IBS'07
Intra Beam Scattering Mini Workshop

The Cockcroft Institute, Daresbury, UK. 28th - 29th August 2007

Intra Beam Scattering Mini Workshop

Cockcroft Institute, Daresbury, UK. Tuesday, 28th - Wednesday, 29th August 2007

Programme

Tuesday 28th August 2007

Venue: The Cockcroft Institute, Walton Rooms A & B and G08

(To see the presentations click on the pdf/ppt tabs)

12:00 **Coach picks up from the Holiday Inn and Daresbury Park Hotels**

12:30 - 14:00 **Registration and Buffet lunch**

14:00 - 14:15 **Opening address**
Swapan Chattopadhyay (Director of the Cockcroft Institute)

14:15 - 14:30 **Orientation** ppt»
Hans Braun

14:30 - 15:00 **Review of IBS measurements at ATF** ppt »
Kiyoshi Kubo

15:00 - 15:30 **IBS for ILC damping ring** ppt »
Andy Wolski

15:30 - 16:00 **Coffee break**

16:00 - 16:30 **IBS for CLIC damping ring** pdf »
Maxim Korostelev

16:30 - 17:00 **Quantum effects in IBS** ppt »
Sergey Nikitin

17:00 - 17:30 **Simulation of CTF-II Emittance Growth Measurements Using the String Space Charge Formalism** pdf »
Richard Talman

17:30 - 18:00 **SC damping Wiggler developments** ppt »
Robert Rossmanith

18:15 **Coach to the Daresbury Park Hotel**

19:00 **Workshop dinner**
Daresbury Park Hotel

Wednesday 29th August 2007

Venue: Daresbury Laboratory, Merrison Lecture Theatre and Atrium

08:00 **Coach pick up from the Holiday Inn and Daresbury Park Hotels**
Coffee on arrival

08:30 - 09:00 **Beyond Piwinski & Bjorken-Mtingwa: Theories, Codes and Benchmarking** ppt »
Jie Wei

09:00 - 09:30 **Lattice design for IBS dominated beams** ppt »
Yannis Papaphilippou

09:30 - 10:00 **IBS at Very Low Beam Energies** pdf »
Andreas Adelmann

10:00 - 10:30 **IBS Effects in a Wiggler-Dominated Light Source** pdf »
Boris Podobedov

10:30 - 11:00 **Coffee Break**

11:00 - 11:30 **Beyond Maxwell – Vlasov: Space Time Correlations** pdf »
Gabriele Bassi

11:30 - 12:00 **CESR-TA** ppt »
David Sagan

12:00 - 12:30 **Polarization measurement at VEPP-4M with the help of IBS** ppt »
Sergey Nikitin

12:30 - 13:30 **TBA**

13:30 **Close of workshop and lunch**

Intrabeam scattering in ATF Damping ring - Review of old studies

Kiyoshi Kubo

2007.08.28

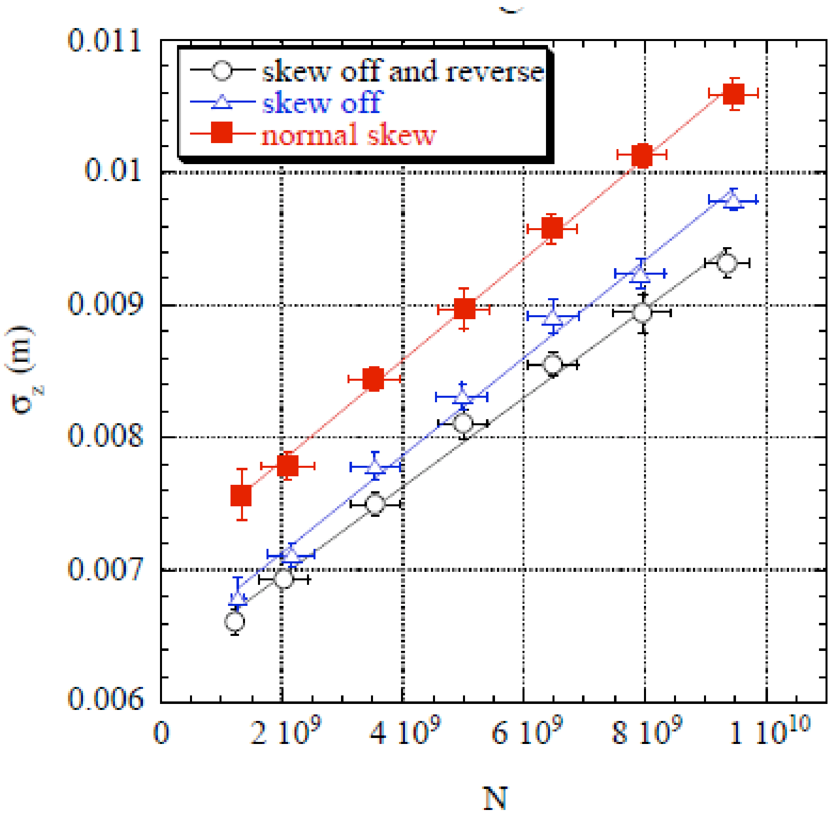
IBS Workshop @ Daresbury

Experiment

- Measured beam parameters
- Momentum spread (extracted beam)
  - Screen monitor at large dispersion in extraction line
- Bunch length (in DR)
  - Streak camera
- Horizontal and vertical emittance (in DR and extracted beam)
  - Laser wire in DR
  - Wire scanners in Extraction line
- As function of
- Bunch intensity
- x-y coupling
  - Normal skew quad correctors (small ε_y →strong IBS)
  - All skew correctors off
  - Half off and half reversed (large ε_y → very weak IBS)
- Results are compared with calculations using SAD

Comparison with Calculation
How to include impedance effect (1)

Bunch length vs. intensity



Strong intensity dependence even for large vertical emittance, where IBS should be very weak.

This came from impedance.

Because Longer bunch length reduces IBS, effect of impedance should be included in calculations

How to include impedance effect(2)

Because SAD is not ready to include impedance, we changed RF cavity voltage for simulating impedance effect.

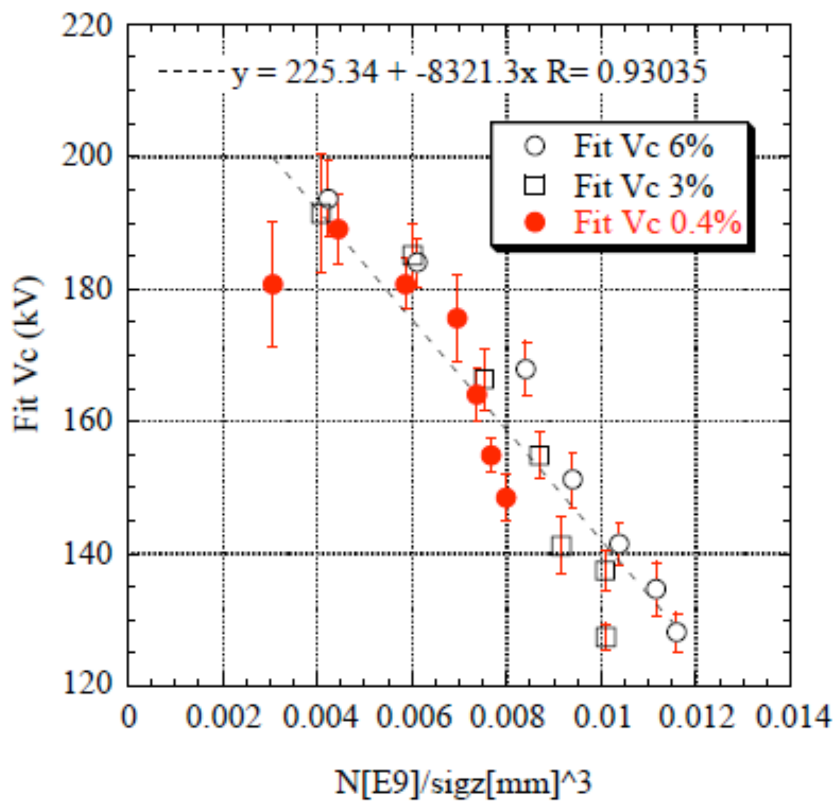
- Assuming pure inductive impedance, the voltage reduction should be a function of

$$N/\sigma_z{}^3$$

- Find Vc with which SAD reproduces experimental data of bunch length.
- Then fit Vc as a function of $N/\sigma_z{}^3$.

How to include impedance effect (3)

Vc with which SAD reproduces experimental data of bunch length vs. N/σ_z^3. *($\varepsilon x/\varepsilon y$ was assumed to be 0.4, 3 and 6%.)*

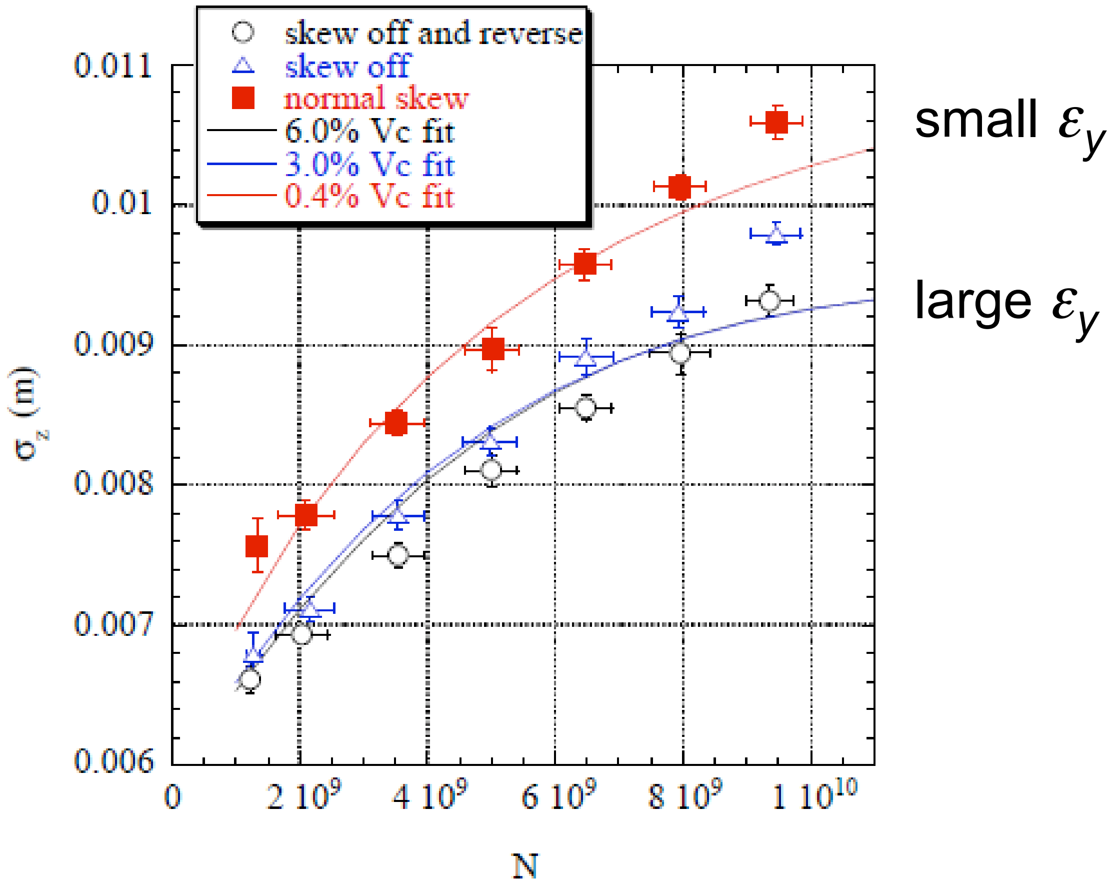


From this plot,

$$Vc[\mathrm{keV}] = 225 - 8321\ N/\sigma_z^3$$

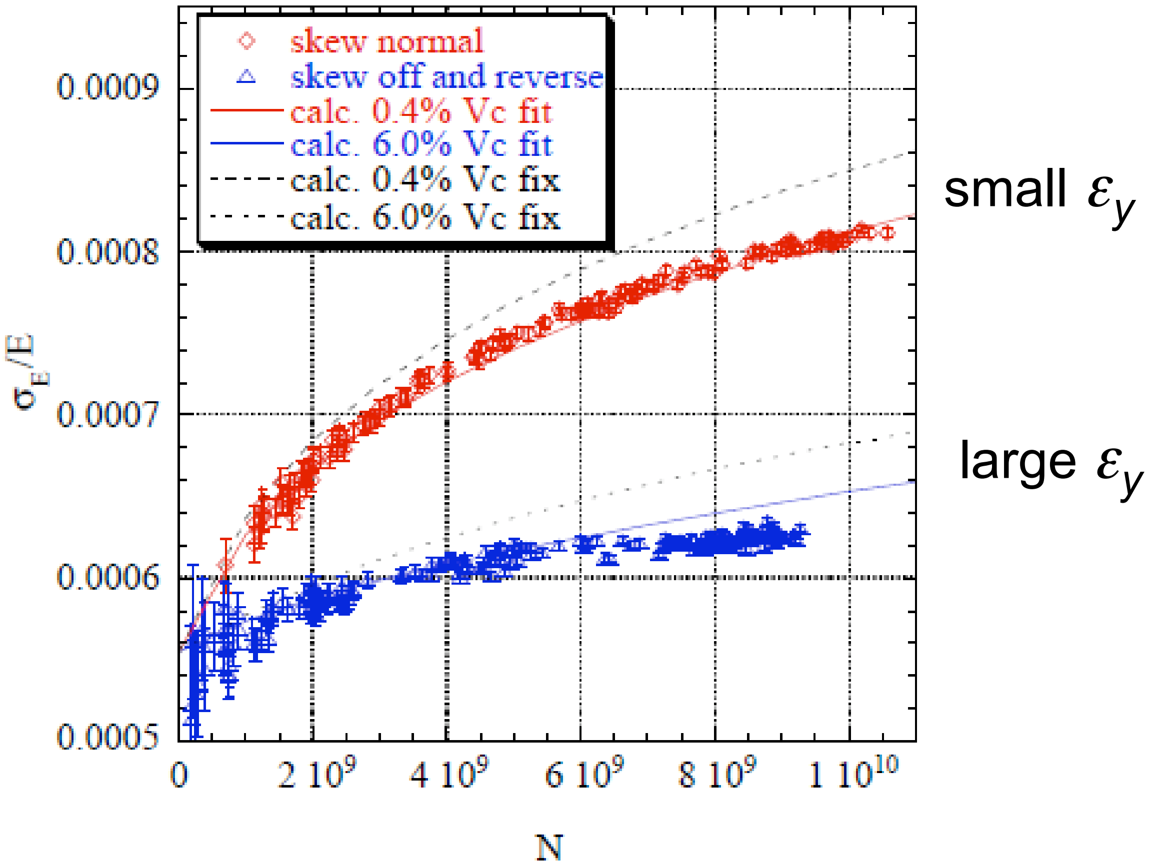
was used for following calculations.

Bunch length vs. intensity



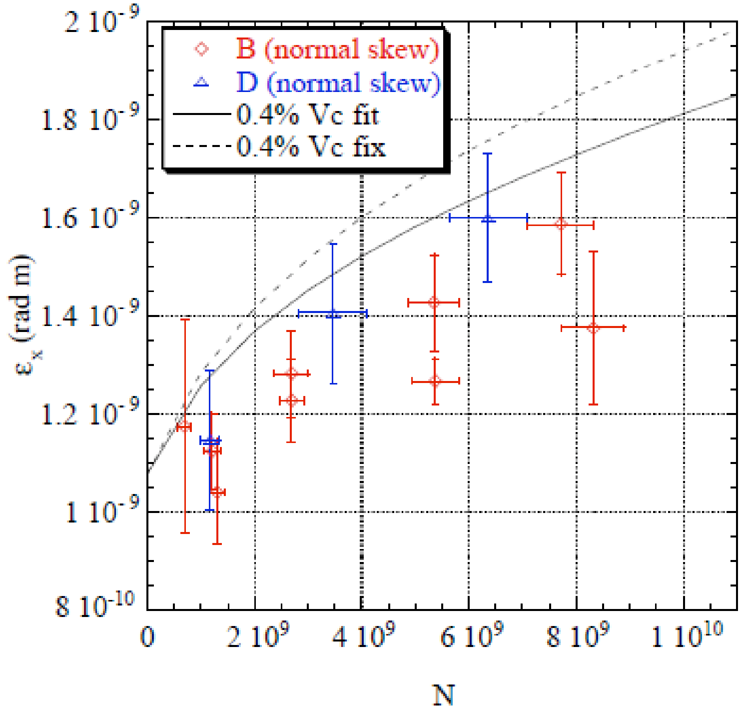
Difference between calculation and measurement may come from non-inductive components of impedance.
Details of impedance model do not significantly affect calculation of momentum spread and transverse emittance.

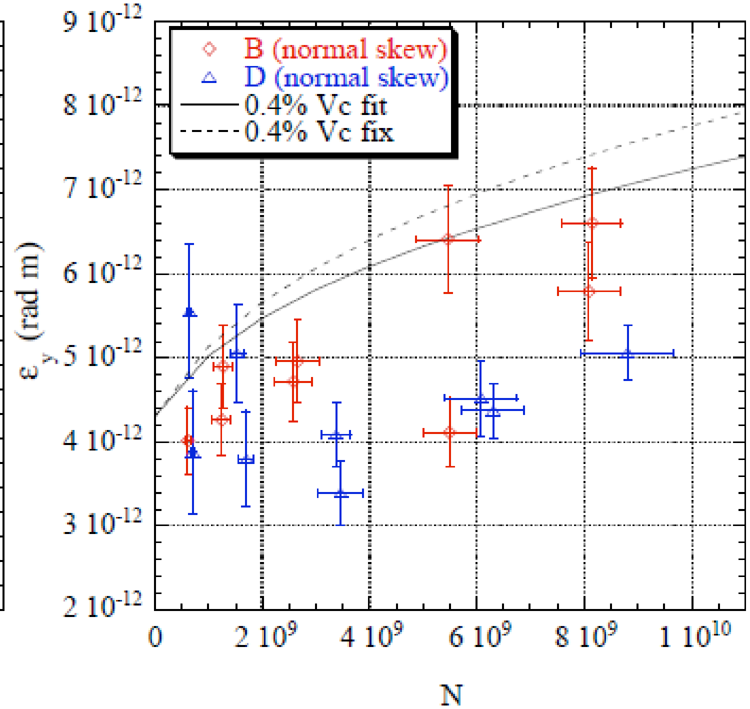
Momentum spread vs. intensity



Calculation with fitted *Vc* (which was fitted to reproduce measured bunch length) agree with measured momentum spread data much better than fixed VC.

