LHC Crab Cavities

Rama Calaga, BNL-LARP

CARE-HHH, Nov 25, 2008

Ack: K. Akai, R. Assaman, J. Barranco, I. Ben-Zvi, O. Bruning, O. Brunner, G. Burt, E. Ciapala, L. Evans, R. Garoby, K. Hosayama, N. Kota, J. P. Koutchouk, T. Linnecar, Z. Li, A. Morita, Y. Morita, K. Oide, R. Tomas, J. Tuckmantel, A. Seryi, N. Solyak, Y. Sun, T. Weiler, L. Xiao, V. Yakovlev, F. Zimmerman

Outline

- History & Motivation
- Project status & global collaboration
- Future plans

Brief History

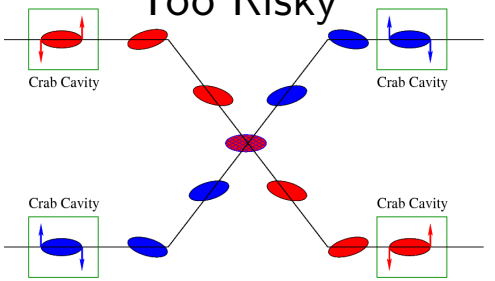
CARE-HHH & LARP

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

Too Risky



KEK–B CCs observes
less gain than expected

More MDs planned
CERN/LARP Participation

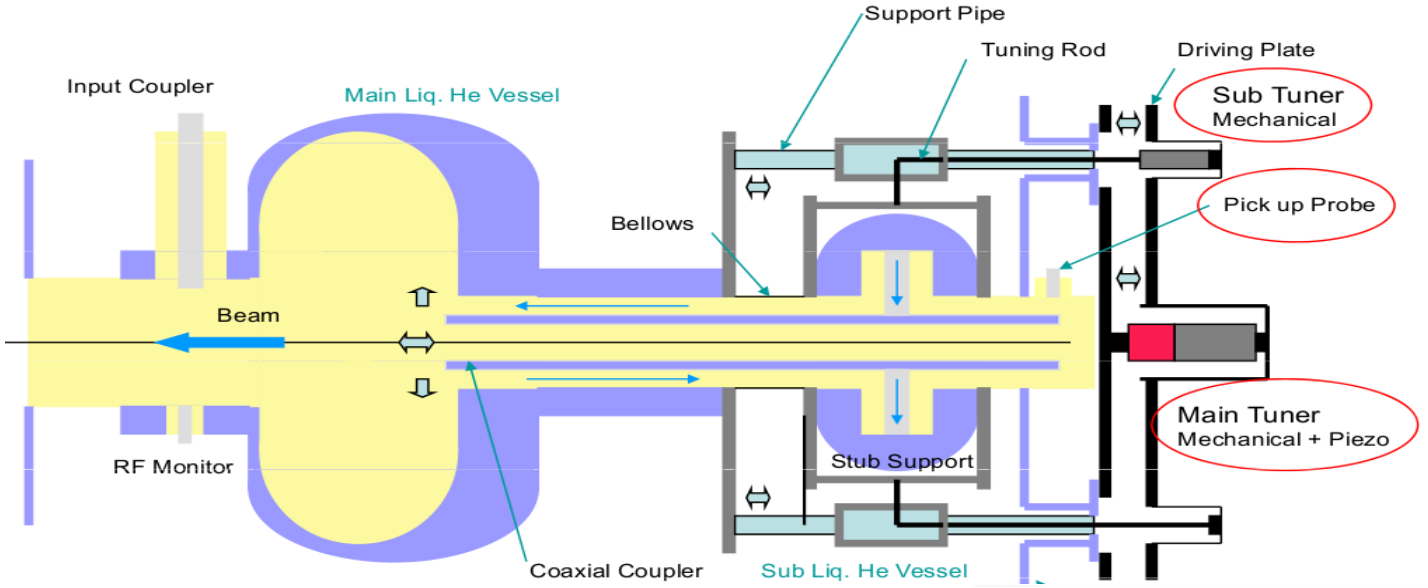
FY08 – LHC–CC08
Global Collaboration
US–LARP/EUCARD–CI–DL/KEK
CERN

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

Future
LHeC, Super KEK–B, LC, ...

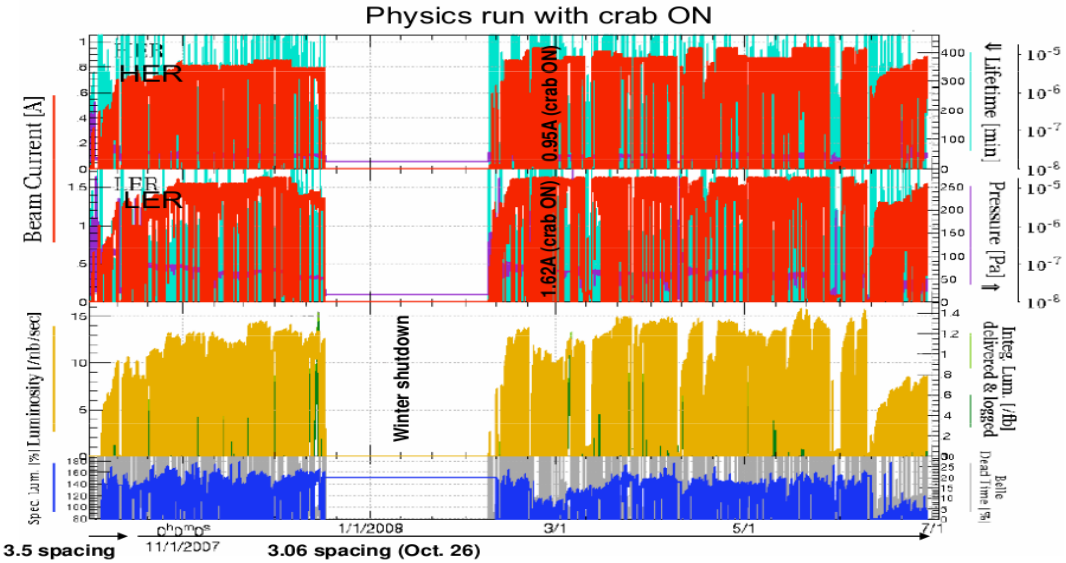
KEK-B Crab Cavities

- No serious instabilities with high currents (1.62/0.9 A) with crab cavities
- Trip rate needs to improved for more reliable operation



Y. Morita et al (KEK-B)

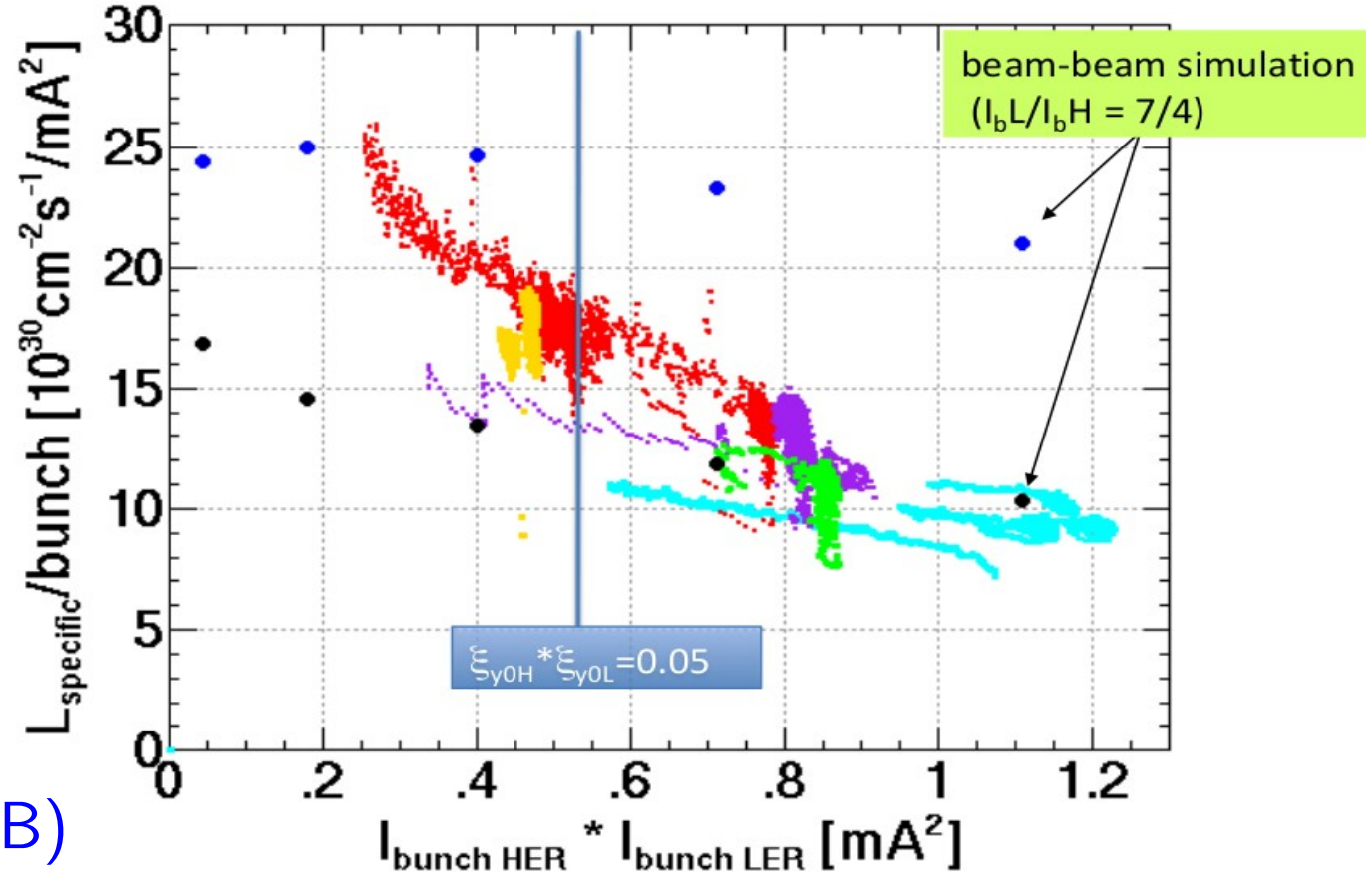
KEK-B experiments to probe many LHC related concerns (Dec 08, Spring 09)



