What's next with SRF?

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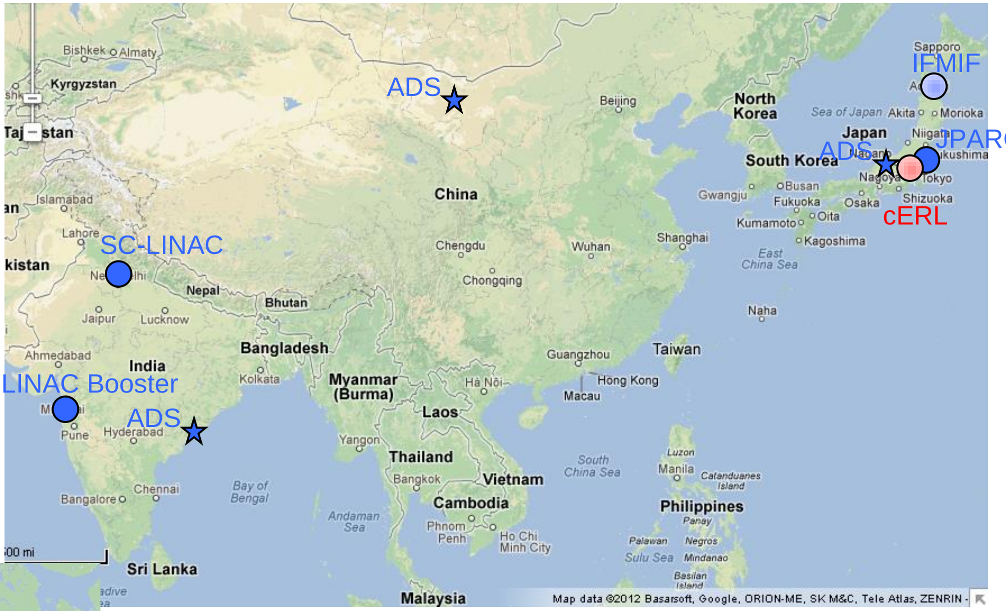
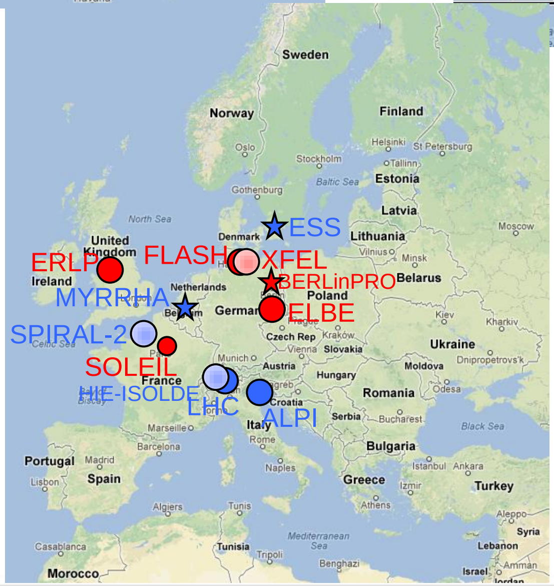
Outline

- Status of SRF
- Historic perspective on thin-film technology for SRF
- Implication of potential Q_0 improvements on future accelerators
- Conclusions

Review Article: C. E. Reece and G. Ciovati, "Superconducting Radio-Frequency Technology R&D for Future Accelerator Applications", *Rev. Accel. Sci. Technol.* **5**, 285 (2012)

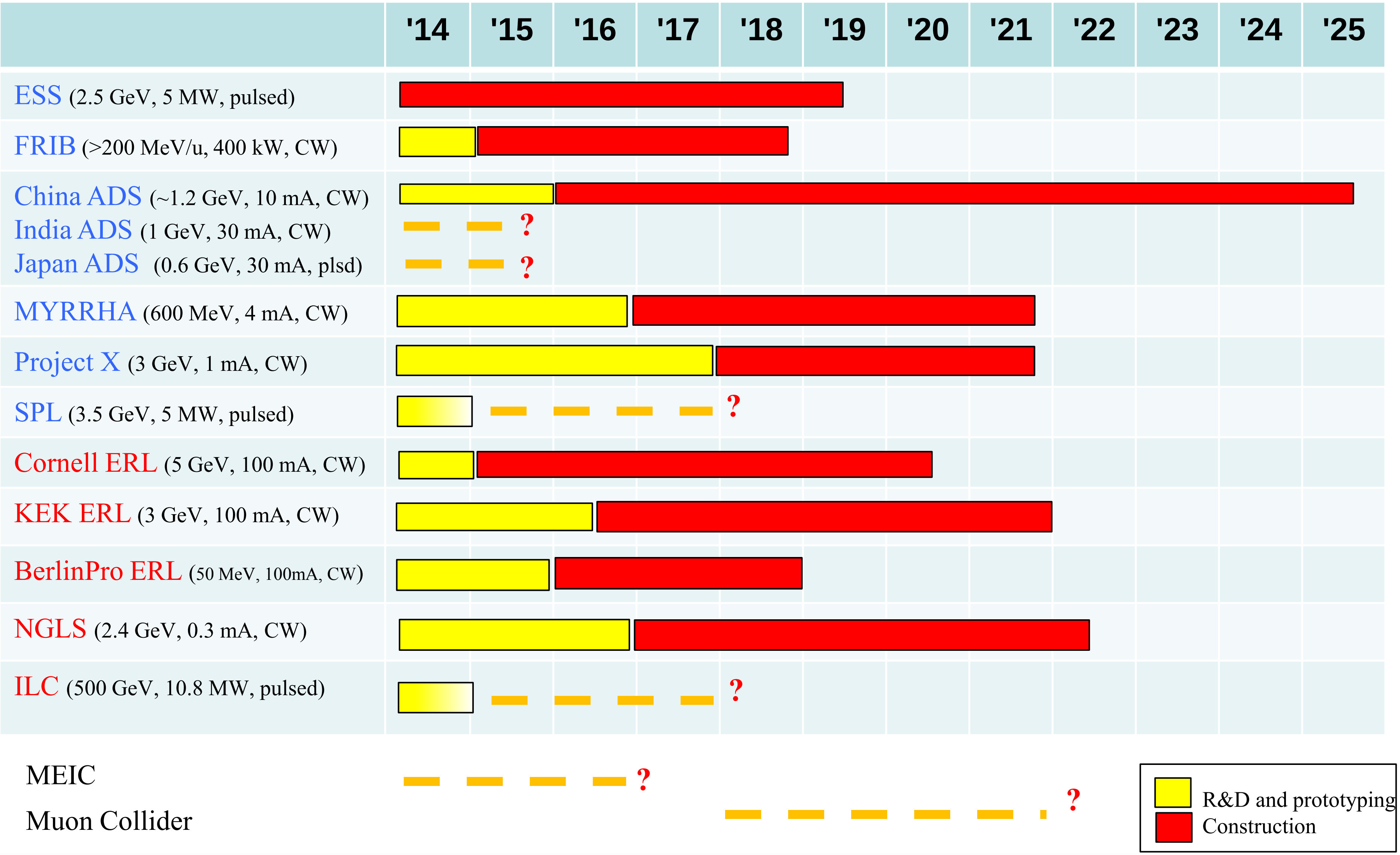
SRF Accelerators in the World (> 5 cavities) · ~2025





