Introduction to Digital Low-Level Radio Frequency Controls in Accelerators

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Lawrence Berkeley National Lab

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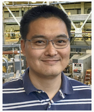
Welcome!

Team

Instructors


Larry Doolittle,
LBNL


Qiang Du,
LBNL


Carlos Serrano,
LBNL

Lecturers


Dmitry Teytelman,
Dimtel

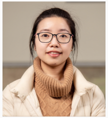

Jeremiah Holzbauer,
FNAL


Tim Berenc,
ANL


Michael Davidsaver,
Osprey DCS

TAs


Shree Murthy,
LBNL


Dan Wang,
LBNL


Keith Penney,
LBNL

Class organization

Class organization

- This course is very much hands-on
- Class structure:
  - Morning: 3 lectures providing background for Labs
  - Afternoon/evening: **Labs**
- Friday dedicated to team project presentations
- This class has 17 students: 5 teams of 3, and 1 team of 2 have been assigned based on your survey questions (technical background)
- Grades: based on Lab notes/answers and results obtained in the team project (no additional homework assignments)

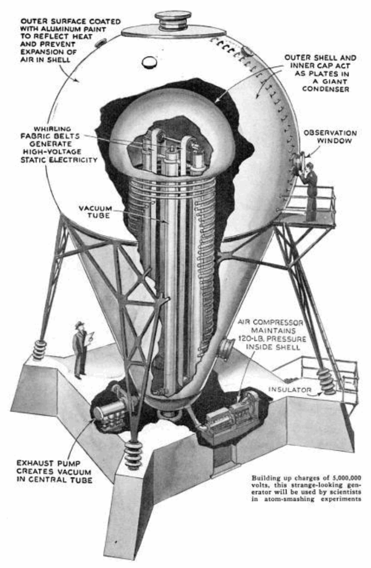
Schedule

Time	Monday (Physics)	Tuesday (Analog/RF)	Wednesday (Digital)	Thursday (Applications)	Friday (Projects)
9:00-10:00	Introduction (C. Serrano)	Analog & RF fundamentals (L. Doolittle)	Introduction to FPGAs (Q. Du)	Laser controls (Q. Du)	Project presentations
10:00-11:00	Theory (L. Doolittle)	Control Theory (D. Teytelman)	DSP Implementations (Q. Du)	SRF Linacs (J. Holzbauer)	Project presentations
11:00-12:00	Modeling & Simulations (C. Serrano)	RF Controls Application (C. Serrano)	Software Controls (M. Davidsaver)	Synchrotrons (T. Berenc)	Project presentations
12:00-13:30	Lunch	Lunch	Lunch	Lunch	Lunch
13:30-18:00	Labs: Lab equipment SRF cavity simulation Crystal characterization RTL simulations	Labs: Cavity characterization LLRF Hardware RTL Simulations (Controls)	Labs: RF Controls (real) EPICS Controls	Project preparation	Adjourn
18:00-19:30	Dinner	Dinner	Dinner	Dinner	
19:30-22:00	Lab tutoring	Lab tutoring	Lab tutoring	Project tutoring	

Technical field overview

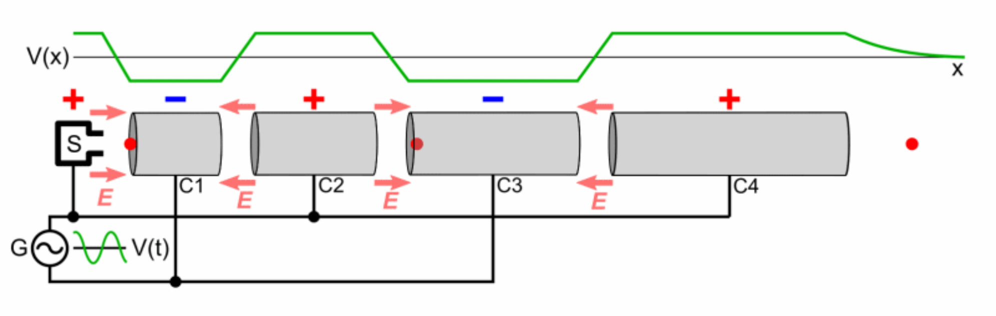
RF in accelerators

- Charged particles experience a force in the presence of an electric field
- The first accelerators used electrostatic fields but were limited in voltage due to electrical breakdown (sparks)



RF in accelerators

- In the 1920s the introduction of varying fields (pulses initially) allowed for acceleration without the need to supply the total voltage differential



