LHC Crab Cavities

Rama Calaga

2nd ICFA Deflecting Cavity Workshop, Sep 1-3, 2010

- LHC Crab Crossing & Roadmap
- Technology & Machine Protection
- Toward First Validation with Protons in SPS

On behalf of the LHC-CC collaboration

LHC-CC10

Announcement of the 4th LHC-CC Workshop series

Venue: CERN

Date: Dec 15-17, 2010

Charge:

1. Can compact cavities for the LHC be realized and made robust with the complex damping schemes ?

2. Are crab cavities compatible with LHC machine protection, or can they be made to be so ?

3. Should a KEKB crab cavity be installed in the SPS for test purposes ?

http://indico.cern.ch/conferenceDisplay.py?confId=100672

(Available Soon)

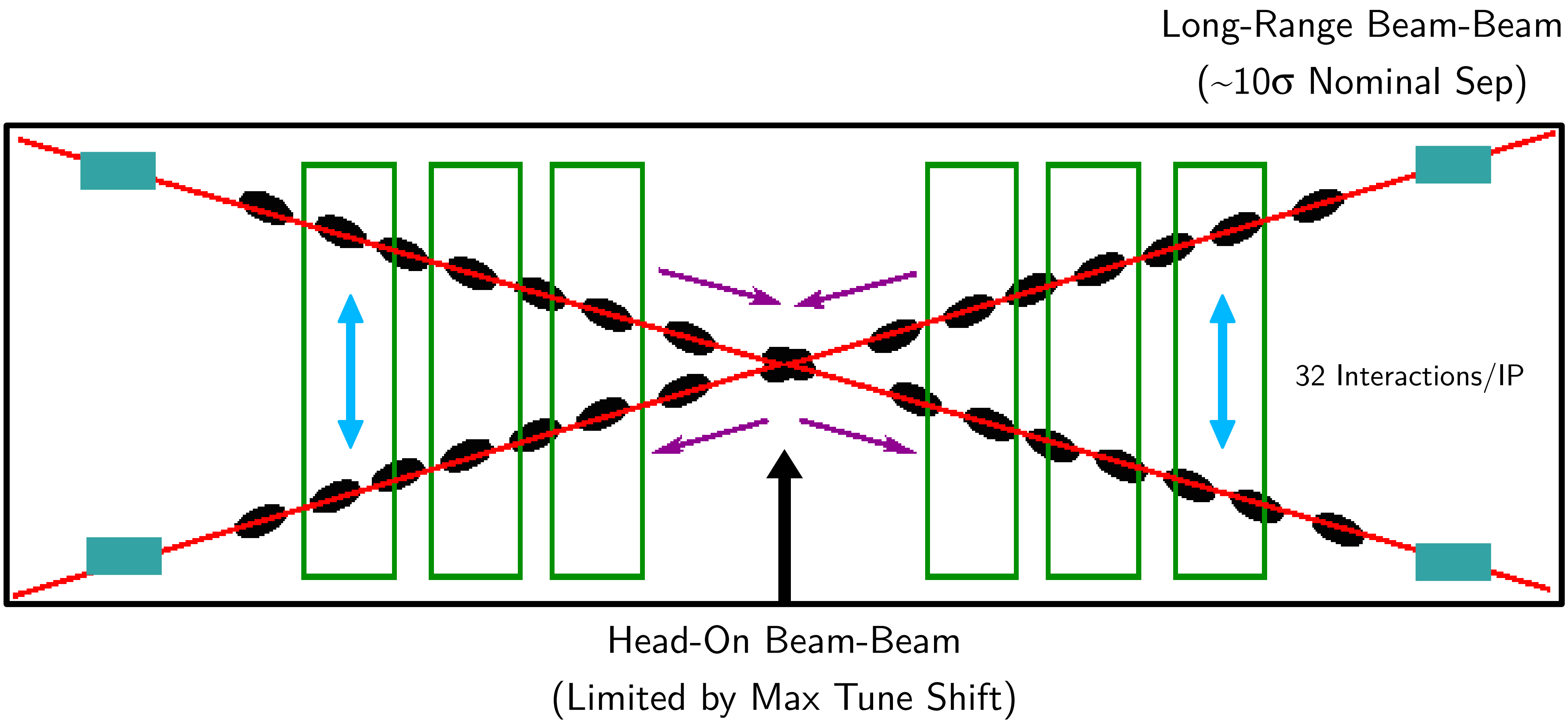
"Upgrade Scenarios"

	Nominal	Ultimate +Crabs	Phase II +Crabs	Phase II +LPA
N_b [x10^{11}]	1.1	1.7-2.3	2.3	4.2
β^* [cm]	55	30-55	14-25	25
θ_c [µrad]	285	315-348	509	381
Pile Up	19	44-111	150	280

- All scenarios aim at x3-10 Luminosity increase
- Luminosity leveling vital → constant luminosity
- Bunch intensity beneficial, NOT easily digestible in the injectors (safety!)

$$L = \frac{1}{4\pi} \frac{f_r n_b}{\beta^* (\gamma \epsilon)} N_b^2 R_\Phi$$

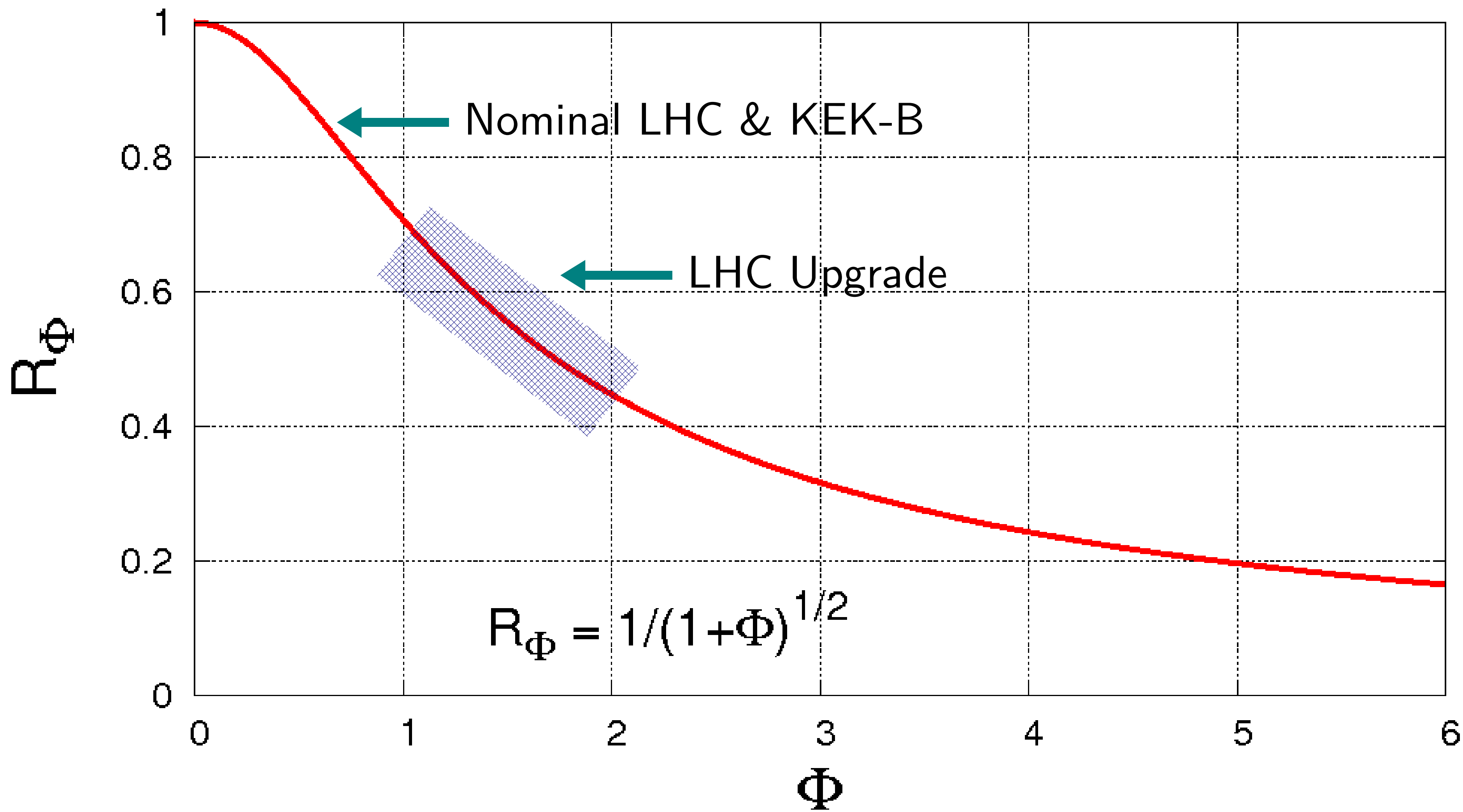
X-Angle & Crab X-ing

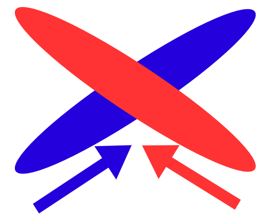


With crab crossing

- Increase peak luminosity with increasing x-angle due LR Beam-Beam
- Increase intensities and smaller emittances beyond head-on beam-beam limit
- Level luminosity (reduce Pile-up, radiation damage)

