SRF Linac Technology Development at Fermilab:

New requirements, challenges and perspectives

Vyacheslav Yakovlev (FNAL)
XXVI Linear Accelerator Conference
September 9, 2012

U.S. DEPARTMENT OF ENERGY

Fermilab

Outlook

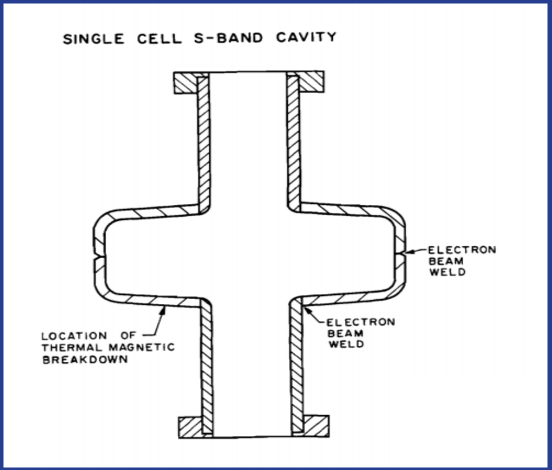
The application of SRF technology to electron and hadron linacs has a long and successful history;

50 –years anniversary, 1962-2012

1961: The first suggestion to apply SC principles to proton accelerator design, A. P. Banford and G. H. Stafford

1962: First measurements of superconducting cavity performance, Stanford High Energy Physics Laboratory (HEPL):

Lead-plated S-band 2856 MHz muffin tin cavities Q_o ~ 1e8-1e9, Bpeak ~ 10 mT



Recently SRF is a well-established technology.

Recent applications of SRF linacs (operating facilities and projects):

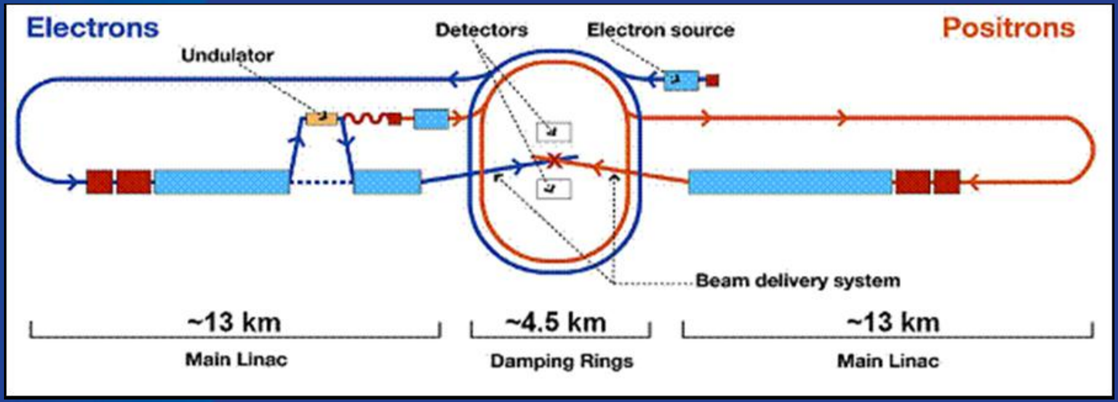
- High Energy Physics,
  - high-energy frontier (SPL***, ILC***),
  - high-intensity frontier (Project-X***);
- X-Ray Light Sources (XFEL**, NGLS***, ERLs***) ;
- Neutron spallation sources (SNS*, ESS***);
- Nuclear Physics, Neutrino physics, Rare Isotope Accelerators (ATLAS*,CEBAF*, FRIB**, SARAF**, ISAC-II*, Spiral-II**, HIE-ISOLDE****, JPARC****, KoRIA***, etc);
- ADS (MYRRHA***, India***, China***).

* in operation;
** under construction;
*** project;
**** facility upgrade using SRF technology.

- Progress in SRF technology is caused in high degree by the development of the ILC project:

- Pulse regime with low duty factor (0.5%):
- -considerably low RF load – Q_0 is not a main issue.
- -Lorentz detuning is an issue.
- Pulse current ~9 mA:
- -microphonics are not a big problem.
- High acceleration gradient is a primary concern (E_{acc} = 35 MeV/m):
- -quench;
- -filed emission;
- -manufacturing yield.

ILC – quest to high gradients.



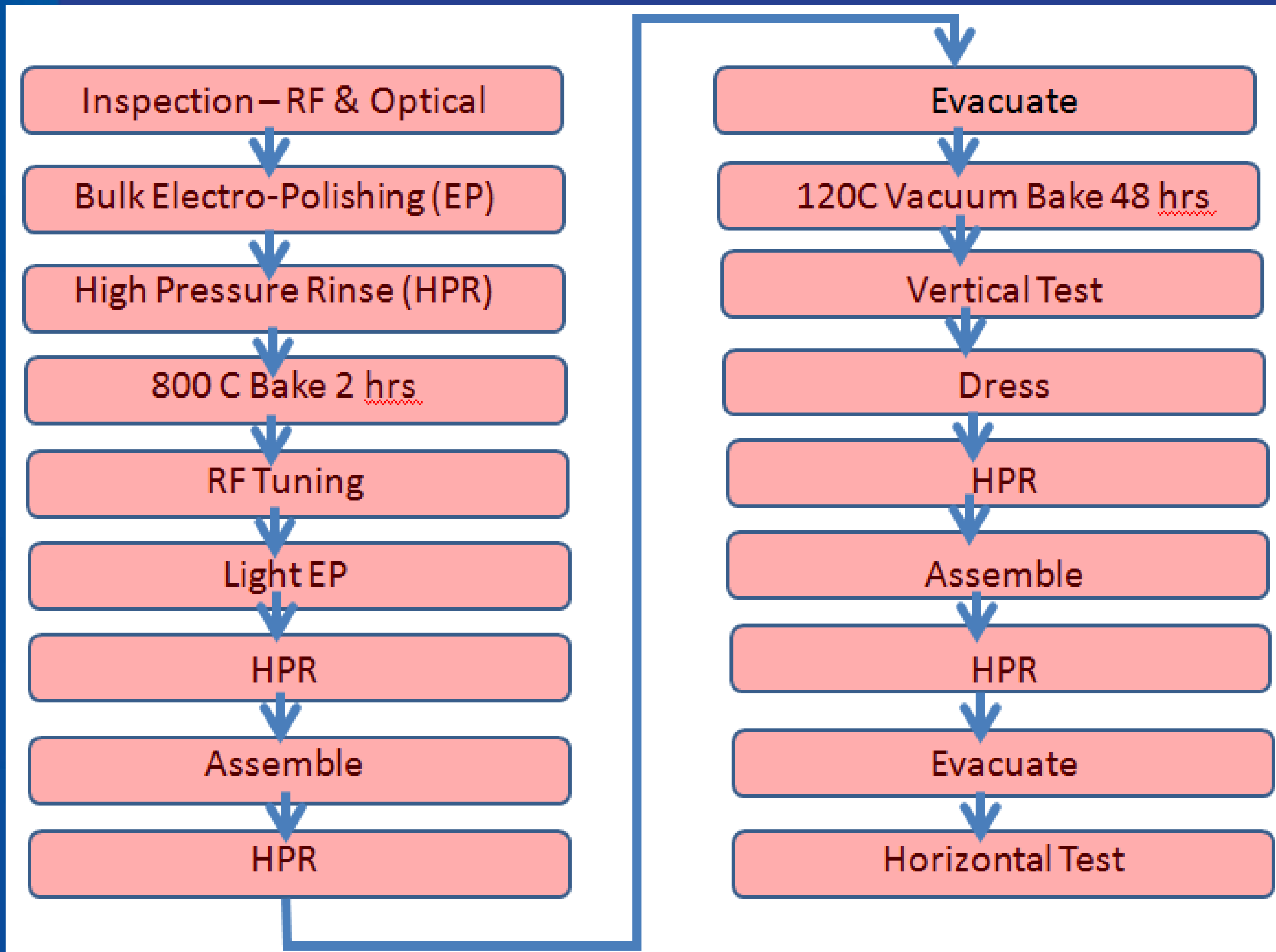
2007 ILC reference design

~16000 cavities!

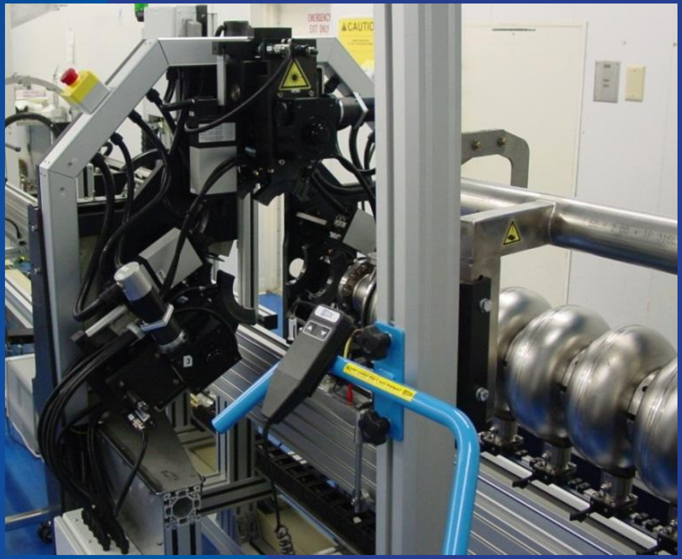
TESLA-type cavity:
-1.3 GHz;
-9 cells;
-35 MeV/m.

ILC: breakthrough to high gradients:
- electro-polishing;
- 120° C baking.

ILC Cavity Processing Basic Recipe:

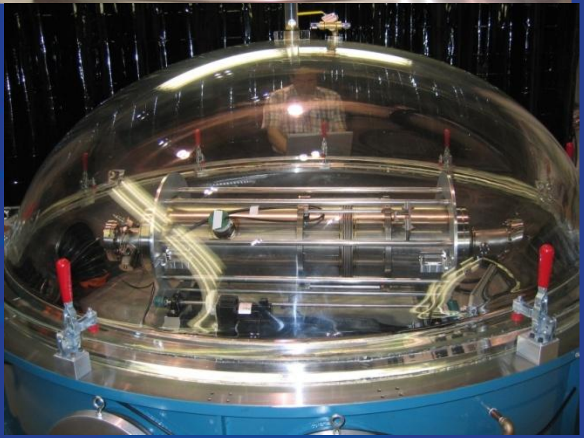


FNAL 1.3 GHz EP Tool.

