Beam Dynamics

Marco Venturini

Center for Beam Physics, LBNL

ILC-DR EDR Kick-Off Meeting.

Daresbury 5-7 November, 2007

Ground covered in this talk

- **Machine impedance and impedance-driven classical instabilities**
- **“Other” collective effects:**
  - Space charge.
  - Intrabeam scattering
  - Touscheck effects
  - CSR (?)

- Issues of beam dynamics related to single-particle dynamics, e-cloud, and fast ion instabilities belong elsewhere

- The material reviewed here fits into the following proposed Work Packages:
  - WP5 (Impedance, classical instabilities)
  - WP9 (‘Other’ collective effects)

Outline

- **Impedance modeling and instabilities (WP5)**
  - Review of pre and post RDR work
  - Plan of action for EDR phase
  - Institutions and people involved

- **'Other' collective effects (WP9)**
  - Short review of pre RDR work
  - List of deliverables
  - Institutions and people involved

Impedance modeling and classical instabilities: WP5

Work on impedance modeling initiated with lattice Configuration Studies

- A first pass at estimating impedance-driven instabilities was made during the baseline Configuration Studies – the OCS lattice considered at the time not too far from the current version of the OCSn lattice.

- Configurations Studies were limited in many ways:
  - Goal to provide relative ranking of various lattices being considered rather than accurate characterization of effects.
  - Estimates of instabilities based on rough (and in some cases admittedly unreliable) analytical models for impedances.
  - Parameters in analytical models determined from measurements on existing machines and/or scaled to design specifications of DR lattices.

- Results from Configurations Studies helped in shaping priorities for further studies. For example:
  - Current thresholds for single-bunch longitudinal instabilities turned out a bit low.
  - Current thresholds for TMCI were well above design current.

Example of impedance modelling and instability estimate for lattice Configuration Studies

- A simple analytical model is used to account for small, mostly inductive machine components (BPMs, bellows, etc).

$$Z_{||}(\omega) = -i\frac{\omega L}{(1 - i\omega a/c)^{3/2}}$$

S. Heifets

- Inductance L and loss factor a in formula estimated by scaling from PEP-II measurements.

$$L = L_{\rm PEP} \sum_i \left(\frac{N_{quads,i}}{N_{\rm PEP}}\right)\left(\frac{b_{\rm PEP}}{b_i}\right)^2 + N_{cav} L_{SC}$$

Boussard-Keil-Schnell formula used to estimate single-bunch longitudinal instability threshold from total impedance

$$\frac{Z}{n} = Z_0\sqrt{\frac{\pi}{2}}\frac{\gamma\alpha_p\sigma_\delta^2\sigma_z}{N_0 r_e}$$

Table 3.26: Microwave instability threshold for the damping rings estimated from the Keil-Schnell-Boussard criterion.

Lattice	Estimated impedance Z/n [mΩ]	Estimated instability threshold Z/n [mΩ]
PPA	475	187
OTW	701	299
OCS	465	134
BRU	726	622
MCH	294	510
DAS	189	95
TESLA	196	100
PEP-II LER	151	92

Work after Configuration Studies

- Started work toward a more accurate characterization of the machine impedance and estimate of the current thresholds for instability.

- Following up on the outcome of the Configuration Studies the initial focus has been placed on the study of longitudinal single-bunch (‘microwave’) instability.

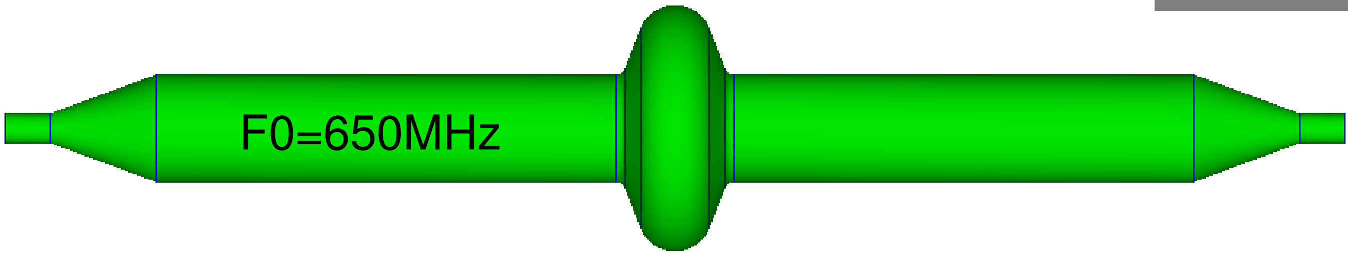
- Began a program (defined at DR Workshop at Cornell, 2006) to generate numerical modeling of the short-range wake potentials for the main components.
  - Design of components scaled from design of devices in existing machines

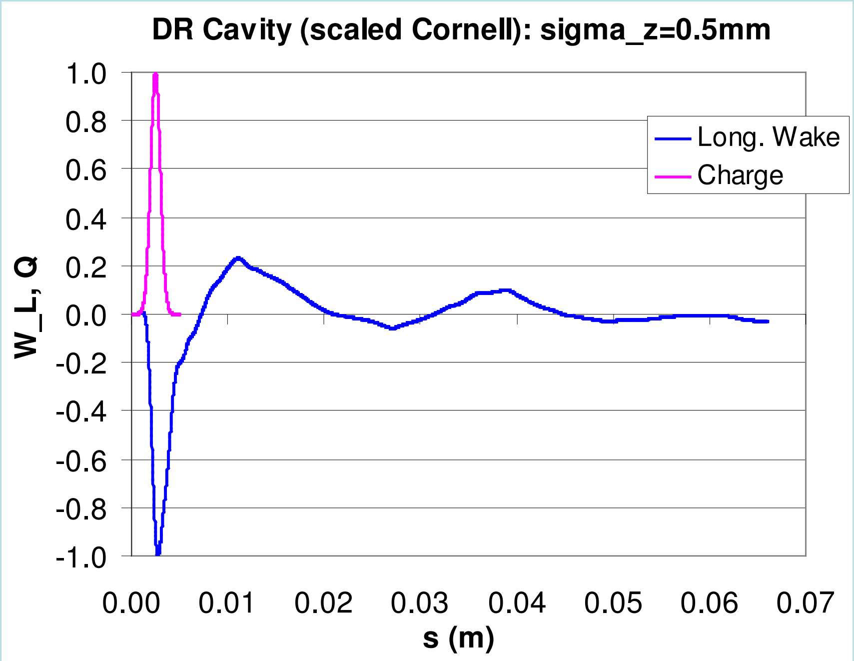
- Conducted bench-mark studies to test a few alternate methods to detect instability in the beam dynamics for a given model of wake potential:
  - Macroparticle simulations
  - Vlasov solver
  - Linearized Vlasov equation (mode analysis; direct solver)