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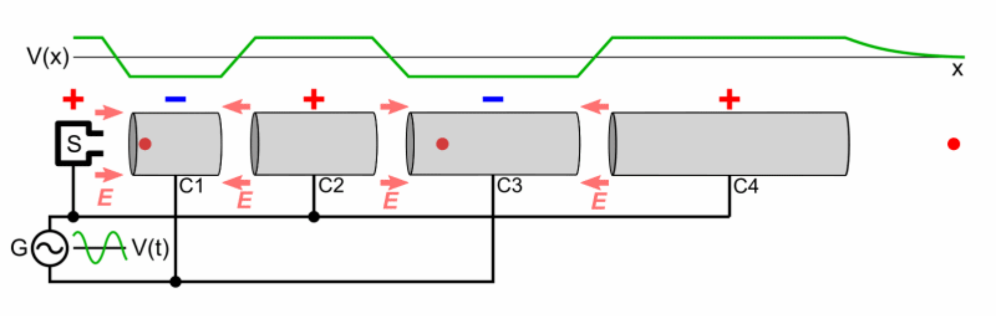

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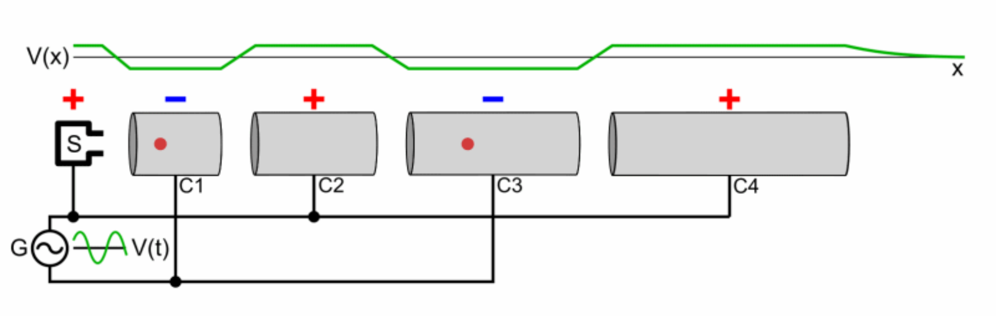

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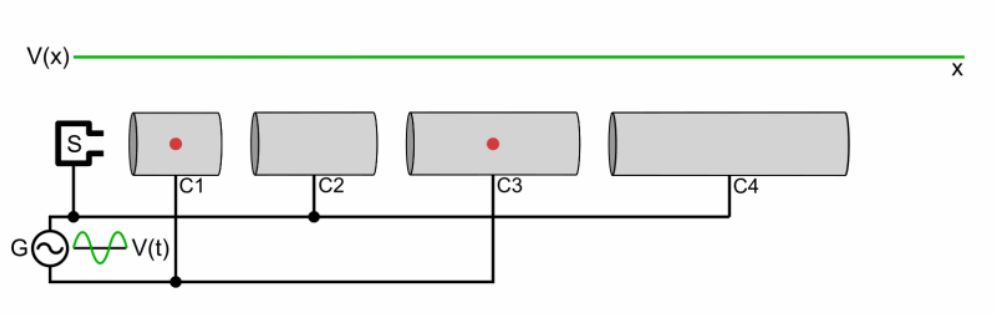

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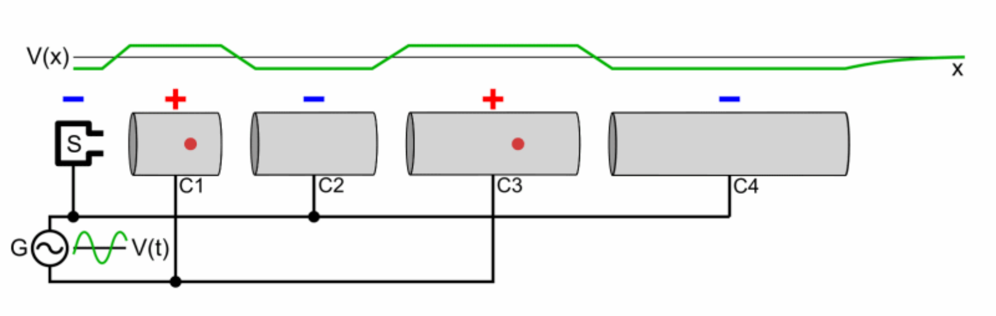

