トシェック散乱によるビームロスの計算結果*

*Beam Loss Due To Touschek Scattering. Simulation Results

2013年8月28日(水）14時00分
ビームダイナミクスWG打ち合わせ

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Introduction
Motivation

In this study my purposes were:

- To perform the beam loss simulation study with ELEGANT tracking code
- To find the beam **loss rate** due to Touschek Scattering effect
- To find the beam loss **positions** and physical **origin** of this loss

Introduction

Methods & Tools

- The particle tracking program ELEGANT* is used for all particle tracking, for momentum aperture determination and Touschek scattering simulation
- Output data was analyzed with use of MATLAB** processing code

* M. Borland, "elegant: A Flexible SDDS-Compliant Code for Accelerator Simulation," Advanced Photon Source LS-287, September 2000.

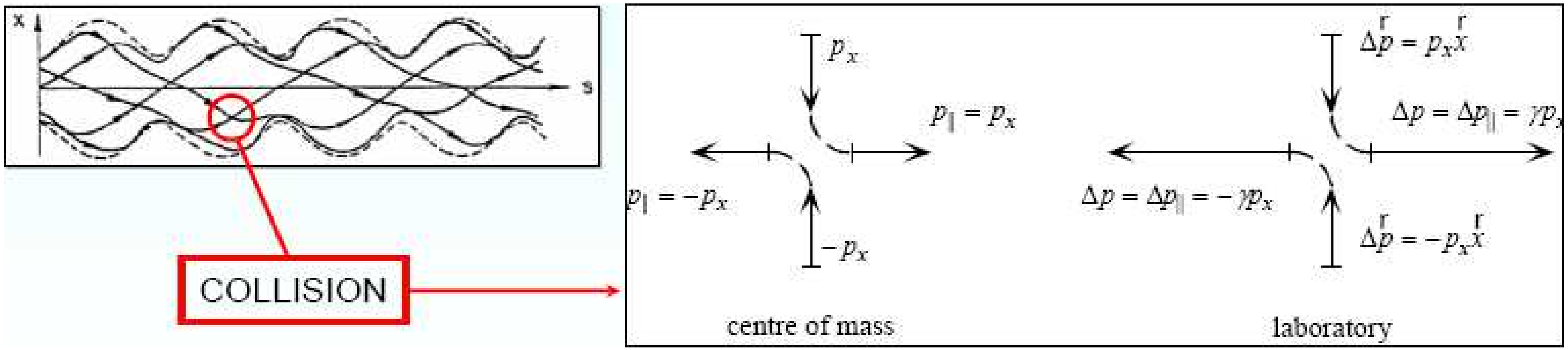
** MATLAB overview, at the MathWorks website

Physics Behind

Touschek Scattering Mechanism (I)

- The Touschek effect is a loss mechanism driven by large angle Coulomb collisions in the electron bunch that lead to momentum transfers into the longitudinal plane. The change in the longitudinal momentum can lead to particle loss if the momentum exceeds the rf acceptance or the transverse (physical or dynamic) momentum acceptance.
- The Touschek effect is one of the limiting mechanism for present day synchrotron radiation sources. The requirement of high brilliance results in an enhanced particle loss via the Touschek effect.

High Brilliance -> Low Emittance -> High Bunch Densities -> -> High Collision Probability



Physics Behind

Touschek Scattering Mechanism* (II)

The Touschek lifetime is given by**

$$\frac{1}{\tau} = -\frac{1}{N}\frac{dN}{dt} = \frac{r_e^2 cN}{8\pi\sigma_x\sigma_y\sigma_z}\frac{1}{\gamma^2\delta_{\max}^3} D\left(\left[\frac{\delta_{\max}\beta_x}{\gamma\sigma_x}\right]^2\right) \quad ***$$

*** touschekScatter.c involve this very formula for LossRate calculation !

```
rateP = a0*sqrt(c0)*F/gamma/gamma/2
rateN = a0*sqrt(c0)*F/gamma/gamma/2
```

Where $D(\varepsilon) \propto \sqrt[3]{\varepsilon}$, N is the number of particles in a bunch, σ_x, σ_y, σ_z are the rms horizontal and vertical beam sizes and bunch length, and δ_{max} is the energy acceptance of the ring.

* C. J. Brocchetta / The Touschek Effect. Large Angle intra-Beam Scattering - CAS - "Synchrotron Radiation and Free Electron Lasers" - Brunnen, Switzerland - 2 to 9 July;
** Andy Wolski / Fourth International Accelerator School for Linear Colliders Beijing, September 2009

Physics Behind
Beam Loss Mechanism*

1. Non-dispersive section (dispersion function=0)

No betatron oscillation occur due to momentum changes in Touschek scattering. Mainly loss occurs when position deviation due to dispersion at downstream dispersive section exceeds the chamber aperture.

