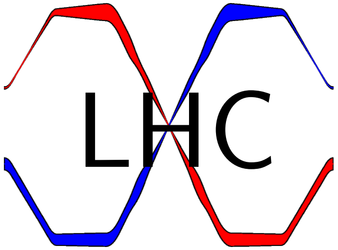
LHC CRAB-CAVITY ASPECTS & STRATEGY

RAMA CALAGA (FOR THE LHC-CC COLLABORATION)

IPAC10, KYOTO, MAY 25, 2010



- LHC Upgrade & Crab Crossing
- New Road Map
- SPS, a first validation step

Special thanks: R. Assmann, B. Burt, M. Cole, R. De-Maria, Y. Funakoshi, B. Hall, J.P. Koutchouk, N. Kota, Z. Li, P .A. McIntosh, A. Morita, Y. Morita, E. Metral, G. Sterbini, N. Solyak, Y. Sun, R. Tomas, J. Tuckmantel, V. Yakovlev, L. Xiao, F. Zimmerman

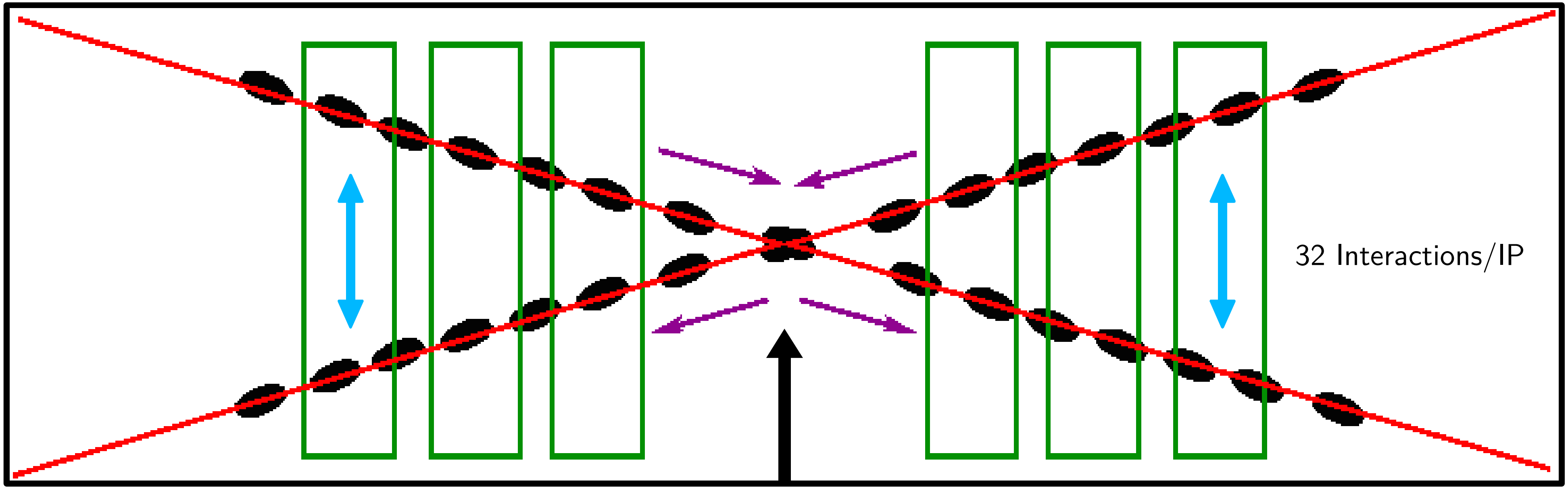
"UPGRADE SCENARIOS"

	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	25-30	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 Problem!



Long-Range Beam-Beam

(~10σ Nominal Sep)

32 Interactions/IP

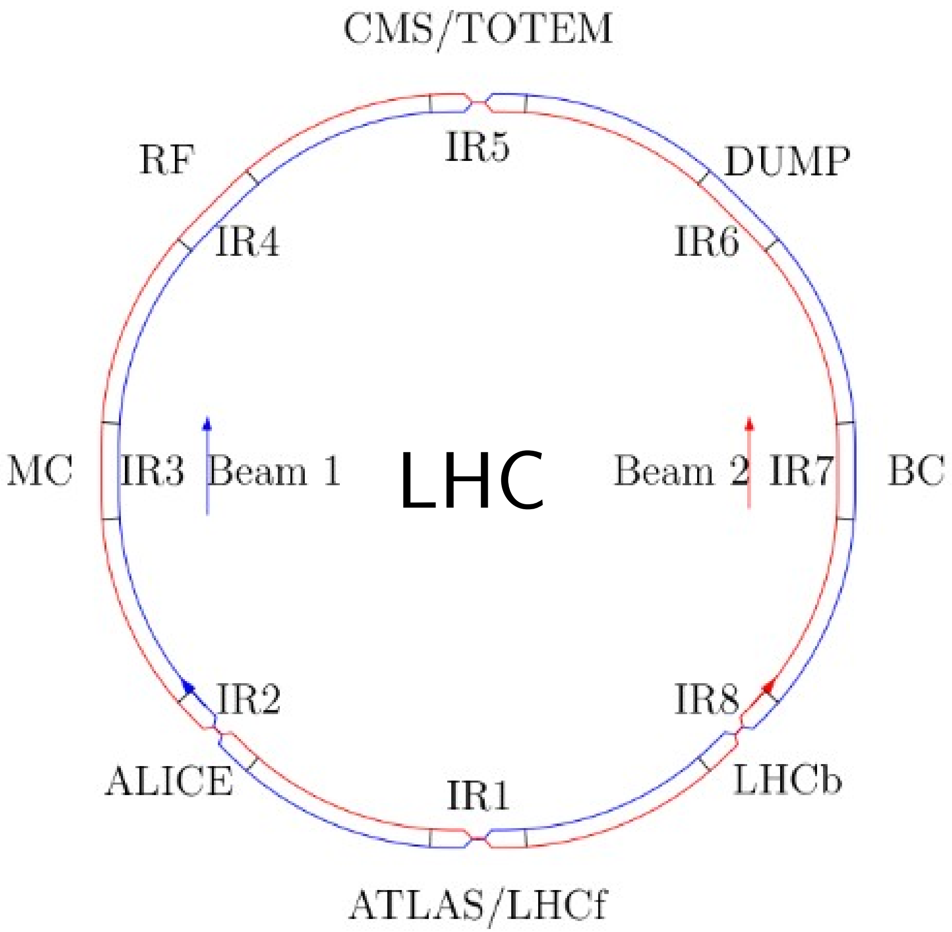
Head-On Beam-Beam

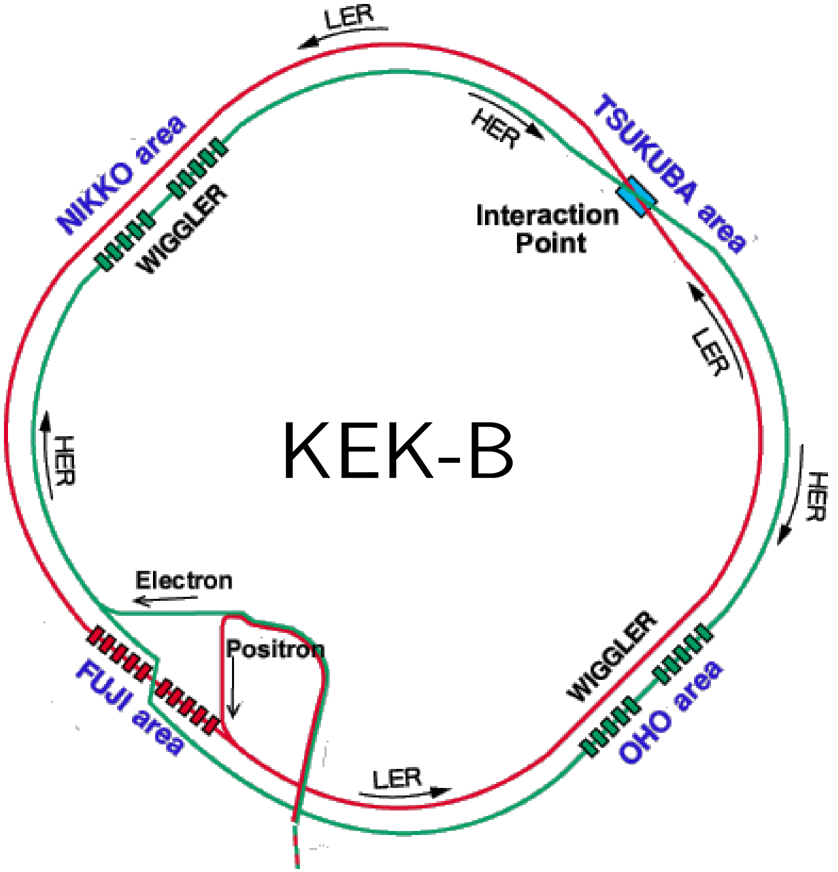
(Limited by Max Tune Shift)

Why Crab Cavities:

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

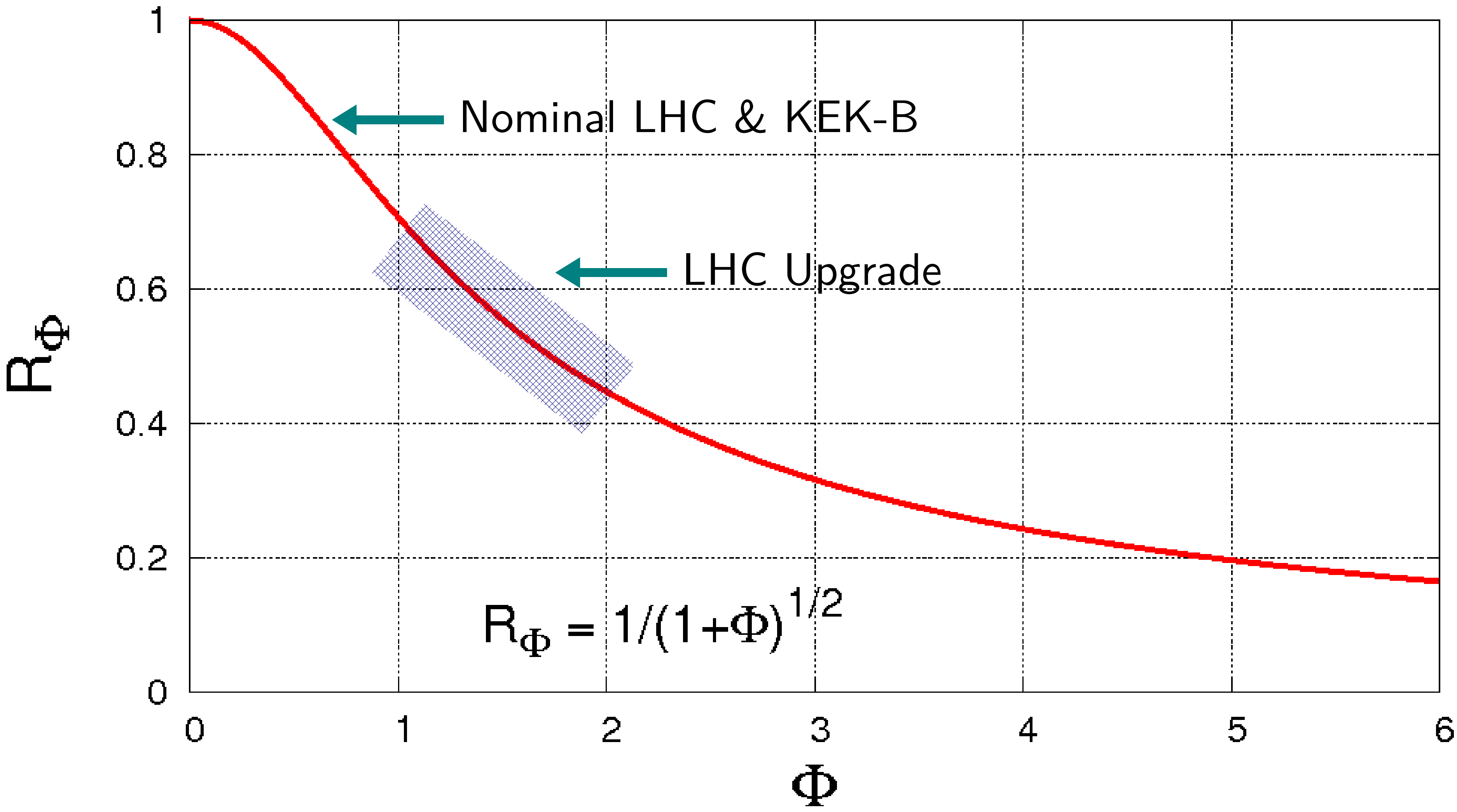
NAIVE COMPARISON

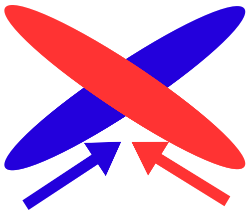




	Energy [GeV]	Circumference [km]	Current [A]	ξ_{BB}	Φ_{Piwinski}	Crab Freq [MHz]	Crab Voltage [MV]
KEK-B	3.5-8.0	3	2.0	0.09	0.75	509	1.5
LHC	7000	27	0.5-0.85	< 0.01	0.6-1.4	400	5-10

REDUCTION FACTOR

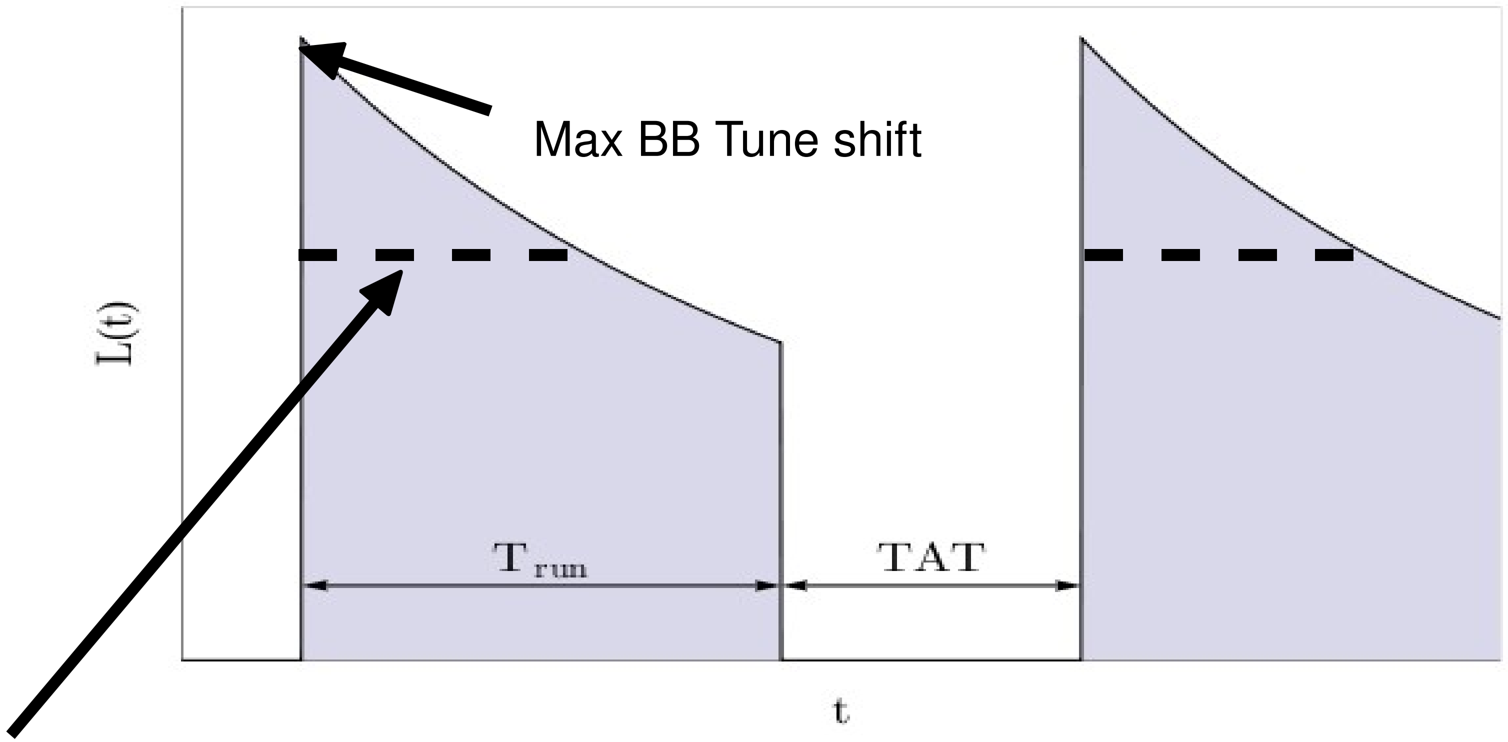




Eff. beam size

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

LUMINOSITY LEVELING



Advantages:

- Constant Luminosity ($\sim$3 x 10^{34})
- Less pile up at start (Nominal $\sim$ 19, Upgrade 100-300 events/crossing)
- Less peak radiation on IR magnets/detector

Crabs → Natural knob w/o lattice change

Graphic courtesy G. Sterbini

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) → 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)

