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# SRF LINAC Simulation

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# Outline

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# Introduction: Objective

- Simulate the acceleration of a proton traveling through the field of a superconducting radio frequency (SRF) cavity

- Determine the number of cavities required to accelerate protons from 2.1 MeV to 1 GeV

Model:

❖ This is a simplified model based on the actual PIP – II linac design

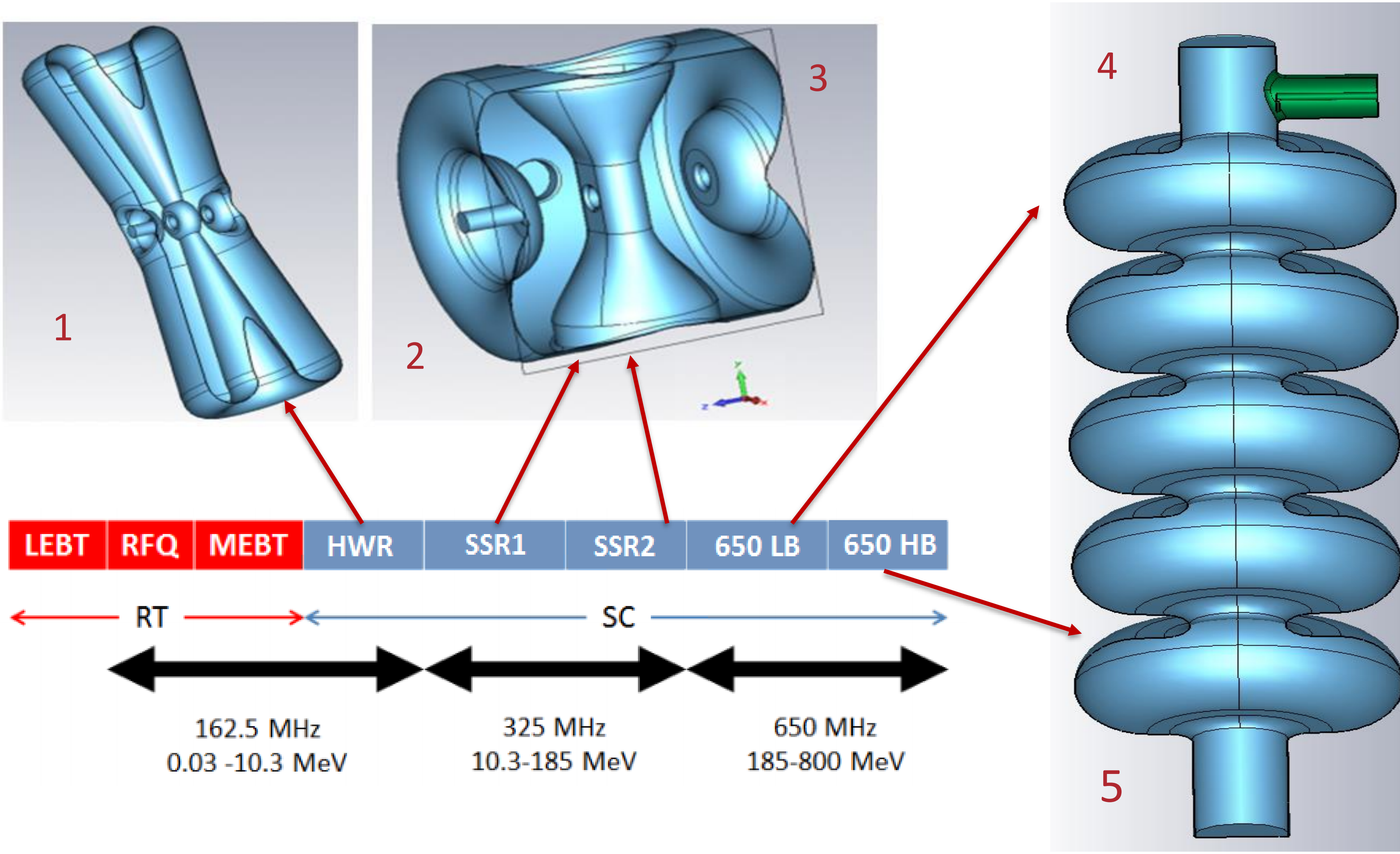
❖ Transverse RF fields and particle dynamics are not considered.

❖ $\beta$ ($\frac{v}{c}$) is considered constant while the particle travels through the cavity

