RF Systems & LHC Integration

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Acknowledgments:

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3rd LHC Crab Cavity WS, 17 Sept 2009

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- RF High Power system requirements
- Possible High Power Realization
- RF feedback requirements: 2-cell cavity
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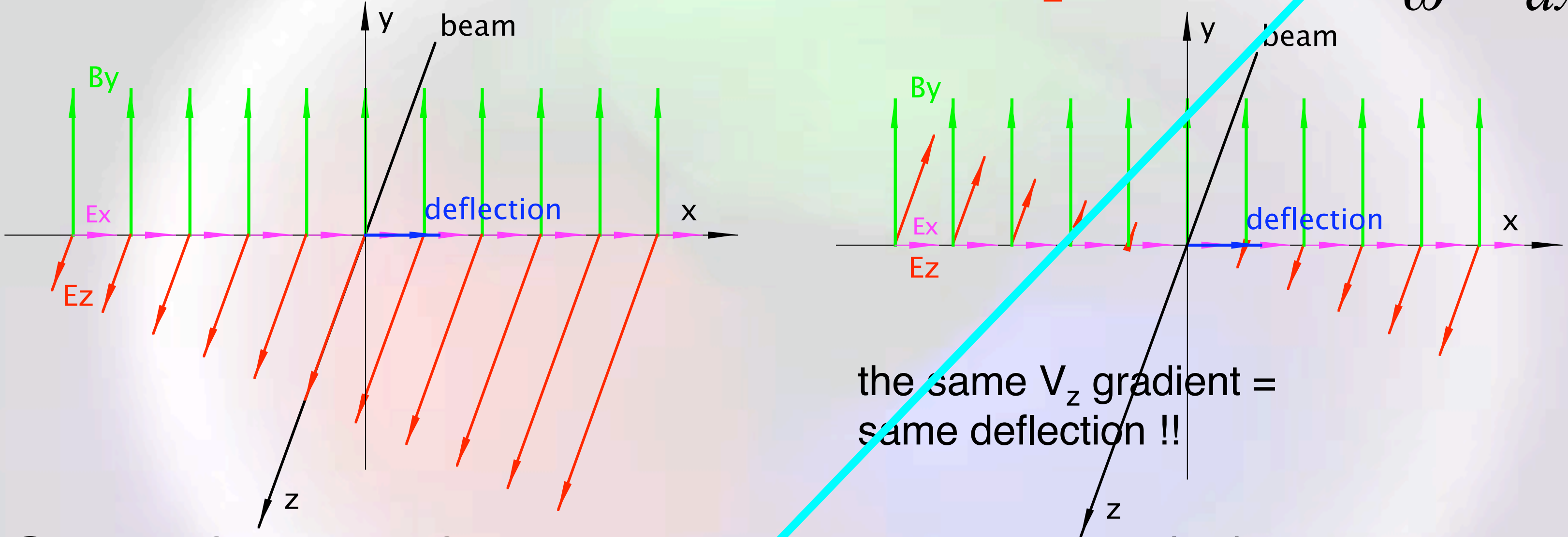
• RF High Power system requirements

Generalized Panofsky-Wenzel theorem

Deflection requires transverse gradient in longitudinal accelerating voltage (←E_z)

$$\Delta p_x = -\frac{\boxed{i\cdot} e}{\omega}\cdot\frac{dV_z}{dx}$$



the same V_z gradient = same deflection !!

Chose field configuration having x_0 that $V_z(x_0) = 0$:

→ no longitudinal beam-cavity interaction (if beam really at x_0)

Δp_x, V_z 90° out of phase

Δp_x, Bunch centre 90° out of phase

(no kick for bunch center !!)

→ **Bunch Center (==I_b), V_z in phase !!!**

(worst phase angle for parasitic longitudinal interaction)

$x_0 == 0$ not possible in real life: allow (limited) deviation Δx_0

→ longitudinal beam-cavity interaction (beam excites cavity)

→ need RF feedback system to counter-act: RF power

(beam power from/to CC is compensated by main RF: coupling)

'Given' are: $(R/Q)_{\perp}=60\ \Omega_{\mathrm{circuit}}$ ($=120\ \Omega_{\mathrm{linac}}$); $V_{\perp}=2.5$ MV; $I_b=0.6$ A

(neglect bunch form factor at 800 MHz, it helps)

Assume: guaranteed $|\Delta x_0| \leq 0.2$ mm (=200 μm!)

(for efficient 'transformation' $V_{\perp}$ to tilt at IP: optical β is made large at CCs:

beam excursions are magnified at CC !!!!)

To be chosen: coupling strength of Main Coupler : Q_{ext}

For small Δx_0: P_{RF} prop. $1/Q_{\mathrm{ext}}$ indep. Δx_0 → high Q_{ext} good

For large Δx_0 : P_{RF} prop. $Q_{\mathrm{ext}} \bullet (\Delta x_0)^2$ → low Q_{ext} good

(derivation in appendix)

$$Q_{ext,opt} = \frac{c \cdot V_\perp}{2\,(R/Q)_\perp \cdot \omega \cdot \Delta x_{0,\max} I_b} \approx 10^7; \qquad BW = 80 \ Hz$$

$$P_{g,r,opt,worst} = \frac{\omega \cdot V_\perp \cdot I_b}{c} \Delta x_{0,\max} \approx 5 \ kW \quad (\Delta f_{detune} \equiv 0); \ P_{\min} = 0$$

Need more power than this:

1) Detuning error (very small bandwidth !!)

2) Feedback needs power reserve

No solid state (tower) at 800 MHz for such power (yet):

Anyway need klystron or IOT

-> more power is available ‘for free’

Assume that we have 30 kW ‘free’ RF power (instead of 5 kW)

$Q_{ext} = 5\ 10^5$ is ‘possible’: BW = 1600 Hz

(impedance of kick mode, phase noise, …)

(derivation in appendix)

• Possible High Power Realization (we are lucky)

The SPS – as LHC injector $f_{SPS} = f_{LHC}/2$ – has a 4th order Higher Harmonic Landau system

→ $f_{Landau} = 2^{*} f_{LHC}$ precisely

as for CC: **801.6.. MHz**

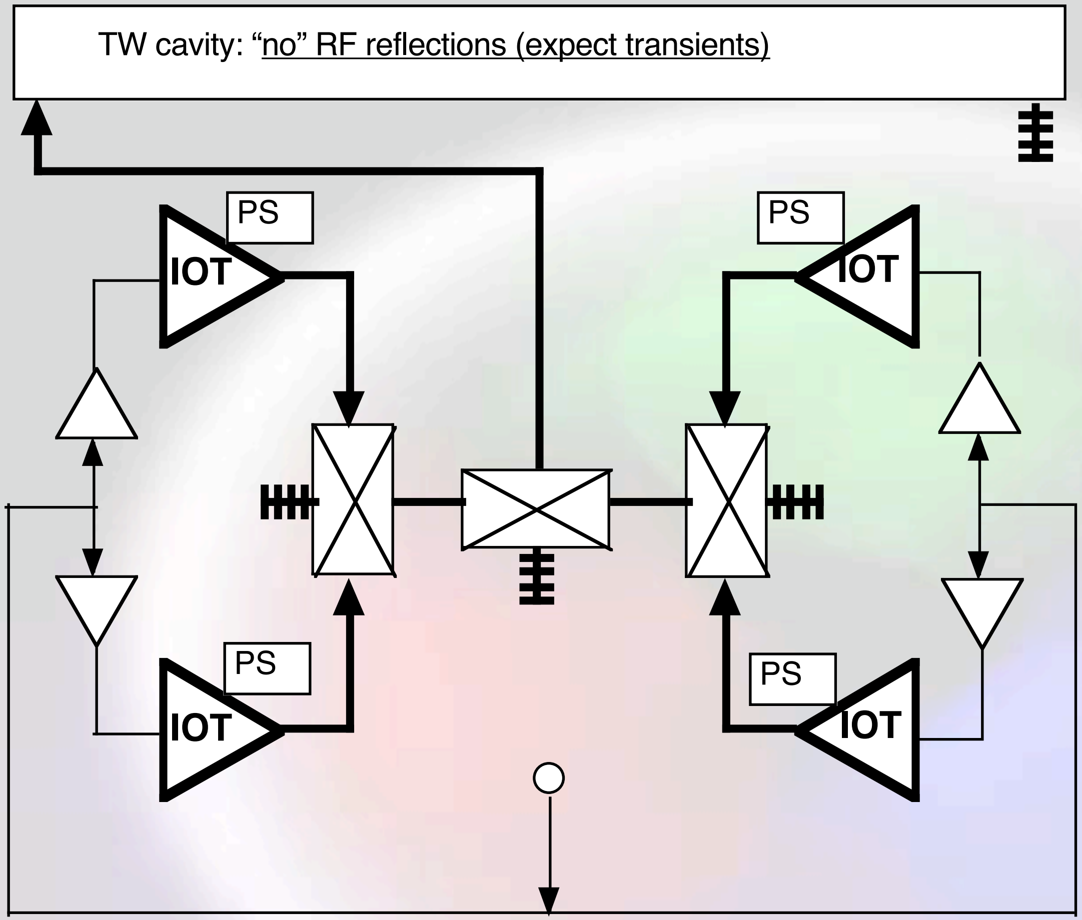
The SPS klystrons/power supplies of this system are dieing of old age: replacement is under way, urgent (high intensity LHC beam depends on it)

