HIGH Q_0 SUPERCONDUCTING CAVITIES FOR CW LINACS

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4th Workshop on Energy for Sustainable Science at Research Infrastructures, ELI-NP, Magurele, Romania

23 November, 2017

Outline

- Large SRF linear accelerators and energy efficiency issue;
- Energy consumption breakdown;
- When and where high Q_0 is essential for SRF linacs;
- State of the art SRF cavity processing technologies;
- N–doping and flux expulsion: from breakthrough discovery to working technology;
- N- infusion: high Q_0 at high gradient;
- Nb_3Sn: technology of the future;
- Summary;
- Acknowledgements.

Motivation

- High power proton and electron superconducting RF linear accelerators are powerful tools for scientific research used to generate secondary particles at high intensities, such as neutrons, neutrinos, muons, for Free Electron Lasers, etc.
- The applications of these facilities have a broad spectrum in the fields of particle physics, condensed matter physics, material science, chemistry, biology, and medicine.
- Another application under discussion is Accelerator Driven Subcritical Reactors (ADS).
- The production of megawatt-class proton and electron beams implies the consumption of electrical power on a large scale.

- For each new generation of accelerator facilities we want better beam current, flux, rate, brightness, luminosity.
  → typically needs more power!

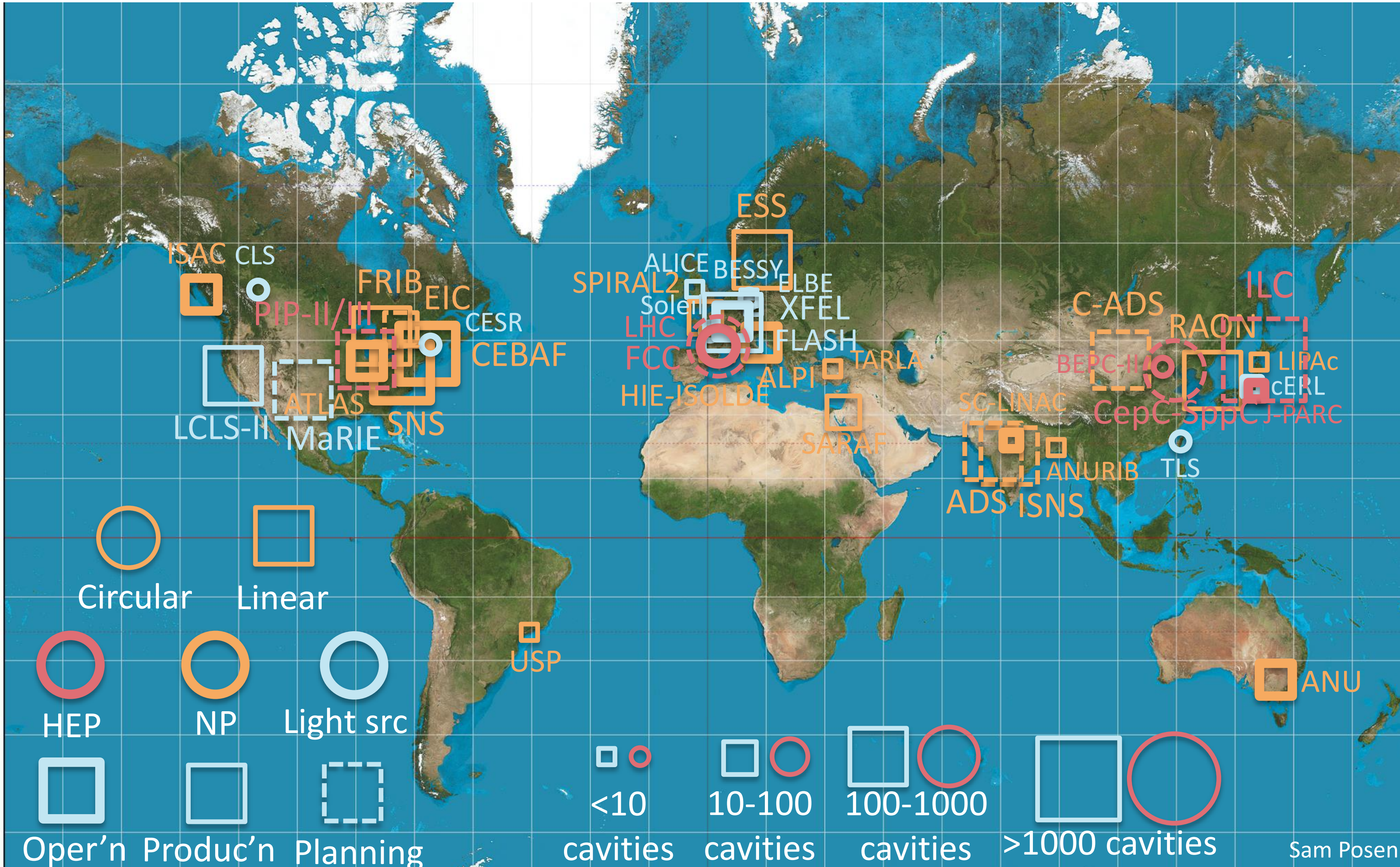
- Acceptance of these projects by authorities and the public becomes increasingly difficult.

→ Thus, one needs to work on the following:

  – Improve efficiency of accelerators;
  – Demonstrate efforts to improve efficiency to funding organizations / to public;
  – Adapt our facilities to new sustainable energy production.

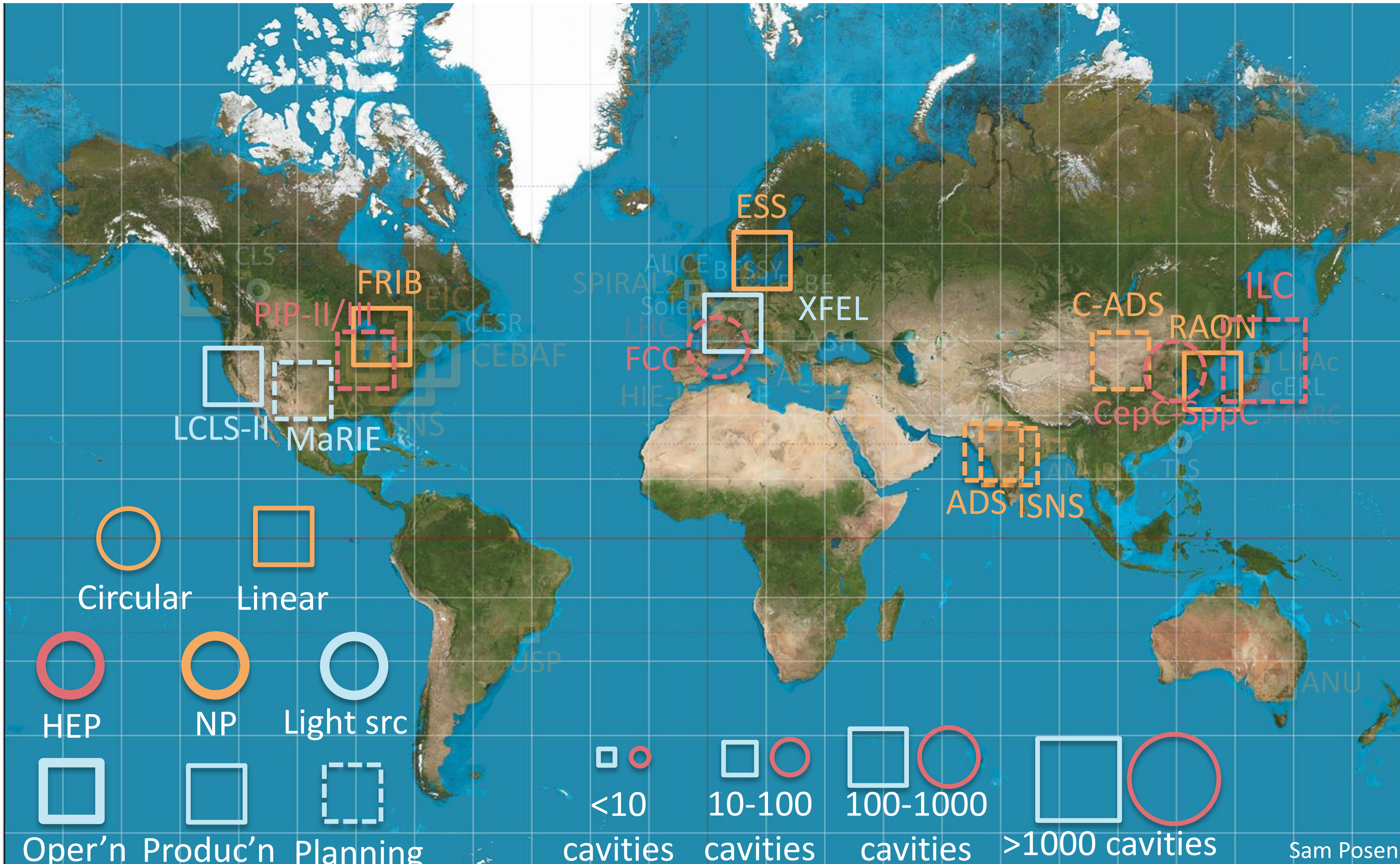
- New projects and operating facilities must focus on improving the energy efficiency with a higher priority.

SRF Accelerators Around the World



Map from Wikipedia. Non-exhaustive facility list.

SRF Accelerators Around the World



Map from Wikipedia. Non-exhaustive facility list.

Large SRF Linear Accelerators:

Linac	Stage	Particle	Application	Operation regime	Duty factor, %	Beam Current, mA	Beam Energy, GeV	Average Power, MW
SNS (USA)	Operation	H^-	Neutron Source	Pulsed	5.85	25	0.957	1.4
XFEL (Germany)	Commissioning	e^-	FEL	Pulsed	0.65	5	17.5	0.57
ESS (Sweden)	Construction	H^+	Neutron Source	Pulsed	4	62.5	2	5
MaRIE (USA)	Concept Study	e^-	FEL	Pulsed	1	8	12	1
ISNS (India)	Concept Study	H^-	Neutron Source	Pulsed	10	10	1	1
LCLS II (USA)	Construction	e^-	FEL	CW	100	0.1-0.3	4	0.4-1.2
PIP II (USA)	Design	H^-	Neutrino Source	CW/Pulsed	100/1.1	2	0.8	1.6/0.016
CIADS (China)	Design	H^+	ADS	CW	100	10	1.5	15
ADSS (India)	Concept Study	H^+	ADS	CW	100	30	1	30

Power Flow in SRF Accelerators

Public grid

Accelerator
- RF
  - HV sources,
  - RF sources,
  - Accelerator structure
- Magnets

beam

Secondary radiation
- Neutrons,
- Neutrinos,
- Synchrotron radiation,
- Etc.

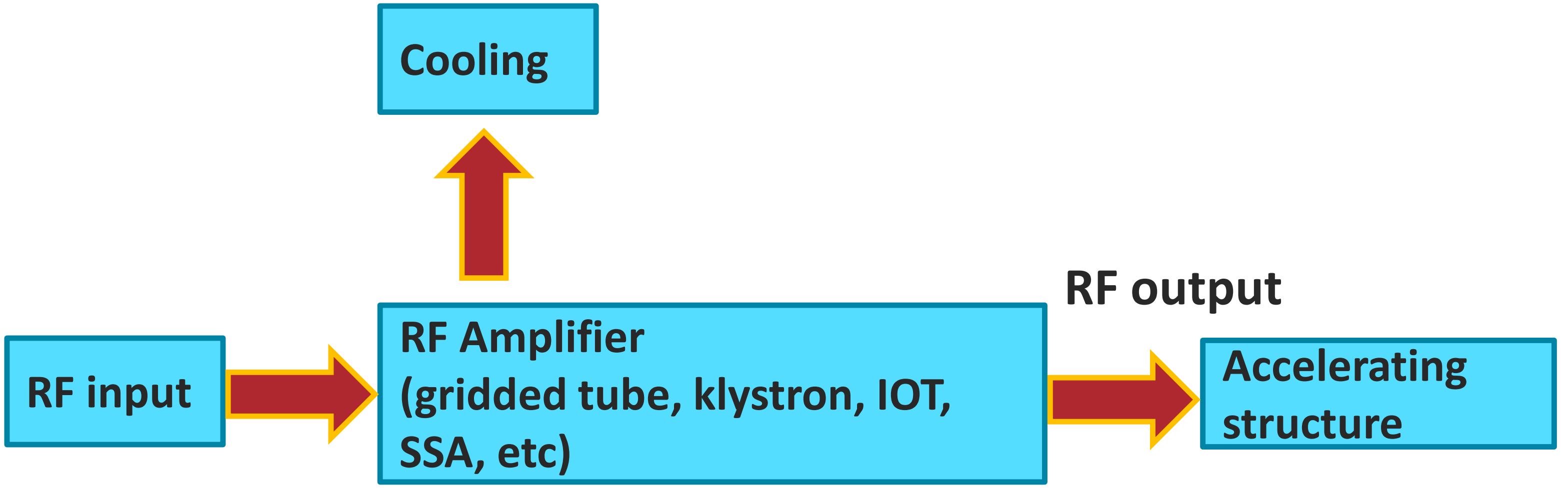
Auxiliary systems
- Cryogenics,
- Cooling,
- Air conditioning,
- Control, diagnostics
- Etc.

