Experimental activity #2: RF pulse compressors

Why?

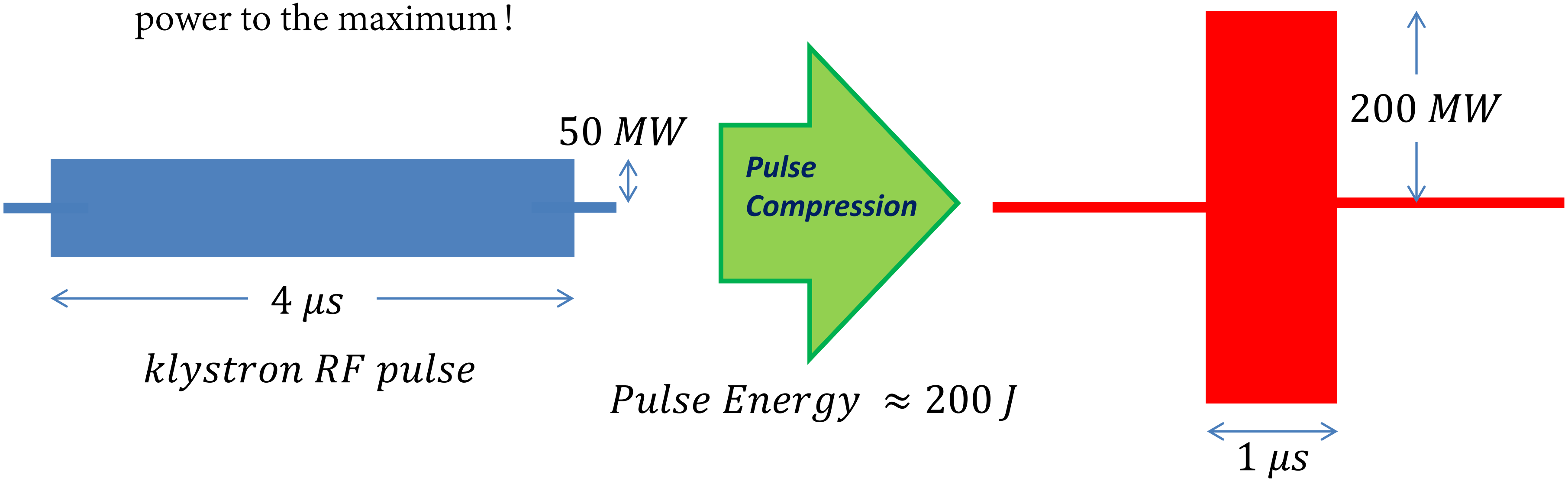
- Real devices widely used in electron linac to increase the available peak power
- Also very instructive, suitable for an RF lab experience
- Based on RF response of resonant cavities and other connection devices (hybrid couplers or circulators)

The problem:

- High accelerating gradients require very high RF power ($P \propto E^2$)
- RF peak power available from klystrons is typically limited to <100 MW. But the duration of the klystron RF pulses ($\approx$ few μs) may largely exceed the typical filling time of an accelerating structure ($< 1\ \mu s$)

The Idea: SLED (Stanford Linac Energy Doubler)

- Let's compress the energy of the RF pulse in about 1 filling time to increase the peak power to the maximum !



- A factor of 4 in power corresponds to a factor of 2 in accelerating gradient, i.e. In beam energy. Smart idea ! But how a large RF power flowing in a waveguide can be manipulated in order to be compressed ?

- This idea has been firstly implemented at SLAC in the 70's [1]. **The compression is obtained by capturing the RF power reflected by high-Q resonant cavities**.

[1] Farkas et al. - SLED A method of doubling SLAC energy

Coupling coefficients of a resonant cavity

- «Real» resonant cavities are NOT perfectly closed volumes, i.e. at least 1 opening (**port**) must be present to allow the RF power to flow in (and out)

- The coupling strength of a port can be measured as the amount of power P_{out} extracted from the cavity through the port itself for a given level of the mode fields inside

- This leads to the definitions of the **external-Q** (Q_{ext}) (in analogy with the definition of the resonance quality factor Q_0) and coupling coefficient of a coupler according to :

$$Q_{ext} = \omega \frac{U}{P_{out}}; \qquad \beta = \frac{Q_0}{Q_{ext}} = \frac{P_{out}}{P_{walls}}$$

