Coupler (FPC & HOM) concepts for compact crab cavities

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2nd revised version including additional information as collected during the workshop

Outline

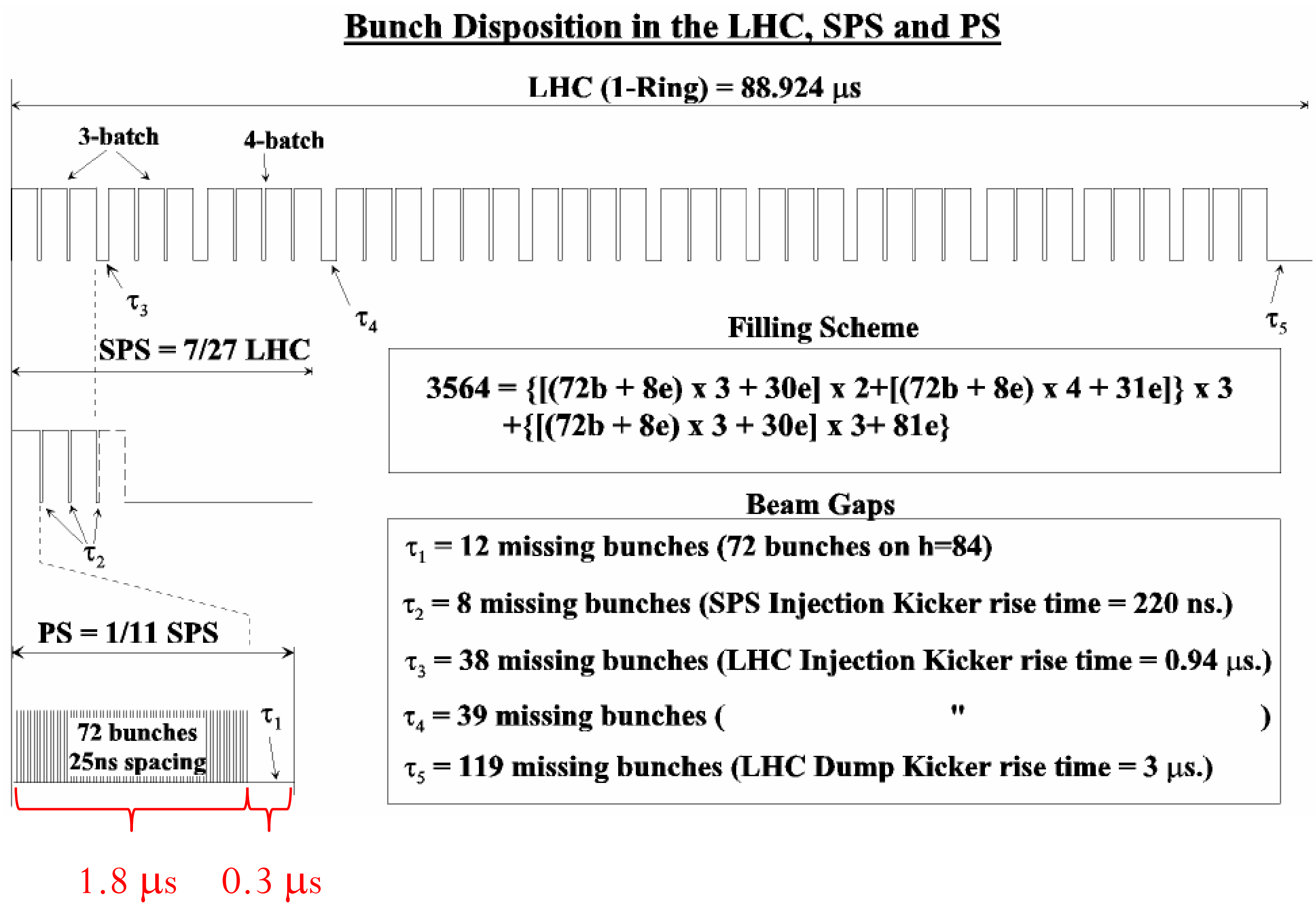
- Spectrum of LHC beam
- Some basic relations [1)]
- Compact crab cavity characteristics
- Coupler/damping, cryogenic and clean work requirements
- Fundamental Power Couplers for Crab Cavities, possible designs [2)]
- Conclusion

1) I owe much of clarification to Joachim Tückmantel: Crab cavities: speed of voltage change, CCinSWG, 27 Nov.2009 (cf. also J. Tückmantel, BE-RF, Cavity-Beam-Transmitter Interaction Formula Collection with Derivation, CERN-ATS-Note-2011-002 TECH, January 24, 2011).

2) The respective slides were provided by Eric Montesinos, whom I gratefully thank.