Red = electrons
Blue = protons/ions

Timelines for future projects



SRF: a reliable technology

Beam availability at SNS [*S.-H. Kim, TTC'12, Newport News, VA*]:

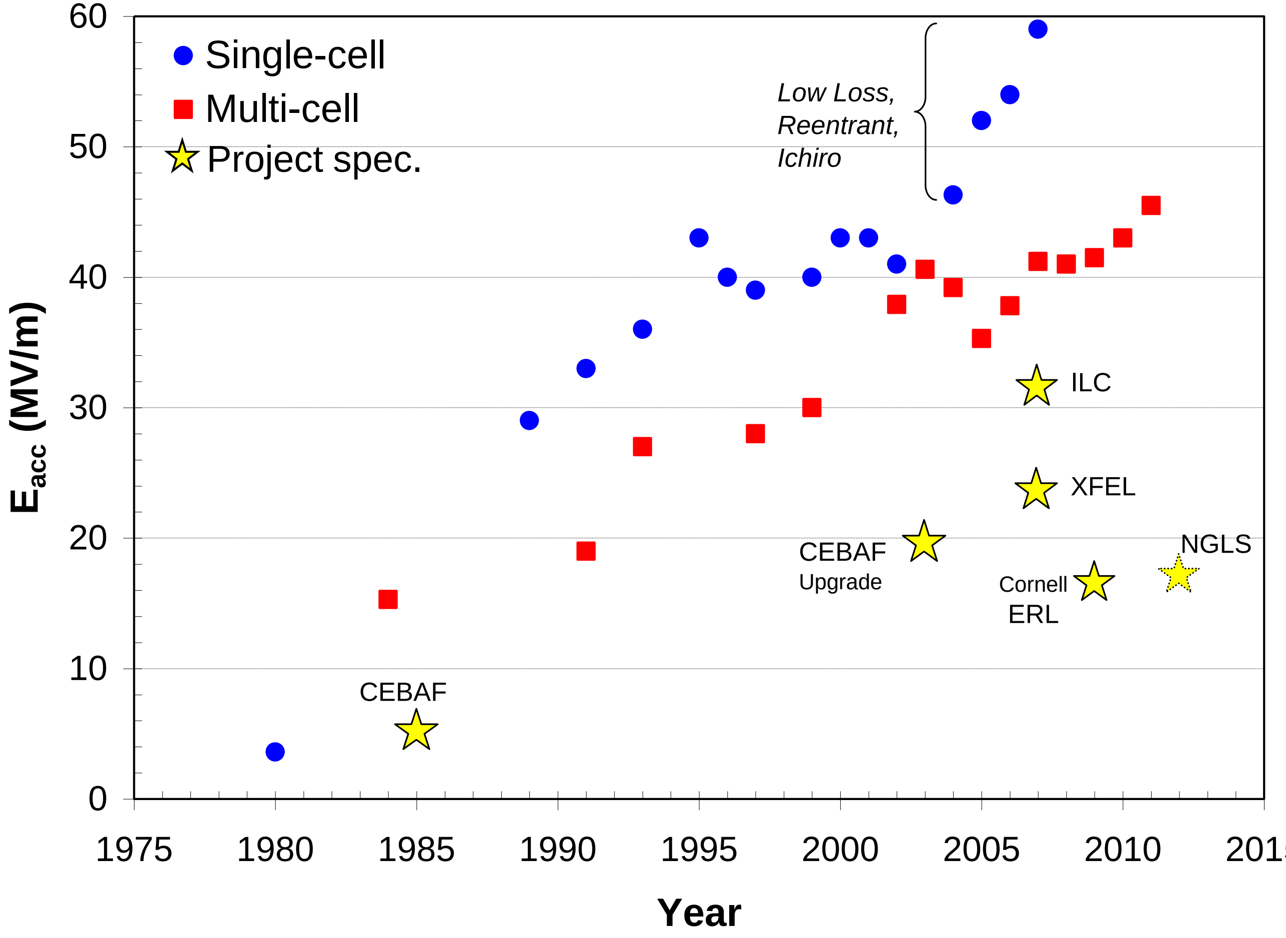
- Average trip (downtime): < 1 trip/day (<5 min/day)
- Whole SCL system: 98 %, SCL cavities/cryomodules/CHL: 99.5 %

Survey of beam availability of SRF accelerators [*A. Hutton and A. Carpenter, PAC'11, New York, NY*]:

- Average downtime from SRF and support systems: 3.7% (mainly RF power and cryo)

All future projects proposed so far rely on bulk Nb technology

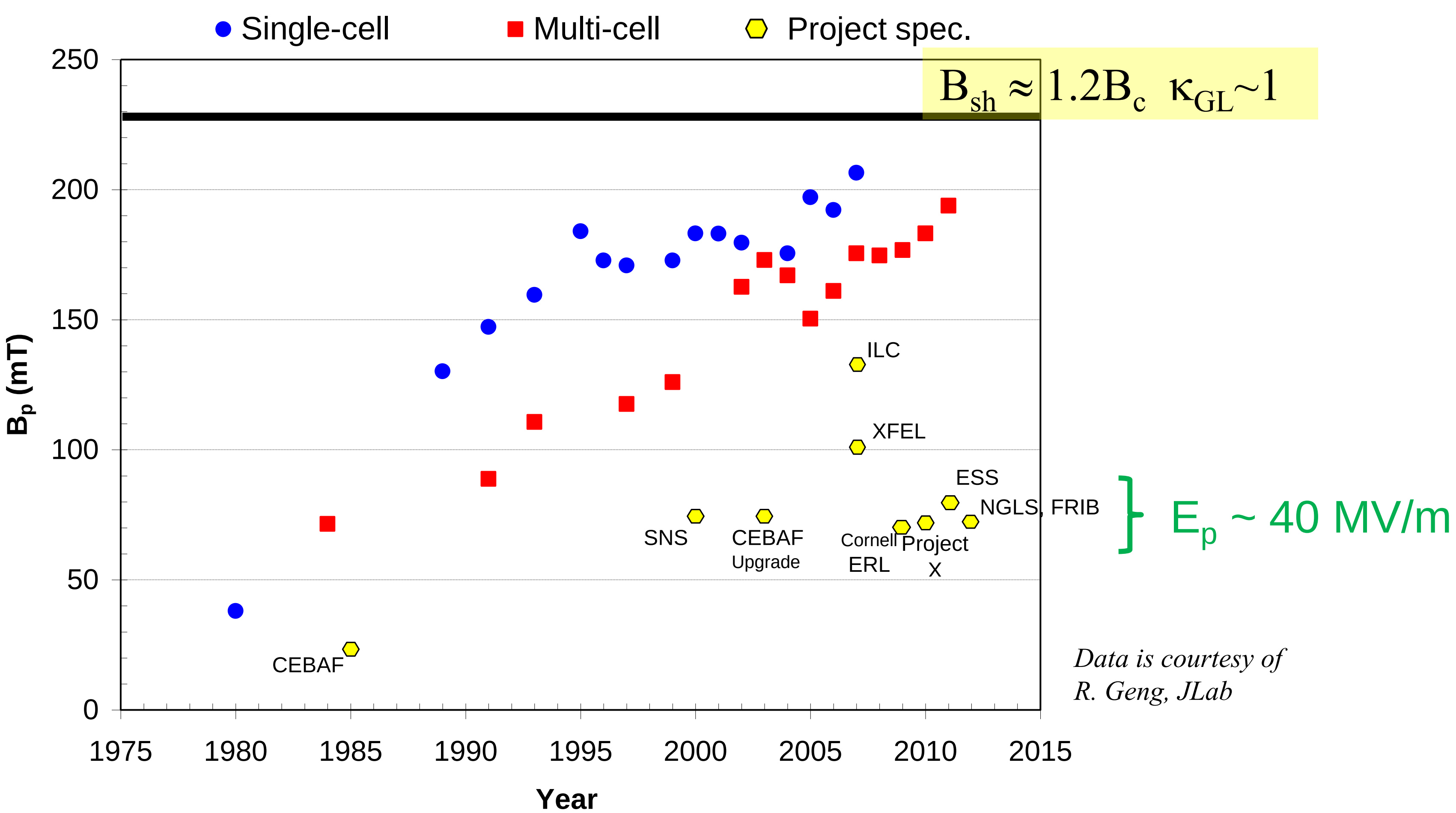
Accelerating gradient, L-Band β=1 cavities



