LHC Beam-Beam Compensator

Status and Prototype Specification

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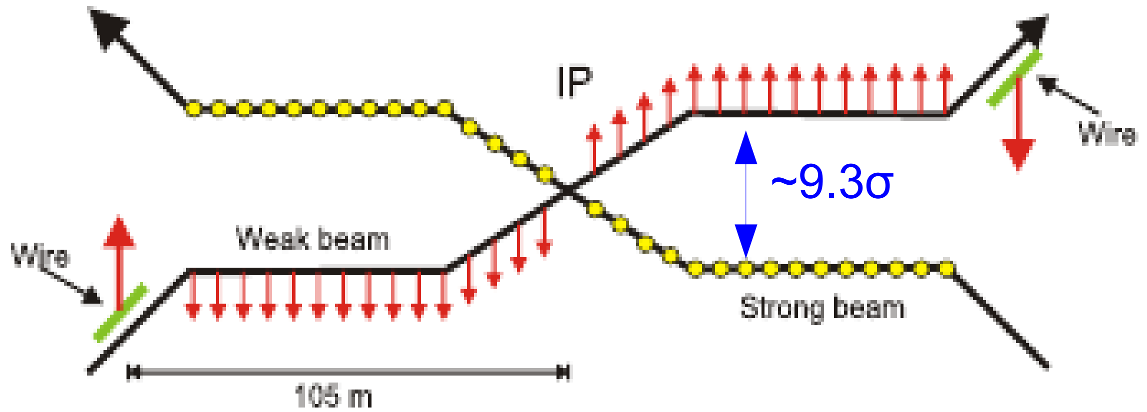
for and with input from:
O. Aberle, R. Assmann (Collimation), A. Bertarelli, A. Dallocchio,
S. Fartoukh, R. Jones, J.-P. Koutchouk, F. Bertinelli, D. Perini,
A. Ravni, T. Rijoff, S. Redaelli (Collimation), R. Veness,
J. Wenninger (MPP), F. Zimmermann (ABP lead), M. Zerlauth

Motivation for Installing a BBC Prototype in the LHC I/II - Passed several Milestones

- Initial proposal based on to J.-P. Koutchouk's note: CERN-SL-2001-048-BI



- Since, SPS wire-wire and RHIC beam-wire experiments demonstrated that:
  (for details → F. Zimmermann, e.g. Chamonix' 11 & http://http://cern-ab-bblr.web.cern.ch/)
  1. *"detrimental wire effect on life-time can be compensated by another wire"*
  2. *Benchmark of numerical tool chain → indication of what to expect at LHC*
  - What could be tested at the SPS and RHIC has been tested,
  - *Still,* no direct/consistent demonstration of beneficial effect on life-times

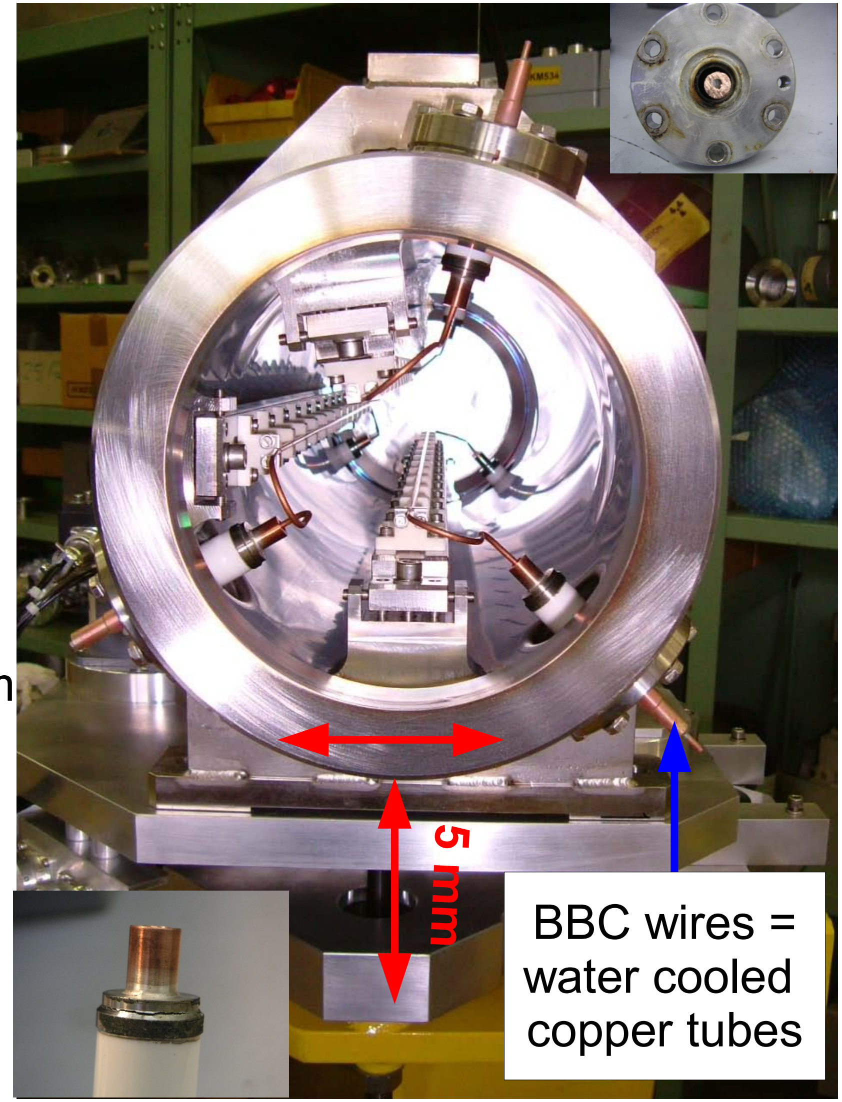
- Further tests require a true long-range beam-beam limited machine...
  → proof-of-principle requires BBC prototype into machine before HL-LHC
- Endorsed by Chamonix'11 (Session8) and LMC (meeting #82)
  "Launch a project for the LRBB compensating wire in present LHC..."

