Fermilab U.S. DEPARTMENT OF ENERGY Office of Science

Engineering for Particle Accelerators

Vyacheslav Yakovlev

U.S. Particle Accelerator School (USPAS)

Education in Beam Physics and Accelerator Technology

19 June 2017

Engineering for Particle Accelerators

Instructors: *Vyacheslav Yakovlev, Timergali Khabiboulline, Thomas Nicol and Vladimir Kashikhin, Fermilab, Batavia*

One-week course at USPAS 2017, Lisle, Il

June 19-23, 2017

Purpose and Audience:

The purpose of this course is to give an engineering foundation to the development of modern particle accelerators. This course is suitable for graduate students, senior undergraduate students, and engineers interested in particle accelerator design and development. The course will focus on large-scale proton superconducting linear particle accelerators.

Prerequisites

Undergraduate-level electromagnetism, classical mechanics, RF and mechanical engineering courses.

It is the responsibility of the student to ensure that he or she meets the course prerequisites or has equivalent experience.

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Objectives

Students will learn basic principles of the engineering design of large-scale proton superconducting linear particle accelerators. Upon completing this course, students will be familiar with the principles, approach, and basic technique of the design of the main components in superconducting linear accelerators, and be able to perform basic analysis on their performance.

Instructional Method

The course will consist of lectures and daily homework assignments on the fundamentals of engineering of superconducting linear particle accelerators.

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Course Content

* The course will cover the fundamentals of accelerator engineering and provide examples and exercises in the practical design of the main accelerator components.

* Topics will include:

- general accelerator layout and parameter optimization; operational regime dependent technology selection;
- general cryomodule design issues, challenges, principles, and approaches;
- RF optimization and design of superconducting RF cavities and components;

Engineering for Particle Accelerators

- cavity processing recipes and procedures; engineering issues and challenges of SRF cavity mechanical design and fabrication;
- problems and techniques for design of focusing elements for superconducting accelerator applications (room-temperature and superconducting);
- diagnostics and alignment;
- cavity and cryomodule testing and commissioning.

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Reading Requirements

It is ***recommended*** that students re-familiarize themselves with the fundamentals of electrodynamics at the level of

“Classical Electrodynamics” (Chapters 1 through 8) by J. D. Jackson, John Wiley & Sons, 3rd edition (1999).

Additional ***suggested*** reference material:

“Handbook of Accelerator Physics and Engineering”, edited by A. W. Chao and M. Tigner, World Scientific, 3rd print (2006);

“RF Superconductivity: Science, Technology, and Applications,” by H. Padamsee, Wiley-VCH (2009).

Engineering for Particle Accelerators

Daily Schedule

Monday 6/19
9:00-12:00 Yakovlev, Lectures: The fundamentals of large scale accelerator engineering.
14:00 -17:00 Yakovlev, Continuation

19:00-24:00 Study and tutoring

Tuesday 6/20
9:00-12:00 Khabiboulline, lectures: SRF cavity EM and mechanical design, RF measurements
and tuning
14:00-17:00 Khabiboulline, Continuation
19:00-24:00 Study and tutoring

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Daily Schedule (cont)

Weds 6/14

9:00-12:00 Nicol, Lectures: Dressed cavity production, Cryomodule design

14:00 -17:00 Nicol, Continuation

19:00-24:00 Study and tutoring

Thursday 6/15

9:00-12:00 Kashikhin, Lectures: Conventional, Permanent, and Superconducting Magnets Design

14:00 -17:00 Kashikhin, Continuation

19:00-24:00 Study and tutoring

Friday 6/16

9:00-12:00 Wrap-up

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USPAS 2017 Students:

Albright, Robert	Lawrence Berkeley National Lab
Alonso, Inigo	European Spallation Source
Alvarez, Henry	SLAC
Antonini, Piergiorgio	INFN
Baketz, Sherry	Fermilab
Berry, Robert	RadiaBeam Technologies
Contreras, Crispin	Michigan State University
Di Ciocchis, Franco	Fermilab and University of Pisa
Gao, Jiani	EPFL and Paul Scherrer Institut
Gurung, Ujir	Cosmos International College
Kiemschies, Oliver	Fermilab
Kutsaev, Sergey	RadiaBeam Technologies
Liu, Zunping	Argonne National Lab
Martin, Brian	Brookhaven National Lab
Patel, Niral	Fermilab and Indiana University
Zhang, Bo	Dexter Magnetic Technologies

Chapter 1.

Accelerators for High Energy Physics and other scientific applications.

Accelerators for High Energy Physics and other scientific applications.

High – Energy Electron accelerators: High Energy Physics, Nuclear Physics, Free-Electron Lasers

High – Energy Proton accelerators: High Energy Physics, Nuclear Physics, source of secondary particles (neutrons, pions, muons, neutrinos), material science, Accelerator-Driven Subcritical reactors (ADS).

Specifics of proton accelerators: protons are non- or weekly relativistic up to high energies: rest mass for protons is 0.938 GeV (compared to 0.511 MeV for electrons).

High Energy Proton accelerators

- Cyclic proton accelerators:

  -Cyclotron

  -Synchrotron
- Linear proton accelerators
- Two principles:

  -Synchronism

  -Autophasing
- Specific acceleration technology and operation mode – pulsed or CW - are determined primarily by the facility purposes, which demand in turn specific properties of the proton beam – energy, power, timing structure, beam quality, etc.

Operating and planned facilities that utilize a high intensity proton driver accelerator.

	Neutrino	Muons	Neutrons	ADS	RIB's
Cyclotron	Daeδalus[1]	PSI-HIPA TRIUMF	PSI-HIPA	AIMA[2] TAMU-800[3]	TRIUMF RIKEN
RCS		J-PARC	J-PARC ISIS CSNS		
FFAG				KURRI +ongoing studies[4]	
s.c. Linac	PIP II [5]	PIP II [5]	SNS ESS ISNS[6]	ADSS[7] CIADS[8]	FRIB

operating
in construction
concept study

1 Decay-at-Rest Experiment for δcp studies At the Laboratory for Underground Science, MIT/INFN-Cat. et al
2 Accelerators for Industrial & med. Applications, reverse bend cyclotron, AIMA company
3 Cyclotron 800MeV, flux coupled stacked magnets, s.c. cavities, strong focusing channels, Texas A&M Univ.
4 FFAG studies, e.g. STFC
5 SRF linac, Proton Improvement Plan-II (PIP-II), Fermilab, Batavia
6 Indian Spallation Neutron Source, Raja Ramanna Centre of Advanced Technology, Indore, India
7 Accelerator Driven Sub-critical System at Bhaba Atomic Research Centre (BARC), Mumbai,India
8 China Initiative Accelerator Driven System, Huizhou, Guangdong Prov. & IMP, Lanzhou, China

High Energy Proton Accelerators, cyclotron

- Cyclotron frequency

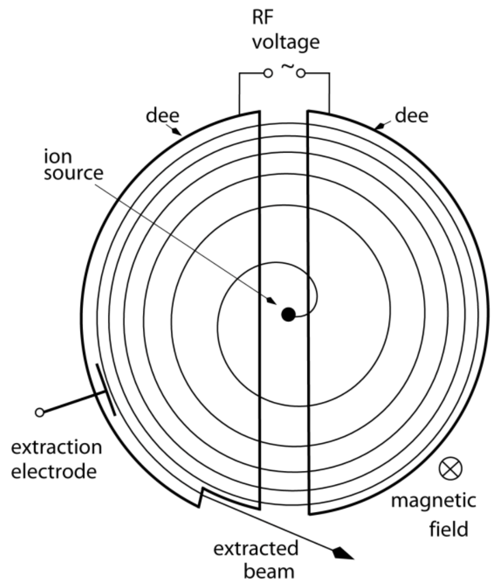
(non-relativistic particle)

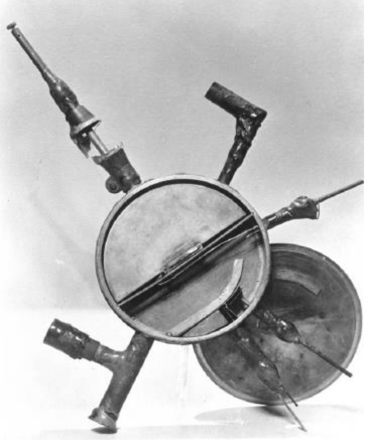
$$\omega = \frac{2\pi}{T} = \frac{q}{m} \cdot B$$

$R = R(E);$

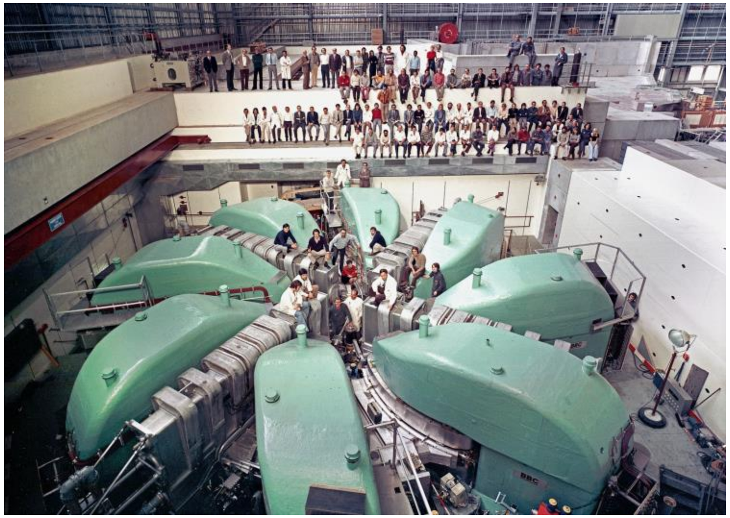
$\omega_{rf} = const$

$B(t) = const$

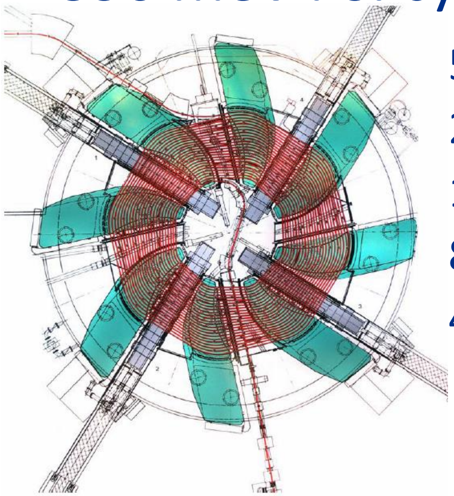




First cyclotron:
1931, Berkeley
1 kV gap voltage
80 kV protons
$25 total cost



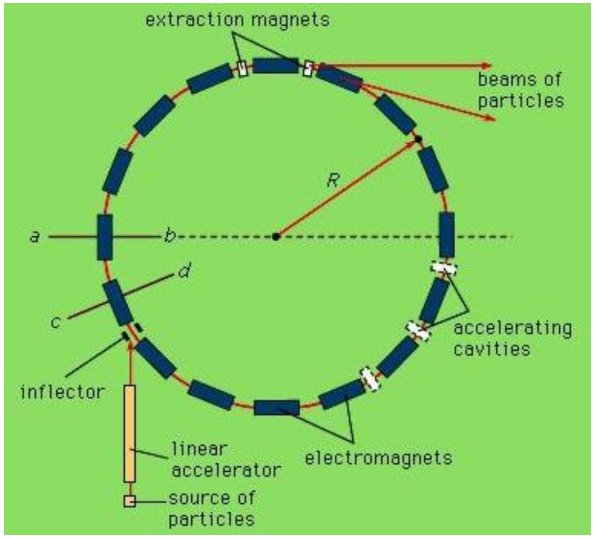
590 MeV PSI cyclotron:

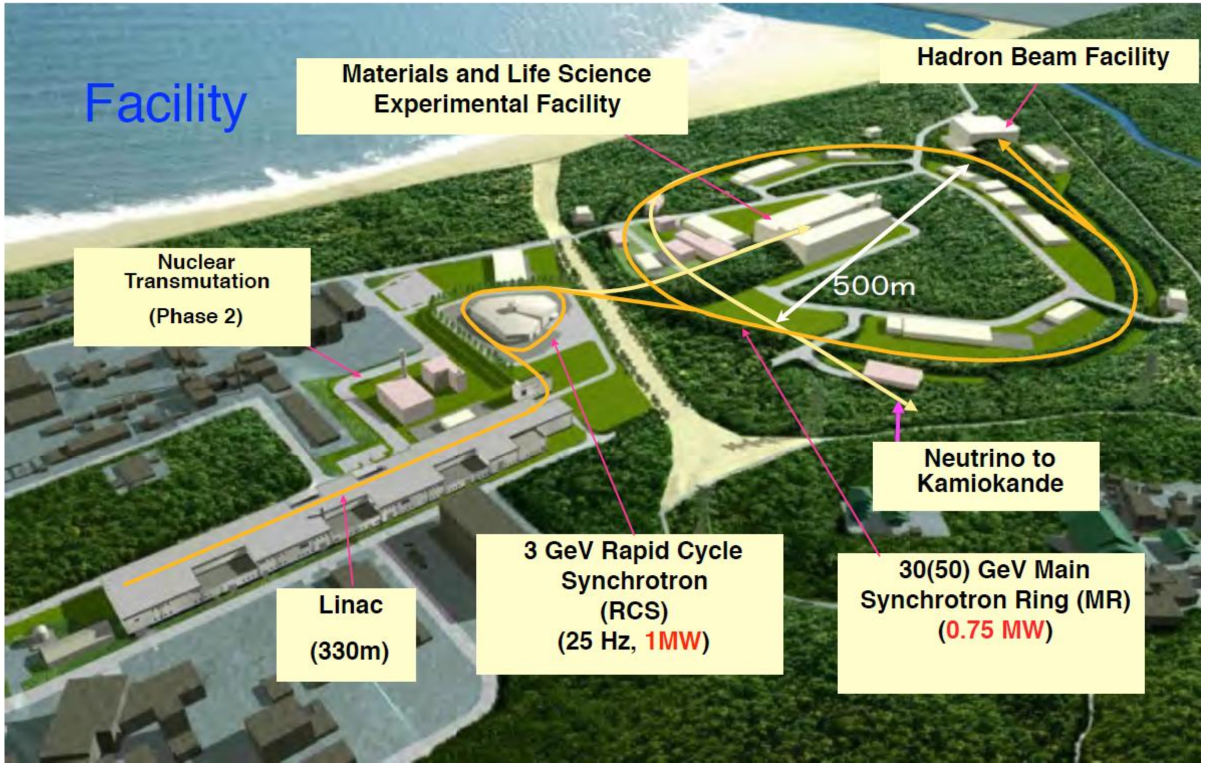


590 MeV, 1.4 MW
2.4 mA
186 turns
8 sector magnets
4 RF gaps

Max proton energy ≲ 0.6 – 0.7 GeV, CW

High Energy Proton Accelerators, synchrotron





$R(E) \sim \text{const};$

$\omega_{rf} = \omega_{rf}(t)$

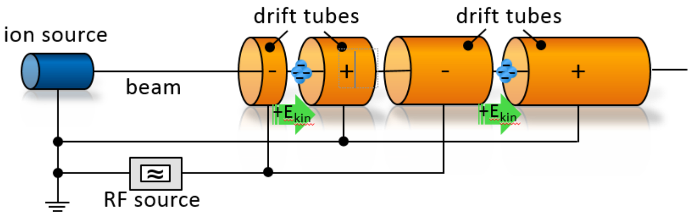
$B = B(t)$

Japan Proton Accelerator Research Complex (J-PARC)

Joint Project between KEK and JAEA

Proton Energy $\gtrsim$ 3 GeV, pulsed operation

High Energy Proton Accelerators, linear accelerator



(Rolf Widerøe, 1927)

Superconducting RF (SRF) Pulsed Linac of the Spallation Neutron Source, ORNL
Energy 1 GeV, beam power 1.4 MW

Proton Energy ≲ 3 GeV, CW and pulsed operation

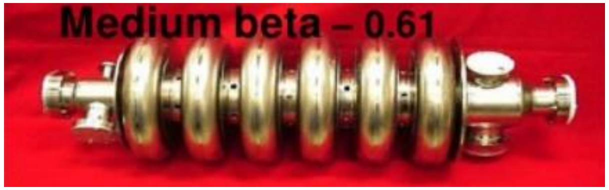
Chapter 2.

RF Cavities for Accelerator Applications

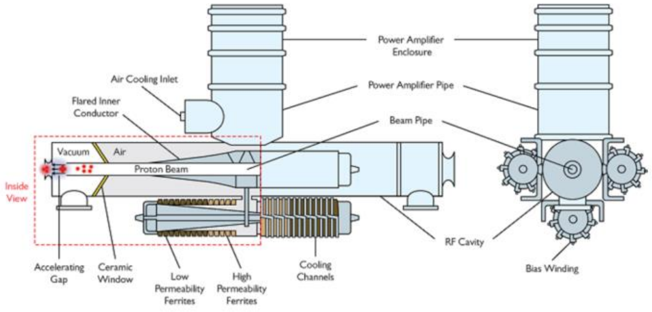
Engineering for Particle Accelerators

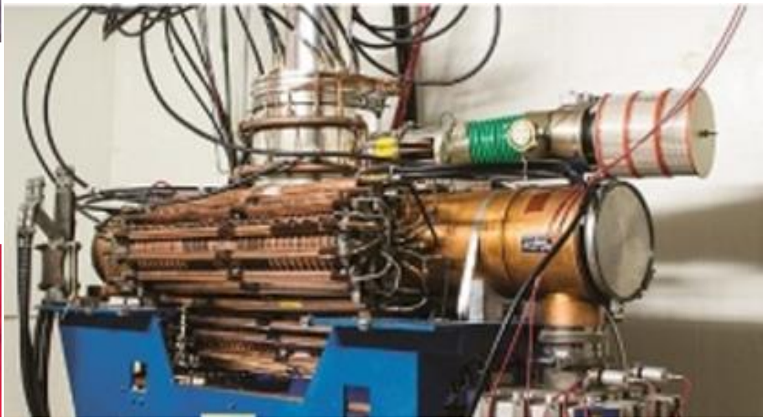
In ALL modern proton accelerators the beam acceleration take place in a resonance standing wave (SW) electromagnetic field excited in an RF cavity.

CW 50.6 MHz cavity of PSI cyclotron. V =1.2 MV



Superconducting 805 MHz multi-cell cavities of SNS linac. V=10-15 MV, DF = 6%.



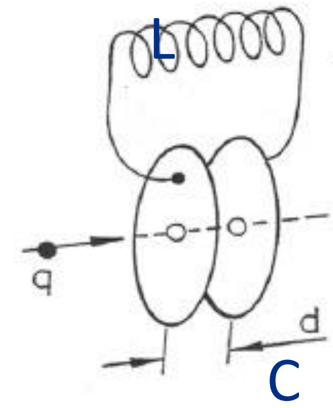


Tunable cavity for FNAL Booster Synchrotron
F=37.8-52.8 MHz. V=60 kV, DF =50%

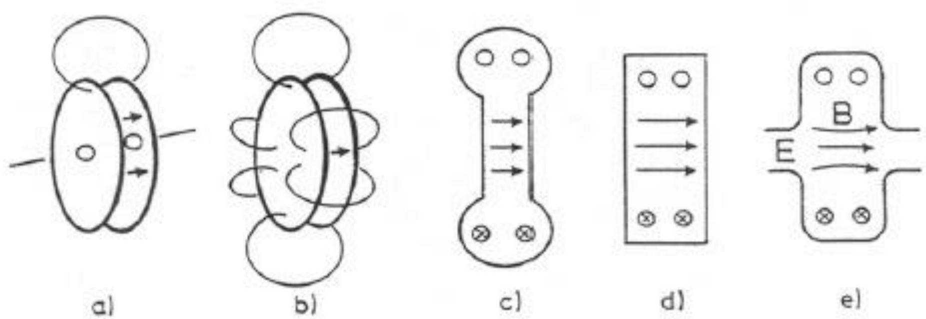
RF cavity:

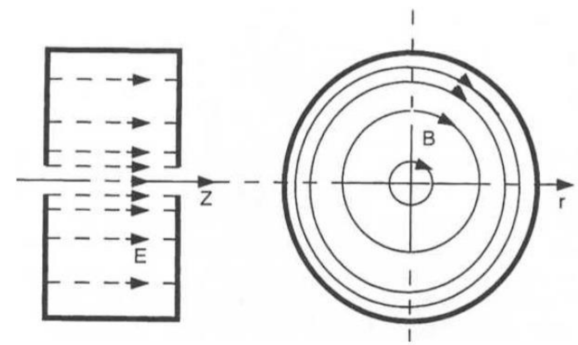
An LC circuit, the simplest form of RF resonator:
This circuit and a resonant cavity share common aspects:

- Energy is stored in the electric and magnetic fields
- Energy is periodically exchanged between electric and magnetic field
- Without any external input, the stored power will turn into heat



From LC circuit to an accelerating cavity:





- Electric field used for acceleration is concentrated near the axis
- Magnetic field is concentrated near the cavity outer wall

Modes in a pillbox RF cavity:

$$\Delta\vec{E} + k^2\vec{E} = 0, \quad \Delta\vec{H} + k^2\vec{H} = 0.$$

where $k = \omega\sqrt{\mu\varepsilon}$

Boundary condtions

$$\vec{n} \times \vec{E} = 0$$

$$\vec{n} \cdot \vec{H} = 0$$

An infinite number of solutions (eigen modes) belong to two families of modes with different field structure and resonant frequencies (eigen frequencies):

- TE - modes have only transverse electric fields,
- TM - modes have only transverse magnetic fields.

For acceleration in longitudinal direction the lowest frequency TM mode is used.

Eigen modes properties:

- Relation between eigen frequency k_m and eigen function $\vec{H}_m$:

$$k_m^2 = \frac{\int\limits_V |\mathrm{rot}\,\vec{H}_m|^2\,dV}{\int\limits_V |\vec{H}_m|^2\,dV}. \qquad \omega_m = ck_m = \frac{k_m}{\sqrt{\mu\varepsilon}}, \quad \lambda_m = \frac{2\pi}{k_m}.$$

- The eigen functions are orthogonal

$$\int\limits_V \vec{E}_m \cdot \vec{E}_n\,dV = 0, \quad \int\limits_V \vec{H}_m \cdot \vec{H}_n\,dV = 0 \text{ if } k_m^2 \neq k_n^2$$

- The average energies stored in electric and magnetic fields are equal

$$\int\limits_V \frac{\mu|H_m|^2}{2}\,dV = \int\limits_V \frac{\varepsilon|E_m|^2}{2}\,dV;$$

Modes in a pillbox RF cavity:

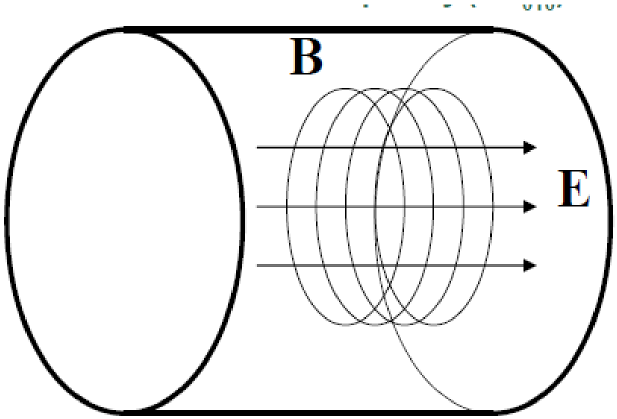
- The modes are classified as TM_{mnp} (TE_{mnp}), where integer indices *m, n,* and *p* correspond to the number of variations E_z (H_z) has in φ, *r,* and *z* directions respectively.
- While TM_{010} mode is used for acceleration and usually is the lowest frequency mode, all other modes are "parasitic" as they may cause various unwanted effects. Those modes are referred to as High-Order Modes (HOMs). Modes with m=0 – "monopole", with m=1 – "dipole", etc.

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

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

$$\omega_{010} = \frac{2.405c}{R}, \quad \eta = \sqrt{\frac{\mu_0}{\varepsilon_0}}$$

$$\lambda_{010} = 2.61R$$

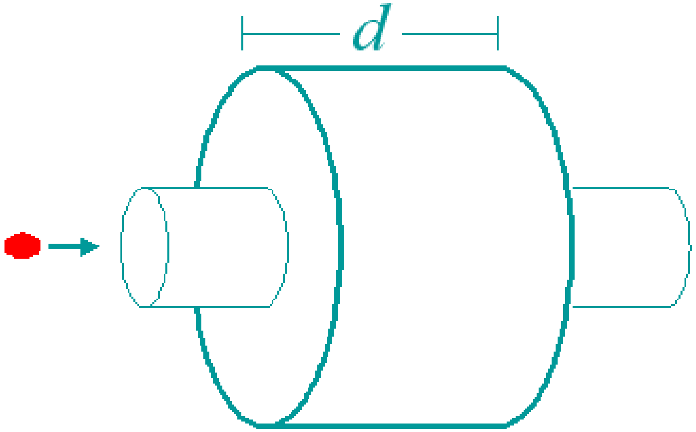


Note that electric and magnetic fields are shifted by 90 deg.

For vacuum η=120π Ohms.

Accelerating voltage and transit time factor:

Assuming charged particles moving along the cavity axis, one can calculate *maximal* accelerating voltage V as



$$V = \left| \int_{-\infty}^{\infty} E_z(\rho = 0, z) e^{i\omega_0 z/\beta c} dz \right|$$

For the pillbox cavity one can integrate this analytically:

$$V = E_0 \left| \int_0^d e^{i\omega_0 z/\beta c} dz \right| = E_0 d \frac{\sin\left(\frac{\omega_0 d}{2\beta c}\right)}{\frac{\omega_0 d}{2\beta c}} = E_0 d \cdot T$$

where T is the transit time factor.

Note that maximal acceleration takes place when the RF field reaches maximum went the particle is the cavity center.

In order to "use" all the field for accelration , $d = \beta\lambda/2$ and $T = 2/\pi$ for the pill box cavity.

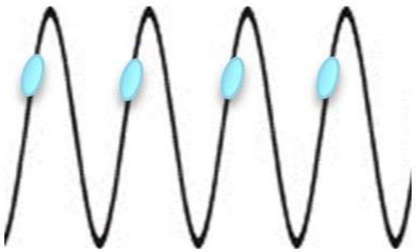
- *Acceleration gradient E is defined as V/d.*

Accelerating voltage and transit time factor:

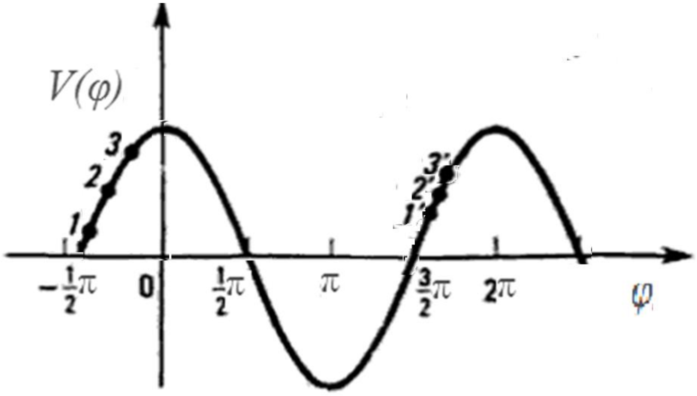
If the charged particle reaches the cavity center in arbitrary phase φ, its energy gain is

$$V(\varphi) = V\cos(\varphi)$$

Acceleration: $-\pi/2 < \varphi < \pi/2$



- *Synchronism:* the particle should reach the center of each acceleration gap in the sameaccelerating phase.
- *Autophasing:* longitudinal dynamics should be stable (no bunch lengthening). For linear accelerator $-\pi/2 < \varphi_s < 0$ (φ_s is the phase of the bunch center)



RF cavity parameters:

- Stored energy U:

$$U = \frac{1}{2}\mu_0 \int_V |\mathbf{H}|^2 dv = \frac{1}{2}\varepsilon_0 \int_V |\mathbf{E}|^2 dv$$

- Losses in the cavity. There are the losses P_c in a cavity caused by fini

surface resistance R_s:

$$P_c = \frac{1}{2} R_s \int_S |\mathbf{H}|^2 ds$$

For normal conducting metal at room temperature (no anomalous skin effect)

$R_s = \frac{1}{\sigma\delta}$, where σ is conductivity and δ is skin depth, $\delta = \frac{1}{\sqrt{\pi f \mu_0 \sigma}}$

Why SRF?

- For copper cavity at RT (σ = 5.7e7 S/m) for f=1.3 GHz one has R_s = 9.5 mOhm.

- For SRF Nb cavity at 2K on has R_s = 8.5 nOhm,

  It is 1.e6 times less!

Therefore, CW and high DF are possible at high gradient, even taking into account "conversion factor" for heat removal at 2K (~1000-1200W/W)

Why SRF?

Thus, SC provides the following benefits for proton linacs:

1. Power consumption is much less

-operating cost savings, better conversion of AC power to beam power

-less RF power sources

2. CW operation at higher gradient possible

- shorter building, capital cost saving
- need fewer cavities for high DF or CW operation
- less beam disruption

3. Freedom to adapt better design for specific accelerator requirements

- large cavity aperture size
- less beam loss, therefore less activation
- HOMs are removed more easily, therefore better beam quality

Why SRF?

Different mechanisms limiting acceleration gradient:

Room Temperature:

•*Breakdown;*

•*Metal fatigue caused by pulse heating;*

•*Cooling problems.* Breakdown limit:

$$E_a \cdot t_p^{1/6} = const$$

E_a~ 20 MV/m (E_{pk}~40 MV/m) @ 1ms or

E_a~ 7 MV/m (E_{pk}~14 MV/m) @ 1sec (CW)

Superconducting:

Breakdown usually is not considered for SC cavity;

Why SRF?

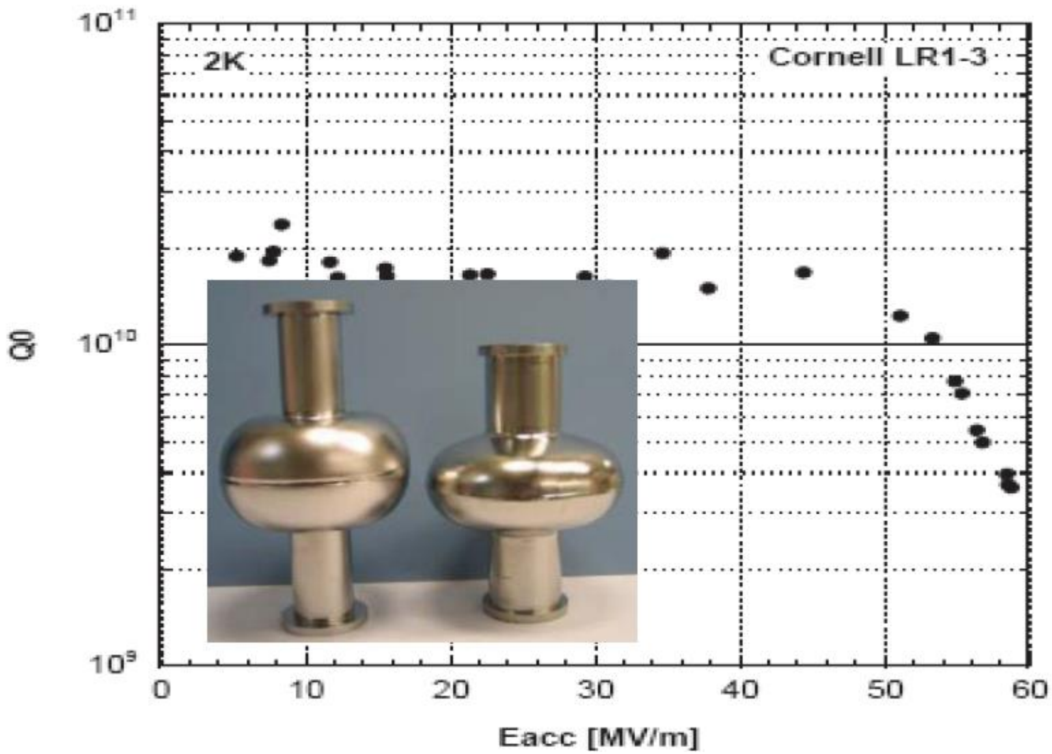
Achieved Limit of SRF electric field

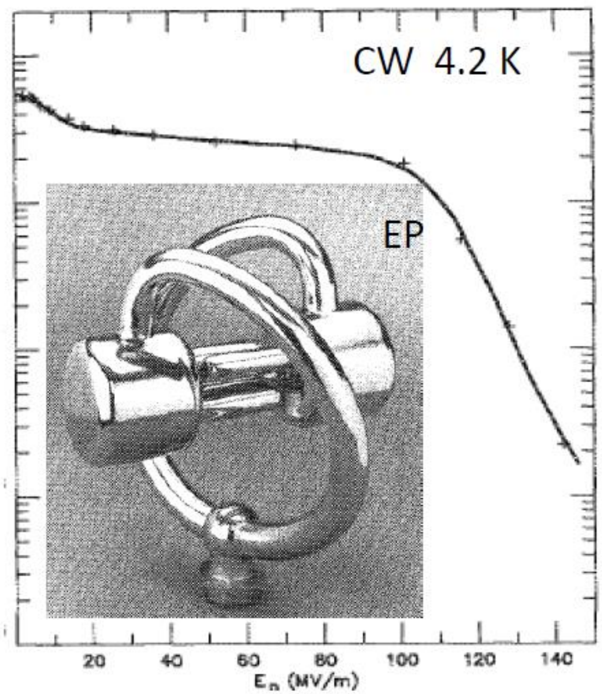
- No known theoretical limit
- 1990: Peak surface field ~130 MV/m in CW and 210 MV/m in 1ms pulse.

