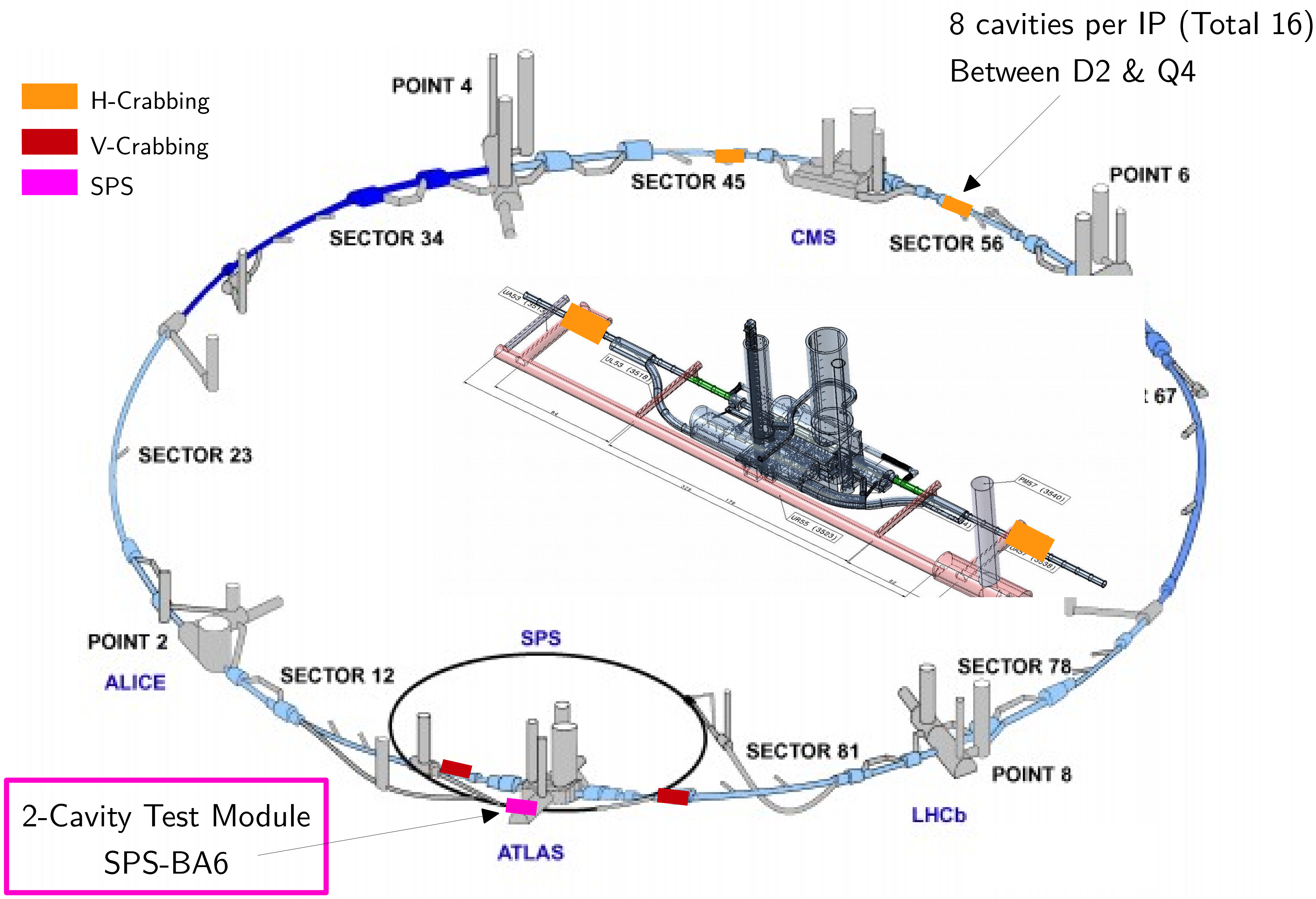
R&D Crab Cavities, HL-LHC

R. Calaga on behalf of HL-LHC WP4

HB2016, Malmo, 6 Jul 2016

Special Acknowledgement: BE-ABP, BE-RF, EN-MME, TE-VSC, USLARP & UK-STFC

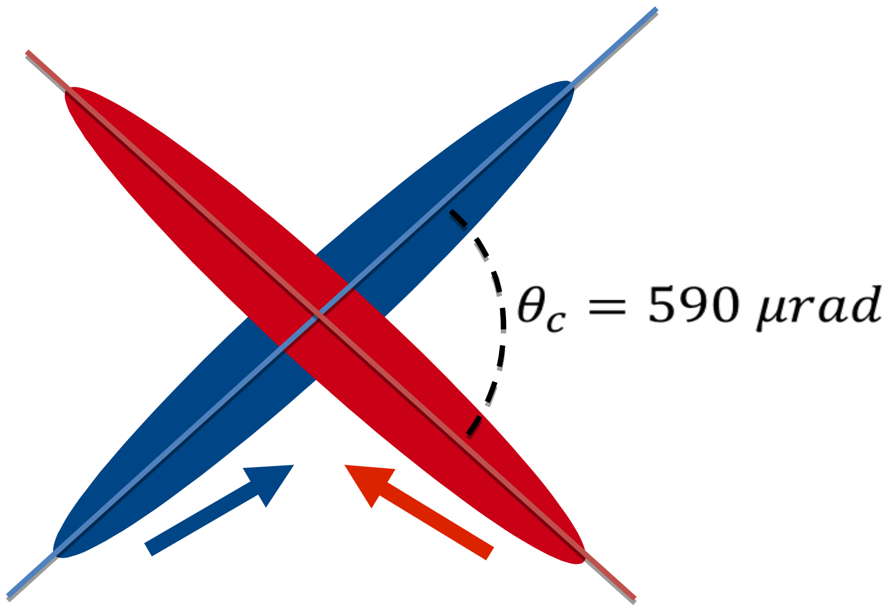
HL-LHC Crab Cavities



Crab Cavities, HL-LHC

Use 8-superconducting crab cavities per IP (ATLAS & CMS) to compensate up to 590 μrad x-angle

Goal: To recover ~ 70% of peak luminosity



Piwinski angle:

$$\Phi = \frac{\sigma_z}{\sigma_x}\left(\frac{\theta_c}{2}\right)$$

σ_z: 7.55 cm

σ_x: ~7 μm

$$V_{crab} = \frac{cE\tan(\phi_c)}{\omega R_{12}} \cdot \frac{2\sin(\pi Q)}{\cos(\phi_{cc-ip} - \pi Q)}$$

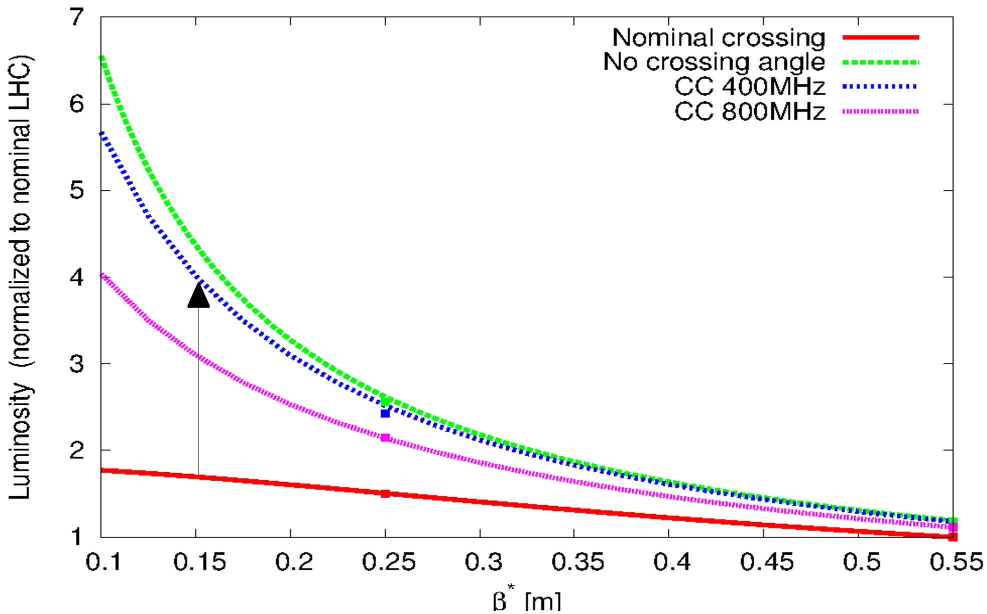
Total voltage ~10-12 MV

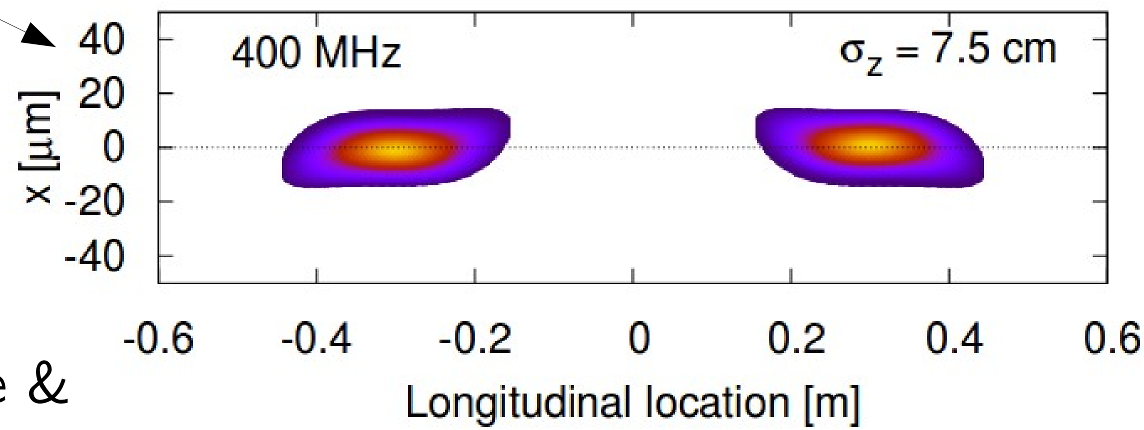
Frequency Choice

LHC bunches are long ($4\sigma = 1$ ns)

