LHC Beam-Beam Compensator

– Status Update –

Ralph J. Steinhagen, CERN

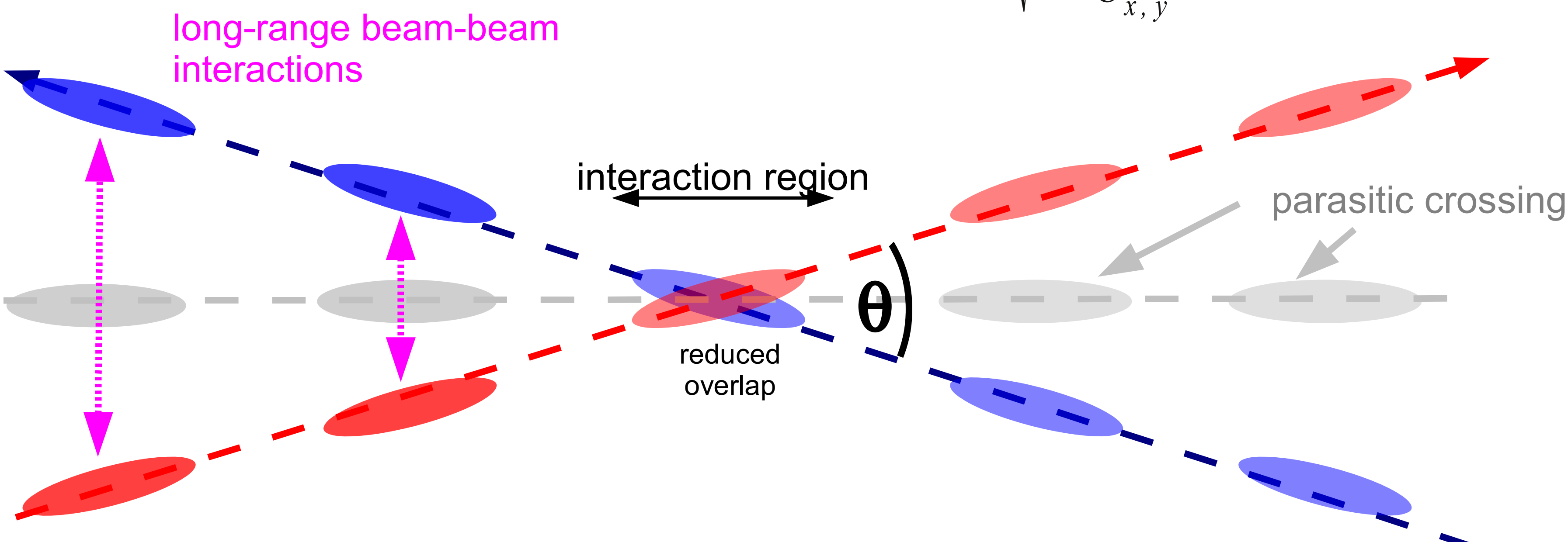
for and with input from:

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

Beam-Beam Interactions in a Nutshell

- Need crossing angle θ to avoid parasitic crossings
  → reduces bunch overlap & luminosity
- Two mitigations:
  - “crab cavities” rotating the bunches before and after the IR
  - beam-beam compensator (BBC) mitigating effect of long-range interactions
  - present LHC: $F_{crossing} \approx 0.7 \rightarrow$ HL-LHC ~ 0.2

$$L = L_0 \cdot F_{crossing} \cdot \ldots \qquad F_{crossing} = \frac{1}{\sqrt{1 + \frac{\sigma_s}{\sigma_{x,y}} \tan(\theta/2)}}$$

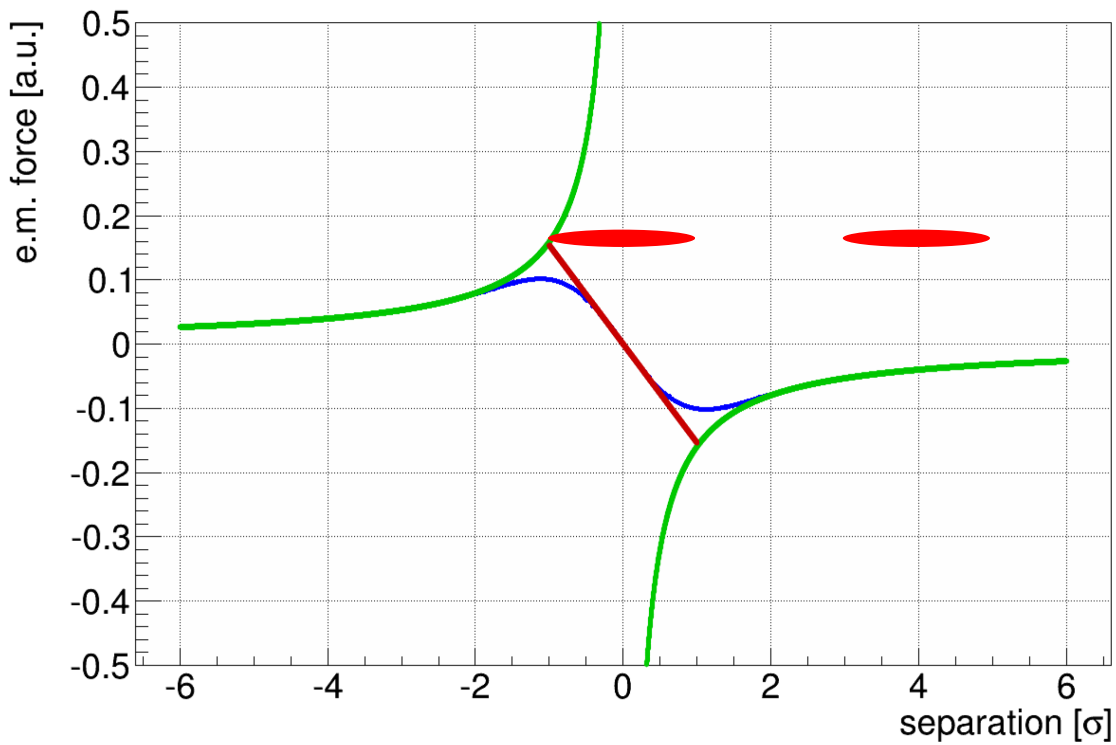


Beam-Beam Field

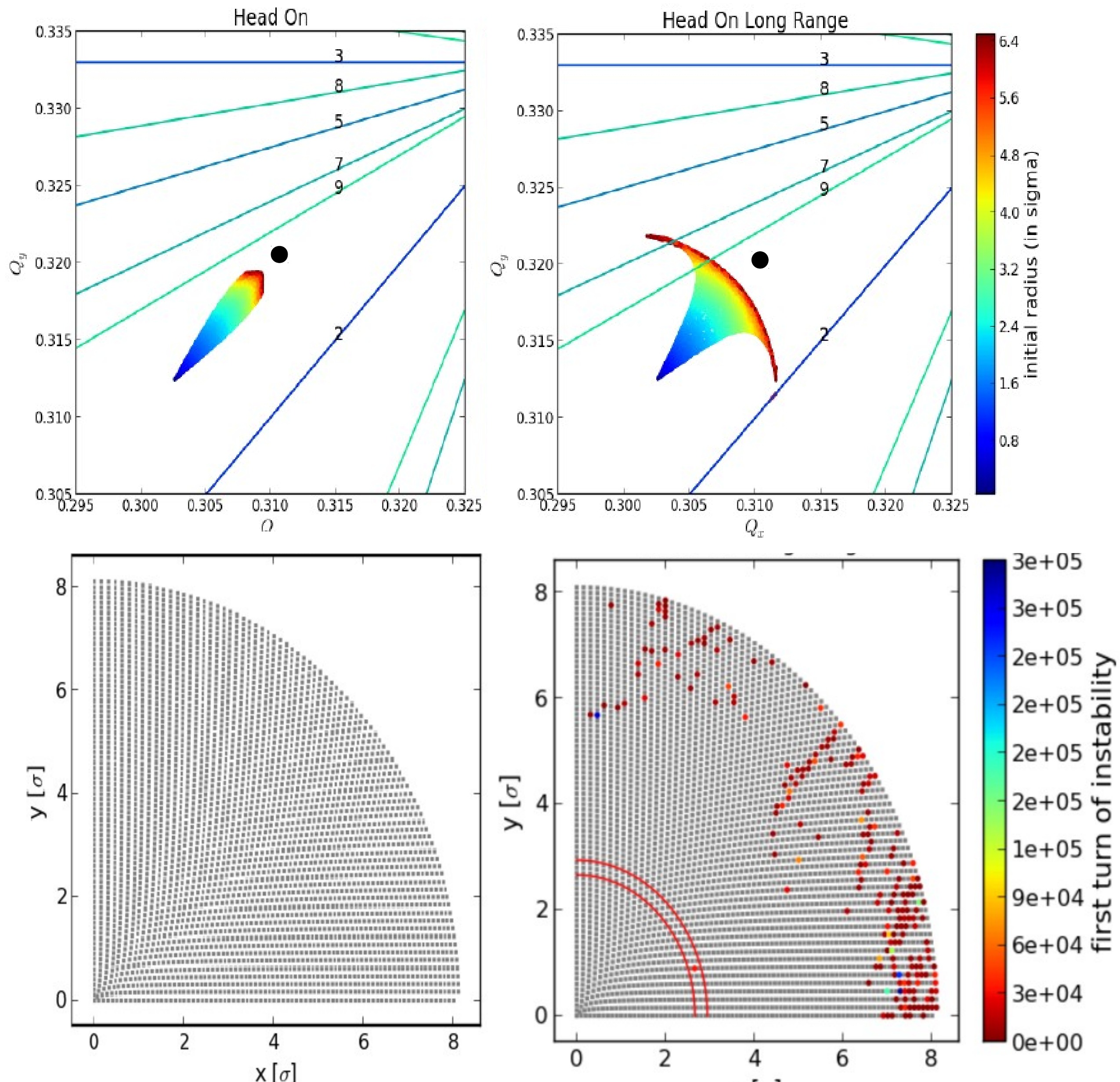
$$E(\vec{r}) = -\frac{Ne(1+\beta^2)}{2\pi\epsilon_0 \; \boldsymbol{r}} \cdot \left[1 - e^{-\frac{1}{2}\left(\frac{\boldsymbol{r}}{\sigma}\right)^2}\right] \cdot \frac{\vec{r}}{\boldsymbol{r}}$$

long-range ~ 1/r

head-on ~ r



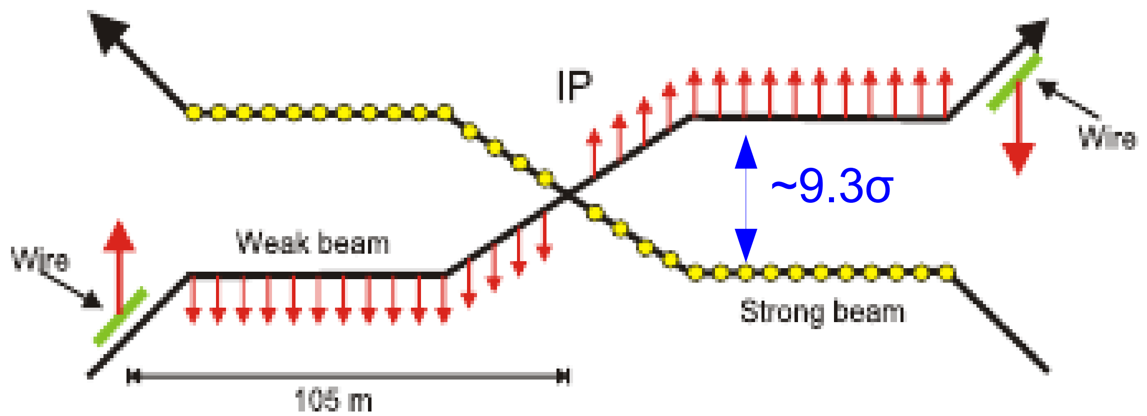
Beam-Beam Interactions – Simulations



analysis: T.Rijoff & F. Zimmermann

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

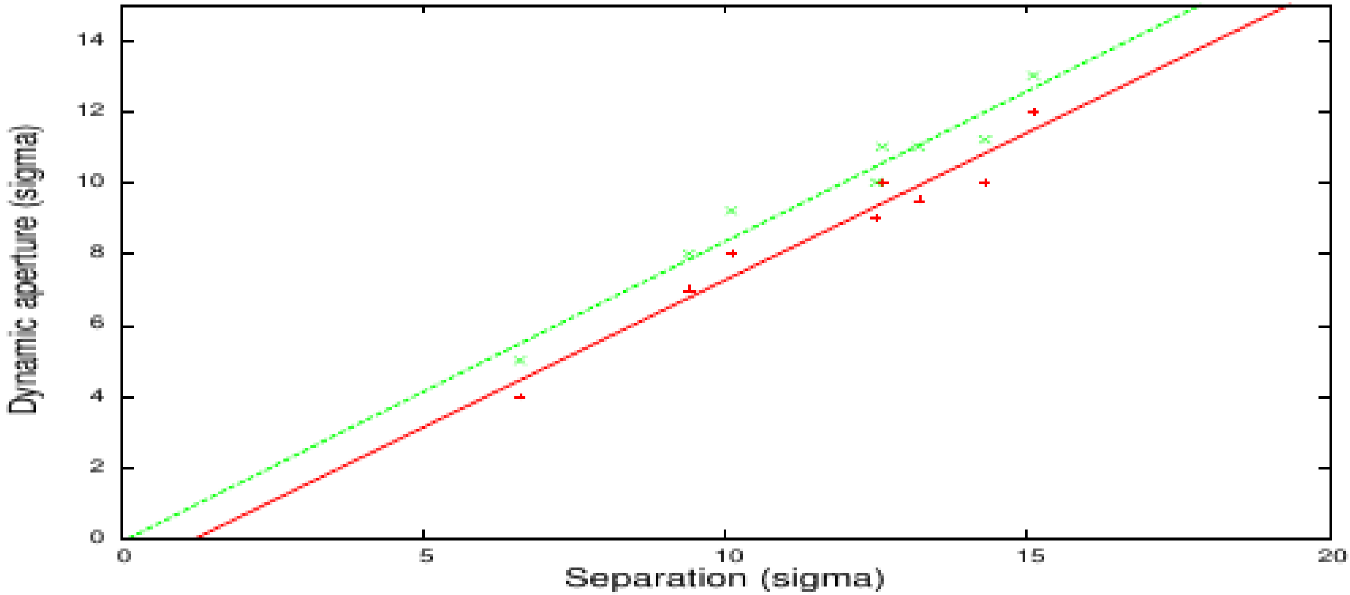
- Initial proposal based on to J.-P. Koutchouk's note: CERN-SL-2001-048-BI