J.Delayen, K.Shepard,"Test a SC rf quadrupole device", Appl.Phys.Lett,57 (1990)

- 2007: Re-entrant cavity: Eacc= 59 MV/m (Epk=125 MV/m,Bs=206.5mT).

(R.L. Geng et. al., PAC07_WEPMS006) – World record in accelerating gradient





Why SRF?

"Practical" gradient limitations for SC cavities

- Surface magnetic field ~ 200 mT (absolute limit?) – "hard" limit
- Field emission, X-ray, starts at ~ 40 MeV/m surface field – "soft" limit
- Thermal breakdown (limits max surface field for F>2GHz for typical thickness of material, can be relaxed for thinner niobium) - "hard" limit
- Multipactoring (in cavity or couplers) - in some cases is "soft" limit
- Medium and high field Q-slopes (cryogenic losses)
- Lorentz detuning and microphonics (frequency change)
- Quality of surface treatment and Assembly

SRF allows significantly higher acceleration gradient than RT at high DF and CW!

RF cavity parameters:

Unloaded quality factor Q_0:

$$Q_0 \equiv \frac{\omega_0 \cdot (\text{stored energy})}{\text{average power loss}} = \frac{\omega_0 U}{P_c} = \frac{\omega_0 \mu_0 \int_V |\mathbf{H}|^2 dv}{R_s \int_S |\mathbf{H}|^2 ds}$$

Quality factor roughly equals to the number or RF cycles times 2π necessary for the stored energy dissipation.

One can see that

$$Q_0 = \frac{G}{R_s}$$

where G is so-called geometrical factor (same for geometrically similar cavities),

$$G = \frac{\omega_0 \mu_0 \int_V |\mathbf{H}|^2 dv}{\int_S |\mathbf{H}|^2 ds}$$

For pillbox cavity G =257 Ohms. Therefore, RT copper pillbox cavity has Q_0 = 2.7e4. For SRF Nb cavity at 2K one has Q_0 = 3e10.

RF cavity parameters:

An important parameter is the cavity shunt impedance R, which determines relation between the cavity accelerating voltage V and power dissipation:

$$R = \frac{V^2}{P_c}$$

Another important parameter is (R/Q), which is necessary to estimate the mode excitation by the accelerated beam. It does not depend on the surface resistance and is the same for geometrically similar cavities:

$$\frac{R}{Q} = \frac{V^2}{\omega_0 U}$$

For pillbox cavity (R/Q)=196 Ohms.

The power loss in the cavity walls is

$$P_c = \frac{V^2 \cdot R_s}{G \cdot (R/Q)}$$

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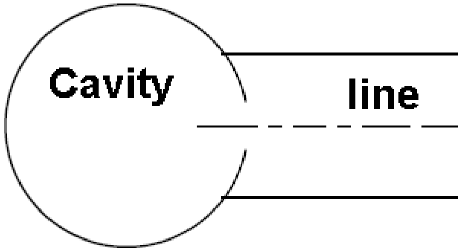
The cavity coupler to the line:

Let's consider the cavity coupled to the feeding line.



If the incident wave is zero (i.e., if the RF source is off), the loss in the cavity is a sum of the wall P_0 loss and the loss coasted by the radiation to the line P_{ext}:

$$P_{tot} = P_0 + P_{ext}$$

$$P_0 = \frac{V^2}{R/Q \cdot Q_0}, \quad P_{ext} = \frac{V^2}{R/Q \cdot Q_{ext}}$$

Where we have defined an external quality factor associated with an input coupler. Such *Q* factors can be identified with all external ports on the cavity: input coupler, RF probe, HOM couplers, beam pipes, etc. The total power loss can be associated with the loaded *Q* factor, which is

$$\frac{1}{Q_L} = \frac{1}{Q_0} + \frac{1}{Q_{ext1}} + \frac{1}{Q_{ext2}} + \ldots$$

Coupling parameter:

For each port a coupling parameter β can be defined as

$\beta \equiv \frac{Q_0}{Q_{ext}}$ and, therefore, $\frac{1}{Q_L} = \frac{1+\beta}{Q_0}$

It tells us how strongly the couplers interact with the cavity. Large implies that the power leaking out of the coupler is large compared to the power dissipated in the cavity walls:

$$P_{ext} = \frac{V^2}{R/Q \cdot Q_{ext}} = \frac{V^2}{R/Q \cdot Q_0} \cdot \beta = \beta P_0$$

In order to maintain the cavity voltage, the RF source should compensate both wall loss and radiation to the line. Therefore, the Rf source should deliver the power to the cavity which is

$$P_{tot} = P_{forw} = (\beta + 1) P_0$$

Cavity excited by the beam:

- If the cavity is excited by the beam with the *average* current I having the bunches separated by the length equal to integer number of RF periods, i.e, in resonance, the excited cavity voltage provides maximal deceleration. The beam power loss is equal to the cavity loss, i.e., radiation and wall loss:

$$-VI = \frac{V^2}{\left(\frac{R}{Q}\right)Q_L} \quad \text{or}$$

$$V = -I\left(\frac{R}{Q}\right)Q_L$$

- The cavity excited by the beam off the resonance, the voltage is

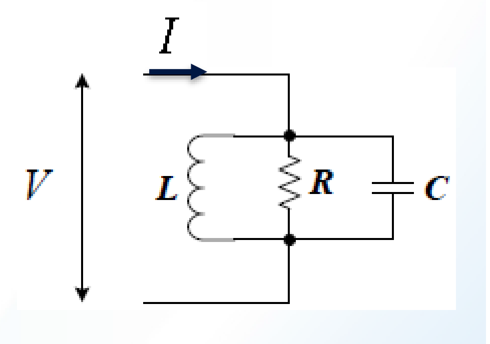
$$V \approx -\frac{I\left(\frac{R}{Q}\right)Q_L}{1 + iQ_L\frac{2\Delta f}{f}}$$

where Δf is the distance between the beam spectrum line and the cavity resonance frequency f.

- Cavity bandwidth:

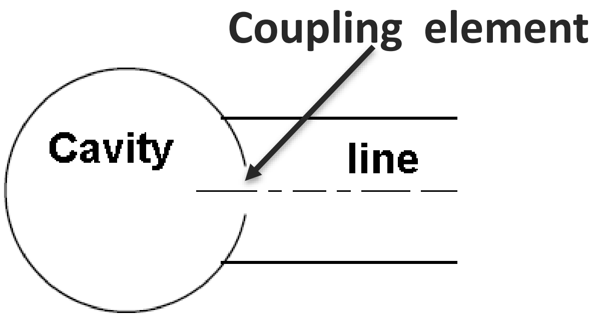
$\delta f = f/Q_L;$

for the acceleration voltage V and the beam current I the cavity should have the bandwidth $\delta f = f \cdot I(R/Q)/V.$



$L=(R/Q)/2\omega;$
$C=2/\omega(R/Q);$
$R= (R/Q)Q_L/2;$
$\omega = 2\pi f$

Cavity operating in pulse regime:



Energy conservation law:

$dU/dt = P_0 - P_{backward} - P_{diss} - P_{beam}$

$P_0 = Y{\cdot}E_0^2$; $P_{backward} = Y{\cdot}(E_0 - E_{rad})^2$, $\beta = P_{rad}/P_{diss}$, $P_{rad} = Y{\cdot}E_{rad}$, $P_{beam} = V(t)I$

$U=V^2/(R/Q)\omega$; $\tau=2Q_L/\omega$.

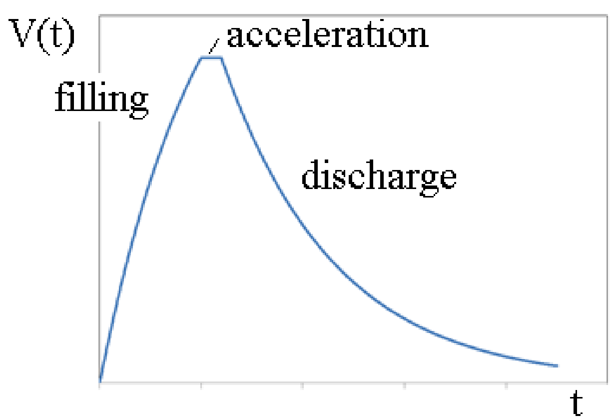
If $\beta>>1$ and $Q_L=V/(R/Q)I$:

❑ RF on:

- $dV/dt=(2V-V(t))/\tau$, filling, no beam, $V(t)=2V(1-exp(-t/\tau))$; $\underline{t_f= \tau ln2}$
- $dV/dt=(V-V(t))/\tau$, acceleration, the beam is on, $V(t)=V$;

❑ RF is off:

$dV/dt=-V(t)/\tau$, the cavity discharge, $V(t)=Vexp(-t/\tau)$.

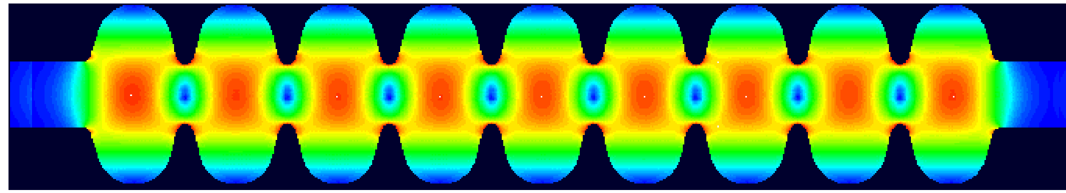


Tools for RF cavity simulations:

I. Field calculations:

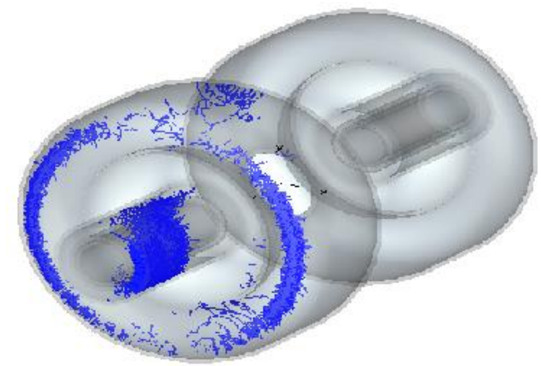
-Spectrum, (r/Q), G, β

-Field enhancement factors



- HFSS (3D);
- CST (3D);
- Omega-3P (3D);
- Analyst (3D);
- Superfish (2D)
- SLANS (2D, high precision of the field calculation).

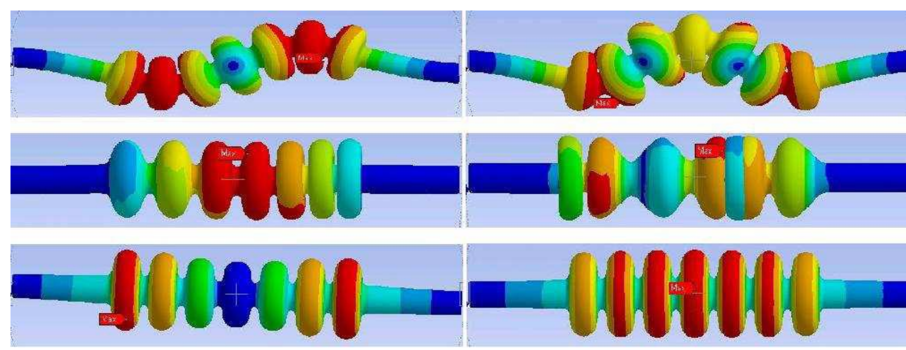
II. Multipactoring (2D, 3D)



- Analyst;
- CST (3D);
- Omega-3P

III. Wakefield simulations (2D, 3D):

- GdfidL;
- PBCI;
- ECHO.



IV. Mechanical simulations:

Lorenz force and Lorenz factor,

Vibrations,

Thermal deformations.

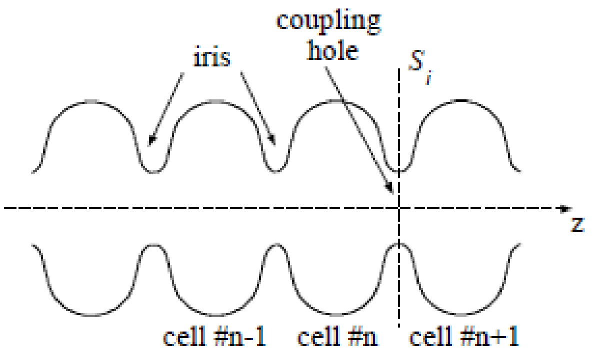
a. ANSYS

Chapter 3.

Multi-Cell SRF Cavities for Accelerators.

Multi-cell RF cavity:

- Single – cell cavities are not convenient in order to achieve high acceleration: a lot of couplers, tuners, etc.
- Multi-cell cavities are used in both RT and SRF accelerators.



- Multi-cell SRF cavity is a standing–wave periodic acceleration structure, operating at the phase advance per period equal to π (i.e, the fields in neighboring cells have the same distribution, but opposite sign).
- In order to provide synchronism with the accelerated particle, period is $\beta\lambda/2$ (in general case it is $\varphi\beta\lambda/2\pi$; φ is phase advance per period).
- The end cells have special design in order to provide field flatness along the structure for <u>operation mode </u>with the phase advance π.

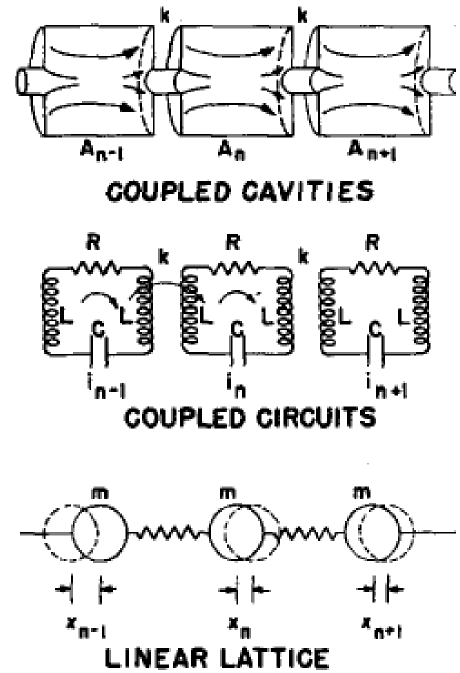
Multi-cell RF cavity:

Coupling between cells splits the frequency of the modes and forms the passband containing the normal modes. The number of normal modes equals to the number of cells N. Equivalent circuit and mechanical model:

$$X_0\left(1-{}^{\omega_0^2}/_{\omega^2}\right)+kX_1=0$$

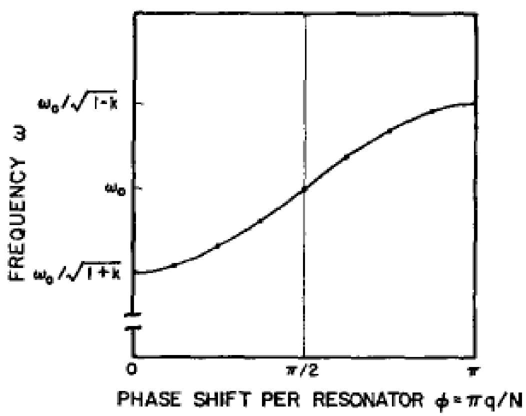
$$X_n\left(1-{}^{\omega_0^2}/_{\omega^2}\right)+k(X_{n-1}+X_{n+1})=0, n=1,2,..N-1$$

$$X_N\left(1-{}^{\omega_0^2}/_{\omega^2}\right)+kX_{N-1}=0$$



Coupling: $k=2(f_\pi-f_0)/(f_\pi+f_0)$
Normal modes: $X_{nq} = A\cos(\pi nq/N)$,
q – mode number, n-cell number;

$$\omega_q^2=\omega_0^2/\left(1+k\cos\frac{\pi q}{N}\right), q=0,1,..N$$



THE REVIEW OF SCIENTIFIC INSTRUMENTS VOLUME 38, NUMBER 11 NOVEMBER 1967

Coupled Resonator Model for Standing Wave Accelerator Tanks*

D. E. Nagle, E. A. Knapp, and B. C. Knapp

Note: the cavity has half-cells in the ends.

Multi-cell RF cavity:

- In the infinitely long structure, or in the finite structure matched on the ends, there may be travelling waves (TW) having arbitrary phase shift per cell φ. Longitudinal wavenumber, therefor, will be $k_z = \varphi/L$. Dispersion equation is the same:

$$\omega(k_z) \approx \omega_0\left(1 - \frac{k}{2}\cos(\varphi)\right) = \omega_0\left(1 - \frac{k}{2}\cos(k_z L)\right)$$

Therefore, the phase velocity $v(\varphi)$ is:

$$v(\varphi) = \frac{\omega(k_z)}{k_z} \approx \frac{\omega_0}{k_z}\left(1 - \frac{k}{2}\cos(\varphi)\right) = c\frac{2\pi L}{\varphi\lambda}\left(1 - \frac{k}{2}\cos(\varphi)\right)$$

And group velocity $v_{gr}(\varphi)$ is

$$v_{gr}(\varphi) = \frac{d\omega}{dk_z} \approx c\frac{\pi k L}{\lambda}\sin(\varphi)$$

For $\varphi = \pi$ group velocity is zero. For $\varphi = \pi/2$ group velocity is maximal.

- For TW in a *periodic structure*:

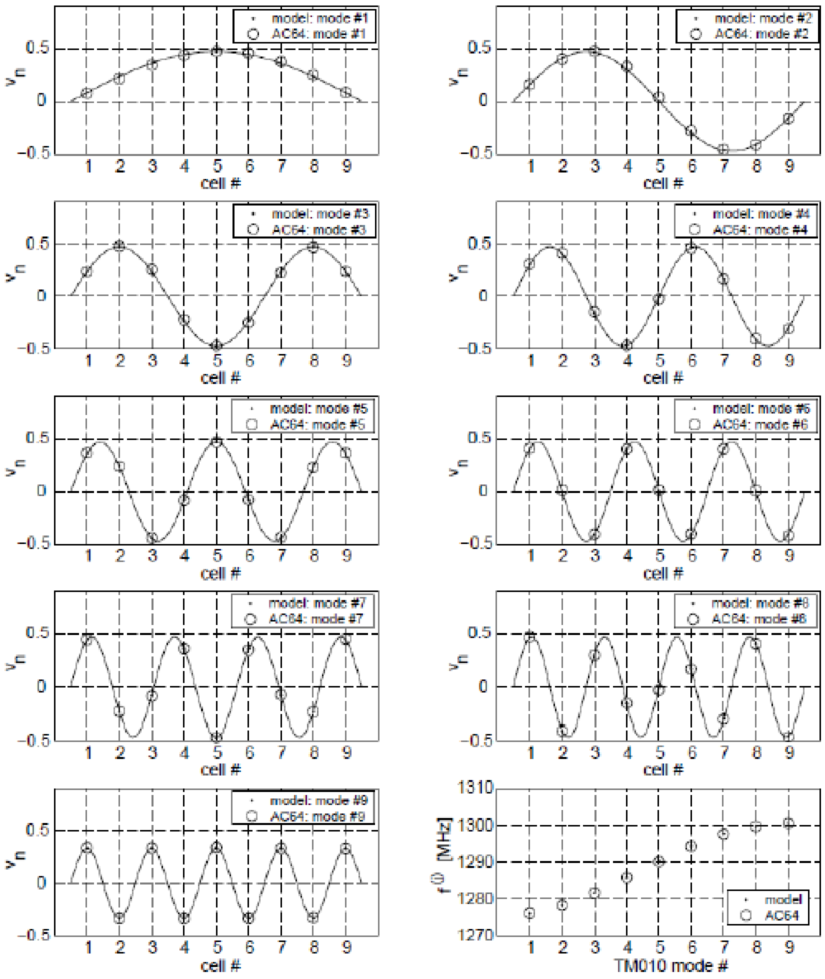
- Average stored energy per unit length for electric field w_E is equals to the average stored energy per unit length for magnetic field w_H (the 1st Bell Theorem):

$$w_E = w_H = w/2$$

- The power P flow is a product of the stored energy per unit length and the group velocity (the 2d Bell Theorem):

$$P = v_{gr} w.$$

Multi-cell RF cavity:



An example of calculated eigen modes amplitudes in a 9-cell TESLA cavity compared to the measured amplitude profiles. Also shown are the calculated and measured eigen frequencies.

The cavity has full size end cells especially tuned in order to get filed flatness for the operating mode.

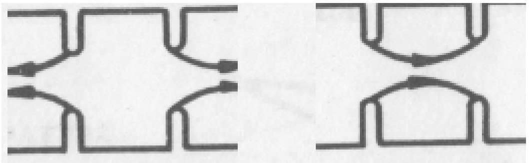
Multi-cell RF cavity:

How the coupling k depends on the coupling aperture radius a?

- Simple estimation for a thin wall:

Let's consider a TW $\pi/2$ mode. It is composed of two SW modes, cos-like and sin-like shifted in phase by $\pi/2$. Sin like mode has odd cells empty, and cos-like mode has even cells empty. On the coupling hole the longitudinal electric filed(it does not depend on radius in the first approximation:)

$$E_{zh} \approx (1+i)E_0/2;$$



cos-like sin-like

Azimuthal magnetic field may be found from Maxwell equation,

$$H_{\varphi h} \sim (1-i)\pi r E_0/2\lambda Z_0 \text{ (}H\text{ is shifted versus }E\text{ by }\pi/2\text{)}$$

Radial electric filed may be found from condition $div(\vec{E}) = 0$:

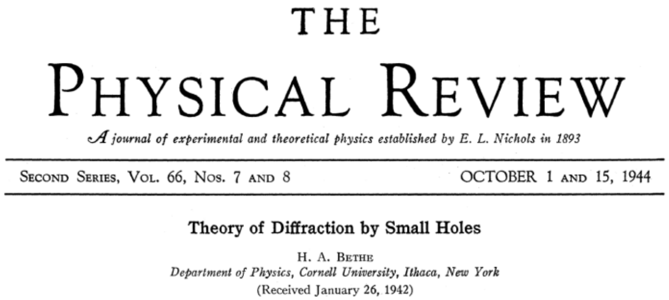
$$E_{rh} \sim (1+i)r/2 \cdot dE_z/dz \approx (1+i)rE_0/4a.$$

Therefore, the pointing vector

$$P \sim \frac{1}{a}\int_0^a r^3 dr \ \sim a^3$$

On the other hand, $k \sim v_{gr} \sim P$, or $k \sim a^3$. For thick wall $k \sim a^\eta$, $\eta > 3$ (field decays in the coupling hole).

- An exact calculation for a small hole in a thin wall:



THE

PHYSICAL REVIEW

A journal of experimental and theoretical physics established by E. L. Nichols in 1893

SECOND SERIES, VOL. 66, NOS. 7 AND 8 OCTOBER 1 AND 15, 1944

Theory of Diffraction by Small Holes

H. A. BETHE

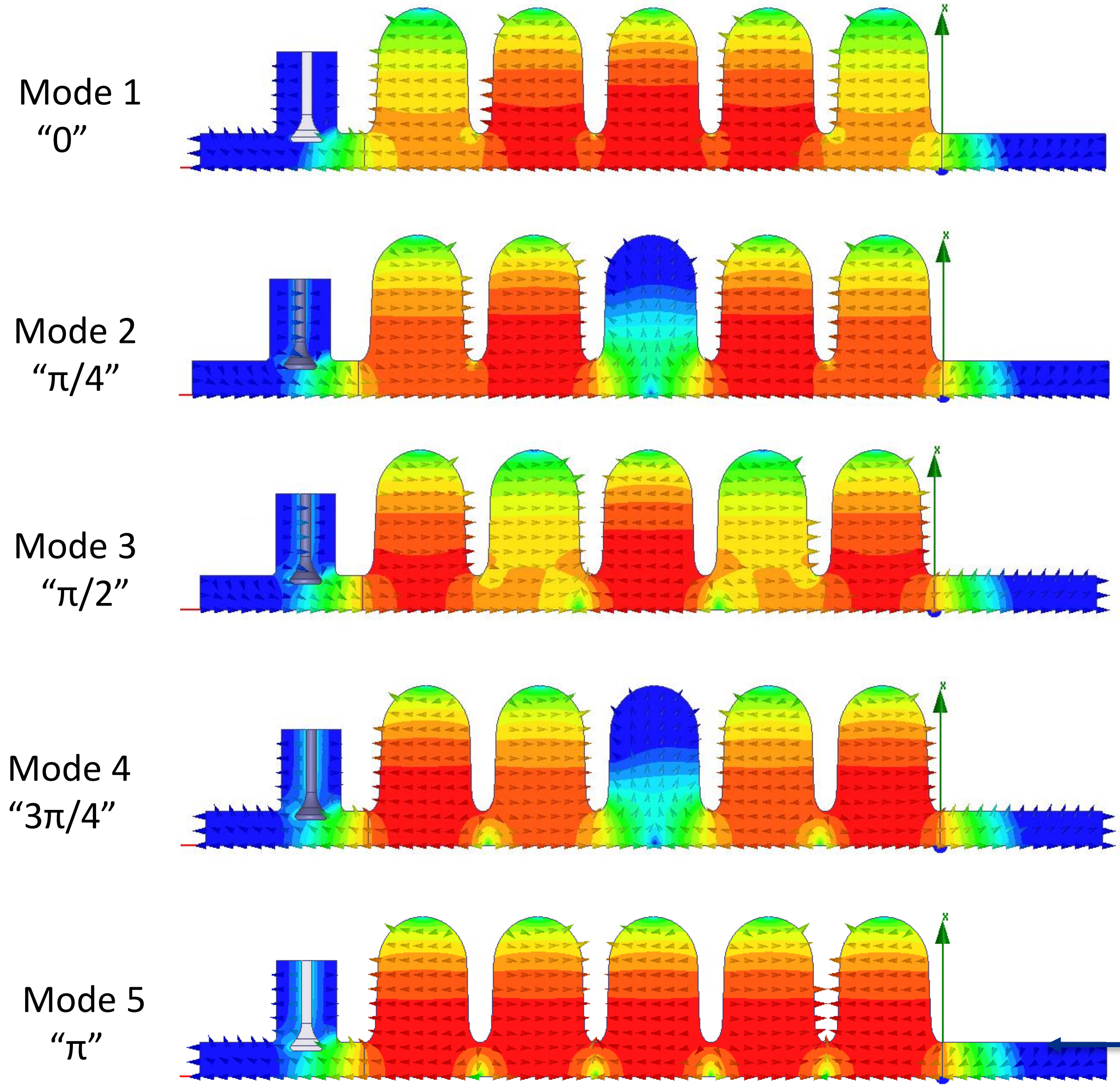
Department of Physics, Cornell University, Ithaca, New York

(Received January 26, 1942)

Sign of k depends on the mode!

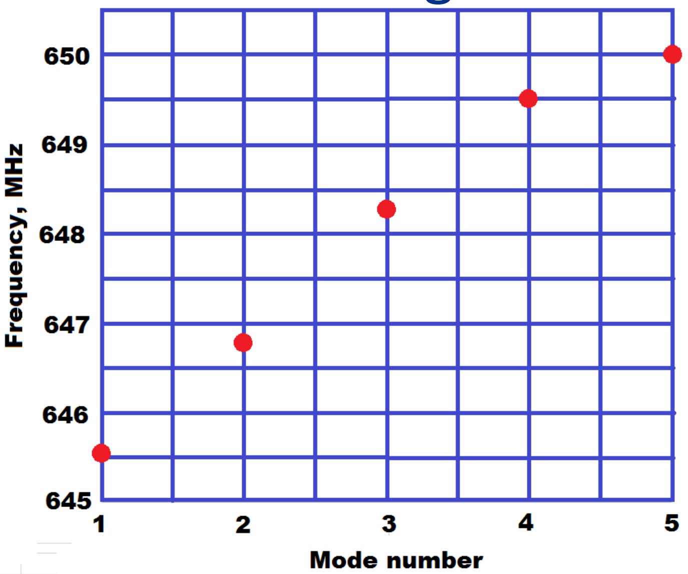
For operating mode $k > 0$.

Normal modes in a standing-wave elliptical cavity:



PIP II 650 MHz cavity

"Brillouin diagram":



$$f(q) \approx f_0\left(1 - \frac{k}{2} cos\,\frac{\pi(q-1)}{(N-1)}\right)$$

q–the mode number;

N- the number of cells;

k- coupling: $k=0.7\%$

Operation mode "π"

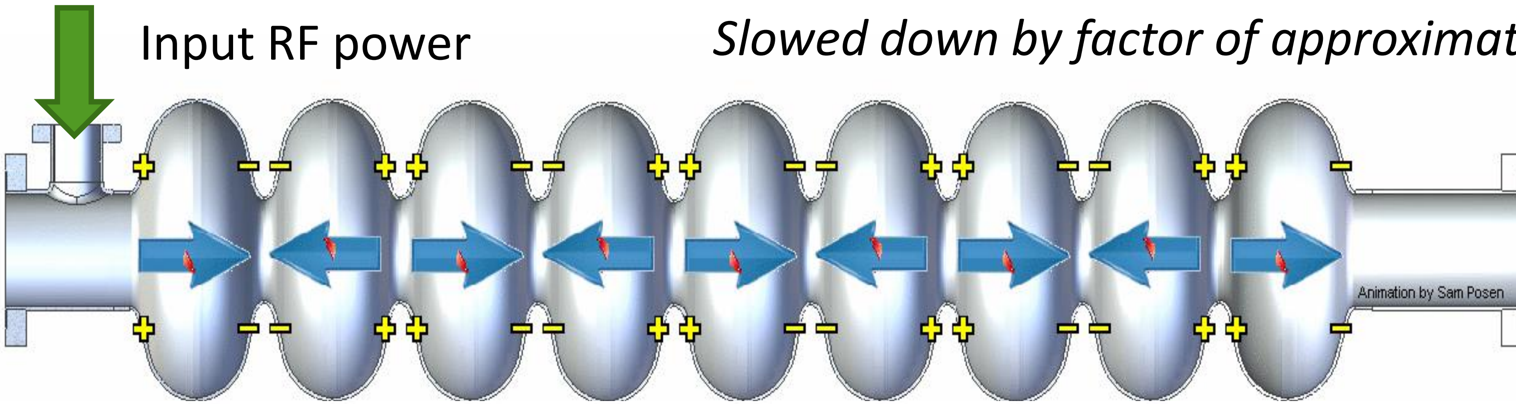
Mult-cell cavities in accelerators:

- Synchronism (EM wave phase velocity ≈ particle velocity)
- High velocity of accelerated particles, $\beta \equiv v/c \gtrsim 0.5$
- RF frequency $\gtrsim$ 200 MHz (transverse size!)
- Operation mode: "π" (standing wave)

1.3 GHz ILC cavity (animation by Sam Posen, FNAL)

Input RF power

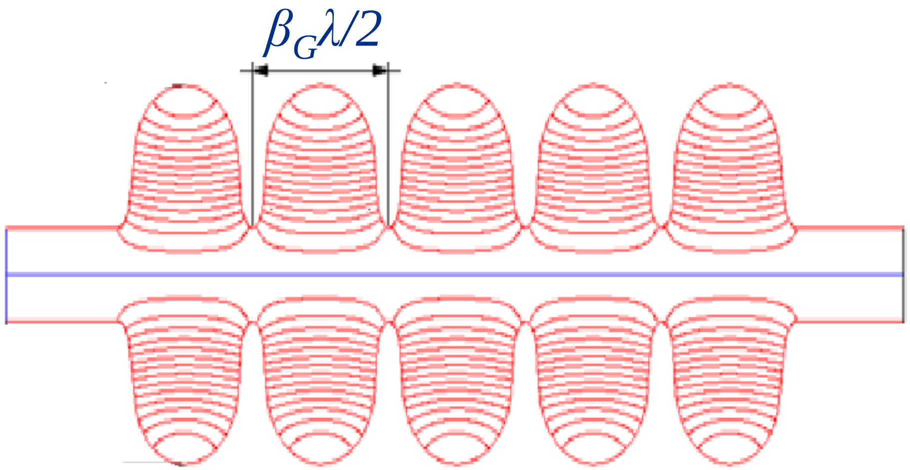
Slowed down by factor of approximately $4x10^9$



~1 m

Parameters of a multi-cell cavity:

- "Geometrical beta": $\beta_G = 2l/\lambda$,
  l is the length of a regular cell,
  λ is wavelength.



