US LARP Beam-Beam and Electron Lens Work

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US LARP DOE Review
July 9-10, 2012

Outline

- Mission of beam-beam and e-lens tasks
- Tevatron and RHIC beam-beam experiments
- Beam-beam simulations
  - Code development
  - Beam-beam in HL-LHC
- Hollow electron beam lens
  - Summary of experimental results
  - CERN/LHC integration
- Plans
  - New Initiative: Optical Stochastic Cooling experiment at Fermilab

LARP Beam-Beam Task

- Goals
  - Develop and maintain simulation tools
  - Support beam-beam related experiments at existing machines (Tevatron, RHIC)
  - Apply expertise for LHC upgrades
- Contributors
  - BNL, LBNL, FNAL, (SLAC)
- Past work highlights
  - Beam-beam effects at Tevatron
  - Long-range compensation with wires
  - Head-on compensation with electron lens
    - Work changed direction to hollow e-beam collimation

Tevatron End-of-Run Beam-Beam Experiments

- During the last two years, the machine was operating in a stable configuration
  - This gave the possibility to plan and carry out beam physics experiments for the benefit of future machines
  - There was strong interest from CERN, BNL, LBNL to study a number of topics at Tevatron before it is switched off forever
- Beam-beam experiments
  - Planned and carried out with strong participation by LARP
  - 43 hours of beam time used in two-week period in August 2011
  - Concentrated on head-on effects

Topics of Tevatron Beam-Beam Experiments

- AC dipole with colliding beams
  - AC dipole is a device that adiabatically excites transverse oscillations of the beam. Turn-by-turn detection of these oscillations allows to restore the beam optics. It is the method currently in use at the LHC
- Effect of Beam-Beam interaction on coherent stability
  - Colliding beams represent a system of coupled oscillators with their eigen-frequencies determined by beam and machine properties. Also, coherent instabilities driven by machine impedance are affected by the nonlinearity of beam-beam interaction
- Beam-Beam resonances vs. transverse separation
- Effect of bunch length to beta-function ratio (betatron phase averaging)

AC Dipole with Beam-Beam

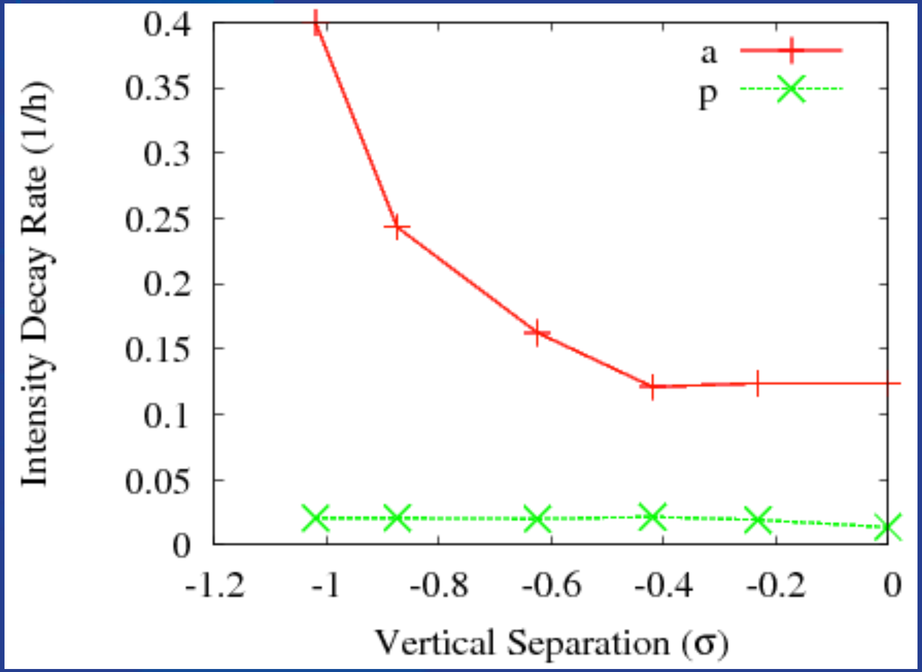
- The goal was to excite the “weak” beam through the strong beam using the AC-dipole
  - We had to reverse the weak-strong set-up since the BPM system operates in a turn-by-turn mode for protons only - use lowest possible proton intensity against nominal low emittance pbars
  - Record the turn-by-turn BPM data around the ring
  - Changes to the linear lattice function due to BB can be derived from a reference measurement with protons only
- Successfully demonstrated the technique with colliding beams (3x3 bunches in collision configuration)! No instability or emittance growth after multiple excitations
- Difficulties
  - “Strong” antiproton beam is also excited
  - Coupling was strong
  - Weak proton beam => BPM noise worse than usual

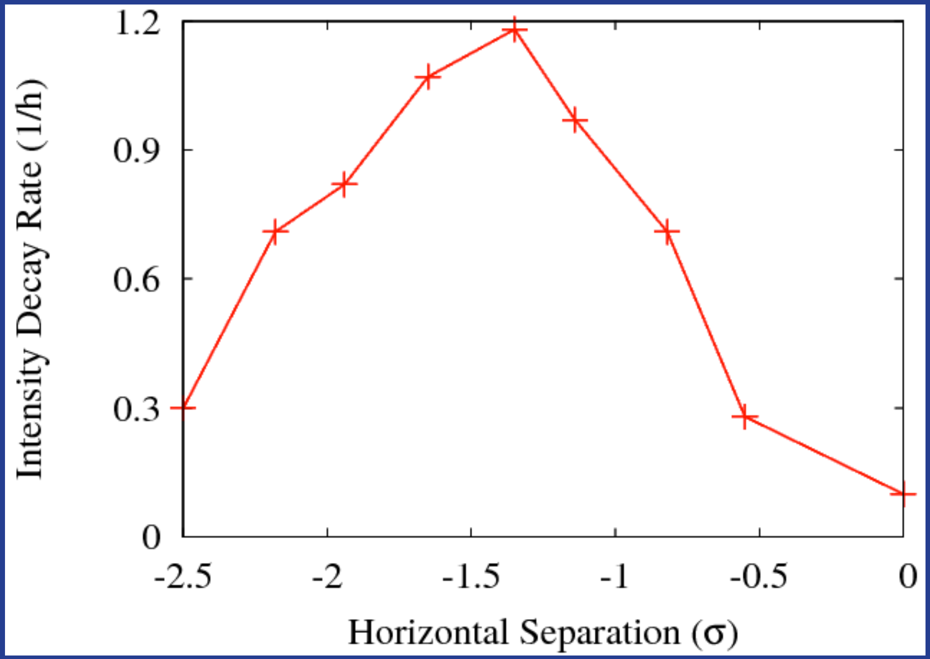
Effect of Beam-Beam on Coherent Stability

- The threshold betatron tune chromaticity vas studied as a function of beam-beam interaction
  - Nominally Tevatron operated at C=+14 without collisions and +5 at collisions
  - It was observed that for the nominal bunch intensity the instability is very fast slightly above C=0, causing a quench
  - During the studies it was verified that whenever beam-beam interaction is present, any chromaticity value can be dialed in without causing the head-tail instability
  - The effect was independent of the tune working point
- Difficulties
  - Studies of the effect of beam brightness were not performed due to unavailable bright antiprotons
  - Instrumentation did not acquire quantitative data on the instability increment

Effect of Transverse Separation

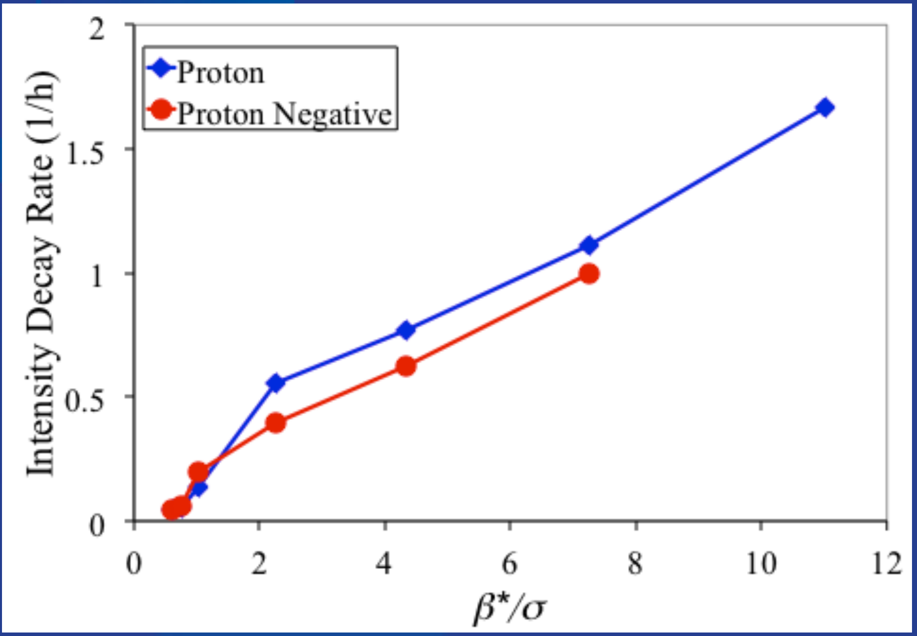
- Transverse separation scans were performed both in the horizontal and vertical plane
  - Emittance growth was not observed during the scans
  - Losses peak at the transverse separation of 1 to 1.5σ, consistent with simulations
  - The effect is working point-dependent

