Normal conducting RF for muon collider

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Alternative title

Normal conducting RF for muon collider

Since I am not at all an expert on muon collider RF systems I propose instead:

An overview of high-gradient, normal-conducting RF developments that may be relevant for a muon collider

A lot of work has been done in recent years on increasing, understanding and applying high-gradients.
Many aspects of this work are relevant for a muon collider.
The work was initially motivated by linear collider studies but now is being pursued by a wide range of applications.

High-gradient development overview

High-gradient prototypes for CLIC:
12 GHz, full length, aperture constrained, HOM mode damping, etc.

Research structures:
Single cell cavities, pulsed dc, different materials, cryo, short pulse

High-gradient prototypes for other electron linacs:
X, C and S-band, typical applications include XFEL, ICS and medical (VHEE and FLASH)

Theory:
RF design – Sc, breakdown loaded voltage
Materials – vacancy and dislocation models
Modeling of field emission and multi-scale modeling of breakdown

Accelerator devices:
Energy spread linearizers, transverse deflectors, typically 12 GHz
Electrostatic septa

Non-accelerator devices:
Making connections to fusion, X-ray tubes, vacuum interrupters

High-fields for low-β protons:
RFQ 350 MHz and proton therapy 3 GHz

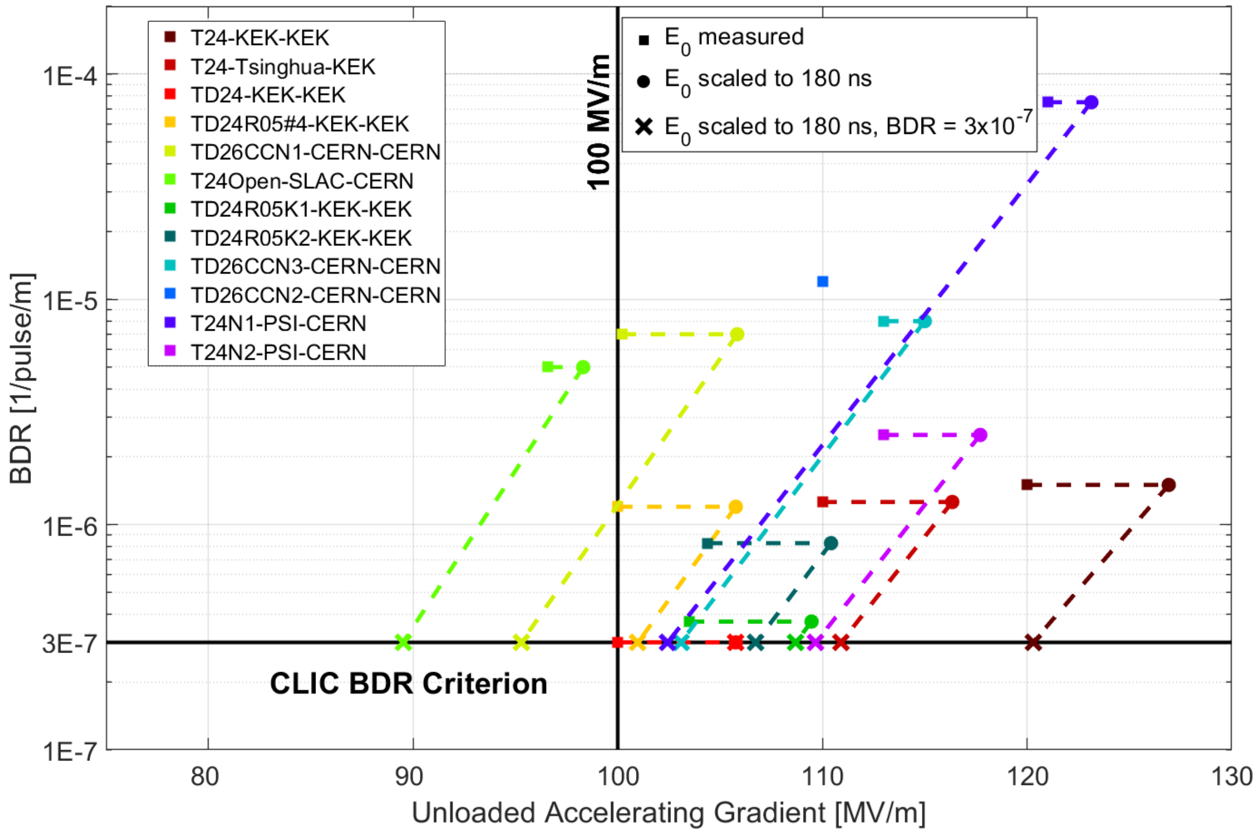
Small selection of examples follow…

What we are looking for

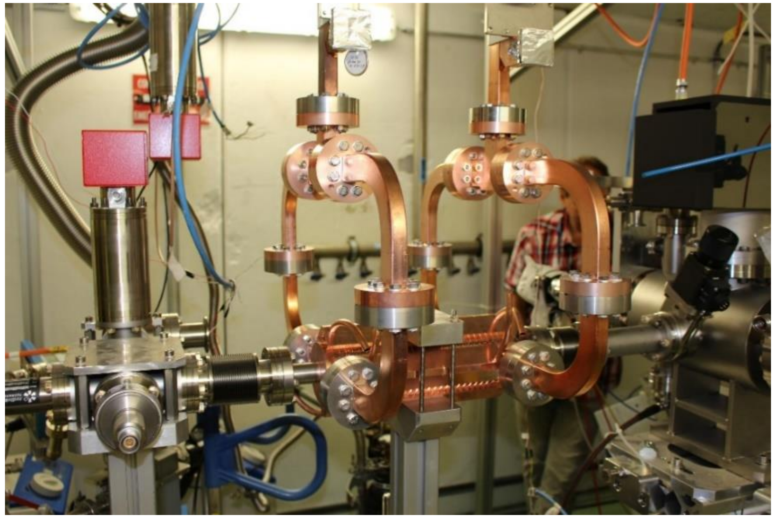
The main challenges for the RF cavities for muon capture and cooling are that they must operate:

