HGS-HIRe for FAIR
Helmholtz Graduate School for Hadron and Ion Research

Module 6
Linac architecture (and limitations)

Injectors for ion and electron linacs

Ion injector (CERN Linac1)

Electron injector (CERN LIL)

3 common problems for protons and electrons after the source, up to ~1 MeV energy:

1. large space charge defocusing
2. particle velocity rapidly increasing
3. need to form the bunches

Solved by a special injector

Ions: RFQ bunching, focusing and accelerating.

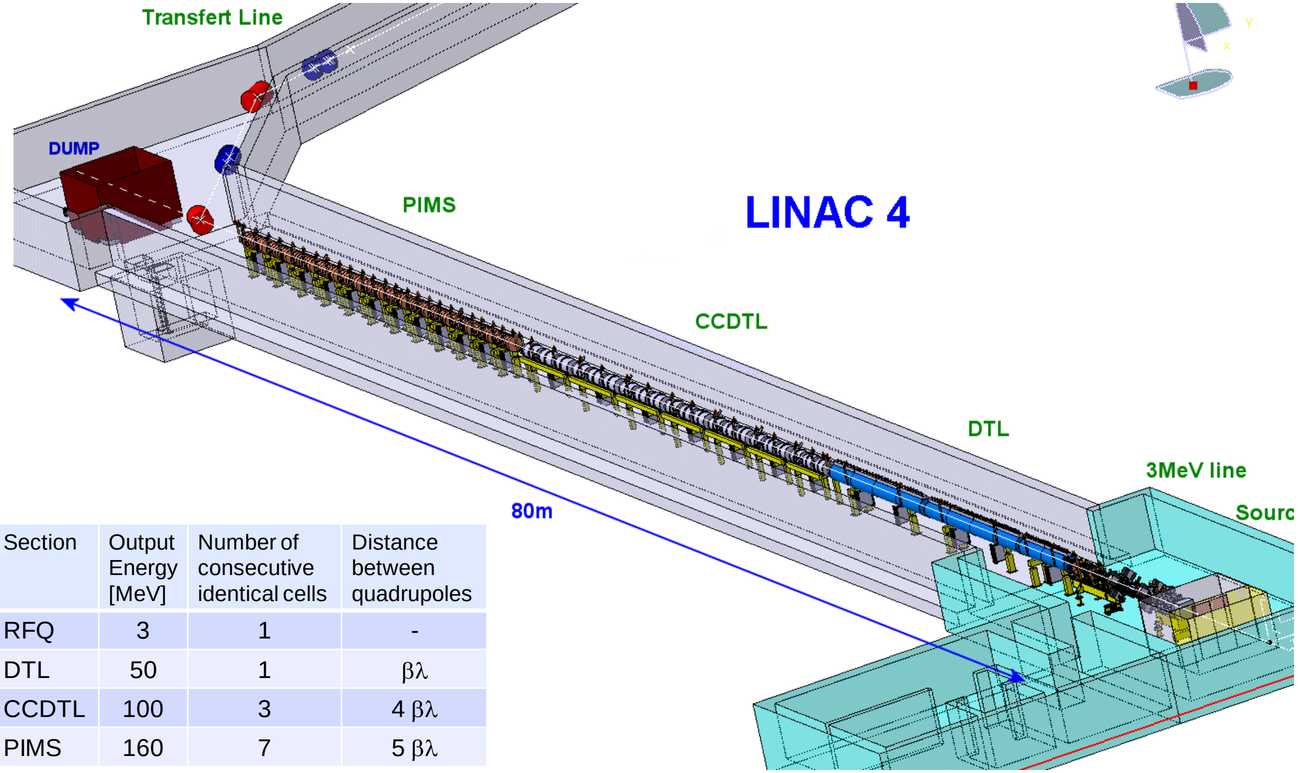
Electrons: Standing wave bunching and pre-accelerating section.

☞ For all particles, the injector is where the emittance is created!

Proton linac architecture – cell length, focusing period

EXAMPLE: the Linac4 project at CERN. H-, 160 MeV energy, 352 MHz.
A 3 MeV injector + 22 multi-cell standing wave accelerating structures of 3 types

DTL: every cell is different, focusing quadrupoles in each drift tube
CCDTL: sequences of 2 identical cells, quadrupoles every 3 cells
PIMS: sequences of 7 identical cells, quadrupoles every 7 cells



Section	Output Energy [MeV]	Number of consecutive identical cells	Distance between quadrupoles
RFQ	3	1	-
DTL	50	1	βλ
CCDTL	100	3	4 βλ
PIMS	160	7	5 βλ

Two basic principles to remember:

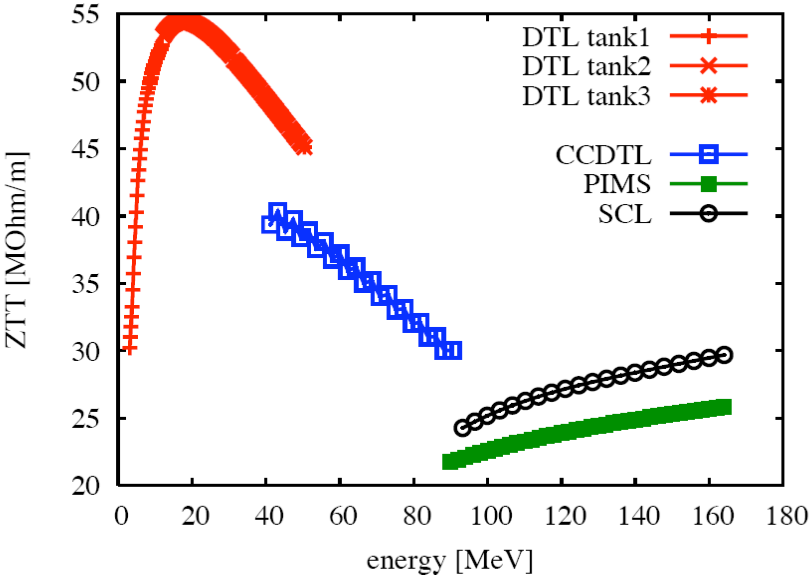
1. As beta increases, phase error between cells of identical length becomes small → we can have short sequences of identical cells (lower construction costs).

2. As beta increases, the distance between focusing elements can increase (more details in 2nd lecture!).

Proton linac architecture – Shunt impedance

A third basic principle:

Every proton linac structure has a characteristic curve of shunt impedance (=acceleration efficiency) as function of energy, which depends on the mode of operation.



DTL	CCDTL	PIMS
Drift Tube Linac	Cell-Coupled Drift Tube Linac	Pi-Mode Structure
18.7 m 3 tanks 3 klystrons	25 m 7 tanks 7 klystrons	22 m 12 tanks 8 klystrons

The choice of the best accelerating structure for a certain energy range depends on shunt impedance, but also on beam dynamics and construction cost.

Effective shunt impedance ZT^2: ratio between voltage (squared) seen by the beam and RF power.

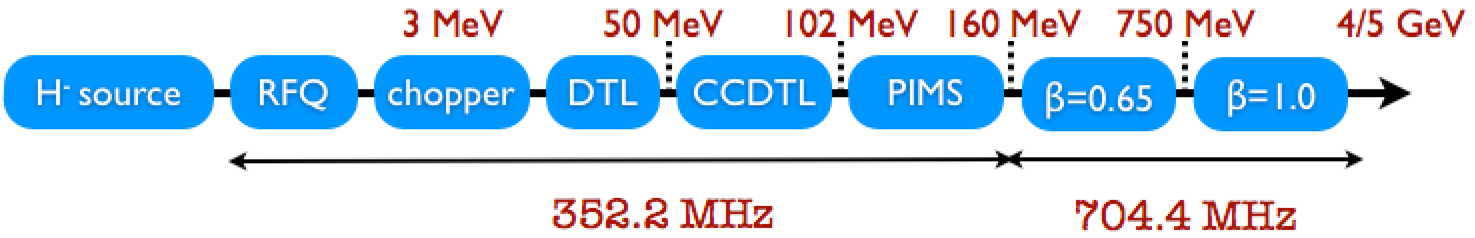
It corresponds to the parallel resistance of the equivalent circuit (apart a factor 2)

$$\Delta W = eE_0T\cos\varphi$$

$$ZT^2 = \frac{V_{eff}^2}{P} = \frac{(E_0T)^2}{P}$$

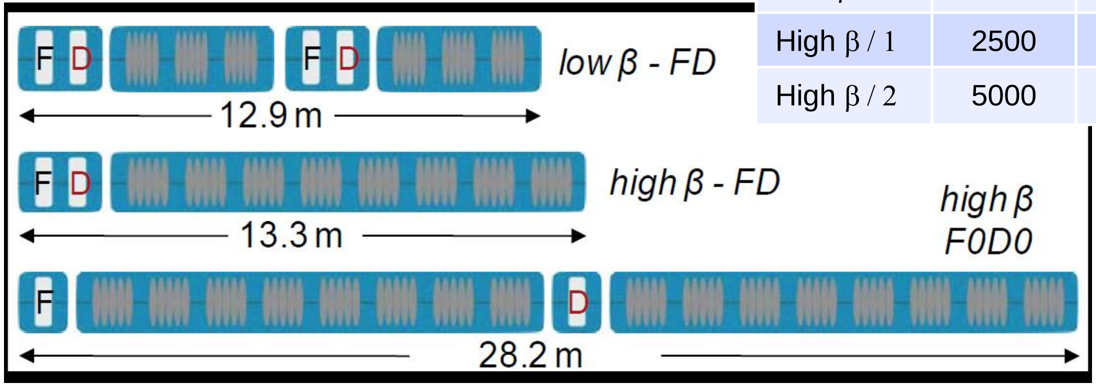
Beyond Linac4: the SPL

Superconducting Proton Linac a CERN project for extending Linac4 up to 5 GeV energy



