# LHC Crab Cavities

Rama Calaga
LARP CM14, April 26-28, 2010

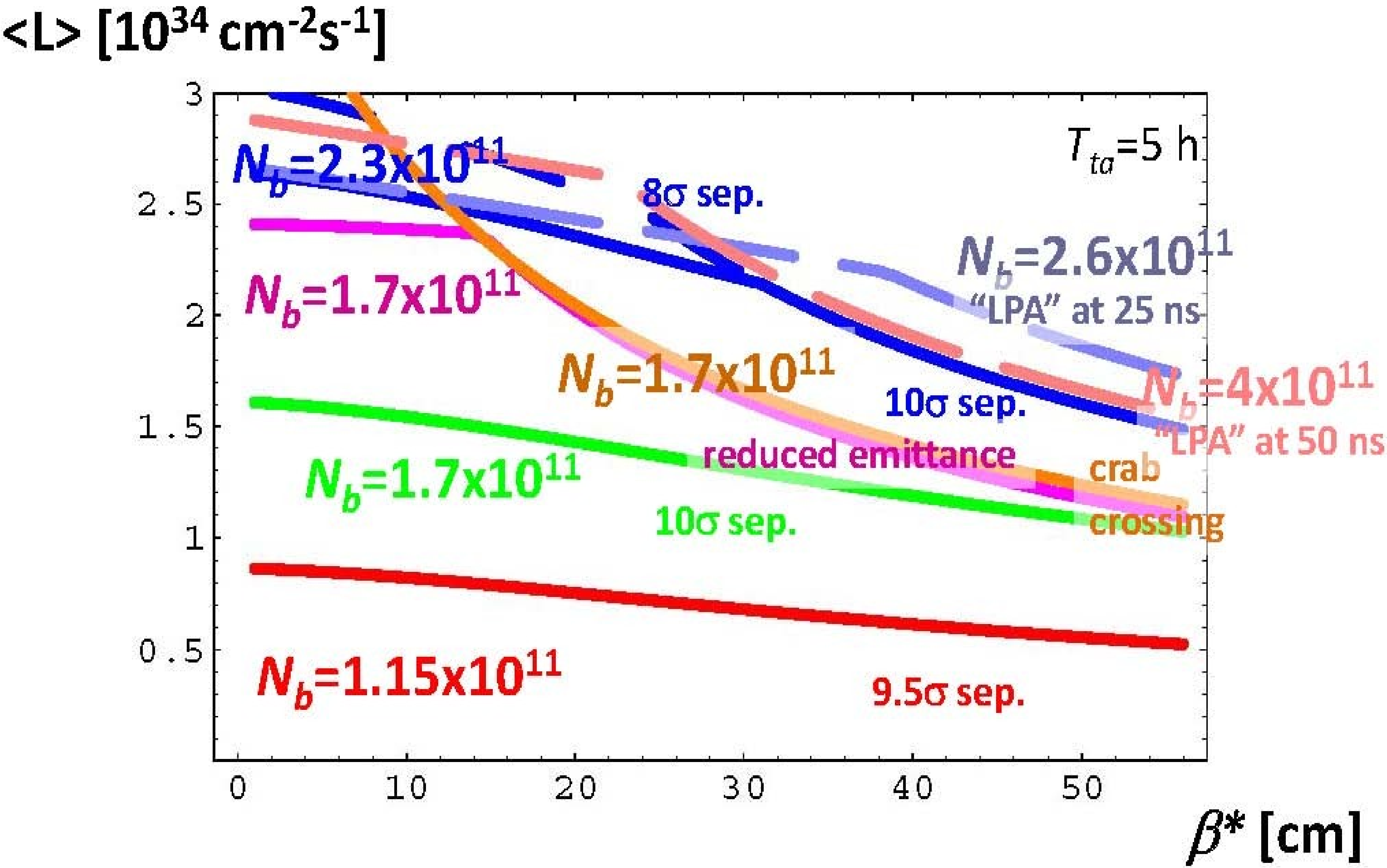
LHC

- Post LHC-CC09 & Chamonix
- R&D Activities
- SPS, a first validation step ?

Ack: R. De-Maria, 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

# Different Upgrade Benefits




Courtesy F. Zimmermann, Chamonix10

†Nominal LHC (55 cm)

# Interpreting Zimmermann

Upgrade scenarios aim at x3-10 Lumi increase

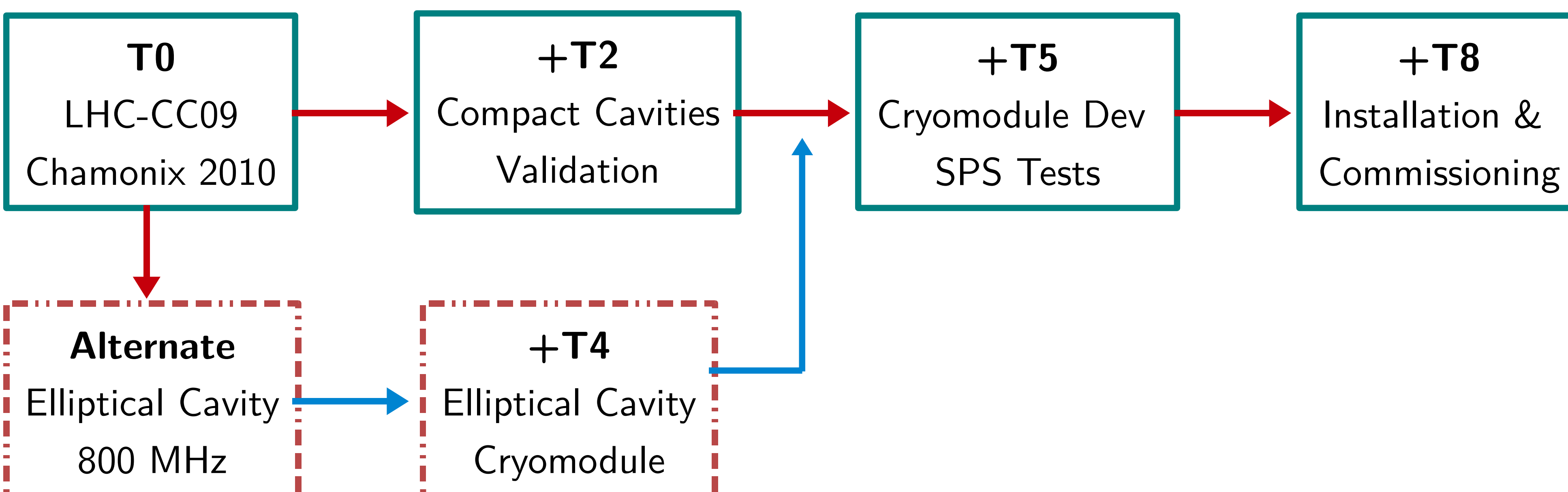
- Bunch Intensity: $1.1 \times 10^{11} \rightarrow 1.7\text{-}2.3 \times 10^{11}$
- Compensate Piwinski Angle ($\beta^*$ 55cm $\rightarrow$ 25cm or smaller)
- Reduce Emittance: 3.5mm $\rightarrow$ 1 mm (new injector chain)