Existing: klystrons 58 kW , 27 kV-5 A power supply (4 kl. / Landau cavity)

- Klystrons get very expensive (main market was TV: “inexistent”)
- Classical tetrodes inefficient at 800 MHz

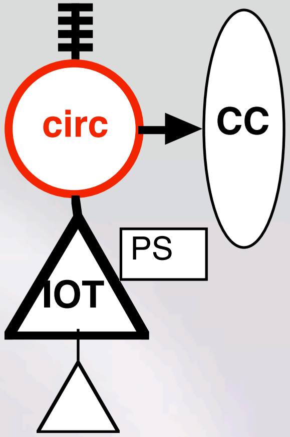
–> IOT (**I**nductive **O**utput **T**ube) are promising “replacement”

(hybrid tetrode-klystron ‘klystrode’ : gain lower than for klystrons)



The (refurbished) SPS Landau installation

60 kW / IOT, **one** 37 kV-3 A power supply **per IOT**, **one** 600 W driver **per IOT**



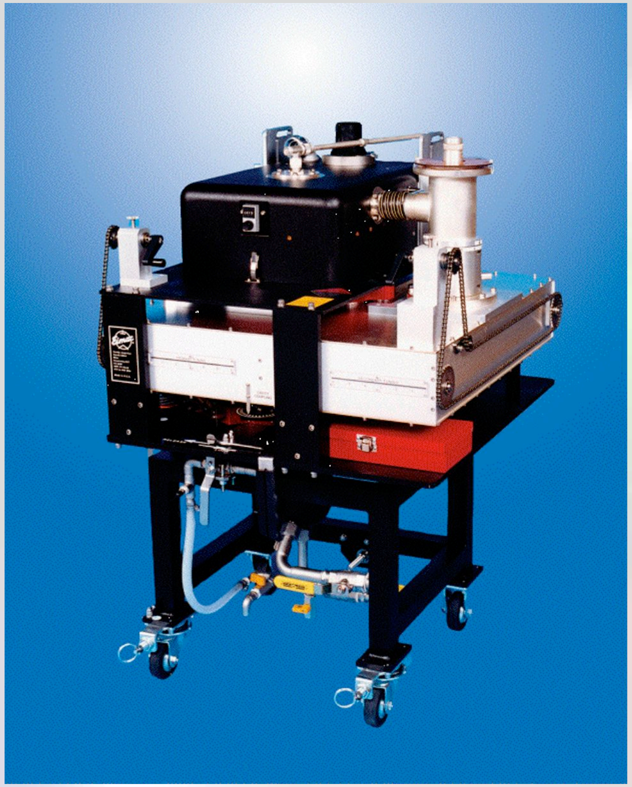
Use ‘existing’ hardware for CC

+ circulator

60 kW power

No extra R&D

Minimum additional work



IOT (klystrode) on chariot with wheels (® CPI)

Integral IOT transmitter with power supply (® Thales)

Delivery Timing (for Landau installation):

- 1 test unit 2010
- 4 units 2011
- 4 units 2012
- for budget reasons: no spares (test unit has to do)

4 units 2011 and 4 units 2012 —> SPS (Landau system)

~~Use ‘old’ klystrons for CC ? PS bulky and may die any day~~

~~very poor man’s option~~

~~… have to run till IOTs arrive~~

Additional transmitter(s) required for CC:

announce soon to modify order

9 -> 10 (11) units, maybe good deal ?

This timing matches well with CC test schedule

Space requirements:

- Transmitter & power supply NOT in tunnel:

no room anyway –> ‘LEP klystron gallery (end)’

- For ACN coax lines: circular hole(s) of 400 mm ∅ exist

between end of LEP klystron gallery and tunnel

…. **BUT** (even it ACN are not yet used: holes still free)

- – coax-lines for 800 MHz are too small to carry 60 kW

(larger ones are overmoded)

(especially inapt in full reflection -> 240 kW equivalent)

- – 800 MHz **wave guides with flange do not pass I^+**

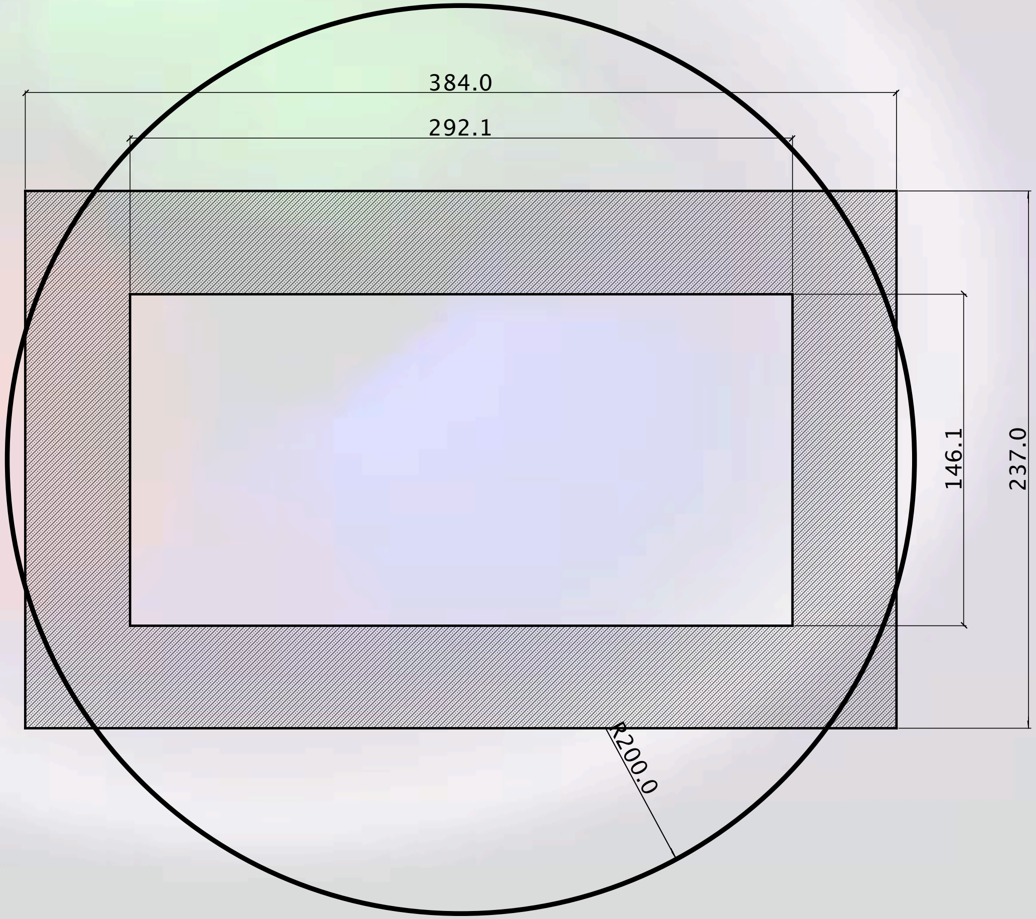
Need to drill a new hole (dirt!!) …. or ->

I^+ WG: 292x146 , flanges: 384x237 [mm]

Bricolage: provided ACN not (yet) installed

- Wave guide in one piece (??): Braze flange ‘free hand’ (tunnel)
- Use flanges with ‘cut corners’

  (RF leaks ???)



