# Part 1: Simulations with SixTrack of loss patterns at $\beta^*$=3.5m

# Part 2: TCT margins and minimum $\beta^*$

R. Bruce,
R.W. Assmann, F. Burkhard, M. Cauchi,
S. Redaelli, G. Valentino, D. Wollmann

# Outline

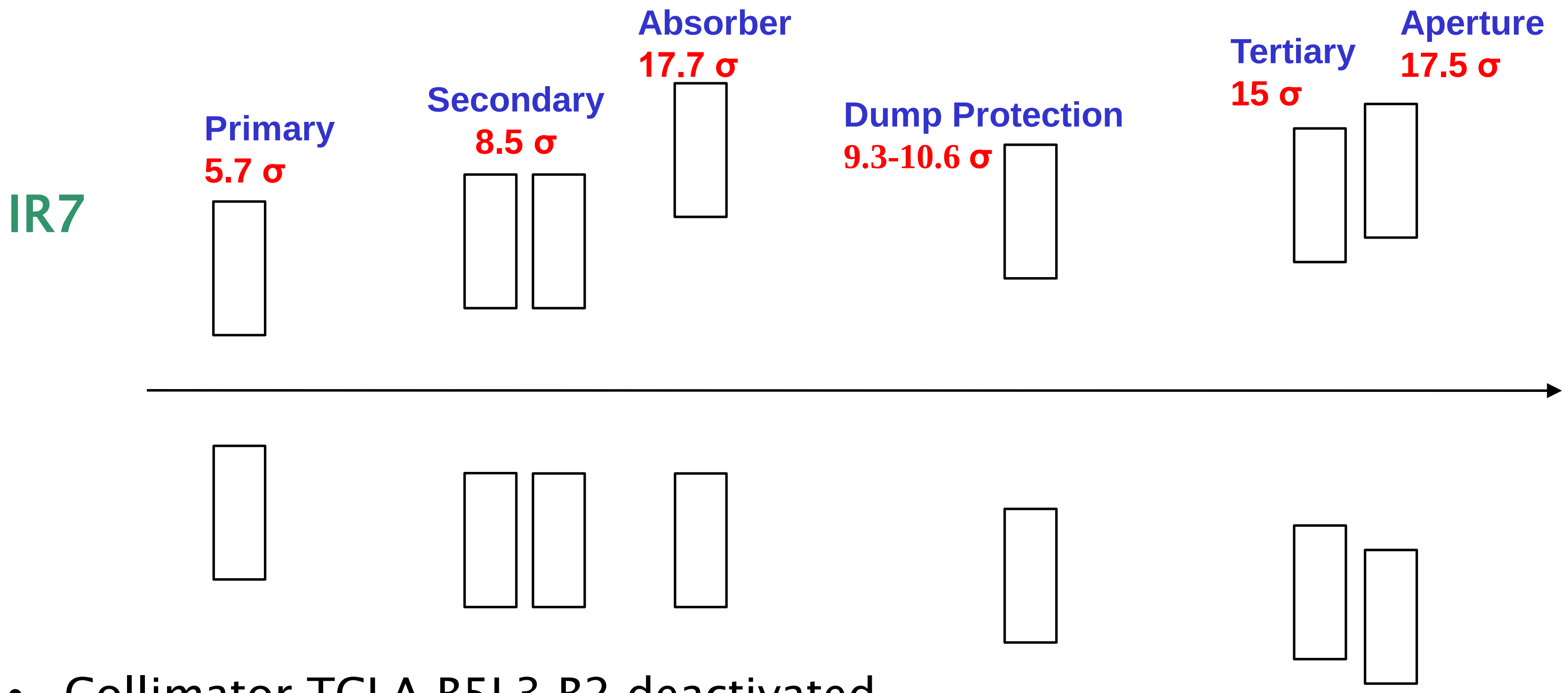
- Part 1: Simulations with SixTrack of loss patterns at $\beta^*=3.5$m
    - Introduction and motivation
    - Simulation setup
    - Results
    - Comparison with measured loss maps
    - Conclusion
- Part 2: TCT margins and minimum $\beta^*$
    - Introduction and motivation
    - Method for calculating top energy aperture margins from measurements at injection
    - Resulting TCT settings for different optics configurations
    - Conclusion

# Introduction and motivation

- SixTrack simulations (combining optical tracking and particle-matter interaction in collimators) previously used to estimate performance of nominal LHC collimation system
- A simulation of the present machine provides very valuable benchmark
- Comparison with measurements gives understanding of machine performance and simulation accuracy
- Output of SixTrack simulation used as starting conditions in other problems (e.g. simulations of experimental background)

