LHC Upgrade

Part 4:
RF systems for the LHC upgrade

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Outline

- This will include the existing RF system …
  … and loads of general reminders

- I limit myself to the LHC, but upgrades will be implemented also to the LHC injector chain.

- Reminders:
  - Synchrotron beam dynamics
  - Impedance
  - Stability limit

- The LHC RF systems
  - acceleration system
  - transverse damper

- The HL-LHC Crab cavity system

N.B.: I'm oversimplifying and not rigorous!
Those experts among you: forgive me – I'll try to reach the others.

Reminder: Synchrotron beam dynamics

- Homogeneous magnetic field – circular motion
- Inertia force = restoring force:

$$\omega\ p = q\ v\ B$$

$$p/q = R\ B$$

- During acceleration (increasing p), B is permanently increased in order to keep R constant.
- Particles with different initial position/angle are kept inside the beam pipe with focusing elements.
- Off momentum particles have a slightly different orbit; this is described by the "*momentum compaction*" α_p :

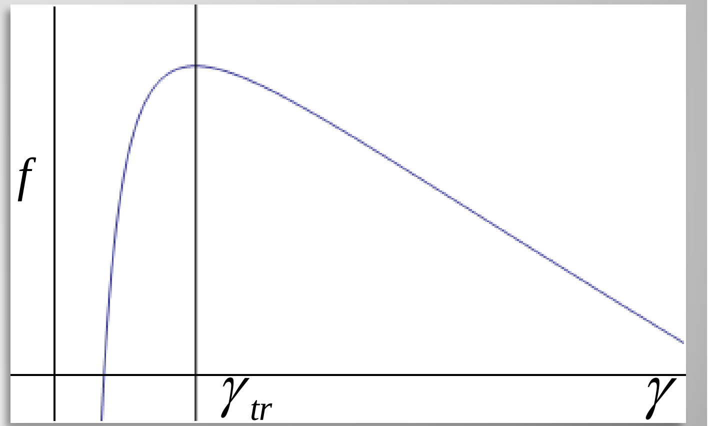
$$\Delta R/R = \alpha_p \cdot \Delta p/p$$

Reminder: Revolution frequency - *transition*

- The revolution frequency f_{rev} results from $f_{rev} = \dfrac{v}{2\pi R}$.
- Off-momentum particles also have a different revolution frequency – and this for two effects:
  1. since they have a different speed,
  2. since they travel a larger distance (due to *momentum compaction*):

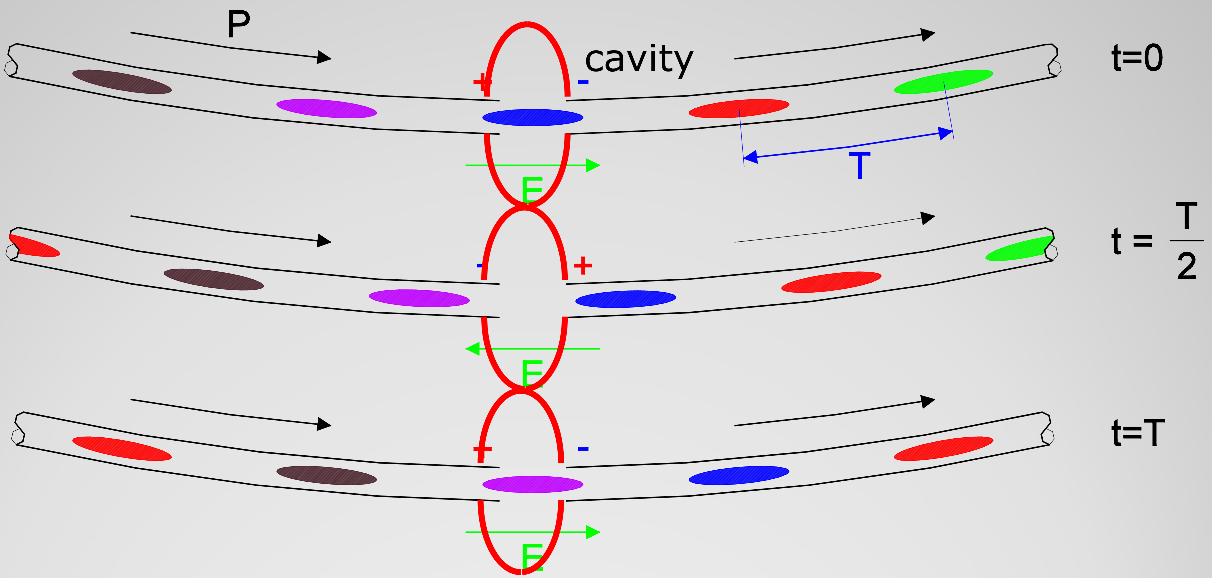
$$\frac{\delta f}{f} = \frac{\delta v}{v} - \frac{\delta R}{R} = \left(\frac{1}{\gamma^2} - \alpha_p \right) \frac{\delta p}{p}$$

- At lower energy effect 1 dominates, i.e. f_{rev} increases with energy.
- At higher energy effect 2 dominates, i.e. f_{rev} decreases with energy.
- The energy γ_{tr} with $\gamma_{tr}^{-2} = \alpha_p$ is called *transition energy*.
- The LHC is operated above transition.



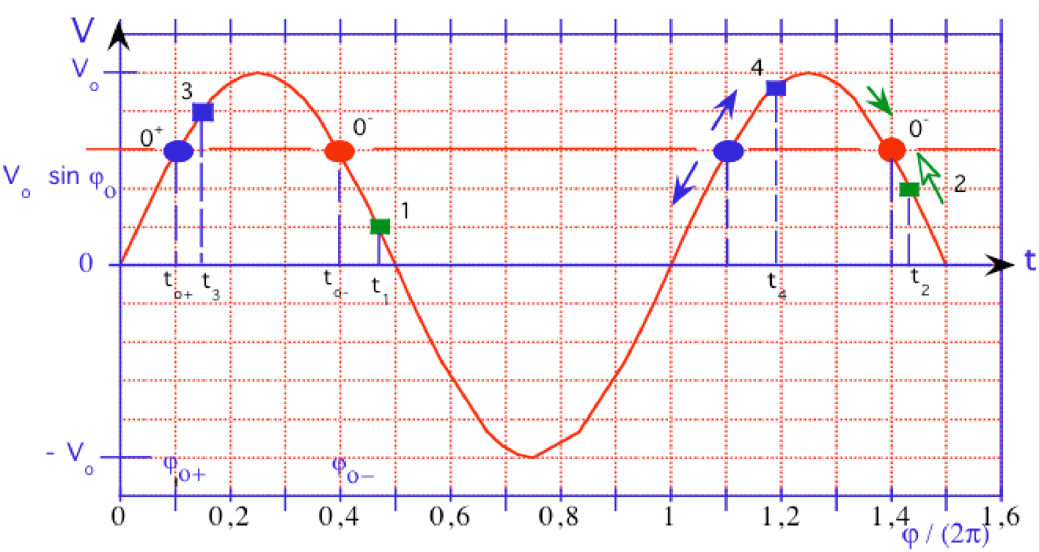
Reminder: Acceleration

- Acceleration takes place by interaction with Radio Frequency (RF) electric fields in so-called *cavities*.
- For this to work, protons come in packages (*bunches* inside of *buckets*)– h buckets fit on the circumference (h: harmonic number).
- The Radio Frequency then has to be $h\,f_{rev}$.



Reminder: Phase stability

- Let the gap voltage in the cavity be $V\sin(\omega t)$;
- A particle traversing it at time (phase) $\omega t_0 = \varphi_0$ changes its energy by $Ve\sin(\varphi_0)$.
- If this is exactly the right amount of energy in order to get to this same gap at exactly the right phase again the next time around, φ_0 is called the synchronous phase.
- It is stable if particles next to it see a restoring force towards it.
- Below *transition* the stable phase is φ_{0+}, above transition it is φ_{0-} .
- When passing transition, the RF phase has to be switched.

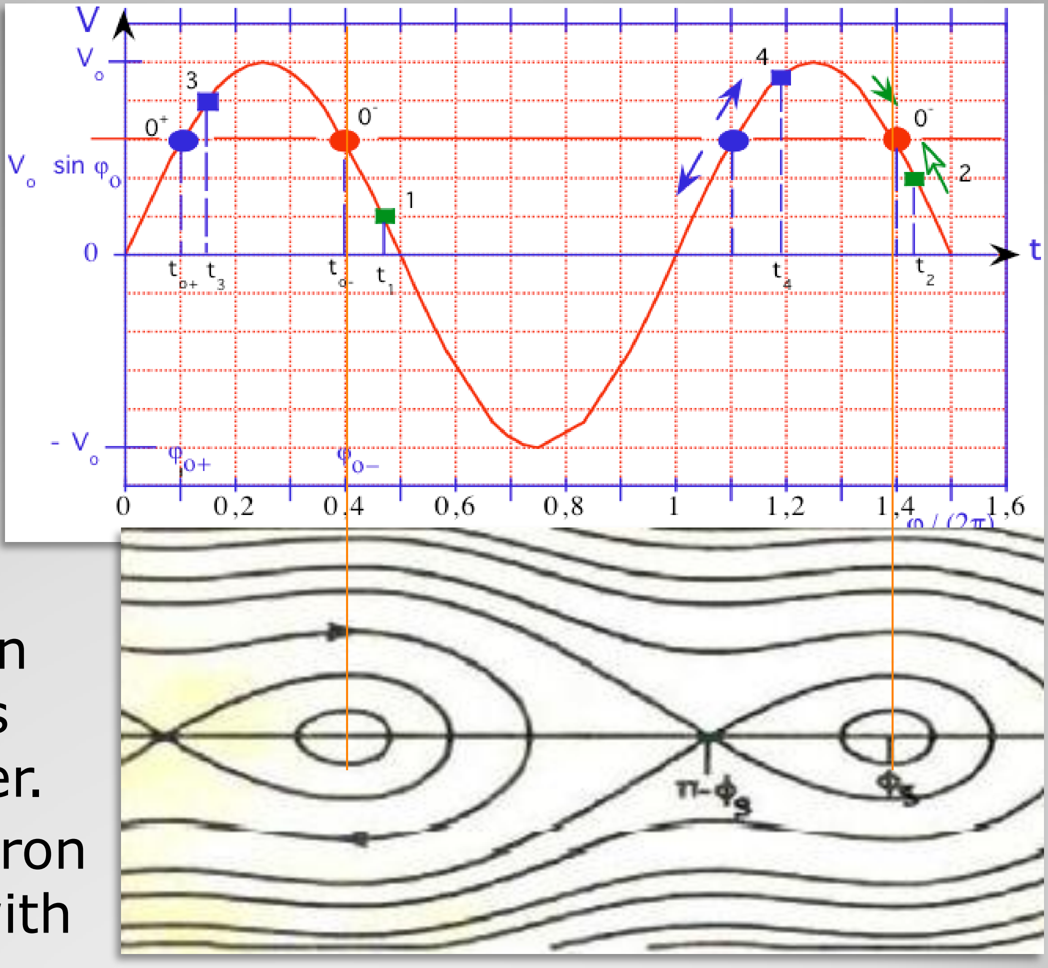


Reminder: Synchrotron motion

- The motion of particles around the stable phase

$$\frac{d^2(\Delta\phi)}{dt^2}+\Omega_s^2(\Delta\phi)^2=0$$

- Example shown: above transition



N.B.: incoherent synchrotron motion keeps the particles of a bunch together.

