SUPERCONDUCTING TECHNOLOGIES

FOR THE NEXT GENERATION OF ACCELERATORS

WORKSHOP

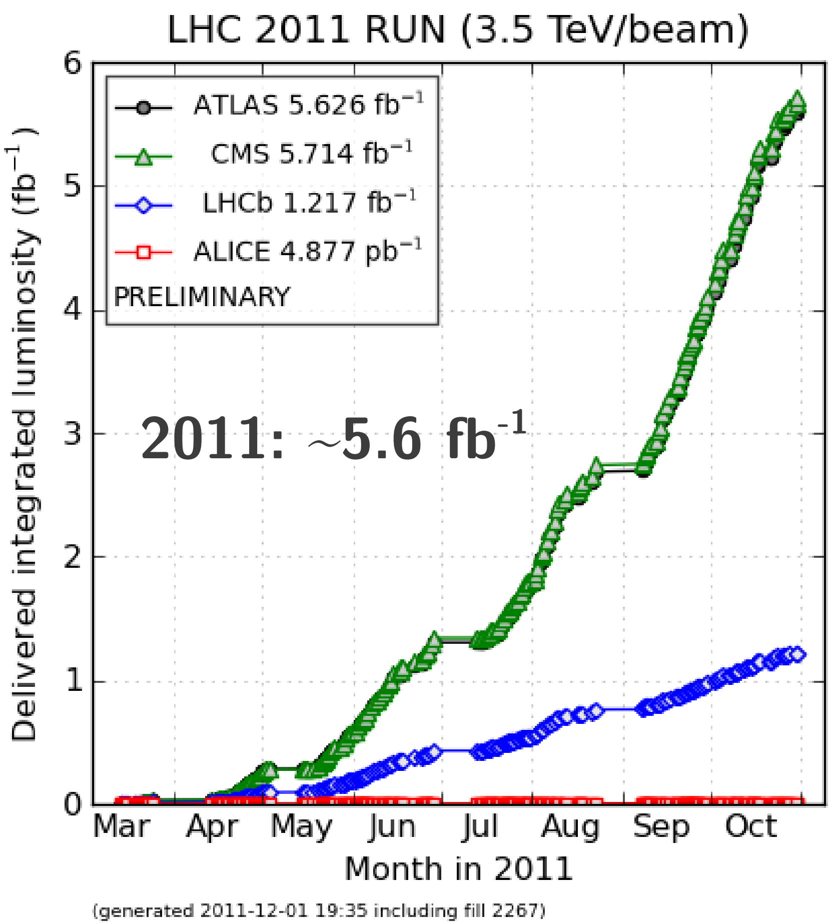
Crab Cavities for LHC Luminosity Upgrade

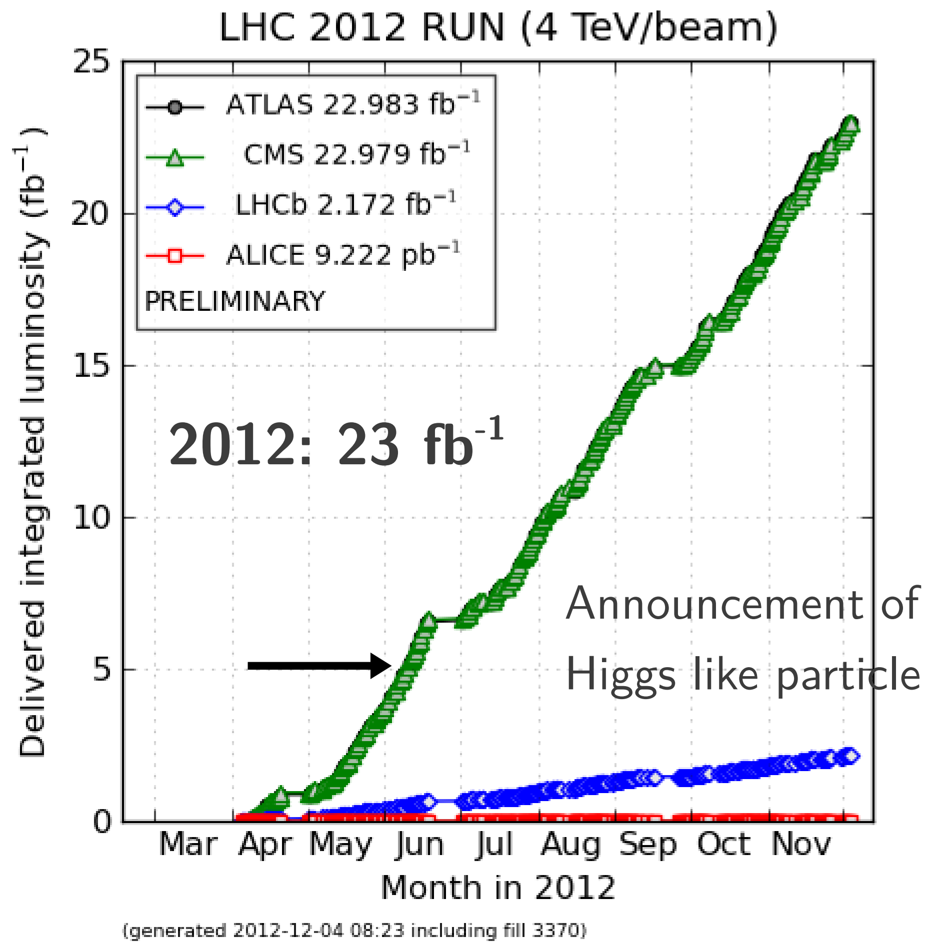
Rama Calaga, CERN

On behalf of the LHC-CC collaboration

Present Performance,LHC

Courtesy: LHC-OP

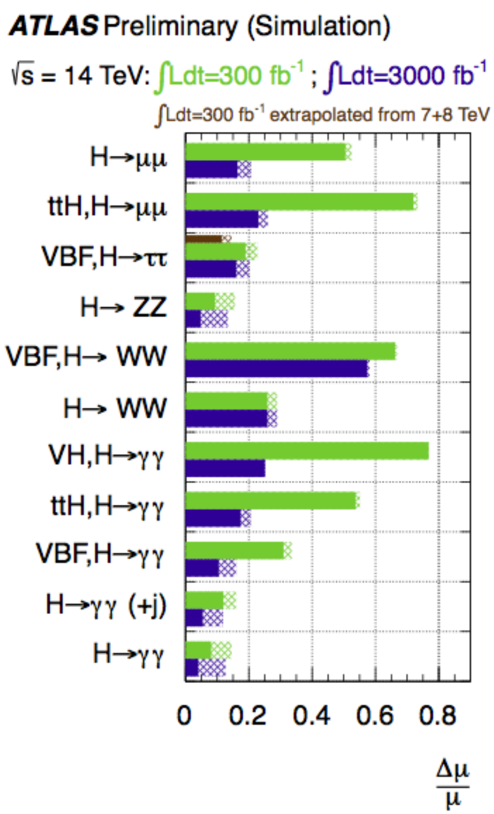


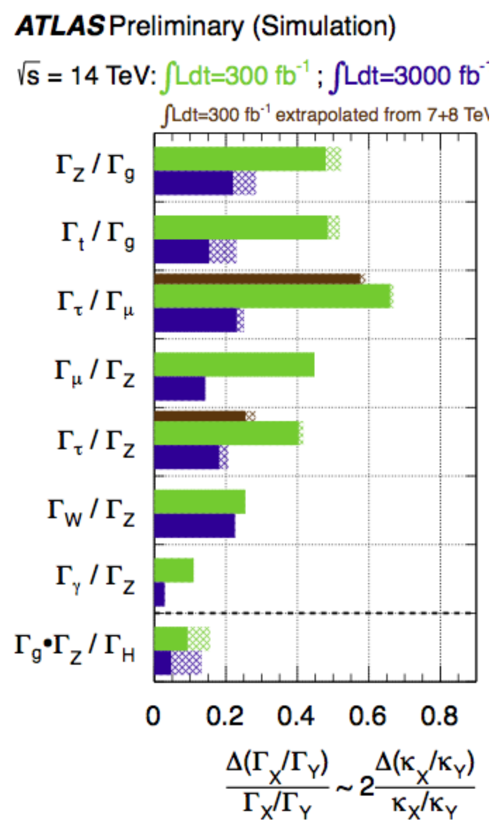


After 1st Shutdown (2014-20) $\rightarrow$ **300+ fb^{-1}** (~60fb^{-1}/yr)

(Higgs mass, spin, indications of strength & couplings to fermions & bosons)

HL-LHC (2022+) → **3000 fb^{-1}** (250-300fb^{-1}/yr)



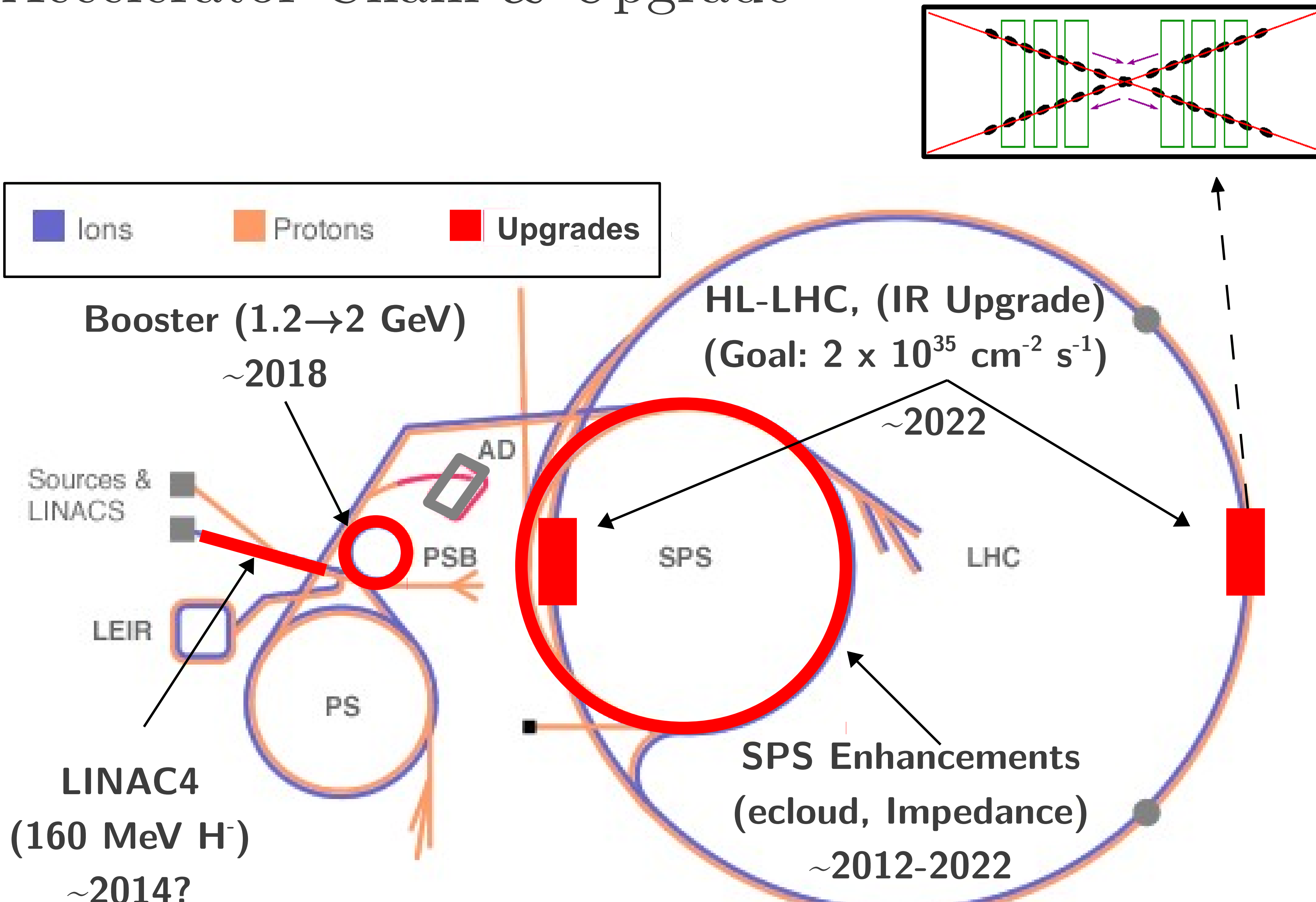


x10 increase has dramatically reduces the uncertainties

(A. Ball, HiLumi-LARP Meeting)

