Scaling VFFAG eRHIC Design

Progress Report 4

Last time:

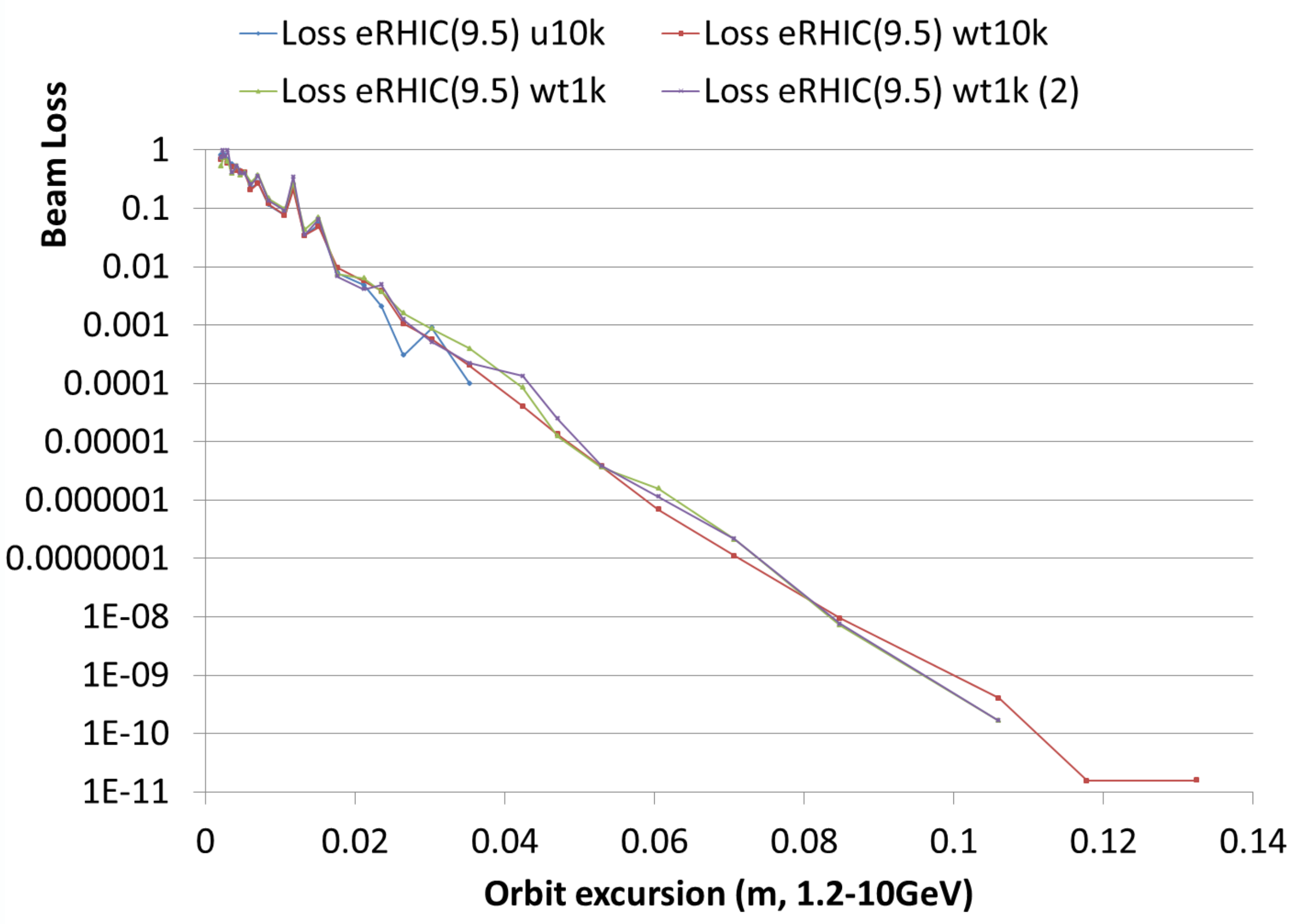
- Found FODO lattices rated for 9.4 and 9.5GeV
  - Extrapolation suggests both allow orbit excursions of less than 7cm (k=30m^-1) with <10^-6 losses
    - But this is without alignment errors
  - Location relative to resonances understood
- 9.5GeV/80% packing factor lattice became baseline for scaling VFFAG arc magnet design
- Synchrotron radiation ~10MW to first order

I. Macroparticle Weighting

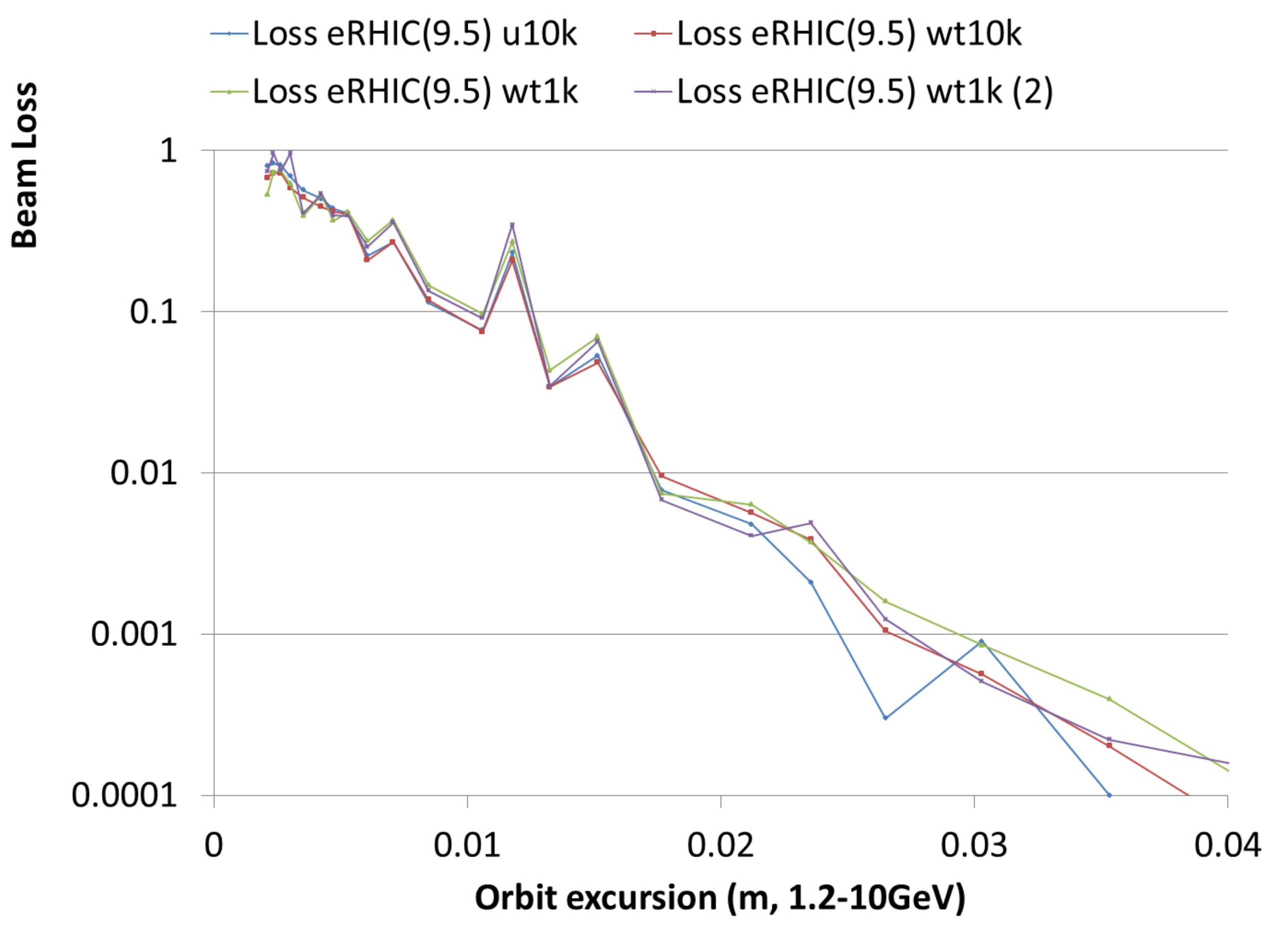
Greater accuracy for tail losses

- Generate macroparticles roughly uniformly as a function of normalised radius out to >10σ
- Weights are w = f(r)/g(r) where:
  - f(r) is desired real phase space density function
  - g(r) is density of generated macroparticles
- Details available in the note on distributions: http://stephenbrooks.org/ral/report/2013-9/4ddist.pdf