KEK-B Crab Crossing

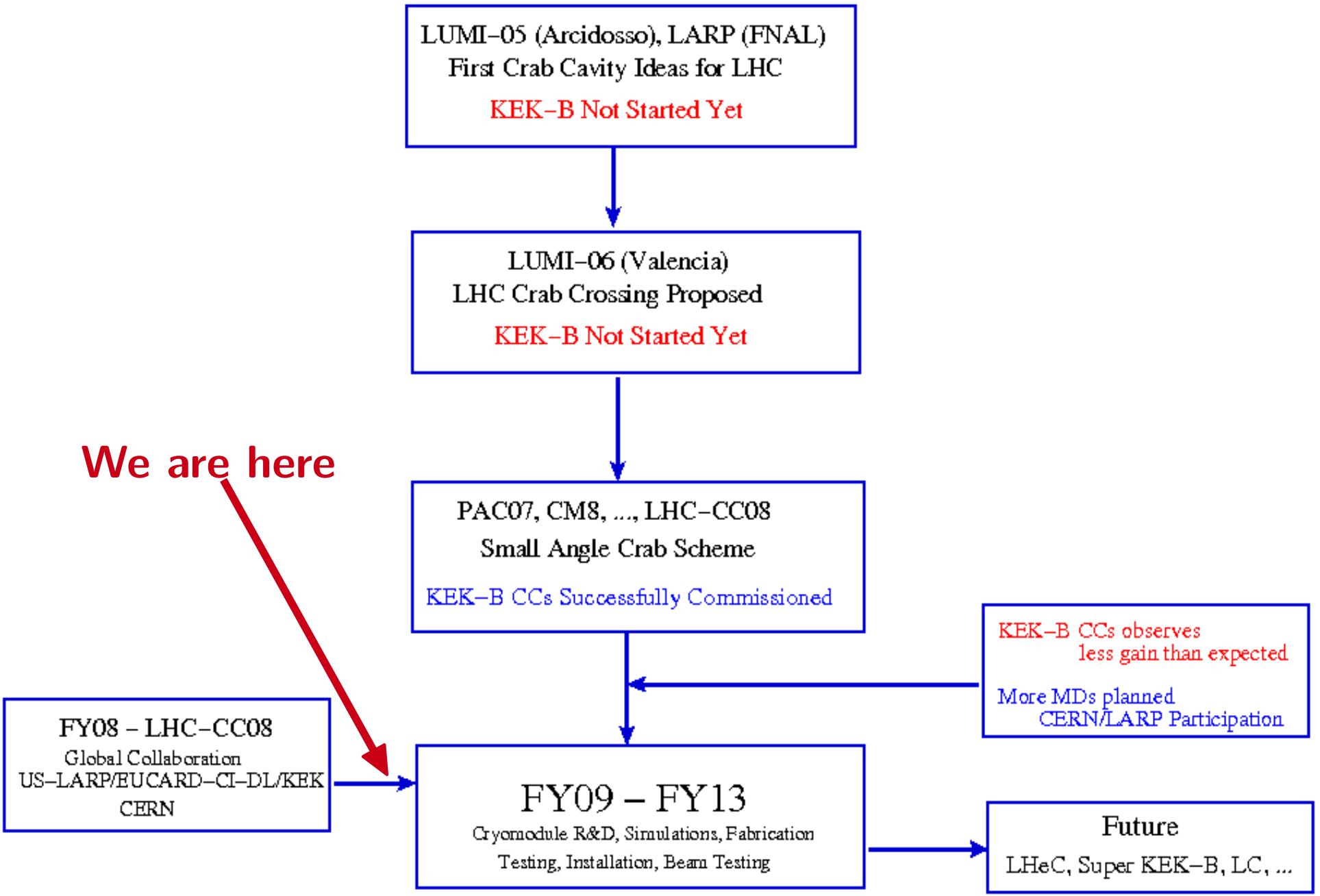
• Successfully commissioned & operated ! Observe degradation in lifetime at very high currents. Also asymmetry in lifetimes with +/- horizontal offsets

• Linear optics, dynamic beam-beam "perhaps" the reason. This will not be concern for LHC due to much smaller beam-beam parameter



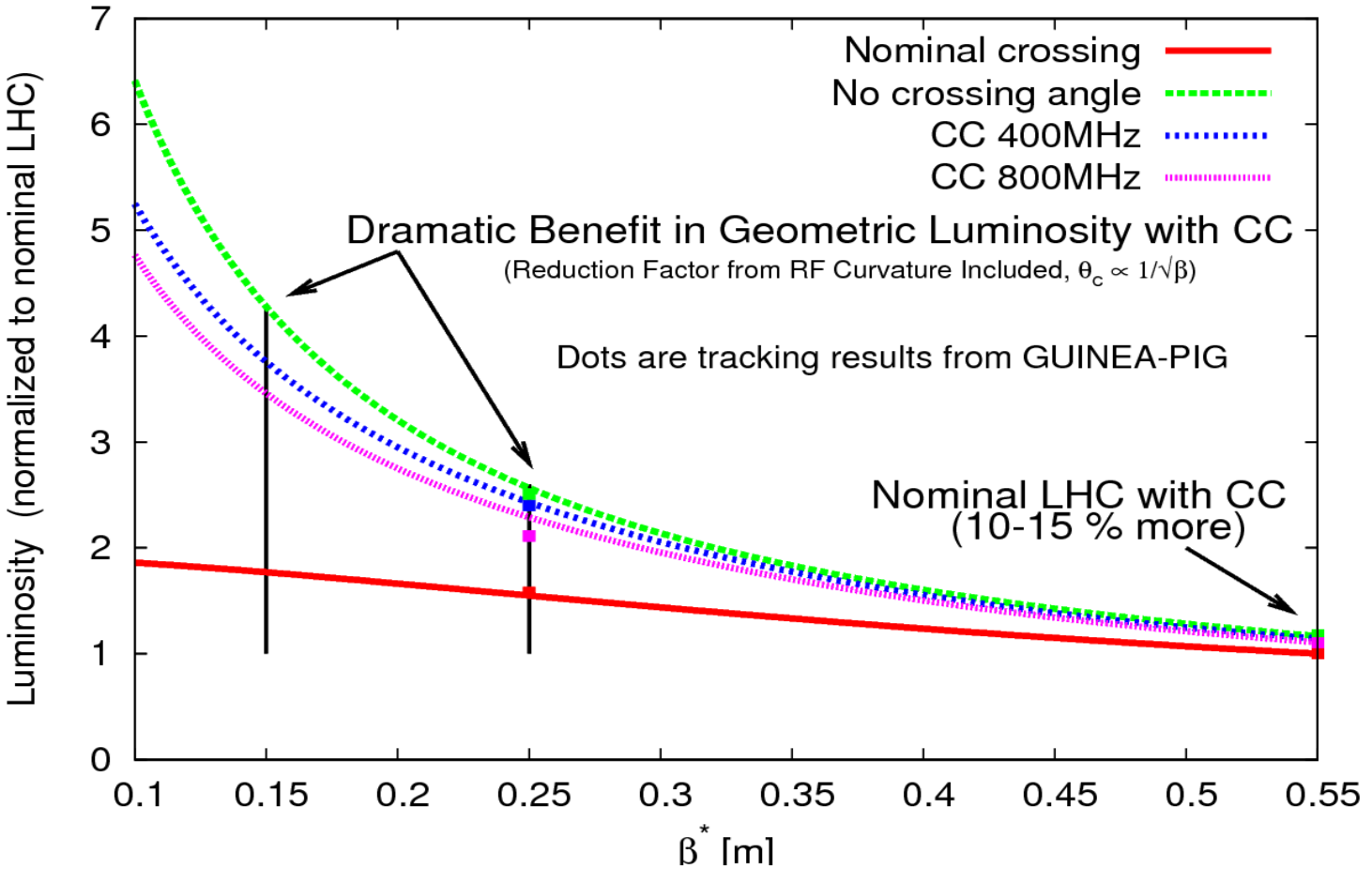
K. Ohmi (KEK-B)

Brief History

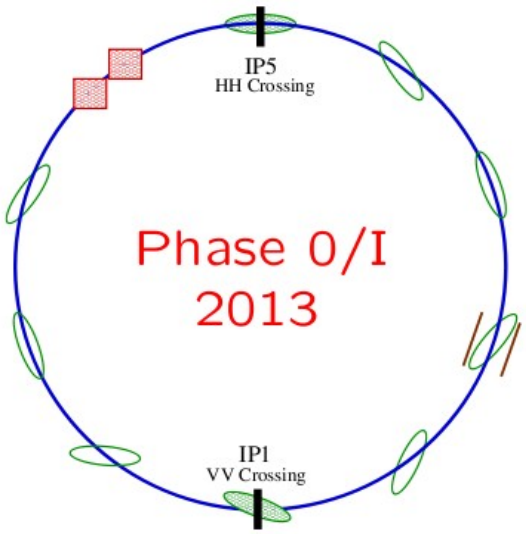


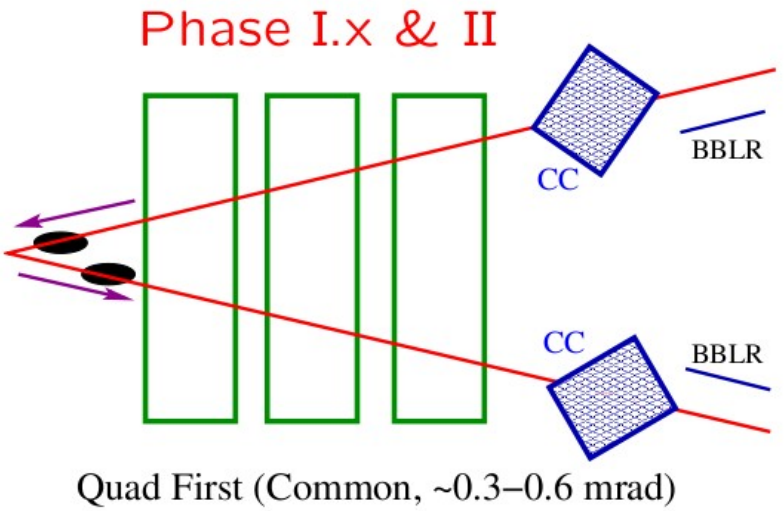
LHC Motivation

- ~ 50% or larger luminosity gain for 25 cm or smaller beta*
- Natural luminosity leveling knob, explore beyond the BB limit
- Global interest in crab cavities technology, exploit synergies



