Crabs in LHC

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Thanks: J. Tuckmantel, F. Caspers

C-AD Seminar - Dec 19th, 2006

Topics

- IR Upgrade & Options
- Crab Crossing: History & Motivation
- Global or Local IR Cavities
- Emittance Growth
  - RF Curvature, Amplitude and Phase Noise
  - Energy Spread, Chromaticity, Non-Linearities
  - Lattice Errors, Coupling, CC Roll
- Baseline Design (400 MHz), RF Requirements
- CC Longitudinal and Transverse Impedance
- Possible Exotic Schemes
- Conclusions

CARE-HHH & LHC IR Upgrade

Upgrade (circa 2015):

Life expectancy of IR Quads $<$ 10 yrs

Objective #1:

To establish a road map for the upgrade of the European accelerator infrastructure - LHC and GSI accelerator complex

Brief Chronology:

- Physics potential (CERN-TH-2002-0787) & accelerator aspects (Report 626)
- LHC IR Upgrade Collaboration Meeting, CERN, March 2002
- Scenarios for the LHC luminosity upgrade (LHC-LUMI-05), Arcidosso, Italy, September 2005
- Towards a Roadmap for the Upgrade of the LHC and GSI Accelerator Complex (LHC-LUMI-06), Valencia, October 2006

Courtesy F. Ruggiero

Upgrade Phases

- Nominal $\rightarrow$ Ultimate ($\sim$ factor of 3)
  - Phase 0: Increase bunch intensity (0.58 $\rightarrow$ 0.86 A)
  - Phase 1: Low beta insertions ($\beta^* = 0.5 \rightarrow 0.25$), increase θ_c, increase bunch intensity (new hardware), 1/2 σ_z (expensive)
- LHC main ring and injector upgrades - Phase 2
  - 2$\times$ number of bunches (e^- cloud ??) or
  - Increase bunch intensity and bunch length
- Increase injection energy to 1 TeV
  - Higher injection energy (Super-SPS) & PS2/PS+
  - Reduce turn-around-time

Upgrade Options

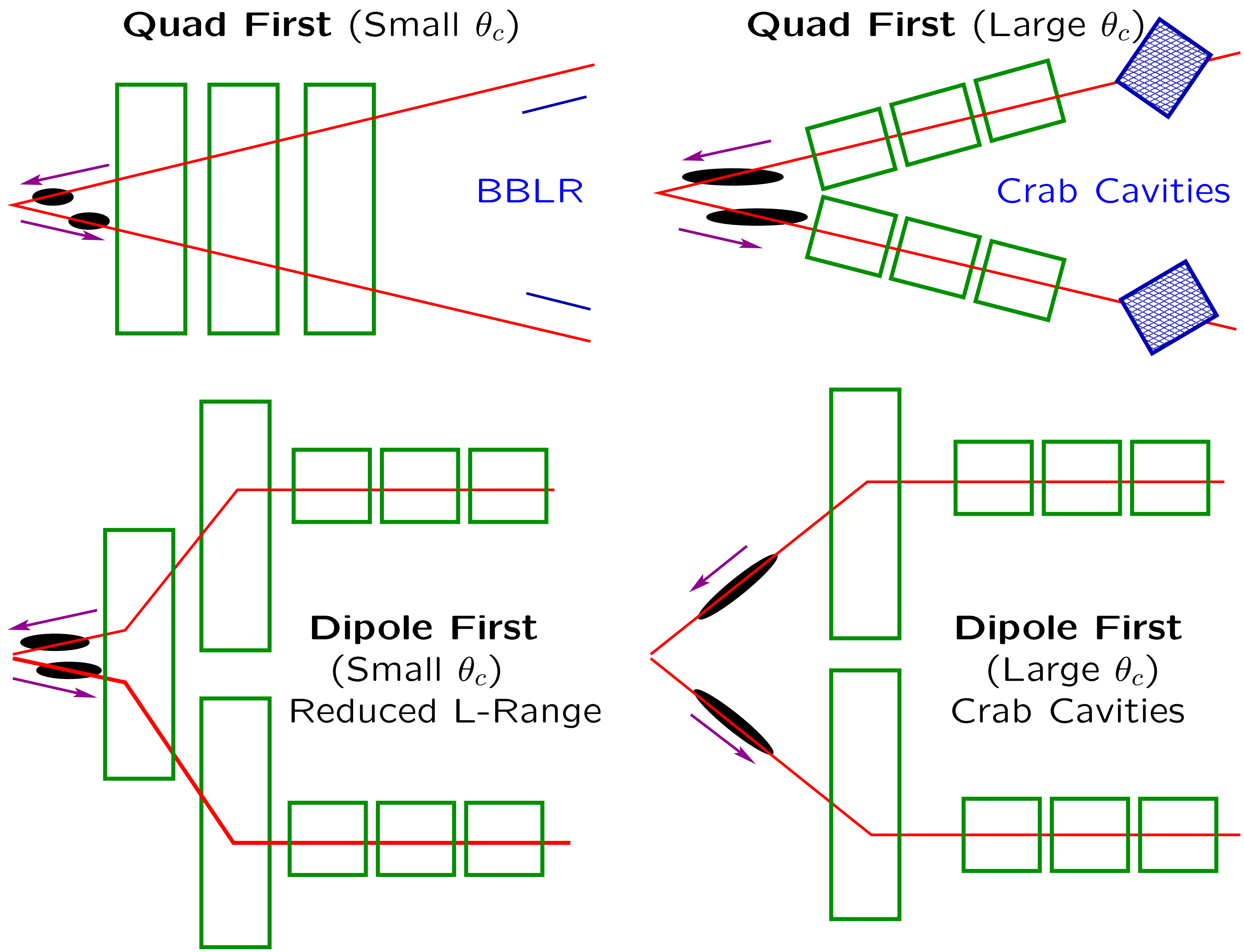
Parameter	Symbol	Nominal	Ultimate	Shorter	Longer
No. of bunches	n_b	2808	2808	5616	936
Protons/bunch	$N_b[10^{11}]$	1.15	1.7	1.7	6.0
Average current	I [A]	0.58	0.86	**1.72**	**1.0**
Bunch spacing	Δt[ns]	25	25	**12.5**	**75**
Norm. Emittance	ϵ_n [μm]	3.75	3.75	3.75	3.75
RMS bunch length	σ_z [cm]	7.55	7.55	3.78	14.4
Beta-Func IP1&IP5	β^* [m]	0.55	0.50	0.25	0.25
Full crossing angle	θ_c [μrad]	285	315	445	430
Piwinski parameter	$\theta_c \sigma_z/(2\sigma^*)$	0.64	0.75	0.75	2.8
Peak luminosity	L $[10^{34}\ cm^{-2}s^{-1}]$	**1.0**	**2.3**	**9.2**	**8.9**
Events per crossing	–	19	44	**88**	**510**
Eff. lumi (TAT=10h)	L $[10^{34}\ cm^{-2}s^{-1}]$	0.4(14.6)	0.8(12.3)	2.4(8.9)	1.9(7.0)
Eff. lumi (TAT=5h)	L $[10^{34}\ cm^{-2}s^{-1}]$	0.5(10.8)	1.0(9.1)	3.3(6.7)	2.7(5.4)

Preliminary Conclusions:

- More average and less peak luminosity (Request from Experiments)
- 12.5 nS spacing - e^- cloud, too much heat load
- Long bunches - Too much PileUp