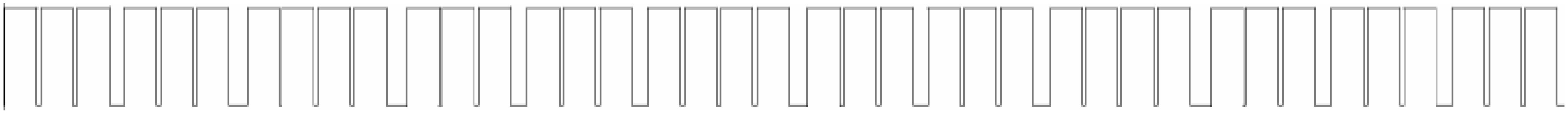
Spectrum of LHC beam 1/2

from LHC design report CERN-2004-003 15 December 2004

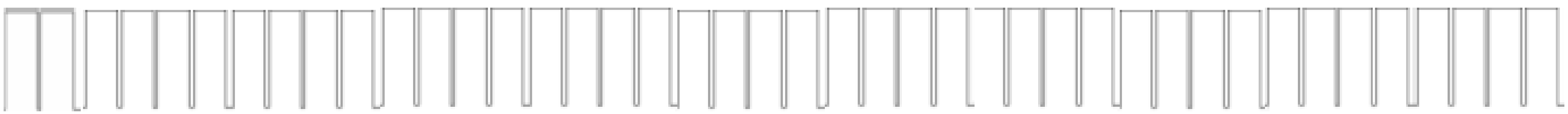


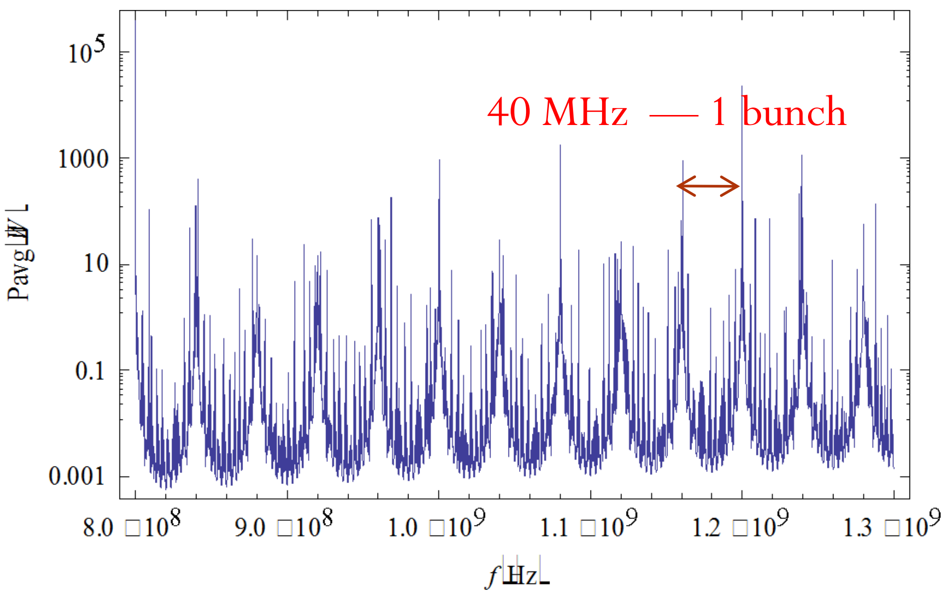
Spectrum of LHC beam 2/2

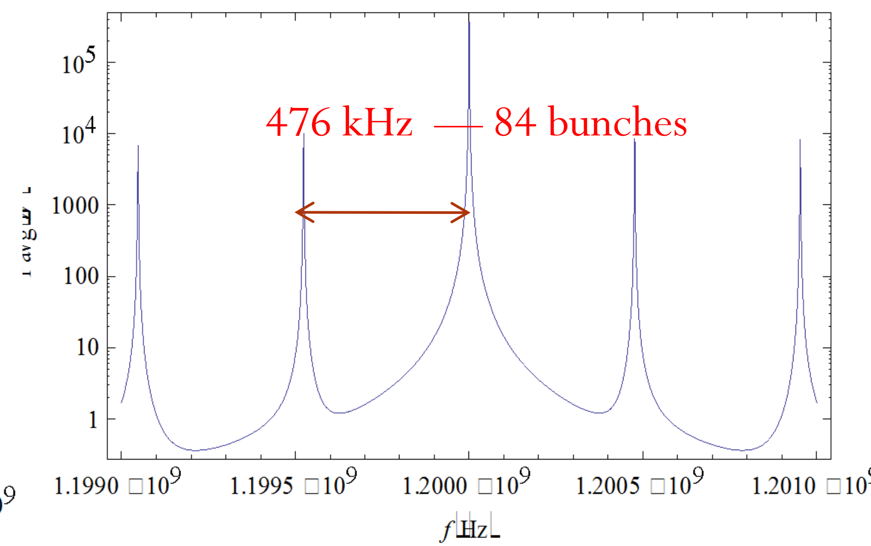
LHC beam approximated by pulsed beam without gaps



replaced by bunch string without gaps (hence preliminary)



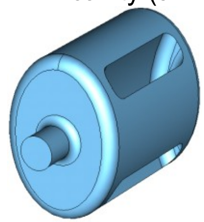
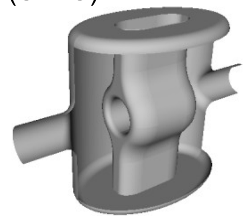
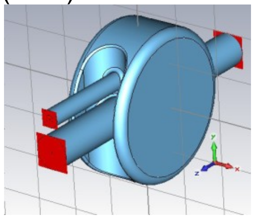