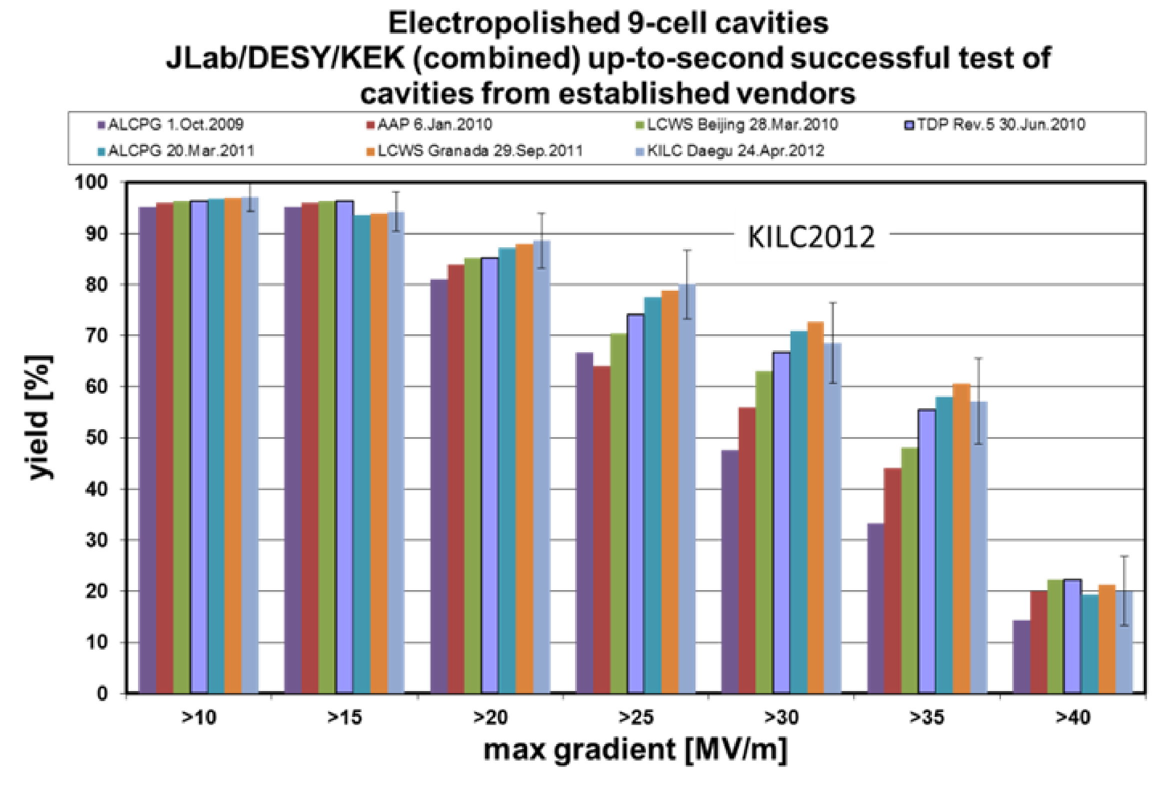


FNAL HPR Tool with 1.3 GHz 9-cell

ILC Cryo-module assembly (FNAL):



ILC gradient yield.
ILC cavities reach 35 MV/m more than half the time after one or two processing cycles



C.M. Ginsburg (FNAL), et al. 24.Apr.2012

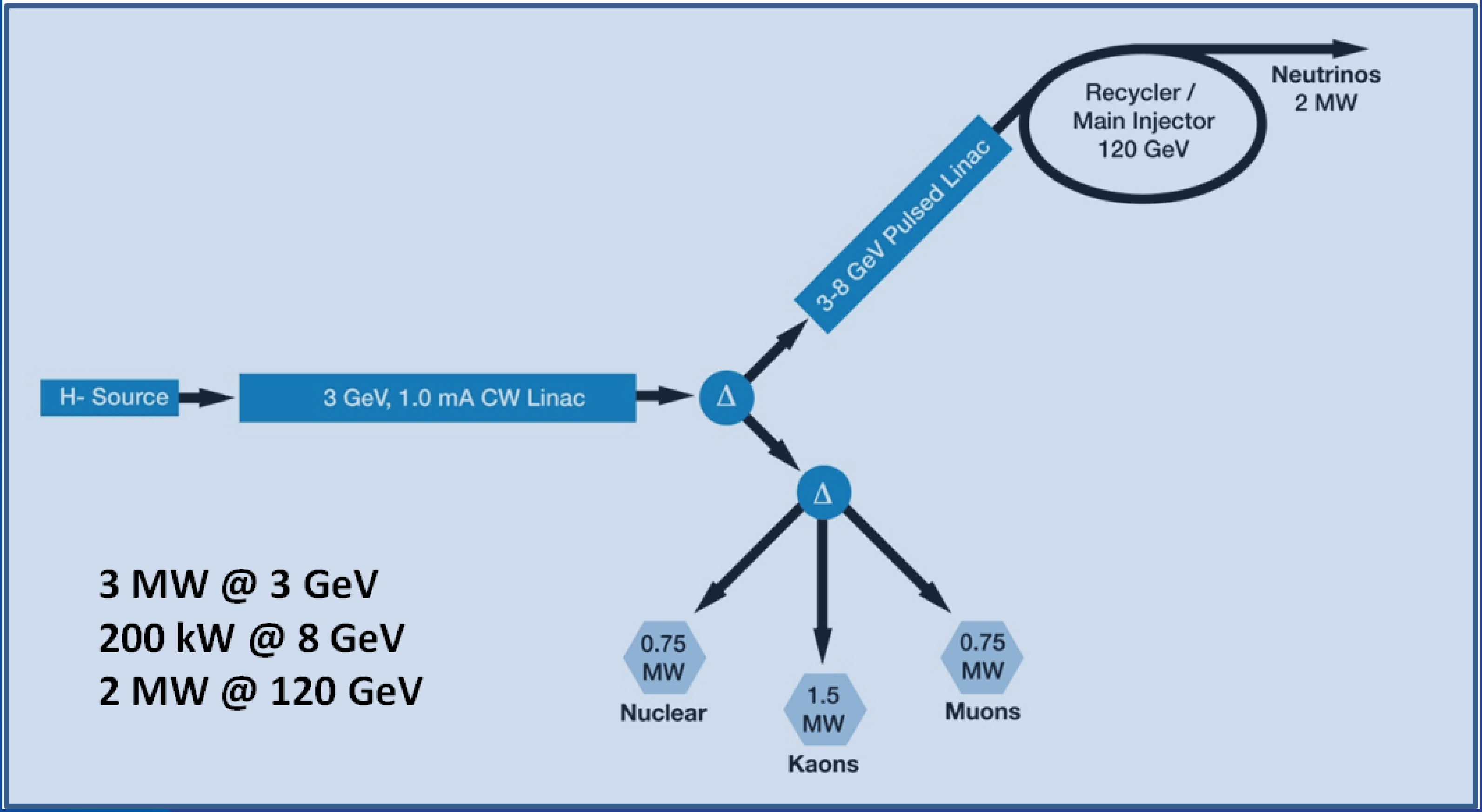
Good progress, good achievements!

New projects of CW SC accelerators:

Project X: Multi-experimental accelerator facility:

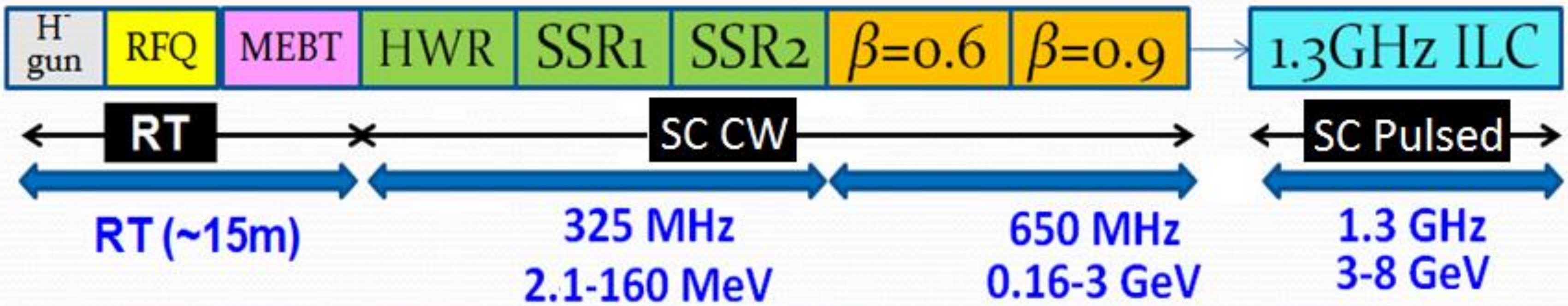
- 1-2 mA H^-
- 2.1 MeV-160 MeV: 162.5 MHz Half – Wave and 325 MHz spoke resonators;
- 160 MeV -3GeV: 650 MHz elliptical cavities (β=0.61 and β=0.9) ;
- 3-8 GeV: 1.3 GHz ILC-type cavity, pulsed (up to 30 msec).

Project X multi-experiment facility:



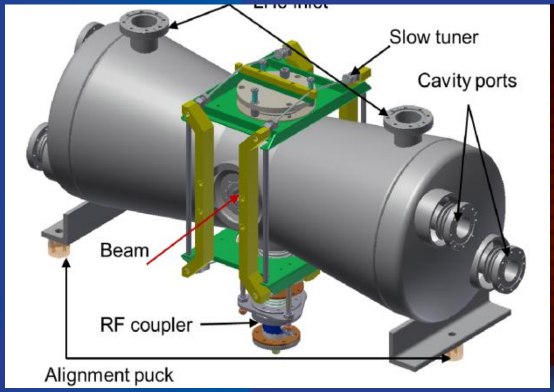
- 3-GeV, 1-mA CW linac provides beam for rare processes program ~3 MW;
- flexible provision for beam requirements supporting multiple users;
- <5% of beam is sent to the Main Injector.

