SSSEPB 2015
Linacs and Bunch Compressors

Lecture #1

8/5/2015

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Schedule

	Monday, Aug 3	Tuesday, Aug 4	Wednesday, Aug 5	Thursday, Aug 6	Friday, Aug 7
8:30	Introduction - C. Pellegrini (0.5)	Introduction to FEL Physics - A. Marinelli (2)	Linacs and Bunch Compressors - T. Raubenheimer (1.5)	Electron Beam Diagnostics - T. Maxwell (1.5)	Presentations (1.5)
9:00	Science with FELs - J. Hastings (1)				
9:30					
10:00	Break (0.5)		Break (0.5)	Break (0.5)	Break (0.5)
10:30	Electron and Photon Beam Physics - Z. Huang (1.5)	Break (0.5)	Linacs and Bunch Compressors - T. Raubenheimer (1.5)	Photon Beam Lines, D. Cocco (1.5)	Presentations (1.5)
11:00		Science and Technology of Undulator Magnets - S. Prestemon (1)			
11:30					
12:00	Lunch (1)	Lunch (1)	Lunch (1)	Lunch (1)	Lunch (1)
12:30					
13:00	Electron and Photon Beam Physics - Z. Huang (1)	High Brightness Electron Sources - D. Dowell (2)	Tours - LCLS, NLCTA, ASTA (2)	Advanced Laser/Plasma Accelerators and Applications - M. Hogan (1)	Presentations (2)
13:30					
14:00	Intro to presentation topics & working groups - G. Marcus (1)			Advanced FEL Topics - E. Hemsing (1)	
14:30					

Topics

Acceleration

- RF Cavities
- NCRF and SCRF Technology

Emittance Preservation

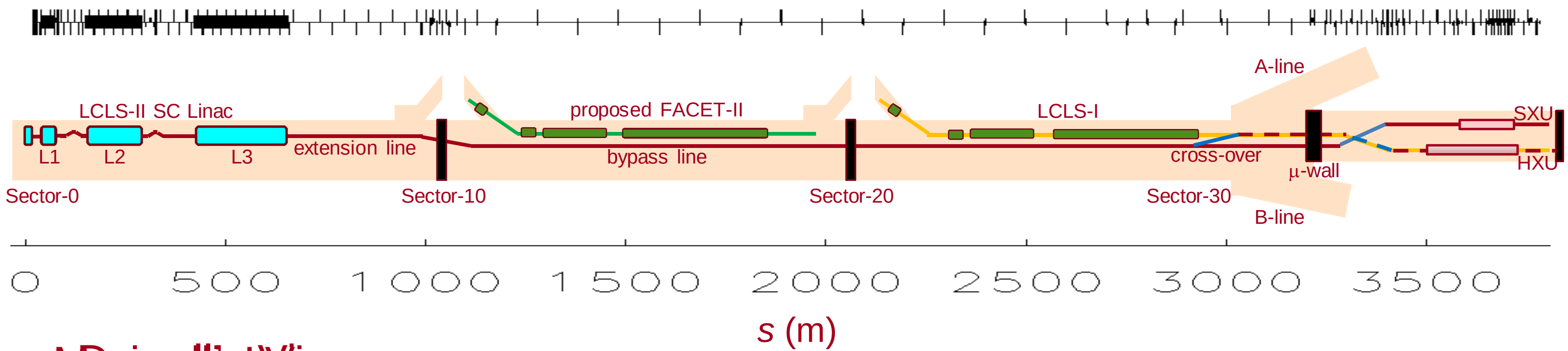
- Phase Space and 6D Emittance
- Synchrotron Radiation
- Wakefields

Bunch Compression

- Linear and Nonlinear Optics
- Space Charge and Wakefields
- Micro-bunching effects

Linac Schematic

LCLS-II Project



Dave Dowell's View

Ago Marinelli's View

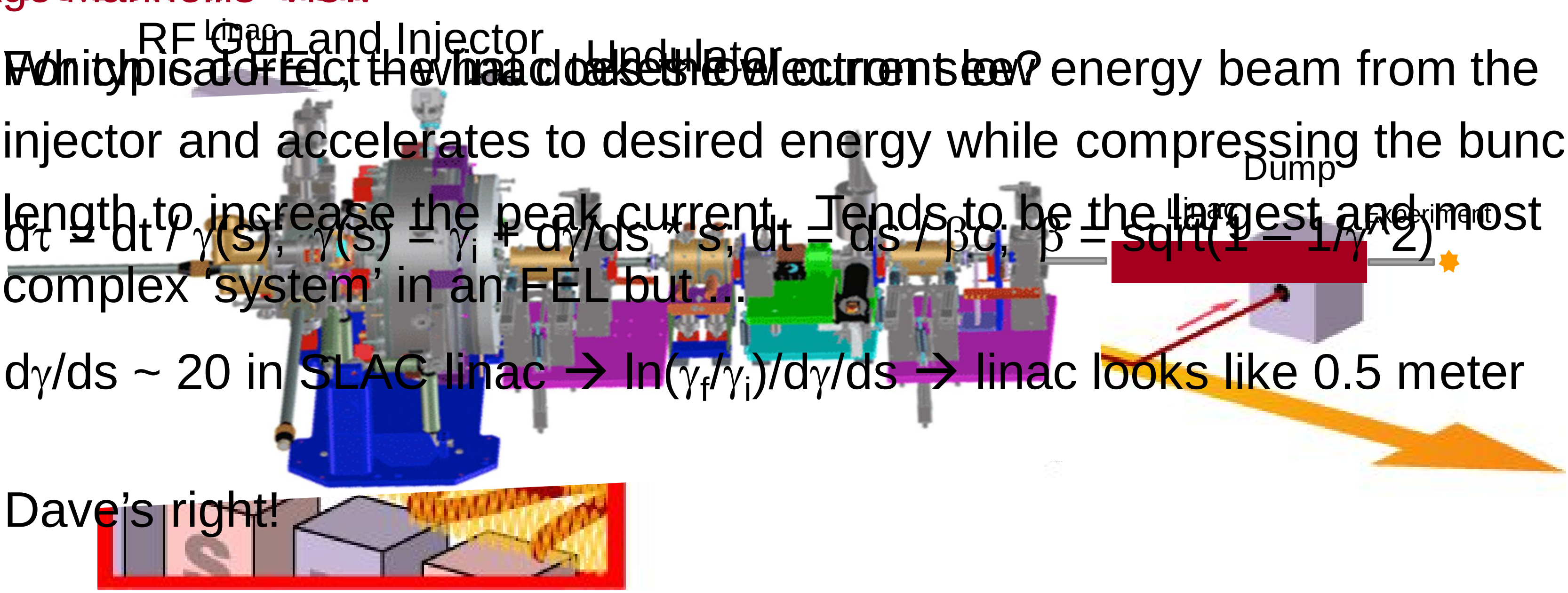
For typical FEL, the linac takes the low energy beam from the injector and accelerates to desired energy while compressing the bunch length to increase the peak current. Tends to be the largest and most complex 'system' in an FEL but…

Which direction does the electron see?

$d\tau = dt / \gamma(s)$; $\gamma(s) = \gamma_i + d\gamma/ds * s$; $dt = ds / \beta c$; $\beta = \mathrm{sqrt}(1 - 1/\gamma^2)$

$d\gamma/ds \sim 20$ in SLAC linac → $\ln(\gamma_f/\gamma_i)/d\gamma/ds$ → linac looks like 0.5 meter

Dave's right!



Lorentz Force

- Lorentz force

$$\boldsymbol{F} = e\boldsymbol{E} + e\boldsymbol{v} \times \boldsymbol{B}$$

- Momentum and energy change

$$\Delta \boldsymbol{p} = \int \boldsymbol{F} dt$$

$$\Delta E = \int \boldsymbol{F} d\boldsymbol{s}$$

$$d\boldsymbol{s} = \boldsymbol{v} dt$$

- **Energy exchange through *E* field only**

$$\Delta E = \int \boldsymbol{F} d\boldsymbol{s} = e \int \boldsymbol{E} \cdot d\boldsymbol{s} + e \int \underbrace{(\boldsymbol{v} \times \boldsymbol{B}) \cdot \boldsymbol{v} dt}_{= 0}$$

No work done by magnetic field!

Longitudinal Acceleration

Have to provide longitudinal electric fields

1. DC voltage – typically breaks down at << 1 MV/m
2. Induction accelerators
3. Microwave (RF) accelerators – NCRF gets up to 100~200 MV/m
4. Laser (high frequency rf) and plasma accelerators – discussed by Hogan

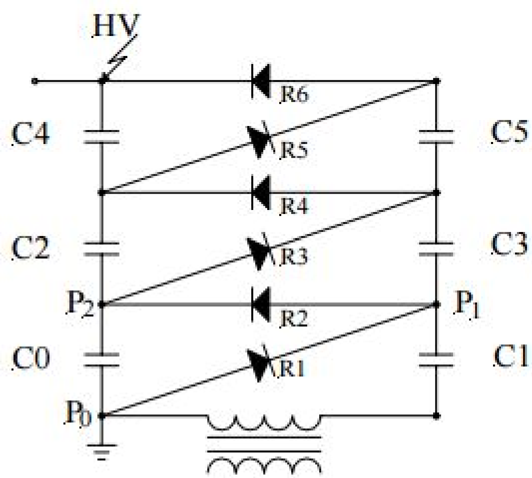
Most FEL's and light sources use high energy $\gamma >> 1$ electrons

Why?

