Role of Advanced Computation in the Design of the International Linear Collider (ILC)

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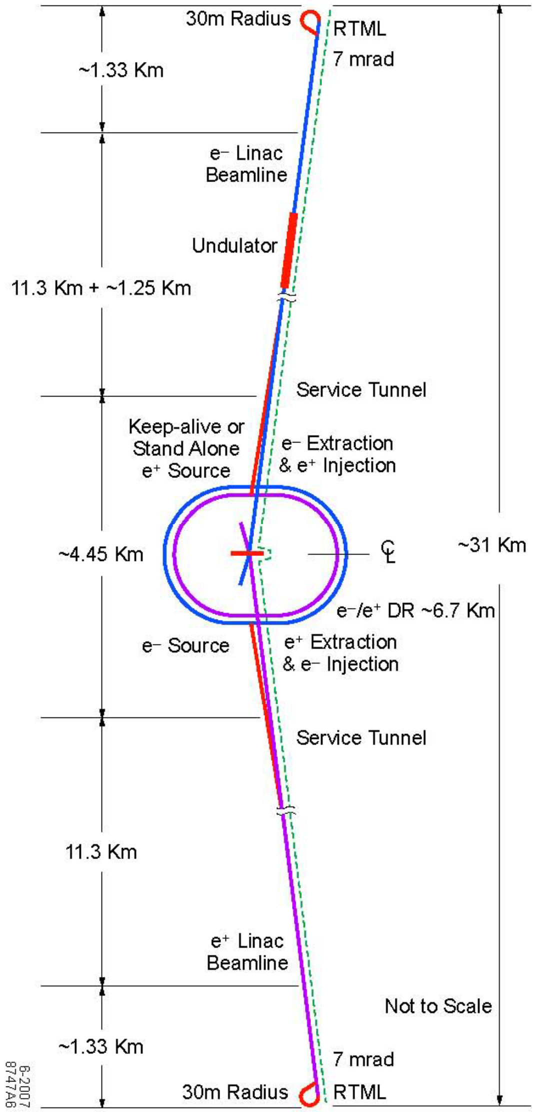
The ILC

- An electron-positron linear collider for exploration of HEP at the *terascale*
  - **Higgs, SUSY**
  - **Dark matter**
  - **Extra dimensions**
- Requirements
  - **Energy reach**
    - From the Z (92 GeV) to 0.5 TeV
    - Future expansion to 1 TeV or more
  - **Integrated Luminosity**
    - 500 fb^{-1} in ~4 years of running
      - Peak luminosity of $2 \times 10^{34}\ \mathrm{cm}^{-2}\ \mathrm{sec}^{-1}$
      - 75-85% availability



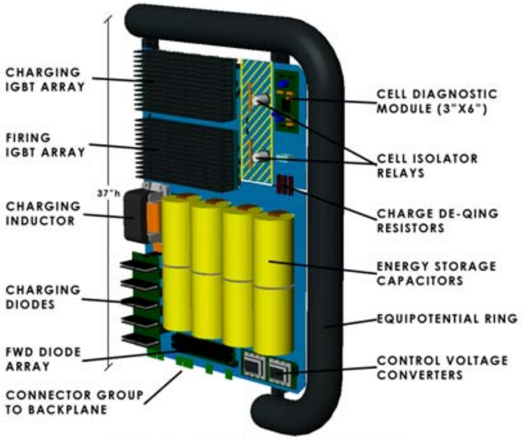
The ILC (2)

- ILC challenges
  - **Accelerating Gradient**
    - Maximize gradient in 1.3 GHz, SC cavities
  - **Luminosity**
    - Need to maintain extremely small emittances
      - Single-bunch effects
      - Multi-bunch effects
  - **Availability**
    - Need to meet typical HEP accelerator availability with
      - 10 x as many potential failure points
      - Extremely complex facility
- Advanced computation has a role in ***all*** of these areas
  - **Various definitions of "advanced"**

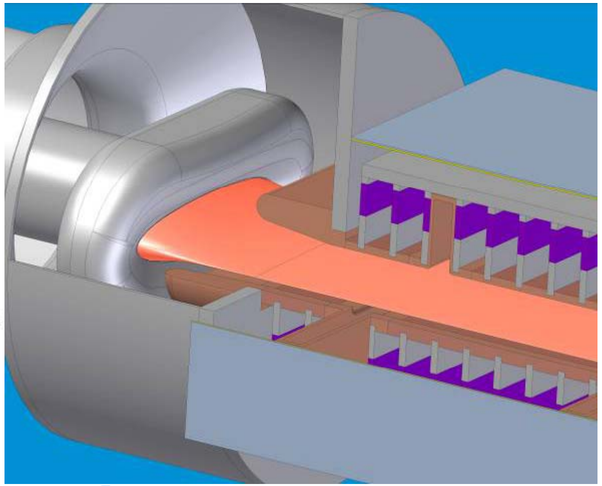
Parameter	ILC	SLC
CM Energy	500 GeV	92 GeV
Luminosity	2×10^{34} $cm^{-2}sec^{-1}$	2×10^{30} $cm^{-2}sec^{-1}$
Gradient	31.5 MV/m	17 MV/m
$\gamma\epsilon_x^*$	10 μm	40 μm
$\gamma\epsilon_y^*$	40 nm	4,000 nm
N_{bunch}	2625	3
t_{bunch}	369 nsec	60 nsec
N_{cavity}	~16,000	~1,000
N_{magnet}	~13,000	~3000?

