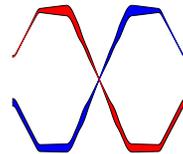

LHC Crab Scheme

R. Calaga, R. Tomás, F. Zimmermann
BNL/LARP, CERN



LHC-CC08: Feb 25, 2008
1st Mini BNL/LARP/CARE-HHH Workshop

Ack & Collaborators

- Brookhaven National Lab
I. Ben-Zvi, R. Calaga, S. Peggs
- CERN
F. Caspers, U. Dorda, Y. Sun, R. Tomás, J. Tuckmantel, F. Zimmermann
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C. Beard, G. Burt, P. McIntosh, A. Kalinin, A. Dexter, P. Goudek, L. Ma
- FNAL
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- Jefferson Lab
H. Wang, R. Rimmer
- KEK
K. Akai, K. Oide, K. Ohmi, Y. Morita, K. Yamamoto
- LBNL
J. Byrd, D. Li
- SLAC
C. Adolphsen, V. Dolgashev, Z. Li, T. Markiewicz, C. Ng, A. Seryi, J. Smith, S. Tantawi, L. Xiao
- ANL, INFN, Tech-X, ...

Central Repository (TWiki)

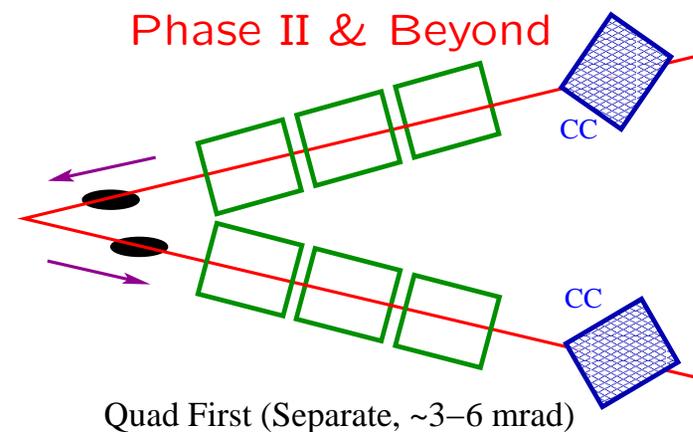
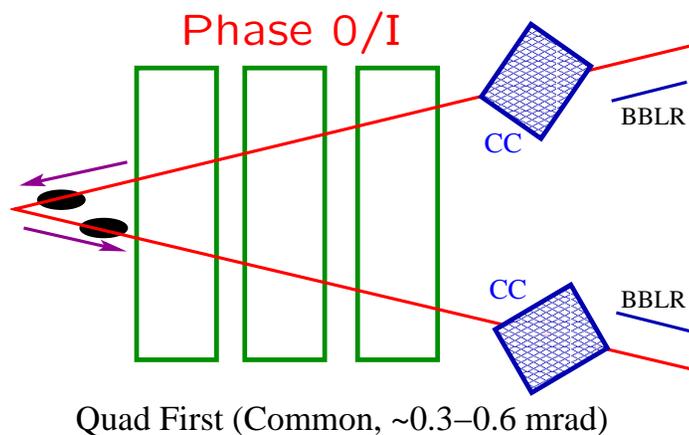
<https://twiki.cern.ch/twiki/bin/view/Main/LHCCrabCavities>

Goal:

- Outline working assumptions
- Distribute the work packages among the collaborators and share the most updated information
 - Optimized cavity design(s) & components
 - Optics, collimation & tracking studies
 - Literature, presentations and minutes
- Maintain regular meetings to discuss specific topics & new developments
- Provide easy access to all available information and avoid duplication of tasks
- The Wiki page and mailing list is currently maintained by BNL/LARP (R. Calaga)

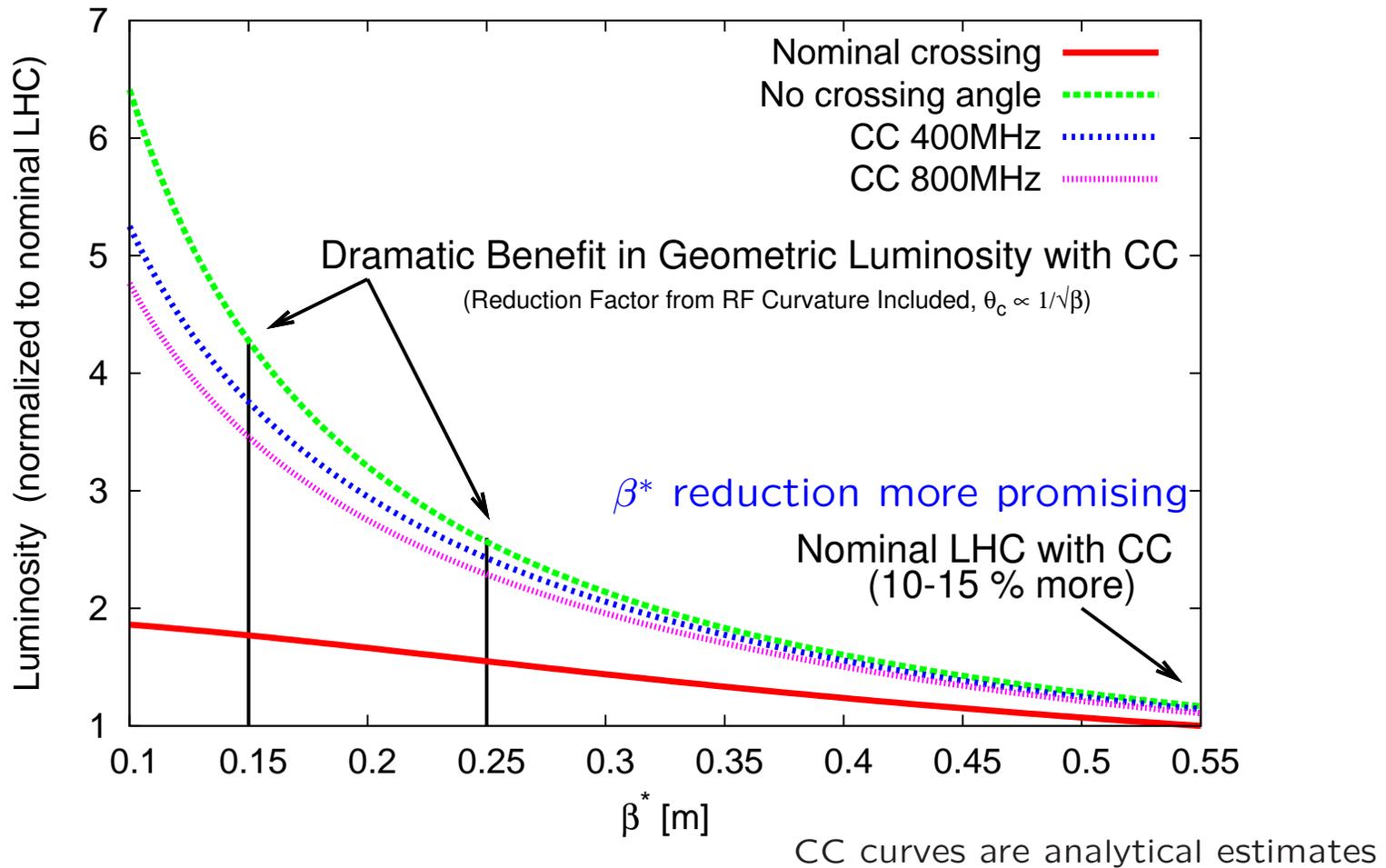
Phased Upgrades

- Phase 0 (Nominal LHC):
 - One crab structure/beam (global cavities @IP4, circa 2010-11)
 - Test SRF limits in deflecting mode & beam testing in LHC/SPS/?
- Phase I (Minimal β^* IR Upgrade, circa 2012-13)
 - New IR optics & magnet parameters to accommodate local cavities (800 MHz)
 - VV crossing scheme favorable, engineering details...
- Phase II (Complete IR Redesign, circa 2016 or beyond)
 - Larger transverse beam separation (>30cm) envisioned
 - Exotic schemes available ? Perhaps separate quad channels ?