Courtesy F. Ruggiero

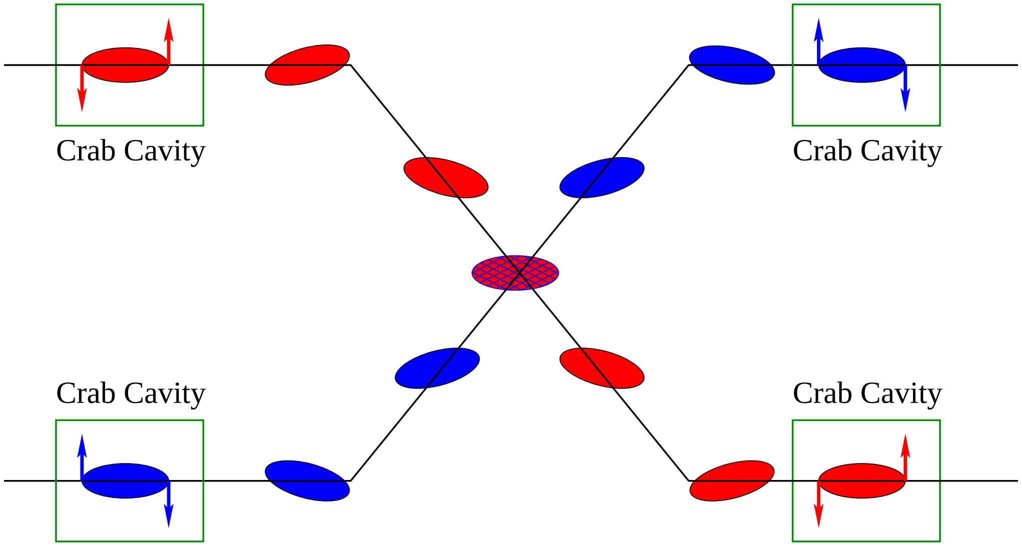
Upgrade Scenarios



Crab Scheme for LHC IR Upgrade

History & Motivation

- 1960: CERN/Karlsruhe - 2.86 GHz Kaon Separation
- 1991: Cornell - 1.5 GHz B-Factory (Prototype: 3×Operating Freq.)
- 1993-now: KEKB - 500 MHz B-Factory (In operation soon)
- 1996-now: ALS, APS, $\cdots$ Synch Light Compression
- 2000-now: FNAL - 3.9 GHz Kaon Sep., ILC Crab Crossing (1.3-3.9 GHz)
- 2005-now: LHC - 400 MHz Crab Crossing

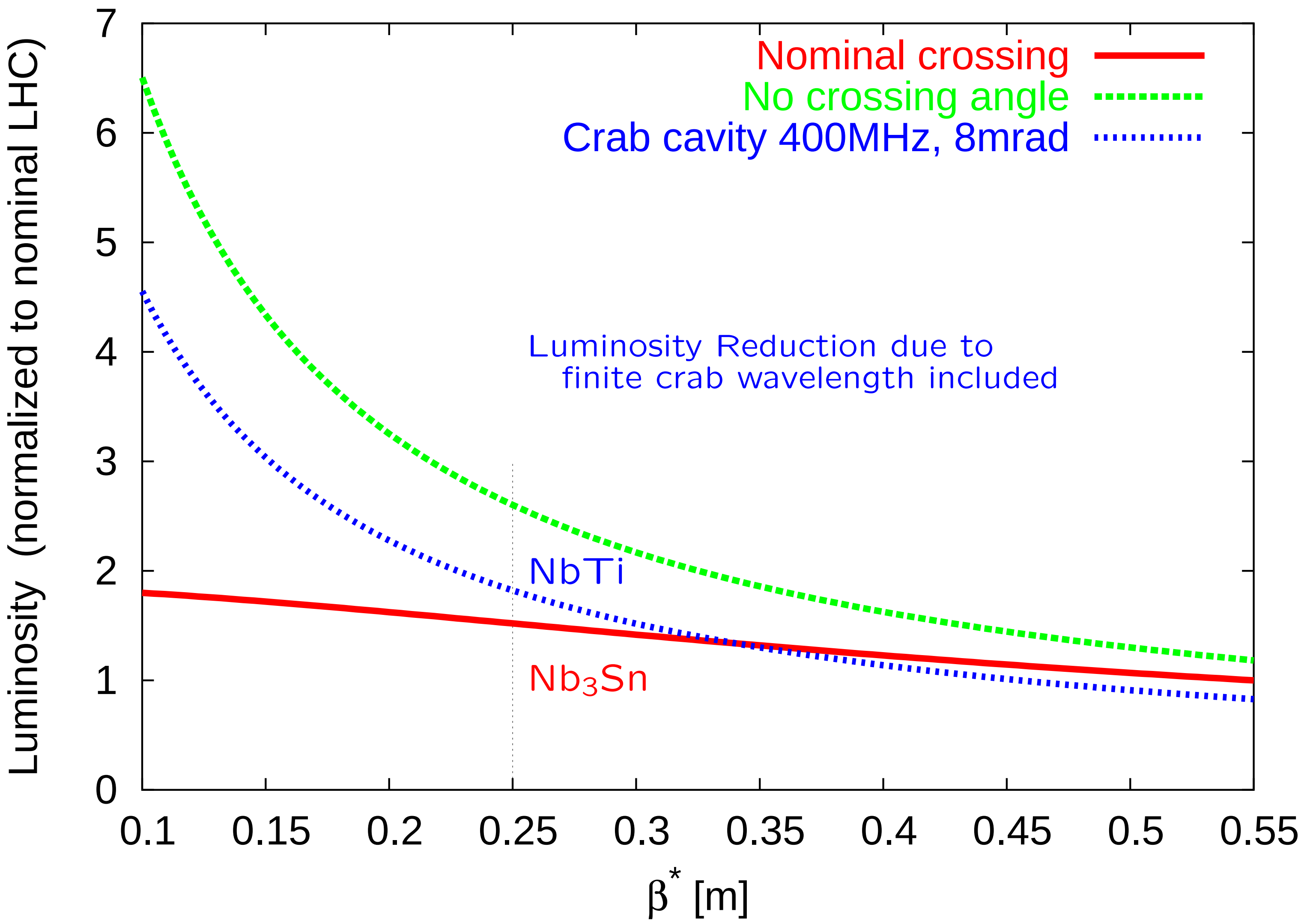


- Geometric luminosity loss

$$\frac{L}{L_\circ} \approx \left[1 + \left(\frac{\sigma_z}{\sigma_x^*} \tan\left(\theta_c/2\right)\right)^2\right]^{1/2}$$

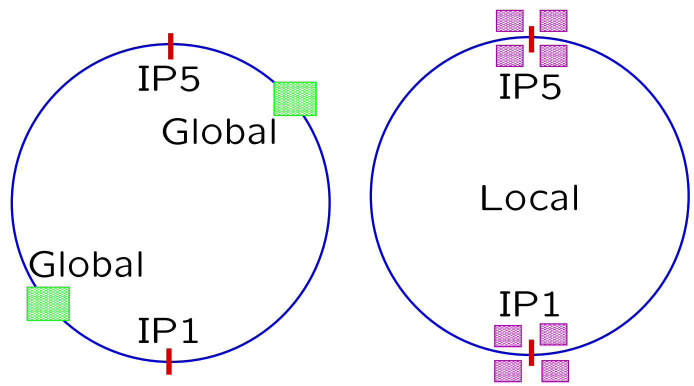
- Long range beam-beam
- Simple IR design (Sep. Quads
- β^* reduction & flexibility