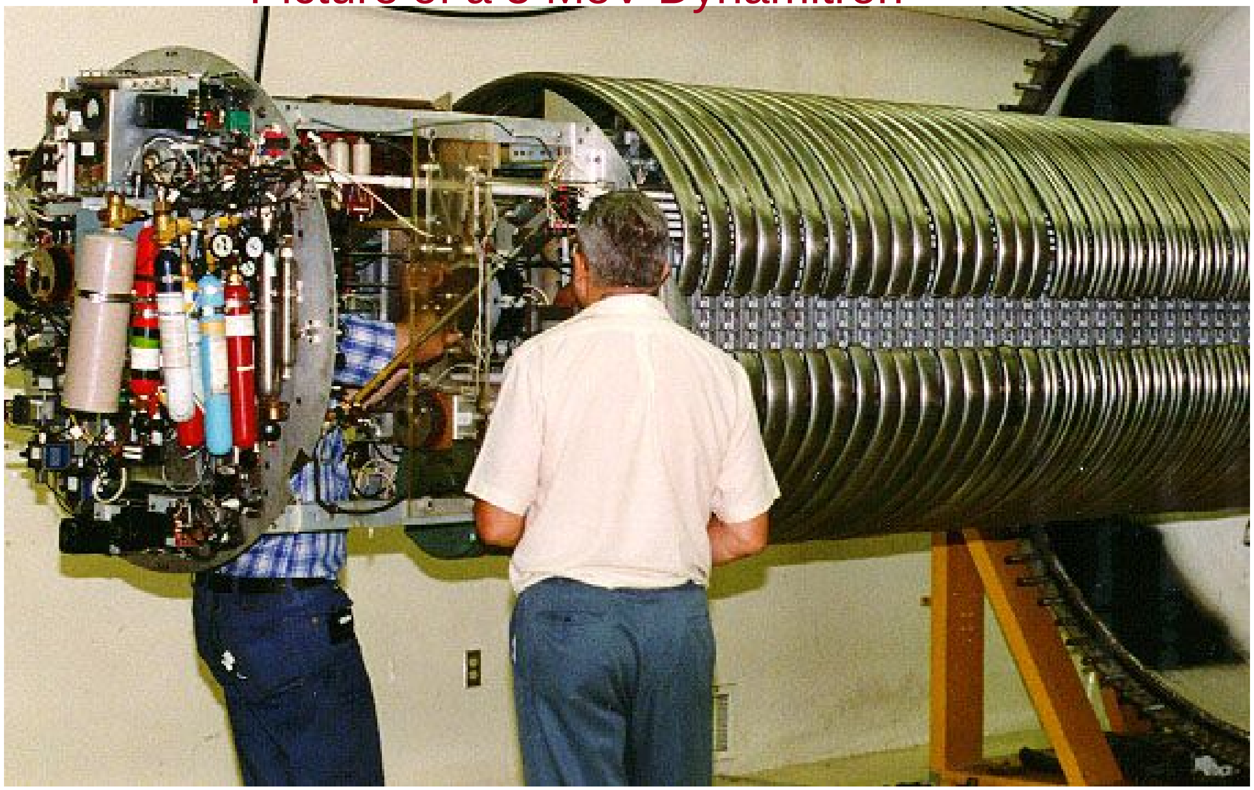
$P_{SR} \sim e^4E^2B^2 / m^4$ → very strong function of particle mass (and charge)

DC Accelerators

Many types of DC accelerators including electrostatic and 'electrodynamic' → latter can produce MW's of beam at a few MeV and are frequently used for irradiation systems such as sterilization or cross-linking of plastics, etc.



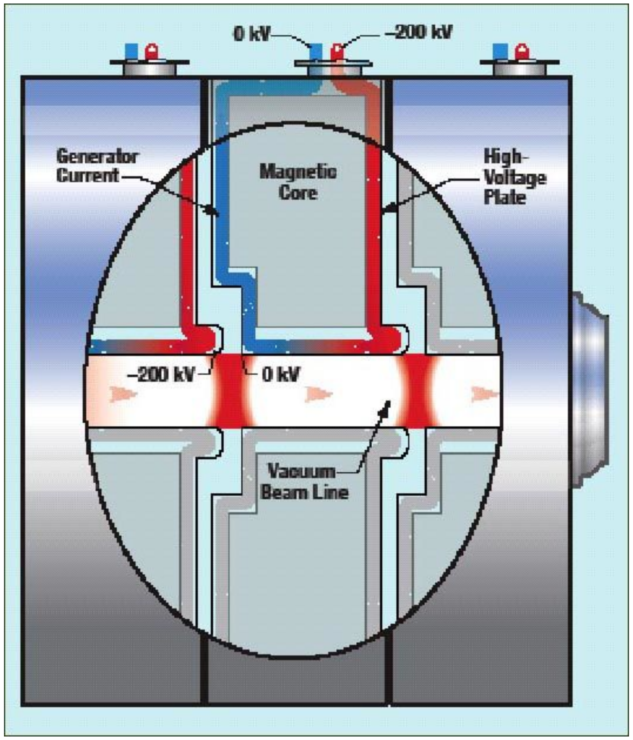
Picture of a 5 MeV Dynamitron



Induction Accelerators

Two type of induction accelerators: betatron and an induction linac.
Both analagous to a transformer where the beam is the secondary coil.

Betatron: the changing magnetic field induces a longitudinal acceleration. Limited to ~300 MeV and low duty cycle.

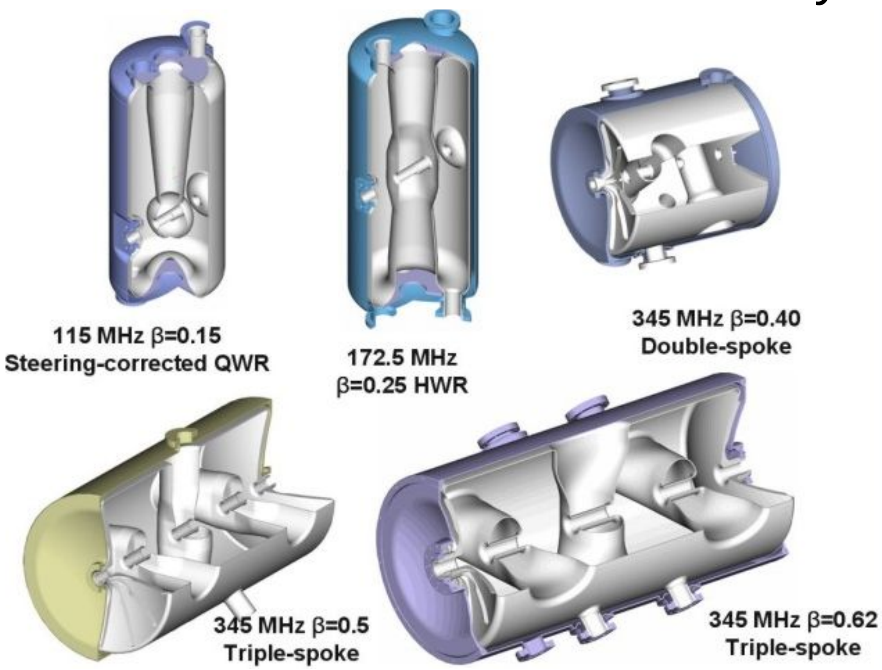


Induction Linac: use the magnetic material to 'hold-off' the current flow → voltage differential

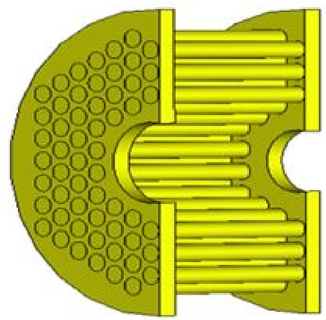
Well matched to very high current but with low gradient of a ~MV/m

Types of Microwave Cavities

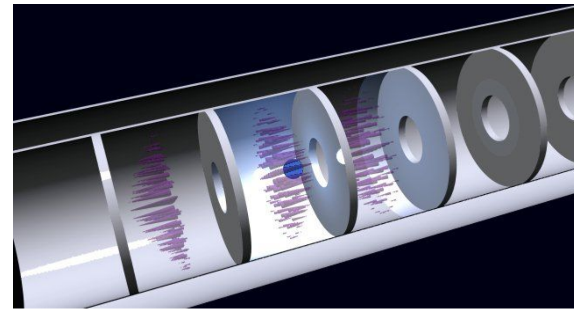
Lots of different microwave cavity configurations!



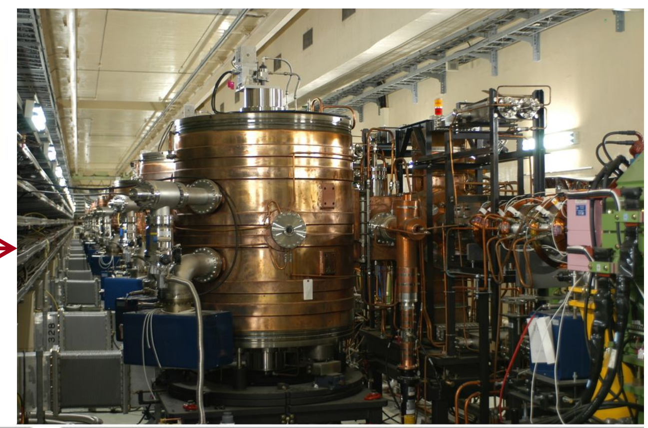
Open band gap



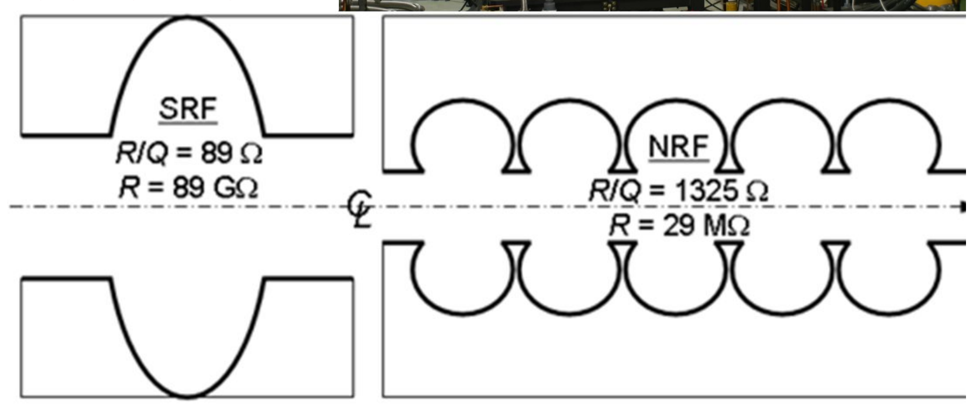
Disk and washer like SLAC



Shintake energy storage cavity



SCRF struct. and re-entrant NCRF



Electron linacs are typically based on TM_{010} cavities having cylindrical geometry with $\beta \sim 1$

Microwave Cavities

In free-space, no net acceleration can arise from a plane wave.