Data is courtesy of R. Geng, JLab

- E_{acc} > 50 MV/m is yet to be achieved in "low B_p" multi-cell cavities
- Average gradient specification of current and future projects is ~20 MV/m

Peak surface magnetic field, bulk Nb, 2 K



Data is courtesy of R. Geng, JLab

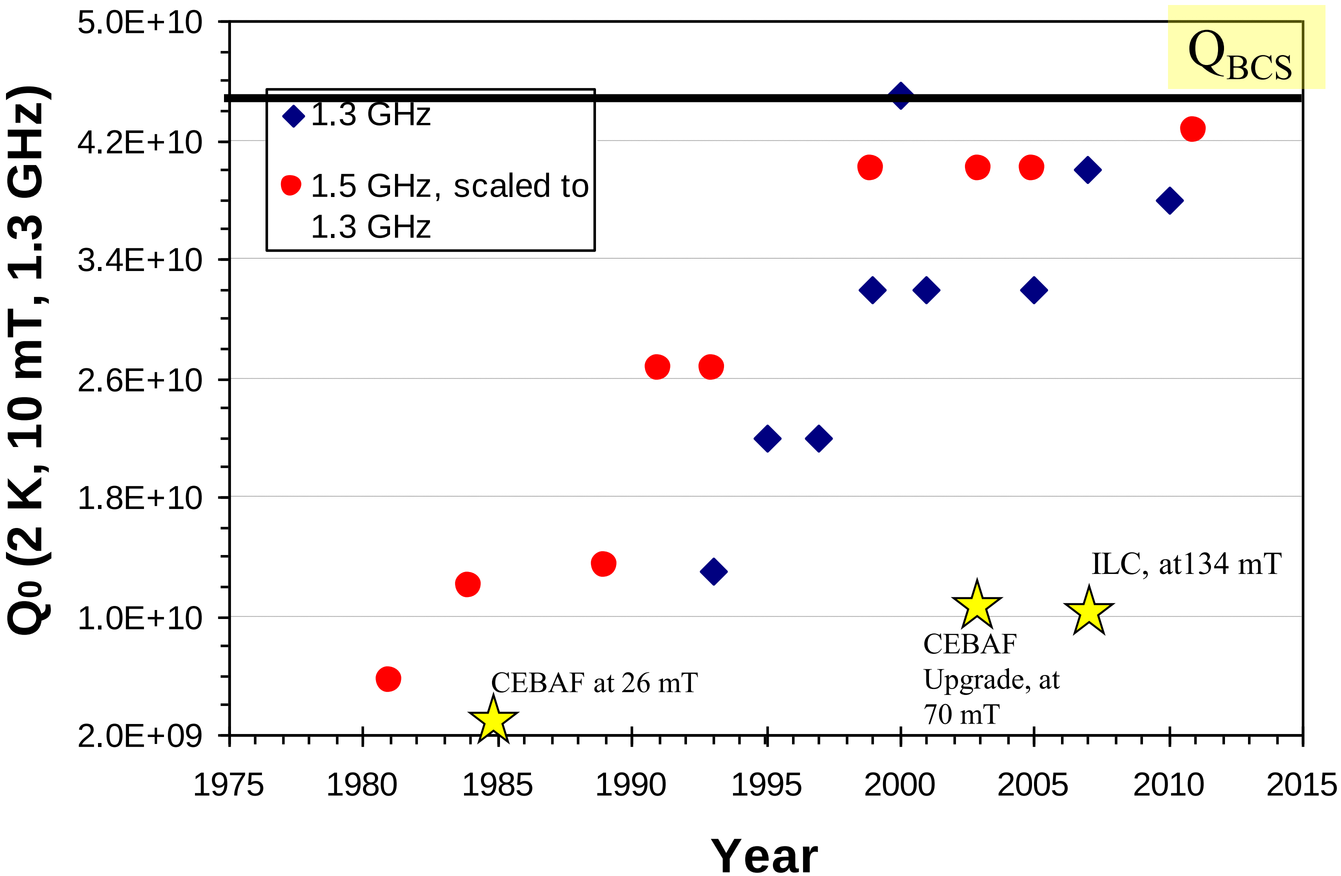
- Most current and future project B_p-spec is lower than highest measured value by a factor ~2.5
- Highest B_p achieved is within 10% of theoretical limit of the material

SRF cavities: future requirements?

- Improve yield (confidence) at high peak surface fields, particularly for low-β cavities [*Proton Linacs*]
  - Field emission control
  - Control of weld related defects

- For many envisioned future SRF accelerator projects [*ERL, CW Linacs*], the push towards increasing accelerating gradients is constrained by the increase in cost from cryogenics and RF power. The push towards **higher Q_0** will be more beneficial.

