Muon Collider and High Gradient RF challenges

Alexej Grudiev (CERN)

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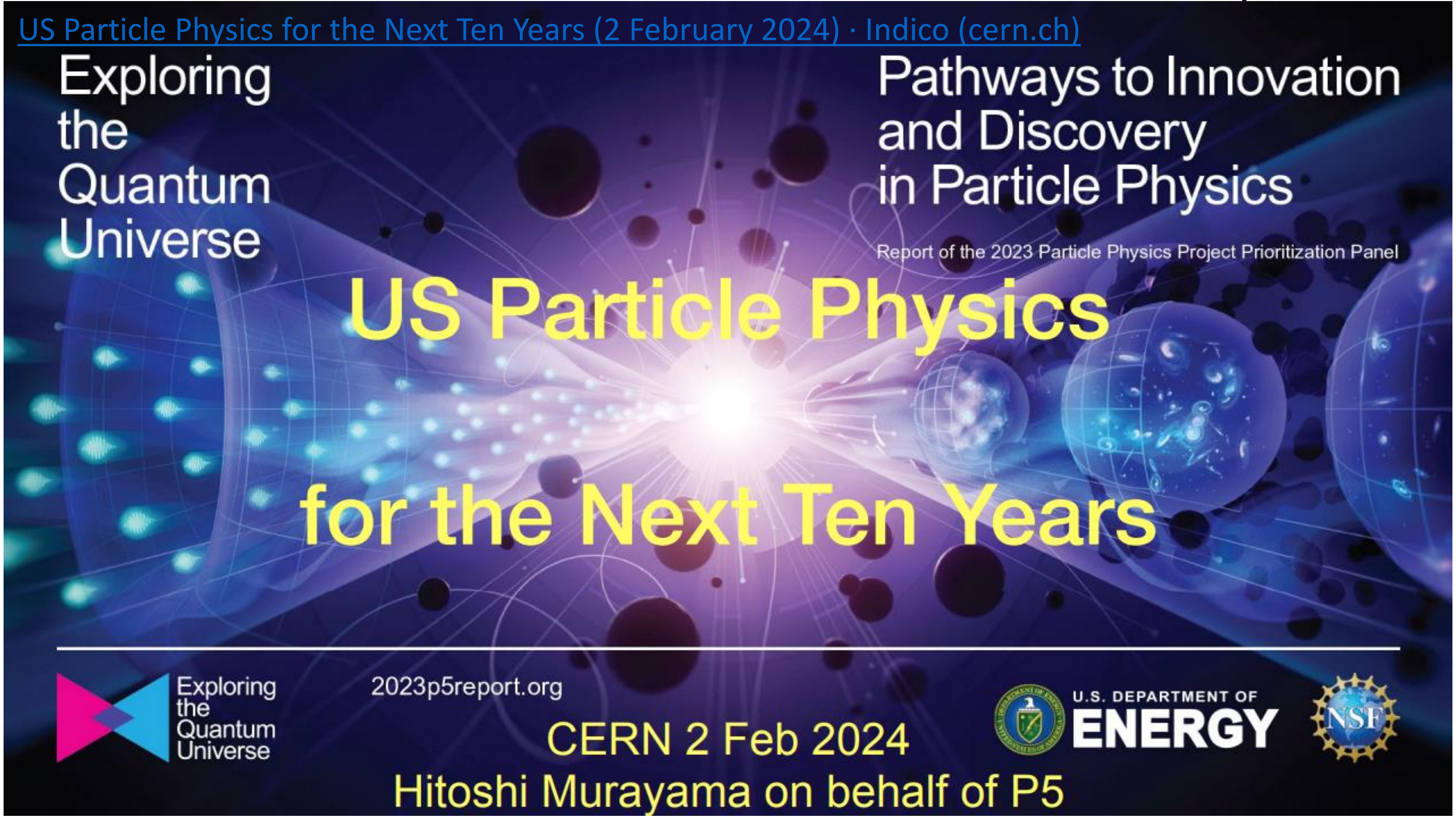
Outline

- Muon collider in the US context. **The "Muon Shot"**
- Introduction to Muon Collider facility
- High Gradient acceleration in strong magnetic fields
  - Needs
  - Current understanding
- Discussion

Muon Collider in the US context: P5 report

[US Particle Physics for the Next Ten Years (2 February 2024) · Indico (cern.ch)]



Exploring
the
Quantum
Universe

Pathways to Innovation
and Discovery
in Particle Physics

Report of the 2023 Particle Physics Project Prioritization Panel

US Particle Physics

for the Next Ten Years

Exploring
the
Quantum
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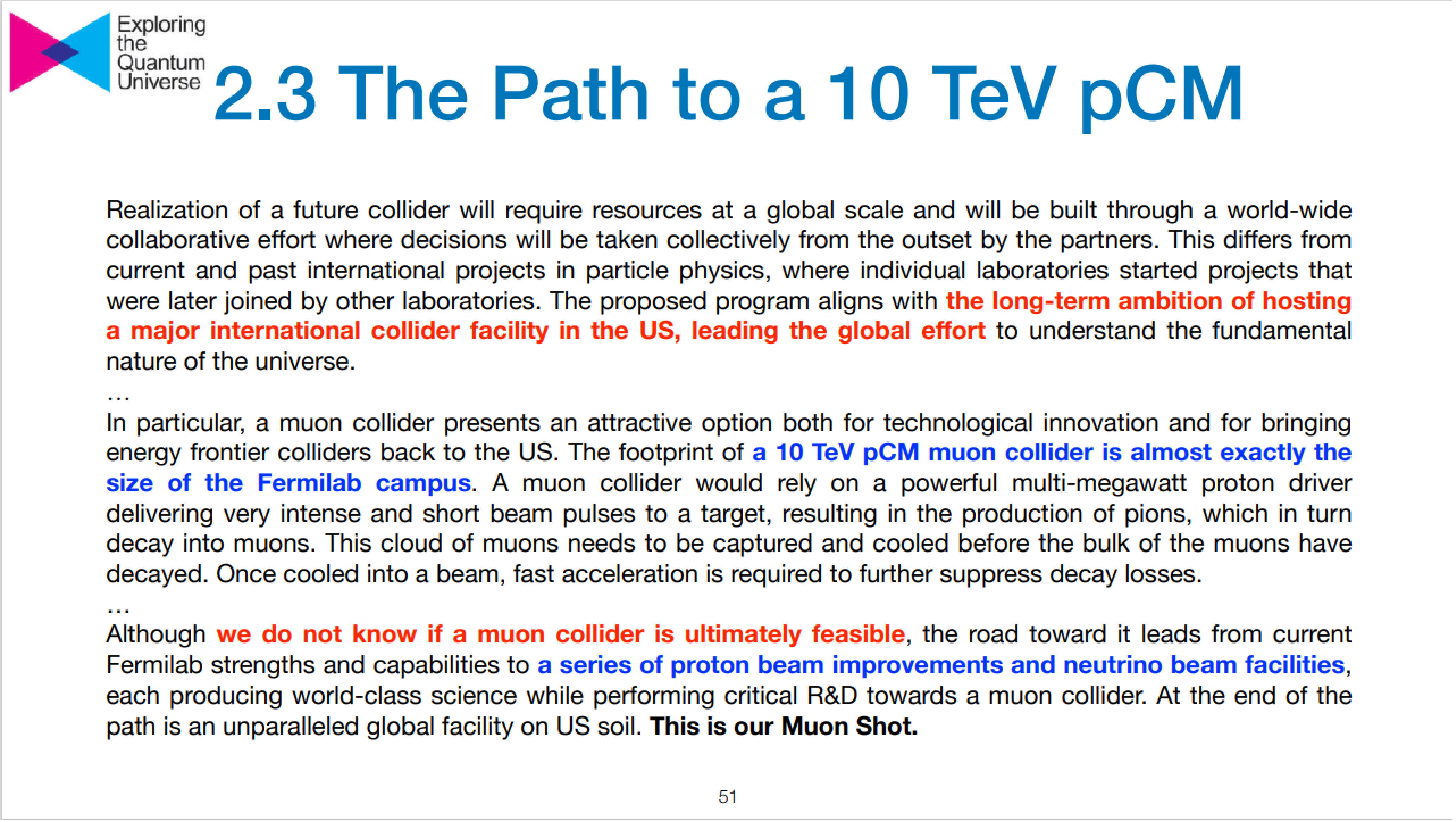
2023p5report.org