Use metallic boundaries to ‘force’ modes that have longitudinal electric fields. Find, modes by solving wave equation ala Jackson or Collins or text of choice. Excite these modes resonantly with rf sources.

For a perfect conductor, no tangential electric field on boundaries and tangential magnetic field is due to surface current

In a real conductor, the skin depth is the attenuation length of the electric/magnetic field. Scales as 1/sqrt(f).

To set scale, in copper, ~1 cm at 60 Hz and ~1 um at 3 GHz.

Cylindrical Microwave Cavities

Solve for longitudinal component of electric or magnetic field

$$\frac{\partial^2 E_{0z}}{\partial r^2} + \frac{1}{r}\frac{\partial E_{0z}}{\partial r} + \frac{1}{r^2}\frac{\partial^2 E_{0z}}{\partial \theta^2} + \left(\frac{\omega^2}{c^2} - k^2\right)E_{0z} = 0$$

Assume longitudinal component has form: $E_z = E_{0z}(r,\theta)\, e^{-i(kz\text{-}wt)}$.

Separate variables and end up with Bessel's Eq for radial dependance along with azimuthal modes of the form $e^{in\theta}$.

Don't worry, we won't do this here!

But it will be a home work problem

RF Acceleration – TM010-mode

$$E_z = E_0 J_0\left(\frac{2.405r}{R}\right)e^{-i\omega t}$$

$$H_z = 0$$

$$H_r = 0$$

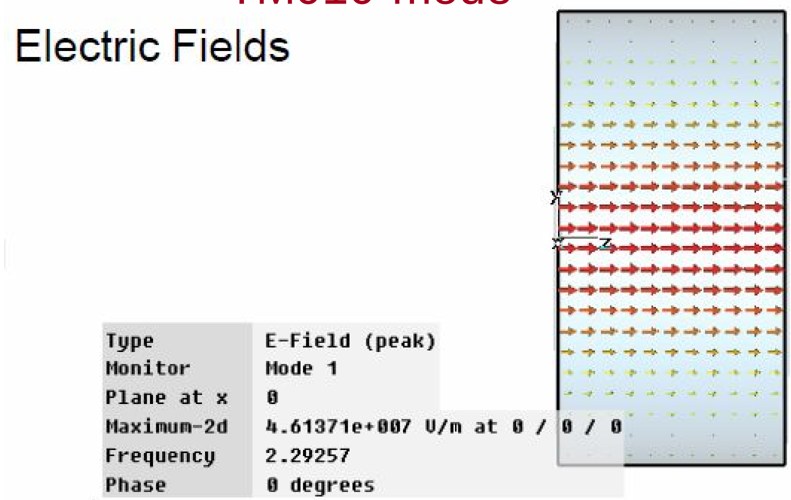
$$H_\varphi = \frac{-i}{Z_0}E_0 J_1\left(\frac{2.405r}{R}\right)e^{-i\omega t}$$

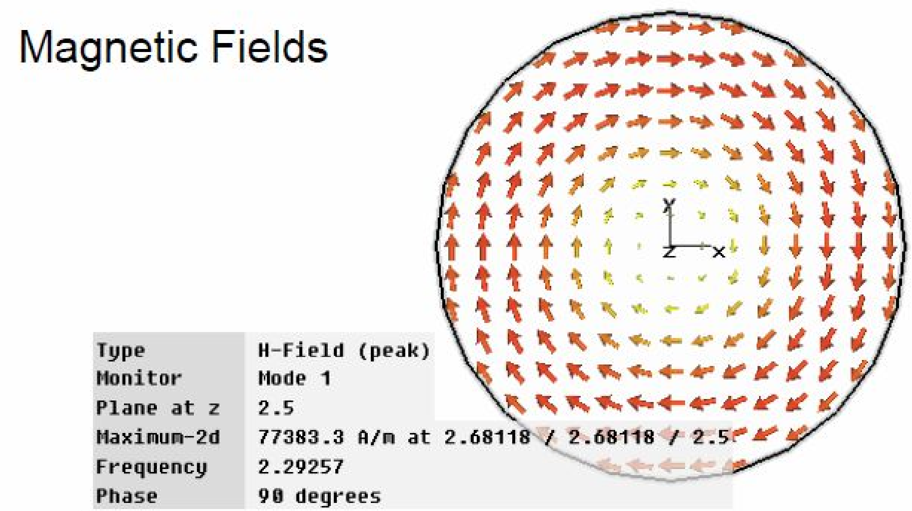
$$E_\varphi = 0$$

$$E_r = 0$$

Longitudinal electric field accelerates particles while azimuthal magnetic field heats cavity walls and causes losses

TM010-mode





Skin Depth and Boundaries

Conduction electrons are accelerated to cancel the magnetic field

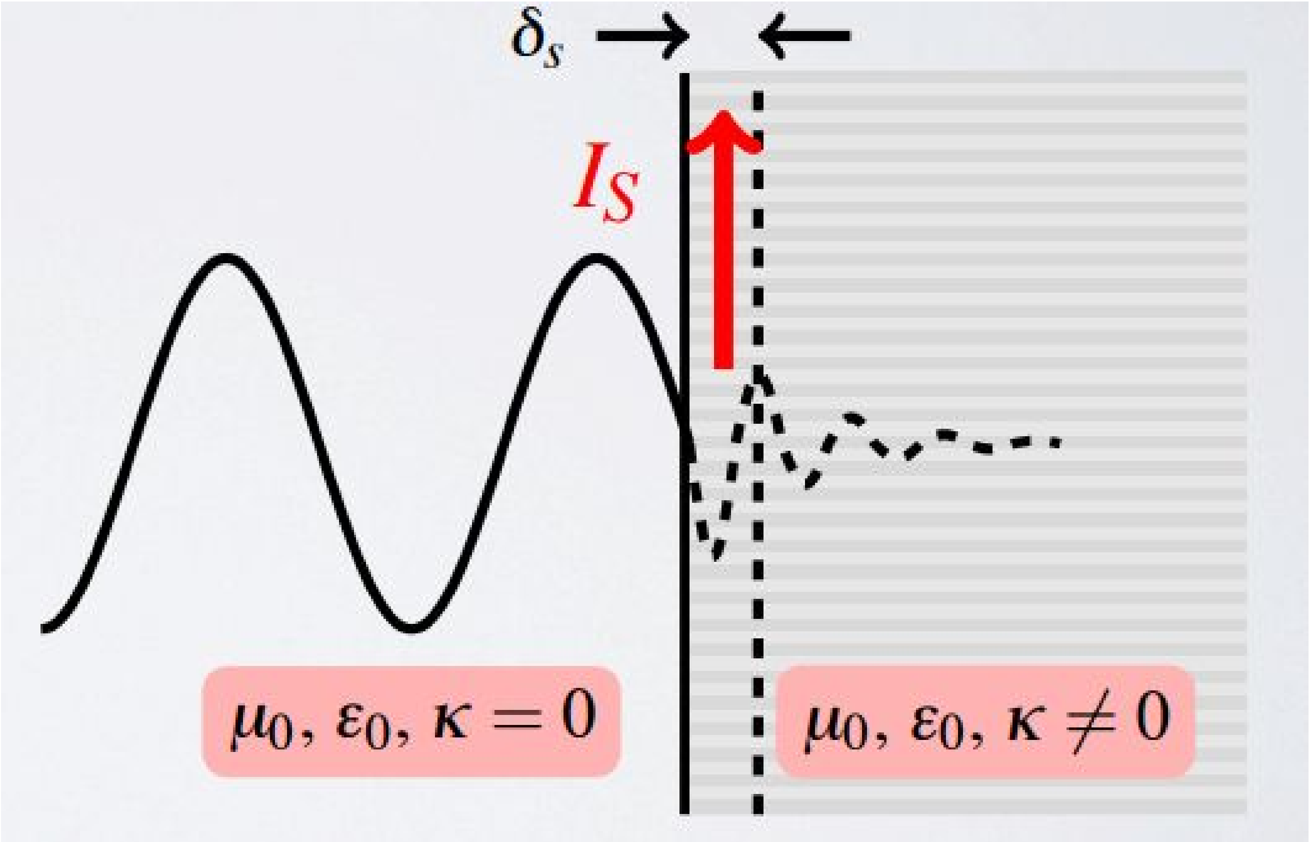
$$\delta = \sqrt{\frac{2}{\sigma\omega\mu_r}}$$

$$R_{surf} = \frac{1}{\delta\sigma}$$

for Copper:

$1/\sigma = 1.7\text{x}10^{-8}\ \Omega\text{m}$

Anybody remember scale of skin depth??



Cavity Energy and Dissipation

The energy storage in scales as field squared (while the acceleration scales as the electric field).

$$U = \frac{\mu_o}{2} \int_v |H|^2 dv$$

Magnetic fields induce currents in walls → power loss in a cavity:

$$P_c = \frac{1}{2} R_{sur} \int |H|^2 dS$$

where R_{sur} is the surface resistance just discussed. The power loss is characterized with the Q which is:

2Pi * Stored Energy / Energy loss per cycle

or

$Q = \omega * U / P_c$

RF Acceleration – Power Limitations

The attenuation of the stored energy in the cavity is given by:

$$U = U_0 e^{-\omega t/Q}$$

For normal conducting cavities, i.e. Copper, Q's are typically ~ 10,000 at 3 GHz. Can be much higher for complicated modes with reduced fiedl at walls but these don't accelerate as well either.

The cavity effectiveness can be quantified by the accelerating field relative to the stored energy:

$$\frac{R}{Q} \equiv \frac{1}{2}\frac{V_a^2}{\omega U} \quad \text{where} \quad V_a = \int E_z e^{iks} ds$$

RF Acceleration – Power Limitations

Power loss

The (R/Q) is just related to the cavity geometry and does not depend on frequency or materials. For accelerator cavities (R/Q) ~ 120 Ω/cavity.

The R in the (R/Q) is the shunt impedance which relates the accelerating voltage to the steady-state input power.

$$R = \frac{1}{2}\frac{V_a^2}{P_c}$$

Example: 3m 2.8 GHz SLAC structure with roughly 80 cells.

