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# MD4224 High Brightness Simulation Summary

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# MD4224

## Motivation

Investigate possible effects of space charge (SC) for injection setup in the Proton Synchrotron (PS), in order to identify the SC contribution to the 30-40% horizontal emittance blow-up ovserved between the PS Booster (PSB) and the PS.

- Static tune scan performed using low energy quadrupoles (LEQs) in horizontal and vertical plane independently.
- High brightness beam, low chromaticity using pole face windings (PFWs), sextupoles for coupling correction.

# Static Tune Scan

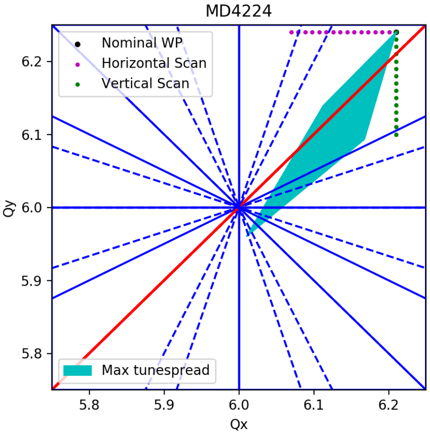



**Figure:** Points included in the MD4224 static tune scan, and estimated tunespread.

# MD4224 Parameters

| Parameter | MD | Simulation |
|---|---|---|
| Intensity $N_p$ [$10^{10}$] | $\approx$72.5 | 72.5 |
| Normalised horizontal RMS emittance $\epsilon_x^n$ [mm mrad] | 1.2 | 1.2 |
| Normalised vertical RMS emittance $\epsilon_y^n$ [mm mrad] | 1 | 1 |
| Bunch length $\sigma_t$[ns] | 140 | 140 |
| Momentum spread $\frac{\Delta p}{p}$ [$10^{-3}$] | 0.87 | 0.87 |
| Horizontal maximum tune spread $\Delta Q_{x,\mathrm{max}}$ | 0.2 | 0.16 |
| Vertical maximum tune spread $\Delta Q_{y,\mathrm{max}}$ | 0.28 | 0.24 |
| Harmonic number $h$ | 9 | 9 |
| RF voltage $V_{rf}$ [kV] | 21.2 | 21.2 |
| Horizontal chromaticity $Q_x'$ | 0.77 | 0.80 |
| Vertical chromaticity $Q_y'$ | -2.85 | -3.05 |
| Kinetic energy of the stored beam [GeV] | 1.4 | 1.4 |
| Relativistic $\beta$ | 0.916 | 0.916 |
| Relativistic $\gamma$ | 2.4921 | 2.4921 |
| Synchrotron Frequency [Hz] | 634 | 634 |