Initial LHC Beam-Beam Compensator Plans

- SPS and donated RHIC design are incompatible for installation in LHC:

- Diff. aperture, beam pipe, mechanics, ...
- Wire needs to be in between beams
- Free-standing wire & RF resonances
  ↔ classic λ/n-antenna (impedance issues)
  - 50 Ohm match not practical (power)
  - Non-trivial RF-Bias-T (power)
- Not robust w.r.t. beam impact
- Moveable tank bears the inherent risk of breaking and of bursting of:
  - bellows ↔ req. movement of > 10 mm

- bursting/water leaks inside the vacuum chamber ie. in response to impact of nominal bunch, n-flux fatigue or 1kW of inherent heat
  → A. Bertarelli's Chamonix'11 talk



→ too big impact on LHC operation in case of failure.

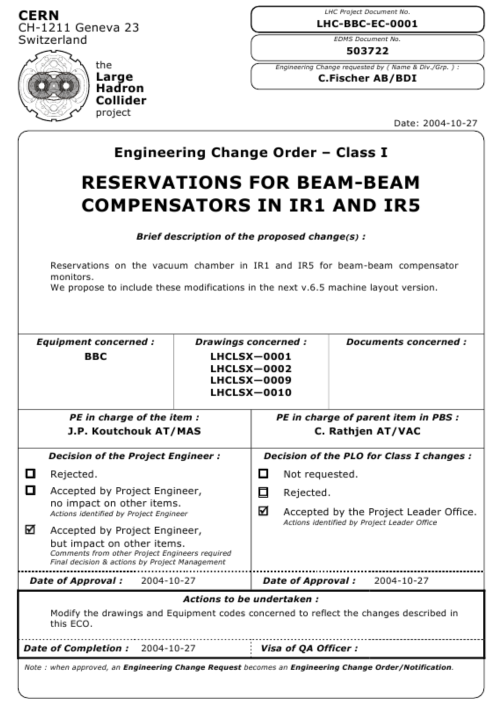
Constraints on proposed LHC BBC Prototype

- LHC-BBC scheme (→ ABP, F. Zimmermann et al.)
  - provide a adequate test-bed to experimentally assess its potential performance for present and future HL-LHC upgrade scenarios
- LHC Machine Protection (discussed/agree with MPP)
  - should either cope with asynchronous beam-dump scenario or not deteriorate machine performance after such an event
- LHC Beam Cleaning (Collimation WG, R. Assmann, S. Redaelli et al.)
  - preserve/provide the same function as present collimator hierarchy
- Practical considerations, 'KISS' – Keep the Impact Simple and Safe:
  - feasibility from an engineering point of view
  - Should not deteriorate present machine performance (e.g. impedance..)
  - required instrumentation to setup, assess and verify its performance

LHC Beam-Beam Compensators Specification I/III

- Reservations around IR1&IR5, LHC-BBC-EC-0001:

	name	Position and longitudinal dimensions
IR1	BBC.4L1	-104.931 m ± 1.5m wrt IP1
	BBC.4R1	104.931 m ± 1.5m wrt IP1
IR5	BBC.4L5	-104.931 m ± 1.5m wrt IP5
	BBC.4R5	104.931 m ± 1.5m wrt IP5


CERN
CH-1211 Geneva 23
Switzerland

the Large Hadron Collider project

LHC Project Document No. LHC-BBC-EC-0001

EDMS Document No. 503722

Engineering Change requested by (Name & Div./Grp.): C.Fischer AB/BDI

Date: 2004-10-27

Engineering Change Order – Class I

RESERVATIONS FOR BEAM-BEAM COMPENSATORS IN IR1 AND IR5

Brief description of the proposed change(s):

Reservations on the vacuum chamber in IR1 and IR5 for beam-beam compensator monitors.
We propose to include these modifications in the next v.6.5 machine layout version.