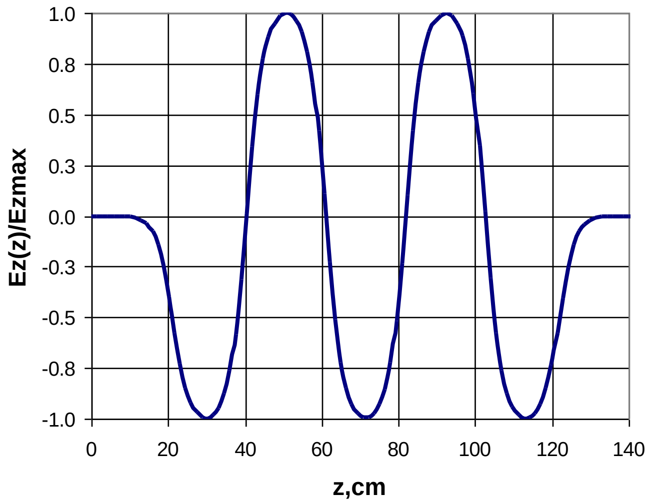
- $R/Q = V^2/\omega U$, V is the energy gain per cavity (in optimal acceleration phase) , $V=V(\beta)$; ω – cyclic operation frequency; U is EM energy stored in a cavity; R/Q is a function of β, as well as V. R/Q is the same for geometrically similar cavities. Decreases when the cavity aperture a increases.
- "Optimal β": value of β, where V (and R/Q) is maximal.
- Acceleration gradient: $E=V/L_{eff}$, $L_{eff} = n\lambda/2$ – effective length, n is the number of cells.

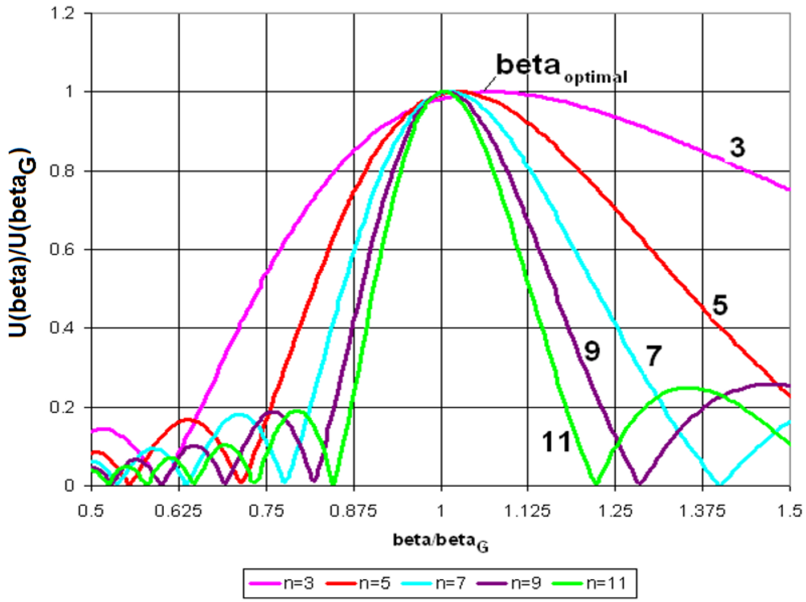
Parameters of a multi-cell cavity (cont)

- Surface electric field enhancement: $K_e = E_{peak}/E$, E_{peak} is maximal surface electric field.
- Surface magnetic field enhancement: $K_m = B_{peak}/E$, B_{peak} is maximal surface
  magnetic field.
- Unloaded quality factor: $Q_0 = \omega U/P_{loss}$, P_{loss} – surface power dissipation.
- *G*-factor: $G=Q_0{*}R_s$, R_s is the surface resistance. *G* is the same for geometrically similar cavities. At fixed gain the losses are proportional to $G{*}(R/Q)$.
- Loaded quality factor: $Q_{load} = \omega U/P$, $P= P_{loss} + P_{load}$; P_{load} – power radiated through the coupling port.
- Coupling: $k=2(f_\pi - f_0)/(f_\pi - f_0)$,

Multi-cell cavity

A multi-cell SRF elliptical cavity is designed for particular $\beta = \beta_G$, but accelerates in a wide range of particle velocities; the range depends on the number of cells in the cavity N. Field distribution for the tuned cavity has equal amplitudes for each cell; longitudinal field distribution for considerably large aperture is close to sinusoidal:





$$\frac{\boldsymbol{V}(\beta)}{\boldsymbol{V}(\beta_{\boldsymbol{optimal}})} = \frac{2\beta}{\pi \boldsymbol{N}}\left(\frac{\sin\left(\frac{\pi \boldsymbol{N}(\beta-\beta_G)}{2\beta}\right)}{\beta-\beta_G} - (-1)^n \frac{\sin\left(\frac{\pi \boldsymbol{N}(\beta+\beta_G)}{2\beta}\right)}{\beta+\beta_G}\right)$$

$$\beta_{optimal} \approx \beta_G\left(1+\frac{6}{\pi^2 N^2}\right)$$

V is the energy gain per cavity.

The cavity containing more cells provides effective acceleration in more narrow particle velocity range!

Why SW π – mode?

Sensitivity versus manufacturing errors :

$$\delta\vec{X}_n = \sum_{n'\neq n} \frac{\vec{X}_{n'}\cdot\left[\frac{\delta f_{0i}^2}{f_0^2}\right]\cdot\vec{X}_n}{\left(\frac{f_{n'}^2}{f_n^2}-1\right)}\cdot\vec{X}_{n'} \sim \frac{\delta f}{f_n - f_{n\pm 1}}$$

For π/2-mode $\delta X/X \sim (\delta f/f)\cdot(N\text{-}1)/k$;

For π-mode $\delta X/X \sim (\delta f/f)\cdot 2(N\text{-}1)^2/k$, much worse than for π/2-mode.

- π/2-mode is much more stable versus frequency perturbations than π-mode!
- For RT TW structures they use π/2-mode or 2π/3-mode (SLAC).
- SRF TW structure does not work: feedback WG is necessary because of negligibly small decay (problems with processing, multipacting).

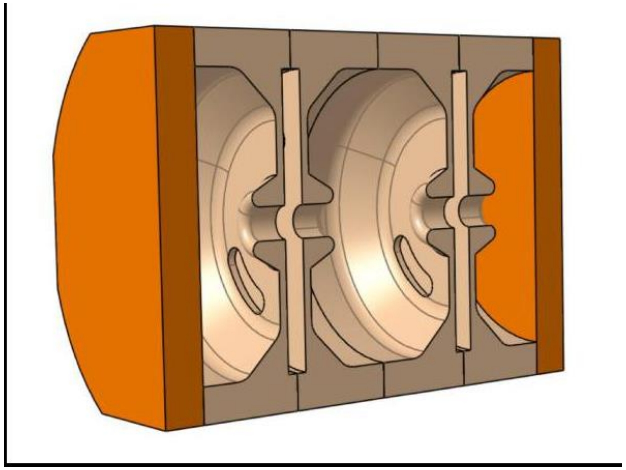
Fermilab

Why SW π – mode?

- The SW modes except π have small acceleration efficiency because most of cavities have small field (in ideal case $X_{ni} \sim \cos(\pi ni/N)$, *n* – mode number, *i*-cell number).
- Bi-periodic structure π/2-mode does not work because it is prone to multipacting in the empty coupling cells and difficult for manufacturing (different cells) and processing (narrow coupling cells).
- π -mode structure is simple, easy for manufacturing and processing.
- Drawback:

  -Big aperture to provide big coupling;

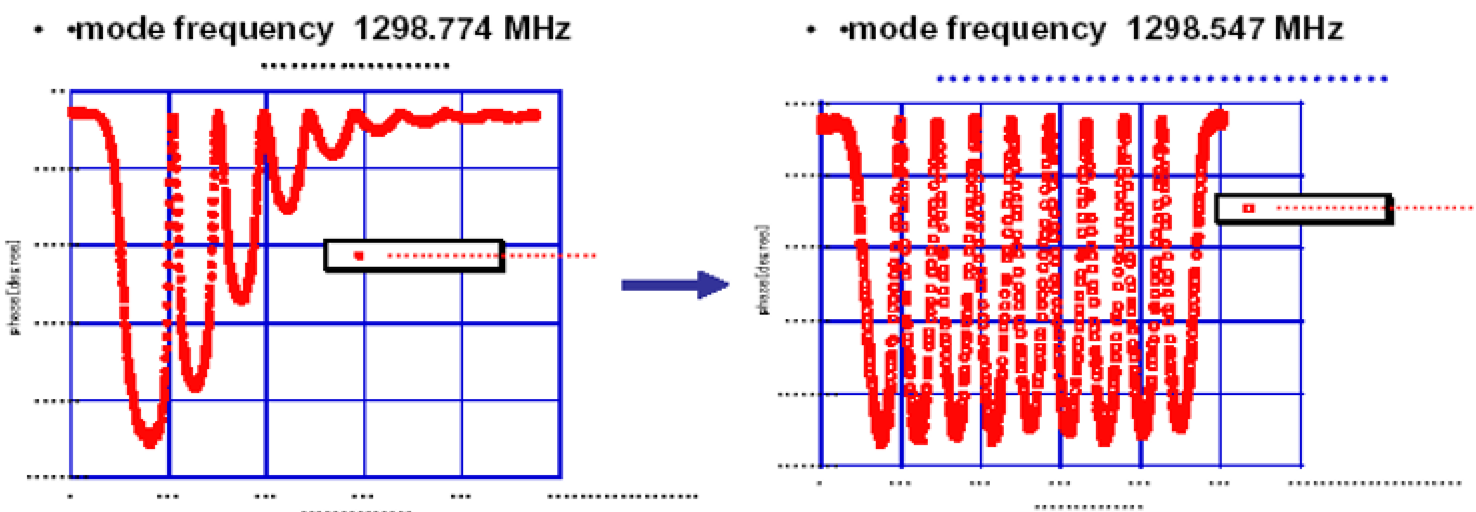
  -Considerably small number of cells N (5-9) for SRF compared to 40-100 for RT).



Why SW π – mode?

Cavity tuning:

- Compensation of the errors caused my manufacturing
- Compensation of the errors caused by cool-down.
- Field flatness
- Tuning the operating mode frequency to resonance.



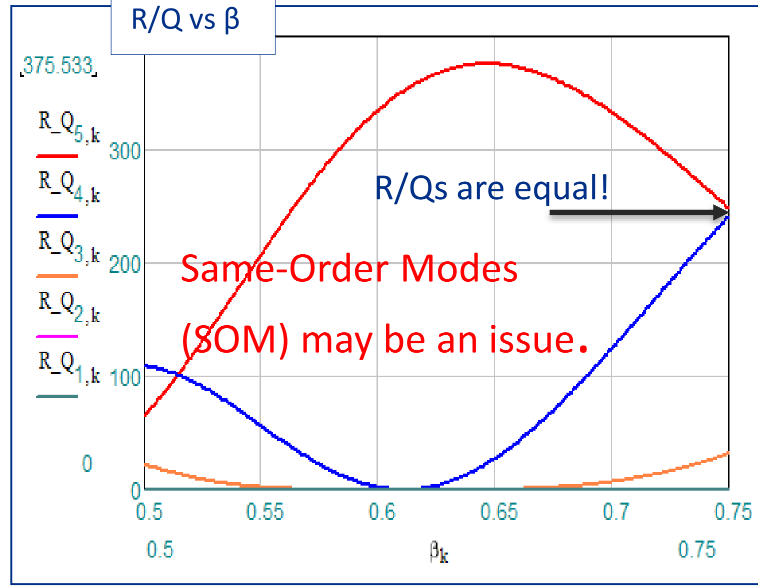
Field flatness = 0.1 %
(as delivered to KEK)

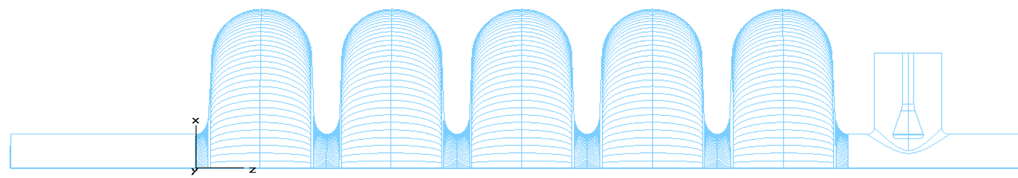
Field flatness = 98 %
(after pre-tuning)

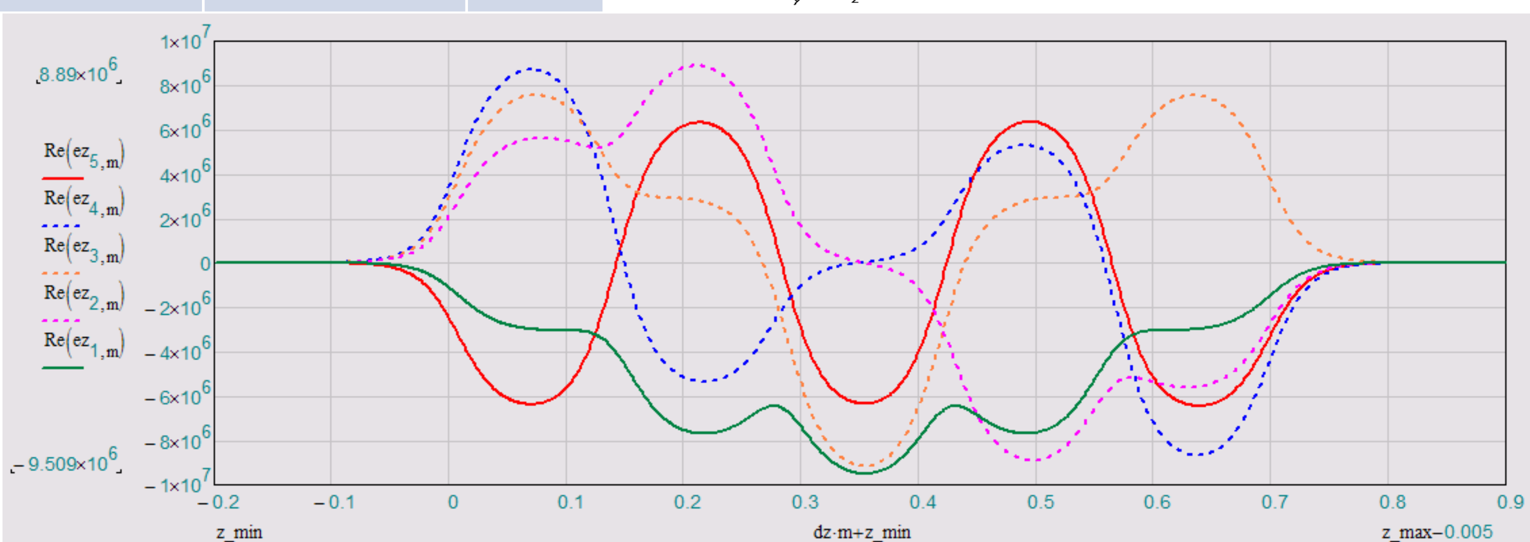
Field flatness in ILC – type cavity before and after pre-tuning.

PIP II β_G=0.61, 650 MHz elliptical cavity:

Mode	Freq [GHz]	$(R/Q)_{opt}[\Omega]$	β_{opt}
0	0.6456	0.5	>0.75
¼ π	0.6468	0.4	0.69
½ π	0.6483	32.1	>0.75
¾ π	0.6495	241.0	>0.75
π	0.6500	375.5	0.65



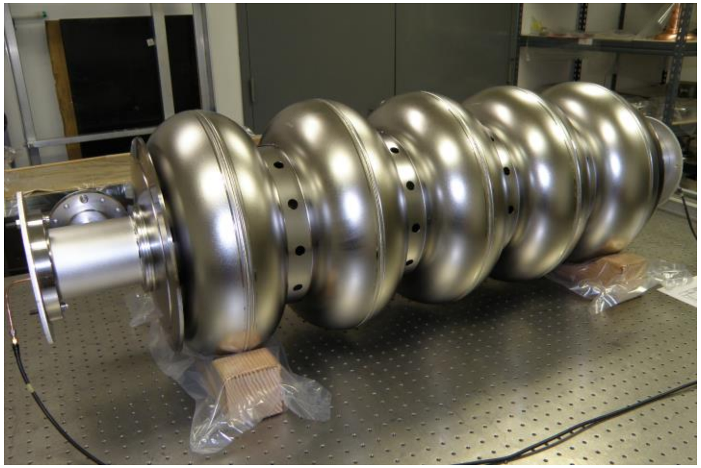




Elliptical cavities:

INFN Milano, 700 MHz, $\beta_G = 0.5$

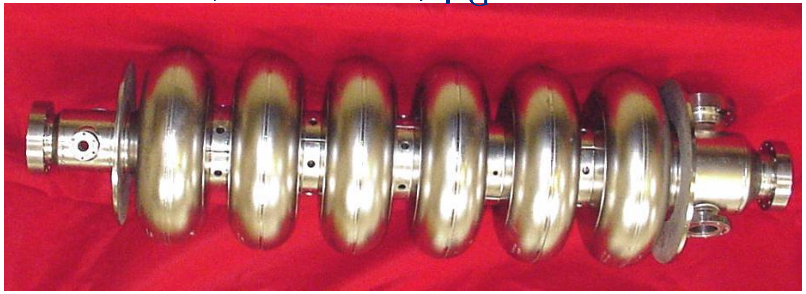
PIP II, 650 MHz, $\beta_G = 0.9$



SNS, 805 MHz, $\beta_G = 0.61$

XFEL, 1300 MHz, $\beta_G = 1$

SNS, 805 MHz, $\beta_G = 0.81$



XFEL, 3900 MHz, $\beta_G = 1$

Multi-cell cavity is not effective for low β:

During acceleration a particle interacts with cylindrical EM waves,

$$E_z(r,z,t) \sim J_0(k_r r)\exp(ik_z z - i\omega t),$$

where $J_0(x)$ is Bessel function.

For acceleration, the cylindrical wave should be synchronous, i.e., it should have phase velocity equal to the particle velocity:

$\omega/k_z = v = c\beta$, or $k_z = \omega/\beta c = k/\beta$ (k is full wavenumber, $k = \omega/c = 2\pi/\lambda$)

On the other hand, for EM wave one has:

$(k)^2 = (k_r)^2 + (k_z)^2$ or $(k_r)^2 = (k)^2 - (k_z)^2 = (k)^2(1-1/\beta^2)$. Thus, $k_r = ik/\beta\gamma$.

- In ultra-relativistic case $k_r \to 0$
- In non-relativistic case $k_r = ik/\beta$ and the synchronous cylindrical wave is

$$E_z(r,z,t) \sim I_0(2\pi r/\lambda\beta)\exp(ikz/\beta - i\omega t),$$

$I_0(x)$ is modified Bessel function.

Multi-cell cavity is not effective for low β:

For small β

$I_0(r) \sim exp(2\pi r/\lambda\beta)$.

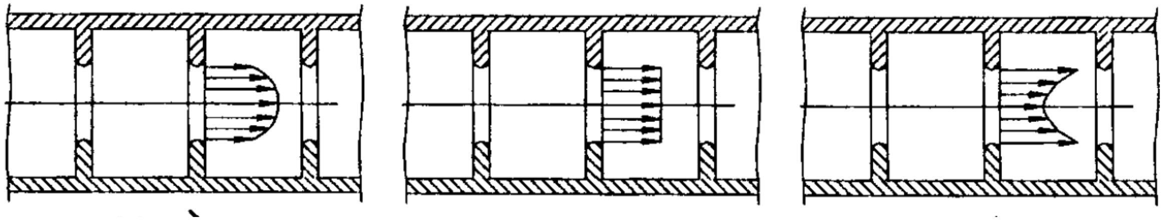
Synchronous EM is concentrated on the cavity periphery, not on the axis! Consequences:

- Small (R/Q):

  $(R/Q) \sim exp(-4\pi a/\lambda\beta)$, a is the cavity aperture radius;
- High K_e

  $K_e \sim exp(2\pi a/\lambda\beta)$;
- High K_m.

  $K_m \sim exp(2\pi a/\lambda\beta)$.

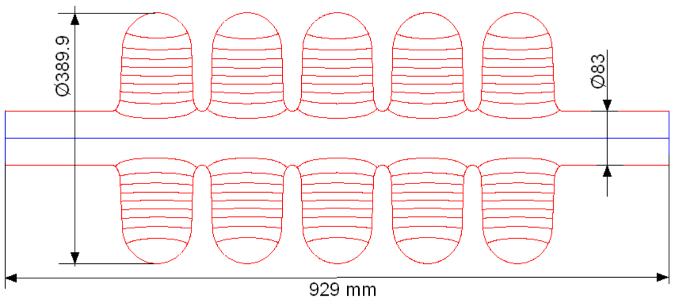


$v>c$ $v=c$ $v<c$

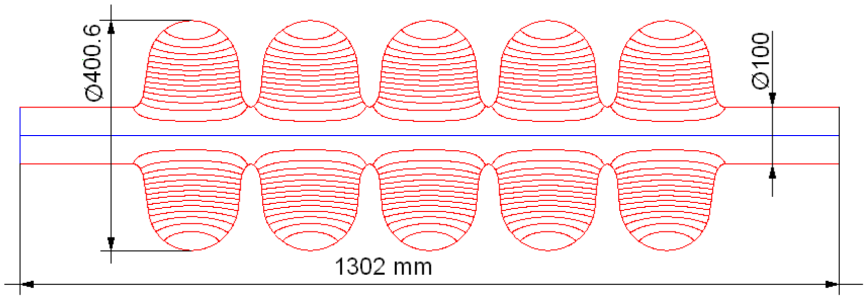
Fermilab

Parameters of an elliptical cavity (cont)

Example for the 650 MHz cavities for PIP II



LB650 (β_G=0.61)



HB650 (β_G=0.9)

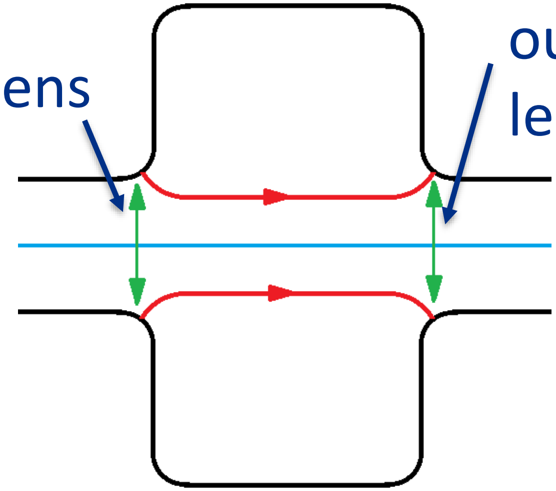
Parameter		LH650	HB650
β_G		0.61	0.9
$\beta_{optimal}$		0.65	0.94
Cavity Length = $n_{cell} \cdot \beta_{geom} \lambda/2$	mm	703	1038
R/Q	Ohm	378	638
G-factor	Ohm	191	255
K_e		2.26	2.0
K_m	mT/(MeV/m)	4.22	3.6
Max. Gain/cavity (on crest)	MeV	11.7	17.7
Acc. Gradient	MV/m	16.6	17
Max surf. electric field	MV/m	37.5	34
Max surf. magnetic field,	mT	70	61.5
Q_0 @ 2K	$\times 10^{10}$	2	3
P_{2K} max	[W]	24	24

Multi-cell cavity is not effective for low β:

RF cavity provides the beam focusing,

$$\frac{1}{F} \sim \frac{\pi}{\beta^3\gamma^3}\frac{V}{U_0}\frac{1}{\lambda}\sin(\varphi_s)$$

- For $\varphi_s < 0$ (necessary for longitudinal stability) the cavity provides defocusing!
- Defocusing:
  - $\sim 1/\beta^3$;
  - $\sim 1/\lambda$.



Defocusing should be compensated by external focusing elements,
-solenoids (low energy);
-quads (high energy).

For small β longer RF wavelength (lower frequency) should be used.

But axisymmetric cavity has very big size, D~3/4 λ

For small β other types of cavities should be used!

Chapter 4.

RF Cavities for Low β Accelerators .

RF cavities for low β:

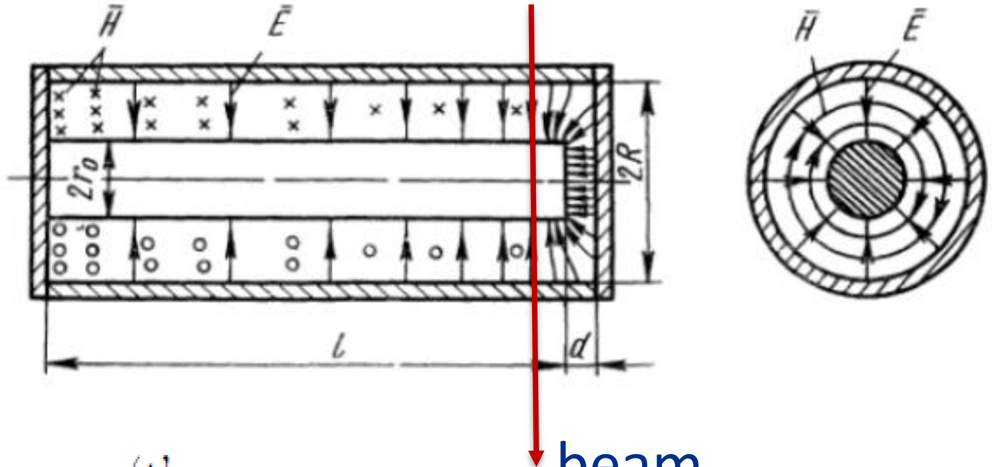
TEM-like cavities:

- Split-ring resonator;
- Quarter-wave resonator;
- Half-wave resonator;
- Spoke resonator.

- Narrow acceleration gap (~βλ) allows concentrate electric field near the axis;
- Aperture ~ 0.02-0.03λ allows acceptable field enhancement;
- Number of gaps in modern cavities is 2 for small beta which allows operation in acceptably wide beta domain. For β > 0.4 multi-gap cavities are used –double- and triple-spoke resonators;
- Focusing elements (typically, solenoids) are placed between the cavities.

RF cavities for low β:

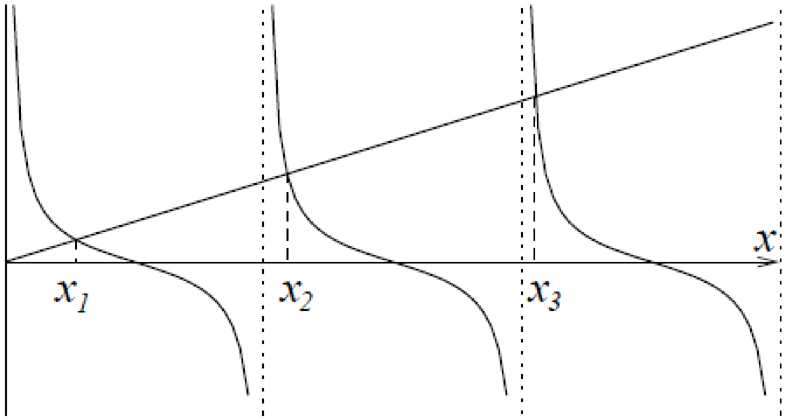
Quarter-wave resonator concept:



Resonance:

$$\frac{1}{j\omega C} + jZ_0 \tan\frac{\omega}{c}l = 0. \quad \text{or} \quad \cot\frac{\omega}{c}l = Z_0\omega C.$$

$$\frac{\omega}{c}l = x, A = \frac{Z_0 C\, c}{l} \longrightarrow \cot x = Ax.$$



Compact (L$\gtrsim\lambda/4$) compared to pillbox (D$\gtrsim 3/4\lambda$).

RF cavities for low β:

Quarter-wave resonator:

•Allows operate at very low frequency ~50 MHz, (and thus, low beta) having acceptable size;

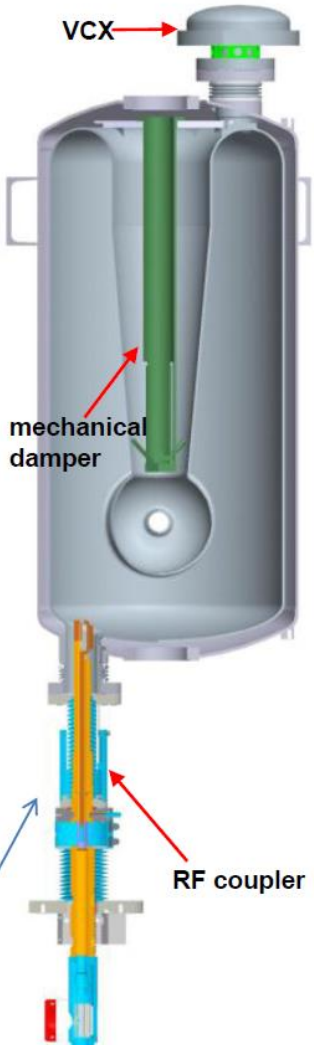
•Has a good (R/Q);

•Low cost and easy access.

But:

•Special means needed to get rid of dipole and quadrupole steering, and

•Provide mechanical stability

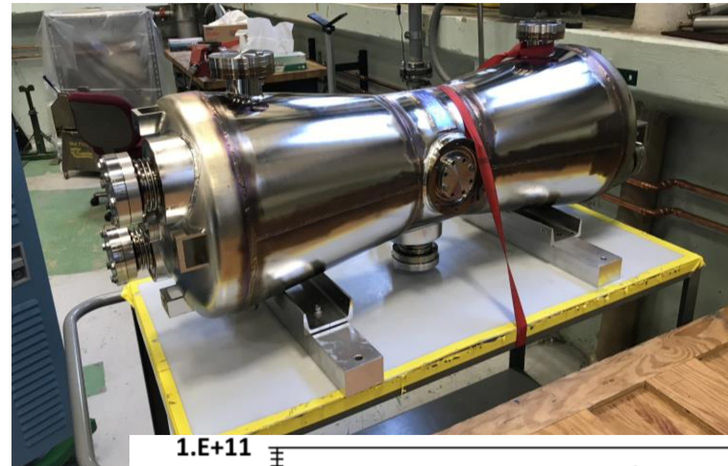


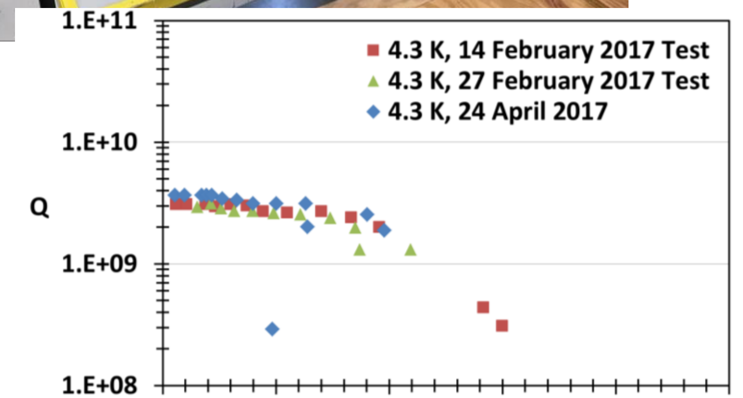
beta=0.14, 109.125 MHz QWR(**Peter N. Ostroumov)**

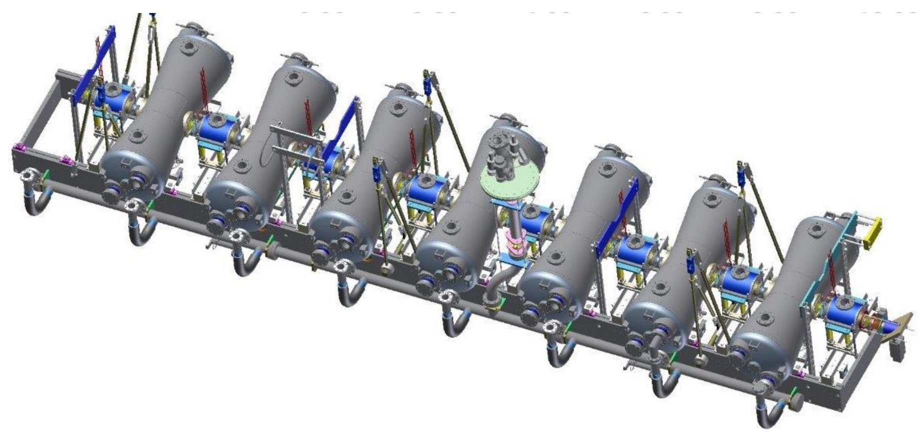
RF cavities for low β:

Half-wave resonator (HWR):
•No dipole steering;
•Lower electric field enhancement;
•High performance;
•Low cost;
•Best at ~200 MHz.