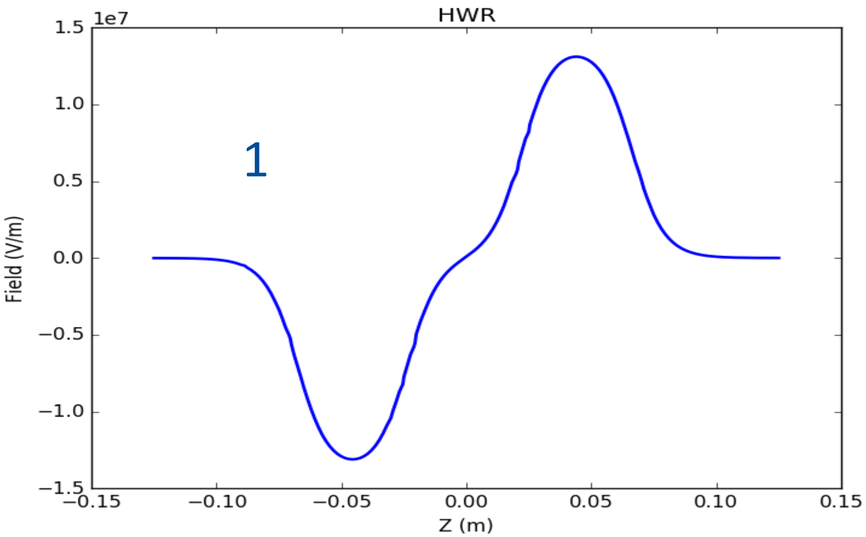
# SRF Cavities

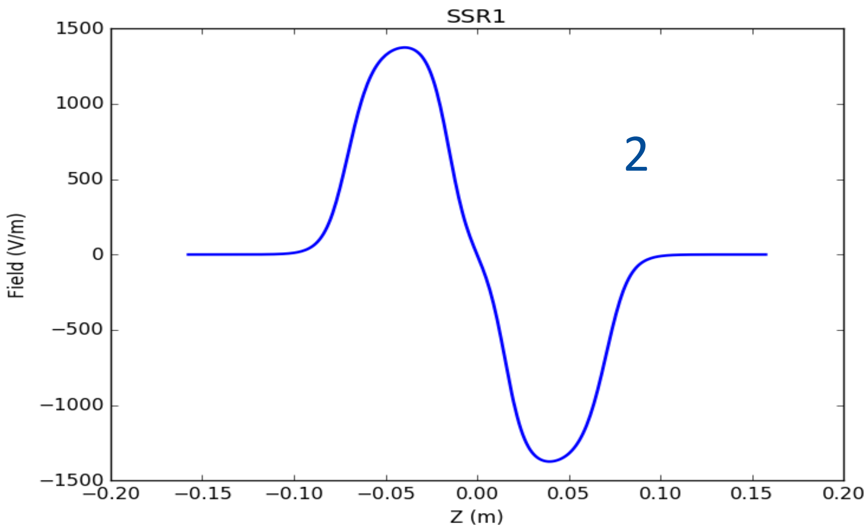
- Electromagnetic fields are excited in the SRF cavity by coupling RF power through an antenna
- The surface resistance of SRF cavities is several orders of magnitude less than NC cavities for a given frequency
- Nearly all RF power goes to the beam
- The level of RF power losses in SRF cavities allows for continuous operation at higher field levels than NC cavities.