**Table:** Beam and machine parameters.

# MD4224 Results: Horizontal

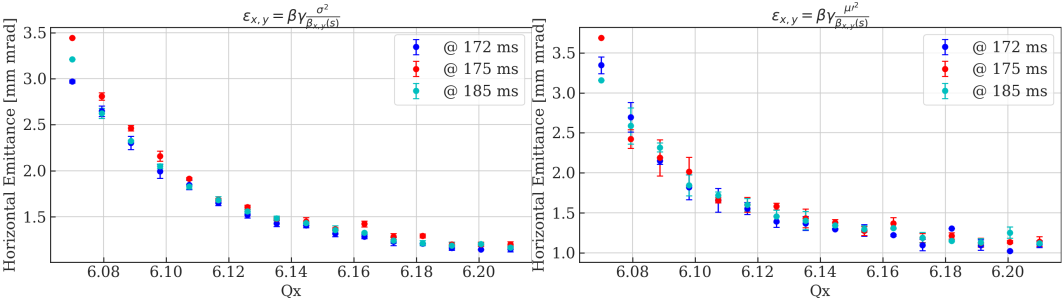



**Figure:** MD4224 horizontal emittances: left using $\sigma$, right using 2nd moment $\mu'$.

# MD4224 Results: Vertical

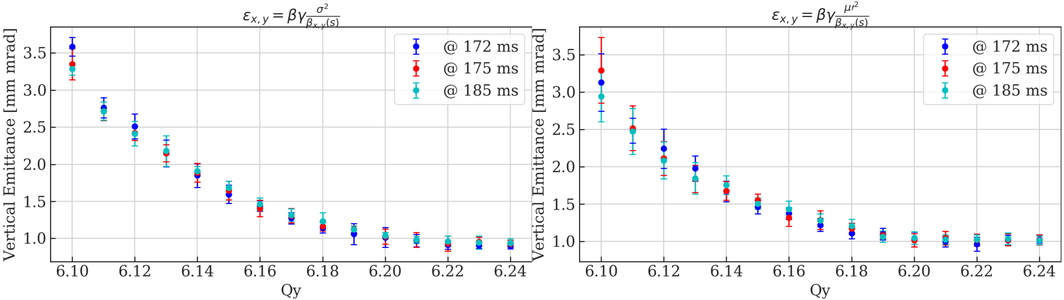



**Figure:** MD4224 vertical emittances: left using $\sigma$, right using 2nd moment $\mu'$.

# MD4224: Summary

- Clear emittance blow up close to the integer in both planes due to bunch core crossing the integer, and corresponding tune spread reduction.
- No dependence on wirescanner measurement time - implies fast blowup.
- Simulations to include only first measurement times (injection + 2 ms, injection + 5 ms) to reduce simulation time.

MD Summary

**Simulations**

Injection Bump

# Lattice Setup in MAD-X

```
pfki1f          =    -0.002562382254 ;
pfki2f          =      0.02189512262 ;
pfki3f          =       0.1160601827 ;

pfki1d          =     0.002381835717 ;
pfki2d          =     -0.02318695986 ;
pfki3d          =       -0.121350943 ;

/*******************************************************************
* Polynomials obtained from measurements of non-linear chromaticity
*               on LHC flat bottom - 01.11.2018
 *******************************************************************/
!2nd dedree polynomial
!Qx = 0.21 + 0.77 x + 60.1 x^2
!Qy = 0.32 - 2.85 x + 10.5 x^2

MQx0 :=  0.21;
MQx1 := 0.77;
MQx2 := 60.1;

MQy0 :=  0.32;
MQy1 := -2.85;
MQy2 := 10.5;

kf = 0.;
kd = 0.;

/*******************************************************************
 * Multipole matching
 *******************************************************************/
use, sequence=PS;
match,use_macro;
        vary,name=PFKI1F;
        vary,name=PFKI1D;
        vary,name=PFKI2F;
        vary,name=PFKI2D;
        vary,name=PFKI3F;
        vary,name=PFKI3D;
        use_macro,name=ptc_chrom_macro;
        constraint,expr= qx0= 1*MQx0;
    constraint,expr= qy0= 1*MQy0;
        constraint,expr= qx1= 1*MQx1;
        constraint,expr= qy1= 1*MQy1;
        constraint,expr= qx2= 2*MQx2;
        constraint,expr= qy2= 2*MQy2;
jacobian,calls=50000,bisec=3;
ENDMATCH;
```

```
/*************************************************************************
 * Next we use a ptc macro to match the tunes in the lattice to
 * desired values tune_x and tune_y.
 *
 * Using model=2, exact=true is recommended.
 *************************************************************************/
tune_x = 0.21;
tune_y = 0.10;

ptc_twiss_tune_macro_false_split: macro={
  ptc_create_universe;
  ptc_create_layout, time=true, model=2, exact=true, method=6, nst=3;
  ptc_twiss, closed_orbit, table = ptc_twiss, icase=56, no=2, summary_table=ptc_twiss_summary;
  qx0=table(ptc_twiss_summary,Q1);
  qy0=table(ptc_twiss_summary,Q2);
  value, qx0, qy0;
  ptc_end;
};

use, sequence=PS;
match, use_macro;
  vary,   name=iqf, step=1.0E-6 ;
  vary,   name=iqd, step=1.0E-6 ;
  USE_MACRO, name=ptc_twiss_tune_macro_false_split;
  CONSTRAINT, expr=  table(ptc_twiss_summary,Q1)= tune_x;
  CONSTRAINT, expr=  table(ptc_twiss_summary,Q2)= tune_y;
  JACOBIAN,calls=10000,bisec=3,TOLERANCE=1.0E-21;
ENDMATCH;
value, IQF, IQD;
```

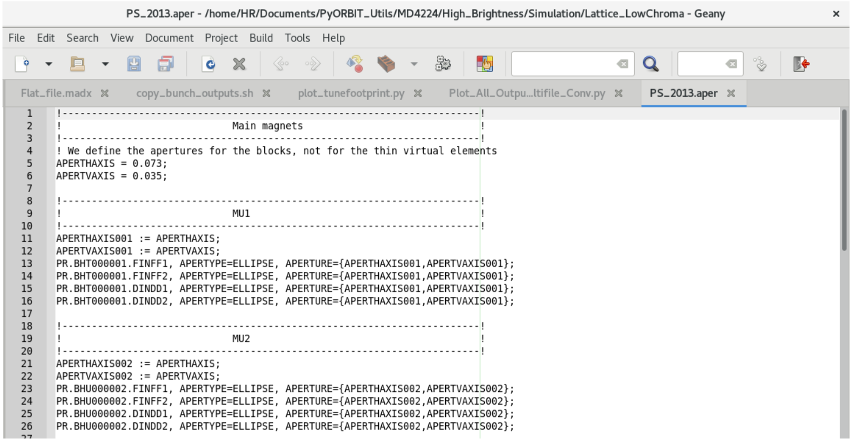
**Figure:** Low chroma using PFWs and tune matching using LEQs in MAD-X.