Some basic relations

	Longitudinal	Transversal
Energy-momentum 4-vector	$E^2 - \boldsymbol{p}^2c^2 = m^2c^4 \rightarrow 0 \Rightarrow E = \lvert\boldsymbol{p}\rvert c$	
	$\Delta p_{II} \cdot c = \Delta E_{II} = eV_{II}$	$\Delta p_{\perp} \cdot c = \Delta E_{\perp} = eV_{\perp}$
Panofsky-Wenzel theorem	$V_{II} = -i \cdot \frac{\omega}{c} \cdot V_{\perp} \cdot x$	
Wave propagation	$Q_{ext}^{opt} = \frac{V_{II}}{2 \cdot (R/Q) \cdot I_{b,DC} \cdot f_b \cdot \sin\Phi}$	$Q_{ext}^{opt} = \frac{V_{\perp}}{2 \cdot (R/Q)_{\perp} \cdot x \cdot I_{b,DC} \cdot f_b \cdot \sin\Phi} \cdot \frac{c}{\omega}$
	$P_g = \frac{1}{2} \cdot \left(\frac{R}{Q}\right) \cdot Q_{ext}^{opt} \cdot \lvert I_{g,r}\rvert^2$ $P_r = 0$	$P_g = \frac{1}{2} \cdot (R/Q)_{\perp} \cdot x^2 \cdot \left(\frac{\omega}{c}\right)^2 \cdot Q_{ext}^{opt} \cdot \lvert I_g\rvert^2$ $P_r = 0$
Legend to symbols	P_r: reflected power P_g: generator power f_b: bunch form factor (close to 1) x : maximum beam offset $I_{b,DC}$: DC beam current V: kick-voltage E: energy of beam $\boldsymbol{p}$: momentum of beam	Φ: Phase angle ω: RF frequency of "crab" mode (R/Q): long. or transversal R/Q value $Q_{ext, opt}$: ext. Q-value of "crab" mode that minimizes the reflected power (this is not necessarily the most favourable option!)

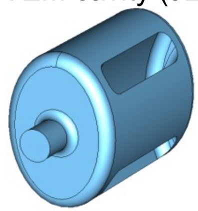
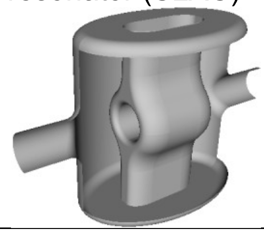
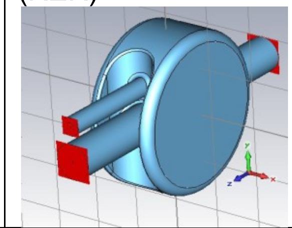
Compact crab cavity characteristics 1/2

	Compact crab cavity candidates under study			
Cavity characteristics **Deflecting mode at 400 MHz** $R/Q = V^2/(2\omega U)$	Parallel bar elliptical TEM cavity (JLAB) 	Half wave spoke resonator (SLAC) 	Four Rod Compact Crab Cavity (Cockcroft) 	Compact crab cavity (KEK) 
Total kick voltage [MV] per beam	10			
Kick voltage [MV] per cavity	5			
Total number of cavities	16 (4 cavities per beam and interaction point)			
Frequency [MHz]	400			
Cavity width/diameter [mm]	295	290	286	150
Cavity height [mm]	406	391.5	236	668
Cavity length [mm]	445	580	408	> 668
Beam pipe Ø [mm]	84	84	84	75
Peak el. field [MV/m]	36	52	62	145 (n/a)
Peak mag. field [mT]	80	97.5	99	250 (n/a, > B_c of Nb)
R/Q_T [Ω] per cavity	131.3	107.5	475	8
Surface resistance @2 / 4.5 K [nΩ][1)]	6/180	8/260	8/260	n/a
Geometry factor [Ω]	108.9	60 (best guess)	70	78
Respective Q-values [10^9]	12/0.4	7/0.2	8/0.3	n/a
Power dissipation [W]	5/160	17/500	3.4/98	n/a

[1)] Derived from a least square fit of a multitude of cavity data: W. Weingarten, On the Field Dependent Surface Resistance Observed in Superconducting Niobium Cavities, Proceedings of SRF2009, Berlin, Germany, TUPPO052.