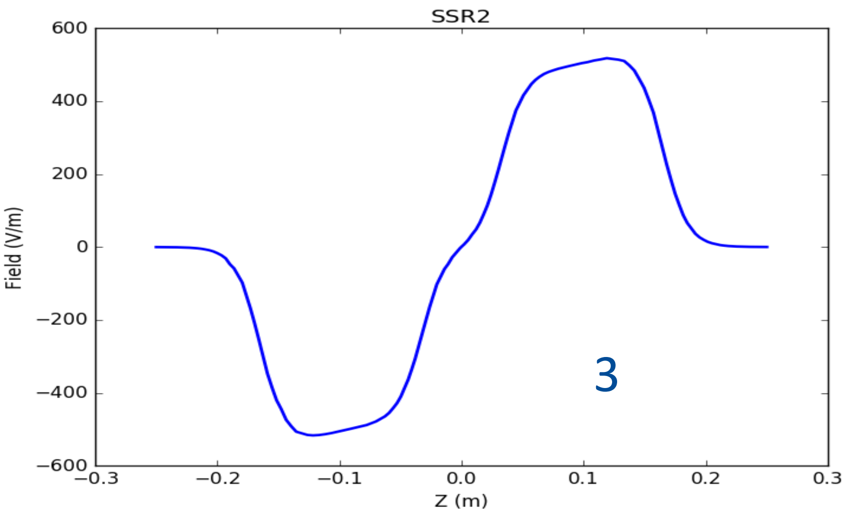
# LINAC Design



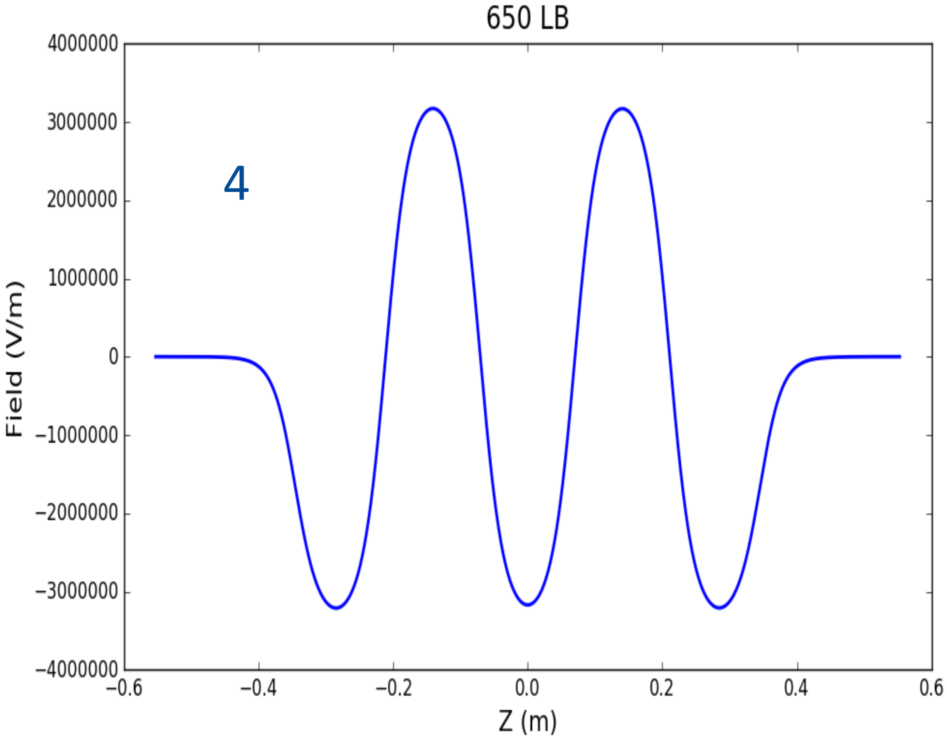
# Cavity Fields

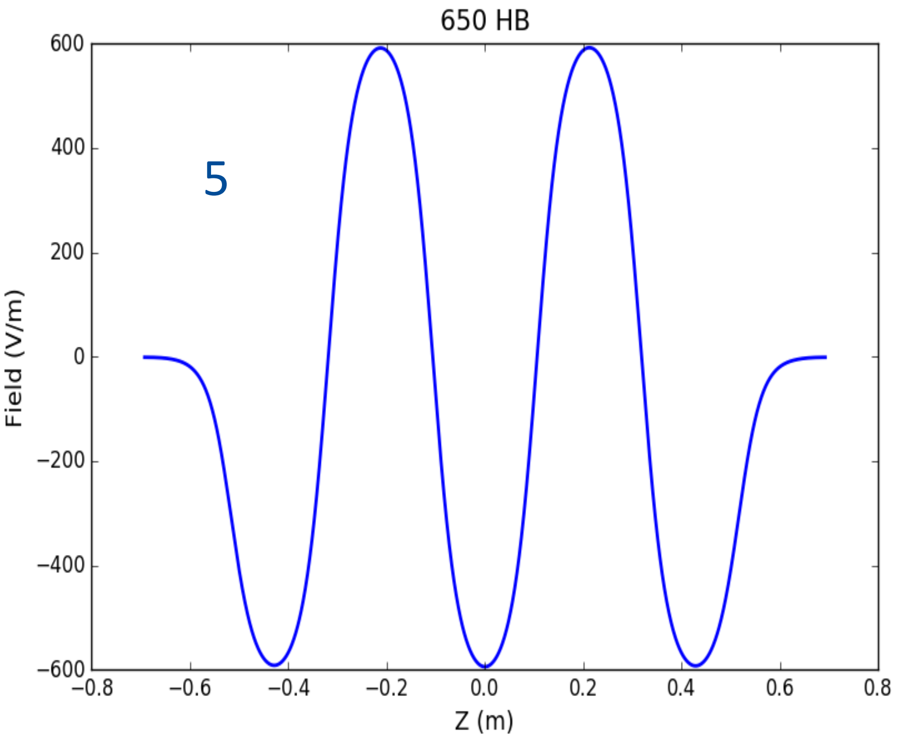


# Cavity Fields



# Particle Energy Gain

$$\Delta W_z = \left| \int_{-l/2}^{l/2} q * E_z(r=0,z) * e^{i\omega t} dz \right|$$

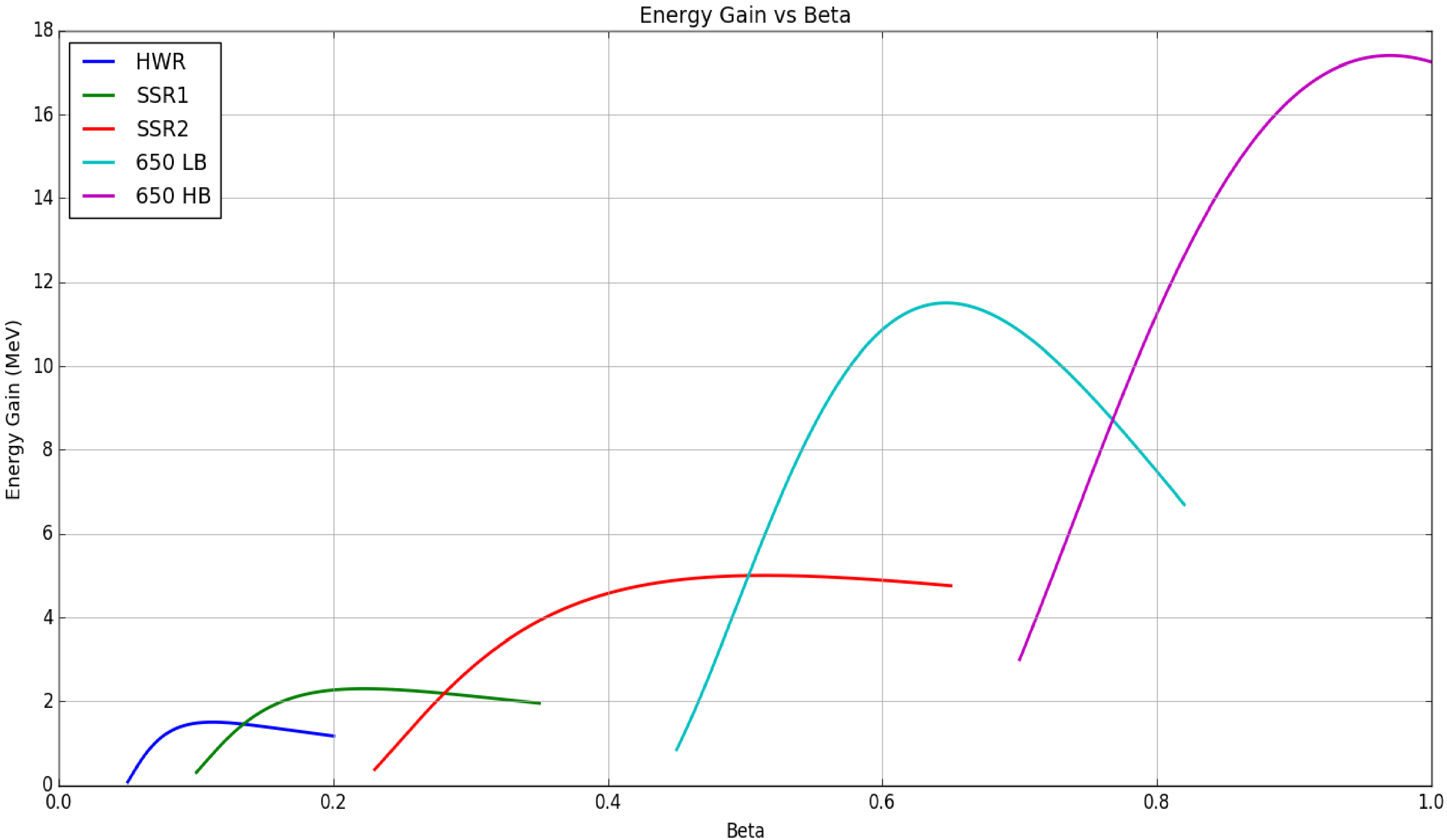
Convert the time dependence to position dependence by taking β as constant through the cavity