Main RF system is 400 MHz

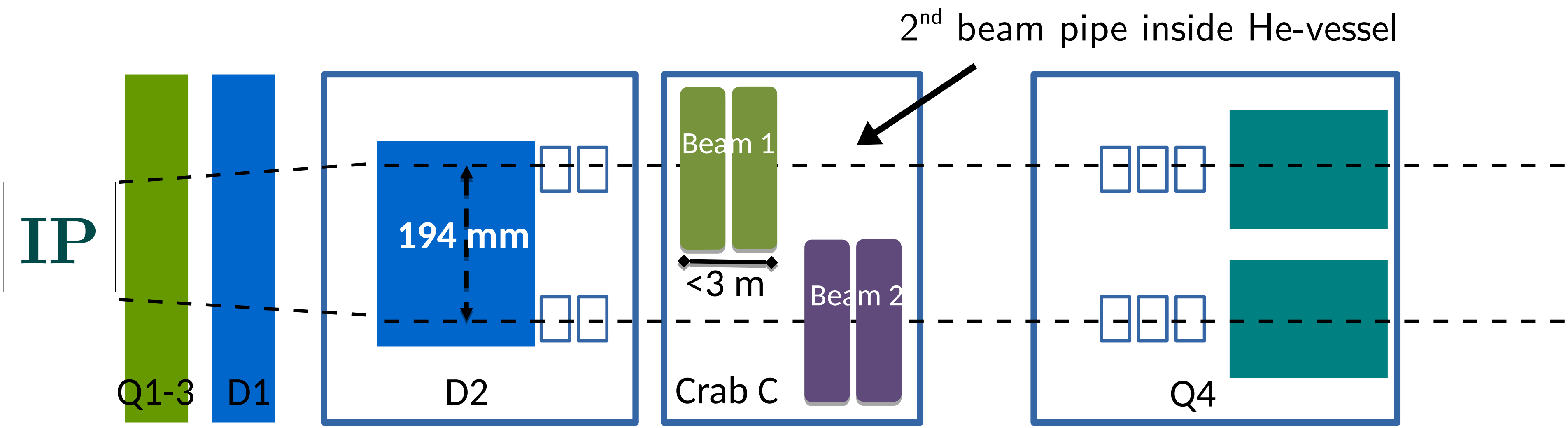
$$L \propto \frac{N_b^2}{\sigma^2} R_\Phi F_{RF}^\Phi$$





400 MHz from crabs is a good compromise between RF curvature & luminosity gain

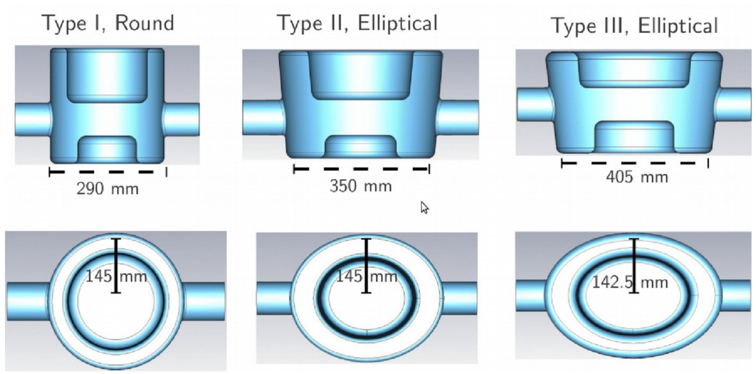
Layout/Parameters



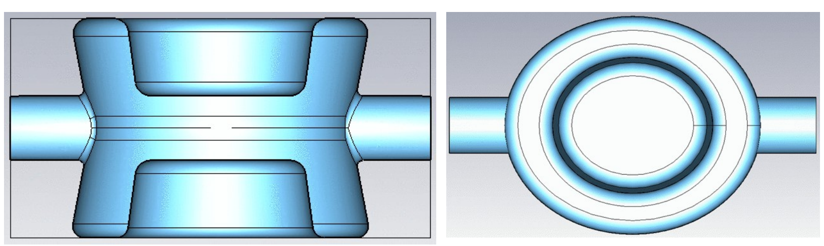
	unit	SPS	LHC	HL-LHC
Energy	TeV	0.026-0.45	7.0	7.0
Bunch length	[ns]	~2.0	1.0	1.0
β* (IP)	[m]	-	55 (40)	15
RF Freq	[MHz]	200.3	400.79	400.79
Voltage	[μrad]	-	300	590
Piwinski Angle		-	0.65	3.14

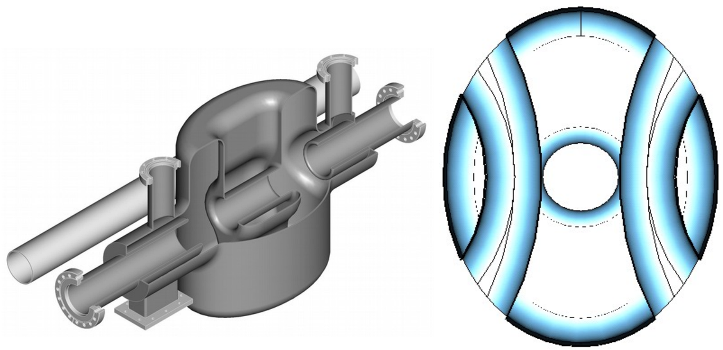
Quasi-TEM Class Cavities

Two cavity types designed (hor/ver) for the LHC

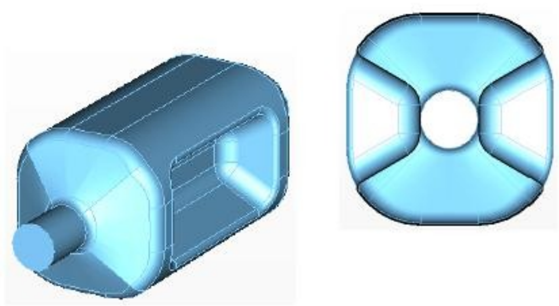


BNL





Joint SLAC-ODU Effort

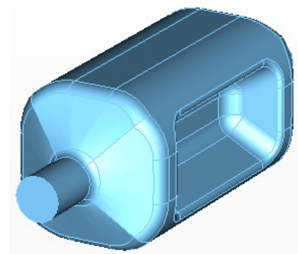


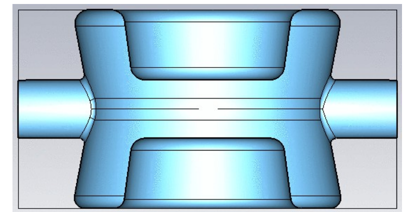
Fundamental mode is the deflecting mode

HOMs are spaced farther away making HOM damping easier

Performance Chart

Kick Voltage: 3.4 MV, 400 MHz

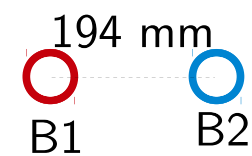




	Double Ridge (ODU-SLAC)	Double Wave (BNL)
Cavity Radius [mm]	**140.5**	**139**
Cavity length [mm]	557	344
Beam Pipe [mm]	84	84
Peak E-Field [MV/m]	33	38
Peak B-Field [mT]	56	70
R_T/Q [Ω]	429	426
Nearest Mode [MHz]	~700	581

Geometrical

RF



$<$ 60 MV/m

$<$ 100 mT

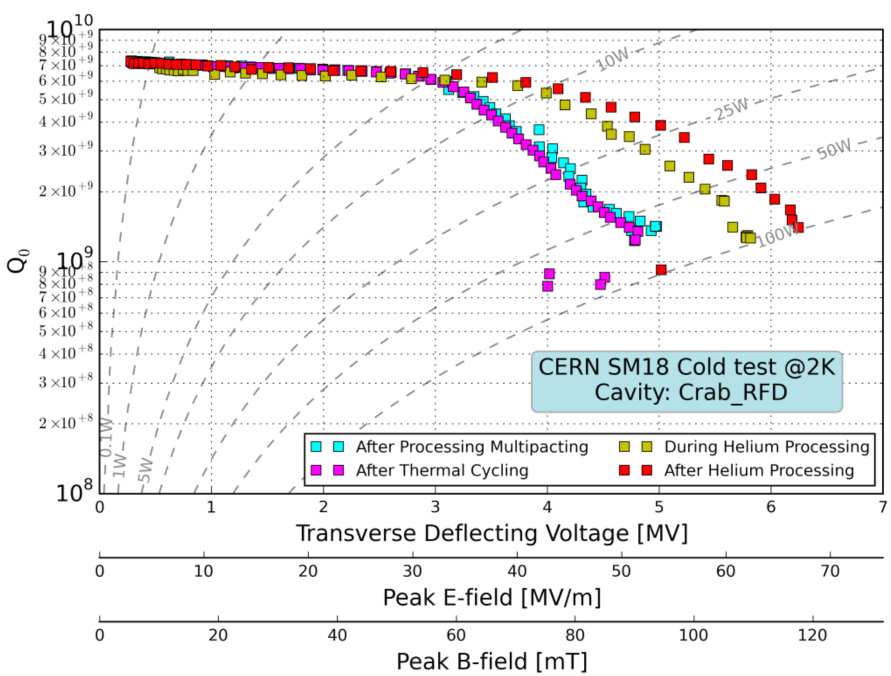
First Prototypes

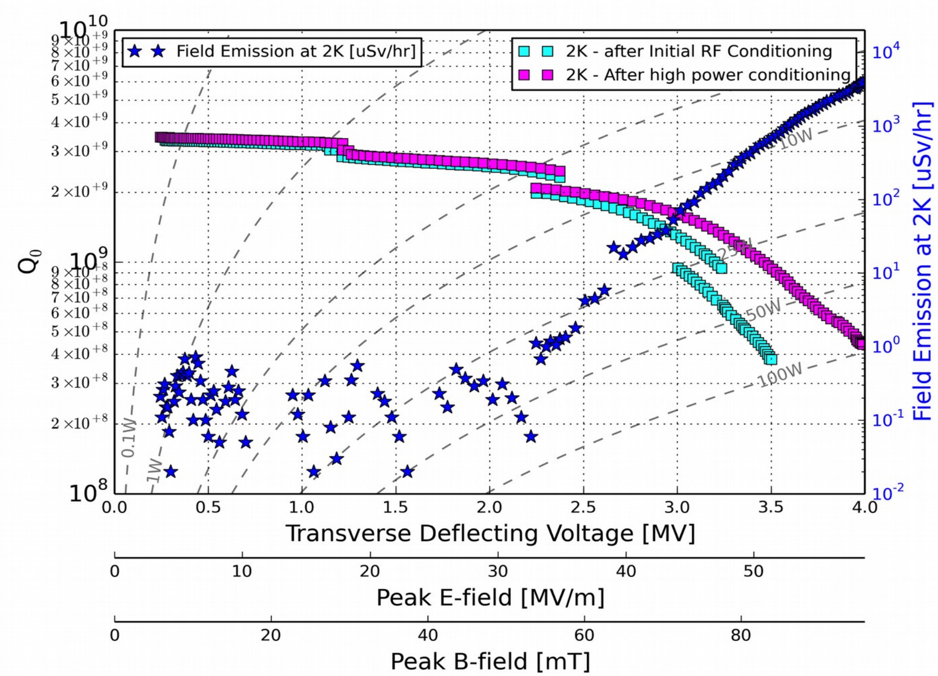
Proof of principle concepts built and kick field demonstrated