# Simulation setup

- Using present machine conditions:
  - Intermediate collimator settings



IR7

**Primary**
5.7 σ

**Secondary**
8.5 σ

**Absorber**
17.7 σ

**Dump Protection**
9.3-10.6 σ

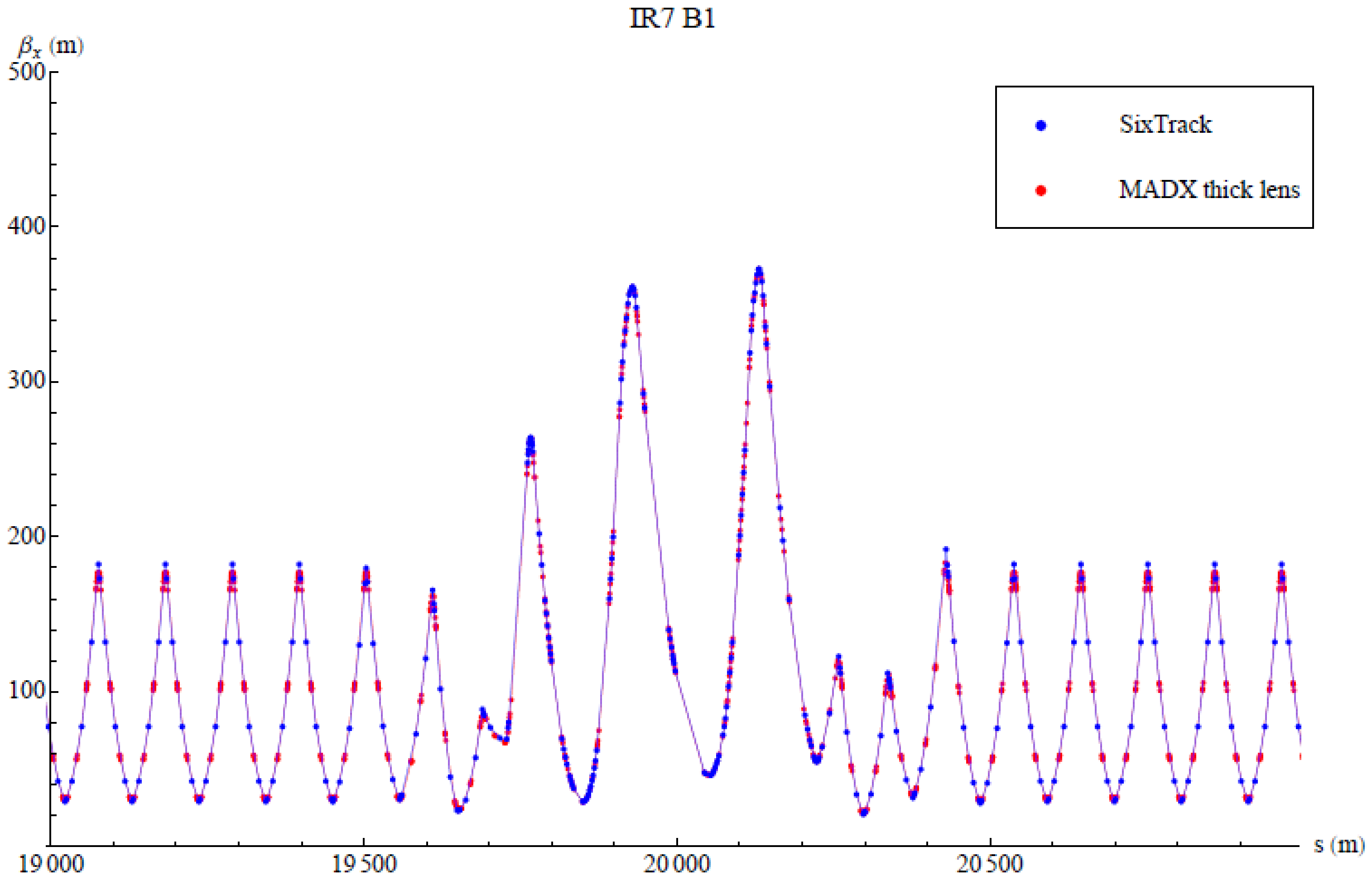
**Tertiary**
15 σ

**Aperture**
17.5 σ

  - Collimator TCLA.B5L3.B2 deactivated

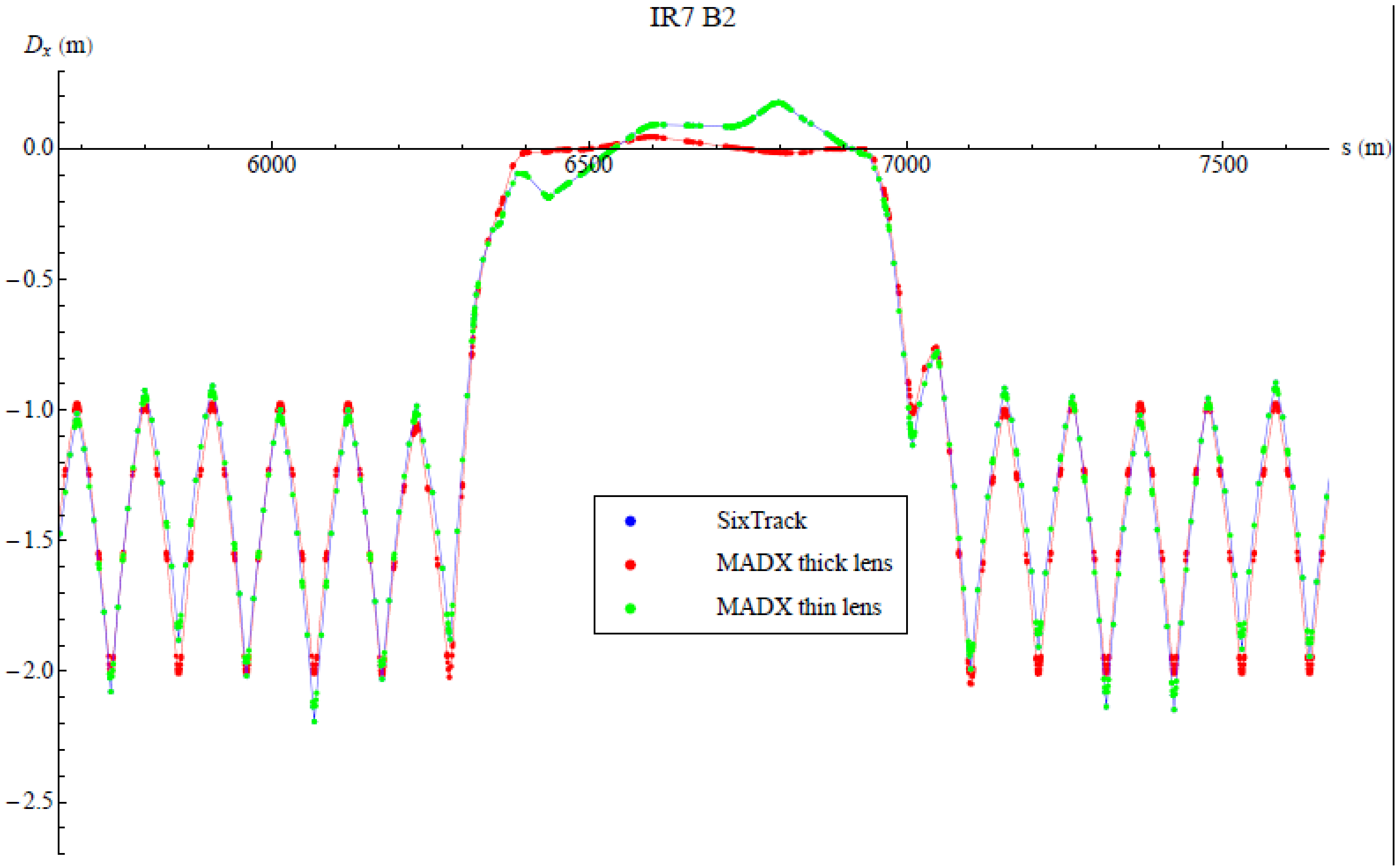
# Optics from MAD-X

$\beta^*=3.5$ m in all IPs, thin lens optics used to create SixTrack input (thanks to M. Giovanozzi and O. Berrig)



# Optics from MAD-X

Good agreement in β-function. Smaller deviations in dispersion.