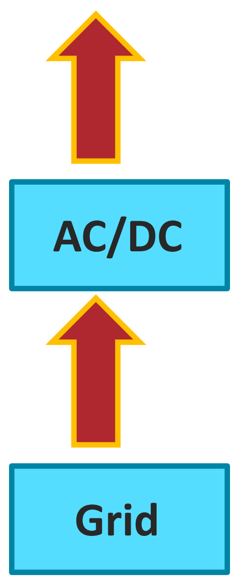
- "Efficiency": we consider a fraction of grid power converted to beam power, i.e., the ratio of the delivered beam power over the accelerator power consumption, including RF, magnetic system, cooling/cryogenics, but neglecting auxiliary systems and experimental facilities.

$$\eta = \frac{P_{beam}}{P_{magnet} + P_{RF} + P_{cooling} + P_{cryogenics}}$$

(P_{RF} and $P_{cooling}$:) depend on beam loading

AC →RF Overall Efficiency





- AC→DC (transformer, switch, HVCM losses and settling time)
- DC→RF (RF source efficiency)
- Amplifier and building cooling

$$\textbf{Overall efficiency} = \frac{P_{RFout}}{P_{RFin}+P_{ACin}+P_{coolers}}$$

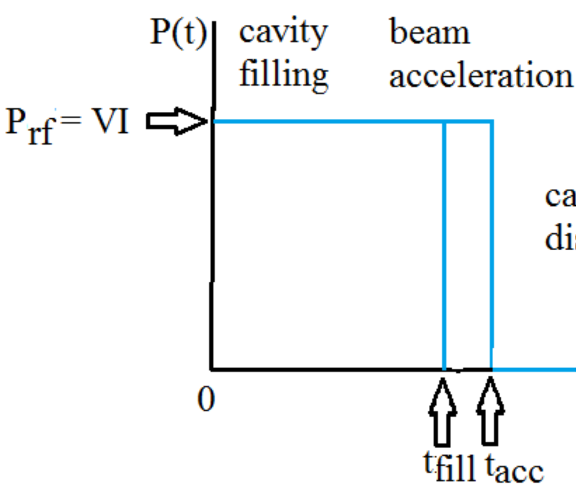
Typically, overall AC →RF efficiency ≲ 50%

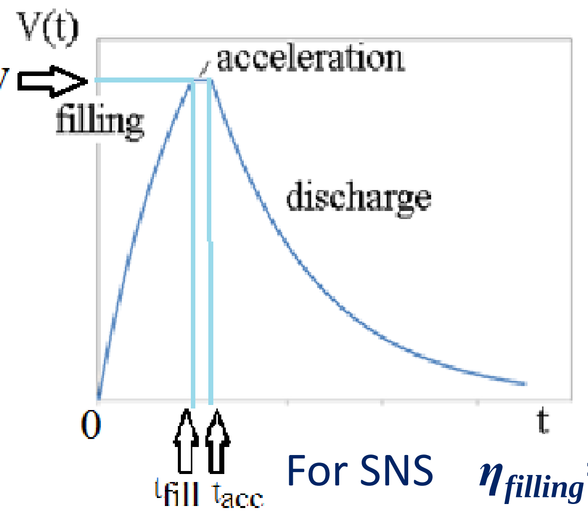
RF →beam Overall Efficiency

- RF cavity filling (pulsed regime)
- Control overhead (~10%)
- Transmission line losses (5-10%)
- Microphonics

Beam Duty Factor: t_{beam}*Rep_rate

RF Duty Factor: (t_{fill}+ t_{beam})*Rep_rate





For SNS $\eta_{filling}$= 85% (q=24e-6 C)

For PIP II $\eta_{filling}$= 5.7% (q=1.1e-6 C)

(pulsed)

$$\eta_{filling}= w_{beam}/(w_{RF})= 1/[2V\cdot \ln 2/(R/Q\cdot\omega\cdot q)+1]$$

where

-V is the cavity voltage,

-I is the beam current,

-ω is cyclic frequency,

-q is the total charge of the protons in the pulse, $q=I^* t_{beam}$

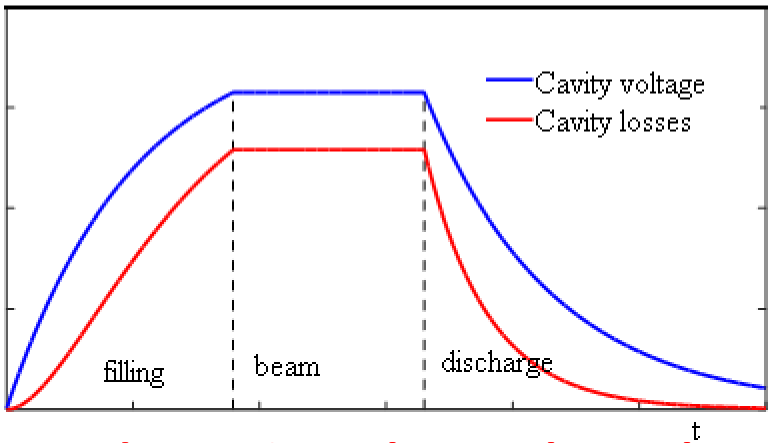
Overall RF→beam efficiency:

- 80-85% CW
- 3-55% (pulsed, strongly depends on the beam loading)

Fermilab

Cryogenics:

- Cryogenics duty factor (CDF):
- Static losses : supports, couplers, beam pipes, radiation) typically 5-6 W/CM for XFEL-type CM;
- Dynamic losses : RF losses in the cavities, losses in the bellows, couplers (typically small)



Cryo Duty Factor: $[t_{beam}+4\tau(\ln 2-1/8)]$*Rep_rate;

$\tau = 2Q_{ext}/\omega$ – time constant, $Q_{ext} \precsim V/(R/Q)/I$.

Dynamic losses/CM $=V^2/(R/Q)/\mathbf{Q_0}$*CDF*N

N- number of cavities /CM,

Q_0 – unloaded quality factor;

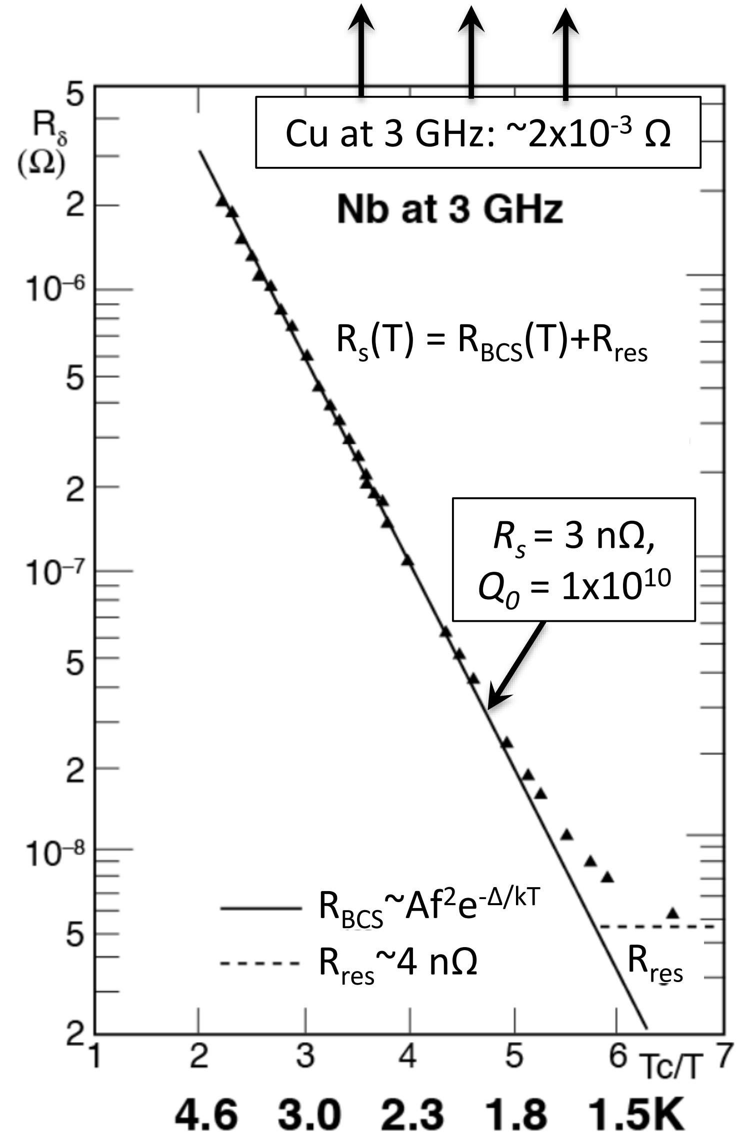
Q_0 determines the total cryo-losses when dynamic losses >> static losses!

(High Cryogenic Duty Factor or/and high acceleration gradient)

For Q_0=1.e10:
XFEL (pulsed, ~1% CDF, V=24MV) ~4 W average per CM ~ 6 W of Static losses per CM
LCLS-II (CW, 100% CDF, V=16 MV) ~210 W average per CM >> 6 W of Static losses per CM

Note on Q_0 and BCS/Residual Surface Resistance

- Q_0 and R_s are related by a geometrical constant G: $Q_0=G/R_s$
- They measure efficiency
- Heat dissipated in the walls of the cavity: $P_{diss} \sim R_s \sim Q_0^{-1}$
- R_s decreases exponentially with decreasing T/T_c but it saturates at low T: residual resistance R_{res}
- Generally we decompose R_s into temperature dependent R_{BCS}(T) and temperature independent R_{res}
- Cavities often operate at ~2 K where both are significant

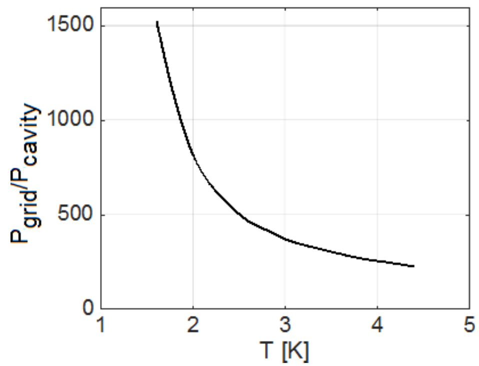


Cryogenic Coefficient Of Performance (COP)*

Accelerating structure, 2K

Cryo-Plant

P_{cavity} →



$$COP(T) = \frac{P_{grid}}{P_{cavity}};$$

P_{grid} ↑

Public grid

For large Helium cryogenic refrigerators

COP (2K) ≈ 850-1000 W/W

- COP depends on uncertainty in the heat load estimate and degradation of the cryogenic system performance*
- For high-DF and CW accelerators cryogenics may impact the entire accelerator efficiency.
- LCLS II: Q_0=1.e10, V=16 MV, P_{2K}~ 210 W/CM→ $P_{grid} \lesssim$ 6 MW compared to the beam power of 1.2 MW (I_{beam}=0.3 mA)

