LHC Beam-Beam Compensator

– Status Update –

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Beam Instrumentation Group, CERN

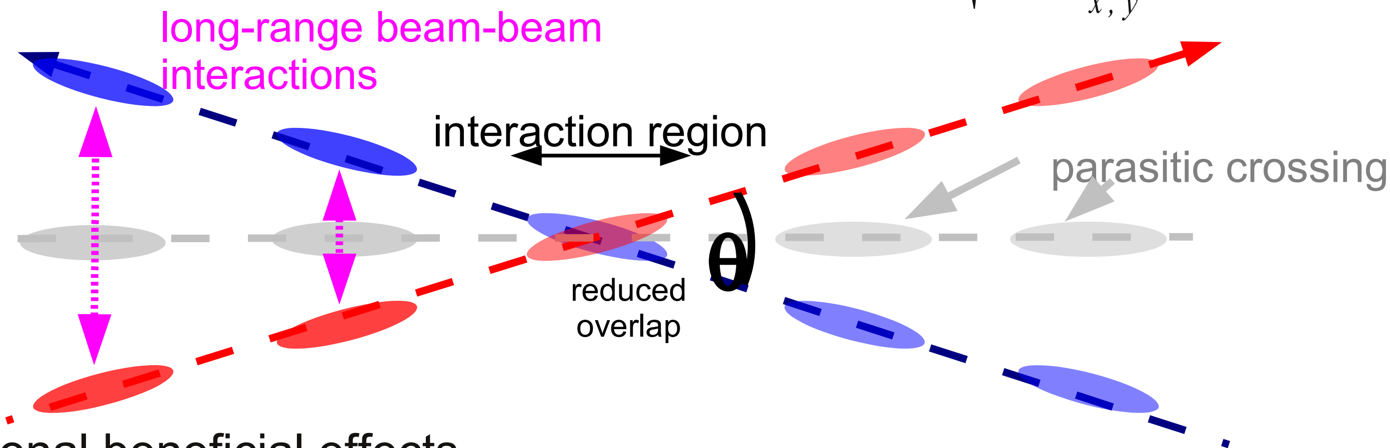
for and with input from:

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), G. Stancari (e-beam lens) 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

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



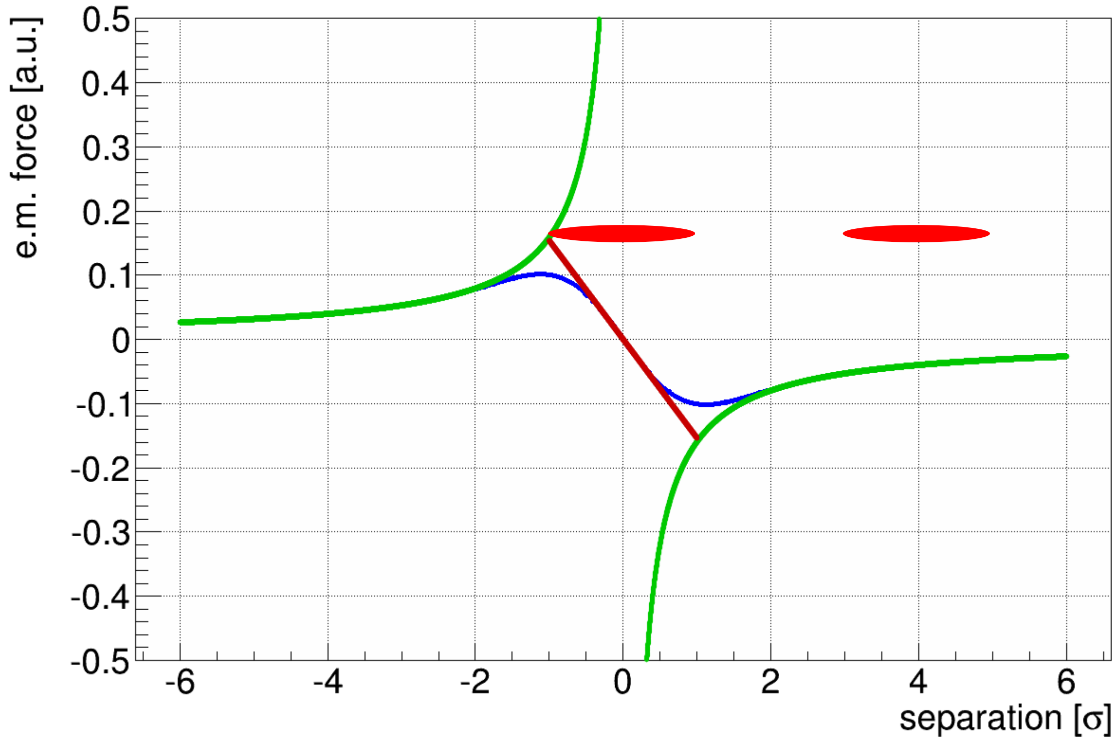
- Additional beneficial effects
  - improves/allows more relaxed collimator settings (more triplet aperture)
  - improved physics-debris loss pattern at TAN (losses more centred)

Beam-Beam Field

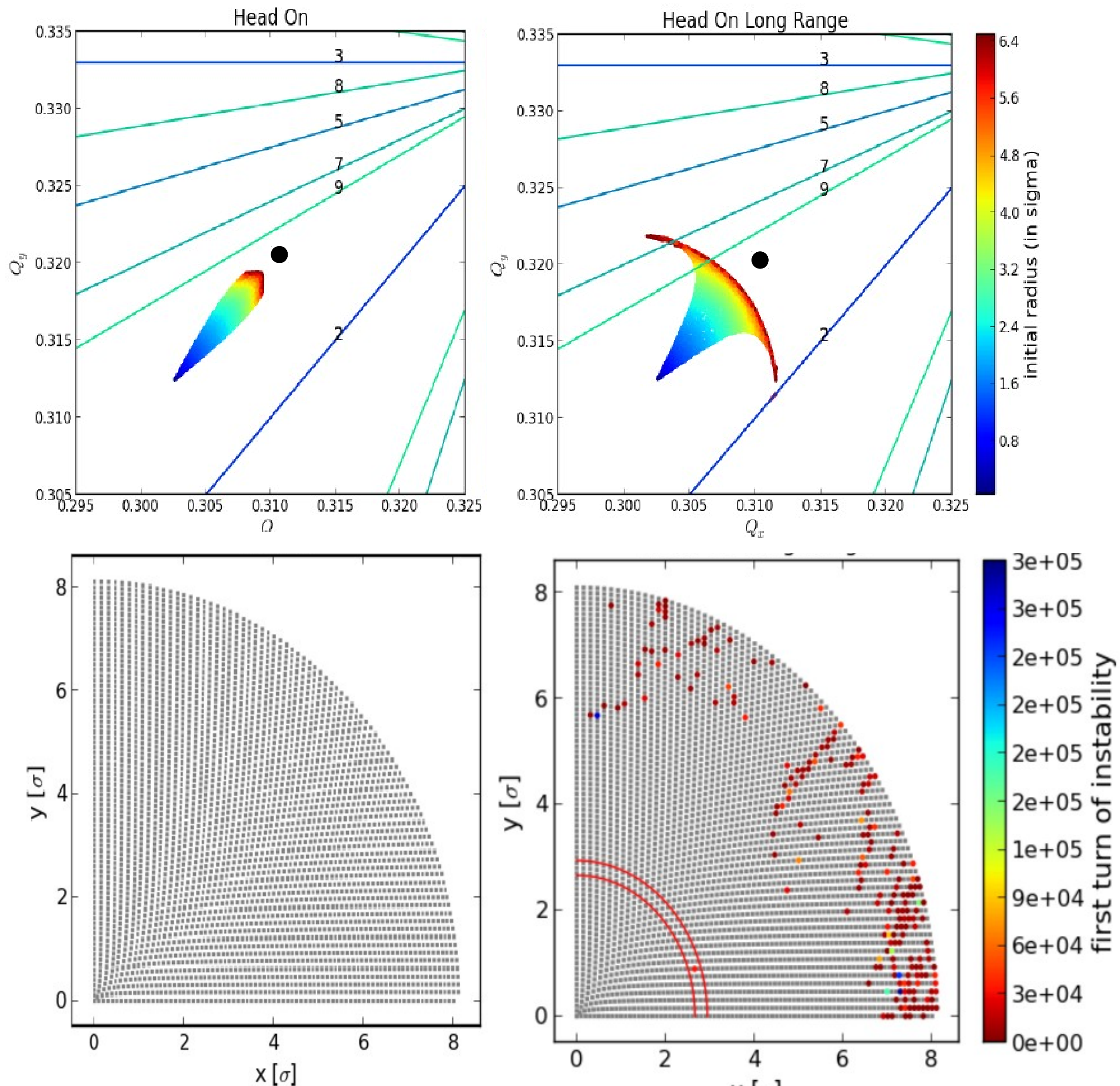
$$E(\vec{r}) = -\frac{Ne(1+\beta^2)}{2\pi\epsilon_0 \; \boldsymbol{r}} \cdot \left[1 - e^{-\frac{1}{2}\left(\frac{r}{\sigma}\right)^2}\right] \cdot \frac{\vec{r}}{\boldsymbol{r}}$$

