Introduction

Basic Principle

Ferro-Electric Material

FE-FRT Prototype

Normal Conducting

ERLs/low beam loading

Storage Ring / high beam loading

Exotic Cavities

Further Examples

Conclusion

Ferro-Electric Fast Reactive Tuner Potential for HEP

N. Shipman[1], I. Ben-Zvi[2], G. Burt[3], A. Castilla[1,3], M. Coly[1], F. Gerigk[1], C. Jing[4], A. Kanareykin[4], A. Macpherson[1], N. Stapley[1], H. Timko[1].

[1]CERN, [2]BNL, [3]Lancanster University, [4]Euclid Techlabs.

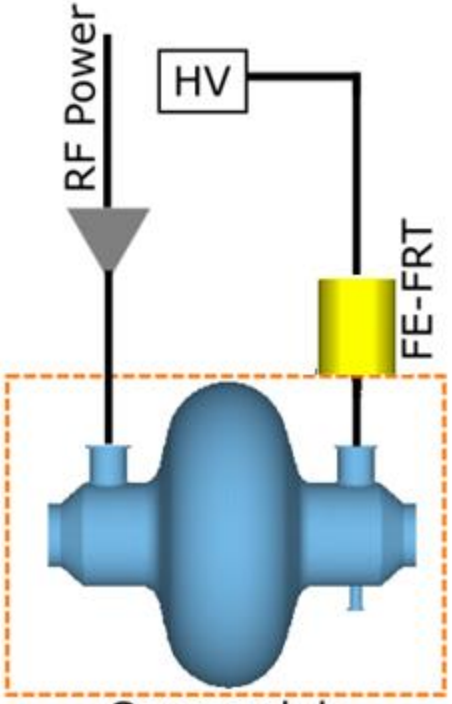
nicholas.shipman@cern.ch

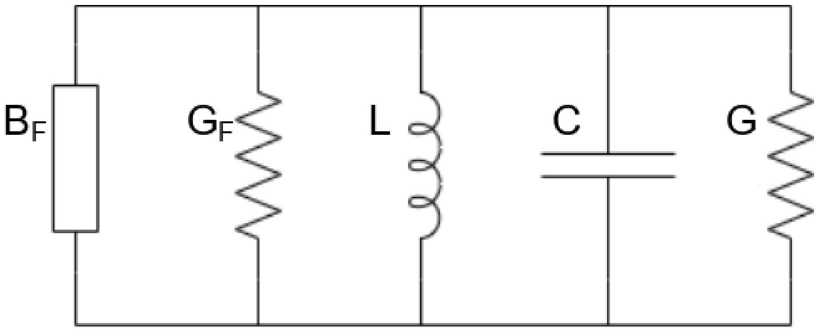
Advanced RF UK Roadmap Meeting 2021

Introduction

- Novel Class of tuner
- Extremely fast <~600ns
- Enormous potential
  - Energy saving
  - Increased luminosity
- Multiple Research Directions
  - RF design
  - Feedback control
  - High Voltage Fast Switching
  - Material Science
- Wide applicability
  - Storage Rings
  - Energy Recovery Linacs
  - Electron Ion Colliders
  - Nb_3Sn/other materials
  - Super conducting and Normal conducting
- Simple and low cost
  - No moving parts
  - Outside liquid helium environment
  - Compact

Basic Principle

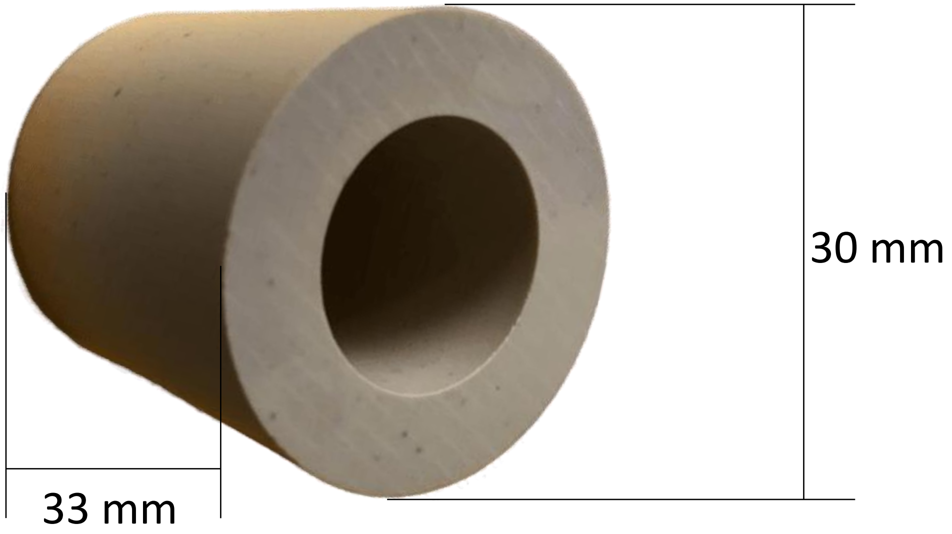




- Tuning Range
  - $$\Delta\omega_F = \frac{\omega_0 \Delta B_F \sqrt{L/C}}{2}$$
- Increase in Bandwidth
  - $$\sigma = \frac{G_F}{C}$$

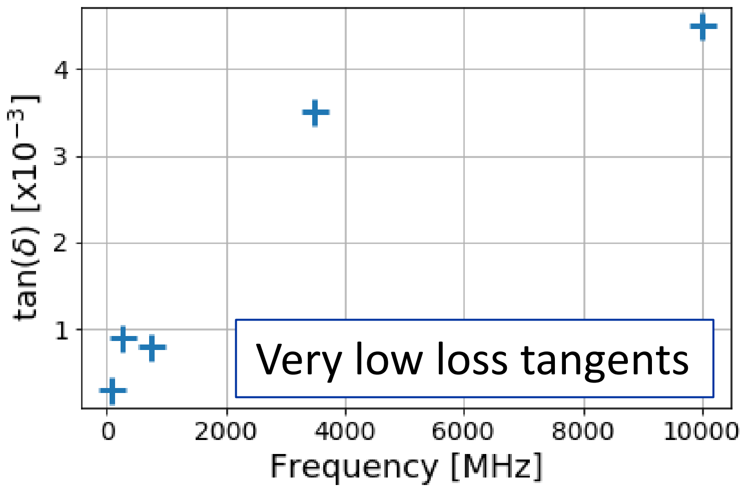
Ferro-Electric Material

Parameter	Value
Relative Permittivity	160
Tunability	1.4
Breakdown Strength	20 Vμm^{-1}
Thermal Conductivity	7.02 Wm^{-1}K^{-1}
Estimated Max. Temperature Rise	50 K



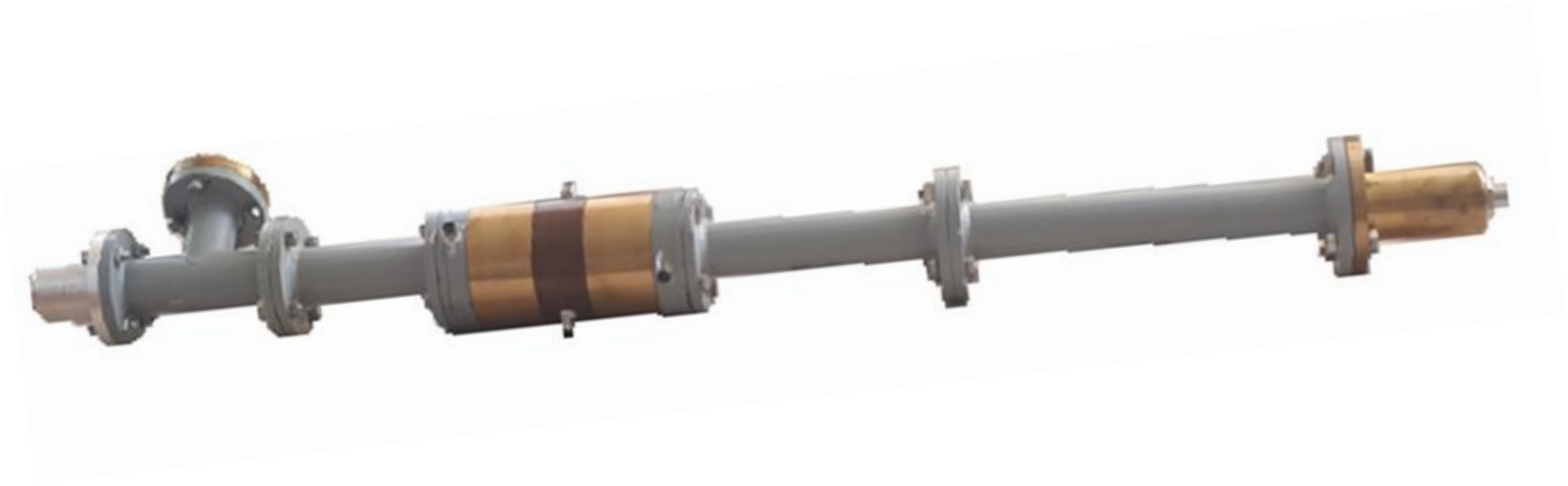
A BST(M) Ferroelectric Sample

Loss tangent measurements



- BST(M) material
  - $BaTiO_3$-$SrTiO_3$ with Mg based additives
- High Tunability
- Low loss tangent
  - Approx. $\propto f$ between 10MHz – 10GHz
- “Low” relative permittivity