# Start Tracking At Wire Scanner Position

```
/*********************************************************************
 * Here we manually edit the sequence (lattice) to install a zero length
 * beam wire scanner at the start of region 64. We then save the new
 * sequence to a file.
 *********************************************************************/
PR.BWSV64     :  MONITOR  , L = 0.0;

seqedit, sequence=PS;
	flatten;
	install, element=PR.BWSV64, at=0.4, from=PS64$START;
	flatten;
endedit;

use, sequence=PS;

seqedit, sequence=PS;
	flatten;
	cycle , start=PR.BWSV64;
	flatten;
endedit;

save,file='./PS.seq';

use, sequence=PS;
```

**Figure:** Inserting vertical wire scanner and starting lattice from this position in MAD-X.

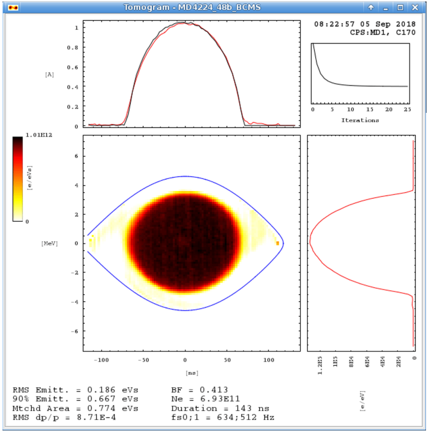
# Apertures

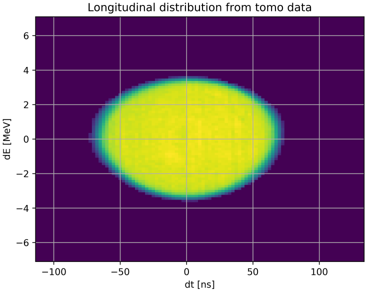



```
!--------------------------------------------------------------------------------!
!                              Main magnets                                       !
!--------------------------------------------------------------------------------!
! We define the apertures for the blocks, not for the thin virtual elements
APERTHAXIS = 0.073;
APERTVAXIS = 0.035;

!--------------------------------------------------------------------------------!
!                              MU1                                                !
!--------------------------------------------------------------------------------!
APERTHAXIS001 := APERTHAXIS;
APERTVAXIS001 := APERTVAXIS;
PR.BHT000001.FINFF1, APERTYPE=ELLIPSE, APERTURE={APERTHAXIS001,APERTVAXIS001};
PR.BHT000001.FINFF2, APERTYPE=ELLIPSE, APERTURE={APERTHAXIS001,APERTVAXIS001};
PR.BHT000001.DINDD1, APERTYPE=ELLIPSE, APERTURE={APERTHAXIS001,APERTVAXIS001};
PR.BHT000001.DINDD2, APERTYPE=ELLIPSE, APERTURE={APERTHAXIS001,APERTVAXIS001};

!--------------------------------------------------------------------------------!
!                              MU2                                                !
!--------------------------------------------------------------------------------!
APERTHAXIS002 := APERTHAXIS;
APERTVAXIS002 := APERTVAXIS;
PR.BHU000002.FINFF1, APERTYPE=ELLIPSE, APERTURE={APERTHAXIS002,APERTVAXIS002};
PR.BHU000002.FINFF2, APERTYPE=ELLIPSE, APERTURE={APERTHAXIS002,APERTVAXIS002};
PR.BHU000002.DINDD1, APERTYPE=ELLIPSE, APERTURE={APERTHAXIS002,APERTVAXIS002};
PR.BHU000002.DINDD2, APERTYPE=ELLIPSE, APERTURE={APERTHAXIS002,APERTVAXIS002};
```

**Figure:** Apertures set using 2013 data.

# Initial Distribution Using Tomo Data (Gaussian in Transverse Planes)



# Other Simulation Considerations

- Convergence tests show SC grid of 128x128x64 and macro-particle number $0.5 \cdot 10^6$ are most efficient.
- Tune scan using PFWs instead of LEQs show very little emittance growth. Further investigation with added quadrupole error to estimate strength required for similar emittance growth?
- Horizontal $\beta$ and dispersion beating observed - as expected due to transfer line dispersion mismatch.
- 2.5D space charge abandoned as results similar to slice-by-slice for $Q_y > 6.14$, disagreement with MD data below this.