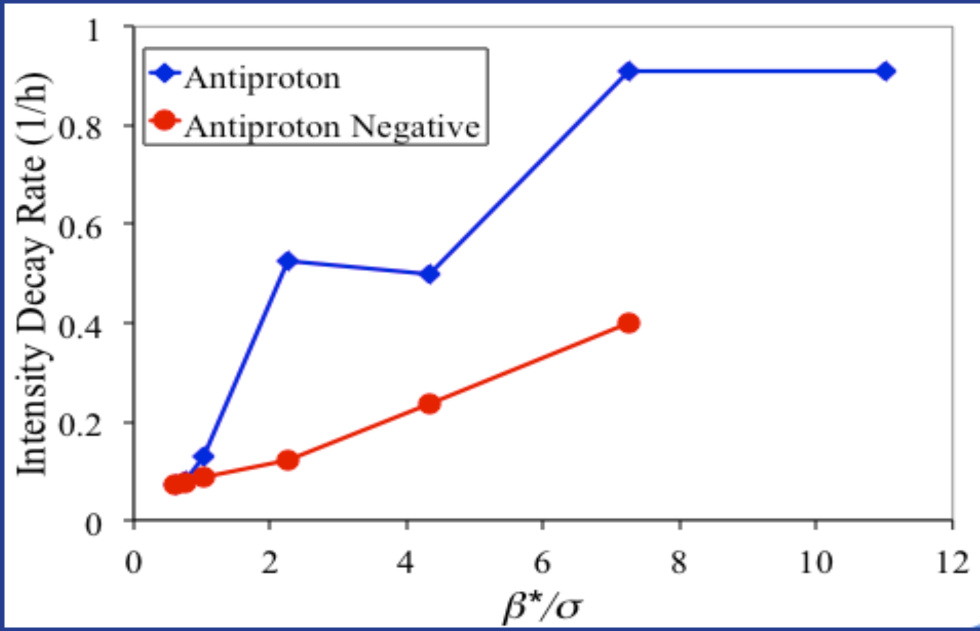




Effect of β^*/σ_z

- The goal was to collide bunches at different bunch length/ beta* ratios
  - This was achieved by cogging (moving antiproton bunches longitudinally wrt protons, thus colliding off beta minimum)
  - Produced excellent data, in qualitative agreement with expectations! Good for benchmarking simulations





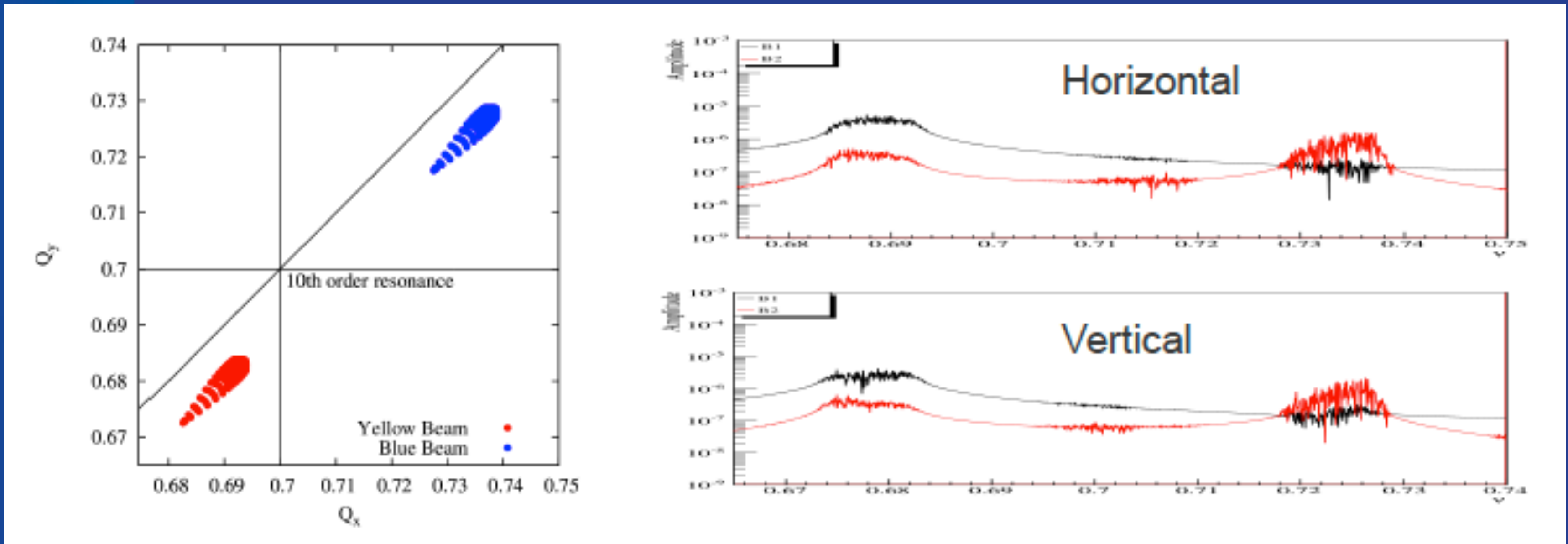
RHIC Beam-Beam Experiments

- At RHIC, beam time is regularly allocated for accelerator physics experiments
- This year several beam-beam studies were performed
  - Coherent beam-beam effects: modes suppression, tune scans
  - Beam beam and noise: white noise, orbit modulations, π-mode excitation
  - Large Piwinski angle was proposed. Due to a lack of time it was not conducted. Synchrotron tune much smaller at RHIC
- The beam-beam and noise experiments were organized in collaboration with CERN

S.White

Suppression of Coherent Beam-Beam Modes

- Coherent modes can be suppresses by splitting the tunes by an amount $\Delta Q > \xi$

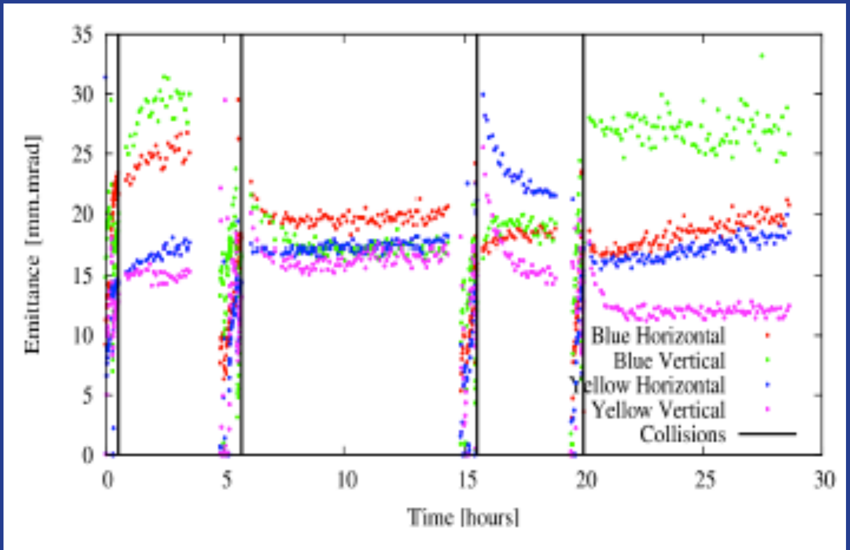


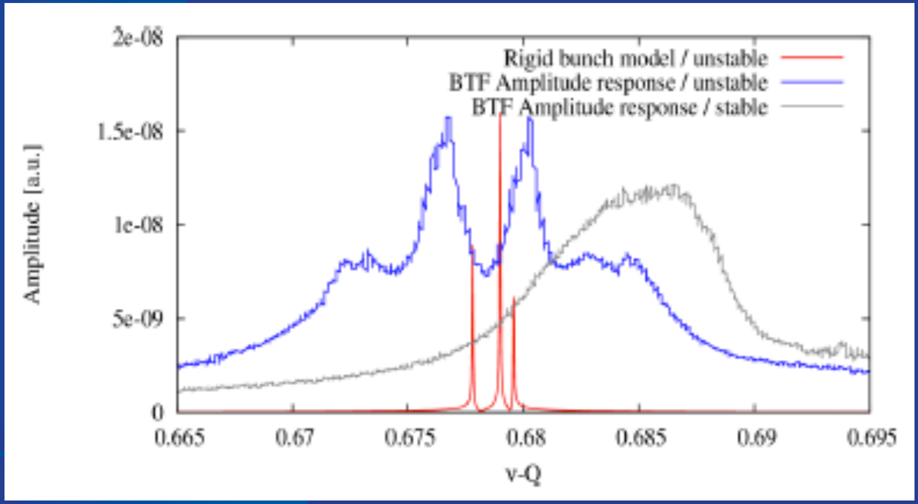
- Past studies (Y. Alexahin et al. LHC Project-Note 226) predicted excitation of coherent beam-beam resonances leading to emittance blow-up
- Interesting to verify experimentally. At RHIC it is possible to move one beam above 7/10 resonance to split the tunes by sufficient amount
- In this configuration simulations show a clear suppression of the modes

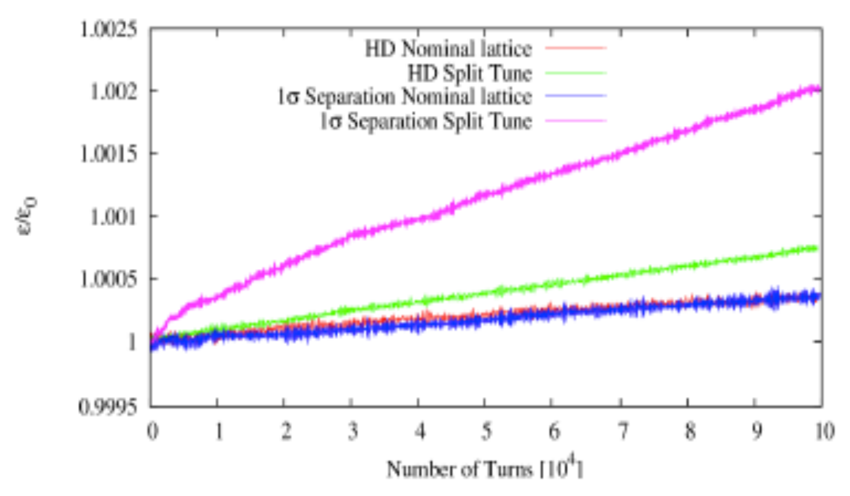
S.White

Experiment at RHIC

- 4 fills done with split tunes
- Strong emittance blow-up observed when going into collision in 3 of them
- Excitation of odd order resonance (offset collision) – tune dependent effect