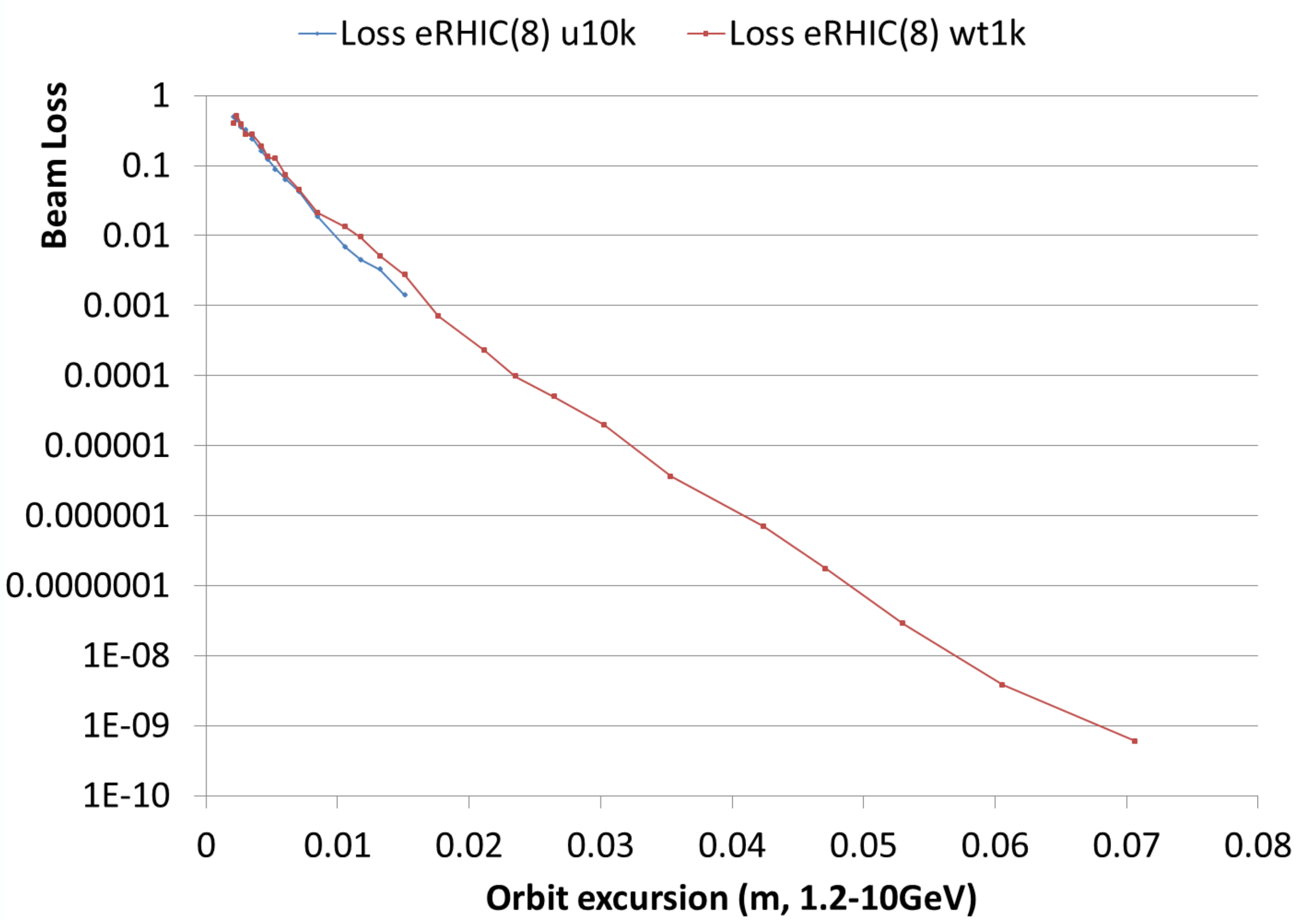
Comparison: 9.5GeV FODO lattice



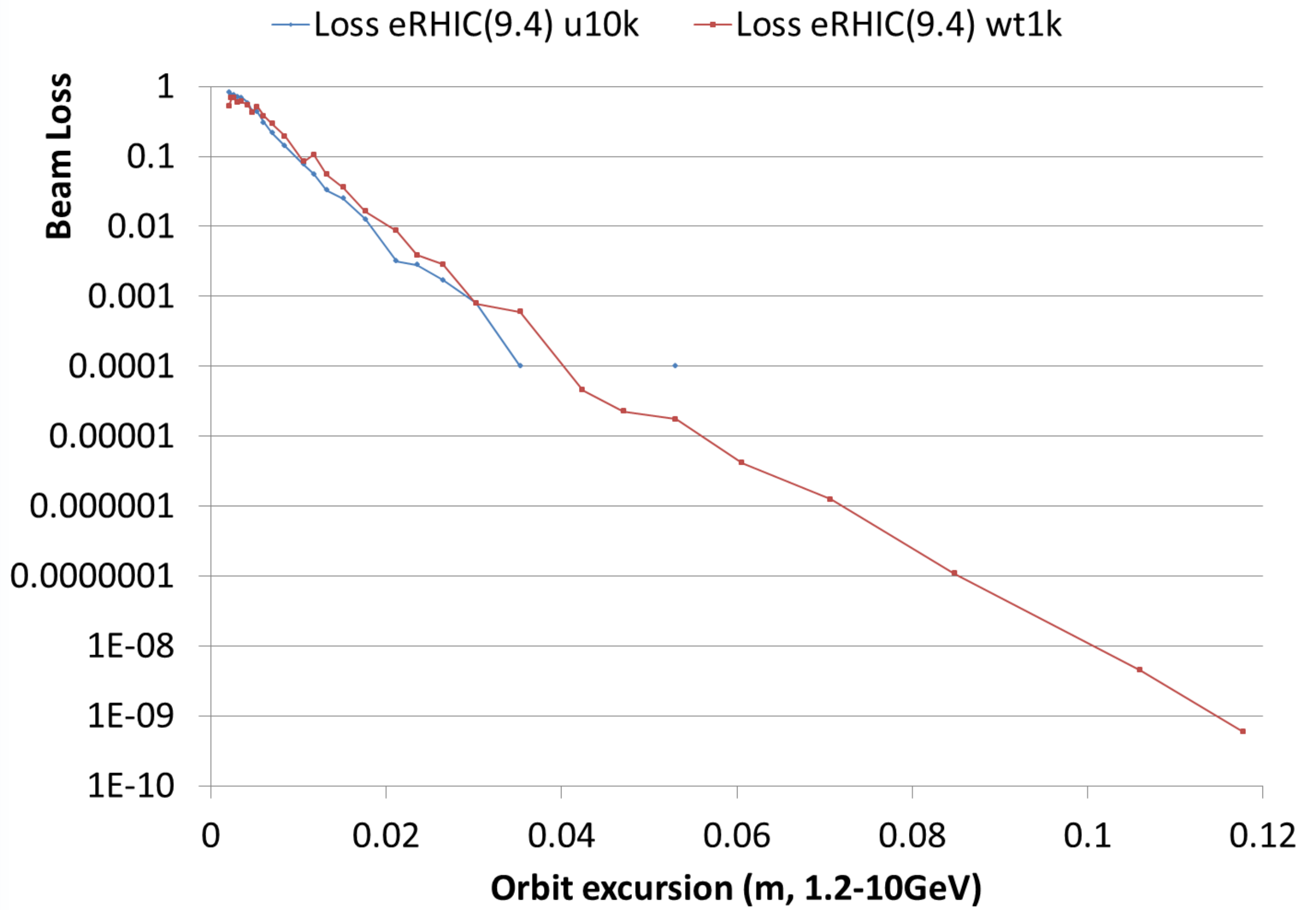
Zoom: ‘resonance’ features remain



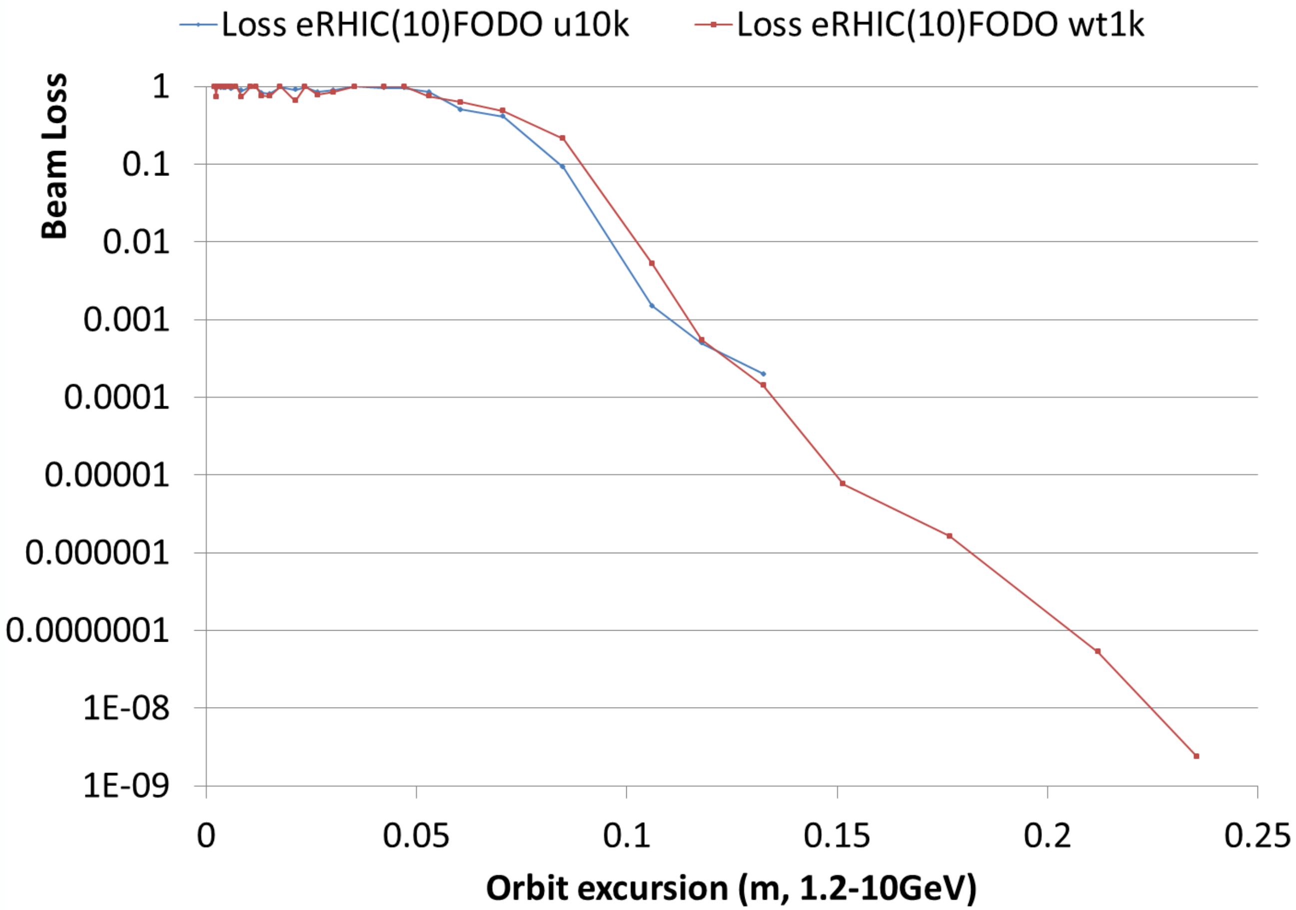
Comparison: 8GeV FODO lattice



Comparison: 9.4GeV FODO lattice



Comparison: 10GeV FODO lattice

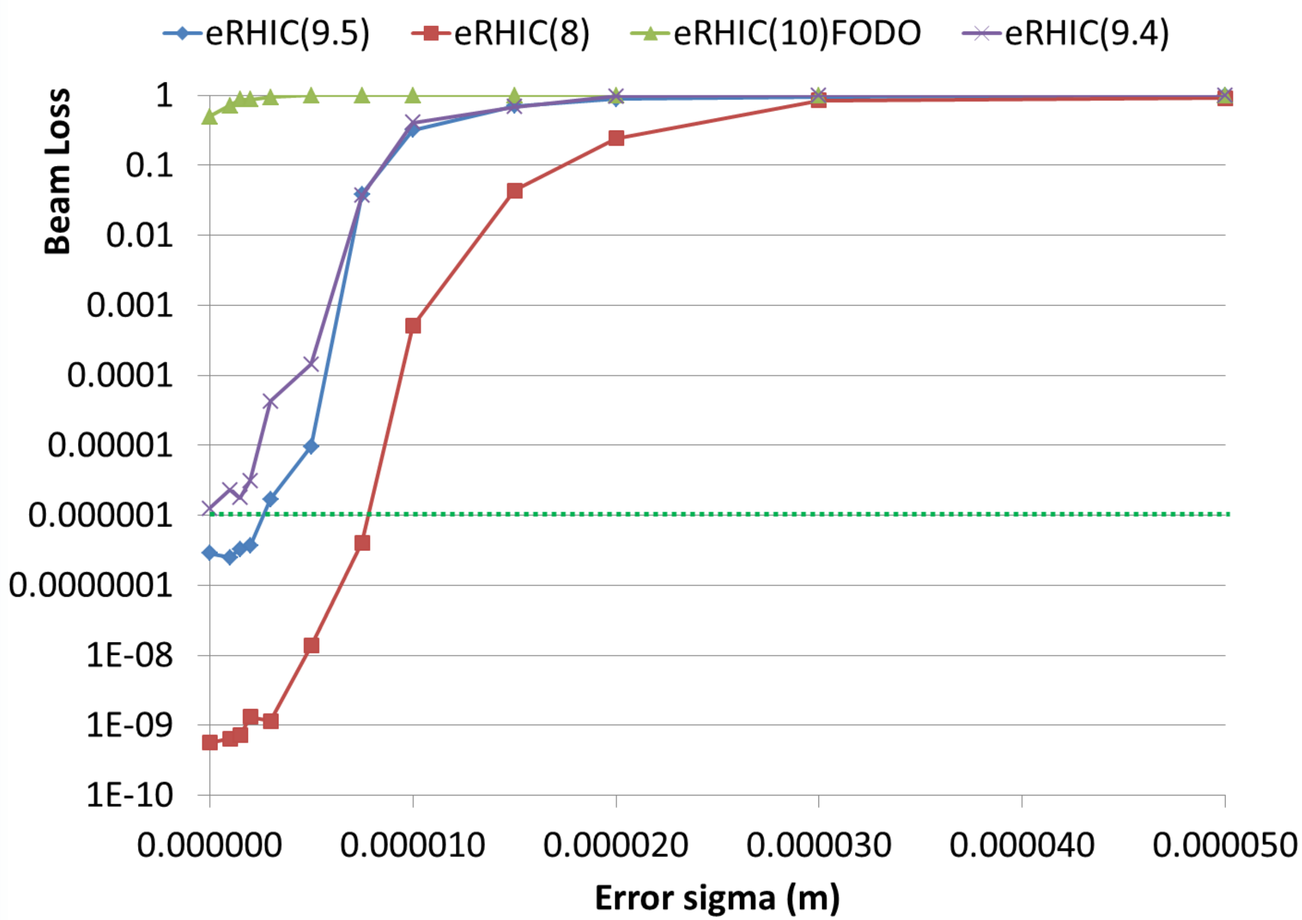


II. Error Studies of FODO Lattice

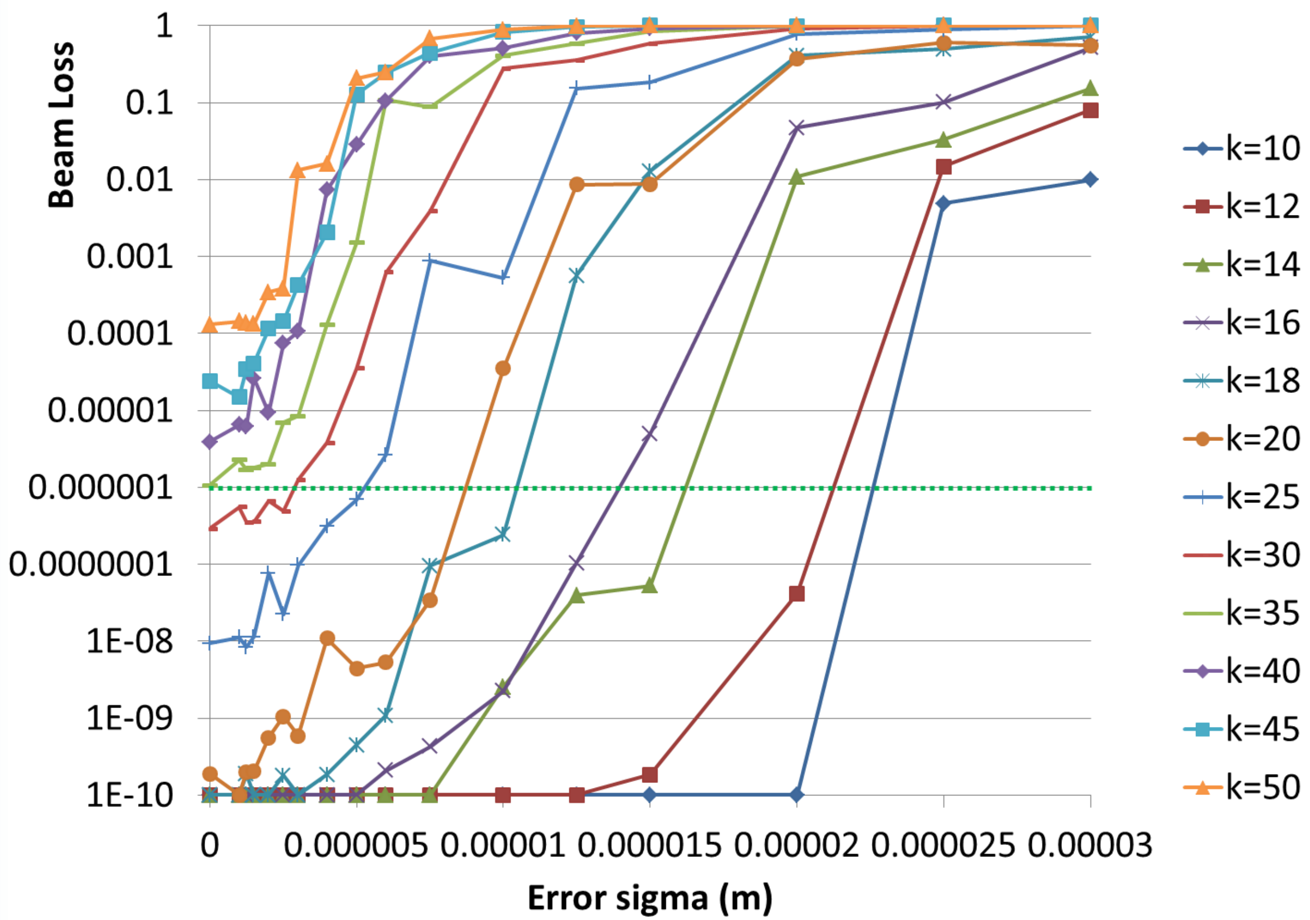
Tracking with translational errors

- Random offsets were generated for each magnet in 500 cells (then reused)
- Error **in each axis** a normal distribution with mean 0 and standard deviation σ
  - RMS 3D distance offset = sqrt(3)σ ~ 1.73σ
  - 99% single axis offset ~ 2.58σ
  - 99% 3D distance offset ~ 3.37σ
- Tracked 2 turns at 1.2GeV, disrupted beam