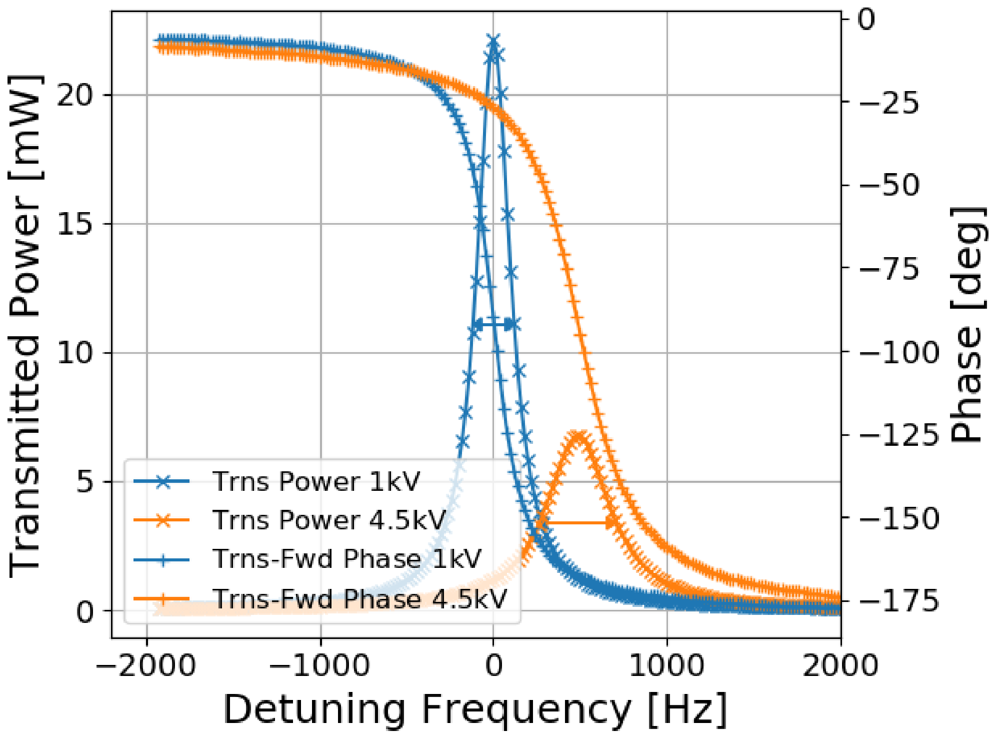
FE-FRT Prototype

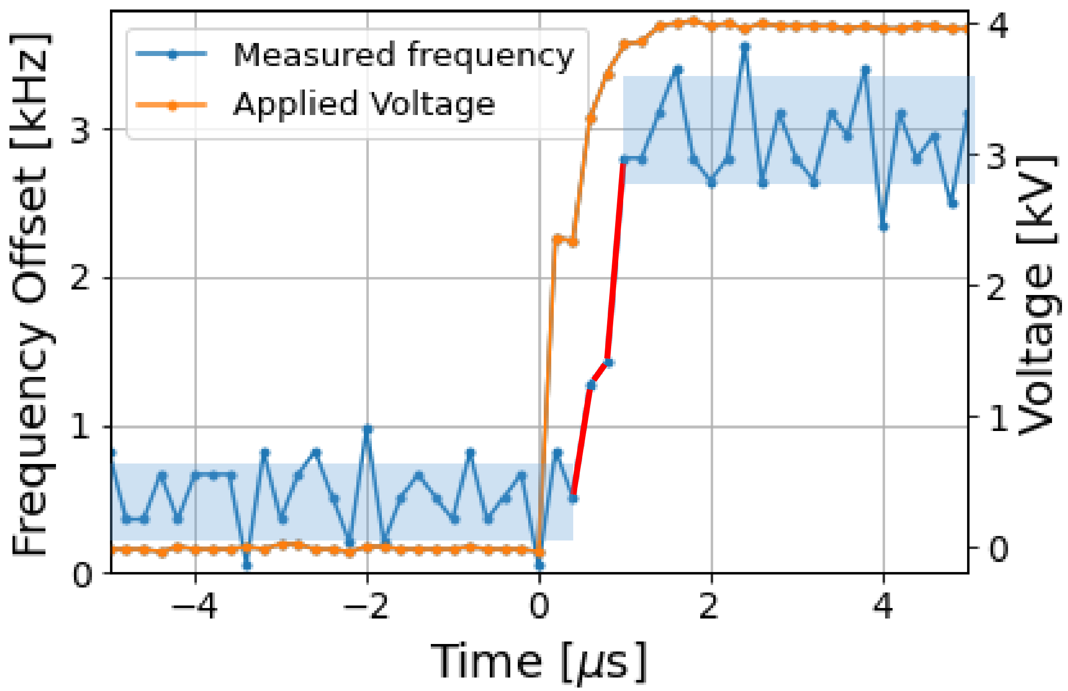


- Our proof of principle device
- Let’s see how it works!

FE-FRT Prototype

FE-FRT Prototype



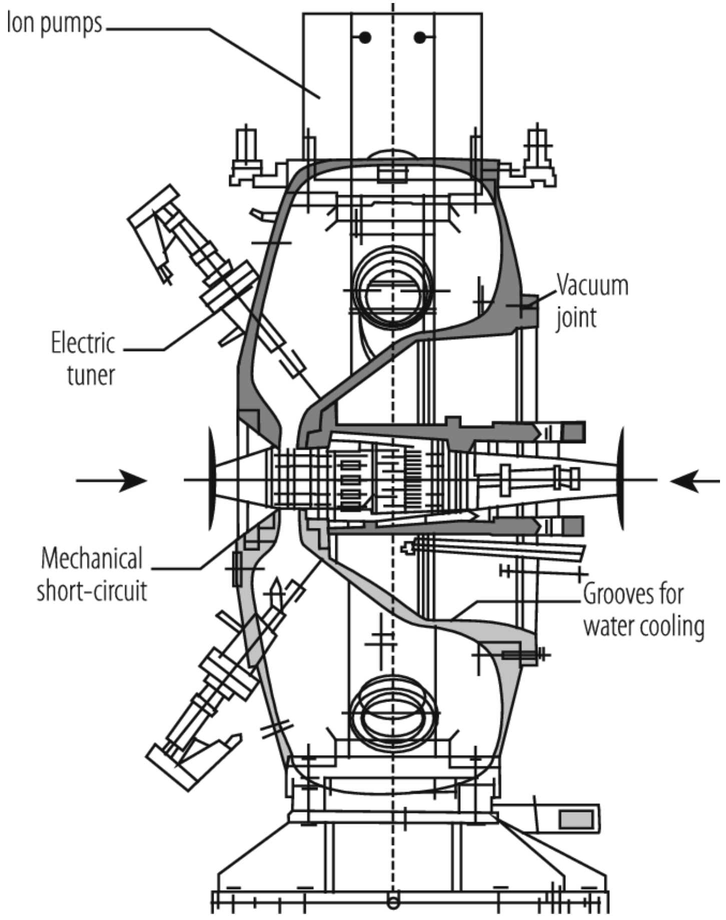


- Change of resonant frequency
- Change of bandwidth

- Frequency shift ~600ns
- External circuit limited

Normal Conducting

PS 80MHz cavity



PS 80MHz cavity diagram: / PS 80MHz installed in PS tunnel:
D. Grier "The PS 80 MHz Cavities" EPAC 1998 / E. Jensen "RF cavities" in "Accelerator Engineering And Technology: Accelerator Technology"

Cavity Parameters

Parameter	Value
f_0	$80\,\mathrm{MHz}$
Q_0	17000
R/Q	56
V	$300\,\mathrm{kV}$
U	$3.2\,\mathrm{J}$

Specifications

Parameter	Value
$\Delta\omega_F$	$2\pi.230\,\mathrm{kHz}$
Q_{0+F}	> 10000

Implications

$$\Delta\mathcal{P}_{reac} = 2U\Delta\omega_F$$
$$\Rightarrow \Delta\mathcal{P}_{reac} > 9.2\,\mathrm{MVar}$$

$$\mathrm{FoM} = \frac{\Delta\omega_F}{\omega_0}\sqrt{Q_F^1 Q_F^2}$$
$$\Rightarrow \mathrm{FoM} > 70$$

FE-FRT could achieve FoM > 100!

