LHC Crab Cavities

Chamonix10, Jan 29, 2010

- Why crab the LHC
- Constraints, schemes & technology
- Potential concerns
- SPS, a first step ?

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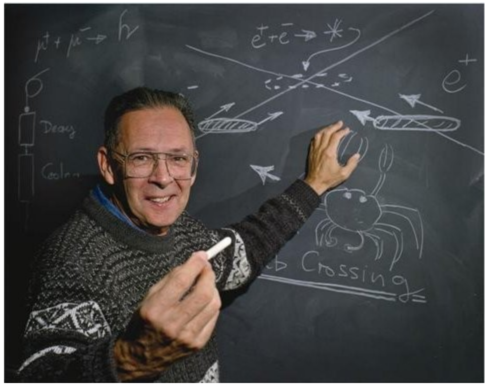
Ack: LHC-CC Team

Why crab the LHC



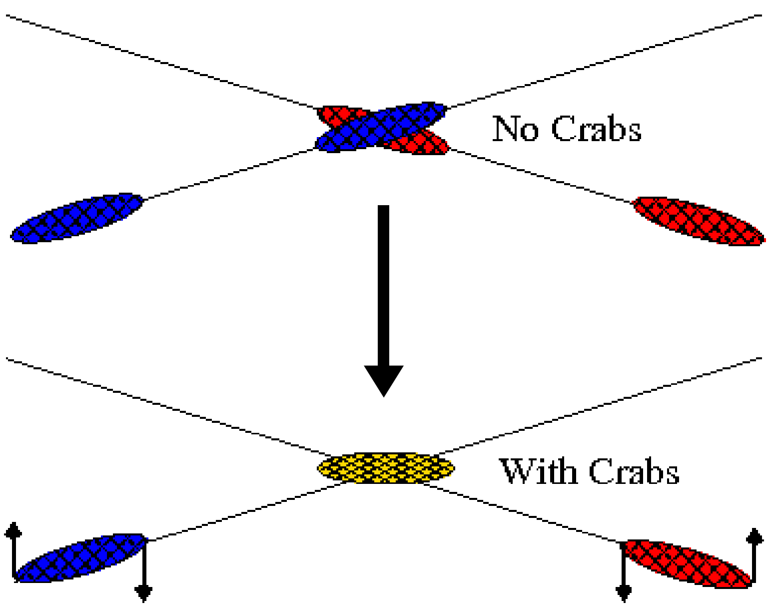
R. Palmer, 1988, LC

Upgrade scenarios aim at x3-10 Lumi increase

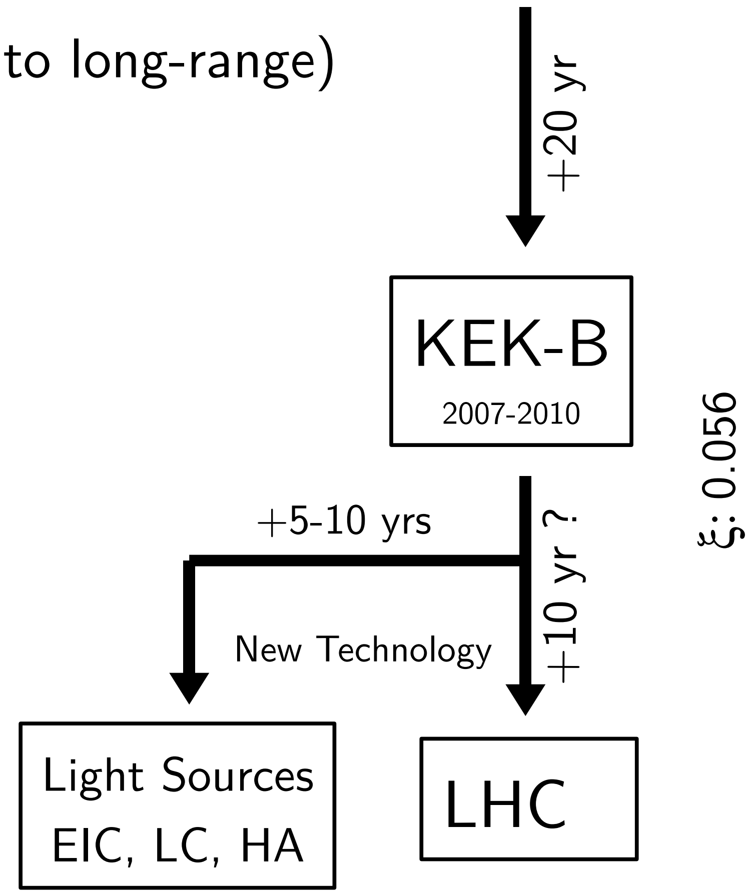
$R(\Phi)\downarrow$, $\varepsilon\downarrow\uparrow$, $N_b\uparrow$

One path: Minimize β^* & R (constant separation due to long-range)