CERN 2 Feb 2024

Hitoshi Murayama on behalf of P5

U.S. DEPARTMENT OF
ENERGY

MC in the US context: P5 recommendations



Exploring the Quantum Universe

2.3 The Path to a 10 TeV pCM

Realization of a future collider will require resources at a global scale and will be built through a world-wide collaborative effort where decisions will be taken collectively from the outset by the partners. This differs from current and past international projects in particle physics, where individual laboratories started projects that were later joined by other laboratories. The proposed program aligns with **the long-term ambition of hosting a major international collider facility in the US, leading the global effort** to understand the fundamental nature of the universe.

…

In particular, a muon collider presents an attractive option both for technological innovation and for bringing energy frontier colliders back to the US. The footprint of **a 10 TeV pCM muon collider is almost exactly the size of the Fermilab campus**. A muon collider would rely on a powerful multi-megawatt proton driver delivering very intense and short beam pulses to a target, resulting in the production of pions, which in turn decay into muons. This cloud of muons needs to be captured and cooled before the bulk of the muons have decayed. Once cooled into a beam, fast acceleration is required to further suppress decay losses.

…

Although **we do not know if a muon collider is ultimately feasible**, the road toward it leads from current Fermilab strengths and capabilities to **a series of proton beam improvements and neutrino beam facilities**, each producing world-class science while performing critical R&D towards a muon collider. At the end of the path is an unparalleled global facility on US soil. **This is our Muon Shot.**

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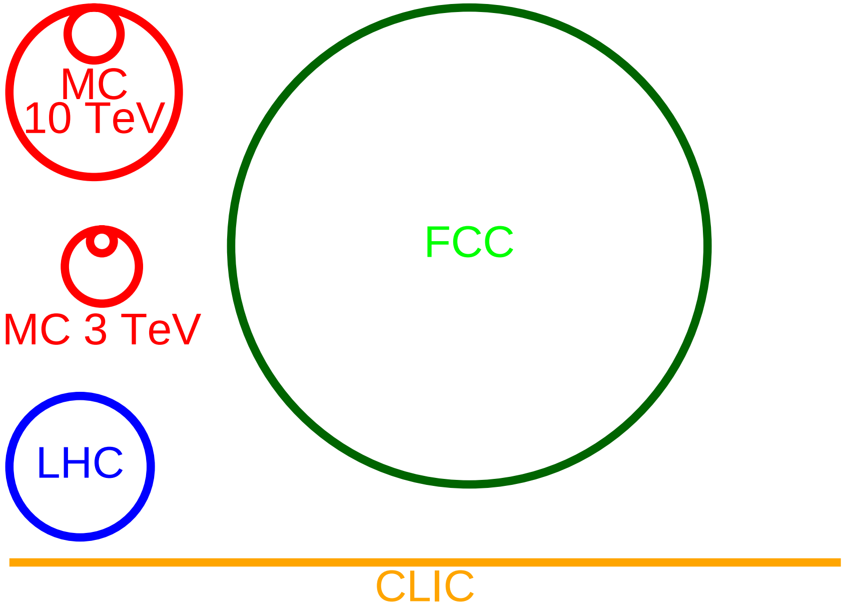
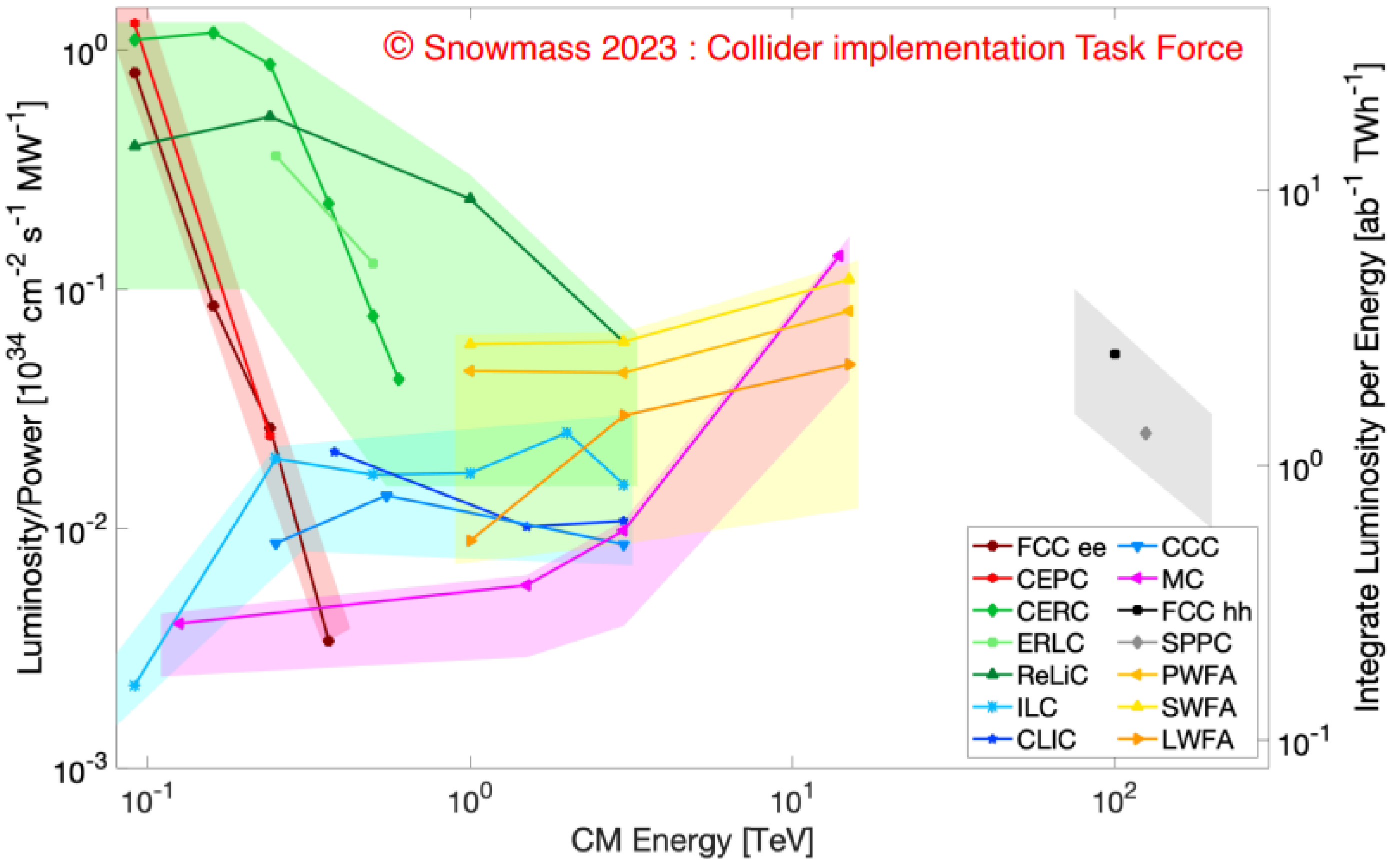
Muon Collider promises: Cost and Sustainability