40 MW for 20 MV/m along 3m structure

Take-Away

Electrons are usually accelerated to high energy (GeV-scale) with microwave rf cavities.

Cavities provide time-dependant longitudinal fields that are characterized by R/Q, R, and Q

R/Q is a constant depending on field geometry while R and Q depend on rf frequency and material

Acceleration field is: V_a = sqrt(2P*R)

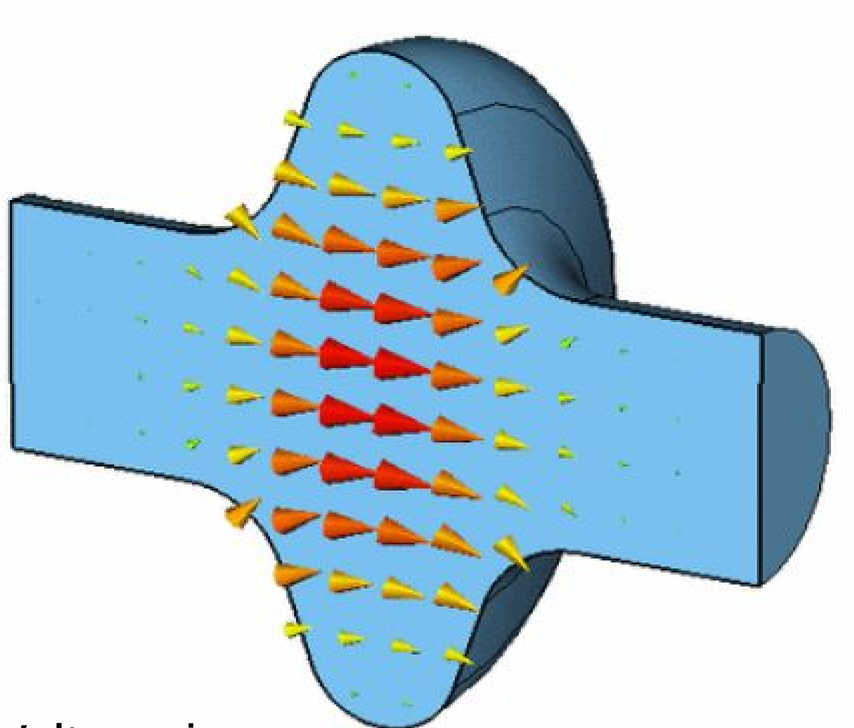
RF Acceleration

Transit time and Phasing

Longitudinal fields oscillate at cavity frequency.

$$\Delta E = eV = e\left|\int_{-L/2}^{+L/2} E_z(z,t)e^{i(kz-\omega t)}dz\right|$$

TM010-mode



The length of the cavity needs to be short enough so the particle passes through within half an rf period or it will lose acceleration

RF power to two cavities is easier the 2*Voltage in one

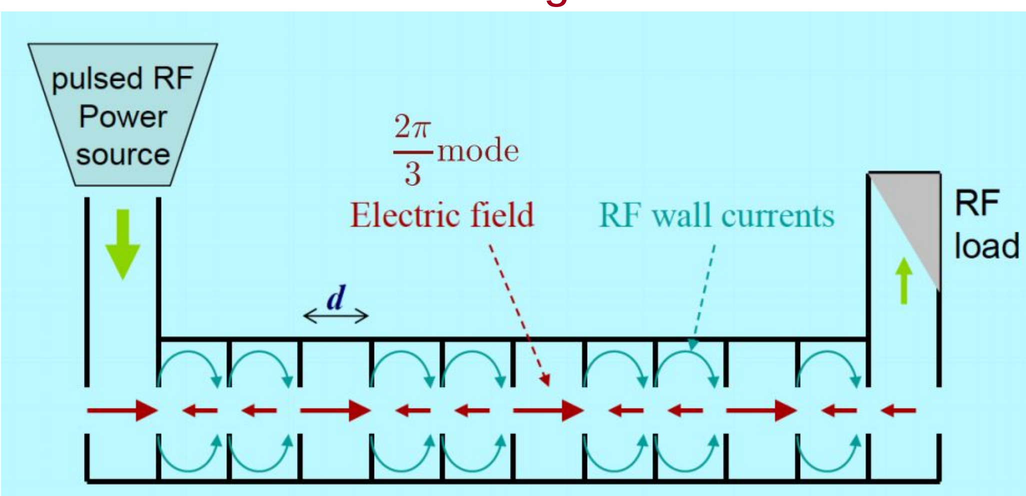
Multiple cavities are phased (timed) to add net acceleration

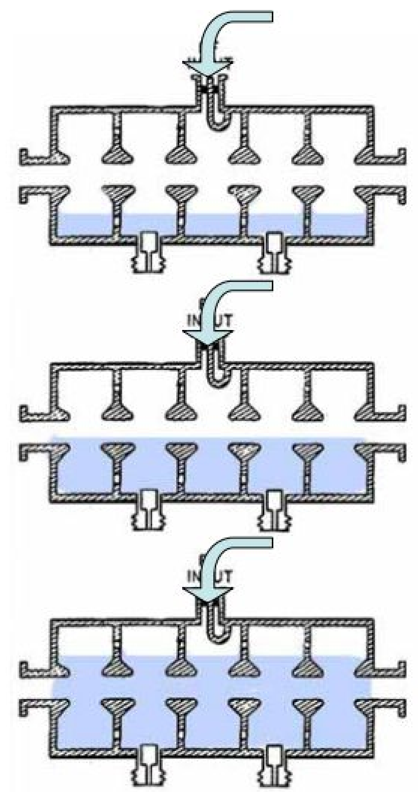
Multi-cell cavities

RF cavity mode structure becomes much more complex with multiple cavities but we'll ignore the detail. Two configurations: traveling wave and standing wave. Lots of discussion on merits!

Standing Wave

Traveling Wave

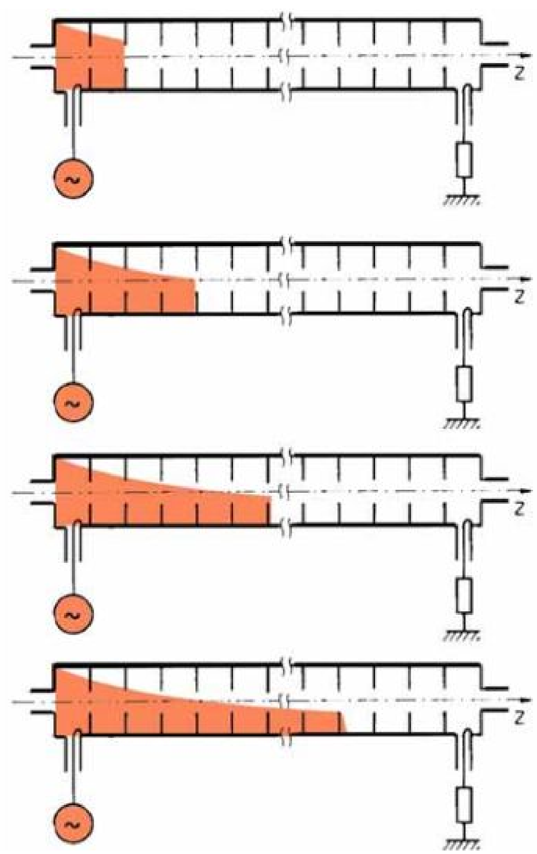




Rf power goes to cavity wall, load, and beam

Traveling Wave vs Standing Wave

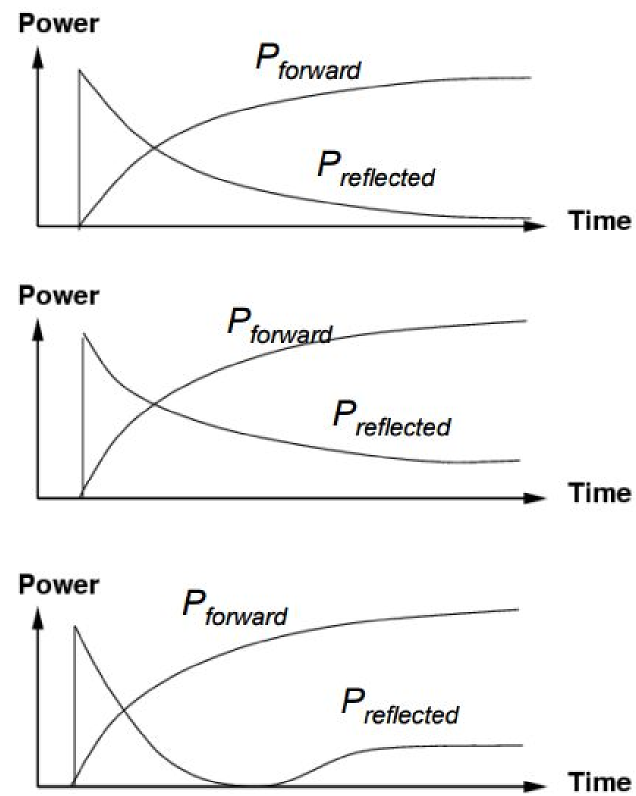
Standing wave cavities fill in time while traveling wave fill in space.



$\beta = 1$. Cavity fills and reflected power goes to zero

$\beta < 1$. Reflected power never goes to zero.

$\beta > 1$. At some point the cavity fields reflect enough power that the transmission line is matched, but the cavity continues to fill.