Compact crab cavity characteristics 2/2

Compact crab cavity candidates under study

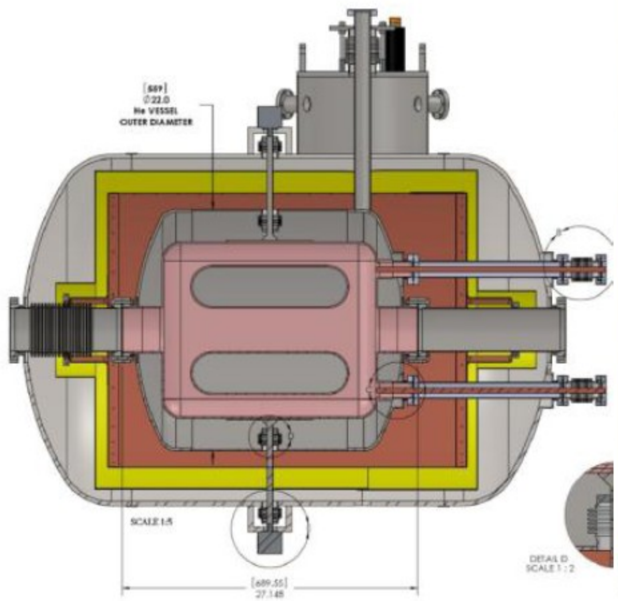
Φ = 90° |x|< 0.5 mm Crab mode at 400 MHz $R/Q = V^2/(2\omega U)$ ("circuit" definition)		Parallel bar elliptical TEM cavity (JLAB) 	Half wave spoke resonator (SLAC) 	Four Rod Compact Crab Cavity (Cockcroft) 	Compact crab cavity (KEK) 
Crab mode	R/Q_T [Ω] per cavity @ f [MHz]	131.3 @ 400	107.5 @ 400	475 @ 400 MHz	8 @ 400 MHz
	Q_{ex}, opt	$6\cdot10^{6}$	$8\cdot10^{6}$	$2\cdot10^{6}$	$1\cdot10^{8}$
	Generator power [kW]	15	15	15	15
Longitudinal mode with largest R/Q	Maximum R/Q [Ω] per cavity @ f [MHz]	~75 @ 680	~90 @ 330	60 @ 375	?
	Max. required Q_{ex} for 10 kW deposited power	200	100	200	?
	Max. required Q_{ex} for 1 MV max voltage build-up	10^{4}	10^{4}	10^{4}	?
	Max. required worst case Q_{ex} for 40 kΩ per cavity[2)]	270	220	330	?
Transverse non-crab mode with largest R/Q_T	Maximum R/Q_T [Ω] per cavity @ f [MHz]	~45 @ 610	~70 @ 880	~40 @ 1050	?
	Max. required Q_{ex} for 0.4 MΩ/m per cavity for 2 identical cavities[2)]	700	310	450	?

[1)]This is not the most prominent but the mode closest to the crab mode, [2)]This number is based on E. Shaposhnikova's talk at LHC-CC10, slide # 19

Coupler/damping, cryogenic and clean work requirements 1/2

- The competition among lower-order modes, same-order modes, and higher-order modes is to a large measure the main technical and engineering issue encountered in crab cavities.
- Fundamental power coupler (FPC)
  - must provide about 15 kW RF power with $Q_{ext} = (2 - 6)\cdot 10^6$ (depending on beam offset)
- HOM/LOM/SOM coupler
  - Must provide Q_{ext} = 100 - 300 for specific modes without affecting the crab mode.
  - Consequence: cavity with large beam tube to guarantee leaking out of all modes seems to be most adequate but at the cost of an effective filter to block the crab mode (an exception is the JLAB cavity)
- Cryogenic needs
  - The dynamic heat load at 2/4.5 K is in the range of 10/100 and even more Watts.
- Clean work
  - The required electromagnetic fields correspond to an equivalent of 25 - 31 MV/m in conventional acc. cavities; hence a crab cavity study can largely profit from the planned upgrade in CERN's SM18 treatment and assembling facilities

Parallel bar TEM cavity (JLAB)



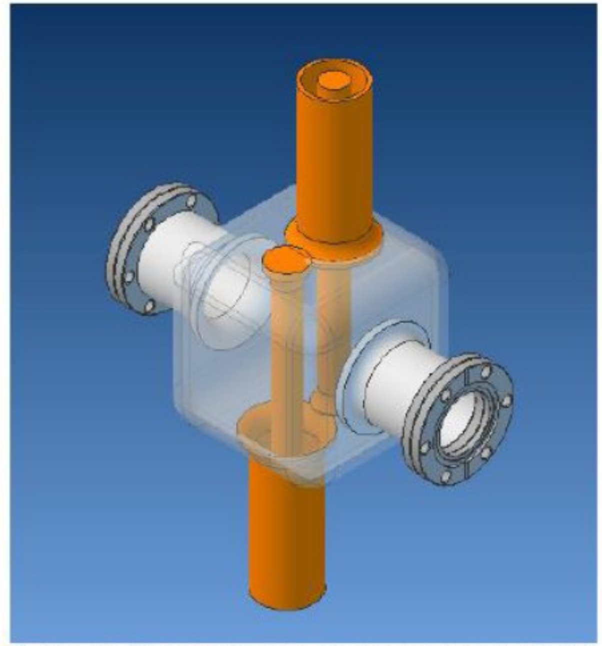
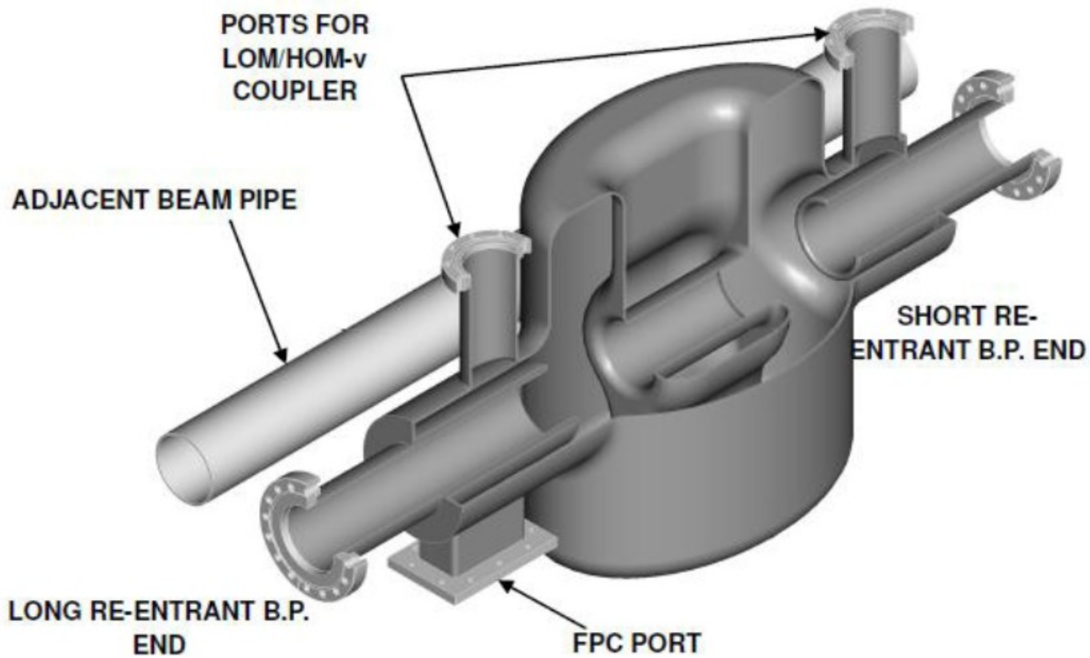


