Design and Prototyping of HL-LHC Double Quarter Wave Crab Cavities

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on behalf of

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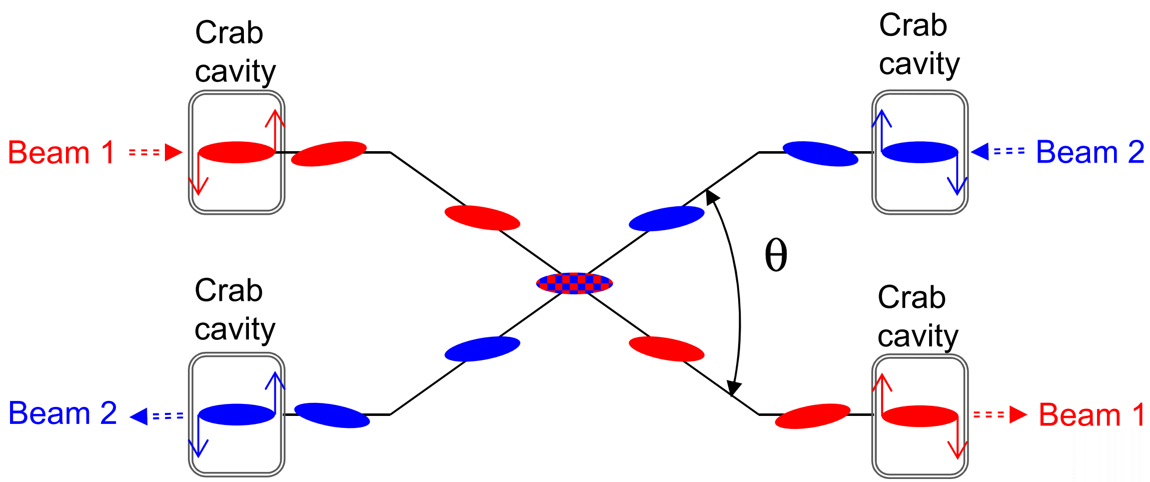
STFC-ULAN *Graeme Burt, Ben Hall, Niklas Templeton*

