CERN Academic Training: LHC Luminosity Upgrade

Crab Cavities

J. Tückmantel **11 June 2009**

Thanks to

Kazunori Akai, Rama Calaga, Kenji Hosoyama

Kazuhito Ohmi, Frank Zimmermann ….

for supplying figures, plots and information

Crab Cavities

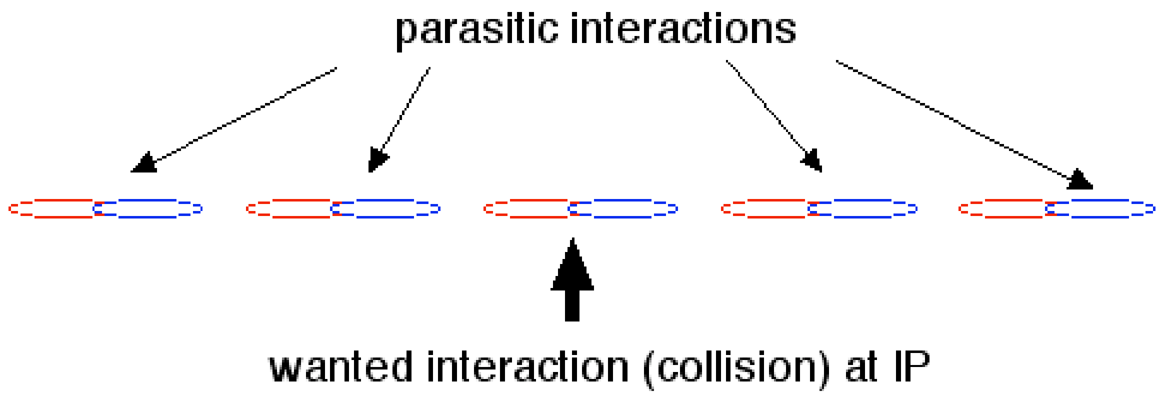
- What is it good for ?
- How to tilt bunches
- The first one: KEK-B Crab Cavity
- Technical difficulties for LHC
- Possible solutions
- Intermediate results from KEK test
- Outlook for LHC …

head-on collision

this proton might encounter this proton: **lumi**

Problem : Parasitic interactions (1 bunch / 25 ns   7.5 m)

electromagnetic + background events

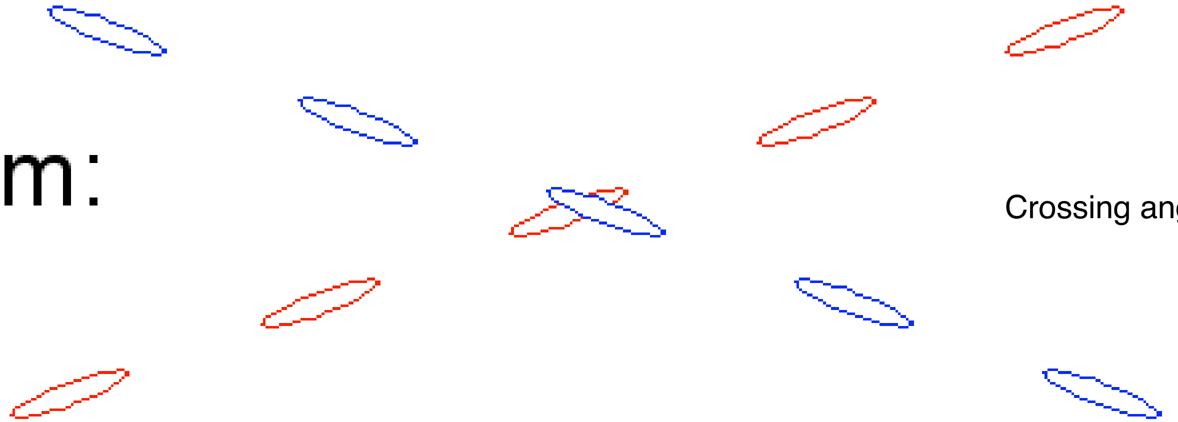


Mutual kicks limit possible bunch charge: loss in possible lumi

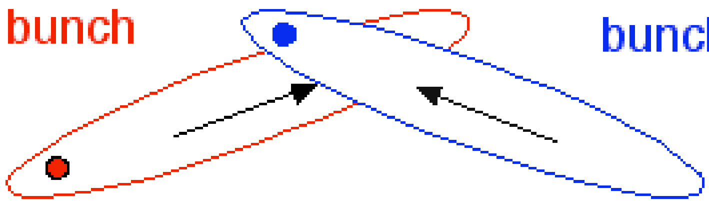
collision with non-zero crossing angle

(essentially) avoids parasitic interactions

Problem:



Crossing angle exaggerated !

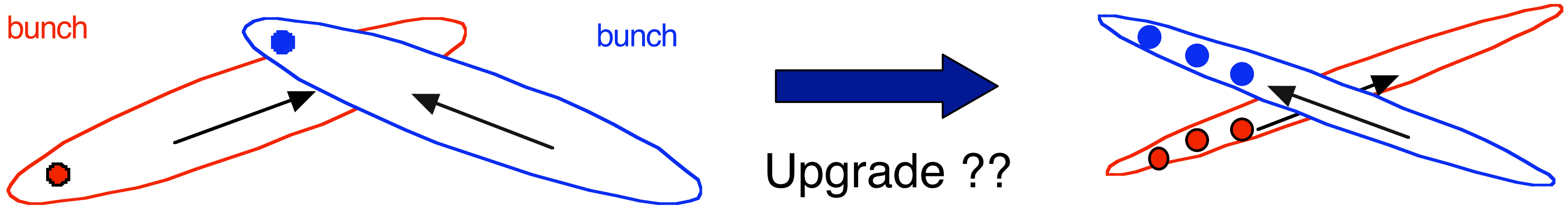


this proton NEVER encounters this proton: **loss in lumi**

Luminosity upgrade: lower β^*

transversely smaller bunches increases p-density:

increase of lumi



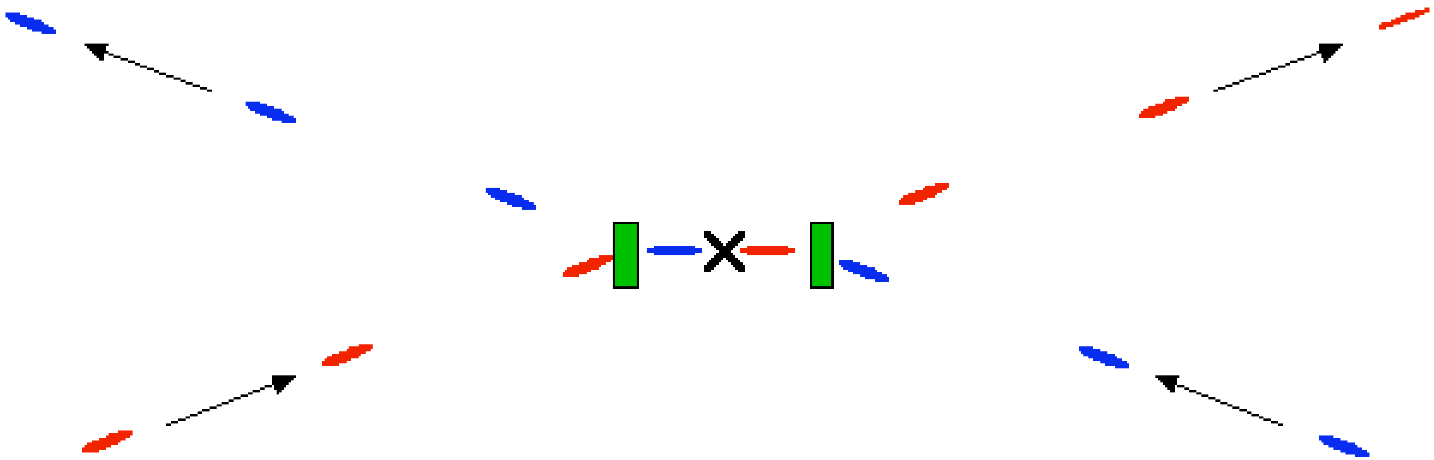
BUT: more protons in the 2 bunches can never to collide

lumi increase much less than ‘expected’

????????? what to do ?????????