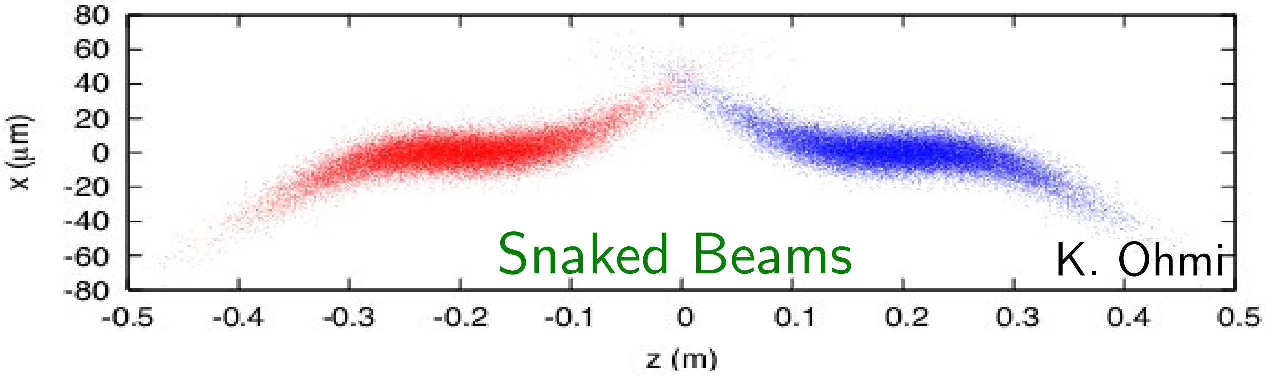
- New design strategy than conventional

LHC machine protection (350 MJ stored energy)

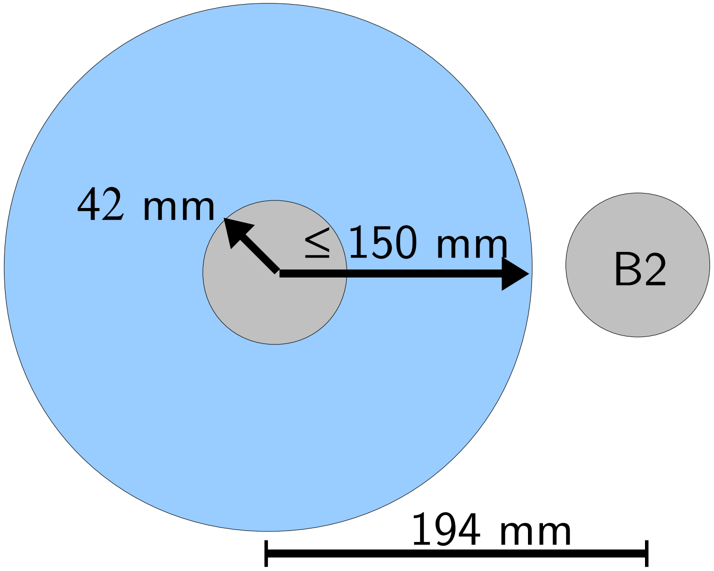
- 5% of nominal bunch beyond damage threshold
- Fast failure detection to safely abort beam

LHC Constraints

Bunch length: 7.55 cm (lowest frequency 800 MHz)



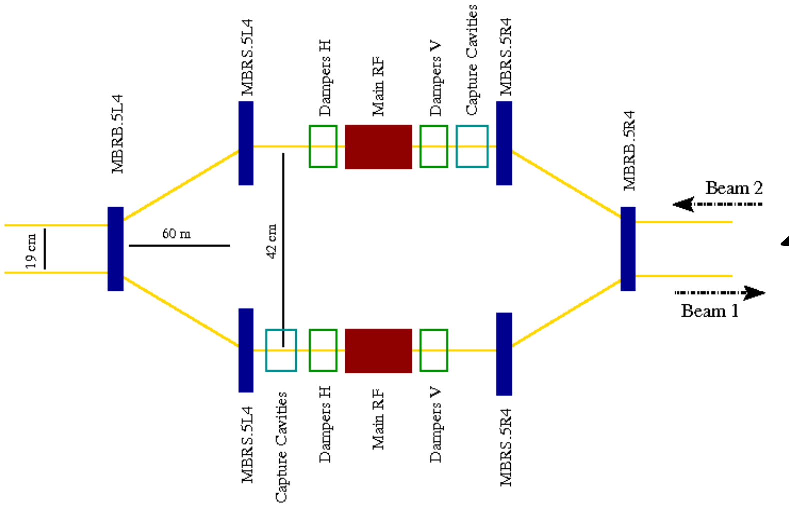
B1-to-B2 separation: 194 mm (PB 800 MHz ~ 250mm radius)



With few exceptions....

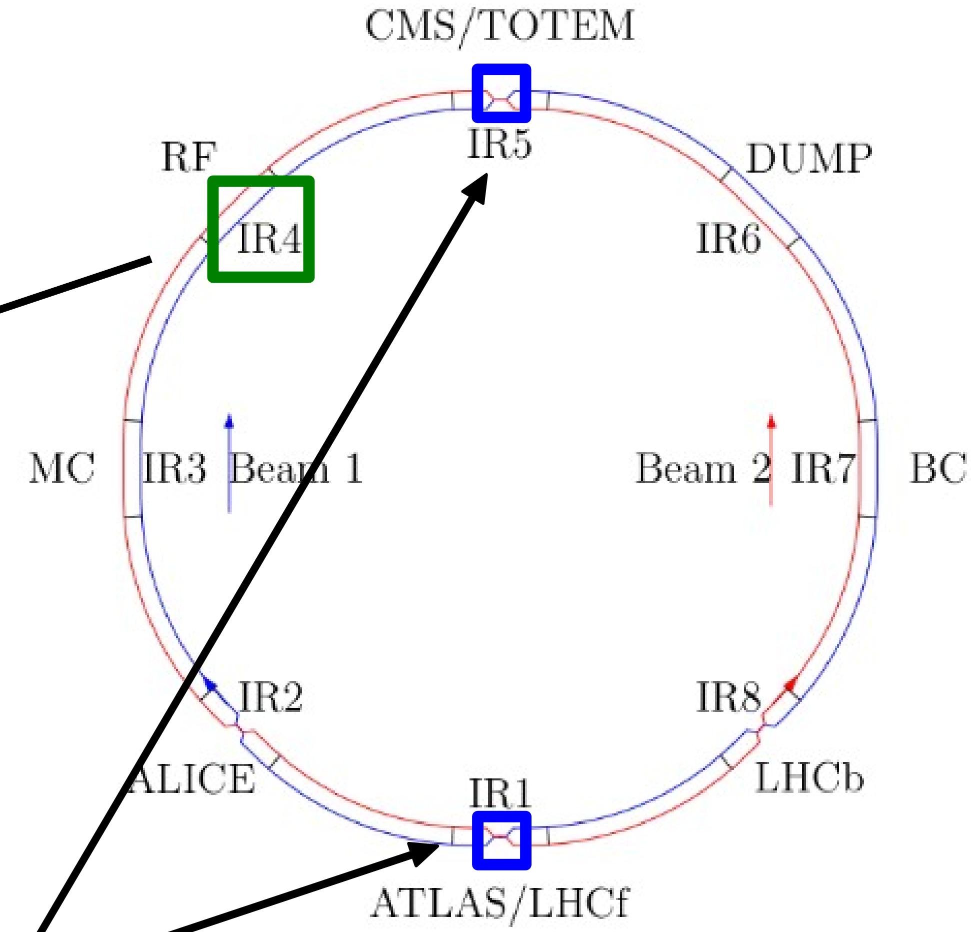
(IR4, collimation, exps)

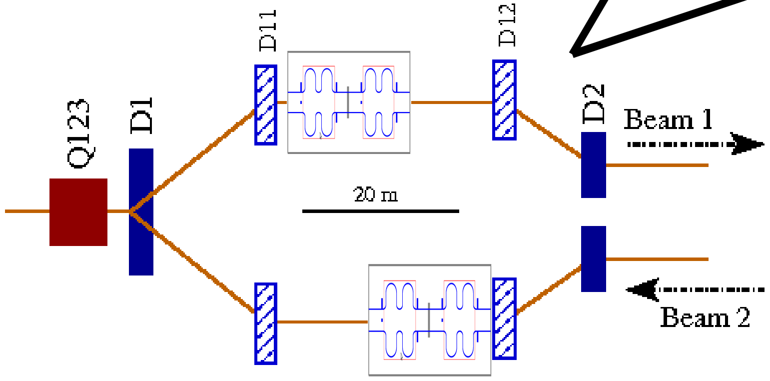
Possible Schemes



Backup Option, Conventional

1-2 Cavities/beam



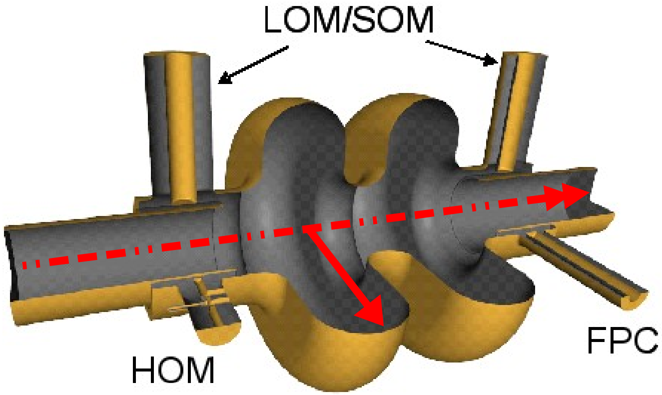


Baseline Option

4 Cavities/IP

Compact cavities -OR- doglegs needed for conventional cavities (impractical)