I. Ben-Zvi, A. Castilla, A. Macpherson, and N. Shipman,"Ultra-High Reactive-Power Ferro-Electric Fast Reactive Tuner"

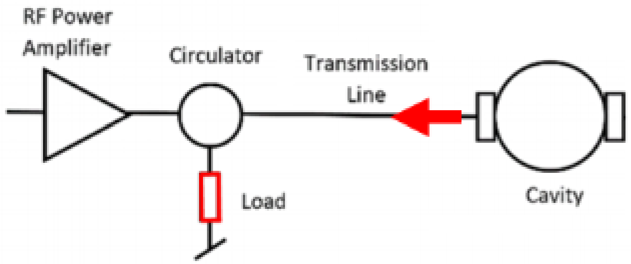
ERLs / low beam loading

- SRF cavities have very low intrinsic bandwidth
- Power needed to maintain voltage with microphonics is:

$$P_{RF} = \frac{V_c^2}{4 R/_Q Q_L} \frac{\beta + 1}{\beta} \left[1 + \left(2 Q_L \frac{\Delta\omega_\mu}{\omega_0} \right)^2 \right]$$

Notation	Meaning
P_{RF}	RF power
V_c	Cavity Voltage
$\Delta\omega_\mu$	Microphonics Detuning
Q_L	Loaded Q
β	Q_0/Q_e

- Overcoupling antenna:
  - Decreases Q_L
  - Increases bandwidth
  - Reduces power
- **Much** more power required than without microphonics
- Power dissipated in load



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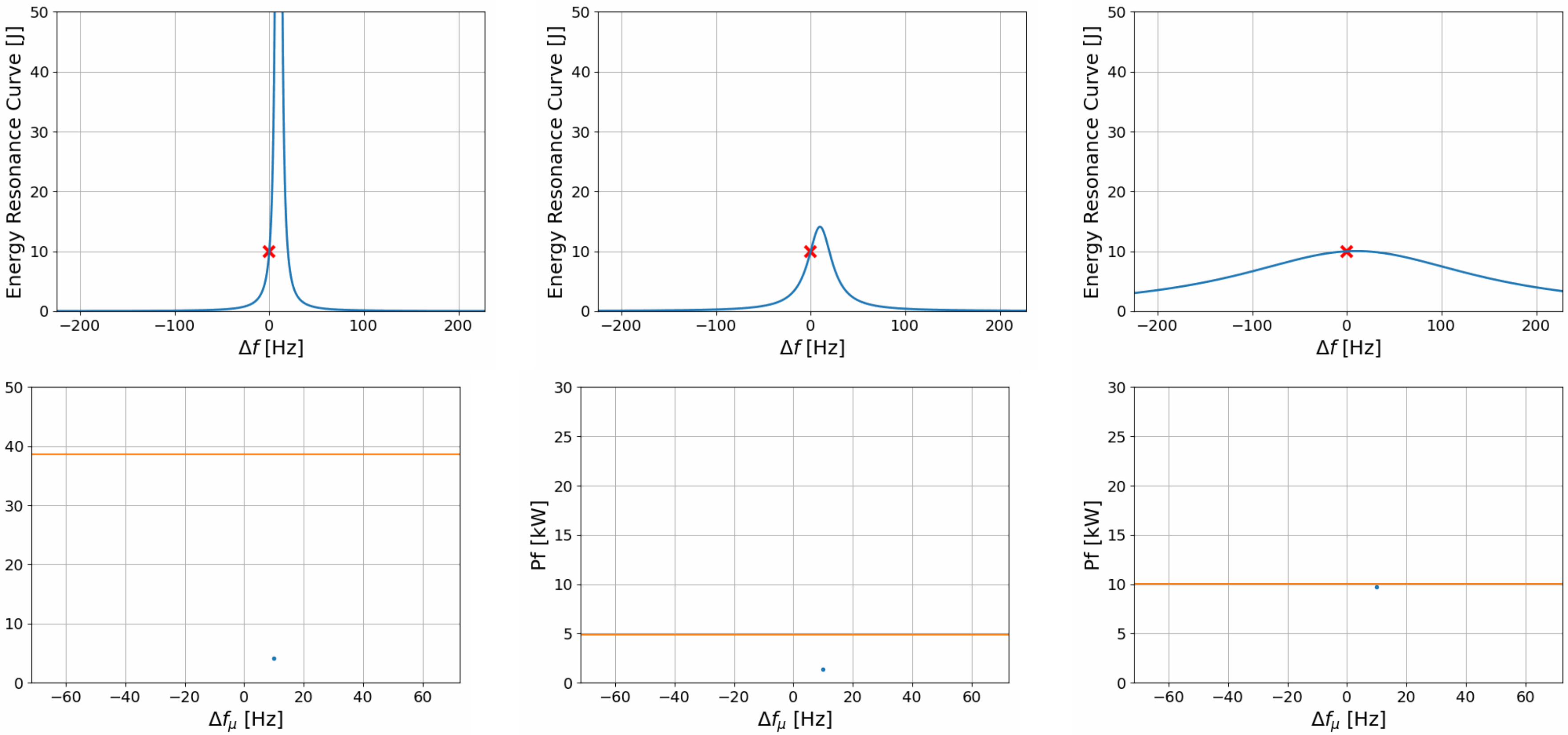
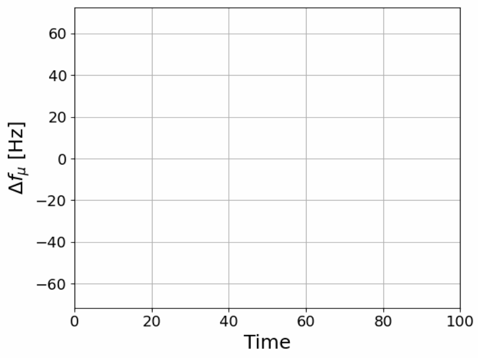


Microphonics vs Time

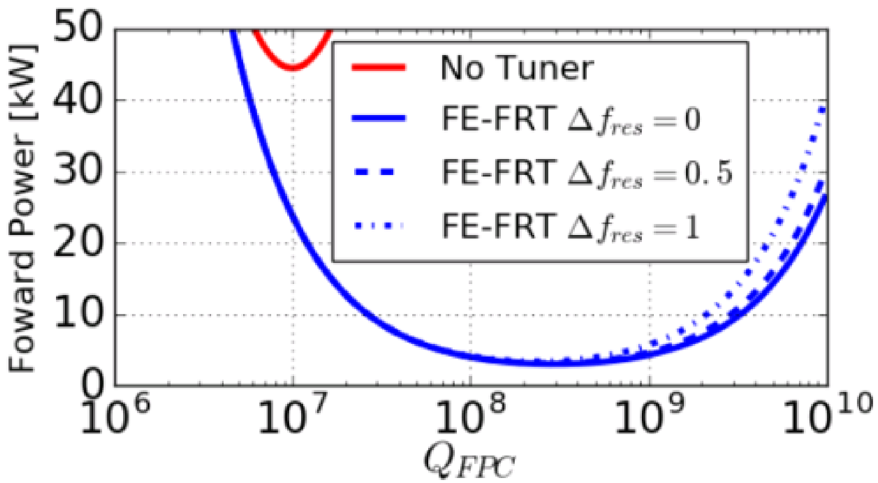


Decreasing Q_L

ERLs / low beam loading

- FE-FRTs could almost completely eliminate microphonics
  - Due to speed and
  - Non-mechanical nature
- Huge power savings
  - Peak power reduced by factor FoM/2
  - Average power reduced by factor FoM/4
- Some power lost in FE-FRT
  - Depends on FoM
- Factor ~15 reduction in peak power predicted for PERLE

PERLE case study



P_{RF} vs. Q_{FPC} for PERLE. Without FE-FRT and with FE-FRT.