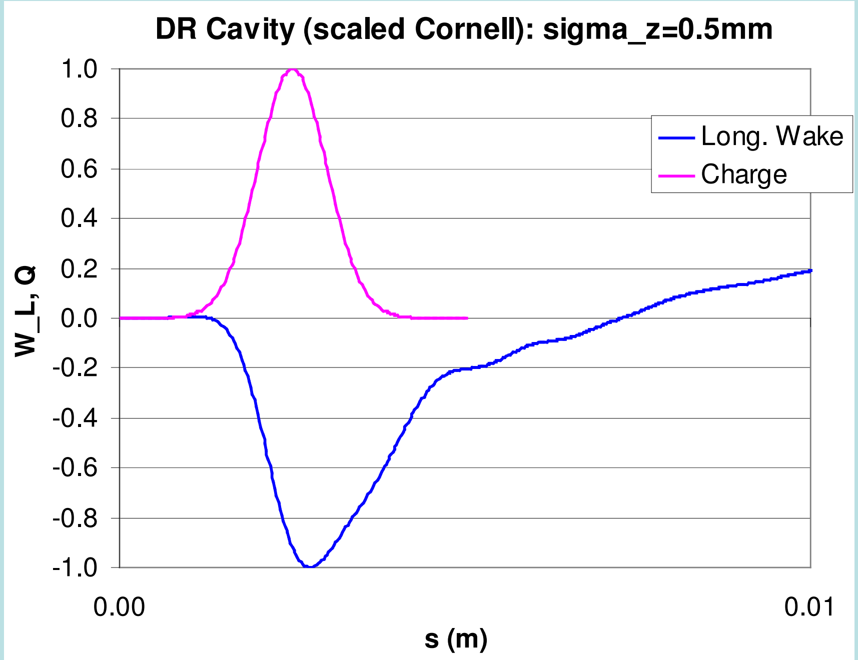
Compiling an impedance census

Component		Priority	Model available?
rf Cavities	2D	High	Yes
Resistive wall	Analytic	High	Yes
Bellows	3D	Low	Yes
BPMs	3D	High	Yes
Antichamber Slots	3D	Medium	Yes
Long. Feedback kickers	3D	Medium	Yes
Trans. Feedback kickers	3D	Medium	Yes
Feedback pickup	3D	Low	No
Inj/Extr kickers	3D	Medium	Yes
Vacuum pump ports	3D	Medium	No
Collimators	3D	Medium	Yes
Taper	2D/3D	High	Yes
Microgrooves (eCloud)	3D		Yes
Clearing electrodes (eCloud)	3D		Yes
CSR from dipoles	Analytic	Low	Yes
CSR from wigglers	Analytic	Low	Yes

Numerical modeling of devices: SC cavities





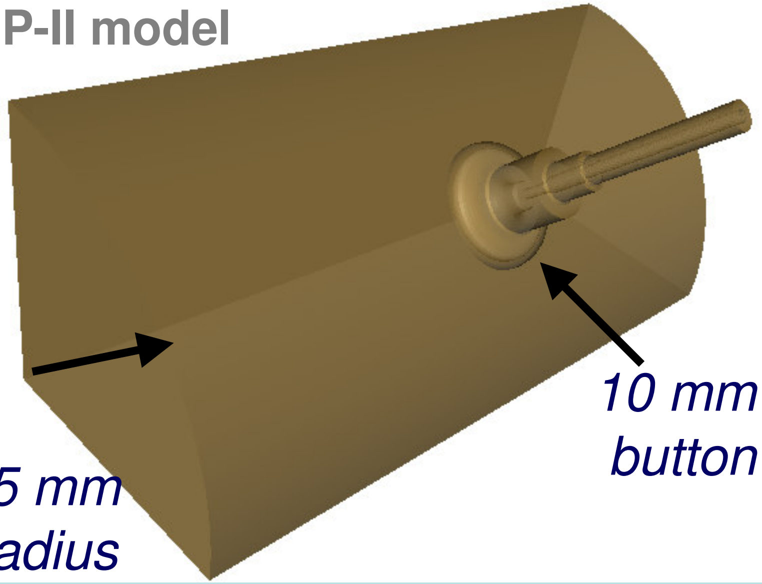


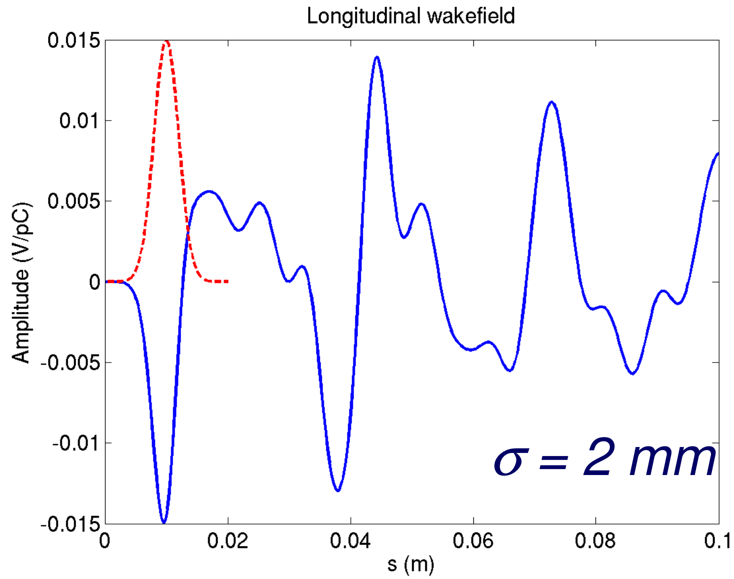
Min/Max = -2.205E+01/ 5.099E+00 V/pC
Loss Factor = -1.617E+01 V/pC