Luminosity scope



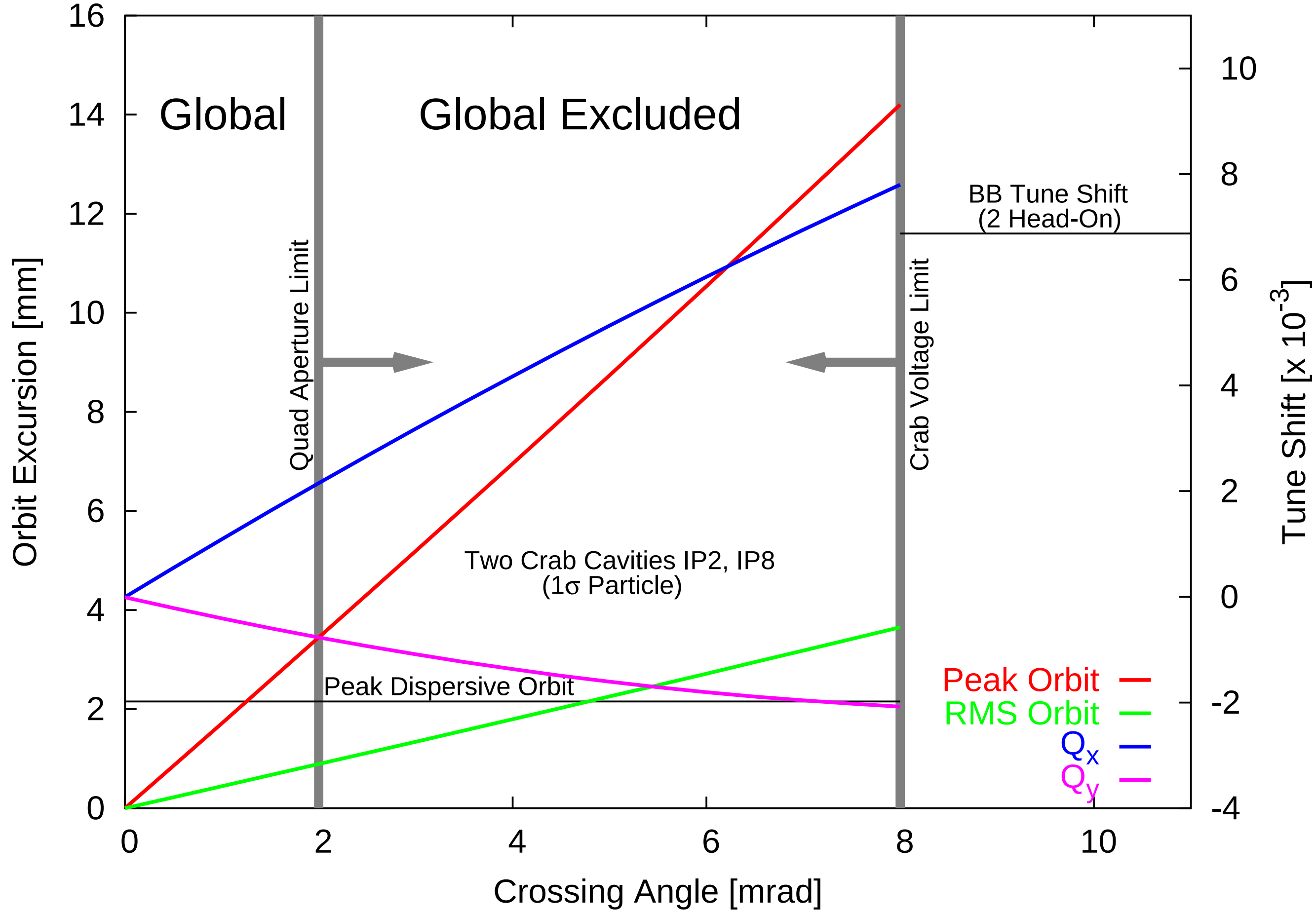
- Crab option gets factor 2 only from optics
- Aim at lower θ_c and lower β^*

Global (Osc. Orbit) or Local (IR) Crab Compensation



The "mrad" Question

Orbit Excursion & Tune Spread



0.4-2 mrad	4-6 mrad	8 mrad
Nom. Quad-First	Sep. Quads (Exotic)	Sep. Quads (Simple)
$V_{crab} < 15$ MV Cavity Simple	$V_{crab} \sim$ 50-70 MV Exotic Cavity	$V_{crab} \sim$ 111 MV Voltage Limit

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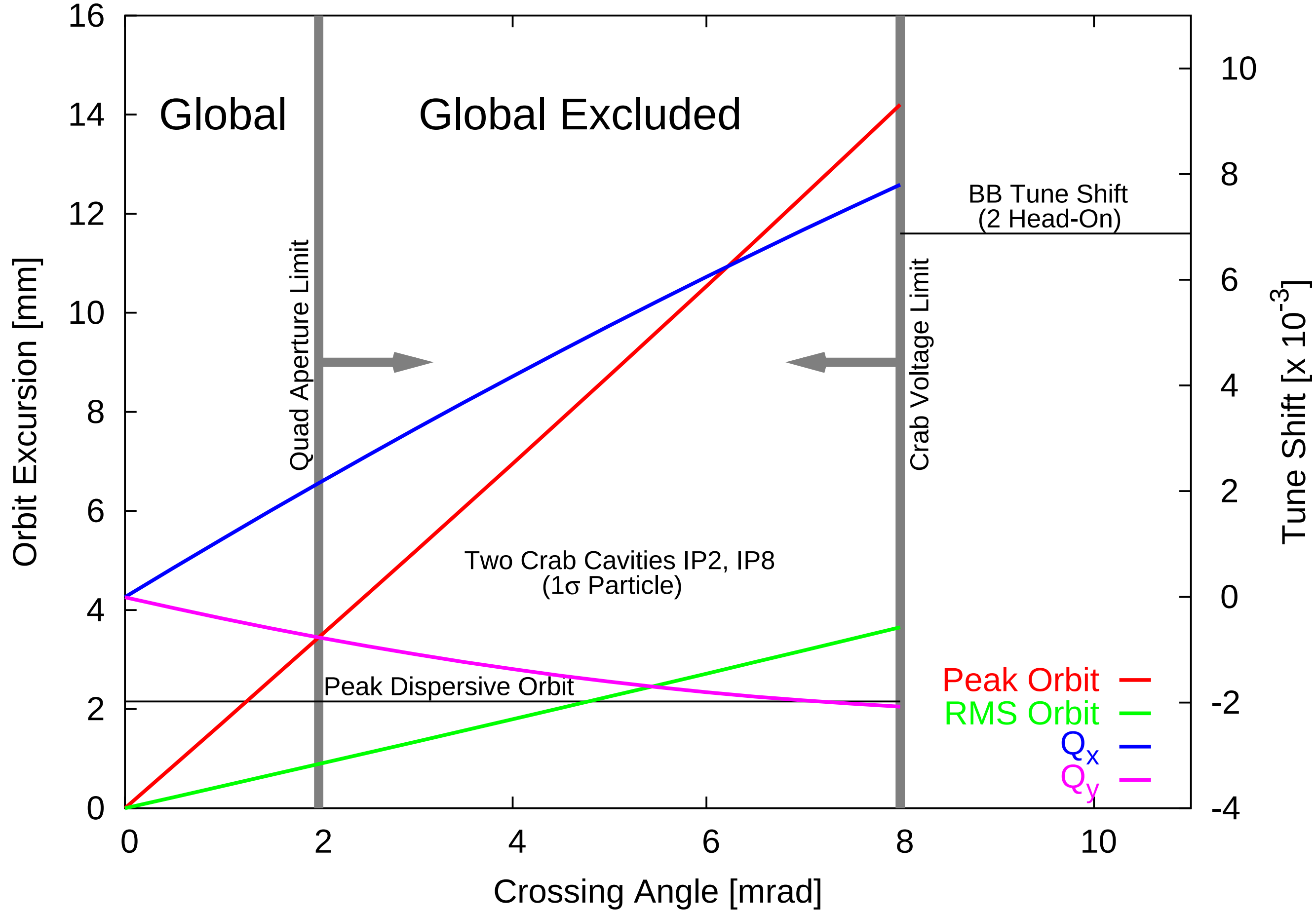