FoM

Figure of Merit is measure of performance given by:

$$\text{FoM} = \frac{\Delta \mathcal{P}_{reac}}{2\sqrt{P^1_{diss} P^2_{diss}}}$$

Can be > 100 depending on frequency and application

Storage Ring High beam loading

RF power required for cavity with beam:

$$P_{RF} = \frac{{}^{R}\!/_{Q} Q_e}{2}\left(\left[\frac{V_c'}{\omega_0 {}^{R}\!/_{Q}} + \frac{V_c}{2 {}^{R}\!/_{Q} Q_L} - I_b \sin\Delta\phi_{bc}\right]^2 + \left[\frac{V_c}{\omega_0 {}^{R}\!/_{Q}}(\phi_c' - \Delta\omega_D) - I_b \cos\Delta\phi_{bc}\right]^2\right)$$

Notation	Meaning
P_{RF}	RF power
V_c	Cavity Voltage
I_b	Beam current
$\Delta\omega_D$	Detuning
$\Delta\phi_{bc}$	Beam – cavity phase

Storage Ring High beam loading

RF power required for cavity with beam:

Can change
Fixed

$$P_{RF} = \frac{{}^{R}/_{Q} Q_e}{2}\left(\left[\frac{V_c'}{\omega_0 {}^{R}/_{Q}} + \frac{V_c}{2 {}^{R}/_{Q} Q_L} - I_b \sin\Delta\phi_{bc}\right]^2 + \left[\frac{V_c}{\omega_0 {}^{R}/_{Q}}(\phi_c' - \Delta\omega_D) - I_b \cos\Delta\phi_{bc}\right]^2\right)$$

Notation	Meaning
P_{RF}	RF power
V_c	Cavity Voltage
I_b	Beam current
$\Delta\omega_D$	Detuning
$\Delta\phi_{bc}$	Beam – cavity phase

Storage Ring High beam loading

Can change

Fixed

RF power required for cavity with beam:

$$P_{RF} = \frac{V^2 Q_e}{8 R/_Q Q_L^2} + \frac{R/_Q Q_e}{2}\left[\frac{V}{\omega_0 R/_Q}(\phi_c' - \Delta\omega_D) - I_b\right]^2$$

Notation	Meaning
P_{RF}	RF power
V_c	Cavity Voltage
I_b	Beam current
$\Delta\omega_D$	Detuning
$\Delta\phi_{bc}$	Beam – cavity phase

Simplifying assumptions

$V_c' = 0$

$\Delta\phi_{bc} = 0$

Storage Ring High beam loading

Can change
Fixed

RF power required for cavity with beam:

$$P_{RF} = A + [B(\phi'_c - \Delta\omega_D) - C I_b]^2$$

Notation	Meaning
P_{RF}	RF power
ϕ'_c	Cavity phase derivative
$\Delta\omega_D$	Detuning
I_b	Beam current

- I_b will change so either:
  - P_{RF} or ϕ_c must change
- Choice between:
  - Increased RF power
  - Cavity phase errors

Storage Ring High beam loading

We propose a new RF powering scheme called **Transient Detuning**

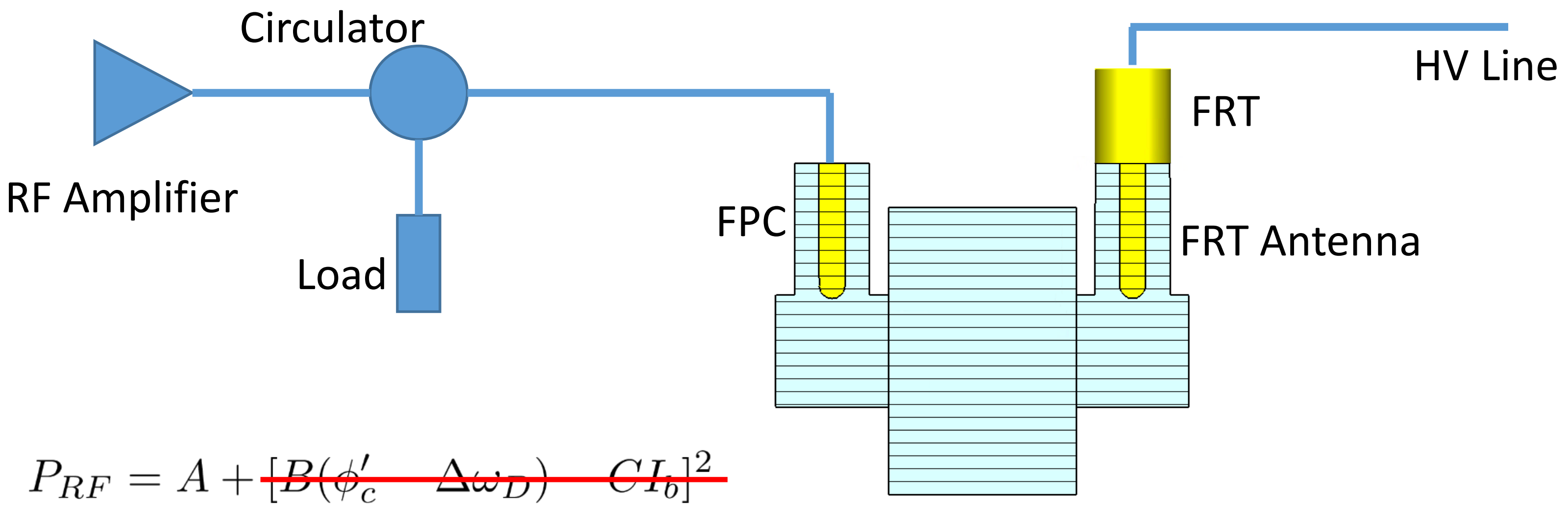
Can change
Fixed

$$P_{RF} = A + [B(\phi_c' - \Delta\omega_D) - CI_b]^2$$

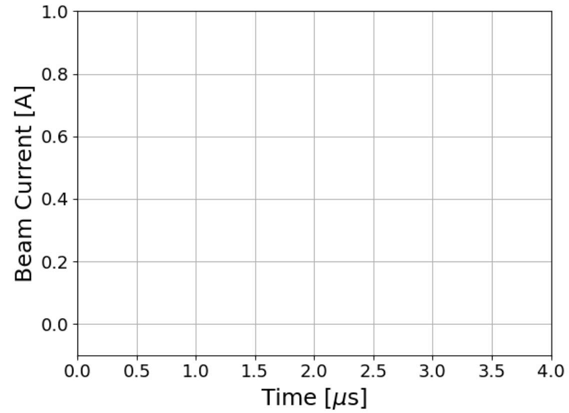
Notation	Meaning
P_{RF}	RF power
ϕ_c'	Cavity phase derivative
$\Delta\omega_D$	Detuning
I_b	Beam current

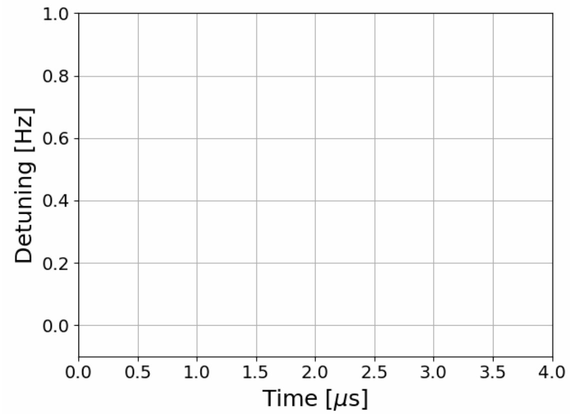
- Use FE-FRT to change $\Delta\omega_D$
  - Reduced average RF power (by up to FoM/2)
  - Increased phase stability
  - Fixed RF bucket position