LBNL *Alex Ratti*

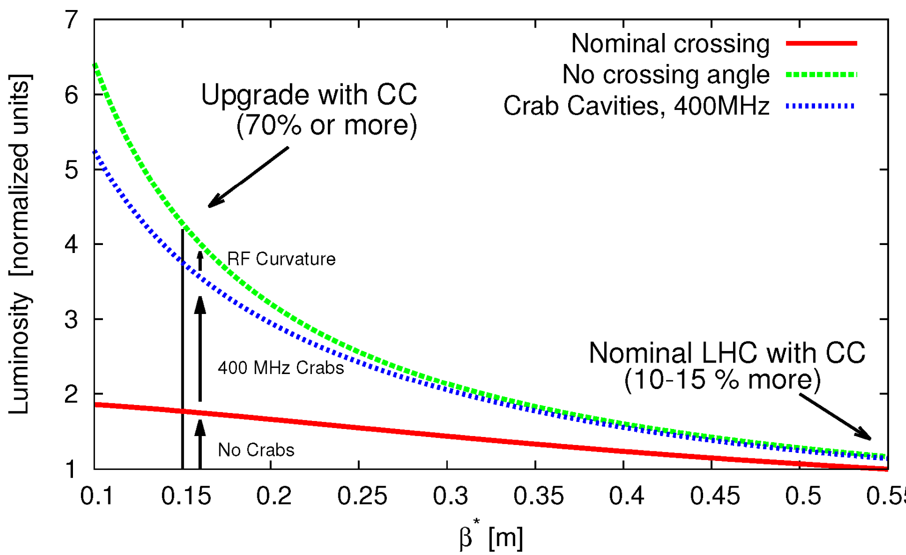
SLAC *Zenghai Li*

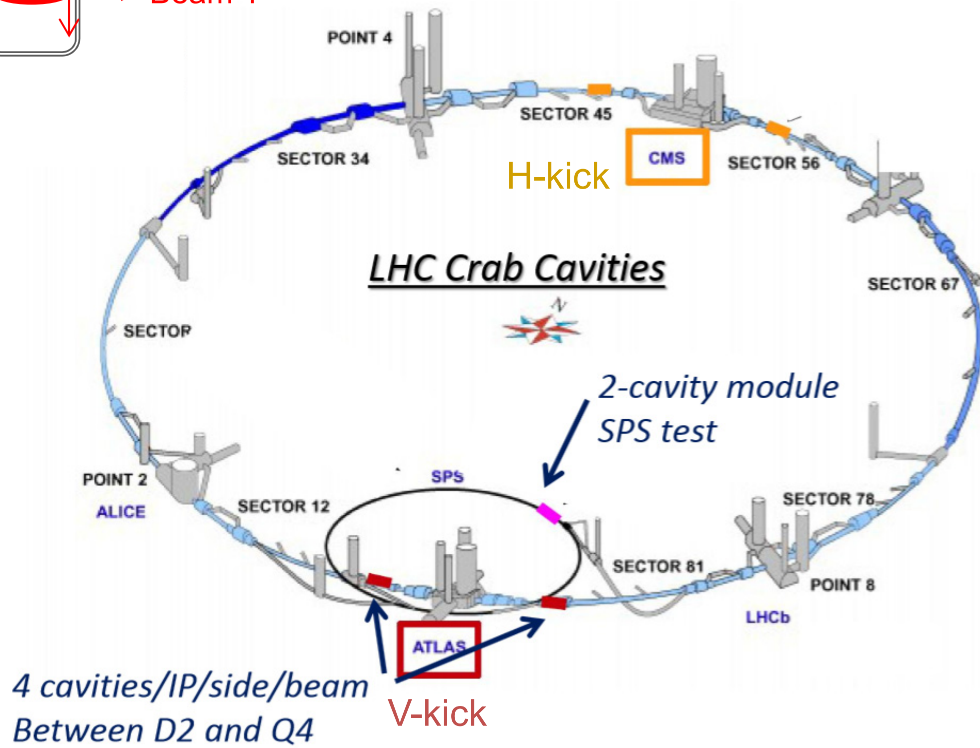
Crab crossing for High Luminosity LHC

→ THXB2: Qiong Wu's talk on Thursday

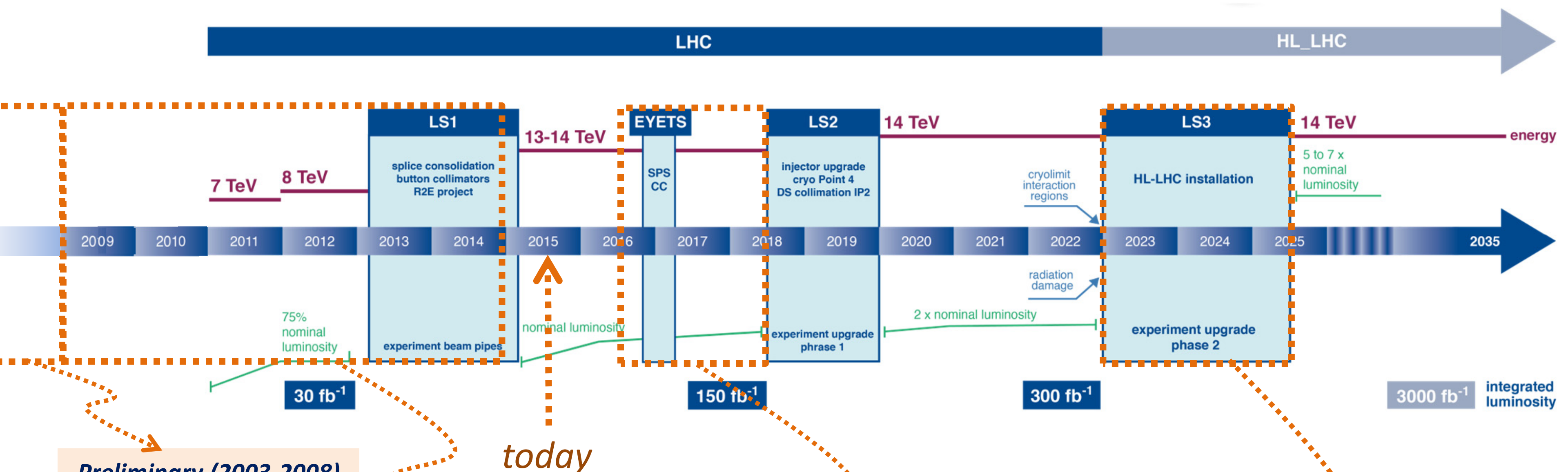


Crab crossing for full exploitation of HiLumi LHC upgrade





High Luminosity LHC – the Crab Cavity program (HiLumi LHC WP4)



Preliminary (2003-2008)
Conceptual design, feasibility study

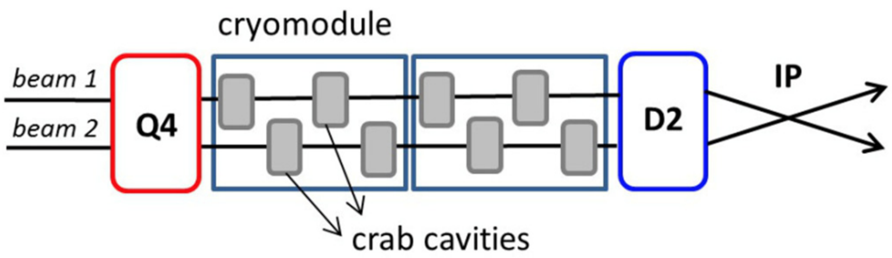
1st stage (2009-2014)
Demonstrate nominal deflecting voltage in cold tests

2nd stage (2012-2018)
Beam tests in SPS of two fully-dressed prototypes

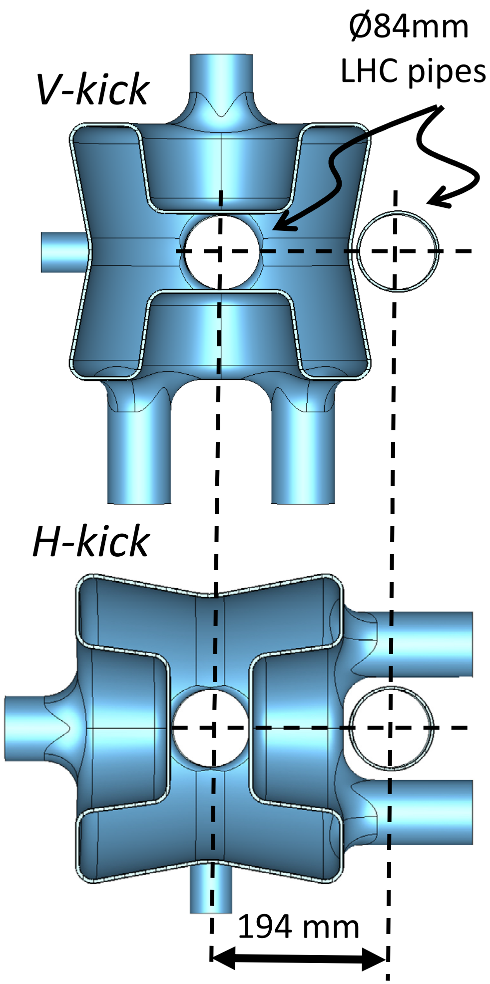
3rd stage (2022-2025)
Installation in LHC

Main requirements for LHC Crab Cavities

- CW operation, large aperture Ø84mm, $Q_0 \sim 10^{10}$ → Nb SRF cavity at 2K
- Crabbing frequency = 400 MHz (like current LHC accelerating cavities) some prior studies done to determine appropriate frequency
- Total deflecting voltage of 12-14 MV provided by 4 cavities:
  - 3.34 MV deflecting voltage per cavity
  - Higher voltage (~ 5MV) interesting for crab kissing or in case of low-performance cavity.
- Design compatible to operate in IP1 (V-kick) and in IP5 (H-kick)
  - Constraints cavity width and height due to adjacent beam pipe
- Limited space (~ 10 m) to allocate 6-8 cavities at each side of IP (3-4 cavities per beam)
- Reduced impact of CCs in LHC impedance budget