Bunch intensity increase more beneficial

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

# New Roadmap, LHC-CC09/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



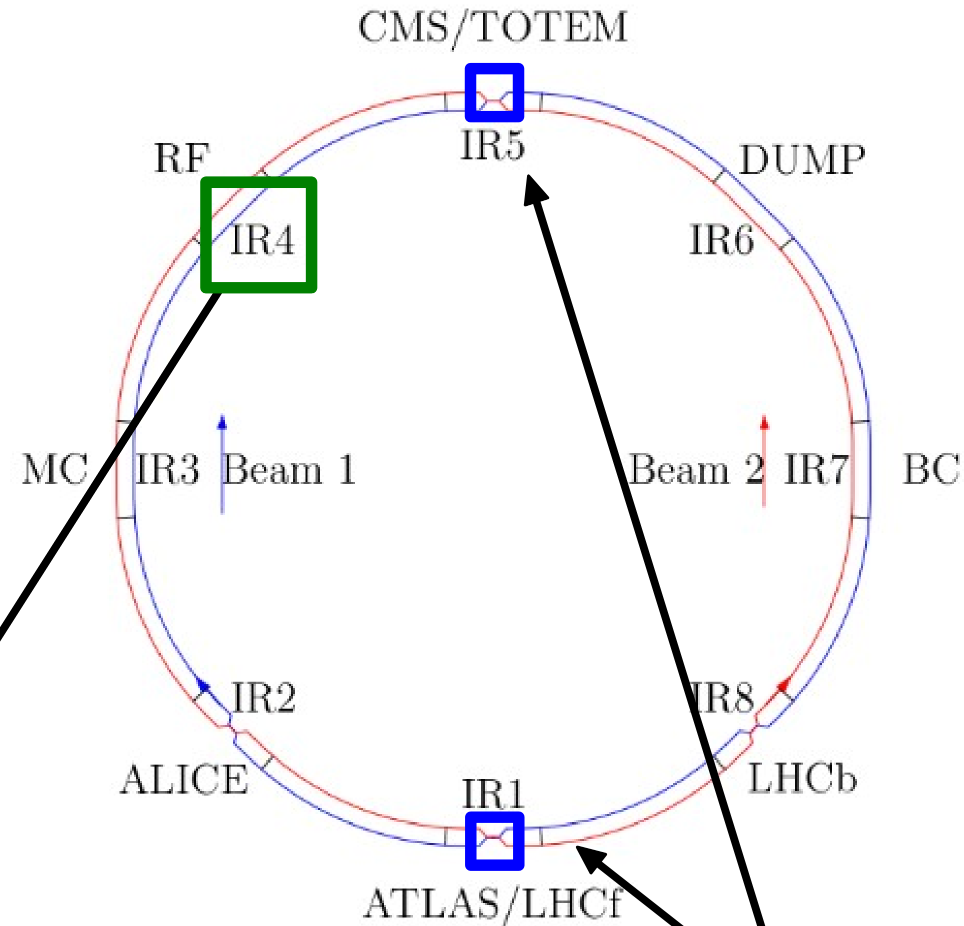

†Time scales approximate

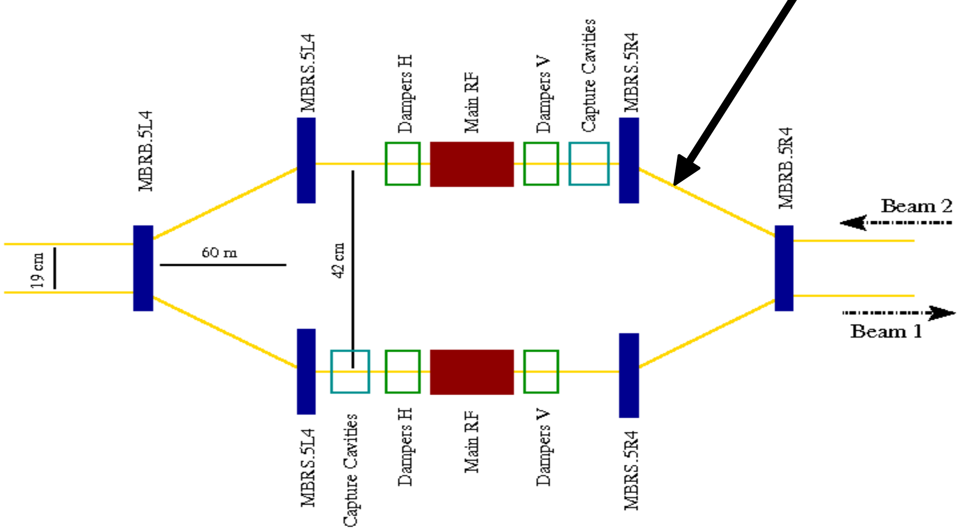
# Possible Schemes

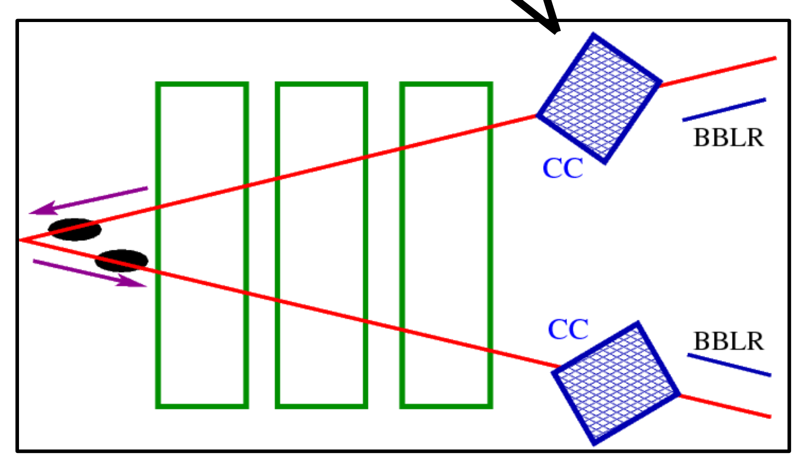
Compact Cavities: Local (IR1/IR5)

Elliptical Cavities: Only Global (IR4)

$\beta^* \leq 25$cm, $\sigma_z$ 7.55cm



# CERN Strategy (Prelim)

E. Ciapala, E. Jensen

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

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

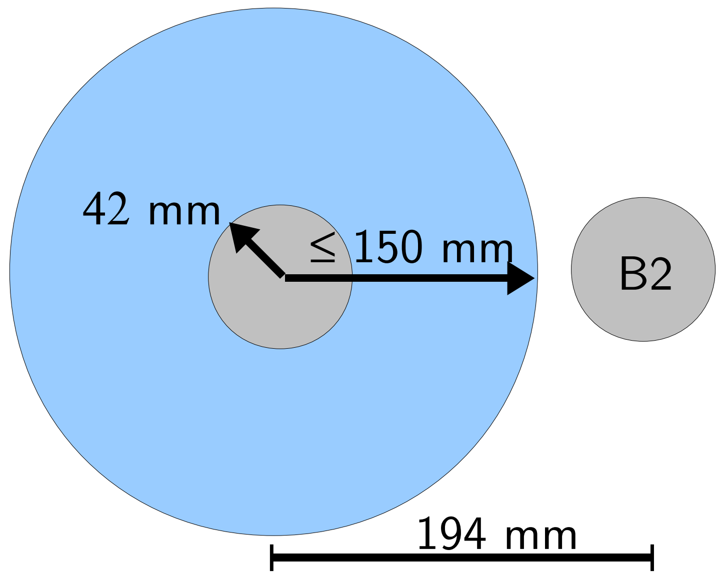
- Baseline: Develop compact cavities consistent with local option
  - 194 mm beam-to-beam separation, 400 MHz

- Alternative (background activity): Elliptical cavities for IR4 global scheme
  - 420 mm beam-to-beam separation, 800 MHz

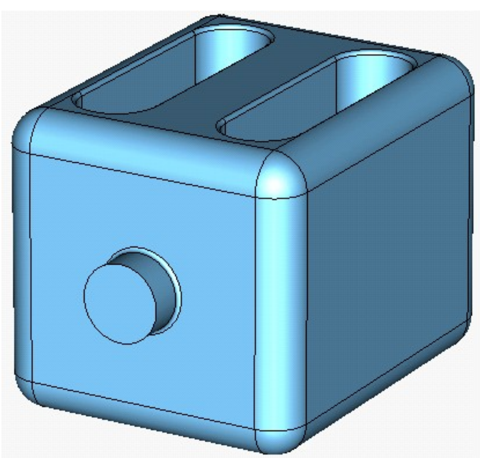
All cavities (including KEK-B) can be potentially tested in SPS for validation