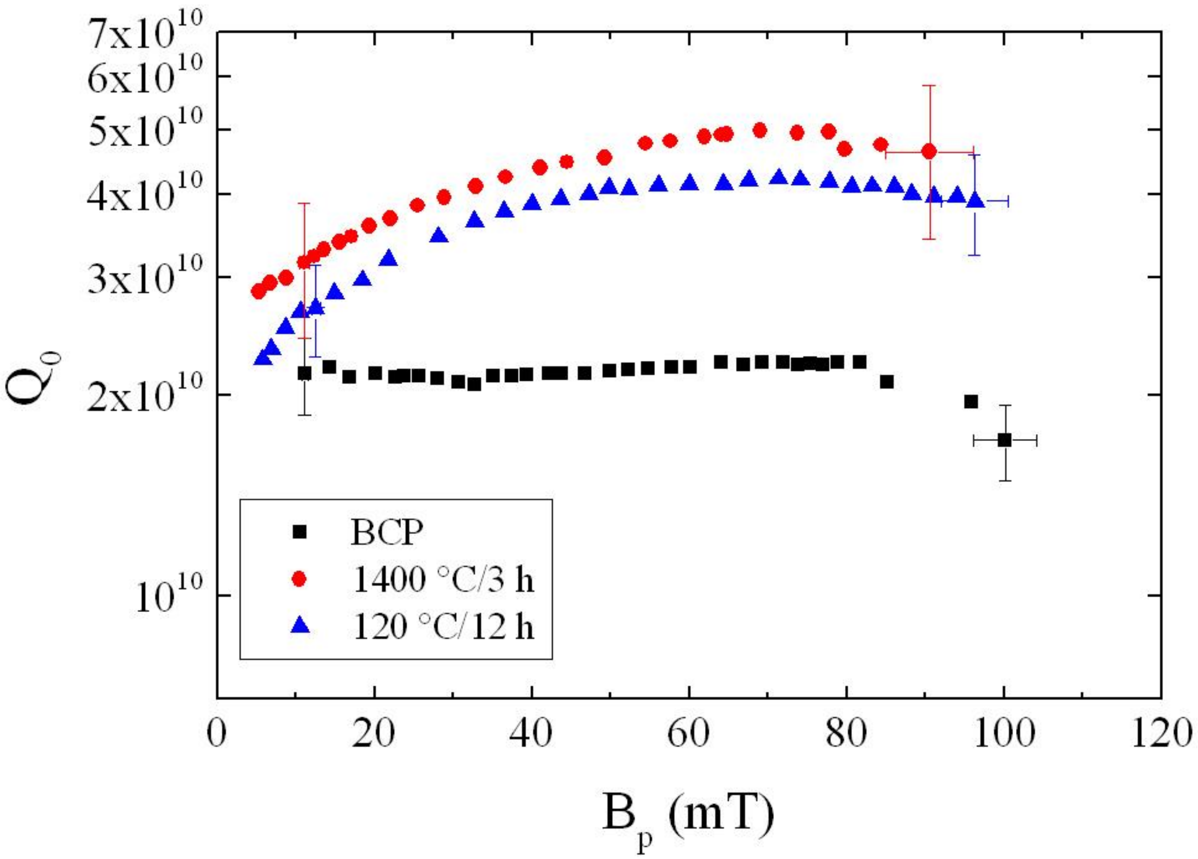
Q_0(2 K), bulk Nb



Compiled by G. Ciovati, JLAB-TN-12-018, 2012

- Highest Q_0 achieved is at the theoretical limit of the material
- Typically Q_0 decreases with increasing rf field

Nb cavities with exceptionally high Q_0(2 K)



Single cell cavity, 1.5 GHz, made from Ingot Nb, RRR~200

P. Dhakal et al., Phys. Rev. ST Accel. Beams. ***16****, 042001 (2013)*

- Recent R&D efforts towards increasing Q_0 are already showing very encouraging results!!!

Ingot Nb technology

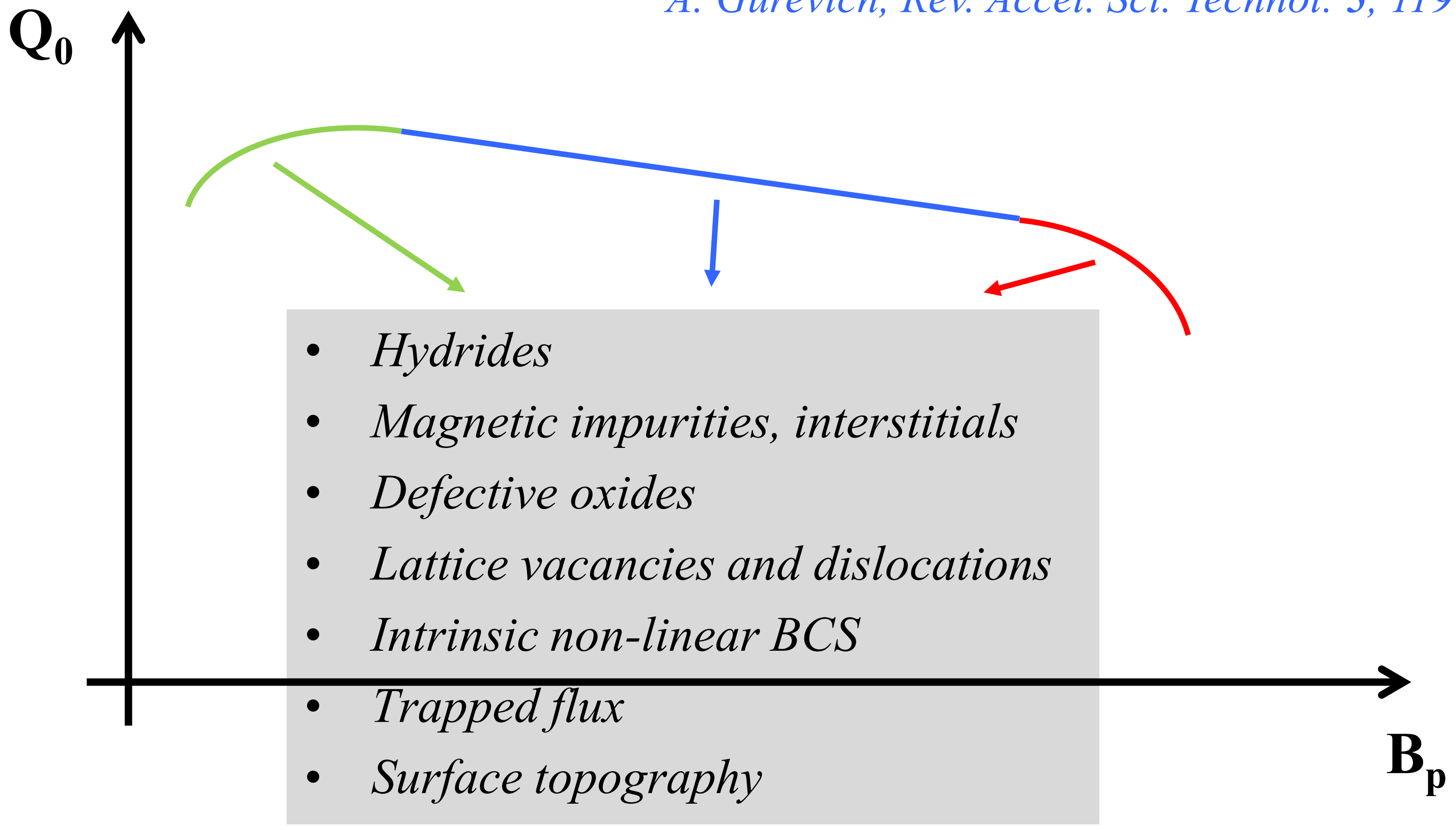
- Cavities built with ingot Nb achieved:
  - Highest accelerating field (~46 MV/m) in a multicell cavity [*W. Singer et al., Phys. Rev. ST Accel. Beams.* ***16****, 012003 (2013)*]
  - Highest Q_0-value at 2.0 K and medium gradient (~20 MV/m) [*P. Dhakal et al., Phys. Rev. ST Accel. Beams.* ***16****, 042001 (2013)*]

- Significant material cost savings are expected, particularly if Ta content up to ~1500 wt.ppm can be used

⇒ Mitigate steep rise in price of high-RRR, fine-grain Nb in the last 3 years

SRF science of Nb: unknowns

A. Gurevich, Rev. Accel. Sci. Technol. ***5****, 119 (2013)*



- *Hydrides*
- *Magnetic impurities, interstitials*
- *Defective oxides*
- *Lattice vacancies and dislocations*
- *Intrinsic non-linear BCS*
- *Trapped flux*
- *Surface topography*

As the cavity performance gets closer to theoretical limits, it is more difficult to isolate a single cause for increased surface resistance

What's better than Nb?