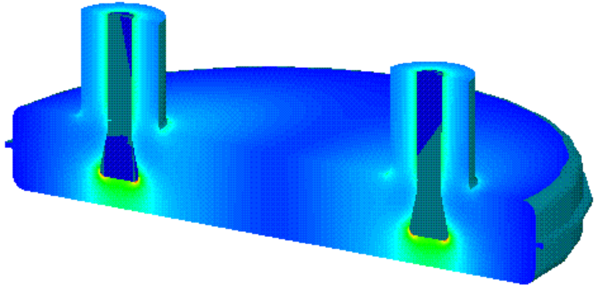
Accelerating Gradient

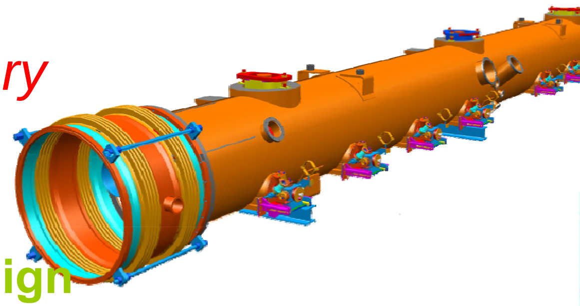
- Baseline design calls for
  - **10 MW modulators and klystrons…**
  - **…feeding RF power through transport system…**
  - **…to the RF couplers…**
  - **…for 26 RF cavities**
- Advanced computing used in designing *every stage* of this process
  - **CAD**
  - **RF component design**
    - EM field solvers
  - **Multipactoring simulations**

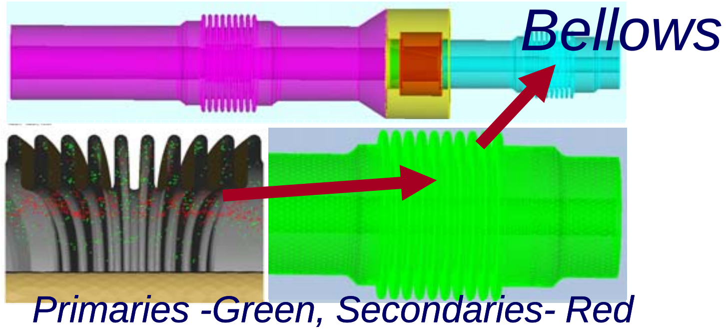


12kV MARX CELL, FRONT VIEW



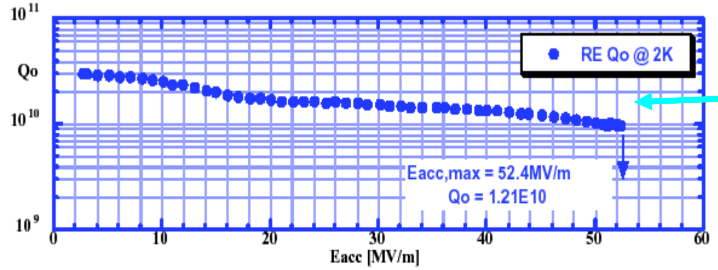


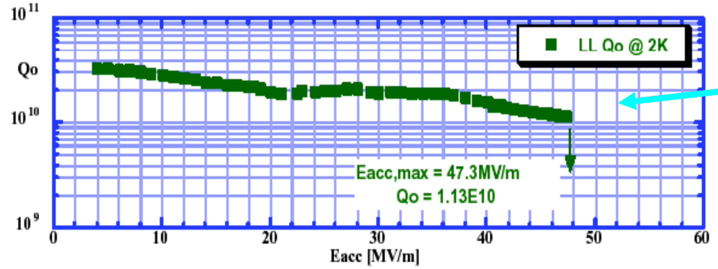


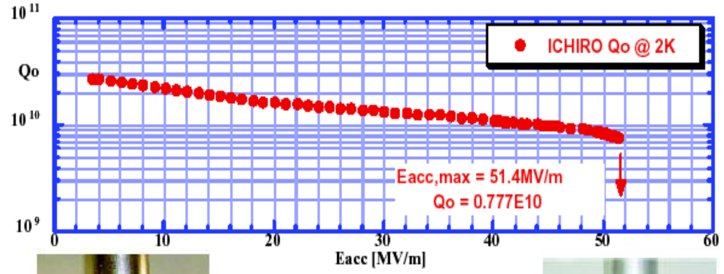


Primaries -Green, Secondaries- Red

Accelerating Gradient (2)