***Arkadiy Klebaner and Jay Theilacker, Project X Collaboration Meeting, 2011**

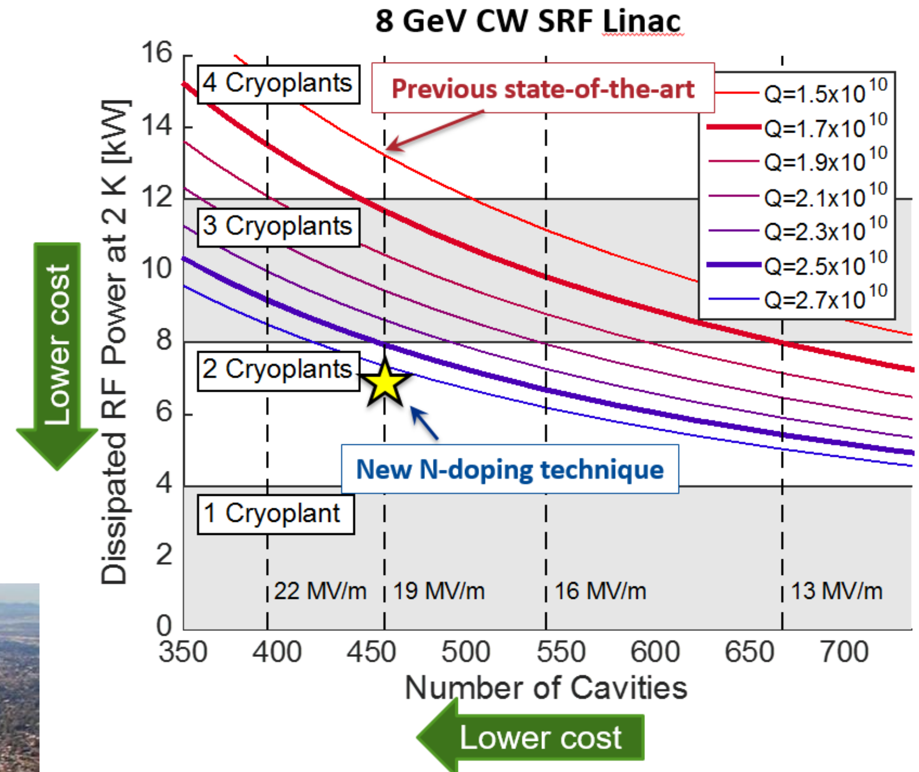
For CW accelerators the refrigeration cost is of the order of several tens of millions $

Jefferson Lab Cryoplant
(completed 2012)
→ SLAC / LCLS-II to be similar ←

Q_0 x 2 ⇒ half cryo-power is required

Linear Coherent Light Source-II (LCLS-II)

- $4\ GeV$, $0.1\ mA$ *CW SRF LINAC*
- 35 CM, 8 cavities/CM + 1 quad
- TESLA-type 1.3 GHz 9-cells cavities
- Specs: $E_{acc} = 16\ MV/m$ with $Q_0 = 2.7 \times 10^{10}$



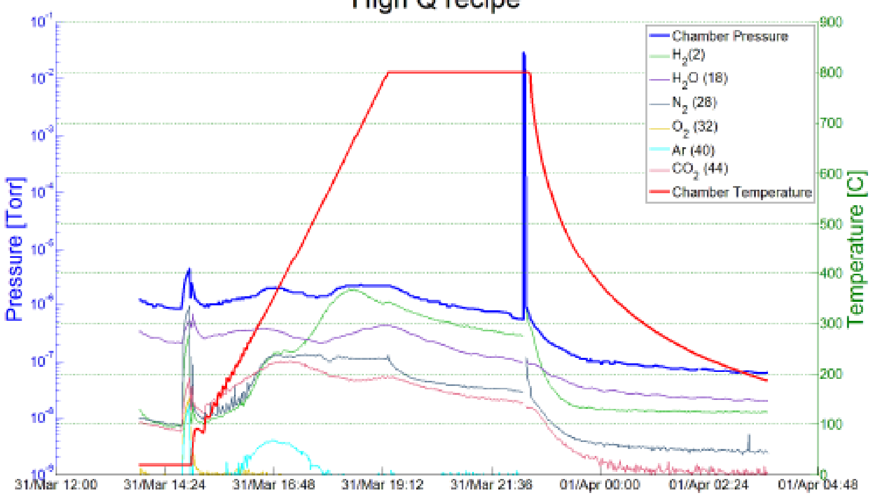
N-doping:

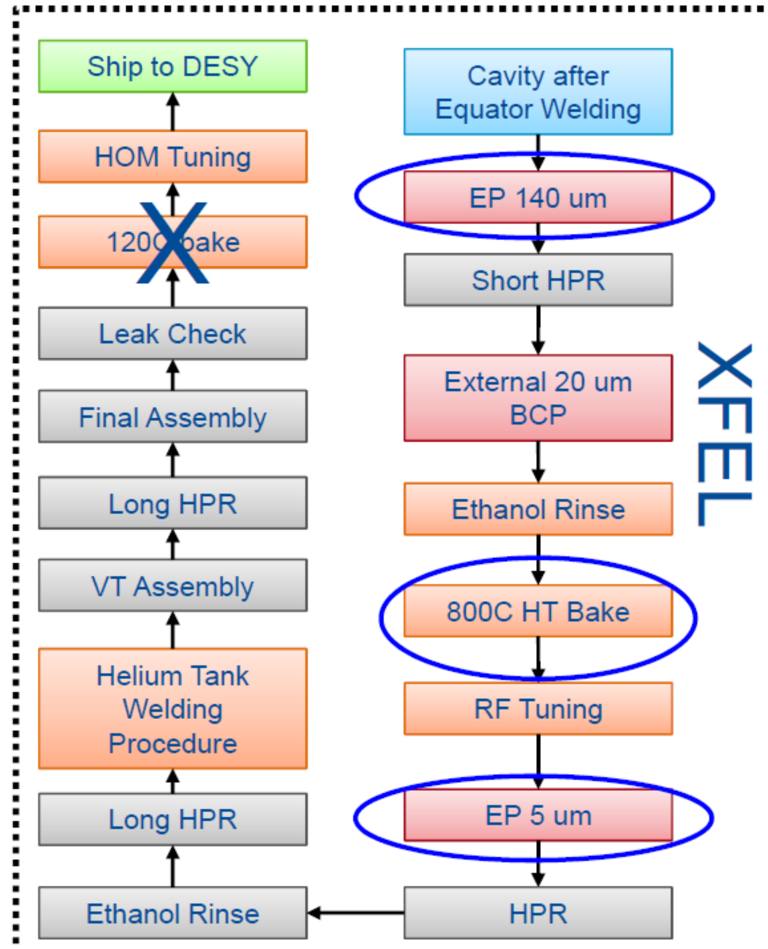
- “Standard” XFEL technology provides ≲1.2e10@2K, 20-23 MeV/m (CM);
- N-doping: discovered in the frame of R&D on the Project-X SC CW linac (A. Grassellino).

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

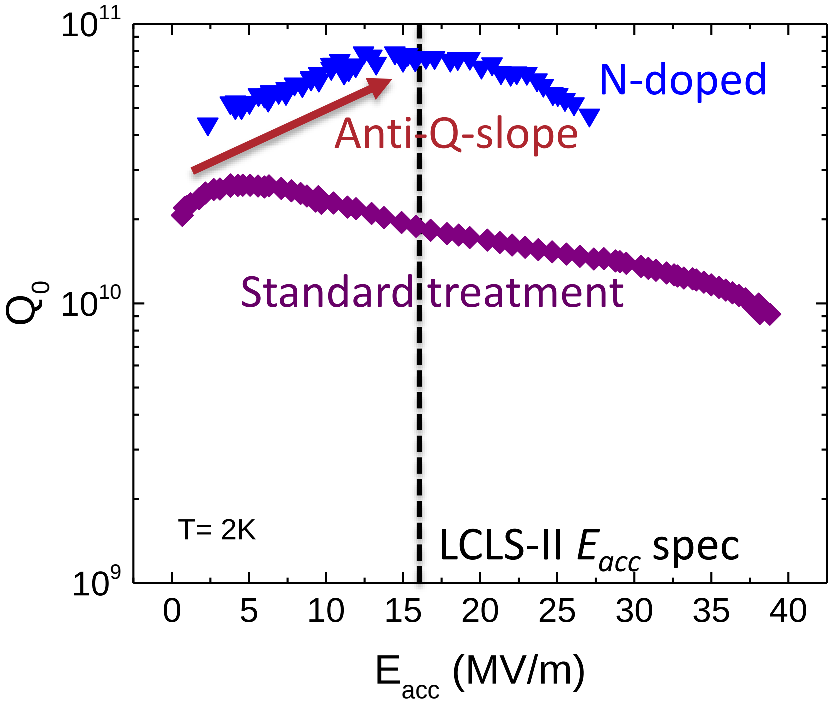
High Q recipe

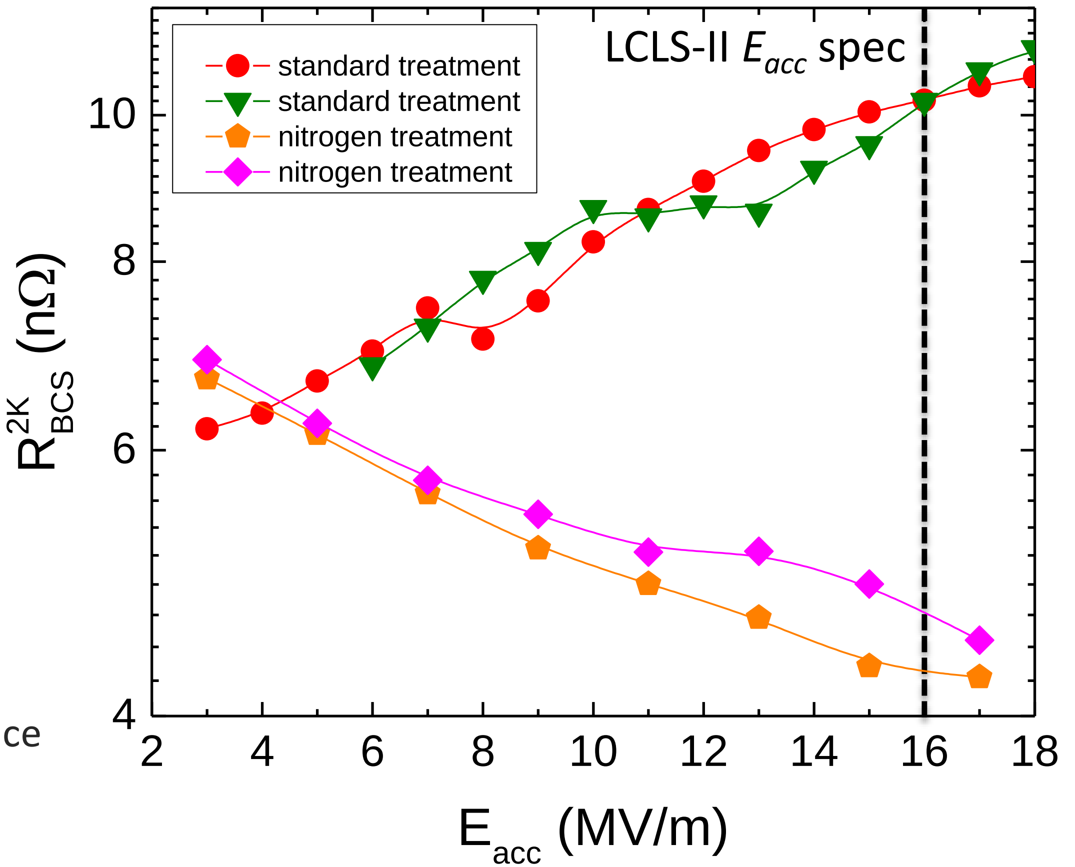




A. Grassellino, N-doping: progress in development and understanding, SRF15

Effect on Surface Resistance (and therefore $Q_0=G/R_s$)