Reduction Factor

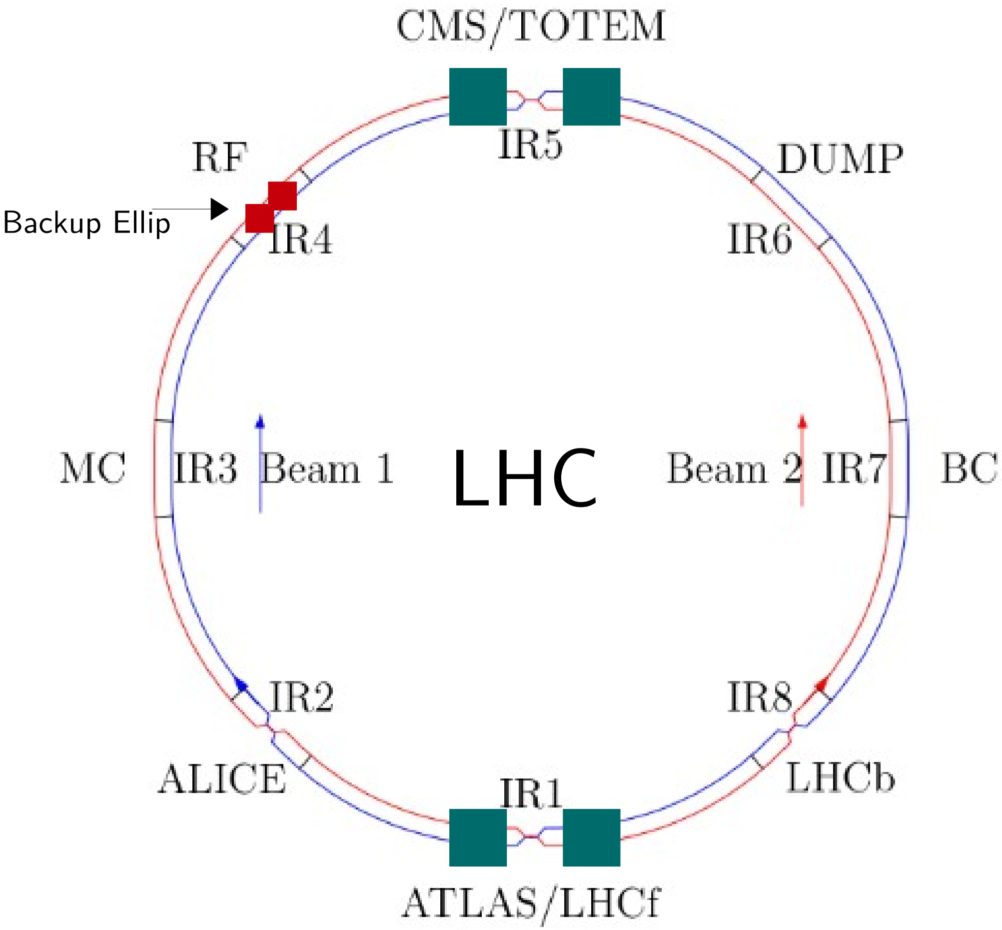


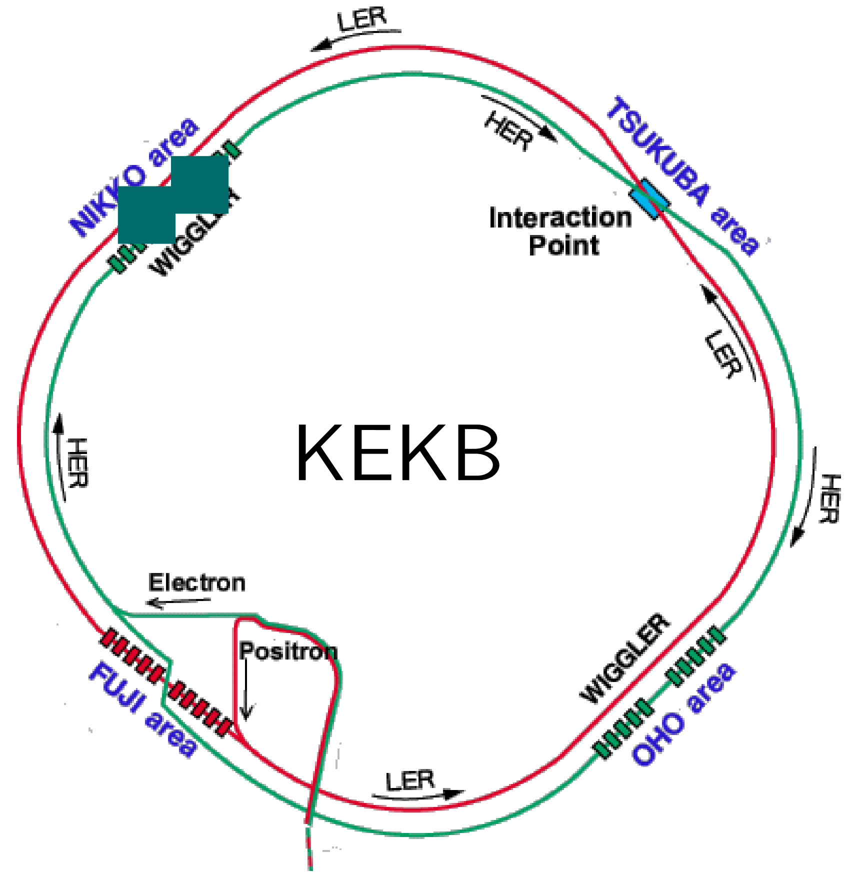


Eff. beam size

$\sigma \rightarrow \sigma/R_\Phi$

Naive Comparison





	Energy [GeV]	Circumference [km]	Current [A]	ξ_{BB}	Φ_{Piwinski}	Crab Freq [MHz]	Crab Voltage [MV]
KEK-B	3.5-8.0	3	2.0	0.09	0.75	509	1.5
LHC	7000	27	0.5-0.85	< 0.01	0.6-1.4	400	5-10

Luminosity Gain, Crabs

Freq: 400 MHz, Volt $<$ 10 MV, β_{cc}: ~5 km

$\{E, {}^{max}\beta_{crab}\}$	3.5 - 5 TeV	7 TeV	
		Increase Peak Luminosity	Increase Int. Luminosity
$\beta^* = 55$ cm	$\varepsilon\downarrow$, $N_b\uparrow$	10%	-
$\beta^* = 30$ cm		40%	19%
$\beta^* = 25$ cm		63%	22%
$\beta^* = 14$ cm		190%	31%

Integrated luminosities:

$N_b = 1.7 \times 10^{11}$, $\beta^* = 0.14$ cm, Run time = 10 hrs, TAT = 5 hrs

(Burn off, IBS, rest gas scattering)

Approx: 265 fb^{-1}/yr (217 fb^{-1}/yr w/o CCs) $\rightarrow$ 2 yr reduction in run time (for 3000 fb^{-1})

Int Luminosities: G. Sterbini

2 Main Challenges, Crabs

SC Technology upgrade (factor 5 gradient or larger)

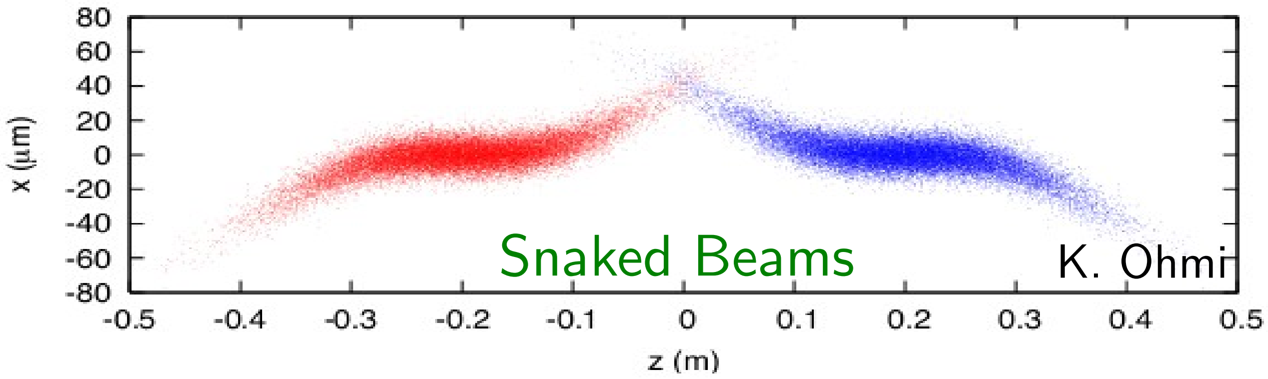
- New design strategy than conventional
- Validate new technology with beam

LHC machine protection (350 MJ stored energy)

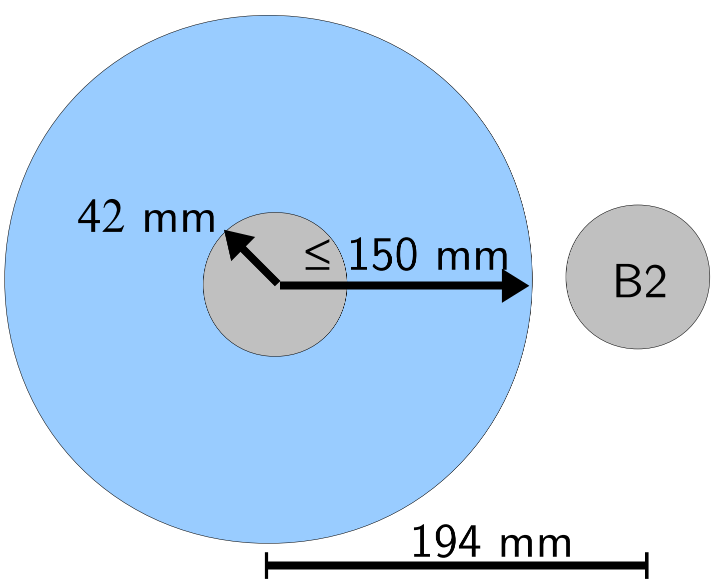
- 5% of nominal bunch @7TeV is beyond damage threshold
- Fast failure detection to safely abort beam

LHC Constraints

Bunch length: 7.55 cm (highest frequency 800 MHz)