One solution: Recover x-angle using crab cavities

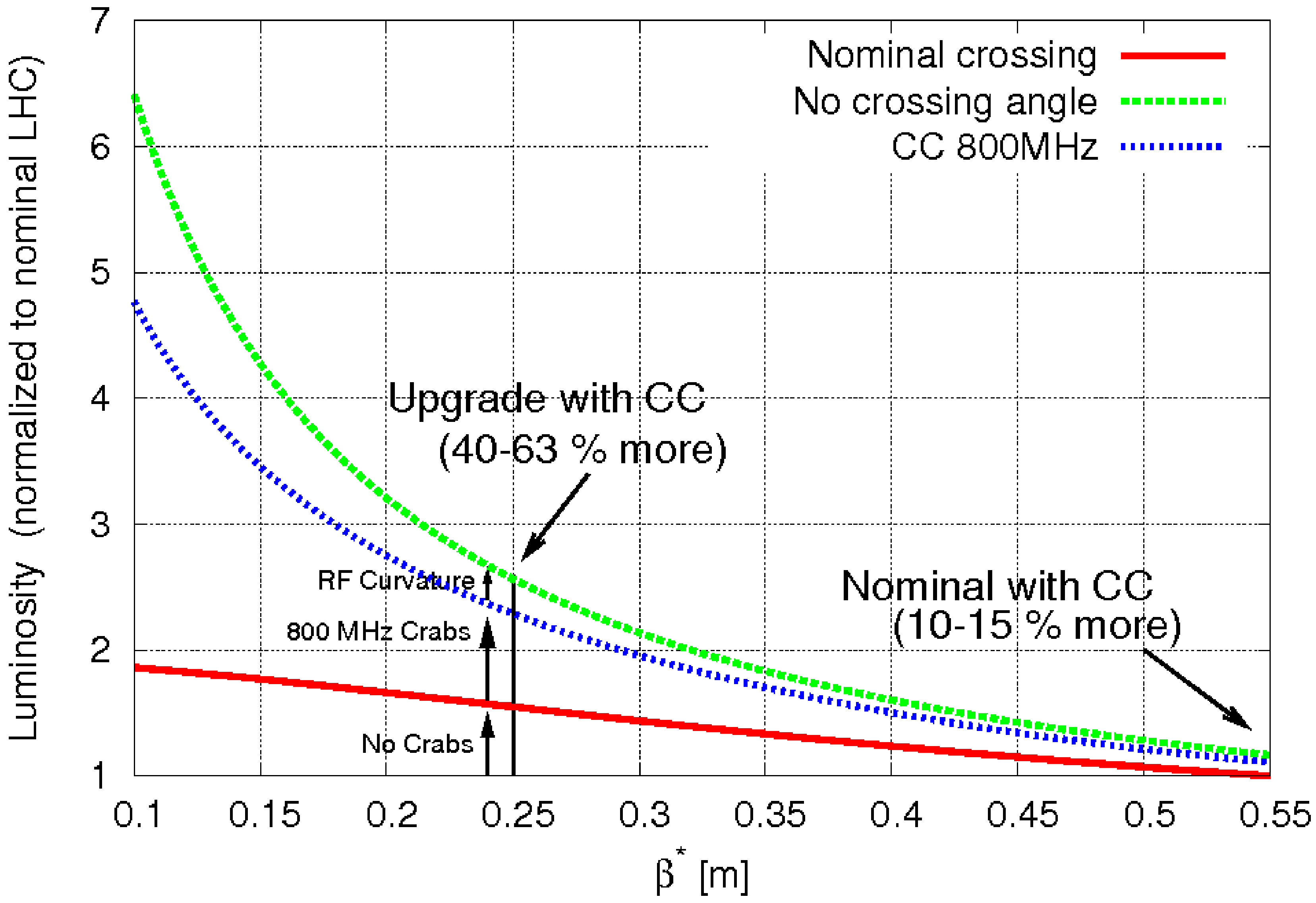


$$x_{IP} = R_{12}\frac{V_{cc}}{E_{\cdot}}\sin(k\sigma_z)$$



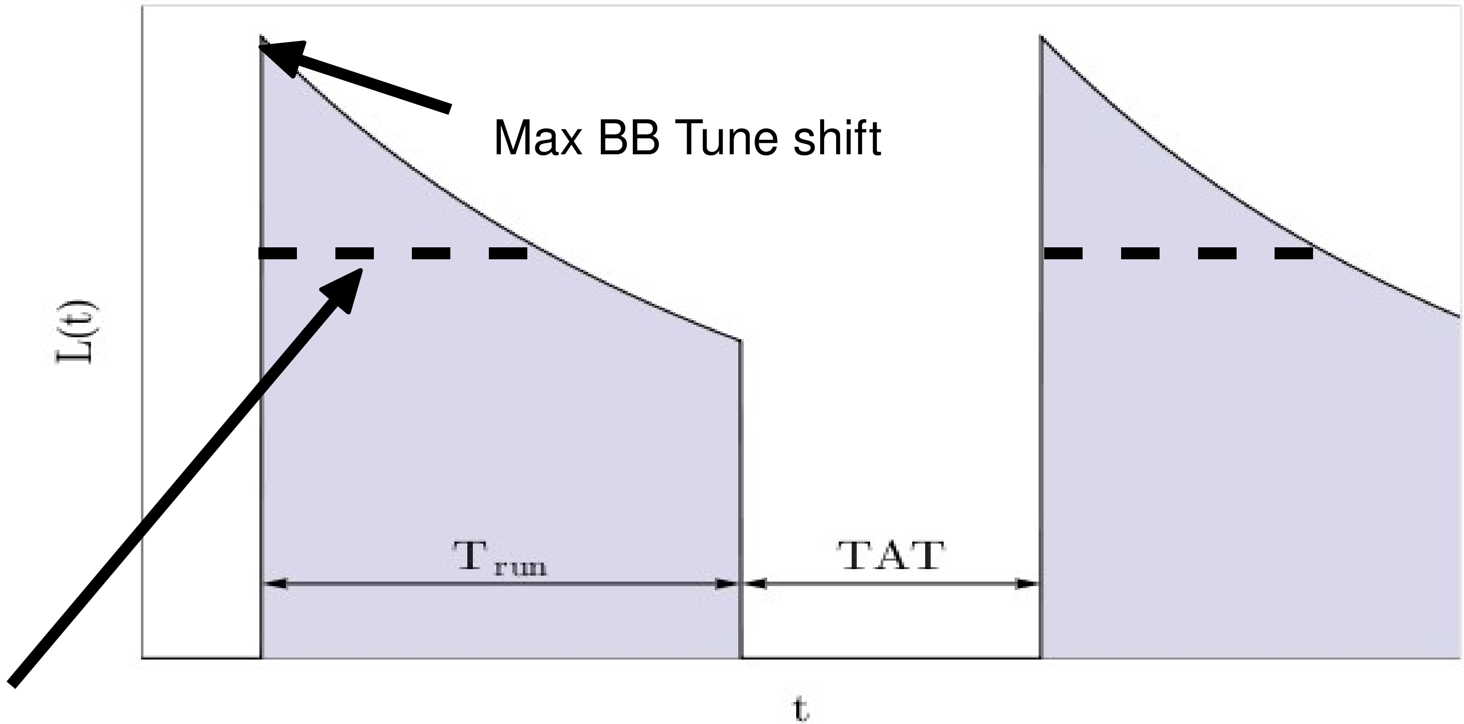
(N_b=1.7 x 10^{11} , β^* = 0.25 cm)

WHAT IS THE GAIN ?



[†]Note: 63% gain with 400 MHz cavities

Luminosity Leveling



Advantages (See J. P. Koutchouk's talk):

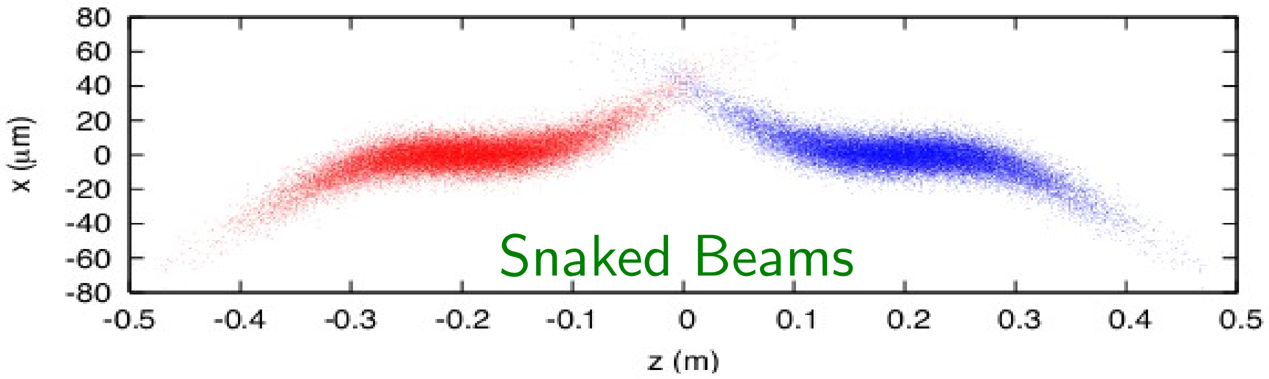
- Constant Luminosity (~3 x 10^{34})
- Less pile up at start
- Less peak radiation on IR magnets/detector

Crabs → Natural knob w/o lattice change

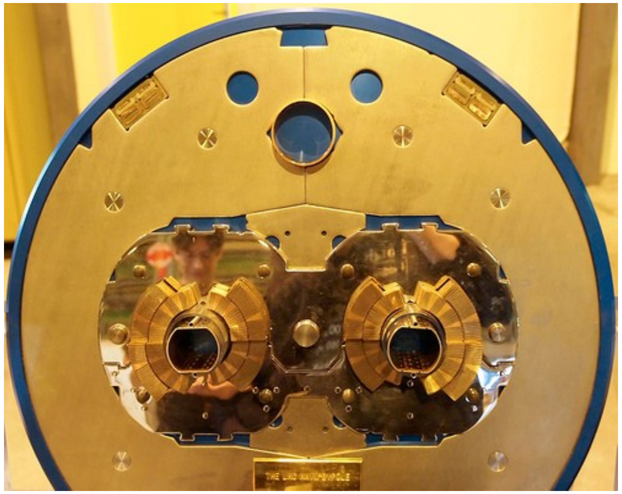
Graphic courtesy G. Sterbini

Two Main BC/Constraints

Bunch length: 7.55 cm (800 MHz, 2.5σ_z is on other side)



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



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

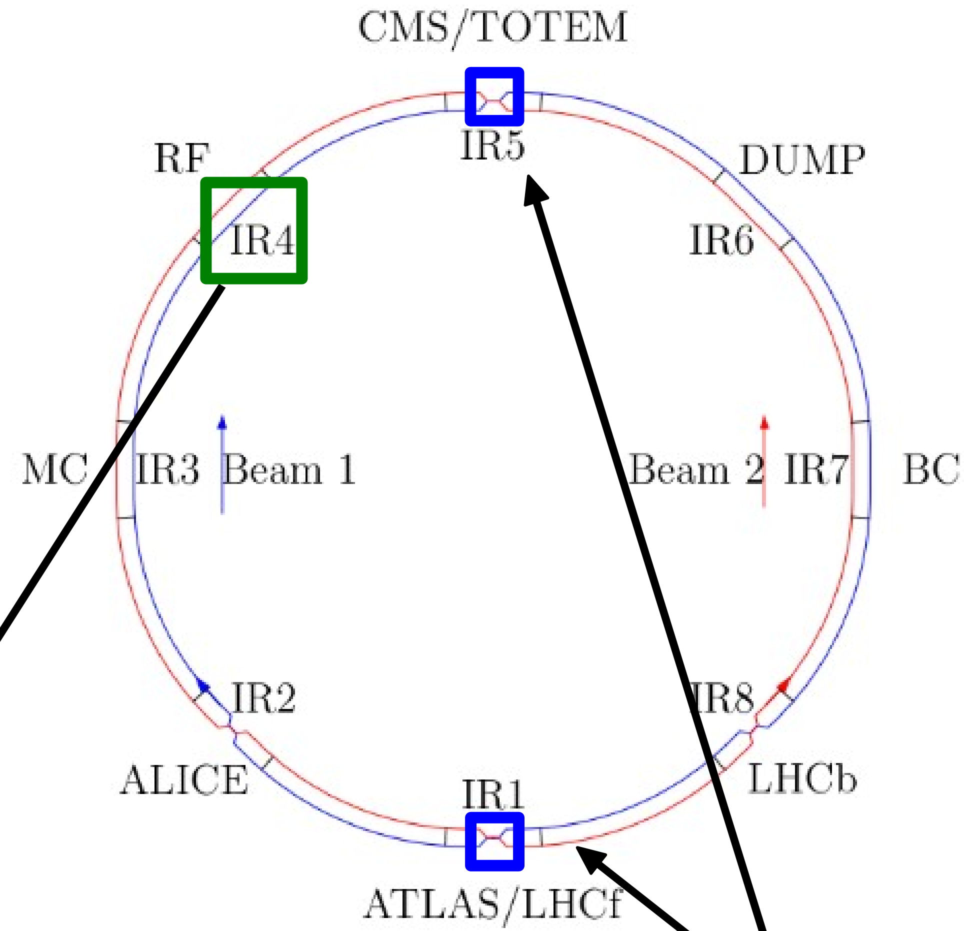
Possible Schemes

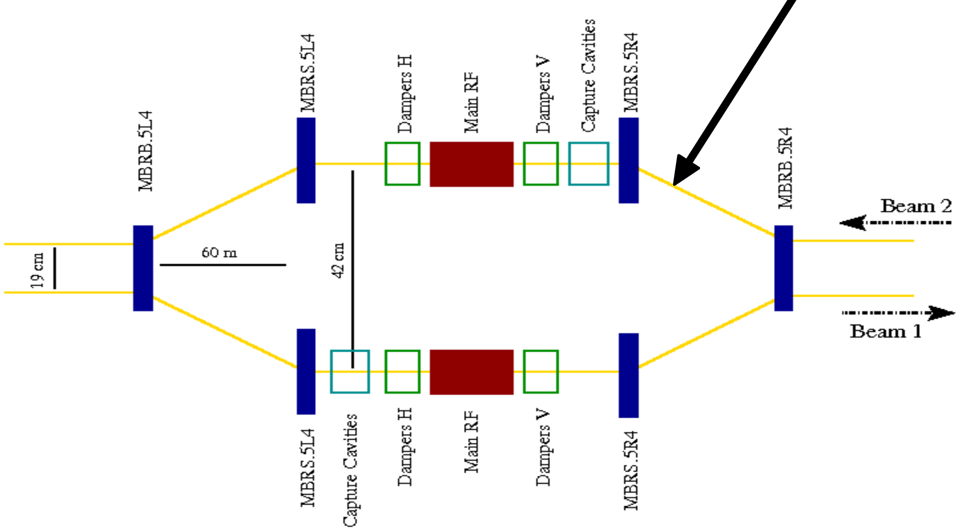
$$V_{crab} = \frac{cE_0 \tan(\theta/2)}{\omega\sqrt{\beta_{cc}\beta(s)}} \frac{\sin(\mu_x/2)}{\cos(\psi_{cc-ip} - \mu_x/2)}$$