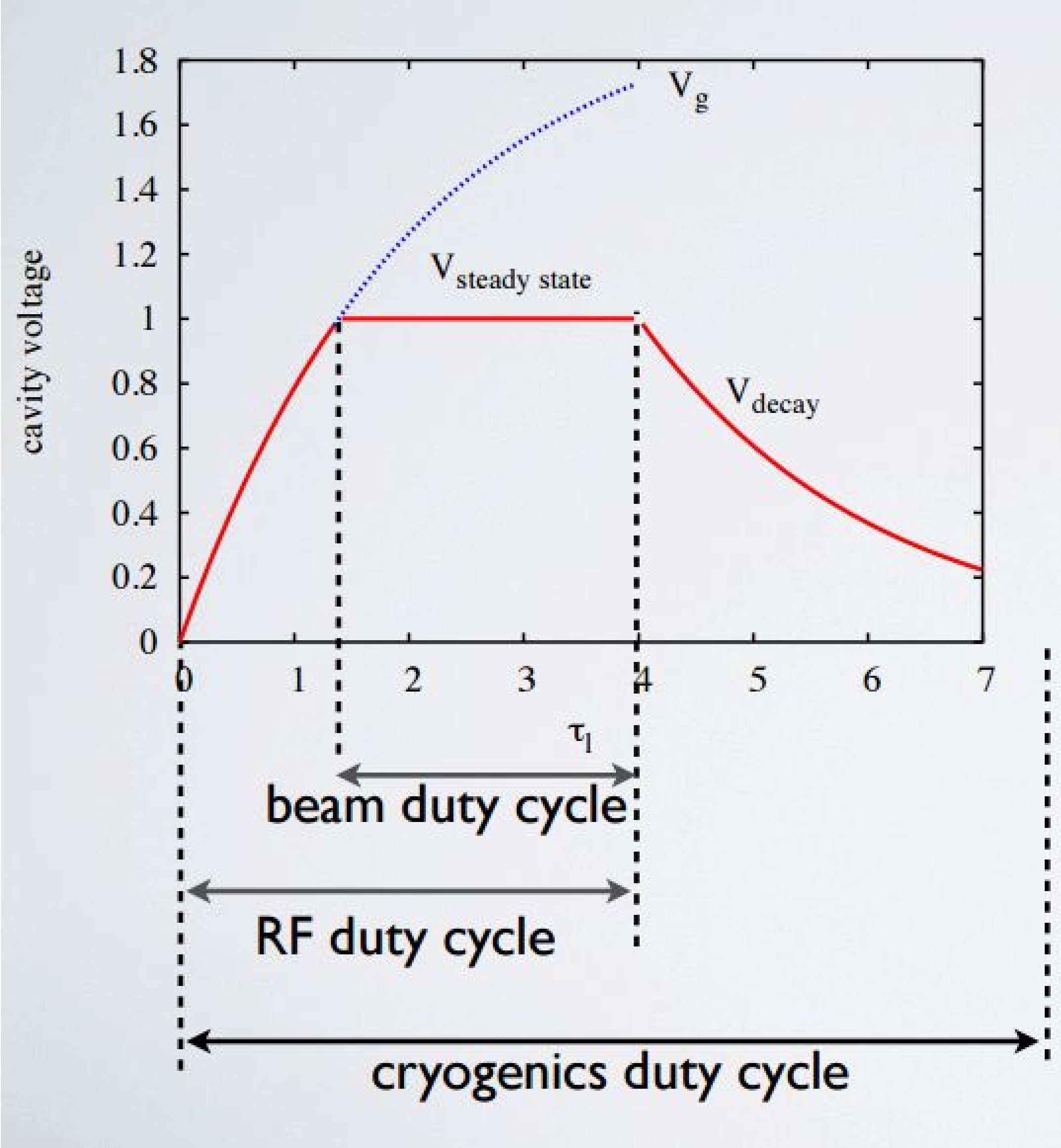
Filling a Standing Wave Cavity

Fill time depends on the coupling to the source (β) but:

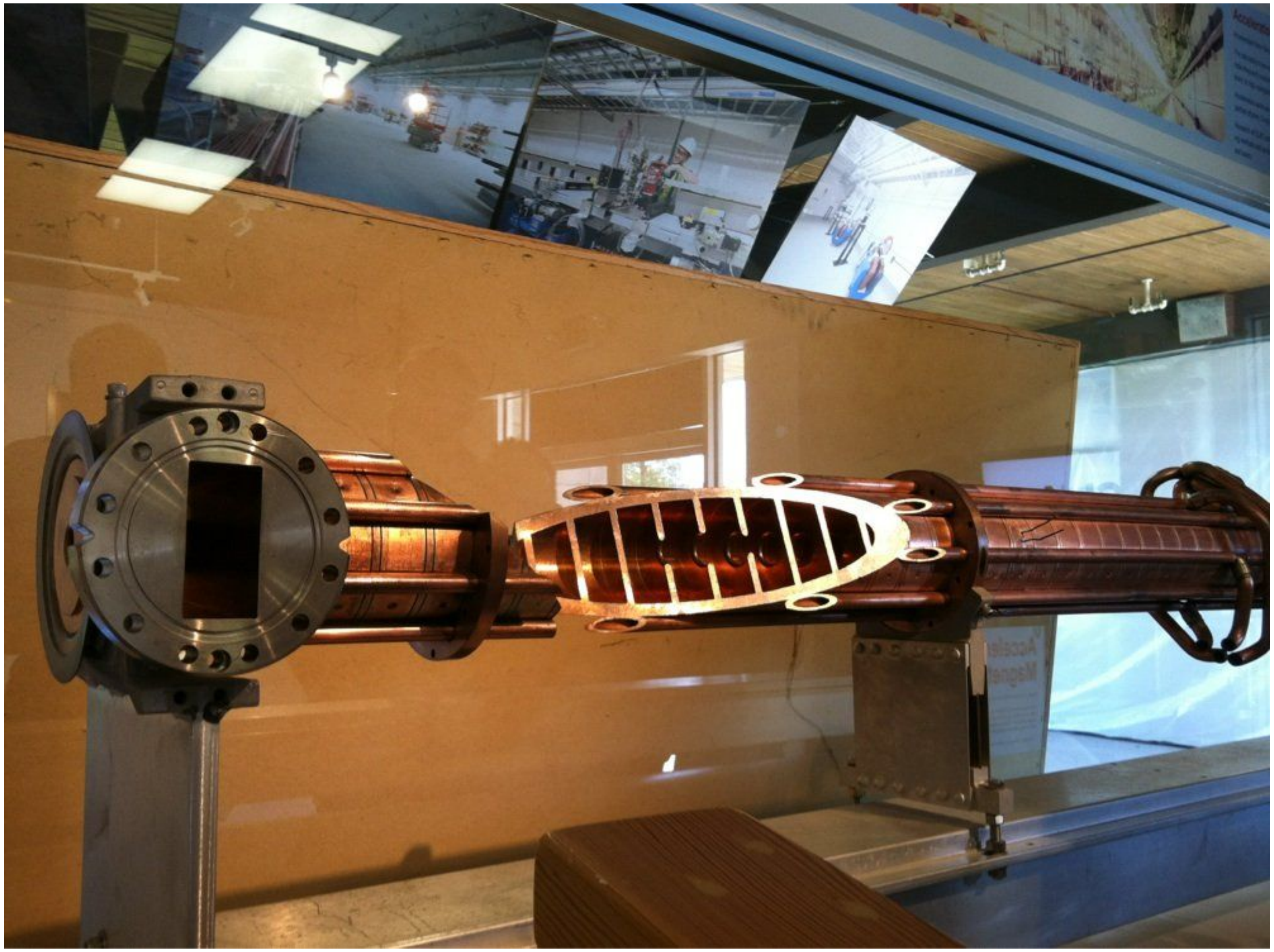
$T_{fill} = 2Q / \omega$

where Q is the 'loaded' Q including both the cavity losses and the external coupling

$\beta = Q_0 / Q_{ext}$



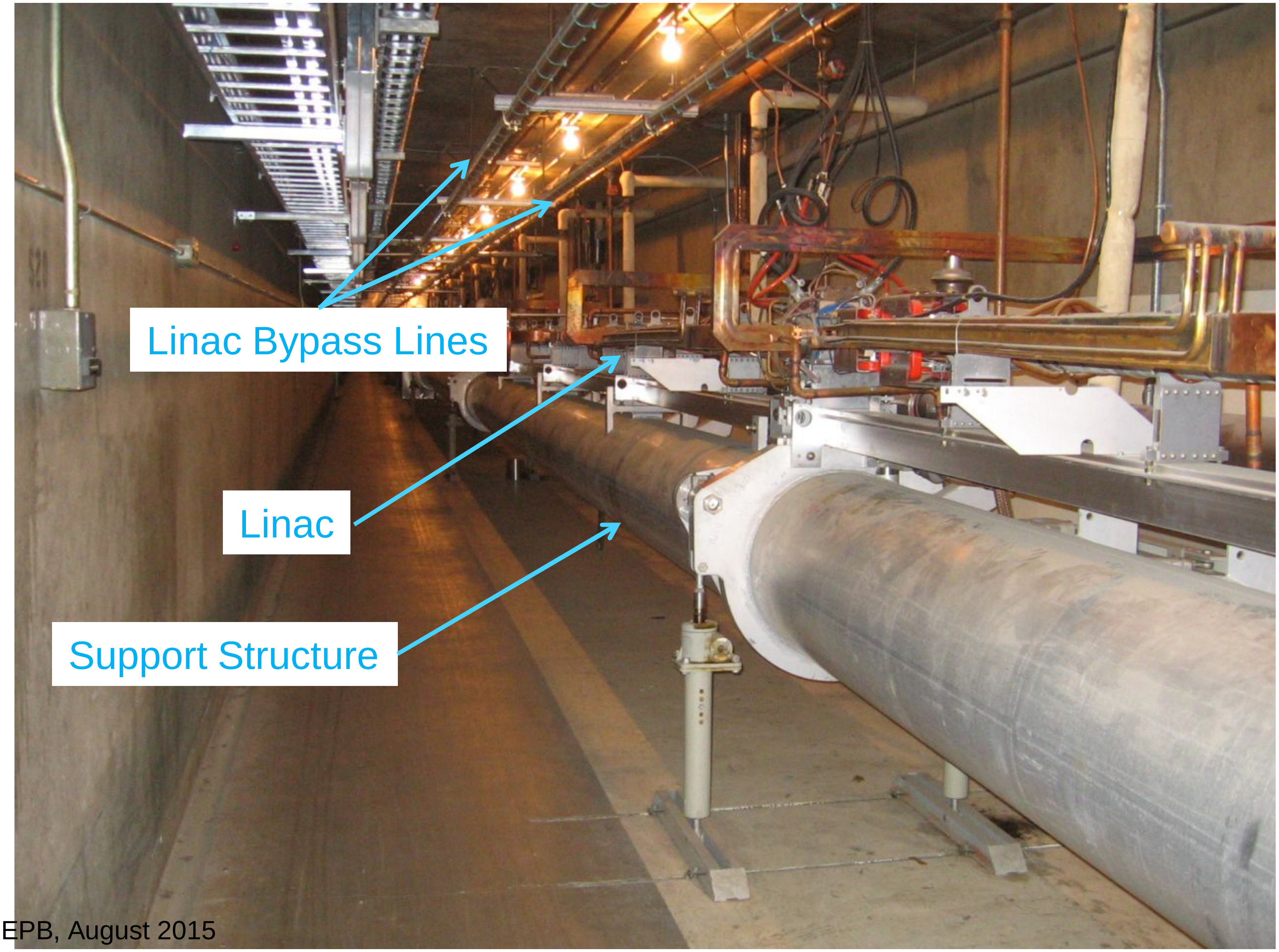
SLAC Accelerator Structure



Group velocity is few % c → 1 us to fill 3 meters

SLAC Linac

3 km 50 GeV S-band Copper Accelerator



Take-Away

Multi-cell cavities are more efficient but more complicated than single cell cavities

