Normal-conducting high-gradient rf systems

CAS on Future Colliders, 4 and 5 March 2018

Walter Wuensch, CERN

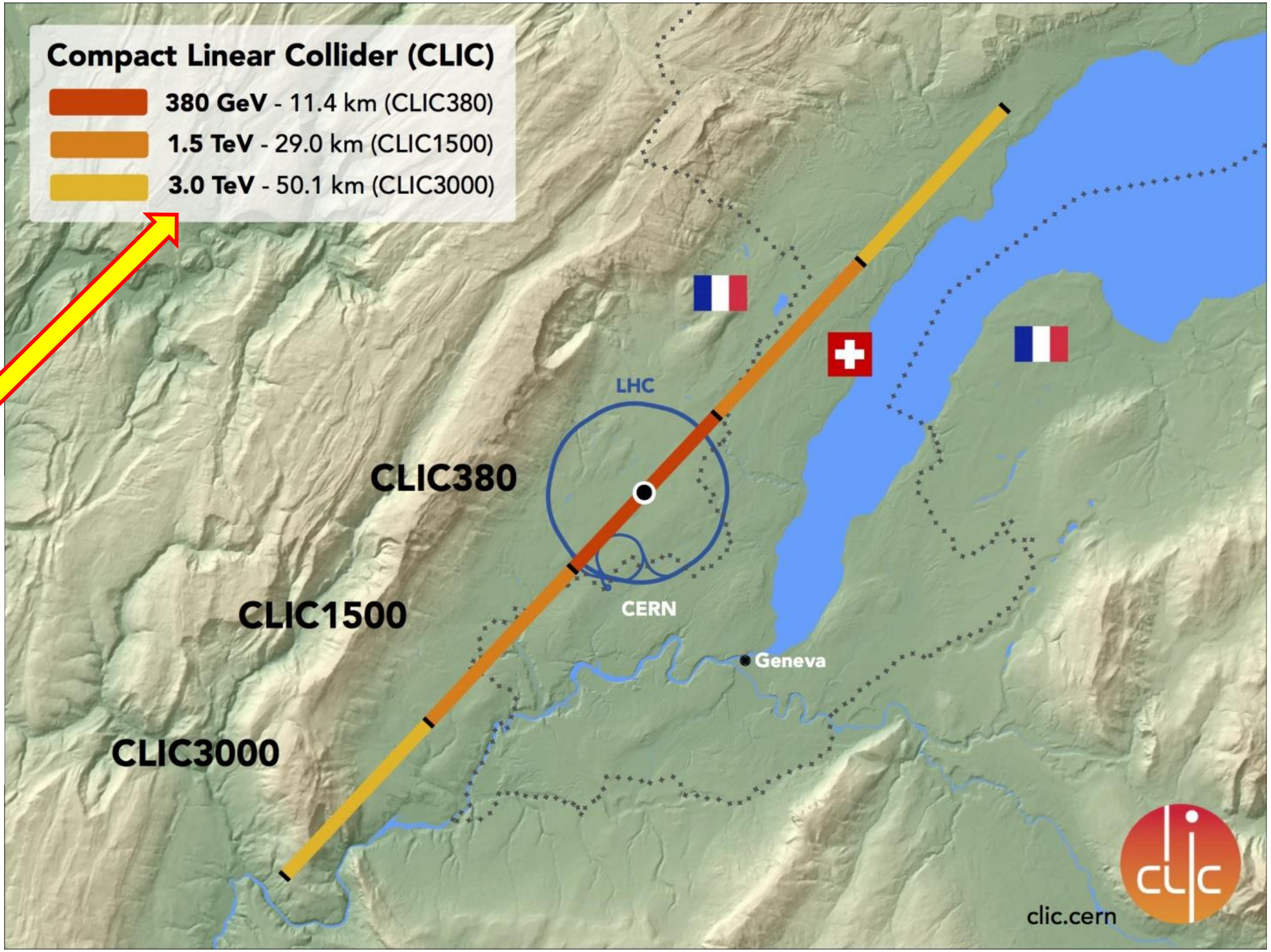
Introduction

Motivation for high gradient

Order of 100 GeV/km

Table 11: Value estimate of CLIC at 380 GeV centre-of-mass energy.

	Value [MCHF of December 2010]
Main beam production	1245
Drive beam production	974
Two-beam accelerators	2038
Interaction region	132
Civil engineering & services	2112
Accelerator control & operational infrastructure	216
Total	6690



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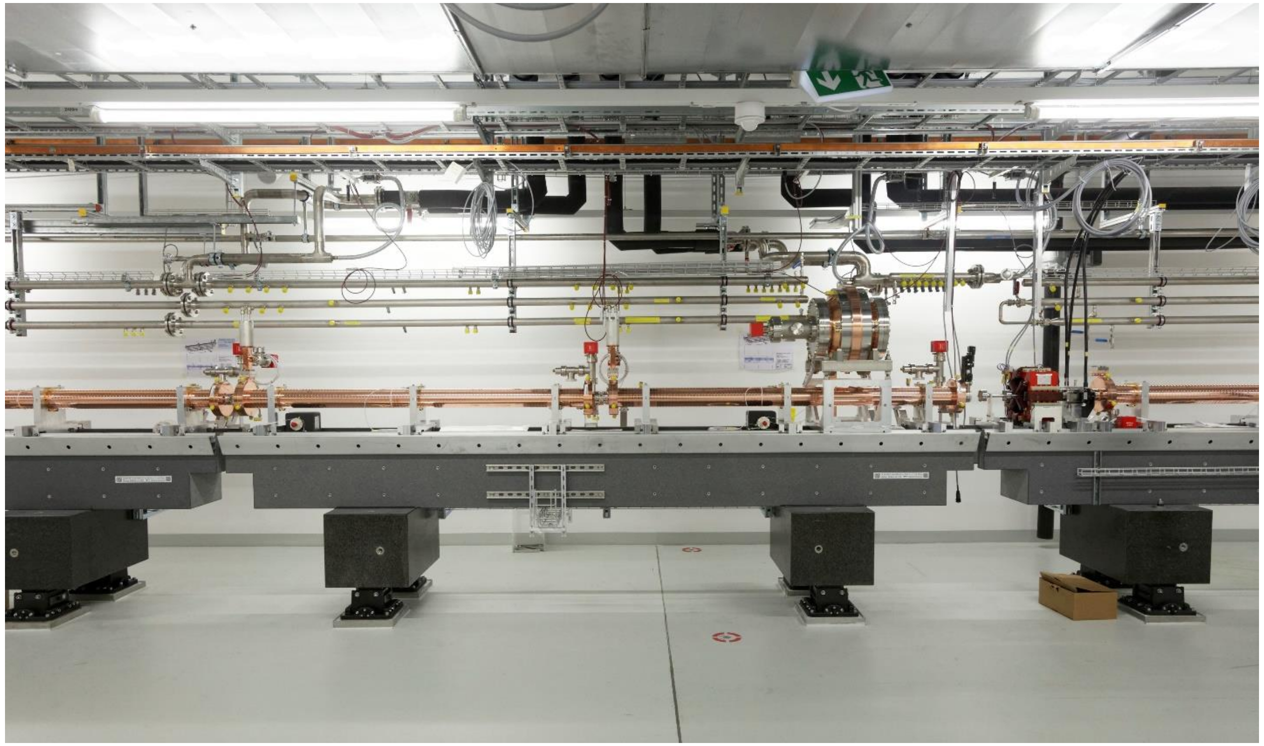
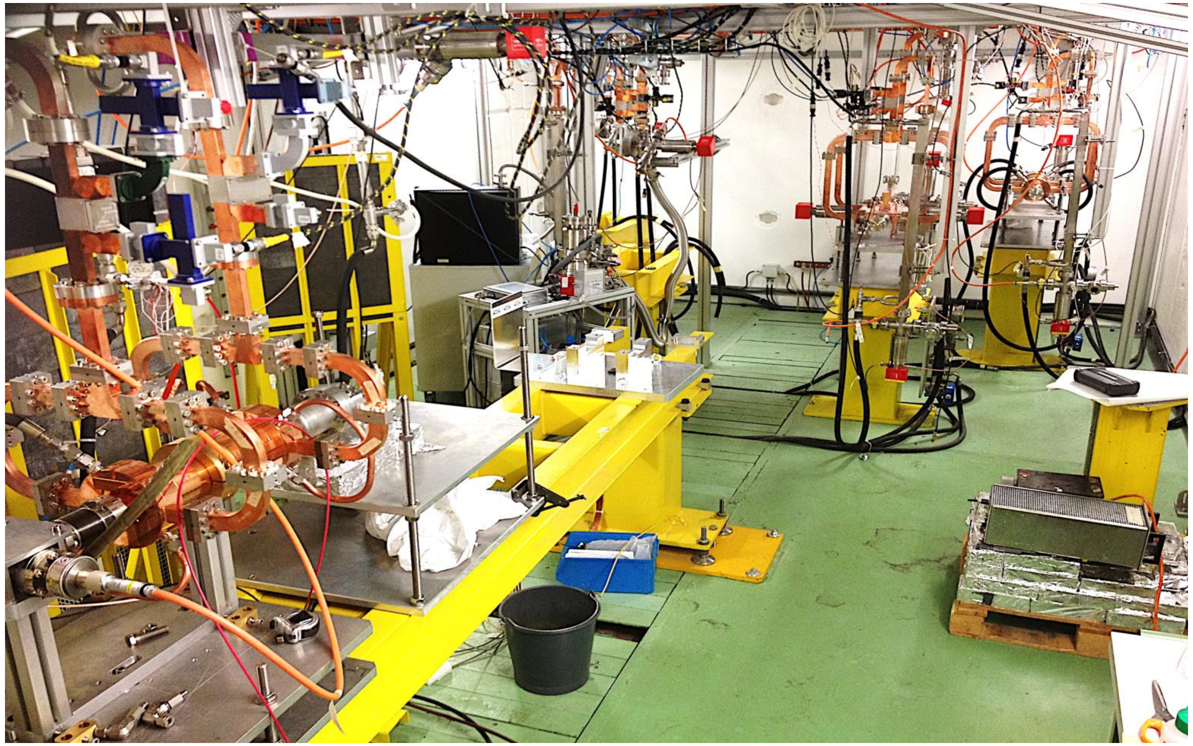
Operational and state-of-the-art





SwissFEL C-band linac:
Just under 30 MV/m

CLIC prototypes:
Over 100 MV/m

Due to limited time, many subjects can only be introduced. For greater depth please see my linear collider school lectures in http://www.linearcollider.org/school/2016 .

My objective is to introduce you to:

- Some of the main concepts
- A familiarity with the hardware systems
- An idea of the insights we have made

Lecture structure

1. Basic concepts of travelling wave accelerating structures
2. High peak rf power production and manipulation
3. High field phenomena in accelerating structures

Lecture structure

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    a. Traveling wave acceleration and periodic boundary conditions
    b. Beam loading
    c. Peak rf power production
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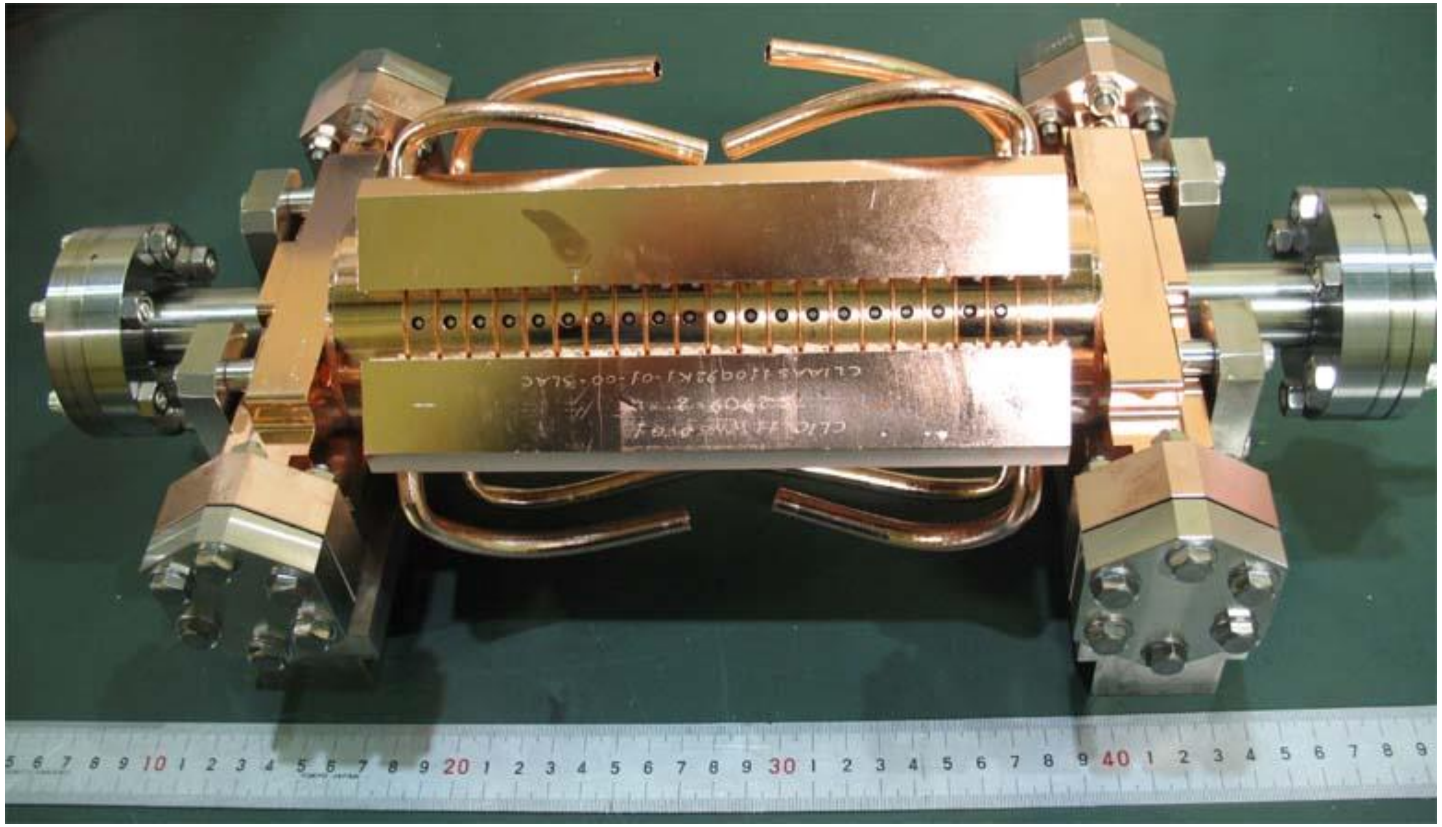
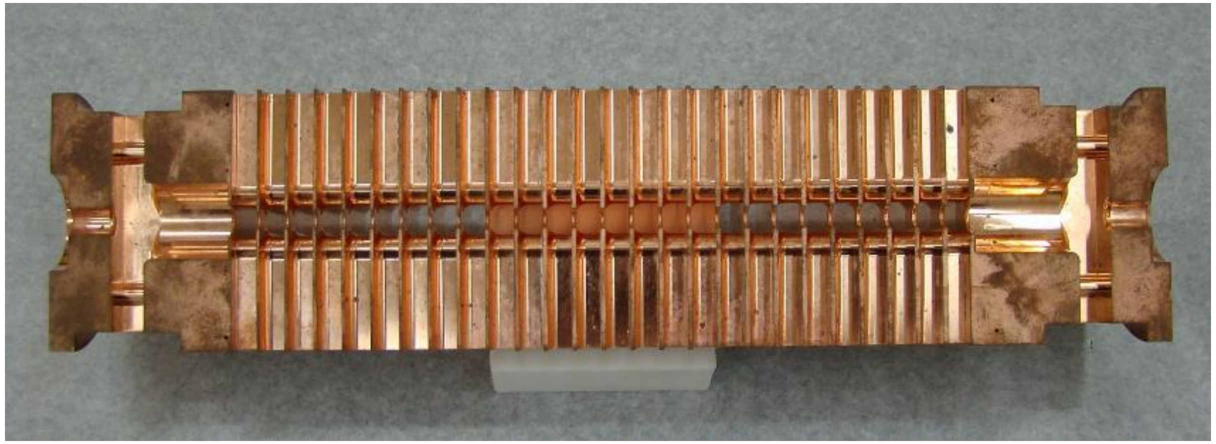
A CLIC prototype accelerating structure.

11.994 GHz X-band
100 MV/m acceleration
Input power ≈50 MW
Pulse length ≈200 ns
Repetition rate 50 Hz

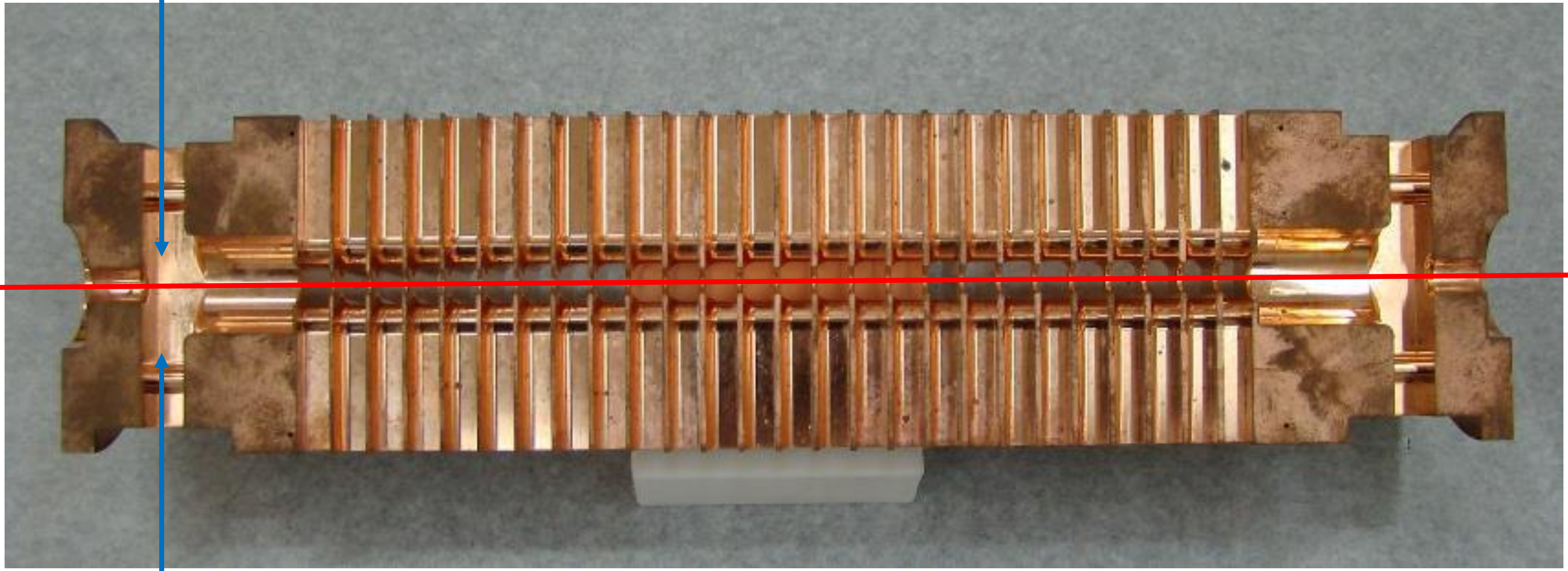


outside



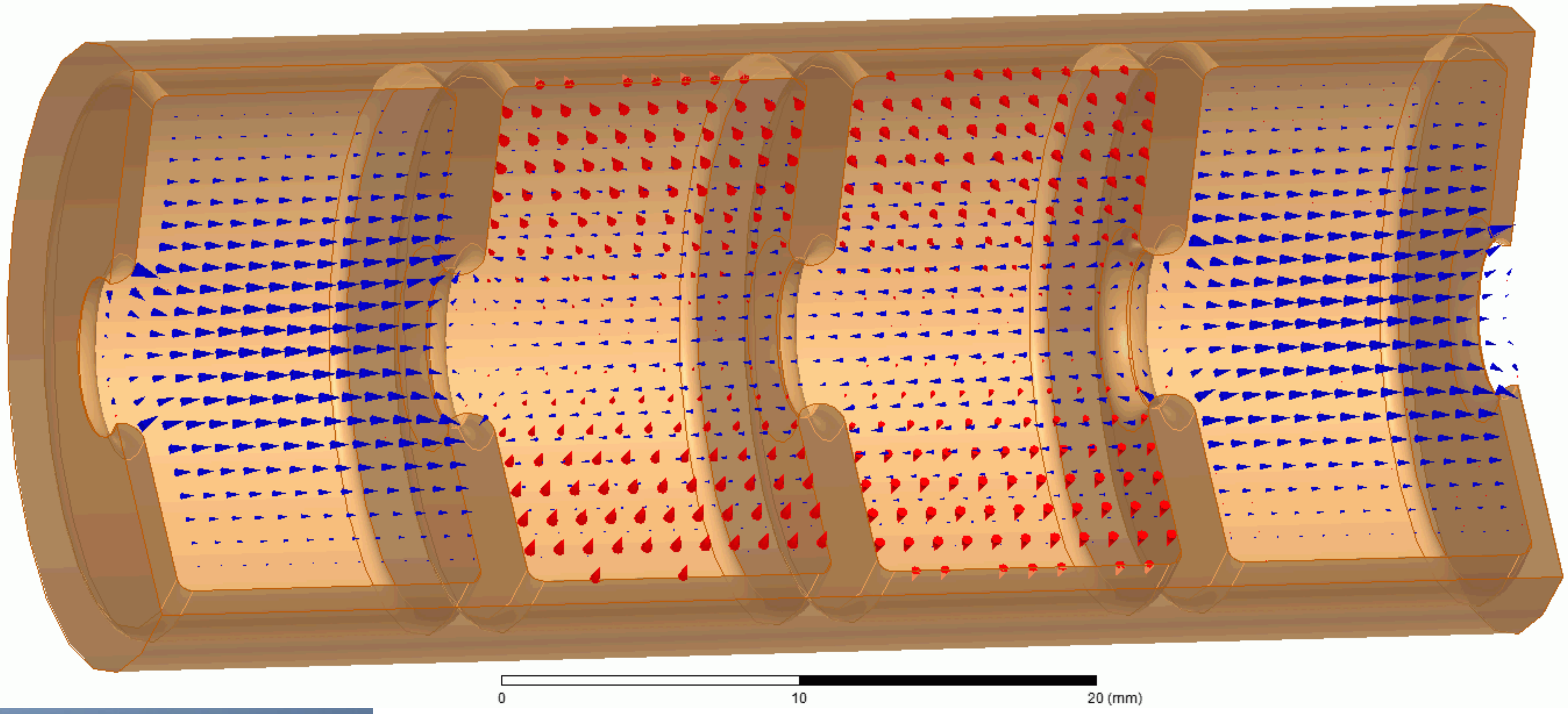
inside

rf power in, approximately 50 MW, fed into the structure symmetrically.