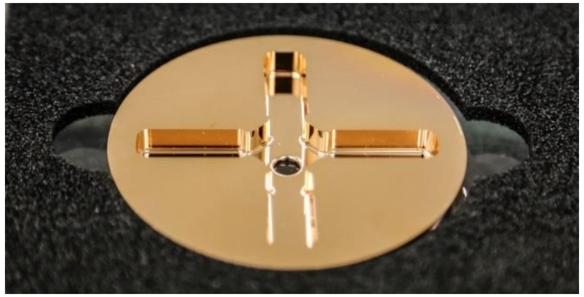
- In a high, >10T, solenoidal magnetic field,
- with high accelerating gradient,
- and be robust against irradiation damage.

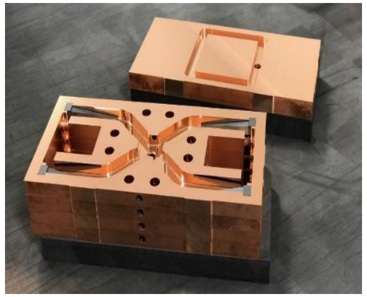
CLIC 12 GHz prototypes – what is possible



Peak surface electric fields about x 2.5 higher





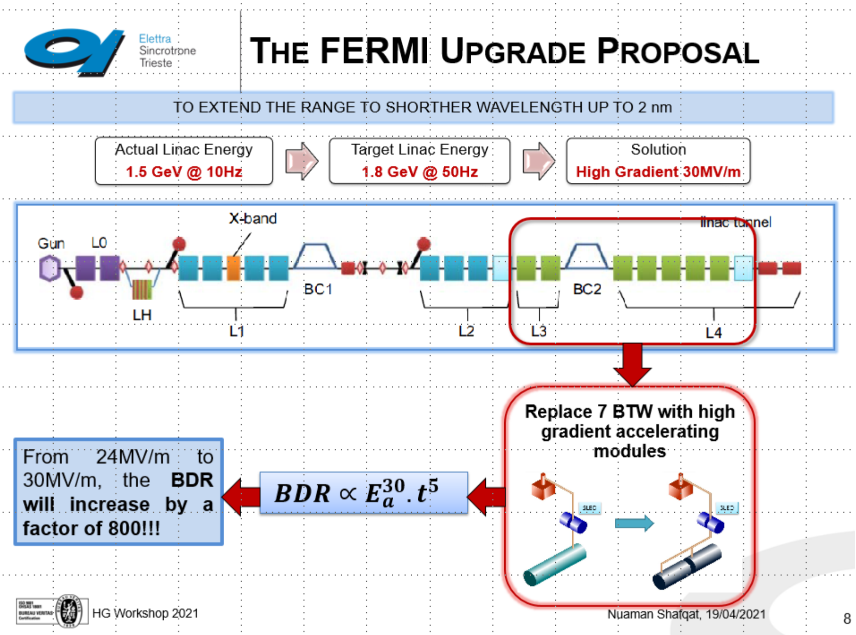


https://doi.org/10.1103/PhysRevAccelBeams.21.061001,
https://doi.org/10.1103/PhysRevAccelBeams.20.052001 etc.

Much of the progress has been in quantifying dependence of gradient on RF design.

FERMI energy upgrade – 3 GHz

Material from Nuaman Shafqat https://indico.fnal.gov/event/22025/contributions/210365/



Elettra Sincrotrone Trieste

THE FERMI UPGRADE PROPOSAL

TO EXTEND THE RANGE TO SHORTHER WAVELENGTH UP TO 2 nm

Actual Linac Energy **1.5 GeV @ 10Hz** → Target Linac Energy **1.8 GeV @ 50Hz** → Solution **High Gradient 30MV/m**

Replace 7 BTW with high gradient accelerating modules

$BDR \propto E_a^{30}.t^5$

From 24MV/m to 30MV/m, the **BDR will increase by a factor of 800!!!**

HG Workshop 2021

Nuaman Shafqat, 19/04/2021

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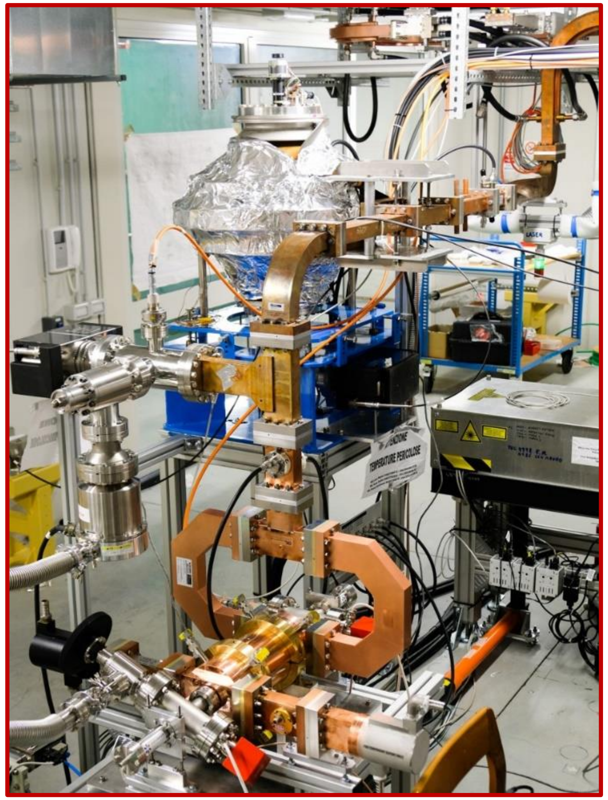