A <u>leveled luminosity</u> with acceptable pile-up mandatory

Accelerator Chain & Upgrade



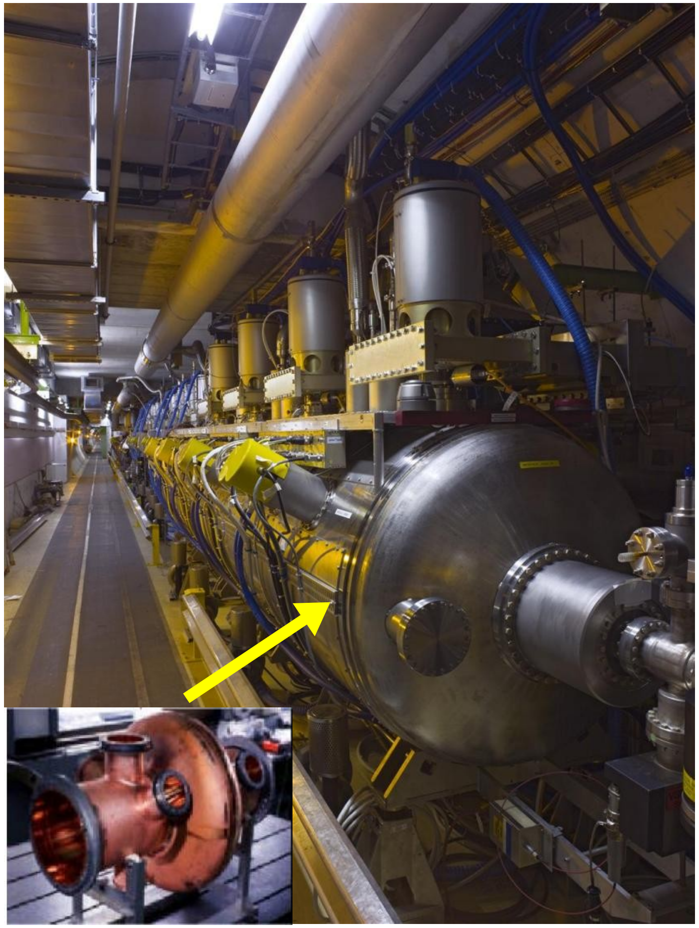
Elucidating the Higgs mechanism...

(*i.e. from which grape the bottle is made of ?*)

To elucidate the Higgs mechanism all three main contenders use extremely demanding SCRF technology:

- High Luminosity LHC: Accelerating RF and Crab Cavities (novel designs & precision timing)
- A circular Higgs Factory collider: 10 to 20 GV of CW SCRF
- A linear Higgs Factory collider, the ILC: 250 GV of pulsed SCRF

LHC RF System



8 SRF cavities/beam (total 16)

Frequency: 400 MHz (Nb-Coated)

Voltage: 2 MV/cavity (5.5 MV/m)

CW high power variable coupler

$1x10^4 < Q_{ext} < 2x10^5$

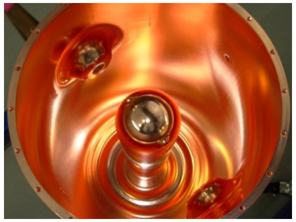
Klystron driven (upto 330 kW)

SM18 installations from 1990s & LEP, minor refurbishing for the LHC

Upgrade towards high performance SRF

HIE-ISOLDE, Nb Sputtered

$Q_0 > 1x10^8$, V=6MV

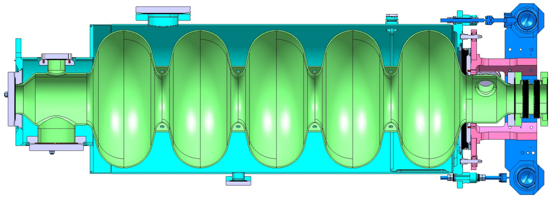


Crab Cavities, Bulk Nb(?)

$Q_0 \sim 1x10^{10}$, V_t=3MV

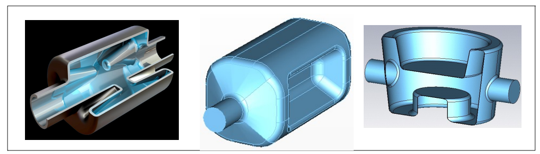
SPL R&D, Bulk Nb

$Q_0 \sim 1x10^{10}$, V~25MV



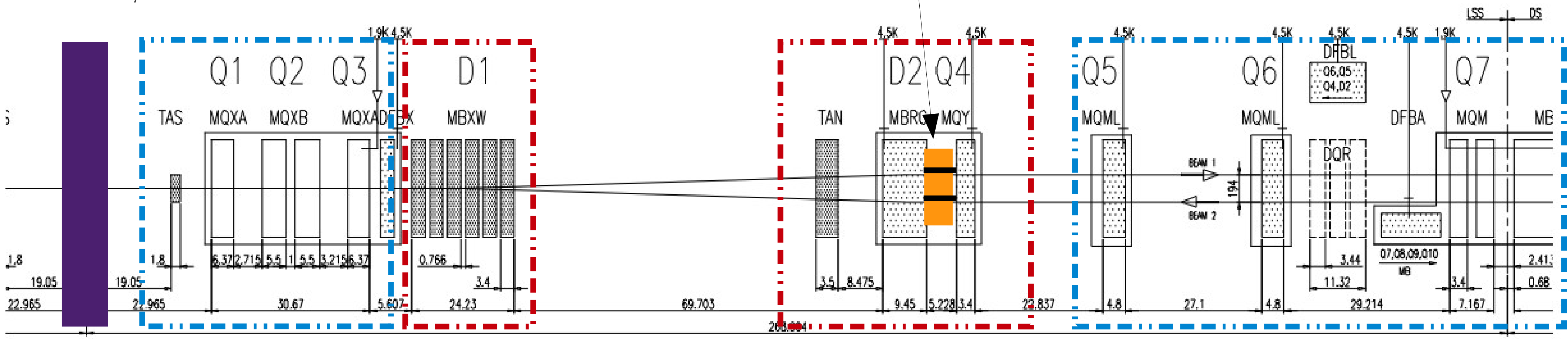
HL-LHC Upgrade

A total of 1.2 km of the LHC to be upgraded



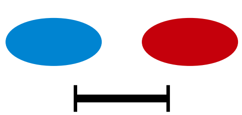
crab cavities, why ?

ATLAS/CMS



~60m common channel

And Beyond



Collision spacing

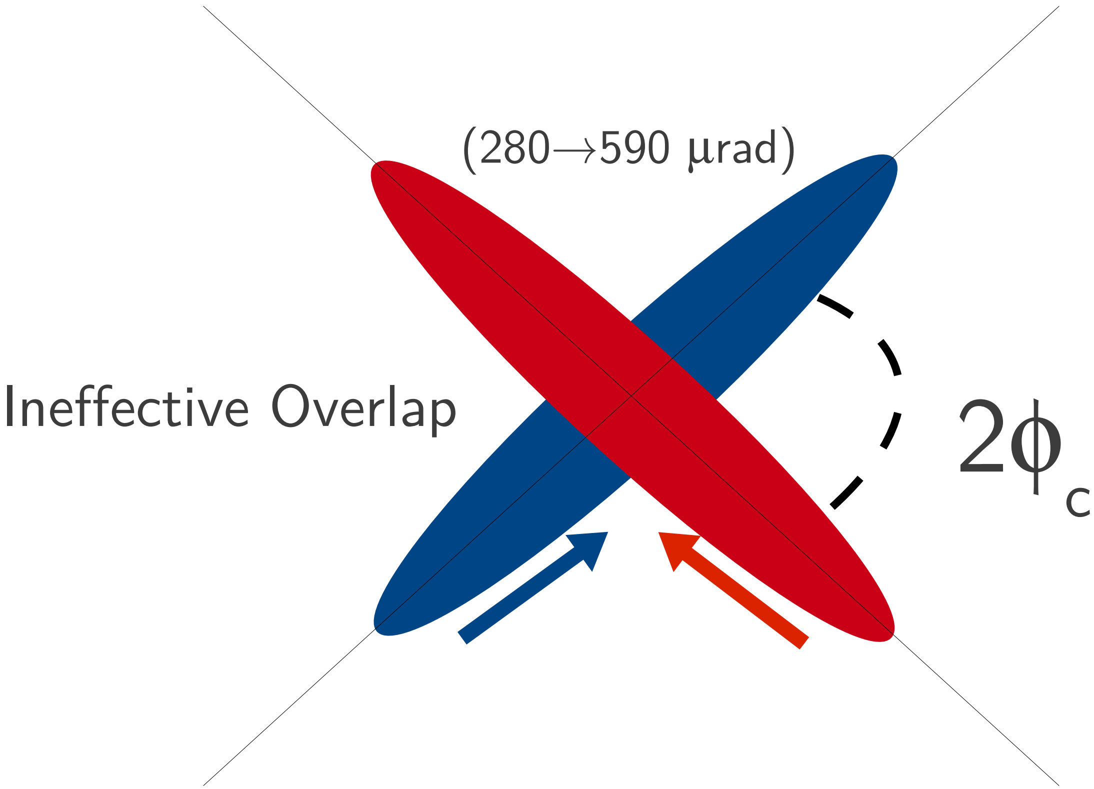
3.75m

32 parasitic collisions/IP → Total 128

(need separate beams with crossing angle)

