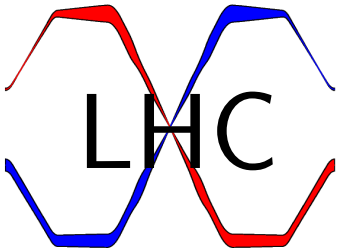
LHC Crab Cavities

EuCARD10, April 14, 2010



- LHC Crabs & Old Roadmap
- Where do we stand today
- SPS, a first validation step ?

R. Calaga, R. De-Maria (BNL), R. Assmann, E. Metral, J.P. Koutchouk, Y. Sun, R. Tomas, J. Tuckmantel,, F. Zimmermann (CERN), N. Solyak, V. Yakovlev (FNAL), Y. Funakoshi, N. Kota, Y. Morita (KEK), G. Burt, B. Hall (LU), P .A. McIntosh (DL/ASTeC), Z. Li, L. Xiao (SLAC)

Ack: LHC-CC Team

Roadmap (Before 2009)

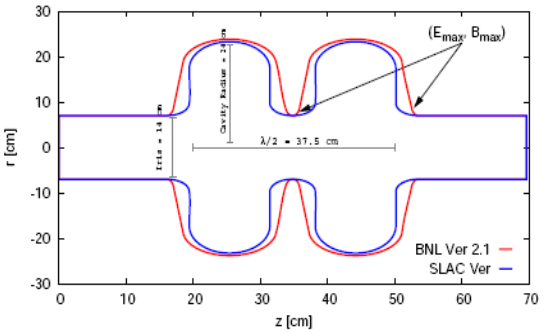
CARE-HHH & LARP

LUMI–05 (Arcidosso), LARP (FNAL)
First Crab Cavity Ideas for LHC
KEK–B Not Started Yet

LUMI–06 (Valencia)
LHC Crab Crossing Proposed
KEK–B Not Started Yet

PAC07, CM8, ..., LHC–CC08
Small Angle Crab Scheme
KEK–B CCs Successfully Commissioned

Two-cell elliptical cavity, Baseline



We are here

FY08 – LHC–CC08
Global Collaboration
US–LARP/EUCARD–CI–DL/KEK
CERN

LHC-CC09

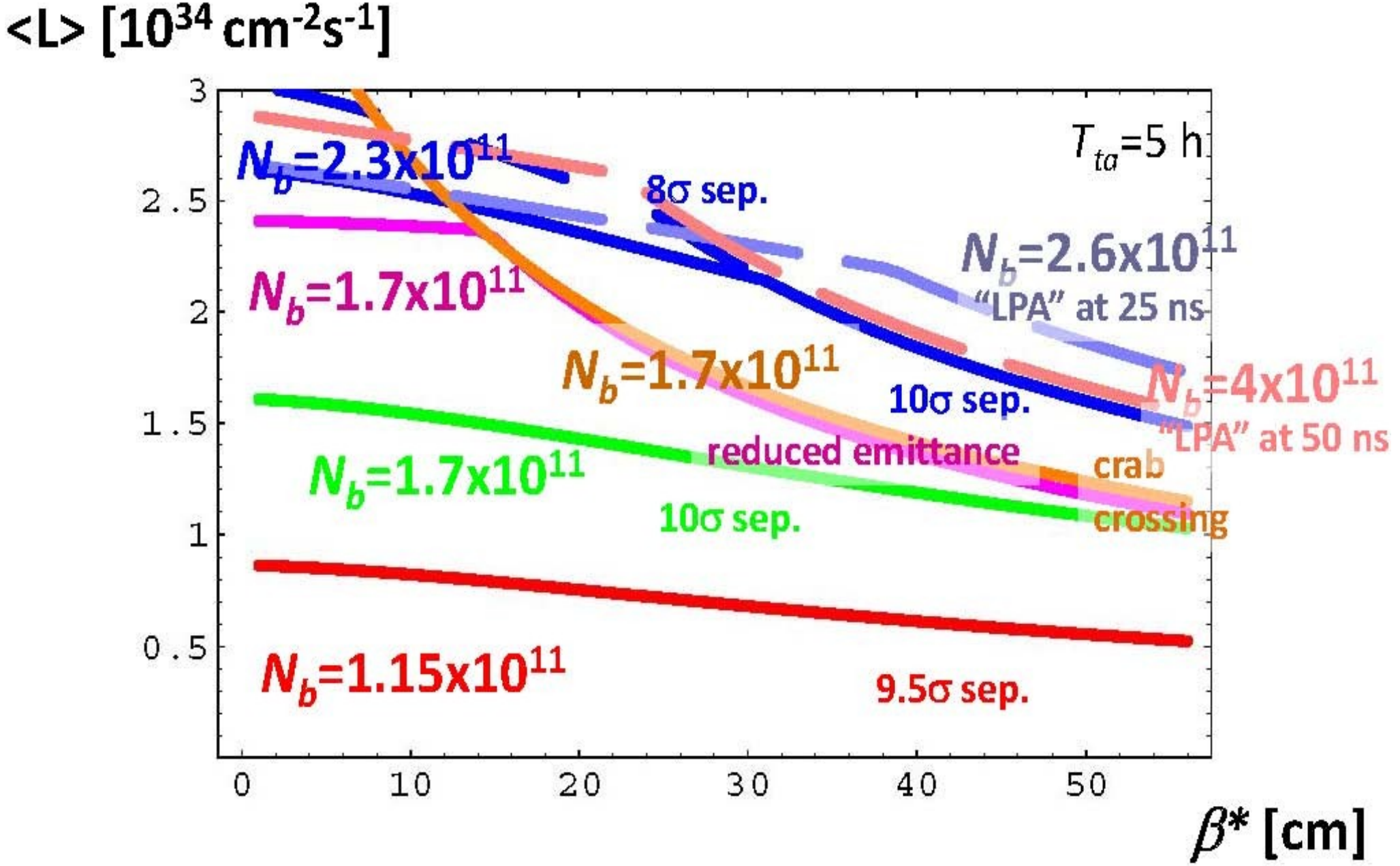
FY09 – FY13
Cryomodule R&D, Simulations, Fabrication
Testing, Installation, Beam Testing

KEK–B CCs observes
less gain than expected

More MDs planned
CERN/LARP Participation

Future
LHeC, Super KEK–B, LC, ...

Different Upgrade Benefits



Courtesy F. Zimmermann, Chamonix10

†Nominal LHC (55 cm)