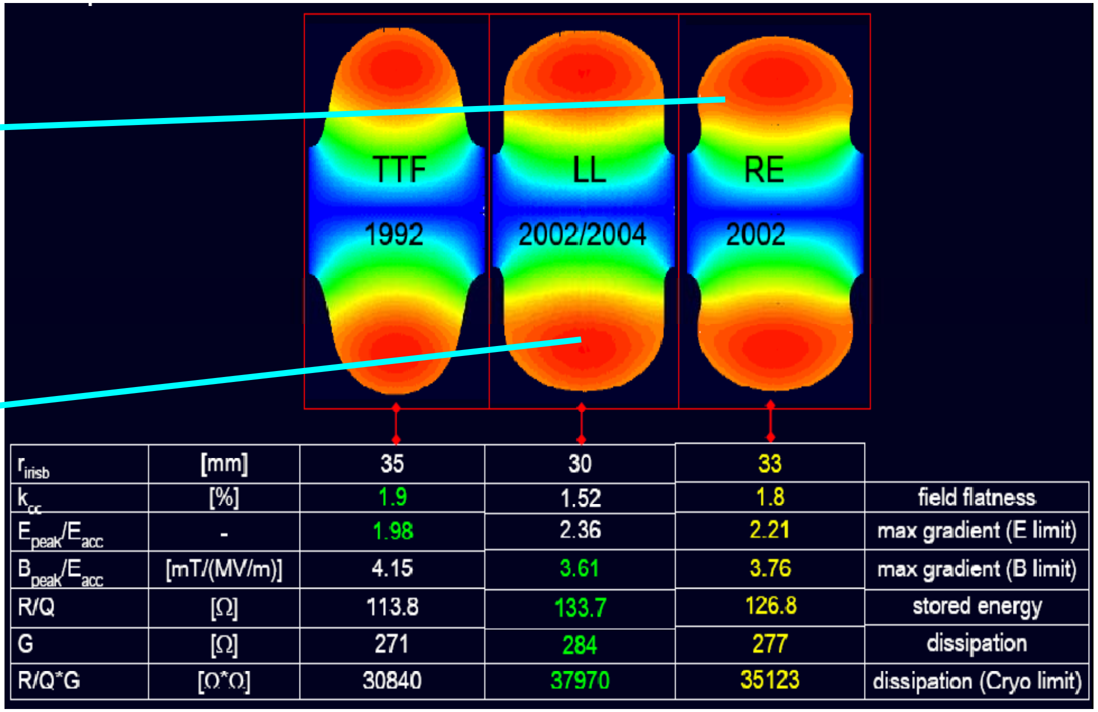






Re-entrant

Low-Loss



r_{irisb}	[mm]	35	30	33	
k_{cc}	[%]	1.9	1.52	1.8	field flatness
E_{peak}/E_{acc}	-	1.98	2.36	2.21	max gradient (E limit)
B_{peak}/E_{acc}	[mT/(MV/m)]	4.15	3.61	3.76	max gradient (B limit)
R/Q	[Ω]	113.8	133.7	126.8	stored energy
G	[Ω]	271	284	277	dissipation
R/Q*G	[Ω*Ω]	30840	37970	35123	dissipation (Cryo limit)

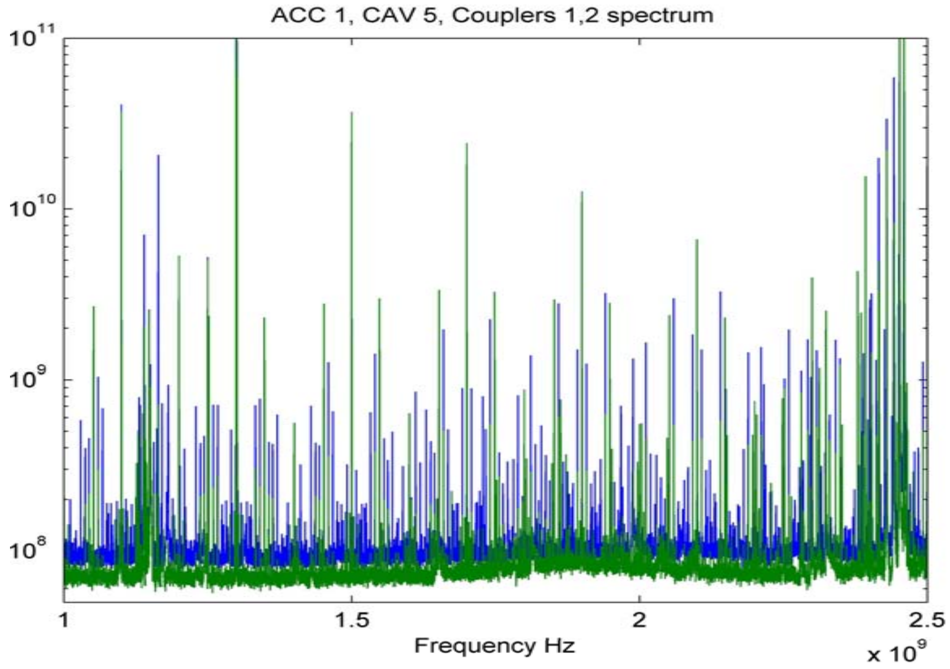
- Limits to TTC cavity gradient
  - **~43 MV/m from critical field (FUNDAMENTAL)**
- Raising gradient limit → reducing surface fields
- HP EM field solvers (plus human imagination) employed
- Real cavities based on these designs work!
  - **Path to 1 TeV upgrade?**