Beam accelerated by 100 MV/m

Electric field
Magnetic field



Beam propagation direction. Beam and phase velocity must be the same.
How can this be arranged?

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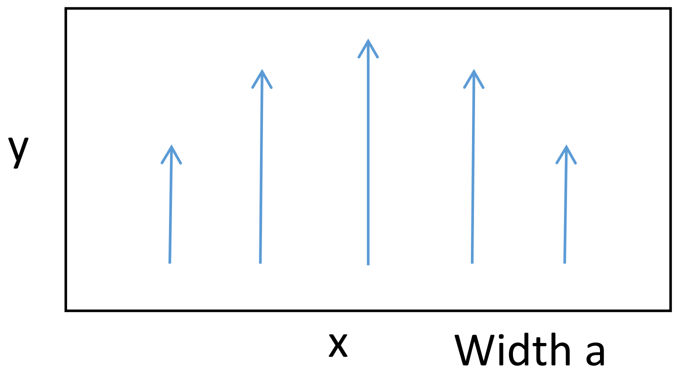
The concept of periodic loading

1. Review dispersion curve of uniform waveguide
2. Introduce periodically loaded waveguide

Uniform (rectangular) waveguide

The lines are electric field



Field solution

$$E_y = E_0 \sin\left(\frac{\pi}{a}x\right)e^{i(\omega t - k_z z)}$$

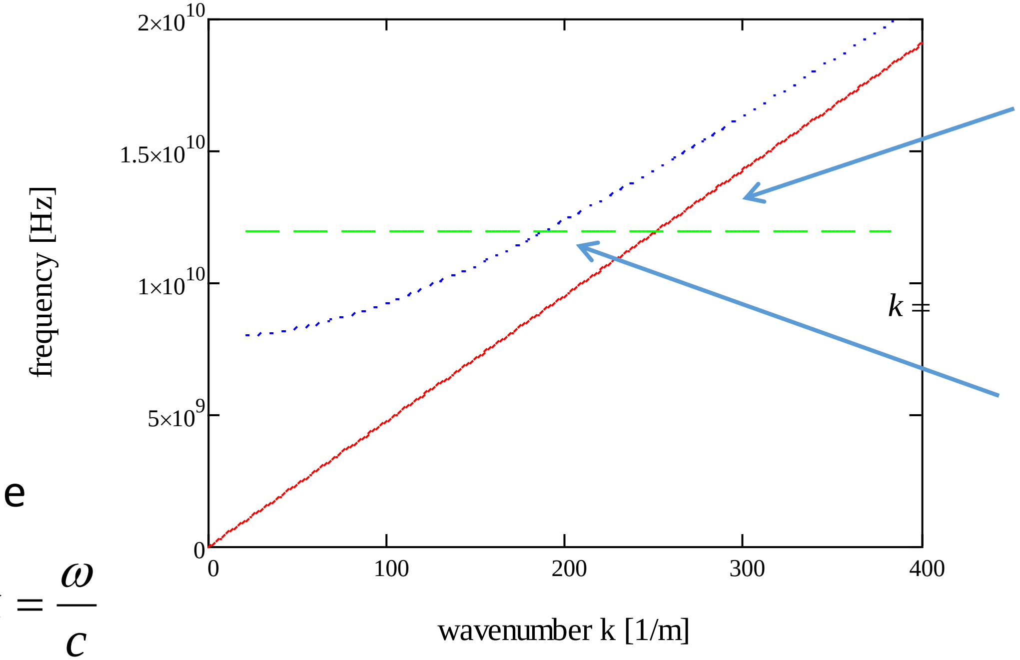
$$k_z = \sqrt{\left(\frac{\omega}{c}\right)^2 - \left(\frac{\pi}{a}\right)^2}$$

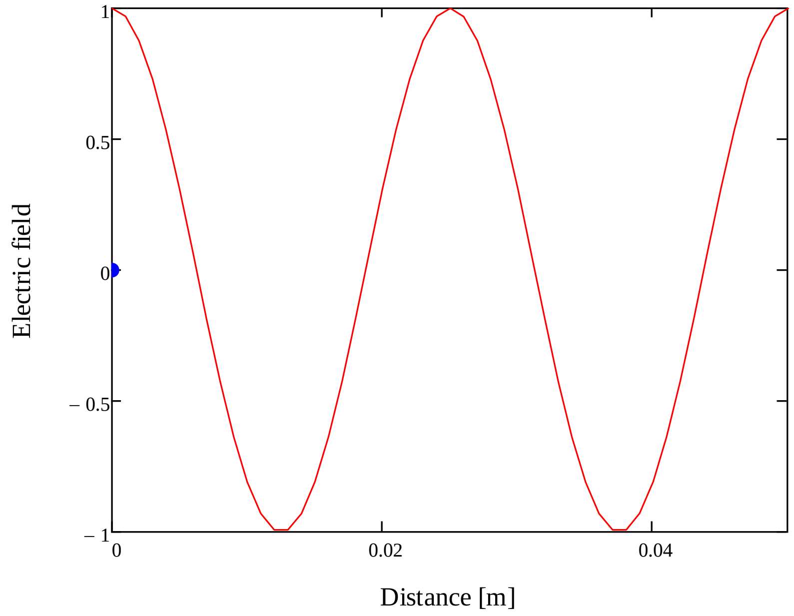
Gives cutoff frequency

The dispersion curve

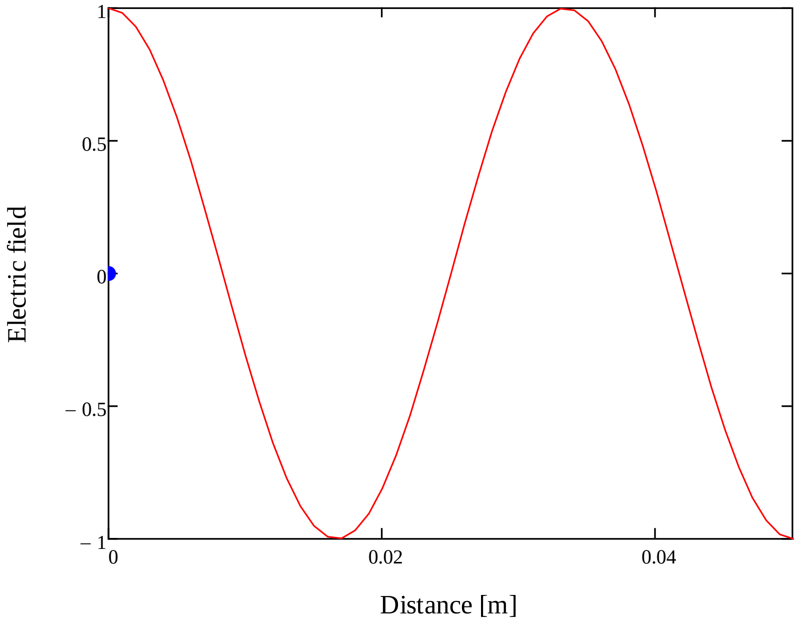
$$v_{phase} = \frac{\omega}{k}$$

$$k = \frac{\omega}{c}\sqrt{1-\left(\frac{\omega_0}{\omega}\right)^2}$$





case 1



case 2

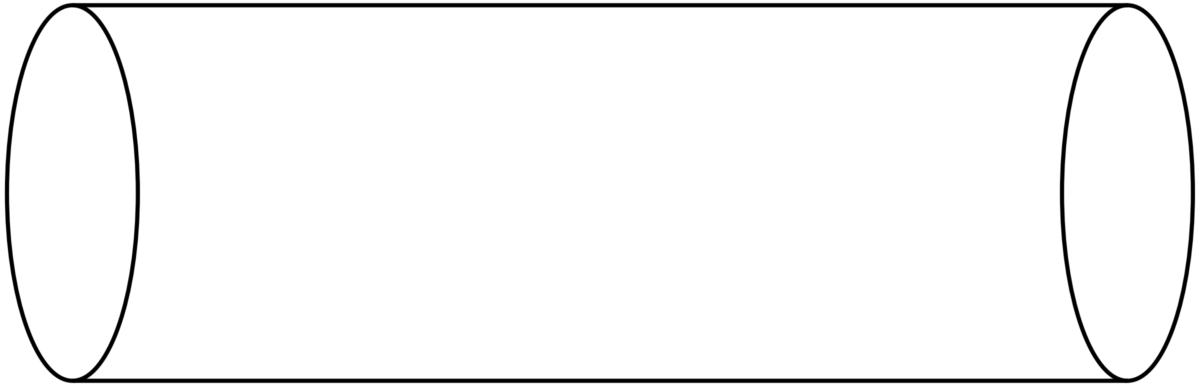
Speed of light line

$$k = \frac{\omega}{c}$$

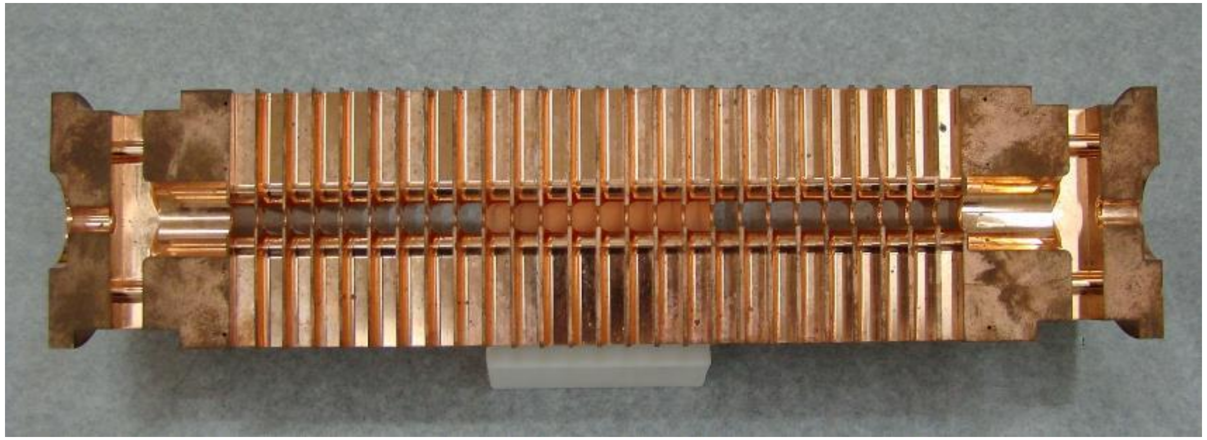
$$e^{i(\omega t - kz)}$$

Horizontal green line: waveguide k is 0.75 of free space k at 11.994 GHz

How do we slow down phase velocity to c?

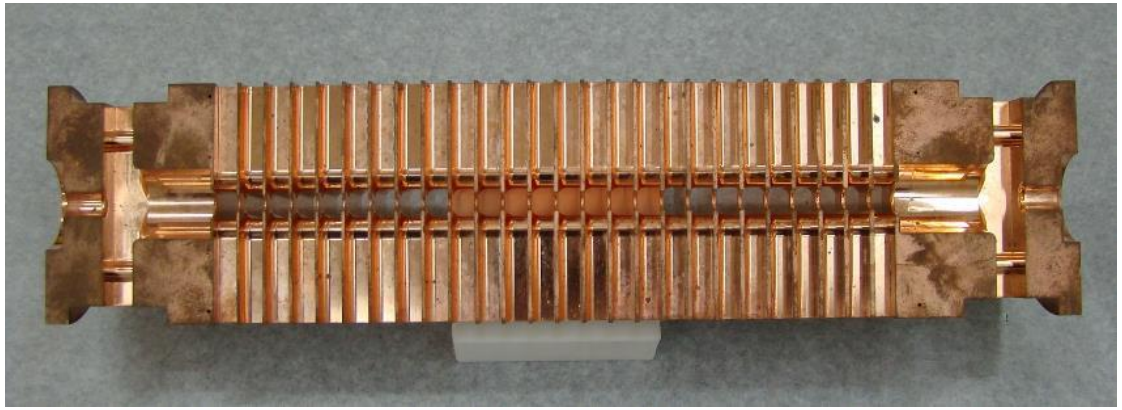


Uniform waveguide

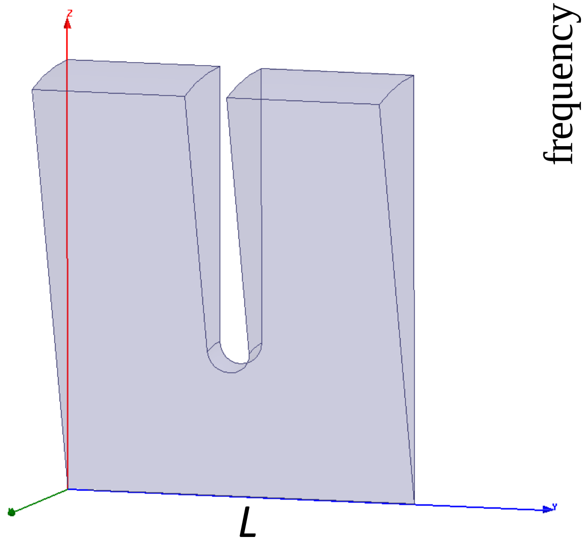


Periodic loading

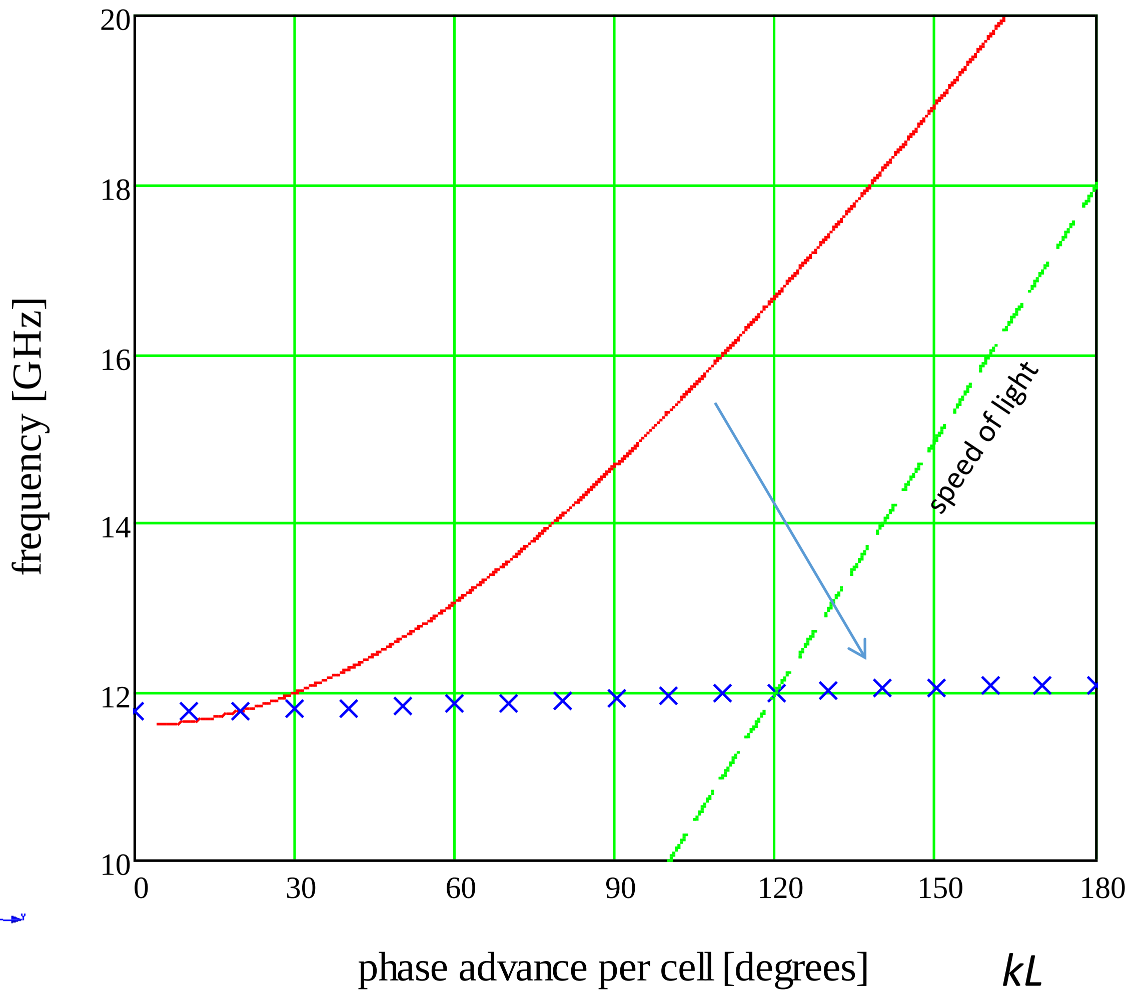
Solve the problem that phase velocity is too high (wavelength is too long) with periodic loading by putting "irises" in the uniform waveguide



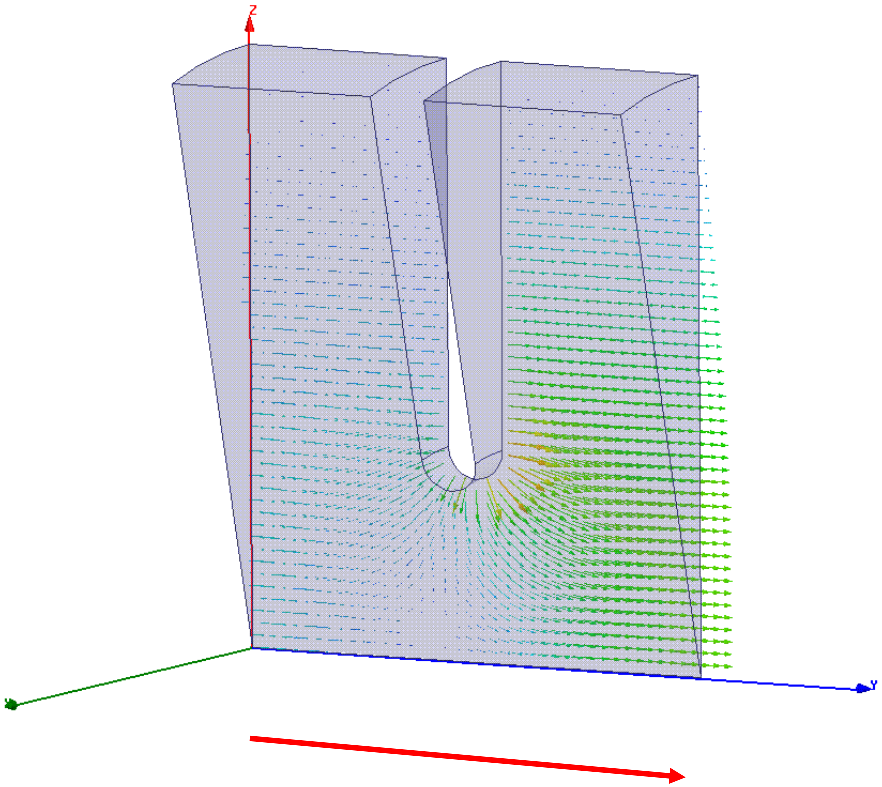
Floquet's theorem states, translated to rf language, that periodic boundary conditions give solution with same field in every cell, just differing by a complex phase advance.

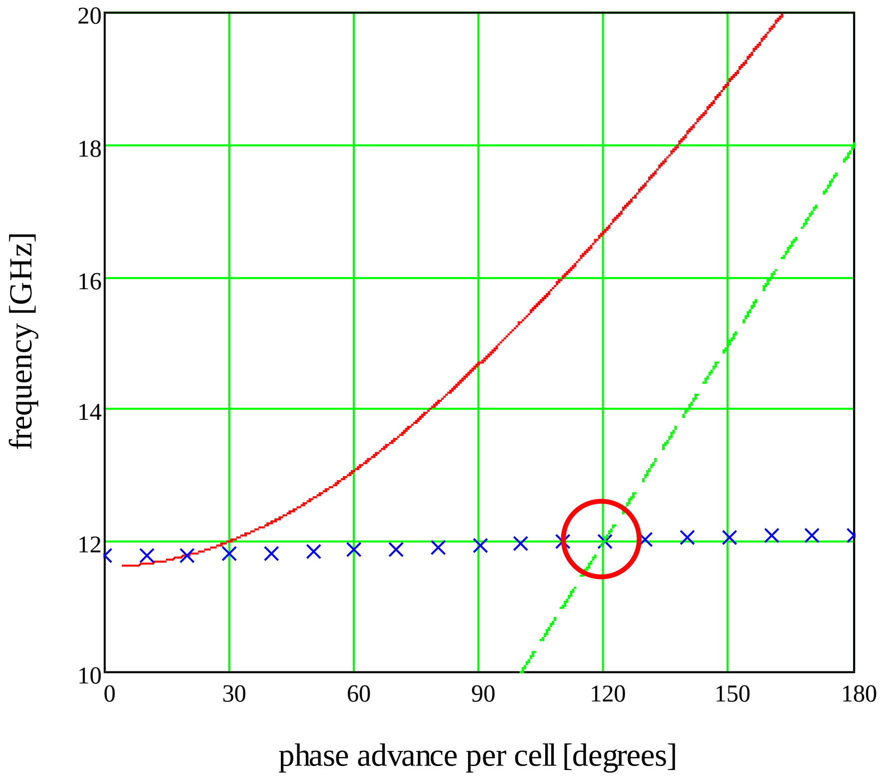


periodic loading



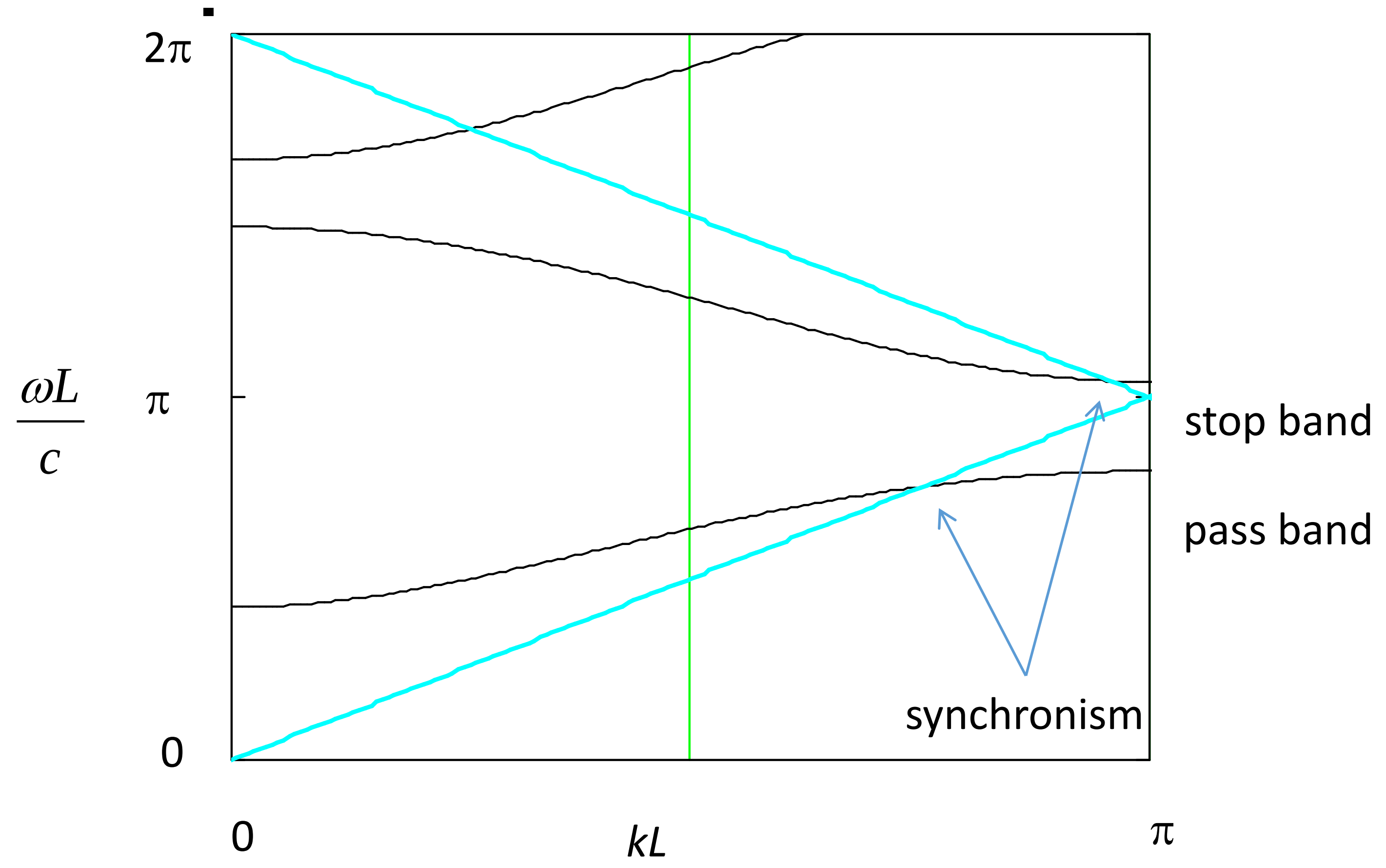
Single cell electric field pattern 2π/3 phase advance