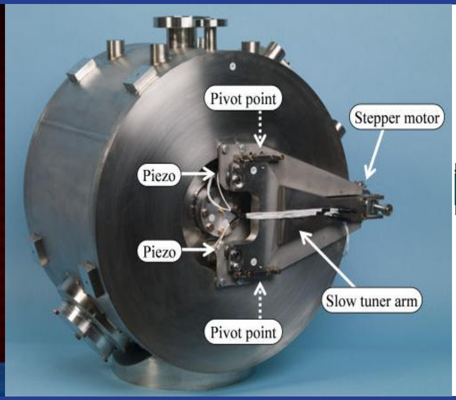
Concepts of SC CW 3GeV and Pulsed 3-8 GeV Linac

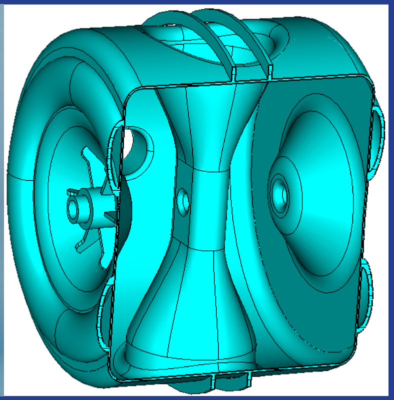


Section	**Freq, MHz**	**Energy(MeV)**	**Cav/mag/CM**	**Type**
HWR (β_G=0.11)	162.5	2.1-10	8 /8/1	HWR, solenoid, 5.26m
SSR1 (β_G=0.22)	325	10-32	16 /8/ 2	SSR, solenoid, 4.76m
SSR2 (β_G=0.47)	325	32-160	36 /20/ 4	SSR, solenoid, 7.77m
LB 650 (β_G=0.61)	650	160-520	42 /14/ 7	5-cell ellip, doublet, 7.1m
HB 650 (β_G=0.9)	650	520-3000	152 / 19 / 19	5-cell ellipt, doubl, 11.2m
ILC 1.3 (β_G=1.0)	1300	3000-8000	224 / 28/ 28	9-cell ellipt., quad, 12.6m

RF Cavities of the Project-X linac:







HWR model, 162.5 MHz (ANL)

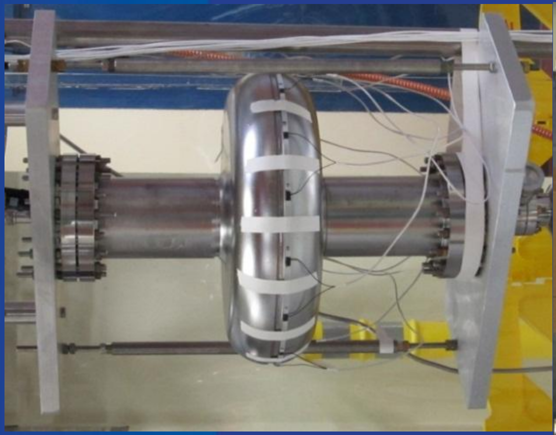
SSR1 photos, 325 MHz (FNAL)

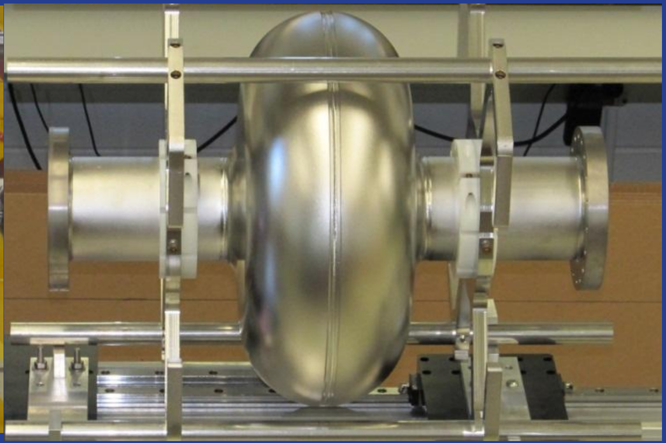
SSR2 model, 325 MHz (FNAL)

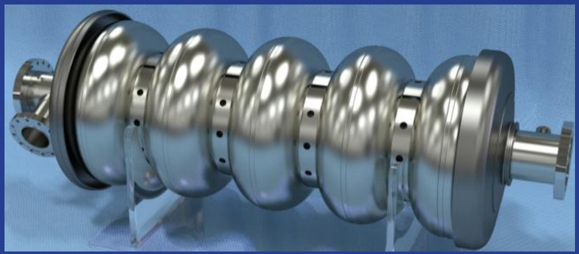
cavity type	β_{geom}	Freq MHz	Beam pipe ø, mm	$V_{acc,\ max}$ MeV	E_{peak} MV/m	B_{peak} mT	R/Q, Ω	G, Ω
HWR	β=0.113	162.5	33	1.8	40	62	225	47.7
SSR1	β=0.215	325	30	1.95	28	70	242	84
SSR2	β=0.47	325	40	3.34	32	60	292	109

HWR and spoke cavities of the Project X front end

Elliptical cavities of the high-energy part of CW linac







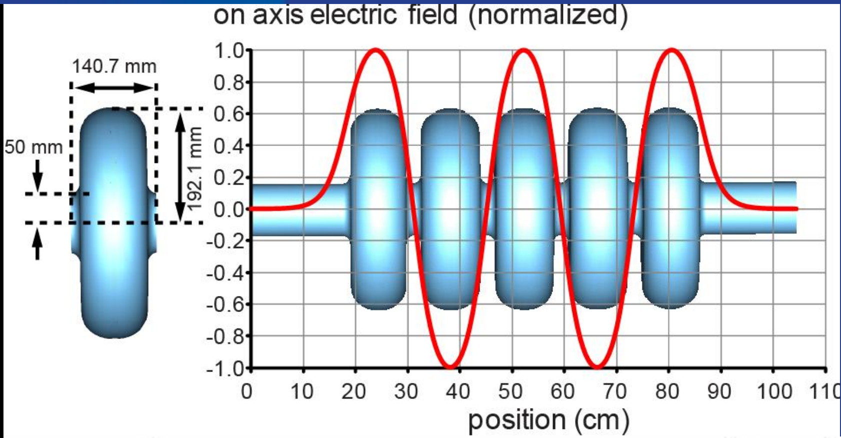
Single-cell prototypes (photos):

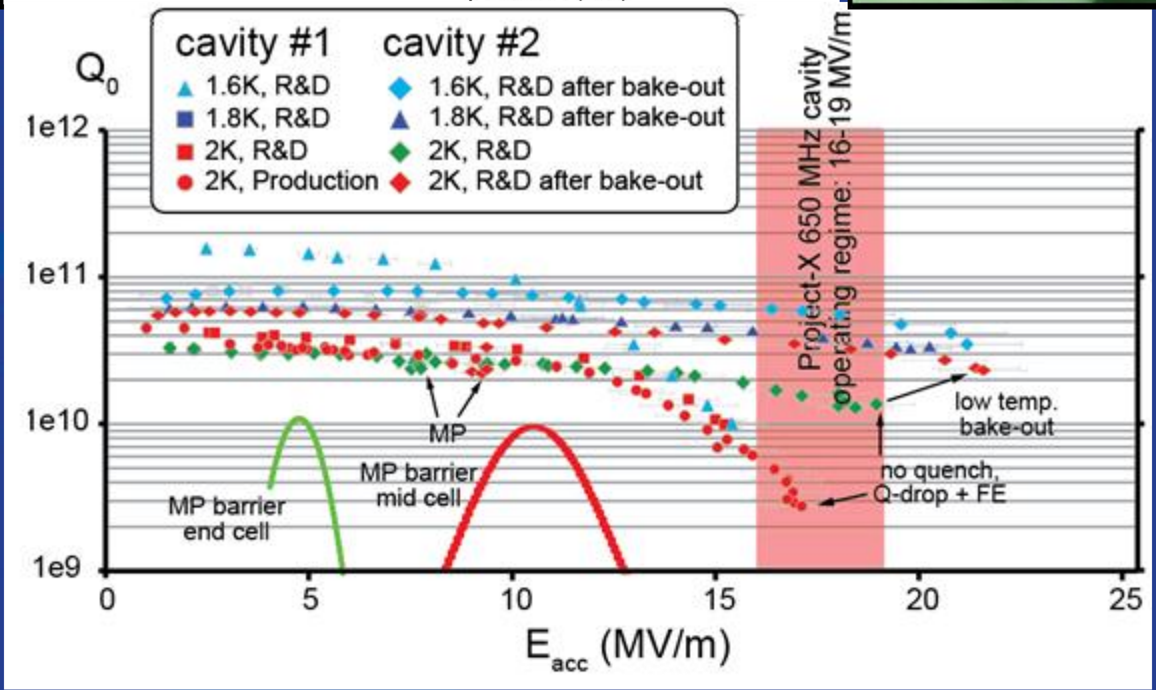
LE 650 MHz (JLAB version) HE 650 MHz (FNAL)

5-cell model, HE650

Parameter		LE650 (FNAL)	HE650(FNAL)
β_{geom}		0.61	0.9
Cavity Length = $n_{cell} \cdot \beta_{geom} \lambda/2$	mm	703	1038
R/Q	Ohm	378	638
G-factor	Ohm	191	255
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	$\times 10^{10}$	1.5	2.0
P_{2K} max	[W]	24	24

JLAB version of the 650 MHz, beta=0.61 cavity for the Project X*





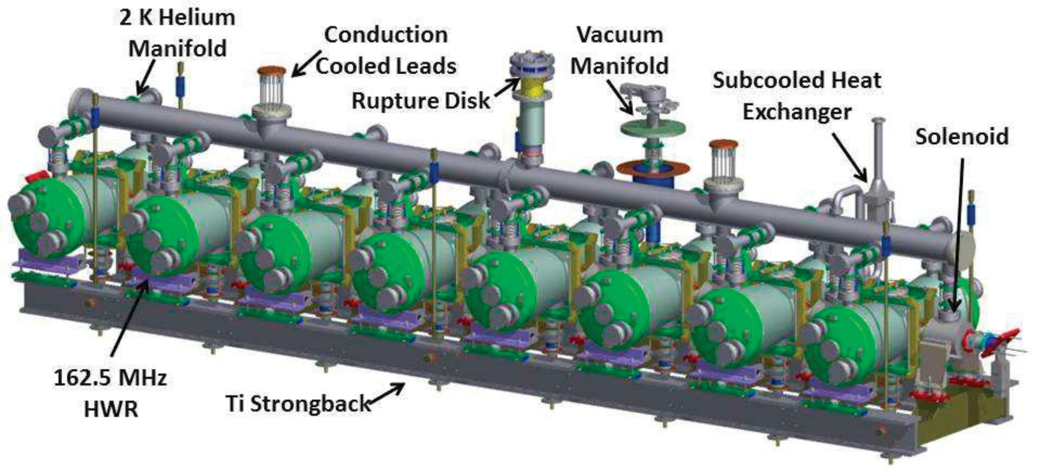
For the cavity #2

Q_0 >2e10 @17MeV/m

*F. Marhauser, et al, IPAC 2011

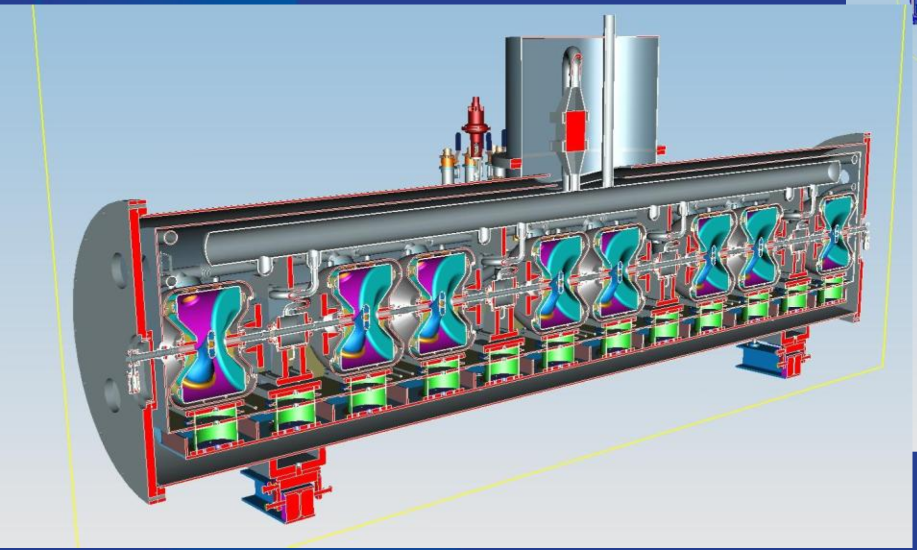
CM designs for Project X CW linac:

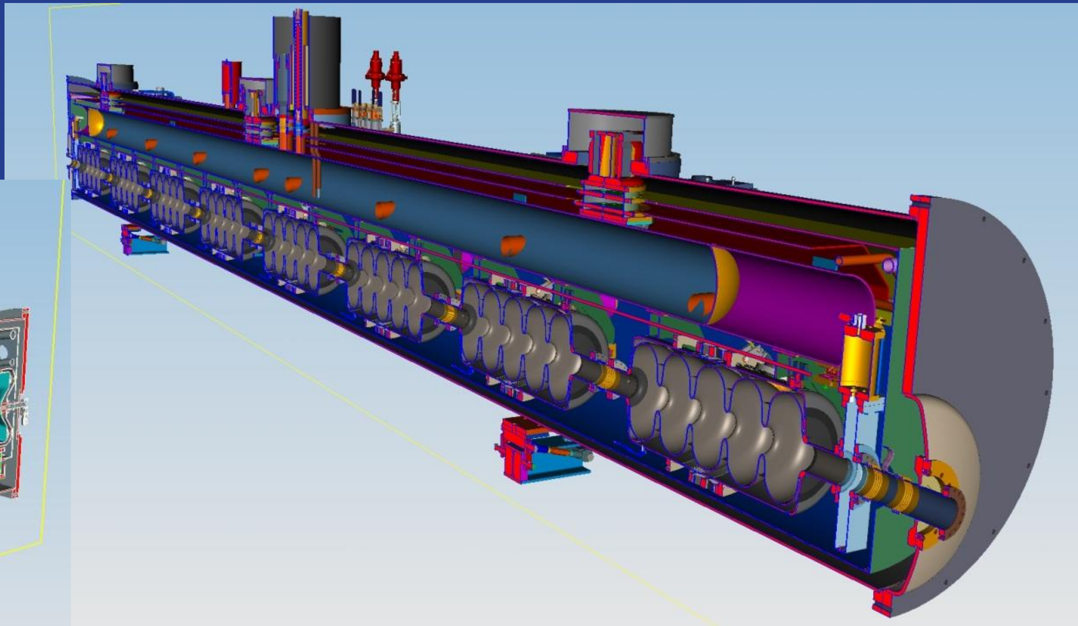
HWR (ANL)



HE650 (FNAL)

SSR1 (FNAL)





CW Operation

RF load:

- ILC: <5 W/cryo-module (0.5 % duty cycle, E_{acc} = 35 MeV/m);
- Project X: ~200 W/cryo-module (100% duty cycle, E_{acc} = 17 MeV/m).
- **For CW operation very high gradient is not an issue.**
- **The issue for CW is high RF load.**

High Q_0 is necessary!

RF load at CW regime determines the power consumption of a cryogenic system and thus:

- Capital cost of the cryogenic system, and thus, project;
  - cost of a cryogenic system ~ (RF load)$^{0.6}$ ~ $Q_0^{-0.6}$ (for fixed gradient – for big projects, LHC experience);
  - cost of the cryogenic system is a significant part of the project cost , ~10%.

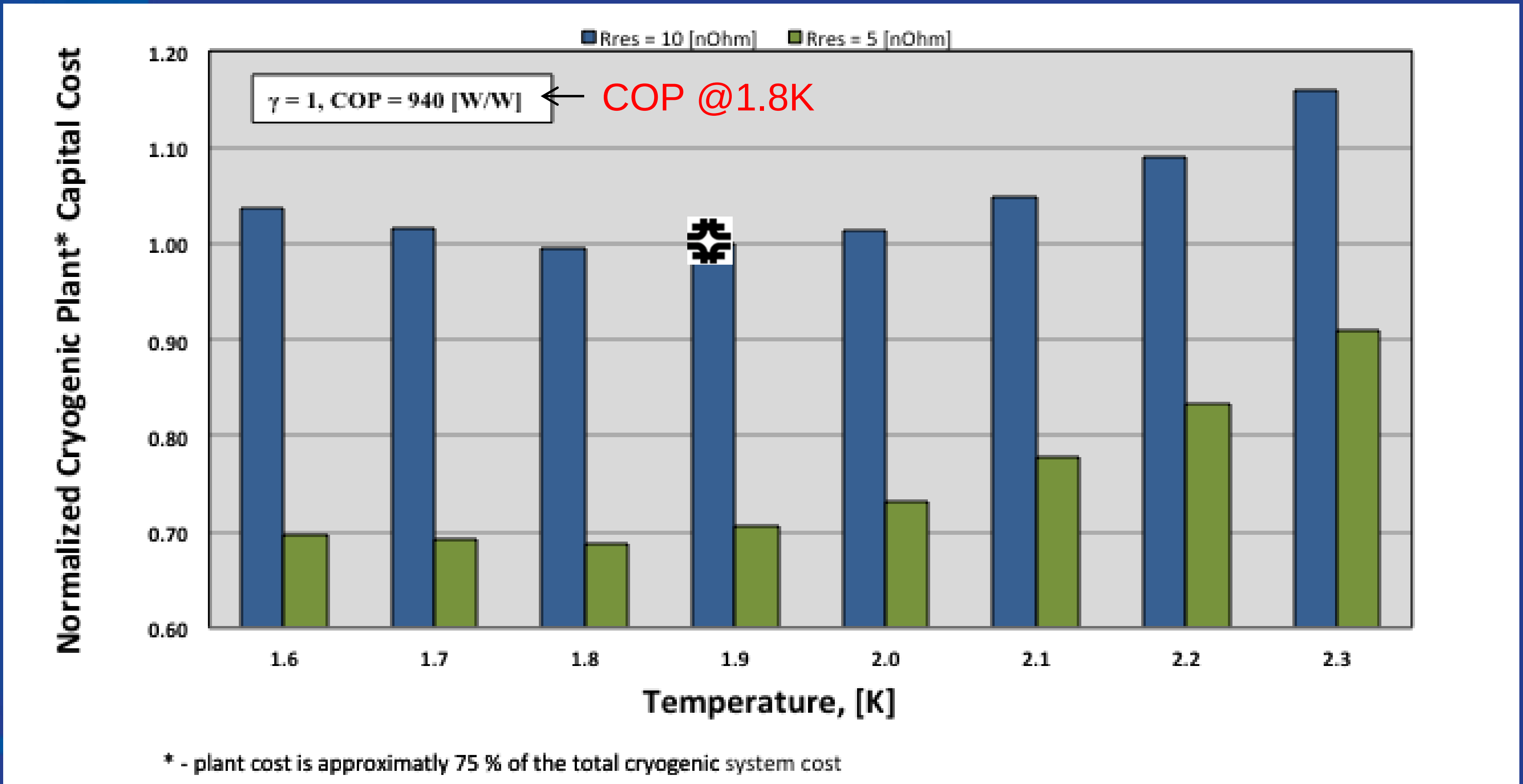
- Operational cost ~ RF load ~ Q_0^{-1} .

- High Q_0 allows higher gradient at CW and, thus, allows lower capital cost of the linac.

- Increase of Q_0 two times may save many tens of M$ for a billion- scale project.

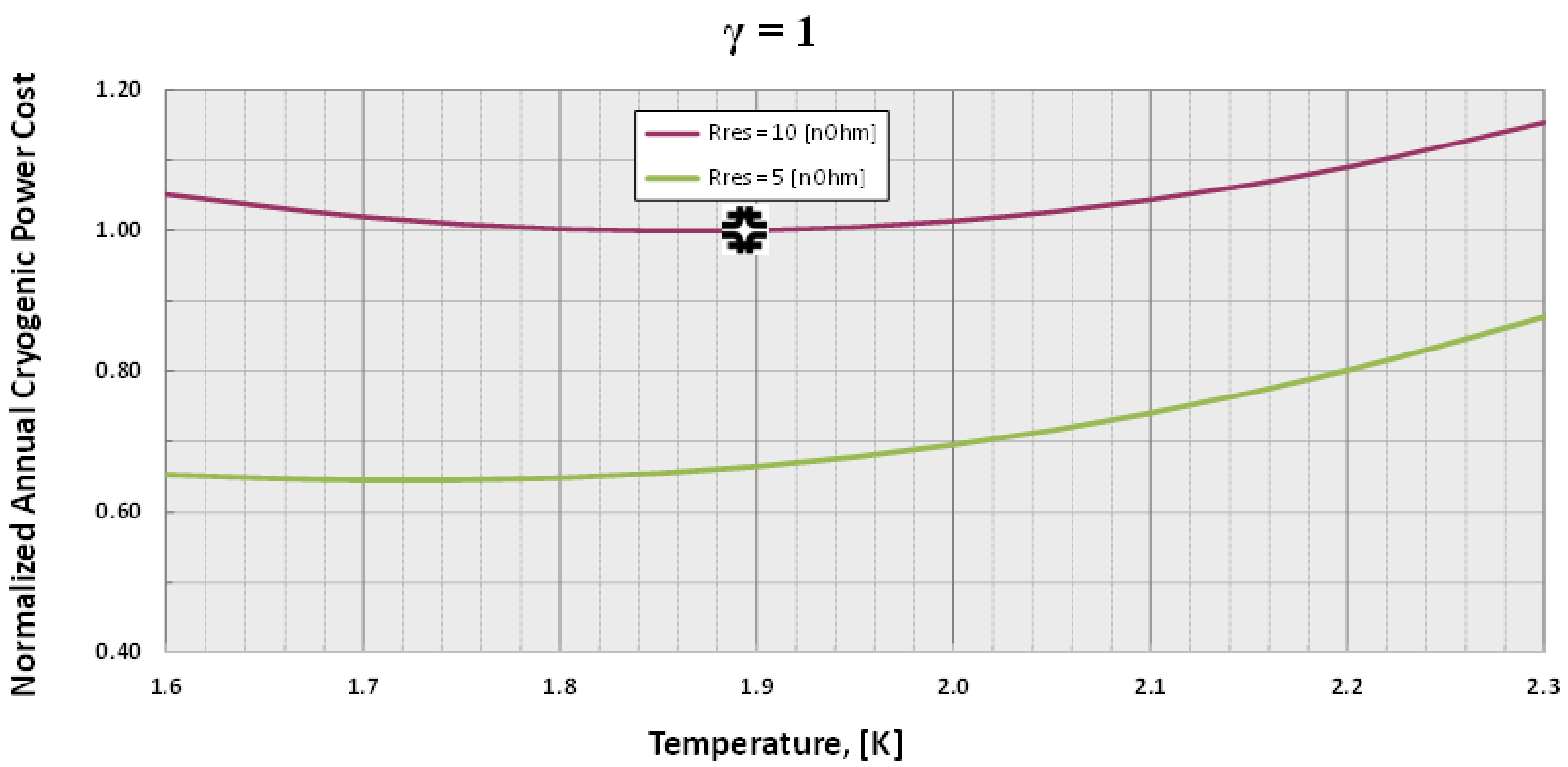
Cryogenic Plant of the Project X

- $Q_0 \Rightarrow R_{surface} \Rightarrow R_{res}$ (residual resistance)
- Medium field Q-slope (described by γ, J. Halbritter's model)
- Cryogenic efficiency, a.k.a. coefficient of performance (COP)