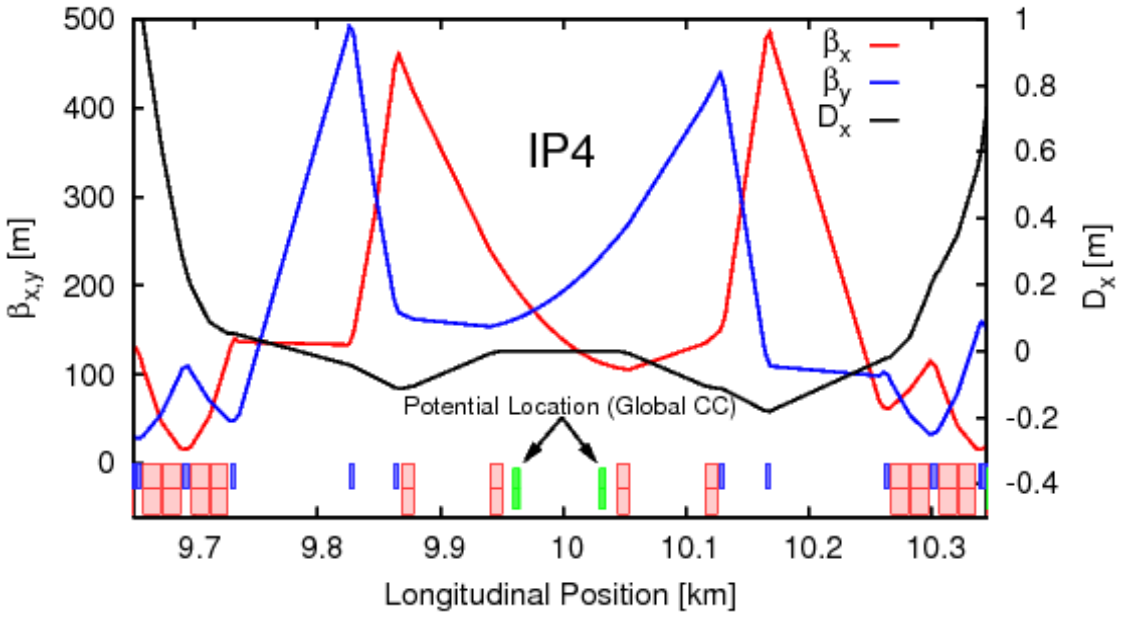
Scenarios





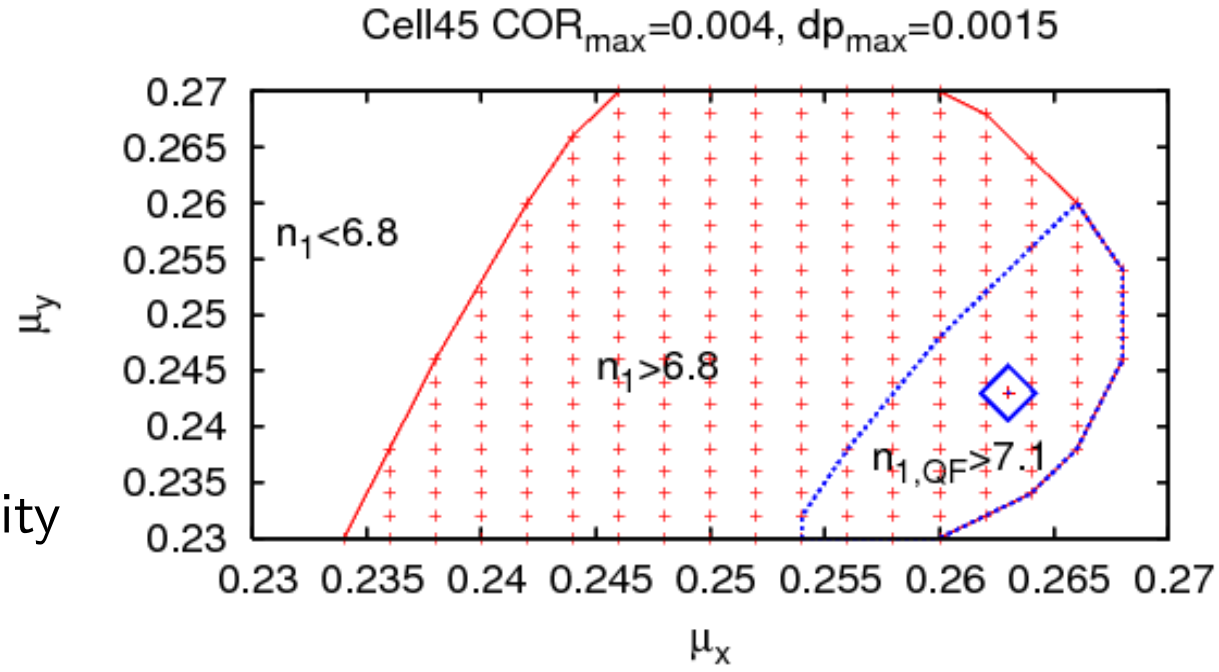
- Prototype test, first critical step (circa 2012-13)
- Proof of principle to progress to full crab crossing (circa 2016)
- 800 MHz elliptical cavities for prototype test is optimum
  - Compromise between RF curvature & physical space

IR4 Optics & Flexibility

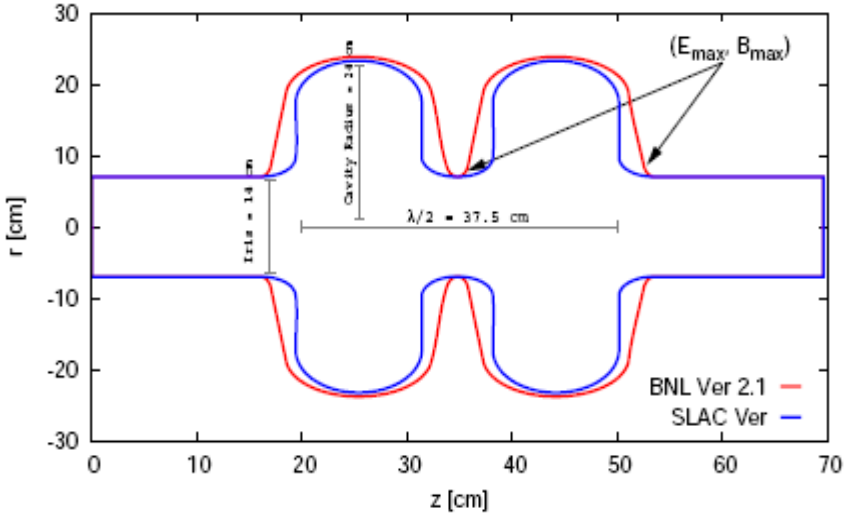


Optics to be modified to increase beta function at the crab cavity

Phase adv scan shows considerable amount of flexibility

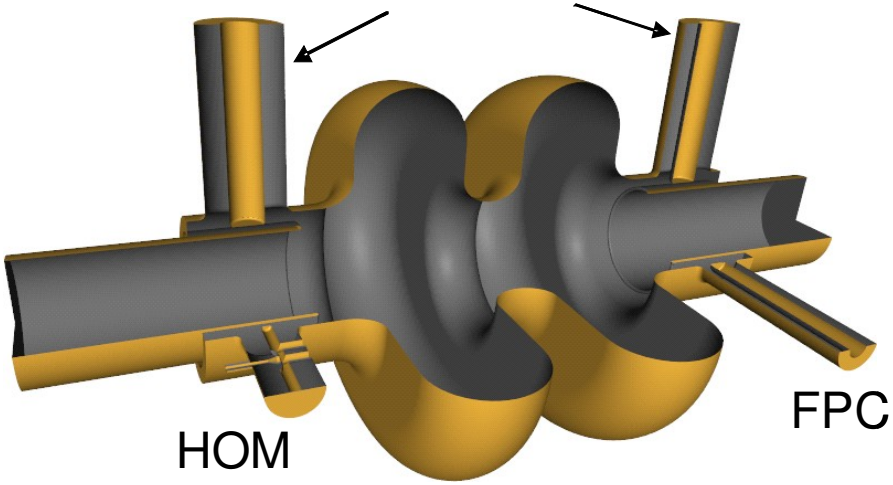


Prototype Cavity/Couplers

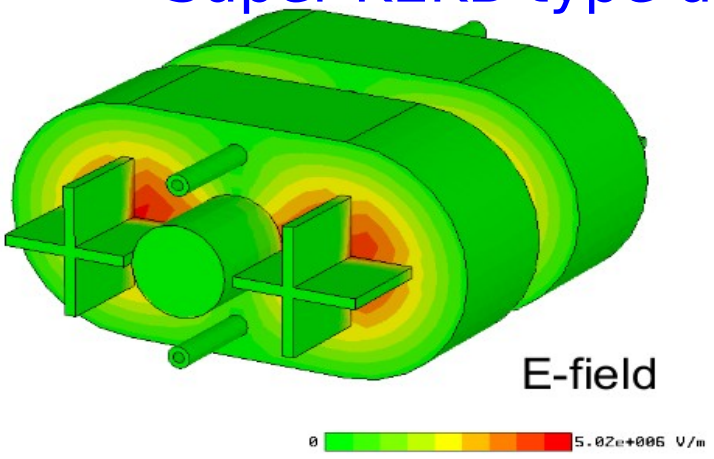


LOM/SOM

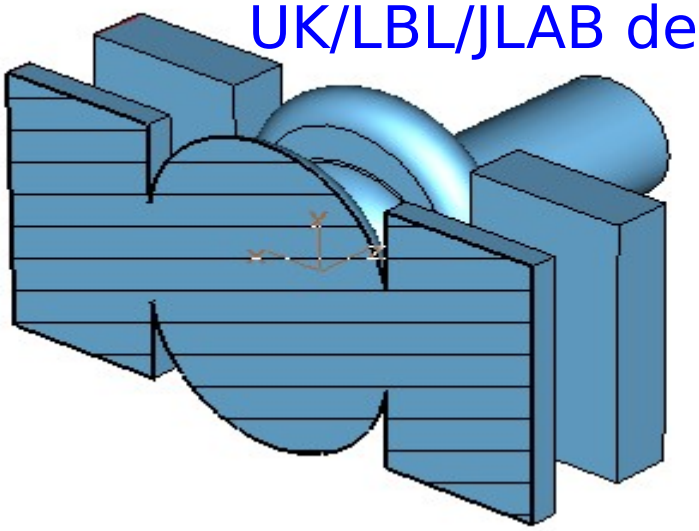
LARP design



Super-KEKB type design



UK/LBL/JLAB design



** Down-Selection within 1yr

Merit Sheet, Down Selection

Gradient of 2.5 MV for 2-Cell Cavity

Parameter	BNL-SLAC		UK	KEK-B
	6 deg	0 deg		
Epk [MV/m]	26	25		
Bpk [mT/MV/m]	154	83		
R/Q [ohms]	128	117		120
cell-to-cell coupling				
Beam pipe radius [cm]	7	6		
Transverse size (Equator Radius)	23.8	23.3		
Loss factor (longitudinal)	0.54	0.43		
Transverse loss factor	2.64	2.16		