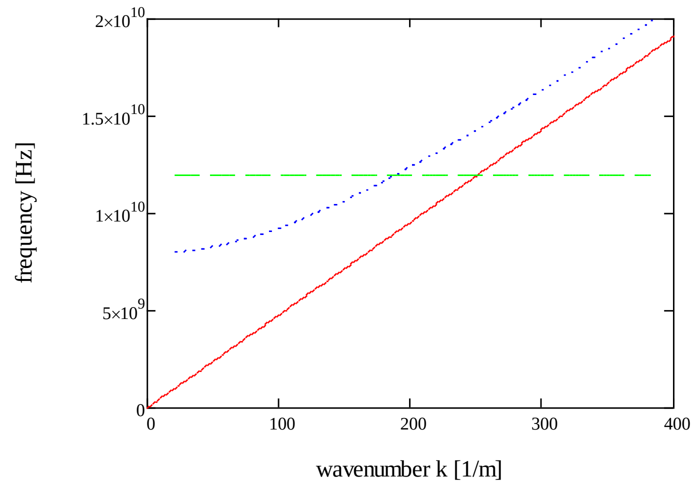


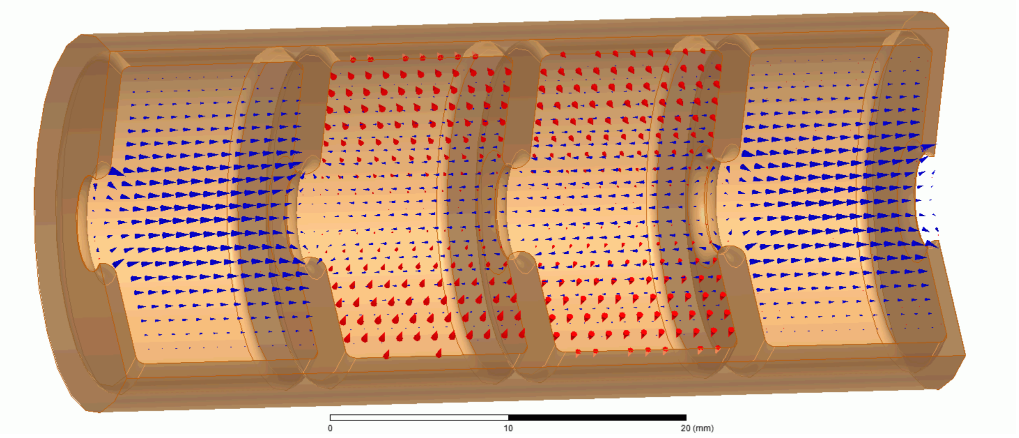


Phase synchronism means time for beam to get across cell is the same as accelerating phase to get across cell.

The Brillouin diagram. Frequency vs phase advance per period, which is *kL.*







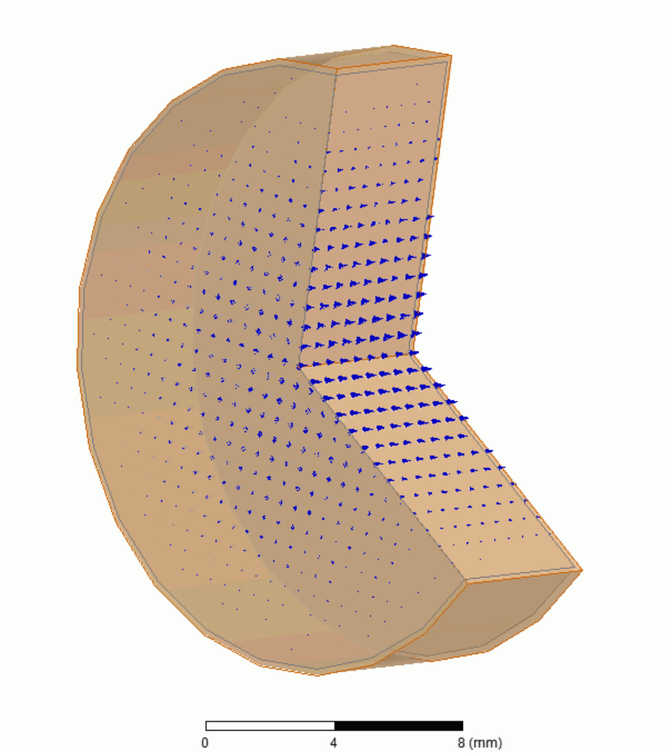
Quantities people use

$$Q = \frac{\omega W}{P_{loss}}$$

Quality factor

$$\frac{R}{Q} = \frac{\left|V_{acc}\right|^2}{\omega W}$$

Ratio of acceleration to stored energy



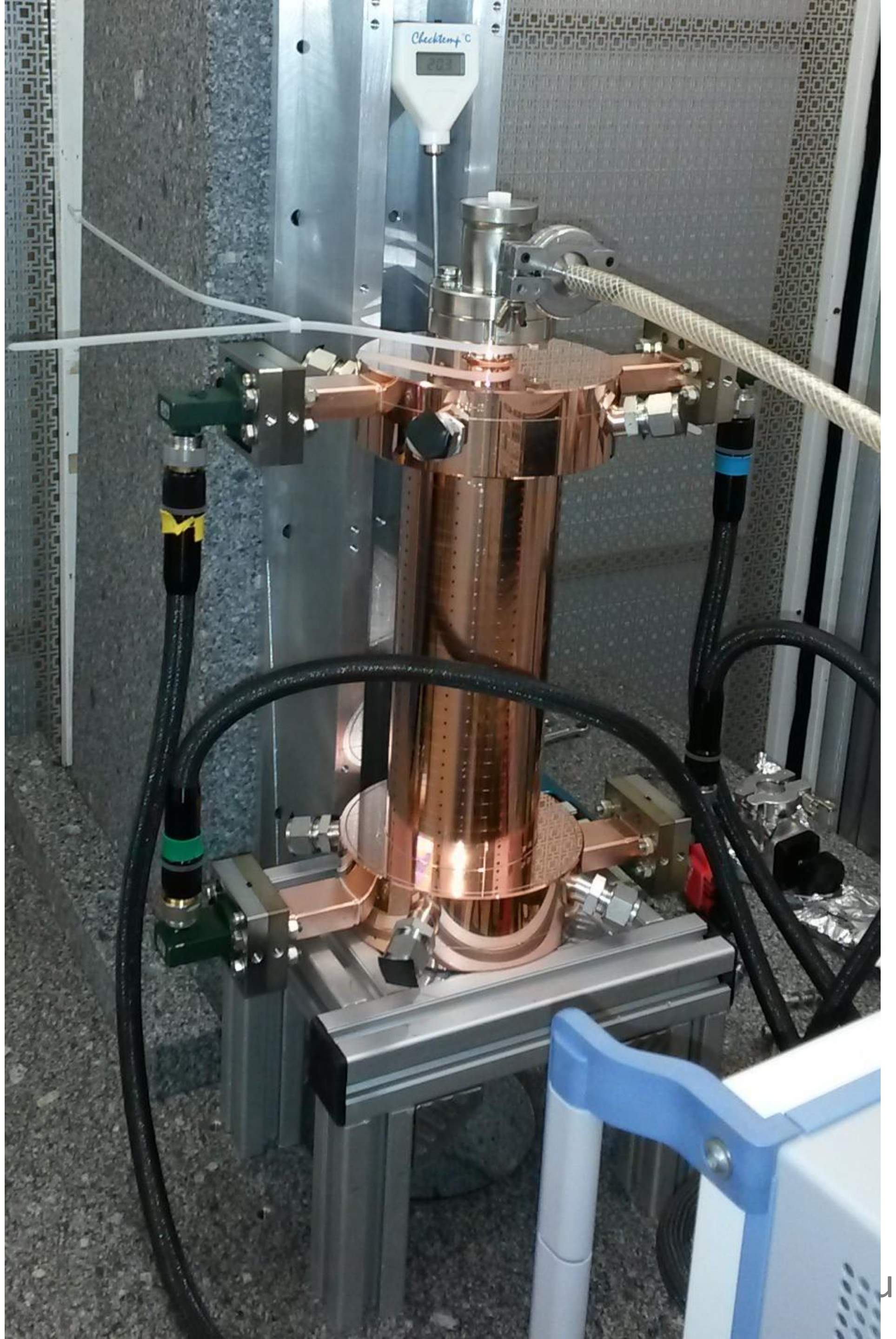
$$R = \frac{\left|V_{acc}\right|^2}{P_{loss}}$$

Shunt impedance [MΩ]
Often the quantity used to optimize cavity design

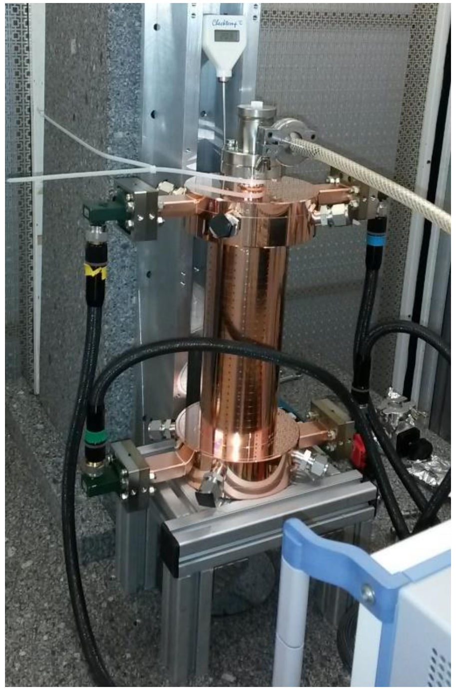
Traveling wave.

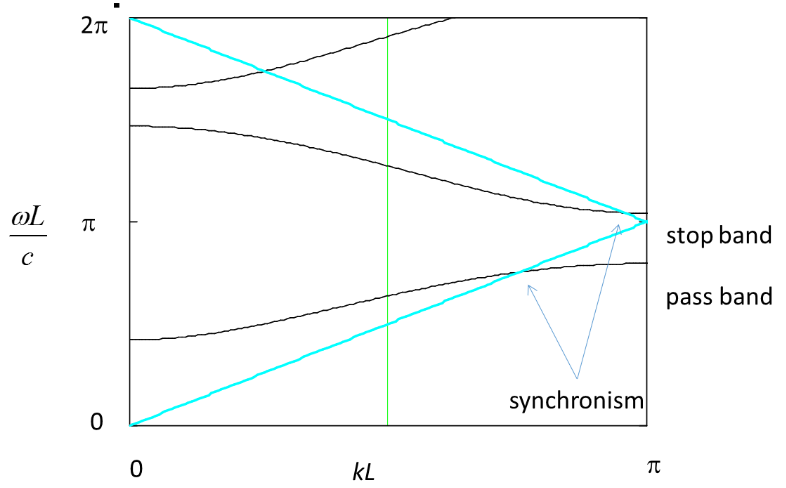
Power is transmitted through the structure like a waveguide, albeit a periodically loaded one.

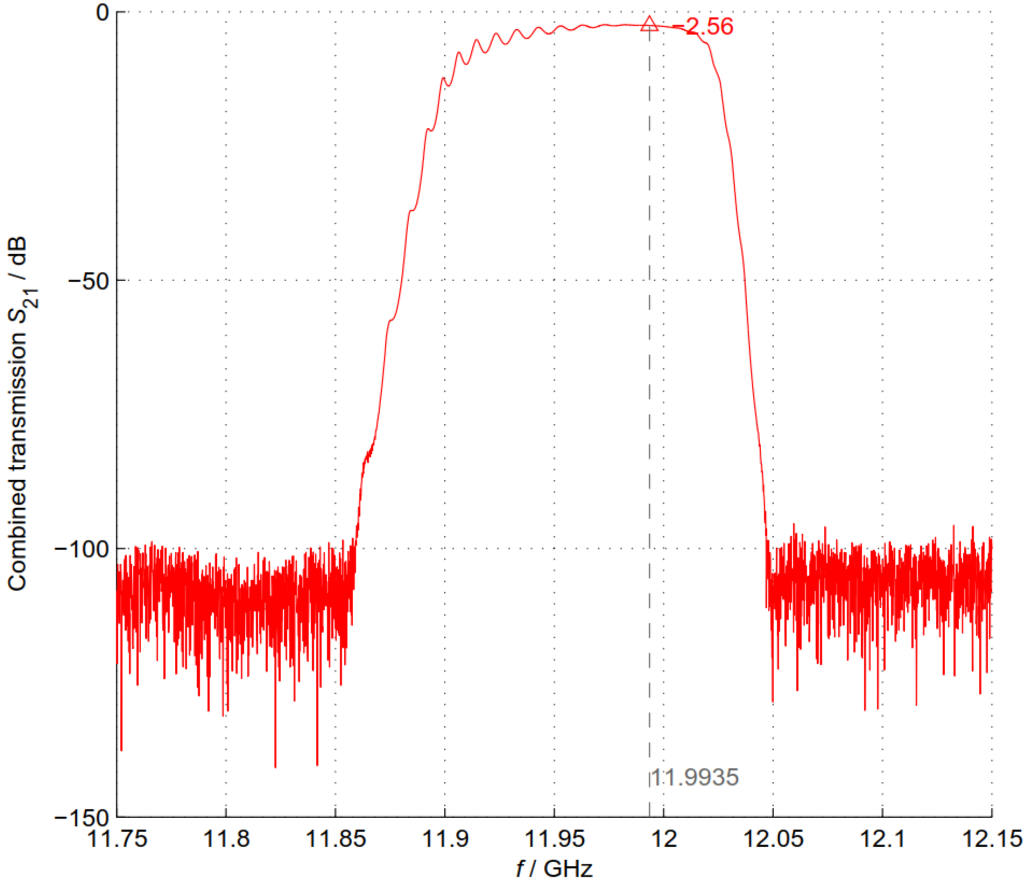
T24 test structure built by PSI under vector network analyzer measurement at CERN.



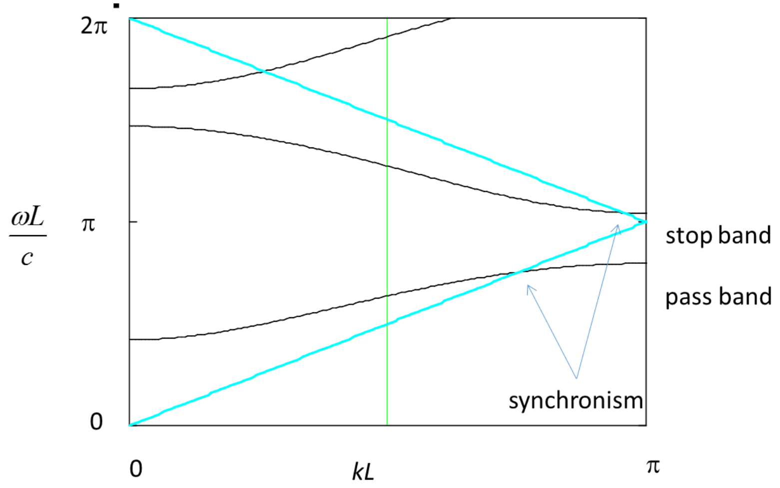
Transmission through structure

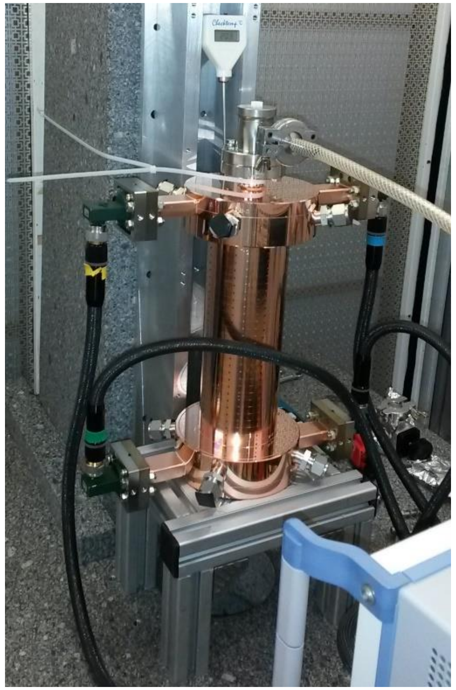


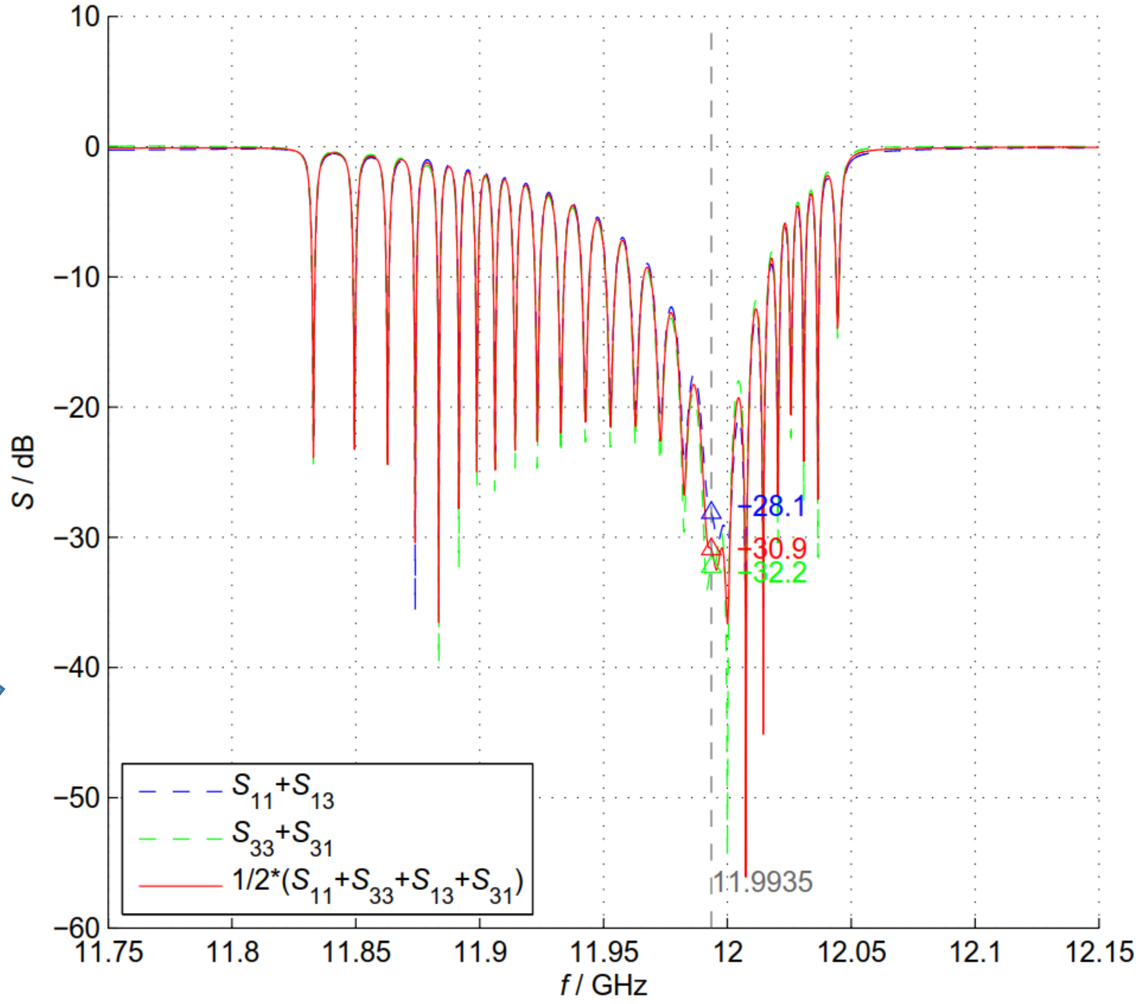




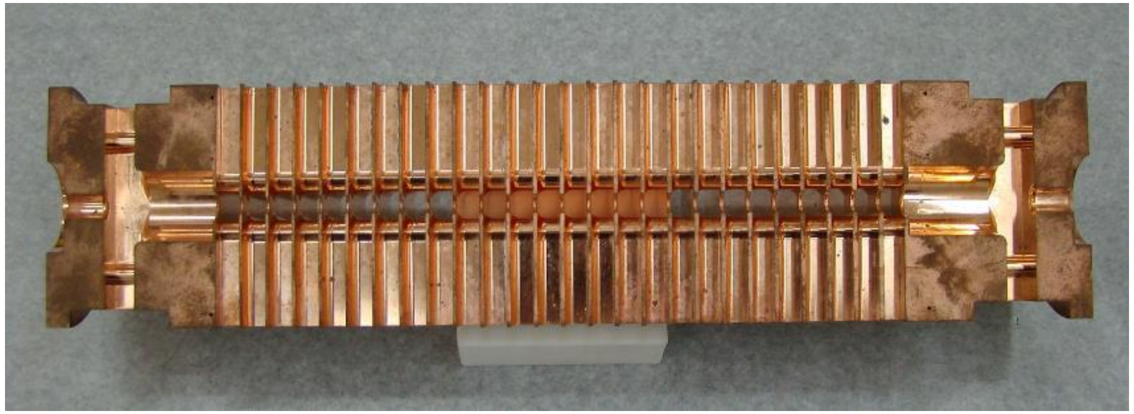
Reflection from structure





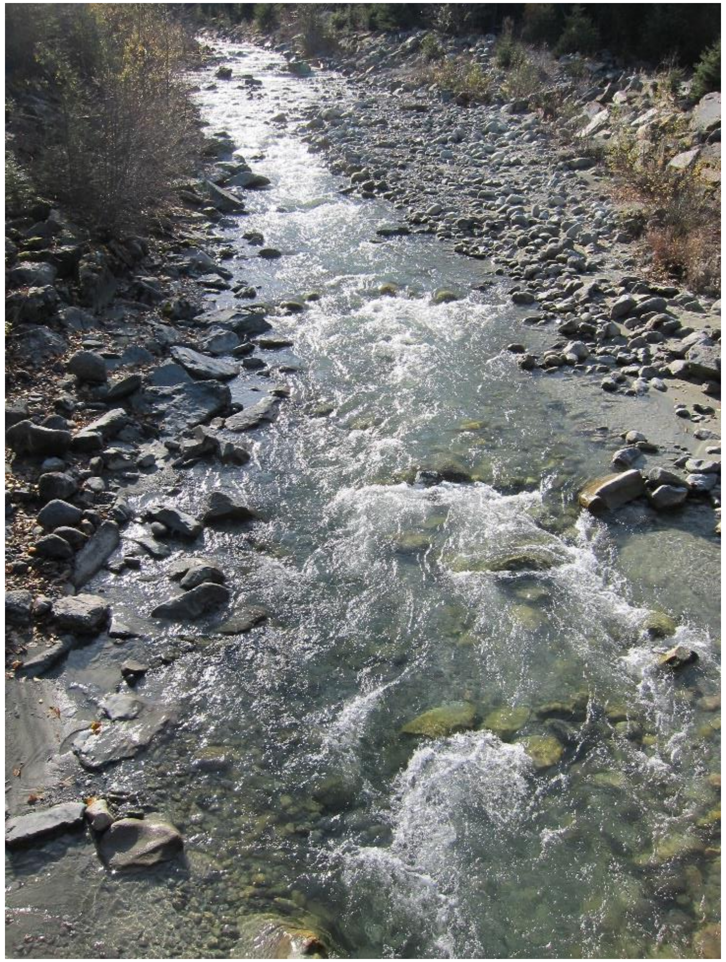


Group velocity



We now go from stored energy to power via group velocity:

$$P = v_g W'$$



Quantities people use with group velocity mixed in

$$\frac{R}{Q} = \frac{|V_{acc}|^2}{\omega W}$$

Ratio of acceleration to stored enery

$$Q = \frac{\omega W}{P_{loss}}$$

Quality factor

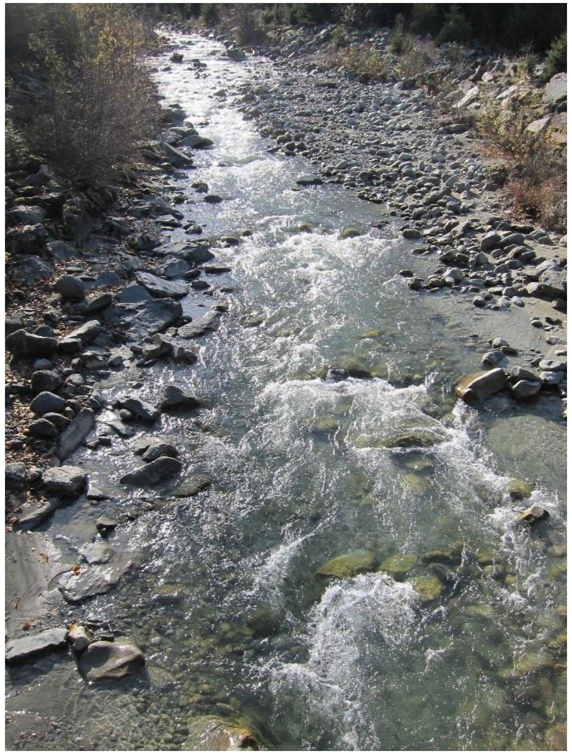
$$R = \frac{|V_{acc}|^2}{P_{loss}}$$

Shunt impedance [MΩ]
Often the quantity used to optimize cavity design

We now go from stored energy to power via group velocity:

$$P = v_g W'$$

$$G = \frac{|V_{acc}|}{l}$$



$$G = \sqrt{\omega \frac{1}{v_g} \frac{R'}{Q} P}$$

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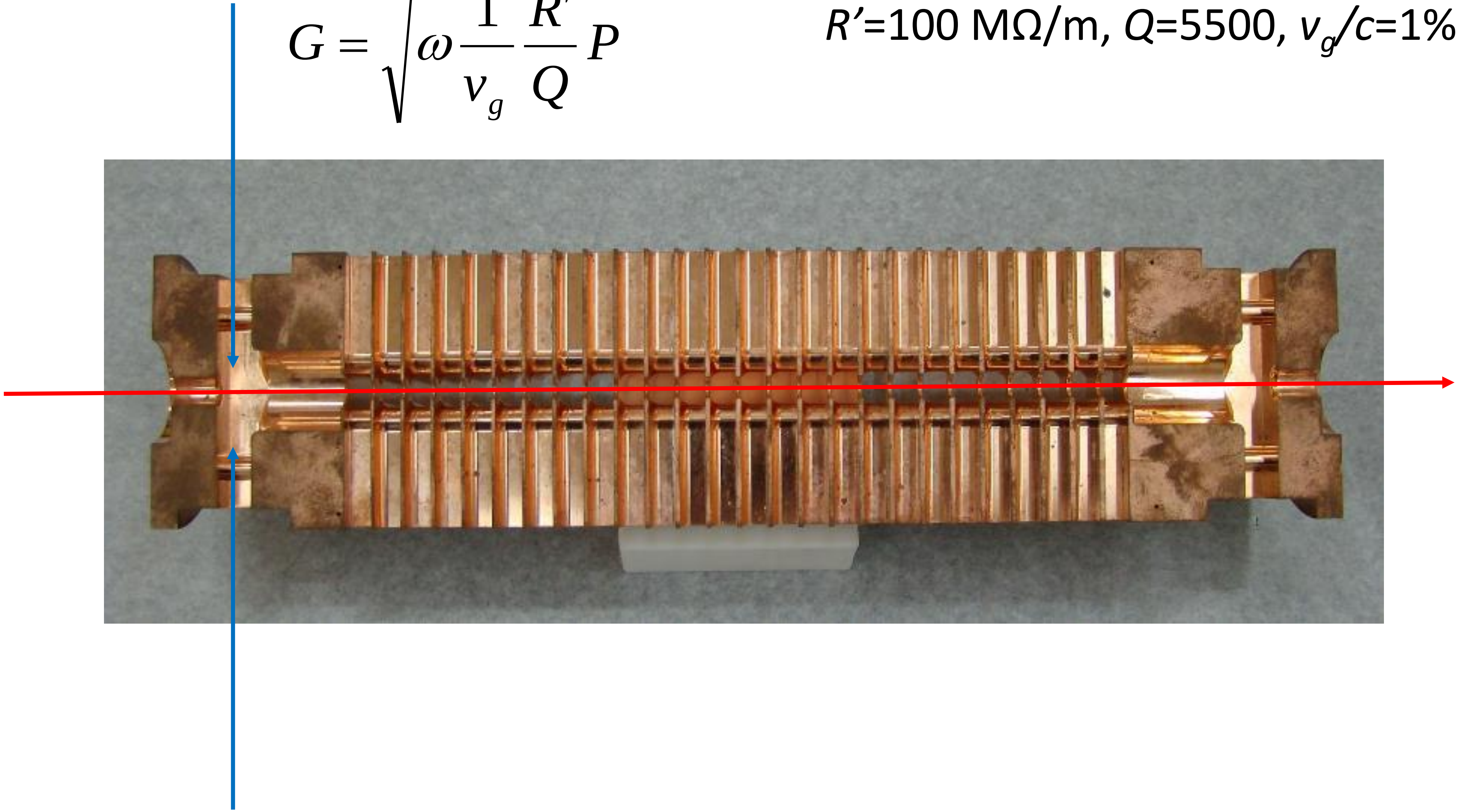
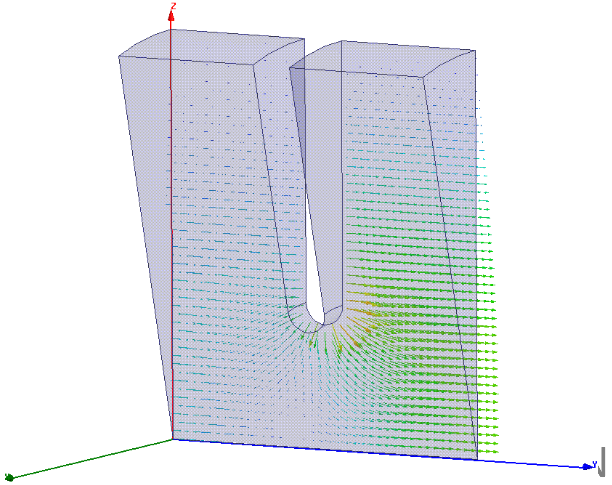
CLIC structure (approximate values):
R'=100 MΩ/m, Q=5500, v_g/c=1%





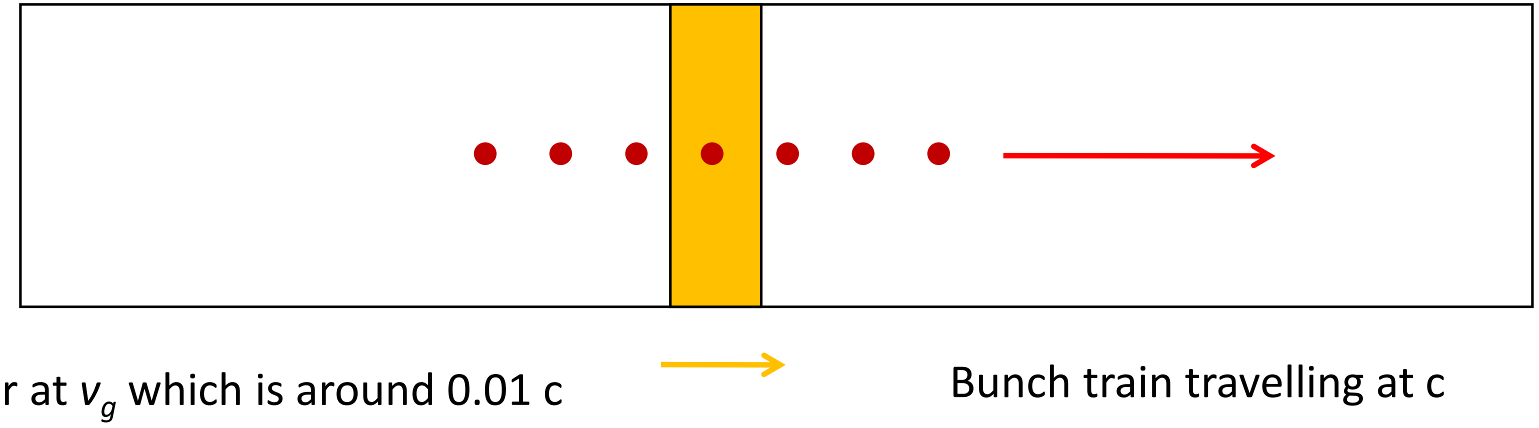
Lecture structure

1. Basic concepts of travelling wave accelerating structures
    a. Traveling wave acceleration and periodic boundary conditions
    b. Beam loading
    c. Peak rf power production
2. High peak rf power production and manipulation
3. High field phenomena in accelerating structures

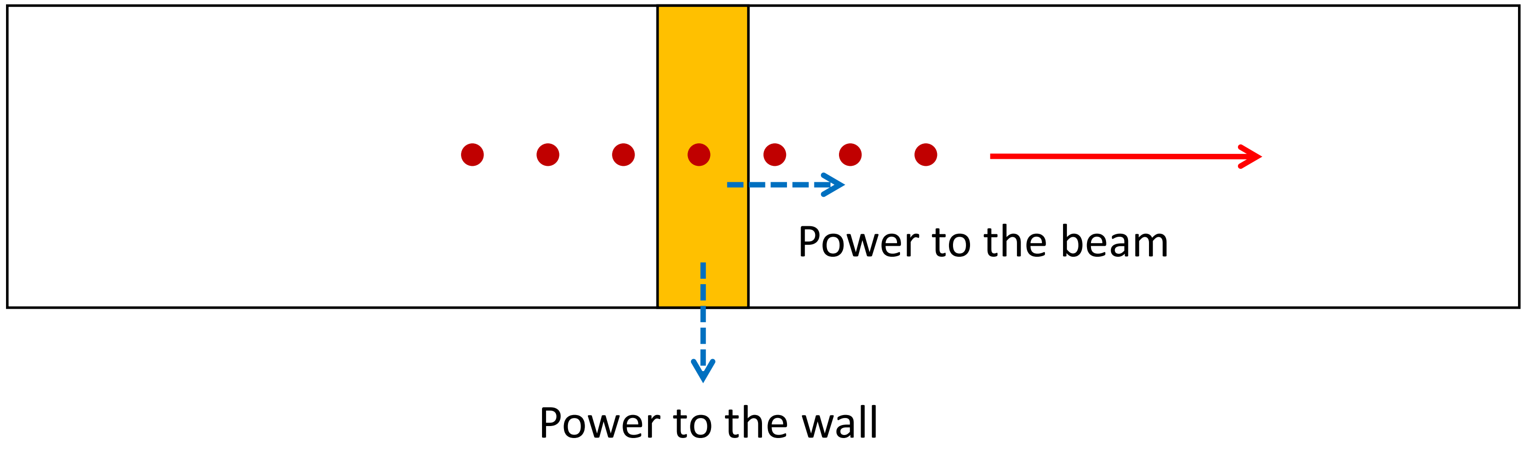
- In order to get high efficiency, in addition to high-gradient, we accelerate a high current beam.
- The beam extracts a significant, 30%, fraction of the rf power fed into the structure.
- Since power goes from rf to beam, fields go down when the beam is there.
- This is known as beam loading.
- We need to have a formalism to deal with this,
- Especially since high-efficiency lowers the gradient. We'll have to optimize.

Power flow and beam loading picture

- Unit length slice of structure with stored energy in yellow.
- The beam propagates much faster than the power.
- Beam is accelerated so extracts from energy slice.
- Another way to see this is the beam adds (180 degrees out of phase in acceleration) voltage to power slice – should derive fundamental theorem of beam loading, please see linear collider school lectures!



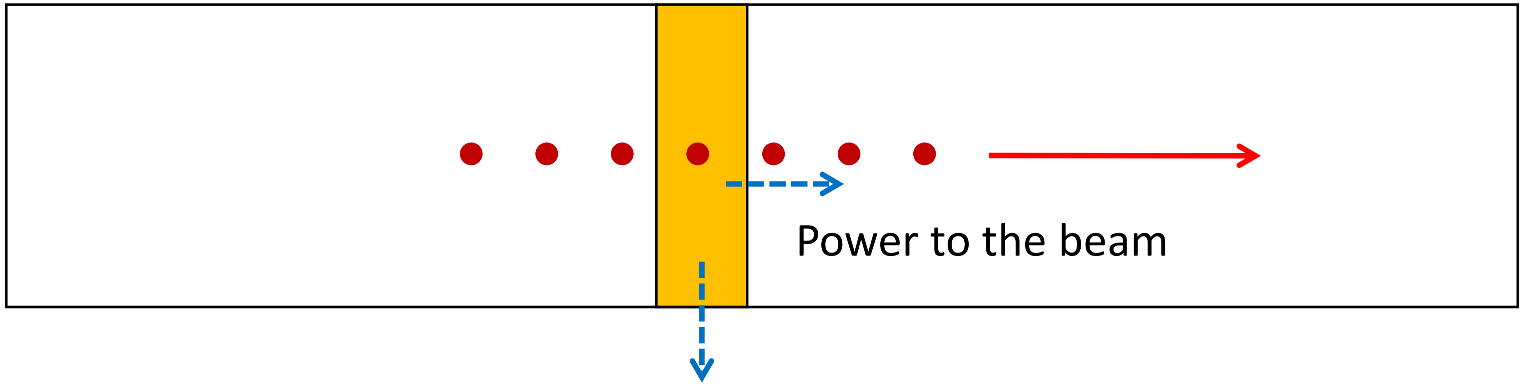
Let’s set up a differential equation based on power conservation



$$\frac{dP}{dz} = -P_{wall} - P_{beam}$$

Cavity walls attenuate power as it propagates.

