Course C: XFEL rf technology

Part 3: rf power sources

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Ninth International Accelerator School for Linear Colliders
Whistler, British Columbia, Canada
26 October to 6 November 2015

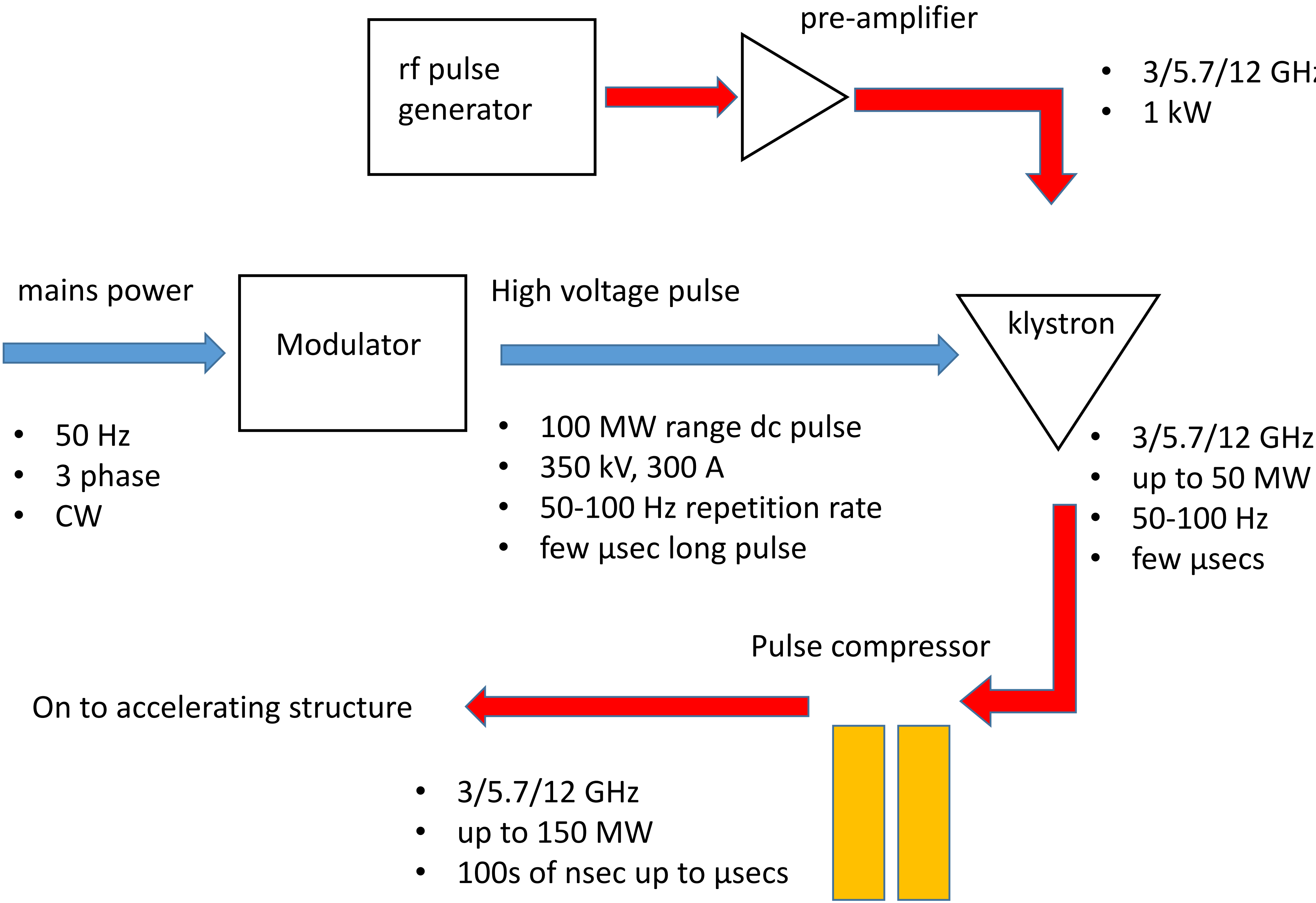
Introduction

Now we will have a look at how to produce the rf power which we have seen how to use for acceleration.

This part of the lecture is mostly descriptive with the objective to give you an overall familiarity.

We are going to talk about power flow and conversion:

- modulator
- klystron
- pulse compressor

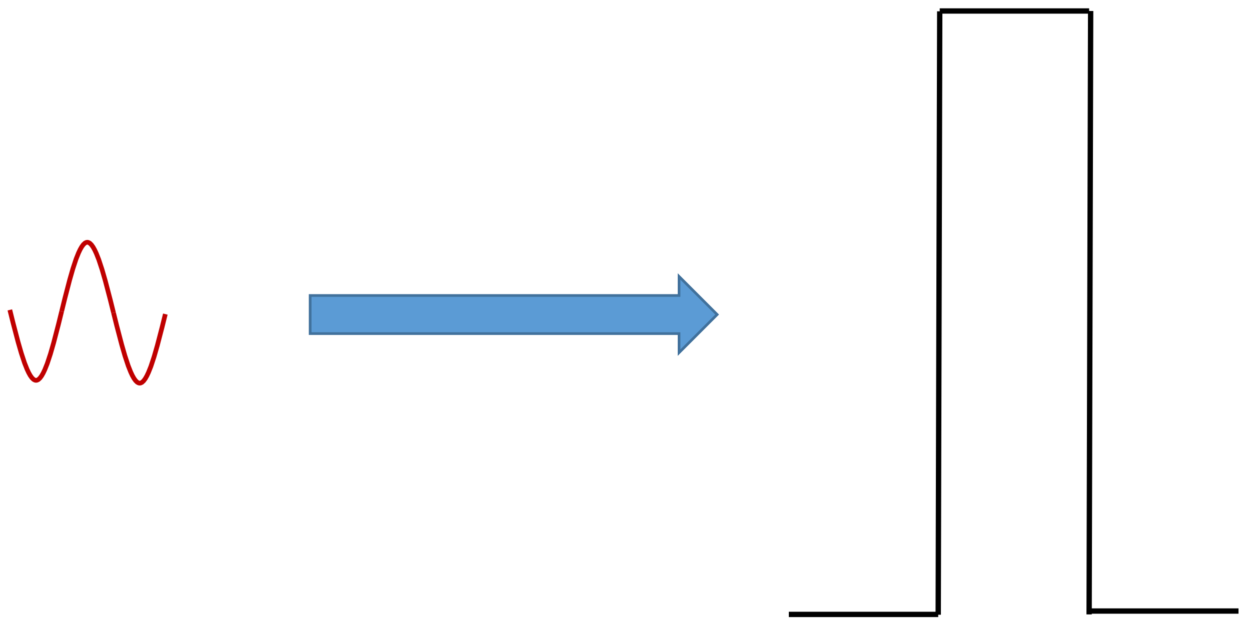

rf pulse generator
pre-amplifier
3/5.7/12 GHz
1 kW
mains power
Modulator
High voltage pulse
klystron
50 Hz
3 phase
CW
100 MW range dc pulse
350 kV, 300 A
50-100 Hz repetition rate
few µsec long pulse
3/5.7/12 GHz
up to 50 MW
50-100 Hz
few µsecs
Pulse compressor
On to accelerating structure
3/5.7/12 GHz
up to 150 MW
100s of nsec up to µsecs

What is a modulator?

We are going to be very superficial on modulators. The objective is to know basically what they are, how they fit in the rf power chain and how they work.

A modulator takes mains power in and outputs a high-voltage, high-current pulse which will feeds a klystron.

Converts AC mains to pulsed high peak power dc pulse. Energy is stored in capacitors.



Rounded numbers for XFEL linacs, be they 3 or 5.7 (or 12) GHz:

A klystron needs a voltage of 350 kV and a current delivered to it of 200 A.

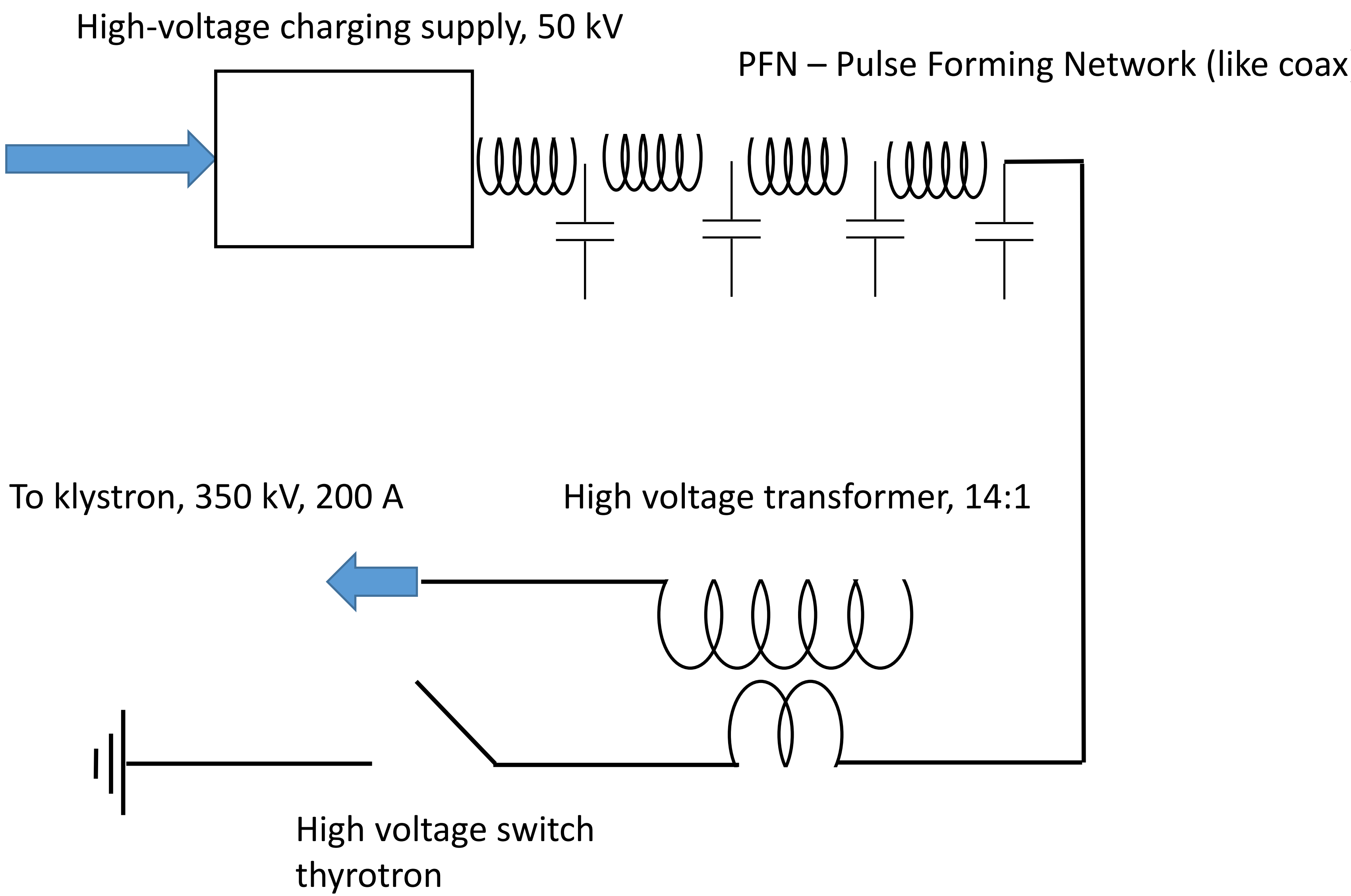
Which gives 70 MW of instantaneous power, which is enough to produce 35 MW of rf power with an efficiency of 50%.

Modulator and rf pulse lengths are in the range of 2 to 5 μsec.

