Crab Cavities

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HL-LHC Kick Off Internal Meeting
Thoiry, France, 15-April-2011

HL-LHC Luminosity Upgrade

Background:

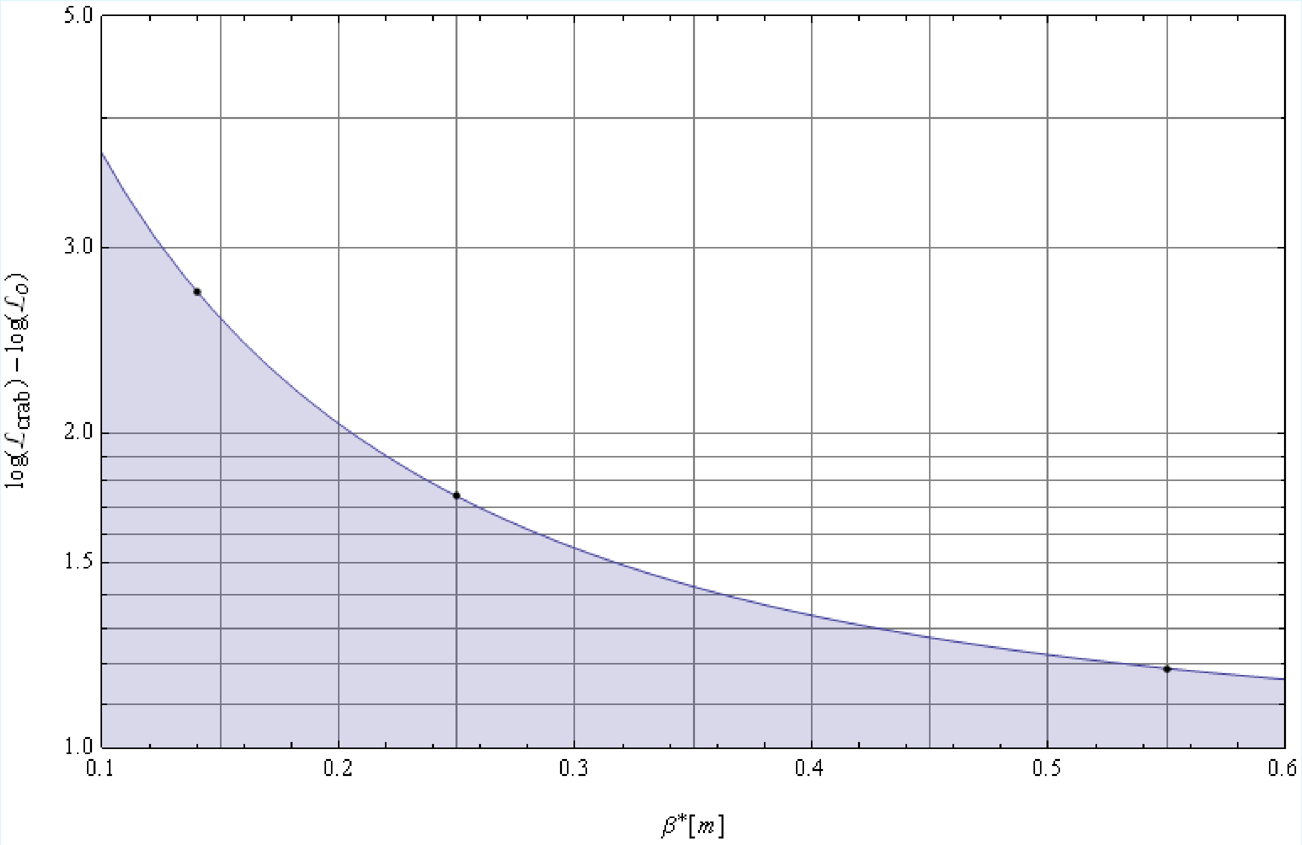
- LHC has collected **50 pb^{-1}** in 2010 and recently exceeded **2.5x10^{32}cm^{-2}s^{-1}**.
- Push towards 7 TeV after 2013/14 shutdown and consolidation.
- After reaching nominal parameters, the challenge is to aggressively pursue the experimental goal of **3 ab^{-1}** during the LHC lifetime.
- This can only be achieved with an LHC upgrade HL-LHC that can reach beyond the ultimate intensities, with β^* well below the nominal 0.55 m and by doing **luminosity levelling** during the coast.
- The IR upgrade will use Nb_3Sn magnets @ 13-15 T, and $\beta^* \approx$ **0.2 m.**

- => Compensation of beam crossing angle becomes essential.
- **Crab Cavities** are the preferred choice…
- They are also the instrument of choice for **luminosity levelling**.