But:
•Special means needed in some cases to get rid of quadrupole effects.



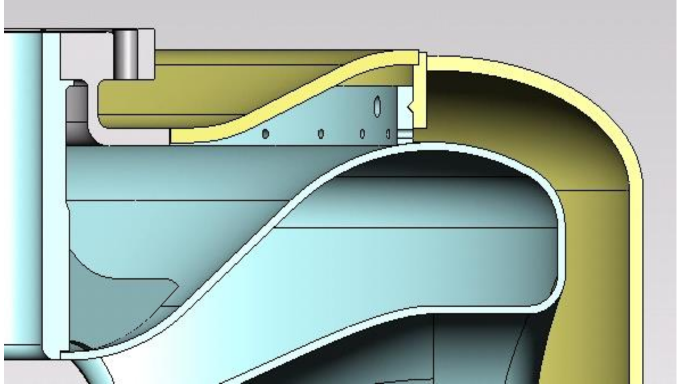




PIP II HWR cavity, 162.5 MHz
(M.Kelli, Z. Conway)

RF cavities for low β:

Spoke resonator

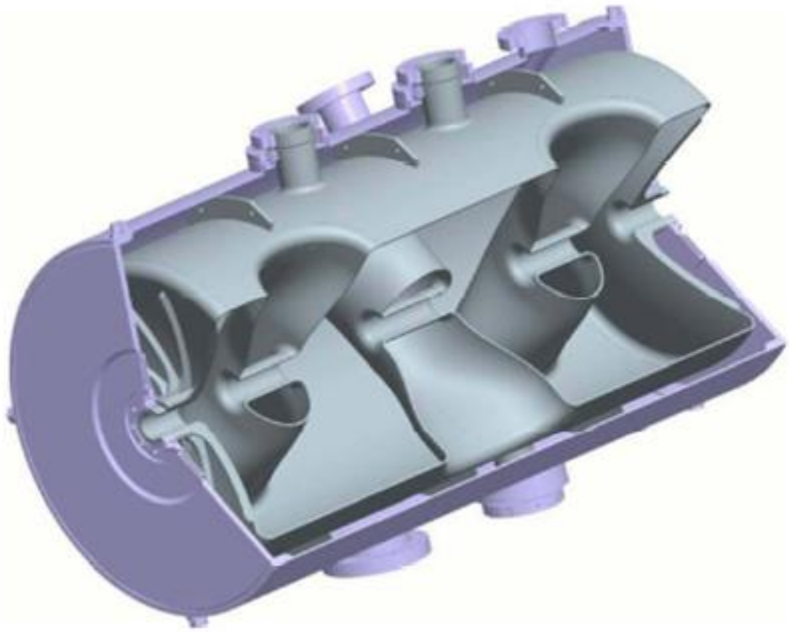


Mechanical coupling of the cavity to the He vessel in order to improve mechanical stability.

FNAL 325 MHz SSR1 cavity layout and photo. β=0.22

RF cavities for low β:

Multi-spoke resonators



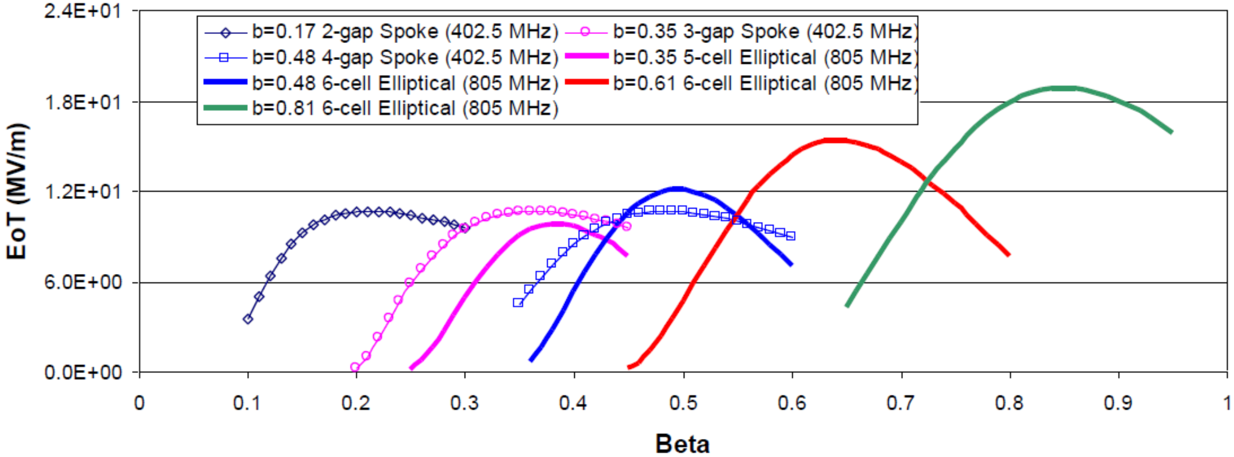
Triple-spoke cavity

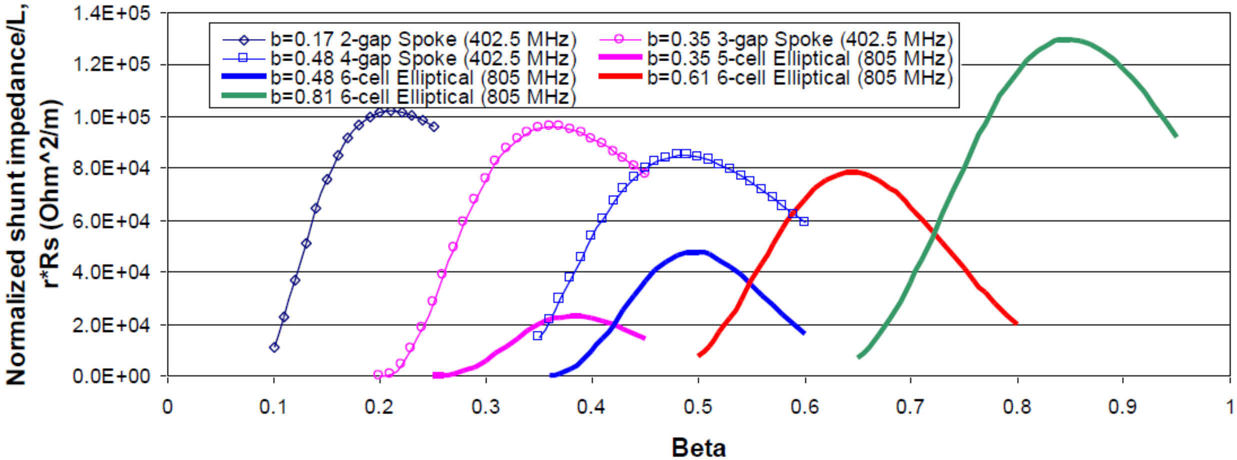
345 MHz, β=0.4,
3-gap spoke cavity
for ion beam acceleration
ANL

Why not multi-spoke for β>0.5?

Comparison of RF properties (elliptical cavity versus spoke cavity)*

Spoke cavities (402.5 MHz) and elliptical cavities (805 MHz) are optimally designed under the same criteria: E_{peak} ≈40 MV/m and B_{peak} ≈ 85 mT. Here EoT is gradient, and r*Rs is R/Q*G per unit length.





For β>0.5-0.6 elliptical cavity is preferable!

*Sang-Ho Kim, Mark Doleans, USPAS, January 2013, Duke University

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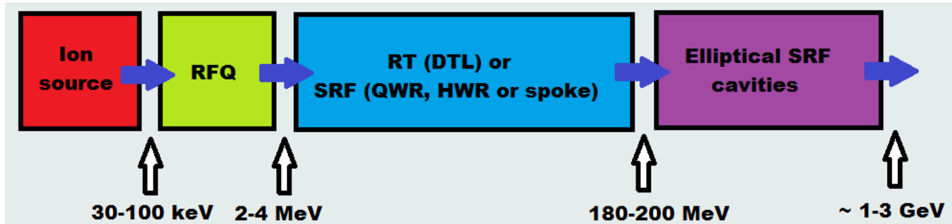
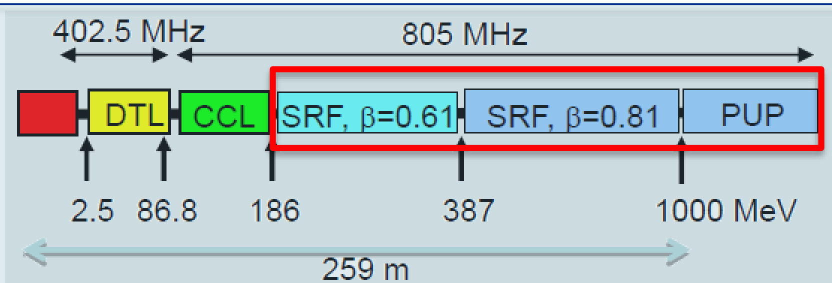
Chapter 5.

Architecture of a GeV–range proton SRF accelerator

Architecture of a GeV–range proton SRF accelerator:

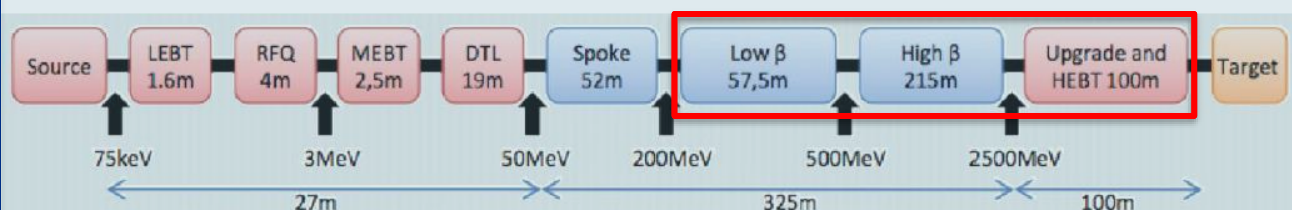
Layout of typical modern proton SRF accelerator.





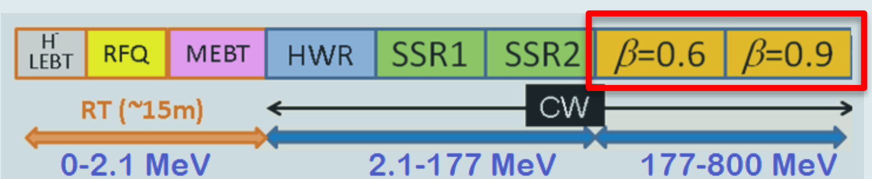
SNS (ORNL): H^- ,1 GeV, 6% DF, 1.44 MW to accumulator ring

In operation



ESS (Lund): p^+, 2.5 GeV, 4% DF, 5 MW to target

Under construction



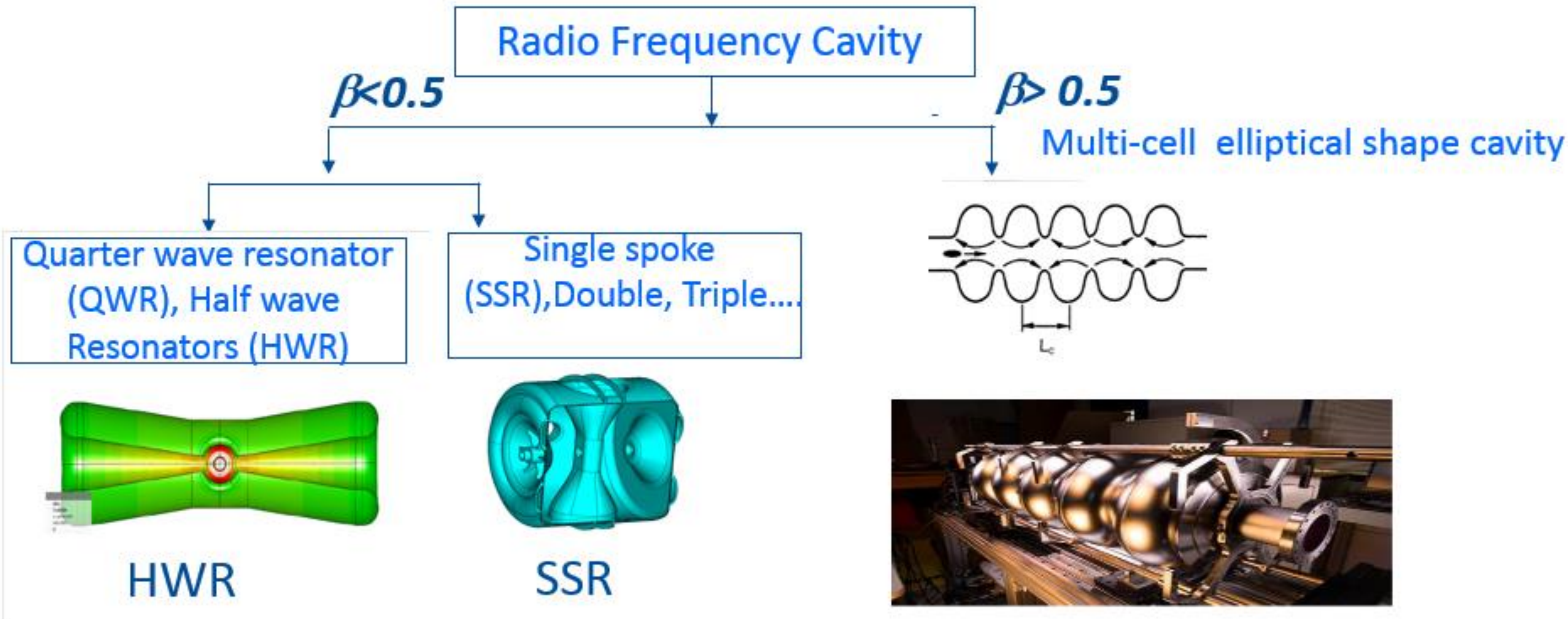
PIP II (FNAL): H^- ,800 MeV, up to 100% DF, up to 1.6 MW

Design

Linac Design Philosophy:

- ❑ RT or SRF frontend?
  - For low duty factor RT frontend (up to ~200 MeV) may be used
  - For high DF or CW SRF is necessary from the beginning
- ❑ Choice of beam line elements
  - Accelerating RF Cavities
  - Focusing Magnets
- ❑ Lattice Design
  - Focusing Period
  - Transition Energy between Sections

RF cavities:



- Lower RF frequency provides better interaction with beam.
- RF defocusing factor is inversely proportional to frequency.
- Lower frequency implies larger RF bucket and hence larger longitudinal acceptance.

RF cavities:

❑ The frequency choices for multi-cell:

- Cavity length is about the same for the same β_G (the same number of couplers, tuners, etc). Typical length ~0.8-1 m depending on β_G (from iris to iris)
- Lower frequencies → bigger size, higher cost, more difficult handling, microphonics
  but: lower losses per unit length (smaller R/Q, but lower R_s); larger aperture (current interception), smaller beam defocusing; smaller number of cells and therefore, smaller a/λ, smaller K_m and K_e and smaller numbers of cavity types.
- Typically , they use 650 – 800 MHz, and 5-7 cells/cavity:
  SNS: 804 MHz, 6 cells/cavity (in operation)
  ESS: 704 MHZ, 5 cells/cavity (under construction)
  PIP II: 650 MHz, 5 cells/cavity (under development)

❑ The frequency choices for the front end:

- Subharmonics of the main frequency.

❑ Acceleration gradient choice (high DF, CW):

- Quench, $B_{peak} \lesssim$70-80 mT
- Field emission, $E_{peak} \lesssim$ 40 MV/m
- Thermal breakdown typically is not an issue for proton linacs.

RF cavities:

- Selection of the maximum accelerating gradients in cavities are made on the basis of :
  - Peak surface magnetic field
  - Peak surface Electrical field
- Choices of peak magnetic fields are derived from:
  - Dynamics heat load due to accelerating mode
  - Cavity quenching.
- Choices of peak surface field is made to avoid field emission

CW Linac assumptions:

- 162.5 MHz: $H_{pk} < 50$mT
- 325 MHz: $H_{pk} < 60$mT
- 650 MHz: $H_{pk} < 70$mT
- $E_{pk} < 40$ MV/m.

Accelerating Gradient in PIP-II Linac

	HWR	SSR1	SSR2	LB650	HB650
Gradient (MV/m)	9.7	10	11.4	15.9	17.8

Focusing elements:

- Normal conducting magnets are cheaper but superconducting magnets are:
  - Compact in size
  - Provide intense magnetic field with low power consumption.
- Lowe energy part of SRF linac typically use solenoidal focusing:
  - Provide Radial focusing
- Intermediate and high energy section of linac use normal conducting doublet focusing.
  - Simplify cavity magnetic shielding requirements
- Correctors are built in each magnets.
- Solenoidal and doublet focussing keeps the beam round in transverse planes.

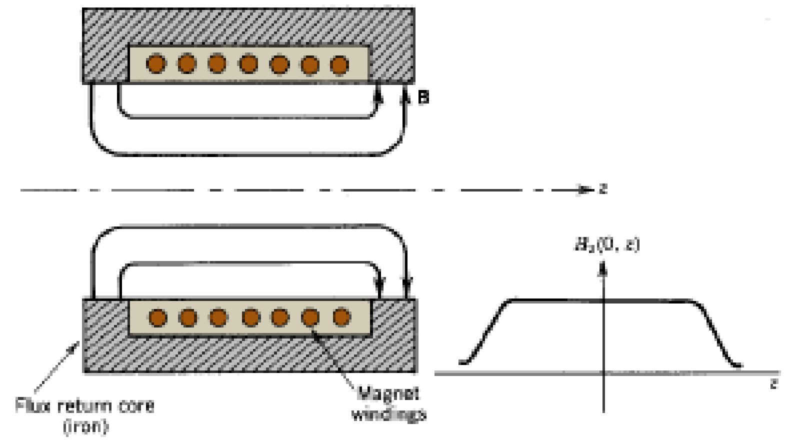
- *Focusing magnets in each section*

Section	HWR	SSR1	SSR2	LB650	HB650
Magnet	S	S	S	FD	FD

S – solenoid, FD – doublet (F : focusing and D: Defocusing quadrupole).

Focusing elements:

❑ Solenoid:

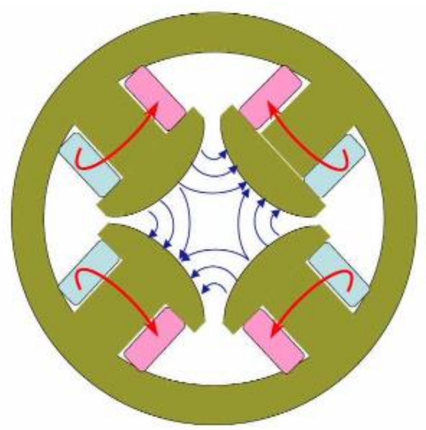


Solenoid focal length *f*:
(non-relativistic case)

$$\frac{1}{f} = \frac{q^2}{8Tm} \int B_z^{\,2} dz$$

- Focal length is proportional to β^2;
- Focal length is inversed proportional to $B_z^2 L$, L is the solenoid length;
- Therefore, solenoid can be used for low β ($\beta<0.5$). For higher β quad is used.

❑ Quadrupole lens:



Quad focal length *f*:

$$\frac{1}{f} = \frac{qB'L}{\gamma\beta mc}$$

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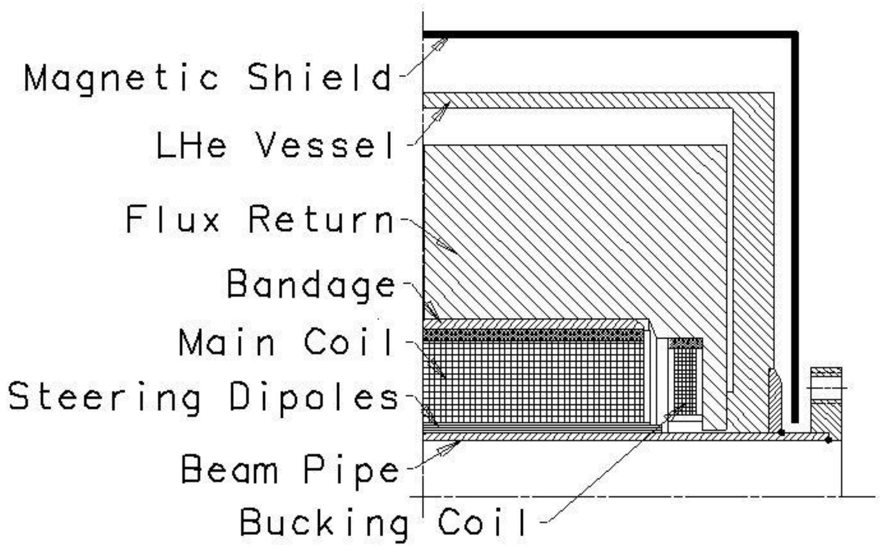
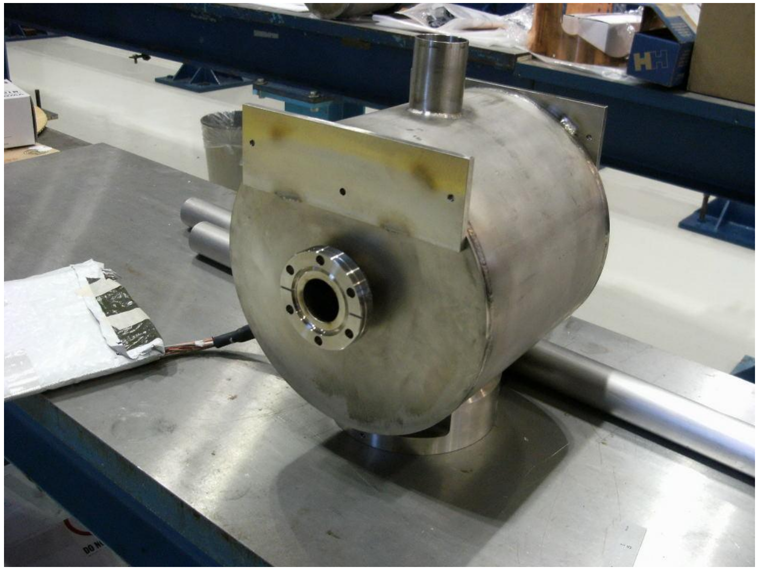
Focusing elements:

For low section SC solenoids are used.

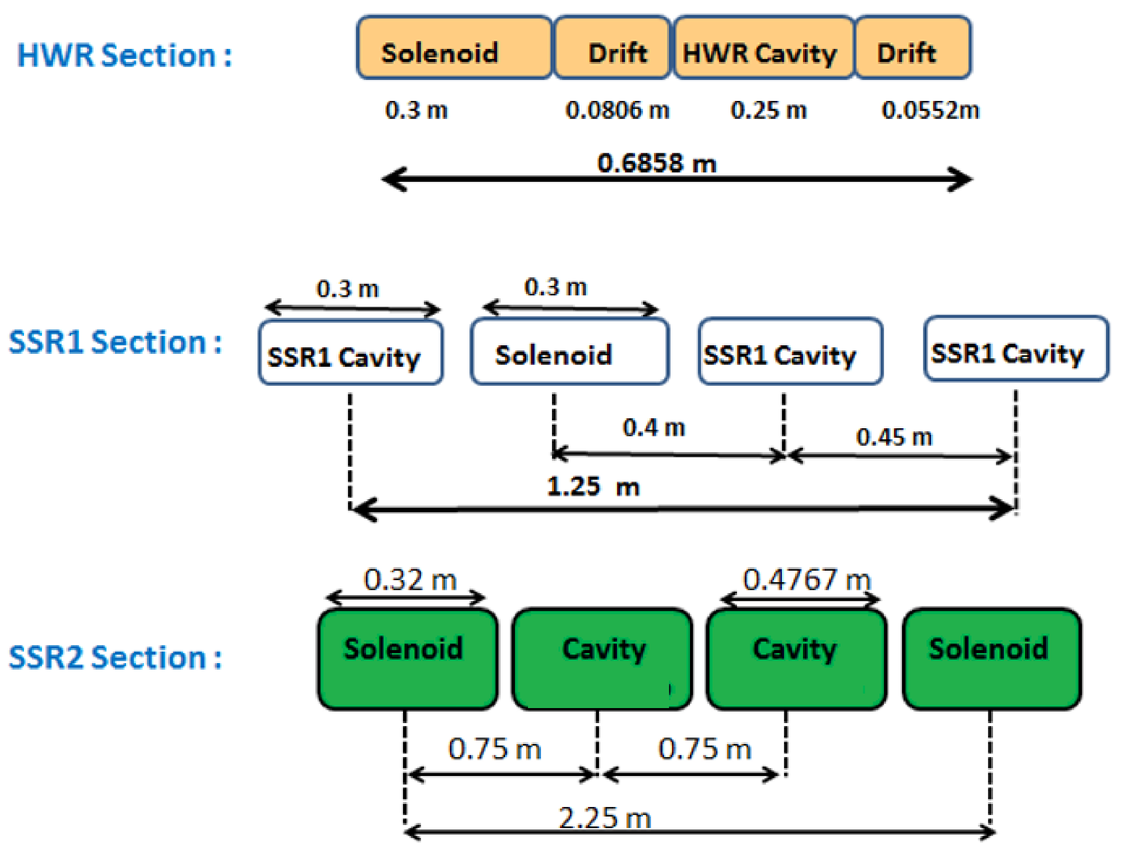
- Simple and inexpensive;
- Filed up to 6-8 T;
- SRF cavity should have < 10 mT on the SRF cavity surface: remnant solenoid field should be compensated
- Solenoid contains correction coils (steering dipoles)
- Alignment (typically <0.3- 0.5 mm, <5 mrad tilt);
- Quench protection;
- Leads





Lattice Design: Focusing Periods

- Length of the focusing period is kept short, especially in the low energy section where beam is non-relativistic and non-linear force may be significant .



Cryomodule Arrangement

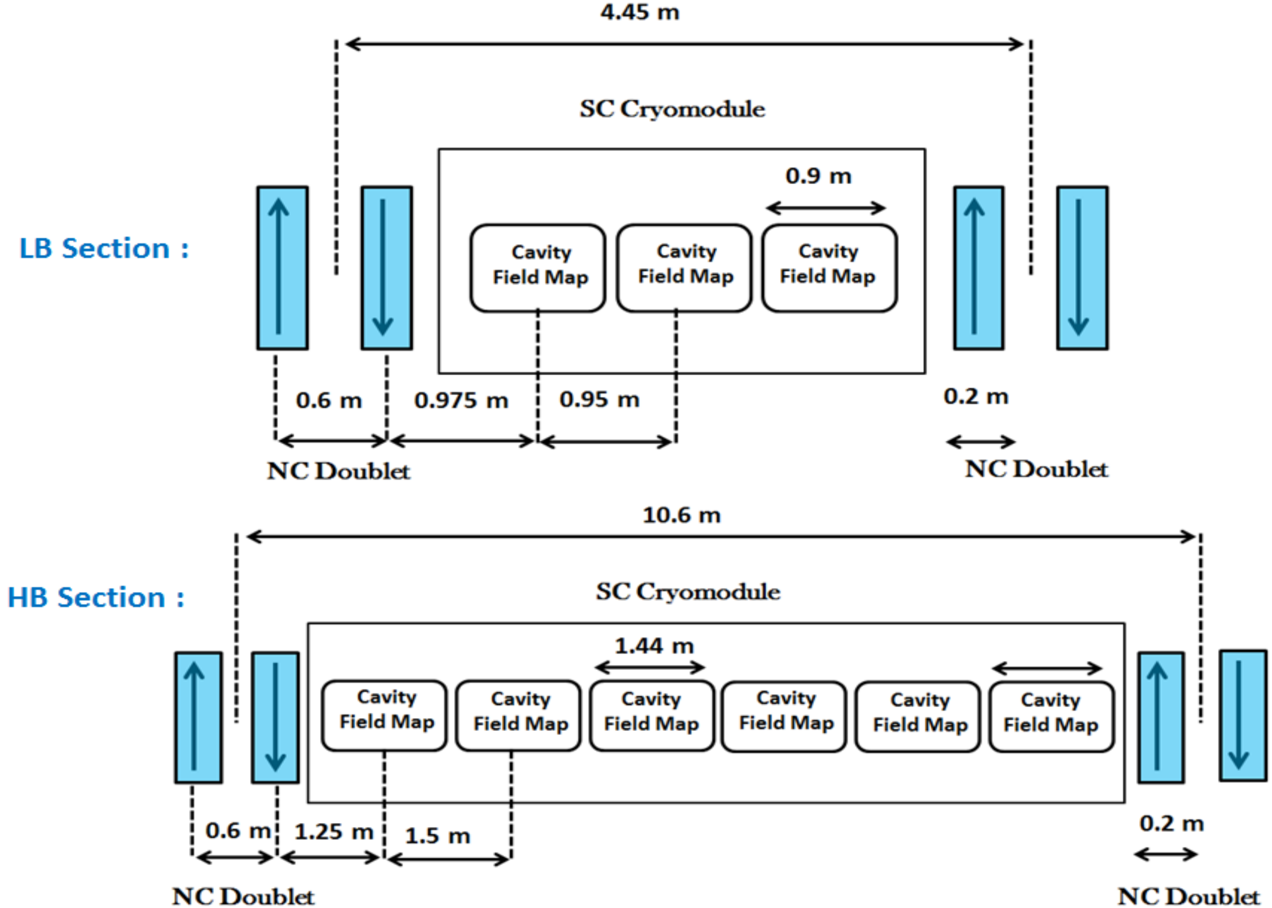
SC-SC-SC-SC-SC-SC-SC-SC

CSC-CSC-CSC-CSC

SCC-SCC-SC

Lattice Design: Focusing Period in High Energy Section

- Frequency jump from 325 MHz to 650 MHz at LB650 MHz section
- Solenoidal focusing is replaced with quadrupole doublet.
- Same family of doublet is used in both LB650 and HB650 sections.



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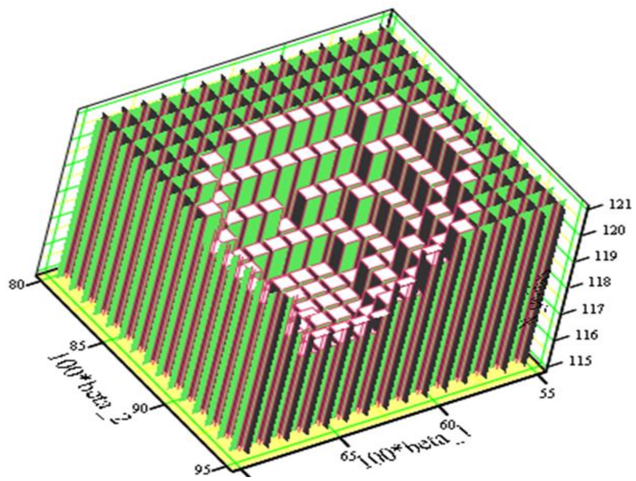
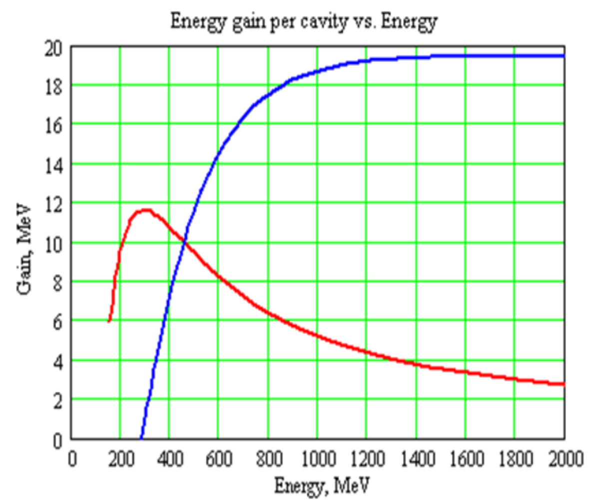
Transition Energy between Sections :

- Transition Energy between Sections (type cavity change). Optimization in order to minimize the number of cavities.
- Beam matching between sections and cryomodules are achieved using elements of each side of transitions. Avoiding abrupt changes in beam envelopes to reduce possibility of halo formations.
- Adiabatic variation in phase advance along linac. Reduces possibility of beam mismatch.