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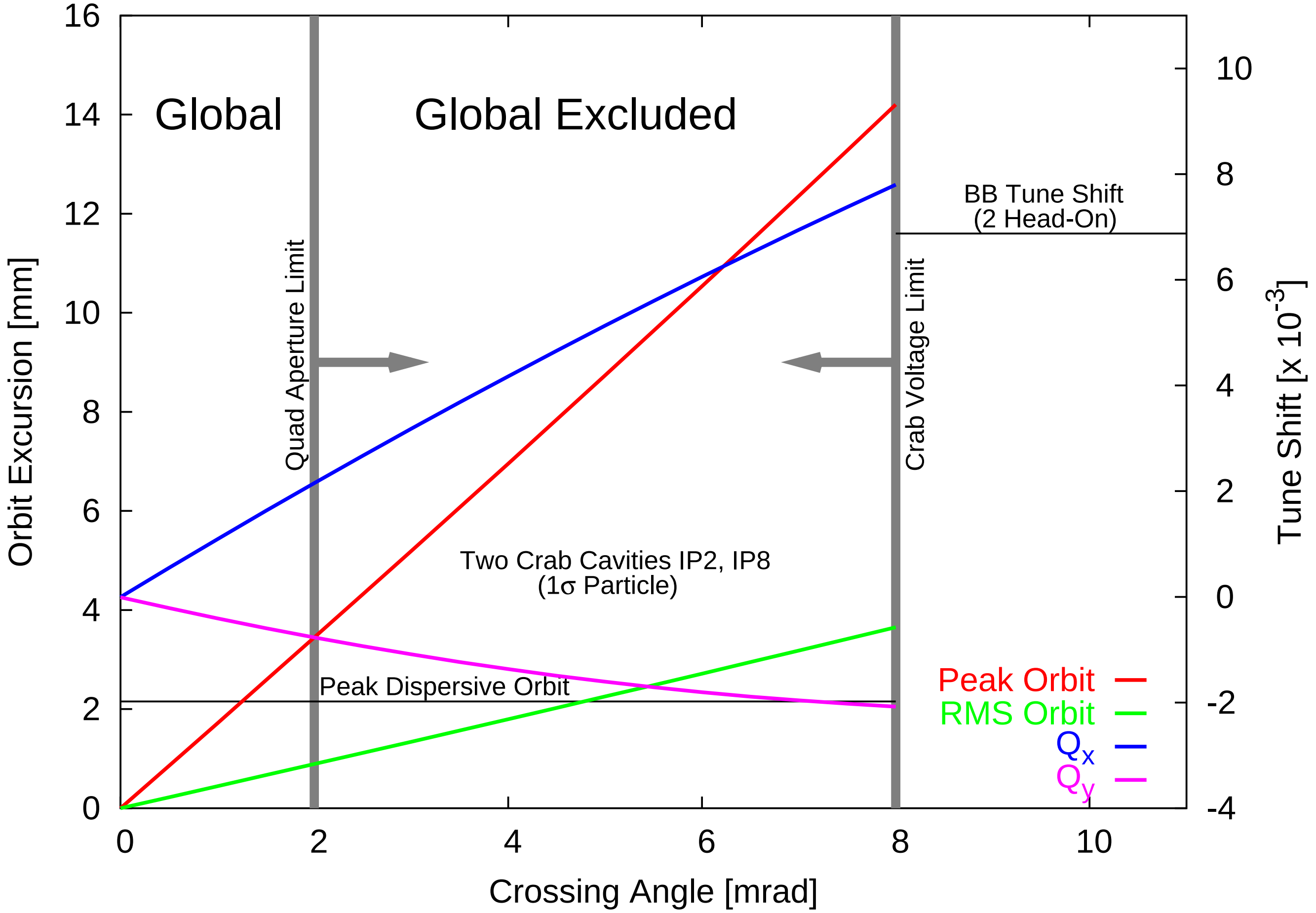

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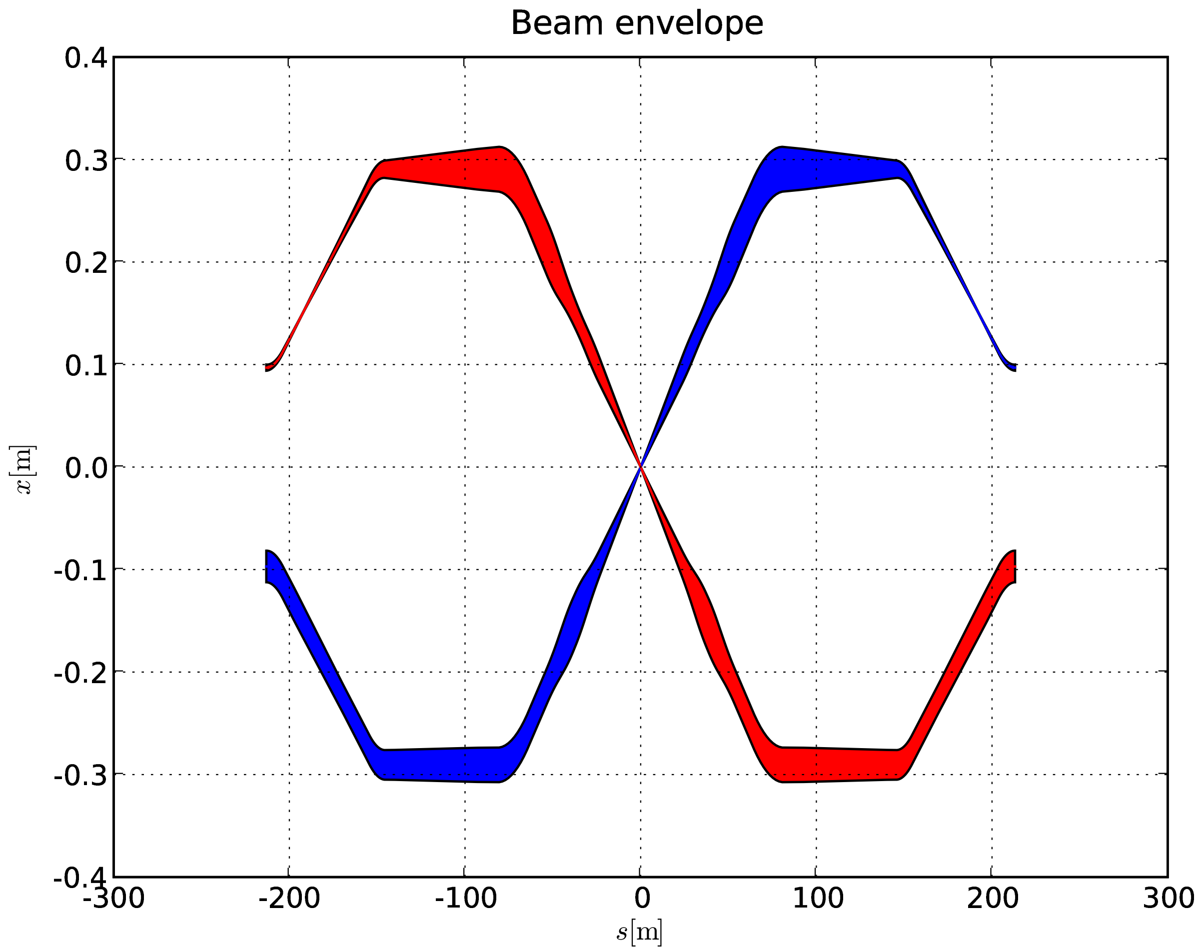
Optics for θ=8mrad



Mag	Aper [mm]	Gradient	L [m
QX1	46	200 T/m	6.3
QX2	63	200 T/m	5.5
QX3	63	200 T/m	5.5
BXA	59	5.3 T	17.
BXB	39	8.6 T	9.0
BXC	42	8.2 T	9.4

