12-14 January 2012 Fermilab

Superconducting RF for linear hadron accelerators

(Introduction to discussion)

Proton Accelerators for Science and Innovation Workshop

Magnets & RF Workgroup

01/13/2012

Slava Yakovlev, FNAL

Fermi National Accelerator Laboratory

Outlook

The application of SRF technology to hadron linacs has a long and successful history.

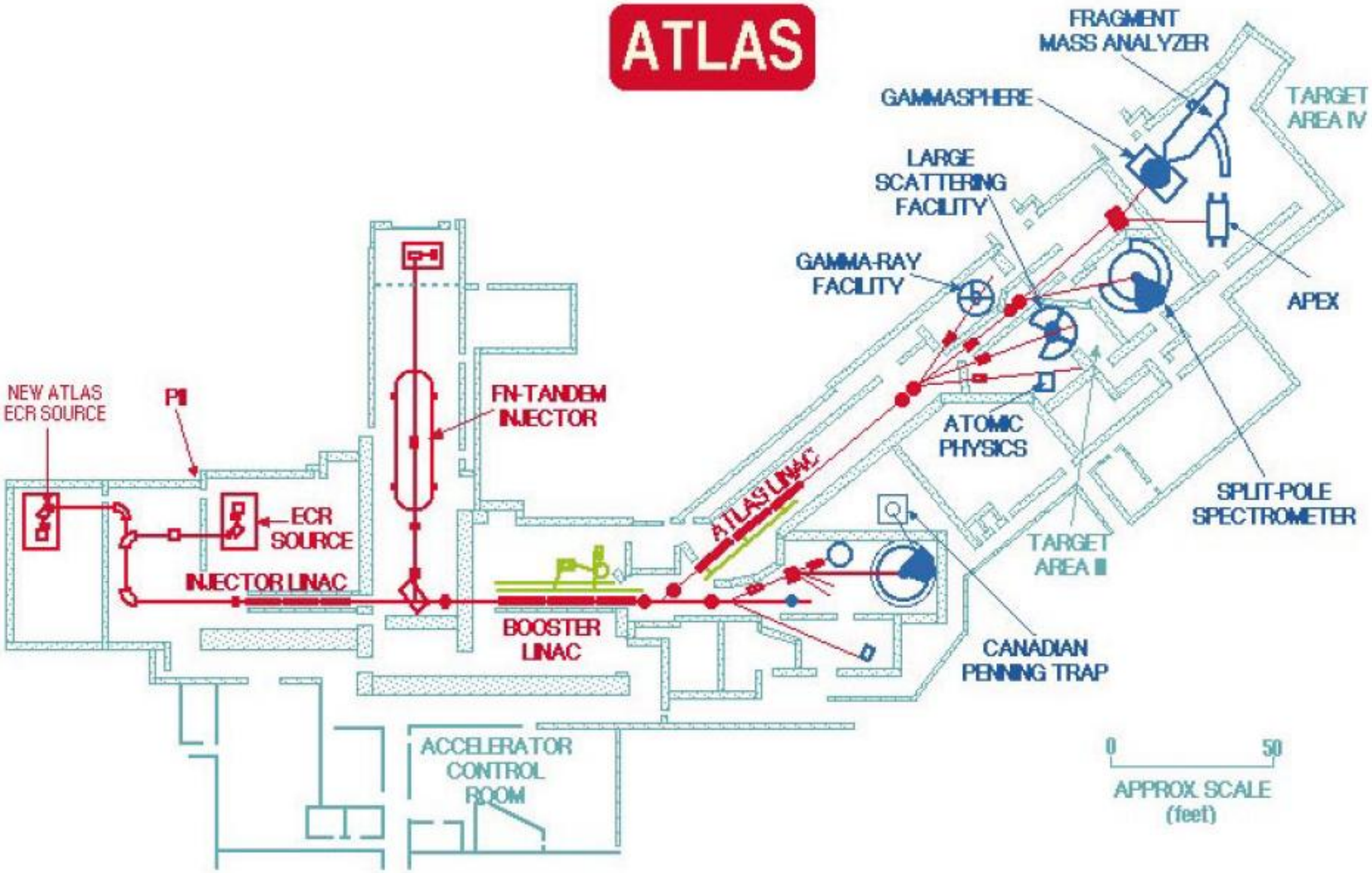
- **Operating Facilities**
  - **ATLAS (ANL)**
  - **ISAC-II (TRIUMF)**
  - **SNS (Oak Ridge)**
- **Facility upgrade using SRF technology**
  - **HIE-ISOLDE (CERN)**
  - **JPARC**

- **New projects**
  - **SPIRAL-2 (GANIL, CEA Saclay, IPN Orsay)**
  - **SARAF (SOREQ)**
  - **FRIB (MSU)**
  - **IFMIF (CEA Saclay)**
  - **SPL (CERN)**
  - **ESS (Lund)**
  - **Project X (Fermilab)**
  - **ADS Project (India)**
  - **ADS Project (China)**
- **Others**

ATLAS, ANL – heavy ions.

-The world's first superconducting accelerator for hadrons (1985);

-A national user facility for nuclear structure and reaction research, nuclear theory, medium energy nuclear research and accelerator research and development;



ATLAS before upgrade

Great variety of accelerated ions;

-12 MV low-velocity linac (PII) 1992

containis 18 cavities:

beta=0.009, 48.5 MHz QWR;

beta=0.015, 48.5 MHz QWR;

beta=0.025, 48.5 MHz QWR;

beta=0.037, 72.75 MHz QWR

-20 MV booster linac 1985

-20 MV ATLAS linac (before upgrade)

Contains 46 cavities :

beta=0.060, 97 MHz split ring;

beta=0.105, 97 MHz split ring;

beta=0.105, 97 MHz split ring.

Acceleration up to 17 MeV/nucleon.

-Upgrade 2009 :

New beta=0.14, 109.125 MHz QWR

-Upgrade 2011-2013 :

New 60.625 MHz CW 2.1 MeV RFQ

New beta=0.077, 72.75 MHz QWR

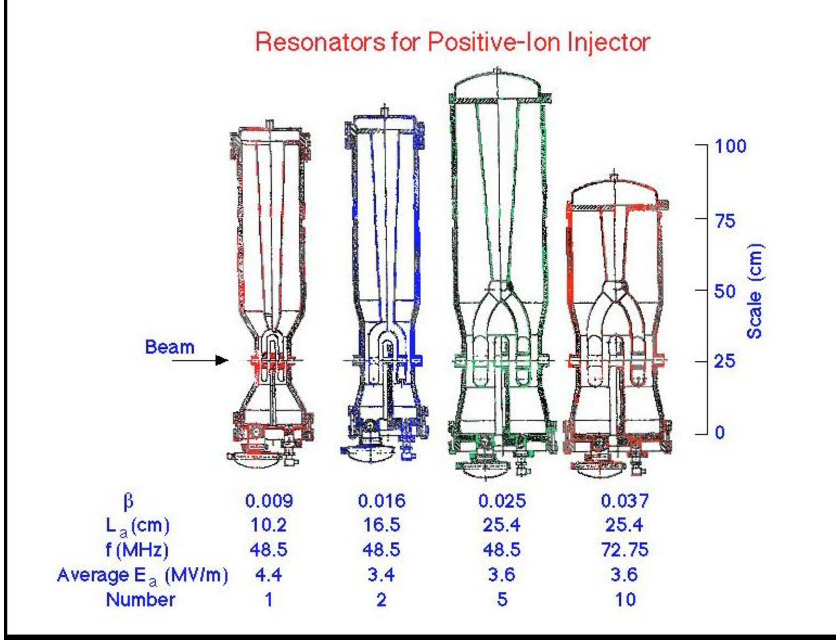
Stable Beams Available from ATLAS

Beam currents listed in the table were obtained with naturally occurring material for the given isotope.

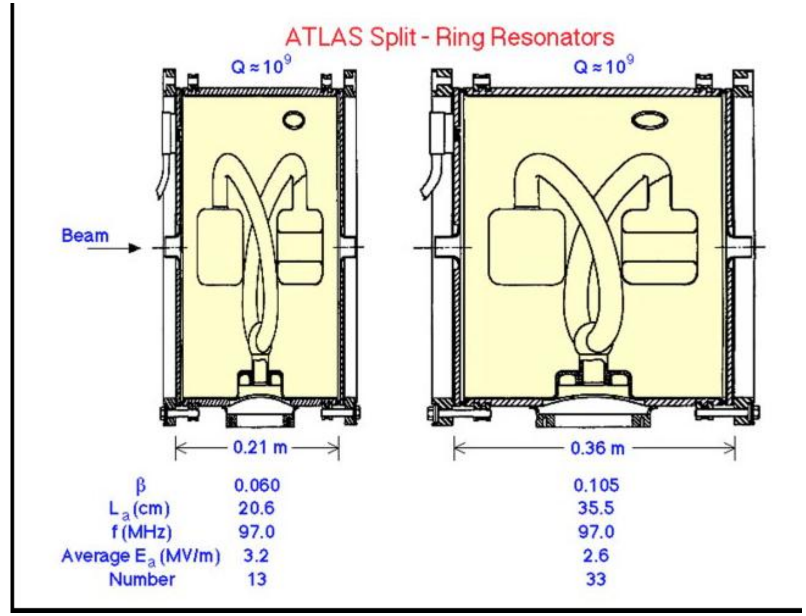
The maximum energy quoted corresponds to that computed with the optimal charge state. Higher energies are possible by using another charge state or by double stripping.