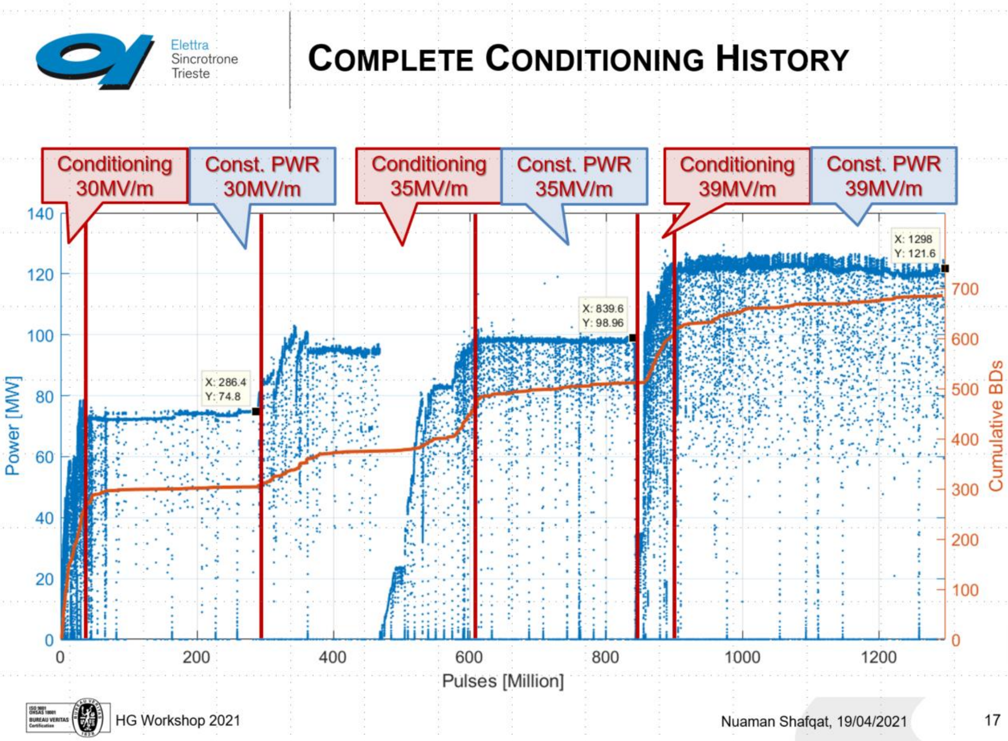

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COMPLETE CONDITIONING HISTORY

HG Workshop 2021

Nuaman Shafqat, 19/04/2021

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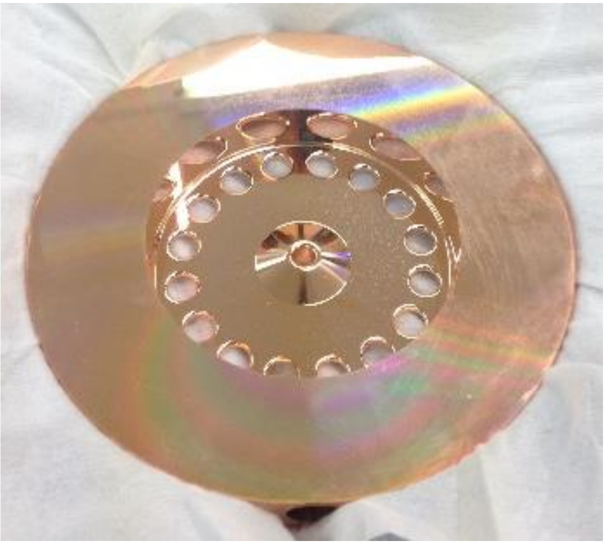
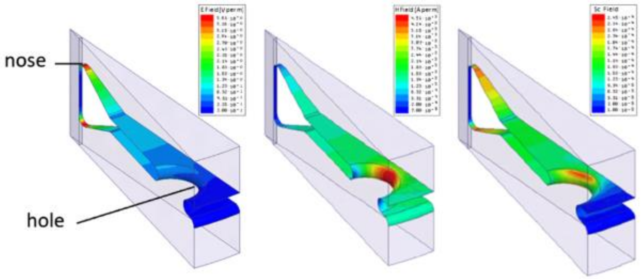
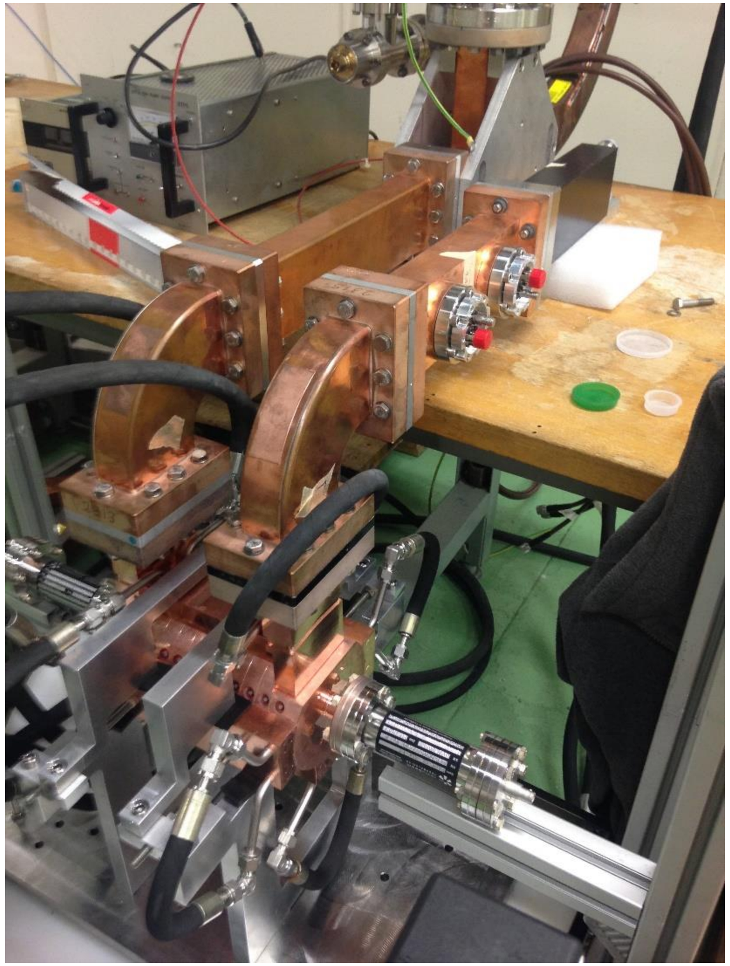
Structure fabricated by PSI