- Reasonable for NbTi
- Q1 design most difficult

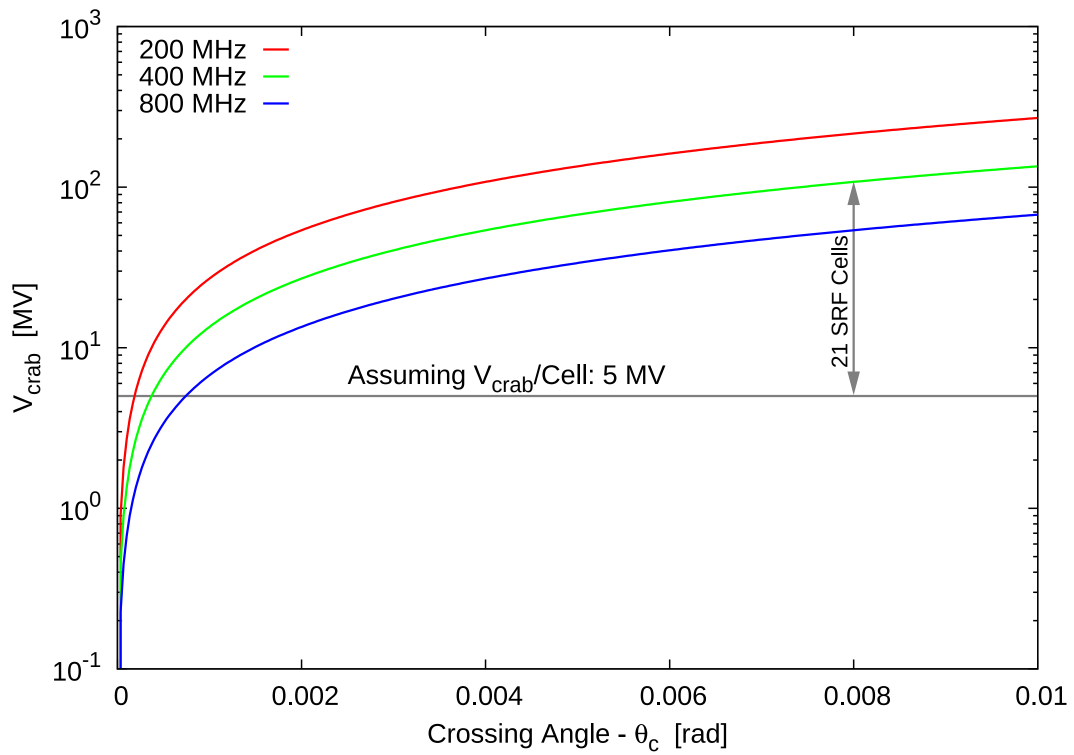
- 3 dipoles & 2 extra quadrupoles needed per side per beam
- Maximize space for the cavities (~25 m)

Crab Voltage Requirement

$$V_{crab} = \frac{cE_0 \tan(\theta_C/2)}{\omega_{RF}\sqrt{\beta_{crab}\beta^*}} \quad \{\sigma_z \ll \lambda_{RF}\}$$

X-Angle	1 mrad	5 mrad	8 mrad
200 MHz	27 MV	134 MV	216 MV
400 MHz	14 MV	67 MV	108 MV
800 MHz	7 MV	34 MV	54 MV

(Assuming $R_{12} = 31$ m)



- Reduce # Cavities
  - Increase Real-Estate Gradient
  - **Increase β_x^* & β_x^{crab} (Flat Bear**
  - Reduce bunch length ($$$) + Increase Frequency ($\times 2$)
- Lower X-Angle
  - Reduce Transverse Dimensions
  - Exotic Shapes

RF Curvature

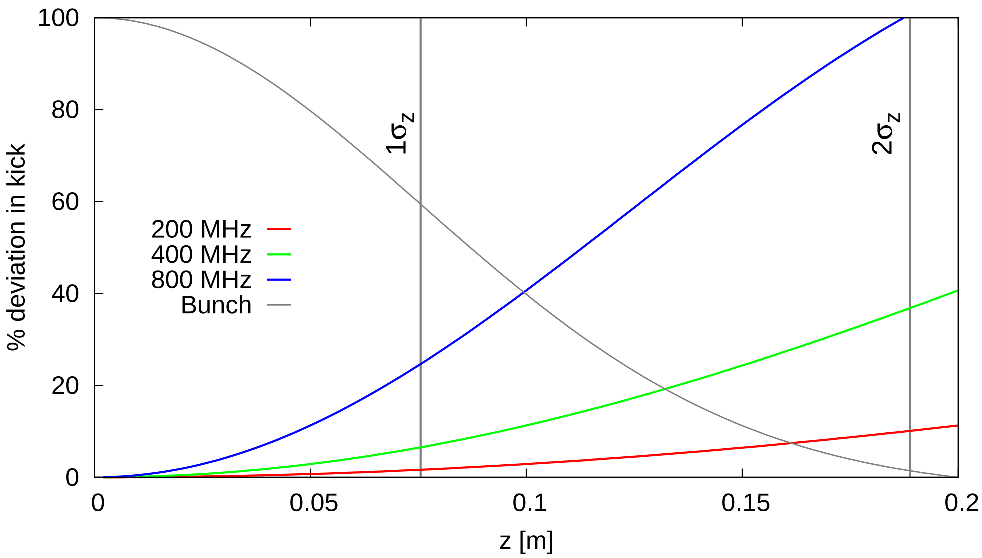
Deviation From Linear Kick:

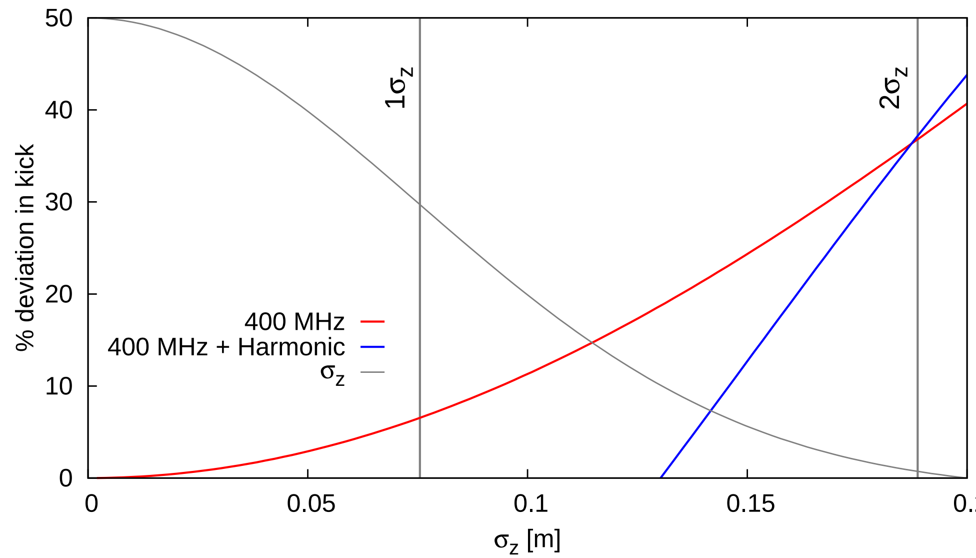
$$\Delta x' \approx \frac{1}{R_{12}} \sin(2\pi z/\lambda_{RF}) \approx \frac{2\pi}{\lambda}\left[z - \frac{2\pi^2 z^3}{3\lambda^2} + \cdots\right]$$