Let's set up a differential equation based on power conservation

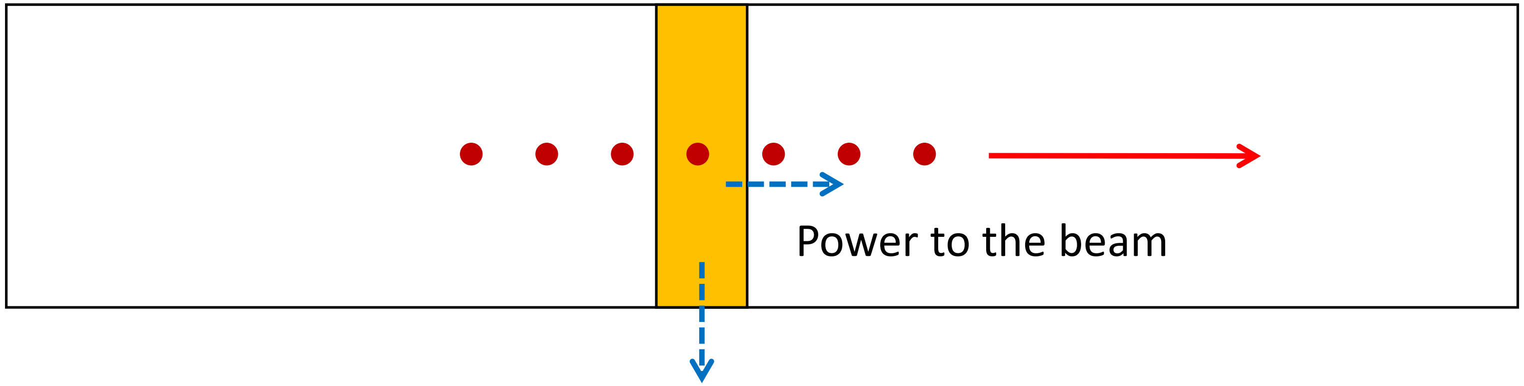


$$\frac{dP}{dz} = -P_{wall} - P_{beam}$$

Wall losses first

$$P_{wall} = \frac{\omega}{Qv_g} P$$

Let's set up a differential equation based on power conservation

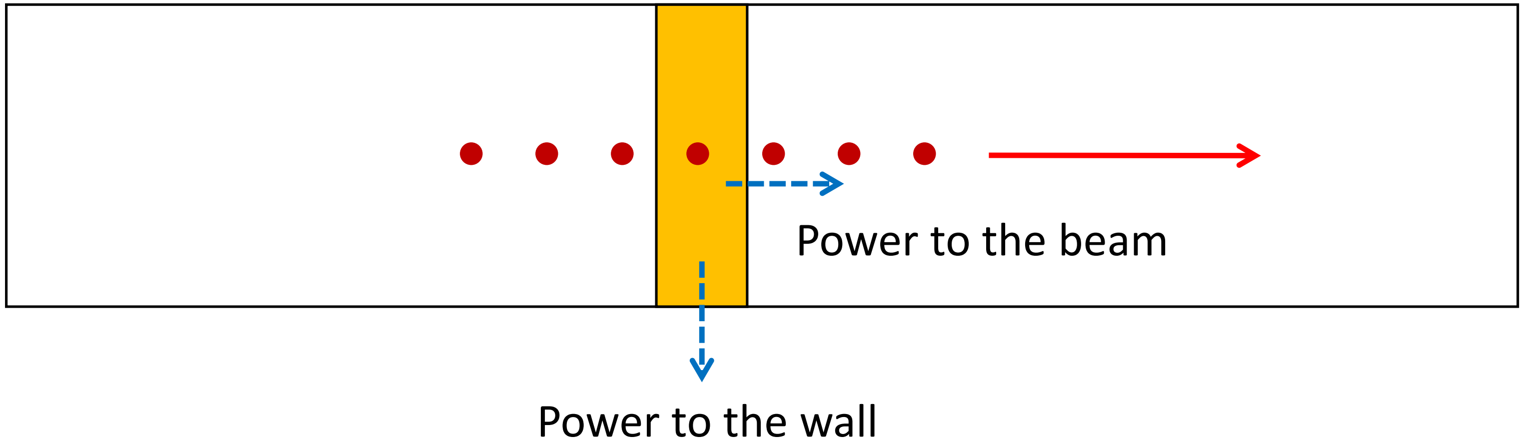


$$\frac{dP}{dz} = -P_{wall} - P_{beam}$$

Next the beam

$$P_{beam} = GI = \sqrt{\frac{\omega}{v_g}\frac{R'}{Q}P}\,I$$

Let's set up a differential equation based on power conservation

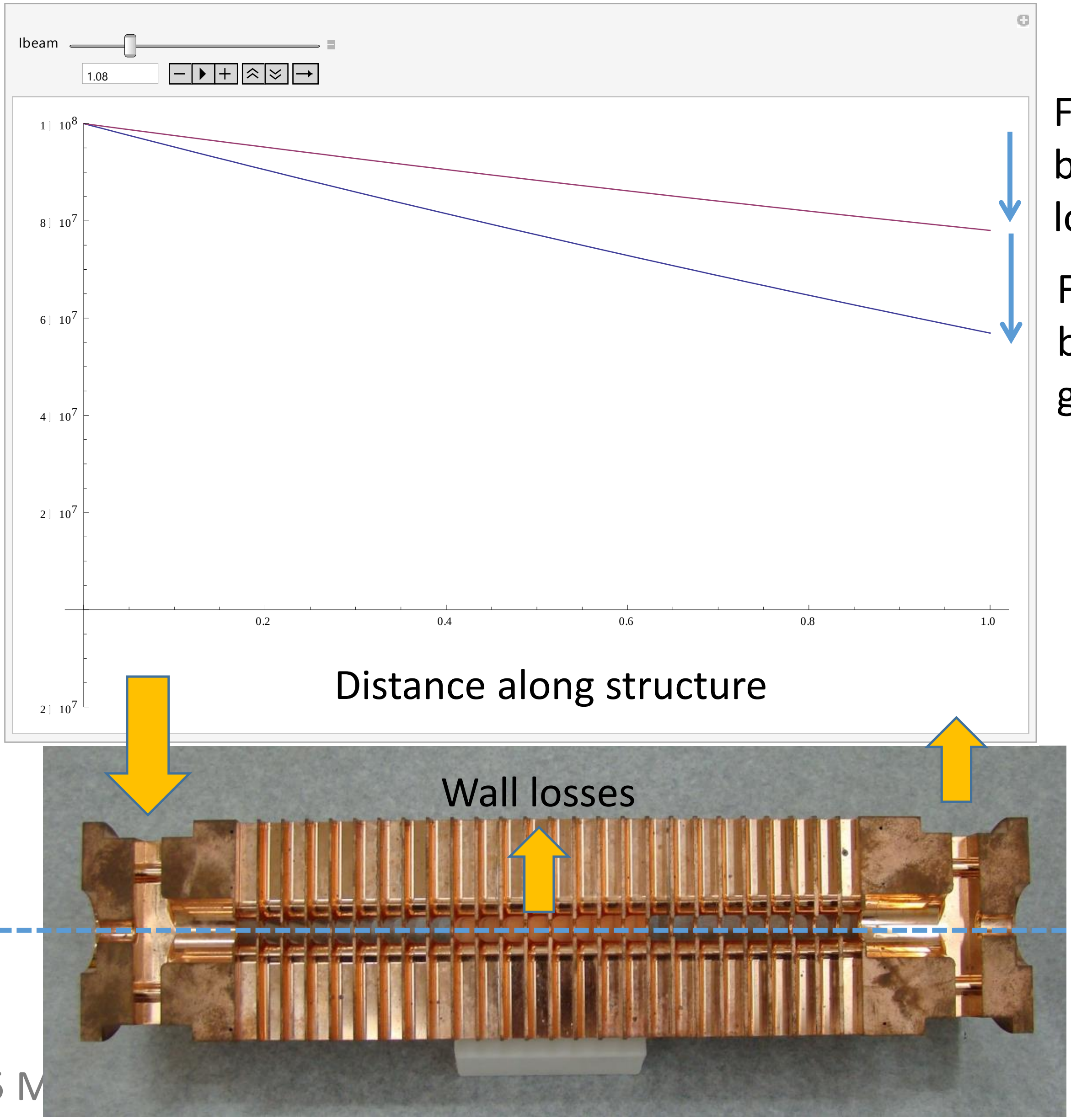


$$\frac{dP}{dz} = -P_{wall} - P_{beam}$$

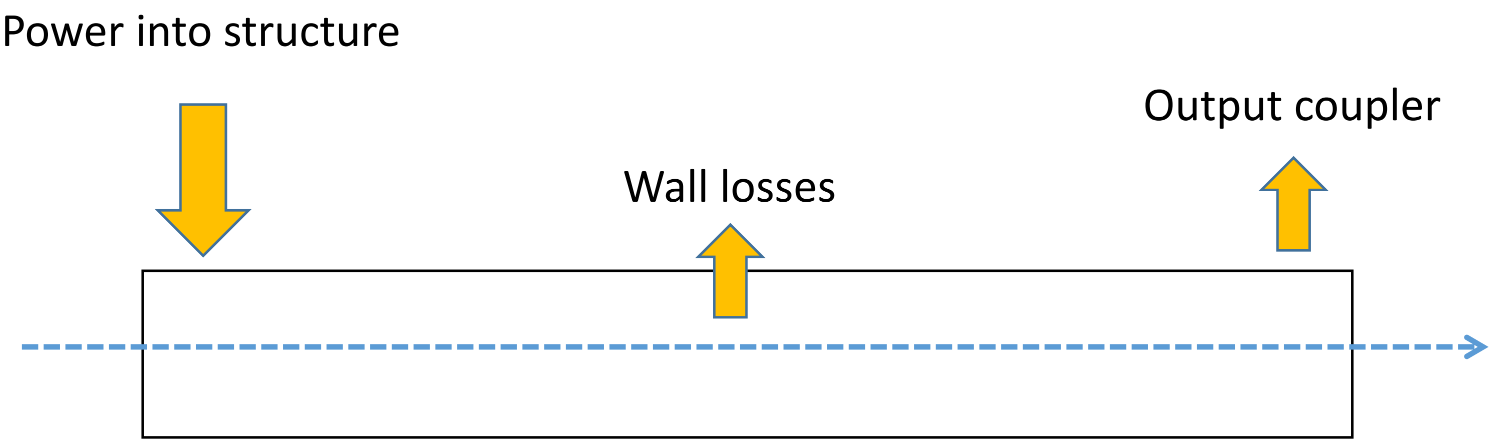
Putting it all together

$$\frac{dP}{dz} = \frac{\omega}{Q v_g} P - \sqrt{\frac{\omega}{v_g} \frac{R'}{Q} P I}$$

An example of the solutions to this equation for constant gradient (all cells are the same):



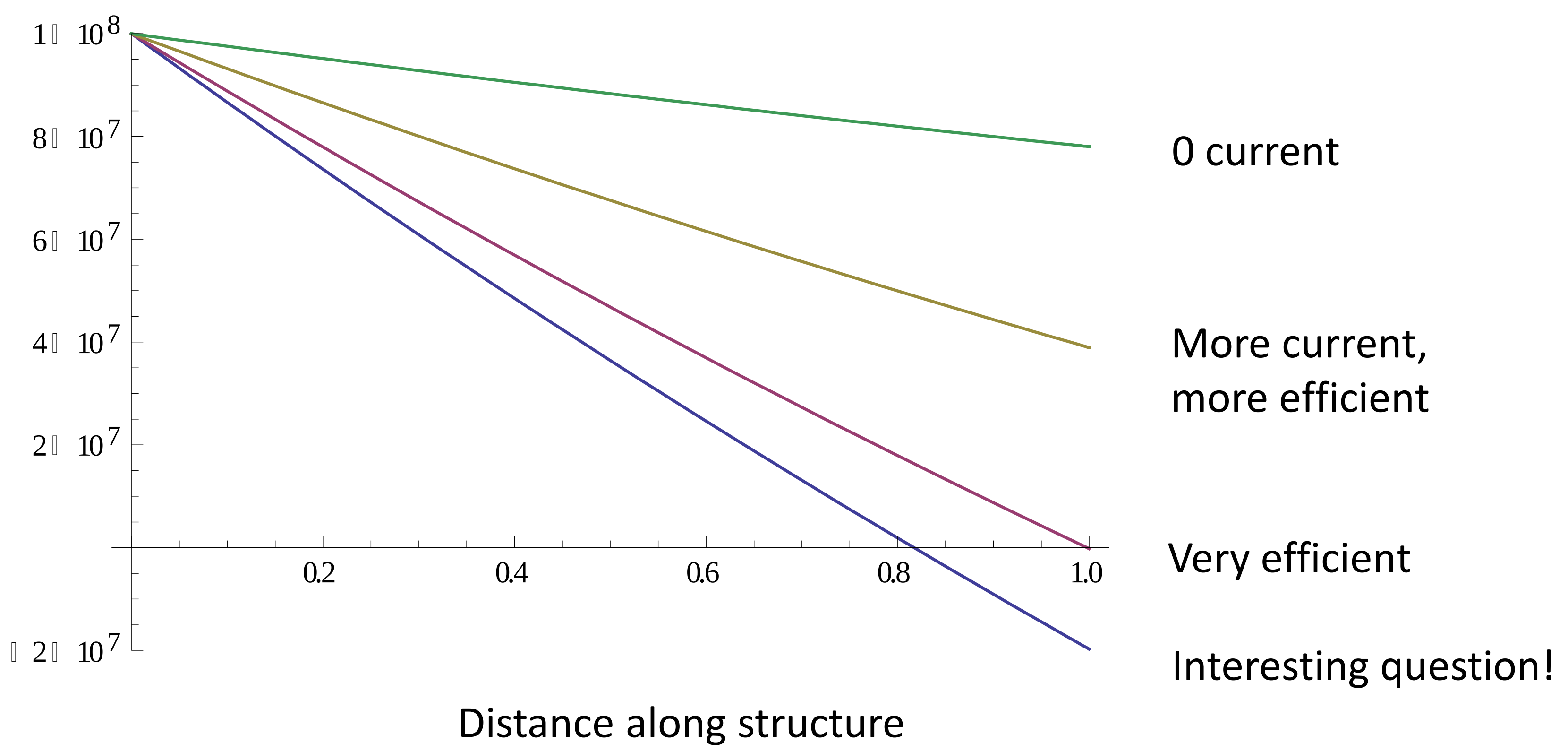
Now we ask ourselves – How efficiently have we converted rf power into beam power?
To ask it using accelerator jargon – What is the rf-to-beam efficiency?
This is one of the most important performance issues for a normal conducting linear collider since it directly affects the overall performance.



Power into beam $\Delta P_{beam} = I\langle G\rangle L$

$$\eta = \frac{\Delta P_{beam}}{P_{in}} = \frac{I}{P_{in}} \int_0^L G(z)dz$$

Different amounts of beam loading and efficiency



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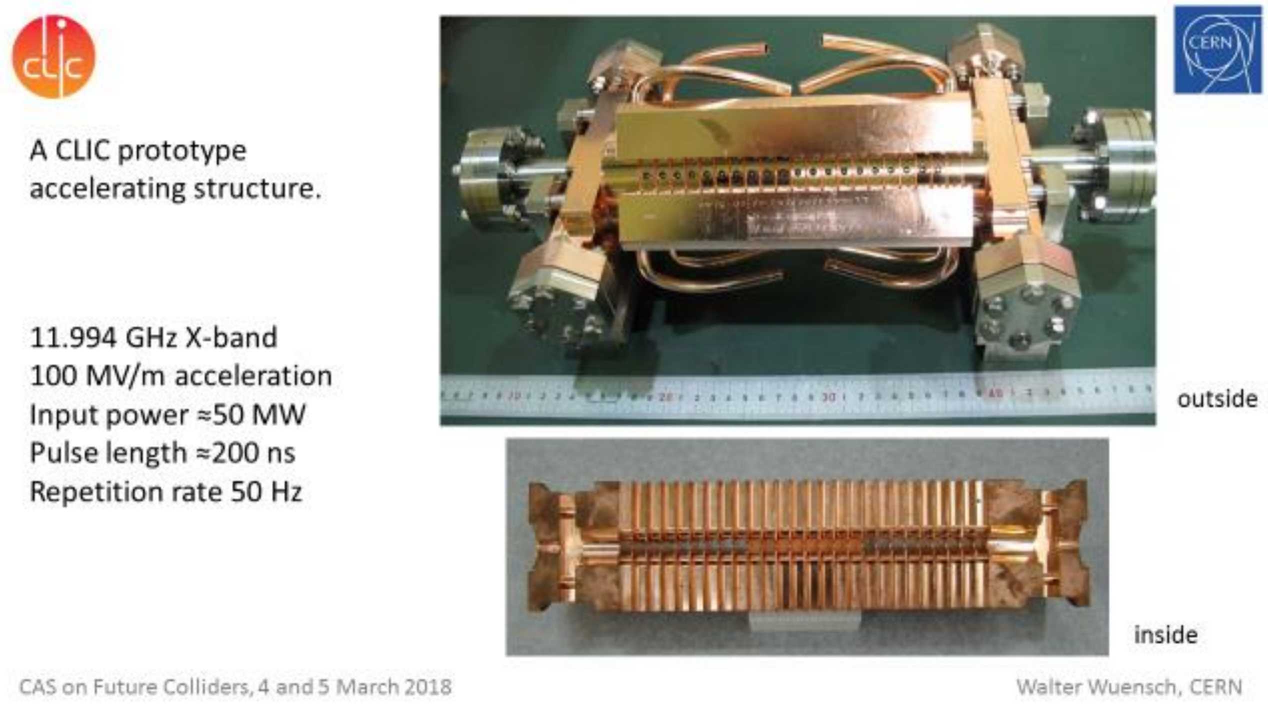
Size of problem

We now know relation between power and gradient.

50 MW/0.25 m= 200 GW/km
Nuclear power plant is around 2 GW
Catastrophe? Not quite,
200 ns*50 Hz=10^{-5}
Normal conducting linacs typically have low duty cycle

But still, how do we produce these high peak powers?



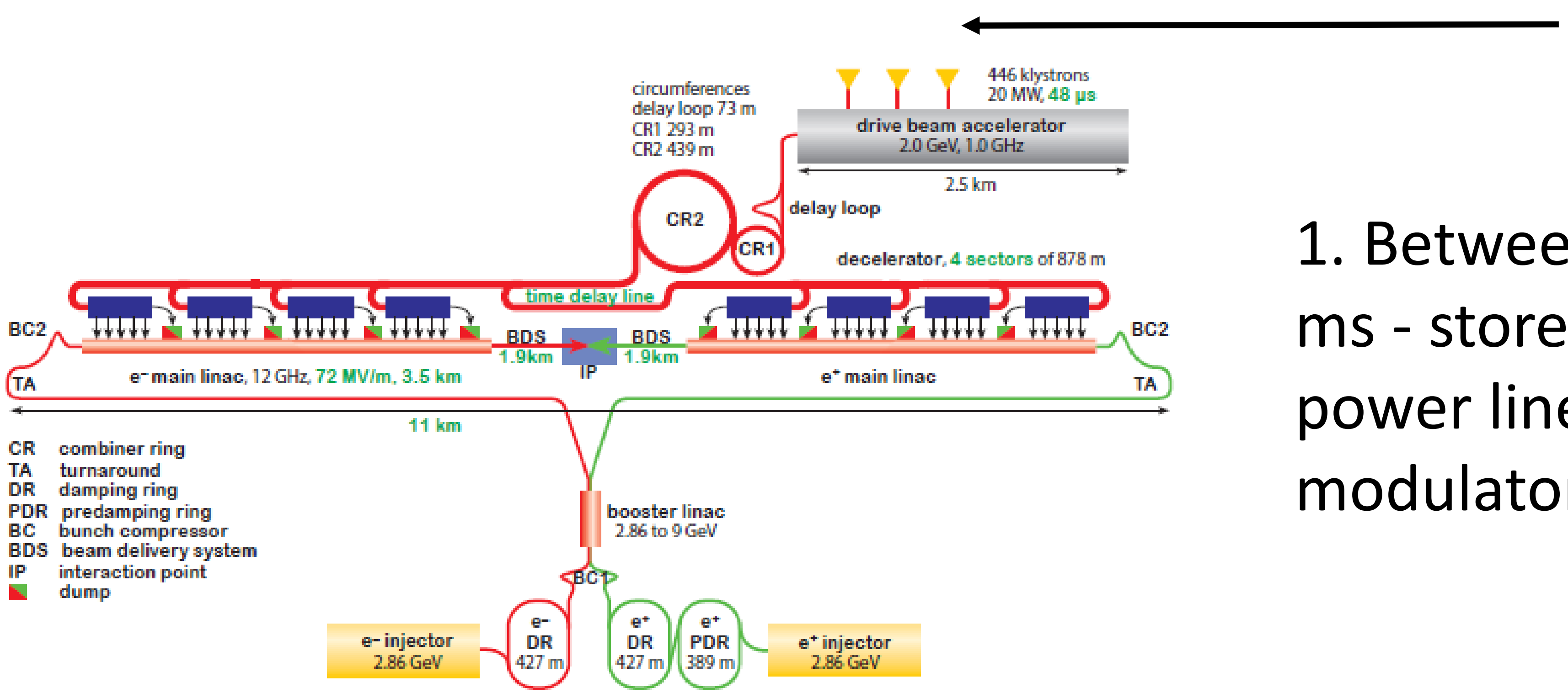
$$G=\sqrt{\omega\frac{1}{v_g}\frac{R'}{Q}P}$$

- Producing peak power is one challenge to having high gradient – we will discuss this now.
- The other is to devise a structure which can tolerate high gradient – we will cover that tomorrow.

So how can we produce 200 MW/m over kilometers? Two options for 380 GeV:

Drive beam vs. direct with klystrons!

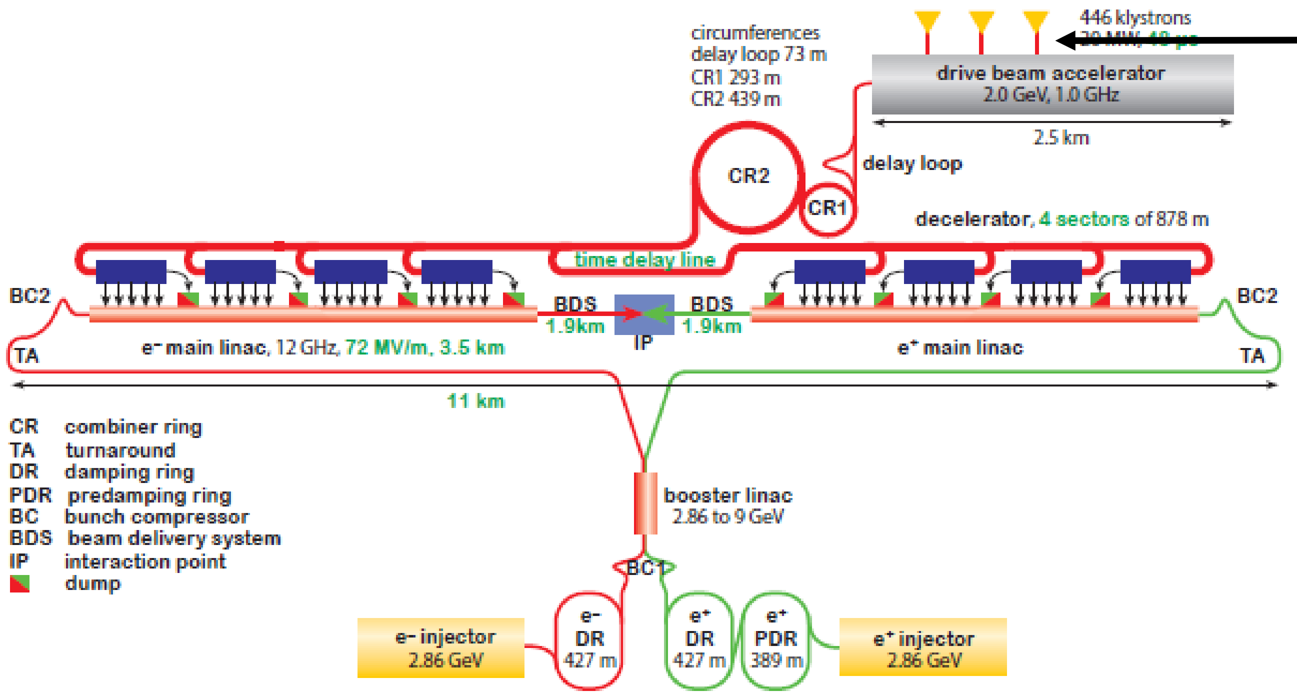
Principles of the drive beam from the point of view of peak power production



1. Between 50 Hz pulses - 20 ms - store energy taken from power lines in capacitors of modulators

20 ms

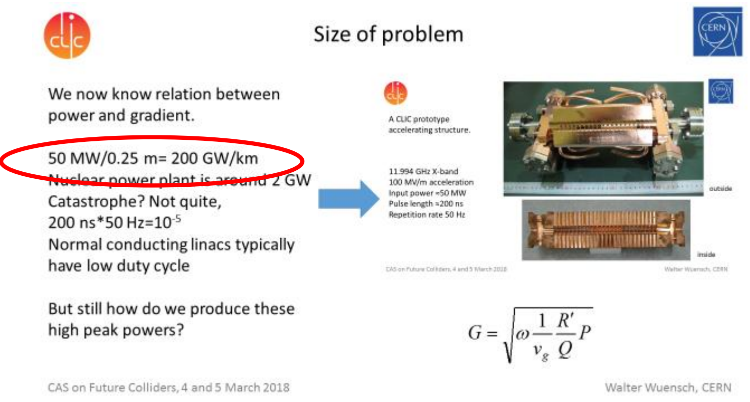
Principles of the drive beam from the point of view of peak power production

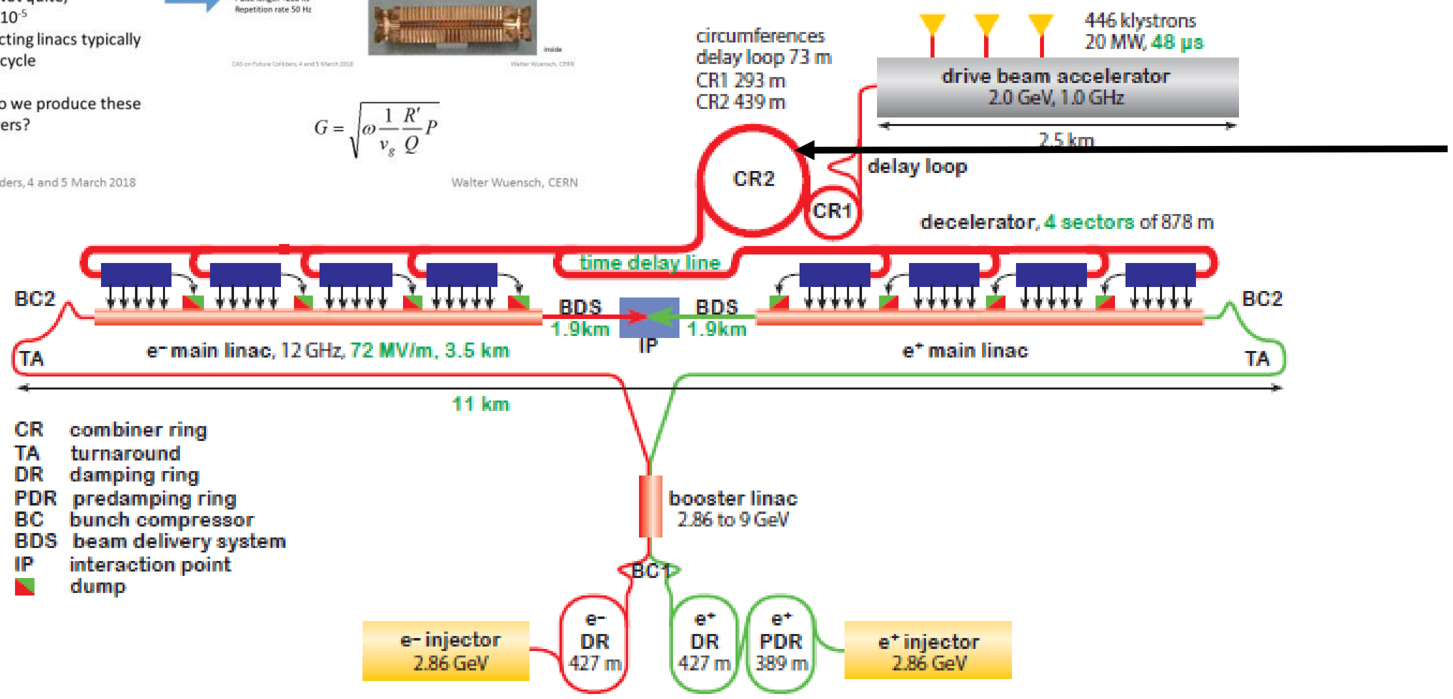


2. Transfer energy stored in capacitors by converting to 1 GHz rf and accelerating 4.2 A beam during 20 μsec to 2 GeV. Gives 8.4 GW beam.