Can be configured in traveling wave or standing wave configurations

- standing wave has single input coupler with reflected power during filling – coupler is tuned to match power flow to extraction
- traveling wave cavities have matched input and output – beam or voltage is tuned to match power flow

Advantages to each in different configurations

Linacs

Many big pulsed linacs are built with traveling wave structures:

SLAC

SACLA (Spring 8 FEL)

PSI FEL

PAL FEL

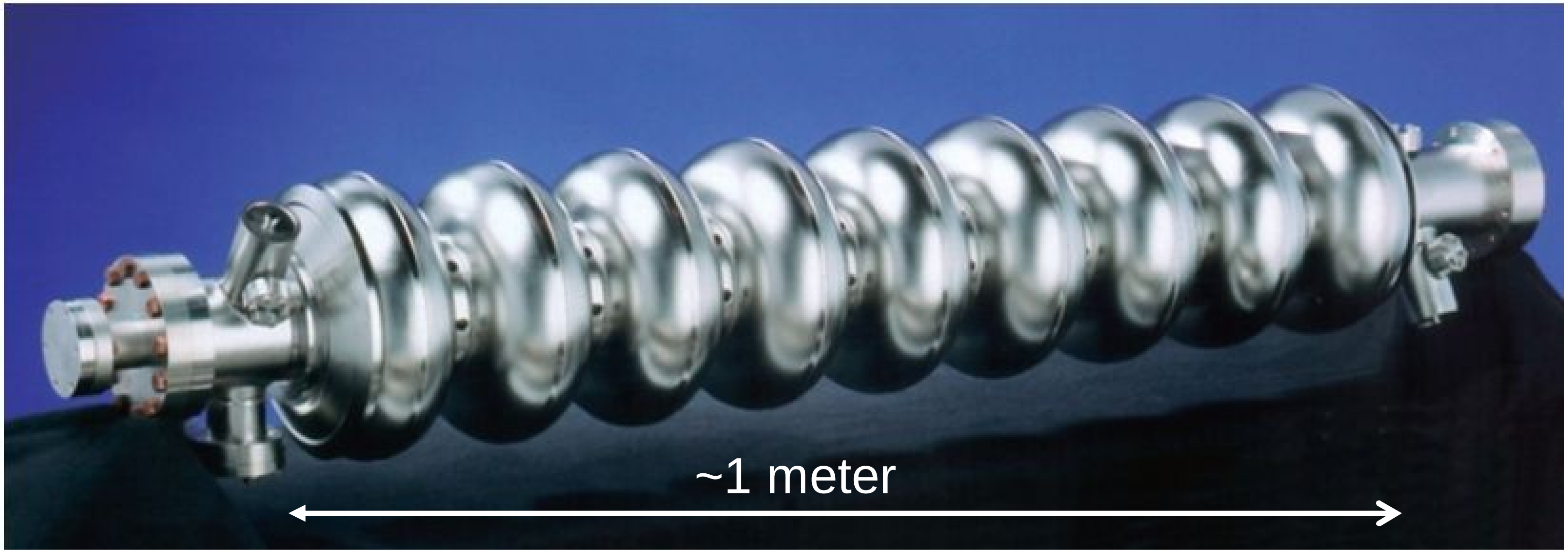
Big superconducting linacs are usually built with standing wave structures:

EuXFEL

LCLS-II

Superconducting RF Cavities

Backbone of the LCLS-II accelerator are the 9-cell 1.3 GHz superconducting rf cavities

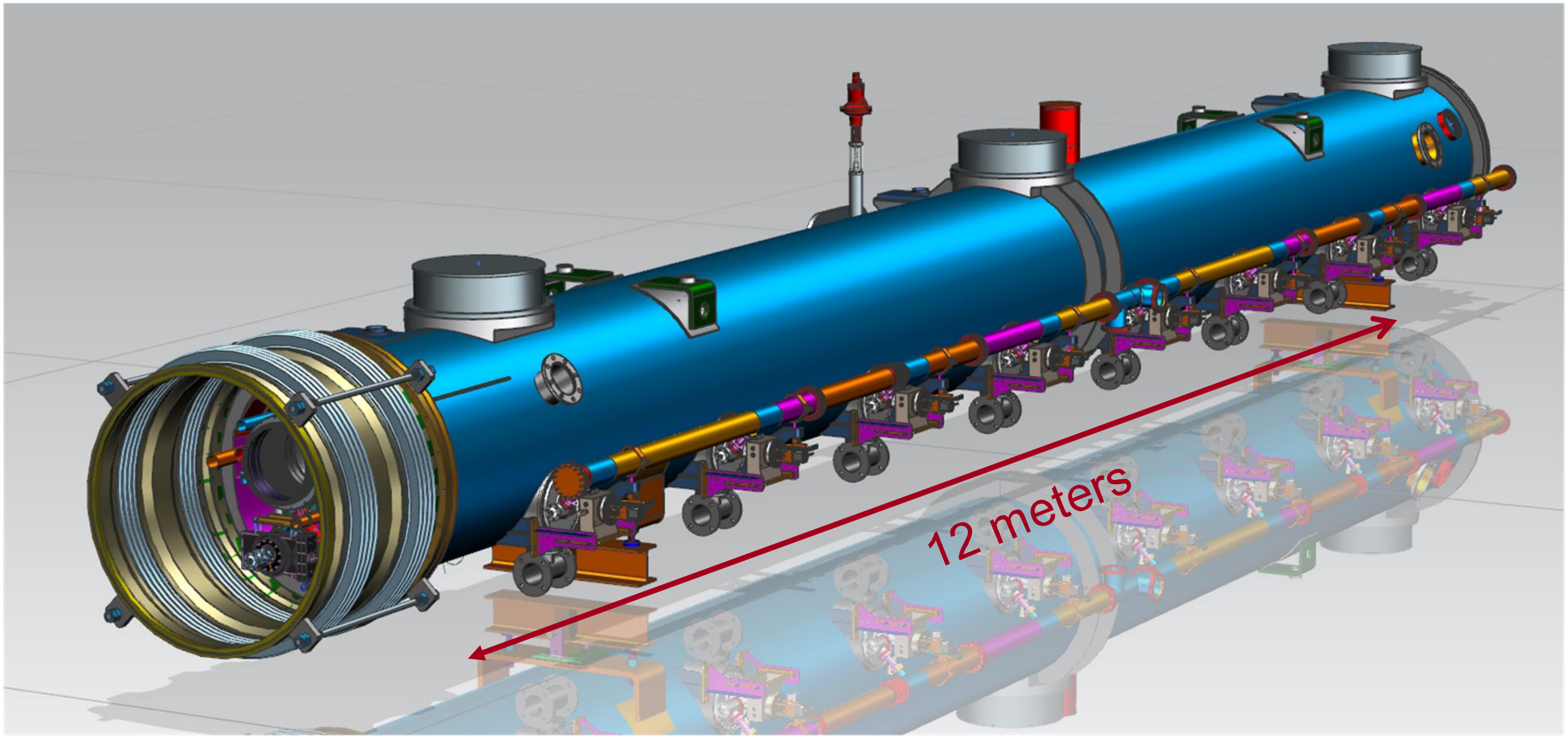


Technology developed in Europe and transferred around world. Hundreds have been fabricated in US, Japan, Europe.

LCLS-II and EuXFEL will use ~1200 combined

LCLS-II Cryomodule
1.3 GHz, modified for CW operation

SLAC



Crymodules will be similar to EuXFEL with modifications for CW operation.   EuXFEL producing 1 module/per week.

Why SCRF Technology?

SCRF Q's are 10^{10} while NCRF Q's are 10^4

Back to cavity parameters:

$$\frac{R}{Q} \equiv \frac{1}{2}\frac{V_a^2}{\omega U} \quad \text{where} \quad V_a = \int E_z e^{iks} ds$$

The (R/Q) is just related to the cavity geometry and does not depend on frequency or materials. For accelerator cavities (R/Q) ~ 120 Ω/cavity

and R in the (R/Q) is the shunt impedance which relates the accelerating voltage to the steady-state input power.

$$R = \frac{1}{2}\frac{V_a^2}{P_c}$$

→ R is 10^6 time higher

Much less power for same accelerating field

SCRF Cavities – Beam Loading

Typical Q_0's for SCRF cavities are 10^6 larger than copper, i.e. 10^{10}. This implies shunt impedances that are similarly 10^6 larger and bandwidths that are a fraction of a Hz.

Now instead of 40 MW into a SLAC structure for 60 MeV in 3 meters, we need 40 Watts!

But what about the beam?