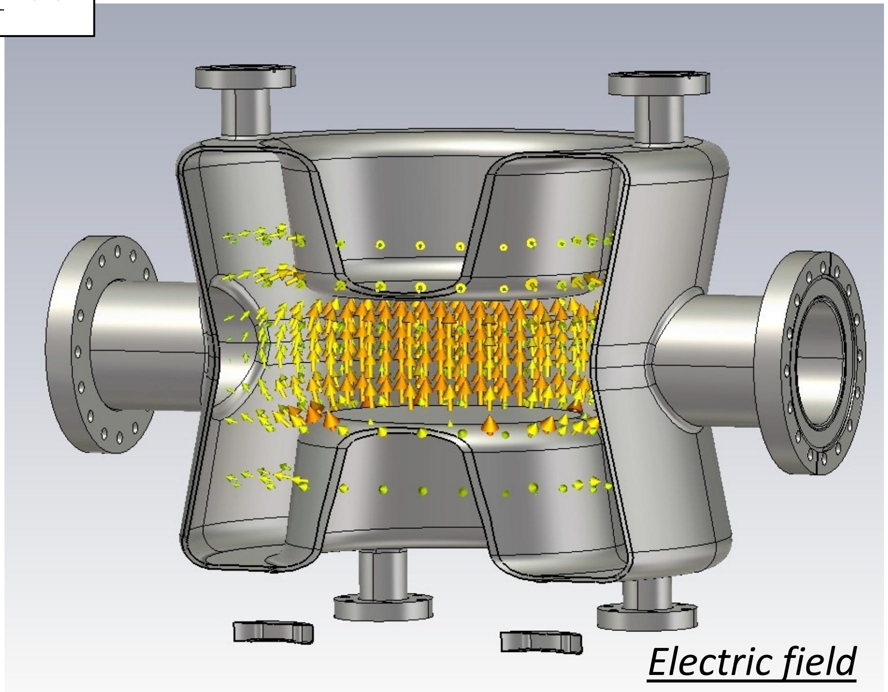


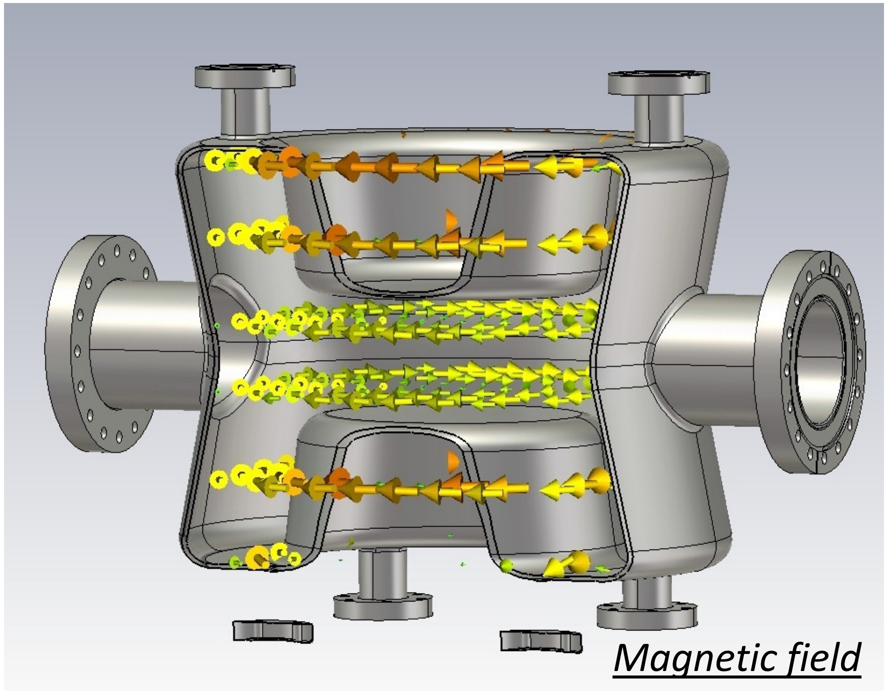
Cavity orientations



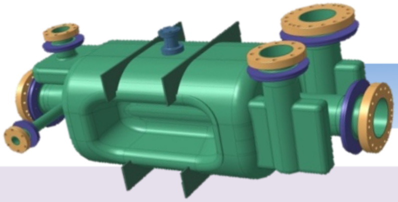
The Double-Quarter Wave (DQW) Crab Cavity by BNL

$f^{(0)}$





- *Deflecting voltage given when bunch is at cavity center and E-field is zero.*
- *Crabbing mode is fundamental mode. 1st HOM is well away from fundamental mode.*
- *From QW to DQW to reduce residual acceleration (still some due to port asymmetry).*

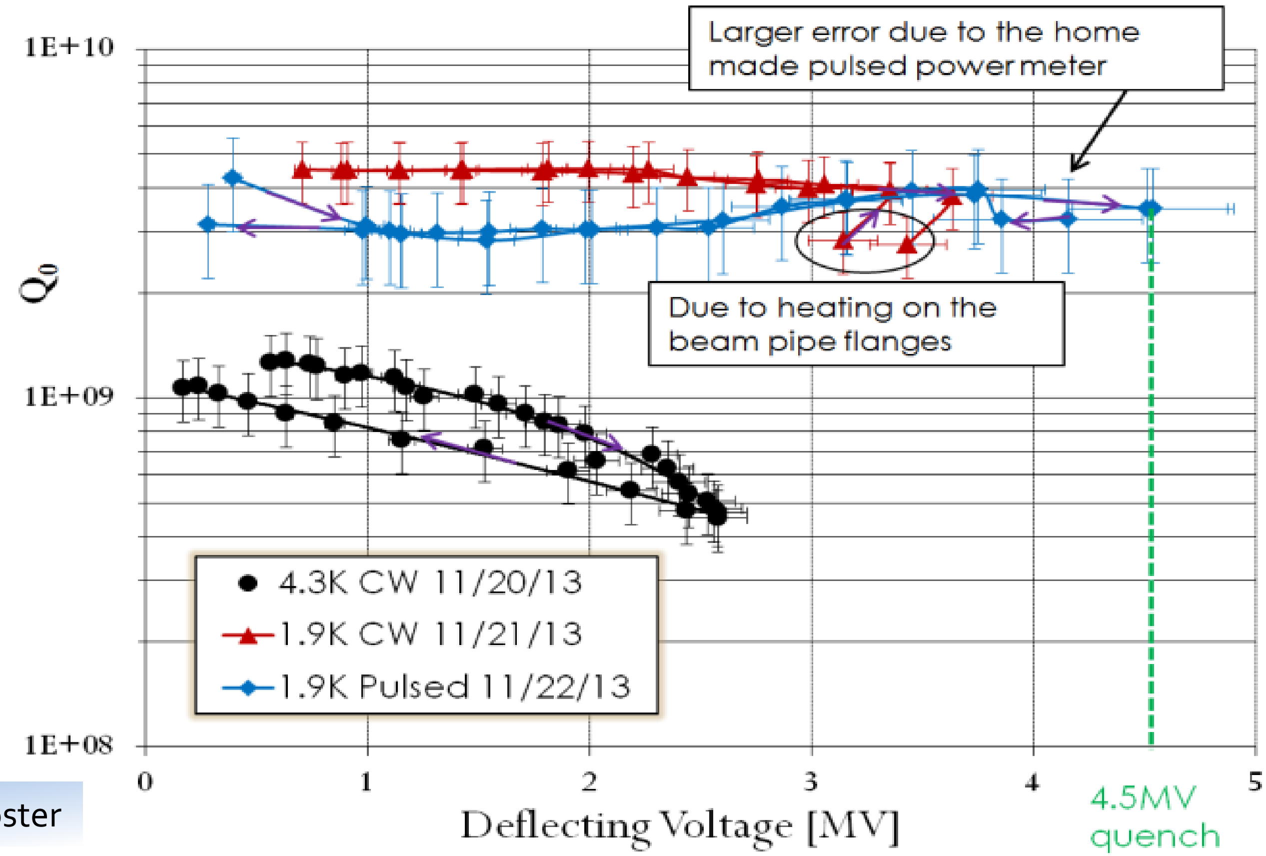


→ ODU/SLAC… RF Dipole Crab Cavity in IPAC15: WEPWI004, WEPWI037, WEPWI039

1st stage: validation of nominal deflecting voltage

PoP DQW cavity with stiffening frame

- *Successful cold test of PoP DQW cavity at BNL in 2014: Q_0 at around 3~4.5e9.*
- *In CW mode, temperature of beam pipe flanges increased.*
- *Reached 4.5MV kick in pulsed mode, limited by quench.*
- *Temperature increase on pickup port blending area.*
- *Quench for Bpk ~110mT and Epk~ 53MV/m.*

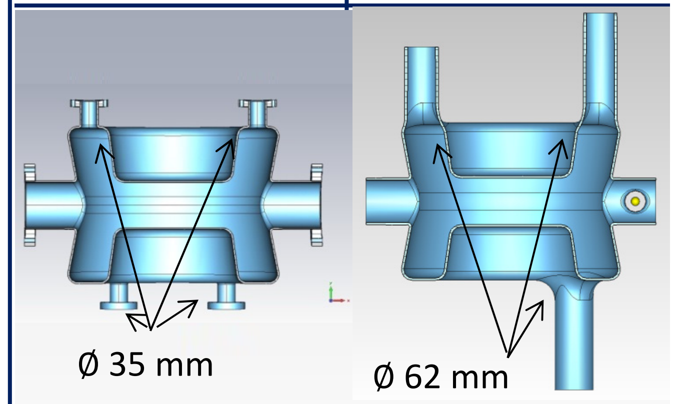


→ WEPWI060: Binping Xiao's poster

2nd stage: DQW cavities for SPS tests

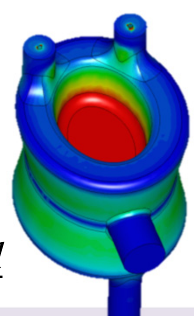
SPS cavity optimized into a more compact design with lower surface magnetic field.