Interpreting Zimmermann

Upgrade scenarios aim at x3-10 Lumi increase

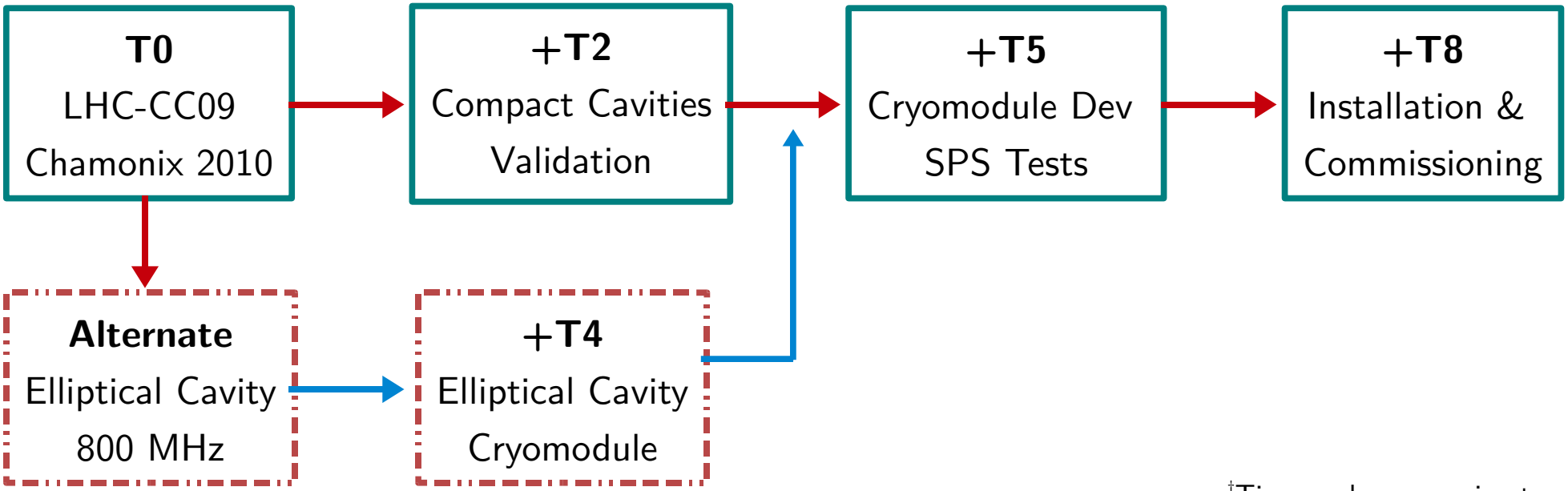
- Bunch Intensity: $1.1 \times 10^{11} \rightarrow 1.7\text{-}2.3 \times 10^{11}$
- Compensate Piwinski Angle (β^* 55cm $\rightarrow$ 25cm or smaller)
- Reduce Emittance: 3.5mm $\rightarrow$ 1 mm (\$\$, IBS)

Bunch intensity increase more beneficial

- BUT, very difficult to digest in injectors & the LHC
- Additional machine protection and collimation issues

New Roadmap, After Chamonix

- 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

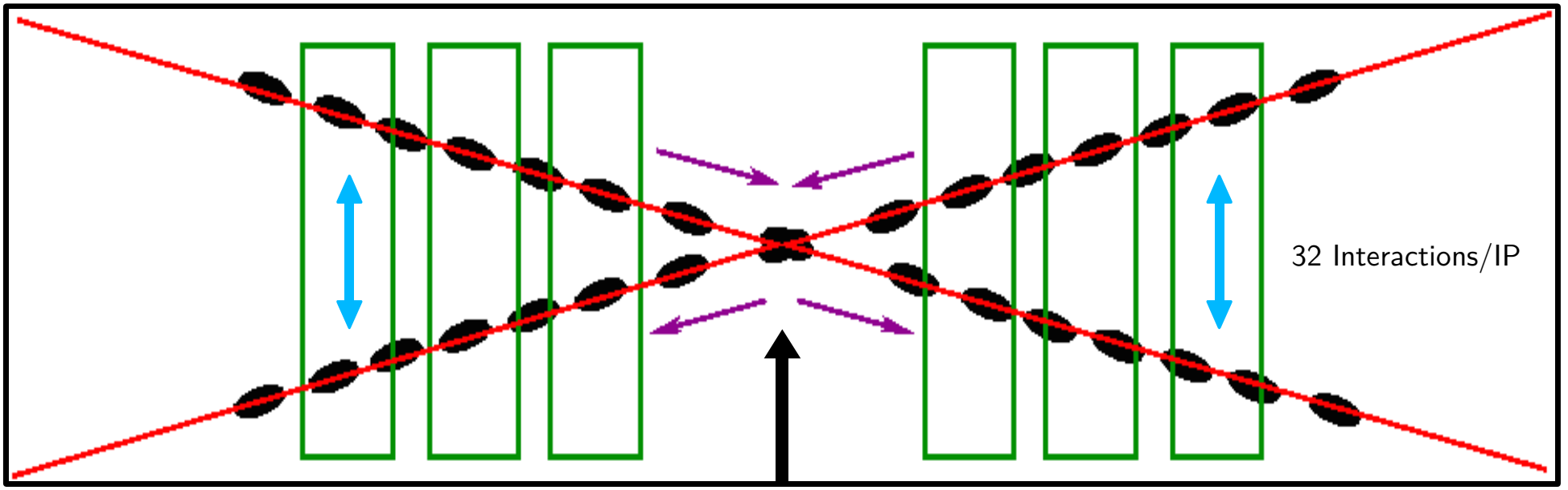


†Time scales approximate

X-Angle Problem!

Long-Range Beam-Beam

(~10σ Nominal Sep)



Head-On Beam-Beam

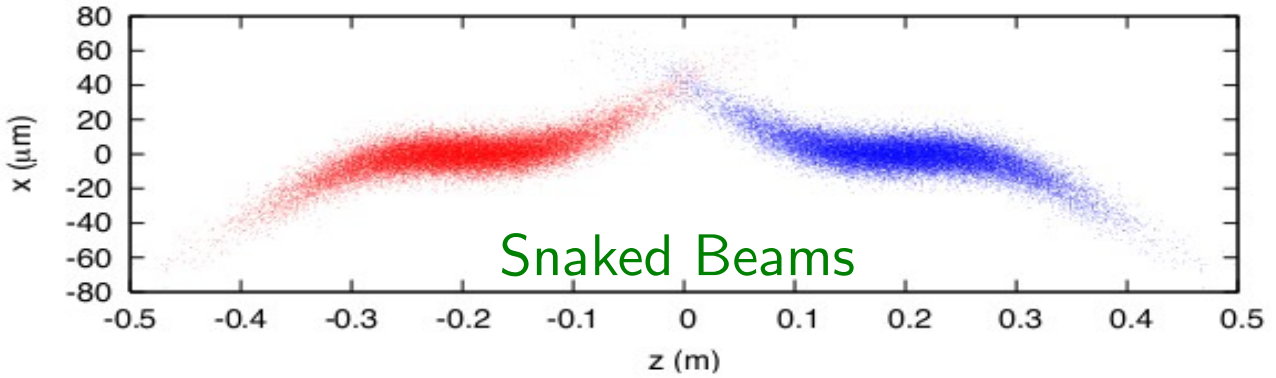
(Limited by Max Tune Shift)

YES CRABS CAN:

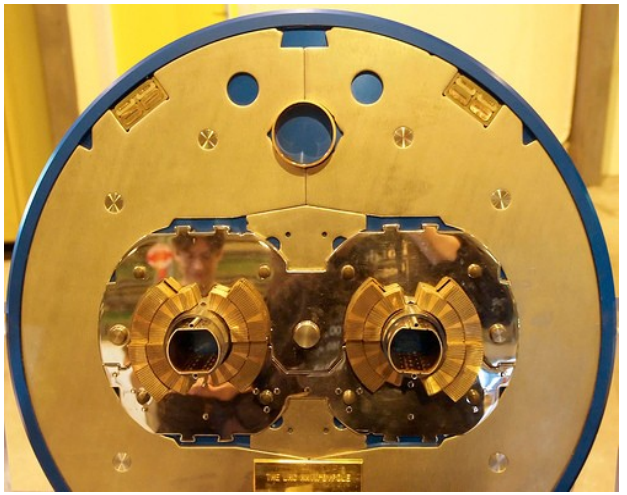
- Increase peak luminosity with increasing x-angle due LR Beam-Beam
- Increase intensities beyond head-on beam-beam limit
- Level luminosity desired by experiments (reduce Pile-up, radiation damage)