LOM, R/Q, Qext				
SOM: R/Q, Qext				
HOMs: R/Q, Qext				
Multipacting				
Fabrication				

Under Construction

Aperture Constraints

Prototype, No problem

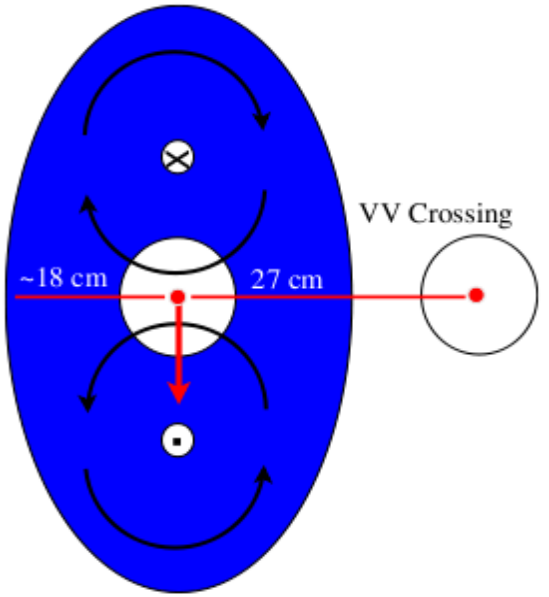
LHC prelim beam-pipe aperture:

Magnet	Ap-H[mm]	Ap-V[mm]	Tesla	L [m]
D1	134	110	7	10
D11	106	70	7	10
Crab Cav	**84** (>110 preferred)		-	-
D12	78	60	4	10
D2 (present)	69	53	3.85	10

Can D_1 be RHIC DX modules ? (being checked by R. Tomás & R. De-Maria)

Cavity Size (units in mm):

	Global (IR4)	Local (IR1-5)
Beam-Beam	420	270
Beam pipe	50	
Avail Space	340-360	190-210
Crab cavities	230	180 (VV)



Aperture Constraints

Local CCs, Very Tight Elliptical Cavities

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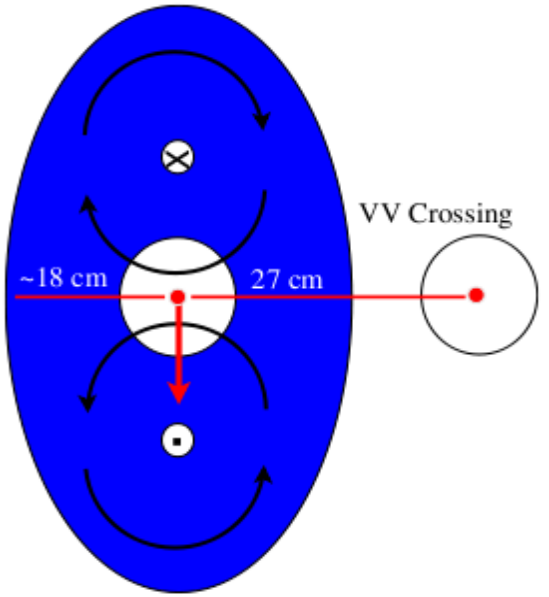
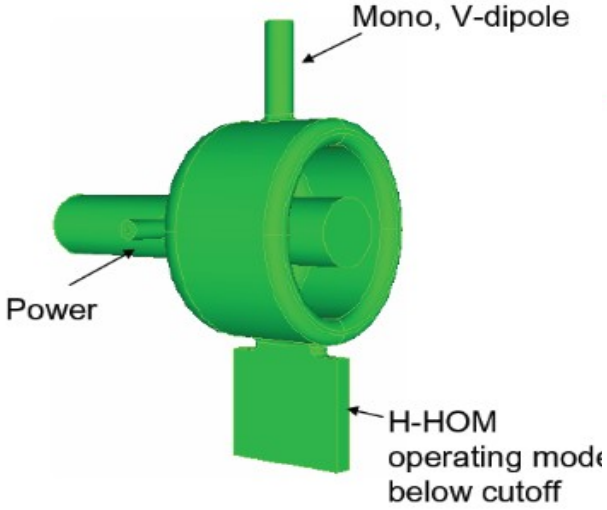
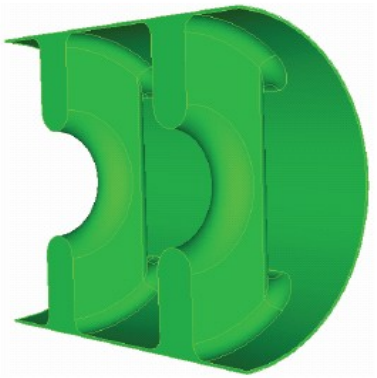