[a] Other isotopes available with currents proportional to their abundance. For more beam current, isotopically enriched material may be used, but the User should, in general, contact the User Liaison or ATLAS Operations to check on the availability of enriched material.
[b] Indicates elements for which isotopically enriched material has been successfully used in the past.
[c] Allowed maximum radiation may limit beam current.
* The maximum energies in Area II are about 0.6 times these values.

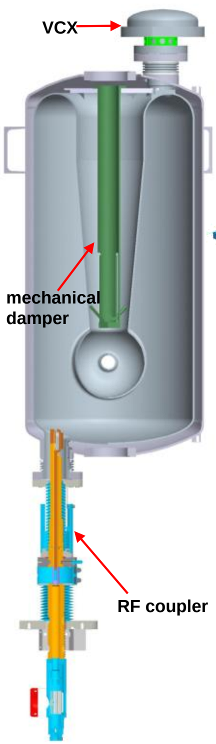
Ion[a]	Maximum Energy (Mev) for Areas III,IV*	Maximum Current at Maximum Energy (pna)	Beam Current at Energy of 6 MeV/u (pnA)
^{7}Li	140	>100[c]	200[c]
^{10}B[b,c]	200	>100	>100
^{12}C[b]	241	100	>1000[c]
^{14}N	244	800[c]	>1000[c]
^{16}O[b]	320	>100	>1000[c]
^{19}F	334	10	50
^{20}Ne	350	1000	>1000[c]
^{24}Mg	415	2	10
^{27}Al	464	10	30
^{28}Si[b]	476	100	>1000
^{32}S[b]	539	100	1000
^{35}Cl	585	12	35
^{40}Ar[b]	660	1000	>1000
^{40}Ca[b]	660	200	>1000
^{48}Tib	778	40	300
^{51}V	816	0.5	2
^{52}Cr	832	10	40
^{56}Fe[b]	882	50	400
^{59}Co	920	10	50
^{58}Ni[b]	911	20	100
^{63}Cu	977	20	100
^{64}Zn	979	4	20
^{74}Ge[b]	1103	2	10
^{80}Se	1160	2	10
^{79}Br	1150	2	10
^{84}Kr[b]	1201	500	>1000
^{90}Zr[b]	1260	140	300
^{98}Mo[b]	1343	1.5	7
^{102}Ru[b]	1377	3	12
^{107}Ag	1418	10	50
^{120}Sn[b]	1512	2	10

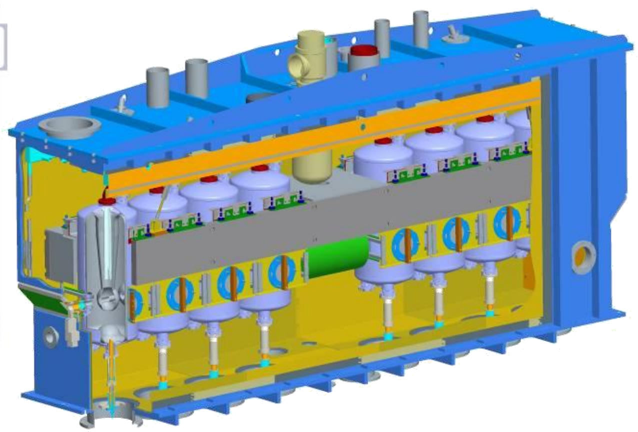


QWR 4-gap cavities cavities for PII (K.W. Shepard et al, 1989)

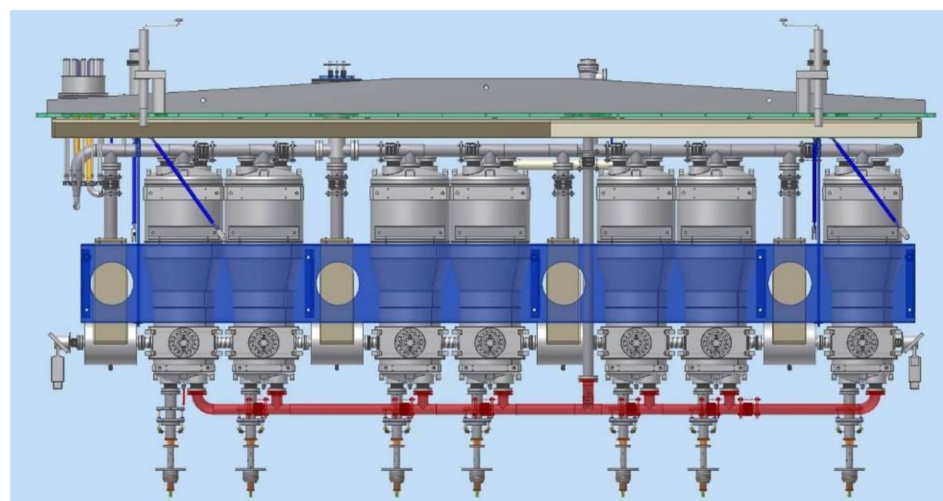


Split ring tree-gap cavity for the booster linac (K.W. Shepard et al, 1983)





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



beta=0.077, 72.75 MHz QWR CM (Peter N. Ostroumov)

Hadron linear accelerators have the following features compared to electron machines:

- The beam current is typically small:
  - nA-μA range for heavy ion accelerators and
  - up to hundred of mA for protons;

- The accelerated particles are non-relativistic, or weakly relativistic.

Why superconductivity for proton accelerator and in what case?

The power consumption of a linac is determined by

- Beam power;
- Ohmic losses in an acceleration structure;
- Losses caused by HOM excitation;
- RF power reflections;
- Efficiency of RF sources;
- Power for focusing elements;
- Power for auxiliary systems.

Regime of operation: pulsed, CW

Ohmic losses in an acceleration cavity:

Ohmic losses P_{loss} are determined by:

- Energy gain per cavity *U*;
- Surface resistance R_s;
- *(R/Q)* factor, which is a ratio of the gain per cavity squared over the reactive power, i.e., energy stored in the cavity *W* by cyclic frequency *ω* : $(R/Q)=U^2/\omega W$. Depends only on the particle velocity and the cavity geometry.
-"geometrical factor" *G*, a product of the cavity unloaded quality factor *Q* by surface resistance R_s: $G=Q\times R_s$. Depends only on the cavity geometry;
- Duty cycle *D*.

$$P_{loss} = \frac{U^2 R_s D}{\left(\frac{R}{Q}\right) G}$$

For normal-conducting cavities R_s is determined by skin-effect: $R_s = sqrt(\omega\mu_0/\sigma)$.

For example, for the frequency 1.3 MHz for Cu one R_s=9 mOhm

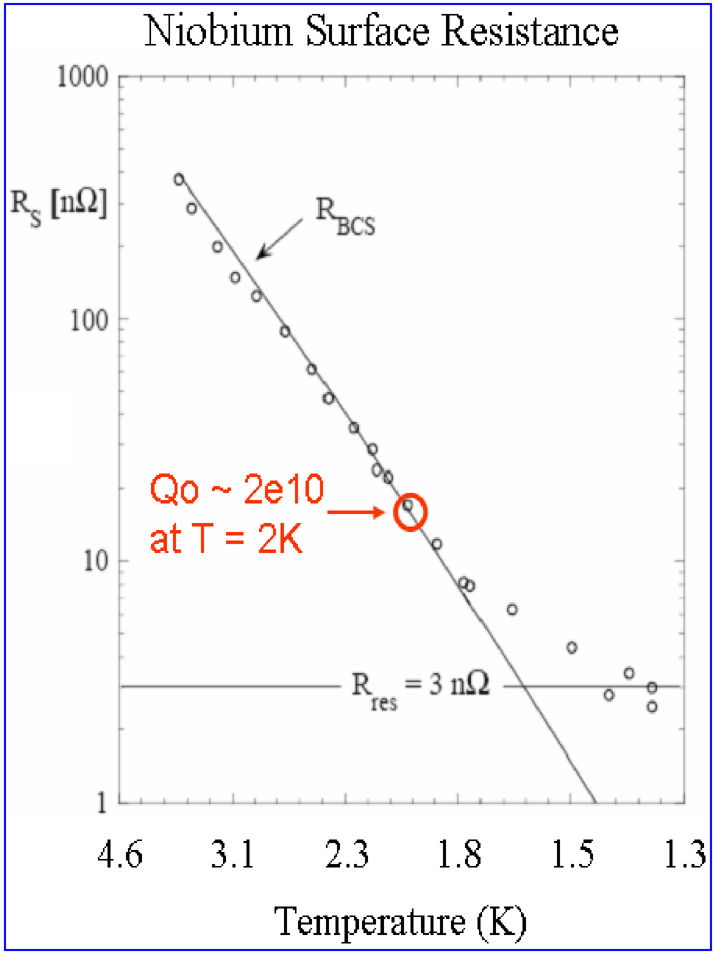
For SC cavity R_s is sum of residual resistance and BCS - resistance : Rs is determined by the surface quality and processing. BCS – resistance :

$$R_{BCS} = \frac{A\omega^2}{T}\exp\left(-\frac{\Delta}{k_B T}\right)$$

Energy gap is a function: $\Delta = \Delta(T, Es)$.

