Single and multiple intra-beam scattering in low emittance rings
(SuperB example)

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Thanks to: T. Demma (LAL)

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Introduction

- Third generation light sources → USRs
- Damping Rings for linear colliders
- High intensity machines (B-factories, LHC upgrade)

all push their design to ultra-low ε

Similar challenges, common issues

- non-linear optics: modeling and correction
- collective effects (ex. IBS)
- Beam lifetime (Touschek effect)
- Stable emittance, no orbit perturbations

- Single & multiple intra-beam scattering affect low ε electron rings:
  - Touschek effect limits the beam lifetime
  - IBS increases the steady-state beam dimensions
- In hadronic and heavy ion machines, IBS increases emittances with time: we focus here on electron machines

Outline

- IBS
  - Some theory, codes and benchmarks
  - Conventional Calculation
  - Tracking code structure (LNF) – SuperB case
  - Prospects for IBS studies with our tracking code

- Touschek
  - Some theory, codes and benchmarks
  - Tracking code structure (LNF) –SuperB, DAFNE case
  - Prospects for Touschek studies with tracking code (USRs)

Challenging target
in such a short time!

IBS calculation

- Programs that solve IBS mostly use the Bjorken-Mtingwa formulation: ZAP, SAD, MAD-X, Elegant, ...
- IBS calculations are CPU-time consuming (a numerical integration at each lattice element)
- Simplified models have been developed (..., Bane)

Recently:

Macroparticle tracking codes based on a binary collision model*

- IBS-TRACK developed at LNF (SuperB, DAFNE)

  uses many parallel processors

- SIRE developed at CERN (CLIC-DR)

* Ref.
[P. Yu, Y. Wang and W. Huang , PRST-AB , **12**, 061301 (2009)]
[N. Alekseev, A. Bolshakov, E. Mustafin and P. Zenkevich , in *Space Dominated Beam Physics for Heavy Ion Fusion*, ed. Y.K. Batygin AIP, New York, **480** (1999) p.31-41]

IBS Calculations Procedure

1. Evaluate equilibrium emittances ε_i and radiation damping times τ_i at low bunch charge
2. Evaluate the IBS growth rates $1/T_i(\varepsilon_i)$ for the given emittances, averaged around the lattice, using the **K. Bane high energy approximation***
3. Calculate the "new equilibrium" emittance from: $\varepsilon_i' = \frac{1}{1-\tau_i/T_i}\varepsilon_i$

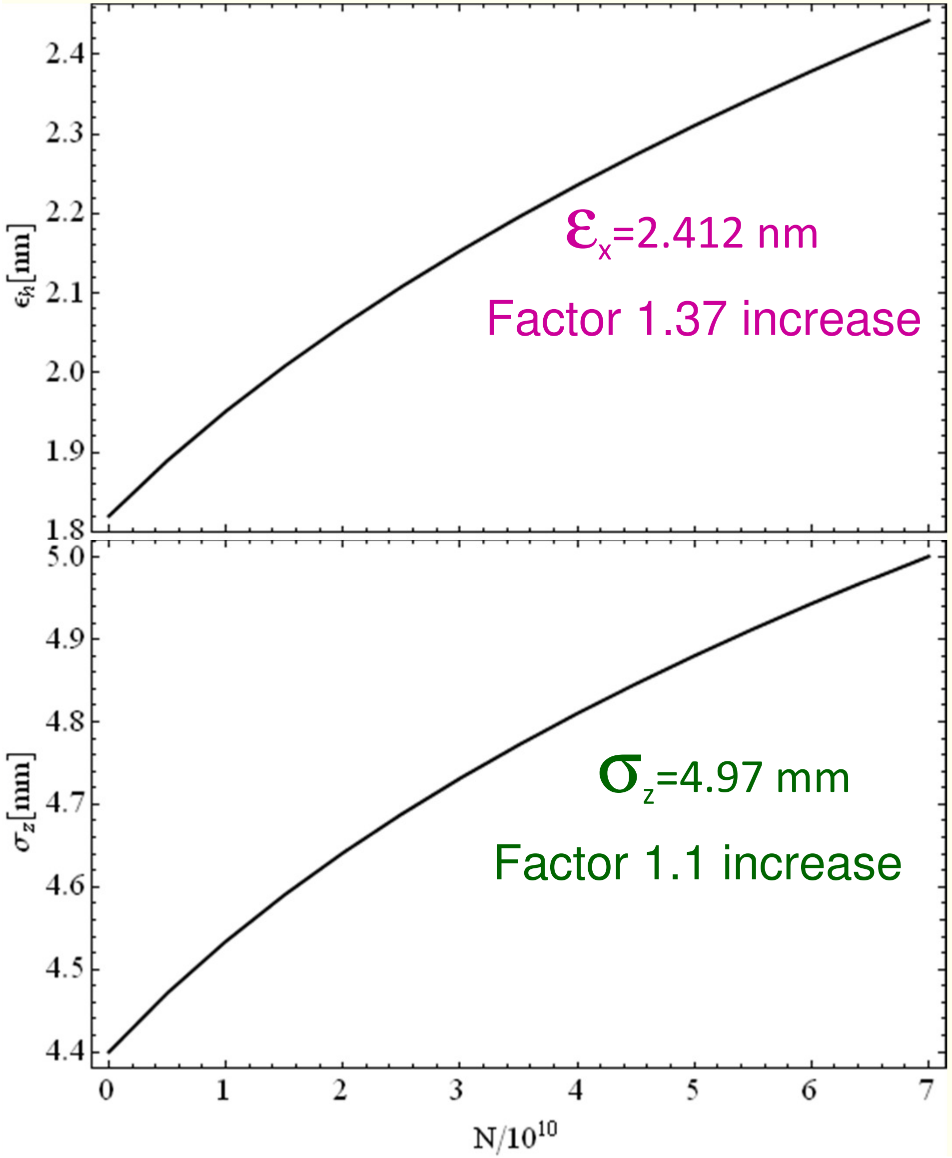
   For the vertical emittance we use* : $\varepsilon_y' = (1-r_\varepsilon)\frac{1}{1-\tau_y/T_y}\varepsilon_y + r_\varepsilon\frac{1}{1-\tau_x/T_x}\varepsilon_y$

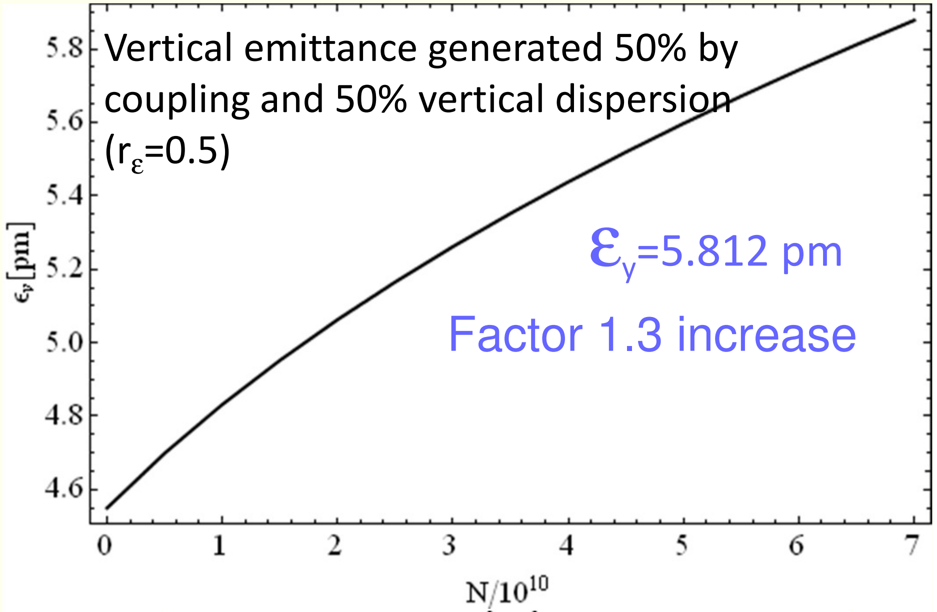
   where r_ε varies from 0 (ε_y generated from dispersion) to 1 (ε_y generated from betatron coupling)
4. Iterate from step 2

* Ref. [K. Bane, EPAC02, p.1442] , [K. Kubo, S.K. Mtingwa and A. Wolski, PRSTAB **8**, 081001 (2005)]

IBS in SuperB LER

V12 lattice @N=6.5 10^{10}





Parameter	Unit	Value
Energy	GeV	4.18
Bunch population	10^{10}	6.5
Circumference	m	1257
Emittances (H/V)	nm/pm	1.82/4.55
Bunch Length	mm	3.99
Momentum spread	%	0.0667
Damping times (H/V/L)	ms	40/40/20
N. of macroparticles	-	10^5
N. of grid cells	-	64x64x64

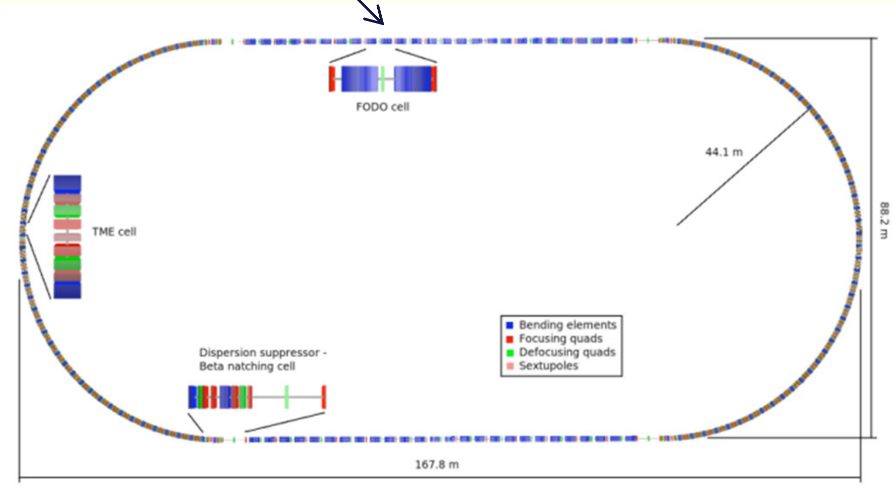
Open questions for further investigations