Power supply for IOT:

180 cm x 200 cm footprint, 250 cm high

(4 racks of equal size, ‘1-man-dismountable’)

IOT with auxiliaries (heater PS, grids PS, driver amplifier, …):

90 cm x 200 cm footprint, 150 cm high

(on wheels, can be displaced ‘1-man-operation’)

One rack for Low Level RF & remote control (+ cryo-link)

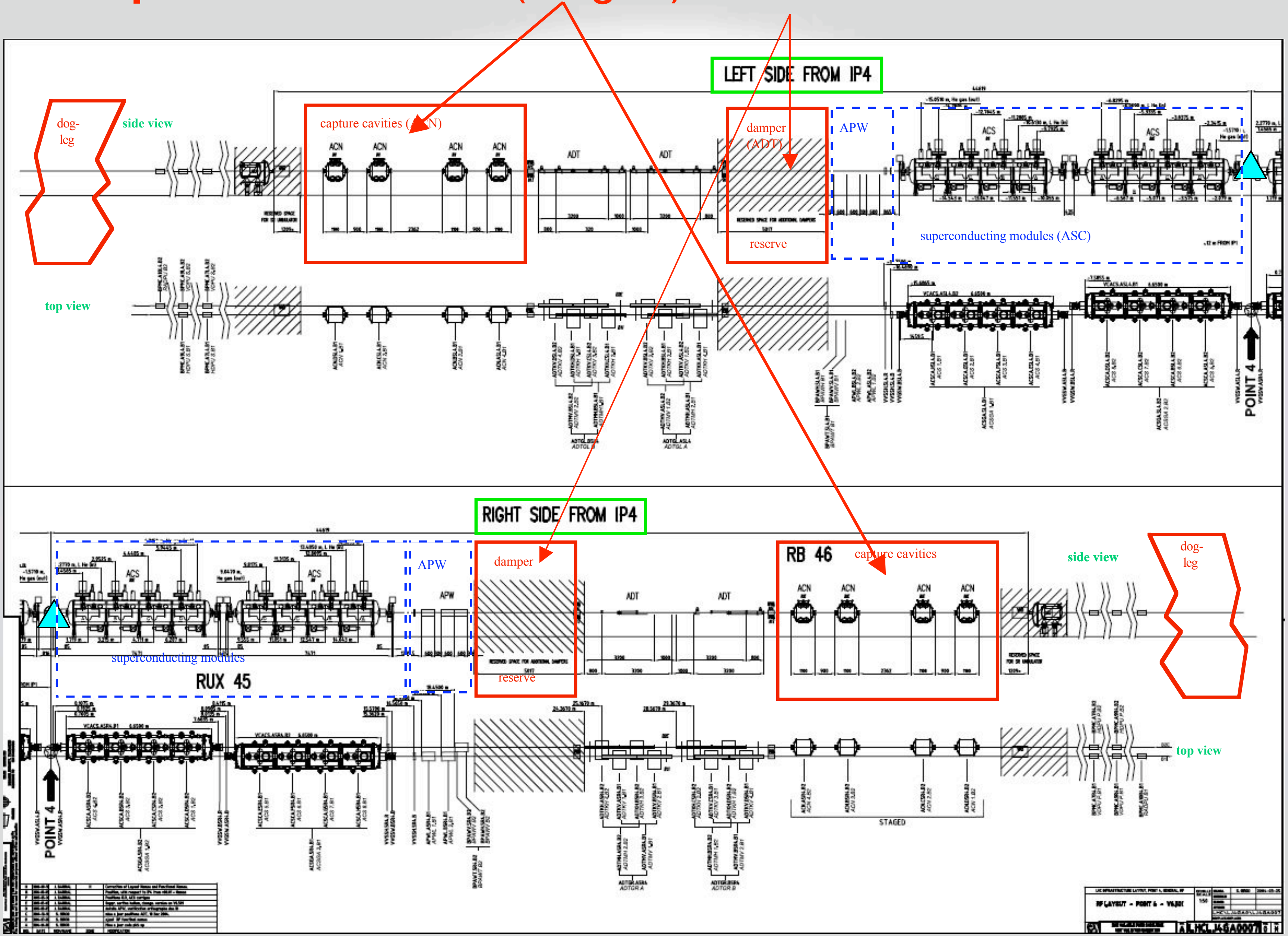
– fits in space foreseen for ACN (if not yet there), else cramped

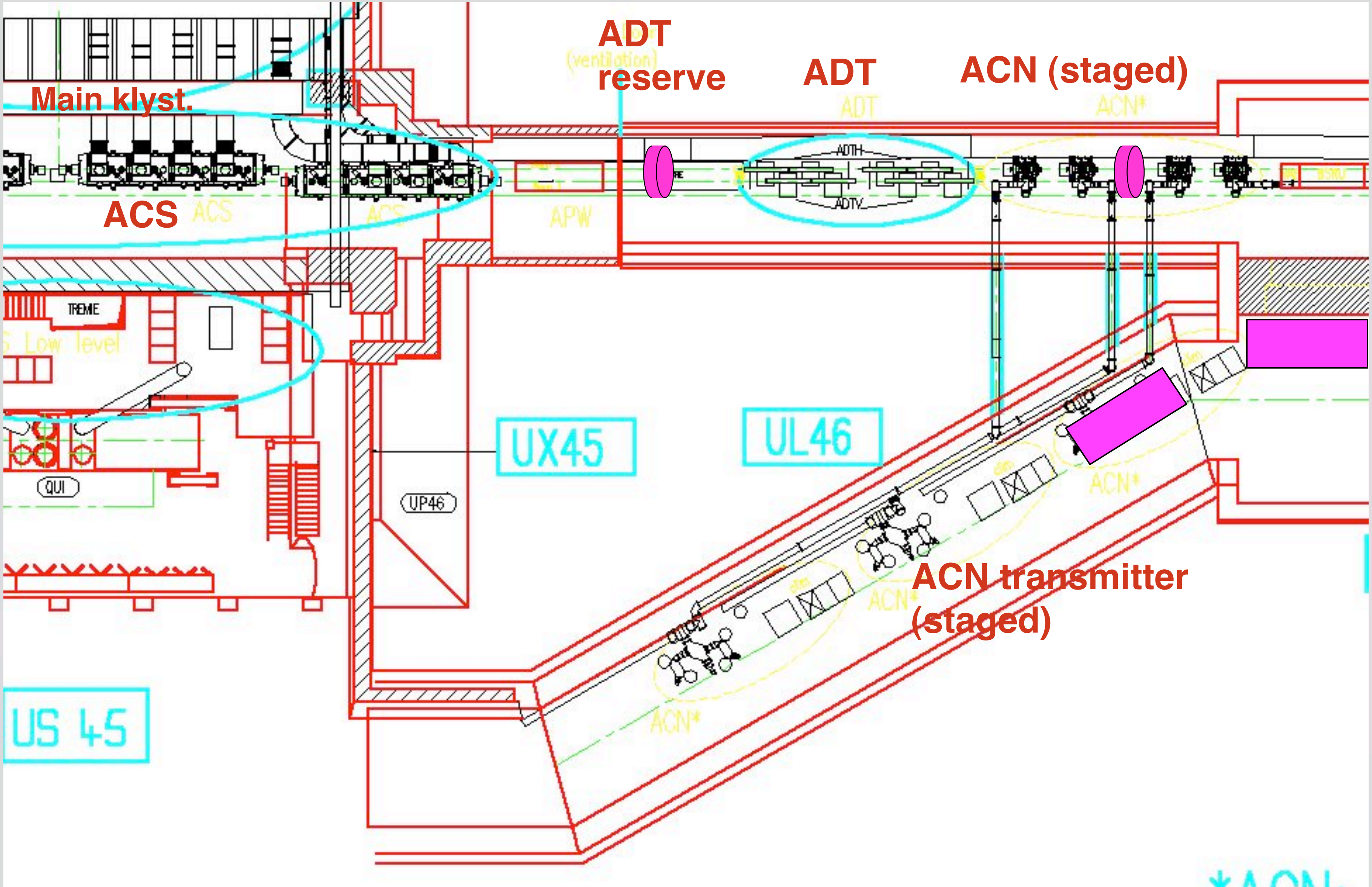
Supply by mains: 400V/ 3 phases (a lot of Amps !!)