$$\omega = 2\pi f \quad , c = \lambda f \quad , k = \frac{2\pi f}{c} \quad and\ \beta = \frac{v}{c}$$

$$\Delta W_z = \left| e \int_0^l E_z(r=0,z) * e^{i(\frac{kz}{\beta})} dz \right|$$

$l$: length of the cavity
$E_z$: cavity field
$\omega$: angular frequency
$\boldsymbol{\lambda}$: wavelength
$v$: particle speed
$c$: speed of light
$f$: EM field frequency
$k$: wavenumber.
$q$: particle charge

# Energy Gain vs β



# K.E to β conversion and $\beta_{OPT}$

$$K.E = (\gamma - 1)m_0c^2,$$

$$\gamma = \frac{K.E + m_0c^2}{m_0c^2} = \frac{K.E\ (in\ MeV) + 938.2720813}{938.2720813}$$

$$where\ rest\ energy = m_0c^2 \quad and \quad \gamma = \frac{1}{\sqrt{1-\beta^2}}$$

The rest energy of a proton = 938.2720813 MeV

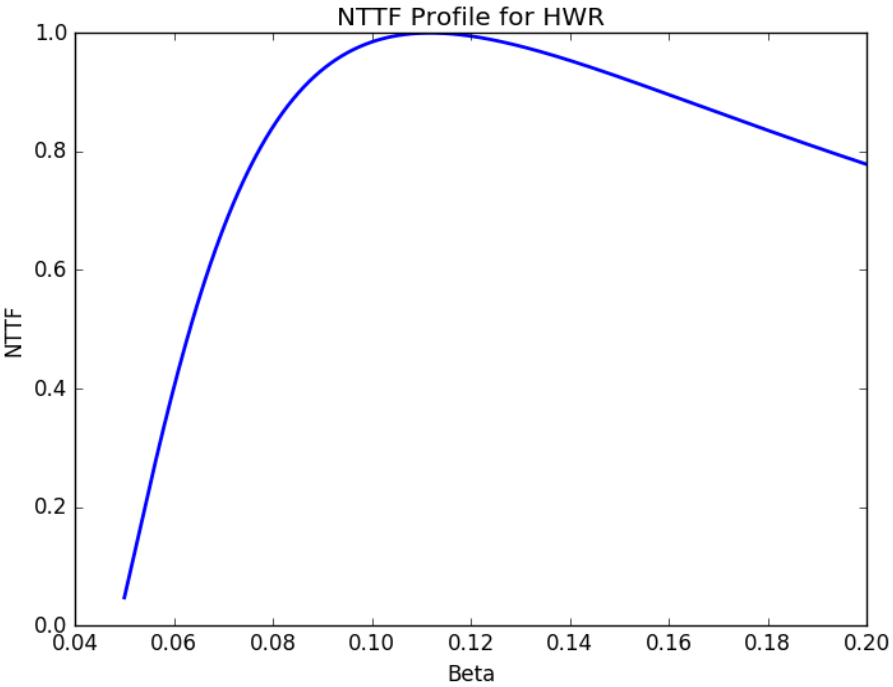
| Cavity Type | $\beta_{OPT}$ |
|---|---|
| HWR (2.1 – 9.5 MeV) | 0.1118 |
| SSR1 (9.5 - 33 MeV) | 0.2222 |
| SSR2 (33 – 160 MeV) | 0.5148 |
| 650 LB (160 – 490 MeV) | 0.6462 |
| 650 HB (490 MeV – 1 GeV) | 0.9700 |