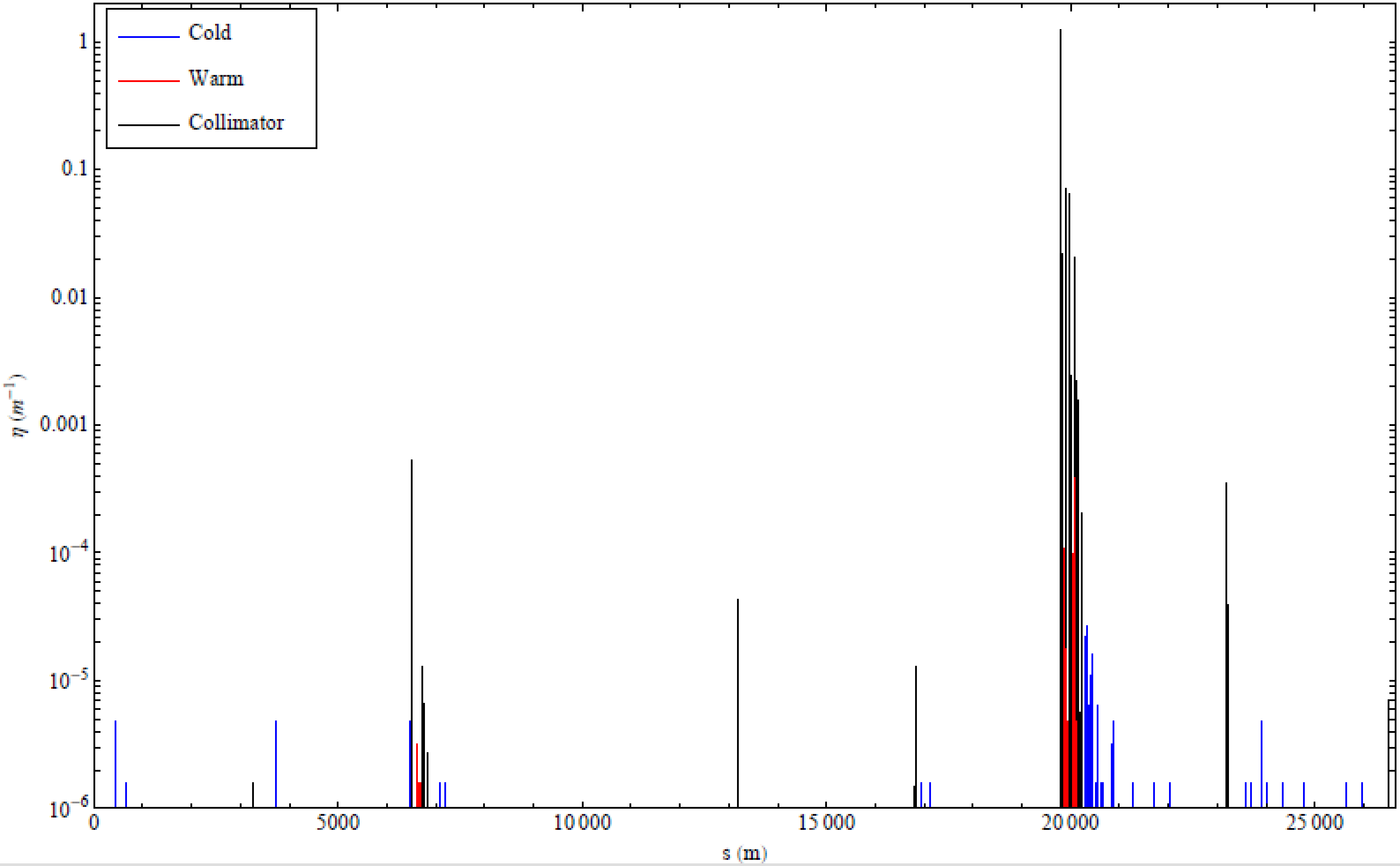


# Simulation setup (2)

- Initial distributions:
  - Pencil beam directly on IR7 horizontal or vertical primary, or
  - Flat distribution in halo plane (spread of 0.0015 σ around 5.7 σ ), Gaussian cut at 3 σ in other transverse plane, energy spread 1.129E-4
  - Results from these distributions very similar – showing only results from pencil beams
- Simulations done for B1 and B2 – showing only B1 (B2 similar)
- 6.4e6 primary particles per simulation (resolution in local cleaning inefficiency: 1.5e-6/m )
  - Statistical uncertainty ~ square root of number of counts in bin
- In total 8 simulations (H and V, 2 beams, 2 distributions)

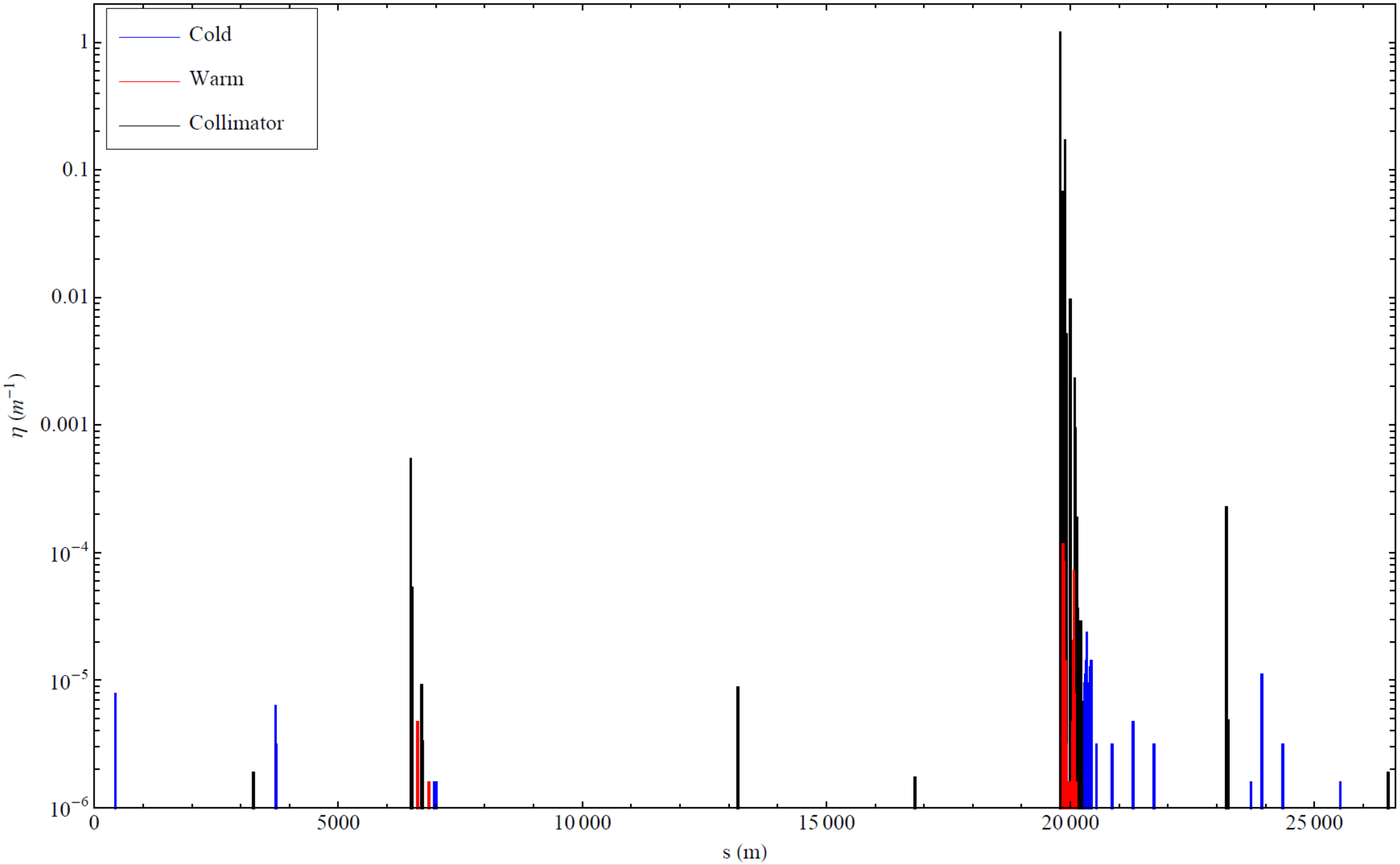
# Results: horizontal halo B1

- Global inefficiency ≈ 1.1e-3
- Highest local cleaning inefficiency in cold region ≈ 2.7e-5