Water cooling system (hook up to main RF system)

… and partly air cooling (for IOTs !)

Two options • at ACN (staged) • at ADT reserve (shorter cryo line)





Top view, right side from IP4

Crab Cavity(ies)

• RF feedback requirements: 2-cell cavity

– Impedance (peak) without FB: $\omega/c\cdot 60\Omega * 5\cdot 10^5 = 500$ MΩ/m;

suppose FB gain 100 (!) : 5 (MΩ/m)/cav (see Elena's talk)

– Mechanical cavity vibration make field shake (low b.width!)

(e.g. pumps, from LHe, 'whistle' by GHe, …)

– Ponderomotive (electro-acoustic) auto-oscillations (LEP2)

$$\boxed{T_{delay} << \frac{Q_{ext}}{8\ f_{res}\ g_{\min}} = \frac{5E5}{8\cdot 800E6[s^{-1}]\cdot 100} = 800\ ns}$$

800 ns : light passes 120 m forward/backward

Wave guides are 'slower', ampli-chain needs delay !!!

Distance cavity-transmitter **<u>around corners</u>**: << 120 m

Low level RF control:

Exists equivalent fast RF vector feedback for 400 MHz main RF:

– adapt (input) filters, LO, …. to 800 MHz ???

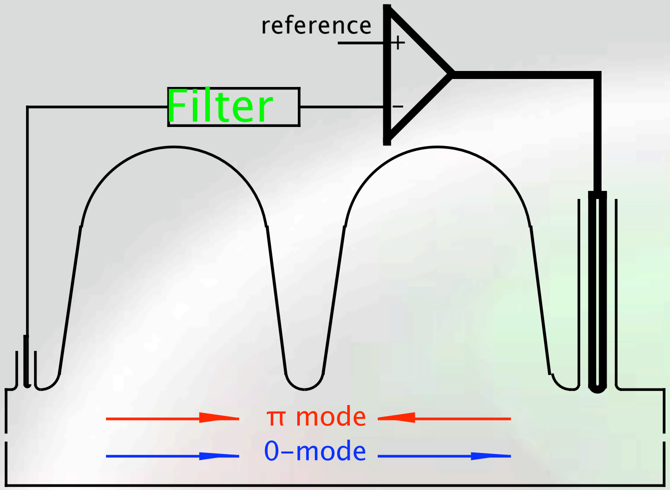
– new card to be developed based on 400 MHz experience ???

Phase stability/locking to be 'better' than for main RF: see later

The Big Difference:

Main RF has single cell cavities, CC is 2-cell cavity

two modes (close f) with opposite symmetry



Reference pick-up not on same cell as power coupler:

avoid direct cross-talk

For phase-adjusted π-mode, 0-mode would auto-oscillate !!

(has nothing to do with beam interaction, low or high (R/Q) !!!)

filter has to ‘turn’ 0-mode signal by 180°

without perturbing π-mode signal (not trivial for close f)

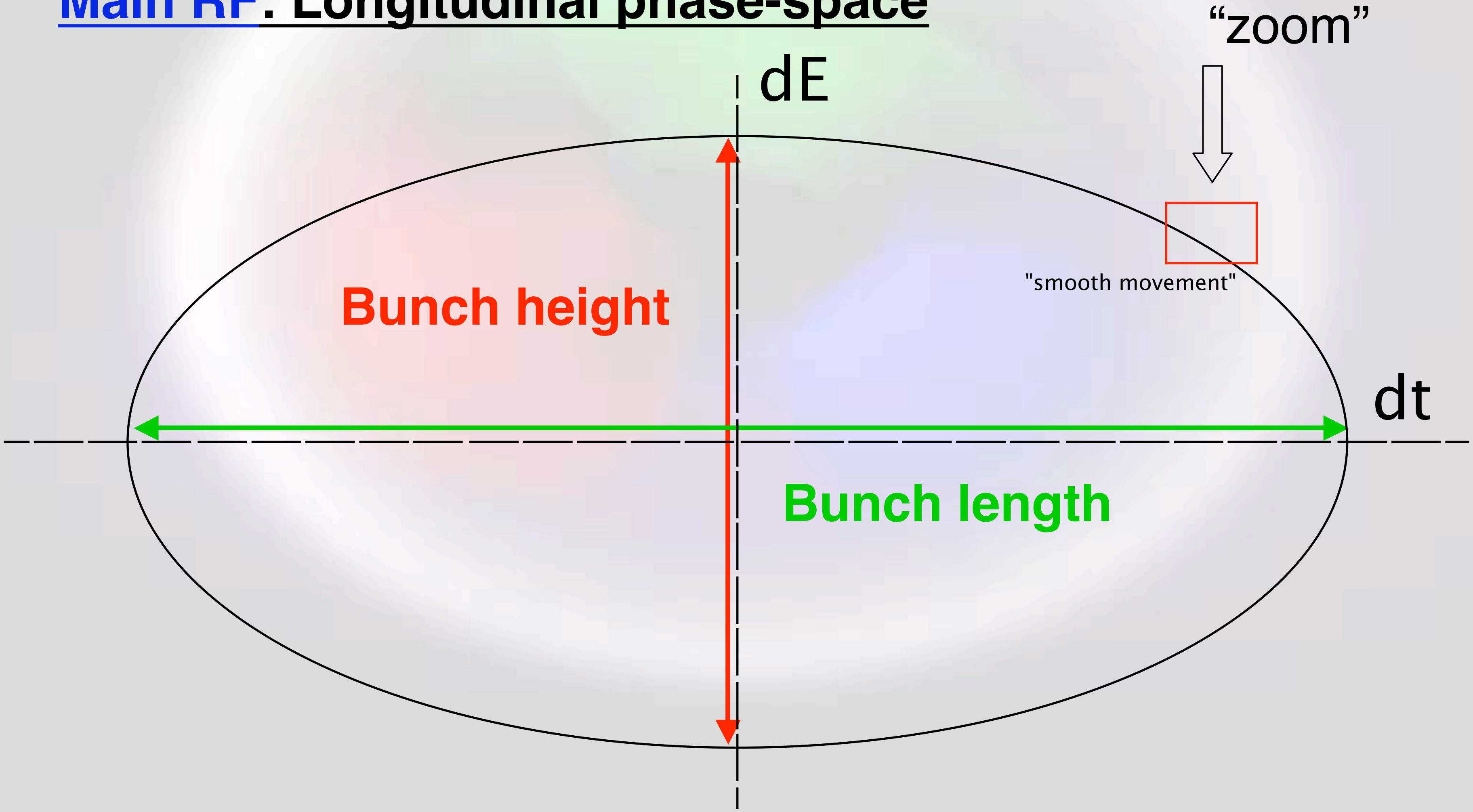
(… experience with 4-cell LEP2 cavities in SPS as injector …)

RF (power) system should also cover 2nd mode: ‘wide band’!!