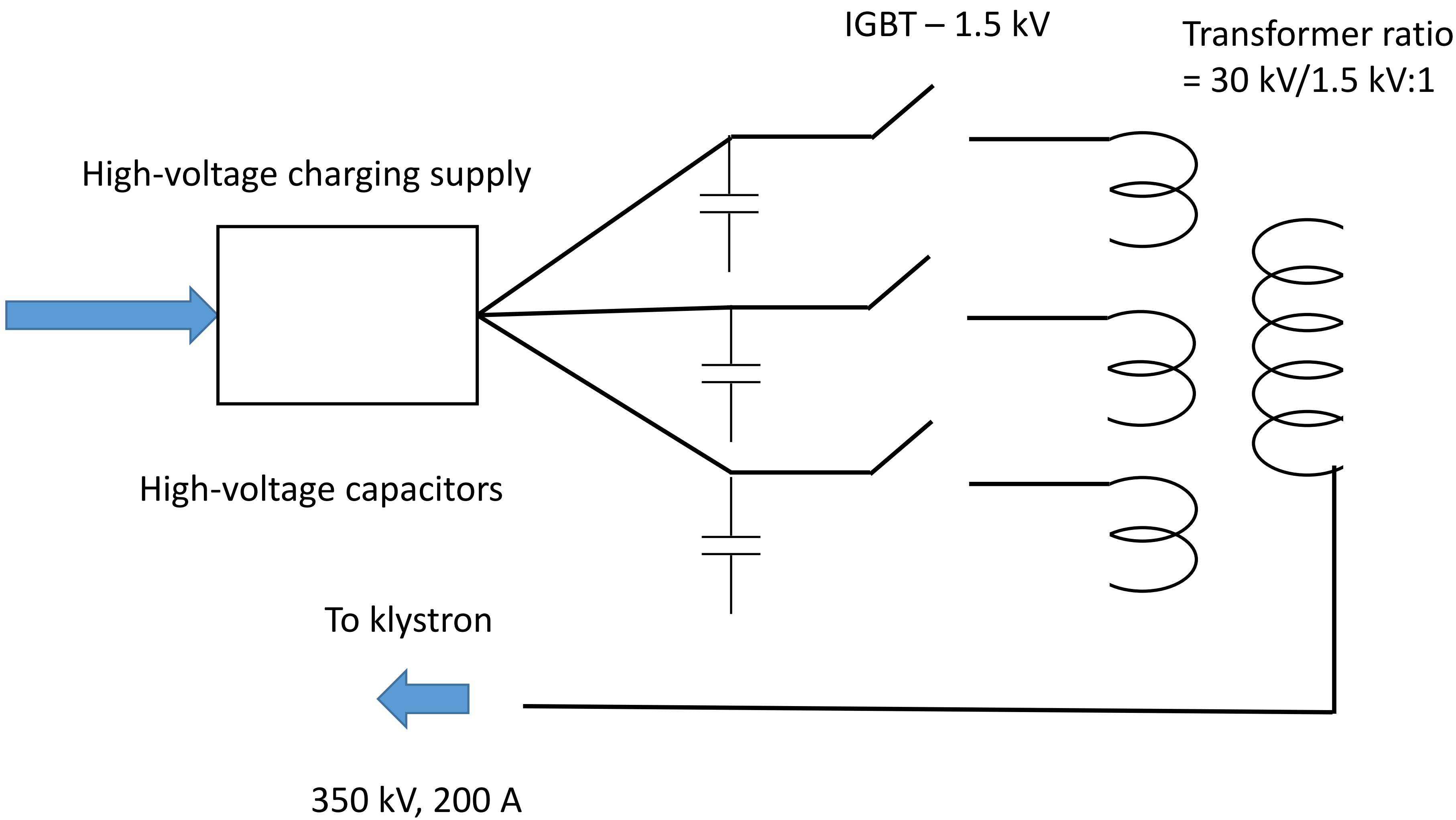
They have 50 to 100 Hz repetition rate.

This gives a duty cycle of around 10^{-4} and average power of 7 kW.

Modulator topology - classical



Modulator topology – Solid state



Popular supplier for XFELs

Control unit

IGBTs

klystron

http://www.scandinovasystems.com/k2-3

Charging supplies

Klystron solenoid power supplies

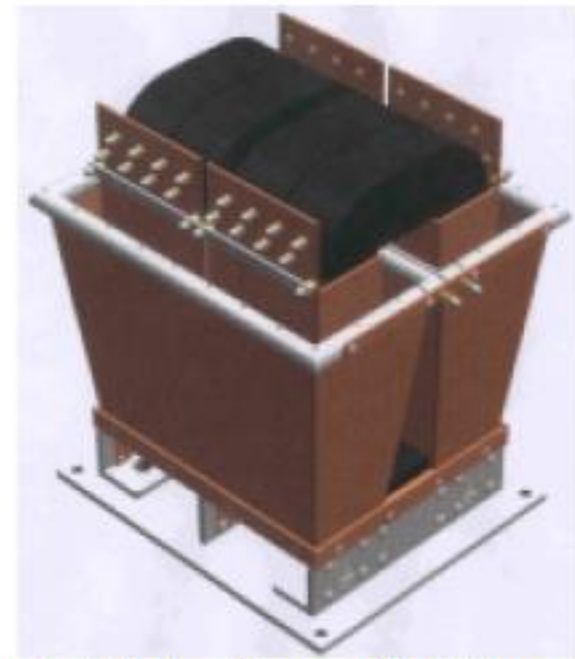
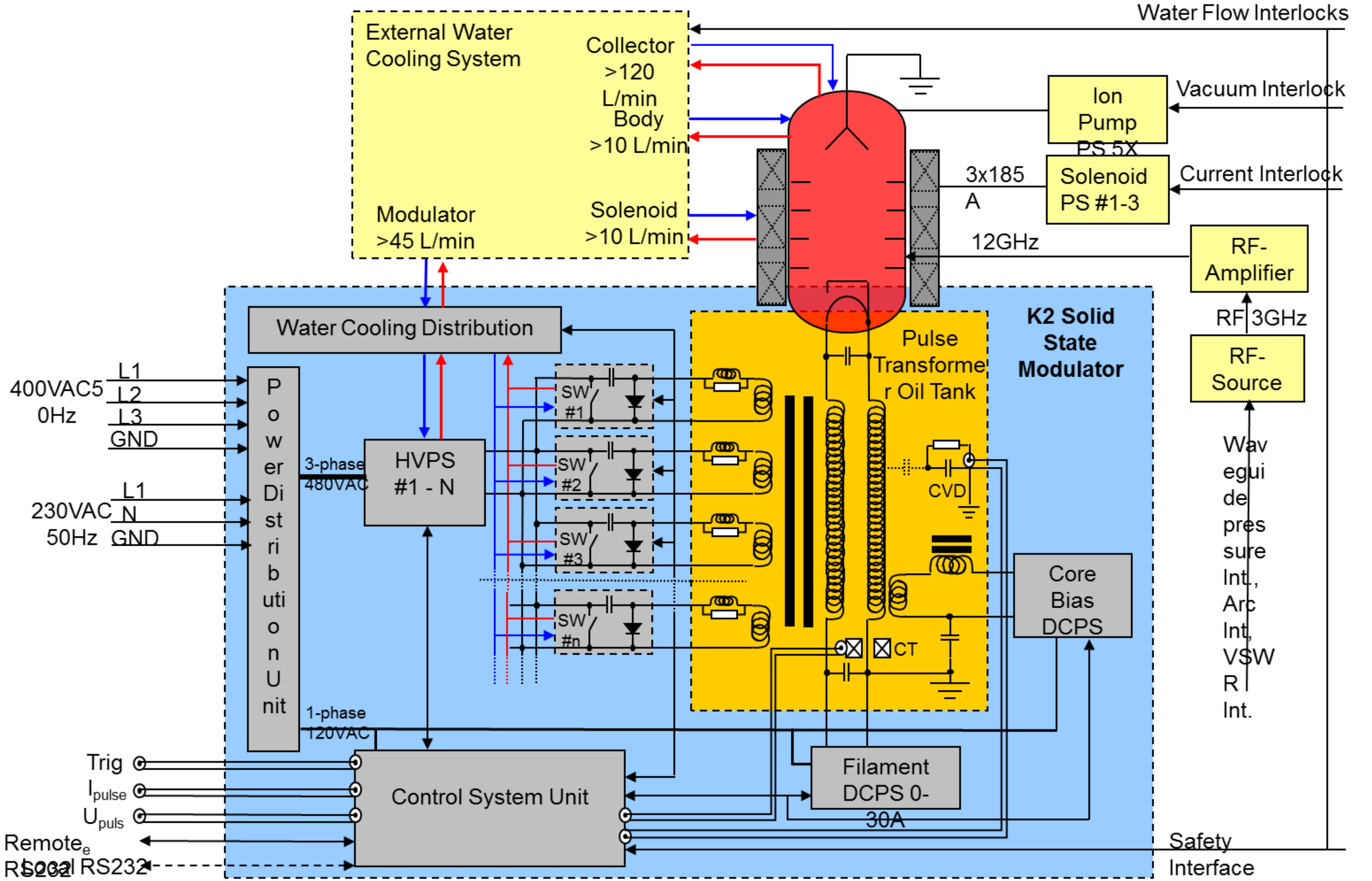


Fig. 1 Pulse transformer with half-turn primary

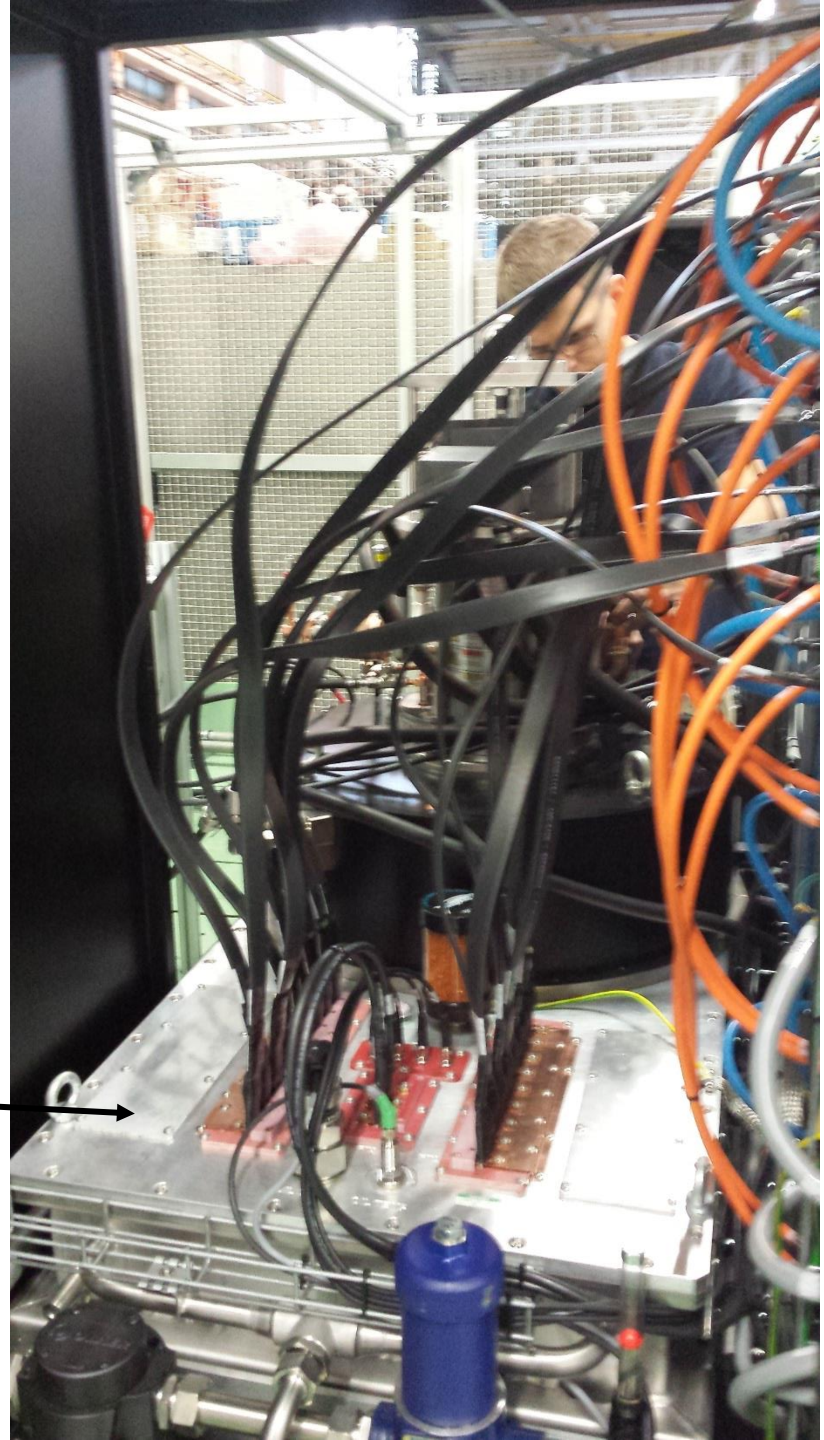
A NEW SOLID STATE HIGH POWER PULSED MODULATOR

Walter Crewson
Crewson Engineering, Inc., Ridgefield, CT, USA
Mikael Lindholm
Scanditronix Medical AB, Uppsala, Sweden
David K Woodburn
D Woodburn & Co Ltd, Caterham, Surrey, England

MODULATOR AND RF SYSTEM, OVERVIEW



Transformer



What is a klystron?