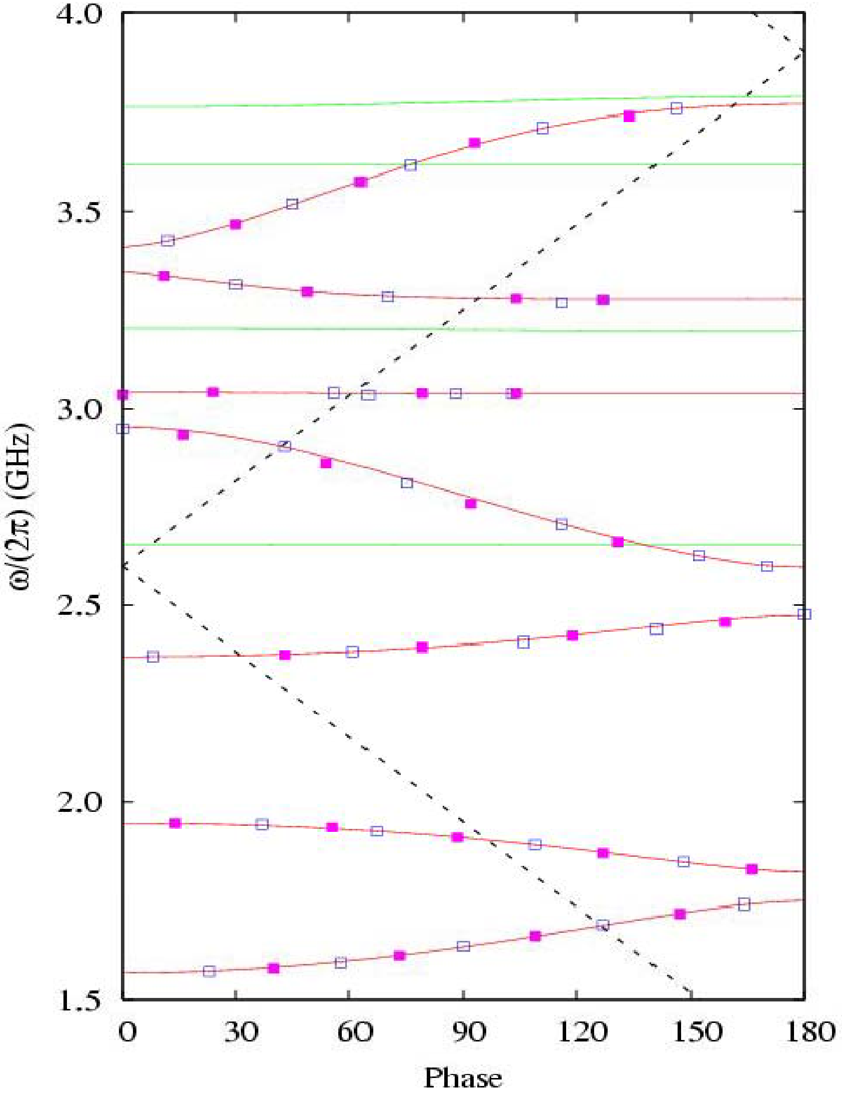
Luminosity Issues

- Need to achieve small emittances in damping rings
  - **Manage “conventional” and “novel” collective effects**
    - “Conventional:” alignment, dynamic aperture, impedance, space charge
    - “Novel:” ion and electron cloud instabilities
- Preserve small emittances in beamlines from DR to IP
  - ***Dilutions from RF cavities***
    - Wakefields (single- and multi-bunch)
    - RF kicks
  - ***Dilutions from other components***
    - Dispersion, coupling
      - Static and dynamic effects
    - Collimator wakefields
  - **Beam-beam effects**
    - Especially for beams with subtle shape distortions

Dilutions from Wakefields

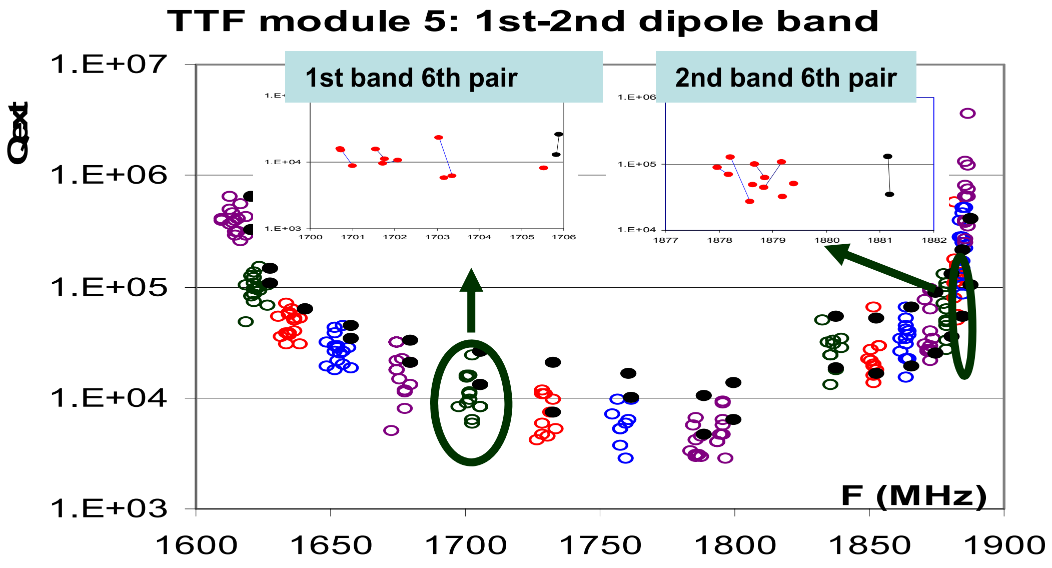
- 1.3 GHz cavity wakes are weak compared to higher frequencies
- In SC cavities wakes tend to stick around ~forever
- In SC cavities trapped modes are possible
- ILC relies on damping and detuning to achieve desired multi-bunch emittance preservation
- Rely heavily on 3-D modeling to understand cavity HOMs