Compact Structure, Phase II

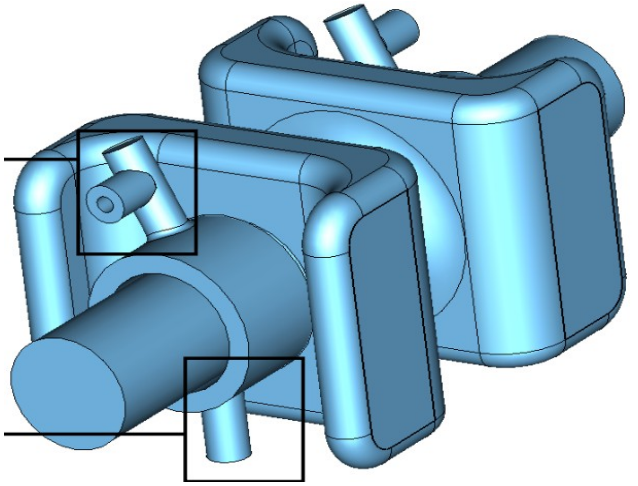
SLAC ½ Wave & Spoke Structures



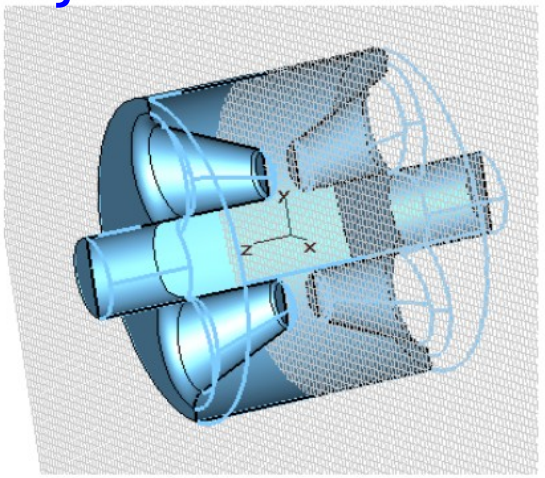


spoke-cell

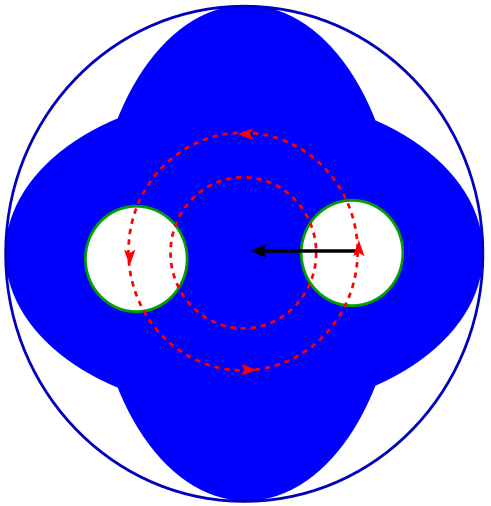
FNAL Mushroom Cavity



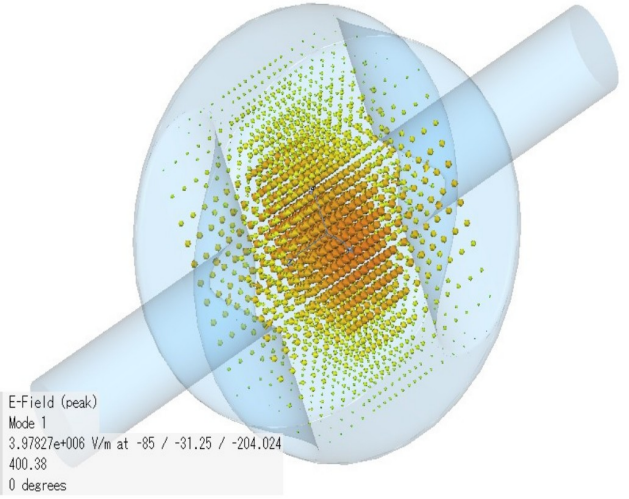
UK-JLAb Rod Structure



BNL TM010, BP Offset

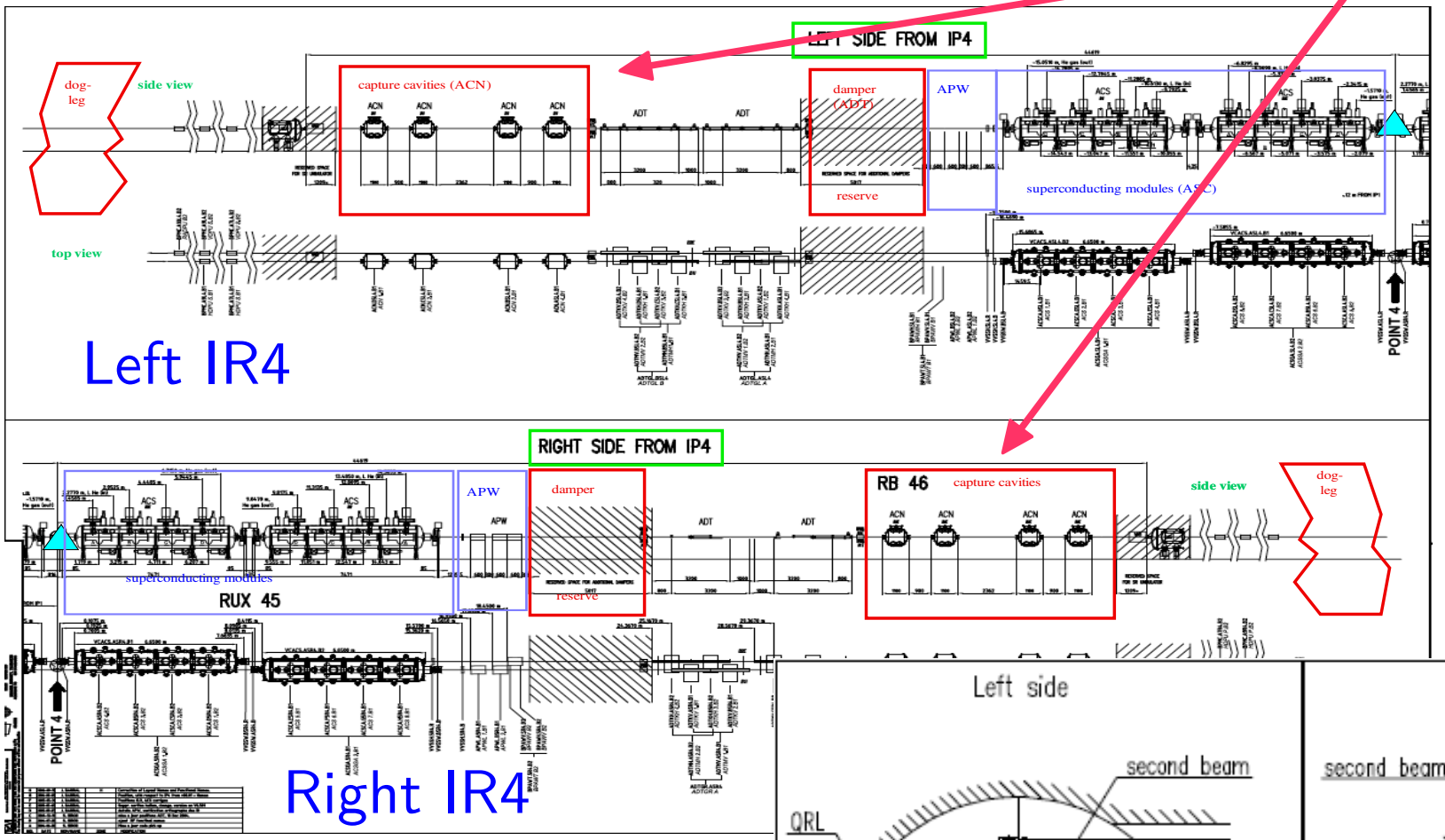


KEK Kota Cavity



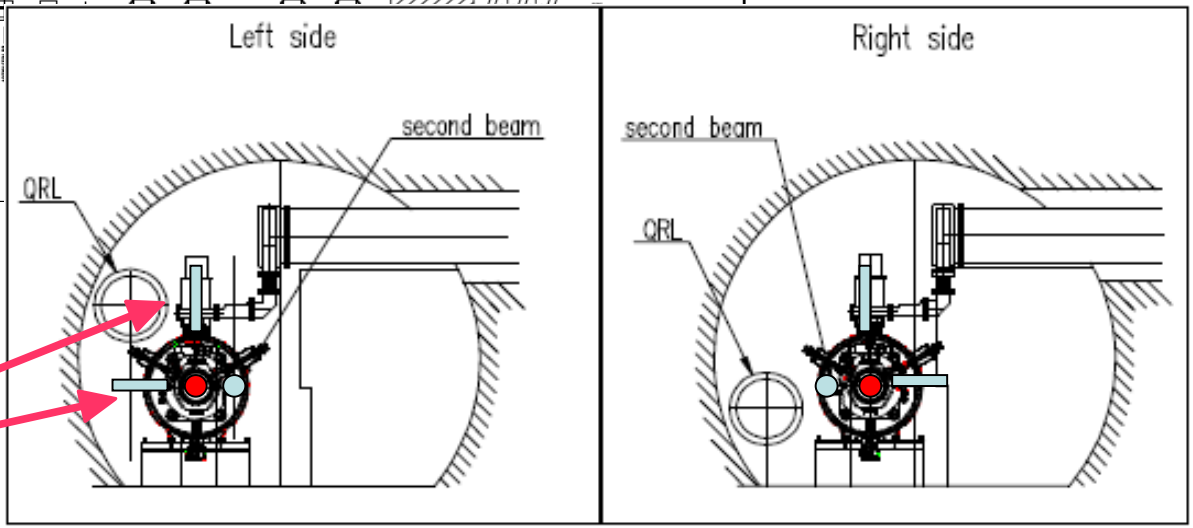
Prototype: IR4 & Cryostat

Potential Locations



Left IR4

Right IR4

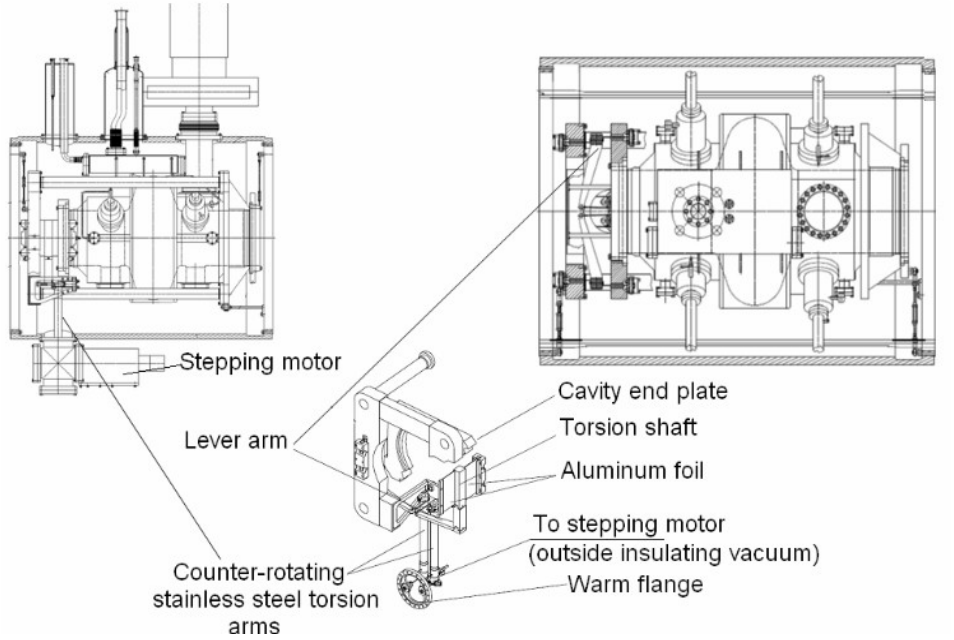


Tunnel cross-section

N. Solyak et al, (FNAL)

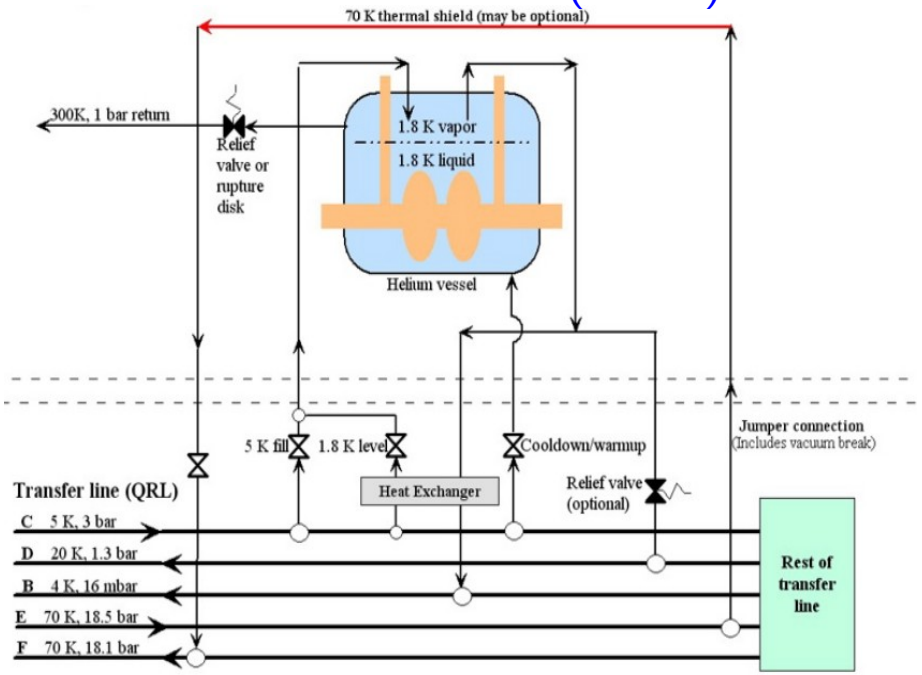
FPC & HOM Couplers

Tuners/Cryo



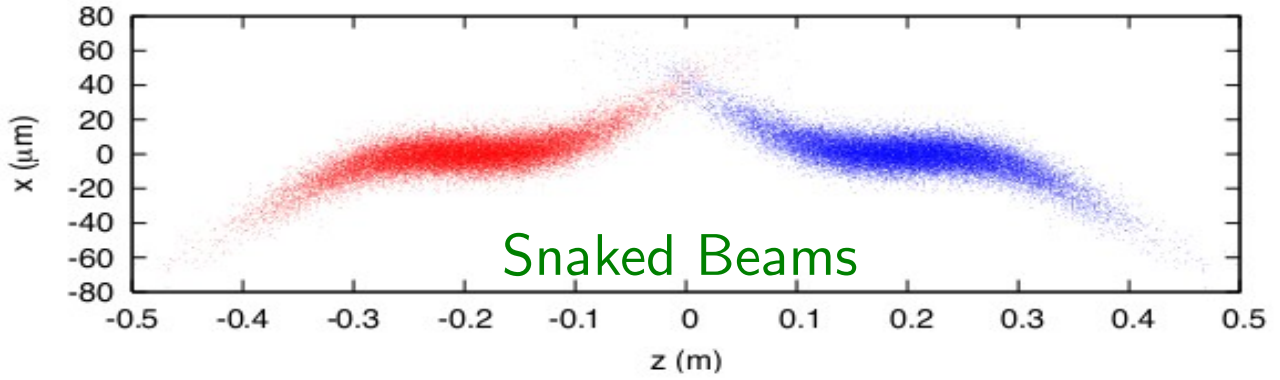
CERN Main RF Tuner

T. Peterson et al (FNAL)



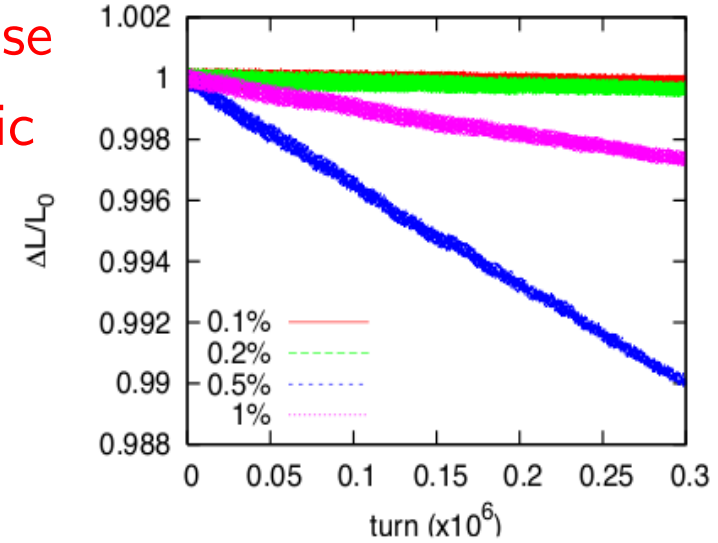
- Use LHC main RF type mechanical tuner, "perhaps coupler-based tuner"
- Evalution of cryo circuit for 2K -or- 4K from the QRL to cavity
- 2K -or- 4K under discussion (4K easier, extension of main RF cryo-line)