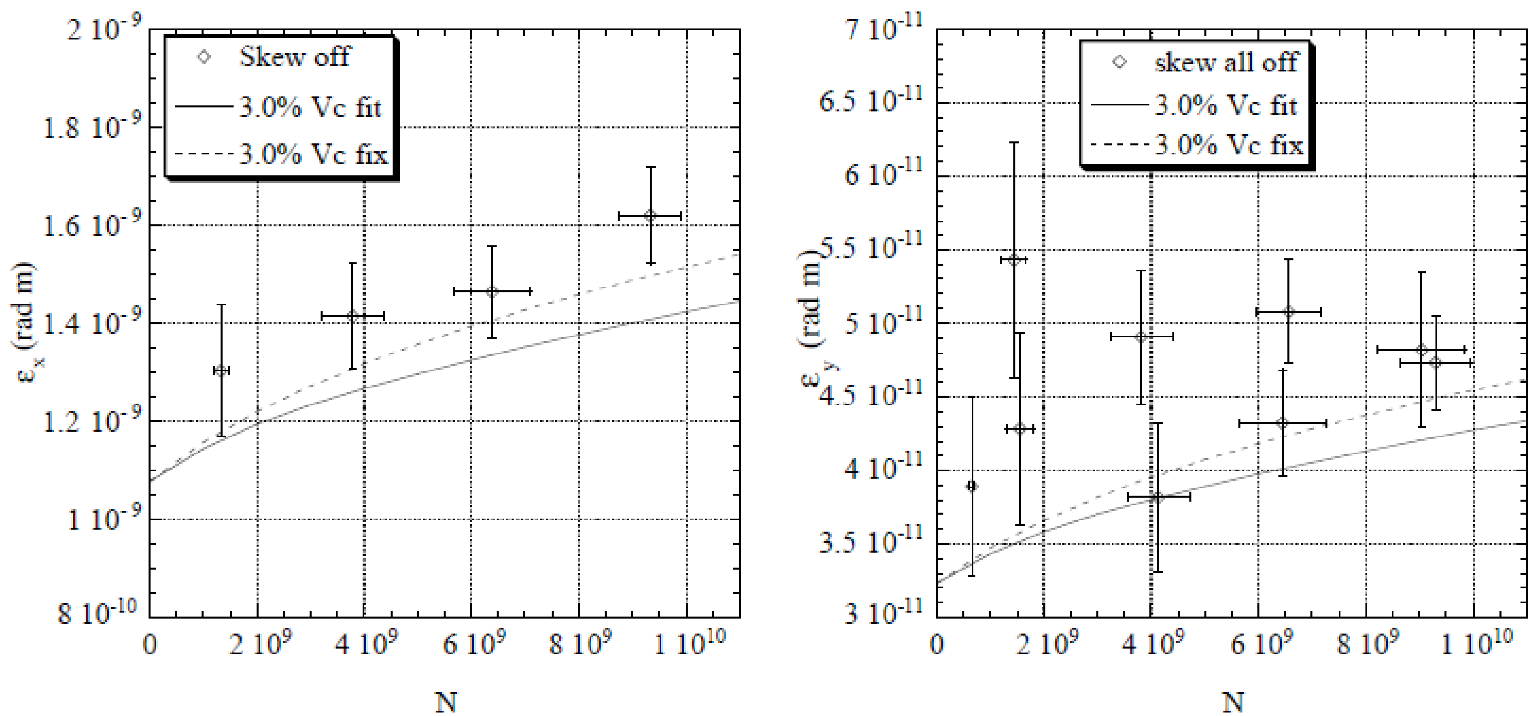
Emittance vs. intensity - normal skew correctors ($\varepsilon_y/\varepsilon_x \sim 0.4\%$)





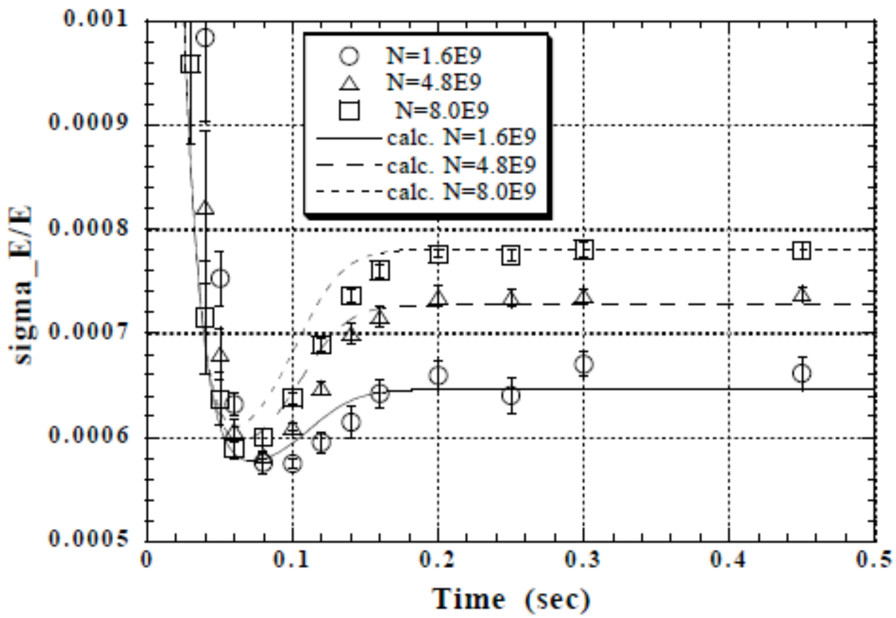
Too large error of measurements to check the model accurately.

Emittance vs. intensity - skew correctors off ($\varepsilon_y/\varepsilon_x \sim 3\%$)



Another observation of clear IBS

Momentum spread vs. time (extraction time after injection.)



Longitudinal damping time ~ 1/2 vertical damping time.

$$\varepsilon_{l,injection}/\varepsilon_{l,equilibrium} << \varepsilon_{y,injection}/\varepsilon_{y,equilibrium}$$

→Vertical emittance is still large when momentum spread reaches equilibrium.

→Further damping of vertical emittance takes time and gradually makes IBS stronger and increases momentum spread.

Issue in Calculations:
"log factor" in SAD (1)

log factor is

$$(\log) \equiv \frac{1}{2}\log\frac{1-\cos\theta_{\max}}{1-\cos\theta_{\min}} = \log\frac{b_{\max}}{b_{\min}}$$

where $\grave{e}_{\max}$ and $\theta_{\min}$ are considered maximum and minimum scattering angle.

Approximately,

$b_{\max}$ is maximum impact parameter.

$b_{\min}$ is minimum impact parameter if $b_{\min} >> \sqrt{2}m\alpha / |p^2|$.

(p is momentum of the particle in CMS.)

Summary

- We observed strong IBS in ATF Damping Ring
- Calculation using SAD is mostly consistent with experimental data.
  - Momentum spread: Agreed well
    - Choice of log factor seems reasonable
  - Bunch length: Hard to use as a model test because it was affected by impedance.
  - Transverse emittance: Not agreed very well.
    - Possibly due to error of measurement.
    - But discrepancy was much smaller than factor 2.

IBS Mini-Workshop

August 2007

Cockcroft Institute, Daresbury, UK

IBS in the ILC Damping Rings

Andy Wolski

University of Liverpool and the Cockcroft Institute

UNIVERSITY OF LIVERPOOL

The Cockcroft Institute
An International Centre for Research in Accelerator Science and Technology

Conclusions

Calculations using two different approximations to the IBS growth rates (Bane's approximation, and the CIMP approximation) are in good agreement with each other, but overestimate the IBS growth when benchmarked against data from the ATF.

For the ILC damping rings, assuming that half the vertical emittance is generated by dispersion and half by betatron coupling, the strongest IBS effects will be observed in the horizontal plane.

For the OCS lattice (closest to the present baseline), the horizontal emittance increases by about 20% at a bunch population of 2×10^{10} particles and an rms bunch length of 6 mm. The vertical emittance growth is approximately 10%.

The present bunch length specification is 9 mm, and operation with bunch population in the range from 1×10^{10} particles to 2×10^{10} particles is envisaged.

IBS should not prevent the specified extracted emittance of 8 um (normalised) being achieved, but some margin should be allowed in the design.

It is probably not desirable to reduce the beam energy in the damping rings below the present specification of 5 GeV.

Open questions

There are more serious effects to worry about, so IBS is not a high priority for the ILC damping rings. Nonetheless, there are some interesting questions to answer, such as:

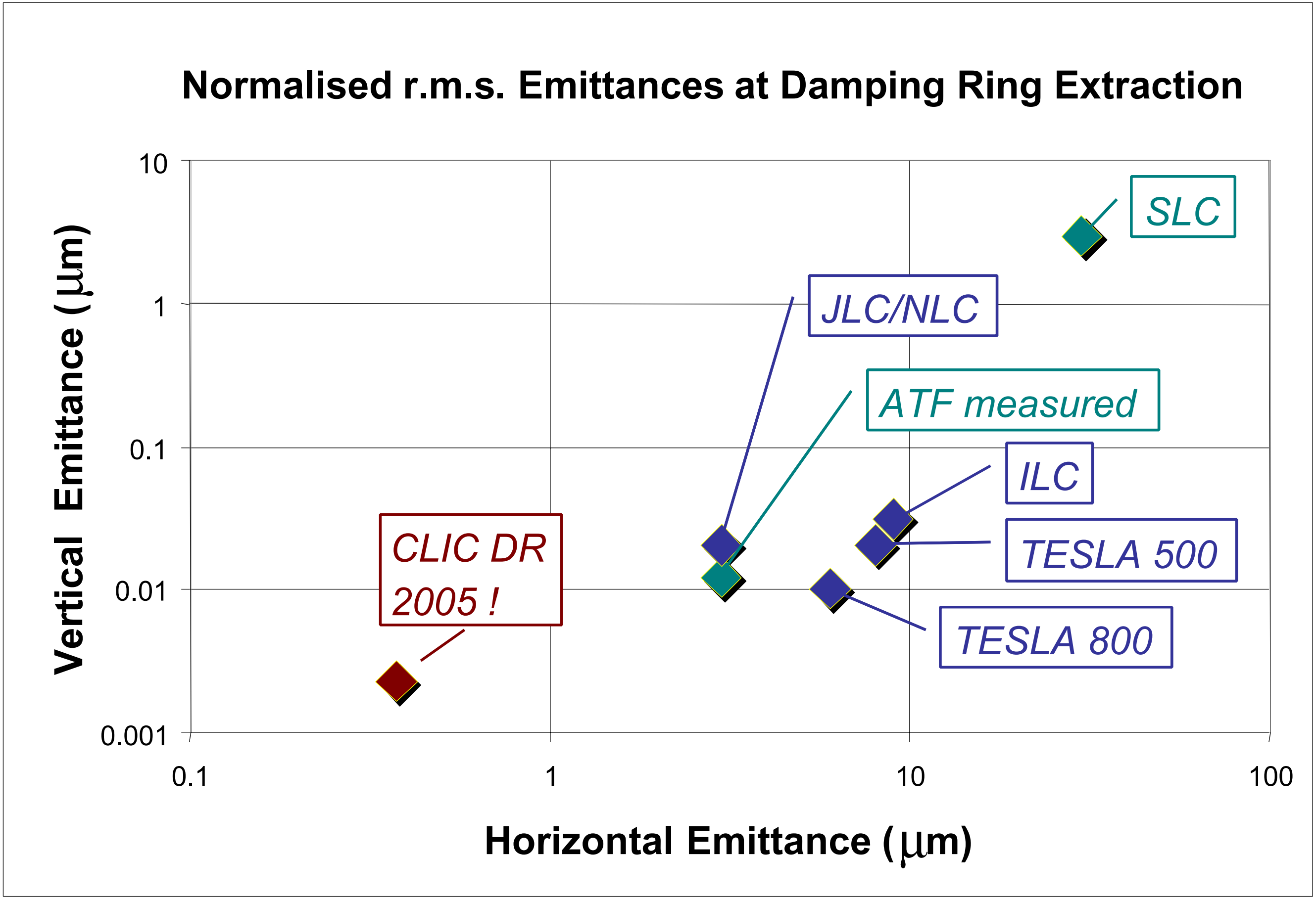
- What is the reason for the discrepancy between our calculations and the ATF data? (Perhaps an inaccurate value for the Coulomb log…)
- What will be the best value of κ to use? We need more input from simulations of low-emittance tuning; and we should probably use a range of values for κ.
- What will be the impact of IBS during the damping process? We have calculated the equilibrium emittances in the presence of IBS, but the beam is extracted before it reaches equilibrium…
- Could IBS affect the beam distribution, perhaps generating tails?

IBS for CLIC damping ring

Frank Zimmermann

Maxim Korostelev

- Motivation and General Introduction
- CLIC Damping Ring Lattice
- Effect of Intra-Beam Scattering
- Non-Linear Optimization of the CLIC Damping Ring Lattice
- Tolerances for Alignment Errors
- Correction of Vertical Dispersion and Betatron Coupling
- Collective Effects in the CLIC Damping Rings
- Summary


Normalised r.m.s. Emittances at Damping Ring Extraction
Vertical Emittance (µm)
Horizontal Emittance (µm)
10
1
0.1
0.01
0.001
0.1
1
10
100
SLC
JLC/NLC
ATF measured
ILC
TESLA 500
TESLA 800
CLIC DR 2005 !

Parameters* of the extracted beam.

Parameter	Symbol	RING 1	RING 2	RING 3	Unit
Bunch population	N_{bp}	2.56	2.56	2.56	$\times 10^9$
Bunches per train	k_{bt}	110	110	110	
Maximum number of bunch trains	N_{trains}^{max}	14	14	12	
Minimum number of bunch trains	N_{trains}^{min}	4	4	4	
Norm. horizontal emittance w/o IBS	$\gamma\epsilon_{x0}$	131	79	95	nm
Norm. horizontal emittance with IBS	$\gamma\epsilon_x$	540	380	430	nm
Norm. vertical emittance with IBS	$\gamma\epsilon_y$	3.4*	2.4*	2.7*	nm
Norm. longitudinal emittance** with IBS	ϵ_t	4990	4985	5000	eVm
RMS bunch length w/o IBS	σ_{s0}	1.21	1.25	1.21	mm
RMS energy spread w/o IBS	$\sigma_{\delta 0}$	0.915	0.113	0.111	%
RMS bunch length with IBS	σ_s	1.65	1.51	1.5	mm
RMS energy spread with IBS	σ_δ	0.125	0.136	0.137	%
Horizontal IBS growth time	T_x	3.89	1.88	2.34	ms
Longitudinal IBS growth time	T_p	5.57	4.403	4.83	ms

* Note that the parameters in this table were computed for the betatron coupling $\epsilon_{y0}/\epsilon_{x0} = 0.0063$ and zero vertical dispersion.

** Note that $\epsilon_t = \gamma\sigma_s\sigma_\delta m_0 c^2$.

Parameter	Symbol	RING 1	RING 2	RING 3	Unit
Energy	E	2.42	2.42	2.42	GeV
Circumference	C	364.96	364.96	300.48	m
Revolution time	T_0	1216.53	1216.53	1001.6	ns
Total length of wigglers	L_w	152	152	96	m
Number of wigglers	N_w	76	76	48	
Length of wiggler	L_{ID}	2	2	2	m
Wiggler peak field	B_w	1.7	2.52	2.52	T
Wiggler period length	λ_w	10	4.5	4.5	cm

Summary

- Complete design of damping ring which reaches CLIC target parameters
- New regime: equilibrium emittance dominated by IBS
- IBS computation scheme was developed
- Nonlinear optimization: reasonable dynamic aperture
- Correction scheme for errors recovers emittance and almost restores dynamic aperture
- Survey of collective effects
- Many other aspects were studied in detail (injection/extraction, nonlinear wiggler field, SR power absorbtion)

QUANTUM LOWER LIMIT ON SCATTERING ANGLE IN THE CALCULATION OF MULTIPLE TOUSCHEK-EFFECT

Sergei Nikitin

BINP Russia

IBS Mini Workshop,
Cockcroft Institute, Daresbury
28-29 August 2007

Questions:

In what conditions a quantum lower limit on scattering angle is important?

If the quantum limit is formally large, can this fact lead to a significant increase of IBS diffusion (beam sizes, energy spread) in comparison with a classical consideration?

Two definitions for a minimal scattering angle
(known from Plasma Physics)

$$\theta_{class} = \frac{2e^2}{\Lambda m V^2}$$

Classical Coulomb interaction

$$\theta_{quant} \approx \frac{\hbar}{\Lambda m V}$$

Consequence of the uncerainty principle

$$\frac{\theta_{class}}{\theta_{quant}} = \frac{2e^2}{\hbar V} < 1$$

Classical definition validity violation: mV^2>50 eV (ep), 40 keV (pp)

Λ

A maximal impact parameter
(Debye radius, a beam size etc.)

❑ Co-Kinetics of the quantum fluctuation (*Q*) and multiple Touschek (*T*) processes

$$u = (\sigma_\gamma/\gamma)^2 = u_Q + u_T$$ the relative energy dispersion

$$v = \mathcal{E}_X = v_Q + v_T$$ the radial phase volume

$$D_u^T = \frac{N r_0^2 c Q_S}{16\pi\gamma^3 R\alpha\sqrt{uv}} \left\langle \frac{\beta_X B(k,\chi_m)}{(\beta_X v + \eta_X^2 u)\sqrt{æ\beta_Y(1+\alpha_X^2)}} \right\rangle$$

$$D_v^T = \frac{N r_0^2 c Q_S}{16\pi\gamma^3 R\alpha\sqrt{uv}} \left\langle \frac{\beta_X B(k,\chi_m)\mathcal{H}}{(\beta_X v + \eta_X^2 u)\sqrt{æ\beta_Y(1+\alpha_X^2)}} \right\rangle$$

Touschek Diffusion coefficients

$$æ = \mathcal{E}_Y/\mathcal{E}_X$$

$$B(k,\chi_m^c) = \sqrt{\pi}k\int_{\chi_m^c}^{\infty}\sqrt{\frac{1}{\chi}}\cdot\ln\left(\frac{\chi}{\chi_m^c}\right)\cdot S(\chi,k)d\chi$$ the classical lower limit

$$B(k,\chi_m^q) = \frac{1}{2}\sqrt{\pi}k\int_{\chi_m^q}^{\infty}\sqrt{\frac{1}{\chi}}\cdot\ln\left(\frac{\chi}{\chi_m^q}\right)\cdot S(\chi,k)d\chi$$ the quantum lower limit

$$u = u_Q + \frac{\tau_E}{2}D_u^T$$

$$v = v_Q + \frac{\tau_X}{2}D_v^T$$

the system of equations to determine the equilibrium values of ***u*** and ***v***

Conclusions

- Formally, a quantum lower limit on scattering angle must be included in consideration of the IBS processes.
  But …
- CLIC and VEPP-4M Touschek calculation examples show that an account of the quantum limit of minimal scattering angle instead of the classical one does not change notably the numerical results.
- This conclusion seems to be true for all existing and designed storage rings since an apparent difference between results of classical and quantum approximation may be only in the non-realistic case of super-dense/super-thin beams.

www.lepp.cornell.edu/public/CBN/2007/CBN 07-11
August, 2007

Emittance Growth Due to Space Charge Forces in an Electron Bunch Compressor

Richard Talman, Cornell Laboratory of
Elementary-Particle Physics
and
Nikolay Malitsky, Brookhaven National Laboratory

EMITTANCE GROWTH DUE TO SPACE CHARGE FORCES IN AN AN ELECTRON BUNCH COMPRESSOR

R. Talman, Daresbury, August 28, 2007

1. Review CTF−II Experiments
2. Puzzling features
   - dependence on bunch dimensions (to be stressed here)
   - CSR shielding, or lack thereof (will not be discussed)
3. Formulation of bunch evolution as intrabeam scattering (IBS) using the UAL string space charge formalism
4. Simulation of CTF−II results:
   - dependence of mean energy loss, energy spread, bunch length and emittances $\gamma\epsilon_x$ and $\gamma\epsilon_y$
   - on bunch charge, chicane settting R_{56}, distance along line, and bunch width (i.e. on β_x)
5. "Standard Chicane" (high energy) simulation
   - Nominal, round beam; $\gamma\epsilon_x$= 1.0mm.mr, $\gamma\epsilon_y$= 1.0mm.mr
   - Ribbon (practical) beam; $\gamma\epsilon_x$= 1.0mm.mr, $\gamma\epsilon_y$= 0.01mm.mr
6. Conclusions
7. Computational practicalities

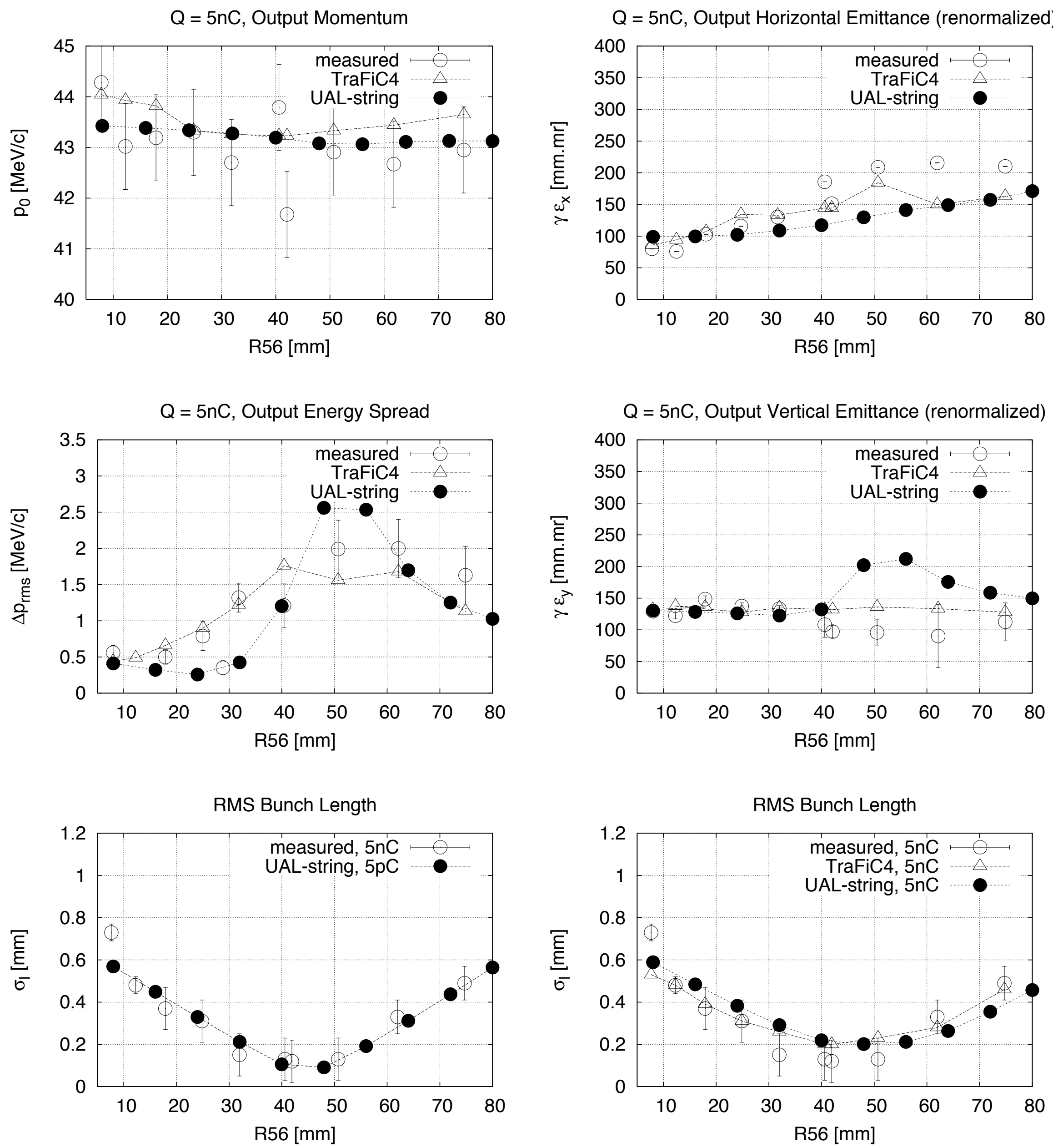


FIGURE 4. $Q = 5\,\mathrm{nC}$ output momentum, energy spread bunch length and emittances. The conversion from "raw" to "renormalized" is discussed in the text. In the bottom graphs the simulations predict a bunch length dependence on bunch charge Q near the minimum. The deviations visible in these graphs suggest that the system parameters (fit empirically without accounting for this dependence) may not be quite right. Is it possible the experimenters *tuned* to minimize the bunch length at the minimum at $Q = 5\,\mathrm{nC}$ rather than at $Q = 0$?