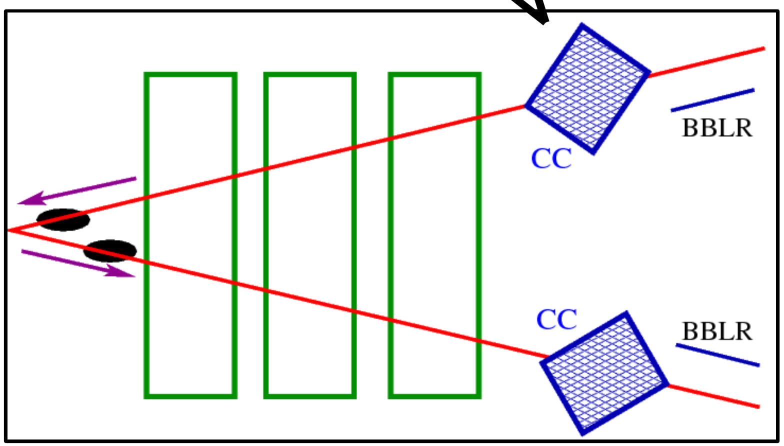
$\beta^* \leq 25$ cm

Crab Freq: 800 (or 400) MHz

Kick Voltage: ~5 (or 10) MV







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

Menu of Schemes

1 Cavity/beam (IR4 – Minimum) ~\$4 M + CE

Highly restrictive ph. adv IP1 ↔ IP5 (and ALICE, LHCb)

HH crossing scheme (nominal – HV)

2 Cavities/beam (IR4 + ?) ~\$6 M + CE

Restrictive phase advance IP1 ↔ IP5

HH or HV crossing possible (depending on ph. adv)

4 Cavities/beam (total, 8 Cav – MP ?) ~\$12 M + CE

Requires new technology

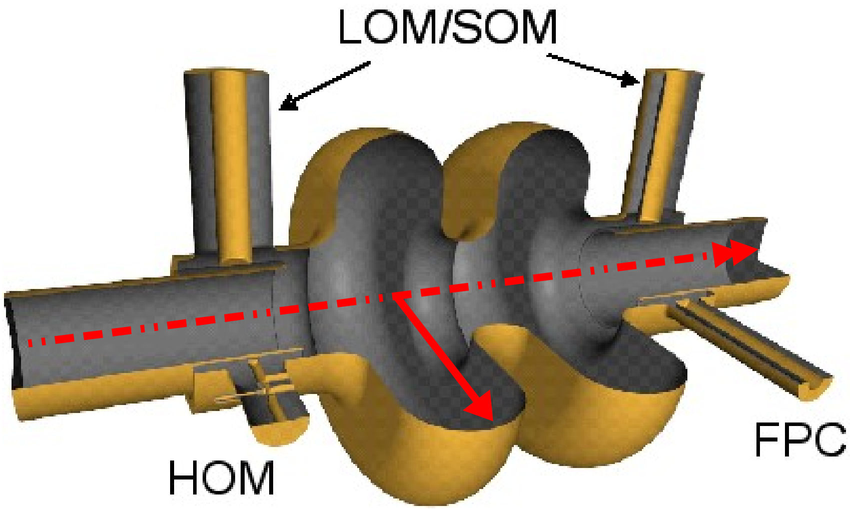
Local IR control of crossing angle & crossing scheme

[†]CE: Civil Engineering, RF, Cryogenics > \$10 M (R. Garoby)

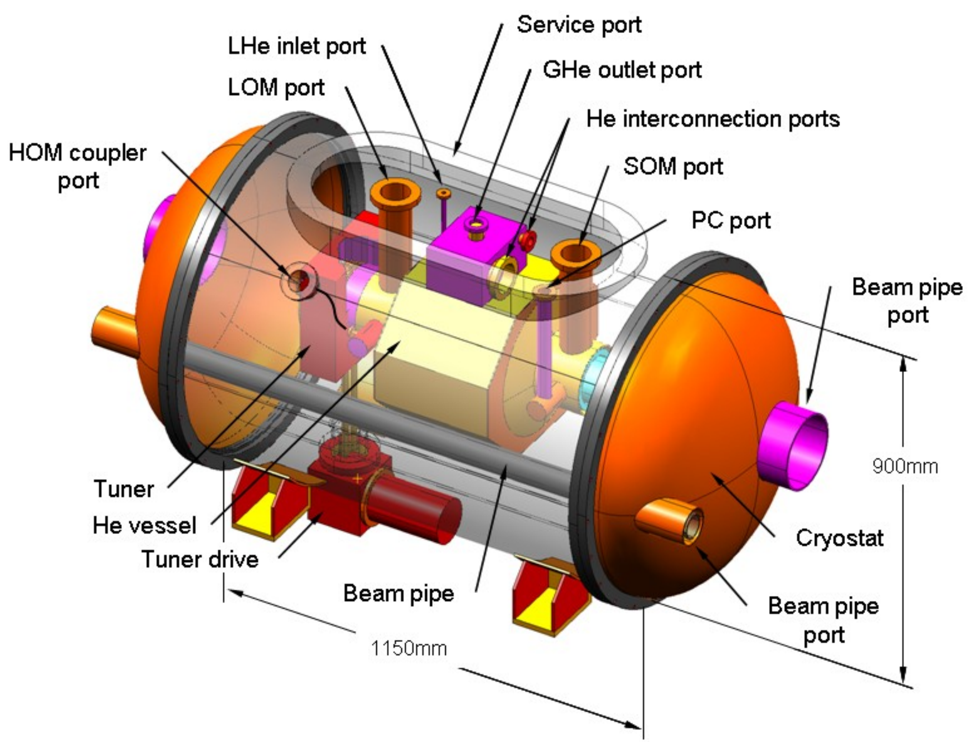
Conventional Cavities

2007-2009!

- 2 cell elliptical cavity @800 MHz
- Strong HOM damping schemes
- Multipacting, thermal, mechanical etc...



~250 mm outer radius



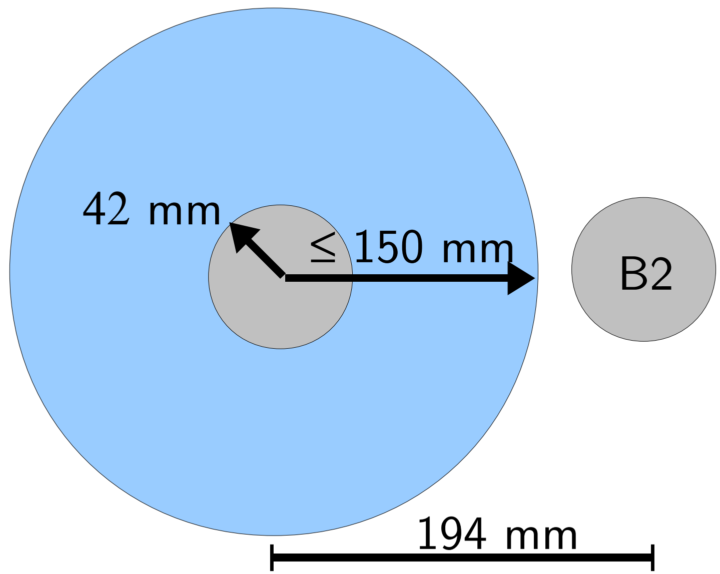
Conceptual cryostat design exists

Exact RF-cryogenic-mechanical interfaces to be finalized

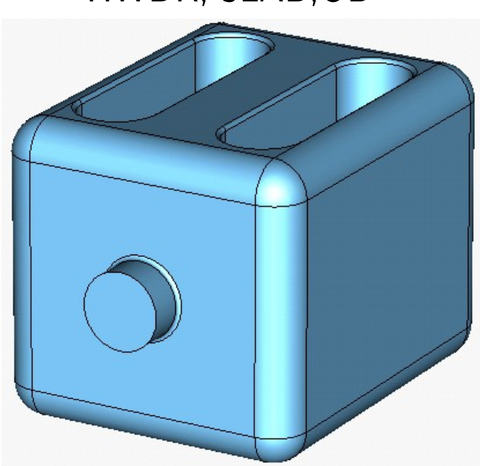
Only possible in IR4

LHC Needs Compact Cavities

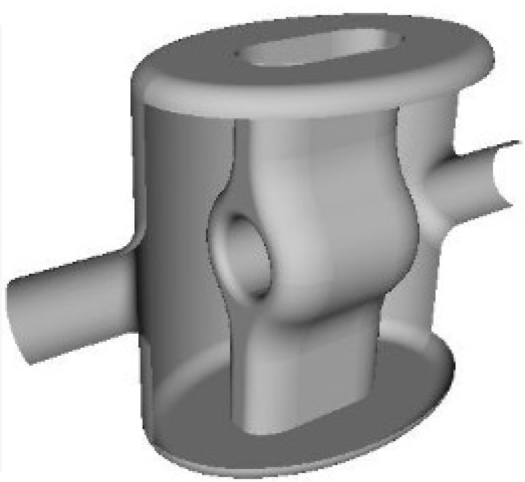
2008-2010



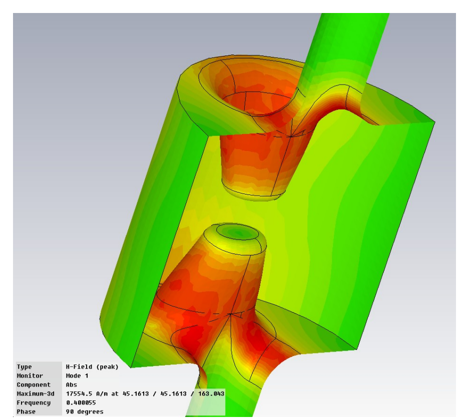
HWDR, JLAB,OD



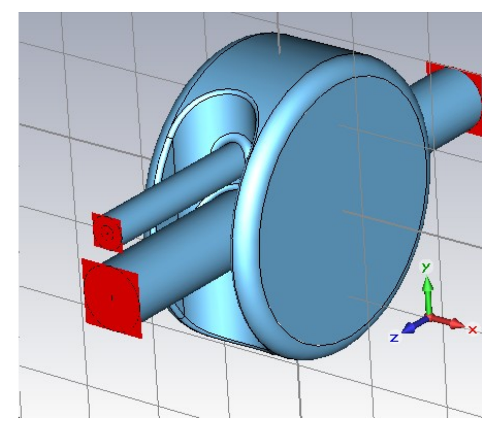
HWSR, SLAC-LARP



DR, UK, TechX



Kota, KEK



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

So what are we afraid of ?