20 ms to 20 μsec

Principles of the drive beam from the point of view of peak power production

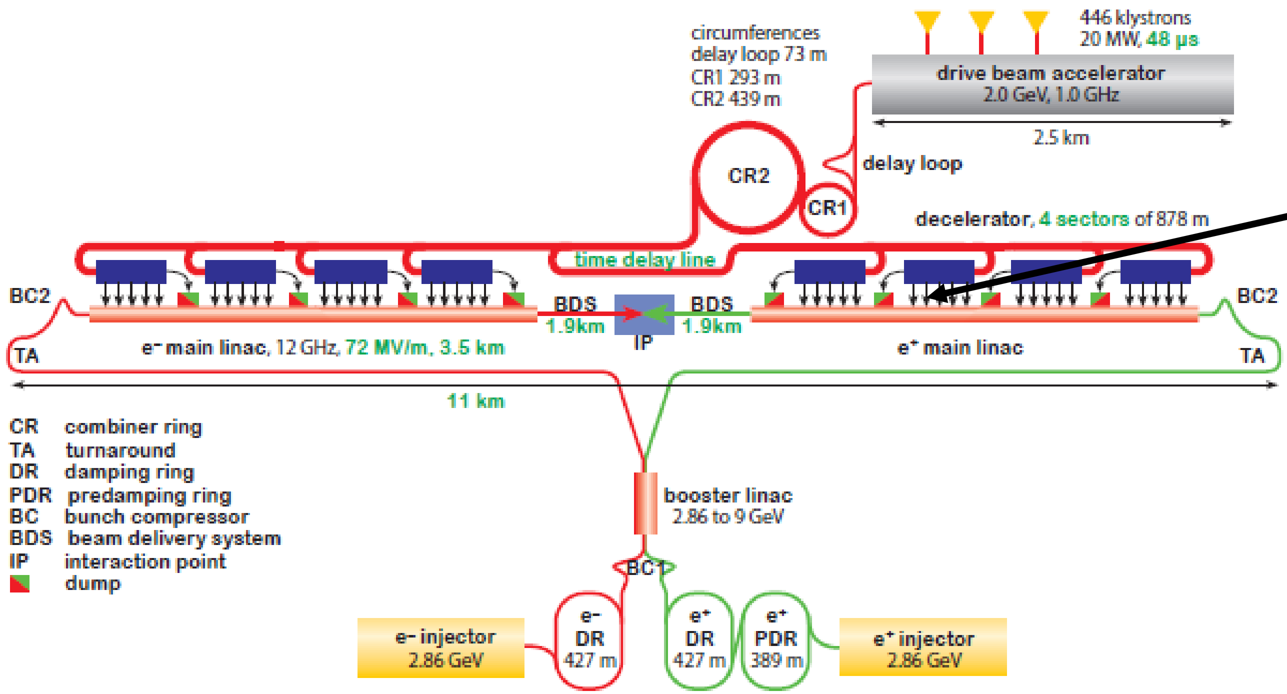




3. Store head of train in loops to wait for tail to catch up. Train length goes from 20 μsec to 8*244 nsec, beam current goes from 4.2 A to 101 A. Beam power is 202 GW.

20 ms to 20 μsec to 244 nsec

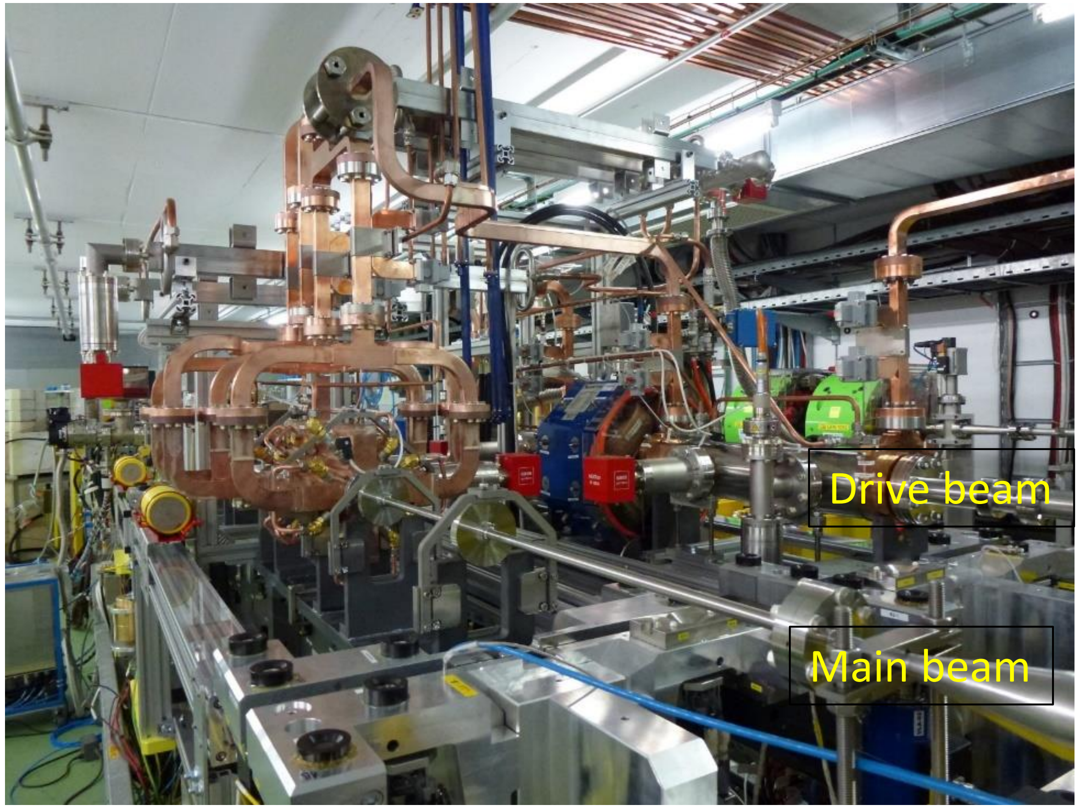
Principles of the drive beam from the point of view of peak power production



5. Decelerate drive beam and extract power in form of 12 GHz rf. Bunch length and spacing allow this. Feed over to accelerator as quickly as possible.

20 ms to 20 μsec to 244 nsec

The other trick – the transformer



Two-beam implemented in CTF3

Decelerate high current, low energy, drive beam in low impedance structure to accelerate low current, high energy main beam.

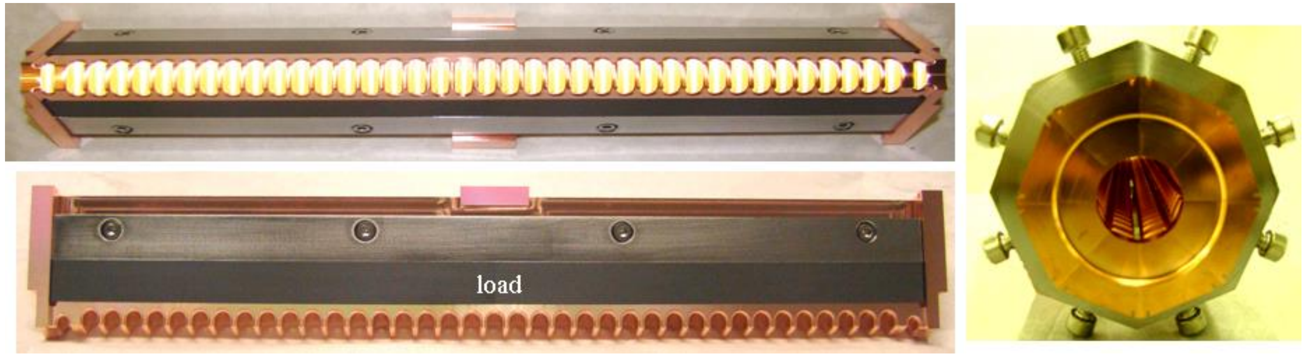
Peak power is conserved but transformed:

101 A and 2 GeV

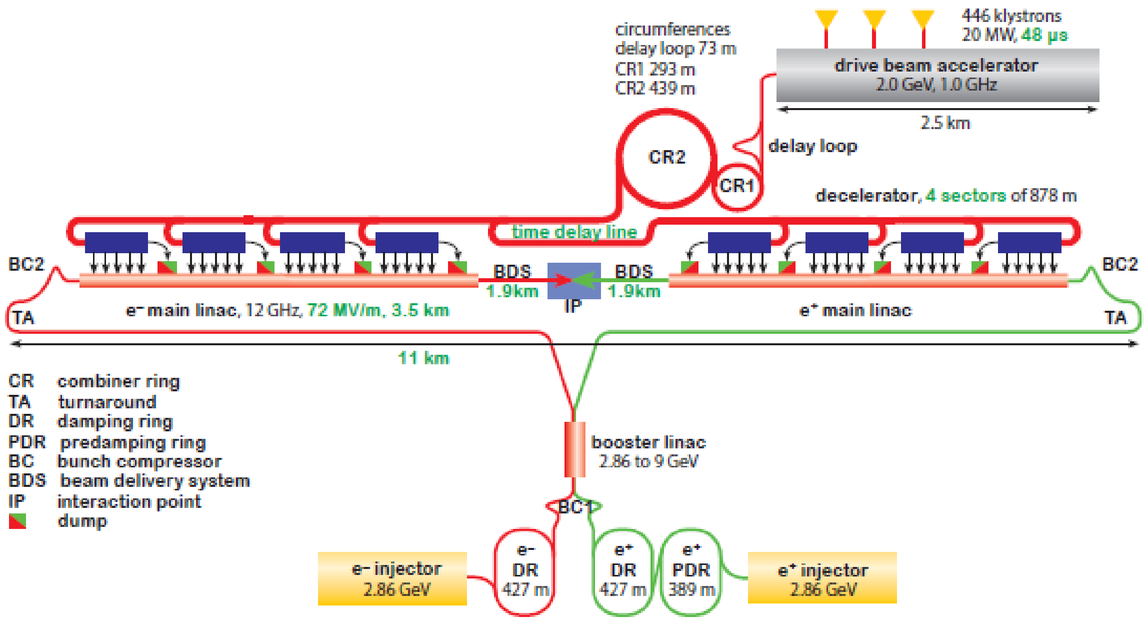
to

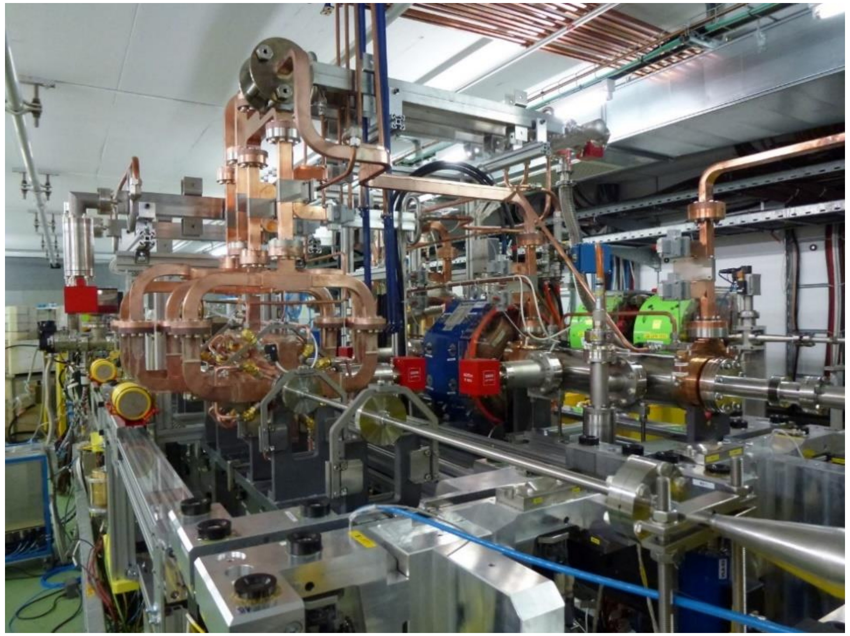
1 A and 180 GeV

(in four stages)



Making the peak power for high-gradient by drive beam



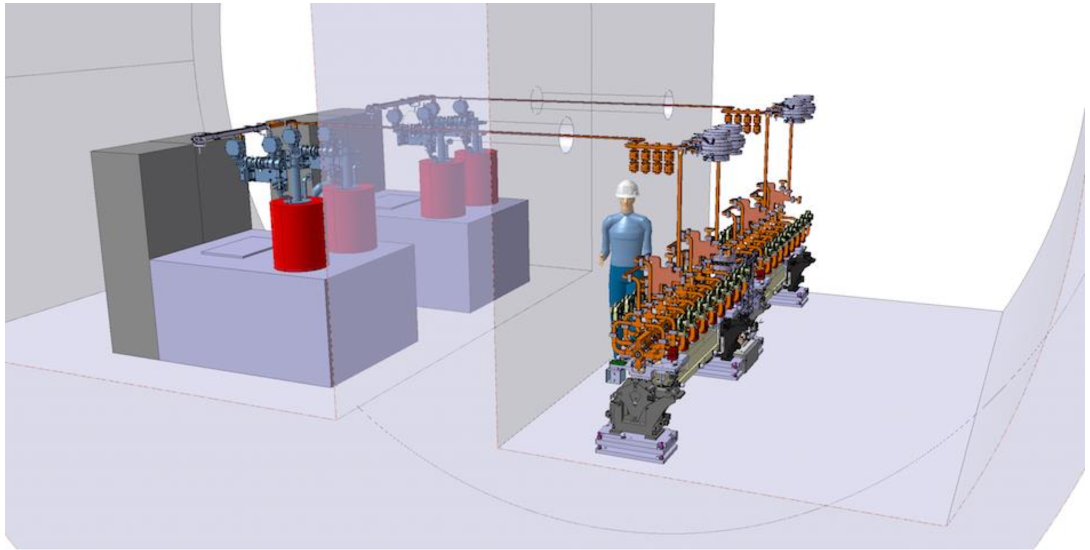


Just big energy storage and compression system. Note this idea also underlies plasma wakefield acceleration.

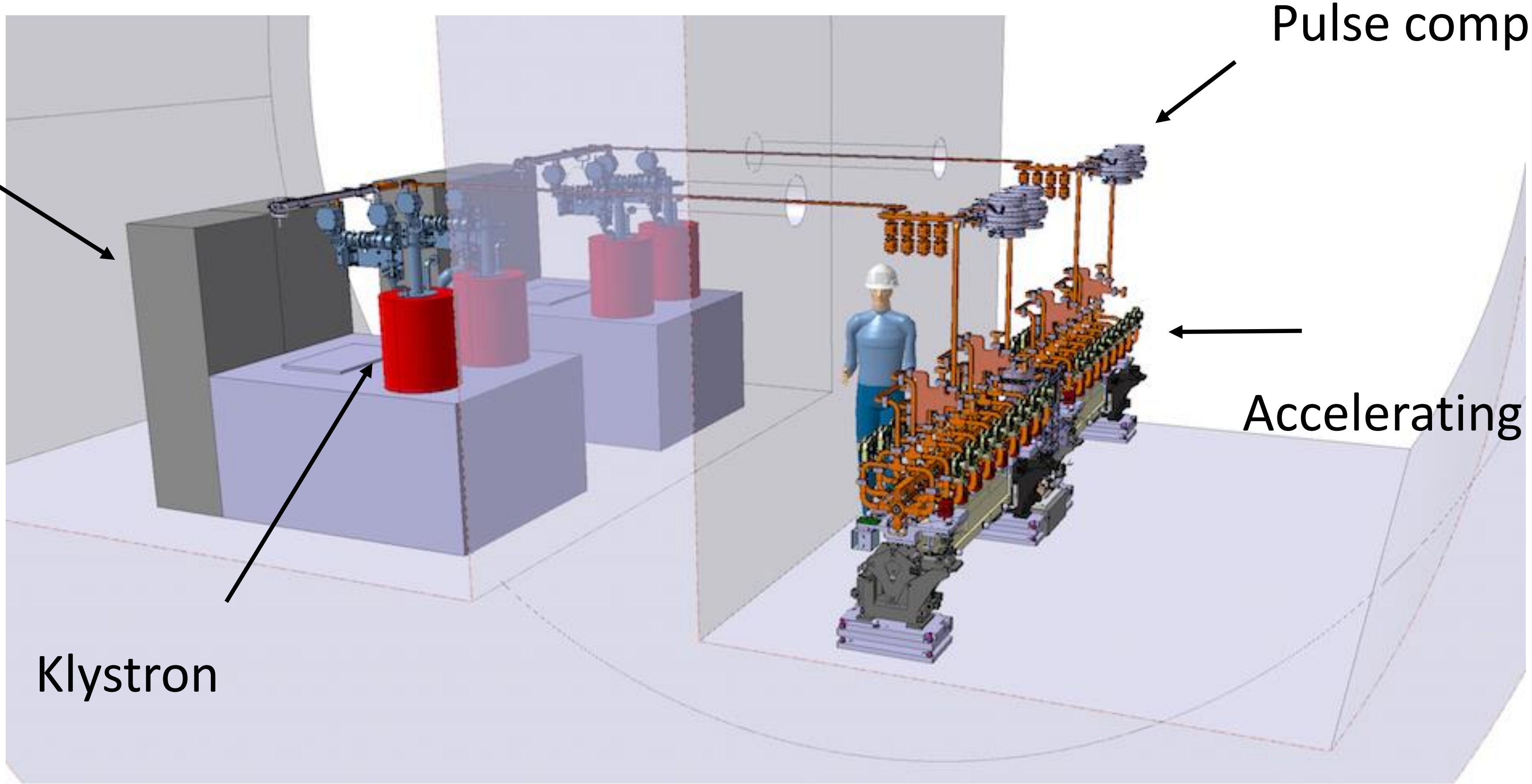
Only the drive beam power to gradient converter is different.

Now power direct from klystrons and rf pulse compressors

- We are now going to study a system based on local production of rf power using klystrons.
- Klystrons are very high power amplifiers, capable of producing peak powers up into the range of 50 MW.
- And we are going to look at rf pulse compressors, which play an equivalent role to the combiner rings in the drive beam scheme.

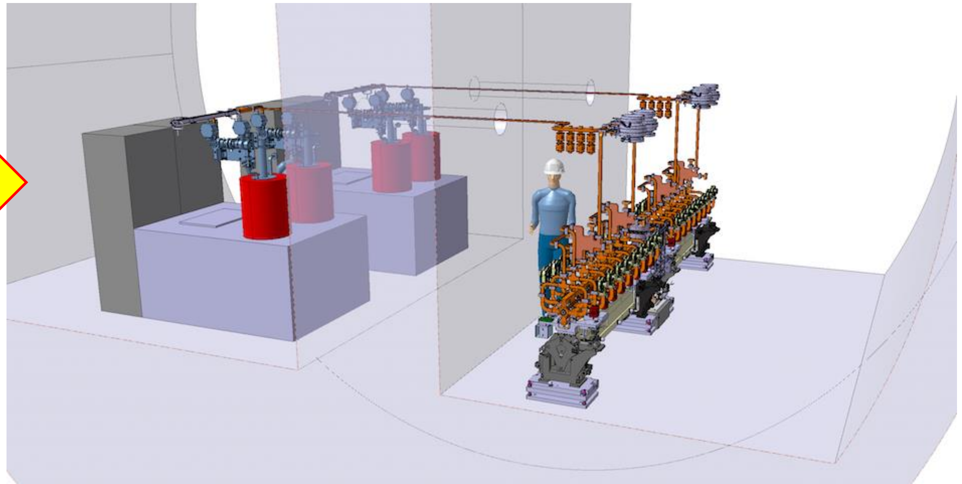


Klystron, pulse compressor overview



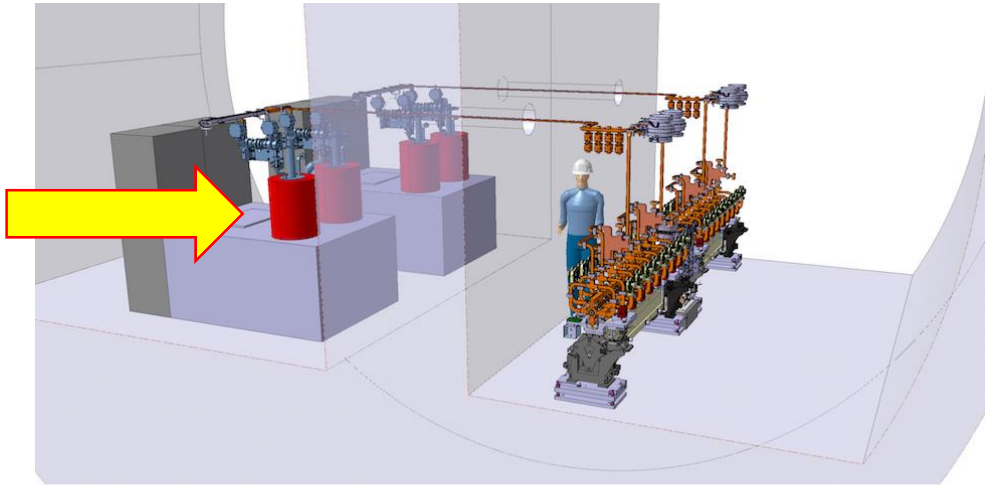
Solid-state modulator

Prototype modulator used in high-gradient test stands.



- Converts mains to 1.5 kV and stores energy in capacitors.
- Switches IGBTs which feed split core transformer
- Secondary on transformer produces (approximate numbers) 400 kV, 200 A pulse, which is 80 MW. Pulse duration is 1.5 µs.
- Note pulse is longer than we need for accelerator.