Anti-Q-slope emerges from the BCS surface resistance decreasing with field

→ **Unexpected, unprecedented**

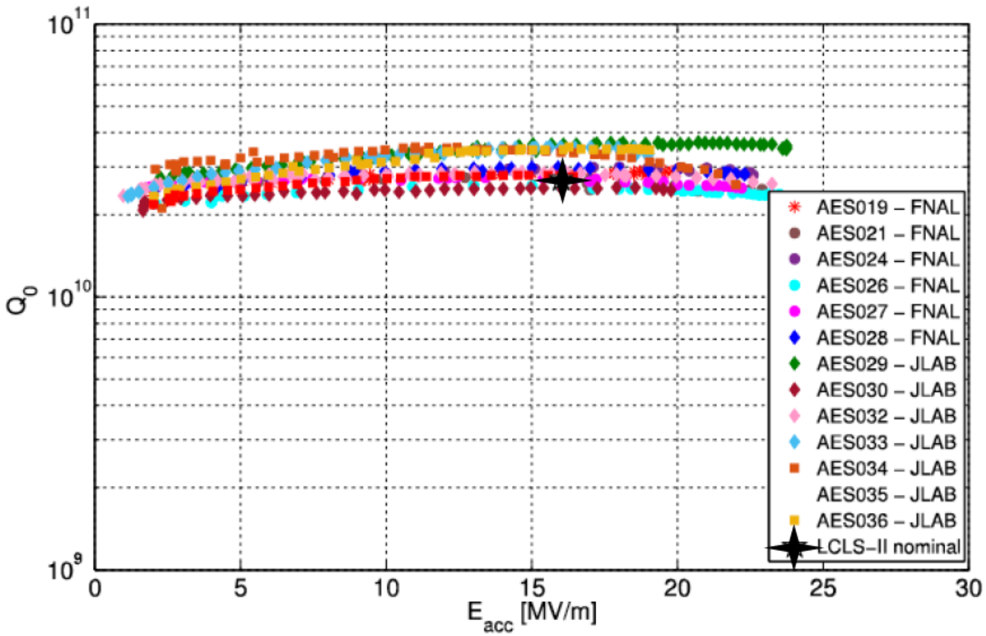
- >2x R_{BCS} improvement at 2 K, 16 MV/m
- Reduced maximum field OK for high duty factor applications

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

A. Romanenko and A. Grassellino, Appl. Phys. Lett. 102, 252603 (2013)

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 LCLS II;
  - 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.

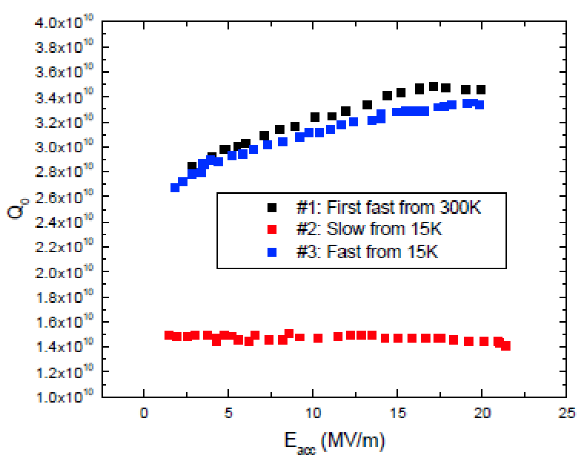
  η is material-dependent!
- For pCM Nb (Wah Chang):

  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



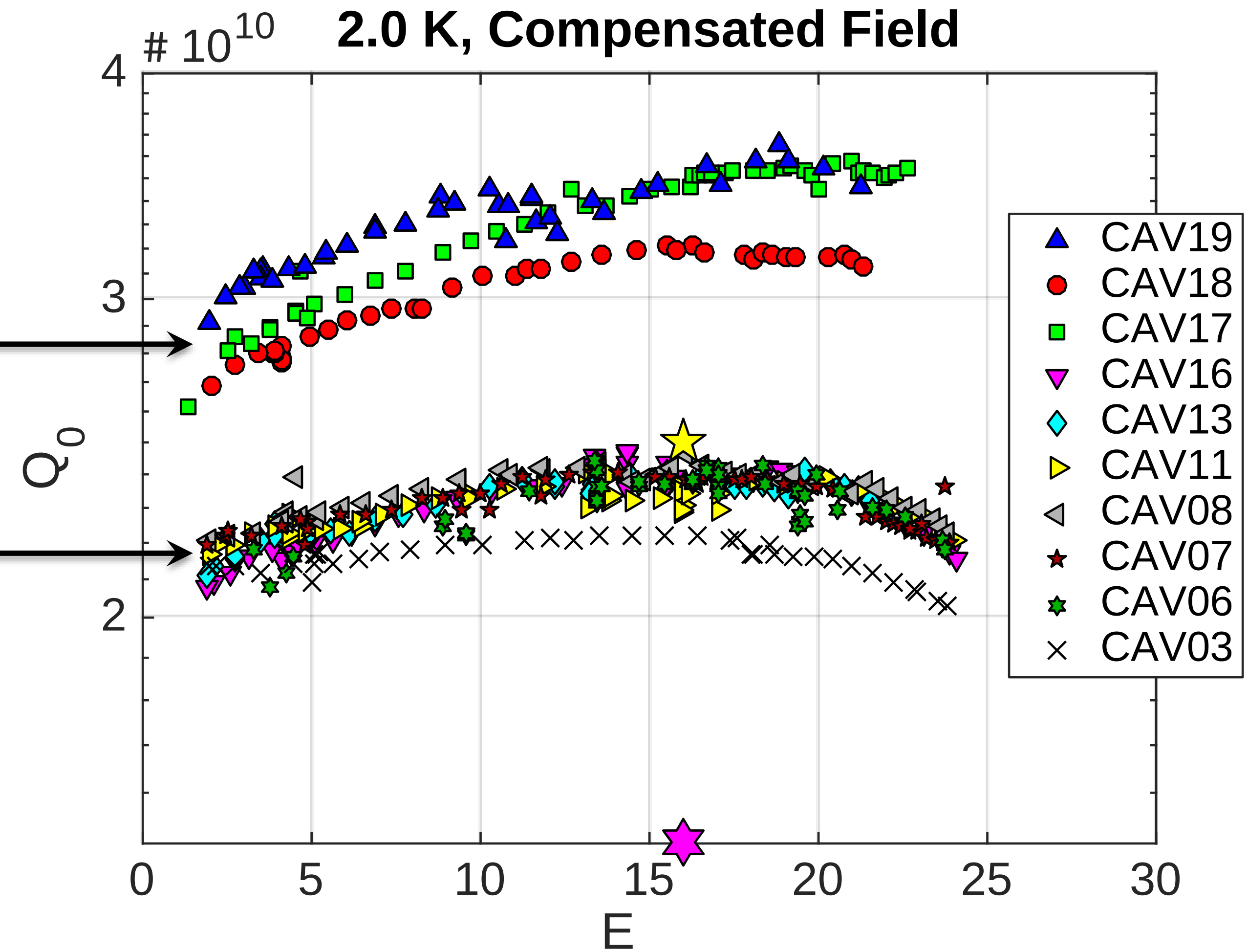
"Fast": 2 – 3 K/minute ,"slow": < 0.5 K/minute

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 .

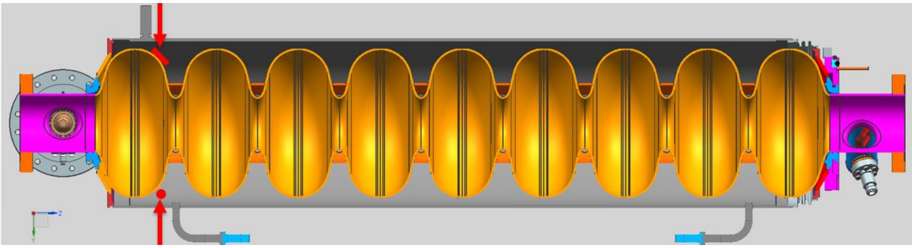
A. Grassellino, A. Romanenko, S Posen, Y. Trenikhina, O. Melnychuk, D.A. Sergatskov, M. Merio, N-doping: progress in development and understanding, Proceedings of SRF15, http://srf2015proc.triumf.ca/prepress/papers/moba06.pdf .

Ambient Magnetic Field Management Methods

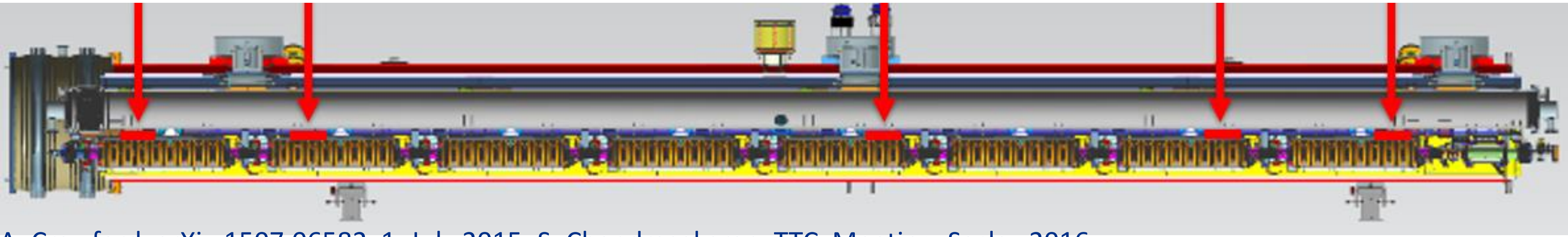
- 2-layer passive magnetic shielding
  - Manufactured from Cryoperm 10
- Strict magnetic hygiene program
  - Material choices
  - Inspection & demagnetization of components near cavities
  - Demagnetization of vacuum vessel
  - Demagnetization of assembled cryomodule / vessel
- Active longitudinal magnetic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



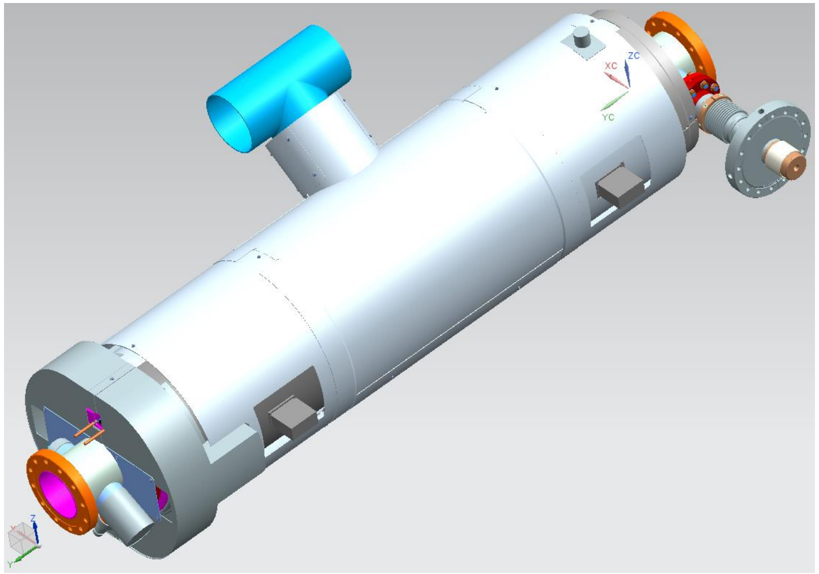
Fluxgates monitored during cryomodule assembly



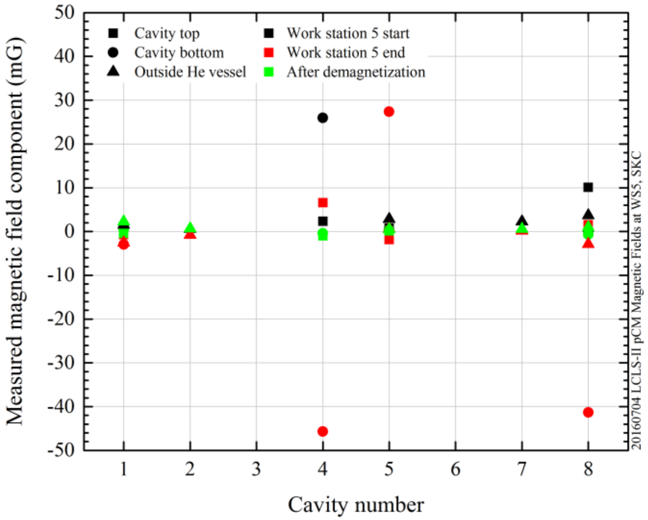
A. Crawford, arXiv:1507.06582v1, July 2015; S. Chandrasekaran, TTC Meeting, Saclay 2016