# Similar Fitting Used For MD And Simulation Data

Procedure similar to that found in Appendix B of:
https://journals.aps.org/prab/abstract/10.1103/PhysRevAccelBeams.20.081006

- 5 parameter Gaussian fit to find mean and $\sigma$.
- $\pm$ 6 $\sigma$ cut to find slope.
- Remove slope.
- 3 parameter Gaussian fit to find centre.
- 2nd moment calculation.

# Fit Example

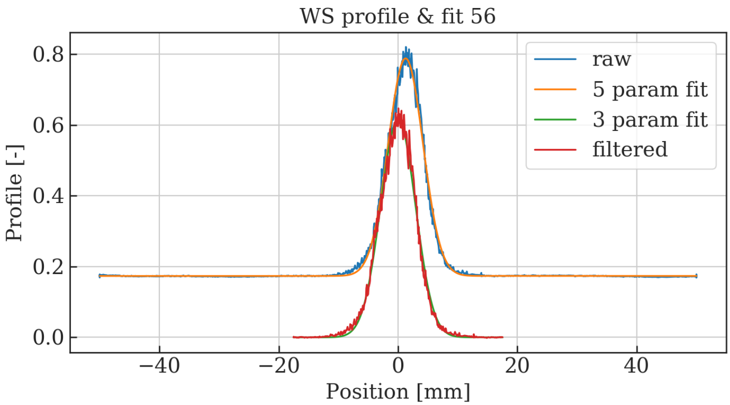



**Figure:** 3 and 5 parameter fit example.

# Fit Example

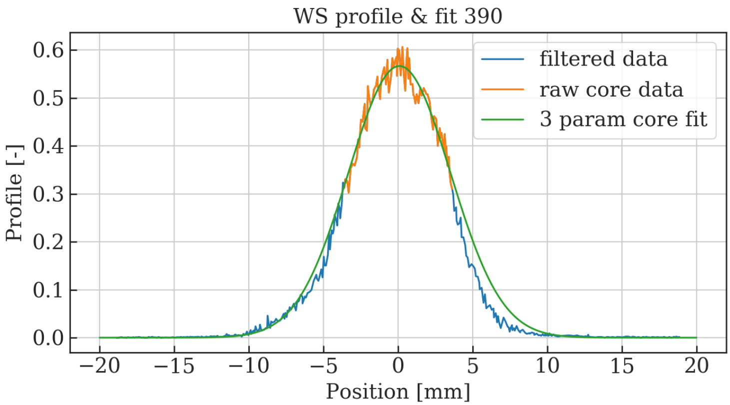



**Figure:** Core fit example.

MD Summary

Simulations

## Injection Bump

# Modelling Injection Bump in MAD-X

- Forked Eugenio Senes' Git repository 'PS-injection-bump'.
- Updated procedure with help from Hannes. Reduced from multiple calls to MAD-X from within python loop, to single MAD-X script with loop.
- Modifications to lattice performed together with Hannes  Alex didn't work for unknown reason.
- Started from scratch and modified PS lattice - worked.

# PyORBIT Procedure

- Script 'BSW_Table_Creator.py' generates input for MAD-X bump.
- MAD-X script iterates through time-steps and generates TFS tables for each magnet ramp.
- script 'PyORBIT_Table_Creator.py' reads TFS tables and creates PTC tables.
- PTC tables read in PTC scripts called by PyORBIT to ramp magnets.

