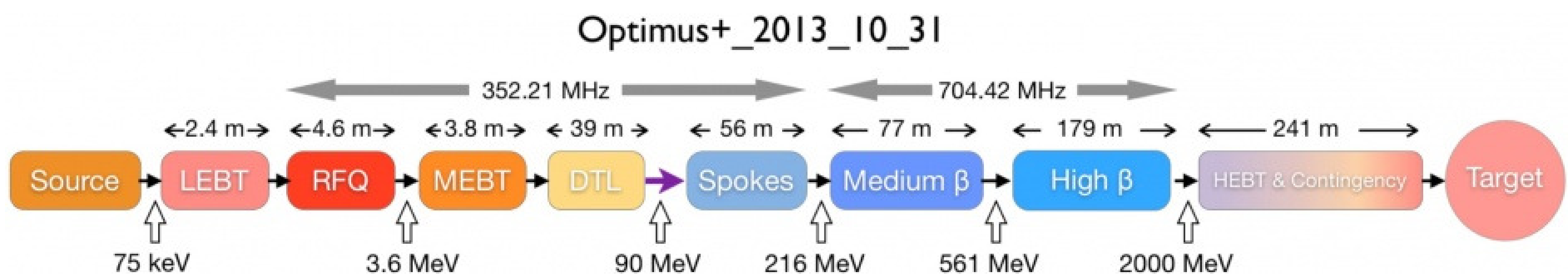
UPPSALA UNIVERSITET

From microscopic to macroscopic dynamics of super-conducting accelerating cavities

Anirban Krishna Bhattacharyya

EUROPEAN SPALLATION SOURCE

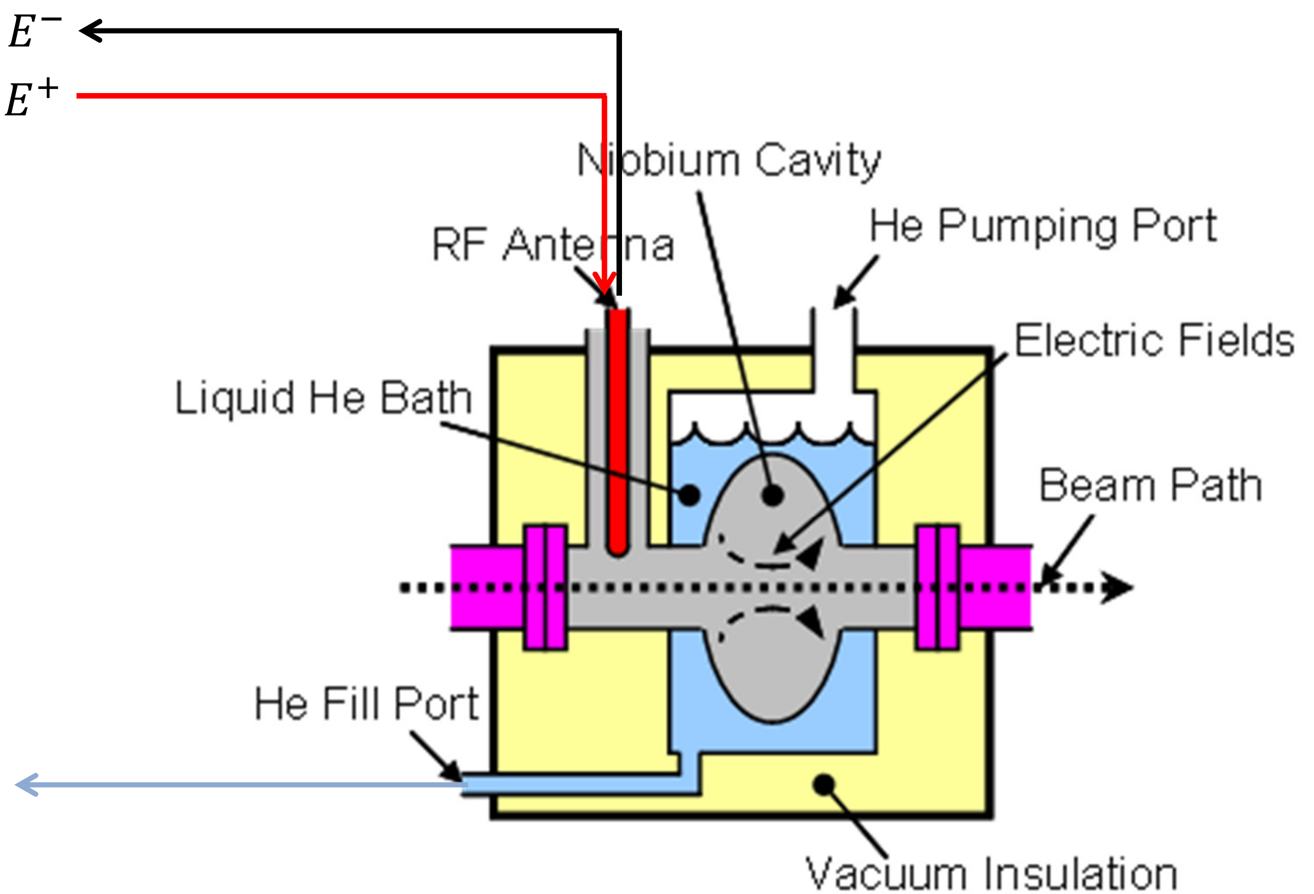
ESS



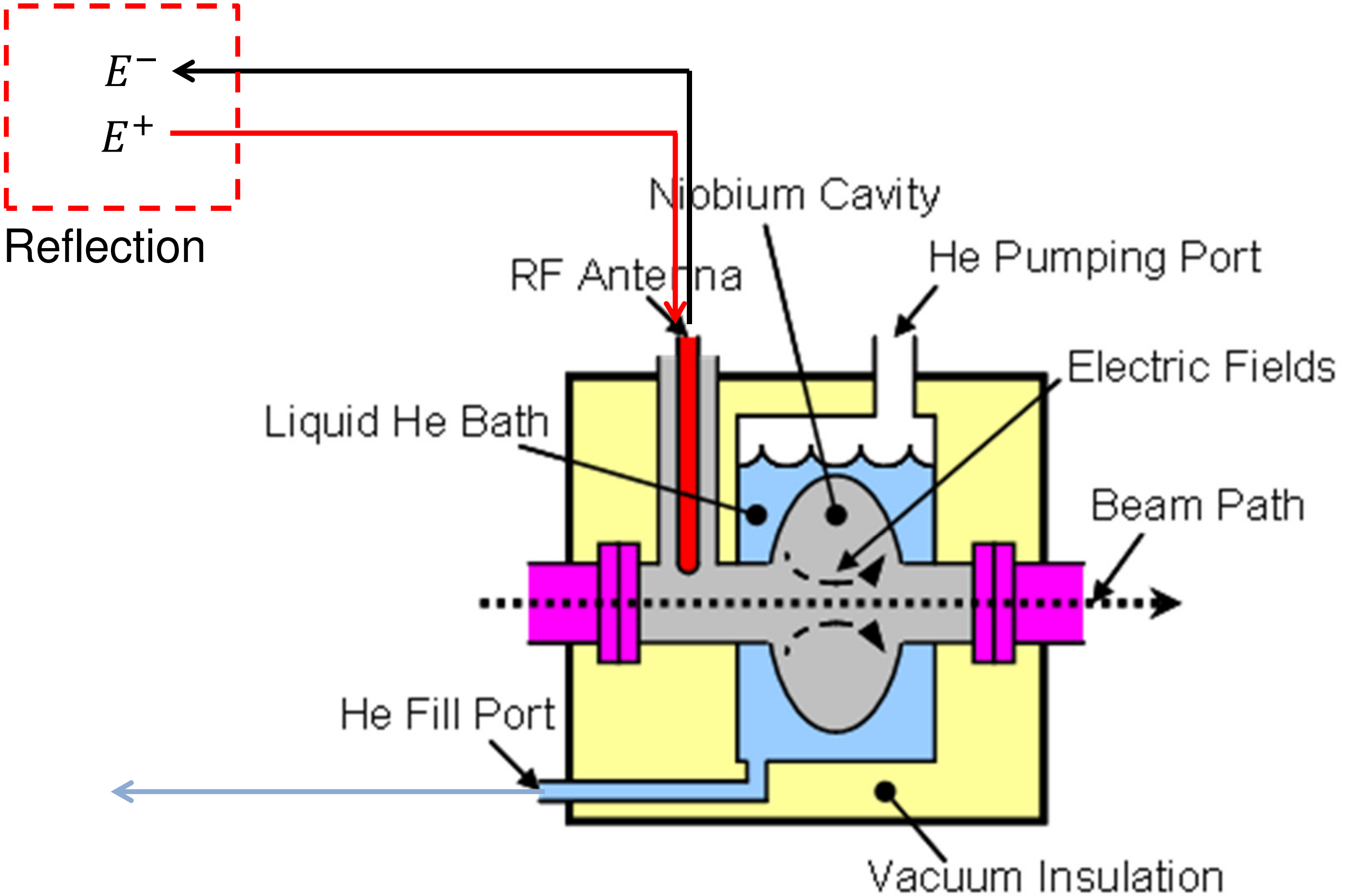
	Length (m)	Input Energy (MeV)	Frequency (MHz)	Geometric β	# of Sections	Temp (K)
RFQ	4.7	75×10^{-3}	352.2	--	1	≈ 300
DTL	19	3	352.2	--	3	≈ 300
Spoke	58	50	352.2	0.5	14 (2c)	≈ 2
Low Beta	108	188	704.4	0.70	16 (4c)	≈ 2
High Beta	196	606	704.4	0.90	15 (8c)	≈ 2
HEBT	100	2500	--	--	--	--

Courtesy Matts Lindroos (ESS)

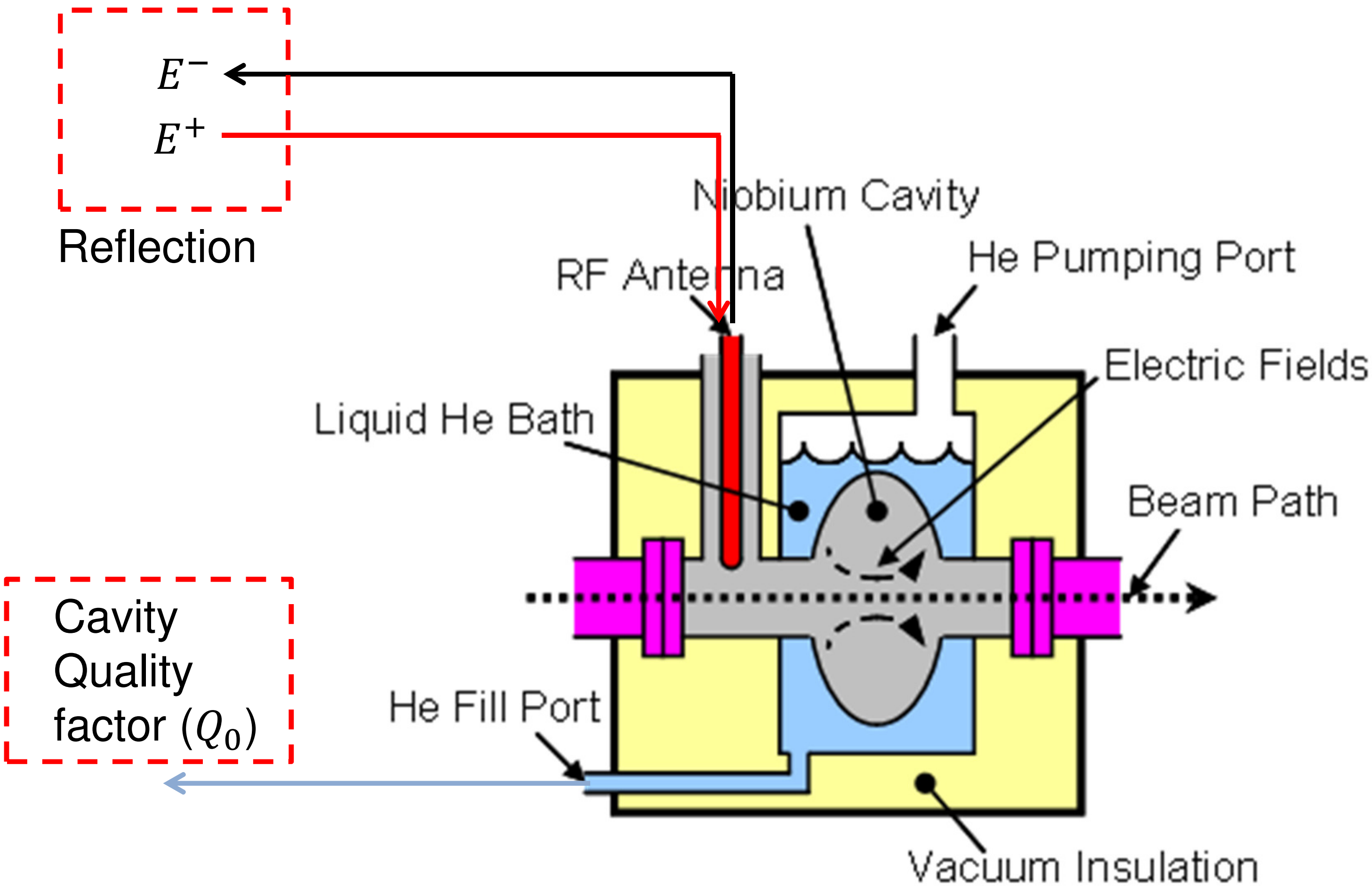
Outline


E^-
E^+
Niobium Cavity
RF Antenna
He Pumping Port
Electric Fields
Liquid He Bath
Beam Path
He Fill Port
Vacuum Insulation

Outline

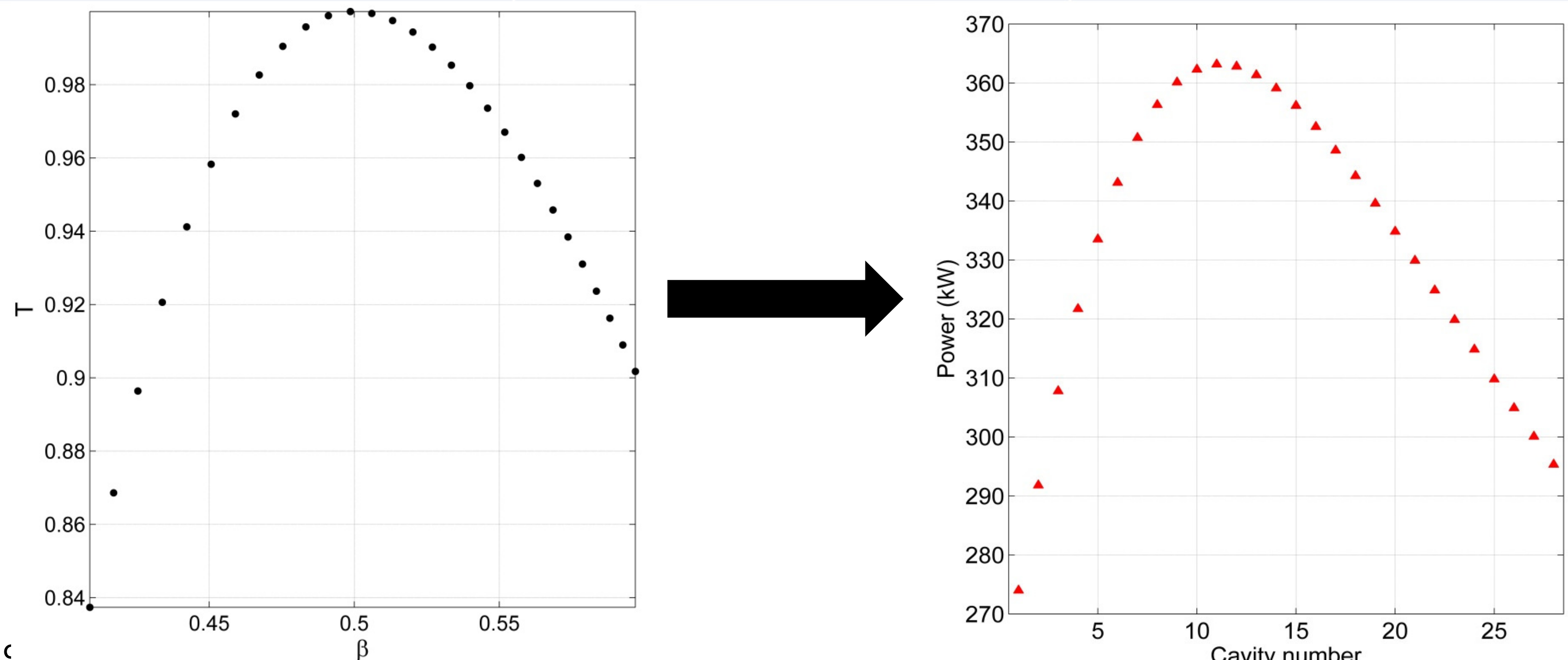

E^-
E^+
Reflection
Niobium Cavity
RF Antenna
He Pumping Port
Electric Fields
Liquid He Bath
Beam Path
He Fill Port
Vacuum Insulation

Outline


E^-
E^+
Reflection
Niobium Cavity
RF Antenna
He Pumping Port
Electric Fields
Liquid He Bath
Beam Path
Cavity Quality factor (Q_0)
He Fill Port
Vacuum Insulation

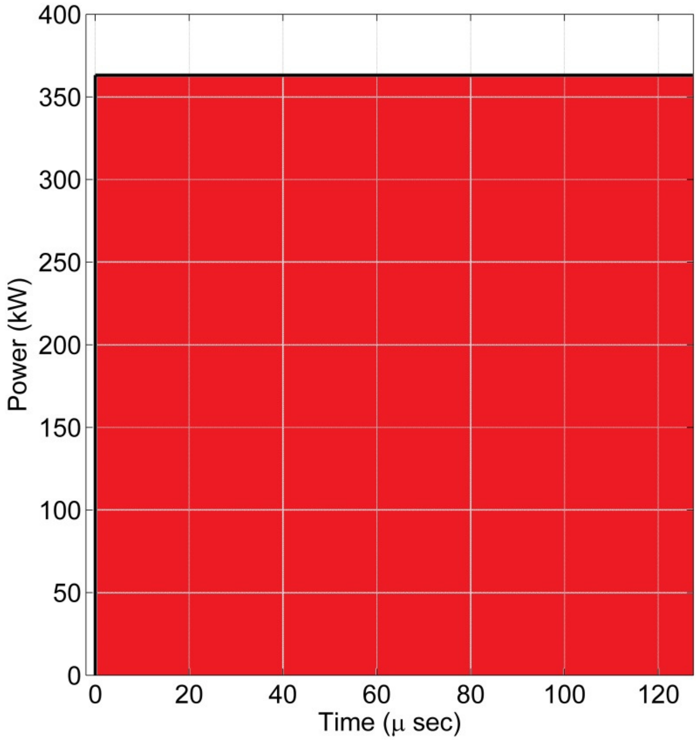
Cavity Parameters

PARAMETER	SYMBOL	VALUE
Geometric beta	β	0.5
Accelerating gaps	n	3
Bare cavity Quality factor	Q_0	1.2×10^{10}
External Quality factor	Q_{ext}	1.76×10^5
Cavity shape constant	R/Q	213 Ω
DC beam current	$I_{b,DC}$	62.5 mA



Step Charging

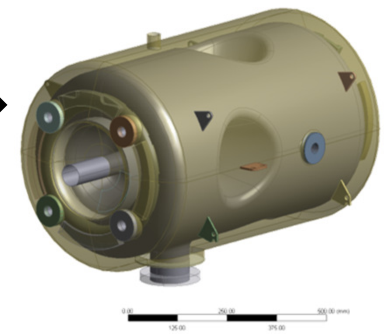
RF Source



Circulator

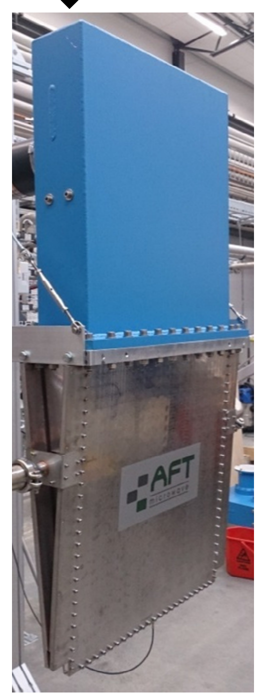
Cavity

Courtesy of P. Duthil



Spoke Cavity
(super - conducting)