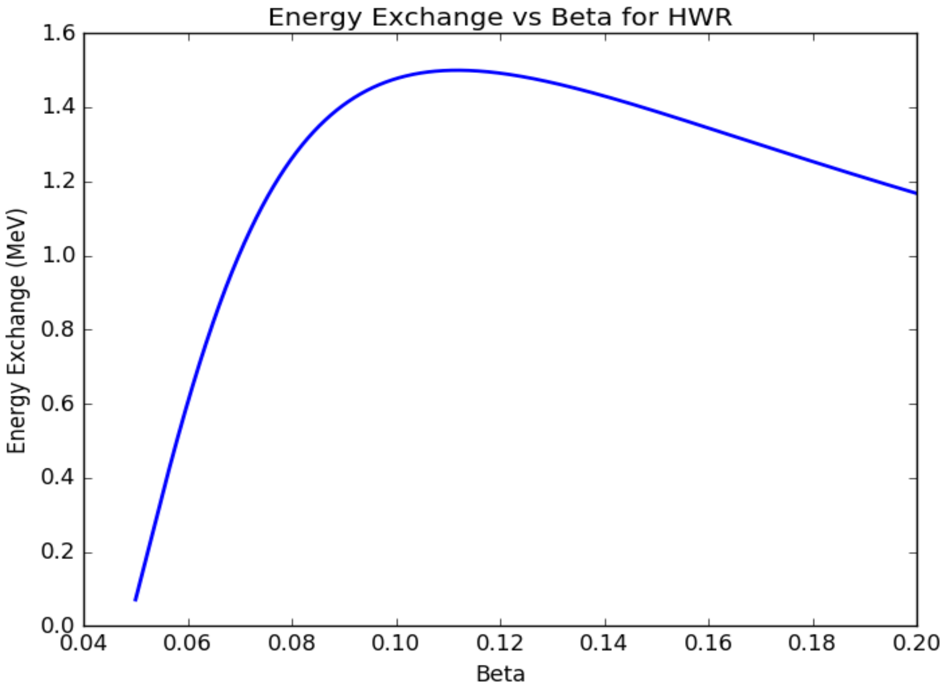
The $\beta_{OPT}$ for each Cavity estimated from the NTTF curves

# NTTF function

- Energy gain vs $\beta$ plot is rescaled to the normalized energy gain.

$$NTTF = \frac{\Delta W(\beta)}{\Delta W_{\beta_{opt}}}$$



# $\Delta W_{max}$

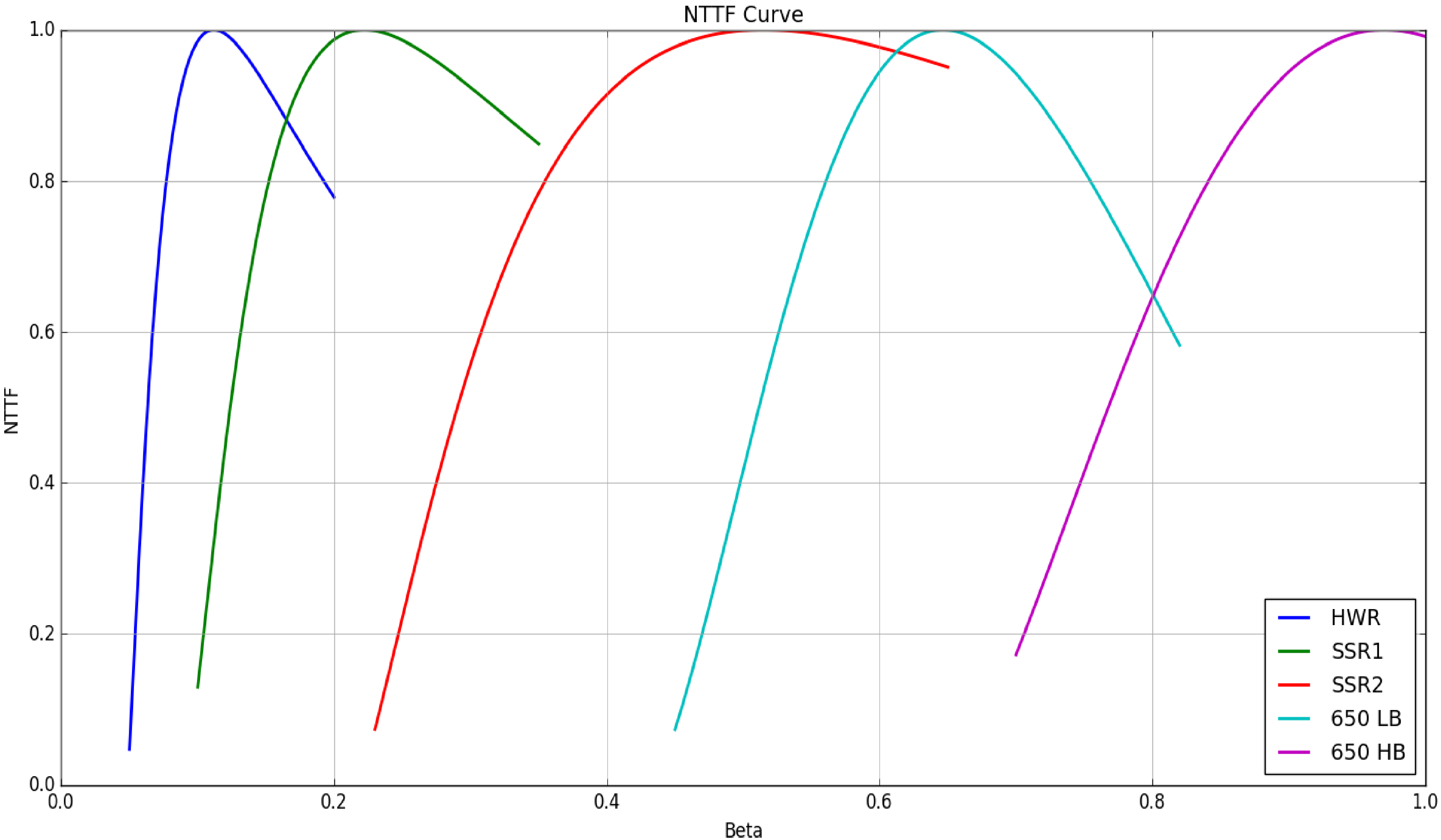
$$\Delta W = \Delta W_{max} * NTTF(\beta)$$

| Cavity Type | $\Delta W_{max}(MeV)$ |
|---|---|
| **HWR (2.1 – 9.5 MeV)** | 1.5 |
| **SSR1 (9.5 - 33 MeV)** | 2.3 |
| **SSR2 (33 – 160 MeV)** | 5 |
| **650 LB (160 – 490 MeV)** | 11.5 |
| **650 HB (490 MeV – 1 GeV)** | 17.4 |