Ambient Magnetic Field Management Methods

Helmholtz coils wound onto vessel directly



2-layer magnetic shields manufactured from Cryoperm 10

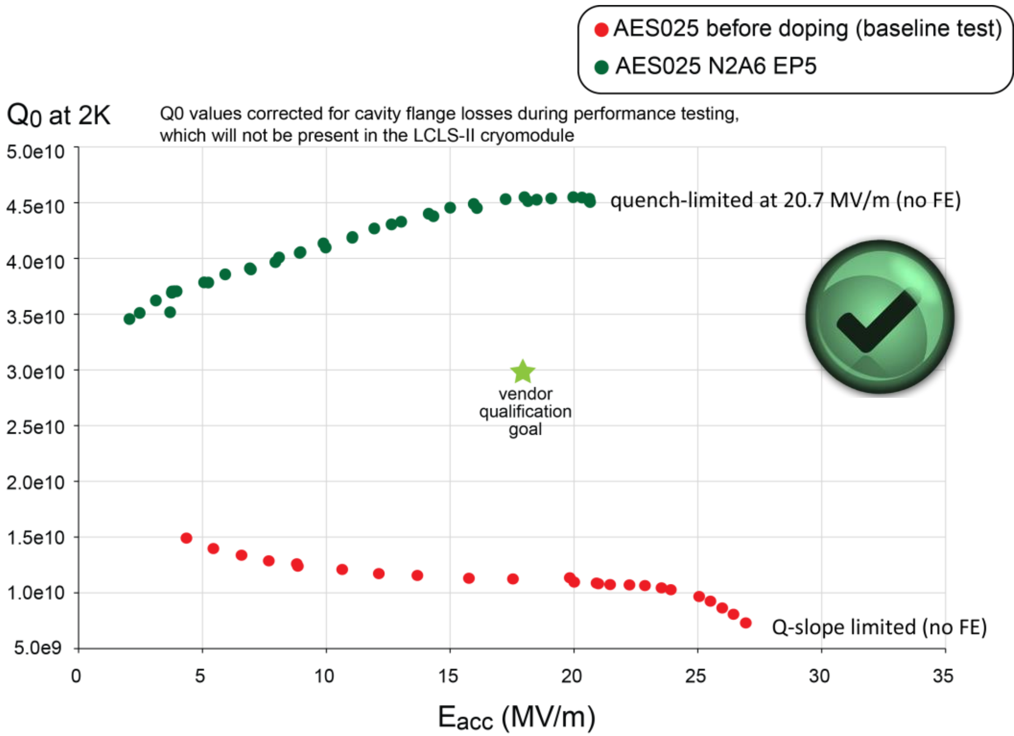


Cryomodule modification: liquid supply valve for 2-phase liquid level, cool-down valve for “fast” cool-down

S. Chandrasekaran, Linac 2016, TUPLR027

Technology Transfer

- SRF cavity vendors: from niobium material to N-doped cavities ready for qualification testing

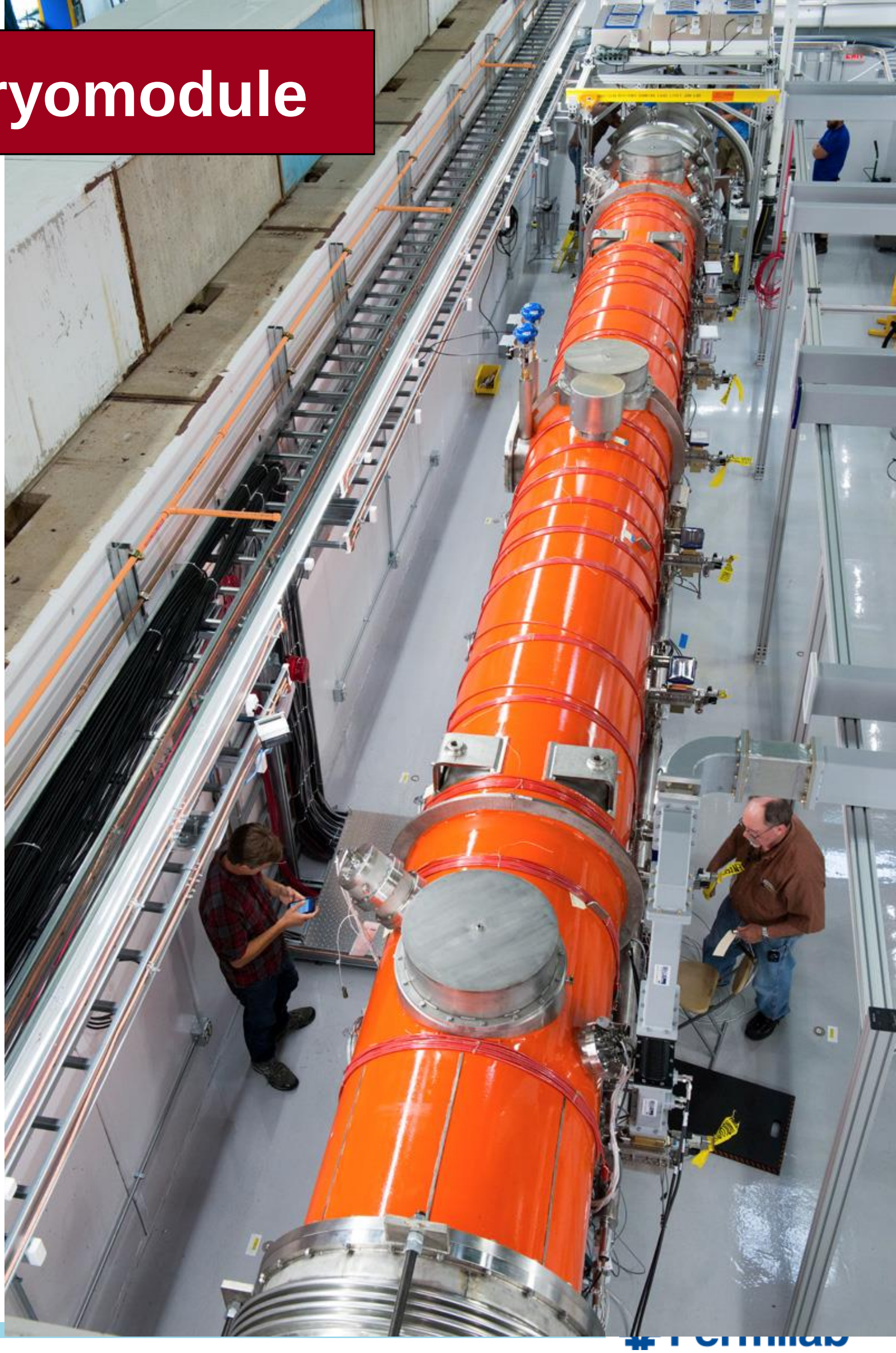


Fermilab Prototype LCLS-II Cryomodule

Cavity	Usable Gradient* [MV/m]	Q0 @16MV/m* 2K Fast Cool Down
TB9AES021	18.2	2.6E+10
TB9AES019	18.8	3.1E+10
TB9AES026	19.8	3.6E+10
TB9AES024	20.5	3.1E+10
TB9AES028	14.2	2.6E+10
TB9AES016	16.9	3.3E+10
TB9AES022	19.4	3.3E+10
TB9AES027	17.5	2.3E+10
Average	**18.2**	**3.0E+10**
Total Voltage	**148.1 MV**	

Spec: 133 MV

Spec: 2.7×10^{10}



N–doping and flux expulsion: from breakthrough discovery to working technology.

F1.3-01	VTS		pCM after RF_Conditioning			
Cavity	Eacc [MV/m]	Q0 16MV/m	Max Eacc	Usable Eacc*	FE onset	Q0@2K 16MV/m
TB9AES021	23	3.08E+10	19.6	18.2	14.6	2.6E+10
TB9AES019	19.5	2.82E+10	19	18.8	15.6	2.6E+10
TB9AES026	21.4	2.57E+10	17.3	17.2	17.4	2.7E+10
TB9AES024	22.4	2.95E+10	21	20.5	21	2.5E+10
TB9AES028	28.4	2.81E+10	14.9	14.2	13.9	2.4E+10
TB9AES016	18	2.75E+10	17.1	16.9	14.5	2.9E+10
TB9AES022	21.2	2.77E+10	20	19.4	12.7	3.2E+10
TB9AES027	22.5	2.75E+10	20	17.5	20	2.5E+10
Average	**22.1**	**2.81E+10**	**18.6**	**17.8**	**16.2**	**2.7E+10**
Tot Voltage	**183.1**		**154.6**	**148.1**		

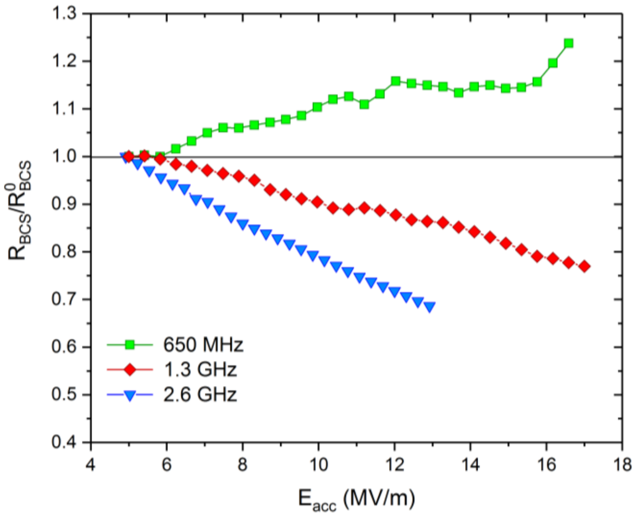
F1.3-03	VTS			CMTF Test			
Cavity	Eacc* [MV/m]	FE onset	Q0 @16MV/m	Max** Eacc	Usable Eacc	FE onset	Q0 @2K 16MV/m
CAV0034	26	No	3.33E+10	21	21.0	No	3.36E+10
CAV0039	24	20.0	3.70E+10	21	21.0	15.1	4.17E+10
CAV0040	24.5	No	3.29E+10	12.2	10.0	No	3.58E+10
CAV0026	21.5	No	3.73E+10	12	9.2	9.2	3.21E+10
CAV0027	29.7	No	3.50E+10	21	21.0	16.8	3.25E+10
CAV0029	23.1	No	3.32E+10	21	21.0	No	4.36E+10
CAV0042	24	No	3.30E+10	21	16.8	11	2.77E+10
CAV0032	22.9	No	2.74E+10	21	21.0	15.4	2.98E+10
Average	**24.5**		**3.36E+10**	**18.8**	**17.6**		**3.46E+10**
T.Voltage	**203.1**				**146.4**		

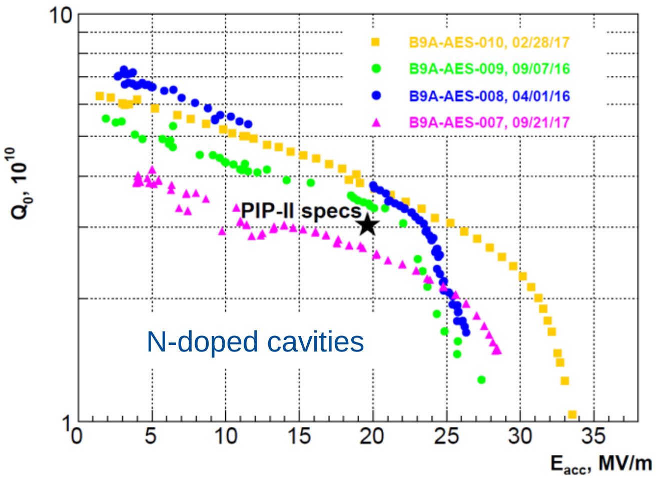
F1.3-02	VTS			CMTF Test			
Cavity	Eacc* [MV/m]	FE onset	Q0 16MV/m	Max** Eacc	Usable Eacc	FE onset	Q0 @2K 16MV/m
CAV0008	24	No	2.46E+10	20.5	20.5	No	1.8E+10
CAV0003	24	No	2.22E+10	21	21.0	No	1.8E+10
CAV0006	23	22	2.38E+10	21	21.0	No	2.0E+10
CAV0007	24	No	2.40E+10	21	21.0	No	1.8E+10
CAV0016	24.1	No	2.41E+10	20.4	18.2	12.5	1.3E+10
CAV0013	23	No	2.40E+10	16.86	16.5	No	1.6E+10
CAV0011	24	No	2.33E+10	20.5	20.5	17.5	1.8E+10
CAV0015	21.4	No	2.82E+10	21	21.0	No	2.0E+10
Average	**23.4**		**2.43E+10**	**20.3**	**20.0**		**1.8e10**
T.Voltage	**194.6**				**165.8**		

F1.3-04	VTS			CMTF Test			
Cavity	Eacc* [MV/m]	FE onset	Q0 16MV/m	Max** Eacc	Usable Eacc	FE onset	Q0 @2K 16MV/m
CAV0052	26.3	No	3.70E+10	21	21.0	no	3.11E+10
CAV0036	20		2.73E+10	21	21.0	15.2	2.38E+10
CAV0019	22.5	No	3.71E+10	21	16.0	12	2.75E+10
CAV0041	26	No	3.53E+10	21	21.0	no	2.91E+10
CAV0030	24	No	3.62E+10	21	21.0	16.5	2.91E+10
CAV0020	20	No	3.50E+10	19.8	19.3	13.9	2.42E+10
CAV0051	25	No	3.36E+10	20	19.6	No	2.55E+10
CAV0221	19.3	No	2.93E+10	19.7	19.5	No	2.77E+10
Average	**23.4**		**3.39E+10**	**20.6**	**19.8**		**2.73E+10**
T. Voltage	**170.0**				**164.4**		

Up to date 6 FNAL CM are tested, 9^{th} CM is under assembly.