Figure 1: Conceptual view of two-bar structure with coaxial RF input

FPC: coaxial and variable, mind idea of Neubauer et al., IPAC'10

LOM/HOM coupler: coaxial and variable, achieved Q_{ex} not known to me; no LOM mode existing, acc. mode (SOM) 12 MHz above crab mode → **well advanced and robust design**

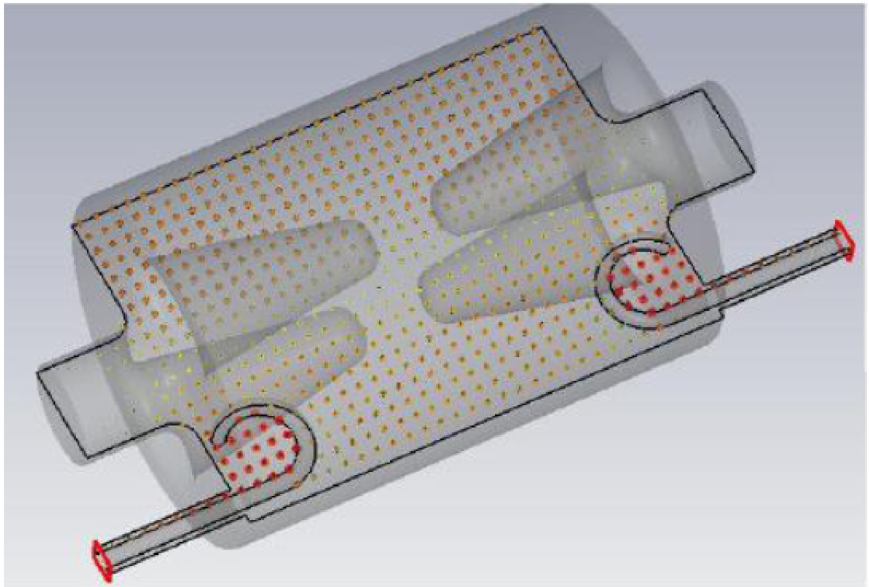
Half wave spoke resonator (SLAC)

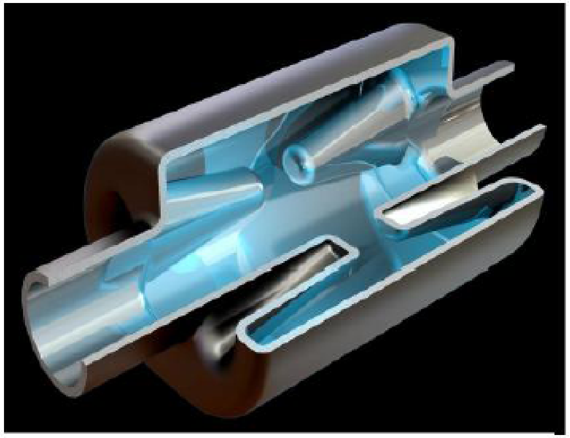


FPC: waveguide coupler

LOM/HOM coupler: coaxial on beam tube with notch filter to reject crab mode, achieved $Q_{ex} < 4\cdot10^4$ for long. modes, no SOM, LOM 65 MHz below deflecting mode; multipacting analysis underway →**well advanced and robust design**

Four Rod Compact Crab Cavity (Cockcroft)