SLAC-PUB 10620
August 2004
Revised
January 2005

High Power Klystrons: Theory and Practice at the
Stanford Linear Accelerator Center *

Part I

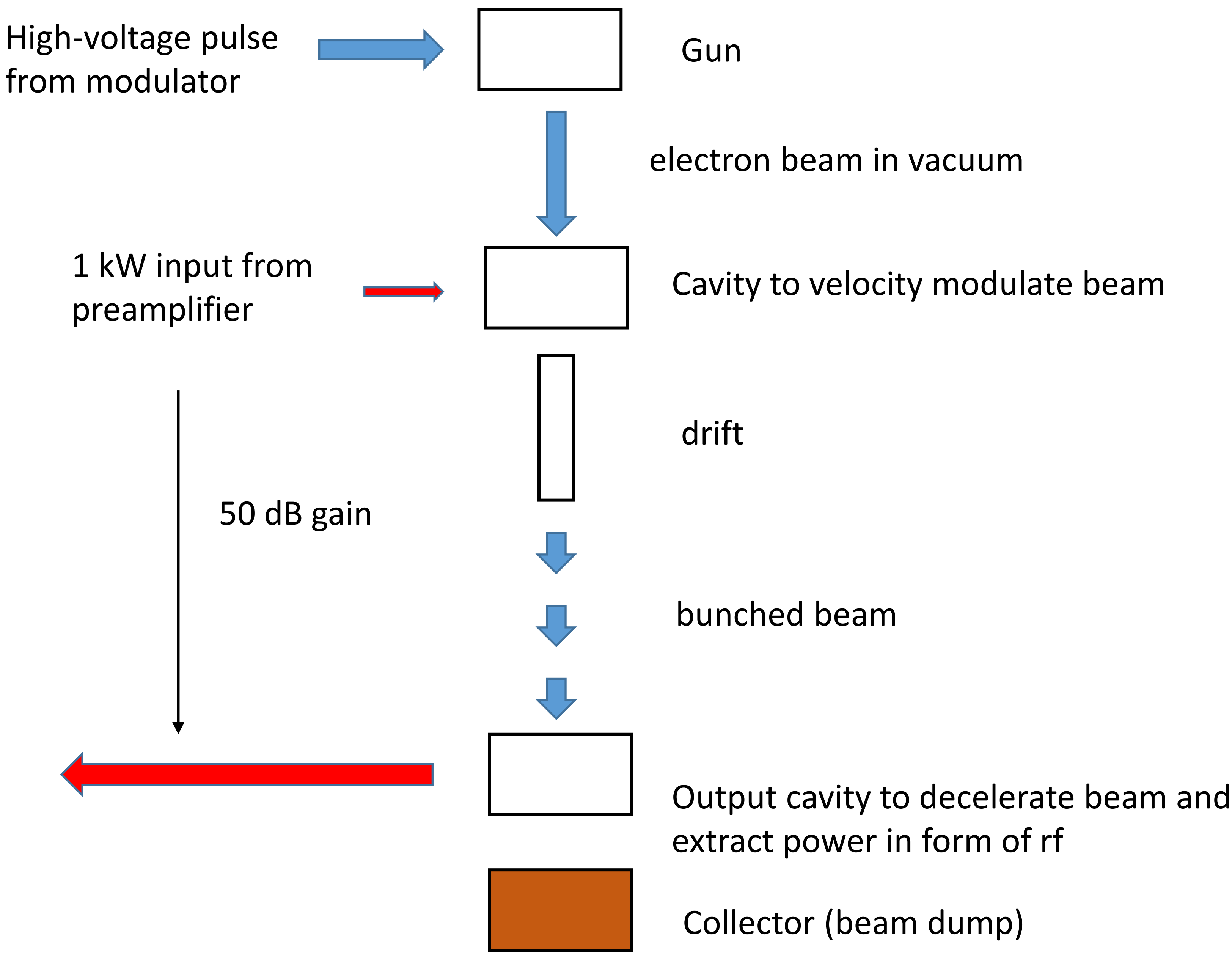
George Caryotakis

Stanford Linear Accelerator Center 2575 Sand Hill Rd.
Menlo Park, CA 94025

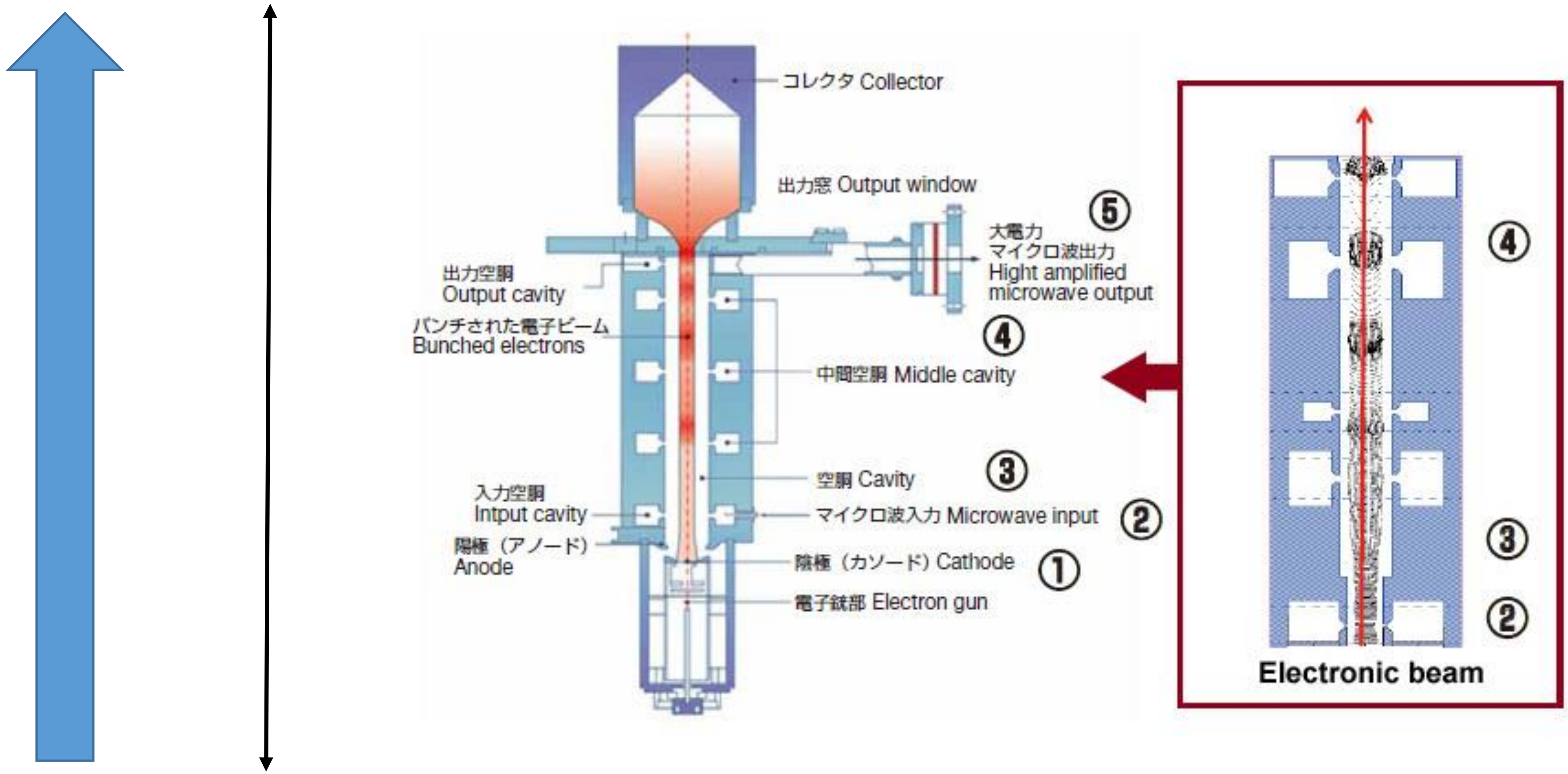
A klystron converts dc power into rf power.

It does this by creating an intense, non-relativistic electron beam flying through vacuum, bunching it through a trick called velocity modulation via an rf cavity and extracting the energy from the bunched beam through interaction with an rf cavity.

A klystron has an rf input and operates as an amplifier.


High-voltage pulse
from modulator
Gun
electron beam in vacuum
1 kW input from
preamplifier
Cavity to velocity modulate beam
drift
50 dB gain
bunched beam
Output cavity to decelerate beam and
extract power in form of rf
Collector (beam dump)

200 A x 350 kV = 70 MW



http://www.toshiba-tetd.co.jp/eng/tech/klystron.htm

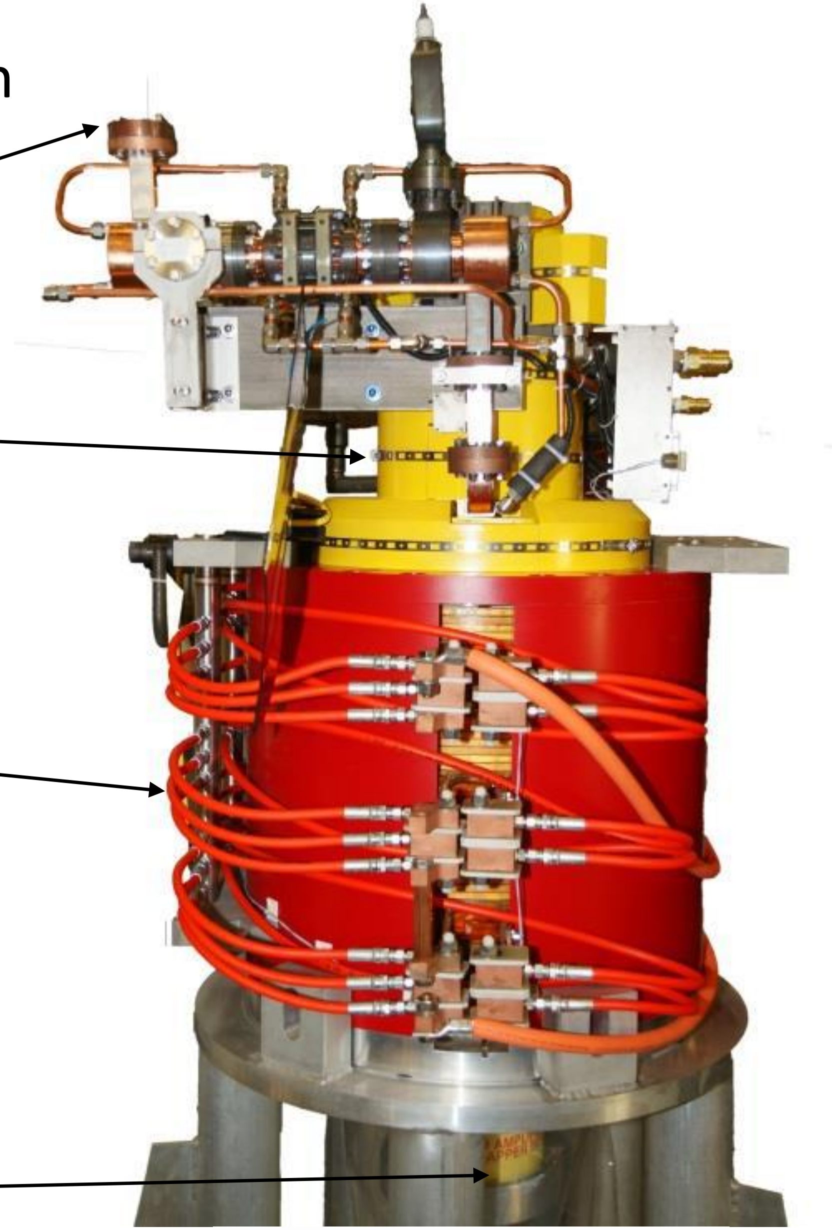
CPI VKX-8311A X-band klystron

Output waveguide

Collector

Focusing solenoid. Beam line and cavities are inside.