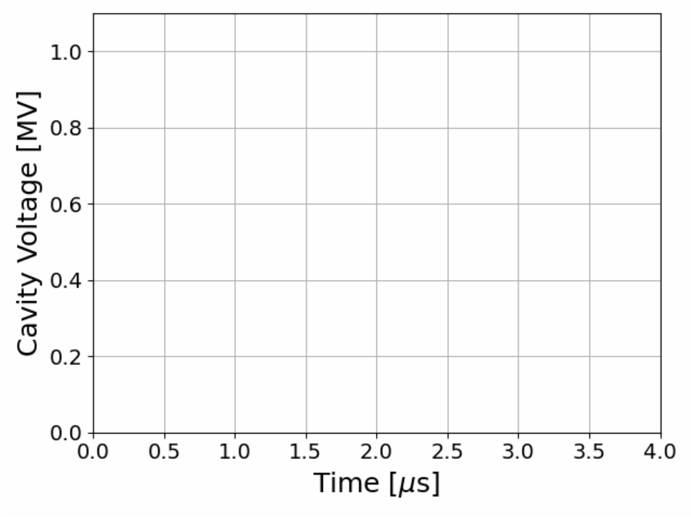
Storage Ring High beam loading

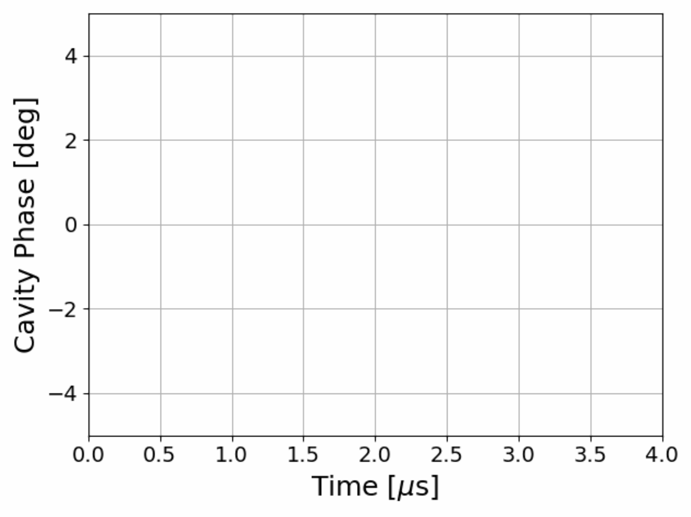


$$P_{RF} = A + \cancel{[B(\phi_c' - \Delta\omega_D) - CI_b]^2}$$



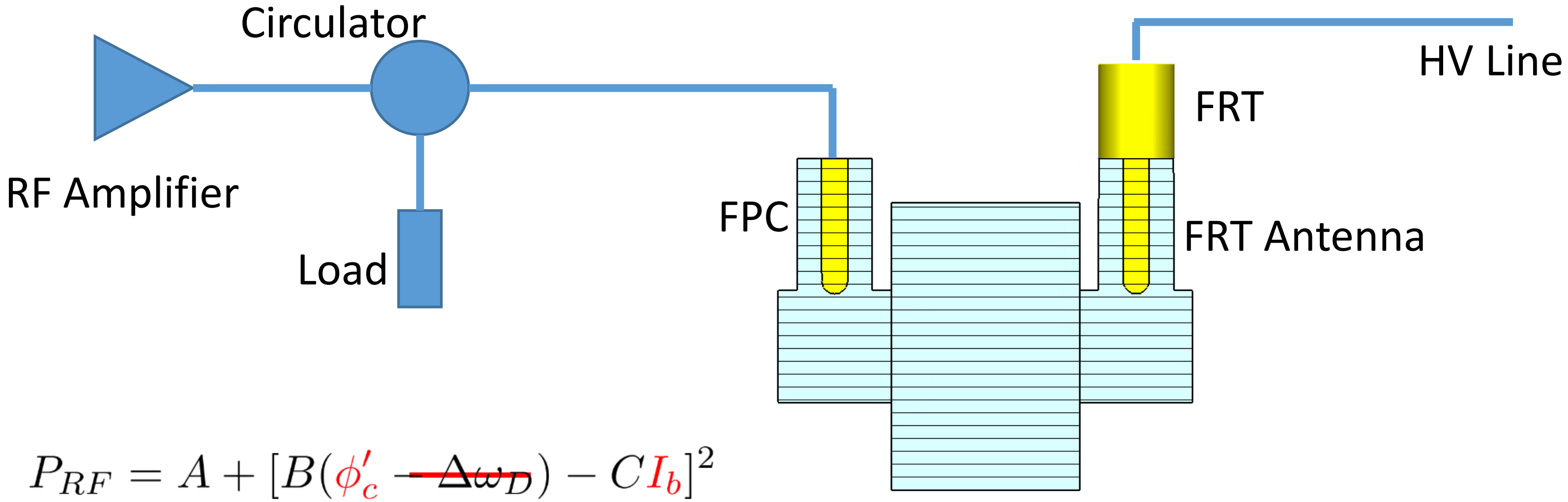




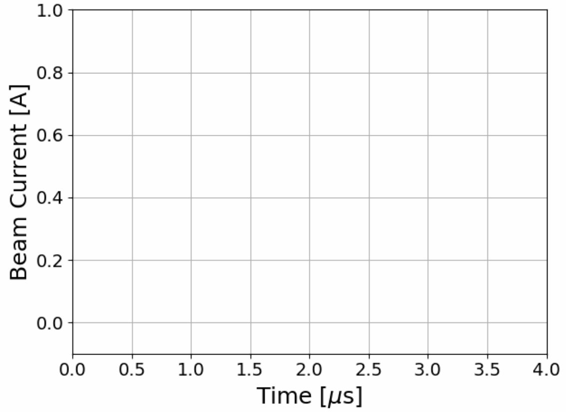


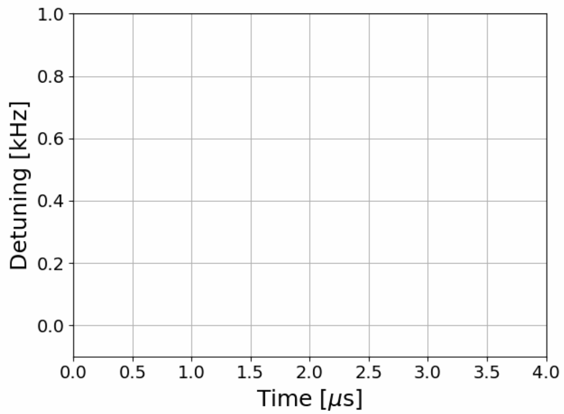
No beam, no detuning

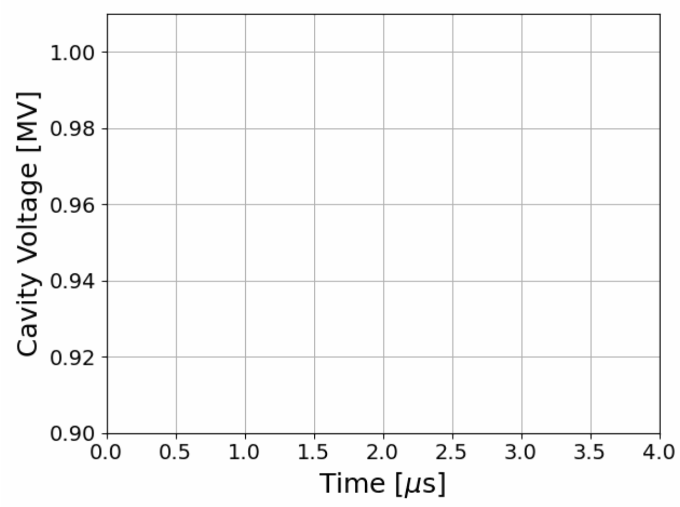
Storage Ring High beam loading

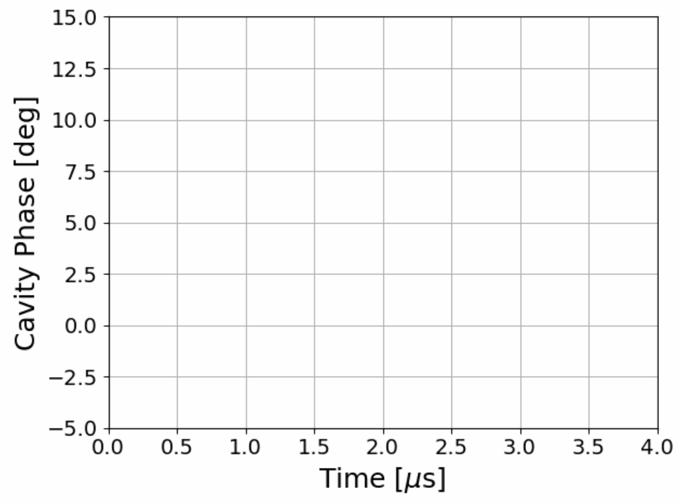


$$P_{RF} = A + [B(\phi_c' \cancel{-\Delta\omega_D}) - C I_b]^2$$