Machine protection

Collimation efficiency & hierarchy (global)

Crab cavity induced noise

Additional longitudinal & transverse impedance

Machine Protection, 350 MJ !!

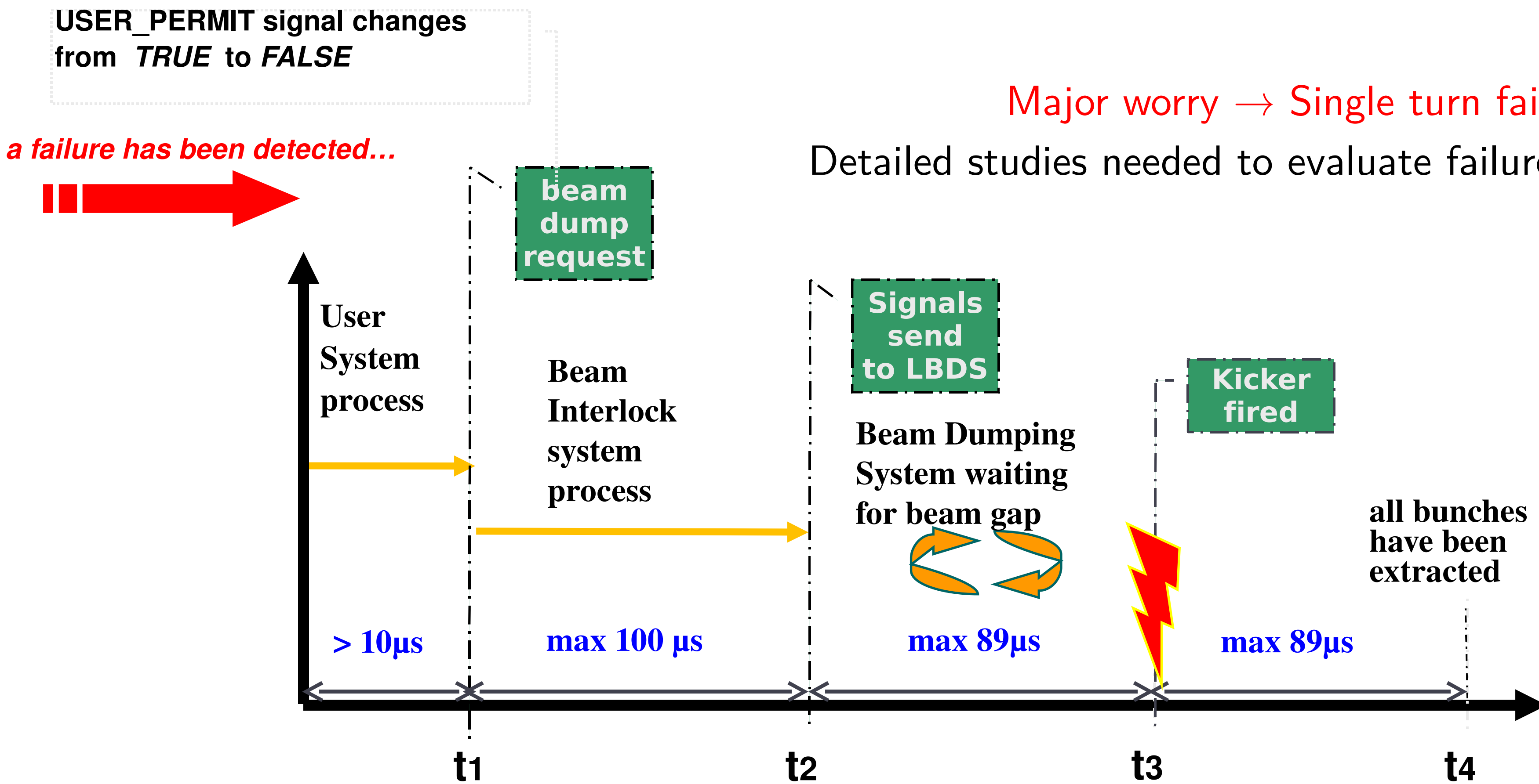
Approx 200 interlock systems

Best/worst case scenario:

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

Major worry → Single turn failure

Detailed studies needed to evaluate failure scenarios



Courtesy J. Wenniger

Failure Scenarios

Single turn failures

- Cavity quench, amplifier, vacuum degradation
- Transmitter trip, feedback failure
- Abrupt crab phase changes due to beam

Differences between local Vs global schemes

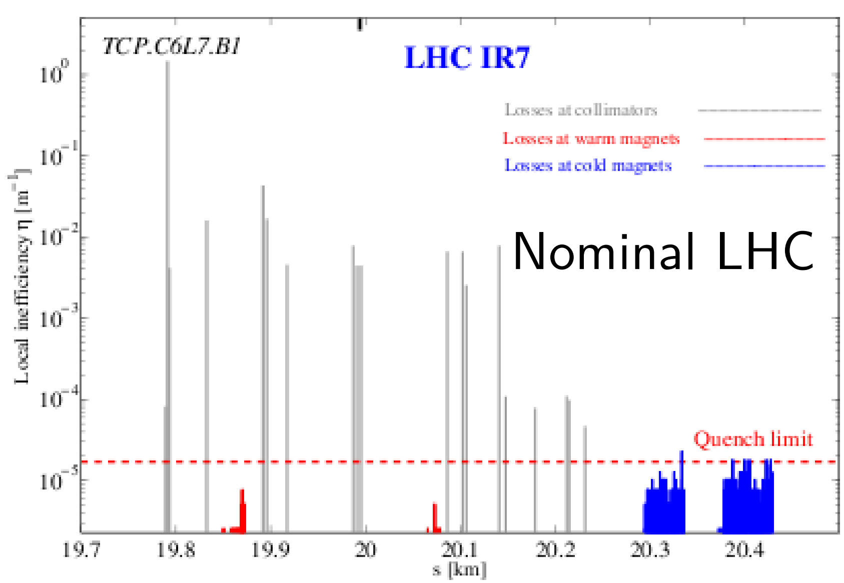
- Global: Beam to cavity
- Local: Cavity to cavity & beam

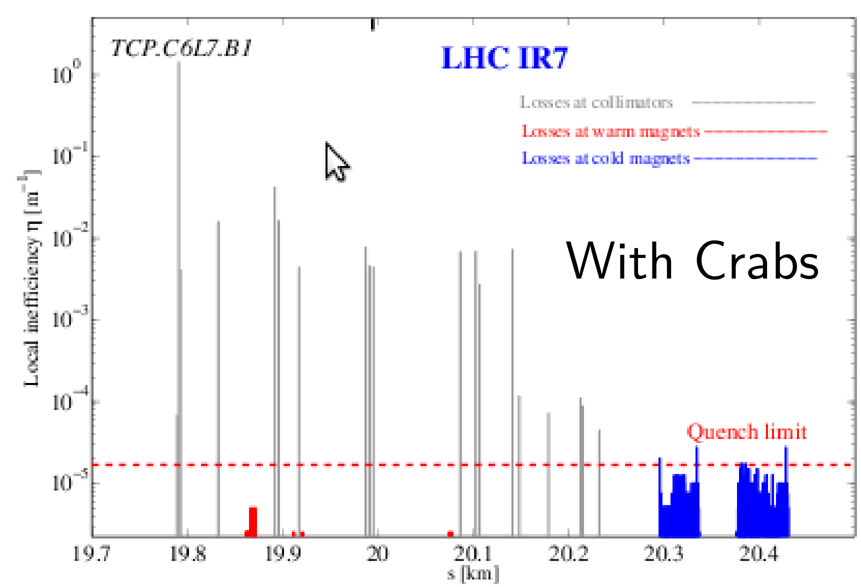
No passive way to guarantee machine protection (Tuckmantel)

- For example higher Qext may not help slow the failure time constant
- Voltage slope determined by unchangeable constants (R/Q, Δx, I...)
- Active orbit and RF feedback a requirement

Collimation (Global Scheme)

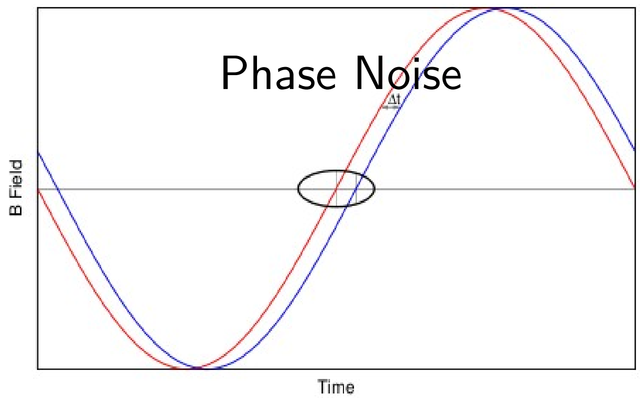
- Loss maps with crabs similar to nominal LHC
  - Additional 0.5σ aperture
  - Hierarchy preserved (primary, secondary, tertiary)
- Maximum DA decrease $\sim 1\sigma$ (13σ nominal)
  - Suppression of synchro-betatron resonances





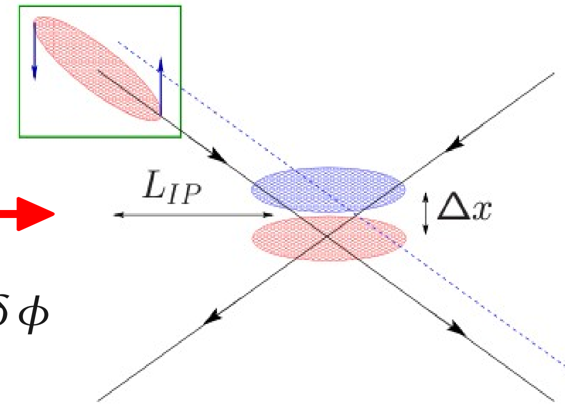
Y. Sun et al. PRST-AB 12, 101002 (2009)

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)