Two designs retained for the LHC (horizontal and vertical)

RF Dipole

Double 1/4-wave

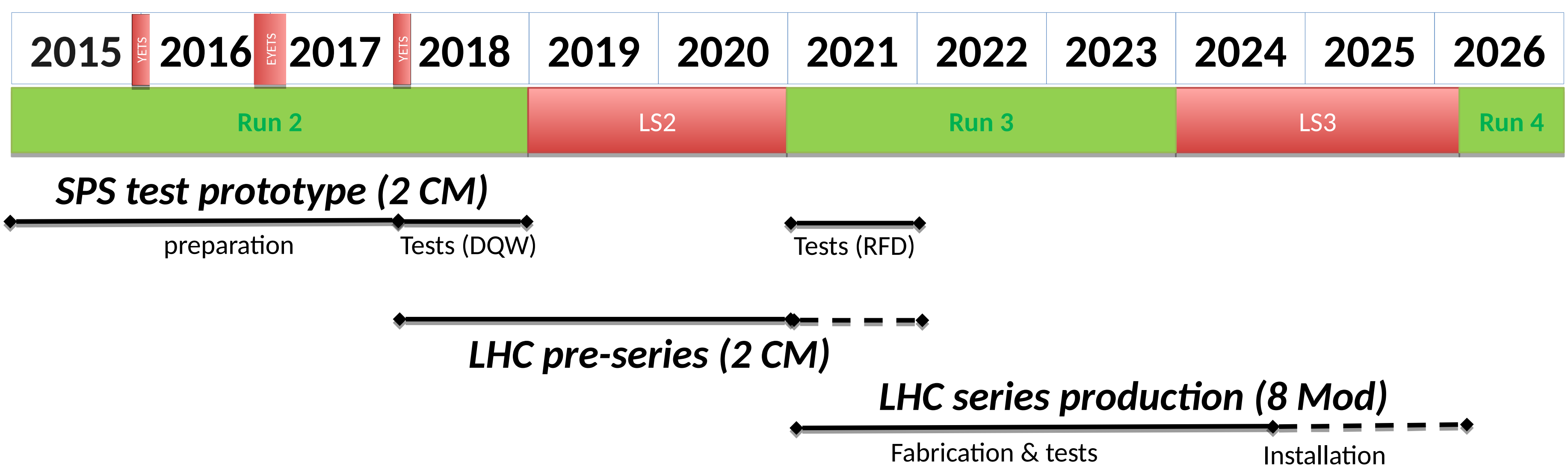




Overall Planning

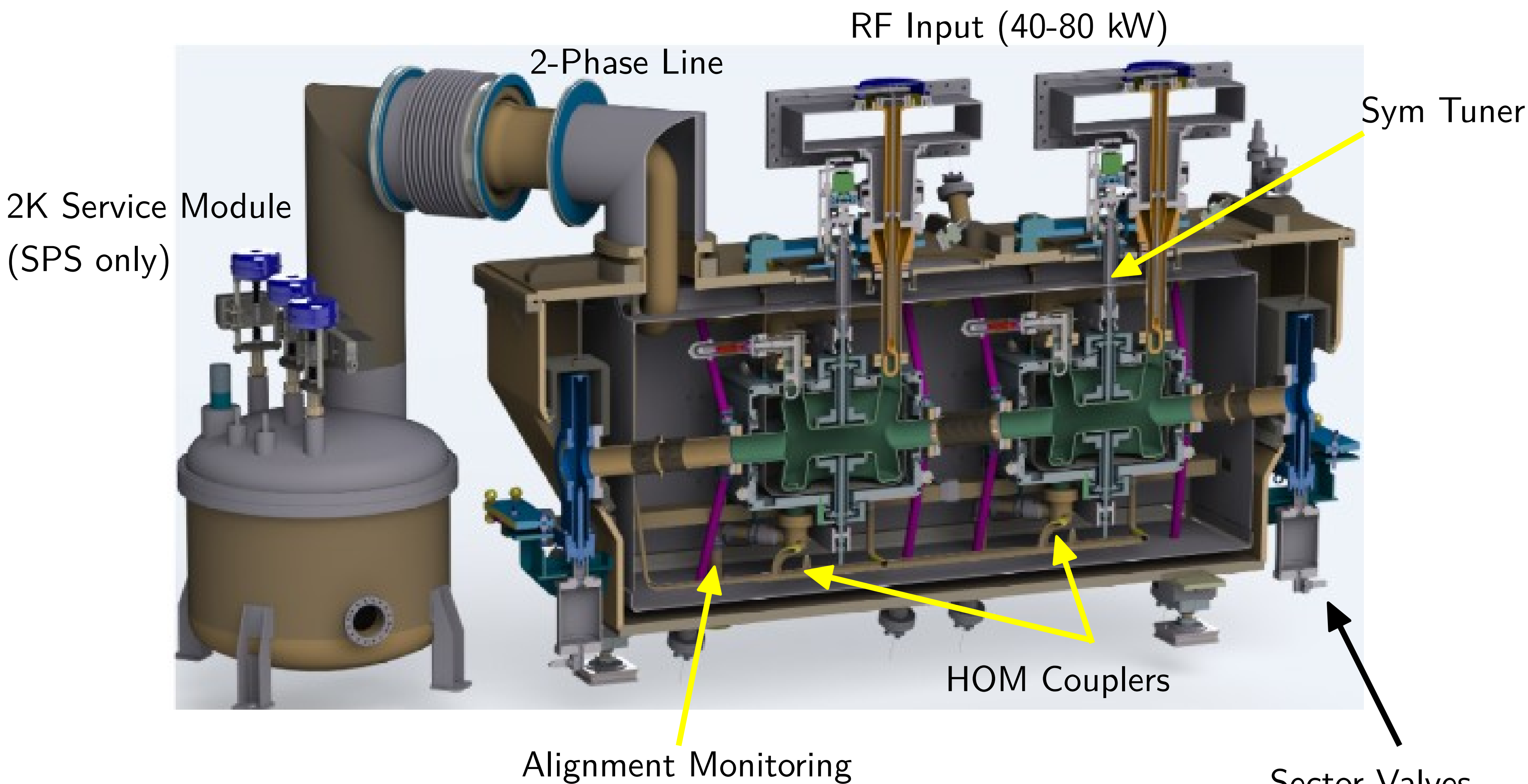
The project in implemented in 2 main phases:

- SPS validation of the technology with proton beams before LS2
- Construction of 8 Modules (16 cavities) by 2025



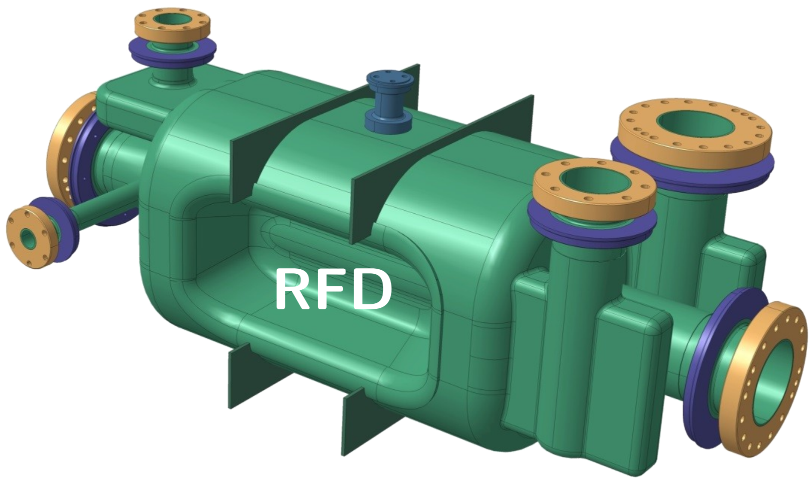
Crab Cavity Cryomodule

Double Quarter Wave

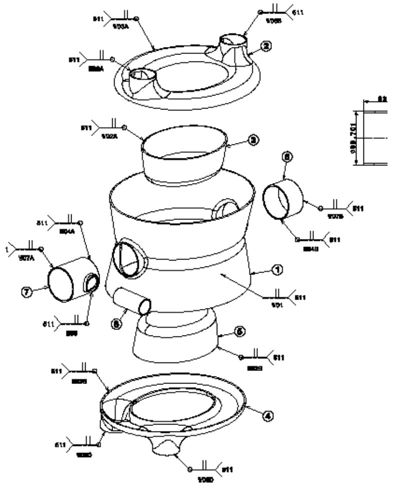


SPS Cavities, CERN

Modifications to the prototypes with strong HOM damping for SPS/LHC



CERN cavity production recently started with DQW cavity shaping & welding trials. 2 DQW cavities to be manufactured by Spring 2017



Cavity Production, US

2+2 cavities under production USLARP/DOE program (Niowave Inc.)