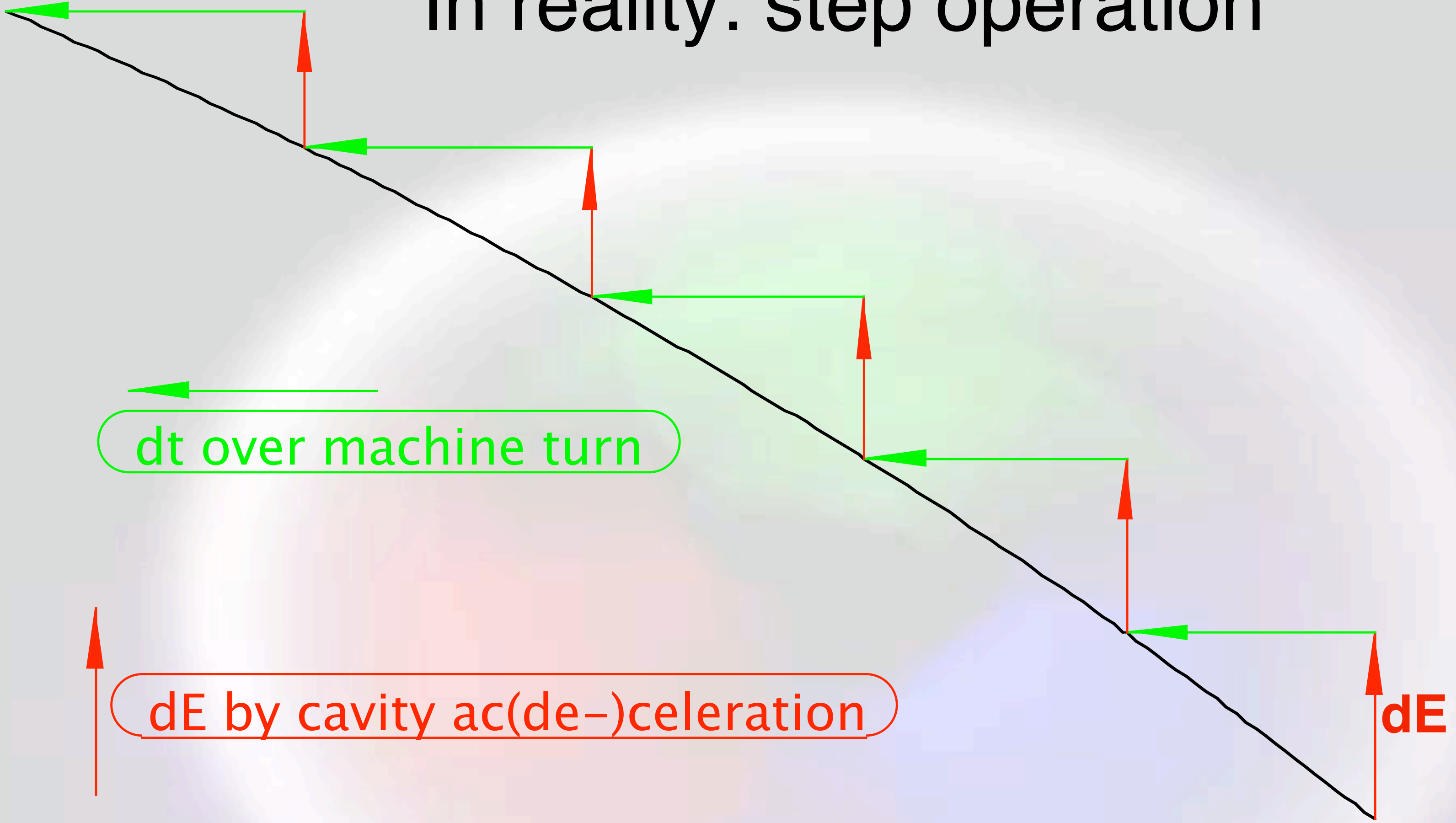
- **RF noise considerations:** (pure “math”, no fuzzy numerical results !!)