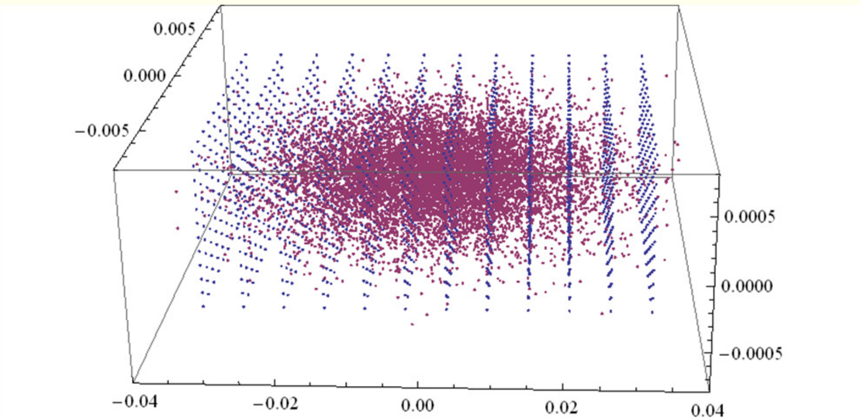
- This approach doesn't tell us the final beam distribution after IBS. In addition, Bane's approximation works for Gaussian beams

- Monte Carlo approach opens new possibilities for studying IBS – non Gaussian- beam tails distribution
- Tracking code that reads a MAD lattice gives large possibilities for investigations IBS effect on vertical emittance sources (vertical dispersion, misalignments, …)

Intra-Beam Scattering Simulation Algorithm

IBS applied at each element of the CLIC DR





- IBS routine implemented in **C-MAD** (M. Pivi SLAC) parallel code: **C**ollective effects & **MAD.**
- Lattice read from MADX files containing Twiss functions and transport matrices
- At each element in the ring, IBS routine:
  - Particles of the beam are grouped in cells.
  - Particles inside a cell are coupled
  - Momentum of particles is changed because of scattering according to BINARY MODEL.
- Particles are transported to the next element.
- Radiation damping and excitation effects are evaluated at each turn.
- Vertical dispersion is included
- Code uniquelly includes: **IBS, Electron Cloud, Radiation Damping & Quantum Excitation**

[M.Pivi, A.Chao, C.Rivetta, T.Demma, M.Boscolo, F.Antoniou, K.Li, Y.Papaphilippou, K.Sonnad, IPAC2012]

Binary Collision algorithm for the IBS*

* Ref.
[P. Yu, Y. Wang and W. Huang , PRST-AB , **12**, 061301 (2009)]
[N. Alekseev, A. Bolshakov, E. Mustafin and P. Zenkevich , in *Space Dominated Beam Physics for Heavy Ion Fusion*, ed. Y.K. Batygin AIP, New York, **480** (1999) p.31-41]

For two particles colliding with each other, the changes in momentum for particle 1 can be expressed as:

$$\xi = \frac{P_1 - P_2}{\gamma P},\ \theta = x'_1 - x'_2,$$

$$\zeta = y'_1 - y'_2,\ \alpha = \frac{\sqrt{\theta^2 + \zeta^2}}{2},$$

φ polar scattering angle

ϕ azimuthal scattering angle

$$\Delta P_{1x} = \frac{P}{2}\left(\left[\zeta\sqrt{1 + \frac{\xi^2}{4\alpha^2}}\sin\phi - \frac{\xi\theta}{2\alpha}\cos\phi\right]\sin\varphi + \theta(\cos\varphi - 1)\right)$$

$$\Delta P_{1y} = \frac{P}{2}\left(\left[\theta\sqrt{1 + \frac{\xi^2}{4\alpha^2}}\sin\phi - \frac{\xi\zeta}{2\alpha}\cos\phi\right]\sin\varphi + \zeta(\cos\varphi - 1)\right)$$

$$\Delta P_{1s} = \frac{P}{2}[2\alpha\gamma\sin\varphi\cos\phi + \gamma\xi(\cos\varphi - 1)],$$

with the equivalent polar angle φ_{eff} and the azimuthal angle ϕ distributing uniformly in [0; 2π], the invariant changes caused by the equivalent random process are the same as that of the IBS in the time interval Δt_s for the beam to pass the element

$$\varphi_{\rm eff} = \frac{2r_0}{\gamma}\sqrt{\frac{\pi c\rho\Delta t_s}{\bar{\beta}^3}L_c}$$

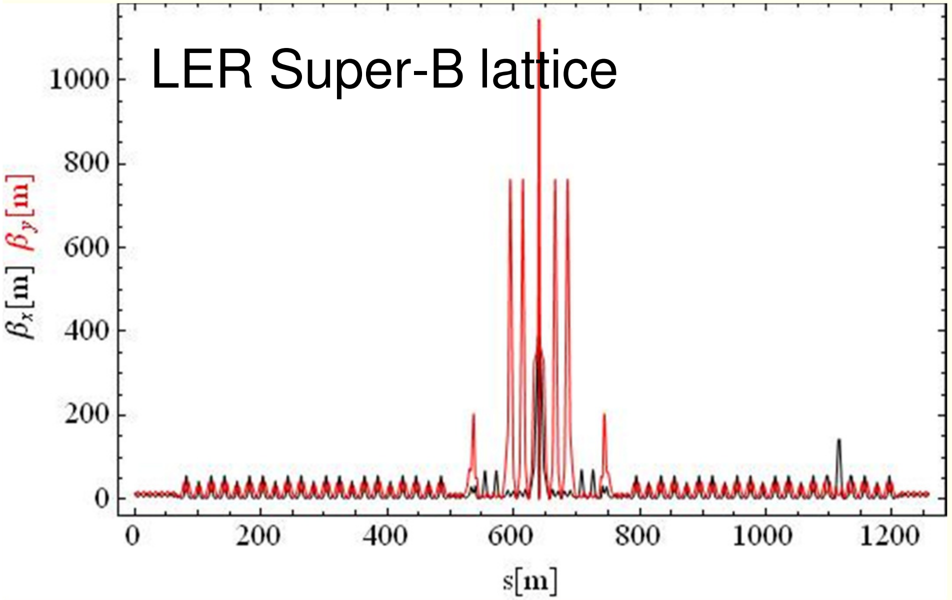
$$\frac{dJ_{1x}}{dt} = \frac{\pi r_0^2}{4\gamma^2\bar{\beta}^3}c\rho L_c\left[-4x'_1\theta + \xi^2 + \zeta^2 + 4\frac{x_{\beta 1}D_x}{\beta_x^2}\gamma\xi + \frac{D_x^2\gamma^2}{\beta_x^2}(\theta^2 + \zeta^2)\right]$$

$$\frac{dJ_{1y}}{dt} = \frac{\pi r_0^2}{4\gamma^2\bar{\beta}^3}c\rho L_c(-4y'_1\zeta + \xi^2 + \theta^2)$$

$$\frac{dJ_{1s}}{dt} = \frac{\pi r_0^2}{4\gamma^2\bar{\beta}^3}c\rho L_c\left(-4\frac{\delta_1}{\gamma}\xi + \zeta^2 + \theta^2\right),$$

SIRE code uses similar implementation
[A. Vivoli and M. Martini, “Intra-beam scattering in the CLIC damping rings”, IPAC2010]

IBS-TRACK vs theoretical models



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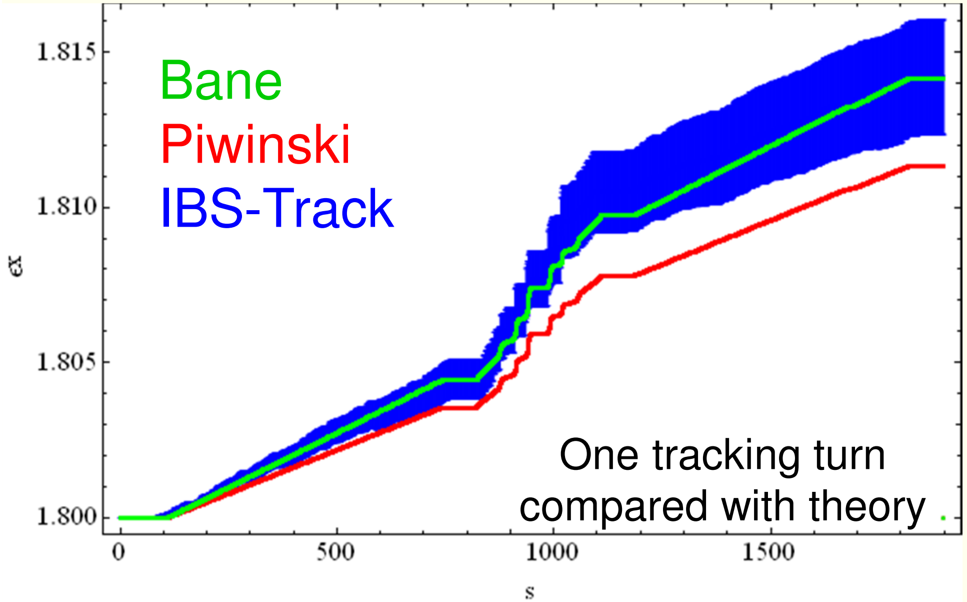


Theoretical models compared with simulations for LER Super-B, using IBS-Track and C-MAD codes: one turn evolution of emittance with Intra-beam scattering.