- Also observed in simulations – requires more detailed analysis

Fermilab

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RHIC Beam-Beam + Noise Experiment

- The beam-beam and noise experiment was fully driven by CERN interests as relevant for operation with crab cavities and transverse damper
- Goal: understand the impact of noise on beam-beam interactions
- Experimental setup:
  - Fill RHIC with bunches of different ξ
  - Inject white noise into the beam and measure emittance blow-up as a function of ξ
- Preliminary results
  - The luminosity decay appears to be linear with noise amplitude $\rightarrow$ to be checked in simulations

LARP Beam-Beam Simulations

- LARP is now heavily involved in HL-LHC beam-beam studies
  - A.Valishev (FNAL) is HL-LHC WP2 Task 2.5 (Beam-Beam) leader
  - S.White (Toohig fellow, BNL) concentrates on beam-beam
  - J.Qiang, S.Paret (LBNL) work on beam-beam with crab cavities
  - D.Shatilov (BINP, Russia) was partially funded by LARP to work at FNAL for 6 months on beam-beam simulations/code development

LARP Beam-Beam Simulations Goals

- Investigate the options for HL-LHC
  - Choice of basic options – β^*, crossing scheme
  - Luminosity levelling techniques
  - Imperfections
- Develop self-consistent simulations of the beam-beam phenomena with other dynamical effects
  - Crab cavity
  - Interplay with machine impedance
- Help understand the experimental data from LHC as it becomes available
  - Also use RHIC and Tevatron experimental data for benchmarking simulations
- Support new ideas

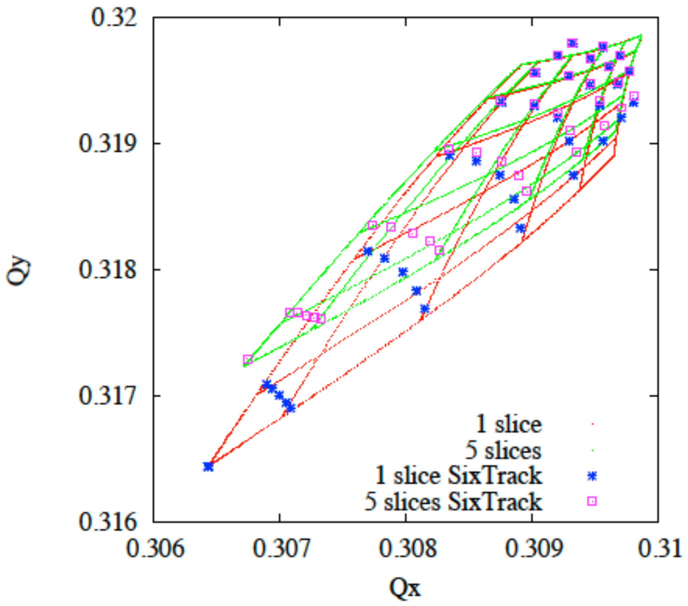
Simulation Methods, HL-LHC Integration

- Begin with madx lattice (WP2 Task 2.1) and performance parameters (Task 2.6)
  - Present performance data (CERN BB group)
  - Impedance models (Task 2.4)
- Tools / Characteristics for evaluation
  - Tune footprint (weak-strong, very fast)
  - Dynamic Aperture (weak-strong, fast)
  - Full-scale multiparticle simulation of intensity and emittance life time (weak-strong, slow)
  - Self-consistent multi-effect simulation (strong-strong, short reach as far as the number of turns, slowest)

Simulation Tools

- Weak-strong
  - SixTrack (F. Schmidt). Well-tested code, the backbone of tracking studies for LHC design.
  - Lifetrac (D. Shatilov). Many years of use for electron machines and Tevatron. Very good support of 6D beam-beam with crossing angle
  - The two codes were benchmarked against each other as part of LARP collaboration. Good agreement for the case of LHC simulations was established.

  (CERN-ATS-Note-2012-040)

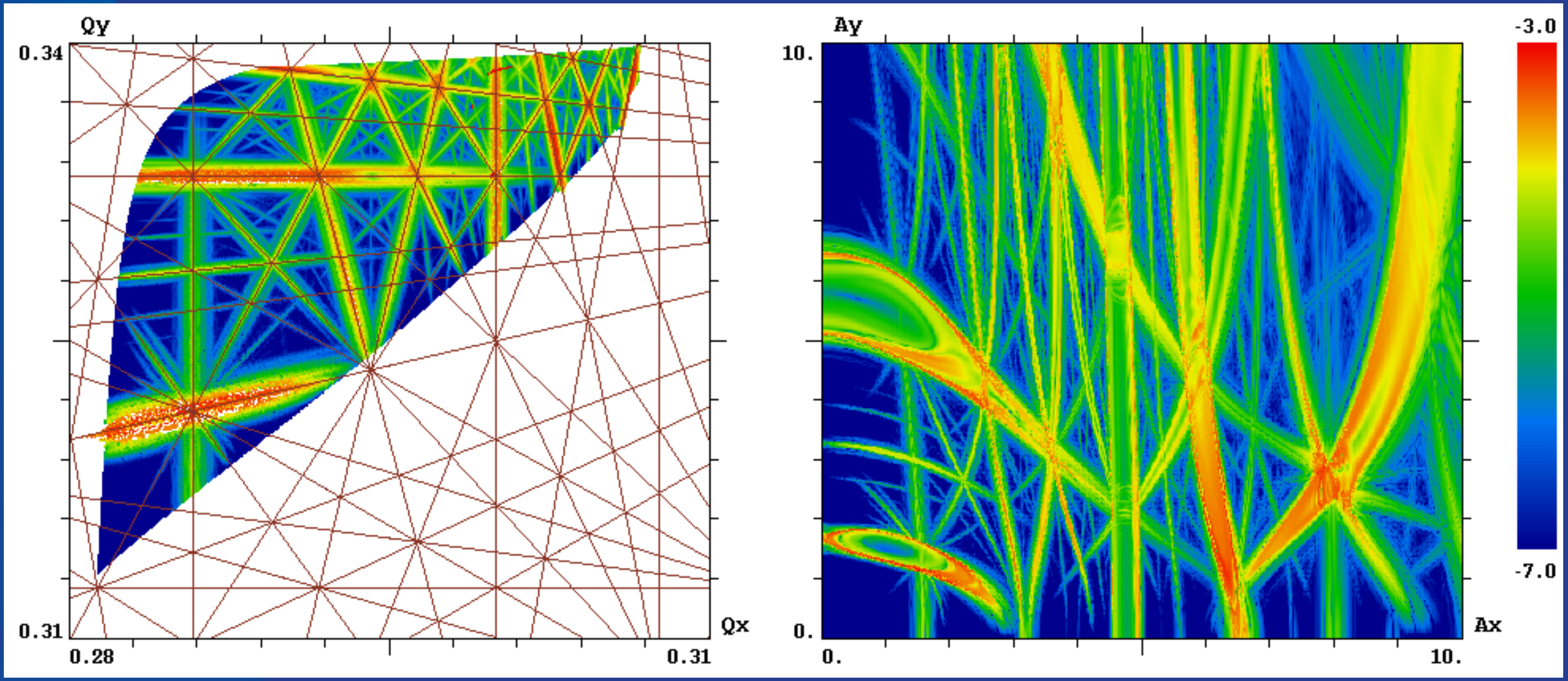


- Strong-Strong
  - BeamBeam3D (J. Qiang). Many users – LBNL, FNAL, BNL
  - BBSIM (T. Sen). Module for crab-cavity

D.Shatilov

Lifetrac

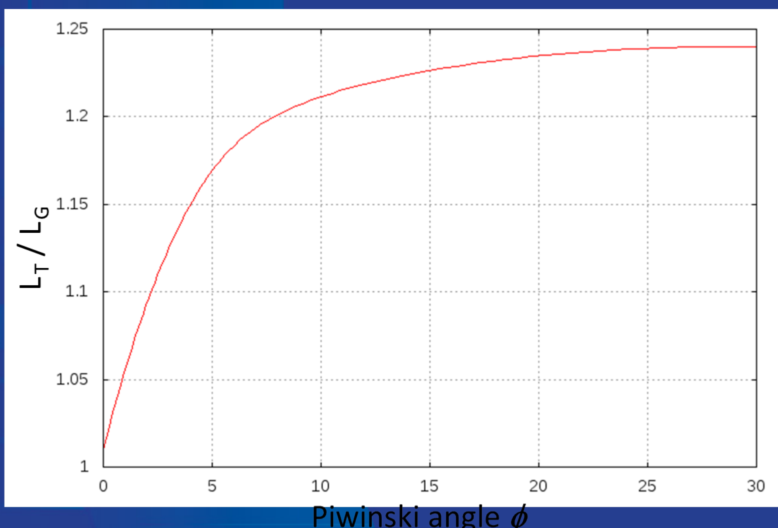
- Weak-strong beam-beam tracking code
  - Frequency Map Analysis (J. Lascar, “The Chaotic Motion of the Solar System: A Numerical Estimate of the Size of the Chaotic Zones”, Icarus 88, 266, 1990)
  - Multi-particle, multi-turn tracking
  - Machine model with full set of features imported from madx – lattice, crossing schemes, nonlinearities

