M4 Working Group -- *Hadron Colliders*

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Steve Peggs, BNL

M4 Participants

- Convenors: Peggs, M.Syphers
- Participants (50+): (500+, DPF equivalent)

•R.Baartman	•R.Diebold	•E.Keil	•B.Parker	•K.Takayama
•W.Barletta	•J.Ellison	•B.King	•R.Pasquinelli	•T.Toyama
•P.Bauer	•G.W.Foster	• M.Lamm	• F.Pilat	•M.Wake
•M.Blaskiewicz	•J.Fox	• P.Limon	•M.Pivi	•P.Wanderer
•A.Burov	•M.Furman	•E.Malamud	•R.Roser	•M.Watanabe
•J.Cardona	•P.Garbincius	•A.McInturff	•M.Ross	•R.Webber
•A.Chao	•H.Glass	•P.McIntyre	•A.Sattarov	•K.Wittenberg
•J.Corlett	•R.Gupta	•N.Mokhov	•T.Sen	•M.Xiao
•L.Cremaldi	•R.Johnson	•T.Murphy	•Y.Shimosaki	•R.Yamada
•D.Denisov	•J.Johnstone	•R.Palmer	•J.Strait	•V.Yarba
	•H.Jostlein		•D.Summers	•A.Zlobin

plus others we missed…??

M4 Sub-group organization

- Design Study Review & Alternative Approaches
  - McIntyre, Yarba, Strait, Foster
- Luminosity & Energy Scaling
  - Bauer
- Lattice Issues
  - Johnstone
- Superbunch
  - Takayama
- Beam Experiments
  - Sen
- Collective Effects
  - Chao, Baartman

M4 Charge summary:

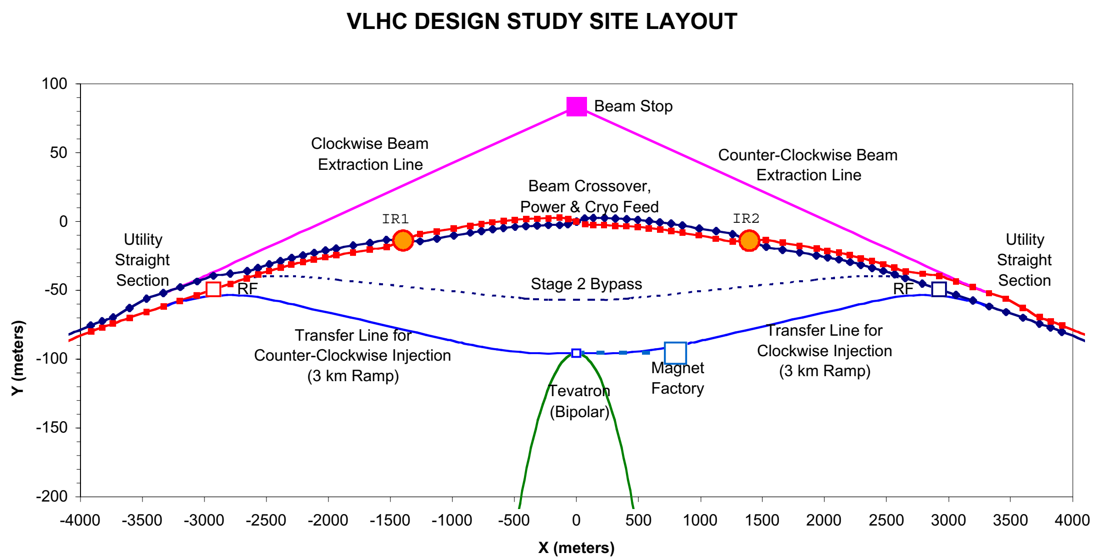
- Develop a vision and a long-term plan for the US hadron collider program.
- Examine the central physics and technology issues, and specify the most critical ones.
- Identify the technology developments and accelerator physics experiments needed to prove a future machine feasible.
- Evaluate and estimate the technological and physics limitations on ultimate energy and luminosity.
- Evaluate the recently completed VLHC feasibility study, and compare with other potential approaches.
- Develop a prioritized R&D plan to establish the above goals, including a cost and schedule estimate.