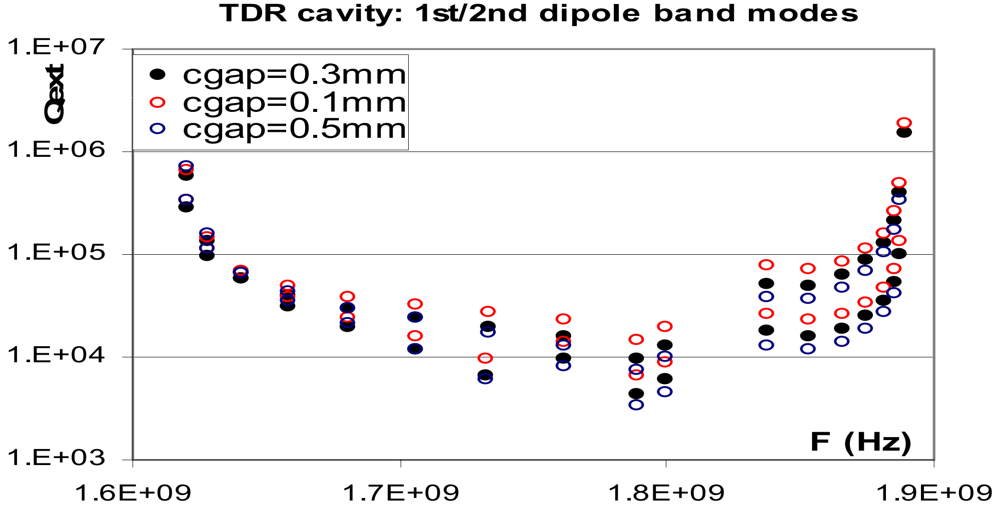




Cavity HOMs

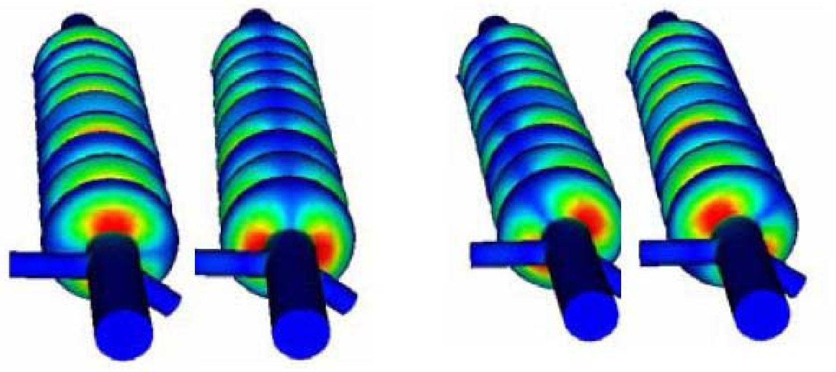
- Comparison of measured HOMs and ideal modeled HOMs reveals
  - **Real HOMs tend to be at lower frequencies**
  - **Polarization Δf larger than expected**
  - **Large spread in Q values**
    - Q > 10^6 for some 2nd band modes!
- Extensive Omega3P modeling to study this
  - **Frequency shift and Δf-pol from particular cavity deformations**
    - Mainly caused by welding on stiffening rings and then retuning
  - **Q shift from variable pickup gap in HOM coupler**

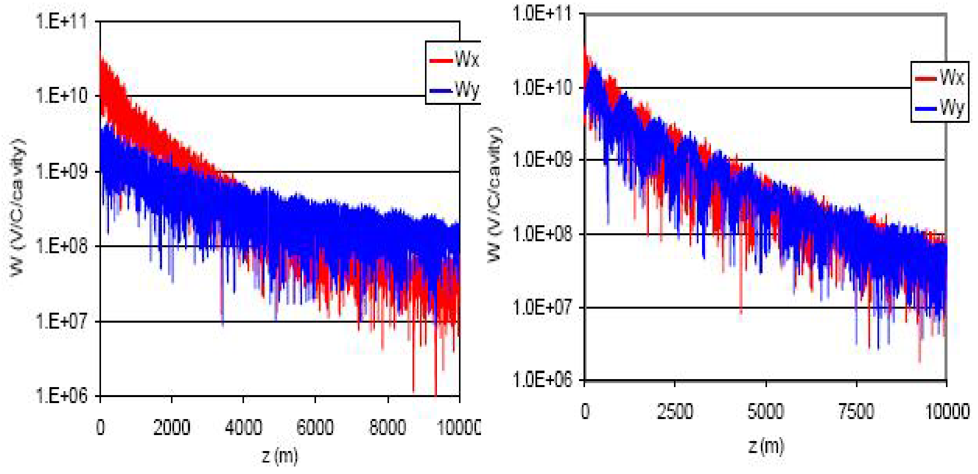

TTF module 5: 1st-2nd dipole band


TDR cavity: 1st/2nd dipole band modes

Cavity HOMs (2)

- Ideal WFs: direction of kick == direction of offset
- Real WFs: eigenmodes can have orientation
  - **Diagonal deformations**
  - **Asymmetry of fundamental and HOM couplers**
- Pretty sensitive
  - **1 cell x 200 µm deformation @ 45 degrees = factor of 5 change in “mode rotation wake”**