Q_0 Field Dependence at Different Frequencies (N-doped)*

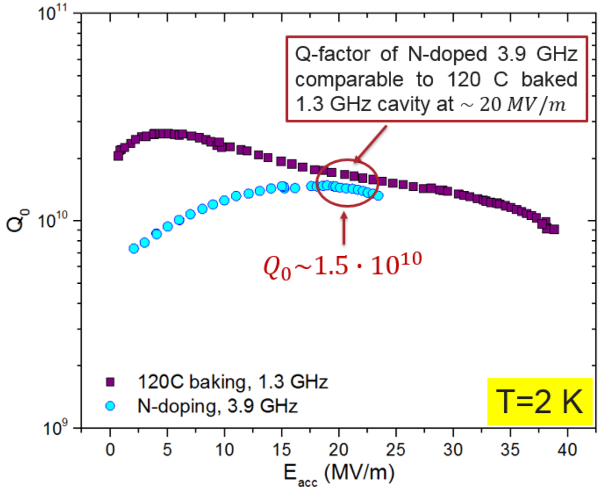




5-cell 650 MHz β=0.9 PIP II cavities

*Negligible radiation < 23 MV/m

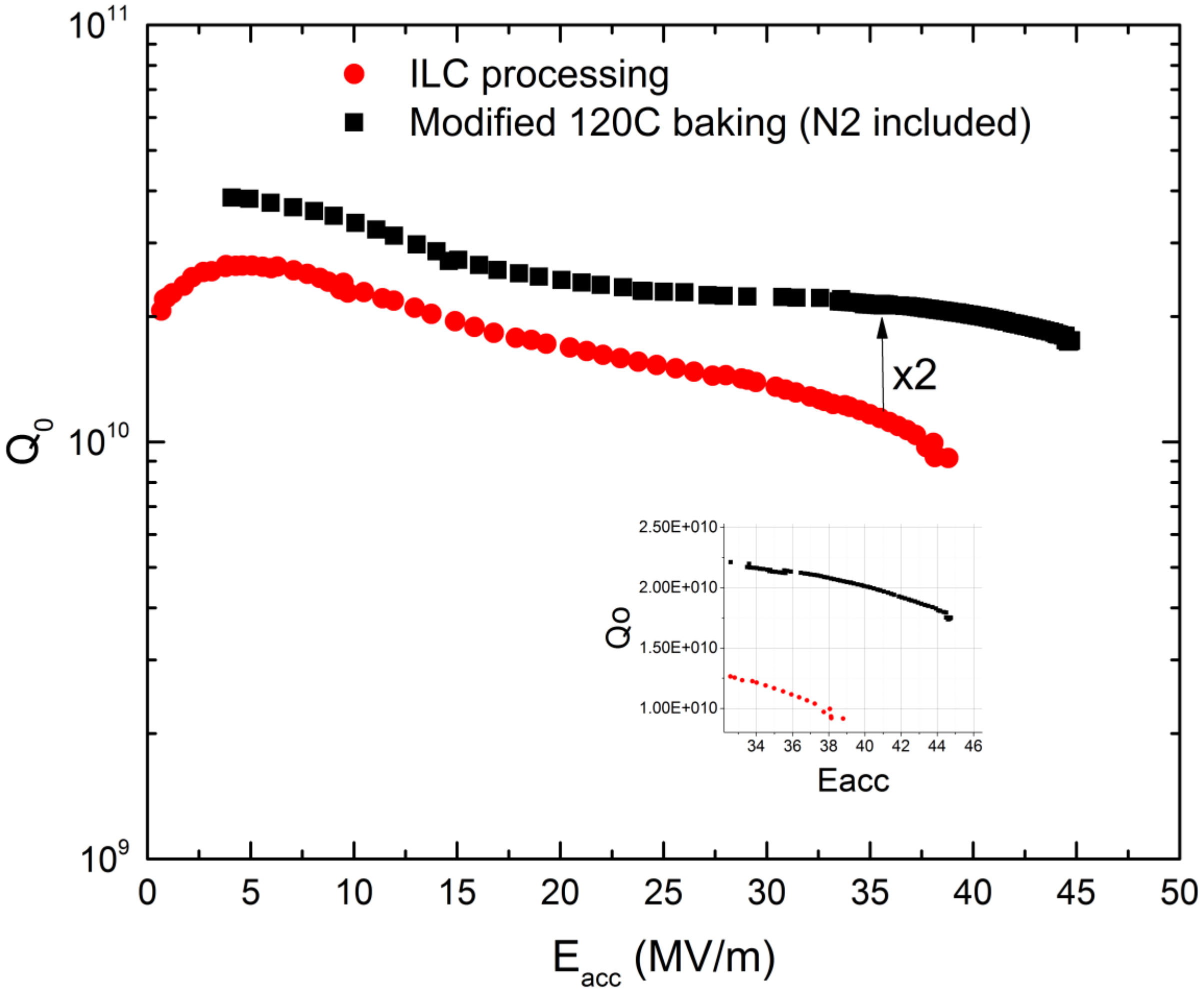
Unprecedented Medium Field Q_0 at 3.9 GHz



*Martina Martinello | TTC Topical Workshop 2017

High Q_0 at high gradient: N-infusion (A. Grassellino).

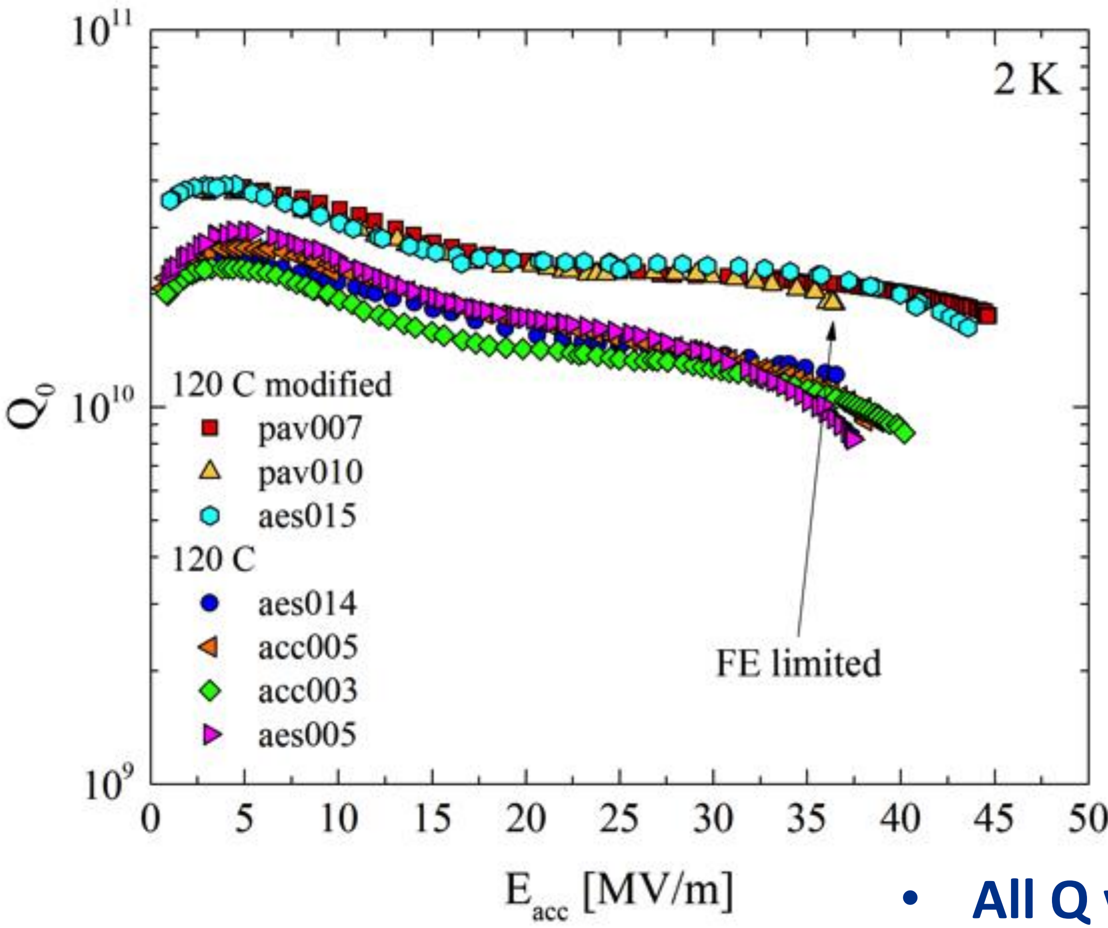
Results comparison :“standard” 120C bake vs “N infused” 120C bake



- Same cavity, sequentially processed, no EP in between
- Achieved: 45.6 MV/m → 194 mT With Q ~ 2e10!
- Q at ~ 35 MV/m ~ 2.3e10
- **All Q vs E curves shown are for 1.3 GHz single cells, T=2K**

Increase in Q factor of two, increase in gradient ~15%

Reproducibility: repeatedly highest Q ever measured >2e10 at very high gradients > 40 MV/m!