For example, for 1.3 GHz and 2K $R_s \approx$10-12 nOhm, <u>or 6 orders smaller</u>!

Much less RF losses! CW regime is possible!



Acceleration efficiency depends on the ratio of P_{loss}/P_{beam}. However, refrigerator efficiency should be taken into account.

"Conversion factor": the power necessary to remove 1 W of losses at cryo temperature. Conversion factor T ~0.7-0.8 kW/W for 2 K.

Thus, for SC cavity operating in CW regime $$\frac{P_{loss}}{P_{beam}} = \frac{U R_s^{SC} T}{\left(\frac{R}{Q}\right) G I_{av}}$$

may be small even for small average current I_{av}.

For RT cavity $$\frac{P_{loss}}{P_{beam}} = \frac{U R_s^{RT} D}{\left(\frac{R}{Q}\right) G I_{av}}$$

for small gain/cavity small duty factor and higher average current (tens of mA) efficiency may be compatible to SC.

Utilization of RT is preferable for the pulse linac front-end with high pulse current, where *U* should be small because of the beam dynamics limitation (for example, in SNS).

Different mechanisms limiting acceleration gradient:

Room Temperature:

- *Breakdown;*
- *Metal fatigue caused by pulse heating;*
- *Cooling problems.*

Breakdown limit:

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

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;

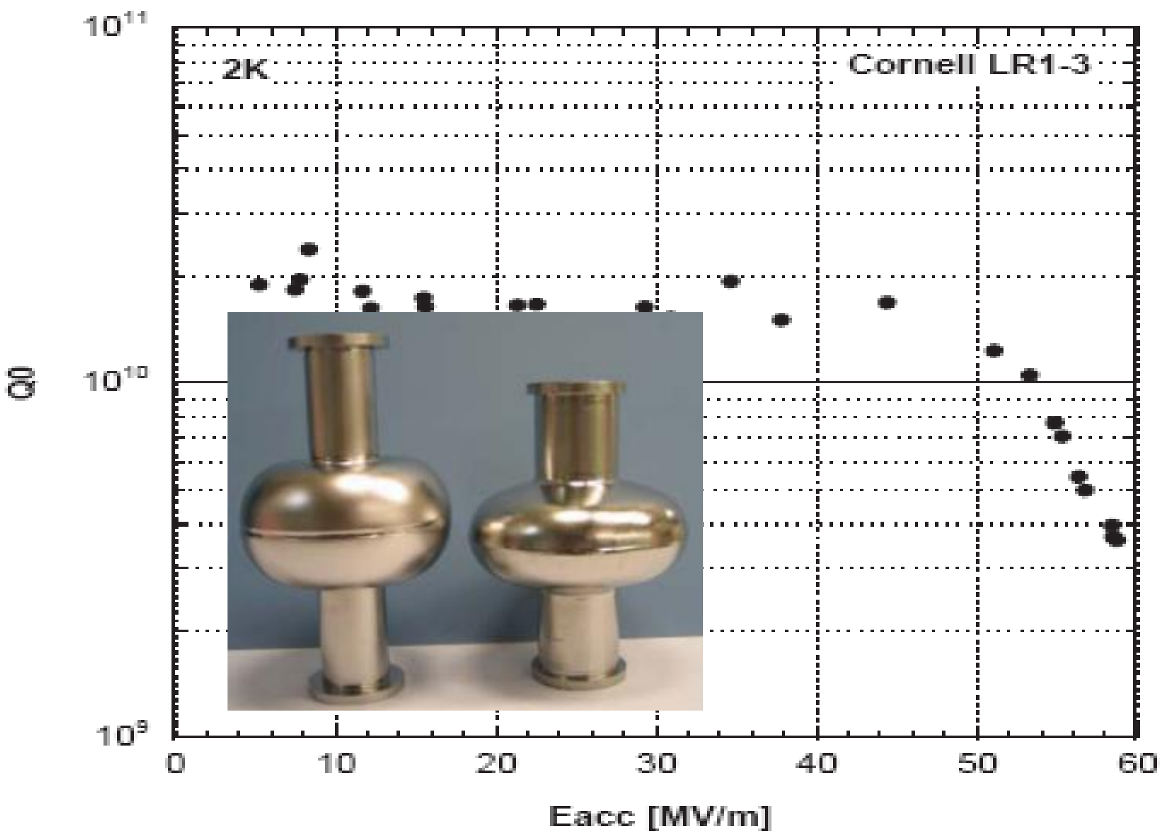
Achieved Limit of SRF electric field

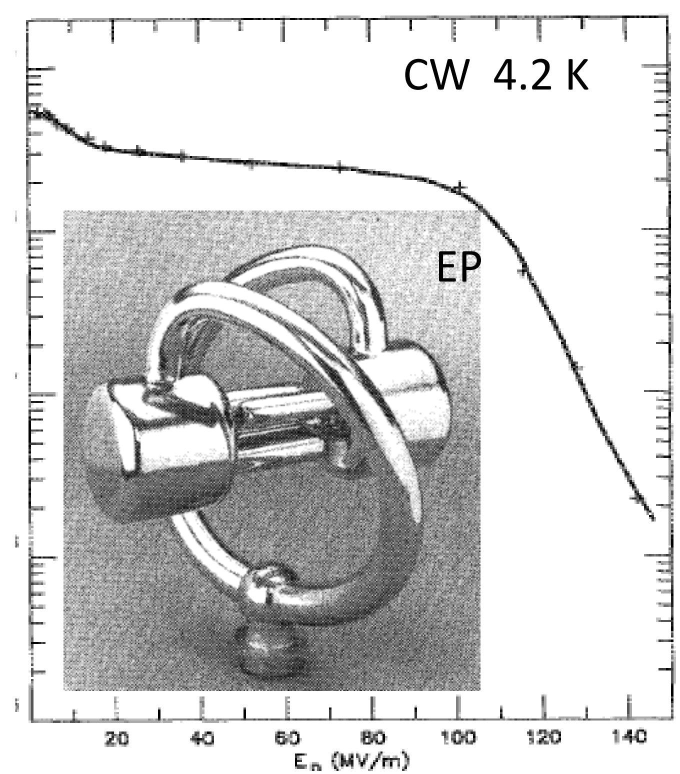
- No known theoretical limit
- 1990: Peak surface field ~130 MV/m in CW and 210 MV/m in 1ms pulse.

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

- 2007: Re-entrant cavity: E_{acc}= 59 MV/m (E_{pk}=125 MV/m,Bs=206.5mT).