Coherent synchrotron motion interacts with the impedance.

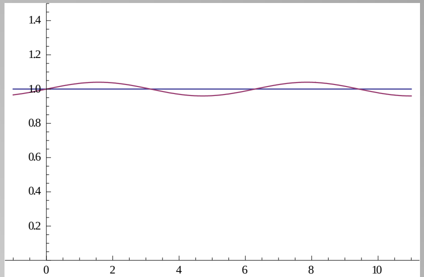
Reminder: Impedance

- The beam current excites fields in the different objects in the accelerator;
- these fields exert a force on the beam.
- In *t*-domain, one talks about **wake fields**.
- In ω-domain, one talks about

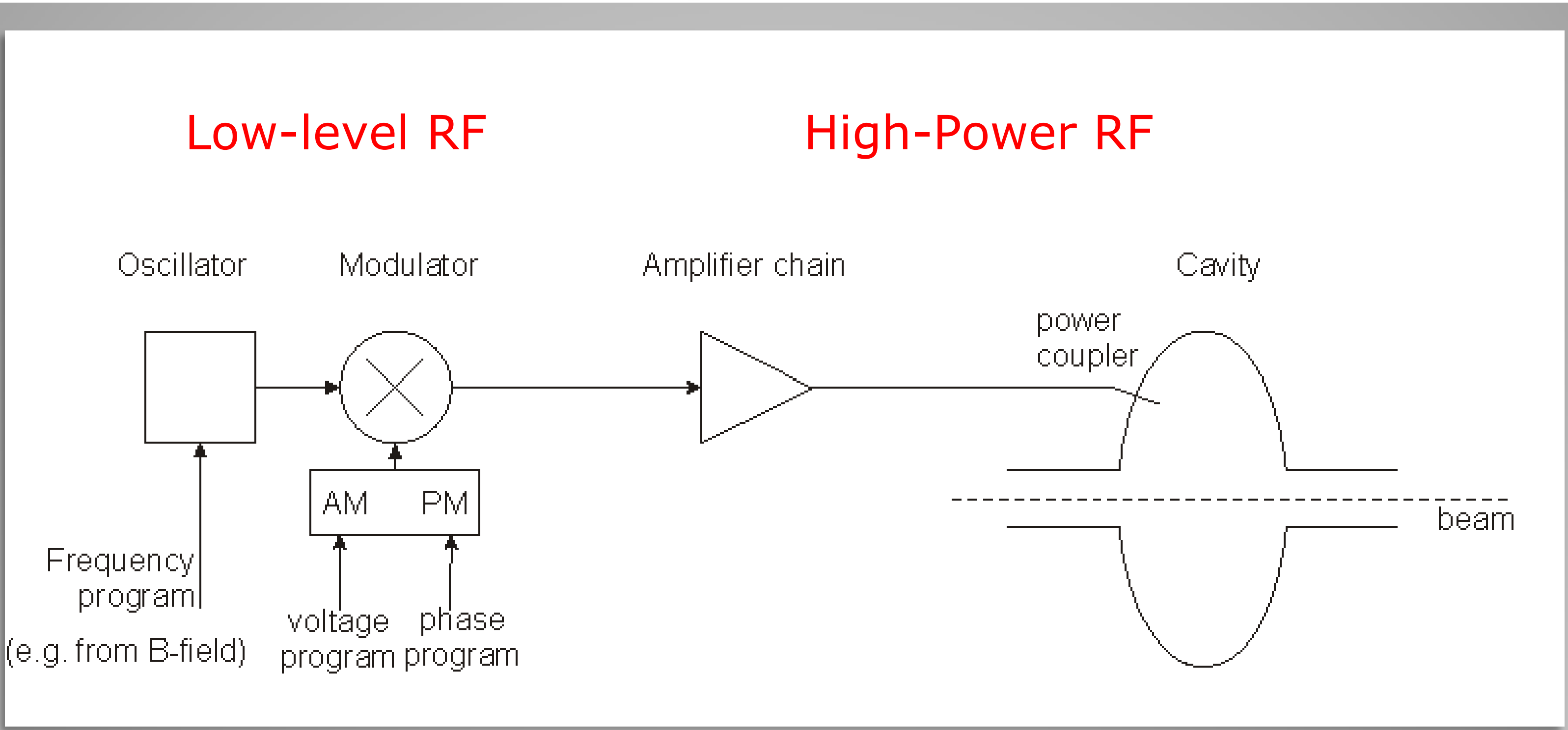
  impedance: $V = \frac{F}{q} = Z(\omega) \cdot I_{beam}$
- $Z(\omega)$ is the Fourier Transform of the wake potential.
- Examples:
  - resistivity in the wall of the vacuum chamber,
  - inductivity in a corrugated wall,
  - resonances in cavities (intentional or spurious).
- Resulting forces can be both longitudinal or transverse.
- Forces can be on the same (head-tail) or subsequent bunches (coupled bunch).
- $Z(\omega)$ can lead to instabilities and sets an upper limit to beam current; forces can be detrimental.

Stability limit

- For simplicity, imagine a coasting, unbunched beam.
- Assume a small perturbation, a sinusoidal density modulation at frequency ω.
- The induced voltage (by the impedance of the machine) is $Z(\omega) \cdot I_{beam}(\omega)$.
- The lattice of the synchrotron will react with an additional modulation of the density.
- This may lead to our assumed perturbation to increase (instable) or to decrease (stable).
- As a result, the overall impedance of the machine must be kept under control ("small").

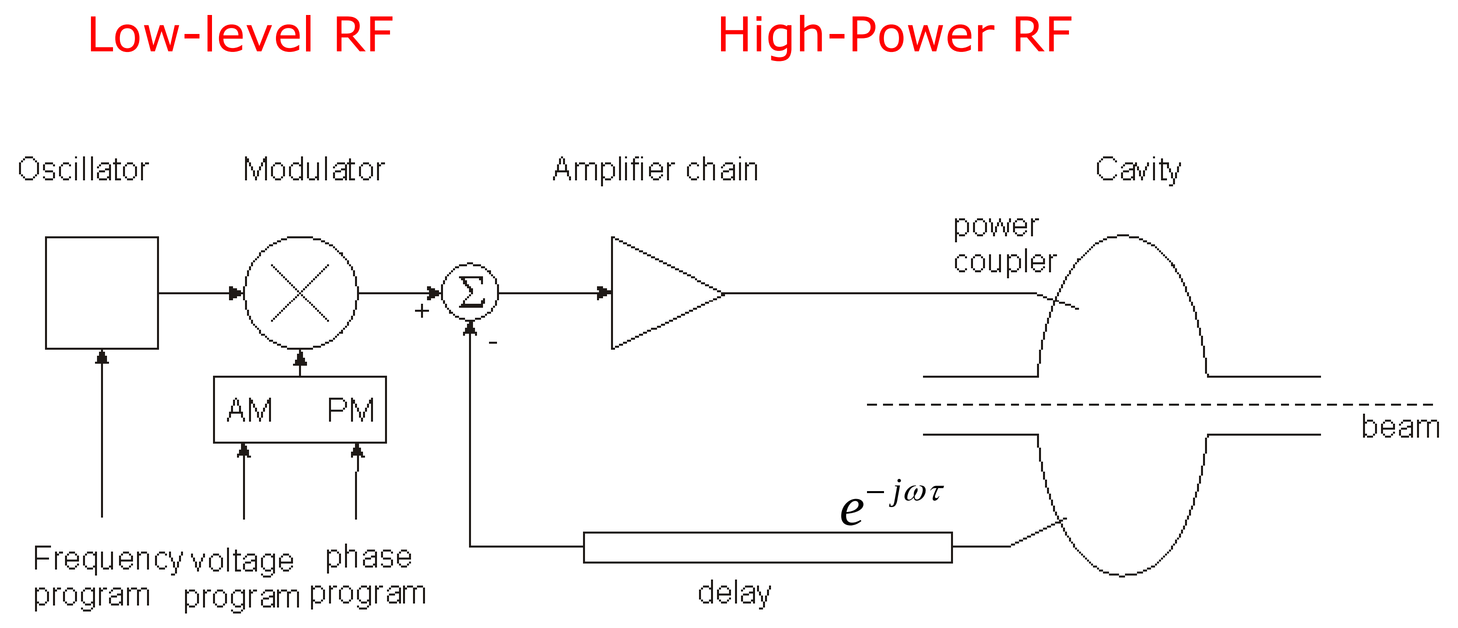


A minimal RF system



- The frequency has to be controlled to follow the magnetic field such that the beam remains in the centre of the vacuum chamber.
- The voltage has to be controlled to allow for capture at injection, a correct bucket area during acceleration, matching before ejection; phase may have to be controlled for transition crossing and for synchronisation before ejection.