Slide from A. Grassellino

- So far three out of 4 cavities processed with this regime have reached 45 MV/m with high Q

- Performed slow cooldown in 10mG and extracted very low sensitivity to B on order of 0.3 nOhm/mG -> very robust for Q preservation

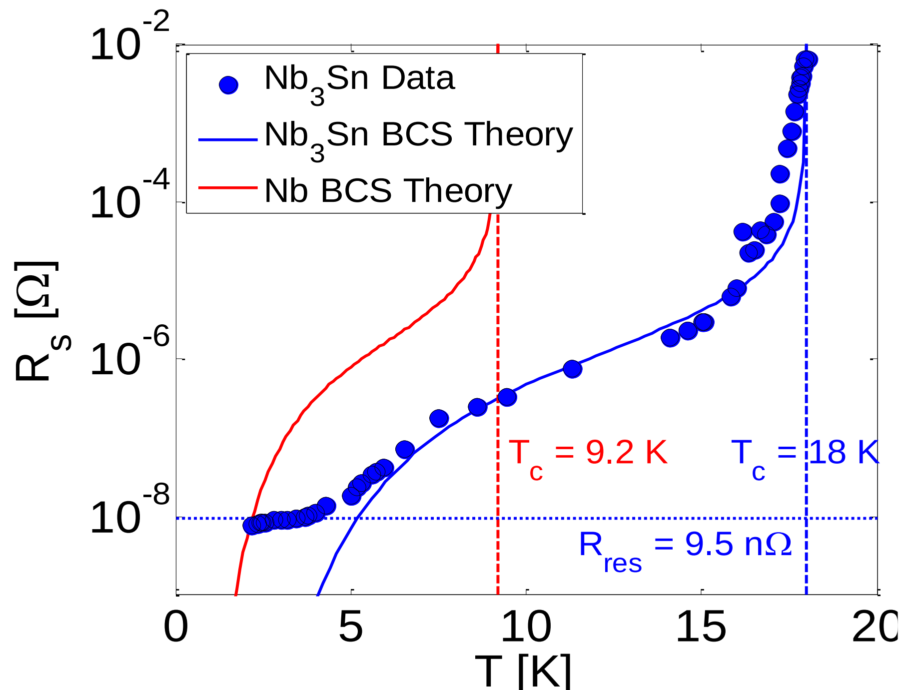
- **All Q vs E curves shown are for 1.3 GHz single cells, T=2K**

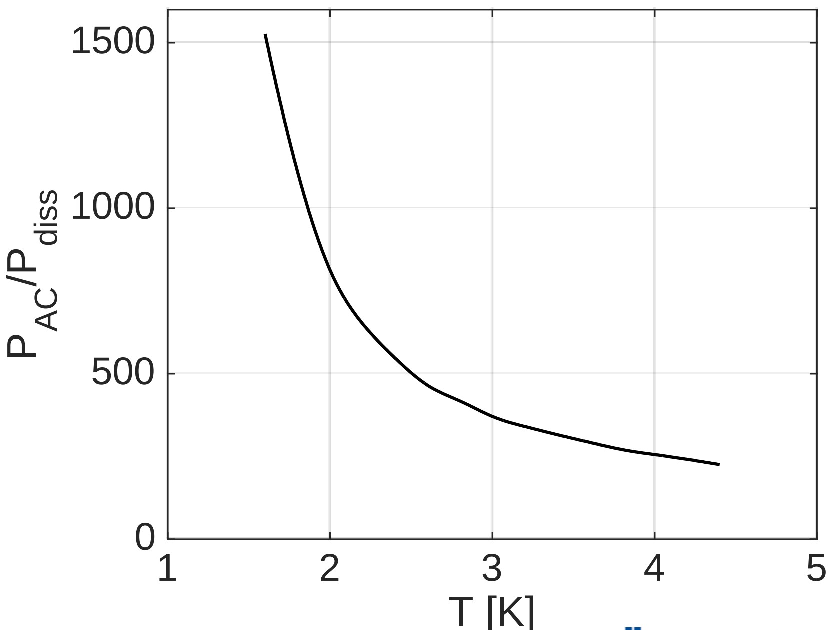
Higher $Q_0(T)$ with Nb_3Sn

- Large T_c ~ 18 K
  - Very small $R_{BCS}(T)$ – $R_{BCS}(T) \sim e^{-1.76T_c/T}$
  - High Q_0 even at relatively high T
- Higher temperature operation
  - Simpler cryogenic plant
  - Higher efficiency

Sumitomo

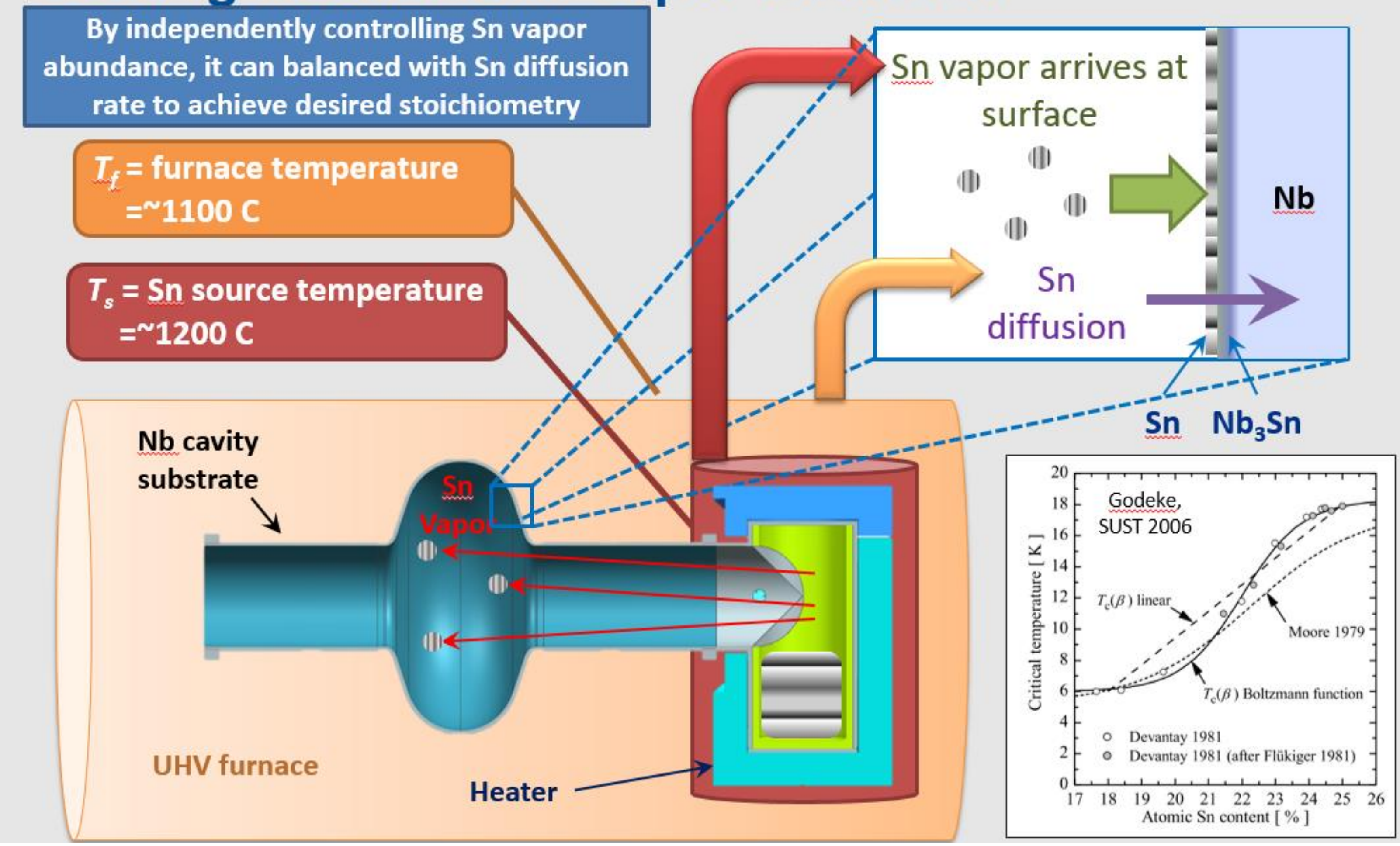
Possibility of cryocooler operation! Industrial accelerators for treatment of wastewater & flue gas, border security…





Nb_3Sn: technology of the future*

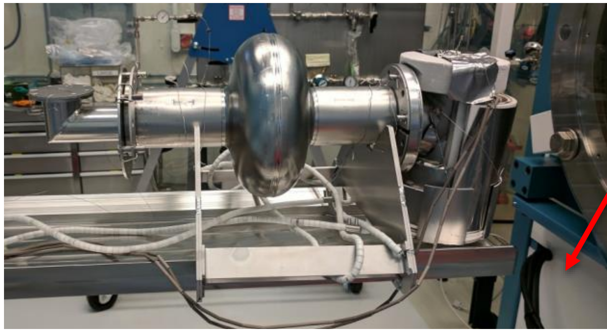
Coating Mechanism: Vapor Diffusion



Technique development: Saur and Wurm, Die Naturwissenchaften 1962, Hillenbrand et al. IEEE Transactions on Magnetics 1977, Peiniger et al, SRF'88.

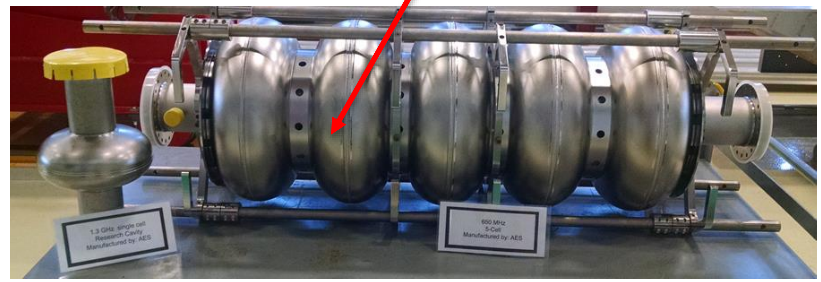
*S. Posen and D.L. Hall, Supercond. Sci. Technol., 30 033004 (2017).

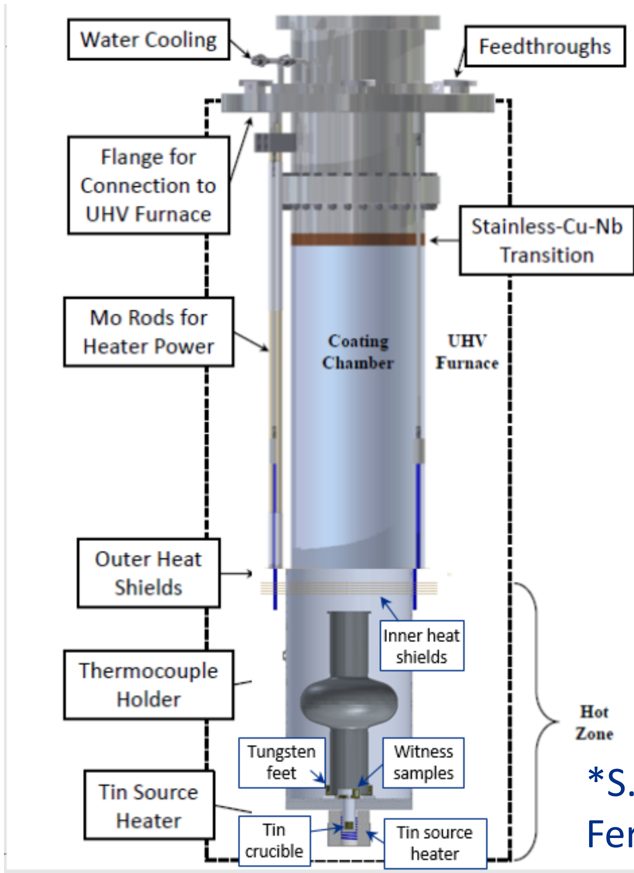
Nb_3Sn: Cornell University – Fermilab*

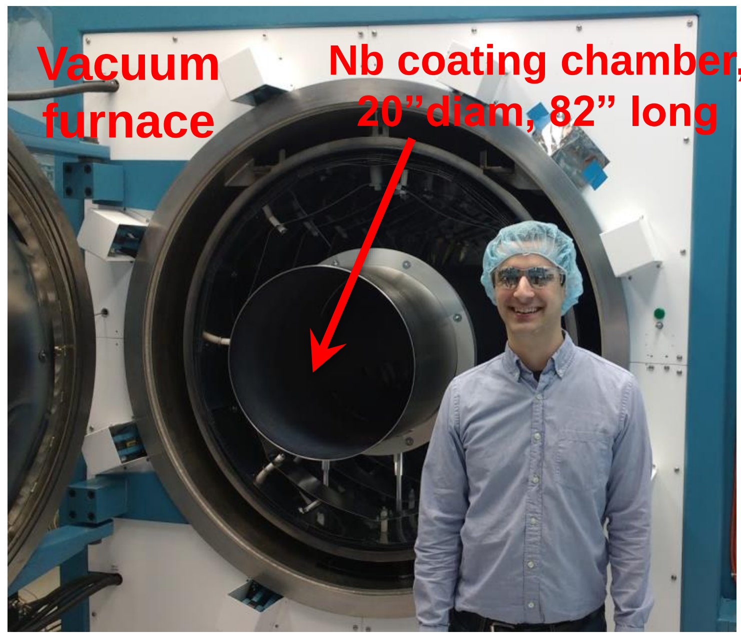


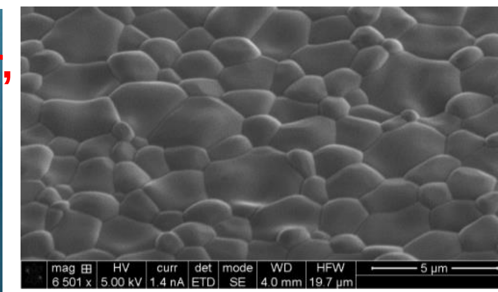
State of the art Nb_3Sn coatings: 1.3 GHz 1-cell