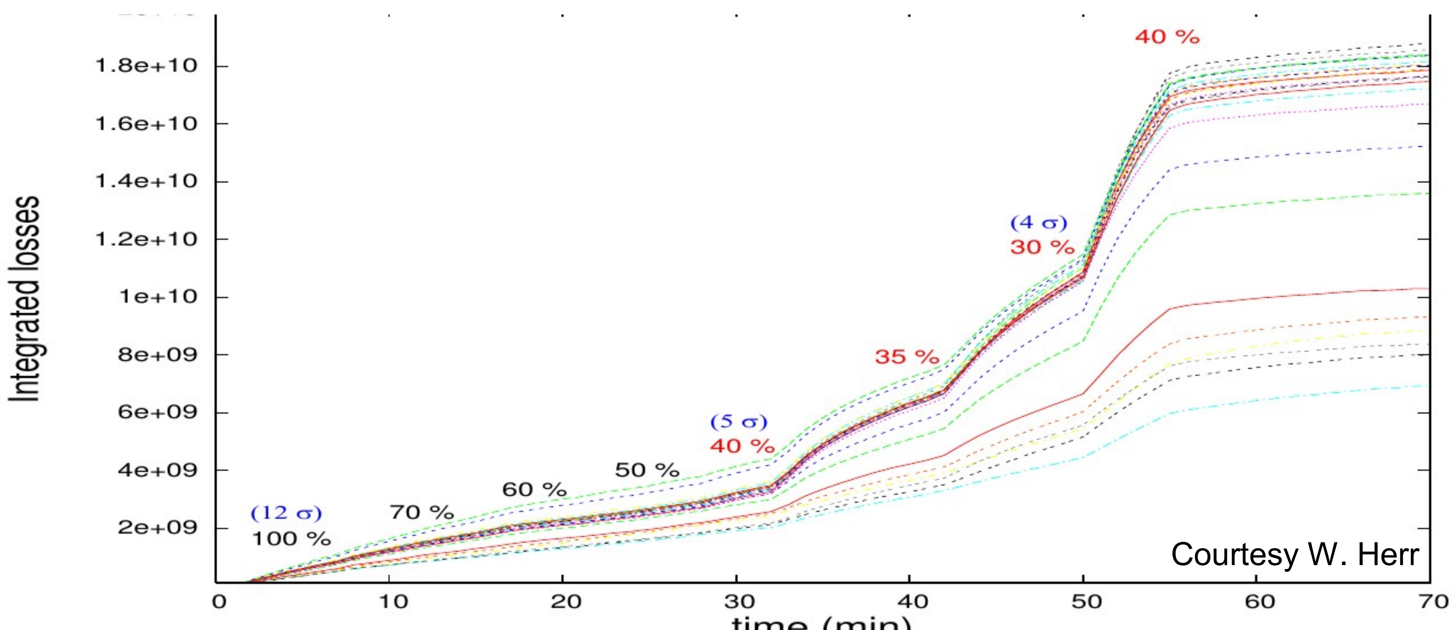


- Since, SPS wire-wire and RHIC beam-wire experiments demonstrated that:
  1. *"detrimental wire effect on life-time can be compensated by another wire"*
  2. *Partial BBC results at RHIC*
  3. *Benchmark of numerical tool chain → indication of what to expect at LHC*

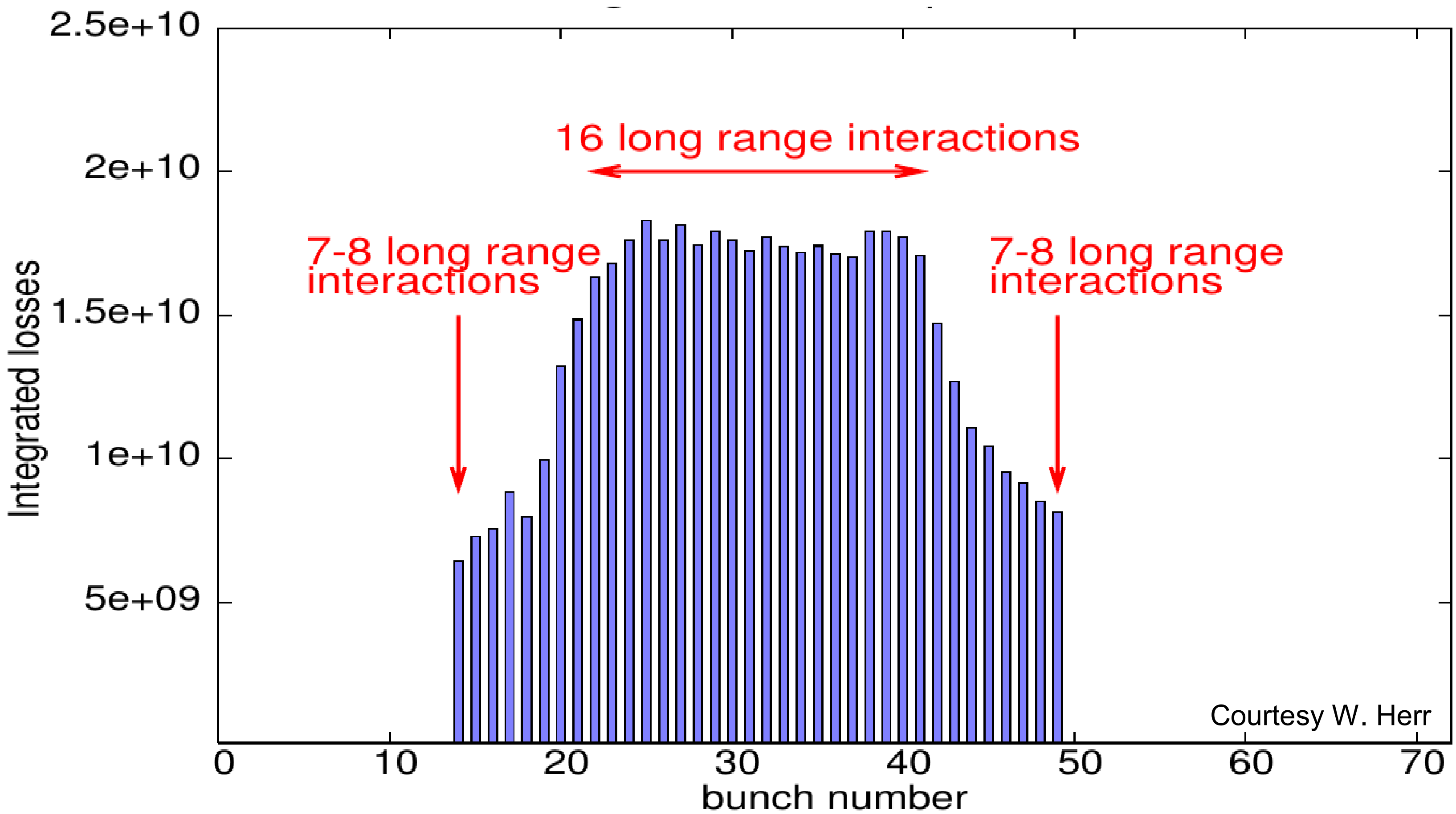
- Further tests require a true long-range beam-beam limited machine...
→ proof-of-principle requires BBC prototype into machine before HL-LHC

Beam-Beam Interactions – LHC Experiments I/II





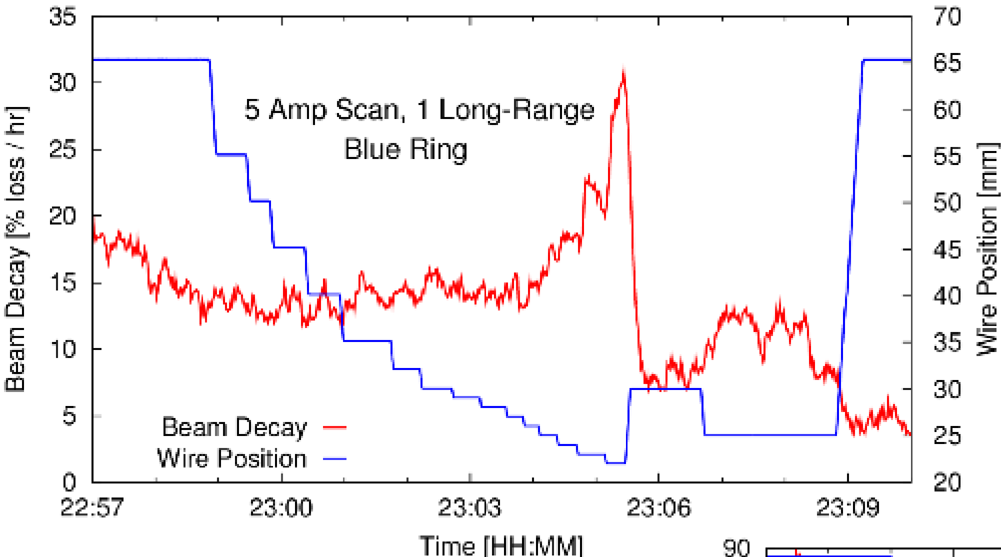
- Distribution of integrated bunch-by-bunch losses across the train



  – more long-range encounter ↔ higher losses

III: LR Compensation Exp, 5A

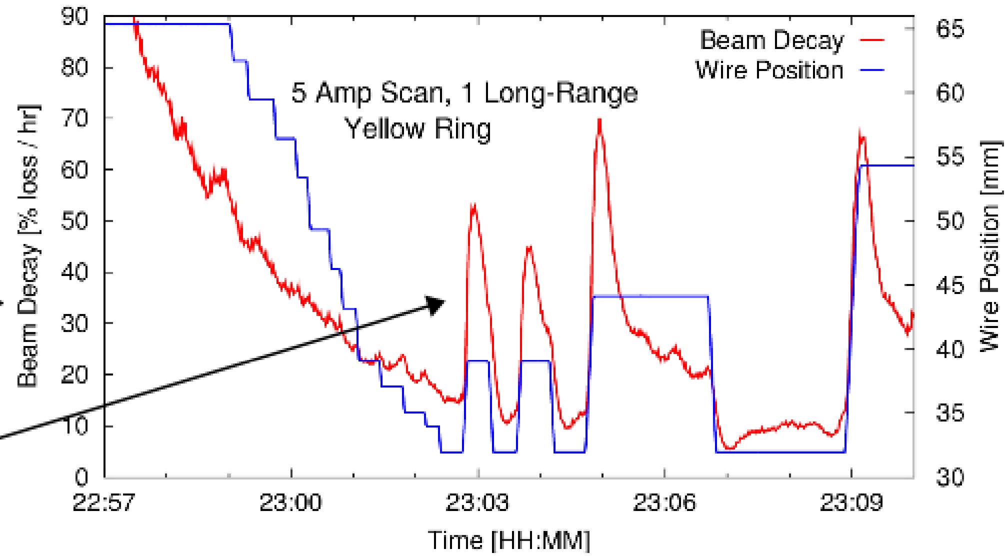
R. Calaga, CERN



Blue Ring

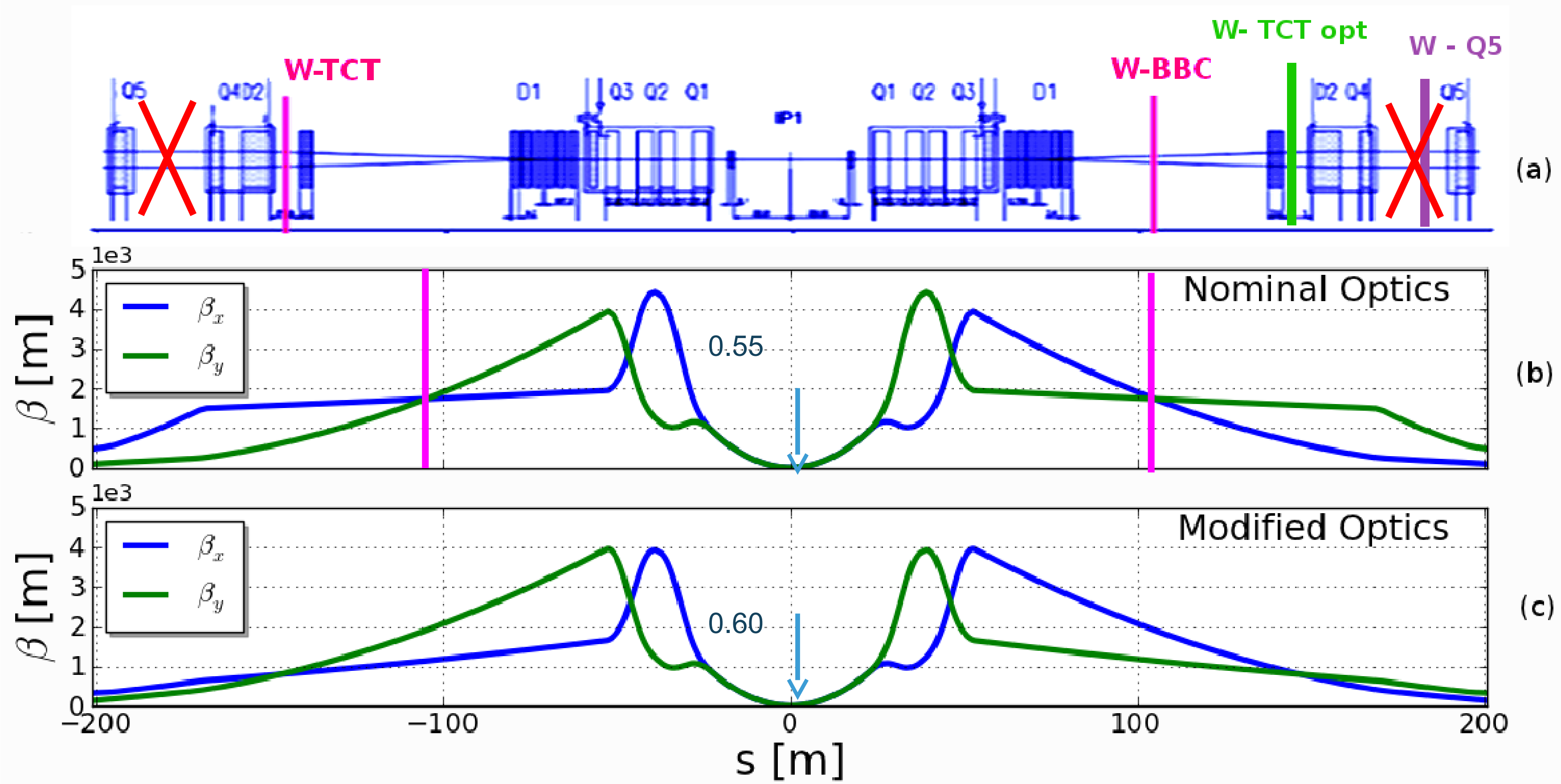
No visible effect

Yellow Ring



Losses increase when compensation is removed !!!