Equipment concerned:	Drawings concerned:	Documents concerned:
BBC	LHCLSX–0001 LHCLSX–0002 LHCLSX–0009 LHCLSX–0010	

PE in charge of the item: J.P. Koutchouk AT/MAS	PE in charge of parent item in PBS: C. Rathjen AT/VAC
Decision of the Project Engineer: ☐ Rejected. ☐ Accepted by Project Engineer, no impact on other items. *Actions identified by Project Engineer* ☑ Accepted by Project Engineer, but impact on other items. *Comments from other Project Engineers required. Final decision & actions by Project Management*	Decision of the PLO for Class I changes: ☐ Not requested. ☐ Rejected. ☑ Accepted by the Project Leader Office. *Actions identified by Project Leader Office*
Date of Approval: 2004-10-27	Date of Approval: 2004-10-27

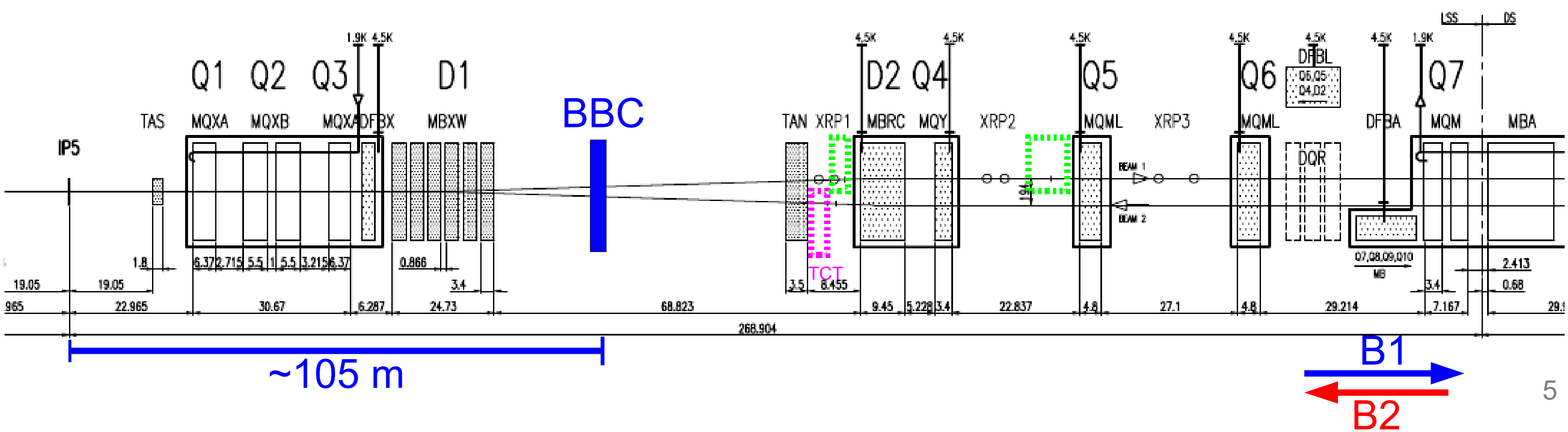
Actions to be undertaken:

Modify the drawings and Equipment codes concerned to reflect the changes described in this ECO.

Date of Completion: 2004-10-27 | Visa of QA Officer:

Note: when approved, an **Engineering Change Request** becomes an **Engineering Change Order/Notification**.

- Min. LRBB → BBC phase advance: $\Delta\mu \approx 2.6°$ (→ 3.1°)
- Symmetric beta-function: $\beta_{x/y} \approx 1000$ m (for $\beta^* = 0.55$ m)
- N.B. single vacuum pipe for B1 & B2:
  110 mm full beam separation (only D1 only)
  (→ 165 mm, if shifted more towards TAN)



Physical Space IR5 Requires Horizontal BBC

reserved location IP → 105 m

TCT and roman pots

Between Q4 and Q5

LHC Beam-Beam Compensators Specification II/III

- Initially 2 BBC per beam/IP planned → H-V pair for one beam only, based on H-V crossing scheme, settled with:
  - 1 x BBC-H.B1 in IR5, and
  - 1 x BBC-V.B1 in IR1
- Wire parameters:
  - Solid wire radius of ~ 1mm → 1kW power dissipation
    - Wire diameter is a trade-off between available aperture and cooling
  - sub-σ level of hor./ver. position control
  - Nominal scheme: $I = I_{peak} \cdot \sqrt{2\pi} \cdot \sigma_s \cdot n_{parasitic}$ = 72 … 350 Am (max.)
  - Pulsed wire to accommodate differences for PACMAN bunches
    → not practical at this stage, stick to DC compensation only
- Further, aim to reuse as much of established infra-structure as possible to aid/simplify controls integration into an operational LHC environment:
  - Collimator type girders, motor control and to embed the wire into jaws
  - standard e.g. LHC-type 600 A power converter (OK w.r.t. ripple requirement)
  - Integration of buttons as done for the TCT to aid the wire re-alignment

Making the BBC compatible with LHC Machine Protection

- Wire-beam distance: average LR beam-beam separation of 9.7 σ
  → implies a-priori similar nominal BBC position
  - closer than present and possibly future TCT settings
  - critical w.r.t. asynch. dump failure mode, in particular for B2 in IP5

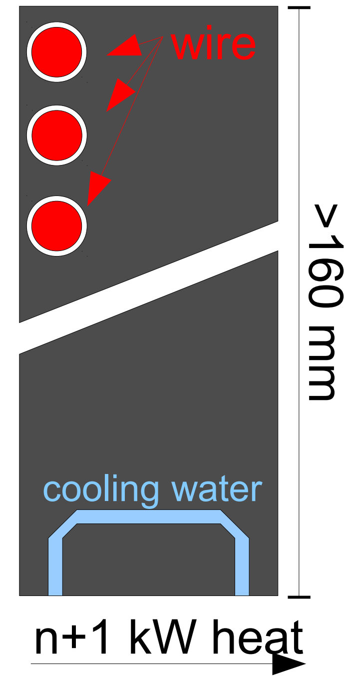
- Not without issues → validated this with MPP (Meeting #48, 2011-08-05)
  - Somewhat relaxed constraints: BBC prototype targeted to be an MD tool → special run conditions, reduced intensity and time which mitigates probability of e.g. asynchronous dump failure impacting the wire (failure rather impacts device rather than machine availability)
  - Conclusion: LHC BBC Prototype will need to be …