CONCLUSIONS

1. CTF−II, 40 MeV, simulation results agree quite well with experiment
   - CSR, though important, is not yet dominant
   - modest (fractional) growth of transverse emittance in most cases
   - less than fully−relativistic effects, Coulomb, Biot−Savart, and CSCF can account for
     - shrinkage/growth of vertical emittance
     - substantial growth of horizontal emittance as beam width is reduced

2. "Standard Chicane", 5 GeV, fair agreement among various simulations
   - CSR dominates
   - No growth of vertical emittance
   - Little (fractional) growth of horizontal emittance even with ribbon beam.

3. Treatment of bunch evolution as IBS using UAL string formulation is
   - computationally quick for short beam lines
   - subject to spurious "halo" generation, which can be suppressed by 1/N −> 0 extrapolation (and/or increased compute time)
   - in any case the halo would have little effect on luminosity/brillianc
   - bunch granularity would lead to true emittance growth
   - Touschek effect halo cannot be simulated (except using Piwinski formulas) but it is neglible in chicanes (though obviously not in rings, for short intense bunches)

SUPERCONDUCTIVE DAMPING WIGGLER DEVELOPMENT

Robert Rossmanith

for

A. Bernhard[2], S. Casalbuoni[1], A. Grau[1], M. Hagelstein[1], M. Kläser[3], B . Kostka[4]. E. Mashkina[4], A. S. Müller[1,2], R. Rossmanith[1], Th. Schneider[3], E. Steffens[4], D. Wollmann[2], T. Baumbach[1,2]
H. H. Braun[5], F. Zimmermann[5]

[1] Inst. for Synchrotron Radiation (ANKA), Research Center Karlsruhe
[2] Lab. For Appl. of Synchrotron Radiation, Univ. Karlsruhe
[3] Inst. f. Technical Physics, Research Center Karlsruhe
[4] Univ. Erlangen-Nürnberg
[5]CERN

Numerous contributions from many colleagues and institutions

Starting point: emittance vs. wiggler period and field

MOPLS134 Proceedings of EPAC 2006, Edinburgh, Scotland

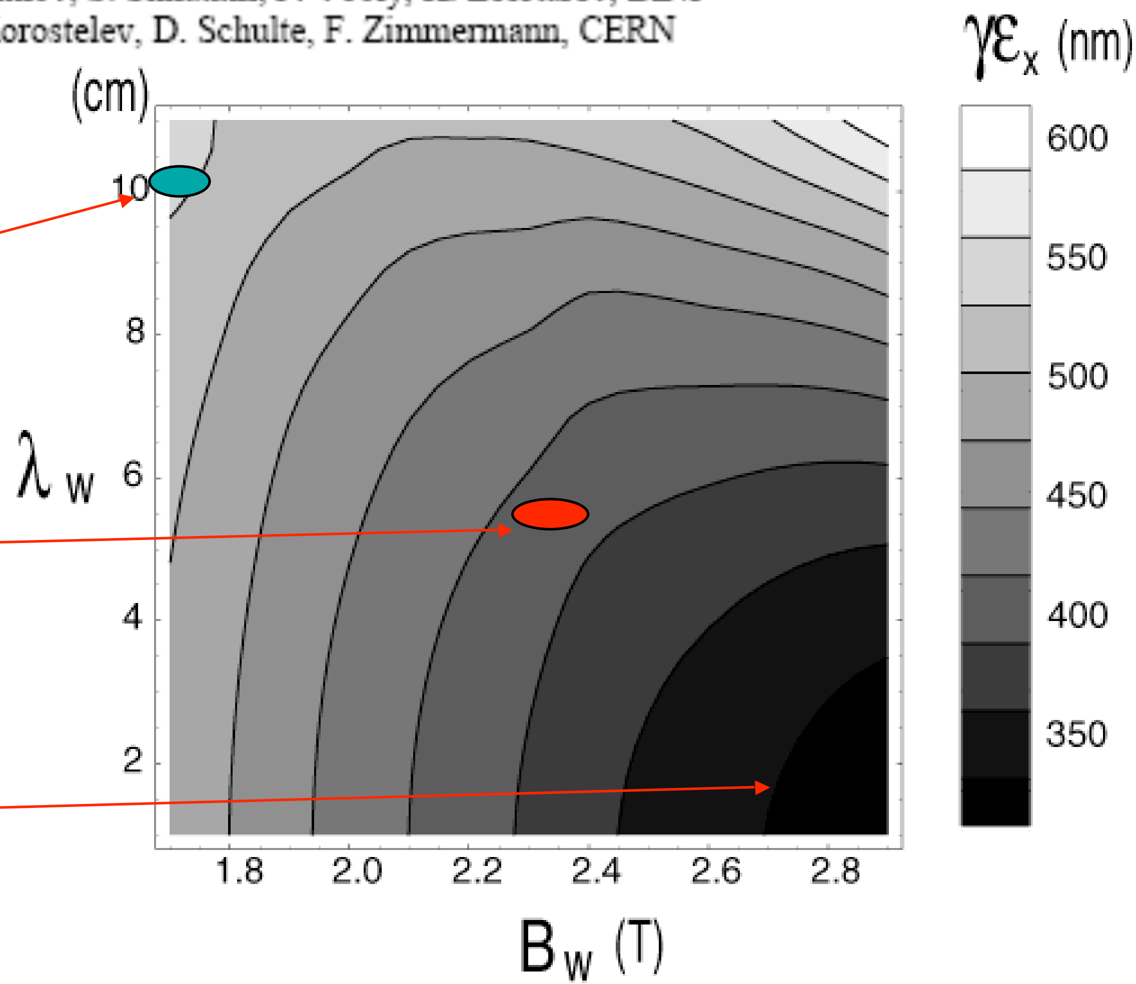
MINIMIZING EMITTANCE FOR THE CLIC DAMPING RING

E. Levitchev, P. Piminov, S. Siniatkin, P. Vobly, K. Zolotarev, BINP
H.H. Braun, M. Korostelev, D. Schulte, F. Zimmermann, CERN

Permanent magnet wiggler

Sc wiggler from BINP

Why not here?

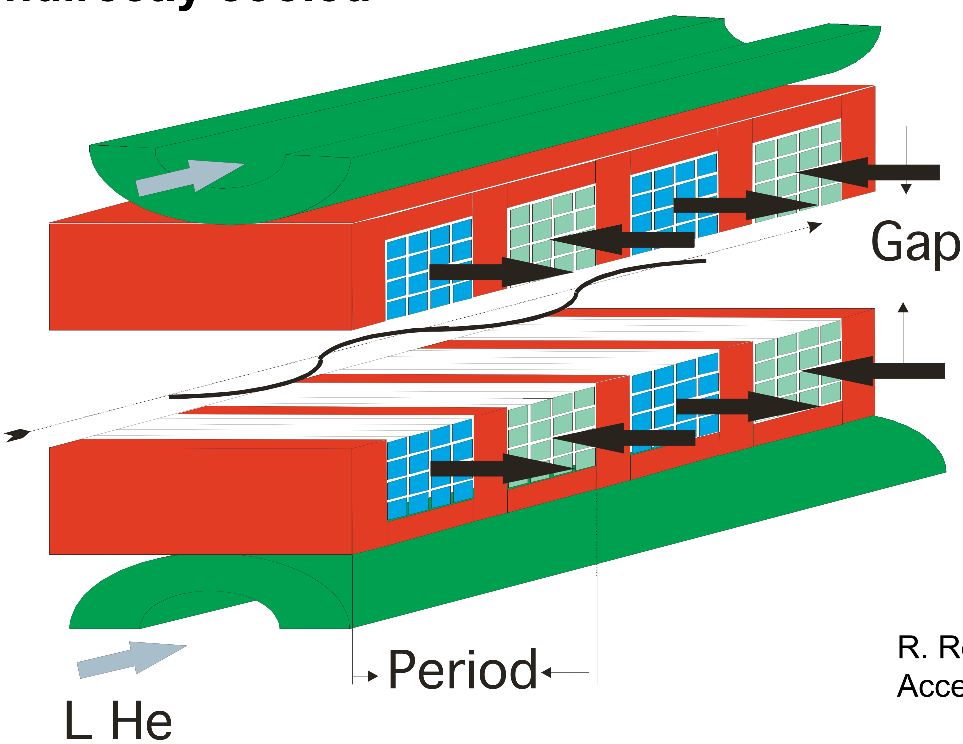


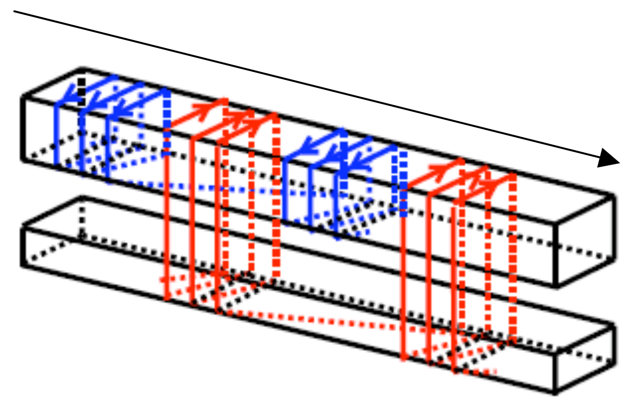
Summary: superconductive wigglers are better for damping rings

But consequences

A.) Wires as close as possible to the beam:

indirectly cooled





R. Rossmanith, H. O. Moser, Proc. European Particle Accelerator Conference 2000, Vienna, Austria

Nowadays established technology: ANKA, Argonne, Berkeley, MAXLAB, ACCEL Instr., Taiwan… (everybody slightly different)

ndirect cooling: no soldered joints ⟹ one wire

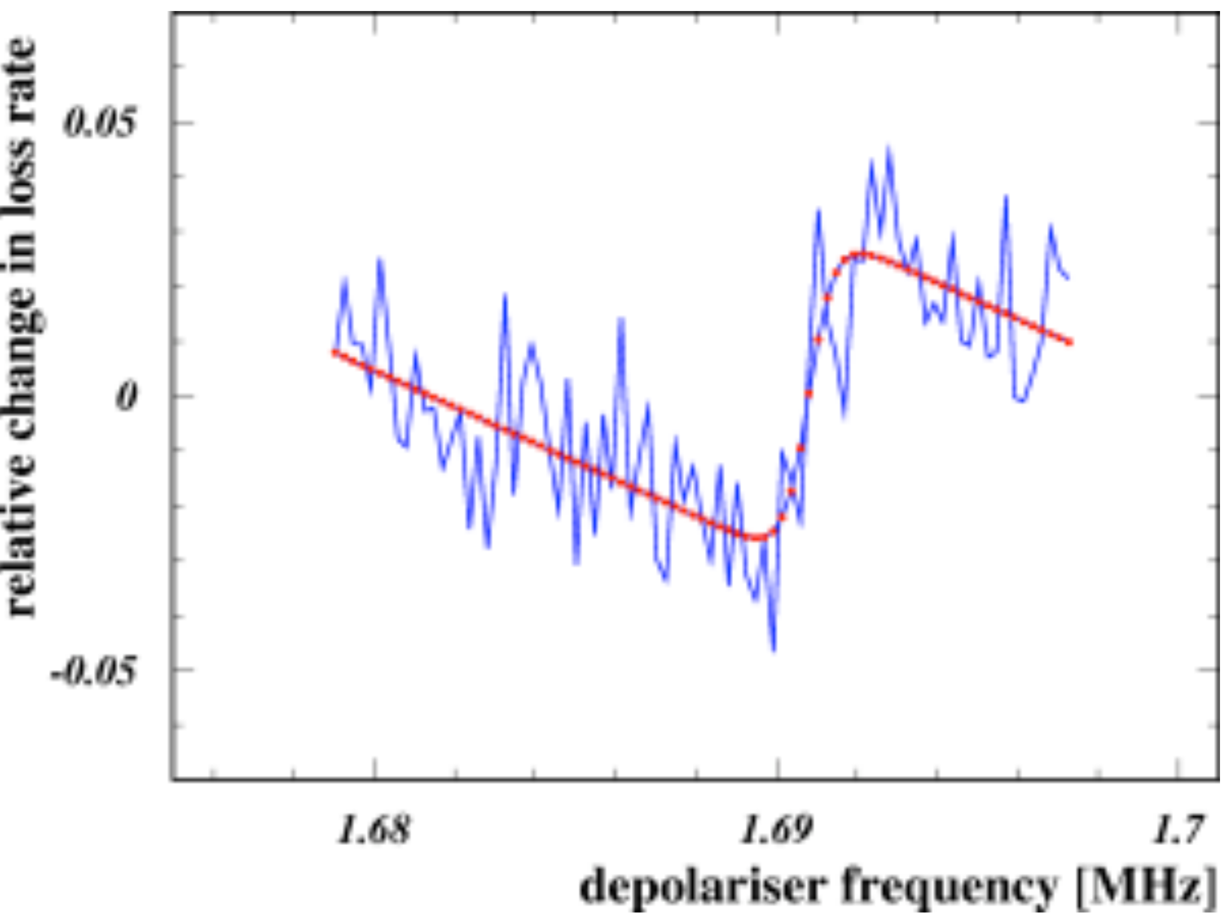
Summary

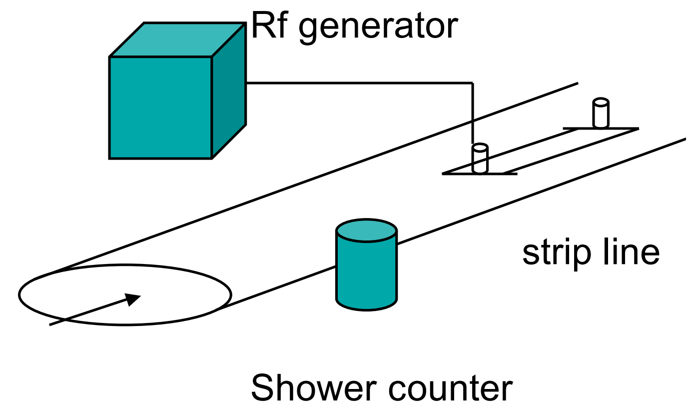
a.) sc wigglers with short period and high field ideal for damping rings

b.) ANKA can build together with an industrial partner a test device and

c.) test it with beam in ANKA

At ANKA exists simple polarimeter based on Touschek effect





Polarization time: ca 8 mi

Plans to convert this simp
device into a permanent
absolute energy monitor

Courtesy: Anke-Susanne Müller, ANKA

Beyond Piwinski & Bjorken-Mtingwa: IBS theories, codes, and benchmarking

Jie Wei

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Institute of High Energy Physics, China (weijie@ihep.ac.cn)

Mini Workshop IBS07

August 28 - 29, 2007

BROOKHAVEN NATIONAL LABORATORY

中国科学院高能物理研究所
Institute of High Energy Physics
Chinese Academy of Sciences

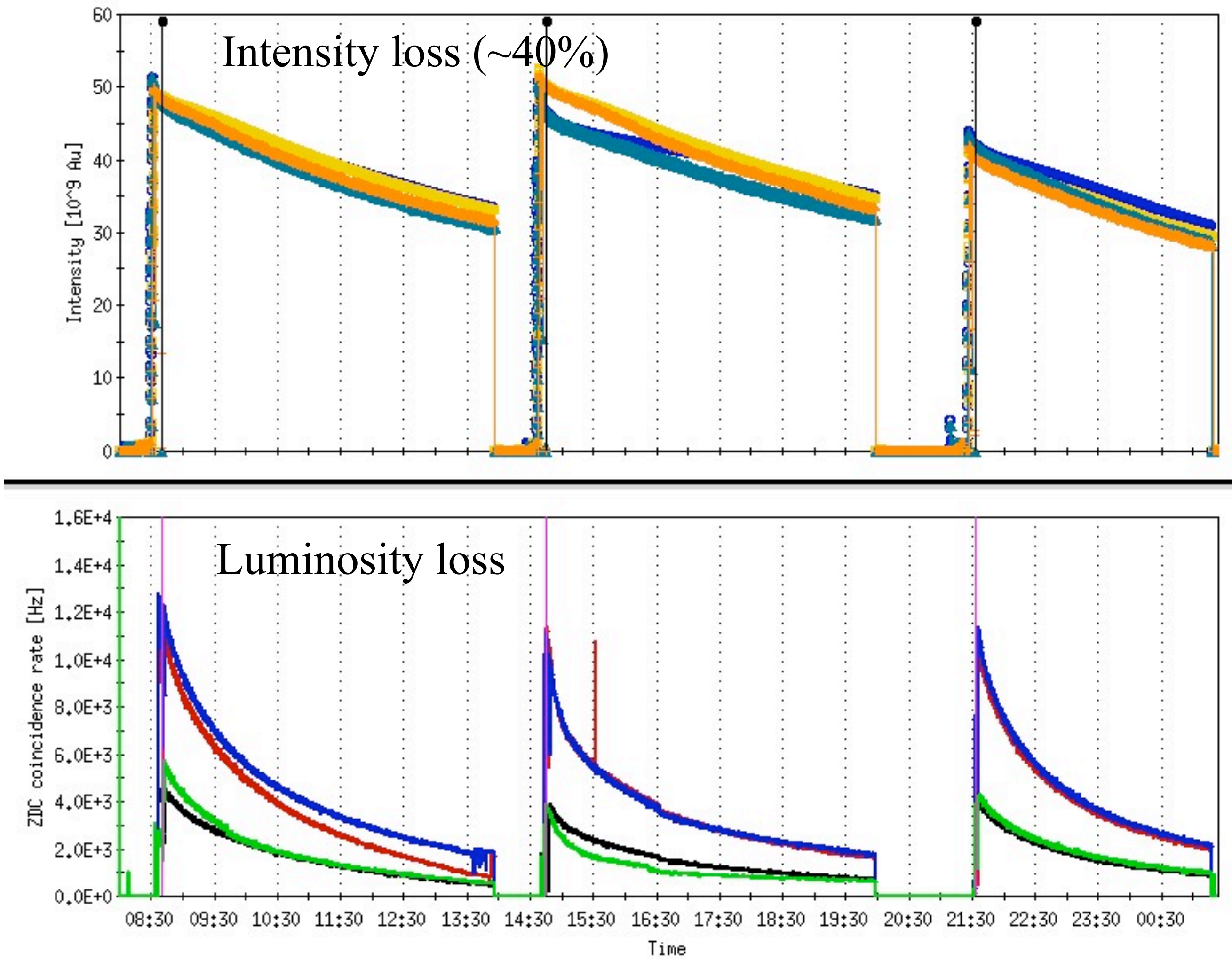
IBS theories (samples)

- Gaussian beam rms growth rates calculation
  - A. Piwinski (1974); J.D. Bjorken/S.K. Mtingwa (1983); M. Martini (1984) – growth rates formulae & integral for general lattices
  - G. Parzen (1987); J. Wei (1993) – scaling laws & asymptotic rules
  - A. Fedotov, J. Wei (2004) – quantitative comparison between models
- Bi-Gaussian beam: beam spread with dense core under cooling
  - G. Parzen (2004) – estimate of IBS growth for e-cooled beam
- Beam profile evolution: beam loss and beam shape study
  - J. Wei, A.G. Ruggiero (1990) Fokker-Planck approach
  - Used in RHIC design to predict beam de-bunching loss
- Particle-by-particle molecular-dynamics simulation
  - J. Wei, X.P. Li, A.M. Sessler (1993) – crystalline beam formation and heating due to Coulomb interactions

IBS examples: beyond Piwinski & Bj-M

- Limited phase space, significant beam loss
  - Relativistic Heavy Ion Collider (RHIC), overwhelming IBS effects due to high charge state of ions: Z^4/A^2 scaling
  - 10-hour store of gold beam
    - » Emittance grows by more than a factor of 4
    - » Beam loss of about 40% escaping RF bucket (de-bunching)
    - » Luminosity decrease by a factor of 10 from start to end
- Low temperature, high particle density "crystalline" state
  - Usually IBS heating rate increases as the 6-D bunch emittance reduces
  - What happens when the emittances are so small that the beam starts to "crystallize"?