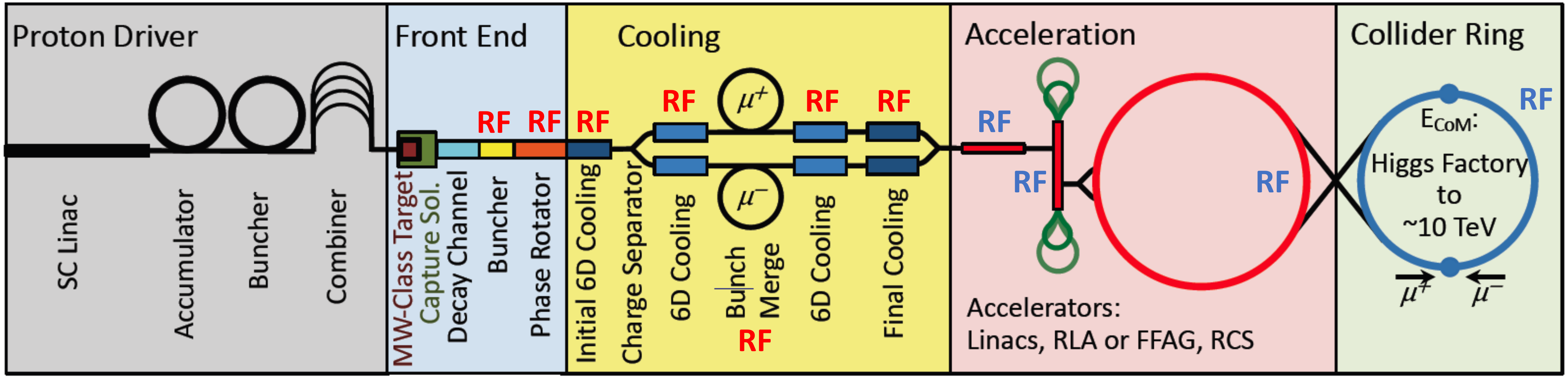
Compactness promises **cost effectiveness**
And low CO_2 footprint for construction

Increasing luminosity per beam power promises **power efficiency**

Staging is possible
Unique opportunity for a **high-energy, high-luminosity lepton collider**

Muon collider schematic layout

Proton driven Muon Collider Concept (MAP collaboration)



Proton driver complex produce high power (few MW) **proton beam**

Proton beam hit the **target** and produce muons

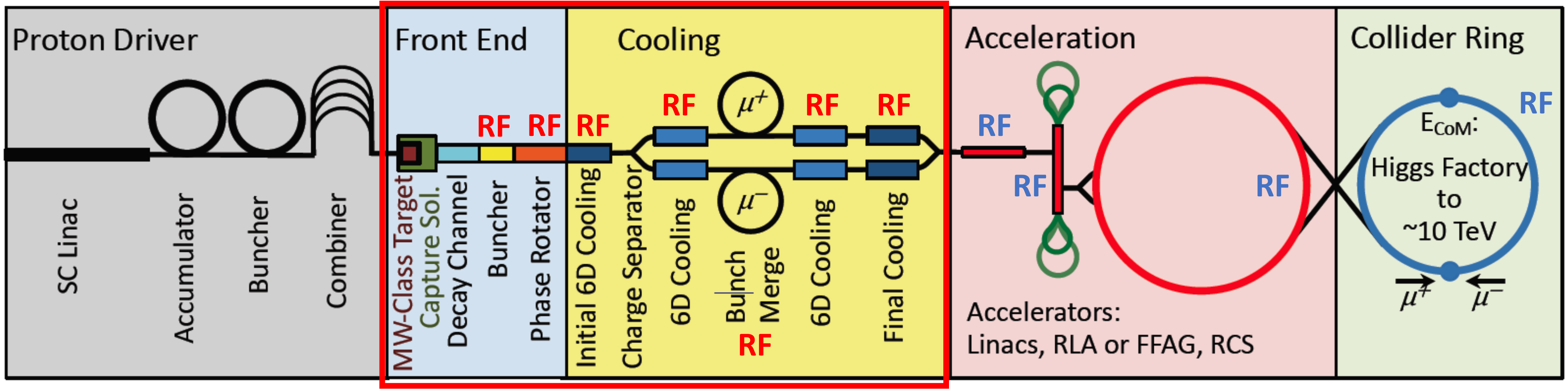
Muons are captured and cooled to produce **low emittance muon beam**

Muon beams are accelerated to **high energy**

Positive and negative muon beams collide

Muon collider and RF system challenges

Proton driven Muon Collider Concept (MAP collaboration)



The main challenge of the Muon Collider is finite ~2us lifetime of the muons.

Normal conducting RF for capture and cooling

- **High-gradient cavities in high magnetic field**
- High charge, Huge beam size, Important beam losses
- Peak RF power

Everything must be fast ! --→ High Gradient !!!

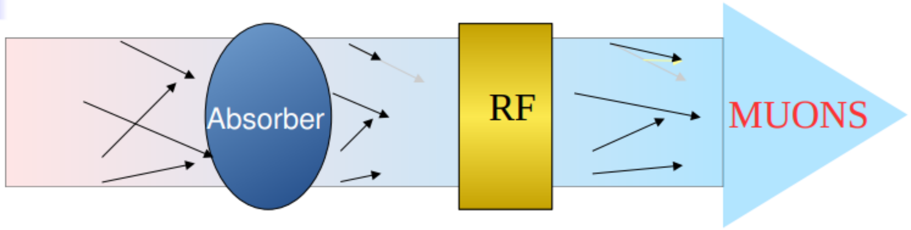
RF system for muon cooling (MAP design)

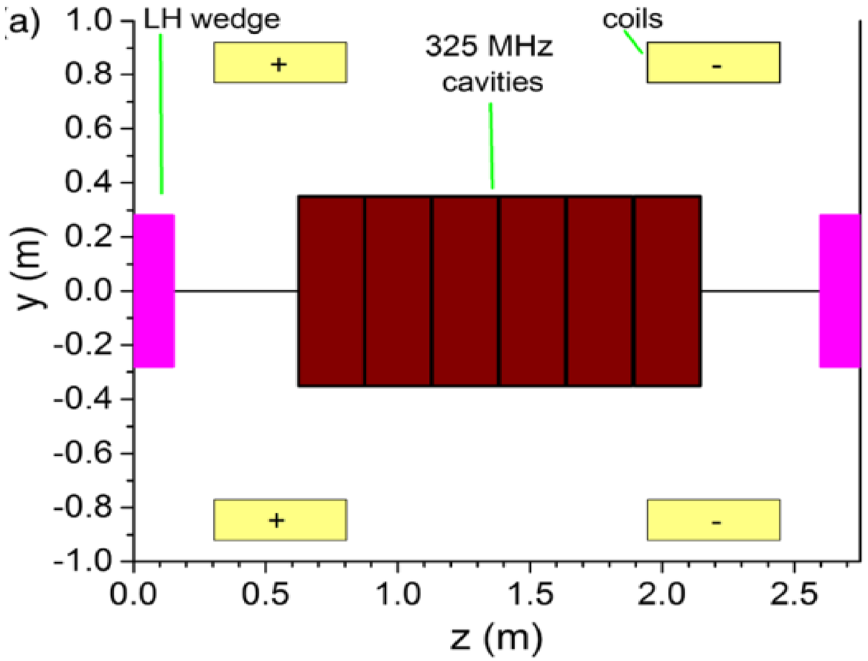
Summarized from:
[David Neuffer](#)
[Chris Rogers](#)