Assumed parameters

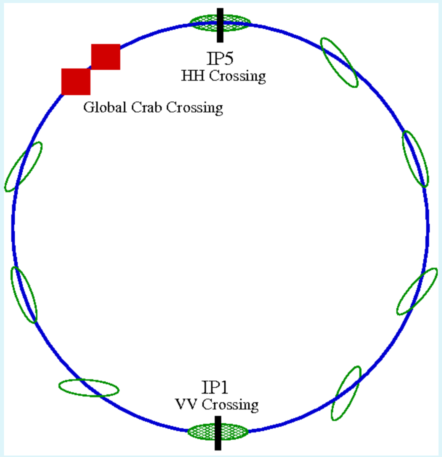
Parameter	*Unit*	*nominal*	*upgrade*
Energy	[TeV]	7	
Protons/Bunch	[10^{11}]	1.15	1.7
Bunch Spacing	[ns]	50…25	
ε_n (x, y)	[μm]	3.75	3.75
σ_z (rms)	[cm]	7.55	
Bunch Length (4 σ)	[ns]	1.0	
Longitudinal Emittance	[eVs]	2.5	
β^* at IP1, IP5	[m]	0.55	0.25…0.14
Betatron Tunes		{64.31, 59.32}	
Piwinski parameter: $\frac{\theta_c \sigma_z}{2 \sigma^*} = \frac{\Delta in \, \sigma_z}{2 \beta^*}$		0.65	1.4…2.5
BB Parameter, ξ , per IP		0.003	0.005…0.008
Crossing-angle: θ_c	[μrad]	285	315…509
Main RF	[MHz]	400	
Crab RF	[MHz]		400
Peak luminosity w/o crab cavity	10^{34} cm^{-2}s^{-1}	1	3.3…3.8
Peak luminosity with crab cavity	10^{34} cm^{-2}s^{-1}	1.2	5.8…10.3
Pile up events per crossing		19	44…280

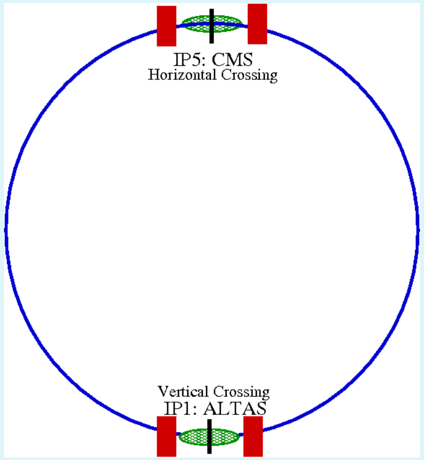
Potential luminosity gain

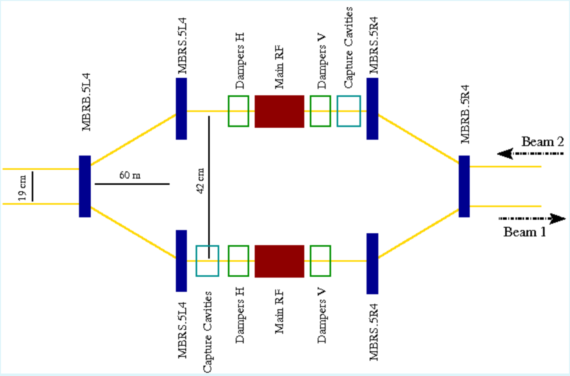


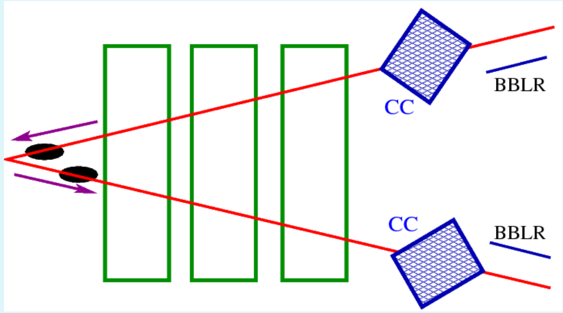
… by CC’s, compensating the geometric loss due to the crossing angle