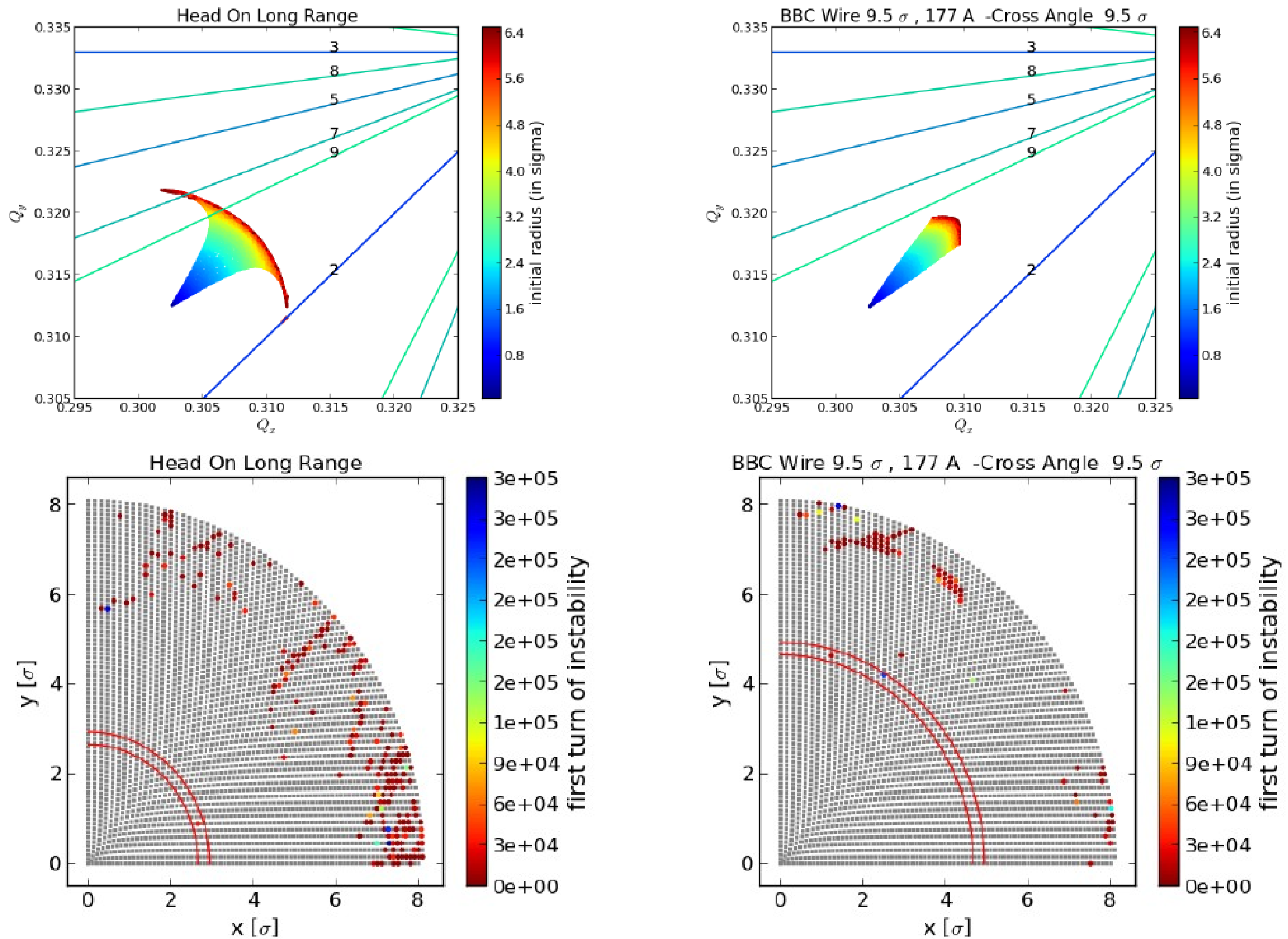
Analysed Cases Summary



Wire position	BBC	TCT	TCT opt
from IP1 [m]	105	-147	150
from IP5 [m]	105	-147	-147

S. Fartoukh, T. Rijoff, F. Zimmermann

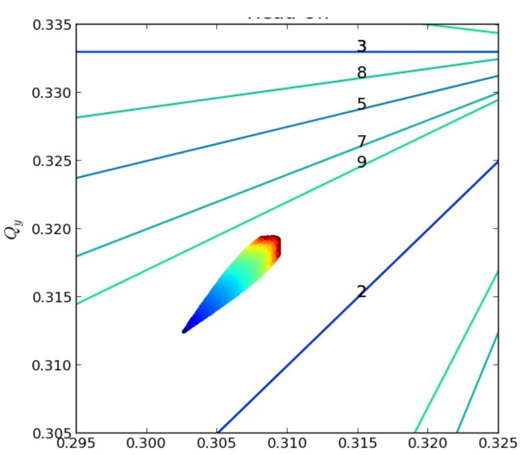
Predicted BBC Performance for Nominal LHC



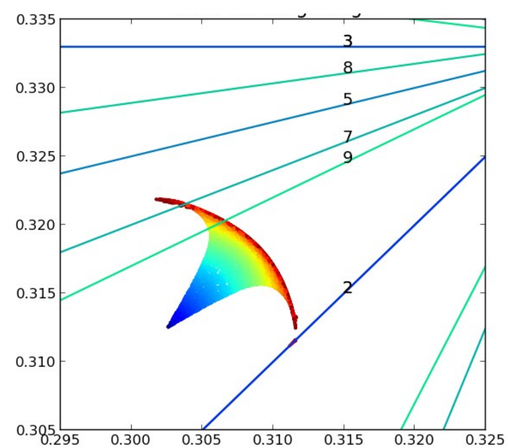
~2σ dynamic aperture gain! → can reduce crossing angle → more Luminosity!

