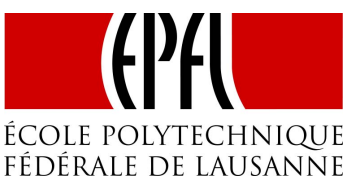
Aperture and protection tolerance for the injection into LHC

F.M. Velotti, C. Bracco,
W. Bartmann, B. Goddard, M. Meddahi,
V. Kain, J. Uythoven...all LIBD WG
and thanks to: R. Bruce, R. De Maria, M. Giovannozzi, S. Redaelli



28th October 2015

Outline

Introduction
- LHC Injection System
- Injection protection devices
- New TDI-S
- Optics

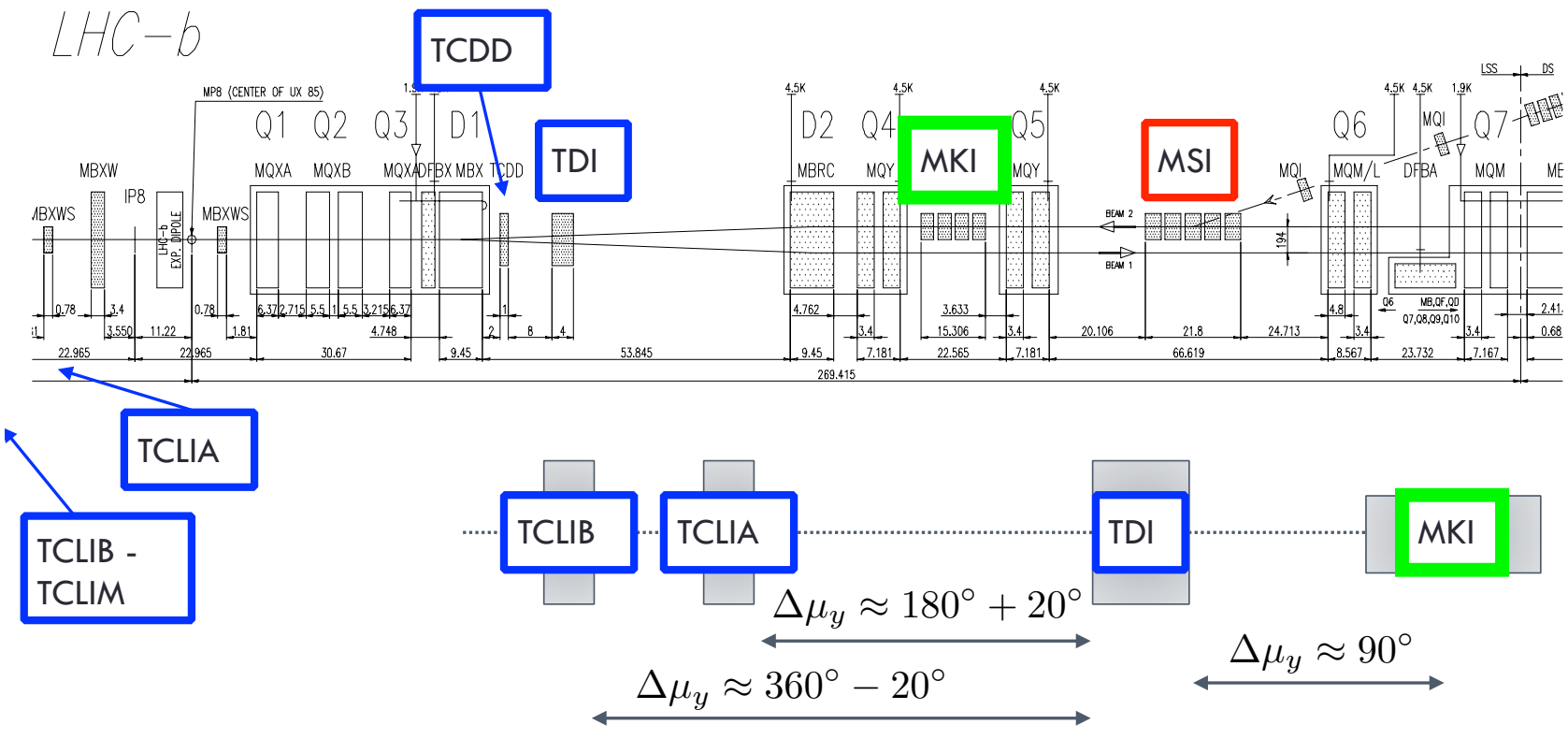
Injection Failures Simulations
- Assumptions
- Beam 1
- Beam 2
- Halo Escaping - Vertical plane
- Halo Escaping - Horizontal plane

Summary and Conclusion

LHC Injection System

The LHC injection system is composed by:

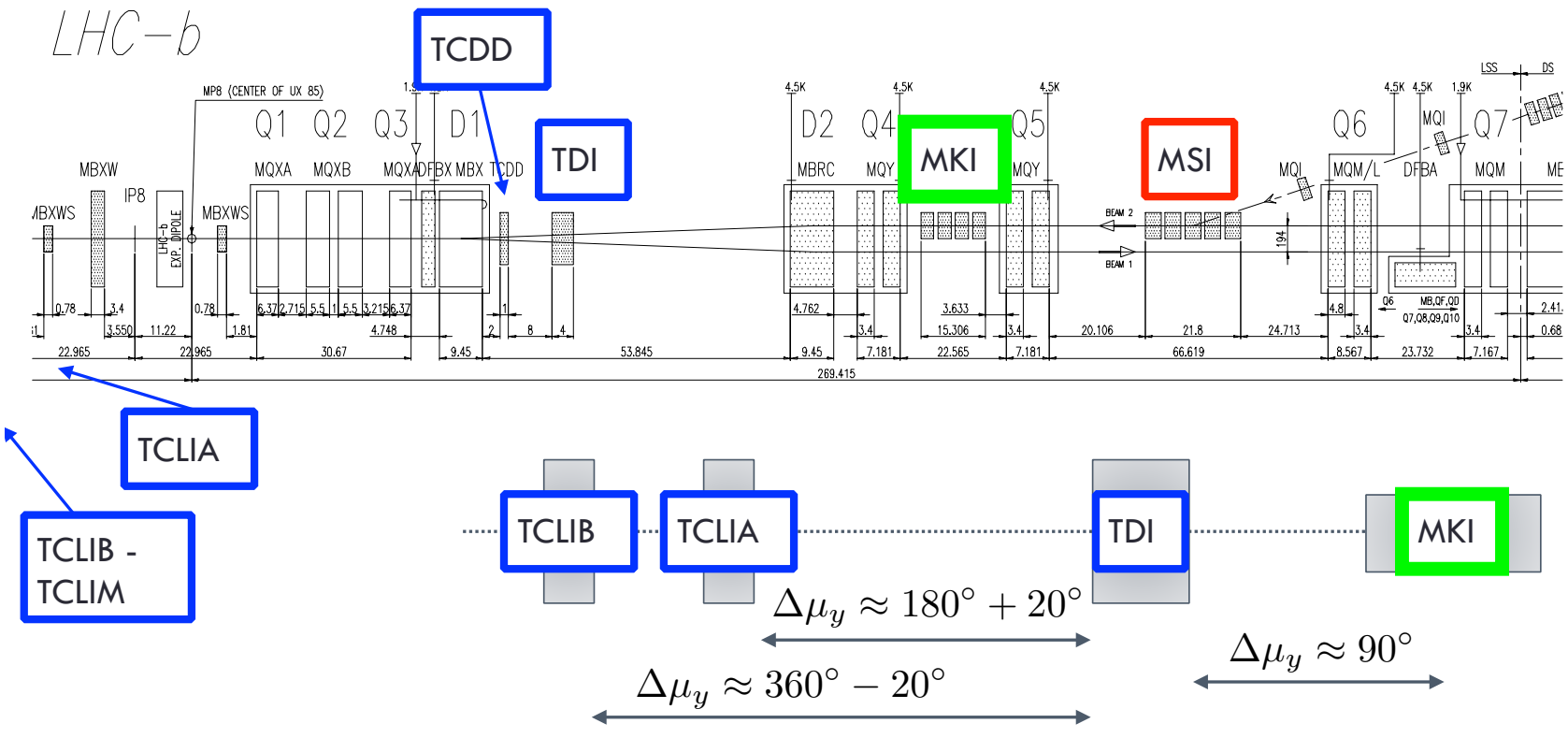
- horizontal septum - MSI;



LHC Injection System

The LHC injection system is composed by:

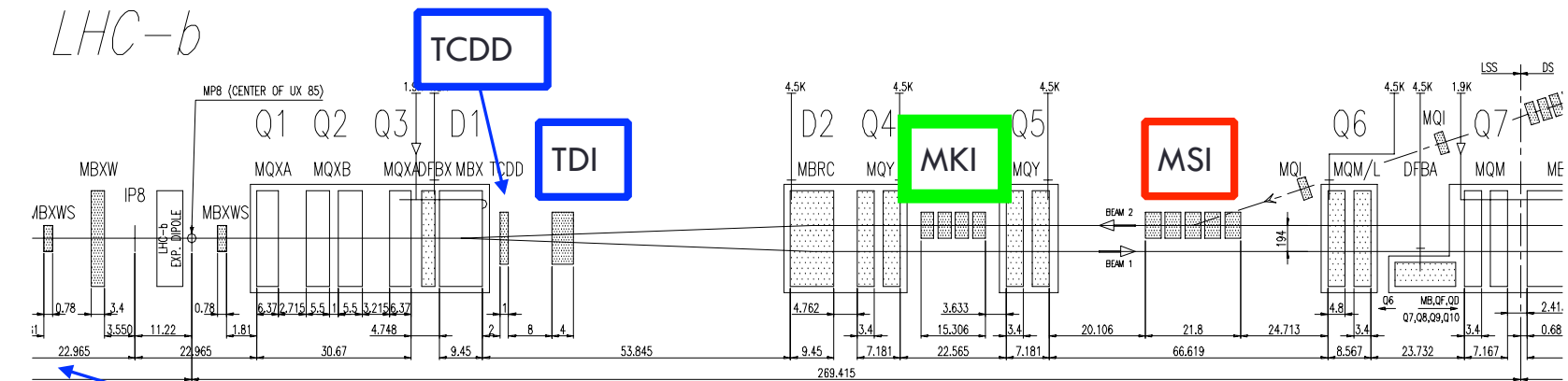
- horizontal septum - MSI;
- quadrupole - Q5;

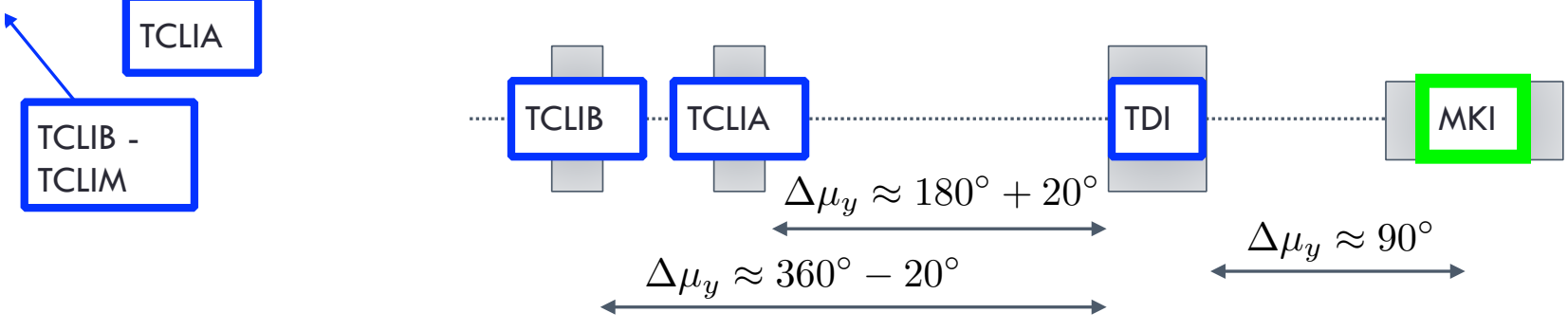


LHC Injection System

The LHC injection system is composed by:

- horizontal septum - MSI;
- quadrupole - Q5;
- vertical kicker - MKI;

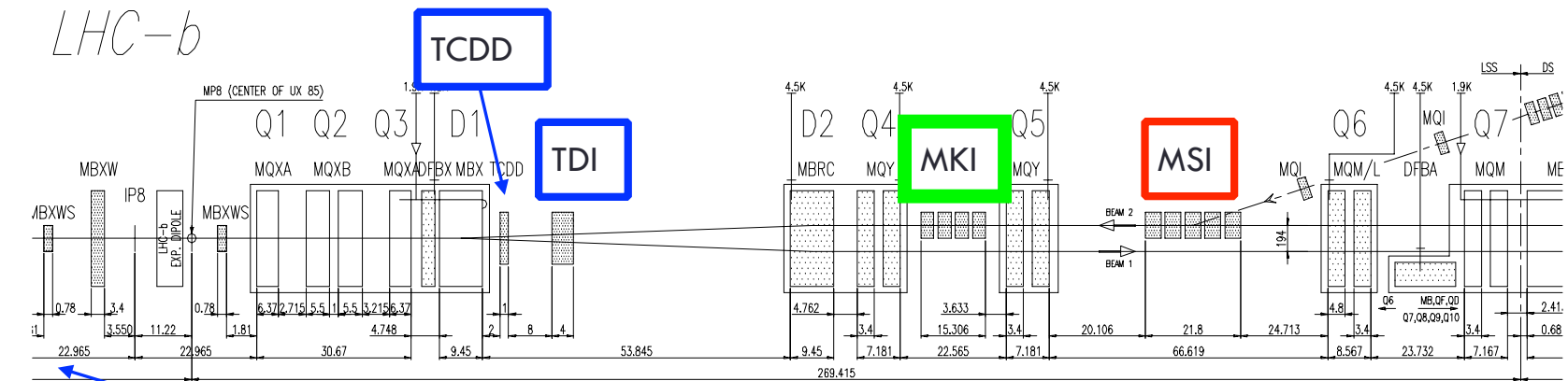




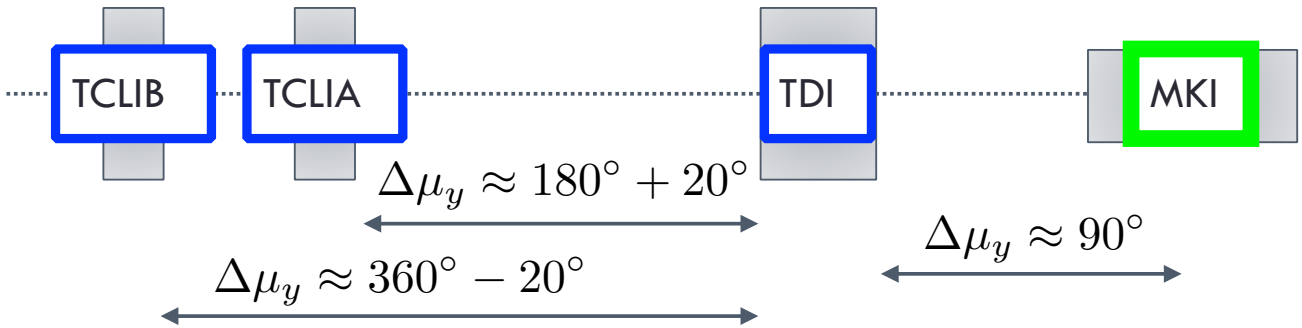
LHC Injection System

The LHC injection system is composed by:

- horizontal septum - MSI;
- quadrupole - Q5;
- vertical kicker - MKI;
- protection devices - TDI, TCLIA/B, TCDD.



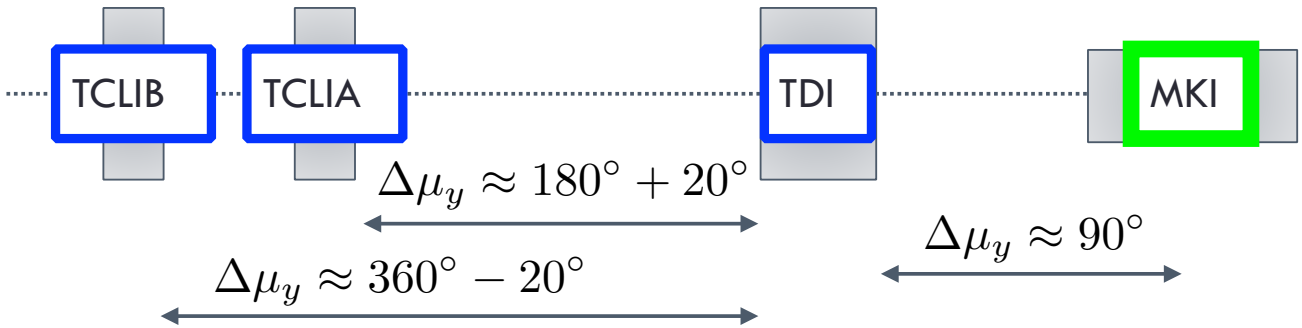
Injection protection devices



TDI:

- $\sim$ 4 m long;
- 2 vertical jaws;
- nominal half gap: 6.8 σ;
- protection against MKI failures.

Injection protection devices



TDI:

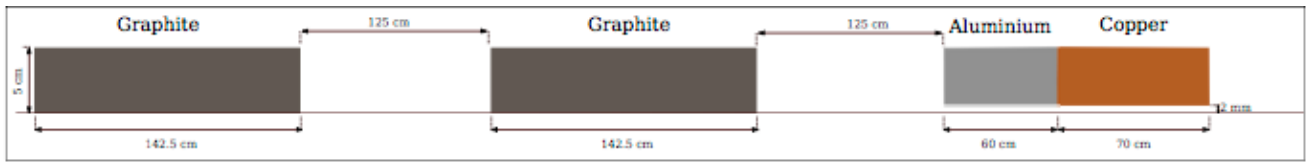
- $\sim$4 m long;
- 2 vertical jaws;
- nominal half gap: 6.8 σ;
- protection against MKI failures.