CPU time ~11s with 64 processors

Three different tools for investigation

- ***K. Bane* model**

  Consolidated procedure that allows fast growth rates estimates

  High energy approximation for Gaussian beams

- **Macroparticle tracking code**

  6-D Monte Carlo, it allows realistic studies

  - It aims at exploring final equilibrium non-Gaussian tails,
  - non-nominal behavior e.g. when vertical emittance gets very small,
  - ε_x, ε_y and ε_z evolution in time

- Novel analytical model that predicts ε_x and ε_z evolution in time for different bunch charges (***from Bane's* model, proposed by A. Chao**)

  Coupled differential equations valid for Gaussian beams

Three methods are in good agreement

Differential equation system for ε_x and ε_z

Radial and longitudinal emittance growths can be predicted by a model that takes the form of a coupled differential equations:

$$\begin{cases} \dot{\varepsilon}_x = -\dfrac{\varepsilon_x(t)}{\tau_x} + \dfrac{\varepsilon_x}{T_x} \\ \dot{\varepsilon}_z = -\dfrac{\varepsilon_z(t)}{\tau_z} + \dfrac{\varepsilon_z}{T_z} \end{cases} \xrightarrow{\text{Bane Model}} \begin{cases} \dot{\varepsilon}_x = -\dfrac{1}{\tau_x / T_{rev}} \left(\varepsilon_x(t) - \varepsilon_{xeq}\right) + \dfrac{N\,a}{\varepsilon_x^{3/4}(t)\ \varepsilon_z(t)} \\ \dot{\varepsilon}_z = -\dfrac{1}{\tau_z / T_{rev}} \left(\varepsilon_z(t) - \varepsilon_{zeq}\right) + \dfrac{N\,b}{\varepsilon_x^{3/4}(t)\ \varepsilon_z(t)} \end{cases}$$

N number of particles per bunch

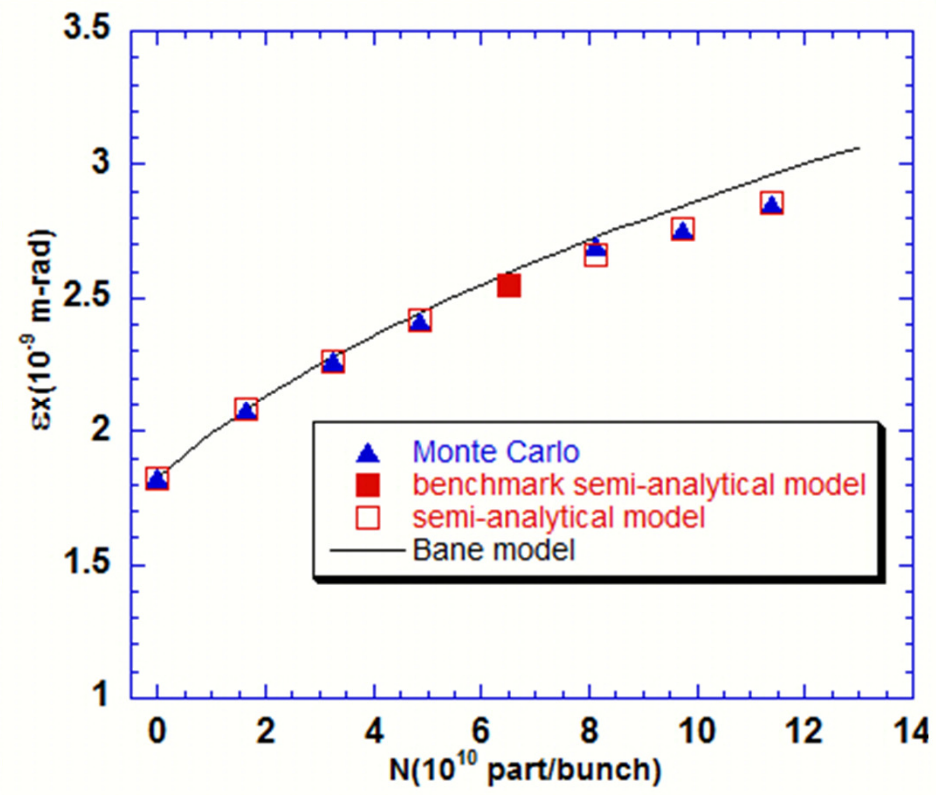
a and **b** coefficients characterizing IBS obtained once by fitting the tracking simulation data for a chosen benchmark case

$$\begin{cases} \varepsilon_x(t=0) = \varepsilon_{x0} \\ \varepsilon_z(t=0) = \varepsilon_{z0} \end{cases}$$

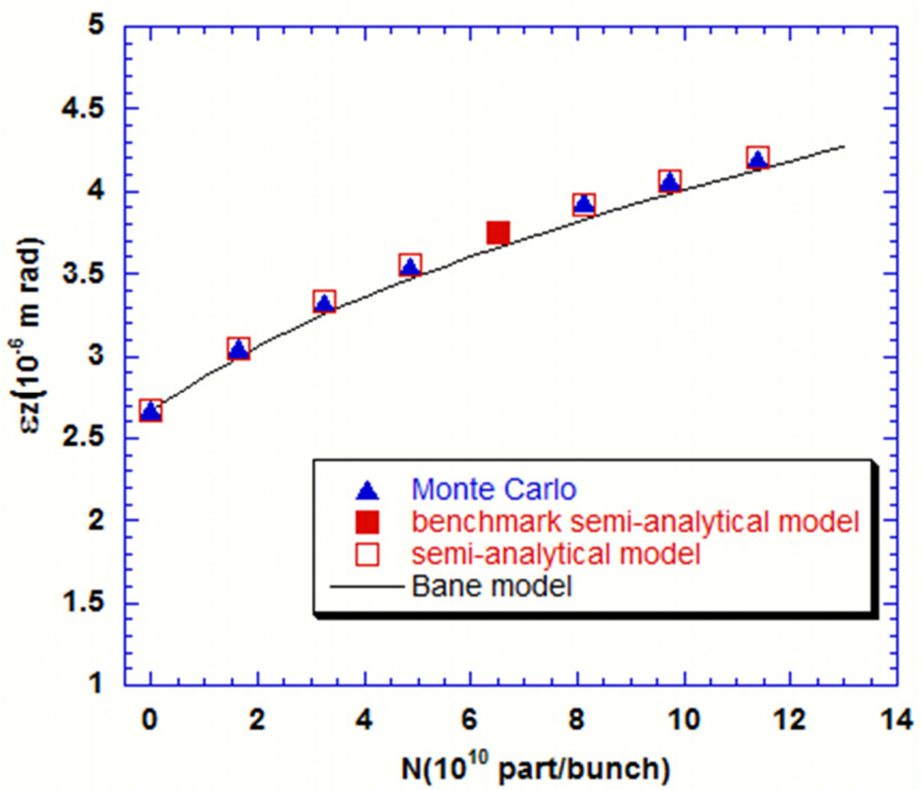
Obtained by fitting the zero bunch intensity case (IBS =0)

Summary plots: LER SuperB

Equilibrium horizontal emittance vs bunch current



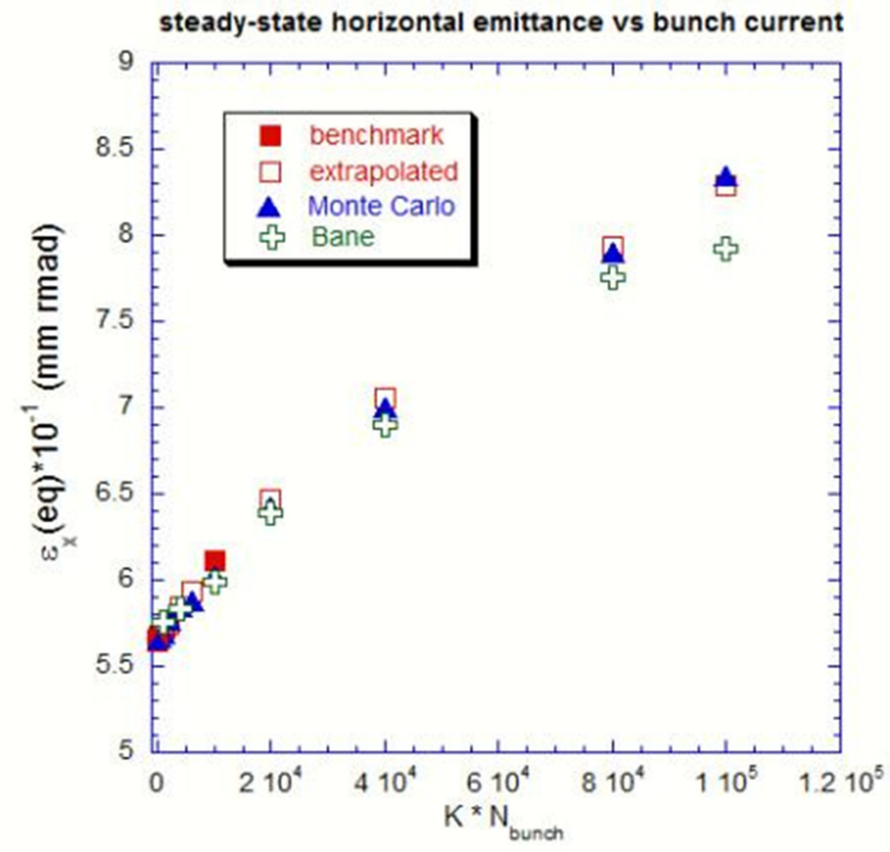
Equilibrium longitudinal emittance vs bunch current

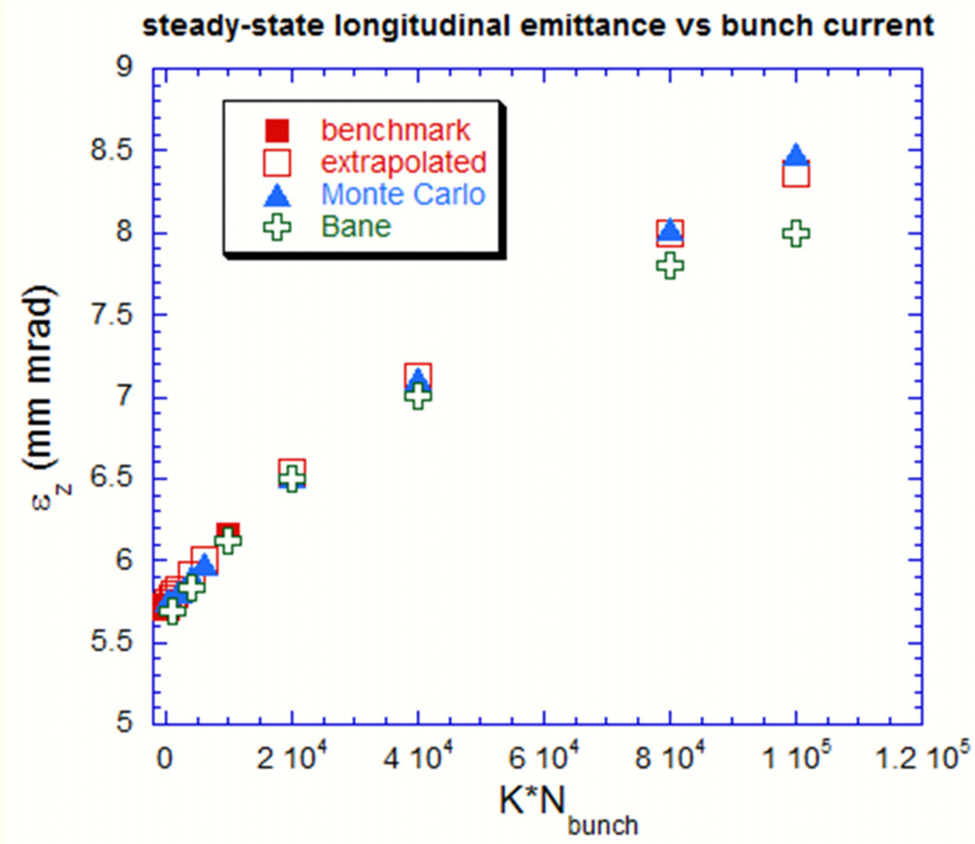


The easy computable semi-analytical approach allows a quick scan of some key design parameters, such as the bunch population