    A)… either operated in the shadow of the TCTs (e.g. 11 σ), or

    B)… provide a similar combined function as the TCTs (e.g. 9.7 σ)
    → so far positive feedback from Collimation WG (Ralph, Stefano et al.) provided the same reliability requirements as the TCTs are met

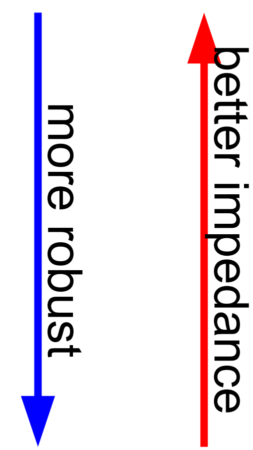
Combined Wire-In-Jaw Design

- Using collimator-type design 'kills several birds with one shot':
  1. provides necessary mechanical stability (N.B. 1 m long wire)
  2. easy wire position control, integration and exchange option
  3. intrinsic heat sink, conducting thermal losses far away to where these can be safely coupled out of the tank
  4. Experience w.r.t. integration BPM buttons, etc.
  5. Depending on jaw-material choice, shielding of RF beam IC to reduce impedance and potential wire resonances
     - Min. insulation + copper surface (skin depth): 0.3 mm tbc.)

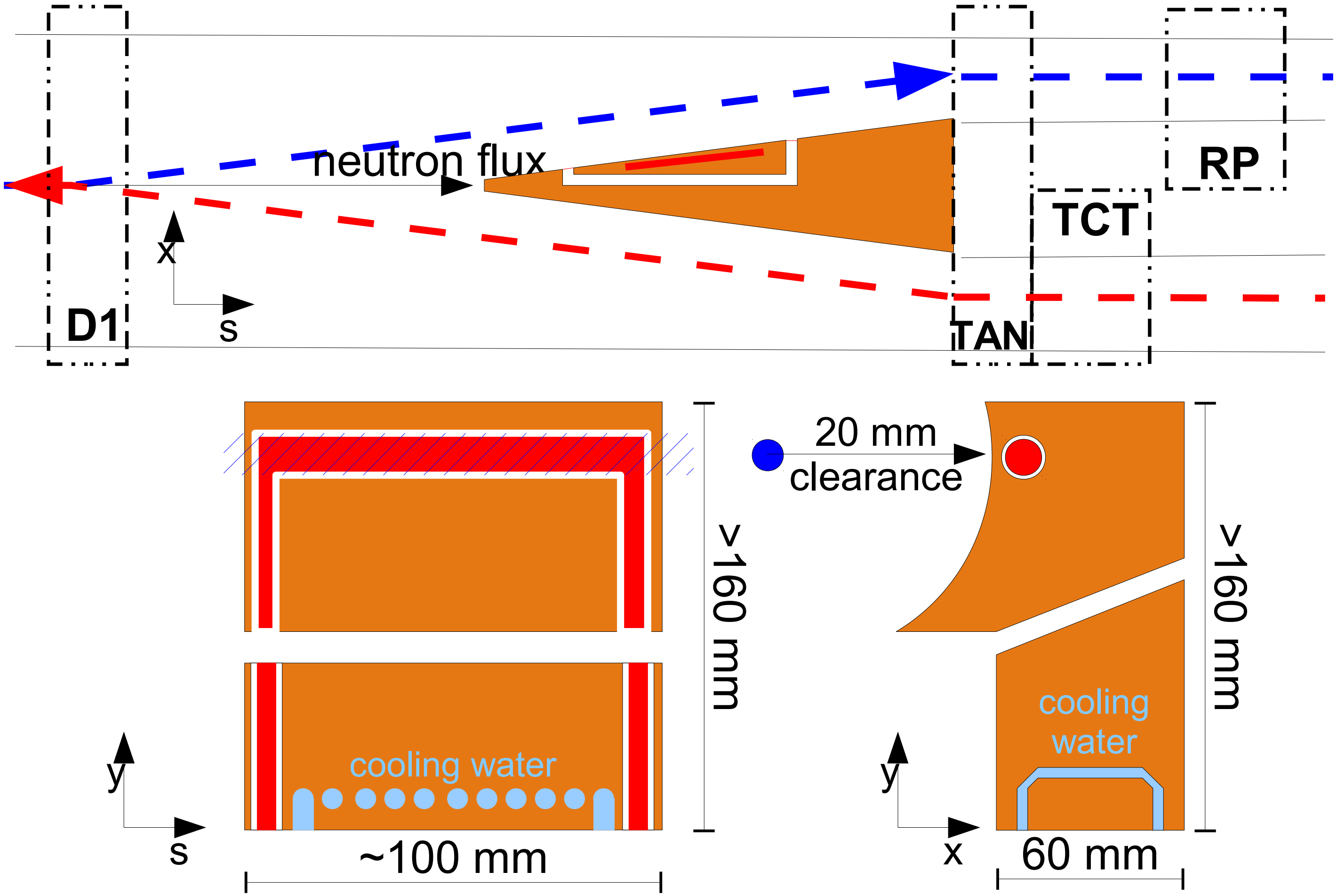


- However, a true 'TCT' like functionality implies some constraints on material choice and trade-off w.r.t. robustness vs. cooling vs. Impedance