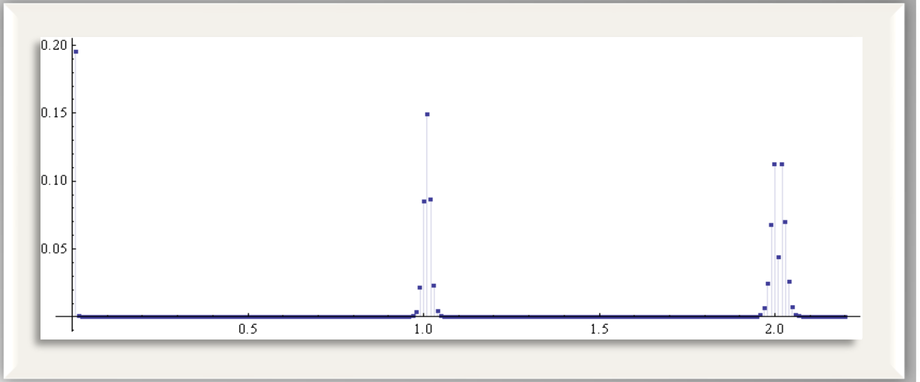
Adding a fast (direct) feedback

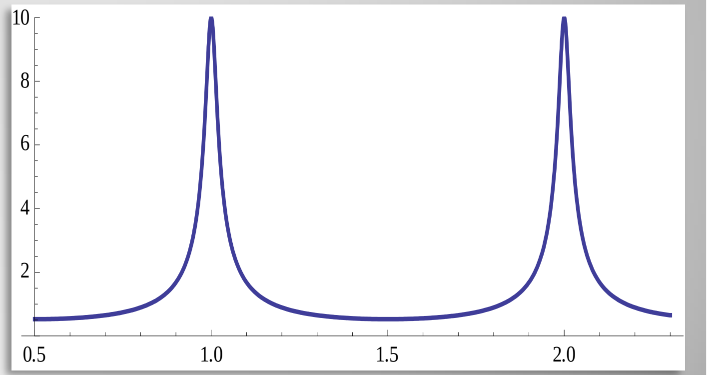


- Compares actual RF voltage and phase with desired and corrects.
- Rapidity limited by total group delay (path lengths) (some 100 ns).
- Unstable if loop gain =1 with total phase shift 180 ° – design requires to stay away from this point (stability margin)
- The group delay limits the gain·bandwidth product.
- Works also to keep voltage at zero for strong beam loading, i.e. it reduces the beam impedance.

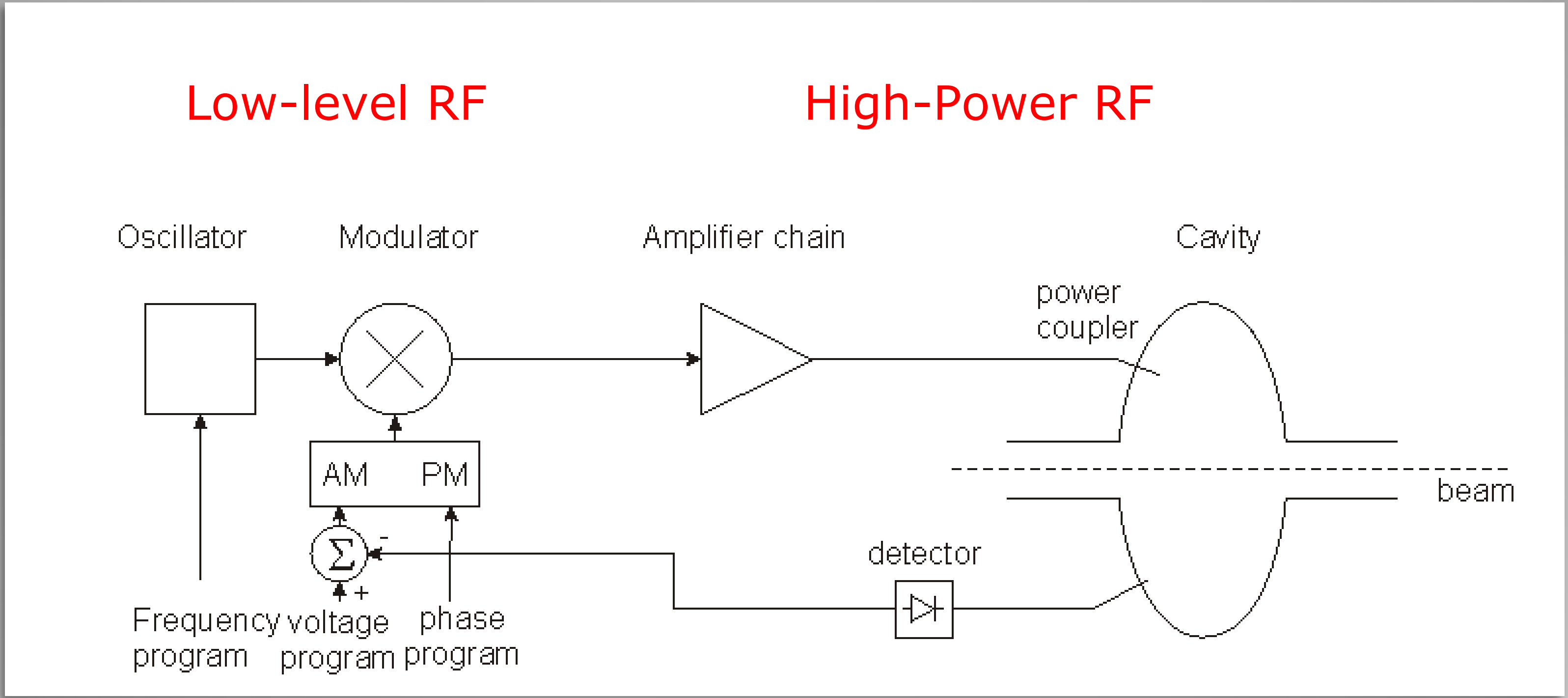
1-turn delay feedback

- The speed of the "fast RF feedback" is limited by the group delay – this is typically a significant fraction of the revolution period.
- How to lower the impedance over many harmonics of the revolution frequency?
- The beam spectrum is limited to relatively narrow bands around the multiples of the revolution frequency.
- Only in these narrow bands the loop gain must be high!
- Install a comb filter! … and extend the group delay to exactly one turn – in this case the loop will have the desired effect and remain stable.



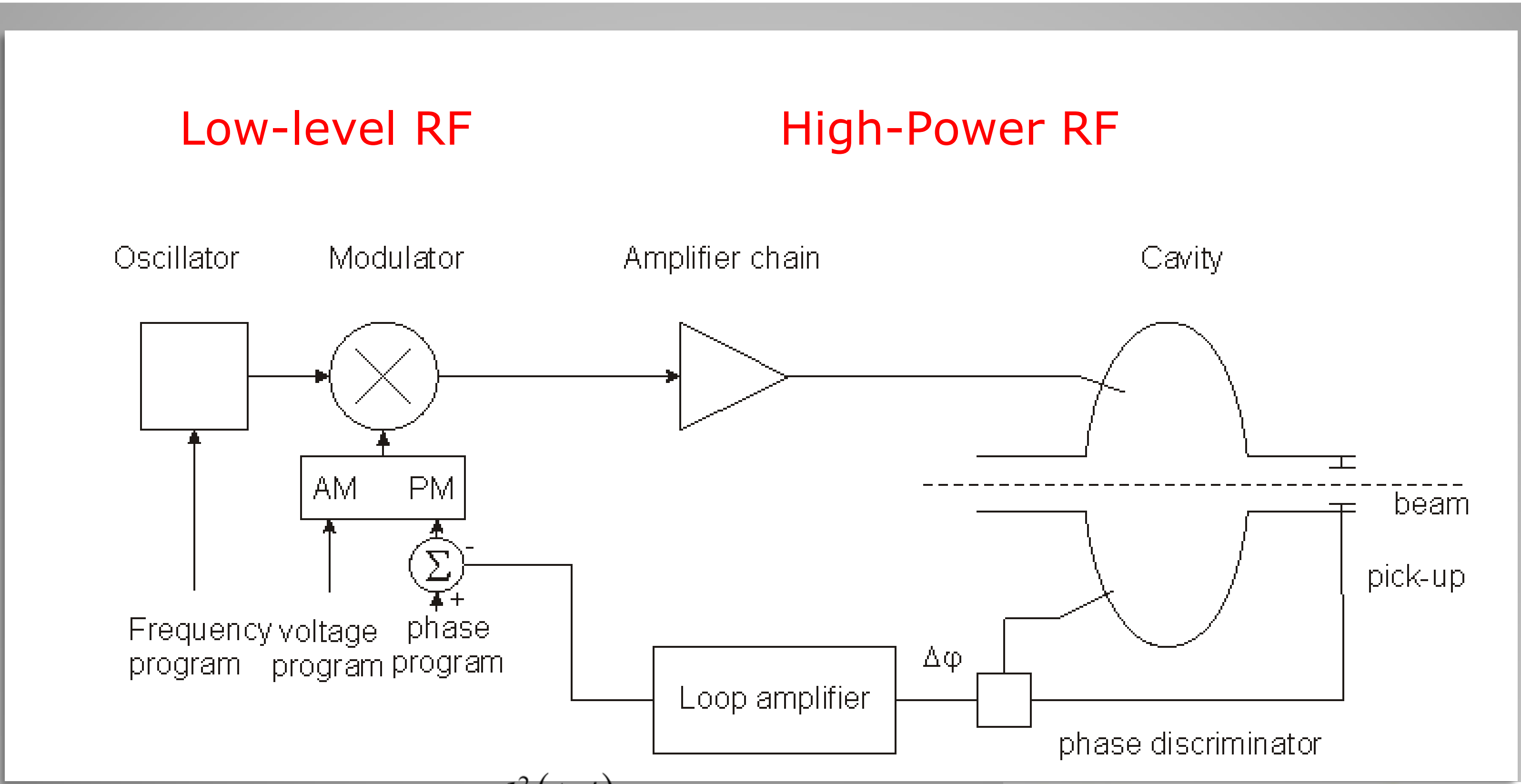


Field amplitude control (AVC)



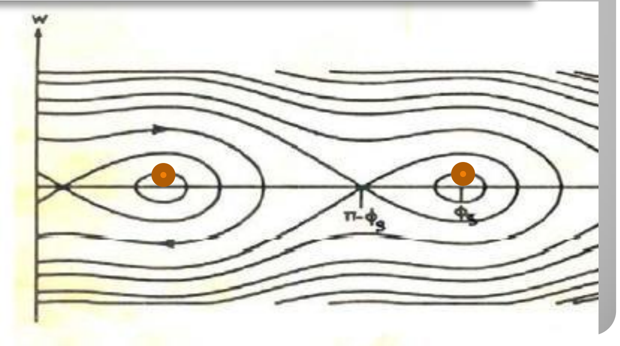
- Compares the detected cavity voltage to the voltage program. The error signal serves to correct the amplitude