Two Main BC/Constraints

Bunch length: 7.55 cm (lowest frequency 800 MHz)



B1-to-B2 separation: 194 mm (PB 800 MHz $\sim$ 250mm radius)



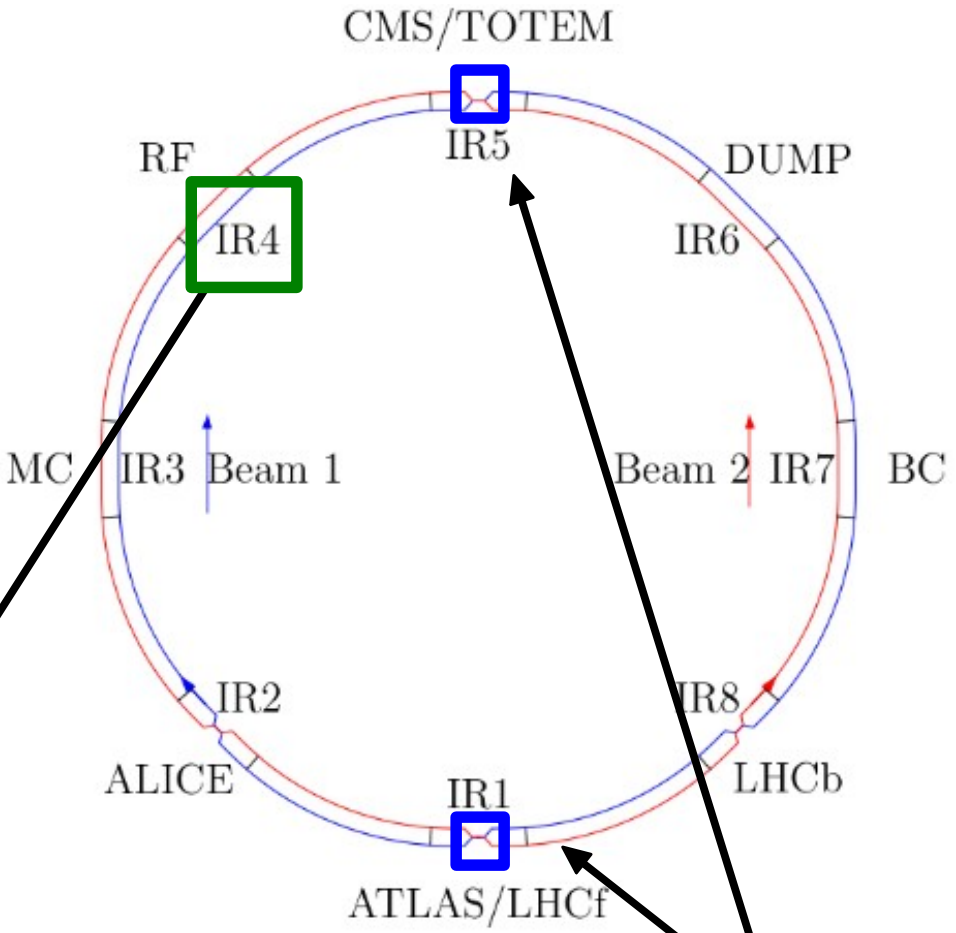
With few exceptions....
(IR4, collimation, exps)

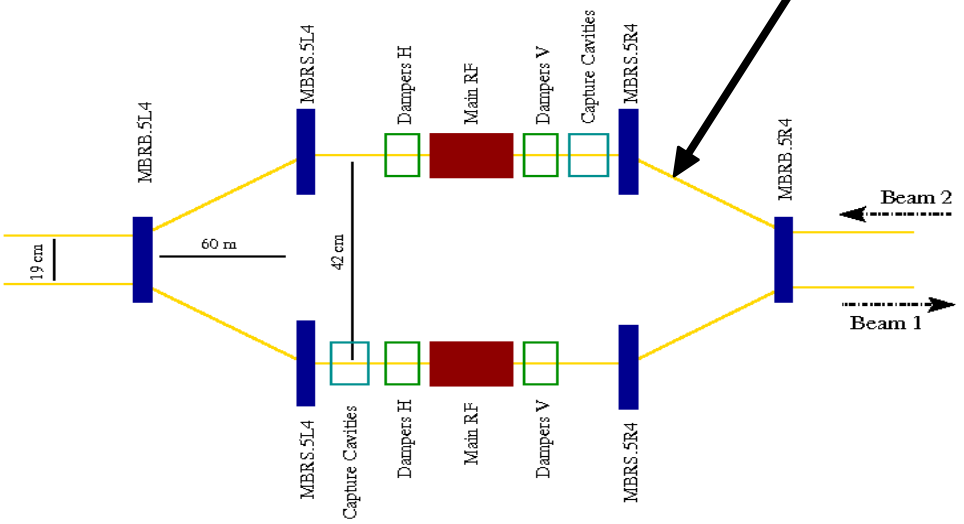
Possible Schemes

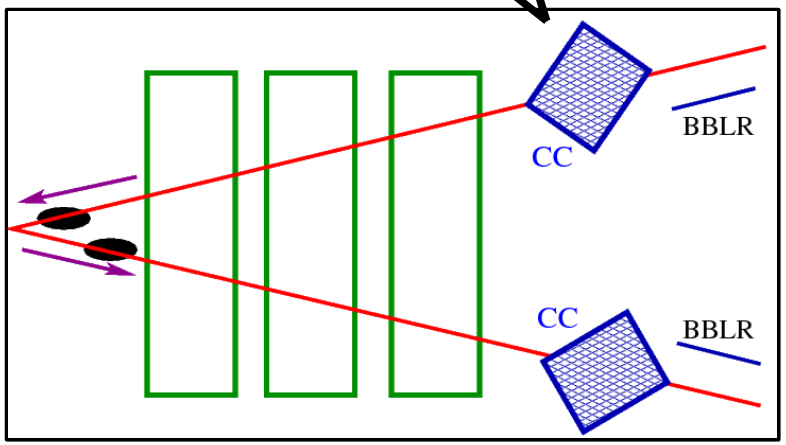
Compact Cavities: Local (IR1/IR5)

Elliptical Cavities: Only Global (IR4)

$\beta^* \leq 25\text{cm}$, σ_z 7.55cm







Aperture Specs

IR4 Specs — Global

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

IR1/5 Specs — Local

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

†2nd beam pipe inside He vessel

CERN Strategy (Prelim)

Goal: Obtain significant luminosity increase via crabs (circa 2018)

Assumption: $\beta^* \leq 25$cm, machine protection validated

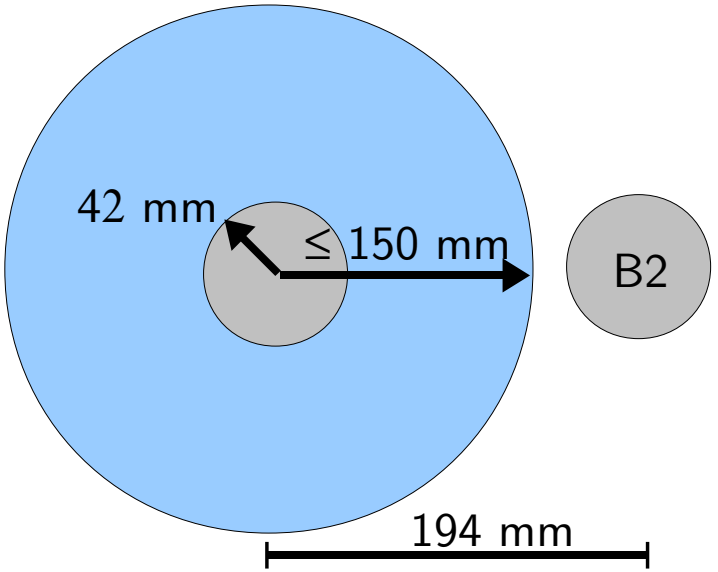
- Baseline: Develop compact cavities consistent with local option
    - 194 mm beam-to-beam separation, 400-800 MHz