long-range ~ 1/r

head-on ~ r



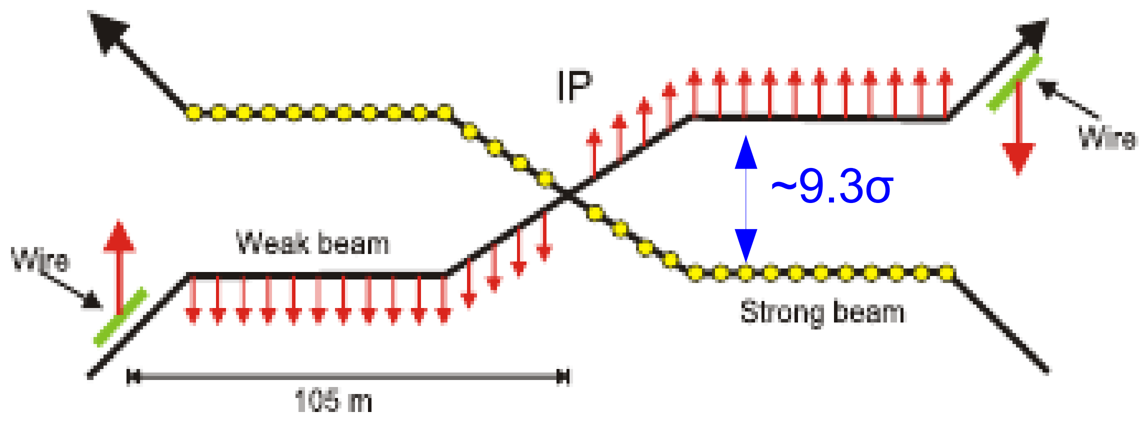
Beam-Beam Interactions – Simulations



analysis: T.Rijoff & F. Zimmermann

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

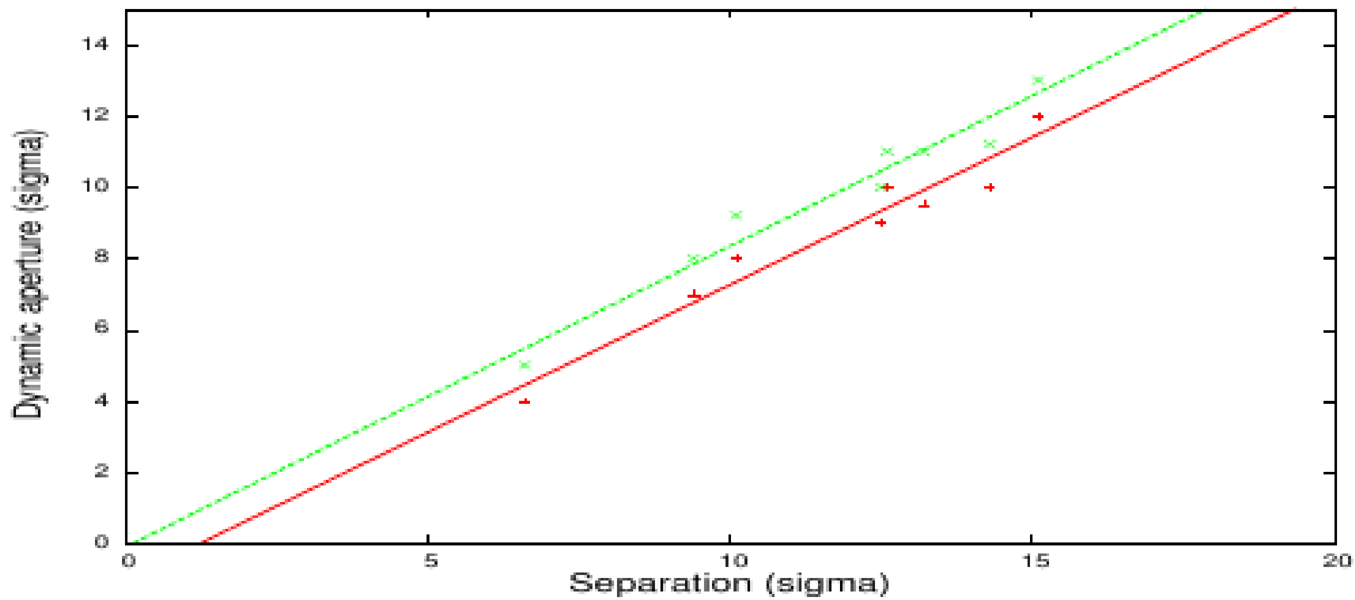
- Initial proposal based on to J.-P. Koutchouk's note: CERN-SL-2001-048-BI

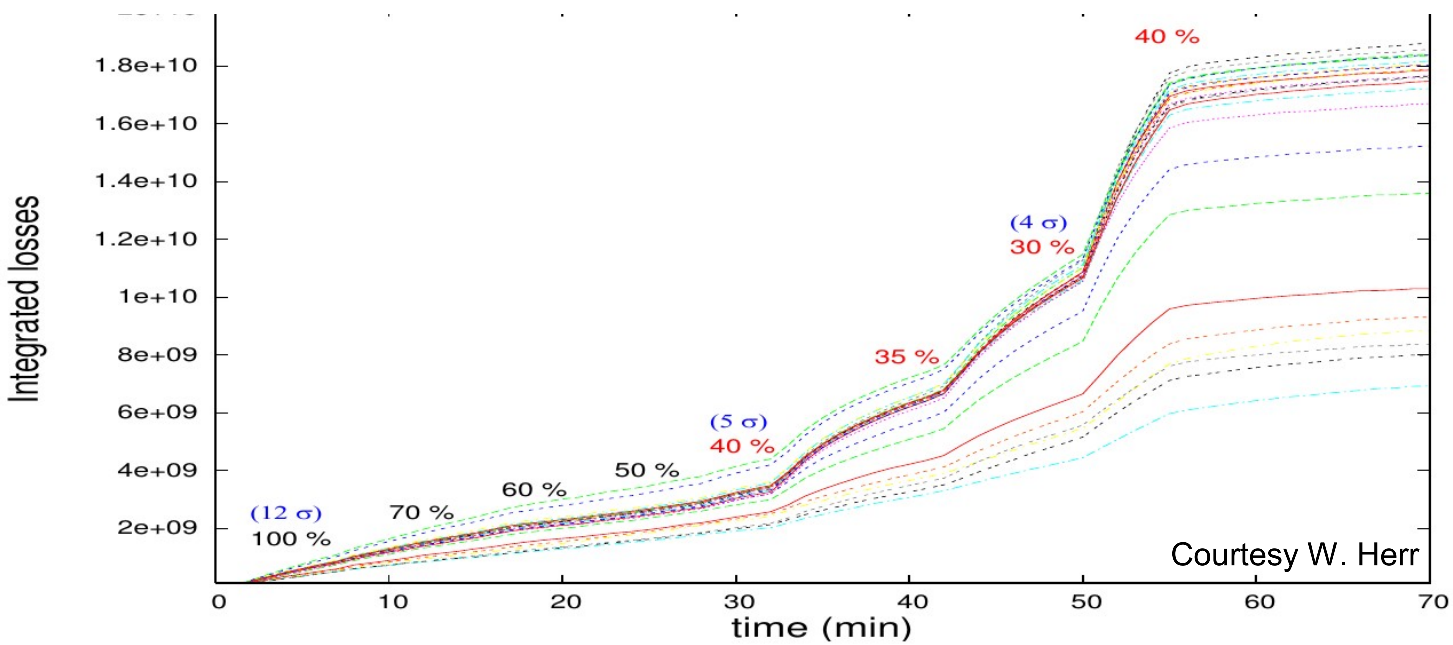


- Since, SPS wire-wire and RHIC beam-wire experiments demonstrated that:
  1. *"detrimental wire effect on life-time can be compensated by another wire"*
  2. *Partial BBC results at RHIC*
  3. *Benchmark of numerical tool chain → indication of what to expect at LHC*

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

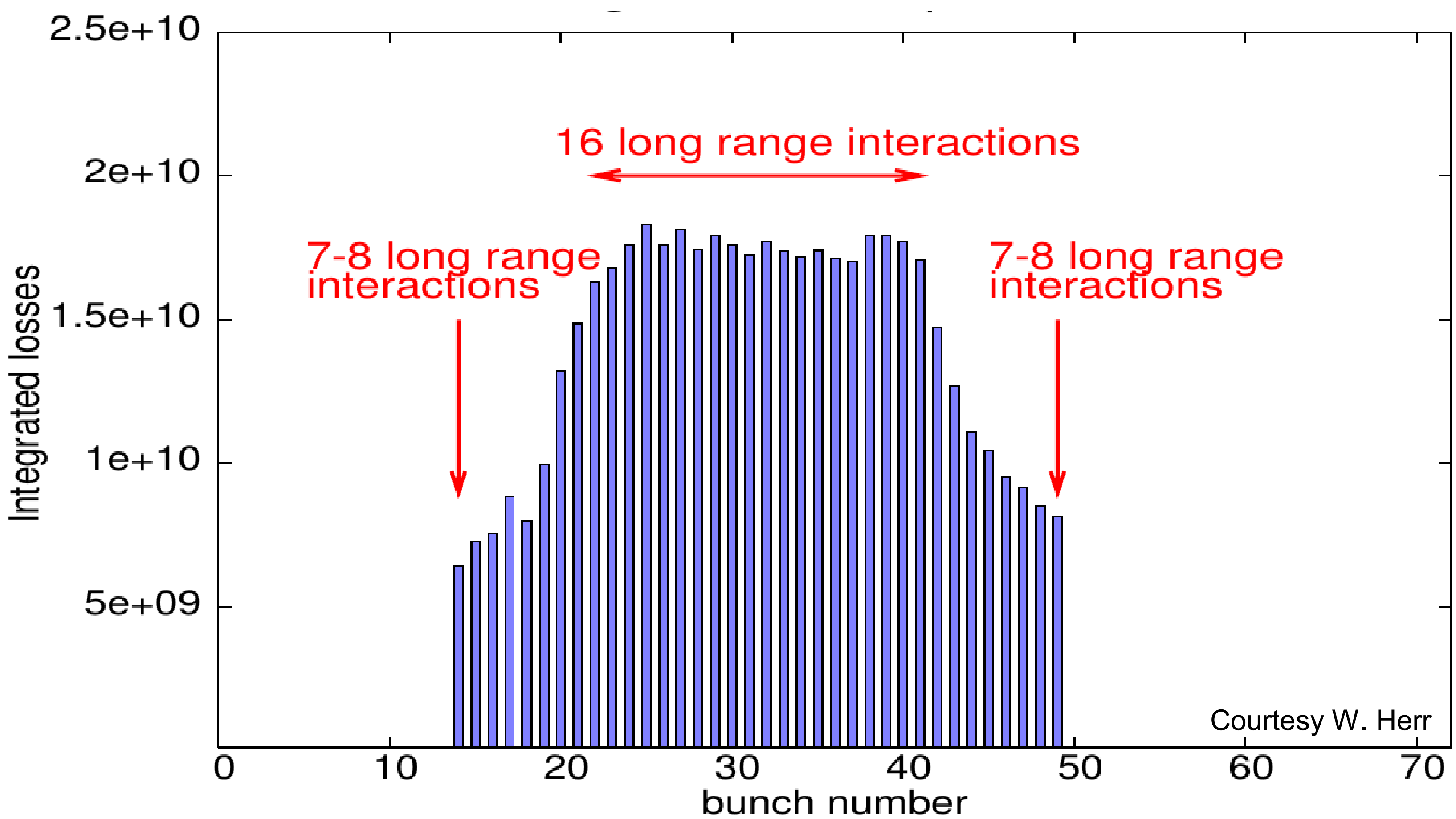
Beam-Beam Interactions – LHC Experiments I/II