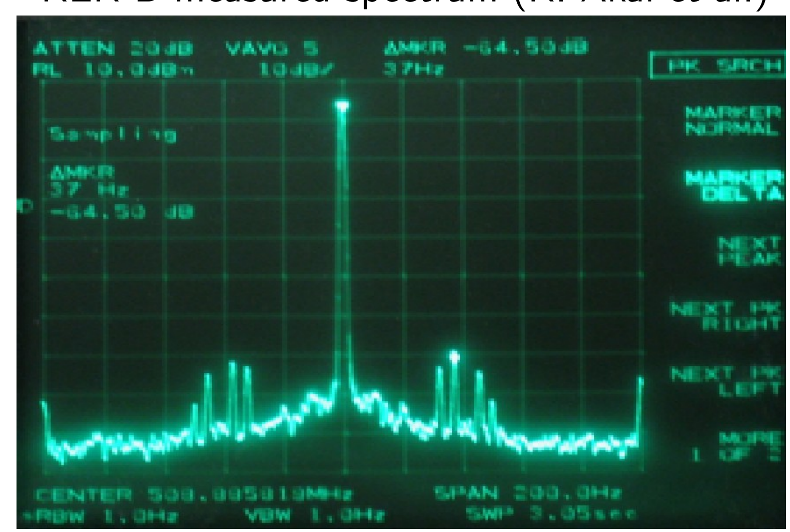
Tolerance relaxed in the case of lumi-leveling

White noise (extremely pessimistic)

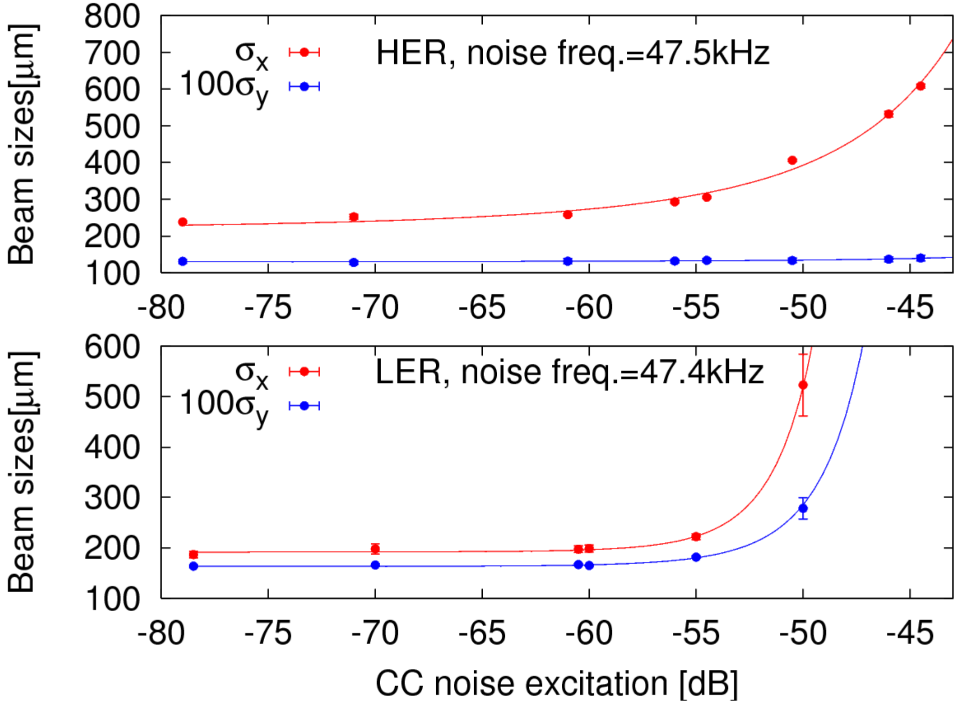
Ohmi: Strong-strong BB ≤ 0.02σ.(τ)

correlation time

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

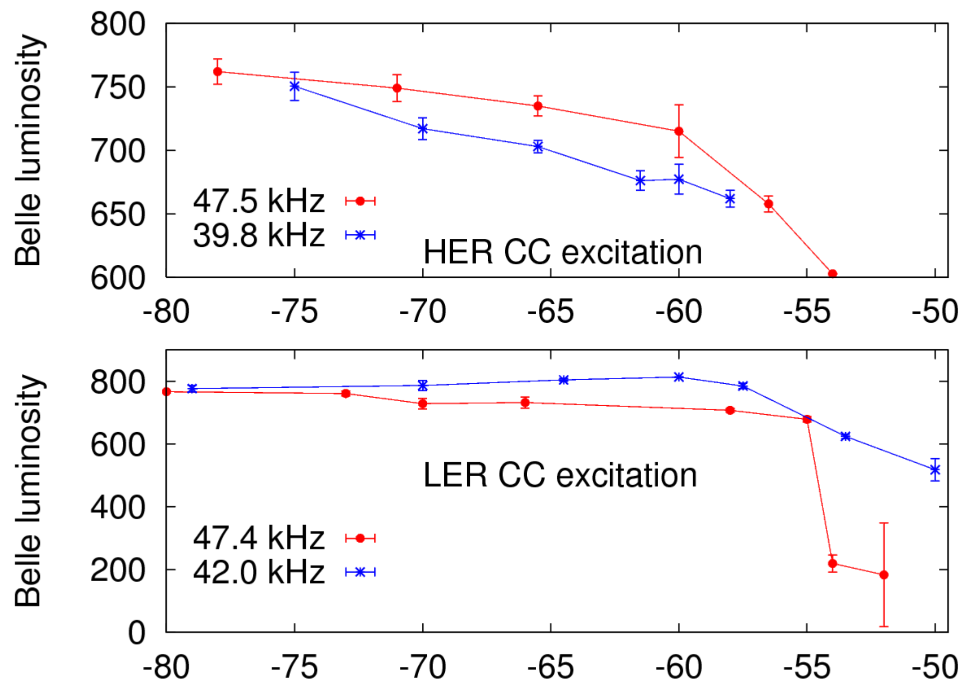


Noise Exps, KEK-B



Single beam noise excitation

Visible effect ∼ -60 db → 0.1^0



Noise excitation with beam-beam

Visible effect ∼ -70 db → 0.03^0

R. Tomas et al., 2008

Impedance Requirements

Longitudinal criteria:

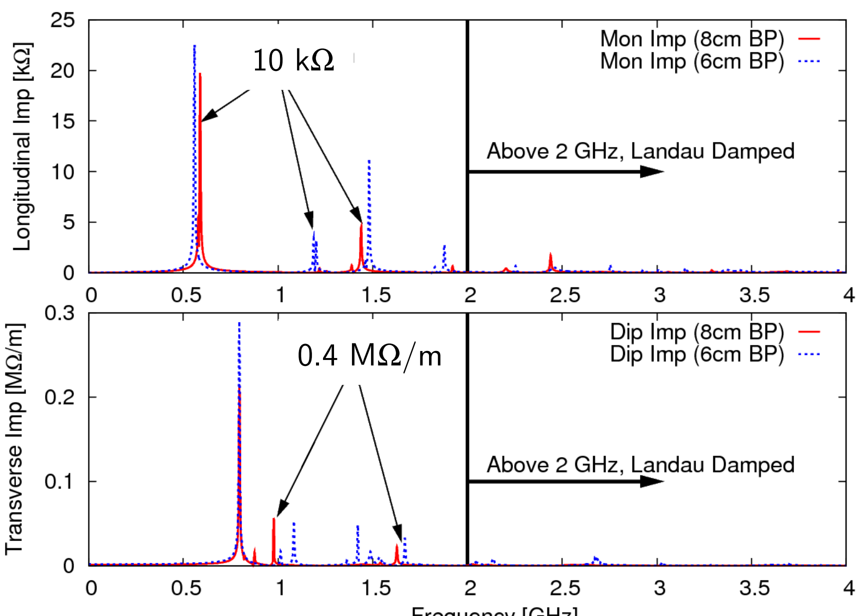
Nominal intensity, 450 GeV: ~60 kΩ (determined by 200 MHz cavities)

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

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

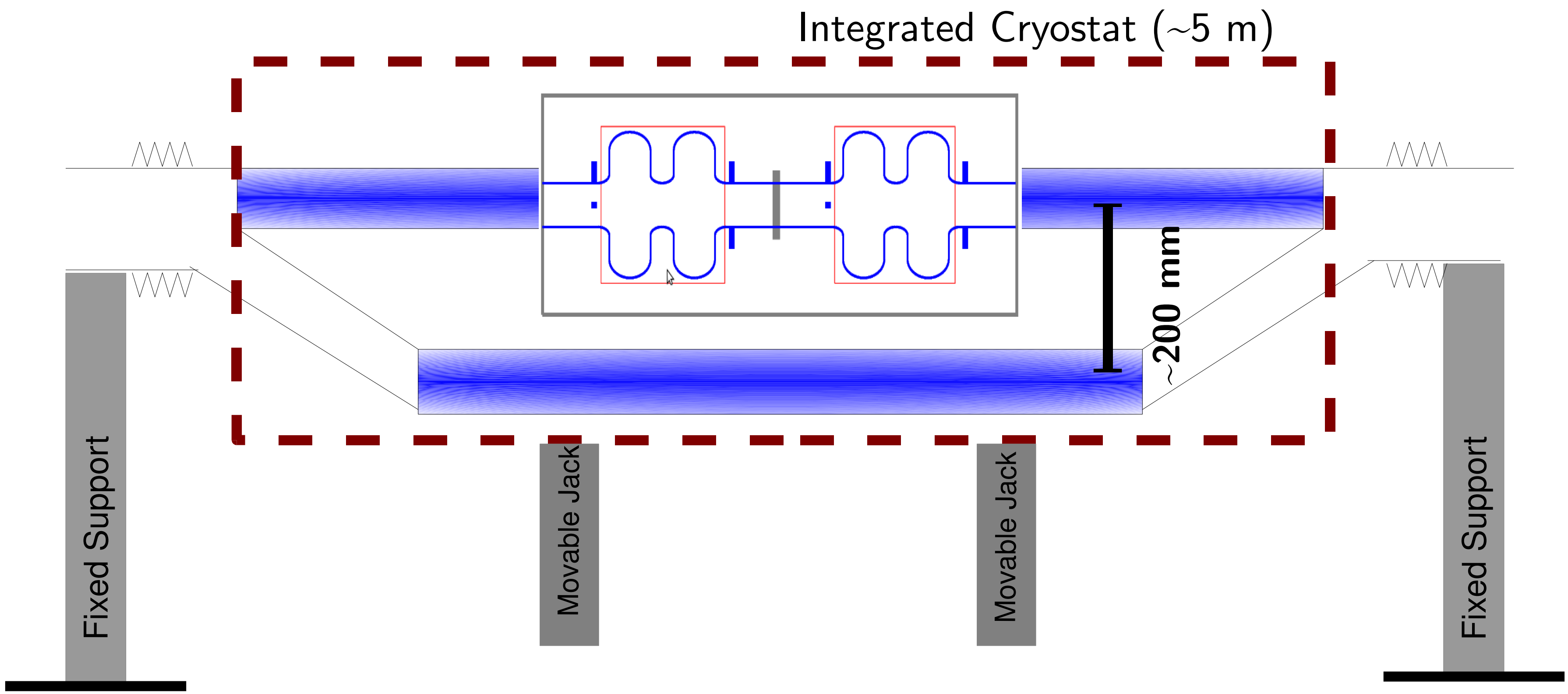
Approx: 265 fb^{-1}/yr (217 fb^{-1}/yr w/o CCs)

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

Vertical Bypass ?



