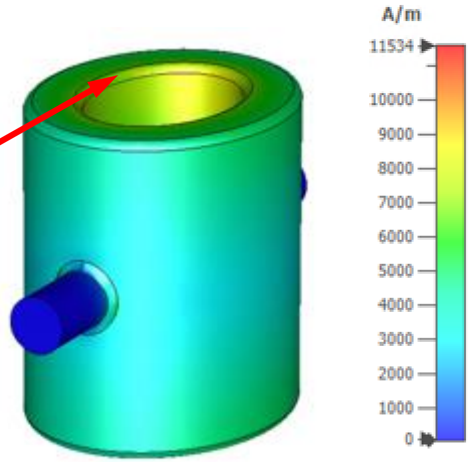
1) Inner wall slope “ai”



2) Ellipticity “EL” = Major radius / minor radius



- The impact of the outer wall slope “ao” on Bpk/Vt was also studied. No benefit was found.
- Inspect thoroughly field map to identify possible “hot spots” which can introduce an 10% error in value of Bpk.
- Rounded dome provides lower Bpk/Vt than classic dome.



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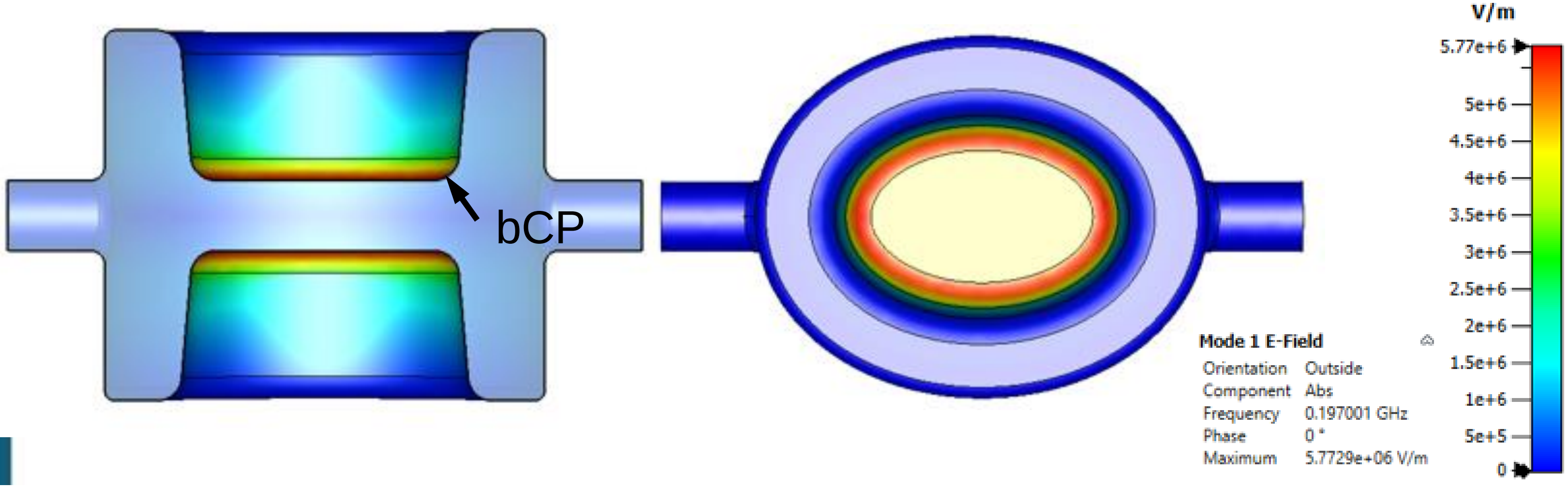
Pathway to low Epk/Vt (I)



Low Epk/Vt in the 197 MHz DQW thanks to:

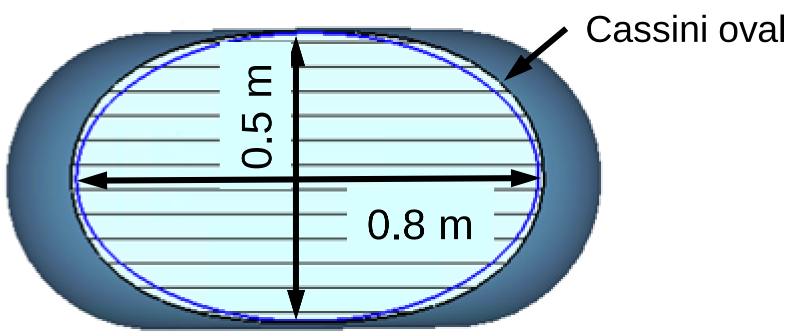
1) Capacitive plate blending "bCP":

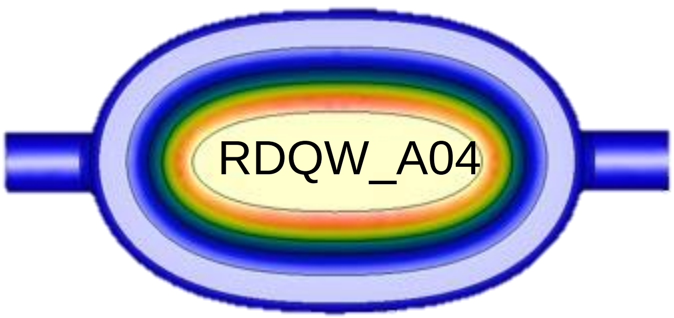
- No significant impact on Rt/Q (i.e. efficiency to provide kick is maintained despite modifying the capacitive plate).
- No impact on Bk/Vt as expected in first-order approximation.
- The "bCP" cannot be increased indefinitely for the elliptical profile.
  [Beyond a certain "bCP" value, the design software is unable to blend the corners by the major radius vertices. The max. "bCP" depends on the ellipticity value "EL" (e.g. for EL = 1.5, max. bCP = 40 mm). Work-around solution: Cassinian profile.]