# Tune Swing Examples

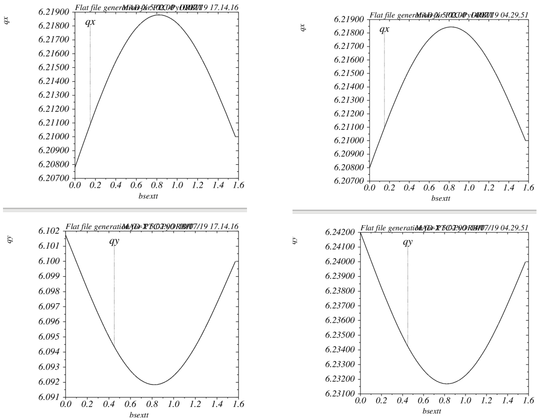



**Figure:** Tune swing for injection bump closure for $Q_y$=6.10 (left) and $Q_y$=6.24 (right)

# Emittance Comparison - No Space Charge

1 turn = $2.287 \cdot 10^{-6}$ s, Half bump = 0.5 ms = 219 turns

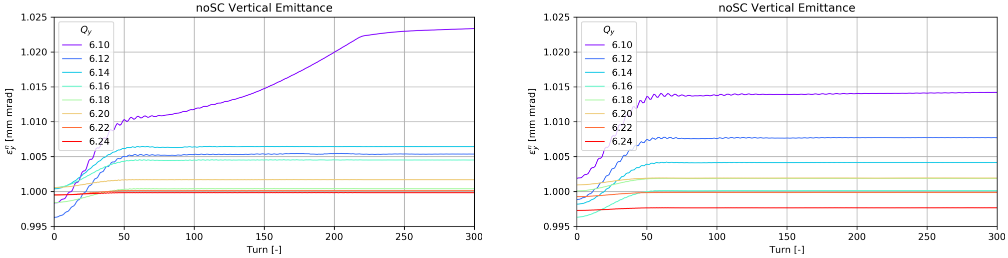



**Figure:** Vertical emittances with (left) and without (right) injection bump, no space charge.

# Emittance Comparison - With Space Charge

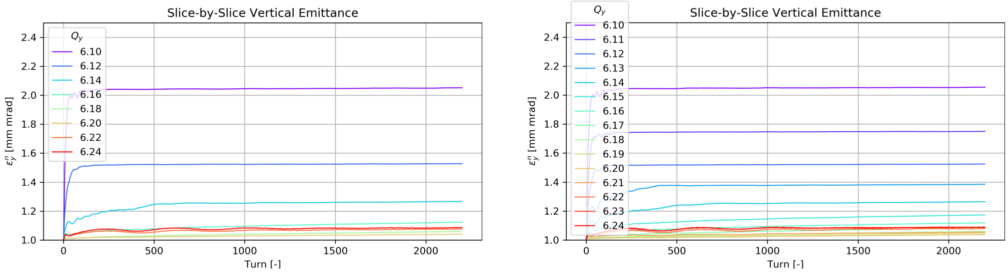



**Figure:** Vertical emittances with (left) and without (right) injection bump, with space charge.

# Emittance Comparison - With Space Charge

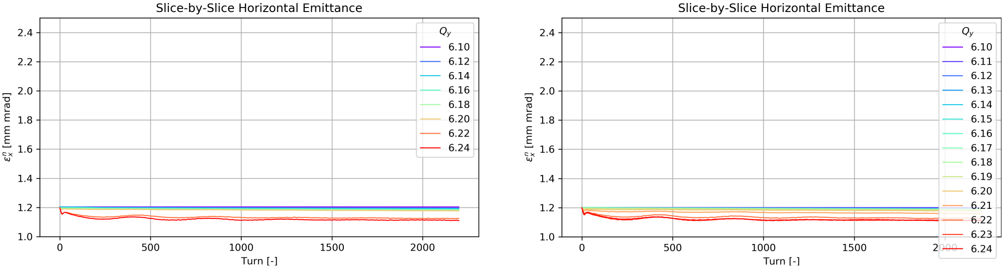



**Figure:** Horizontal emittances with (left) and without (right) injection bump, with space charge.

# Final Emittances From $\sigma$

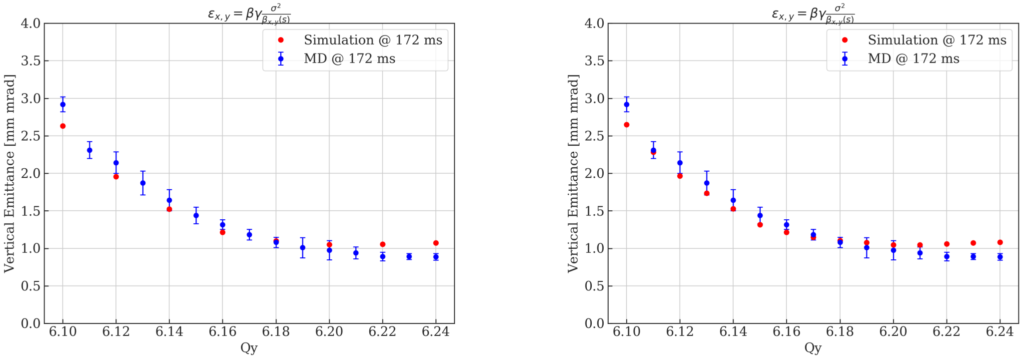