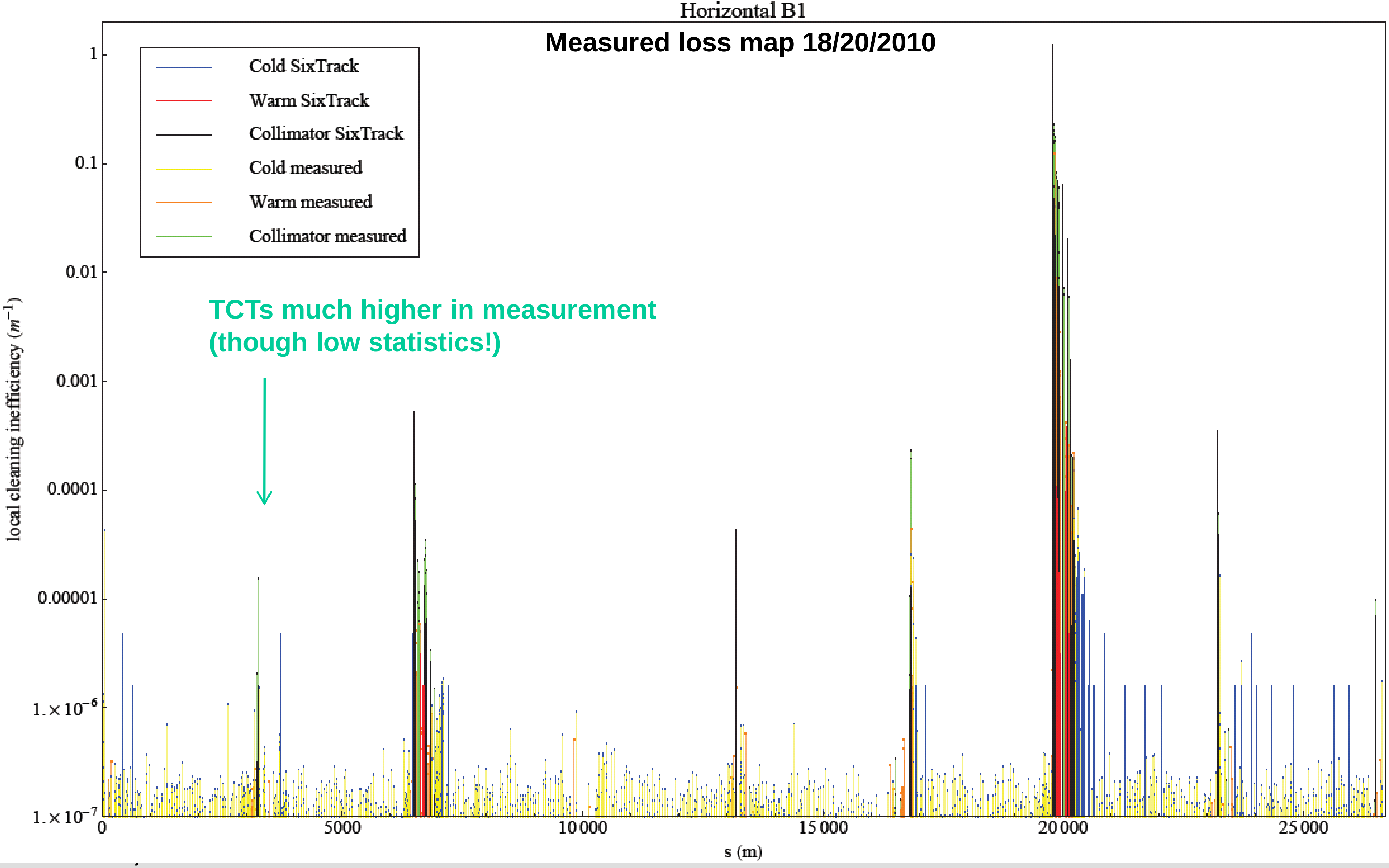


# Results: vertical halo B1

- Global inefficiency ≈ 8.2e-4
- Highest local cleaning inefficiency in cold region ≈ 2.3e-5



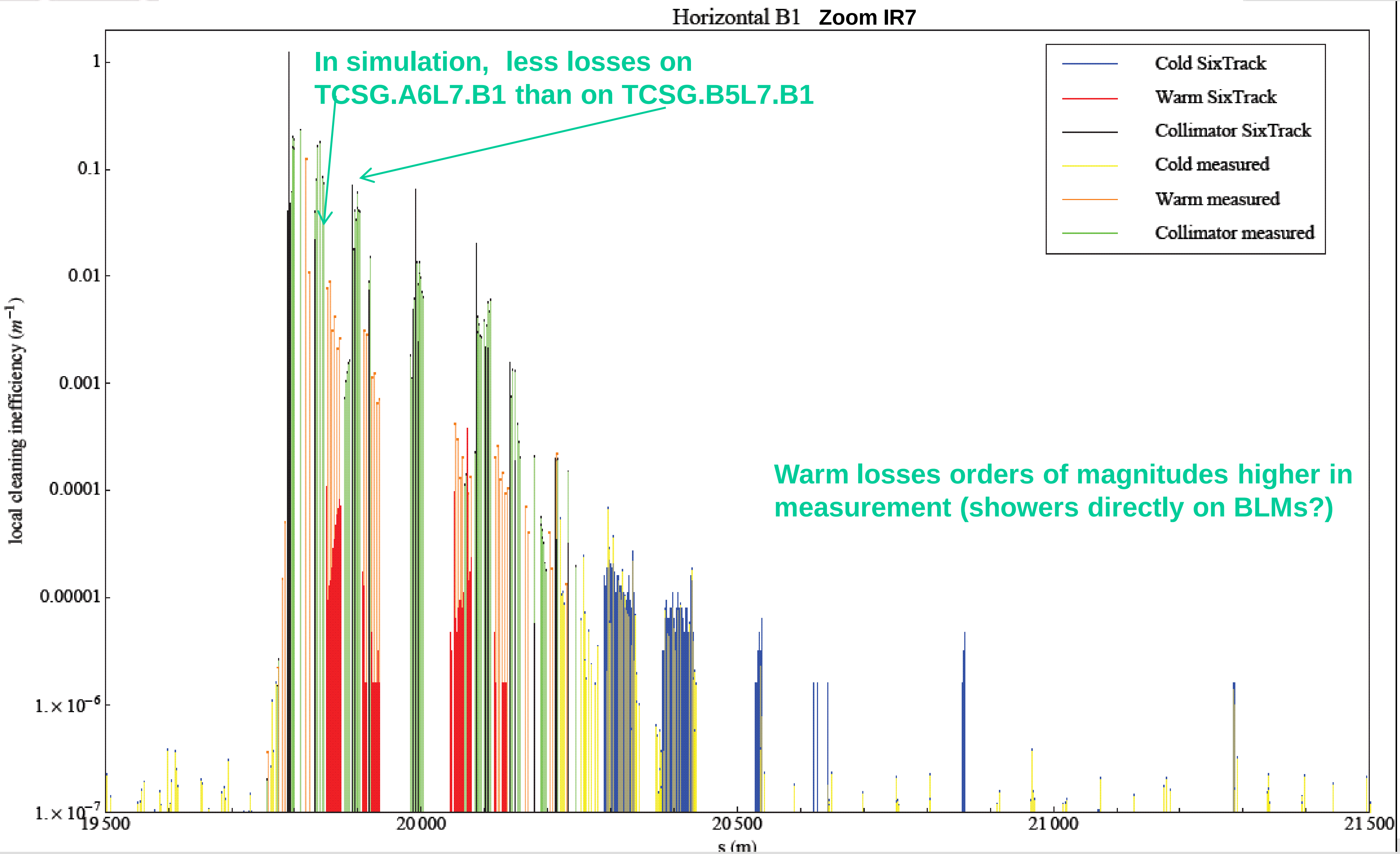
# Comparison with measured loss map



**Measured loss map 18/20/2010**

**TCTs much higher in measurement (though low statistics!)**

# Comparison with measured loss map



In simulation, less losses on TCSG.A6L7.B1 than on TCSG.B5L7.B1

Warm losses orders of magnitudes higher in measurement (showers directly on BLMs?)