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



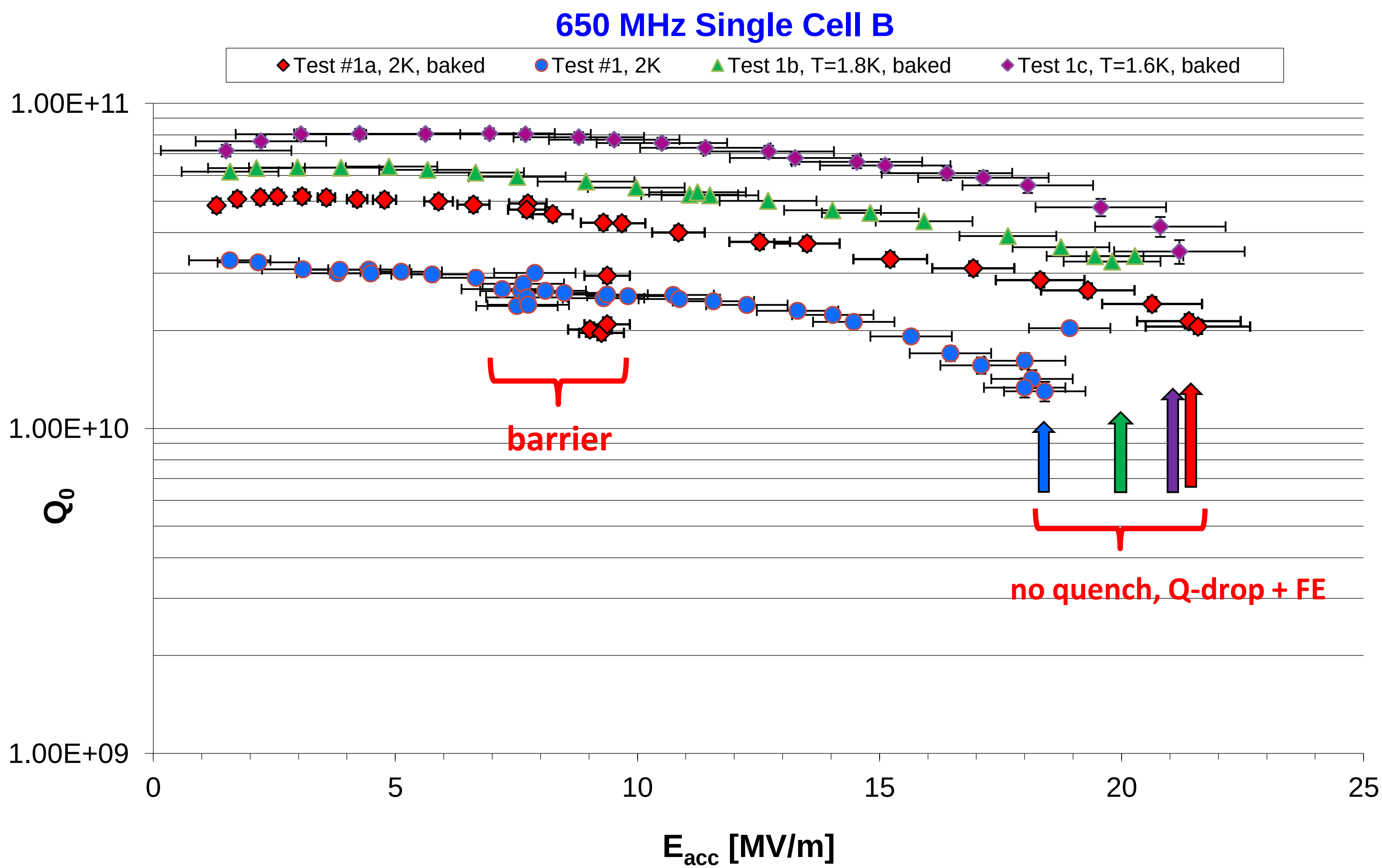


"Practical" gradient limitations for SC cavities

- 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

SC allows significantly higher acceleration gradient than RT!

Cavity "B" for the Project X CW linac, JLAB



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 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

Beam dynamics issues determining the operating RF wavelength and cavity type.

- During acceleration a particle interacts with synchronous cylindrical EM wave,
  $E_z(r,z,t) \sim I_0(2\pi r/\lambda\beta\gamma)exp(ikz/\beta\text{-}i\omega t)$, $I_0\,(x)$ is modified Bessel function.

  $\lambda >> a/\beta$, a – cavity aperture.

- RF cavity provides defocusing of the accelerated beam, defocusing ~$1/\lambda\beta$. External focusing is necessary for compensation.

- On the other hand,
  $a >> \sigma_x = (\varepsilon_{norm}\beta_{foc}/\beta\gamma)^{1/2}$, *where:* $\beta_{foc} \sim$ *period of focusing system*
- Tolerances scale as $\sim\beta\lambda$.

Thus, for small velocity one should use longer wavelength, or lower RF frequency.

Example: ATLAS

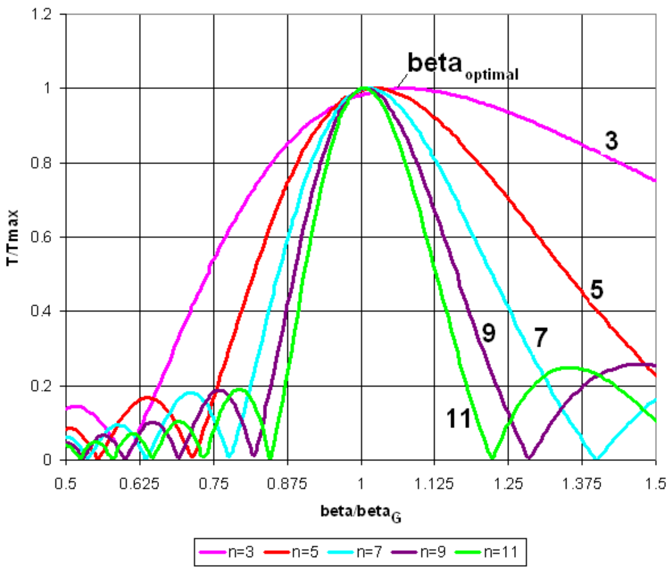
beta=0.009, 48.5 MHz QWR;
beta=0.015, 48.5 MHz QWR;
beta=0.025, 48.5 MHz QWR;
beta=0.037, 72.75 MHz QWR
beta=0.060, 97 MHz split ring;
beta=0.105, 97 MHz split ring.
beta=0.14, 109.125 MHz QWR

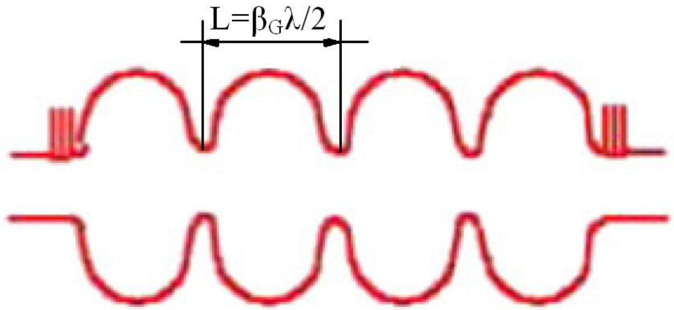
Bunch sequence frequency is 12.125 MHz

Cavity type:

Axi-symmetrical multi-cell acceleration structure typically used for electron linacs does not work at low beta:

•Aperture is to be large enough - 0.25-0.3 λ in order to provide coupling between the cells high enough for field flatness;
•In this case, $a/\beta\lambda \geq 1$ for small β, and thus, field enhancement is high:
•Electric field is concentrated near the aperture, not on the axis - poor R/Q
•Big transverse size
•Sharp dependence of gain on the beta for multi-cell cavity:





n is the number of cells in a cavity.

Other types of accelerator cavities are used for small beta - low-frequency TEM-type cavities:

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

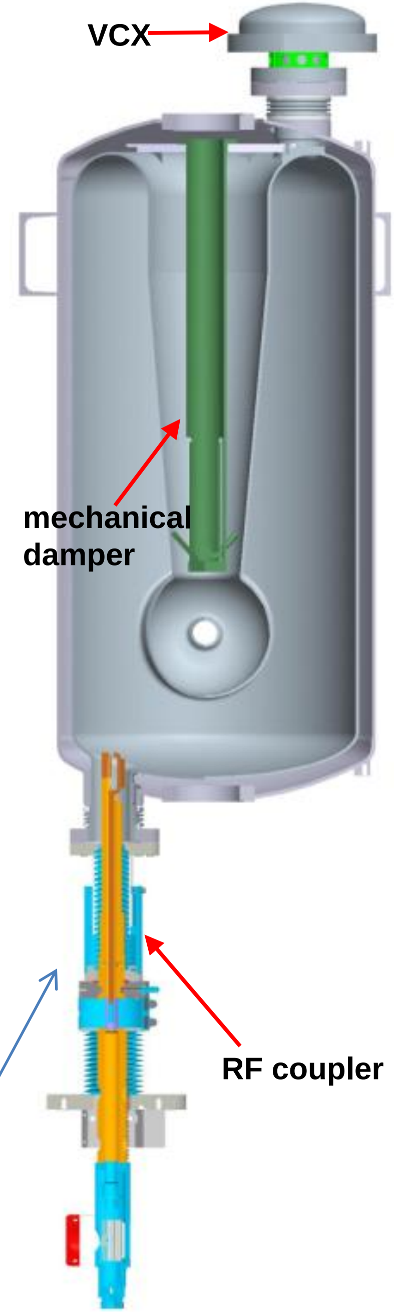
•Narrow acceleration gap (~βλ) allows concentrate electric field near the axis;
•Aperture ~ 0.02-0.03λ allows acceptable field enhancement;
•Number of gaps in modern cavities is 2 for small beta which allows operation in acceptably wide beta domain. For beta >0.4 multi-gap cavities are used –double-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

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)**

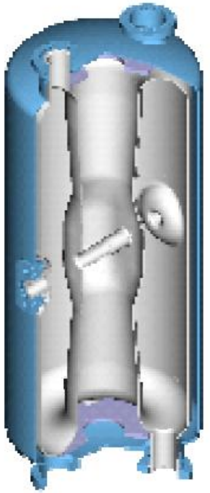


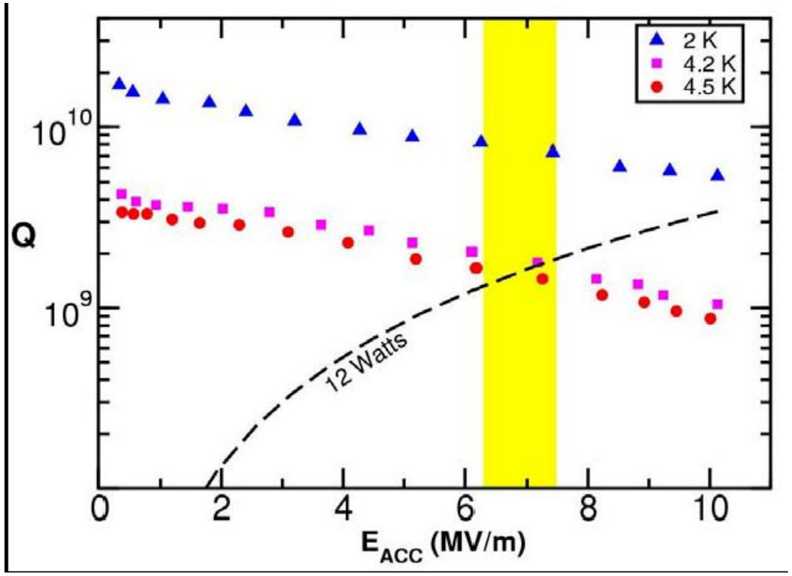
Half-wave resonator (HWR)

- 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.