Upgrade → reduce beam size by factor ~2

Consequence → approx double the crossing angle

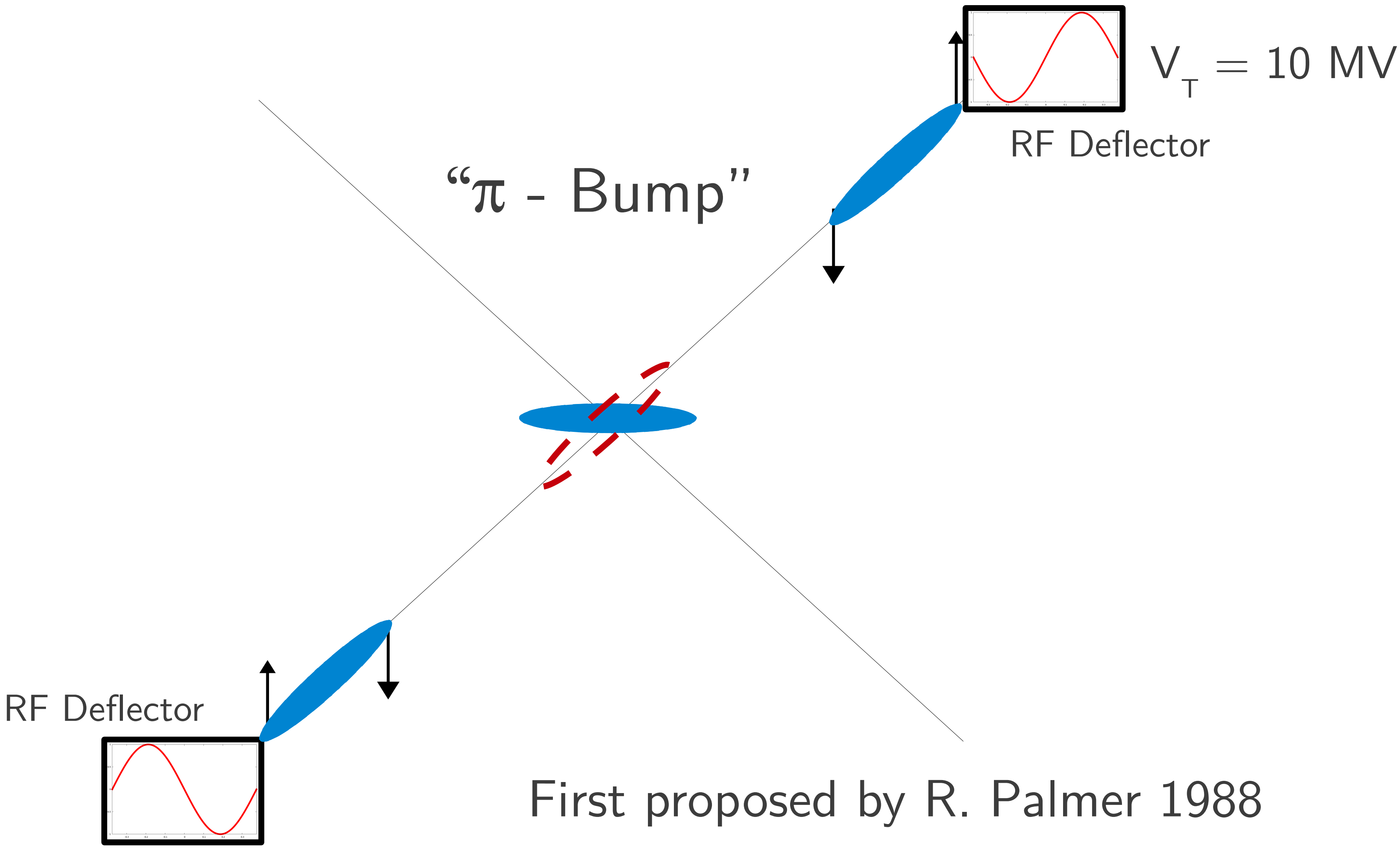


$$\Phi = \frac{\sigma_z}{\sigma_x} \phi_c$$

$$L = \frac{L_{HO}}{\sqrt{1+\Phi^2}}$$

L = only 30% of available L_{HO}

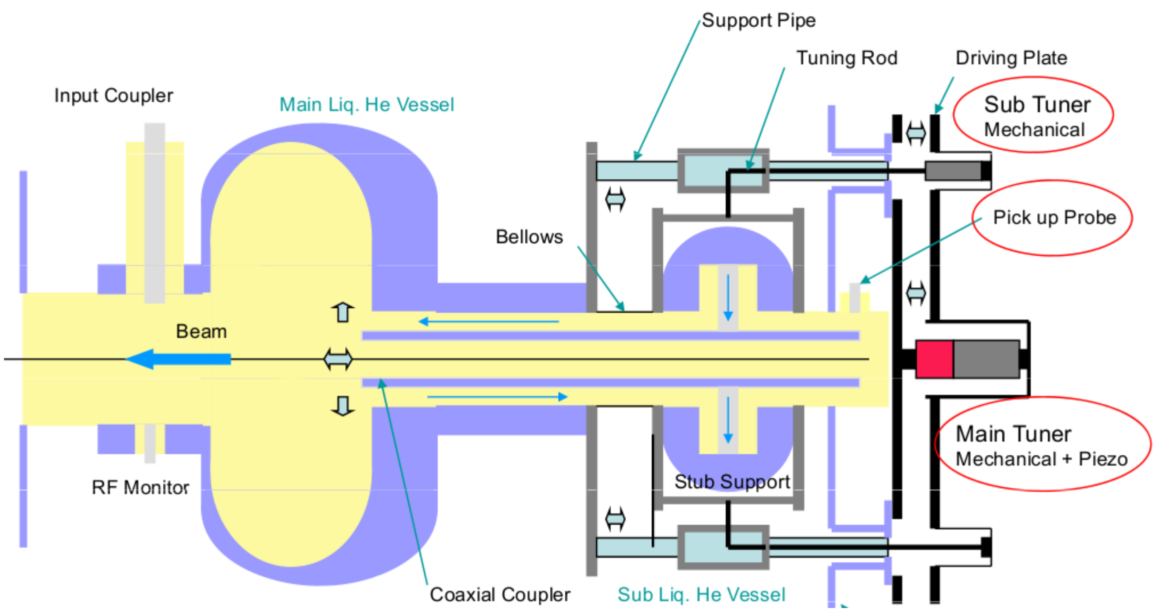
To Recover Almost Everything



First proposed by R. Palmer 1988

Applied to circular e^+e^- collider 2007

"1st" $e^{\pm}$ Crab Cavity, KEKB



LONG R&D, but short lifetime (2007-2010)

KEK: 508.9 MHz, 2MV

Power: 50-120 kW

(Qext: 2×10^5, BW: 2.55 kHz)

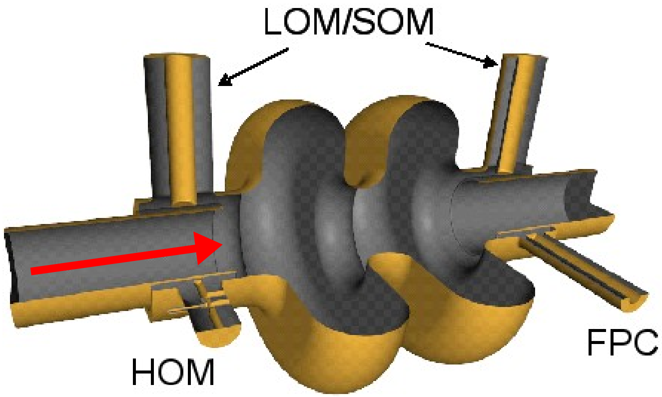
LHC Elliptical Cavities
(2006-2009)

Conceptually simple, but practically difficult (KEKB experience)

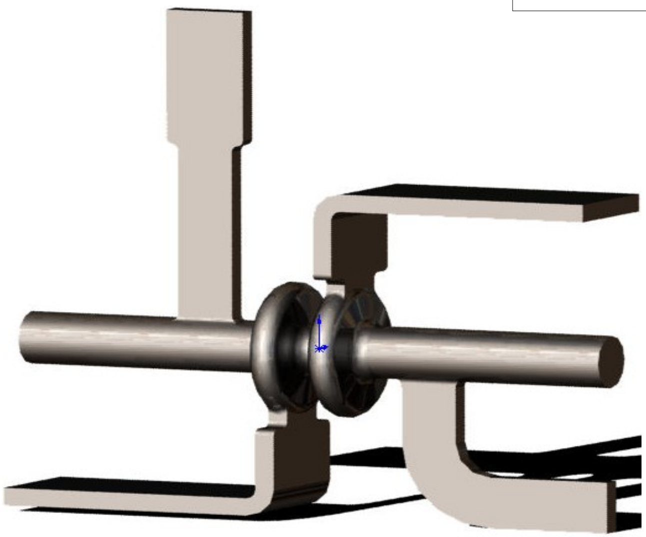
Incompatible constraints:

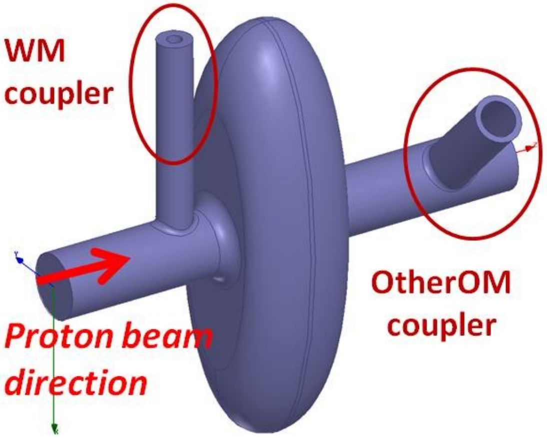
- Low Frequency (long proton bunches)
- Transversely compact (beam pipe separation small)

2009 decision to focus on "compact cavities"



2-cell version, USLARP
L. Xiao et al.


2-cell version, LU-DL
G. Burt et al.

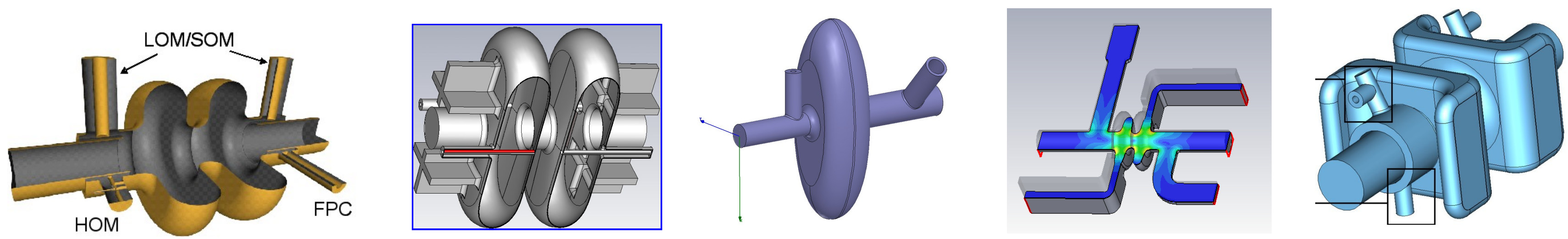


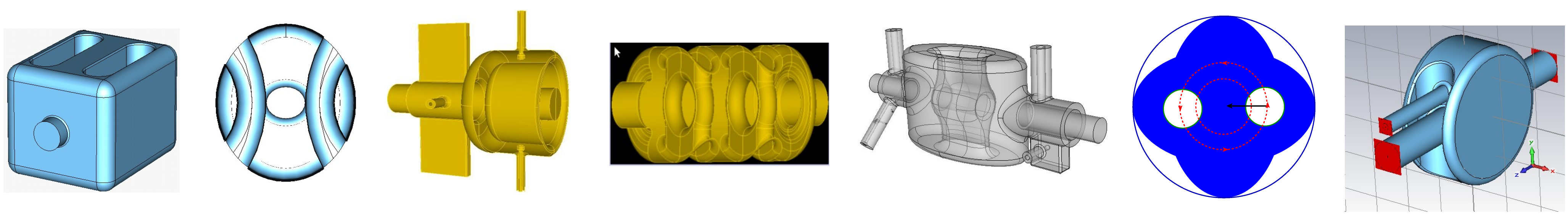
1-cell version, CERN,
L. Ficcadenti et al.

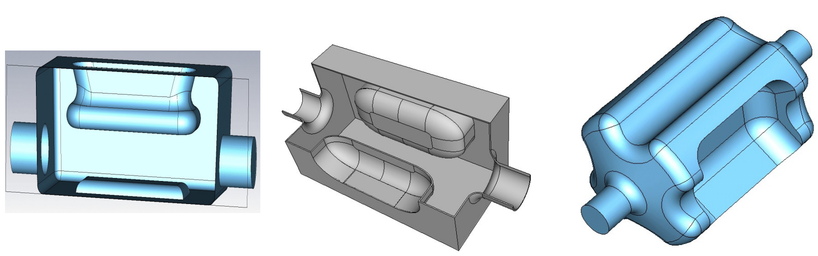
Elliptical → Compact Cavities

(BNL, CERN, LU-CI-DL, FNAL, KEK, ODU/JLAB, SLAC)