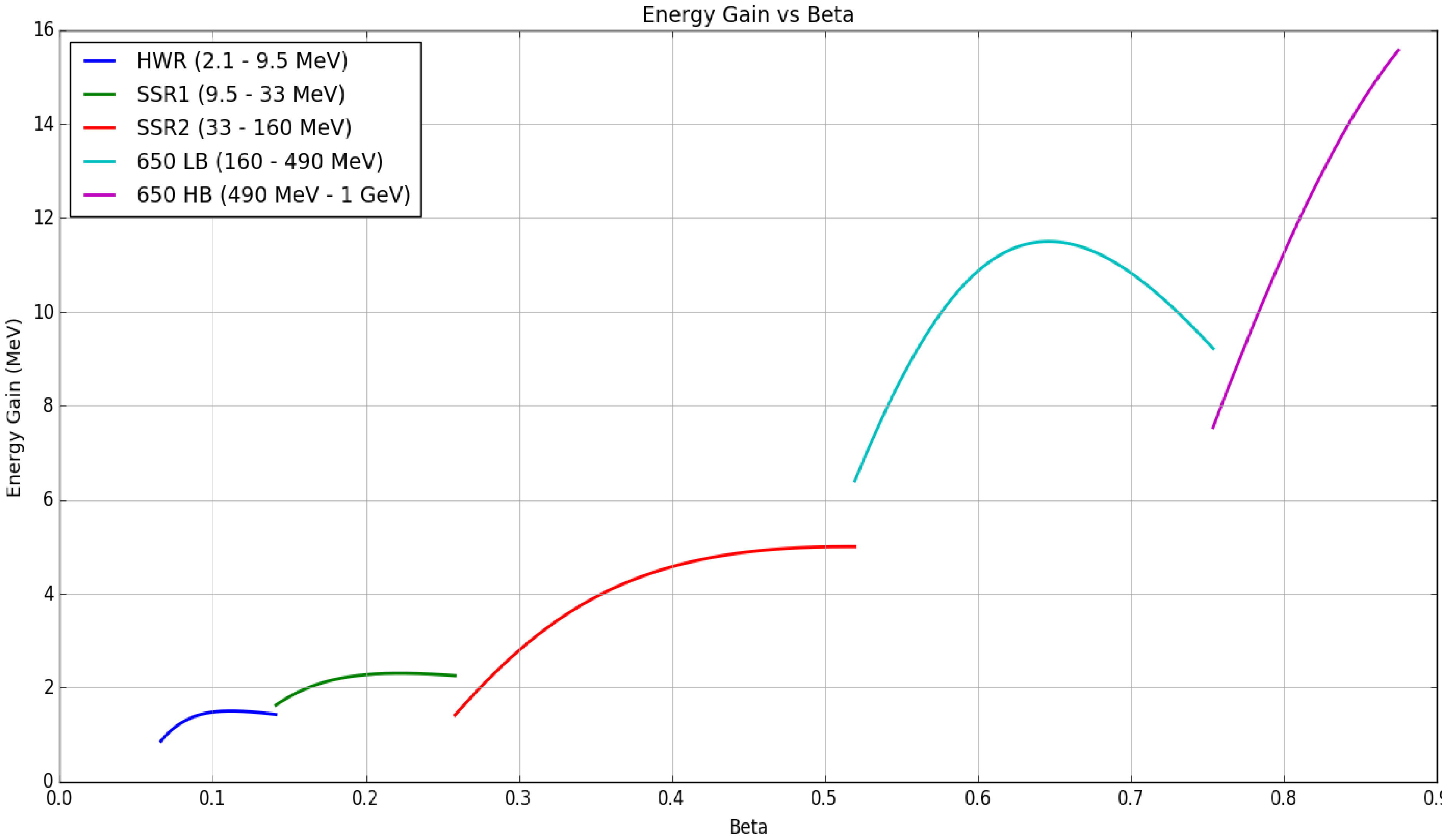
*The Cavity Types and their corresponding* $\Delta W_{max}$.

The maximum energy gain ($\Delta W_{max}$) for a cavity depends on the maximum surface fields the cavity can withstand.

# NTTF Curve


NTTF Curve
1.0
0.8
0.6
0.4
0.2
0.0
NTTF
0.0
0.2
0.4
0.6
0.8
1.0
Beta
HWR
SSR1
SSR2
650 LB
650 HB