# Observations

- Highest cold peak from measurements is ~ 2e-4 (almost factor 10 above simulation result, but no imperfections used in simulation – consistent with earlier results)
- Measured and simulated highest cold peaks found within 37 m.
- TCT leakage much lower in simulation (up to 1 order of magnitude)
- Vertical TCTs in IR2 and IR5 see higher losses than horizontal TCT with horizontal halo. Confirmed by measurements
- Leakage to IR3 accurate within 50%
- Local deviations of smaller peaks, though too low statistics to study these (very small) losses
- With TCTs at 15 σ, losses in TCTs in IR1 and IR5 lower by factor ~80 compared to 7 TeV simulations by Thomas with TCTs at 8.3 σ

# Conclusions

- Loss pattern in present machine ($\beta^*$=3.5m, intermediate collimator settings) simulated with SixTrack

- Simulated global inefficiency ≈ 1e−3

- Highest simulated local inefficiency in cold parts ≈ 2.7e−5

- Overall good agreement between measurements and simulations

- Some smaller discrepancies still to be understood

# TCT margins and minimum $\beta^*$

R. Bruce, R.W. Assmann

# Outline

- Introduction and motivation

- Method for calculating top energy aperture margins from measurements at injection

- Resulting TCT settings for different optics configurations

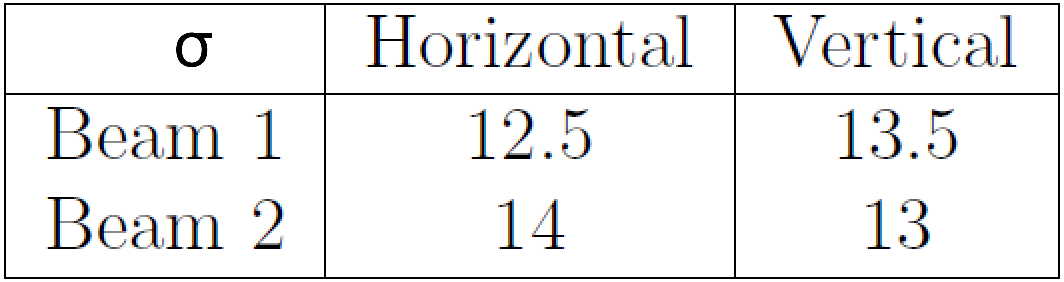
- Conclusion

# Introduction

- Present TCT settings based on aperture calculations using the n1-method
  - n1=maximum acceptable primary collimator opening, in units of beam σ, that still provides a protection of the mechanical aperture against losses from the secondary beam halo
  - n1 calculated with MAD-X, taking into account ideal aperture and optics. Then adding misalignments, β-beat and orbit offsets within given tolerances
  - May result in too pessimistic results!
- Alternative method: use aperture measurements performed at injection and scaling laws to calculate aperture at top energy
- As we will see, this is not possible in a general case, but can be done in the LHC triplet due to the special geometry of the problem

# Aperture measurements

- Global aperture measurements performed in September 2010 (*R. Assmann, R. Giachino, M. Giovannozzi, D. Jacquet, L. Ponce, S. Redaelli, J. Wenninger, see presentation in LHCCWG):*



| σ | Horizontal | Vertical |
|---|---|---|
| Beam 1 | 12.5 | 13.5 |
| Beam 2 | 14 | 13 |

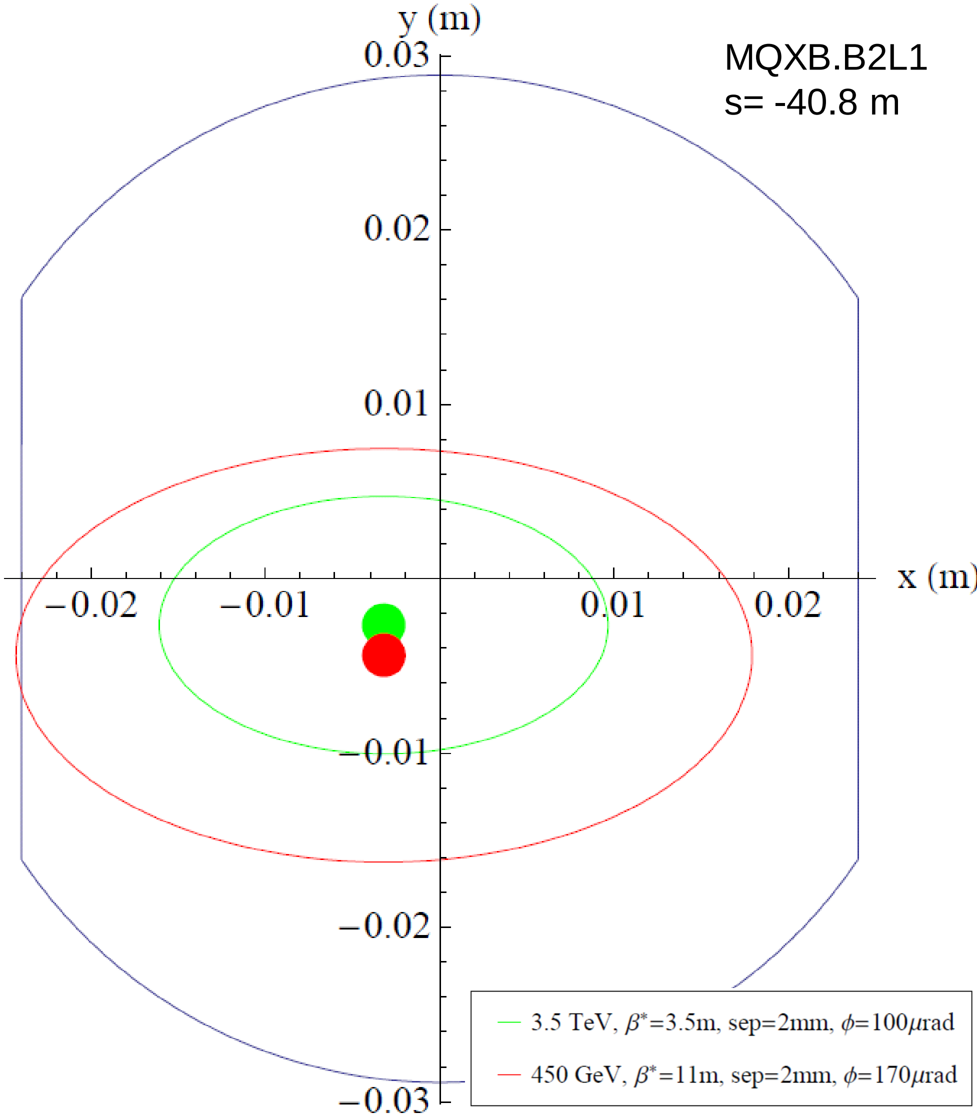
- Pessimistic assumption: triplet aperture must be larger than global aperture