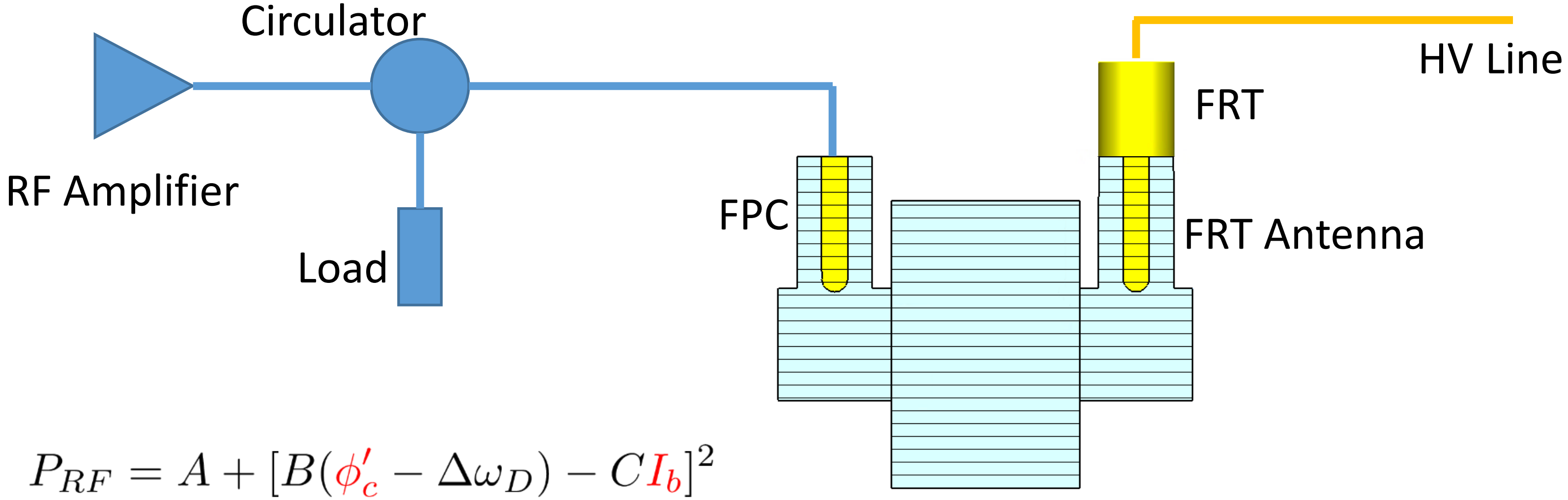




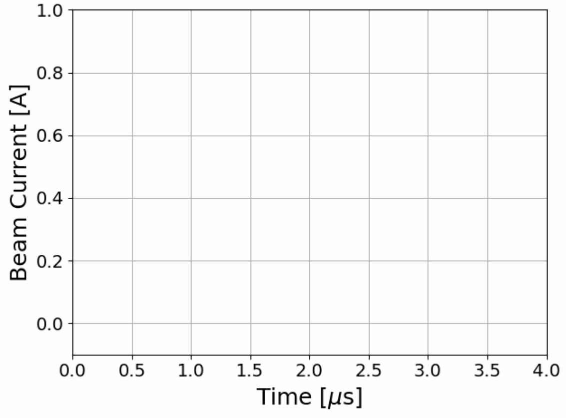


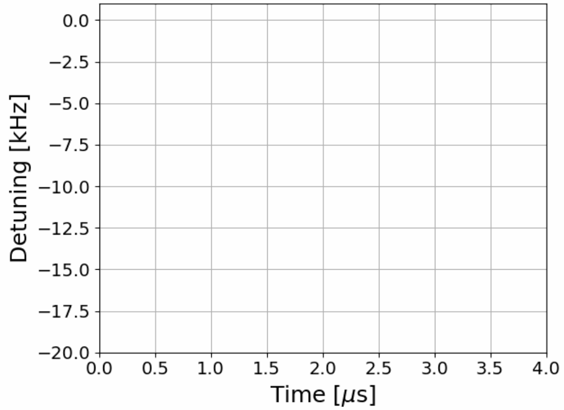
Beam, no detuning

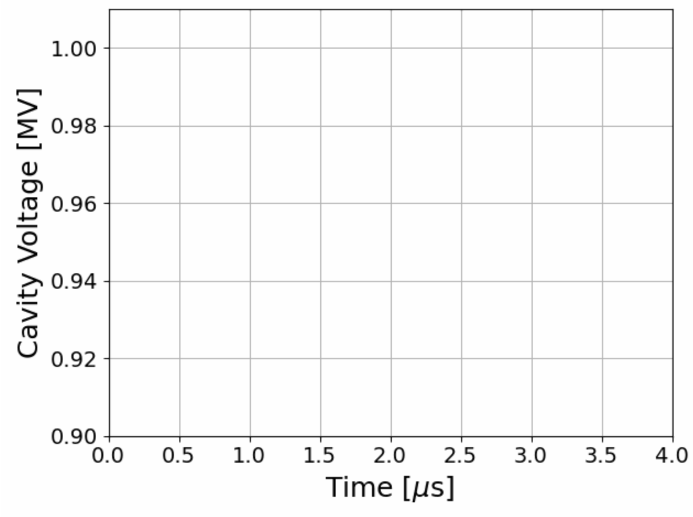
Storage Ring High beam loading

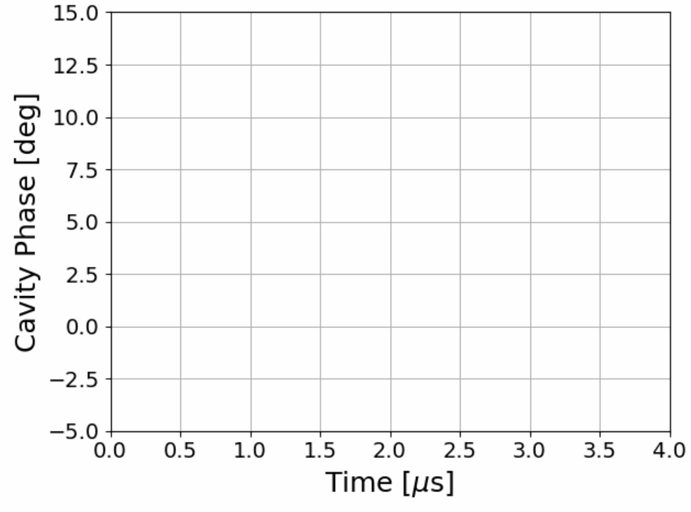


$$P_{RF} = A + [B(\phi'_c - \Delta\omega_D) - C I_b]^2$$



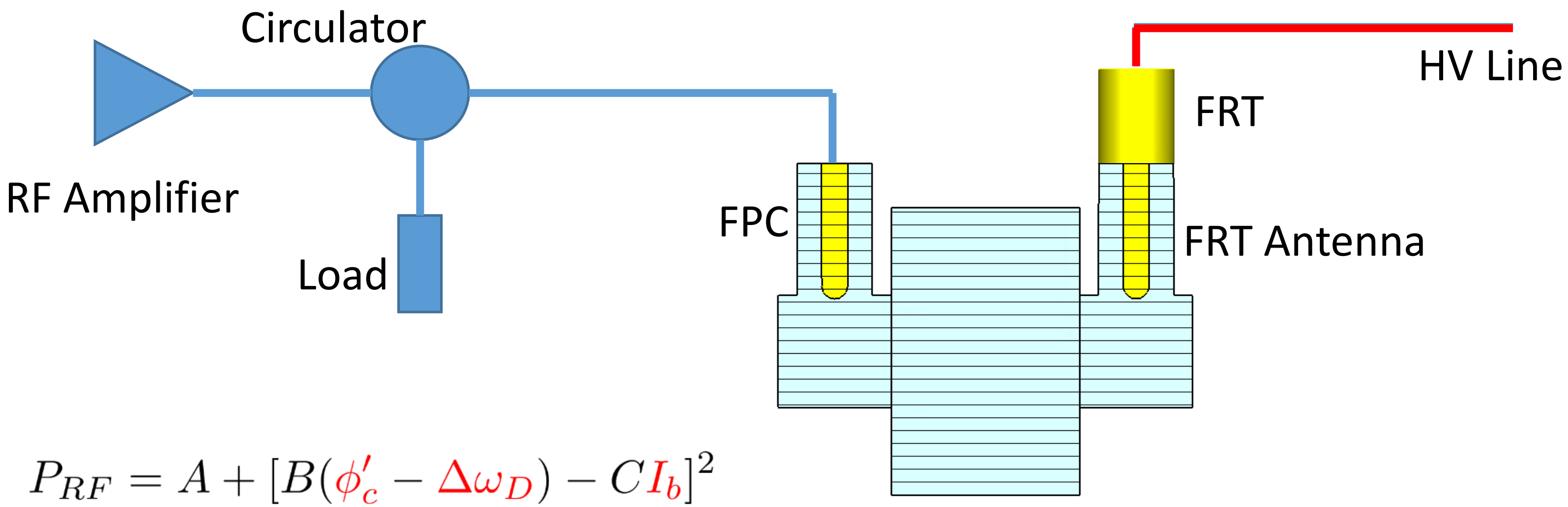




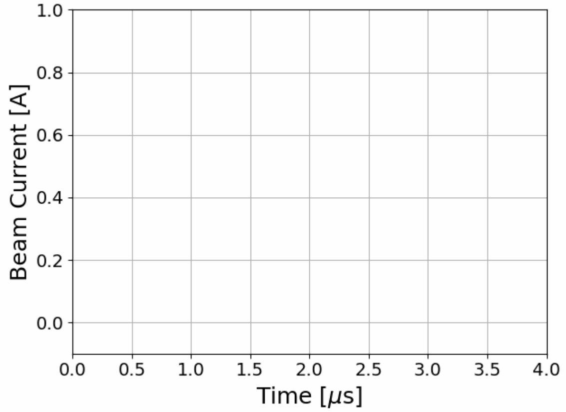


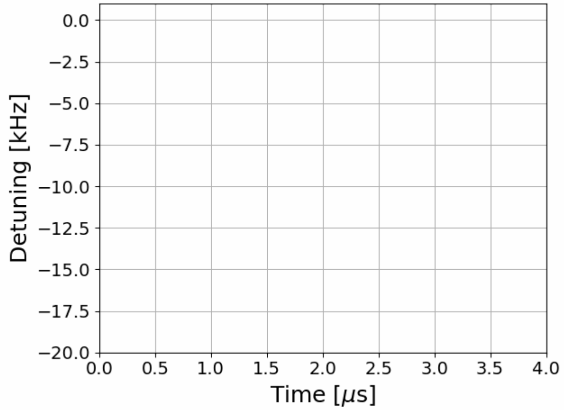
Beam,
fixed detuning

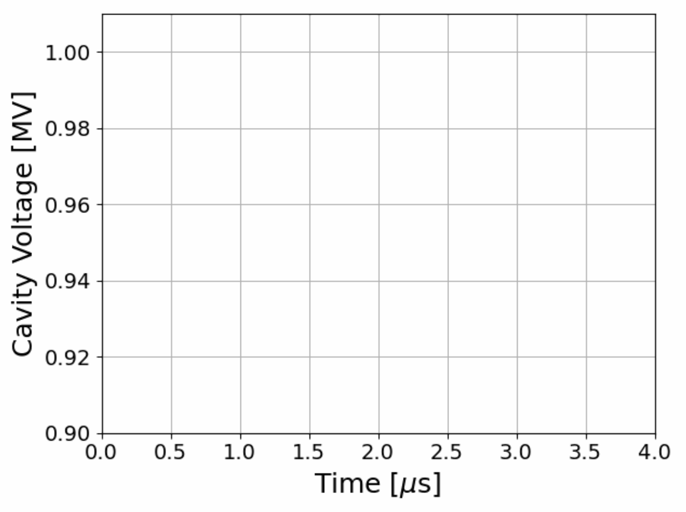
Storage Ring High beam loading

