Electromagnetic simulations of the He6-CRES RF system

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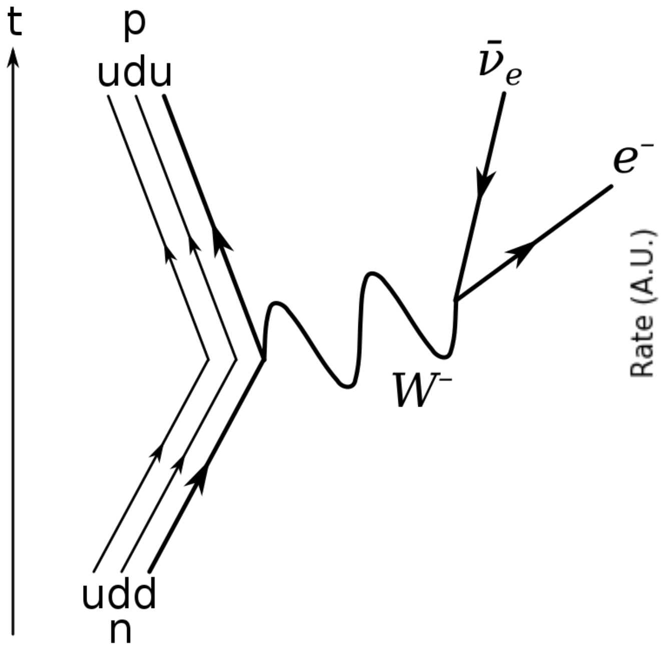
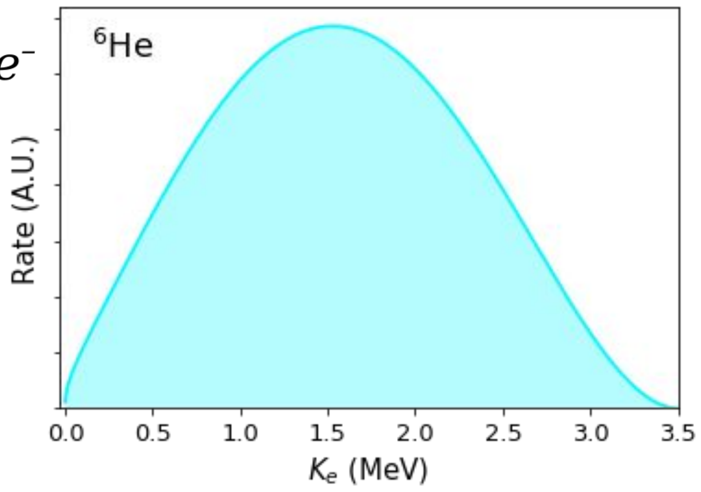
^{6}He-CRES

Beta decay, a historic physics laboratory



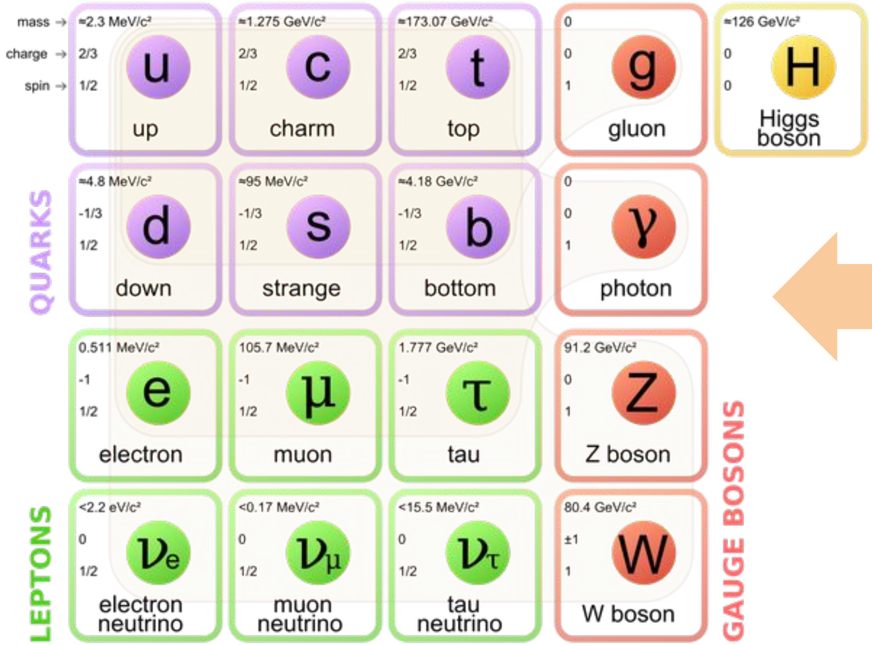
Or positron emission
$p \rightarrow n + e^+ + \nu_e$,
through W^+ boson