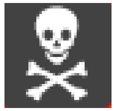
A ‘newer’ idea: “D0” (J.P. Koutchouk, ...)

beams have same charge: put a “little” magnet close to IP
—> inside the detector



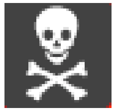
Problems:

- Magnet (+Supports, cable, ...) make shadow for forward event-tracks



HE physicist

- Magnet is ‘cooked’ + radiation-damaged



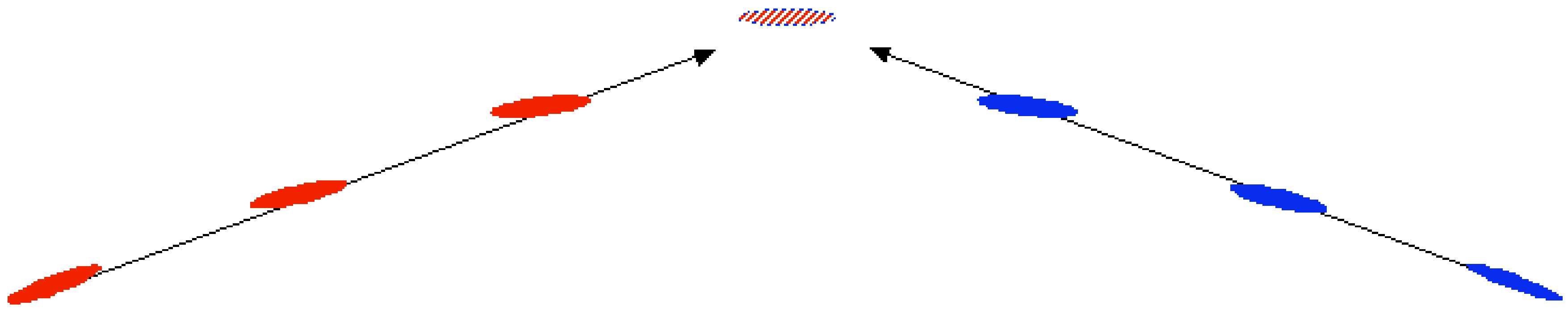
Magnet specialist

(also ‘hybrid’ : D0 (not completely head-on) with crab cavities)

‘Older’ idea: **Crab Crossing**

(B. Palmer for Linear Colliders 1988,
K. Oide & K. Yokoya for circular colliders 1989)

‘Somewhat before’ collision tilt-kick bunches such that they collide ‘head-on’ with small common transverse speed



Original idea (today called ‘local’ scheme):

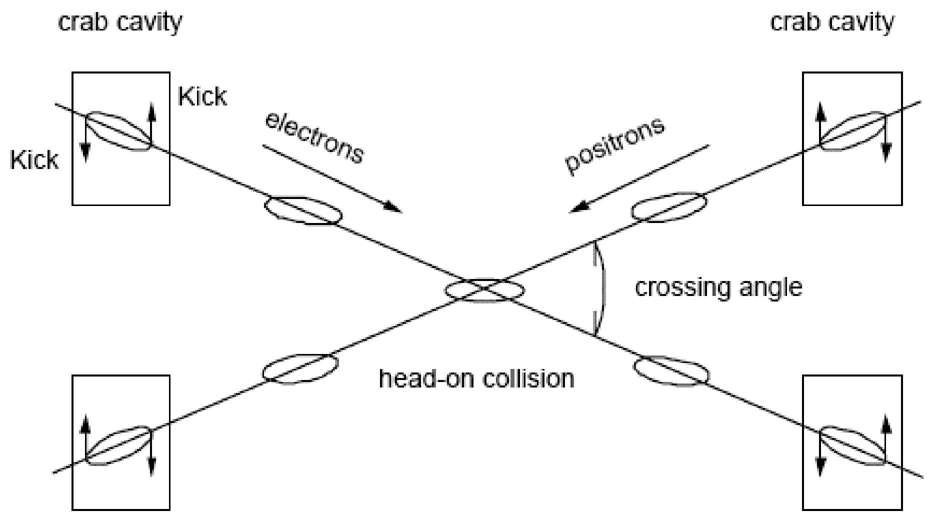
stop (compensate) tilting movement after collision

LOCAL SCHEME:

Compensation after the IP (experiment):

Bunches behave ‘as usual’ elsewhere

Crab crossing



Palmer for LC (1988)
Oide and Yokoya for storage rings (1989)

Recent simulations by Ohmi showed significant increase of luminosity by several times by the crab crossing.

Crab cavity for the B-factories (K. Akai, KEK)

GLOBAL SCHEME:

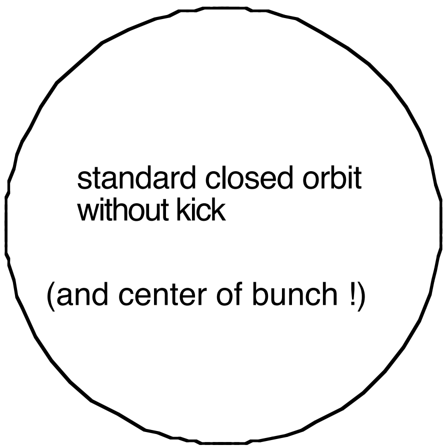
No compensation:
Bunches snake around the machine

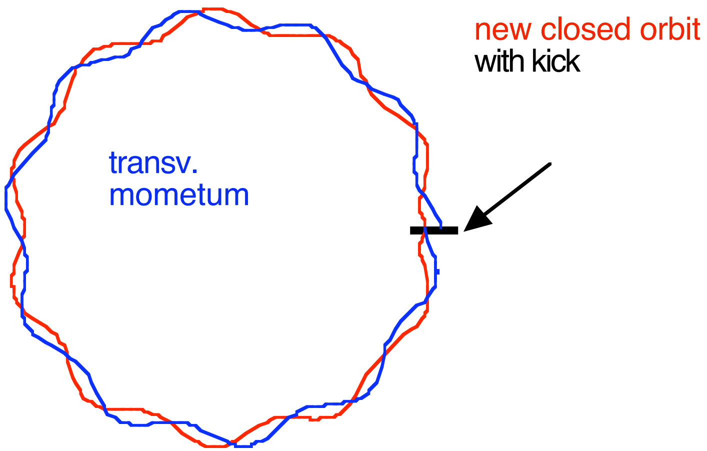
(collimation !!)

First reaction an <u>global scheme</u> (not only mine):

They are crazy … (… repetitive ?, .. integer tune, ….)

BUT: each kicked particle gets its <u>own (stable) closed orbit</u>





Real particles β-tron oscillate around it 'as usual'

Problem: Bunches may 'scratch along' collimators …

(longitudinal synchrotron motion: very slow = adiabatic)

An **additional purpose** of crab cavities:

Lumi levelling

If exponential decay of lumi is dominated by

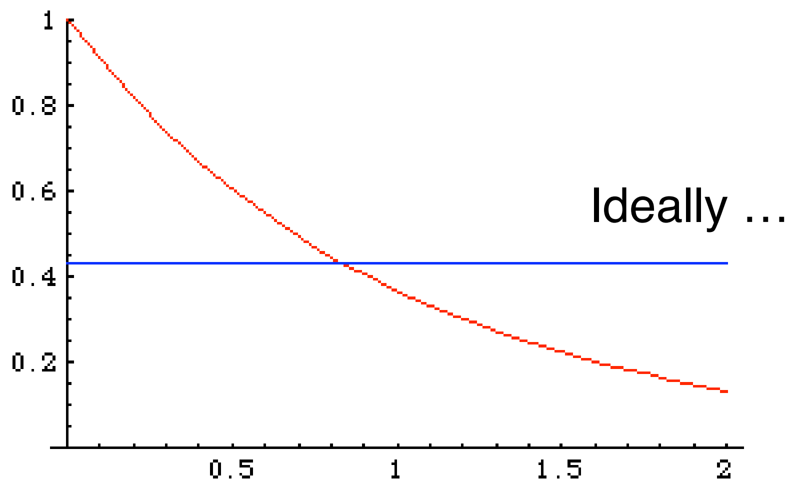
p-consumption by p-p-collisions (*)

Save the initial (initially “too big” (pile-up)) lumi for later

= “constant” lumi

Start coast not perfectly head-on

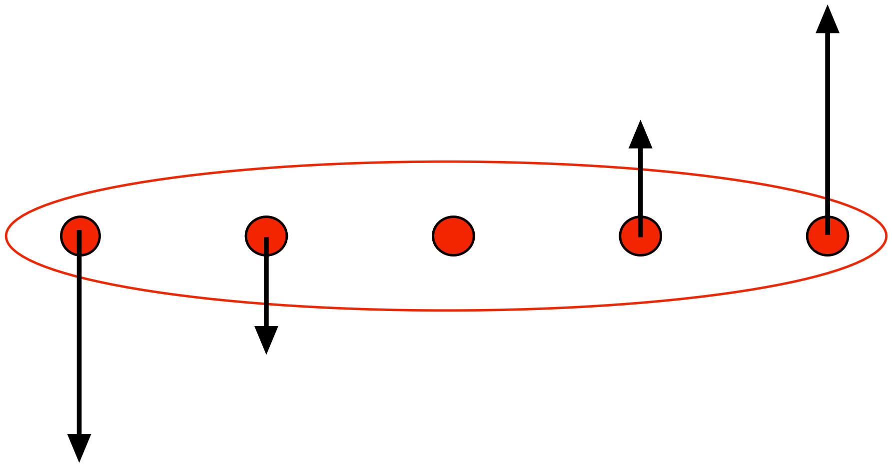
Go **more and more** to head-on with time



(*) else LHC would ‘overheat’

For both schemes:

Needed: Linear kick-slope



Required quality of linearity ???