# Cavities with Compact Footprint

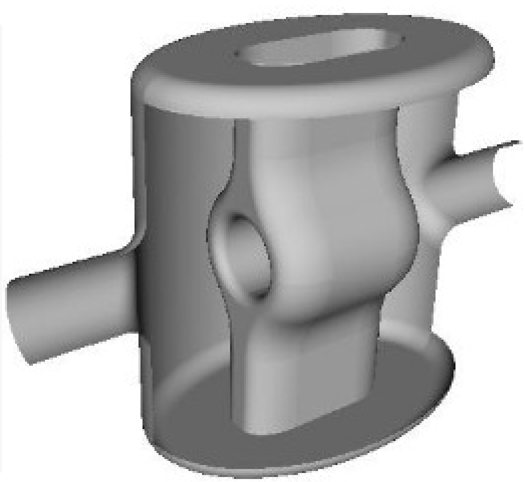
2008-2010



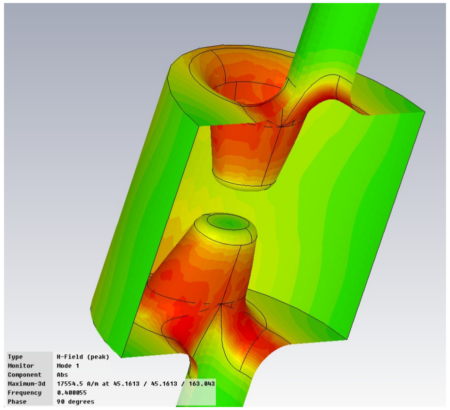

HWDR, JLAB,OD



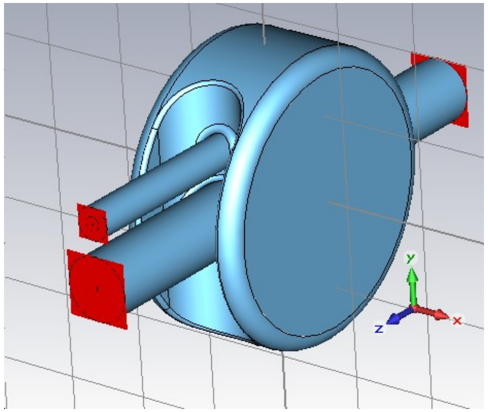
HWSR, SLAC-LARP



DR, UK, TechX



Kota, KEK



Compact cavities aiming at small footprint & 400 MHz, 5 MV/cavity

# Performance Chart, CCC

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 | 140 | 150 |
| | Cavity Height [mm] | 382 | 194 | 230 | 668 |
| | Beam Pipe [mm] | 50 | 45 | 45 | 75 |
| RF | Peak E-Field | 29 | 65 | 62 | 85 |
| | Peak B-Field | 94 | 135 | 113 | 328 |
| | $R_T/Q$ | 319 | 275 | 800 | - |

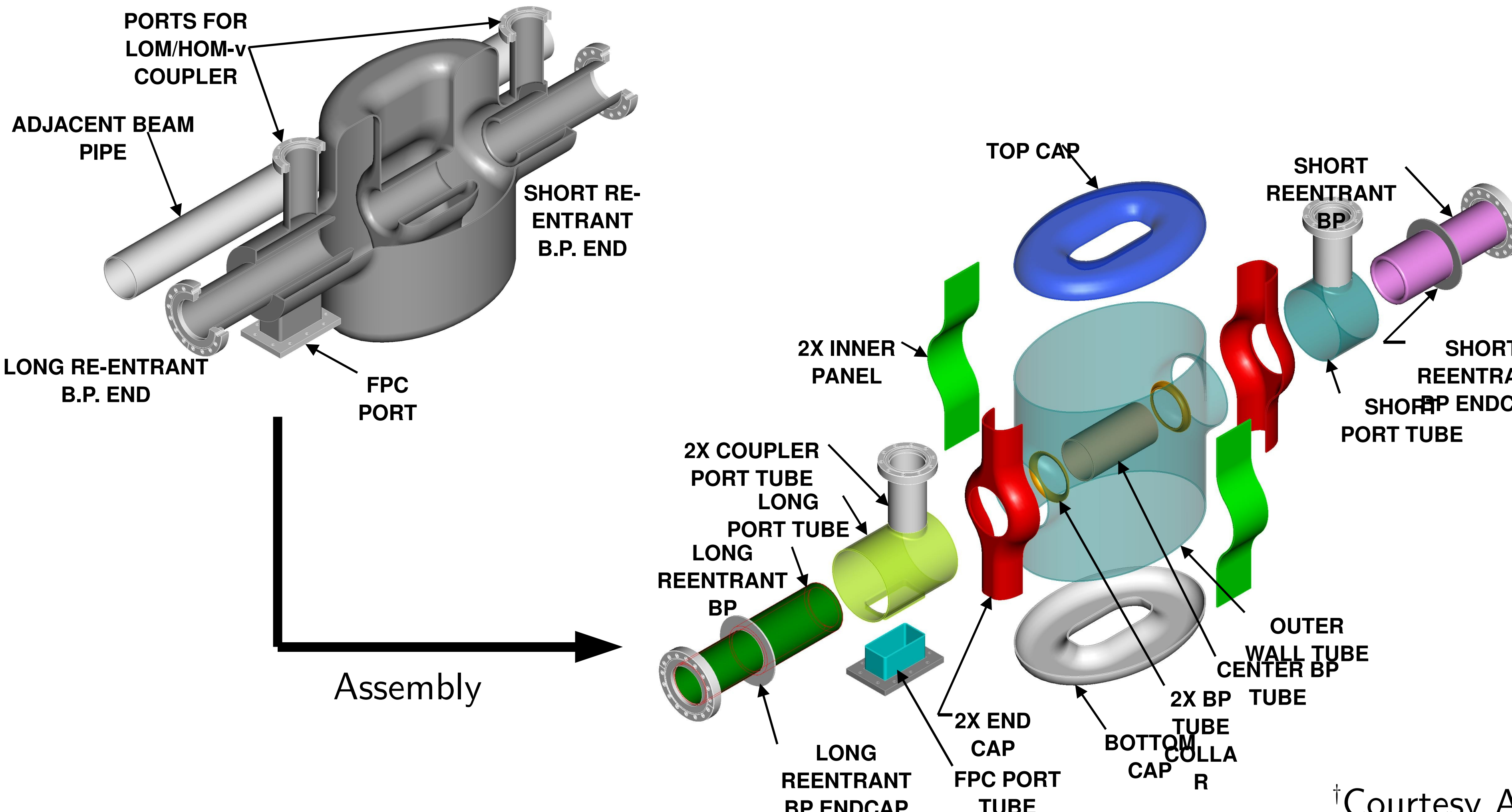
To be discussed in crab session

†Exact voltage depends on cavity placement & optics

†Cavity parameters are evolving

# Example: Comp Cav R&D (LARP-AES)

- Detailed multipacting analysis of cavity & couplers - LARP
- Cavity engineering (mechanical & thermal analysis) - AES