TCLIA/B:

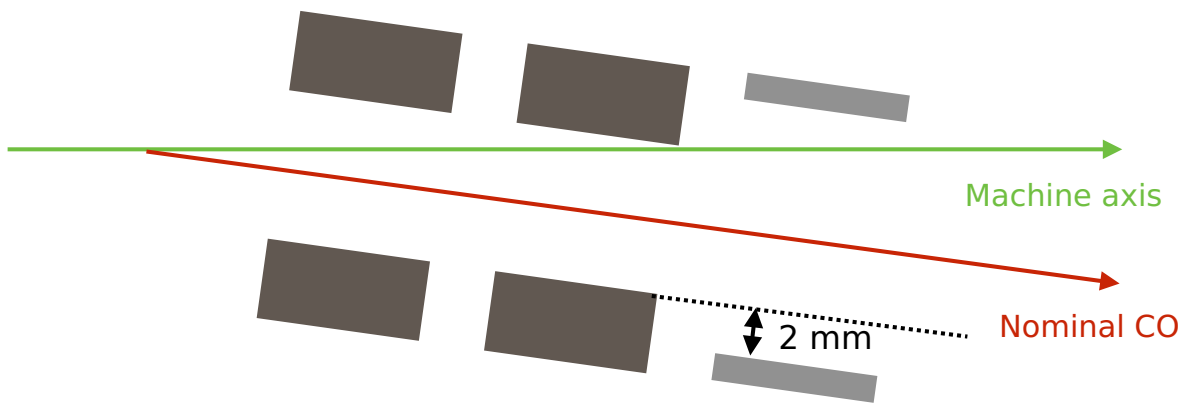
- 1 m;
- 2 vertical jaws;
- nominal half gap: 6.8/8.3 σ;
- protection against phase-advance errors between MKI and TDI.

New TDI-S

- For HL-LHC a new TDI is foreseen to be installed;

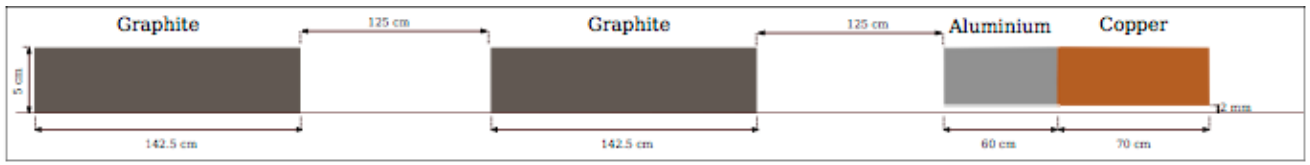


Courtesy of A. Lechner

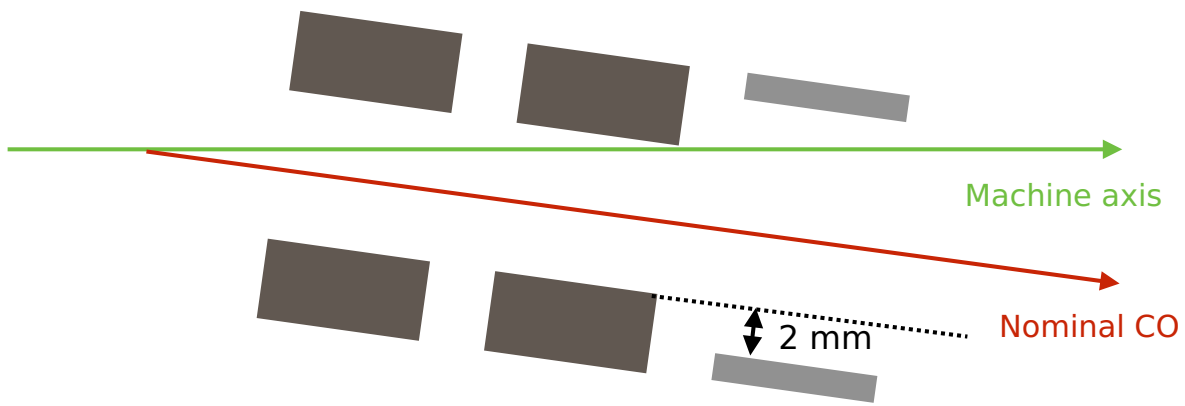


New TDI-S

- For HL-LHC a new TDI is foreseen to be installed;
- to date, the most likely design foresees:
  - 3 separate blocks: 2 of graphite (R4550 or similar) and 1 block of higher Z material (the following simulations have been done assuming aluminium);

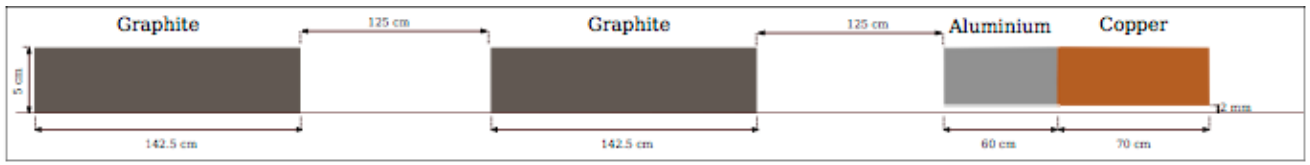


Courtesy of A. Lechner

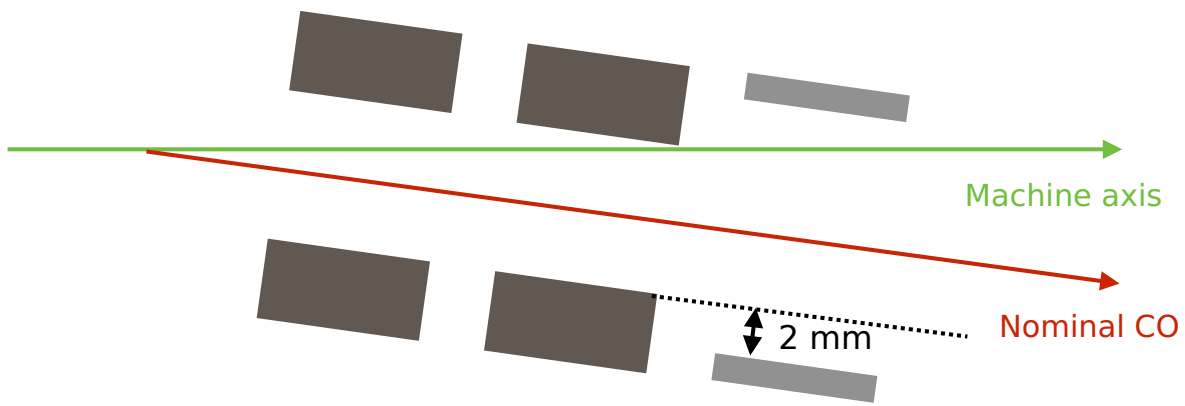


New TDI-S

- For HL-LHC a new TDI is foreseen to be installed;
- to date, the most likely design foresees:
  - 3 separate blocks: 2 of graphite (R4550 or similar) and 1 block of higher Z material (the following simulations have been done assuming aluminium);
- the last block has 2 mm larger aperture than the others.