Global scheme vs. Local scheme 1/2





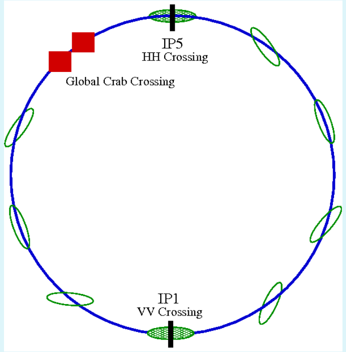


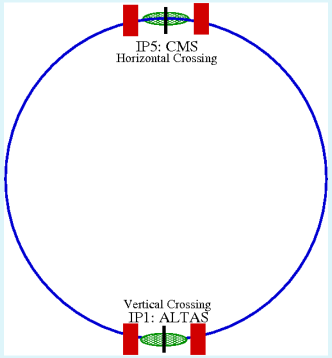


Global scheme, allows for elliptical CC's at one (or two) locations

Local scheme, CC's up- and downstream of each IP, requires compact cavities

Global scheme vs. Local scheme 2/2





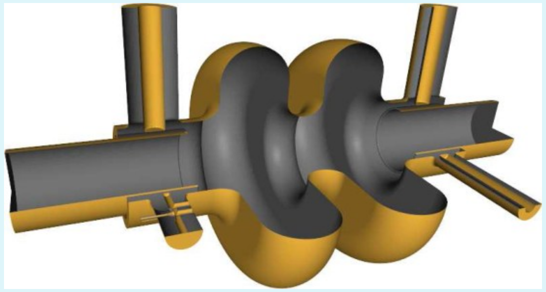
- Requires less cavities (2),
- cavities central - possibly at P4 (larger separation),
- allows for elliptical CC's,
- constraining betatron phase advance,
- difficult for H and V crossing!

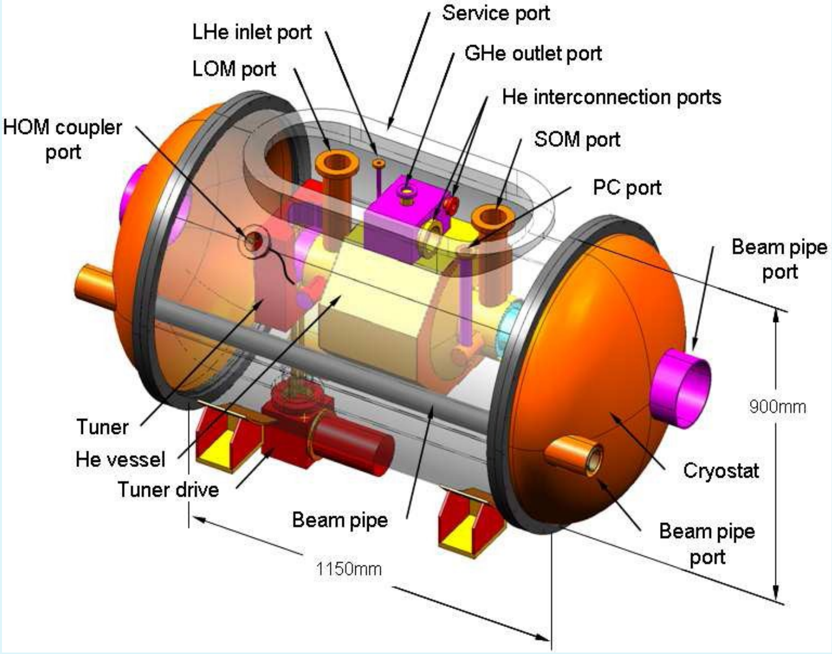
- At least 2 cavities per beam per IP (8),
- cavities to fit with smaller beam separation (194 mm),
- requires Compact CC's,
- orbit distortions compensated,
- allows H and V crossing!