Crab cavity problems → Uninterrupted operation

Cheaper and compact compared to 7 TeV dog-legs

Bypass derived from SPS-COLDEX

LHC-CC09 Guideline

1. Following the success of KEKB, CERN must pursue the use of crab cavities for the LHC, since the potential luminosity increase is significant.

2. A final crab-cavity implementation for the LHC has not yet been settled. Both “local” and “global” crabbing schemes are still under consideration for the LHC upgrade phase II. Future R&D should focus on compact cavities which are suitable for both schemes.

3. One possible show-stopper has been highlighted: machine protection, which is critical for LHC. The effect of fast cavity changes needs to be looked at with high priority. Mitigation schemes will be studied.

4. Another important issue is the impedance. During acceleration, the detuning, strong damping need to be examined carefully.

5. High reliability of the crab cavities is essential; the trip rate should not perturb LHC beam operation.

6. Validation cavity tests in the LHC itself are not deemed essential. It is considered plausible to install a new system in the LHC without having tested a prototype in the LHC beforehand.

7. Demonstration experiments should focus on the differences between electrons and protons (e.g. crab-cavity noise with beam-beam tune spread; impedance; beam loading) and on reliability & machine protection.

8. A beam test with a KEKB crab cavity in another proton machine is considered useful, meaningful and sufficient (for deciding on a full crab-cavity implementation in LHC) if it addresses the concerns.

9. Possible modifications of LHC IR4 during the 2013/14 shutdown should be studied to evaluate the feasibility of installing and testing crab-cavity prototypes, and of accommodating a possible global crab-cavity scheme.

10. The timing of the crab-cavity implementation should be matched to the short and long-term goals and to the overall CERN schedule, and be in phase with the experiment upgrades.

11. The crab-cavity infrastructure should be included in all other LHC upgrades scenarios.

12. Crab cavities can increase the LHC luminosity without an accompanying increase in beam intensity, thereby avoiding negative side effects associated with high intensity and high stored beam energy. This opinion has been endorsed by the general-purpose high-luminosity experiments.

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 2^{nd} 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