**Figure:** Final emittances with (left) and without (right) injection bump closure.

# Final Emittances From $\mu'$

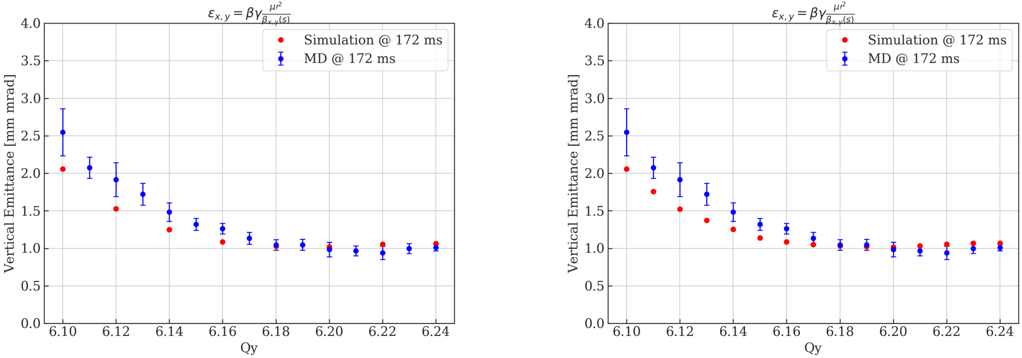
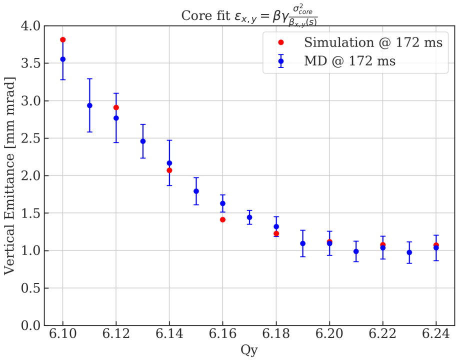



**Figure:** Final emittances with (left) and without (right) injection bump closure.

# Final Emittances From $\sigma$ Core Fit



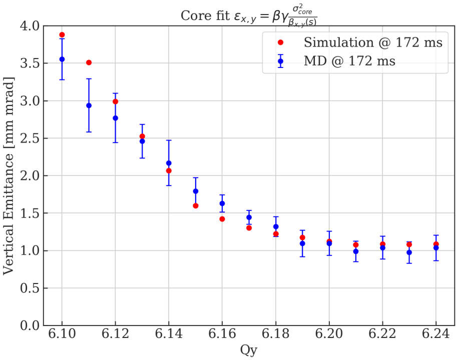
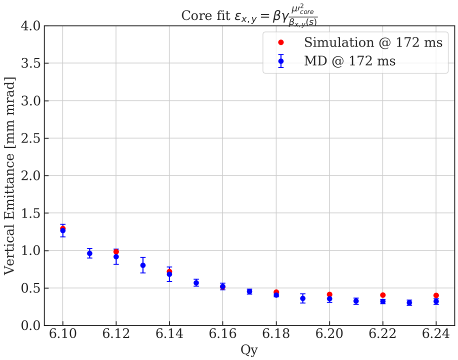




**Figure:** Final emittances with (left) and without (right) injection bump closure.

# Final Emittances From $\mu'$ Core Fit



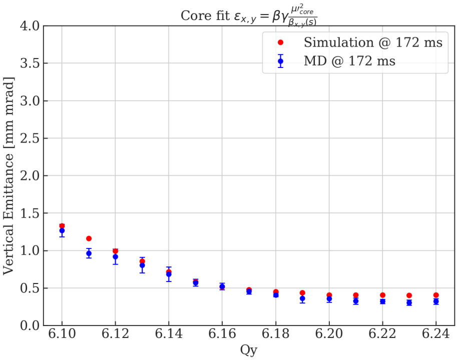




**Figure:** Final emittances with (left) and without (right) injection bump closure.

# Bunch Profile Comparisons $Q_y = 6.24$

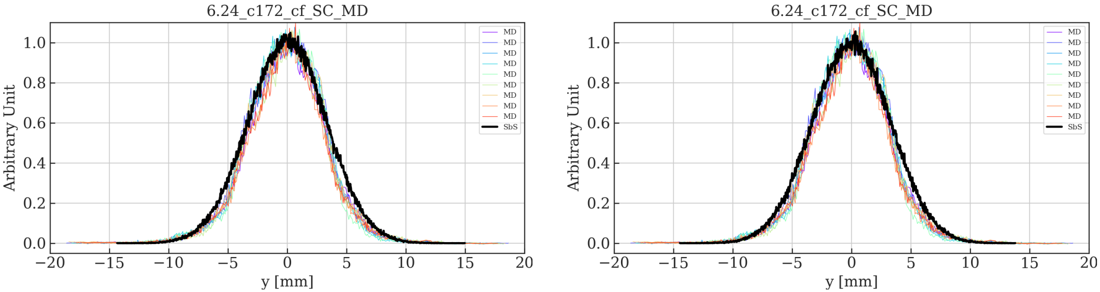
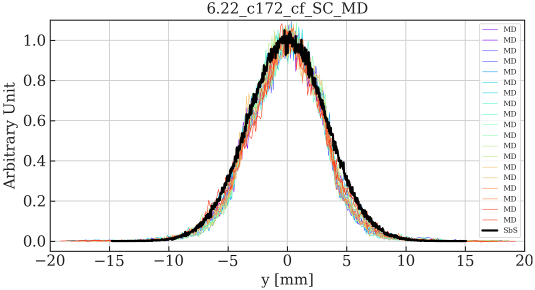