Summary plots: DAFNE

$\varepsilon_{x,z}$ vs bunch current





MacroParticleNumber=40000

σ_z=12.0*10^{-3}

δp=4.8*10^{-4}

NTurn=1000 (≈10 damping times)

$\epsilon_x=(5.63*10^{-4})/\gamma$

$\epsilon_y=(3.56*10^{-5})/\gamma$

$\tau_x = 1000^{-1} * 0.042$

$\tau_y = 1000^{-1} * 0.037$

$\tau_s = 1000^{-1} * 0.017$

Prospects for IBS Monte Carlo

- Both tracking codes (LNF/CERN), that implement the Zenkevich-Bolshakov algorithm, have been successfully benchmarked with conventional theories (i.e. growth rates by K. Bane) and with the novel semi-analytical model
- LNF code benchmarked with SLS real data [F. Antoniou *et al*., IPAC2012], planned also with CESR-TA data.
- LNF code is parallelized, implemented in CMAD
- Developments such as the inclusion of coupling, vertical dispersion induced by misalignments already included
- Interesting aspects of the IBS such as its impact on damping process and on generation of non Gaussian tails may be investigated with such a multi-particles tracking code.
- detailed beam tails studies planned
- Studies for the limiting case of extremely low-ε rings (USRs) planned.

Touschek effect -Introduction

The Coulomb scattering between particles in a stored bunch induces an energy exchange between transverse and longitudinal motions.

In this process small transverse momentum fluctuations are transformed into magnified longitudinal fluctuations due to the relativistic Lorentz factor in the transformation.

Off-momentum particles can exceed the rf momentum acceptance, or they may hit the aperture when displaced by dispersion. In both cases they get lost.

This process results in a finite lifetime of a bunched beam.

Theory (only some):

- Touschek effect: first theory by Bruno Touschek (1962): for a flat beam and for non-relativistic energies of the colliding particles in their beam frame
- C. Bernardini *et al., PRL 10 p.407 (1963)*
- Bruck and Le Duff, International Conf. High Energy Accelerators, Frascati (1965)
- Piwinski, HEAC74, p.405-409 Stanford (1974)
- It was then generalized for arbitrary energies, round beams and dispersion, complete calculation is in Piwinski DESY 98-179 (1998)

- See Ref. in A. Piwinski in “Handbook”, ed. by Chao and Tigner, World Scientific (1999)

Touschek Scattering in low-ε rings

Touschek effect is determined by many parameters, as:

- Beam energy
- Bunch density (emittance, bunch charge)
- H-invariant, dispersion and phase advance
- Physical aperture

But, for a given machine with a given lattice:

- non-linear dynamics
- momentum aperture

real limit of the low ε storage rings performance

Optimize Touschek lifetime means to optimize non-linear dynamics:

- Low–ε rings have greater particle density, leading to a higher rate of scattering events
- Low–ε rings tend to have reduced momentum acceptance, leading to a higher rate of loss for Touschek scattered particles

Touschek effect calculation

- **There are different ways to calculate Touschek lifetime:**
  - Give the machine momentum acceptance as input, and calculate the formula of the Touschek lifetime averaging on the whole lattice
  - Calculate the local momentum acceptance through the lattice elements and calculate the formula for each small section of the lattice and then sum up
  - Perform tracking of macroparticles with non-linear kicks included, so the momentum acceptance is calculated for each macroparticle, dynamic aperture calculated intrinsically

$\Downarrow$

- **Most accurate estimate done with a macroparticle tracking code with the Monte Carlo technique**
  - *S. Khan, Proc. of EPAC 1994 – Bessy II*
  - *A. Xiao and M. Borland,* Phys.Rev.ST-AB 13 074201 (2010) pp10
  - *M.Boscolo and P. Raimondi,* Phys.Rev.ST-AB 15 104201 (2012) pp11 and ref. therein

LNF Tracking code Monte Carlo

- The lattice is imported from MAD8
- At each element in the ring a set of macroparticles is extracted from a Gaussian distribution in the two transverse planes and with a proper energy deviation weighted by the very nonlinear dependence of the Touschek scattering probability

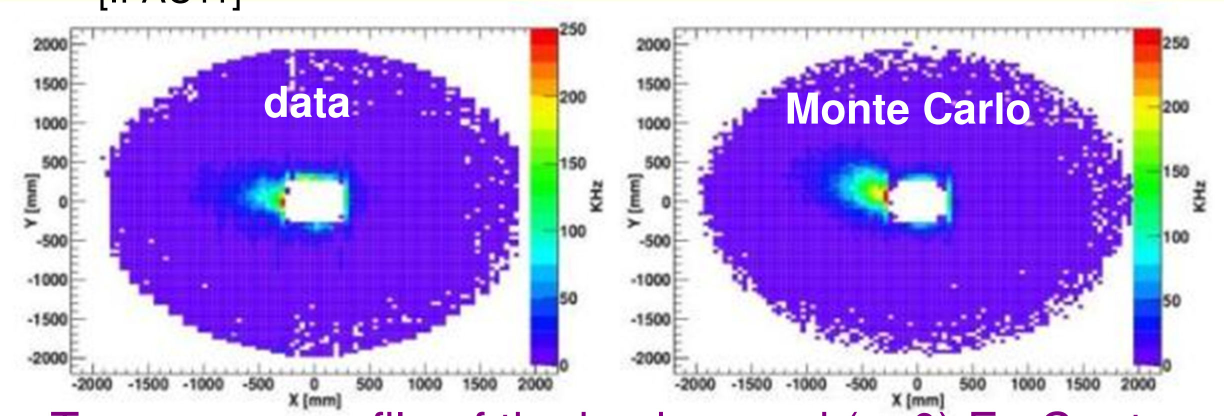
$$\frac{1}{\tau} = \frac{\sqrt{\pi} r_e^2 c N}{\gamma^3 (4\pi)^{3/2} V \sigma_x' \delta_\varepsilon^{\,2}} C(u_{\min}) \qquad \delta_\varepsilon = \frac{\Delta E}{E} \qquad u_{\min} = \left(\frac{\delta_\varepsilon}{\gamma \sigma_x'}\right)^2 \qquad \sigma_x' = \sqrt{\frac{\varepsilon_x}{\beta} + \sigma_p^2 \left(D_x' + D_x \frac{\alpha_x}{\beta_x}\right)^2}$$

$$C(u_{min}) = \int_{u_{min}}^{\infty} \frac{1}{u^2} \left[u - u_{min} - \frac{1}{2} \ln\left(\frac{u}{u_{min}}\right)\right] e^{-u} du$$

- 4-D tracking in the transverse dimensions through every element;
- once per turn the macroparticle’s energy deviation is compared to rf acceptance. Loss location not determined, not need to track for few damping times
- $>10^6$ macroparticles tracked for few machine turns or until they are lost
- Benchmarked with DAFNE measured data, showing good agreement
- (Detailed loss particles analysis useful for background studies in colliders)

Benchmark with DAFNE real data

[IPAC11]



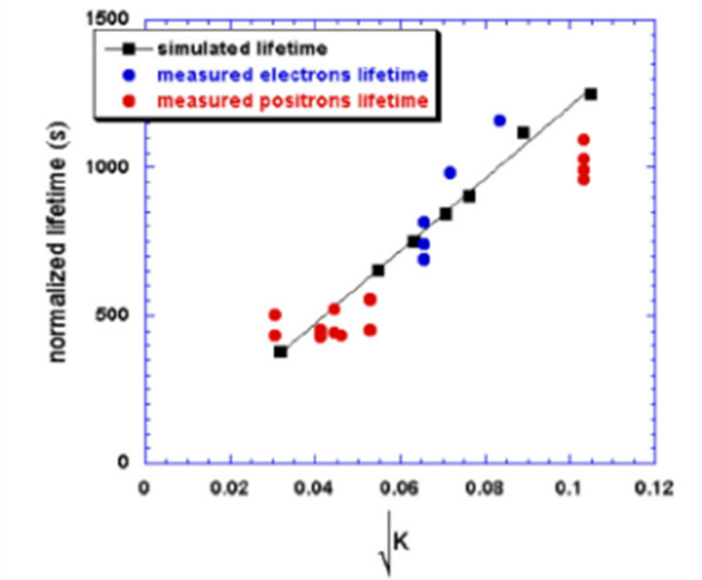
Transverse profile of the background (z<0) EmC rates

N_{part}/bunch	$2\cdot10^{10}$
I_{bunch} (mA)	10
ε_x (μm)	0.26
Coupling (%)	0.1- 0. 4
σ_z (cm)	1.4
β_x*(m)	0.25
β_y*(mm)	9

See also

- M. Boscolo et al. PAC01 P.2032
- M. Boscolo, M. Antonelli and S. Guiducci, EPAC02 p.1238
-

M. Boscolo et al. / Nuclear Instruments and Methods in Physics Research A 621 (2010) 121–129



MONTE CARLO SIMULATION FOR THE … Phys. Rev. ST Accel. Beams 15, 104201 (2012)