Region	Length [m]	N of cavities	Frequencies [MHz]	Gradient [MV/m]	Magnetic field [T]	Peak RF power [MW/cav.]
Buncher	21	54	490 - 366	0 - 15		1.3
Rotator	24	64	366 – 326	**20**		2.4
Initial Cooler	126	360	325	**25**	**2**	**3.7**
Cooler 1	400	1605 x2	**325, 650**	**22, 30**	**2-3, 4-6**	**4, 2**
Bunch merge	130	26 x2	108 - 1950	**~ 10**		
Cooler 2	420	1746 x2	**325, 650**	**22, 30**	**2-5, 8-13**	**4, 2**
Final Cooling	140	96 x2	325 - 20			
Total	~1300	**7424**				**=> ~20GW**

It is a very large and complex RF system with high peak power

Ionisation Cooling





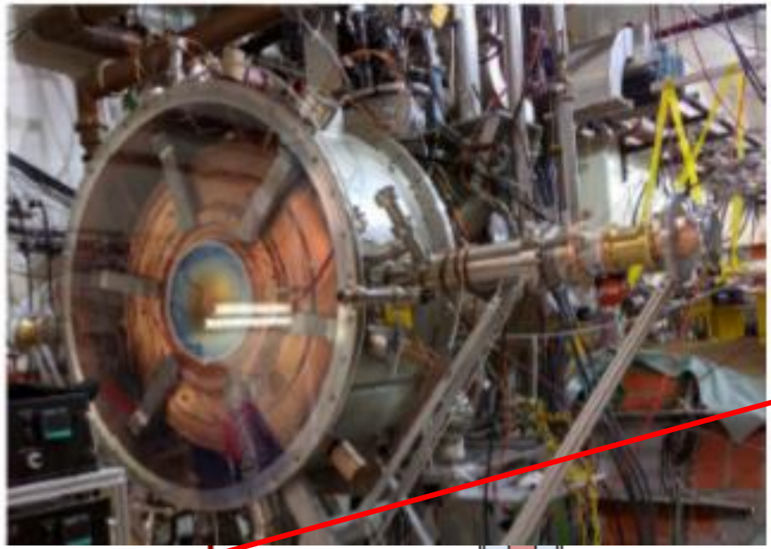
State-of-the-Art: RF cavities for muon cooling

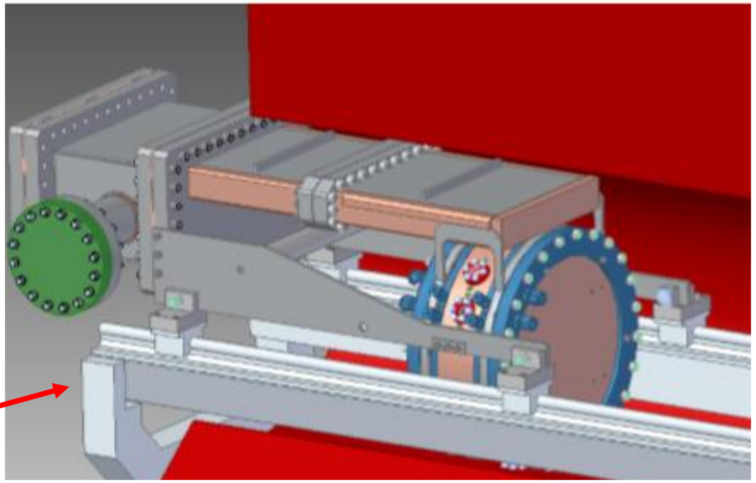
Challenges:

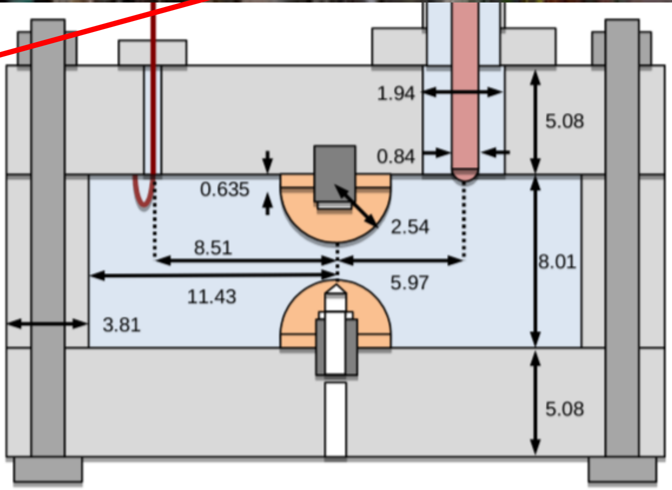
- High Gradient
- High magnetic field
- High radiation
- Technology far from been common

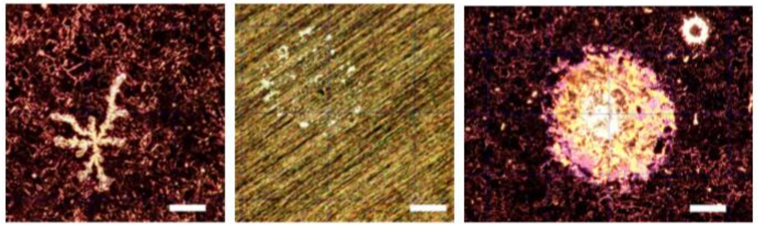
State of the art (not complete):

- MICE 200 MHz RF module prototype: 4T, 10 MV/m, 1ms@1Hz
- 800 MHz **beryllium** cavity: 3T, **50 MV/m**, 30us@10Hz
- **Gas** filled RF cavity: Small gap, 800 MHz, >50 MV/m