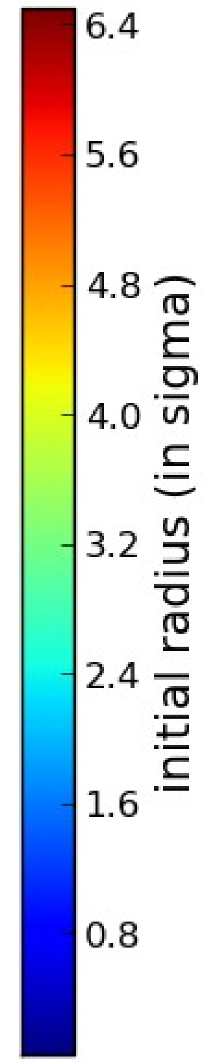
Best Tune Results

Head on

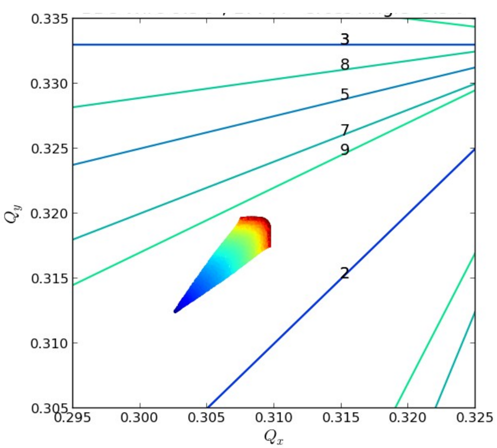


Head on Long Range

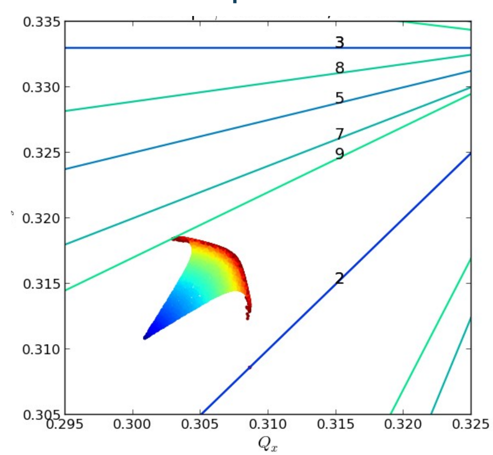




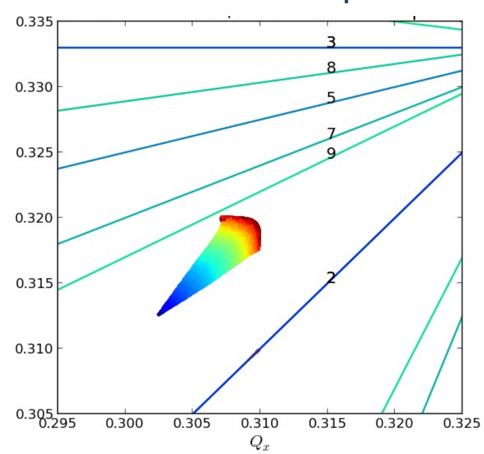
BBC Wire



TCT optimized



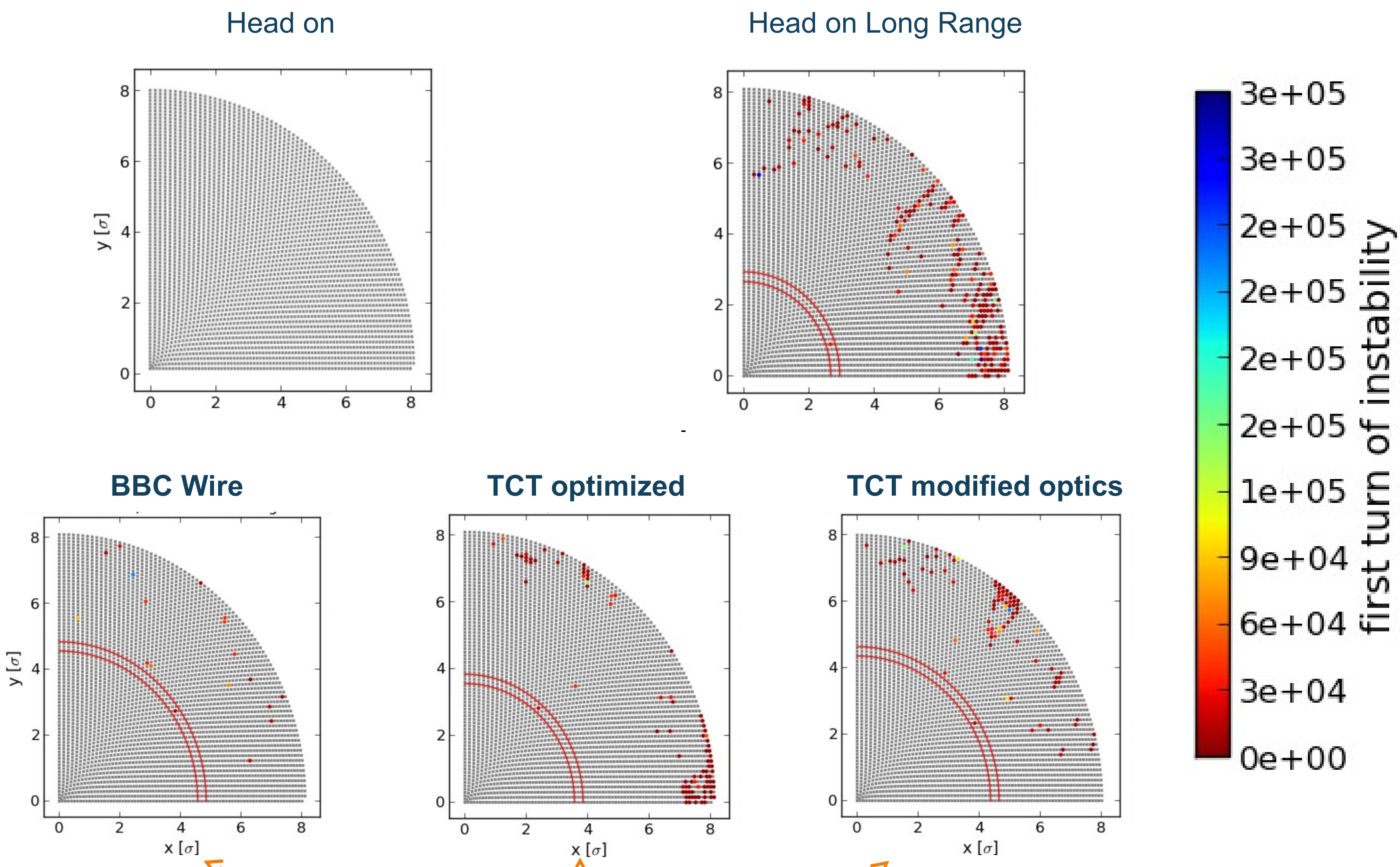
TCT modified optics



Wire at 9.5 σ – 177 A

T. Rijoff, F. Zimmermann

Best Stability Results



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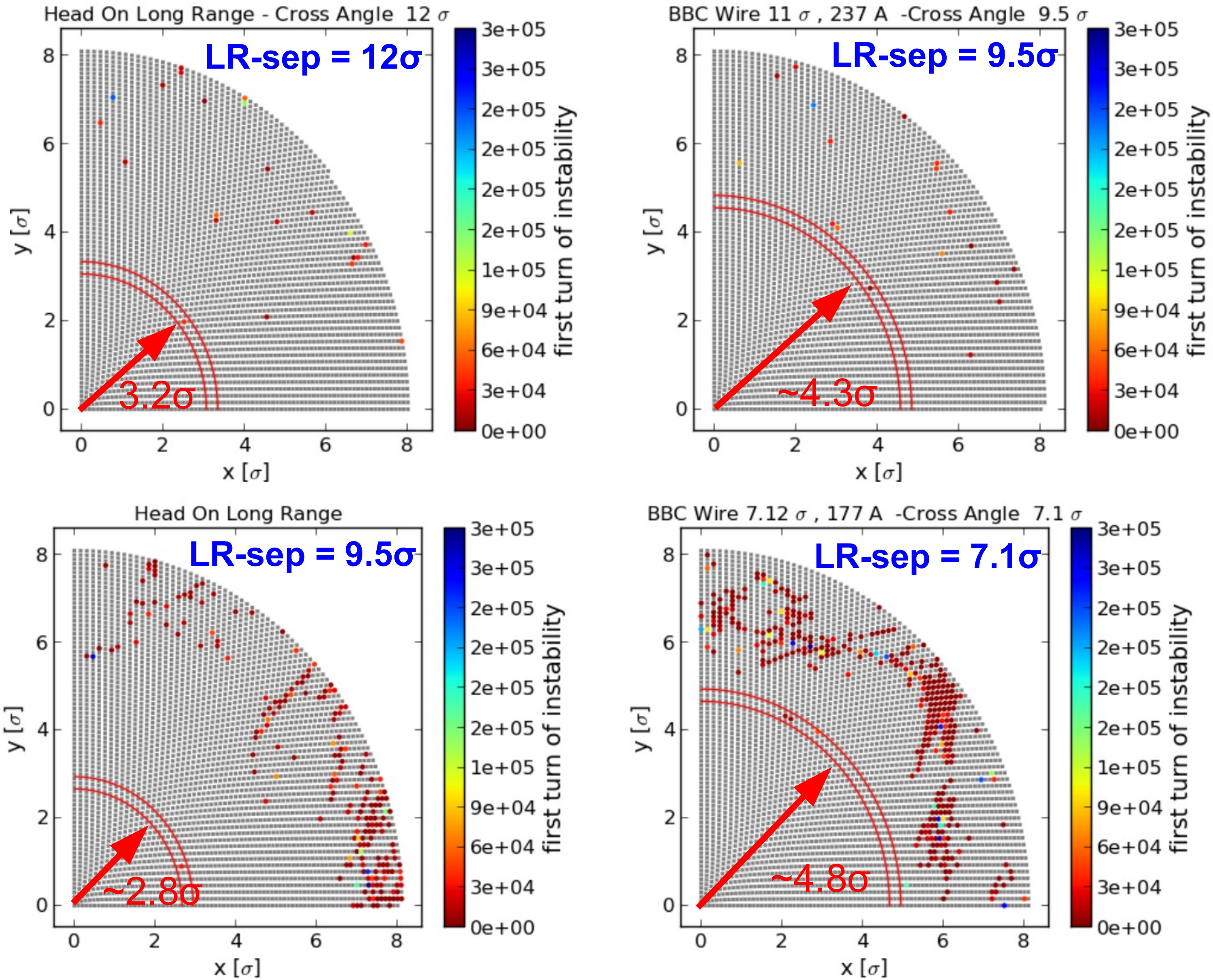
Wire at 11 σ – 237 A

Nominal BBC – Crossing Angle Reduction Performance



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Post-LS1 BBC Prototype – Test Scenario

Additional Slide
(post presentation discussion)

- Scenario to be tested post-LS1 to benchmark existing simulations
  - N.B. Will need to blow-up the beam to nominal ie. 3.75 um emittances for the tests

Transverse position [σ]	Current A	Unstables Particles [%]	Minimum Radius [σ]
HoLr		5.7	2.8
9.5	177	2.4	3.7
11	177	3.4	5.6
11	237	2.6	3.7

Table 4.16: Summary of the stability test for TCT opt β , using the nominal LHC optics and performing the tests for differents transverse positions and current values, with nominal crossing angle.

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Initial SPS Prototype Proof-of-Concept Design

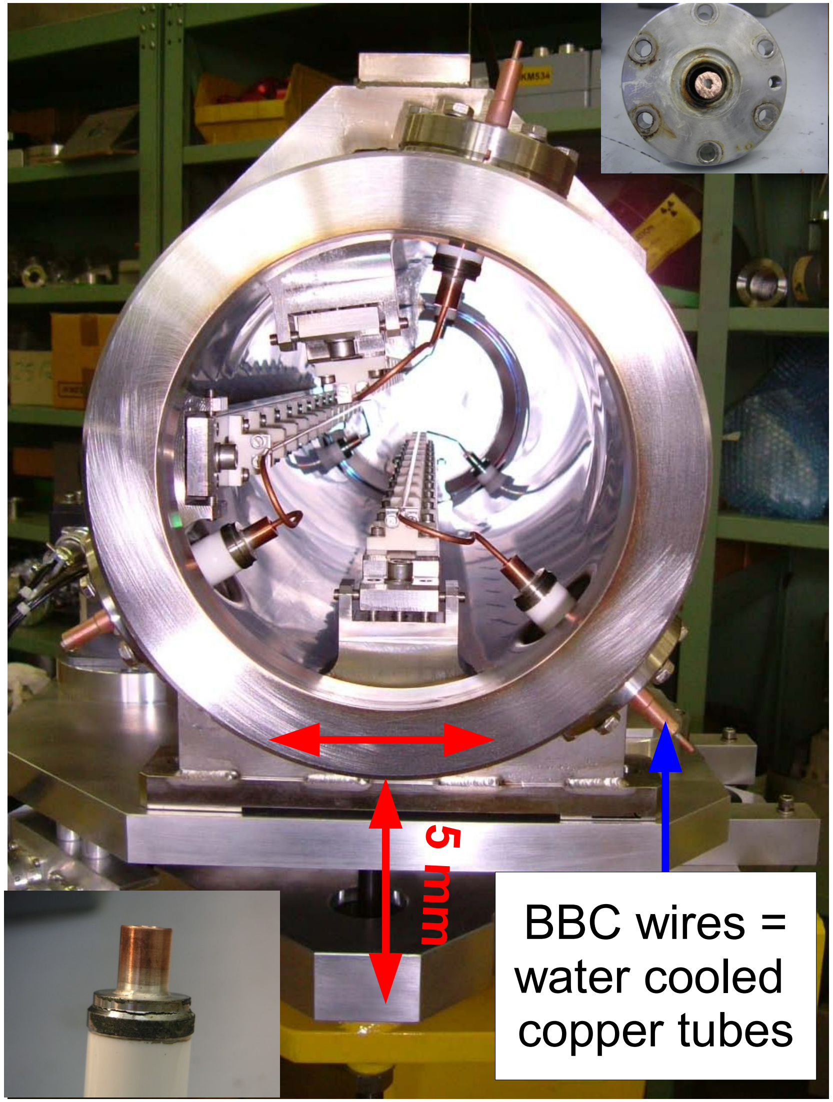
- SPS & RHIC-type design incompatible for installation in LHC:

- Wire needs to be in between beams
- Some inherent risks with moveable tanks
  - require movement > 10 mm

- …

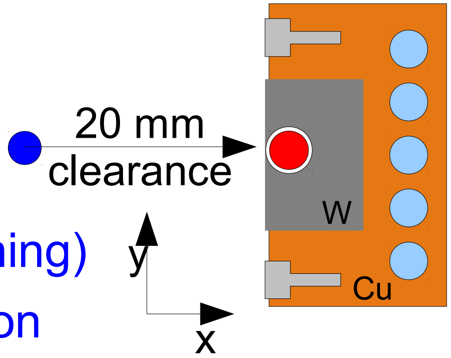
- Free-standing wire & RF resonances
  - classic *λ/2*-antenna
  - impedance issues
    (very large β between D1 and TAN)
- Not robust w.r.t. beam impact (MP)
  - water cooled wire inside vacuum and very close to beam

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



Summary of LHC BBC Prototype Specifications

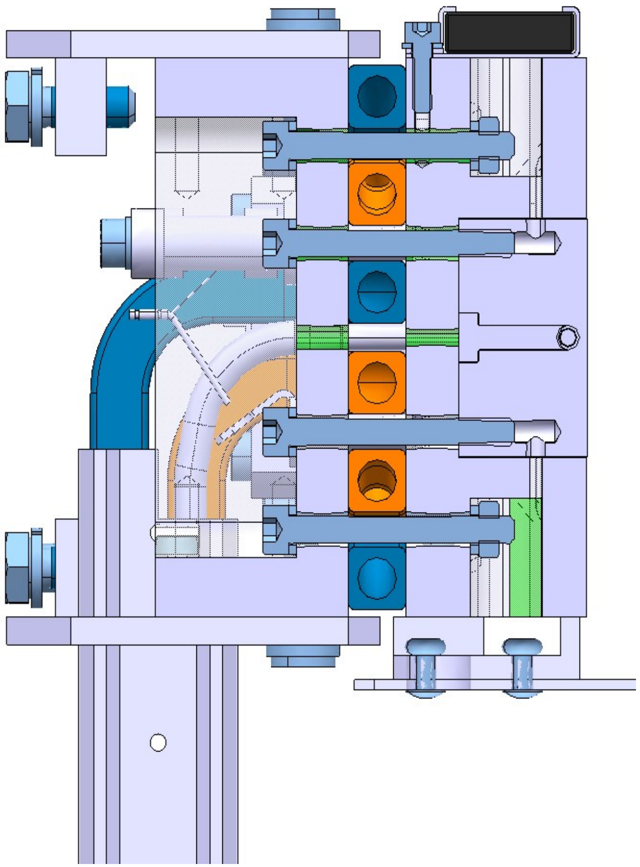
- Wire-in-jaw design:
  - Embedded (insulated) Cu wire inside W block
  - Possibility of 1+n wires (spare/redundancy)?
  - >100 um between wire and cleaning surface (RF screening)
  - more compatible w.r.t. collimation and machine protection

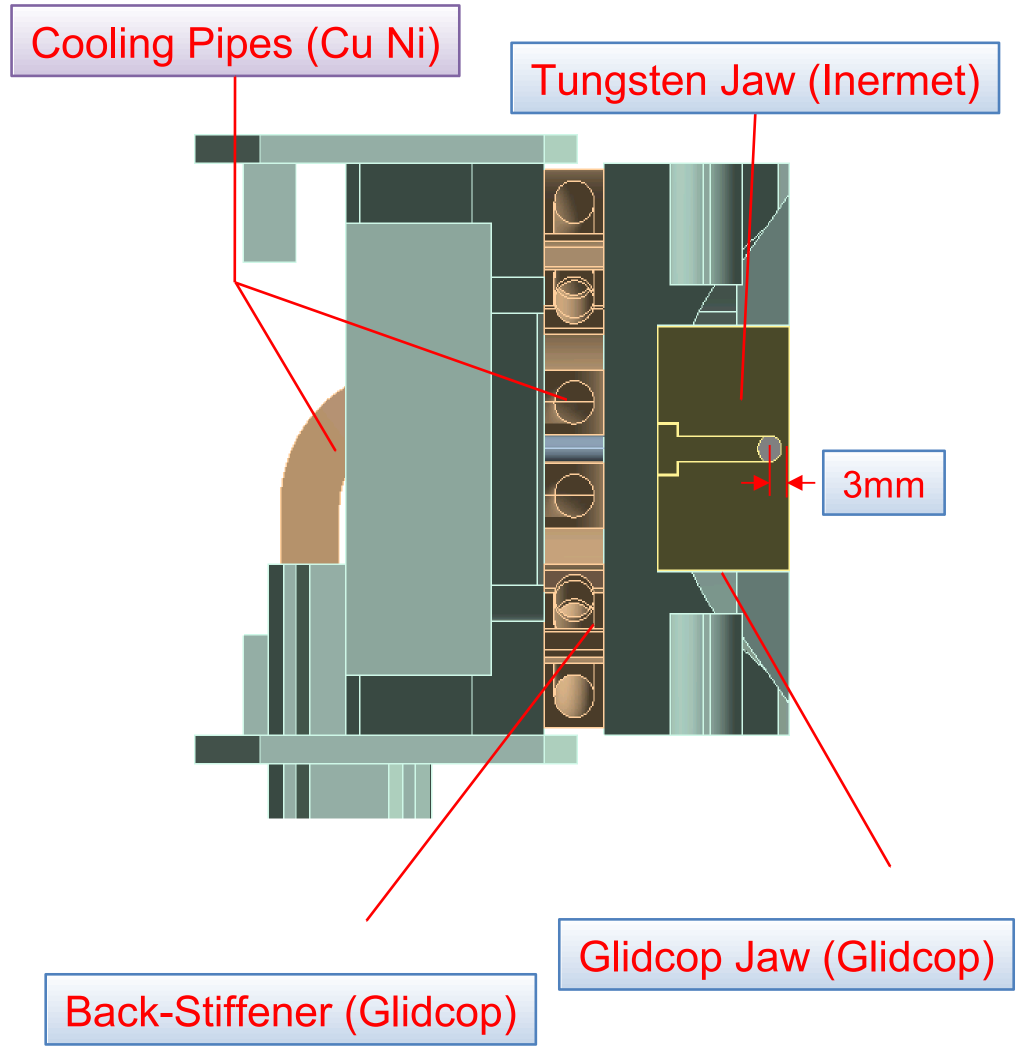


- Wire parameters:
  - Solid (round) wire radius of ~ 1mm and e.g. 1 m length
  - sub-σ level of hor./ver. position control (e.g. 0.1 mm)
  - nom. scheme: $I \cdot l_{wire} = I_{peak} \cdot \sqrt{2\pi} \cdot \sigma_s \cdot n_{parasitic} \cdot l_{wire}$ = 72 … 350 Am (max.)
  - DC compensation only
  - cooled via passive heat transfer (1 kW)