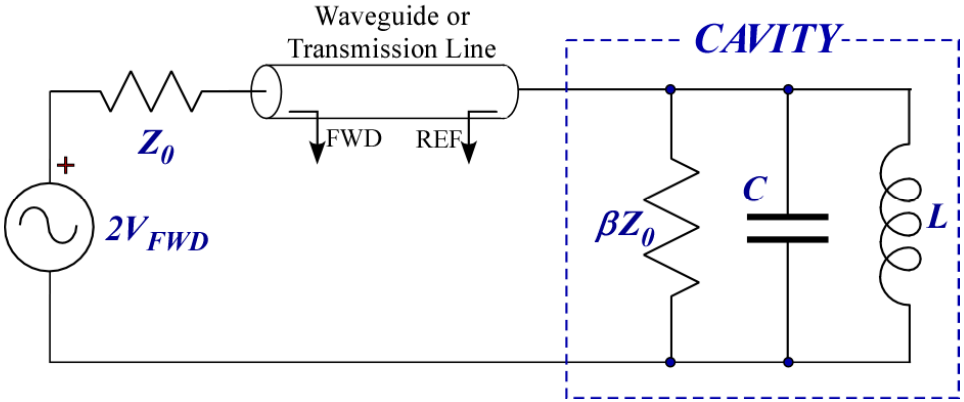
where Q_0 is the usual quality factor of the resonant mode, related only to the dissipation on the cavity walls

The extra-power that flows through the cavity couplers may significantly change the characteristics of the resonance. This effect is known as “cavity loading”. The loaded cavity Q-factor is lowered by the power coupled out through the cavity ports and results to be:

$$Q_L = \omega \frac{U}{P_{Tot}} = \omega \frac{U}{P_{walls} + \sum P_{out_n}} \rightarrow \frac{1}{Q_L} = \frac{P_{walls}}{\omega U} + \sum \frac{P_{out_n}}{\omega U} \rightarrow \begin{cases} \dfrac{1}{Q_L} = \dfrac{1}{Q_0} + \sum \dfrac{1}{Q_{ext_n}} \\ \dfrac{1}{Q_L} = \dfrac{1 + \sum \beta_n}{Q_0} \end{cases}$$

Wave reflection in guide terminated on a resonant load

- A resonant cavity is a non-matched load for a waveguide or a transmission line, and can be modeled as an RLC parallel circuit.



$$Z_{cav}(s) = \beta\, Z_0 \frac{s/(\omega_0 Q_0)}{(s/\omega_0)^2 + s/(\omega_0 Q_0) + 1}$$

β = input coupling coefficient

$${\omega_0}^2 = \frac{1}{LC}, \qquad Q_0 = \omega_0 \beta Z_0 C$$

- An RF wave travelling from the generator toward the cavity is **always** partially reflected at the cavity input. The reflected wave can be calculated according to:

$$V_{REF} = V_{FWD}\, \frac{Z_{cav} - Z_0}{Z_{cav} + Z_0}$$

Cavity reflected waves and input coupling coefficient

- In the previous equation, if we substitute the expression for Z_{cav}, the reflected wave becomes function of the coupling coefficient:

Lorentzian network transfer function

$$V_{REF} = V_{FWD}\,\frac{Z_{cav} - Z_0}{Z_{cav} + Z_0} = V_{FWD}\left[\frac{2\beta}{\beta+1}\,\frac{s/\omega_0 Q_L}{(s/\omega_0)^2 + s/\omega_0 Q_L + 1} - 1\right]$$

- Depending on the value of β, 3 practical situations can occur:

$\beta < 1$	undercoupling
$\beta = 1$	critical coupling
$\beta > 1$	overcoupling

What are we going to do:

1. Calculate and plot the Lorentzian network response when V_{IN}: *Step pulse*, *Rectangular pulse*

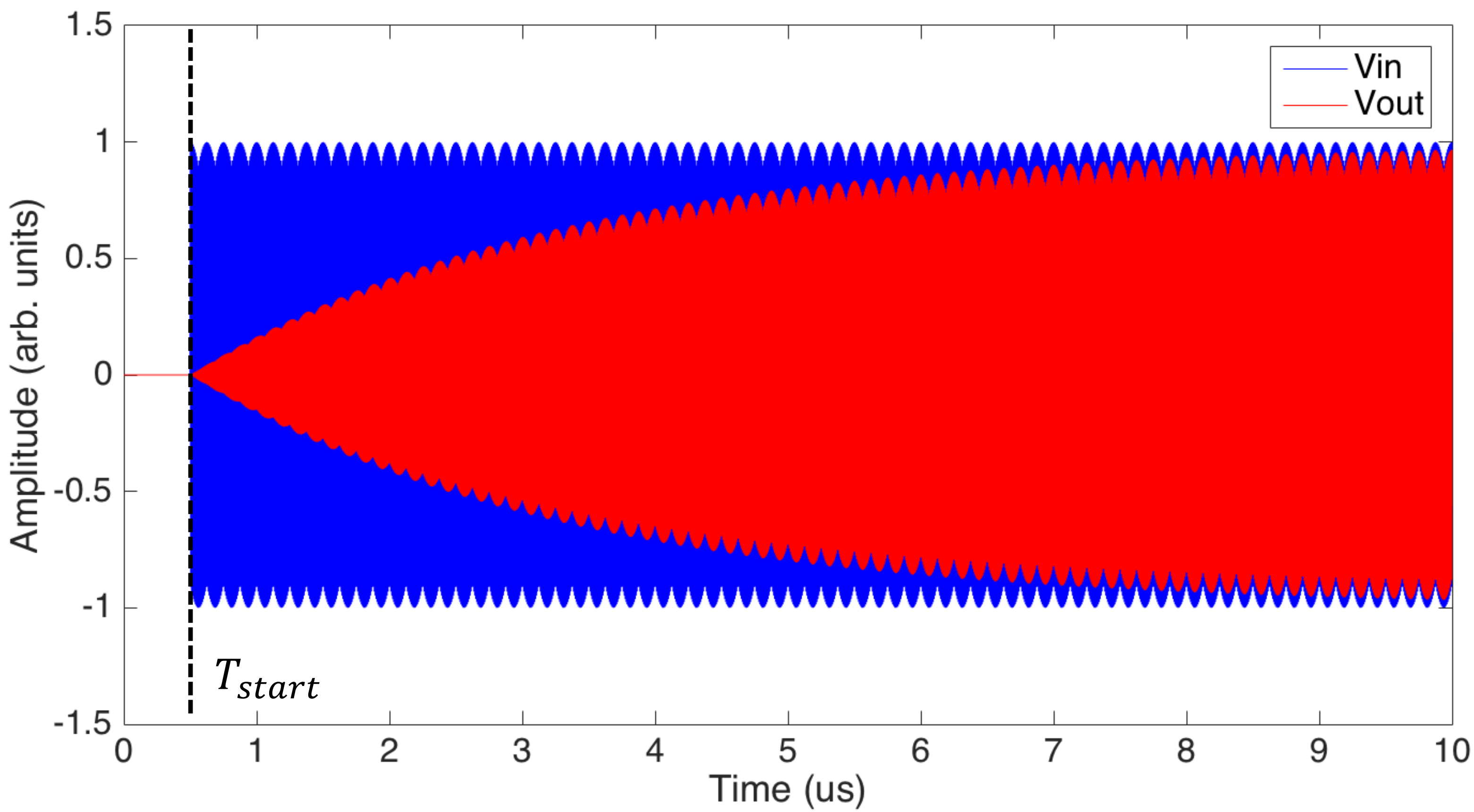
2. Calculate and plot the cavity reflected wave when V_{FWD}: *Step pulse*, *Rectangular pulse*

Lorentzian network response: RF step pulse

The response of a Lorentzian network to an RF step pulse is:

$$V_{in}(t) = V_0 \cdot 1(t - T_{start}) \cdot cos(\omega_0(t - T_{start}))$$

$$V_{out}(t) = V_0 \cdot 1(t - T_{start}) \cdot cos(\omega_0(t - T_{start})) \cdot \left(1 - e^{-(t - T_{start})/\tau}\right); \qquad with\ \tau = 2Q_L/\omega_0$$



$Q_L = 25000; \omega_0 = 2856\ MHz; T_{start} = 0.5\ \mu s;\ \tau \approx 2.8 \mu s$