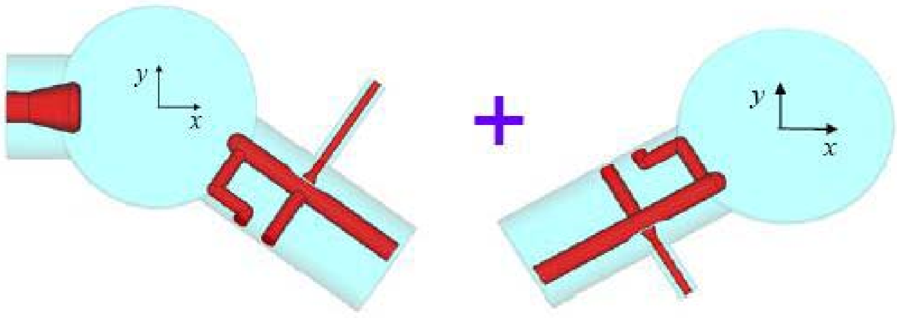


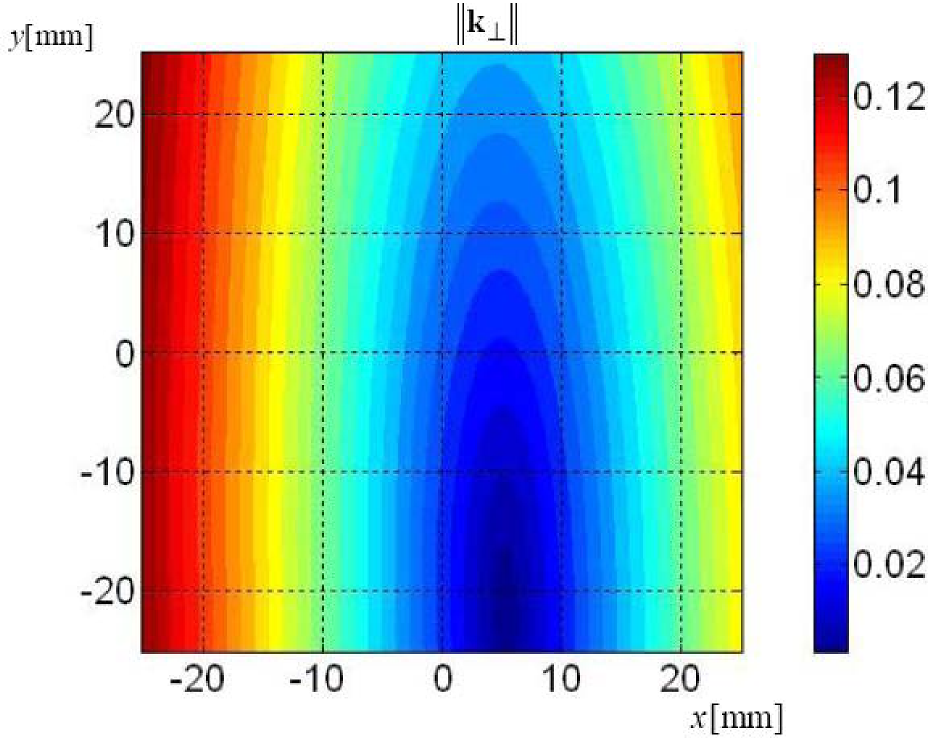


Single-Bunch Effects

- Asymmetry of couplers leads to asymmetric cavity fields
  - **SRWF – head-tail proportional to bunch charge**
  - **RF kick – head-tail kick ~independent of bunch charge**

- Big effect!





Beam Optical Effects

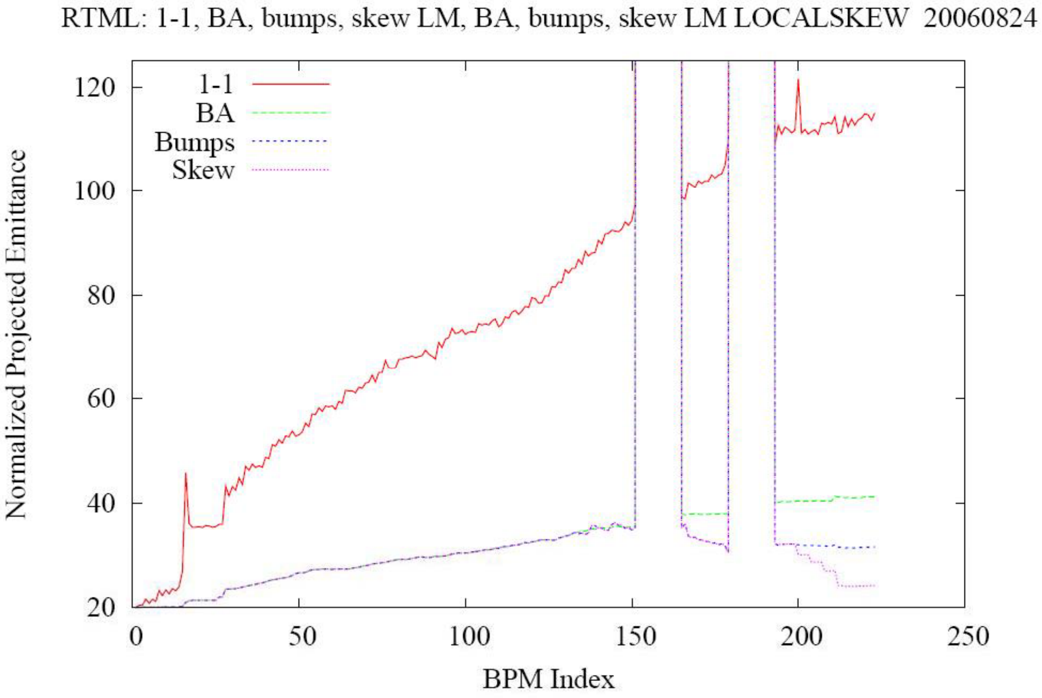
- Effects of misalignments / errors well understood
  - **Unlike cavities, where we're still asking, "What happens when the beam passes through off-center"**
- Different computational issues
  - **Simulating wide variety of beam tuning and diagnostic procedures…**
  - **… with inputs that are as realistic as possible…**
  - **…and evolution in time**
    - Time scales of nanoseconds to years
- Emphasis is on *flexibility* and high throughput of relatively simple beam dynamics computations