A. Klebaner

Annual Operating Cost for the Project X

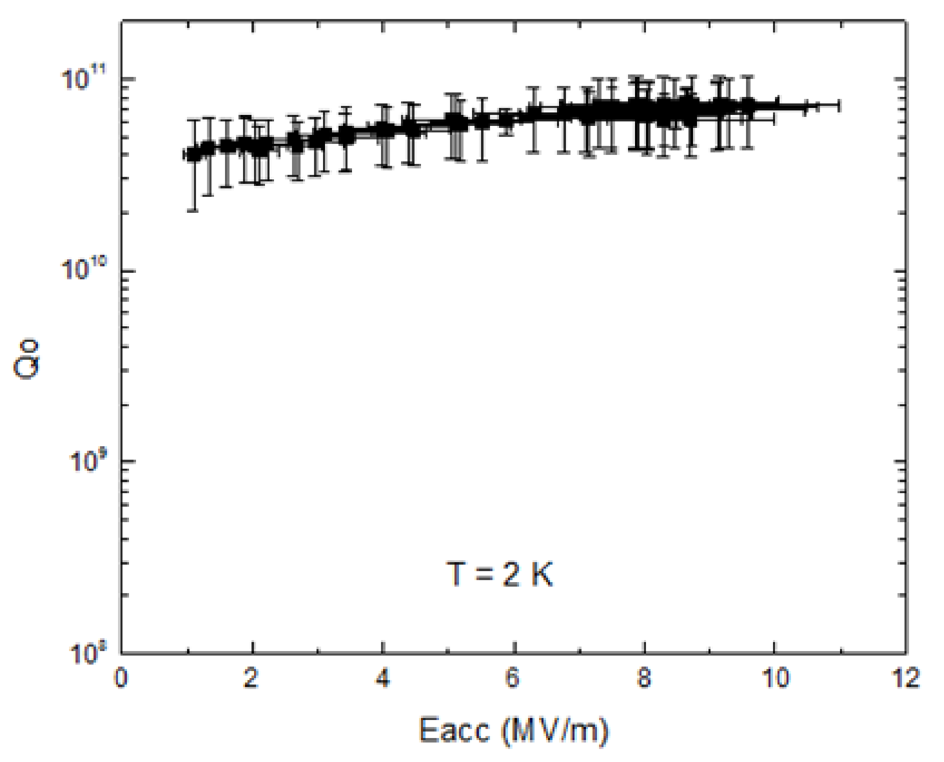


A. Klebaner

Different approaches to improve Q_0:

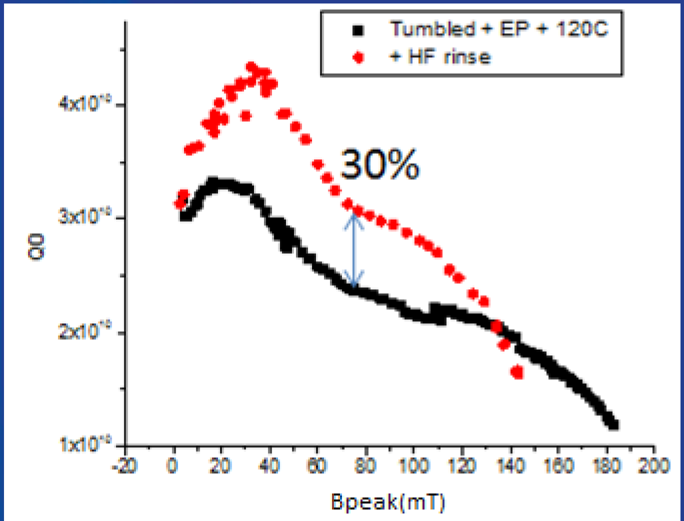
NbN (A. Grassellino, Fermilab)

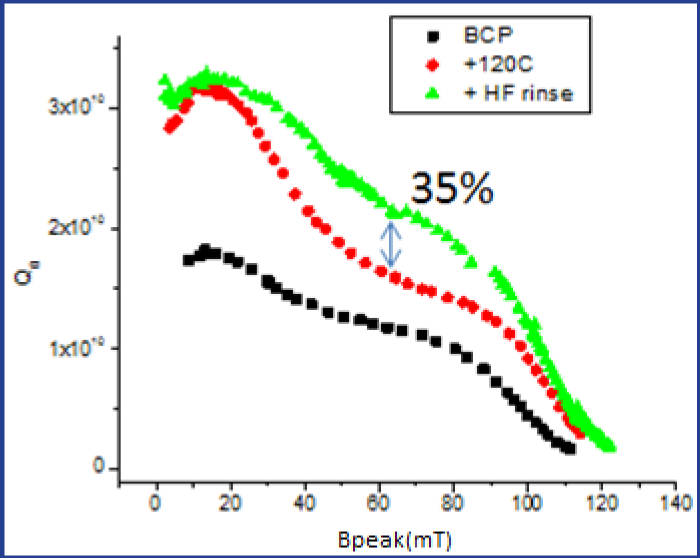
- NbN: superconductor with higher Tc (~16K, compared to 9.2K for Nb);
- Potential for lower surface resistance than Nb;
- Material made via bulk diffusion: simple and inexpensive modification to standard Nb treatments. Large grain Nb is used;
- First result at FNAL: world record Q ~ 7.5e10 at 2K and 10MV/m for a 1.3GHz single cell E_{acc} for a 1.3GHz single cell, residual resistance <0.5 nOhm!

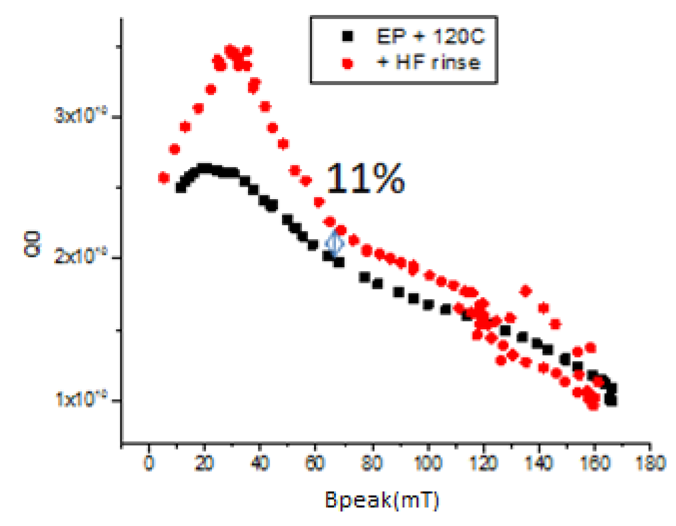


A. Grassellino, LINAC 2012

HF rinse for high Q: Simple higher Q_0 recipe



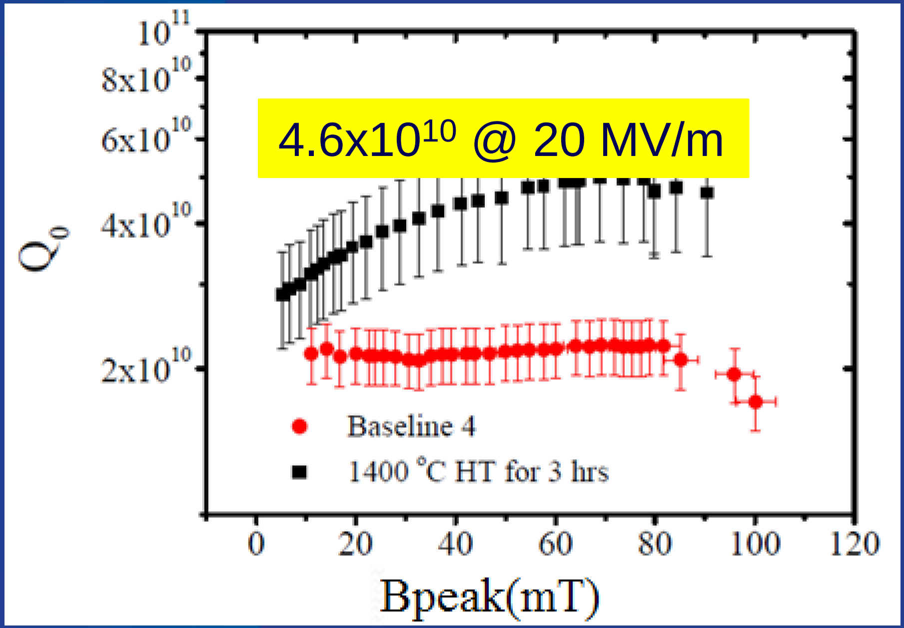




- Single HF rinse (5 min) followed by water rinse is beneficial for the medium field Q value – gains of up to 35% measured at 70 mT
- f=1.3 GHz;
- Bpeak/Eacc=4.26 mT/MeV/m