Comparison requirements main RF - crab RF

Main RF: Longitudinal phase-space



In reality: step operation



dt over machine turn

dE by cavity ac(de–)celeration

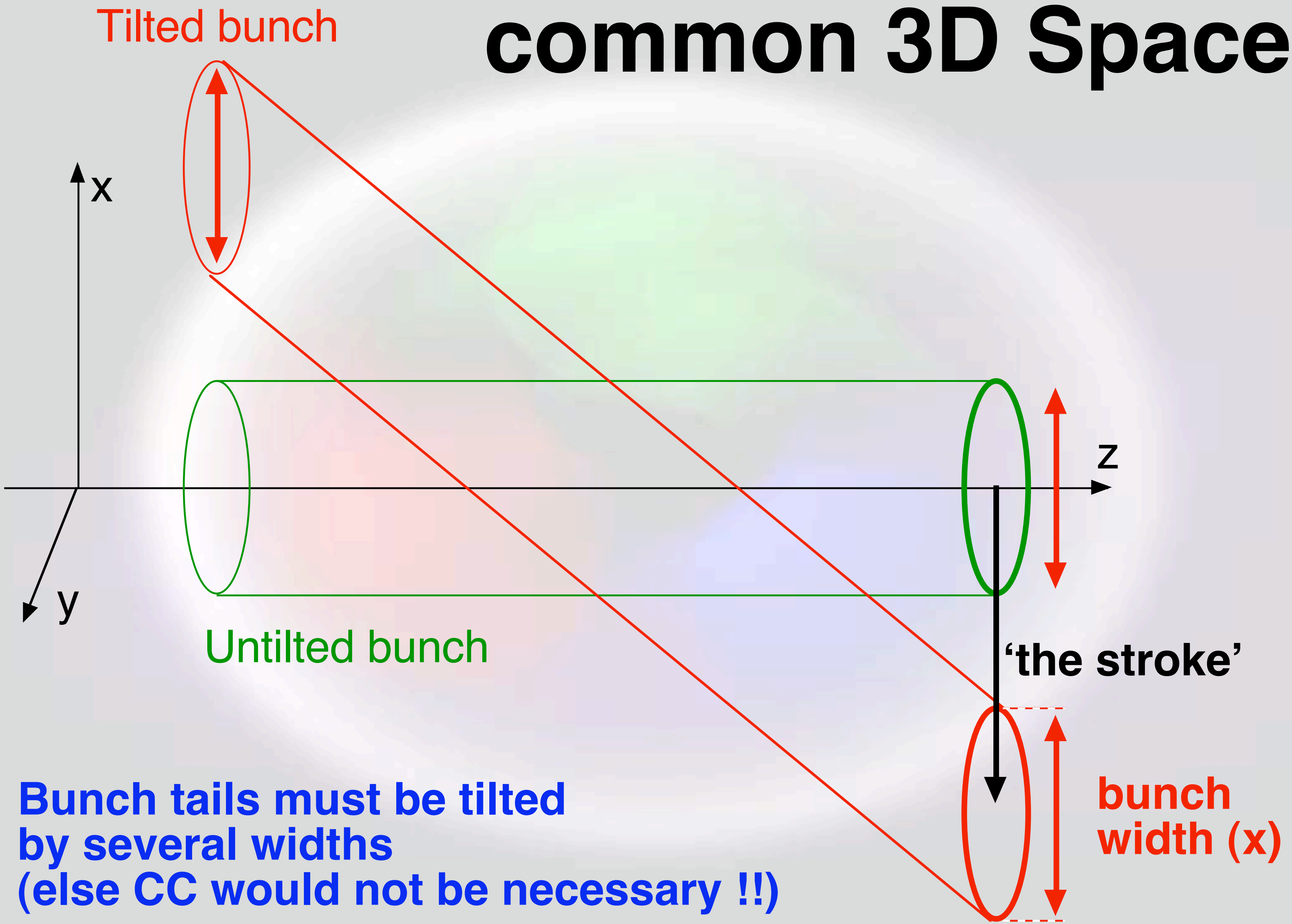
dE

f_s=25 Hz (coast) <—> 25 ph.sp-turns/s; f_{rev}=11200 Hz (strokes/s) ->

$$\mathbf{dE_{rms} = (BH/2)*\sin(2\pi\ 25/11200)/\sqrt{2} = BH\ /\ 200}$$

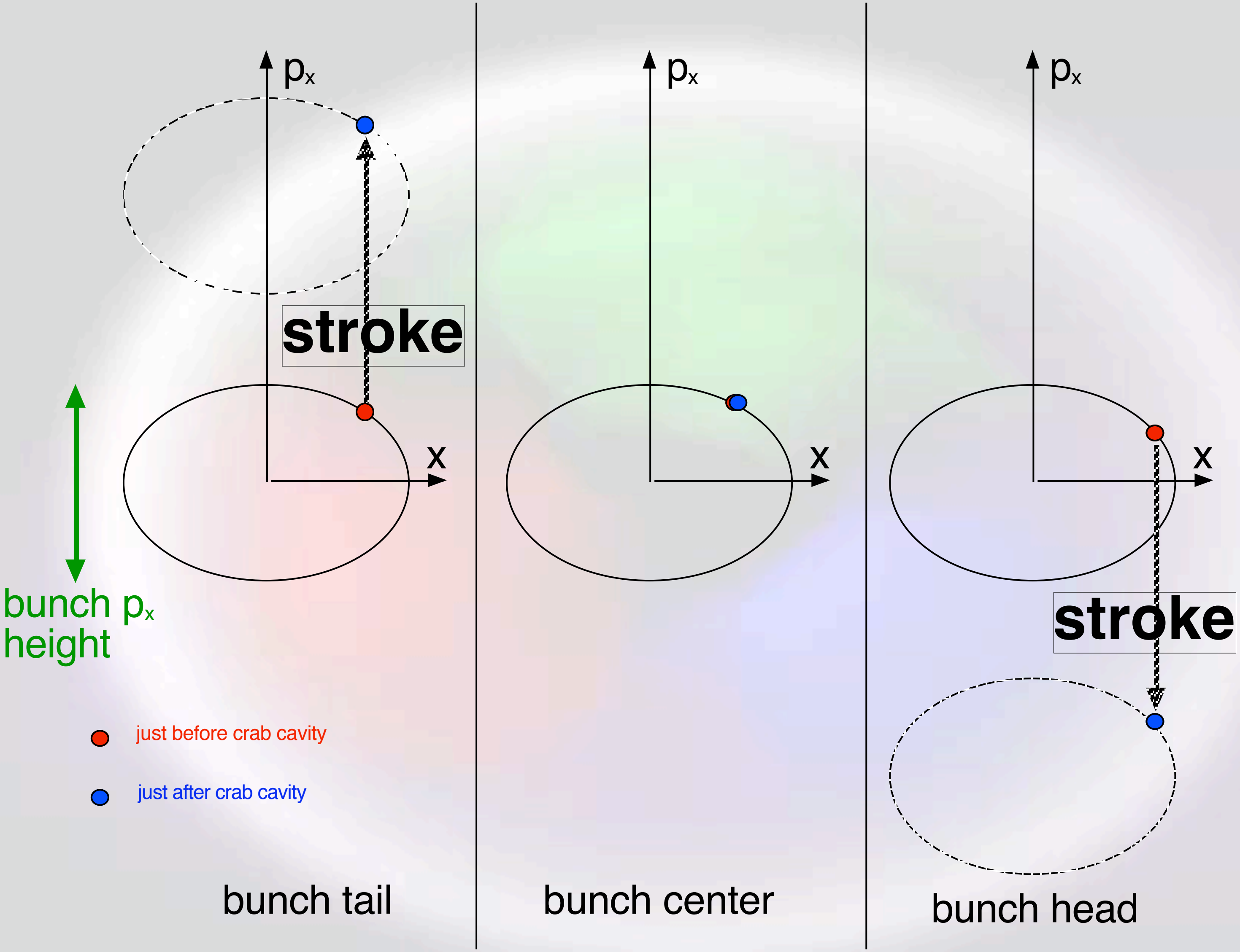
The 'stroke' is a small fraction of the bunch dimension

common 3D Space

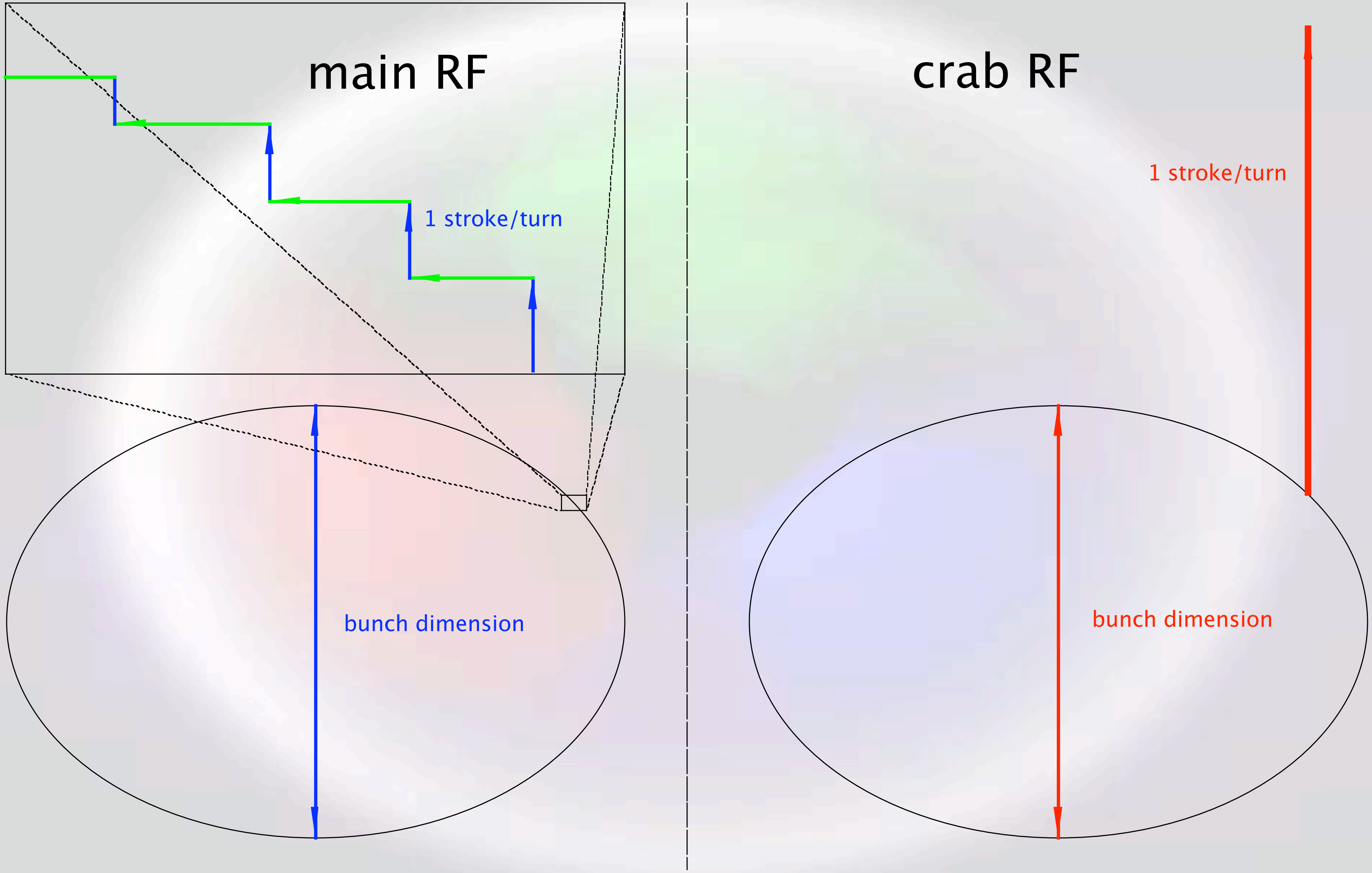


Bunch tails must be tilted by several widths (else CC would not be necessary !!)