# Calculation procedure

- Find s-value of limiting aperture with MAD-X (h and v)
- Assume injection aperture equal to global limit
- Because of geometry, only one plane matters
- Scale beam size to pre-collision (larger $\beta_x$ and $\gamma$), add orbit offsets in relevant plane from MAD-X

$$|u_i| + n_i\sigma_i = |u_p| + n_p\sigma_p$$

- Solve for top energy aperture
- 2D problem reduced to 1D



MQXB.B2L1
s= -40.8 m

# Calculation with tolerances

- Calculation above assumes same β-beat at this s-location at injection and squeeze, and orbit shift given by MAD-X
- Worst case: assume β-function larger by factor λ at squeeze and smaller by λ at injection
- Include additional orbit offset δu. Solve again for aperture at squeeze

$$n_p = \frac{|u_i| - |u_p| - \delta u + n_i \sigma_i}{\sigma_p} = \frac{|u_i| - |u_p| - \delta u}{\sqrt{\beta_p \lambda \epsilon_n / \gamma_p}} + \frac{n_i}{\lambda} \sqrt{\frac{\beta_{ui} \gamma_p}{\beta_{up} \gamma_i}}$$

- On the other hand, note that assumption that global limit occurs in triplet is already very pessimistic!

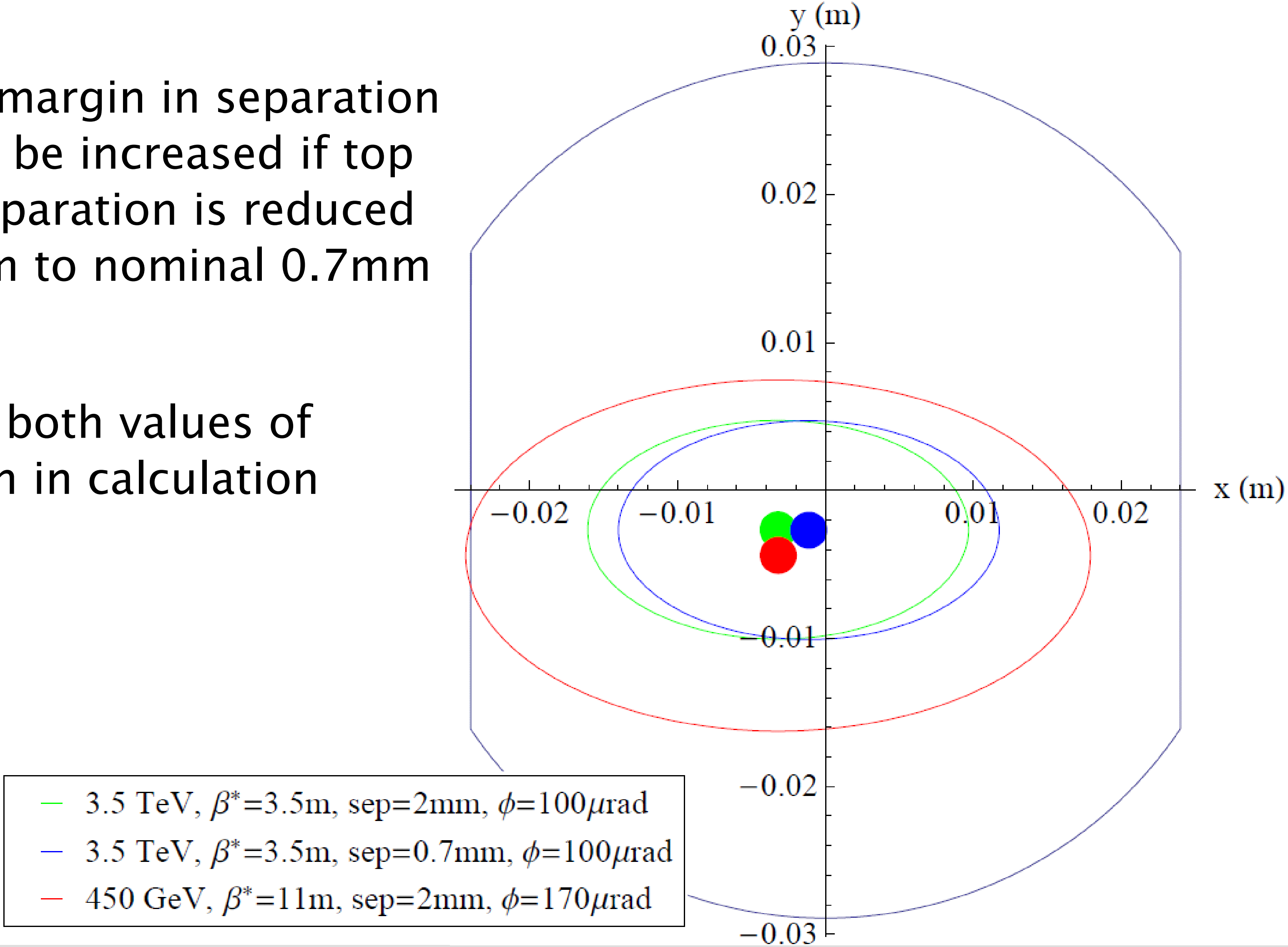
# Calculation setup

- Two sets of calculations performed:
  - $\lambda$=1 and $\delta u$=0 (more optimistic case)
  - $\lambda$=1.1 (20% $\beta$-beat) and $\delta u$=1mm
- For each set, calculated TCT settings assuming 2.5 $\sigma$ margin to aperture in the configurations $\beta$=2.0, 2.5, 3.0, 3.5 m
- All experimental IRs considered, both beams
- Horizontal and vertical planes treated separately to get rid of problem where aperture bottleneck jumps between different s-locations
- Bottleneck in separation plane (normally the limiting one) always in triplet of incoming beam, bottleneck in crossing plane on outgoing beam