- Alternative (parallel activity): Elliptical cavities in IR4, Global scheme
    - 420 mm beam-to-beam separation, 800 MHz

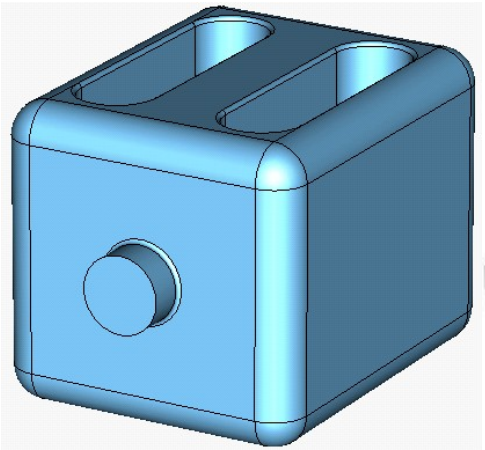
All cavities (including KEK-B) can be potentially tested in SPS for validation

LHC Needs Compact Cavities

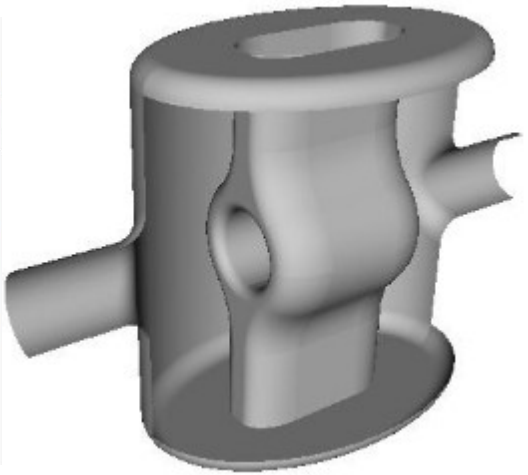
2008-2010



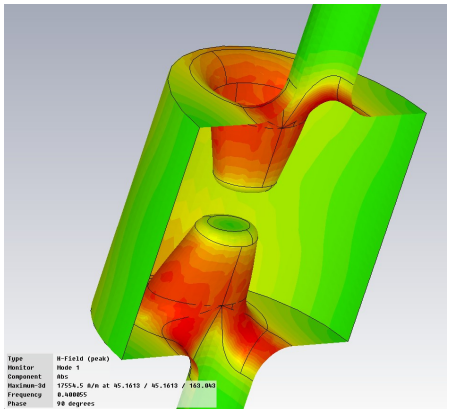
HWDR, JLAB,OD



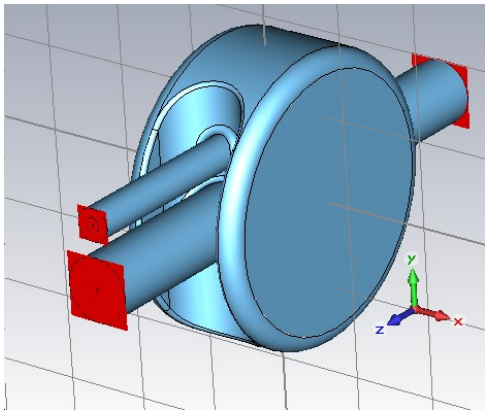
HWSR, SLAC-LARP



DR, UK, TechX



Kota, KEK



Compact cavities aiming at small footprint & 400 MHz, 3-8 MV/cavity

Performance Chart

Kick Voltage: 5 MV, 400 MHz

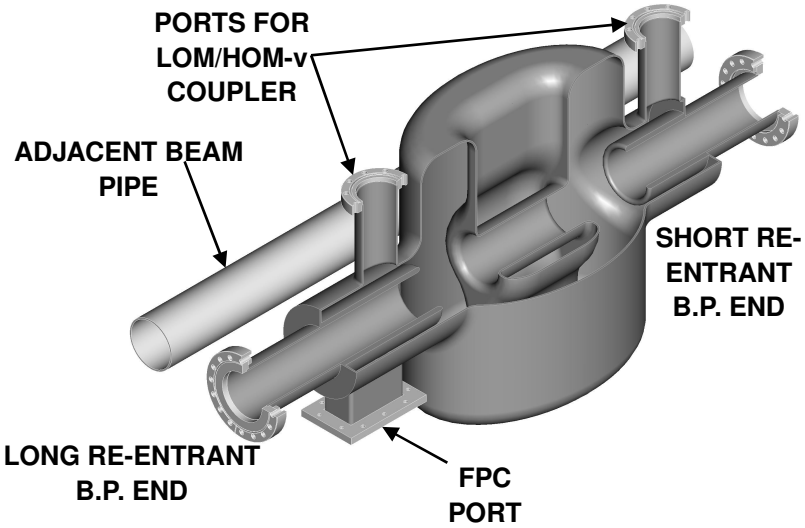
		HWDR (J. Delayen)	HWSR (Z. Li)	4-Rod (G. Burt)	Rotated Pillbox (N. Kota)
Geometrical	Cavity Radius [mm]	200	140	150	150
	Cavity Height [mm]	382	194	169	668
	Beam Pipe [mm]	50	45	45	75
RF	Peak E-Field	29	65	103	85
	Peak B-Field	94	135	113	328
	R_T/Q	319	275	667(?)	-