Klystron

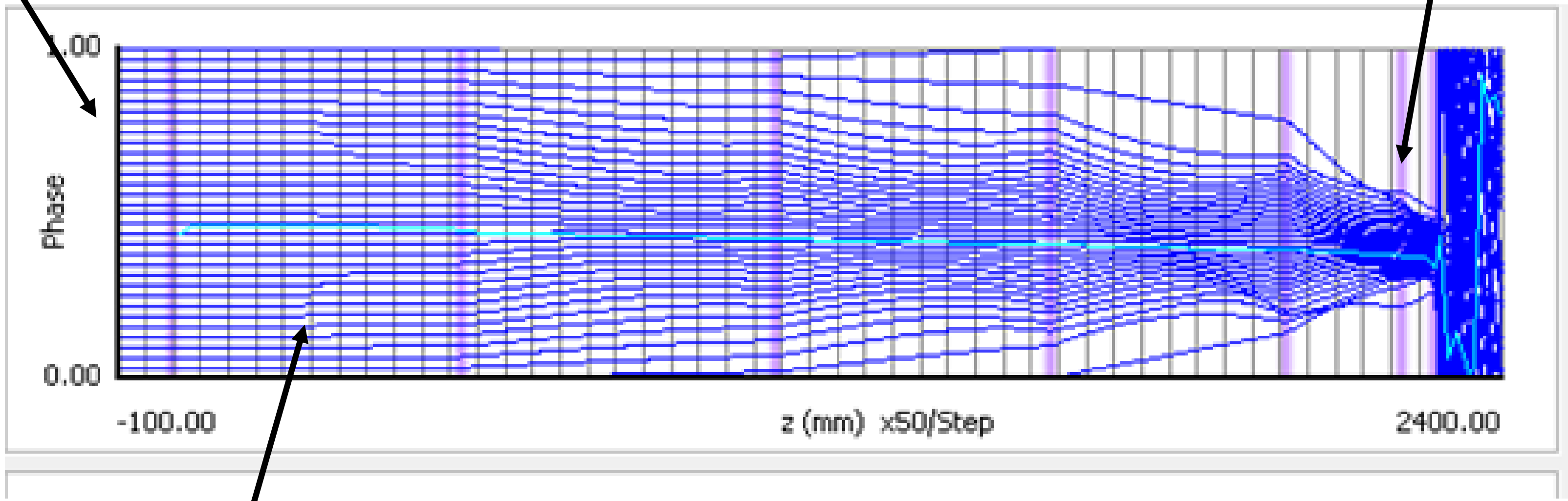


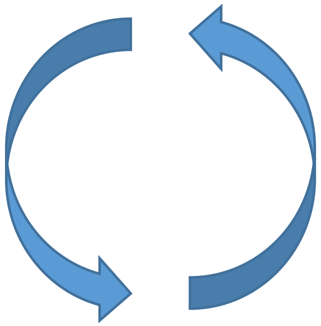
- Pulse from modulator is converted to a current in vacuum inside the klystron, approximately 400 keV and 200 A.
- This is done by emitting electrons from a cathode, making a vacuum diode.
- 400 keV is sub-relativistic. This allows the beam to be bunched through a velocity modulation.
- Power is extracted by cavity which decelerates the bunched beam.

How a klystron works

Uniform beam in time

Bunched beam,
current rises and falls



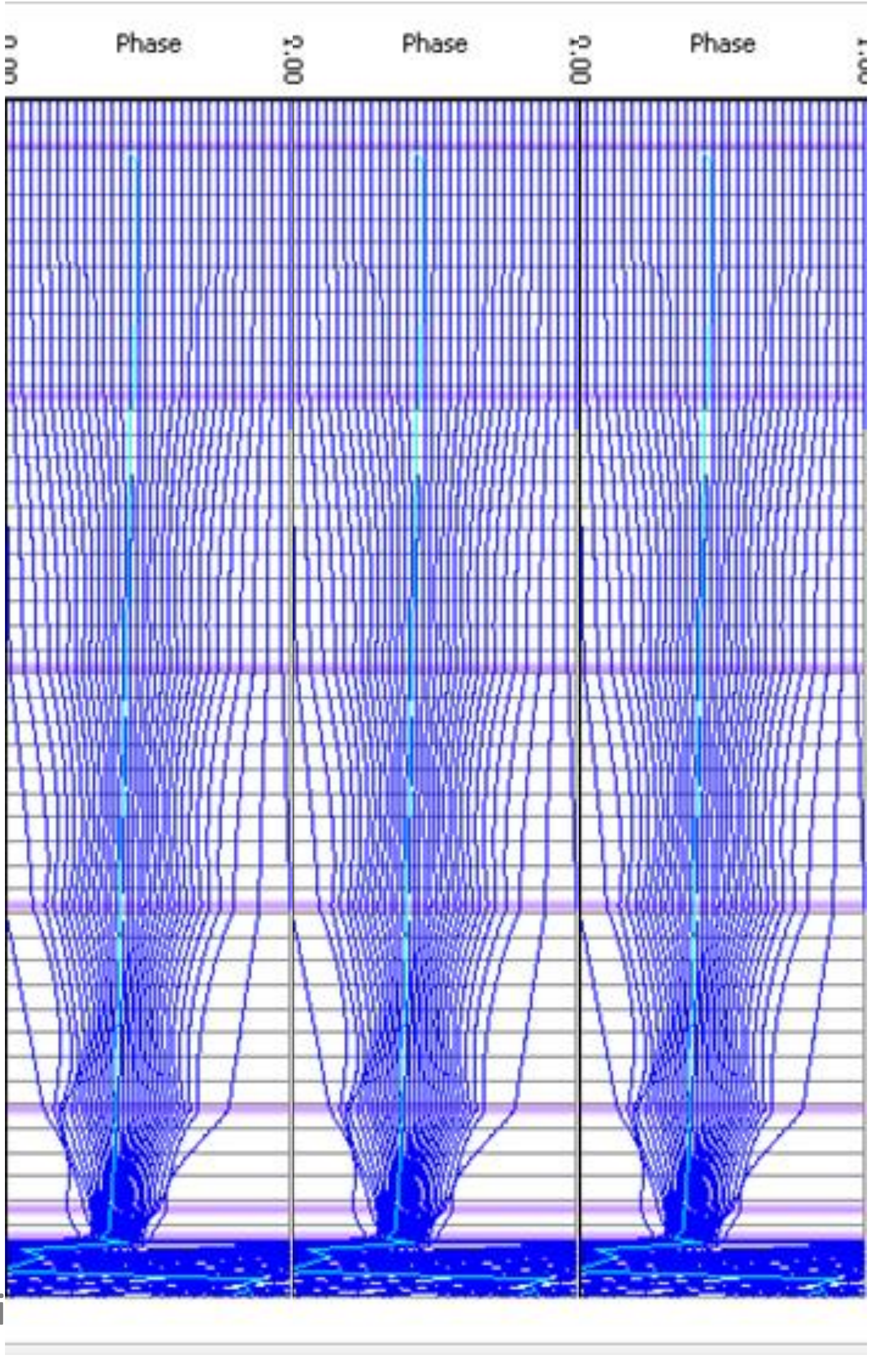


Movie loop plays
over and over

beginning of velocity modulation

Distance along klystron

Applegate diagram



Gun

continuous electron beam in vacuum

Cavity to velocity modulate beam

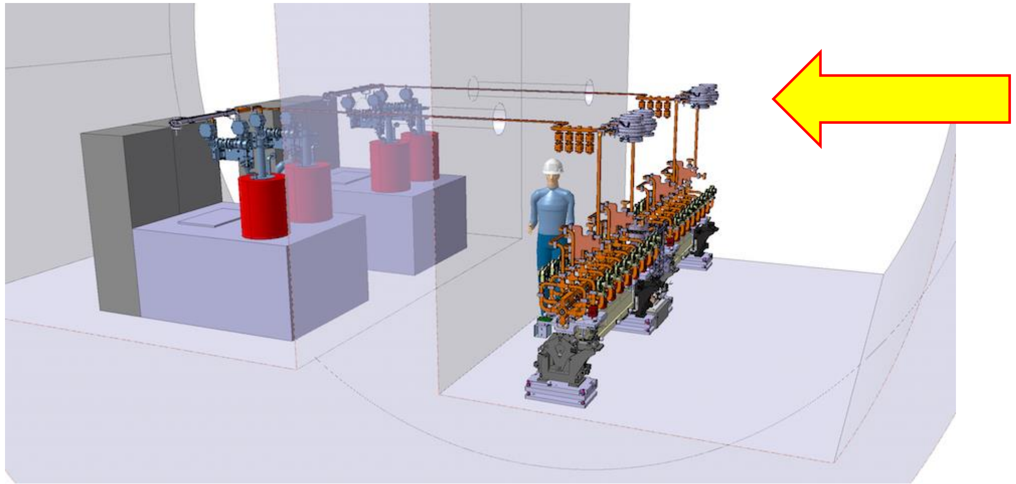
drift

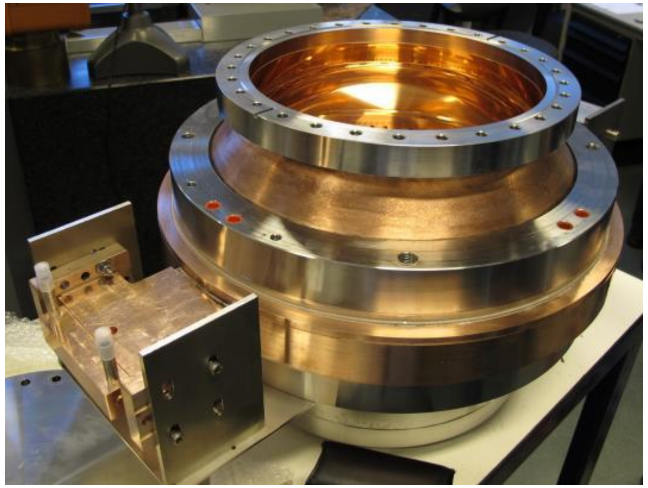
bunching beam

Output cavity to decelerate beam and extract power in form of rf

Collector (beam dump)

Pulse compressor



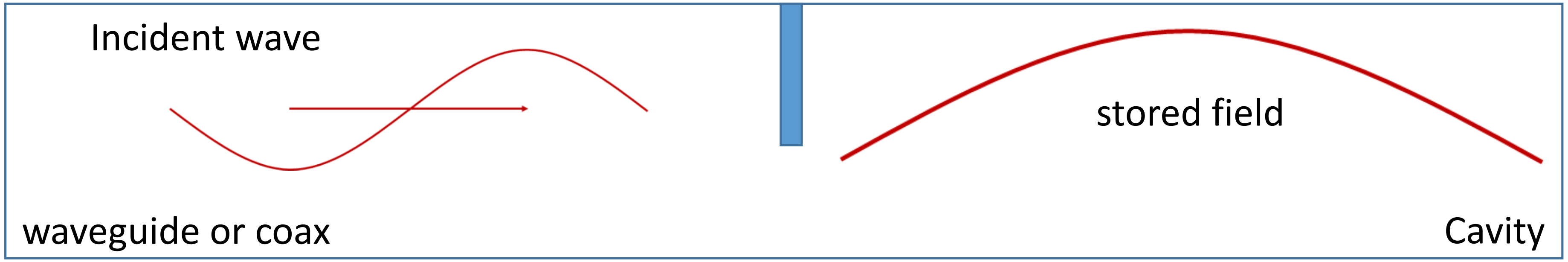


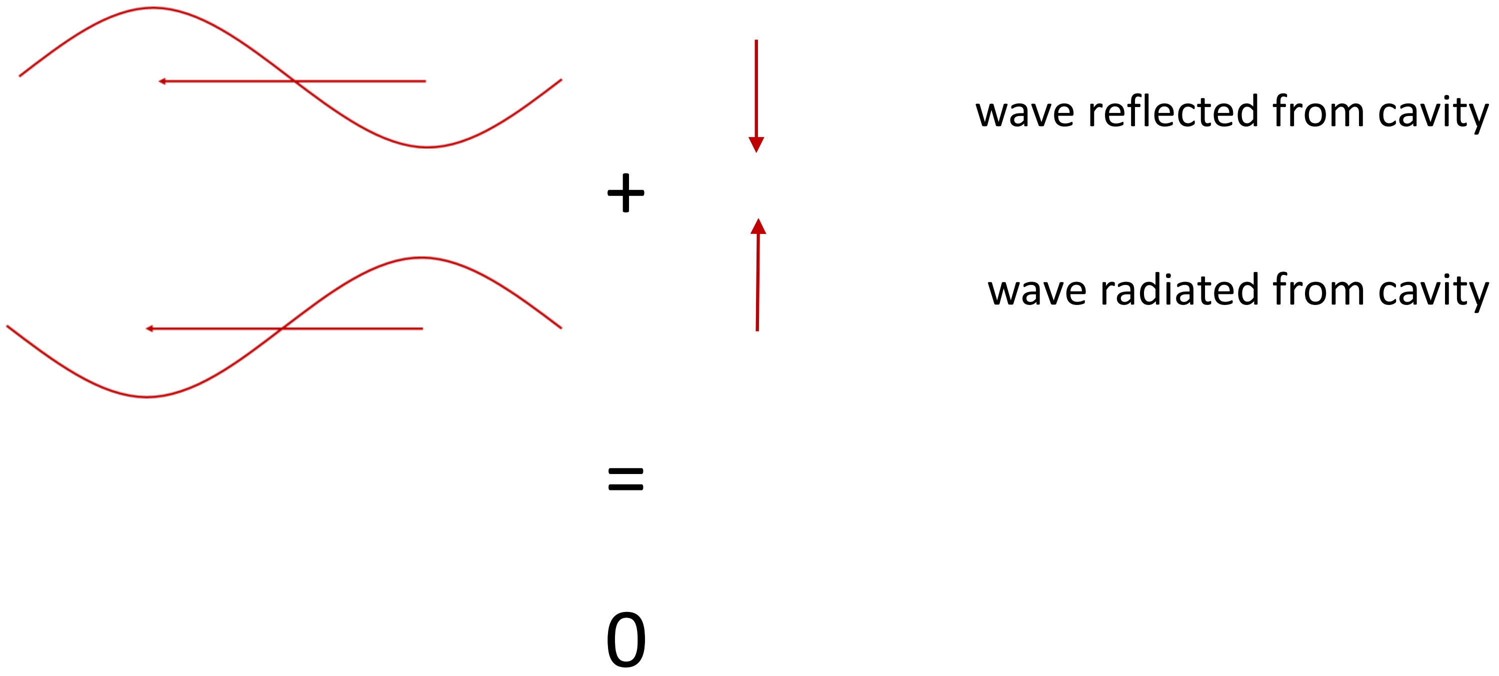
C-Band pulse compressor in SwissFEL

X-Band pulse compressor in test area

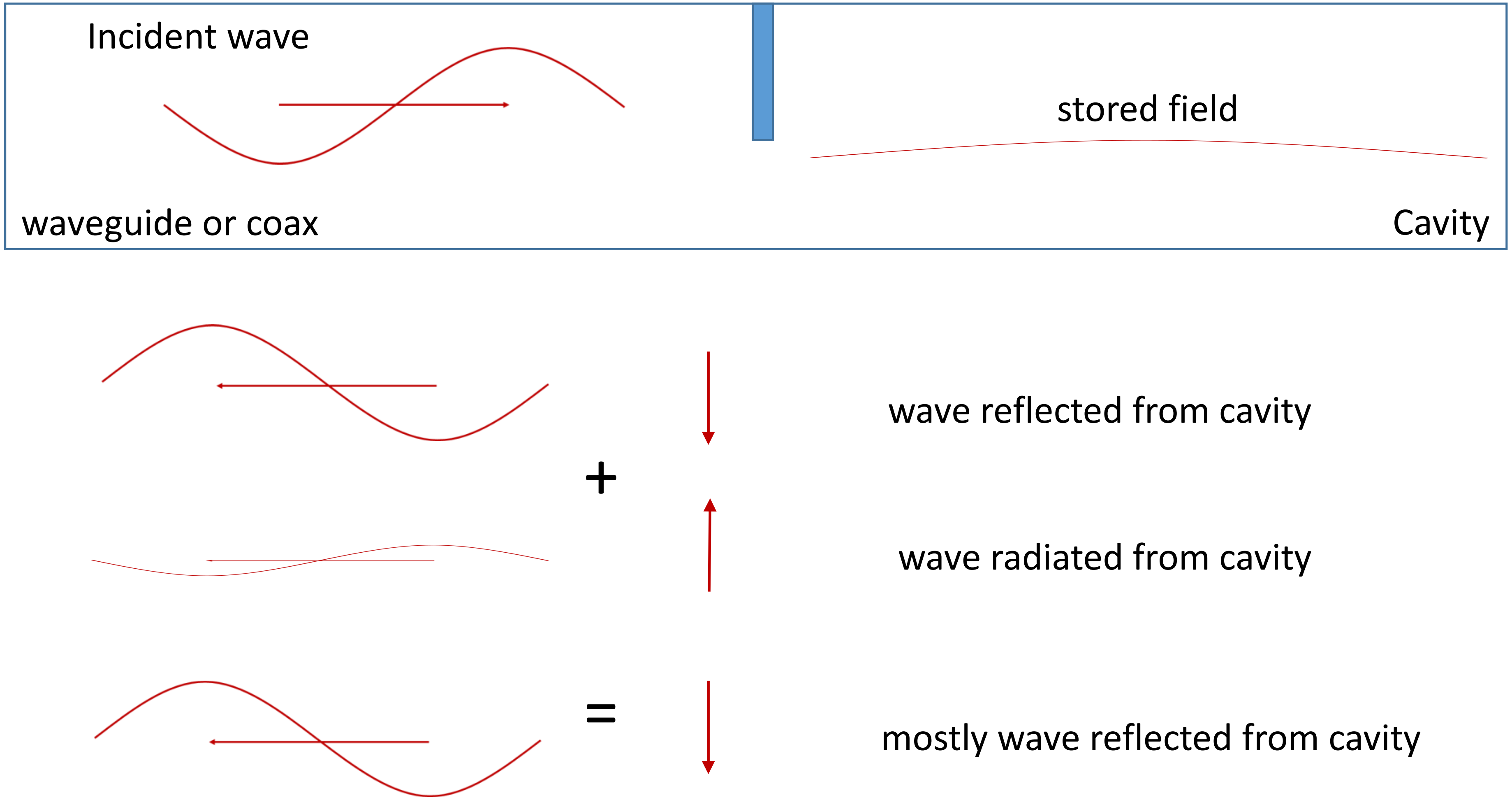
- Store rf power in high-quality factor cavity during long, 1.5 µs pulse. Pulse length from klystron is given by modulator, and becomes inefficient much shorter due to rise and fall times.
- Quickly drain cavity by implementing phase flip trick (next slides).

Critically coupled cavity on resonance and in steady state

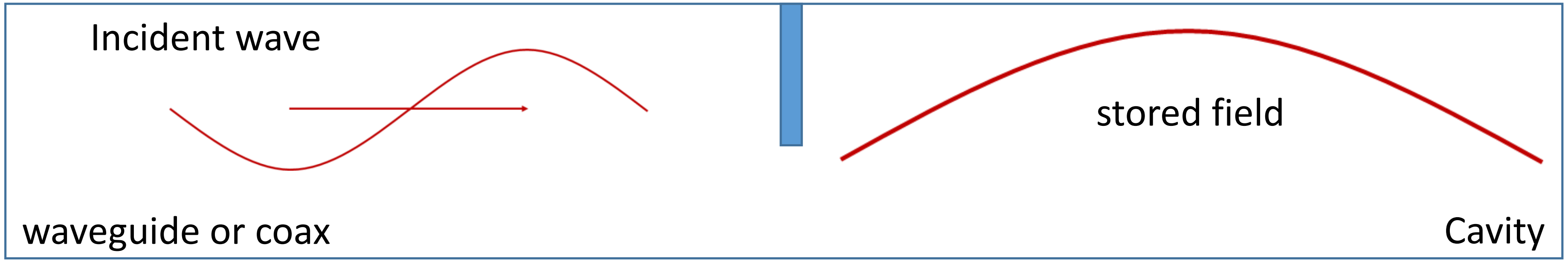


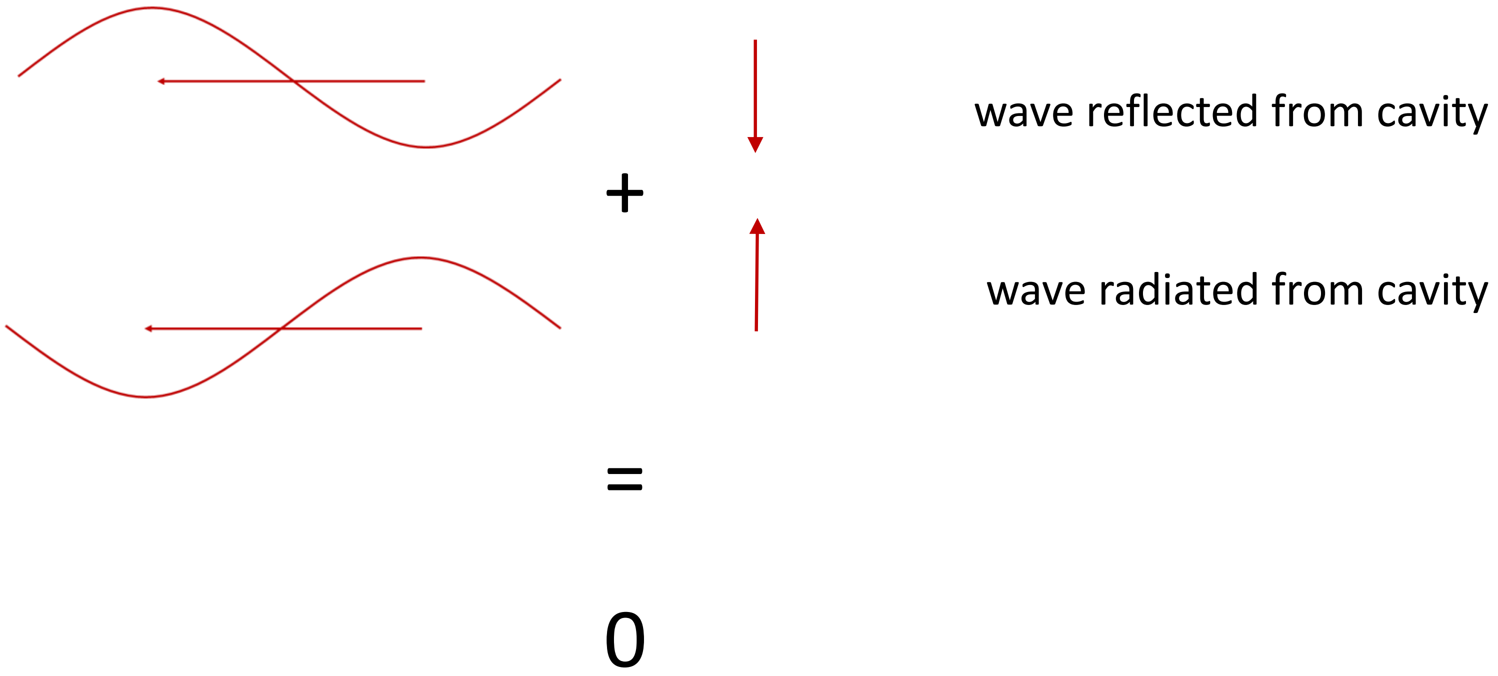


Critically coupled cavity on resonance, initial fill

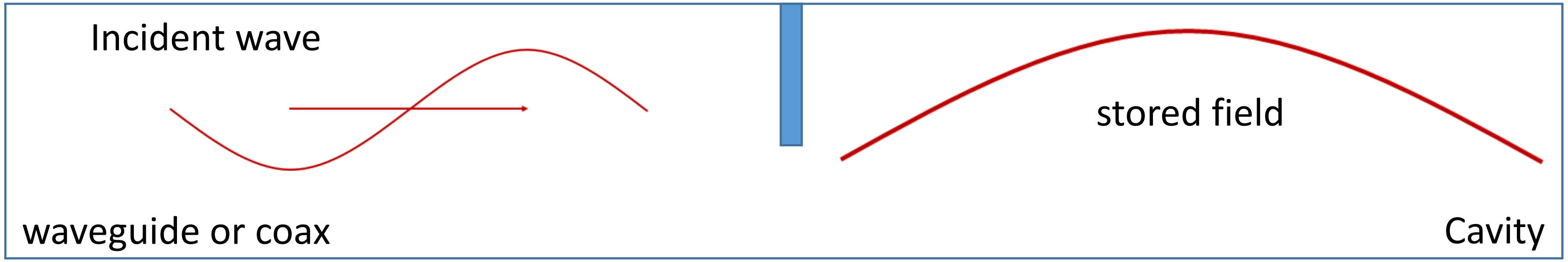


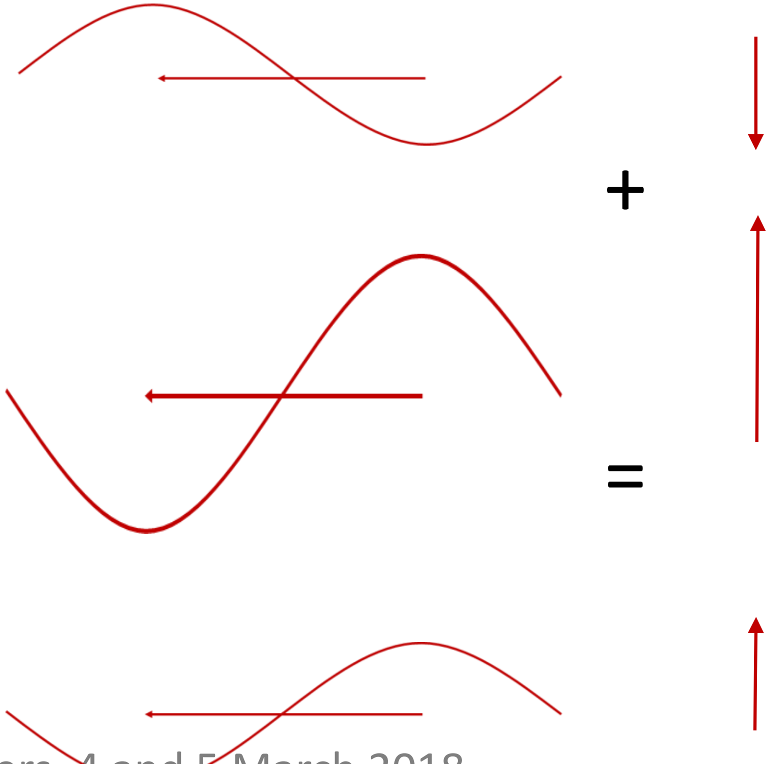
Critically coupled cavity on resonance and in steady state