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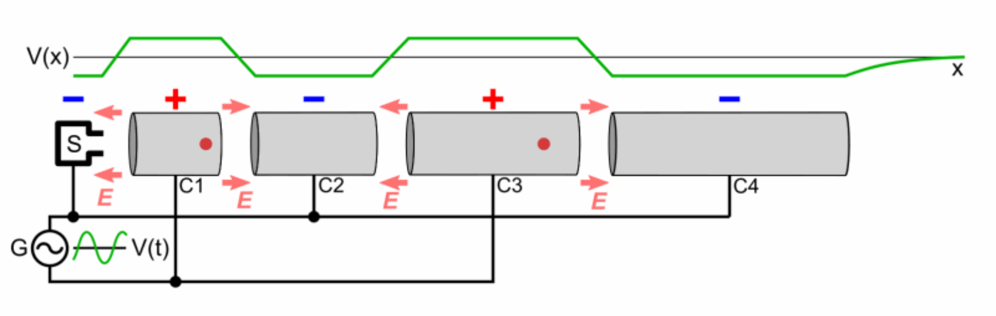

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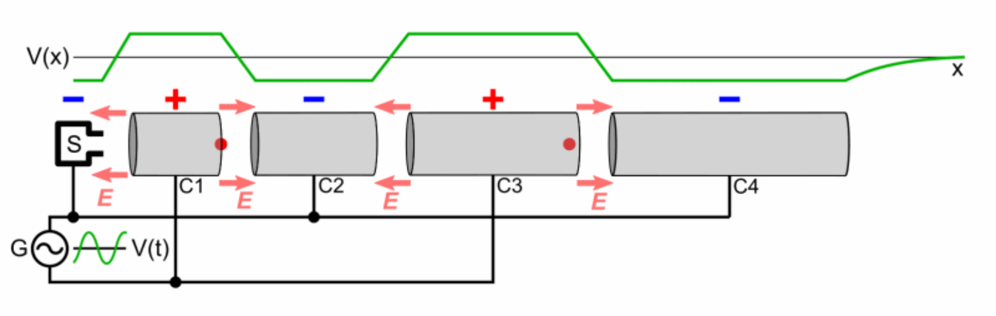

RF in accelerators (end)

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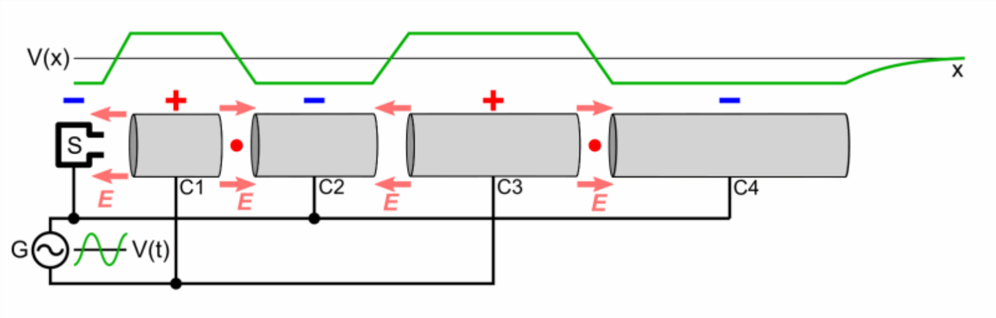
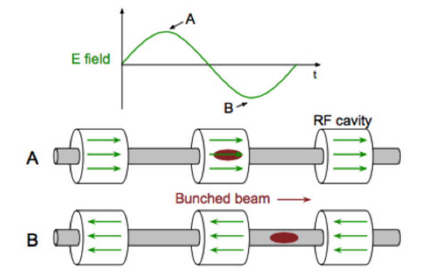


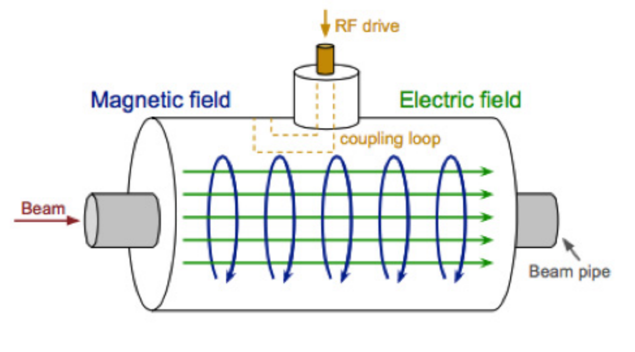
RF in accelerators

- With the development of the radar in WWII and advances in communications, higher power and higher frequency equipment became available, enabling what we know today as RF accelerators