Beam-Beam Interactions – LHC Experiments II/II

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

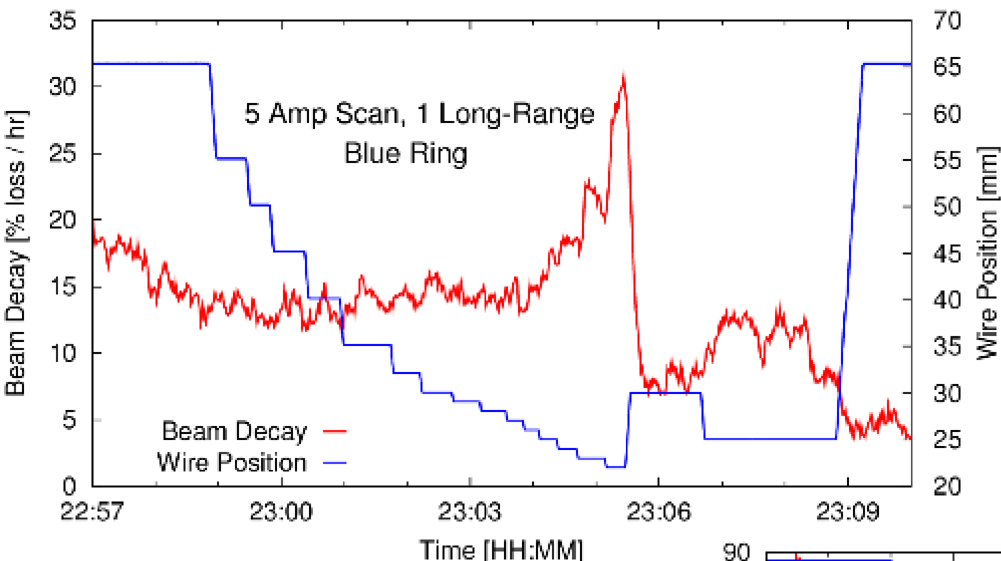


  – more long-range encounter ↔ higher losses

Beam-Beam Interactions – RHIC Experiments

III: LRC Compensation Exp, 5A

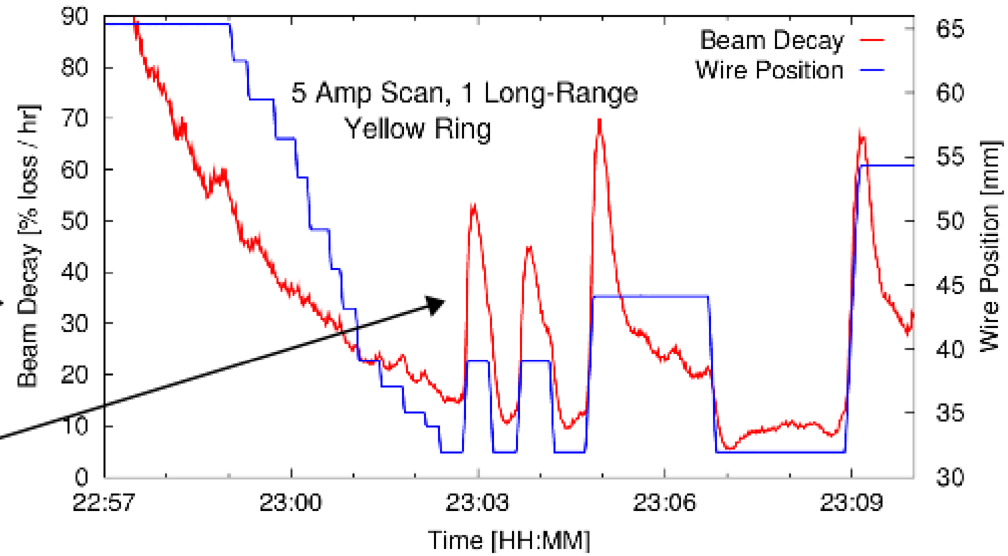
R. Calaga, CERN



Blue Ring

No visible effect

Yellow Ring



Losses increase when compensation is removed !!!

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

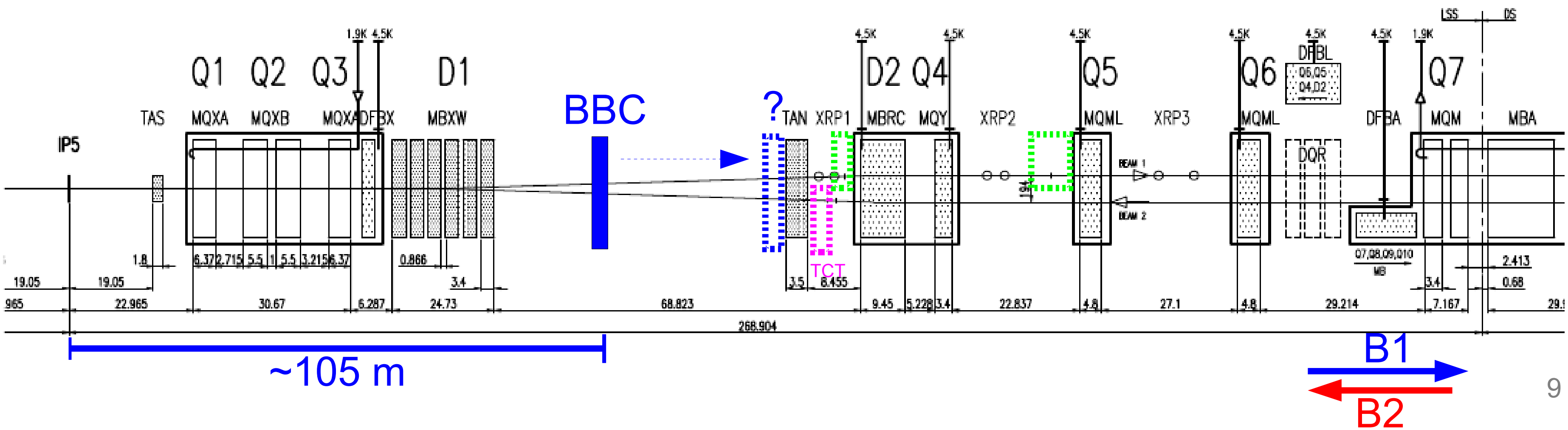
Decision of the Project Engineer :	Decision of the PLO for Class I changes :
☐ Rejected.	☐ Not requested.
☐ Accepted by Project Engineer, no impact on other items. *Actions identified by Project Engineer*	☐ Rejected.
☑ Accepted by Project Engineer, but impact on other items. *Comments from other Project Engineers required. Final decision & actions by Project Management*	☑ 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 :

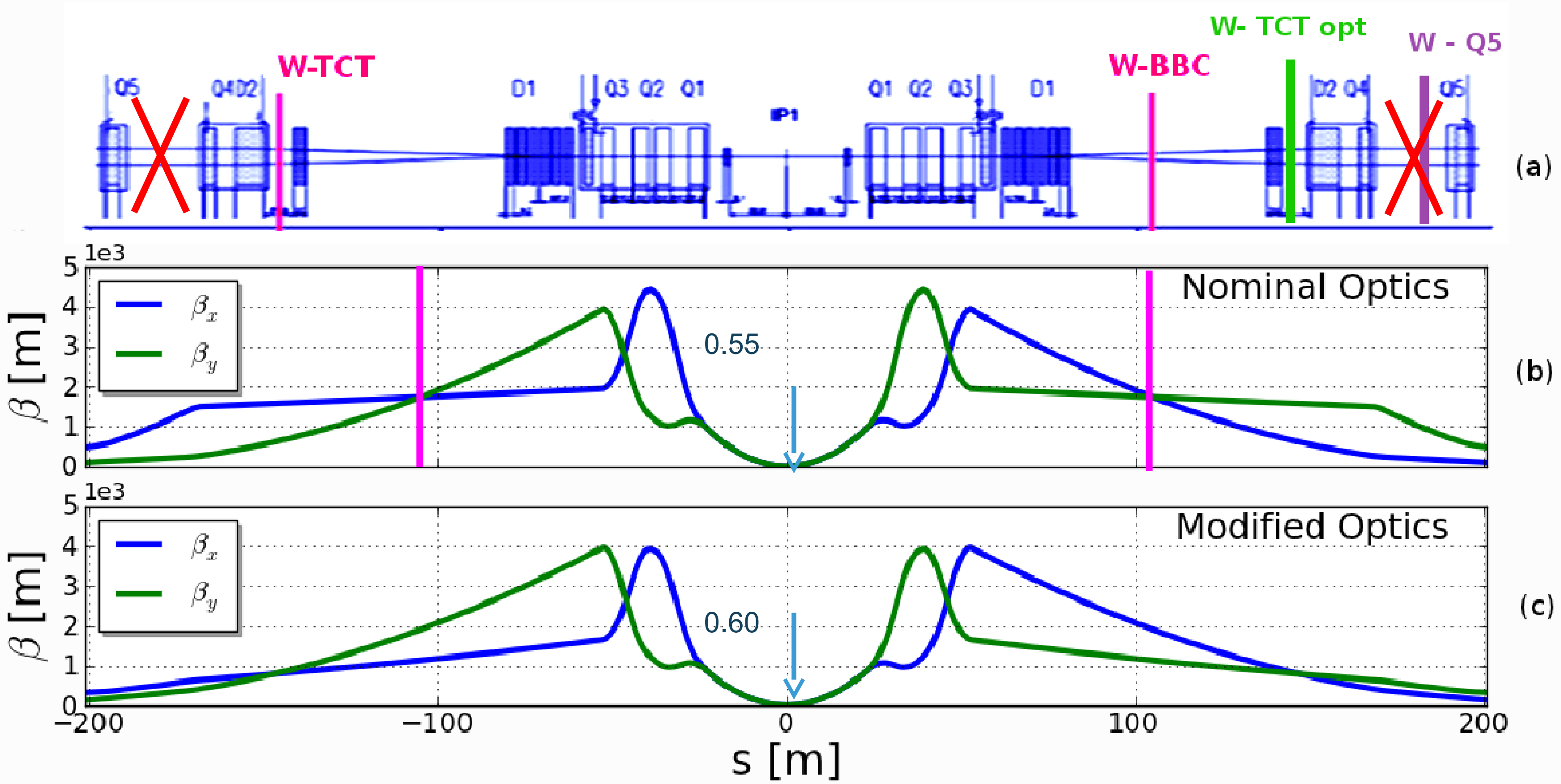
Modify the drawings and Equipment codes concerned to reflect the changes described in this ECO.

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

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



Analysed Cases Summary



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

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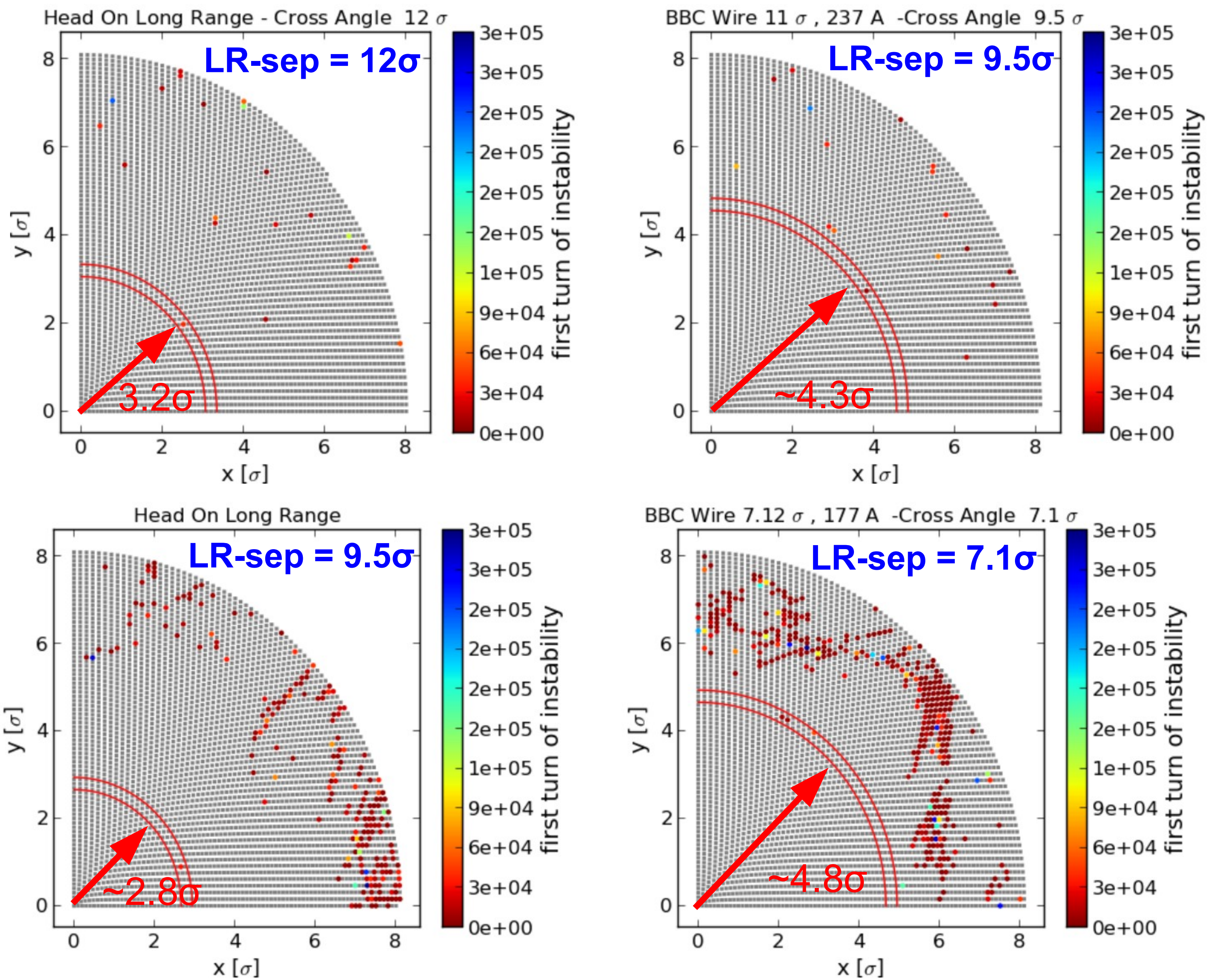
Nominal BBC – Crossing Angle Reduction Performance



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Post-LS1 BBC Prototype – Test Scenario

- 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.