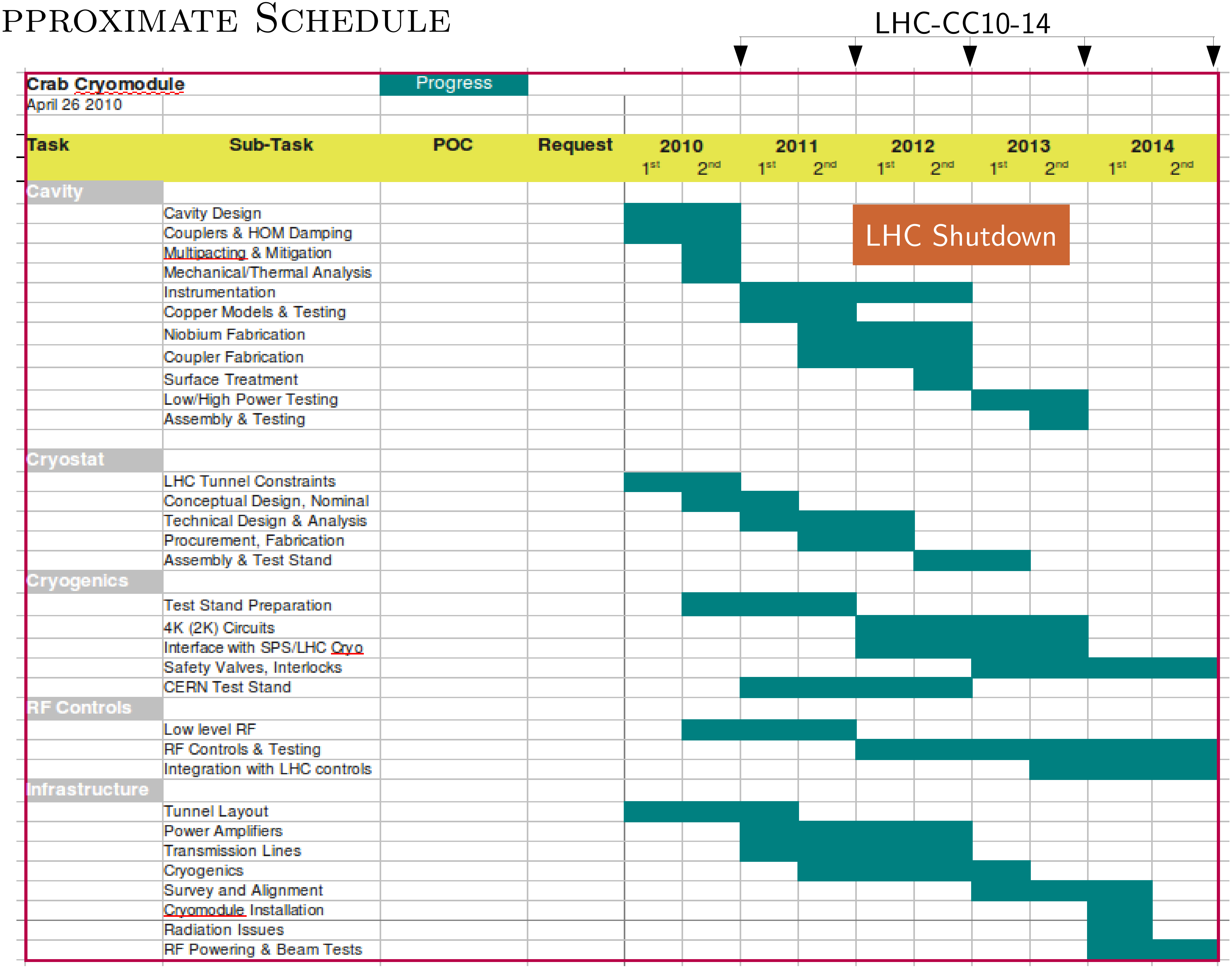

†Courtesy AES

# 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

To be discussed in crab session

# Approximate Schedule




Schedule Mainly Focused on SPS Test, LHC Installation Follows

# Simulations, Past & Present

## Machine protection (LARP, CERN)

- 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 (CERN)

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

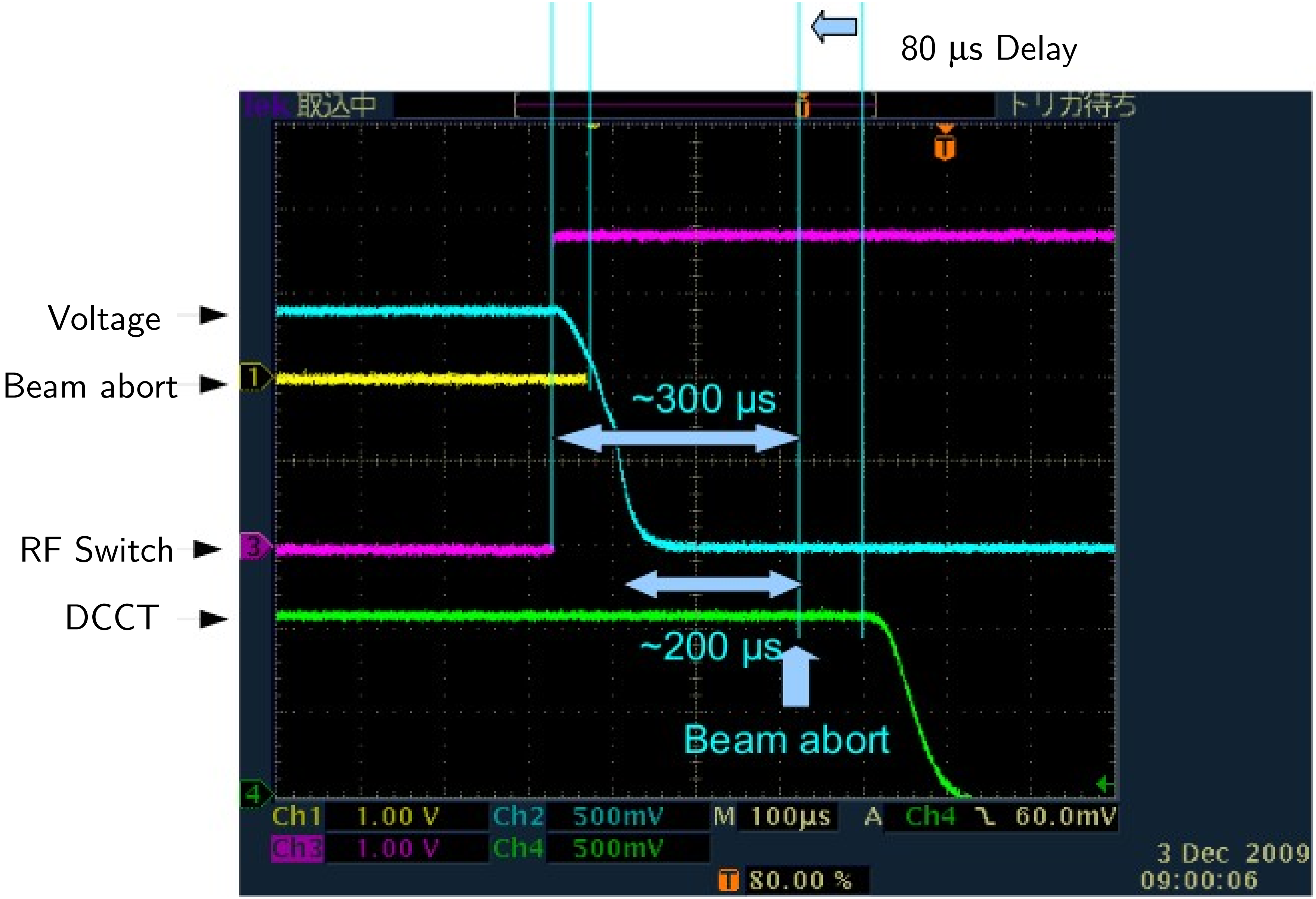
## Crab cavity induced noise, Beam-Beam (KEK-B, LARP)

- 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 (LARP, CERN)

- 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)