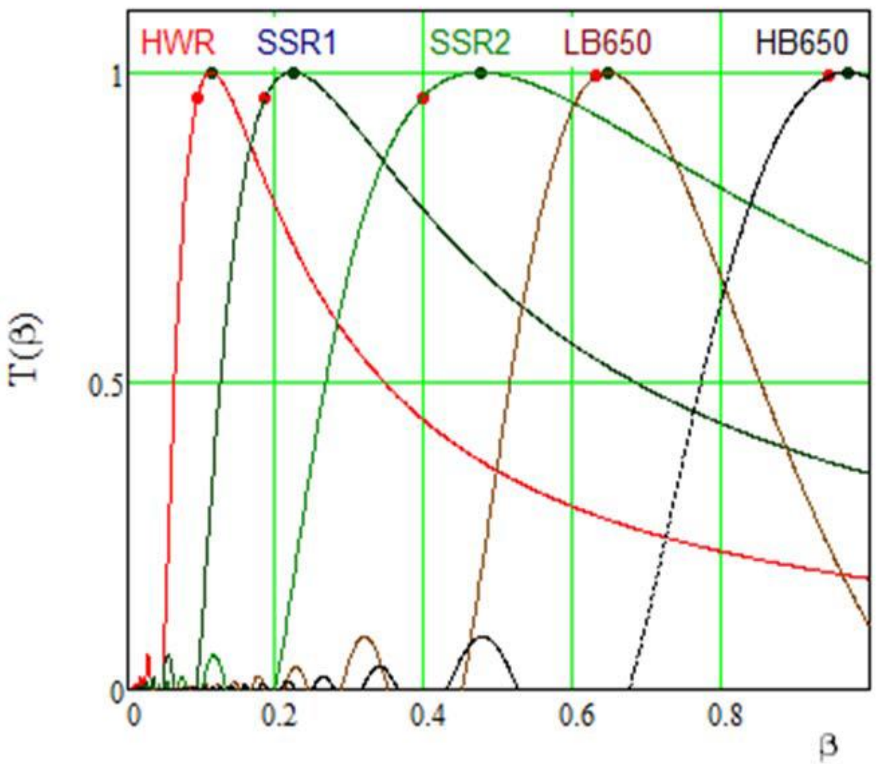


Number of cavities required for acceleration from 185 to 800 MeV versus cavity beta in the LB650 and HB650 sections (left) and the energy gain per cavity versus particle energy (right) for LB650 (red curve) and HB650 (blue curve) cavities.

Architecture of a GeV–range proton SRF accelerator:

Correct selections of transitional energy provide better optimization of real estate gradient and reduction in total number of beam line elements.

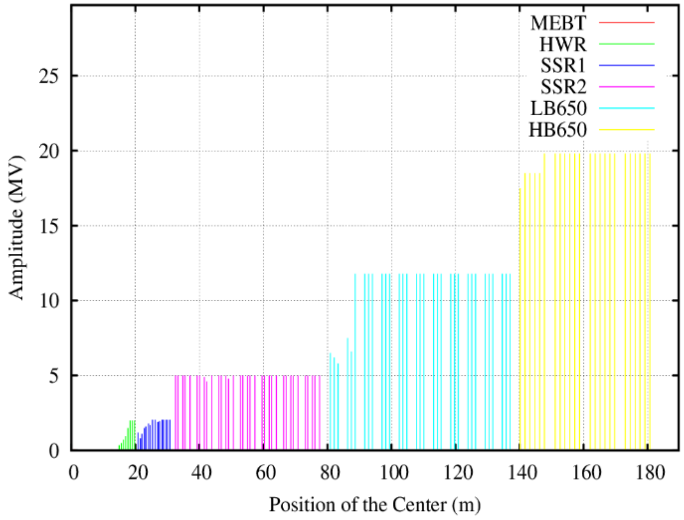
Transition time factor v/s beta



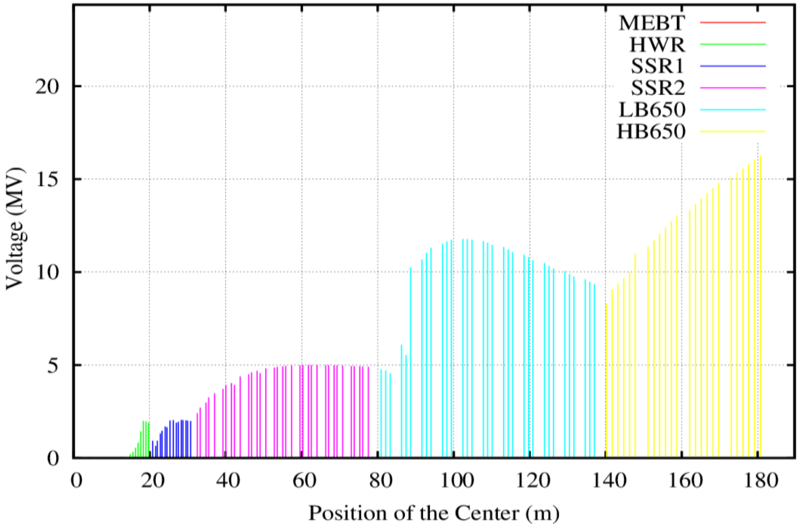
Sections	Initial Energy (MeV)	Design Beta	Beta range
HWR	2.1	0.094	0.067 -0.147
SSR1	10.3	0.186	0.147-0.266
SSR2	35	0.398	0.266-0.55
LB 650	185	0.61	0.55-0.758
HB 650	500	0.92	0.758-0.842

Acceleration voltage distribution

Voltage Amplitude in Cavities

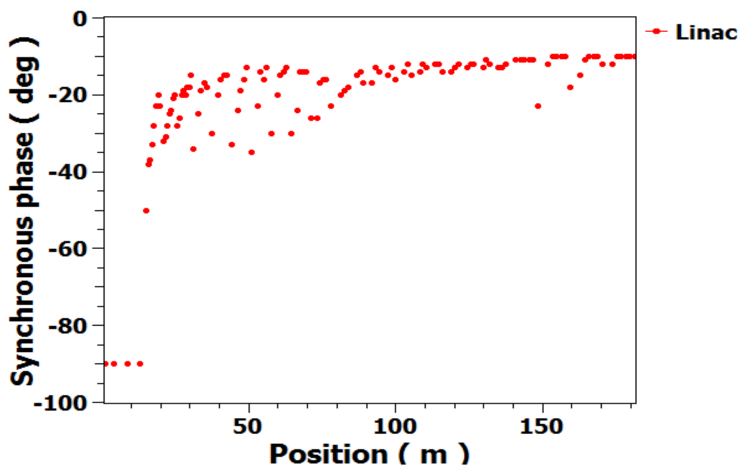


Voltage gain by beam



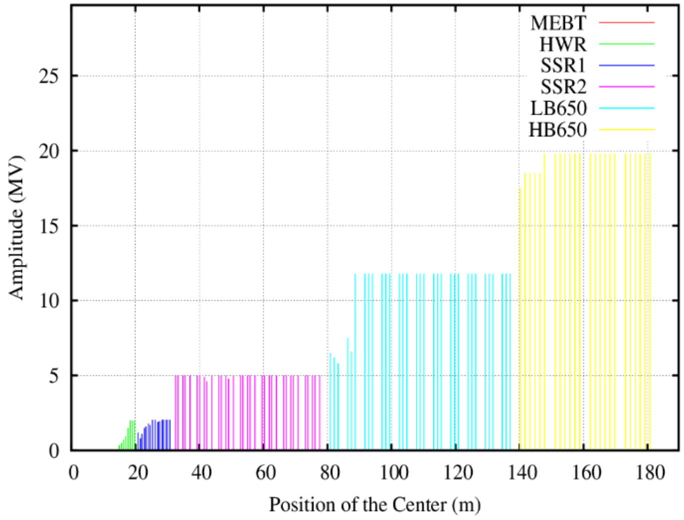
- Maximum Energy gain in PIP-II SC cavities

	HWR	SSR1	SSR2	LB650	HB650
Max. Egain (MeV)	2	2.05	5	11.9	19.9

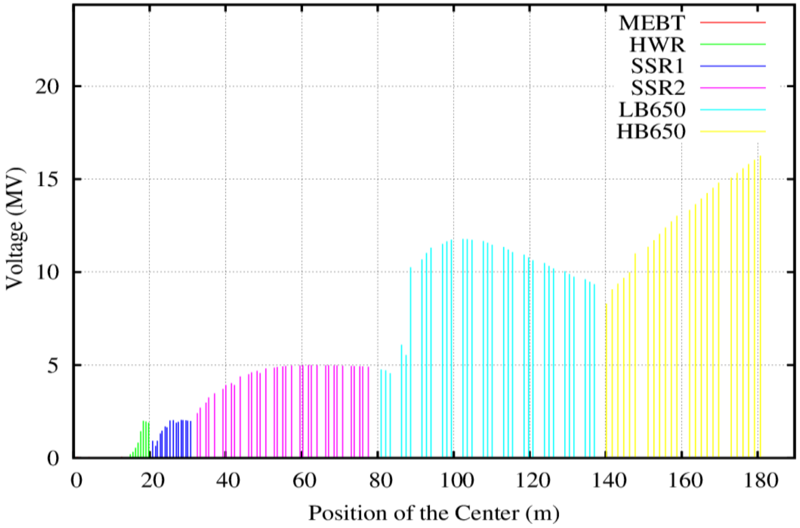


Acceleration voltage distribution

Voltage Amplitude in Cavities



Voltage gain by beam



- Maximum Energy gain in PIP-II SC cavities

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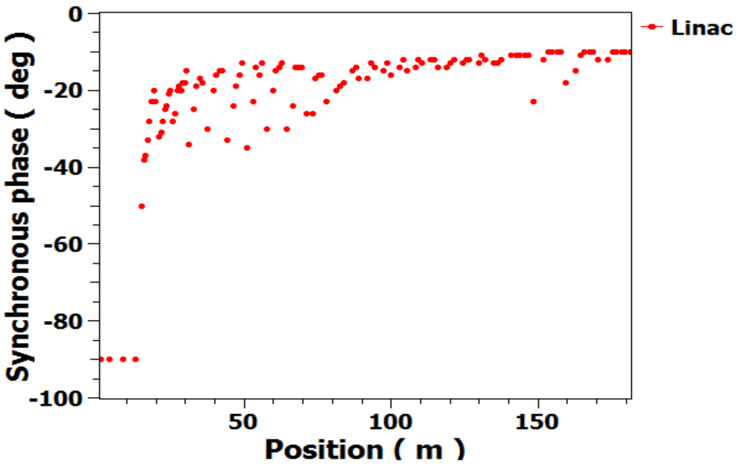

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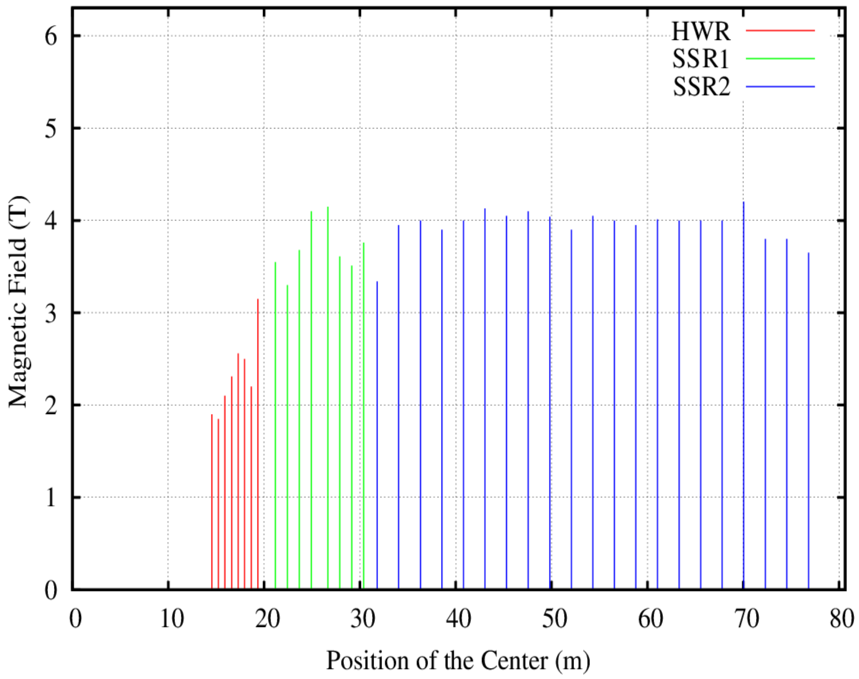
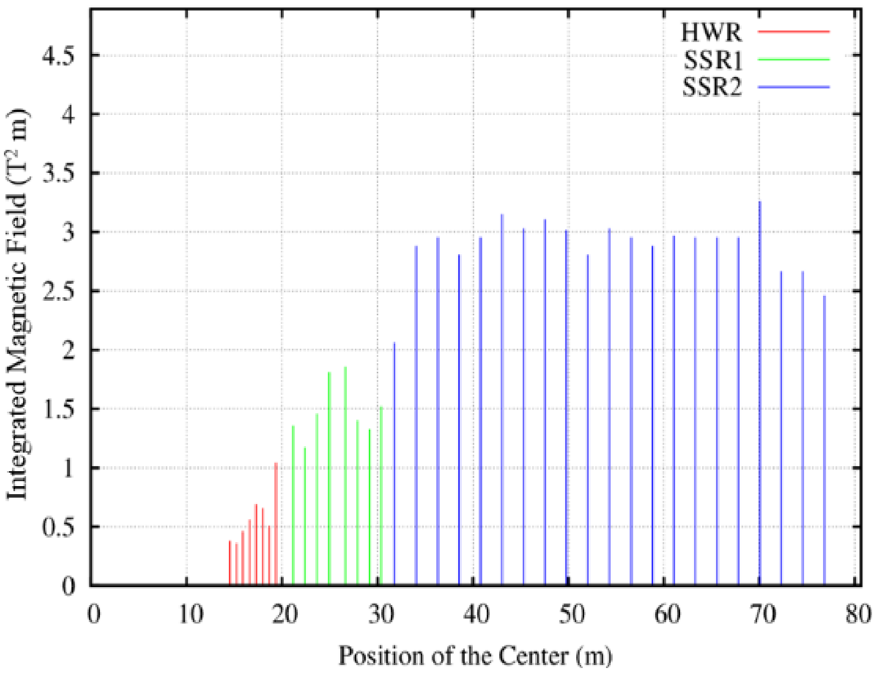
Fields in Solenoids

Magnetic Field Amplitude



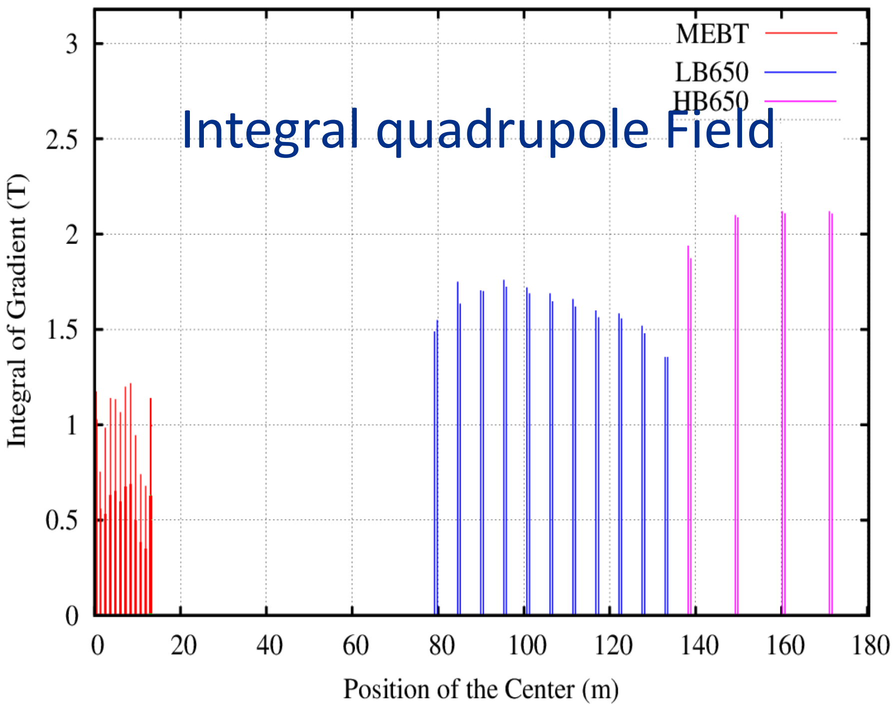
Integral Magnetic Field



- Design specification for peak magnetic field in solenoids is 6T.

Integral Fields in Quadrupoles:

- Quadrupoles in PIP-II SC linac are designed to operate at Room Temperature.
- Design specification for warm quadrupoles in SC linac is 3 T.

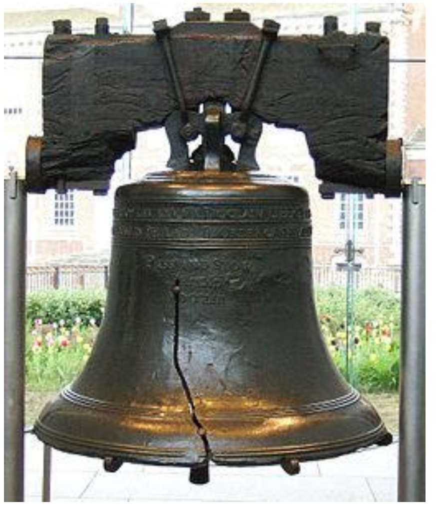


Chapter 6.

General issues for SRF Cavity Design for Proton Linear Accelerators

General issues

- High DF or CW operation → cryo-losses → high Q_0 is desired;
  - High Q_0 allows lower cost of a cryo-system and operational cost.
  - High Q_0 allows higher gradient at CW and, thus, allows lower capital cost of the linac.
  - Q_0 Improvement:
    - -Improvement of cavity processing recipes;
    - -High Q_0 preservation in CM.
  - The goal is to achieve Q_0 >2.5e10- 4e10 in CM



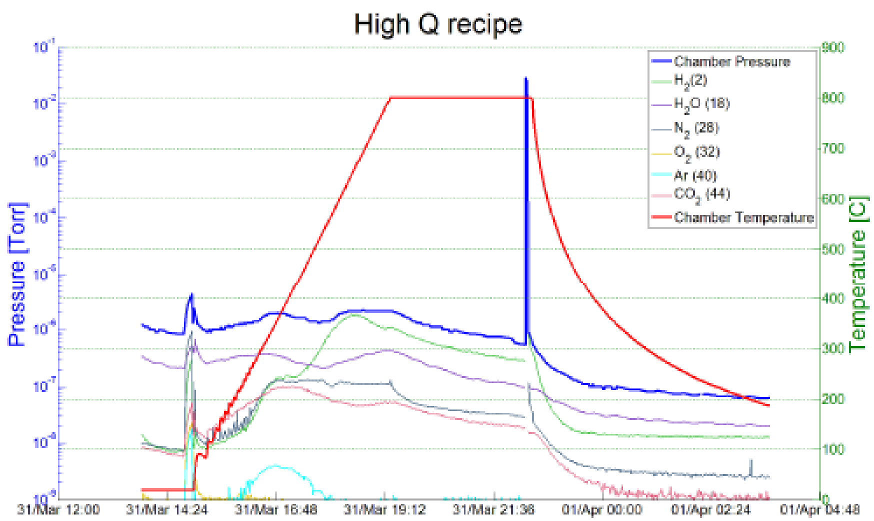
- High-Order Modes;
- Low beam loading → microphonics;
- Lorentz Force Detune (LFD) may be an issue in a pulsed mode.
- Multipacting

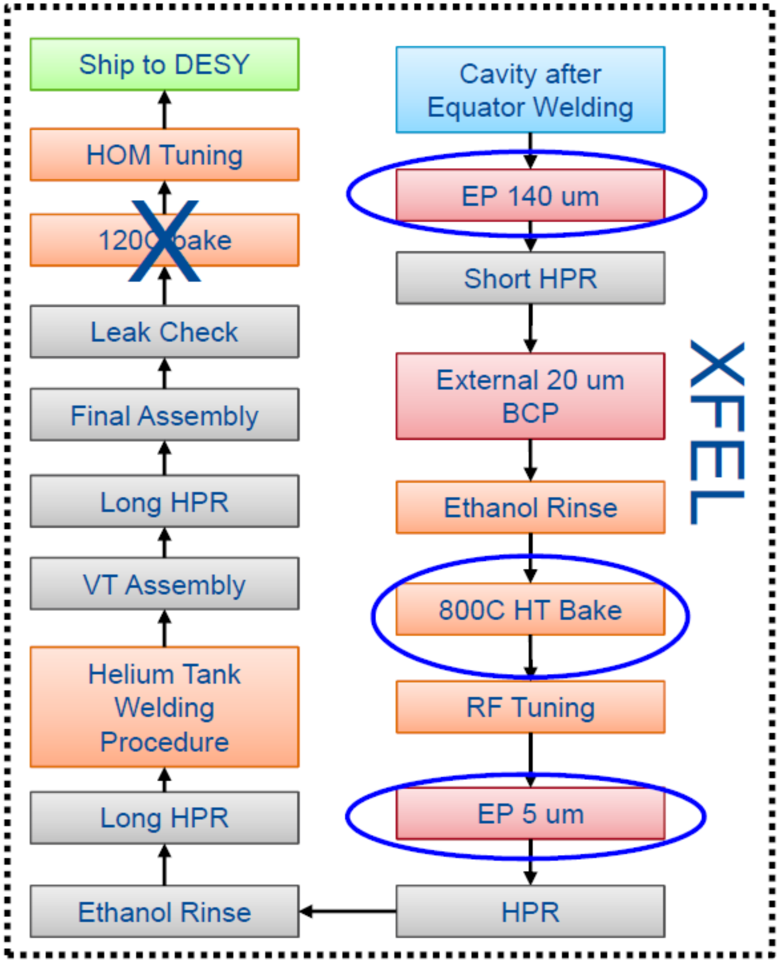
Recent breakthrough in Q_0 increase: N-doping.

- "Standard" XFEL technology provides ~1.4e10@2K, 20-23 MeV/m (CM);
- N-doping: discovered in the frame of R&D on the Project-X SC CW linac (A. Grassellino).

Cavity Treatment:

- Bulk EP
- 800 C anneal for 3 hours in vacuum
- 2 minutes @ 800C nitrogen diffusion
- 800 C for 6 minutes in vacuum
- Vacuum cooling
- 5 microns EP

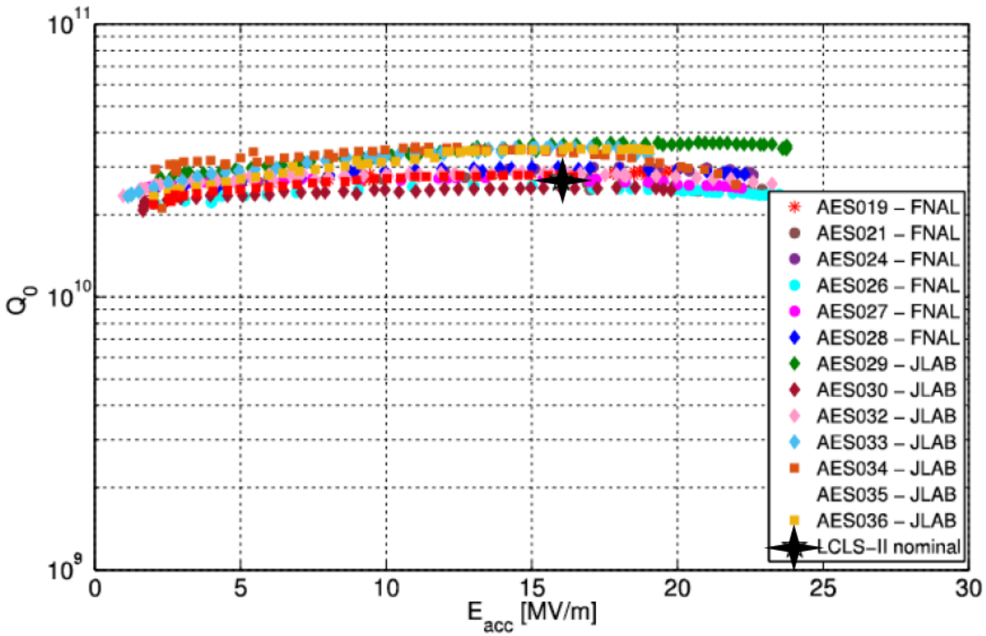




A. Grassellino, N-doping: progress in development and understanding, SRF15

N-doping:

- Provides Q_0 2.5-3 times higher than "standard" processing.
- Trade-off:
  - Lower acceleration gradient, 20-22 MeV/m – not an issue for proton linacs;
  - Higher sensitivity to the residual magnetic field.
- Remedy:
  - Magnetic hygiene and shielding improvement
  - Fast cooldown



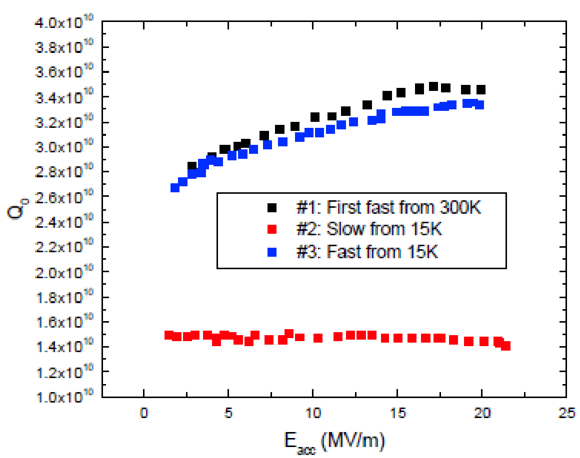
VTS test results of dressed prototype cavities

A. Grassellino, N-doping: progress in development and understanding, SRF15

Fast cooldown

- $Q_0=G/R_s$; R_s=10 nOhm for Q_0=2.7e10
  $R_s=R_0+R_{BCS}+R_{TF}$,
  $R_{TF}=s*\eta*B_{res}$, s is sensitivity to residual magnetic field B_{res}, η is flux expulsion efficiency.
  η is material-dependent!
- For pCM Nb (Wah Chang):
  R_{BCS}=4.5 nOhm, R_0=1-2 nOhm, $R_{TF}\approx$1 Ohm for 5mG → Q_0=3.5e10
- For production material:
  Change heat treatment temperature from 800 C to 900 C+ deeper EP (S. Posen):
  R_{BCS}=4.5 nOhm, $R_0 \approx$ 2 nOhm, $R_{TF} \approx$2 Ohm for $B_{res} \approx$ 5mG → Q_0 >3e10

Dressed N_2 doped 9 cell Sensitivity Test at 2K



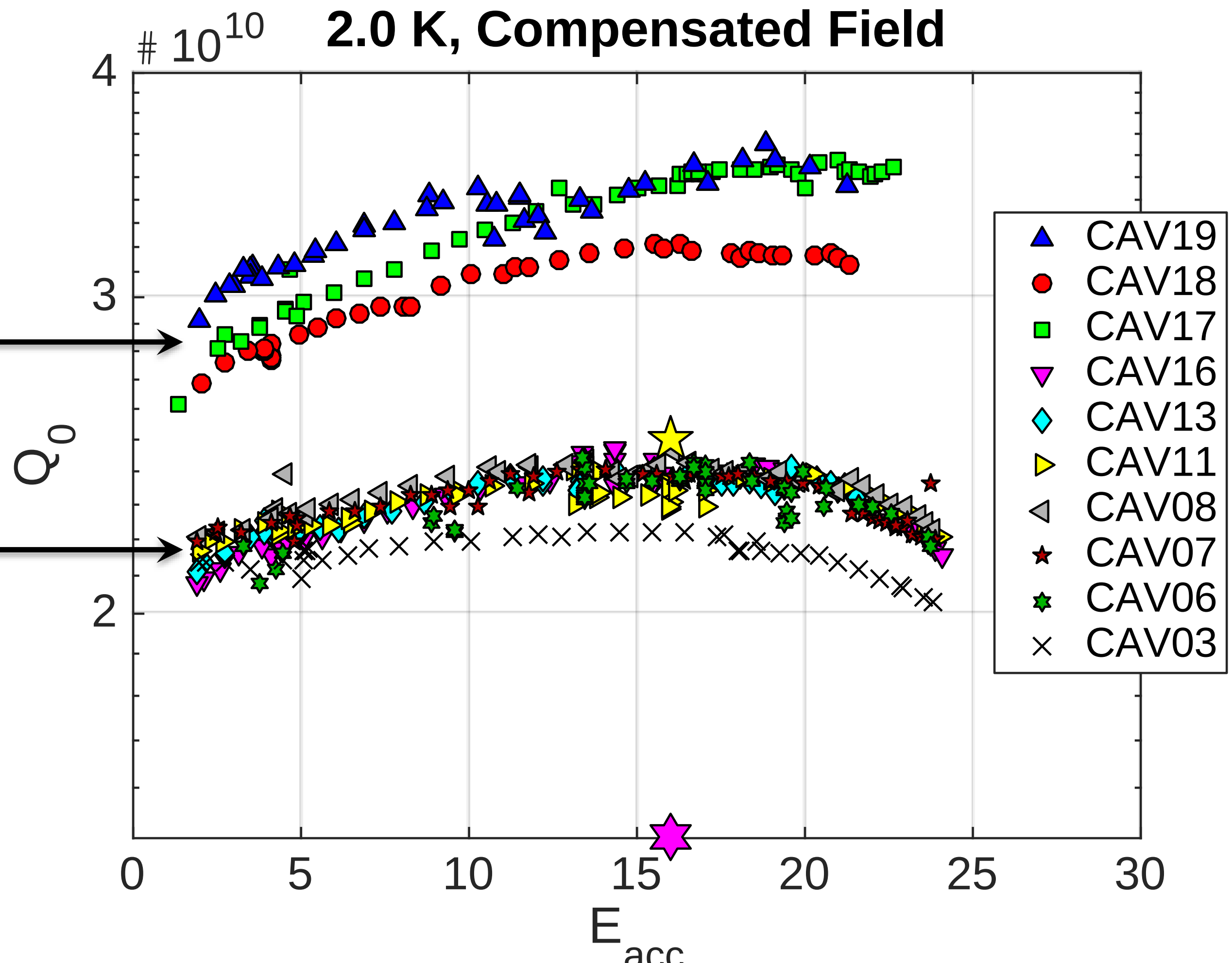
“Fast”: 2 – 3 K/minute ,“slow”: < 0.5 K/minute

A. Grassellino, N-doping: progress in development and understanding, SRF15

Impact of Modified LCLS-II Recipe on Q_0

Cavities 17, 18, 19: modified recipe - 900 C degas, ~200 µm EP, 2min/6min N doping at 800 C

Cavities 03…16: First production tests at Fermilab, baseline LCLS-II recipe - 800 C degas, ~130 µm EP, 2min/6min N doping at 800 C



Studies leading to modified recipe:

S. Posen, M. Checchin, A. C. Crawford, A. Grassellino, M. Martinello, O. S. Melnychuk, A. Romanenko, D. A. Sergatskov and Y. Trenikhina, *Efficient expulsion of magnetic flux in superconducting radiofrequency cavities for high Q_0 applications*, J. Appl. Phys. **119**, 213903 (2016), dx.doi.org/10.1063/1.4953087 .

A. Romanenko, A. Grassellino, A. C. Crawford, D. A. Sergatskov and O. Melnychuk, *Ultra-high quality factors in superconducting niobium cavities in ambient magnetic fields up to 190 mG*, Appl. Phys. Lett. **105**, 234103 (2014); http://dx.doi.org/10.1063/1.4903808 .

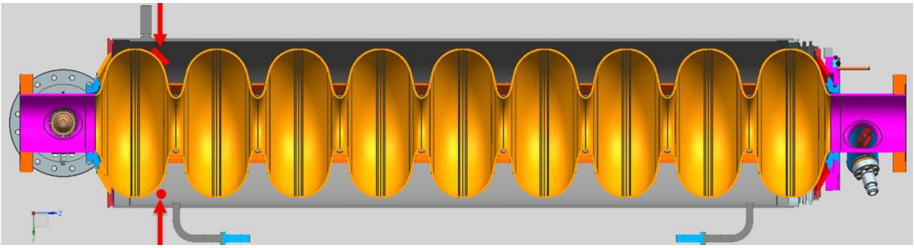
A. Grassellino, A. Romanenko, S Posen, Y. Trenikhina, O. Melnychuk, D.A. Sergatskov, M. Merio, N-doping: progress in development and understanding, Proceedings of SRF15, http://srf2015proc.triumf.ca/prepress/papers/moba06.pdf .