- Initially two units: BBC-H.xL5.B1 & BBC-V.xR1.B1
  - same location as present TCTP & planned TCL collimator
- Reuse as much of established infra-structure as possible (collimator type girders/motor control, LHC-type 600 A PC)

Combined Collimator & BBC Function
Improved Wire-in-Jaw Design I/II

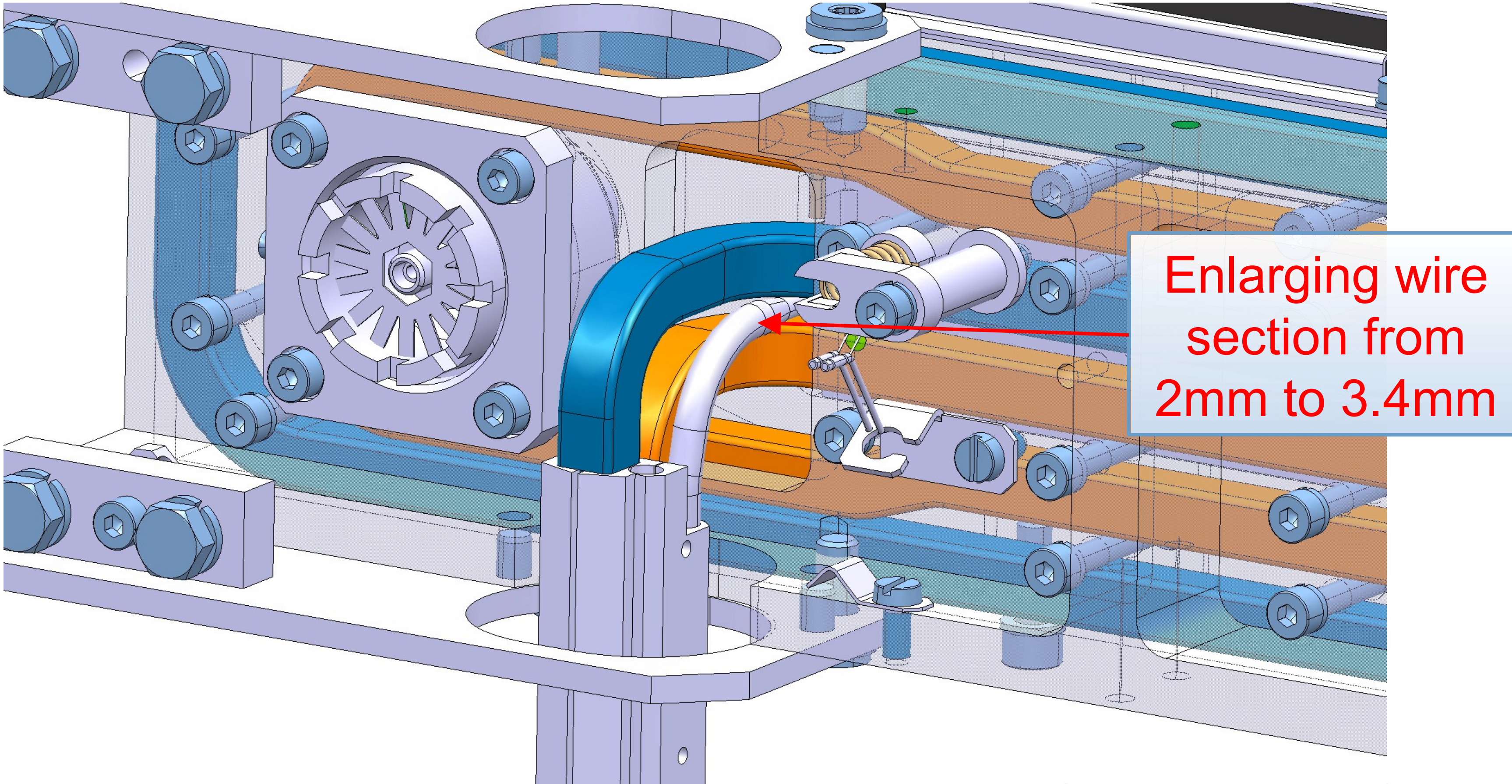




G. Maitrejean, L. Gentini

details → A. Bertarelli's talk

Combined Collimator & BBC Function
Improved Wire-in-Jaw Design II/II



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- BBC-enhanced design re-uses ~100% of existing TCTP collimator design
- Additional heat-load in jaws and feed-throughs seems under control

Two-Stage BBC Approach I/II – Initial Post-LS1 proof-of-concept

- Primary aim: benchmark existing simulations and predictions prior to LS-2

- Initial wire-in-TCTP-jaw design seems to be feasible
  - Thermal, cleaning & impedance issues seem to be under control
  - Pending: worst-case beam impact scenario studies
    - i.e. asynchronous beam dump spraying 1-15 nom. bunches onto jaw N.B. TCTP (W jaw) is known to fail "badly" but additional wire should not significantly deteriorate the situation further → A. Bertarelli's talk

- Allow to test the predictions but may not achieve the best-possible performance under nominal (HL-) LHC conditions
  - test require ε = 3.5 - 3.75 um vs. nominal $\varepsilon \approx$ 2.0 um
  - larger phase-advance w.r.t. nominal BBC
  - limited min. wire-in-jaw-to-beam distance

Two-Stage BBC Approach II/II – Possible Nominal BBC Installation for HL-LHC

- Primary aim: improve luminosity via reduced crossing-angle & BBC mitigating long-range beam-beam interactions

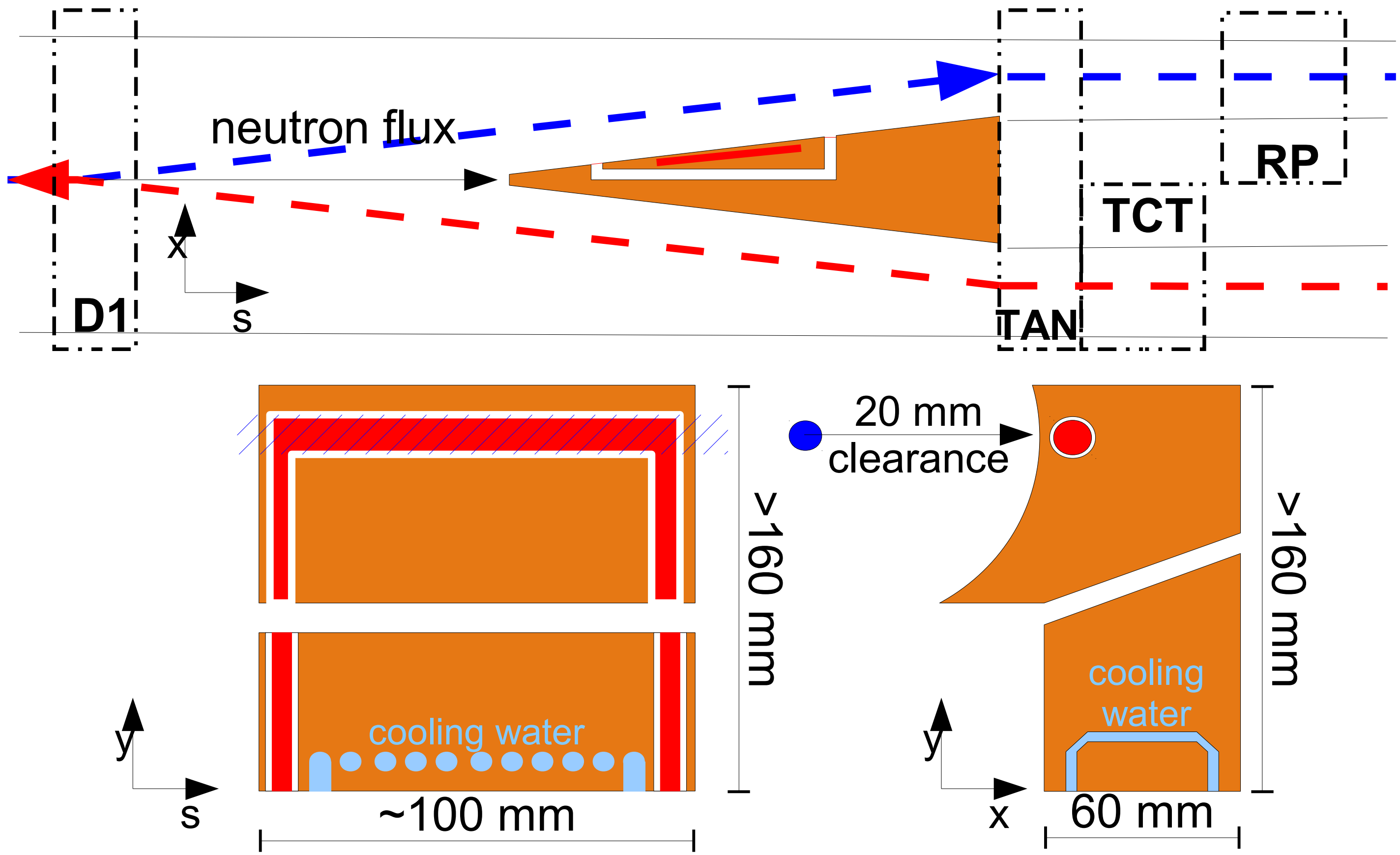
- Several independent predictions, all consistent and quite promising w.r.t. potential to reduce the crossing angle, however

- Two inconvenient BBC constraints (from engineering/operation/MP point of view):
  a) needs to be close to the D1 (i.e. in common beam pipe)
  b) Similar "wire"-to-beam distances as the targeted beam-beam separation

- Three (/more?) nominal implementation options for HL-LHC:
  1. Wire-in-jaw design → scale TCTP exp. and integrate between D1-TAN
  2. For reference only: Simulate 'wire' effect through external fields
  3. Simulate 'wire' field through e-beam running || to the p-beam

  → all three options are challenging w.r.t. design and integration
  … following slides give a glimpse on some of the issues

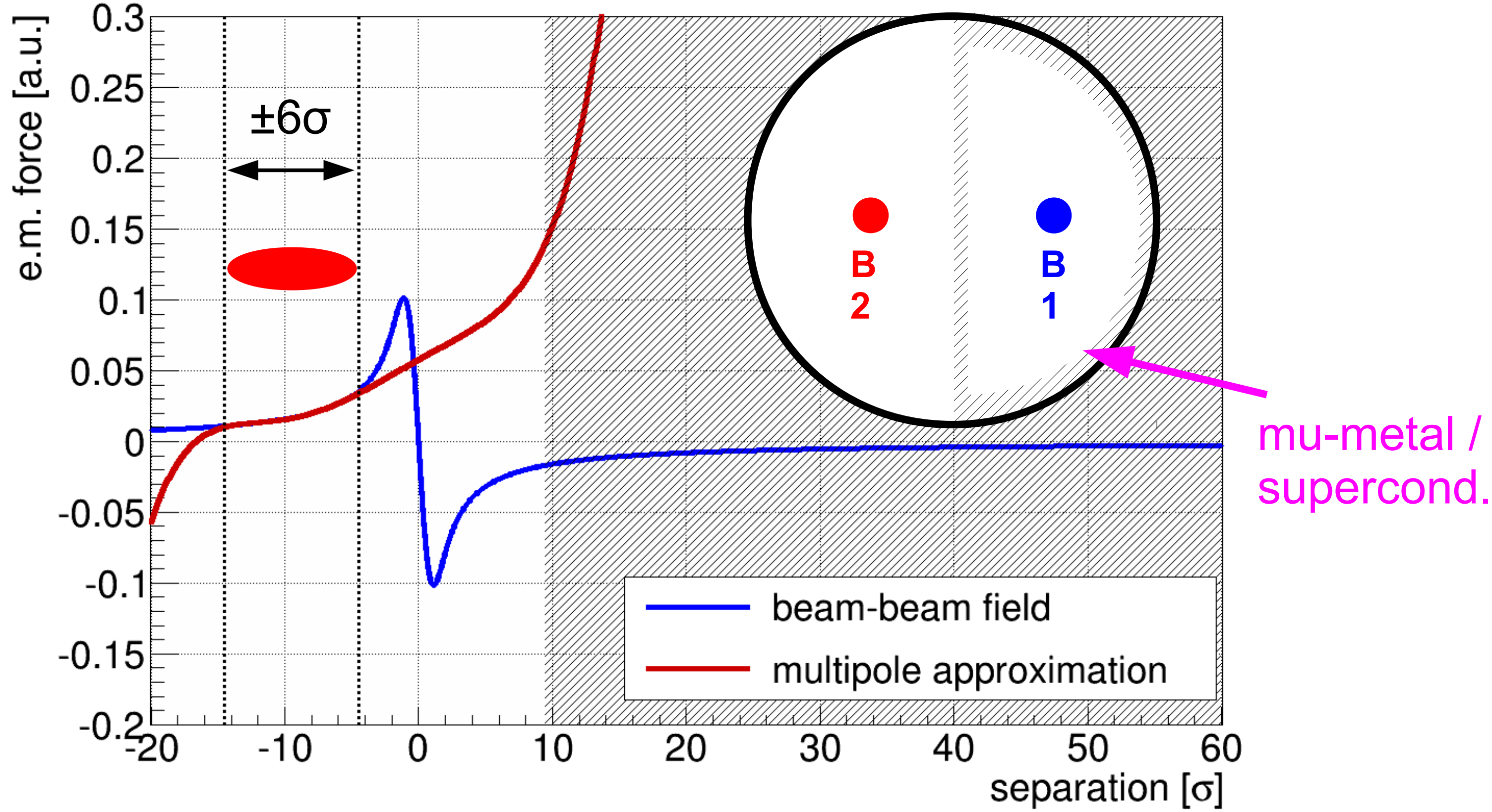
HL-LHC Option 1: Scalled Wire-in-Jaw Design placed between D1 ↔ TAN