Luminosity Reduction:

$$R = \frac{\sqrt{1+\cos(\theta_c)}}{\sqrt{2\pi}\sigma_z}\int_{-\infty}^{\infty} \exp\left(-\frac{s^2(1+\cos(\theta_c))}{2\sigma_z^2} - \frac{\sin(\theta_c/2)(-k_c s + \sin(k_c s))^2}{k_c^2\sigma_x^2}\right)$$

$$\approx 25 - 30\% \quad (8 \text{ mrad}, \ 400\text{MHz})$$



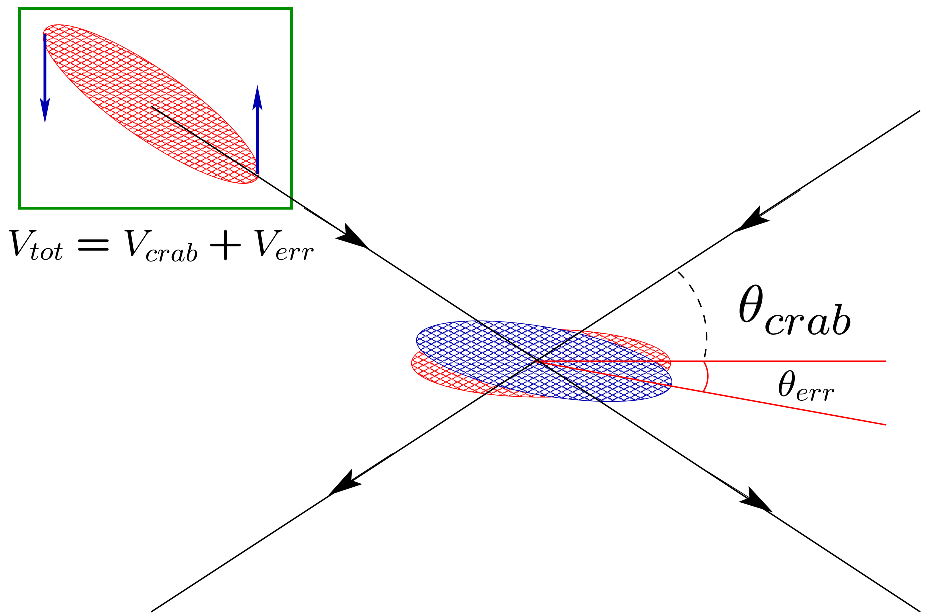


Noise Tolerances

Amp. jitter introduces additional X-Angle:

$$\Delta x' = \frac{\theta_c}{2R_{12}} \left(\frac{\Delta V_\perp}{V_\perp} \right) z$$

$$\frac{\Delta V_\perp}{V_\perp} \approx \frac{\theta_{err}}{\theta_c} \ll \frac{1}{\tan(\theta_c/2)} \frac{\sigma_x^*}{\sigma_z}$$



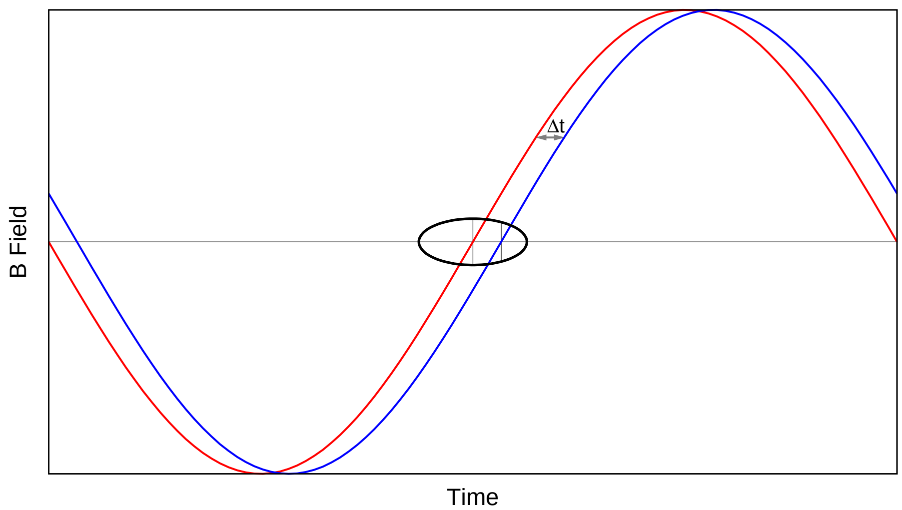
X-Angle: 8 mrad $\longrightarrow \frac{\Delta V_c}{V_c} < 0.04\% \rightarrow \theta_{err} \approx 3\mu rad$ (Available Today)

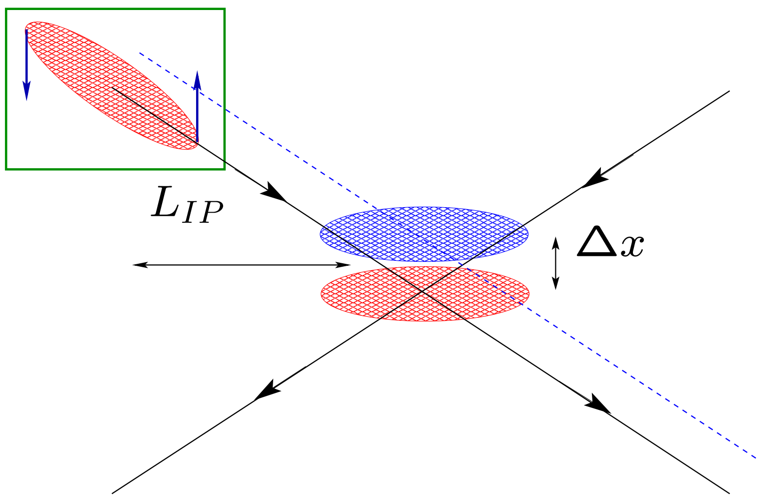
Noise Tolerances

Phase jitter introduces random offset:

$$\Delta x_{IP} = \frac{c\theta_c}{\omega_{RF}}\delta\phi$$

$$\left(\frac{\Delta\epsilon_x}{\Delta t}\right)_{BB} \approx n_{IP} f_r \frac{8\pi^2\xi^2}{\beta_x^*}(\Delta x)^2, \qquad \left(\frac{\Delta\epsilon_x}{\Delta t}\right)_{CC} \approx n_{IP} \frac{f_r}{2\beta^*}\left(\frac{c\theta_c}{2\omega}\Delta\phi_c\right)^2$$





X-Angle: 8 mrad & $\Delta\epsilon/\Delta t = 10\%/\text{Hr}$

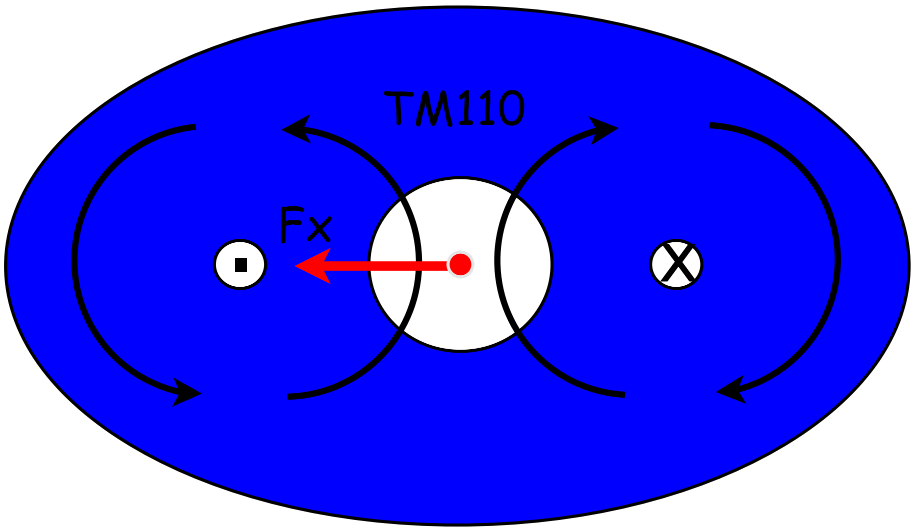
$\Delta\phi_{BB} \leq 0.001^\circ$, $\Delta\phi_{CC} < 10^{-4}$ deg ($\Delta x/\sigma_x^* < 10^{-3}$ perhaps too pessimistic)