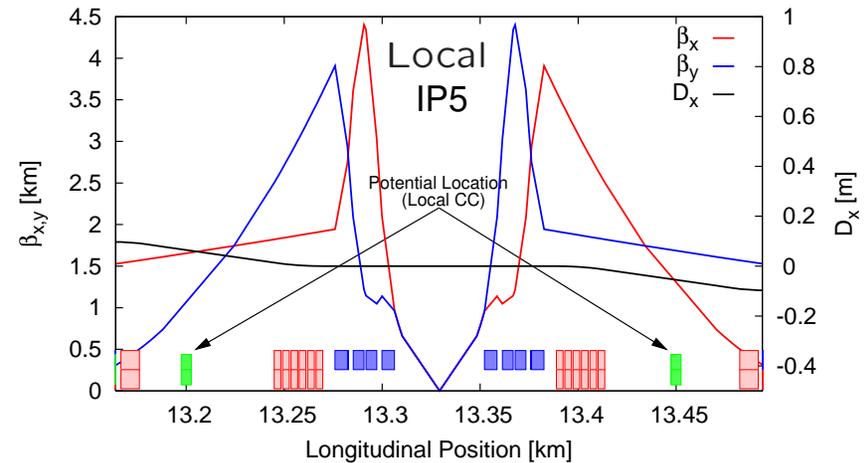
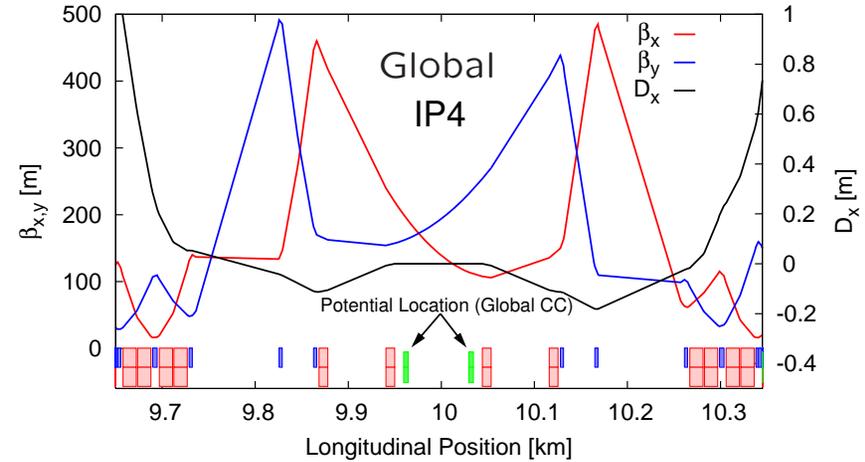
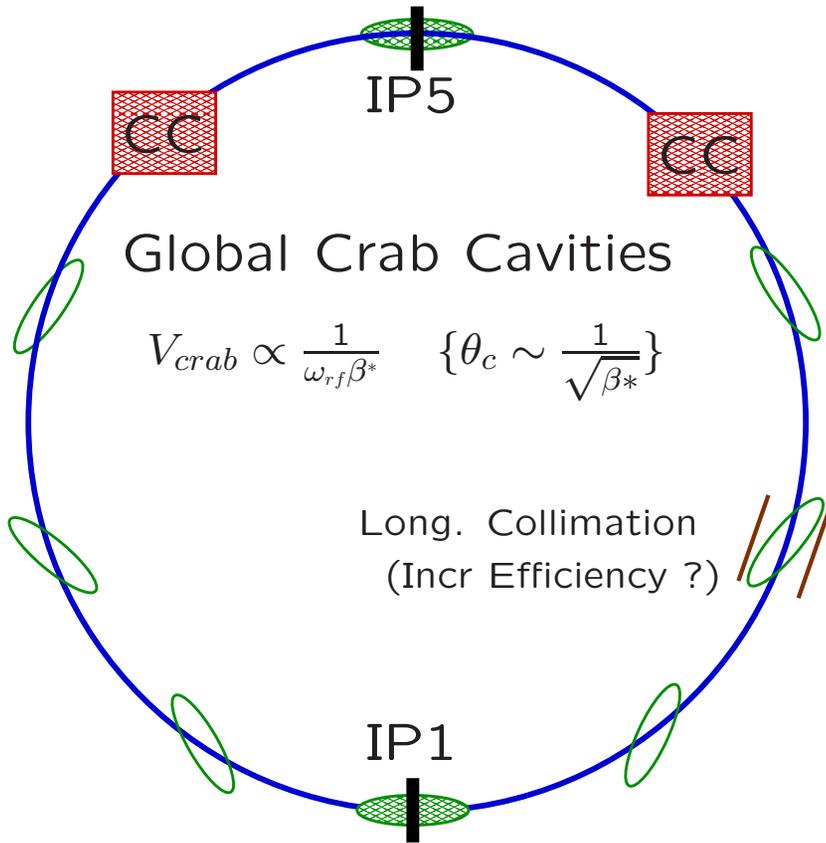


Geometric Luminosity

$$\text{X-Angle Reduction Factor: } \frac{L}{L_0} \approx \left[1 + \left(\frac{\sigma_z}{\sigma_x^*} \tan(\theta_c/2) \right)^2 \right]^{1/2}$$