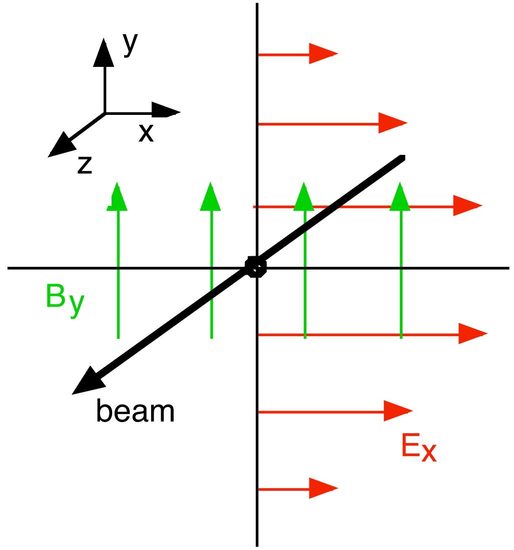
Luminosity simulations guide for the limits

Slightly 'bent' kick is allowed (RF wave form !)

How to transversely kick-**slope** particles in the real world ?

variable (=RF) fields

first idea: transverse E-field



Panofsky-Wenzel theorem

(… amongst other facts …)

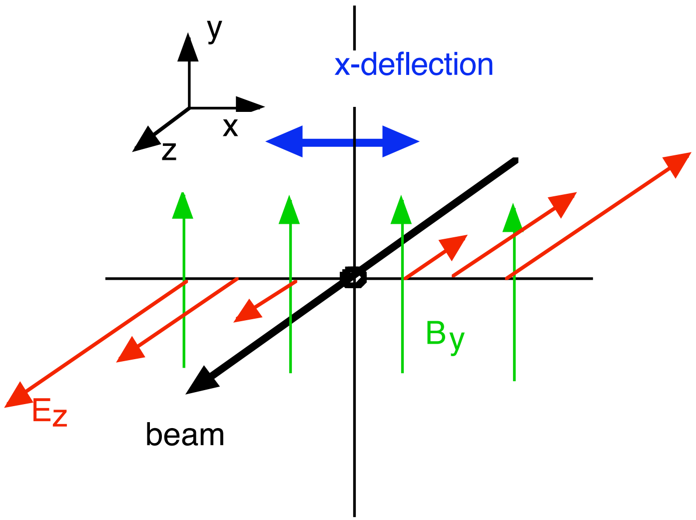
Only transverse E fields (TE-modes) don't do the job:

Together with the by Maxwell associated B-fields the kick, integrated along the structure,

adds up to a **perfect zero kick !!!**

Works: perpendicular B-fields **(TM modes):**

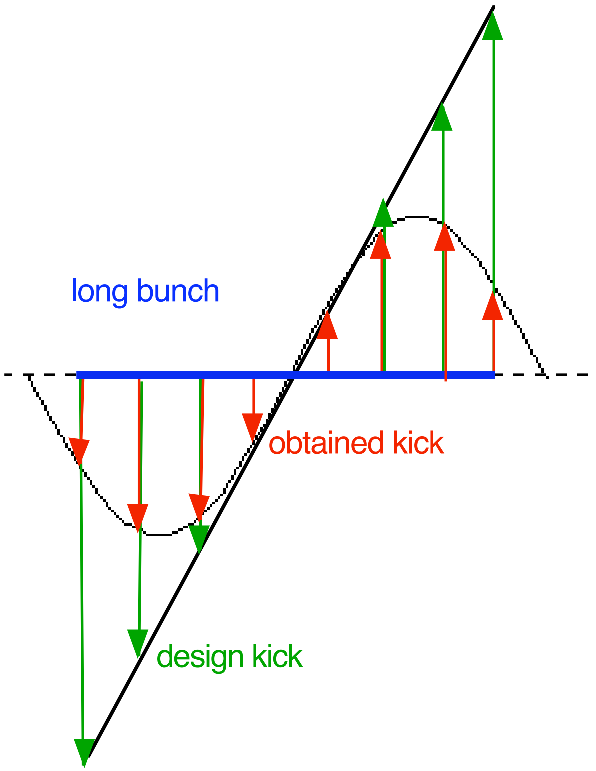
Maxwell: dE_z/dx is unavoidable !!

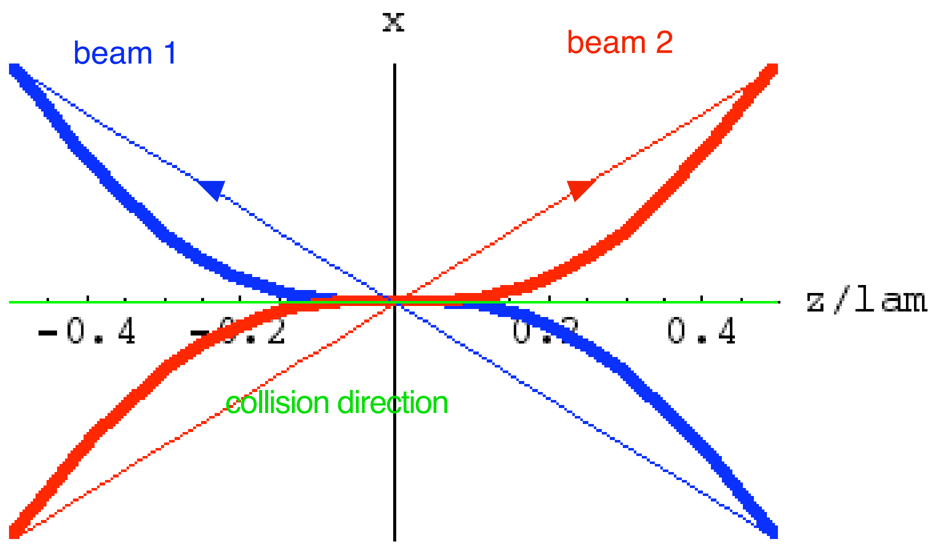


Longitudinal E_z makes accelerating =

‘parasitic’ interaction: beam on $E_z = 0$

- Kick-**slope** proportional kick$_{amplitude}$*f_{RF} : **high f_{RF} is good**
- **Dimension of cavity** scales as $1/f_{RF}$: **high f_{RF} is good**
- If bunch-length ≈ λ_{RF}: **crooked bunches**: **high f_{RF} is bad**





For LHC 400 MHz (= main RF): still good linearity

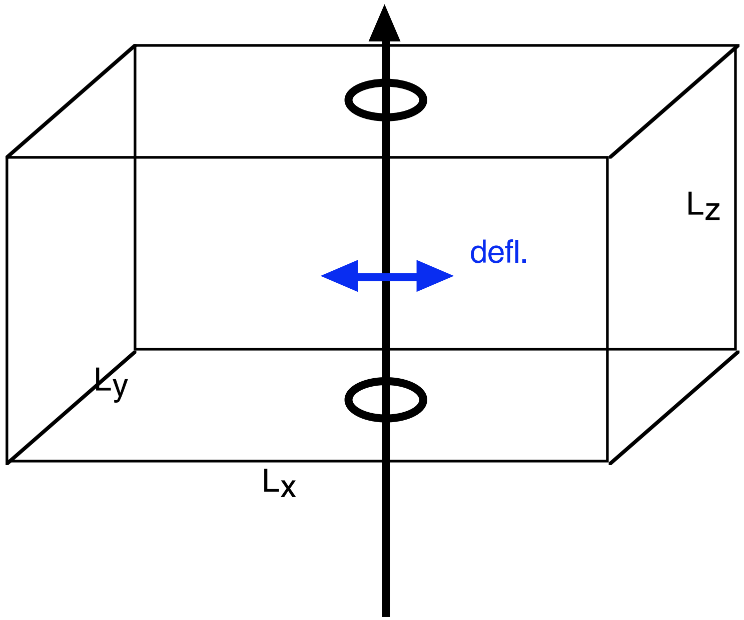
800 MHz: crooked bunches but cavity size 'acceptable'

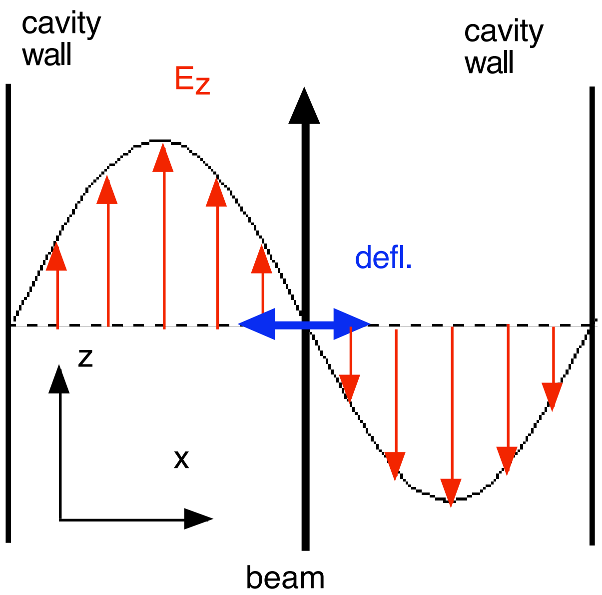
The size of the cavity:

Estimation by a 'box cavity'

1) need dE_z/dx 2) beam on $E_z=0$

For a 'classical' design there are no miracles(*)





(*) as cavity outside smaller than inside

Superconducting - normal conducting ?