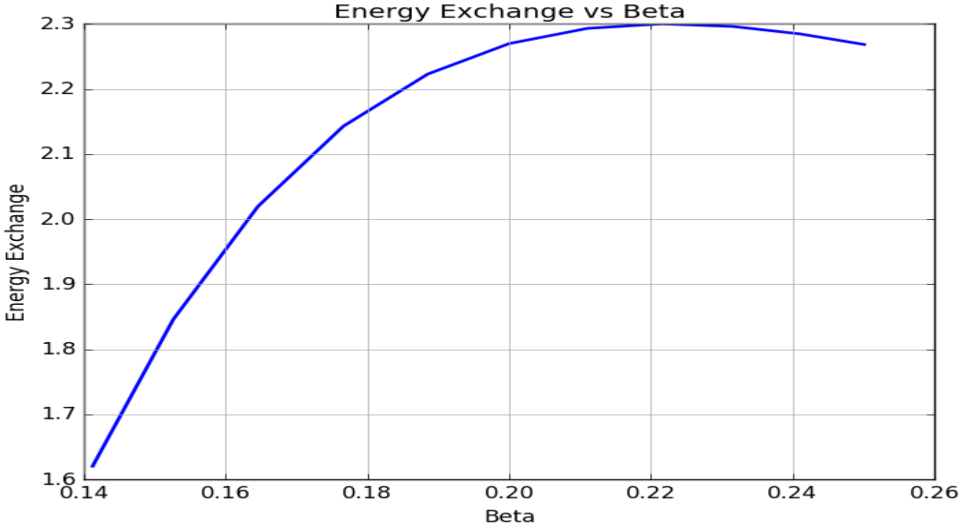
# Energy Gain vs β

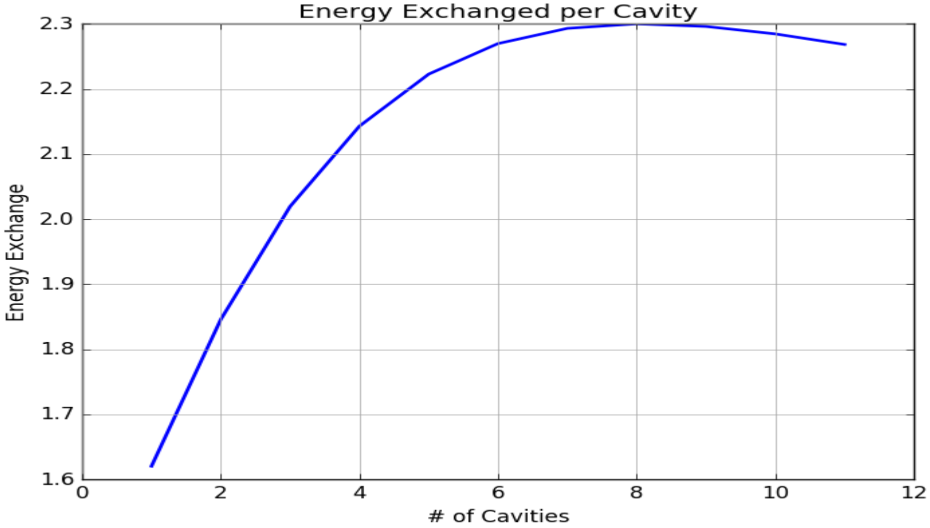


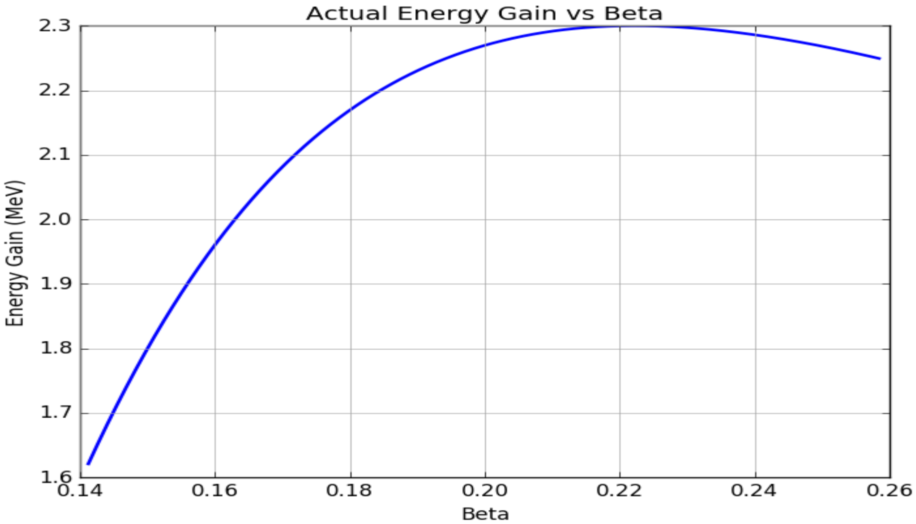
# Result: # of Cavities

| Cavity Type | Energy Range (MeV) | # of Cavities | |
|---|---|---|---|
| | | This Model | PIP - II linac lattice version 6.0 |
| HWR | 2.1 – 9.5 | 6 | 8 |
| SSR1 | 9.5 – 33 | 11 | 16 |
| SSR2 | 33 – 160 | 33 | 30 |
| 650 LB | 160 – 490 | 33 | 36 |
| 650 HB | 490 – 1000 | 43 | 42 |
| Total | 2.1 - 1000 | 126 | 132 |