	Th. Cond.	El. Cond.	δ@40 MHz	δ@1 GHz
	[W m^{-1} K^{-1}]	[Ω m]	[μm]	[μm]
Copper	401	$1.7\cdot10^{-8}$	~10	~2
Tungsten	173	$5.6\cdot10^{-8}$	~10	~2
SiC*	360 - 490	$8.3\cdot10^{-3}$ - 3	~mm	~mm
Carbon		$3\cdot10^{-6}$ … $8\cdot10^{-4}$		
Diamond	900...2320...41k	$\sim10^{12}$		



Proposed LHC Beam-Beam Compensators Prototypes I/III – Option I (nominal 'white paper'): between D1 ↔ TAN

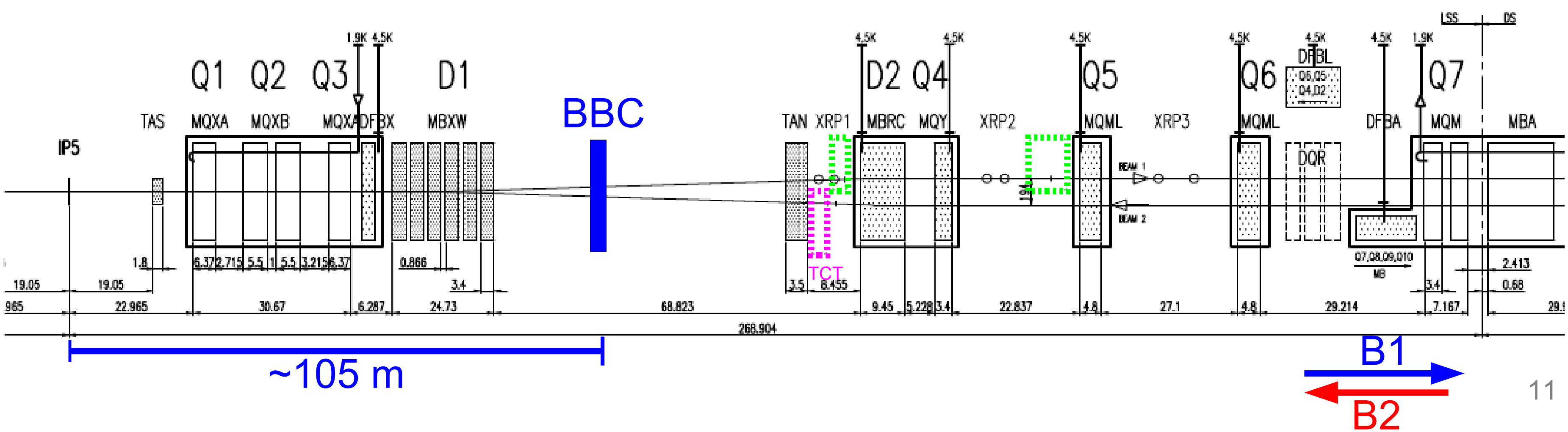


- Non-neglible *n*-flux, impedance and TAN aspects need detailed simulations
- Materials choices: Cu, W, Carbon, SiC (doping issues?), (CVD) Diamond
- Major design and qualification effort, unlikely to be ready before LS1!

Proposed LHC Beam-Beam Compensators Prototypes II/III – Option I (nominal 'white paper'): between D1 ↔ TAN

- The ideal/reserved BBC location is more challenging
  - Physical margin of 110 mm & $\beta_{x/y} \approx$ 1000 m (for β^*= 0.55 m), depends highly on planned HL-LHC scenario, cons./safe assumption: $\sigma \approx$ 0.7 … 1 mm for nominal optic, ε=3.6 μm and 7TeV → 3.5 TeV
    - would gain for larger β^* and/or smaller ε, e.g. 2 μm

- Assuming that we require a minimum physical 20 sigma clearance (x2) for the BBC in the parking position → leaves only about 70 mm for BBC