Calculations by C. Ng

Numerical modeling of devices: BPMs

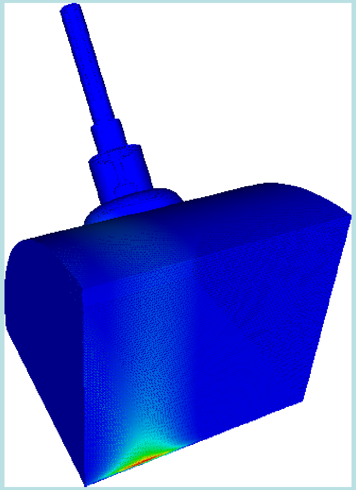
PEP-II model

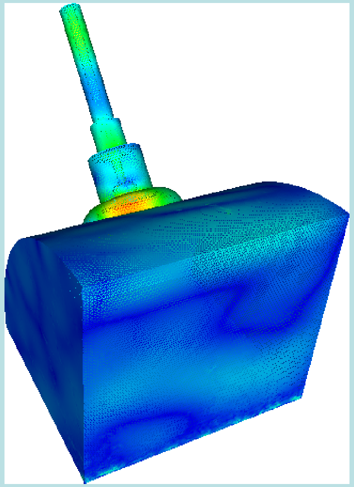


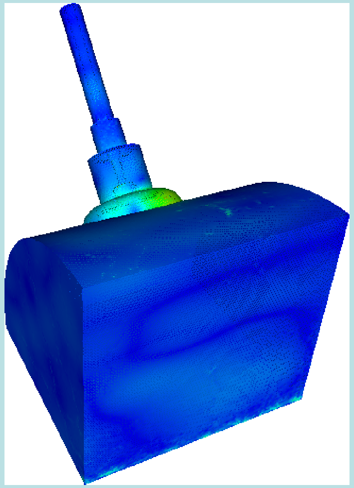


3D code T3P used

Snapshots of beam transit



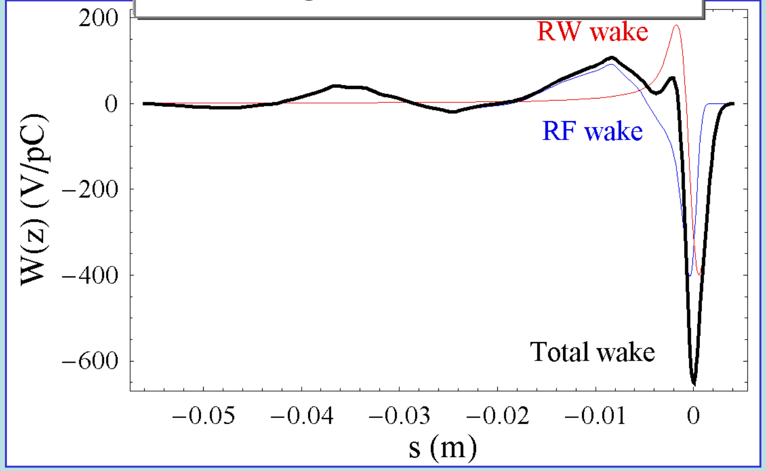




Calculations by (C. Ng)

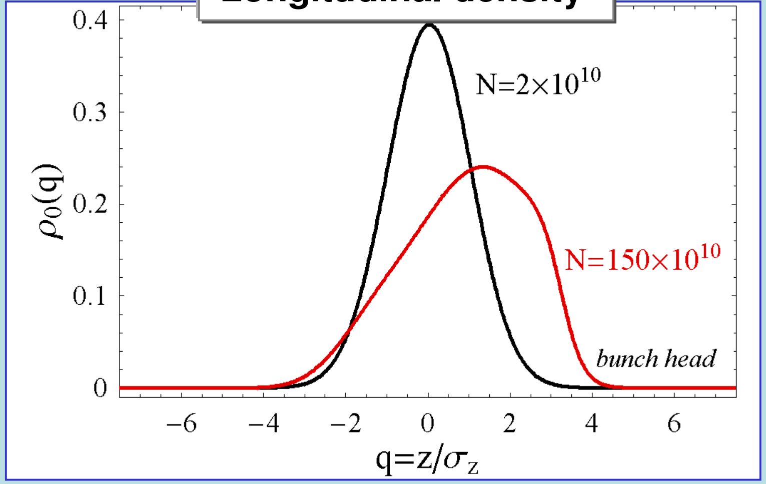
Preliminary (and largely incomplete) estimate of current threshold

Longitudinal wake potential including rf-cavities and RW

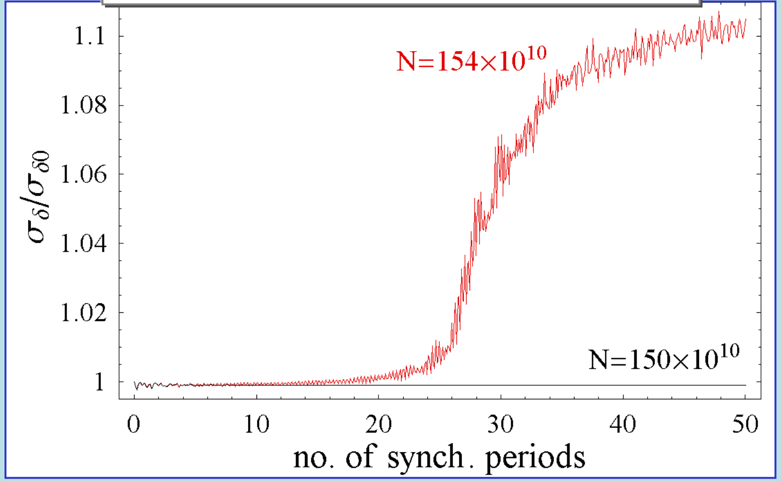


- Longitudinal dynamics simulated with Vlasov solver
- Incomplete wake-potential including only rf-cavity and RW effects
- Resulting critical current for instability well above design value

Longitudinal density



Relative energy spread vs time



PAC07 FRPMS061

Plans of action: WP5

- Proposed Managers: C. Ng and G. Stupakov (SLAC)
  - SLAC to be the Principal Institution
- The list of deliverables and milestones is still being worked on by the WP managers but a basic outline is in place (next 3 slides)
  - Resources so far have mostly been available (and work has been mostly carried out) at SLAC, LBNL
  - Resources have recently become available at Cockcroft Inst. and ANL
  - Plan for integrating/expanding efforts to be carried out over next 1 ½ month
- The description of deliverables due to A. Wolski by the end of this week will still be incomplete.
- A more definite plan to be expected by the end of the ILC DRs workshop in Dec. at KEK
  - All people involved in this WP expected to be present or represented at workshop

Impedance Calculations

- **Broadband impedance**
  - Identify major components that contribute to the impedance budget
  - Calculate short-range wakefields for single-bunch stability studies
- **Narrowband impedance**
  - Identify trapped modes in cavity-type structures
  - Provide HOM parameters for coupled-bunch stability studies
- **Beam Heating**
  - Identify sources of HOM heating
  - Investigate damping schemes to mitigate HOM effects
- **Engineering Prototyping**
  - Contribute to integrated analysis including rf, thermal and structural effects
  - Include transfer impedances of pickup devices

Schedule for Impedance Calculations

- **Year 1**

  - Impedance modeling using scaled models
  - Determine longitudinal and transverse wakefields for single-bunch stability studies
  - Determine HOMs in rf cavity for coupled-bunch stability studies

- **Year 2**
  - Repeat calculations of broadband impedance using improved models of technical designs
  - Investigate effectiveness of absorbers in damping HOMs in rf cavity

- **Year 3**
  - Integrated analysis including rf, thermal and mechanical effects of ring components for optimized technical designs
  - Finalize impedance calculations using models of engineering prototypes

Instabilities Calculations

Preliminary tasks

- Develop a database structure for storing of the results of the impedance and instabilities calculations
- Identify software packages for instabilities calculations

Single bunch instabilities

- Simulate microwave instability of the bunch using model wakefields for broadband impedance.
- Calculate thresholds for TMCI

Multibunch instabilities

- Given the wakefield of the cavities and resistive wall, calculate the growth rates of the multibunch instabilities

Contributions from the Cockcroft I., *et al.*

- Task 2.1: Damping Rings Beam Dynamics (Manager: A. Wolski)
  - –**Evaluate impedance-driven instability thresholds and growth rates.**
  - –**Evaluate the effects of beam loading, injection/extraction transients and long-range wake fields in the damping rings under a range of operational conditions.**
  - –Develop techniques for low-emittance tuning.