# Simulation Plots for SSR1



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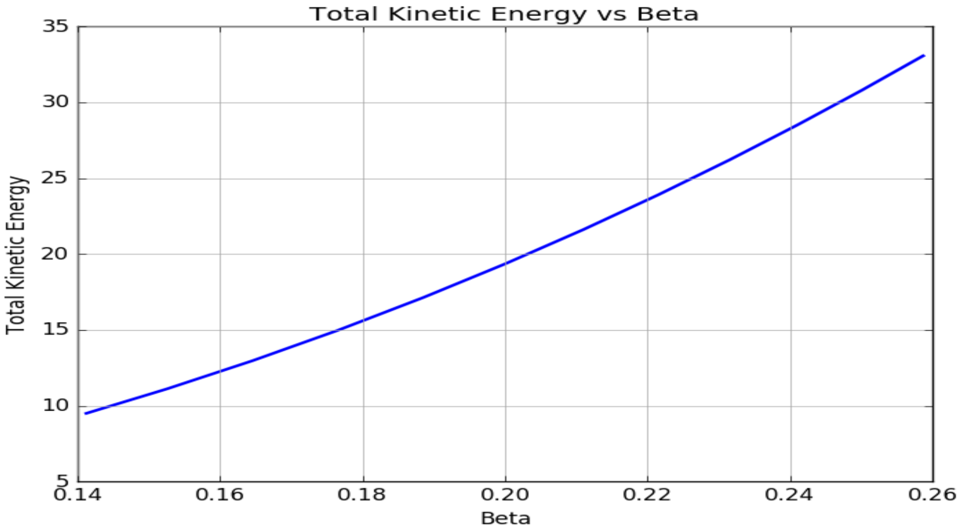


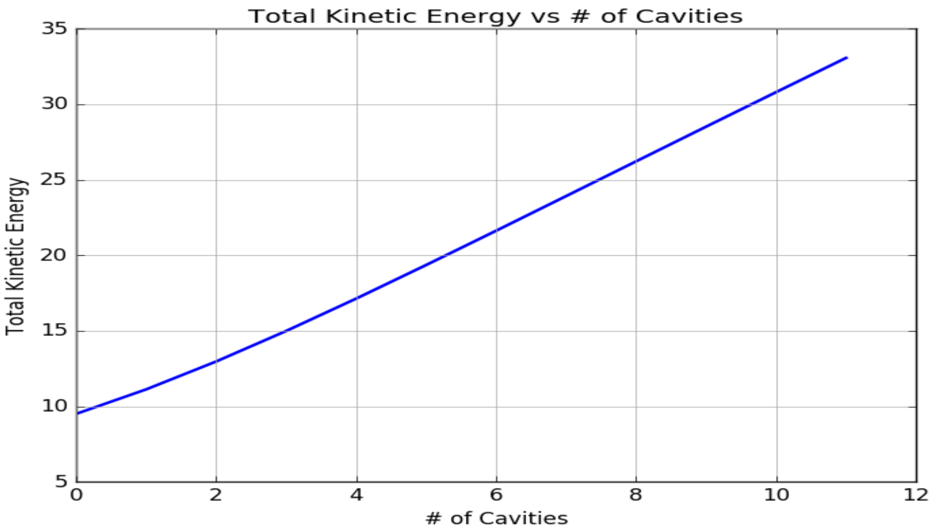


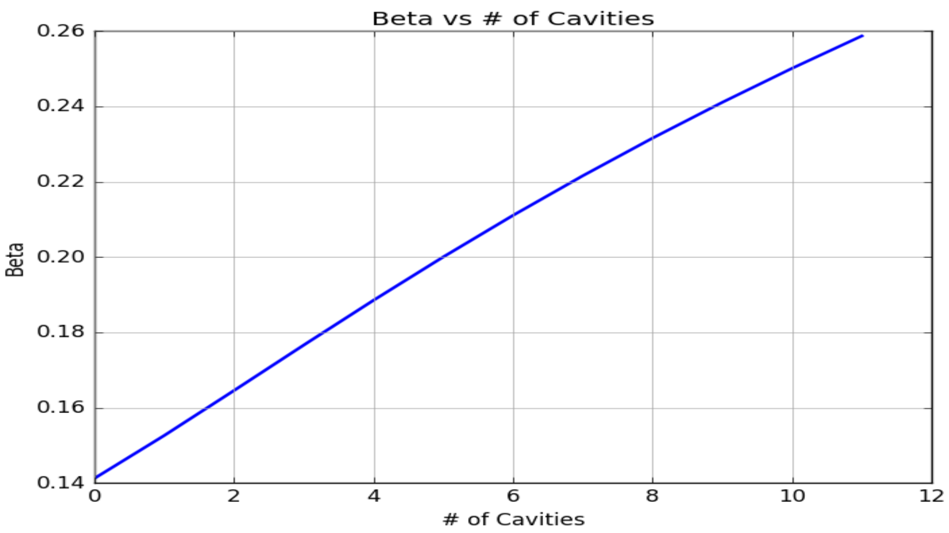

# Summary

- Objective: Determine the number of cavities required to accelerate a proton from 2.1 MeV to 1 GeV.

- LINAC Model
  - Transverse RF fields and particle dynamics are not considered.
  - $\beta$ is considered constant while the particle travels through the cavity

- The accelerator simulation to determine the number of cavities needed involved:
  - Determining the energy gain for each cavity as a function of particle $\beta$
  - Calculating the NTTF for each cavity type
  - Calculating the number of cavities needed

# References


- Padamsee, Hasan, Jens Knobloch, and Tom Hays. *RF Superconductivity for Accelerators.* Morlenbach, Germany: WILEY - VCH Verlag GmbH & Co. KGaA, 2009. p (43) Print.
- The Full Wiki. *Superconducting Radio Frequency*. Web. Aug 2016.
- Oak Ridge National Laboratory. *Fundamentals of Superconductors*. Apr. 1, 1996. Web. August 2016.
- U.S. Particle Accelerator School. *Lecture 4: RF Acceleration in RF Acceleration in Linacs Part 1*. Web. Aug 2016.

# Acknowledgements


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- Mentors: David Peterson and Gustavo Cancelo

- SIST Committee

# Questions?