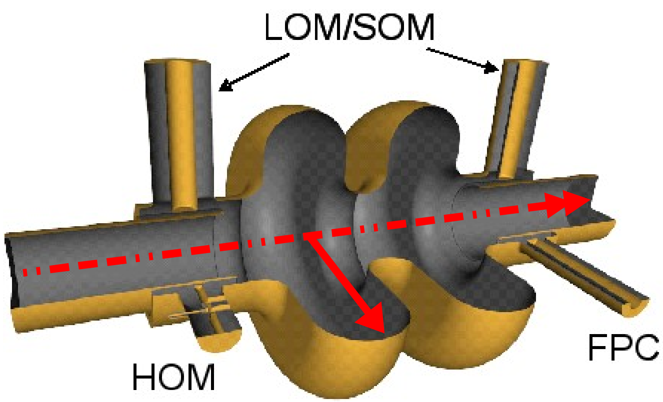


B1-to-B2 separation: 194 mm (PB 800 MHz ~ 250mm radius)



With few exceptions....
(IR4, collimation, exps)

Conventional to Compact

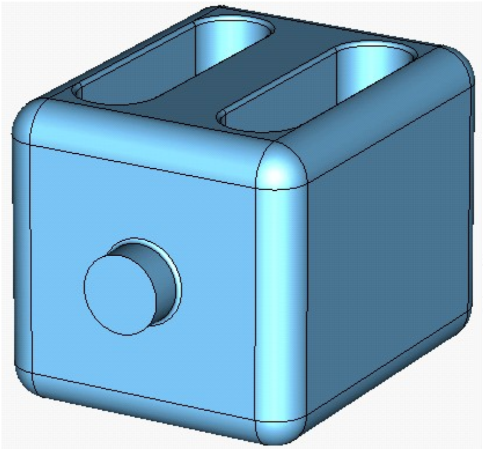


~250 mm outer radius

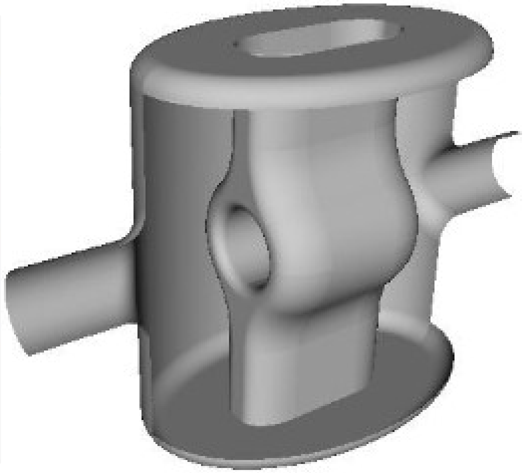
(Not compatible in most of the LHC ring)

Compact cavities aiming at small footprint (150 mm) & 400 MHz, 5-10 MV/cavity

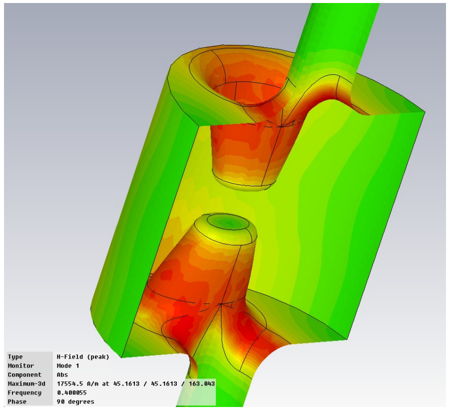
HWDR, JLAB,OD



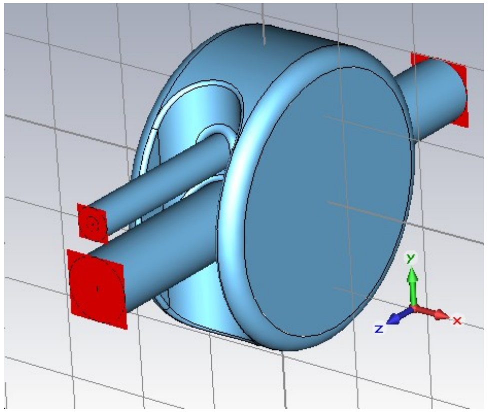
HWSR, SLAC-LARP



DR, UK, TechX



Rotated Pillbox, KEK



Performance Chart

Kick Voltage: 5 MV, 400 MHz

		HWDR (J. Delayen)	HWSR (Z. Li)	4-Rod (G. Burt)	Rotated Pillbox (N. Kota)
Geometrical	Cavity Radius [mm]	**200**	**140**	**150**	**150**
	Cavity Height [mm]	382	194	169	668
	Beam Pipe [mm]	50	45	45	75
RF	Peak E-Field	29	65	103	85
	Peak B-Field	94	135	113	328
	R_T/Q	319	275	667(?)	-

†Exact voltage depends on cavity placement & optics

†Cavity parameters are evolving

New Roadmap, HL-LHC

One LHC upgrade for the interaction foreseen for 2021

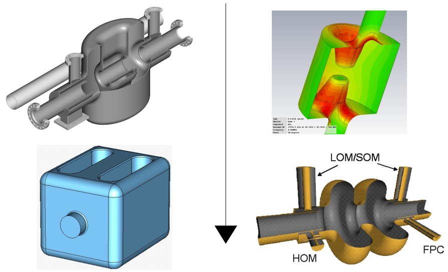
- Nb_3Sn for large aperture high gradient inner triplets
- Crab cavities to realize the full potential of the IR region upgrade

Detailed project report for crabs to outline R&D and construction (under preparation)

- Focus on R&D of compact cavities, technology choice ~2015
- Mitigate all machine protection issues
- Potential use of SPS-dogleg as a testbed

Roadmap for Crabs

US/EuCARD Effort



Compact Cavity R&D
2013

Couplers + Cryostat
2015

CERN Lead

Project Document
December 2010

Infrastructure SPS/LHC
2012-13

Cryomodule(s) Testing, SPS
2015

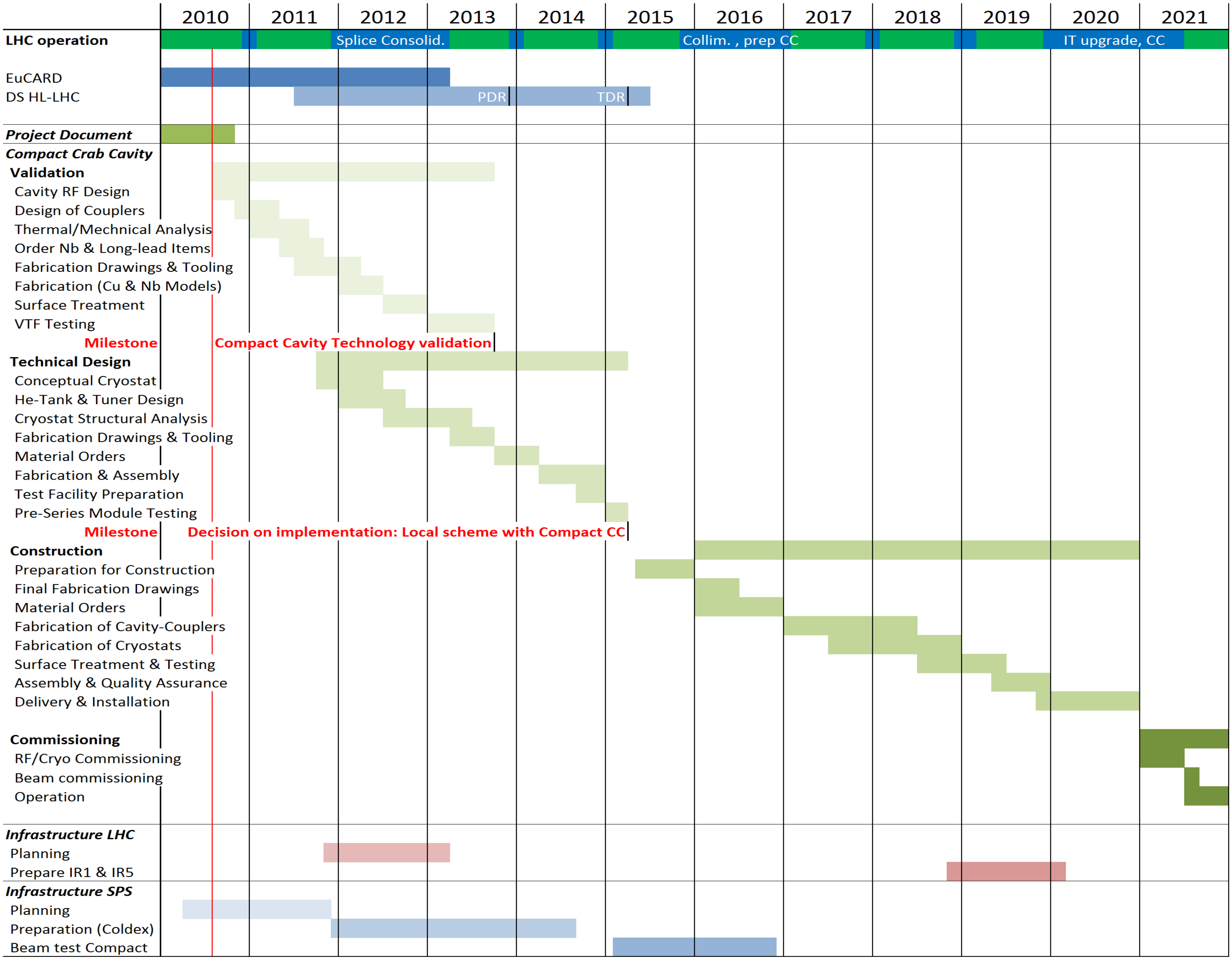
KEK Effort

KEK-B Cavity, SPS
2012-13

?