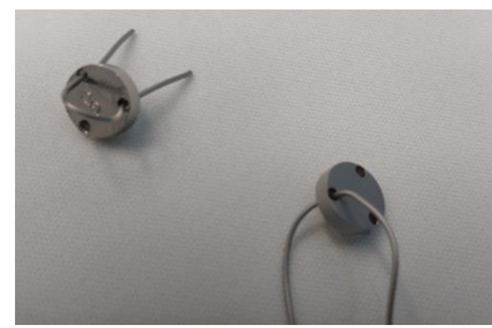
Scale up to 1.3 GHz 9-cell & 650 MHz 5-cell











*S. Posen, State-of-the-Art Superconducting RF Technology for Accelerators, Fermilab Colloquium, 2017

Cornell University Results

Fermilab Results

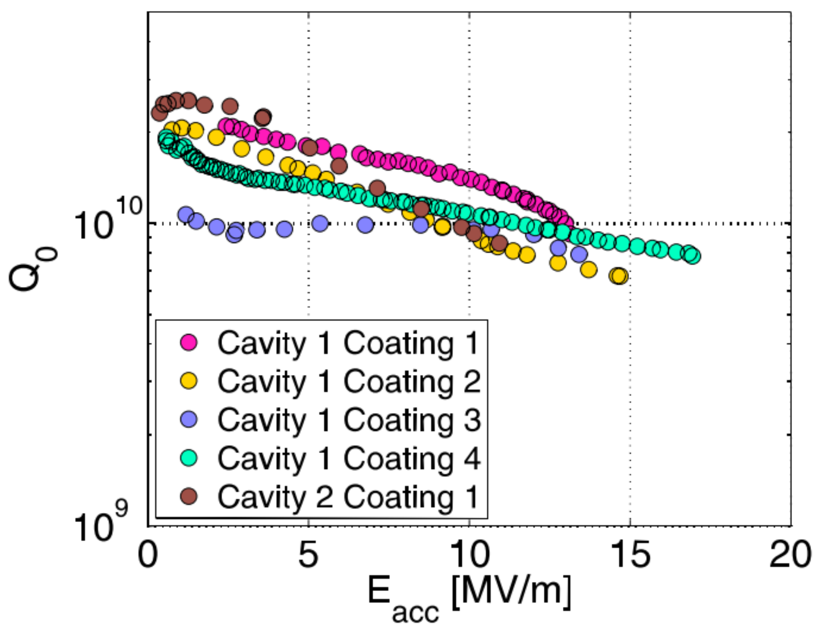
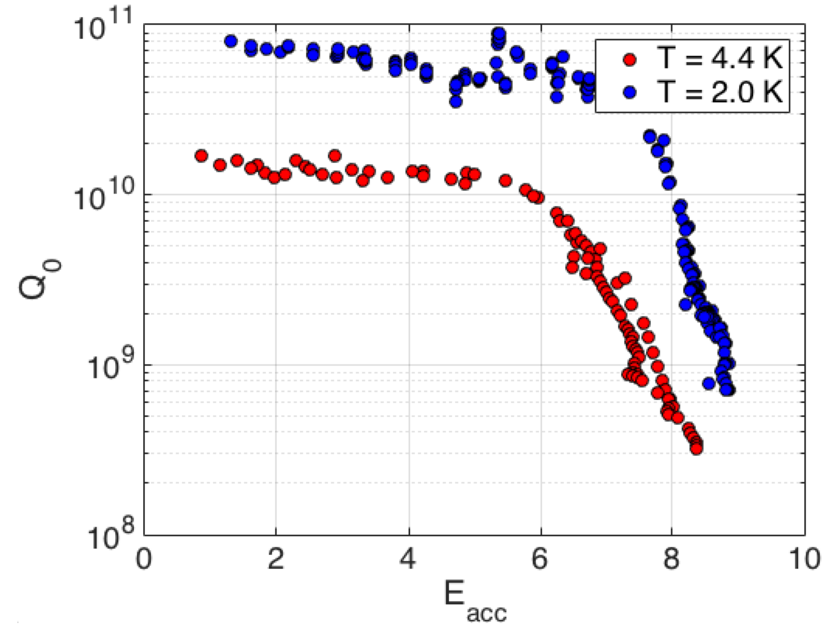


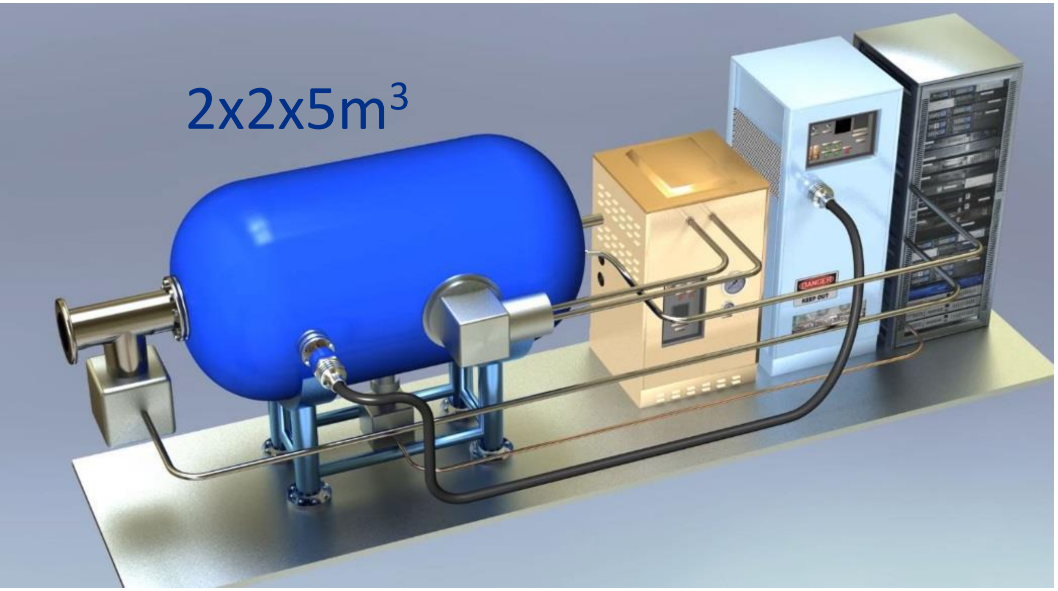
FIG. 1. Q_0 at 4.2 K as a function of E_{acc} for five Nb_3Sn coatings of single cell 1.3 GHz SRF cavities. Uncertainty in Q_0 and E_{acc} is approximately 10%.

S. Posen and M. Liepe, Phys. Rev. ST Accel. Beams 17, 112001 (2014).



- Current focus on 1-cell cavities and in particular strong Q-slope
- So far some type of strong Q-slope observed in all tests
- Working with Northwestern materials science to explore role of microstructure

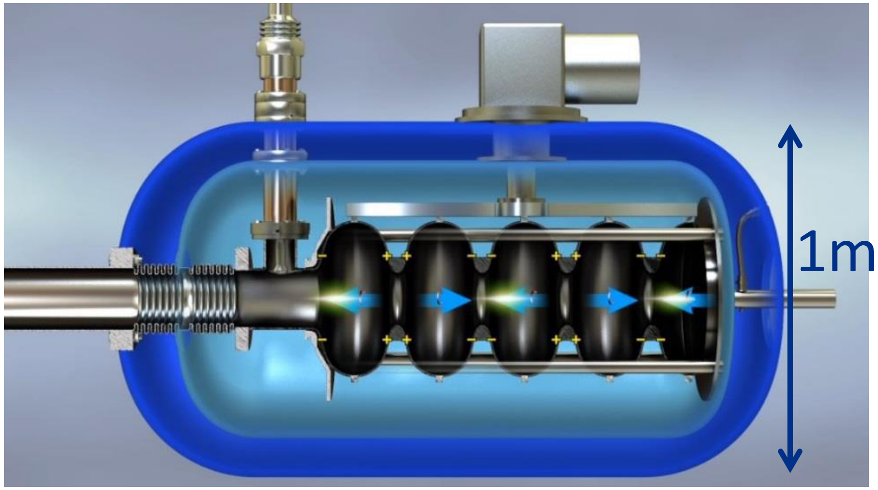
IARC Industrial SRF accelerator project based on Nb_3Sn*



- Low cost
- High efficiency
- RF frequency: 650 MHz
- Nb3Sn 4.5-cell cavity
- Operation temperature ~5K
- Conduction cooling (no He vessel)
- Cryo-cooler
- Magnetron-based RF source
- Built-in multi-frequency RF gun
- Energy: 10 MeV
- Power: 250 kW CW

Applications:
- Pavement improvement
- Civil water treatment

*R.D. Kephart, et al., SRF2015



Summary

- New projects of large high-duty factor and CW SRF linac demand low cryogenic losses and therefore, high Q_0
- New SRF cavity processing technologies
  - N-doping
  - Fast cooling

  are moved from discovery to industry opening the door for large CW linac construction (LCLS II, PIP II, ADS, etc.).
- Nitrogen infusion technology allows high Q_0 at high gradient – very attractive for future liniear colliders (ILC?)
- Nb_3Sn allows very high Q_0 at higher operating temperature, ~4K, which would cause a revolution in SRF for accelerator application (especially for industrial accelerators).

Acknowledgements

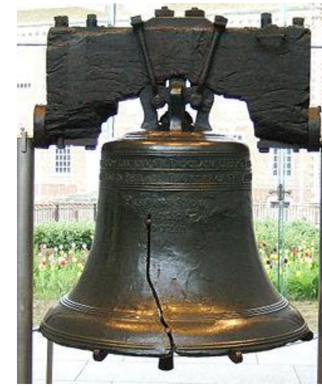
I would thank our colleagues from Fermilab, who made a great job developing SRF technology for accelerators, and who provided the information for this presentation:

- Anna Grassellino;
- Robert Kephart
- Arkadiy Klebaner;
- Martina Martinello;
- Sam Posen;
- Nikolay Solyak;
- Jay Theilacker;

and many others.

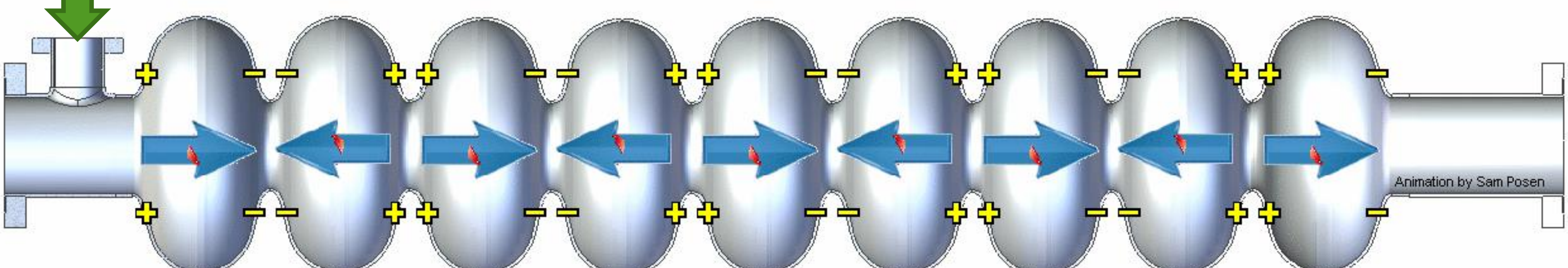
Particle Acceleration via SRF Cavities

- **Superconducting radiofrequency (SRF) cavities**
- High quality EM resonators: Typical $Q_0 > 10^{10}$
- Over billions of cycles, large electric field generated
- Particle beam gains energy as it passes through



Input RF power at 1.3 GHz

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



Niobium

~1 m

Images from linearcollider.org, WIkipedia