Electromagnetic quantity *(Microwave Studio [5] simulations)*		**Unit**
Crab mode frequency f_0	400	MHz
Nearest mode frequency f_1	570	MHz
Deflecting voltage V_t [1]	3.34	MV
Deflecting gradient V_t/L_{cavity} [2]	9.5	MV/m
Accelerating voltage V_{acc} [2]	15	kV
Electric field center offset	0.23	mm
Peak surface electric field E_{pk} [2]	37	MV/m
Peak surface magnetic field B_{pk} [2]	72	mT
Stored energy U [2]	10	J
R_t/Q	429	Ω
Geometric factor G	87	Ω

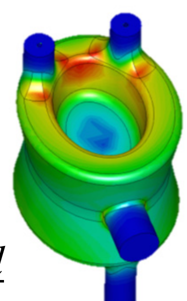


	PoP DQWCC	SPS DQWCC
R_t/Q [Ohm]	400	430
G [Ohm]	85	87
E_{pk} [MV/m]	38	37
B_{pk} [mT]	80	72

f(0)



E-field



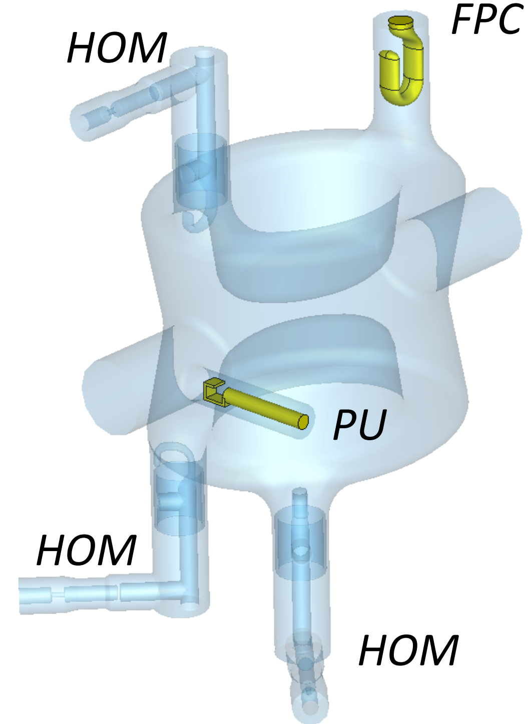
H-field

Expected performances from PoP DQW cold test results

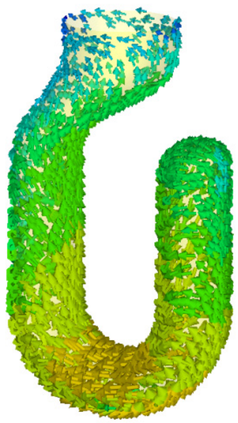
Quench for **SPS DQWCC extrapolated** to Vt~ **5.1 MV** using measured quench voltage of PoP cavity.

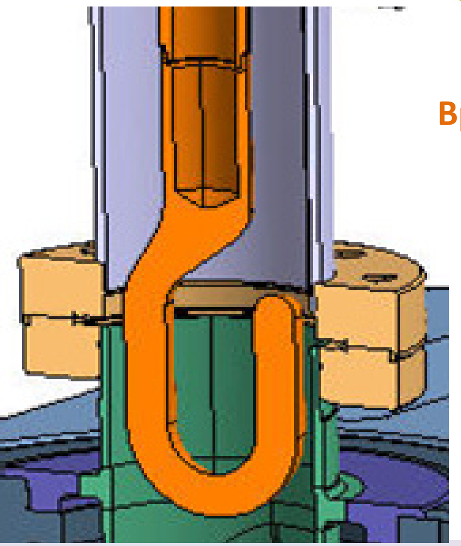
SPS DQWCC – Fundamental Power Coupler and Pick-Up

- *Hook-type antennae for well coupling with magnetic field.*
- *Detachable from cavity to ease installation.*
- *Active cooling for FPC and HOM down to hook bending.*

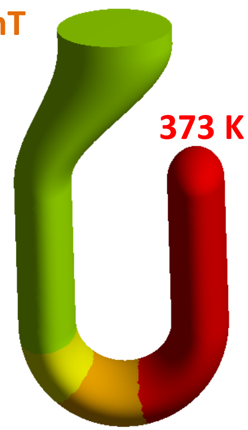


<u>FPC antenna</u> (Cu):
Qext $^{f(0)}$ is 5.3x10^5, 40kW enough to feed cavity. Optimized design to reduce Pdiss on hook tip.

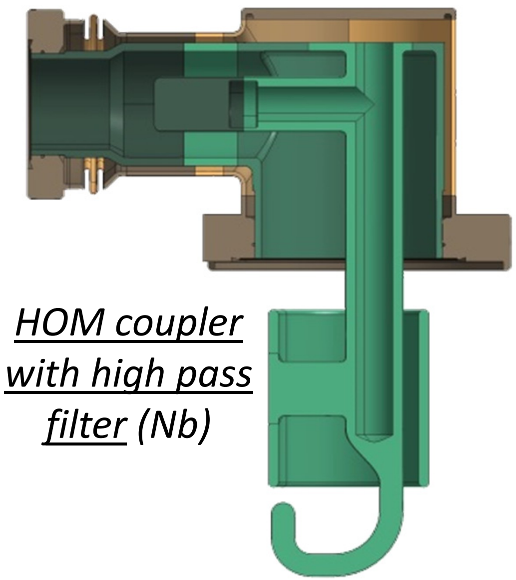




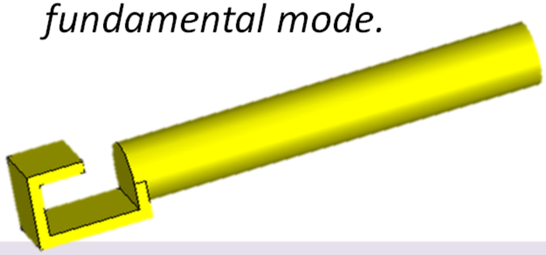
Bpk ~ 10 mT



<u>HOM coupler with high pass filter</u> (Nb)



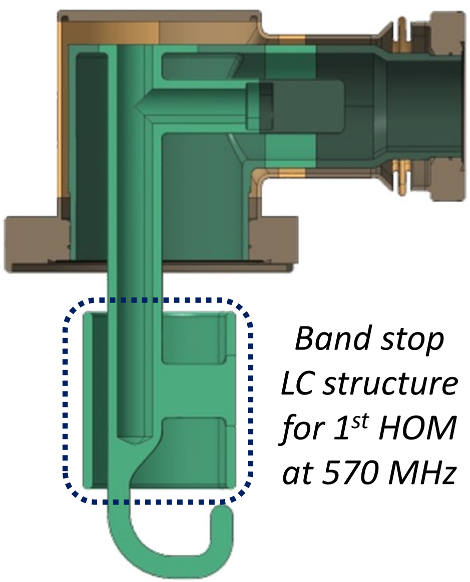
<u>Pick-up antenna</u> (Cu):
Qext $^{f(0)}$ is 1.6x10^{10}, extracts about 1.5W of fundamental mode.