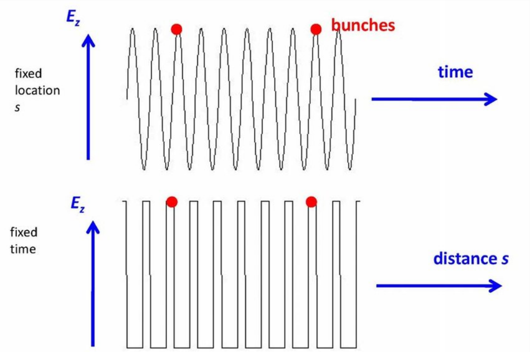
RF cavity

- A RF cavity is a metallic chamber that contains an electromagnetic field, used primarily to accelerate particles
- A resonator (like any other) that stores energy when excited with an RF signal at its resonant frequency



Timing of bunches with RF field

- A particle beam is not continuous but "packed" in bunches
- The electromagnetic resonance period of a cavity is a multiple of the spacing between bunches



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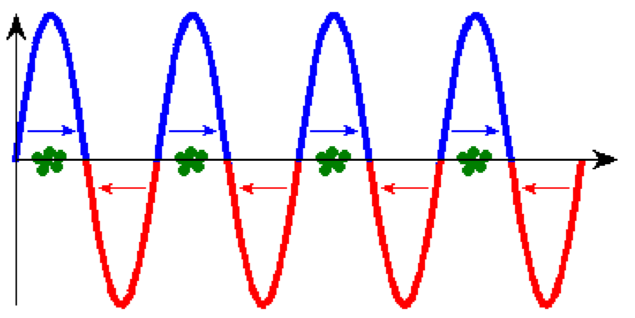

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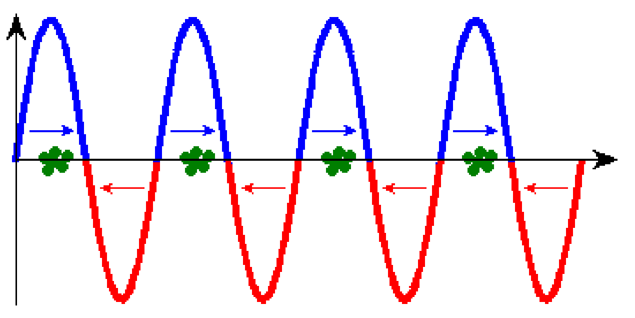

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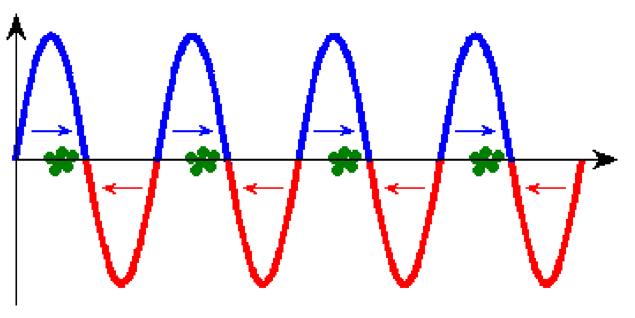

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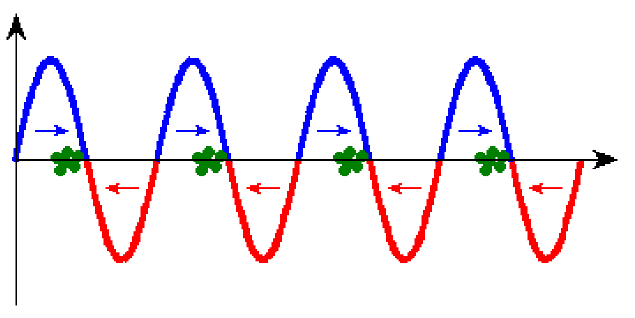

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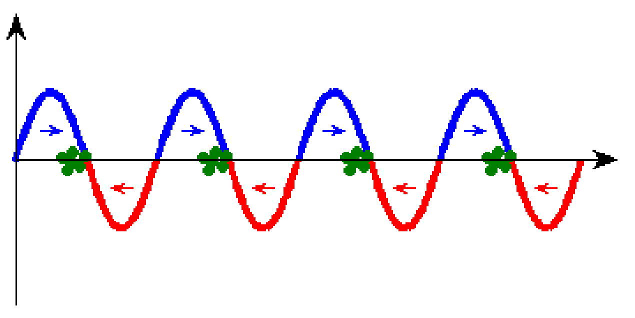