Beam phase loop

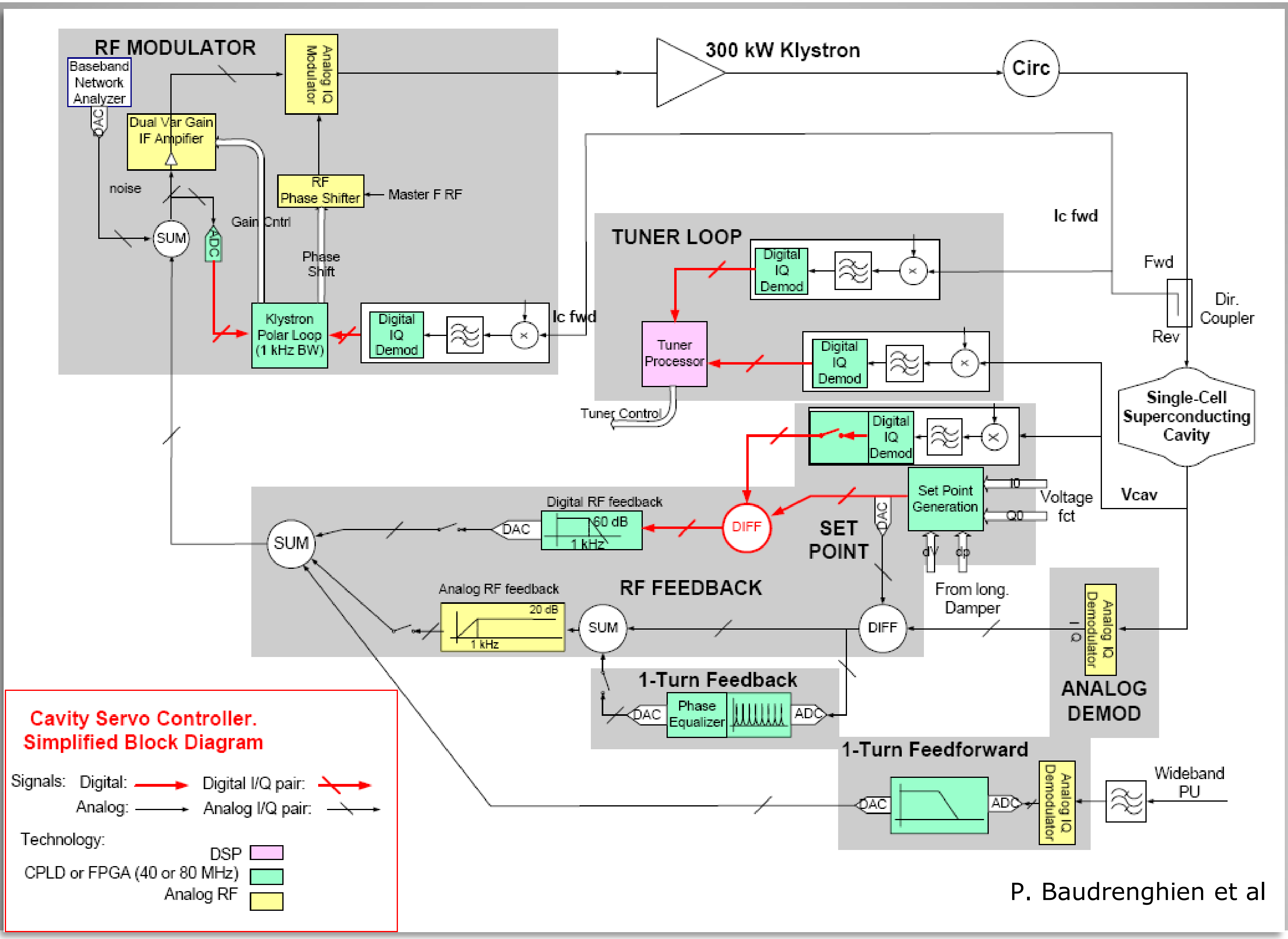


- Longitudinal motion: $\frac{d^2(\Delta\phi)}{dt^2}+\Omega_s^2(\Delta\phi)^2=0$
- Loop amplifier transfer function designed to damp synchrotron oscillation.

  Modified equation: $\frac{d^2(\Delta\phi)}{dt^2}+\alpha\frac{d(\Delta\phi)}{dt}+\Omega_s^2(\Delta\phi)^2=0$



LHC RF System (1/2)



Cavity Servo Controller. Simplified Block Diagram

P. Baudrenghien et al

LHC RF System (2/2)