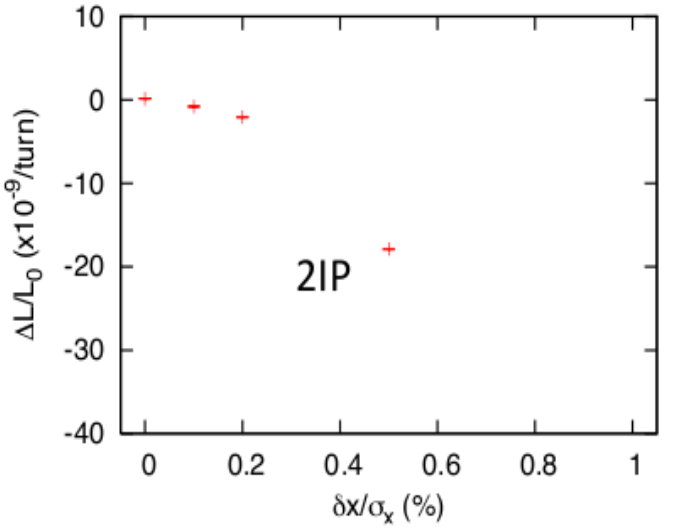
Noise & Beam-Beam (K.Ohmi)



- Strong-strong and weak-strong BB simulations show no problem with 800 MHz
- Noise tolerances from SS simulations for fast noise is ~0.1% for 1-day lifetime

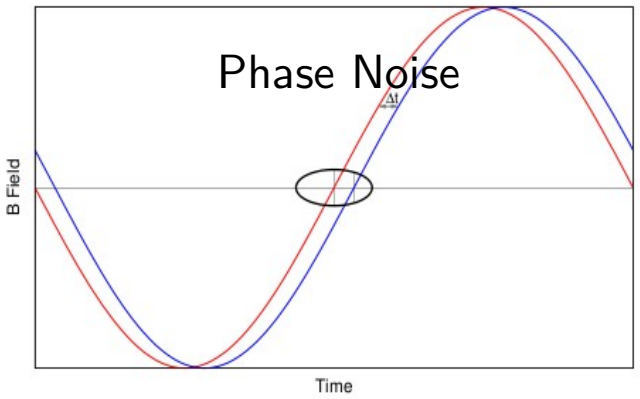
White Noise
Pessimistic



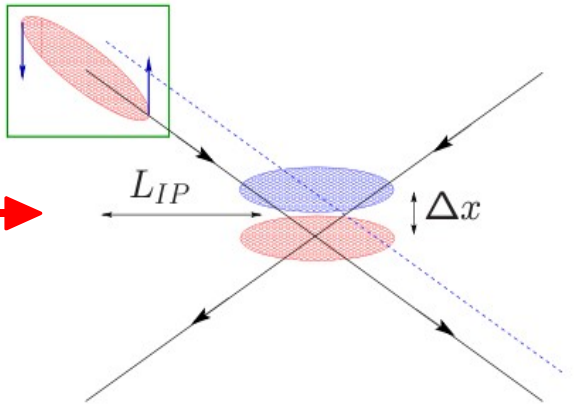


Noise & Beam-Beam

Possible with today's technology

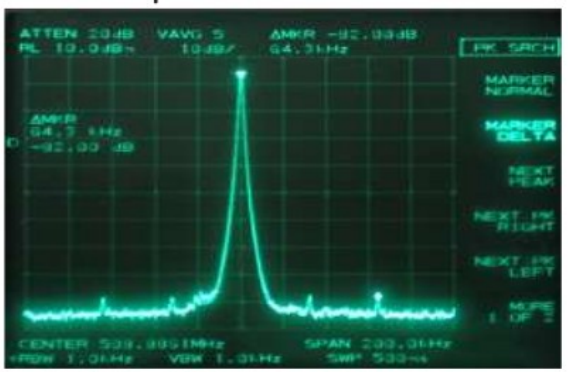


IP Offsets



- Phase noise within tolerances even with pessimistic white noise (~1x10^{-3} deg)
- KEK-B measurements show that noise side-bands are NOT white, weak-strong simulations show almost no emittance growth for the noise amplitude

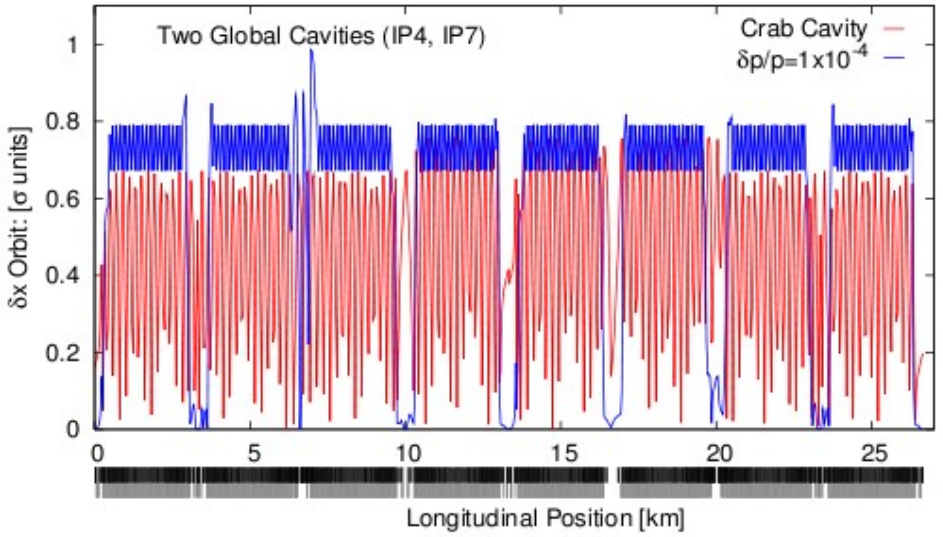
Span 200 Hz KEK-B Span 200 kHz

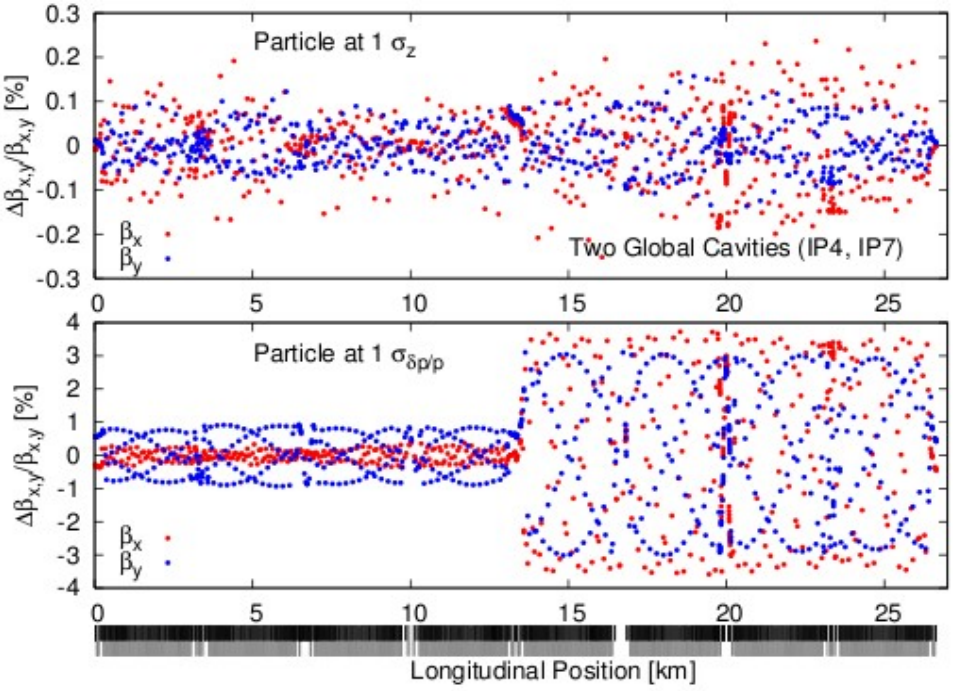


More KEK-B experiments anticipated

Collimation & Aperture

- Additional aperture due to head-tail oscillations (z-dispersion)
- Beta-beat induced from the crab cavity is negligible compared to chromatic beta-beat