Beam Optics (2)

- ILC beam optics work has moved away from closed-form programs…
  - **LIAR, DIMAD, etc.**
- …towards beam dynamics library packages
  - **Write your own program to take advantage of well-understood libraries**
  - **Much more flexibility**
  - **Somewhat more work for the users**
- Several packages in use today
  - **BMAD (F90)**
  - **PLACET (?/Tcl-Tk/Octave)**
  - **Merlin (C++)**
  - **Lucretia (Matlab/C)**
- *Different meaning* of “advanced computing”
  - **Emphasis not on consumption of massive # of FLOPs**
    - Though we like to do that, too!
  - **Emphasis on flexibility of the code**
    - To model the accelerator as *realistically* as possible!
      - To the extent possible, integrating a lot of heretofore discrete simulation areas
        - » IE, not too fun to use one code to simulate linac, one for BDS, one for IR, one for beam-beam effect, one for dumpline
    - Countervailing pressure: make the models as simple, general, and understandable as possible

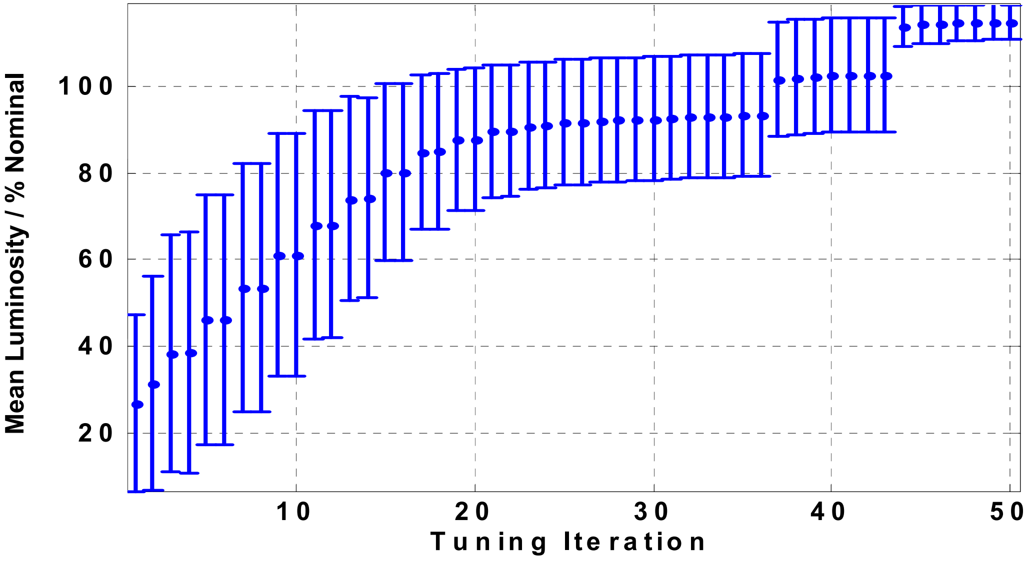
Optics Tuning -- Examples

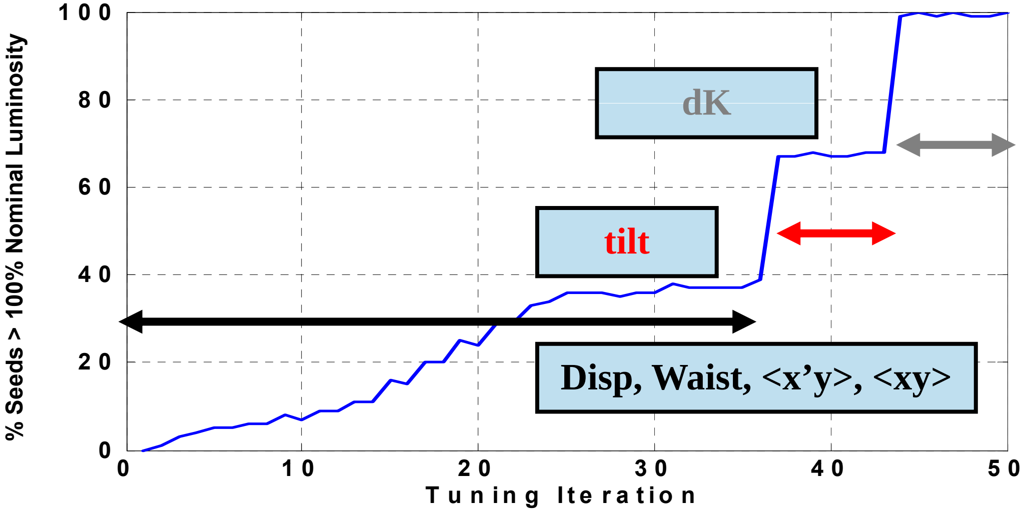
- ILC Turnaround and Spin Rotator
  - **Strong coupling and dispersion terms from misalignments, rolls, strength errors**
  - **A number of correction strategies used**
    - Orbit tuning
    - Global dispersion control
    - Global coupling control
- Simulation performed using BMAD library
  - **Average over 100 seeds**