2. Dispersive section

Betatron oscillation amplitude changes due to position deviation from dispersion.

Loss occurs when deviation due to the beta oscillations exceeds the chamber aperture.

* 中村さんとのディスカッションからの。

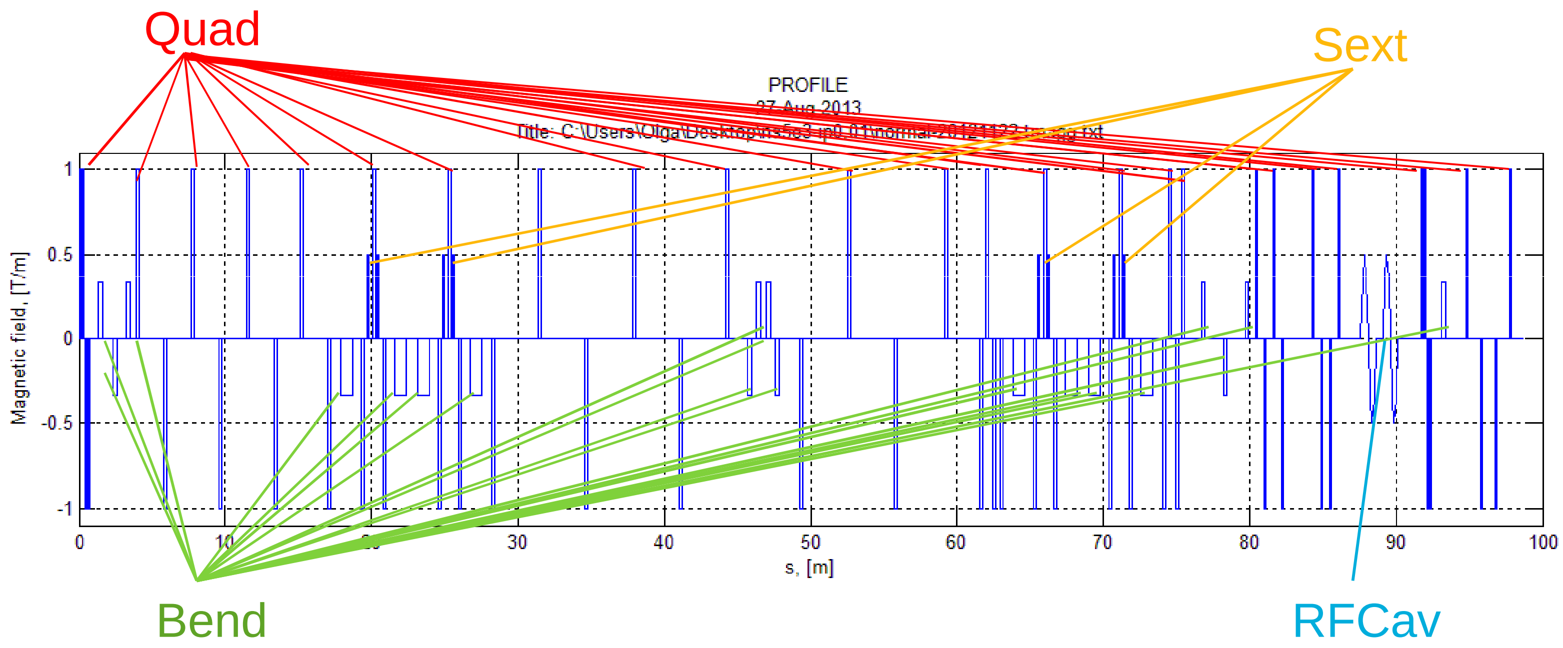
Input Data
Beam parameters

Main Parameters*	cERL	Simulation
Maximum energy	65 – 245 MeV	59 – 233 MeV
Current	10 – 100 mA	10 mA
Charge per bunch	7.7 – 77 pC	7.7 pC
Repetition	1.3 GHz	1.3 GHz
Normalized emittance	0.1 – 1.0 mm-mrad	0.3 mm-mrad
Energy spread	< 3 x 10-4	3 x 10-4
Bunch length • low emittance • bunch compression	• 1 – 3 ps • 0.1 ps	• 3 ps