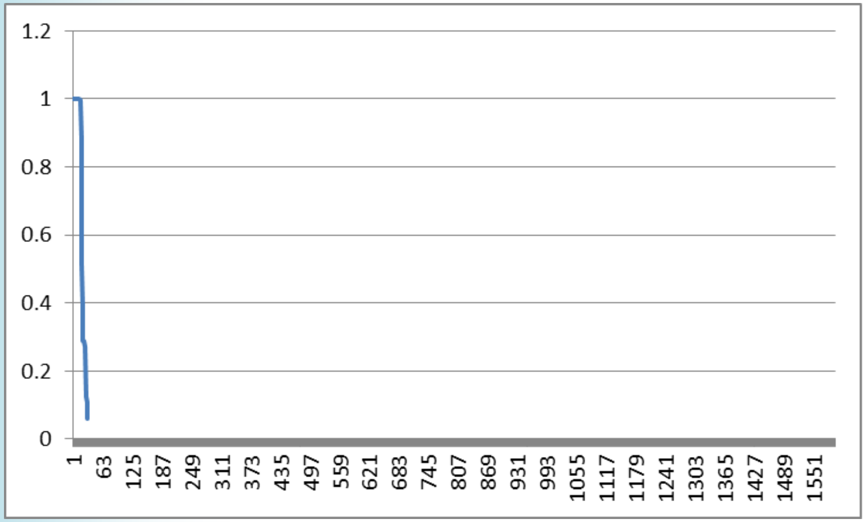
Beam loss vs. error sigma

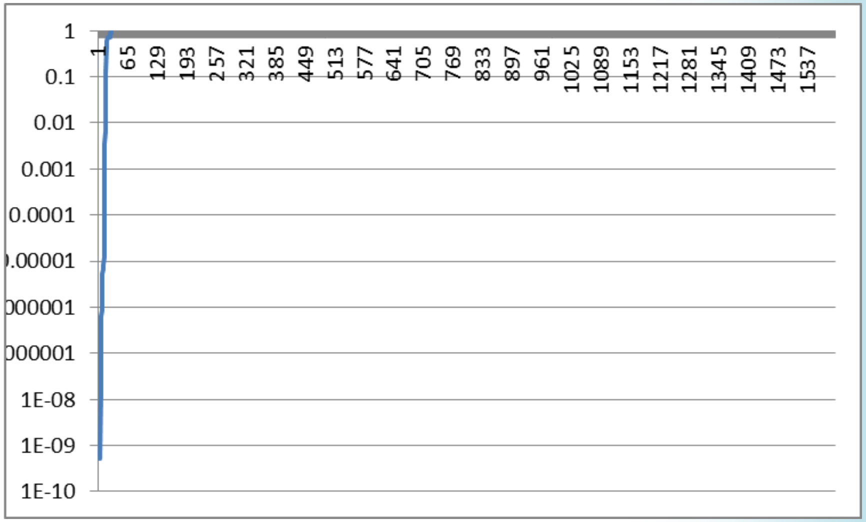


Loss vs. k and σ for 9.5GeV lattice

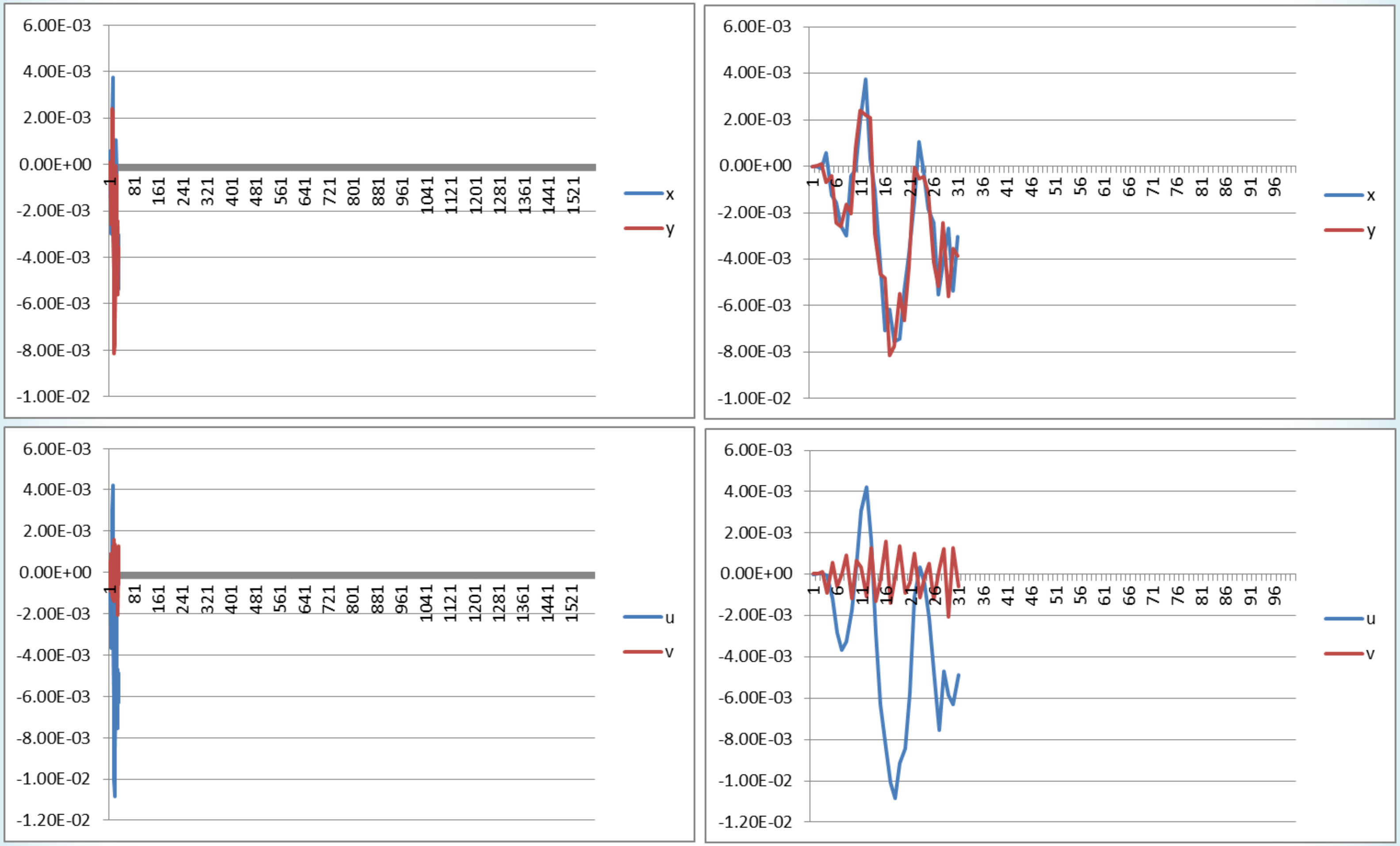


σ=100um transmission

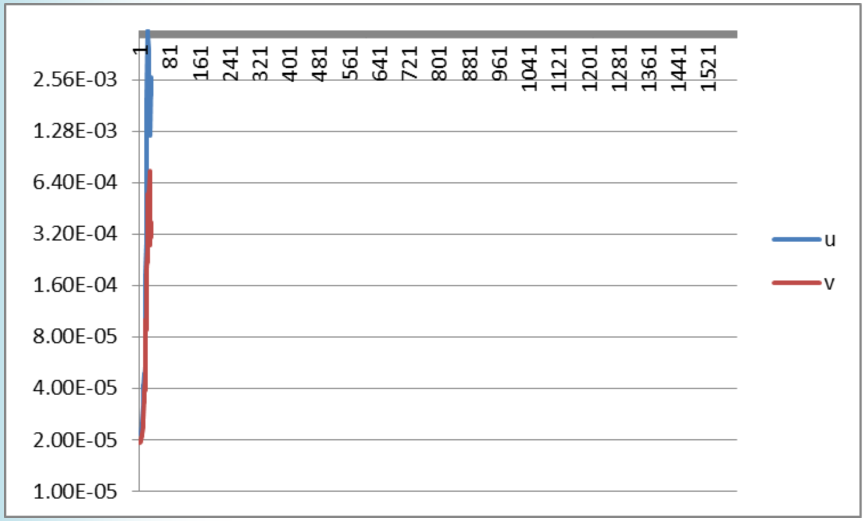


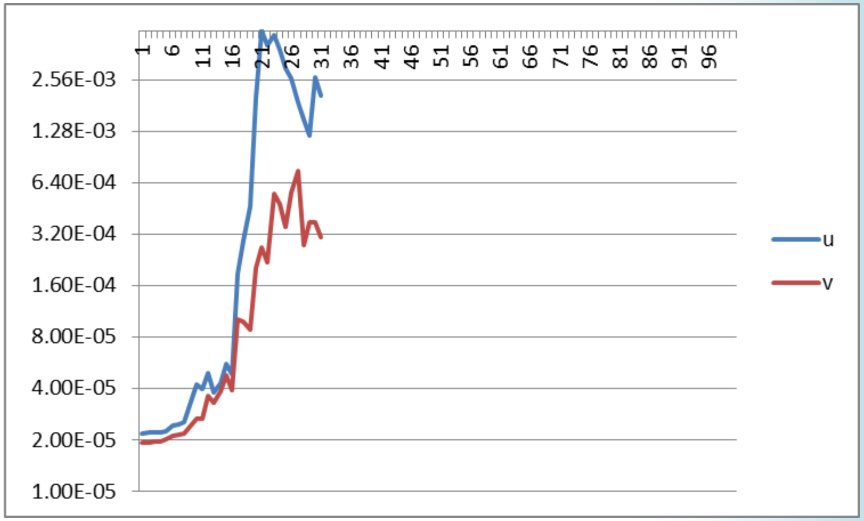


σ=100um beam centroid

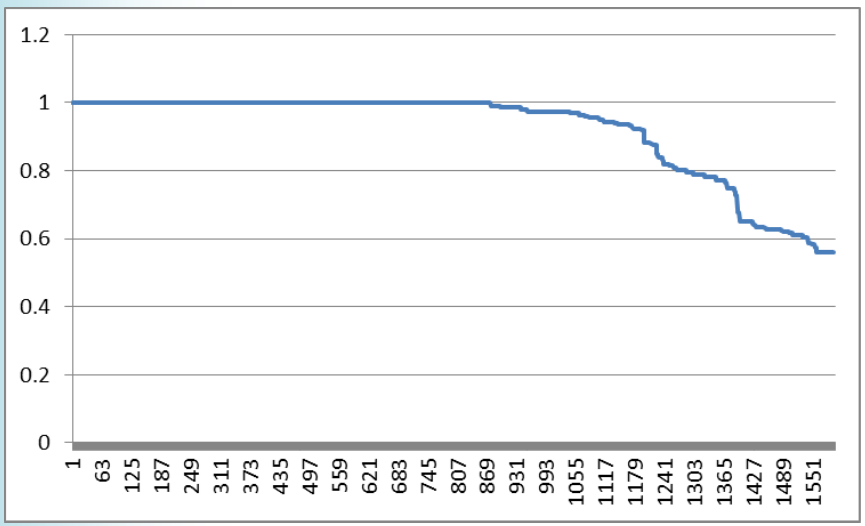


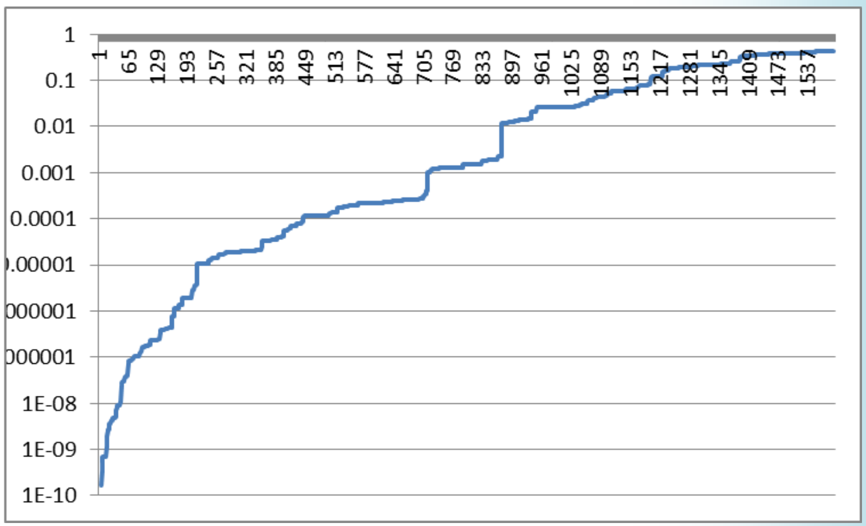
σ=100um norm. RMS emittances



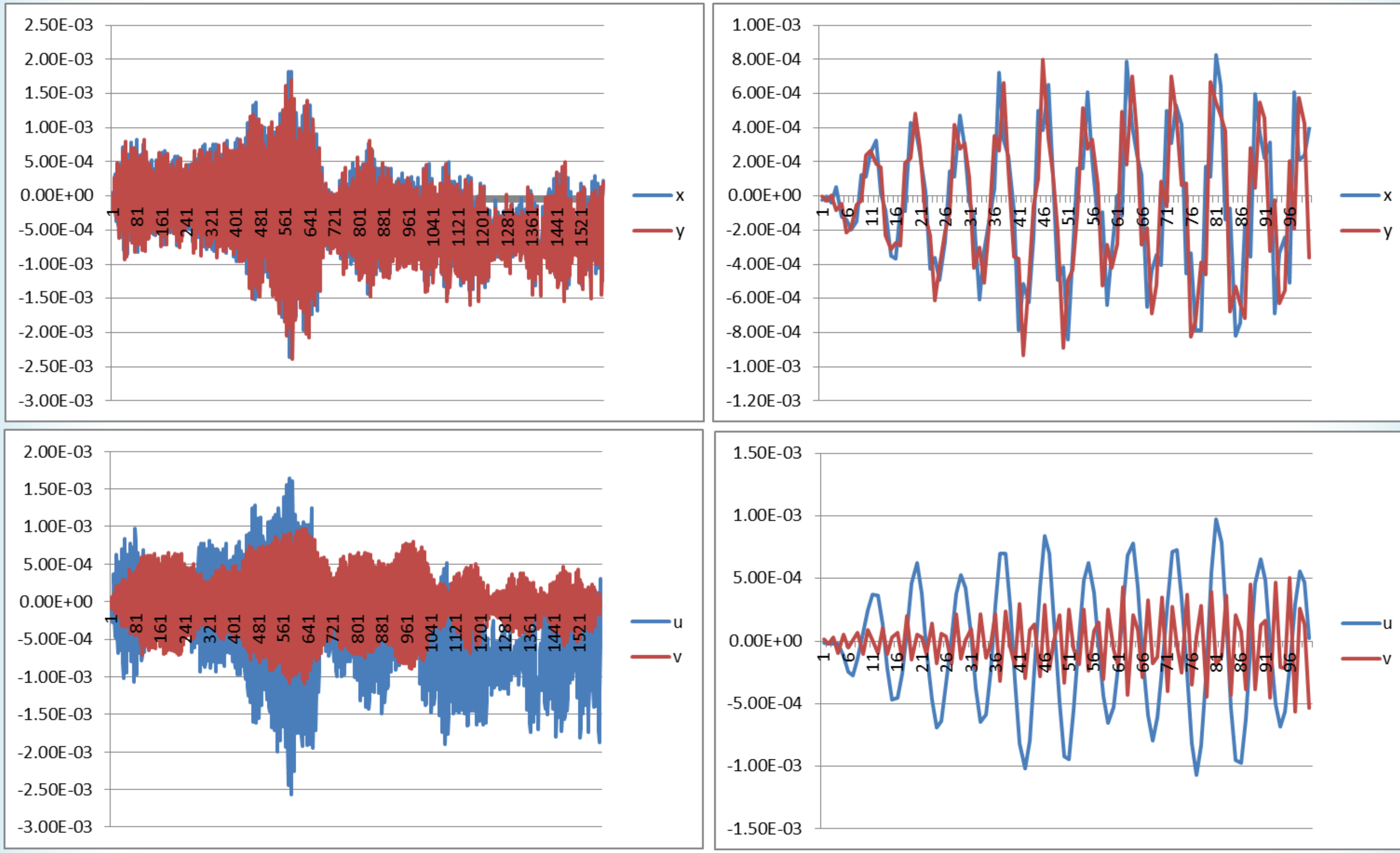


σ=10um transmission

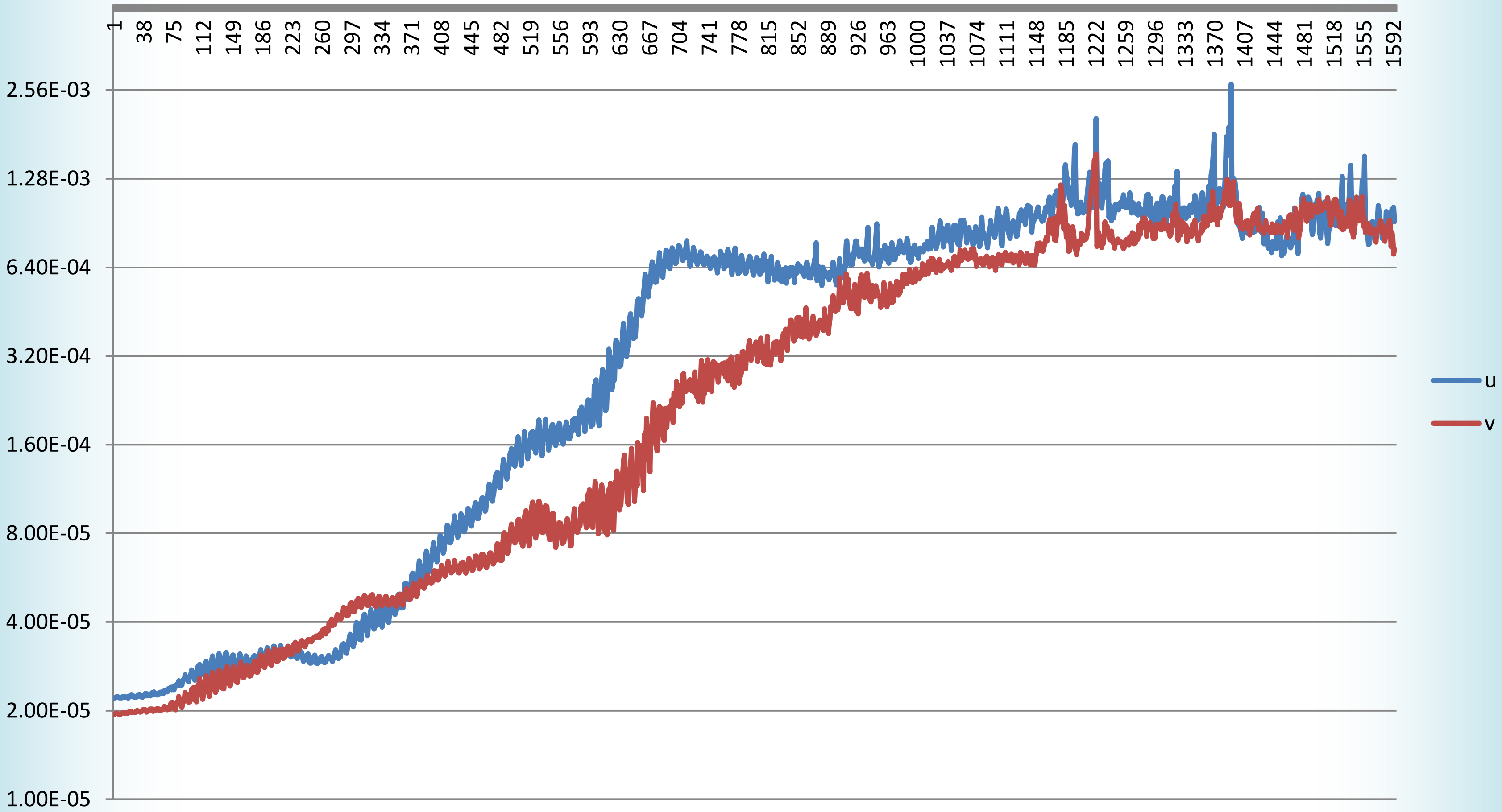




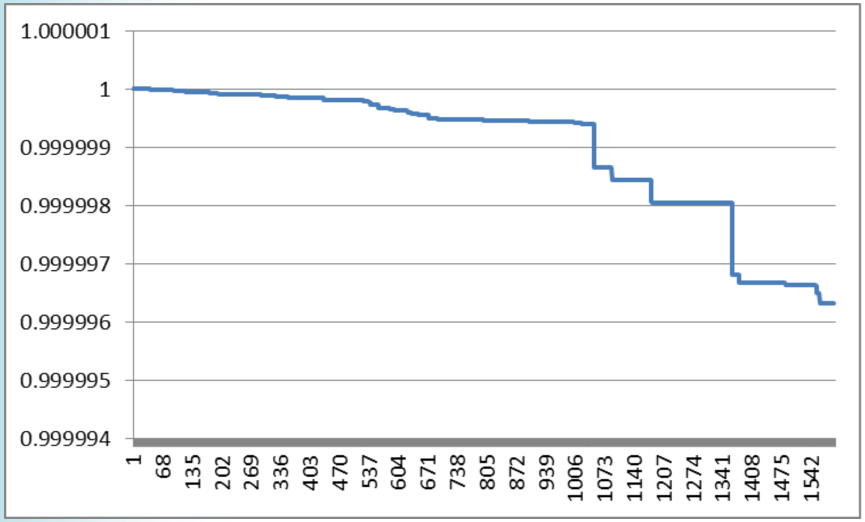