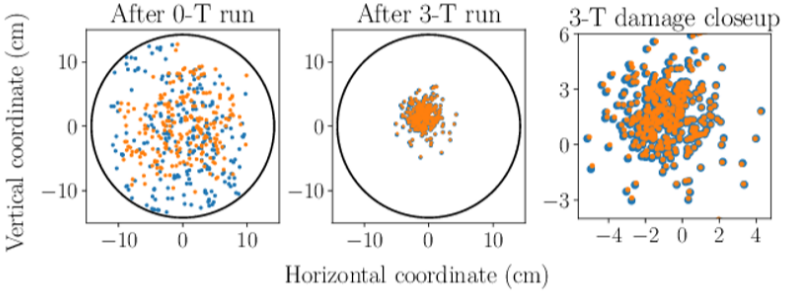








(a) Cu, 0 T (b) Be, 0 T (c) Cu, 3 T

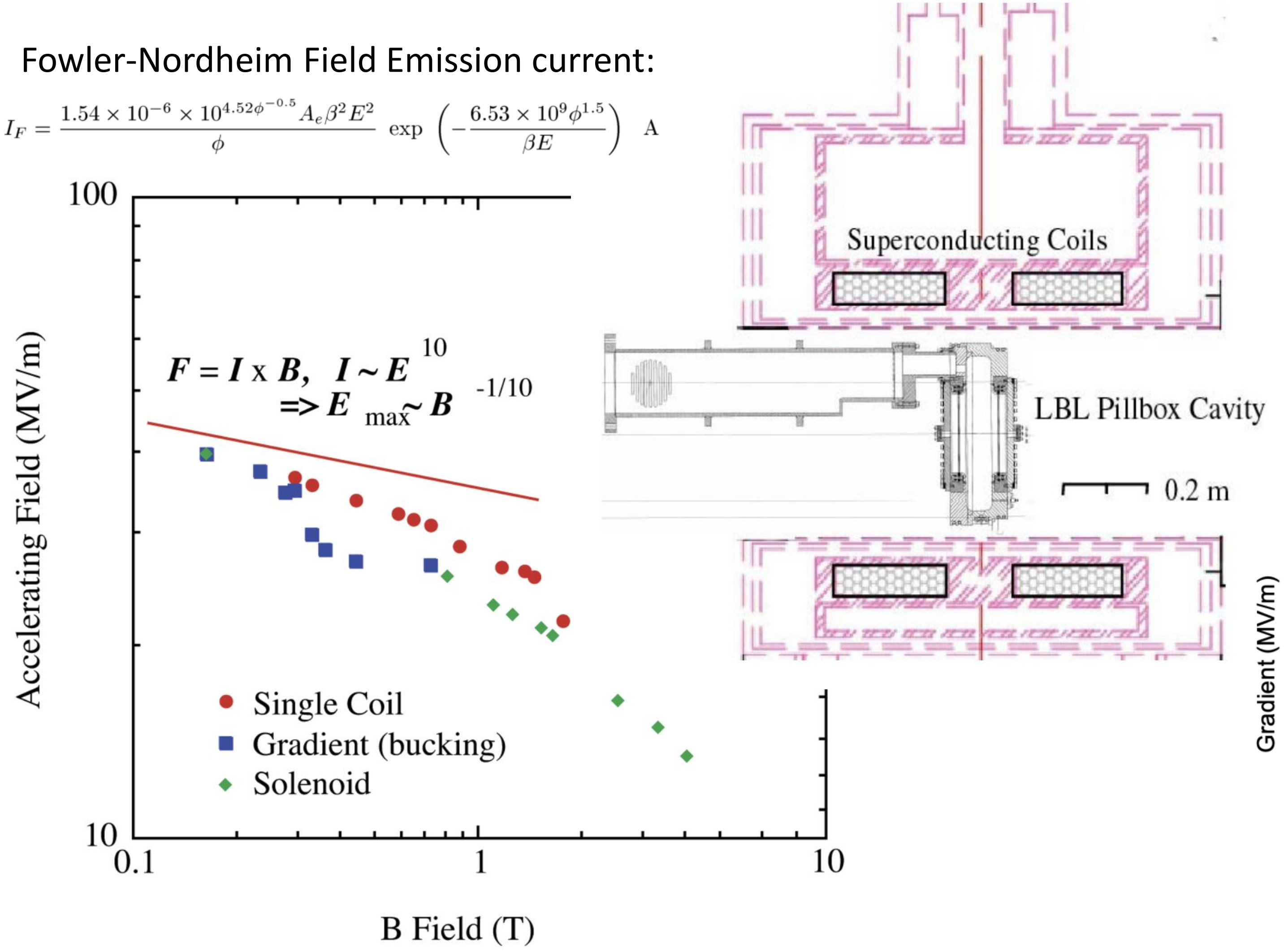


Initial results in 805 MHz pill box Cu cavity and a ‘local’ model

A. Moretti *et al.*, Effects of high solenoidal magnetic fields on rf accelerating cavities, **Phys.Rev.Acc.Beams** 8, 072001 (**2005**)

Fowler-Nordheim Field Emission current:

$$I_F = \frac{1.54\times10^{-6}\times10^{4.52\phi^{-0.5}}A_e\beta^2E^2}{\phi}\ \exp\left(-\frac{6.53\times10^9\phi^{1.5}}{\beta E}\right)\ \mathrm{A}$$



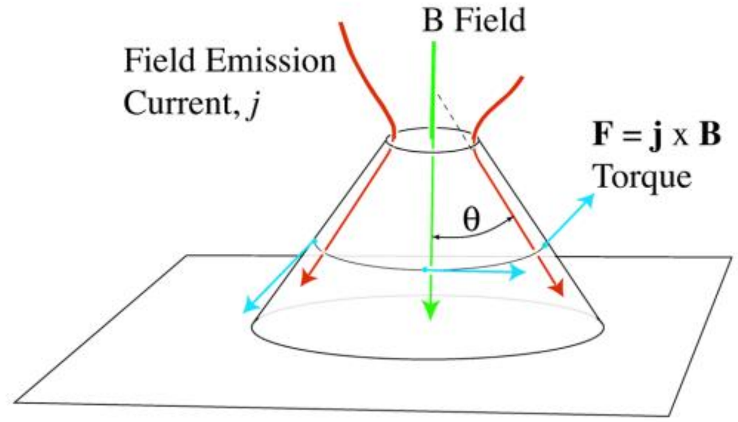
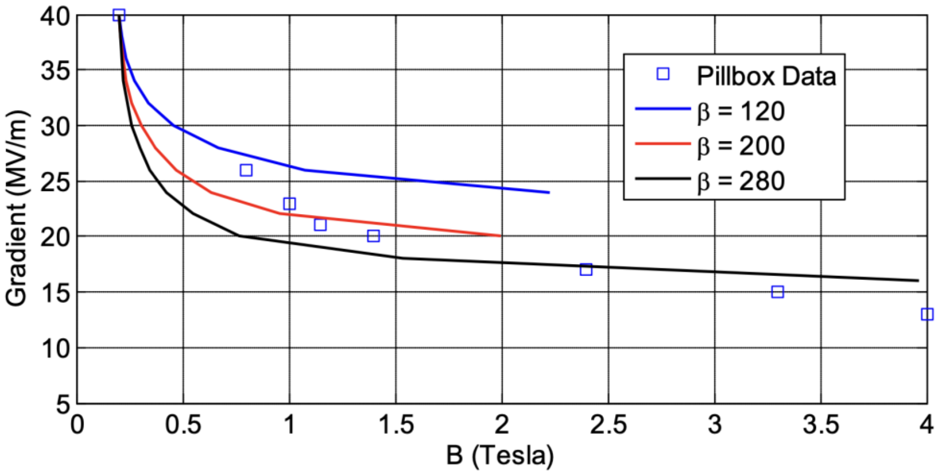
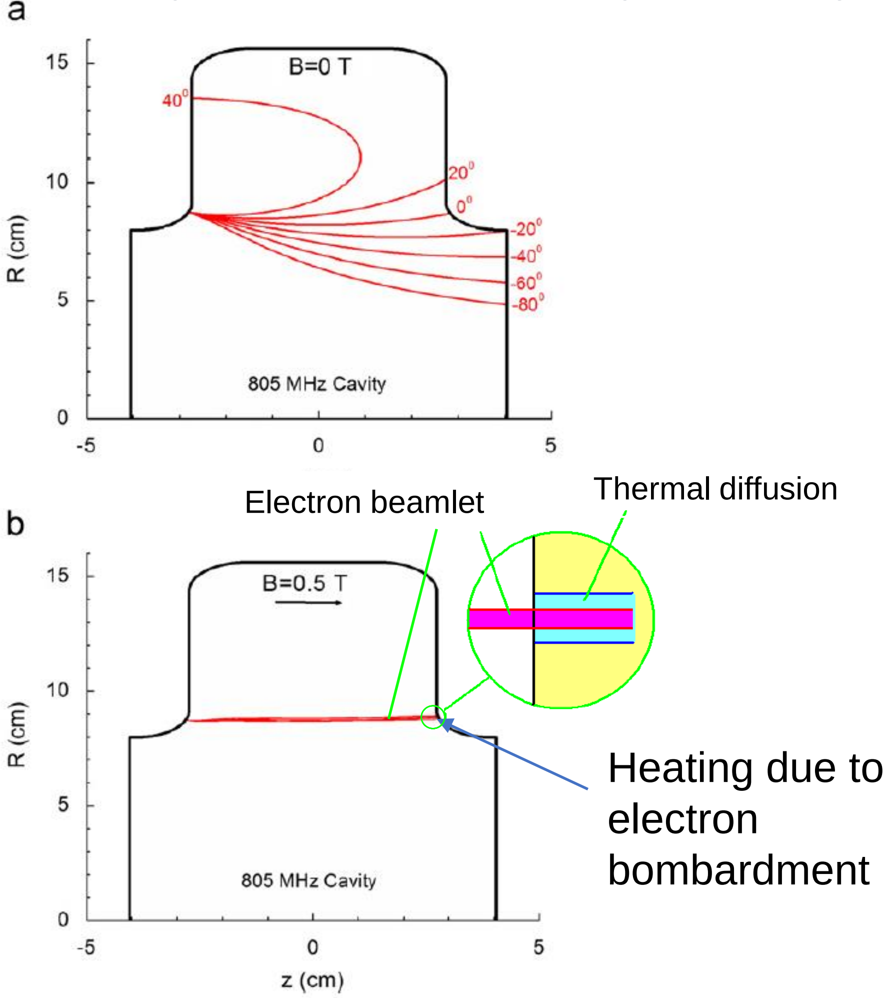