Load



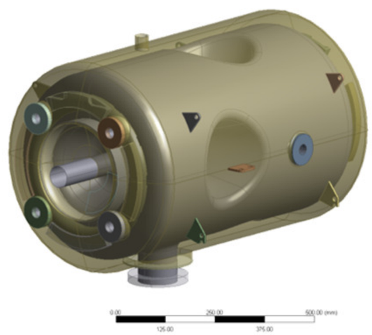
Step Charging

RF Source

Circulator

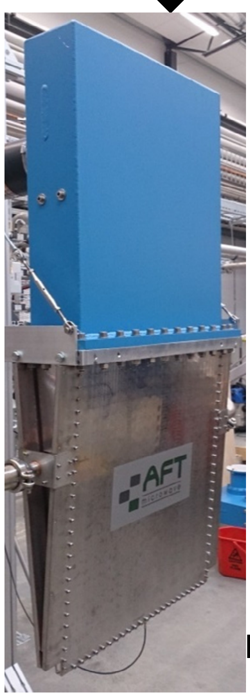
Cavity

Courtesy of P. Duthil

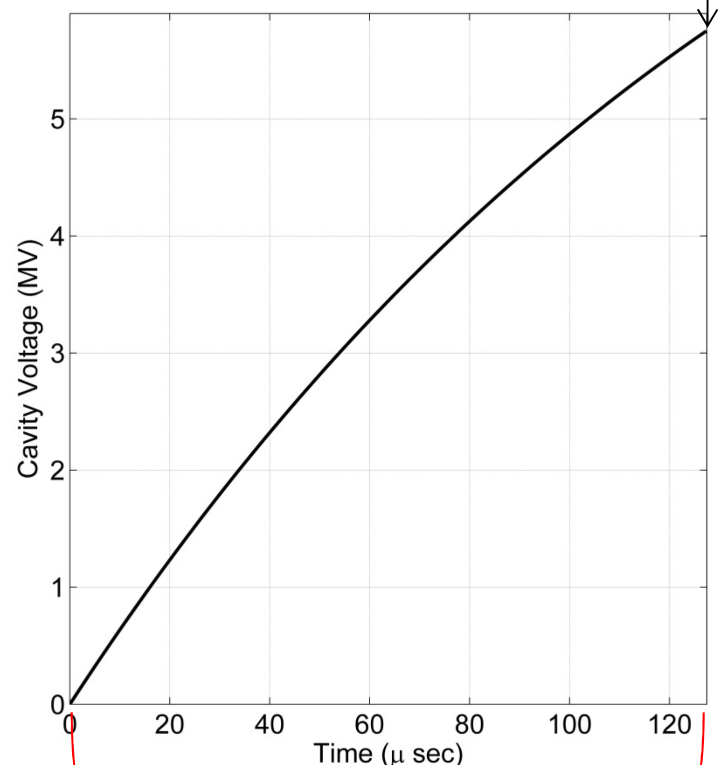


Spoke Cavity
(super - conducting)

Load



Beam injection t_i



Charging time

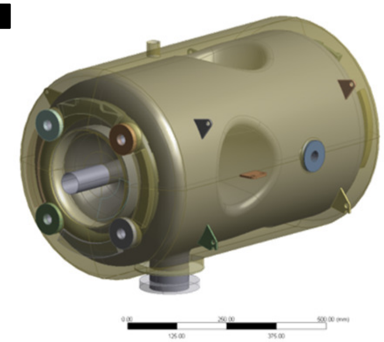
Step Charging

RF Source

Circulator

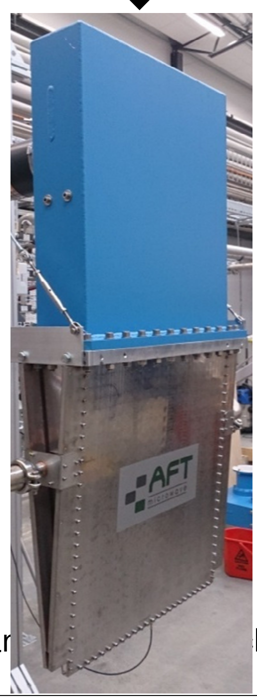
Cavity

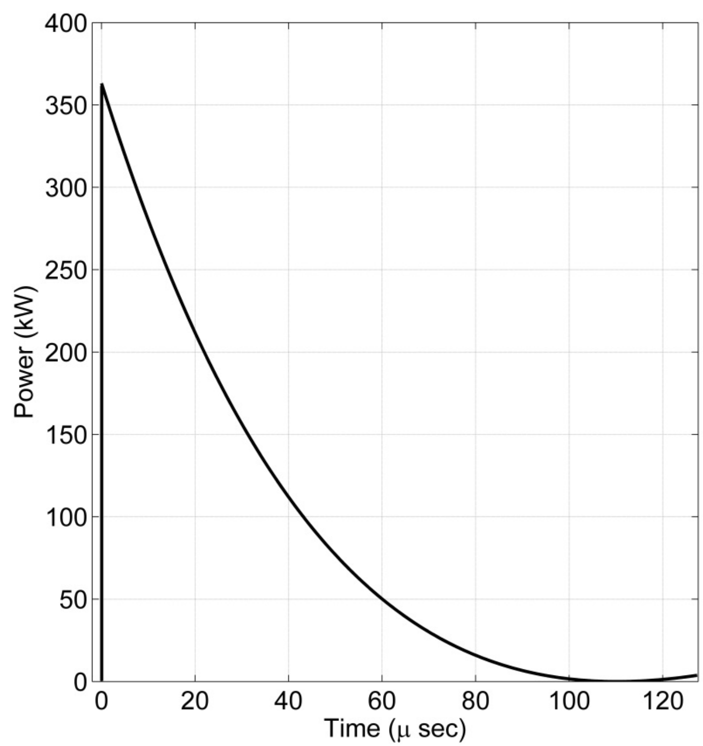
Courtesy of P. Duthil



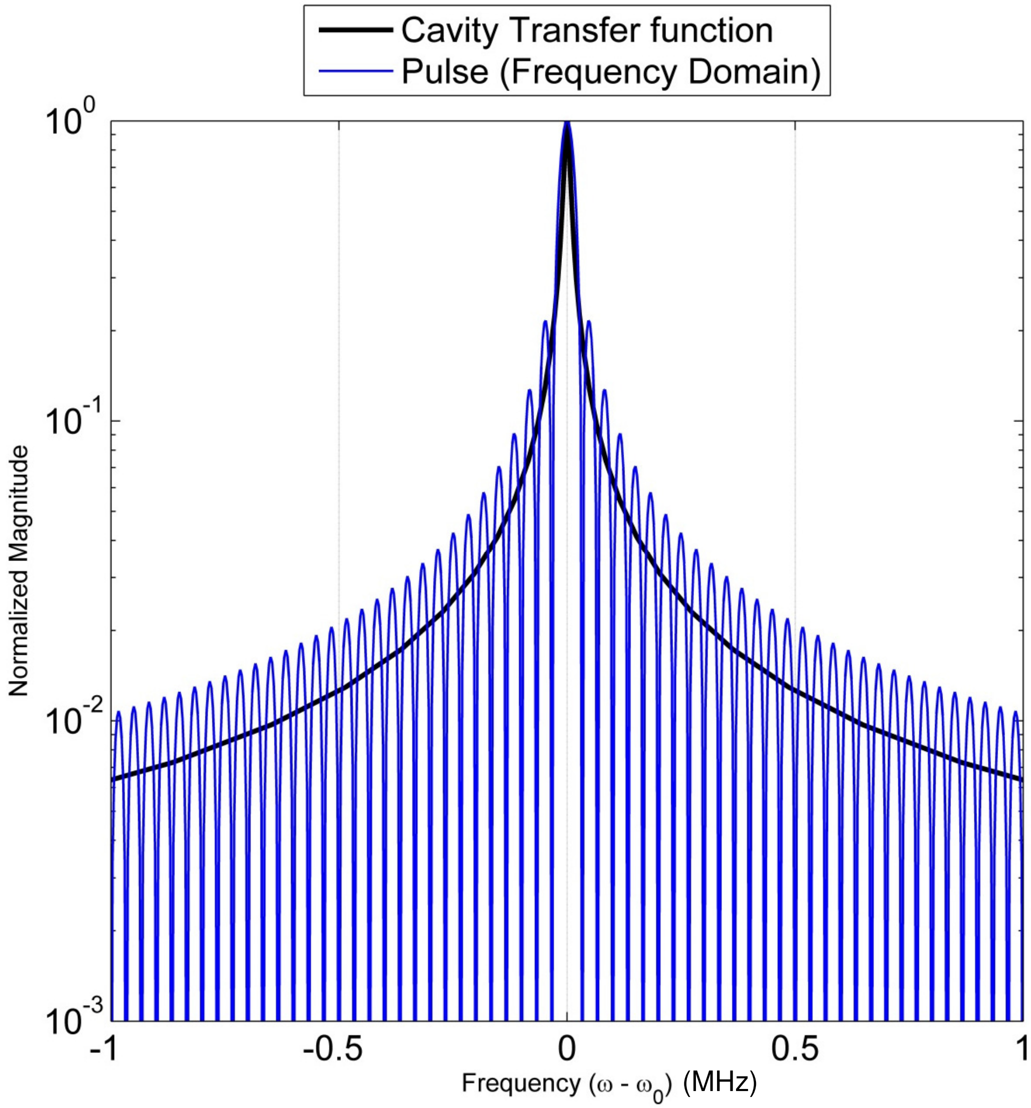
Spoke Cavity
(super - conducting)

Load

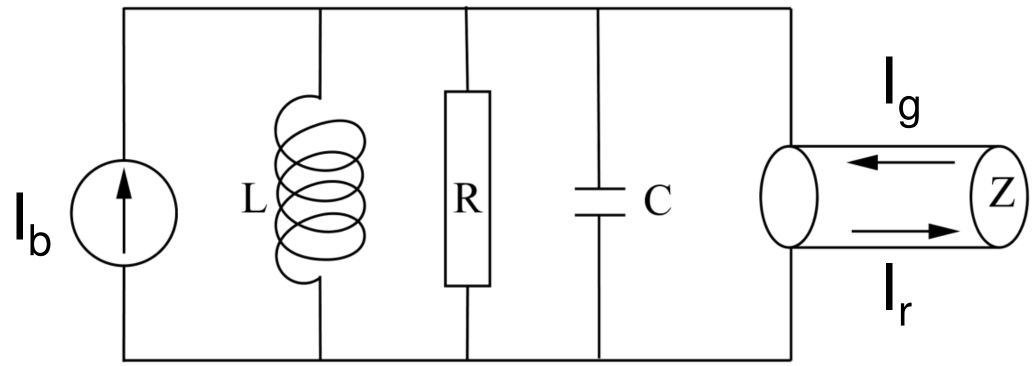




Step Charging (Frequency domain)



Optimal Charging



- Instantaneous cavity voltage $(V(t))$

$$t_F \dot{V}(t) + \left(1 - i\frac{2\Delta\omega}{\omega}Q_L\right)V(t) = 2Z_L T I_g(t)$$

Filling time (Natural time scale) → t_F

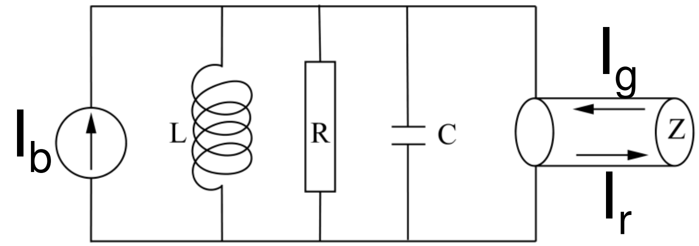
Loaded Quality factor → Q_L

Loaded cavity impedance → Z_L

Generator current → $I_g(t)$

$V(t)$ → V_c (Nominal cavity voltage)

Optimal Charging



- Instantaneous cavity voltage$(V(t))$

$$t_F\dot{V}(t) + \left(1 - i\frac{2\Delta\omega}{\omega}Q_L\right)V(t) = 2Z_LTI_g(t)$$

Filling time (Natural time scale) → t_F; Loaded Quality factor → Q_L; Loaded cavity impedance → Z_L; Generator current → $I_g(t)$

- Reflected current

$$I_r(t) = \frac{V(t)}{2(R/Q)T}\left(\frac{1}{Q_{ext}} - \frac{1}{Q_0} + 2i\frac{\Delta\omega}{\omega}\right) - \dot{V}(t)\frac{1}{\omega(R/Q)T}$$

External Quality factor → Q_{ext}; Bare cavity Quality factor → Q_0

UPPSALA UNIVERSITET

Optimal Charging

- Instantaneous cavity voltage

$$t_F \dot{V}(t) + \left(1 - i\frac{2\Delta\omega}{\omega} Q_L\right) V(t) = 2 Z_L T I_g(t)$$

Filling time

Loaded Q

Loaded impedance

Generator current

- Reflected current

$$I_r(t) = \frac{V(t)}{2(R/Q)T}\left(\frac{1}{Q_{ext}} - \frac{1}{Q_0} + 2i\frac{\Delta\omega}{\omega}\right) - \dot{V}(t)\frac{1}{\omega(R/Q)T}$$

External Q

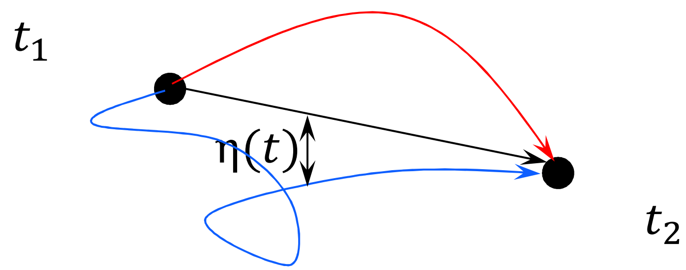
Bare cavity Q

- Reflected energy $(\Delta\omega = 0)$

$$\frac{1}{2}\frac{Q_{ext}}{(R/Q)T^2}\int_0^{\hat{t}_i}\left|\frac{V(\tilde{t})}{2}\left(\frac{1}{Q_{ext}} - \frac{1}{Q_0}\right) - \frac{\mathrm{d}V(\tilde{t})}{\mathrm{d}\tilde{t}}\frac{1}{\omega}\right|^2 \mathrm{d}\tilde{t}$$

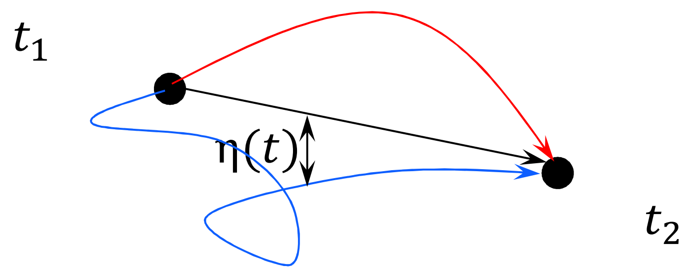
$$V(t) = V_c \text{ at } t = \hat{t}_i$$

Minimum Action: Example from classical mechanics



$$S = \int_{t_1}^{t_2} (K.E. - P.E.)\,dt = \int_{t_1}^{t_2} L\,dt = \int_{t_1}^{t_2} [\frac{1}{2} m \left(\frac{dx}{dt}\right)^2 - V(x)]\mathrm{dt}$$

Minimum Action: Example from classical mechanics



$$S = \int_{t_1}^{t_2} (K.E. - P.E.)\,dt = \int_{t_1}^{t_2} L\,dt = \int_{t_1}^{t_2} [\tfrac{1}{2} m \left(\frac{dx}{dt}\right)^2 - V(x)]\mathrm{dt}$$

$$L(V, \dot{V}, t) = \frac{1}{2} \frac{Q_{ext}}{(R/Q)T^2} \left| \frac{V(\tilde{t})}{2} \left(\frac{1}{Q_{ext}} - \frac{1}{Q_0} \right) - \frac{\mathrm{d}V(\tilde{t})}{\mathrm{d}\tilde{t}} \frac{1}{\omega} \right|^2 \mathrm{d}\tilde{t}$$

$$\frac{\partial L}{\partial V} - \frac{\mathrm{d}}{\mathrm{d}t} \frac{\partial L}{\partial \dot{V}} = 0$$

Optimal Charging

- The concept of minimum action,

$$\frac{\partial L}{\partial V} - \frac{\mathrm{d}}{\mathrm{d}t}\frac{\partial L}{\partial \dot{V}} = 0$$

Find optimal $V(t)$ and $\dot{V}(t)$ such that $L(V, \dot{V}, t)$ is minimum.

Optimal charging profile

$$V^o(\tau) = V_c \frac{\sinh(\tau)}{\sinh(\hat{\tau}_i)},$$

$$I_g^o(\tau) = \frac{V_c}{2TZ_L}\frac{\exp\tau}{\sinh(\hat{\tau}_i)}$$

$$\tau = \frac{t}{t_F},\ \hat{\tau}_i = \frac{\hat{t}_i}{t_F}$$

Optimal Charging

- The concept of minimum action,

$$\frac{\partial L}{\partial V} - \frac{\mathrm{d}}{\mathrm{d}t}\frac{\partial L}{\partial \dot{V}} = 0$$