10 Cryomodules
2020

Baseline Compact-CC Timeline



Post RF-Design

- Cavity fabrication, stiffening (?), Helium-vessel
- Surface treatment (BCP, EP ?) & assembly
- Optical inspection & thermal mapping
- Cavity testing (2K/4K), instrumentation & field validation
- Cryomodule (generic or specific)
  - Vertical couplers & access points
  - Tuning system (compression or bellows)
- RF power and controls
- Horizontal RF testing & CERN test stand (SM18) $\rightarrow$ SPS Tests

Simulations

Machine protection

Problem identified (LHC-CC09), 3 turn window

Loss map simulations underway for failure scenarios

Mitigation of fast failures required (detection & feedback)

Collimation efficiency & hierarchy

Additional 0.5σ aperture, suppression of synchro-betatron resonances

Hierarchy preserved (primary, secondary, tertiary)

Crab induced noise, Beam-Beam (measured, 30 Hz - 32 kHz)

BB simulations: Weak-strong $\leq 0.1\sigma$, Strong-strong BB $\leq 0.02\sigma.(\tau)$

Resume dedicated simulations between sigma-pi mode

Additional machine impedance

Longitudinal: ~60 kΩ nominal, ~20 kΩ upgrade

Transverse: ~2.5 MΩ/m nominal, ~0.8 MΩ/m upgrade (Norm - $\beta/\langle\beta\rangle$)

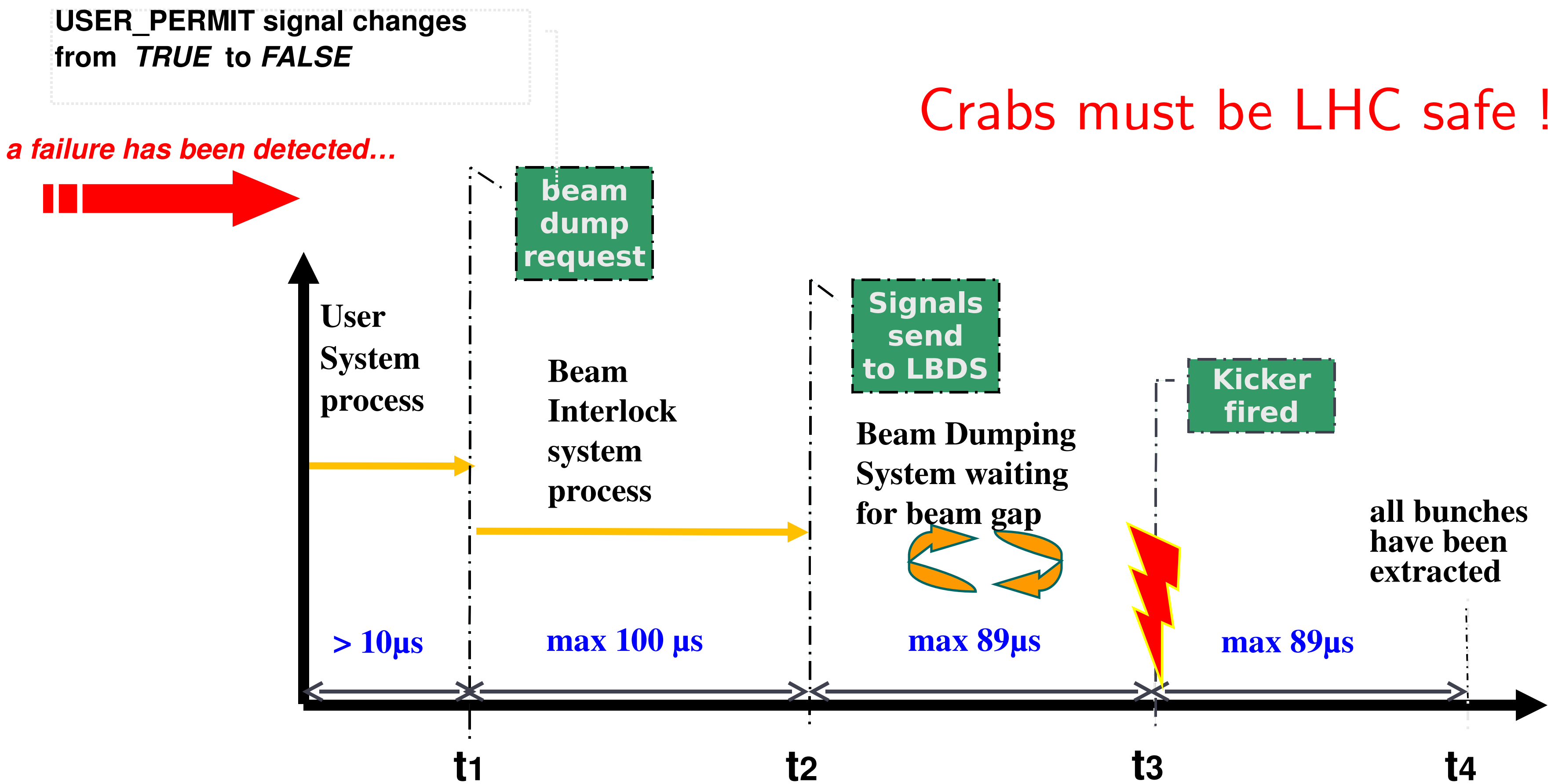
Detailed studies for individual cavity design modes required

Machine Protection, 350 MJ !!

100's of interlock systems $\rightarrow$ complex

Best/worst case scenario:

Detection - 40µs (½ turn), response - 3 turns



Crabs must be LHC safe !!

Courtesy J. Wenniger

Some Failure Scenarios

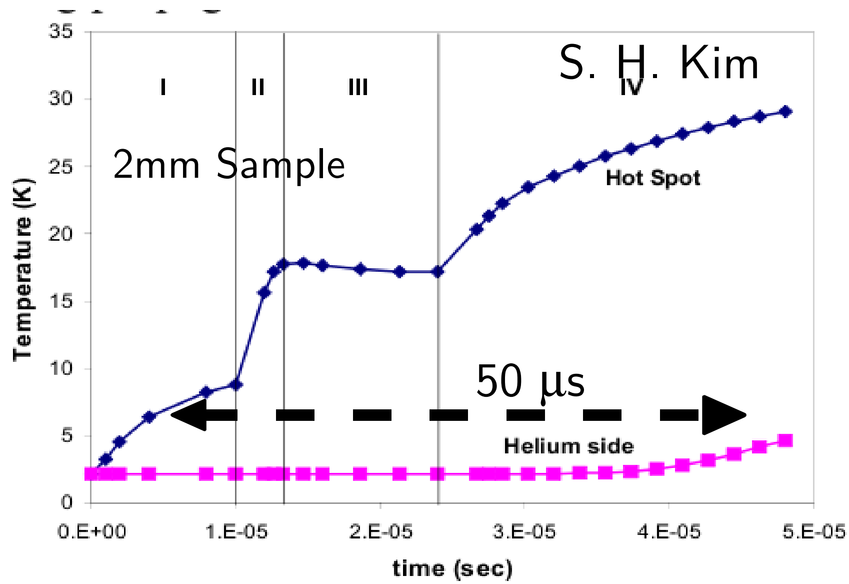
Time scales:

Power supply trips (50-300 Hz $>$ 7 ms) $\rightarrow$ greater than 300 turns

RF arcing (few µs) $\rightarrow$ Response of cavity voltage/phase slower

Mechanical changes (100's of ms) $\rightarrow$ high Q SC cavity

Quench, abrupt amplitude or phase changes



No passive way to guarantee machine protection

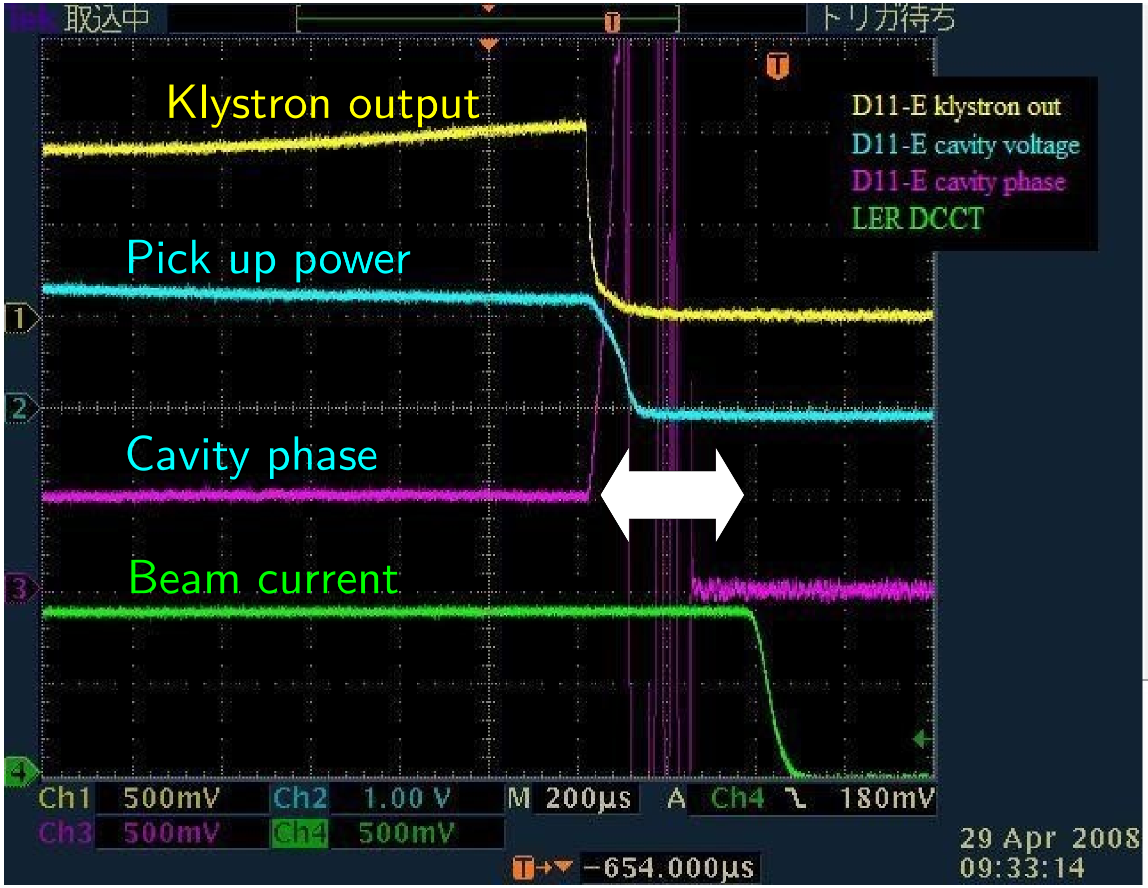
Qext may not help for beam driven failure time constant