One Rack contains 1 complete cavity controler

From: LHC Project Report 1172

LHC SC RF, 4 cavity module, 400 MHz

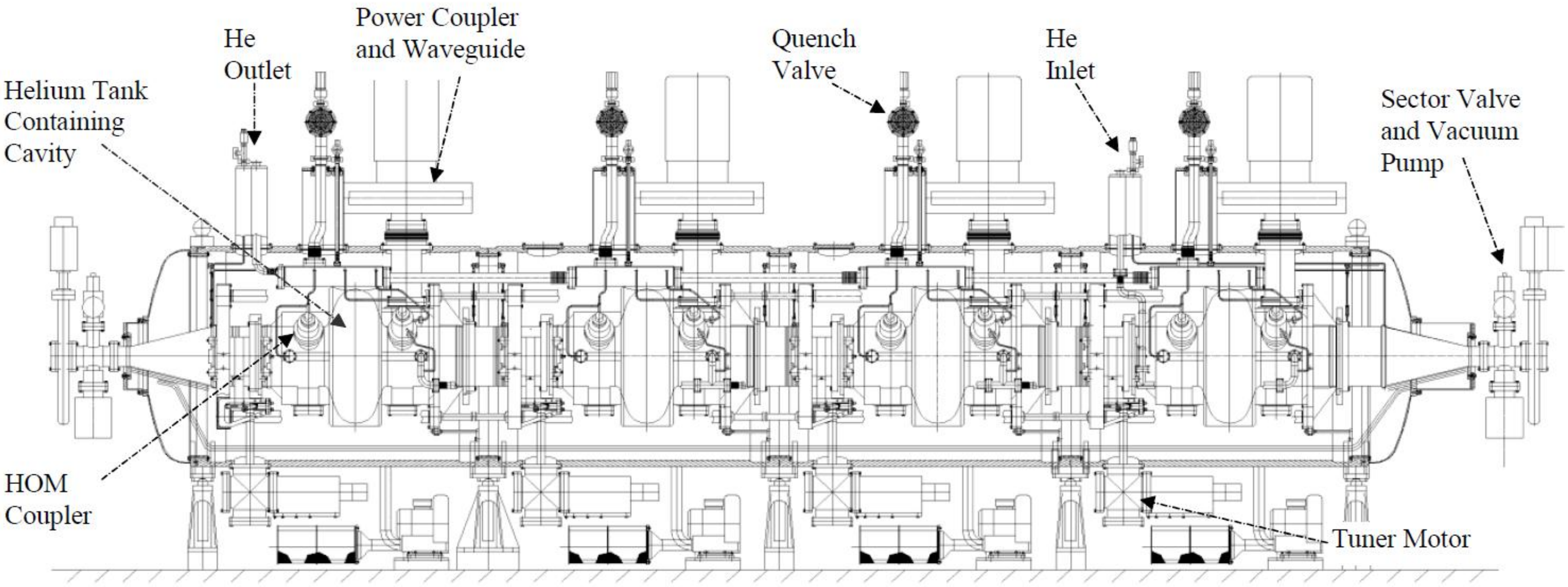


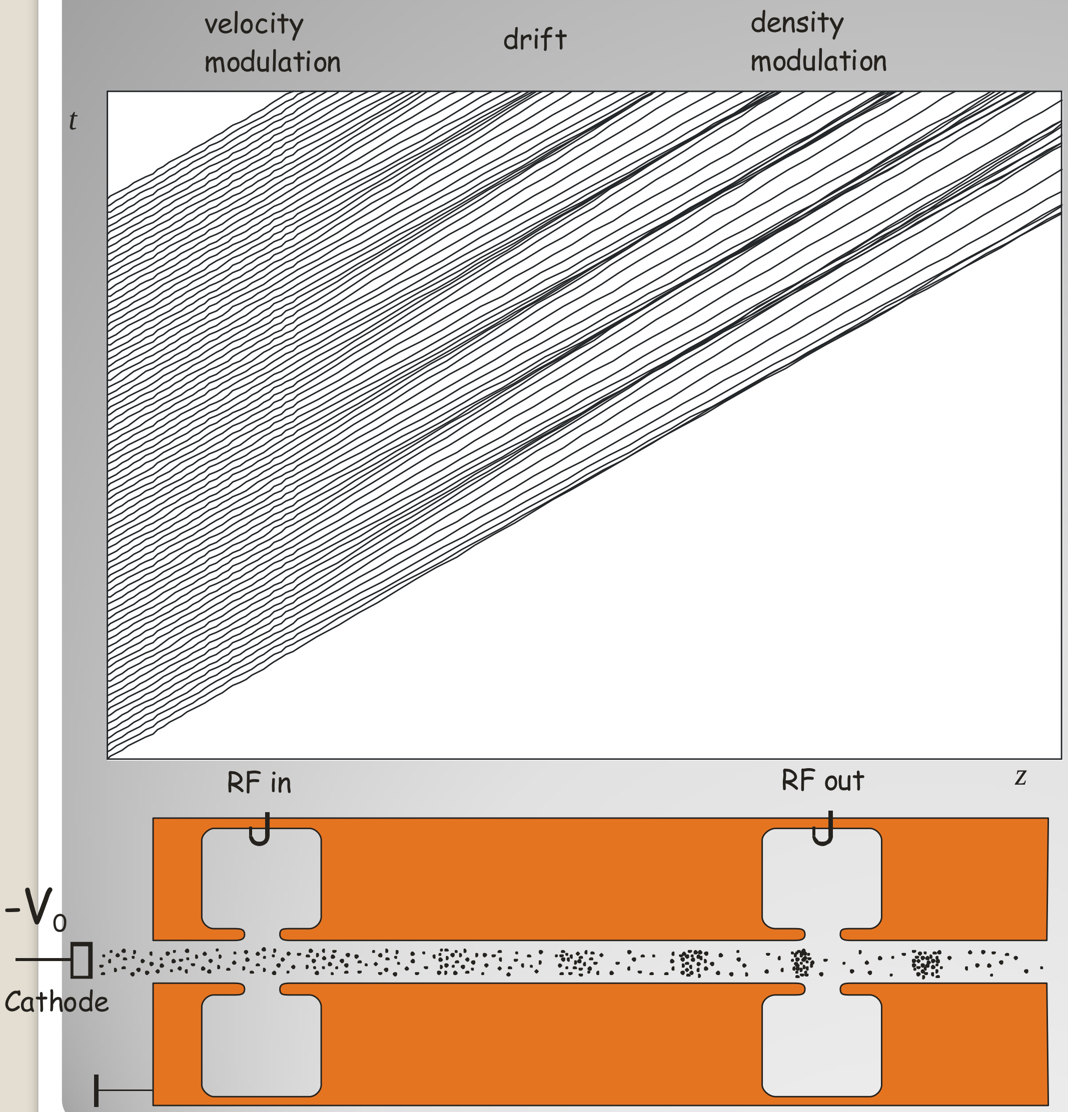
Figure 6.1: Four-Cavity Cryomodule

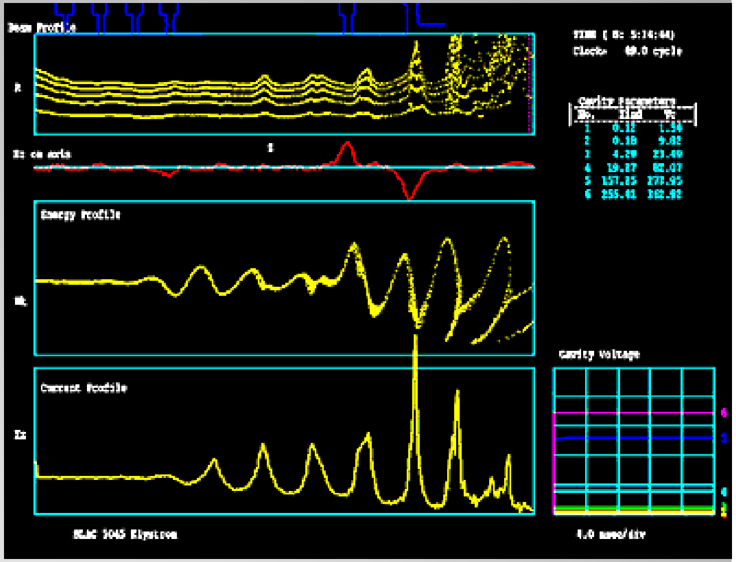
LHC SC RF, 4 cavity module, 400 MHz

LHC 400 MHz Cavities in the tunnel

2 cryomodules (x 4 cavities) left of IR4
(similar right of IR4)
8 cavities per beam

Klystron principle





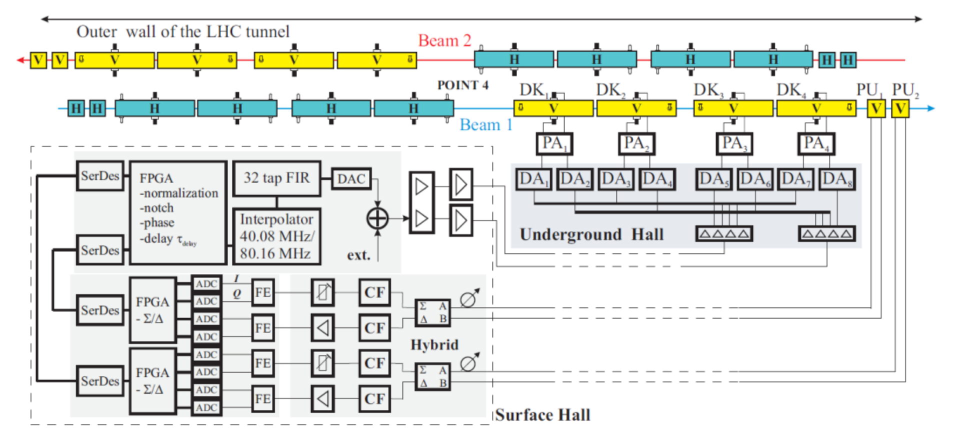
LHC RF power: klystrons

CERN LHC klystron:
(58 kV, 9.3 A)
400 MHz, 300 kW CW RF,
Efficiency 62 %.

One klystron feeds 1 cavity to reach 2 MV accelerating voltage.

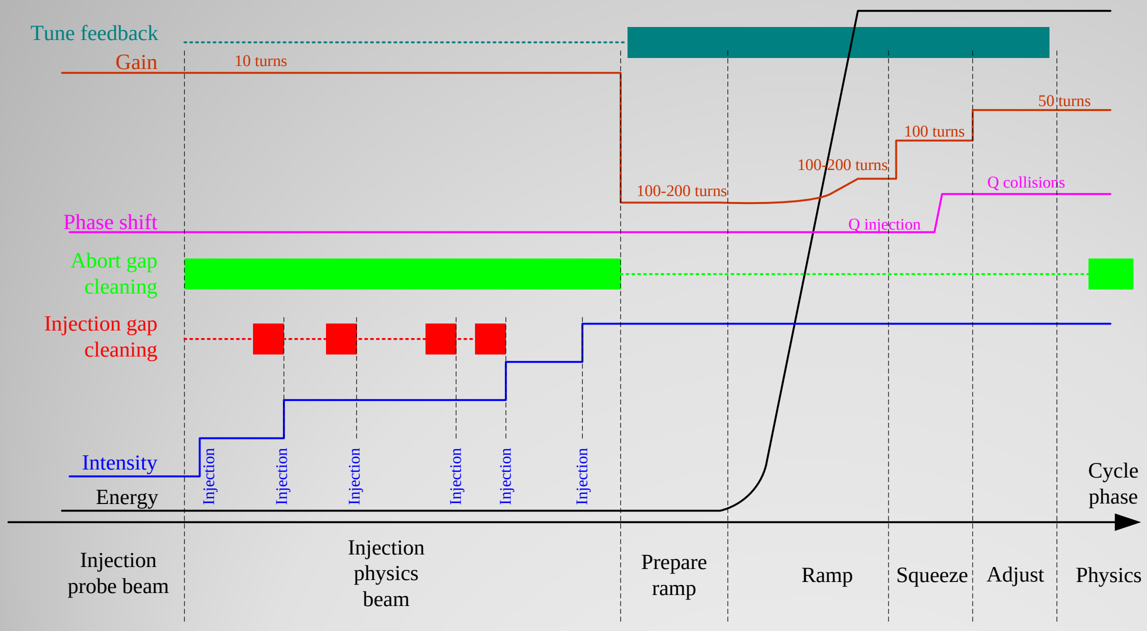
Cavern UX45: LHC Power station, 16 klystrons

LHC Transverse Damper

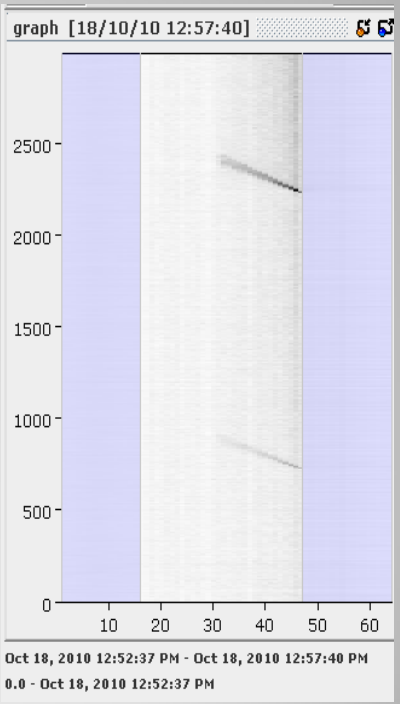


Transverse damper system

- Purpose:
  - To damp transverse injection errors,
  - to create a clean gap for injection and abort
  - to keep beam stable transversely.



  - Maybe in the future to counteract e-cloud…



Oct 18, 2010 12:52:37 PM - Oct 18, 2010 12:57:40 PM
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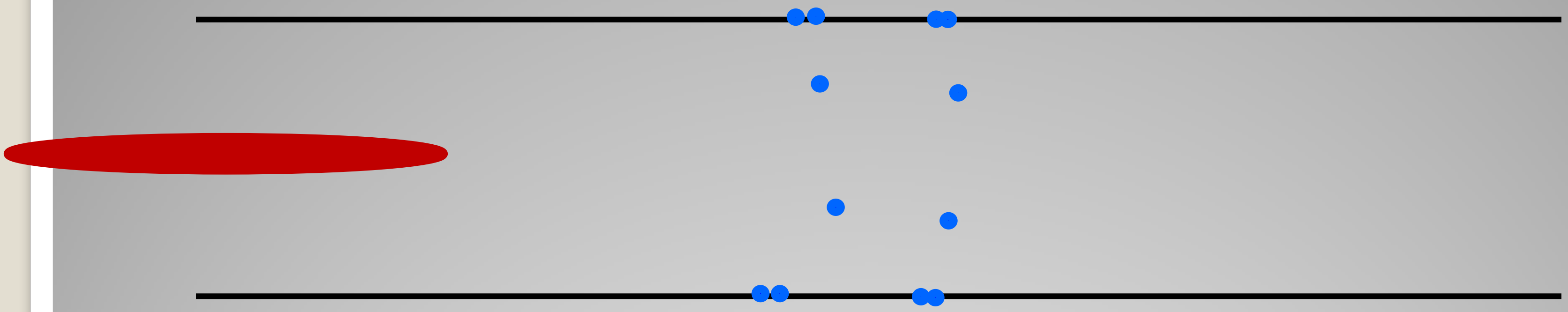
Abort gap cleaning

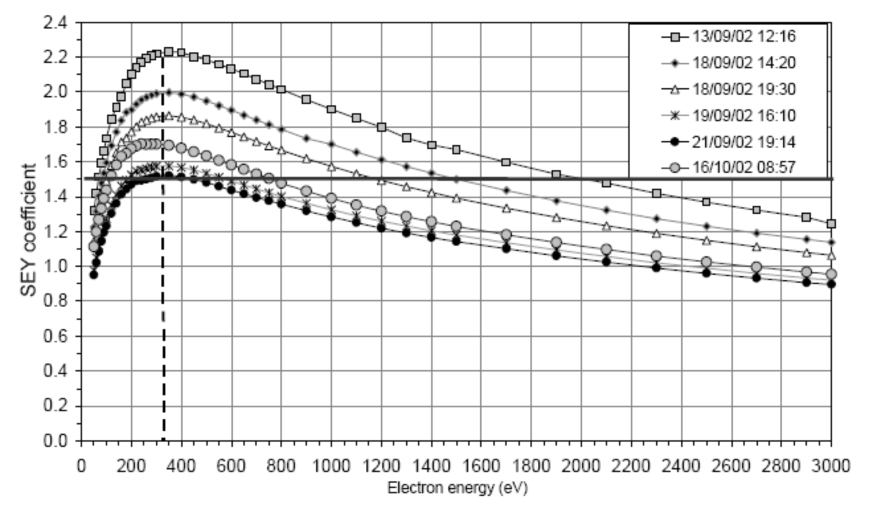
“e-cloud” – limiting the beam current



- A passing proton bunch (red) attracts electrons (blue)present in the beam pipe and accelerates them towards the opposite side of the beam chamber.
- Hitting the surface results in the emission of secondary electrons – depending on the secondary emission yield (SEY) and the energy of the impacting electrons potentially more than the impacting primary electrons.
- For illustration we assume SEY=2.
- When the next proton bunch passes, the whole repeats itself, but the electron density increases. It will reach a steady state since new emissions are counteracted by the potential of the electron cloud.
- If the distance between proton bunches is similar to the time of flight of the electrons, there will be a resonant effect (similar to *multipacting*).
- The interaction of the e-cloud with the proton bunches will deflect them and may – depending on the proton intensity – lead to beam loss.
- This is a serious limitation in the LHC (and the SPS).