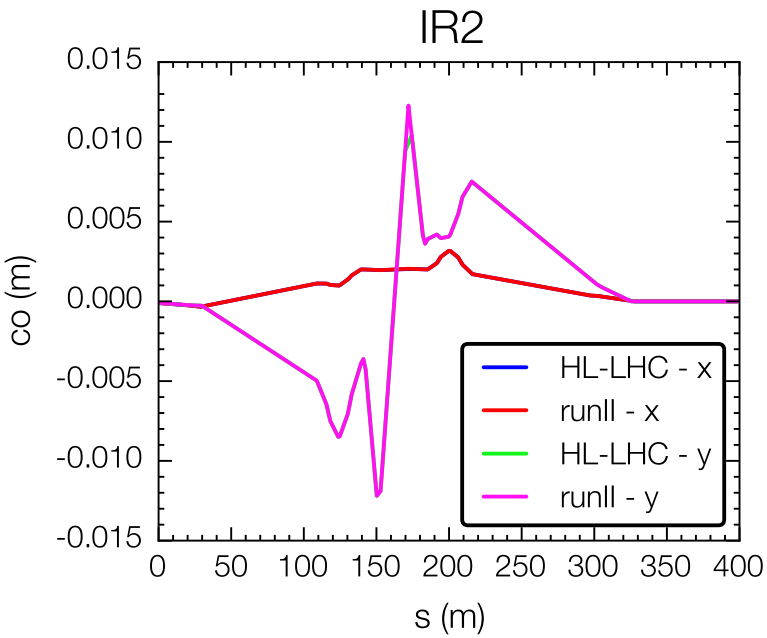


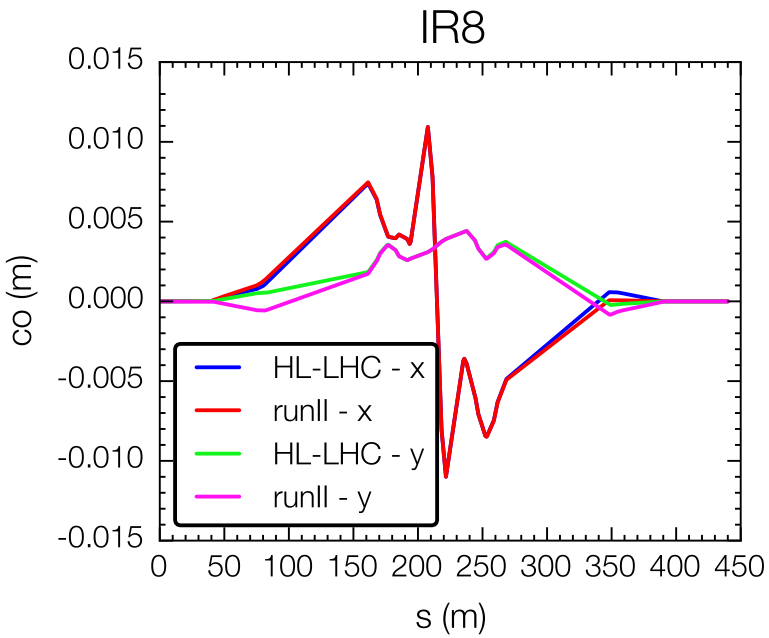
Courtesy of A. Lechner



Optics

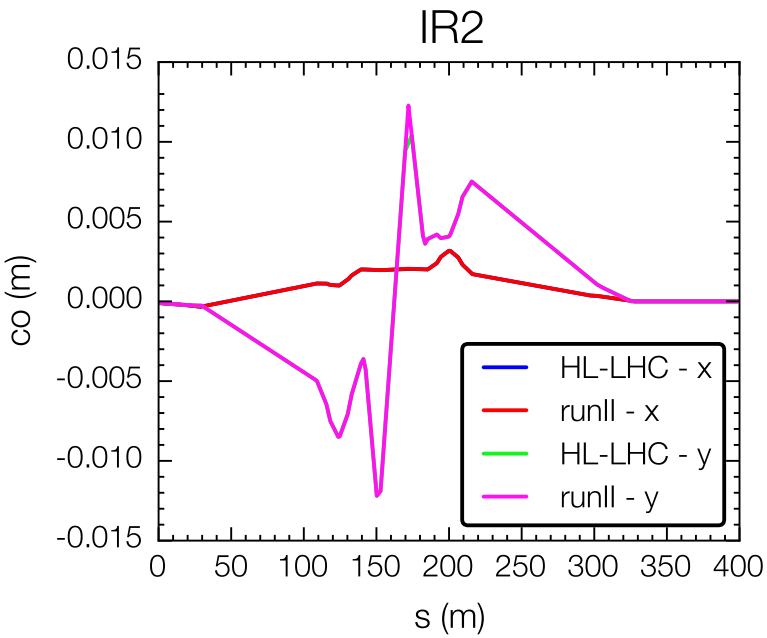
- Optics HLLHC v1.1 used for simulations;

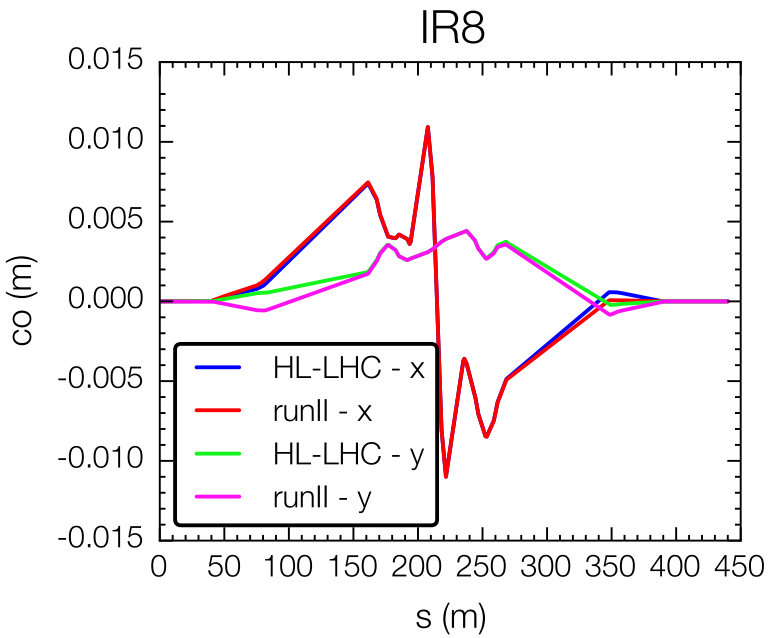




Optics

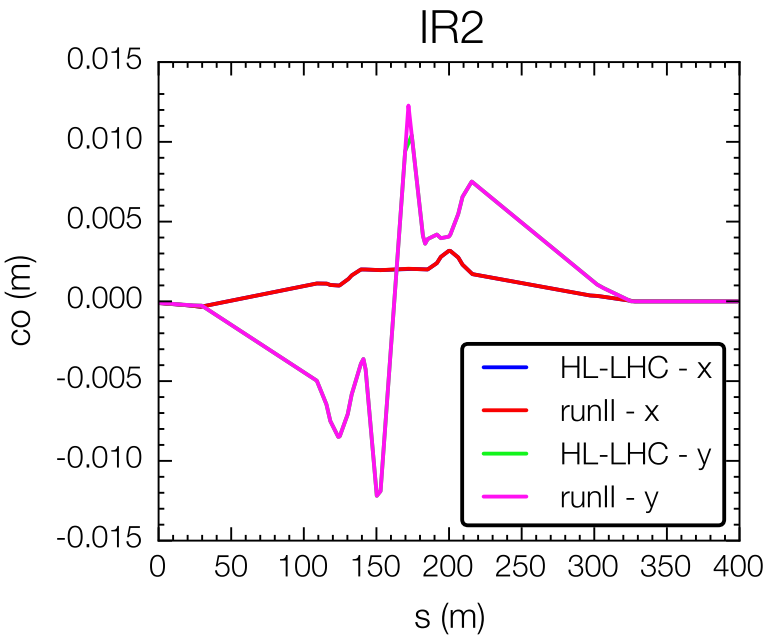
- Optics HLLHC v1.1 used for simulations;
- basically no differences between HLLHC v1.1 and the present optics (runII);

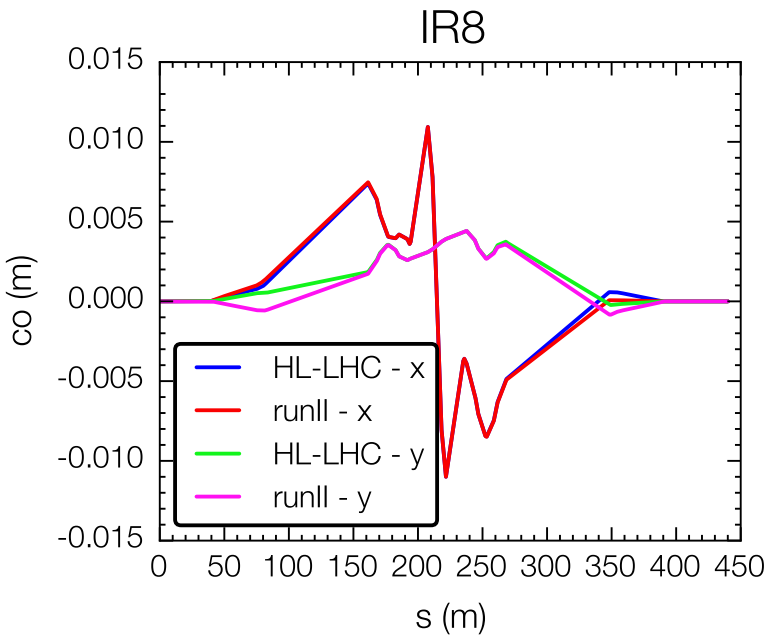




Optics

- Optics HLLHC v1.1 used for simulations;
- basically no differences between HLLHC v1.1 and the present optics (runII);
- also crossing and separation schemes in both IR2 and IR8 almost unchanged.





Assumptions

- The MKI deflects the injected beam onto the nominal LHC orbit → it has been assumed $\theta = 0.85$ mrad;

Assumptions

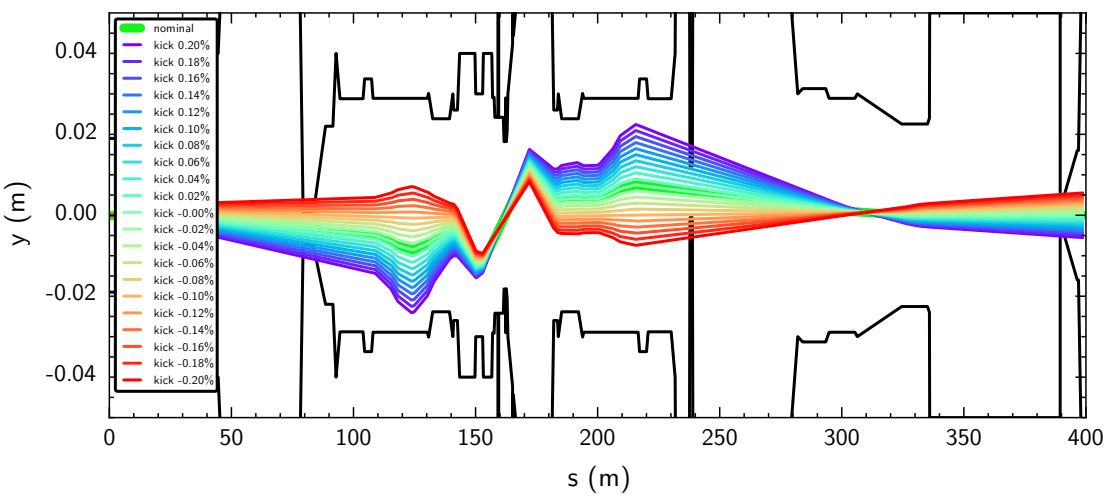
- The MKI deflects the injected beam onto the nominal LHC orbit → it has been assumed $\theta = 0.85$ mrad;
- MKI failures can of course affect both injected and circulating beam:
  - for the injected beam, the MKI strength can be considered between 0 and 125% (where 100% is nominal);
  - for the circulating beam, the MKI strength can be considered between 0 (nominal) and 100%;
  - above 100% (for the circulating beam) it becomes double failure → this is considered beyond design;

Assumptions

- The MKI deflects the injected beam onto the nominal LHC orbit → it has been assumed $\theta = 0.85$ mrad;
- MKI failures can of course affect both injected and circulating beam:
  - for the injected beam, the MKI strength can be considered between 0 and 125% (where 100% is nominal);
  - for the circulating beam, the MKI strength can be considered between 0 (nominal) and 100%;
  - above 100% (for the circulating beam) it becomes double failure → this is considered beyond design;
- above |20|% the impact parameter onto the TDI is above 5σ hence almost the whole beam will be lost on the TDI.