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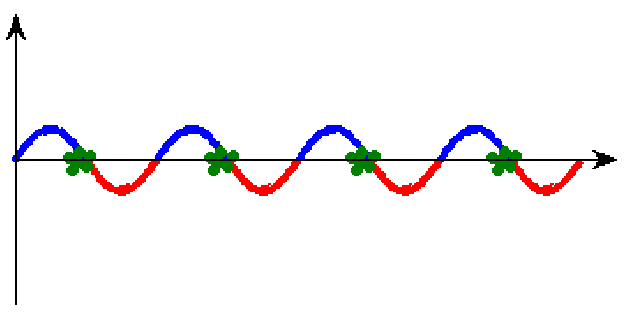

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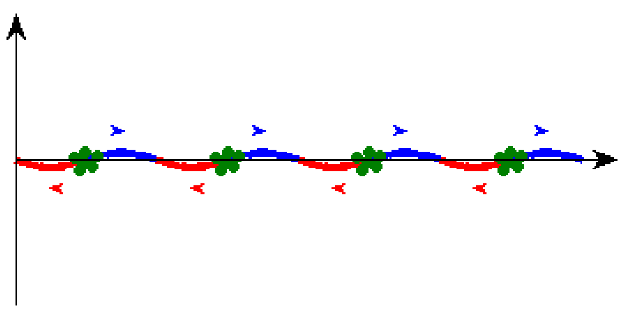

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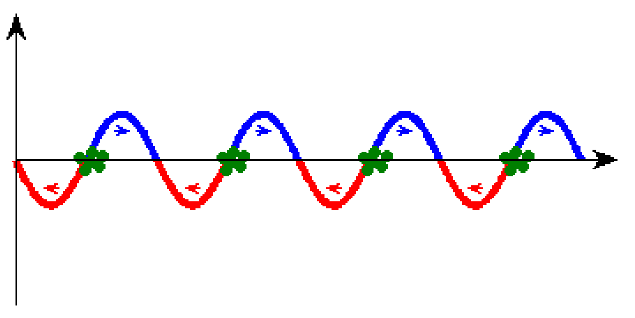

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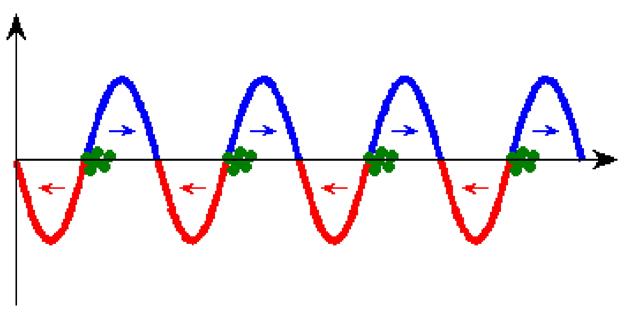

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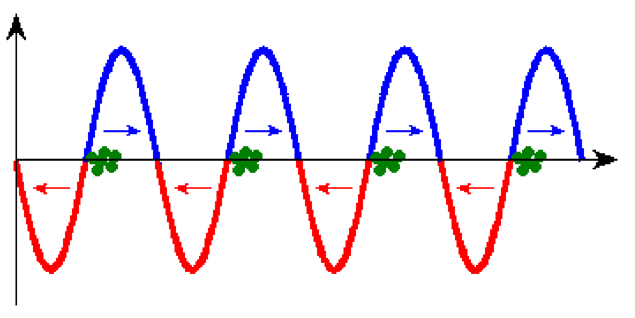

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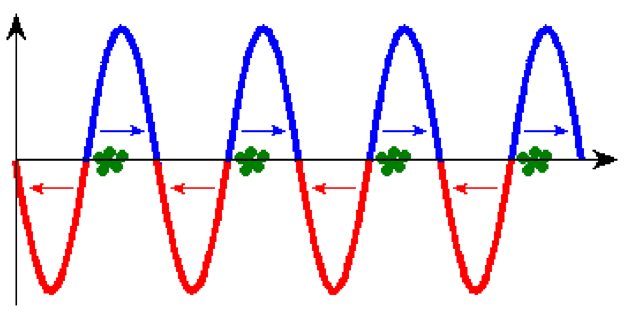