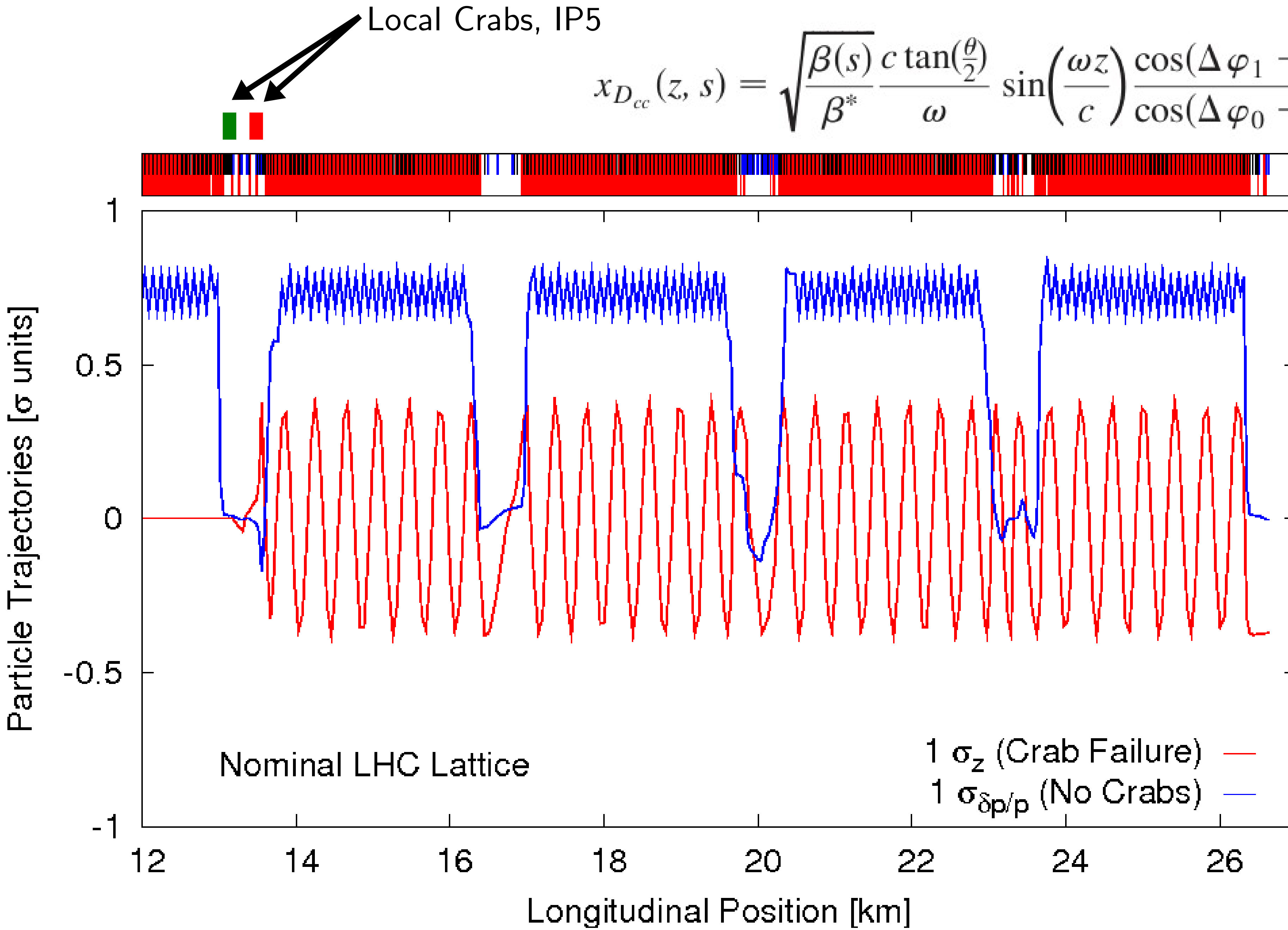
# RF Trip & Beam Abort (KEK-B)




Trip → Beam Abort in LHC time ~3 Turns

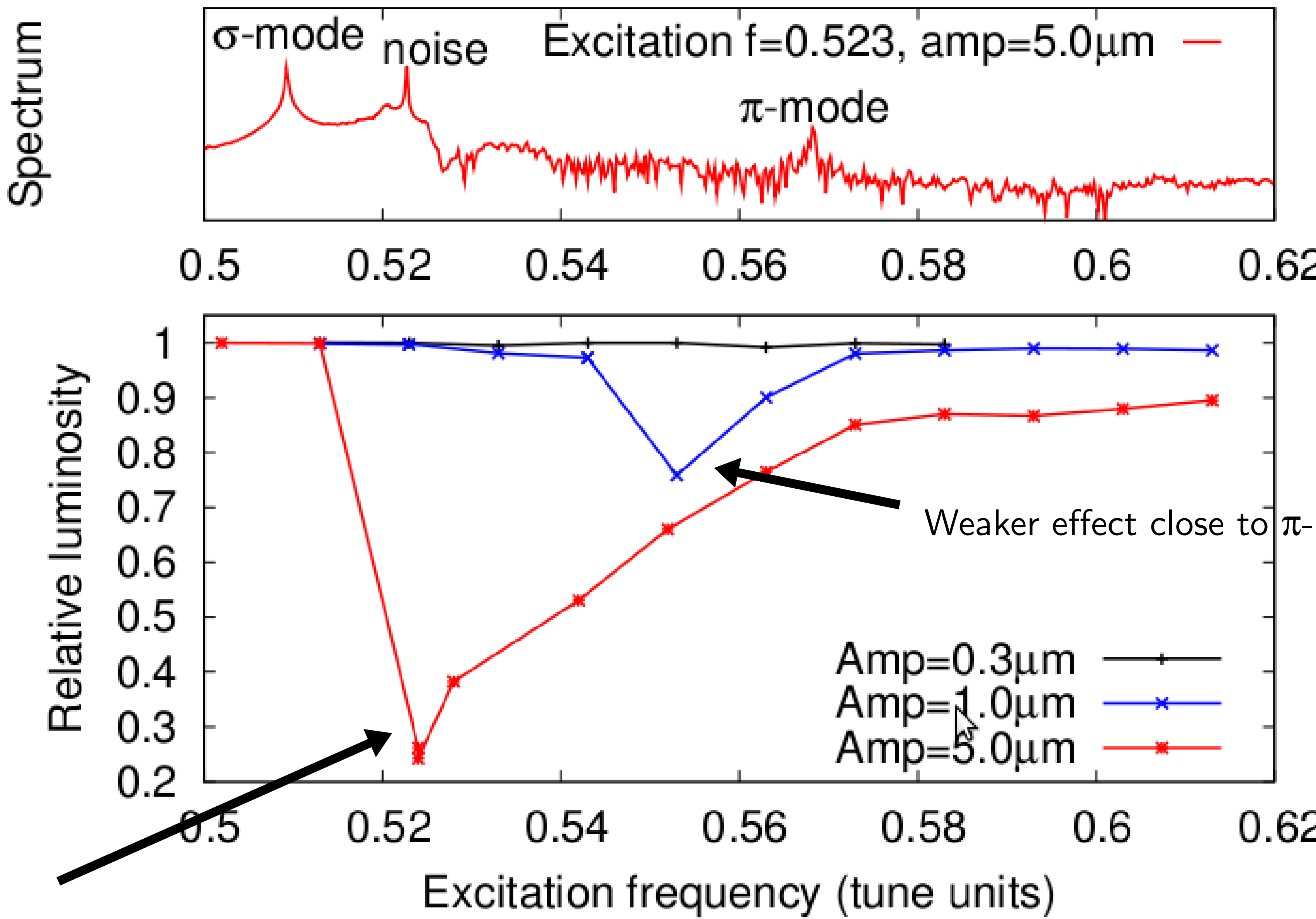
# Crab Failure, Voltage

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



# Noise Exps, KEK-B

Agreement between simulations/measurements




Weaker effect close to π-mode

Strong effect close to σ-mode

R. Tomas et al., 2008

# OP Scenarios

- Commissioning (Cryomodule Validation)
  - Installation, cryogenics, RF commissioning, low intensity tests
- Injection/Ramp (Orbit control)
  - Cavity detuned (~5 kHz) & damped
  - "Zero voltage", injection optics
- Top energy (Crabbing & leveling)
  - 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, $\beta_{cc}$: ~5 km

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

Int Luminosities: G. Sterbini

# SPS Tests, WG

Courtesy E. Metral

No real showstoppers were identified.