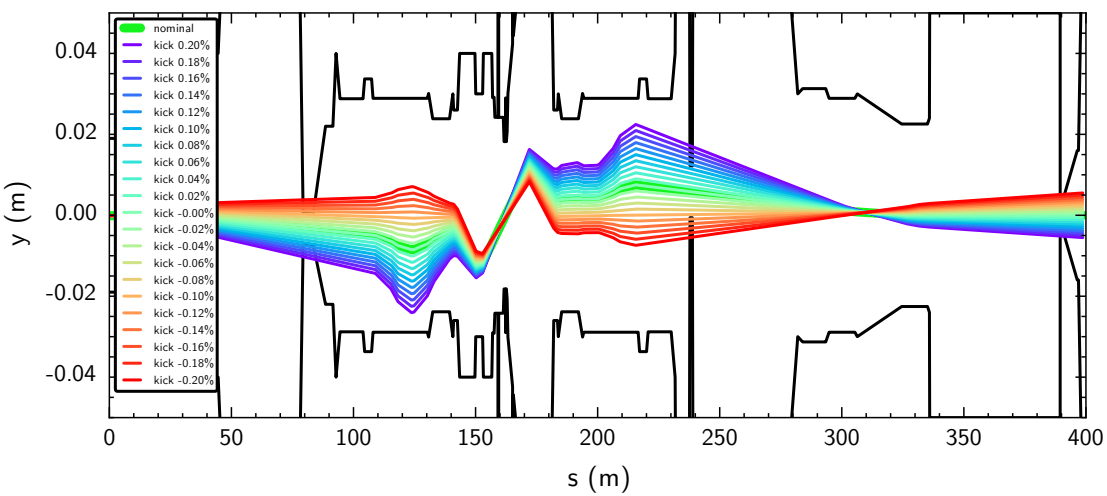
Assumptions

- The following studies are done using:
  - MKI strength of ~ 11% of the nominal for B1 ⇒ grazing (zero impact parameter);
  - MKI strength of ~ 9.5% of the nominal for B2 ⇒ grazing (zero impact parameter);



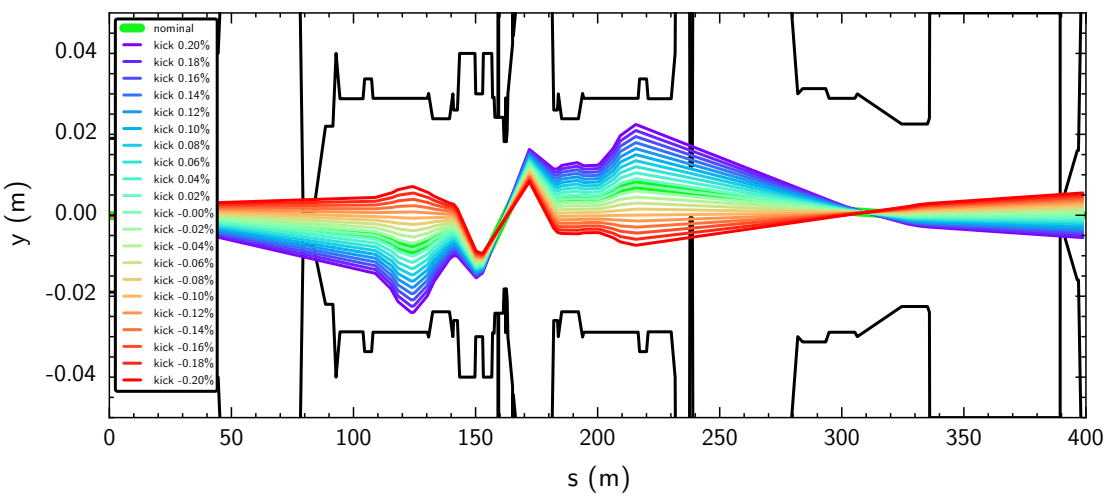
Assumptions

- The following studies are done using:
  - MKI strength of ~ 11% of the nominal for B1 ⇒ grazing (zero impact parameter);
  - MKI strength of ~ 9.5% of the nominal for B2 ⇒ grazing (zero impact parameter);
  - tracking of the primaries done using MADX + `pycollimate` (IPAC15 for more details);



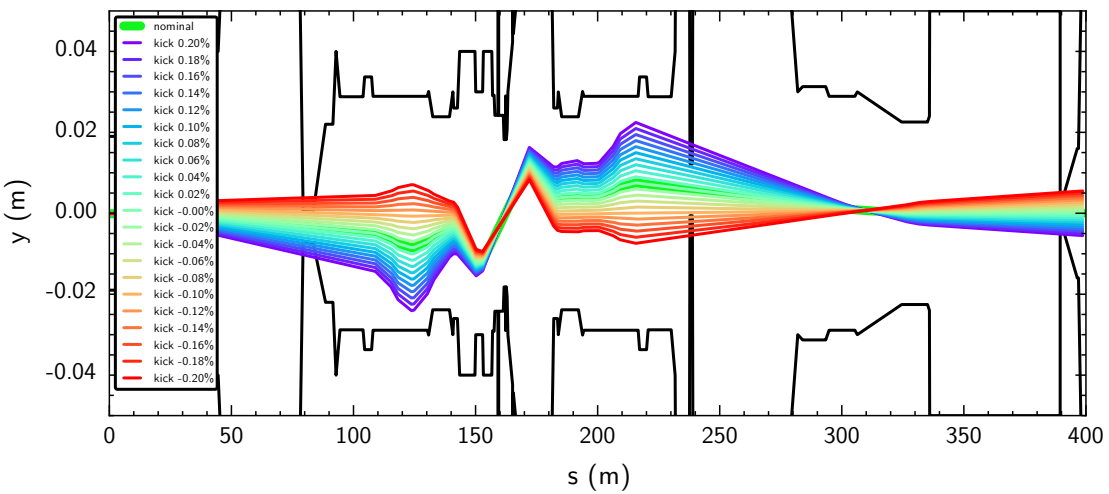
Assumptions

- The following studies are done using:
  - MKI strength of $\sim 11\%$ of the nominal for B1 $\Rightarrow$ grazing (zero impact parameter);
  - MKI strength of $\sim 9.5\%$ of the nominal for B2 $\Rightarrow$ grazing (zero impact parameter);
  - tracking of the primaries done using MADX + `pycollimate` (IPAC15 for more details);
  - Normalised emittance used $\Rightarrow \epsilon_{x,y}^{N} = 1.37\ \pi$mm.mrad;



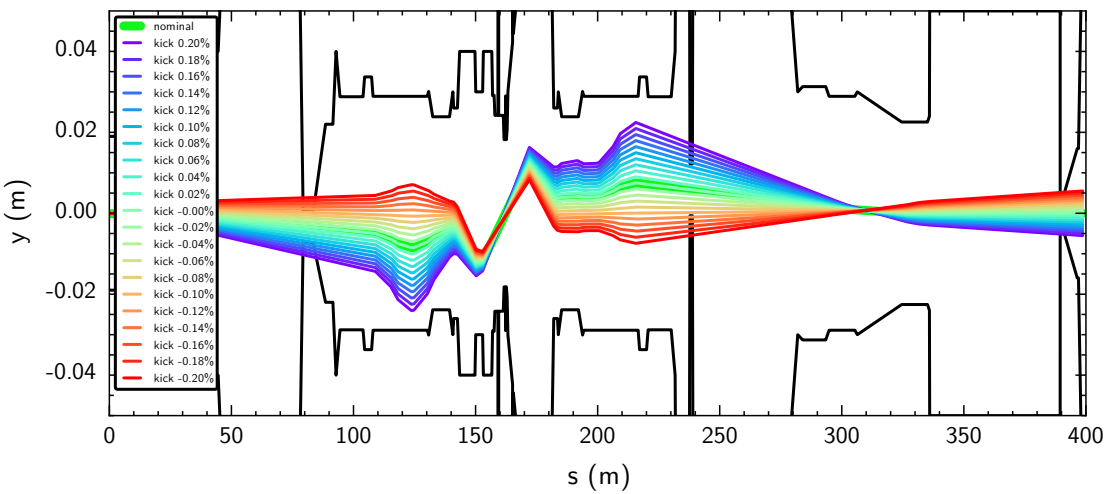
Assumptions

- The following studies are done using:
  - MKI strength of $\sim 11\%$ of the nominal for B1 $\Rightarrow$ grazing (zero impact parameter);
  - MKI strength of $\sim 9.5\%$ of the nominal for B2 $\Rightarrow$ grazing (zero impact parameter);
  - tracking of the primaries done using MADX + `pycollimate` (IPAC15 for more details);
  - Normalised emittance used $\Rightarrow \epsilon_{x,y}^{N} = 1.37\ \pi$mm.mrad;
  - TDI-S, TCLIA and TCLIB nominal half-gaps $6.8\sigma_y$ $\Rightarrow$ scenario 0;