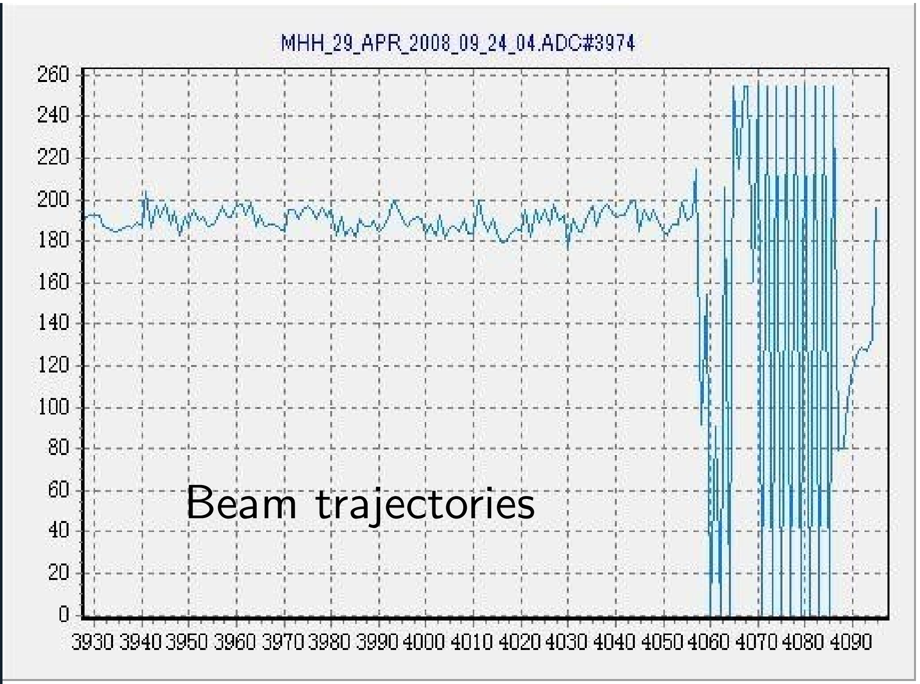
Voltage slope determined by unchangeable constants (R/Q, Δx, I...)

Active orbit and RF feedback a requirement (cavity to cavity across IR $\sim$1µs)

Some info courtesy J. Tuckmantel

RF Trip: Another Case (KEKB)

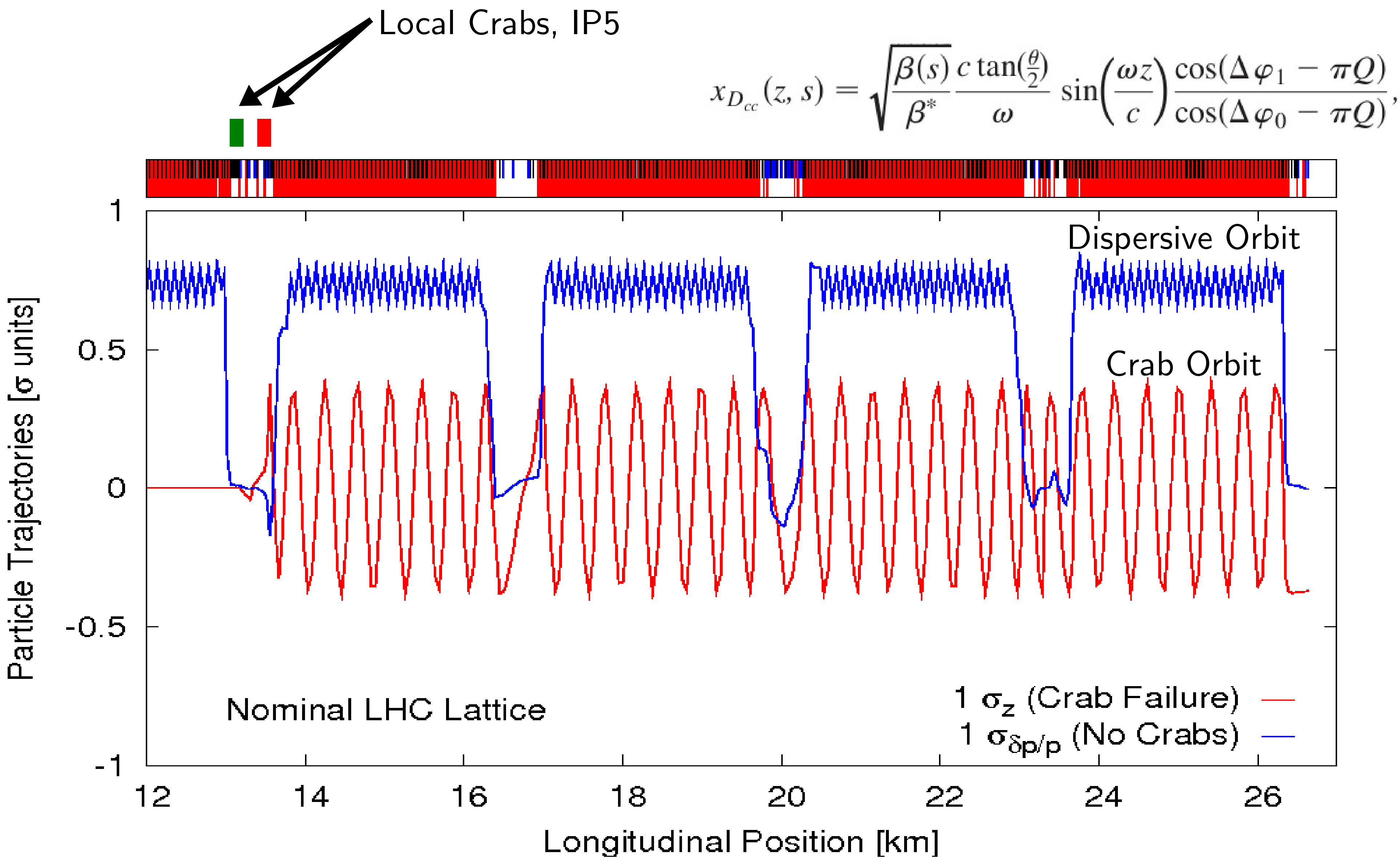




Intentional/non-intentional phase changes → corresponding orbit changes and beam losses

Approx time scale → 400 ms (4 turns)

Left-Right Voltage Failure

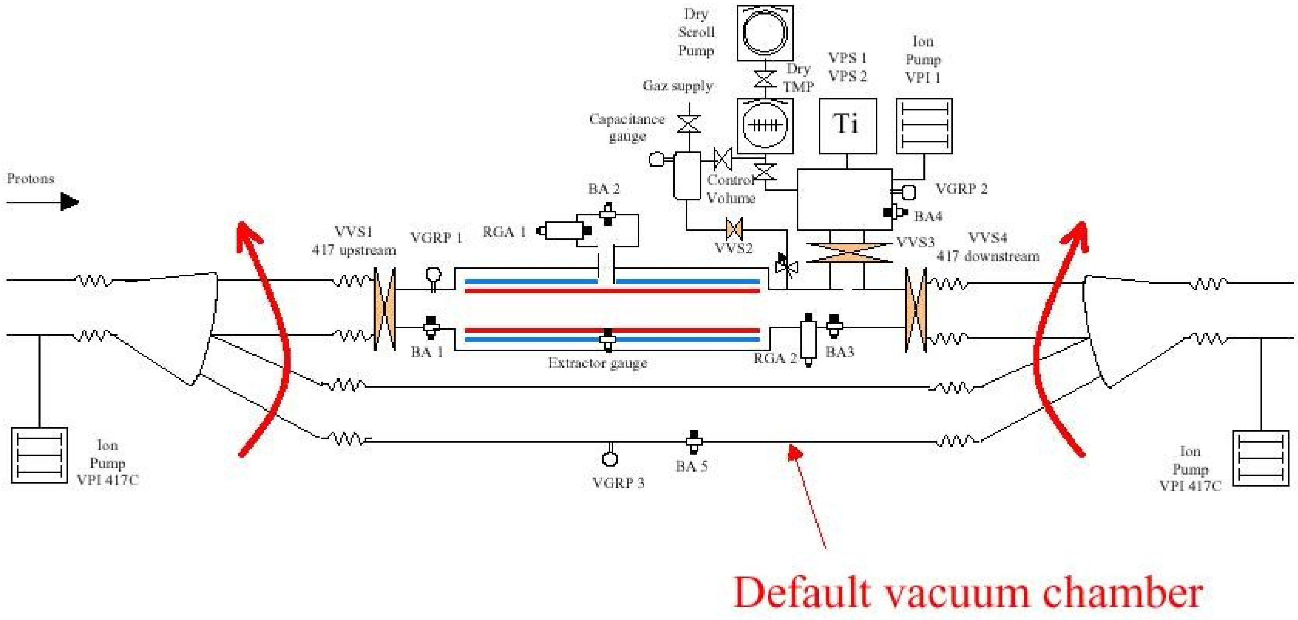


Tracking loss maps needed to determine exact impact

SPS Tests

Crabs potentially in SPS is at COLDEX.41737 (4020 m, LSS4)

Crab Bypass similar to COLDEX to move it out of the way during high intensity operation