- s-wave superconductor
- Higher T_c, higher energy gap, higher H_{sh}
- Low normal-state resistivity

Material	T_c (K)	H_c [T]	H_{c1} [mT]	H_{c2} [T]	$\lambda(0)$ [nm]	Δ [meV]	H_{sh} [mT]
Nb	9.2	0.2	170	0.4	40	1.5	0.24
NbN	16.2	~0.23	20	15-25	200	2.6	~0.19
(NbTi)N	17.5	~0.28	30	~20	~200	3.0	~0.24
Nb_3Sn	18	~0.5	40	30	85	3.1	~0.42
MgB_2	40	~0.32	20-60	3.5-60	140	2.3; 7.1	~0.27

$H_{sh} \approx 1.2 H_c$ $\kappa \sim 1$, $T \sim T_c$
$H_{sh} \approx 0.84 H_c$ $\kappa >> 1$, $T << T_c$

Note: SC properties of thin films can change significantly depending on the preparation method

The H_{c1} conundrum

- Theoretically, the field at which the vortex-free state becomes unstable is H_{sh}
- However, $R_s(H_{sh}) \sim R_n$ [$\varepsilon_g(H_{sh})=0$ in clean limit, $\varepsilon_g(H_{sh})=0.32\Delta_0$ in dirty limit]. [*F. Pei-Jen Lin and A. Gurevich, Phys. Rev. B **85**, 054513 (2012)*]
- Defects in technical SC films could lower the surface barrier down to H_{c1} causing strong rf losses above ~20-50 mT

Multilayer approach

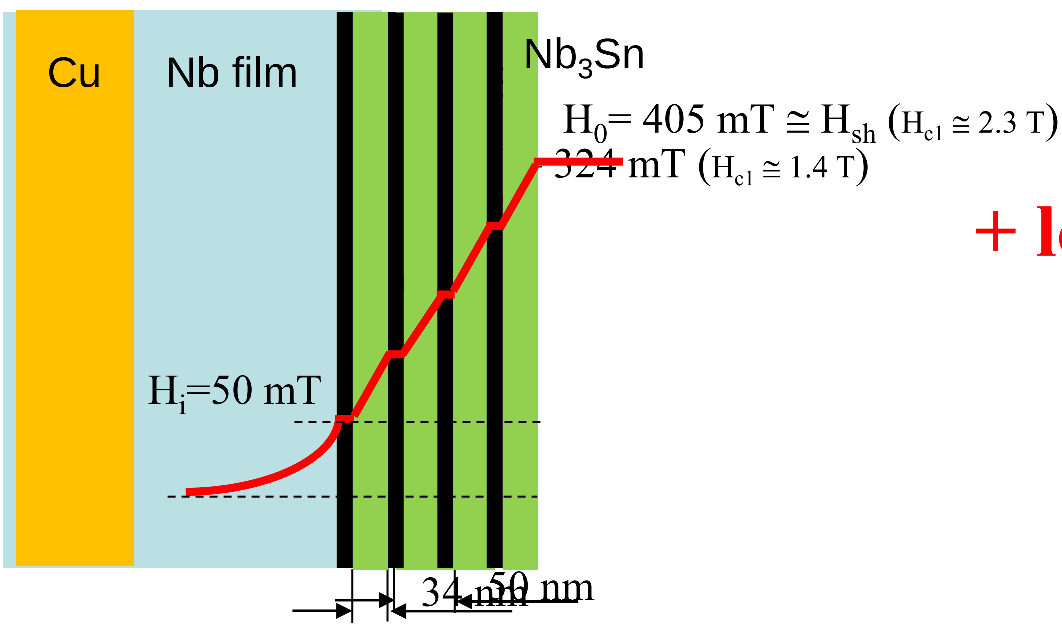
- Enhancement of H_{c1} in films with thickness $d < \lambda$ [*A. A. Abrikosov, Sov. Phys. JETP* ***19****, 988 (1964)*]

$$H_{c1} = \frac{2\phi_0}{\pi d^2}\left(\ln\frac{d}{\xi} - 0.07\right)$$

- S-I-S films with d < λ on Nb [*A. Gurevich, Appl. Phys. Lett.* ***88****, 012511 (2006)*]

$$H_i = H_0 \exp(-Nd/\lambda)$$

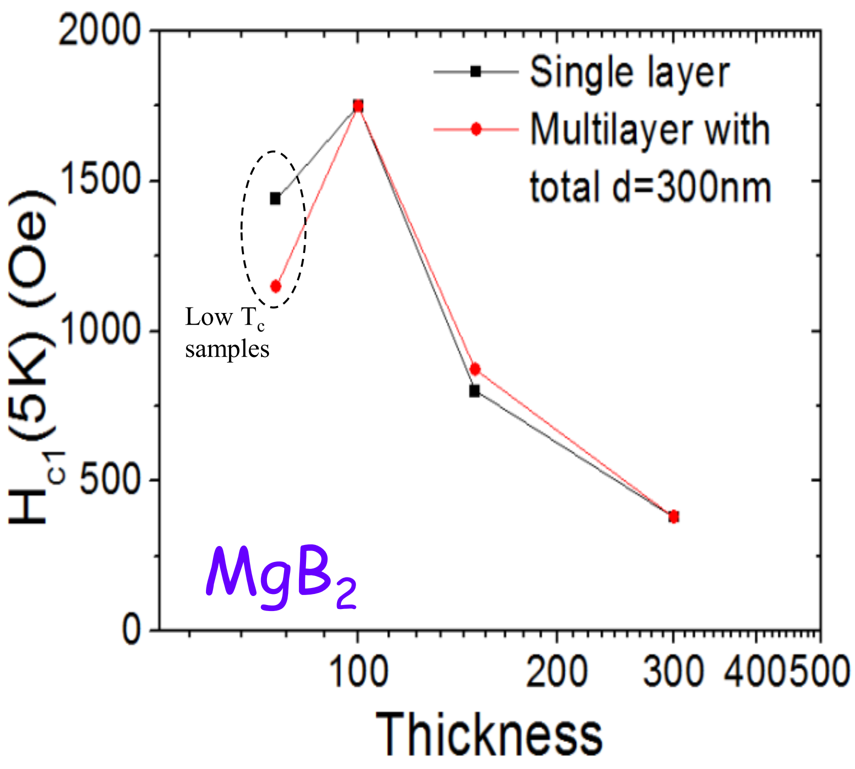
Example: Nb_3Sn (λ=65 nm, ξ=3 nm)