# Reducing separation?

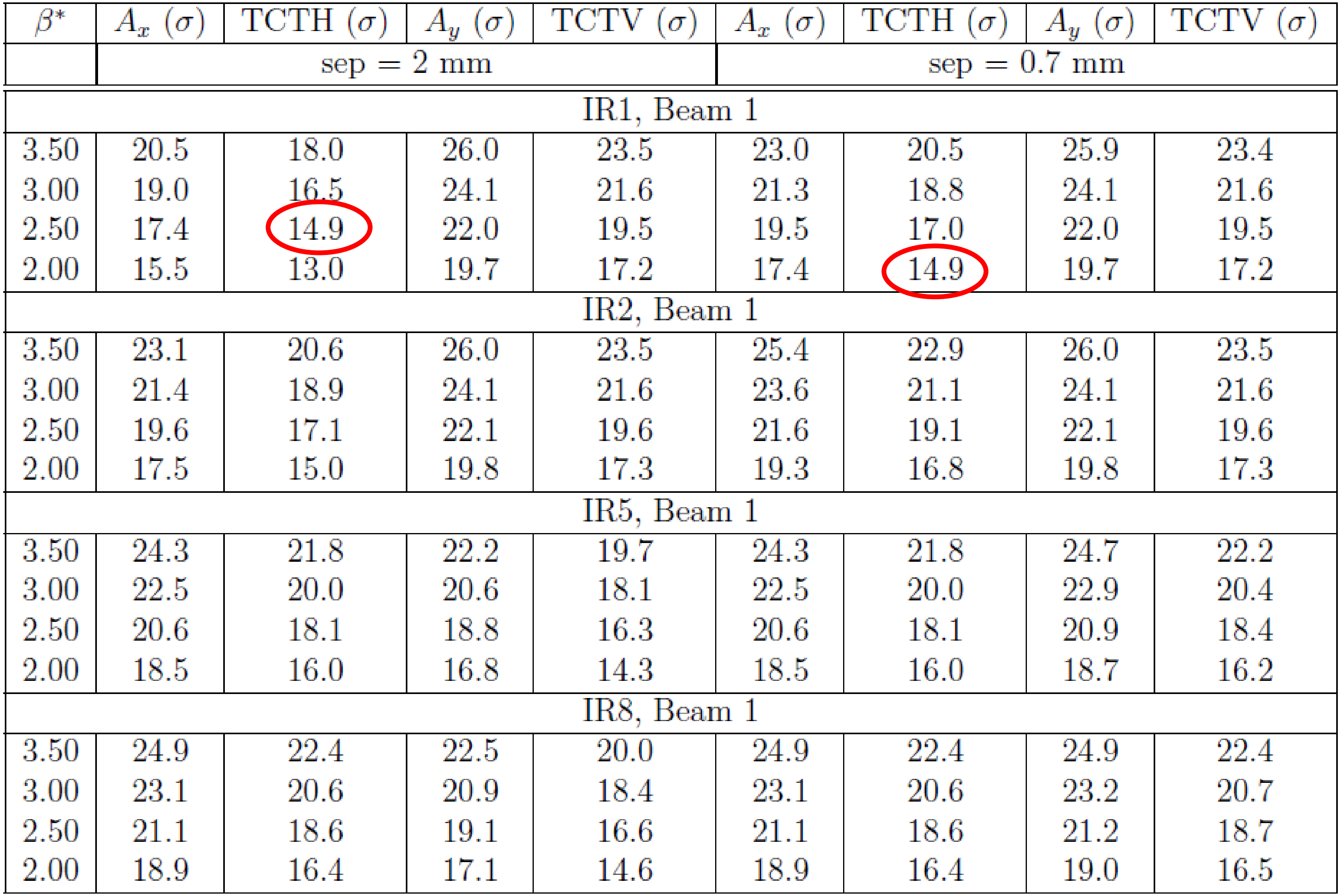
- Aperture margin in separation plane can be increased if top energy separation is reduced from 2mm to nominal 0.7mm