Meeting organization

- Daily sessions (8:30): discussion and sub-group reports
- Scheduled talks/discussions:
  - Tue 7/3 -- intro to VLHC design study; group organization
  - Thu 7/5 -- alternative approaches
  - Fri 7/6 -- magnets (joint w/ T2)
  - Sat 7/7 -- IR/magnets (joint w/ T1, T2)
  - Mon 7/9 -- superbunch
  - Tue 7/10 -- IR issues (joint w/ T1, E4),
instrumentation/diagnostics (joint w/ T9)
  - Fri 7/13 -- collective effects
  - Sat 7/14 -- beam-beam (joint w/ M2,M3,M5)
  - Tue 7/17 -- beam experiments, lattice issues

Design Study evaluation and Alternative Approaches

- Design Study reference point
  - Stage 1 -- 20 TeV, 2 T, 10^{34} $cm^{-2}sec^{-1}$
  - Stage 2 -- 175 TeV, 10 T, 2×10^{34} $cm^{-2}sec^{-1}$
- Accelerator physics and technical issues are in hand today



Design Study evaluation and Alternative Approaches

- Reviewed VLHC Design Study, with 2T Stage 1, 10T Stage 2
- Most (not all) agree 2-stage approach is best for long-term
- A "Stage 1" must be at energy frontier (≥3 to 5 x LHC)
- Design Study was a "point design"; other fields? other sizes?
  - **Stage 1**: 2, 3, 4T ? **Stage 2**: 8, 10, 12T ? **Single Stage**??
- Working Group looked at a range of possible alternatives:
  - Higher fields for Stage 1 and Stage 2
  - Injector located on Fermilab site
  - A "Giga-Z" collider design sharing tunnel with such an on-site injector
  - A ~400 GeV e^+e^- collider (VLLC) design sharing main tunnel
  - Acceleration of proton superbunches using induction acceleration devices (discussed more later in talk)

Design Study evaluation and Alternative Approaches

Recommend considering two new scenarios that merit further study:

	•Case A		•Case B	
	•Stage 1	•Stage 2	•Injector	•Collider
•Beam energy (TeV)	•25	•75-100	•5	•75-100
•Magnetic Field (T)	•3	•10-13	•11	•10-13
•Circumference (km)	•200	•200	•15	•200

Case A: modified version of Design Report, using superferric magnets, providing higher Stage 1 collision energy

Case B: single stage, requiring new injector

Design Study evaluation and Alternative Approaches

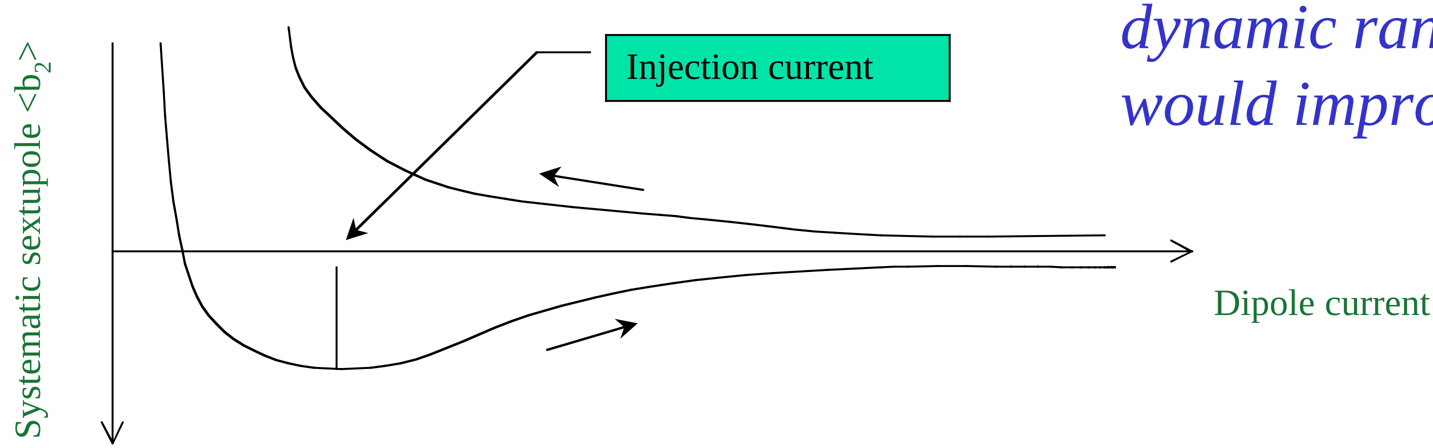
- The parameter space in the vicinity of both “cases” should be examined in detail for optimization of parameters and cost drivers