Conventional to Compact

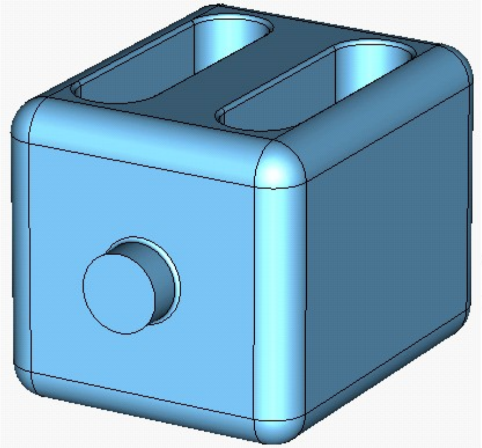


~250 mm outer radius

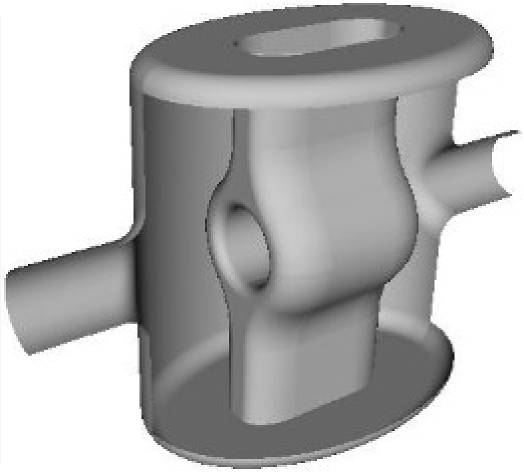
(Not compatible in most of the LHC ring)

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

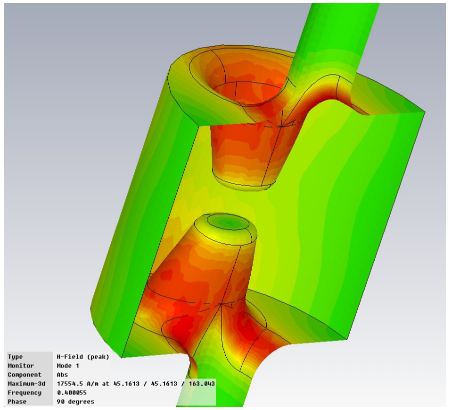
WEPEC084
HWDR, JLAB,OD



MOPEC022
HWSR, SLAC-LARP

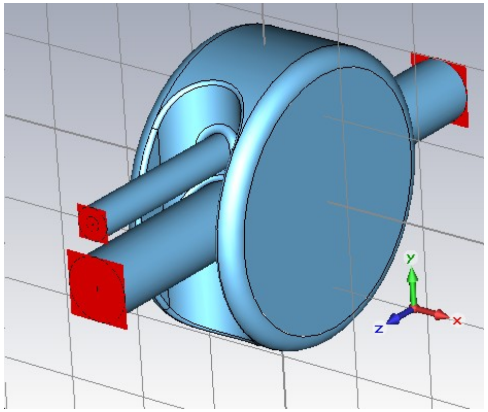


WEPEC049
DR, UK, TechX



Type H-Field (peak)
Monitor Mode 1
Component Abs
Maximum-3d 17554.5 A/m at 45.1613 / 45.1613 / 163.043
Frequency 0.400055
Phase 90 degrees

Rotated Pillbox, KEK



Performance Chart

Kick Voltage: 5 MV, 400 MHz

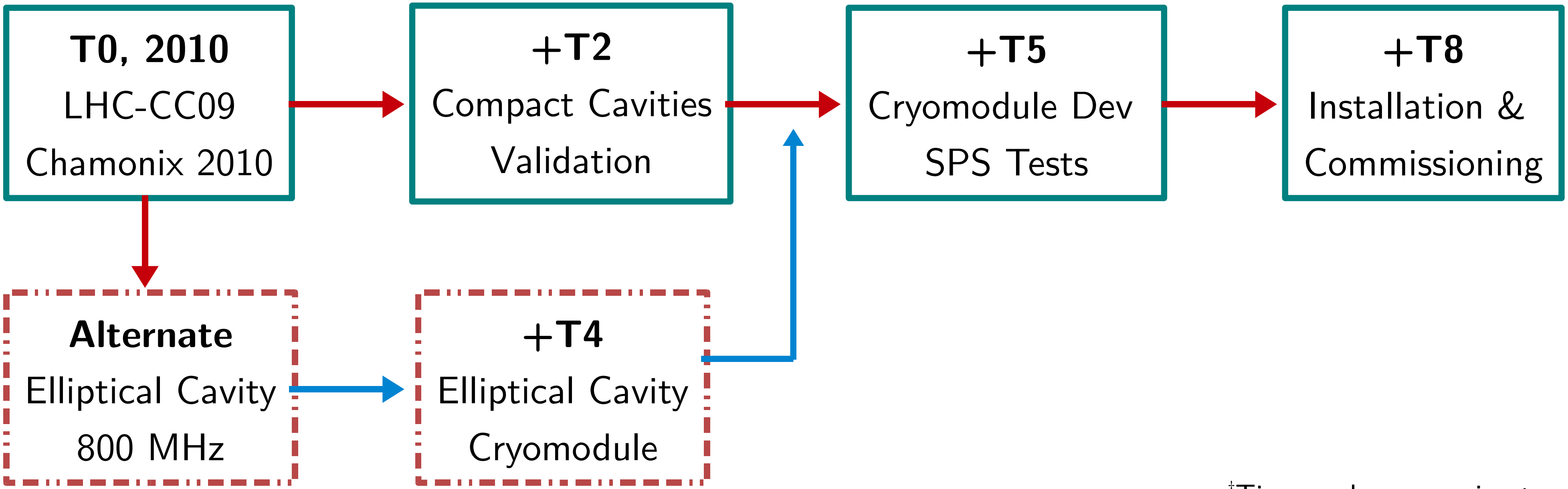
		HWDR (J. Delayen)	HWSR (Z. Li)	4-Rod (G. Burt)	Rotated Pillbox (N. Kota)
Geometrical	Cavity Radius [mm]	**200**	**140**	**150**	**150**
	Cavity Height [mm]	382	194	169	668
	Beam Pipe [mm]	50	45	45	75
RF	Peak E-Field	29	65	103	85
	Peak B-Field	94	135	113	328
	R_T/Q	319	275	667(?)	-

†Exact voltage depends on cavity placement & optics

†Cavity parameters are evolving

NEW ROADMAP

- CERN must pursue crab crossing following KEK-B success
- Both local (baseline) & global should pursued
- High reliability (cavity, machine protection, impedance & mitigation)
- No validation in LHC required (ex: SPS as test bed with KEK-B cavities)
- Coordination & timing: both short term & long term upgrades of LHC