A. Romanenko, Fermilab APT Seminar, 2012, also TTC Meeting'2011

Jlab 1400C RF Test



- f=1.3 GHz;
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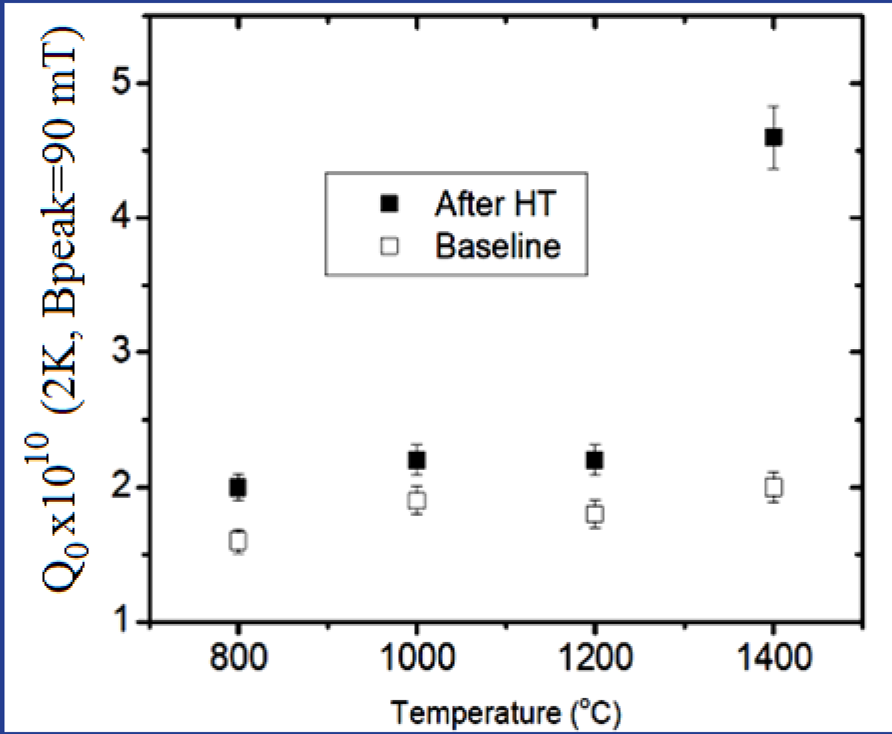
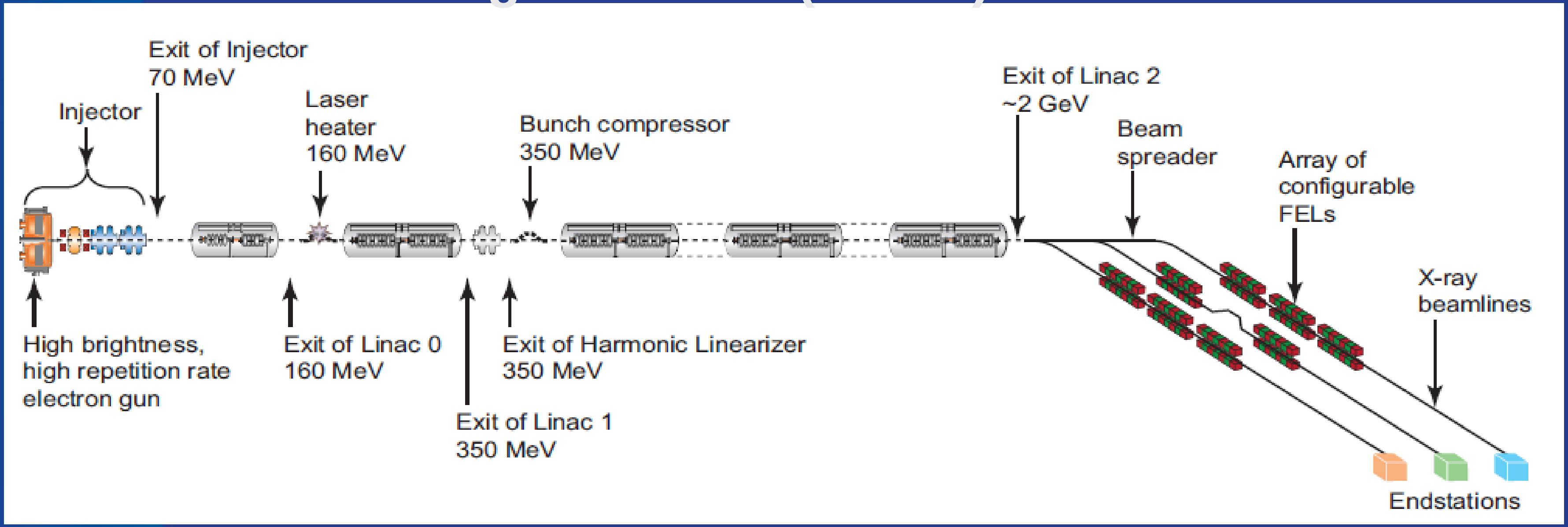


Dhakal et al, IPAC 12, WEPPC091

CEBAF upgrade standard process average Q_0(2K, 70 mT= 1.2±0.7x10^{10}

New projects of CW linacs:

- **Next Generation Light Source (NGLS)*:**

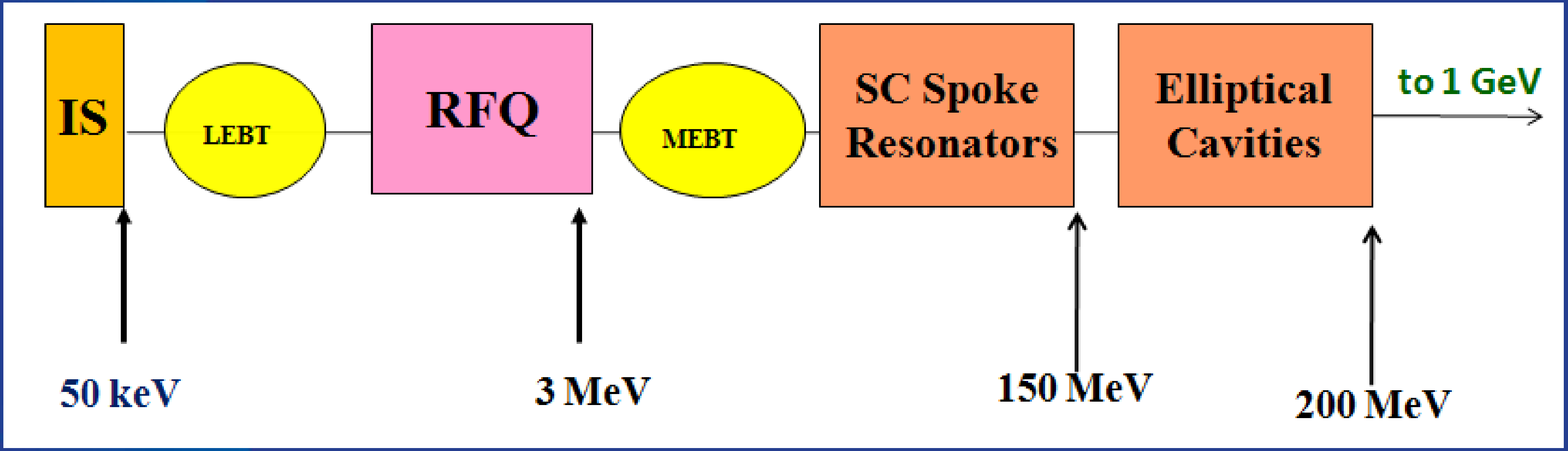


Energy, GeV	~2
Operation mode	CW
Average current, mA	0.3-1
Bunch rep. rate, MHz	1
Bunch population, nC	0.3-1

*J.N. Corlett, LINAC 2012

SRF Accelerator for Indian ADS

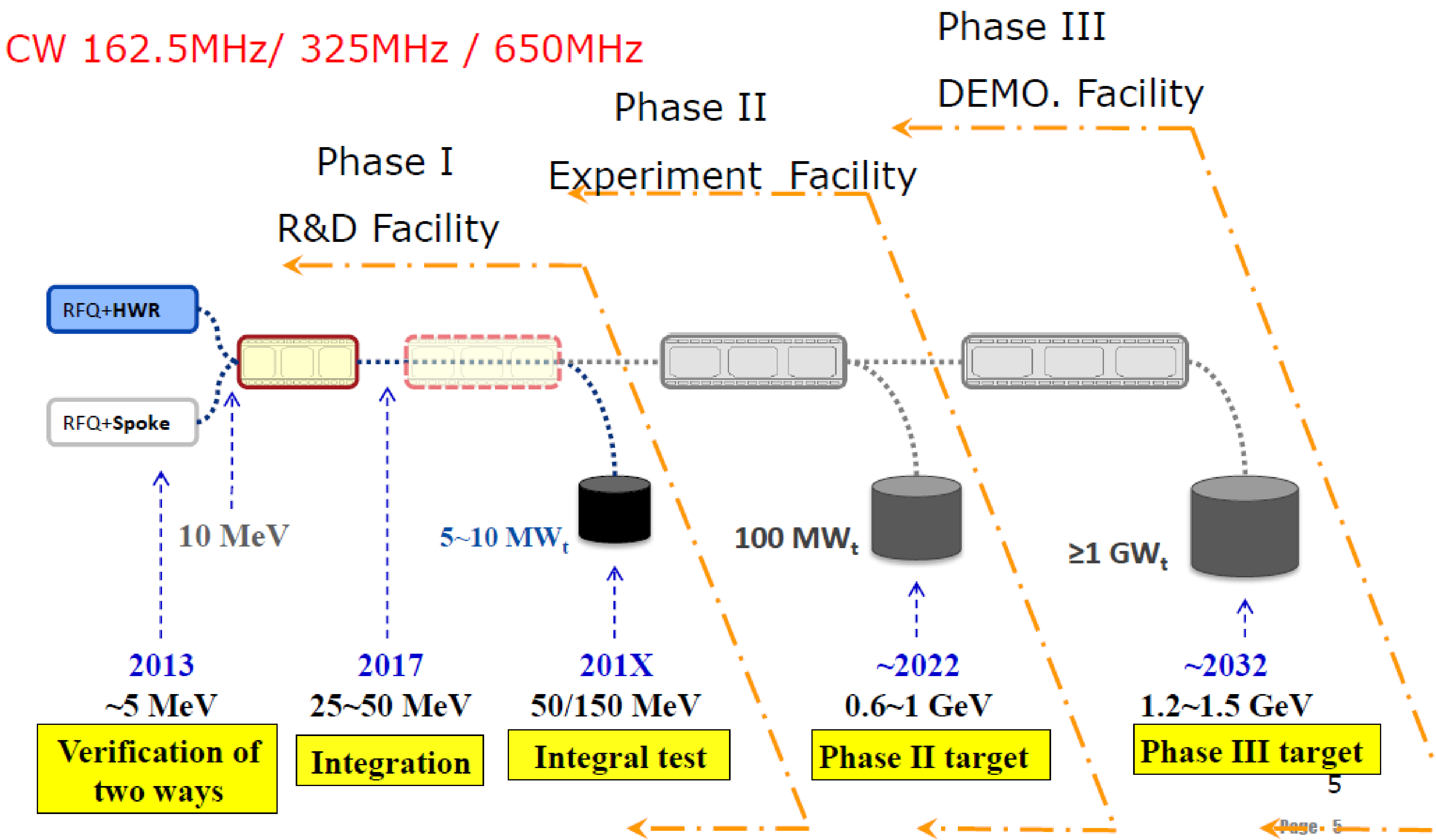
Scheme for 200 MeV High Intensity Proton Accelerator (a front end of the 1 GeV Linac)