Au-Au luminosity limit: intra-beam scattering



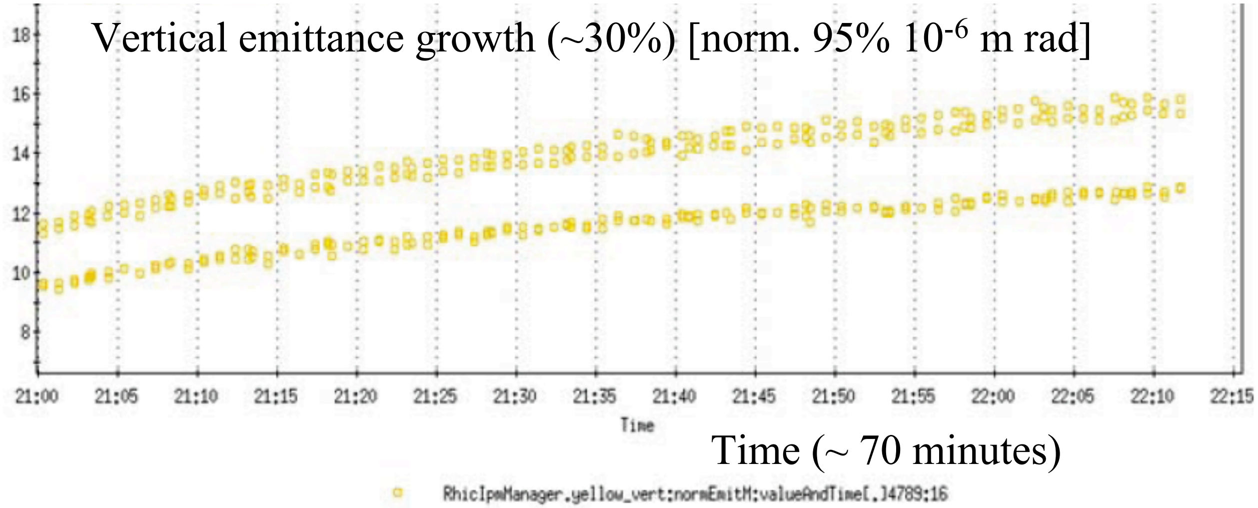
Time (~5 hour per fill)

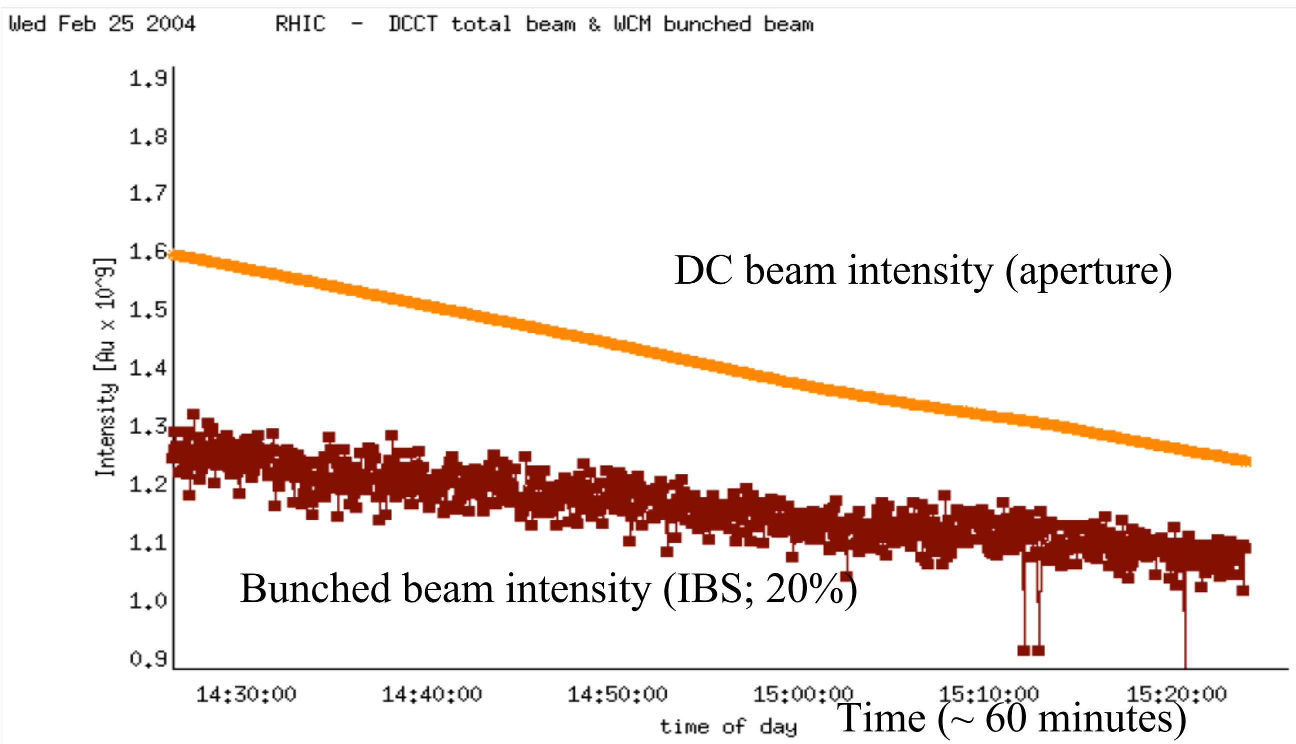
- Luminosity loss – frequent refill
  - Transverse emittance growth
  - Longitudinal growth & beam loss due to RF voltage limitation
- De-bunching & physics background – beam gap cleaning

中國科學院高能物理研究所 Institute of High Energy Physics Chinese Academy of Sciences

BROOKHAVEN NATIONAL LABORATORY

IBS beam experiment diagnostics





- Transverse
  - Ionization profile monitor
  - Simultaneous measurement of emittance on different bunches
  - Constant improvements over electron-cloud interference
- Longitudinal
  - Wall current monitor
  - Measurement of intensity & profile

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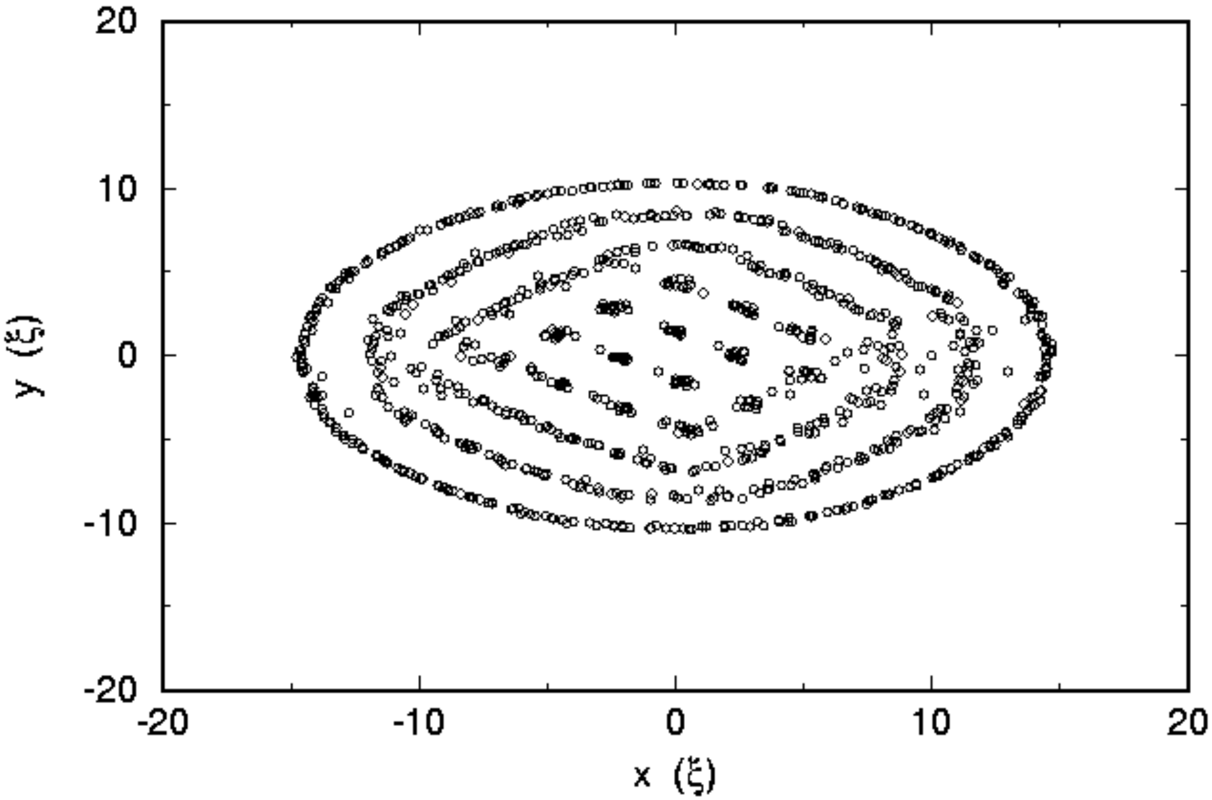
Multi-layer beam simulated in actual ring



- Characteristic distance:

$$\xi = \left(\frac{r_0 \rho^2}{\beta^2 \gamma^2} \right)^{1/3}$$

  - (1 -- 100 μm)

- Typical (lab frame) inter-particle distance:

$$\Delta = 1.6 \xi \gamma^{-1} \nu_{eff}^{-2/3}$$

$$\nu_{eff}^2 = \min\left(\nu_y^2, \nu_x^2 - \gamma^2\right)$$

- Highest density:

$$\lambda_{ave} = \frac{\beta^2 \gamma^3 \nu_{ave}^2}{2 r_0 \rho^2}$$

Closed orbit + phonon modes

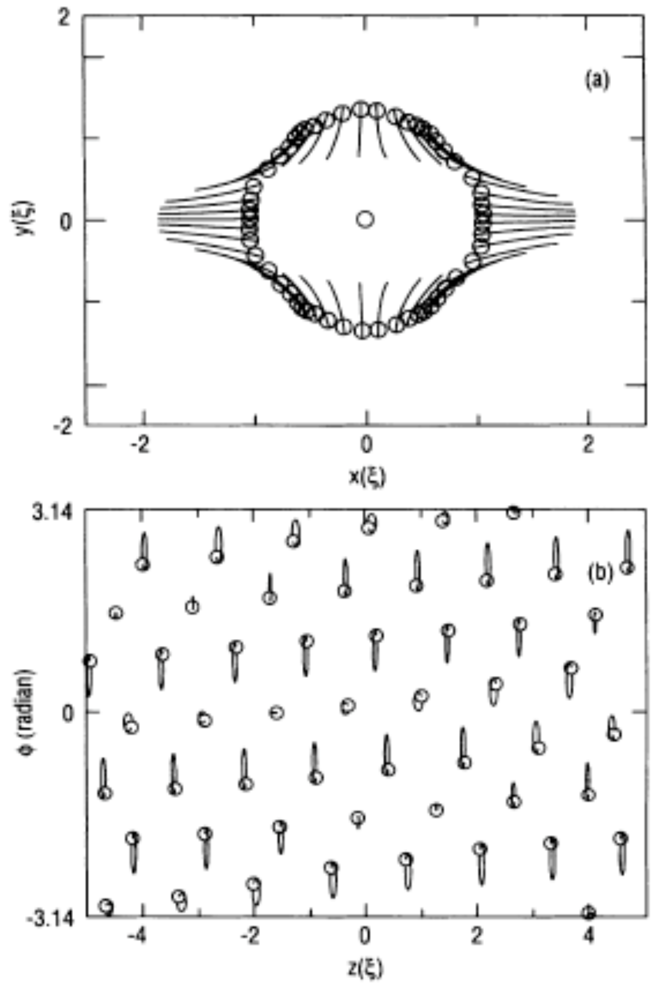


FIG. 1. A 3D structure with particle positions projected (a) into the x-y plane and (b) into the ϕ-z plane, where ϕ is the polar angle. The lattice is a FODO lattice with constant bending with $\nu_x = 2.7$ and $\nu_y = 2.3$, and the particle energy is $\gamma = 1.4$. The total number of particles is 60, and the MD period length is 10ξ. The particles move periodically in time, with the solid lines showing their trajectories and the circles indicating their position at the start and end of the each lattice period.

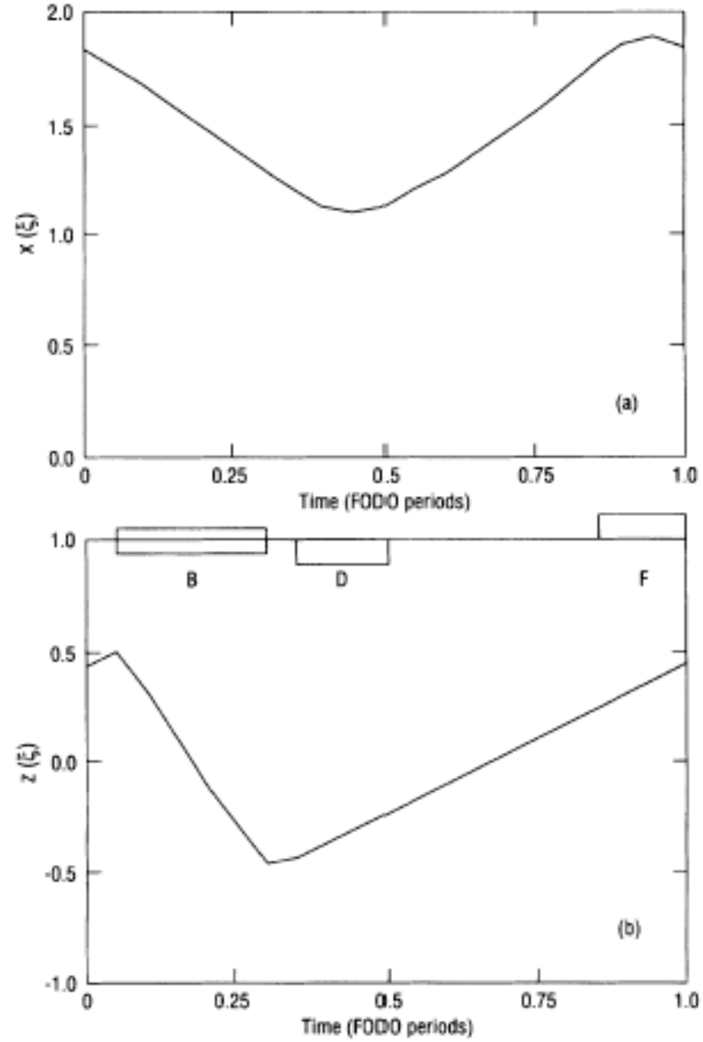
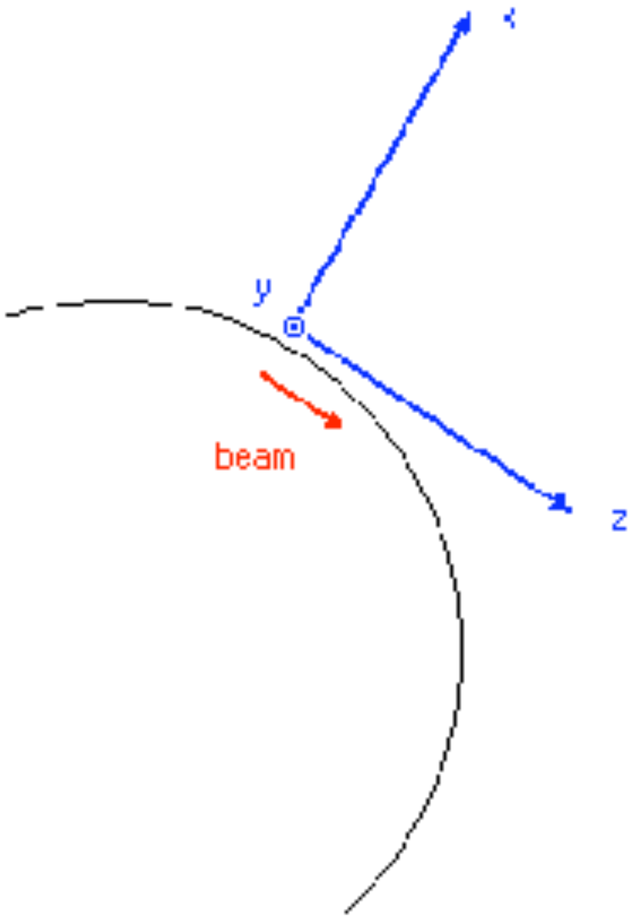


FIG. 2. The effect of shear. In this study $N = 40$, $L = 40\xi$. The cell of one of the particles with largest horizontal displacement (and no vertical displacement) is shown. Motion occurs both (a) in the x direction (breathing) and (b) in the z direction (shear). Lattice components in one of the 10 periods are displayed on the figure: B is a bend section; F is a focusing section; and D is a deforming section.