• In (not pulsed) CW operation sc cavities can keep much higher fields than nc ones (factor 10 … 30)

-> Less cavities required (and less underground RF)
-> less parasitic impedance (limits beam current)

• Today's proven SC RF technology requires certain restrictions
(• acid & water surface treatment • multipacting • ….)
-> use "smooth, simple" cavities (*) : (too ?) **'large'**

1) Use 'classical' SC shape (shorter R&D, lower risk: as KEK-B)
2) Opt for nc compact shapes, check LHC impedance balance
3) Try compact shapes in sc version (longer R&D, higher risk)

(*) "elliptical" cell cross section; but (generally) have circular symmetry around the beam axis

The eternal 'Higher' Order Modes (HOM) problem …

= many unavoidable cavity modes, driven by the beam,

-> causing beam stability problems (+power) if unhandled:

Need damping HOMs but **leave alone the working mode**

In standard accelerating cavities all such modes are higher in frequency ('H' !!) than working one.

In round kick-cavity working dipole-mode has 2 polarizations

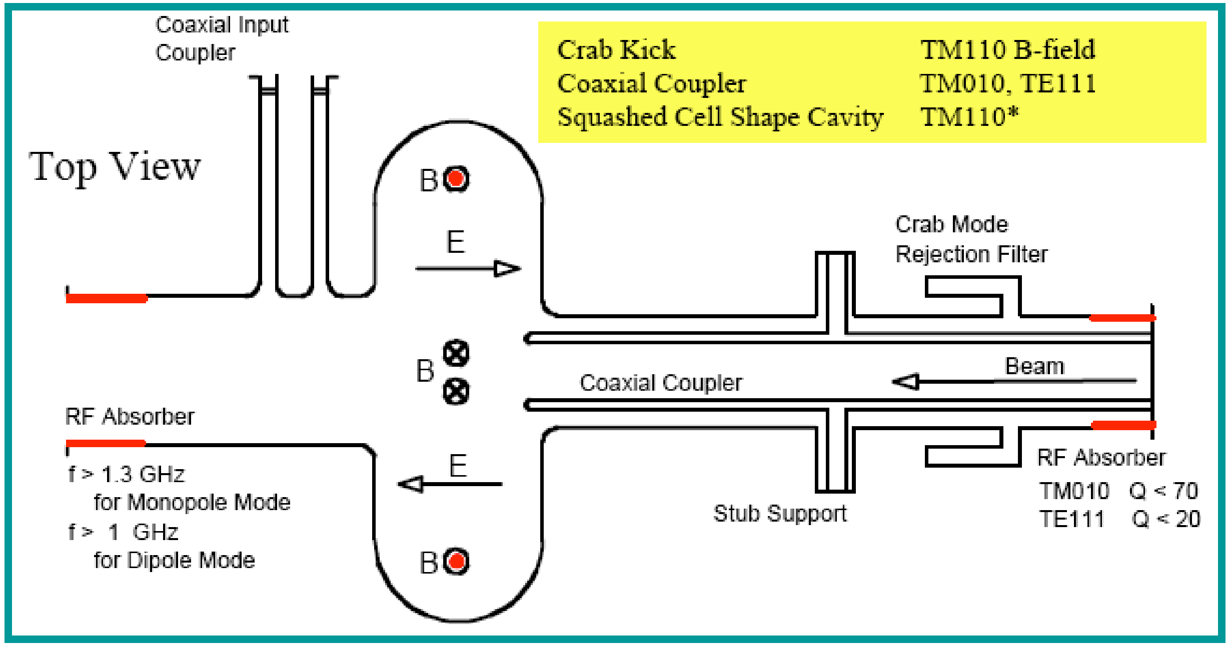
at same frequency: difficult to keep apart

('bath tub') **squashed cavity**: separates these frequencies

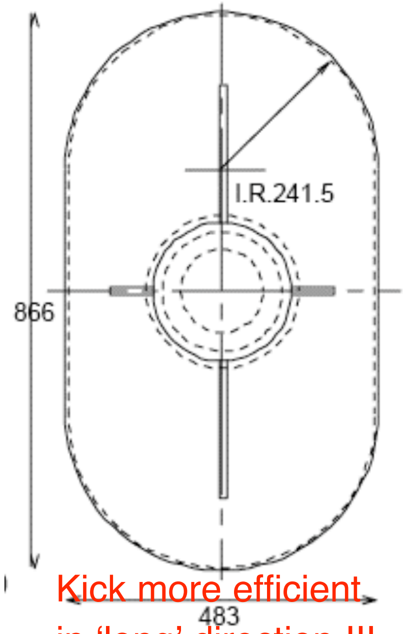
'Tricks': exploit field symmetries, special filtered couplers, use cut-off limit as stop filter, … to leave alone the working mode

New lingo: Same Order Mode (SOM) = other polarity; Lower Order Mode (LOM) =lowest acc. mode

Conceptual Design of KEKB Crab Cavity 508 MHz

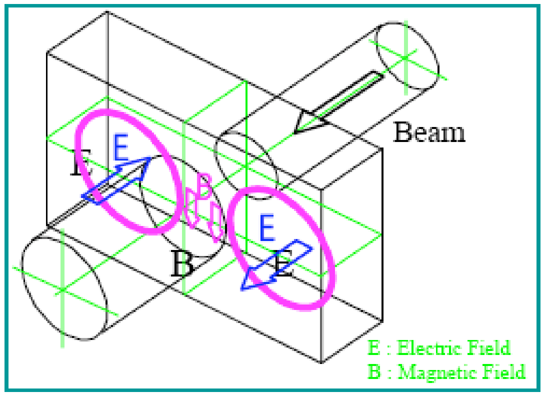


" bathtub "



Kick more efficient in 'long' direction !!!

Squashed Cell Shape Cavity



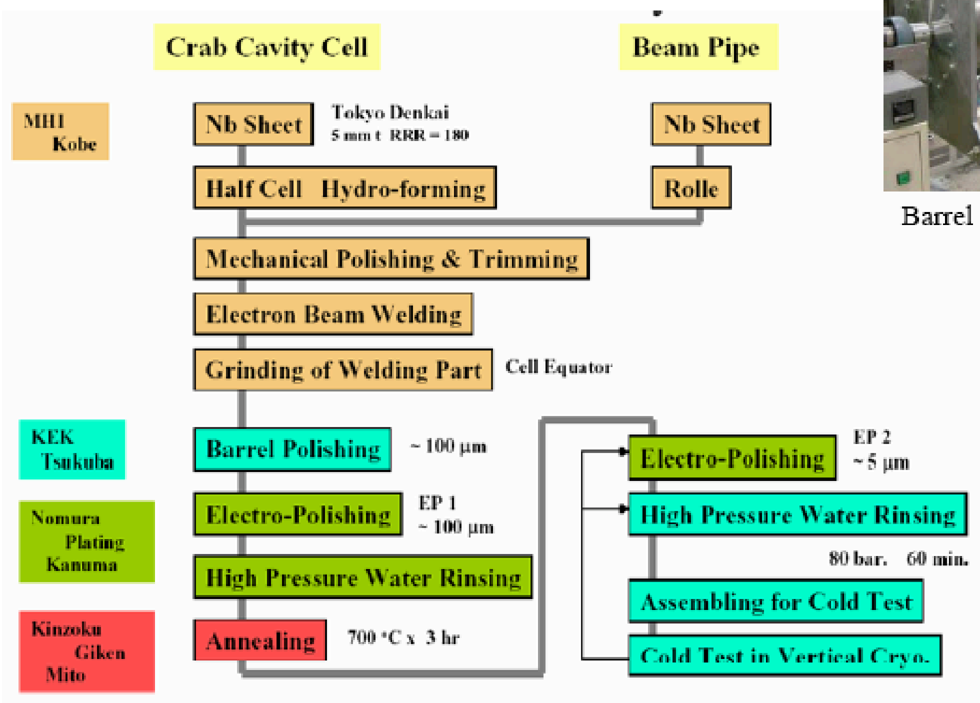
- The squashed cell shape cavity scheme was studied extensively by Akai at Cornell in 1991 and 1992 for CESR-B under KEK-Cornell collaboration.

We adopted this design as "base design"!