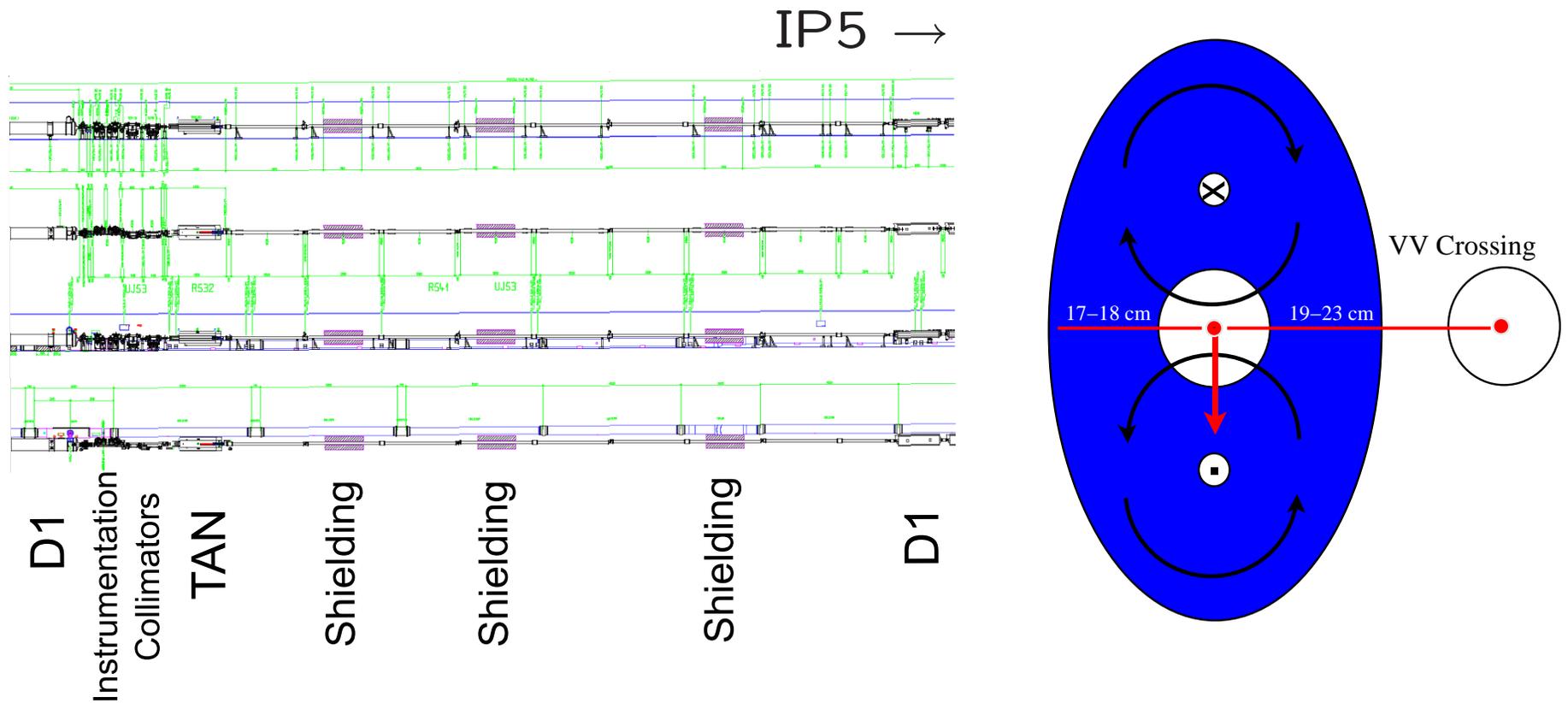
Small θ_c (0.3-0.6 mrad)



Par	Unit	Nominal [G]		Upgrade [L]	
$IP_{\{1,5\}} \beta^*$	[cm]	55		25 (8_{ES})	
β_{CC}	[km]	0.13	0.38	3.0	4.5
CC Volt	[MV]	2.0	5.8	5.4 (9.5)	3.7 (6.4)

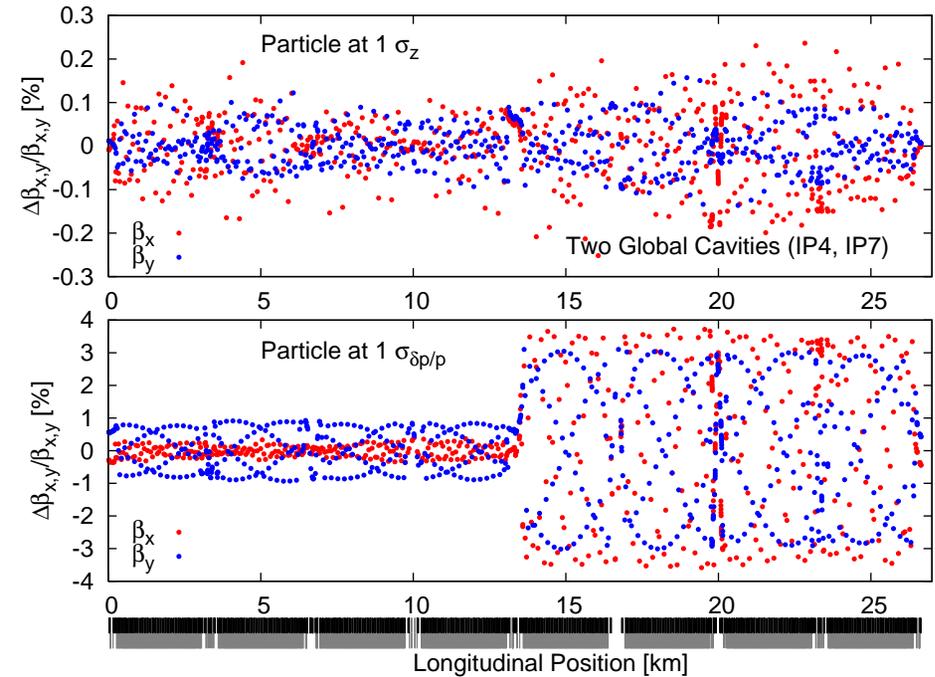
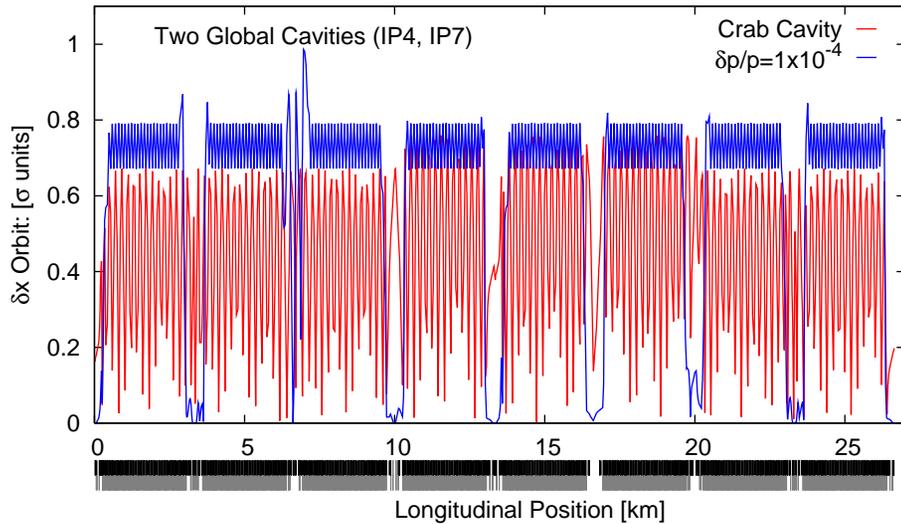
Local Scheme: Space Challenge

- Longitudinal Space $\sim 10\text{-}15\text{ m}$ (Local, staggered cavities, common cryostat)
- **Transverse for nominal $\sim 19\text{ cm}$, tight margin (VV Crossing)**
- Require clever He vessel + integrated cryostat design to accommodate two beams



Optics Issues

- Horizontal orbit & beta-beat: Collimation issues ?



- Error in β_{crab} & $\Delta \phi_{cc \rightarrow ip}$ similar to ΔV_{crab} error:

$$\Delta \phi_{err} \sim 0.25^\circ \Rightarrow \theta_{res} < 1 \mu rad$$

Tunable via optics and/or voltage (optimize using luminosity & lifetime)

— See collimation talk, R. Assmann

Optics Issues Contd.