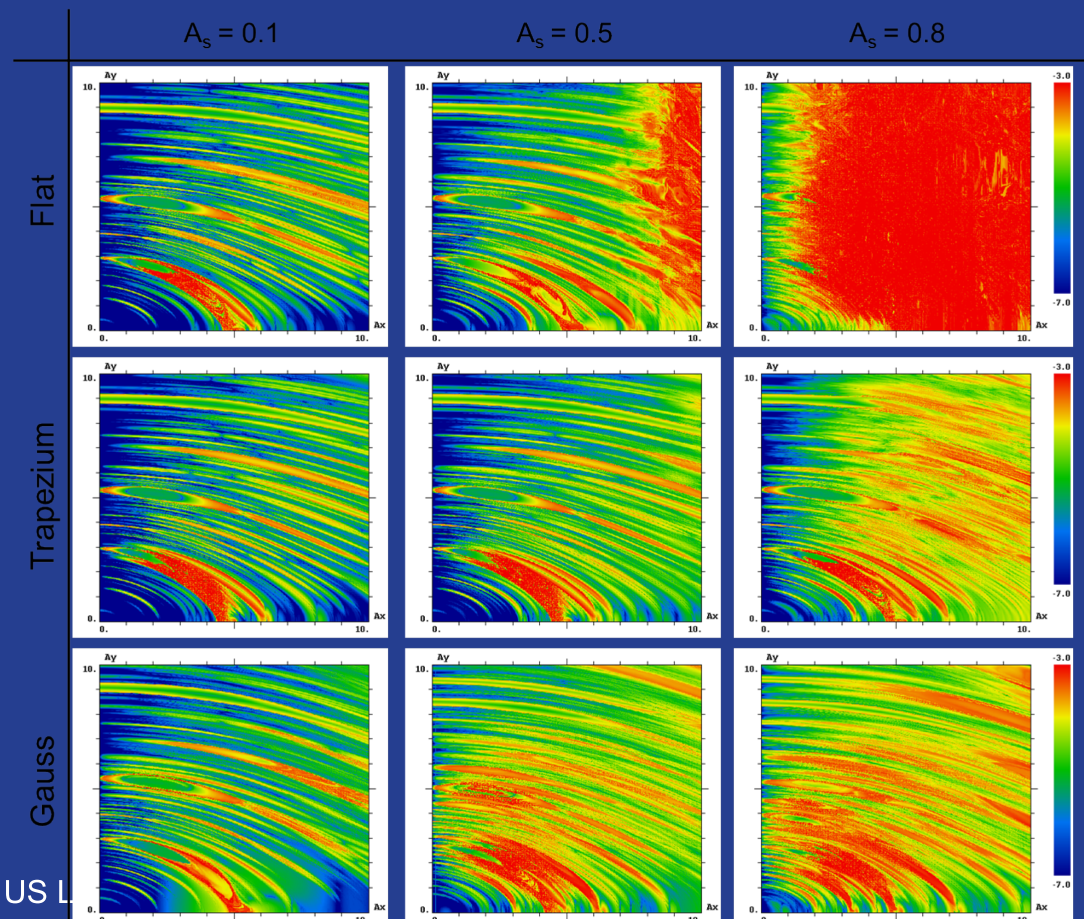


D.Shatilov, M.Zobov

Study of Flat-Bunch Option

- Found that luminosity gain is highly dependent on the actual longitudinal profile and Piwinski angle. For realistic case the gain much less than √
- Studied limitations due to synchro-betatron dynamics



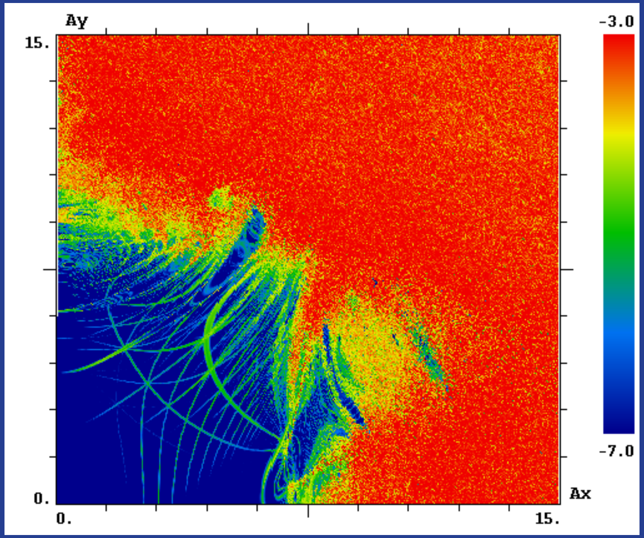


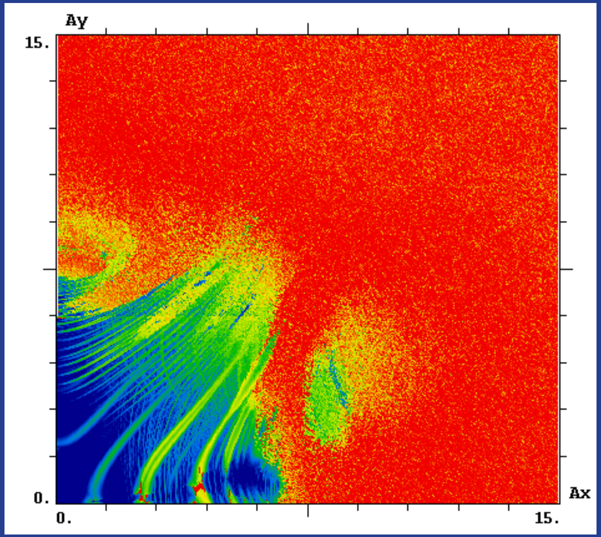
D.Shatilov

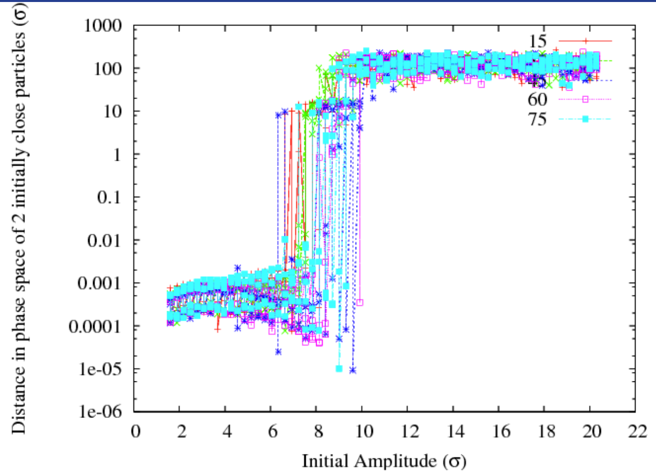
Evaluation of HL-LHC Options (Ongoing)

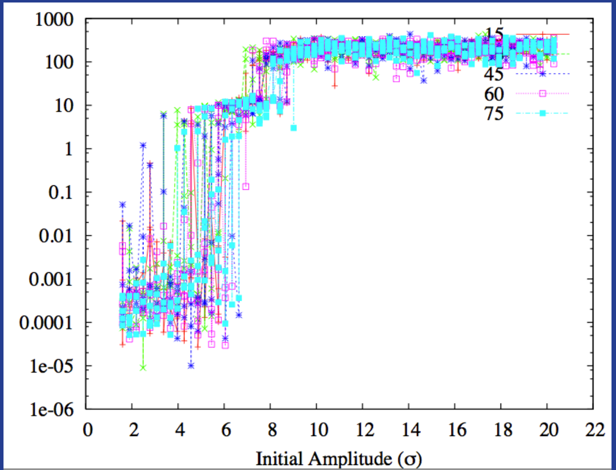
- FMA and DA for β^*=15 cm HL-LHC optics