- Frequency: 325 and 650 MHz
- Current : 30 mA

P. Singh, SRF -2011

ADS Roadmap in China

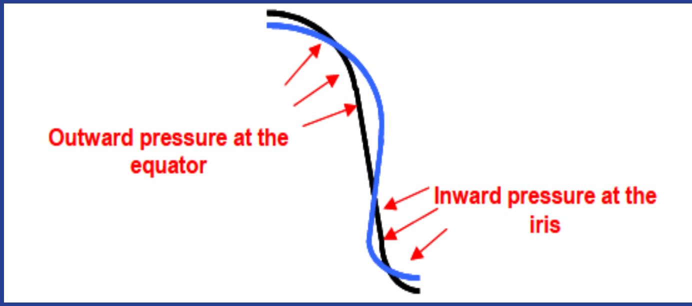


Shinian Fu, SRF 2011

Narrow bandwidth of the PX cavities caused by low beam loading:

•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)
$\Delta f_{Lorentz} = k_L E_{acc}^2$, k_L- Lorentz coefficient, E_{acc} – acceleration gradient.
For ILC cavity k_L~ -1 Hz/(MeV/m)^2. For CW Lorenz detuning is 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 =30-130 Hz/mbar (ILC)

*Matthias Liepe, Project X Collaboration meeting, Fermilab, 2011

Power overhead caused by microphonics:

- Loaded Q:
  $Q_{load} = U/(R/Q)/I_{beam}$;.
  Q_{load}(PX HE 650MHz)=**2.8e7**;

- Bandwidth Δf :
  Δf= f/Q;
  Δf(PX 650 MHz) = **23** 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 Project X HE 650 MHz section, I=1mA, V=17.7 MeV (G=17 MeV/m), (r/Q)=638 Ohm, acceleration phase of -15°:

σ_f Hz	$6 \cdot \sigma_f$ Hz	Power overhead
1	6	1.07
2	12	**1.23**
3	18	**1.44**
4	24	**1.67**
5	30	**1.92**
6	36	**2.17**

σ_f must be less than ~2 Hz for <20% 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 (option- operation at 2K).

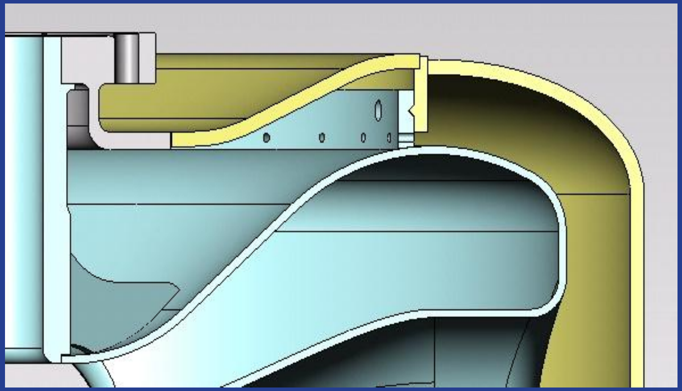
•Reducing the sensitivity of the cavity resonant frequency to variations in the helium bath pressure (df/dP).

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

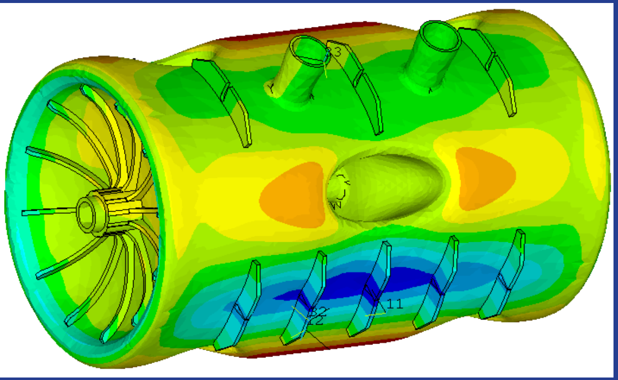
•Actively damping cavity vibrations using a fast mechanical or electromagnetic tuner driven by feedback from measurements of the cavity resonant frequency.

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

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



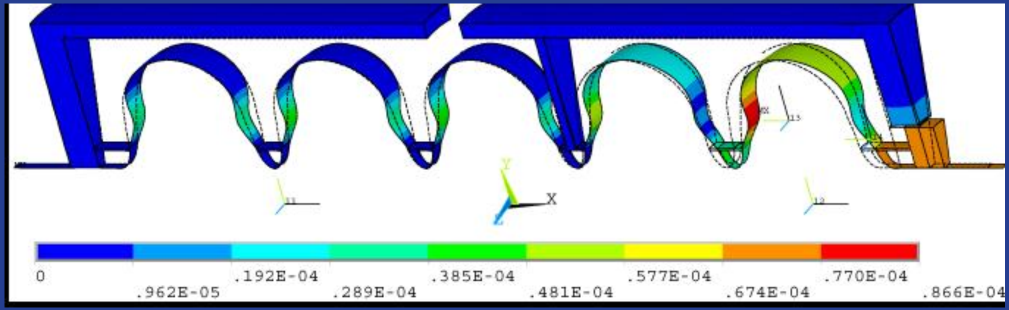
1. Mechanical coupling of a cavity and a He vessel (L. Ristori, et al)



2. “Self-compensated cavity” (Z. Conway, P. Ostroumov, et al)

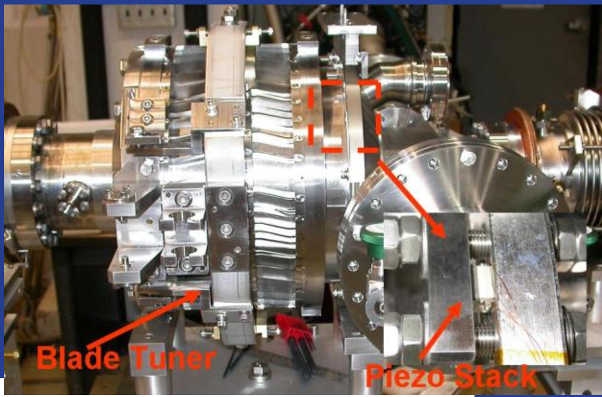
$$\Delta f \propto -\frac{1}{4}\int_{\Gamma}\left[\mu_0\left|\vec{H}_0(\vec{x})\right|^2 - \varepsilon_0\left|\vec{E}_0(\vec{x})\right|^2\right]u(\vec{x},t)\,da$$

$$\int_{\Gamma}\left[\mu_0\left|\vec{H}_0(\vec{x})\right|^2\right]u(\vec{x},t)\,da \approx \int_{\Gamma}\left[\mu_0\left|\vec{E}_0(\vec{x})\right|^2\right]u(\vec{x},t)\,da$$



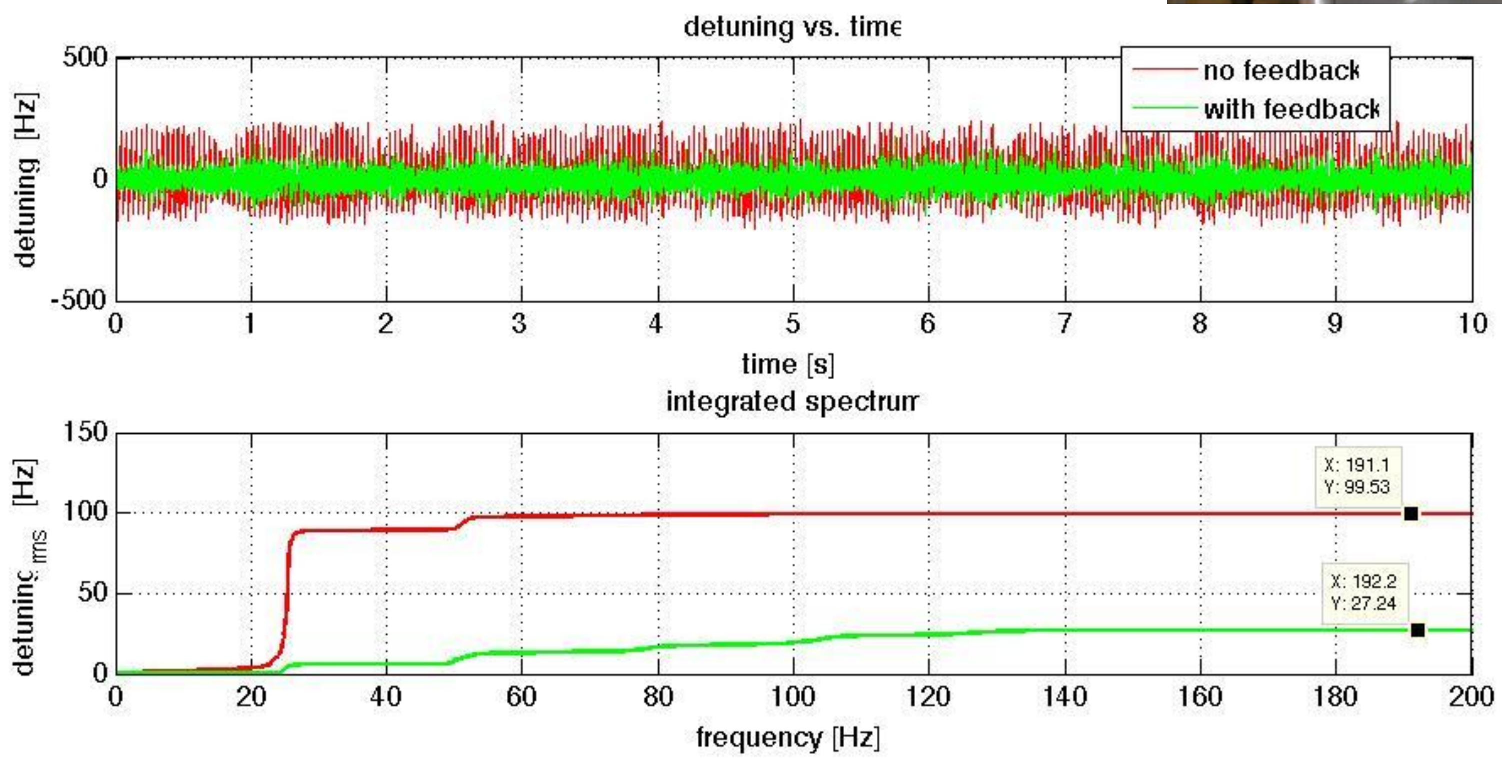
3. “Self-tuning cavity” (E. Zaplatin)