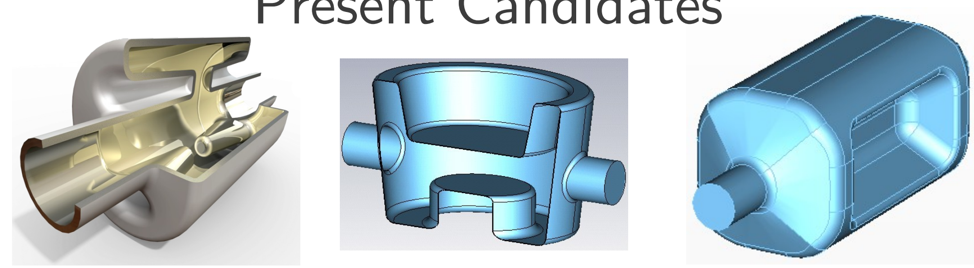
∼4yr of design evolution



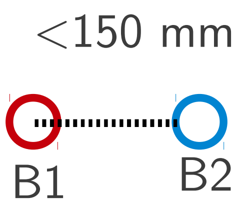


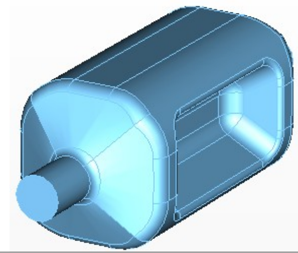


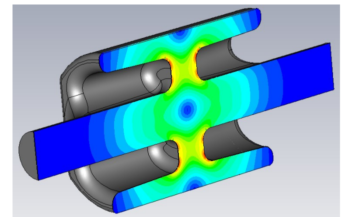
Present Candidates

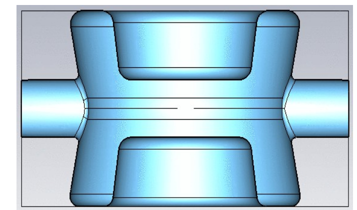


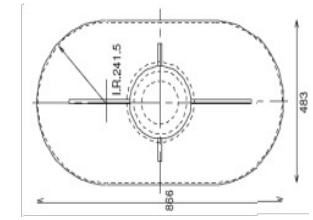
Kick Voltage: 3 MV, 400 MHz











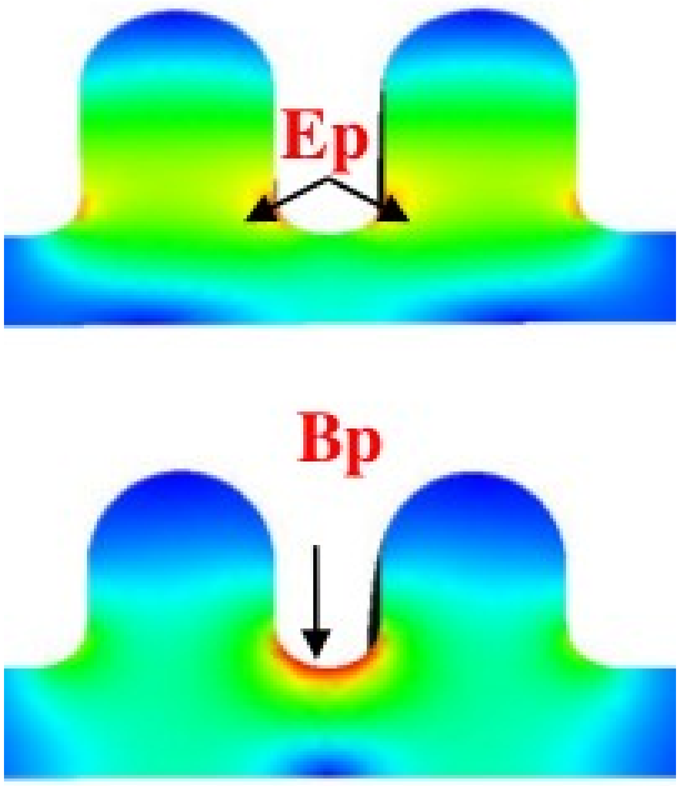
Geometrical

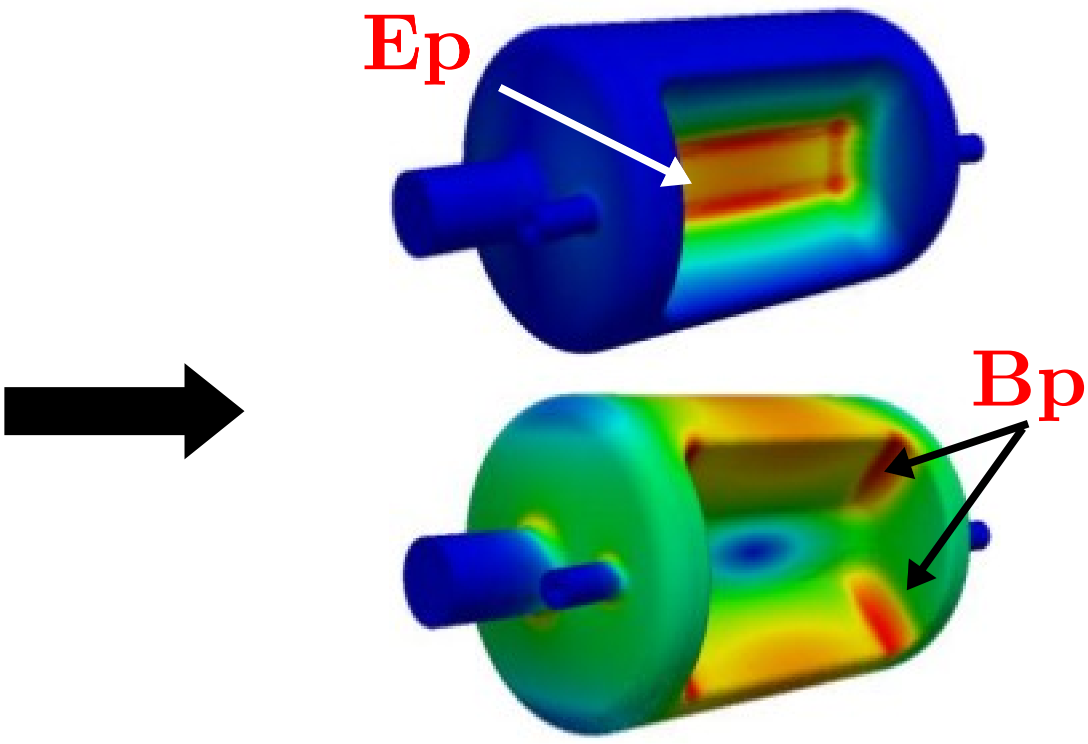
RF

	RF Dipole (ODU-SLAC)	4-Rod (UK)	¼ Wave (BNL)	KEKB
Cavity Radius [mm]	**147.5**	**143/118**	**142.5**	**550**
Cavity length [mm]	597	500	331	375
Beam Pipe [mm]	84	84	84	305
Peak E-Field [MV/m]	34	32	32	34
Peak B-Field [mT]	61	60.5	57	98
R_T/Q [Ω]	336	915	395	47
Nearest Mode [MHz]	584	371-378	582	~350

Redistribution of peak surface fields

(And compact due to quasi TEM-like mode)





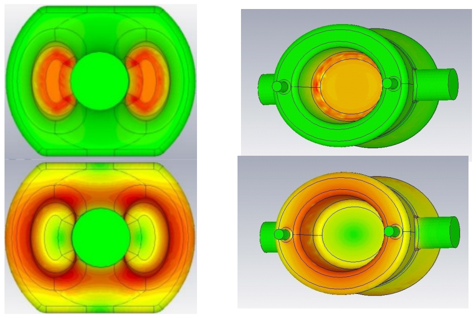
x3-4 bigger transversely

40% higher Bp

x6 smaller R/Q

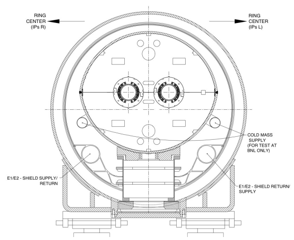
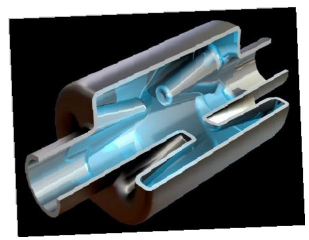
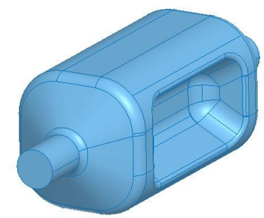
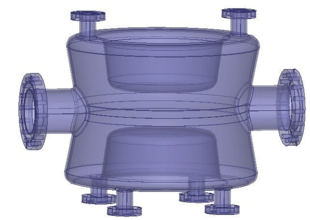
Same with

other designs



Field Quality (Usually Neglected)

Like IR magnets, higher order components of the deflecting field important

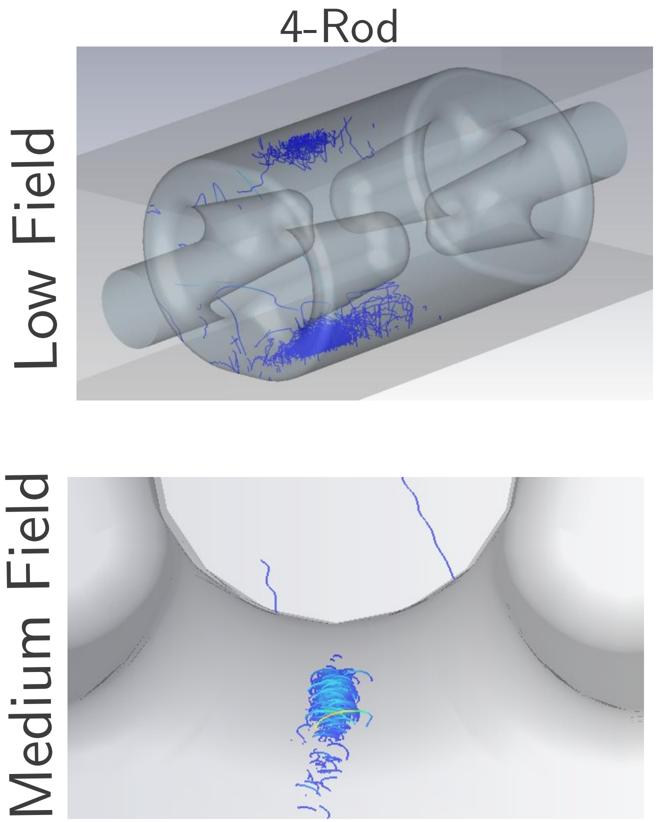
mTm/m^{n-1}	MBRC	4-Rod	Pbar/DRidge	¼-wave
b_2	55	0	0	0
b_3	7510	1162	4526	1076
b_4	82700	84	11	92
b_5	2.9×10^6	-2.29×10^6	-0.4×10^6	-0.1×10^6
b_6	52×10^6	0	0	0
b_7	560×10^6	-638×10^6	700×10^6	7×10^6

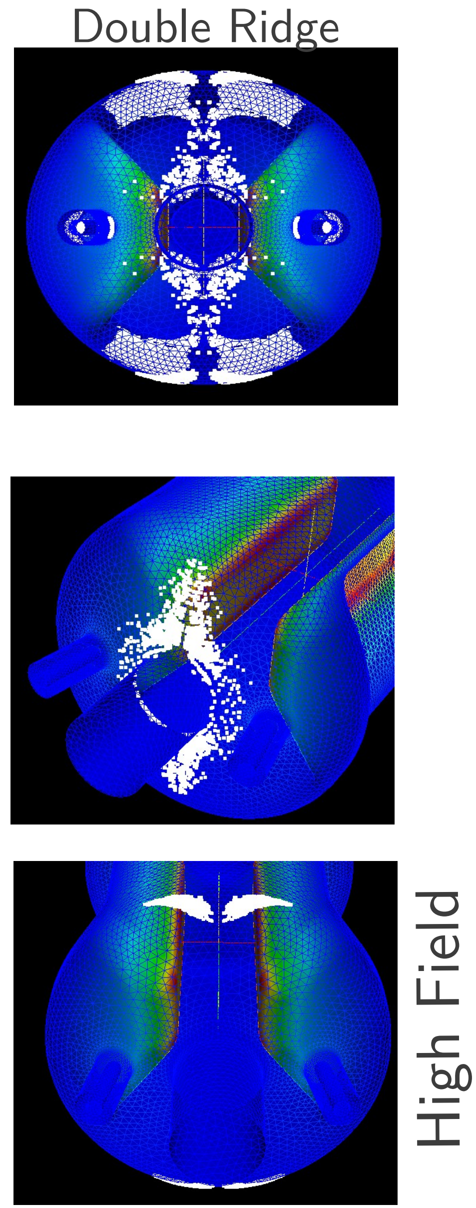
Orbit stability 750µm

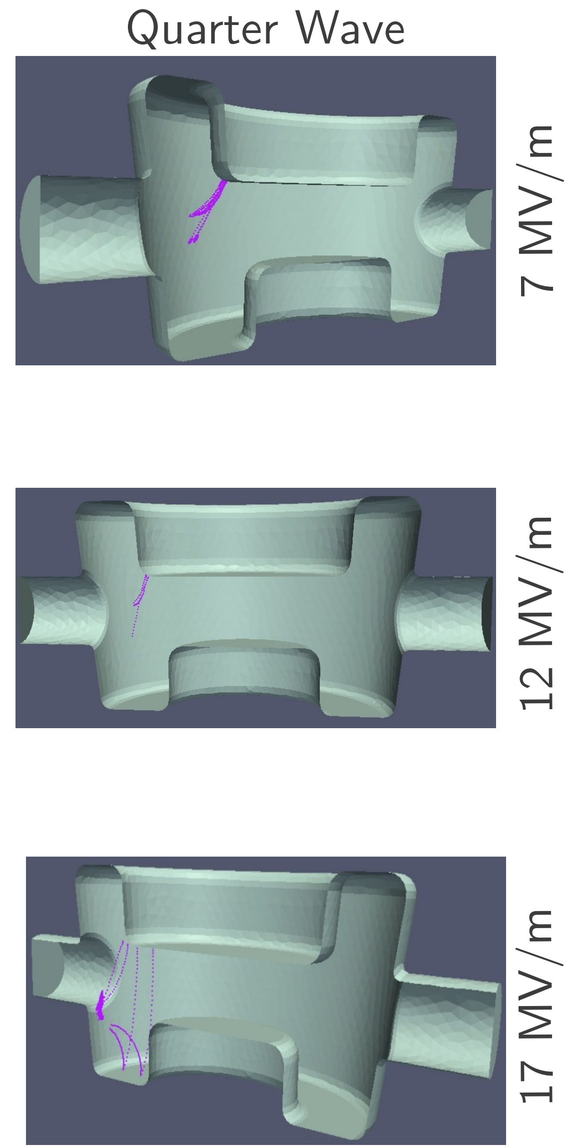
Precision Engineering

Multipacting of complex 3D geometries

require sophisticated analysis (ex: ACE3P code)