Secondary Emission Yield (SEY)

- Typical behaviour of the SEY as function of the energy of the impacting primary electrons for different conditioning.



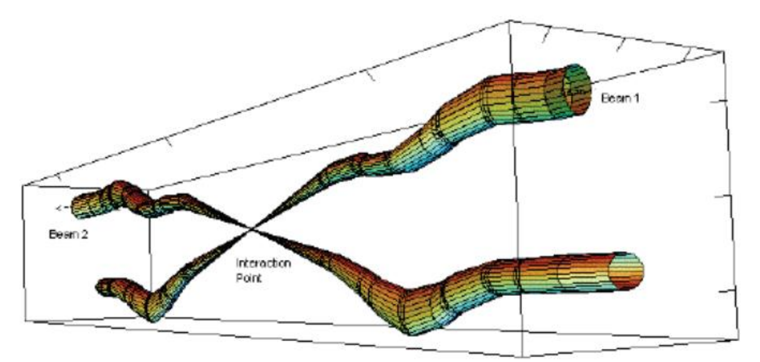
- In order to reduce the adverse effects of e-cloud, one may
  - change the bunch spacing,
  - condition the vacuum chamber surface, e.g. by controlled particle loss (scrubbing – see above diagram),
  - coat the inside of the vacuum chamber (Ti, TiN, NEG, a-C, ...),
  - change the geometry of surface aspect of the vacuum chamber (longitudinal corrugation or roughen surface),
  - apply additional electric (clearing electrode) or magnetic fields deflect electrons thus destroying the resonance condition,
  - Maybe implement a very fast (wide-band) transverse damper to correct proton trajectories.

LHC Luminosity upgrade

High
Luminosity
LHC

Crab Cavities

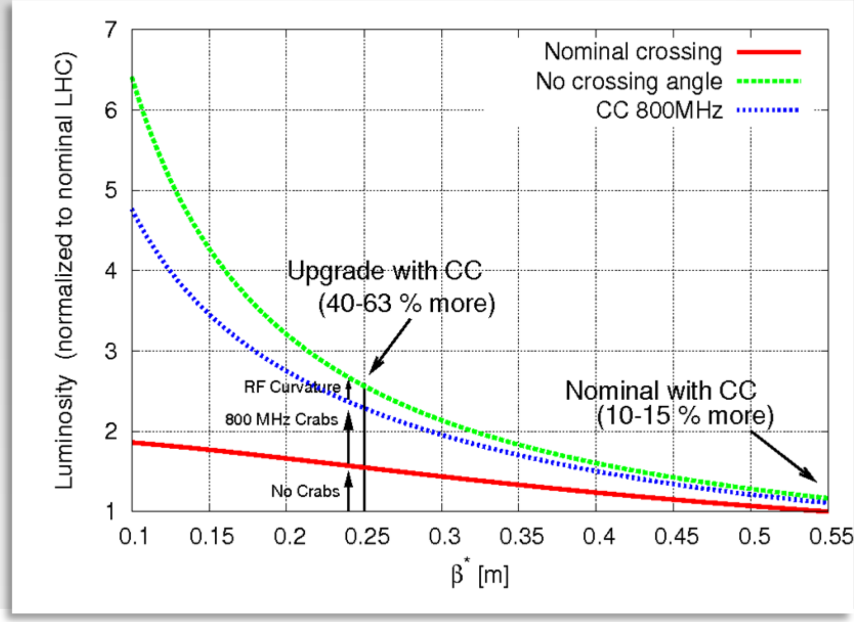
Crab Cavities – context



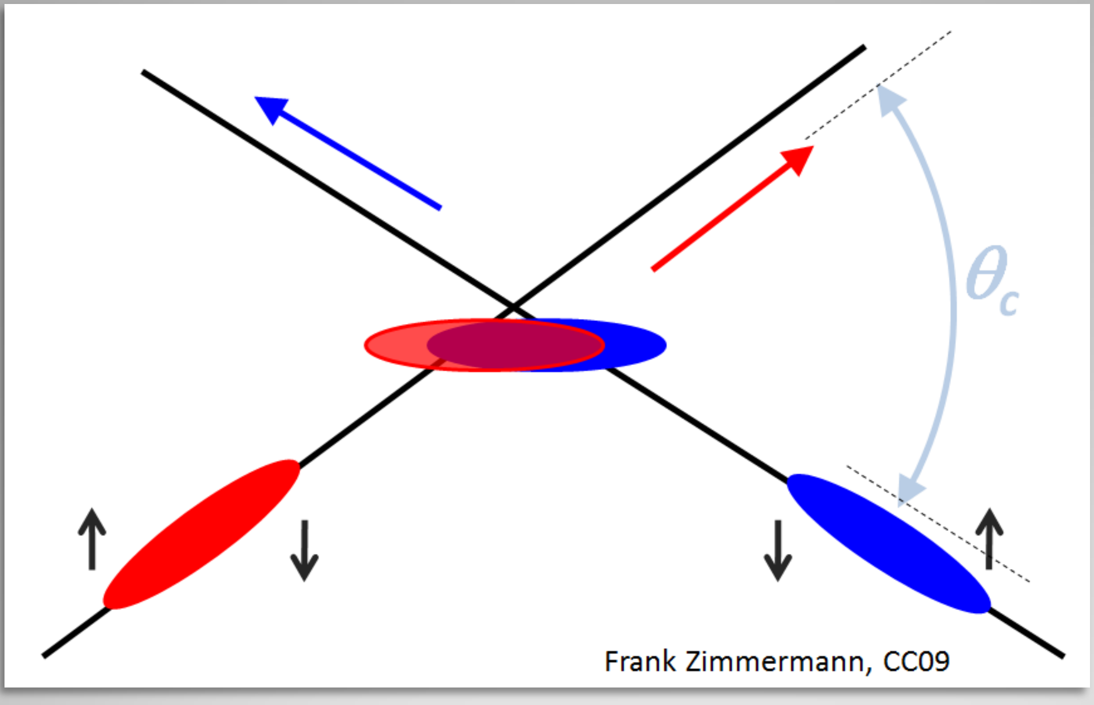
Relative beam sizes around IP1 (Atlas) in collision

- Many bunches require **non-zero crossing angle** to avoid parasitic collisions and to reduce beam-beam effects;
- With non-zero crossing angle, luminosity gain by squeezing beams further is small (red curve below).

- Crab cavities can compensate for this geometric effect and thus allow for a luminosity increase of about 50 % at $\beta*$ of 25 cm.
- In addition, crab cavities provide a knob for **luminosity levelling**;
- This allows optimizing for **integrated** rather than peak **luminosity**!



Principle of Crab Cavity operation

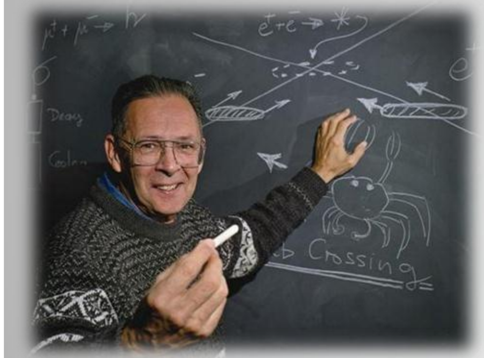


Frank Zimmermann, CC09

RF crab cavity deflects head and tail in opposite direction so that collision is effectively "head on" for luminosity and tune shift

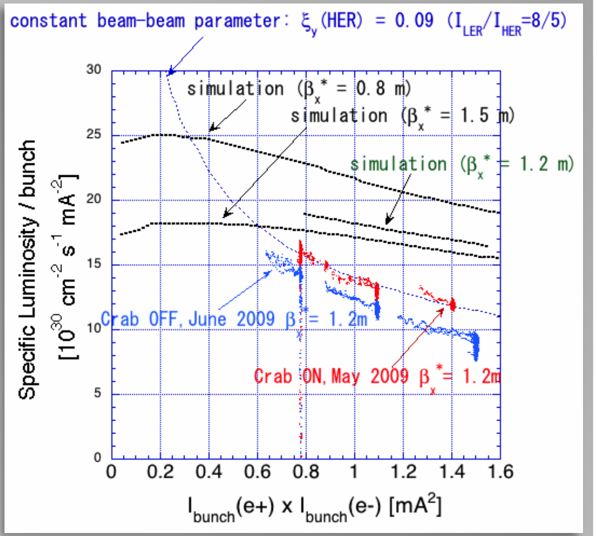
Bunch centroids still cross at an angle (easy separation)