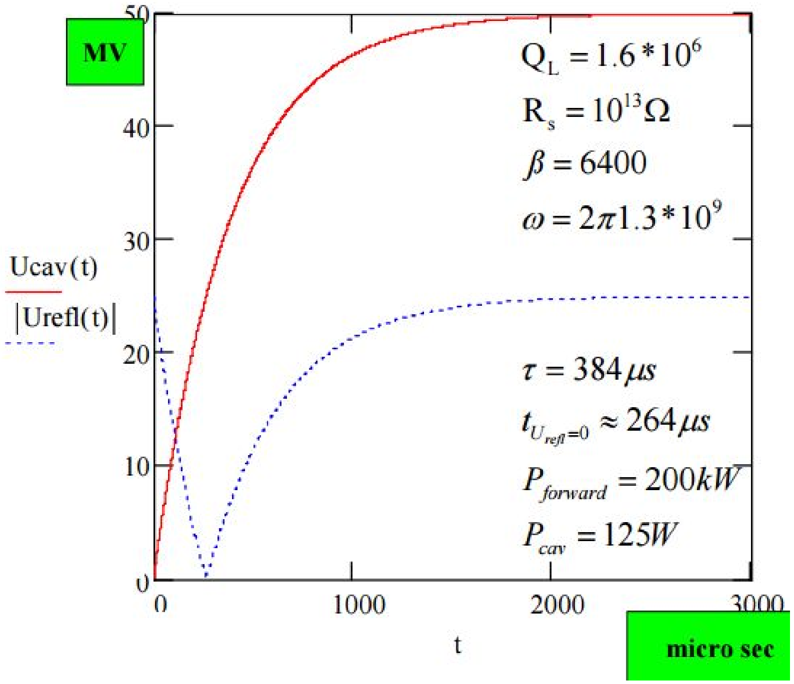
Need to couple external power source to the beam. Described in terms of an 'external Q'.

$$Q_{ext} = \frac{\omega U}{P_{beam}}$$

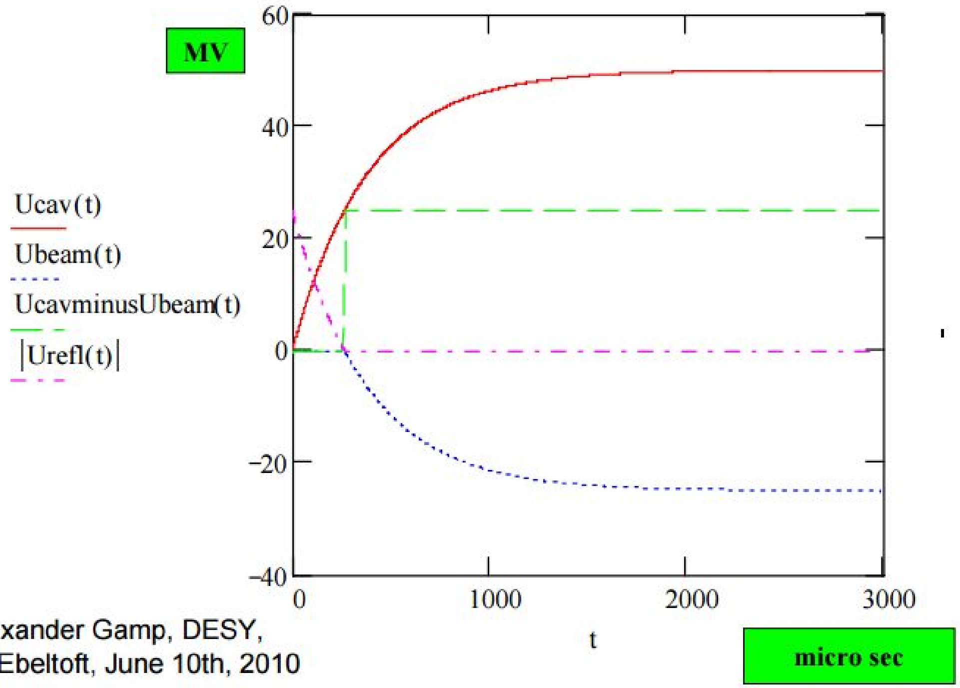
Filling SCRF Cavity

SLAC

Without Beam



With Beam



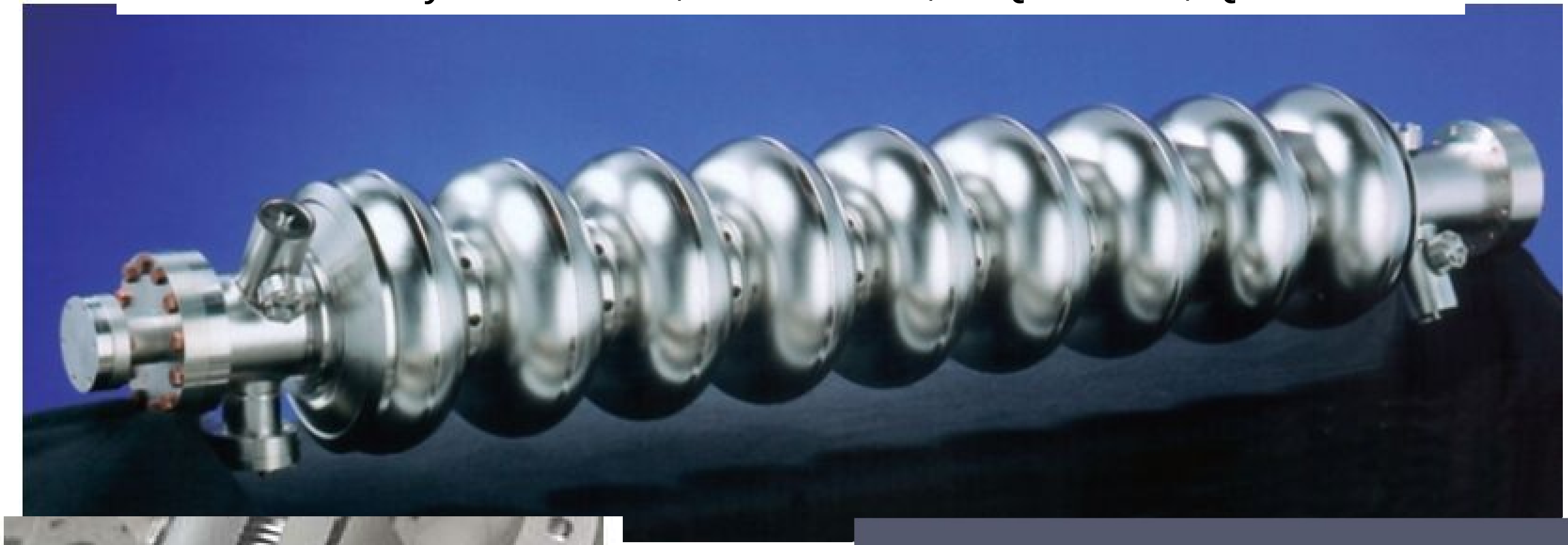
Alexander Gamp, DESY,
CAS, Ebeltoft, June 10th, 2010

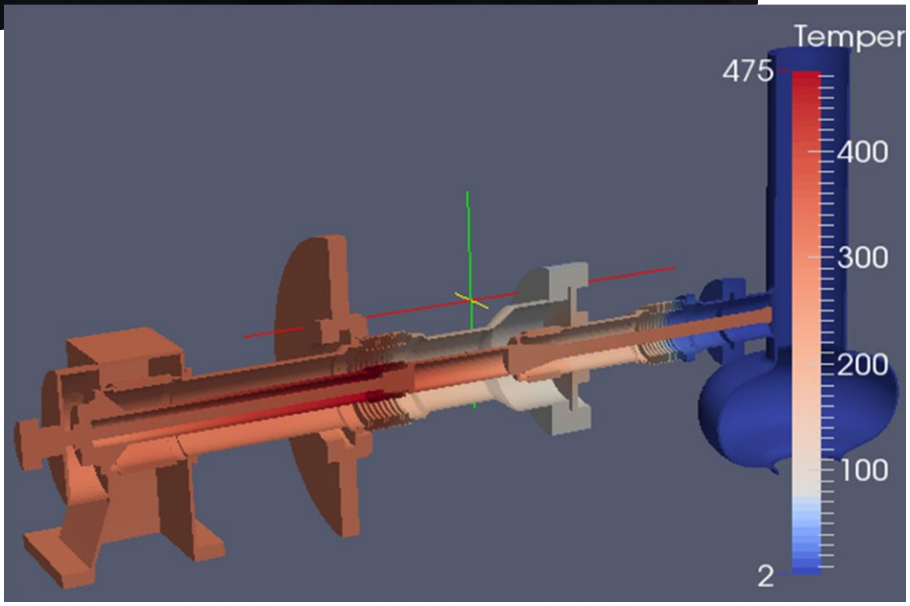
In matched configuration, cavity voltage is ½ that without beam; beam removes 99.9% of energy.

SCRF Cavities

Cavities and Couplers

9-cell π/2 cavity at 1.3 GHz; L = 1.038m; R/Q ~ 1036; Q > 1×10^{10}





SCRF Cavities – Why resistance at all?

SCRF cavities have much lower power loss! In DC, superconductors are essentially free of dissapation. In microwave regime, the magnetic field penetrates and accelerates Cooper pairs as well as any free electrons → Ohmic losses.

In the two-fluid model, the BCS resistance is:

$$R_{BCS} = \frac{C}{T}\omega^2\Lambda^3\sigma_n l \exp(-\frac{1.76T_c}{T})$$

where σ_n is the normal-state conductivity and Λ is the effective London penetration depth:

$$\Lambda = \lambda_L\sqrt{1 + \xi_0/l}$$

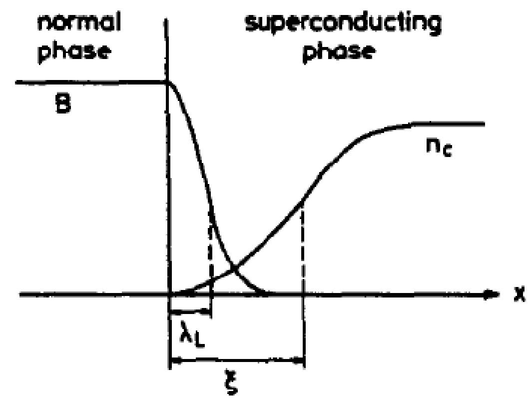
and λ_L is the London penetration, ξ_0 is the coherence length, and *l* is the mean free path of the unpaired electrons.