* K. Harada, M. Shimada, A. Ueda , Y. Kobayashi, T. Miyajima, R. Hajima , N. Nakamura / Lattice design of the compact ERL for first commissioning; Proceedings of the 7th Annual Meeting of Particle Accelerator Society of Japan (August 4-6, 2010, Himeji, Japan)

Input Data
Lattice file

Lattice
(normal-20121122.new)*



* 島田さんからのELEGANTファイルを使用
see also: http://pfconrg07.kek.jp:8082/trac/cERL-Lattice/wiki

Input Data

touscheckScatter.c routine*

The total scattering rate ignored from tracking. This will greatly increase the tracking speed. This number should be much less than the total loss rate. For example, if the total loss rate is 50% of the total scattering rate, then ignore 5% (0.05) of the scattering particles will cause some of 10% error. But the simulation is greatly speed up.

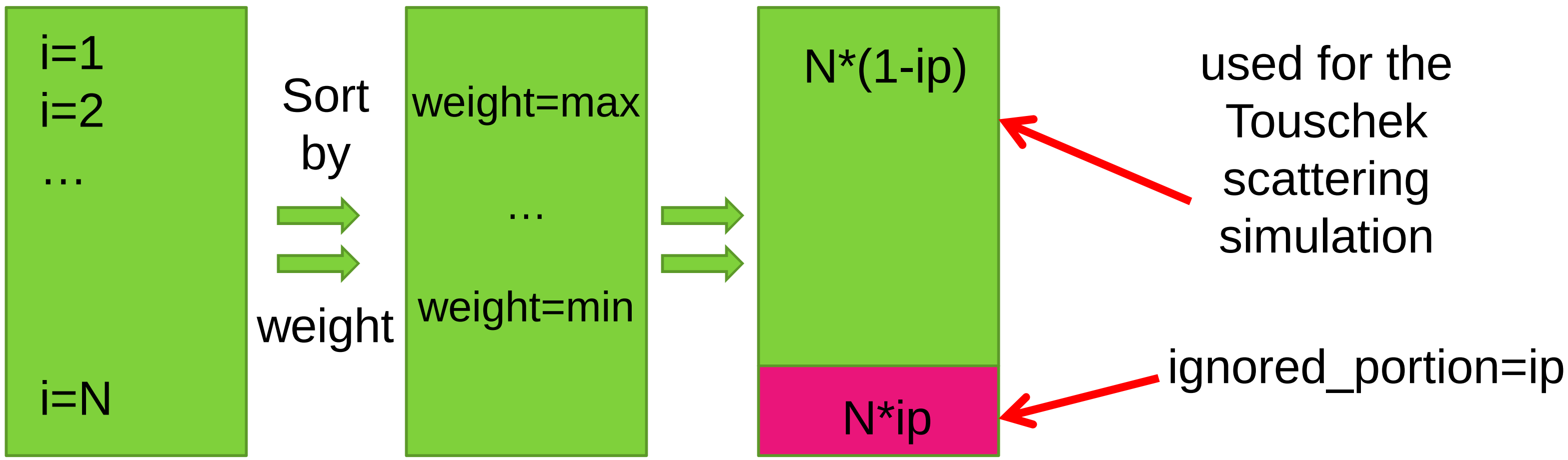
```
&touschek_scatter
        frequency = 1.3e9,
        charge = 7.7e-12,
        emit_nx = 3e-7,
        emit_ny = 3e-7,
        sigma_dp = 3e-4,
        sigma_s = 900e-6,
        distribution_cutoff[0] = 5*5
        Momentum_Aperture = normal-20121122-t.mmap,
        Momentum_Aperture_scale = 1,
        bunch = %s-%03ld.bun,
        loss = %s-%03ld.los,
        !distribution = %s-%03ld.dis,
        output=%s-%03ld.out
        !initial = %s-%03ld.ini,
        verbosity=2,
        i_start = 7,
        i_end = 7,
        do_track = 1,
        nbins=100
        n_simulated = 5000000,
        ignored_portion = 0.0,
        match_position_only = 1,
        overwrite_files=1,
&end
```

Bin number used for the distribution and initial table.

The total number of simulated scattered particles with $\delta > \delta m$. Small value will cause unstable simulation rate.