Earliest availability, Dec 2010, estimate SPS test date Dec 2012 – May 2013

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

Collimation with integrated instrumentation

1st (SLAC) collimator sees no effect & full crab effect at $2^{nd}$ second (CERN) collimator

Integration

Removal of COLDEX ~2-3 weeks, cryogenics refurbish ~ 200kCHF

RF Power: IOTs (1-2), 400 kCHF & space requirements

After 2 MHz tuning at KEK-B, re-assembly and test at SM18?

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

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

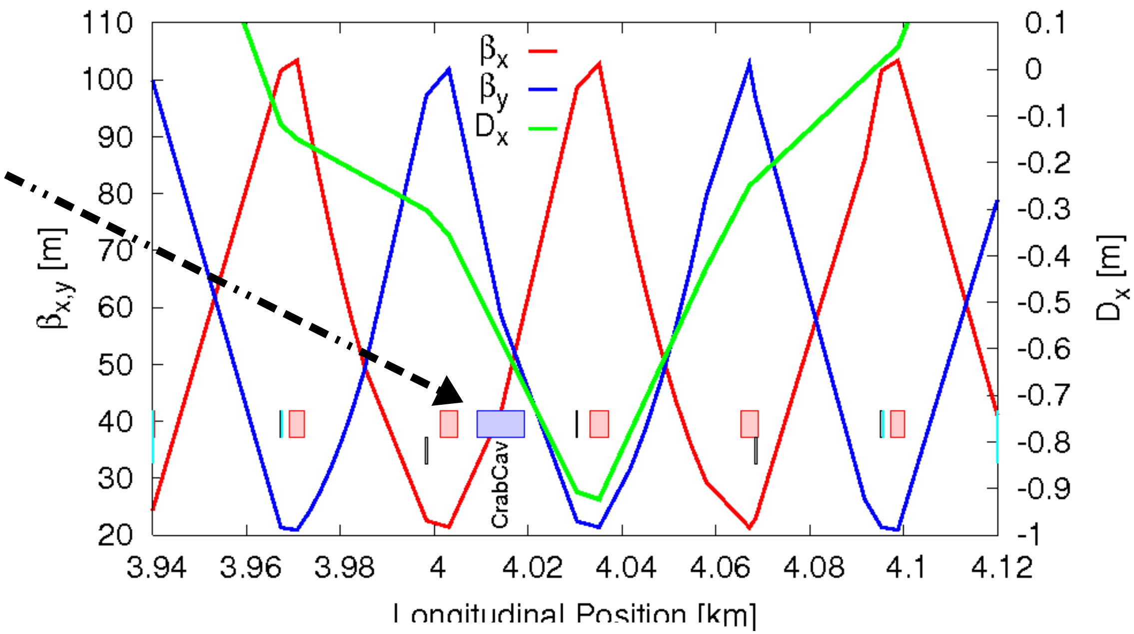
Technical details (RF connections, cryogenics, size, weight etc... ) needs to be sorted out