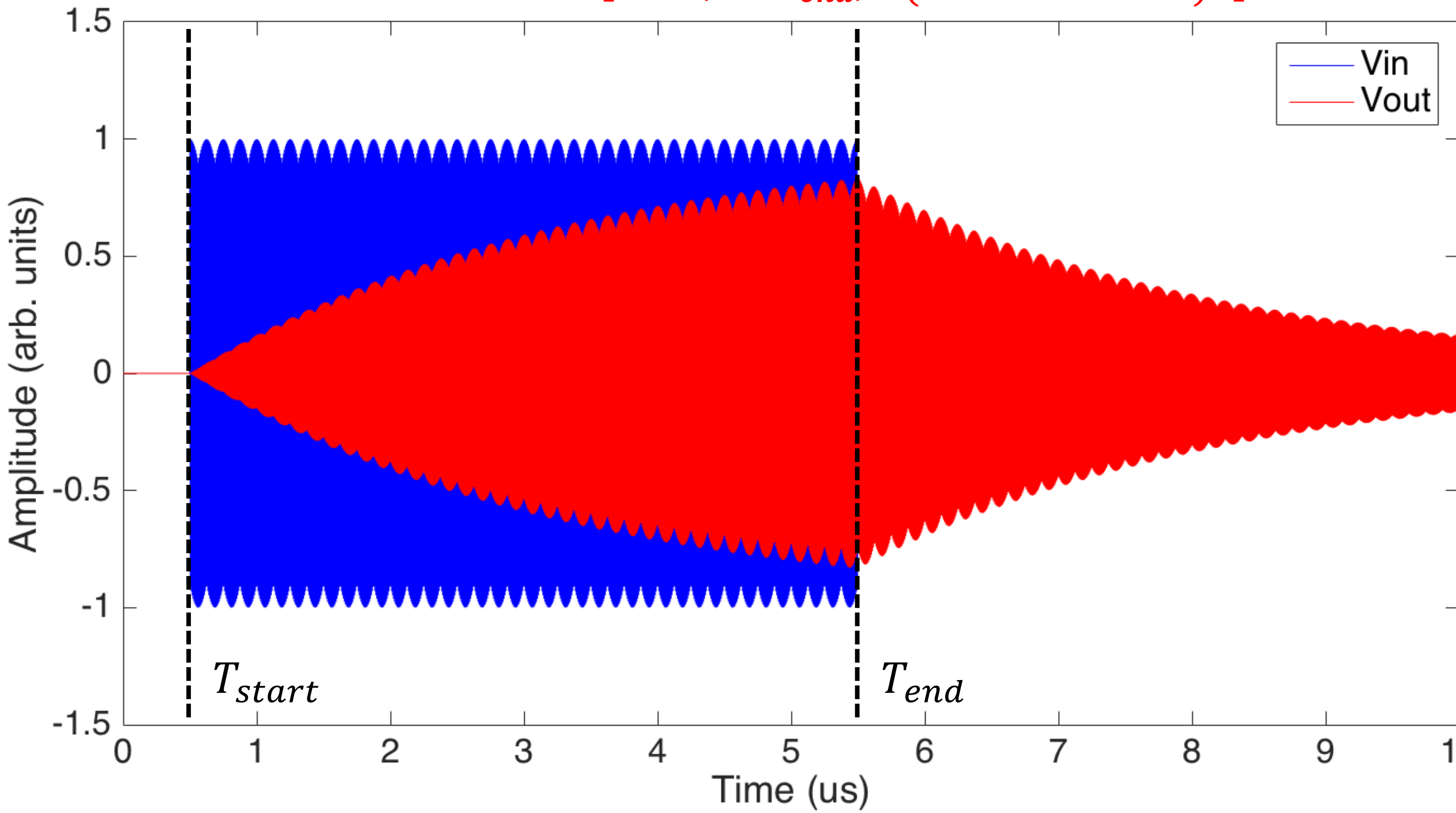
Lorentzian network response: RF rectangular pulse

The response of a Lorentzian network to an RF rectangular pulse is:

$$V_{in}(t) = V_0 \cdot cos(\omega_0(t - T_{start})) \cdot [1(t - T_{start}) - 1(t - T_{end})]$$

$$V_{out}(t) = V_0 \cdot cos(\omega_0(t - T_{start})) \cdot \begin{bmatrix} 1(t - T_{start}) \cdot \left(1 - e^{-(t - T_{start})/\tau}\right) + \\ -1(t - T_{end}) \cdot \left(1 - e^{-(t - T_{end})/\tau}\right) \end{bmatrix}$$

with $\tau = 2Q_L/\omega_0$



$Q_L = 25000; \omega_0 = 2856\ MHz; T_{start} = 0.5\ \mu s; T_{end} = 5.5\ \mu s;\ \tau \approx 2.8 \mu s$

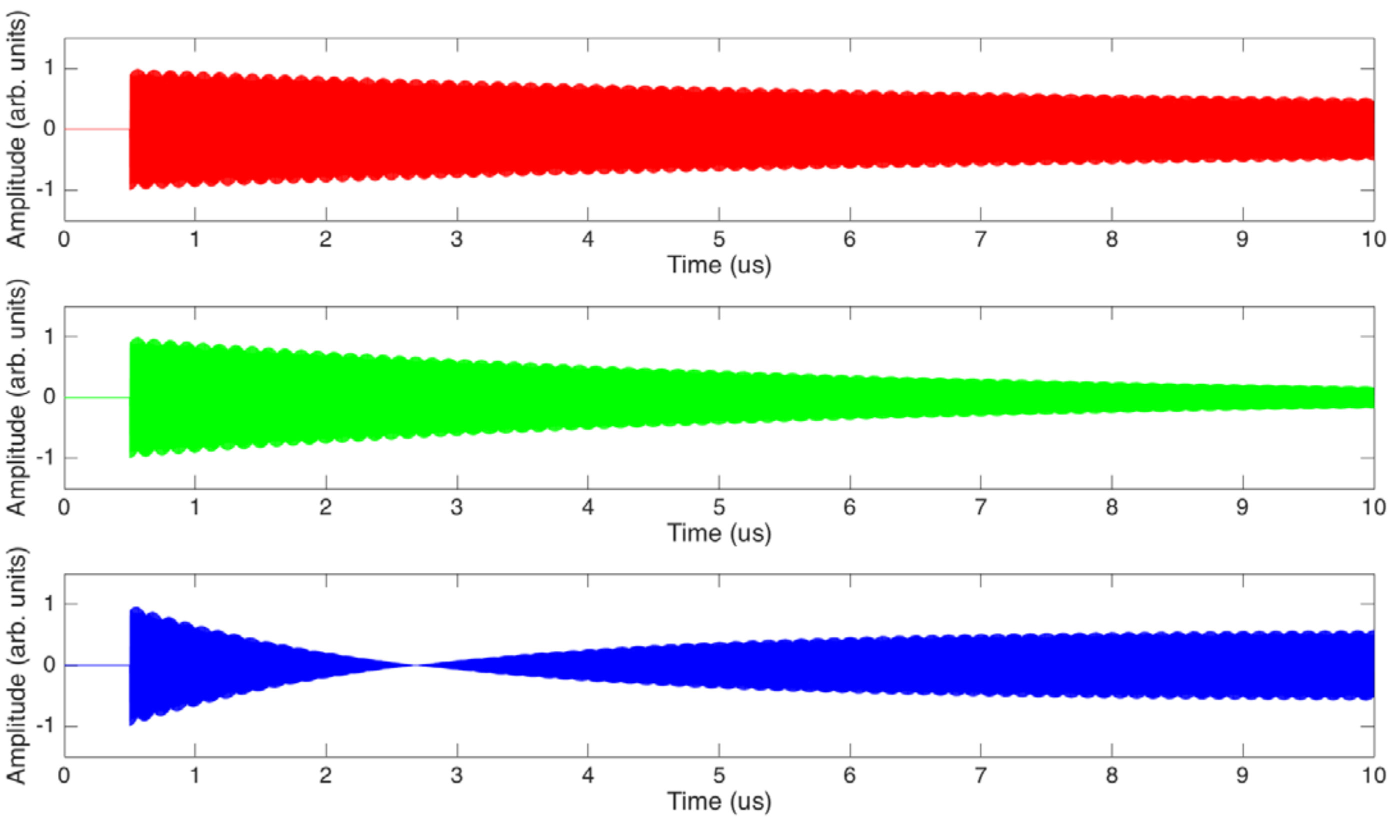
RF step pulse reflected by a resonant cavity