Global scheme | **Local scheme**

Elliptical CC's

- Technology relatively "well known" -> less risk

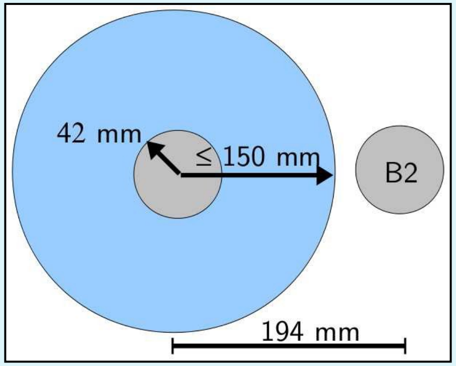


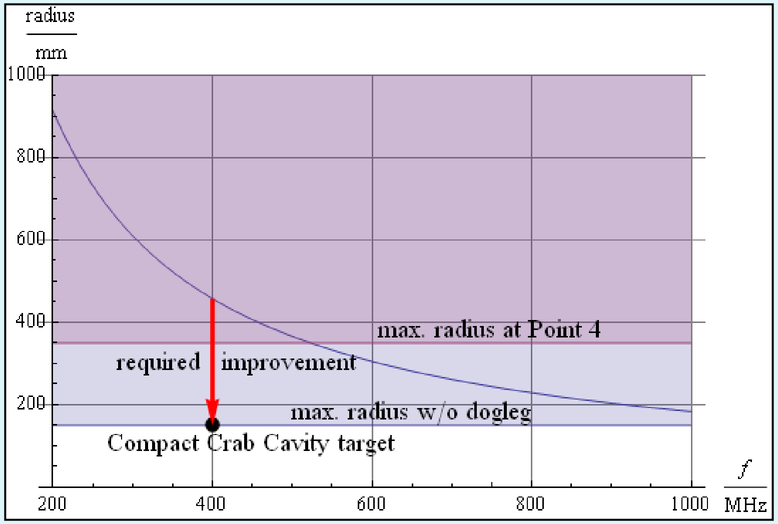


Cryostat design exists (from LARP) compatible with P4 (800 MHz)

Compact CC's

- The challenge: a normal RF cavity requires a transverse dimension > 0.609 λ !
- For 400 MHz, this means > 460 mm.
- The LHC beams are separated 194 mm (0.26 λ)!





- We're looking at something very unconventional!
- Have to cope with V or H crossing! (?)

Classes of CC's

1. TM type

   $E_z(x) = -E_z(-x)$ ➔ Kick force dominated by $v \times B_y$

   - Variations of elliptical cavity ...
   - Half-wave resonator (SLAC, Zenghai Li)
   - Mushroom cavity (FNAL, Nikolay Solyak)
   - Longitudinal rods (JLAB, H. Wang/CI, G. Burt)

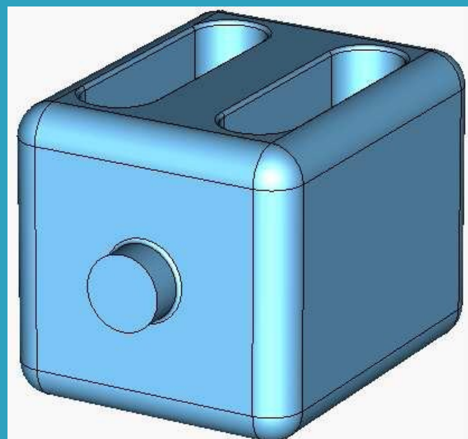
2. TE type (Panofsky-Wenzel: $j\omega \vec{F}_\perp = \nabla_\perp F_z$!)

   $B_y = 0$ ➔ Kick force dominated by E_x

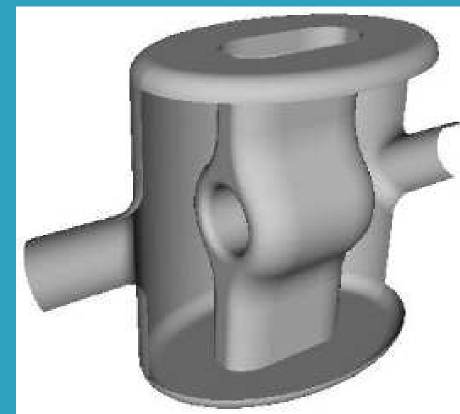
   - "transverse pillbox" (Kota Nakanishi)
   - Parallel bars or spokes:
     - Figure-of-8 (CI, Graeme Burt, Peter McIntosh)
     - Spoke cavity (SLAC, Zenghai Li)
     - Parallel bar cavity (JLAB/ODU, Jean Delayen)

Ideas for Compact CC's

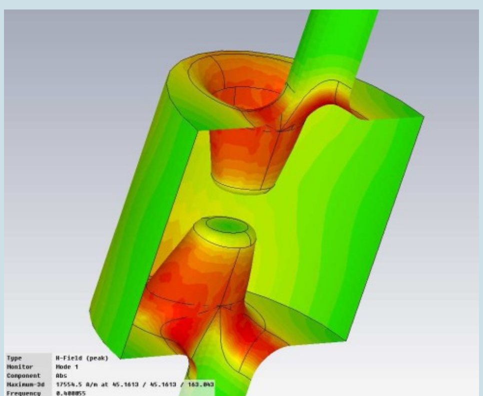
Parallel bar cavity (ODU)