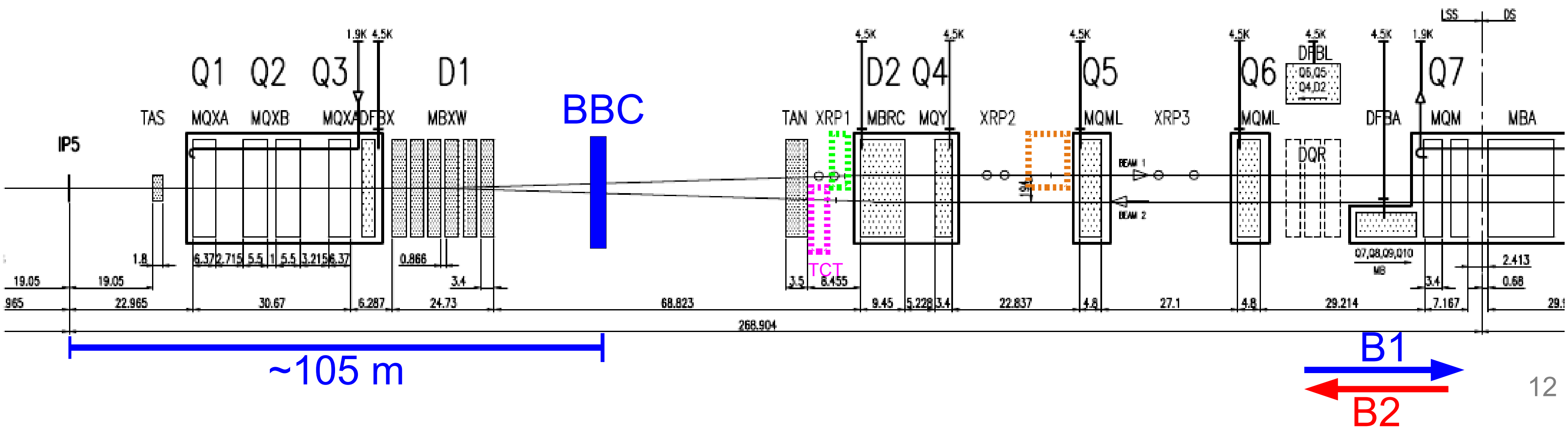


Proposed LHC Beam-Beam Compensators Prototypes III/III – Option II TCT-like BBC

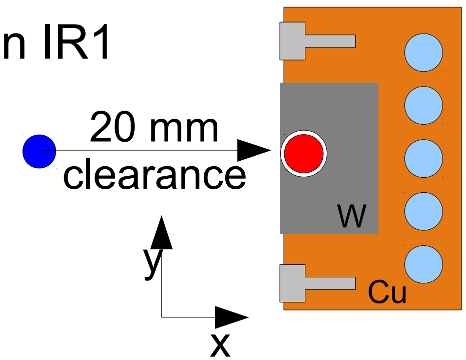
- Alternate options implying an easier integration and potential LS1 installation
  - B) Combined TCT-BBC at the present TCT locations
    - some constraints on material
  - C) Replacing roman pots (BBC targets HL-LHC)
  - D) ~~Between Q4 & Q5 → not possible from physics pov~~

  Addressed by Tatiana's talk

- Advantage could re-use even the same vacuum tank design as TCTs
  - Possible integration in LS1, final installation during shorter TS afterwards
  - beside n-flux, other aperture and MP issues remain the same
  - Need some early indication to prepare machine for additional vacuum valves, BPM and control cables, water, power cables, etc.



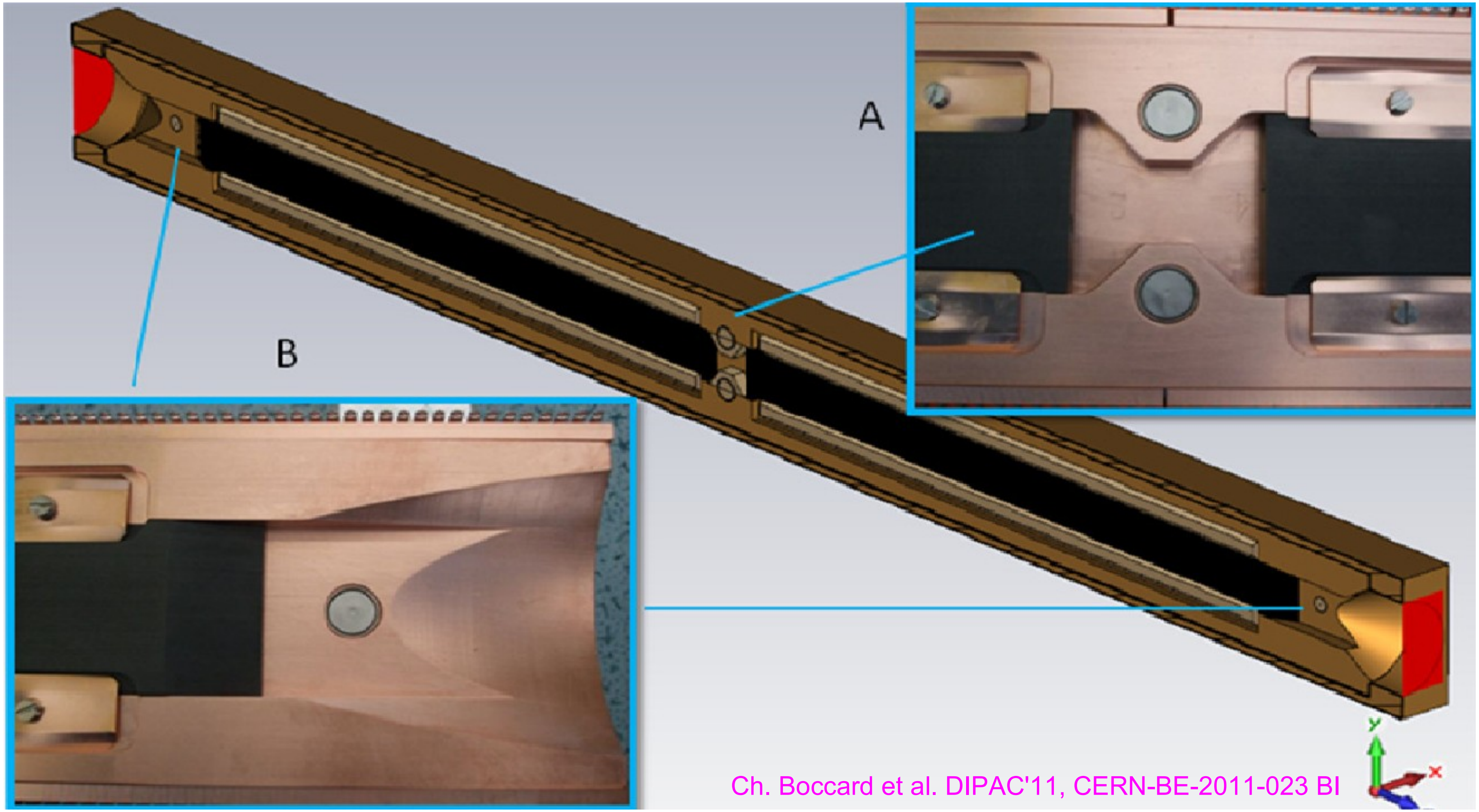
Summary of LHC BBC Prototype Specifications