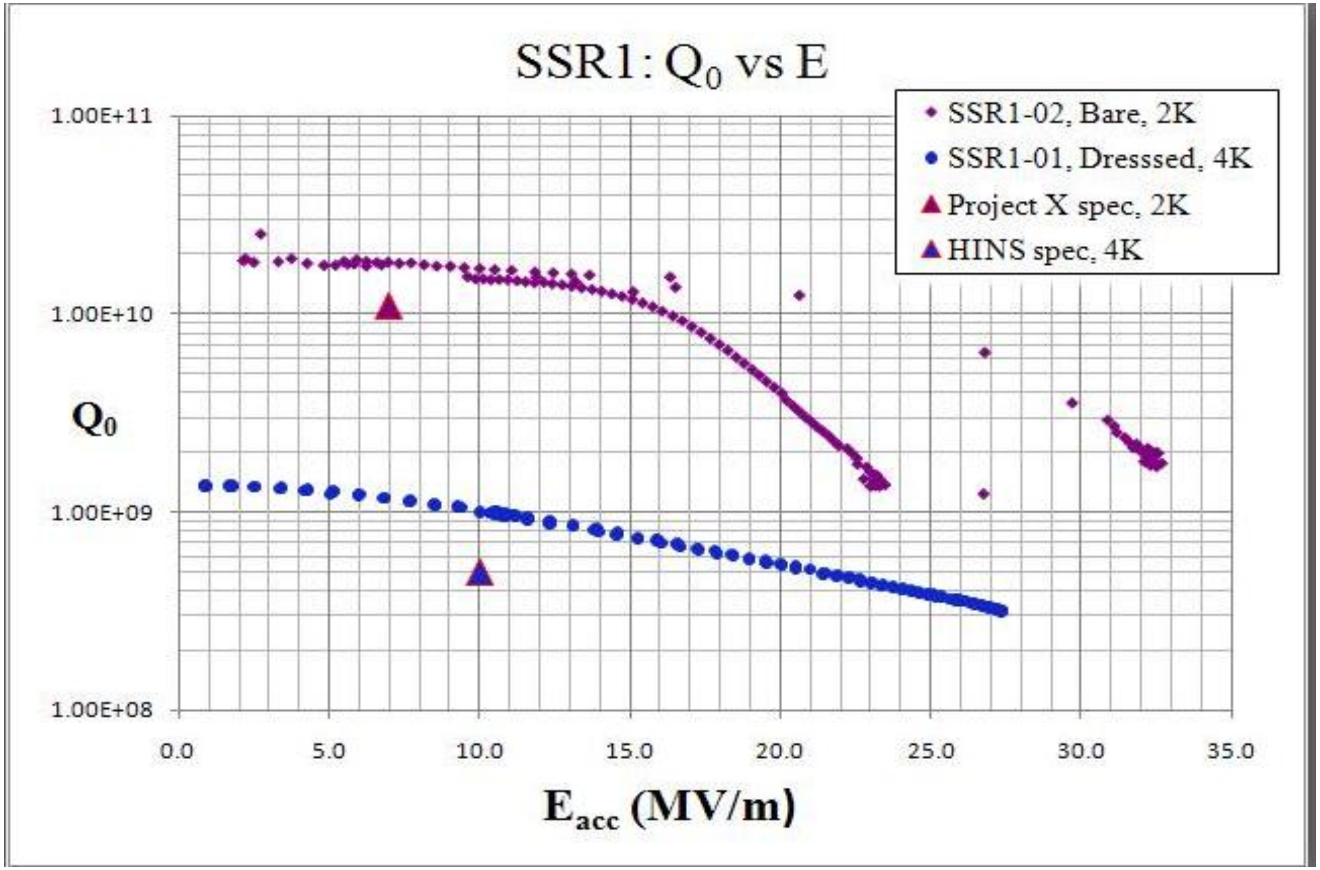




170 MHz HWR (M.P. Kelly et al, ANL)

Spoke cavity:

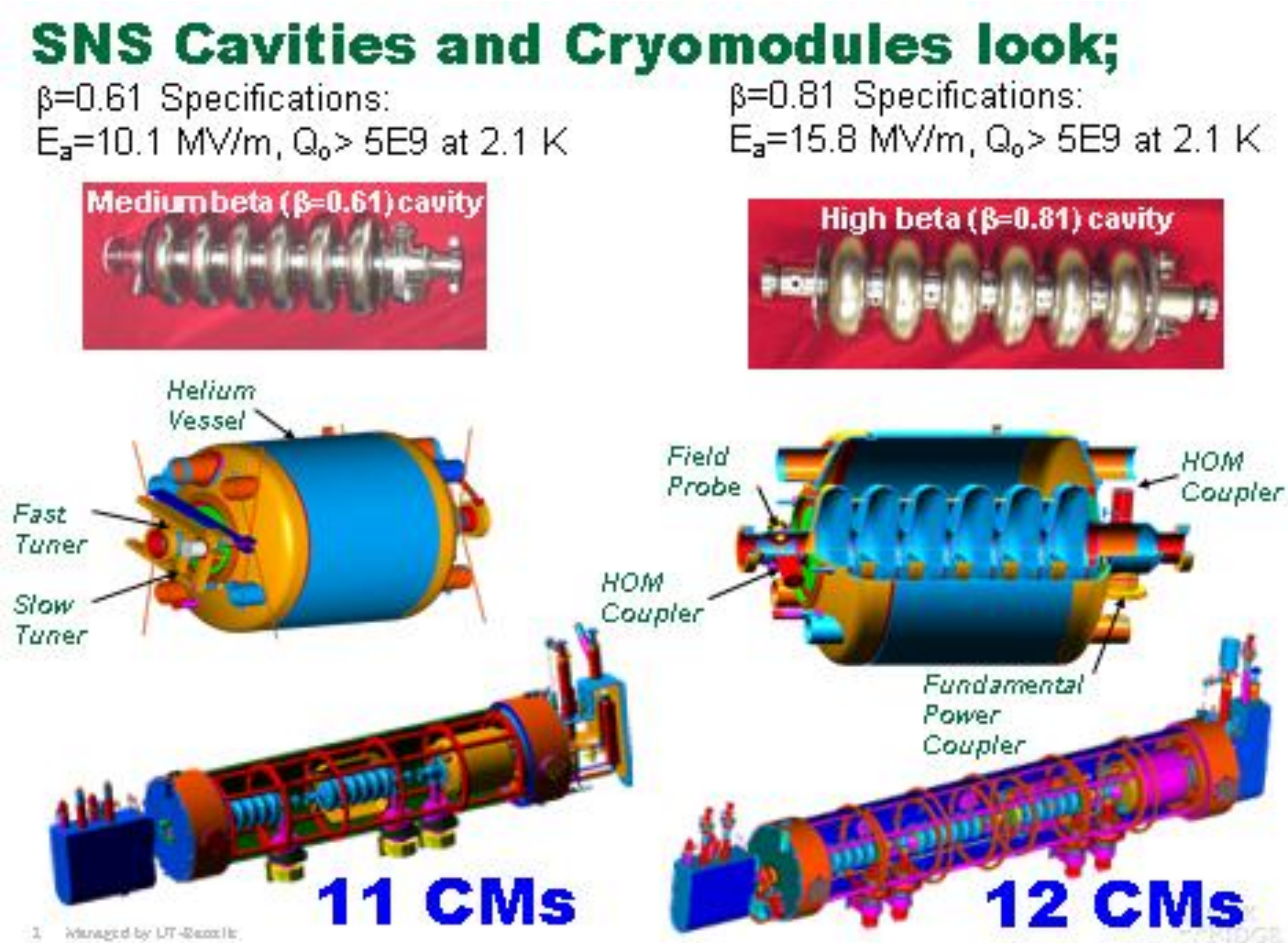
FNAL 325 MHz SSR1 cavity layout and photo.
β=0.22



- Two SSR1 spoke resonators performed well in vertical dewar tests at 2K; one of these was tested dressed at 4K.
- Proof of principle shown in plot: bare cavity exceeded Project X specification; dressed cavity at 4K exceeded the HINS specification.