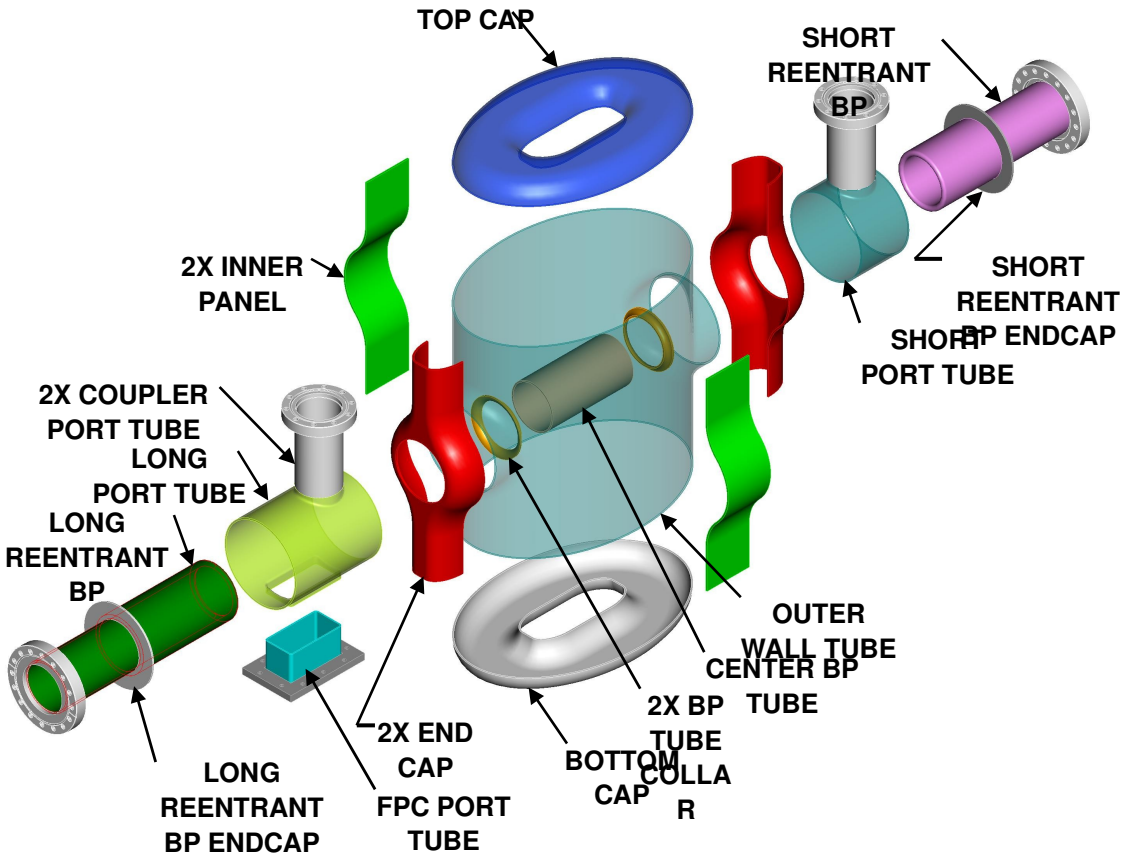
†Exact voltage depends on cavity placement & optics

†Cavity parameters are evolving

Ex: Compact Cav R&D (LARP-AES)

- Cavity engineering (mechanical & thermal analysis), tuning system
- Detailed multipacting analysis of cavity & couplers
- Cavity fabrication, He-vessel, surface treatment & assembly
- Cavity testing (2K/4K), instrumentation & peak field validation





[†]Courtesy AES

Beam Studies

Machine protection

- Approx 200 interlock systems
- Best/worst case scenario: Detection - 40μs (½ turn), response - 3 turns
- Specifications of crab cavity RF & feedback to ensure safe operation

Collimation efficiency & hierarchy (Y. Sun et al.)

- Additional 0.5σ aperture, suppression of synchro-betatron resonances
- Hierarchy preserved (primary, secondary, tertiary)

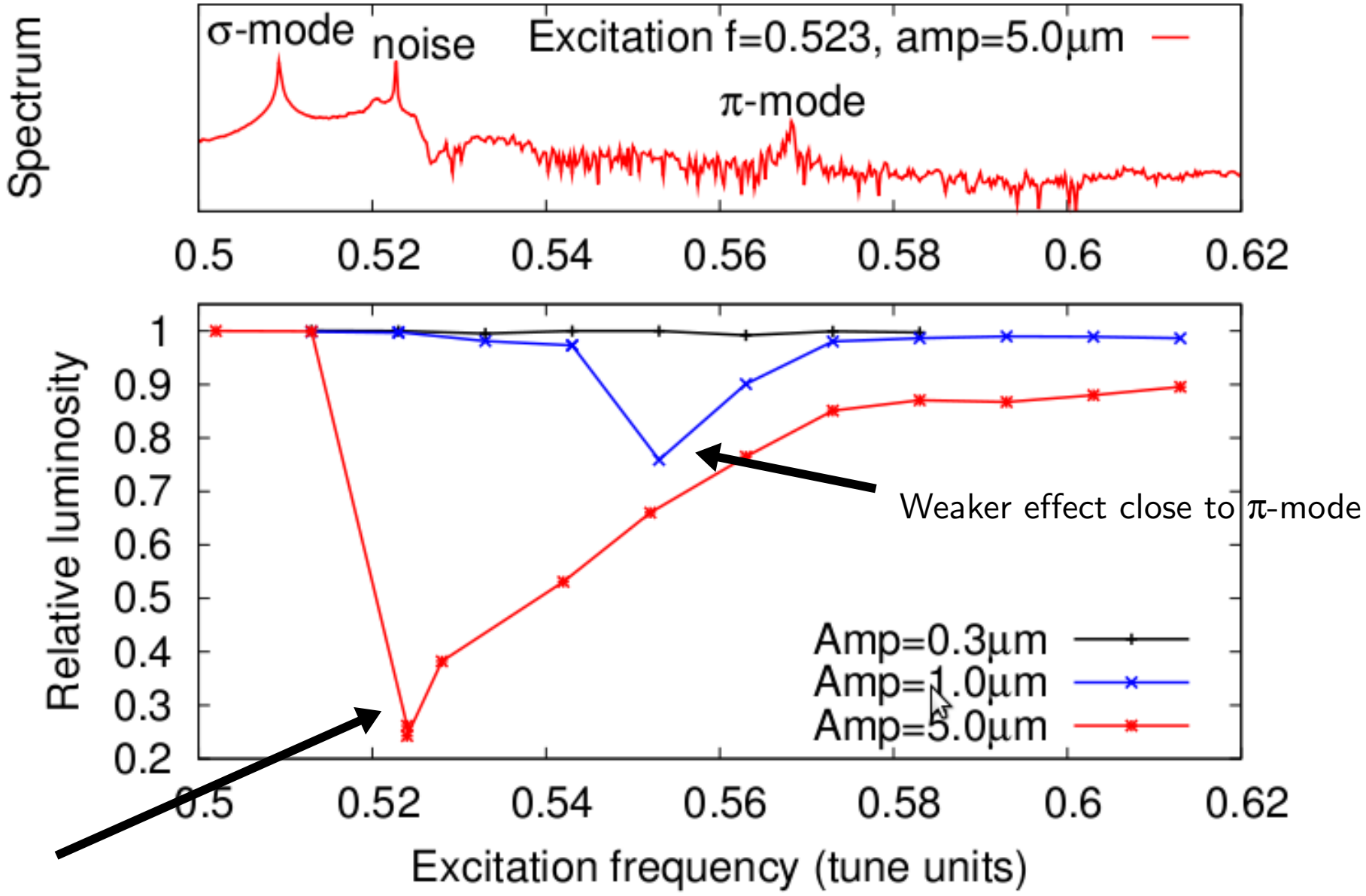
Crab cavity induced noise, Beam-Beam (KEK-B)

- Modulated noise (measured, 30 Hz - 32 kHz)
- BB simulations: Weak-strong $\leq 0.1\sigma$, Strong-strong BB $\leq 0.02\sigma.(\tau)$

Additional machine impedance

- Longitudinal: ~60 kΩ nominal, ~20 kΩ upgrade
- Transverse: ~2.5 MΩ/m nominal, ~0.8 MΩ/m upgrade (Norm - $\beta/\langle\beta\rangle$)
- Damping: $Q_{ext} \sim 10^2 - 10^3$ (depending on R/Q)

Noise Exps, KEK-B



Strong effect close to σ-mode

R. Tomas et al., 2008

OP Scenarios

- Commissioning
  - Installation, cryogenics, RF commissioning, low intensity tests
- Injection/Ramp
  - Cavity detuned (~5 kHz) & damped
  - "Zero voltage", injection optics
- Top energy
  - Cavity re-tuning & adiabatic voltage ramping (9-90 ms)
  - Crab-β un-squeeze/squeeze
  - Anti-crab → fully crabbed for maximum lumi-gain

Integrated luminosities:

$N_b = 1.7 \times 10^{11}$, $\beta^* = 0.25$ 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)

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

$\{E, {}^{max}\beta_{crab}\}$	3 TeV	5 TeV	7 TeV	
			Peak Lumi	Int Lumi/yr
$\beta^* = 25$ cm	$\varepsilon\downarrow$, $N_b\uparrow$		63%	22%
$\beta^* = 30$ cm			40%	19%
$\beta^* = 55$ cm			10%	-

Int Luminosities: G. Sterbini

SPS Tests, WG

No real showstoppers were identified.