Ambient Magnetic Field Management Methods

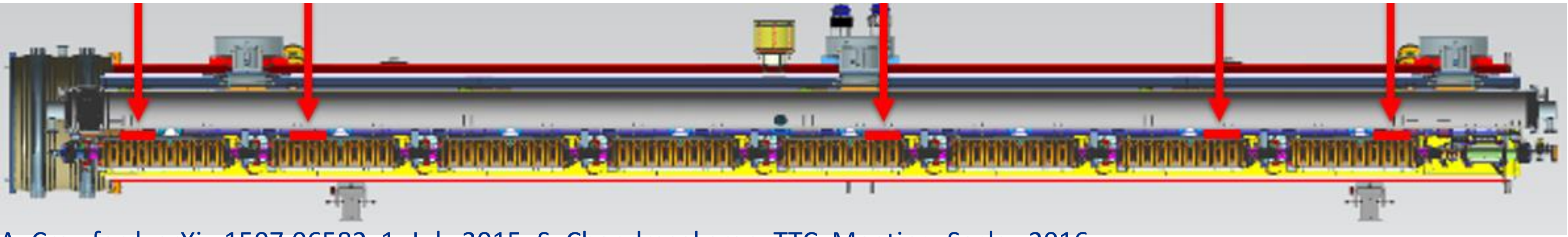
- 2-layer passive magnetic shielding
  - Manufactured from Cryoperm 10
- Strict magnetic hygiene program
  - Material choices
  - Inspection & demagnetization of components near cavities
  - Demagnetization of vacuum vessel
  - Demagnetization of assembled cryomodule / vessel
- Active longitudinal magnetic field cancellation

Magnetic field diagnostics:

- 4 cavities instrumented with fluxgates inside helium vessel (2 fluxgates/cavity)
- 5 fluxgates outside the cavities mounted between the two layers of magnetic shields



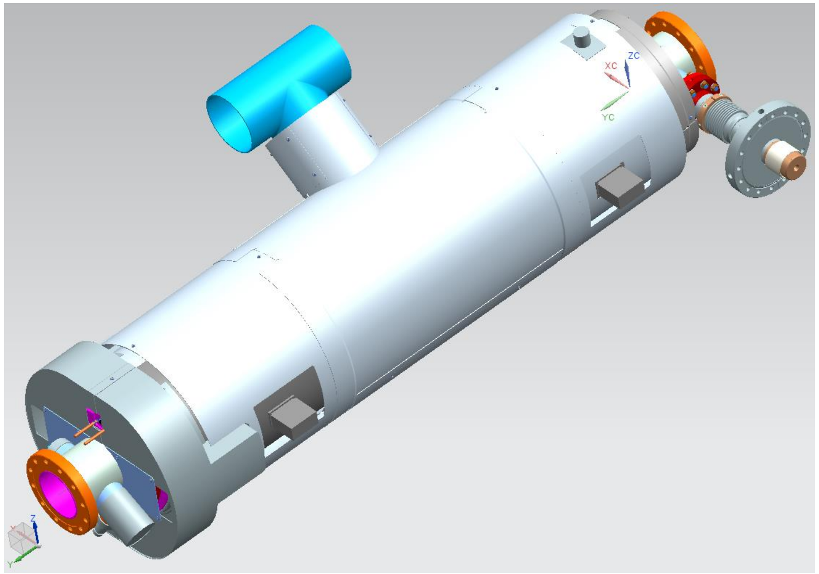
Fluxgates monitored during cryomodule assembly

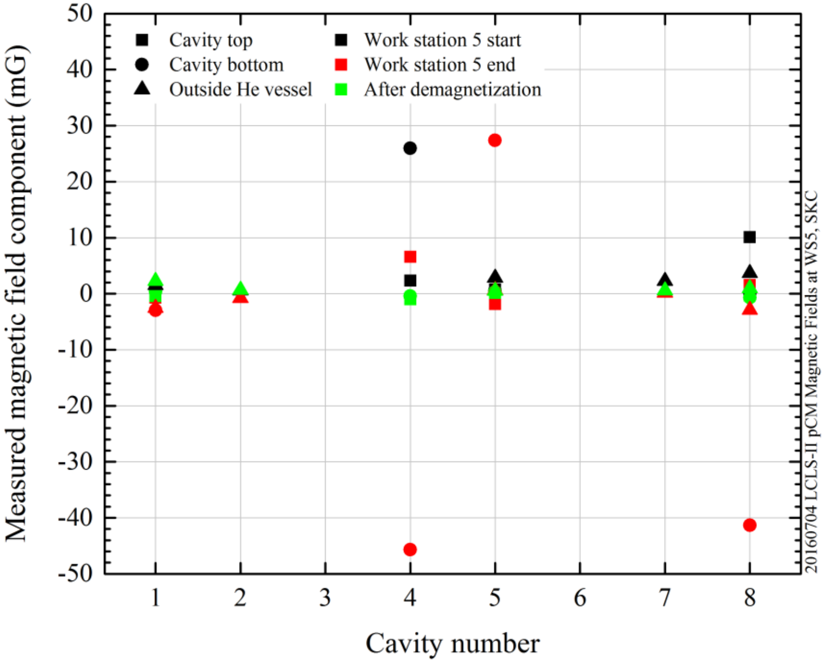


A. Crawford, arXiv:1507.06582v1, July 2015; S. Chandrasekaran, TTC Meeting, Saclay 2016

Ambient Magnetic Field Management Methods

Helmholtz coils wound onto vessel directly





2-layer magnetic shields manufactured from Cryoperm 10

S. Chandrasekaran, Linac 2016, TUPLR027

Fermilab

Prototype Cryomodule Latest Preliminary Results

- Cryomodule remnant field ≈ 1 mG
- Fast cool down in a cryomodule demonstrated
- Q0 ≈ 2.7e10 in a CW cryomodule

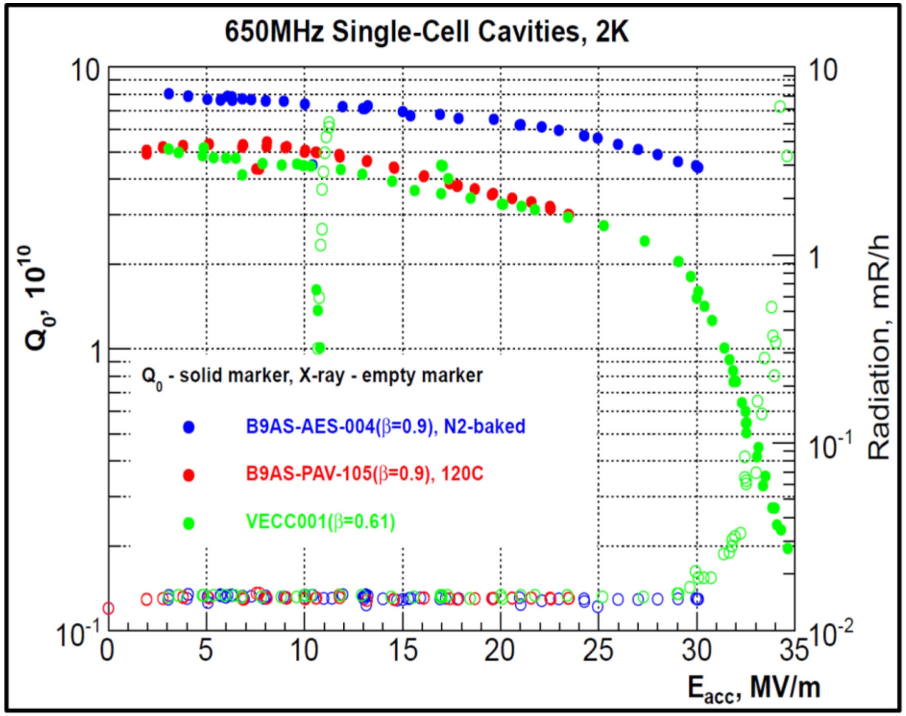
	VTS		pCM after RF_Conditioning			
Cavity	**Max Gradient [MV/m]**	**Q0 @16MV/m**	**Max Gradient*** [MV/m]**	**Usable Gradient* [MV/m]**	**FE onset [MV/m]**	**Q0 @16MV/m 2K** extrapolated**
TB9AES021	23	3.1E+10	19.6	18.2	14.6	2.6E+10
TB9AES019	19.5	2.8E+10	19	18.8	15.6	2.6E+10
TB9AES026	21.4	2.6E+10	17.3	17.2	17.4	2.7E+10
TB9AES024	22.4	3.0E+10	21	20.5	21	2.5E+10
TB9AES028	28.4	2.8E+10	14.9	14.2	13.9	2.4E+10
TB9AES016	18	2.8E+10	17.1	16.9	14.5	2.9E+10
TB9AES022	21.2	2.8E+10	20	19.4	12.7	3.2E+10
TB9AES027	22.5	2.8E+10	20	17.5	20	2.5E+10
Average	**22.1**	**2.8E+10**	**18.6**	**17.8**	**16.2**	**2.7E+10**
Total Voltage	**183.1 MV**		**154.6**	**148.1**		

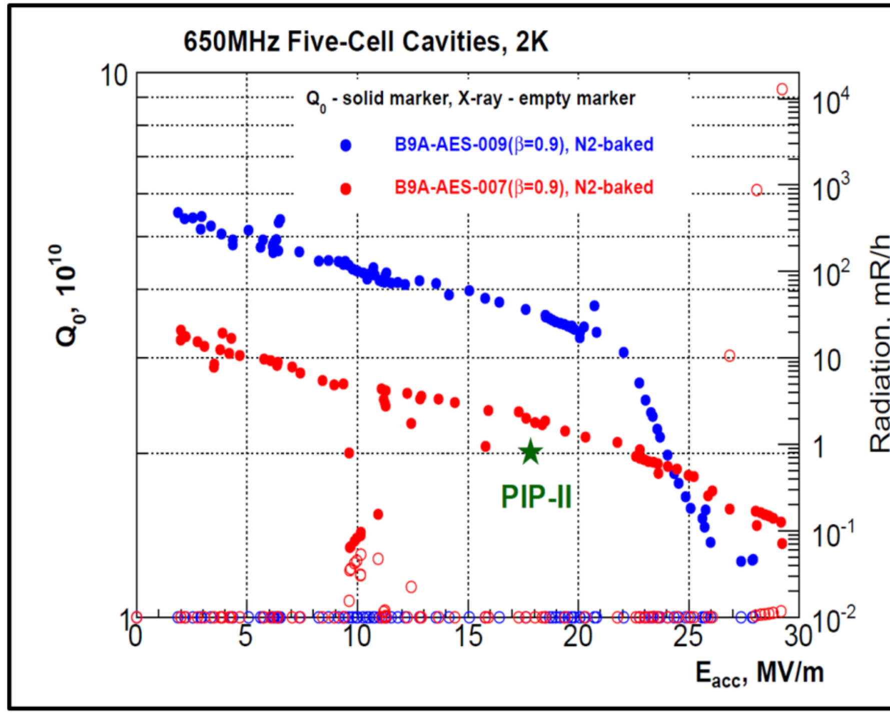
***Usable Gradient: demonstrated to stably run CW, FE < 50 mR/h, no dark current

**Fast cooldown from 45K, >40 g/sec, extrapolated from 2.11K

G. Wu, FNAL SRF Department meeting, 24 October 2016, https://indico.fnal.gov/conferenceDisplay.py?confId=13185

650 MHz elliptical cavity performance testing at FNAL





Single-cell B=0.90 and B=0.61 test results.

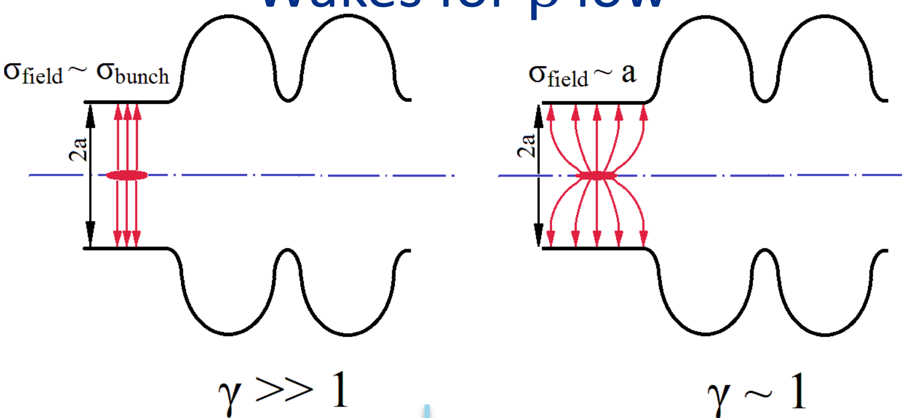
Five-cell B=0.90 test results.

*A. M. Rowe, et al , CAVITY PROCESSING AND PREPARATION OF 650 MHz ELLIPTICAL CELL CAVITIES FOR PIP-II, LINAC 2016

High-Order Modes in elliptical SRF cavities

- Specifics of Higher Order Mode effects in the elliptical cavities of proton linacs:
  - Non-relativistic beam;
  - Small current and small bunch population;
  - No feedback (linac);
  - Complicated beam timing structure (dense frequency spectrum).

Wakes for β low



HE electron linac (ILC, XFEL or NGLS)

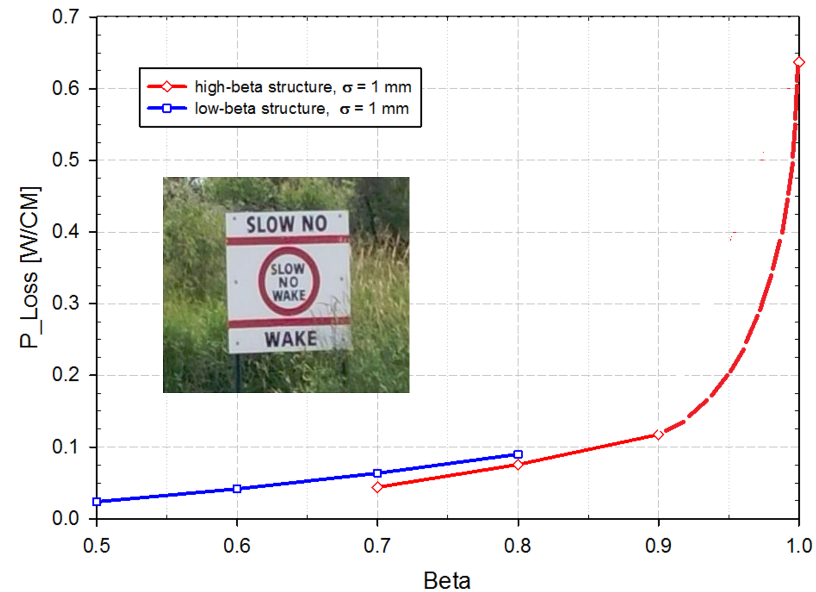
$f_{max} \sim c/\sigma_{bunch}$

for $\sigma_{bunch} = 50\mu$, $f_{max} < 6$ THz

Proton linac

$f_{max} \sim c/a$

for a = 50mm, $f_{max} < 6$ GHz



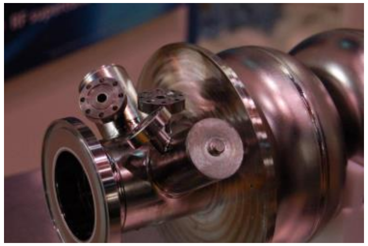
Diffraction losses are determined by σ_{field}, $P \sim (\sigma_{field})^{-1/2}$

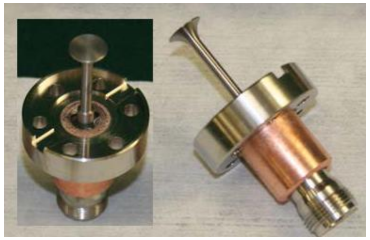
High-Order Modes in elliptical SRF cavities (cont)

- Possible issues:
  - Trapped modes;
  - Resonance excitation of HOMs;
  - Collective effects – transverse (BBU) and longitudinal (klystron-type instability);

  ↓

  - Additional cryo-losses;
  - Emittance dilution (longitudinal and transverse).





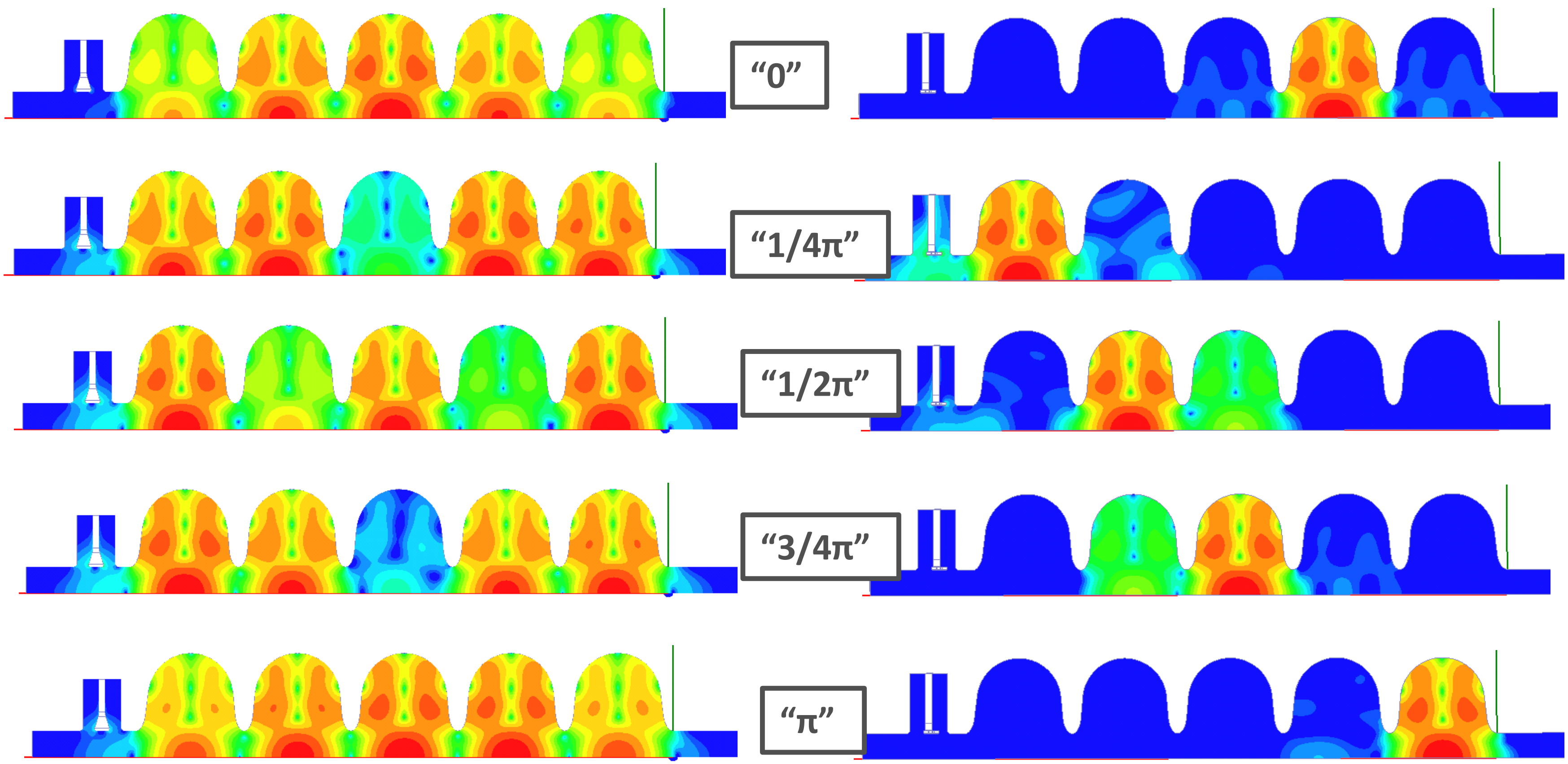
- HOM damper is a vulnerable, expensive and complicated part of SC acceleration cavity (problems – heating, multipacting, etc; additional hardware – cables, feed-through, connectors, loads). HOM dampers may limit a cavity performance and reduce operation reliability;

"To damp, or not to damp?"

Trapped Modes in elliptical SRF cavities

For some modes *k (coupling)* may be very small (electric coupling is compensated by magnetic coupling). Because of manufacturing errors the field distribution may change, the mode will not be coupled to the FC or beam pipe, and have high Q_{load} – so called trapped modes.

An example of a bad cavity design containing a trapped mode:

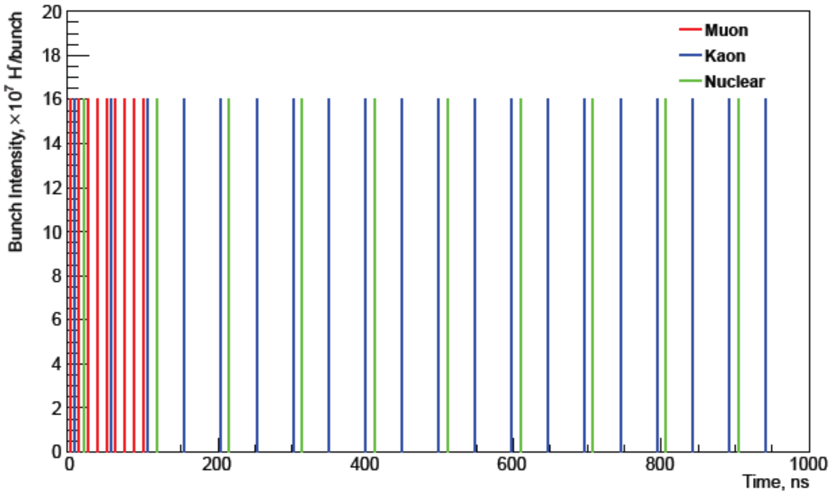


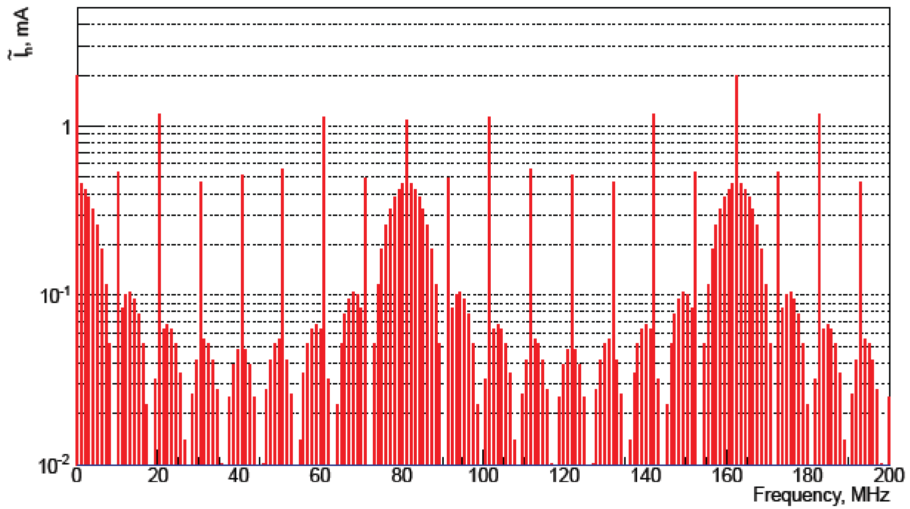
HOMs in an ideal cavity.

HOMs in a "realistic" cavity, i.e., in presence of misalignments.

In both cases the operating mode is tuned to correct frequency and field flatness.

Resonance excitation of HOMs in elliptical SRF cavities



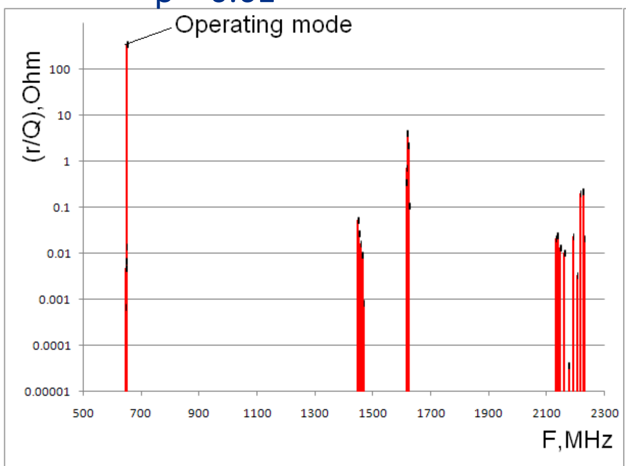


Example of the beam structure for multi-experimental proton driver (Project X)

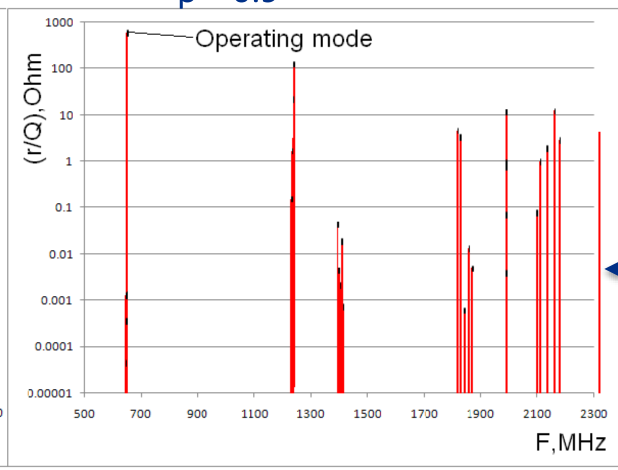
The beam current spectrum may be dense: for PX it contains

- ● harmonics of the bunch sequence frequency of 10.15 MHz and
- ● sidebands of the harmonics of 81.25 MHz separated by 1 MHz.

β = 0.61



β = 0.9



R/Q spectrum of the cavities

Resonance excitation of HOMs in elliptical SRF cavities

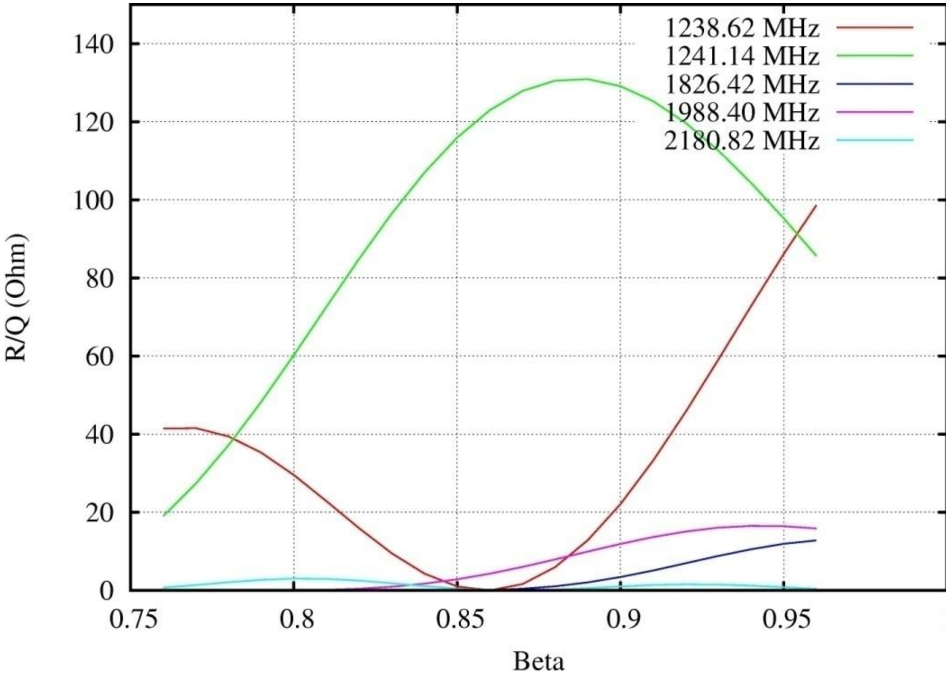
HOM have frequency spread caused by manufacturing errors:

❖For 1.3 GHz ILC cavity r.m.s. spread σ_f of the resonance frequencies is 6-9 MHz depending on the pass band;

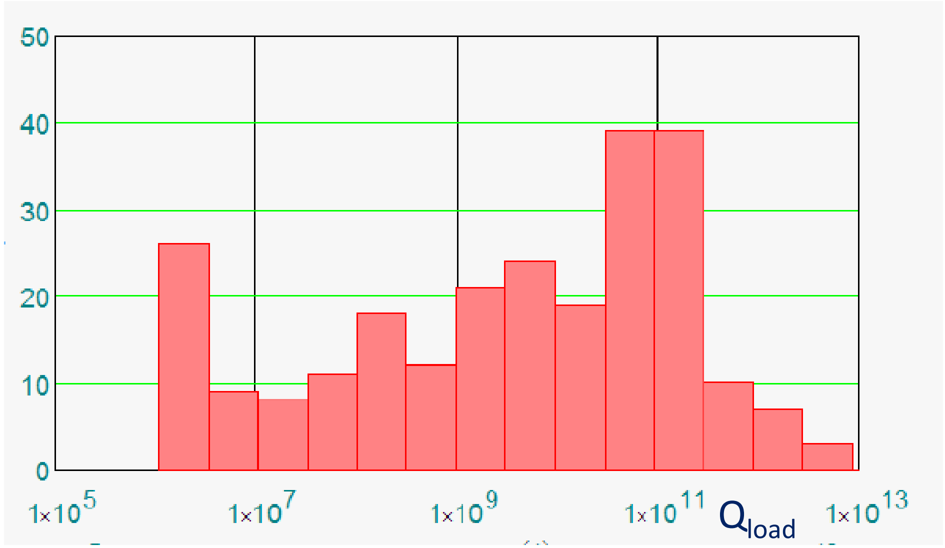
❖Cornell: $\sigma_f \approx 10.9 \cdot 10^{-4} \times (f_{HOM} - f_0)$,

❖SNS: $\sigma_f \approx (9.6 \cdot 10^{-4} - 13.4 \cdot 10^{-4}) \times (f_{HOM} - f_0)$;

$$\Delta f_{max} = |f_{HOM,calculated} - f_{HOM,measured}| \sim \sigma_f$$



(R/Q) for HOM modes depends on the particle velocity β (650 MHz, β=0.9 cavity)

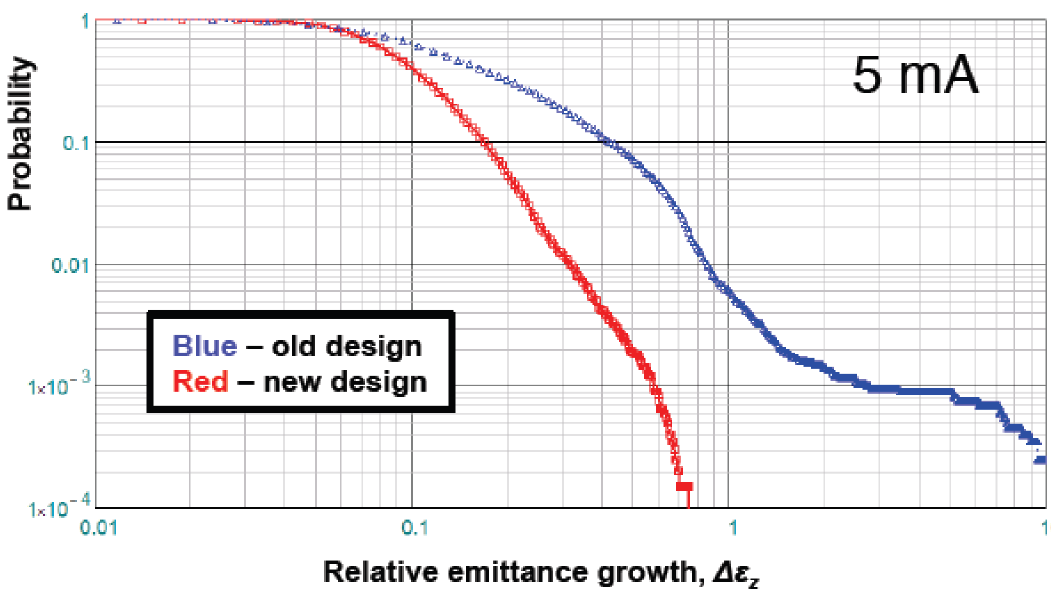


Variation of Q_{load} for 5th passband (650 MHz, β=0.9 cavity)

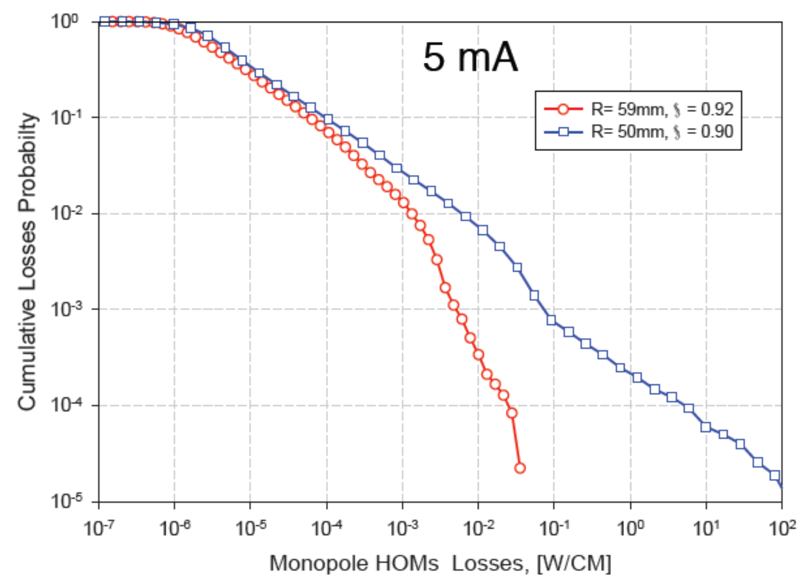
Resonance excitation of HOMs in elliptical SRF cavities (cont)

- Longitudinal emittance dilution does not take place if $\delta f >> f \dfrac{\tilde{I}(R/Q)\sigma_t}{4\sqrt{2}\varepsilon_z}$
  For typical parameters for proton linacs $\delta f >> 10\text{-}100$ Hz.