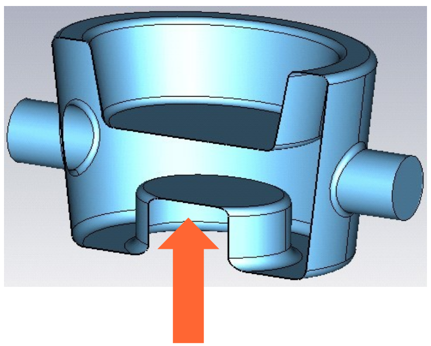




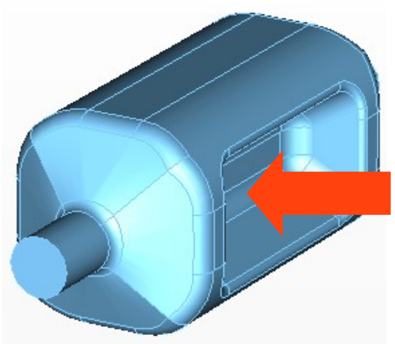
No serious barriers

RF conditioning sufficient

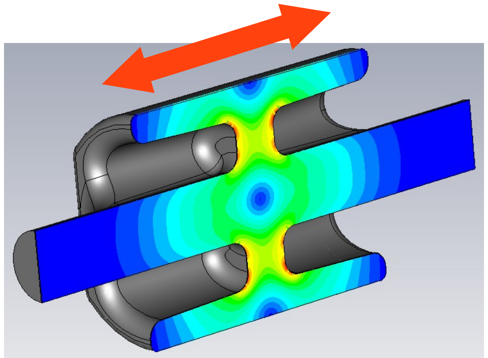
Compact Freq Tuning & integrated He-vessel



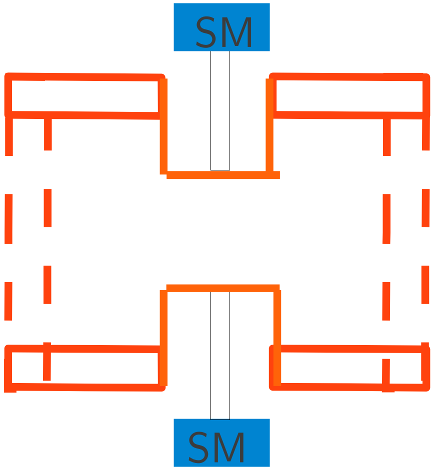
Up/down motion



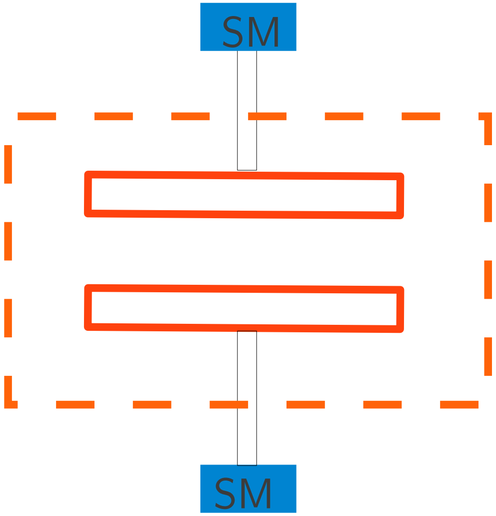
Push/pull ridges



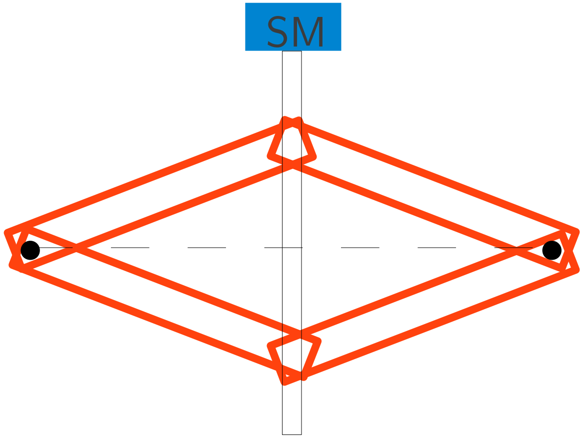
Scissor jack type mechanism



Tuner integrated He-Vessel



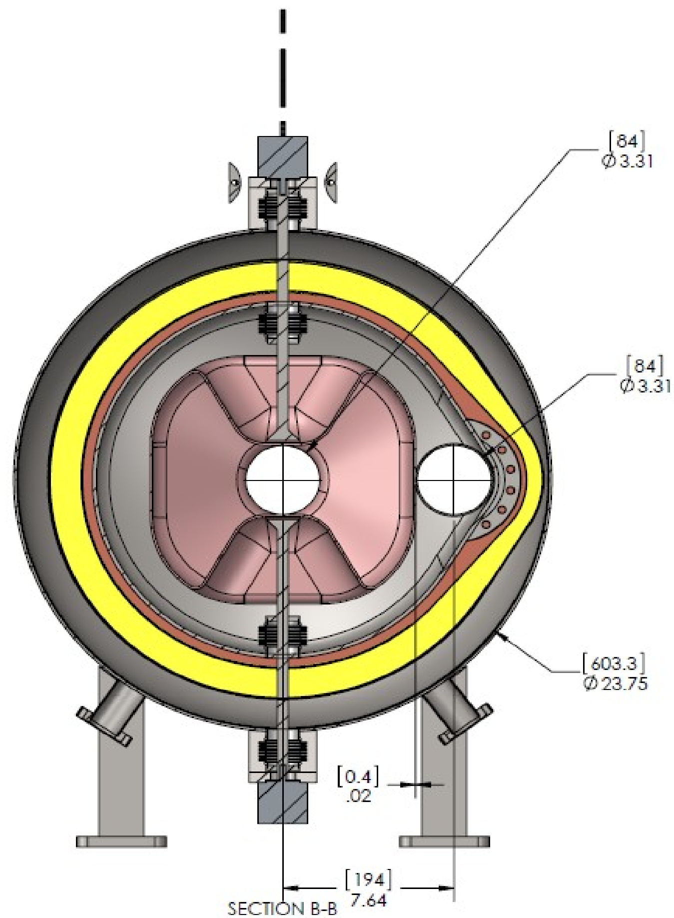
Tuner penetrating He-Vessel

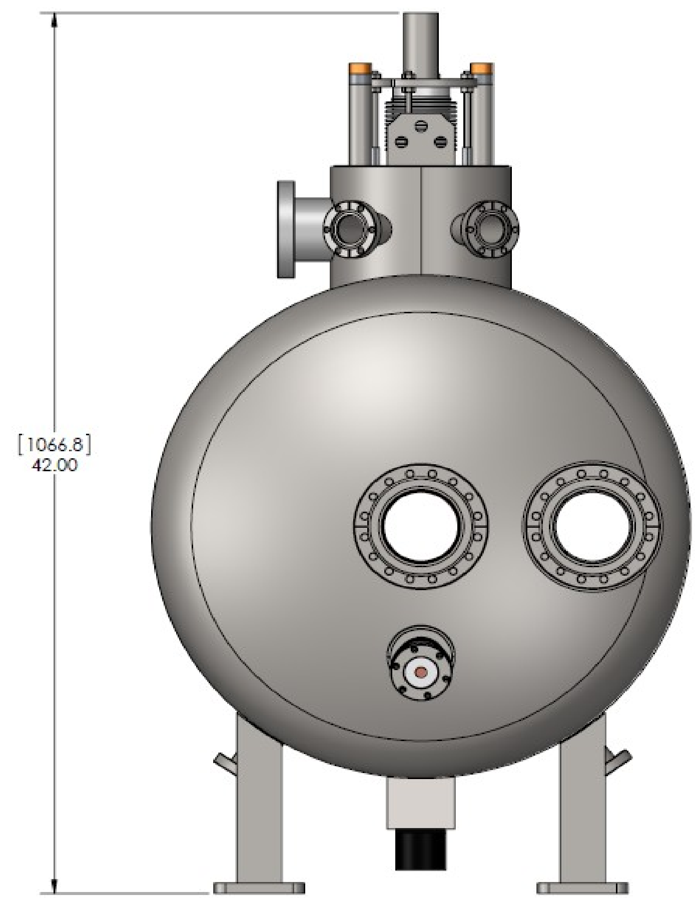


CEBAF Tuner

First Cryostat Ideas: Challenging Technical R&D Ahead

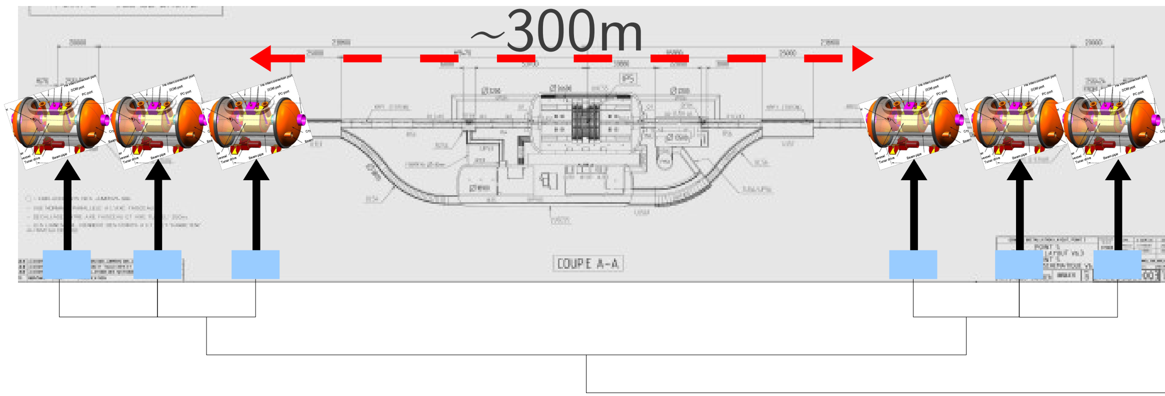
Integration, alignment, thermal management...