https://doi.org/10.1016/j.nima.2020.164473

High-gradient, β=0.38, 3 GHz for protons







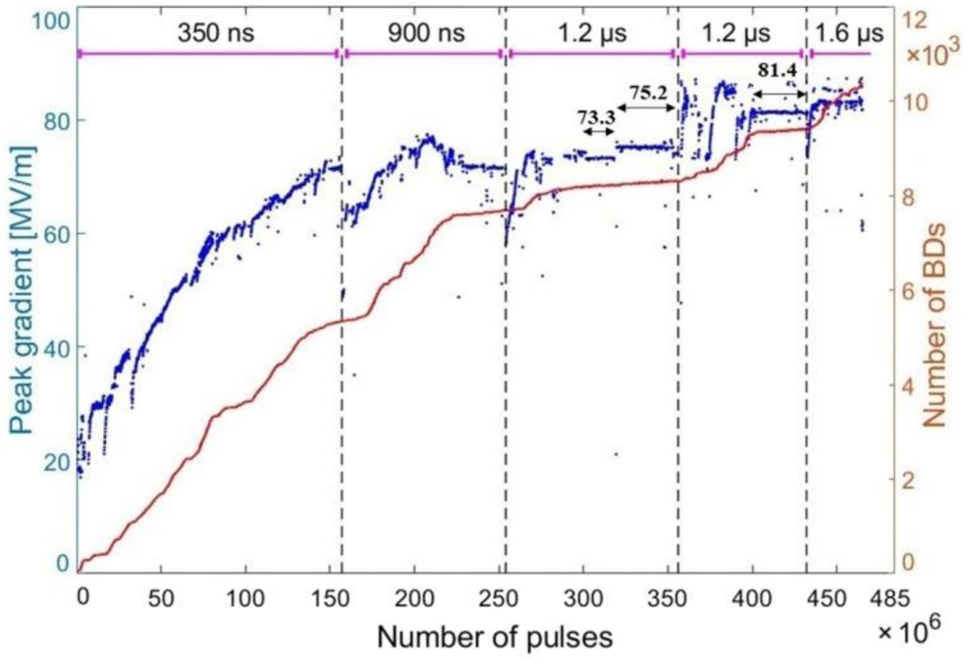
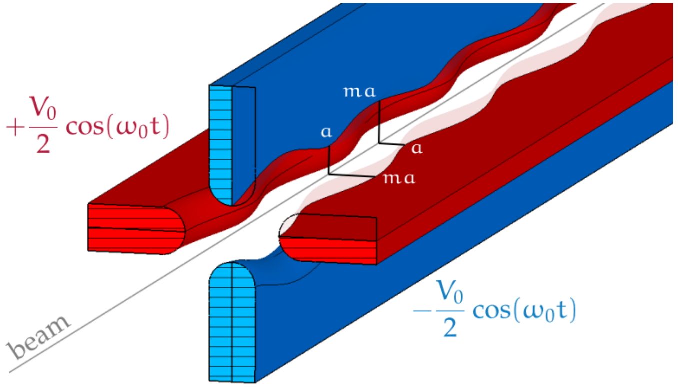


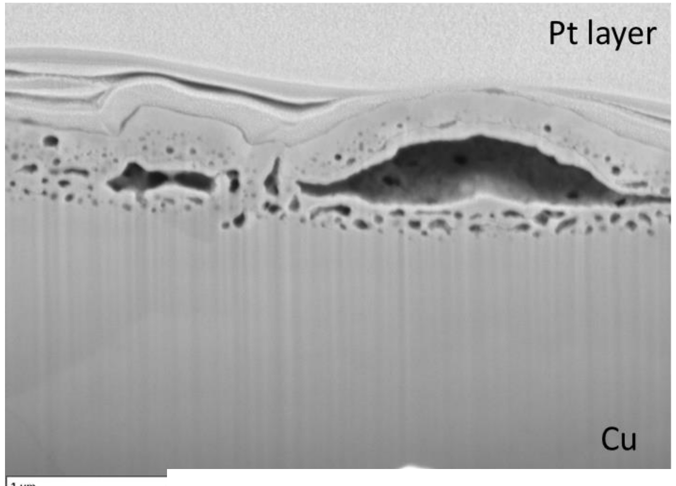
FIG. 8. Conditioning history of the BTW accelerating structure. The plot shows the accelerating gradient in the first cell (blue) and accumulated number of BDs (red) versus the number of pulses, with pulse lengths indicated at the top.