*http://www.aps.anl.gov/Accelerator_Systems_Division/Accelerator_Operations_Physics/manuals/elegant_latest/node71.html

Input Data
Ignored_portion



- For each electron (i) of the total number N, a beam loss rate is calculated

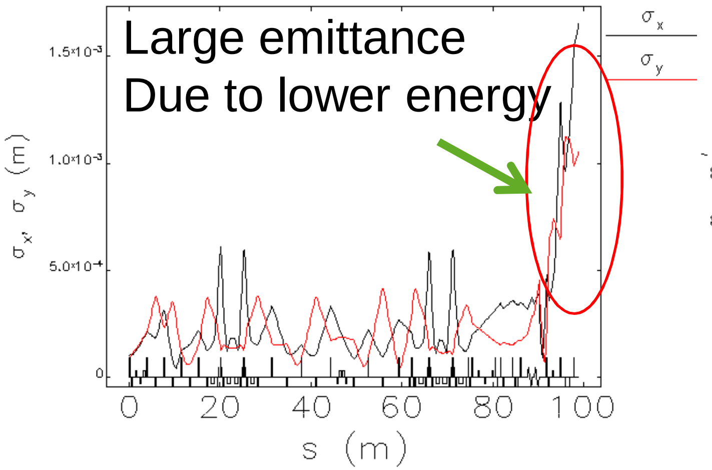
  weight[i] ~ Touschek scattering rate, where 1<=i<=N.

- Then sort the weight[i] in order and pick up N*(1-ignored_portion) electrons with largest weight, and do loss simulation.
- So, N*ignored_portion electrons with smallest weights are ignored.

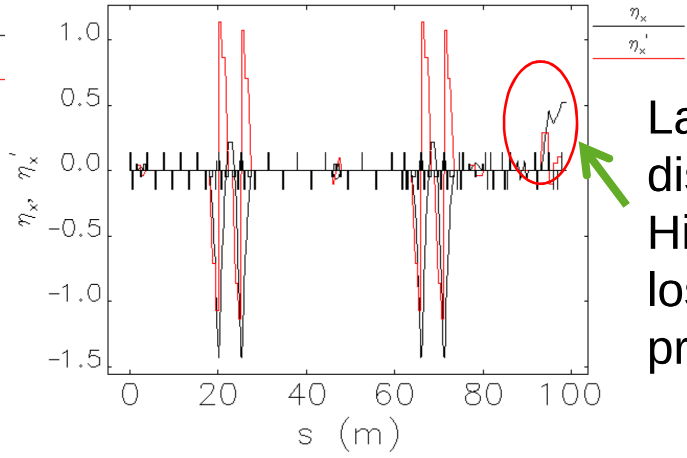
Results

Comparison of Beam Size and Aperture

Transverse Beam Size

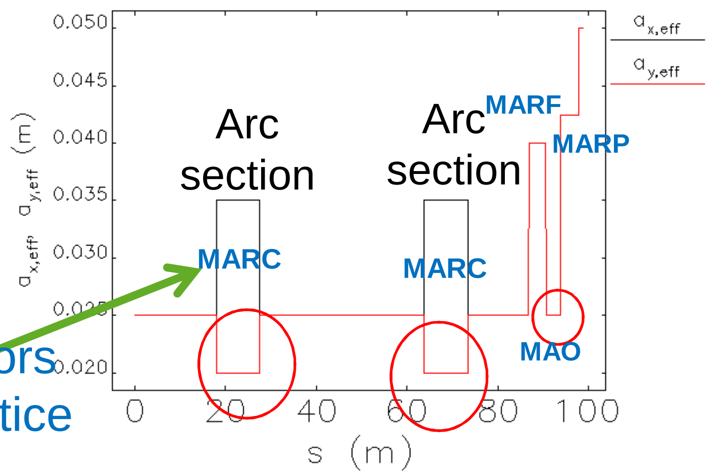


Dispersion



Large dispersion
Higher beam loss probability

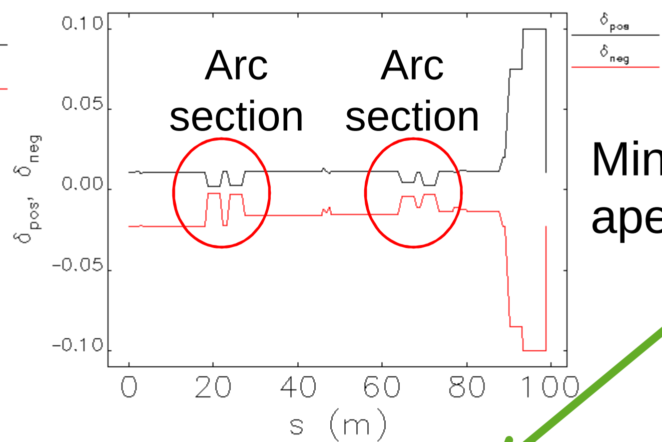
Transverse Aperture



Collimators in the lattice

Local minima of aperture

Momentum Aperture



Minima of aperture

Large beam loss probability?