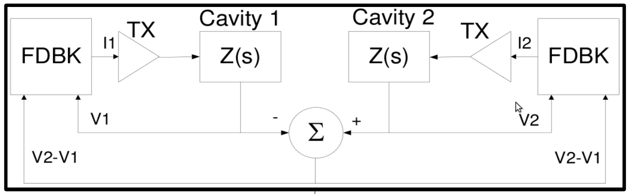


Courtesy: J. Delayen. Niowave

Precise control of voltage & phase



LLRF (Coupled feedback)



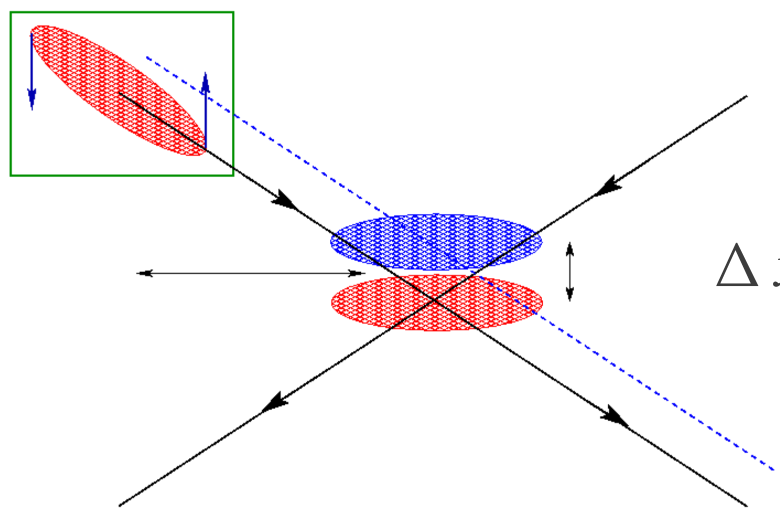
P. Baudrenghien

Main RF phase jitter

$\Delta\phi = 0.005^0$ @400 MHz

For Crabs (θc=570μrad):

Δx_{IP} = 0.3μm (5% of σ_x^*)



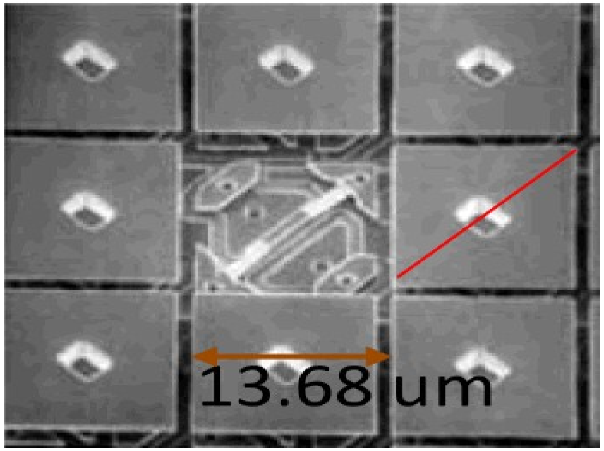
$$\Delta x_{IP} = \frac{\theta_c}{k_{RF}} \delta\phi$$

Instrumentation

Transverse/longitudinal coupling may require beyond standard devices

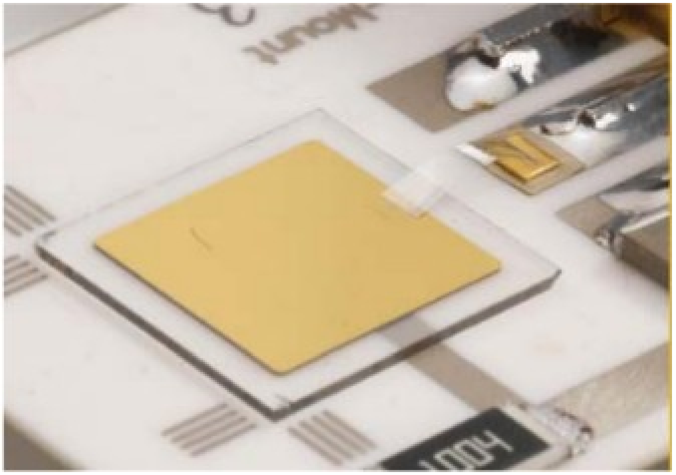
- Cavity field/phase itself is an excellent diagnostic
- Head-tail monitors , streak cameras $\rightarrow$ tilt & orbit measurements
- Halo monitoring & fast beam loss monitors $\rightarrow$ machine protection

Digital Micro-Mirrors
(Beam Halo-Monitoring)



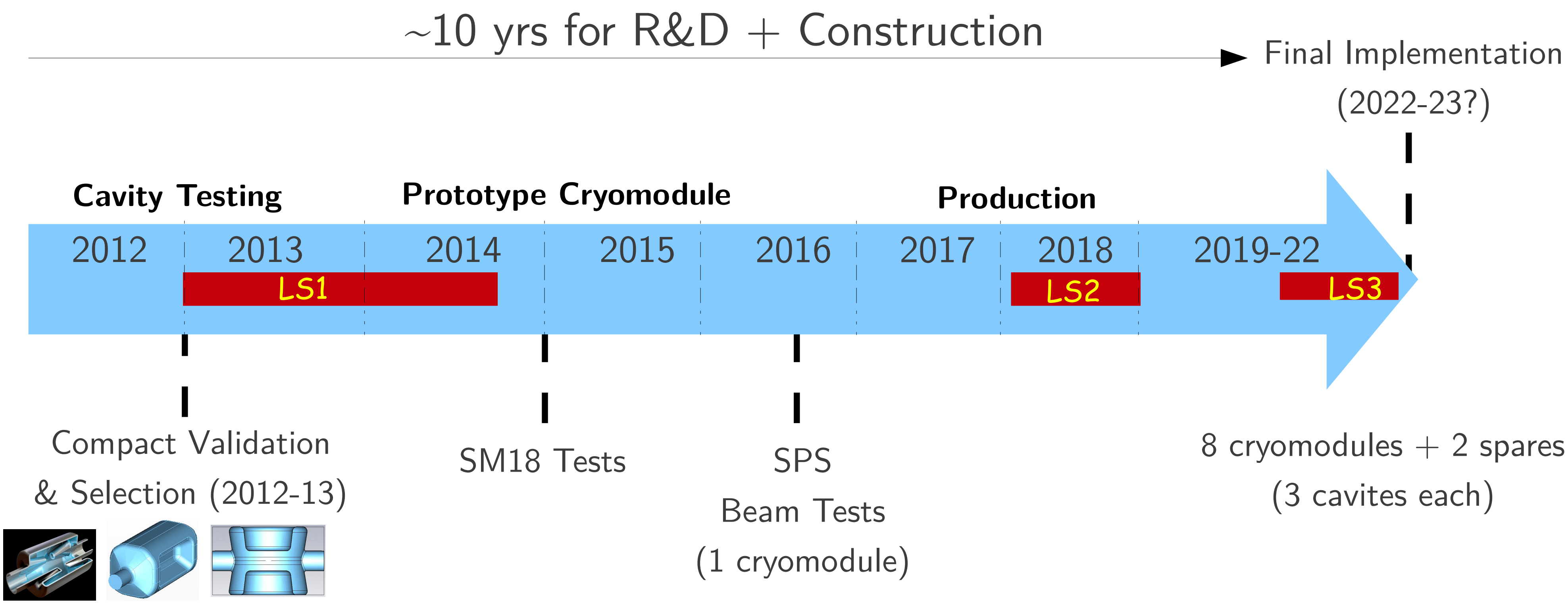
A. Fischer, SLAC

CVD Diamond Detectors
(Fast Beam Loss Monitors)