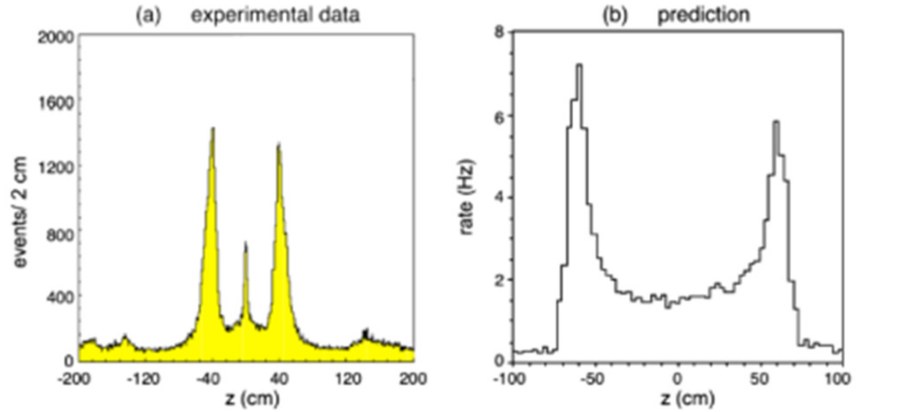
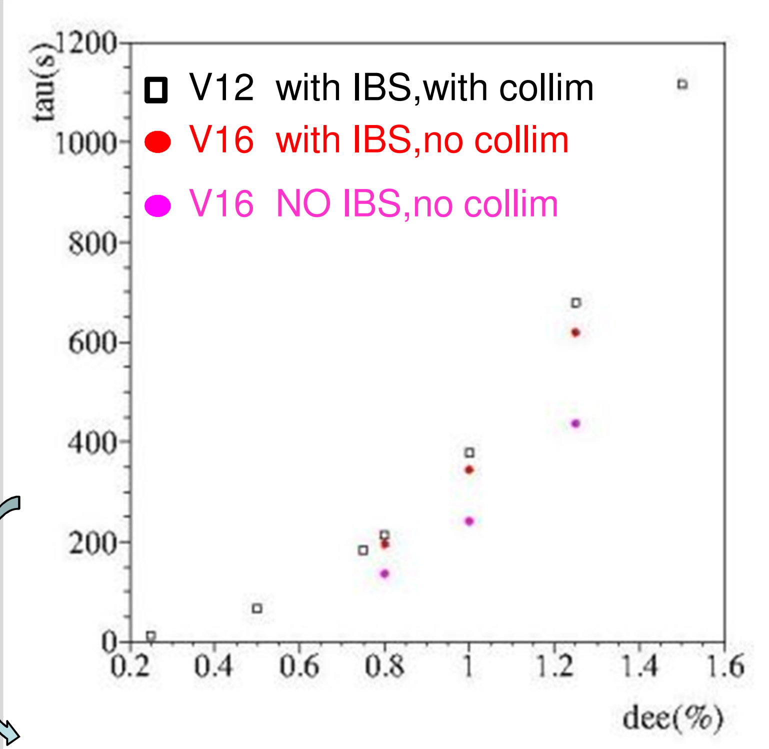


FIG. 12. (a) High rate of localized monotracks (protons) in KLOE until 2001 understood as photo-production $ep(n) \to \Lambda e \to p\pi^0(\pi^-)e$, induced by Touschek particles hitting the beam pipe support; (b) prediction from full simulation of Touschek particles into detector.

SuperB-LER Touschek lifetime vs ΔE/E

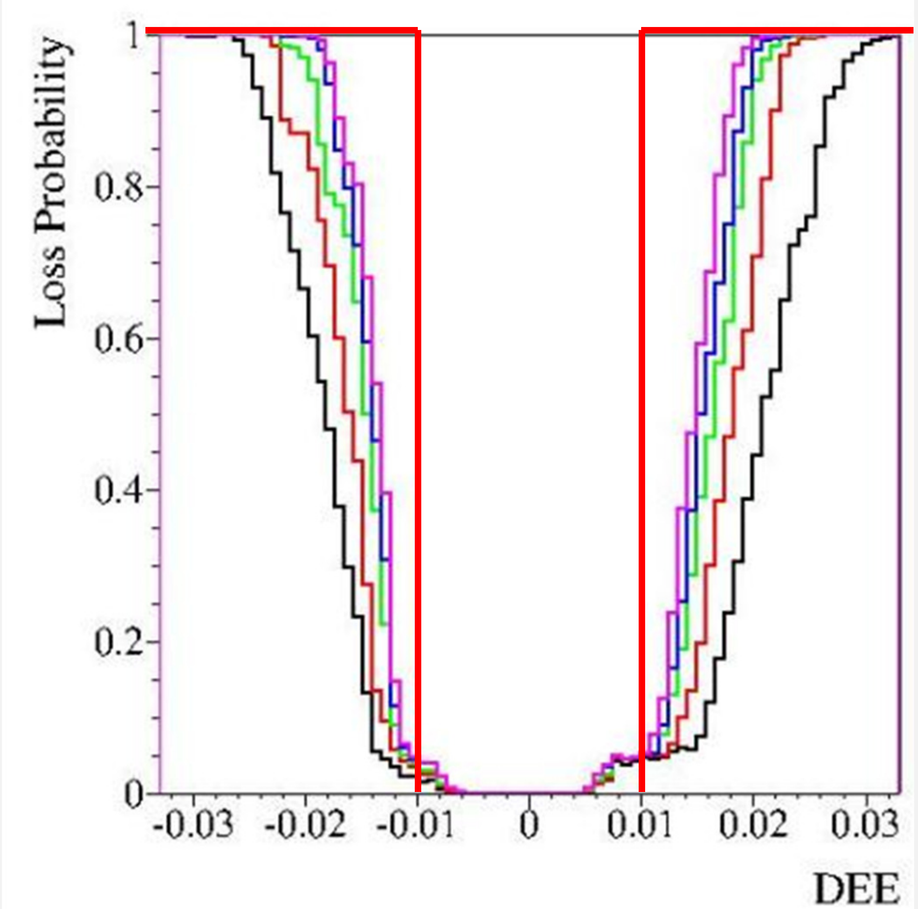
No tracking mode: quick estimate of Touschek lifetime for a given momentum aperture → useful to find the required momentum aperture



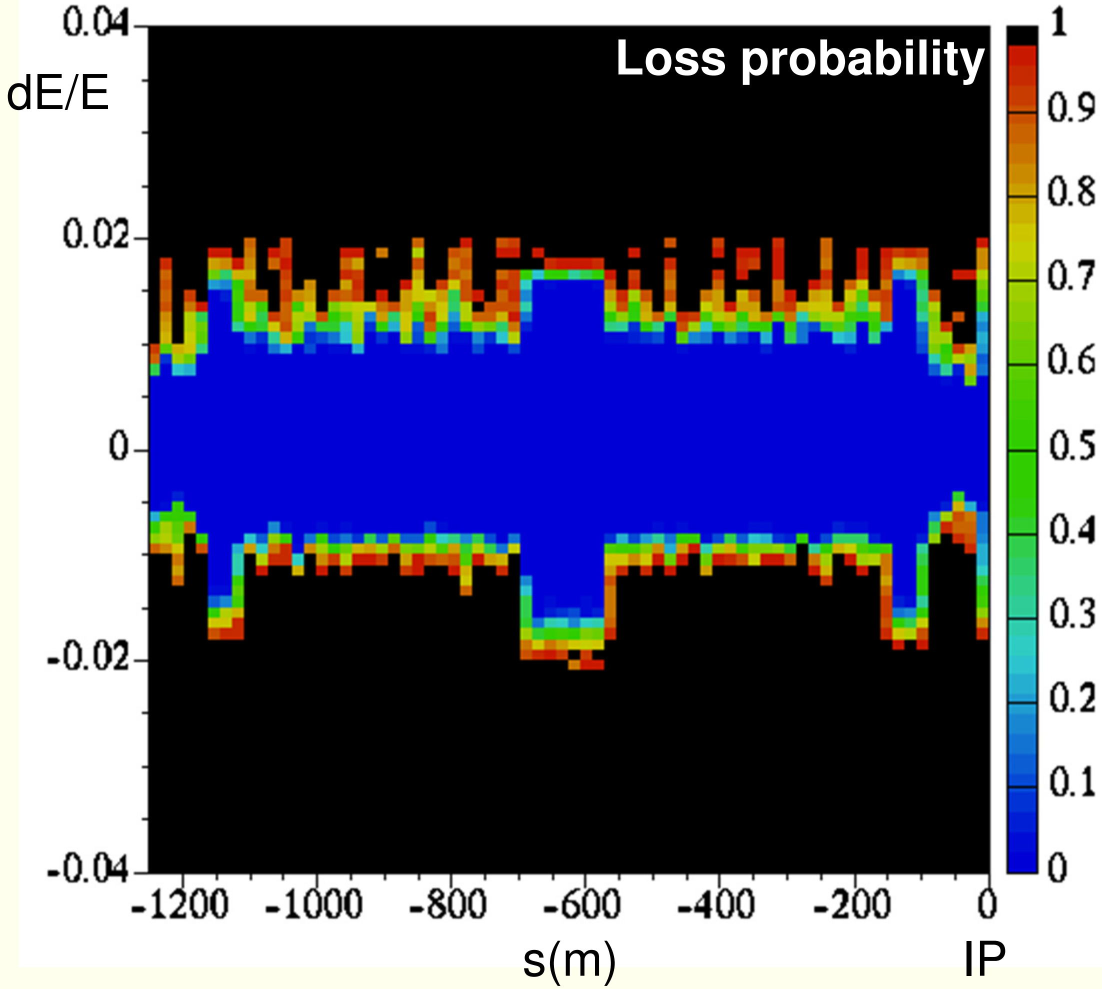
τ_{Tou} > 5min if mom. Acc.>0.9-1%

V16 (Pantaleo) I_b =2.45 mA $\varepsilon_{x\,(nat)}$=1.7 nm

efficiency is calculated from tracking- more realistic description of nonlinear dynamics than assume that particles with |Δp/p|>1% are lost



Momentum aperture



Not simply an s dependent momentum aperture

A.Xiao,M.Borland, PAC07 p.3457

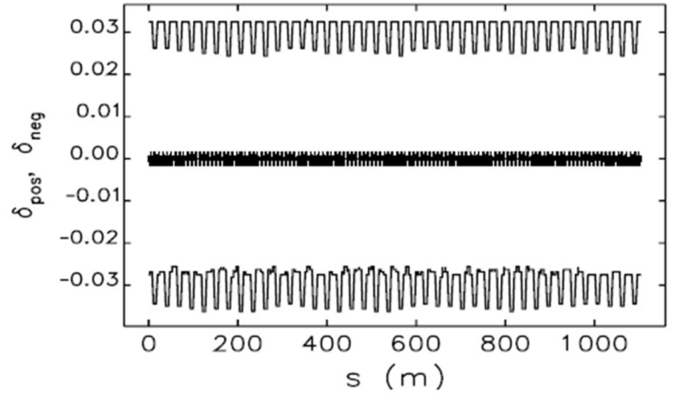
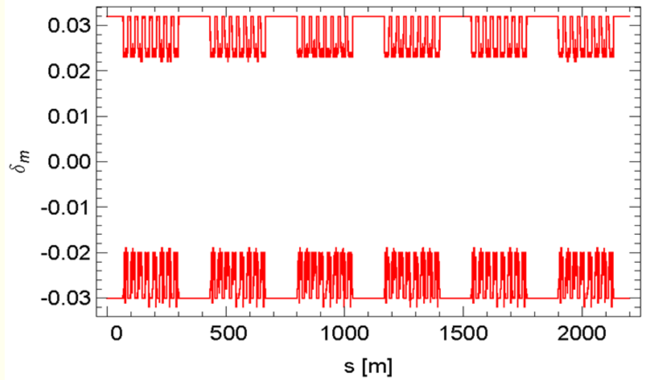


Figure 1: Momentum aperture of the APS.