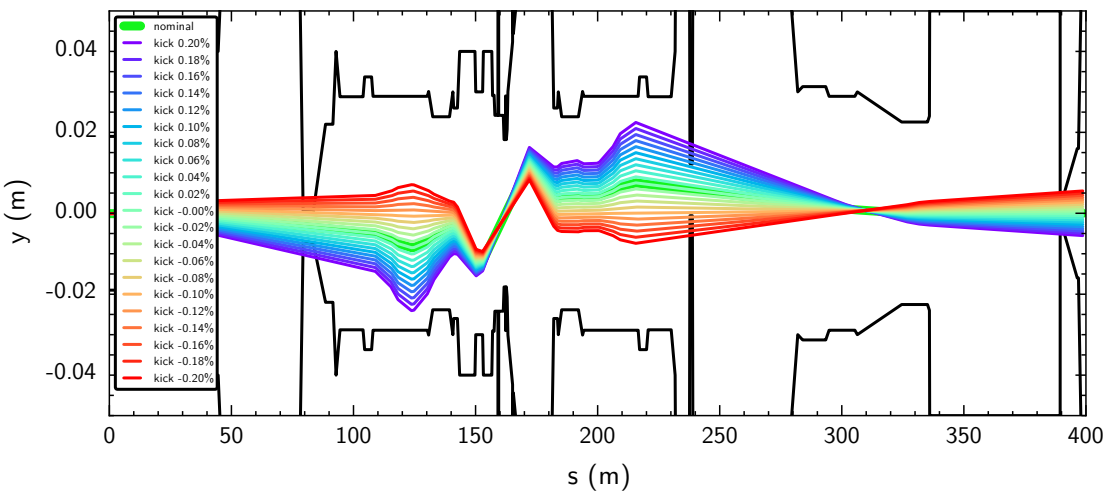
Assumptions

- The following studies are done using:
  - MKI strength of $\sim 11\%$ of the nominal for B1 $\Rightarrow$ grazing (zero impact parameter);
  - MKI strength of $\sim 9.5\%$ of the nominal for B2 $\Rightarrow$ grazing (zero impact parameter);
  - tracking of the primaries done using MADX + `pycollimate` (IPAC15 for more details);
  - Normalised emittance used $\Rightarrow \epsilon^N_{x,y} = 1.37\ \pi$mm.mrad;
  - TDI-S, TCLIA and TCLIB nominal half-gaps $6.8\sigma_y$ $\Rightarrow$ scenario 0;
  - TDI-S half-gap of $7.8\sigma_y$ and TCLIA/B with half-gap of $6.8\sigma_y$ $\Rightarrow$ scenario 1 ;



Assumptions

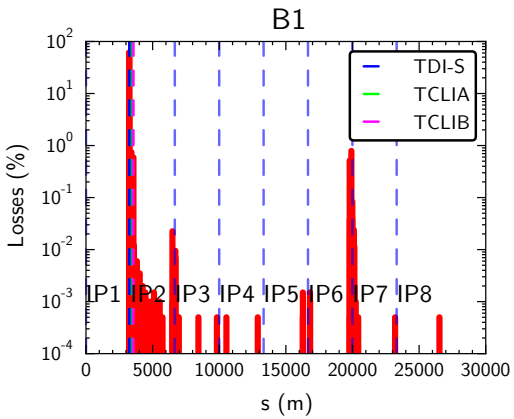
- The following studies are done using:
  - MKI strength of ~ 11% of the nominal for B1 ⇒ grazing (zero impact parameter);
  - MKI strength of ~ 9.5% of the nominal for B2 ⇒ grazing (zero impact parameter);
  - tracking of the primaries done using MADX + `pycollimate` (IPAC15 for more details);
  - Normalised emittance used ⇒ $\epsilon^N_{x,y} = 1.37\ \pi$mm.mrad;
  - TDI-S, TCLIA and TCLIB nominal half-gaps $6.8\sigma_y$ ⇒ scenario 0;
  - TDI-S half-gap of $7.8\sigma_y$ and TCLIA/B with half-gap of $6.8\sigma_y$ ⇒ scenario 1 ;
  - TDI-S, TCLIA and TCLIB half-gaps $7.8\sigma_y$ ⇒ scenario 2 ;



Loss maps at injection - Beam 1

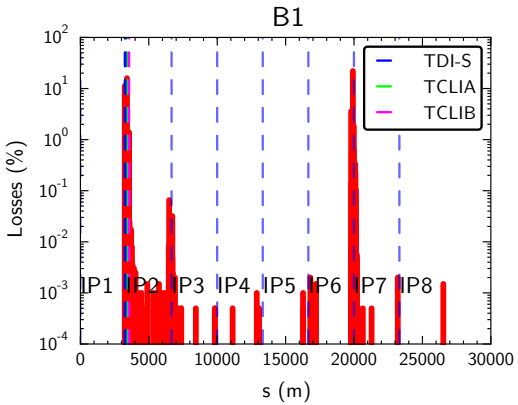
Scenario 0

- TDI-S, TCLIA and TCLIB at 6.8 σ_y and grazing impact on the TDI-S
- tracking for 1 turn:



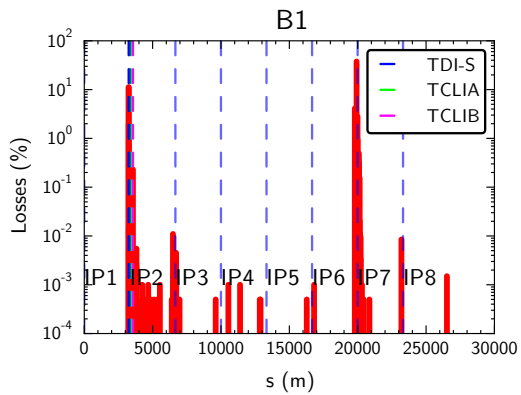
Scenario 1

- TDI-S at 7.8 σ_y, TCLIA and TCLIB at 6.8 σ_y and grazing impact on the TDI-S
- tracking for 1 turn:



Scenario 2

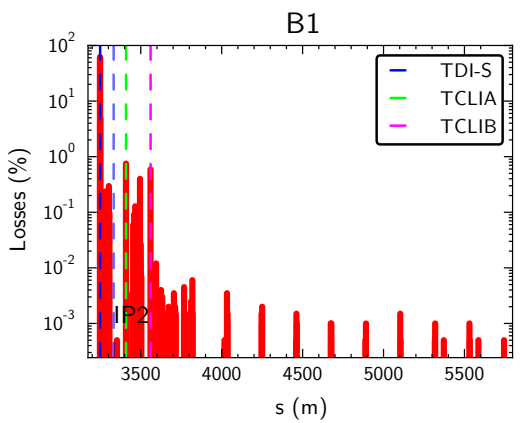
- TDI-S, TCLIA and TCLIB at 7.8 σ_y and 1 σ impact on the TDI-S
- tracking for 1 turn:



Loss maps at injection - Beam 1

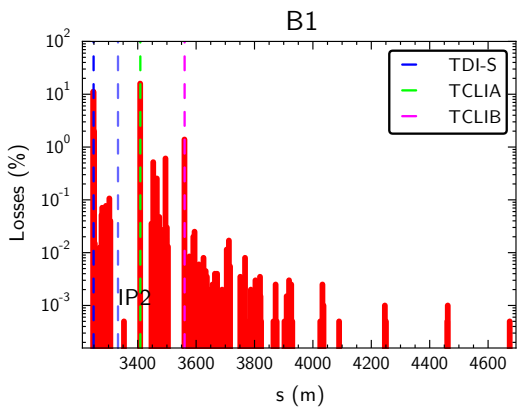
Scenario 0

- TDI-S, TCLIA and TCLIB at 6.8 σ_y and grazing impact on the TDI-S
- tracking for 1 turn:



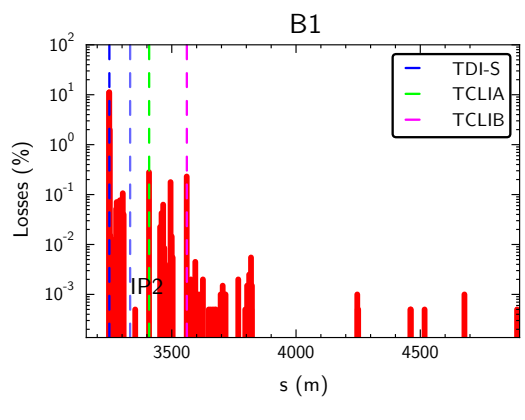
Scenario 1

- TDI-S at 7.8 σ_y, TCLIA and TCLIB at 6.8 σ_y and grazing impact on the TDI-S
- tracking for 1 turn:



Scenario 2

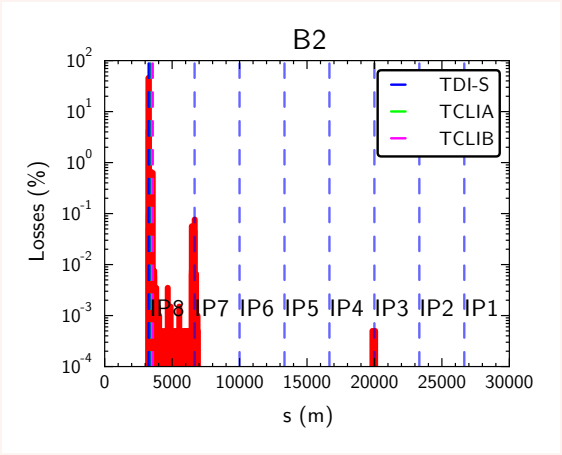
- TDI-S, TCLIA and TCLIB at 7.8 σ_y and 1 σ impact on the TDI-S
- tracking for 1 turn:



Loss maps at injection - Beam 2

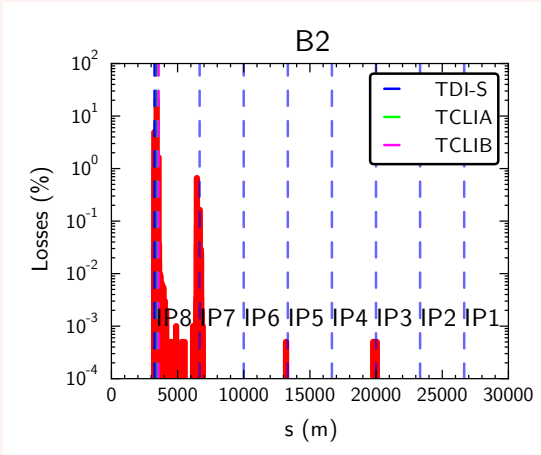
Scenario 0

- TDI-S, TCLIA and TCLIB at 6.8 σ_y and grazing impact on the TDI-S
- tracking for 1 turn:



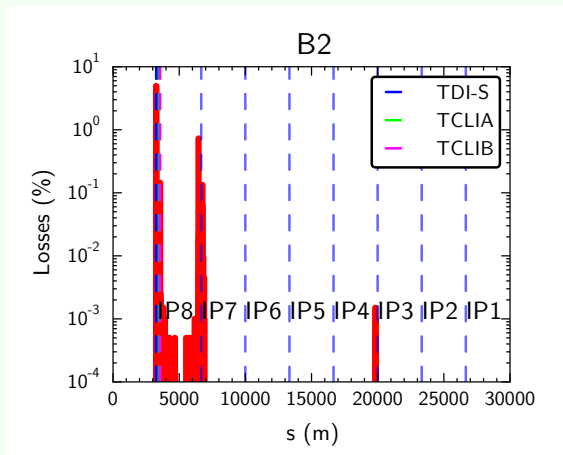
Scenario 1

- TDI-S at 7.8 σ_y, TCLIA and TCLIB at 6.8 σ_y and grazing impact on the TDI-S
- tracking for 1 turn:



Scenario 2

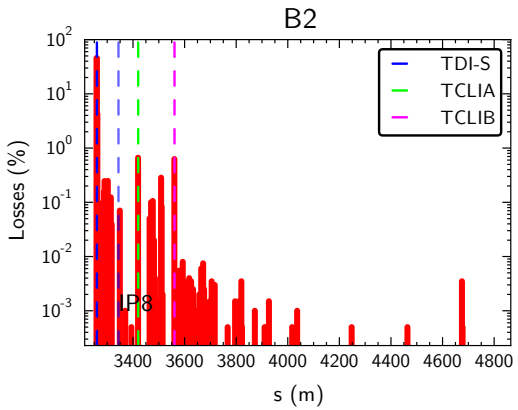
- TDI-S, TCLIA and TCLIB at 7.8 σ_y and 1 σ impact on the TDI-S
- tracking for 1 turn:



Loss maps at injection - Beam 2

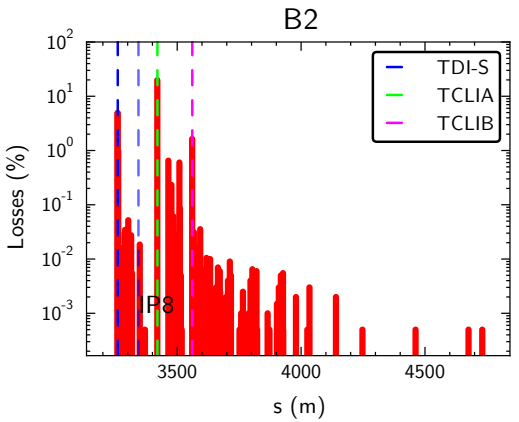
Scenario 0

- TDI-S, TCLIA and TCLIB at 6.8 σ_y and grazing impact on the TDI-S
- tracking for 1 turn:



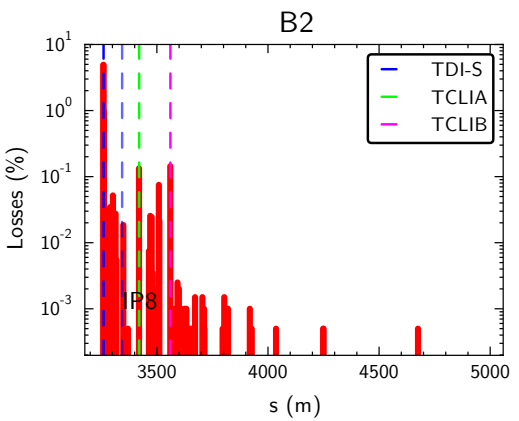
Scenario 1

- TDI-S at 7.8 σ_y, TCLIA and TCLIB at 6.8 σ_y and grazing impact on the TDI-S
- tracking for 1 turn:



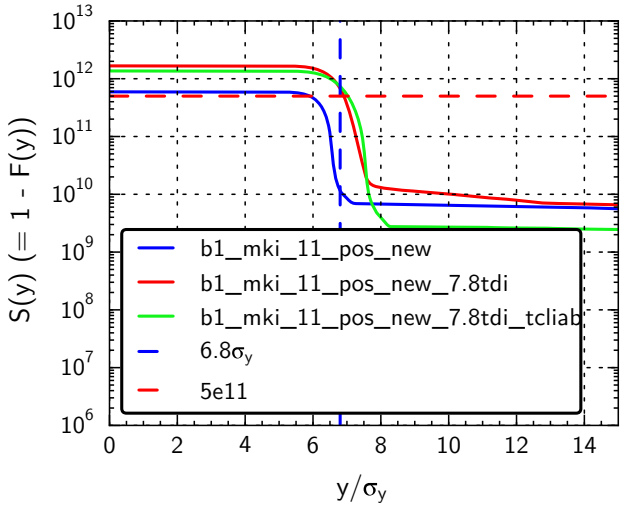
Scenario 2

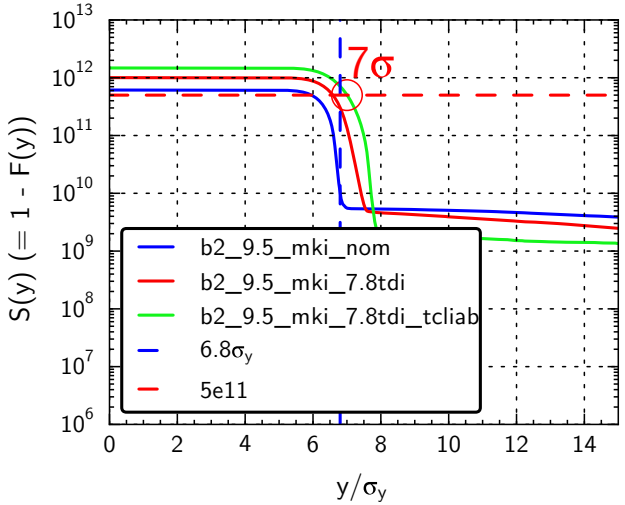
- TDI-S, TCLIA and TCLIB at 7.8 σ_y and 1 σ impact on the TDI-S
- tracking for 1 turn:



Halo Escaping - Vertical plane

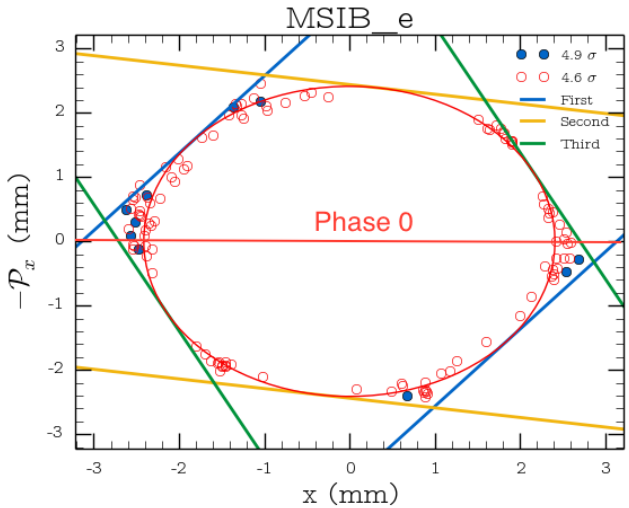
- The halo escaping the injection protection system can be calculated with the survival function;
- macro particles tracked 2×10^5, normalised to the beam intensity $I = 288 \times 2.2 \times 10^{11}$ p^+;
- the max amplitude escaping the protection system with intensity above safe flag beam (5×10^{11} p^+) is 7 σ (for the vertical plane);
- $Y/\sigma_y = \sqrt{y^2 + (\alpha_y y + \beta_y y')^2}/\sqrt{\epsilon \beta_y}$.