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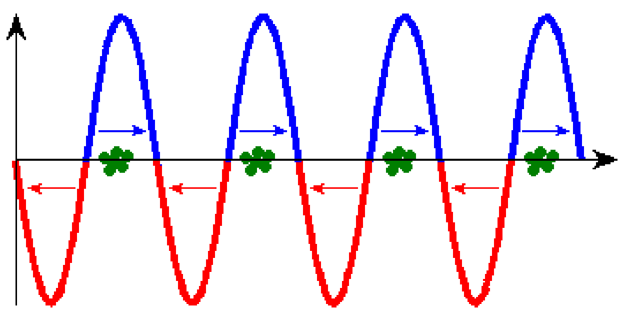
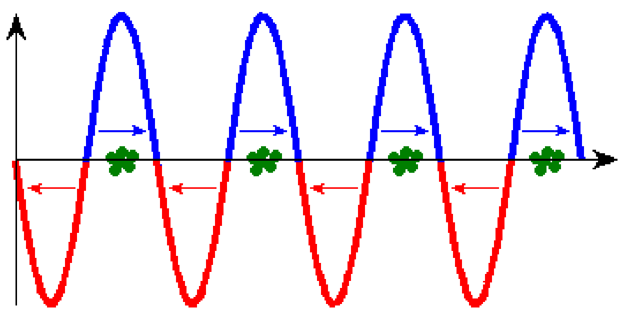
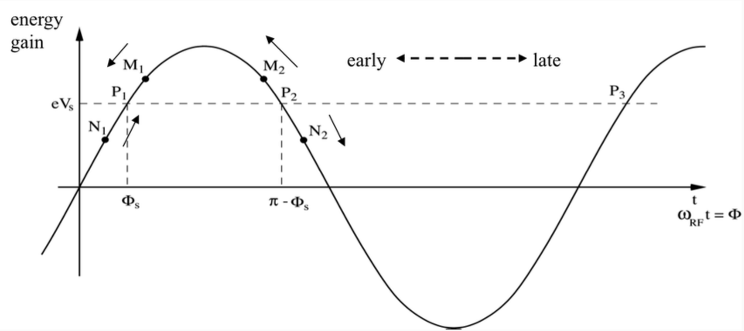


Timing of bunches with RF field (end)



Phase stability



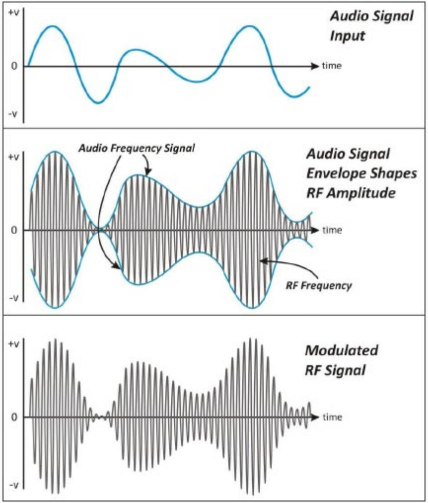
What is LLRF?

- LLRF is the application of techniques in different fields of Physics & Engineering to the precise control of electromagnetic fields in resonant cavities in an accelerator
- This course attempts to give you a glimpse of these fields and how they come together in accelerator controls:
    - Physics (day 1, today!)
    - RF/Analog electronics (day 2)
    - Digital electronics (including Digital Signal Processing) and software (day 3)
    - Examples of implementations based on the scientific application (day 4)

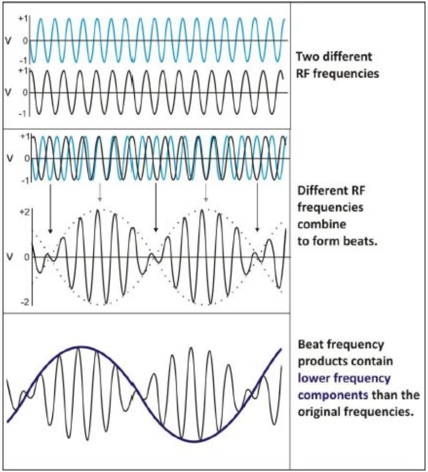
Trick # 1: Radio

- A LLRF system is a fancy radio, and it steals radio transmission and detection techniques from the radio industry
- A radio, or a fiber communication system from your ISP, modulates an RF or optical signal to exchange information
- LLRF systems feed a carrier signal into an RF cavity, then measures any amplitude and phase modulations using traditional radio detection techniques (disturbances rather than communication signals)
- Using that information it applies feedback control techniques to reduce those disturbances and keep the desired carrier field in the cavity