- Looked at properties of a VL**L**C using the VLHC Design Study layout -- directly compatible, as are above 200 km alternatives
    - ~400 GeV , 10^{34} cm^{-2} sec^{-1}, good energy resolution; unpolarized
    - Note: VL**M**C is not compatible with the large circumference ring

- Case B includes a 15km injector; its layout would be compatible with a Giga-Z collider: double-ring, polarized e^+e^- collider supporting high luminosity at the Z-mass

Design Study evaluation and Alternative Approaches

- High Field magnet development
  - Joint sessions with T2 showed many improvements in high field magnet designs, including minimum conductor designs and suppression of persistent current effects
  - Snap-back of persistent currents (e.g., generating large chromaticity swings at beginning of ramp) may no longer be a problem

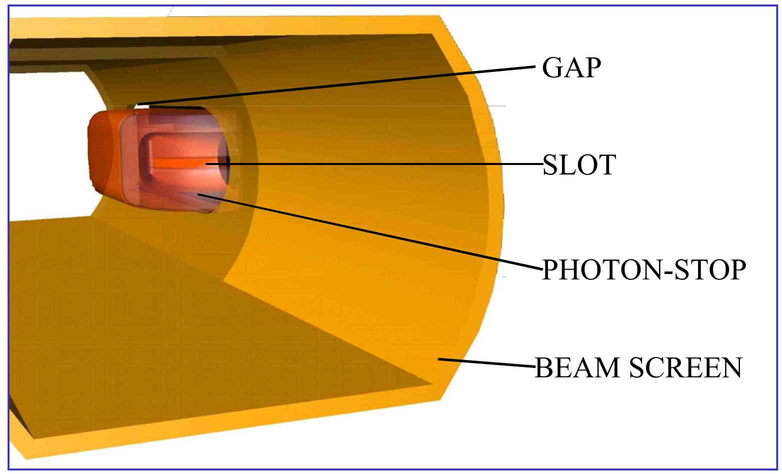


dynamic range would improve …

Scaling of Luminosity and Energy

- Design Study looks at one "point" in a parameter space rich in technologically possible VLHC's
  - Low field ring performance close to being limited by collective instabilities.
  - For high field ring, product of luminosity and energy has a maximum value limited by total synchrotron radiated power tolerated by cryo system (~100 MW wall power, say)
  - "Photon stops" -- exciting development!

- breaks nominal total synchrotron radiation power constraint
- potentially allows order of magnitude increases in the high field luminosity



Scaling of Luminosity and Energy

- photon stops are more easily engineered into larger circumference rings (stops can be incorporated into magnet design, or magnet interface design).
- moves the operational limits of high energy colliders to:
  - the ability to engineer beam absorption systems to handle high stored energy of beams
  - development of interaction region magnets to handle high power of debris from the interaction points
  - all need further R&D…
- Look at range of possible high energy VLHC designs, assuming synchrotron radiation dominated environment…

Scaling of Luminosity and Energy

- Primary accelerator limitations to ultimate energy and luminosity:
  - Synchrotron radiation power
  - Proton collision debris power in the IR
  - Stored energy per beam
  - Beam-beam tune shift
- Look at scaling of above with energy, radius (using various magnet technologies)
- Require minimum luminosity, and demand synchrotron radiation dominated environment to take advantage of beam emittance damping…