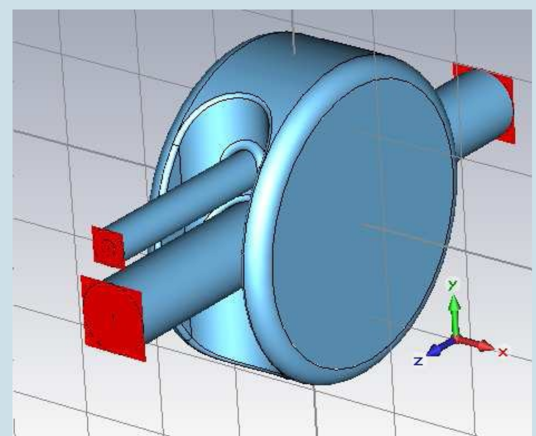
Half wave resonator (SLAC)



Four bar cavity (U Lancaster)



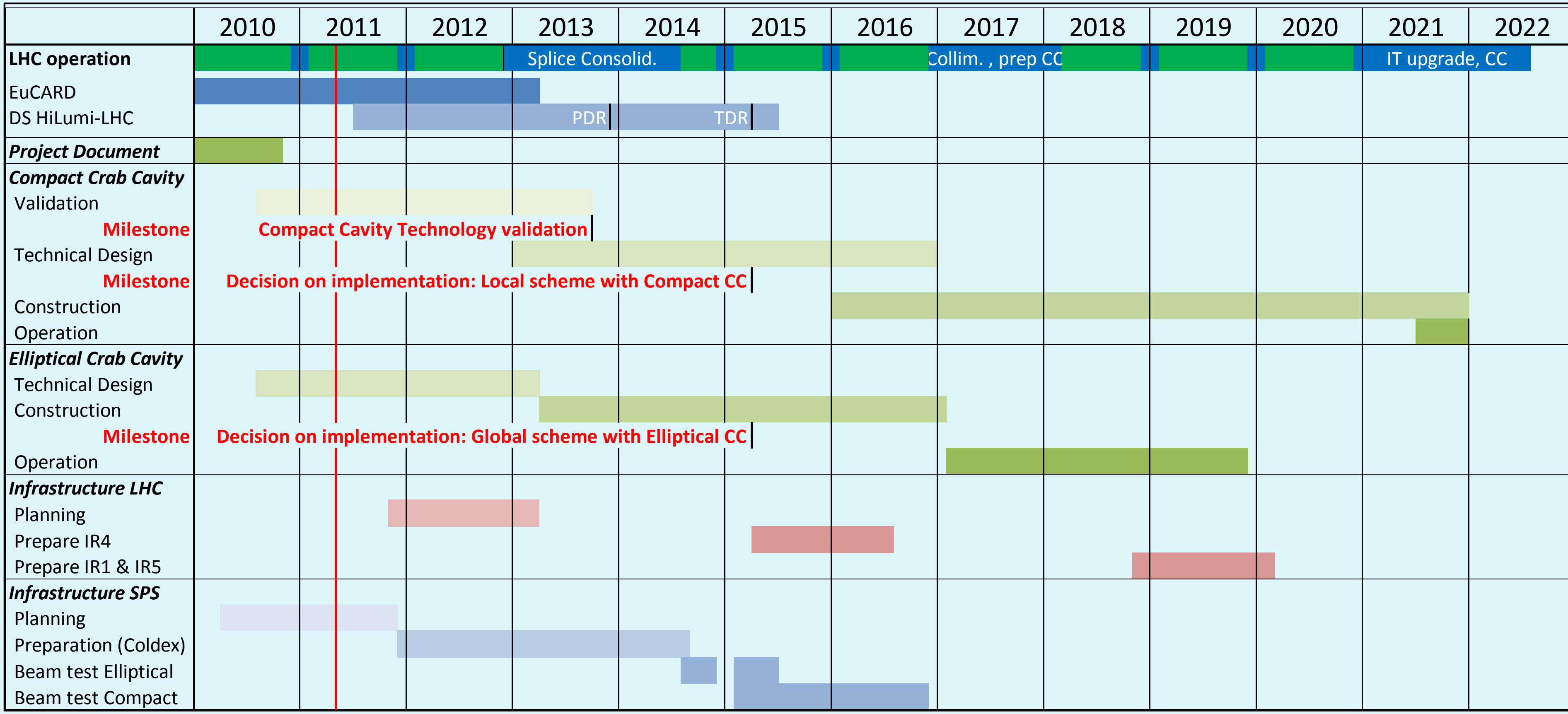
Kota cavity (KEK)



The risks

- These Compact CC's do not exist – will they work?
  - technology validation required asap!
  - need a fallback solution if they fail!
- Not only the cavity shape, also the damping of HOM's LOM's and SOM's as well as power coupling is new
  - requires ideas and verification!
- What if a cavity fails or trips?
  - must find a way to make them invisible!
  - must study failure scenarios for machine protection (very important!)