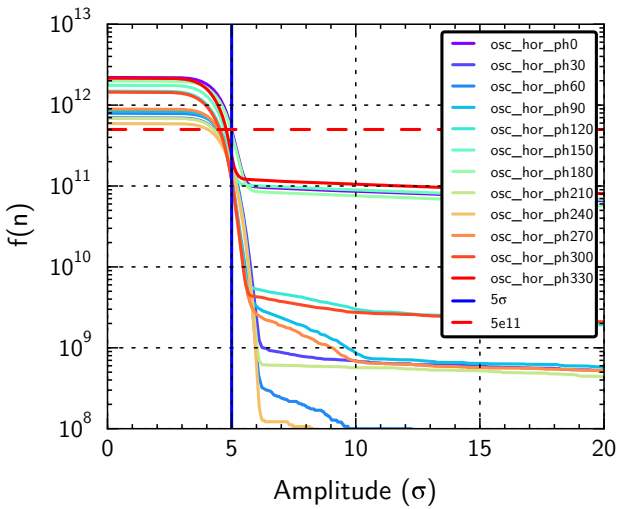




Halo Escaping - Horizontal plane

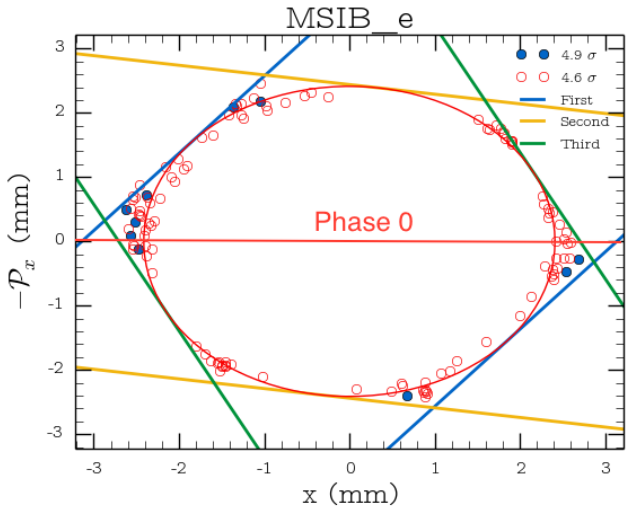
- The maximum error we can have at the TCDIs is estimated to be 1.4 σ;
- the maximum amplitude escaping the TCDIs is $g_{TCDI}/\cos(\Delta\psi/2)$ (without intercepting the TCDIs);
- with a 5 σ oscillation in the line, for a very unlucky phase, the beam core ($\sim \pm 1\ \sigma$) could escape the TL collimation system completely;
- maximum amplitude escaping the TL collimators with intensity above safe beam flag is 7.4 σ_x.

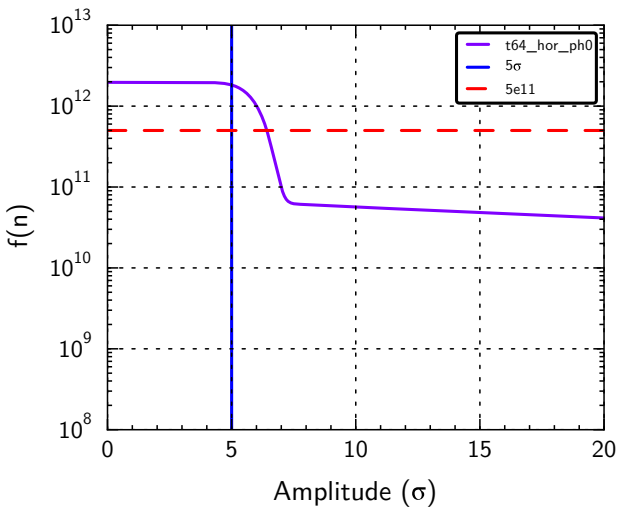




Halo Escaping - Horizontal plane

- The maximum error we can have at the TCDIs is estimated to be 1.4 σ;
- the maximum amplitude escaping the TCDIs is $g_{TCDI}/\cos(\Delta\psi/2)$ (without intercepting the TCDIs);
- with a 5 σ oscillation in the line, for a very unlucky phase, the beam core ($\sim \pm 1\ \sigma$) could escape the TL collimation system completely;
- maximum amplitude escaping the TL collimators with intensity above safe beam flag is 7.4 σ_x.





Summary and Conclusion

- The maximum primary halo amplitude escaping the injection protection system, in case of MKI failure (kick of 6.8 σ at the TDI) and with intensity above the safe beam flag, is 7 σ_y;
- for the horizontal plane, the only protection is given by the TCDIs (injection protection elements are only vertical) $\Rightarrow$ the primary halo with intensity above the safe beam flag is 7.4 σ_x;
- the tolerances that should be included, in order to consider realistic machine configurations, are:
  - $1.5 + 1.5\ \sigma$ for orbit and injection oscillations;
  - 5% of beta-beat;
  - $\delta_p = 0.6 \times 10^{-3}$ and $k_D = 1.4$.
- this gives a total of 10.3 σ_y and 11.05 σ_x for the vertical and horizontal plane respectively.

Summary and Conclusion

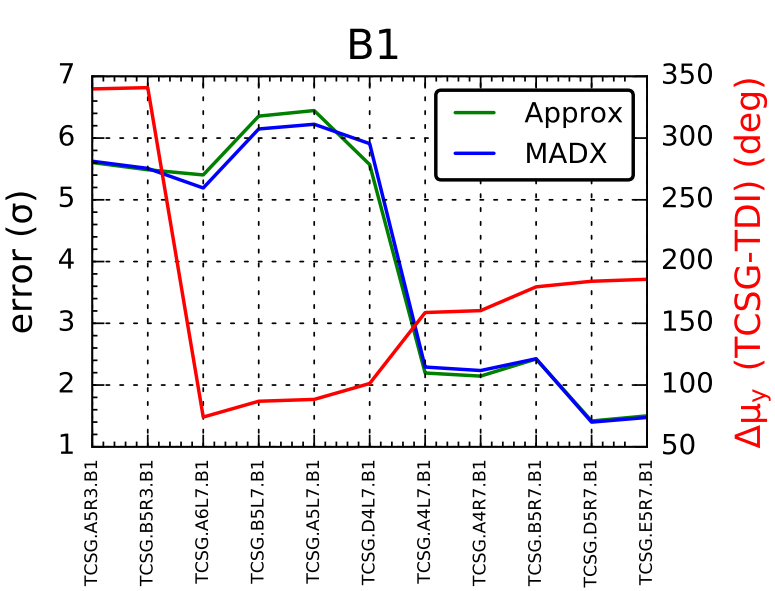
- The current settings of the injection protection elements guarantee the localisation of the losses in case of MKI failures in the injection regions;
- different settings would move the losses elsewhere in the machine (e.g. IR7);
- the present TCDI settings permit to achieve the required protection;

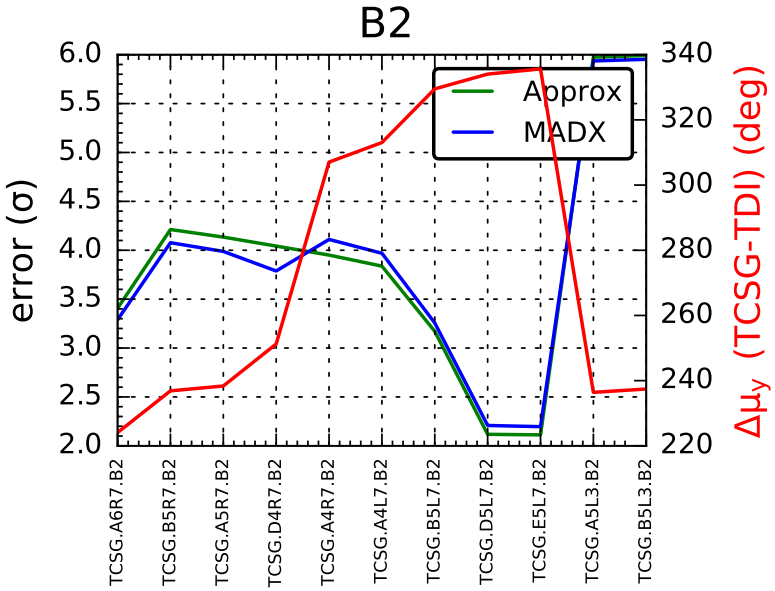
Outlook:

- due to the large part of the beam surviving the first turn ($\sim 50\%$) the tracking has been extended;
- this will translate in higher load on some of the collimators (TCLIB especially);
- evaluation with simulations the different possible settings of TCLIB.

Thank you!

Backup


B1
error (σ)
Δμy (TCSG-TDI) (deg)
Approx
MADX
TCSG.A5R3.B1
TCSG.B5R3.B1
TCSG.A6L7.B1
TCSG.B5L7.B1
TCSG.A5L7.B1
TCSG.D4L7.B1
TCSG.A4L7.B1
TCSG.A4R7.B1
TCSG.B5R7.B1
TCSG.D5R7.B1
TCSG.E5R7.B1


B2
error (σ)
Δμy (TCSG-TDI) (deg)
Approx
MADX
TCSG.A6R7.B2
TCSG.B5R7.B2
TCSG.A5R7.B2
TCSG.D4R7.B2
TCSG.A4R7.B2
TCSG.A4L7.B2
TCSG.B5L7.B2
TCSG.D5L7.B2
TCSG.E5L7.B2
TCSG.A5L3.B2
TCSG.B5L3.B2