σ=10um beam centroid

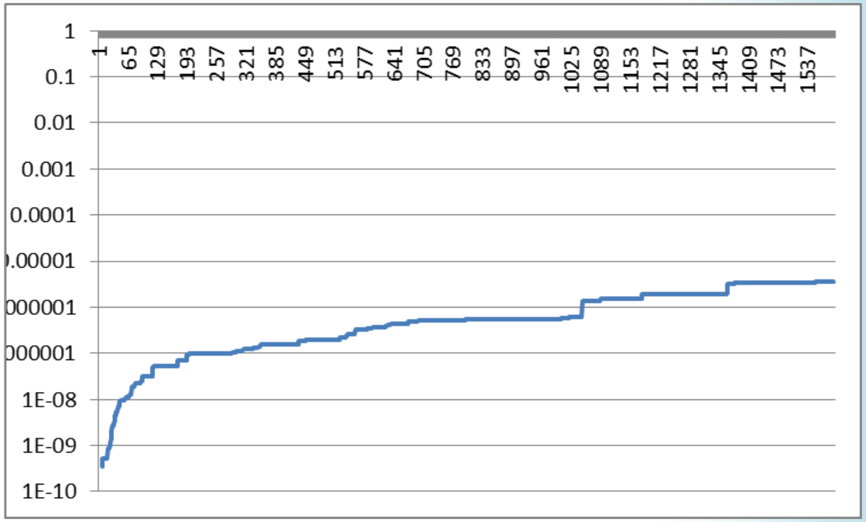


σ=10um norm. RMS emittances

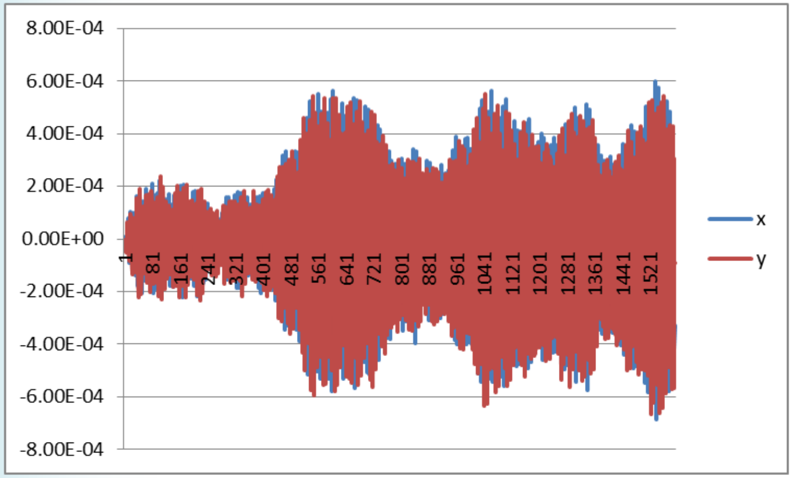


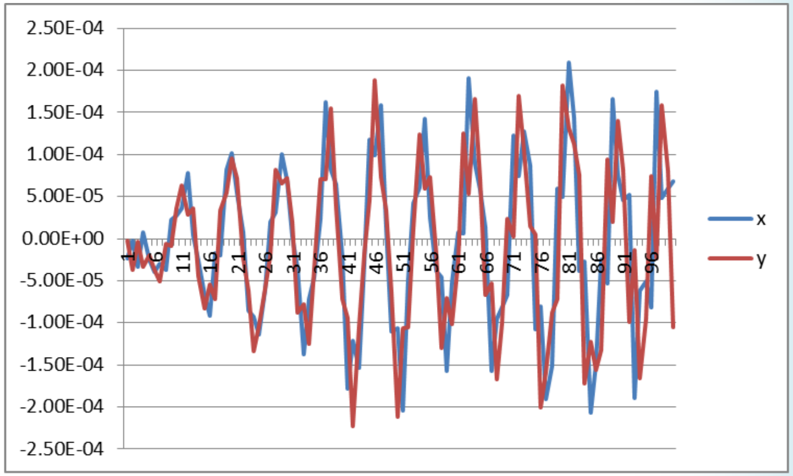
σ=2.5um transmission

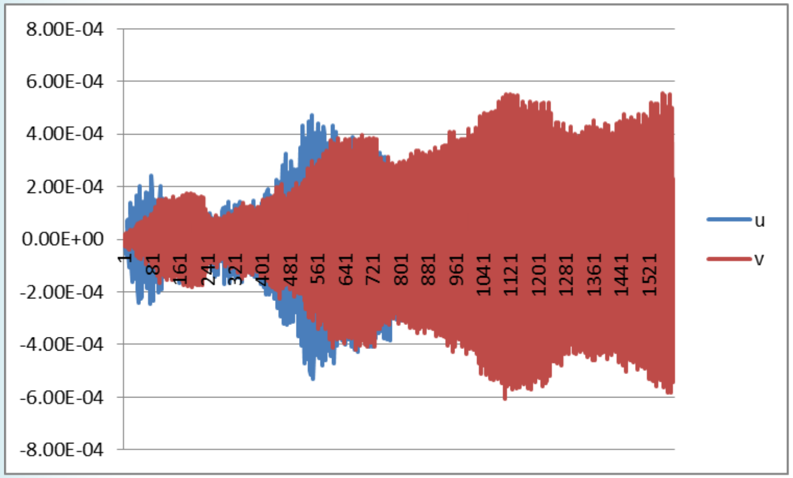


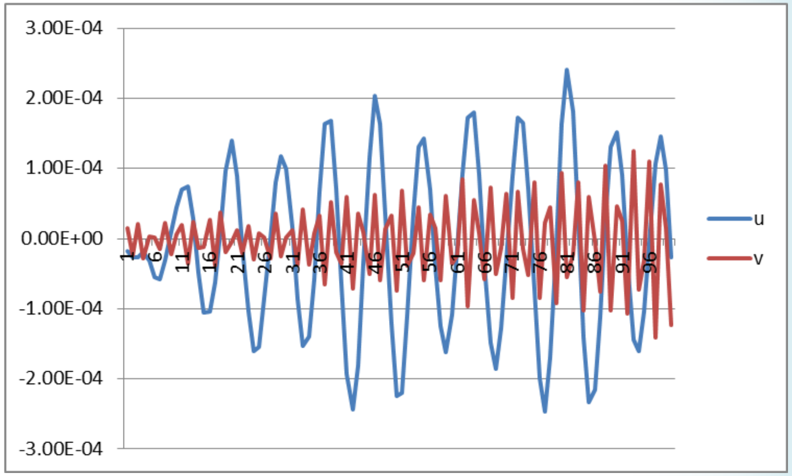


σ=2.5um beam centroid

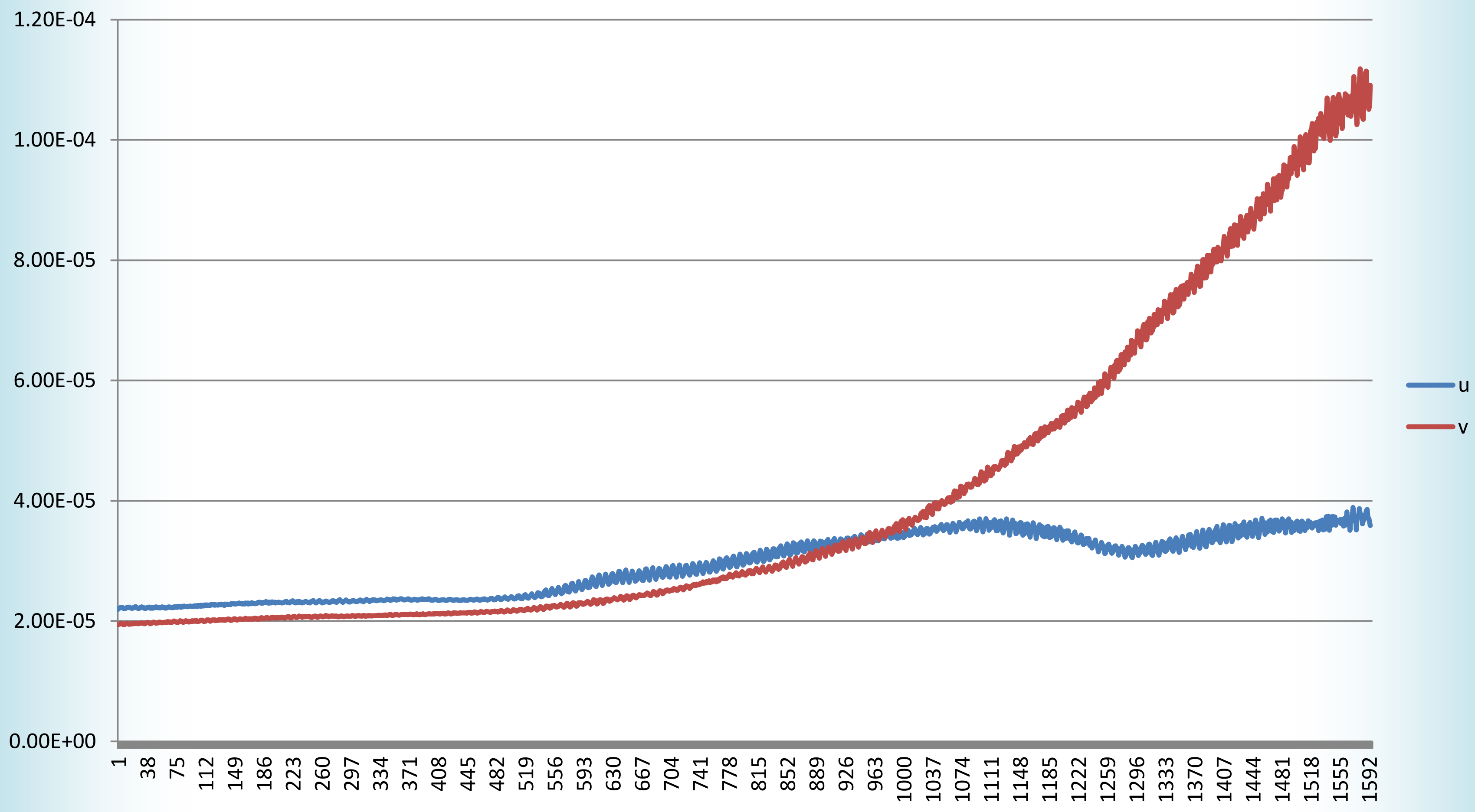




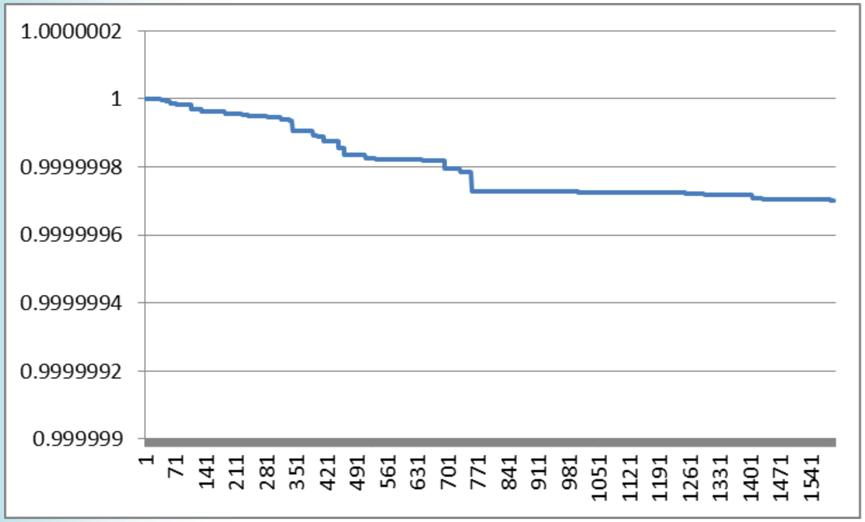


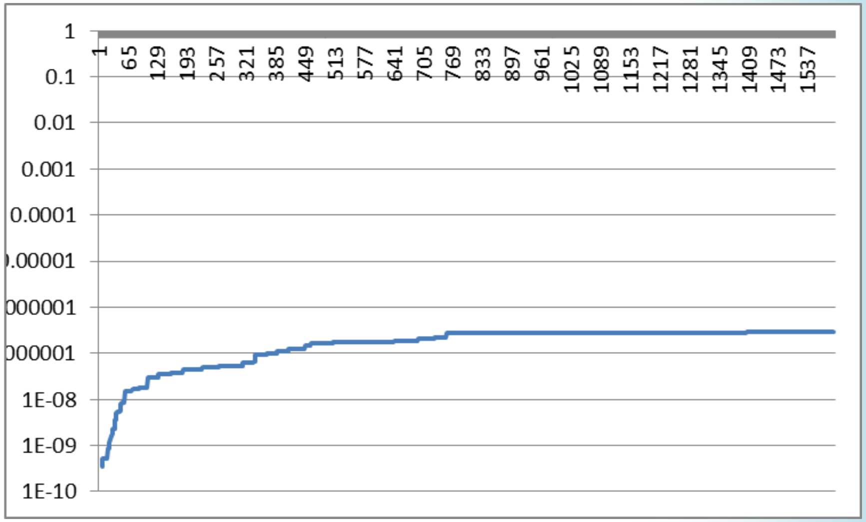


σ=2.5um norm. RMS emittances

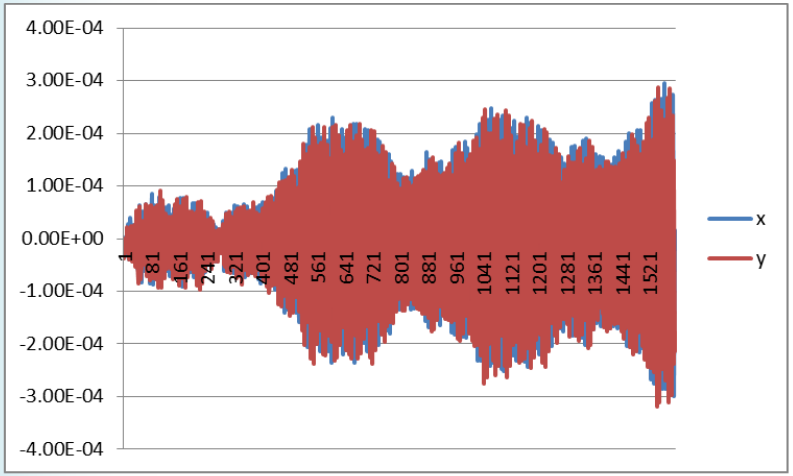


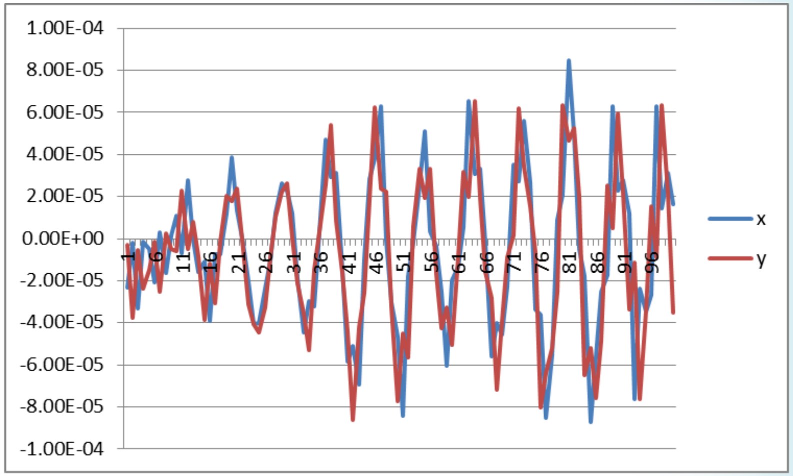
σ=1um transmission