Gun

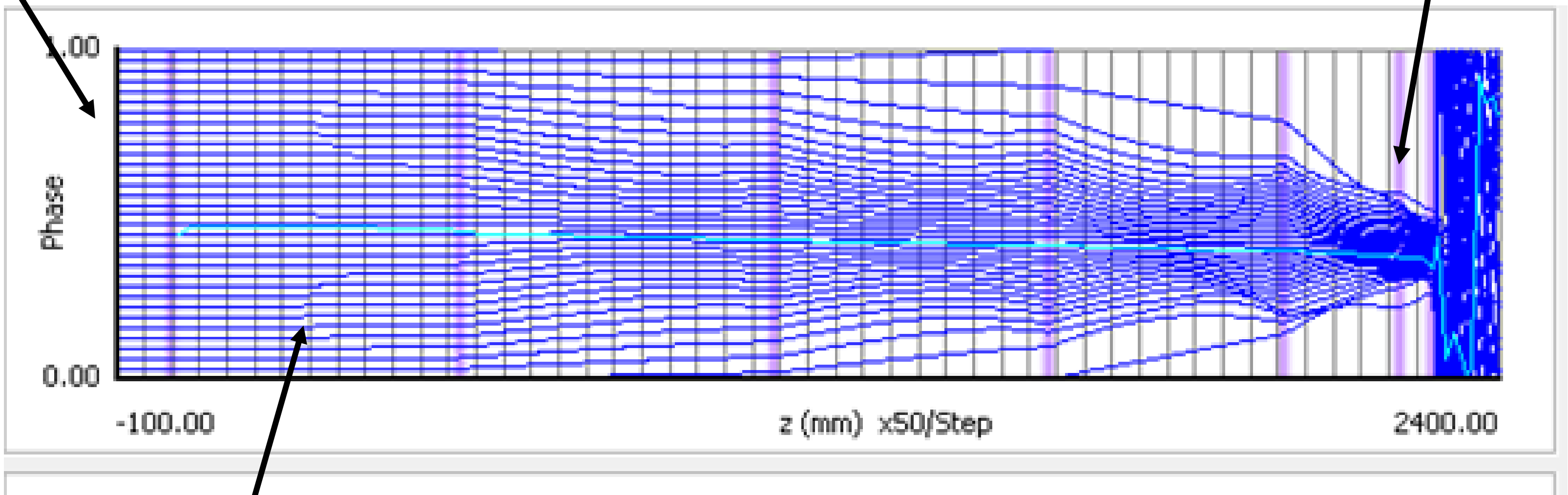


Communications & Power Industries

Applegate diagram

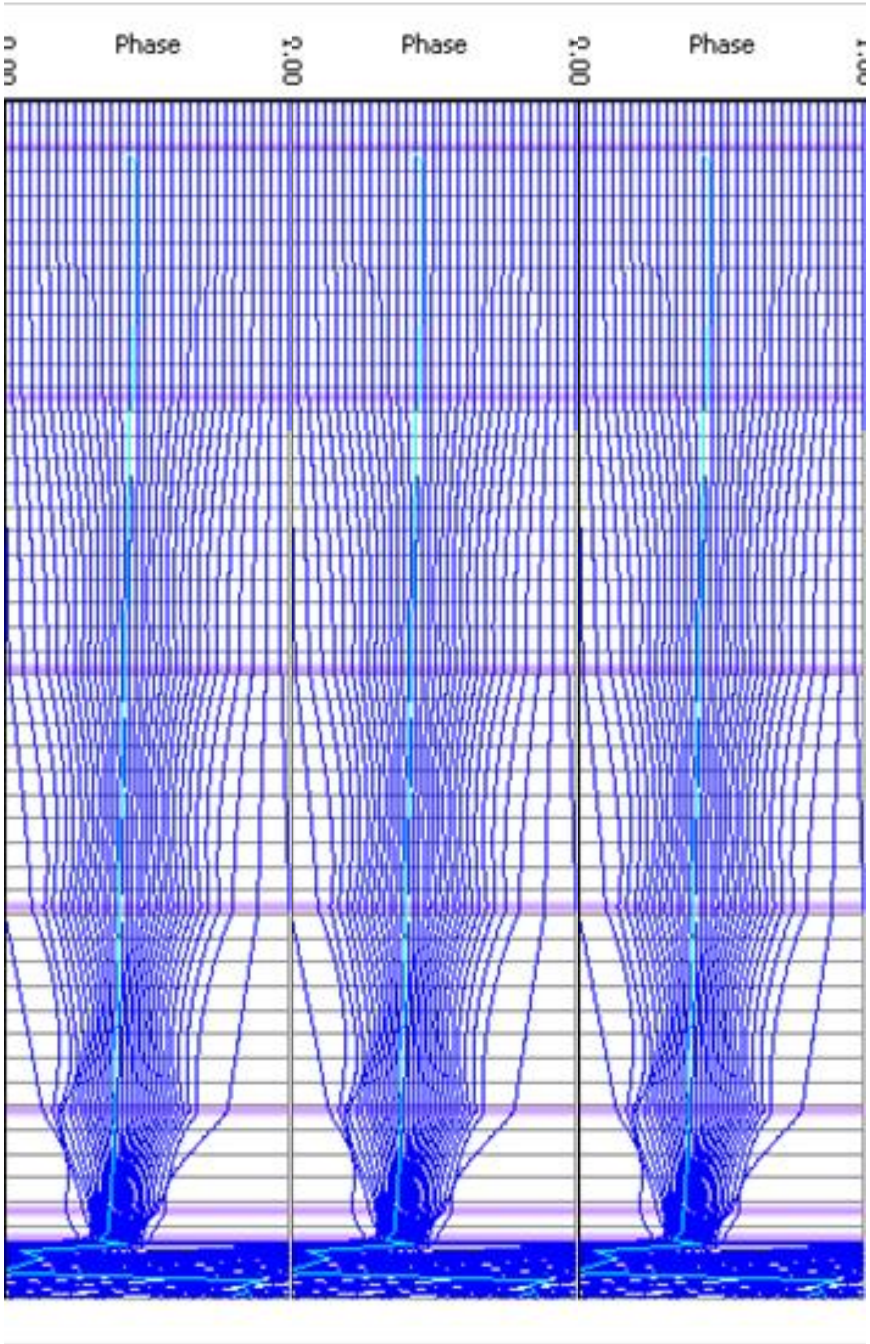
Uniform beam

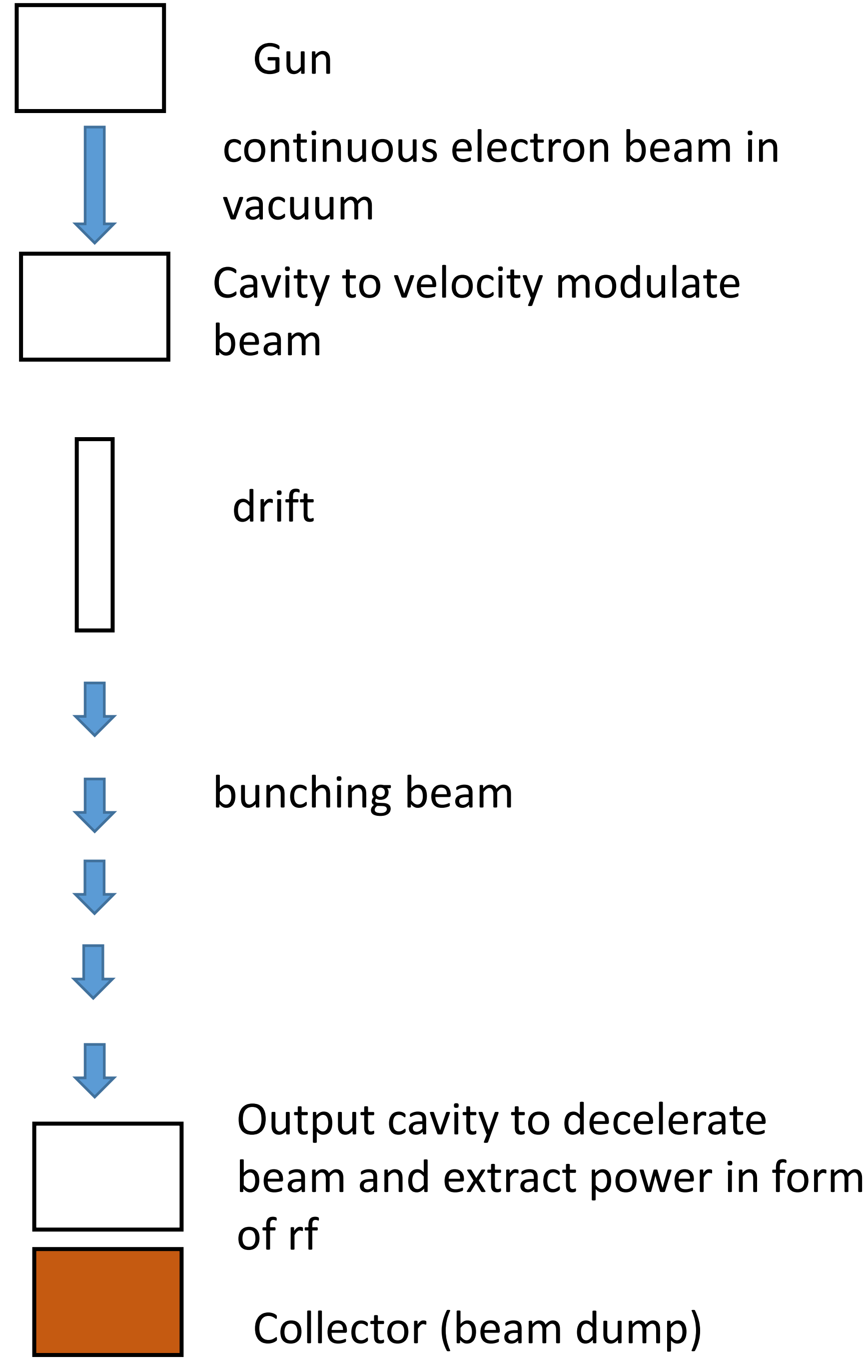
Bunched beam



Distance along klystron

beginning of velocity modulation


Phase
Phase
Phase


Gun
continuous electron beam in vacuum
Cavity to velocity modulate beam
drift
bunching beam
Output cavity to decelerate beam and extract power in form of rf
Collector (beam dump)

rf pulse compressors

What is a pulse compressor?

Most generally, a pulse compressor takes an rf pulse and, conserving energy, makes it shorter and higher power.

This will allow you to feed more accelerating structures with each klystron, reducing the cost of your linac.

It's a very useful trick because the natural time scale for the high-voltage modulator which drives a klystron is of the order of microseconds.

An accelerating structure fill time is of the order of 100 nanoseconds.

Hence there is mismatch in timescales which we can use to our advantage.

How does it work?