Molecular dynamics approaches



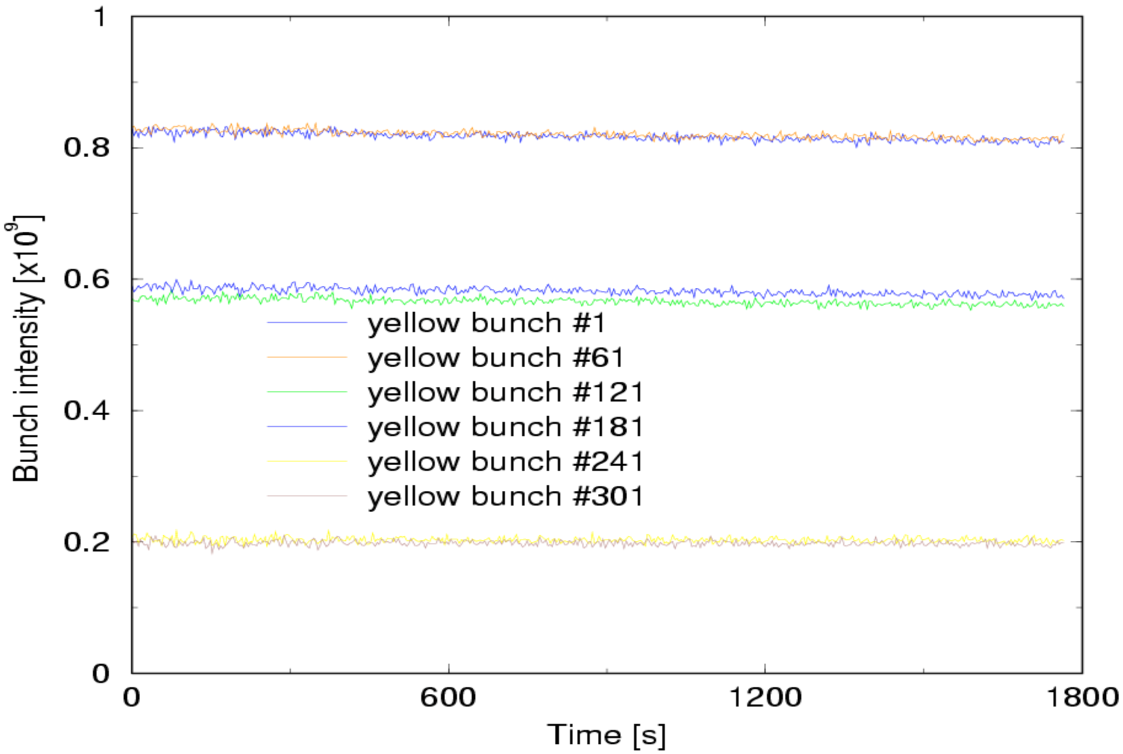
- Use beam rest frame:
  - Non-relativistic motion of particles
  - Easy to adopt the molecular dynamics methods
  - Crystallization: zero temperature
- Derivation of equations of motion:
  - Use general relativity formalism -- EOM in tensor forms
  - Find the coordinate system transformation
  - Transform the EOM from lab frame to the beam rest frame
- Use Molecular Dynamics methods

•J. Wei, "General relativity derivation of beam rest-frame Hamiltonian", Proc. Particle Accelerator Conference, Chicago, 1678-1680 (2001)

•J. Wei, X.-P. Li, A.M. Sessler, BNL Report 52381 (1993); PAC'93, 3527 (1993)

Dedicated IBS studies during year 2004

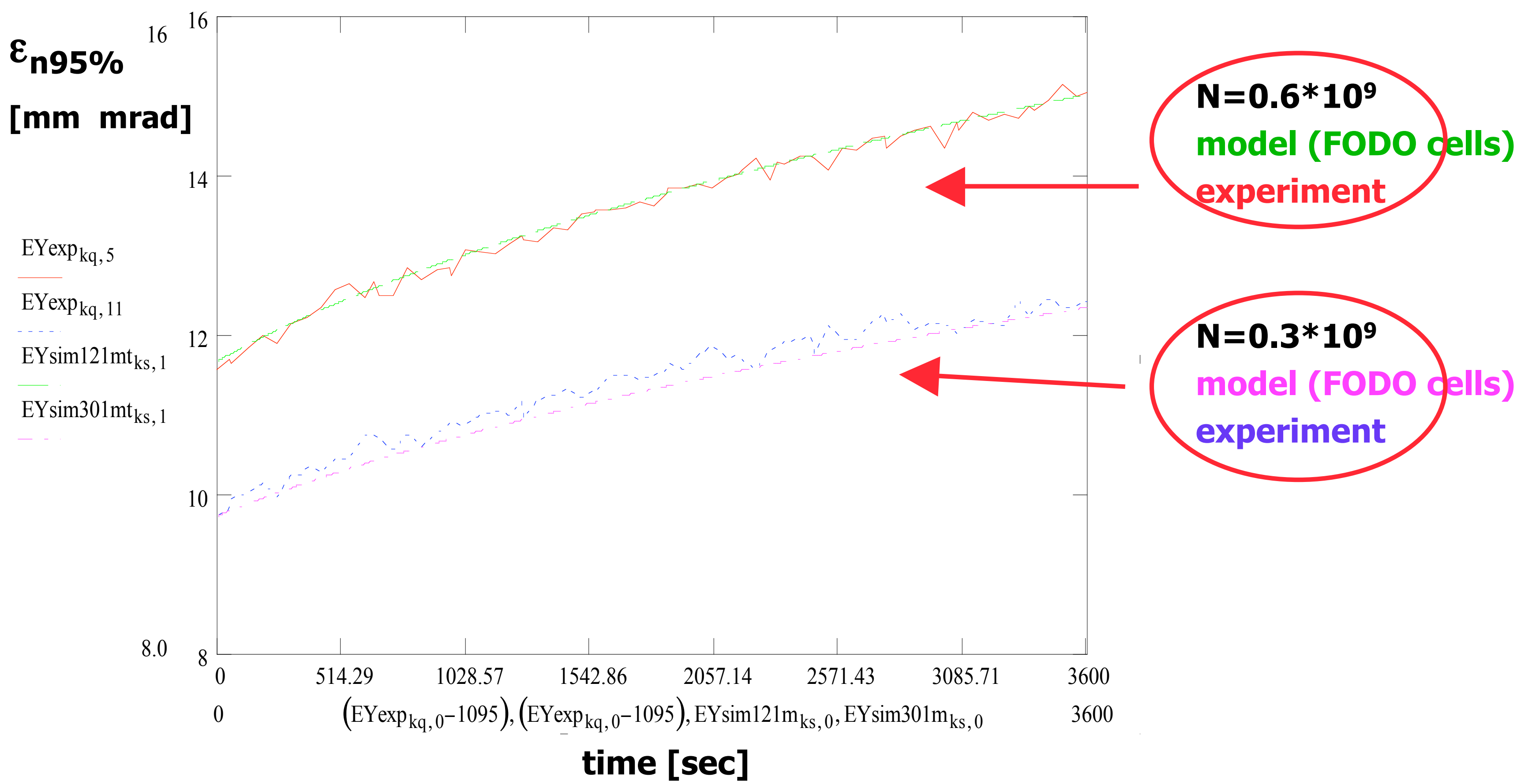
- Several studies done in previous runs; latest beam experiments: January - March, 2004
- Simultaneous IBS measurement under different intensities
  - Each of the two rings contain 6 bunches of 3 intensities
  - Gaussian-like beam in one ring, longitudinal hollow beam in the other



Transverse emittance bench-marking

- Agreement satisfactory (dispersion uncertainty within 40%); uncertainty is in the coupling condition and actual machine dispersion

Vertical emittance



Summary

- The mechanism of intra-beam scattering is well understood.
- The theory of Piwinski & Bjorken-Mtingwa is usually good within a factor of 2 in growth rates under proper conditions (Gaussian distribution, coupling …)
- Several efforts were made as an extension or beyond these theories
  - Approximate/analytical formulae and scaling laws
  - Fokker-Planck solver for the longitudinal phase space (tail, loss, hollow bunch …)
  - Molecular dynamics method for ultra-low emittance beams
- Benchmarking is satisfactory given measurement and machine uncertainties

The Cockcroft Institute
An International Centre for Research in Accelerator Science and Technology

Lattice design for IBS dominated beams

Yannis PAPAPHILIPPOU

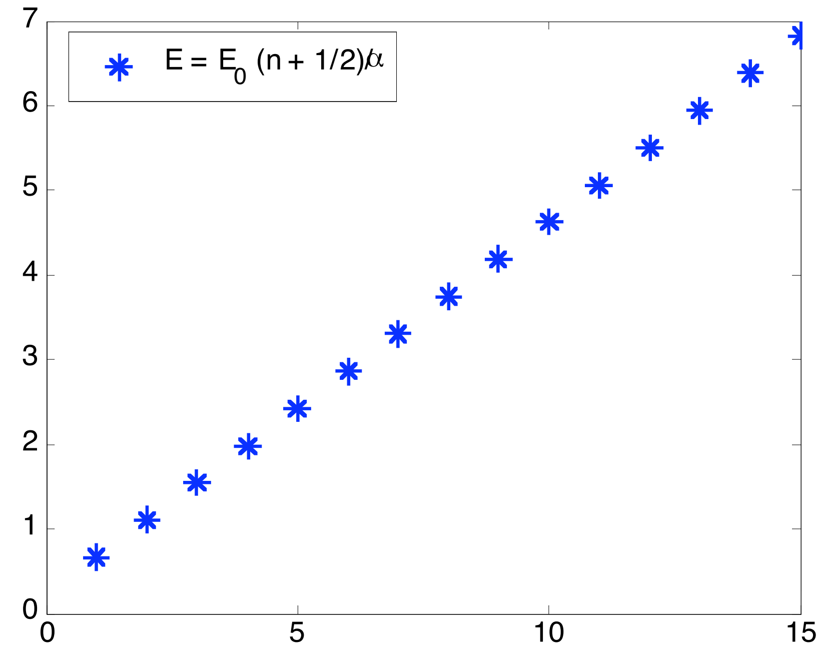
IBS '07 – Intra Beam Scattering mini workshop,

The Cockcroft Institute, Daresbury, UK.

August 28-29th, 2007

Ring energy

- Choice dictated by spin tune (half integer) for maintaining high-spin polarisation
- Frozen on early design stage
- Advantage of lower energies:
  - For same equilibrium emittance
    $$C \propto \gamma^3 \text{ and } \alpha_p \propto \gamma^{-2}$$
    i.e. smaller circumference and radiated power (cost), high momentum compaction (longitudinal stability).
- Advantages of higher energy
  - For fixed damping fraction due to wigglers and wiggler peak field,
    $$B_d \propto \gamma^{-3} \text{ and } L_w \propto \gamma^{-1}$$
    i.e. easier magnetic design (lower main field) and smaller total wiggler length
- IBS emittance growth increases with energy
  - IBS growth rate is energy independent.
  - It may become more important in higher energies as compared to the damping rate if number of stored bunch trains is increased with the circumference. Than the damping time scales as γ^3



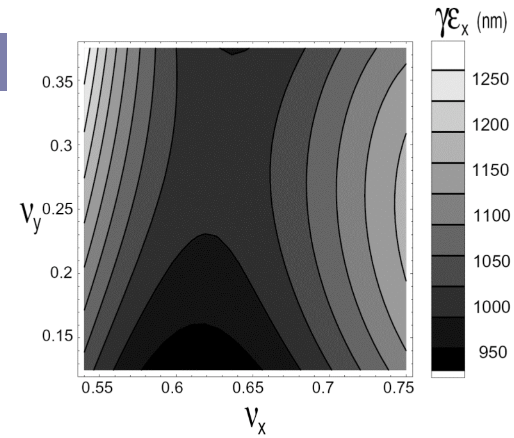
$$\tau_{IBS}^{-1} \propto \frac{N\langle H\rangle}{\gamma\epsilon_x\gamma\epsilon_y\gamma\epsilon_z} \propto \frac{N\gamma^3}{\gamma\epsilon_x\gamma\epsilon_y\gamma\epsilon_z} = \frac{N}{\epsilon_x\epsilon_y\epsilon_z}$$

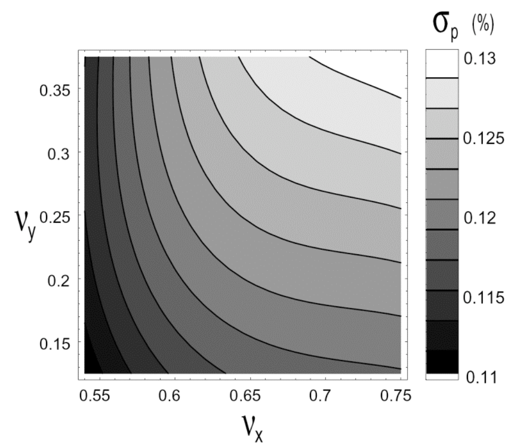
$$\tau_y \leq \frac{N_t}{fN_\tau} \propto \frac{C}{fN_\tau} \propto \frac{\gamma^3}{fN_\tau}$$

(P. Emma, T. Raubenheimer PRSTAB, 2001)

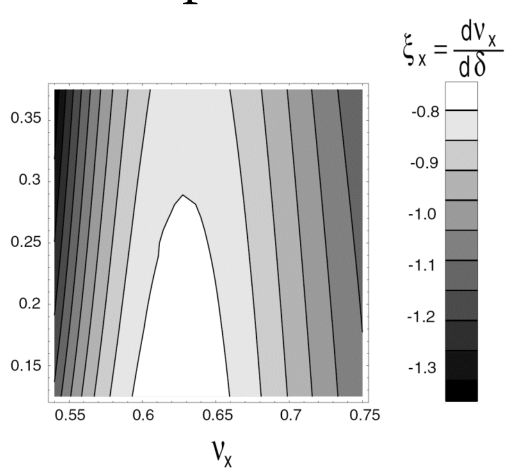
Phase advance choice with IBS

- Horizontal phase advance for minimum horizontal emittance with IBS, is found in an area of small horizontal beta and moderate dispersion functions (between 1.2-1.3π, for CLIC damping rings)
- Optimal vertical phase advance quite low (0.2π)
- The lowest longitudinal emittance is achieved for high horizontal and low vertical phase advances
- The optimal point may have to be compromised due to chromaticity considerations and dynamic aperture optimisation

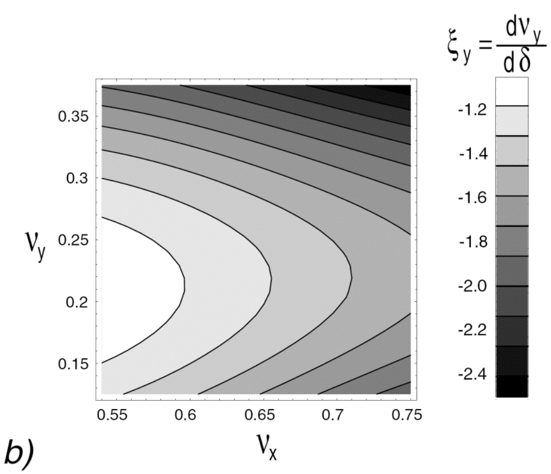




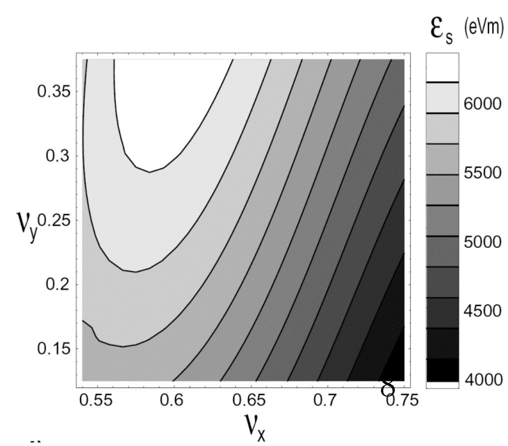
(M. Korostelev, PhD Thesis EPFL, 2006)



a)

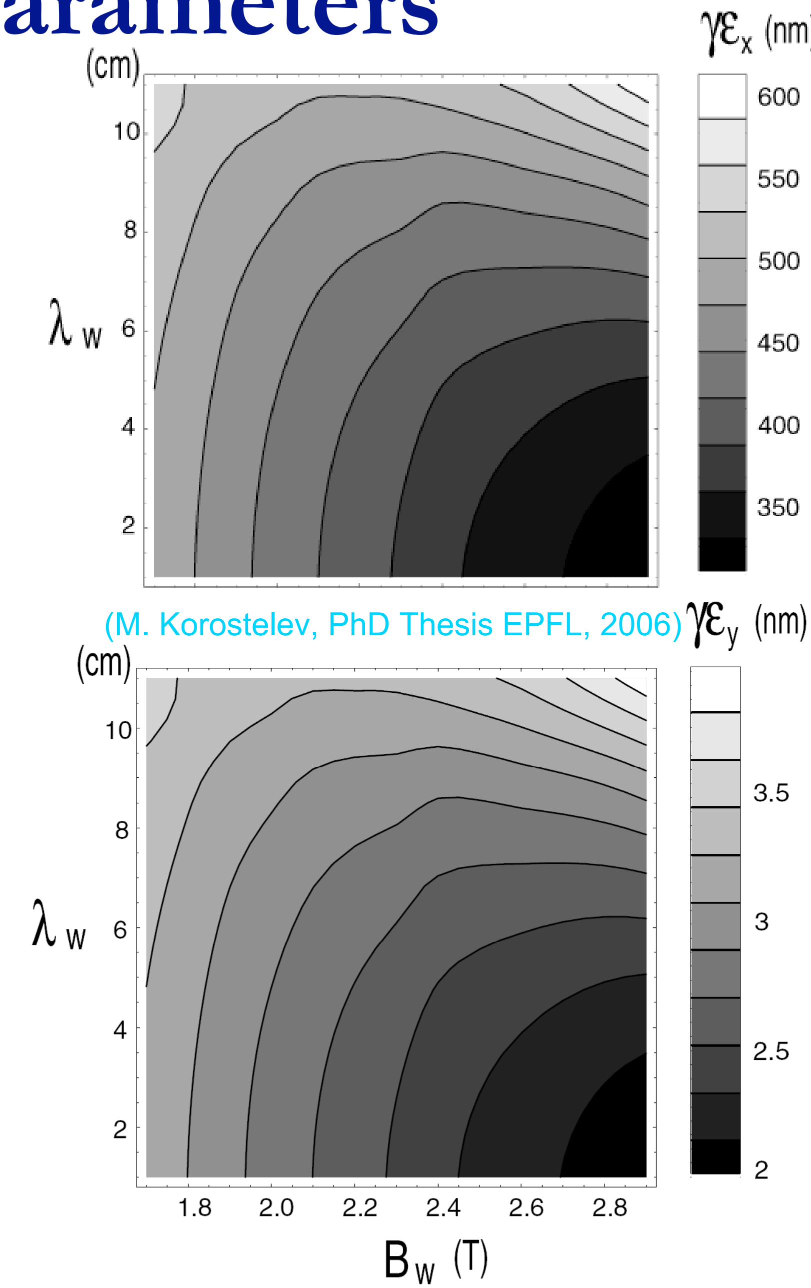


b)

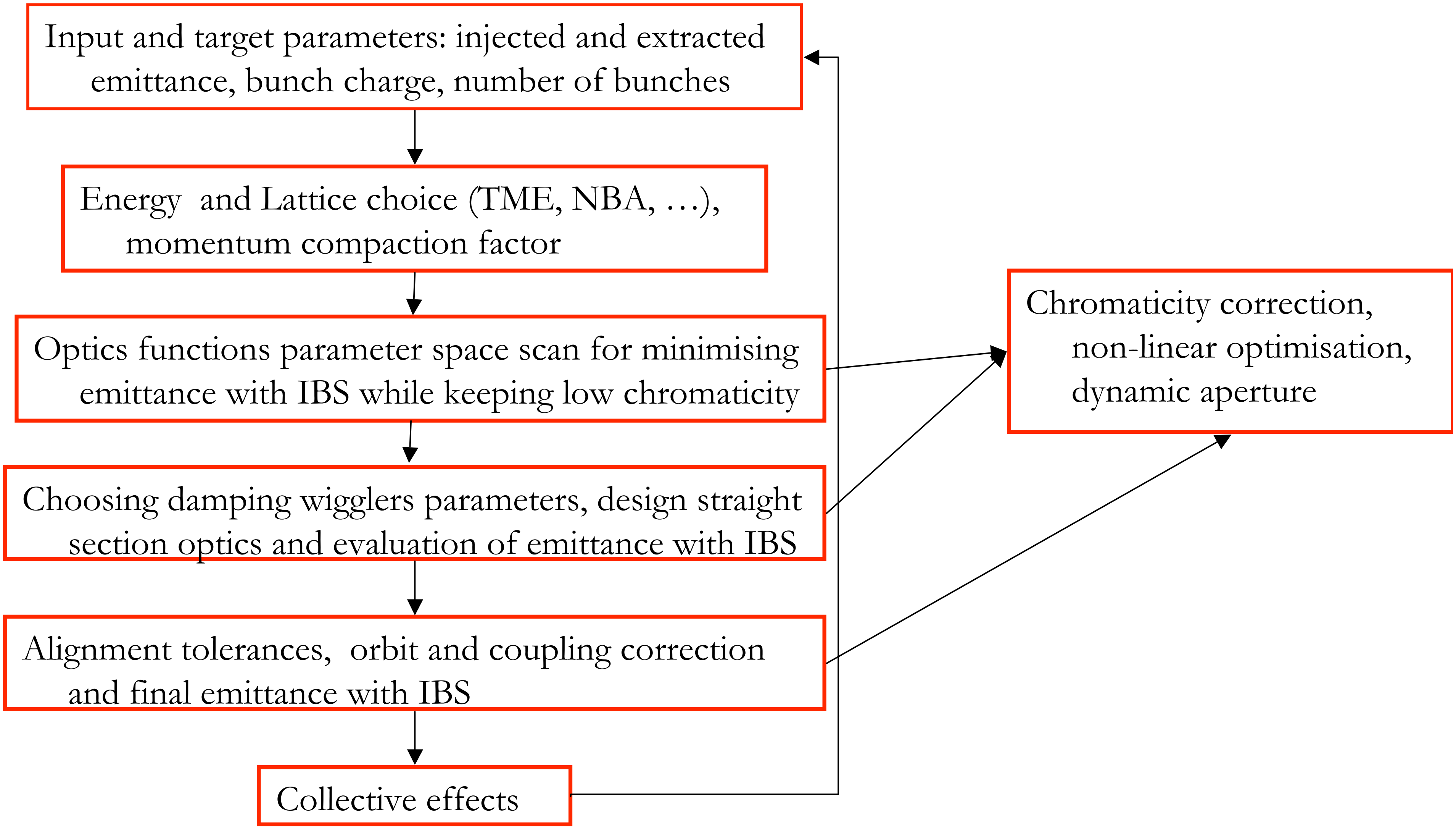


Damping wiggler parameters

- Damping wigglers are used to increase radiation damping and reduce the effect of IBS in order to reach target emittances
- The total length of wigglers is chosen by its dependence with the peak wiggler field and relative damping factor
- The optics of the wiggler straight section are optimised, as for the arcs. in order to both decrease the final emittance, keeping the optics functions and chromatic ring properties reasonable
- For higher wiggler field and smaller period the transverse emittance computed with IBS gets smaller
- The longitudinal emittance has a different optimum but it can be controlled with the RF voltage
- The choice of the wiggler parameters is finally dictated by their technological feasibility