The reflected wave of a resonant cavity to an RF step pulse has the following transfer function:

$$V_{REF} = V_{FWD}\left[\frac{2\beta}{\beta+1}\,\frac{s/\omega_0 Q_L}{(s/\omega_0)^2 + s/\omega_0 Q_L + 1} - 1\right]$$

In time domain:

$$V_{FWD}(t) = V_0 \cdot 1(t) \cdot cos(\omega_0 t); \quad V_{REF}(t) = V_0 \cdot 1(t) \cdot cos(\omega_0 t) \cdot \left[\frac{2\beta}{\beta+1}\left(1 - e^{-t/\tau}\right) - 1\right]$$



Undercoupled, $\beta < 1$

Critically coupled, $\beta = 1$

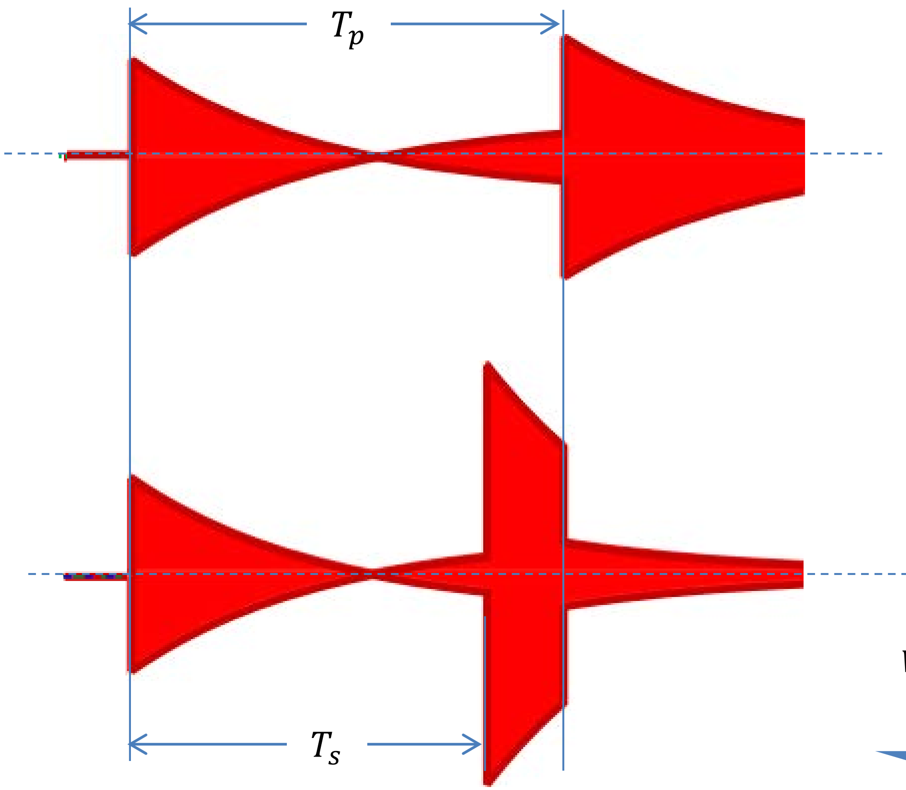
Overcoupled, $\beta > 1$

RF rectangular pulse reflected by an over-coupled resonant cavity

The wave reflected by an over-coupled cavity excited by a rectangular RF pulse is:

$$V_{FWD}(t) = V_0 \cdot cos(\omega_0 t) \cdot [1(t) \; - 1(t - T_p)]$$

$$V_{RFL}(t) = V_0 \cdot cos(\omega_0 t) \cdot \left\{1(t)\left[\frac{2\beta}{\beta+1}\left(1 - e^{-t/\tau}\right) - 1\right] - 1(t - T_p)\left[\frac{2\beta}{\beta+1}\left(1 - e^{-(t-T_p)/\tau}\right) - 1\right]\right\}$$



The RFL peak field is maximum at the end of the FWD pulse, and its value exceeds the peak of the FWD itself.

This effect can be enhanced by forcing a 180° phase jump in the driving pulse at a certain time before the end of the pulse. By doing that we induce an equivalent step in the driving signal of double amplitude which adds in phase with the signal originated by the first rising front of the driving RF pulse.

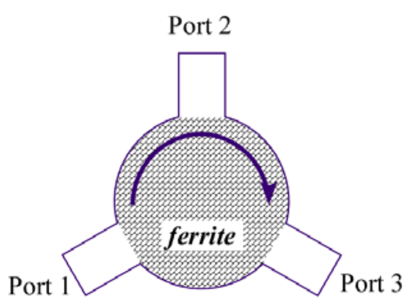
$$V_{FWD}(t) = V_0 \cdot cos(\omega_0 t) \cdot [1(t) \; - 2 \cdot 1(t - T_s) + 1(t - T_p)]$$

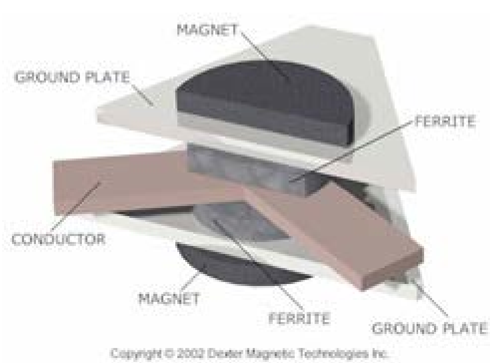
$$V_{RFL}(t) = V_0 \cdot cos(\omega_0 t) \cdot \left\{1(t)\left[\frac{2\beta}{\beta+1}\left(1 - e^{-t/\tau}\right) - 1\right] - 2 \cdot 1(t - T_s)\left[\frac{2\beta}{\beta+1}\left(1 - e^{-(t-T_s)/\tau}\right) - 1\right] + 1(t - T_p)\left[\frac{2\beta}{\beta+1}\left(1 - e^{-(t-T_p)/\tau}\right) - 1\right]\right\}$$

How to route the power flow towards the accelerator (and not towards the power units)

Circulators are **non-reciprocal** (typically) **3-ports** devices whose scattering matrix is ideally given by:

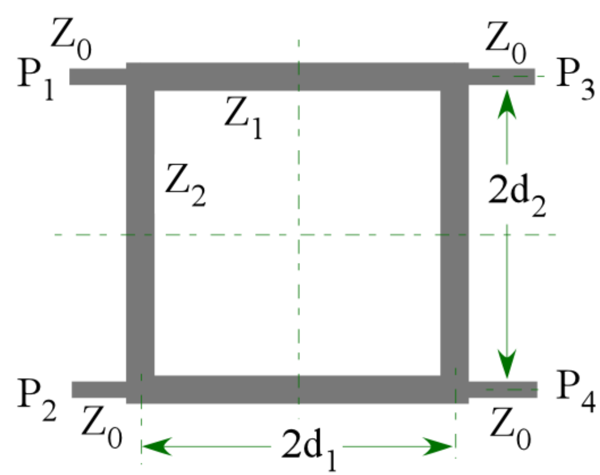
$$S = \begin{pmatrix} 0 & 0 & 1 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \end{pmatrix}$$