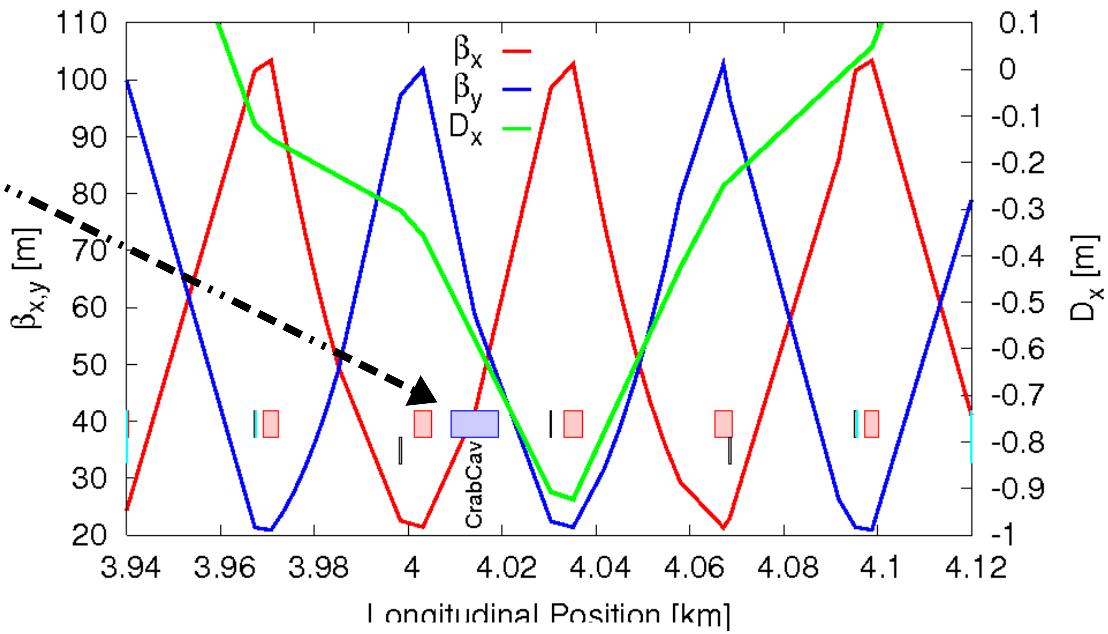
Courtesy E. Metral

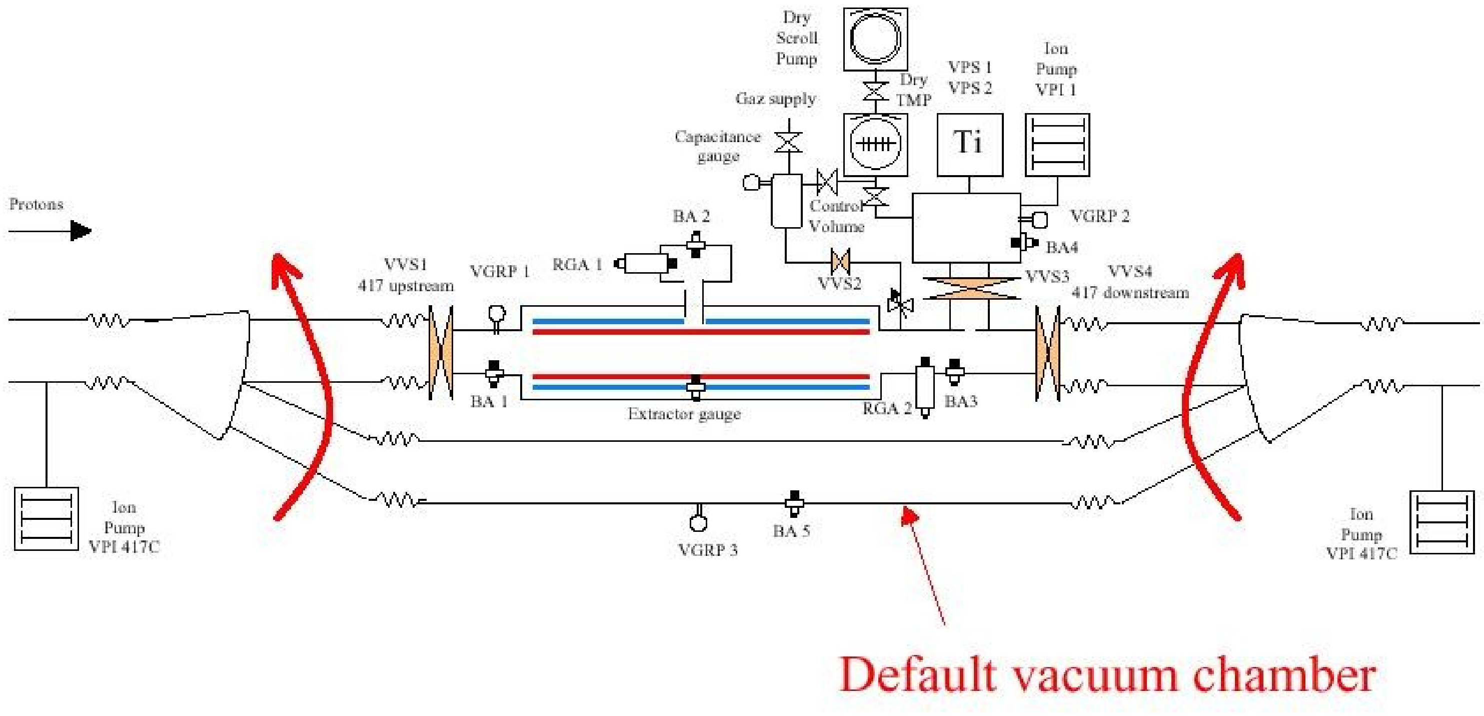
Coldex Location

Longitudinal Position: 4009 m +/- 5m

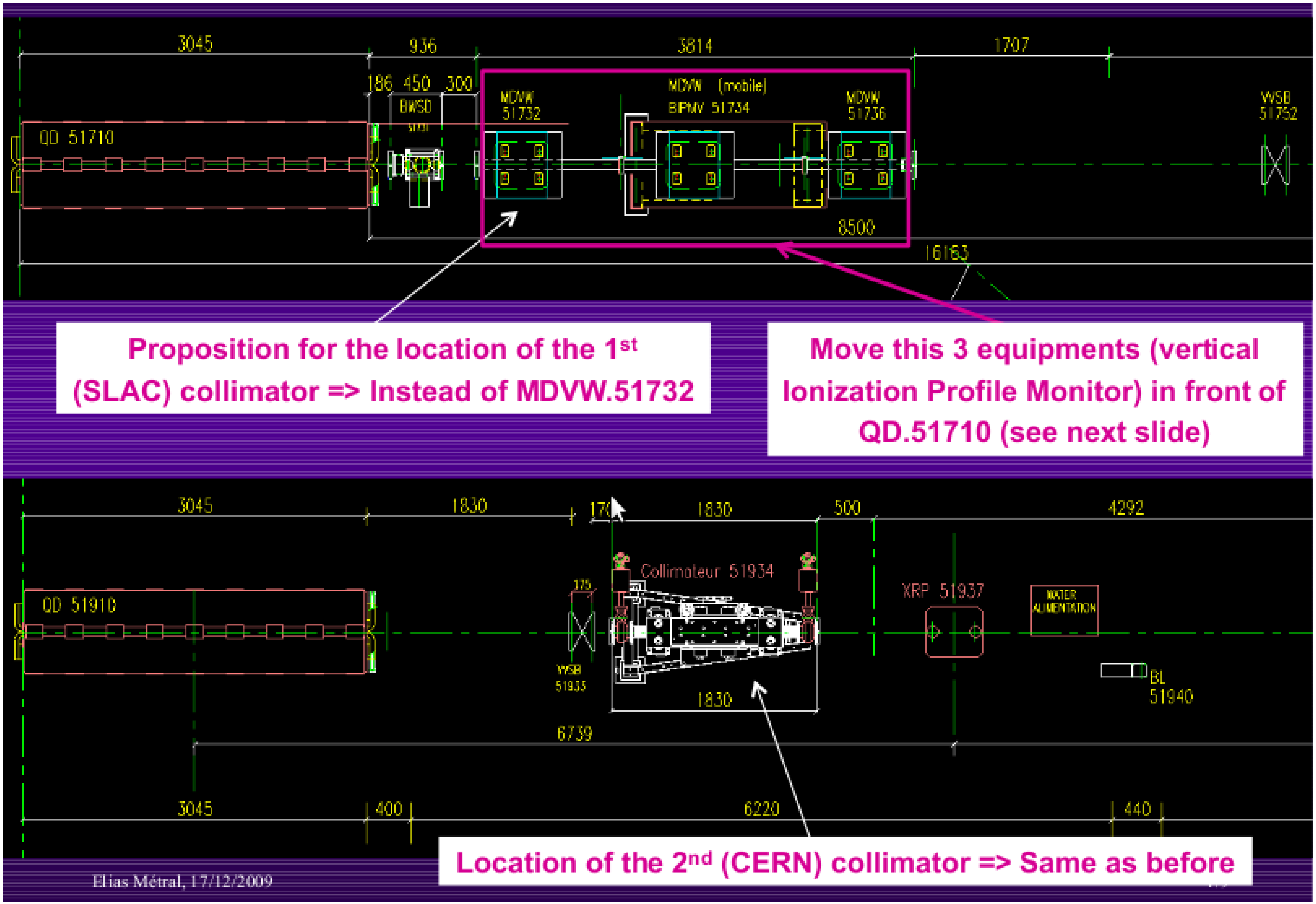
Total length: 10.72 m

βx, βy: 30.3m, 76.8m





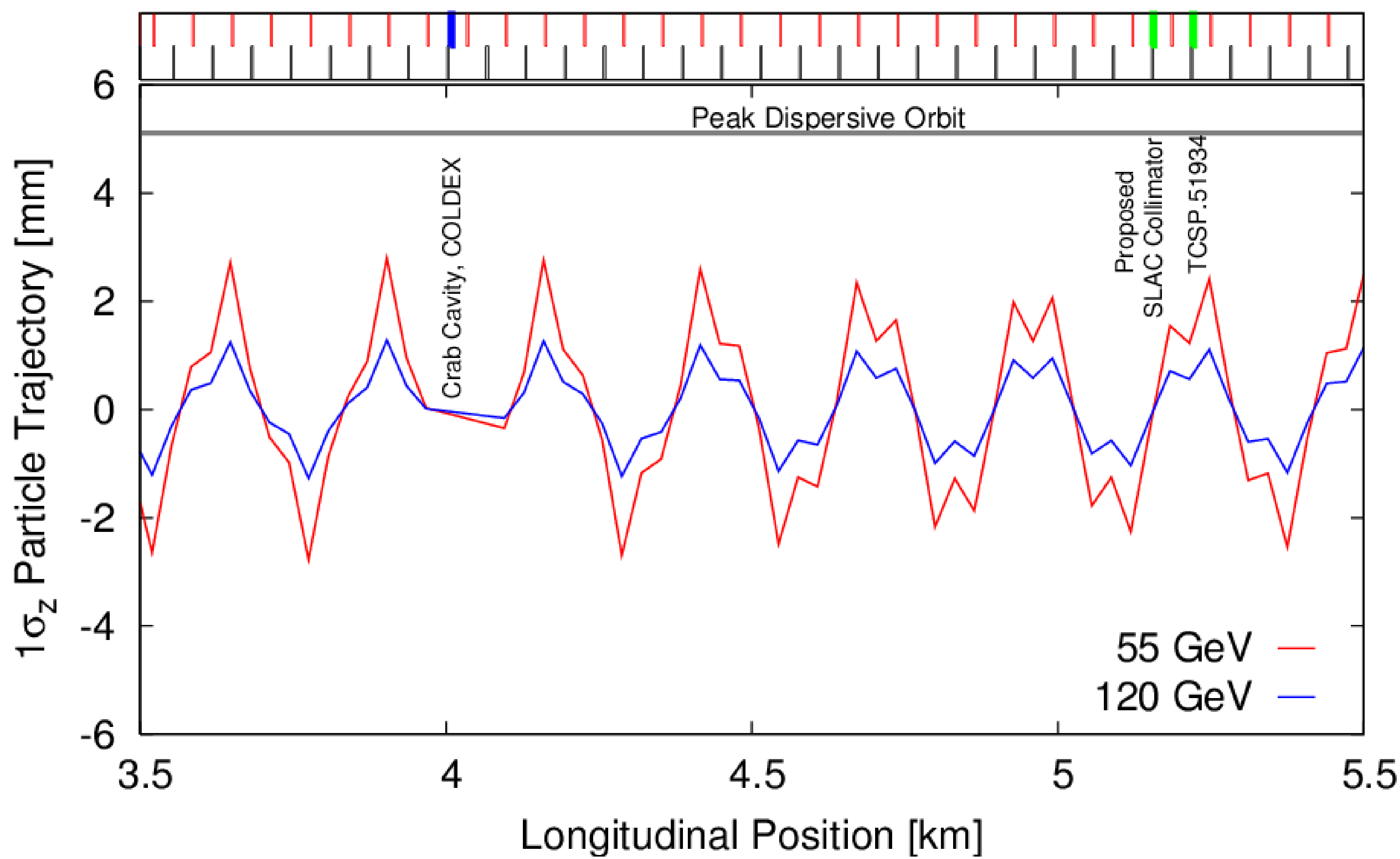
Collimator Locations



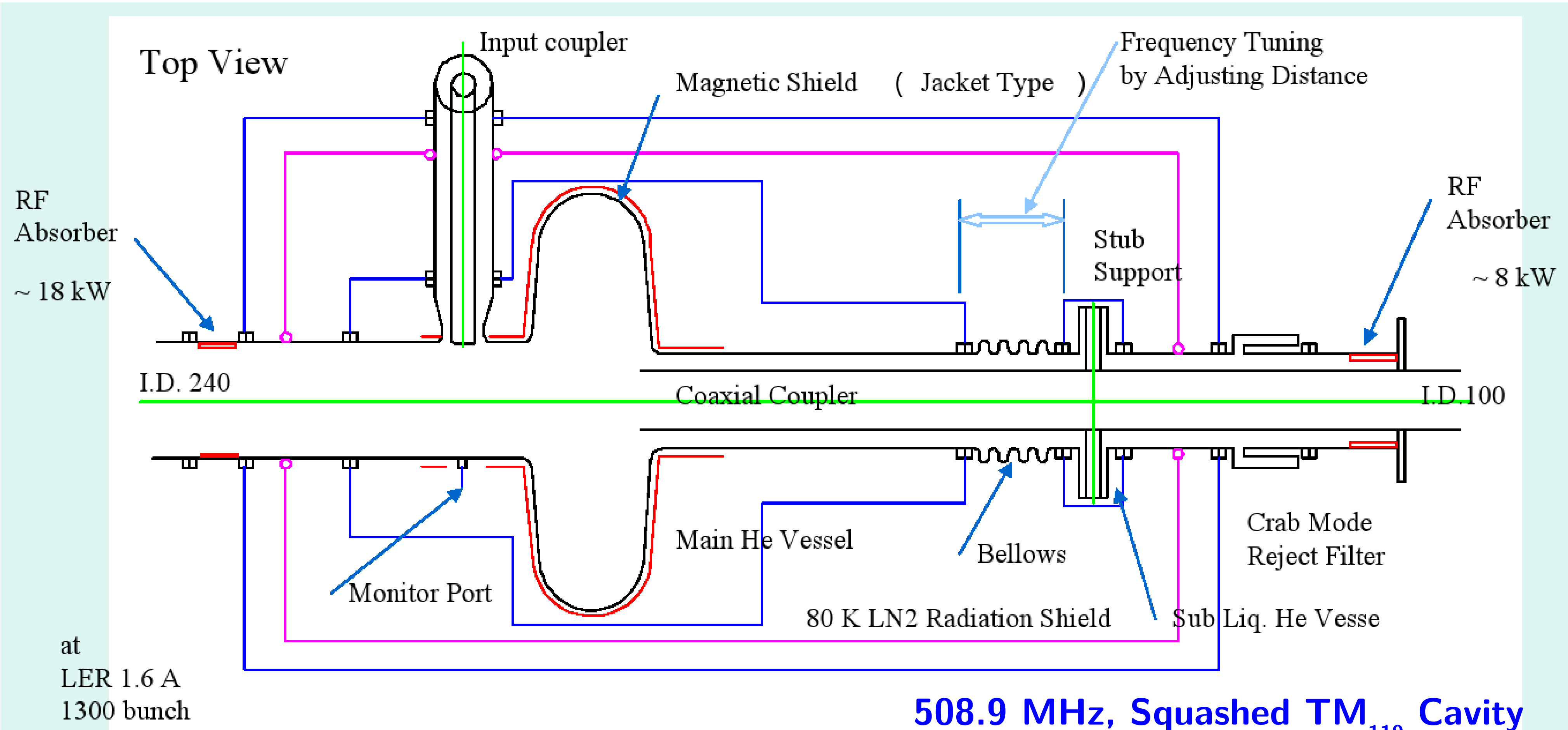
Orbits in SPS

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

Head-tail monitor can detect sub-millimeter variations



KEK Cavities



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)