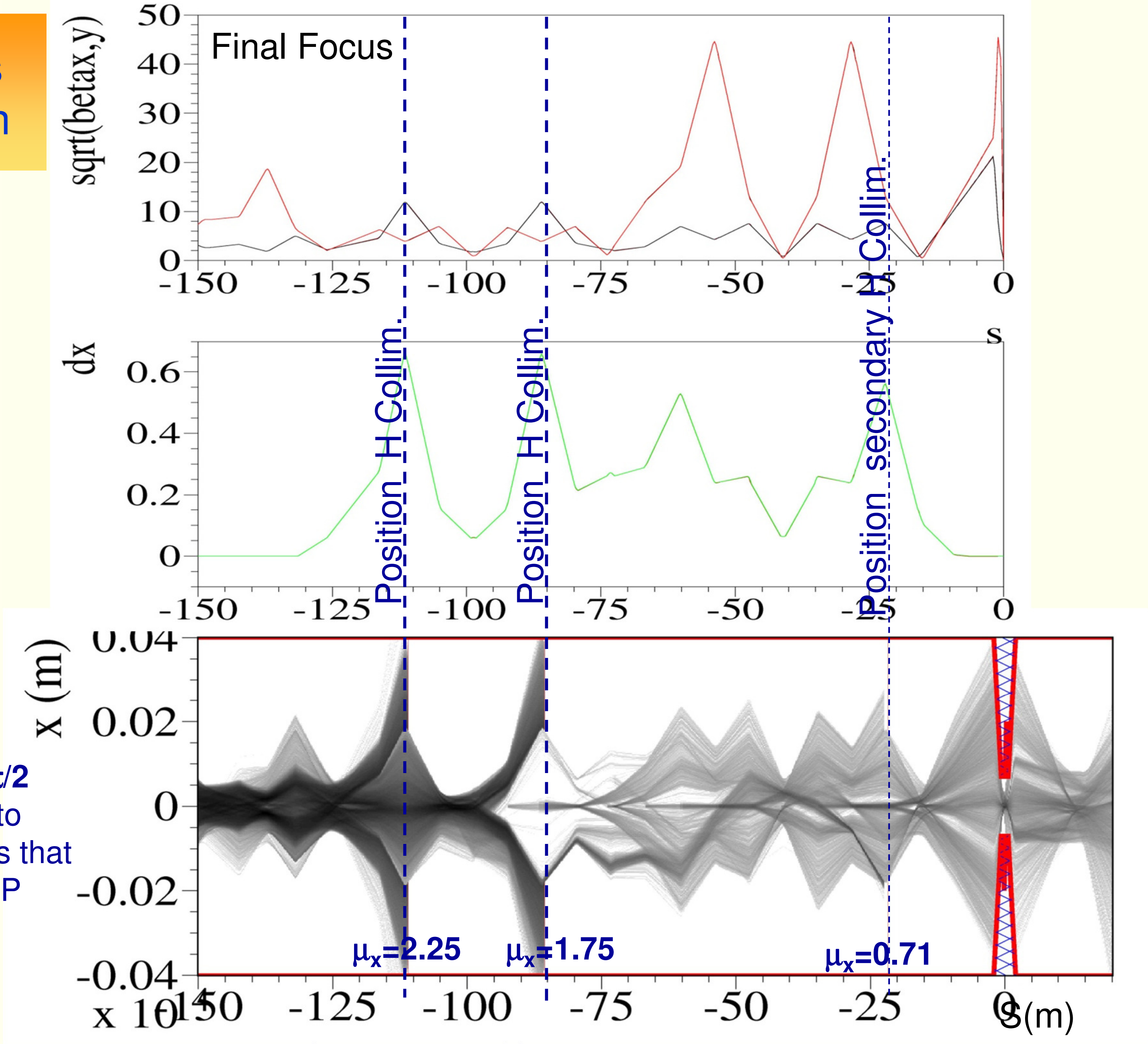
momentum aperture



PEP-X Y. Cai, SLAC
FLS-2012, March 2012 22

Collimators optimization

HER SuperB



collimators at **n·π/2** upstream the IP to intercept particles that would be lost at IP

Conclusions

- **IBS**: 6D macroparticle tracking code based on a binary collision model developed and parallelized (implemented in CMAD)
- The LER-SuperB case simulated and benchmarked with semi-analytical models. Benchmarked also with SLS real data.
- Prediction for non-Gaussian tails in distribution.
- **Touschek lifetime** calculated with 4D tracking code with Monte Carlo technique allowing a more realistic evaluation of momentum acceptance and, in turn, of Touschek lifetime.
- Benchmarked with DAFNE real data
- Extension to extremely low-ε rings planned soon.

- IBS in LER-SuperB causes about 40% emittance growth
- Touschek lifetime: dominates in DAFNE, LER-SuperB lifetime dominated by radiative Bhabhas, but Touschek is close to this limit (especially when crab sextupoles are turned on!)

Back-up

SuperB Parameter list

Parameter	Units	Base Line HER (e+)	Base Line LER (e-)	Low Emittance HER (e+)	Low Emittance LER (e-)	High Current HER (e+)	High Current LER (e-)	τ/charm HER (e+)	τ/charm LER (e-)
LUMINOSITY (10^{36})	cm^{-2} s^{-1}	1		1		1		1	
Energy	GeV	6,7	4,18	6,7	4,18	6,7	4,18	2,58	1,61
Circumference	m	1195		1195		1195		1195	
X-Angle (full)	mrad	60		60		60		60	
Piwinski angle	rad	20,11	17,25	29,42	23,91	13,12	10,67	8,00	6,50
β_x @ IP	cm	2,6	3,2	2,6	3,2	5,06	6,22	6,76	8,32
β_y @ IP	cm	0,0253	0,0205	0,0179	0,0145	0,0292	0,0237	0,0658	0,0533
Coupling (full current)	%	0,25	0,25	0,25	0,25	0,5	0,5	0,25	0,25
ε_x (without IBS)	nm	2,00	1,7	1,00	0,91	1,97	1,82	1,97	1,82
ε_x (with IBS)	nm	2,14	2,363	1,00	1,23	2,00	2,46	5,20	6,4
ε_y	pm	5,35	5,9075	2,5	3,075	10	12,3	13	16
σ_x @ IP	μm	7,459	8,696	5,099	6,274	10,060	12,370	18,749	23,076
σ_y @ IP	μm	0,037	0,035	0,021	0,021	0,054	0,054	0,092	0,092
Σ_x	μm	11,457		8,085		15,944		29,732	
Σ_y	μm	0,051		0,030		0,076		0,131	
σ_L (0 current)	mm	4,69	4,29	4,73	4,34	4,03	3,65	4,75	4,36
σ_L (full current)	mm	5	5	5	5	4,4	4,4	5	5
Beam current	mA	1892	2447	1460	1888	3094	4000	1365	1766
Buckets distance	#	2		2		1		1	
Buckets distance	ns	4,20		4,20		2,10		2,10	
Ion gap	%	2		2		2		2	
RF frequency	MHz	476		476		476		476	
Harmonic number		1998		1998		1998		1998	
Number of bunches		442		442		884		884	
N. Particle/bunch (10^{10})		5,08	6,56	3,92	5,06	4,15	5,36	1,83	2,37
Tune shift x		0,0026	0,0040	0,0020	0,0031	0,0053	0,0081	0,0063	0,0096
Tune shift y		0,1089	0,1033	0,0980	0,0981	0,0752	0,0755	0,1000	0,1001
Long. damping time	msec	13	18,0	13,4	20,3	13,4	20,3	26,8	40,6
Energy Loss/turn	MeV	2,11	0,865	2,11	0,865	2,11	0,865	0,4	0,166
σ_E (zero current)	δE/E	6,10E-04	7,00E-04	6,43E-04	7,34E-04	6,43E-04	7,34E-04	6,94E-04	7,34E-04
σ_E (with IBS)	δE/E	6,28E-04	7,91E-04						
CM σ_E	δE/E	4,75E-04		5,00E-04		5,00E-04		5,26E-04	
Total lifetime	min	4,23	4,48	3,05	3,00	7,08	7,73	11,41	6,79
Total RF Power	MW	16,38		12,37		28,83		2,81	

Baseline + other 2 options:
- **Lower y-emittance**
- **Higher currents (twice bunches)**