- Task 2.2: Damping Rings Vacuum Systems (Manager: O. Malyshev)
  - –Calculate the average pressure and pressure profile in the damping rings and, in the context of the results of these calculations, evaluate the technology options for the damping rings.
  - –**Produce technical designs for components in the vacuum chamber in the arcs and straights, and use these designs for developing an impedance model**.

Courtesy of A. Wolski

Impedance Computation at ANL

- **Resources**
  - Xiaowei Dong (0.25 FTE), Yong-Chul Chae (0.1 FTE)
  - Linux cluster with 120 cores (4 core/node * 30 nodes) and 480 GB of total memory
  - Parallelized 3D EM code GdfidL
- **Experience in Computing Wake Potentials**
  - Regular APS storage ring with bunch lengths σ_z= 1, 2, 5 mm
    - 8.4 cm x 4.2 cm
  - Reduced APS storage ring chamber with bunch length σ_z= 5 mm
    - 4.0 cm x 2.0 cm
    - All chamber components scaled by a factor of two in transverse dimension without new design
- **Deliverables**
  - Assuming the APS components in the DR, we will deliver the total wake potential of σ_z=1 or 2 mm of the ring in the first year by July, 2008
  - Refine and update as the mechanical design changes

Courtesy of Yong-Chul Chae

Resources available/pledged

Institution	FTE/yr	
SLAC (Principal Institution), USA	1	Impedance modeling; single, multi-bunch instabilities
ANL, USA	0.35	
Cockcroft Institute, UK	2	Impedance modeling, multi-bunch instabilities, transients
IHEP, China	??	
KEK, Japan	1	Experimental characterization of instabilities at ATF
LBNL, USA	0.2*	Single bunch instabilities

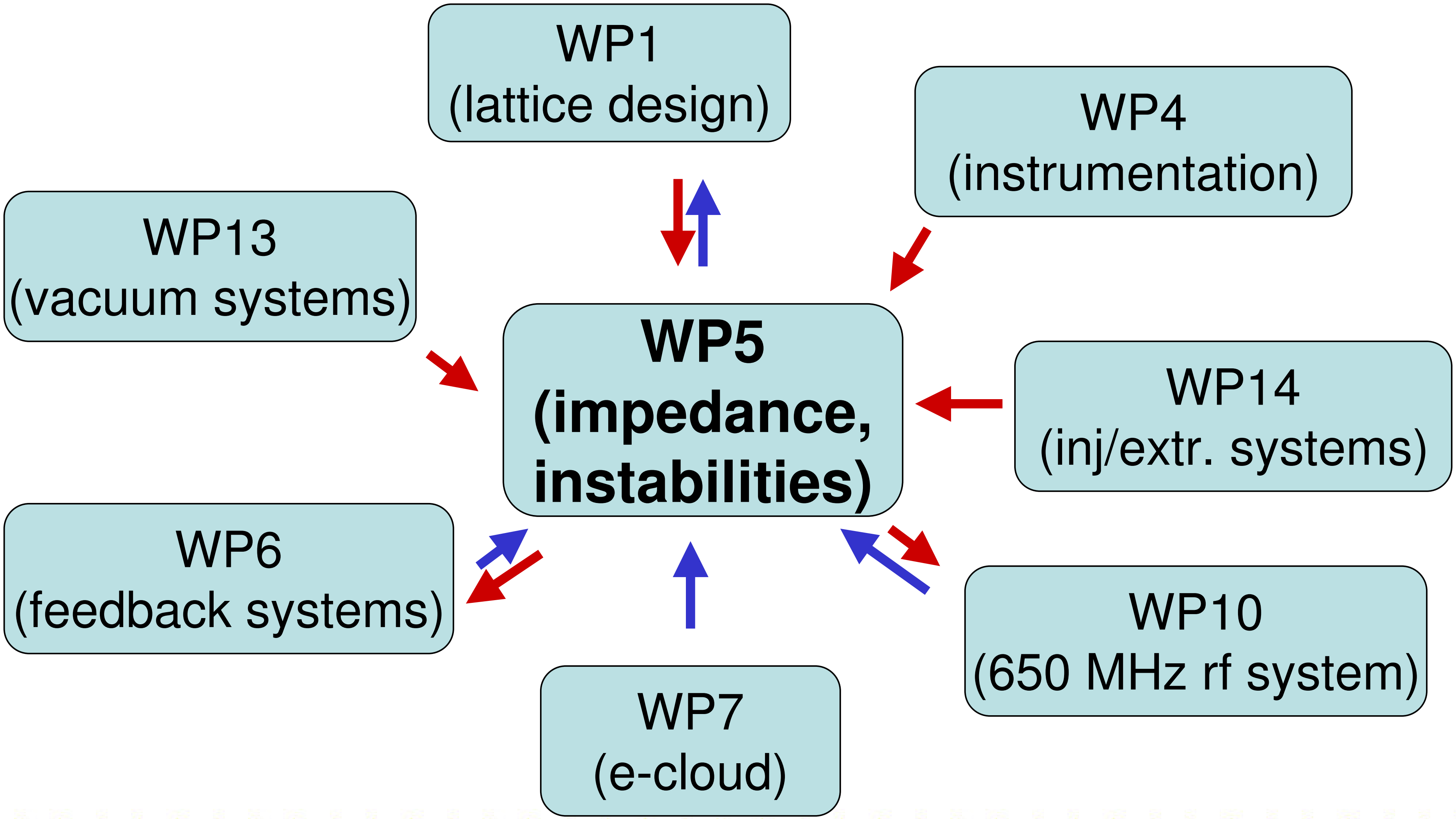
Modeling of kickers impedance by LNF?

**Does not include 0.5 FTE committed for physics design of cavities*

Names break-down

- **SLAC** (*Principal Institution*)
  - C. Ng, Z. Li (numerical impedance modeling)
  - K. Bane, S. Heifets, G. Stupakov (instabilities)
- **ANL**
  - Y-C Chae, X. Dong (numerical impedance modeling)
- **Cockcroft Institute**
  - A. Wolski, M. Korostelev , ... (numerical impedance modeling, instabilities)
- **LBNL**
  - J. Byrd, D. Li, M. Venturini (instabilities, cavity impedance modeling)