Superconducting, 4.5 K

Fabrication of KEKB Crab Cavity

Forming of Half-Cells



Barrel Polishing 312Hr

High Pressure Water Rinsing

Electro Polishing

Annealing

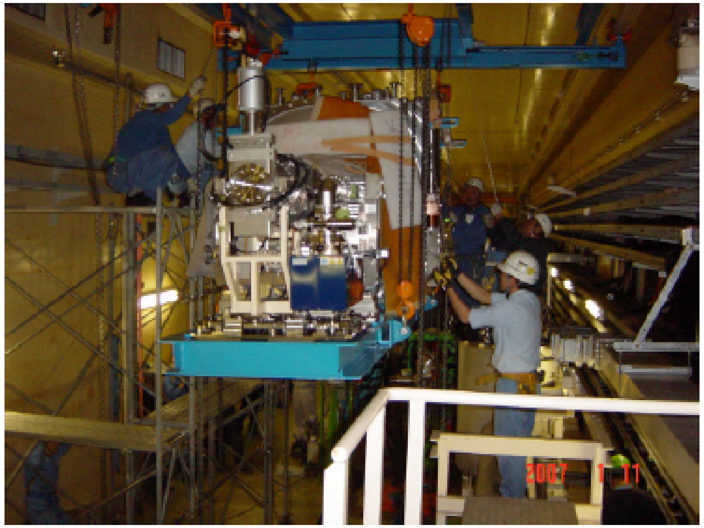
Assembling

Installation & Commissioning of Crab Cavities

Global option

Installation of Crab Cavities
for HER Jan. 8, 2007,
for LER Jan. 11, 2007

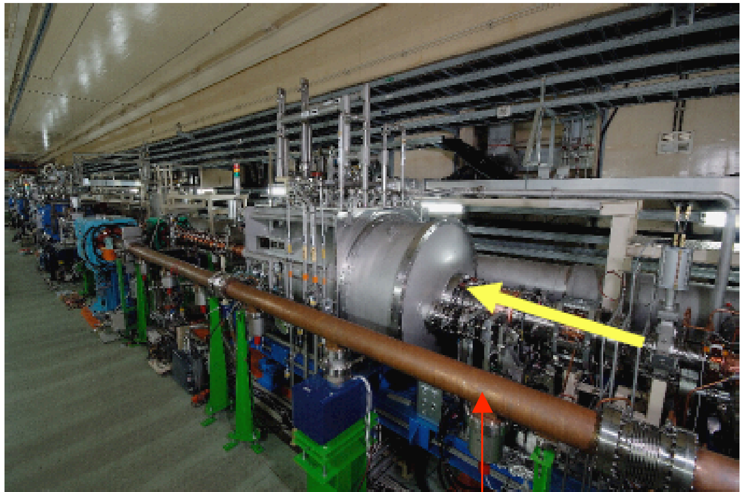
Crab Cavity for HER



Carrying the Crab cavity using crane track

Cool-down of Crab Cavities
Jan. 29 , 2007

Beam Operation Start
Feb. 13



Crab Cavity for LER

Counter-rotating beam

THE big problem in LHC:

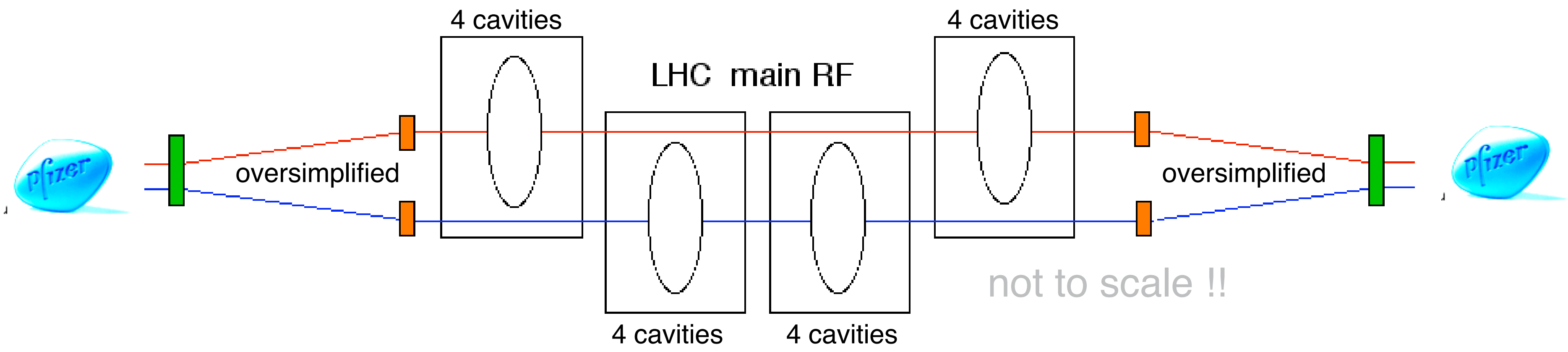
The beam-beam distance = **19 cm** (nearly) **everywhere**

Rule: Never both beams in the same 'metal box' (*)

(el. mag. beam-beam coupling: instabilities): **no 2 in 1 cavity**

ONLY at IP4, **the RF home**, beams are bent apart to **42 cm**

7 TeV beam is very stiff, need very strong "doglegs"



(*) without any IP even better LHC beams !! To be discussed with experimenters …

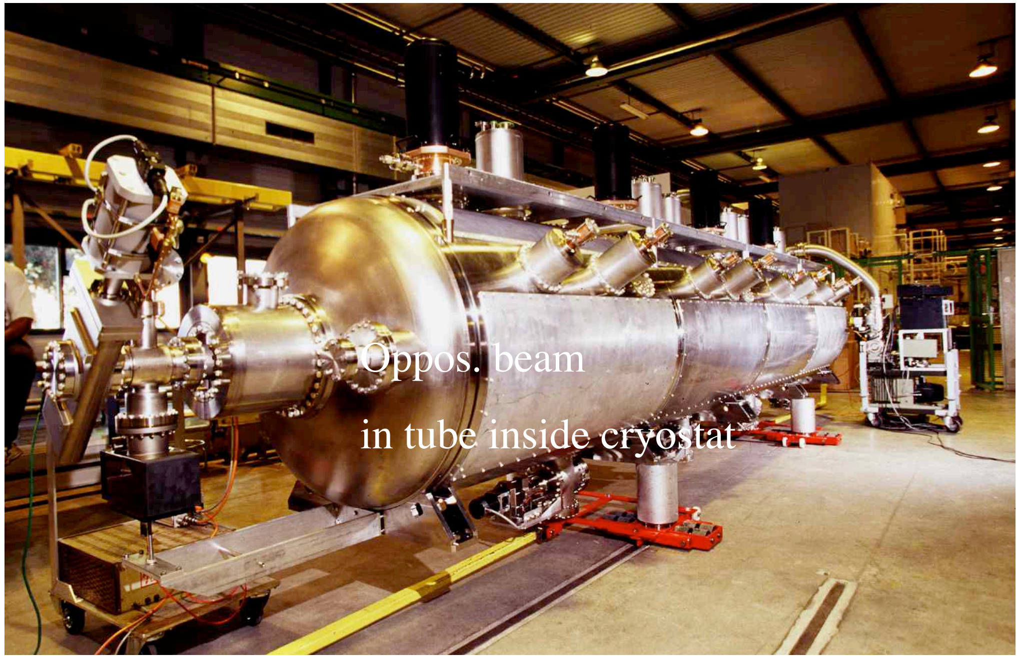
As ‘gauge’: the LHC main RF system @ 400 MHz (circ. cav.)

beam-beam exceptionally spread to 42 cm at IP4

(required magnets very difficult for 7 TeV and $$$$)