Baseline:
- **Higher emittance due to IBS**
- **Asymmetric beam currents**

RF power includes SR and HOM

Tau/charm threshold

DAFNE Parameter list

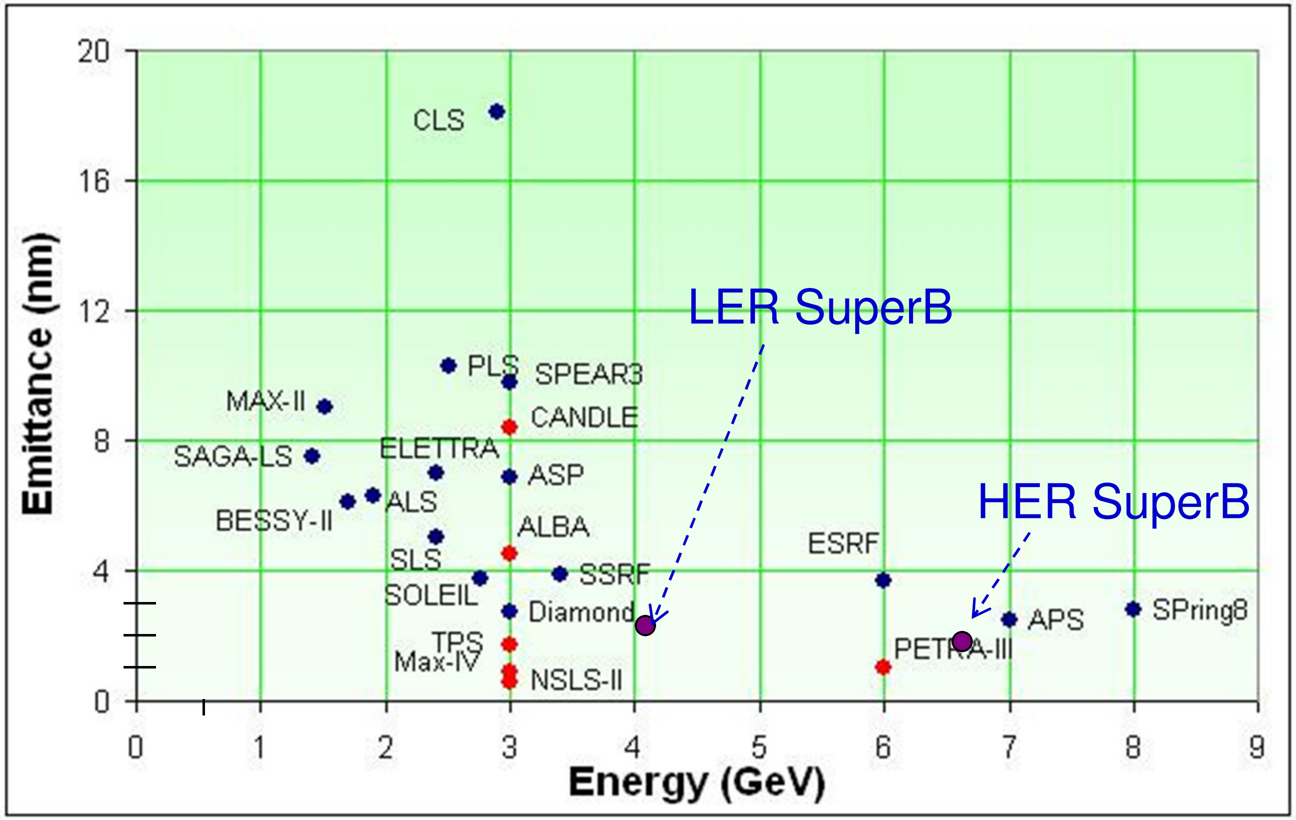
DAΦNE parameter	Value
Maximum beam energy	510 MeV
Time between collisions	2.7 ns
Circumference	98 m
Magnetic length of dipole	Outer ring: 1.2 m and inner ring: 1.0 m
# of dipoles	8 per ring
RF frequency	356 MHz
# of bunches per ring	100–105 (120 buckets)
Peak luminosity ($\mathcal{L}_{peak}$)	$4.53 \times 10^{32}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$
Turn-around time	2 min (topping up)
Beam radius	H: 260 μm at IP V: 4.8 μm
Transverse emittance (π rad m)	H: 260×10^{-9} and V: 2.6×10^{-9}
Energy spread	0.4×10^{-3}
Full crossing angle	50 mrad
Free space at IP	29.5 cm
Peak magnetic field	1.2 T
# of quadrupoles	48 per ring
Bunch length	2 cm at 15 mA
# of particles per bunch	e^- : 3.2×10^{10} and e^+ : 2.1×10^{10}
Luminosity lifetime	0.2 h
Average beam current	e^- : 1.5 A and e^+ : 1.0 A
Amplitude function β at IP	H: 0.26 m and V: 0.009 m
Beam-beam tune shift per crossing	440×10^{-4} at $\mathcal{L}_{peak}$

Parameters used in the IR designs

(Mike Sullivan, Dec. 11)

Parameter	HER	LER	
Energy (GeV)	6.70	4.18	
Current (A)	1.89	2.45	
Beta X* (mm)	26	32	(26)
Beta Y* (mm)	0.253	0.205	(0.274)
Emittance X (nm-rad)	2.00	2.46	
Emittance Y (pm-rad)	5.0	6.15	
Sigma X (μm)	7.21	8.87	
Sigma Y (nm)	36	36	
Crossing angle (mrad)	+/- 30		

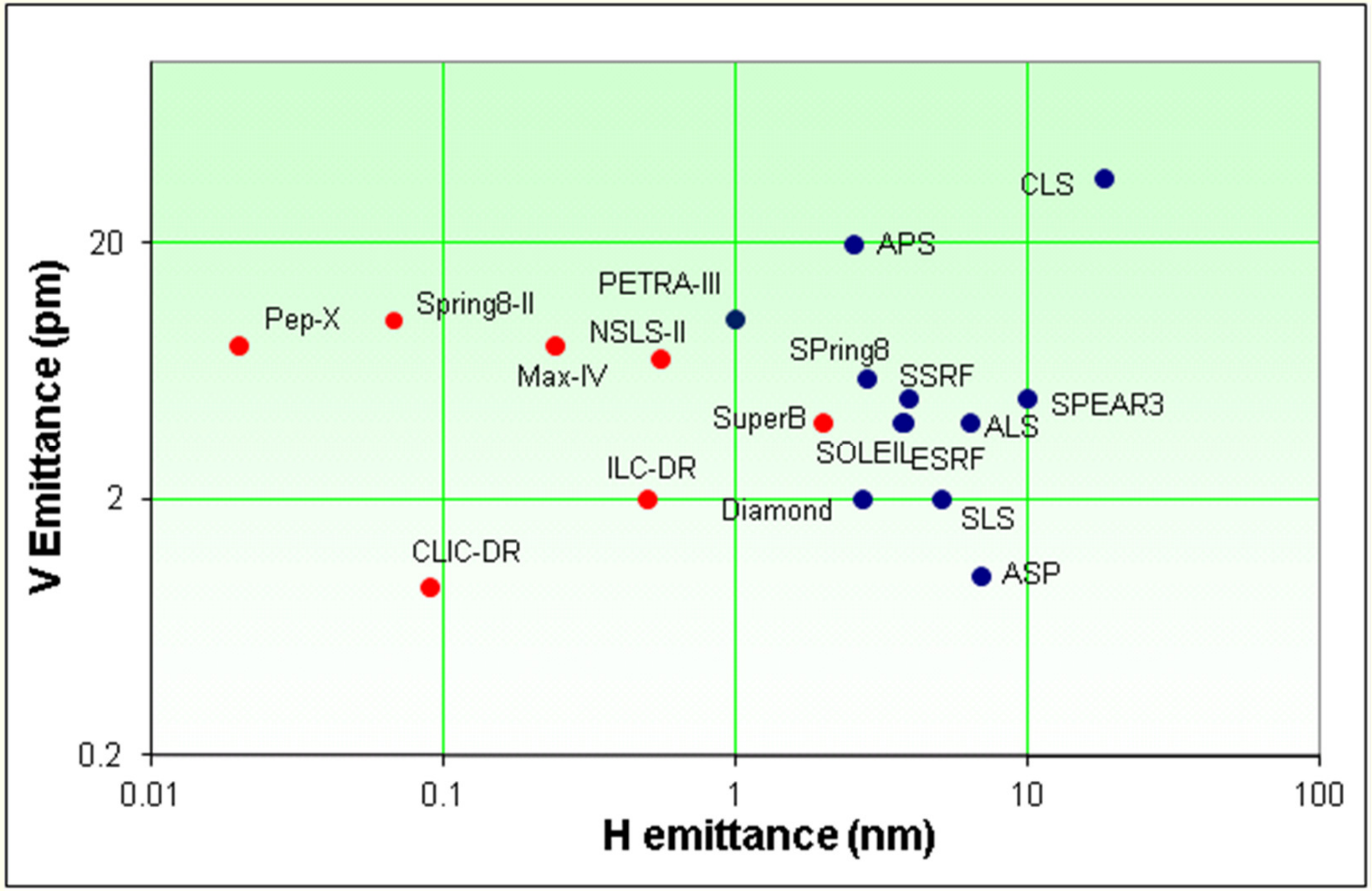
Storage Ring Light Sources



Courtesy of R. Bartolini

SUPERB	HER	LER
Emittance X (nm-rad)	2.00	2.46
Emittance Y (pm-rad)	5.0	6.15
Energy (GeV)	6.7	4.18

Emittance in 3rd GLS, DR and colliders



Courtesy of R. Bartolini

Radiation Damping and Quantum Excitation in IBS-TRACK

• Normalized coordinates are defined by Twiss (B) and Dispersion (H) matrix :

$$\vec{X} = B\,H\,\vec{x}$$

•Synchrotron Radiation is taken into account with the following map:

$$\begin{pmatrix} X_1 \\ X_2 \end{pmatrix} = \lambda_x \begin{pmatrix} X_1 \\ X_2 \end{pmatrix} + \sqrt{\varepsilon_x (1-\lambda_x^{\;2})} \begin{pmatrix} \hat{r}_1 \\ \hat{r}_2 \end{pmatrix}$$

$$\begin{pmatrix} X_5 \\ X_6 \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ 0 & \lambda_z^{\;2} \end{pmatrix} \begin{pmatrix} X_5 \\ X_6 \end{pmatrix} + \begin{pmatrix} 0 \\ \sqrt{\varepsilon_z (1-\lambda_z^{\;4})}\,\hat{r}_5 \end{pmatrix}$$