$A_s = 0$ | $A_s = 1$









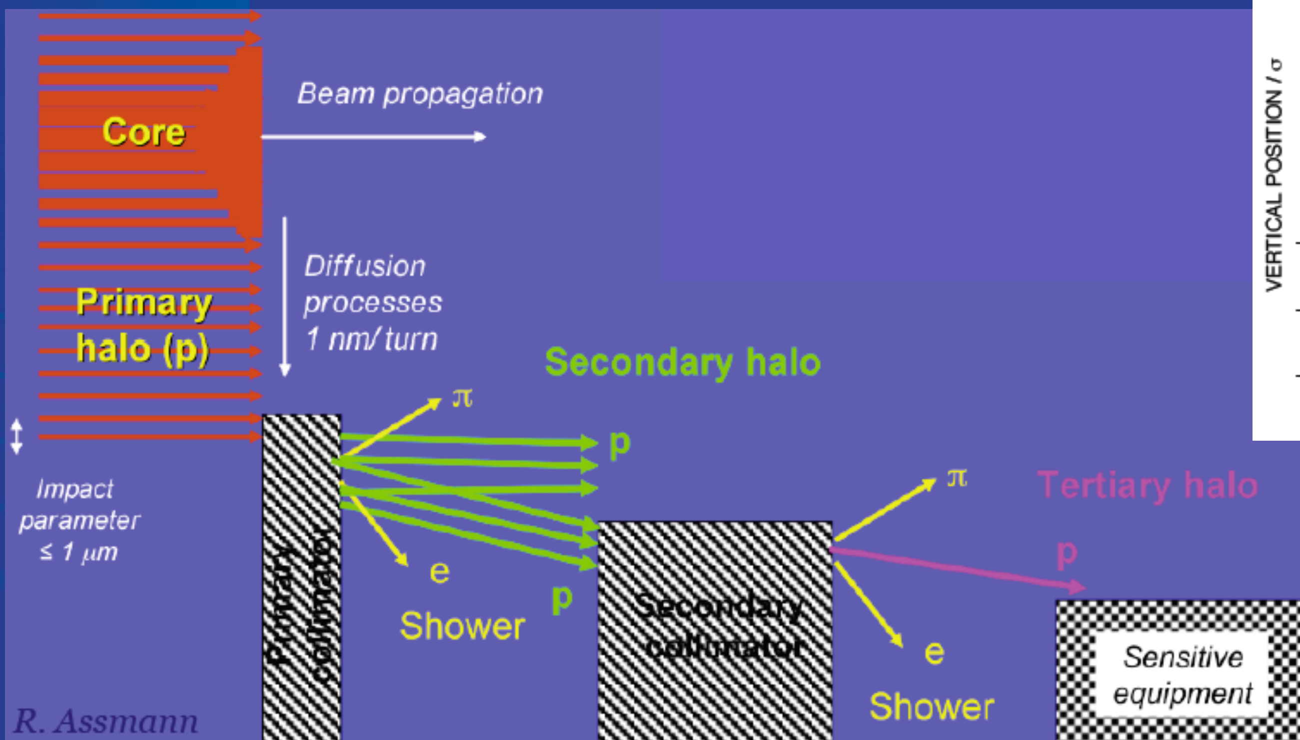
S.White

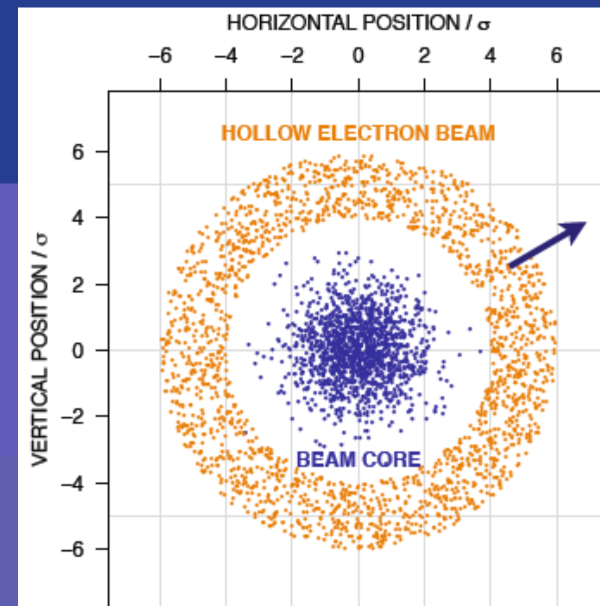
Simulation of Interplay of Impedance and Beam-Beam (Ongoing)

- Instabilities were observed in collision at the LHC. The actual cure is to run with the transverse damper on in collision: emittance blow up
- HL-LHC will run with significantly higher bunch intensity – issues?
- We have a well benchmarked strong-strong beam-beam code (BB3D, J. Qiang)
  - Added impedance model → resistive wall and broadband resonator implemented for multi-bunch
  - Benchmark against hea-dtail ongoing using SPS lattice which was already extensively studied – plan also to cross-check model against VEPP data
  - The challenge would be to simulate a full LHC train with head-on and long-range interactions → the code needs significant development in terms of computing efficiency to achieve this goal (multi-bunch parallelization?)

Hollow Electron Beam Collimator (Diffuser) The Concept

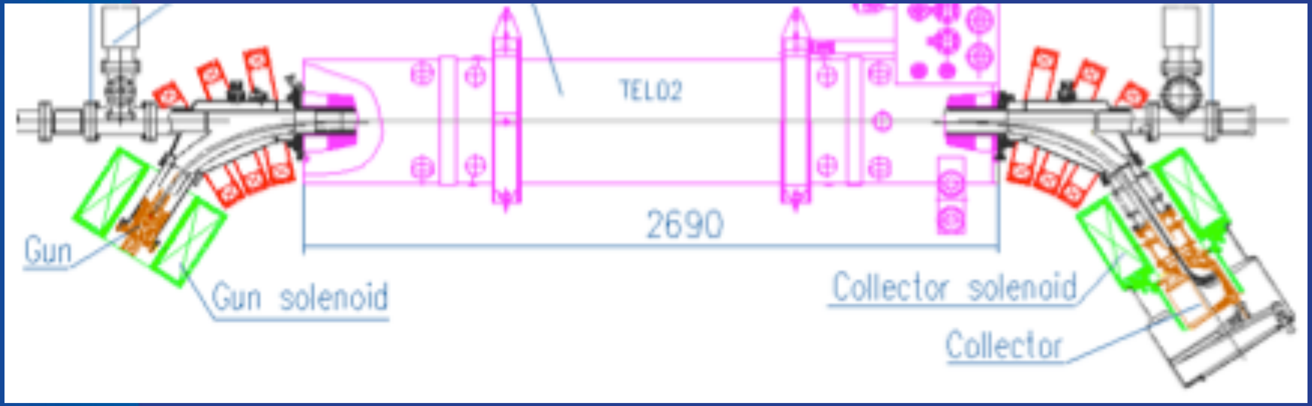
- Enhance diffusion for halo particles to decrease halo population and suppress loss spikes
  - No material damage – compatible with high power
  - Low impedance

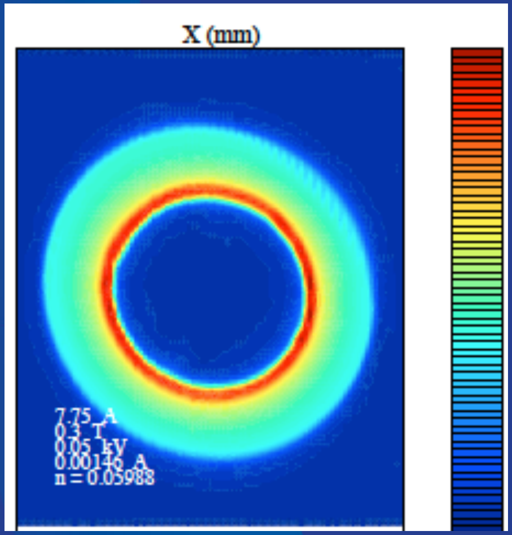


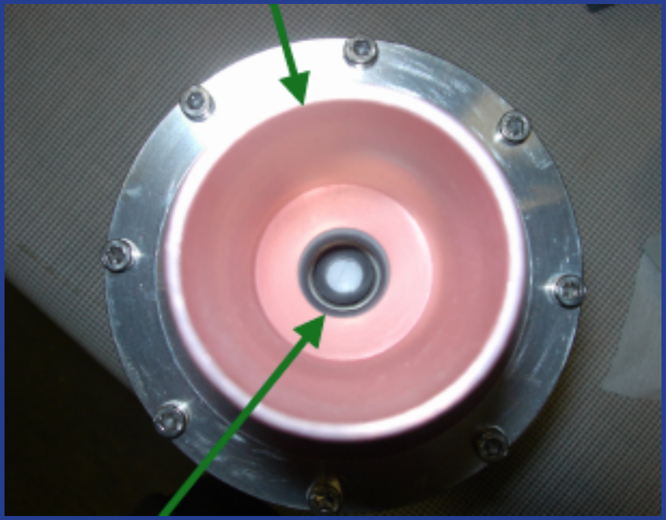


V.Shiltsev et al EPAC08

Collimation with Hollow Electron Beams
Modification of Tevatron Electron Lens TEL-2







Tungsten dispenser cathode with convex surface. Diameter 15mm, hole 9mm

G.Stancari

Status of HEBC

- Tevatron experiments (Oct. '10 - Sep. '11) provided experimental foundation
- Main results
  - compatibility with collider operations
  - alignment is reliable and reproducible
  - smooth halo removal
  - removal rate vs. particle amplitude
  - negligible effects on the core (particle removal or emittance growth)
  - transverse beam diffusion enhancement
  - suppression of loss-rate fluctuations (beam jitter, tune changes)
  - effects on collimation efficiency
- First results:
  - Phys. Rev. Lett. 107, 084802 (2011)
  - IPAC11, p. 1939
  - APS/DPF Proceedings, arXiv:1110.0144 [physics.acc-ph]