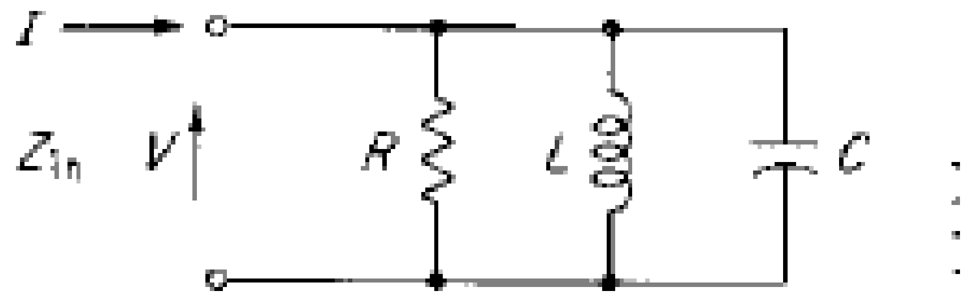
Pulse compressors use a high Q resonant cavity to store an incoming pulse and a phase flip to discharge the cavity very quickly.

So let's review a bit of cavity theory.

Then look at the phase flip.

Then some of the practical details and some real pulse compressors.

Input impedance to a resonant cavity – frequency picture



$$Z_{in} = \left(\frac{1}{R} + \frac{1}{i\omega L} + i\omega C\right)^{-1}$$

At resonance energy stored in the inductor and capacitor is the same so:

$$\omega_0 = \frac{1}{\sqrt{LC}}$$

You get the *Q* from stored energy in the system divided by the energy lost per cycle and it works out to:

$$Q_0 = \frac{R}{\omega_0 L}$$

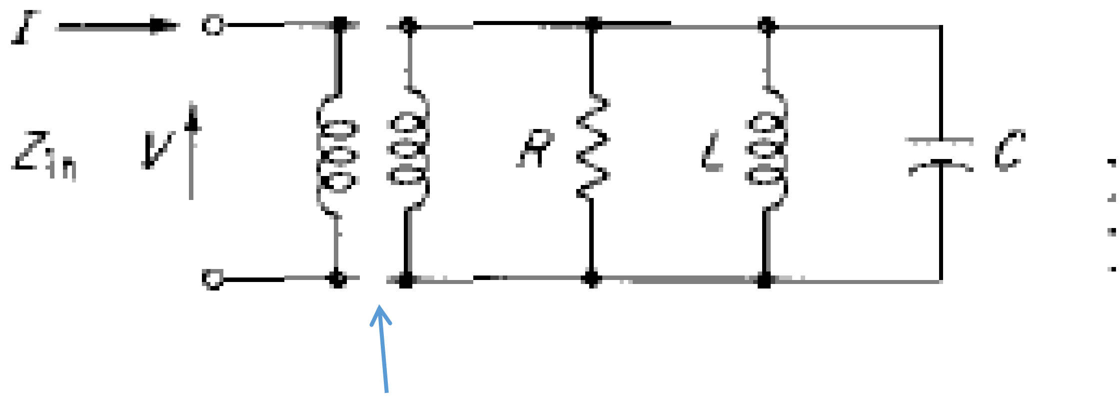
Rewriting

$$Z_{in} = \left(\frac{1}{R} - i\,\frac{Q_0}{R}\frac{\omega_0}{\omega} + i\,\frac{Q_0}{R}\frac{\omega}{\omega_0}\right)^{-1}$$

$$= R\left(1 + iQ_0\left(\frac{\omega_0}{\omega} - \frac{\omega}{\omega_0}\right)\right)^{-1}$$

$$= R(1 + iQ_0\nu)^{-1}$$

Where: $\nu = \left(\frac{\omega_0}{\omega} - \frac{\omega}{\omega_0}\right)$



ideal transformer with coupling β

$$Z_{in} = \beta(1 + iQ_0\nu)^{-1}$$

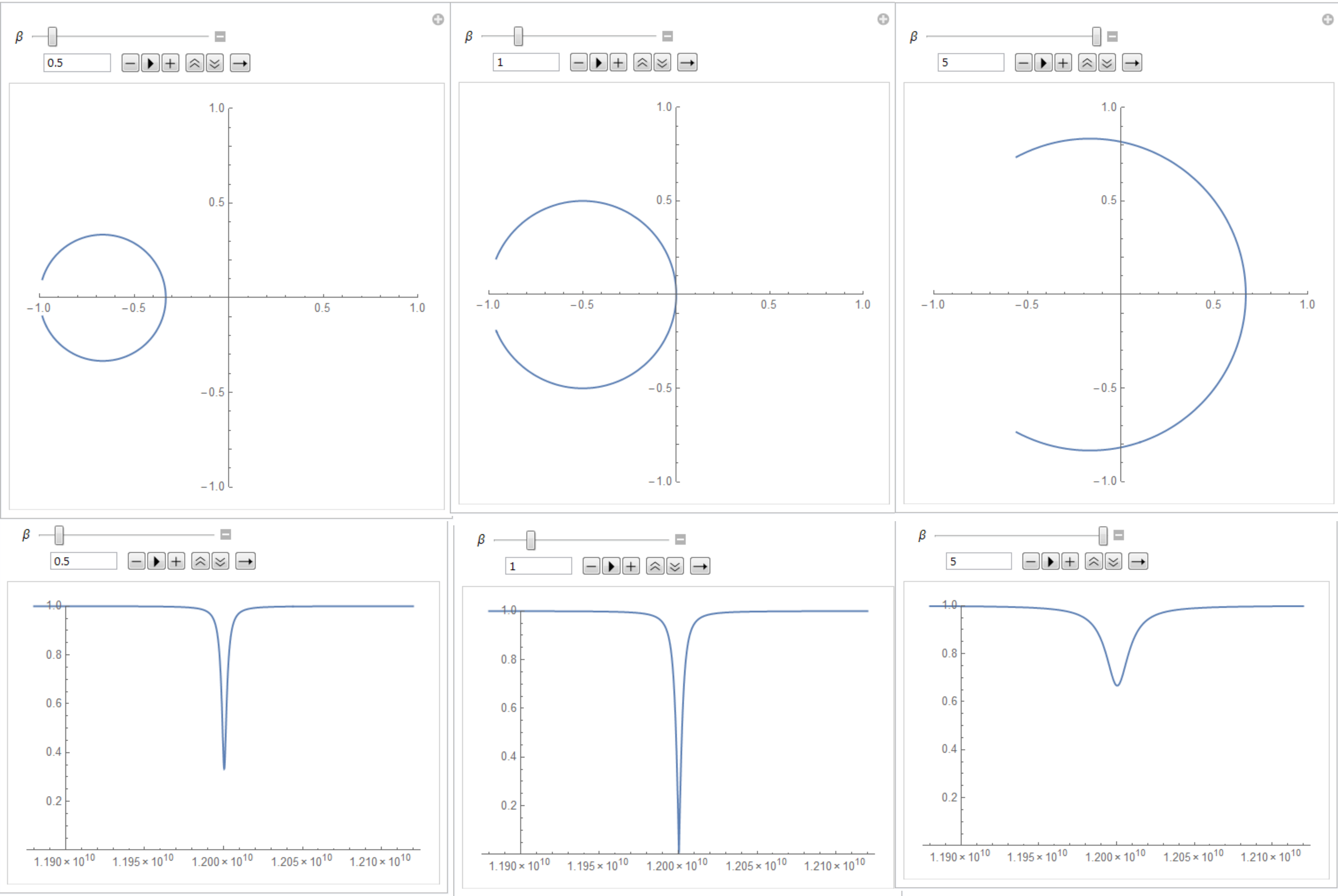
$$\nu = \left(\frac{\omega_0}{\omega} - \frac{\omega}{\omega_0}\right)$$

$$\Gamma = \frac{\frac{Z_{in}}{Z_0} - 1}{\frac{Z_{in}}{Z_0} - 1} = \frac{\beta - (1 + iQ_0\nu)}{\beta + (1 + iQ_0\nu)}$$

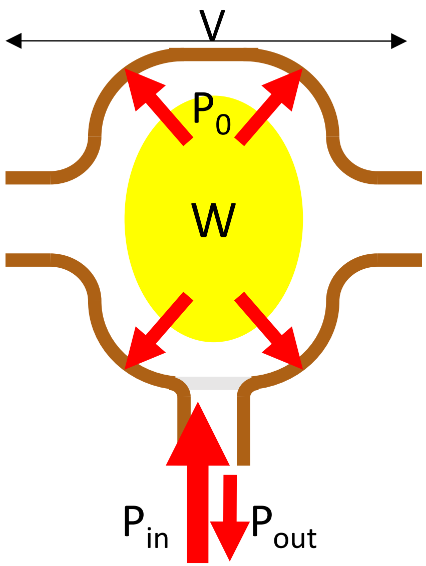
$$\frac{1}{Q_l} = \frac{1}{Q_{ext}} + \frac{1}{Q_0}$$

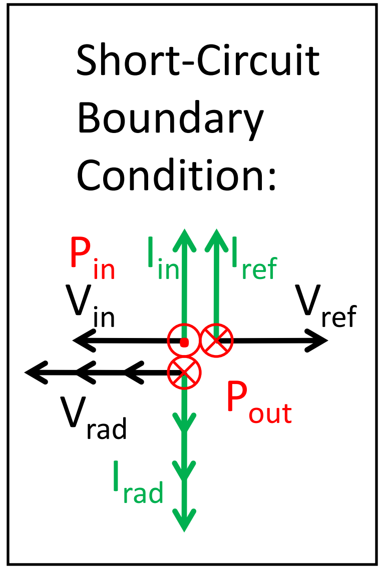
$$\beta = \frac{Q_0}{Q_{ext}}$$

$$\Gamma = \frac{\beta - (1 + iQ_0\nu)}{\beta + (1 + iQ_0\nu)} \qquad \nu = \left(\frac{\omega_0}{\omega} - \frac{\omega}{\omega_0}\right)$$



Energy conservation in a cavity without beam (reminder):





$$P_{in} = P_{out} + P_0 + \frac{dW}{dt}$$

where

$$P_{in} = \frac{\hat{V}_{in}^2}{Z}; P_{out} = \frac{(\hat{V}_{rad} + \hat{V}_{ref})^2}{Z}; \hat{V}_{in} = -\hat{V}_{ref}$$

$$P_0 = \frac{\hat{V}^2}{R} = \frac{\omega W}{Q_0}; \quad \frac{\omega W}{Q_{ext}} = \frac{\hat{V}_{rad}^2}{Z}$$

what results in

$$2\hat{V}_{in}\sqrt{\frac{1}{\beta}\frac{R}{Z}} = \left(1 + \frac{1}{\beta}\right)\hat{V} + \frac{2Q_0}{\beta\omega}\frac{d\hat{V}}{dt}$$

for a step-function excitation :

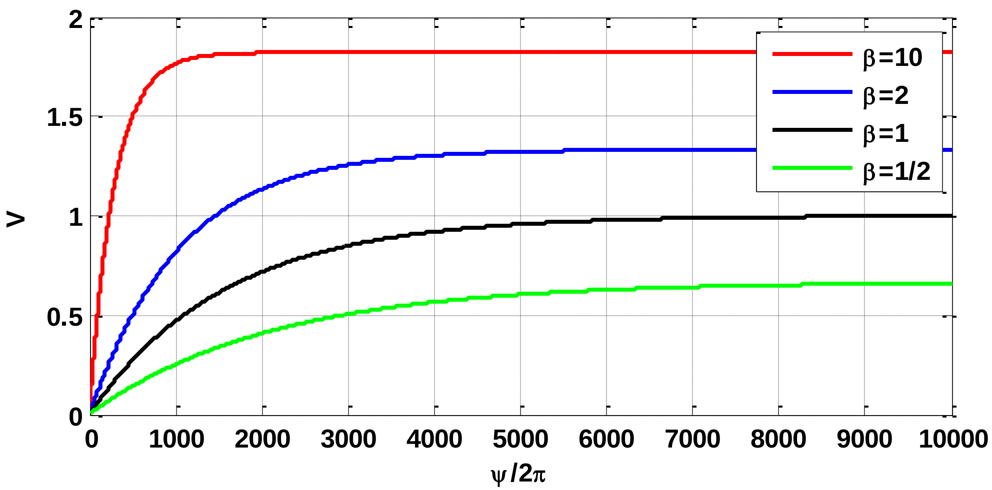
$$\hat{V}_{in}(t)\sqrt{\frac{1}{\beta}\frac{R}{Z}} = \begin{cases} 0, t < 0 \\ 1, t \geq 0 \end{cases};$$

$$\hat{V}(t) = \frac{2\beta}{1+\beta}\left(1 - e^{-\frac{\omega t}{2Q_L}}\right);$$