T. Rijoff, F. Zimmermann

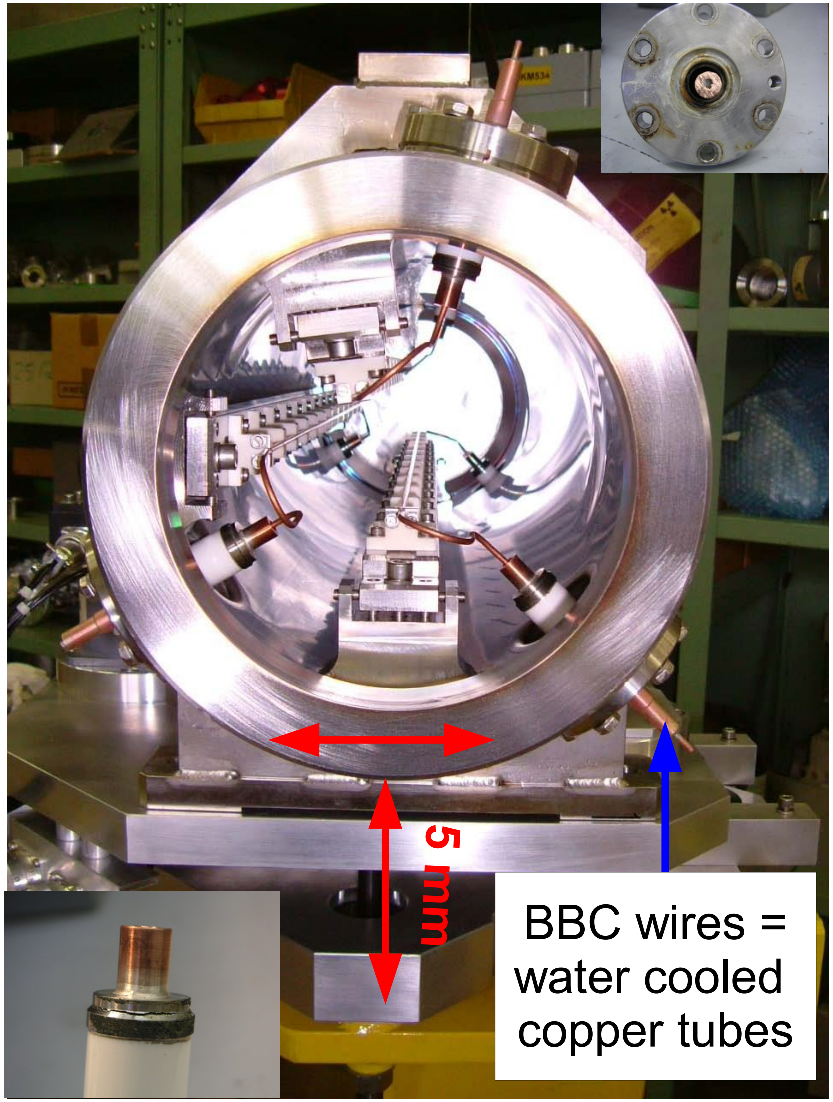
Initial SPS Prototype Proof-of-Concept Design

- 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.



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

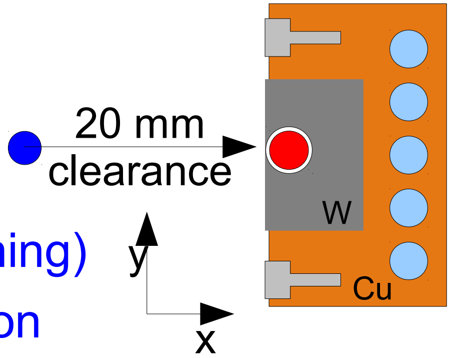
- Primary aim: benchmark existing simulations and predictions prior to LS-2

- 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

Summary of LHC BBC Prototype Specifications

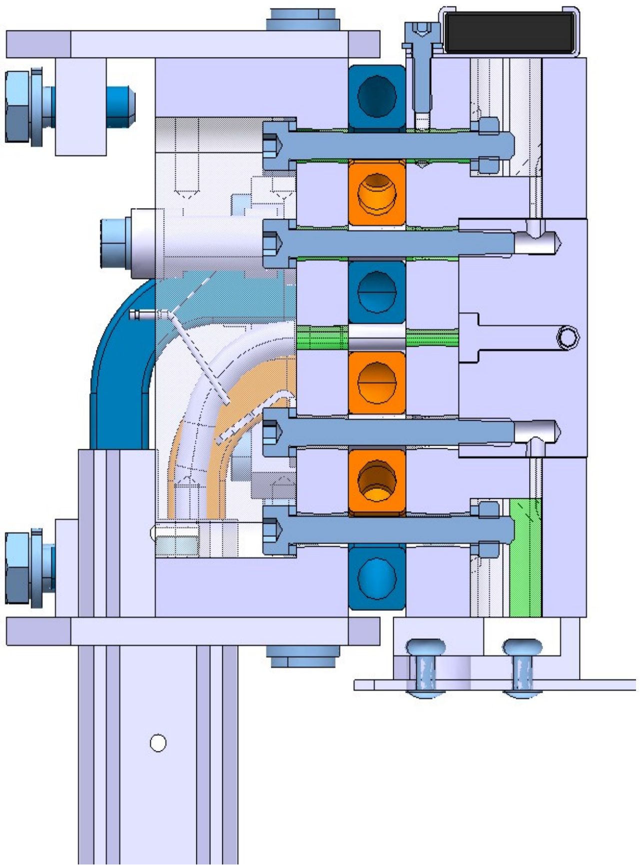
- Wire-in-jaw design:
  - Embedded (insulated) Cu wire inside W block
  - Possibility of 1+n wires (spare/redundancy)?
  - >100 um between wire and cleaning surface (RF screening)
  - more compatible w.r.t. collimation and machine protection

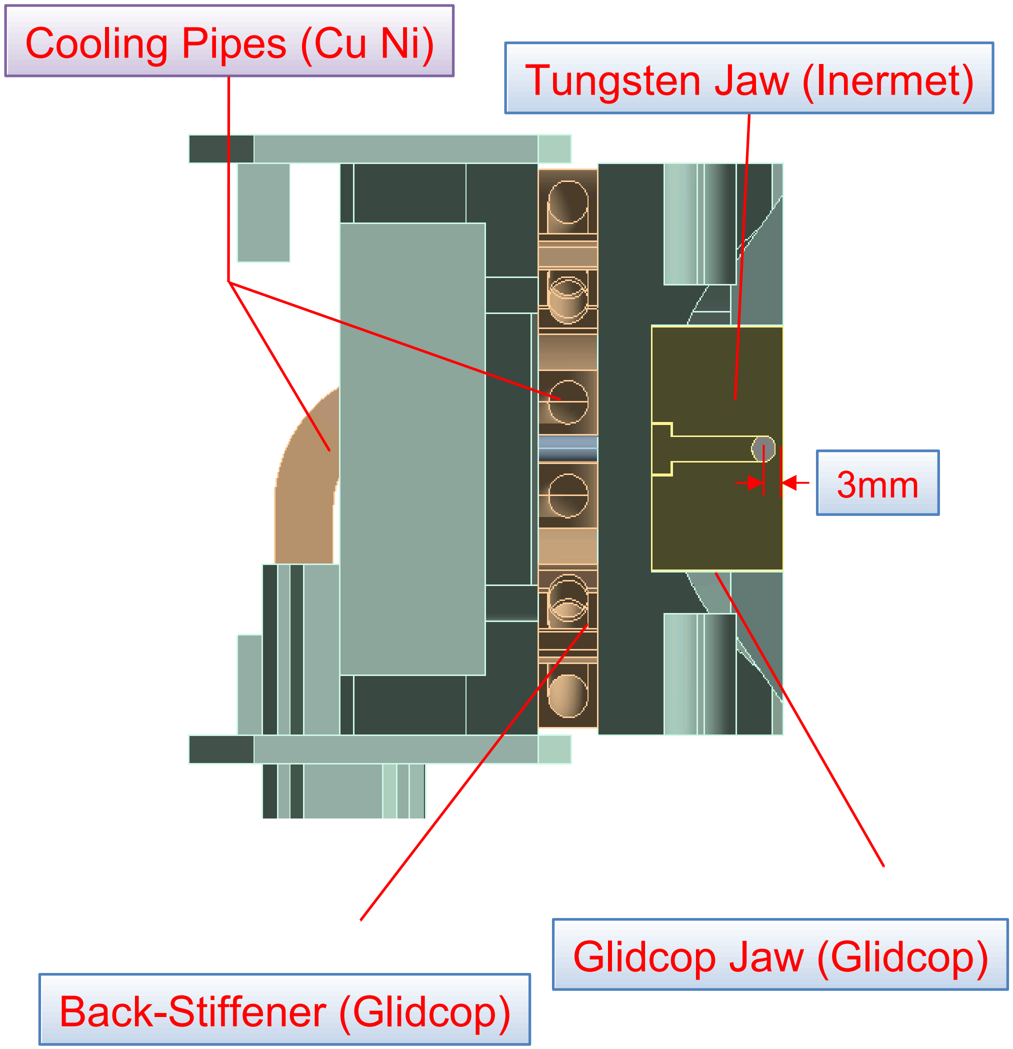


- Wire parameters:
  - Solid (round) wire radius of ~ 1mm and e.g. 1 m length
  - sub-σ level of hor./ver. position control (e.g. 0.1 mm)
  - nom. scheme: $I \cdot l_{wire} = I_{peak} \cdot \sqrt{2\pi} \cdot \sigma_s \cdot n_{parasitic} \cdot l_{wire}$ = 72 … 350 Am (max.)
  - DC compensation only
 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