SPS beam tests, 2010 to check lifetime @55GeV coast with 2μm norm emittance

Machine protection

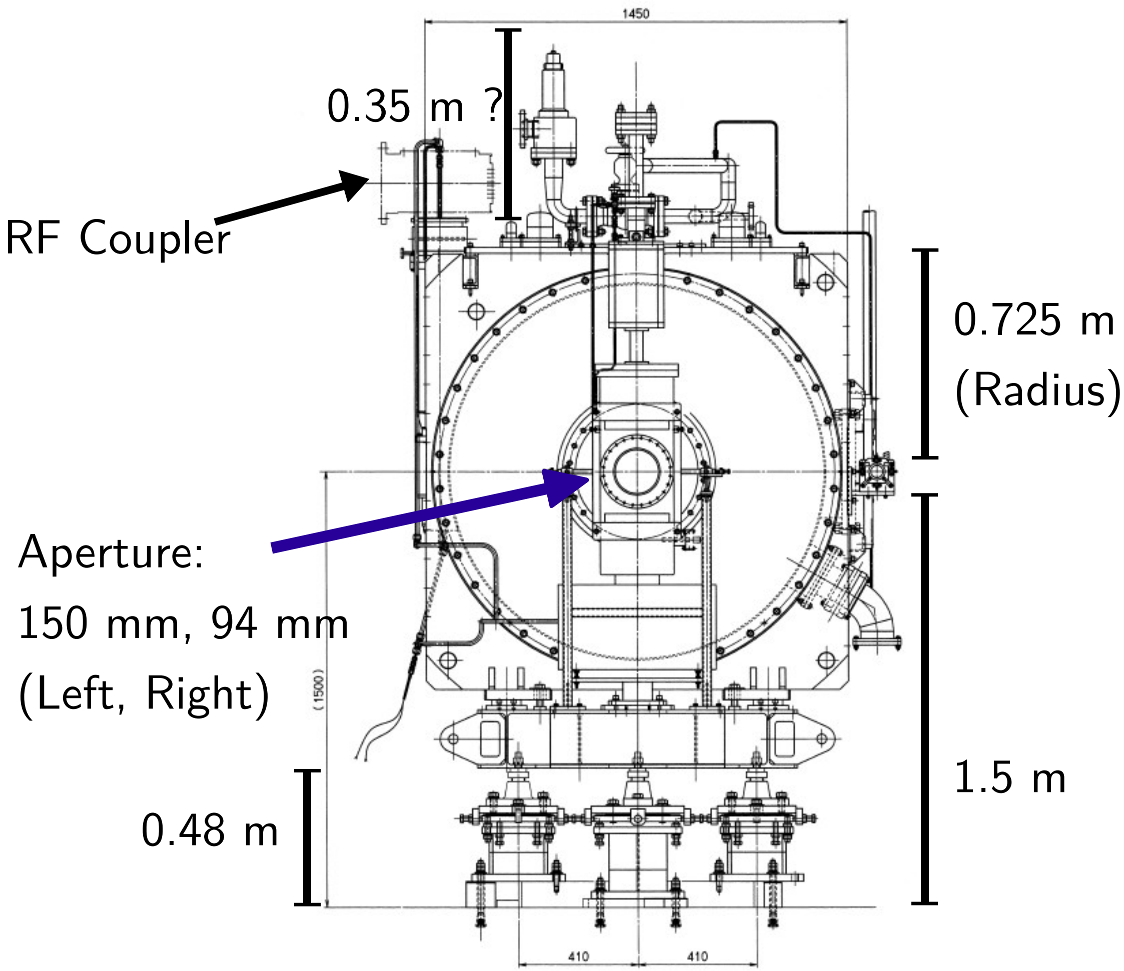
- Setup with 2 collimators: No effect at 1st & full crab effect at 2nd second collimator
- Primary goal is beam measurement (No implementation of interlocks, BPMs-fast & RF-slow)
- Failure scenarios (for example: abrupt voltage/phase changes, RF trips etc..)

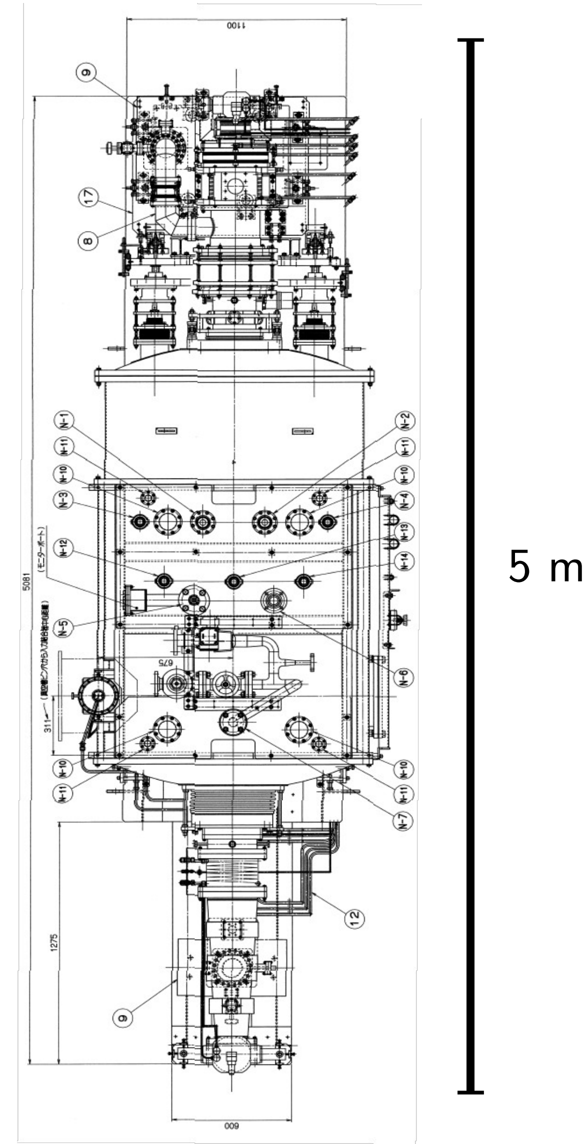
Details: http://emetral.web.cern.ch/emetral/CCinS/CCinS.htm

Courtesy E. Metral

KEKB Cryostat

Weight: 5830.5 kg





Crab voltage: {HER, LER} - 1.6 MV, 1.5 MV (design: 1.44 MV)

Operational voltage: {HER, LER} - 1.4 MV, 0.9 MV

Trip rate: Average 1/day (HER), 0 for LER (from up to 25)

Potentially available in end of 2012 (major modifications required)

Courtesy KEK-B

Pros/Cons Of Diff Cavities, SPS Tests

	800 MHz Ellip Cavity	400 MHz Compact	509 MHz KEKB Cavity
Frequency	N/A	N/A	2 MHz static tuning
Voltage	2.5 MV	5.0 MV	1.5 MV
Temperature	2K	2-4 K	4K
Qext	1×10^6		2×10^5
Helium Volume	~50-100 L		400L
Heat Load	-	-	S :10 W, D: 50 W
Cavity Tuner	-	-	1 kHz/s (200 kHz max)
Module Weight	< 2 Tons	< 2 Tons	5 Tons
Module Length	~2 m	~1 m	5 m
Module Height	< 1 m	< 1 m	1.5 m

Table is only preliminary

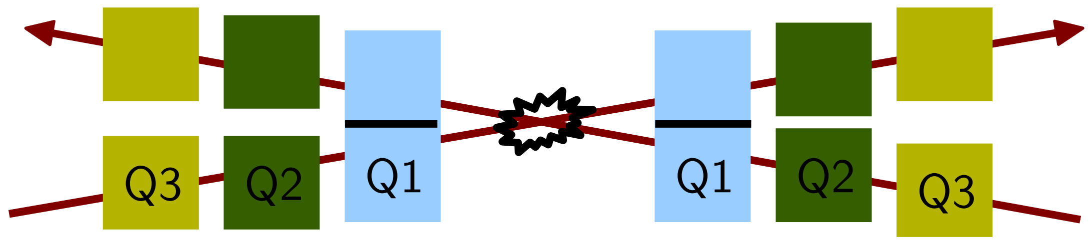
Conclusions

- Key motivation & challenges
  - Luminosity gain & leveling with reducing β^* at the beam-beam limit
  - Technical challenge to develop and validate compact cavities
  - Ensure machine protection under abrupt cavity failure modes
- Crab program under HL-LHC
  - Establish a complete resource loaded compact R&D and construction
  - Pursue backup options in parallel
- SPS tests
  - Validate differences between protons & electrons
  - KEK-B cavity (2012), LHC compact/elliptical cavity (2015-16)

Many thanks to all the LHC-CC collaborators

LHC

A1: Possible Future



Proposed in 2006 but was abandoned due to large x-angle (5 mrad ?)

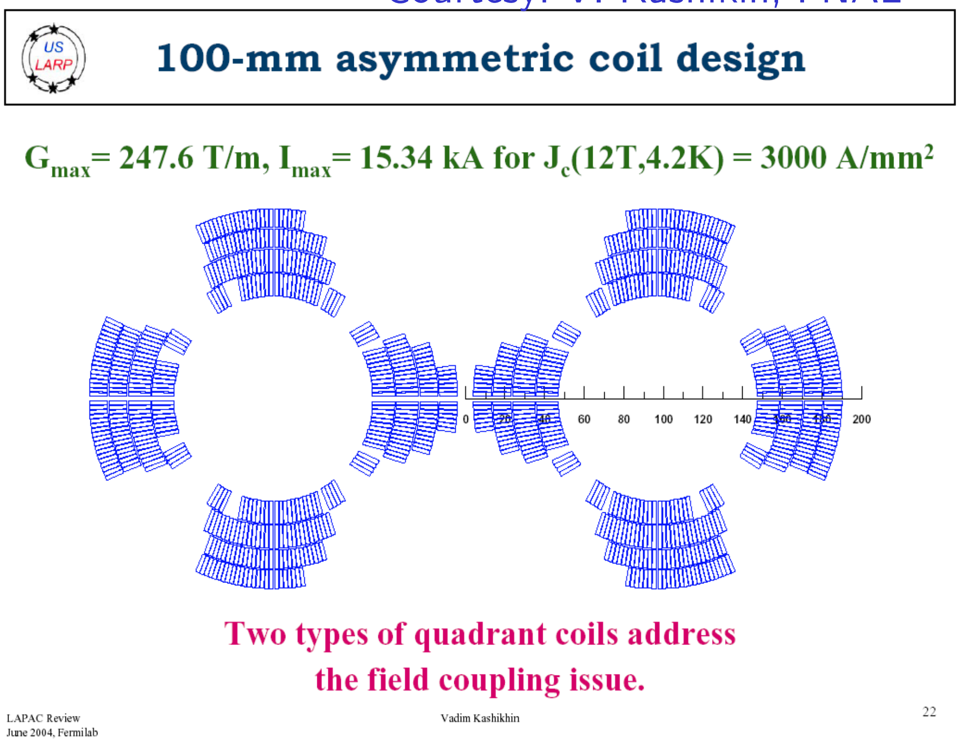
+

Flat Beams ?