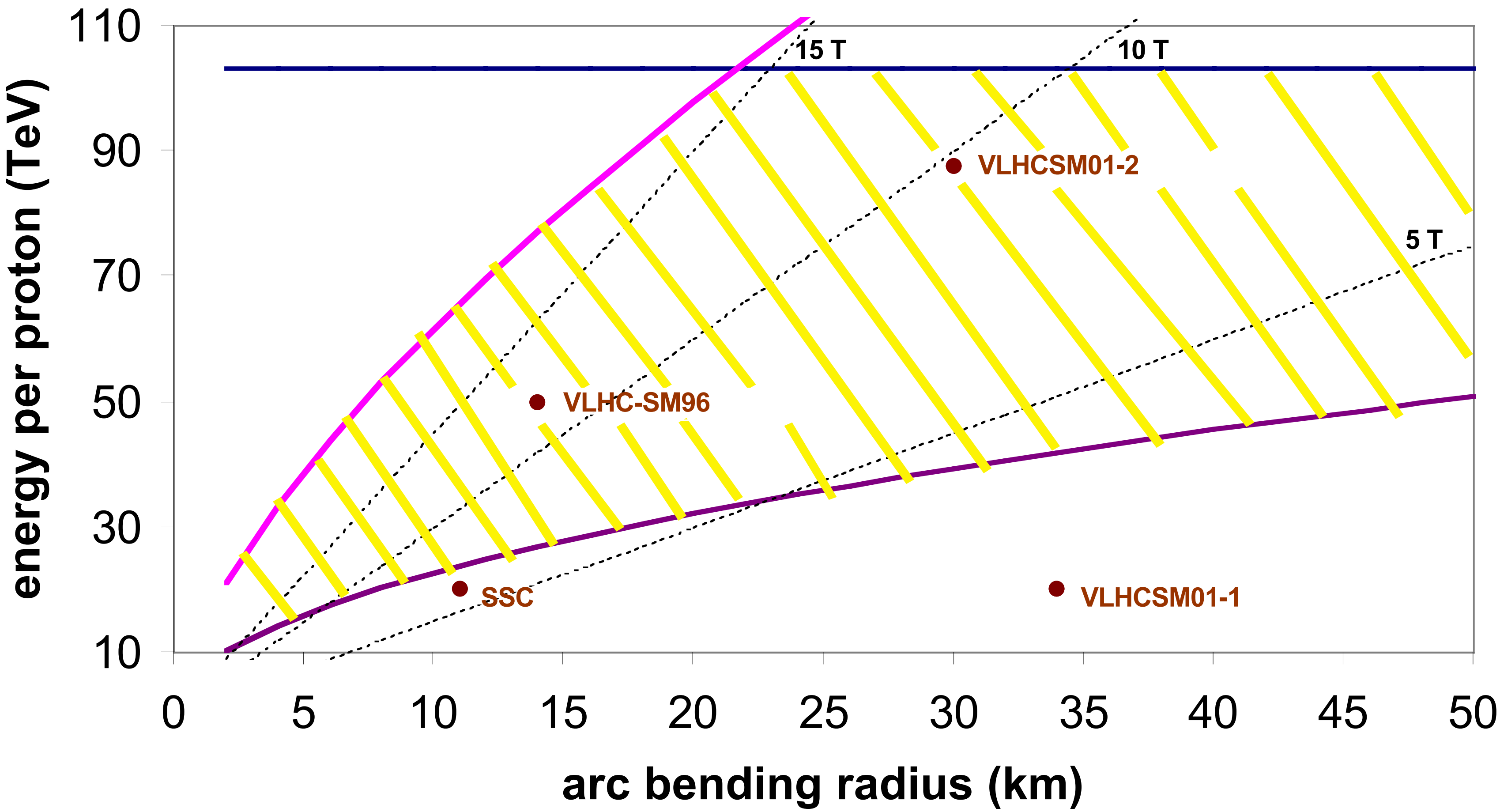
Scaling of Luminosity and Energy

- Example:
  - Make following assumptions:
    - β^* = 0.3 m (design study)
    - Bunch spacing = 12 nsec
    - Operate at beam-beam tune shift limit = 0.008
  - With following (semi-arbitrary, but reasonable) limits:
    - Peak synch. rad. power per beam = 5 W/m
    - Peak single IR debris power = 50 kW/beam
    - Max. beam-beam tune shift parameter = 0.008
    - Average beam stored energy = 5 GJ
    - Luminosity lifetime = 2 x radiation damping time
    - Minimum luminosity = 2 x 10^{34} cm^{-2} sec^{-1}

SR dominated VLHC's…

Courtesy P. Bauer, FNAL

P_{SR}<10 (5) W/m/beam peak (average), P_{IR}<100 kW/IR, τ_L/τ_{rad}>2, Number of events per crossing < 60, Luminosity>2 10^{34} $cm^{-2}sec^{-1}$



Scaling of Luminosity and Energy

- In previous plot, the accessible region is bounded above by the max. S.R. allowed in the arcs, until the energy is reached (about 100 TeV per beam) where the min. luminosity ($2x10^{34}$) generates the debris power limit.
- Both upper and lower boundaries are at $2x10^{34}$, and higher luminosity designs exist in between. Should have luminosity contours mapped out soon.
- The plot does not assume the use of photon stops for S.R. heat removal. This would move upper boundary to higher energies.