Optimal charging profile

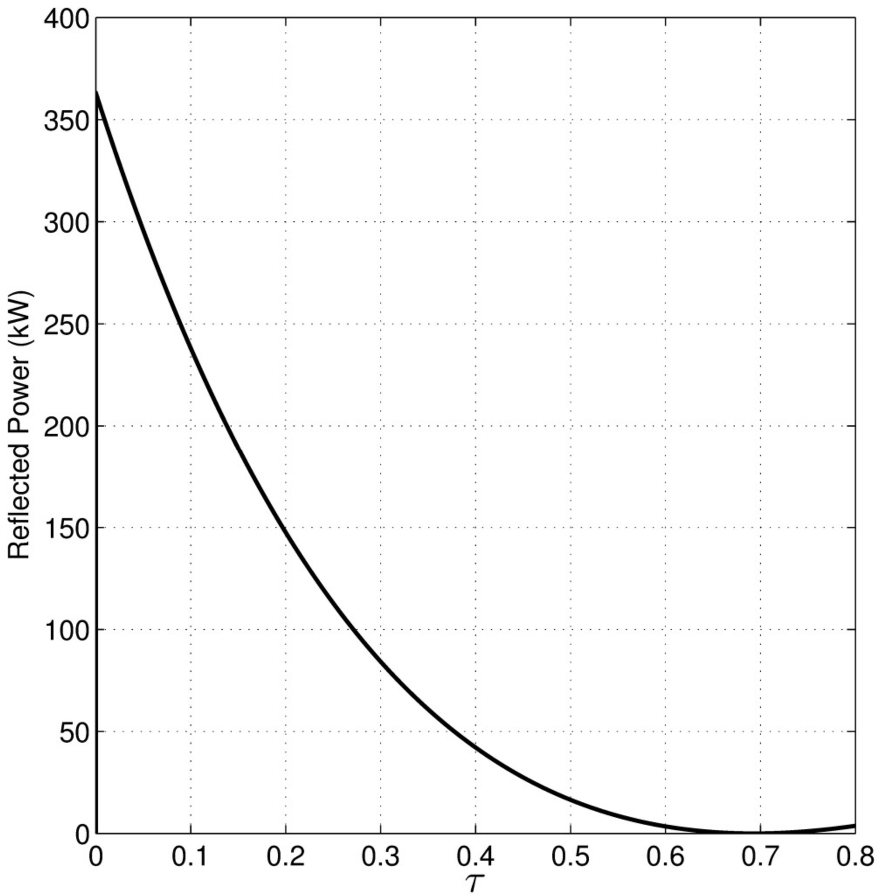
$$V^o(\tau) = V_c \frac{\sinh(\tau)}{\sinh(\hat{\tau}_i)},$$

$$I_g^o(\tau) = \frac{V_c}{2TZ_L}\frac{\exp\tau}{\sinh(\hat{\tau}_i)}$$

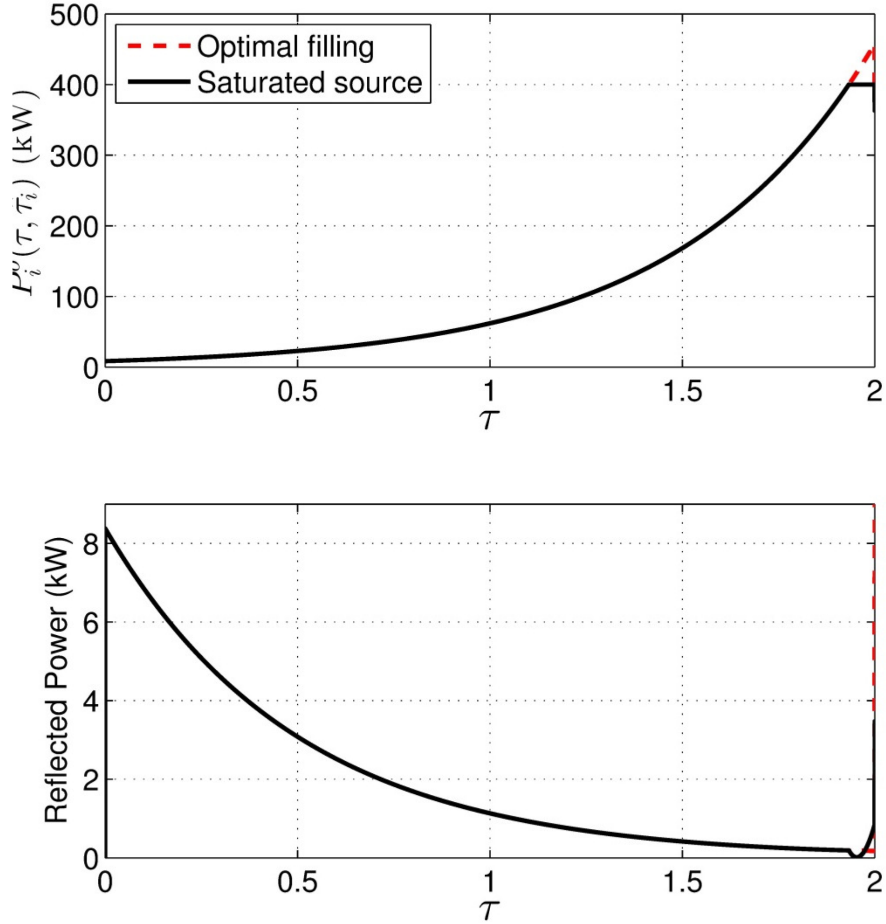
$$\tau = \frac{t}{t_F}, \hat{\tau}_i = \frac{\hat{t}_i}{t_F}$$

Free parameter

Effect of Optimal filling

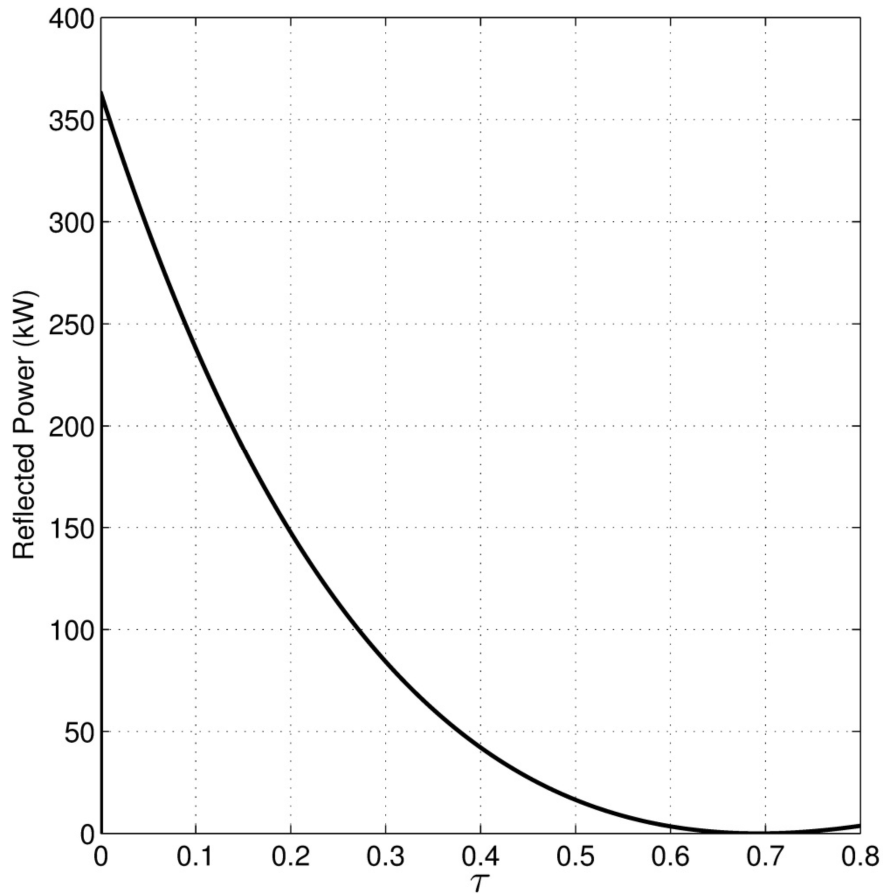


Step filling

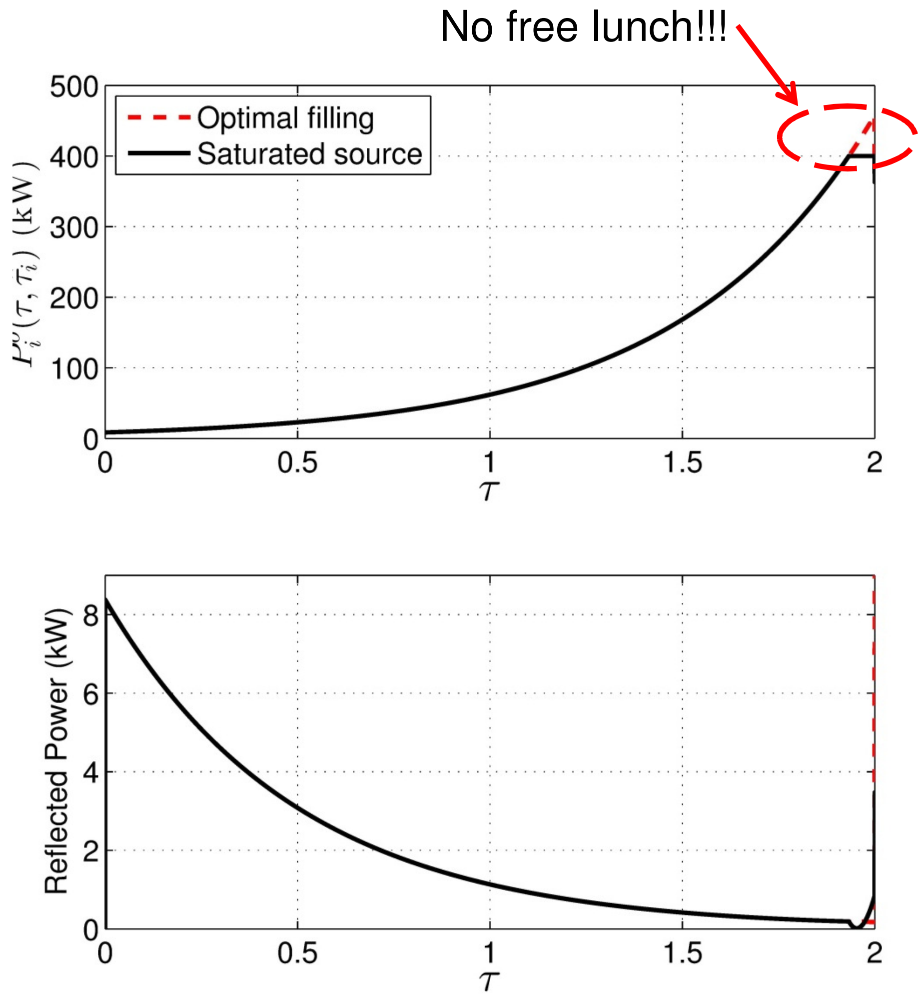


Optimal filling

Effect of Optimal filling

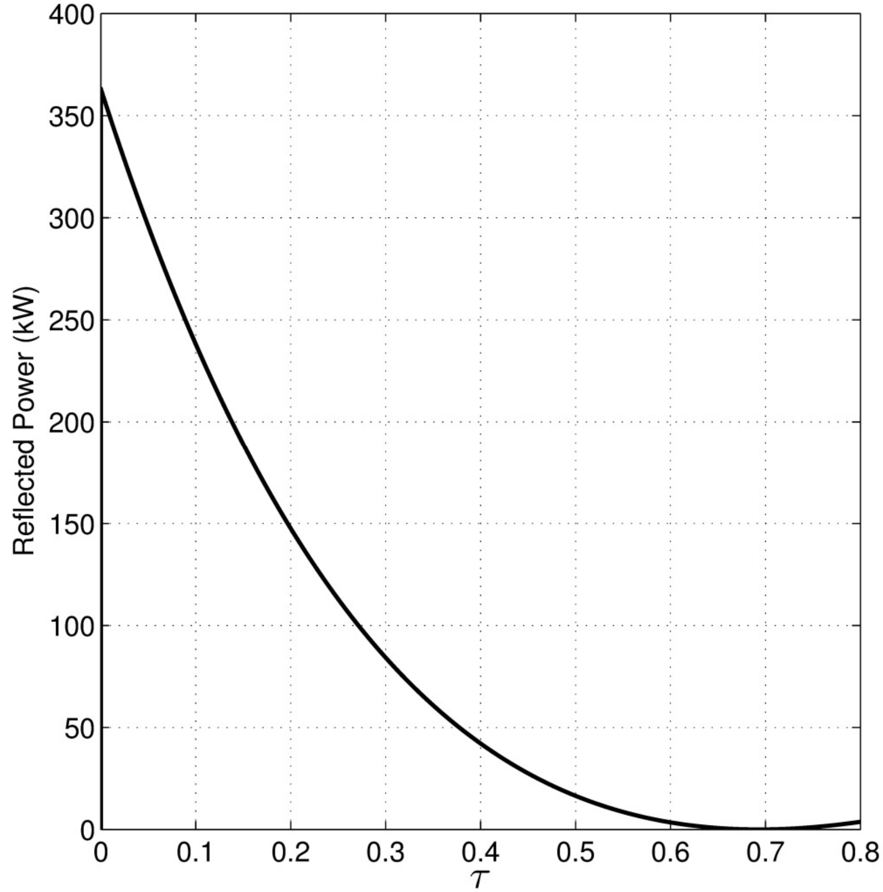


Step filling

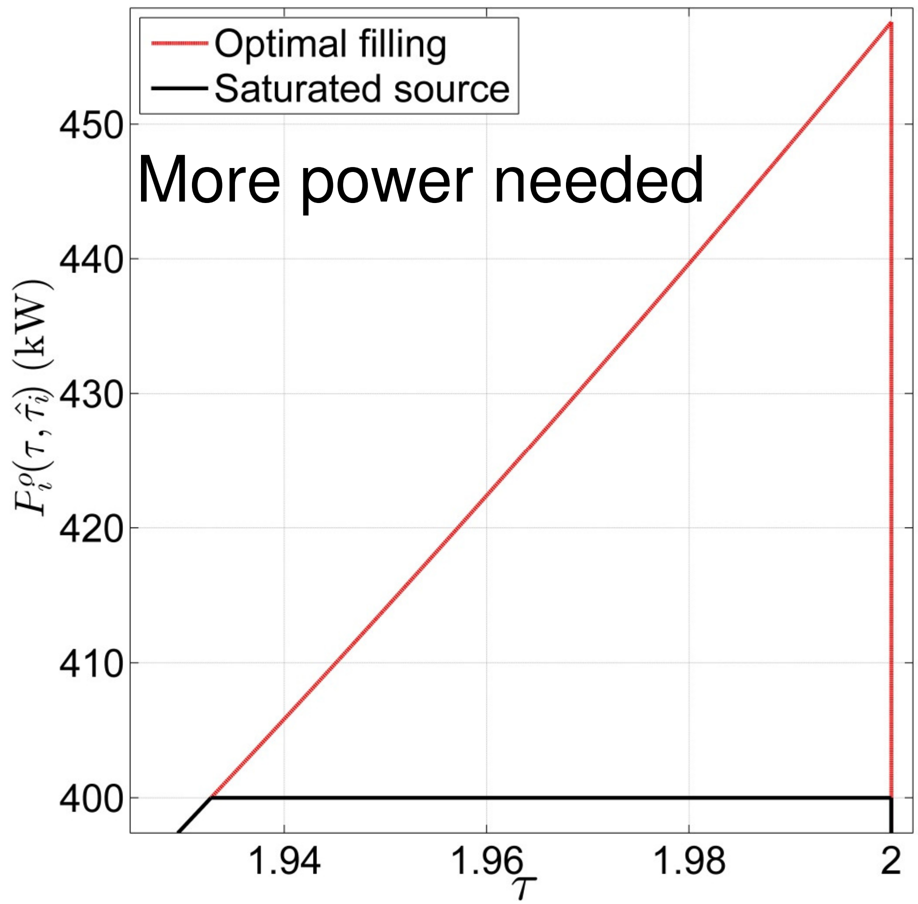


Optimal filling

Effect of Optimal filling

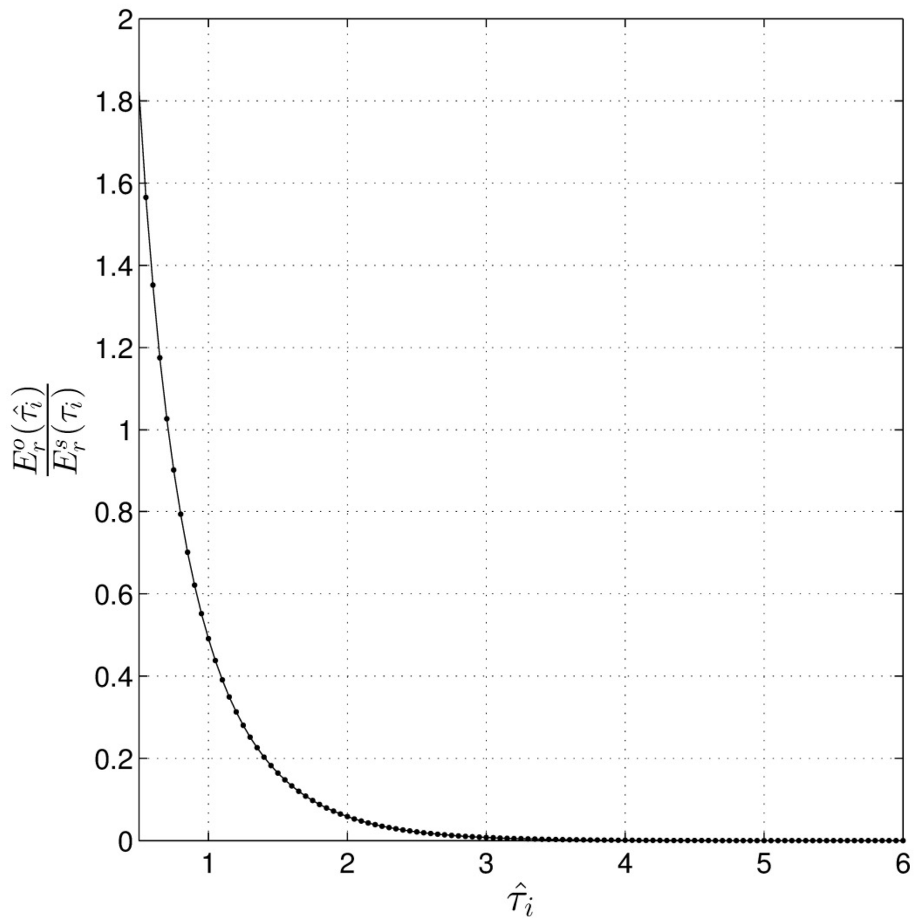


Step filling

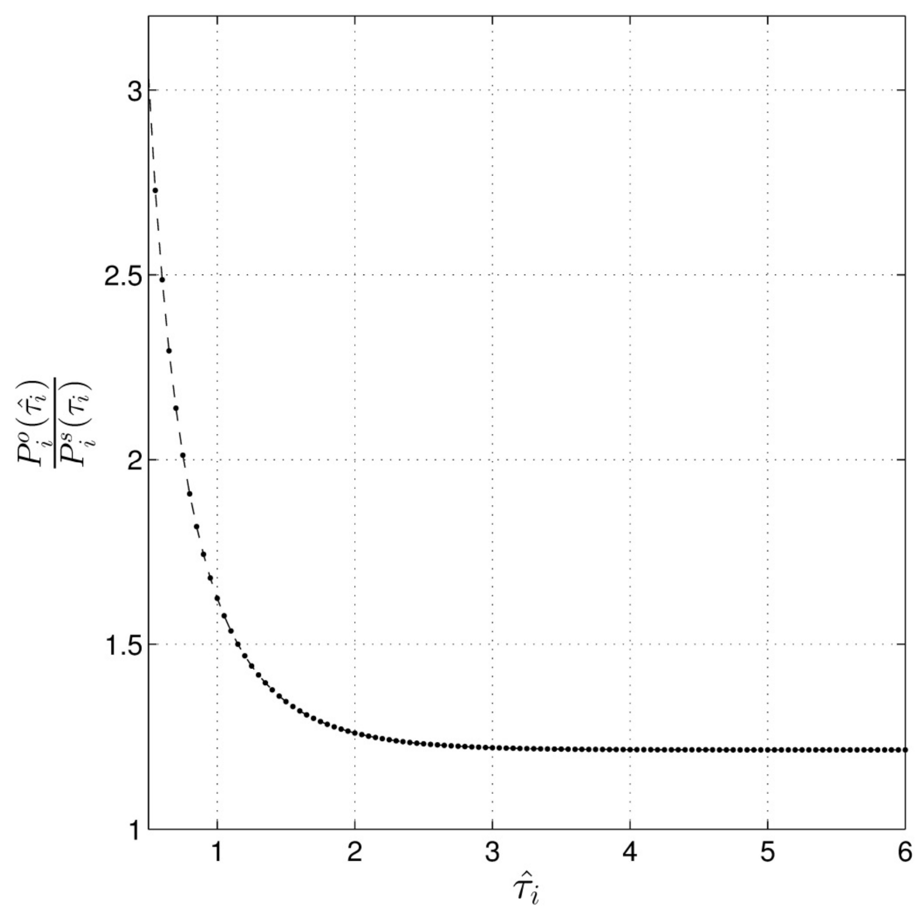


Optimal filling

Effect of charging time ($\frac{\hat{t}_i}{t_F}$)