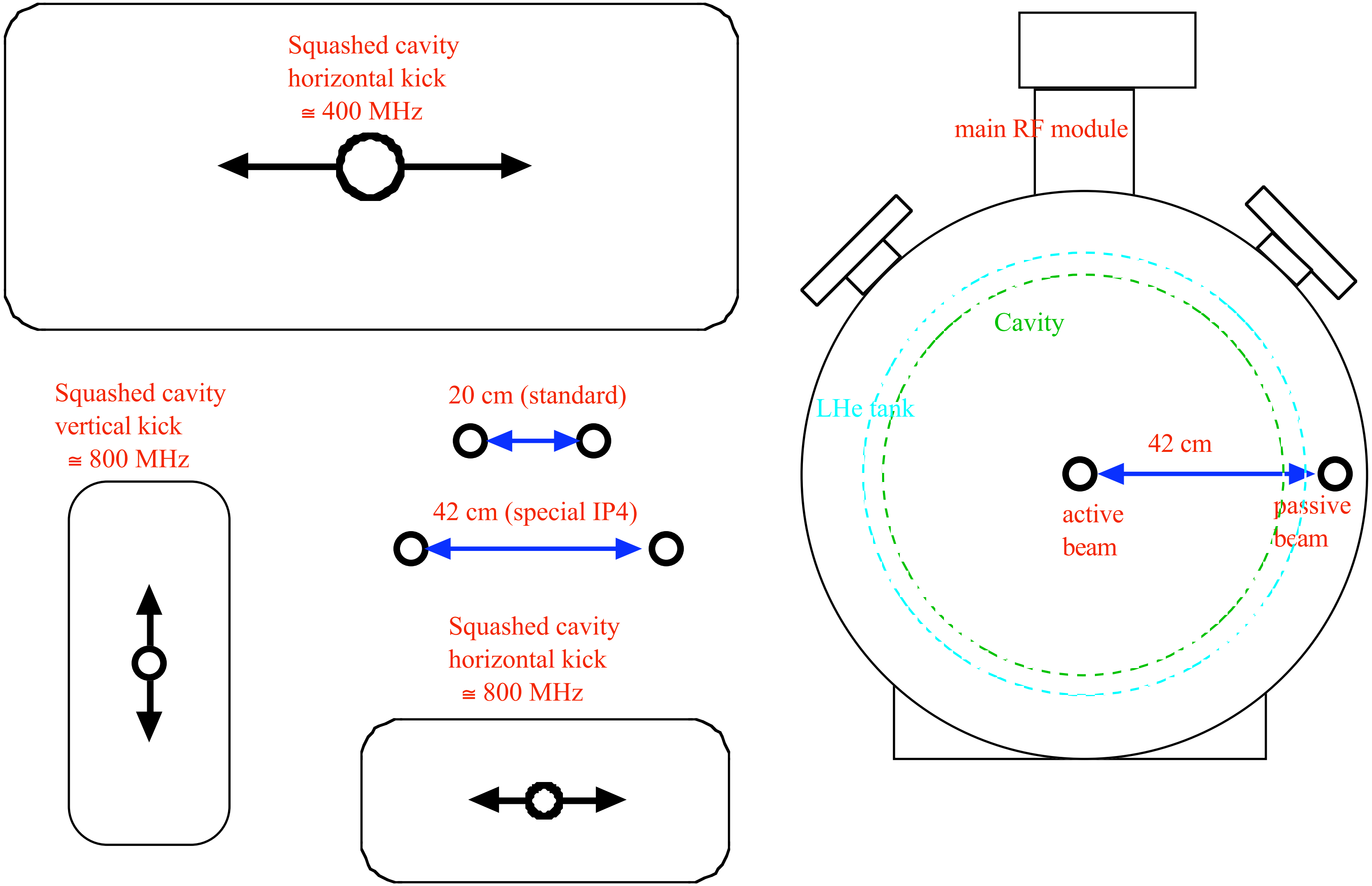
$r_{400MHz,main}$ = 345 mm fits next to opposite beam

Accelerated beam

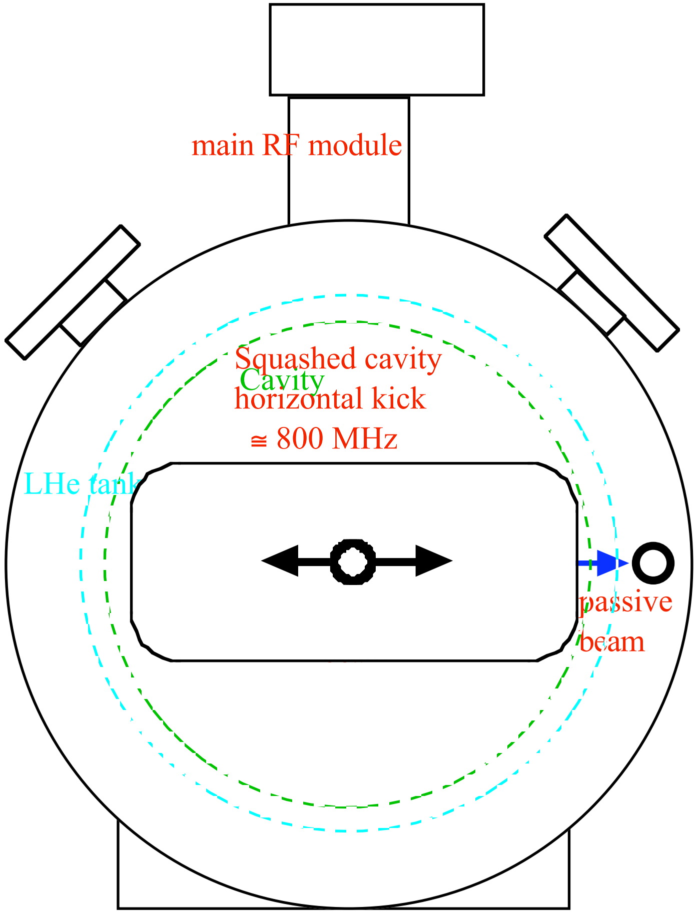


$1/2\ L_x \leq 35$ cm

Sketch of the main dimensions, an overview



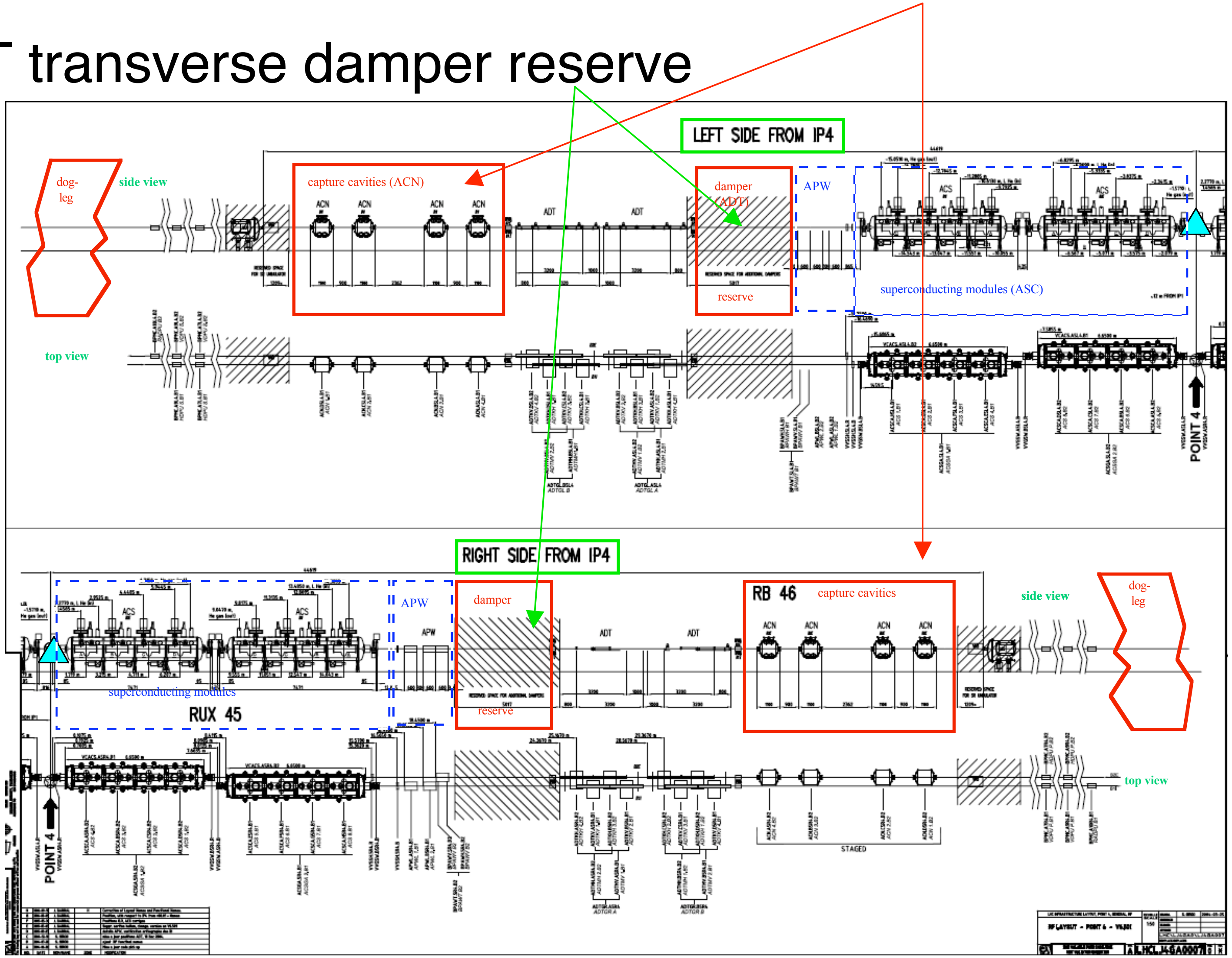
Compare to main (accelerating) module: transverse space **800 MHz crab fits at IP4**(*)



(*) but nowhere else … or need a special dogleg

Possible (test-) locations at IP4:

- ACN (staged) capture cavities
- ADT transverse damper reserve



Problem:

Both ‘target areas’ are already ear-marked !!