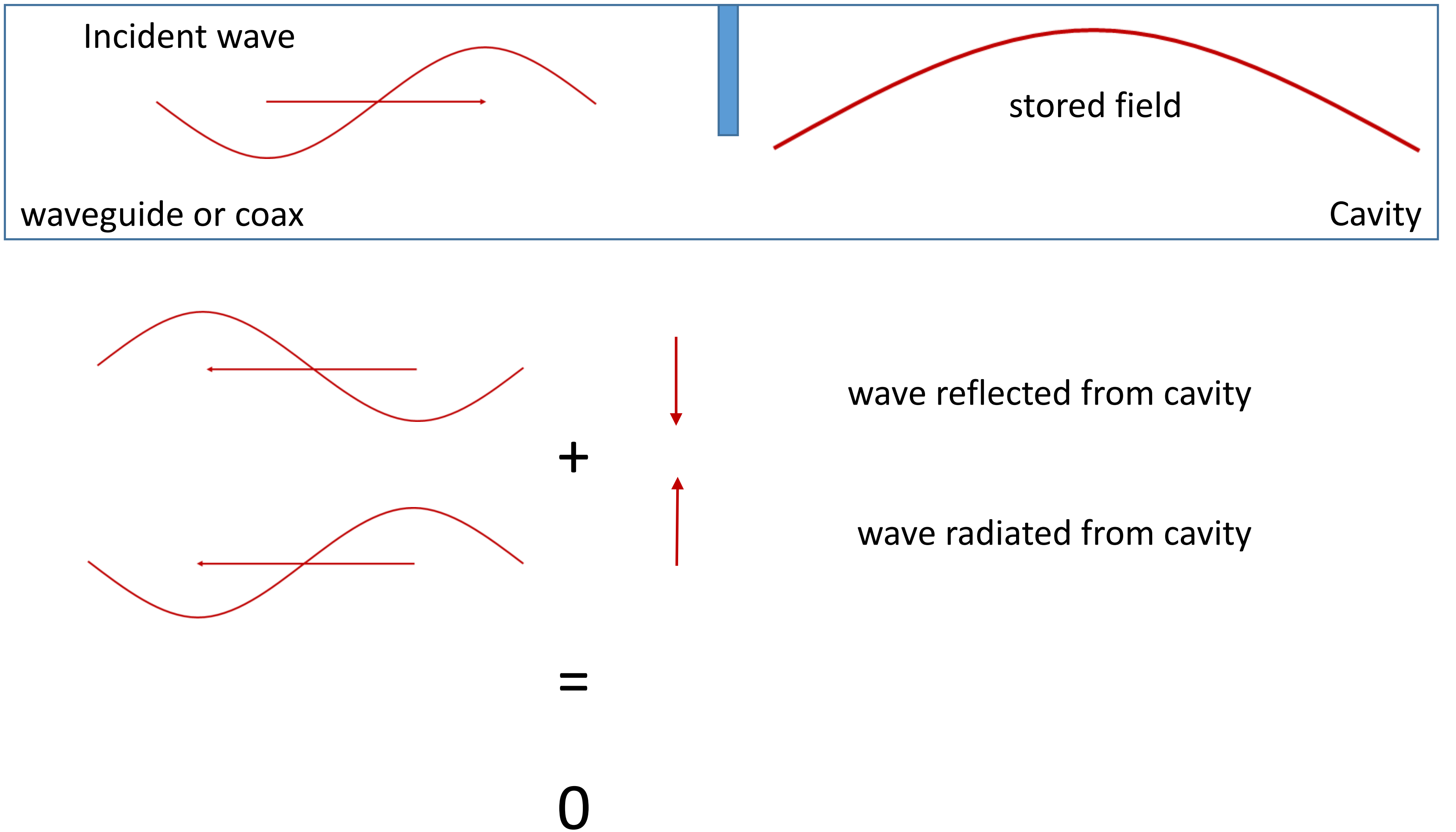
where :

$$Q_L = \frac{Q_0}{1+\beta} - \text{loaded } Q - \text{factor}$$

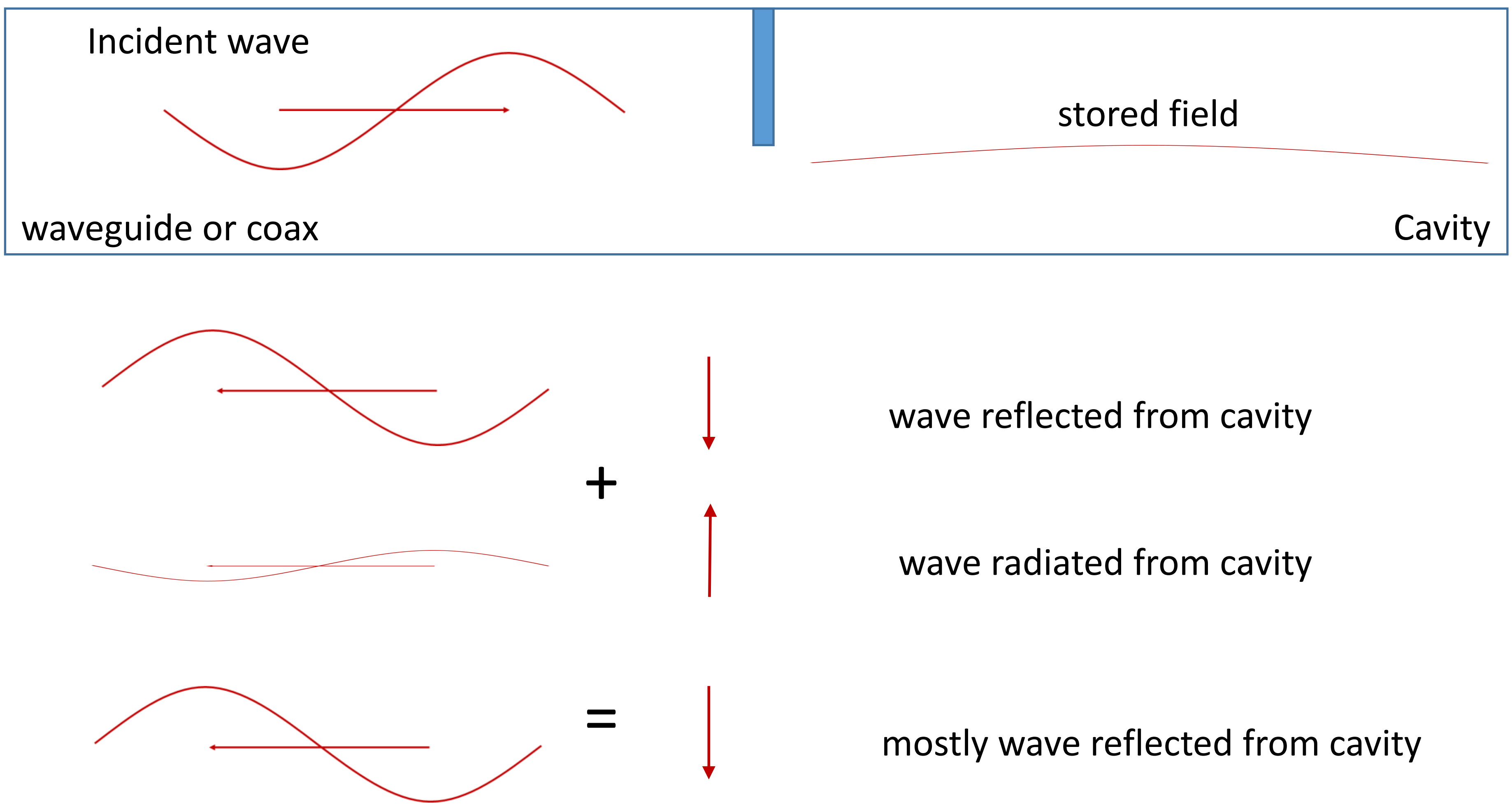
Matching condition: $V_{rad} = V_{in}$, only if $\beta=1$



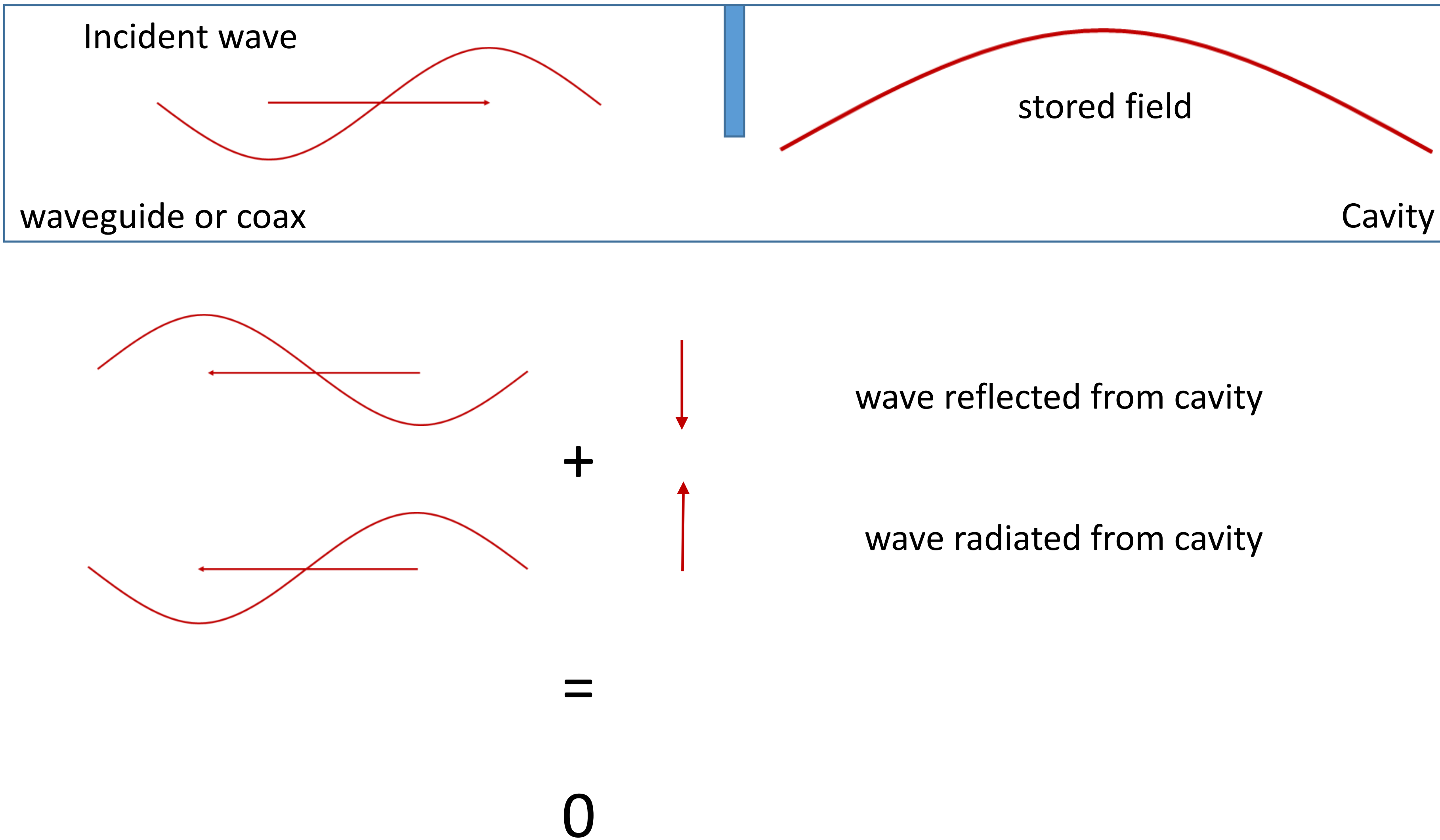
Critically coupled cavity on resonance and in steady state