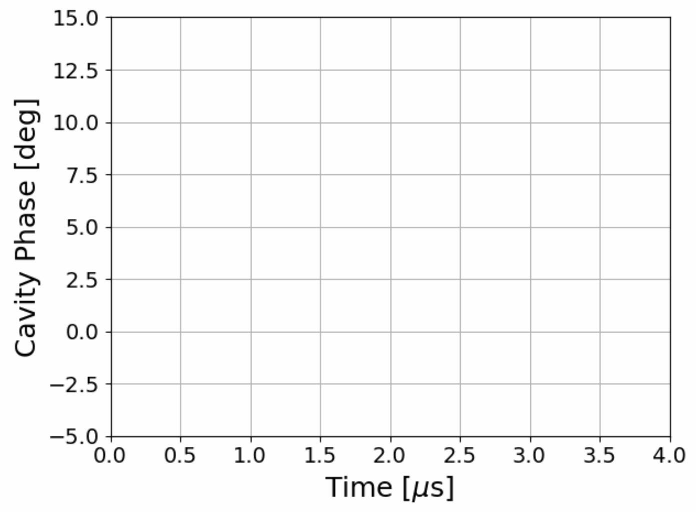


$$P_{RF} = A + [B(\phi'_c - \Delta\omega_D) - C I_b]^2$$



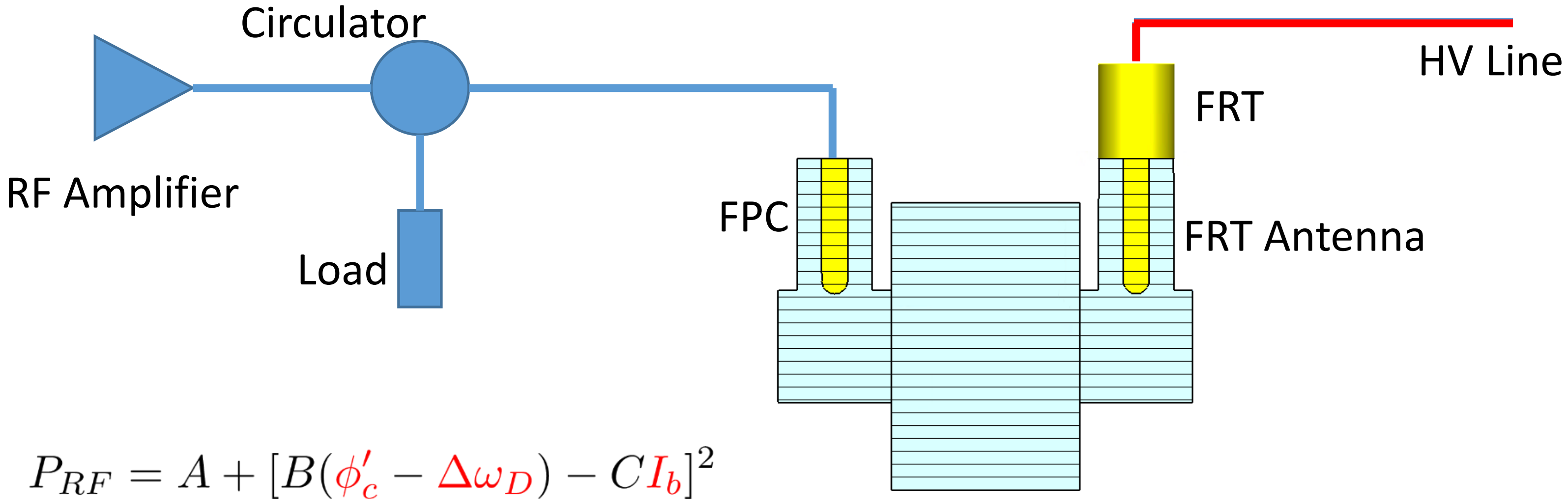


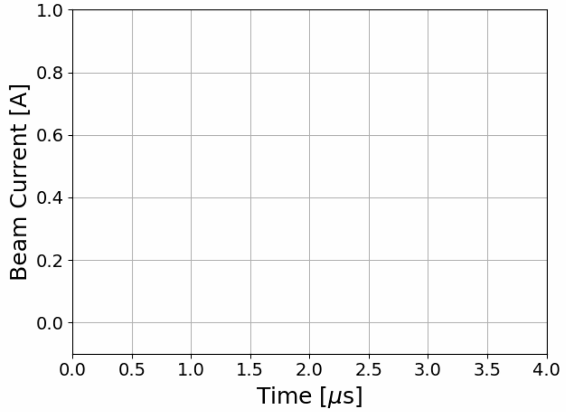




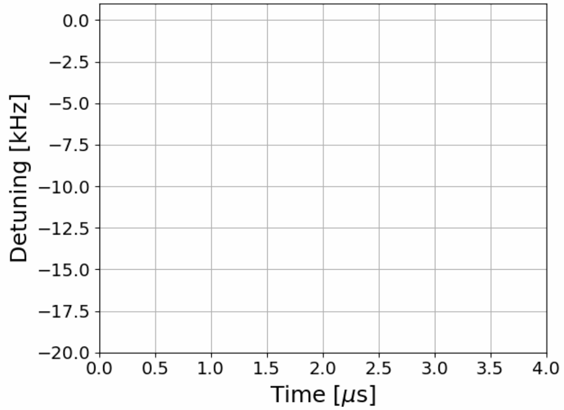
Beam,
transient detuning

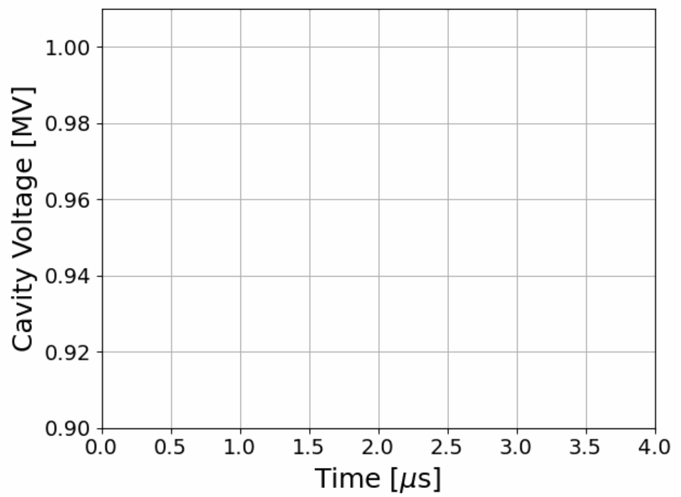
Storage Ring High beam loading

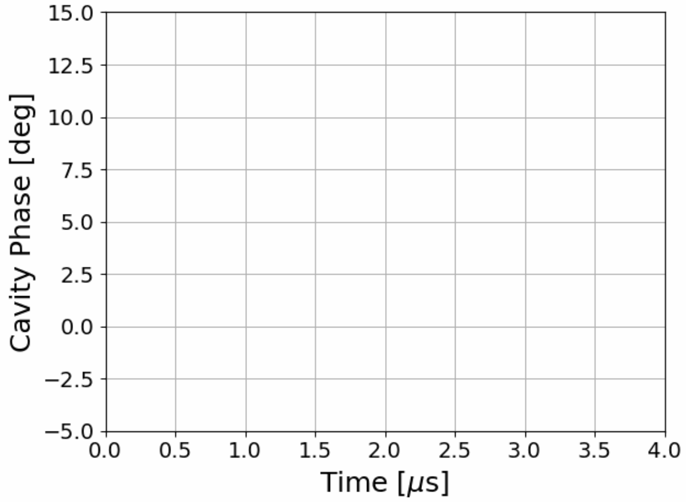




$$P_{RF} = A + [B(\phi_c' - \Delta\omega_D) - CI_b]^2$$



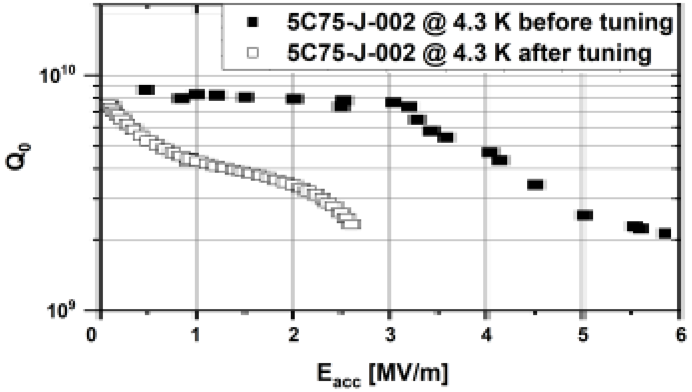




First look into feasibility for HL-LHC injection underway!