No parasitic collisions

Independent & easy IR optics

Courtesy: V. Kashikin, FNAL



R. Gupta, BNL & Crab Team

A2: LHC Aperture Specs

IR4 Specs

Magnet	Aper-H [mm]	Beam-to-Beam Separation [mm]	Max Outer Radius [mm]	L [m]
D_3	69	420	395	9.45
Crabs	84	220 (300)	195	10
D_4 + Q5	73	194	169	15.5

Global

IR1/5 Specs

Magnet	Aper-H [mm]	Beam-to-Beam Separation [mm]	Max Outer Radius [mm]	L [m]
D_1	134	-	-	10
Crabs	84	194	150	10
D_2	69	-	-	10

Local

†2^{nd} beam pipe inside He vessel

A3: Impedance Requirements

Longitudinal criteria:

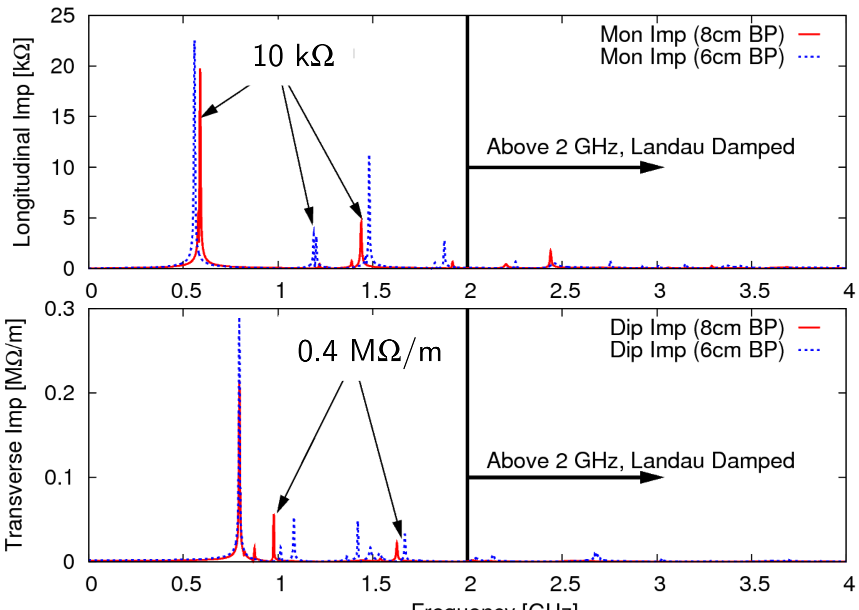
Nominal intensity, 450 GeV: ~60 kΩ (determined by 200 MHz cavities)

Upgrade intensity: ~10 kΩ – two cavities

Transverse criteria:

Nominal intensity, 450 GeV: ~2.5 MΩ/m – single cavity

Upgrade intensity: ~0.4 MΩ/m – two cavities (additional factor of $\beta/\langle\beta\rangle$)

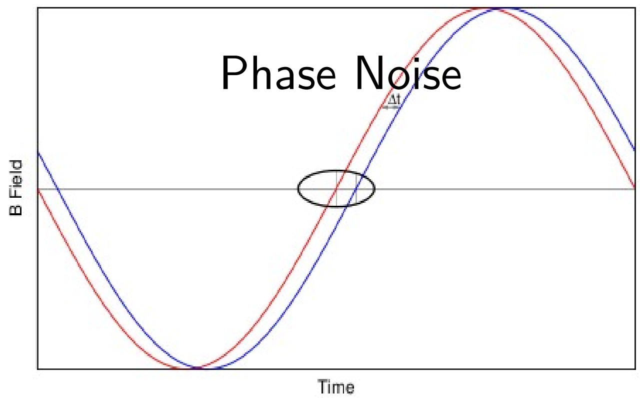


Conventional cavity spectrum

	Freq [GHz]	R/Q [Ω]	Q_{ext}
Monopole	0.54	35.17	~10-100
	0.69	194.52	
Dipole	0.80	117.26	10^6
	0.81	0.46	~10^2-10^3
	0.89	93.4	
	0.90	6.79	

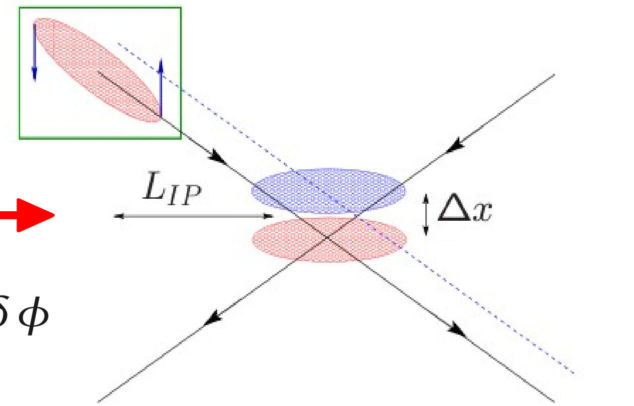
** Main RF cavities, $Q_{ext} \sim 10^2$ - 10^3

A4: Crab Phase Noise



IP Offsets

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



$$\frac{\Delta \epsilon_x}{\Delta t} \propto \frac{\xi^2}{\beta^*}\,\Delta x^2$$

Modulated noise (measured, 30 Hz - 32 kHz)

Prelim BB simulations ≤ 0.1σ (10%/hr)

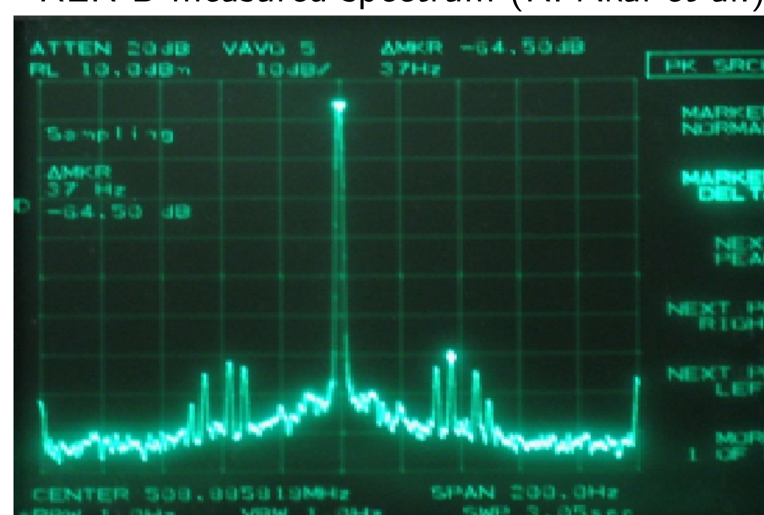
Tolerance relaxed in the case of lumi-leveling

White noise (extremely pessimistic)

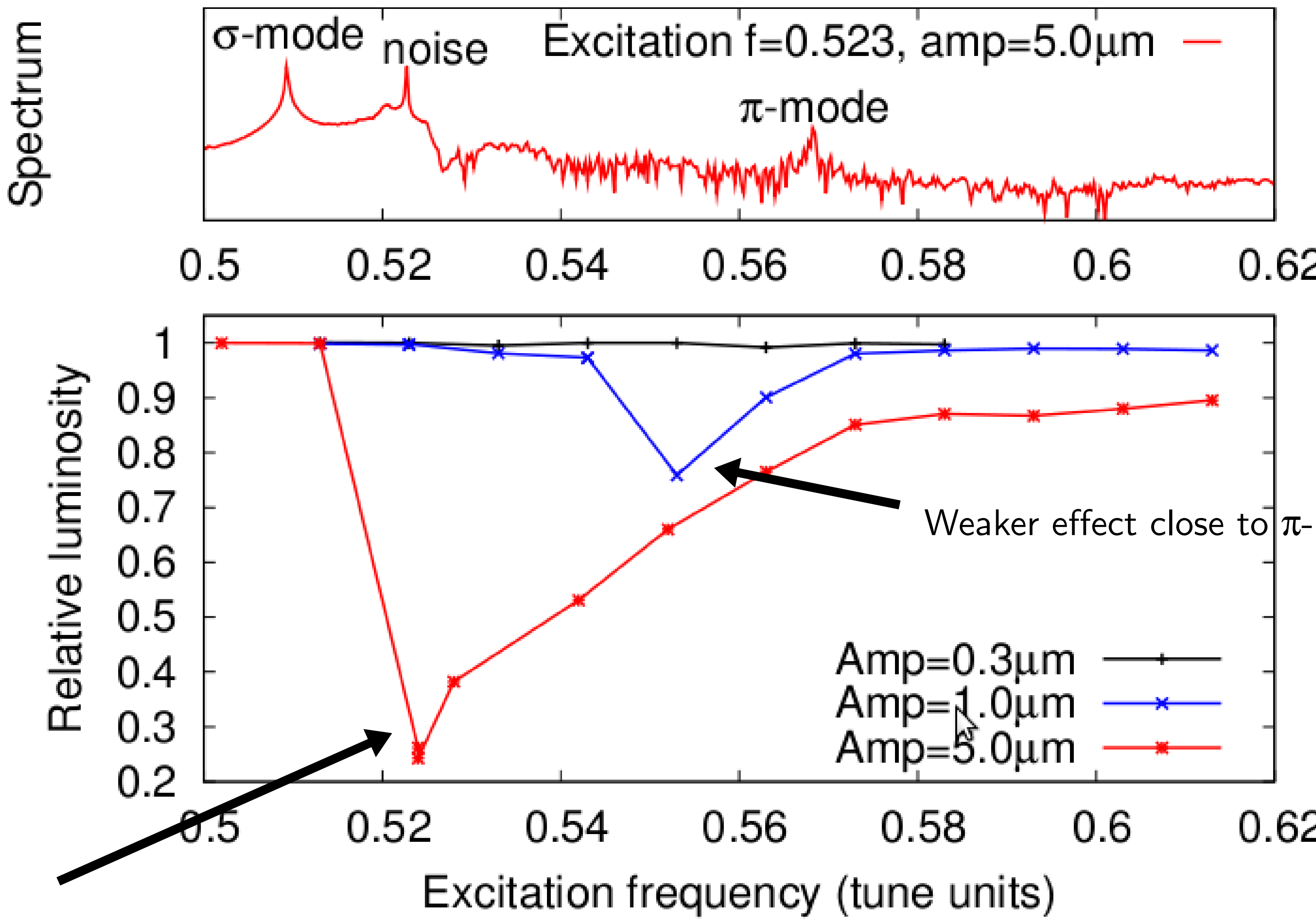
Ohmi: Strong-strong BB ≤ 0.02σ.(τ)

correlation time

KEK-B measured spectrum (K. Akai et al.)