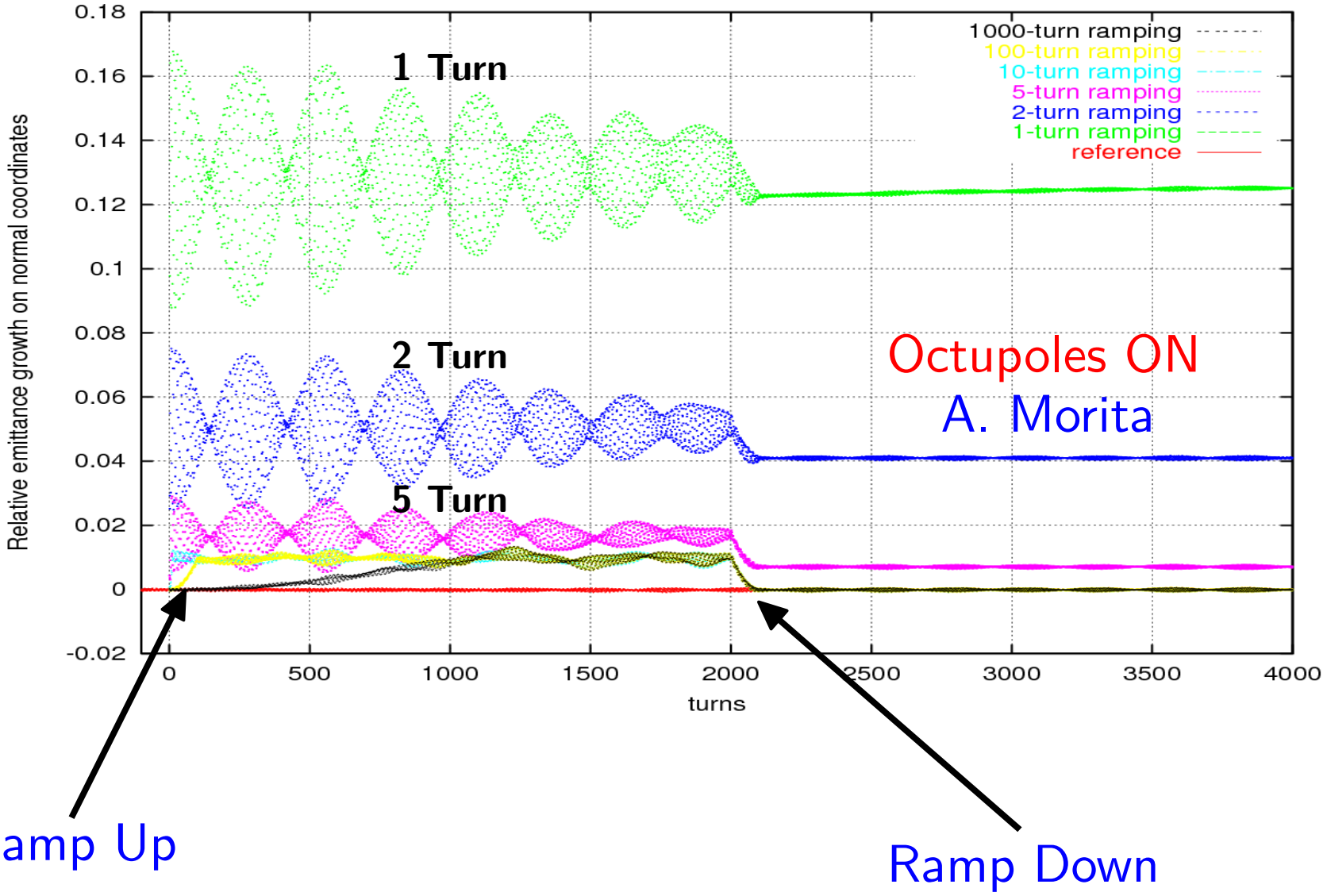




Detailed tracking underway with crab cavities to compare loss maps & cleaning efficiency. Perhaps a modification of the nominal collimation scheme if needed

Crab Cavity Ramping

More than 10 turns has negligible emittance growth (natural for high-Q cavities)



CERN Workshop, Aug 21, 2008

Purpose

Establish CERN interest in installation, various validity requirements and a firm plan for the crab cavity installation into the LHC compatible with the phase I upgrade.

Statement of Interest

Date: 07/23/2008
To: workshop organizers
Cc: Lyn Evans

J. P. Koutchouk

After discussion with the LHC Project Manager (Lyn Evans), I will be in position in the August miniworkshop to say that CERN is indeed interested by the R&D on crab cavities, given their large potential in increasing the LHC performance. It shall be possible to install crab cavities as soon as they are available, at the condition that they cause no loss of performance, i.e. that they are properly integrated and are not seen by the beam when not used.

The interest of KEK, in addition to US-LARP and FP7-EuCARD is very much welcome.

Given the potential & possibility for leveling, experiments support strongly and are willing to put CC commissioning in the general schedule (A. Nessi, ATLAS)

Some Recommendations, CERN

- Hardware must be extensively tested before installation in the tunnel & LHC performance shall not be reduced, even if hardware fails

- The time available to build hardware.... leaves no other possibility than elliptical cavities at 800 MHz
  - Moreover, the detailed layout of the insertions for Phase 2 and their integration in the tunnel is not yet known. For both of these reasons, I think unrealistic to state that the hardware developed for the validation test will be the one finally used in operation.

- A large enough effect on luminosity must be aimed at for the demonstration to be convincing. Setting the goal at $\sim+10\%$ implies the installation of two crab structure to provide $\sim$5MV kick voltage/beam

A comprehensive list of requirements for the cryomodule installation and beam testing layout will be prepared by CERN in due time.

Contributions

- LARP
  - FY09 is good and expected to ramp up in the following years
  - All proposed activities to continue, focus on cavity/coupler
- UK/CERN
  - FP7 Budget allocated sufficient for:
    - Cavity/coupler studies, LLRF, warm model & testing (UK)
    - Beam simulations, optics and installation issues (CERN)
  - Perhaps an increase in the following yrs, experimental contributions (?)
- KEK
  - Cavity/coupler simulations based on super KEK-B type structure
  - Waiting for funding approval, will contribute in the framework of the collaboration
- SBIRs
  - AES-BNL/FNAL/LBL/SLAC (cavity, couplers, cryostat, tuner)
- Other Collaborators
  - Tsinghua University: Warm models & testing (in collaboration with UK work)
  - Jlab: Very interested. Some activity ongoing on rod type compact structures