Over coupled cavity on resonance and in steady state



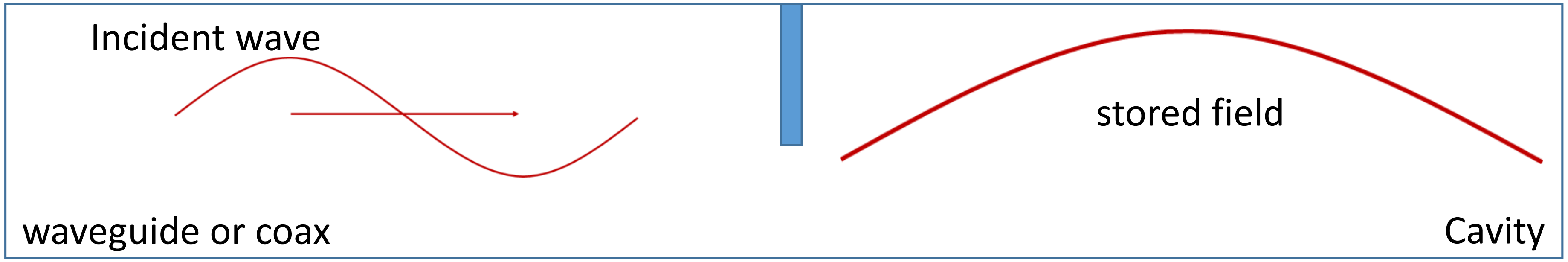


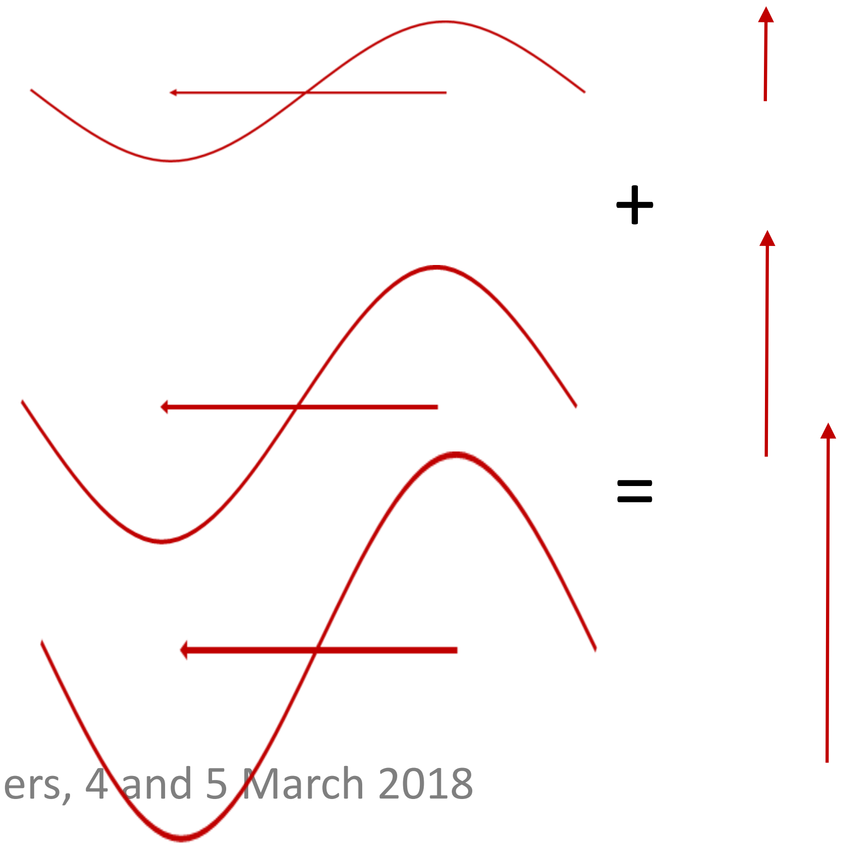
wave reflected from cavity

wave radiated from cavity

Wave amplitude equal to incident wave, so conserves energy

Now flip the phase of incoming signal



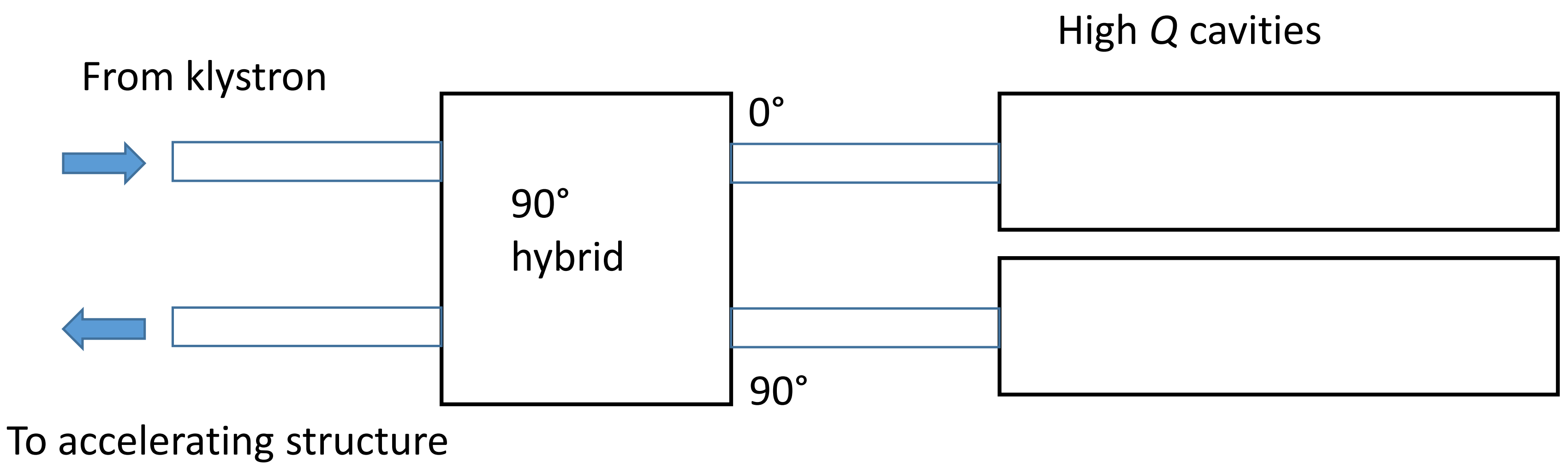


wave reflected from cavity

wave radiated from cavity

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

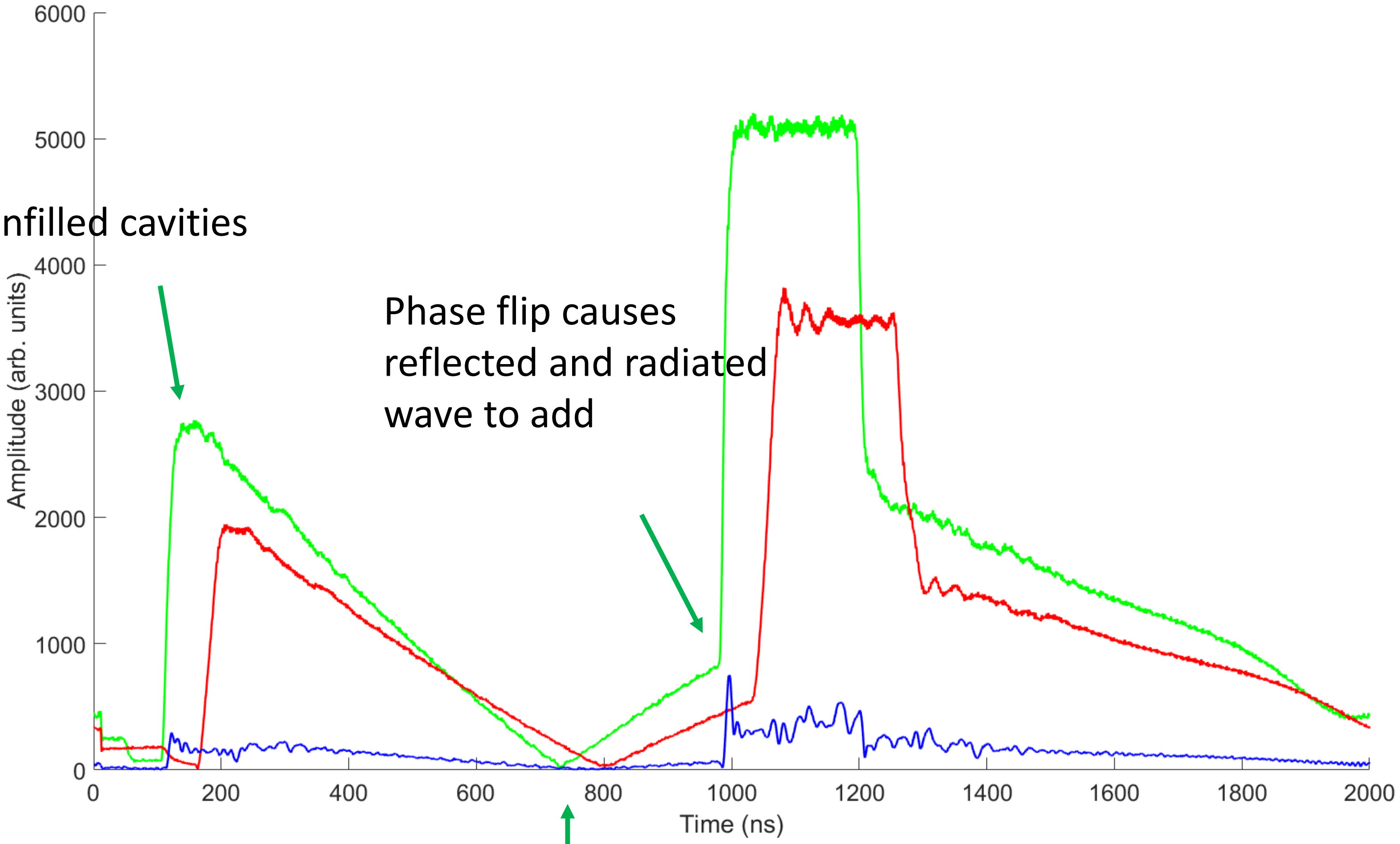
How to get the signal to go in the right direction



A real compressed 12 GHz pulse

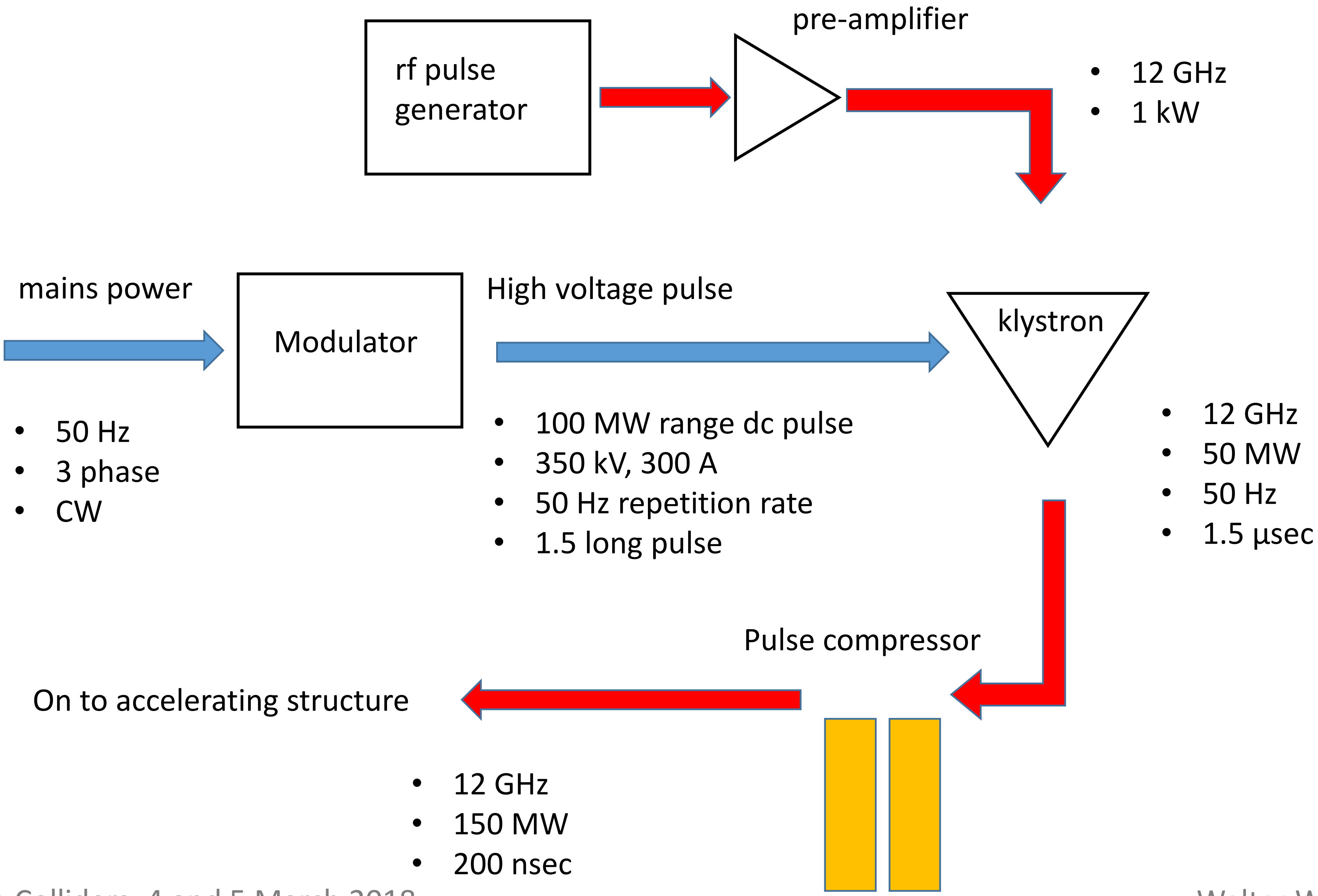
Initial reflection from unfilled cavities

Phase flip causes reflected and radiated wave to add

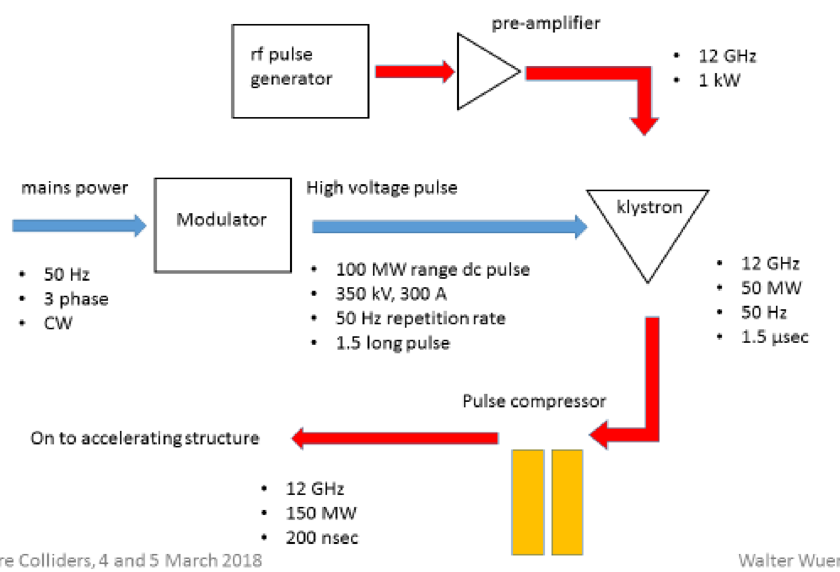


Reflected wave is equal to radiated wave at one point when cavity fills

J. Paszkiewicz


rf pulse generator
pre-amplifier
• 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 Hz repetition rate
• 1.5 long pulse
• 12 GHz
• 50 MW
• 50 Hz
• 1.5 µsec
Pulse compressor
On to accelerating structure
• 12 GHz
• 150 MW
• 200 nsec


ScandiNova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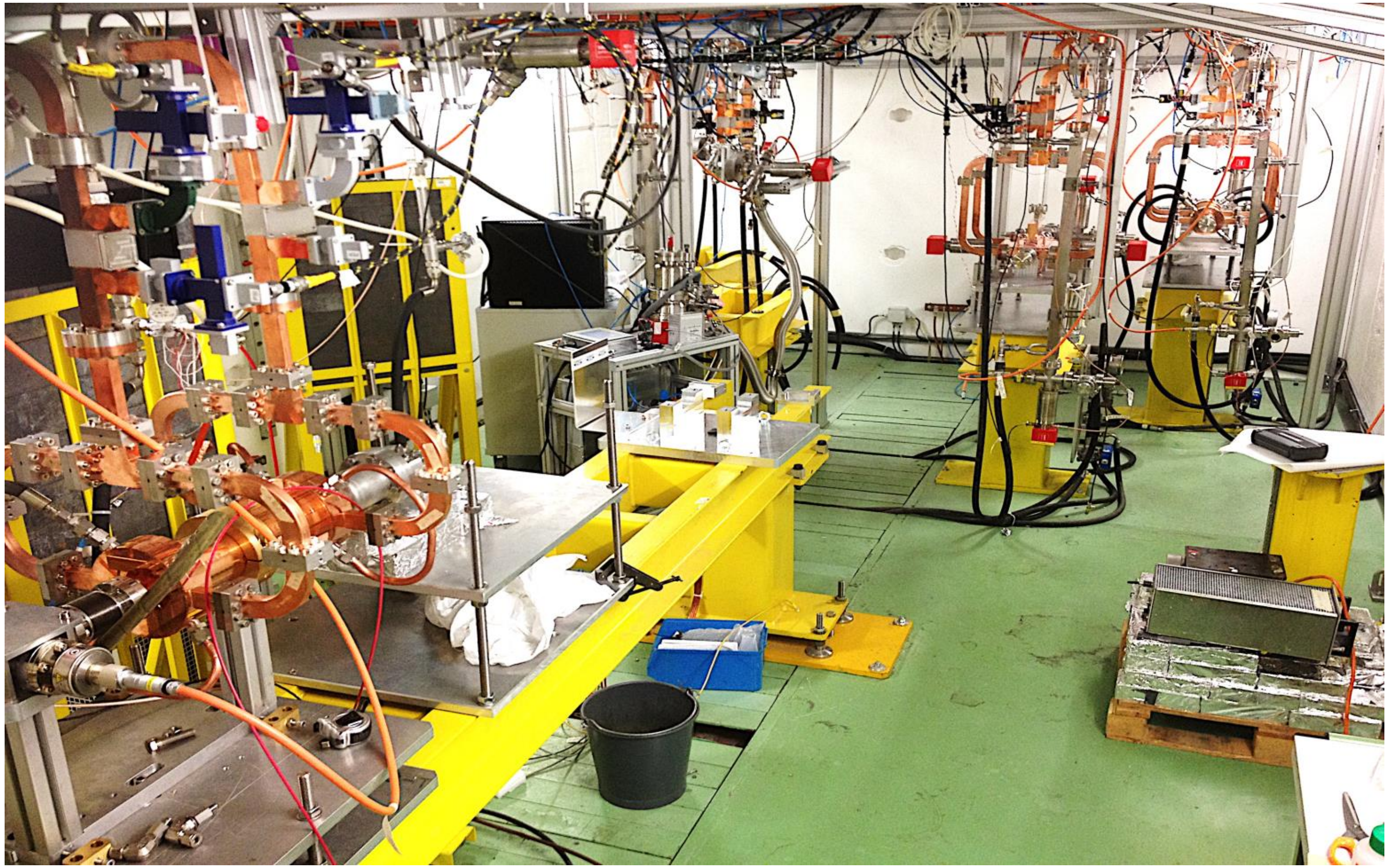
klystron
• 12 GHz
• 50 MW
• 50 Hz
• 1.5 μsec
Pulse compressor
On to accelerating structure
• 12 GHz
• 150 MW
• 200 nsec

On the other side of the wall

So we can now make the peak power.
But what happens when we thump the accelerating structure with 50 MW?
Something called vacuum breakdown. Very complicated and we address next.



Xbox-2 and 3 bunker for accelerating structure tests