- Crab Cavity will be used in KEKB until June 2010 (at the earliest)
- An estimate that the crab cavity could only be used/tested in the SPS in 2012.

The best location in SPS is at COLDEX.41737 (4020 m, LSS4)

- Big cavern & available cryogenics, A first time estimate to remove COLDEX is ~ 2-3 weeks.
- A first cost estimate to change the PLC and for the supervision of the old cryogenics system (TCF20) is ~ 200 kCHF.

Collimation :With the proposition, the phase advances

- 1st (SLAC) collimator sees no effect & full crab effect at 2nd second (CERN) collimator
- Integrated BPM (bunch by bunch measurements ?)

Integration

- Laser scanning of COLDEX area, mostly done, removal of COLDEX ~2-3 weeks, cryogenics refurbish ~ 200kCHF
- IOTs (1-2), 400 kCHF & space requirements
- After tuning at KEK-B, re-assembly and test with RF & cryogenics at SM18?

SPS beam tests

- 2010 MDs to check lifetime @55GeV coast with 2μm norm emittance
- 100 ns bunch spacing – 511 MHz (spaces 4 x 25)

Machine protection

- Primary goal is beam measurement (No implementation of interlocks, BPMs-fast & RF-slow)
- Failure scenarios (for example: measure evolution of RF phase and effect on the beam)

Crab Bypass

- Similar to COLDEX to move it out of the way during high intensity operation
- Technical details (RF connections, cryogenics, size, weight etc...) needs to be sorted out