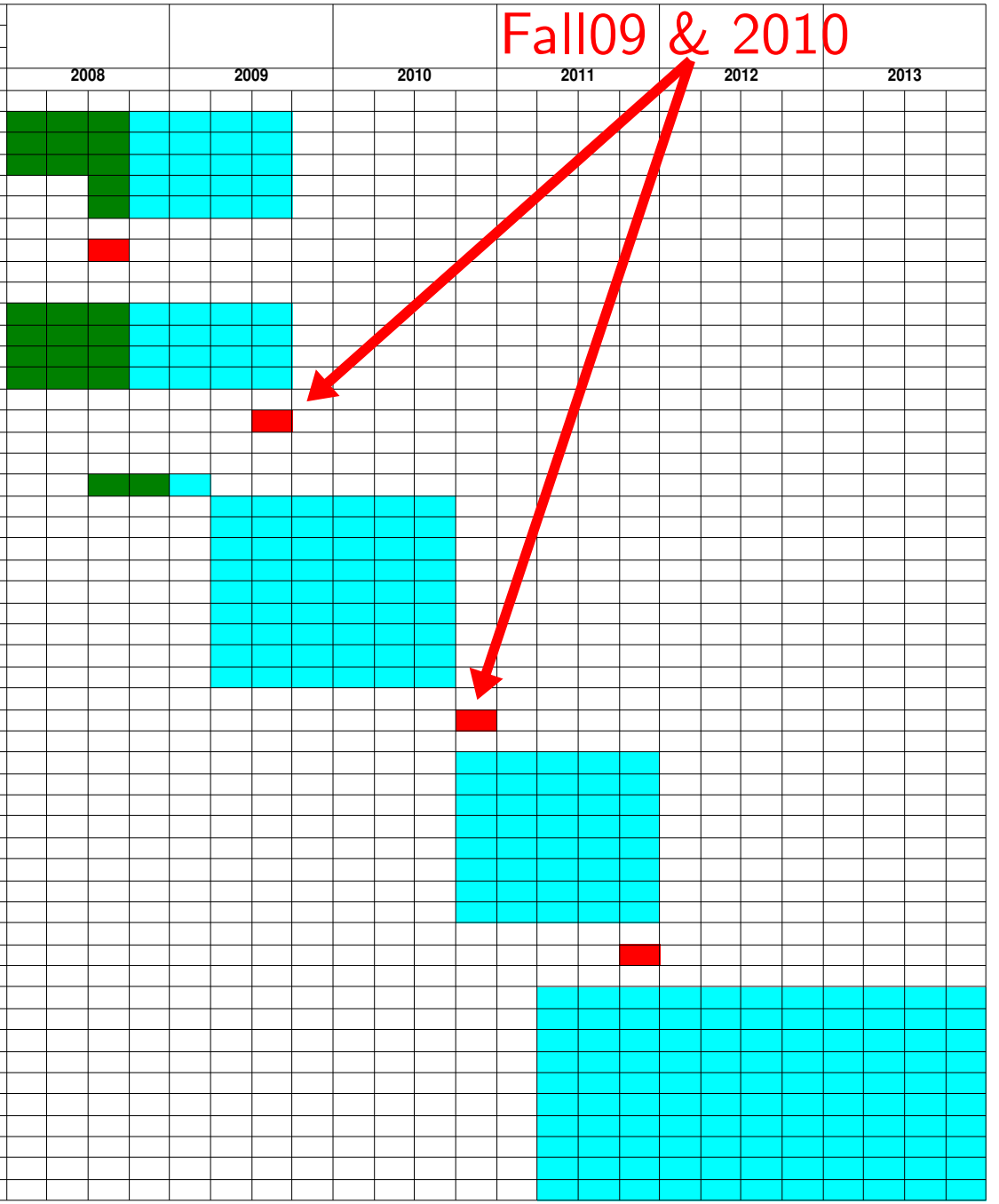
Preliminary Schedule

Critical Reviews

Fall09 & 2010

LHC Crab Cavities
Rama Calaga

WBS	Task	POC	Status	Start Date	Finish Date
1	**Beam Simulations**				
1.1	Beam-beam	Sen/Calaga	In progress	05/01/06	08/30/09
1.3	Optics	Tomas	In progress	05/01/06	08/30/09
1.4	Impedance	Zimmermann	In progress	02/01/08	08/30/09
1.2	Collimation	Tomas	In progress	08/21/08	08/30/09
1.5	OP Scenarios	Calaga	In progress	12/01/08	08/30/09
	Program Review (CM11)				
2	**Cryomodule R&D**				
2.1	Cavity Design	Calaga	In progress	01/01/06	08/30/09
2.2	Coupler Design	Seryi	In progress	03/01/08	08/30/09
2.3	Cryostat Design	Solyak	In progress	03/01/08	08/30/09
2.4	Tuner	Solyak	In progress	03/01/08	08/30/09
	Confirmation of Parameters				
3	**Cryomodule Validation**				
3.1	Space Constraints	Ciapala	In progress	08/21/08	03/15/09
3.2	Personal & Hardware	CERN	Not Started	03/15/09	11/01/10
3.3	Tunnel Layout	CERN	Not Started	03/15/09	11/01/10
3.4	Cryogenics	CERN	Not Started	03/15/09	11/01/10
3.5	Survey & Alignment	CERN	Not Started	03/15/09	11/01/10
3.6	Radiation Issues	CERN	Not Started	03/15/09	11/01/10
3.7	Cavity Control	CERN	Not Started	03/15/09	11/01/10
3.8	Synchronization Control	CERN	Not Started	03/15/09	11/01/10
3.9	Slow Control	CERN	Not Started	03/15/09	11/01/10
3.1	RF Power	CERN	Not Started	03/15/09	11/01/10
	Design Review				
4	**Fabrication**		Not Started	11/01/10	05/01/11
4.1	Cavity Fabrication		Not Started	11/01/10	05/01/11
4.2	Main Coupler		Not Started	11/01/10	05/01/11
4.3	LOM/SOM/HOM Couplers		Not Started	11/01/10	05/01/11
4.4	Cryostat		Not Started	11/01/10	05/01/11
4.5	Tuner		Not Started	11/01/10	05/01/11
4.6	RF Power Source		Not Started	11/01/10	05/01/11
4.7	LLRF		Not Started	11/01/10	05/01/11
	Inspection Review				
5	**Assembly**		Not Started	05/01/11	12/31/13
5.1	Cavity VTA		Not Started	05/01/11	12/31/13
5.2	Cav/Coupler Assembly		Not Started	05/01/11	12/31/13
5.3	Cav/Coupler Testing		Not Started	05/01/11	12/31/13
5.4	Cryostat Integration		Not Started	05/01/11	12/31/13
5.5	Full Systems Test		Not Started	05/01/11	12/31/13
5.6	Tunnel Prep		Not Started	05/01/11	12/31/13
5.6	Installation		Not Started	05/01/11	12/31/13
5.7	Survey & Alignment		Not Started	05/01/11	12/31/13
5.8	RF Powering		Not Started	05/01/11	12/31/13



Conclusions

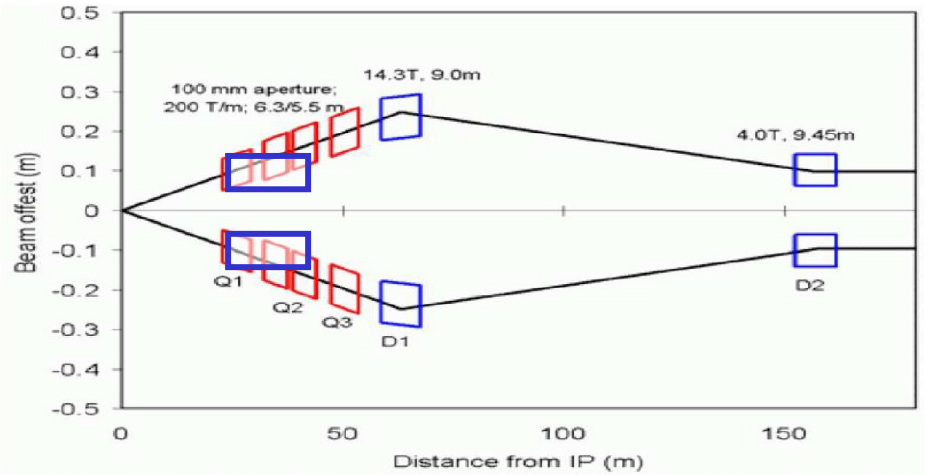
- The strong potential and global interest in R&D for crab cavity technology makes it most ideal for LHC upgrade

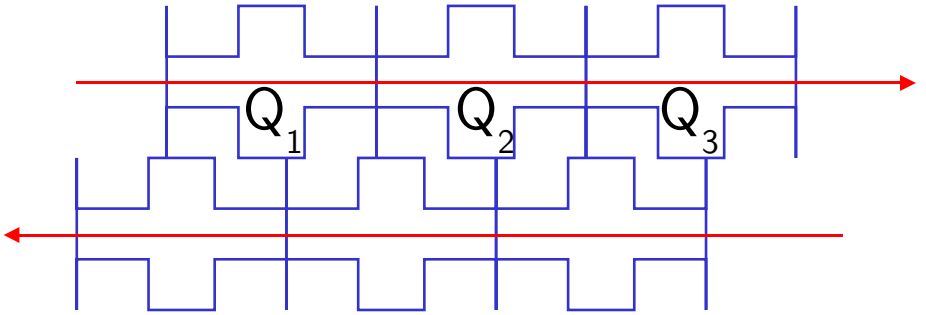
- Significant amount of R&D (CARE/KEK/LARP) has moved the concept of crab cavities to a substantial project (2004-08)

- Main challenge is to converge to a "single design" and resolve several hardware/operational concerns which will launch the fabrication phase (circa 2010-11)

- FY09 & future is very promising, first proof of principle in the LHC is critical

For the far future...



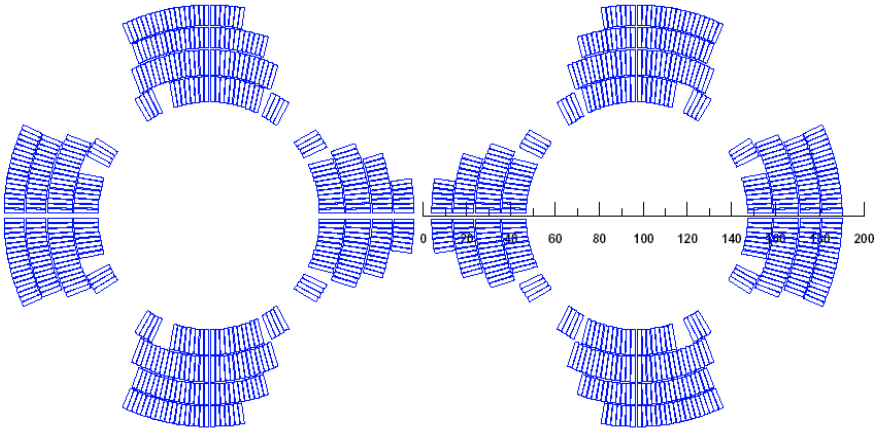


Courtesy: V. Kashikin, FNAL

US LARP

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.

Proposed in 2006 but could be considered if crab crossing is commissioned in phase I

Minimum X-Angle (4mrad ?)

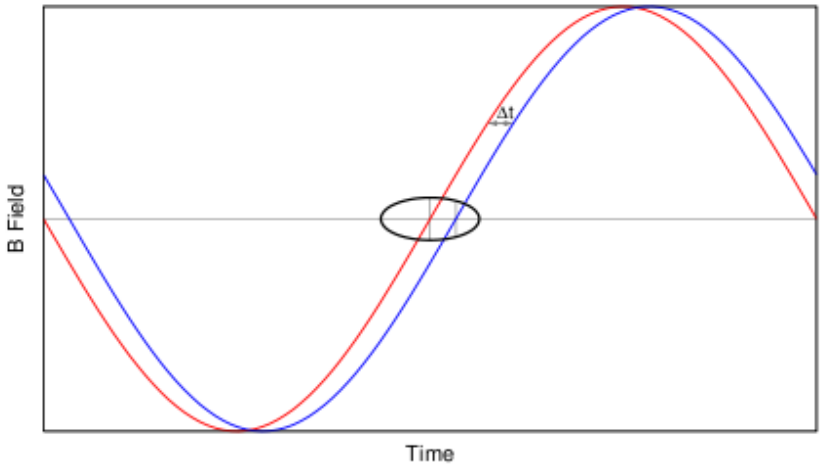
+

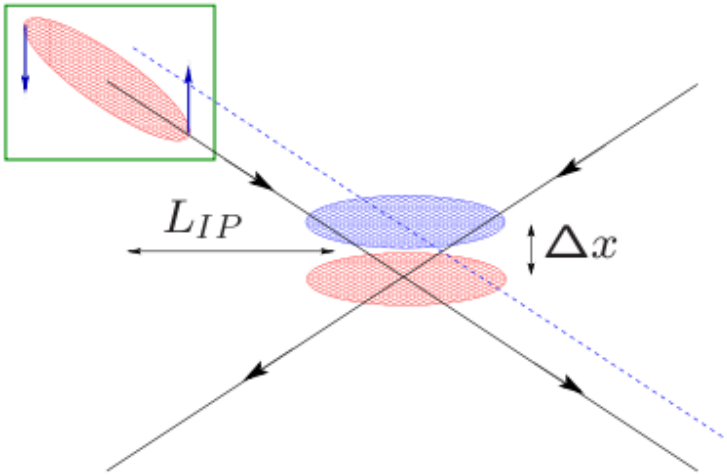
(Flat beams)

Backup: Noise & Beam-Beam

Phase jitter introduces random offset:

$$\left(\frac{\Delta\epsilon_x}{\Delta t}\right)_{BB} \approx n_{IP} f_r \frac{8\pi^2\xi^2}{\beta_x^*}(\Delta x)^2 \qquad \left\{\Delta x_{IP} = \frac{c\theta_c}{\omega_{RF}}\delta\phi\right\}$$





Random Dip Kicks: $\frac{1}{\epsilon}\frac{\Delta\epsilon_x}{\Delta t} \approx \frac{f_r(1-s_0)}{4\sigma_x^*\left(1+\frac{g}{2\pi|\xi|}\right)^2}(\Delta x)^2$ [Y. Alexahin]

For 1% Emittance Growth/Hr, gain=0.2 (Random turn-to-turn)

Jitter Estimate	Amp.	Phase	
		Beam-Beam	Dip. Kicks
Analytical	$\sim 0.04\%$	0.01° (0.006°)	0.006° (0.003°)
Simulation (WS)		0.002°	-
Simulation (SS, K. Ohmi)		$< 0.001^\circ$	
Feasible Today	0.01%	0.003°	

Backup: FY08 Milestones

- 1st LHC-CC workshop – big step forward to start international collaboration
- CERN consensus & strong support for LHC-CC prototype & installation in phase I commissioning stage
- Regular meetings to focus R&D of cryomodule, significant progress in design achieved in short period (7 months)
- IR4 location established by CERN-RF group for potential installation
- Preliminary beam simulations (beam-beam, collimation and impedance estimates) predict no show stopper
- Convergence to a baseline design within 1 year and design review in 2 years