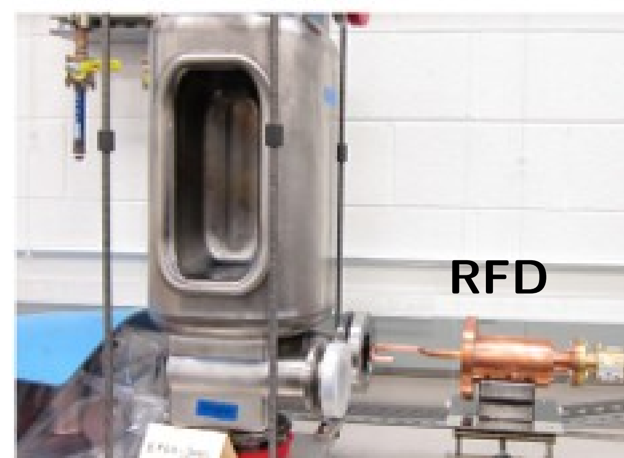
DQW




RFD



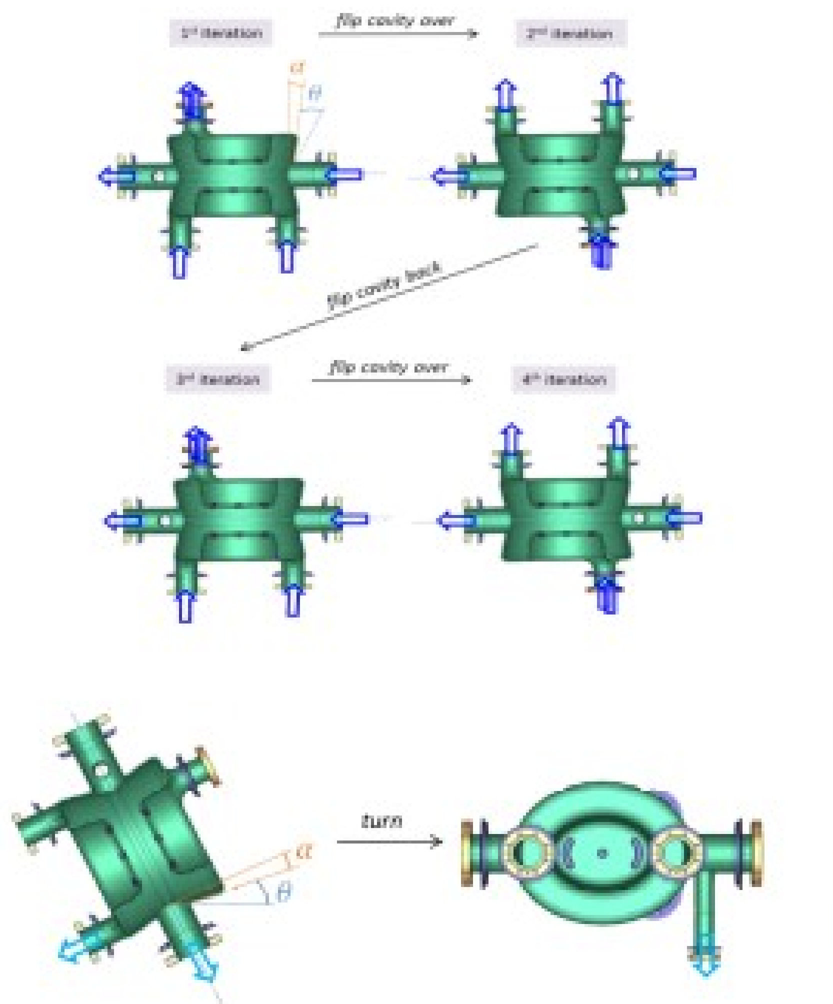

Frequency Trimming
& final welding



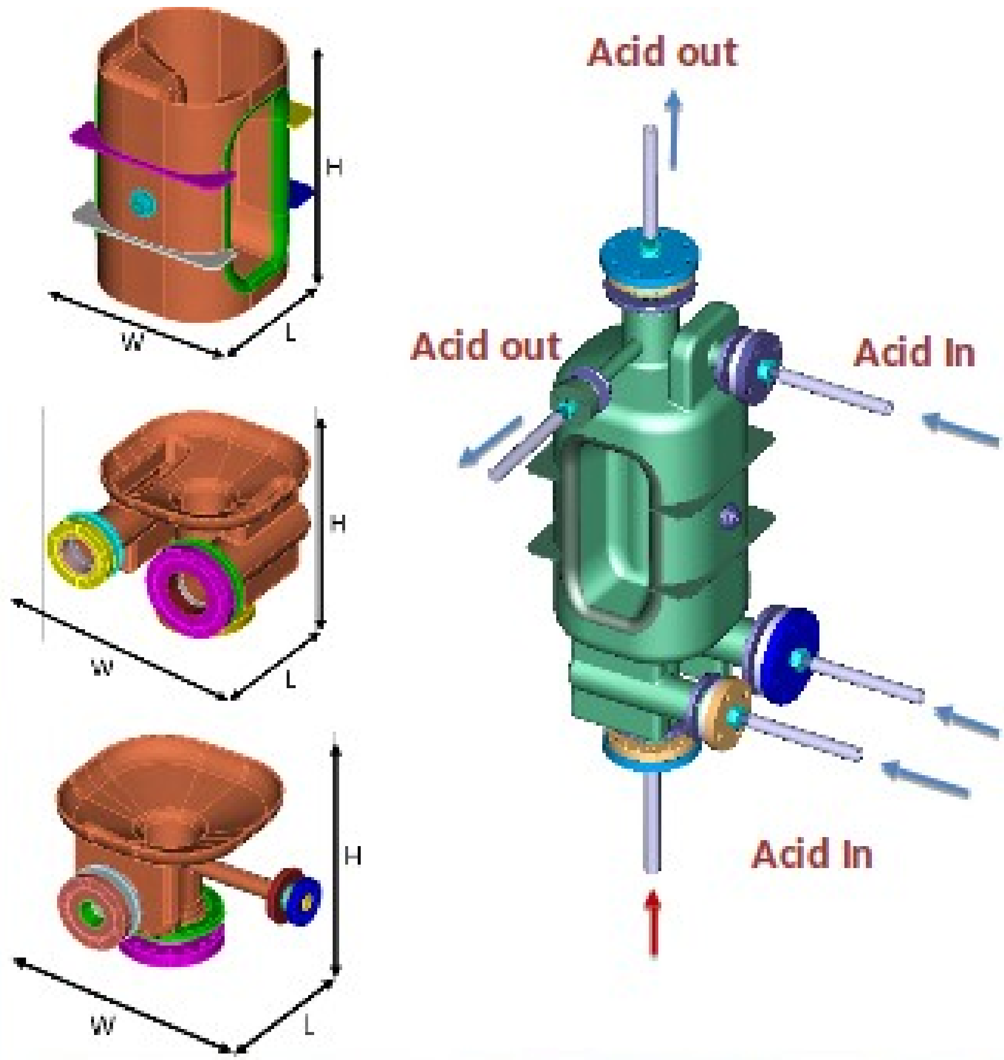
Surface Treatment

Surface treatment is non-trivial with these geometries

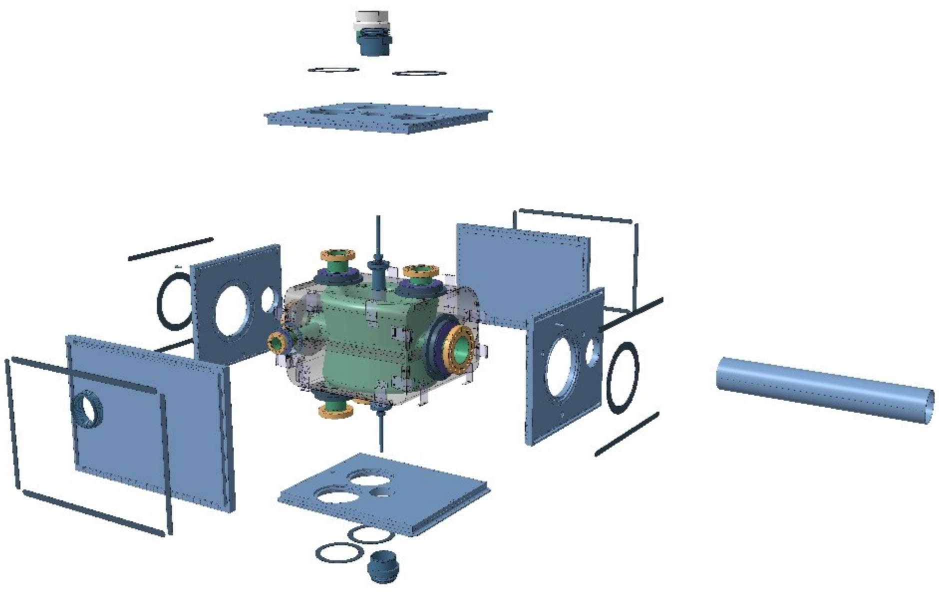
Chemistry on fully assembled cavity



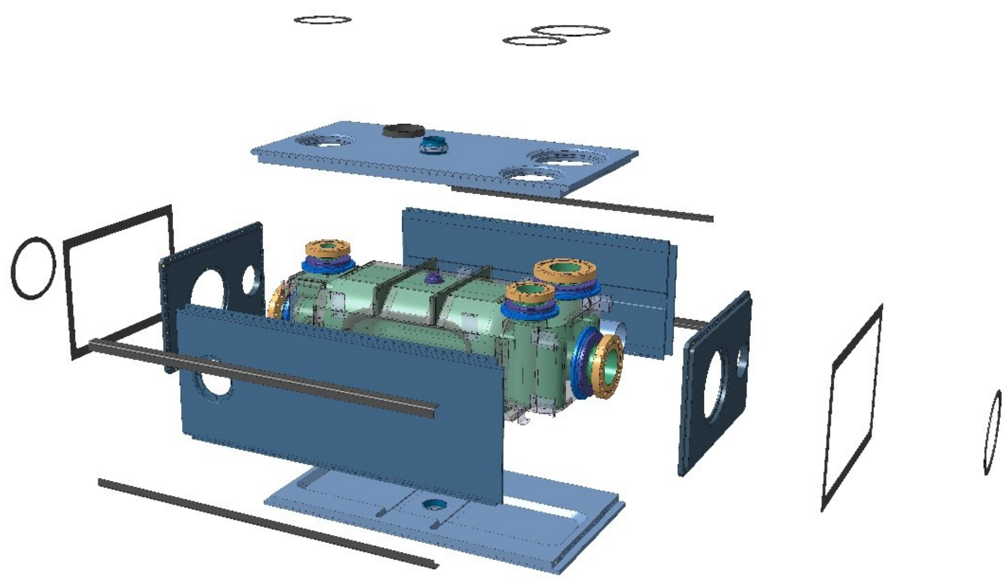
Chemistry on intermediate parts



Helium Vessel



Novel bolted He-vessel design with superficial welds for leak - guarantees minimal stress during entire life cycle