- Initially two units: 1 x BBC-H.B1 in IR5, and 1 x BBC-V.B1 in IR1
  - same location as present TCTs
- Reuse as much of established infra-structure as possible (collimator type girders/motor control, LHC-type 600 A PC)
- Wire-in-jaw design:
  - Embedded (insulated) Cu wire inside W block
  - Possibility of 1+n wires (spare/redundancy)?
  - 100 um between wire and active cleaning surface (RF screening)
- Wire parameters:
  - Solid (round) wire radius of ~ 1mm and 1 m length
  - sub-σ level of hor./ver. position control (e.g. 0.1 mm)
  - nom. scheme: $I \cdot l_{wire} = I_{peak} \cdot \sqrt{2\pi} \cdot \sigma_s \cdot n_{parasitic} \cdot l_{wire}$ = 72 … 350 Am (max.)
  - DC compensation only
  - cooled via passive heat transfer (1 kW)
- Additional beam instrumentation
  - BPM 2x2 buttons (for wire re-alignment, tbd.)
  - Additional (fast) BLMs, bunch-by-bunch orbit and Q diagnostics (tbd.)

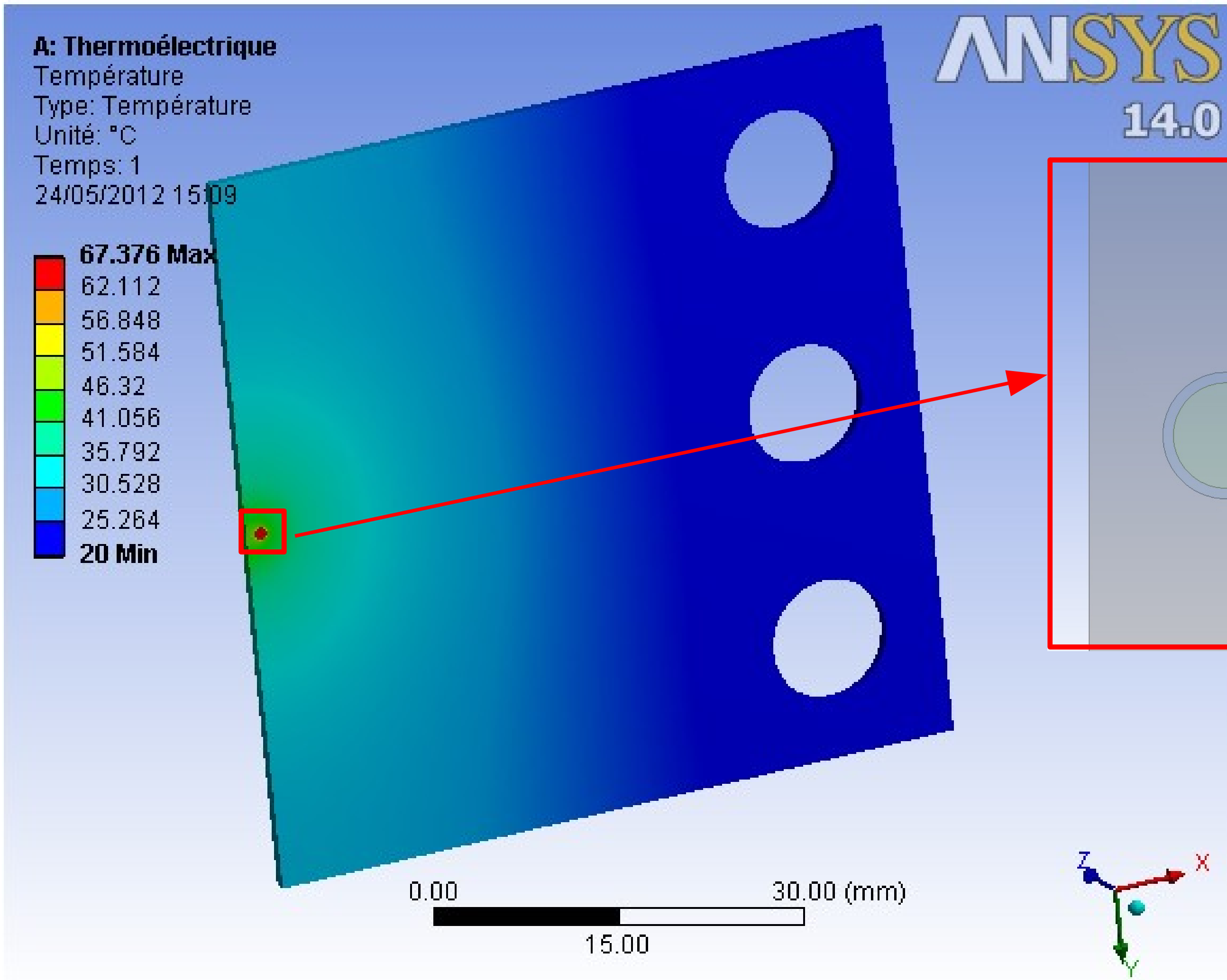
Example: SPS Prototype Design

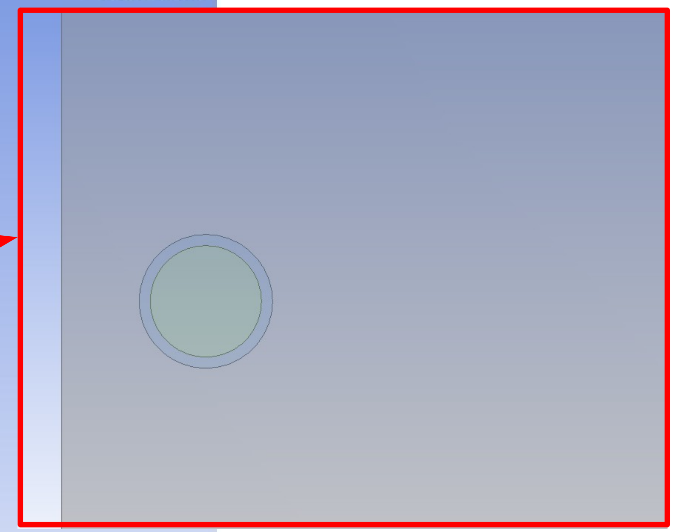
- Design functionally tested w.r.t. BPM response, integration etc.



- Main required modifications: wire-in-jaw, larger buttons → cable/water routing

Preliminary Ansys Results (Axel Ravni, BI-ML) I/II





350 A through
Cu wire Ø=1mm
0.1mm Ceramic Insul.
Tungsten block
Cooling@20°C

Finite-Element and analytic estimates agree for given (perfect) conditions
to be further studied → more specific model and lab-mock-up test

Work Items:

- Mechanical re-design of TCT wire-in-jaw design
- Mechanical feasibility, material and vacuum compatibility tests
  - mechanical and electrical constraints, vacuum compatibility
    → lab mock-up test to validate design (Axel Ravni, BI-ML)
- Impact on machine impedance and pick-up response
- Preparation of technical infrastructure in LS1 (mainly cables, EPC crates)
  → need a decision soon to proceed
- Beam cleaning and robustness simulations (FLUKA)
- Add. R&D and beam instrumentation
- BBC prototype construction