Scaling of Luminosity and Energy

- Luminosity burn-off: $L \sim N/T_{store}$
- Beam-beam saturation: $\varepsilon \sim N\xi_{max}$
- Collision debris power: $P_{IP} \sim N$
- Stored beam energy: $U \sim N$

- Photon stops allow higher bunch intensities, more luminosity, and more robust (larger) emittances
- But, collision debris power and stored energy become even more critical!

Scaling of Luminosity and Energy

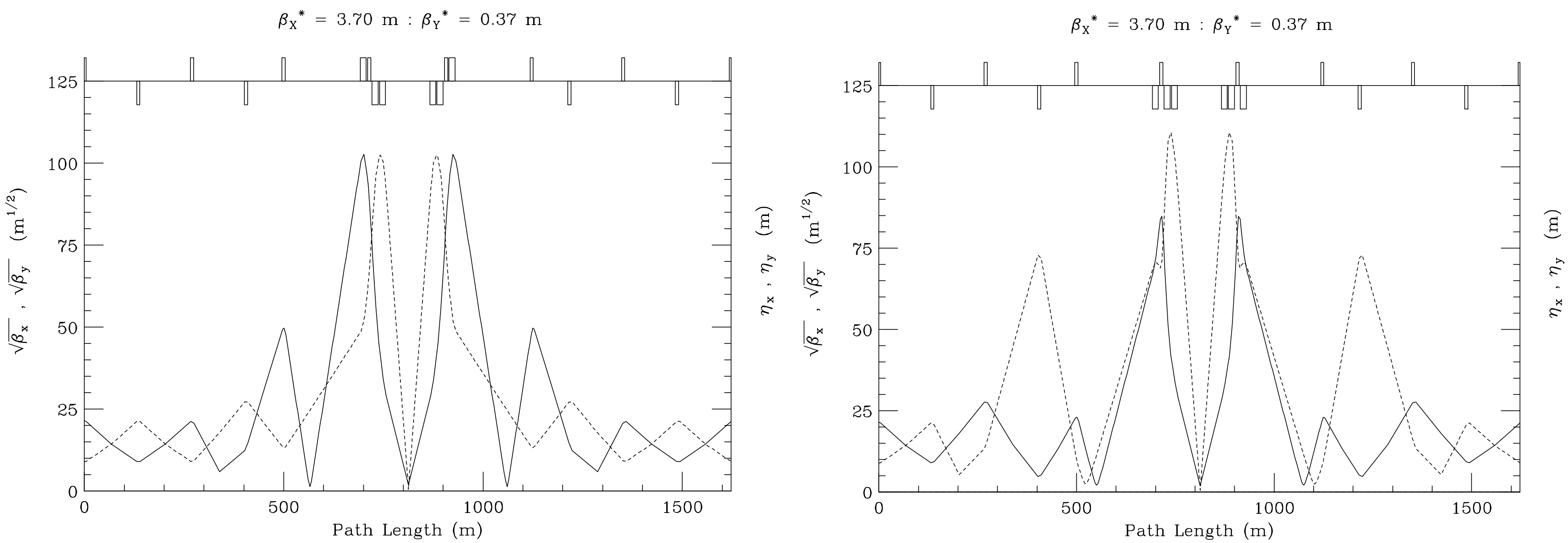
		Design Study	Photon Stops
Beam energy	[TeV]	87.5	87.5
Circumference	[km]	233	233
Collision Beta H/V	[m]	3.7/0.37	3.7/0.37
Initial bunch intensity	[10^9]	**7.5**	**30**
Dipole linear heat load	[W/m]	4.7	**18.7**
S.R. power, per beam	[MW]	0.88	**3.5**
Peak luminosity	[$cm^{-2}sec^{-1}$]	$2x10^{34}$	**$8.5x10^{34}$**
Emittance H/V (plateau)	[mm]	0.16/0.016	**0.69/0.069**
Collision debris power, per IP	[kW]	73	**292**
Stored energy, per beam	[GJ]	3.9	**15.6**

Lattice Issues

- Various lattice issues examined:
  - Beam extraction/abort systems at high energies
  - Beam separation schemes
  - VLHC lattice consistent w/ VLLC
- Most work was performed on IR designs
  - Round to flat transition