- Transverse emittance dilution does not take place if $\delta f \ll \dfrac{c x_0 \tilde{I}(R/Q)_1}{8\sqrt{2}\pi\beta\gamma U_0\sqrt{\varepsilon/\beta_f}}$ Not an issue!
  For typical parameters for proton linacs $\delta f >> 1\text{-}10$ Hz.



PIP II SRF linac



Cryo load caused by HOMS

Resonance excitation of HOMs in elliptical SRF cavities (cont)

Collective effects:

- Beam break –up (BBU) , transverse.
- “Klystron-type” , longitudinal.

Why collective effects is not an issue for SRF proton linacs with elliptical cavities:

- No feedback as in ERLs (or CEBAF);
- Different cavity types with different frequencies and different HOM spectrum are used;
- Frequency spread of HOMs in each cavity type, caused by manufacturing errors;
- Velocity dependence of the (R/Q);
- Small – compared to electron linacs -beam current.

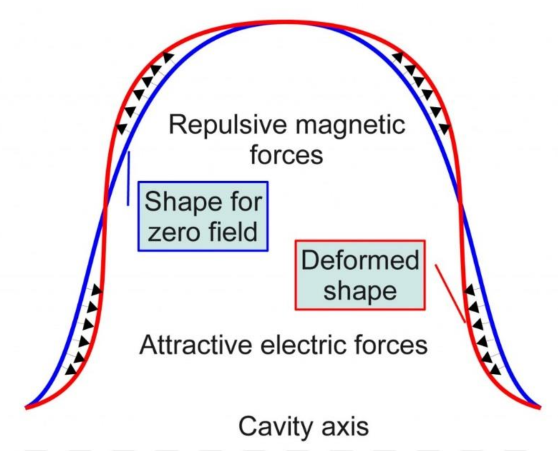
No HOM dampers!

- No HOM dampers in SNS upgrade cavities (I_{beam} =26 mA);
- No HOM dampers in ESS cavities (I_{beam} =50 mA);
- No HOM dampers in PIP II cavities (I_{beam} up to 5 mA);
- Probably, HOM dampers will be necessary for future high – current drivers for ADS.

Microphonics and LFD:

Narrow bandwidth of the cavities caused by low beam loading:

- $Q_{load} = U/(R/Q)/I_{beam}$ - very high for small beam current of few mA, Q_{load} ~1e7-1e8;
- Cavity bandwidth: f/Q_{load} ~tens of Hz.



$$P_s = \frac{1}{4}\left(\mu|\vec{H}|^2 - \varepsilon_0|\vec{E}|^2\right)$$

$$\Delta f_0 = (f_0)_2 - (f_0)_1 = -K\,E_{acc}^2$$

•Pressure variation in the surrounding He bath:

$\Delta f_{He} = df/dP \times \delta P$, δP~0.05-0.1 mbar at 2 K.

df/dP =30-130 Hz/mbar (ILC)

•Internal and external vibration sources (microphonics);

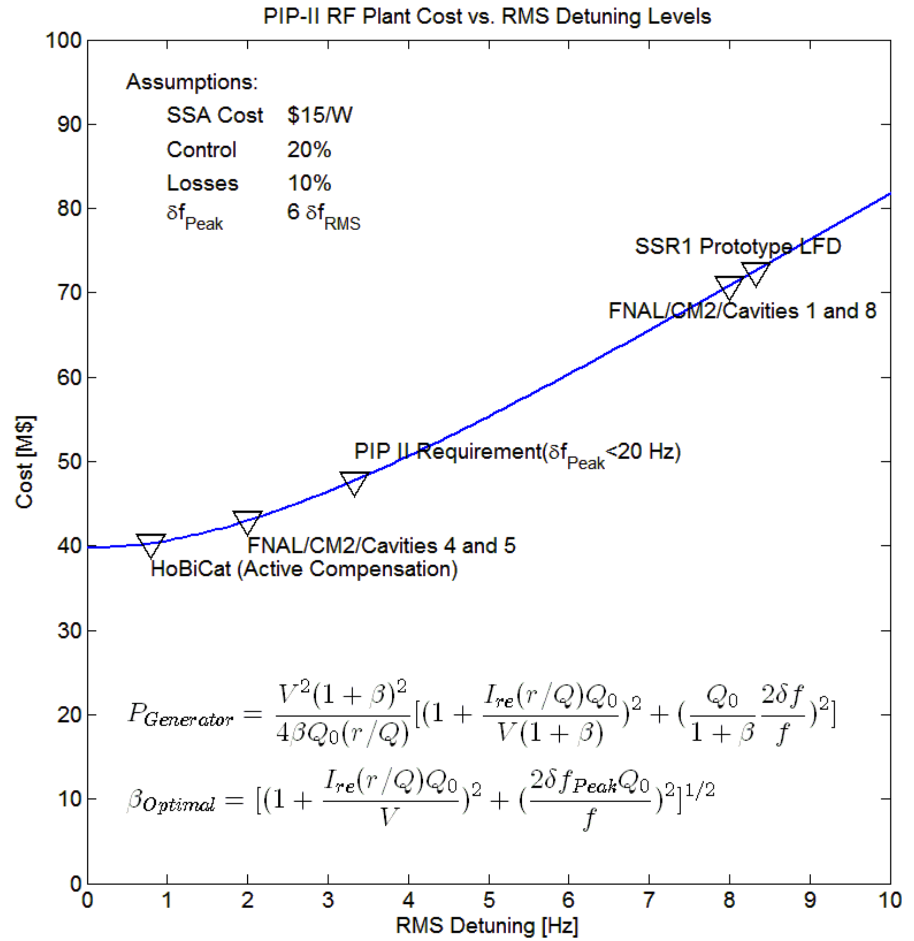
•Radiation pressure from the RF field, Lorentz Force Detuning (in pulsed mode).

$\Delta f_{LFD} = k_L E^2$, k_L- Lorentz coefficient,

For typical elliptical cavities k_L~ -1 Hz/(MeV/m)^2.

Microphonics :

- Detuned cavities require more RF power to maintain constant gradient
- Providing sufficient reserve increases both the capital cost of the RF plant and the operating cost of the machine
- **PEAK** detuning drives the RF costs
- Beam will be lost if RF reserve is insufficient to overcome PEAK detuning



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PIP-II in the Context of Other Future SRF Accelerators

- As cavity gradients rise matched bandwidths narrow
- Minimizing detuning is critical for narrowband machines
- PIP-II presents a unique challenge because of the combination of narrow bandwidths and pulsed operation

				Mode	Gradient	Current	Frequency	Half Bandwidth	LFD	Peak Detuning	Peak Detuning/BW	LFD/BW
					MV/m	mA	MHz	Hz	Hz	Hz		
Wideband CW												
ARIEL	TRIUMF		e-	CW	10	10	1300	220				
SPIRAL-II		30 MeV, 5 mA protons -> Heavy Ions	Ion	CW	11	0.15-5	88	176				
Wideband Pulsed												
XFEL	DESY	18 GeV electrons – for Xray Free Electron Laser – Pulsed)	e-	Pulsed	23.6	5	1300	185	550			**3**
ESS	Sweden	1 – 2 GeV, 5 MW Neutron Source ESS - pulsed	p	Pulsed	21	62.5	704	500	400			**1**
Narrowband CW												
CEBAF Upgrade	JLAB	Upgrade 6.5 GeV => 12 GeV electrons	e-	CW	20	0.47	1497	25		10	**0.40**	
LCLS-II	SLAC	4 GeV electrons –CW XFEL (Xray Free Electron Laser)	e-	CW	16	0.06	1300	16		10	**0.63**	
FRIB	MSU	500 kW, heavy ion beams for nuclear astrophysics	Ion	CW	7.9	0.7	322	15		20	**1.33**	
cERL	KEK											
Narrowband Pulsed												
PIP-II	Fermilab	High Intensity Proton Linac for Neutrino Beams	p	Pulsed	17.8	2	650	30	300	20	**0.67**	**10**

http://accelconf.web.cern.ch/AccelConf/IPAC2015/talks/thzms3_talk.pdf

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Microphonics Control Strategies

Microphonics can be mitigated by taking some combination of any or all of the following measures:

- **Providing sufficient reserve RF power to compensate for the expected peak detuning levels.**

- **Improving the regulation of the bath pressure to minimize the magnitude of cyclic variations and transients.**

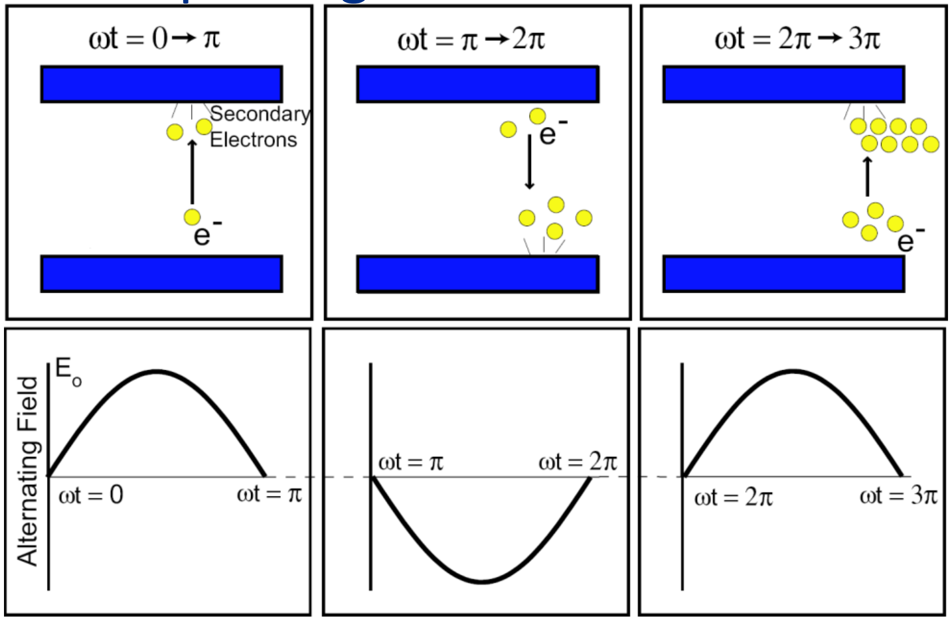
- **Reducing the sensitivity of the cavity resonant frequency to variations in the helium bath pressure (df/dP).**

- **Minimizing the acoustic energy transmitted to the cavity by external vibration sources.**

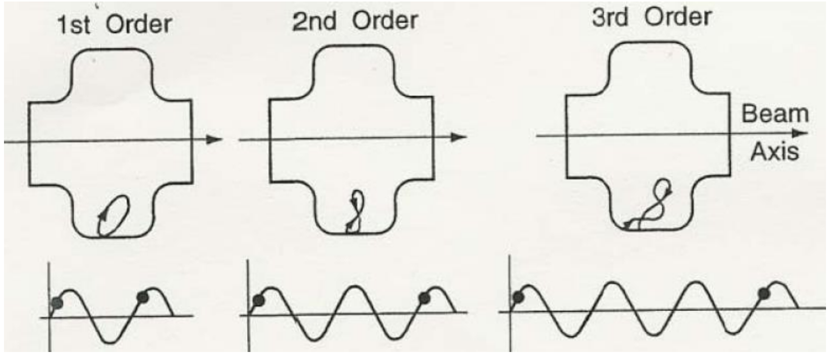
- **Actively damping cavity vibrations using a fast mechanical or electromagnetic tuner driven by feedback from measurements of the cavity resonant frequency.**

The optimal combination of measures may differ for different cavity types.

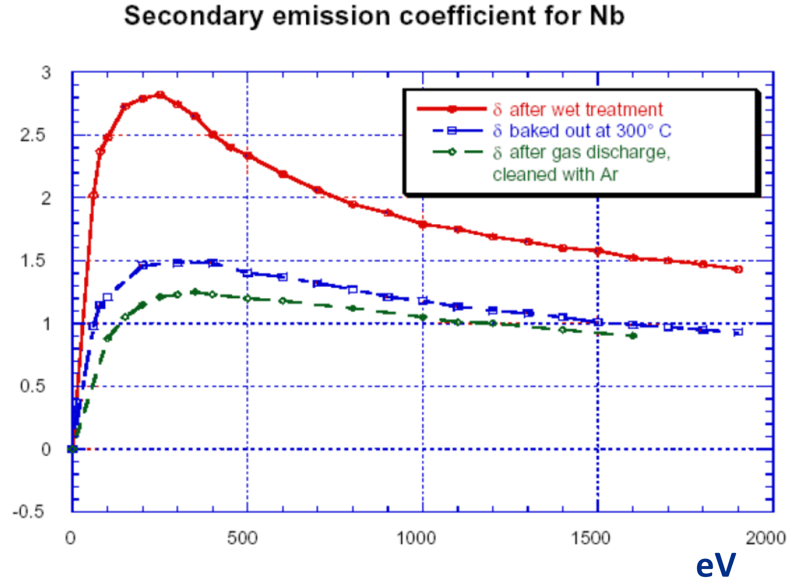
Multipacting in SRF cavities

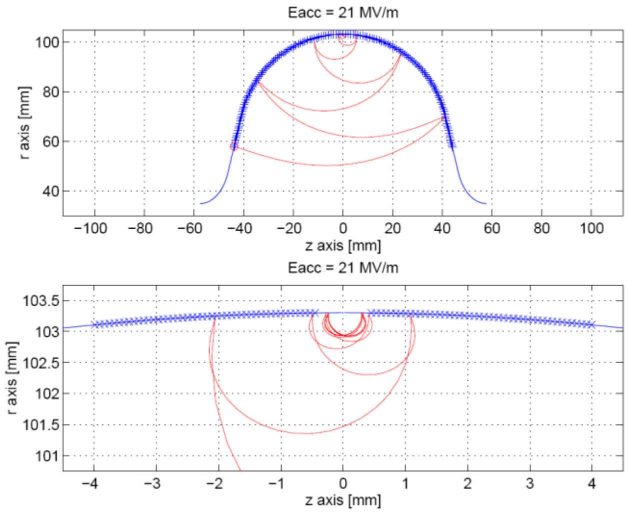


Multipactor discharge with an electric field oscillating between two metal electrodes.



Typical one-point multipactor trajectories for orders 1, 2 and 3.





Two point MP in 1.3GHz TESLA cavity. 2D simulations

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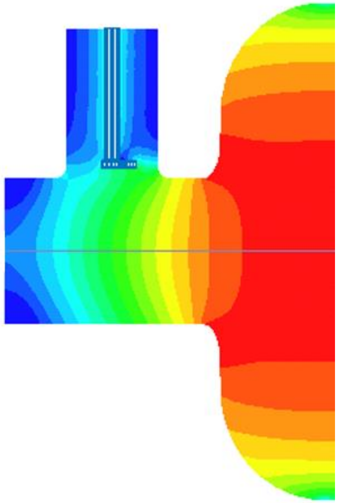
Chapter 7.

SRF Cavity Design Approaches for Proton Linear Accelerators

Design approaches

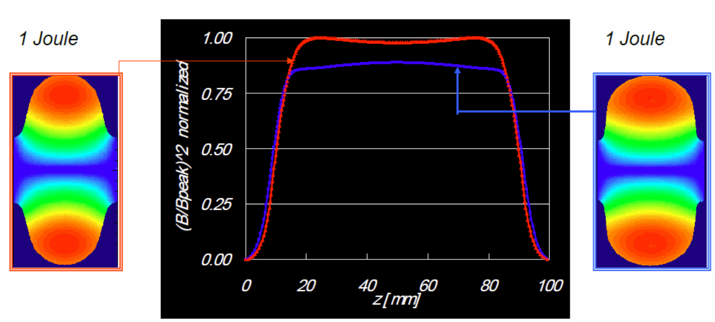
- **Aperture choice:**
- Smaller aperture → smaller field enhancement factors, higher R/Q;
- Limitations:
  - beam losses,
  - field flatness,
  - mechanical stability,
  - surface processing,
  - Q_{load} (coupling to the main coupler)
  - HOMs (trapped modes)

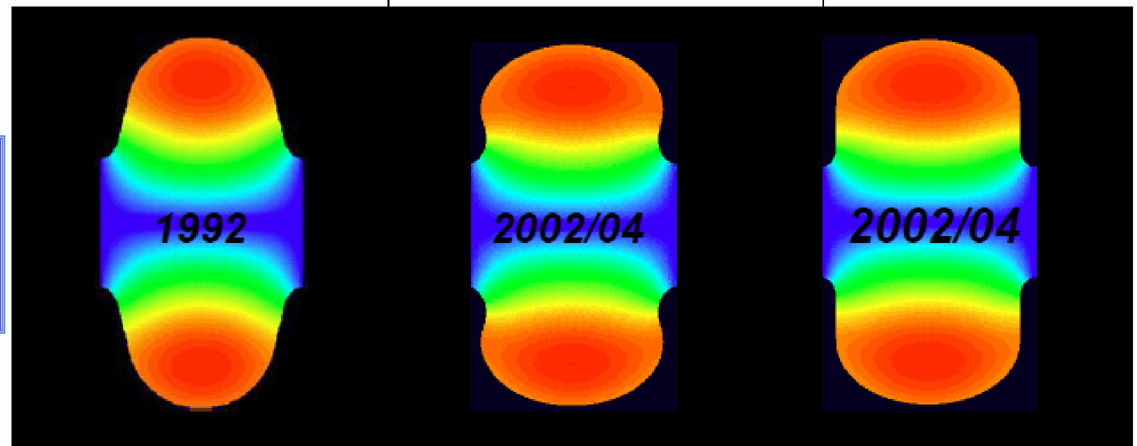


SNS (805 MHz): 2a=86mm (β=0.61), 2a/λ = 0.23
2a=98mm (β=0.81), 2a/λ = 0.26
HIPPI (704 MHz): 2a=80mm (β=0.47), 2a/λ = 0.19
PIP II (650 MHz): 2a=83mm (β=0.61), 2a/λ = 0.18
2a=100 mm (β=0.9), 2a/λ = 0.22

Design approaches

Cavity shape*:



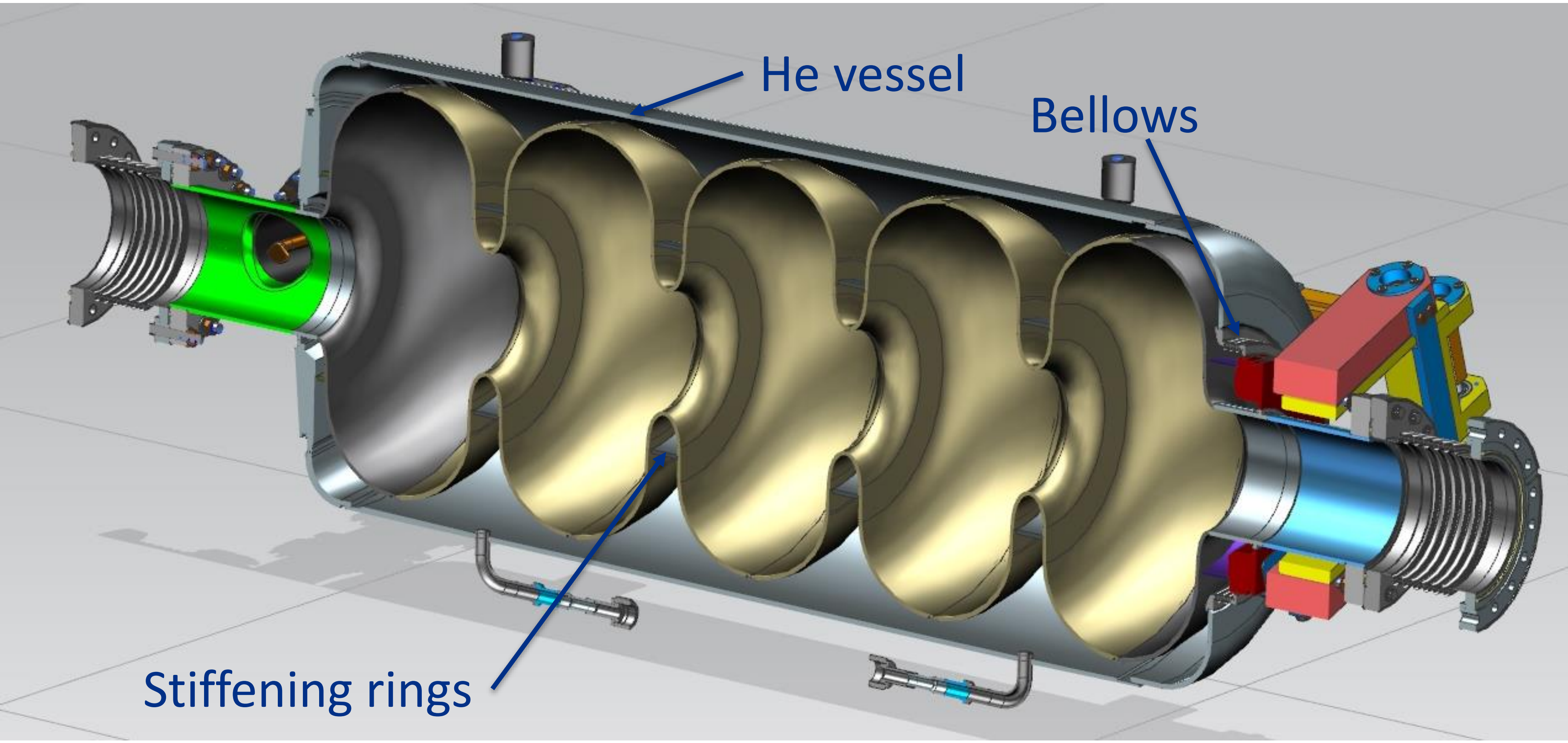


		TESLA optimized E_{peak}/E_{acc}	Re-entrant optimized B_{peak}/E_{acc}	LL optimized B_{peak}/E_{acc}
r_i	[mm]	35	30	30
k_{cc}	[%]	1.9	1.56	1.52
E_{peak}/E_{acc}	-	1.98	2.30	2.36
B_{peak}/E_{acc}	[mT/(MV/m)]	4.15	3.57	3.61
R/Q	[Ω]	113.8	135	133.7
G	[Ω]	271	284.3	284
R/Q*G	[Ω*Ω]	30840	38380	37970
$k_\perp$ (σ_z=1mm)	[V/pC/cm²]	0.23	0.38	0.38
$k_\parallel$ (σ_z=1mm)	[V/pC]	1.46	1.75	1.72

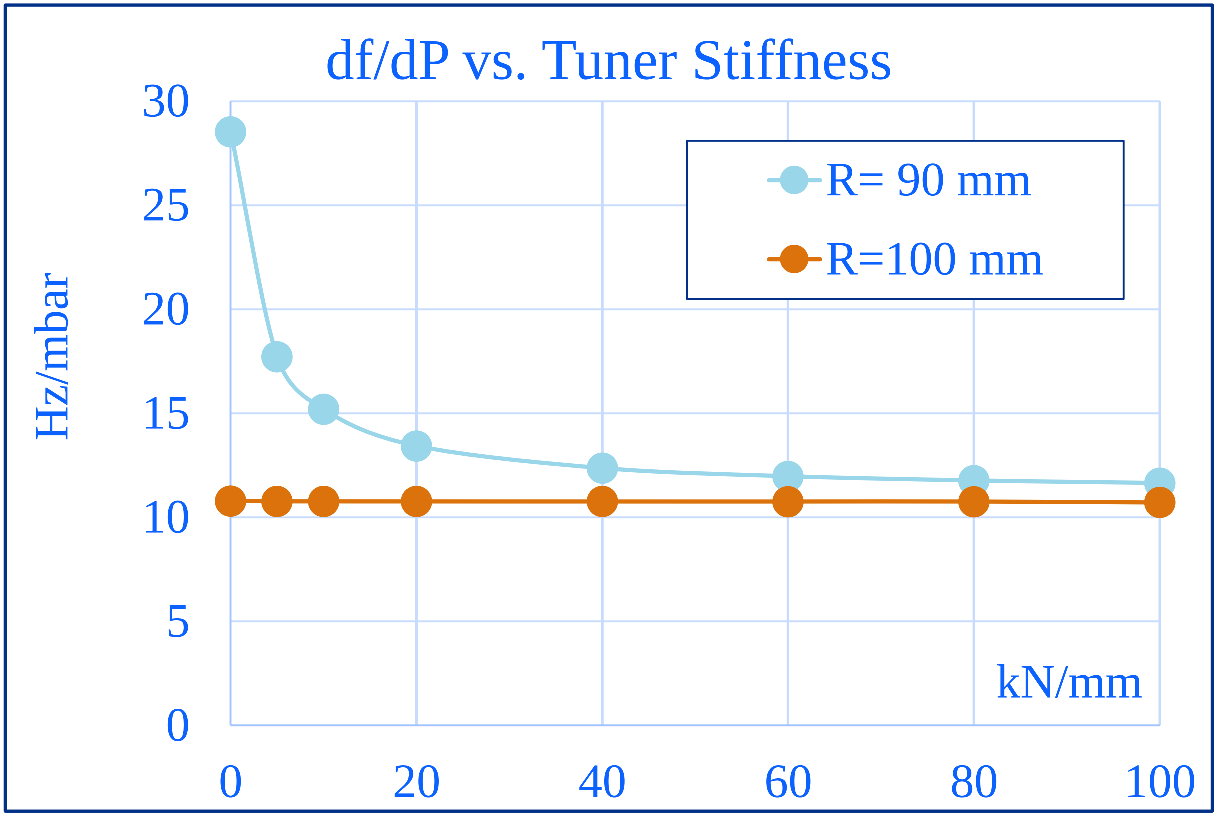
Issues with processing for Re-entrant and LL

*J. Sekutowicz

Design approaches. Mechanical stiffness

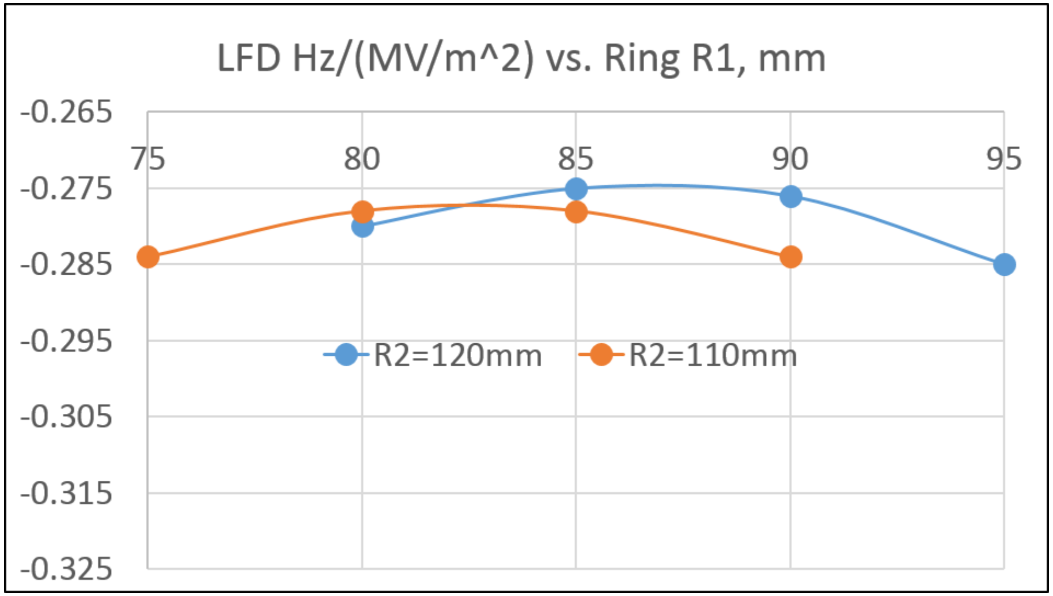


Design approaches, df/dP optimization

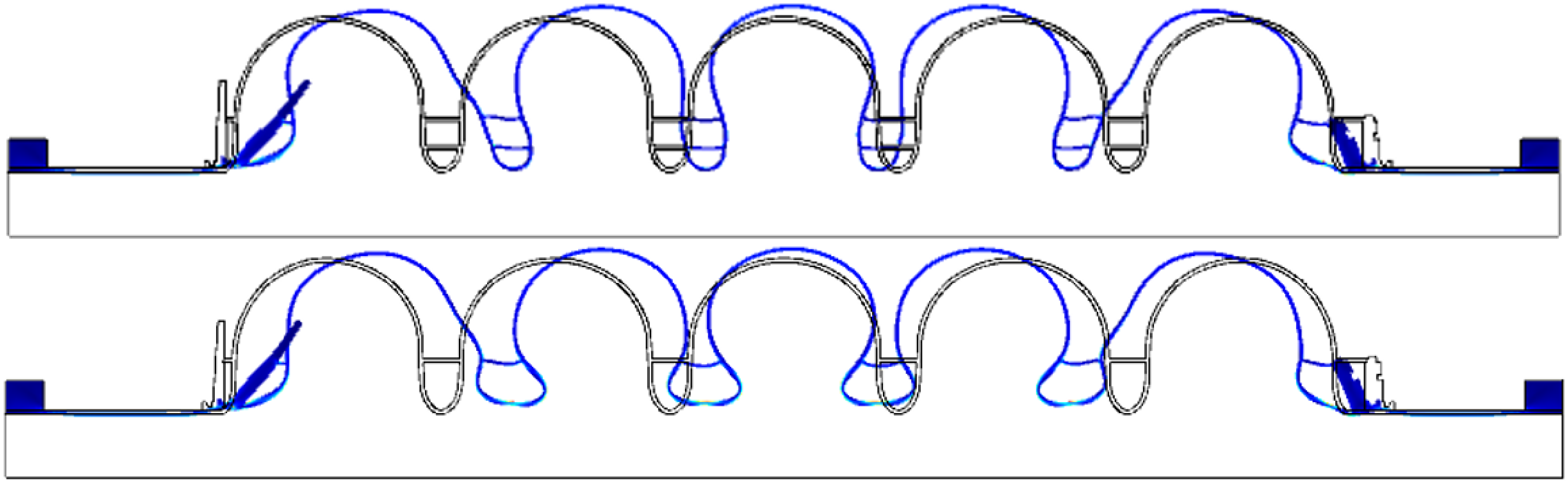


df/dP for stiffening ring R = 90 mm vs. 100 mm
Bellows radius of OD=125 mm

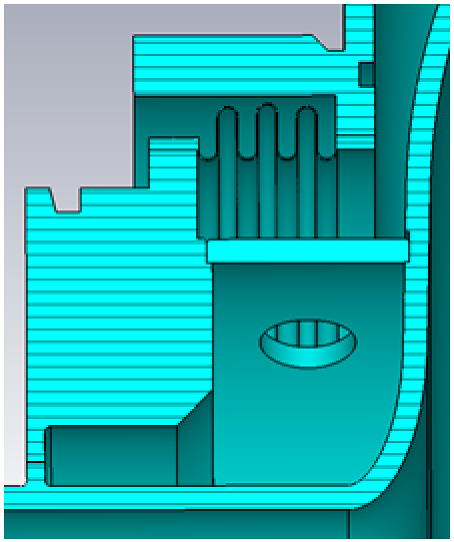
Design approaches, LFD minimization.