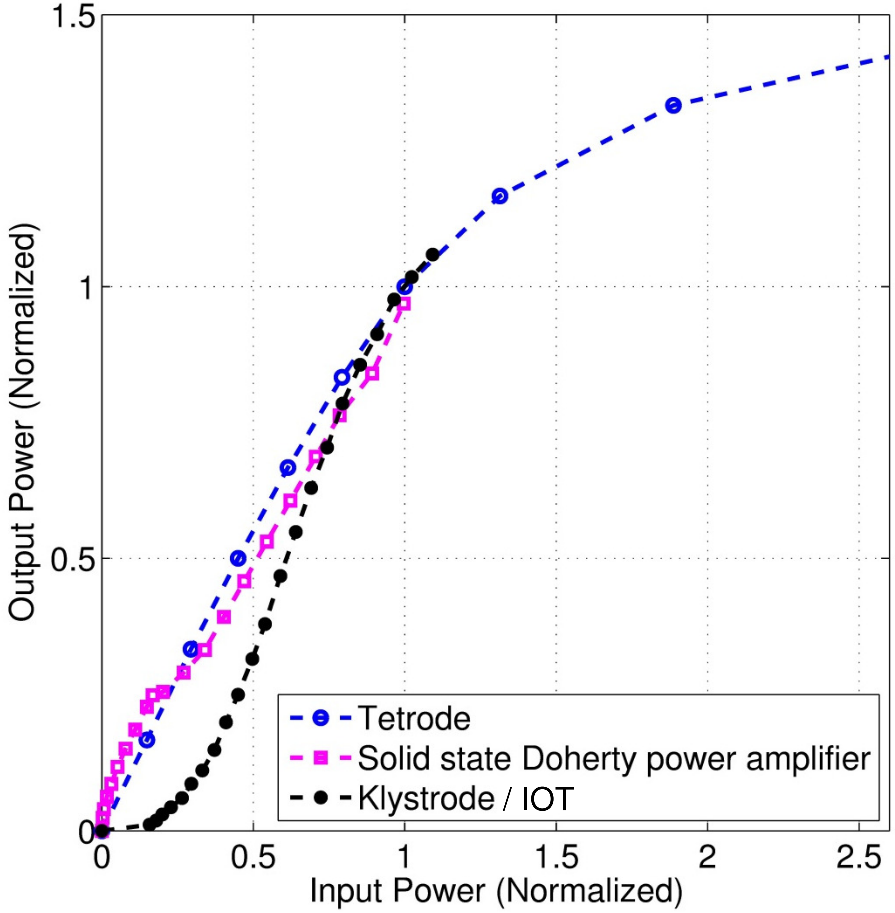


Relative reflected energy

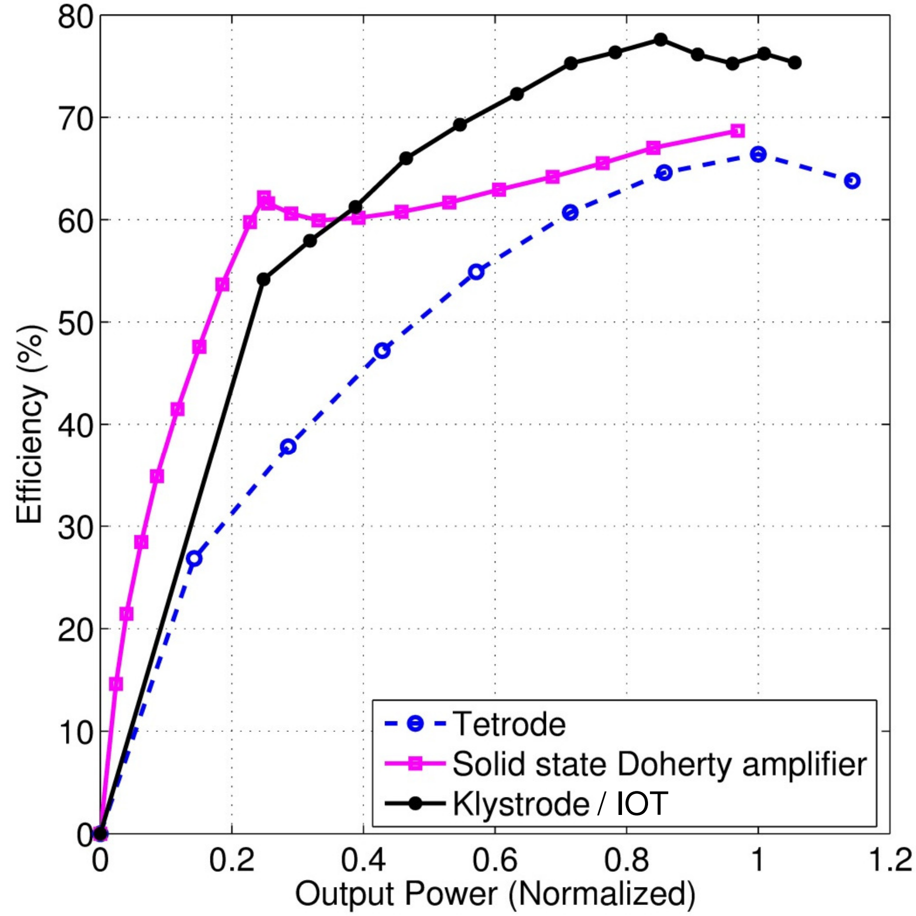


Peak generator power

Practical sources



Gain characteristics



Efficiency characteristics

Practical sources

W. Doherty, A new high efficiency power amplifier for modulated waves, Radio Engineers, Proceedings of the Institute of 24 (9) (1936) 1163–1182. doi:10.1109/JRPROC.1936.228468.

B. Kim, J. Kim, I. Kim, J. Cha, The doherty power amplifier, Microwave Magazine, IEEE 7 (5) (2006) 42–50. doi:10.1109/MW-M.2006.247914.

R. Pengelly, N-way rf power amplifier with increased backoff power and power added efficiency, wO Patent App. PCT/US2003/002,365 (Aug. 7 2003).
URL http://www.google.com/patents/WO2003065573A1?cl=en

P. Colantonio, F. Giannini, R. Giofr, L. Piazzon, The doherty power ampli fier, INTERNATIONAL JOURNAL OF MICROWAVE AND OPTICAL TECHNOLOGY 5 (6) (2010) 419–430.

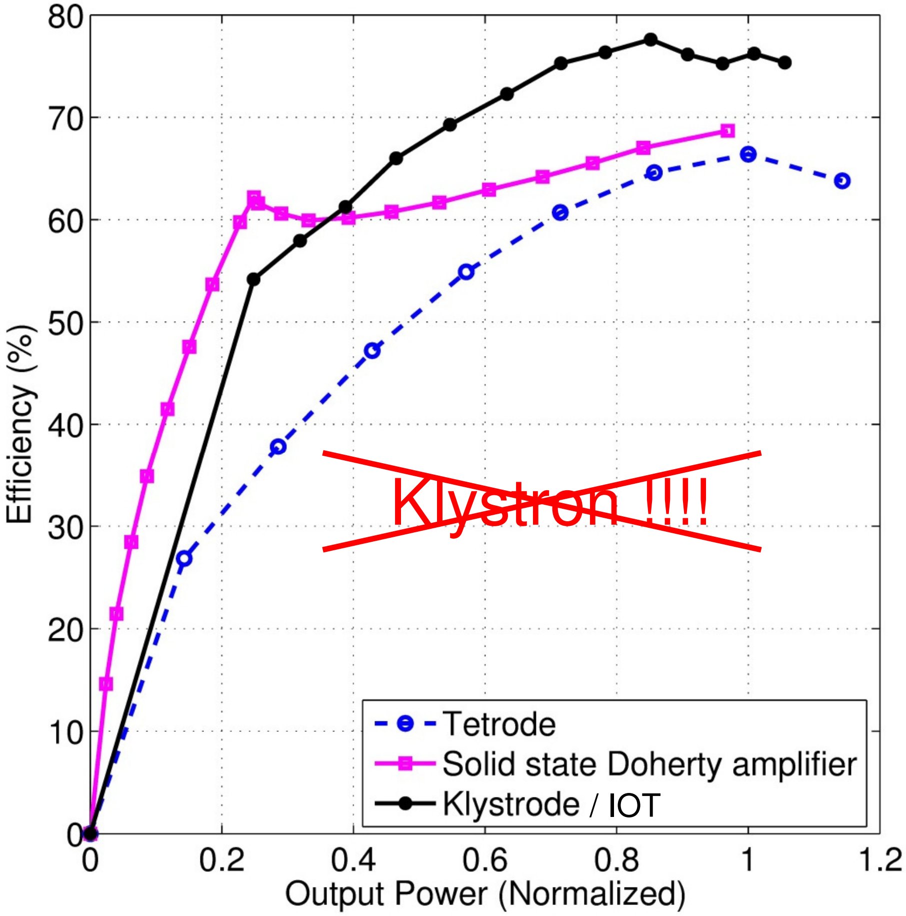
G. Ahn, M. su Kim, H. chul Park, S. chan Jung, J. ho Van, H. Cho, S. wook Kwon, J.-H. Jeong, K. hoon Lim, J. Y. Kim, S. C. Song, C.-S. Park, Y. Yang, Design of a high-efficiency and high-power inverted doherty amplifier, Microwave Theory and Techniques, IEEE Transactions on 55 (6) (2007) 1105–1111. doi:10.1109/TMTT.2007.896807.

NXP Semiconductors, AN10967 BLF578 demo for 352 MHz 1kW CW power, 2nd Edition, application note (November 2012).

D. Rees, D. Keffeler, W. Roybal, P. Tallerico, Characterization of a Klystrode as a RF Source for High-Average-Power Accelerators, Conf.Proc. C950501 (1995) 1521.

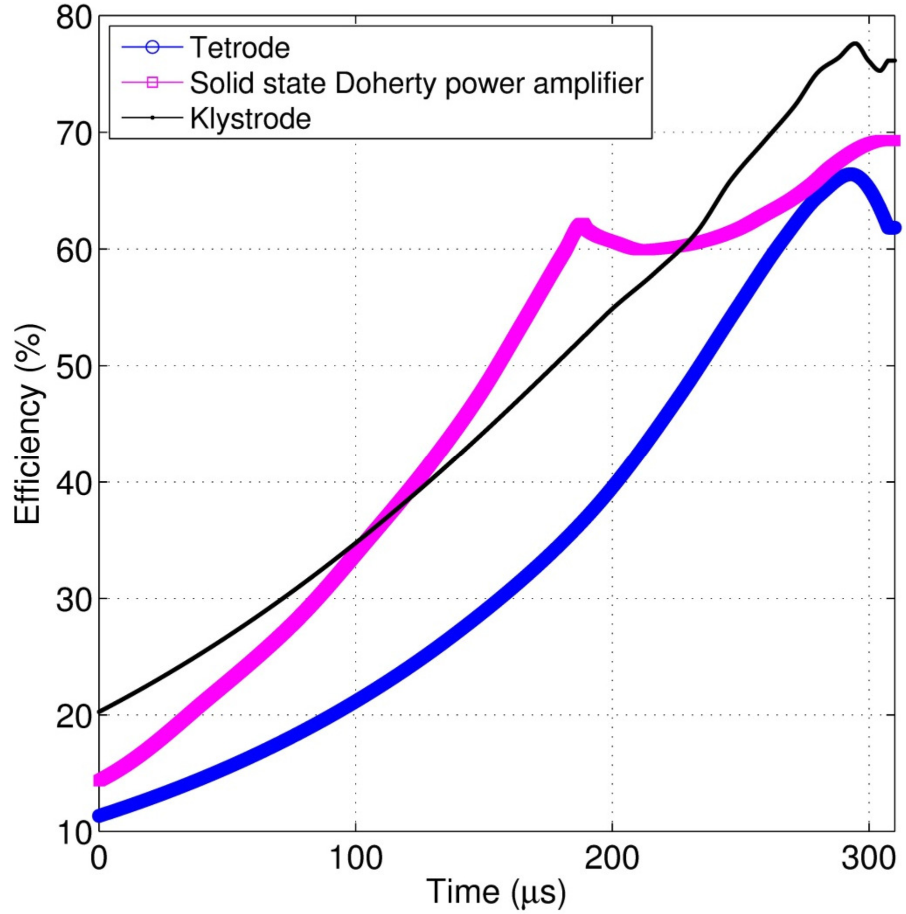
E. Montesinos, Tetrode power amplifiers, in: TIARA Workshop on RF Power Generation for Accelerators, Uppsala University, A˚ ngstr¨om Laboratory, 2013.

N. Pupeter, Significant increase of efficiency of solid state amplifiers due to improved ac/dc conversion and adaption of p1 point to actual operating power, in: EnEfficient RF Sources, Cockcroft Institute, 2014.

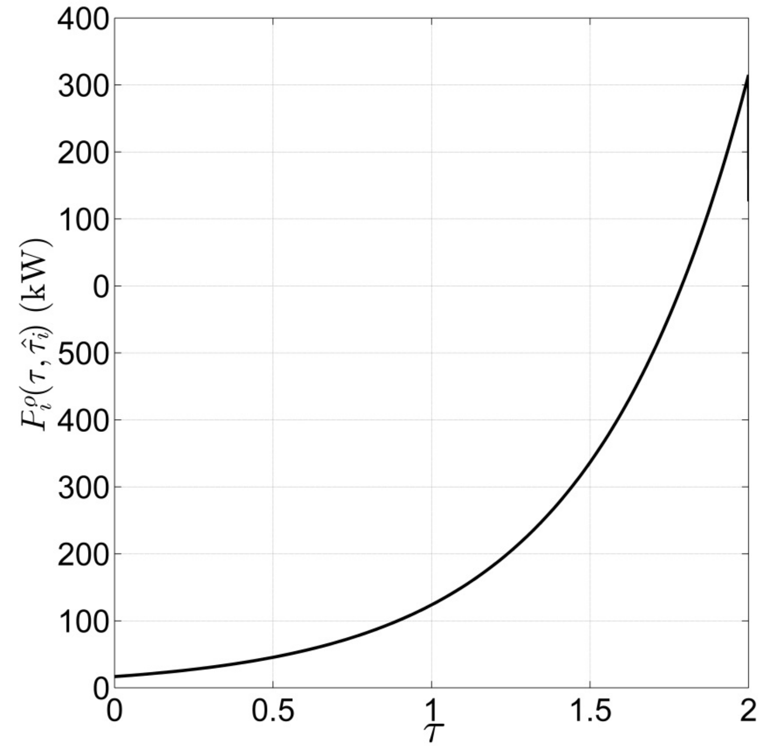


Efficiency characteristics

Practical sources



Source efficiency during filling



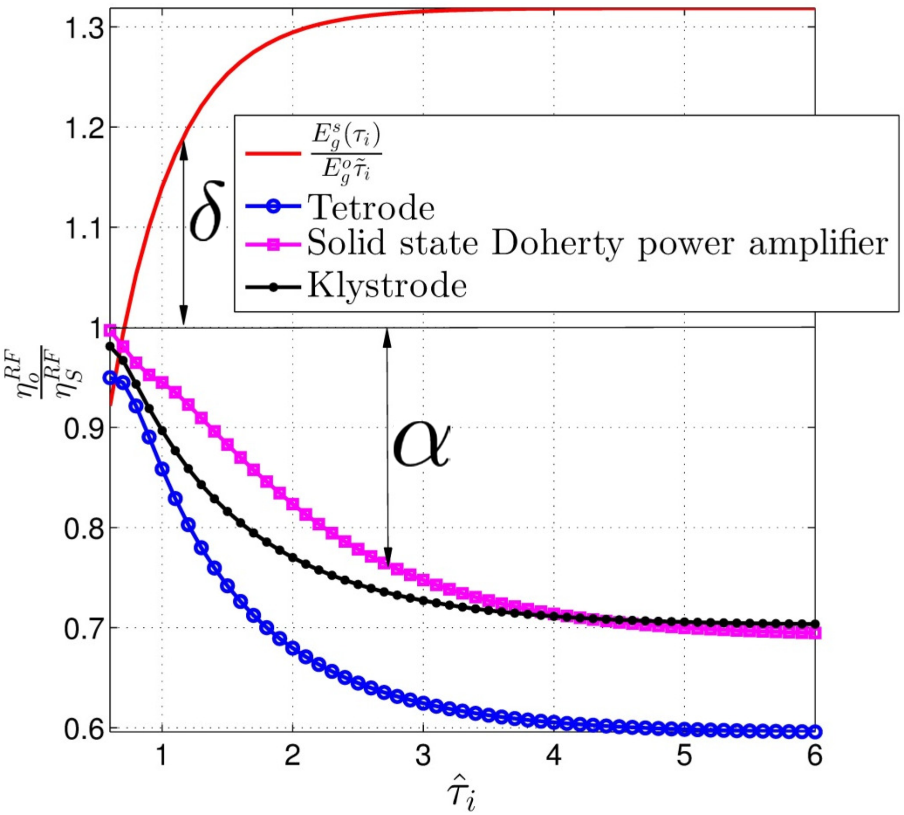
$$\hat{\tau}_i = 2$$

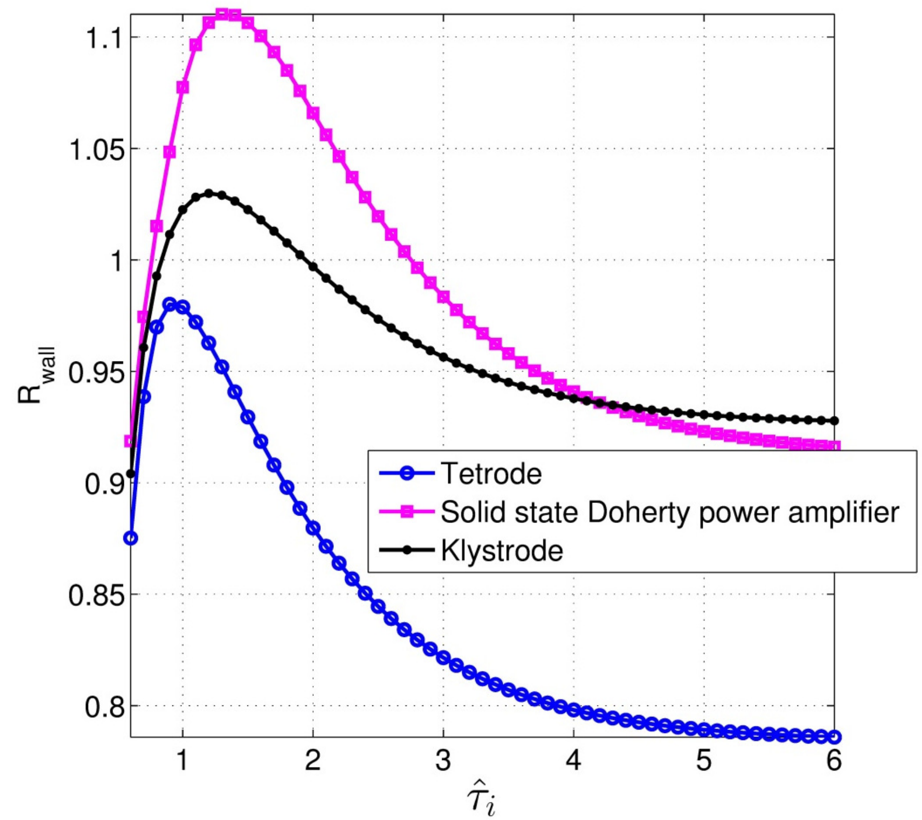
$$R_{wall} \approx 1 + \delta - \alpha$$