# Coldex Location

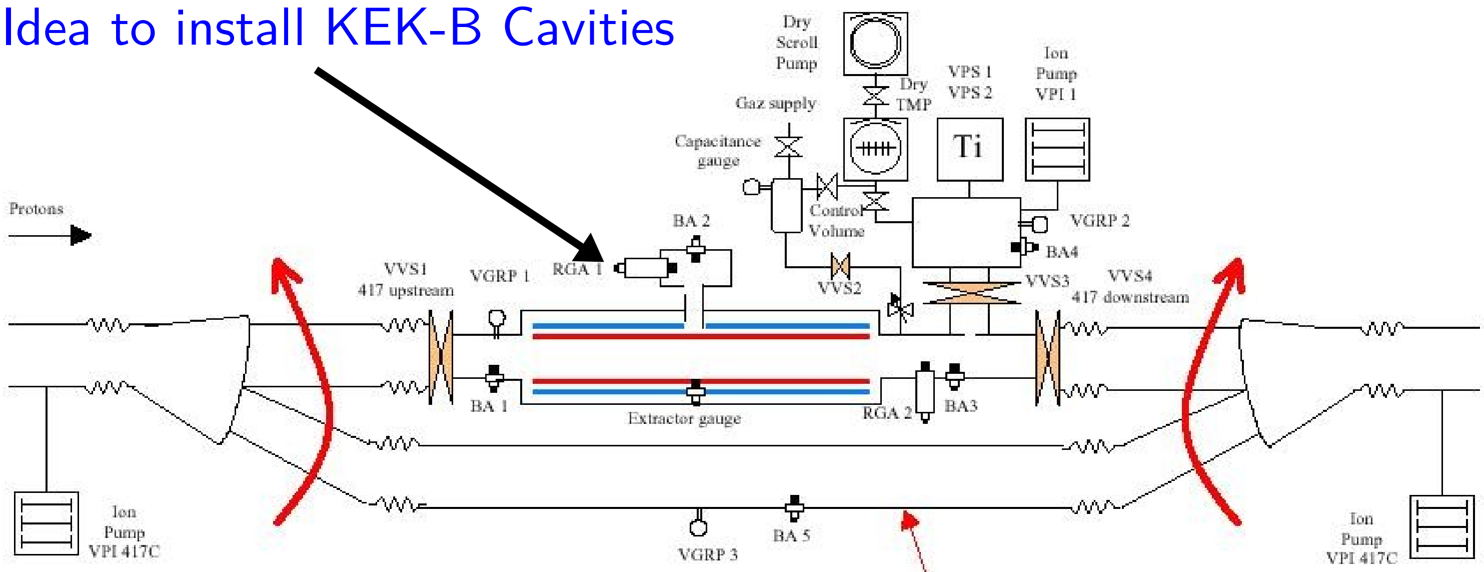
Longitudinal Position: 4009 m +/- 5m

Total length: 10.72 m

βx, βy: 30.3m, 76.8m




Idea to install KEK-B Cavities

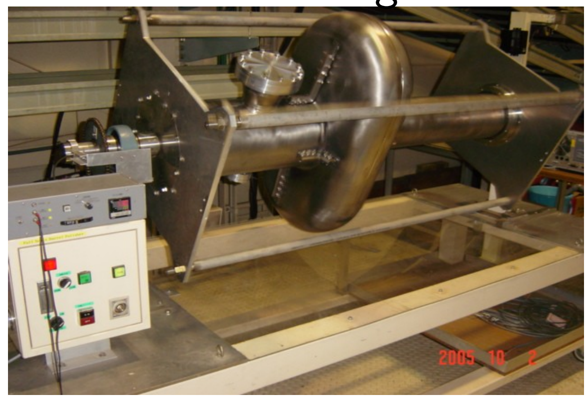



Default vacuum chamber

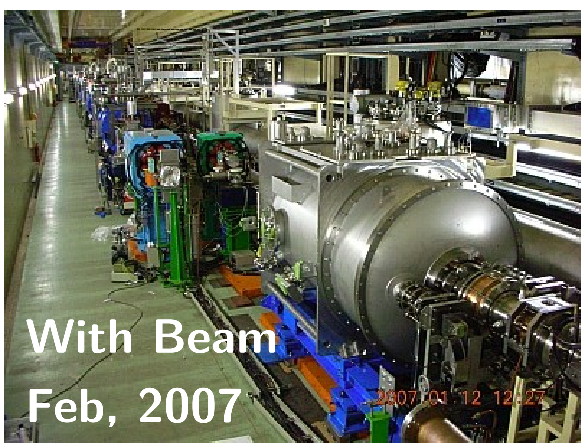
# KEK-B Cavities

Fabrication

Processing



Assembly


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

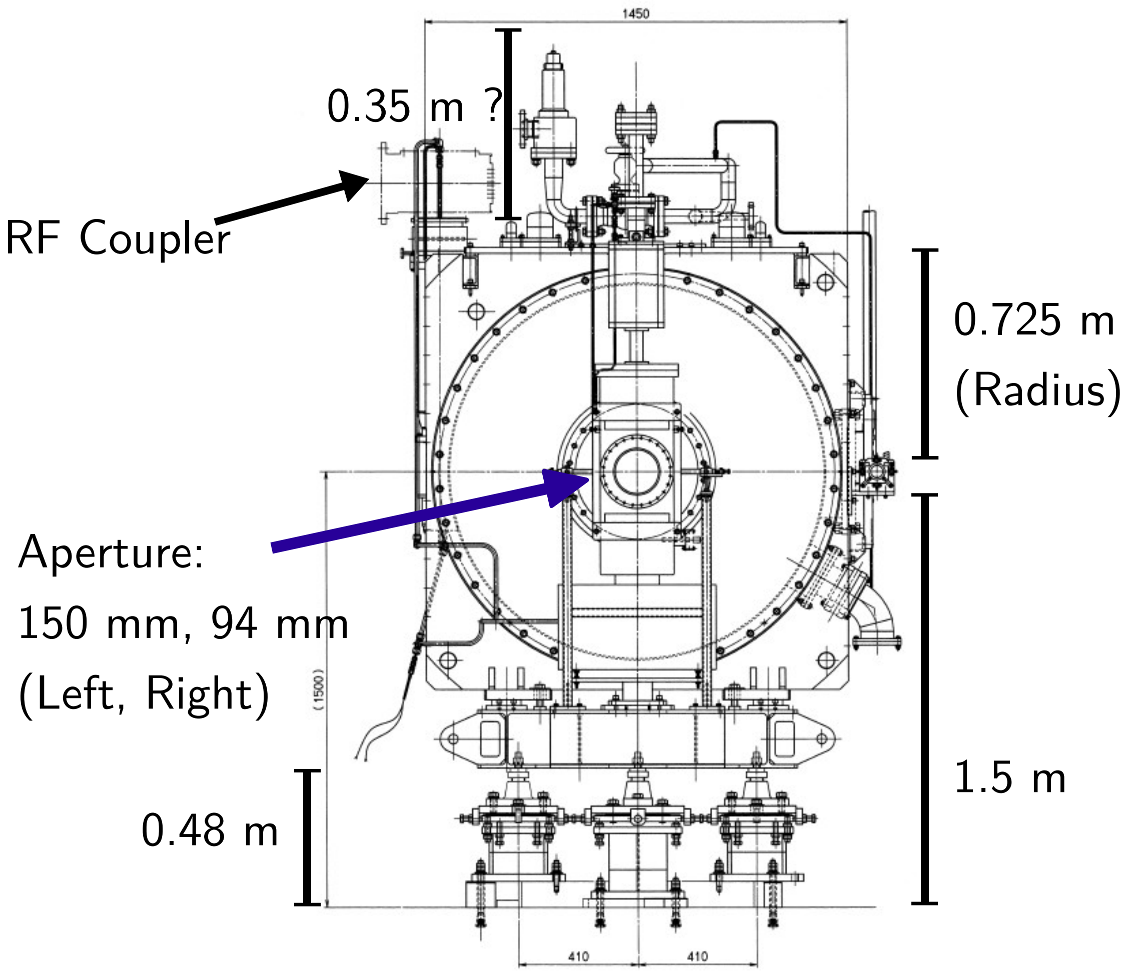
High current operation: 4-5 months

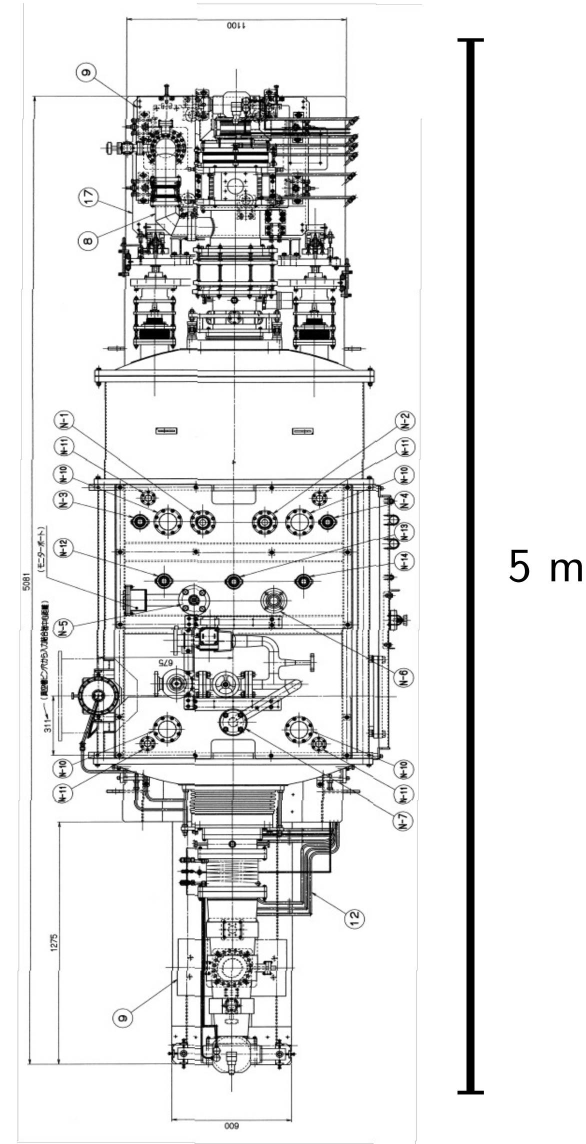
World record luminosity: ~2 yrs (aperture & chromatic coupling)

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

# Pros/Cons Of Diff Cavities, SPS Tests

| | 800 MHz LHC Cavity | 509 MHz KEK-B Cavity |
|---|---|---|
| Frequency | - | 2 MHz static tuning |
| Voltage | 2.5 MV | 1.5 MV |
| Temperature | 2K | 4K |
| Qext | $1\text{x}10^6$ | $2\text{x}10^5$ |
| Helium Volume | ~50-100 L | 400L |
| Heat Load | - | S :10 W, D: 50 W |
| Cavity Tuner | | 1 kHz/s (200 kHz max) |
| Module Weight | - | 5 Tons |
| Module Length | ~2 m | 5 m |
| Cavity Height | $< 1$ m | 1.5 m |