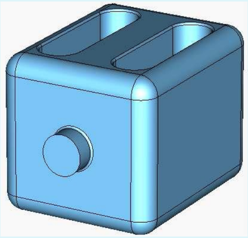
Crab Cavity project – the plan

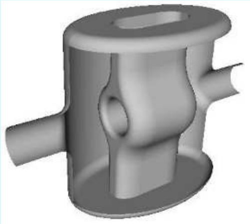


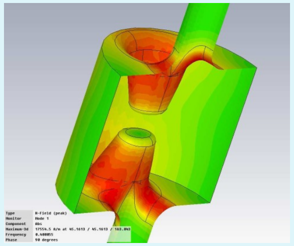
Crab cavity project – the partners

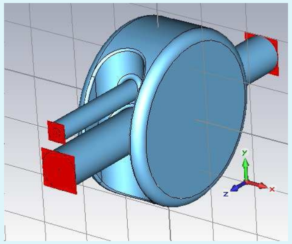
- CERN
- US-LARP + JLAB/ODU (active in CC R&D, SC RF technology)
- KEK (CC experience, SC RF technology)
- CEA/CNRS (SC RF Technology, cryostats)
- …

Proposed Strategy for Crab Cavities









Main Goal : Compact Crab Cavities for LHC Local Scheme
(Generally following CC09 & CC10 workshop recommendations)

- Complete conceptual designs of the main candidates
- Validate by 2013 (demonstrate kick fields in test cryostat).

- Down-select to at least two designs, with full spec. and mechanical drawings of the cavities. Conceptual designs for tuner and He tank, the SOM, HOM and LOM coupler and the cryostat!

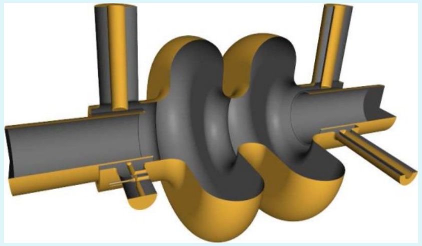
- Hardware prototyping and test on above, tooling, construction of prototype bare cavities prototypes, surface treatments and tests to confirm gradient and performance. Test in SPS. Decision point 2015!

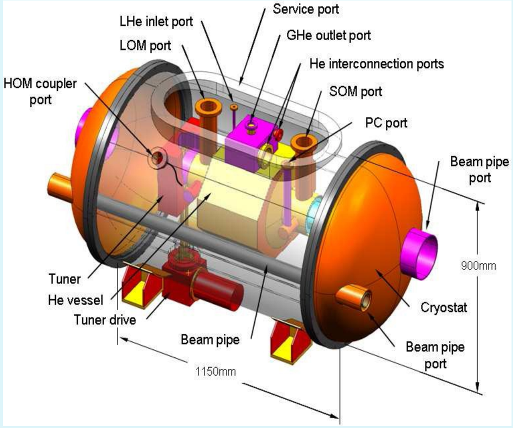
- Production

Back-up strategy for Crab Cavities

Retain a conventional cavity option in the unlikely event of major unforeseen 'show stopper' with all compacts…

- Would entail significant civil engineering costs and use of dogleg sections in the IRs, but this would still be acceptable, in view of the importance gaining back luminosity from the crossing angle.
- A straightforward conventional cavity installation in IR 4 as a global scheme would serve as an alternate option in the worst case. To this end, for the TDR, a full mechanical design of the elliptical cavity, its accessories and the elliptical cavity cryostat is also envisaged.
- Decision point 2015 – stop if Compact CC's are validated!





HL-LHC CC relevant projects

- EuCARD WP10.4 “LHC Crab Cavities”: development of 4-rod cavity ongoing (primarily Lancaster, G. Burt)
- US-LARP has a successful program running, including CC design (R. Calaga, Z. Li, …)
- Design study Hi-Lumi LHC, recently accepted with excellent marks – will cover design and some prototyping! Includes partners in Europe and worldwide.
- French “Grand Emprumpt”

First estimate of budget

CCs - COST ESTIMATE - For Overall HL-LHC Estimate, Feb 2011, E. Ciapala, E. Jensen, L. Rossi