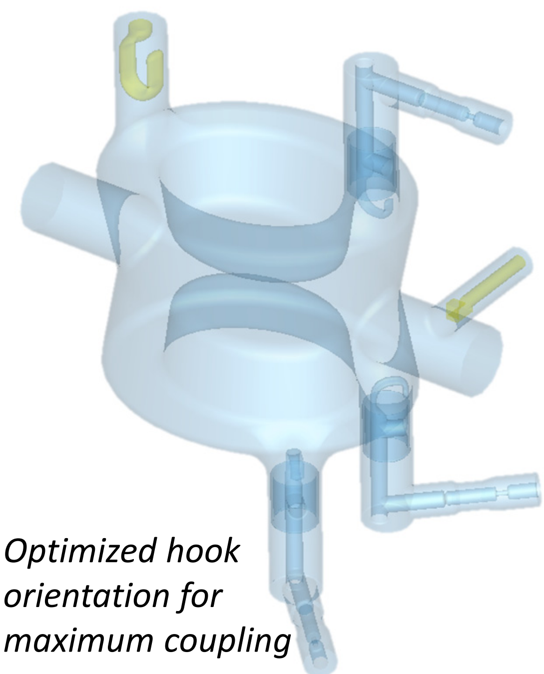


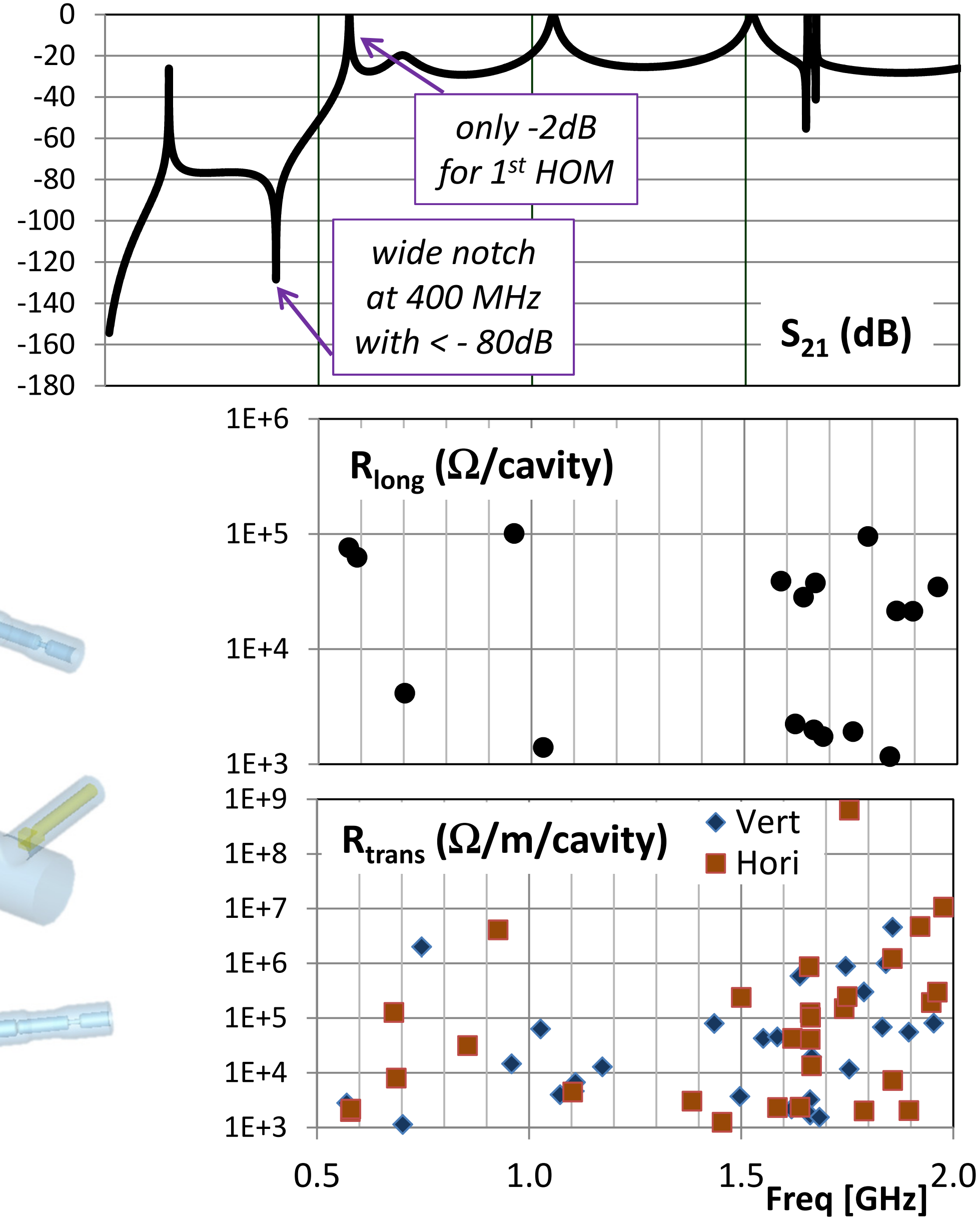
SPS DQWCC – *HOM filters*

[Collaboration BNL-STFC]

- *Chebychev-type filter*
- *Optimized design to reduce impedances*
- *Space constraint in cryomodule*
  - → *HOM filter tube with elbow*
- *First prototype being manufactured at CERN.*

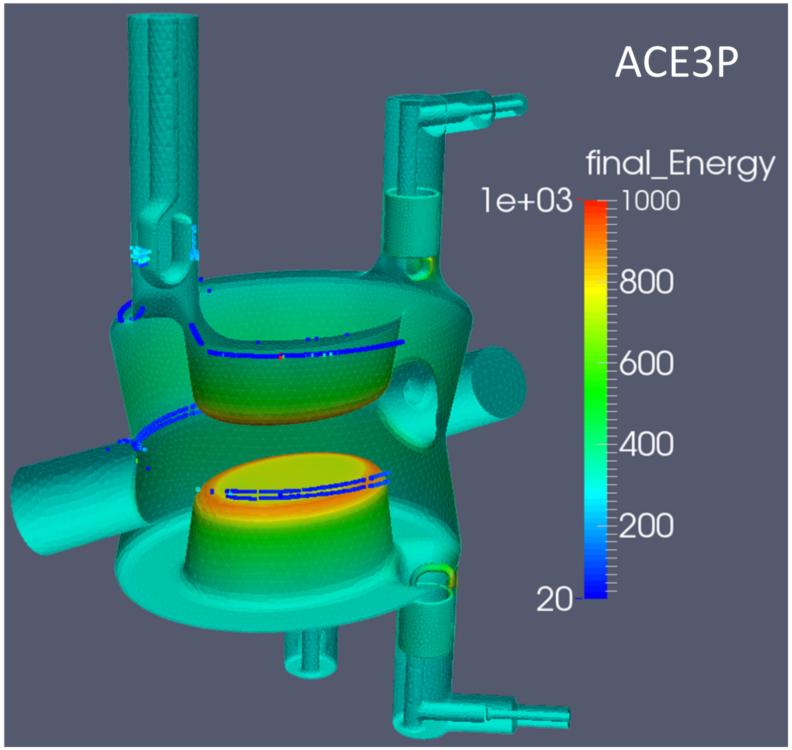






SPS DQWCC – *Multipacting*

[Collaboration SLAC-STFC]



CAVITY BODY

- Multipacting found at low deflecting voltages (~0.1 MV). Same band found for PoP DQW but was quickly processed.
- Weak signatures in port blending.