Table is only preliminary

# 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 ?)

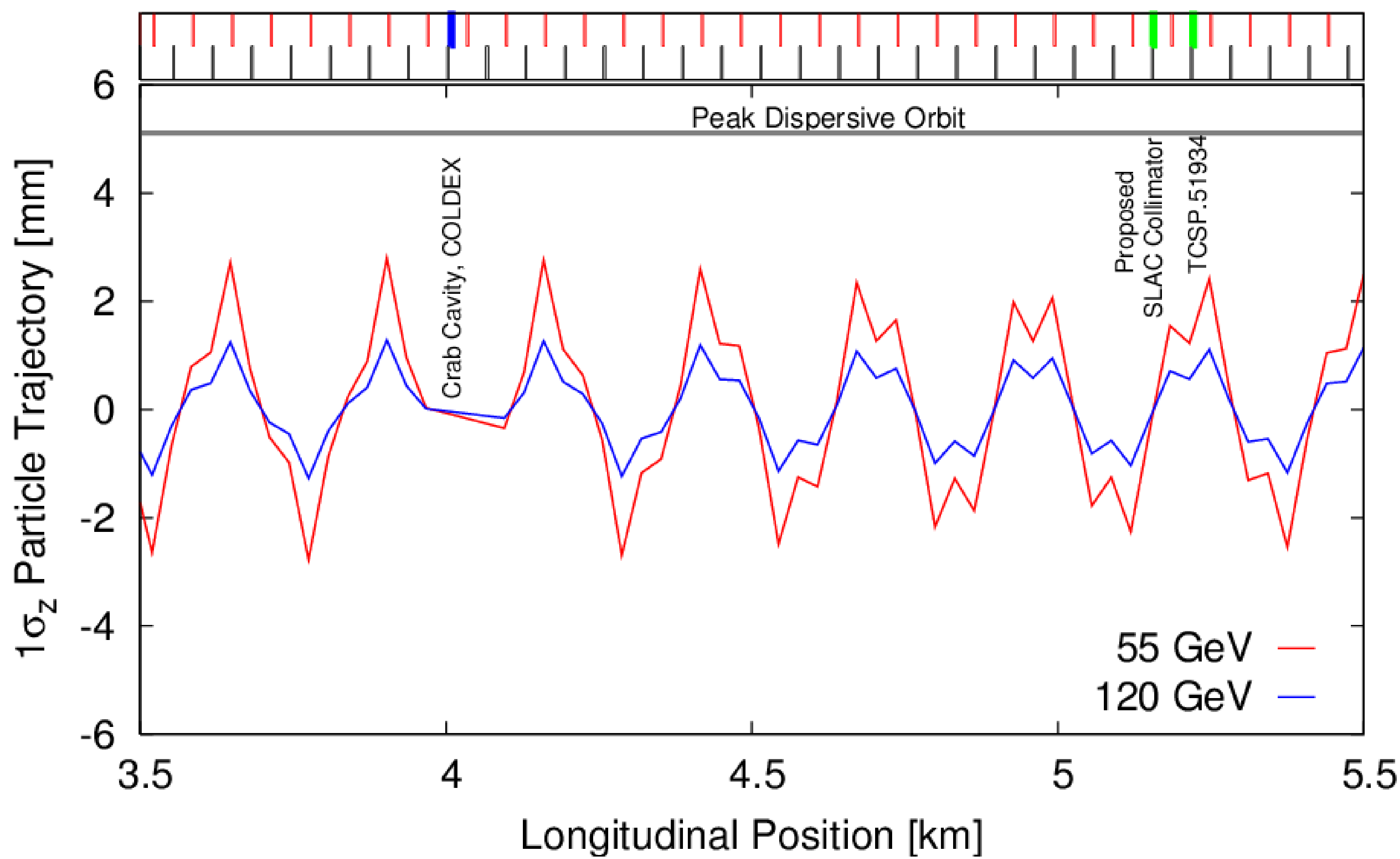
- Intensity dependent measurements (emittance blow-up, impedance)
  - Coherent tune shift and impedance
  - Instabilities
  - Beam-beam effects (BBLR – tune scan, current scan)
  - Other non-linearities (octupoles)

- 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

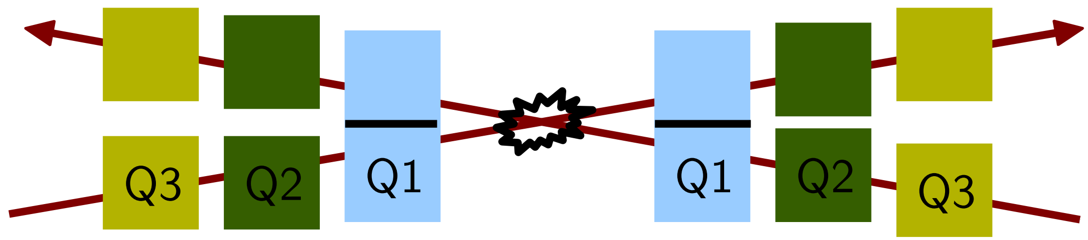
# Orbits in SPS

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

Head-tail monitor can detect sub-millimeter variations



# Possible Next Step

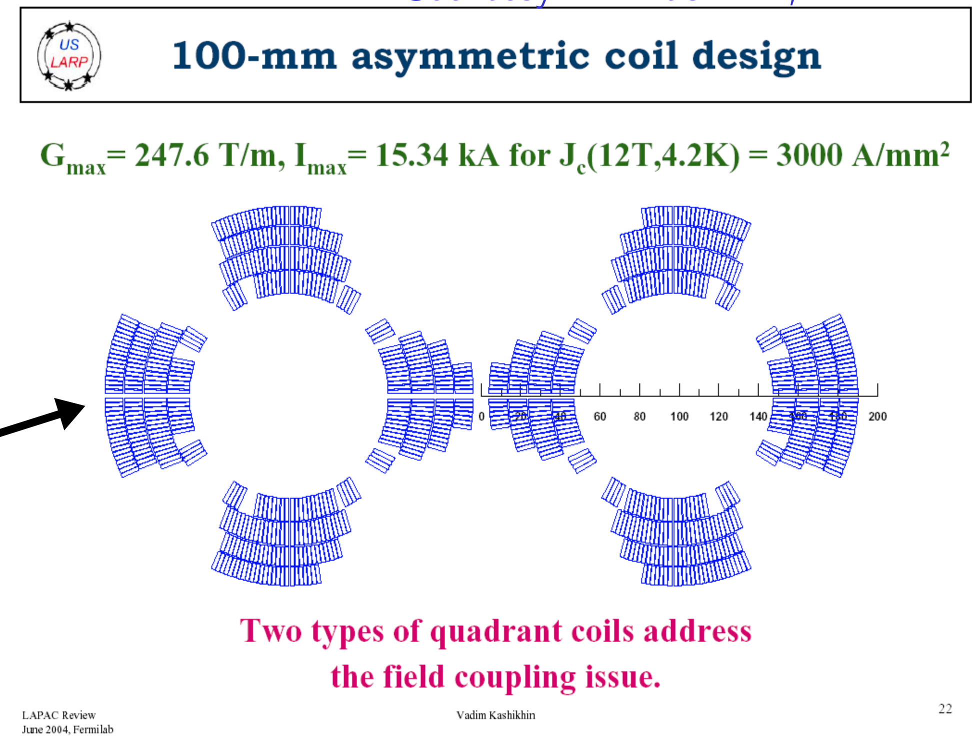



Large X-Angle (5 mrad ?) + Flat Beams ?

- No parasitic collisions
- Independent & easy IR optics

Future LARP-EuCARD Activity (?)

Courtesy: V. Kashikin, FNAL



# Conclusions

- Post Chamonix reaction
  - Most positive, LARP contribution via cryomodule/beam studies vital
  - Actual fabrication funds external (starting point SBIR/STTR)
- Future Strategy in view of LHC commissioning
  - Aggressive R&D on compacts to immediately solve any issues
  - Fall back solution to elliptical is well advanced
- SPS tests
  - Validate differences between protons & electrons
  - KEK-B or LHC cavity (2012-13) in SPS for beam testing
- Safety
  - Machine protection needs detailed study to evaluate failure modes
  - Appropriate feedback to guarantee MP at ultimate intensities

# LARP Activities, 2010-11

BNL – R. Calaga

- Machine protection studies (with CERN)
- Establish SPS tests requirements and goals
- Coordinate LARP-SBIR compact cavity development

SLAC. LBNL – Z. Li, J. Qiang

- RF optimization of HWSR compact $\rightarrow$ SBIR
- Detailed geometry of power coupler and HOM damping (with FNAL)
- Multipacting, tolerance studies, LHC beam-beam studies

FNAL – V. Yakovlev

- Multipacting and mechanical studies of HWSR
- Cryomodule concept development for baseline compact cavity

Jlab – J. Delayan

- HWDR cavity development and demonstration (STTR funds)