A5: Noise Exps, KEKB



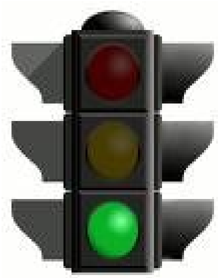
Weaker effect close to π-mode

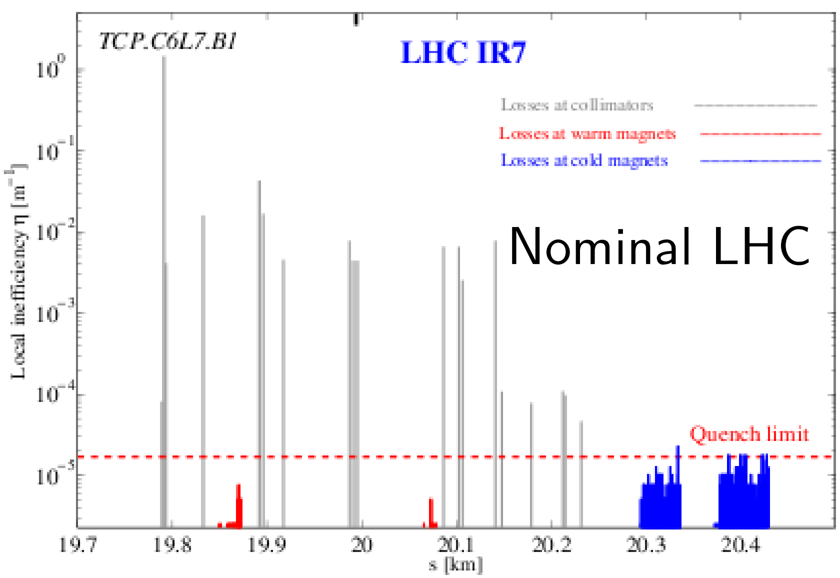
Strong effect close to σ-mode

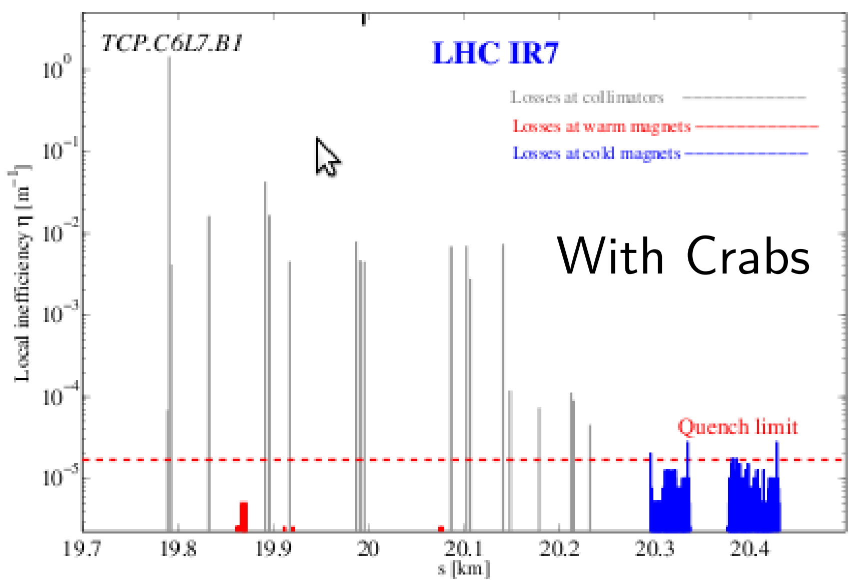
R. Tomas et al., 2008

A6: Collimation (Global Scheme)

- Loss maps with crabs similar to nominal LHC
  - Additional 0.5σ aperture
  - Hierarchy preserved (primary, secondary, tertiary)
- Maximum DA decrease $\sim 1\sigma$ (13σ nominal)
  - Suppression of synchro-betatron resonances





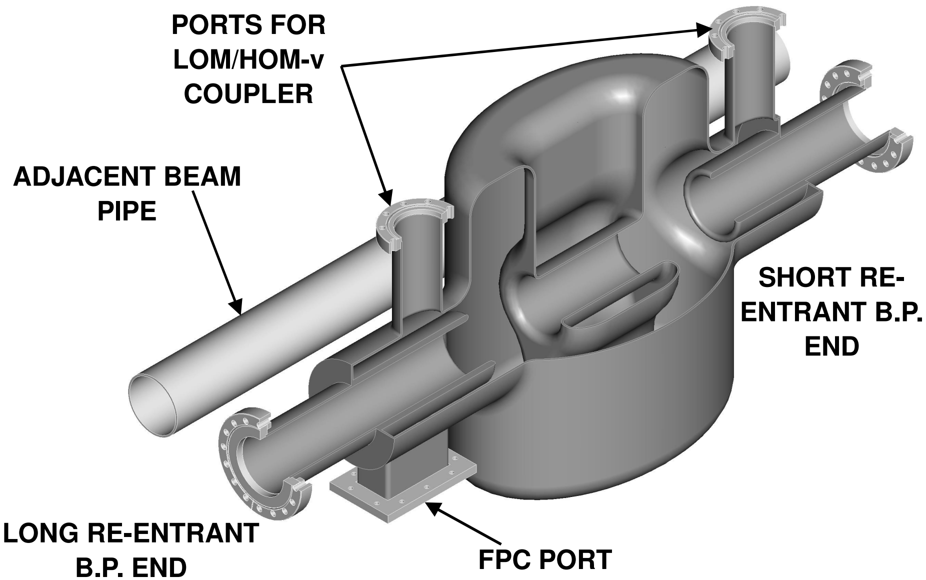


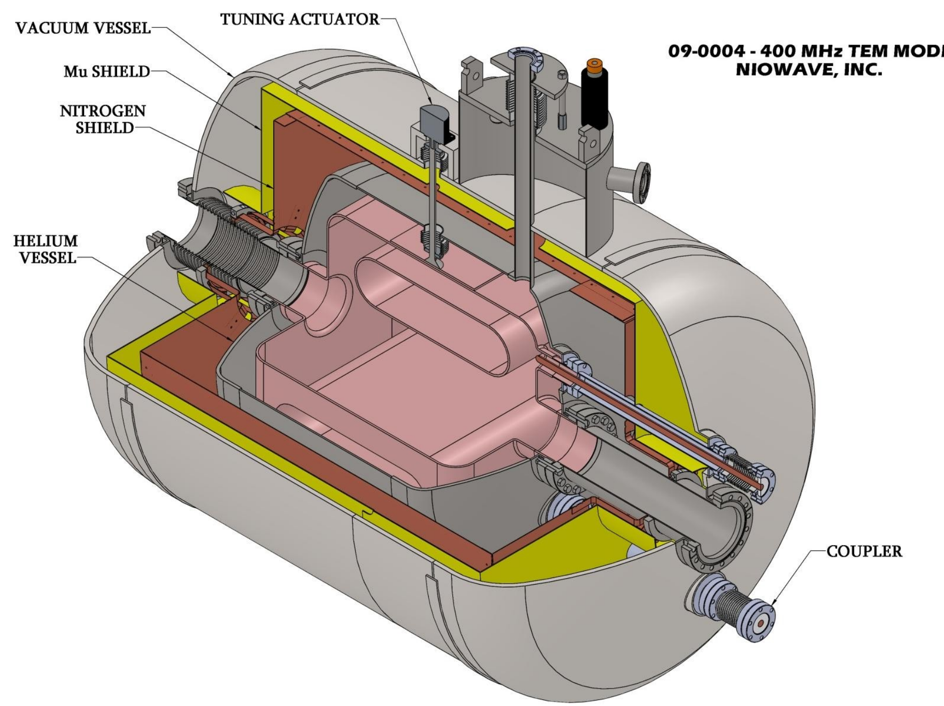
Y. Sun et al. PRST-AB 12, 101002 (2009)

A7: SPS Test Objectives, Protons

- Safe beam operation (low intensity) & reliability
  - Tests, measurements (orbits, tunes emittances, optics, noise)
  - Voltage ramping & adiabaticity
  - Collimation, scrapers to reduction of physical aperture with & w/o crabs
  - DA measurements (possible ?)
- Intensity dependent measurements (emittance blow-up, impedance)
  - Coherent tune shift and impedance
  - Instabilities
  - Beam-beam effects (BBLR – tune scan, current scan)
  - Other non-linearities (octupoles)
- Operational scenarios
  - Accumulation of beam with crab-on & crab off
  - Beam loading with & w/o RF feedback & orbit control
  - RF trips and effects on the beam
  - Energy dependent effects
  - Long term effects with crab-on, coasting 120 GeV

New Technology Challenges





Foreseen Challenges

- Multipacting
- Fabrication & field validation
- Tuning & HOM damping
- Integration (SPS & LHC)

†Courtesy AES, Niowave