FPC PORT

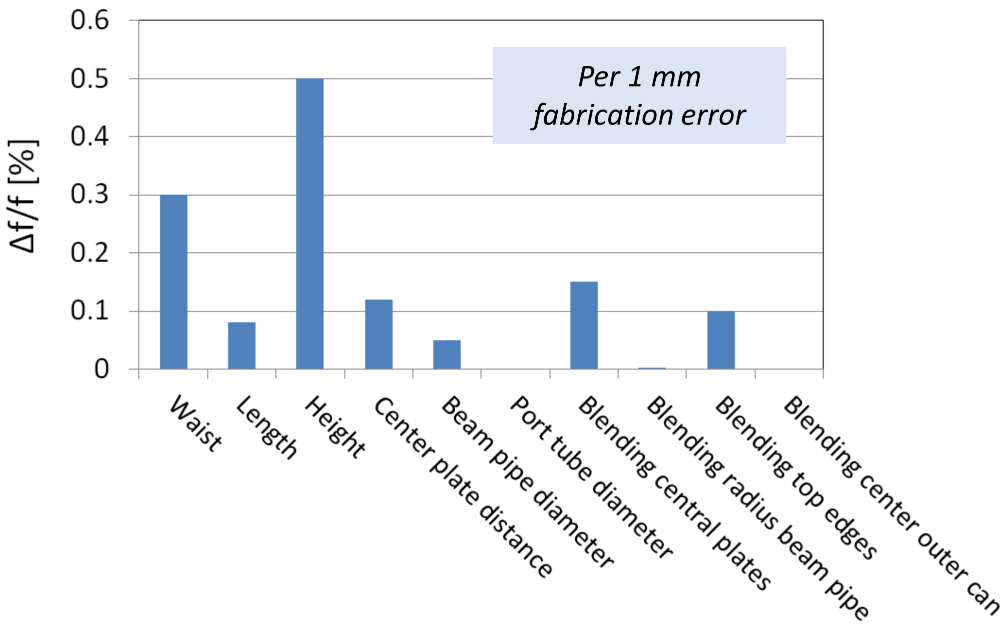
- Will require high-power conditioning.

HOM FILTERS

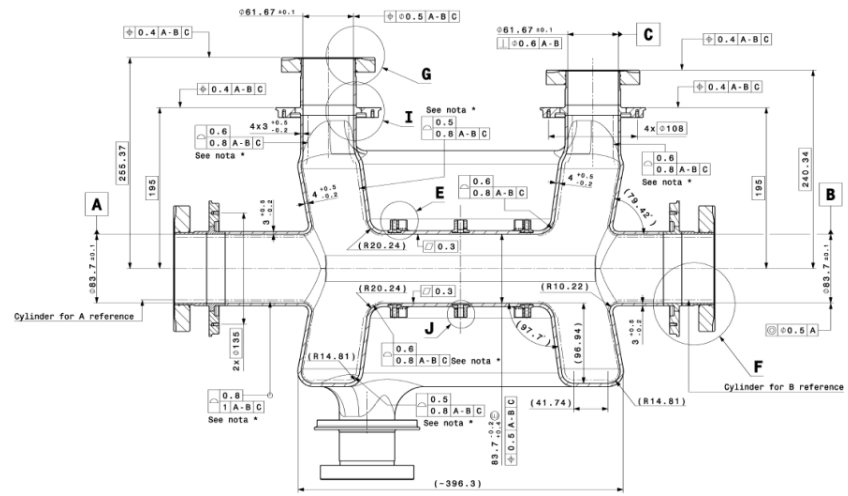
- Optimized design does not show critical multipacting signatures.

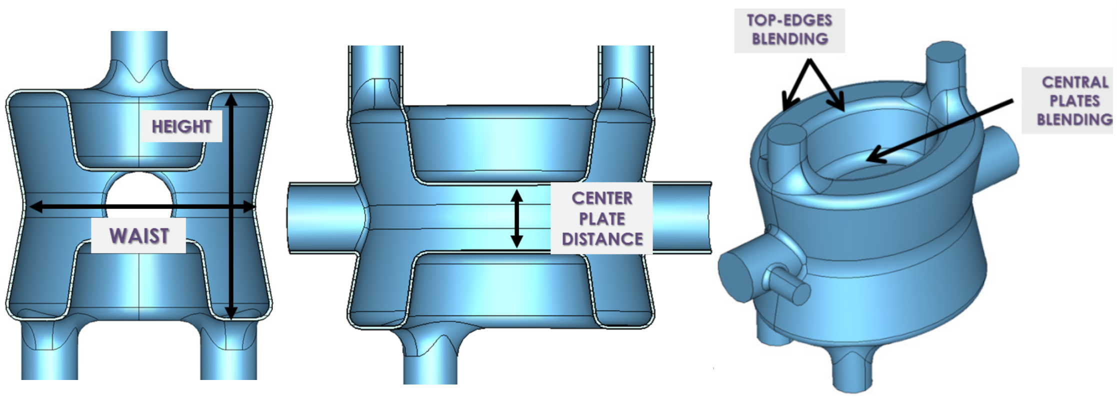
SPS DQWCC – Prototyping

- *Cavity height and waist are the most sensitive geometry parameters.*



- *Tighter tolerance specified for these regions in functional spec drawing.*



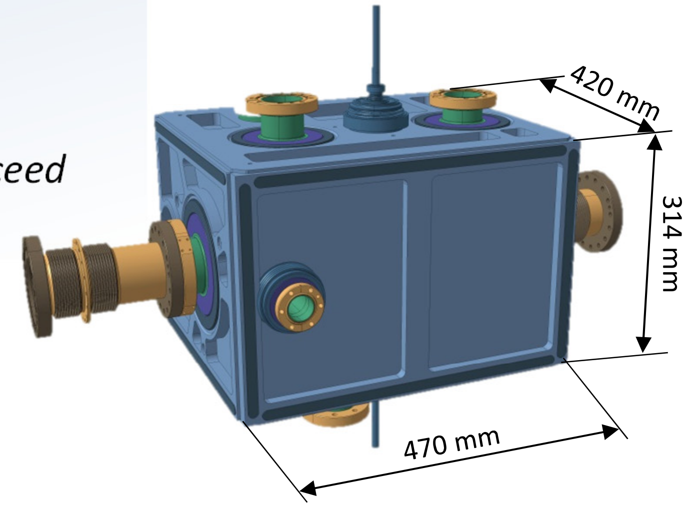


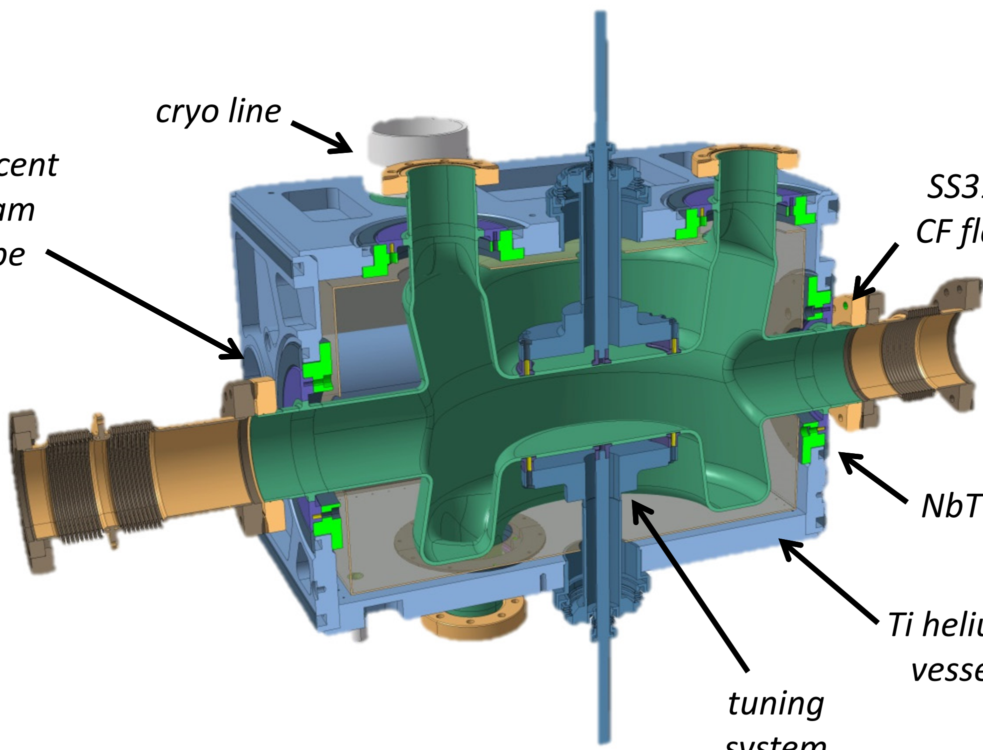
- *Geometry provided for fabrication dimensioned to account for shrinkage associated to cooldown and chemistry.*