+ lower R_s

Enhancement of H_{c1} in very-thin films

- Experimental confirmation of H_{c1} enhancement in "very-thin" ($d < \lambda$) films was found for Nb, NbN and MgB_2 samples by DC magnetization measurements



Teng Xi, ASC 2012, Portland, OR

Thin-film R&D: historic perspective

- Nb/Cu films at CERN

1980

R&D on
sputterin

1985

R&D on
sputterin

1992

LEP cavity production
(272 cavities, 4×10^9 @ 6 MV/m, 4.2 K)

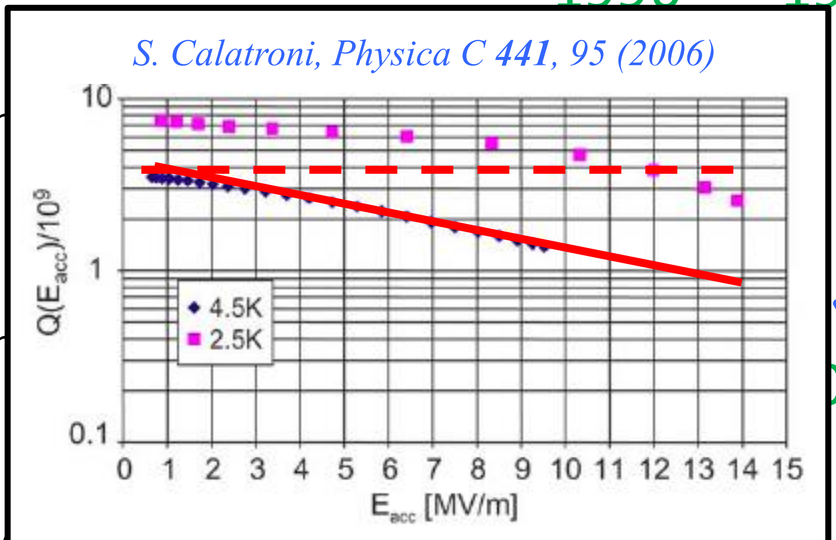
1996

1996 1996

ıvities (20 cavities, 5.5 MV/m, 4.2 K)

R&D on low-β cavity application and ultimate performance

003



- ~7 years R&D
- Technology met projects specs.
- Origin of Q-slope unclear

Thin-film R&D: historic perspective

- Nb/Cu films at INFN-Legnaro

1991 → 1996: R&D on DC biased diode sputtering

2003 → 2007: R&D on magnetron sputtering

1998 → 2003: ALPI cavity production (44 cavities, 4.4 MV/m @ 7 W, 4.2 K)

- ~5 years R&D
- Technology met project specs.

Nb_3Sn: a case of missed opportunity

P. Kneisel, "History of Nb_3Sn Developments for Superconducting RF Cavities – A Review", JLab Technical Note TN-12-016

- Activities at many labs throughout the world (Siemens AG, Kernforschungszentrum Karlsruhe, Uni Wuppertal, JLab/Univ. Wuppertal, CERN, Cornell Univ., SLAC, Stanford) since 1973

1973 → 1983

Siemens: TE, TM cavities @ 9.7 GHz, B_{max} ~ 90 mT
Q_{max} ~2×10^9 at 4.2 K

1989 → 1997

Univ. Wuppertal: elliptical cavities, B_{max} ~ 50 mT
Q_{max}~1×10^{10} at 4.2 K @ 1.5 GHz and 10 mT

After ~14 years, R&D activities have re-started at Cornell Univ. and JLab

Thin film R&D activities: recent history

Nb

2002

JLab: energetic deposition by ECR

2005 **CERN**: HiPiMS

2010 **JLab/AAS, Corp**: Coaxial energetic deposition

LBNL: HiPiMS

present

Nb and A15 compounds

2005

INFN-Legnaro: Nb_3Sn, NbN, V_3Si

2008

ANL: NbN, (NbTi)N, NbSi

Saclay: NbN

2010

JLab: (NbTi)N

present

MgB_2

2003

PSU/Temple Univ.: HPCVD

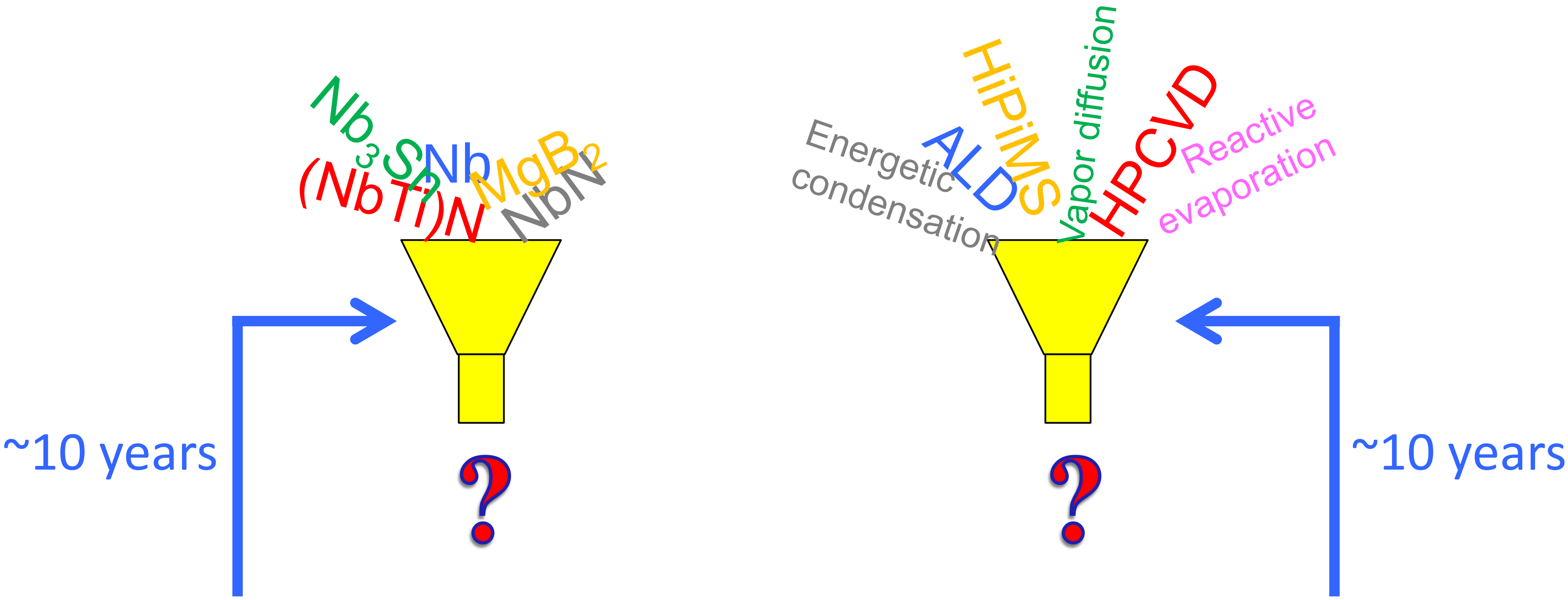
2005

LANL/ST, Inc.: Reactive evaporation

present

- > ~5 years R&D already
- Mostly techniques development, very few RF measurements