1) The capture cavities (ACN) are only needed for higher beam current, presently staged

   ‘push all ACN longitudinally together’ to make room: does not work out

2) The damper (ADT) reserve might never be needed

   (at least that’s what we think today …)

Have to ‘feel’ the machine first before a better prognosis can be given …

LARP (or KEK ?) might build such a cavity (pair)

… nobody wants to arrive with a good cavity and be told: “the area is already occupied by ….”

Also required under ground:

Cryogenic supply

(normally 2K, test ≈ acceptable 4.5 K, 'steal' from main RF)

RF transmitter (≤ 20 kW @ 800 MHz)

('borrow' spare from SPS Landau system, new 60 kW IOT)

Cooling water ('steal' from main RF)

Controls, link to cryogenics, link to main RF, vacuum, ….

First results from the KEK-B crab cavity test

Life is complex (nothing new ..):

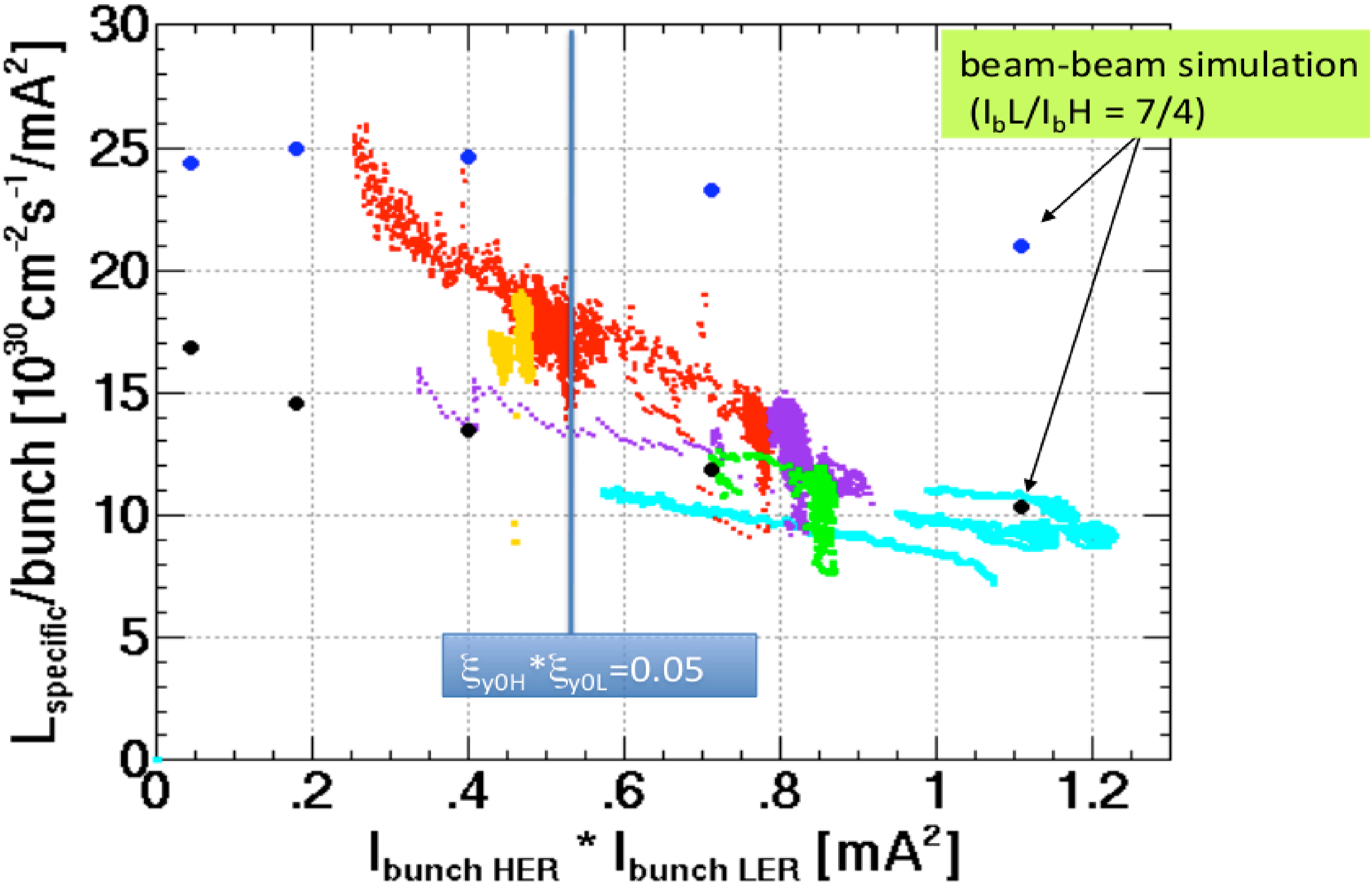
Optimizing lumi without crabbing and then ramp up crabbing does not (nec.) lead to the optimum setting …

There are 12 ‘buttons’, all not ‘orthogonal’: Changing one parameter using button 5 slightly degrades another parameter, to be recovered by button 9, which then ….

<u>A true 12 dimensional problem: difficult to find the optimum</u>

(phrase at KEK: “narrow peak on a broad shoulder”)

For low intensities the <u>specific</u> lumi (i.e. per charge) follows simulation predictions; but drops when increasing beam current (a beam-beam effect)



beam-beam simulation
(I_bL/I_bH = 7/4)
$\xi_{y0H} * \xi_{y0L}$=0.05
$L_{specific}$/bunch [$10^{30}cm^{-2}s^{-1}/mA^2$]
$I_{bunch\ HER} * I_{bunch\ LER}$ [mA^2]
0
.2
.4
.6
.8
1
1.2
30
25
20
15
10
5
0

For a painful period:

- when increasing beam current, specific lumi decreases

  (also beam life-time)

- 'pre-crab' total lumi just recovered at lower current !

But recently (installation of skew sextupoles, empirically tuned)

Lumi with crab cavities outclasses all previous KEK-B records

(… and still improving ...)

Red-hot news:

(after adding skew sextupoles for optics corrections)

On May 6, 2009, KEK-B broke the **world luminosity record**

and achieved a luminosity (*) of

$$1.96 \times 10^{34}/(\mathrm{cm}^2\ \mathrm{sec})$$

using **the crab cavities**.

This new record is almost a factor of two higher than the original design luminosity of KEKB.

…. the background remained in good condition ….

(*) LHC design lumi (IP1 and IP5) $1\mathrm{x}10^{34}$

The 'RF noise problem' (or perhaps it is none ?)

All <u>stable</u> kick-errors add a little 'global option component'

(for local option, no real problem)

but if kick strength **<u>jitters</u>**

-> emittance can be blown up: **loss of lumi** … and beam

Main noise source: RF noise on crab RF system

7 TeV p: synchrotron radiation loss 7 keV/turn = 'inexistent'

-> cannot count on synchrotron radiation damping ($\tau \approx 12$ h)

(in contrast to e-machines (KEK-B): need test in hadron ring)

The path to lumi upgrade with crab cavities in LHC:

1) A **test cavity** (-pair, one per beam): global option

@800 MHz, SC, installed at IP4: **use LHC ‘as is’**

-> predict the lumi-increase to be achieved

should be significantly ‘above noise’

2) The KEK test results should give more valuable info

3) The ‘noise problem (?)’ has to be studied theoretically

and by parallel experiments (including the test cavity)

4) **Big LHC lumi upgrade**: lowering β^* with

- a) 4 crab systems per detector (doglegs / comp. cav)
- b) Global system at IP4 (or …) … collimators !!
- c) …. with “D0” ….

Apart from the classical design (as KEK-B cavity)

1) ‘close to classical’ about ‘RF superconductivity compatible’

need still some R&D (=experienced people, $$$ and **time**)

but ‘low risk’ of real failure

2) compact cavities, designed very slim to fit ‘everywhere’

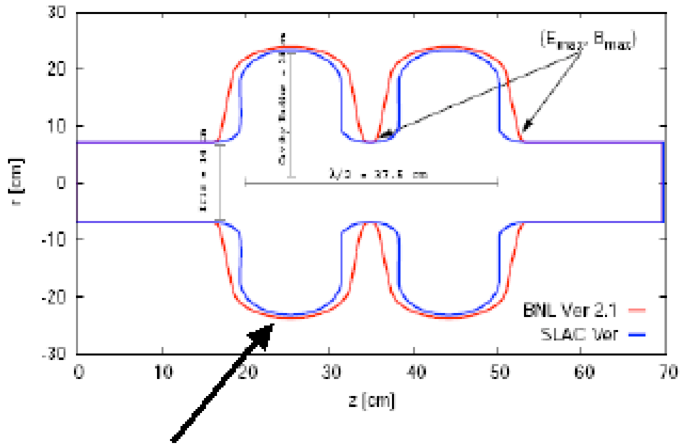
transgressing today’s (high field, β=1) SC RF technology

need much more R&D (=experienced people, $$$ and **time**)