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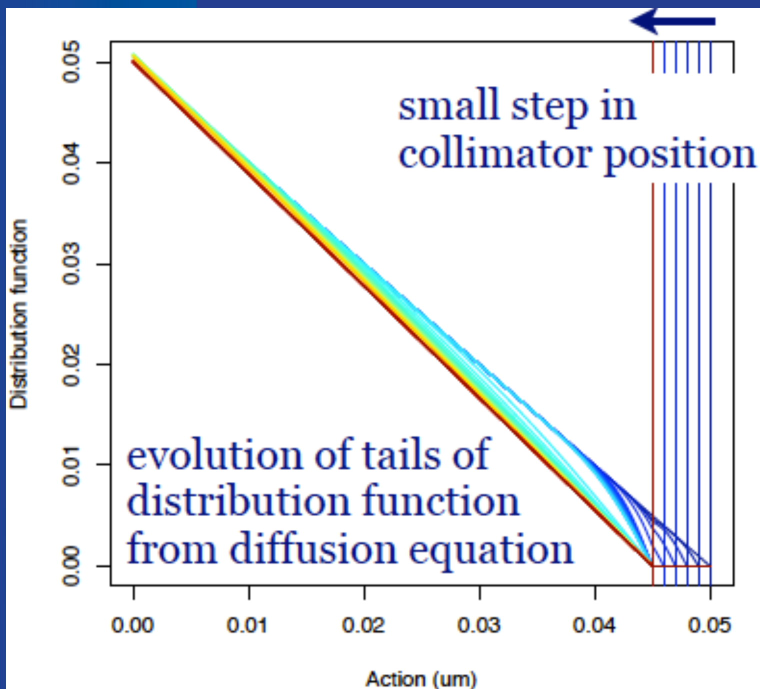
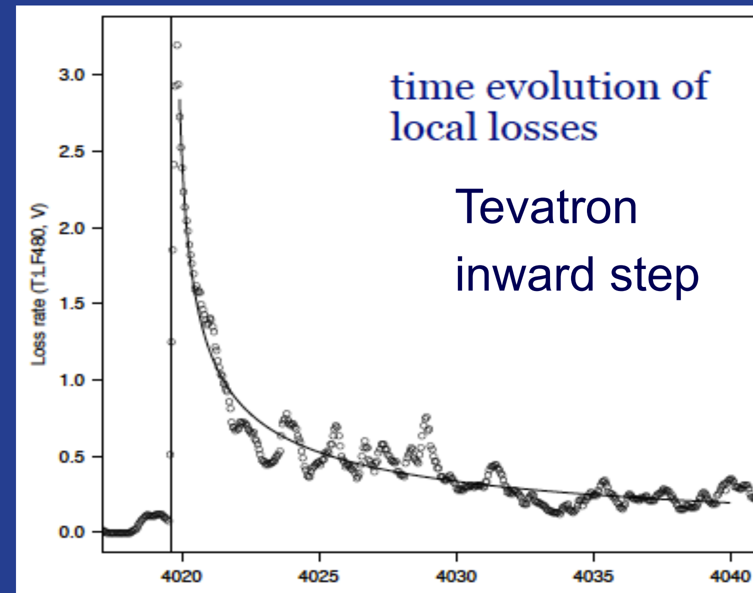
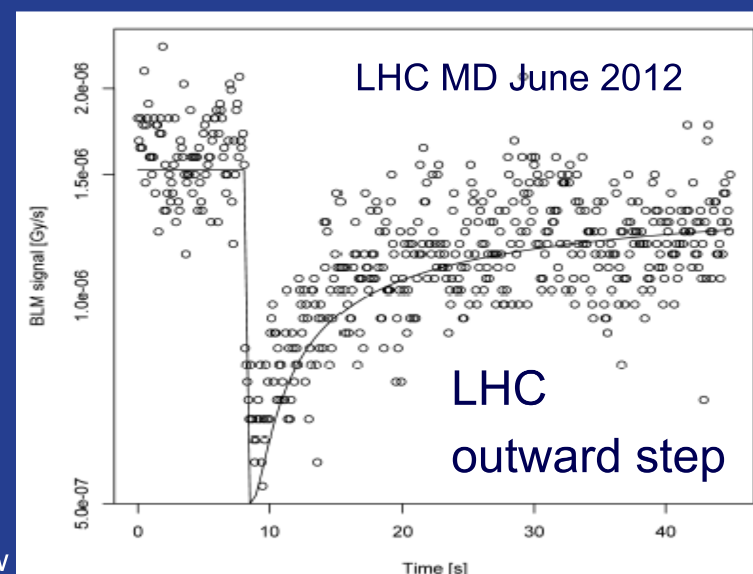
Diffusion Measurements at the Tevatron and LHC







Mess and Seidel, NIM A 351, 279 (1994)

observed loss rate; collimator step and position; background

$$L(t) = a_1 \left\{ 1 + \frac{|\Delta x_c| / x_c}{\sqrt{\pi R (t - t_0)}} \right\} + a_0$$

normalization (intensity, efficiency, ...); parameter related to diffusion rate

$$D = R \cdot x_c^4 / \beta_c^2$$

Time (s)

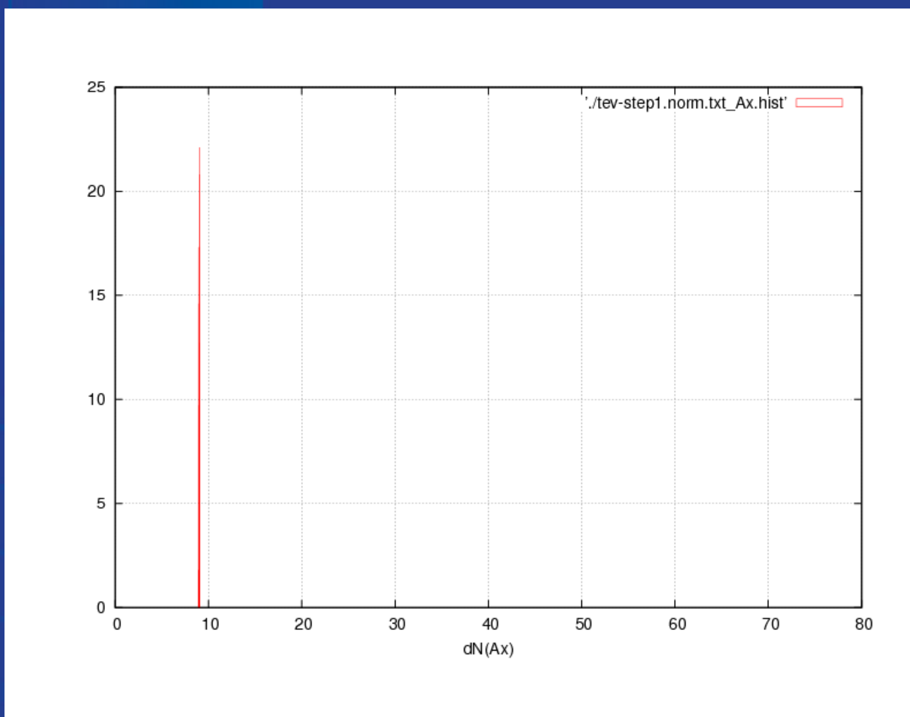
G.Stancari

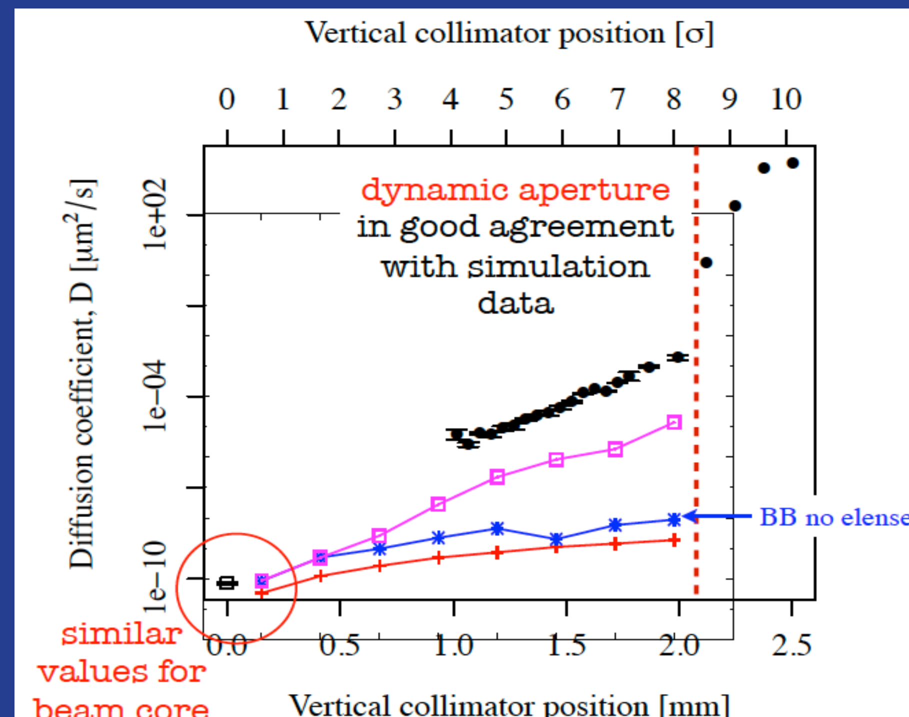
Current Directions

- Numerical simulations
  - Understanding of Tevatron observations
  - Predictions for LHC
  - Main observables
    - halo removal rates
    - diffusion enhancement
- Development of hollow electron guns
  - Preserve design/testing technology
  - Produce prototypes for LHC
- TEL2 integration in LHC/SPS
  - Preparatory work at FNAL
  - Scientific and technical aspects

Simulations of Diffusion in Tevatron (ongoing)

- Macro-particle simulation
  - The goal is to reproduce Tevatron observations
  - With/without beam-beam and HEBC