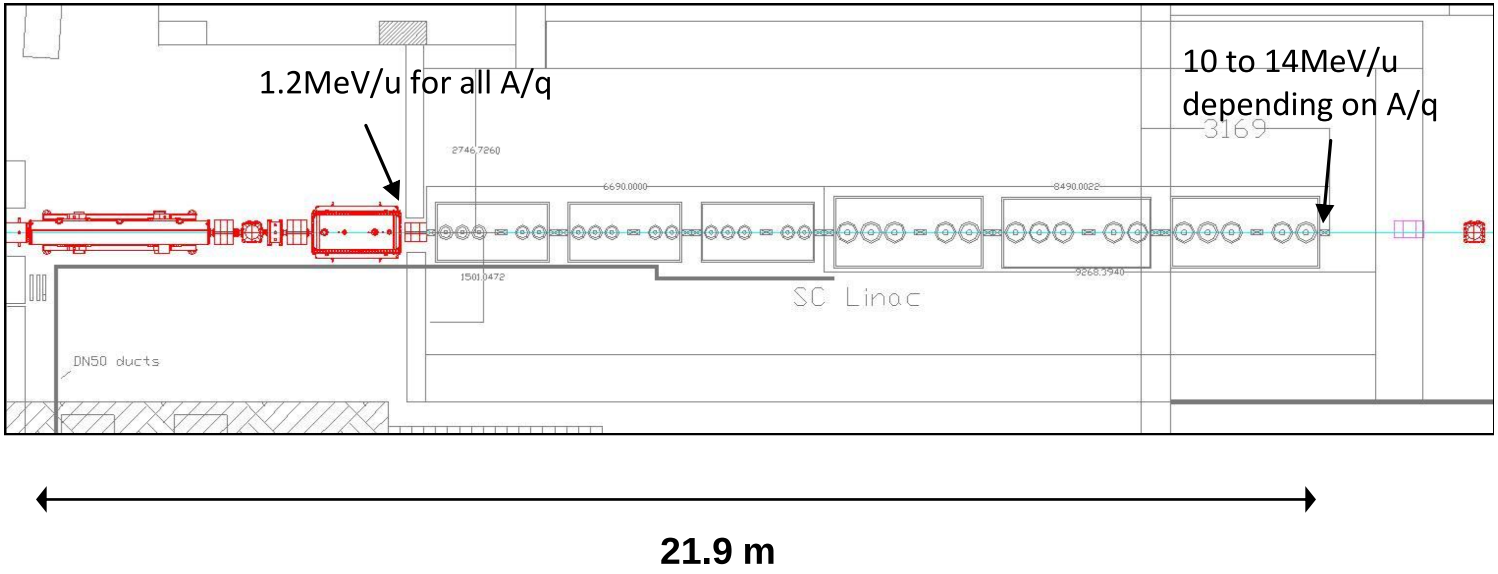
low-beta:
20 cryo-modules with 3 cavities/cryo-module
high-beta -FD:
13 cryo-modules with 8 cavities/module
high-beta -FODO:
10 cryo-modules with 8 cavities/module

Section	Output Energy [MeV]	Lattice	Number of RF gaps between quadrupoles	Number of RF gaps per period	Number of consecutive identical cells
DTL	50	F0D0	1	2	1
CCDTL	102	F0D0	3	6	3
PIMS	160	F0D0	12	24	12
Low β	750	FD	15	15	300
High β / 1	2500	FD	35	35	920
High β / 2	5000	F0D0	35	70	



Heavy Ion Linac Architecture

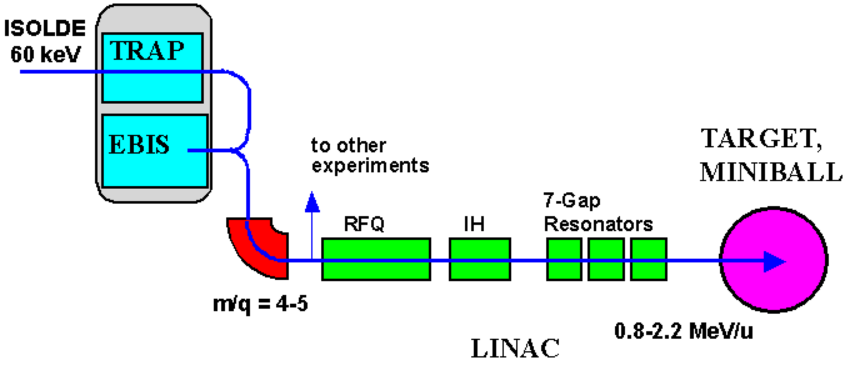
EXAMPLE: the **REX upgrade project at CERN-ISOLDE**. Post-acceleration of radioactive ions with different A/q up to energy in the range 2-10 MeV.
An injector (source, charge breeder, RFQ) + a sequence of short (few gaps) standing wave accelerating structures at frequency 101-202 MHz, normal conducting at low energy (Interdigital, IH) and superconducting (Quarter Wave Resonators) at high energy → mix of NC-SC, different structures, different frequencies.



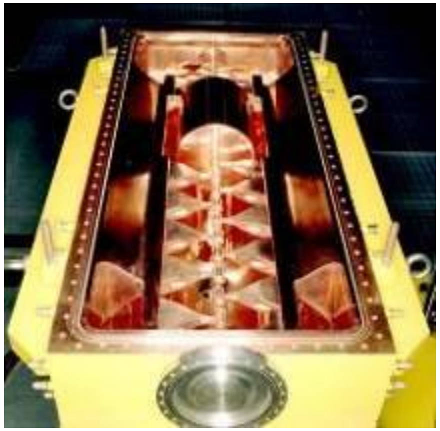
Examples: a heavy ion linac

Particle source

Accelerating structures

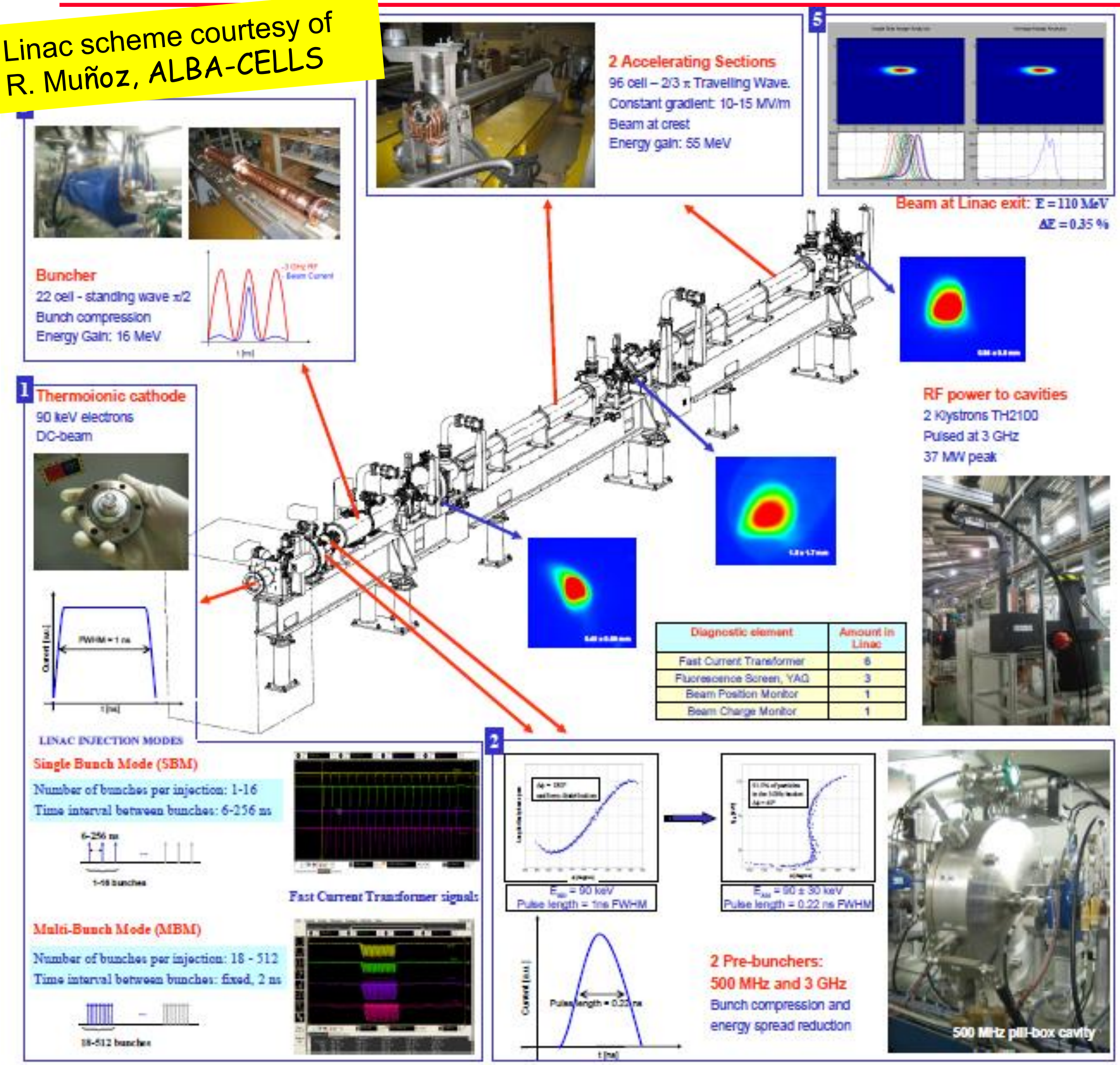


The REX heavy-ion post accelerators at CERN. It is made of 5 short standing wave accelerating structures at 100 MHz, spaced by focusing elements.