Strategy for lattice design in IBS dominated beams

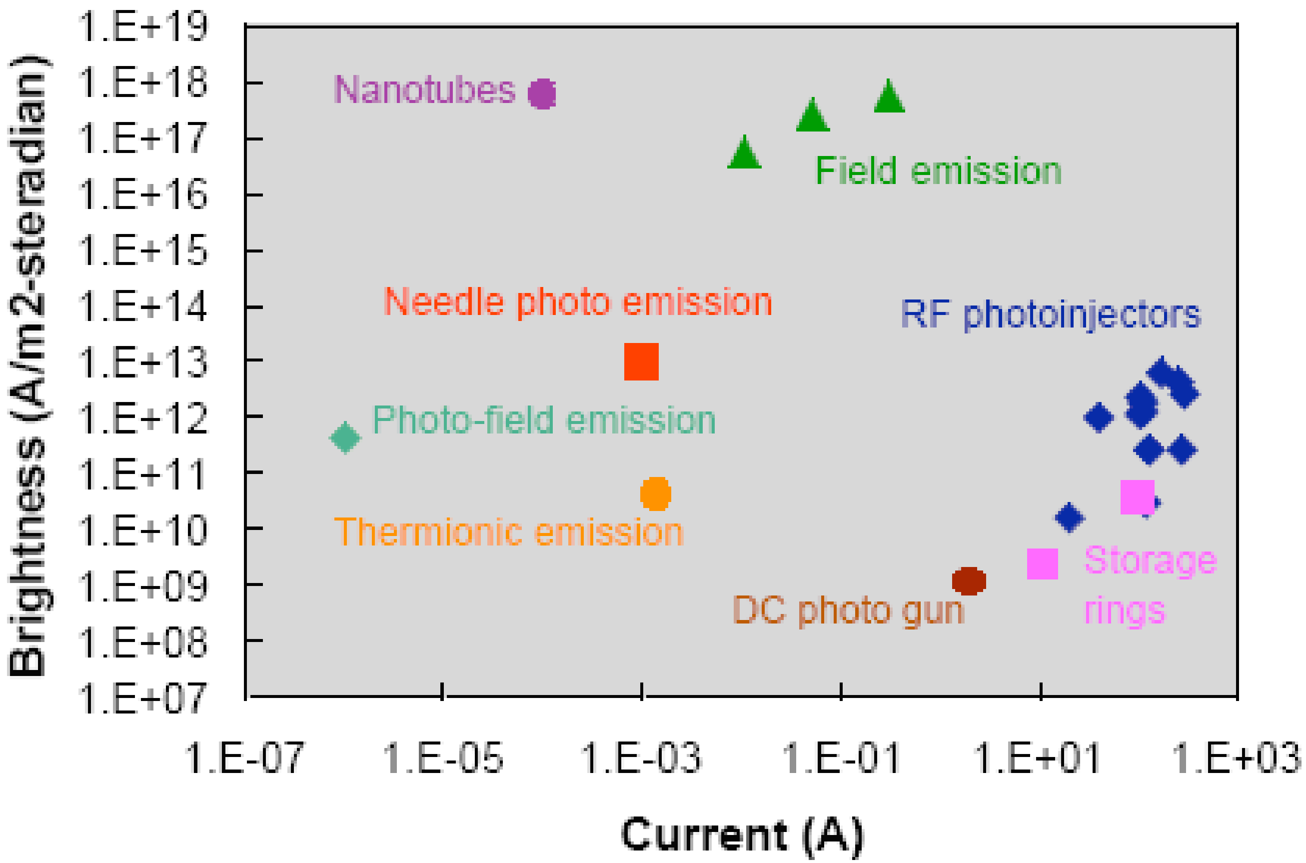


Concluding remarks

- In the case of IBS dominated beams, all lattice parameters can be optimised for reaching the target emittance including IBS
- The effect of IBS is evaluated “a posteriori”, i.e. after setting up the basic features of the lattice
- An iterative process can be used in order to scan the full parameter space and reach the optimum, using numerical tools
- Lack of a unique tool for executing all the optimisation steps and reiterate if needed. A MATLAB based package using the accelerator toolbox should be a good choice
- An interesting idea would be to derive analytically the optics parameters for reaching minimum IBS dominated emittance (J.Jowett) in selected lattices (FODO, TME,…)

IBS at Very Low Beam Energies

Andreas Adelmann (PSI)
Ji Qiang, Robert Ryne (LBNL)
Salman Habib (LANL)



(Source: C. Brau – Erice 2005)

- Historical notes
- The Boersch effect
- Experimental Data with BD relevance
- Two Numerical Models and First Results
- Summary and Outlook

PAUL SCHERRER INSTITUT

Historical notes cont.

The energy broadening arises from **Coulomb collisions between** the electrons in the beam. Several models have been derived mostly in the context of **electron microscopy, lithography** and plasma physics:
A comparison/parameterization of 5 models can be found in:

Energy broadening in electron beams: A comparison of existing theories and MC-simulations
G.H. Jansen, T.R. Groves, and W. Stickel
J. Vac. Sci. Technol. B 3 (1), Jan/Feb 1985

An overview on coulomb interactions in "Particle Beams" prior to 1993 can be found in:

Coulomb Interactions in Particle Beams
G.H. Jansen
Advances in ELECTRONICS and ELECTRON PHYSICS Supplement 21
Academic Press

Energy broadening in electron beams: A comparison of existing theories and MC-simulations

G.H. Jansen, T.R. Groves, and W. Stickel

J. Vac. Sci. Technol. B 3 (1), Jan/Feb 1985

- Round waist radius $\mathbf{r_0}$, in between two f-lenses.
- Uniform density
- Energy spread proportional to **F**

In all of the theories, the energy spread can be expressed by the formula

$$\frac{\langle \Delta E^2 \rangle^{1/2}}{E} = \left(\frac{m}{8e\epsilon_0^2}\right)^{1/4} F(\bar{r}_0, \bar{\lambda}, K) \cdot \sqrt{\frac{I}{V^{3/2}}},$$

where $\bar{r}_0$, $\bar{\lambda}$, and K are dimensionless parameters given by

$$\bar{r}_0 = \frac{8\pi\epsilon_0}{e} \alpha_0^2 \cdot V \cdot r_0;$$

$$\bar{\lambda} = \frac{1}{8\pi\epsilon_0} \sqrt{\frac{m}{2e}} \frac{I}{\alpha_0^2 V^{3/2}};$$

$$K = \frac{\alpha_0 L}{r_0}.$$

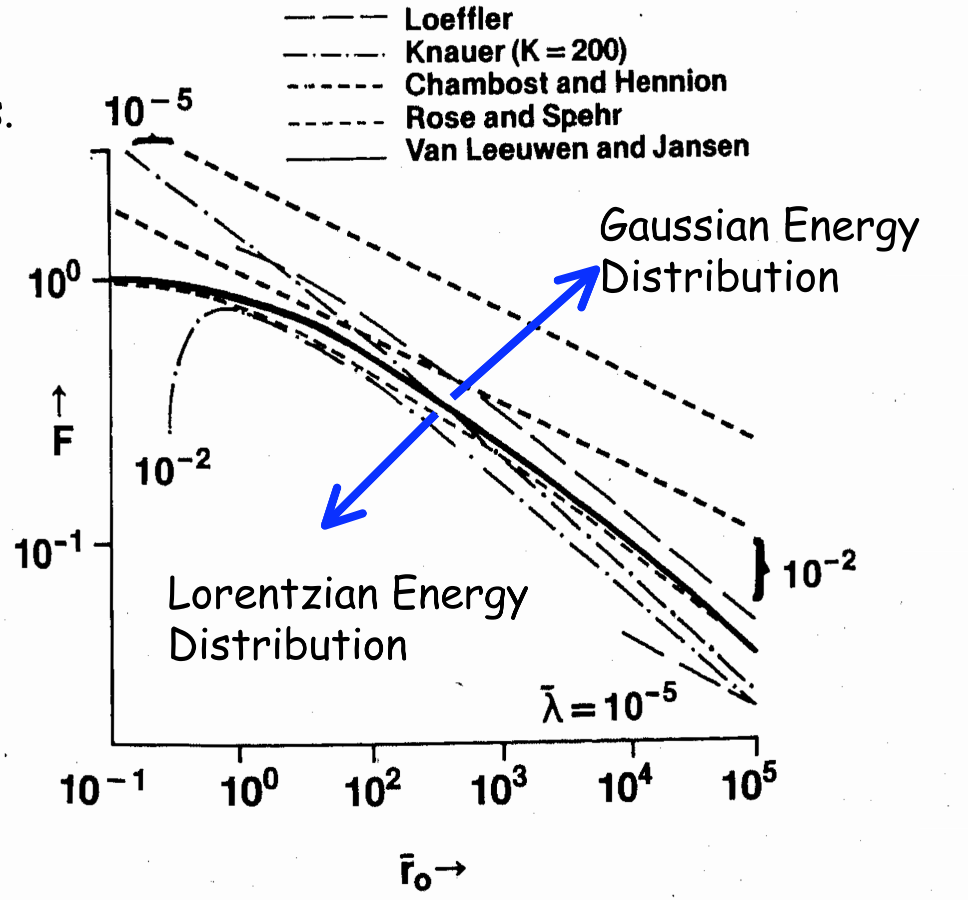


FIG. 1. Comparison of Boersch effect theories. The dimensionless function F is evaluated for each of the analytic theories, where the rms energy spread is proportional to F. The dimensionless parameters $\bar{r}_0$, $\bar{\lambda}$, and K are functions of the experimental parameters, and are defined in Eq. (1).

Energy broadening in electron beams: A comparison of existing theories and MC-simulations

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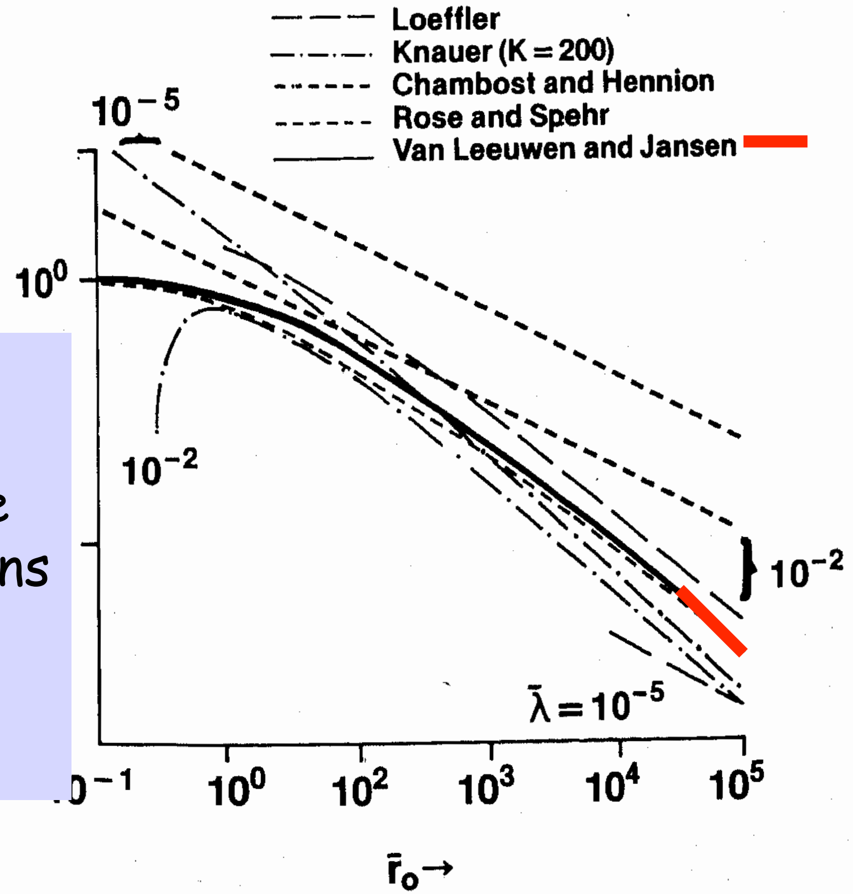
J. Vac. Sci. Technol. B 3 (1), Jan/Feb 1985

- Round waist radius **r_0**, in between two f-lenses.
- Uniform density
- Energy spread proportional to **F**

One Conclusion of their paper:
significant disagreement exists among the various theories. In order to resolve some of these differences MC simulations can be used as an independent check.
This is part 2 of the paper …. enjoy.



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The Boersch Effect

Zeitschrift für Physik, Bd. 139, S. 115—146 (1954).

Experimentelle Bestimmung der Energieverteilung in thermisch ausgelösten Elektronenstrahlen*.

Von

H. BOERSCH**.

(Mitteilung aus der Physikalisch-Technischen Bundesanstalt Braunschweig.)

Mit 19 Figuren im Text.

(Eingegangen am 18. März 1954.)

The Boersch Effect is a temperature relaxation process via Coulomb collisions:
(27 keV e-beam, thermionic gun, measure dE in waist)

Initial condition is an anisotropic temperature distribution: $T_\perp << T_{||}$

Coulomb collisions try to equilibrate this anisotropic state (relaxation).

Consider now only L-T effects, [L-L effects see Reference at page 14]

Setup: keV, e-beam confined by an axial magnetic field. We follow now Ichimaru and Rosenbluth (Physics of Fluids Vol. 13 Number 11, p 2778)

$$\frac{dT_\perp}{dt} = -\frac{1}{2}\frac{dT_{||}}{dt} = -\frac{T_\perp - T_{||}}{\tau} \quad \text{with} \quad \frac{1}{\tau} = \frac{8\sqrt{\pi} n q^4}{15(4\pi\epsilon_0)^2\sqrt{m}(k_B T_{eff})^{3/2}} \ln\Lambda$$

$$\frac{1}{(T_{eff})^{3/2}} = \int_{-1}^{1} \frac{15}{4} \frac{\mu^2(1-\mu^2)}{\{(1-\mu^2 T_\perp + \mu^2 T_{||}\}^{3/2}} d\mu \qquad \ln\Lambda \approx \ln\frac{\lambda_d}{b_{90}}$$

Conclusions

- Until present the Boersch effect was not considered a limiting factor in particle accelerator related beam physics
- In the quest for lowest emittance electron beams, ideas using current densities in the O(100 kA/mm^2) range are under consideration, where the Boersch effect eventually must be considered w.r.t. beam quality
- First simulations including collisions clearly show an effect of collisions in the mentioned region, not seen in (self consistent) mean field calculations
- A full blown framework for particle transport including collisions is in development, the crucial part (collision-operator) is ready: tested and validated

Outlook

- compare future e-gun regimes with existing analytic approaches

- further develop the Langevin approach to be used in e-guns
  - $$\frac{\partial f}{\partial t} + \mathbf{v} \cdot \frac{\partial f}{\partial \mathbf{r}} + \boxed{\frac{\mathbf{F}}{m}} \cdot \frac{\partial f}{\partial \mathbf{v}} = -\frac{\partial}{\partial \mathbf{v}} \cdot \mathbf{F_d} f + \frac{1}{2} \frac{\partial^2}{\partial \mathbf{v} \partial \mathbf{v}} : \mathbf{D} f$$

- try to asses the collisions experimentally in the frame of our Low Emittance Gun (LEG) development and connect experiment with theory and simulations:
  - we were extracting 500 mA from a single tip

    (R. Ganter et.al NIMA 565 (2006) 423-429).

IBS Effects in a Wiggler-Dominated Light Source

Boris Podobedov
Brookhaven National Lab
National Synchrotron Light Source

Lingyun Yang
Indiana University

IBS'07, Daresbury, UK
August 29, 2007

Office of Science
U.S. DEPARTMENT OF ENERGY

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BROOKHAVEN SCIENCE ASSOCIATES

Outline & Preliminaries

- Introduction
  - Motivation and light source specifics
  - Wiggler-dominated LS
- Effects of wigglers/undulators (No IBS)
- Analytical results on IBS through Bane's formalism
- ZAP simulations
- SAD simulations (preliminary)
- Summary and conclusions

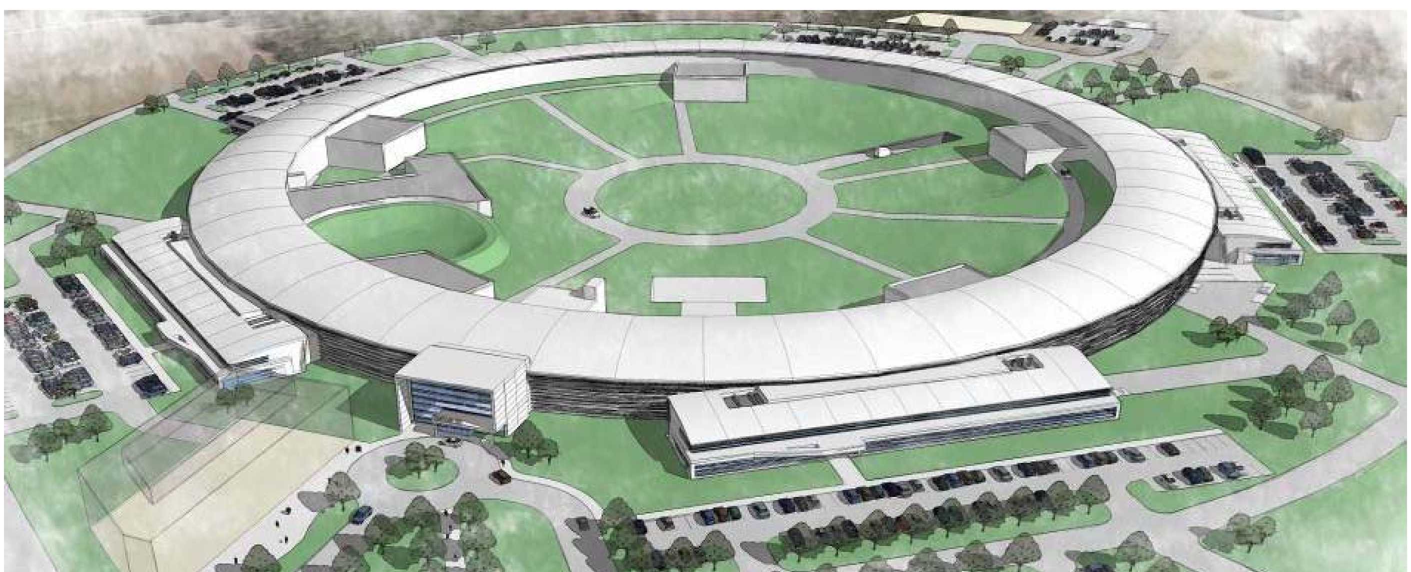
IBS results are described in our PAC'07 paper

- I only talk about Multiple Intra Beam Scattering
- Collective effects (such as potential well distortion, etc) are ignored
- I don't include harmonic RF (which reduces IBS even further)
- Most estimates are for CDR DBA30 NSLS-II lattice
- We looked for worst case estimate