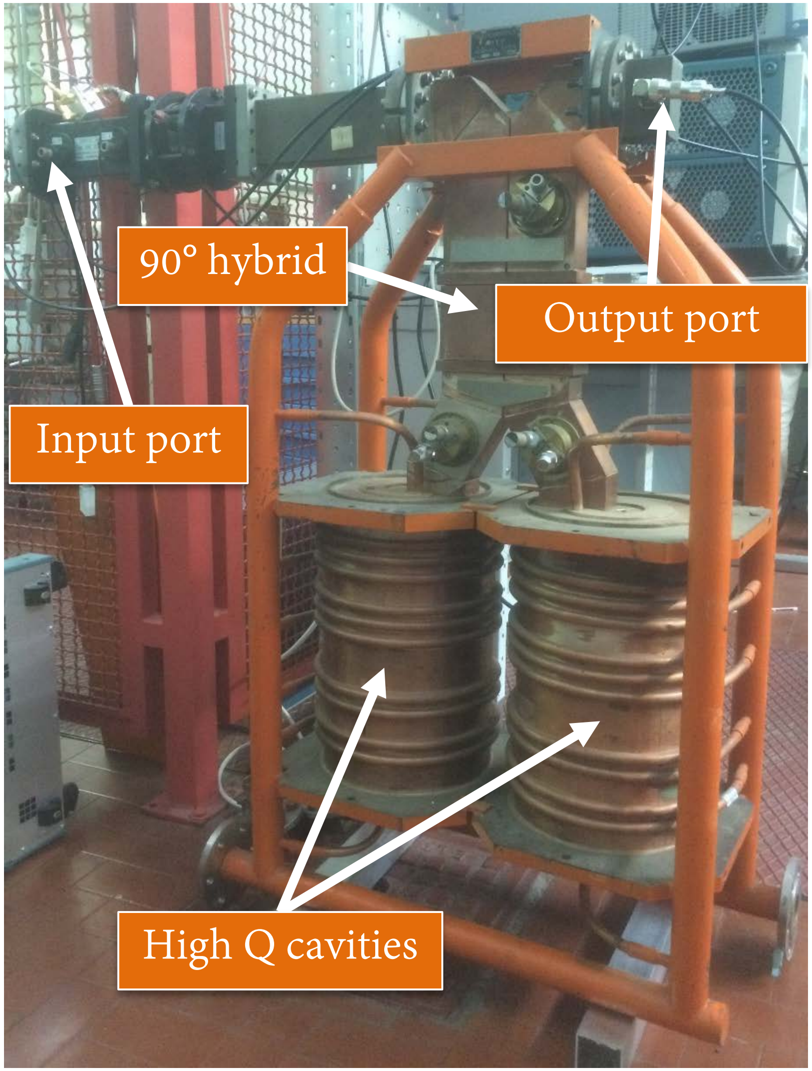
90° hybrids are **non-reciprocal** (typically) **4-ports** devices whose scattering matrix is ideally given by:

$$\| S \| = -\frac{1}{\sqrt{2}} \begin{pmatrix} 0 & 0 & j & 1 \\ 0 & 0 & 1 & j \\ j & 1 & 0 & 0 \\ 1 & j & 0 & 0 \end{pmatrix}$$



Experimental activity #2

1. Introduction:
   - Measure environmental conditions and calculate SLED tuning frequency (working temperature T_r = 35 °C, and nominal frequency f_{RF} = 2856 MHz)
2. Time domain: set-up of the RF pulse
   - CW signal at f_{LP} from signal generator
   - Stanford setup (5 us, 100 Hz, TTL HighZ)
   - RF Switch setup
   - Oscilloscope cross-check
3. Frequency domain: realization of the 180° phase jump
   - Design of a 180° phase shifting circuit
   - Functionality cross-check of the 180° phase shifter provided
   - Actual phase shift measurement
   - Generation and timing regulation of the trigger signals
   - Oscilloscope cross check (30 dB att. 500 mV/div)
4. Time domain: SLED tuning with rectangular input pulse (no 180° phase jump)
   1. Cavity n.1 optimization
   2. Cavity n.2 optimization
   3. Tuning optimizing SLED output
5. Time domain: visualization of SLED output pulse with 180° phase jump
   1. Fine frequency tuning of the SLED pulse
   2. Qualitative measurement of energy/power gain
   3. Scan T_{jump} vs energy gain



Hint: SLED tuning

WHY ?

If the resonant frequencies of the 2 cavities are not the same and/or equal to the operating frequency (2856 MHz for S-band linacs) the SLED can produce high reflections at the input port, causing breakdowns in the input waveguide or near the klystron window.

HOW ?

Generally frequency tuning is done in air and with low RF power. For this reason the measurement needs to account for several environmental variation with respect to nominal conditions: room temperature, pressure, humidity and air (instead of vacuum).

$$f_{LP}(MHz) = f_{HP}(MHz) + \Delta f_T(MHz) - \Delta f_a(MHz)$$

Where:

f_{HP} is the SLED nominal working frequency = 2856 MHz

f_{LP} is the SLED resonant frequency to be tuned at low power, room temperature and in air

Δf_T is the frequency correction for temperature

Δf_a is the frequency correction for pressure and humidity

Hint: SLED tuning (finding f_{LP})

EMPIRICAL FORMULAE (from SLAC & IHEP experience)

$$\Delta f_T = 0.045\,(T_r - T_m)\;\;[MHz] \quad \rightarrow \quad 45\;kHz/°C$$

$$\Delta f_a = \frac{0.2856}{273 + T_m}\left\{798 + p_w\left[0.9\left(1 + \frac{5580}{T_m}\right) - 1.05\right]\right\}\;\;[MHz]$$

$$p_w = \frac{R}{100}\left(4.58 + 0.092 \cdot T_m^{1.65}\right)\;\;[MHz]$$

Where:

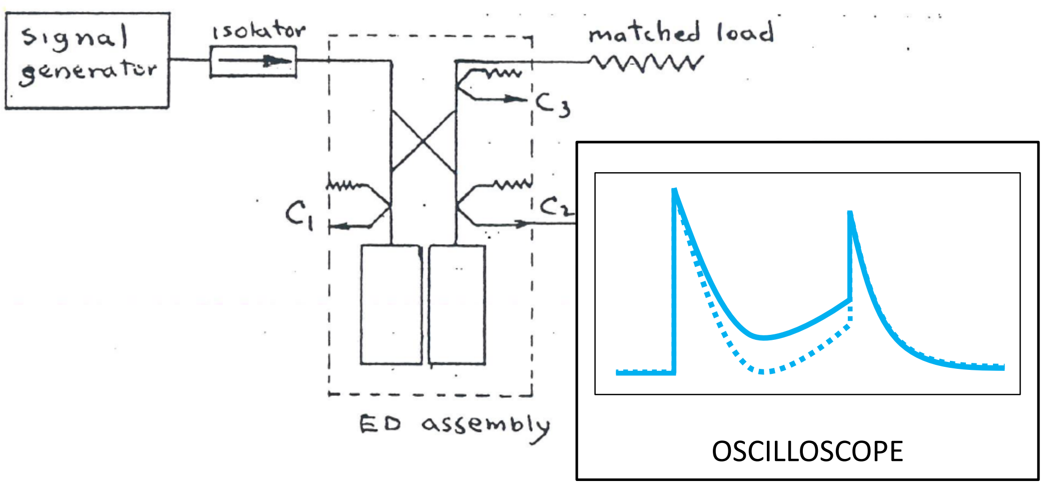
T_r is the operating temperature (in °C) in high power;

T_m is the room temperature (in °C) during low power measurement;

R is the relative humidity (in %) during low power measurement.

Hint: SLED tuning (single cavities)

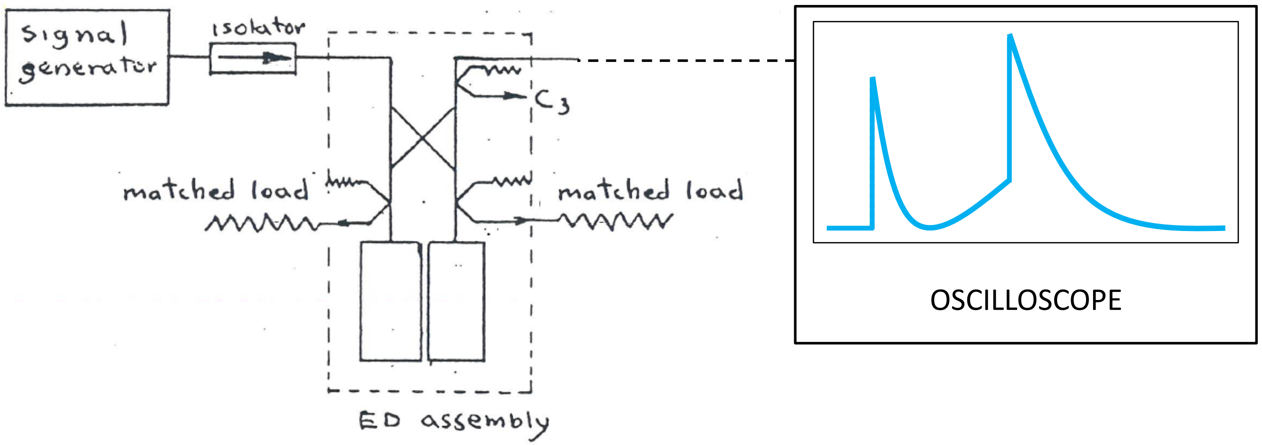
- Connect the output waveguide to a matched load;
- Set-up the RF pulse:
  1. CW signal at f_{LP}
  2. Pulsed signal at f_{LP} (5 us length, 100 Hz rep. rate)
- Display the reflection signal from each cavity on an oscilloscope (use a flat pulse without phase reversal). The connections should look like the scheme below:



- Rotate the tuning screw to tune the resonant frequency of the cavity to have a minimum (dashed line). Repeat the procedure a couple of times for fine tuning.
- Check the input VSWR: it should not be higher than 1.2

Hint: SLED tuning (sum of 2 cavities)

- Once the cavities are individually tuned, the output signal of the SLED (without phase jump) should look like the one below:



- Rotate the tuning screw to fine-tune the SLED output

- If the cavities do not have the same response (different Q_0 or different β), the optimum might not be where one expects…