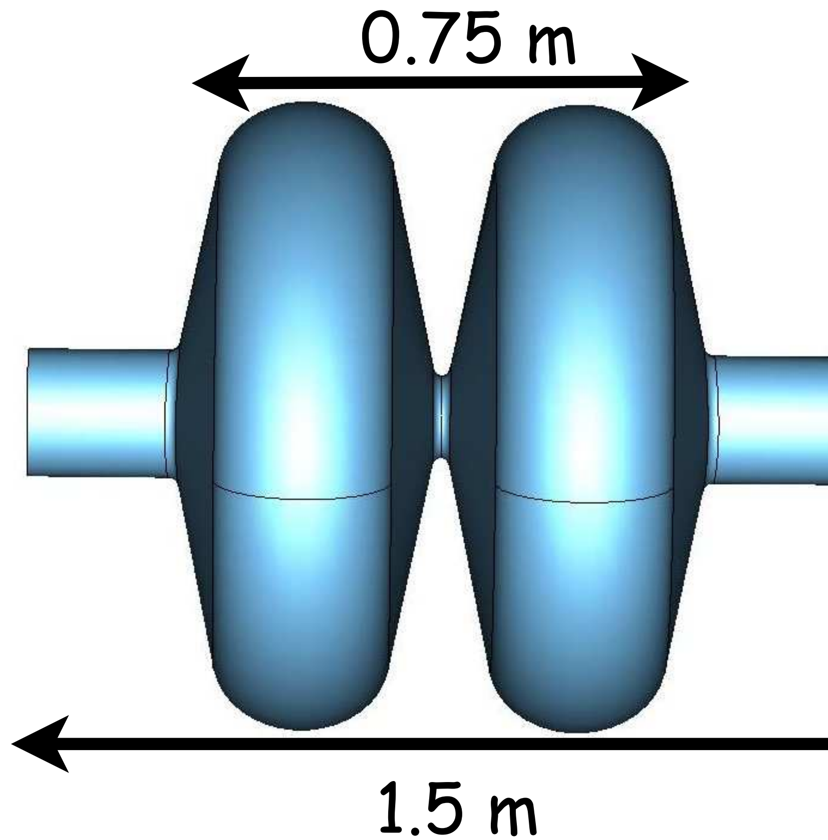
$\Delta\phi_{rel} = 0.003^\circ$ (feasible → ILC)

Tolerances maybe relaxed due to transverse feedback

Ohmi's simulations show tolerances to be ∼10 larger (better)

Baseline: Elliptical & Squashed

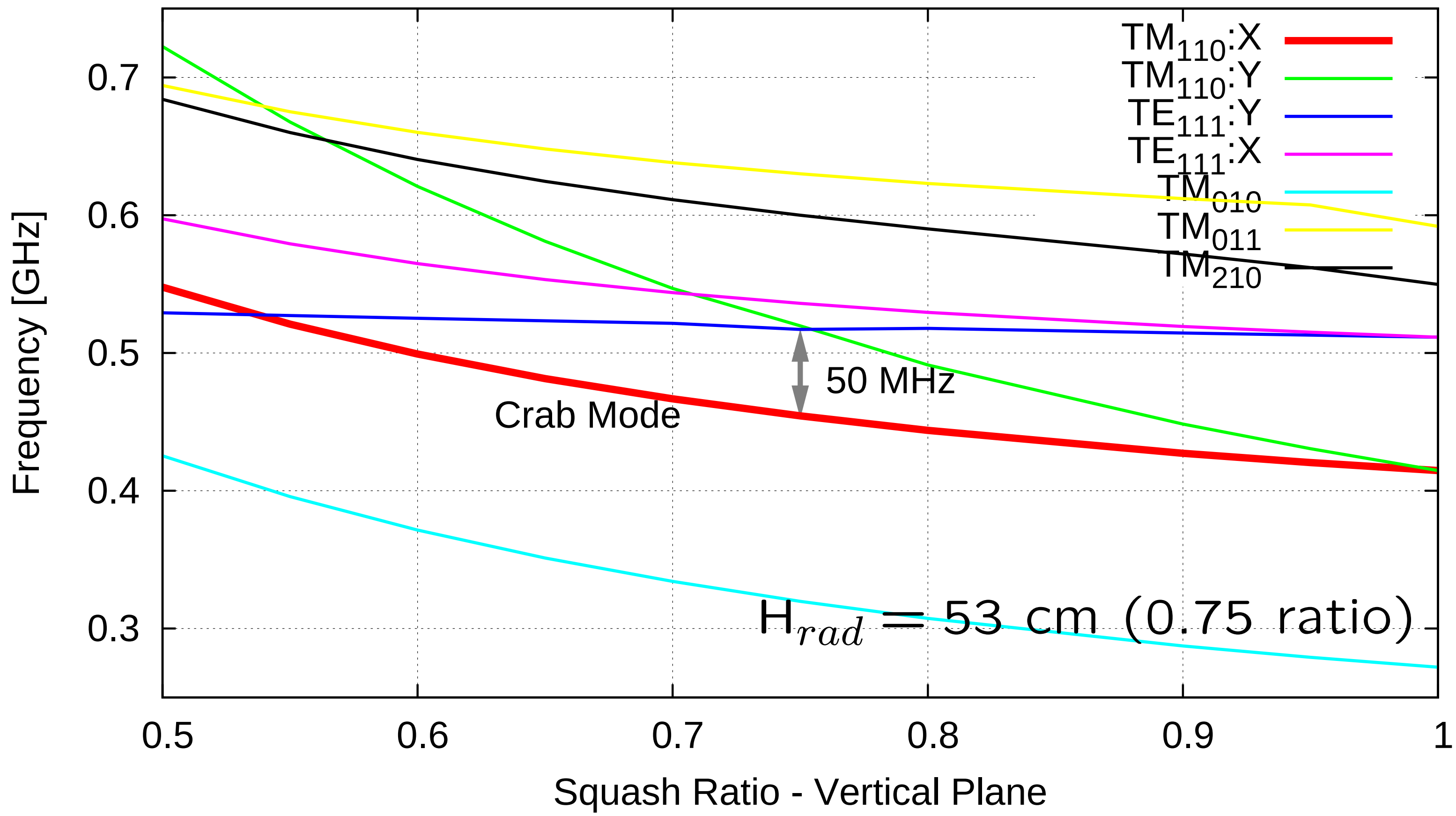




Half Cell Length, $L = \frac{\lambda\beta}{4}$	18.75 [cm]
Two Cells + Beam Pipe	$\sim$ 1.5 [m]
Horizontal Eq. Radius, R_{iris}	**53 [cm]**
Horizontal Eq. Radius, R_{iris}	37.5 [cm]
Squash Ratio	0.75
Beam Pipe Radius	15 [cm]
Wall Angle, α	$\sim$ 6 [deg]
Equator Dome Radius	12.0 [cm]
Cavity Beta, $\beta = \frac{v}{c}$	1.0

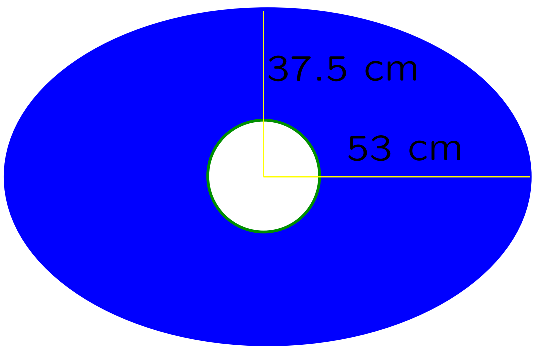
- Two Cells $\sim$ 5 MV/Structure
- LOM + HOM Couplers
- Polarize for mode separation
- Tuners, Cryostat, $\cdots$

Parasitic Mode Separation



For $H_{rad} < 50$ cm

- Reduce squash ratio
- Optimize cavity shape and beam pipe



Prelim RF Parameters

Quality Factor:

$$Q_0 \approx 10^9 \text{ (BCS @ 2K)}$$

$$Q_{ext} \approx 10^6 - 10^7 \text{ (Tuning \& RF control)}$$

Crab Voltage:

$$V_\perp = \sqrt{\omega U \frac{R_\perp}{Q_0}}, \qquad \frac{R_\perp}{Q_0} = \frac{1}{(kr)^2 \omega U} \int_0^L E_{z(r=r_0)} e^{ikz} dz$$

Beam Power (1 Amp):

$$P_B \approx 50 \text{ kW/mm}$$

Peak Fields ($V_{kick} = 5$ MV):