**Figure:** Bunch profiles comparing simulation with MD data with (left) and without (right) injection bump closure.

# Bunch Profile Comparisons $Q_y = 6.22$



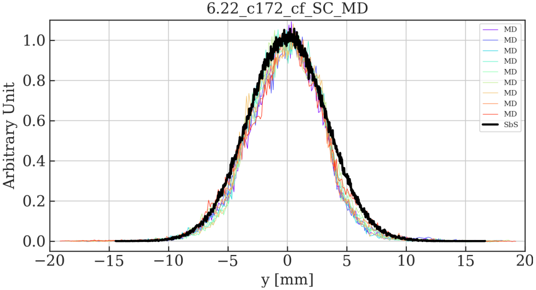




**Figure:** Bunch profiles comparing simulation with MD data with (left) and without (right) injection bump closure.

# Bunch Profile Comparisons $Q_y$ = 6.20

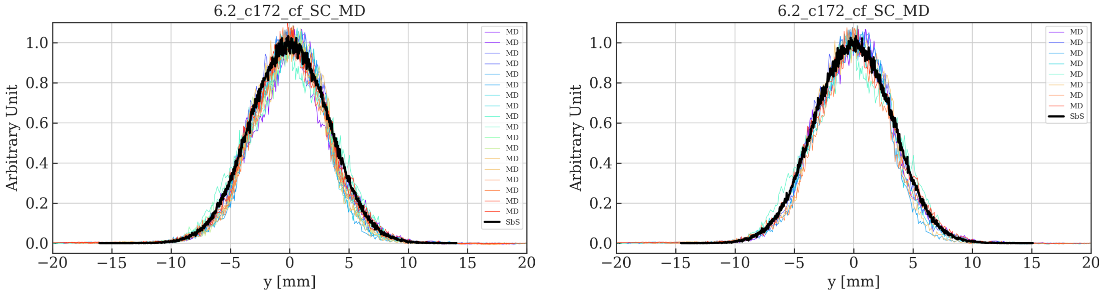
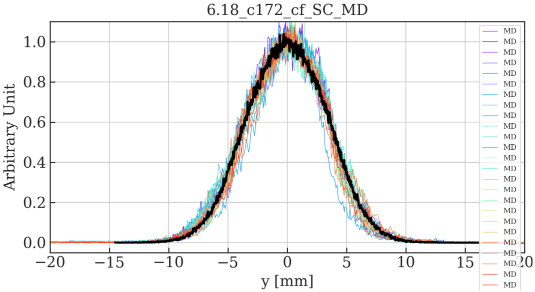