ビー

平成25年8月29日

Results

Bug fix for touscheckScatter.c

- Line 549

```
weight_ave = tsptr->totalWeight/tsptr->simuCount
```

tsptr->simuCount : number of lost particles

If it is 0, the code crashes.

It occurs frequently when a loss rate is low.

Corrected the line as follows;

```
If (totalWeight/tsptr->simuCount >0)
        weight_ave = tsptr->totalWeight/tsptr->simuCount;
else
        weight_ave = tsptr->totalWeight;
```

Results

Simulation Statistics (I)

n_simulated = 5e+6; ignored_portion = 0.01; nbins = 1000			
	particles generated	selected for tracking	survived tracking
TSO#1-169	359,940,537	275,992	9,771
TSO#170-319	162,774,063	222,034	38
TSO#320-469	292,231,414	124,636	248
TSO#470-616	5,076,924	2,962	2,124
Total	**820,022,938**	**625,624**	**12,199**
n_simulated = 5e+6; ignored_portion = 0.001; nbins = 100			
	particles generated	selected for tracking	survived tracking
TSO#1-169	359,940,537	884,894	28,105
TSO#170-319	162,774,063	721,306	227
TSO#320-469	292,231,414	410,560	1,089
TSO#470-616	5,076,924	9,530	7,521
Total	**820,022,938**	**2,026,290**	**36,942**

Results

Simulation Statistics (II)

n_simulated = 5e+7; ignored_portion = 0.01; nbins = 100			
	particles generated	selected for tracking	survived tracking
TSO#1-66	69,912,715	141,679	9,293
TSO#67-169	2,377,895,843	548,491	1,524
TSO#170-319	392,823,610	349,812	24
TSO#320-469	5,076,924	584,366	1,253
TSO#470-482	45,775	351	12
TSO#483-535	30,887	499	0
TSO#536-536	76	2	0
TSO#537-593	103	3	0
TSO#594-616	12,201,621	4,921	4,921
Total	**5,371,422,423**	**1,630,124**	**17,027**

Results

Time of Calculation**

n_simulated = 5e+6, ignored_portion = 0.001 nbins=100	
TSO#1-169	23:09
TSO#170-319	24:52
TSO#320-469	17:20
TSO#470-616	24:26
Average	**22:27**

n_simulated = 5e+6, ignored_portion = 0.01 nbins=1000	
TSO#1-169	20:58
TSO#170-319	23:58
TSO#320-469	16:57
TSO#470-616	24:30
Average	**21:36**

4 CPU worked in parallel

n_simulated = 5e+7, ignored_portion = 0.01 nbins=100	
TSO#1-169	27:28
TSO#170-319	25:34
TSO#320-469	23:08
TSO#470-616	24:25
Average	**25:24**

n_simulated = 5e+6, ignored_portion = 0.00 nbins=100	
TSO#1-1	17:14
TSO#2-616	NaN
Average	**17:14**