x-Phase-space



The ‘stroke’ is several times the bunch dimension



main RF

1 stroke/turn

bunch dimension

longitudinal phase space

crab RF

1 stroke/turn

bunch dimension

transverse phase space

At each passage of the

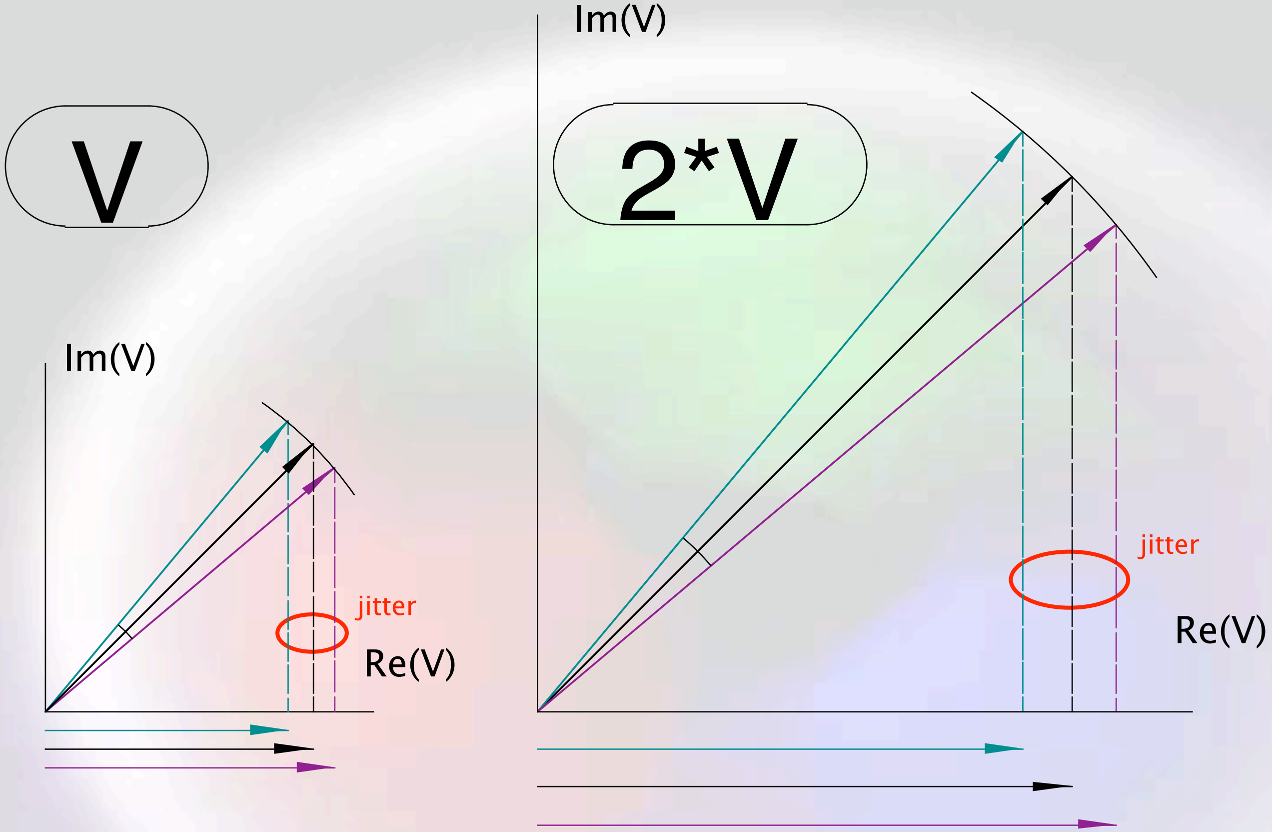
(**main** / **crab**) cavity

the **stroke** corresponds to a

(**small fraction** / **multiple**)
1/200 2.5 (.. say ..)

of the (corresponding) **bunch dimension**

Phase noise (generally most dangerous one)



For same noise: Absolute jitter scales with (design) stroke !!!

(**Amplitude noise**: same law for linear amplification;
somewhat different if noise created in high-power end
but ‘more power - more noise’ holds)

Intermediate Conclusion:

For same growth rate relative to bunch dimension, crab phase **jitter** has to be 200*2.5 = **500 times lower** (amplitude ratio)
than main RF (-54 dB ‘power’ in “RF speak”)

What about **main RF** noise: **much lower than limit ??**

- ppBar (SPS) nearly died from RF noise : bunch blow-up !!

  (—> there would have been no $W^{\pm}$, Z detection with Nobel-prize !!)

  only RF improvements (in electronics) saved the day

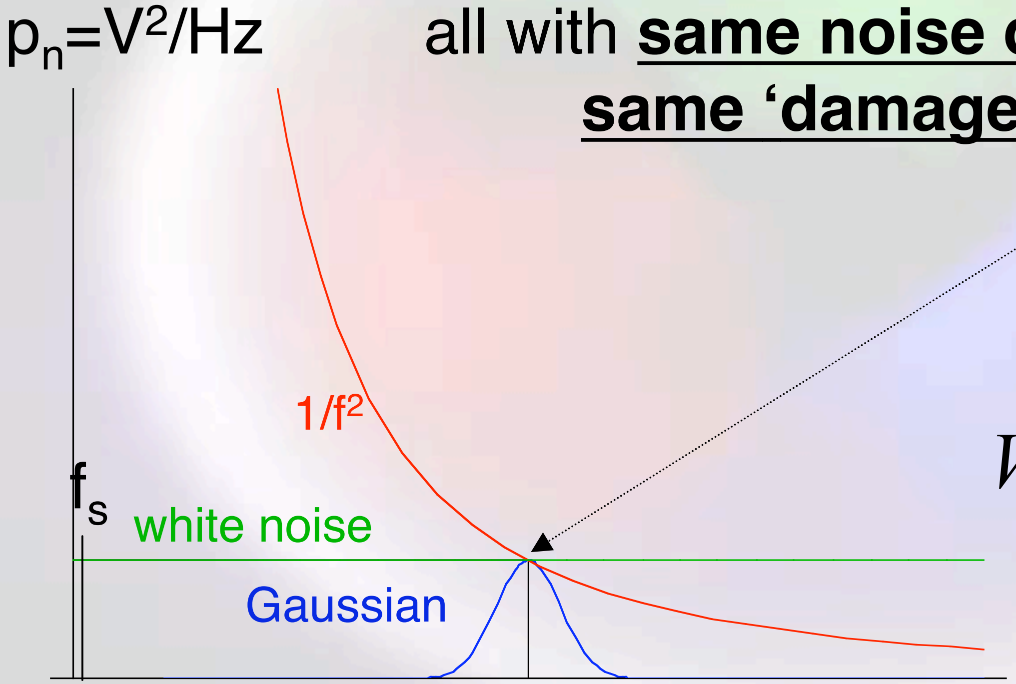
- LHC uses ‘noisy’ klystrons: polar loop to ‘recover’
  + simulations/calculations indicate: it should work out
    (but not orders of magnitude reserve)
  + first LHC coast for 30 minutes (@450 GeV/c):
    observation: beam did not diffuse away
    (f_s OK; bunch shape measurements foreseen for following coasts … still waiting for)

Main RF has NO (big) **‘reserve’** concerning noise **!!!**

Only the noise density at “the” frequency (really) perturbs

Main RF: synchrotron frequency $f_s \approx 25$ Hz (7 TeV coast)
Crab RF : betatron frequency (*) $f_\beta \approx 3$ kHz

noise power (p_n) spectra (examples)
all with **same noise density at f_β**
same ‘damage’



$$V_{rms} = \sqrt{\int_0^{f_{rev}} p_n(f)\,df}$$

(*) precisely the synchroton sidebands of f_β: $f=f_\beta \pm f_s \approx f_\beta$

$$\mathbf{V_{rms}} \ll \mathbf{V_{rms}} \ll \mathbf{V_{rms}}$$

Good news (bad news to come ..)