- Coupling:

- Introduces vertical θ_c & offset (prelim estimate):

$$\begin{aligned} & \text{Quad tilt Errs} \sim 30 \mu\text{rad} \\ \Delta Q_{min} \sim 5 \times 10^{-3} & \Rightarrow \theta_{c,y} < 10 \mu\text{rad} \end{aligned}$$

- VV Crossing introduces vertical dispersion

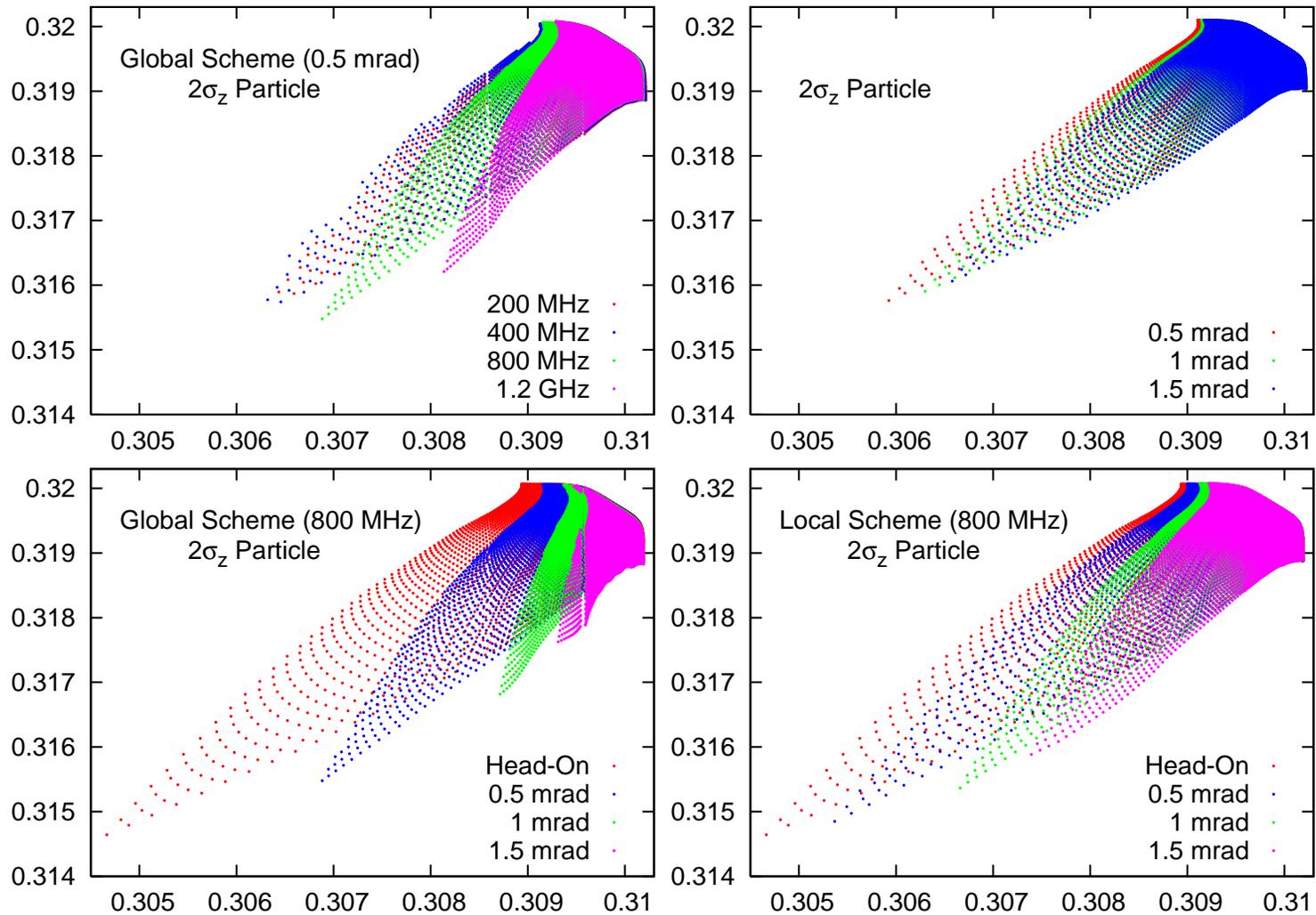
- * Nominal is hybrid scheme (HH→@IP5 & VV→@IP1)

$$D_y: \{\text{RMS, Peak}\} = \{0.18 \text{ m, } 1.17 \text{ m}\}$$

- * Cancellation of LRBB effects (Diff IP offsets, tunes & orbits along the bunch train).
- * Phase I upgrade: can it be VV crossing ?? Stronger footprint folding, but effect on beam lifetime & stability is not clear ? Need LHC beam to verify different crossing schemes.

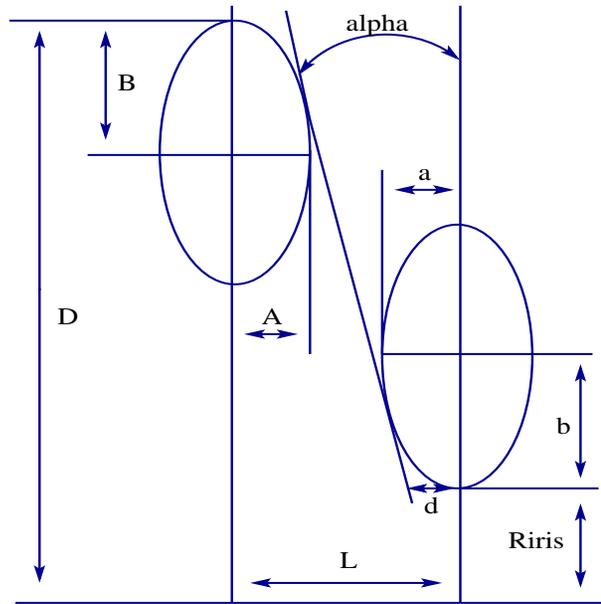
- Impact of Non-Linearities:(simulations needed)

Preliminary Tracking (WS)