* TSO = Touschek Scattering Objects. Total amount is 616

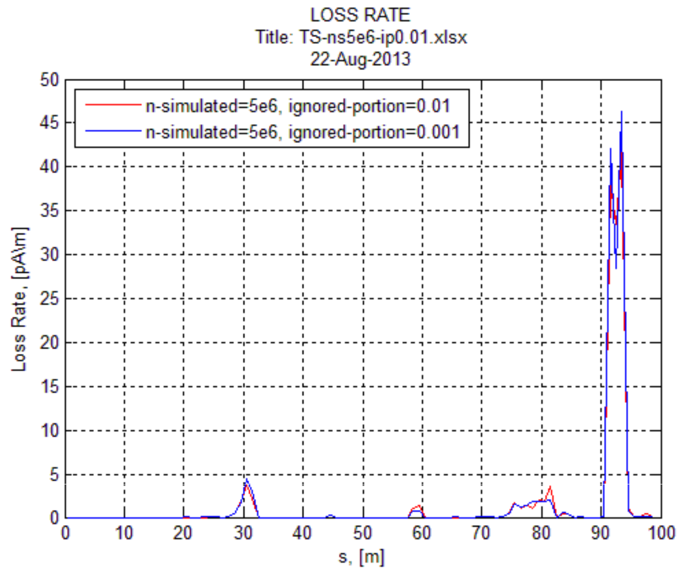
4 CPU worked one by one

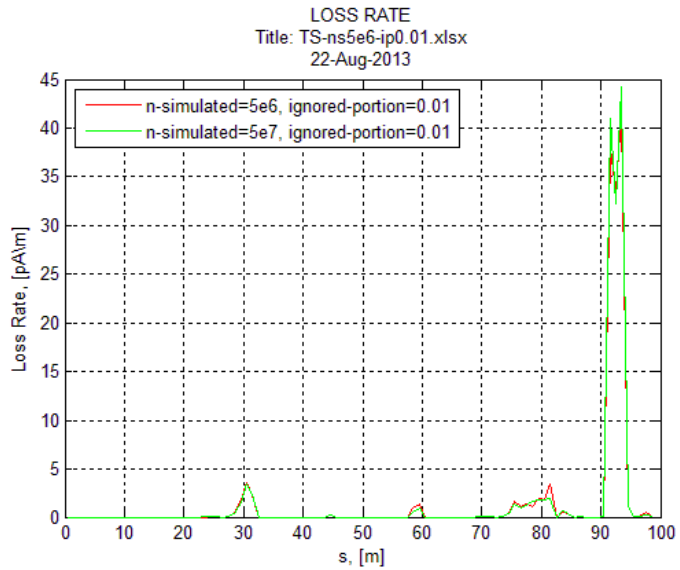
Routine Is crushed Bug?!

**Dell Precision T3500 (4 CPU Intel Xeon E5630-2.553GH)

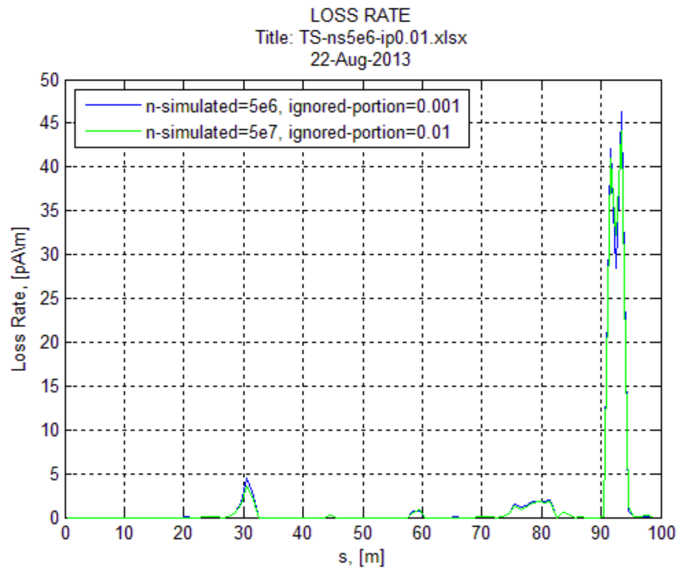
Results

Parameter Optimization (I)





- n_simulated = 5e+6 → 5e+7 improves the statistics by 10 times;
- ignored_portion = 0.001 → 0.01 speeds up the calculation in several hours (e.g. 3 hours)



Results

Parameter Optimization (II)

- nbins = 100 → 1000 provides smooth plots but does not influence on the calculation speed essentially

Fixed!

nbins=1000				
ignored_porti on	n_simulated	Electrons for tracking	Time of Calculation	Efficiency [part. / min]
0.0	5e+6	NaN	→∞	NaN
0.01	5e+6	625,624	86:24	~120
0.001	5e+6	2,026,290	89:48	~376
0.01	5e+7	1,630,124	101:36	~267