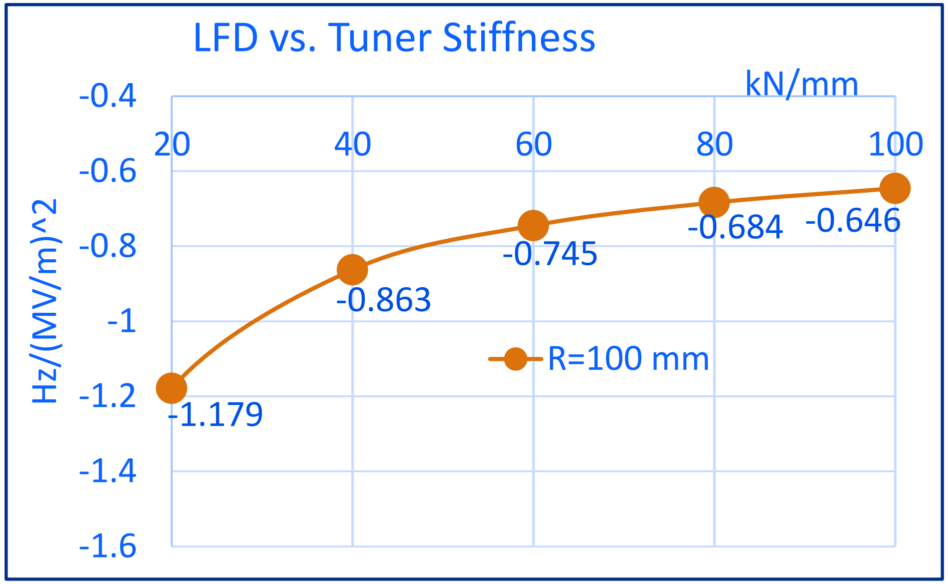


For 2 rings LFD~-0.275 Hz/(MV/m)^2 for 1 ring LFD~-0.38 Hz/(MV/m)^2. Because the difference in LFD value for one and two rings options is not essential and the complexity of production of the cavity with two rings is high enough, it is reasonable to use one ring option

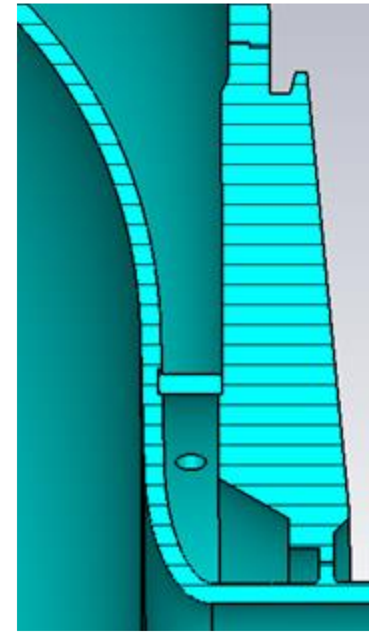


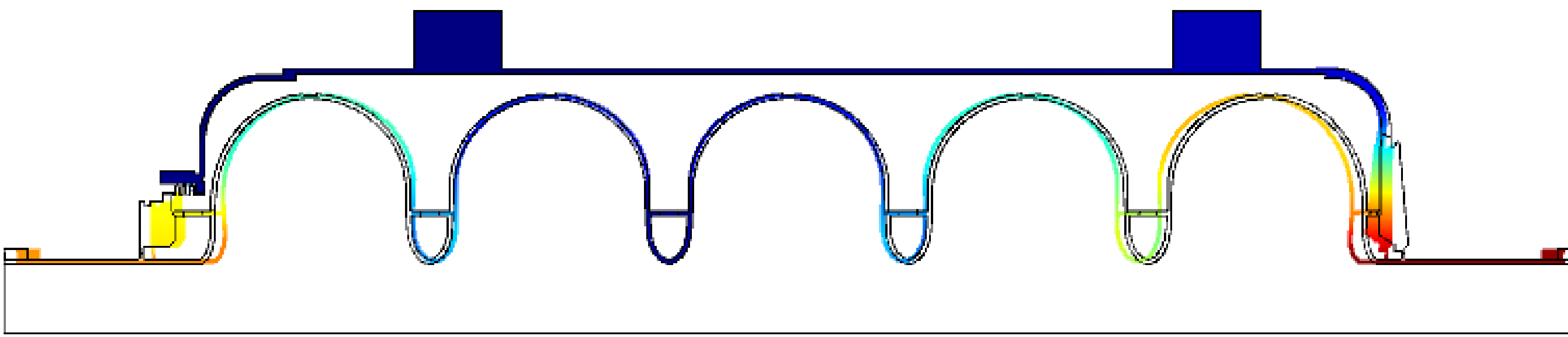
Design approaches, LFD optimization





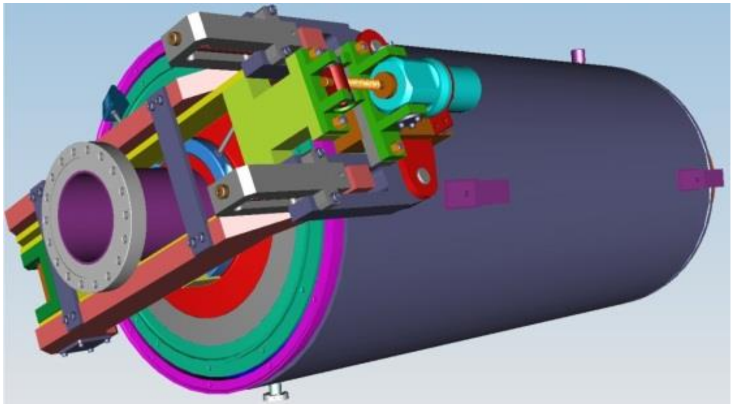
LFD for dressed cavity with R=100 mm stiffening rings



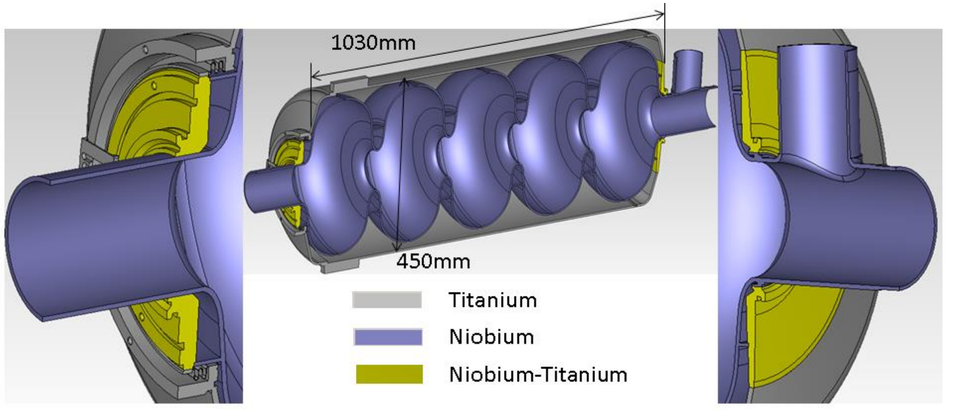


Design approaches, an elliptical cavity tuner options

Blade Tuner – scaled ILC:
- High df/dP,
- Insufficient tuning efficiency

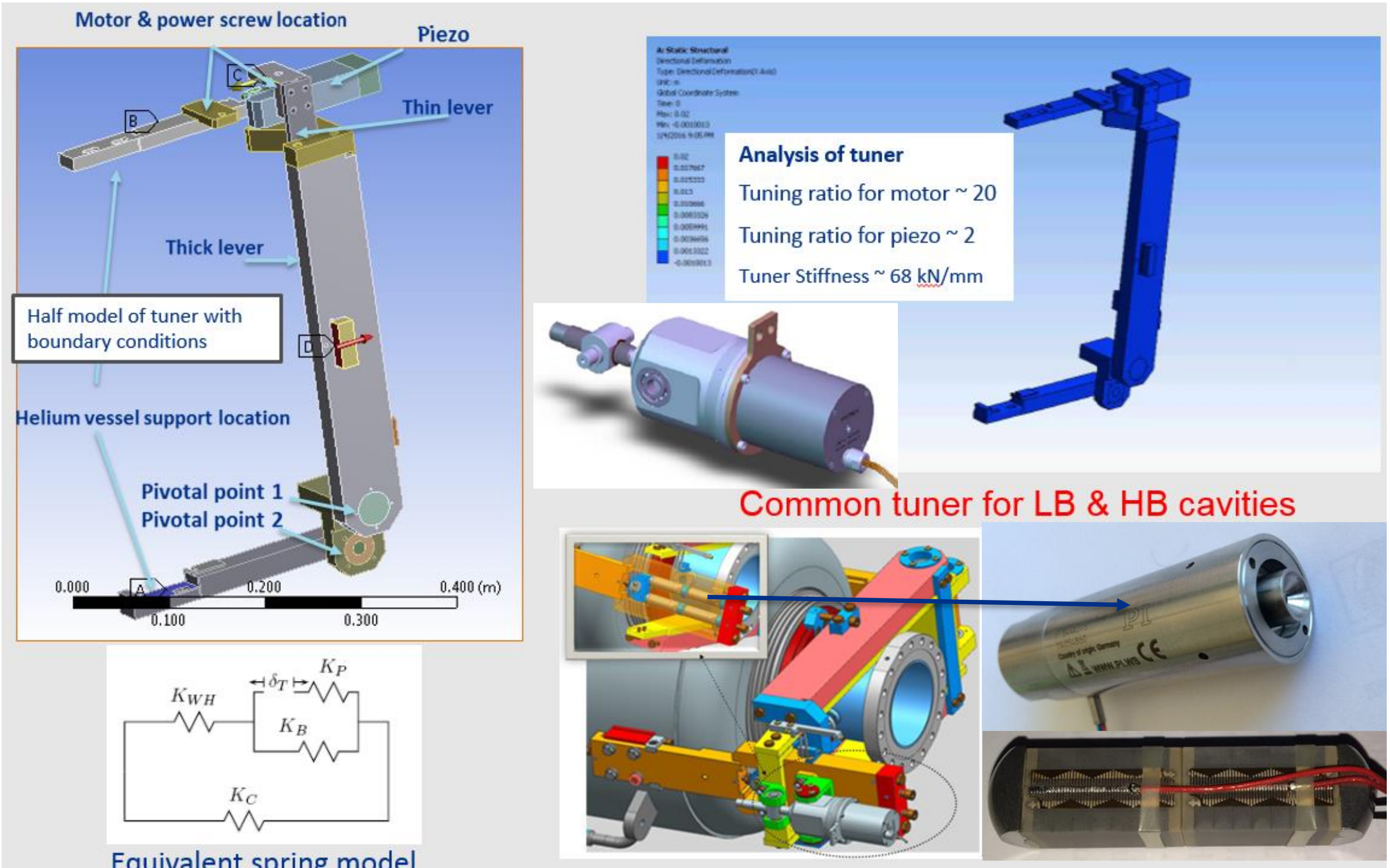


Lever Tuner design:
- Low df/dP,
- Mechanical resonances > 60 Hz;
- Good tunability;
- Less expensive.



Design approaches, the tuner

- Coarse tuner (step motor) – for the cavity tuning after cooldown, range ~100 kHz
- Fine tuner (piezo) – for microphonics and LFD compensation, range ~ 1kHz

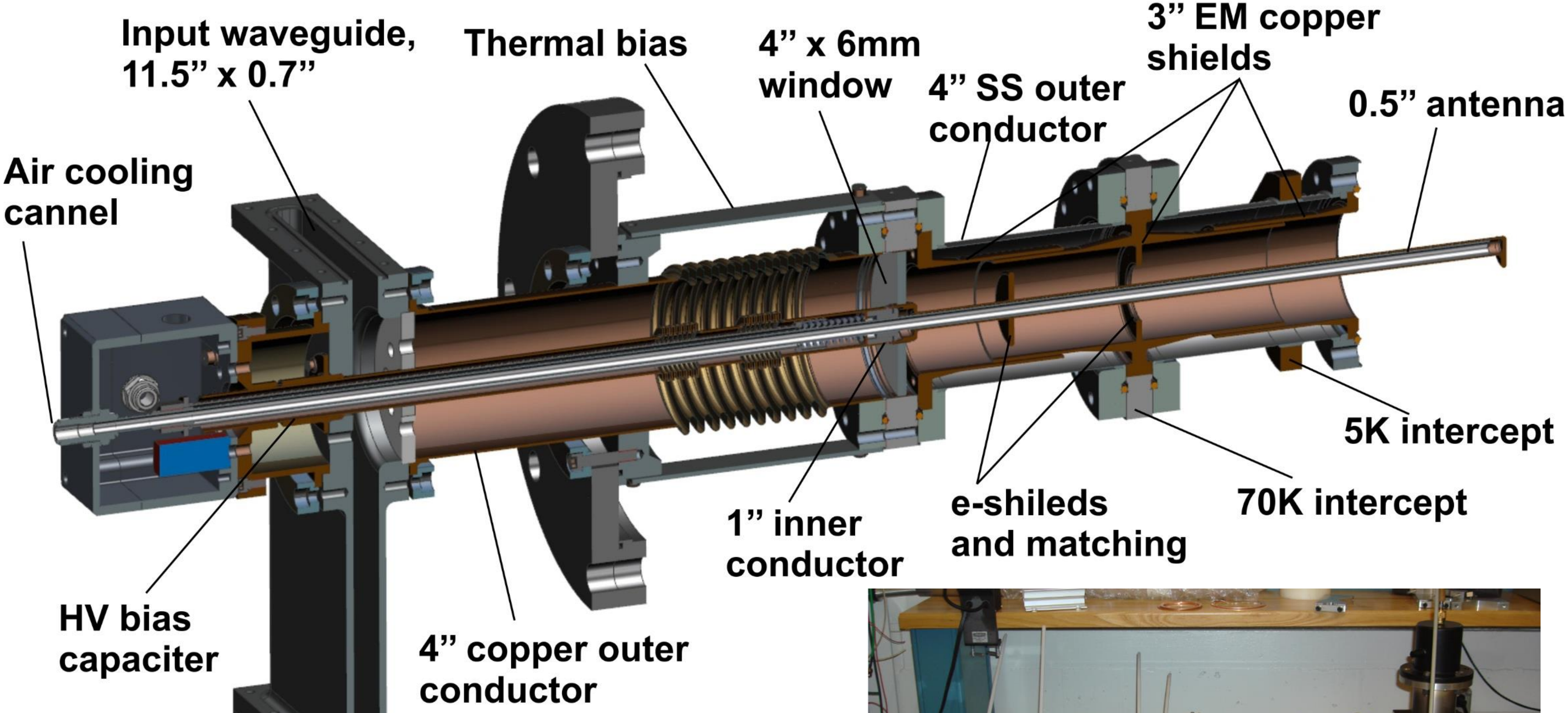


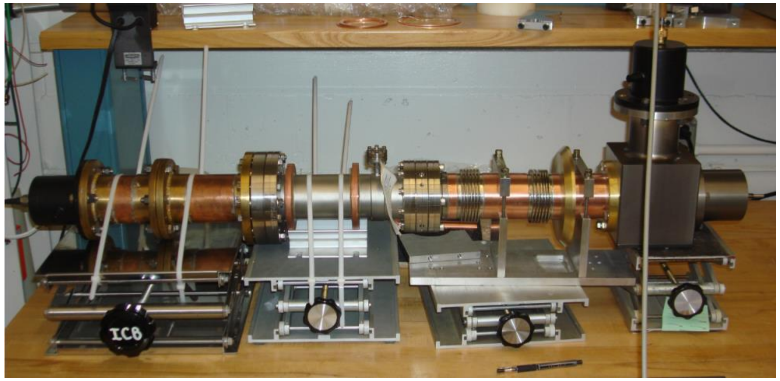
Couplers for SRF cavities:

- ❑ The couplers should transfer RF power to the cavity operating at cryo temperature
- \- High pulsed power (hundreds of kW for pulsed operation - SNS, ESS) → good electric strength
- \- High average power (up to 100 kW in CW – PIP II) → low dynamic losses, sufficient cooling (air, He)
- \- Low static losses
- \- Good vacuum properties
- ❑ Issues:
- \- MP in the vacuum part → DC bias
- \- Copper plating (chips)
- ❑ Design choices:
- \- One window versus two windows
- \- Type of cooling

Couplers for SRF cavities:

Coupler for PIP II LB/HB 650

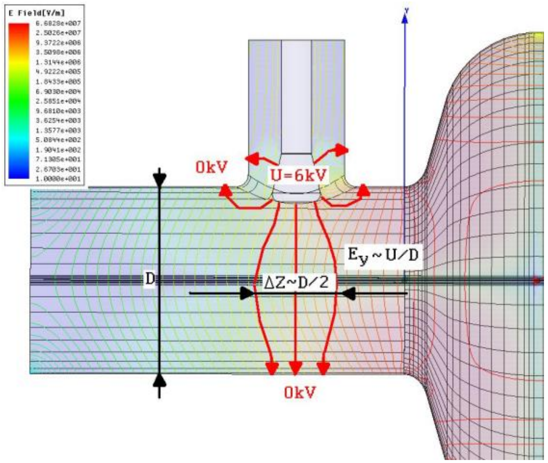


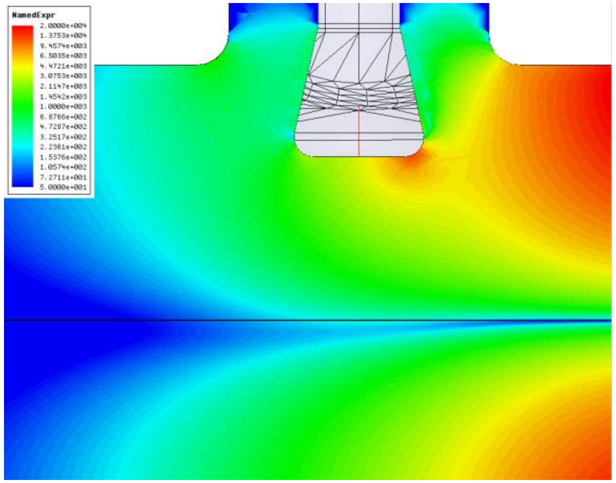


Average power up to 100 kW

RF kick caused by the input and HOM couplers.

Simple estimations of the transverse
fields caused by the main coupler:





RF voltage*:*
U=(2PZ)$^{1/2}$, *Z*–coax impedance;
for *P*=300 kW and *Z*≈70 Ohms
U ≈ 6 kV

Transverse kick:

$$v = \frac{\Delta p_y c}{\Delta U_{acc}} \approx \frac{U}{2U_{acc}} = \frac{6kV}{2\times 30MV} = 10^{-4}$$

Transverse kick caused by the couplers acts on a bunch the same direction for all the RF cavities of the linac.

Real part may be compensated by the linac feedback system;

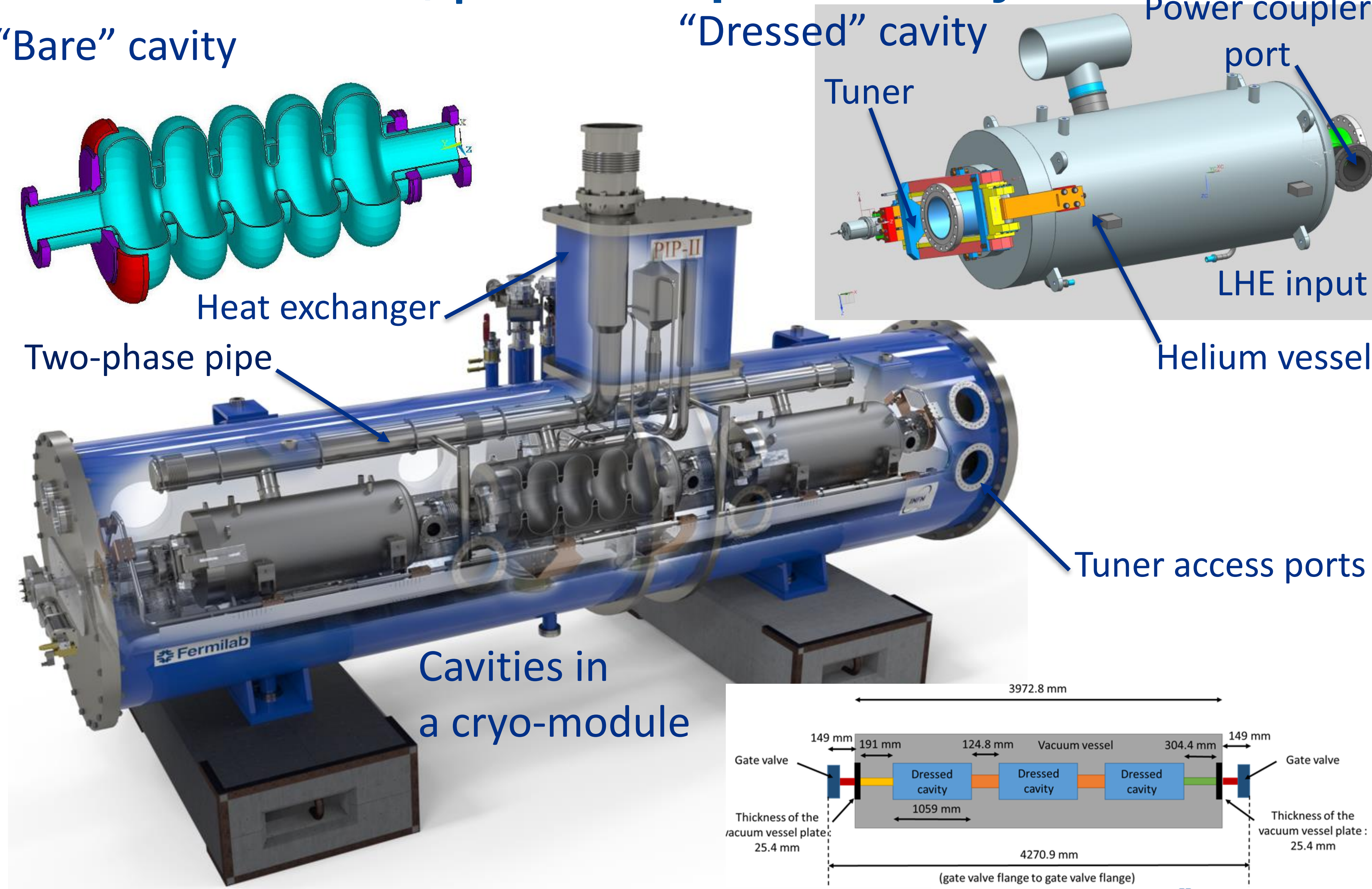
Imaginary part dives the beam emittance dilution (here β is beta-function, σ is the bunch length, and U_0 is the initial beam energy):

$$\gamma\varepsilon \approx \gamma(z_{\max})y_{\max}y'_{\max} = \frac{\pi^2 v^2 E^2 \sigma^2 \beta^3 \gamma_0}{\lambda_{RF}^2 U_0^2}$$

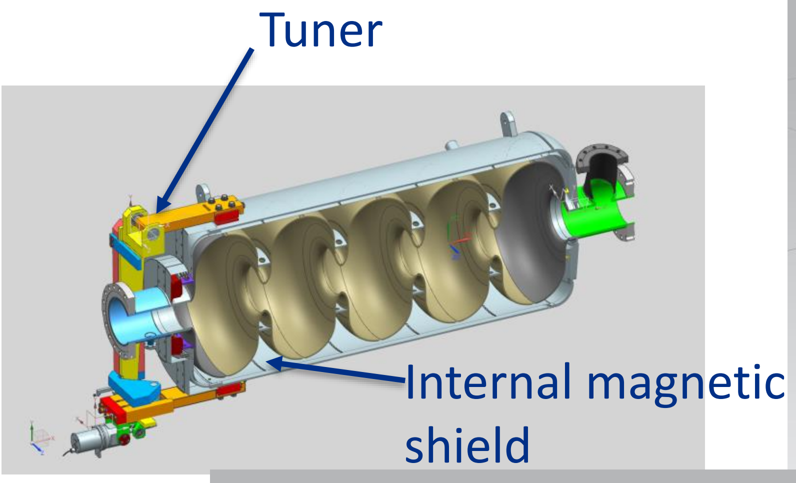
Vacuum vessels

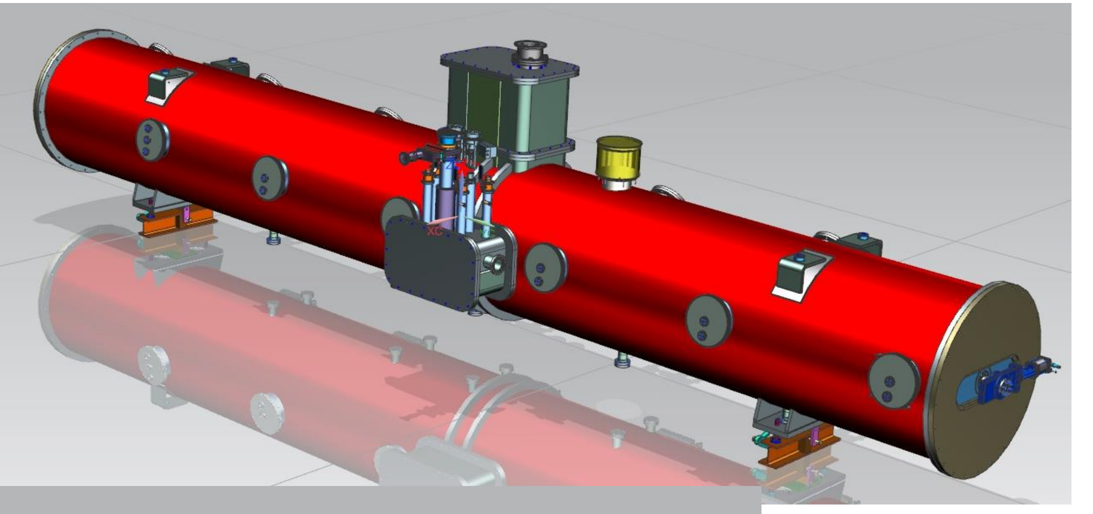
- The outermost cryostat component that:
  - Contains the insulating vacuum.
  - Serves as the major structural element to which all other systems are attached to the accelerator tunnel floor.
  - Serves as a pressure containment vessel in the event of a failure in an internal cryogen line.
- The design for internal and external pressure are addressed by the ASME Boiler and Pressure Vessel Code, Section VIII, Divisions 1 and 2 and specific workplace codes.
- Insulating vacuum is generally in the 1e10^{-6} torr range, but can be as low as 1e10^{-4}. The lower the better.

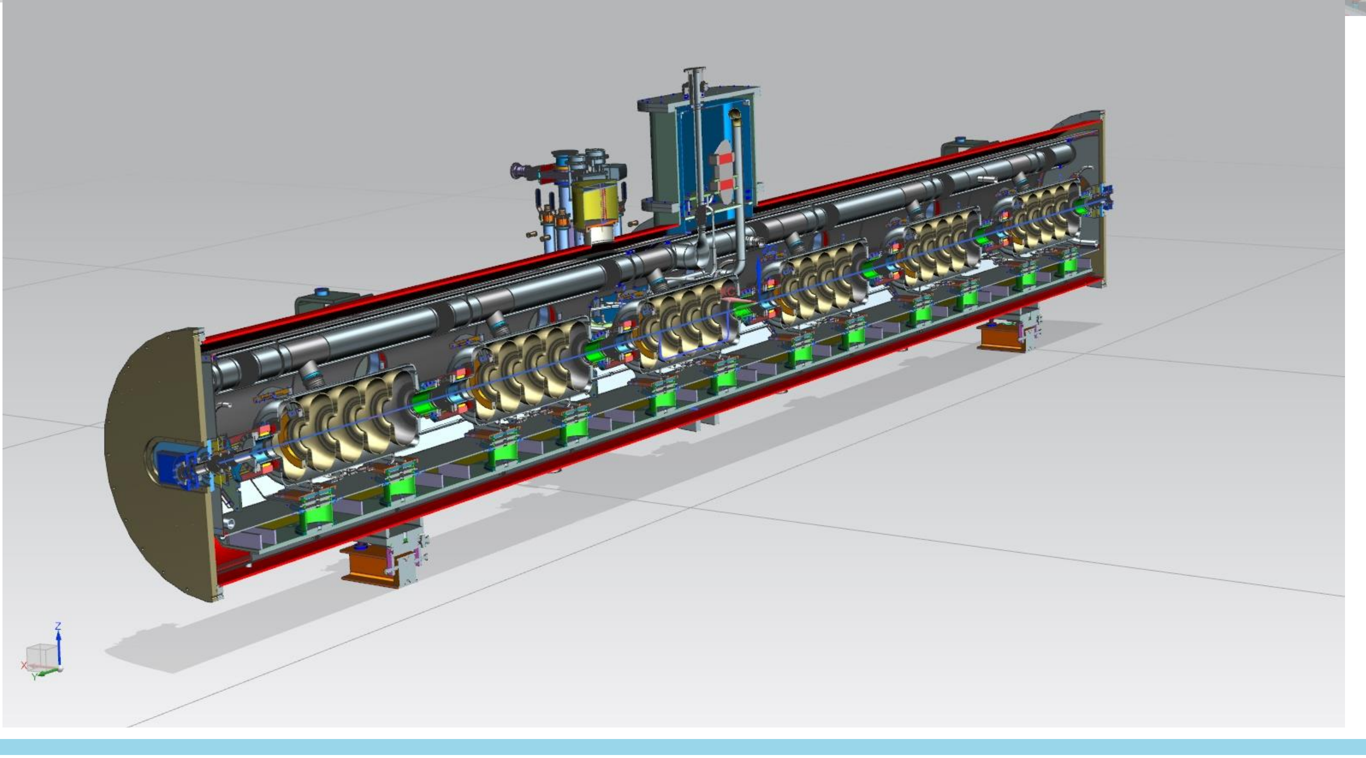
CM for 650 MHz, β=0.61 elliptical cavity for PIP II



CM for 650 MHz, β=0.9 elliptical cavity for PIP II







Homework

Task 1. SRF 5-cell cavity designed for PIP II has the following parameters:

- Operating frequency is 650 MHz
- Acceleration voltage V is 20 MV
- R/Q is 620 Ohm
- Q_0 at operation voltage is 3e10
- The beam current I is 2 mA

Estimate for CW operation:

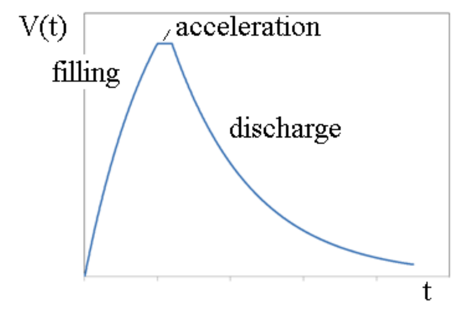
- The cavity loaded Q, $Q_L = V/(I \cdot (R/Q))$
- The cavity time constant, $\tau = 2Q_L/\omega$.
- The cavity bandwidth , $\delta f = f/Q_L$;
- Loss power in the cavity walls;
- The power transferred to the beam;
- Power required for refrigeration (conversion factor 1.e3 W/W,
- i.e., in order to remove 1 W from the cavity wall one needs wall plug power of 1 kW);
- Acceleration efficiency, the beam power over the sum of the beam power and power required for refrigeration.

Homework

Task 2. PIP II SRF accelerator has CW capability, but will operate in the pulsed mode as an injector to the booster ring. The beam and cavity parameters are the same as for CW, Task 1. The beam pulse t_{beam} is 0.55 msec, repletion rate is 20 Hz. The beam appears when the cavity voltage reaches the operating value V, and backward wave (from the cavity to the RF source) is zero. Note that this wave is a sum of the reflection from the coupling element (which is equal to the incident wave), and the wave radiated from the cavity to the line. In the beginning of the cavity filling, the radiation is zero (the cavity is empty), and the backward wave is equal to reflection from the coupling element, and thus, to the incident wave. If there is no beam, the backward wave is again equal to the incident wave (no losses in the cavity) after the voltage reaches its maximal value, but it is again the sum of the wave reflected from the coupling element and radiated wave. It can be only if the radiated wave is two times larger than the wave reflected from the coupling element, and has opposite sign. It means that the beam appears when the cavity field reaches half of the maximal value (zero backward wave, the reflected wave is equal to the radiated wave, and they compensate each other). The cavity voltage, thus, increases during the filling as $V(t) = 2V(1-\exp(-t/\tau))$, τ is the time constant, $\tau = 2Q_L/\omega$. Filling is over when $V(t_{fill}) = V$, and therefore, the filling time t_{fill} is equal to $\tau\cdot\ln 2$. After the beam ends, the RF source is turned off, and cavity discharges as $V(t) = V\exp(-t/\tau)$. Thus, the cavity voltage has the following behavior:

Homework

- $V(t) = 2V(1\text{-}exp(-t/\tau))$, $0<t< t_{fill}= \tau\cdot ln2$ - filling; RF is on, no beam;
- $V(t) = V$, the beam acceleration; RF is on; $0<t<t_{beam}$, $t=0$ corresponds to the end of filling process and beginning of acceleration
- $V(t) = Vexp(-t/\tau)$, cavity discharge; RF is off, no beam. $t=0$ corresponds to the end of acceleration and beginning of discharge



Estimate:
- Energy, delivered by the RF source <u>to the beam</u> during the pulse;
- Total energy, delivered by the RF source during the pulse;
- Total energy dissipated in the cavity wall during the pulse;
- Energy, required for refrigeration;
- Beam power /cavity (20 GHz repetition rate);
- Average RF power/cavity;
- Power necessary for refrigeration/cavity;
- Acceleration efficiency.

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