Lattice Issues -- IR design

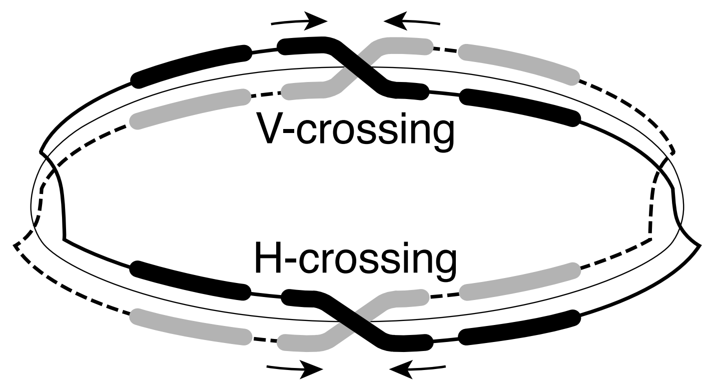
Smooth transition from doublet (flat beam) to triplet (round beam) possible…



Doublet Optics --------->> Triplet Optics

Superbunch Option

- Route to very high luminosity
- Use induction acceleration modules -- 25 kV/m -- to generate very long bunches bounded by “barrier buckets”
- More particles occupy the accelerator circumference, therefore higher beam current and higher luminosity (~ 15x)



Superbunch Option

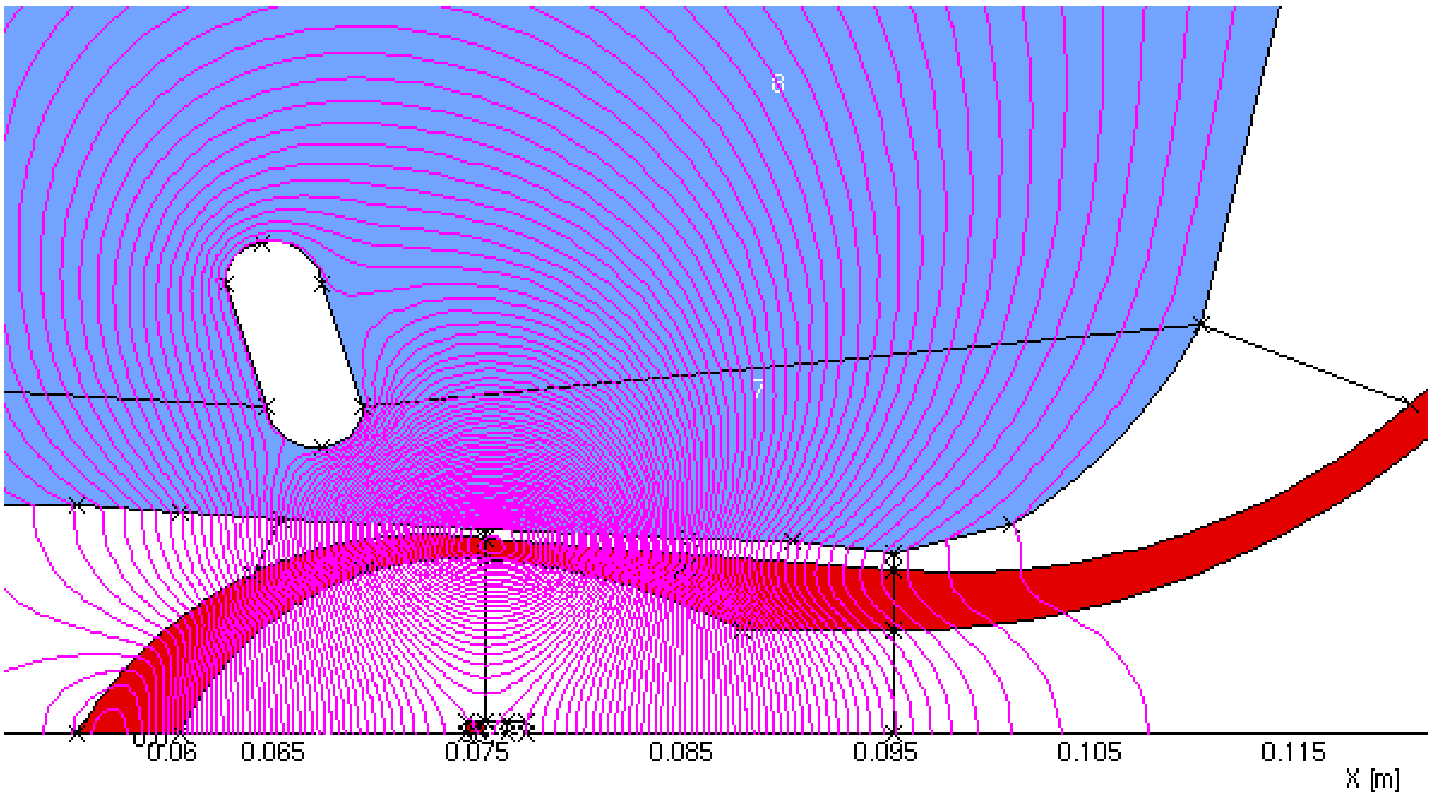
- While beam *is* bunched, the bunches are long -- behaves more like continuous beam
  - Do experiments want “unbunched” events?
  - ~15x the synchrotron radiation and beam stored energy -- therefore, perhaps only viable for a “Stage 1” machine
  - (Note: interesting for “proton driver” or fixed target accelerators as well…)
- Hardware tests of cavities and circuit designs are underway in Japan
- Needs beam demonstration -- KEK 12 GeV PS test due 2002; future Fermilab MI demonstration also proposed
- Superbunch collective effects and the potential of stochastic cooling need further study