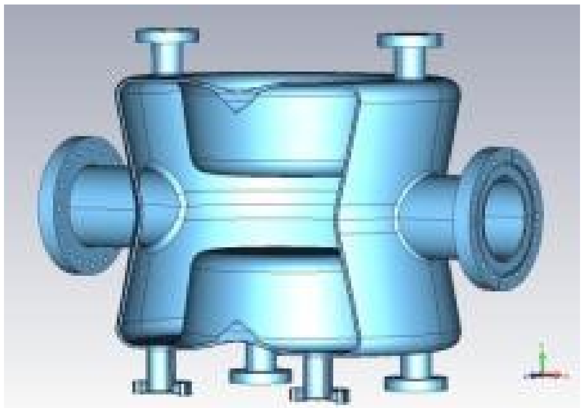


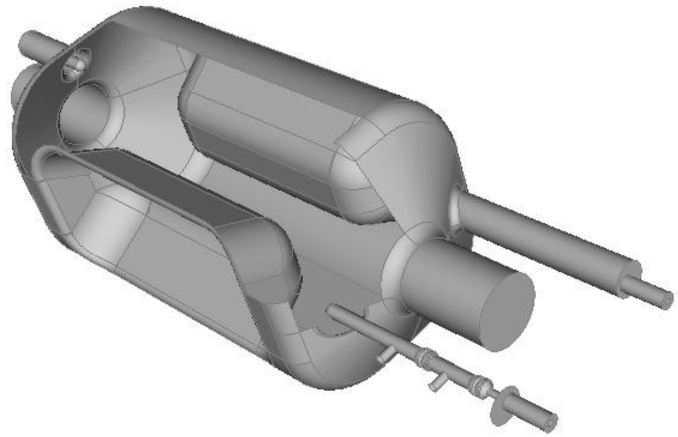
B. Dehning, CERN

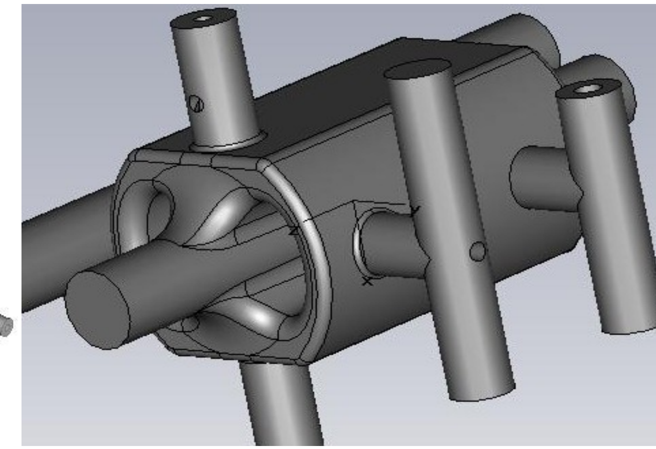
Planning Overview



All Prototypes in Bulk Niobium

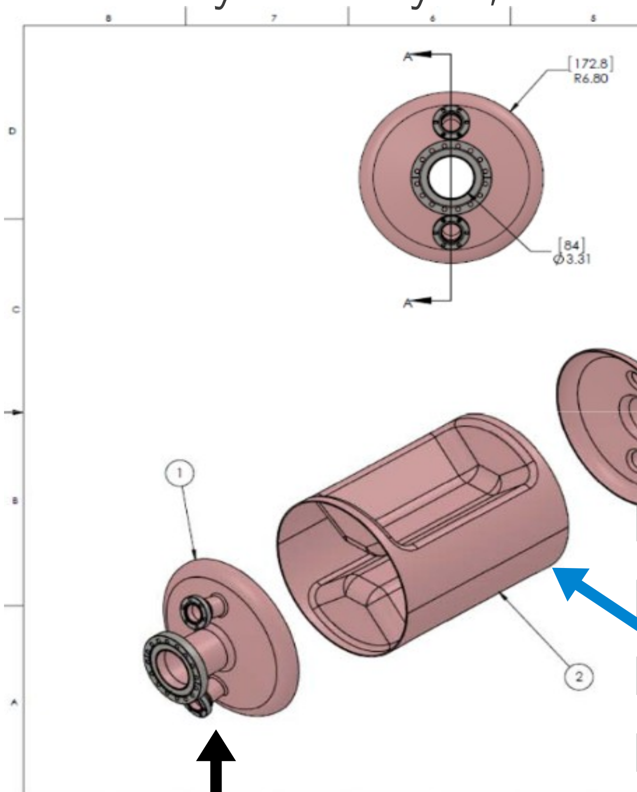


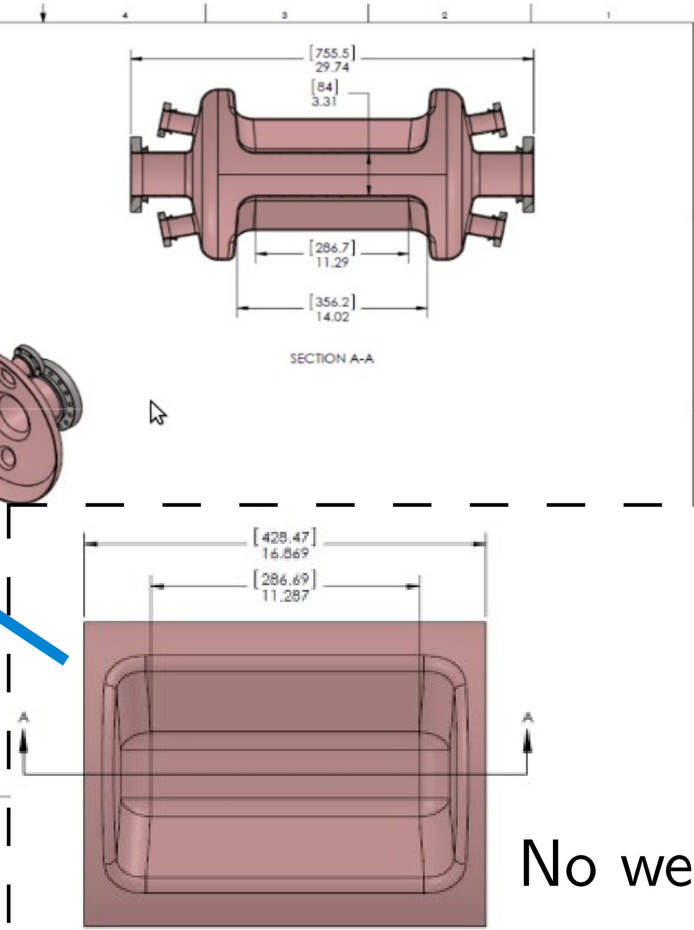




RF Dipole Fabrication

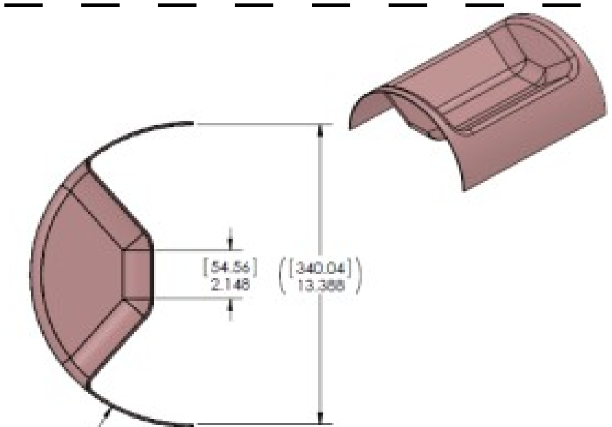
Courtesy:J. Delayan, Niowave Inc.

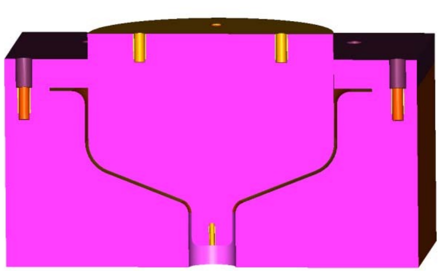




Inner ridges in 2-parts

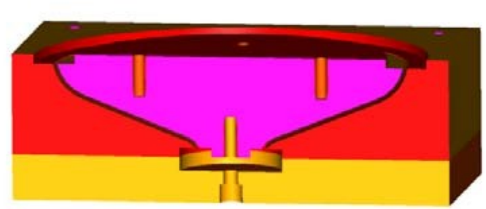
No welds





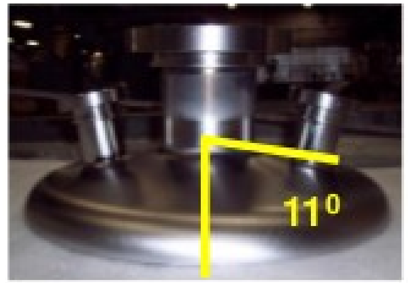
Endcap forming

& machining

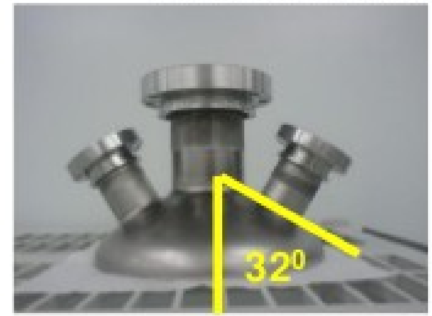


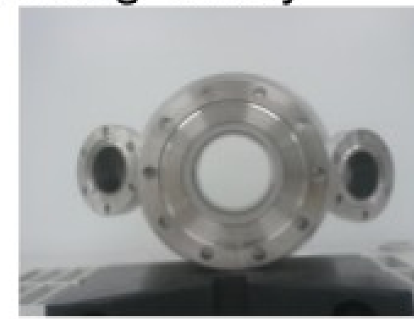
400 & 750 MHz RF-Dipole Cavity Fabrication

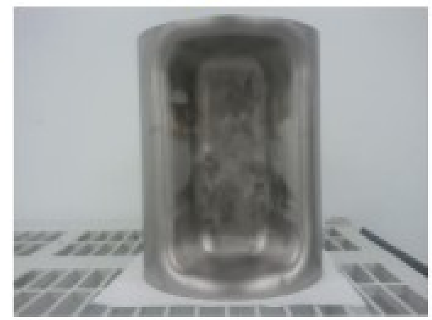
400 MHz Crabbing Cavity



750 MHz Crabbing Cavity





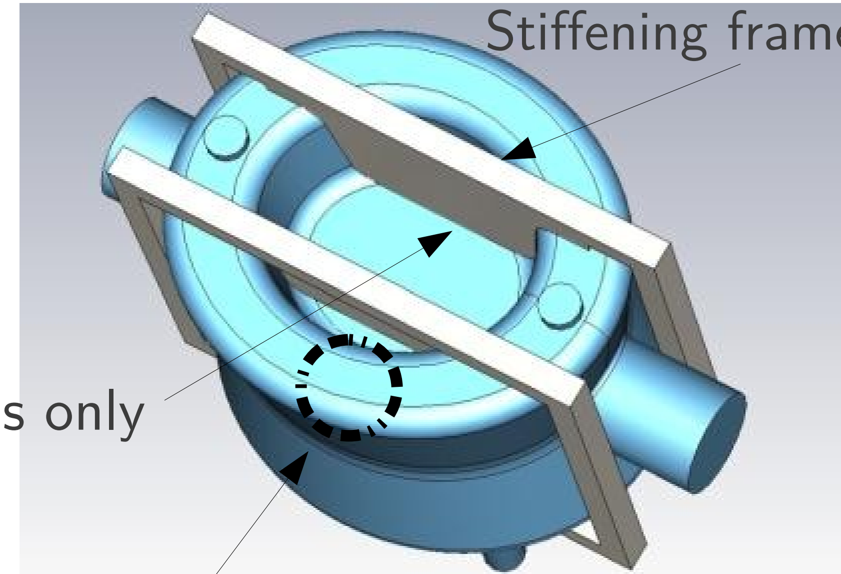


Courtesy:J. Delayan, Niowave Inc.

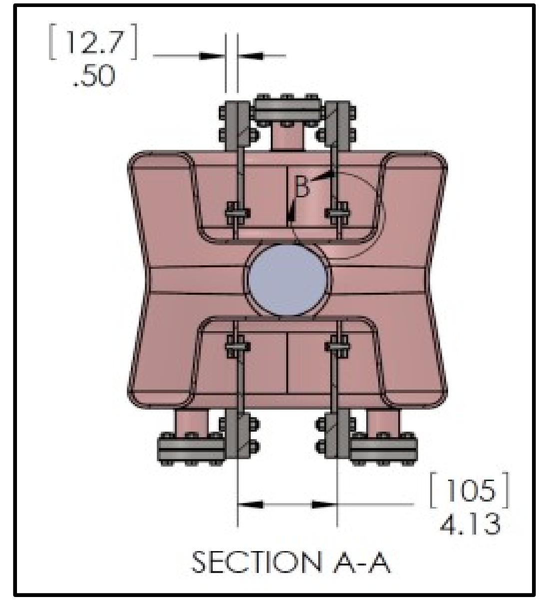
Quarter Wave Prototype

Courtesy: I. Ben-Zvi et al.

Stiffening frames



Welds only



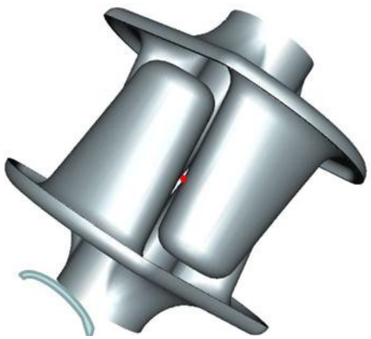
Stiffen with solid Nb ?

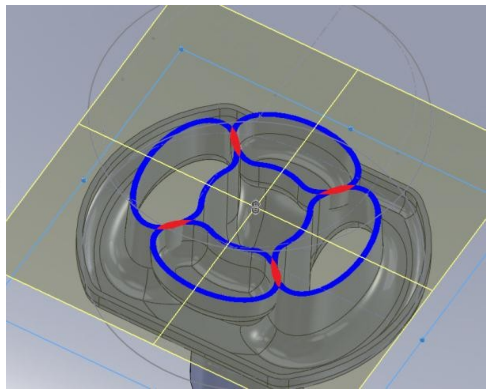
Elegant solution by balancing forces

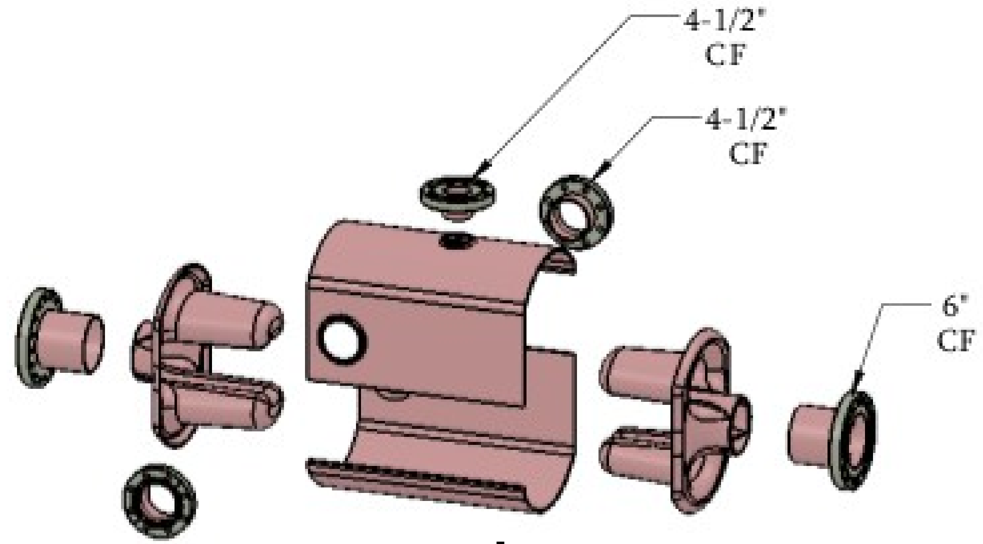
Top/bottom rings

4Rod Prototype

Courtesy: G. Burt, Niowave Inc.