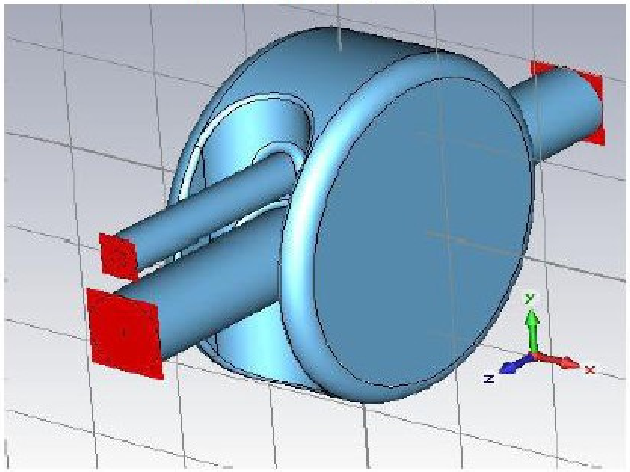
FPC: on cell waveguide coupler

LOM/HOM coupler: on cell waveguide coupler, achieved Q_{ex} ~ 100; on cell coaxial loop couplers under study, meet requirement Q_{ex} ~ 70

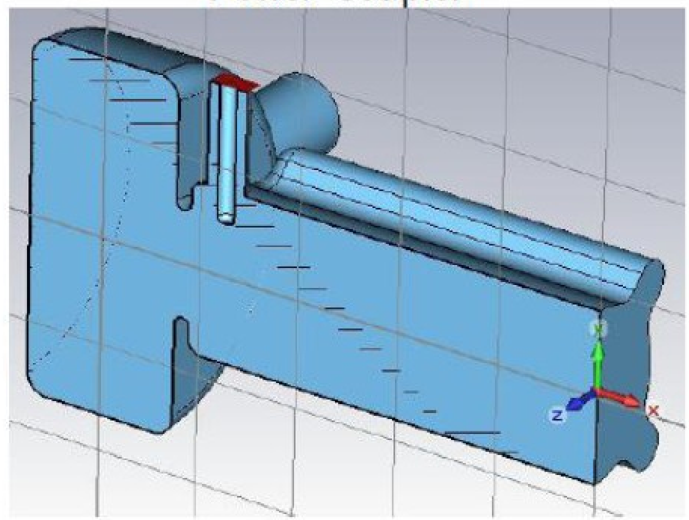
→ promising ongoing design

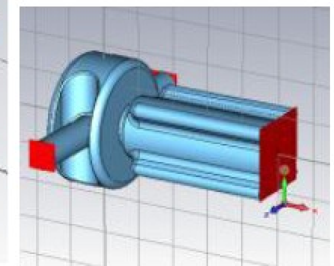
Compact crab cavity (KEK)

HOM Damping



Power Coupler





FPC: coaxial, $Q_{ex} \sim 10^5 - 10^6$

LOM/HOM coupler: alternative damping schemes: “fluted” beam tube, $Q_{ex} > 150$, or coaxial, $Q_{ex} > 1480$, crab mode is lowest mode → **promising ongoing design, but RF field too large (beyond the critical field of Nb) for the specific requirements of LHC**

Conclusion

- The compact crab cavity for the LHC is challenging in obtaining the large electromagnetic fields (31 MV/m equivalent to acc. cavity) - an additional argument in favor of the planned refurbishment of the SRF infrastructure in SM18.
- The competition among lower-order modes, same-order modes, and higher-order modes is to a large measure the main technical and engineering issue encountered in crab cavities;

  The damping studies for LOM,SOM and HOM must go on.
- The fundamental power is low (tens of kW depending on tolerated beam offset).
- There exist several well advanced and robust designs.

Fundamental Power Couplers for Crab Cavities

- Depending on the cavity design and available space around the cavity, several solutions can be considered

- We recently launched at CERN several Fundamental Power Couplers developments which cover various window types:

  - SPL coaxial disk window coupler

  - SPL/ESRF/SOLEIL/APS coaxial cylindrical window coupler

  - Linac 4 waveguide disk window coupler

f_0	400 MHz
Average Power	15 kW
Q_{ext} of input coupler	Fixed
Coolant	Air cooled

- Even if designing a new Fundamental Power Coupler will never be an easy job, we can try to design a new coupler to meet the proposed parameters and fit any cavity design

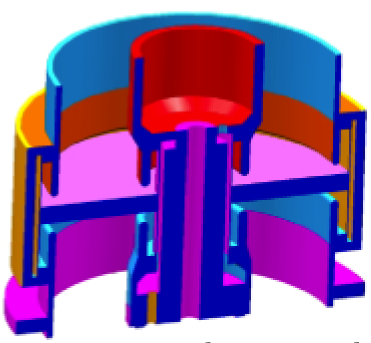
Thank you for your attention

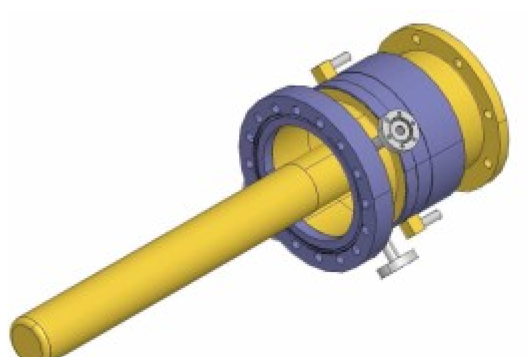
Men do not stumble over mountains, but over mole hills
- Confucius -