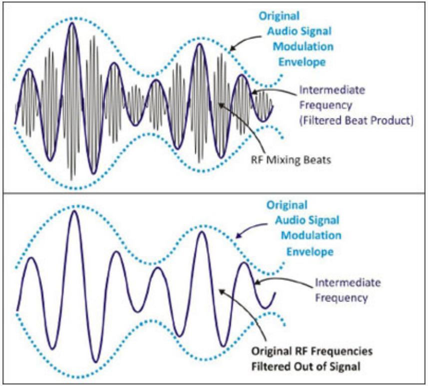
Communicating audio signals at RF



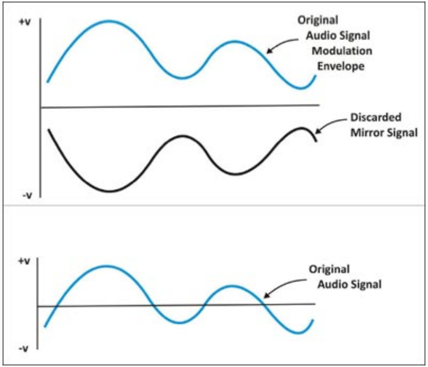
Concept of a mixer



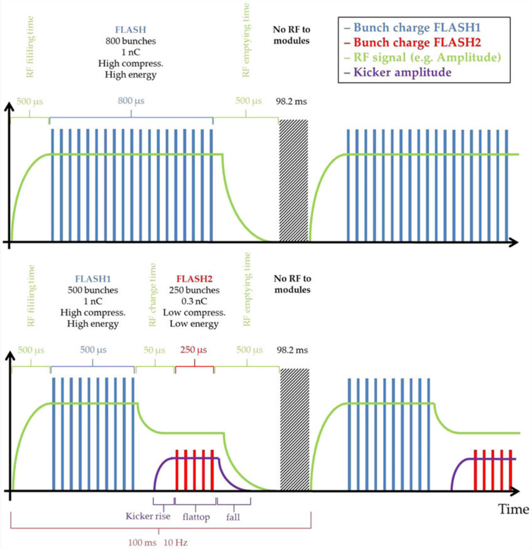
Detecting audio signals from RF



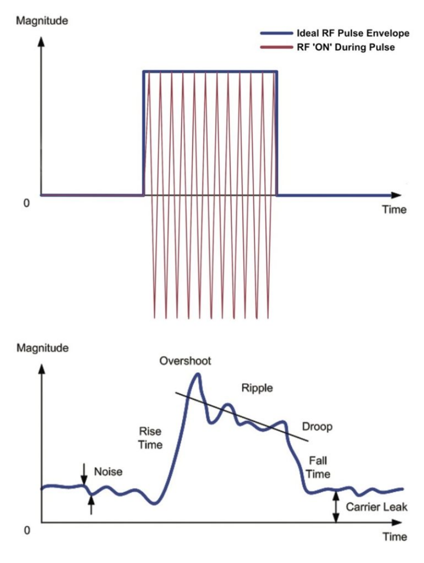
Reconstructing original audio signal



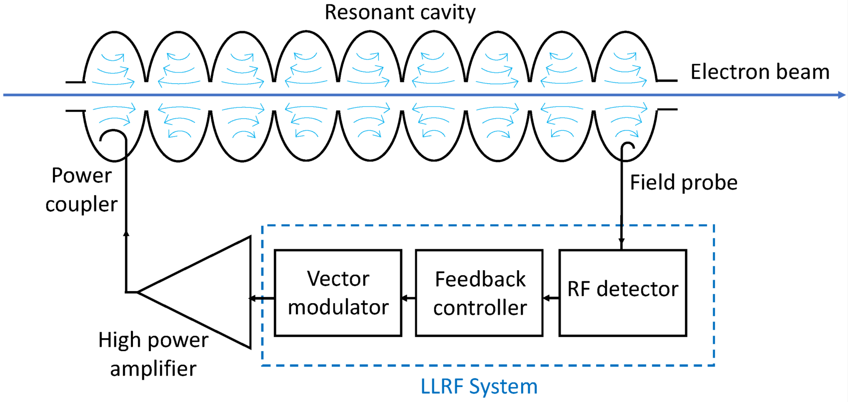
Typical plot in a LLRF paper



Reading an RF pulse



Basic RF (amplitude & phase) controls

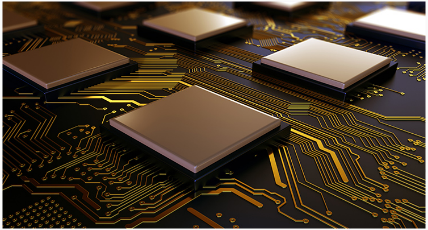


Trick # 2: Circuit analysis & control theory

- All components in a LLRF system (including the cavity itself) can be represented as linear components for the purposes of system analysis
- There are extensive formalisms and mathematical tools (from linear algebra using complex numbers and exponentials, to the analysis of harmonic oscillators) that allow for simple and effective manipulation of system responses
- These tools are very powerful to apply for both analytically and numerically: Think Laplace and Z transforms, circuit analysis and control theory
- The LLRF field is mature enough that one can predict system behaviour, noise sensitivities and stability considerations (based on control theory) before a system is built: driving the engineering design and implementation adapted to the cavity stability requirements