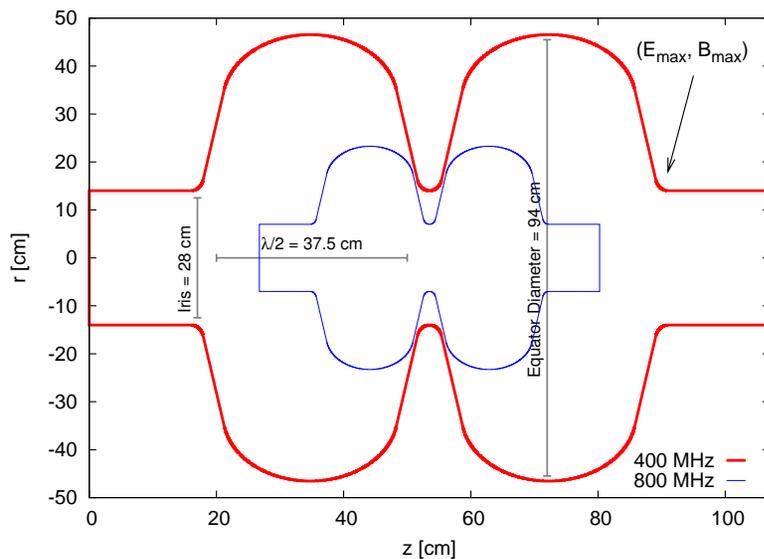
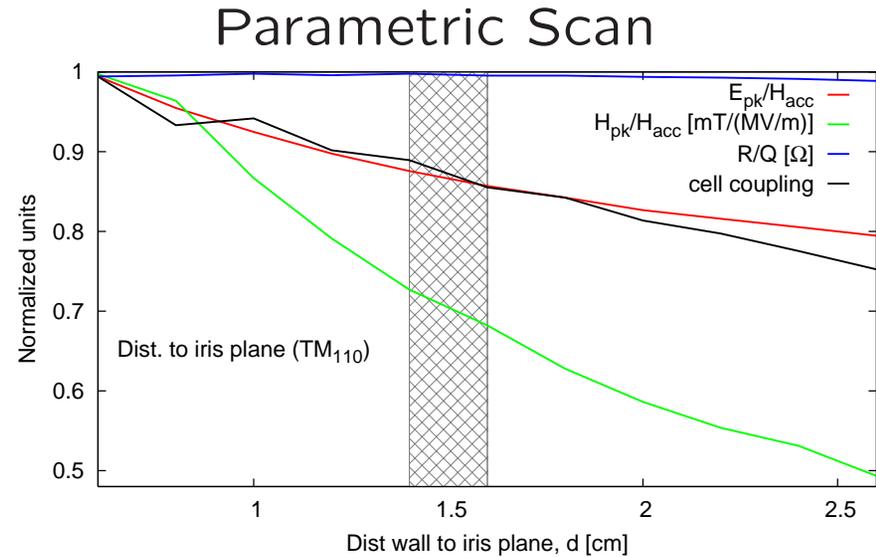


- No significant effect visible for phase I (~ 0.5 mrad)
- Lattice errors need to be included for further investigation

Cavity Optimization



— Pierini et al. Parametrization



Parameter	Crab Cavity	
Frequency [MHz]	400	800
Iris Radius, R_{iris} [cm]	14	8.0
Wall Angle, α [deg]	10	10
Equatorial Ellipse, $R = \frac{B}{A}$	1.0	1.0
Iris Ellipse, $r = \frac{b}{a}$	1.5	1.5
Cav wall to iris, d [cm]	1.5	2.0
Half Cell Length, $L = \frac{\lambda\beta}{4}$ [cm]	18.75	9.375
Equator Height, D [cm]	47	23
Cavity Beta, $\beta = \frac{v}{c}$	1.0	1.0

Some RF Jargon

- Shunt Imp:

$$\frac{R_{\perp}}{Q_0} = \frac{1}{(kr)^2 \omega U} \int_0^L E_z(r=r_0) e^{ikz} dz$$

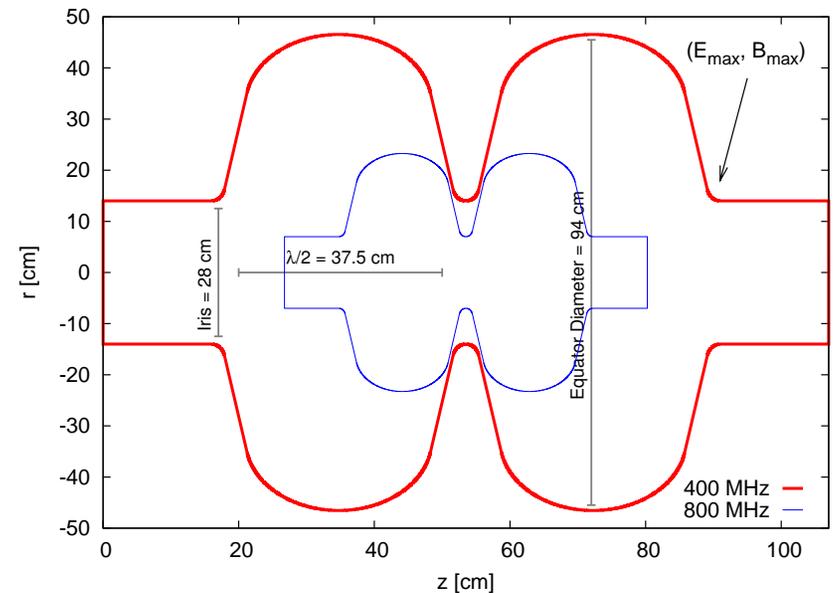
$$\approx 120 \Omega \{800 \text{ MHz}, 2 \text{ Cells}\}$$

- Orbit Offset in CC ($< 1\text{mm}$):