Crab Cavities History: 1988 to 2009

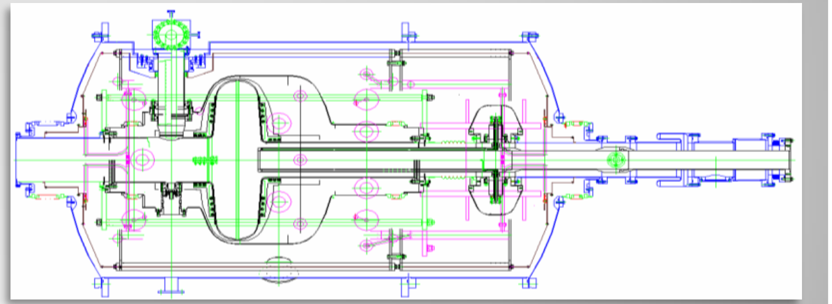


R. Palmer, 1988, LC

K. Hosoyama, 2010



Elliptical Technology

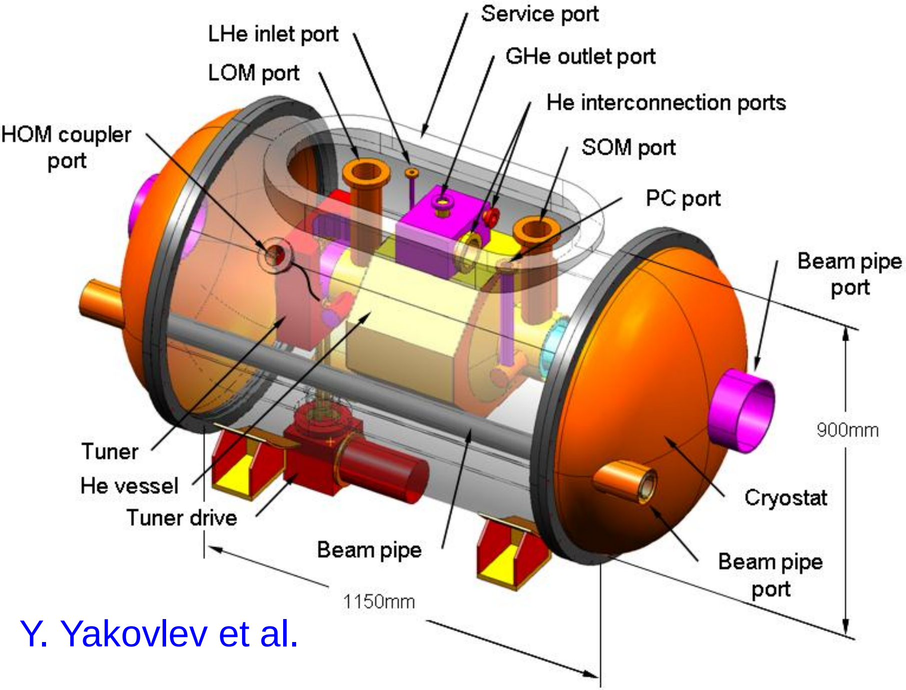


In operation at KEKB 2007 - 2011

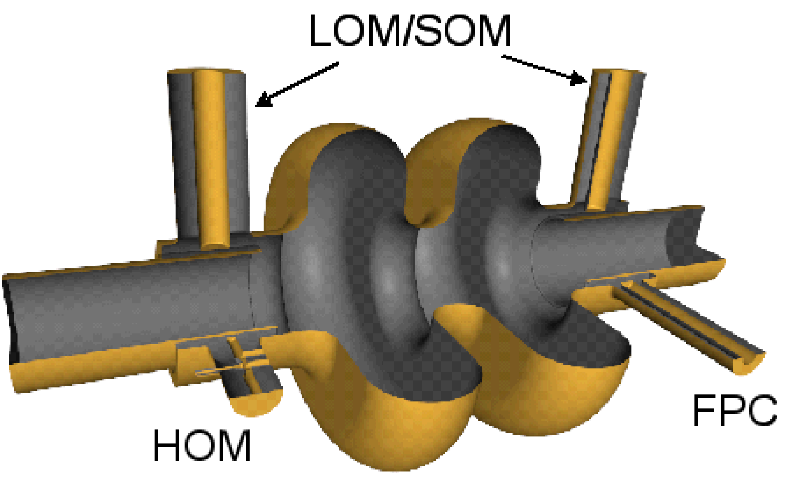
→ ***world record luminosity!***

Crab Cavities for LHC

- Proposed 2005 US-LARP
- First concentrated on elliptical cavities



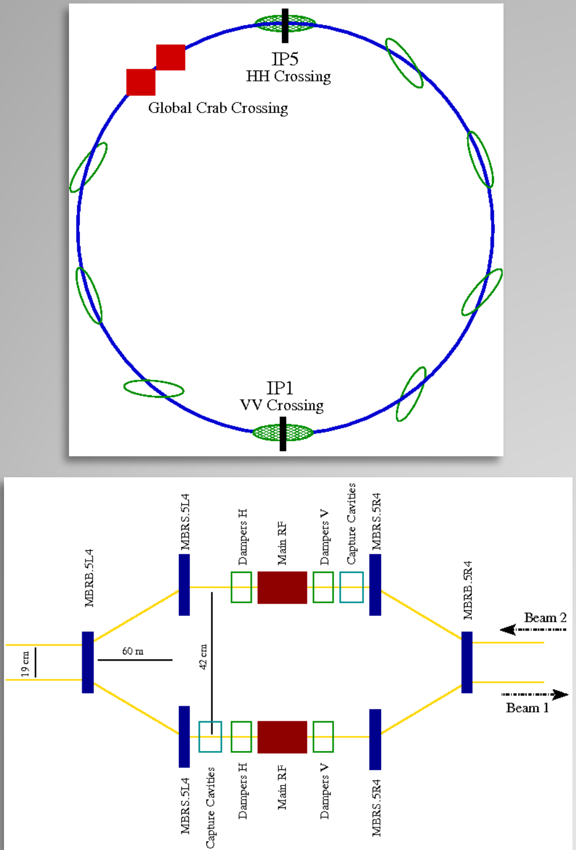
Y. Yakovlev et al.



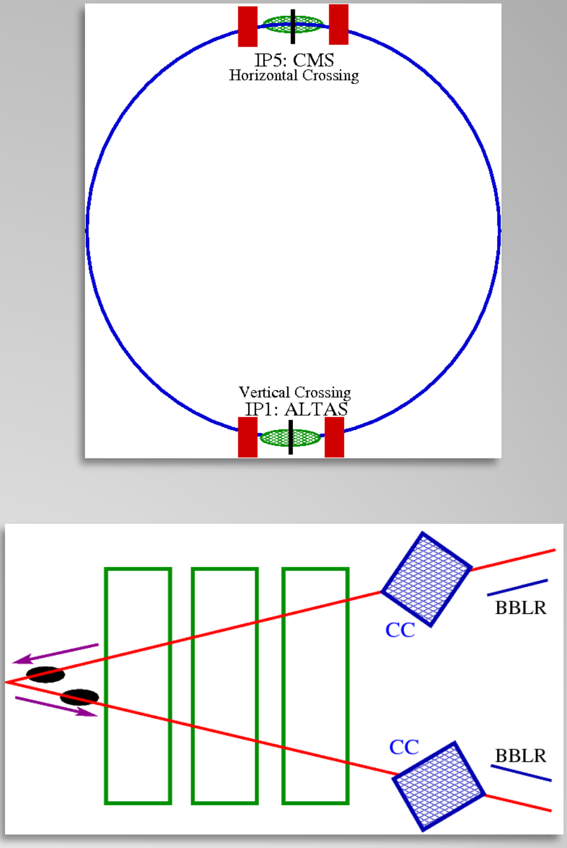
L. Xiao et al.

~250 mm outer radius

Local versus global crabbing scheme (1/2)



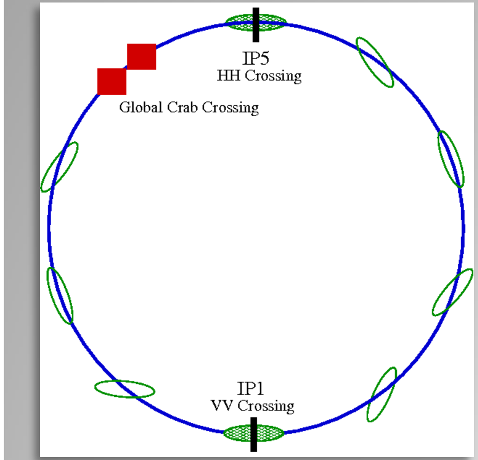
Global scheme, allows for elliptical CC's at one (or two) locations



Local scheme, CC's up- and downstream of each IP, requires compact cavities

Local versus global crabbing scheme (2/2)

Global Scheme:



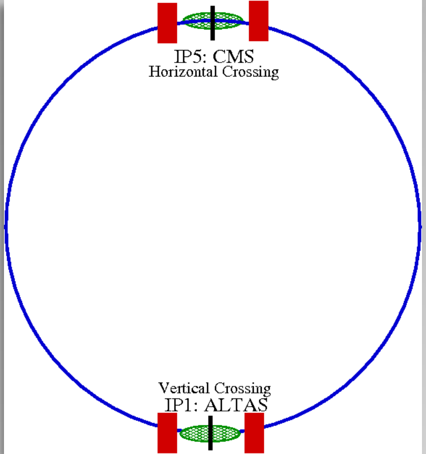
Advantages:

- Only one cavity per beam;
- Larger beam separation near IP4;
- Elliptical cavity of known technology.

Disadvantages:

- Constraining betatron phase advance;
- Requires larger collimator settings;
- Works only for H or V crossing;
- Only 800 MHz or higher fits.
- Fit only in IR4

Local Scheme:



Advantages:

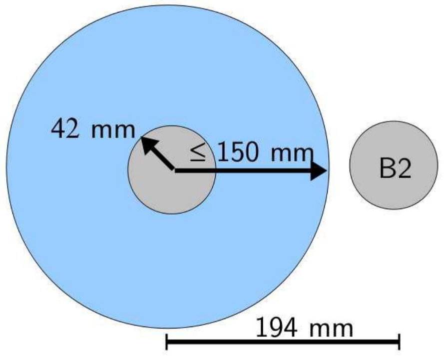
- Individual luminosity control at each IP;
- Adapted to H or V crossing;
- Orbit perturbed only locally;
- Could work lower f – better performance.

Disadvantages/concerns:

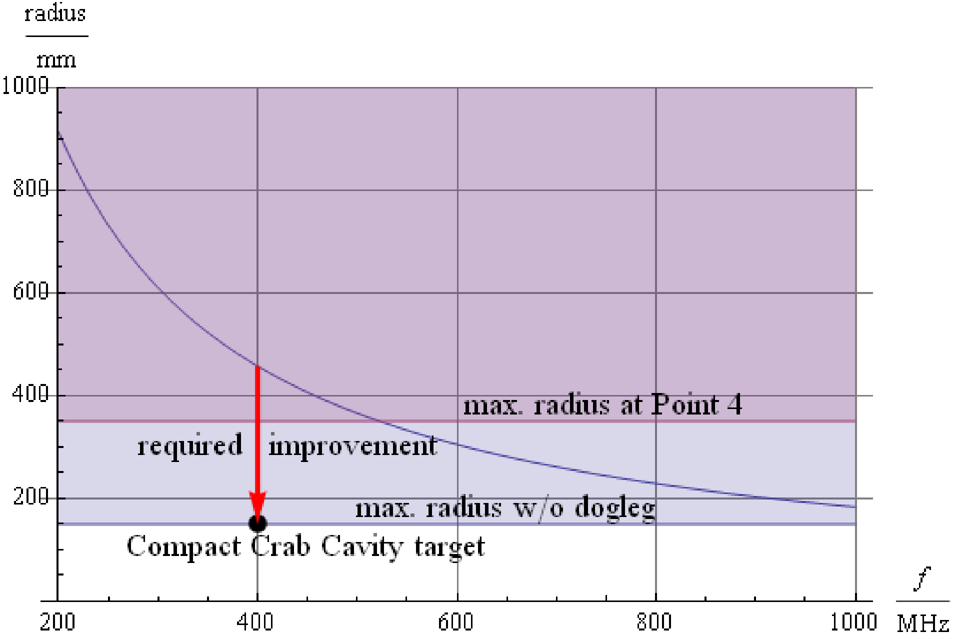
- Requires novel **Compact Cavities** (194 mm separation), well advancing, but not yet validated;
- Requires 4 cavities per IP;
- What if 1 cavity trips?