- Non-neglible *n*-flux, impedance and TAN aspects need detailed simulations
- Major design and qualification effort → basically another collimator
  - materials choices: Cu, W, Carbon, SiC, (CVD) Diamond, ...
- Ideally targeting a 6-7σ distance (from a physics point-of-view)
  → de-facto becoming a primary collimator next to the experiments
  (IMHO: “.. a very challenging scenario”)

HL-LHC Option 2 – more for reference purposes: Local 'wire'-like Gradient using External Magnetic Fields

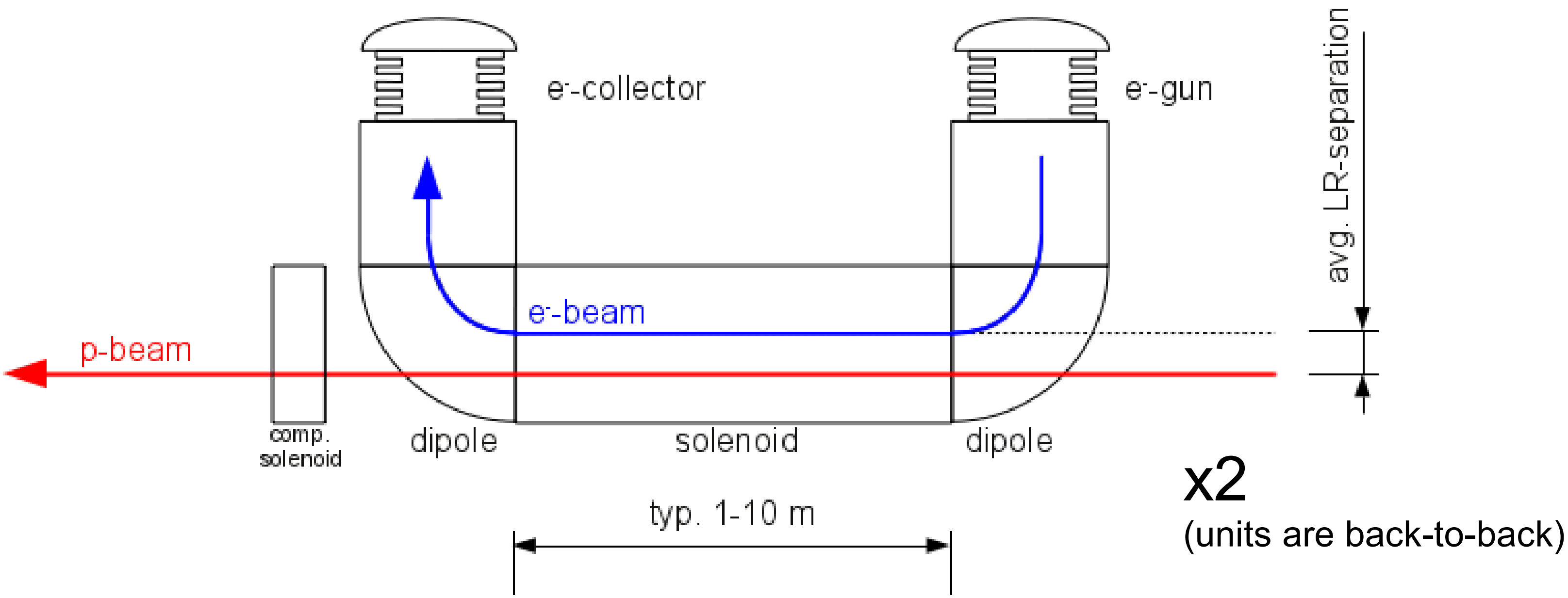
- Long-range approximation with 8-10-pole off-centre multi-pole field



- Septum-like design: mu-metal or superconductor to magnetically shield between B1/B2 aperture (n-flux may be limiting factor)
- Needs further investigation – numerically possible but may required magnetic peak-fields beyond what can be done with superconductors

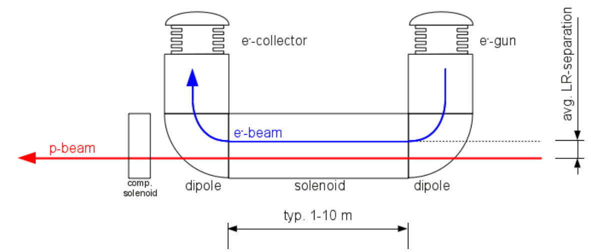
HL-LHC Option 3: Local e-beam simulating 'wire'-like Field I/II

- E-beam has by-design perfect 'wire' field distribution



- similar to existing e-cooler, (hollow-) e-lenses used at Tevatron & RHIC, however: offset e-beam! → much lower requirements on transverse e-beam parameters (i.e. beam size, profile distribution etc.)
- Still need large solenoid field to stiffen e-beam rigidity
- no solid material close to beam → chance of being MP compatible @6-7σ

HL-LHC Option 3:
Local e-beam simulating 'wire'-like Field II/II



- Rationale:
  - 'current x length' ~ 100 Am/unit needed
    - i.e. '100 A over 1 m' or '10 A over 10 m'
  - Commercial solutions deliver ~ 10-35++ A (IOTs and Klystrons)
  - simulations indicated beam profile not being critical
  - Leverage experience with existing e-cooler and -lens systems
  - Potential to do bunch-by-bunch compensation of pacman bunches
- Limiting factor – required solenoid field ↔ energy of e-beam
  - from a head-on impedance perspective (Burov et al., PhysRevE.59.3605):

$$B \geq B_{th} \approx 1.3 \frac{e N_{\bar{p}} \sqrt{\xi_x \xi_y}}{a^2 \sqrt{\Delta \nu \nu_s}} \longrightarrow \begin{array}{ll} \text{FNAL:} & 1.2\ \text{T} \\ \text{BNL:} & 14\ \text{T} \end{array}$$

FNAL: $\xi_{x/y} \approx 0.01$, $N_p = 6 \cdot 10^{10}$, $\nu_s = 1 \cdot 10^{-3}$, $\Delta\nu = 0.01$, $a \approx 1.0$ mm
RHIC: $\xi_{x/y} \approx 0.011$, $N_p = 3 \cdot 10^{11}$, $\nu_s = 5 \cdot 10^{-4}$, $\Delta\nu = 0.011$, $a \approx 0.8$ mm

  - LHC $\nu_s = 2 ... 5 \cdot 10^{-3}$ → 10x smaller field due to larger ν_s
- However: LR e-beam need further detailed studies/simulations

CPII/THales: VKP-9050, IOT8505, TH 794, TH 795, TH 2177

Conclusion

- Sim.: nominal BBC (D1-TAN) may allow crossing angle reduction by ~2σ

- BBC proof-of-concept to be deployed to confirm predictions prior to LS-2 – however: reduced performance and for a non-nominal/MD-type scenario
  - test require ε = 3.5 - 3.75 um vs. nominal ε ≈ 2.0 um
  - larger phase-advance between long-range encounter and TCTPs
  - limited min. wire-in-jaw-to-beam distance

- Inconvenient BBC scaling:
  - needs to be close to the D1 (i.e. in common beam pipe, n-flux, impedance)
  - "wire" will be as close to the beam as the targeted beam-beam separation

- Two more-realistic nominal implementation options for HL-LHC:
  - Wire-in-jaw design → scale TCTP exp. and integrate between D1-TAN
    - Need to respect collimator hierarchy for cleaning & MP
  - Simulate 'wire' field effect through e-beam running || to the p-beam
    - Technology seems to be available but still not trivial ↔ strong synergies with (hollow-) e-lens experience Tevatron/RHIC

Outlook

- Efforts to deploy 2 wire-in-jaw based BBC before LS2
  → aim: confirm simulation scaling and gain experience for nominal design
  - Cabling and supporting infratructure being prepared during LS1
  - BBC-TCTP style device to be installed during first long stop after LS1

- Assessment of beam-beam compensation prototype prior to LS2, two possible outcomes
  A) best case: scale wire-in-TCTP design for HL-LHC
  B) back-up option: integrate LR-BBC at nominal location (D1-TAN)

- Need to start full-system design/integration for HL-LHC soon

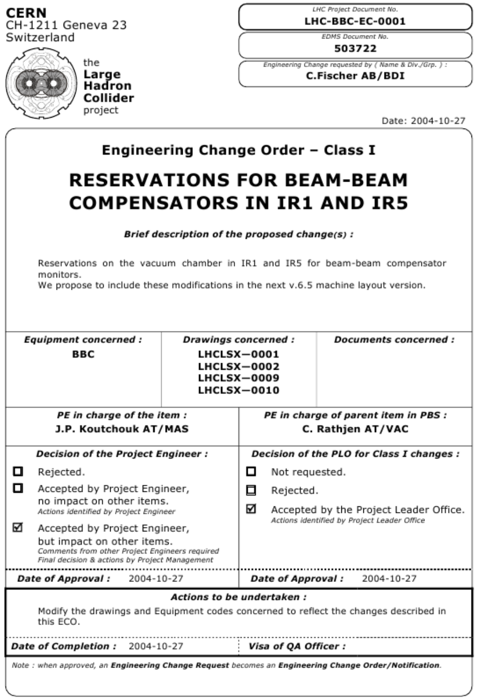
Reserve slides

Initial Plans: LHC Beam-Beam Compensators 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

- 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)



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 :	PE in charge of parent item in PBS :
J.P. Koutchouk AT/MAS	C. Rathjen AT/VAC

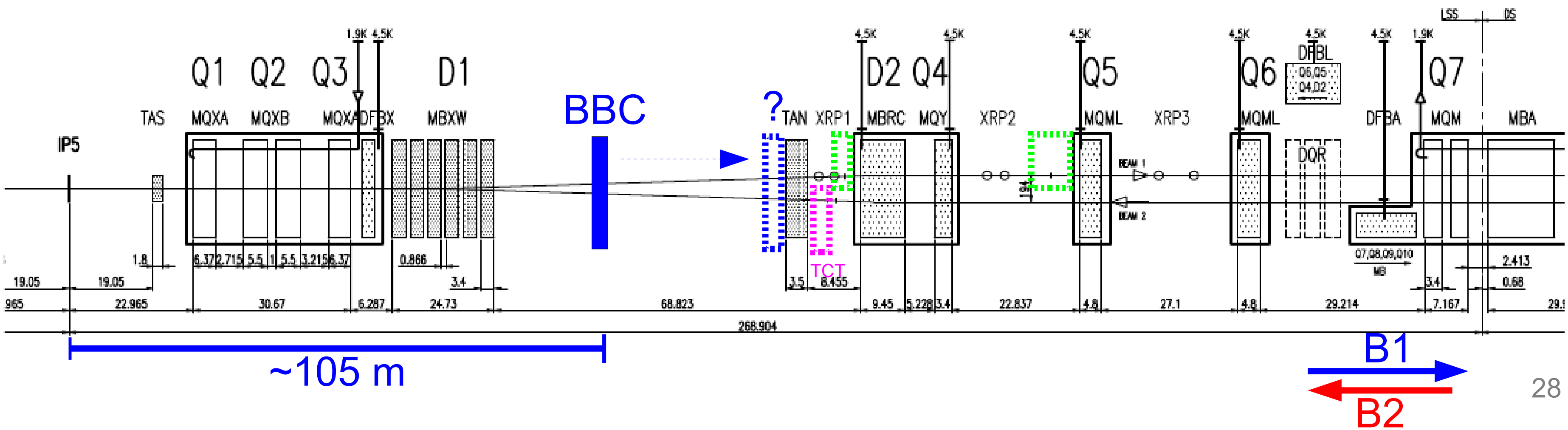
Decision of the Project Engineer :	Decision of the PLO for Class I changes :
☐ Rejected. ☐ Accepted by Project Engineer, no impact on other items. *Actions identified by Project Engineer* ☑ Accepted by Project Engineer, but impact on other items. *Comments from other Project Engineers required. Final decision & actions by Project Management*	☐ 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 :

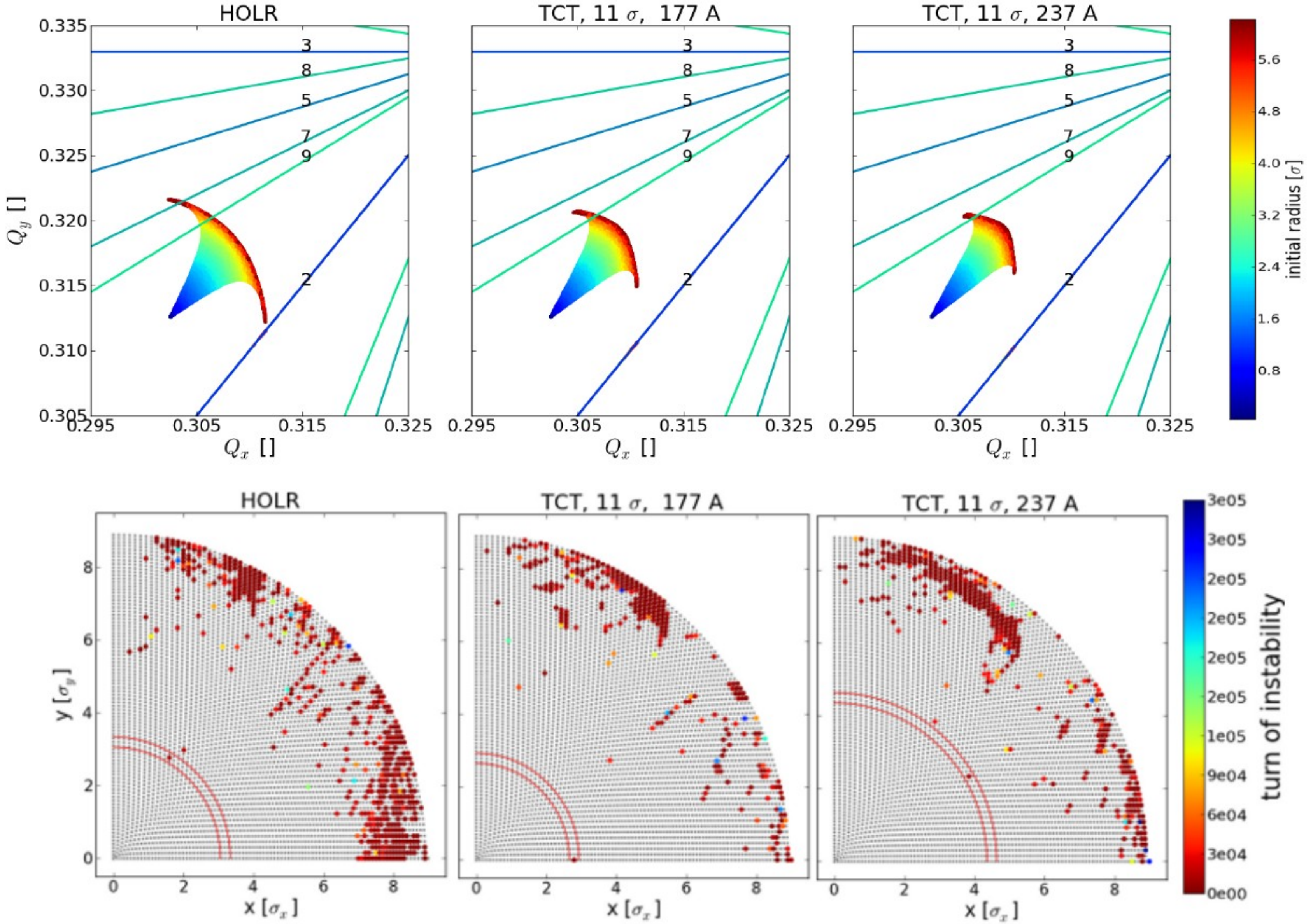
Modify the drawings and Equipment codes concerned to reflect the changes described in this ECO.