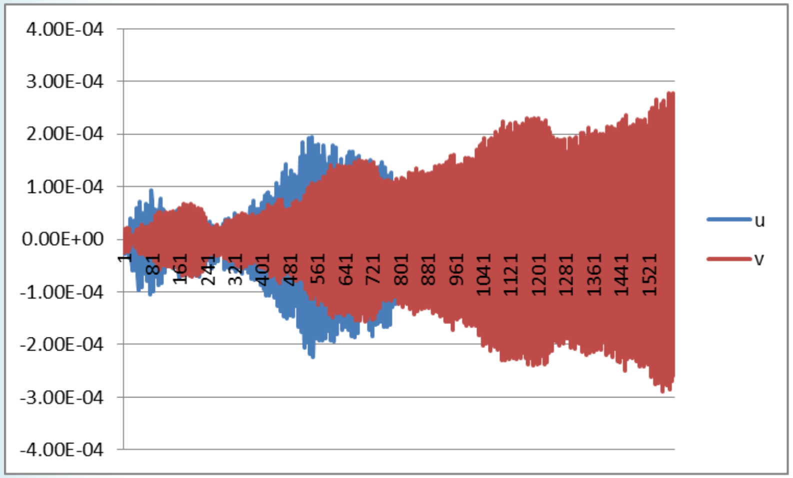


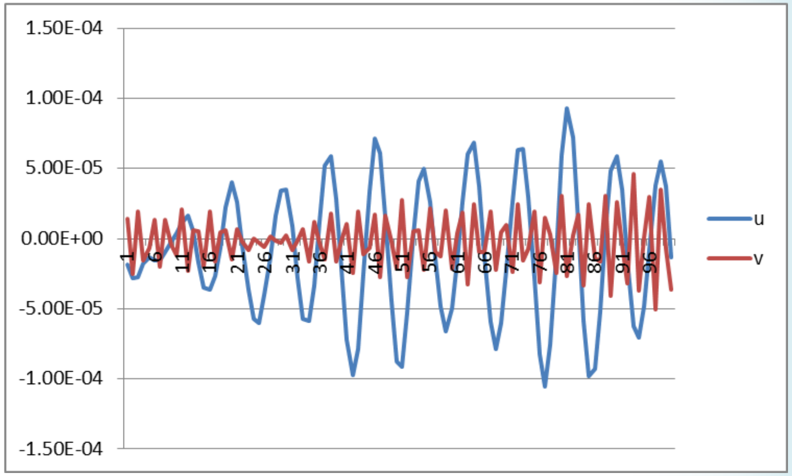


σ=1um beam centroid

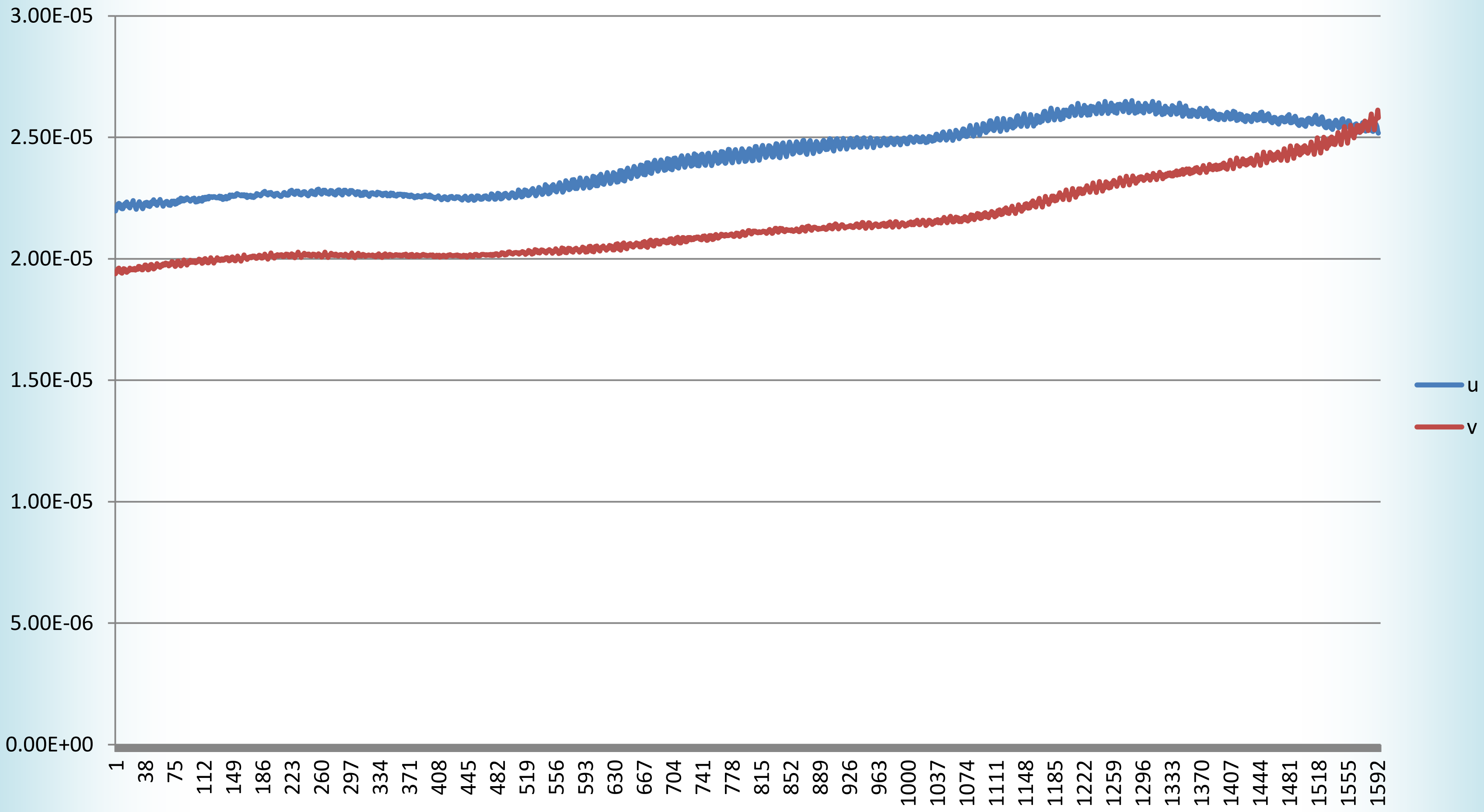




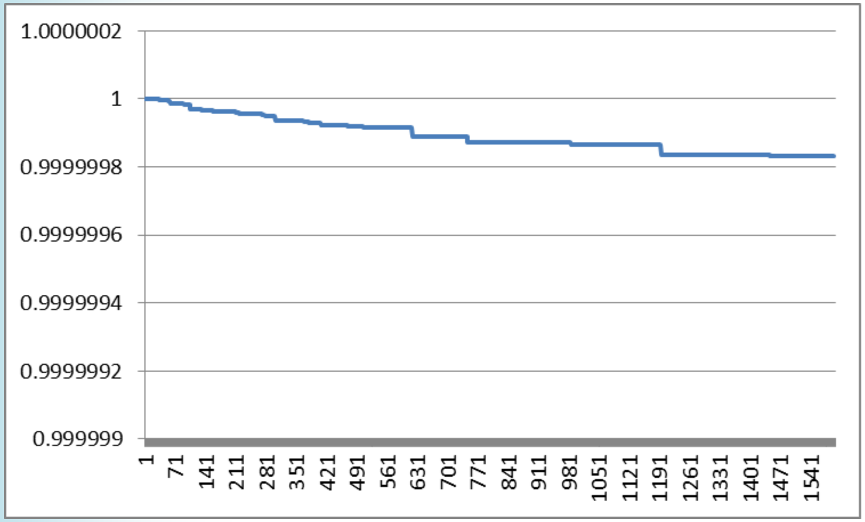


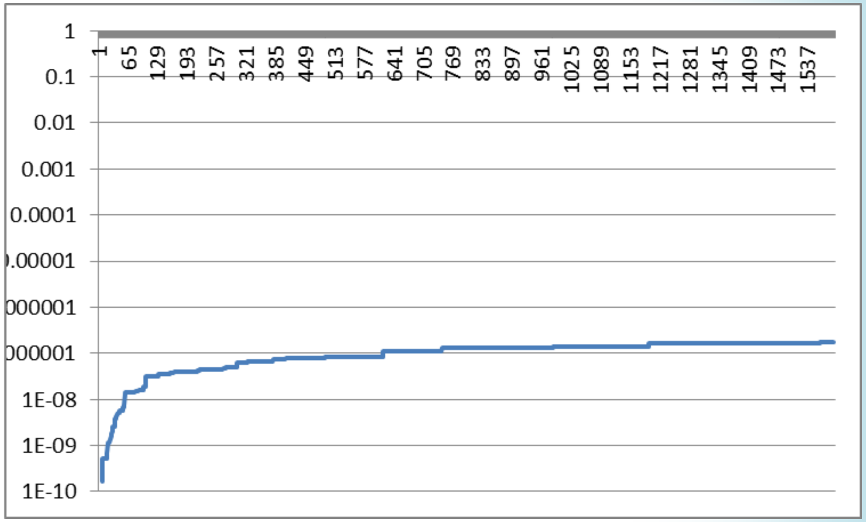


σ=1um norm. RMS emittances

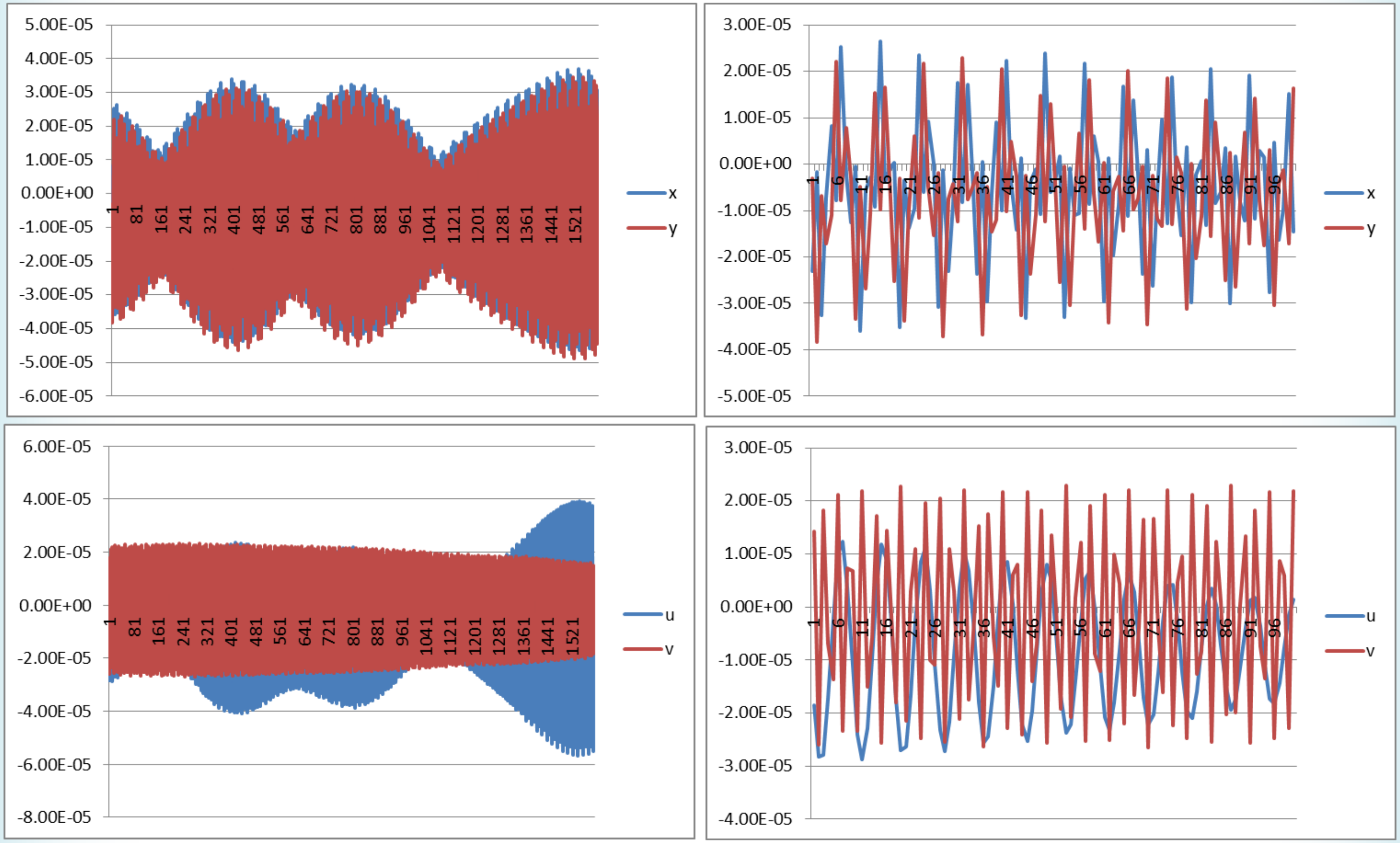


σ=0 transmission

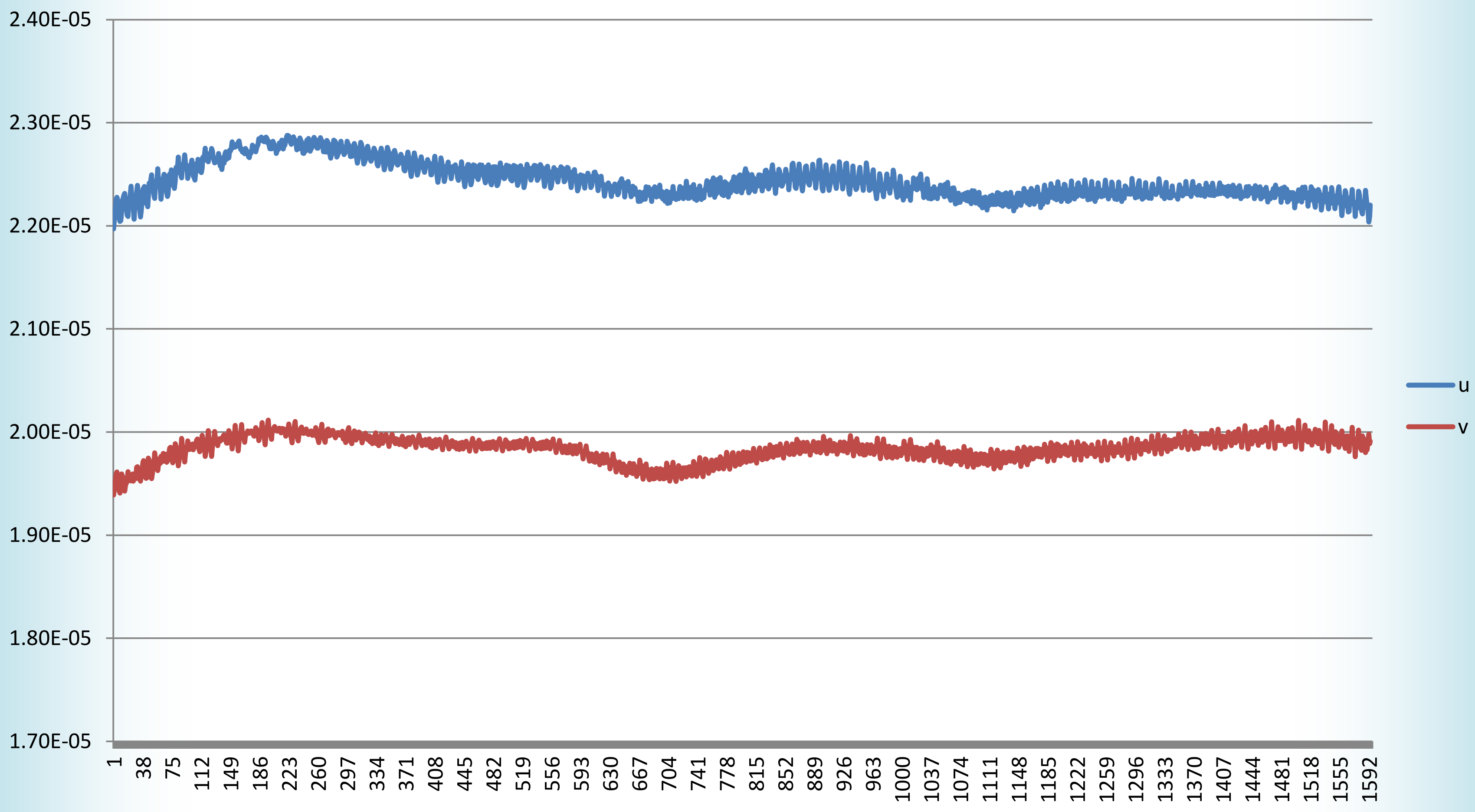




σ=0 beam centroid



σ=0 norm. RMS emittances

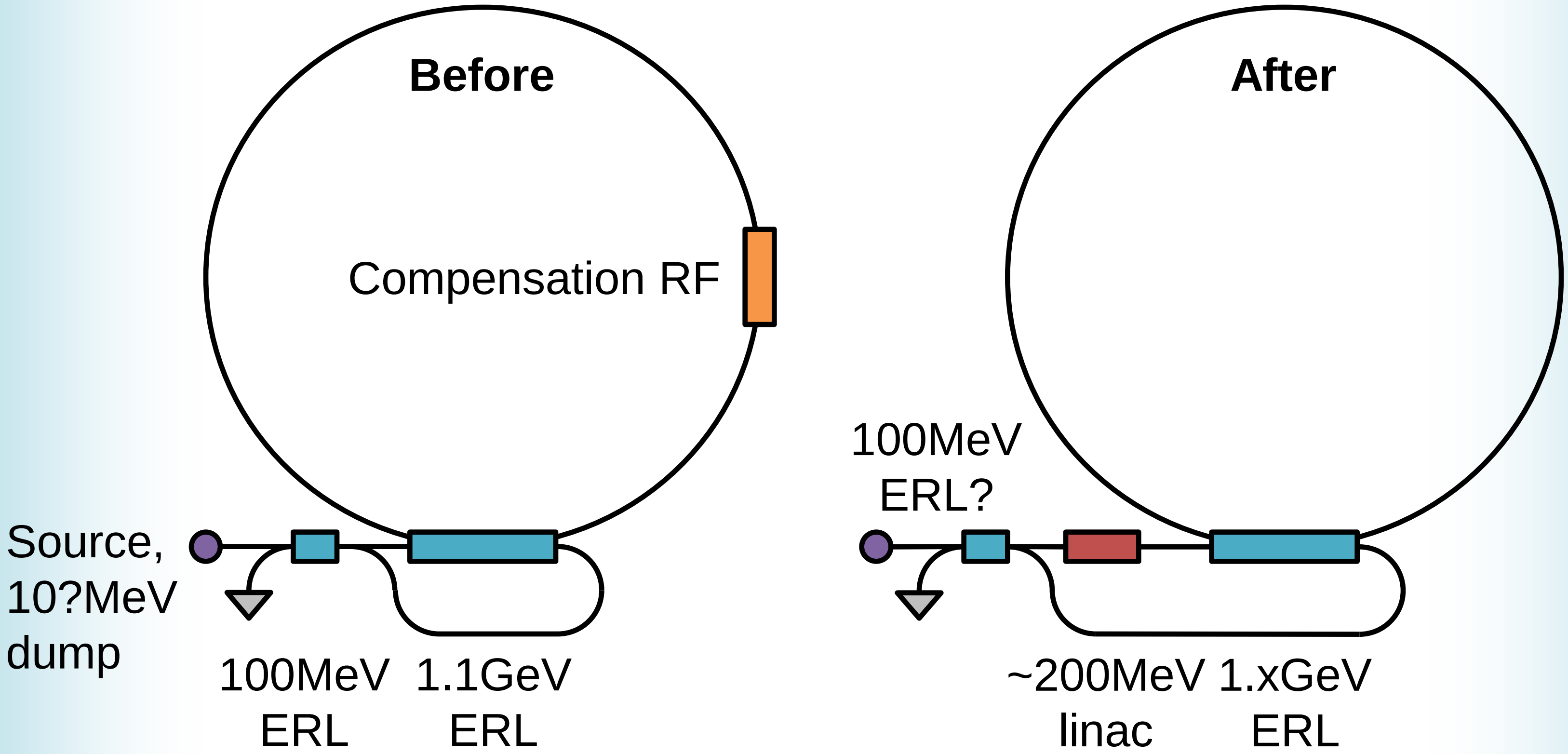


III. Synchrotron Radiation Losses

Compensation-free designs

- FFAG arcs transmit a continuum of energies so don’t strictly speaking need compensation of synchrotron energy losses