**Figure:** Bunch profiles comparing simulation with MD data with (left) and without (right) injection bump closure.

# Bunch Profile Comparisons $Q_y$ = 6.18



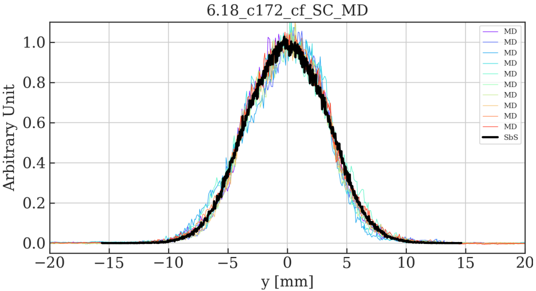




**Figure:** Bunch profiles comparing simulation with MD data with (left) and without (right) injection bump closure.

# Bunch Profile Comparisons $Q_y = 6.16$

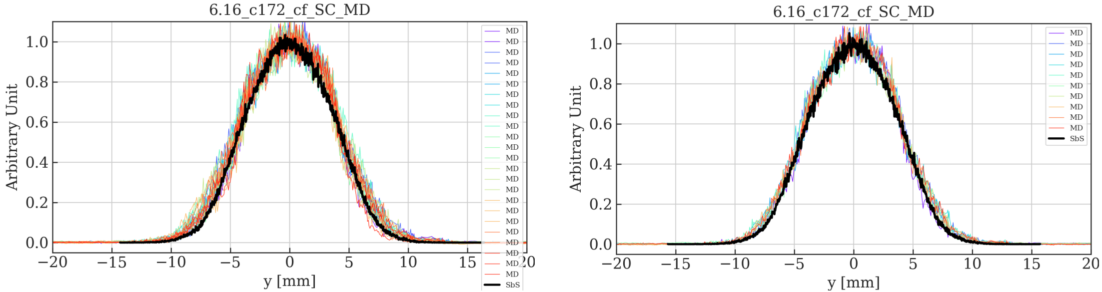
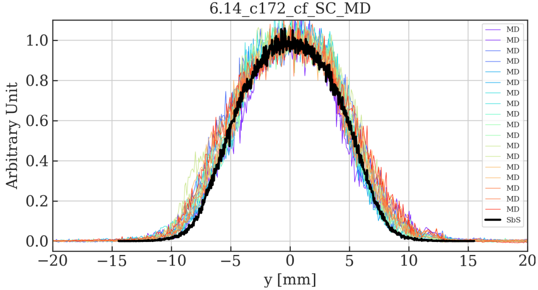



**Figure:** Bunch profiles comparing simulation with MD data with (left) and without (right) injection bump closure.

# Bunch Profile Comparisons $Q_y = 6.14$



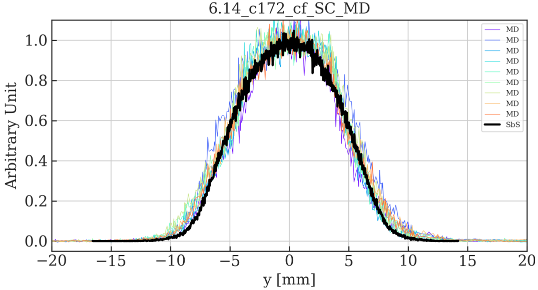




**Figure:** Bunch profiles comparing simulation with MD data with (left) and without (right) injection bump closure.

# Bunch Profile Comparisons $Q_y = 6.12$

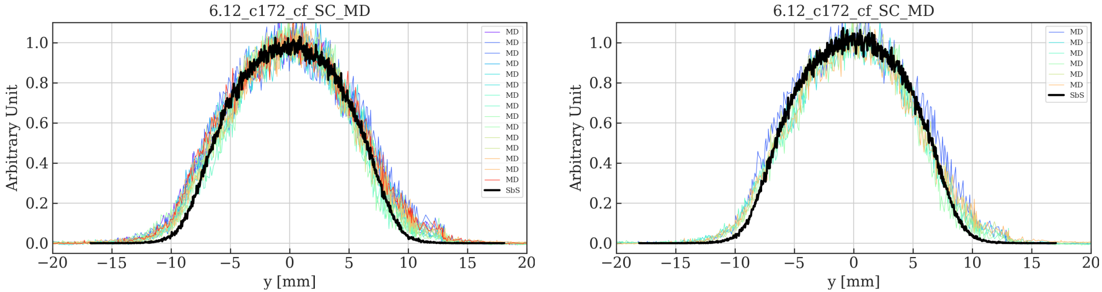



**Figure:** Bunch profiles comparing simulation with MD data with (left) and without (right) injection bump closure.

# Bunch Profile Comparisons $Q_y = 6.10$

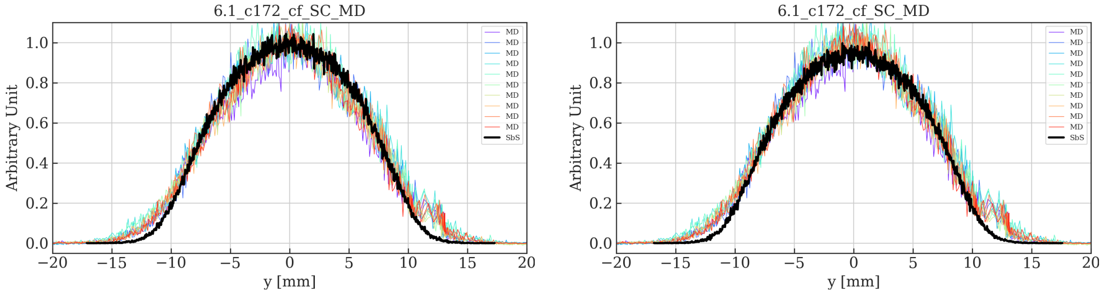



**Figure:** Bunch profiles comparing simulation with MD data with (left) and without (right) injection bump closure.

# Summary

- Eugenio's scripts updated to create PyORBIT tables for injection bump closure.
- With no space charge the difference in emittance growth is clear only for the smallest vertical tune.
- With space charge the difference in emittance growth appears negligible.

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