C. Ginsburg

For beta>0.5 elliptical multi-cell cavities are used:



S-H Kim, SNS

Proton/ion beam focusing:

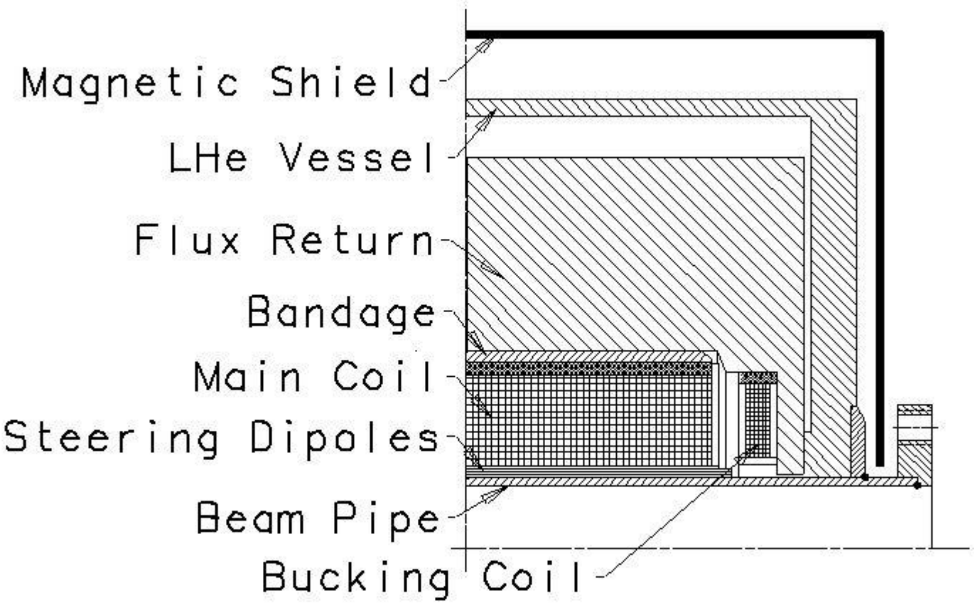
For small ion beam energy SC solenoid focusing is used:

- Simple and inexpensive;
- Modest fields (<6 T);
- $F \sim W^2/\int B^2 dz$ – quadratic.

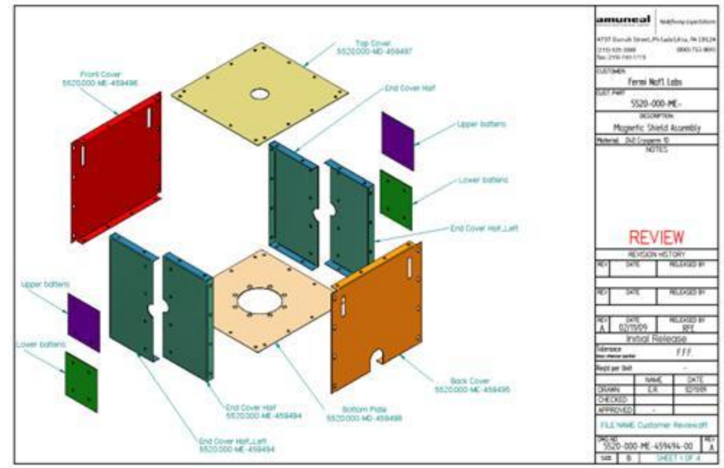
- Field shielding (<1 mT on the cavity surface);
- Alignment (typically <0.3- 0.5 mm, <5 mrad tilt);
- Fit the focusing period;
- Quench protection;
- Leads.

For high energy > 150-200 MeV –RT quads (SNS).