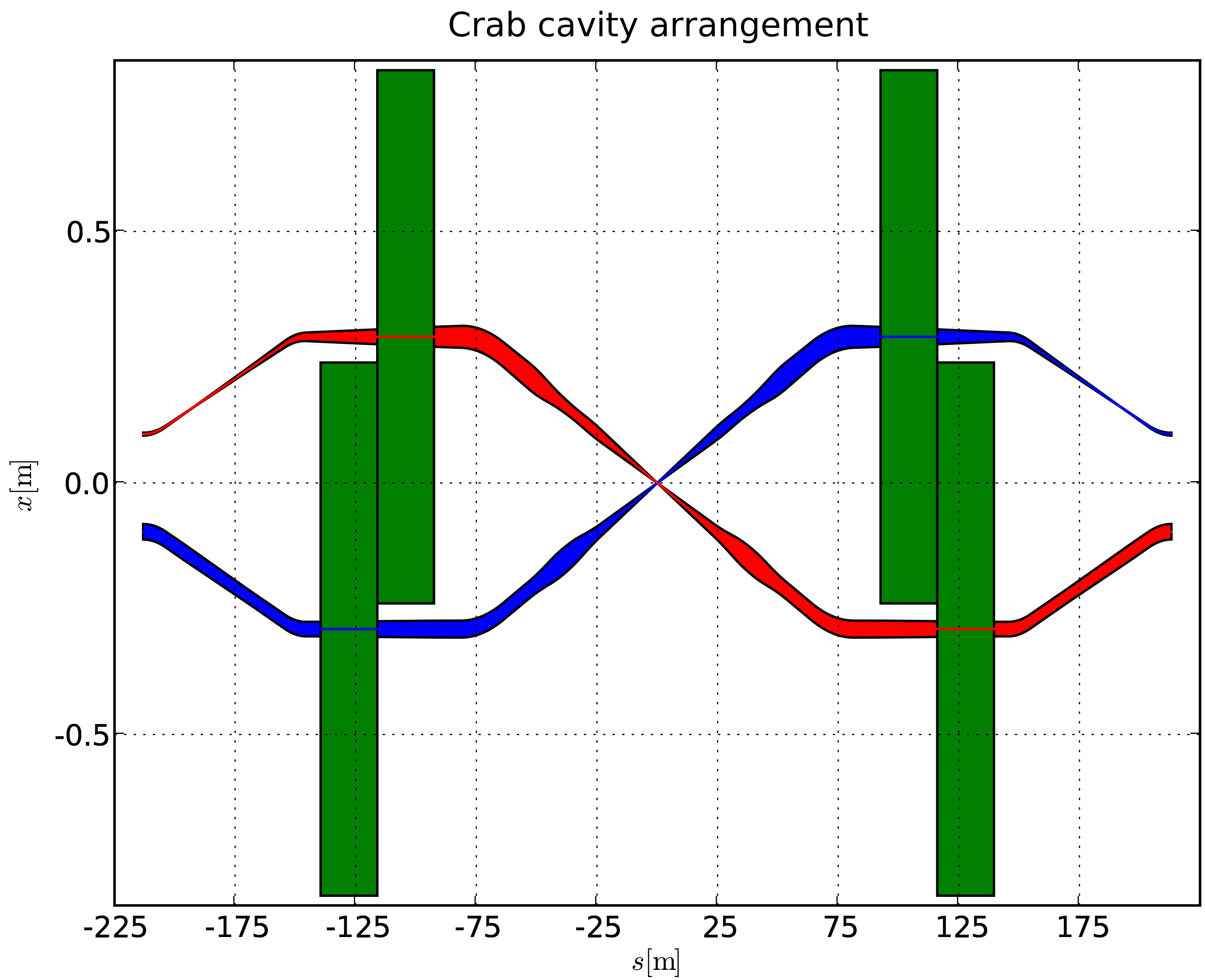
$$E_{peak} < 25 \text{ MV/m (no limitation)}$$

$$B_{peak} < 150 \text{ Oe (Max Limit - 2200-2400 Oe)}$$

Acc. cavities $\sim$ 500-700 Oe $\rightarrow$ 50 MV/m E$_{acc}$

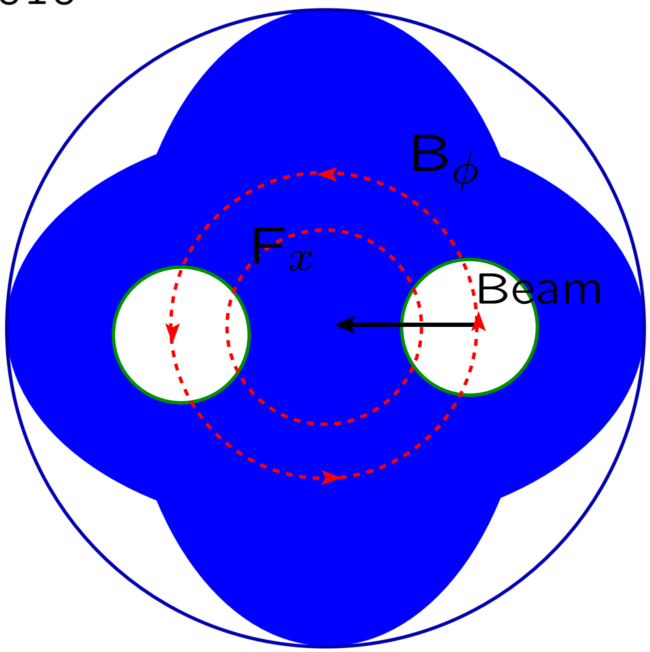
Optimization of RF parameters needed for higher gradient

Crab cavity arrangement - 400 MHz



Some Exotic Concepts

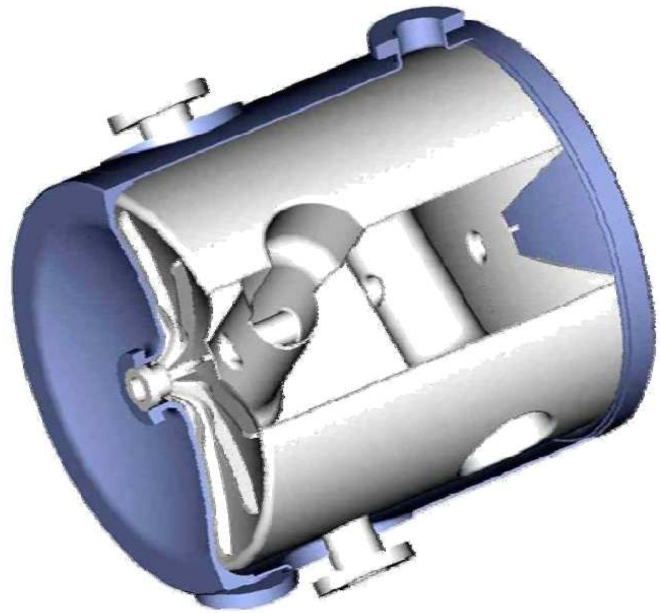
TM_{010} Mode:



- Advantages: Smaller transverse dimensions, high R/Q, high gradient, simpler design (HOM's, couplers, etc...)

- Disadvantages: Transverse wakefields, multipacting needs evaluation, beam loading and others

Spoke Cavities:



- Advantages: More compact than TM_{110} cavities, mechanically stable

- Disadvantages: Complicated design (significant R&D), lower gradient (??), multipacting

Conclusions

- X-Angle scheme with crab cavities attractive, but large θ_c risky
- Issues with RF frequency & cavity dimensions need R&D
- Noise estimates for phase tolerance looks too pessimistic
  - Multiparticle simulations for noise tolerances
  - Include machine details ($\delta E/E$, ξ_x, lattice Errors, coupling, etc..)
- R&D Effort: CERN, BNL, & LBNL (Optics, Cavity Design, RF Control, etc..)
- Exoctic schemes may alleviate space problems
- Benefit from ILC crab cavity activity