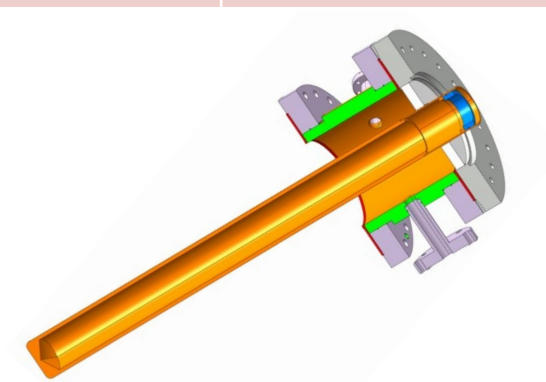
Spare slides

Coaxial Disk windows

Coupler	Frequency [MHz]	Average Power [kW]	Peak power [kW]	# in operation or constructed
SPS	200	550	800	16
KEKB	509	300	1420	8
CEA-HIPPI	704	120	1200	2
IHEP	500	150	270	2
JPARK	972	30	2200	23
SNS	805	78	2000	93
SPL	704	100	1000	Prototyping ongoing

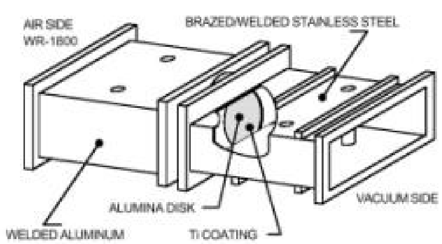


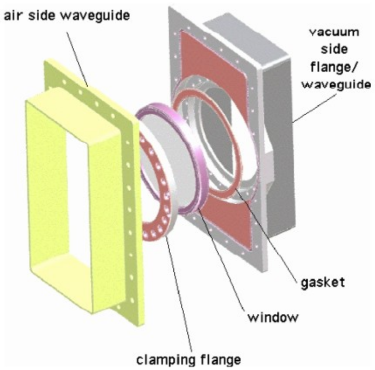


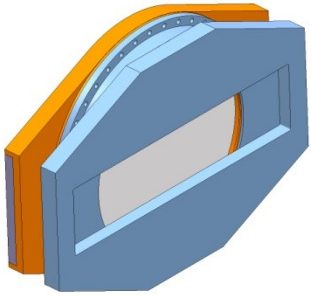


Waveguide windows

Coupler	Frequency [MHz]	Average Power [kW]	Peak power [kW]	# in operation or constructed
SPS	801	225	225 (more ?)	8
Cornell	500	350	350	4
FNAL / TTF II	1300	4.5	1000	32
LBNL	700	800	800	4
Linac 4	352	140	1400	Prototyping ongoing

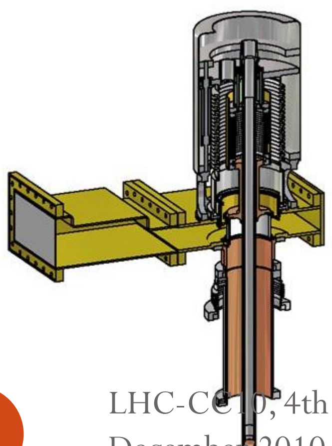


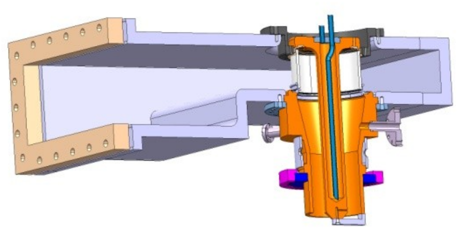


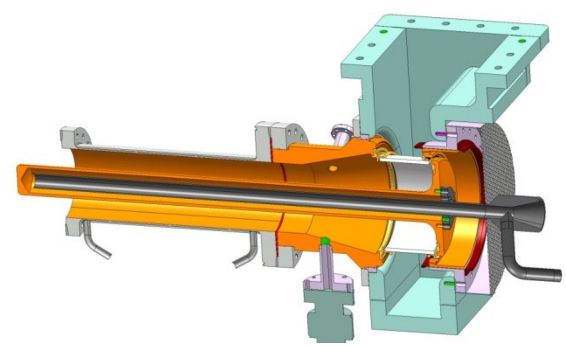


One cylindrical window

Coupler	Frequency [MHz]	Average Power [kW]	Peak power [kW]	# in operation or constructed
LHC	400	550 sw cw, (i.e 2200 tw cw)	i.e. 2200 tw cw	16
LEP	352	550 tw cw	565 tw cw	252
SPS (1976-2000)	200	375	500	16
SPL	704	100	1000	Prototyping ongoing
ESRF / Soleil / APS	352	500	1000	Prototyping ongoing