RF Gain → δ

Source loss → α

Practical sources

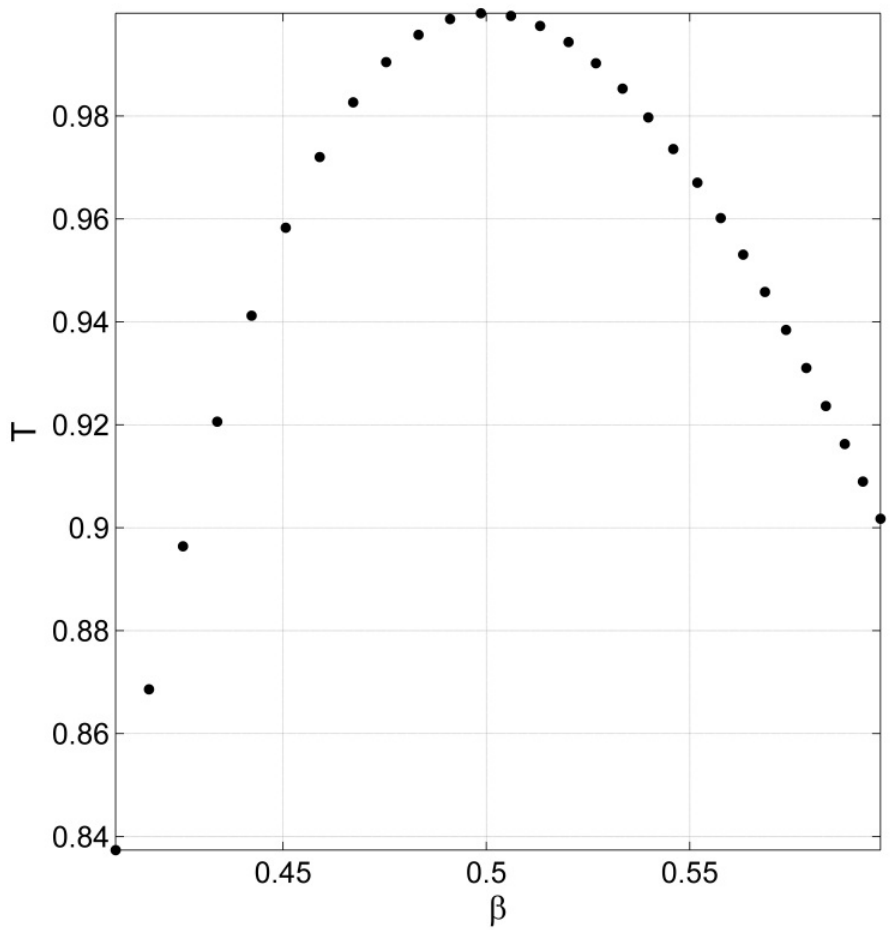




Tetrodes can be run in Doherty architecture

UPPSALA UNIVERSITET

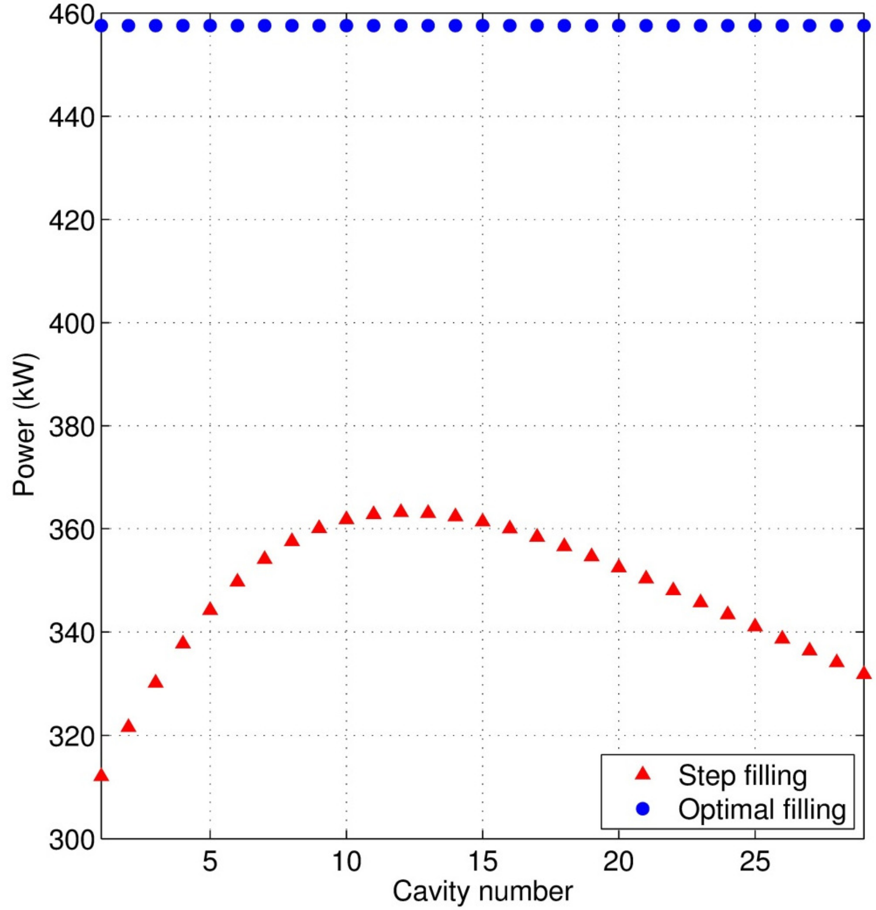
Effect of Transit time factor



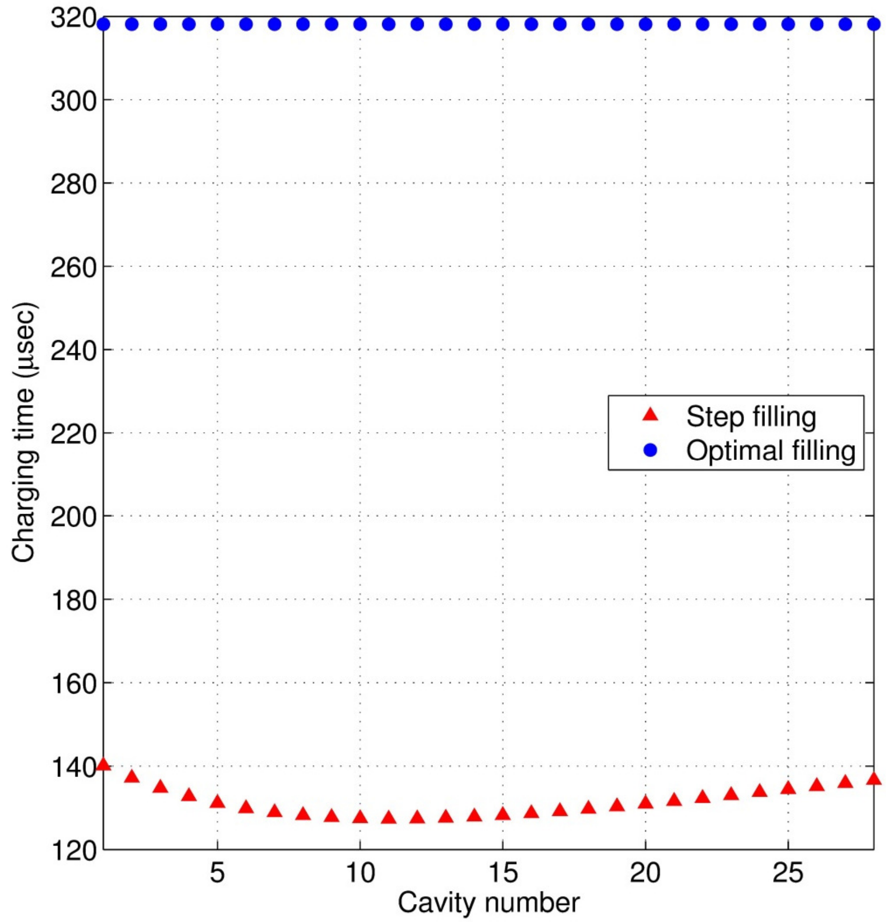
Variation Along Spoke LINAC

Effect of Transit time factor

Beam injection time, $\hat{t_i} = 2t_F$

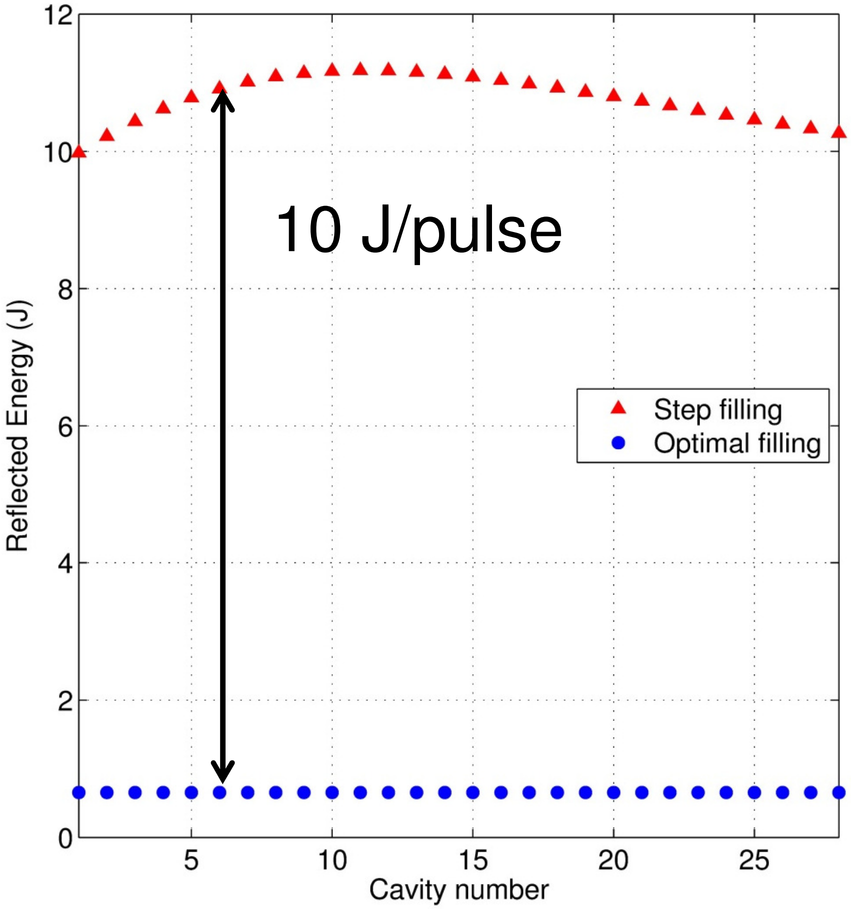


Peak power



Charging time

Effect of Transit time factor



ESS operation: 14 Hz pulse rate

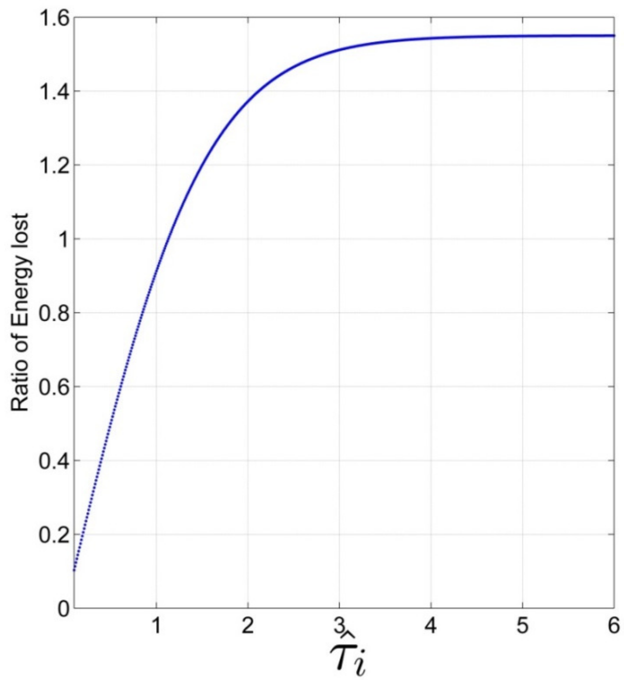
140 J/sec saved per cavity

Assuming 8000 hours/year of operation 1.12 MWhrs saved per cavity
2 SEK/kWhr => 2240 SEK

26 Spoke cavities, 20 years of operation, => 1.16 MSEK

Cryogenic considerations

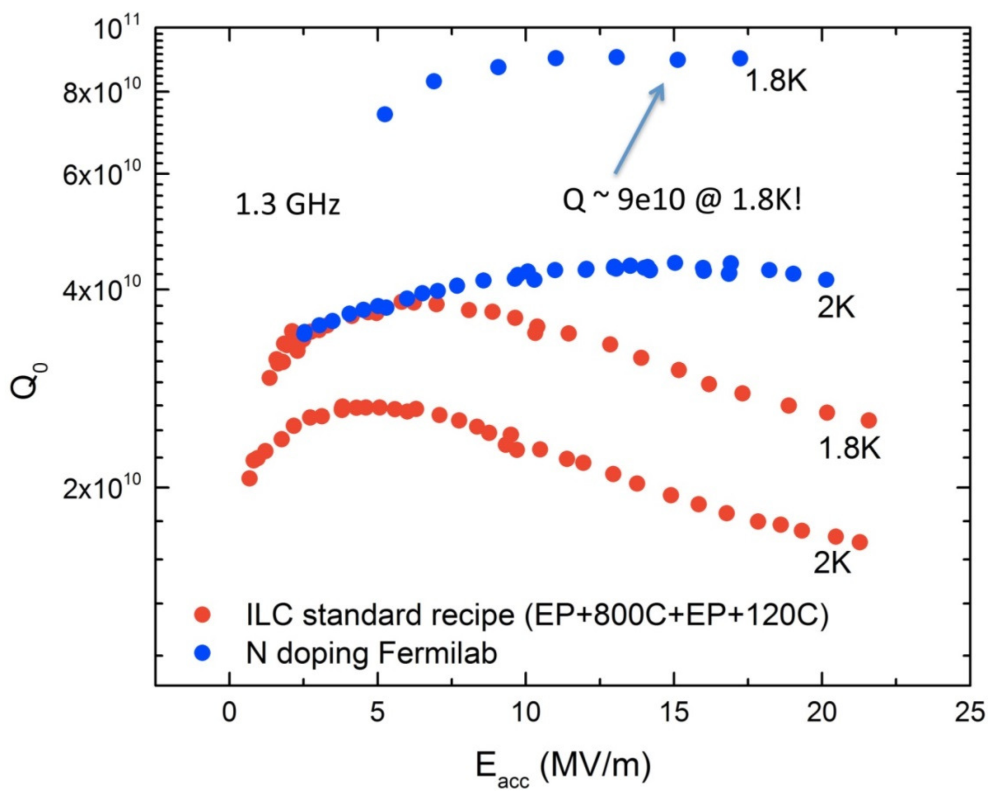
- Losses on cavity surface $P_d = \frac{\omega_0 U}{Q_0} = \frac{\omega_0 \frac{\mu_0}{2} \int_0^{\hat{t}_i} |B|^2 dV}{Q_0}$
- $|B|^2 \propto |V|^2$
- Ratio of energy loss



Q_0 → Intrinsic quality of the resonant structure

Cavity Quality factor

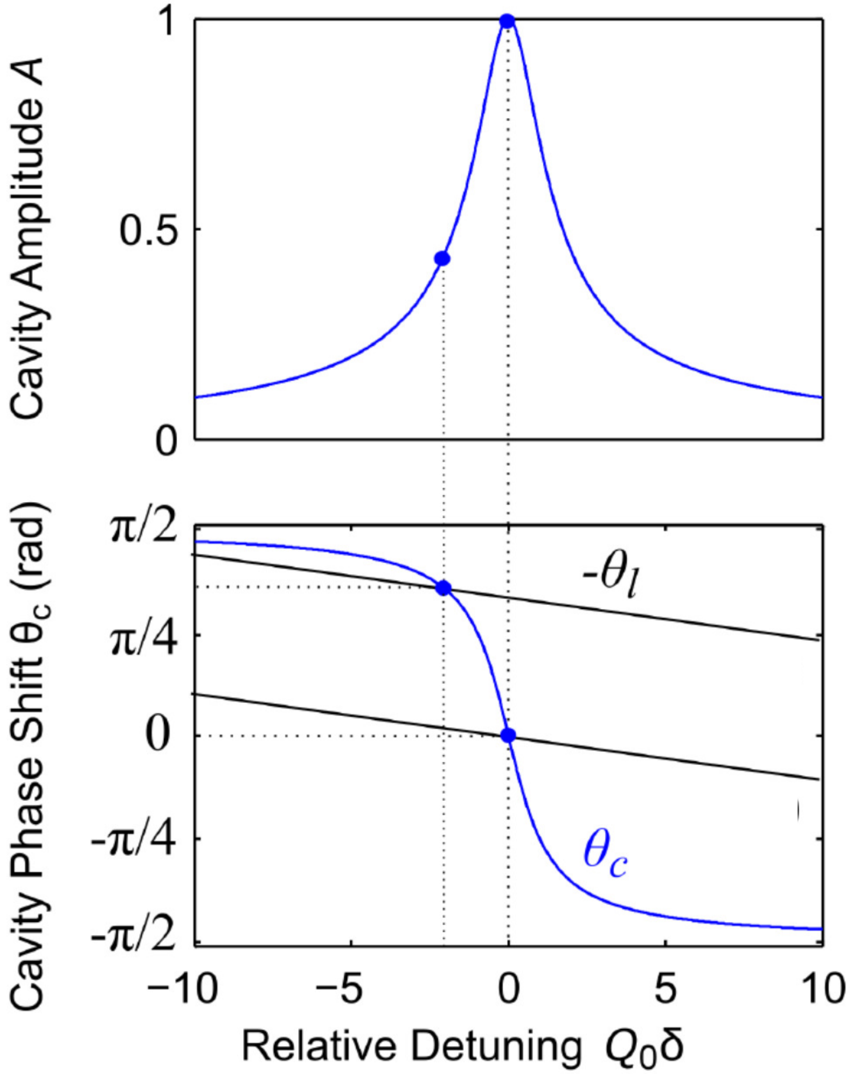
- To measure Quality factor of bare ESS superconducting spoke cavities
- Vertical tests in horizontal cryostat



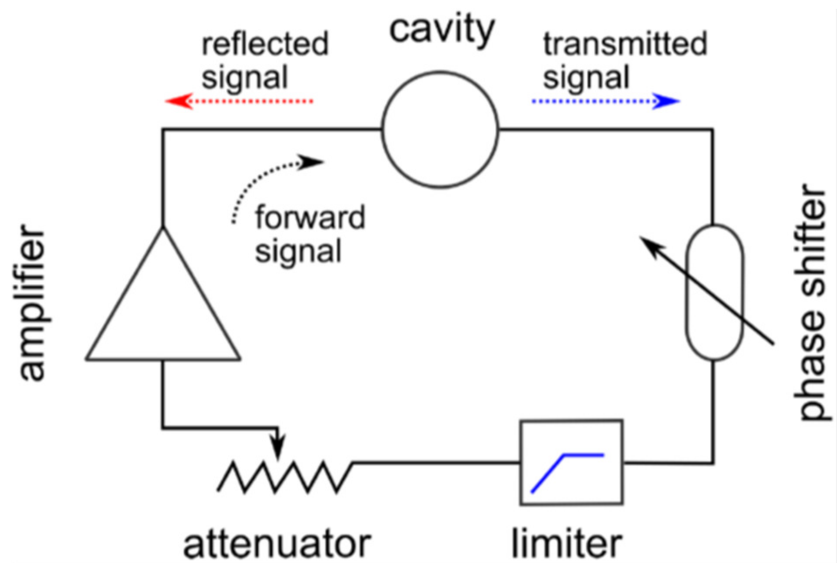
http://newsline.linearcollider.org/2013/11/21/a-little-dirt-never-hurt/cavity-performance/

Cavity resonator and self-excited loop

$$\ddot{V} + \frac{\omega_c}{Q_L}\dot{V} + \omega_c{}^2 V = 2\omega_c (R/Q)\dot{I}_i \qquad Q_L = \left(Q_0{}^{-1} + Q_{ext}{}^{-1}\right)^{-1}$$