Best choice

Results

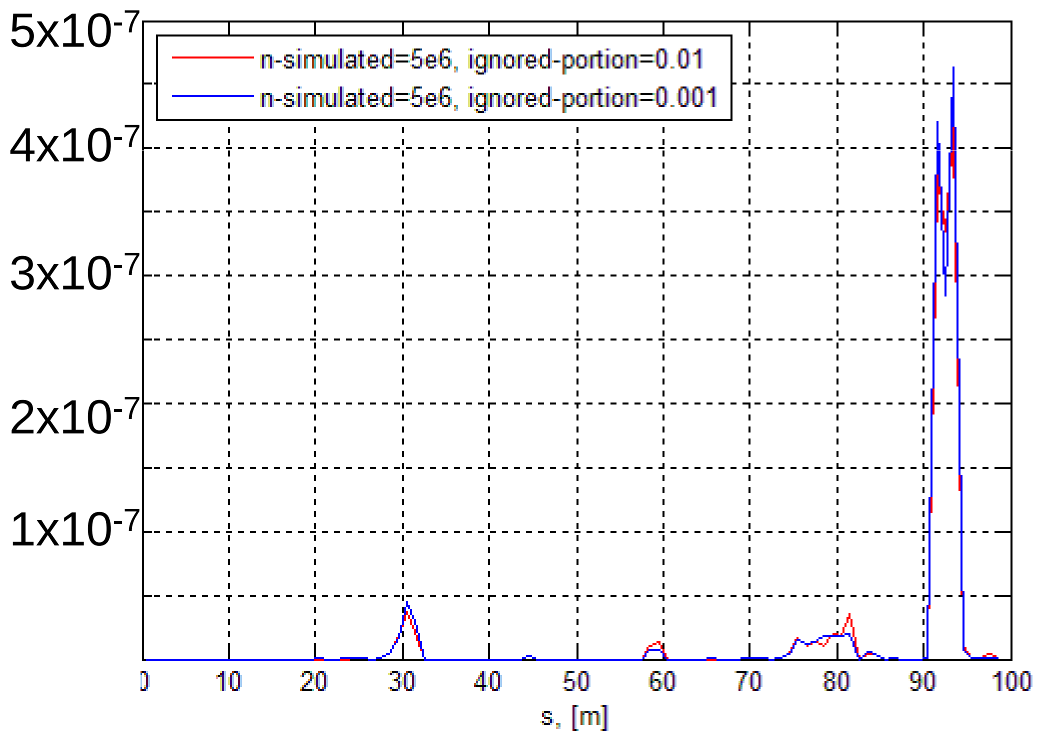
Beam Loss Fraction (%) normalized by number of beam electrons

- Electron current : Ie = 1.3×10^{9} [frequency] x 7.7×10^{-12} [C]=10^{-2} [A]
- Beam Loss Rate : Rl [A/m]
- Beam loss fraction : Fl (/m)

  = Rl / 10^{-2} (/m)

  = Rl x 10^{4} (%/m)

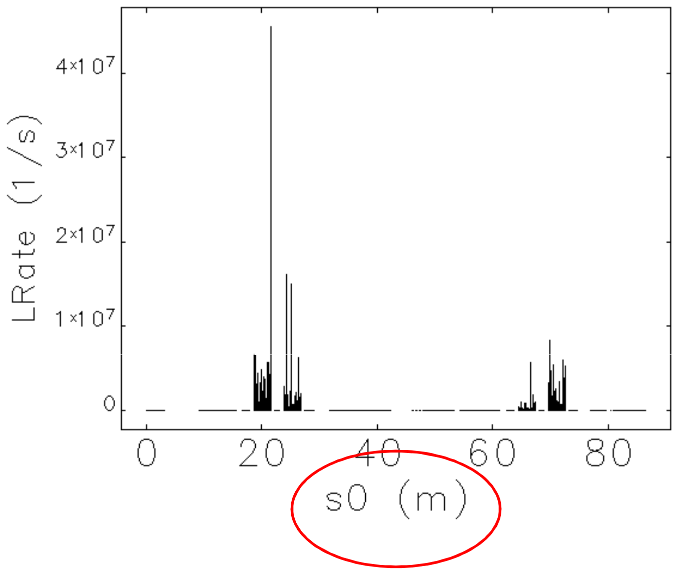
Loss fraction (%/m)

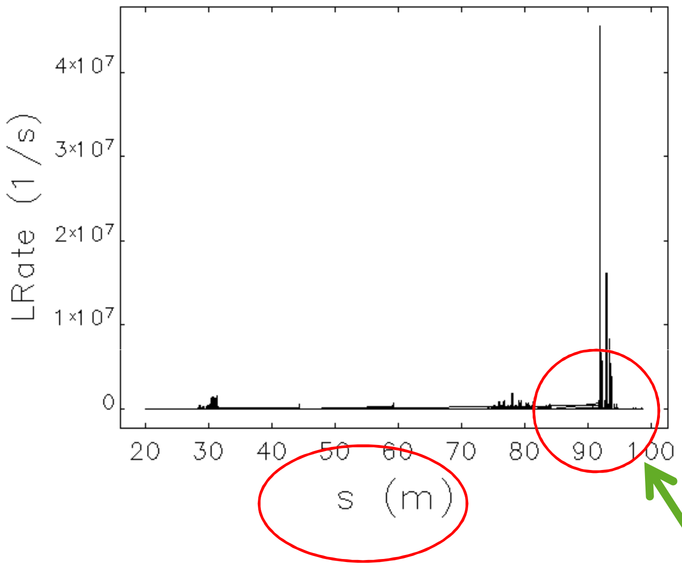


Results

Beam Loss Distributions (I)