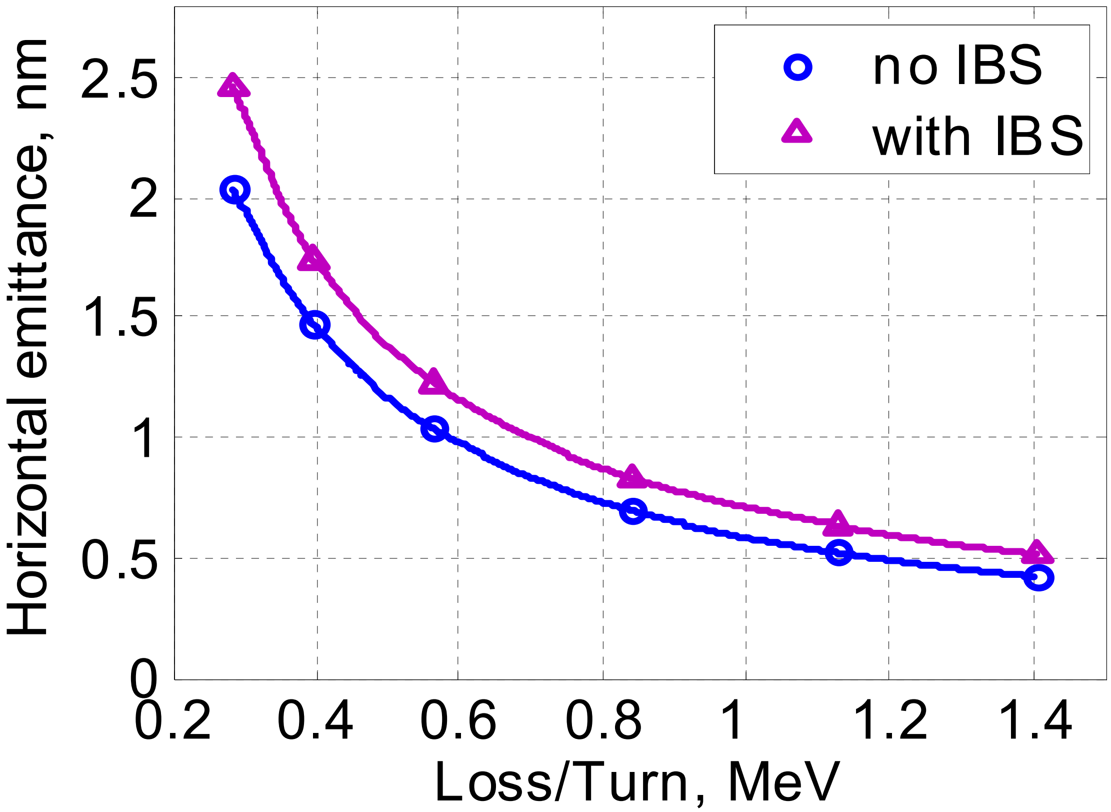
Parameters for NSLS-II IBS Calculations

Energy	3.0 GeV	**Energy Spread**	**<**0.1%
Circumference	**~8**00 m	**RF Frequency**	500 MHz
Number of Periods	30DBA	**RF Bucket Height**	3%
Length Long Straights	**8.**6 & 6.6 m	**Synchrotron Tune**	~0.009
Emittance (h,v)	2-0.5 nm, 8 pm	**RMS Bunch Length**	15ps
Betatron Coupling	**>**0.5%	**Maximum Current**	500ma
Dipole Bend Radius	25m	**Current per Bunch**	0.48ma

More details at http://www.bnl.gov/nsls2/project/CDR



ZAP Calculations



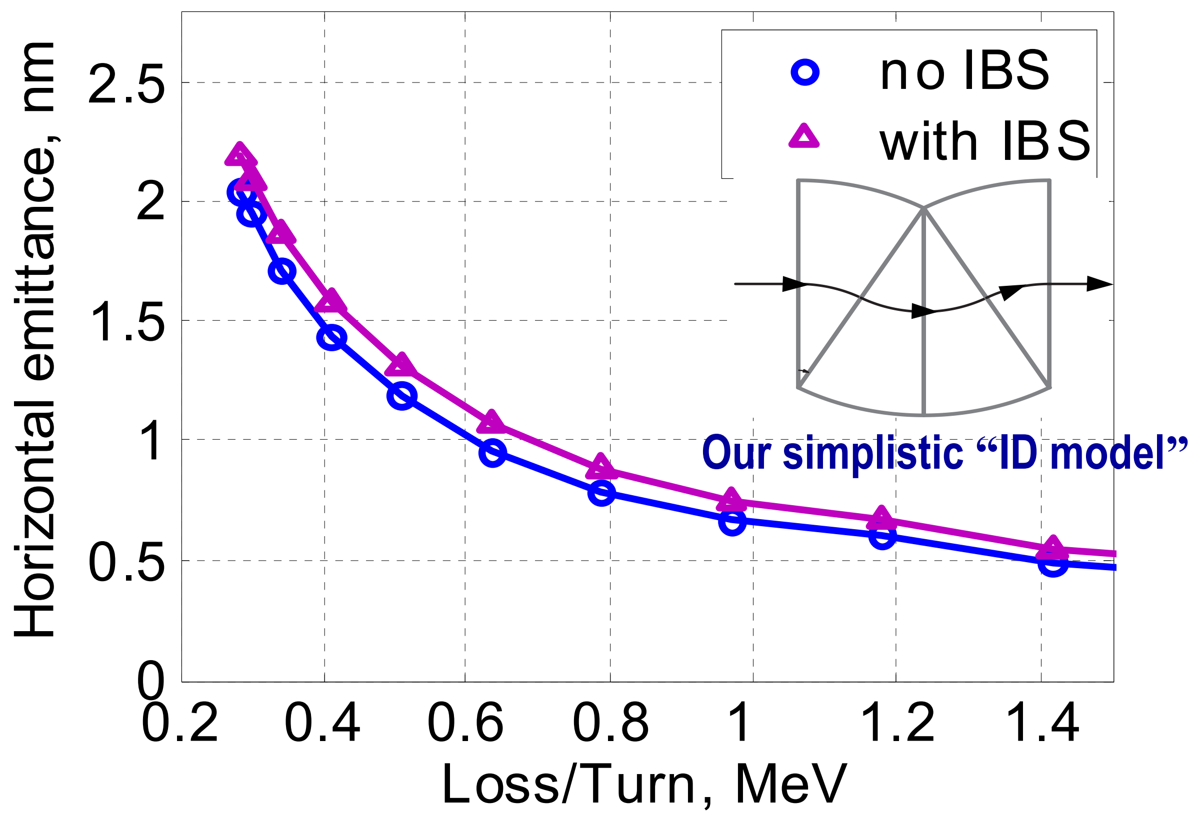
- ZAP uses 2D B-M algorithm (OK for flat beams in a LS).
- Computes growth rates, then iterates to find the equilibrium.
- for wiggler ε_x, $\delta E/E$, τ_{rad}, scaled "by hand" for radiation losses
- No tail cut in the Coulomb (log)=~17

IBS-induced emittance blow-up is ~20% and it is ~independent of energy loss!

Adding SAD (accelerator code by K. Oide)

WHY SAD ?

- Comprehensive (and well documented) IBS treatment, allows for full 3D coupling
- Full-blown lattice code
- Put ID model in the lattice and get self-consistent beam sizes



IBS-induced emittance blow-up is ~10% and it is ~independent of energy loss! Much of the difference ZAP/SAD is due to Coulomb log.

Work in progress with more realistic wiggler models.

Summary and Conclusions

- In a wiggler-dominated light source increased IBS rates due to denser bunches are offset by the increase in radiation damping.
- The magnitude of the IBS-induced emittance blow-up in a wiggler-dominated light source appears to be fairly independent of the emittance.
- IBS-induced relative emittance blow-up for NSLS-II should not exceed 20% at nominal bunch intensity (and several conservative assumptions) and therefore it should not present a problem.
- Want to repeat SAD calculations for realistic ID models; also check the case when vertical beam size is controlled by dispersion (not coupling).
- Experimental verification (at least when wiggler-dominated) is still lacking.

Beyond Vlasov Maxwell: Space-Time Correlations

Gabriele Bassi

The Cockcroft Institute and University of Liverpool

1. Introduction
2. Klimontovich Equation
3. Average Over Initial Conditions
4. Vlasov Maxwell Equation
5. Vlasov Poisson Equation
6. BBGKY Hierarchy
7. Generalized BBGKY Hierarchy

Introduction

- **Motivation**: Intrabeam Scattering (IBS) a very important collective effect in beam dynamics.

  IBS may degrade the beam quality an cause emittance growth

- A limitation of existing IBS models: assume Gaussian beams, not self-consistent

- Proposed method: study IBS within the framework of non-equilibrium statistical mechanics
  - Klimontovich approach
  - BBGKY hierarchy: space correlations, corrections to the Vlasov-Poisson equation
  - Generalized BBGKY hierarchy: space-time correlations, corrections to the Vlasov-Maxwell equation

BBGKY hierarchy I

Define

$$f_p(\mathbf{x}_1, \mathbf{v}_1, ..., \mathbf{x}_p, \mathbf{v}_p, t) := \int d\mathbf{x}_{p+10} d\mathbf{v}_{p+10} ... d\mathbf{x}_{N0} d\mathbf{v}_{N0}$$

$$\Psi(\mathbf{X}_1^{-1}(t, t_0, \mathbf{x}_1, \mathbf{v}_1), \mathbf{V}_1^{-1}(t, t_0, \mathbf{x}_1, \mathbf{v}_1), ..,$$

$$\mathbf{X}_p^{-1}(t, t_0, \mathbf{x}_p, \mathbf{v}_p), \mathbf{V}_p^{-1}(t, t_0, \mathbf{x}_p, \mathbf{v}_p), \mathbf{x}_{p+10} \mathbf{v}_{p+10}, .., \mathbf{x}_{N0}, \mathbf{v}_{N0}, t_0)$$

It follows (first equation of the hierarchy)

$$f_{1t}(\mathbf{x}, \mathbf{v}, t) \; + \; \mathbf{v} \cdot \nabla_{\mathbf{x}} f_1(\mathbf{x}, \mathbf{v}, t) \; - \; \frac{q}{m} \nabla_{\mathbf{v}} \cdot \int d\mathbf{x}' d\mathbf{v}' \left[\nabla_{\mathbf{x}} \frac{1}{\mid \mathbf{x} - \mathbf{x}' \mid} \right] f_2(\mathbf{x}', \mathbf{v}', \mathbf{x}, \mathbf{v}, t) = 0$$

Future work I

- Generalized BBGKY hierarchy
- Corrections to Vlasov-Maxwell equation
- Corrections to Vlasov-Poisson equation
- Approximate account of retardation effects

Remark: A Vlasov-Maxwell solver has been developed and successfully applied to realistic systems:

J. A. Ellison, G. Bassi, K. Heinemann, M. Venturini, R. Warnock, *Self-Consistent Computation of Electromagnetic Fields and Phase Space Densities for Particles on Curved Orbits*, Proceedings of PAC2007.

USE OF IBS
IN THE PRECISION EXPERIMENTS WITH POLARIZED BEAMS AT VEPP-4M

Sergei Nikitin

for VEPP-4M and KEDR teams

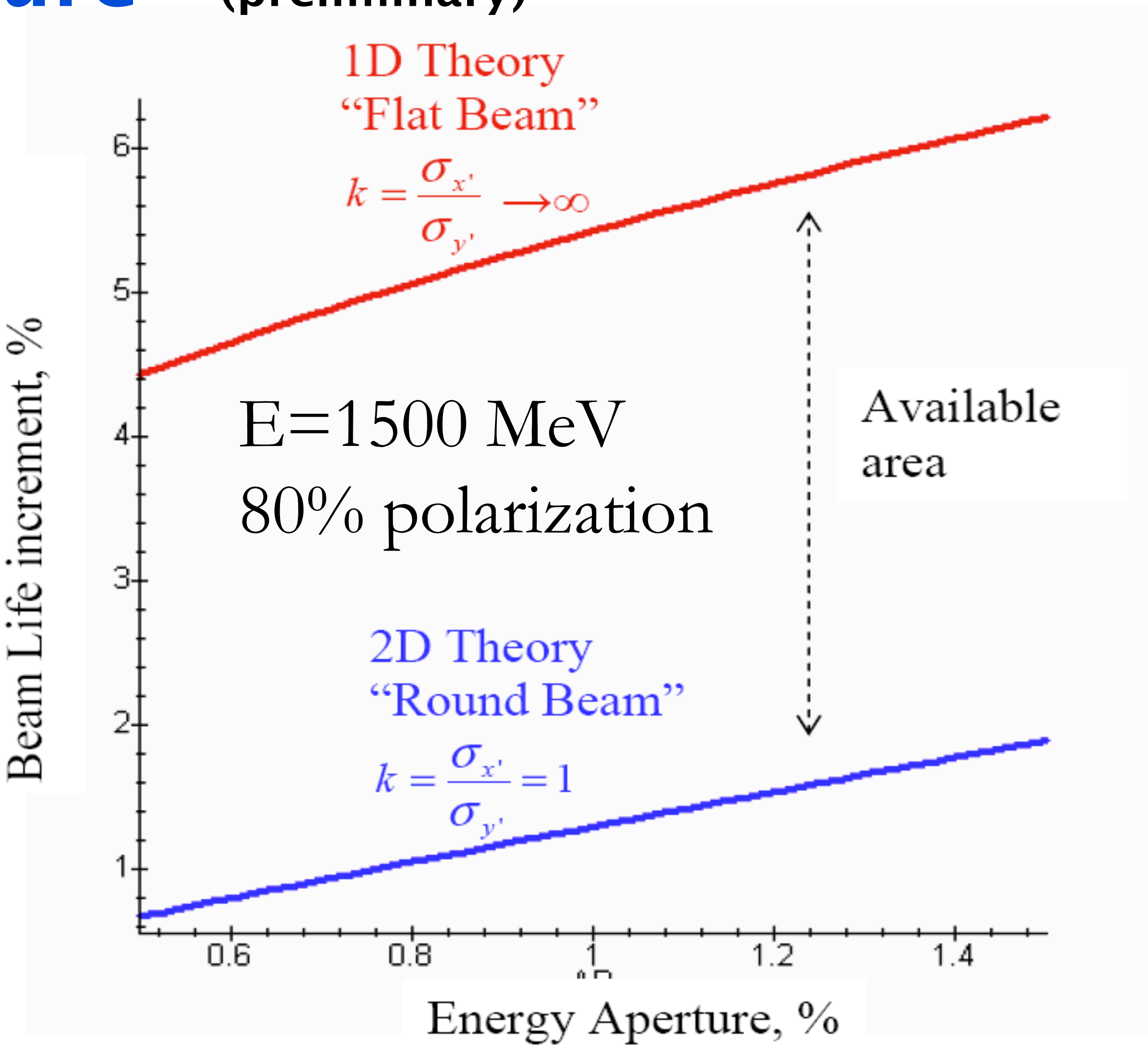
IBS Mini Workshop,
Cockcroft Institute, Daresbury

28-29 August 2007

CONTENT

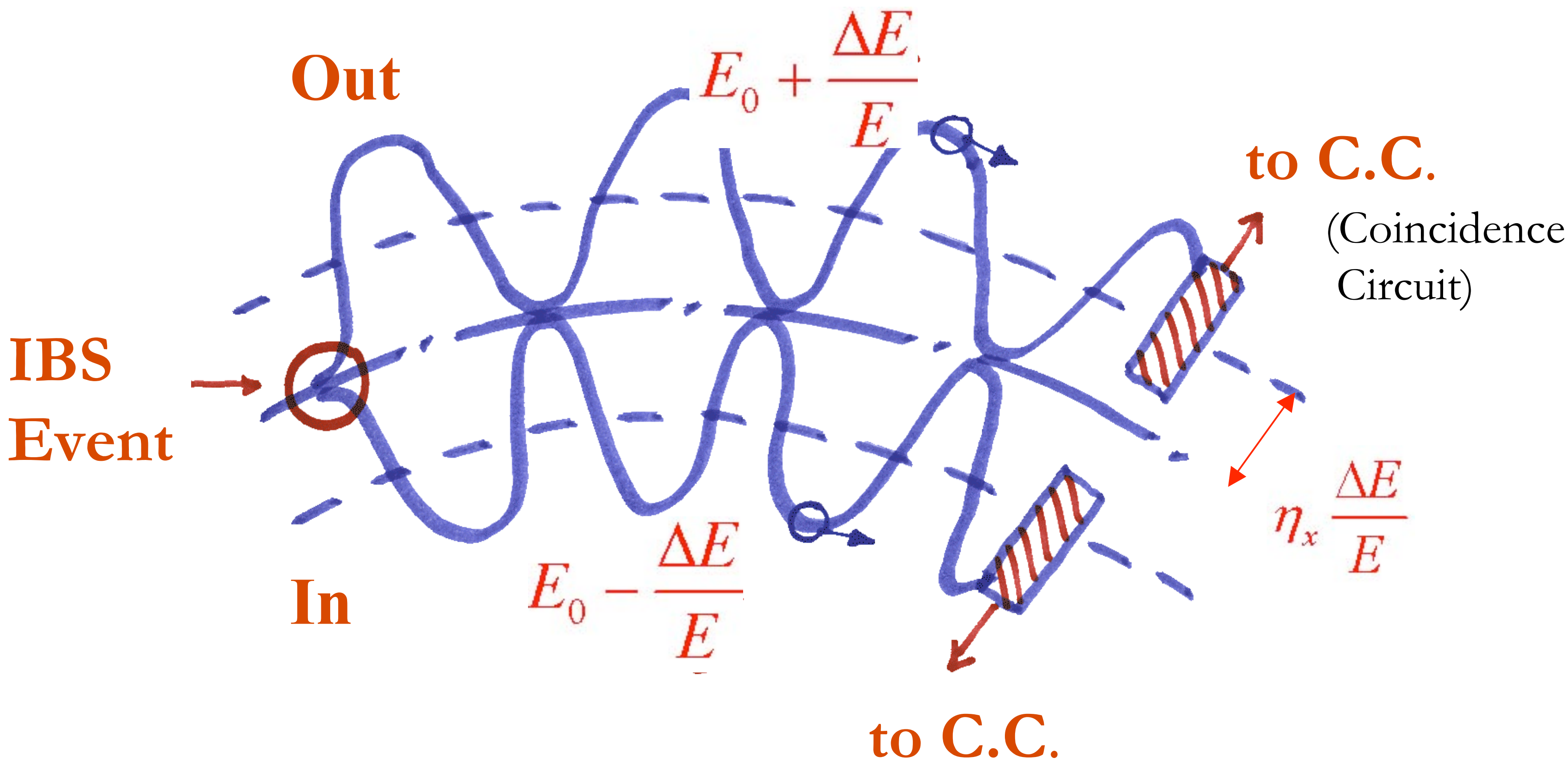
- IBS features in the viewpoint of Beam Polarization
- IBS-based polarimeter: realization and comparison of calculation and experiment
- Resonant Depolarization technique
- Precision experiments with polarized beams using IBS polarimeter

Beam Lifetime increment due to Polarization calculated vs. Energy Aperture **(preliminary)**



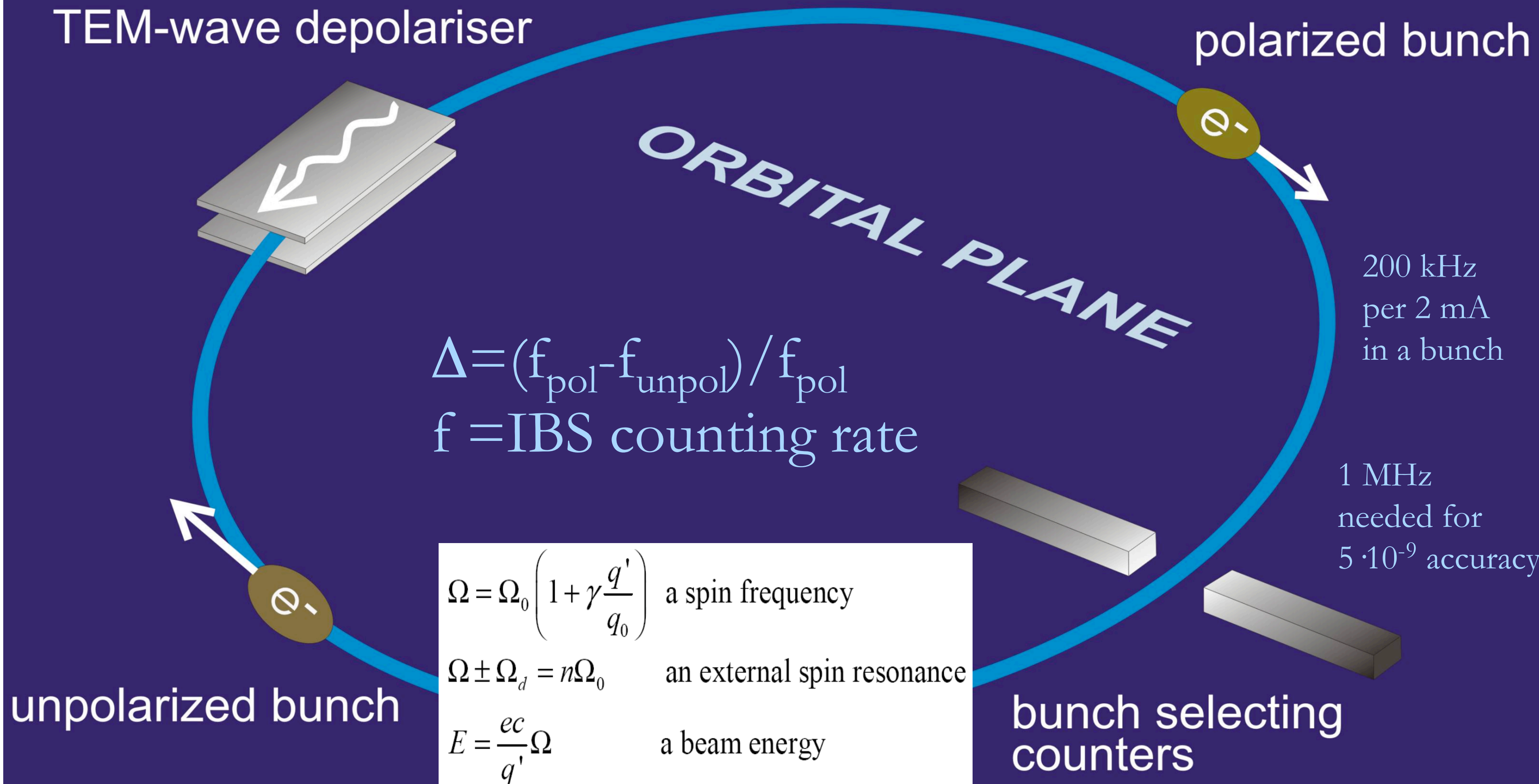
- Polarization contribution to the beam emittance and energy spread is negligible.
- Depolarization influence of IBS is usually small because of its insignificant contribution to energy diffusion as compared with SR.
- Practically, a few percent change in Beam Lifetime related to Polarization is too small to be measured because of large systematic errors.
- Another way, the detecting of Touschek particles in conjunction with the resonant depolarization technique, is effectively applied to observe Beam Polarization as well as to measure Beam Energy.