Dependencies



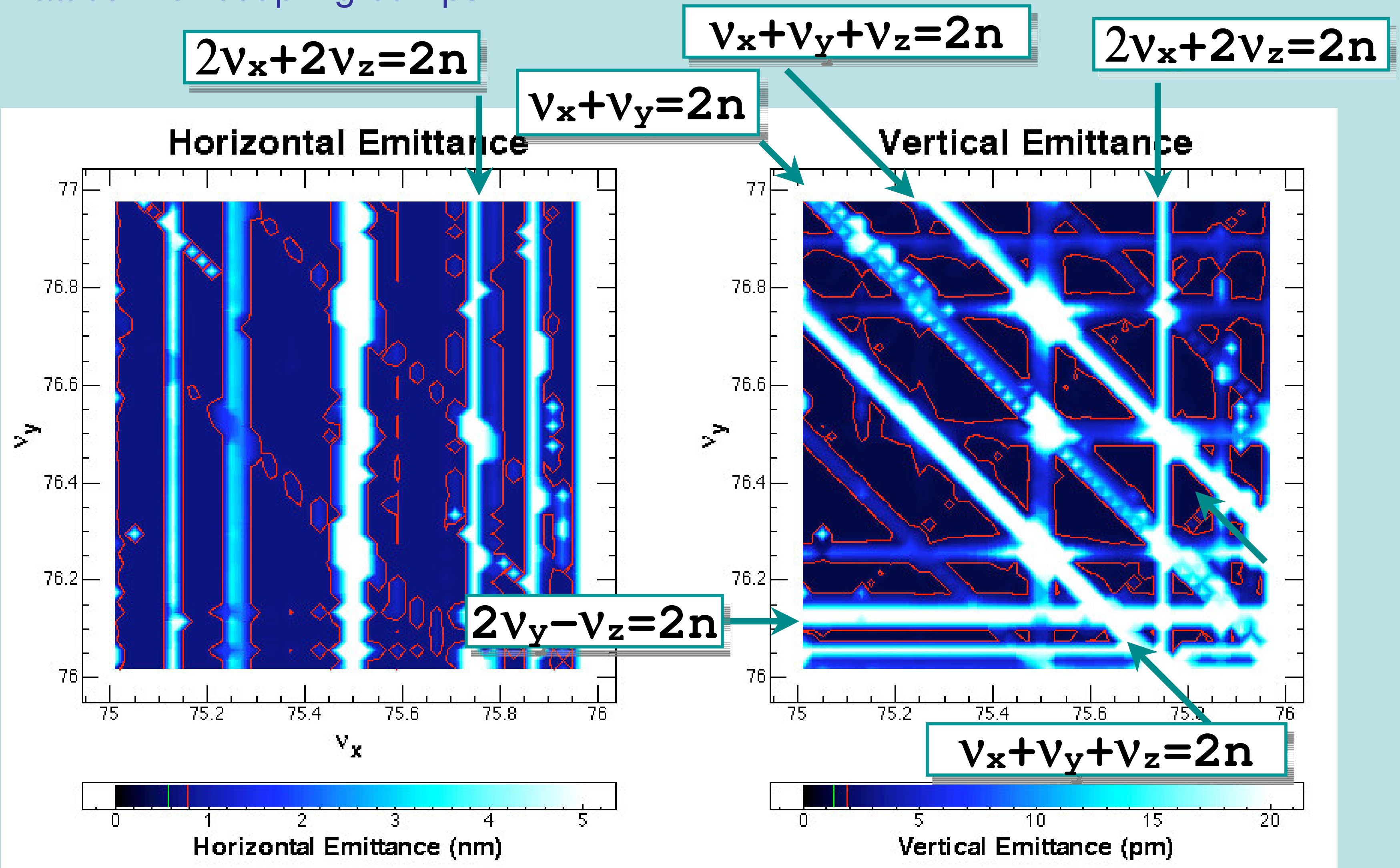
`Other' Collective Effects: WP9

‘Other’ collective effects have relatively lower priority

- These are ‘back burner’ effects.
  - Not expected to pose fundamental problems but have to be looked. into to avoid surprises or obtain numbers useful for operation.
  - They may affect optimization of lattice, working point
- **Space charge**:
  - Could have been a more serious concern if the longer ‘dogbone’ lattice configurations had been chosen. Simulations for OCS lattice so far do not indicate difficulties.
- **IBS:**
  - Existing models should be adequate. But experience with operation of e-ring where IBS is relevant is limited.
- **Touschek effect**:
  - Dominates lifetime. A very short lifetime may affect commissioning.

Space-charge effects for `dogbones' were found to be severe

MCH lattice with coupling bumps

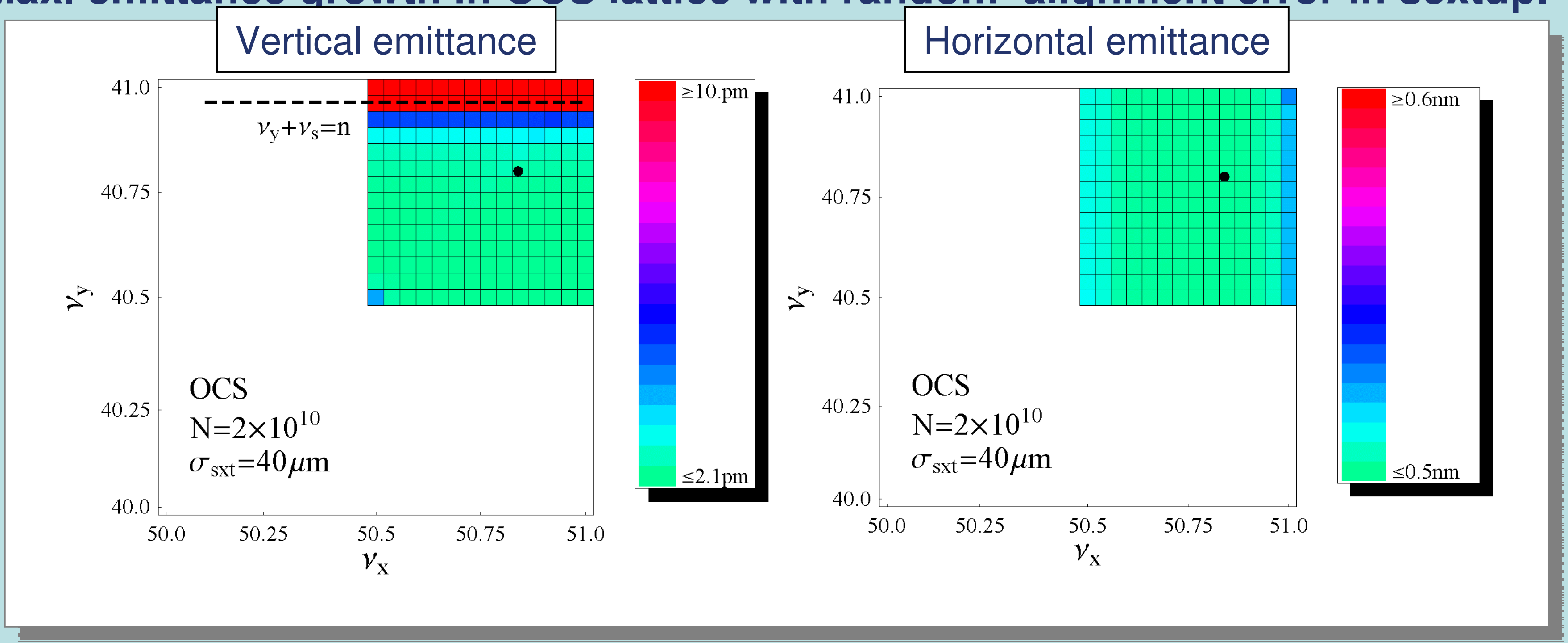


Simulations by K. Oide using SAD

Space-charge will enlarge resonance widths

- Effects in OCS lattice not as severe as in longer lattices but can still be noticeable (particularly in non-ideal lattice). Vertical linear tuneshift ~0.08