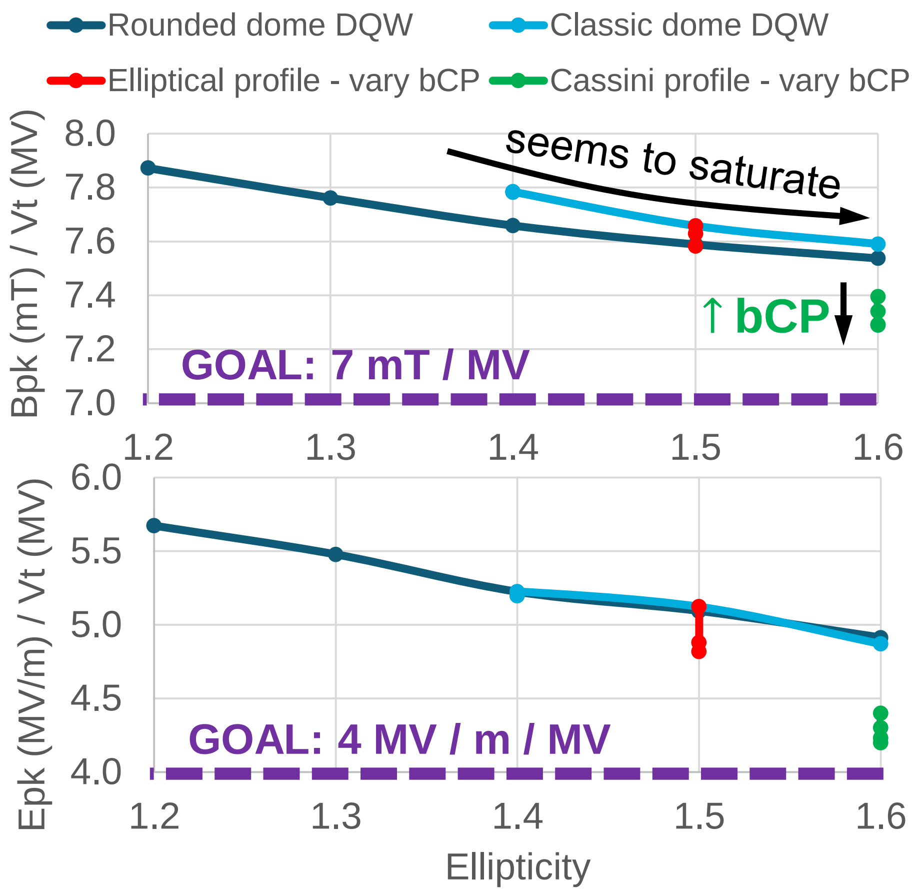
Pathway to low Epk/Vt (II)

2) ~~Racetrack~~ Cassinian profile:

- **Cassini oval** is just a planar section of a **spindle torus.**







- Finds significantly **lower Epk/ Vt and Bpk/ Vt than any other DQW geometry**, with **remarkable** values for figures of merit: **Vt / Epk / L** = 0.30 **and Vt / Bpk / L** = 0.17 MV/mT/m, Epk ~ 48 MV/m and Bpk ~ 84 mT for Vt = 11.5 MV.

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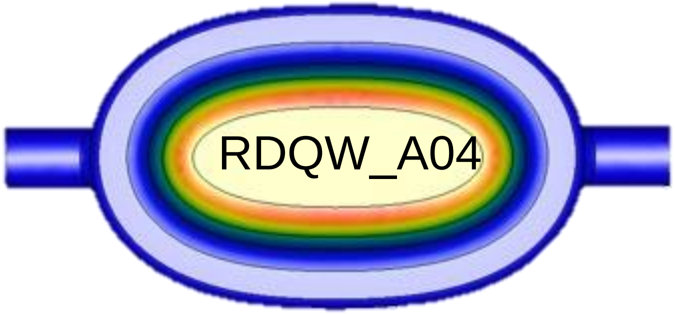
Best 197 MHz DQW in terms of peak fields

Parameter description (all mm unless spec	Name	RDQW_A04
Aperture	AP	100
Distance between capacitive plates	CD	100
Beam pipe diameter	BPD	100
Beam pipe diameter tappered section	BPD2	NA
Beam pipe length	BPL	200
Beam pipe tapper length	BPT	NA
Blend capacitive plate (radius)	b_CP	50
Blend outer conductor	b_OC	15
Blend inner conductor	b_IC	35
Blend beam pipe (radius)	b_BP	20
Outer conductor diameter	OCD	500
Inner conductor diameter	ICD	250
Inductor length	IL	184.25
Gap between conductors	(OCD-ICD) / 2	125
Ratio coaxial conductors	OCD/ICD	2
Ellipticity	E or EL	1.6
Inner wall angle (deg)	ai	5
Outer wall angle (deg)	ao	NA
Electromagnetic quantities		
Resonant frequency	freq [GHz]	0.197
Epk/Vt	Epk/Vt [1/m]	4.20
Bpk/Vt	Bpk/Vt [mT/MV]	7.29
Epk (Vt NOM)	Epk_NOM [MV/m]	34.86
Bpk (Vt NOM)	Bpk_NOM [mT]	60.52
Transverse impedance over Q	Rt/Q [Ohm]	1028
Surface resistance (copper model)	Rs [Ohm]	3.66E-03
Quality factor (copper model)	Q0	2.15E+04
Geometric factor	G	78.73



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