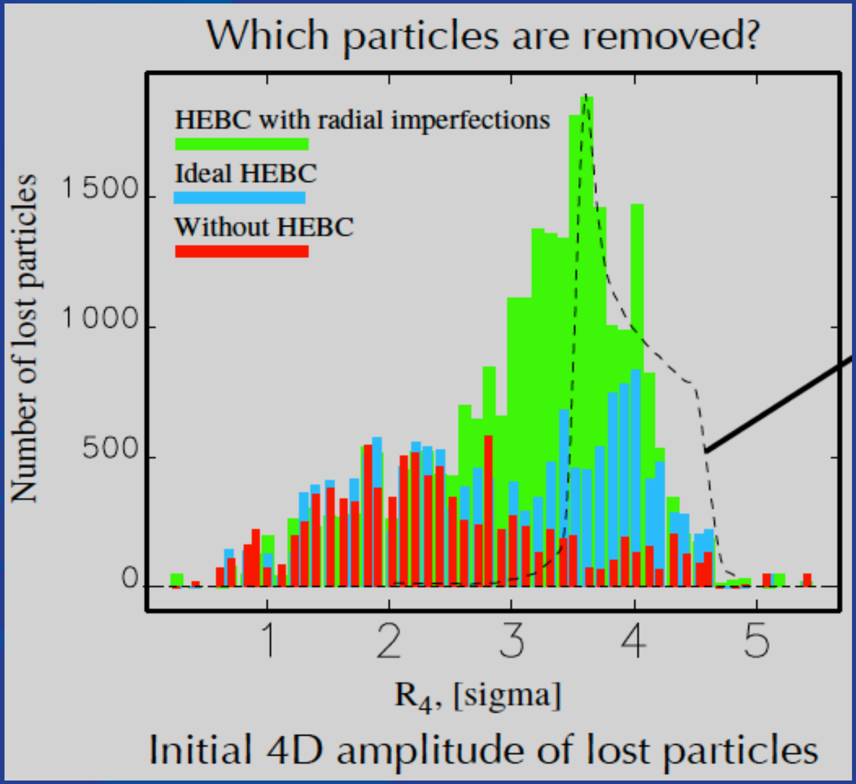


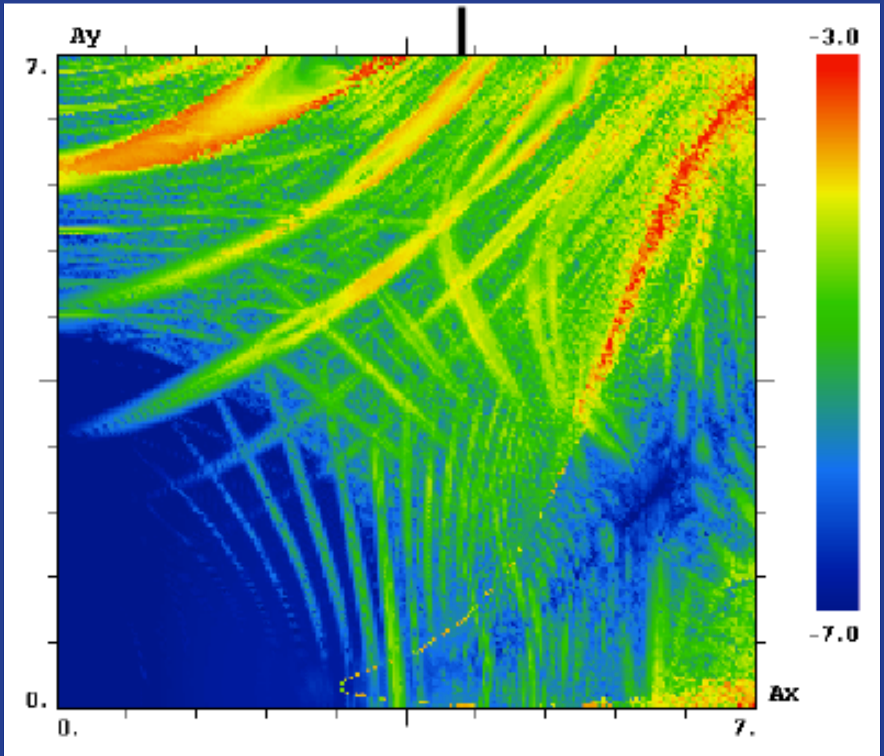
Fermilab

I.Morozov

Simulations of HEBC in Tevatron and LHC (ongoing)

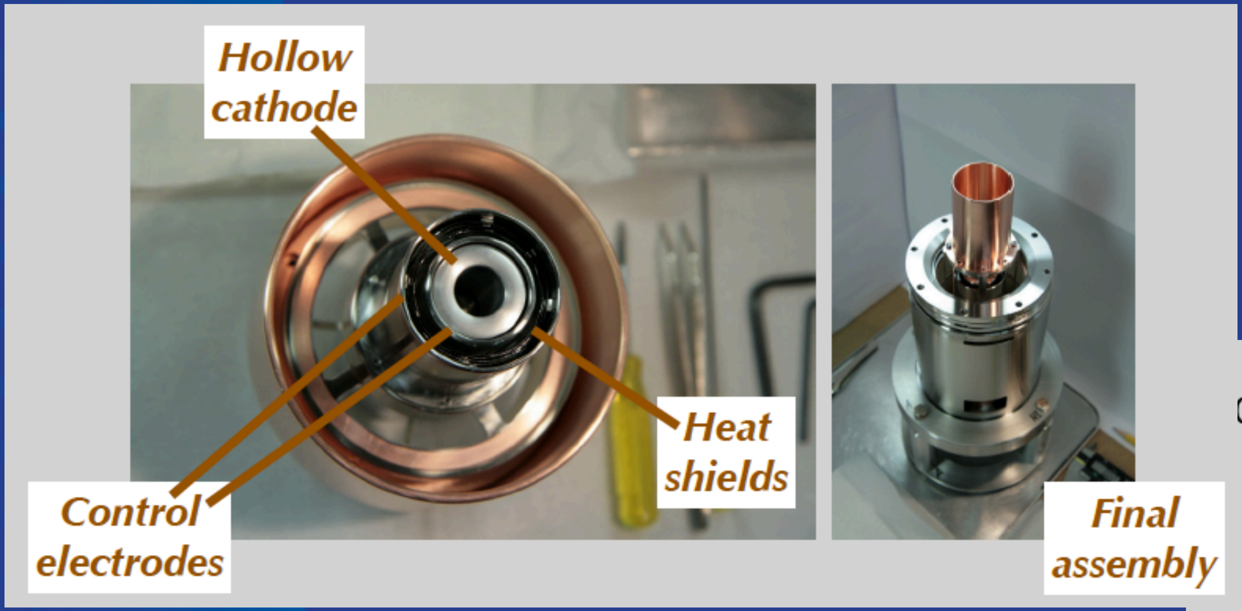
- Macro-particle simulation
  - The goal is to reproduce Tevatron observations
  - Predict TEL-2 performance in LHC (or SPS)



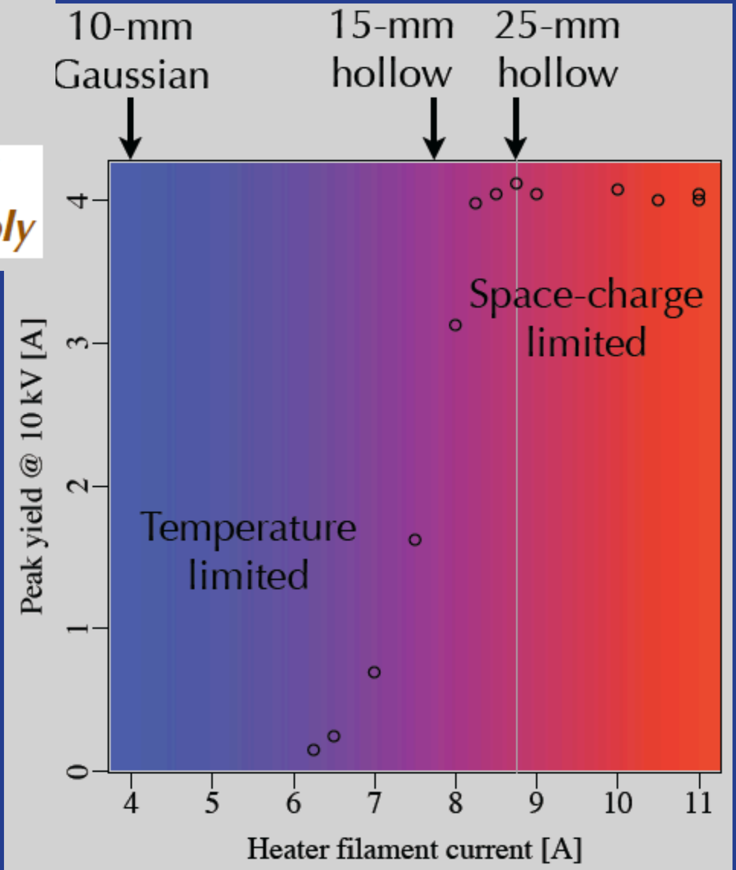


A.Didenko

New 25-mm Hollow Gun



- 25 mm outer diameter, 13.5 inner diameter
- Designed with LHC in mind: 2.2 A at 5 kV, 6.3 A at 10 kV
- Goal: test technical feasibility of stronger scraper
- Characterized at Fermilab electron-lens test stand



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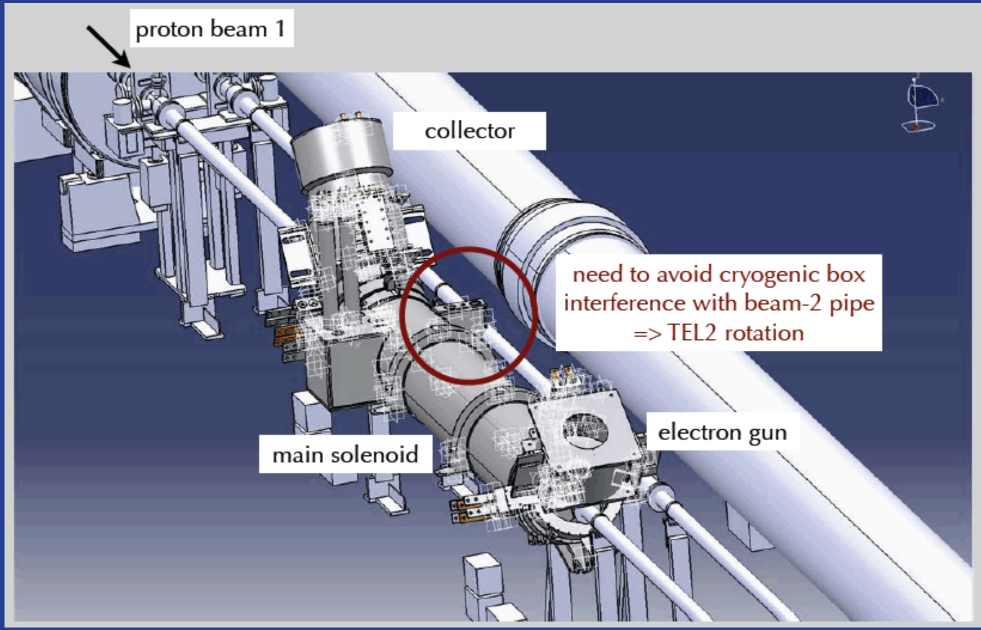
Application of HEBC at CERN