Collective Effects

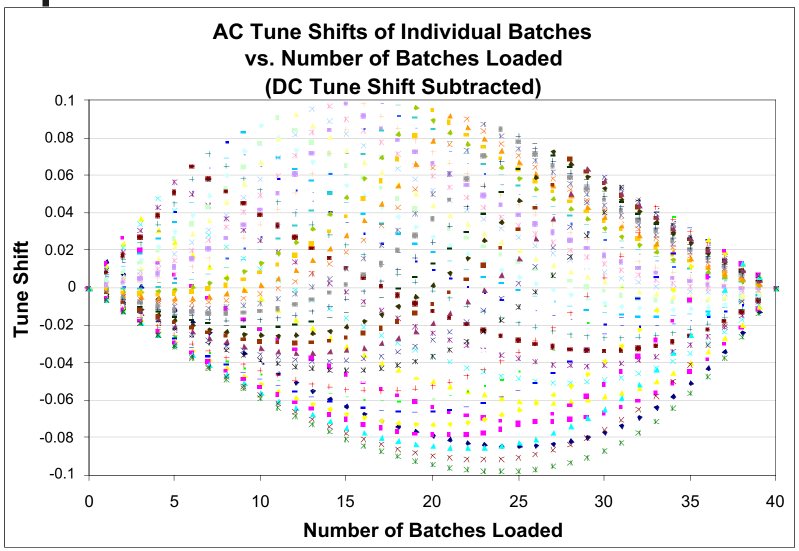
- Large circumference and small aperture of VLHC serve to increase the transverse impedance. More troublesome for “stage 1” due to lower particle energy
- Resistive wall instability
  - Growth time less than one turn at 2.6 x 10^{10}/bunch
  - Requires feedback system -- workable
- Transverse Mode Coupling Instability (TMCI)
  - The TMCI has been observed in many electron rings (PETRA, PEP, VEPP-4, LEP), but not in proton machines.
  - Deal with by injecting low intensity bunches, and coalescing at higher energy (3-5 TeV, say) where threshold is higher
  - Electron clouds formed by multipactoring may enhance TMCI effect
- Tune shift from eddy currents
  - Coherent tune shift variations along partially filled ring due to resistive wall wake fields.

Collective Effects -- eddy currents

Magnetic field distribution caused by beam pipe eddy currents after ten bunches with current 0.19 A pass by…