Optics Tuning – Examples (2)

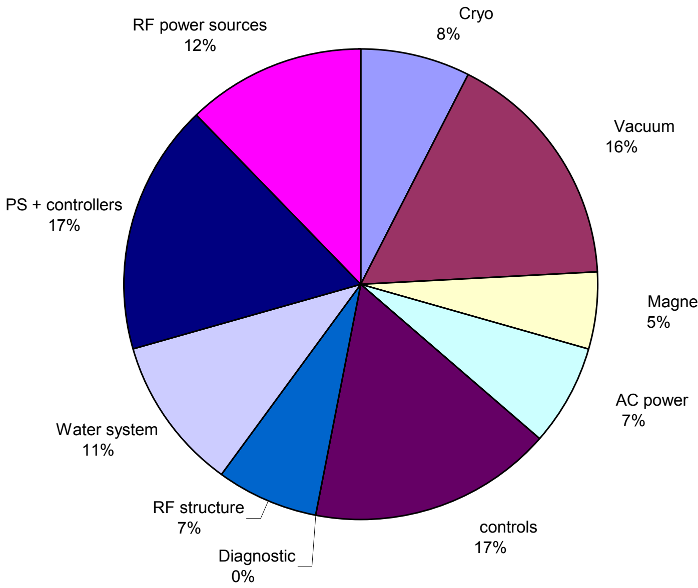
- BDS Tuning
  - In addition to usual dispersion, copuling errors
    - Waist (z position of focus)
    - Sextupoles
      - Chromaticity
      - Geometric sextupole
    - Octupoles!
- Extremely complex tuning algorithm
  - Initial orbit via BBA and magnet movers
  - Global correction via large number of knobs
- Simulated using Lucretia
  - 100 seeds





Accelerator Availability

- ILC goal of 75% availability for lumi production
  - Comparable to B-factories but with much larger numbr of failure points
- ILC needs to do better
- Need to understand what that means
  - Which availabilities need to be improved?
  - Where can we tolerate single points of failure?
  - What facility layout choices are good/bad?
- AvailSim, a flexible Matlab simulation package
  - Time-domain simulation
  - Tunable assumptions about layout, component failures, etc.



Device	Improvement factor A that gives 17% downtime for 2 tunnel undulator e+ source	Downtime (%) due to these devices for 2 tunnel undulator e+ source with strong keep_alive	Nominal MTBF (hours)	Nominal MTTR (hours)
magnets - water cooled	**20**	0.4	1,000,000	8
power supply controllers	**10**	0.6	100,000	1
flow switches	**10**	0.5	250,000	1
water instrumention near pump	**10**	0.2	30,000	2
power supplies	**5**	0.2	200,000	2
kicker pulser	**5**	0.3	100,000	2
coupler interlock sensors	**5**	0.2	1,000,000	1
collimators and beam stoppers	**5**	0.3	100,000	8
all electronics modules	**3**	1.0	100,000	1
AC breakers < 500 kW		0.8	360,000	2
vacuum valve controllers		1.1	190,000	2
regional MPS system		1.1	5,000	1
power supply - corrector		0.9	400,000	1
vacuum valves		0.8	1,000,000	4
water pumps		0.4	120,000	4
modulator		0.4	50,000	4
klystron - linac		0.8	40,000	8
coupler interlock electronics		0.4	1,000,000	1
vacuum pumps		0.9	10,000,000	4
controls backbone		0.8	300,000	1

Limitations and Future Developments

- EM Modeling
  - **Emphasis has been on single components or small clusters of components**
  - **Would like to expand our field of view**
    - Consider modes of a 26-cavity ILC RF unit *as an integrated object*
    - Other, similar expansions – DR simulations with impedance, ions, ecloud (multi-physics)
  - **SciDAC COMPASS Project**
    - "Community Petascale Project for Accelerator Science and Simulation"

Limitations / Future Developments

- Beam Optics modeling
  - **Becoming compute-bound over the last few years**
    - 2003 ILC Technical Review Committee report – spent 6 CPU months producing 1 plot!
    - Complexity of the physics – magnetostatic optics, wakefields, beam-beam interaction
    - Time scales – sub-microseconds to weeks
  - **Moving to take advantage of high-powered computing**
    - Multi-threaded, massively parallel, buzzword-compliant
  - **Important to include all the phenomena we want in a sufficiently transparent and flexible way**
    - Ground motion is a good example!
    - IR solenoids which wrap around beamline components is another
    - And don’t get me started about modeling the undulator for positron production…

Availability Simulations

- Not at all compute-bound
- Need to improve interfacing between accelerator design and AvailSim
  - **Right now user hand-codes magnet counts, power supply stringing, etc.**
  - **Can we get that from the lattice file instead?**
    - May need to expand definition of lattice file
      - Which we may want to do anyway…
- Some amount of concern about the input assumptions
  - **IE, worry about “GIGO” effect**
  - **Probably done the best we can**
    - Gathered information about failure rates, recovery times from most HEP labs on Earth

Acknowledgements

Thanks to the worldwide ILC Accelerator Design Team

(Especially the ones whose talks and papers I raided for figures!)