The vessel provides the needed structural integrity & controlled tuning interface to the outside environment

Internal cold-magnetic shield for better stray field control (x60 reduction)

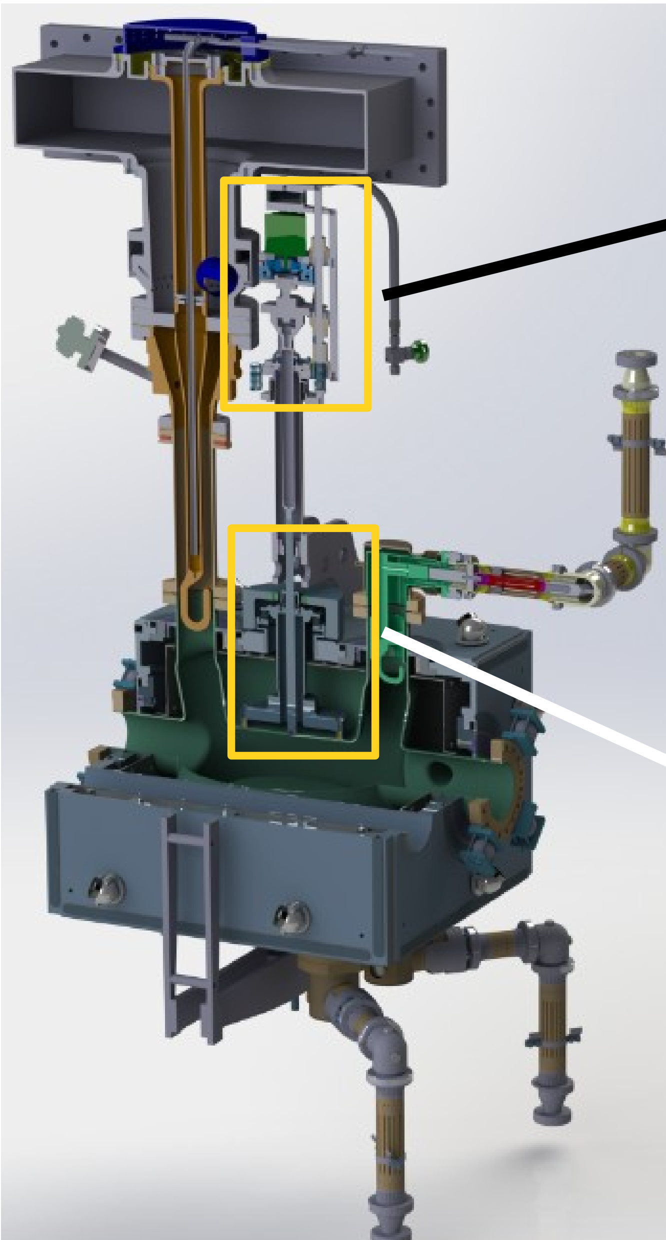
He-Vessel Prototype

Full scale model built with the complete assembly & welding sequence qualified

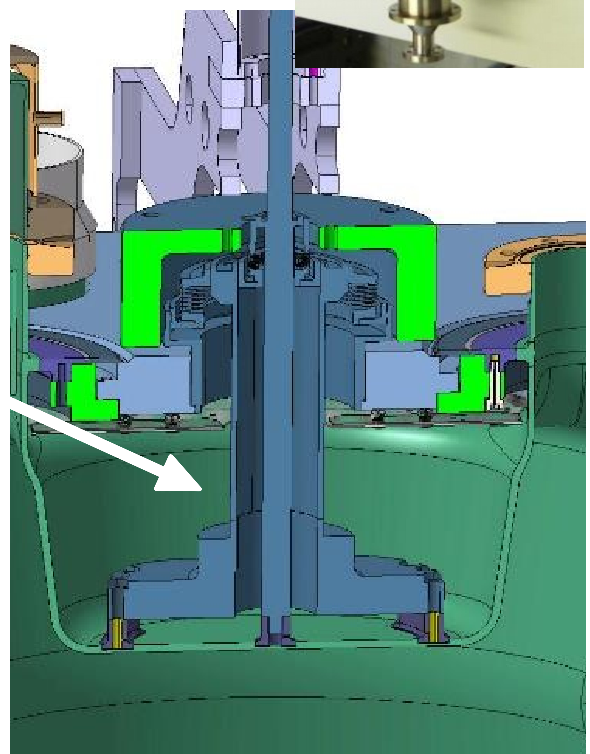
Pressure test (2.6 bar) & leak tests

Position sensors and metrology during the assembly sequence reveals a peak deformation of upto approx 250 µm during the assembly.

Frequency Tuner



Actuation system to be tested with an existing cavity



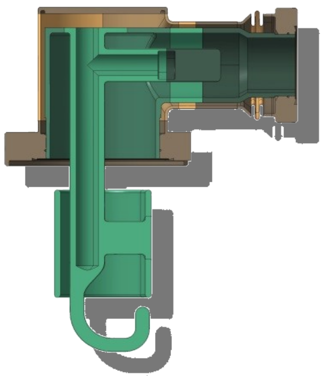
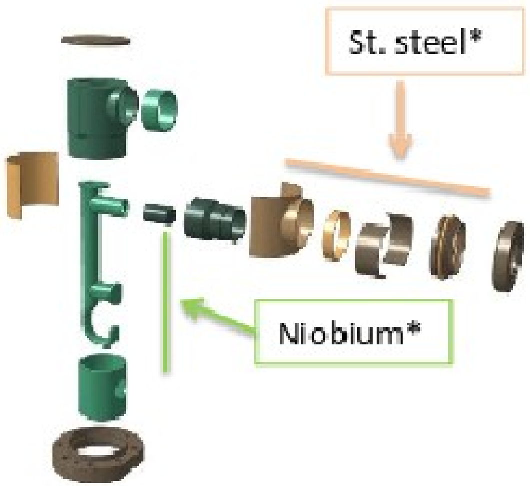
Concentric Ti-cylinders to push/pull the capacitive plates <u>symmetrically</u>

For RFD, the body is tuned in similar fashion

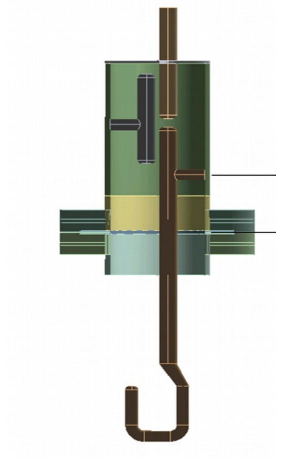
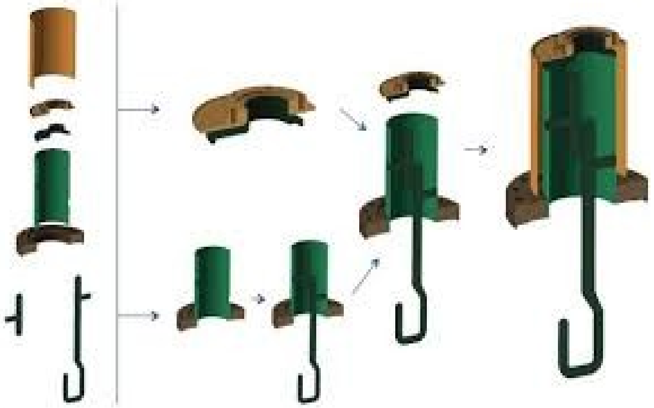
Precision ~0.5 μm (100 Hz)
Cavity BW = 800 Hz

HOM Couplers

Two types of “broadband” lumped element couplers for DQW/RFD (additional probes for specific HOMs)



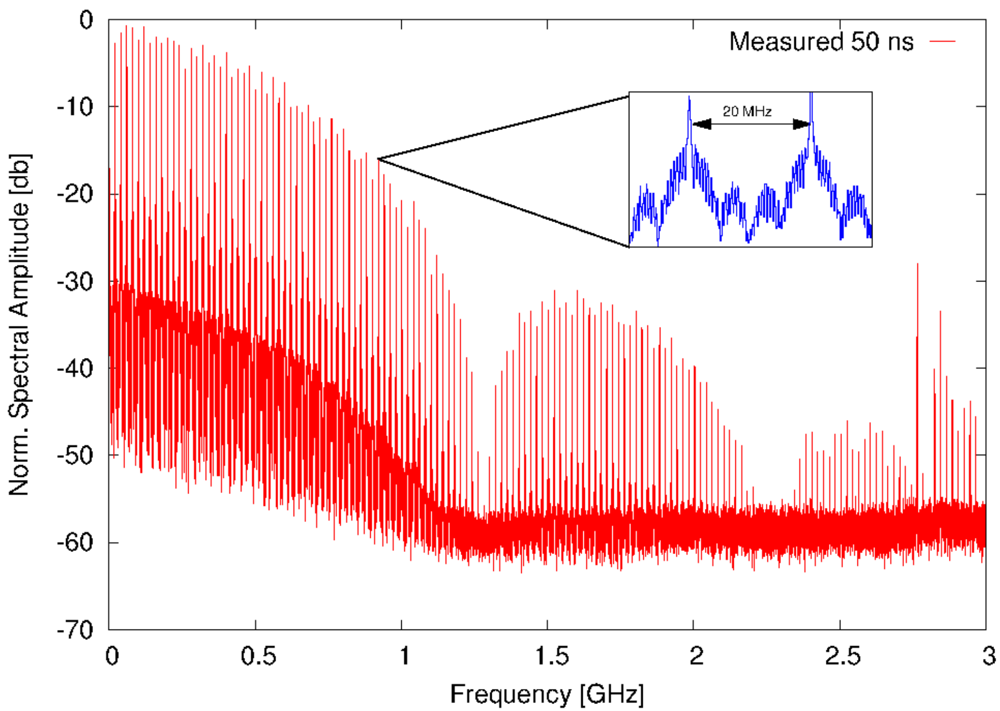




VHOM HHOM

Specially design HOM test boxes for coupler verification & conditioning

Higher Order Modes

The circulating high beam current (1.1 A) and dense spectrum of the LHC filling scheme implies <u>strong HOM damping</u>