- Including both values of separation in calculation



# Preliminary results (1)

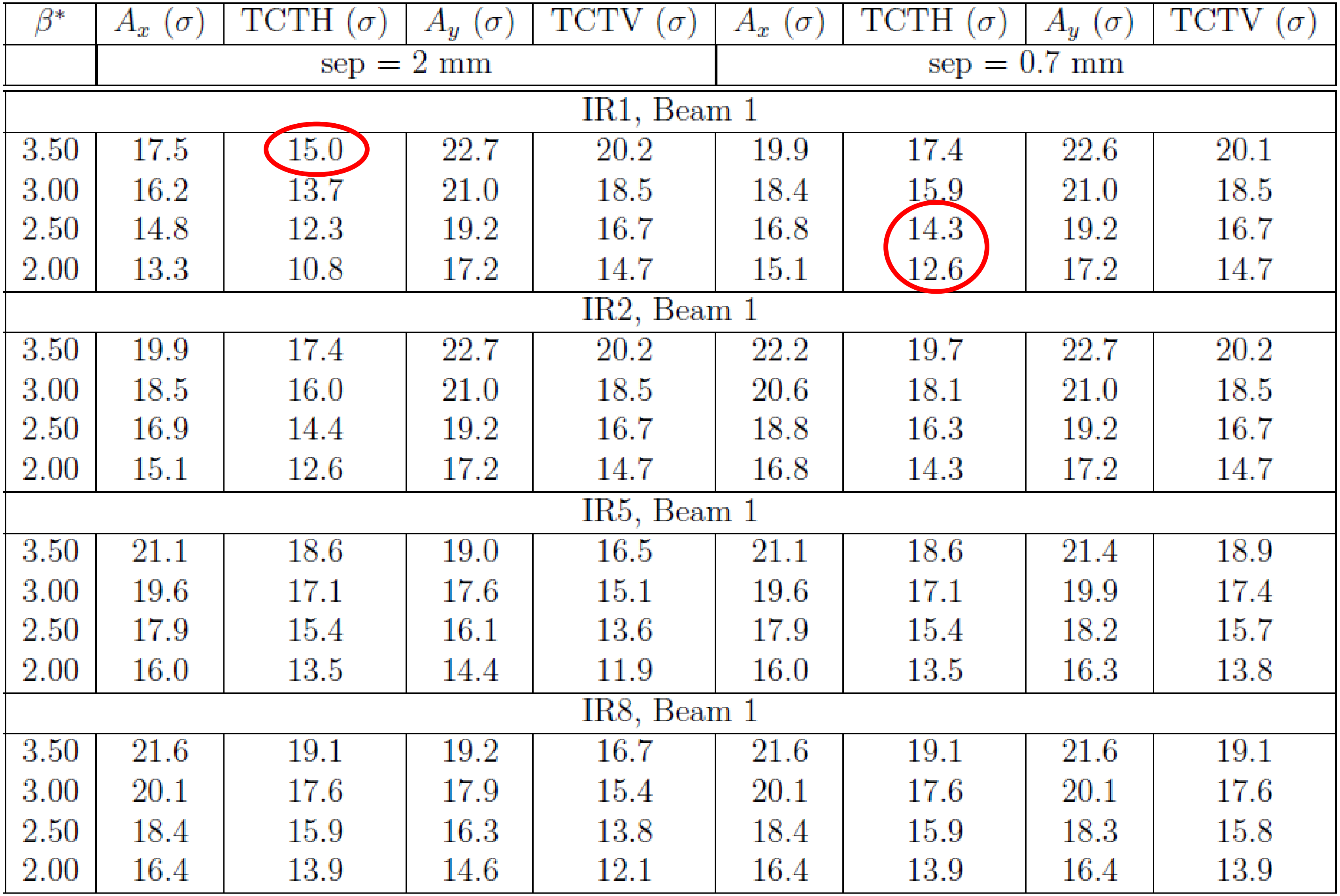
**B1,**
**λ=1,**
**δu=0**



| $\beta^*$ | $A_x$ ($\sigma$) | TCTH ($\sigma$) | $A_y$ ($\sigma$) | TCTV ($\sigma$) | $A_x$ ($\sigma$) | TCTH ($\sigma$) | $A_y$ ($\sigma$) | TCTV ($\sigma$) |
|---|---|---|---|---|---|---|---|---|
| | sep = 2 mm | | | | sep = 0.7 mm | | | |
| IR1, Beam 1 | | | | | | | | |
| 3.50 | 20.5 | 18.0 | 26.0 | 23.5 | 23.0 | 20.5 | 25.9 | 23.4 |
| 3.00 | 19.0 | 16.5 | 24.1 | 21.6 | 21.3 | 18.8 | 24.1 | 21.6 |
| 2.50 | 17.4 | 14.9 | 22.0 | 19.5 | 19.5 | 17.0 | 22.0 | 19.5 |
| 2.00 | 15.5 | 13.0 | 19.7 | 17.2 | 17.4 | 14.9 | 19.7 | 17.2 |
| IR2, Beam 1 | | | | | | | | |
| 3.50 | 23.1 | 20.6 | 26.0 | 23.5 | 25.4 | 22.9 | 26.0 | 23.5 |
| 3.00 | 21.4 | 18.9 | 24.1 | 21.6 | 23.6 | 21.1 | 24.1 | 21.6 |
| 2.50 | 19.6 | 17.1 | 22.1 | 19.6 | 21.6 | 19.1 | 22.1 | 19.6 |
| 2.00 | 17.5 | 15.0 | 19.8 | 17.3 | 19.3 | 16.8 | 19.8 | 17.3 |
| IR5, Beam 1 | | | | | | | | |
| 3.50 | 24.3 | 21.8 | 22.2 | 19.7 | 24.3 | 21.8 | 24.7 | 22.2 |
| 3.00 | 22.5 | 20.0 | 20.6 | 18.1 | 22.5 | 20.0 | 22.9 | 20.4 |
| 2.50 | 20.6 | 18.1 | 18.8 | 16.3 | 20.6 | 18.1 | 20.9 | 18.4 |
| 2.00 | 18.5 | 16.0 | 16.8 | 14.3 | 18.5 | 16.0 | 18.7 | 16.2 |
| IR8, Beam 1 | | | | | | | | |
| 3.50 | 24.9 | 22.4 | 22.5 | 20.0 | 24.9 | 22.4 | 24.9 | 22.4 |
| 3.00 | 23.1 | 20.6 | 20.9 | 18.4 | 23.1 | 20.6 | 23.2 | 20.7 |
| 2.50 | 21.1 | 18.6 | 19.1 | 16.6 | 21.1 | 18.6 | 21.2 | 18.7 |
| 2.00 | 18.9 | 16.4 | 17.1 | 14.6 | 18.9 | 16.4 | 19.0 | 16.5 |

# Preliminary results (2)

**B1,**
**λ=1.1,**
**δu=1 mm**



| $\beta^*$ | $A_x$ ($\sigma$) | TCTH ($\sigma$) | $A_y$ ($\sigma$) | TCTV ($\sigma$) | $A_x$ ($\sigma$) | TCTH ($\sigma$) | $A_y$ ($\sigma$) | TCTV ($\sigma$) |
|---|---|---|---|---|---|---|---|---|
| | sep = 2 mm | | | | sep = 0.7 mm | | | |
| IR1, Beam 1 | | | | | | | | |
| 3.50 | 17.5 | 15.0 | 22.7 | 20.2 | 19.9 | 17.4 | 22.6 | 20.1 |
| 3.00 | 16.2 | 13.7 | 21.0 | 18.5 | 18.4 | 15.9 | 21.0 | 18.5 |
| 2.50 | 14.8 | 12.3 | 19.2 | 16.7 | 16.8 | 14.3 | 19.2 | 16.7 |
| 2.00 | 13.3 | 10.8 | 17.2 | 14.7 | 15.1 | 12.6 | 17.2 | 14.7 |
| IR2, Beam 1 | | | | | | | | |
| 3.50 | 19.9 | 17.4 | 22.7 | 20.2 | 22.2 | 19.7 | 22.7 | 20.2 |
| 3.00 | 18.5 | 16.0 | 21.0 | 18.5 | 20.6 | 18.1 | 21.0 | 18.5 |
| 2.50 | 16.9 | 14.4 | 19.2 | 16.7 | 18.8 | 16.3 | 19.2 | 16.7 |
| 2.00 | 15.1 | 12.6 | 17.2 | 14.7 | 16.8 | 14.3 | 17.2 | 14.7 |
| IR5, Beam 1 | | | | | | | | |
| 3.50 | 21.1 | 18.6 | 19.0 | 16.5 | 21.1 | 18.6 | 21.4 | 18.9 |
| 3.00 | 19.6 | 17.1 | 17.6 | 15.1 | 19.6 | 17.1 | 19.9 | 17.4 |
| 2.50 | 17.9 | 15.4 | 16.1 | 13.6 | 17.9 | 15.4 | 18.2 | 15.7 |
| 2.00 | 16.0 | 13.5 | 14.4 | 11.9 | 16.0 | 13.5 | 16.3 | 13.8 |
| IR8, Beam 1 | | | | | | | | |
| 3.50 | 21.6 | 19.1 | 19.2 | 16.7 | 21.6 | 19.1 | 21.6 | 19.1 |
| 3.00 | 20.1 | 17.6 | 17.9 | 15.4 | 20.1 | 17.6 | 20.1 | 17.6 |
| 2.50 | 18.4 | 15.9 | 16.3 | 13.8 | 18.4 | 15.9 | 18.3 | 15.8 |
| 2.00 | 16.4 | 13.9 | 14.6 | 12.1 | 16.4 | 13.9 | 16.4 | 13.9 |

# Conclusions (1)

- Apertures at top energy and squeeze calculated from measurements at injection – alternative to standard n1 calculation
- Possible only in special cases where geometry allows 2D problem to be reduced to 1D
  - Possible in triplets in experimental IRs
- Pessimistic assumption of global aperture limit in triplet
- More detailed measurement of the local triplet aperture at injection could be very useful to refine calculations

# Conclusions (2)

- With no difference in β-beat and nominal orbit shifts, we can squeeze to β*=2.5m keeping present TCT settings and approximate margins
- With no difference in β-beat and nominal orbit shifts, we can squeeze to β*=2.0m keeping present TCT settings and approximate margins if separation is reduced to 0.7 mm
- With 20% β-beat and 1mm additional orbit drift, we can squeeze to β*=2.5m if separation is reduced to 0.7 mm and TCTs moved in to 14.3 σ (or if margin TCT-aperture reduced by 0.7 σ)
- To squeeze to β*=2.0m, TCTs would have to move in to 12.6 σ, or we have to reduce margin between TCT and aperture
- We could try a configuration that seems realistic (e.g. β*=2.5m). Start with low intensity, do loss map and maybe asynchronous dump test. If triplet aperture is protected by TCT, this configuration can be used during operation

# Backup slide: n1

- Available aperture traditionally expressed in n1 (largest setting in sigma of primary collimator such that the local aperture is protected from secondary halo)
- In MAD-X, n1 is varied until the cut of the secondary collimators touches aperture, tolerances taken into account