Electron linac architecture

Linac scheme courtesy of
R. Muñoz, ALBA-CELLS



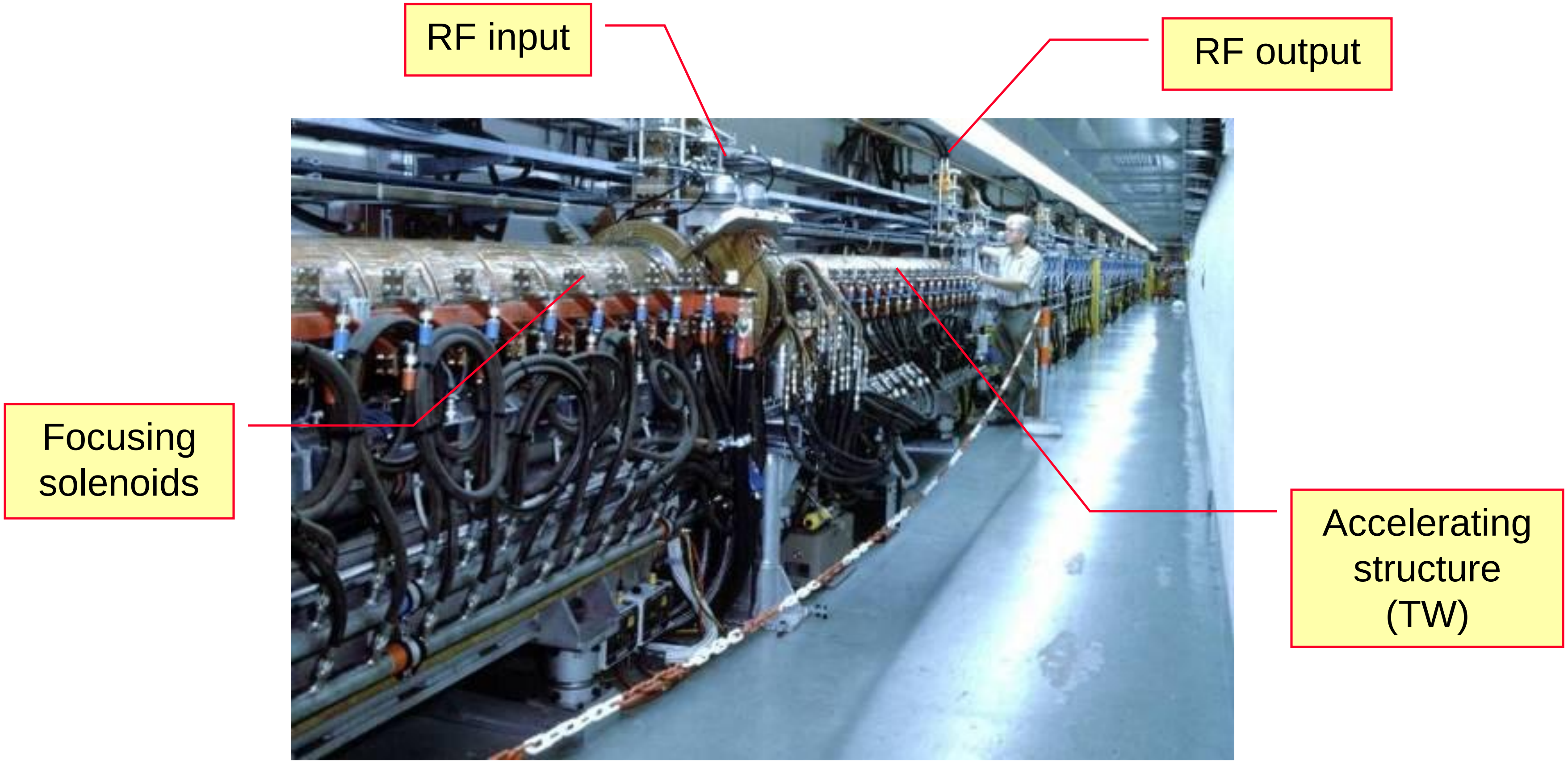
Diagnostic element	Amount in Linac
Fast Current Transformer	6
Fluorescence Screen, YAG	3
Beam Position Monitor	1
Beam Charge Monitor	1

EXAMPLE:
injector linac of the ALBA Synchrotron Light Facility (Barcelona):

100 MeV electron linac supplied by Thales in 2008. Produces a beam up to 4 nC/bunch in either single or multi-bunch mode at repetition rate up to 5 Hz. Normalized beam emittance below 30 π mm mrad.

Injector + sequence of identical multi-cell traveling wave accelerating structures.

Examples: an electron linac



The old CERN LIL (LEP Injector Linac) accelerating structures (3 GHz). The TW structure is surrounded by focusing solenoids, required for the positrons.

Examples: a TW accelerating structure

A 3 GHz LIL accelerating structure used for CTF3. It is 4.5 meters long and provides an energy gain of 45 MeV. One can see 3 quadrupoles around the RF structure.

Linac architecture: superconductivity

Advantages:

- \- Much smaller RF system (only beam power) → prefer low current/high duty
- Large aperture (lower beam loss in the SC section).
- Lower operating costs (electricity consumption).

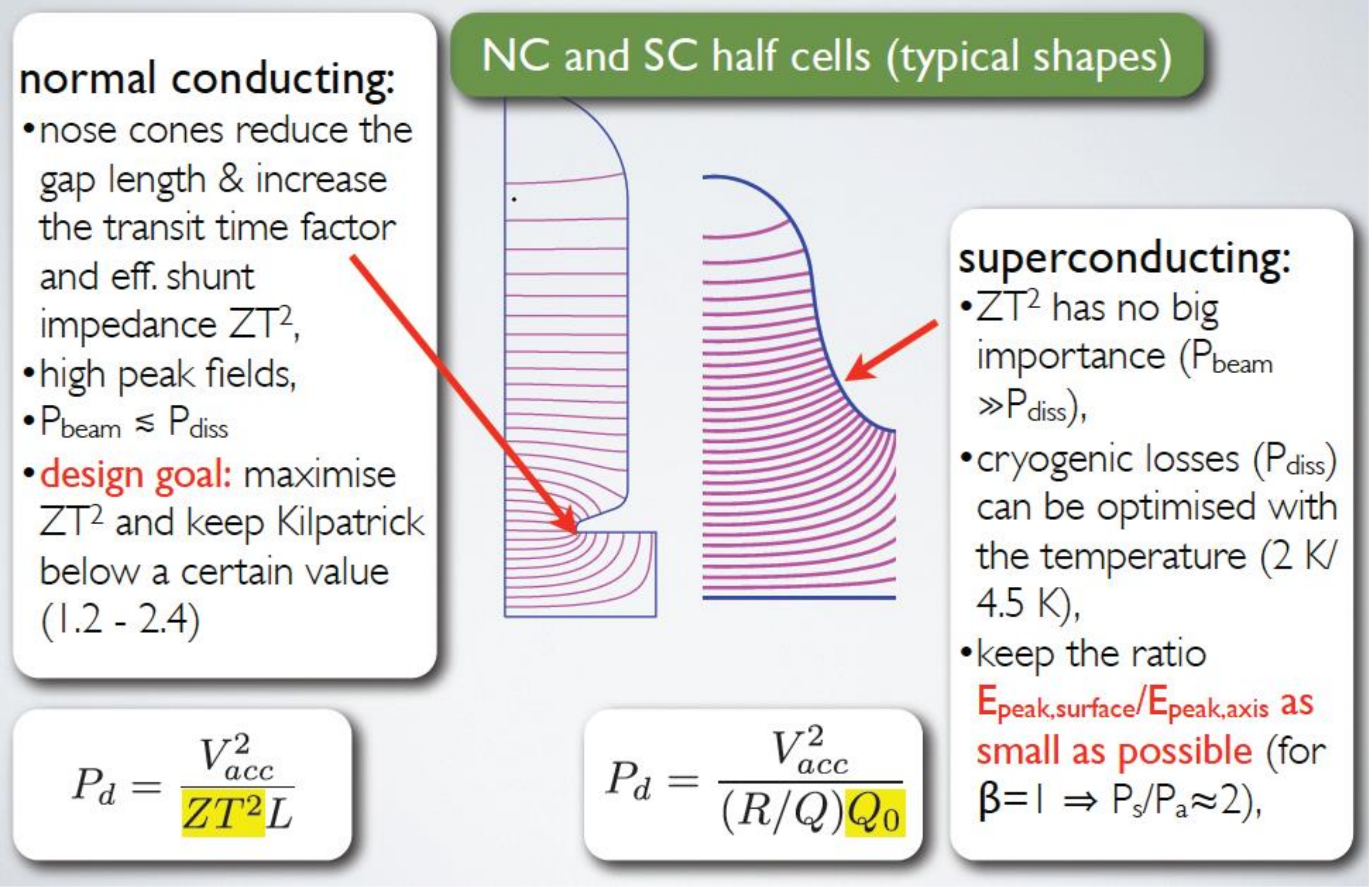
Disadvantages:

- Need cryogenic system (in pulsed machines, size dominated by static loss → prefer low repetition frequency or CW to minimize filling time/beam time).
- Need cold/warm transitions to accommodate quadrupoles → becomes more expensive at low energy (short focusing periods).
- Individual gradients difficult to predict (large spread) → need large safety margin in gradient at low energy.

Conclusions:

1. Superconductivity gives a large advantage in cost at high energy / high duty cycle.
2. At low energy / low duty cycle superconducting sections become expensive.

Comparing NC and SC



normal conducting:

- nose cones reduce the gap length & increase the transit time factor and eff. shunt impedance ZT^2,
- high peak fields,
- $P_{beam} \lesssim P_{diss}$
- design goal: maximise ZT^2 and keep Kilpatrick below a certain value (1.2 - 2.4)

$$P_d = \frac{V_{acc}^2}{ZT^2 L}$$

NC and SC half cells (typical shapes)

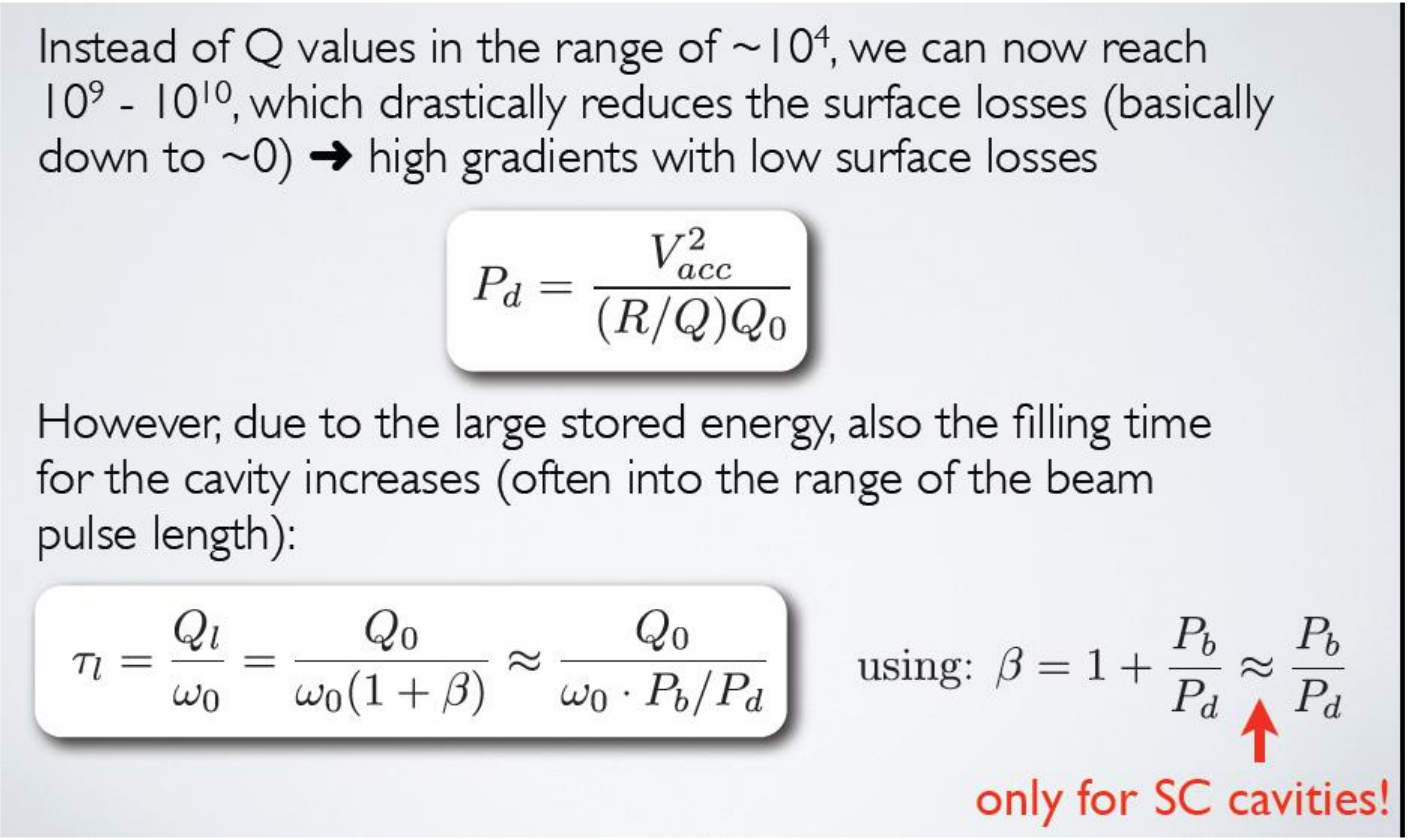
superconducting:

- ZT^2 has no big importance ($P_{beam} \gg P_{diss}$),
- cryogenic losses (P_{diss}) can be optimised with the temperature (2 K/ 4.5 K),
- keep the ratio $E_{peak,surface}/E_{peak,axis}$ as small as possible (for $\beta=1 \Rightarrow P_s/P_a \approx 2$),

$$P_d = \frac{V_{acc}^2}{(R/Q)Q_0}$$

This and the next few slides courtesy of F. Gerigk, CERN

When are SC cavities attractive?



Instead of Q values in the range of ~10^4, we can now reach 10^9 - 10^{10}, which drastically reduces the surface losses (basically down to ~0) ➜ high gradients with low surface losses

$$\boxed{P_d = \frac{V_{acc}^2}{(R/Q)Q_0}}$$

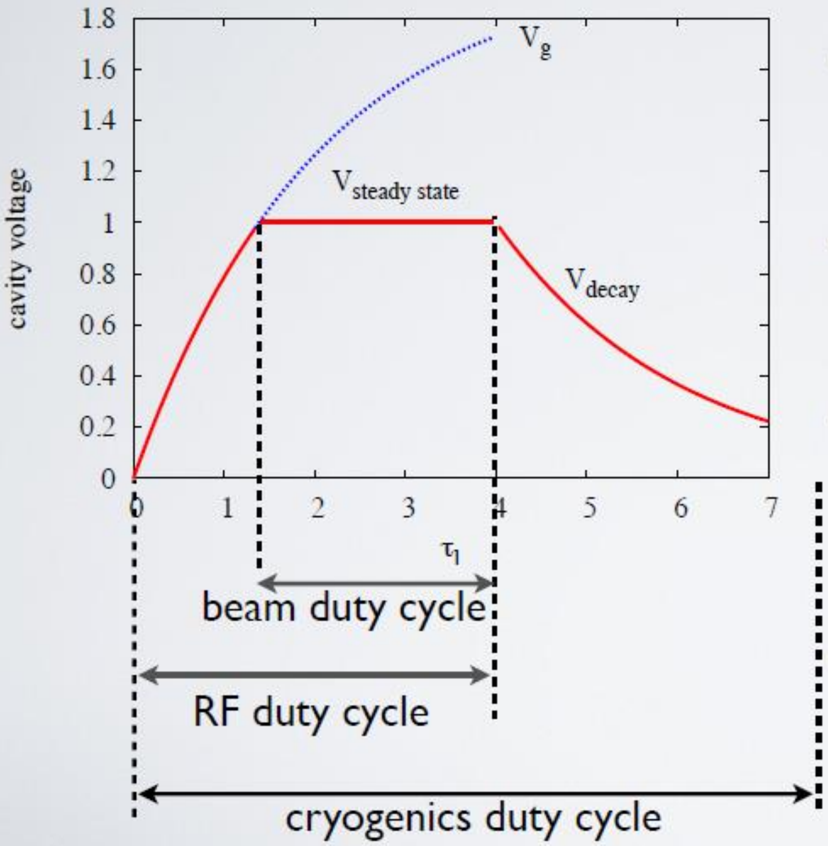
However, due to the large stored energy, also the filling time for the cavity increases (often into the range of the beam pulse length):

$$\boxed{\tau_l = \frac{Q_l}{\omega_0} = \frac{Q_0}{\omega_0(1+\beta)} \approx \frac{Q_0}{\omega_0 \cdot P_b/P_d}}$$

using: $\beta = 1 + \frac{P_b}{P_d} \underset{\uparrow}{\approx} \frac{P_b}{P_d}$