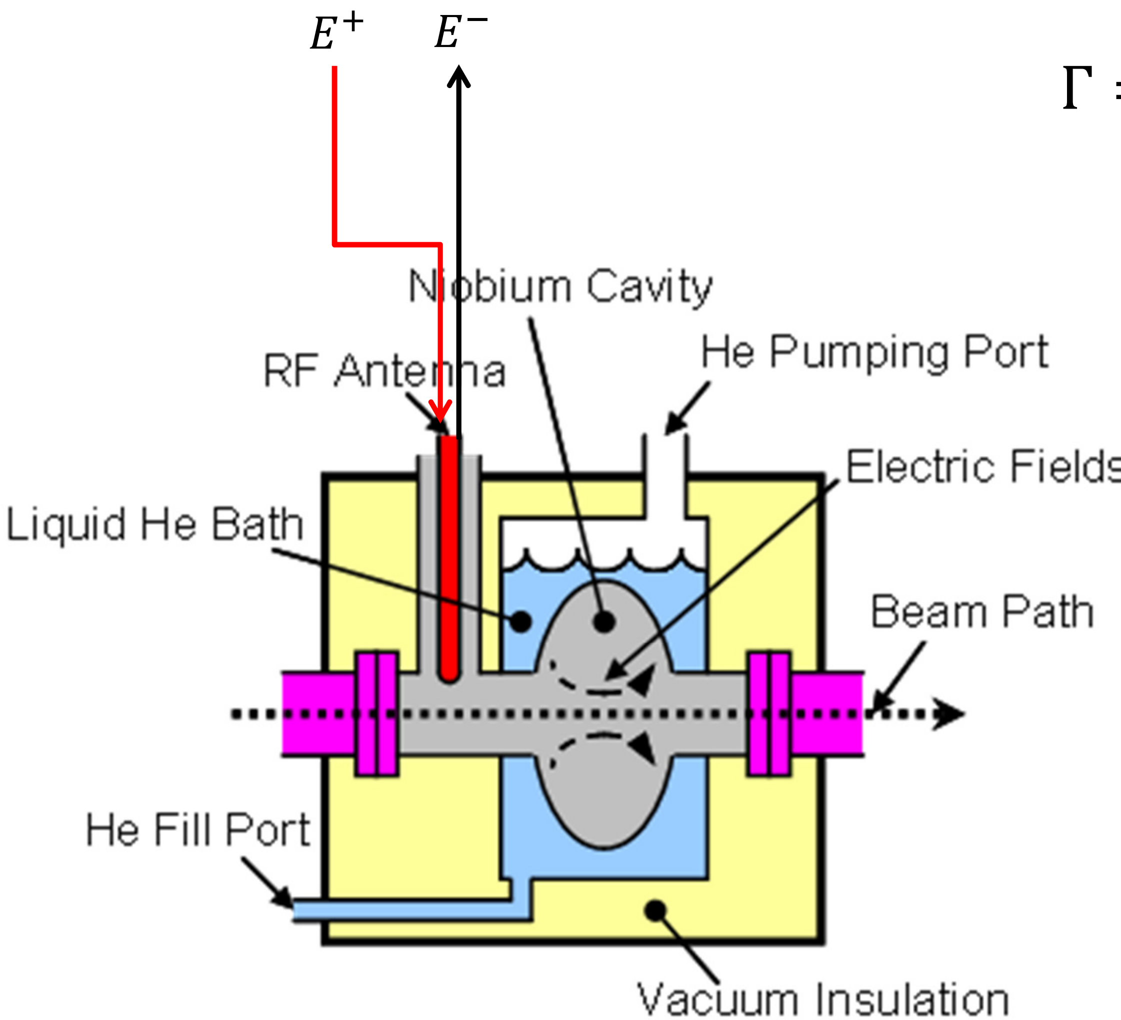


Self-excited loop



$$\theta_c(\omega) + \theta_l(\omega) = 2\pi n$$

Reflection coefficient

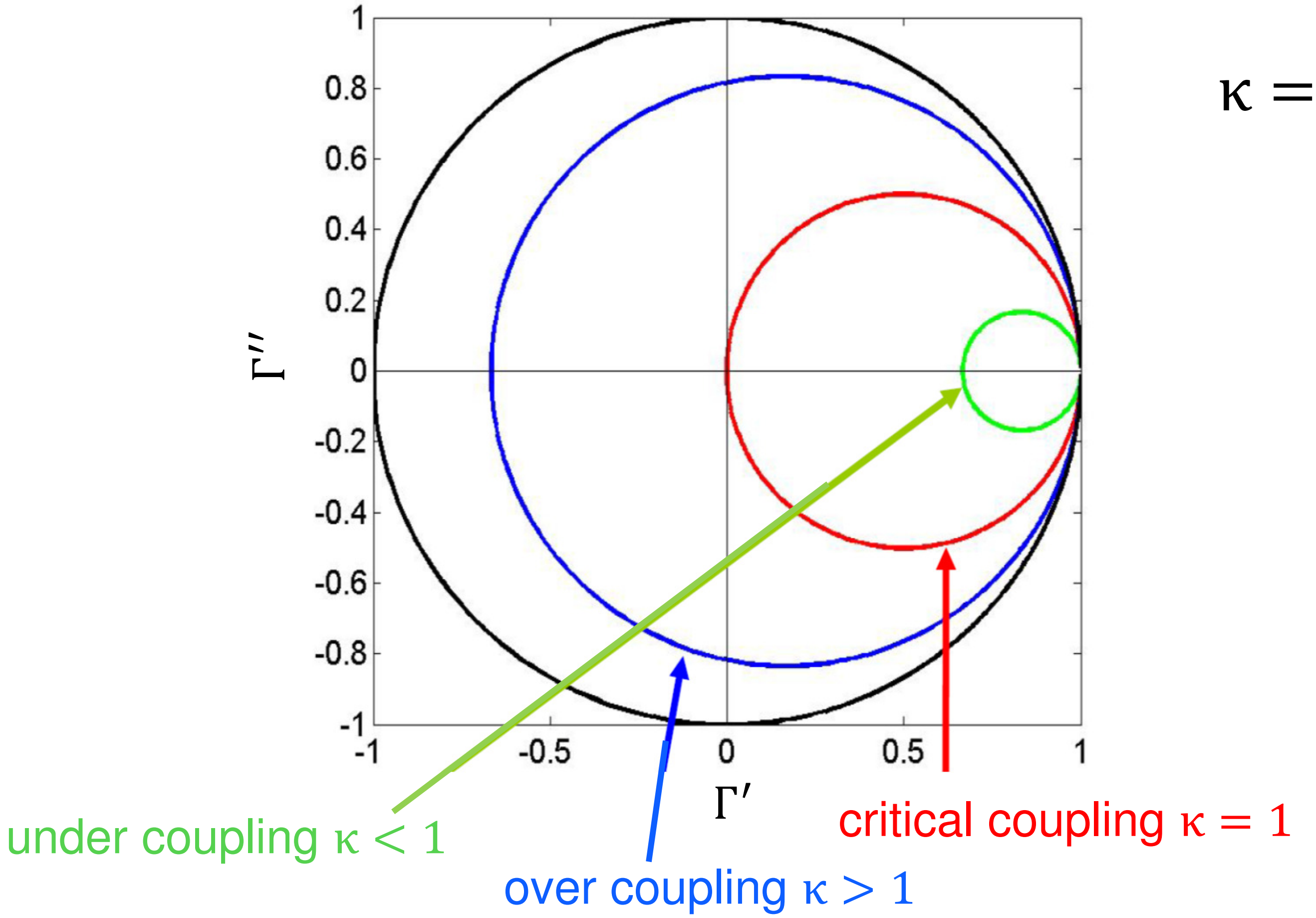


$$\Gamma = \frac{E^-}{E^+} = \frac{\kappa - 1 + iQ_0\delta}{\kappa + 1 - iQ_0\delta}$$

$$\delta = \frac{Q_{ext} + Q_0}{Q_{ext}Q_0}\tan\theta_c$$

Reflection coefficient

$$\left(\Gamma' + \frac{1}{1+\kappa}\right)^2 + \Gamma''^2 = \left(\frac{\kappa}{1+\kappa}\right)^2$$

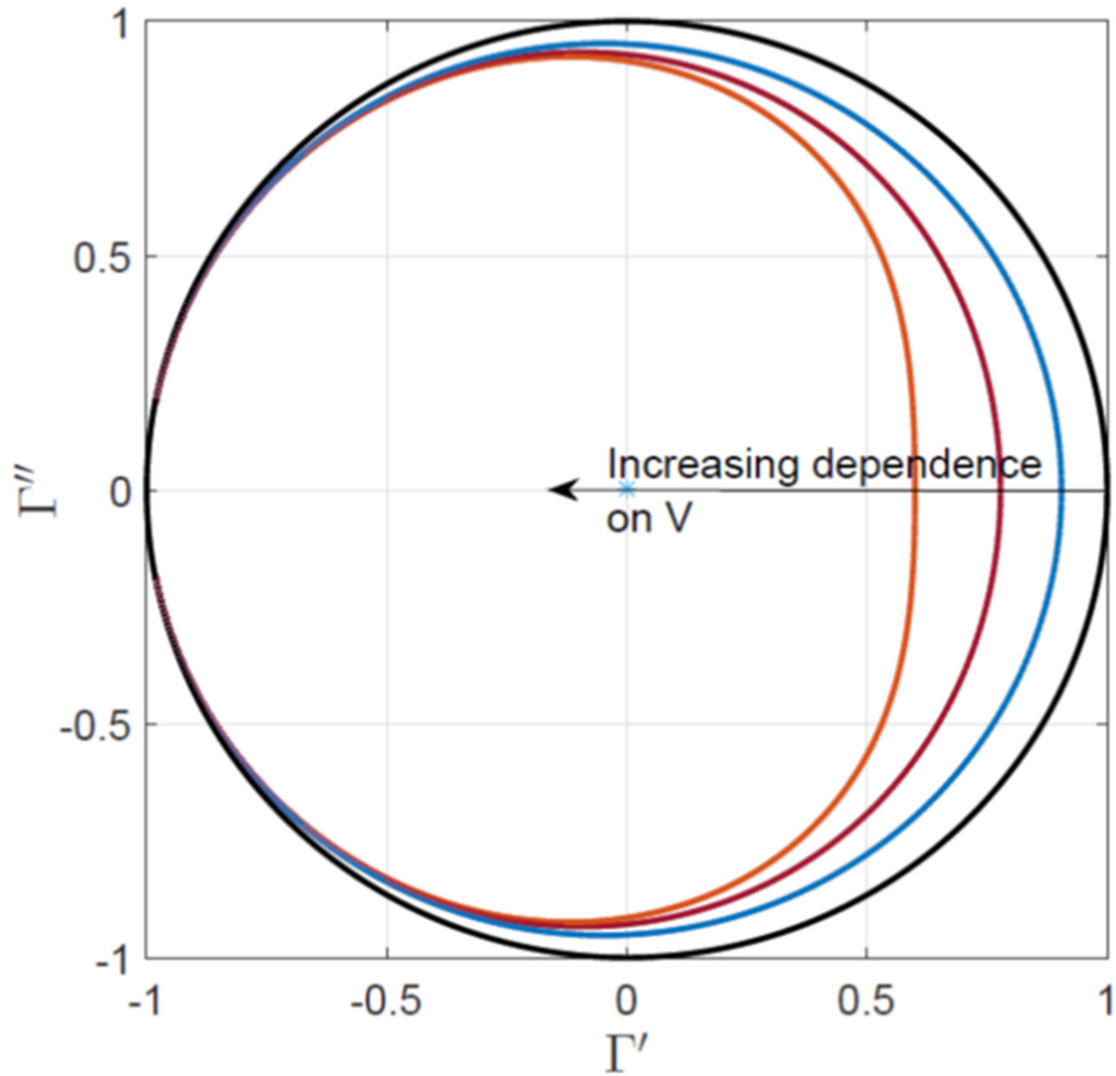


$$\kappa = \frac{Q_0}{Q_{ext}} = \frac{1}{\frac{1}{r} - 1}$$

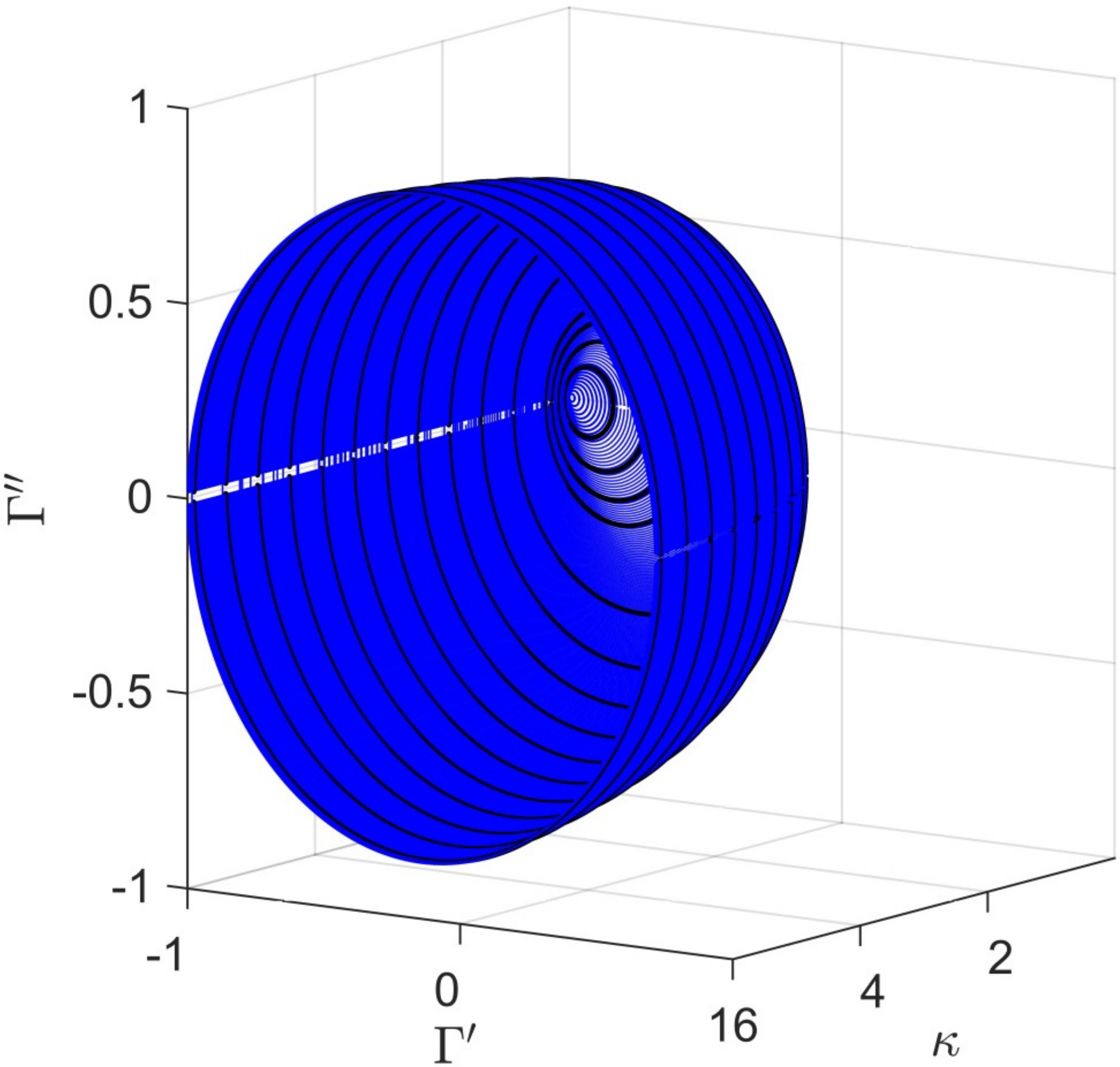
Superconducting cavity

$$\left(\Gamma' + \frac{1}{1+\kappa}\right)^2 + \Gamma''^2 = \left(\frac{\kappa}{1+\kappa}\right)^2$$

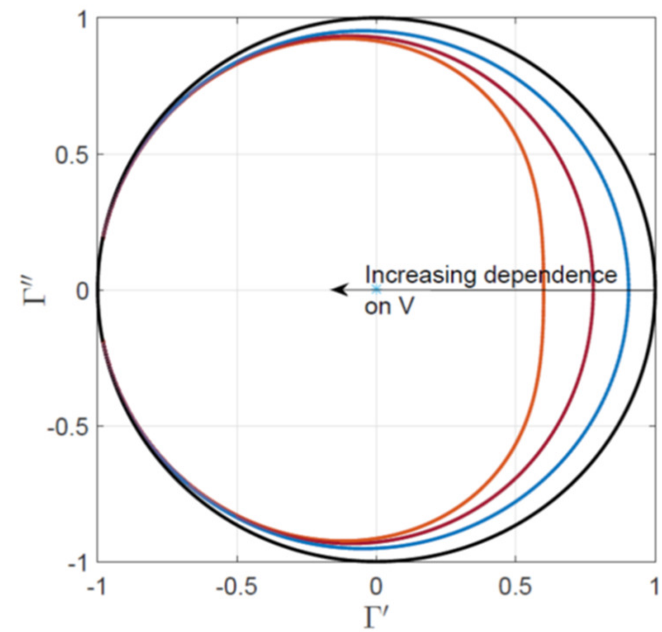
$$\kappa = \frac{Q_0(V)}{Q_{ext}}$$



Reflection co-efficient, Q-circle and surface

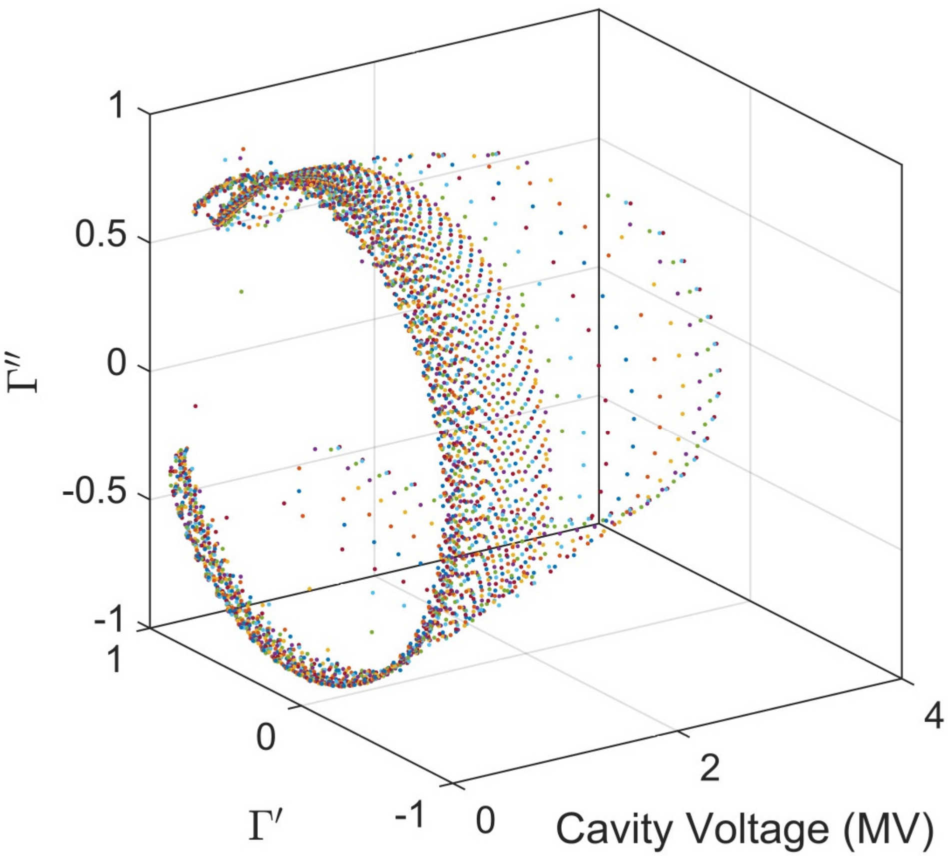


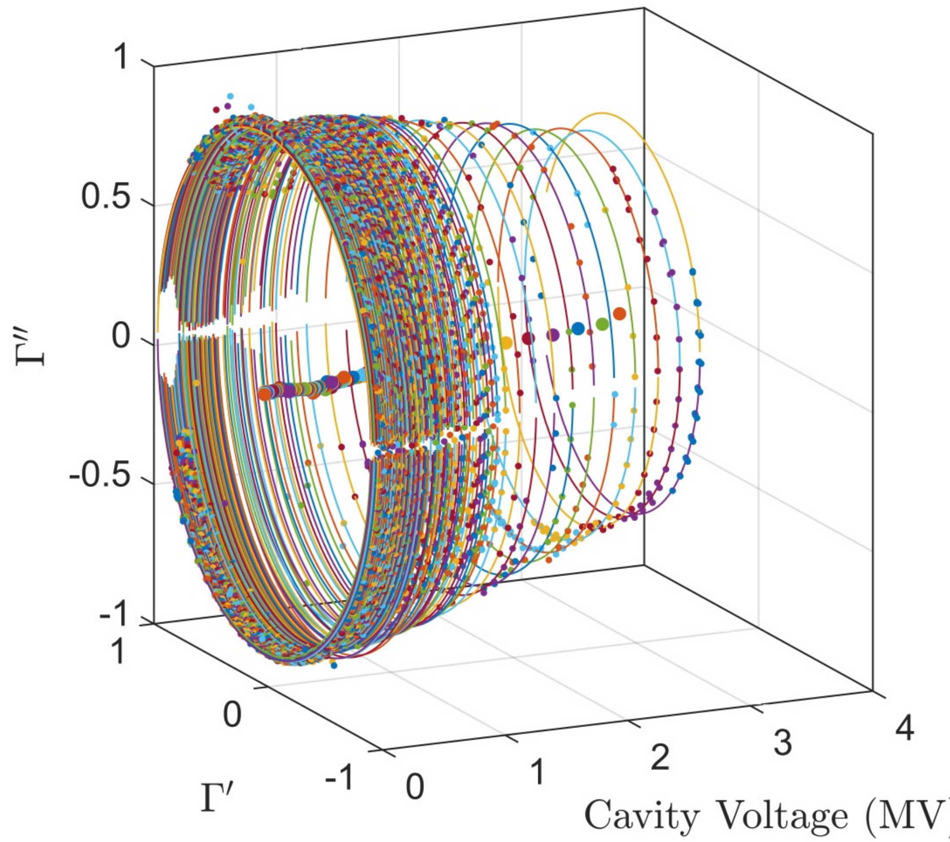
$$\left(\Gamma' + \frac{1}{1+\kappa}\right)^2 + \Gamma''^2 = \left(\frac{\kappa}{1+\kappa}\right)^2$$