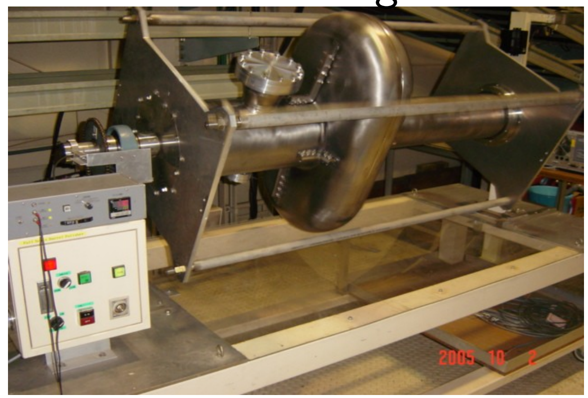
ΔQ_{bb}=0.056 (no CC), 0.09 (with CC), 0.15 (predicted)

Courtesy KEK-B

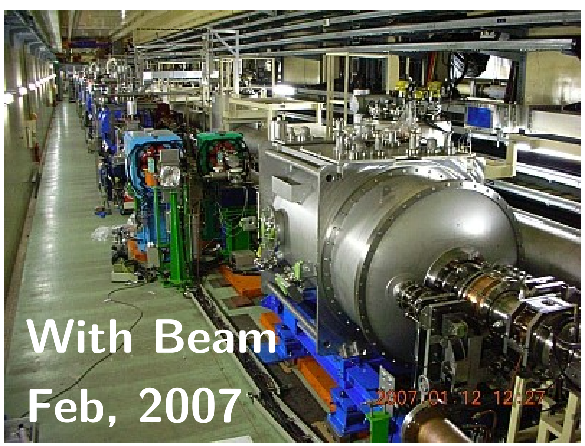
KEK-B Cavities

Fabrication

Processing



Assembly



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

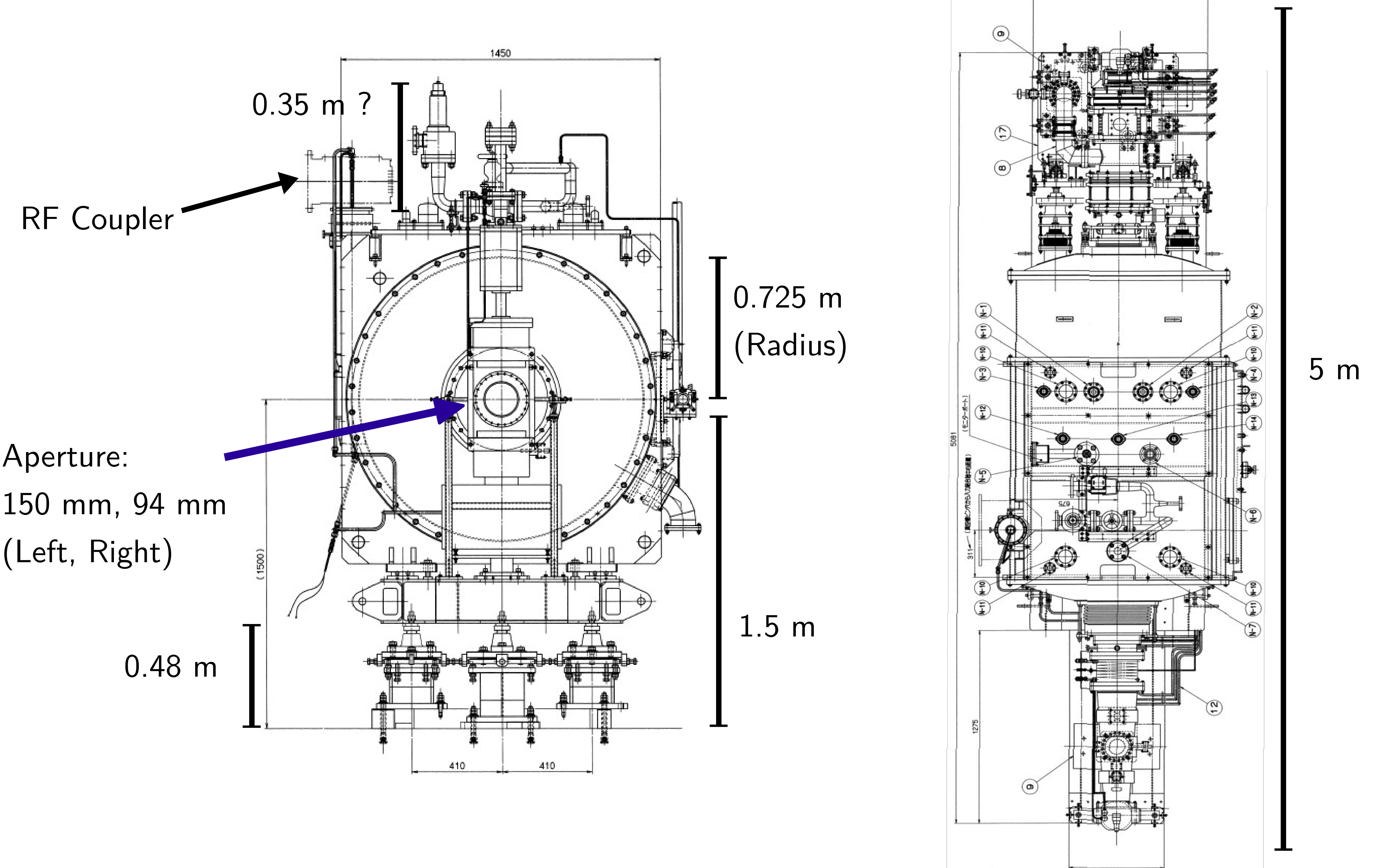
High current operation: 4-5 months

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

Courtesy KEK-B

KEK-B Cryostat

Weight: 5830.5 kg



Courtesy KEK-B

Prelim RF & Cryo Specs

Heat load

- Static: 15 W (He), 110 W (LN2)
- Dynamic: 50 W (He) corresponds to 1.5 MV kick

Volume of the Helium vessel: 400 L

- Both liquid and gas volumes are connected
- Cryogenic interfaces (Byonet drawings on web - .igs, .dwg)

Frequency tuning

- Static: 2 MHz possible for SPS 100ns bunch spacing
- Dynamic: 1 kHz/s, maximum range: 200 kHz (operations – 100 kHz)

RF power (Cavity $Q_0 > 1e9$)

- Presently using: 1.3-2 x 1×10^5 (55-120 kW)
- Alt Available: 1-1.3 x 1×10^6 (20 kW)

Feedback

- Orbit feedback (slow, 1 sec)

Courtesy KEK-B

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

Conclusions

- Key motivation: luminosity gain & leveling
  - Mainly a technical challenge but exciting R&D benefiting beyond LHC

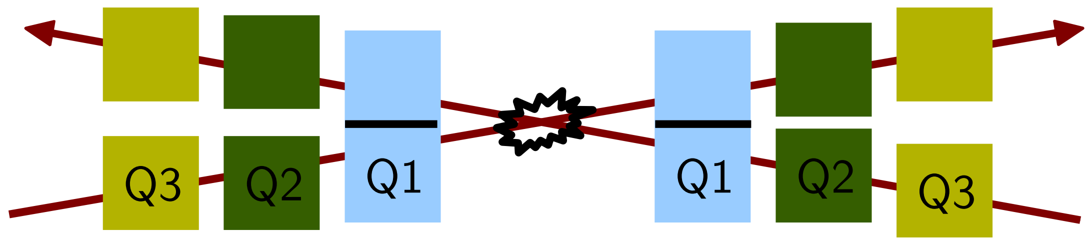
- KEK-B experience vital for LHC
  - Successful commissioning and operation with high currents (ξ: 0.09)
  - Noise experiments, OP scenarios for LHC

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

- Safety
  - Machine protection needs detailed study to evaluate failure modes
  - Device appropriate feedback to guarantee MP at ultimate intensities

"Crabs are safe in your garage, but that is not why they are built"

A1: Possible Future

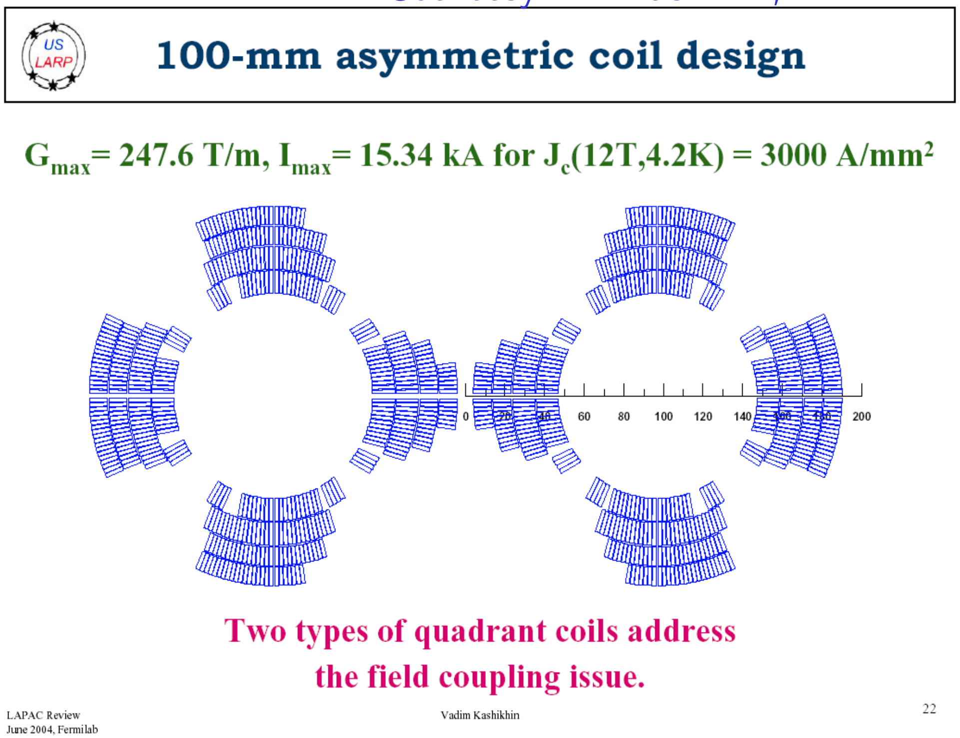


Proposed in 2006 but was abandoned due to large x-angle (5 mrad ?)

+

Flat Beams ?

Courtesy: V. Kashikin, FNAL



No parasitic collisions

Independent & easy IR optics

R. Gupta, BNL & Crab Team