T0, 2010
LHC-CC09
Chamonix 2010

+T2
Compact Cavities
Validation

+T5
Cryomodule Dev
SPS Tests

+T8
Installation &
Commissioning

Alternate
Elliptical Cavity
800 MHz

+T4
Elliptical Cavity
Cryomodule

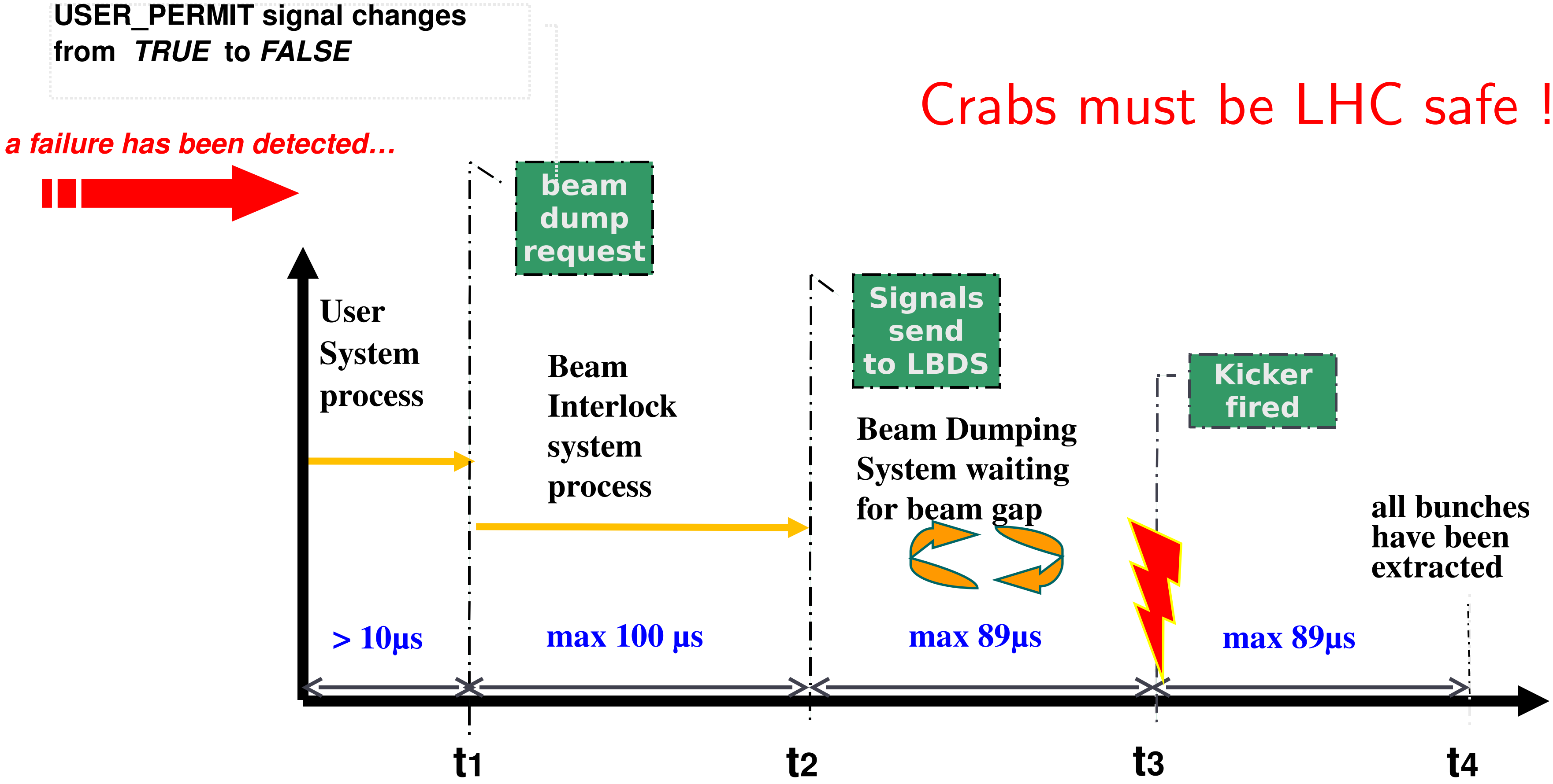
[†] Time scales approximate

MACHINE PROTECTION, 350 MJ !!

100's of interlock systems → complex

Best/worst case scenario:

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



USER_PERMIT signal changes from *TRUE* to *FALSE*

a failure has been detected…

beam dump request

User System process

Beam Interlock system process

Signals send to LBDS

Beam Dumping System waiting for beam gap

Kicker fired

all bunches have been extracted

> 10μs

max 100 μs

max 89μs

max 89μs

t1

t2

t3

t4

Crabs must be LHC safe !!

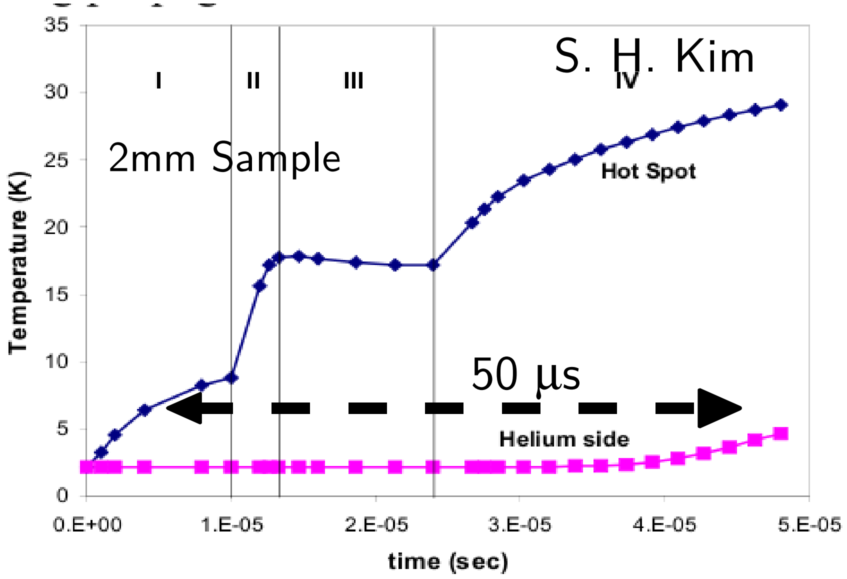
Courtesy J. Wenniger

Some Failure Scenarios

WEPEC022,
KEK Cavities

Time scales:

- Power supply trips (50-300 Hz $>$ 7 ms) → greater than 300 turns
- RF arcing (few µs) → Response of cavity voltage/phase slower
- Mechanical changes (100's of ms) → high Q SC cavity
- Quench, abrupt amplitude or phase changes



No passive way to guarantee machine protection

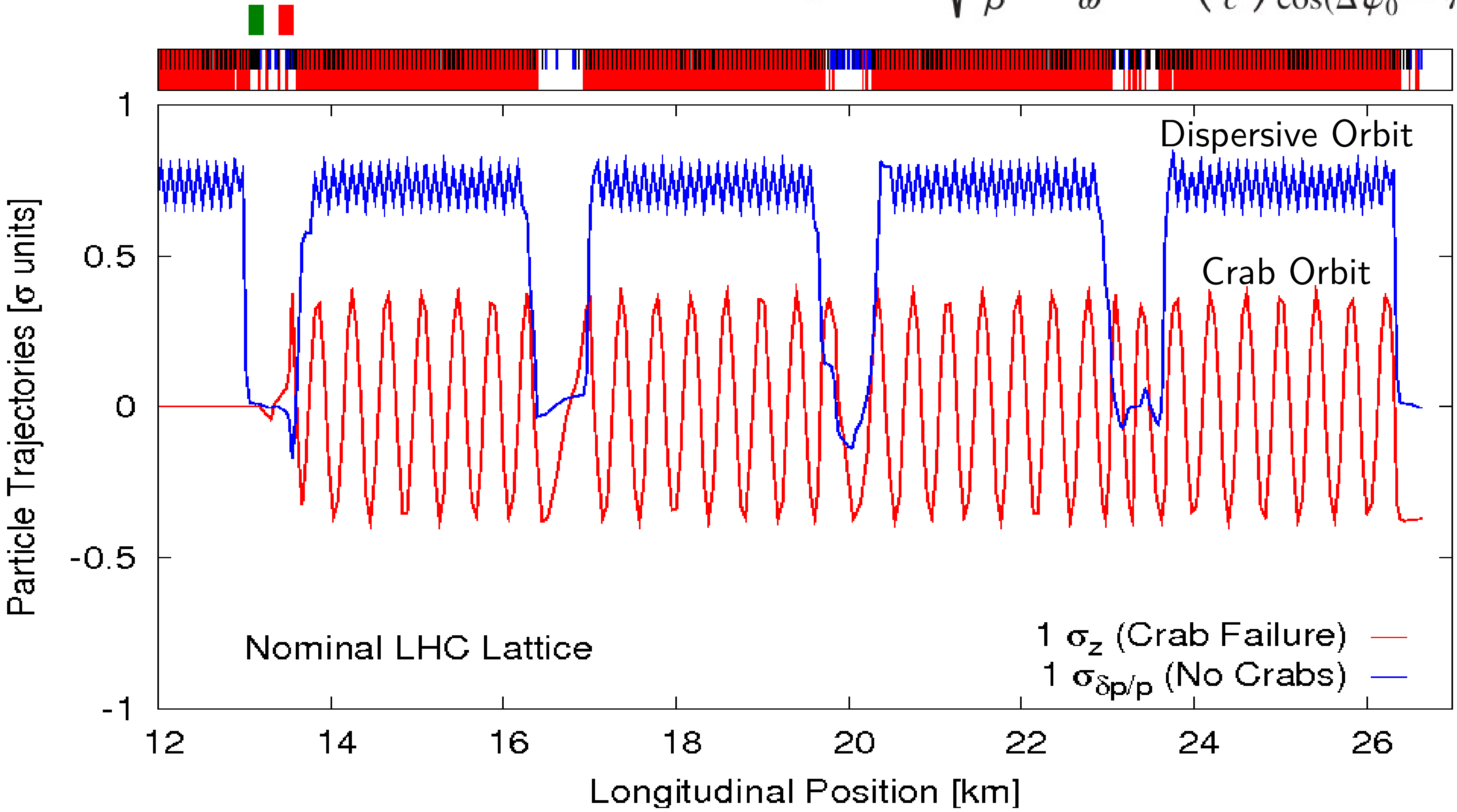
- Qext may not help for beam driven failure time constant
- Voltage slope determined by unchangeable constants (R/Q, Δx, I...)
- Active orbit and RF feedback a requirement (cavity to cavity across IR ~1µs)

Some info courtesy J. Tuckmantel

LEFT-RIGHT VOLTAGE FAILURE

Local Crabs, IP5

$$x_{D_{cc}}(z,s) = \sqrt{\frac{\beta(s)}{\beta^*}}\,\frac{c\tan(\frac{\theta}{2})}{\omega}\,\sin\left(\frac{\omega z}{c}\right)\frac{\cos(\Delta\varphi_1 - \pi Q)}{\cos(\Delta\varphi_0 - \pi Q)},$$