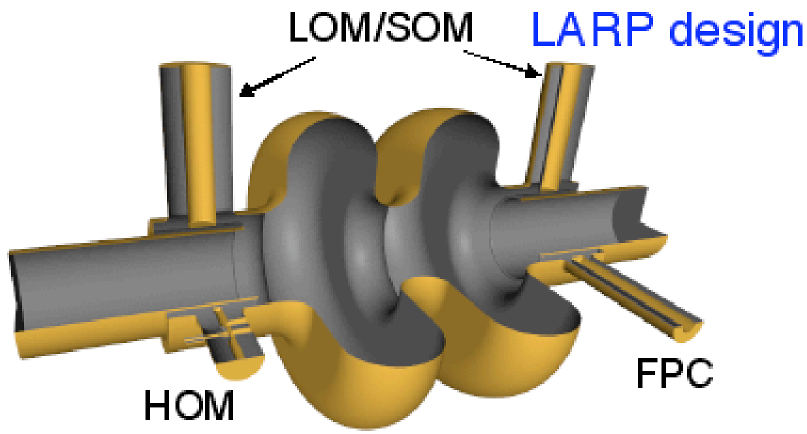
might not live up fully to expectations (as CW SC incarnation)

Prototype Cavity/Couplers

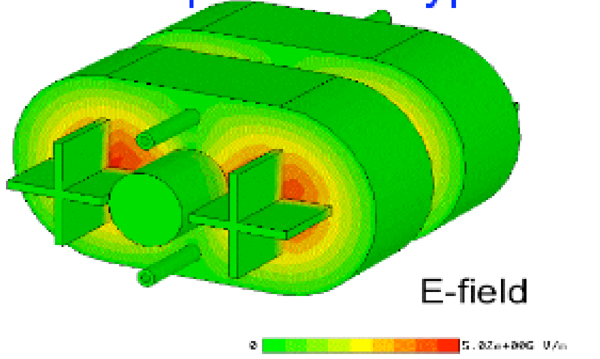
Exist only in silicon (CPU)



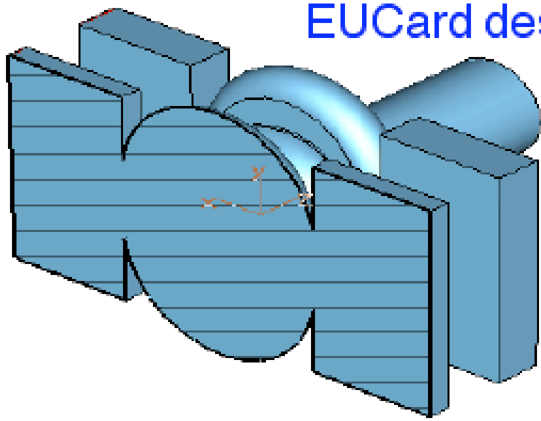
Note the cavity radius ~ 23 cm



Super-KEKB type design



EUCard design

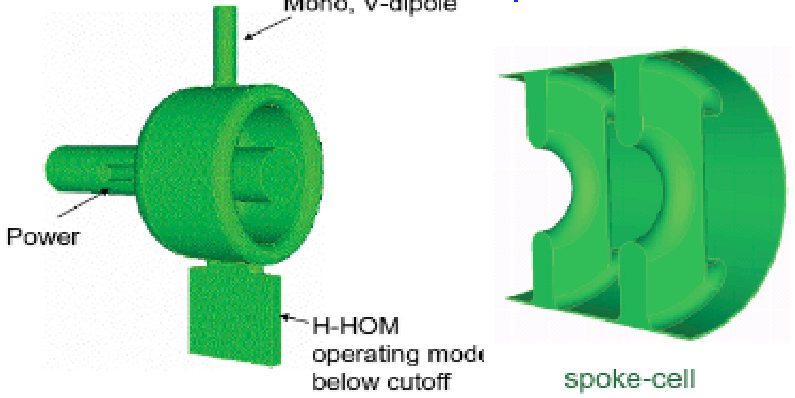


** Down-Selection within 1yr

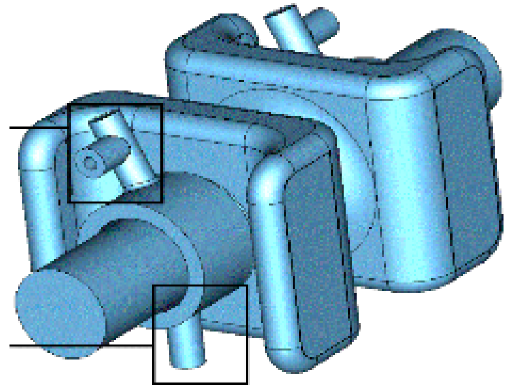
Compact Structure, Phase II

Exist only in silicon (CPU)

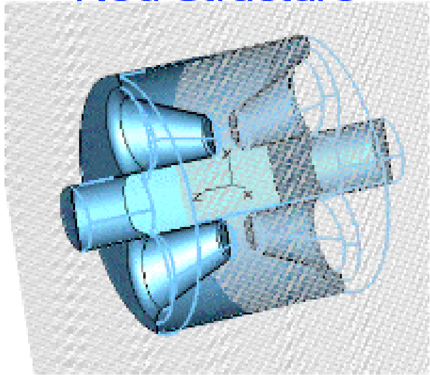
SLAC _ Wave & Spoke Structures



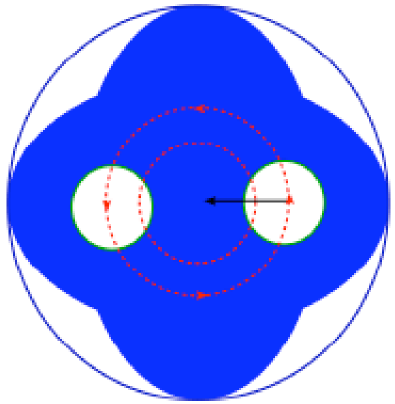
FNAL Mushroom Cavity



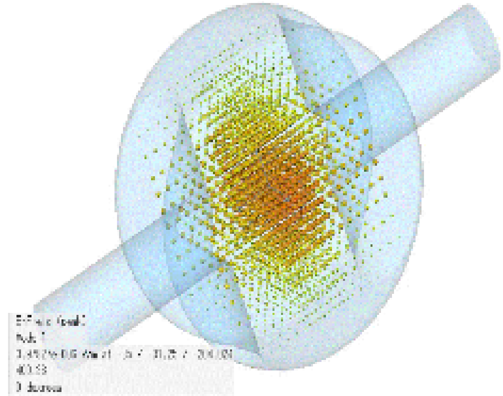
EUCard,UK-JLAb
Rod Structure



BNL TM010, BP Offset



KEK Kota Cavity



Summary:

• Crab Cavities are (in context of a β^*-squeeze) a very promising path for lumi upgrade; lumi-levelling.

• A first cavity is under test (at KEK-B) and shows very encouraging results (world lumi record !!)

• A test in LHC is essential to demonstrate an increase of lumi in a hadron collider (there is little doubt that tilting of bunches can be done ...)

• In parallel compact cavities (in SC incarnation) – fitting at 19 cm beam separation – have to be developed, built and tested; else doglegs at each experiment or local option IP4

• The management has to support this activity with sufficient staff and budget: time is running ….

A personnel (politically not correct ?) view:

- Several L upgrade options incorporate the crabbing scheme:
  keep door open Crab Cavities for LHC lumi upgrade
  (SC version for ‘stable field’ ≠ CLIC, ILC pulsed version)

- Today the investment ($$$ and ‘FTE’s) into crab cavities (compared to e.g. CLIC) are ‘absolutely ridiculous’
  (won’t tell you details, too ashamed)

  Not paid by CERN but ‘externals’ as LARP, EUCard, …

Only as a yardstick (no ‘nostalgia’):

• For the LEP2 project at CERN the first operational industry made 4-cavity module arrived about 12 years after $t_{R\&D}$=0.

(how many modules followed of less importance here, only few Crabs)

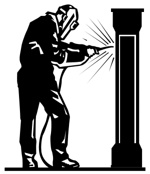
Group of about 20 (!) people of which only 5-6 ‘academics’, with INTEGRATED experienced technicians, mechanics, …

(… one needs arms, not (so much) brains)

+ support by CERN workshops and their experts

… most gone without any replacement (“out-farming”)

• KEK-B crab cavity: 1991 start R&D; installation in KEK-B: 2007

• (0.3 + 0.2 + 0.5) FTE (modern math) <<  (1 old fashioned real guy)

Need a critical mass at one location (not nec. @ CERN) !!!

- A proof-of-principle test has to be made

in LHC – where else: the only **hadron** collider

- Crab cavities have to be built (not only from silicon in CPUs):

  Technology deviates from 'known' SC RF one

  For compact cavities: even more open questions

Need 'political' support from HEP community

time is running …..

and don't say: "Get out of our way with these tests, we are making lumi now ...."

Thank you for listening!