- Pre-installation prototyping and HW integration tests (Lab-cycling)
- Controls integration
- Future R&D and miscellaneous

Preliminary Cost Estimates and Planning - DRAFT

item	LHC Long-Range Beam-Beam Compensator Planning				DRAFT – TO BE DISCUSSED
item	Description	FTE	Costs [kCHF]	Time [y]	Comments/Resources last updated: 2011-10-25, rstein
1	Re-design and re-validation of TCT wire-in-jaw design	0.2	99	1	EN-MME
2	Feasibility, material and vacuum compatibility tests	1.0	412	1	EN-MME, BE-BI-ML (fellow)
3	Evaluation of pick-up response and impact on machine impedance	1.5	0	0	BE-BI-QP, BE-ABP-ICE
	Impact on beam cleaning and robustness studies (FLUKA)				EN-STI?
4	Preparation of technical infrastructure in LS1	0.2	75	0	
5	Additional R&D and beam instrumentation	2.0	120	0	BE-BI
6	BBC prototype construction	0.1	396	1.5	EN-STI, 1 + 2 prototypes, tbc. (O. Aberle)
7	Pre-Installation and HW Integration Tests	0.1	20	0.5	EN-STI, BE-BI
8	Controls integration	1.0			BE-CO?
9	Final installation of TCT with wire-in-jaw design		20	0.1	
10	Future R&D and physics potential evaluation	1.0			ABP-LCU
11	Final operational design, deployment and coordination				
	Total:	**7.1**	**1142**	**2.6**	no contingency/delays included (e.g. SPS prototype)
	Costs for 2012:		247		
	Costs for 2013:		734.736	(approx)	
	primary item				
	conditional activity, can only proceed if primary item is achieved				
	parallel activity				

	2011		2012				2013				2014				2015			
Working Package	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Constraints							LS1										Winter TS	
Mechanics & Design			1: TCT wire-in-jaw Design					6: Prototype				6: LHC BBC Construction					9: final inst.	
Feasibility (material and vacuum)				2: Cooling/Insulation						Integration/Reliability Test								
Pre-Inst. and HW Integration Tests						BBC Technical Infrastructure												
Validation and Re-iterations				3: BI,Imped., FLUKA					Controls Integration									
R&D tbd.																		

Reserve slides