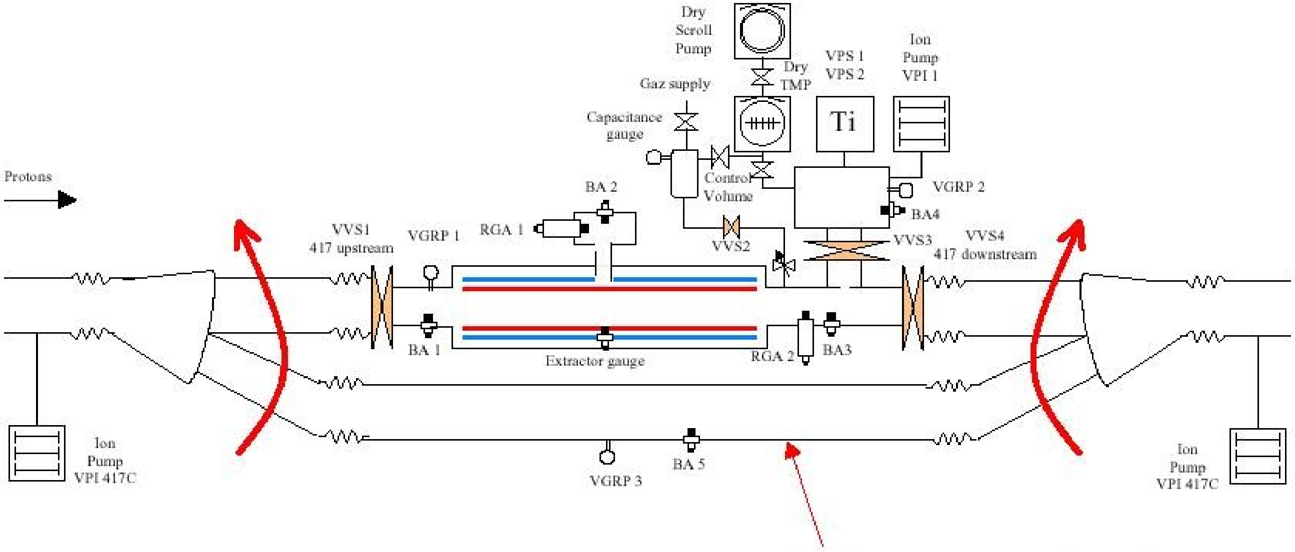


Change in 180^0 phase → factor 2

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



Default vacuum chamber

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

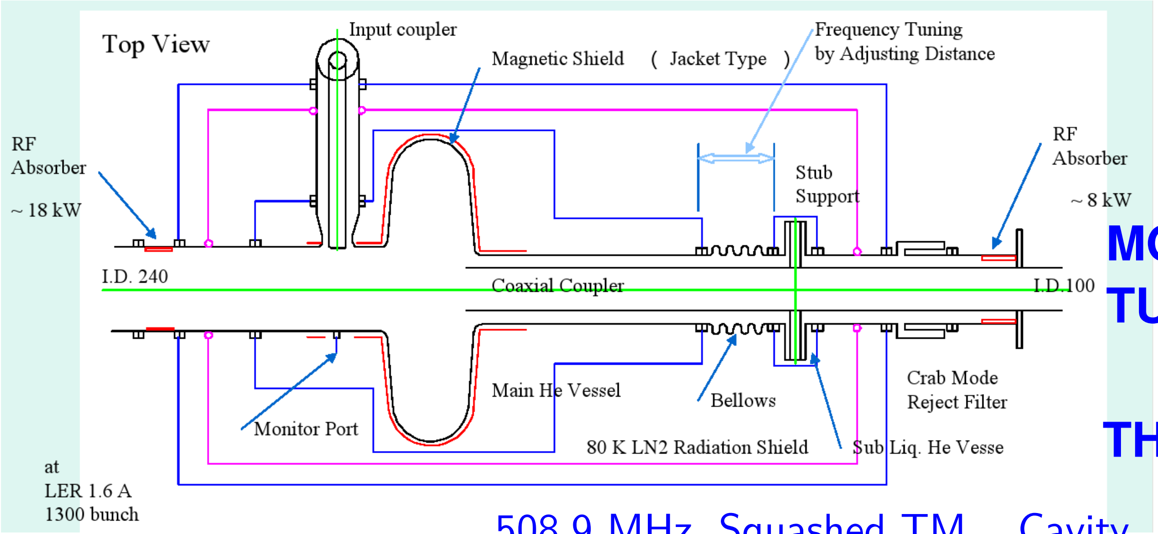
KEK Cavities in SPS

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

No show stoppers to test the KEK-B cavity in SPS

Modifications required to adapt to SPS (for example: static freq change ~2 MHz)

Earliest possible: End of 2012



MOOCMH03
TUPEB011

THPE093

508.9 MHz, Squashed TM_{110} Cavity

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)

Graphic/Cavity Info: Courtesy KEK-B

Conclusions

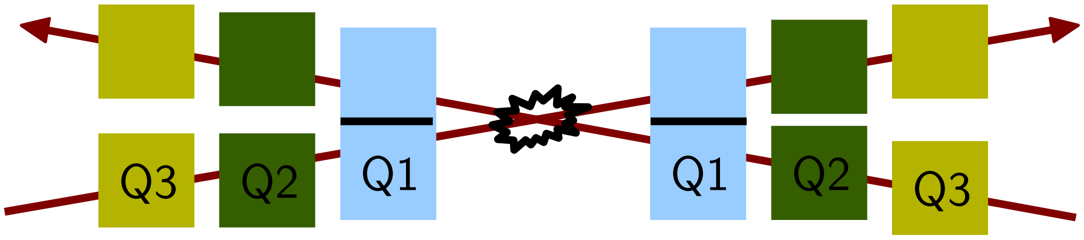
- Key motivation
  - Luminosity gain & leveling with reducing β^*
  - Technical challenge to develop and validate compact cavities
  - Ensure machine protection under different cavity failure modes

- KEK-B experience
  - Vital operational experience with high currents
  - Dedicated experiments to identify potential issues for LHC (ex: phase noise)

- SPS tests
  - Validate differences between protons & electrons
  - KEK-B cavity (2012), LHC compact cavity (2014 – 15)

Many thanks to all the LHC-CC collaborators

A1: Possible Future



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

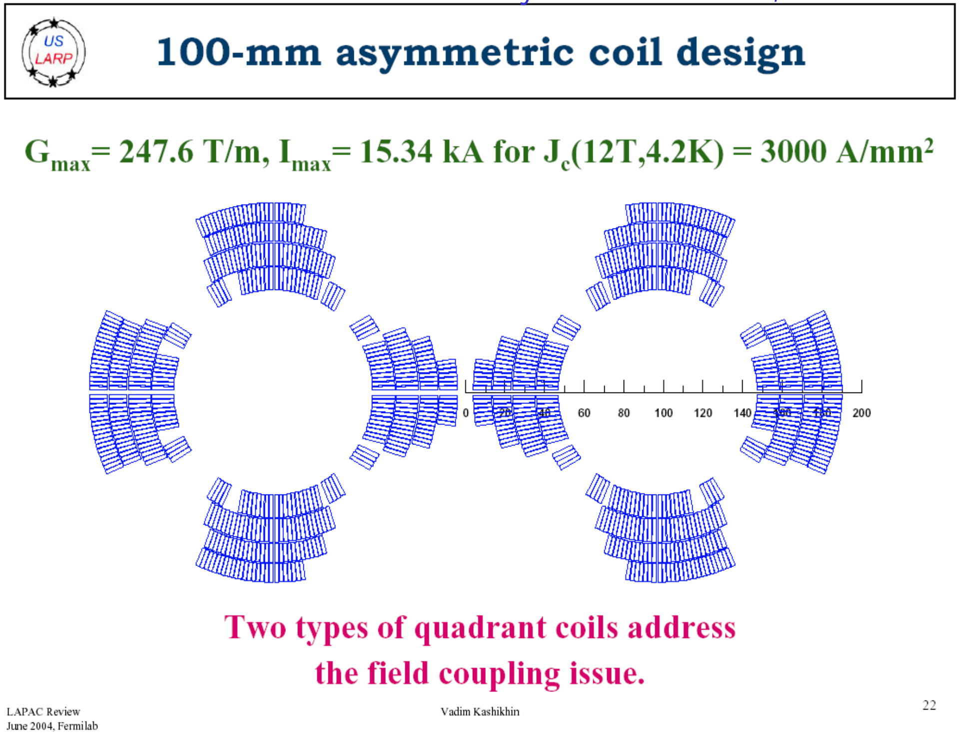
+

Flat Beams ?

No parasitic collisions

Independent & easy IR optics

Courtesy: V. Kashikin, FNAL



100-mm asymmetric coil design

G_{max}= 247.6 T/m, I_{max}= 15.34 kA for J_c(12T,4.2K) = 3000 A/mm²

Two types of quadrant coils address the field coupling issue.