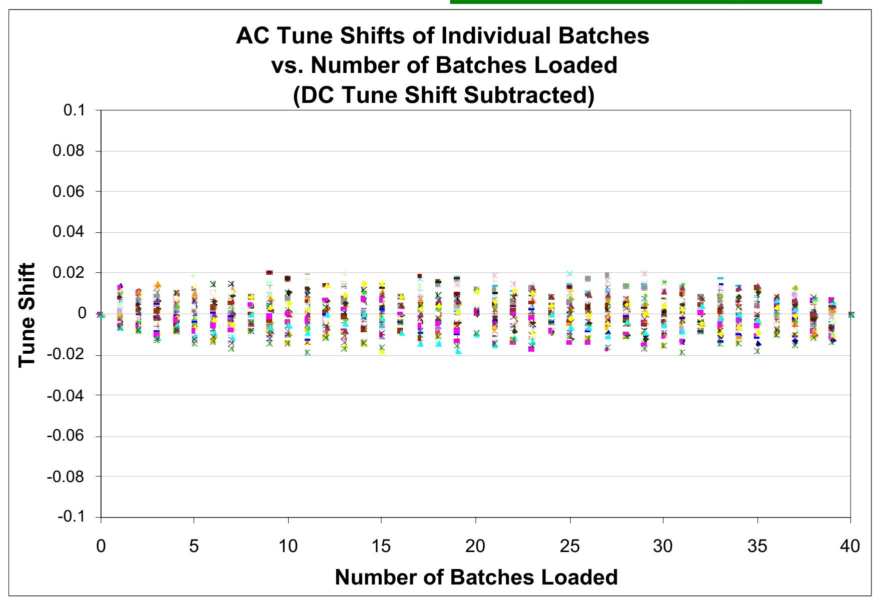


Filling patterns to reduce tune shifts



STANDARD FILLING SEQUENCE -- sequential filling

BALANCED FILLING SEQUENCE -- interleaved filling



Beam Experiments

- Develop plan for well-prepared beam based experiments at existing facilities to investigate physics and technologies to aid in designing less expensive and better performing VLHC
- Major experimental sub-topics might include
  - Feedback systems for Resistive Wall instability
  - Control of orbits, tunes, chromaticity
  - Superbunch demonstration
  - Slow Diffusion
  - Long-range beam-beam compensation
  - Beam-vacuum interactions

Beam Experiments

- Slow Diffusion
  - High energy synchrotrons will rely on radiation damping for small emittances; other competing sources for emittance growth?
- Long range beam-beam compensation
  - Tevatron electron lens will help establish expected performance of VLHC; needs further beam studies
- Beam-vacuum interactions
  - Photon stops interesting, but need confirmation of beam impedance and vacuum characteristics
  - Also, need tests of secondary e^- production rates for the superconducting collider environment
- Collaborative experiments provide natural context in which to examine a Global Accelerator Network for remote accelerator operation

Future VLHC R&D

- Instabilities
  - Impedance budget and estimates; photon stops, etc.
  - TMCI threshold (experiment: induce using Tevatron e^- lens?)
  - Collective feedback system specs.
  - Closed Orbit tolerances in vicinity of Feedback pick-ups
- Diffusion
  - Ground motion, modulational diffusion, Intra-Beam Scattering, Beam-Beam induced diffusion, etc.
- Lattice Design
  - IR optics (doublet & triplet), vertical dispersion suppression, beam abort, collimation, crossing angles/planes, optimum half cell length.

Future VLHC R&D

- Simulation/Scaling
  - Particle tracking, energy deposition, dynamic optics. Is the operational aperture more critical than the dynamic aperture? Feedback on closed orbits, tunes, and chromaticities. Arc and IR correction schemes. IR debris distributions.
  - Further study of luminosity versus energy, cryogenic power load, IR energy deposition,number of events per crossing, and capital or operating costs.
  - Is operational aperture (measured in mm) more critical than the dynamic aperture (measured in beam sigmas)?
- Beam experiments

Summary

- The "point design" studied this year shows a staged VLHC (40, ~200 TeV) is feasible, with no insurmountable challenges
- Further work can provide a more optimized design:
  - Look at various fields (e.g., superferric magnets for "stage 1") for improvements to vacuum, wall impedance, other performance parameters
  - May wish to consider "single-stage" approach for higher energies sooner
  - Effectiveness of photon stops and their engineering design
  - Continue to study superbunch approach, IR designs, new instrumentation and diagnostics, beam dynamics issues, …
- Organized VLHC-motivated beam studies should become part of the national program

Summary (speaker's opinion)

- The "point design" studied this year shows that a 40+ TeV collider is STILL a viable near-term option
- While a linear collider is an important asset for our field, the next (>LHC) generation hadron collider, VLHC, is *THE* next high energy frontier accelerator
  - Remember: LHC design was updated - several times - to try to "compete" with another 40 TeV collider…
  - It is known how to do this; it was basically known 15 years ago
  - Now, however, we have an opportunity to offer an improved design with higher luminosity at near the same cost (lower with further study?), and a straightforward upgrade strategy
  - A VLHC *has* to be part of our strategic plan