ip = 0.001
ns=5e+6





Original scatter point

Final loss point

Local minimum of transverse aperture + betatron oscillation

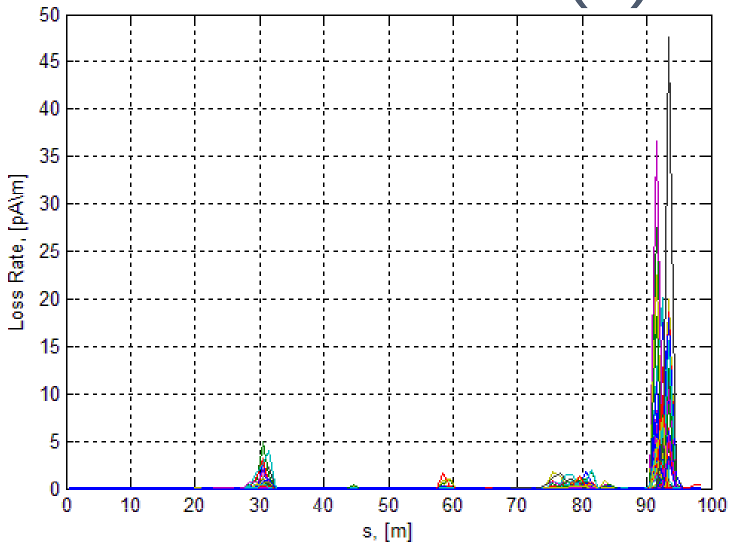
Lost electrons originate at positions with smallest momentum apertures

Results

Beam Loss Distributions (II)

*.out file
Beam Loss Rate

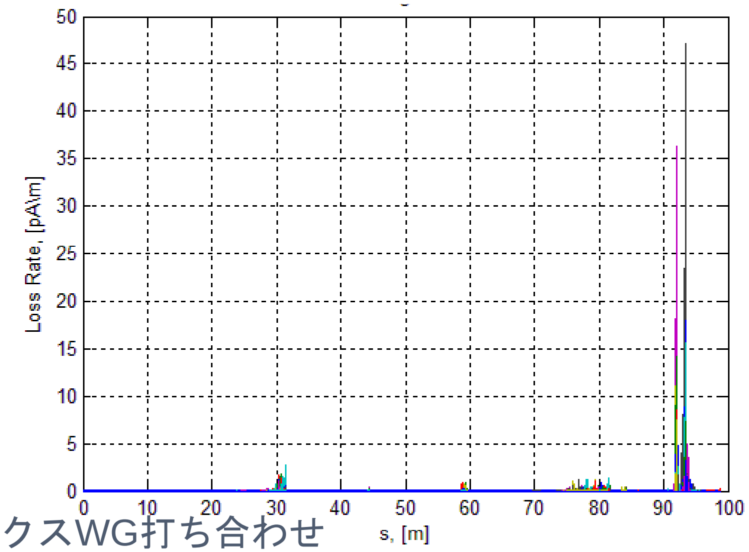
ip = 0.001
ns=5e+6
nbins=100



Default
(loss sampling = every 1m)
touscheckScatter.c
lossDis=chbook1("s","m",
0,sTotal,sTotal)
Number of bins= sTotal
(bin size = 1m)

Found how to calculate beam loss in finer s sampling points!

ip = 0.001
ns=5e+6
nbins=1000



Modified
(loss sampling = every 0.1m)
touscheckScatter.c
lossDis=chbook1("s","m",
0,sTotal,sTotal*10)
Number of bins= sTotal*10
(bin size = 0.1m)

Conclusion
Summary

- Beam loss due to Touschek Scattering has been studied with Elegant
- Maximum loss rate of 45 pA/m is observed at s = 93m where betatron oscillations are large due to deceleration and with a 2.5cm x 2.5cm collimator in the Lattice
- The maximum loss corresponds to the beam loss fraction of 4.5×10^{-9} %/m
- The origins of the loss are Touschek scatterings in the two arc sections

Conclusion
Future work

- We are planning to add the residual gas scattering simulation with use of the subroutine library for relativistic charged-particle dynamics (Bmad) to this study
- The Touschek lifetime improves with increased bunch energy spread that comes from the multibunch instabilities => Energy spread study

Conclusion
Acknowledgements

- Thanks to Professor Nakamura-san and Assistant Professor Shimada-san for important advises, useful criticism and fruitful discussions during preparation of this results
- Special thanks to Sako-san (J-PARC) for the technical support and for the help with programming code manipulations

Thank you for attention!

Appendix A:
Momentum