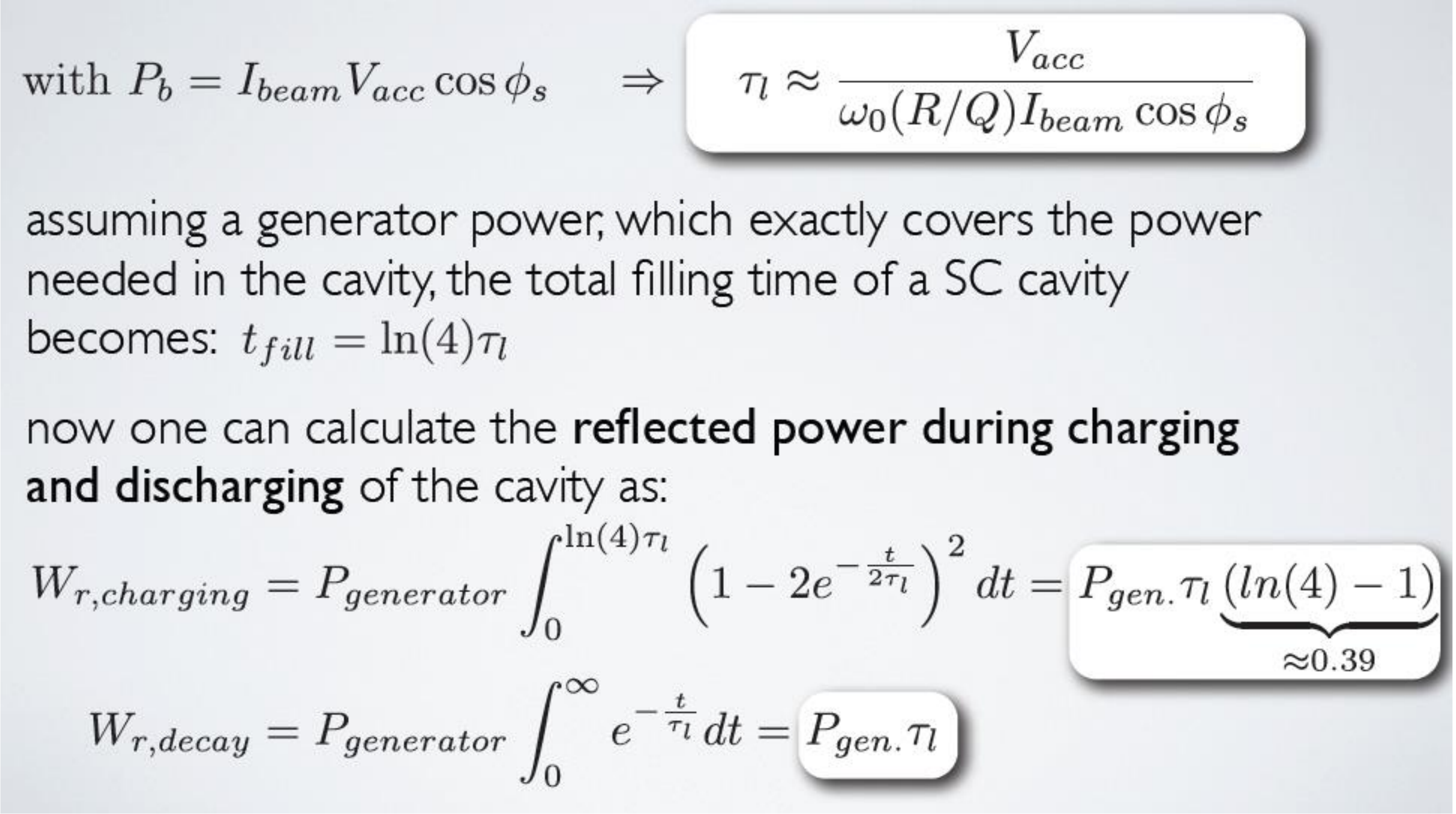
only for SC cavities!

Pulsed operation for SC cavities



- **beam duty cycle:** covers only the beam-on time,
- **RF duty cycle:** RF system is on and needs power (modulators, klystrons)
- **cryo-duty cycle:** cryo-system needs to provide cooling (cryo-plant, cryo-modules, RF coupler, RF loads)
- RF and cryo-duty cycle have to be calculated as **integrals** of voltage over time.

Energy consumption



with $P_b = I_{beam} V_{acc} \cos\phi_s$ $\Rightarrow$ $\boxed{\tau_l \approx \frac{V_{acc}}{\omega_0 (R/Q) I_{beam} \cos\phi_s}}$

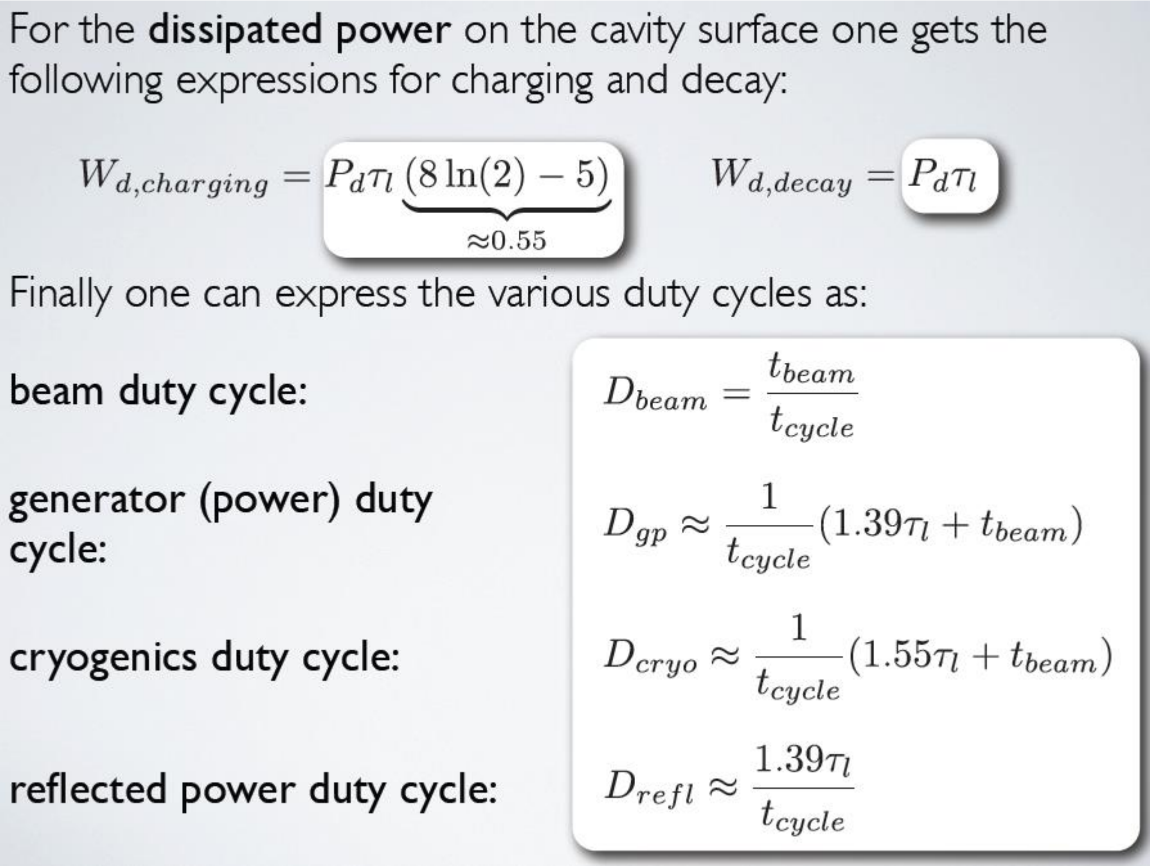
assuming a generator power, which exactly covers the power needed in the cavity, the total filling time of a SC cavity becomes: $t_{fill} = \ln(4)\tau_l$

now one can calculate the **reflected power during charging and discharging** of the cavity as:

$$W_{r,charging} = P_{generator} \int_0^{\ln(4)\tau_l} \left(1 - 2e^{-\frac{t}{2\tau_l}}\right)^2 dt = \boxed{P_{gen.}\tau_l \underbrace{(ln(4) - 1)}_{\approx 0.39}}$$

$$W_{r,decay} = P_{generator} \int_0^{\infty} e^{-\frac{t}{\tau_l}} dt = \boxed{P_{gen.}\tau_l}$$