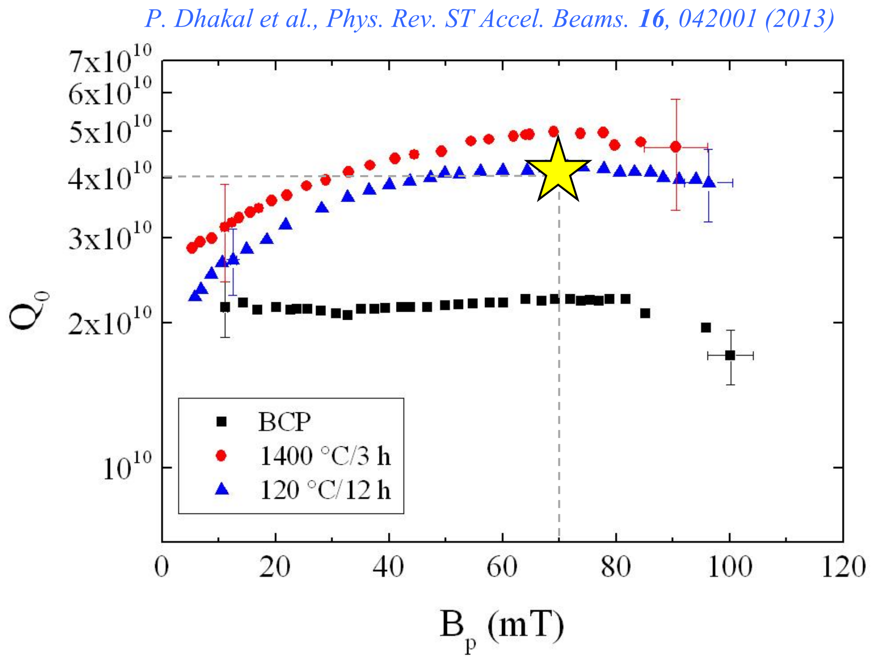
Thin film development: future outlook

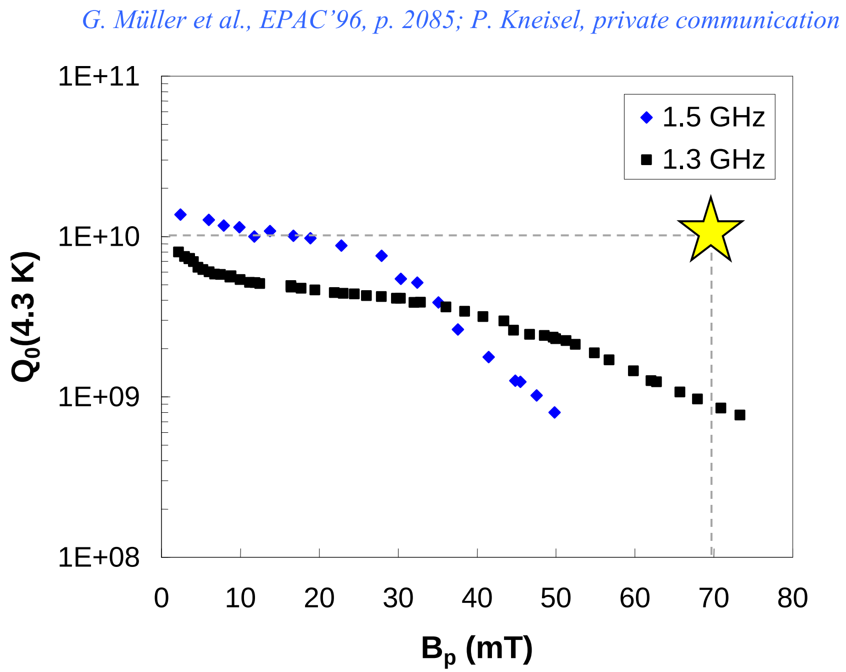


Might need a large *accelerator project* or small accelerator project with large market potential which *have to be built with specs. that bulk Nb technology cannot satisfy*

(e.g. Muon Collider?)

Nb at 2 K or Nb_3Sn at 4.2 K?





- Suppose that SRF technology will evolve to meet the following specs. on multi-cell cavities
  - $Q_0 = 4\times10^{10}$ at 2 K, 1.5 GHz, 70 mT (**Nb**)
  - $Q_0 = 1\times10^{10}$ at 4.2 K, 1.5 GHz, 70 mT (**Nb_3Sn**)

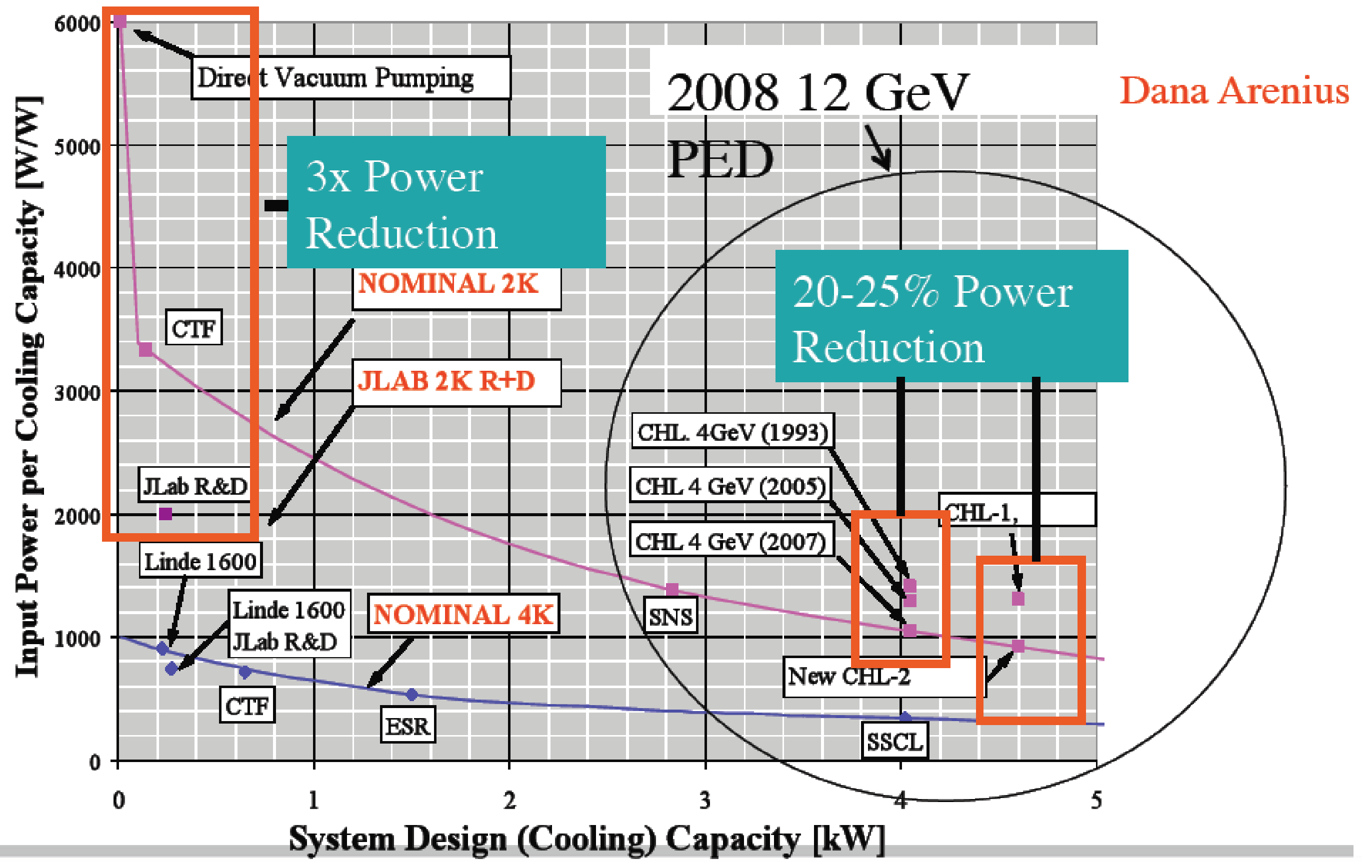
Which will have greater impact?