Trick # 3: FPGAs

- A major breakthrough in the LLRF field in the beginning of the 2000s was the introduction of Field Programmable Field Arrays (FPGAs) as a real-time computational engine
- There are numerous advantages of signal processing in the digital domain vs the previous implementations in analog in terms of performance and stability (see next slide), and FPGAs can be re-programmed on the spot!



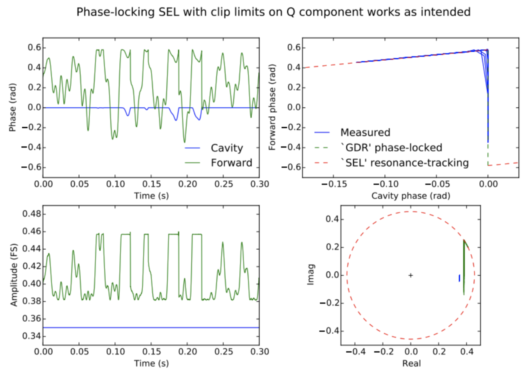
FPGA DSP as an analog component

	DSP	"Real" analog
noise	yes	yes
$1/f$ noise	no	yes
drift	no	yes
temp. coeff.	no	yes
group delay	yes	yes
saturation	yes	yes
distortion	no	yes
crosstalk	no	yes
imperfect cal.	no	yes
power dissipation	yes	yes
simulatable	yes	yes
remote updates	yes	no

- Delay of FPGA DSP has two parts: computational delay (usually 10's of ns) and the unavoidable component of the filter it implements, *e.g.*, 200 kHz single-pole low-pass filter has 800 ns group delay
- Noise added by FPGA DSP is a tradeoff with resources used; can always be made smaller than the input ADC noise; think "Noise Figure"

Connecting FPGAs and computers

- An FPGA could control a cavity forever working offline, but if not connected to a computer we cannot see what they are doing
- The job of a LLRF engineer is 90% of the time performing the following sequence:
    1. Set up the experiment
    2. Acquire data
    3. Analyze the data
- We will do a lot of that in this course, actually what this course is all about!

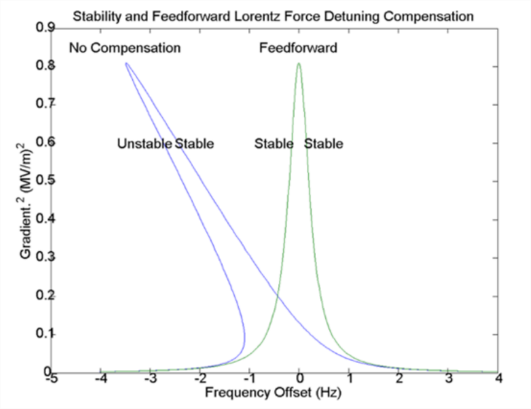


Everything is relative

- When there is more than one cavity in an accelerator, the definition of both frequency and phase has to be common (shared)
- The frequency reference (think of the period of a common clock) is usually shared with a timing system: e.g. White Rabbit, or event-based system common in Synchrotron light sources
- In some instances, a phase reference distribution system is also needed:think of a reset signal for a counter on that common clock
- Timing & synchronization systems use similar techniques and technology as LLRF: see USPAS course next week

Resonance controls

- The the EM field in a cavity is entirely defined by three parameters: amplitude, phase & frequency
- Resonance controls deals with frequency (separate feedback loop)
- There are different mechanisms to control its resonance, but it always has to do with the cavity geometry
- Cavity detuning the difference between the cavity resonance frequency and the accelerator frequency reference (everything is relative!)



Final remarks

- As you can see, the LLRF field is wide and has many components to it from different fields of Science and Engineering
- Please interact with your peers and the teaching team, hack the Lab exercises, try your own ideas, let's make this interactive
- We are doing this (course) for the first time, please give us feedback
- We are here to help and make the most out of this course, we hope you enjoy it!