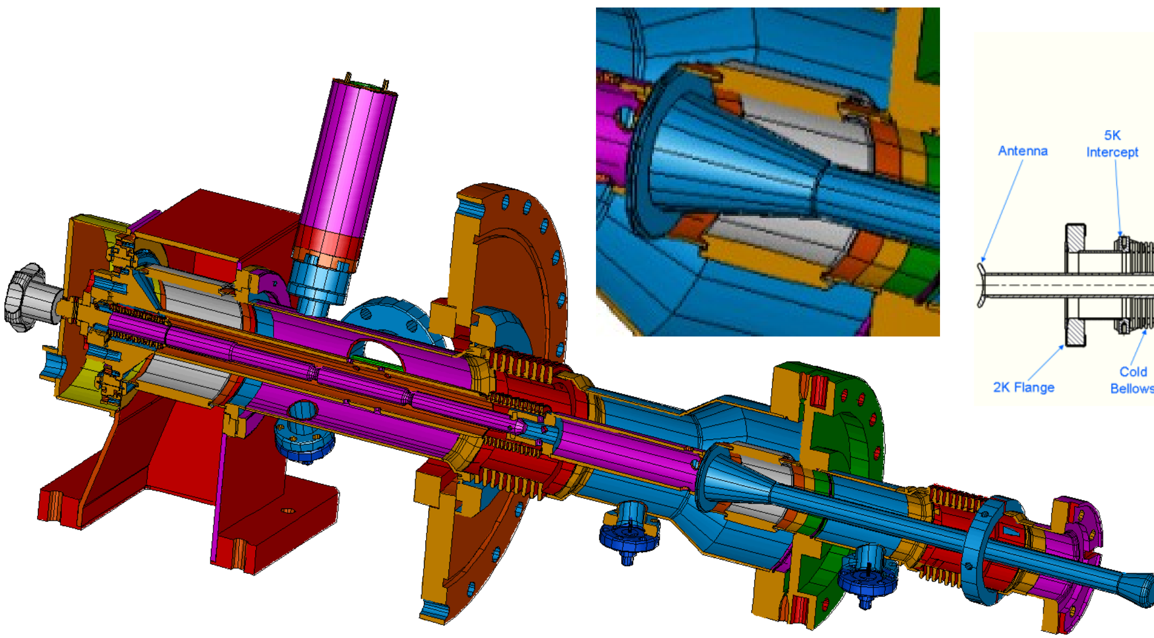


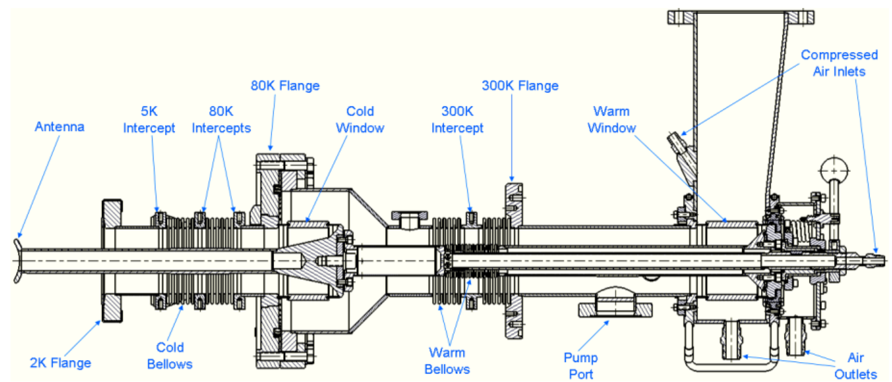




Two cylindrical windows

Coupler	Frequency [MHz]	Average Power [kW]	Peak power [kW]	# in operation or constructed
TTF family - XFEL	1300	4.5	1100	16 (+ 1064)
Cornell ERL	1300	75	75	2





Cold window (beam vacuum / coupler vacuum) is difficult to cool down enough for high average power coupler

Engineering points for Fundamental Power Couplers

- RF power capability
  - Minimize heat load
  - Gas coolant (air preferably) is preferred to liquid coolant to ease beam vacuum leak detection in case of failure
- Ceramic design:
  - The critical item of a power coupler is the main ceramic.
  - The coupler robustness mainly depends on the ceramic design
  - Single ceramic room temperature window couplers have proven to be reliable
  - Brazing and EB welding needed
- Coupler design:
  - Modeling
  - Ceramic location in E-field minimum
  - Prototyping
  - Matching and VSWR
  - Bandwidth
  - Q_{ext}, tuning
  - Multipacting simulation
  - Monitoring (vacuum, e- probe, arc detector)
- Coatings:
  - Plating or/and sputtering
  - Multipacting suppression (Ti, TiN)

Engineering points for Fundamental Power Couplers

- Mechanical:
  - Clean room cleaning and assembly to guarantee high field
  - High pressure rinsing
  - Contamination during beam vacuum part assembly
  - Easy installation
  - Integration with the cryomodule

- Easy operation
  - Maintenance (air blowers, water pumps)
  - Failure consequences
  - Repair
  - Spares

- RF Conditioning
  - Vacuum bakeout
  - High vacuum pumping for shorter processes
  - Short pulses up to full power, with pulse length increased to cw with vacuum feedback conditioning method
  - DC biasing
  - Temperature sensors
  - Room temperature testing
  - High power tests benches available from the beginning

- **Cost**

Long tradition at CERN

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THE KARLSRUHE – CERN SUPERCONDUCTING RF SEPARATOR

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