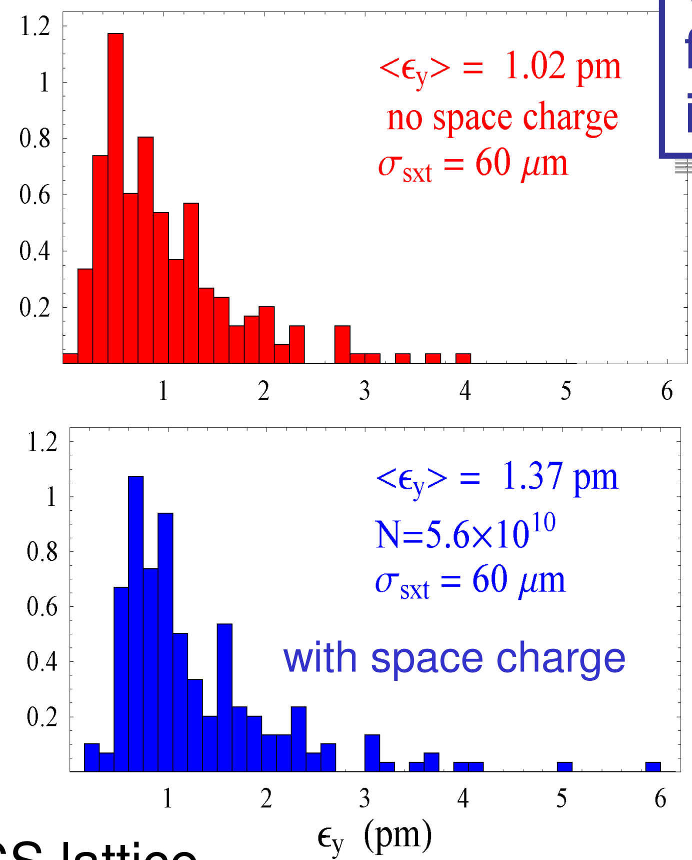
Max. emittance growth in OCS lattice with random alignment error in sextup.



Simulations using MLI/Impact – weak-strong model of space-charge

Interplay of space-charge and radiation effects

Distribution of equilibrium emittance w/o and w/ space charge for several realizations of sext. errors in non-ideal lattice



OCS lattice

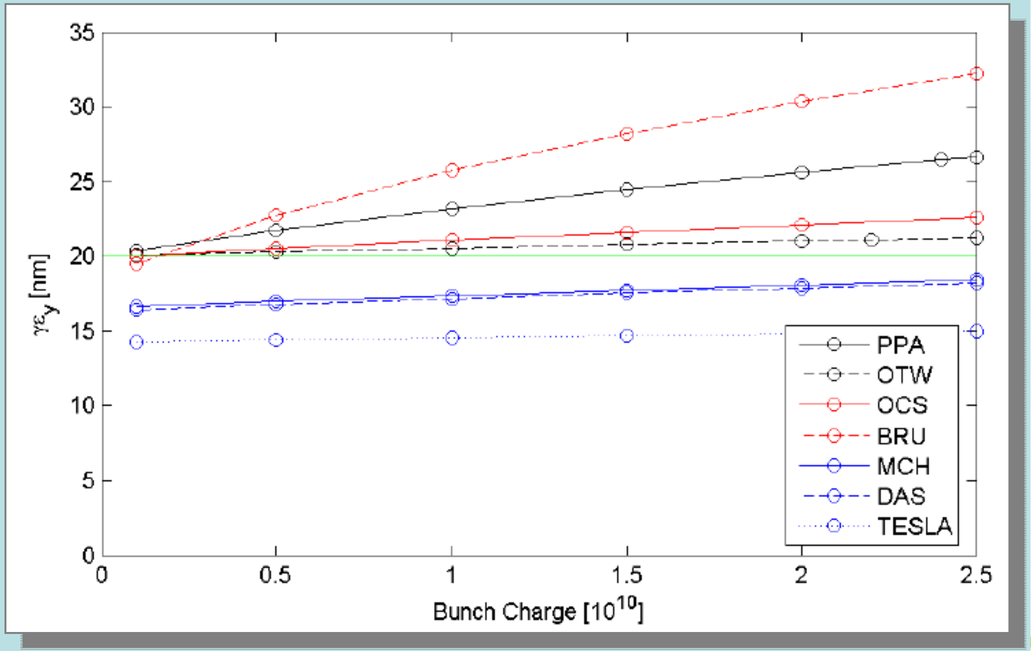
EPAC06

- Space charge may
  - modify linear coupling in non-ideal lattice
  - affect vertical equilibrium emittance as determined by radiation
- Effect was found to be negligible for design bunch population

IBS is not a concern

- IBS should not interfere with achievement of desired extraction emittance (assuming the design damping time for positron ring)
- No serious attempt yet to optimize choice of damping time for electron ring (a smaller damping time could make IBS more relevant)
- Improvement over current estimates would come from calculating *extracted* (*vs.* equilibrium) emittances.

Equilibrium emittance vs bunch population



Touschek effect will limit beam lifetime significantly

- Touschek lifetime expected to be significantly larger than damping time …
- … but is still a relevant quantity to determine (a relatively short beam lifetime may affect commissioning)

Comparison of BMAD calculation of Touschek lifetimes for various Proposed DR lattices with those found in the ILCDR Design Configuration Report (*courtesy of M. Palmer*)

	BMAD		DRCR	
Equation	Piwinski	Wiedemann	Wiedemann	
Lattice	Lifetime (min)	Lifetime (min)	Lifetime (min)	Bmad - DRCR Variation (%)
PPA	13	16	16	0.067
OTW	16	17	17	0.028
OCS	32	35	33	0.038
BRU	16	17	18	0.048
MCH	67	71	68	0.025
DAS	40	42	44	0.039
TESLA	47	50	50	0.029

Plans of action: WP9

- Two formal deliverables to be proposed:
  - **Scattering effects**: IBS rates and impact of IBS on beam emittance at extraction. Touschek life-time
  - **Space-charge effects**

- The only ‘strong’ coupling with other Work Packages is with WP1 (Lattice design)

Resources available/pledged for WP9

Institution	FTE/yr	
LBNL (Principal Institution), USA	0.3	Space charge, CSR, (IBS?)
Cornell, USA	0.3*	IBS, Touschek lifetime
Fermilab, USA	0.5	Space charge, (multi-physics?)
LNF, Italy	0.2**	IBS

*includes IBS work on CESR-TA

** IBS work on DAΦNE

Tasks in deliverable for scattering effects

- Evaluation of growth rates; equilibrium emittances; emittances at extractions (not necessarily equal to equilibrium emittances).
- Optimization of amount of damping required by e-ring
  - Phase space volume at injection quite smaller for e^- than e^+. A smaller no. of wiggler insertions in e^--ring (compared to e^+-ring) may not compromise performance while saving on cost.
- Readiness to evaluate implications of changes in baseline lattice
- Keep track of Touschek lifetime.