SC duty cycles



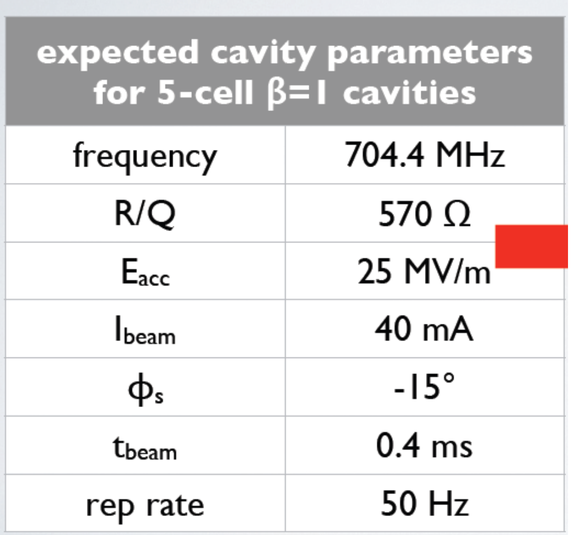
For the **dissipated power** on the cavity surface one gets the following expressions for charging and decay:

$$W_{d,charging} = \boxed{P_d \tau_l \underbrace{(8\ln(2) - 5)}_{\approx 0.55}} \qquad W_{d,decay} = \boxed{P_d \tau_l}$$

Finally one can express the various duty cycles as:

beam duty cycle:	$D_{beam} = \frac{t_{beam}}{t_{cycle}}$
generator (power) duty cycle:	$D_{gp} \approx \frac{1}{t_{cycle}}(1.39\tau_l + t_{beam})$
cryogenics duty cycle:	$D_{cryo} \approx \frac{1}{t_{cycle}}(1.55\tau_l + t_{beam})$
reflected power duty cycle:	$D_{refl} \approx \frac{1.39\tau_l}{t_{cycle}}$

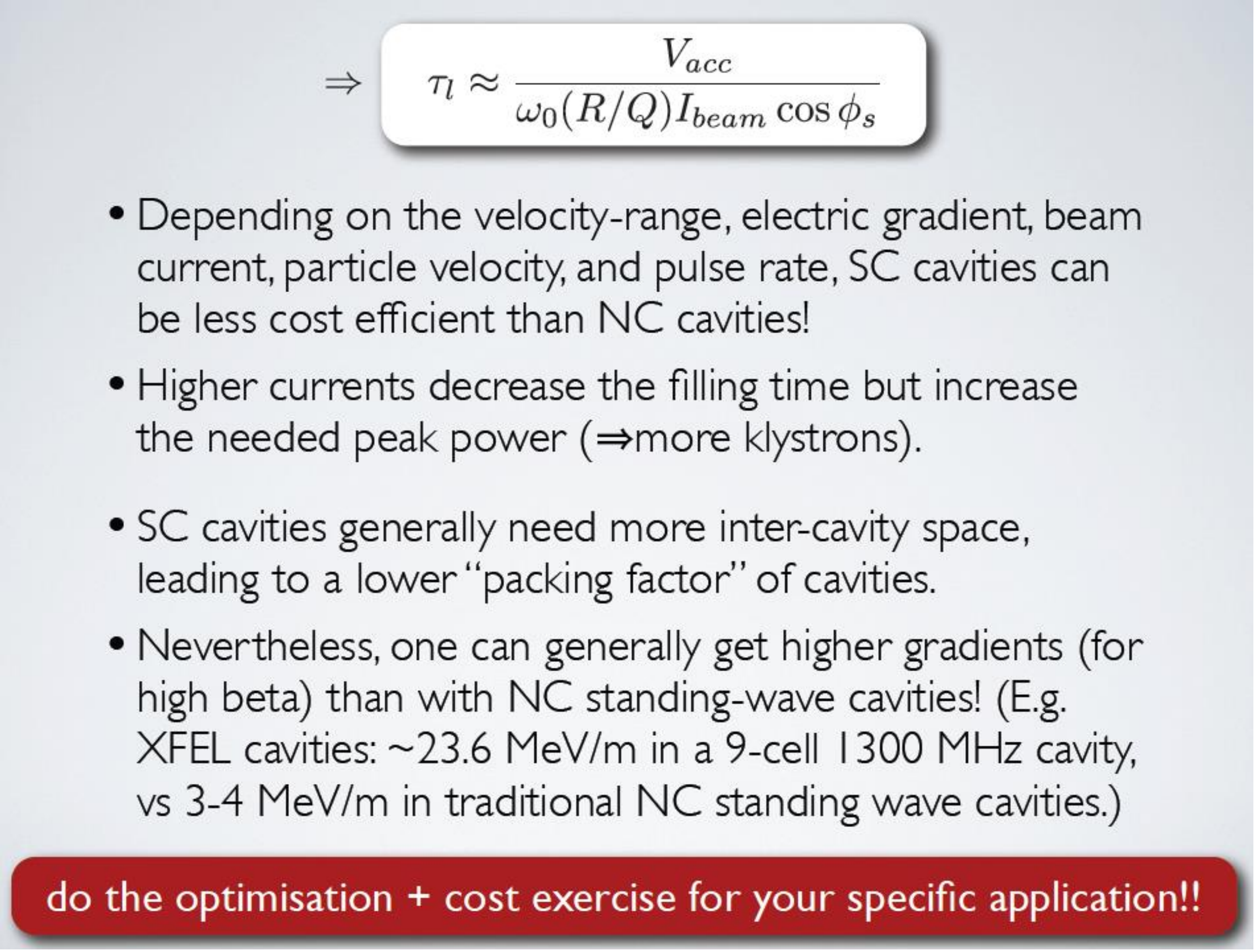
Example: the CERN SPL design



expected cavity parameters for 5-cell β=1 cavities	
frequency	704.4 MHz
R/Q	570 Ω
E_{acc}	25 MV/m
I_{beam}	40 mA
ϕ_s	-15°
t_{beam}	0.4 ms
rep rate	50 Hz

$$\tau_l = 0.27\,ms$$
$$t_{fill} = 0.38\,ms$$
$$D_{beam} = 2\%$$
$$D_{gp} = 3.89\%$$
$$D_{cryo} = 4.11\%$$

Some conclusions



$$\Rightarrow \quad \boxed{\tau_l \approx \frac{V_{acc}}{\omega_0 (R/Q) I_{beam} \cos\phi_s}}$$

- Depending on the velocity-range, electric gradient, beam current, particle velocity, and pulse rate, SC cavities can be less cost efficient than NC cavities!
- Higher currents decrease the filling time but increase the needed peak power (⇒more klystrons).
- SC cavities generally need more inter-cavity space, leading to a lower "packing factor" of cavities.
- Nevertheless, one can generally get higher gradients (for high beta) than with NC standing-wave cavities! (E.g. XFEL cavities: ~23.6 MeV/m in a 9-cell 1300 MHz cavity, vs 3-4 MeV/m in traditional NC standing wave cavities.)

do the optimisation + cost exercise for your specific application!!

Transition warm/cold

The RFQ must be normal conducting (construction problems / inherent beam loss).

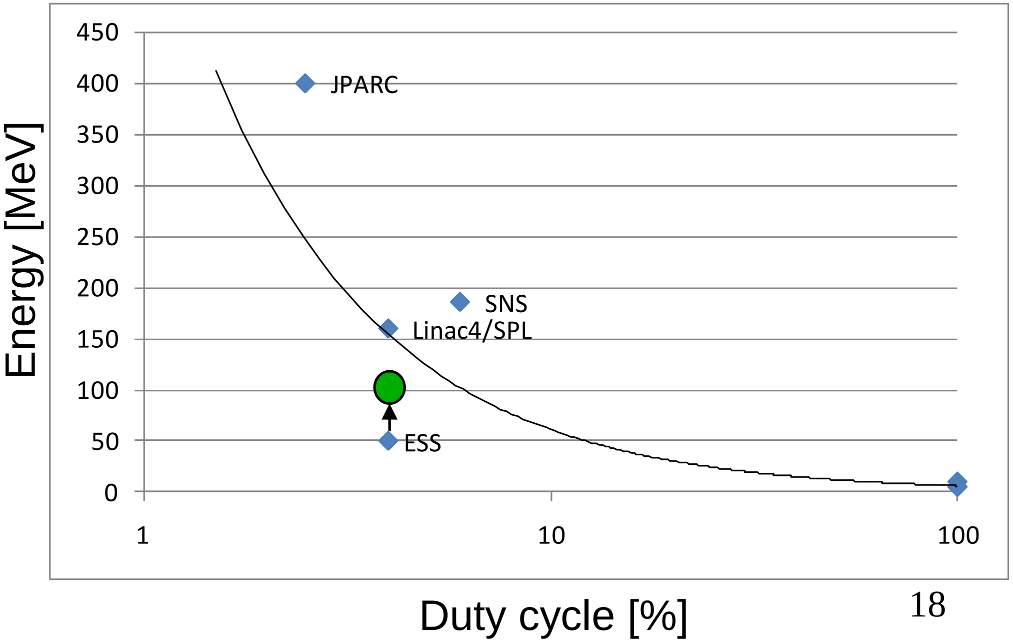
Modern high-energy (>200 MeV) sections should be superconducting.

But where is the optimum transition energy between normal and superconducting?

The answer is in the cost → the economics has to be worked out correctly !