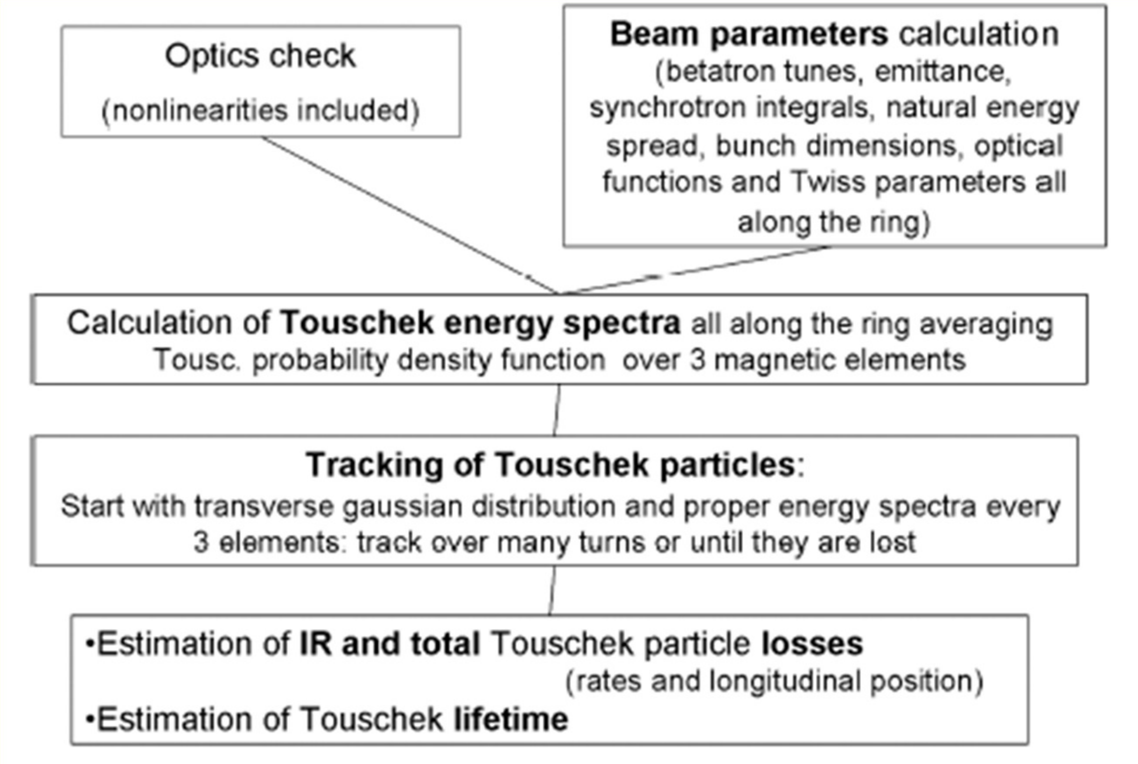
$\lambda_i = \exp(-1/\tau_i)$

$\hat{r}$: unit Gaussian random

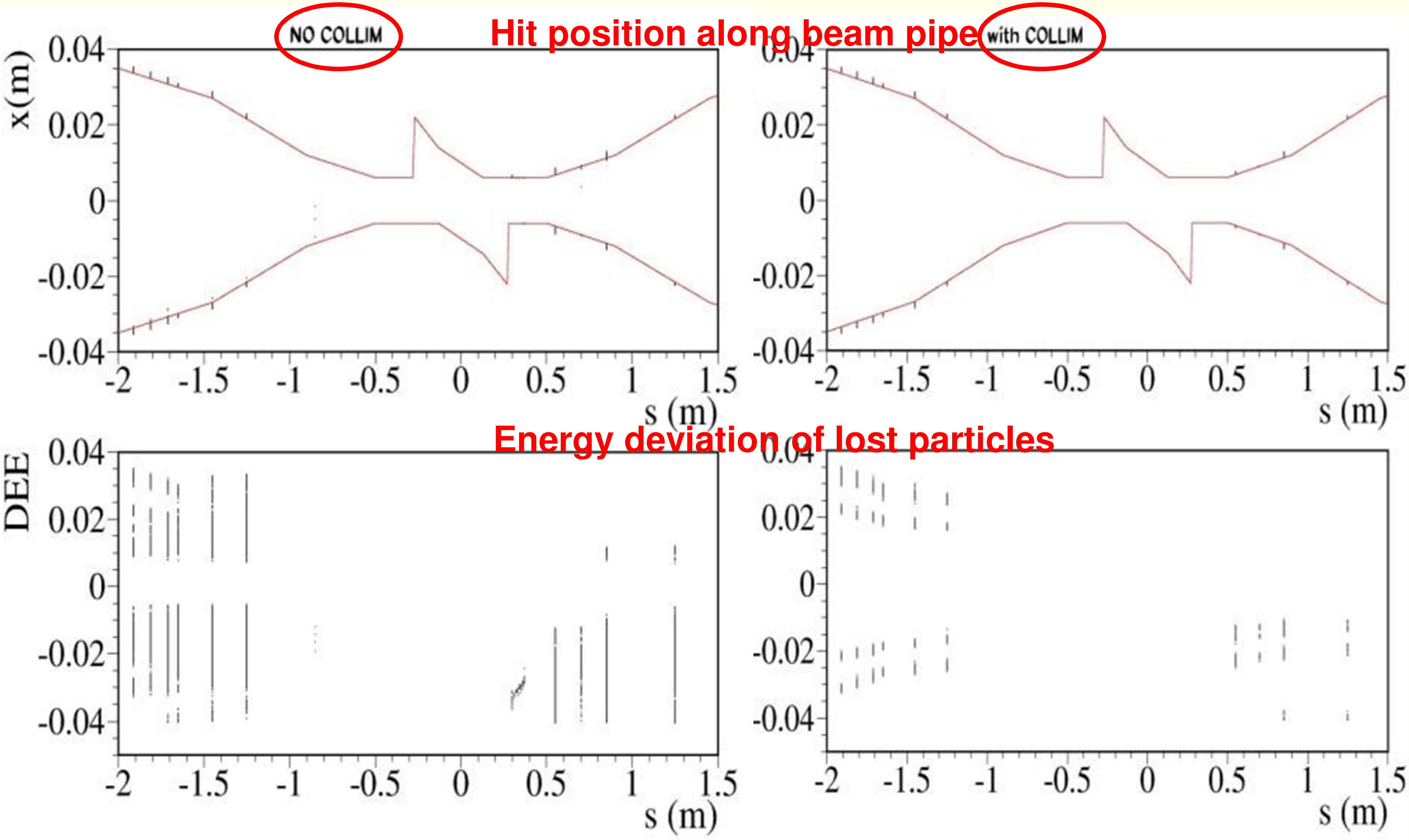
•Switch back to physical coordinates by:

$$\vec{x} = (B\,H)^{-1}\,\vec{X}$$

Flowchart of the Monte Carlo Touschek simulation



IR lost particles of the LER



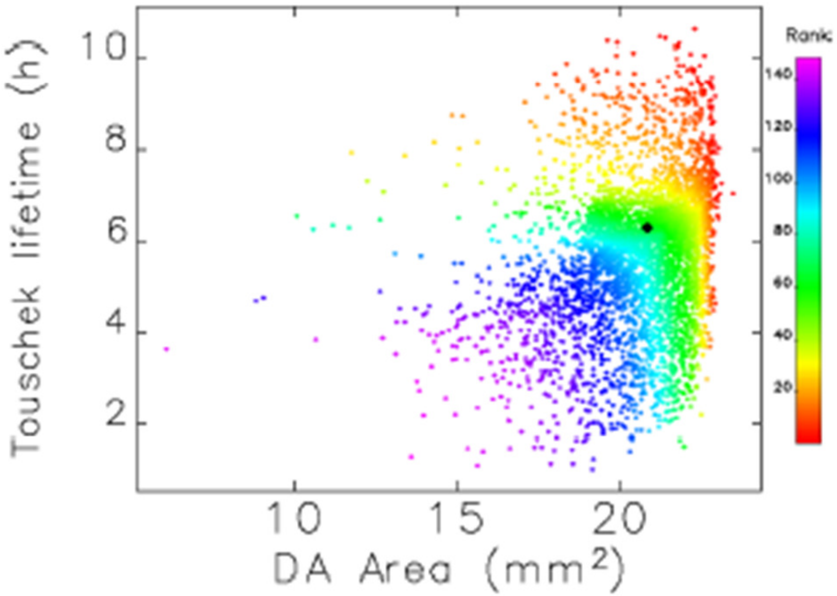
Touschek lifetime
with Monte Carlo tracking code STAR
for LER SuperB

lattice	emittance	collimators	Tau (s)	Tau(min)
v12yuri	No ibs enx=1.9nm	No collim	**447**	**7.4**
v12yuri	With ibs enx=2.46nm	No collim	611	10.2
v12yuri	With ibs enx=2.46nm	With collim	420	7
v16	No ibs enx=1.7nm	No collim	**452**	**7.5**
v16	With ibs enx=2.38nm	No collim	629	10.2

V16 and V12 have comparable Touschek lifetimes

Direct Optimization of Nonlinear Dynamics[1-6]

- Optimize quantities determined by tracking, e.g., dynamic acceptance, momentum acceptance, Touschek lifetime, diffusion rates
  - Made possible by increases in computing power
  - Often used with multi-objective optimizer
- Tune linear lattice as well as sextupoles, octupoles



Example of direct optimization of APS dynamic acceptance and Touschek lifetime

1: H. Shang, PAC 2005, 4230-4232.
2: M. Borland, PAC 2009, 3850-3852; APS LS 319 (2010).
3: C. Steier *et al.*, IPAC2010, 4746-4749.
4: C. Sun *et al.*, PAC 2011, 793-795.
5: L. Yang, PRSTAB 14, 054001 (2011).
6: W. Gao, PRSTAB 14, 094001 (2011).

Touschek scattering in USRs

One may think that the reduction of emittance will lead to reduction of the lifetime.

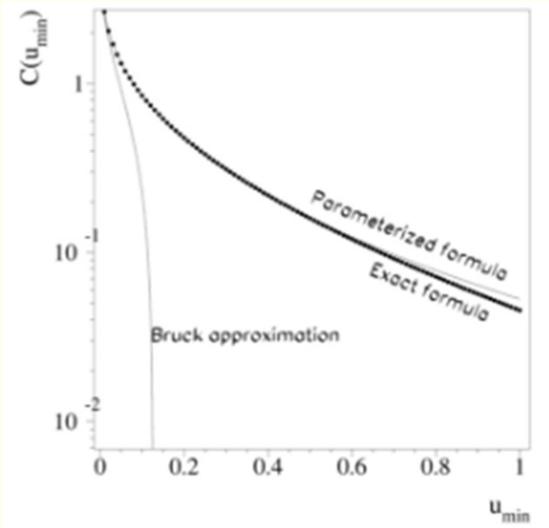
For a fixed energy acceptance, there is a threshold after which reduction of emittance causes exponential increase of the lifetime.

The reason is that, if transverse emittance is smal enough, transverse momentum is insufficient to kick particles outside the momentum acceptance, and Touschek lifetime increases.

USRs look at emittances below this threshold

I plan to extend Touschek simulation to this region, with STAR code. Need to extend the formula, as it is parametrized to work in the DAFNE and SuperB present conditions

$$u_{\min} = \left(\frac{\varepsilon}{\gamma \sigma'_x} \right)^2$$ at most 1



Conclusions

General R&D Items for USRs

All related to single and multiple intra-beam scattering that in this sense result key issues for USRs

- beam dynamics: good knowledge
- round beam
- Compact and strong magnets (sextupoles)
- Higher harmonic RF system to lengthen the beam
- Precise magnet alignment
- Accurate beam position monitors
- Undulator with shorter period

- High energy USRs: running at full coupling sufficient mitigation
- Low energy USRs: harmonic cavities and damping wigglers necessary

Longitudinal beam dynamics will be the key to break the barrier of the ultimate brightness in the storage-ring-based light source.