Non-Resonant Case:

$$P_{HOM} = \left(\Sigma k_n - k_0\right) . q . I_b$$

Resonant Case:

$$P_{HOM} = I_b^{2.} \frac{R}{Q} . Q_L . F_n^2$$

HOM Power can be from <u>100 W to a few kW</u> (numerical computation)

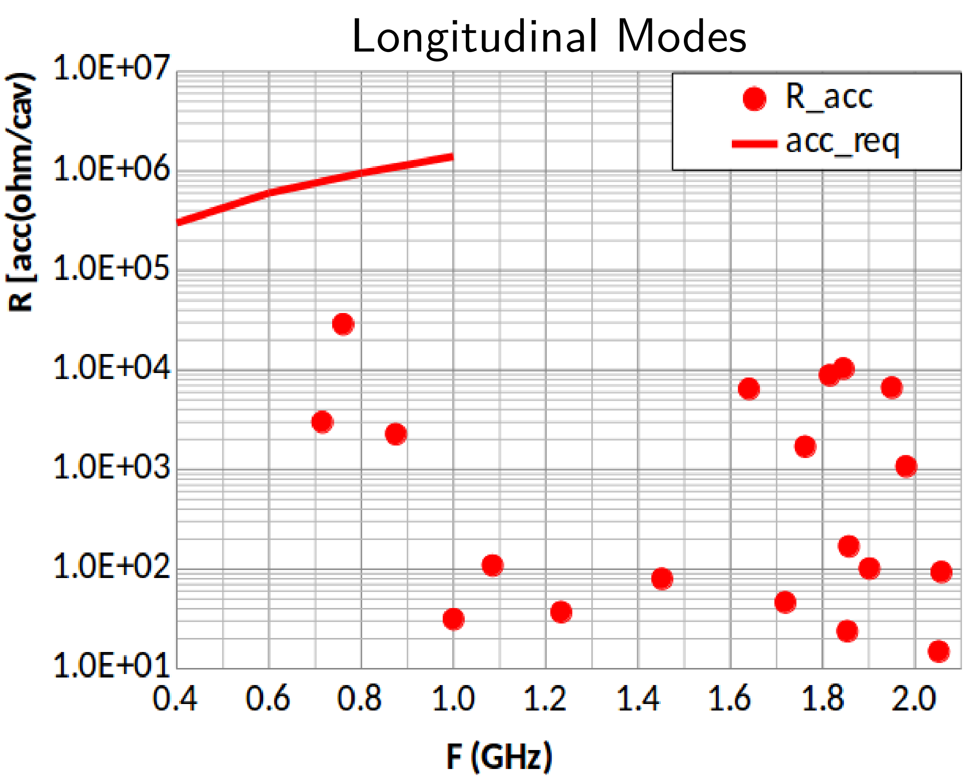
Exact HOM frequency & overlap with beam spectrum hard to predict

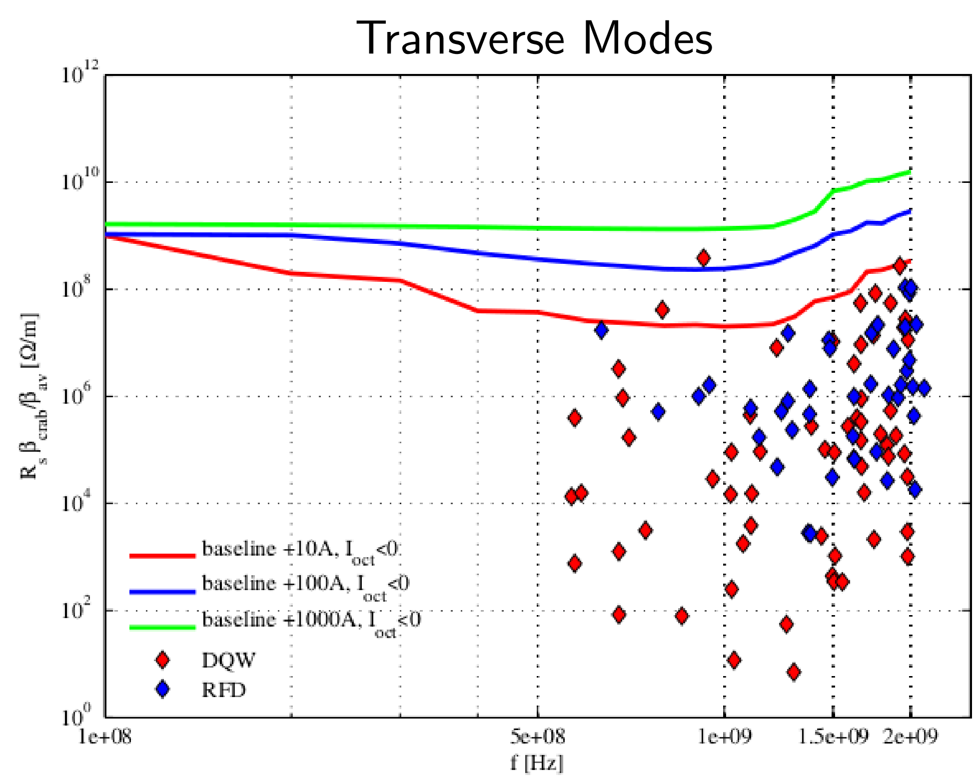
Impedance Budget

Due to the 8-cavities/beam with 1.1 A and the placement at high-b location has strict impedance budget

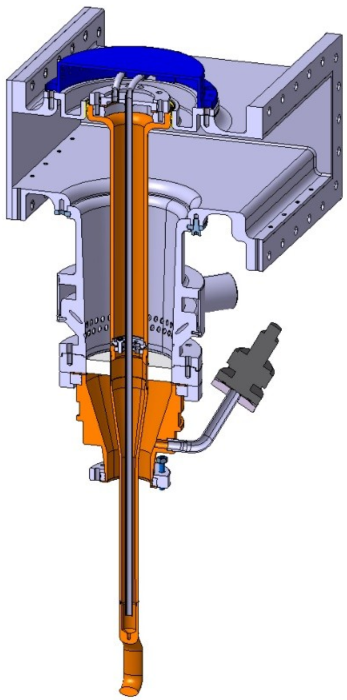
Longitudinal budget of 200 kΩ total (7.0 TeV)

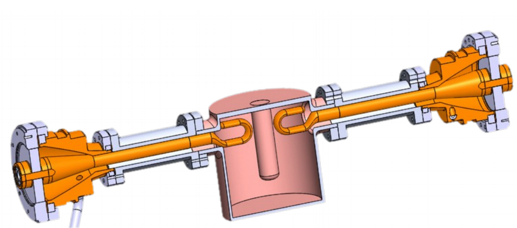
Transverse budget ~0.5 MΩ/m



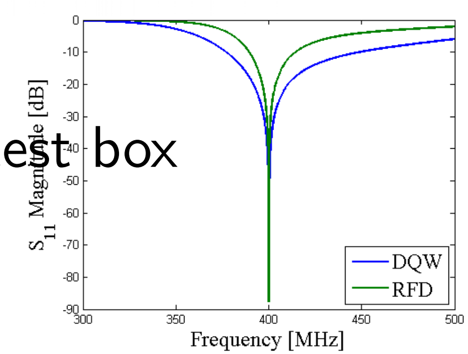


Power Coupler & Amplifier





λ/4 FPC test box



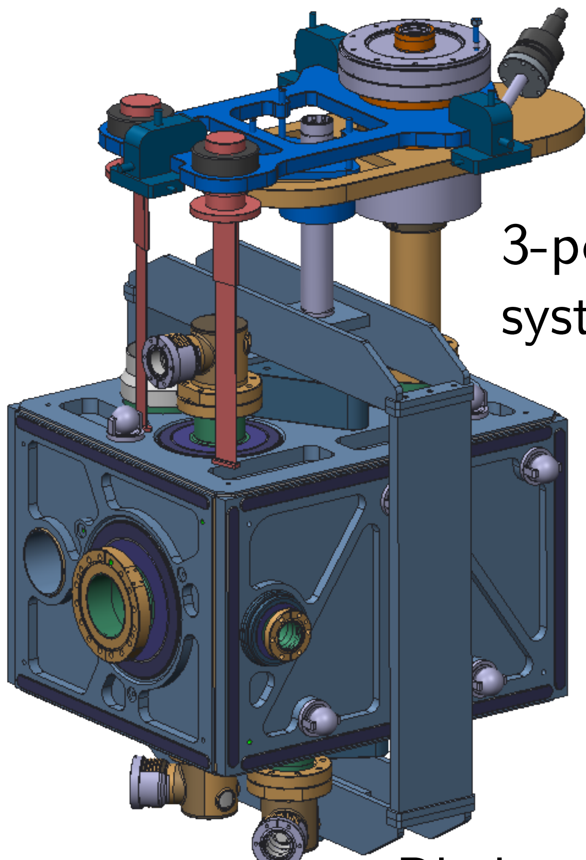
Re-use existing SPS-800 MHz IOT trolley with modified cavity output

Recently tested up to 60 kW-CW

Cavity Alignment

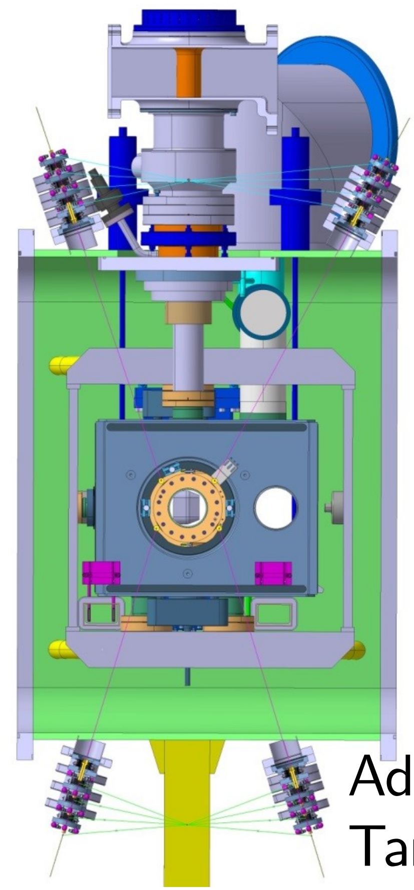
Baseline solution for the LHC to maintain the intra-cavity transverse displacements to within 0.5 mm