$$V_b \approx Q_L I_b \frac{R_{\perp}}{Q} (\delta x)$$

$$\approx 0.1 \text{ MV/mm}$$

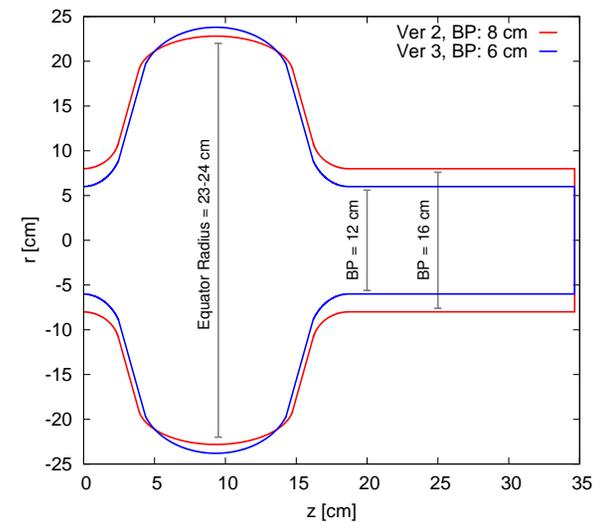
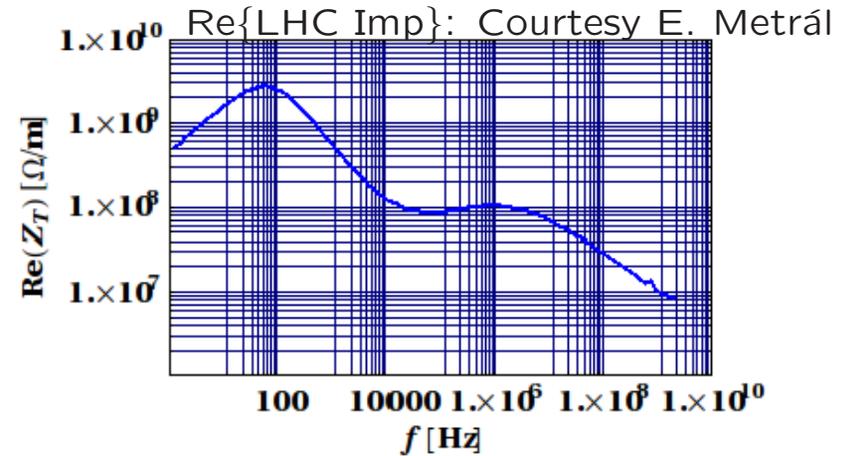
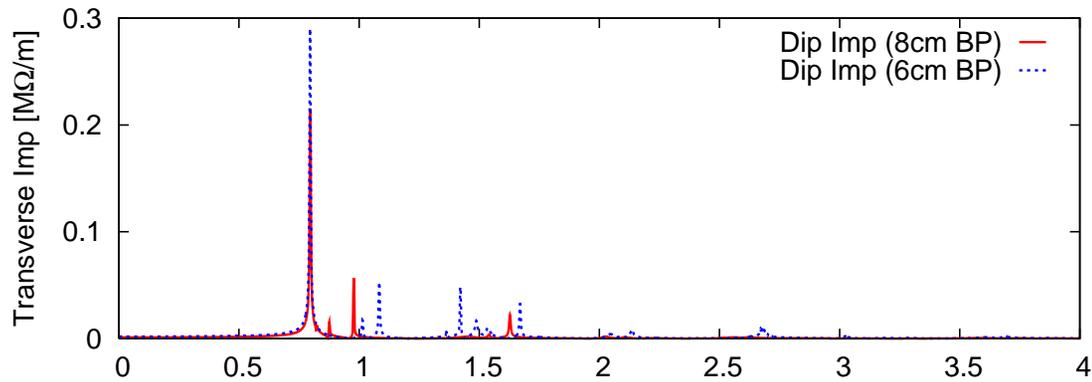
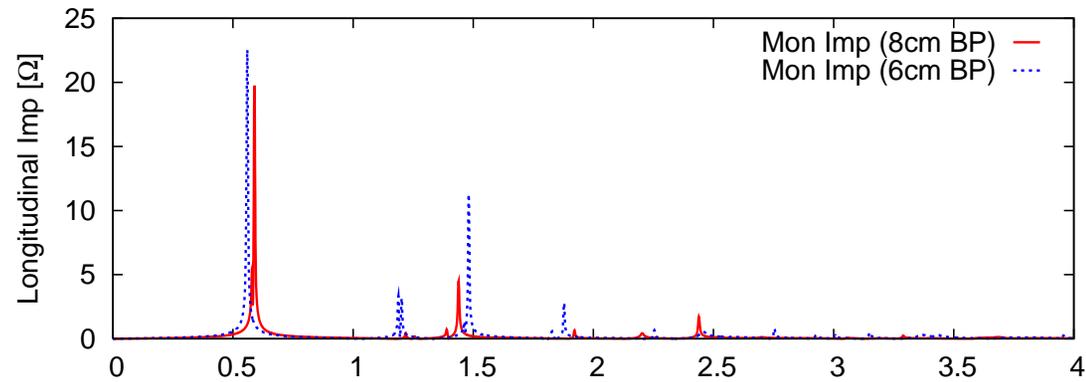
$$\{Q_L = 10^6, I_b = 0.85 \text{ A}\}$$



Par	Unit	Ver 2	Ver 3	SLAC Variant	TESLA	Limit
CC Voltage	[MV/m]	5.0			-	-
E_{peak}	[MV/m]	40.8	26.28	25	70-90	Field Emission
B_{peak}	[mT]	157.5	154	83	150-190	220 mT
R_{\perp}/Q	[Ω]	91	128	117	-	-

- Power Requirements (2 - 20 kW, $Q_L = [10^5 - 10^6]$):
 - Beam loading, conditioning ~ 50 kW (commercially available)
 - Microphonics, Lorentz force detuning...

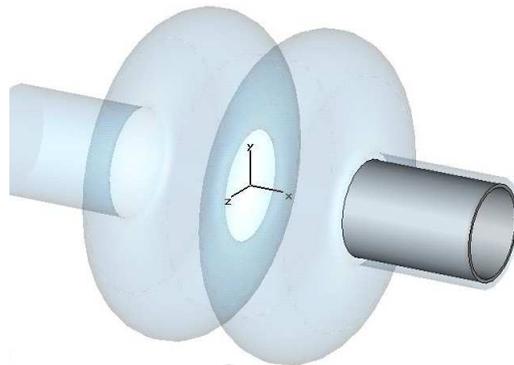
CC Impedance Spectrum



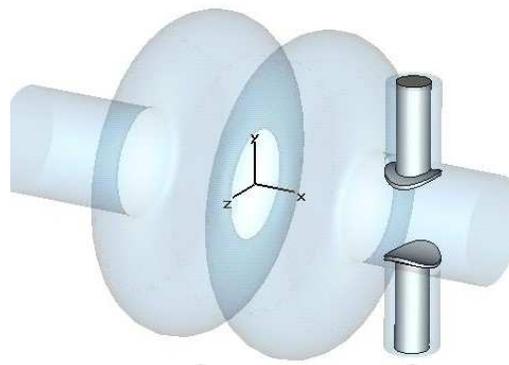
Loss Factors	Unit	BP: 8cm	BP: 6cm
Longitudinal: $k_{ }$	[V/pC]	8.4×10^{-2}	5.7×10^{-1}
Transverse: k_{\perp}	[V/pC/m]	1.53	2.50
HOM Power, 0.5 A (0.85 A)	[kW]	1.48 (2.5)	10.0 (17.1)

Couplers & Tuners

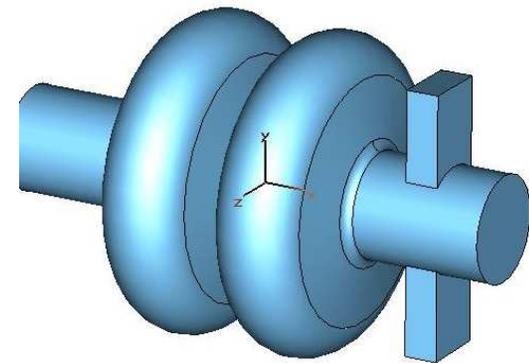
- Couplers:
 - Kick Mode: Co-axial Coupler
 - LOM: Beam Pipe Coax (KEK, $Q_{ext} \sim 10^2$), **Fragile**
Waveguide coupler (LBNL, $Q_{ext} \sim 10^3$), **Damping Sufficient ?**
New concepts (Radial BP Coax)
 - HOM: Beam pipe coax (KEK), Additional couplers (CW Power Capability)