YEAR		*2011*	*2012*	*2013*	*2014*	*2015*	*2016*	*2017*	*2018*	*2019*	*2020*	*TOTALS*
Totals	GTΣ FTE	16.5	21	24.9	13.1	5.5	19.6	21.2	20.7	16.1	8	*166.6*
	GTΣ MCHF	4.45	6.9	6.95	4.35	3.6	10.25	14.5	21.25	18.15	7	*97.4*
R&D Compact Crab (Design/Prototype/Test in SPS)	TΣ FTE	13	16	13.5	5	5	3.6	1.5				*57.6*
	TΣ MCHF	3.55	5.6	3.4	2.35	3.3	1.15	0.1				*19.45*
Elliptical Crab cavities (Design/Prototype/Test in SPS)	TΣ FTE	3.5	5	11.4	8.1	0.5	0.5					*29*
	TΣ MCHF	0.9	1.3	3.55	2	0.3	0.3					*8.35*
Construction of Cavities	TΣ FTE						5.5	5.5	5.5	4.5		*21*
	TΣ MCHF						3.5	5.5	6.5	5.5		*21*
Construction of cryostats	TΣ FTE						3	4	4	3	2	*16*
	TΣ MCHF						4	5.5	11	8.5	5	*34*
RF Power System	TΣ FTE						2.5	2.5	3	3	3	*14*
	TΣ MCHF						1	1.5	1.75	2.25	1	*7.5*
LLRF & controls	TΣ FTE						4.5	6.5	7	5	3	*26*
	TΣ MCHF						0.3	1	1.1	1.9	1	*5.3*
Infrastructure & installation	TΣ FTE							1.2	1.2	0.6		*3*
	TΣ MCHF							0.9	0.9	0		*1.8*
Totals (Check)	*GTΣ FTE*	*16.5*	*21*	*24.9*	*13.1*	*5.5*	*19.6*	*21.2*	*20.7*	*16.1*	*8*	*166.6*
	GTΣ MCHF	*4.45*	*6.9*	*6.95*	*4.35*	*3.6*	*10.25*	*14.5*	*21.25*	*18.15*	*7*	*97.4*

Total cost: 170 FTEy, 100 MCHF (Design Study WP4: 40 FTEy, 2.2 MCHF)

FP7 DS HiLumi-LHC, WP4:

Task 1: **Coordination and Communication** (CERN, LARP, ULANC)	10 kCHF	8 pm
Task 2: **Support studies** • Tunnel preparation SPS and LHC (CERN) • Local IR layout and spatial integration (CERN, BNL) • Effect of phase noise , LLRF system conceptual design (CERN, ULANC, KEK, BNL, LBNL, SLAC) • RF power system specification (CERN, ULANC) • Operational aspects (how to commission/make invisible) (CERN, CNRS, BNL) • Interlocks and fast Feedback (CERN, LBNL)	18 kCHF	121 pm
Task 3: **Compact Crab Cavity design** • Cavity and cryomodule specifications (CERN, CEA, CNRS, STFC, ULANC, BNL, FNAL, ODU, SLAC, KEK) • Design optimisation for novel schemes (STFC, ULANC, BNL, ODU, SLAC, KEK) • Conceptual design of SOM, HOM and LOM couplers (STFC, ULANC, BNL, ODU, SLAC, KEK) • Conceptual design of helium tank and cryostat (CEA, CNRS, STFC, ULANC, BNL, FNAL, ODU, SLAC, KEK) • Multipacting simulations of cavity & couplers (STFC, ULANC, ODU, SLAC, KEK) • FEM simulations: mechanical & thermal aspects (STFC, ULANC, BNL, ODU, SLAC, KEK)	576 kCHF	235 pm
Task 4: **Elliptical Crab Cavity Technical design** • Coupler development and testing (CERN, CNRS, KEK) • Tuner design and mock up on copper models (CERN, • Study of mechanical effects: resonances, microphonics (CERN, • Cavity performance with couplers and horizontal cryostat (CERN, • Performance difference between 2 K & 4 K (CERN, • Cryostat and He Tank Design (CERN, CNRS	13.5 kCHF	86 pm
Task 5: **Compact Crab Cavity Prototyping and Test** • Construction of models to refine manufacturing techniques and tooling (CERN, ODU, KEK) • Fabrication of prototype niobium cavity (ODU, KEK) • Make the final CC design down-selection (CERN, ULANC, STFC, all US)	1,588 kCHF	28 pm

CC project status

- Recent developments

LHC CC10 Workshop (12/2010)

Charge:

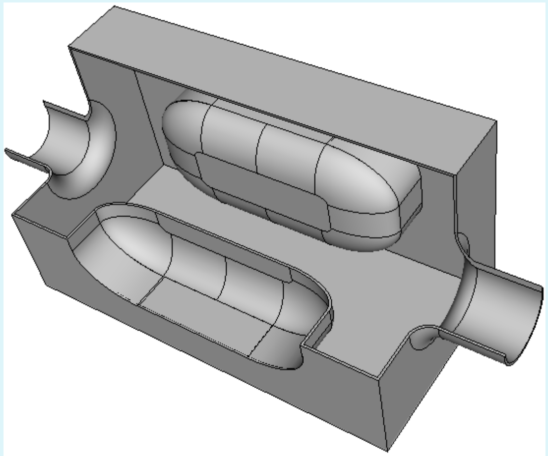
1. Can compact cavities for the LHC be realized with the complex damping schemes?
   Answer: 3-4 viable candidates, dual crossing scheme solution