  - All examples given for “9.5GeV” FODO lattice
  - Assumed FFAG straights radiate same rate as arcs
- Constraints:
  - My FFAG arcs won’t transmit beam below 1.2GeV
  - Assumed ring linac won’t transmit below 100MeV

Schematic changes



9-pass 10GeV (worst)

Injection: 568 MeV
Linac: 1.081 GeV
Passes: 9
Current: 50 mA

0	0.568 GeV	0 MeV	0 MW
1	1.64892 GeV	0.0849605 MeV	0.00424802 MW
2	2.72928 GeV	0.63777 MeV	0.0318886 MW
3	3.80786 GeV	2.41825 MeV	0.12091 MW
4	4.88231 GeV	6.54436 MeV	0.32722 MW
5	5.94886 GeV	14.4553 MeV	0.72276 MW
6	7.00203 GeV	27.8299 MeV	1.3915 MW
7	8.03459 GeV	48.4435 MeV	2.42217 MW
8	9.03763 GeV	77.952 MeV	3.8976 MW
9	10.001 GeV	117.616 MeV	5.8808 MW
10	8.84847 GeV	71.5514 MeV	3.57757 MW
11	7.7261 GeV	41.3659 MeV	2.0683 MW
12	6.62285 GeV	22.2469 MeV	1.11234 MW
13	5.53106 GeV	10.7924 MeV	0.53962 MW
14	4.44557 GeV	4.49568 MeV	0.22478 MW
15	3.36309 GeV	1.47088 MeV	0.0735441 MW
16	2.28178 GeV	0.31154 MeV	0.0155772 MW
Min. arc:	1.20076 GeV	0.0238958 MeV	0.00119479 MW
Extraction:	0.11976 GeV	2.38257e-006 MeV	1.19129e-007 MW
	Max: 10.001 GeV	Total: 448.241 MeV	Total: 22.412 MW