FIG. 4. (Color) Forces due to field emission currents are present in the field emitters.



A ‘global’ model: beamlet focused by magnetic field

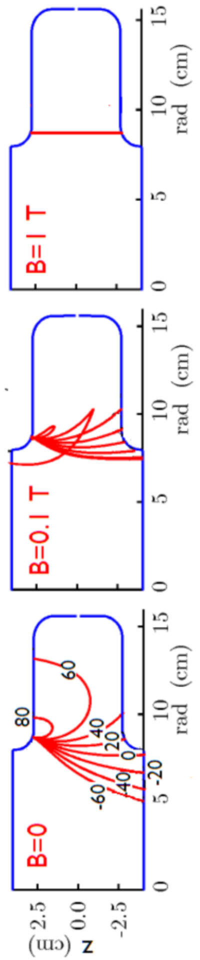
Numerical simulations showed trajectories of beamlets in the presence of the 805 MHz pillbox cavity



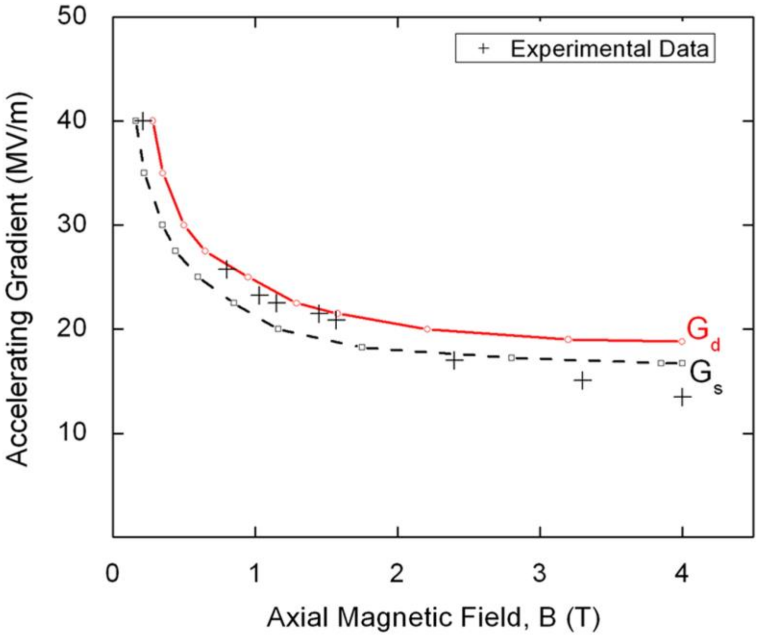
Electron beamlet

Thermal diffusion

Heating due to electron bombardment



- Model developed by US labs, checked against measurements in high B. papers: Palmer et.al PRAB 2009, Stratakis et.al NIMPR 2010
- Model predicts local temperature rise ΔT due to electron bombardment
- Breakdown occurs when $\Delta T > \Delta T_{plastic}$



Poisson ratio

Yield strength

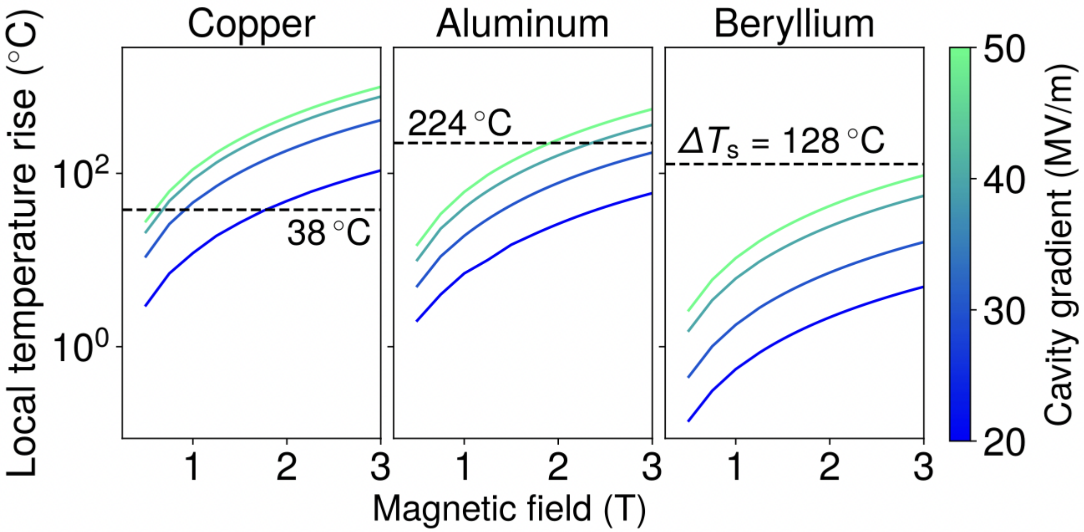
$$= \Delta T_{plastic} = \frac{2(1-\nu)\sigma_t}{E\alpha_{th}}$$

Elastic modulus

Linear expansion

$\Delta T_{plastic}$:
38 °C for Cu,
129 °C for Be,
224 °C for Al

MuCool 805 MHz cavity with modular plates

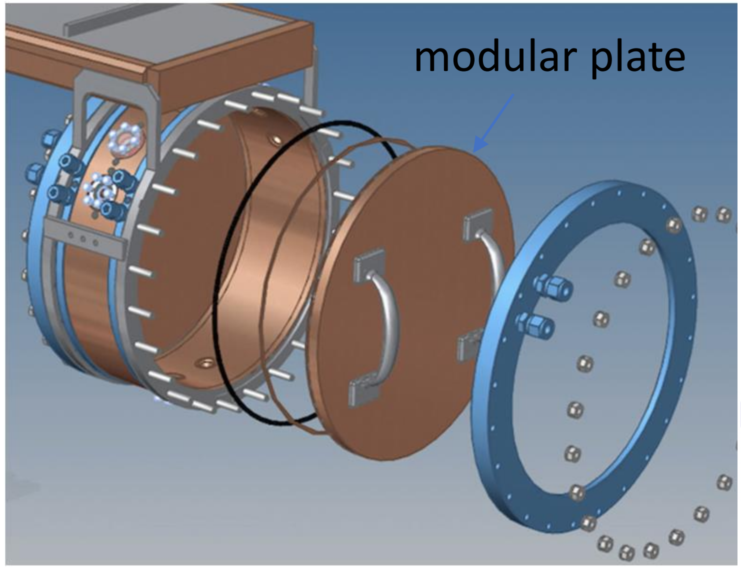


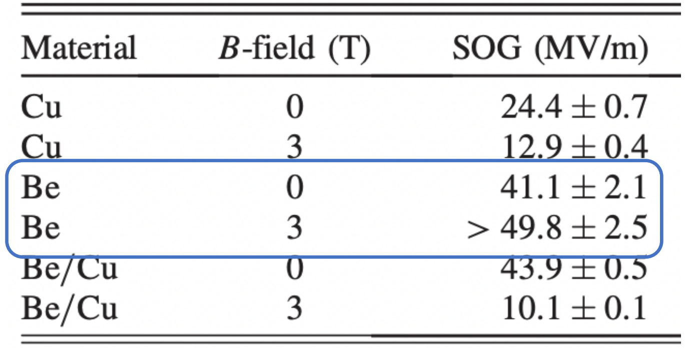
Operation of normal-conducting rf cavities in multi-Tesla magnetic fields for muon ionization cooling: A feasibility demonstration