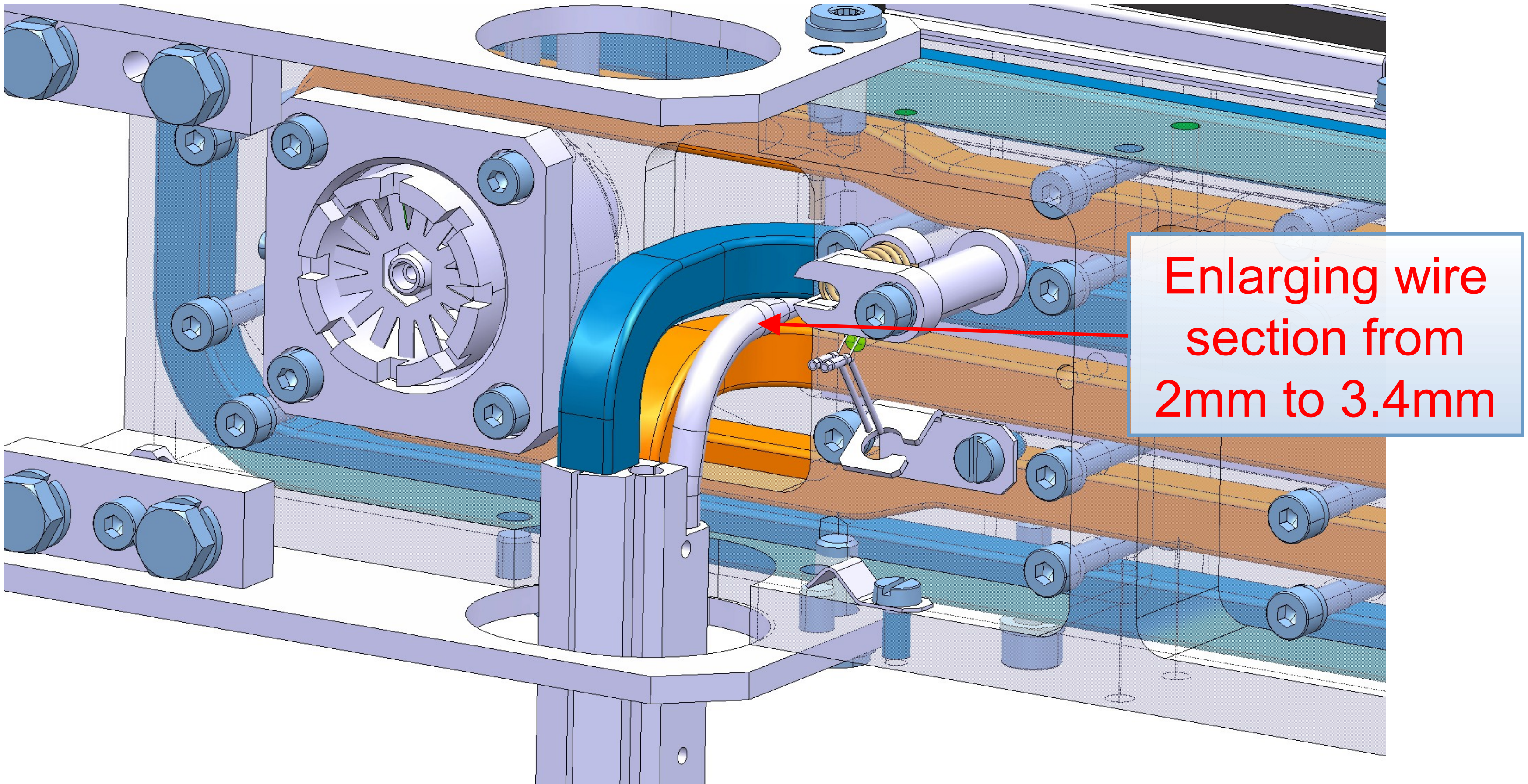
Combined Collimator & BBC Function
Improved Wire-in-Jaw Design I/II





G. Maitrejean, L. Gentini

details → A. Bertarelli's talk



G. Maitrejean, L. Gentini

- 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 II/II
– Possible Nominal BBC Installation for HL-LHC

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

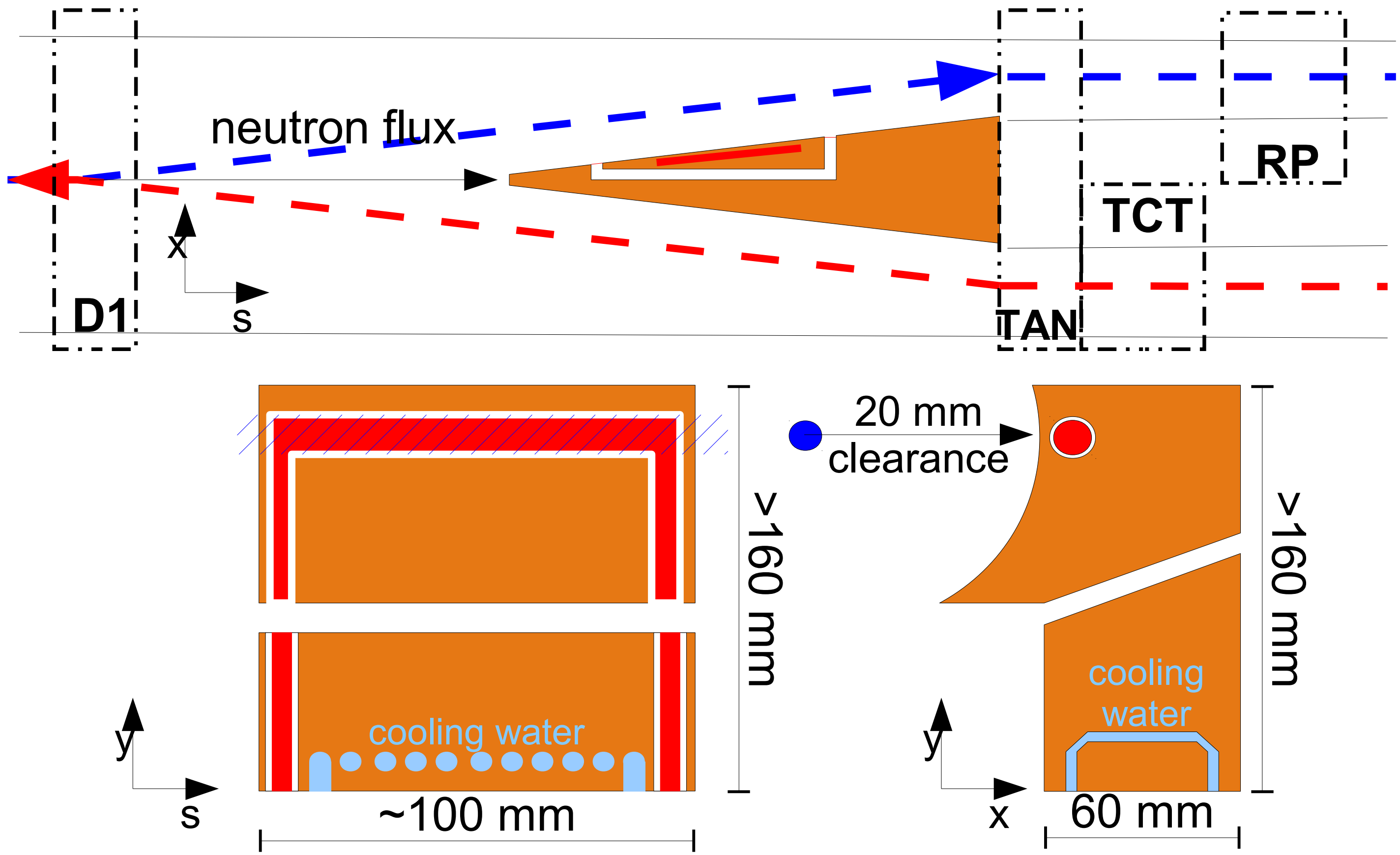
- Several independent predictions, all consistent and quite promising w.r.t. potential to reduce the crossing angle, however

- 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

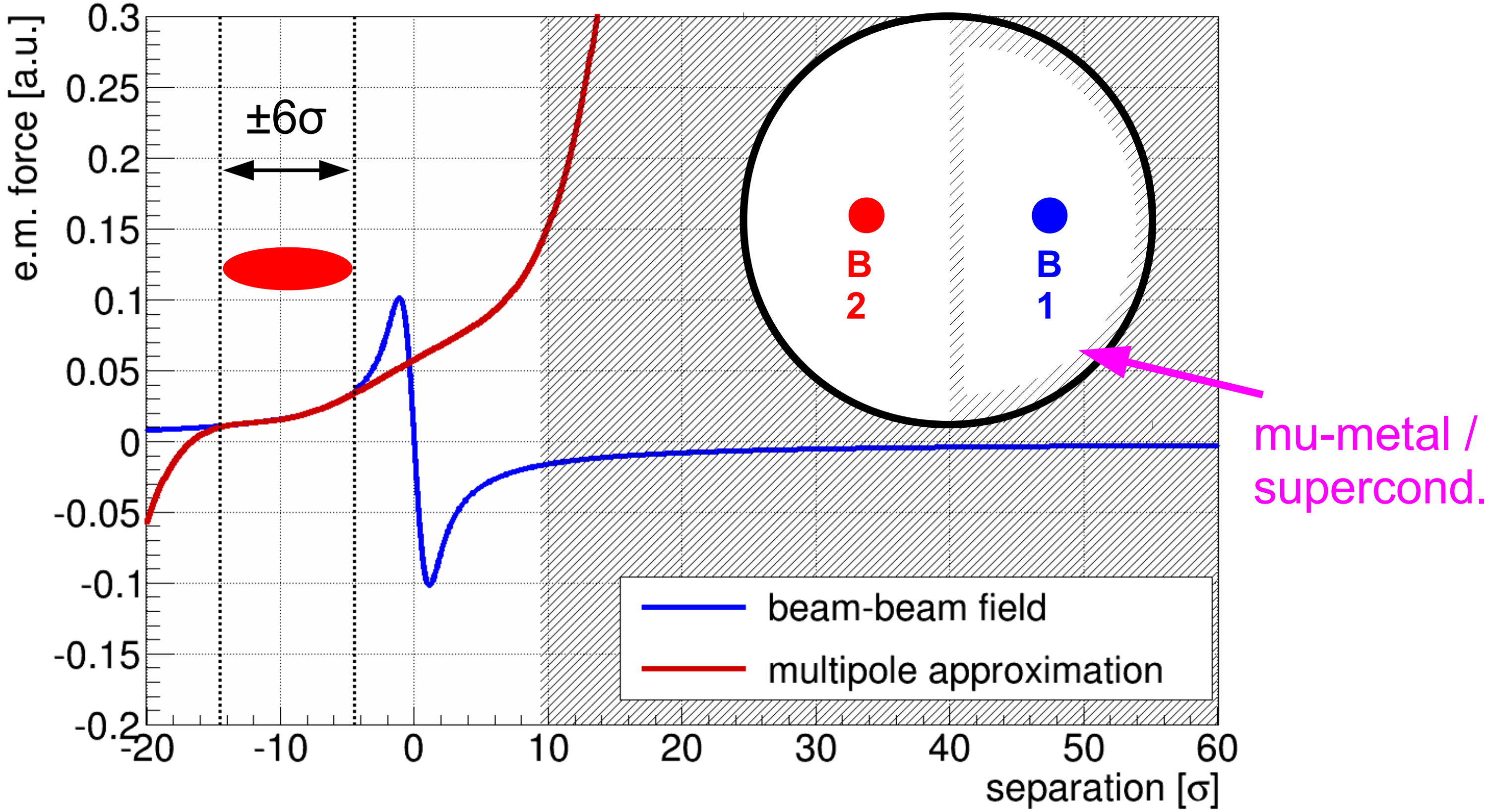
HL-LHC Option 1:
Scalled Wire-in-Jaw Design placed between D1 ↔ TAN