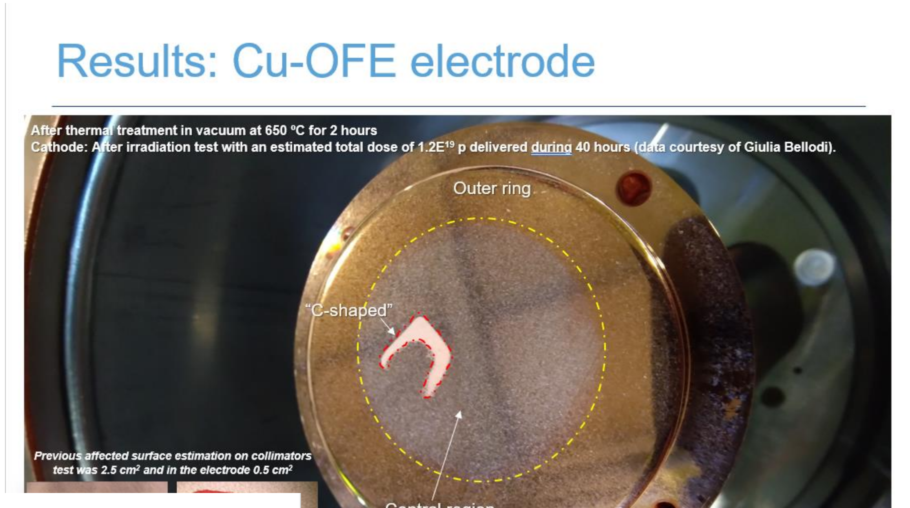
https://doi.org/10.1103/PhysRevAccelBeams.23.084801

LINAC4 RFQ – 350 MHz and beam loss

From A. Grudiev https://indico.fnal.gov/event/22025/contributions/210496/





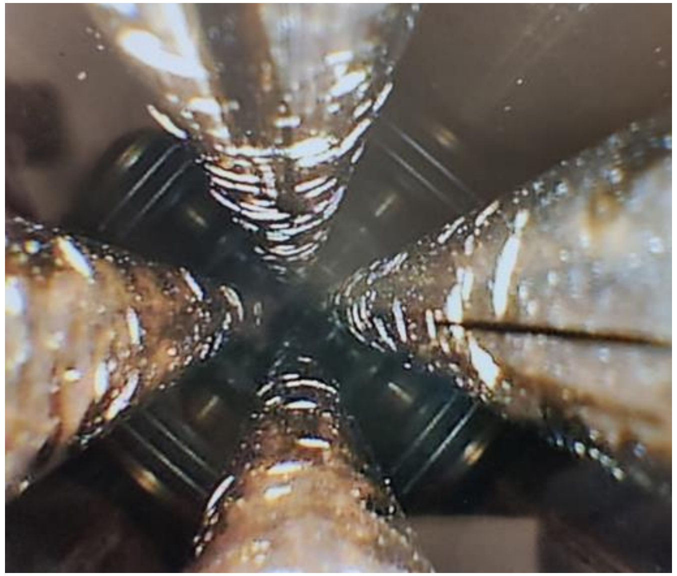


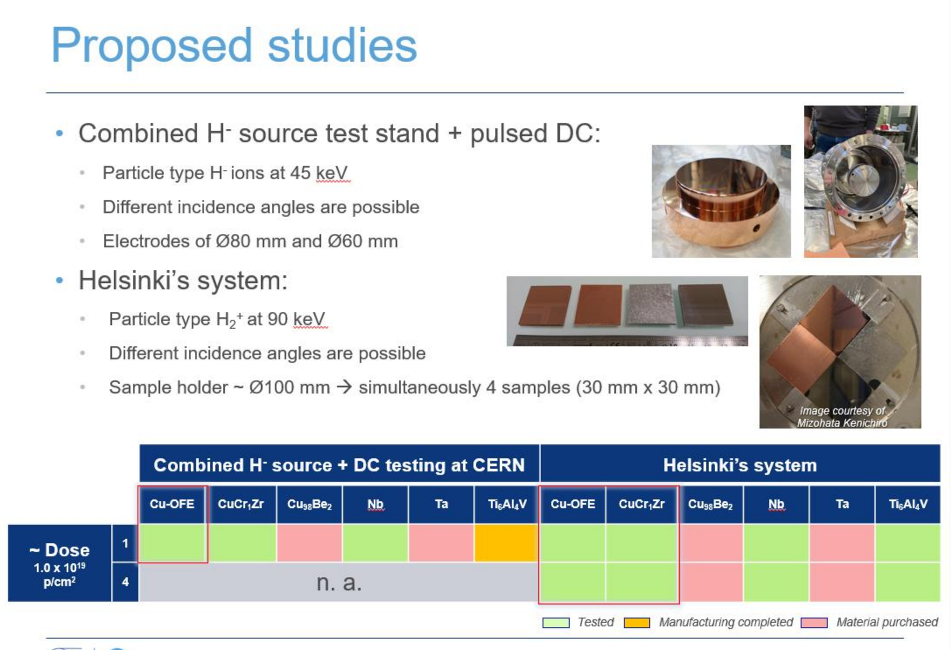
Results: Cu-OFE electrode

After thermal treatment in vacuum at 650 ºC for 2 hours
Cathode: After irradiation test with an estimated total dose of 1.2E^{19} p delivered during 40 hours (data courtesy of Giulia Bellodi).