D. Bowring, A. Bross, P. Lane, M. Leonova, A. Moretti, D. Neuffer, R. Pasquinelli, D. Peterson, M. Popovic, D. Stratakis, K. Yonehara, A. Kochemirovskiy, Y. Torun, C. Adolphsen, L. Ge, A. Haase, Z. Li, D. Martin, M. Chung, D. Li, T. Luo, B. Freemire, A. Liu, and M. Palmer

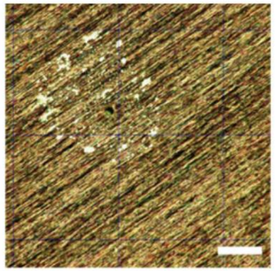
Phys. Rev. Accel. Beams **23**, 072001 – Published 2 July 2020

FIG. 2. Semi-log plot of local ΔT for Cu, Al, and Be cavities at various gradients and across a range of solenoidal magnetic field strengths. ΔT_s [Eq. (4)] is indicated in each plot by a horizontal, dashed line. Note that for Be, the local temperature rise is lower than ΔT_s for a broad range of gradients and magnetic fields.

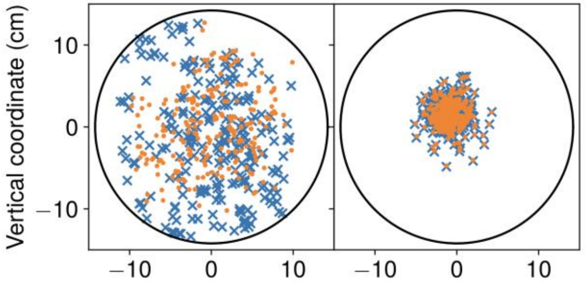




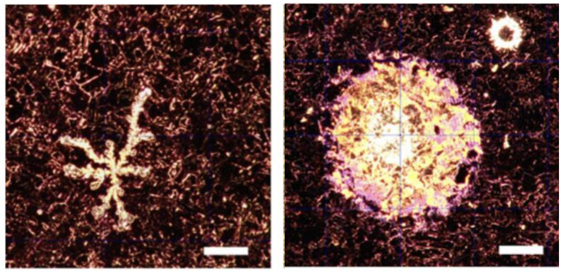
Material	*B*-field (T)	SOG (MV/m)
Cu	0	24.4 ± 0.7
Cu	3	12.9 ± 0.4
Be	0	41.1 ± 2.1
Be	3	> 49.8 ± 2.5
Be/Cu	0	43.9 ± 0.5
Be/Cu	3	10.1 ± 0.1



Be: 0 & 3 T



Cu: 0 T **Cu: 3 T**

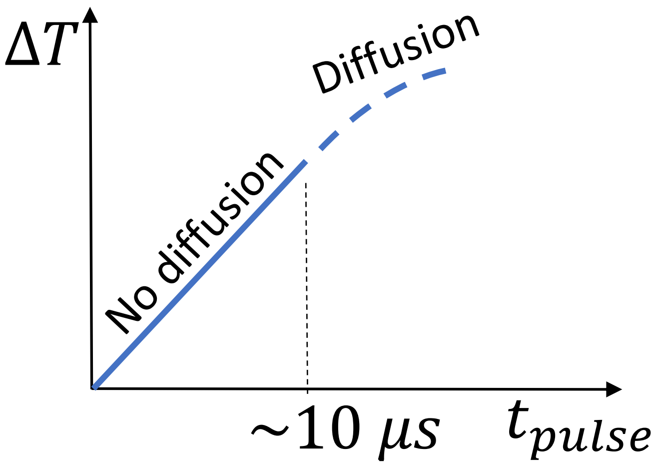


- Strong indication that Al could be a good middle ground between safety of Cu and performance of Be.

Scaling using no-diffusion beamlet model

The breakdown model can be simplified: for short pulses ($t_{pulse} < 10\ \mu s$) we can neglect heat diffusion in the wall.

Then the breakdown condition $B(E_{acc})$ is given by (S. Arsenyev, 2021):



$$\underset{\substack{\uparrow\\\text{Magnetic field}\\\text{at breakdown}}}{B^2} = \underbrace{\rho C_s \overbrace{\frac{2(1-\nu)\sigma_t}{E\alpha_{th}}}^{\Delta T_{\text{plastic}}}}_{\text{Wall material properties}} \times \frac{e\pi\xi^2}{I_{em}^{\frac{1}{3}}\left(\frac{dE}{dz}\right)} \times \frac{1}{\text{t}_{\text{pulse}}}$$

Cavity-dependent constant

Pulse length

Electron energy loss

Field Emission current $I(E_{acc})$

This equation provides scaling laws of $B(E_{acc})$ on different parameters. Mitigation solutions that follow from this equation:

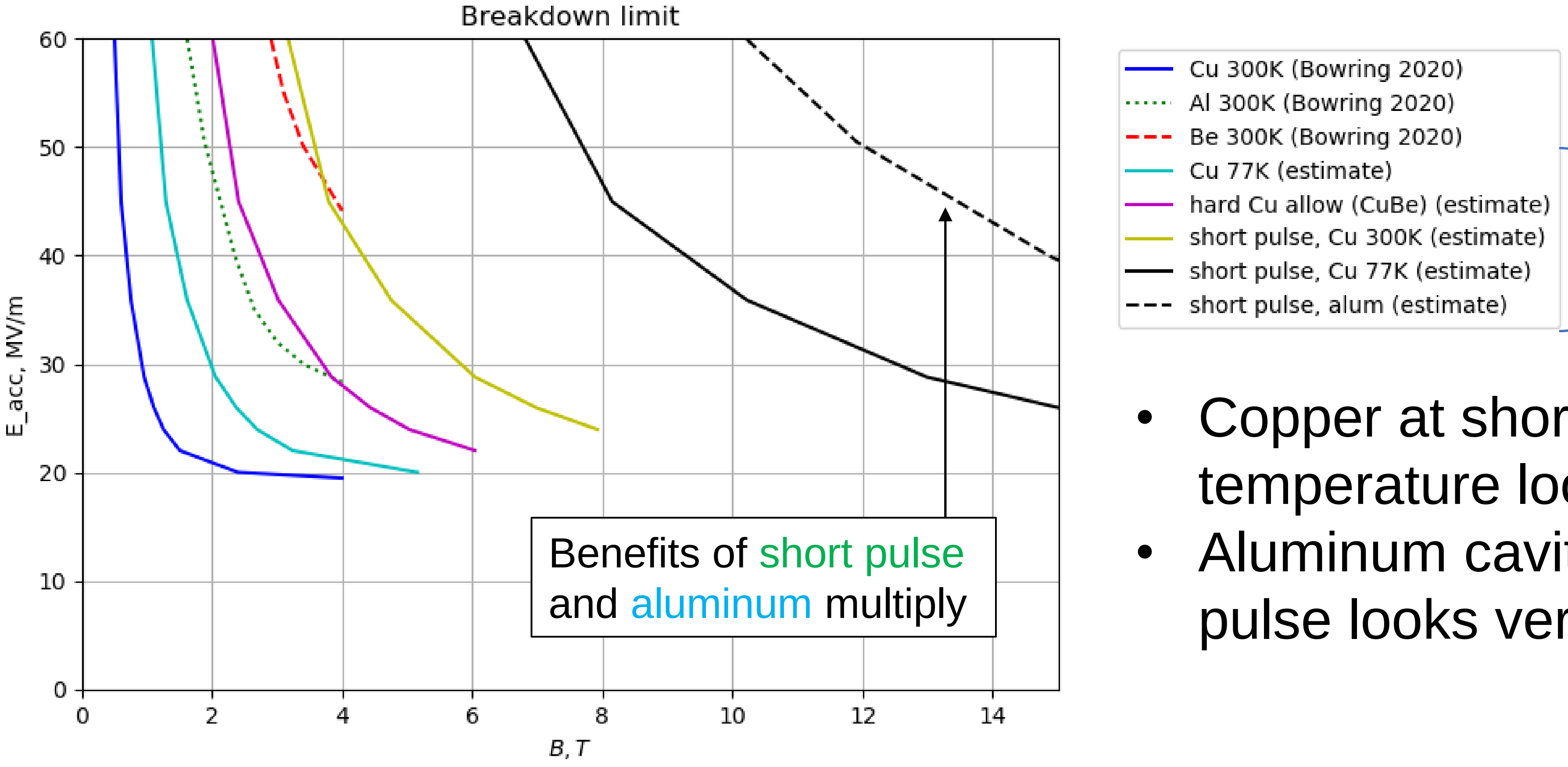
- Very short pulse (sub μs)
- Different wall materials (Al, hard copper alloys)
- Low temperature (nitrogen cooling 70 K)
- Cavity shape optimization

When combined, benefits from different solutions would multiply

A. Grudiev, MeVArC 2024

Comparing breakdown mitigation ideas

This plot is not intended to give absolute values for breakdown threshold, but only a feeling of which solutions can be more promising. We scale curves from MUCOOL cavity study ($t_{pulse} = 20\ \mu s > 10\ \mu s$ so the no-diffusion model applies only approximately)



Benefits of short pulse and aluminum multiply

Scaled from the first 3 curves using the scaling model (previous slide)

- Copper at short pulse and low temperature looks better
- Aluminum cavity with a short pulse looks very promising

A. Grudiev, MeVArC 2024

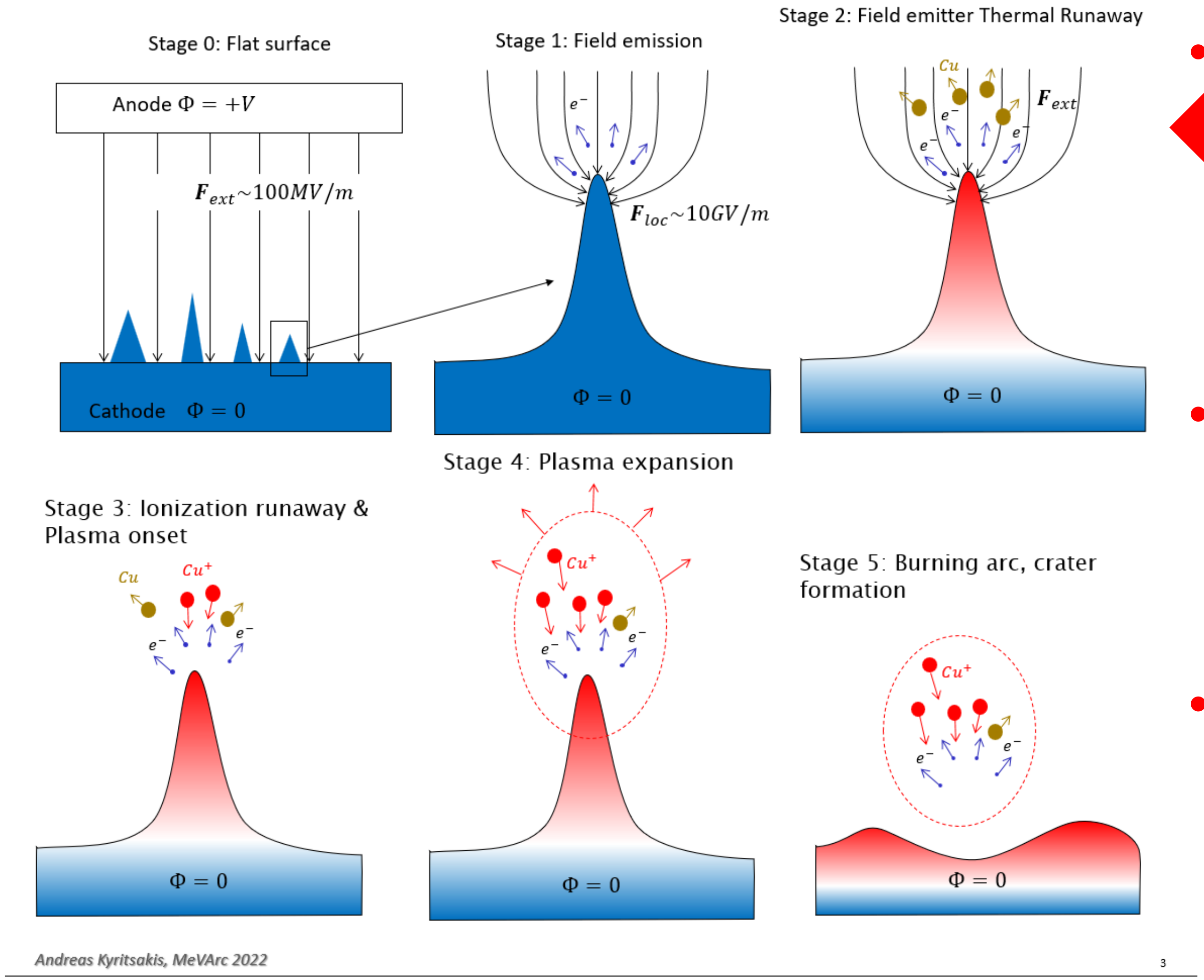
R&D directions for NRF cavity tests in high B field

- **Need high gradient RF test stand(s) with B field up to ~10T**

  Test cavities for technology development

  - Frequency: ideally 300 to 700 MHz range
    - tests at higher frequencies useful, but need some rescaling to MCC f range
  - Gradients from 25 to 50 MV/m
  - **Short RF pulses** (<10μs)
  - **Magnetic field: ~10T, different field configurations**
  - Different materials: Cu, Be, **Al**, …
  - Different temperatures: 300K -> **70K** ->…
  - Different cavity shapes ?

Discussion: Other possible mechanisms ?



Stage 0: Flat surface

Stage 1: Field emission

Stage 2: Field emitter Thermal Runaway

Stage 3: Ionization runaway & Plasma onset

Stage 4: Plasma expansion

Stage 5: Burning arc, crater formation

Andreas Kyritsakis, MeVArc 2022

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- What happens to this picture if strong magnetic field is applied ?
- Can we simulate this and make predictions?
- Can we measure it in DC setups ?

[A. Kyritsakis et. al., *J. Phys. D: Appl. Phys.* 51 225203 (2018)]