Brownian ($1/f^2$) noise power density $^{(*)}$:

(same behavior for both RF systems)

Relative noise power ratio

(main:crab)=($1/25^2$):($1/3000^2$) = $(120:1)^2$

(amplitude ratio 1:120, power ratio 42 dB in RF-speak)

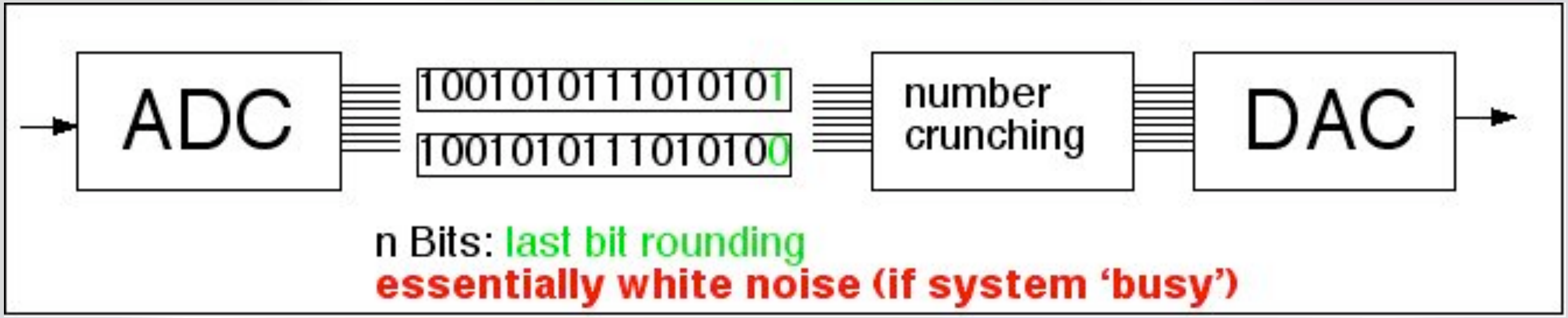
About compensates $(1:500)^2$ (-54 dB):

(at the limit, still factor 4 in amplitude (12 dB) missing)

(*) … there is also pink 1/f noise … (120:1 scaling only : bad)

Bad news:

(not only …) digital systems have white noise



n Bits: last bit rounding

essentially white noise (if system 'busy')

Relative amplitude noise: $<\delta a \,/\, a_{peak}>_{rms} \approx 1 / 2^n$

RF (I/Q) data: also $\approx 1 / 2^n$ radian rms phase noise

To 'recover' **factor 500**: **9 bit more precision** required

Also cryostat & … designers: pay attention …

e.g. a free 80 cm steel-bar oscillates around 3 kHz !!!

• Other and Non-RF issues

- Detuning control: Conserve Δf during injection and …

  (while enforcing $V_\perp = 0$ by RF power: CC invisible)

- Interlock chain

  - basic functions: “copy/paste” from main RF (800 MHz!)
  - transverse (kick direction) beam position; RF power

- Link to machine protection

  - protect LHC from CC mishaps (phase jump, ….)
  - protect CC from LHC mishaps (beam displacement,..)

- tunnel installation
  installed cavity has to respect ‘transport zone’ for other objects
  (check objects sticking out as power coupler, He-plugs, …)

- transport
  weight: no problem compared to main dipoles
  size: check objects sticking out as …
  chariot or fit CERN standard transport equipment in tunnel

- alignment
  - active:
    coarse (manual) adjustment jacks
    fine transverse adjustment cryostat/cavity by remote controls
  - passive:
    respect alignment zone for surveyors (field of view)

- Cryomodule interfaces and safety

(*) CERN standard rupture disk(s) on cavity volume – accident
(? also on insulation vacuum ?)

(*) CERN standard self-closing valve(s) – ‘short’ overpress.

(*) CERN standard LHe and GHe plugs

(*) CERN standard LHe level gauge(s)

(*) CERN standard He pressure gauge(s)

(*) CERN standard T-sensors for operation (cool/warm up)

(*) can be supplied/ should be ordered by CERN (standardization)

- vacuum

  (*) Both cavity ends equipped with RF compensated valves
  (? ‘space’ for ‘opposing’ valves to lock machine-vacuum ?)
  Connections to both vacuua (.., He processing, …)
  (? permanent high vacuum pump for insulation vacuum ?)
  (? permanent ultra high vacuum pump on cavity volume ?)

- sensors and control

  2 RF probes: one for feedback exclusively (cross talk)
  fast RF vector feedback (? 1-turn delay (US: comb filter) FB ?)
  link to cryogenics (regulation) for level, press, T gauges
  remote control from/to control room

- RF reference signal:

  400 MHz is present at IP4: phase stable cable, f-doubler

(*) can be supplied/ should be ordered by CERN (standardization)

- cooling and ventilation
  water cooling IOT and HOM loads: tap main RF system
  IOT needs air cooling

- radiation issues and shielding
  Electronics has to be outside the tunnel in shielded area
  (parallel tunnel segment / chicane)

- electric supplies: 230/400V, 50 Hz
  transmitter power: IOT 400 V, 3 phase, many A
  (tap at ?)
  electricity available at cavity in tunnel: pumps
  plugs: Swiss standard (also on French site and in tunnel)

- compressed air
  vacuum valves operated by compressed air
  (supply required at cavity)

Summary:

- For $|\Delta x_0| \leq 200\mu m$ and perfectly tuned (stable) cavity:

  5 kW RF power sufficient —> 80 Hz BW / $Q_{ext}=2\cdot10^7$

- Better choice : 30 kW –> 1600 Hz BW / $Q_{ext} \approx 5\cdot10^5$

  (real world –> 60 kW : transmitter ‘available’)

- Add to ‘existing’ order (on time) 1(2) additional transmitter(s)

  no R&D work, minimal work for installation

- RF power transfer might require a new hole (limestone)

  or (if ACN still absent) some ‘RF bricolage’

- 2-cell structure: requires study for feedback (filter !)

- RF noise is still not completely settled (hadron machine !)

Thank you for listening!

Choice of Q_{ext} for minimum power

$$I_{g,r} = \left(\frac{c \cdot V_\perp}{2\,(R/Q)_\perp \cdot \omega \cdot \Delta x_0 \;\; Q_{ext}} \pm I_b \right)$$

g: '+'　　r: '–'

Cavity on tune Δf=0

$$P_{g,r} = \tfrac{1}{2}(R/Q)_\perp\, \omega^2 / c^2 \cdot \Delta x_0^2 \;\; Q_{ext} \cdot I_{g,r}^2$$

Required **g**enerator and **r**eflected power (on tune)

Q_{ext} is (power wise) optimum if for worst requirement

(at largest Δx_0) reflected power is zero

$$Q_{ext,opt} = \frac{c \cdot V_\perp}{2\,(R/Q)_\perp \cdot \omega \cdot \Delta x_{0,\max} I_b} \longrightarrow I_{g,r,opt} = I_b \left(\frac{\Delta x_{0,\max}}{\Delta x_0} \pm 1 \right)$$

$$P_{g,r,opt} = \frac{\omega \cdot V_\perp \cdot I_b}{c} \frac{\left(\Delta x_{0,\max} \pm \Delta x_0\right)^2}{4 \cdot \Delta x_{0,\max}}$$

$$P_{g,opt,\max} = \frac{\omega \cdot V_\perp \cdot I_b}{c} \Delta x_{0,\max}$$

if perfectly on tune !!

Effect of detuning (error):

$$\Delta I_{g,r} = i \bullet \frac{\Delta\omega}{\omega} \frac{V_\perp}{(R/Q)_\perp} \frac{c}{\omega \cdot \Delta x_0}$$

.. in quadrature !!

$$\Delta P_{g,r}(\Delta\omega) = \frac{\omega \cdot V_\perp \cdot I_b}{c} \cdot \Delta x_{0,\max} \cdot \left(\frac{\Delta\omega \cdot Q_{ext}}{\omega} \right)^2$$

Lowest Q_{ext} for given power (and given other parameter):

highest possible system bandwidth

$$P_{g,r} = \tfrac{1}{2}(R/Q)_\perp \omega^2/c^2 \cdot \Delta x_0^2 \;\; Q_{ext} \cdot I_{g,r}^2 = A \cdot Q_{ext} \;\; \cdot I_{g,r}^2$$

$$I_{g,r} = \left(\frac{c \cdot V_\perp}{2\,(R/Q)_\perp \cdot \omega \cdot \Delta x_0 \;\; Q_{ext}} \pm I_b \right) = B/Q_{ext} \pm I_b$$

$$P_g = A \cdot Q_{ext} \;\; \cdot \left(B/Q_{ext} + I_b \right)^2$$ available ‘free’ power

Allows to lower Q_{ext} to

$$Q_{ext,\min} = \frac{cV_\perp^2}{2(R/Q)_\perp \left(-I_b V_\perp \omega \Delta x_0 + 2c\left(P + \sqrt{P\left(P - I_b V_\perp \omega \Delta x_0 / c\right)} \right) \right)}$$