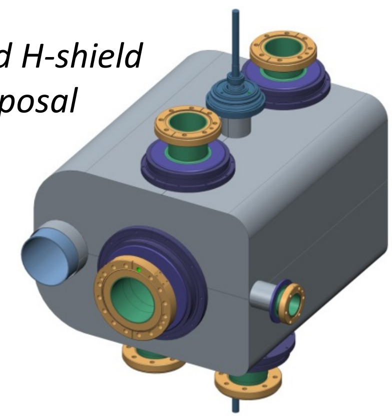
Thermal: 300K → 2K	-573 MHz
BCP: 150μm + 30μm + 30μm	170 MHz

SPS DQWCC – *helium vessel & tuner* [Collaboration CERN-STFC-BNL]

- *Helium vessel made of titanium*
  → rigid connections; additional stiffening to ports (inductive region)
- *Hosts tuning system and cold magnetic shielding*
- *Prep rings for eventual disassembly*
- *Adjacent beam pipe enclosed in helium vessel*
- *Comprehensive mechanical studies to ensure stress does not exceed material limits on cavity.*

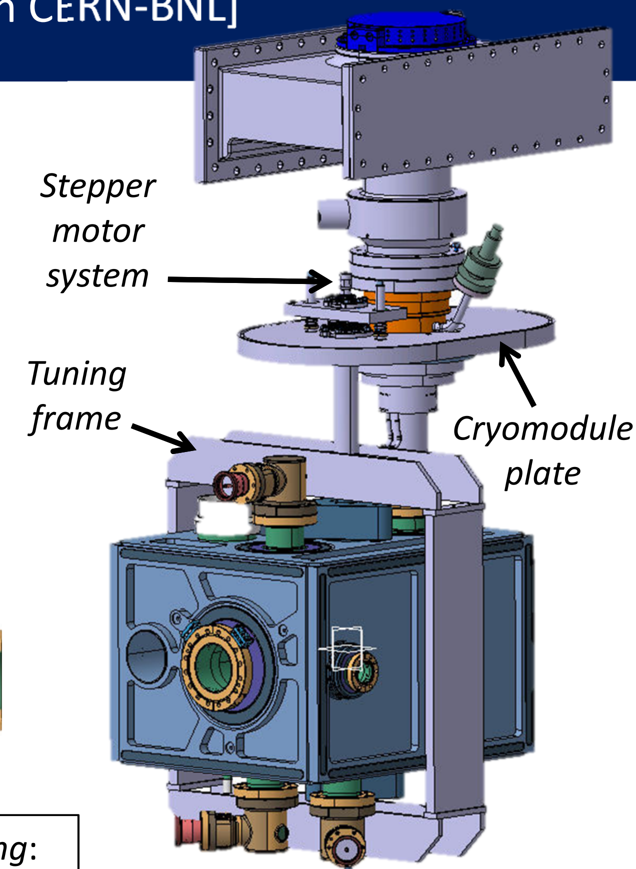


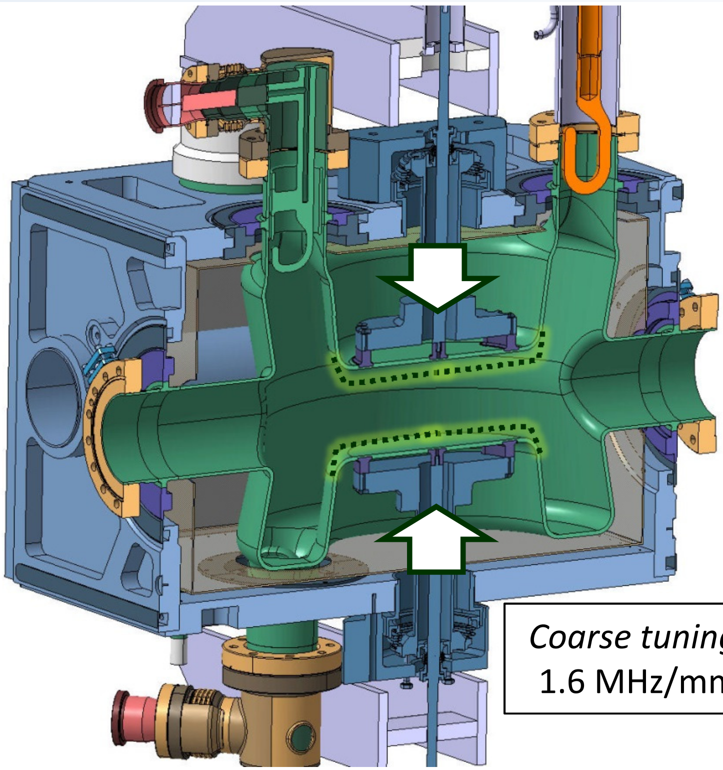


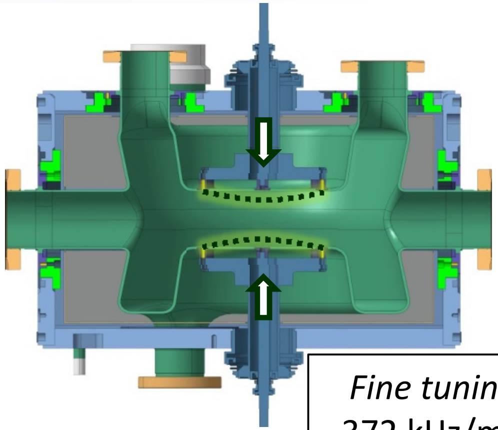


SPS DQWCC – *tuning system* [Collaboration CERN-BNL]

- *Tuner actuation on cavity plates (capacitive region).*
- *Provides additional stiffening to central plates during cooldown and pressure changes.*
- *Tuning frame used for symmetric actuation. However, asymmetric deformation of cavity plates due to port distribution.*
- *Pretty close to finalization. Plans for testing tuning system.*