- Above tasks to be carried out by investigators at Cornell in conjunction with similar estimates needed for design/operation of CesrTA

- Further experimental validation of theory (DAΦNE, CesrTA). KEKB?

IBS in CesrTA

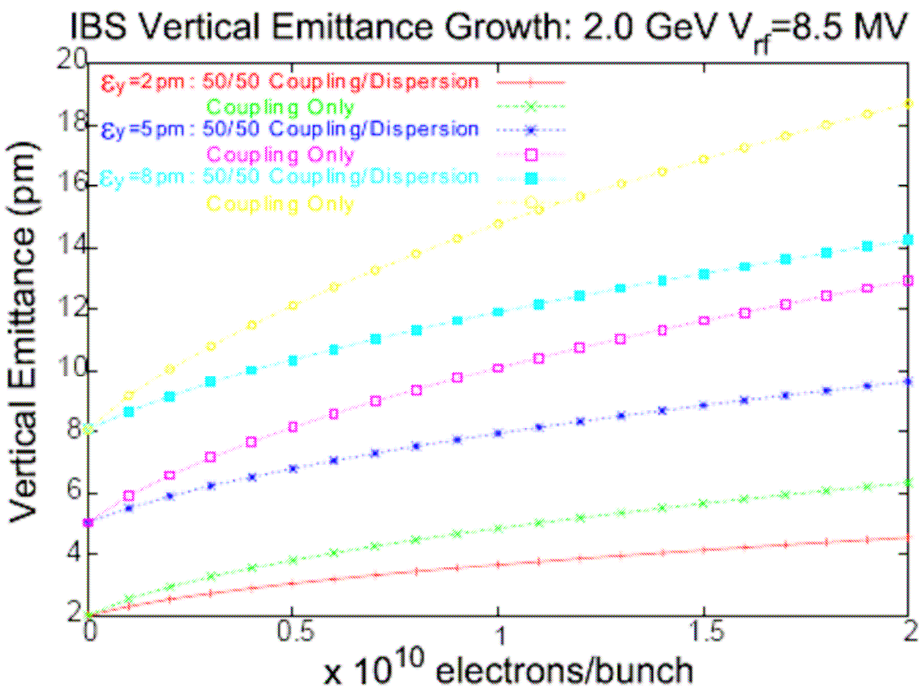
- Recent Cornell efforts have focused on simulations in support of the CesrTA program
  - CesrTA will operate in a regime with significant IBS and lifetimes limited by the Touschek lifetime
  - IBS calculations have recently been added to the BMAD framework.
  - We expect IBS studies to form an integral part of the CesrTA program in order to understand the low emittance performance of the ring. This will provide an opportunity to simulate the ILC DR using codes validated experimentally.

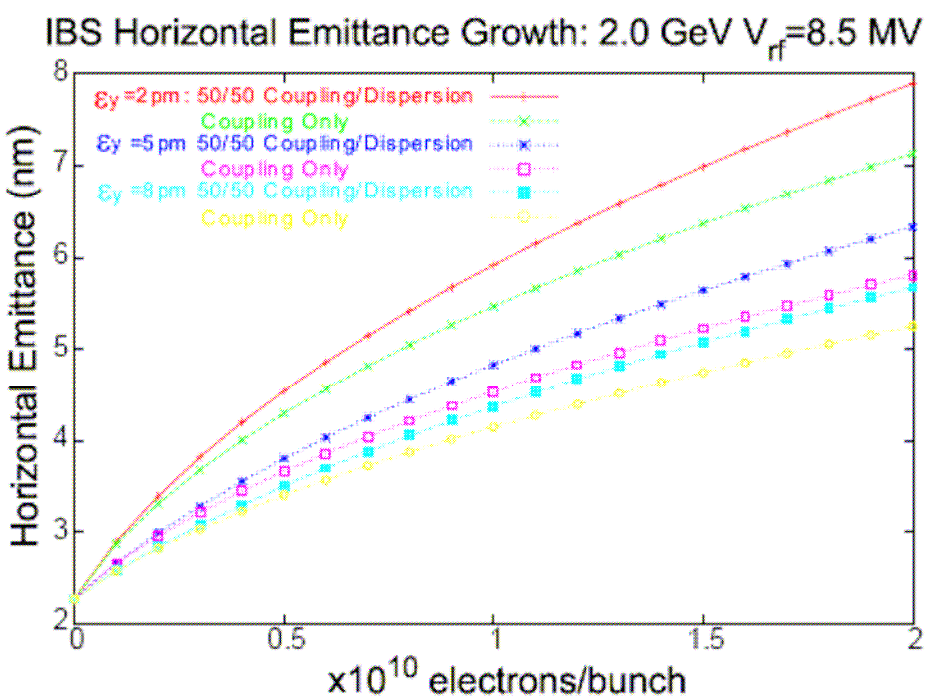
Courtesy of M. Palmer

IBS in CesrTA (Transverse Beam Size)

In CesrTA the horizontal and vertical beam size is strongly current dependent:

Analysis follows procedure outlined by A. Wolski.
Calculation using BMAD

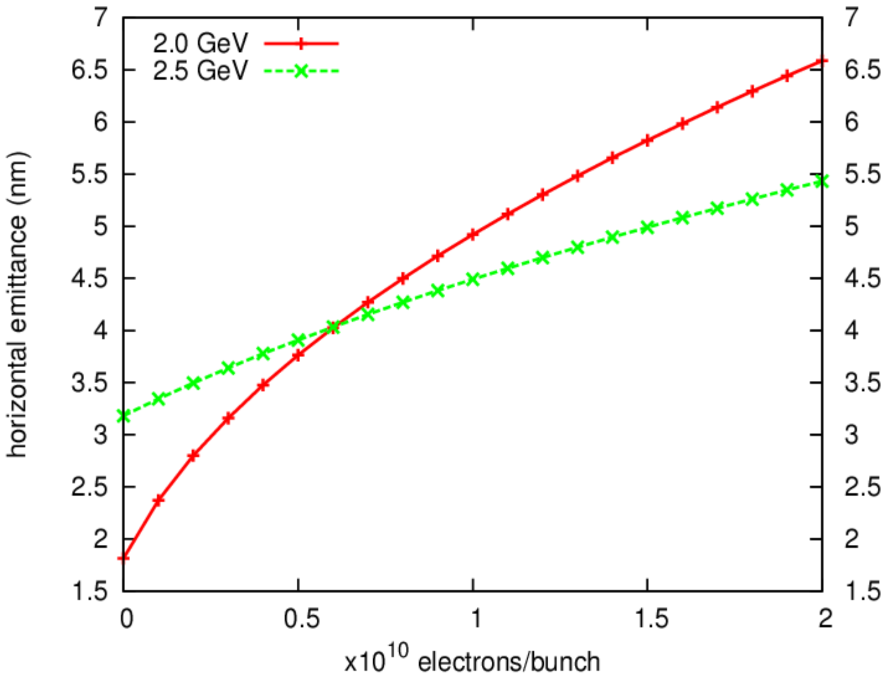




Courtesy of M. Palmer

IBS Energy Dependence

Energy flexibility of CesrTA and strong IBS energy dependence offers a flexible way to study, control and understand IBS contributions to emittance relative to other physics under consideration:



Courtesy of M. Palmer

IBS Activity at LNF

- IBS not a high priority for the ILC damping rings.
- Nonetheless, there are still some interesting questions, *e.g.* :
    - Could IBS affect the beam distribution, perhaps generating tails?
- The information on the beam distribution is useful for the start to-end simulations on low emittance transport
- The proposed activity for LNF is to measure the transverse distribution of the Beam in DAΦNE using a moving flag.