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

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

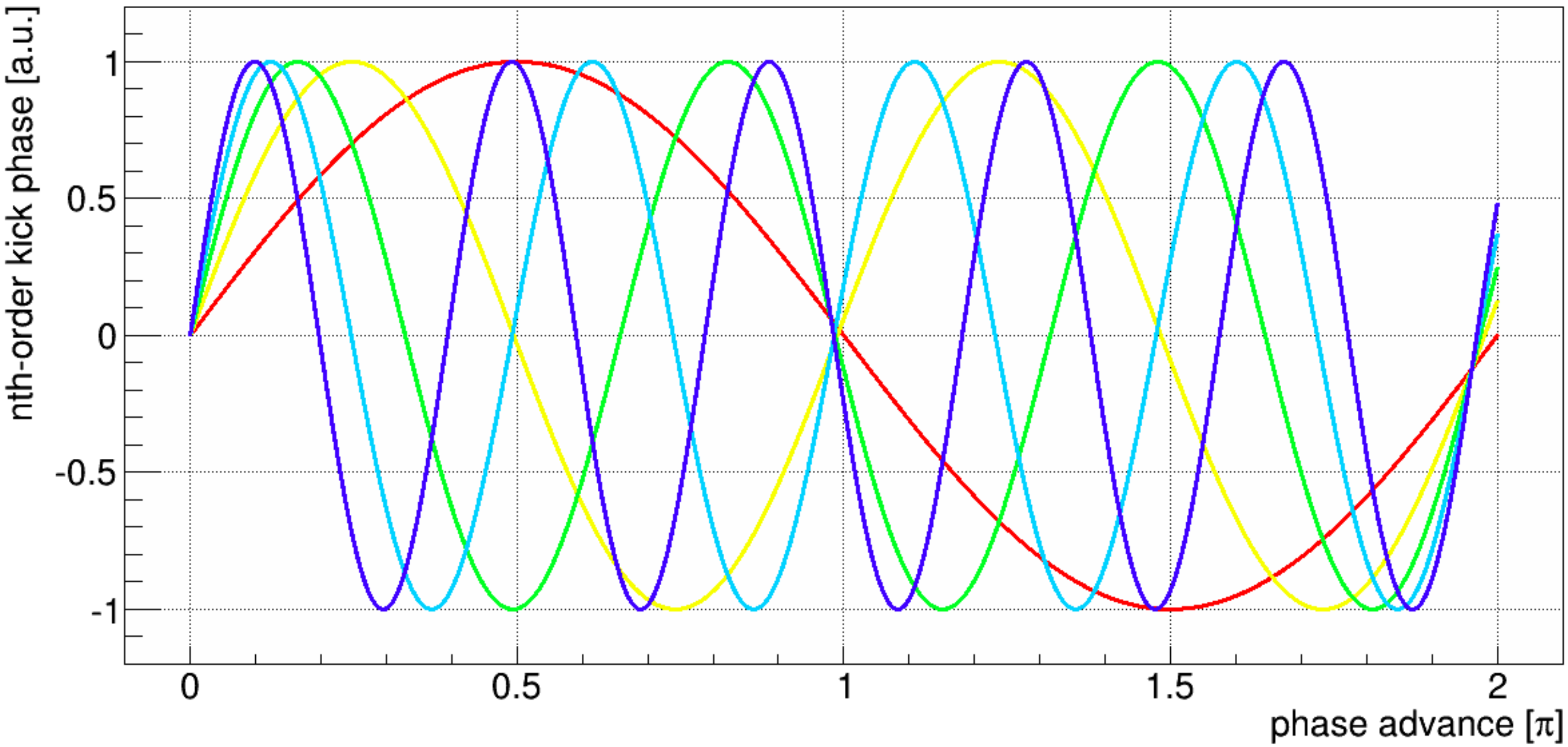


LHC BBC Simulation
Compensating inc. BB-Separation Distance with I_w^2

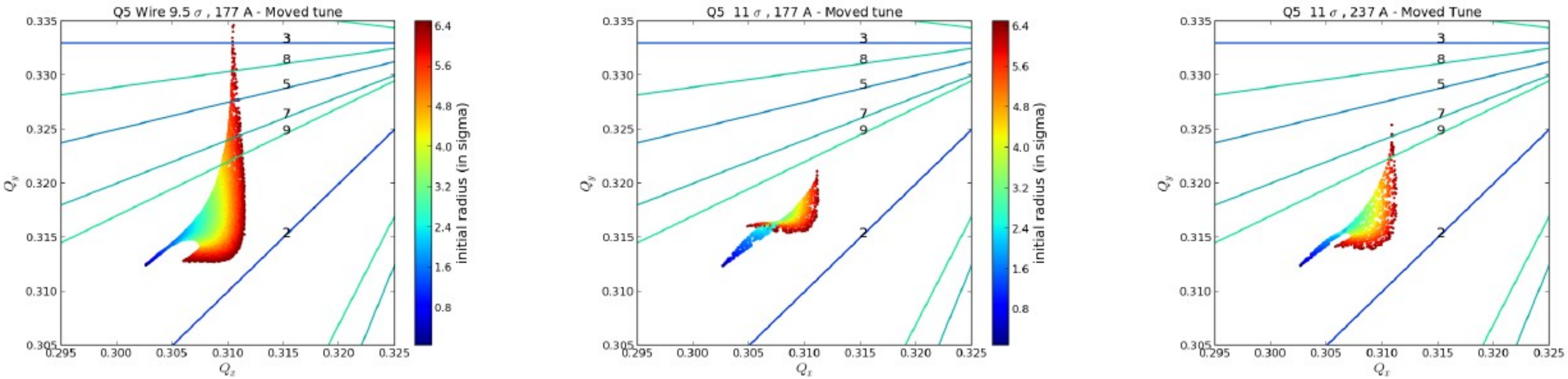


Why BBC has to be local

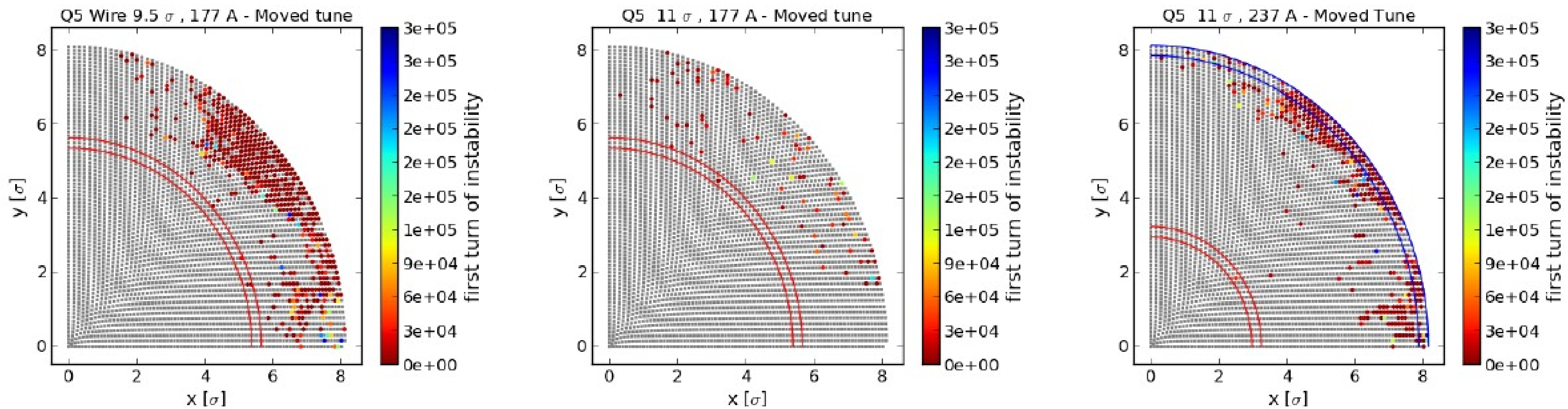
- Ideal location only at '0' or 'multiples of 2π'
  - Unfortunately any other quadrupole, sextupole, octupole error between LR-BB effect and BBC thwarts the good correction (here 2% error)



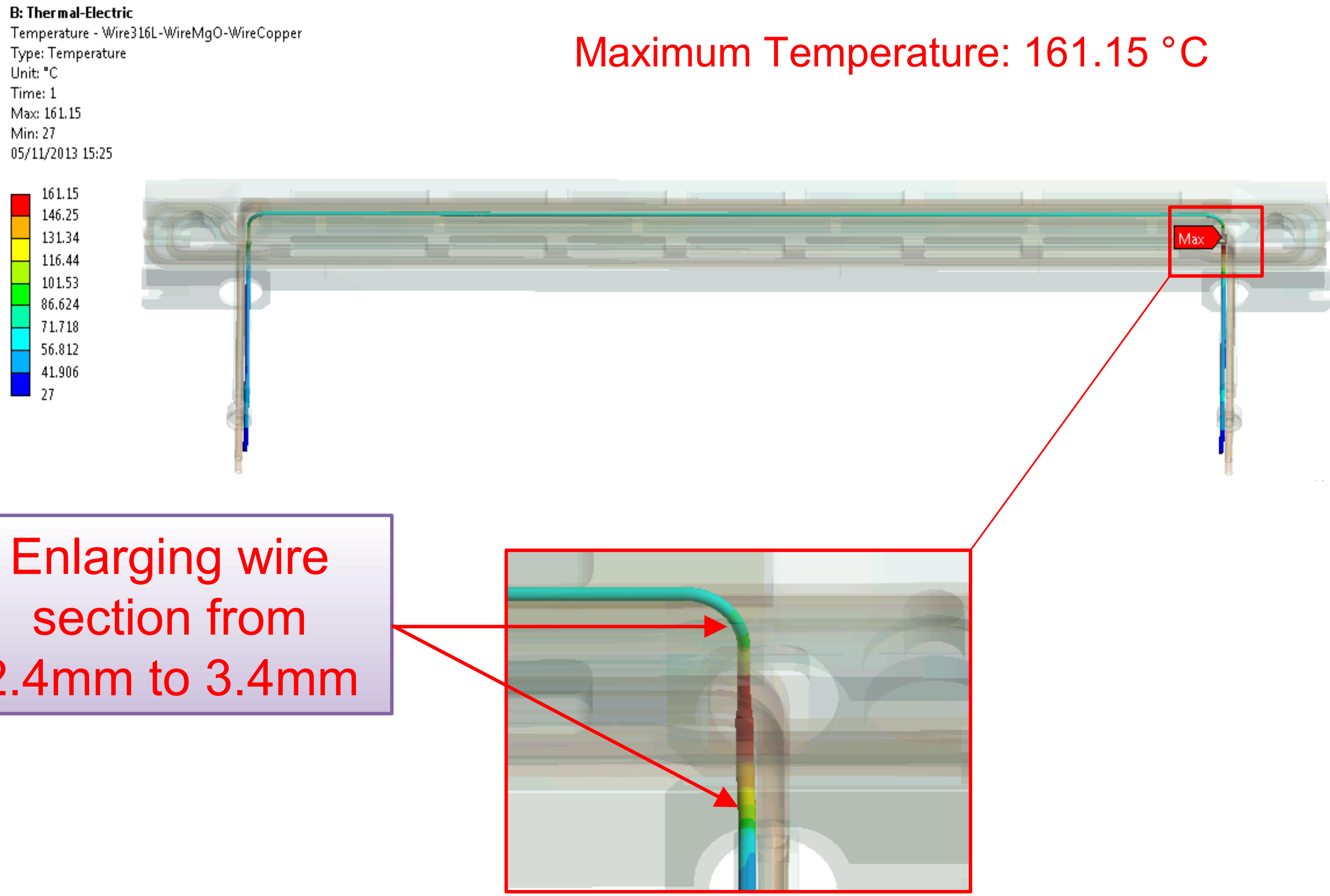
BBC at Q5



Q5 Wire 9.5 σ , 177 A - Moved tune
Q5 11 σ , 177 A - Moved tune
Q5 11 σ , 237 A - Moved Tune
initial radius (in sigma)



Q5 Wire 9.5 σ , 177 A - Moved tune
Q5 11 σ , 177 A - Moved tune
Q5 11 σ , 237 A - Moved Tune
first turn of instability
x [σ]
y [σ]