Previous affected surface estimation on collimators test was 2.5 cm^2 and in the electrode 0.5 cm^2

Image courtesy of Sebastien Bertolo





Proposed studies

- Combined H$^-$ source test stand + pulsed DC:
  - Particle type H$^-$ ions at 45 keV
  - Different incidence angles are possible
  - Electrodes of Ø80 mm and Ø60 mm
- Helsinki's system:
  - Particle type H_2^+ at 90 keV
  - Different incidence angles are possible
  - Sample holder ~ Ø100 mm → simultaneously 4 samples (30 mm x 30 mm)

Image courtesy of Mizohata Kenichiro

		Combined H$^-$ source + DC testing at CERN						Helsinki's system					
		Cu-OFE	CuCr$_1$Zr	Cu$_{98}$Be$_2$	Nb	Ta	Ti$_6$Al$_4$V	Cu-OFE	CuCr$_1$Zr	Cu$_{98}$Be$_2$	Nb	Ta	Ti$_6$Al$_4$V
~ Dose 1.0 x 10^{19} p/cm^2	1	🟩	🟩	🟥	🟩	🟥	🟧	🟩	🟩	🟥	🟩	🟥	🟩
	4	n. a.						🟩	🟩	🟥	🟩	🟥	🟩

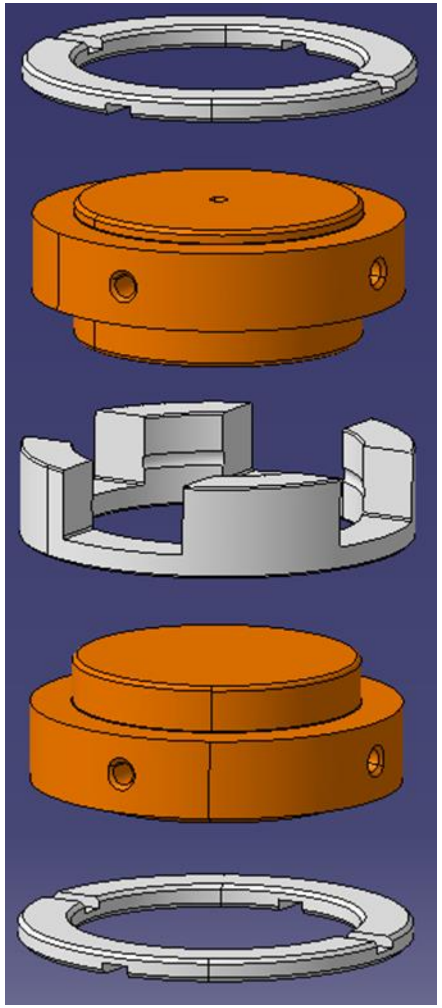
🟩 *Tested* 🟧 *Manufacturing completed* 🟥 *Material purchased*

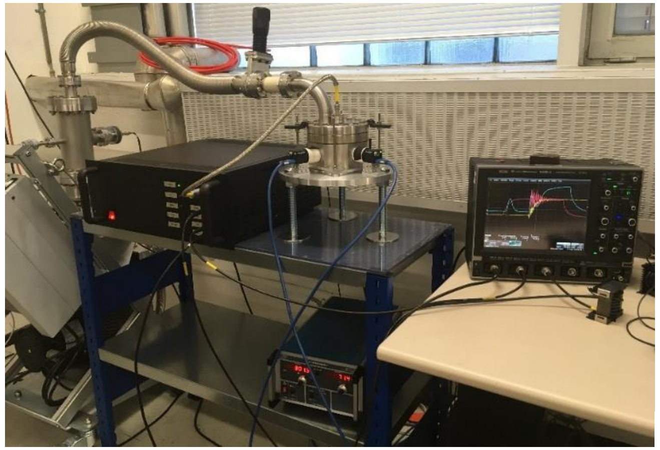
Pulsed dc system

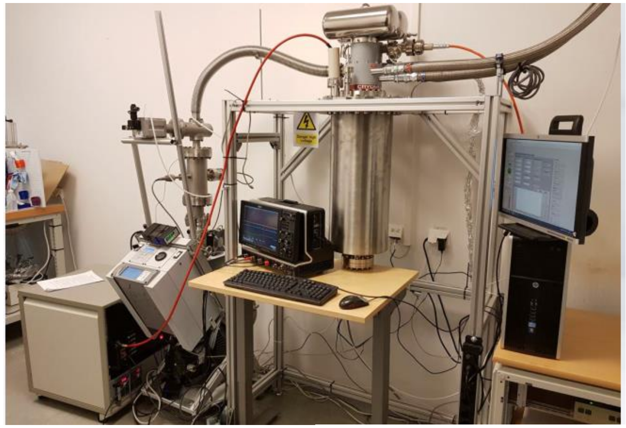
International
MUON Collider
Collaboration