(Recall: 1 mm offset in the cavity amounts to ~40 kW of RF power)



3-point supporting system

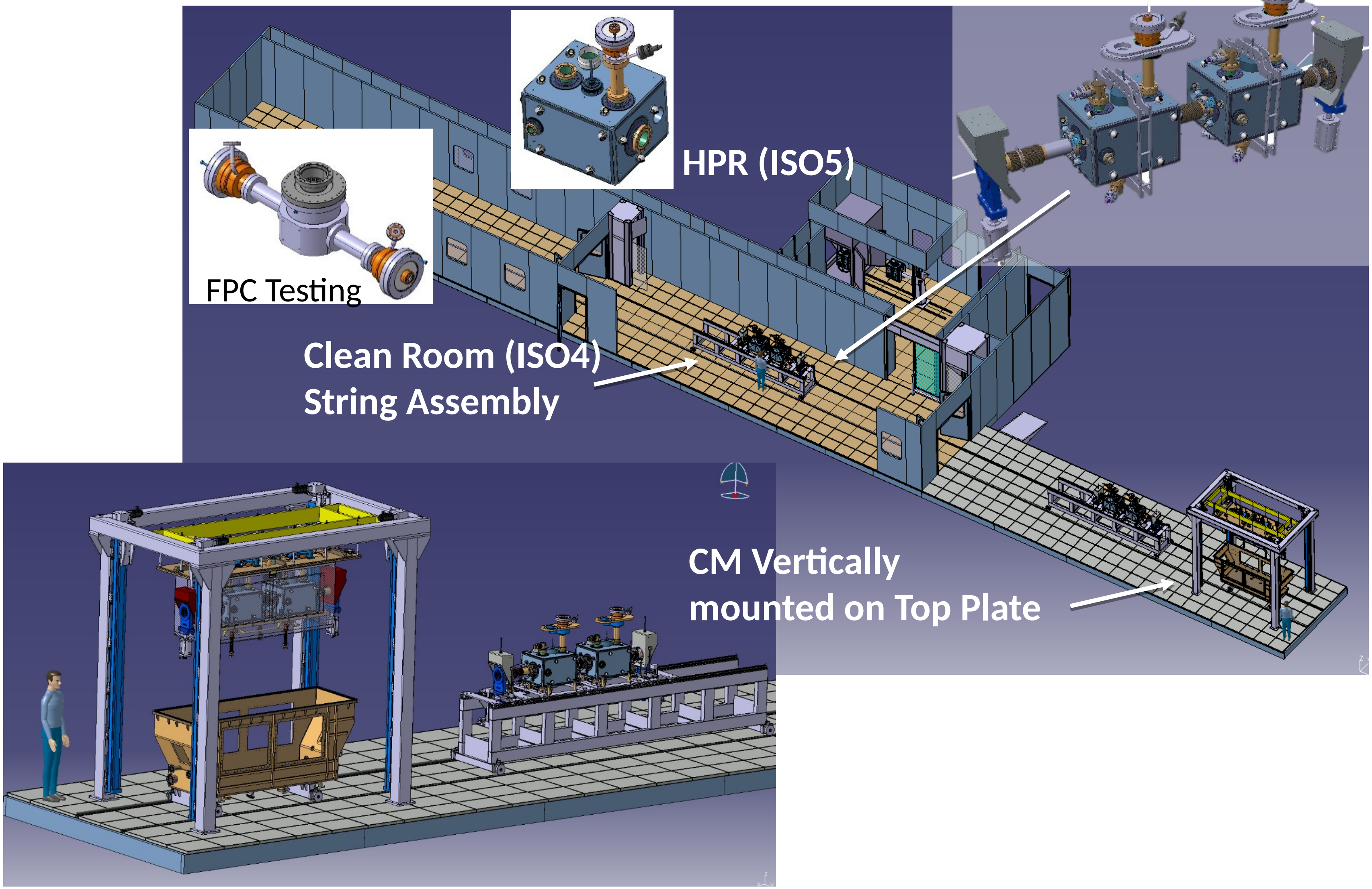
Blade-type flexures for additional stiffness



FSI targets on cavity flanges

Additonal BCAM – Wire Targets for SPS tests

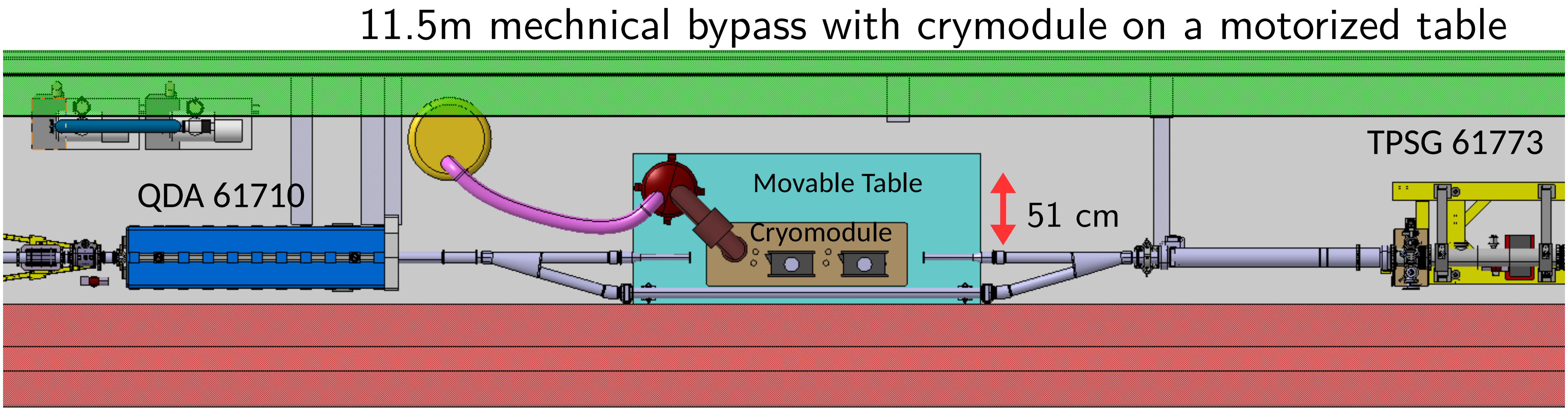
Cryomodule Assembly



Tight alignment tolerances during full assembly (< 0.5mm)

Cryostating using a top plate assembly

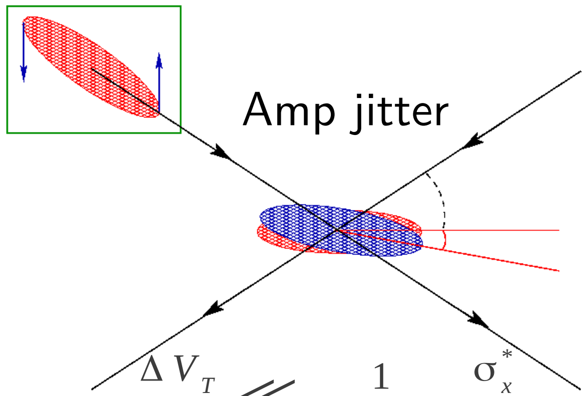
SPS Installation



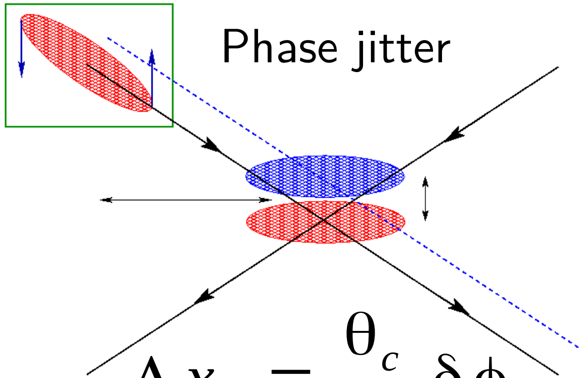
Multiple vacuum sectorization valves for efficient pumping and module replacement. RF circulators/loads & cryogenic service module on movable table (51 cm movement)

Once installed in 2017, it will be a unique facility capable of testing SRF cavities with high energy proton beams (up to 450 GeV)

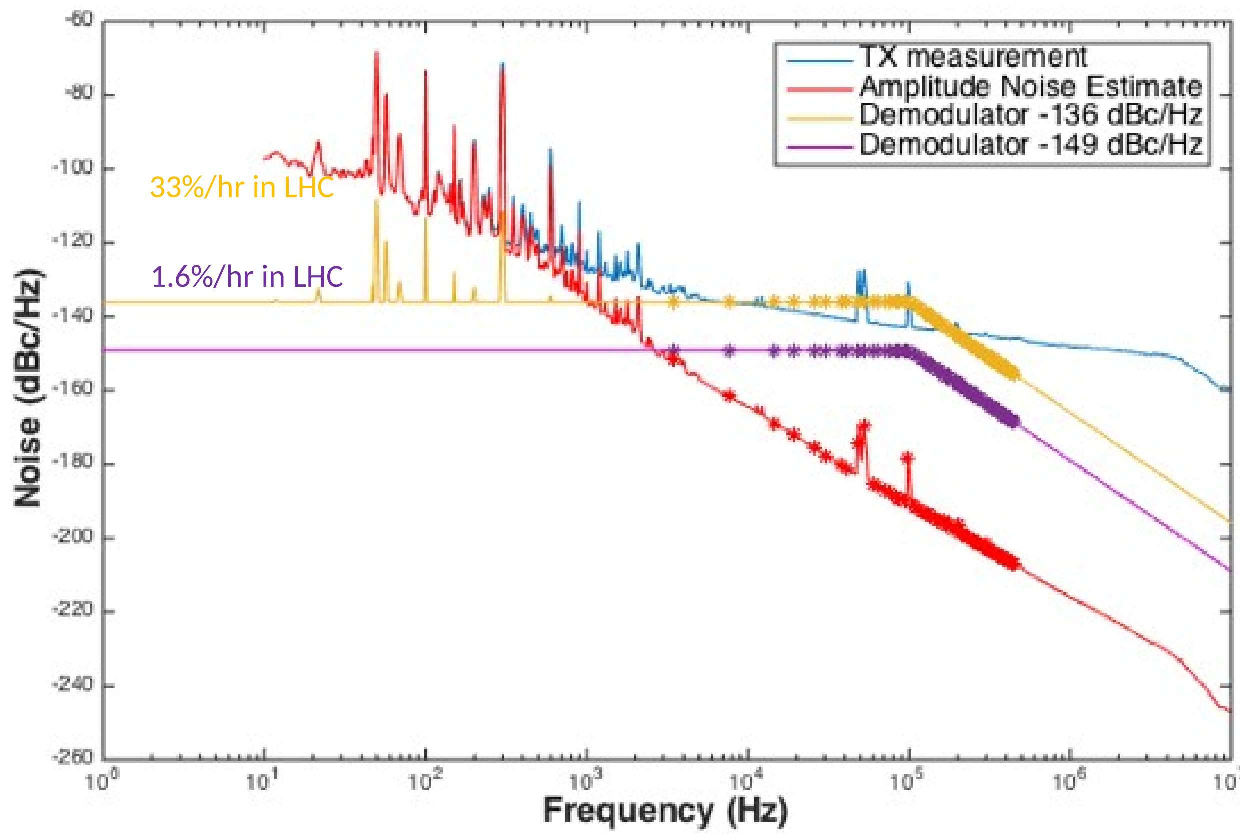
RF Noise



$$\frac{\Delta V_T}{V_T} \ll \frac{1}{\tan(\theta/2)} \frac{\sigma_x^*}{\sigma_z}$$