Touschek Electron Couple Detection



Note: If "Touschek" dominates over "Gas-Beam" one can use a sum of the counter rates instead of their logical production

TWO BUNCH TECHNIQUE



$\Delta=(f_{pol}-f_{unpol})/f_{pol}$

f =IBS counting rate

$\Omega = \Omega_0 \left(1+\gamma \frac{q'}{q_0}\right)$ a spin frequency

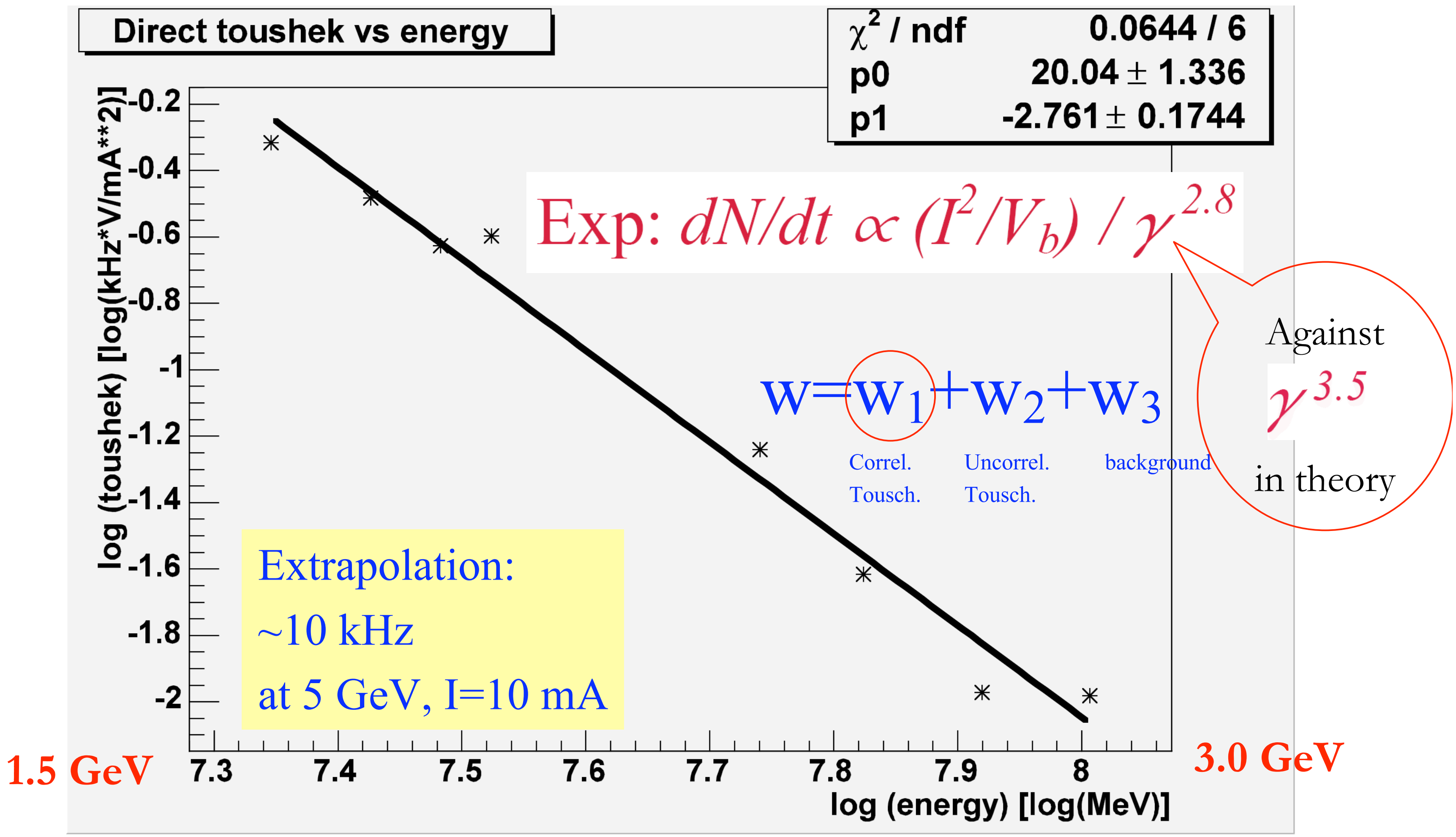
$\Omega \pm \Omega_d = n\Omega_0$ an external spin resonance

$E = \frac{ec}{q'}\Omega$ a beam energy

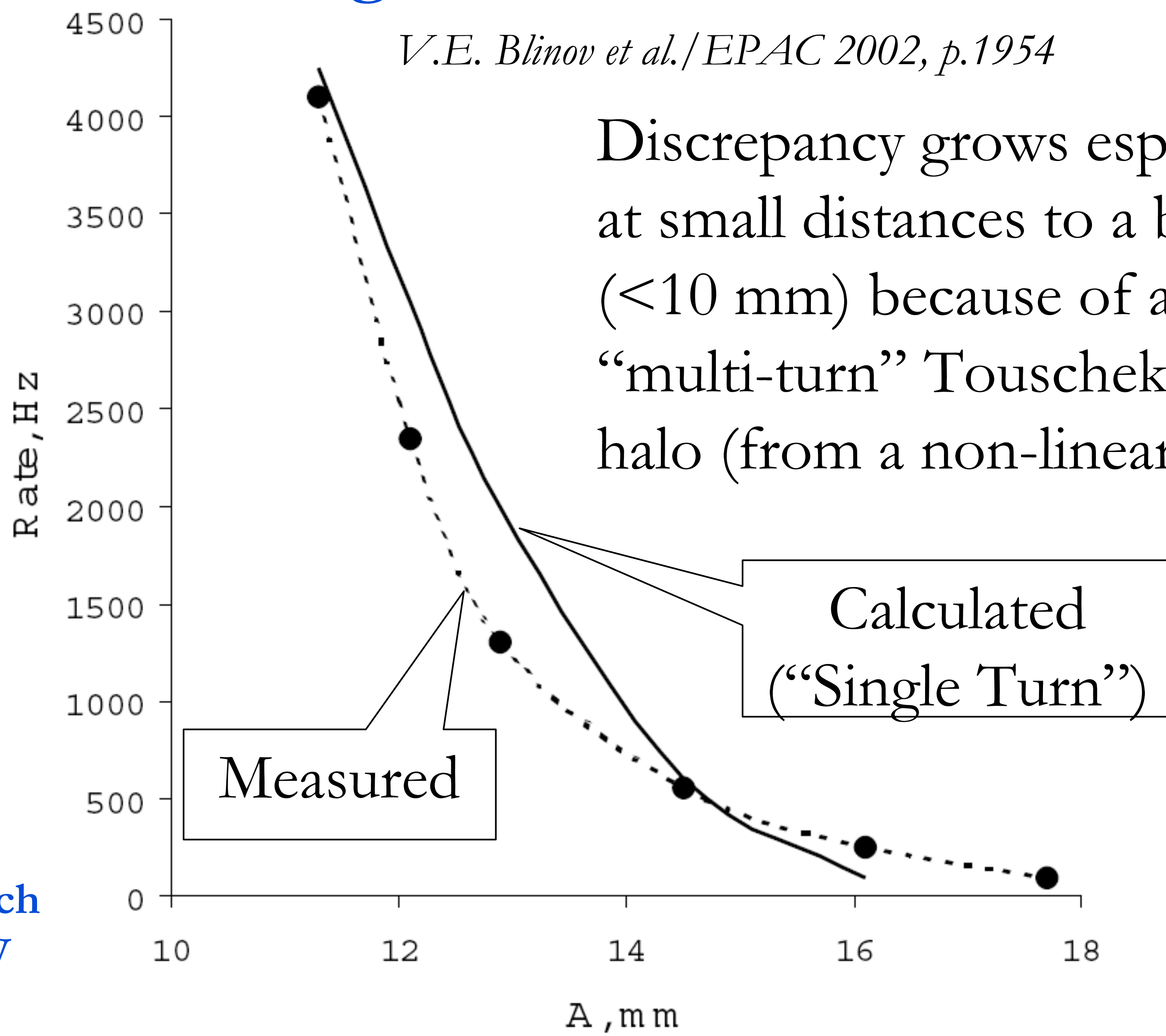
measured vs. Beam Energy

(preliminary)

(1.5-3 GeV, VEPP-4M, 2006; a random coincidence contribution subtracted)



Counting Rate vs. Counter Distance



Discrepancy grows especially at small distances to a beam (<10 mm) because of a "multi-turn" Touschek and halo (from a non-linearity).

2 mA/bunch
1548 MeV

Energy calibration by IBS polarimeter with an accuracy of 10^{-6} in the Psi' mass measurement

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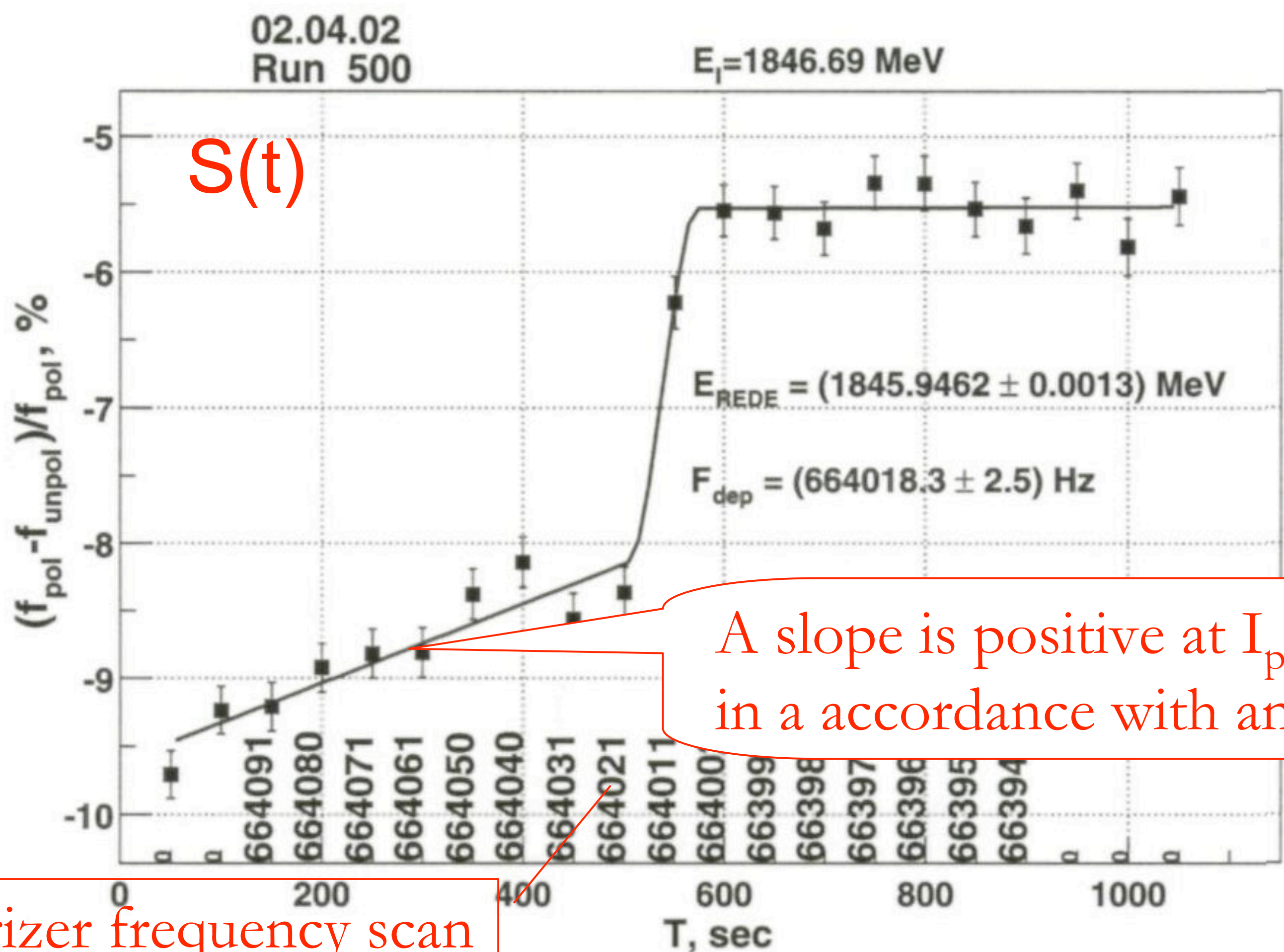


A slope is positive at $I_{pol}<I_{unpol}$ in a accordance with an estimate

Depolarizer frequency scan

Results of J/Psi and Psi' mass measurements

$J/\psi,\ \psi'$ – meson masses measurement
$(\Delta m/m = 4 \cdot 10^{-6},\ 7 \cdot 10^{-6})$

$$M_{J/\psi} = 3096.917 \pm 0.010 \pm 0.007\ \text{MeV}$$

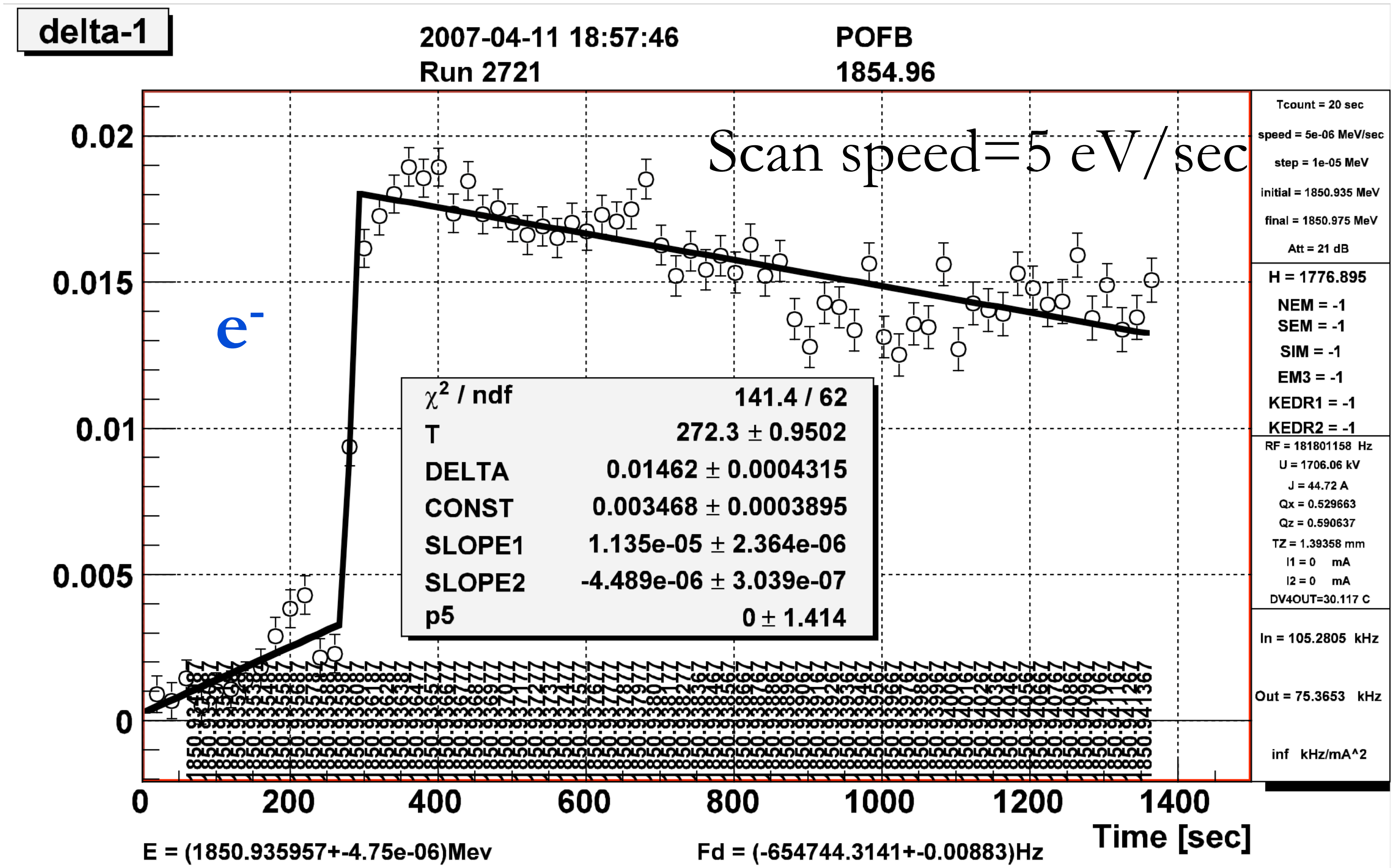
$$M_{\psi'} = 3686.111 \pm 0.025 \pm 0.009\ \text{MeV}$$

The achieved accuracy of measurement of J/Psi- and Psi'- meson masses surpasses the world-average one in 3 and 4 times, accordingly. The relative accuracy of J/Psi meson mass is 4x10^-6, that is the absolute record of accuracy in measurement of narrow short-lived resonances.

Particle	Δm/m, ppm
n	0.04
p	0.04
e	0.04
μ	0.09
$\pi^{\pm}$	2.5
J/ψ	4.0
π^0	4.5
ψ'	7.2

Depolarization frequency resolution $3 \cdot 10^{-9}$ (5 eV). (Accuracy in CPT Test should not be worse than 10^{-9})

non-published



Discussion

- High efficient IBS-based polarimeter is developed for various precision experiments with polarized beams
- J/Psi, Psi' and tau-lepton masses are defined more accurately
- Record resolution in the depolarization frequency of $3 \cdot 10^{-9}$ (and $2 \cdot 10^{-8}$ in e-e- spin frequency comparison) achieved gives an incentive to next studies of possibility to realize the CPT Test experiment at a storage ring
- Developed methods and skills may be useful in a study of other IBS aspects (for example, the Touschek background in the section with the detector)

Thank you very much!