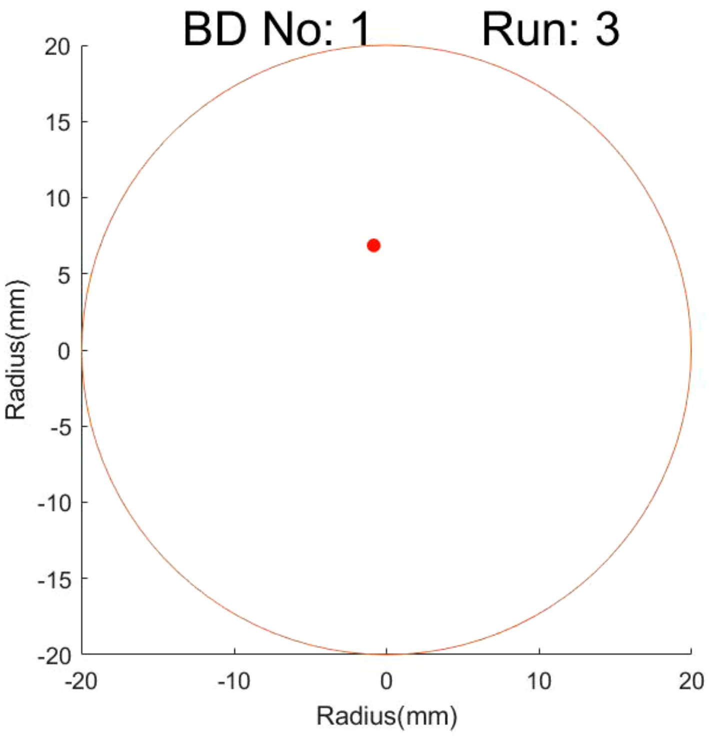
Pulsed DC

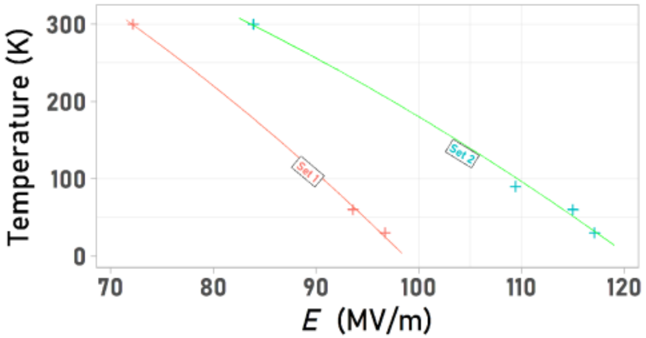
CERN











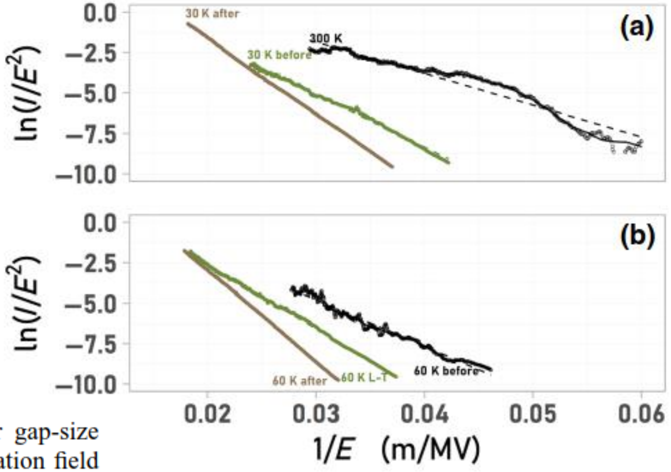


TABLE I. Field holding capacity compensated for gap-size effect. Estimated saturation field $E_{\rm sat}^{\rm est}$, measured saturation field $E_{\rm sat}$, and relative change $\Delta E/E$ between them, for conditioning runs at different temperatures T.

	Electrode set 1			Electrode set 2		
T (K)	$E_{\rm sat}^{\rm est}$ (MV/m)	$E_{\rm sat}$ (MV/m)	$\Delta E/E$ (%)	$E_{\rm sat}^{\rm est}$ (MV/m)	$E_{\rm sat}$ (MV/m)	$\Delta E/E$ (%)
30	67.4	96.7	43	78.3	117.1	50
60	67.7	93.6	38	78.6	115.0	46
90	...	...	...	78.9	109.4	39
300	72.2	72.2	0	83.9	83.9	0