Maximum Temperature: 161.15 °C

Enlarging wire section from 2.4mm to 3.4mm

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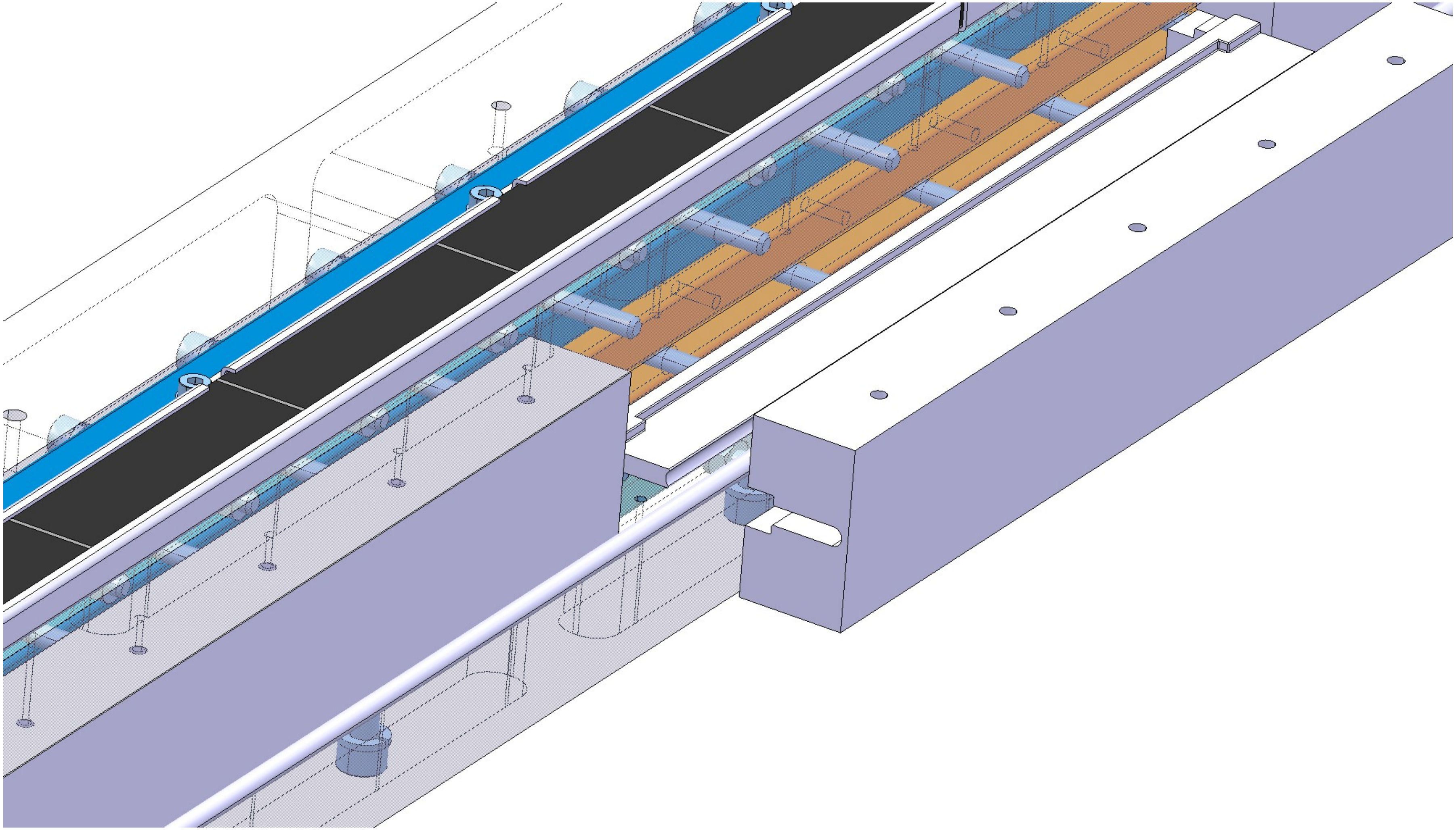
BBC-TCTP Cut-Away – Single Wire



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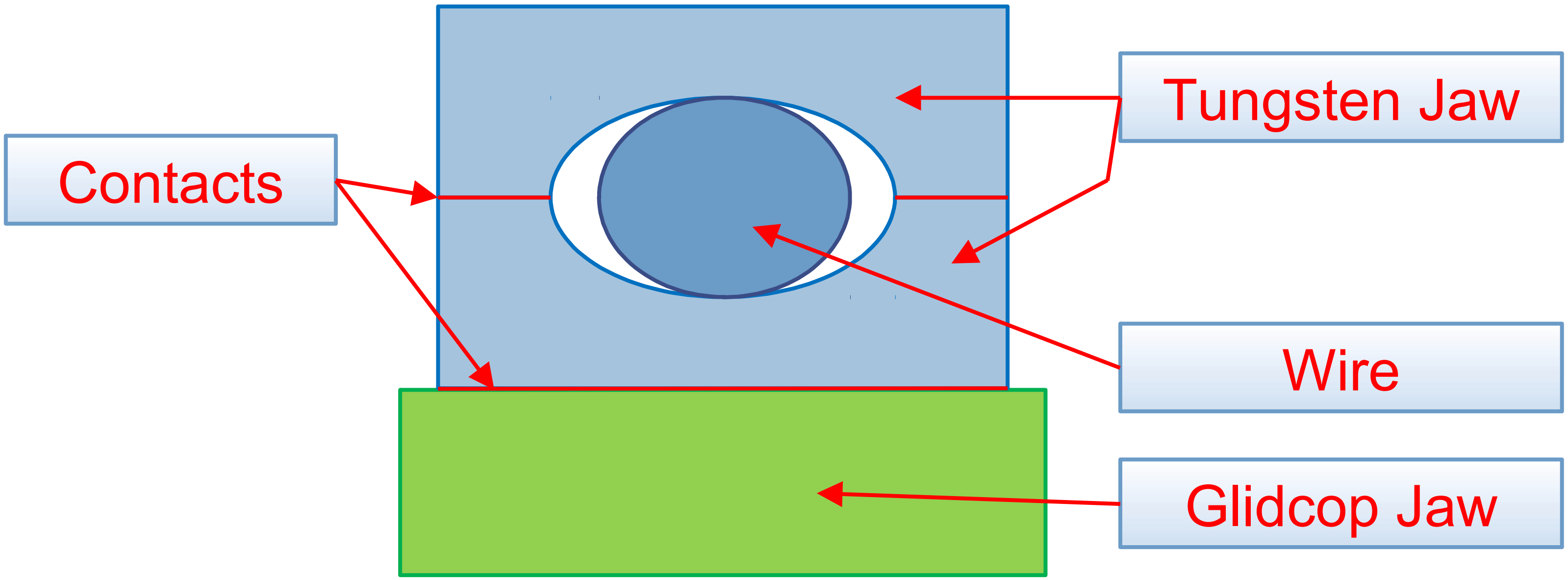
- Ensuring best contact between Collimator parts and Thermocoax wire



- Assessing Mechanical properties of the Thermocoax wire:
  - Ultimate strength
  - Thermal expansion
  - Maximum admissible temperature
  - …

- Mechanical response of the Collimator

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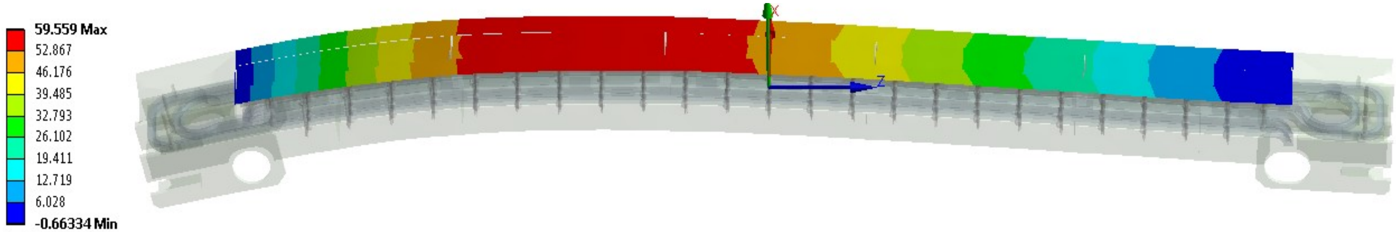
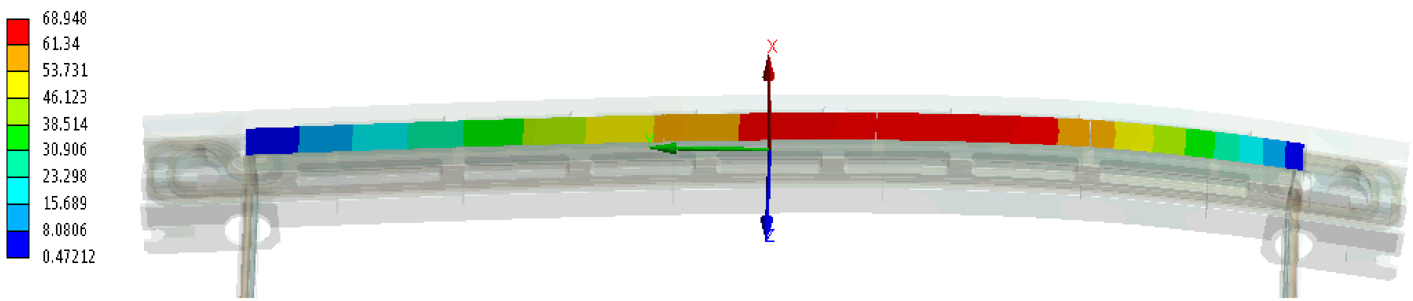
BBC-TCTP Mechanical Response to Heat-Load

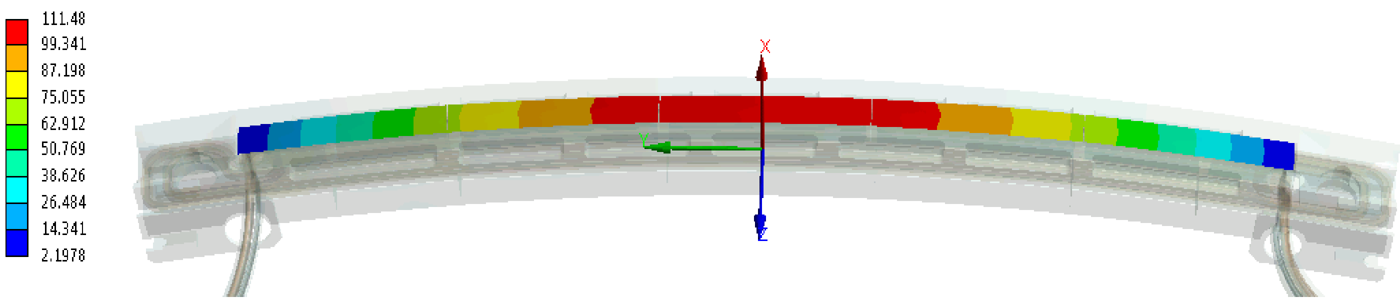
TCTP Collimator **WITHOUT** BBC – Beam heat generation only



TCTP Collimator **WITH** BBC – Thermal deflection: beam heat generation only



TCTP Collimator **WITH** BBC – Thermal deflection: wire heat generation only



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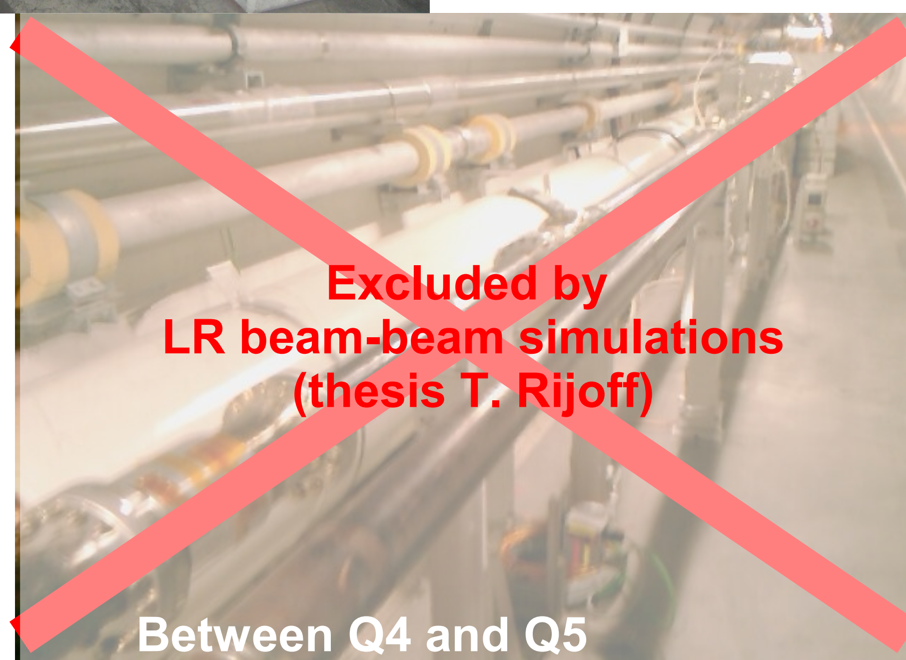
Physical Space IR5
Requires Horizontal BBC



Wire Linear Tune Shift

$$\Delta Q_x = -\frac{\mu_0 L_w I_w}{2\pi B_d \rho}\frac{\beta_x}{4\pi}\left(-\frac{2 d x_w^2}{\left(d x_w^2 + d y_w^2\right)^2} + \frac{1}{d x_w^2 + d y_w^2}\right)$$

$$\Delta Q_y = -\frac{\mu_0 L_w I_w}{2\pi B_d \rho}\frac{\beta_y}{4\pi}\left(-\frac{2 d y_w^2}{\left(d x_w^2 + d y_w^2\right)^2} + \frac{1}{d x_w^2 + d y_w^2}\right)$$

$$d^2 = x_w^2 + y_w^2$$

μ_0 = free permeability

L_w = wire length

I_w = wire current

$B_d\rho$ = magnetic rigidity

$\beta_{x,y}$=betatron function

(x_w , y_w) = wire coordinates

$$\delta(\vec{r}) = -\frac{2Nr_0}{\gamma \; r} \cdot \left[1 - e^{-\frac{1}{4}\left(\frac{r}{\sigma}\right)^2}\right] \cdot \frac{\vec{r}}{r}$$