- 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

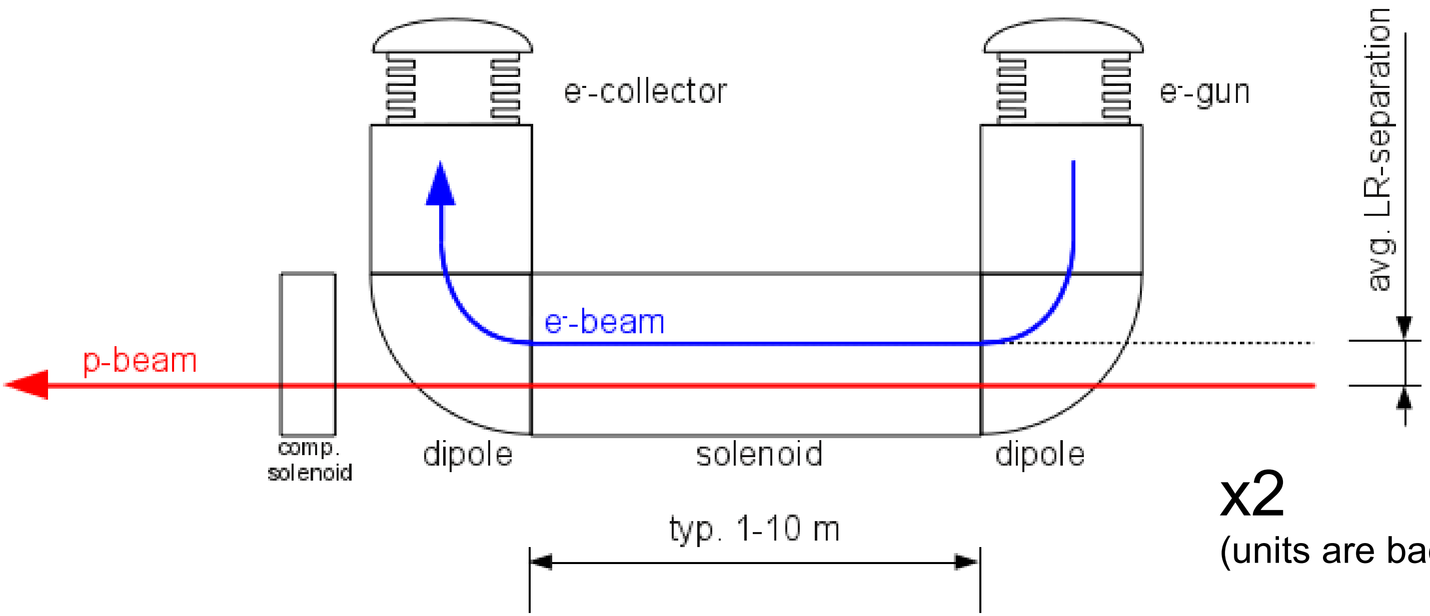
- Long-range approximation with 8-10-pole off-centre multi-pole field



- 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

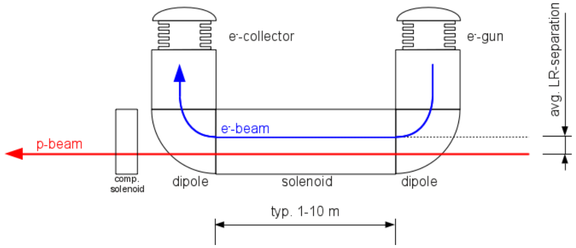
- E-beam has by-design perfect 'wire' field distribution



x2
(units are back-to-back)

- similar to existing e-cooler, (hollow-) e-lenses used at Tevatron & RHIC, however: offset e-beam! → <u>much</u> 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):

$$B \geq B_{th} \approx 1.3 \frac{e N_p^- \sqrt{\xi_x \xi_y}}{a^2 \sqrt{\Delta \nu \nu_s}} \longrightarrow$$

FNAL: 1.2 T
BNL: 14 T

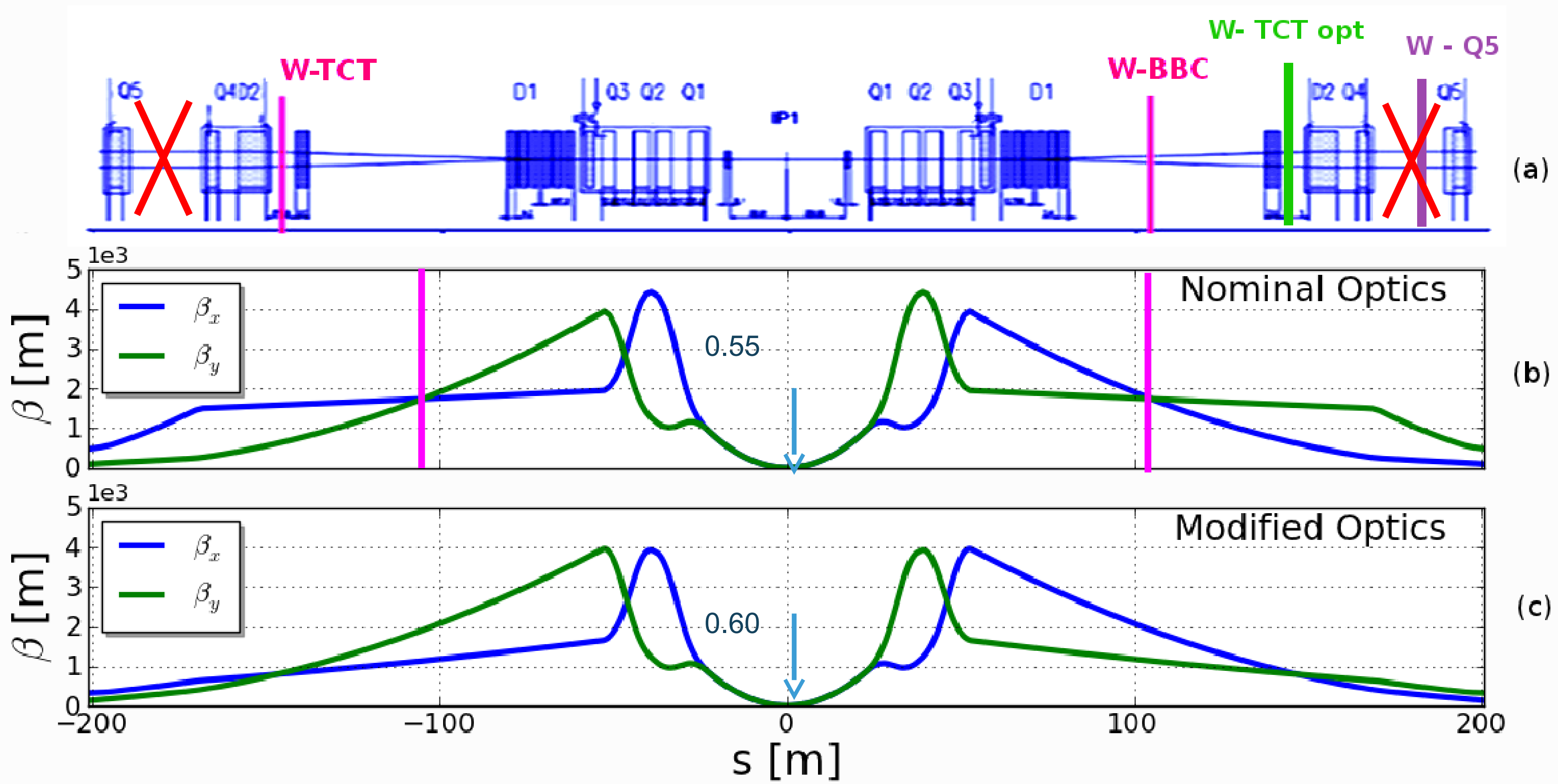
FNAL: $\xi_{x/y} \approx 0.01$, $N_p = 6 \cdot 10^{10}$, $\nu_s = 1 \cdot 10^{-3}$, $\Delta\nu = 0.01$, $a \approx 1.0$ mm
RHIC: $\xi_{x/y} \approx 0.011$, $N_p = 3 \cdot 10^{11}$, $\nu_s = 5 \cdot 10^{-4}$, $\Delta\nu = 0.011$, $a \approx 0.8$ mm

  - LHC $\nu_s = 2 \ldots 5 \cdot 10^{-3}$ → 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

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

Conclusion I/II

- 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

- 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
  - best case: scale wire-in-TCTP design for HL-LHC
  - back-up option: integrate LR-BBC at nominal location (D1-TAN)

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

Conclusion II/II

- 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

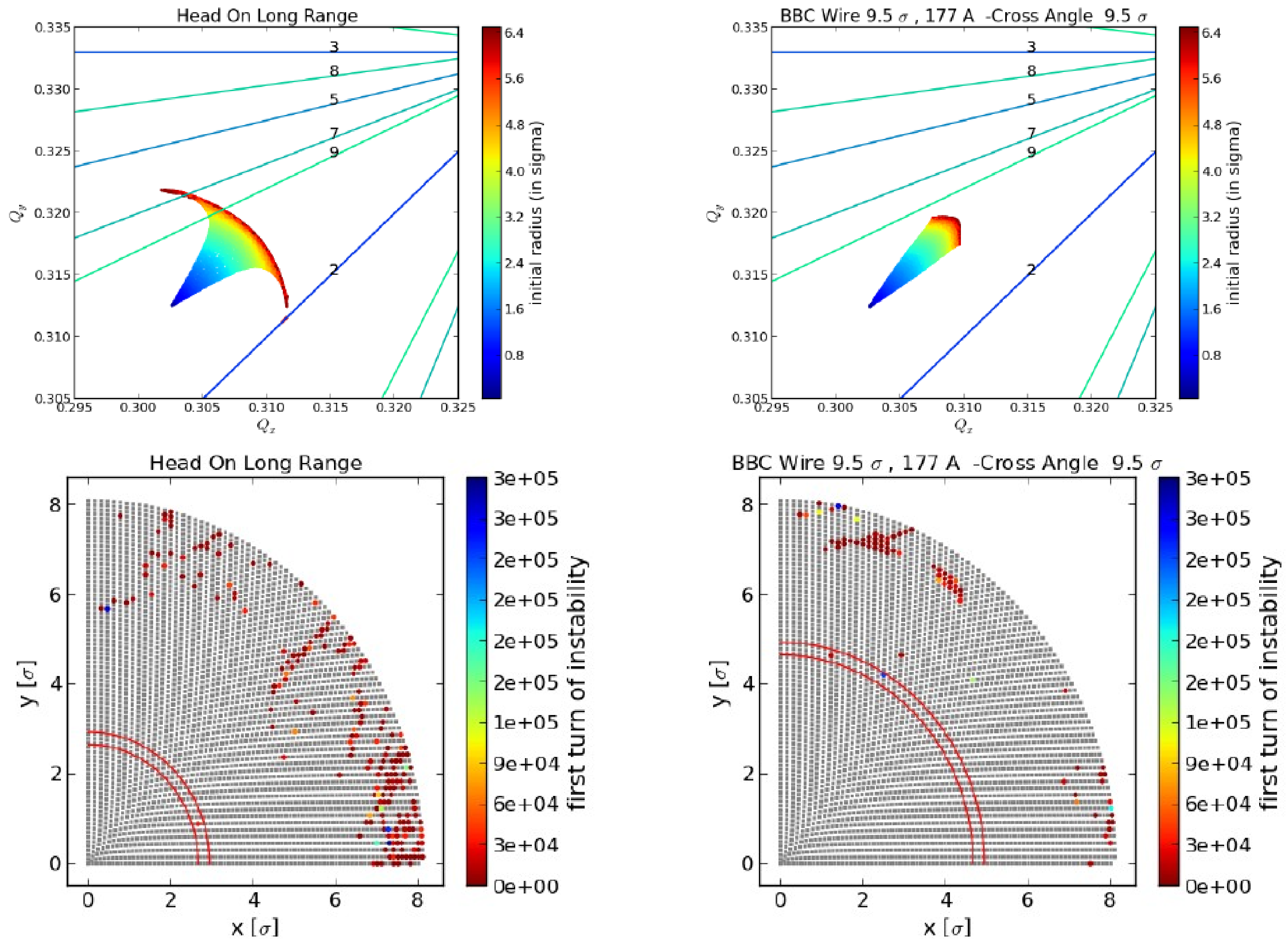
- Two more-realistic/promising nominal implementation options for HL-LHC:
  A) Wire-in-jaw design → scale TCTP exp. and integrate between D1-TAN
    - Need to respect collimator hierarchy for cleaning & MP