UPPSALA UNIVERSITET

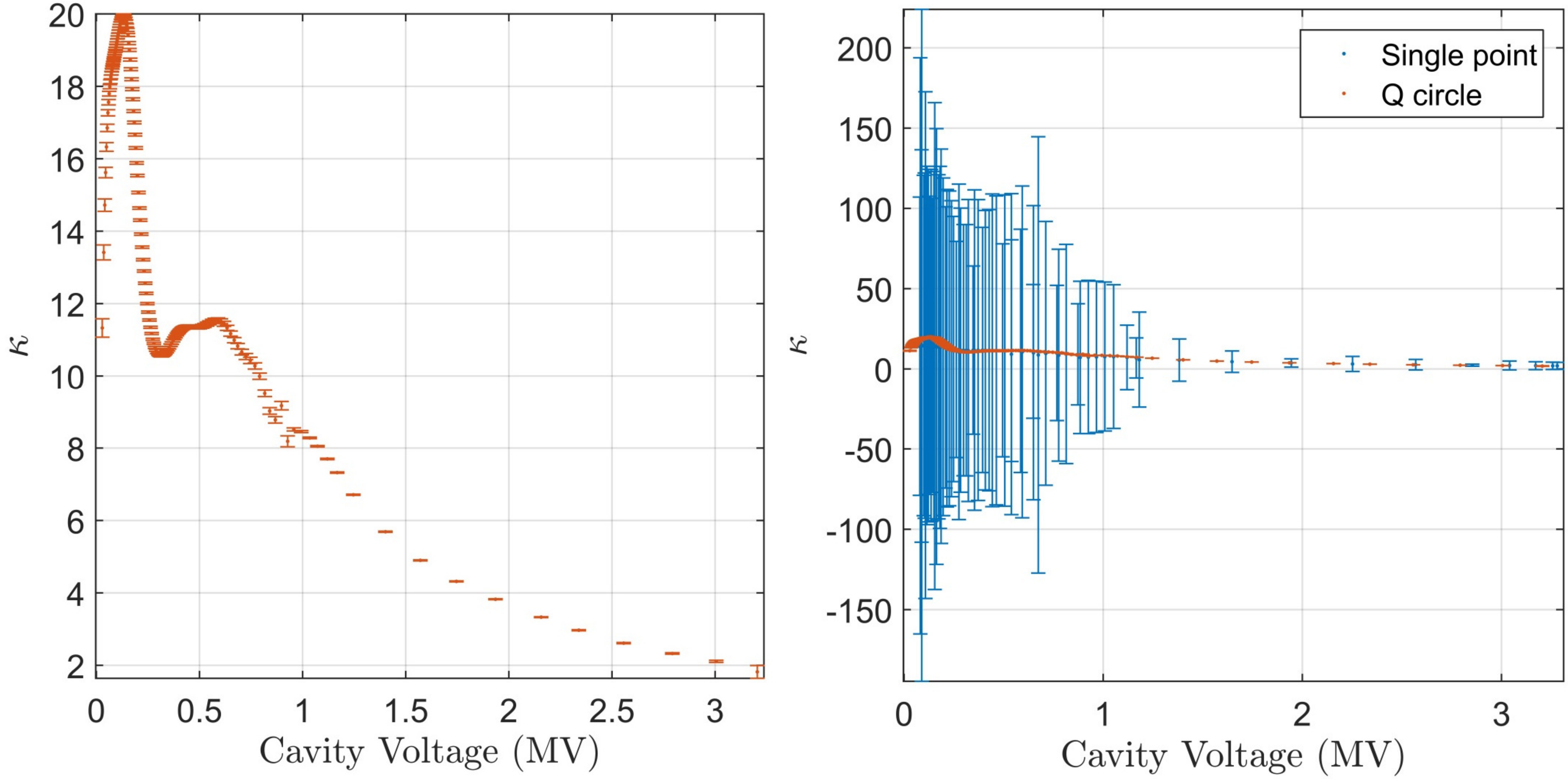
Q-surface



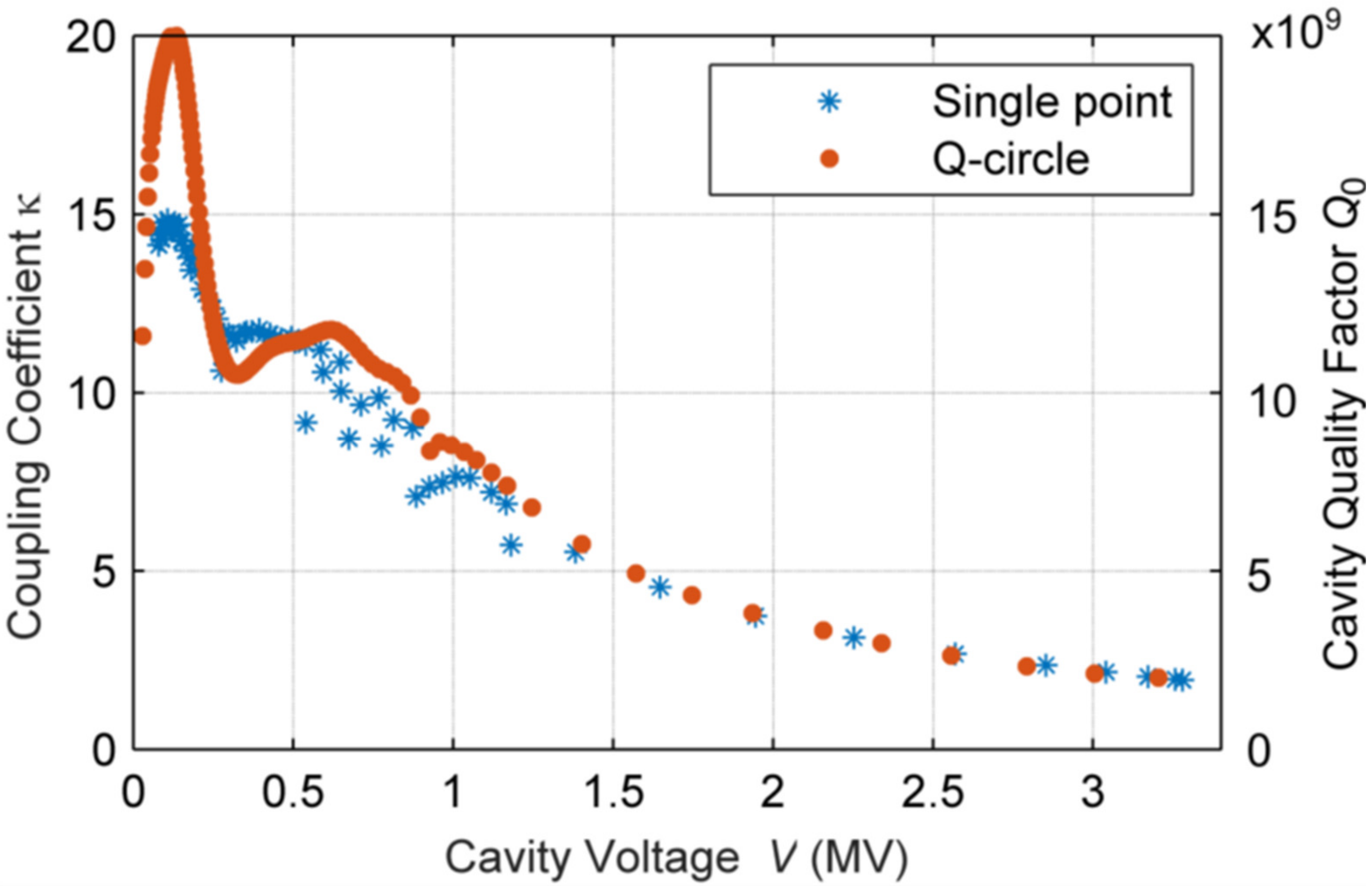


Q-slope

Double-spoke cavity



Q-slope

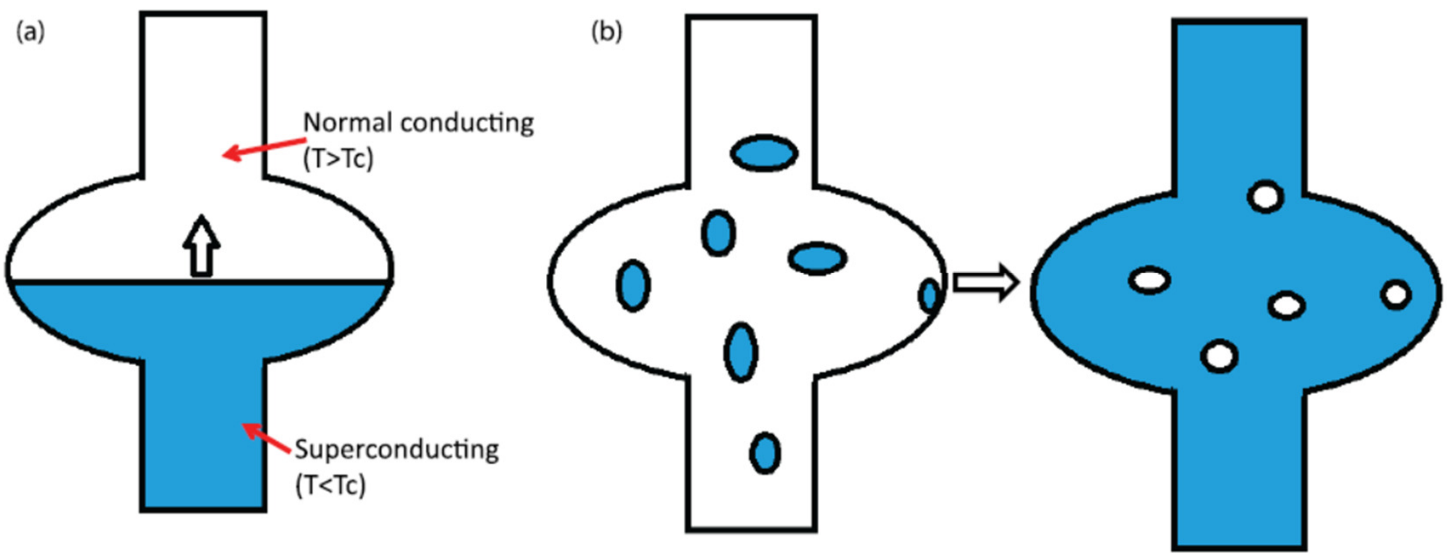


x10^9
Single point
Q-circle
Coupling Coefficient κ
Cavity Quality Factor Q0
Cavity Voltage V (MV)
20
15
10
5
0
0
0.5
1
1.5
2
2.5
3

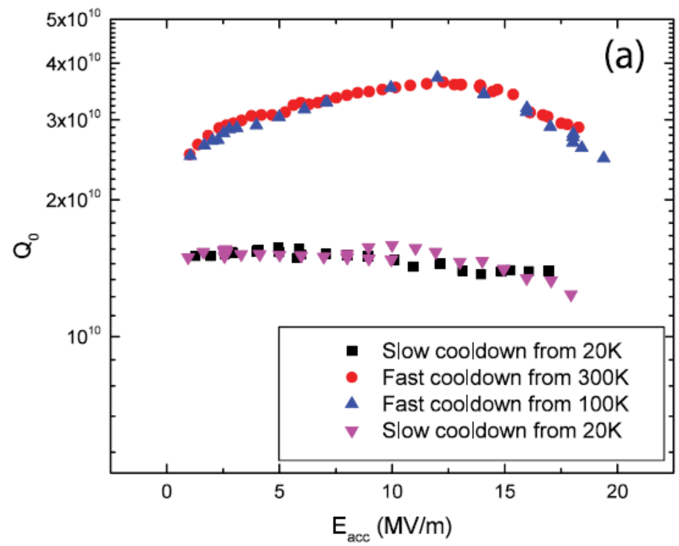
Effect of cooling rate on Q_0

Residual resistance depends on trapped magnetic field

- Helmholtz Zentrum Berlin (HZB): magnetic field are generated by thermal currents.
- HZB & Cornell: Slow cooling to reduce thermal currents.
- Fermilab: Magnetic field (ambient) can be expelled by large temperature gradients creating a quick propagating super-conducting phase front.



Effect of cooling rate on Q_0



APPLIED PHYSICS LETTERS **105**, 234103 (2014)

Ultra-high quality factors in superconducting niobium cavities in ambient magnetic fields up to 190 mG

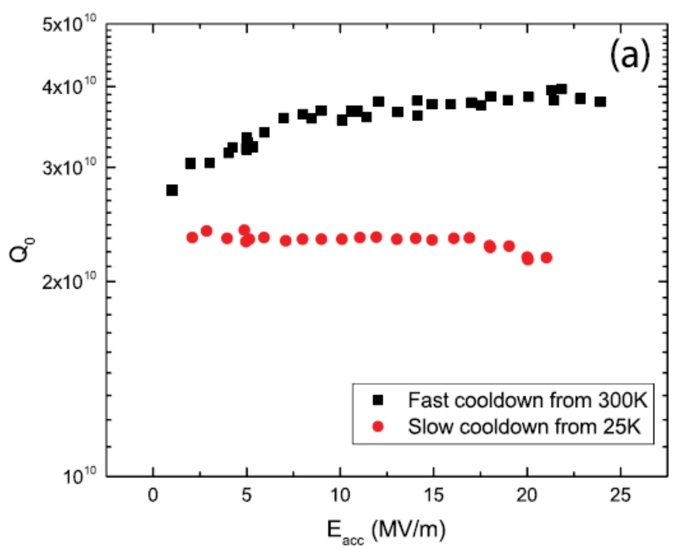
A. Romanenko,[a)] A. Grassellino, A. C. Crawford, D. A. Sergatskov, and O. Melnychuk
Fermi National Accelerator Laboratory, Batavia, Illinois 60510, USA

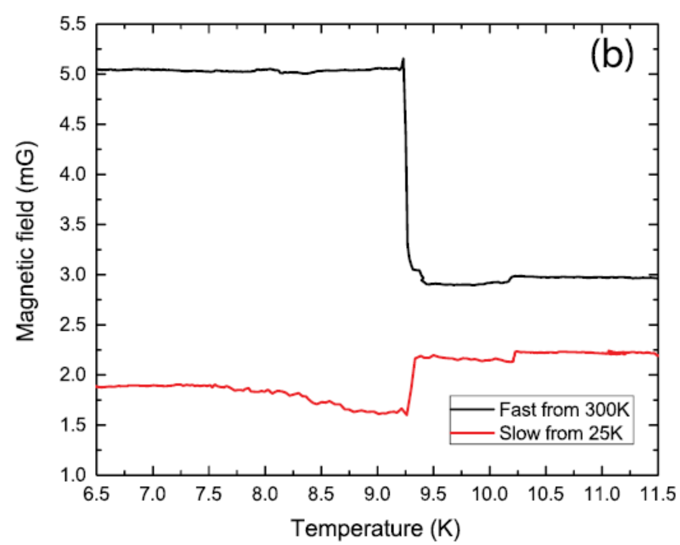
(Received 29 October 2014; accepted 27 November 2014; published online 10 December 2014)

JOURNAL OF APPLIED PHYSICS **115**, 184903 (2014)

Dependence of the residual surface resistance of superconducting radio frequency cavities on the cooling dynamics around T_c

A. Romanenko,[a)] A. Grassellino,[b)] O. Melnychuk, and D. A. Sergatskov
Fermi National Accelerator Laboratory, Batavia, Illinois 60510, USA





Ginzburg-Landau Equations

$$\frac{1}{D}\left(\frac{\partial}{\partial t}+i2e\phi\right)\psi=-\left(\frac{\nabla}{i}-2e\mathbf{A}\right)^2\psi-\frac{1}{\xi(T)^2}\left(|\psi|^2-1\right)\psi,$$

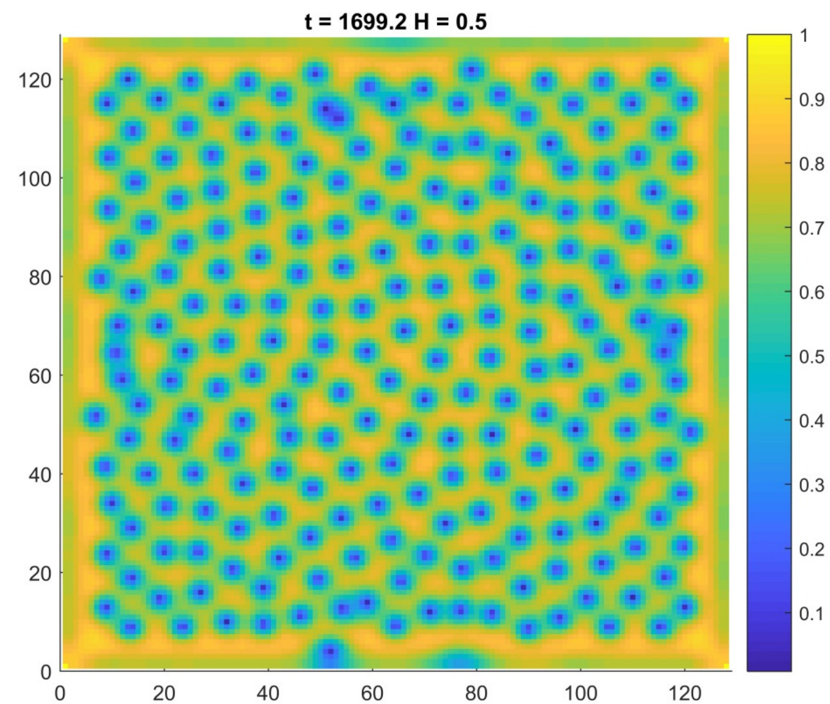
$$\mathbf{J}=\sigma\left(-\nabla\phi-\frac{\partial\mathbf{A}}{\partial t}\right)+\frac{1}{8\pi e\lambda(T)^2}\text{Real}\left[\psi^*\left(\frac{\nabla}{i}-2e\mathbf{A}\right)\psi\right].$$