Active Microphonics Compensation in the ERL Injector



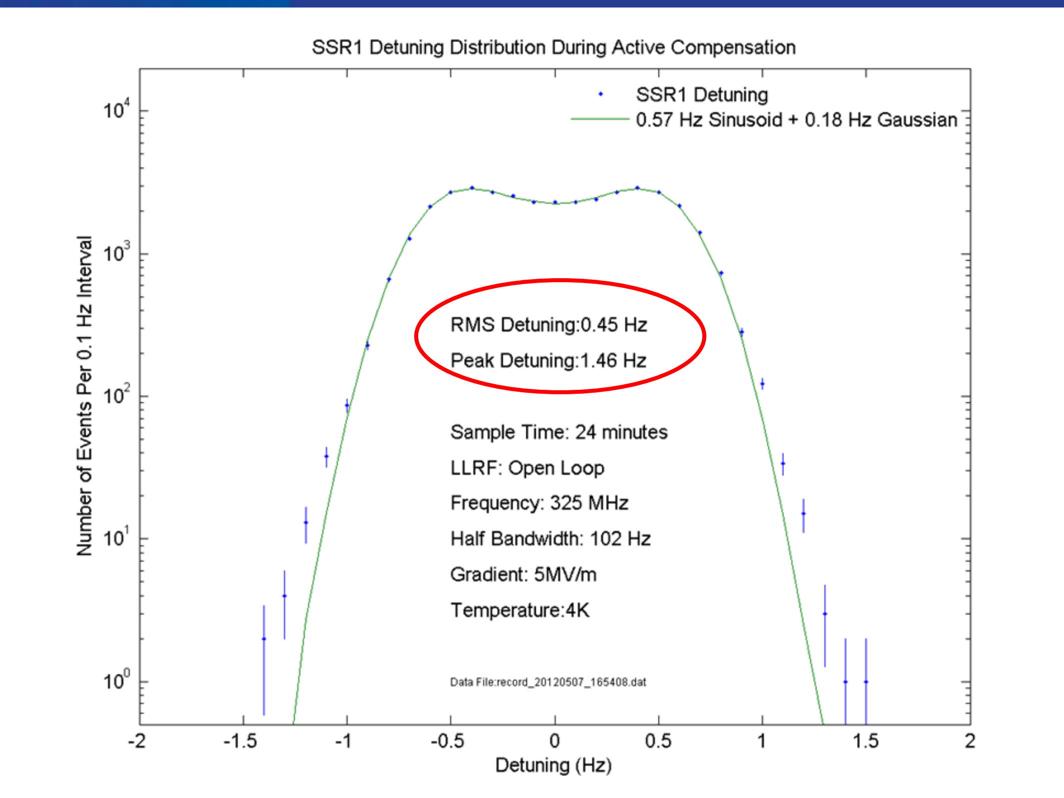
Piezo Feedback on Cavity Frequency:

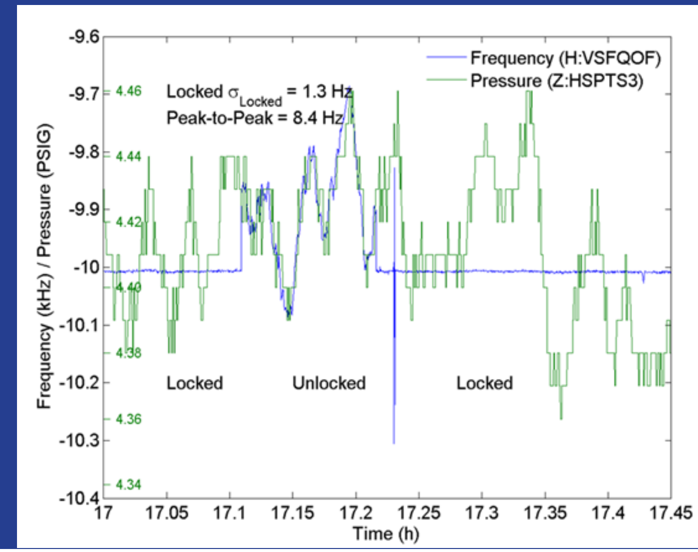
⇒ Reduces rms microphonics by up to 70%!

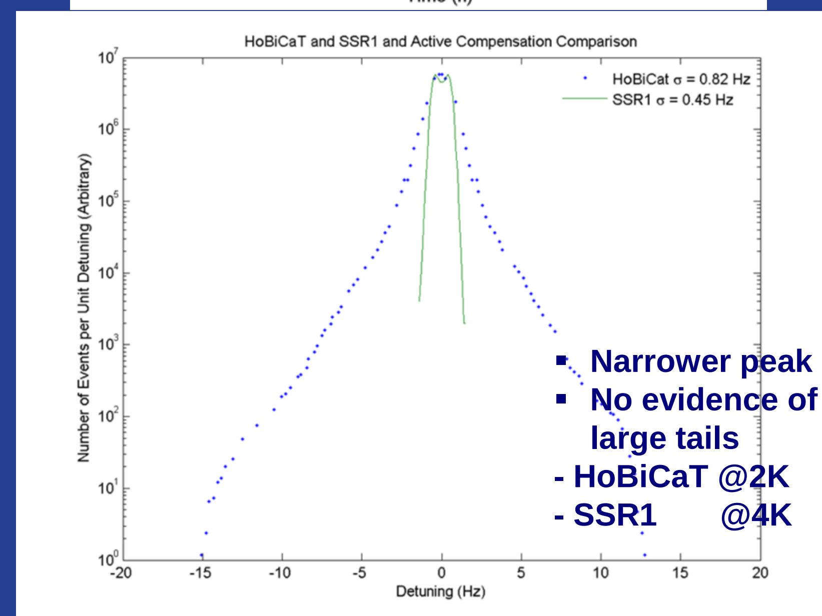


Matthias Liepe, Cornell University, PAC2005

SSR1 Active Microphonics Control (Fermilab)





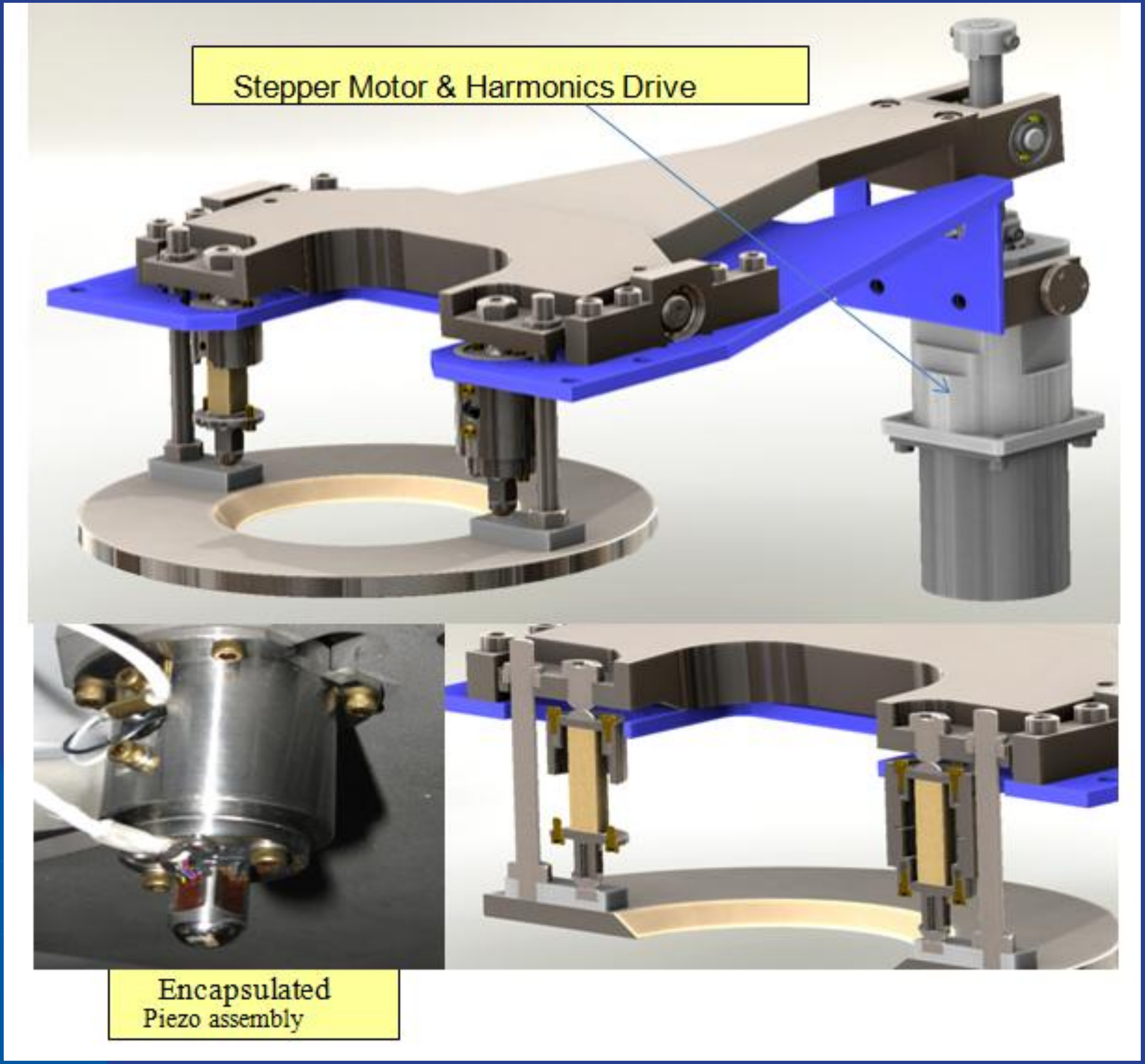


- Narrower peak
- No evidence of large tails

- HoBiCaT @2K
- SSR1 @4K

W. Schappert, Yu. Pischalnikov, IPAC2012

Slow and Fast Tuner Development (FNAL)



Conclusions

- SRF for linear accelerators has a long and successful history;
- SRF for ILC is well-developed, and international team has made good progress in achieving high accelerating gradient;
- New CW projects for large linacs - Project X, NGLS, ADS projects, ERL's, etc. - need not high gradient, but high Q_0 at modest gradient. New SC material research concentrates on the achievement of high Q_0..
- Another critical issue for new CW projects is microphonics. Dedicated research is ongoing to develop both passive and active means for microphonics compensation suitable for large SC linacs with low beam loading.

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