  B) 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

- BBC should be between D1 and TAN (4 devices/beam: [L/R][1/5].B[1/2])
  - Estimated length: ±15 m/device (was ±1.5 m/device)
  - The precise location will depend on the technology:
    - e-beam (solenoid) or superconducting multipole → close to D1
    - wire-based device → closer to TAN

Reserve slides

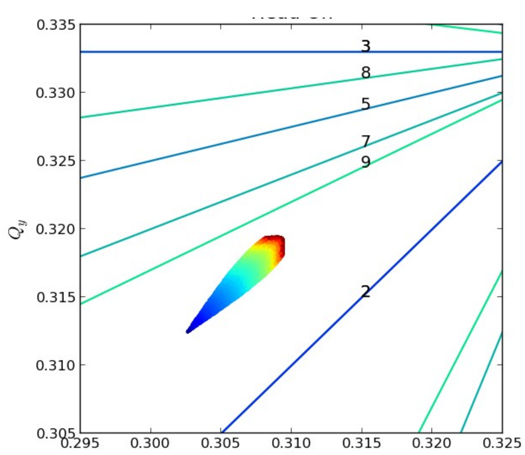
Predicted BBC Performance for Nominal LHC



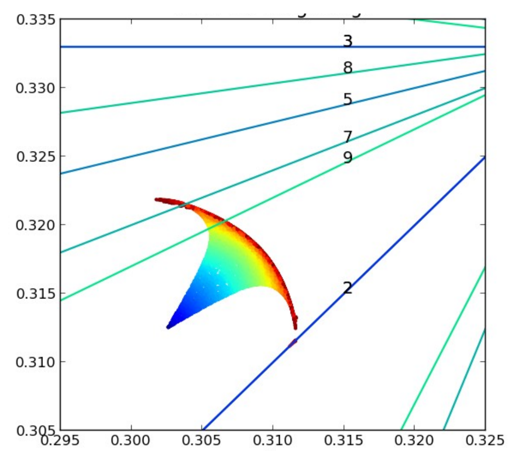
~2σ dynamic aperture gain! → can reduce crossing angle → more Luminosity!

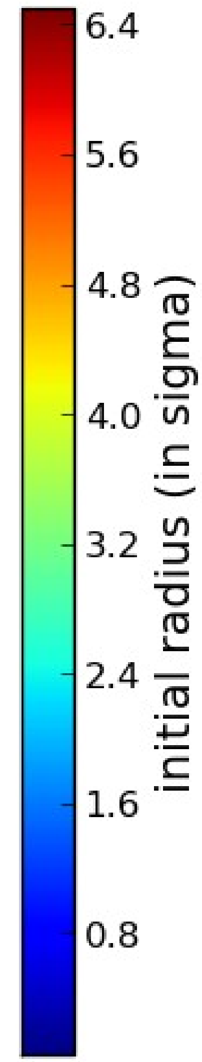
Best Tune Results

Head on

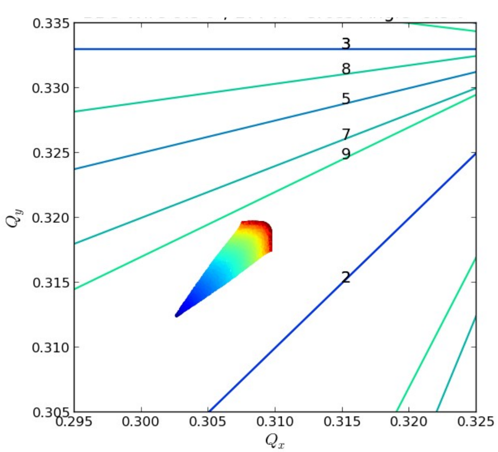


Head on Long Range

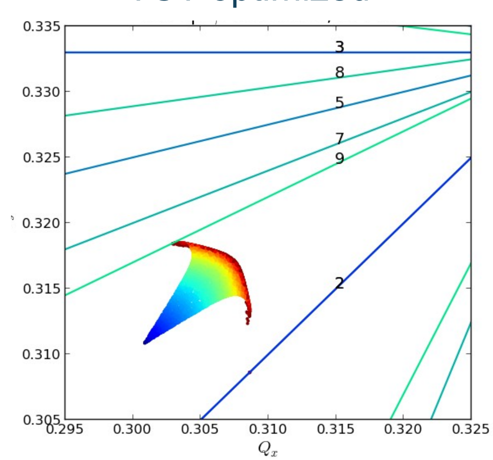




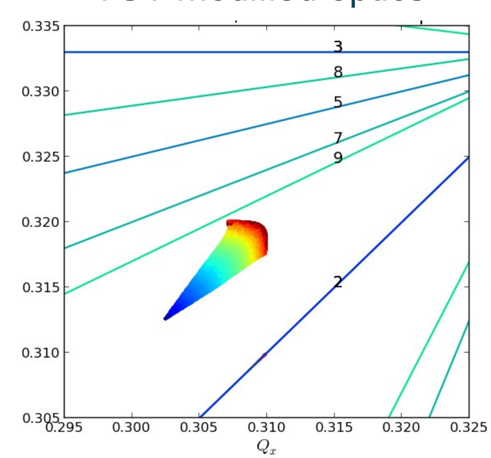
BBC Wire



TCT optimized



TCT modified optics



Wire at 9.5 σ – 177 A

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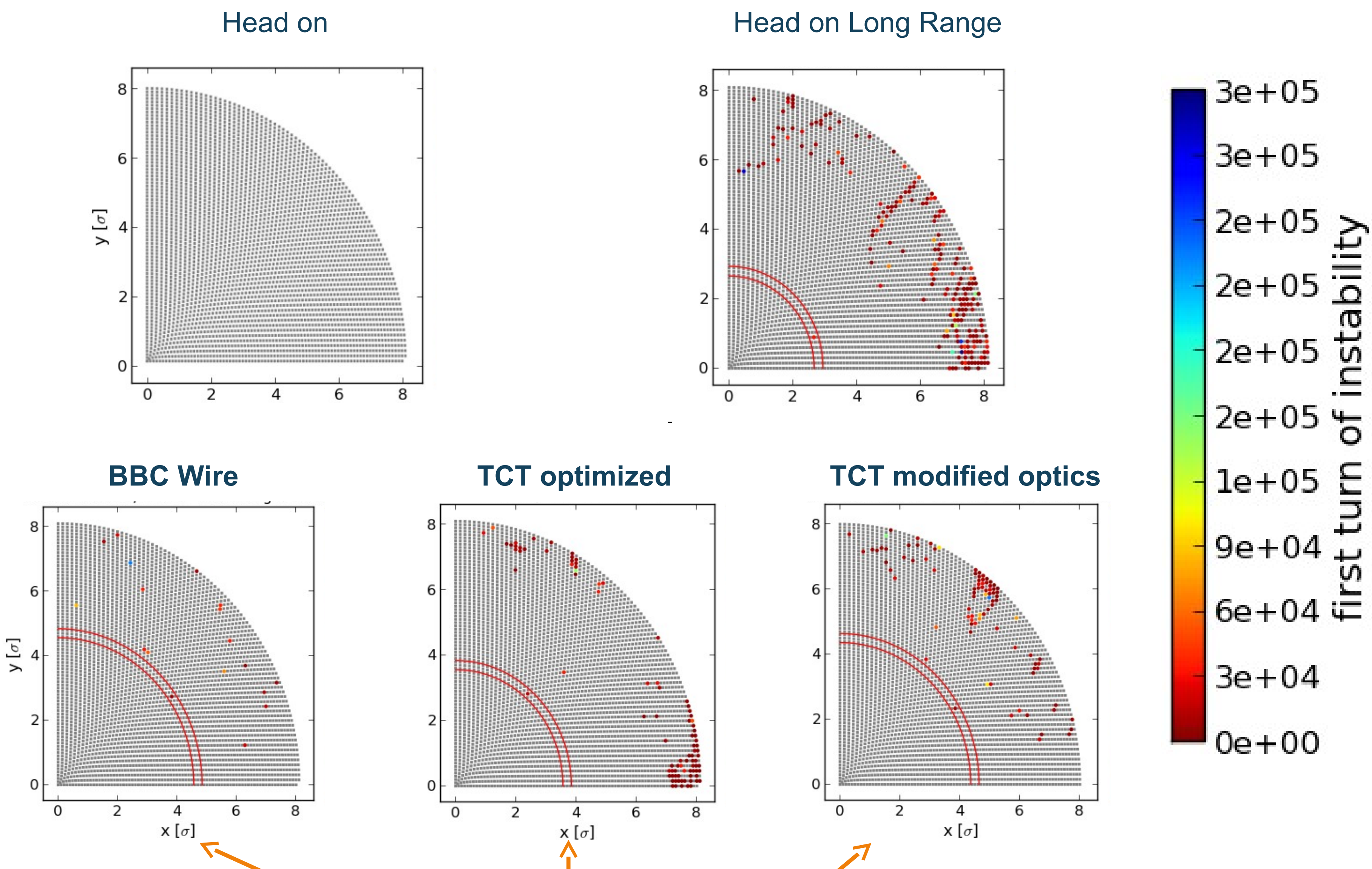
Best Stability Results