ADS and Light Sources

- Consider the impact of Nb cavity with $Q_0(70\ \text{mT}, 2\ \text{K}) = 4\times10^{10}$ or Nb_3Sn cavity with $Q_0(70\ \text{mT}, 4.2\ \text{K}) = 1\times10^{10}$ on:
  - two possible accelerators which would lead to a wide-spread use of SRF:
    - 1 GeV, 20 mA, CW proton Linac for *Accelerator Driven Systems* (ADS)
    - *Compact Light Source* (CLS)
  - a "one-of-a-kind" research accelerator: 2.4 GeV, 0.3 mA, CW electron Linac for *Next Generation Light Source* (NGLS)

Estimates of power consumption

- $\mathbf{P_{diss}} = E_{acc}^2 L^2/(R/Q)Q_0 \propto \mathbf{1/Q_0}$
- Cryoplant overcapacity factor = 1.54
- COP_{inv} from



Example: CW Linac for ADS

- 20 mA, CW, SNS-style Linac with a β=0.61 section (186 MeV → 375 MeV and a β=0.81 section (375 MeV → 1 GeV) with 805 MHz elliptical cavities

	β=0.61		β=0.81	
	Nb at 2 K	Nb_3Sn at 4.2 K	Nb at 2 K	Nb_3Sn at 4.2 K
E_{acc} (B_p = 70 mT)	12 MV/m		15.9	
No. of cells	6		5	
No. cavities	30		60	
No. cryomodules	10		15	
Power Coupler RF Power	135 kW		220 kW	
Q_0 (70 mT)	4×10^{10}	1×10^{10}	4×10^{10}	1×10^{10}
Avg. dynamic losses/module	11.3 W	45.2 W	27 W	108.3 W
Static losses/module	20 W	60 W	20 W	60 W

	Nb at 2 K	Nb_3Sn at 4.2 K
Total heat load	1019 W	3576 W
Cryo-plant cooling capacity	1.57 kW	5.5 kW
Efficiency	2000 W/W	350 W/W
AC Power for Cryo	3.1 MW	1.9 MW
RF Power	20 MW	
AC Power for RF (60% efficiency)	33 MW	

Compared to ~4.5 MW with Q_0 of 8×10^9 achievable today with Nb at 2.0 K

Cost of 4.2 K cryo-plant ~20% less than the 2 K one

AC Power for Cryo ~10% AC Power for RF

Example: Compact Light Source

- CW, 1 mA avg., 20 MeV electron Linac for Compton Sources [*G. Krafft and G. Priebe, Rev. Accel. Sci. Tech.* ***3****, 147 (2010) 147*]
- Operation at 4.5 K is the only option (operational and capital cost of small 2 K cryo-plant is too high)
- Bulk Nb cavities at low-frequency (400 MHz) allows building such accelerator with < 200 W cooling power at 4.5 K

	Current design (Nb)	**Nb_3Sn**
Frequency	400 MHz	1.5 GHz
No. of cells	3	7
No. cavities	2	
Q_0(4.5 K)	3.5×10^9	1×10^{10}
Accelerating gradient	7.7 MV/m	12 MV/m
R/Q	468 Ω	869 Ω
Total dynamic losses	88 W	17 W

With Nb_3Sn:
- lower operating and cryoplant cost
- lower cavities material cost
- smaller cryostat

Example: NGLS

- 2.4 GeV, 0.3 mA, CW electron Linac for NGLS with 1.3 GHz ILC-type cavities [*J. Cortlett, "NGLS Outline and Functional Requirements", Workshop on CW SCRF Linacs for X-ray Laser Applications, Fermilab, September 26, 2012*]

	Current design	High Q Nb at 2 K	Nb_3Sn at 4.2 K
Operating temperature	**1.8 K**	**2.0 K**	**4.2 K**
Average operating gradient		~16 MV/m	
Average Q0	2×10^{10}	4×10^{10}	1×10^{10}
No. cavities		189	
No. cryomodules		27	
Dynamic losses/module	114 W	57 W	228 W
Static losses/module	6 W	6 W	18 W
Cryo-plant cooling capacity (with overcapacity factor of 1.5)	4.86 kW	1.7 kW	6.64 kW
Efficiency	1000 W/W	2000 W/W	350 W/W
AC Power for Cryo	4.86 MW	3.4 MW	2.3 MW
AC Power for RF		~6 MW	
Relative cost of Cryo-Plant	1.5	~1.2-1.3	1

Compared to current design:

- ~20-30% cost reduction in both capital and operational costs with high-Q Nb at 2.0 K
- ~50% cost reduction in both capital and operational costs with Nb_3Sn at 4.2 K

Conclusions (1)

- SRF is the technology of choice for new accelerators for scientific research

- Cavities based on bulk Nb technology satisfy the requirements of SRF accelerators for the next decade
  - Current specs are at ~half of the Nb potential
  - A significant margin could be gained with advances to improve reliability at high-Q and high-field

- Ingot Nb has emerged as a better option than standard fine-grain Nb for improved performance and reduced cost

Conclusions (2)

- Nb R&D over the last decade (ingot Nb, furnace treatments) show that the science of Nb for SRF is not at the end

- SRF-based accelerators could become widespread tools for electric power generation (ADS) and for compact light sources

Conclusions (3)

- Efforts in thin-film developments are been pursued by many labs/universities since the past 5-10 years
- In few cases, coating of real cavities have begun

  Sustained effort for at least the next 5-10 years and the "drive" of a real accelerator project which can only be built with cavities other than Nb might be needed.

- Nb_3Sn is (again) one of the most promising alternatives to bulk Nb
  - if new experiments will confirm limits in the Siemens/Wuppertal technique to produce cavities with $\sim 1\times 10^{10}$ at 4.2 K and $E_{acc}\sim 15$ MV/m, a "minimalistic" multi-layer approach [bulk Nb/insulator/thin Nb_3Sn] could be a possible solution (however this cannot use the Siemens/Wupp. technology)
- Improvements in efficiency with bulk Nb at 2 K and thin-films at 4.2 K would significantly reduce cost

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Thank you for your attention