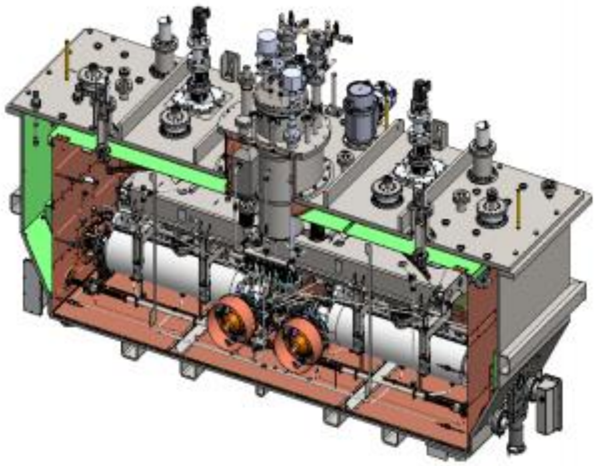
Exotic Cavities

Degradation of Nb_3Sn cavity performance after mechanical tuning



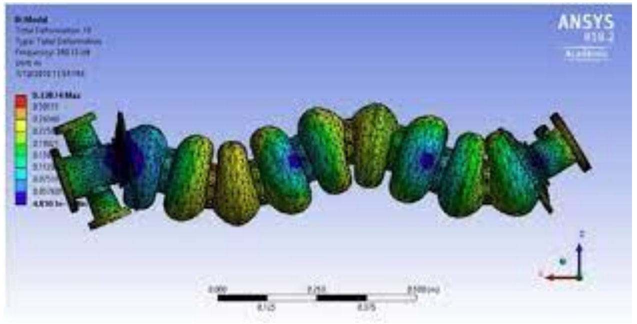
G. Eremeev et al., “RF Performance Sensitivity to Tuning of Nb_3Sn Coated CEBAF Cavities,” in SRF2019, Dresden,2019.

TRIUMF’s accelerator cryomodule



N. Muller et al., “TRIUMF’S INJECTOR AND ACCELERATOR CRYOMODULES” in SRF2015, Whistler, 2015.

TRIUMF’s accelerating cavity microphonics simulation



S. Koscielniak, “STATUS AND ISSUES (MICROPHONICS, LFD, MPS) WITH TRIUMF ARIEL E-LINAC COMMISSIONING,” in SRF2019, Dresden,2019.

- Nb_3Sn performance degraded with mechanical tuning
- There may be a material science solution
- FE-FRT can provide alternate solution

- Cryomodules and cavities are already complicated.
- Often much effort and constraints also imposed by microphonics.
- What could we do if these were lifted?

Further Examples

HIE-ISOLDE

Thomas Hortala "LS2 Report: first beam inside the upgraded HIE-ISOLDE facility"

- 92% of max. energy has been achieved[1] limited by:
  - Field emission in some cavities
  - Microphonics when mechanical tuning system is on
  - FPC power limited to 200W
- FE-FRT could offer very elegant improvement by:
  - Allowing operation at lower bandwidths and critical coupling
  - reducing RF power required per cavity to ~20W
  - allowing max. energy with existing installed power and FPCs

[1]Walter Delsolaro private communication

Further Examples

EIC 197 MHz hadron crab cavities

Bob Rimmer *"SRF Challenges and R&D for the EIC"*

- Hadron beam sweeps through broad range of frequency
- Must prevent revolution harmonics exciting high-impedance modes
- During injection, heavy damping or:
- ~950kHz tuning range required[1]
  - Can the cavity take this much mechanical deformation – maybe?
  - Could an FE-FRT be used – probably not

Preliminary idea:
Use an FE-FRT to quickly jump cavity mode resonances over revolution lines during abort gap.

[1]Qiong Wu private communication

Further Examples

UK-XFEL

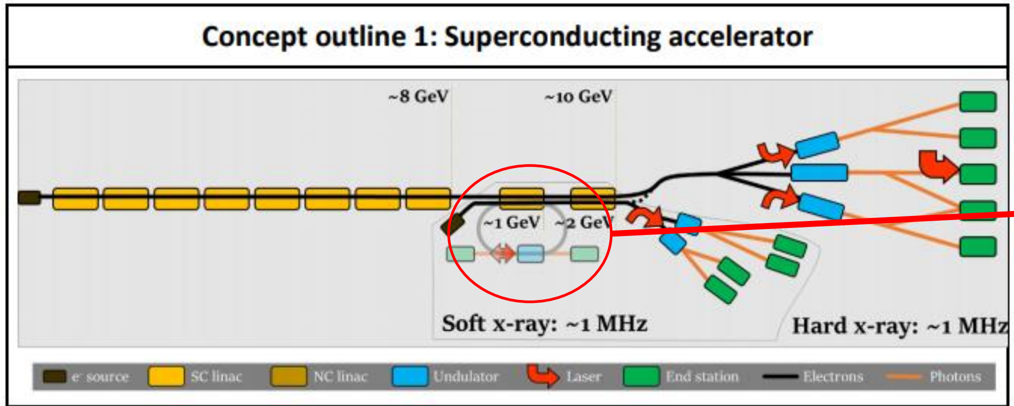
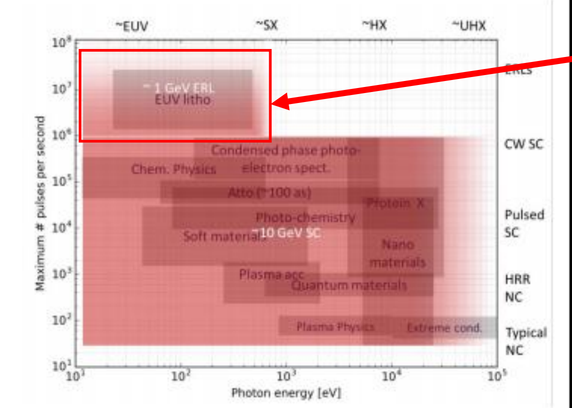


Figure A1.2: UK XFEL Concept outline 1: superconducting accelerator.

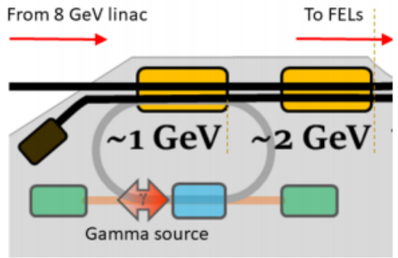
The above schematic shows the layout for a ~10 GeV superconducting accelerator facility proposed to meet the science requirements.

The plot to the right shows how such a technical solution would cover the repetition rate-photon energy requirements of the science case.

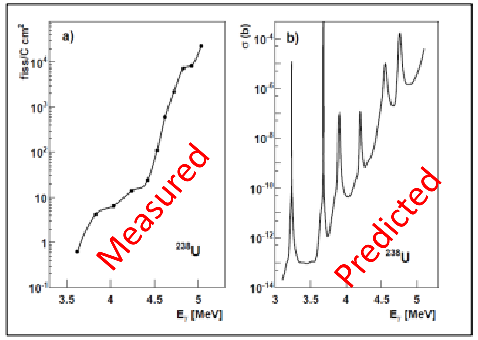


All plots taken from “UK XFEL Science Case” (2020). ed. by J. Marangos

UK-XFEL SC-ERL driven ICS gamma source



- An ERL would give 100-fold increase in flux:
  - Enable new science reach



“Perspectives for photofission studies with highly brilliant, monochromatic γ-ray beams” P. G. Thirolf et. al., EPJ Web of Conferences 38, 08001 (2012)

- An FE-FRT would reduce RF power required by ERL > 10-fold:
  - Reduced running costs
  - Reduction in installation cost

Conclusion

- Whatever you build you want an FE-FRT!
  - Low beam loading machines
  - High beam loading machines
  - Nb_3Sn or other exotic cavities
  - Normal conducting cavities
- Accelerator Examples just from this talk:
  - PERLE
  - PS
  - HL-LHC
  - UK-XFEL
  - HIE-ISOLDE
  - EIC
- FE-FRTs massively reduce RF power:
  - Important for societal acceptance of future HEP machines
- FE-FRTs improve physics reach
  - Increased luminosity
  - Improved beam quality
- Next steps:
  - Reduce losses exhibited in prototype
  - Demonstrate high power operation
  - New FE-FRT for frequency switching under development at CERN

Thank you!

Thank you all for listening!

Any questions?