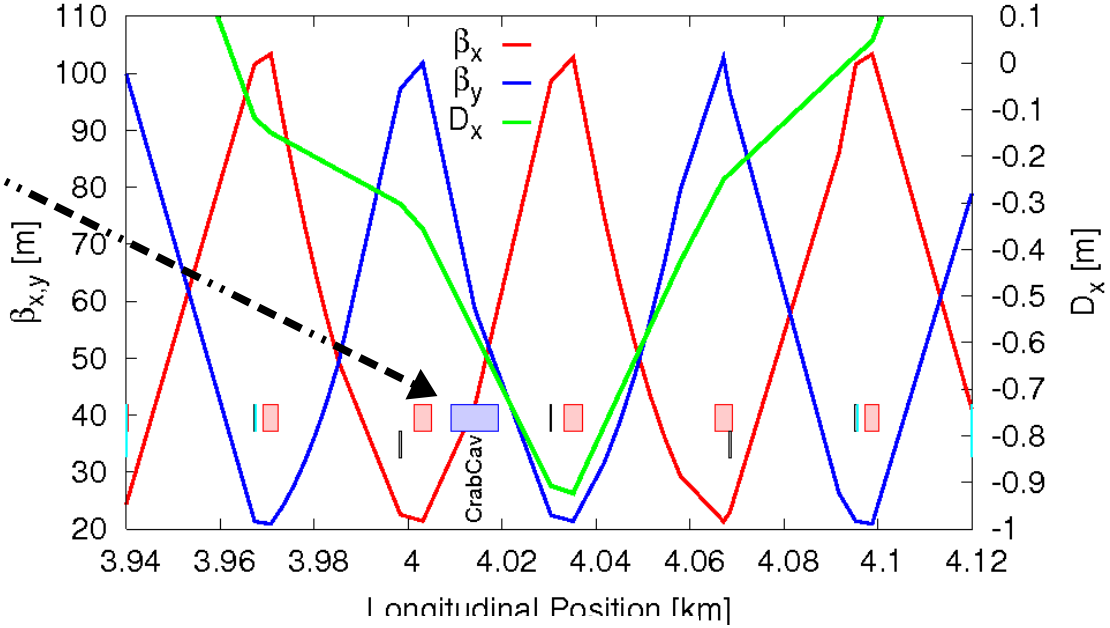
Courtesy E. Metral

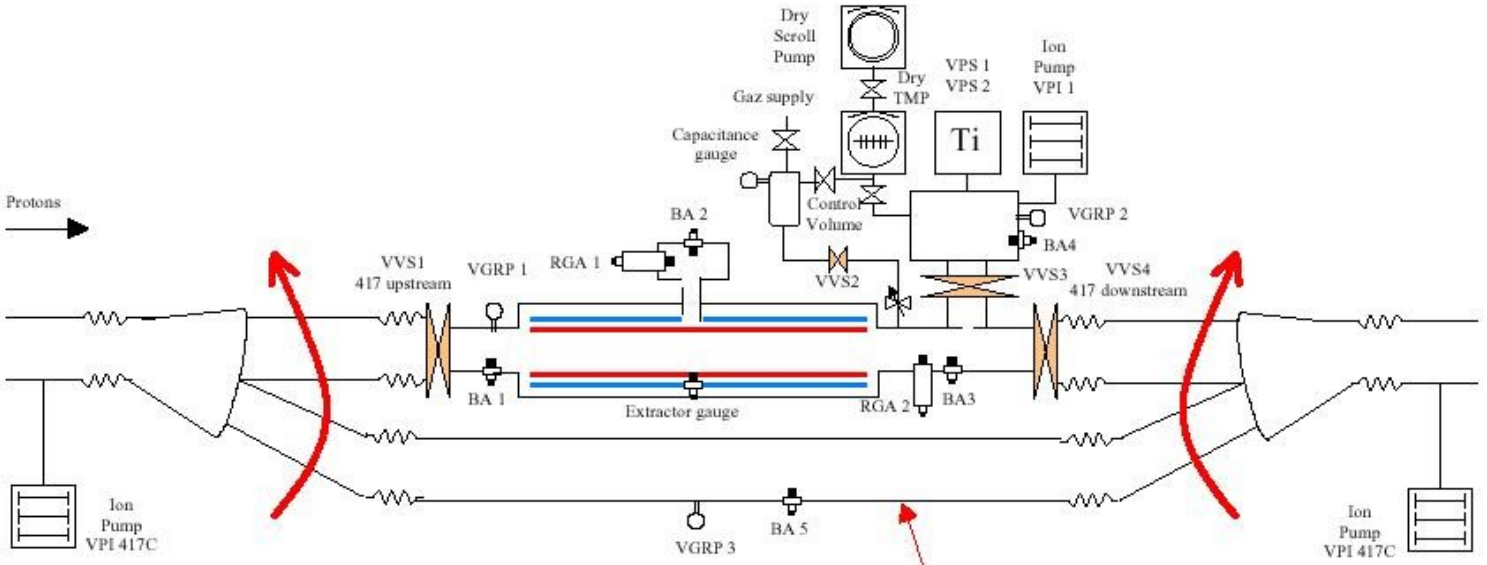
Coldex Location

Longitudinal Position: 4009 m +/- 5m

Total length: 10.72 m

βx, βy: 30.3m, 76.8m



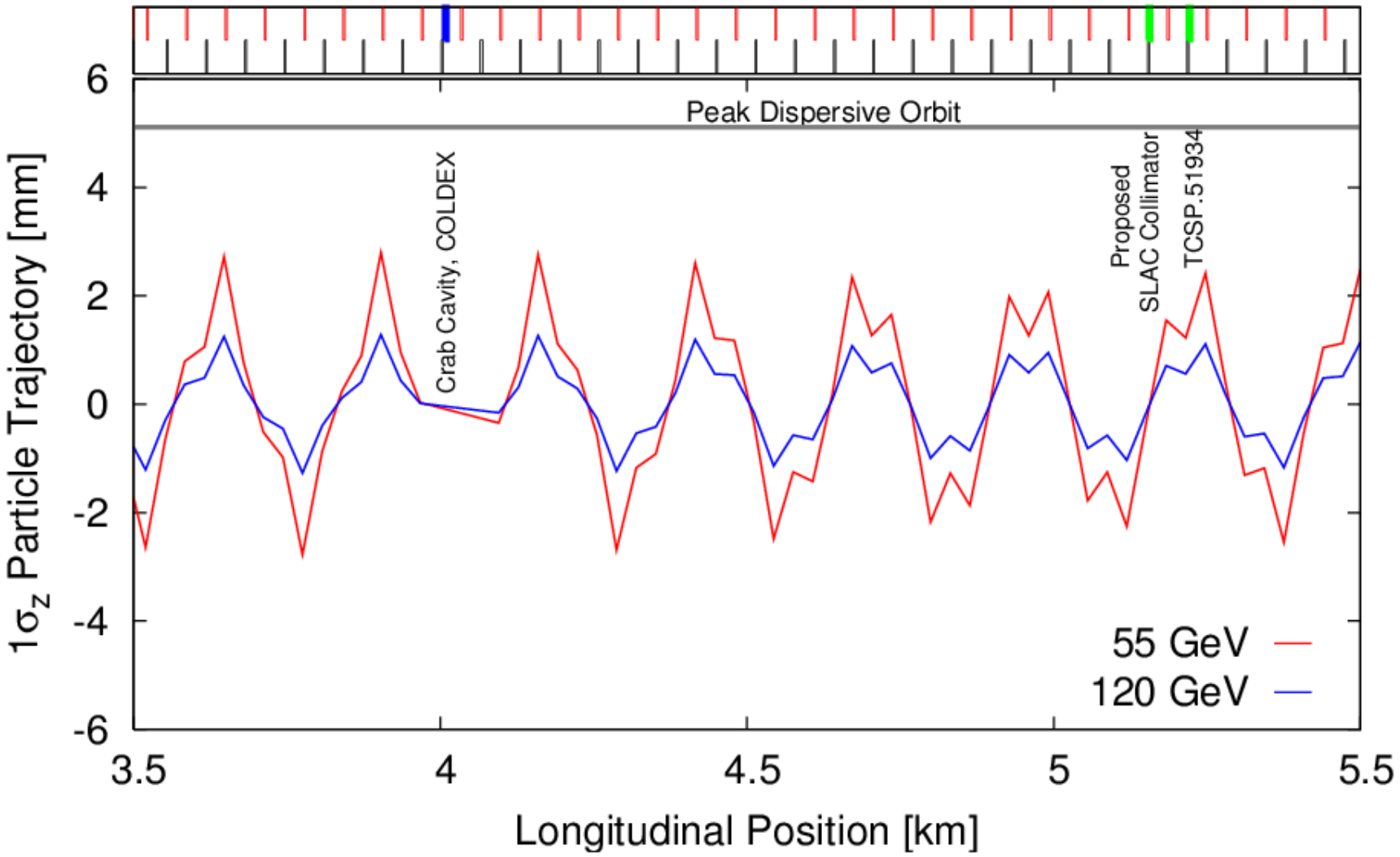


Default vacuum chamber

Orbits in SPS

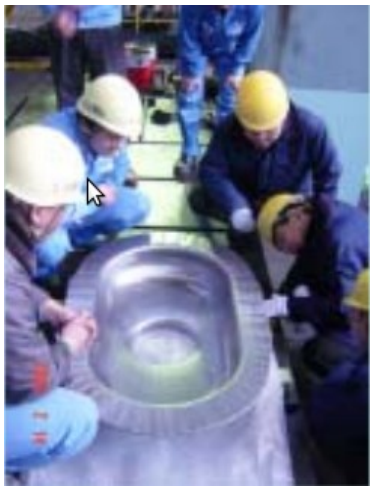
The intra-bunch orbit deviation in the limit of SPS BPMs (± 1.5 - 3 mm)