Overview of warm/cold transition energies for linacs (operating and in design)

Project	Duty Cycle [%]	Transition Energy [MeV]
SNS	6	186
JPARC	2.5	400
Linac4/SPL	4	160
ESS	4	90
Project-X	100	10
EUROTRANS	100	5
EURISOL	100	5
IFMIF/EVEDA	100	5



The choice of the frequency

approximate scaling laws for linear accelerators:

➲ RF defocusing (ion linacs)	~ frequency
➲ Cell length (=$\beta\lambda/2$)	~ (frequency)$^{-1}$
➲ Maximum surface electric field	~ (frequency)$^{1/2}$
➲ Shunt impedance (power efficiency)	~ (frequency)$^{1/2}$
➲ Accelerating structure dimensions	~ (frequency)$^{-1}$
➲ Machining tolerances	~ (frequency)$^{-1}$

- Higher frequencies are economically convenient (shorter, less RF power, higher gradients possible) but limitation comes from mechanical precision in construction (tight tolerances are expensive!) and beam dynamics for ion linacs at low energy.
- Electron linacs tend to use higher frequencies (0.5-12 GHz) than ion linacs. Standard frequency 3 GHz (10 cm wavelength). No limitations from beam dynamics, iris in TW structure requires less accurate machining than nose in SW structure.
- Proton linacs use lower frequencies (100-800 MHz), increasing with energy (ex.: 350 – 700 MHz): compromise between focusing, cost and size.
- Heavy ion linacs tend to use even lower frequencies (30-200 MHz), dominated by the low beta in the first sections (CERN lead ion RFQ at 100MHz, 25 keV/u: $\beta\lambda/2$=3.5mm !)

Linac architecture: optimum gradient (NC)

Note that the optimum design gradient (E_0T) in a normal-conducting linac is not necessarily the highest achievable (limited by sparking).

The cost of a linear accelerator is made of 2 terms:
- a “structure” cost proportional to linac length
- an “RF” cost proportional to total RF power

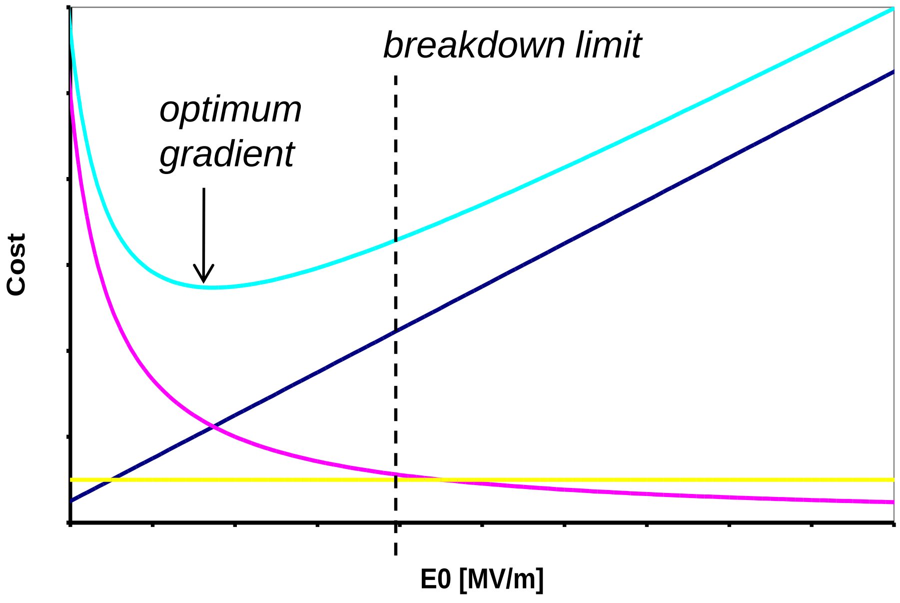
$$\boxed{C = C_s l + C_{RF} P}$$

C_s, C_{RF} unit costs (€/m, €/W)

$$\boxed{l \propto 1/E_0T}$$

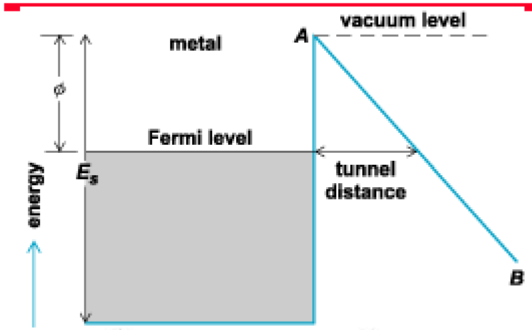
$$\boxed{P \propto (E_0T)^2 l \propto E_0T} \Rightarrow C \propto C_s \frac{1}{E_0T} + C_{RF} E_0 T$$

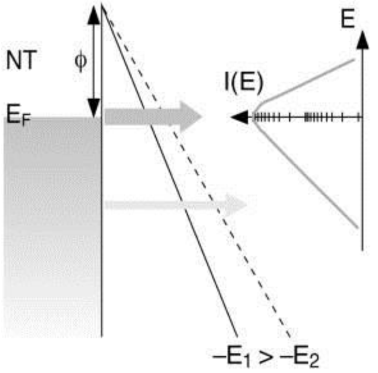
Overall cost is the sum of a structure term decreasing with the gradient and of an RF term increasing with the gradient → there is an optimum gradient minimizing cost.

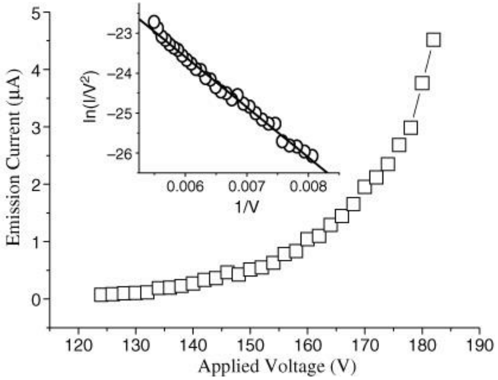


Example: for Linac4
C_S … ~200 kCHF/m
C_{RF}…~0.6 CHF/W (recuperating LEP equipment)
E_0T … ~ 3 – 4 MV/m

On the breakdown limit…







The origin of breakdowns is **FIELD EMISSION**:
Tunneling of electrons through the potential barrier at the boundary metal/vacuum in presence of an applied voltage. Increasing the surface electric field reduces the barrier and increases the number of escaping electrons. The temperature enhances the emitted current (field assisted thermoionic emission).

Quantum mechanics fenomenon, can be calculated: Fowler-Nordheim relation:

$$J(E)=\frac{1.54\cdot 10^{-10}}{\phi}\cdot E^{2}\cdot \exp\left(-\frac{3.21\cdot 10^{-9}\cdot \phi^{3/2}}{E}\right)$$

Current density (A/cm²) emitted by a metal of extraction potential Φ with an applied electric field E, in the limit case of T→0 (with some additional approximations).

The current goes up very quickly (exponential);
a F.-N. behaviour is characterised by a linear ln(I/V)=f(1/V)

Breakdown and impurities

Looking at the numbers, for copper the F.E. current starts to become important only for fields in the region of few GV/m, well beyond normal operating fields in the order of 10-40 MV/m.

(E=1 GV/m → J=5e-17 A/m^2, E=5 GV/m → J=7e11 A/m^2 !!)

But: the theory is valid for smooth and perfect surfaces. A real electrode has marks coming from machining (finite surface roughness) and contains impurities incrusted on the surface (grains). Both these elements increase the surface field (edges for the roughness and dielectric constant for the impurities).

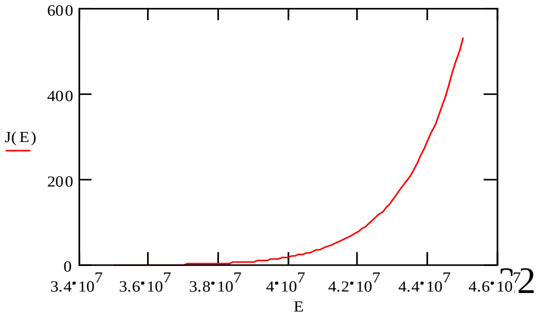
“Mountain and snow”: The real field on the surface is *βE*, adding an “enhancement” factor β.

$$J(E) = 4.83 \cdot 10^{-11} \cdot (\beta \cdot E)^{2.5} \cdot \exp\left(-\frac{6.55 \cdot 10^{10}}{\beta \cdot E}\right)$$

F.-N. formula for copper, with the enhancement factor

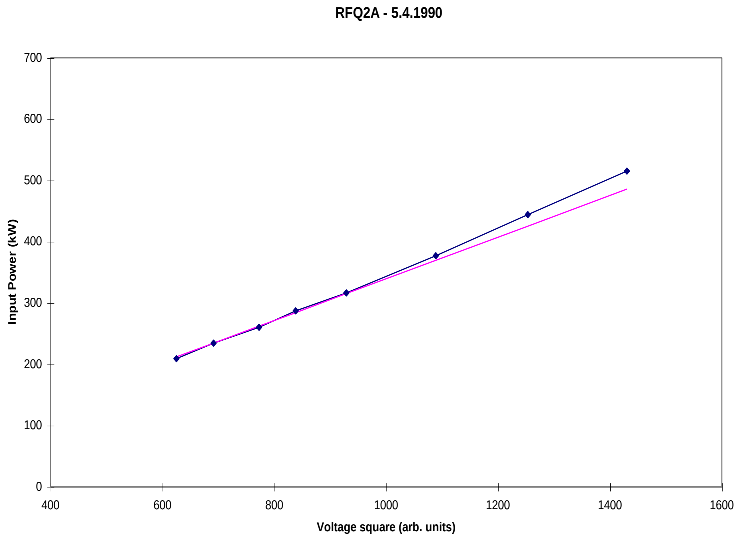
Field emission current is a pre-breakdown phenomenon. When the current at a certain spot goes beyond a certain limit a breakdown starts (the real physics of the phenomenon is still under discussion).