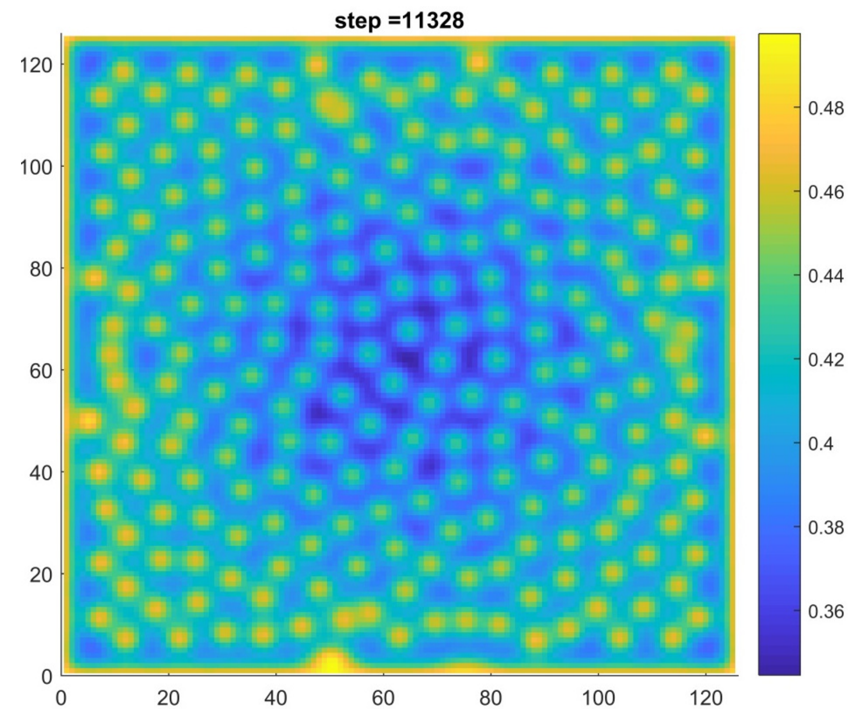
Journal of Computational Physics **179**, 127–139 (2002)
doi:10.1006/jcph.2002.7047

A Fast Semi-Implicit Finite-Difference Method for the TDGL Equations

T. Winiecki and C. S. Adams

Department of Physics, University of Durham, Rochester Building, South Road, Durham, DH1 3LE, United Kingdom



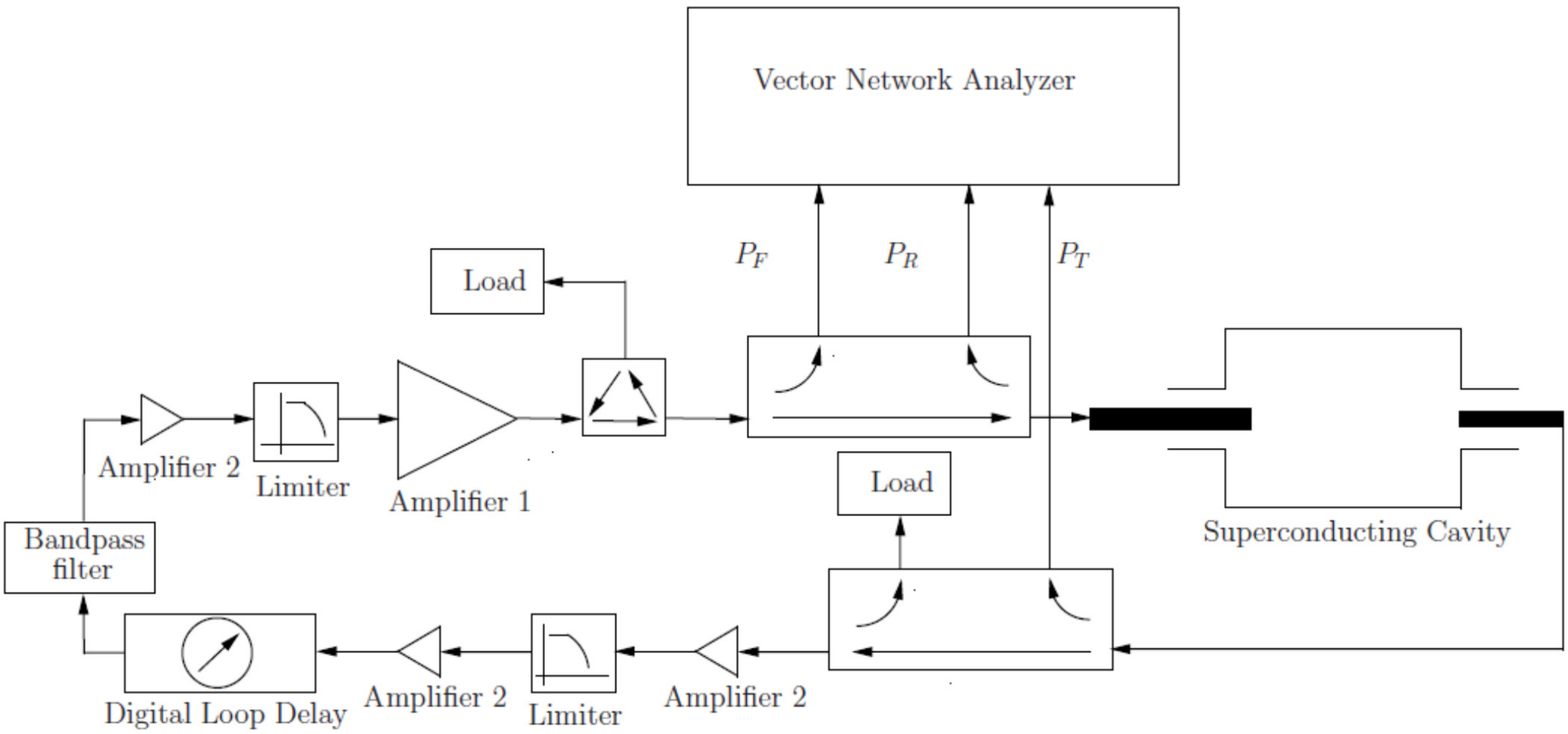


Conclusion

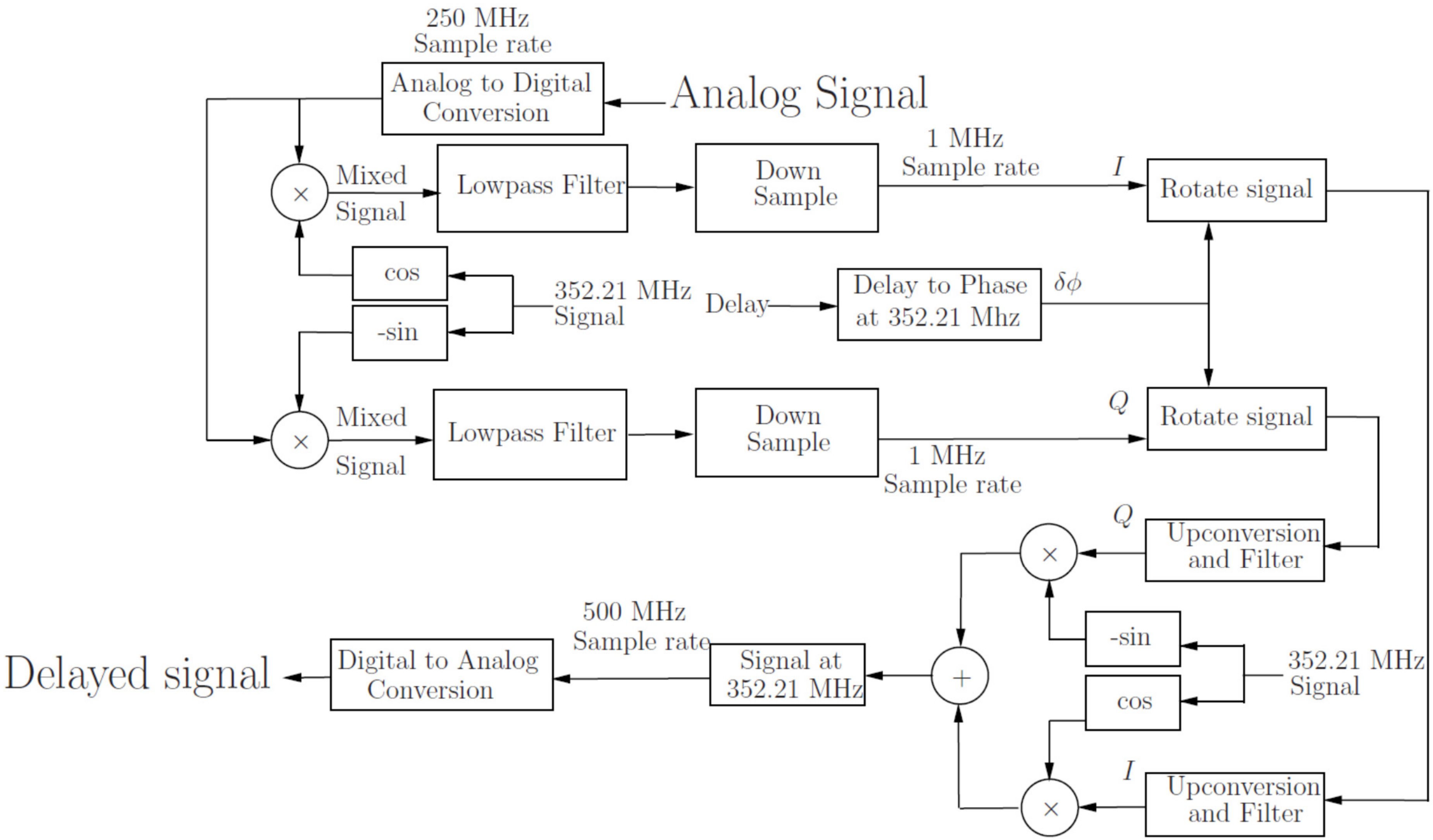
- Reflected energy and thus waste can be reduced by proposed filling profile.
- But physical factors provide constraints which require increased investigation to better understand the super-conducting cavity.
- The proposed Q_0 measurement technique provides a means of accurately characterising the gradient dependent character of the super-conducting cavities.
- The rate of cooling has been found to influence cavity Q_0 and the G-L equations provide a means of theoretically explaining experimental observations.

Thank You

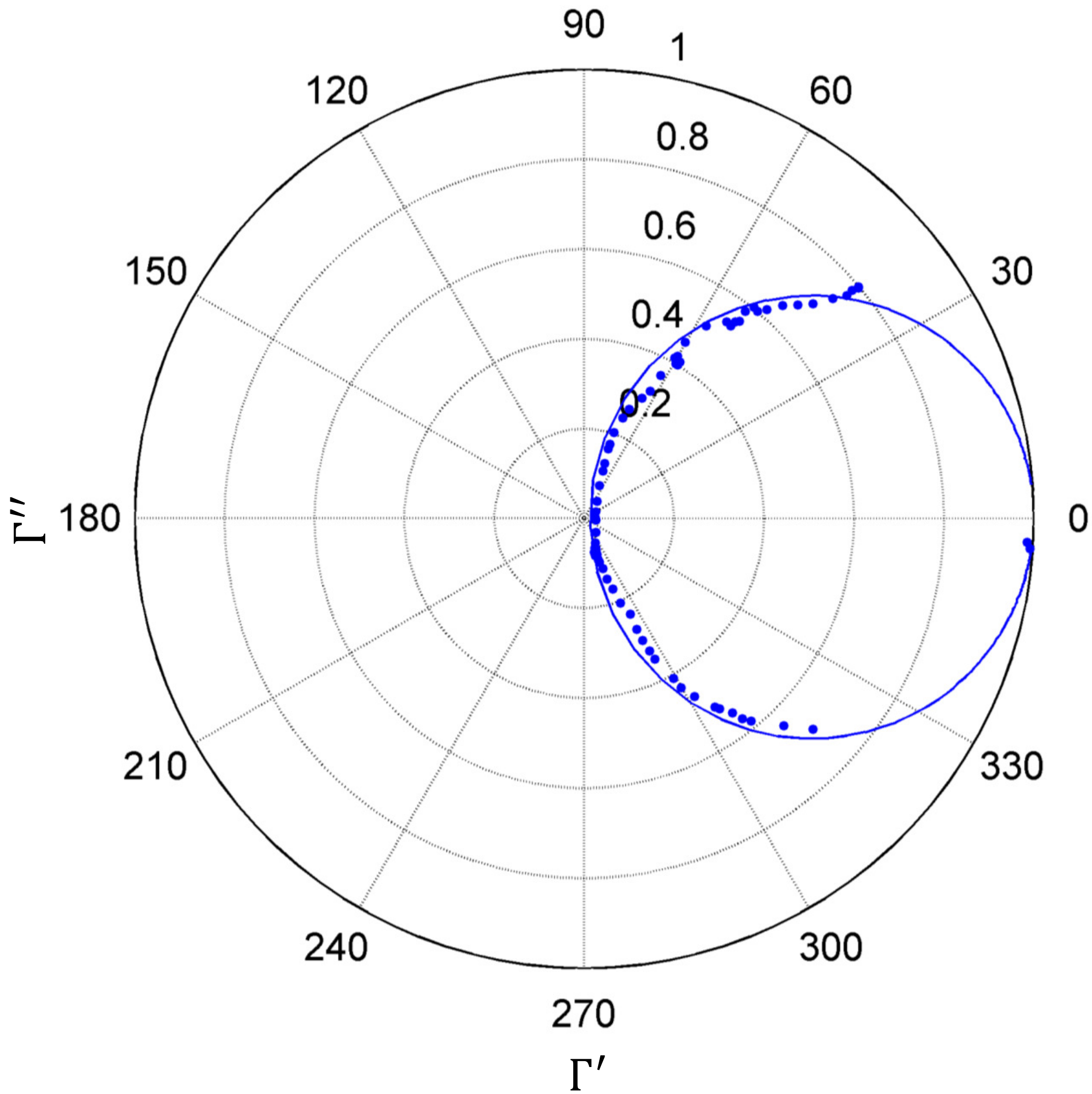
Experimental setup



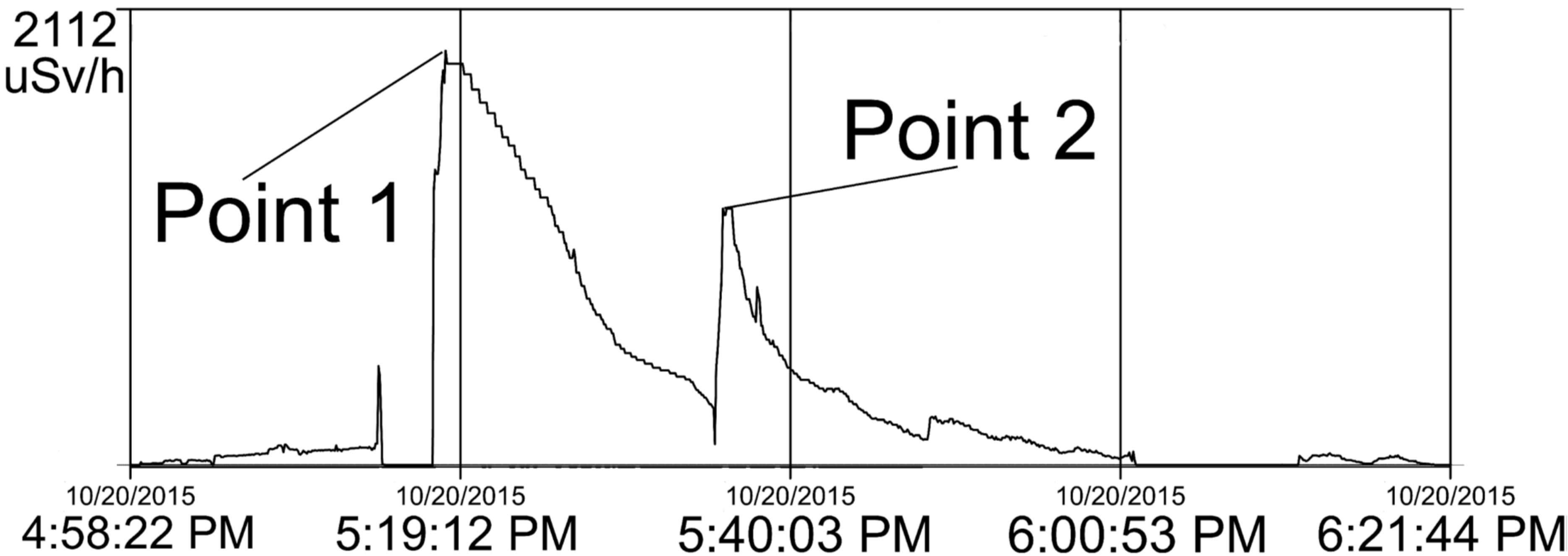
Digital loop delay



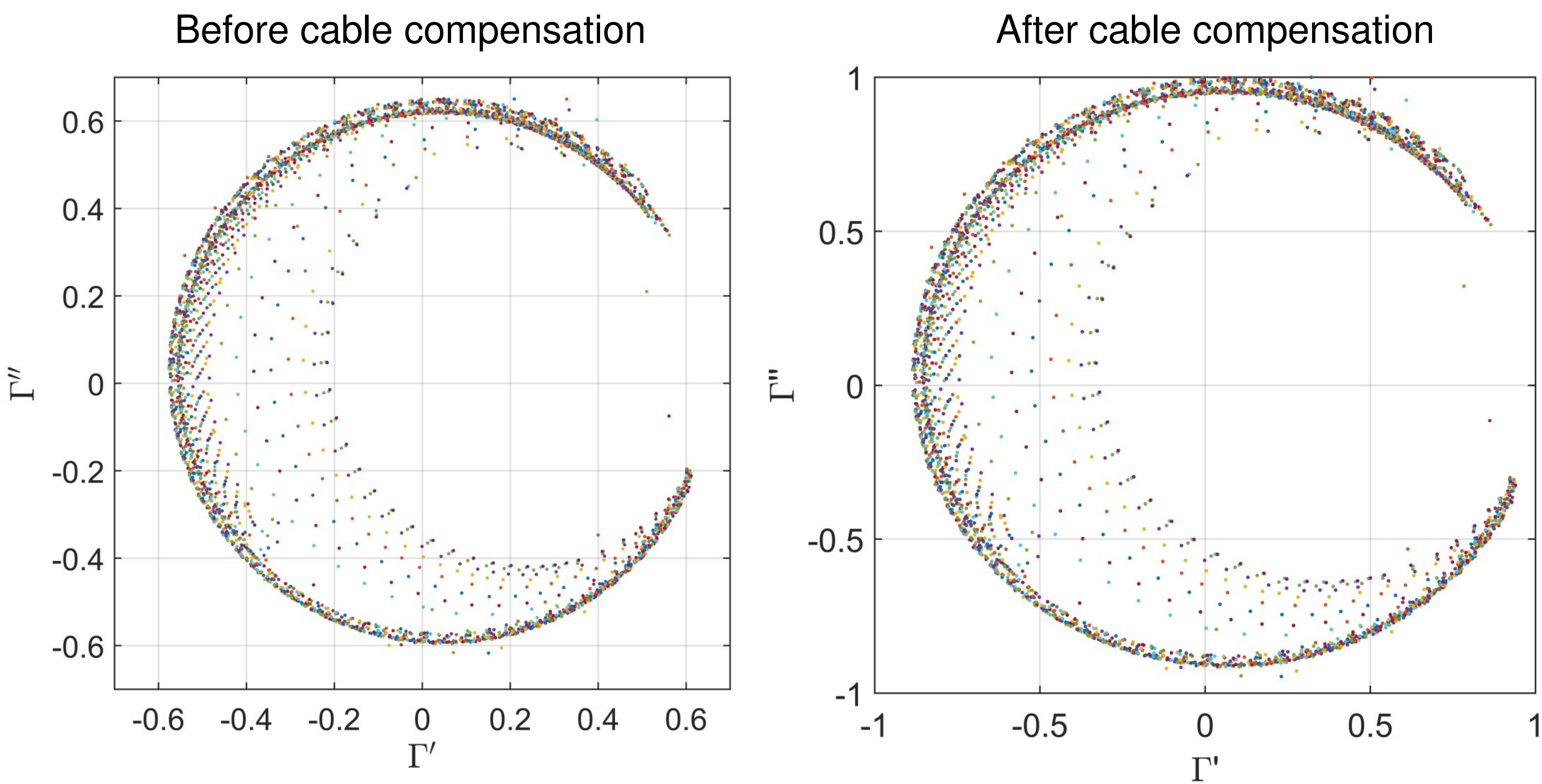
Normal conducting cavity



Cavity conditioning



Reflection coefficient



Doherty Architecture