Compact Crab Cavities are needed!

- The nominal LHC beam separation in the LHC is 194 mm;
- Conventional (elliptical) cavities scale with λ – they are too large even at 800 MHz!



- … but at higher *f*, the RF curvature is non-linear!
- This is a real challenge!



Two “classes” of compact  cavities

1. TM type

   $E_z(x) = -E_z(-x)$ ➔ Kick force dominated by $v \times B_y$

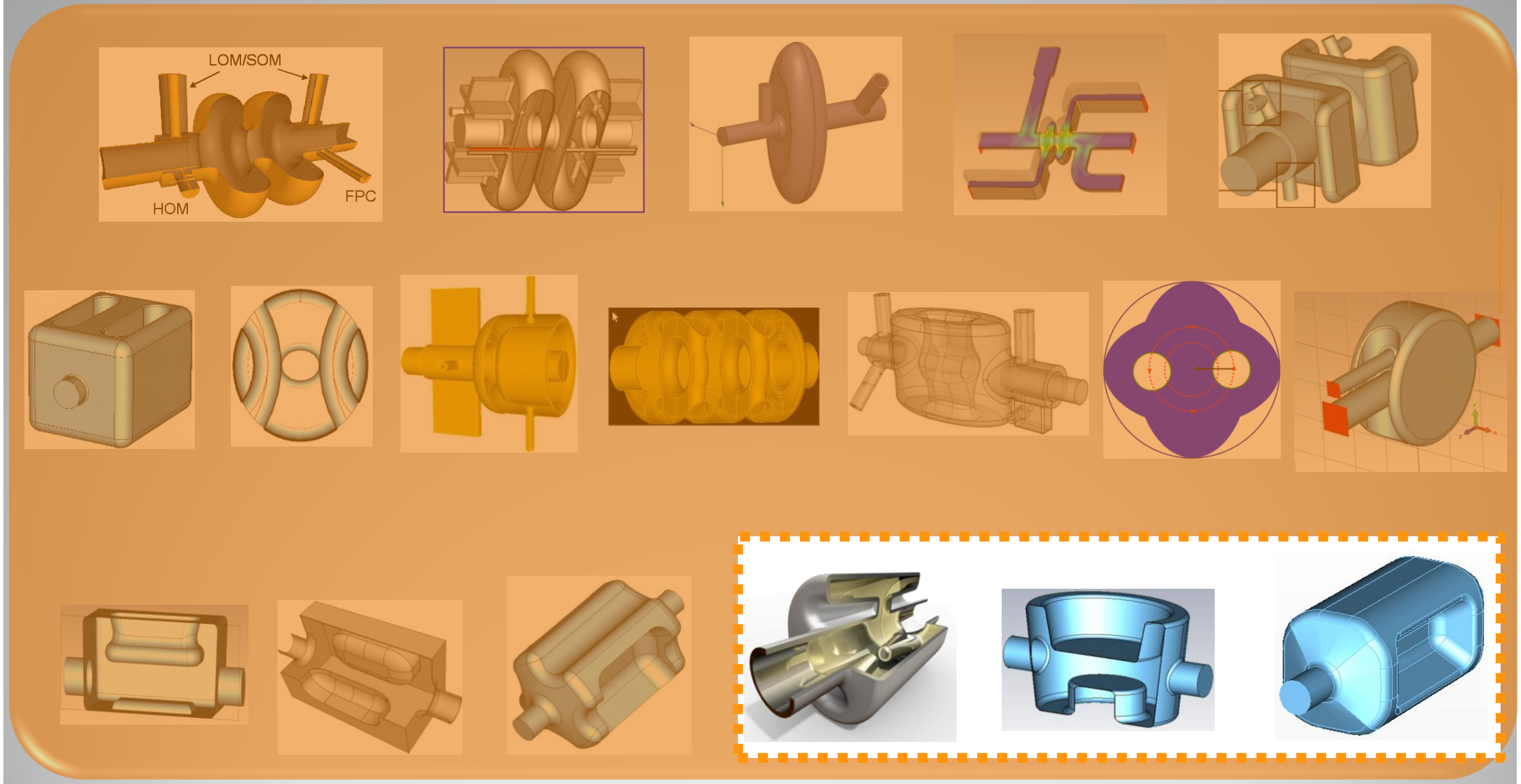
   - ◦ Variations of elliptical cavity …
   - ◦ Half-wave resonator (SLAC)
   - ◦ Mushroom cavity (FNAL)
   - ◦ Longitudinal rods (JLAB, ULANC)

2. TE type (Panofsky-Wenzel: $j\omega \vec{F}_\perp = \nabla_\perp F_z$!)

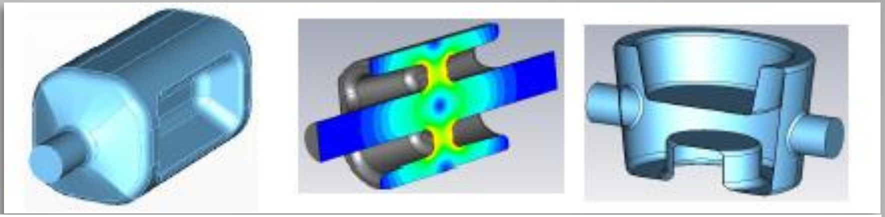
   $B_y = 0$ ➔ Kick force dominated by E_x

   - ◦ “transverse pillbox” (KEK)
   - ◦ Parallel bars or spokes:
     - Figure-of-8 (CI)
     - Spoke cavity (SLAC)
     - Parallel bar cavity (JLAB, ODU)

A very interesting and novel field!

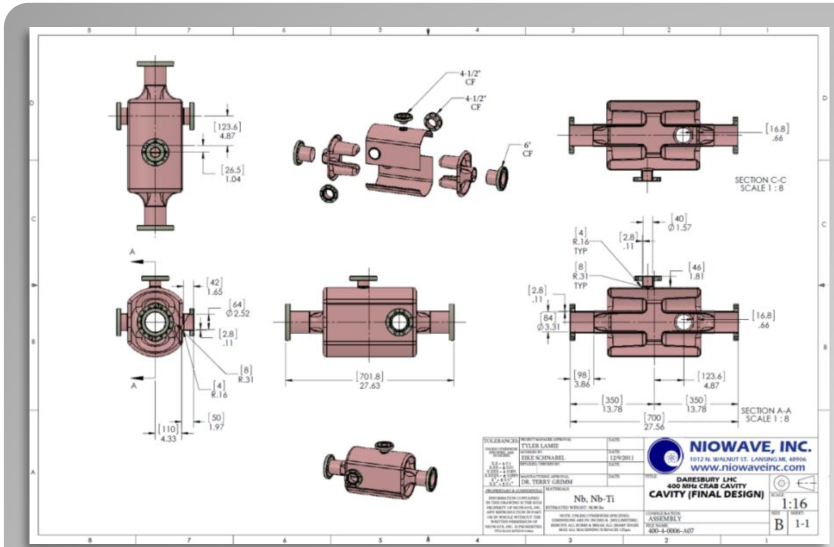


Present 400 MHz contenders

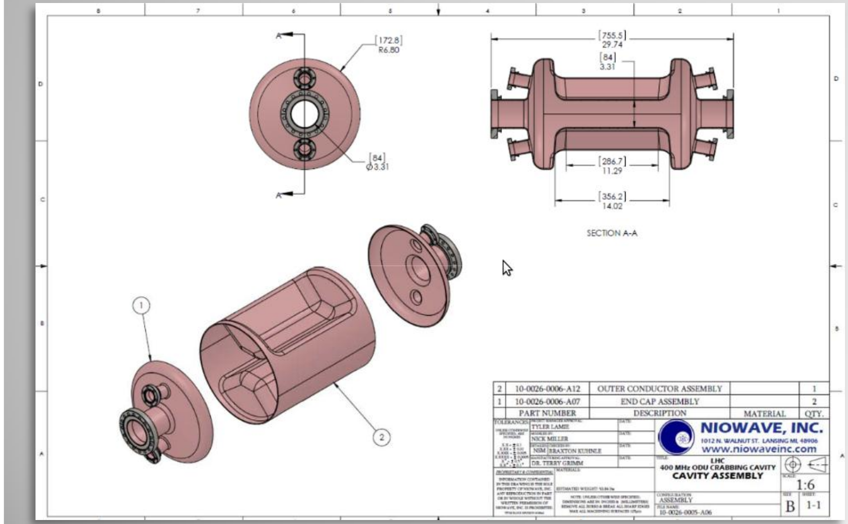


Values for 400 MHz, 3 MV integrated kick	Double ridge (ODU/SLAC)	LHC-4R (ULANC)	¼ Wave (BNL)
Cavity radius [mm]	147.5	143/118	142/122
Cavity length [mm]	597	500	380
Beam Pipe radius [mm]	42	42	42
Peak E-field [MV/m]	33	32	47
Peak B-Field [mT]	56	60.5	71
RT/Q [Ω]	287	915	318
Nearest OOM [MHz]	584	371-378	575

Challenge: SC RF technology



March 2012:



May 2012:

on-going R&D

Summary – LHC Upgrade RF

- **LHC RF System** consists of acceleration system and transverse damper system.
- Elaborate beam control to keep beams stable at all energies and intensities.
- 16 SC single-cell 400 MHz cavities in 4 cryostats designed for 16 MV/beam.
- LHC luminosity upgrade requires compact **Crab Cavities**, which initiated challenging R&D on SC RF Technology.

Thank you very much!