End plates from solid ingot

Wire EDM pre-forms from ingot

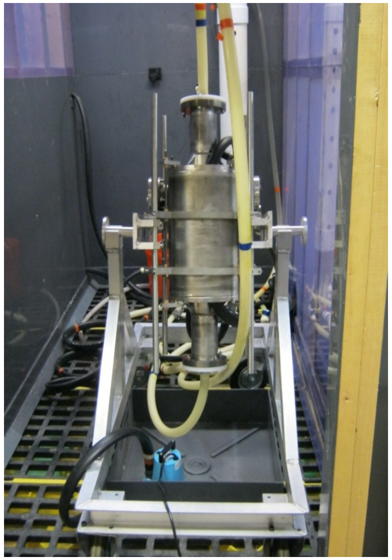
Machine all surfaces

Outer shell in two-part sheet metal

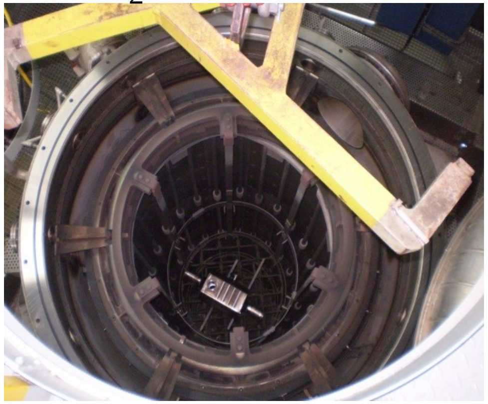
4Rod Cavity Treatment @CERN

Surface Treatment

Niowave



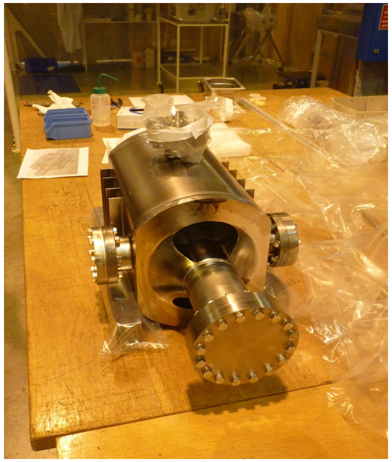
H_2 Degassing



600^0C, 48 hrs

RF Measurements

SM18

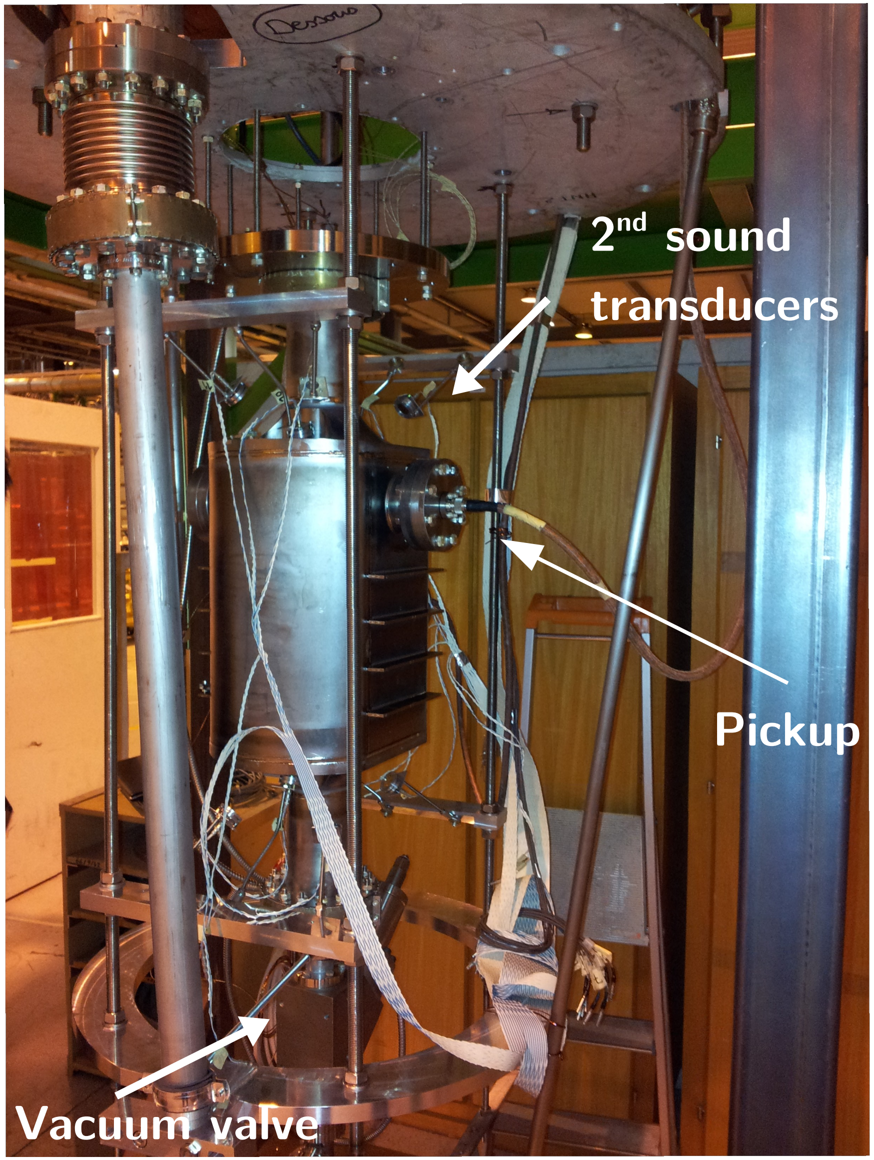


High Press Rinsing

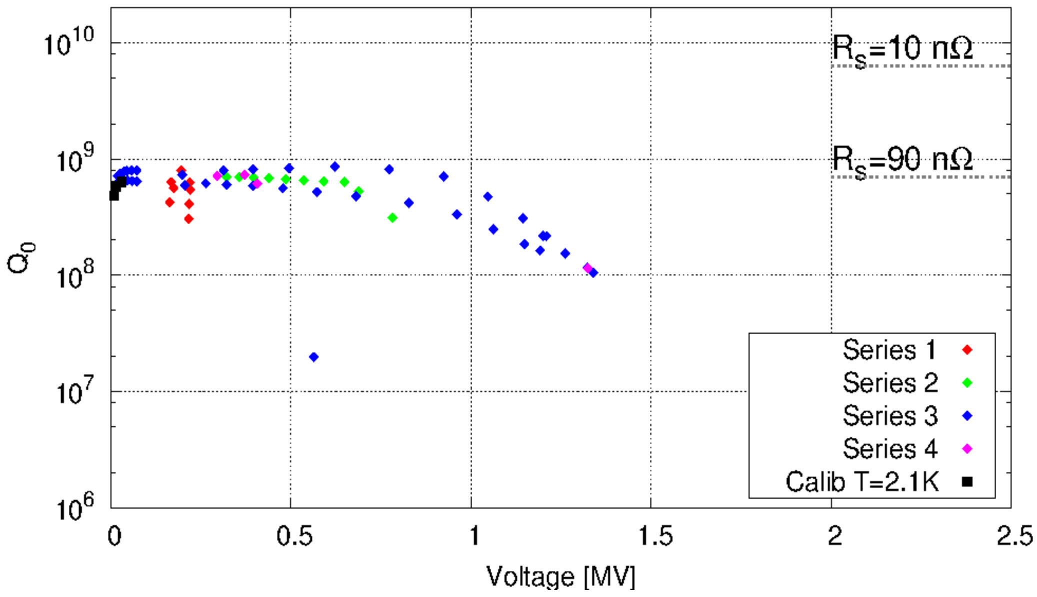
(Bldg 118)

1st Cold test performed Nov 19-23

SM18 Vertical Test Insert



A vacuum leak (& time) prevented us from testing to nominal gradients



Outlook I

Three novel concepts for LHC crab cavities

- A new path for the deflecting (SRF) world $\rightarrow$ R&D
- Emerging applications (light sources, proton linacs, x-band...)
- Industry at the core of engineering development

LHC Crab Cavity Challenge

- Demonstration of reliability, transparency & flexibility with SPS beam
- Tight mechanical tolerances (fabrication, integration), Radiation

Precision Beam-RF control (key challenge)

- For all deflecting applications (colliders, bunch compression, diagnostics)

Outlook II

Potential mitigation of fast cavity quench

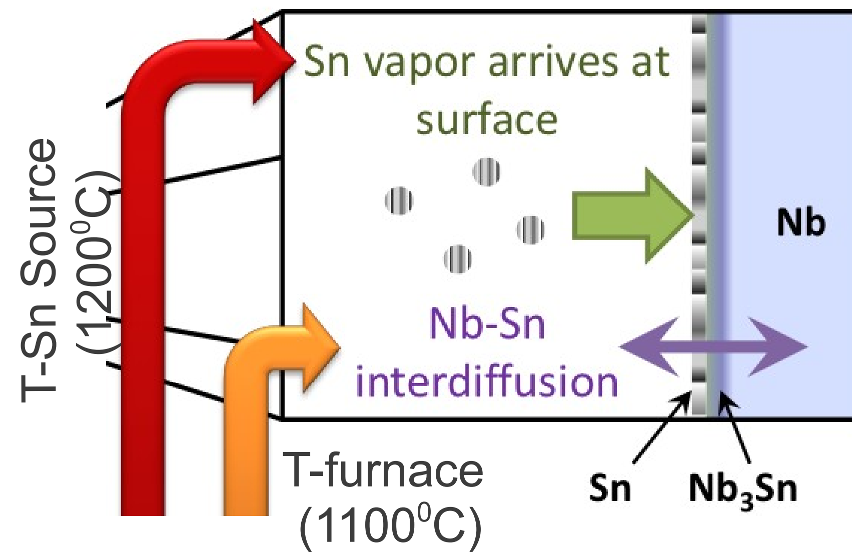
Nb-coatings on copper substrate

(S. Calatroni, CERN)

LEP, LHC, HIE-ISOLDE

Vapor diffusion Sn → Nb cavities

(S. Posen, Cornell)



Nb3Sn Coated Cavities

Lower R_{BCS} & Higher H_{sh}

Outlook III

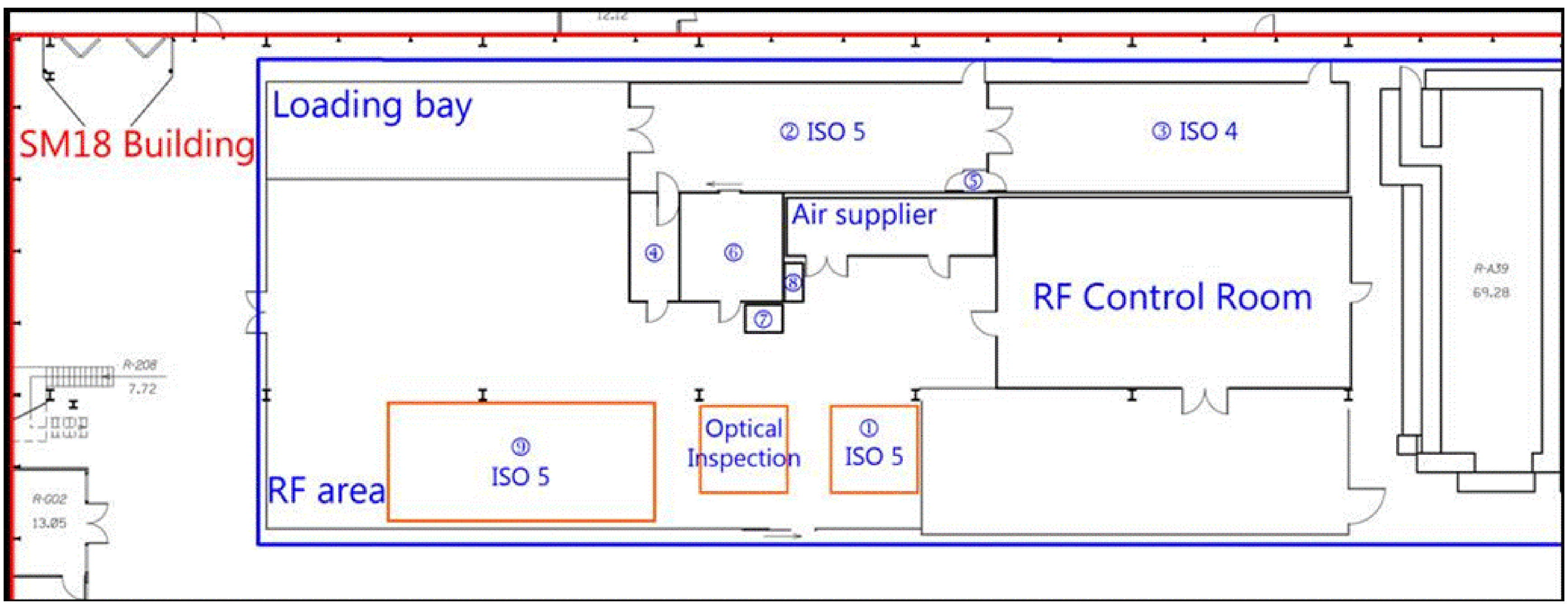
3D-Printing of Nb-Cavities (?)

(Over a beer conversation with G. Kirby)

The klein bottle opener ($72)

Major upgrade of SM18 → Handle modern high performance cavities

- Upgrade of clean rooms
- New high pressure rinsing & ultra-pure water for cavities/components
- Improved cryo & 2K operation
- Modern diagnostics equipment (2nd sound, kyoto telescope..)



Courtesy: J. Chambrillon