BP Coax



Power Coupler: Coax



Waveguide Coupler

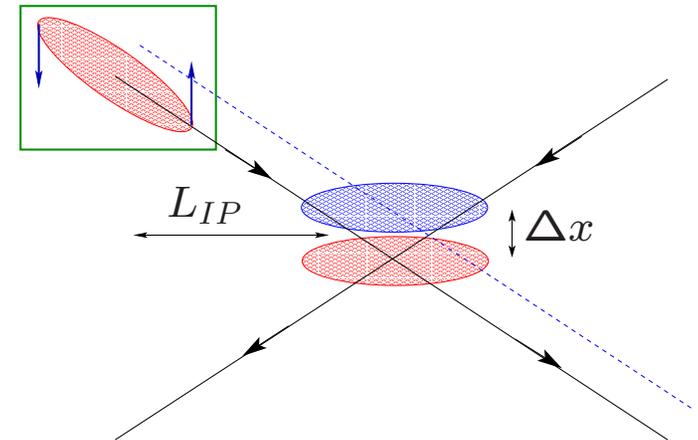
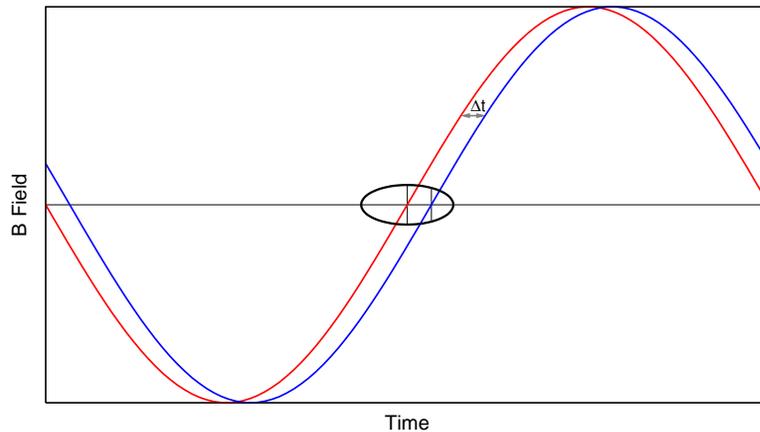
- Tuners:
 - BP coax tuning (Effective & Simple)
 - Conventional tuners (Iris based tuner, Peak Fields→Iris)

— see talk by G. Burt

Noise Tolerances

Phase jitter introduces random offset:

$$\left(\frac{\Delta\epsilon_x}{\Delta t}\right)_{BB} \approx n_{IP} f_r \frac{8\pi^2 \xi^2}{\beta_x^*} (\Delta x)^2 \quad \left\{ \Delta x_{IP} = \frac{c\theta_c}{\omega_{RF}} \delta\phi \right\}$$



Random Dip Kicks: $\frac{1}{\epsilon} \frac{\Delta\epsilon_x}{\Delta t} \approx \frac{f_r(1-s_0)}{4\sigma_x^* \left(1 + \frac{q}{2\pi|\xi|}\right)^2} (\Delta x)^2$ [Y. Alexahin]

For 1% Emittance Growth/Hr, gain=0.2 (Random turn-to-turn)

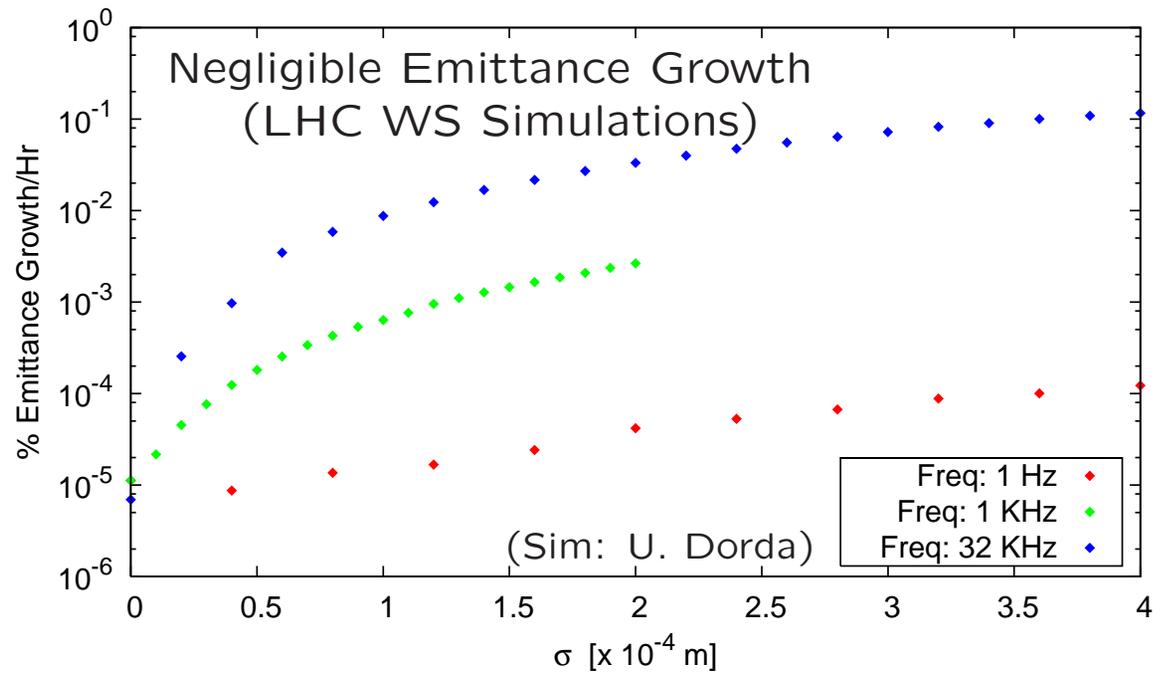
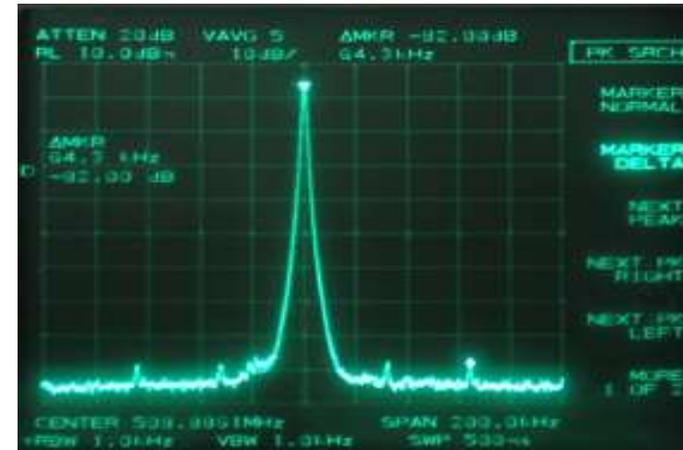
Jitter Estimate	Amp.	Phase	
		Beam-Beam	Dip. Kicks
Analytical Simulation (WS)	~ 0.04%	0.01° (0.006°)	0.006° (0.003°)
		0.002°	-
Simulation (SS, K. Ohmi)		< 0.001°	
Feasible Today	0.01%	0.003°	