$$\Delta x_{IP} = \frac{\theta_c}{k_{RF}} \delta\phi$$



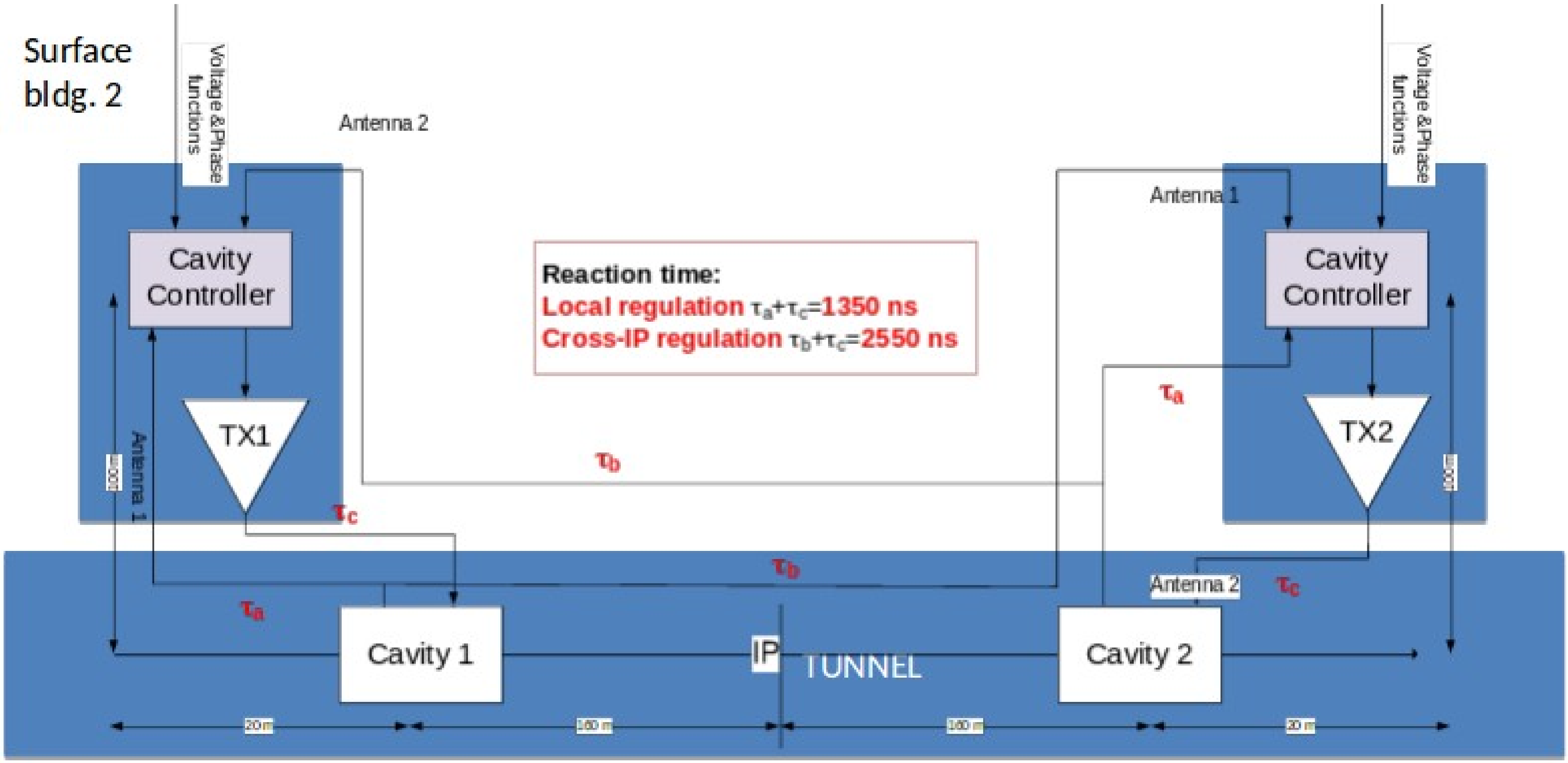
Ongoing simulations & SPS tests to define the final specification for LHC-LLRF

Proposal for amplitude noise reduction with damper & noise shaping for bunch tail population control

LLRF & IP Cross Control

Fast regulation: Maintain cavity phase w.r.t to bunch, reduction of the FM impedance & noise reduction

Slow regulation: IP regulation for closure of crab bump both during stable operation and during cavity failures



Final Remarks

The R&D towards the SPS beam tests is a vital step before their implementation in the LHC.

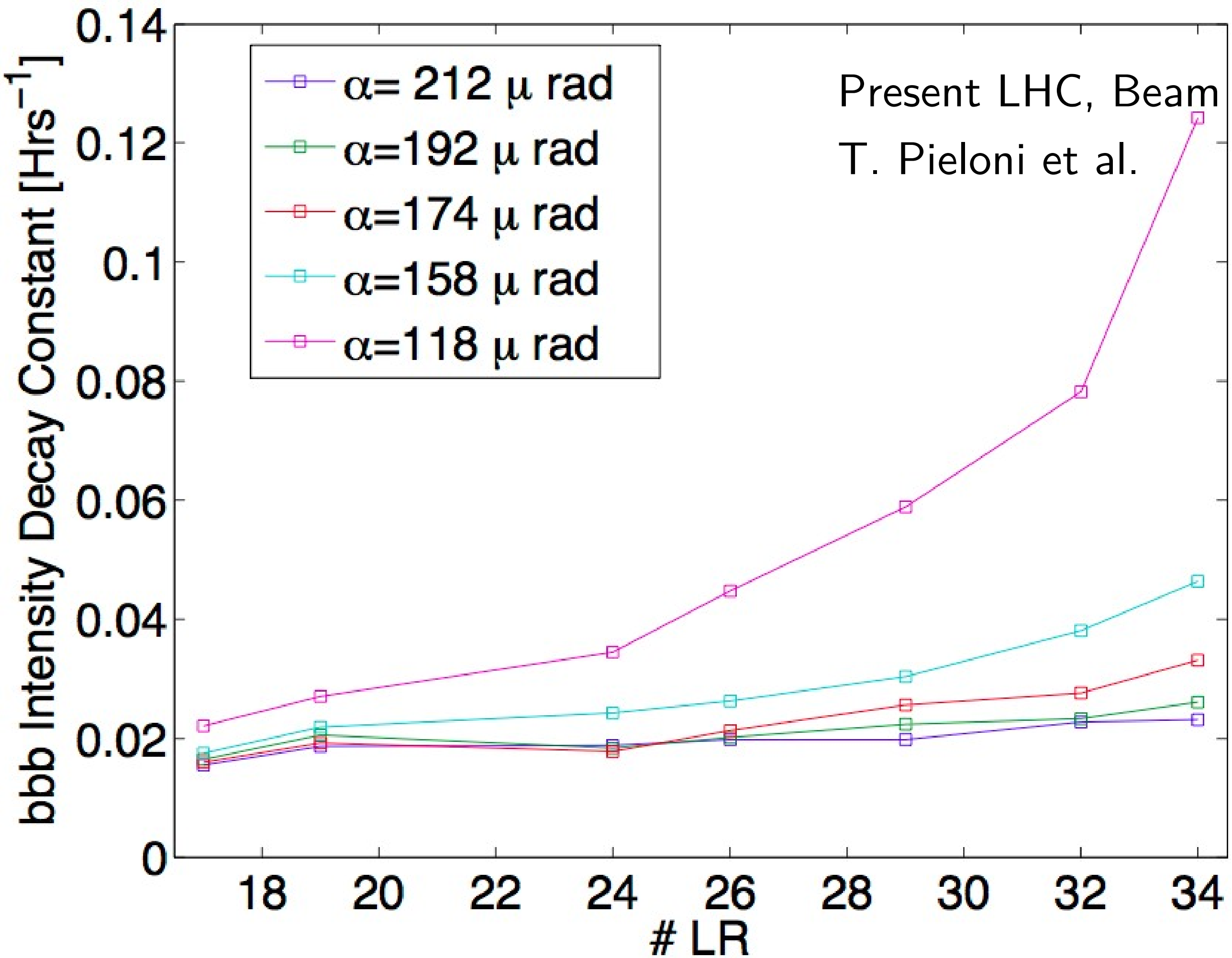
Several new & novel concepts for the cavity/cryomodule components due to complex requirements for the LHC

The new class of deflecting cavities have become an important part of the SCRF community and will play a strong role in beam manipulations in many future machines

A1: Need for a Crossing Angle

4 interaction regions with ~120m common beam-pipe for 2-beams at each IR

- It imples 120(+) parasitic encounters
- Large crossing angle needed (8-12σ) to separate the beams



Present LHC, Beam Experiment

T. Pieloni et al.

A2: Cavity Surface Treatment

Complex shapes of the crab cavities requires fluid dynamics simulations

- Optimum inlet/outlet ports
- Minimize the std. deviation of the acid flow rate for uniform etching