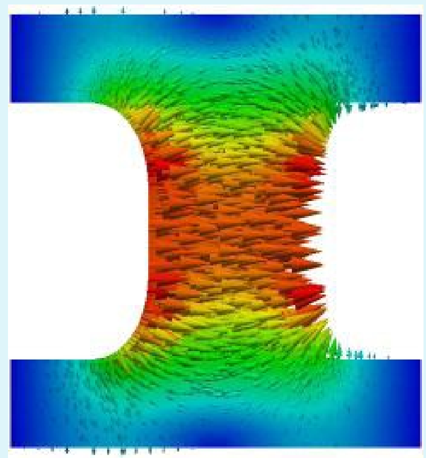
2. Are crab cavities compatible with LHC machine protection, or can they be made to be so ?
   Answer: More analysis with realistic cavity failures, lattices and upgrade collimation required
3. Should a KEKB crab cavity be installed in the SPS for test purposes ?
   Answer: NO

ACTION ITEMS:

1. Refined roadmap to be sketched by CERN-RF at LMC by summer 2011
2. Detailed cavity specifications for both crossing schemes, immediate prototyping essential!
3. SPS test program needs prioritization with detailed experimental program!
4. Other applications of crabs in LHC should be investigated!

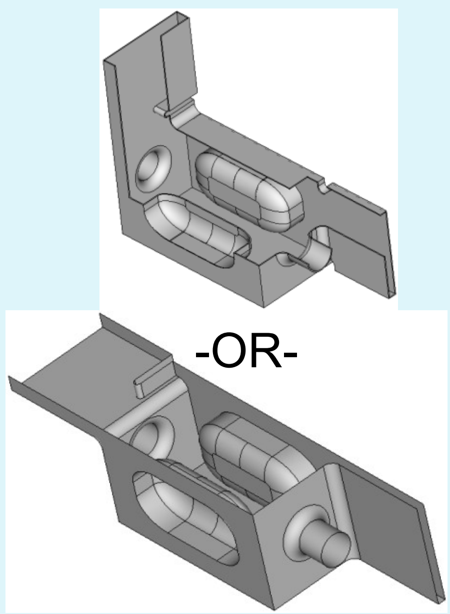
Ridged Waveguide Concept, SLAC

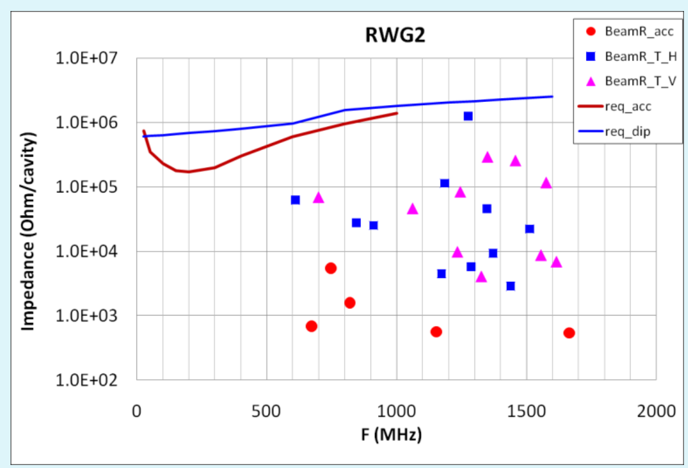




Frequency	400 MHz
Waveguide cutoff	352 MHz
R/Q	300 Ohms
Epeak	45 MV/m
Bpeak	94 mT

Ideas for
HOM Damping





After HiLumi-LHC: Production of CCs

⇒ **A substantial program involving:**

- Completion of specifications for cavity production, couplers, cryostats and other components,
- Launching series production of cavities, couplers and other cavity components,
- Launching series production of cryostats,
- Launching series production of RF and power equipment,
- Successful low power testing of series bare cavities,
- Completion of clean room assembly of series cavities and their ancillaries in their cryostats,
- Successful power testing of the completed series cryomodules in the dedicated test stand,
- Test in SPS of a completed CC cryomodule.

Other systems:

- RF SYSTEM – RF POWER, LLRF
- CRYOGENICS
- CONTROLS