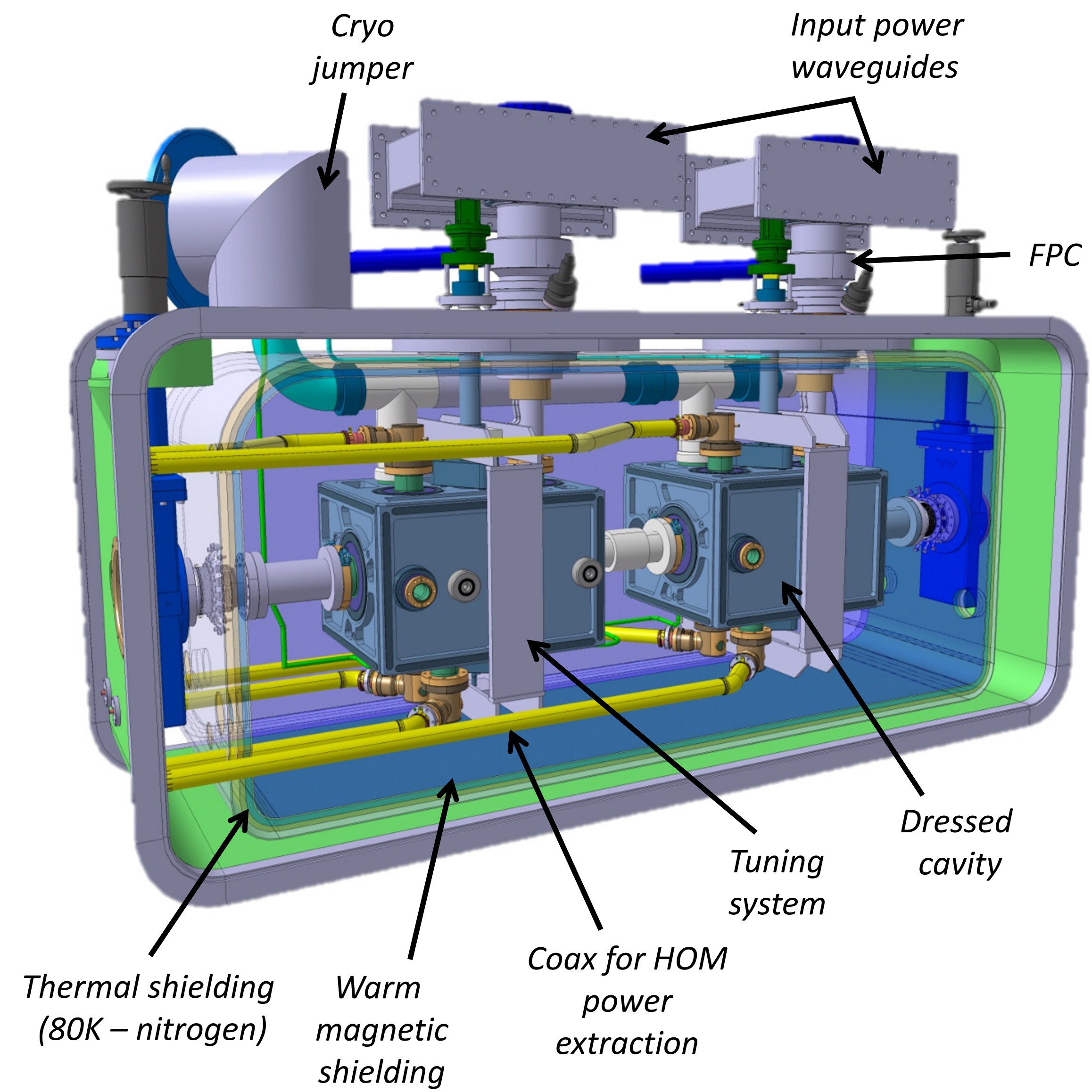
Tuning scenarios / strategy:

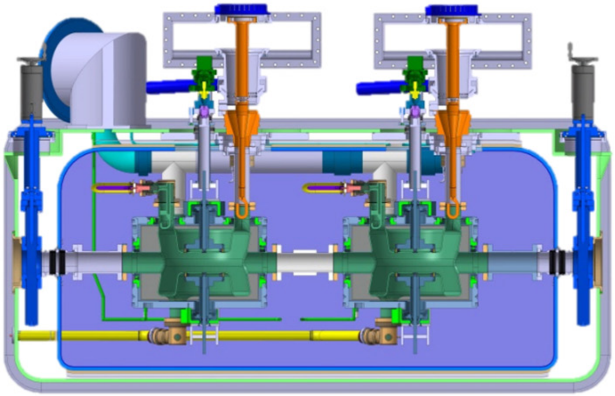
- *Pre-tuning (after assembly of cavity and vessel)*
- *Slow tuning*
- *Fast tuning – piezo*

Pressure sensitivity	0.1 Hz/mbar
Lorentz force detuning*	< 1 Hz

SPS DQWCC - *cryomodule*

[Collaboration CERN-STFC]

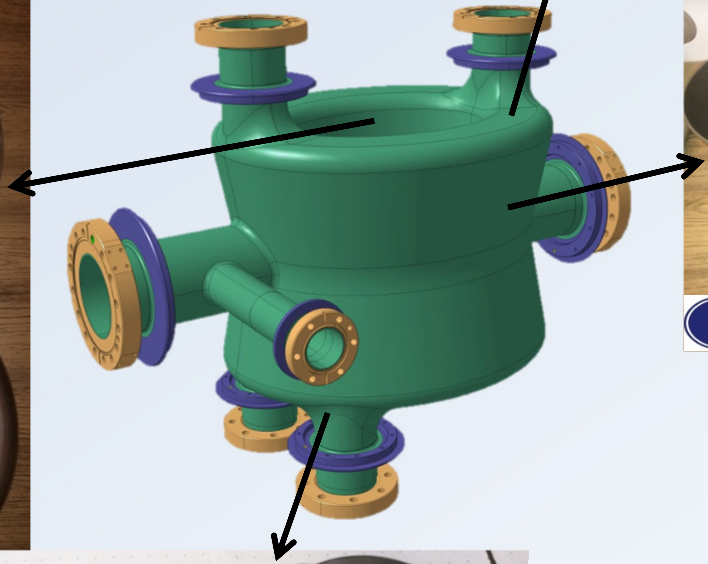




- *Cryomodule for 2 dressed DQW cavities in vertical kick configuration.*
- *Side-loaded cryomodule for fast access during commissioning.*

SPS DQWCC – *production status*

- *Parts for 2 SPS DQW prototypes by Niowave*
- *Formed from Nb RRR>300 sheets*
- *4mm thick for cavity body; 3mm for port tubes*
- *Almost ready for EBW*



- *First HOM filter prototype being manufactured at CERN*

Summary and outlook

- **Cold tests of PoP DQW** cavity demonstrated required nominal deflecting voltage.

- Improved **DQW cavity design for SPS tests**: reduced Bpk, satisfy LHC space constraints, include HOM filters.
  - Cavity and HOM filter designs for SPS test completed.
  - Next steps after EBW:
    1. Heavy BCP, high T bake, light BCP + HPR and bare cavity cold test at BNL in 2016.
    2. Assembly to LHe vessel, light BCP + HPR, pre-tuning, dressed cavity cold test at BNL, assembly into cryomodule, installation in SPS.
  - First HOM filter prototype being manufactured at CERN.

- Appropriate **cavity stiffening** provided by rigid connection of cavity ports to vessel and tuning system

- **Compact vessel** for compact cavity.
  - Design is being finalized.
  - Assembly to cavity in 2016.

- Manifold tuning: **pre-tuning + push-pull + piezo**
  - Tuning system will be tested soon.

Still a long way to go… *Looking forward to testing the cavities with beam in SPS*

Thanks for your attention

Acknowledgements to Niowave

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