Wire at 11 σ – 237 A

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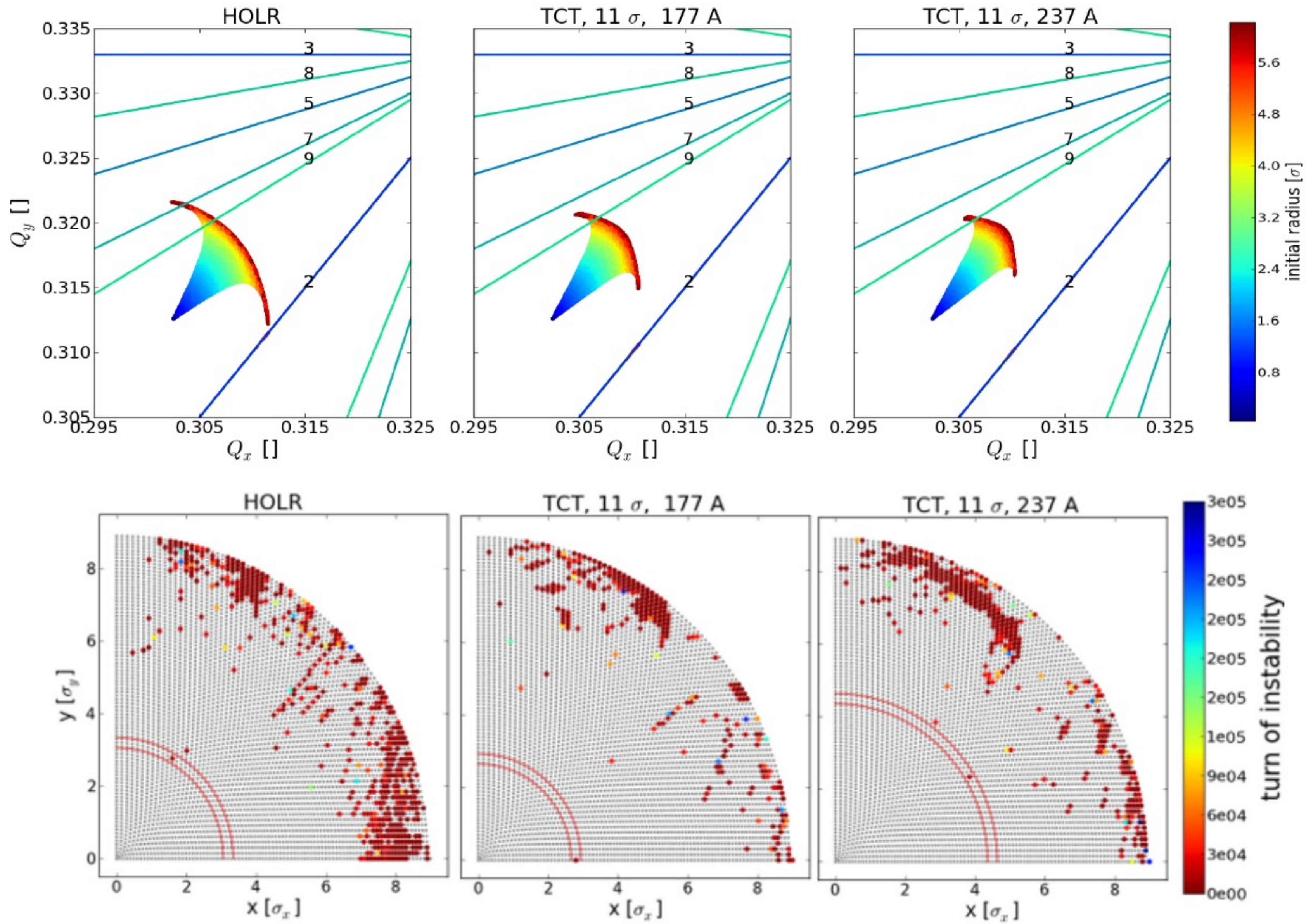
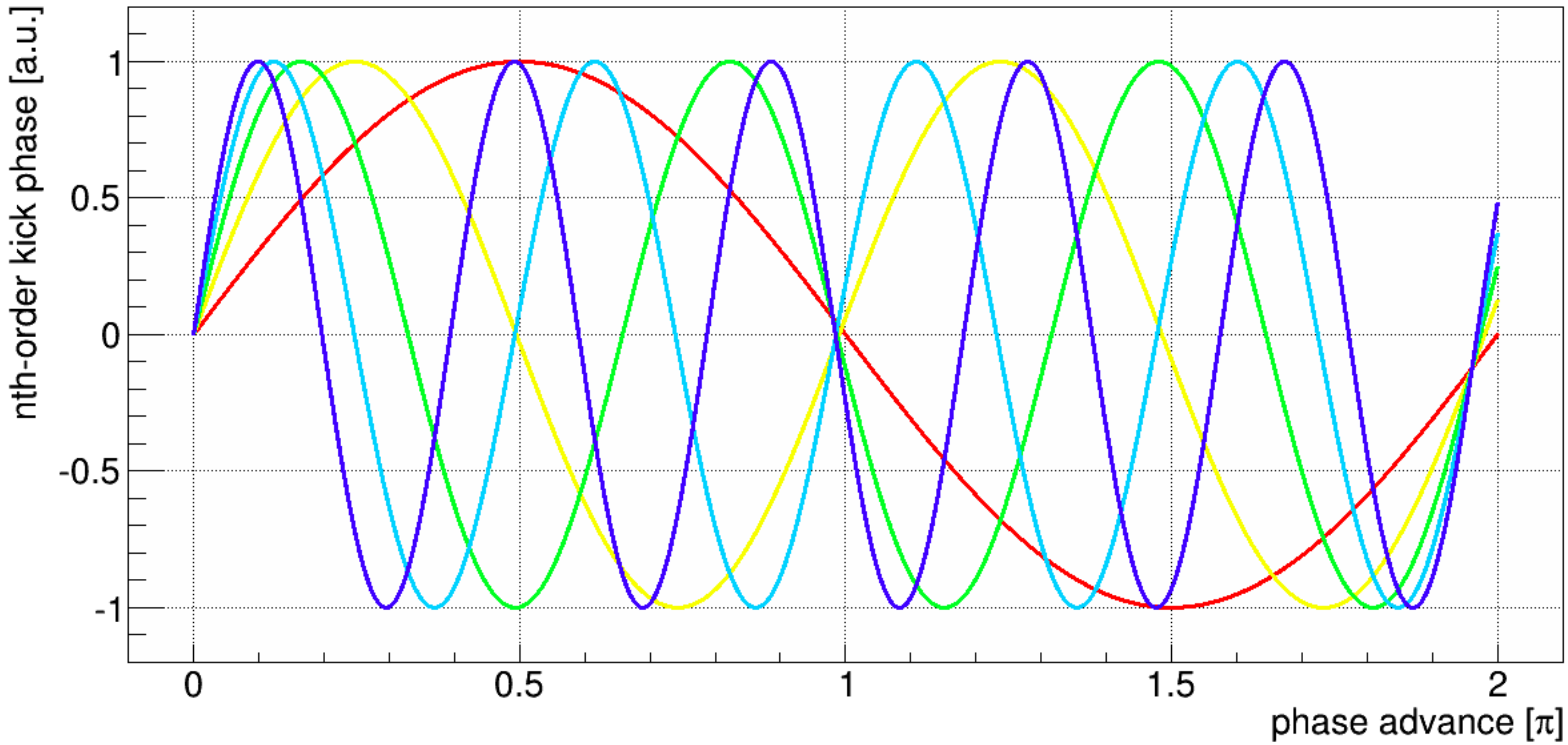
LHC BBC Simulation
Compensating inc. BB-Separation Distance with I_w^2

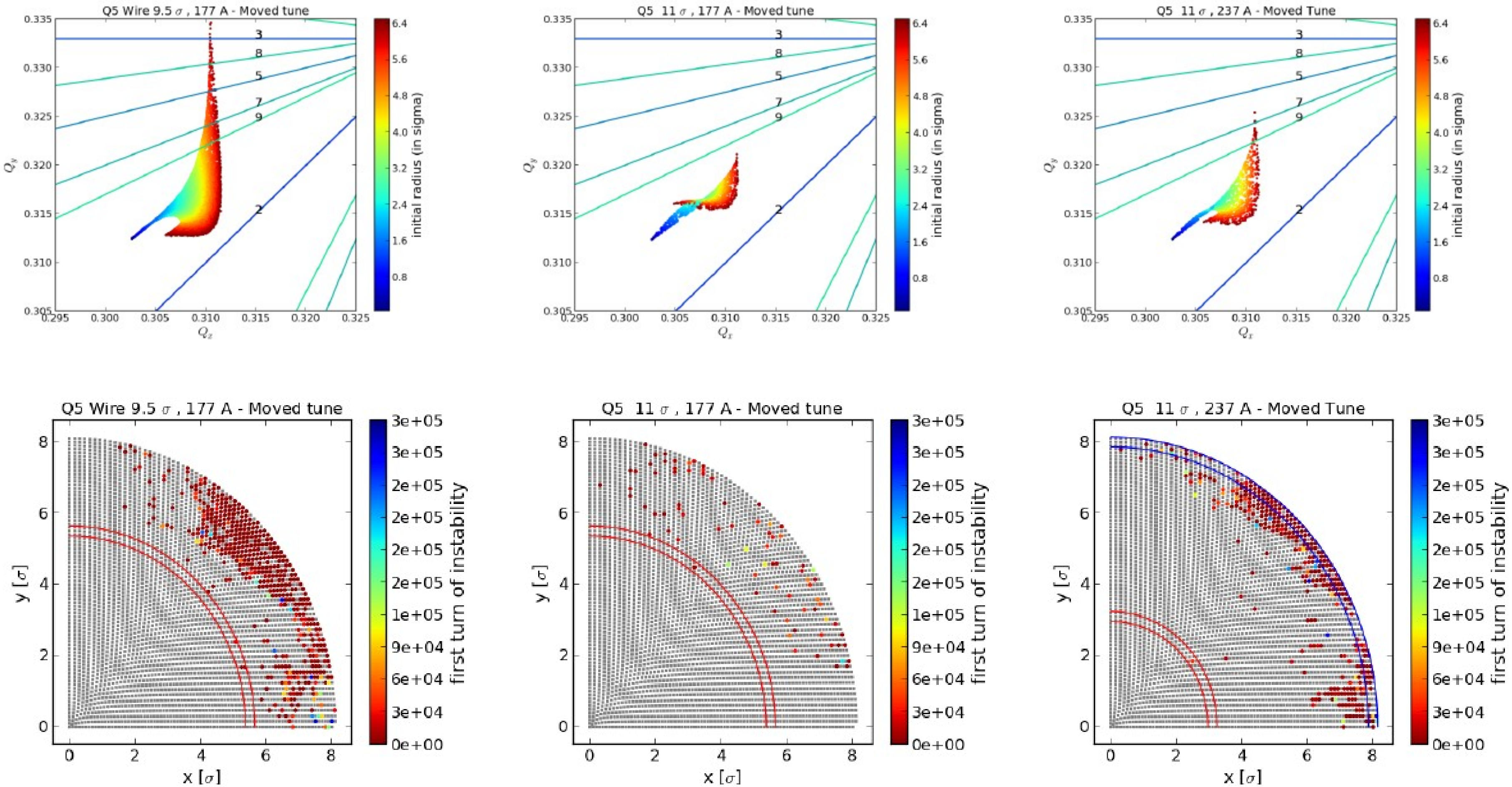


Why BBC has to be local

- 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
Q_x
Q_y
initial radius (in sigma)
3
8
5
7
9
2
Q5 Wire 9.5 σ , 177 A - Moved tune
Q5 11 σ , 177 A - Moved tune
Q5 11 σ , 237 A - Moved Tune
x [σ]
y [σ]
first turn of instability

Wire Linear Tune Shift

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

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

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

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

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