- Purpose:
  - study physics of hollow electron beam collimation in LHC
  - complement primary collimators
  - flexible halo control
- Practical considerations:
  - preparatory studies possible during dead time of accelerator complex (beam alignment, pulse synchronization)
  - can be operated parasitically (abort gap, few bunches, end of fill)
  - safe: can always be turned off
  - potentially high physics payoff for relatively low cost and low risk
- When and where?
  - LHC or SPS
    - LHC more interesting, better beam and diagnostics
    - SPS higher availability, easier installation
  - Is LS1 installation feasible? Schedule:
    - LHC/SPS dynamics simulations and integration, impedance budget – finish in August
    - Proposal to LMC in September

TEL-2 Integration Study in LHC: IR4/RB44

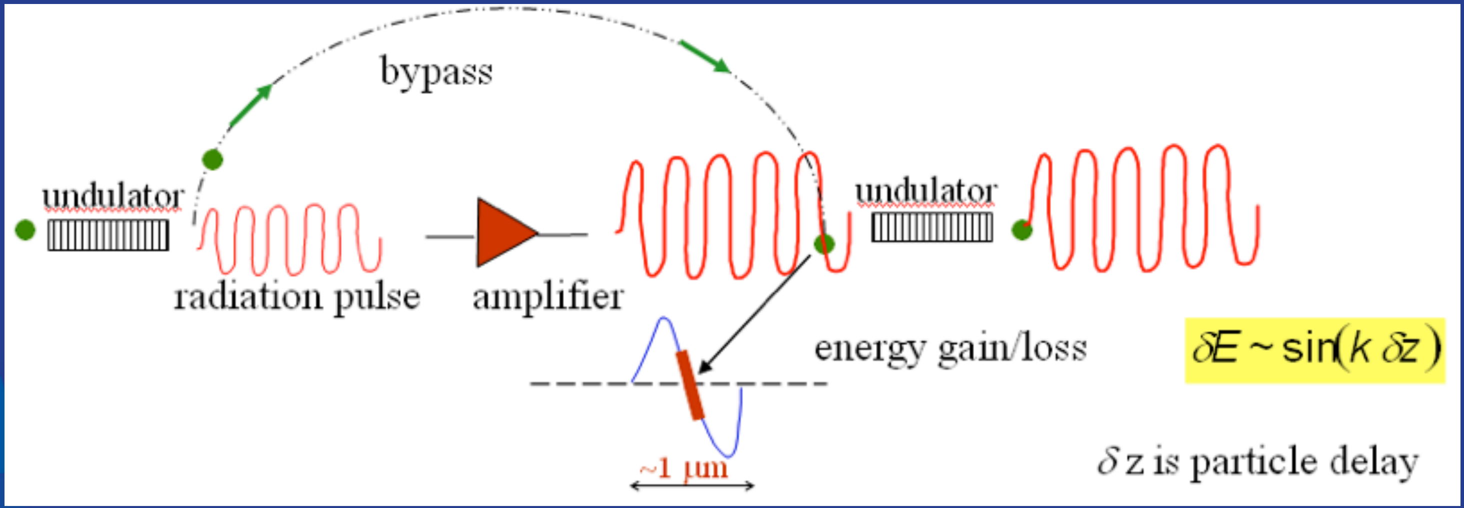


- Physical space is tight but mechanical integration seems feasible
- No liquid N_2 available. Possible solutions: use high pressure helium (requires TEL2 tests) or reduce pressure. Substantial cryogenic work may be required
- Some preparatory work can be done at Fermilab:
  - vacuum and cryogenic checks
  - residual radioactivity

V.Lebedev

New (for LARP) Idea:
Optical Stochastic Cooling

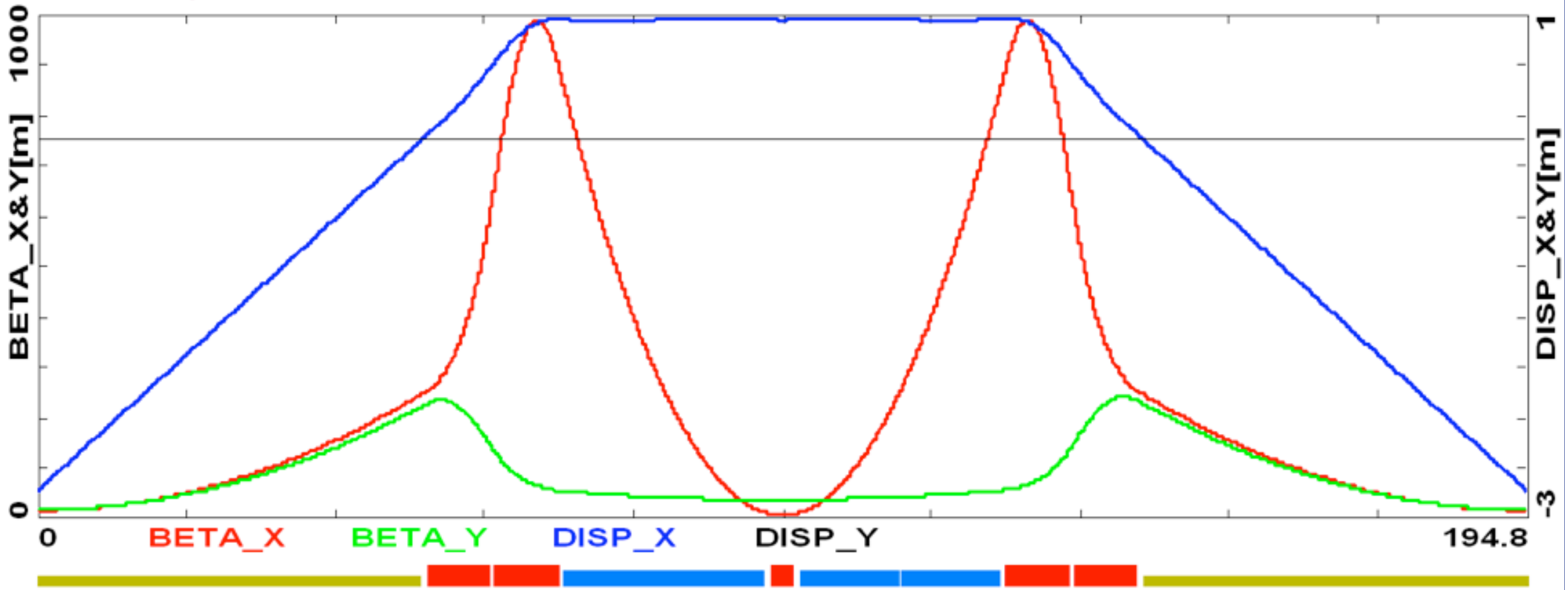
- Suggested by Zolotorev, Zholents and Mikhailichenko (1994)
- Never tested experimentally
- OSC obeys the same principles as the microwave stochastic cooling, but exploits the superior bandwidth of optical amplifiers ~10^{14} Hz
- Undulator can be used as pickup & kicker
- Pick-up and Kicker should be installed at locations with nonzero dispersion to have both ⊥ and L cooling



OSC for LHC

Beam energy	6 TeV
Bunch population	$1.5 \cdot 10^{11}$
Number of bunches	2808
Initial rms norm. emittance	2 mm mrad
Initial momentum spread	$0.95 \cdot 10^{-4}$
Basic Wave Length of OSC	0.2 μm
Undulator type	helical
Undulator parameter	1.93
Undulator magnetic field	11 T
Undulator period	3.5 m
Number of periods	29
Undulator length	100 m
Total power of SR from one undulator	37 W
Longitudinal cooling range	3σ
Transverse cooling range	5.5σ
Longitudinal emittance cooling time	5.5 h
Transverse emittance cooling time, $\tau_x = \tau_x$	4 h

OSC for LHC



Beta-functions and dispersion for OSC section;
Only half of each undulator shown (yellow rectangles)

Total length of cooling section	300 m
Magnetic field in dipole chicane	10 T
Dipole length	12.7 m
Horizontal beam offset in chicane	100 mm
Delay in the chicane	0.52 mm
M_{56}	0.96 mm
Partial M_{56}	0.26 mm

Parameters of Quadrupoles

	L [m]	G [kG/cm]
Qf	8	20.43
Qd	8	-17.95
Qc	3	-4.5

V.Lebedev

OSC for LHC

- Passive optical stochastic cooling is sufficient to prevent emittance dilution and perform luminosity leveling
  - Alternative to crab cavity and other luminosity leveling techniques
- Cooling effectiveness grows with wiggler magnetic field
  - Using larger B would increase cooling
  - The parameters of proposed setup can be achieved with modern technology
- Beam optics manipulations allows one to adjust distribution of cooling decrements between different degrees of freedom
- Experimental proof is necessary
  - It can be performed in a small ring with electrons (E~150 MeV)
  - Fermilab is constructing IOTA ring for accelerator physics experiments with option to include OSC
  - Should LHC be interested in this technology, it fits well the mission of LARP to participate in the proof-of-principle experiment and perform studies of integration into the LHC

Summary

- LARP beam-beam task is well integrated into HL-LHC study
  - Good team formed over years
    - + now a Toohig fellow S.White
  - Expect to make valuable contribution to the luminosity upgrade studies
- Hollow Electron Beam lens Collimator is a promising technology that was developed by LARP
  - Plan to perform a test at CERN
    - Proposal to LMC in September
  - Work on details of application at the LHC ongoing
    - Toohig fellow V.Previtali
- Propose Optical Stochastic Cooling for luminosity leveling
  - Support proof-of-principle experiment at Fermilab?