Field emission current is often called « dark current » and can be measured.

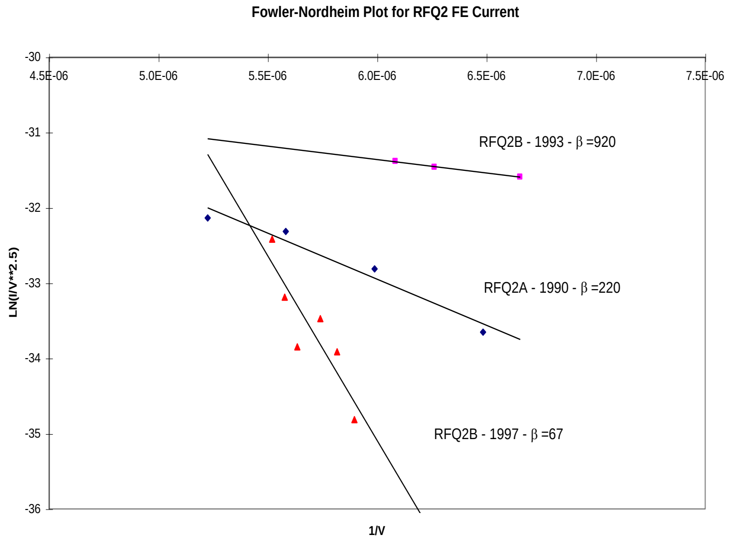


Copper, β=60

Measurement of dark current



Plotting RF power measured at the input of the cavity as function of cavity voltage square (arbitrary units, measures on a pick-up loop at the cavity) we see above a certain power the appearance of dark current accelerated on the gap and absorbing power.



Considering that the dark current power is proportional to gap voltage and to current intensity, we can plot ln(I/V)=f(1/V); the slope of the curve is the enhancement factor.

CERN RFQ2:
β=220 electrodes as out of the workshop
β=920 after a heavy pollution from hydrocarbons from the vacuum system
β=67 after long conditioning

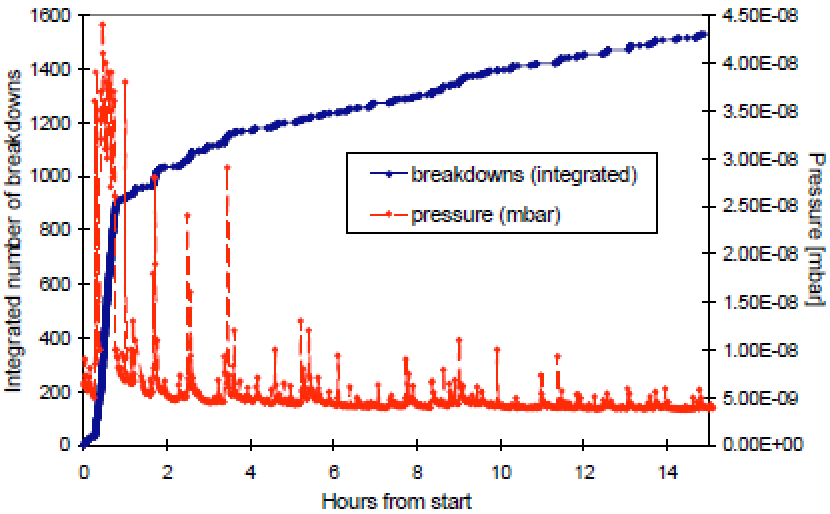
Breakdowns and conditioning

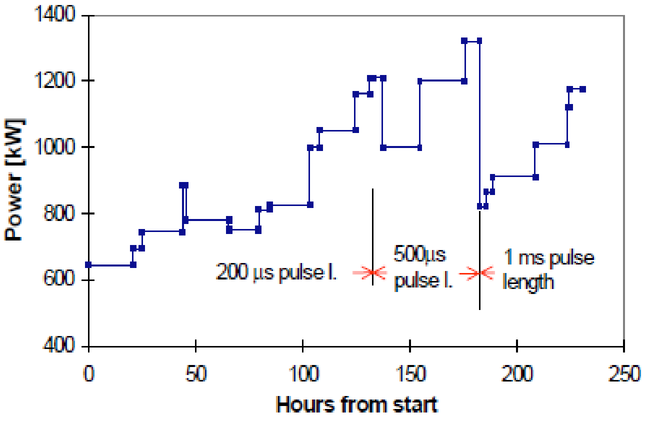
Increasing the voltage, in one or few points the F.-E. current will go above the threshold and start a breakdown.

But the breakdown will reconfigure the surface and there is a certain probability that the new surface will be better (melted spikes, degazed impurities) → we can continue and condition the cavity.

At some point, the number of emitting spots will be so high that we will always find a sparking point → limit of conditioning.

Note that breakdown is a statistic phenomenon. We cannot define a breakdown threshold, instead we can speak of sparking rate (number of breakdown per unit time) as funtion of voltage. The rate is decreased by conditioning; it will decrease asymptotically towards a limiting value.





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The Kilpatrick field

CERN

W. Kilpatrick in 1956 fitted some experimental data on breakdown “levels” in RF regime with a F.-N. type formula, assuming that the breakdown is ignited by the impact on the surface of an ion accelerated on the gap, with energy W:

$$WE^2 \exp(-17/E) = 1.8$$

In the late 60’s at Los Alamos they introduced a calculation of the ion velocity based on gap and frequency (the ion has a transit time factor!) → frequency dependant version of the Kilpatrick criterion:

$$f = 1.64E^2 \exp(-8.5/E)$$

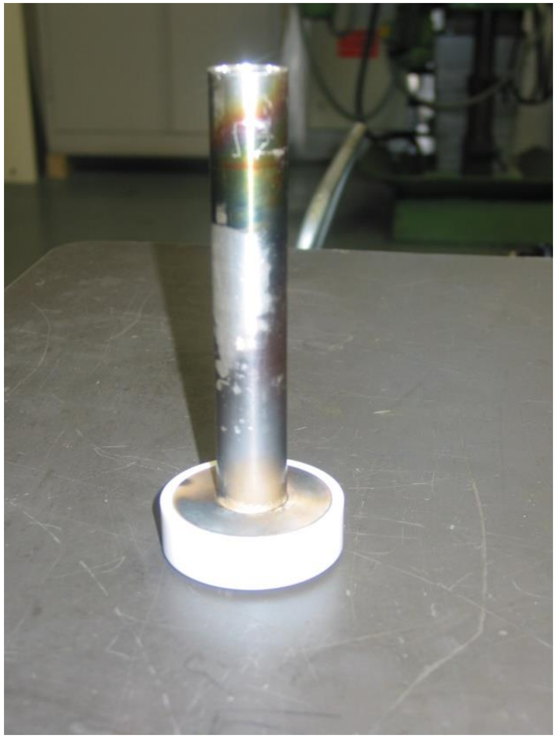
This formula is still used as a reference in the design of linear accelerators! For a given frequency, allows to calculate the “Kilpatrick field”.

Very useful and a good reference, with some caveats:

1. It gives the famous result that maximum field goes as √f ; although demonstrated in several cases, now it is not considered as a fixed law and in particular does not hold >10 GHz, where other phenomena take place.
2. It is not valid for small gaps and low frequencies, where we approach instead the limits for DC field;
3. It gives the wrong message that there is a breakdown threshold;
4. The experimental data were taken in the 50’s with bad vacuums, nowadays a cavity can operate at a few times the Kilpatrick limit.

Usual maximum fields range from about 1 Kilpatrick (CW systems high reliability) to 2.5 Kilpatrick (RFQ2)

Multipactoring



The inner conductor of a coaxial coupler that was (probably by mistake) silver plated and then installed in a CERN linac cavity in 1978. Multipactoring went on for 25 years during normal operation sputtering silver on the window, until it eventually short circuited a Friday night in 2003 stopping all CERN accelerators…

Electron resonance due to secondary emitted electrons from the surfaces.
Occurs at low voltages and can completely stop normal operation of a cavity.

Some causes of multipactoring:

- Dirty surfaces (impurities emitting electrons)
- Air pockets (providing ions and electrons)
- Parallel plate and coaxial geometries (well-defined electron path)
- High pulsing rates (remaining electrons)
- Presence of silver (secondary emission >1)
- Vicinity of a ceramic insulator (high sec. emission)
- Bad luck…

Some cures:

- Conditioning: long times in the mp. region, possibly at higher repetition frequency, heating the surfaces to oxidize them and thus reduce the secondary emission coefficient below 1. Adding a frequency modulation increases the conditioned surface.
- Some paints (aquadag) were used in the past but are not very good for the vacuum.

Questions on Module 6 ?

- Linac architecture
- Superconductivity
- Choice of frequency and gradient
- Field emission, breakdowns, dark current