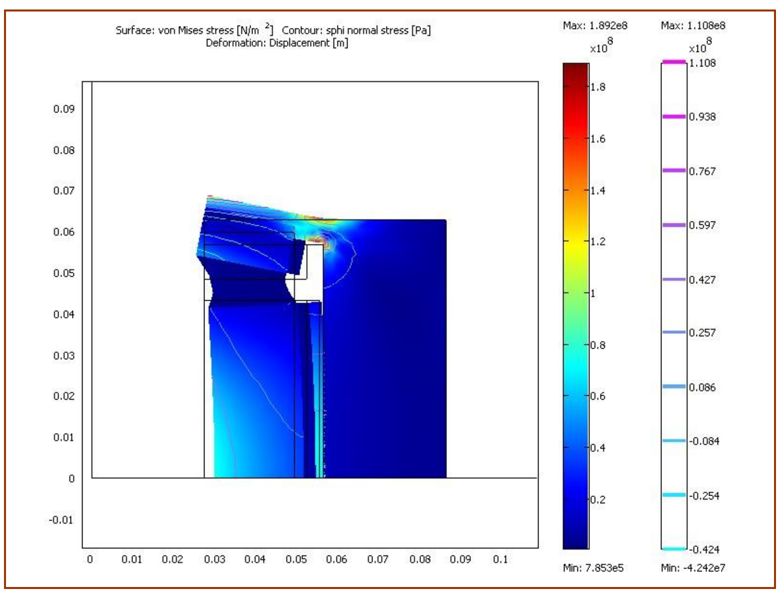
Main Design Features



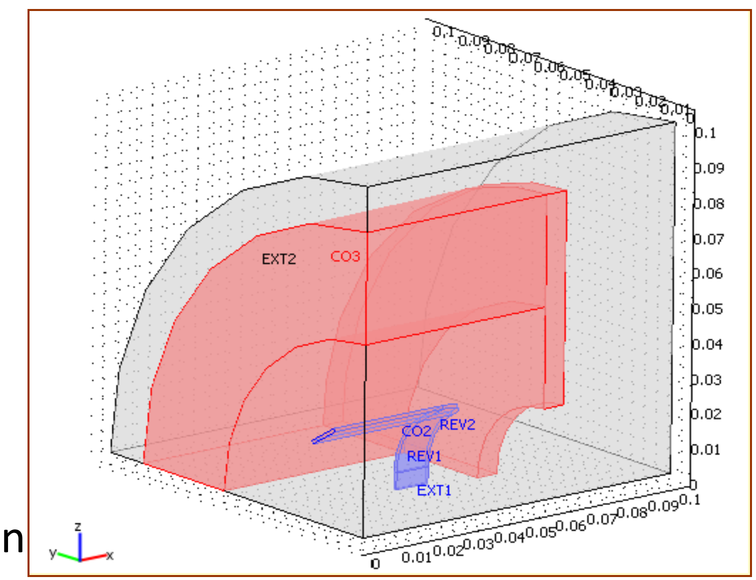
Magnetic shield



Internal Forces → Pre-stress is needed



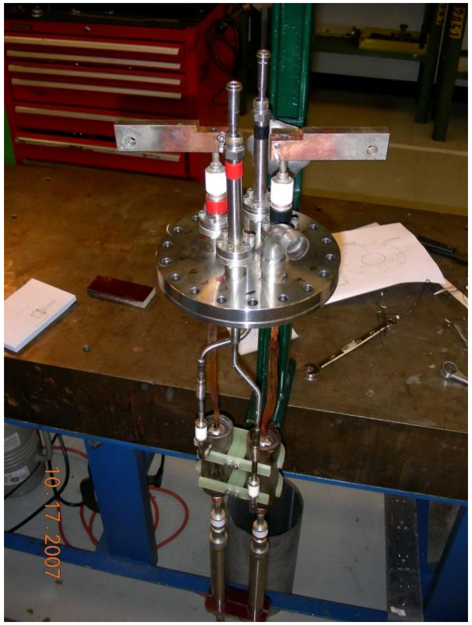
Steering dipole concept



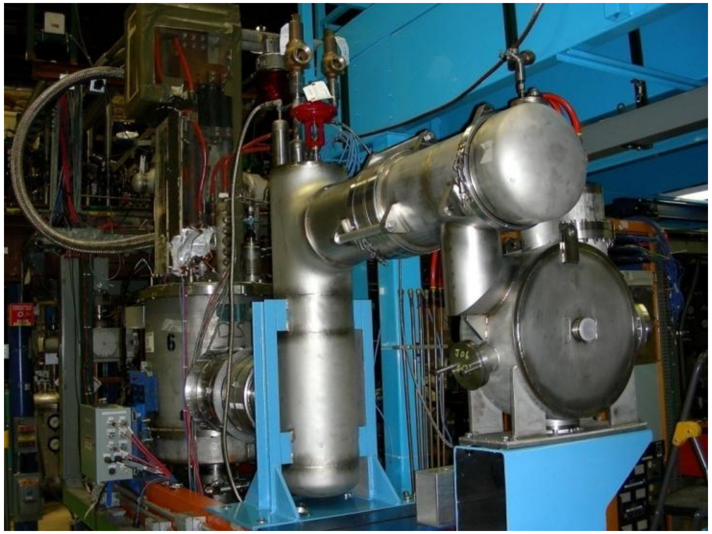
Yu. Tereshkin

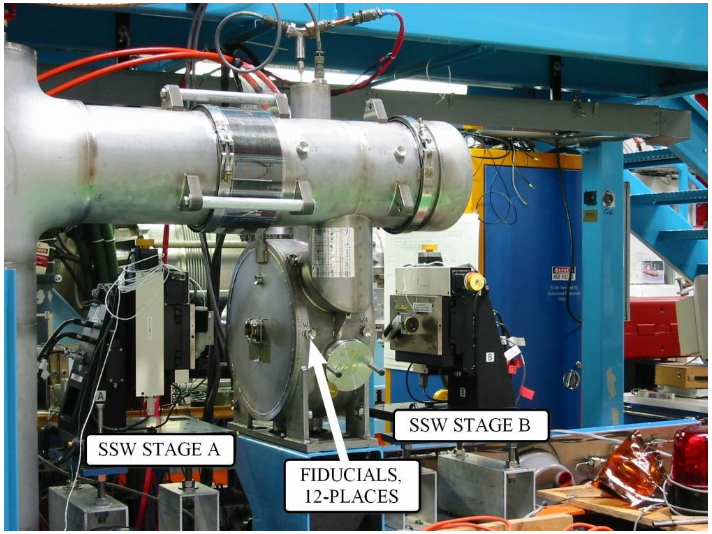
Lenses for the Room Temperature Section

Assembly



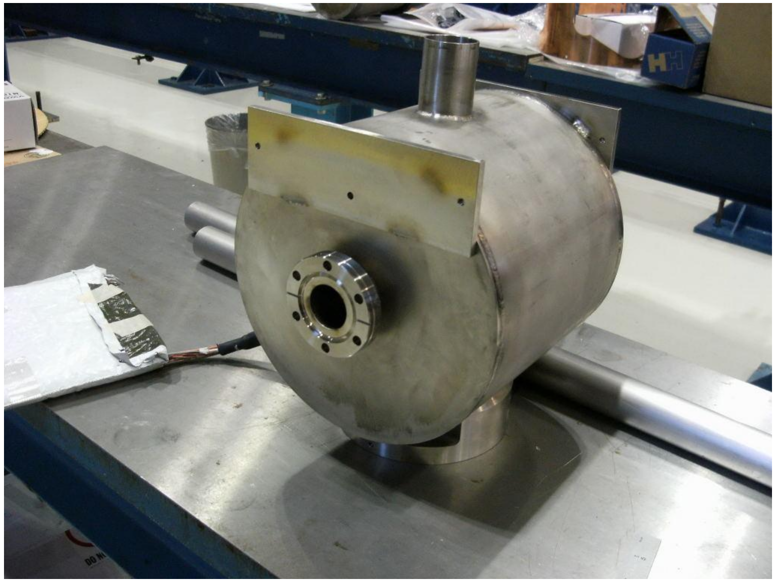
Testing



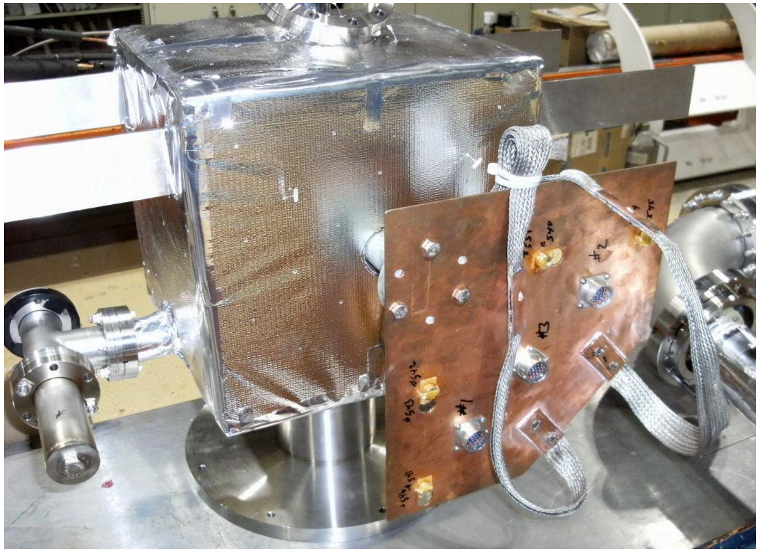


Lenses for the SSR1 Section

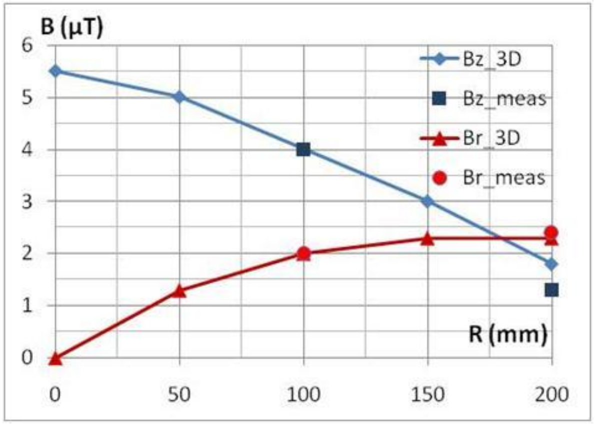
Cold mass assembled and tested



Prototype assembled for testing



Magnetic shielding R&D - completed

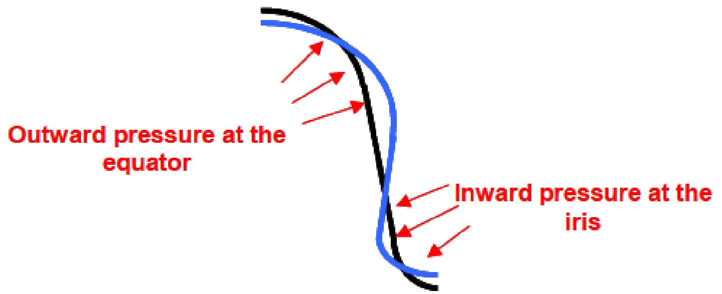


Low beam loading in SRF cavities:

•Lorentz detuning;
•Microphonics.

•$Q_{load} = U/(R/Q)/I_{beam}$ - very high for small beam current<1 mA, Q_{load} ~1e7-1e8;

•Cavity bandwidth: f/Q_{load} ~tens of Hz.



•Lorentz detuning – cavity detuning caused by the cavity wall deformation by ponderomotive forces of RF field (M.M. Karliner, 1968)
$\Delta f_{Lorentz} = k_L G^2$, k_L- Lorentz coefficient, G – acceleration gradient.
For SNS cavity k_L~ -3 Hz/(MeV/m)^2. For CW or for modest gradient (~15 MeV/m) and high beam current (~20-30 mA) not a problem.

•Microphonics – cavity resonance frequency changes caused by the cavity wall vibration. Main source of vibration – He pressure fluctuations δP.
$\Delta f_m = df/dP \times \delta P$, δP~0.05-0.1 mbar at 2 K. df/dP =130 Hz/mbar (ILC)

Power overhead caused by microphonics:

- Loaded Q:
  Q_{load} = U/(R/Q)/I_{beam} ;.
  Q_{load}(PX 650MHz)=**3.4e7**;

- Bandwidth Δf :
  Δf= f/Q;
  Δf(PX 650 MHz) = **19** Hz;

- Required power from RF source P_g for optimal coupling at r.m.s microphonic amplitude δf and the energy gain per cavity *V*:

$$P_g = \frac{V^2(1+\beta)^2}{4\beta Q_0(r/Q)}\left[\left(1+\frac{I_{\mathrm{Re}}(r/Q)Q_0}{V(1+\beta)}\right)^2+\left(\frac{Q_0}{1+\beta}\frac{2\delta f}{f}\right)^2\right]$$

$$\beta_{opt} = \left[\left(1+\frac{I_{\mathrm{Re}}(r/Q)Q_0}{V}\right)^2+\left(\frac{2\delta f Q_0}{f}\right)^2\right]^{1/2}$$

I_{Re} and I_{Im} are real and imaginary part of the current,
$I_{Re}=I_{beam}\cdot\cos(\varphi)$, φ - acceleration phase.

Example: for PX, I=1mA, V=17 MeV, $(r/Q)_{650}$=525 Ohm, acceleration phase of -15°.

Δf Hz	$6\cdot\Delta f$ Hz	Power overhead
1	6	1.15
2	12	1.38
3	18	1.64
4	24	1.92
5	30	2.21
6	36	2.50

Δf must me less than *1* Hz for ~15% power overhead!

How much detuning can we expect in realistic modules?