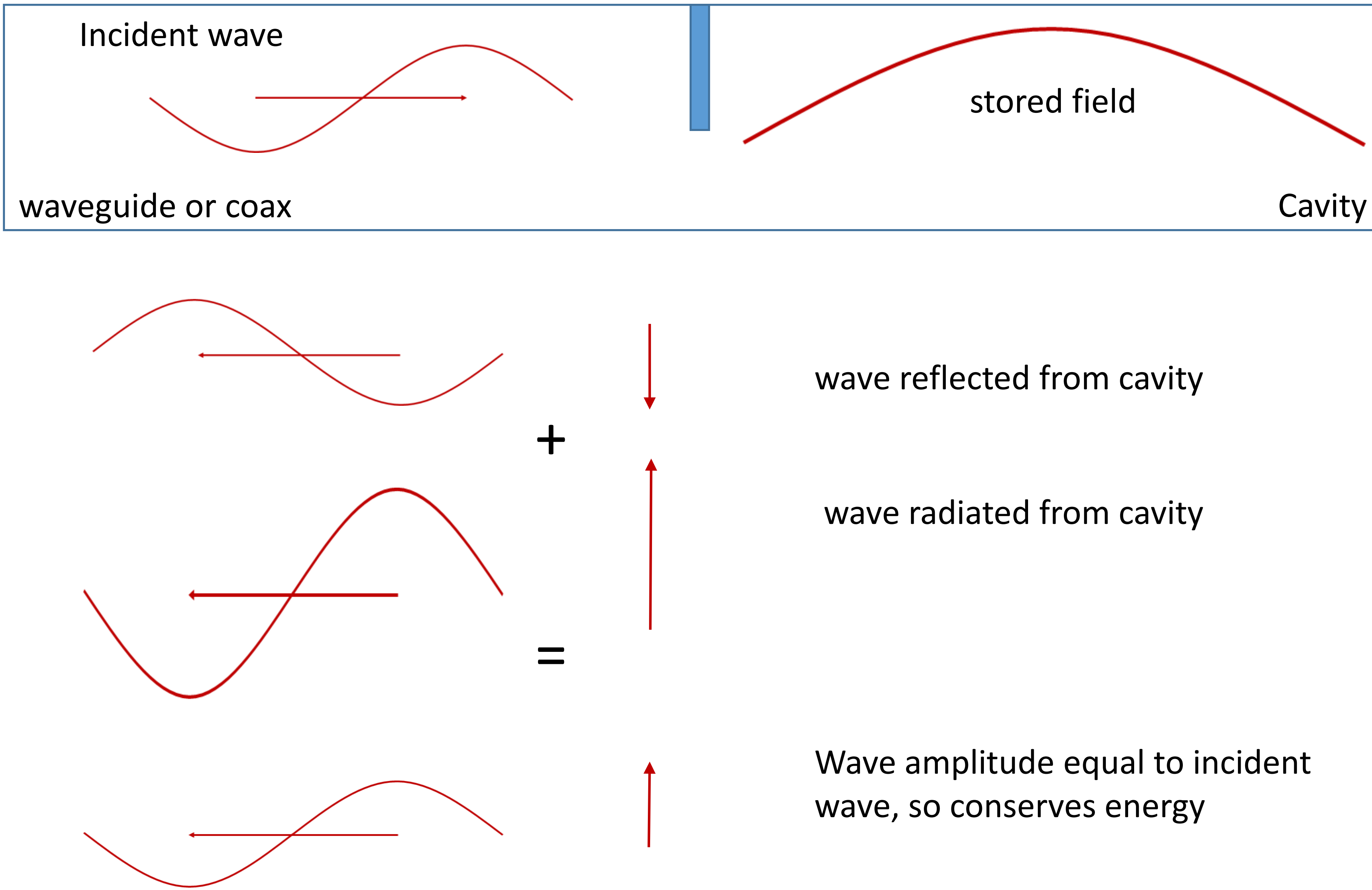
Critically coupled cavity on resonance, initial fill



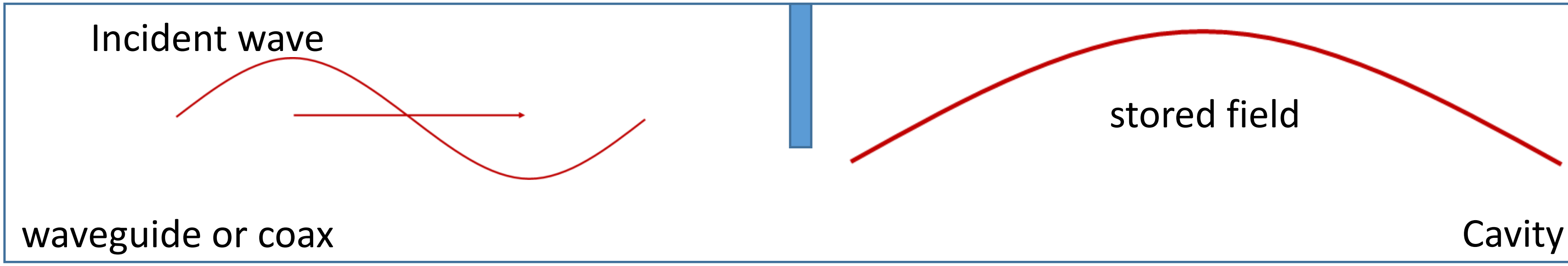
Critically coupled cavity on resonance and in steady state