LAPAC Review
June 2004, Fermilab

Vadim Kashikhin

22

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

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†2nd beam pipe inside He vessel

A3: IMPEDANCE REQUIREMENTS

Longitudinal criteria:

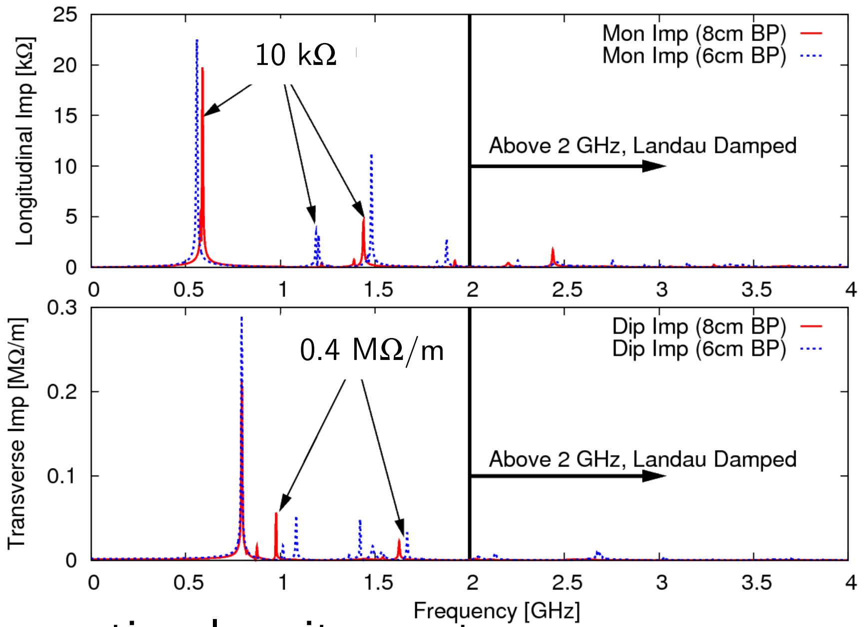
Nominal intensity, 450 GeV: ∼60 kΩ (determined by 200 MHz cavities)

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 β/⟨β⟩)

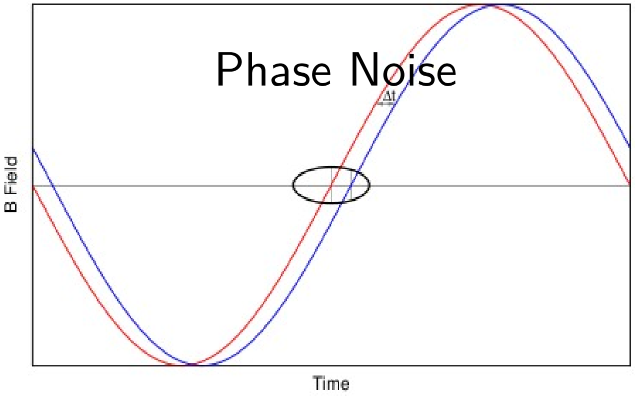


Conventional cavity spectrum

	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	

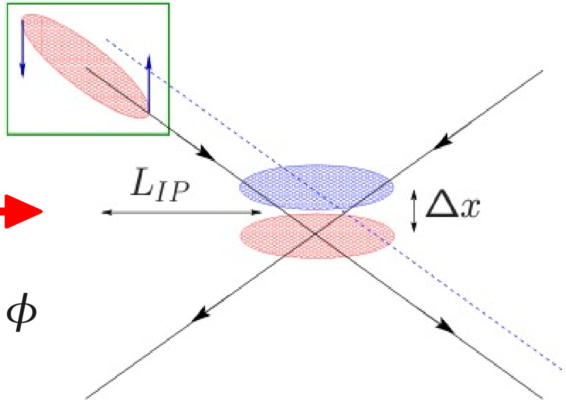
** Main RF cavities, $Q_{ext} \sim 10^2$ - 10^3

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)

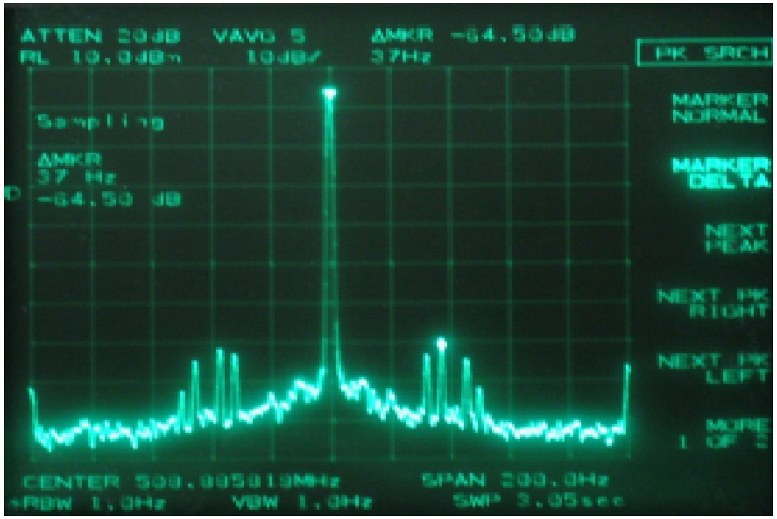
- Prelim BB simulations ≤ 0.1σ (10%/hr)
- Tolerance relaxed in the case of lumi-leveling

White noise (extremely pessimistic)

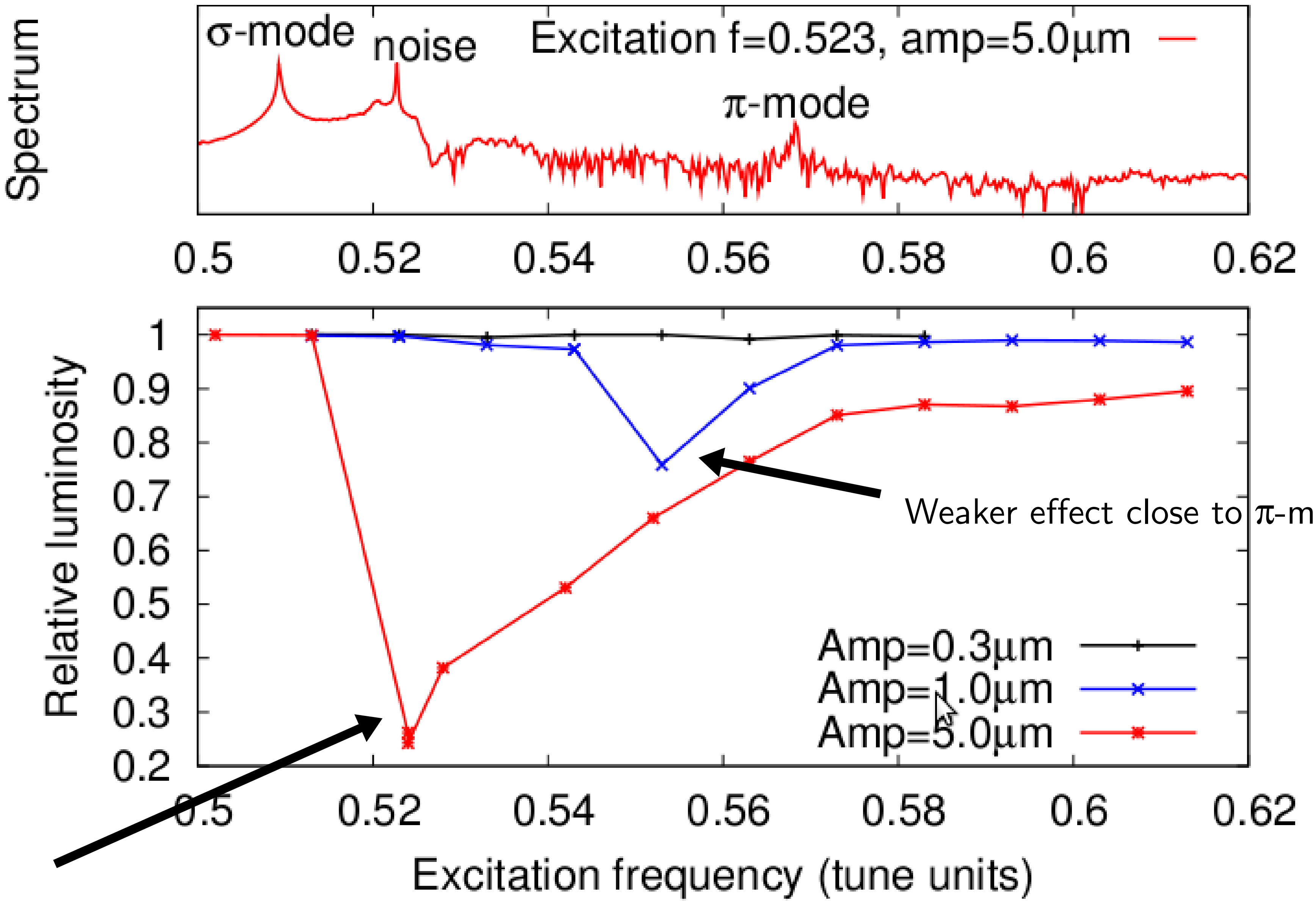
- Ohmi: Strong-strong BB ≤ 0.02σ.(τ)