Courtesy of S. Guiducci

Tasks in deliverable for space-charge effects

- Evaluation of space-charge effects for current lattice and scan of tune space for optimization of working point using weak-strong model of space charge
  - Task to be completed in 2008; MV (LBNL)
  - Calculation using MLI/Impact, single processor.
- Evaluation of space-charge effects using refined model of space charge (some degree of self-consistency)
  - Task to be completed over ~1-2 yrs.; P. Spentzouris, J. Amundson (FNAL)
  - Code to be used (Synergia) requires more testing/development for application to DRs. Multiple processors.
  - May allow for inclusion of additional collective effects ('multi-physics')

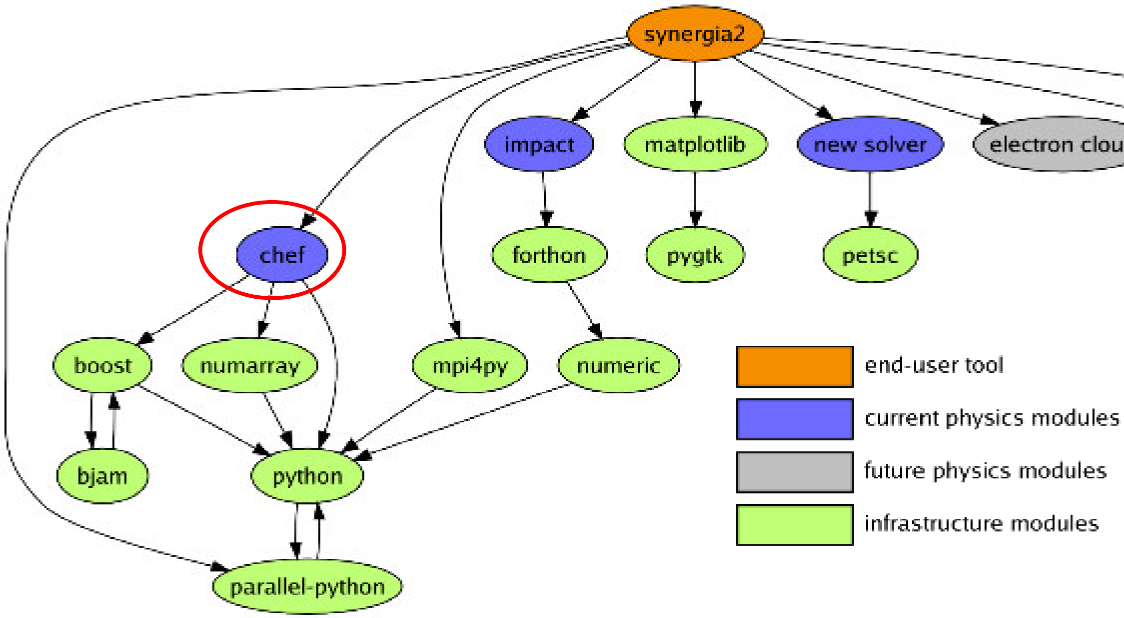
FNAL space-charge & multi-physics DR modeling

- We propose to use Synergia to model first space-charge effects, then add impedance and IBS
- Use the same lattice as the optics design
  - Employ higher order maps if necessary
  - Use both 2D and 3D space charge
  - Add impedance effects, when impedance values become available
  - Eventually add IBS model
- Emphasis on studying emittance dilution

Courtesy of P. Spentzouris

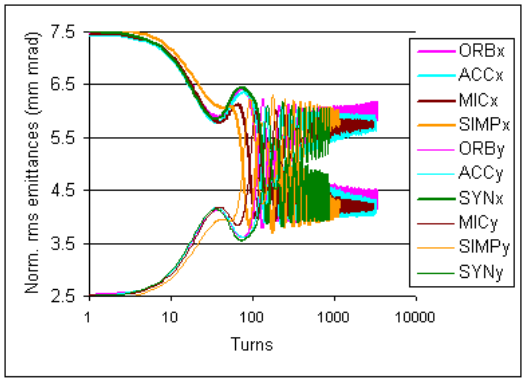
Fermilab & SciDAC code: the Synergia framework

PAC07, TUZBC02

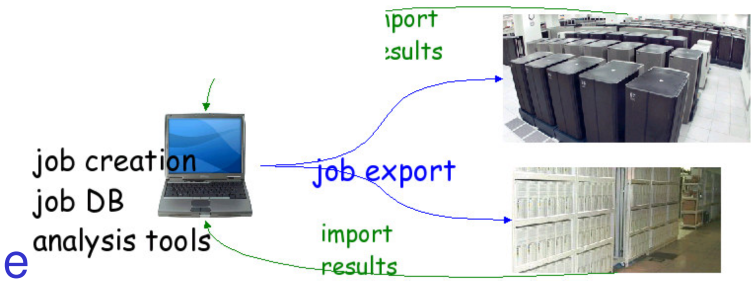


3D, parallel, high order optics

Multi-physics (space-charge, impedance) state of the art numerical libraries



Synergia: mature code (JCP06), participated in International space-charge benchmark effort lead by I.Hofmann



Easy to use interface

Courtesy of P. Spentzouris

Conclusions

- Activities covered in this talk belong:
  - WP5: Impedance and impedance driven instabilities
  - WP9: “Other” collective instabilities
- Concerning WP9: Definition of tasks, plans of action, assignments of duties mostly in place. Resources pledged should be adequate.
  - However: most IBS work for the DRs to be done at Cornell using resources made available for CesrTA. We are assuming that the CesrTA proposal will materialize at least in some minimal form
- Concerning WP5: Work toward EDR has already started. Outline of deliverable in place. Fine tuning and assignment of tasks, integration of efforts among institutions, still to be completed.
  - ILC-DR workshop at KEK should make it possible to finalize the planning

Acknowledgements

- Many thanks to: K. Bane, J. Byrd, Y-C. Chae, C. Ng, G. Stupakov, L. Emery, S. Guiducci, D. Li, M. Palmer, D. Sagan, I. Reichel, P. Spentzouris, J. Urakawa, A. Wolski,