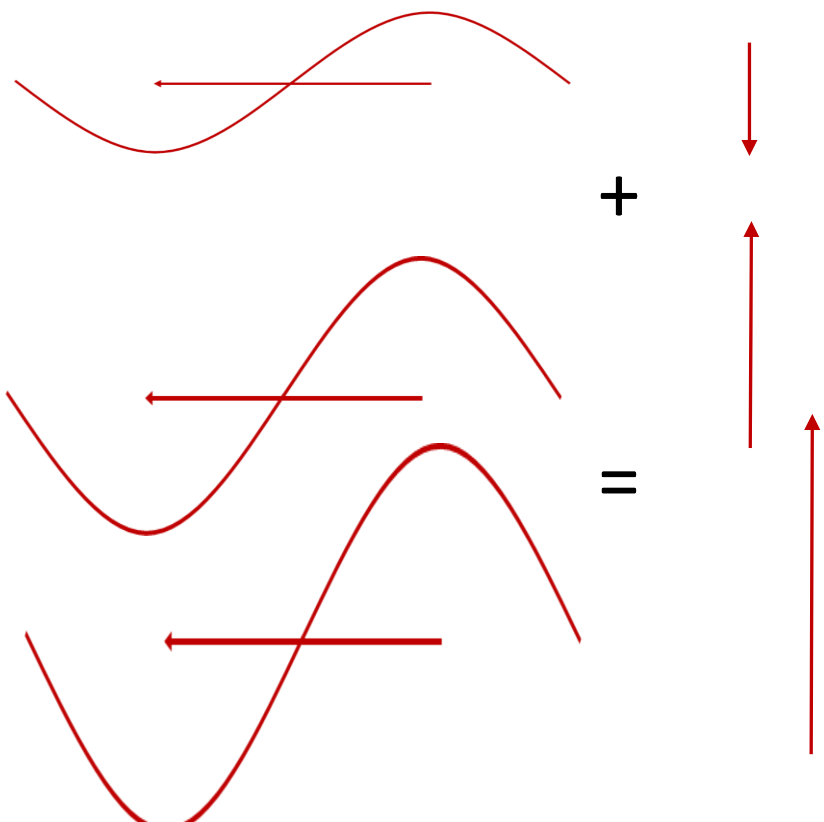


Over coupled cavity on resonance and in steady state



Now flip the phase of incoming signal



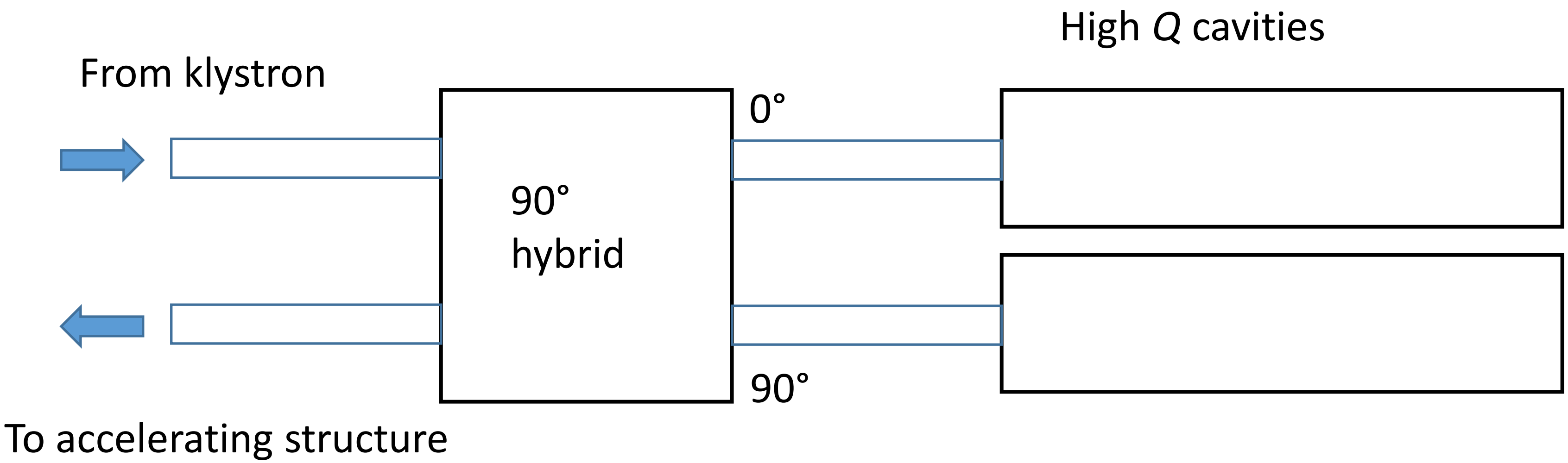


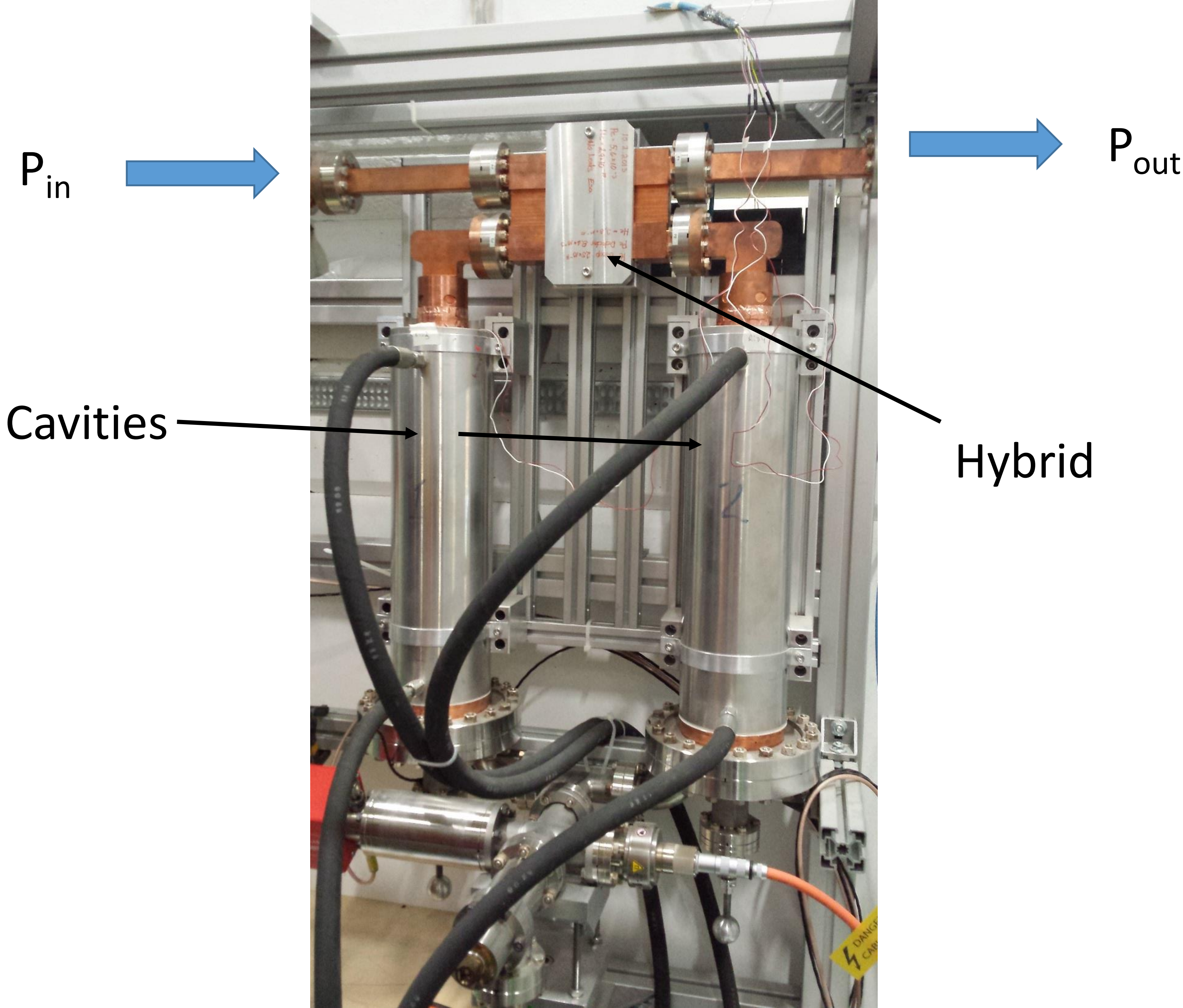
wave reflected from cavity

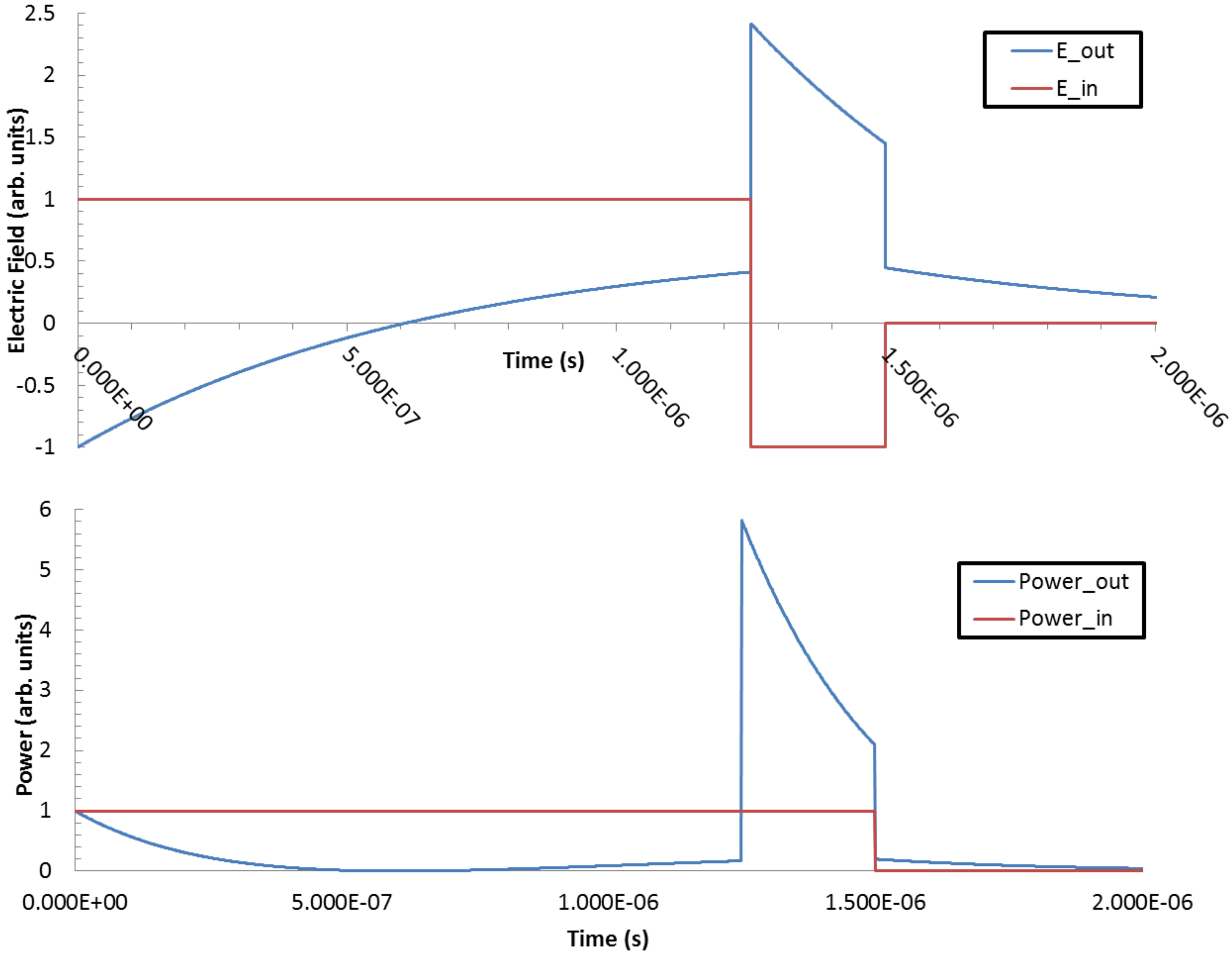
wave radiated from cavity

Amplitude goes from 1 to 3 which is 9 times the power!!!

How to get the signal to go in the right direction




P_{in}
P_{out}
Cavities
Hybrid



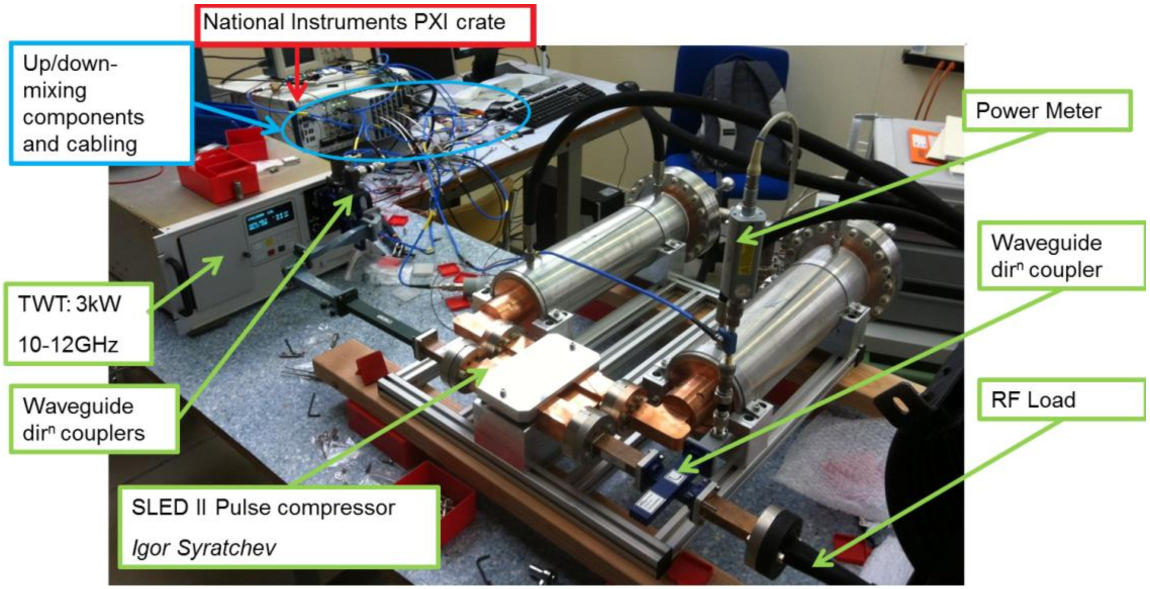
2.5
2
1.5
1
0.5
0
-0.5
-1
Electric Field (arb. units)
Time (s)
0.000E+00
5.000E-07
1.000E-06
1.500E-06
2.000E-06
E_out
E_in
6
5
4
3
2
1
0
Power (arb. units)
0.000E+00
5.000E-07
1.000E-06
1.500E-06
2.000E-06
Time (s)
Power_out
Power_in

B. Woolley

In reality of course the power gain is less than 9. In fact it is typically around 2-3.

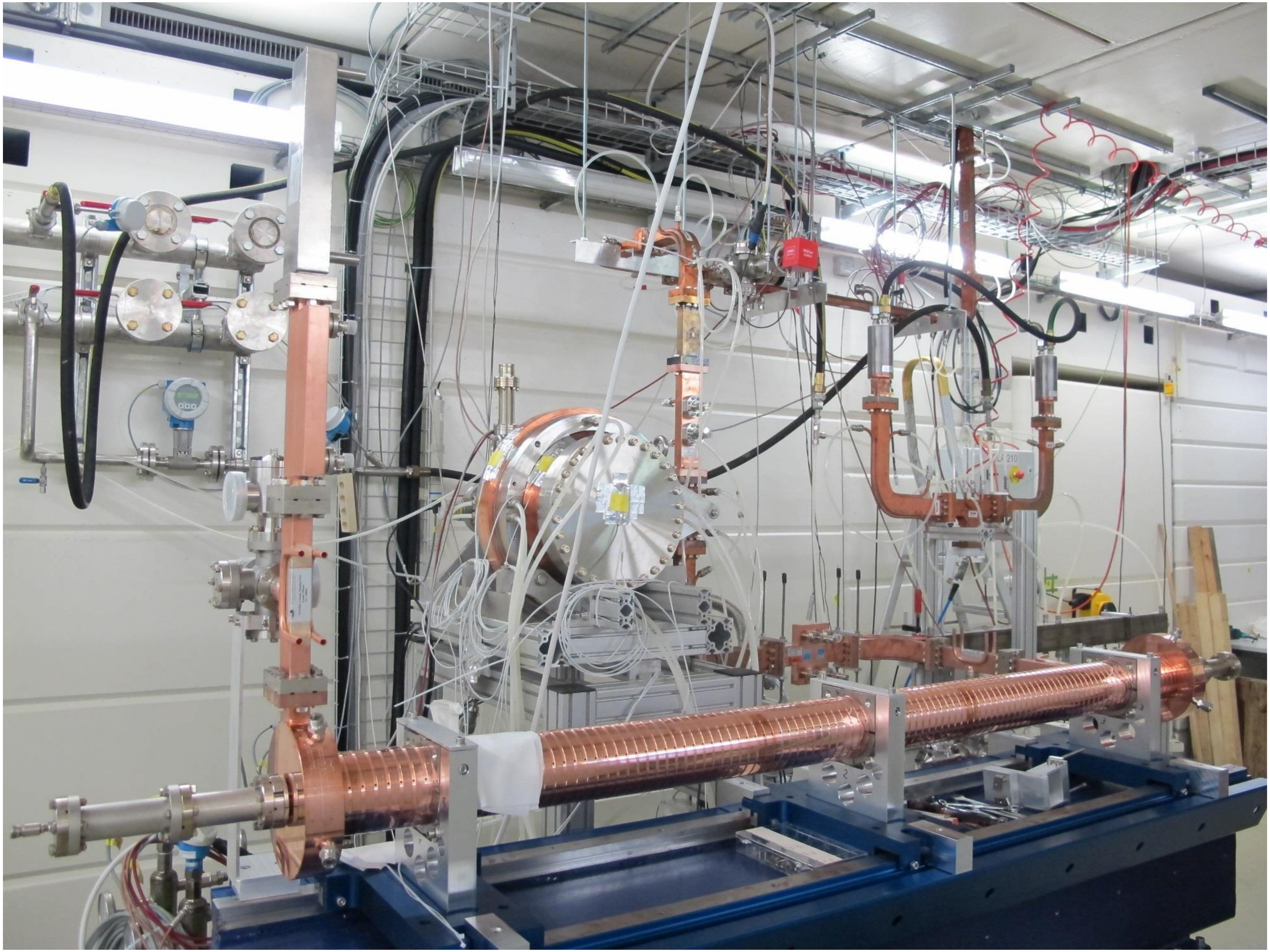
This is primarily due to finite *Q* in the storage cavity.

Reducing losses in the storage cavity has led to a many different designs of pulse compressor.



CLIC XBox test stand pulse compressor.

SwissFEL BOC (Barrel Open Cavity)



SwissFEL rf module