correlation time

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



A5: NOISE EXPS, KEK-B



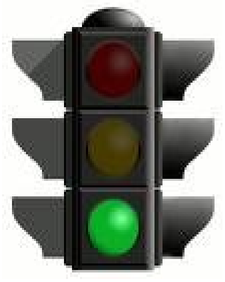
Weaker effect close to π-mode

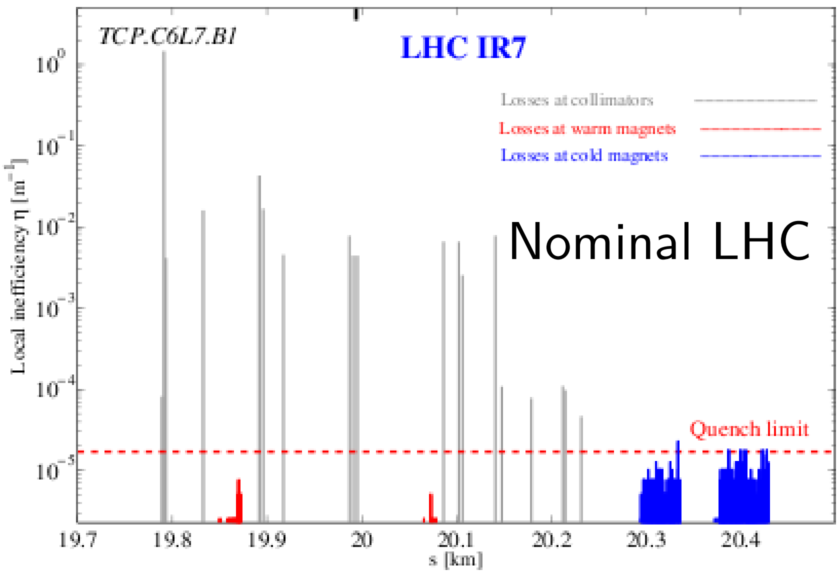
Strong effect close to σ-mode

R. Tomas et al., 2008

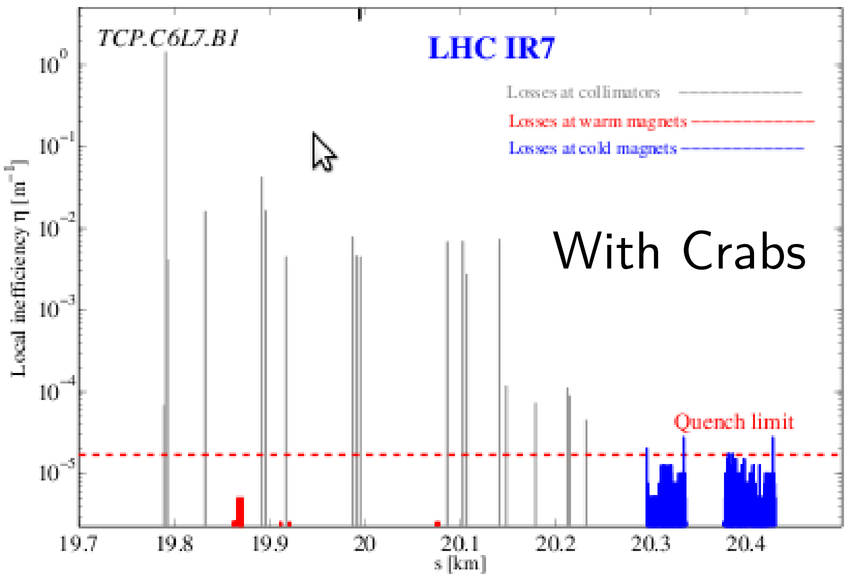
A6: COLLIMATION (GLOBAL SCHEME)

- 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





Nominal LHC



With Crabs

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

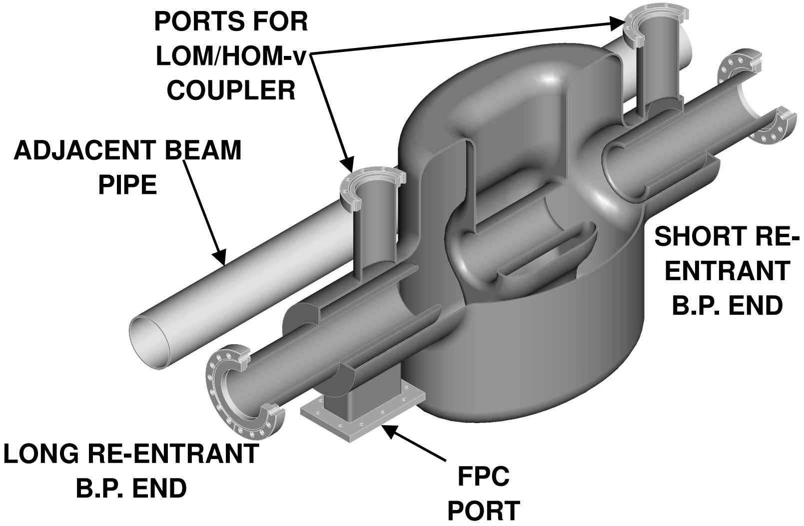
A7: SPS TEST OBJECTIVES, PROTONS

- 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 ?)

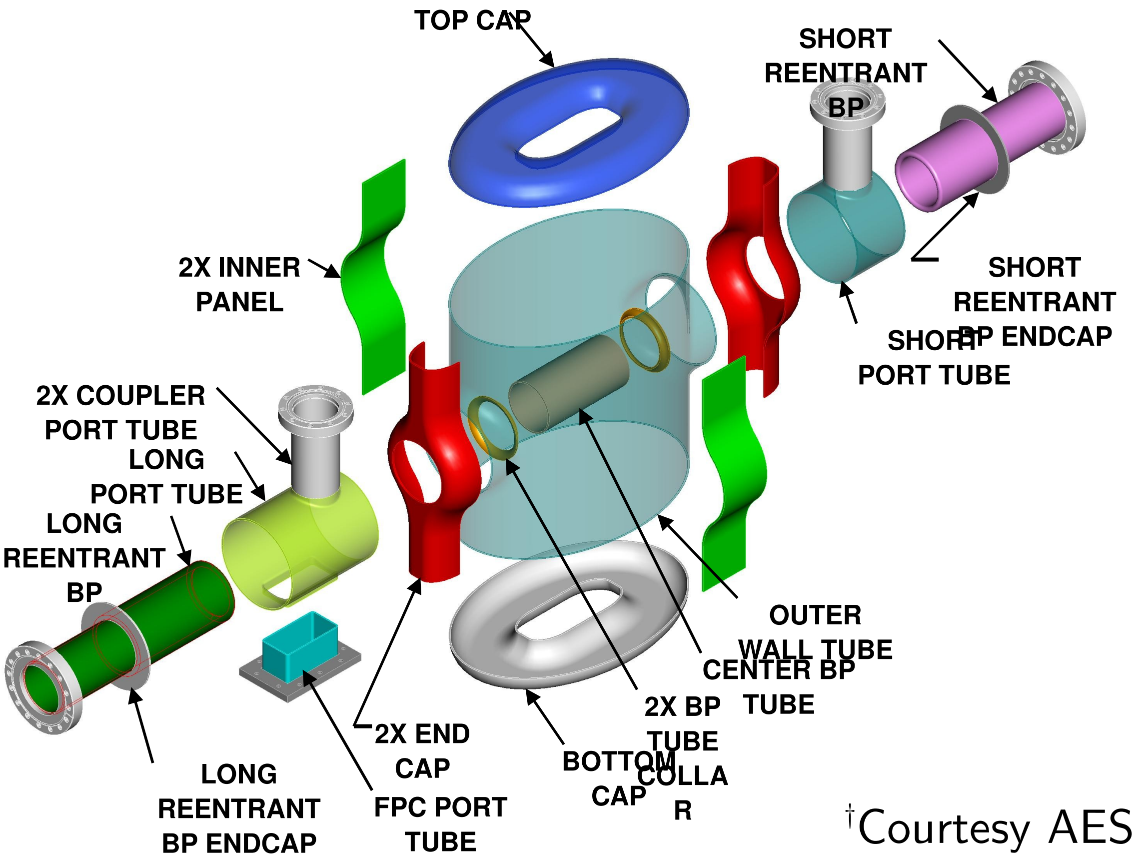
- Intensity dependent measurements (emittance blow-up, impedance)
  - Coherent tune shift and impedance
  - Instabilities
  - Beam-beam effects (BBLR – tune scan, current scan)
  - Other non-linearities (octupoles)

- 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

A8: Compact Cavity (LARP-AES)



Assembly Process



†Courtesy AES

Foreseen Challenges

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