Modulated Jitter

Span 200 Hz

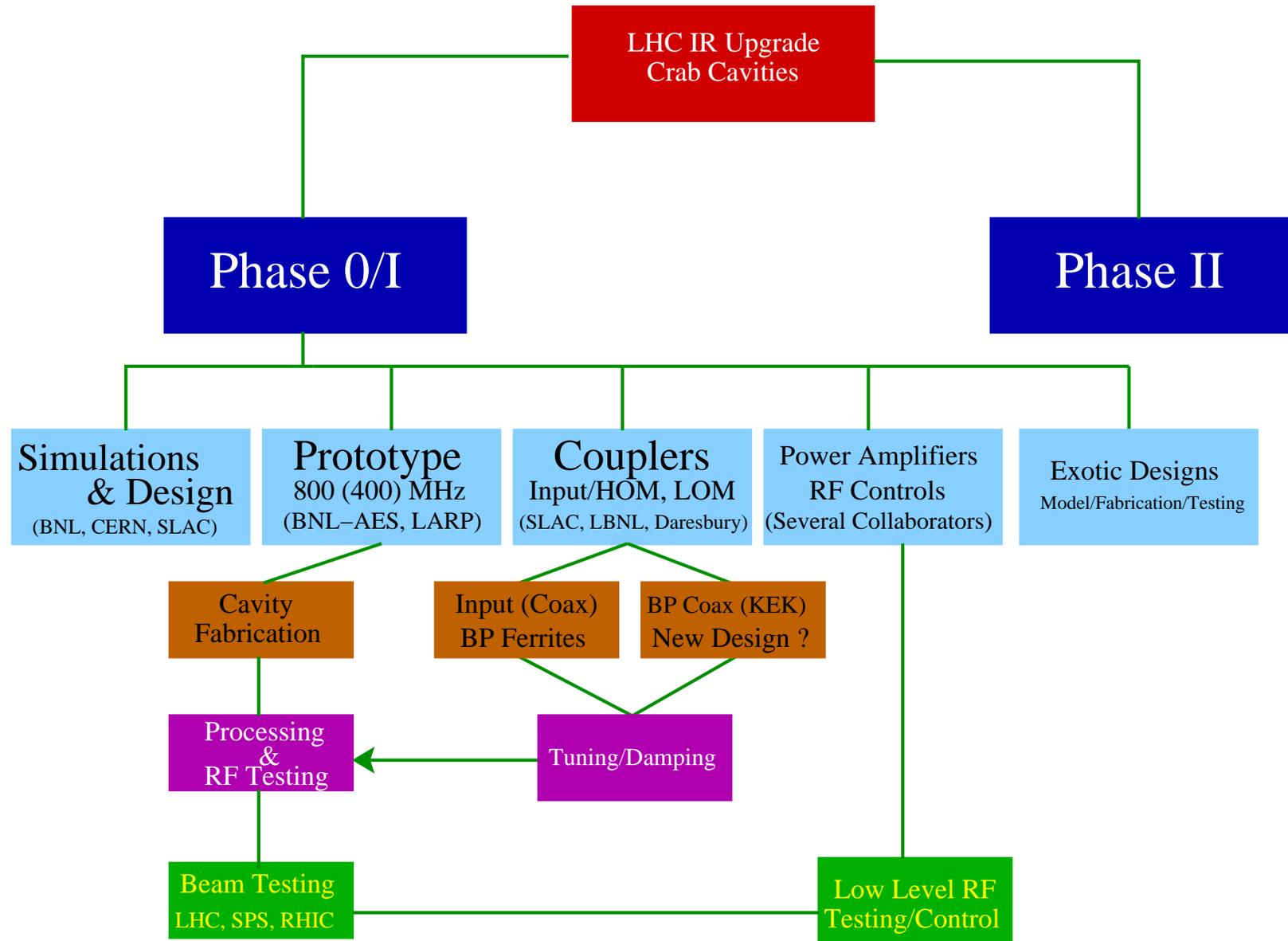
KEK-B

Span 200 kHz



— Measurements courtesy KEK-B

R&D Proposal

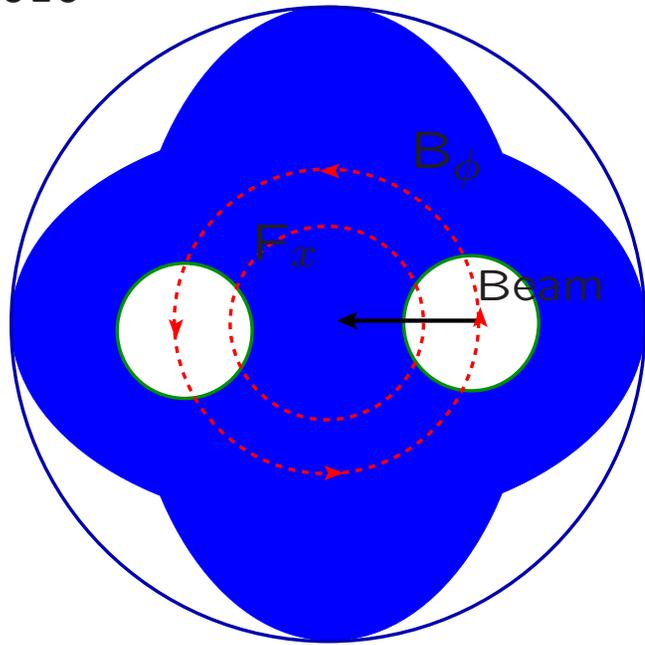


Conclusions

- Dramatic benefit ($\times 2.5$ or larger) on luminosity gain with β^* & luminosity leveling is trivial and transparent
- 800 MHz prototype for Phase 0 ($\theta_c < 0.3$ mrad, global)
 - Final design of cavity (Fall 2008) and coupler (2009)
 - Mechanical design & fabrication (2009-10)
 - SRF & beam testing (2010-11 ?)
- Refined Phase I optics with integrated cavities in the IR ($\theta_c < 0.5$ mrad, local)
- **Novel ideas for compact cavities** \longrightarrow **less beam-line engineering**
- Noise issues do not appear to be problem, more SS simulations needed for benchmarking (LBNL, KEK-B, CERN)
- Investigate collimation inefficiencies & compare loss maps from nominal
- Global Collaboration: BNL, CERN, DL/CI, FNAL, JLAB, KEK-B, LBNL, SLAC, Tech-X...
- 2nd LHC-CC workshop, circa Oct 2008 to review progress

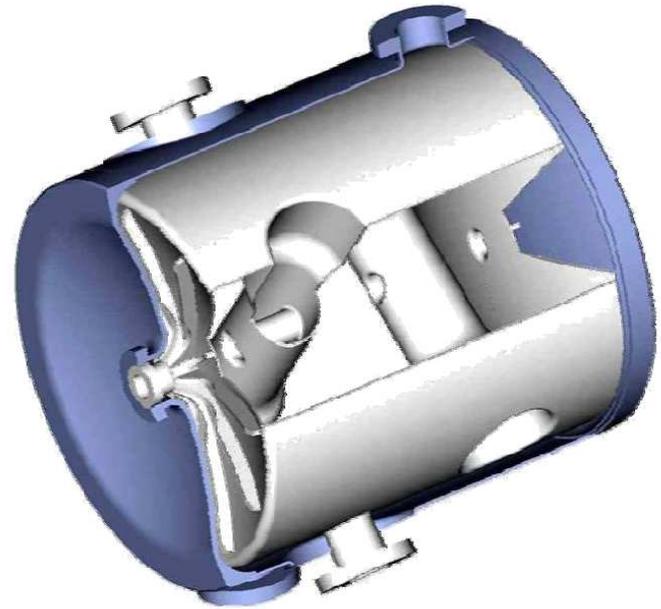
Exotic Cavity Discussion

TM₀₁₀ Mode:



- Advantages: Smaller transverse dimensions, high R/Q, high gradient, simpler design (HOMs, couplers, etc...)
- Disadvantages: Transverse wakefields, multipacting needs evaluation, beam loading and others

Spoke Cavities:



- Advantages: More compact than TM₁₁₀ cavities, mechanically stable
- Disadvantages: Complicated design (significant R&D), lower gradient (??), multipacting

Luminosity Leveling