https://doi.org/10.1103/PhysRevApplied.14.061002

High-gradient theory

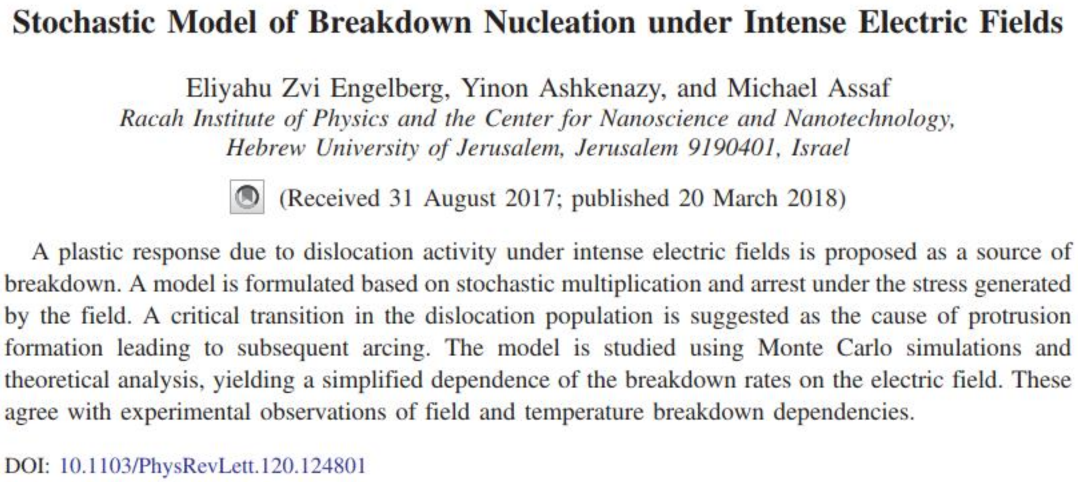
RF design

S_c has been the workhorse for CLIC and application structures.
Gives gradient limit based on maximum local power flow density so includes electric and magnetic field.
https://doi.org/10.1103/PhysRevSTAB.12.102001
Now breakdown-loaded field limit. Also power flow but includes loading of fields by incipient breakdown.
Extends range of applicability.
PhD thesis of Jan Paszkiewicz
http://cds.cern.ch/record/2749494/

Fundamentals of breakdown

Vacancy and dislocation (bulk) models give breakdown rate as a function of gradient – a fundamental measureable dependency that we reproducibly observe as BDR α E^{30}.
https://doi.org/10.1103/PhysRevSTAB.15.071002
https://doi.org/10.1103/PhysRevLett.120.124801
Surface dynamics under strong electric fields
https://doi.org/10.1103/PhysRevB.99.205418
Breakdown plasma simulation
https://doi.org/10.1002/ctpp.201400069

High-gradient theory - example



Stochastic Model of Breakdown Nucleation under Intense Electric Fields

Eliyahu Zvi Engelberg, Yinon Ashkenazy, and Michael Assaf
Racah Institute of Physics and the Center for Nanoscience and Nanotechnology,
Hebrew University of Jerusalem, Jerusalem 9190401, Israel

(Received 31 August 2017; published 20 March 2018)

A plastic response due to dislocation activity under intense electric fields is proposed as a source of breakdown. A model is formulated based on stochastic multiplication and arrest under the stress generated by the field. A critical transition in the dislocation population is suggested as the cause of protrusion formation leading to subsequent arcing. The model is studied using Monte Carlo simulations and theoretical analysis, yielding a simplified dependence of the breakdown rates on the electric field. These agree with experimental observations of field and temperature breakdown dependencies.

DOI: 10.1103/PhysRevLett.120.124801

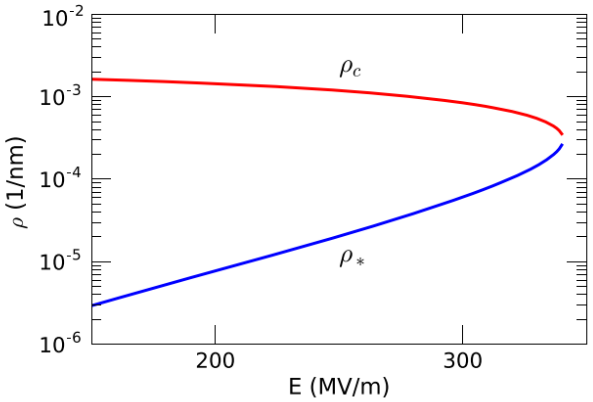


FIG. 1. Fixed points of the dynamical equations for ρ, attracting (ρ_*) and repelling (ρ_c), as functions of E, demonstrating the existence of a bifurcation point.

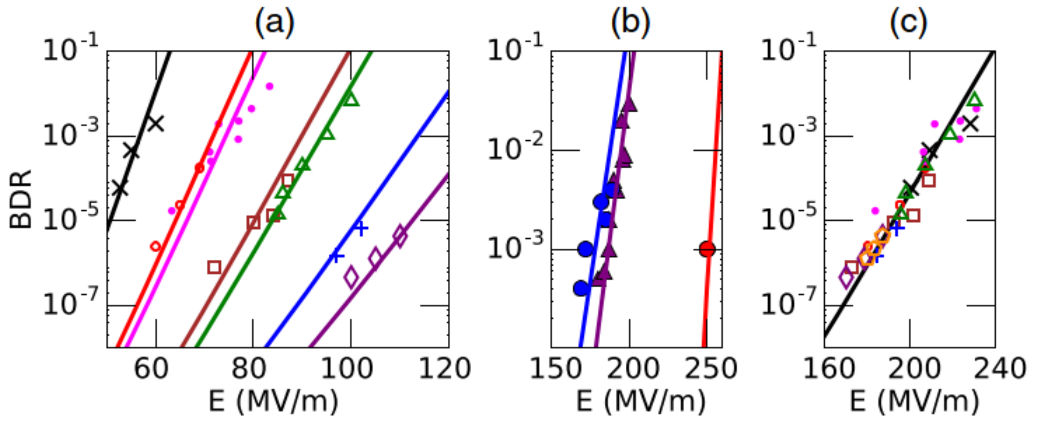


FIG. 3. Experimental BDRs with fitted theoretical lines using Eq. (7): (a) BDR versus E for various Cu accelerating structures [11]. (b) BDR variation with E at room temperature (two lines on the left) and at 45 K (line on the right) [51]. (c) BDR versus E for various Cu accelerating structures [11,52], with E rescaled so that all measurements are fitted with $\beta = 4.8$.

Conclusions

There are many successful and ongoing developments in high-gradient normal conducting RF that are of relevance for the muon cooling.

We look forward to including muon cooling specific RF requirements in these studies.

More information

HG workshop series
High-gradient RF
https://indico.fnal.gov/event/22025/

MeVArc workshop series
Fundamentals of vacuum breakdown
https://indico.cern.ch/event/966437/