Head-tail monitor can detect sub-millimeter variations

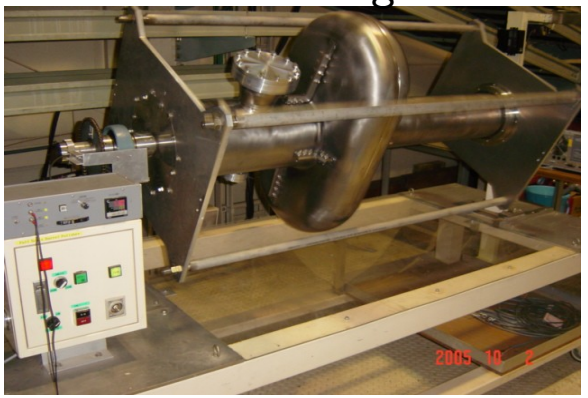


KEK-B Cavities

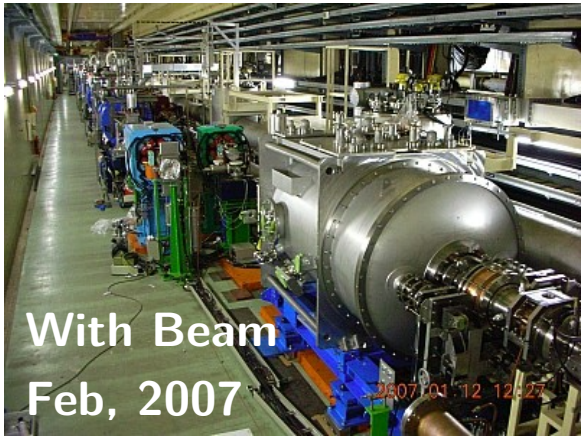
Fabrication



Processing



Assembly



RF & beam commissioning with low currents: 2-3 weeks

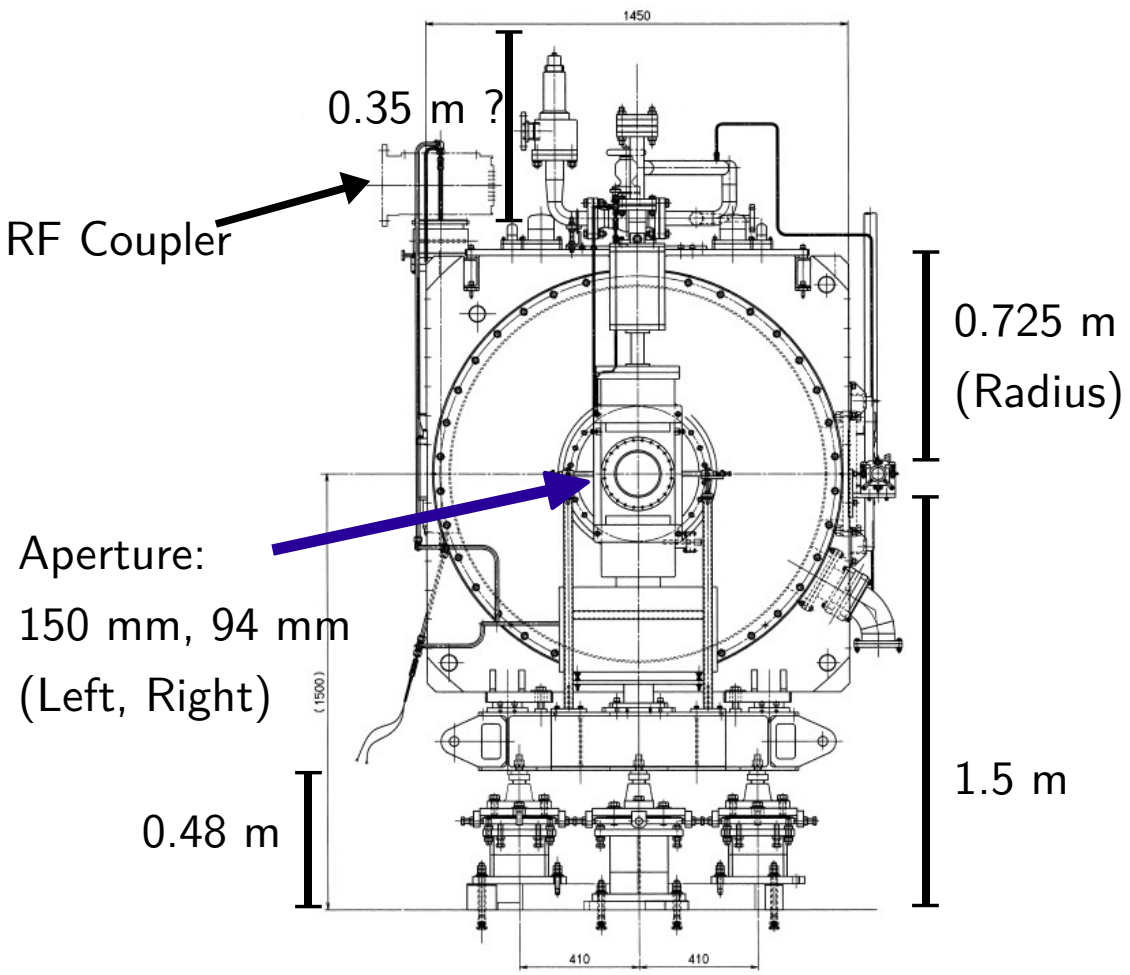
High current operation: 4-5 months

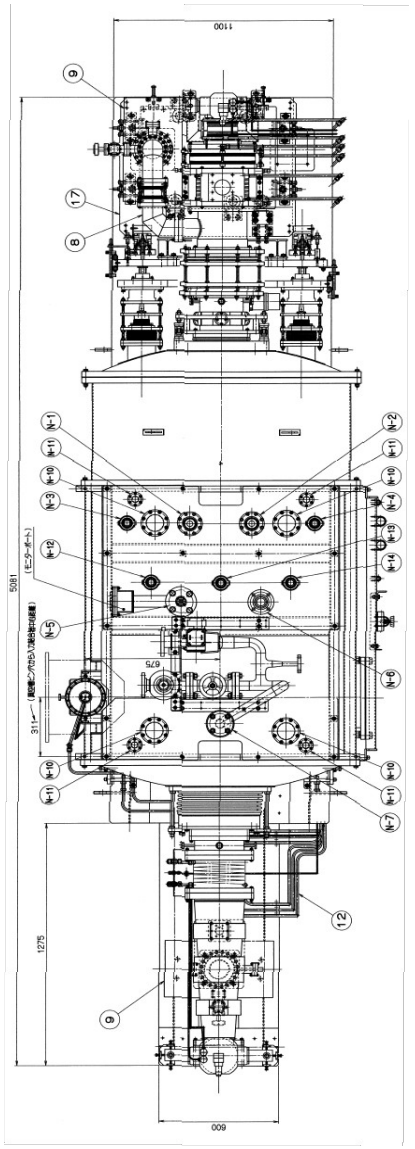
World record luminosity: ~2 yrs (aperture & chromatic coupling)

Courtesy KEK-B

KEK-B Cryostat

Weight: 5830.5 kg





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

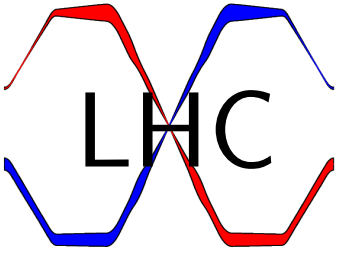
Operational voltage: {HER, LER} - 1.4 MV, 0.9 MV

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

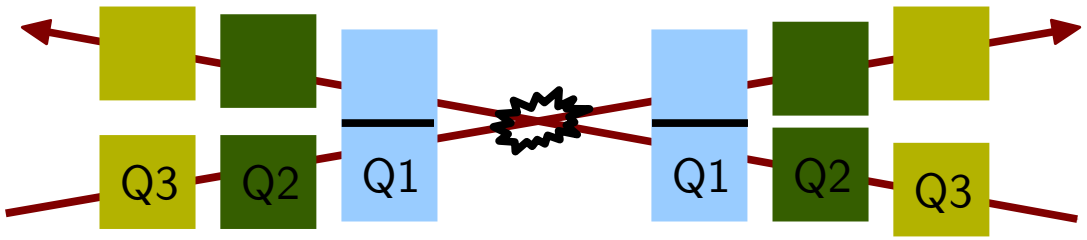
Courtesy KEK-B

Conclusions

- Key motivation: luminosity gain & leveling
  - R&D of compact cavities compatible with LHC environment
  - Benefits extending to LHeC and other deflecting cavity applications
- KEK-B experience vital for LHC
  - Successful commissioning and operation with high currents (ξ: 0.09)
  - Noise experiments, OP scenarios for LHC
- SPS tests
  - Validate differences between protons & electrons
  - KEK-B or LHC cavity (2012) in SPS for beam testing
- Safety
  - Machine protection needs detailed study to evaluate failure modes
  - Appropriate feedback to guarantee MP at ultimate intensities



A1: Possible Future



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

+

Flat Beams ?

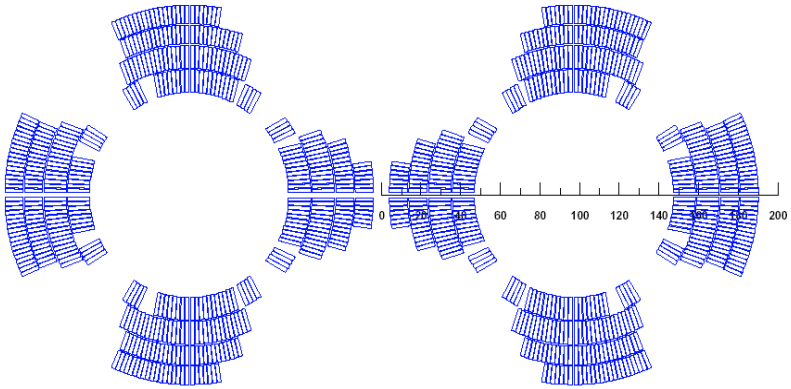
No parasitic collisions

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/mm^2



Two types of quadrant coils address the field coupling issue.

LAPAC Review
June 2004, Fermilab

Vadim Kashikhin

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R. Gupta, BNL & Crab Team