Machine	σ [Hz]	6σ [Hz]	Comments
CEBAF	2.5 (average)	15 (average)	significant fluctuation between cavities
ELBE	1 (average)	6 (average)	
SNS	1 to 6	6 to 36	significant fluctuation between cavities
TJNAF FEL	0.6 to 1.3	3.6 to 7.8	center cavities more quiet
TTF	2 to 7 (pulsed)	12 to 42 (pulsed)	significant fluctuation between cavities

J. Knobloch, 37th ICFA Advanced Beam Dynamics Workshop on Future Light Sources

Special efforts to reduce microphonics are necessary!

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.***

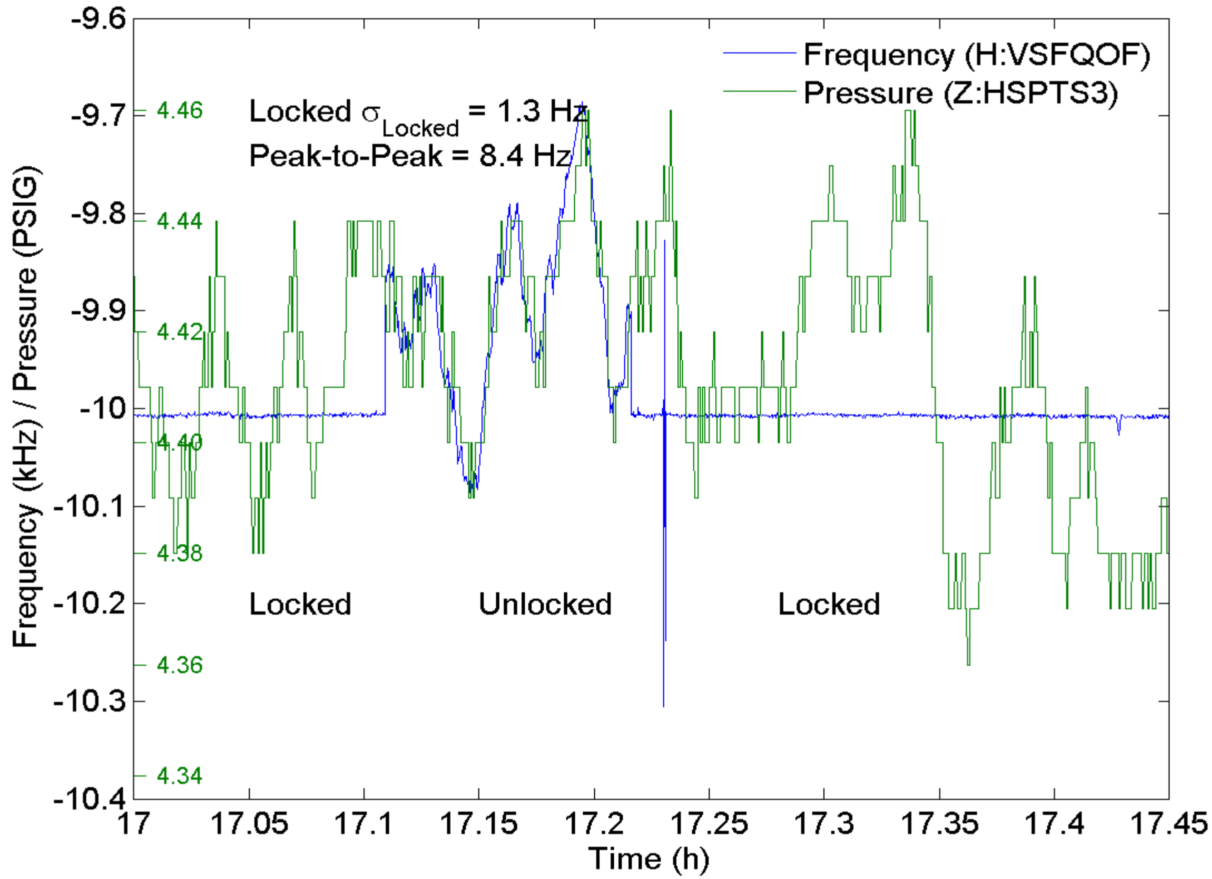
The optimal combination of measures may differ for different cavity types.

*ACTIVE MICROPHONICS COMPENSATION**

SSR1:

Test Conditions:

- 4.5K;
- Cavity bandwidth of about 1.5 Hz;
- df/dP = 140Hz/torr;
- dP_{PTP}~=5 torr
- LLRF tracking resonant frequency of cavity

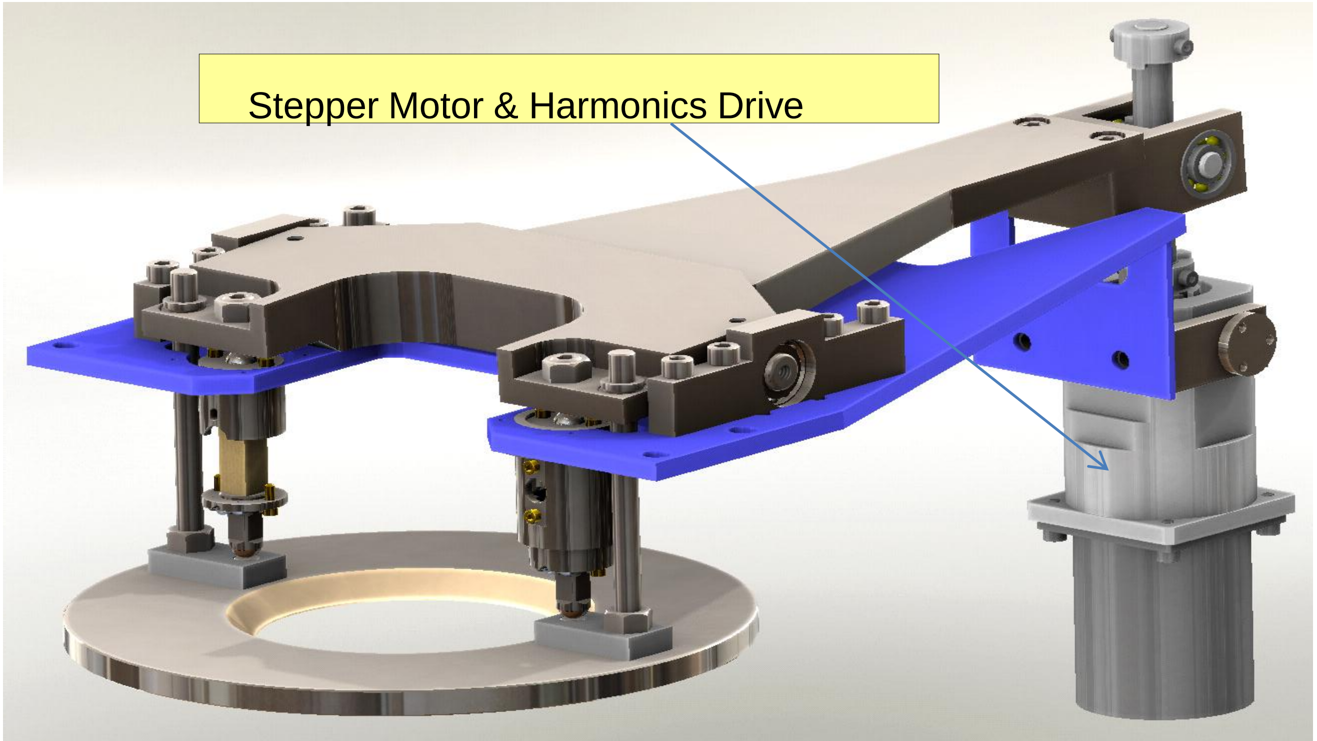


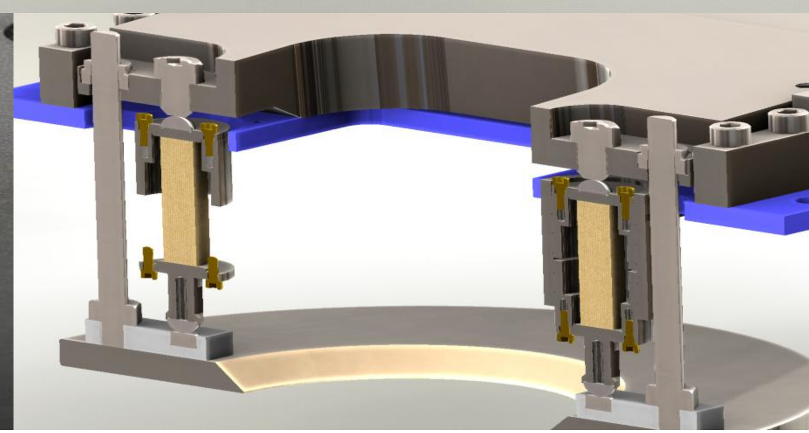
Reduced pressure related variations in cavity frequency from several hundreds Hz to

Δf <= 1.3 Hz RMS

W. Schappert, Yu. Pischalnikov

Slow and Fast Tuner Development





Encapsulated
Piezo assembly

- SRF for hadron linear accelerators has a long and successful history,
- SRF for hadron linear accelerators has successful present and future.

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