P. Schmuser, Prog. Part. Nucl. Phys. 49 (2002) 155-244

Aside: Superconducting Materials (I)

Two types of superconductors: Type I and Type II

Type I are classic superconducts: do not allow any magnetic field into bulk material (Meissner Effect). Typically have a critical field H_c of 0.1T.



Type II have two transitions: H_{c1} and H_{c2} where quantized flux is allowed into the material between the two states. Type II arise when London penetration is greater than the coherence length ($\lambda_L > \xi$). Most SC alloys are Type II because of shorter coherence length. H_{c2} can be ~10T.

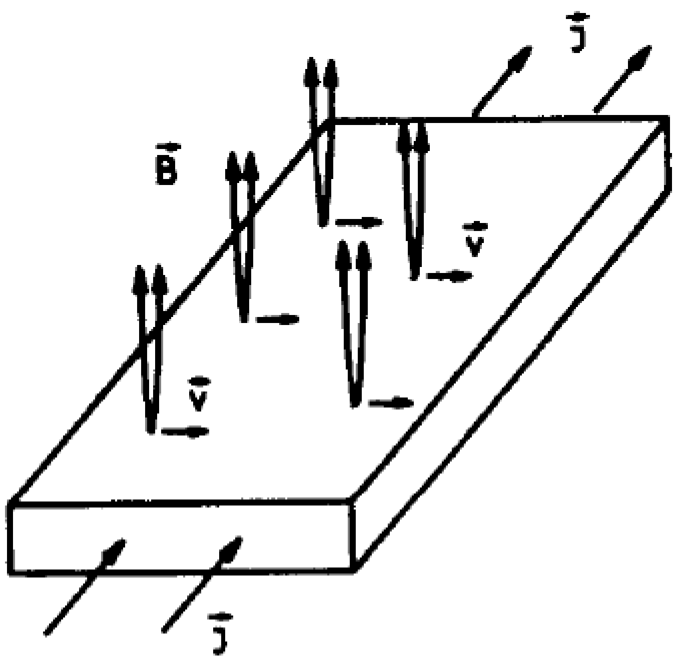
All SC magnets and SC cavities are Type II

material	In	Pb	Sn	Nb
λ_L [nm]	24	32	≈ 30	32
ξ [nm]	360	510	≈ 170	39

P. Schmuser, Prog. Part. Nucl. Phys. 49 (2002) 155-244

Aside: Superconducting Materials (II)

Type II superconductors can be further sub-divided into 'hard' and 'soft'. An example of a 'hard' materal is NbTi – typically used for SC magnets. Hard materials pin the fluxoids and prevent them from moving while in soft materials fluxoids can flow.



In high field magnets, fluxoid flow leads to an effective resistance. Defects in hard alloys pin the fluxoids and prevent losses.

But generates eddy currents and hysteresis
→ bad for rf cavities

Nb is a soft Type II but only has Hc2 of 200 mT at 2K

SCRF Cavities – Rf Frequency Choice

In practice, the surface resistance also has a residual term R_{res} due to impurities, lattice distortion, and trapped magnetic flux at a few nΩ's.

The losses depend on the product of conductor area and surface resistance → R_{BCS} losses scale as ω while R_{res} losses scale as 1/ ω. R_{BCS} dominates at high frequencies and vise versa.

Typical SCRF cavities operate in 300 to 3,000 MHz range to balance contributions. Of course, cost of cavity and cryomodule scales as $1/\omega^2$.

1.3 GHz was chosen for TESLA linear collider due to availability of pulsed rf sources.

Jlab CEBAF 12 GeV Upgrade 4.5 K cold-box (Linde) 'CHL 2'
JLG LIFT

Current SCRF R&D focus

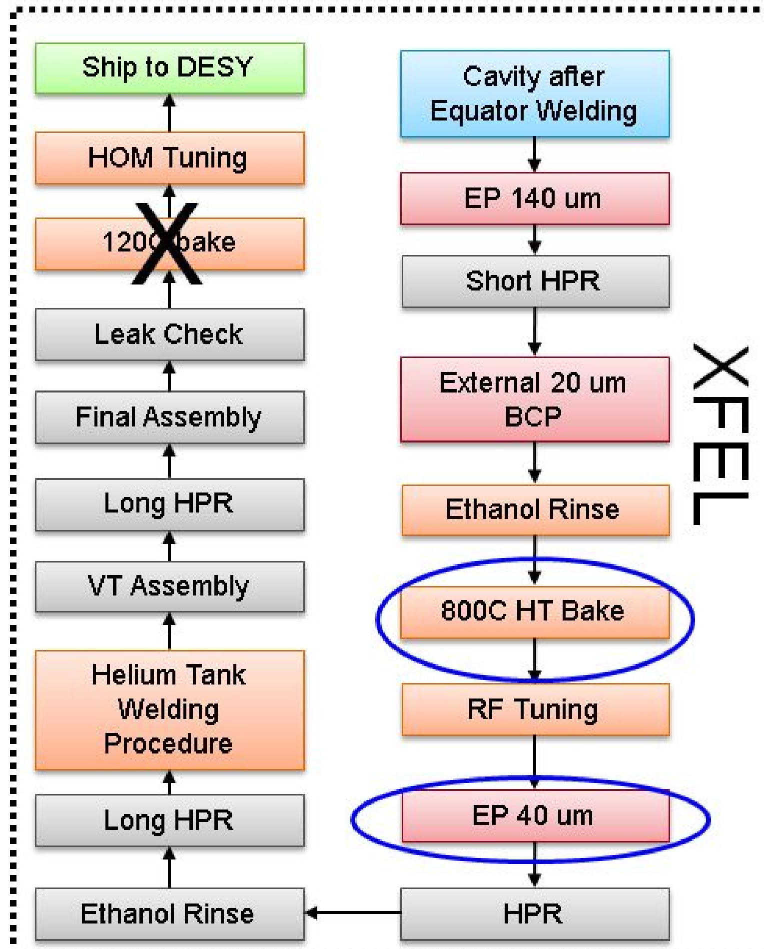
Tune materials for higher Q0

SCRF offers huge promise for high power accelerators but still very expensive. Because of Carnot, even 40 W at 2K is a big heat load.

→ Develop higher Q0 cavities

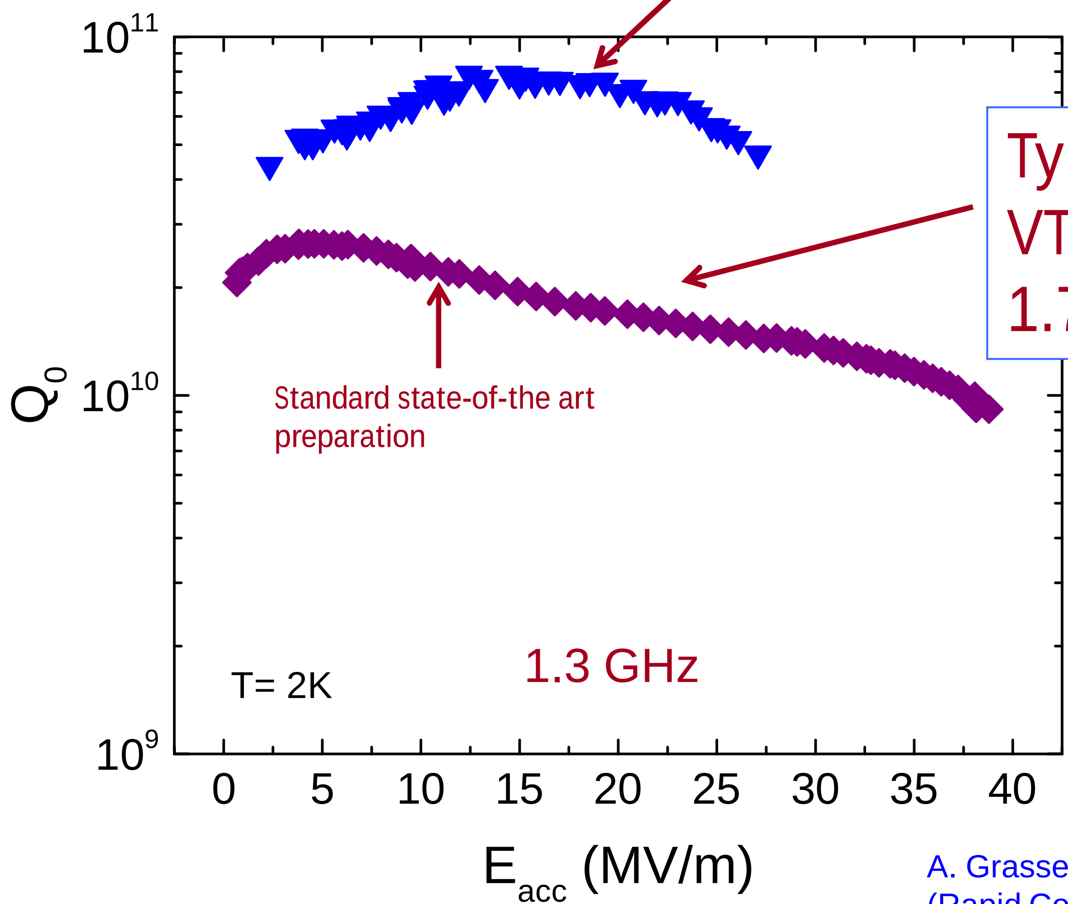
Lots of options: lower rf frequency, different materials, different processing.

Changing frequency and/or material takes years to understand. Changing process can be tested and implemented quickly.



Nitrogen doping: a breakthrough in Q

Record after nitrogen doping – up to 4 times higher Q! Average values obtained on nine cell Q(2K, 16MV/m)~ 3.5e10



Typical Q obtained in VTS with 120C bake ~ 1.7e10 at 2K, 16 MV/m

This is a 60M$ saving for LCLS-II!

A. Grassellino et al, 2013 Supercond. Sci. Technol. **26** 102001 (Rapid Communication)

Take-Away

RF Superconductivity can provide very highly efficient transfer of rf power to beam however can do this with NCRF as well using very short very high power pulsed rf and high power beams.

SCRF Q's are 10^6 times higher and NCRF and high Q means all processes can slow down. Peak powers are decreased and can consider CW operation for beams that are taylored to user desires.

Challenge is that you need cryogenics!

Very active R&D on developing SCRF technology