9-pass 9GeV

Injection: 532 MeV
Linac: 0.963 GeV
Passes: 9
Current: 50 mA

0	0.532 GeV	0 MeV	0 MW
1	1.49494 GeV	0.0574035 MeV	0.00287017 MW
2	2.45752 GeV	0.41921 MeV	0.0209604 MW
3	3.41895 GeV	1.57113 MeV	0.0785563 MW
4	4.37773 GeV	4.22711 MeV	0.21136 MW
5	5.33141 GeV	9.31275 MeV	0.46564 MW
6	6.27648 GeV	17.9276 MeV	0.89638 MW
7	7.20821 GeV	31.278 MeV	1.5639 MW
8	8.12063 GeV	50.5721 MeV	2.52861 MW
9	9.00676 GeV	76.8785 MeV	3.84392 MW
10	7.99624 GeV	47.5171 MeV	2.37585 MW
11	7.00536 GeV	27.8832 MeV	1.39416 MW
12	6.02712 GeV	15.234 MeV	0.7617 MW
13	5.05659 GeV	7.53219 MeV	0.37661 MW
14	4.09037 GeV	3.22071 MeV	0.16104 MW
15	3.12627 GeV	1.09815 MeV	0.0549077 MW
16	2.16302 GeV	0.25157 MeV	0.0125785 MW
Min. arc:	1.2 GeV	0.023835 MeV	0.00119175 MW
Extraction:	0.237 GeV	3.63865e-005 MeV	1.81933e-006 MW
	Max: 9.00676 GeV	Total: 295.005 MeV	Total: 14.7502 MW

6-pass 10GeV

Injection: 403 MeV
Linac: 1.636 GeV
Passes: 6
Current: 50 mA

0	0.403 GeV	0 MeV	0 MW
1	2.0388 GeV	0.19857 MeV	0.00992846 MW
2	3.67271 GeV	2.09253 MeV	0.10463 MW
3	5.29962 GeV	9.09201 MeV	0.4546 MW
4	6.90924 GeV	26.3756 MeV	1.31878 MW
5	8.48486 GeV	60.38 MeV	3.019 MW
6	10.0031 GeV	117.718 MeV	5.88589 MW
7	8.31159 GeV	55.5495 MeV	2.77747 MW
8	6.65294 GeV	22.6559 MeV	1.1328 MW
9	5.00968 GeV	7.25598 MeV	0.3628 MW
10	3.3722 GeV	1.48688 MeV	0.0743439 MW
Min. arc:	1.73609 GeV	0.1044 MeV	0.00522008 MW
Extraction:	0.10009 GeV	1.16442e-006 MeV	5.82208e-008 MW
	Max: 10.0031 GeV	Total: 302.909 MeV	Total: 15.1455 MW

6-pass 9GeV (<10MW)

Injection: 297 MeV
Linac: 1.474 GeV
Passes: 6
Current: 50 mA

0	0.297 GeV	0 MeV	0 MW
1	1.77089 GeV	0.11303 MeV	0.00565131 MW
2	3.24361 GeV	1.27264 MeV	0.0636318 MW
3	4.71194 GeV	5.67607 MeV	0.2838 MW
4	6.16921 GeV	16.7283 MeV	0.83641 MW
5	7.60441 GeV	38.8014 MeV	1.94007 MW
6	9.0017 GeV	76.704 MeV	3.8352 MW
7	7.49118 GeV	36.5251 MeV	1.82625 MW
8	6.0022 GeV	14.9827 MeV	0.74913 MW
9	4.52338 GeV	4.8193 MeV	0.24097 MW
10	3.04838 GeV	0.9927 MeV	0.0496349 MW
Min. arc:	1.57431 GeV	0.0705987 MeV	0.00352993 MW
Extraction:	0.10031 GeV	1.17483e-006 MeV	5.87414e-008 MW
	Max: 9.0017 GeV	Total: 196.686 MeV	Total: 9.83429 MW

6-pass 9GeV to 13.5GeV, 6.1mA

Injection: 297 MeV
Linac: 1.436 GeV
Passes: 10
Current: 6.1 mA

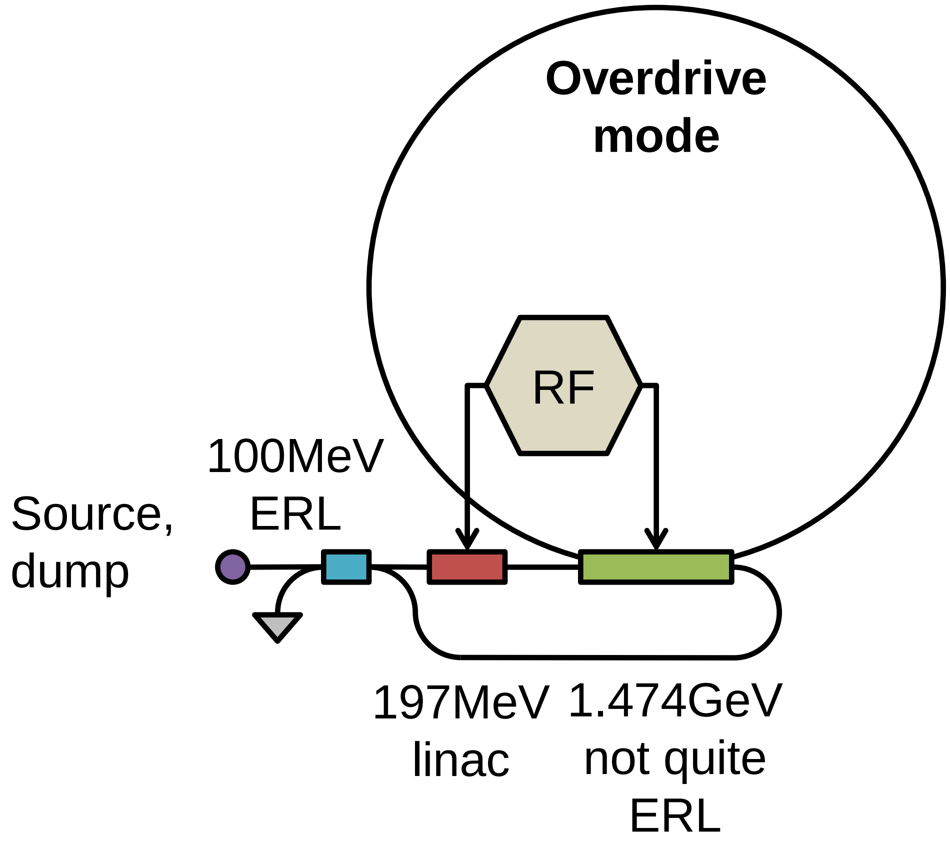
0	0.297 GeV	0 MeV	0 MW
1	1.7329 GeV	0.10364 MeV	0.000632176 MW
2	3.16774 GeV	1.15762 MeV	0.00706146 MW
3	4.59859 GeV	5.14846 MeV	0.0314056 MW
4	6.01943 GeV	15.1562 MeV	0.0924527 MW
5	7.42028 GeV	35.1523 MeV	0.21443 MW
6	8.78673 GeV	69.5519 MeV	0.42427 MW
7	10.1003 GeV	122.443 MeV	0.7469 MW
8	11.3397 GeV	196.537 MeV	1.19888 MW
9	12.4837 GeV	292.095 MeV	1.78178 MW
10	13.5134 GeV	406.258 MeV	2.47817 MW
11	11.8425 GeV	234.922 MeV	1.43302 MW
12	10.2752 GeV	131.315 MeV	0.80102 MW
13	8.77014 GeV	69.0218 MeV	0.42103 MW
14	7.3012 GeV	32.9348 MeV	0.2009 MW
15	5.85167 GeV	13.5304 MeV	0.0825355 MW
16	4.41131 GeV	4.35853 MeV	0.026587 MW
17	2.97441 GeV	0.89976 MeV	0.00548855 MW
18	1.53835 GeV	0.0643659 MeV	0.000392632 MW
Min. arc:	0.10235 GeV	1.27289e-006 MeV	7.76462e-009 MW
Extraction:	nan GeV	nan MeV	nan MW
	Max: 13.5134 GeV	Total: 1630.65 MeV	Total: 9.94696 MW

6-pass 9GeV to 14.9GeV, 3.3mA

Injection: 297 MeV
Linac: 1.406 GeV
Passes: 12
Current: 3.3 mA

0	0.297 GeV	0 MeV	0 MW
1	1.7029 GeV	0.0966451 MeV	0.000318929 MW
2	3.10783 GeV	1.07246 MeV	0.00353912 MW
3	4.50907 GeV	4.75853 MeV	0.0157032 MW
4	5.90108 GeV	13.9948 MeV	0.0461829 MW
5	7.27462 GeV	32.4546 MeV	0.1071 MW
6	8.61637 GeV	64.2545 MeV	0.21204 MW
7	9.90909 GeV	113.278 MeV	0.37382 MW
8	11.1329 GeV	182.239 MeV	0.60139 MW
9	12.2672 GeV	271.694 MeV	0.89659 MW
10	13.2938 GeV	379.371 MeV	1.25192 MW
11	14.1996 GeV	500.197 MeV	1.65065 MW
12	14.9784 GeV	627.174 MeV	2.06967 MW
13	13.2037 GeV	368.754 MeV	1.21689 MW
14	11.5832 GeV	214.461 MeV	0.70772 MW
15	10.0569 GeV	120.314 MeV	0.39704 MW
16	8.5875 GeV	63.3882 MeV	0.20918 MW
17	7.1512 GeV	30.2941 MeV	0.09997 MW
18	5.73274 GeV	12.4601 MeV	0.0411184 MW
19	4.32273 GeV	4.01837 MeV	0.0132606 MW
20	2.91589 GeV	0.83099 MeV	0.00274227 MW
21	1.50983 GeV	0.059725 MeV	0.000197092 MW
22	0.10383 GeV	1.34817e-006 MeV	4.44896e-009 MW
Min. arc:	nan GeV	nan MeV	nan MW
Extraction:	nan GeV	nan MeV	nan MW
	Max: 14.9784 GeV	Total: 3005.17 MeV	Total: 9.91705 MW

This may or may not be practical?



4-pass 10GeV (~10MW, long linac)

Injection: 312 MeV
Linac: 2.464 GeV
Passes: 4
Current: 50 mA

0	0.312 GeV	0 MeV	0 MW
1	2.77532 GeV	0.68192 MeV	0.0340961 MW
2	5.23069 GeV	8.62704 MeV	0.43135 MW
3	7.65484 GeV	39.8491 MeV	1.99246 MW
4	10.0012 GeV	117.626 MeV	5.88128 MW
5	7.50051 GeV	36.7087 MeV	1.83543 MW
6	5.02914 GeV	7.3696 MeV	0.36848 MW
Min. arc:	2.56464 GeV	0.49723 MeV	0.0248615 MW
Extraction:	0.10064 GeV	1.19016e-006 MeV	5.9508e-008 MW
	Max: 10.0012 GeV	Total: 211.359 MeV	Total: 10.568 MW

IV. VFFAG Options Comparison

FFAG type	Synchrotron radiation	Dynamic aperture / error tolerance	Time of flight	Energy range / multiple rings
Vertical (nonlinear) scaling ** #	10MW at 9-10GeV	Not impossible but difficult	1-beta effect only	Infinite / one ring
Vertical linear nonscaling * ##	Potentially to 20GeV 50mA	Better?	Unknown but better than horizontal FFAG	Probably factor 3x / two rings for 10GeV, three rings for 20-30
Vertical nonlinear nonscaling *** ###	Potentially to 20GeV 50mA	Also bad?	At least as good as linear nonscaling VFFAG	At least as good as linear nonscaling VFFAG
Horizontal linear nonscaling * ##	20GeV OK	Linear magnets	Problematic	Two/three rings
Non-FFAG	20GeV OK	Presumably good	Each ring exact	Too many rings

*, **, *** indicate complexity of magnets and correction

#, ##, ### indicate conceptual difficulty

V. Future Work

Next steps (if scaling VFFAG)

- Develop "straight" cell for full ring lattice
- Work with magnet and FFAG splitter designers
- Decide on RF/linac energies
- Open issues:
  - Emittance growth from SR photon emission
  - Coherent synchrotron radiation?
- "End-to-end" tracking of full ring
  - Eventually track with fieldmaps from magnet

Next steps (if non-scaling VFFAG)

- Try linear field NS-VFFAG first ("Davidtron")
  - Much less synchrotron radiation
  - Expect better dynamic aperture
  - Easier to build (correct and understand!) magnets
  - Will likely need a cascade of rings 1-3, 3-10 etc.
- Develop quadrupole field models for Muon1 and/or VFFAG tracker code
- Try to search and understand lattice space