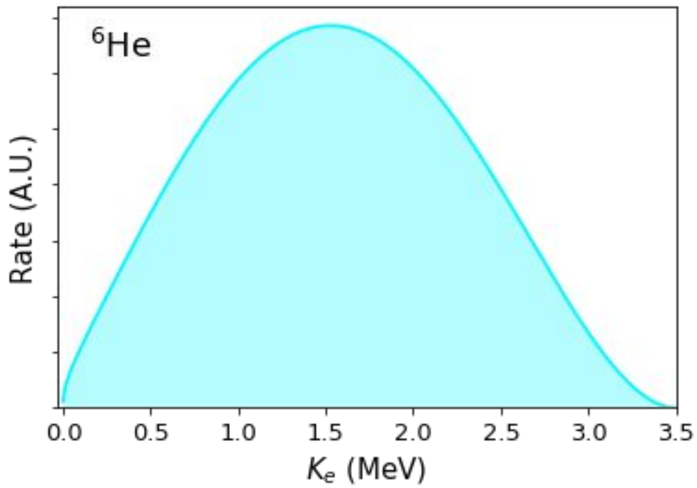
Pauli (1930) theorizes **neutrinos** to explain continuous energy spectrum and conservation of angular momentum in beta decay

Wu experiment (1956) discovers **parity violation** in beta decay

Beta decay: new physics?



?



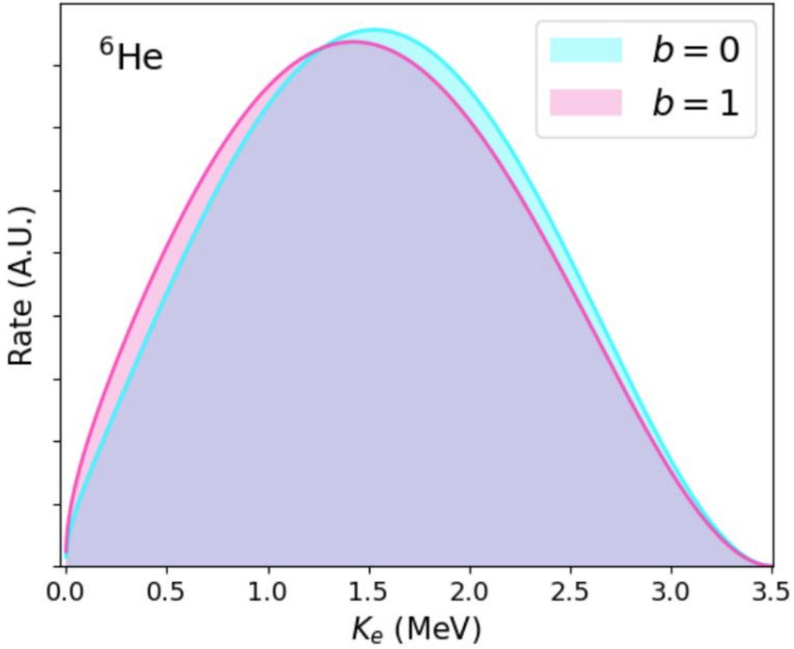
$$\frac{dN_{obs}}{dE} \approx \frac{dN}{dE}\left(1 + b_{Fierz}\frac{m_e}{E_e}\right)$$

Non-standard interactions

(*b_{Fierz}* exaggerated)

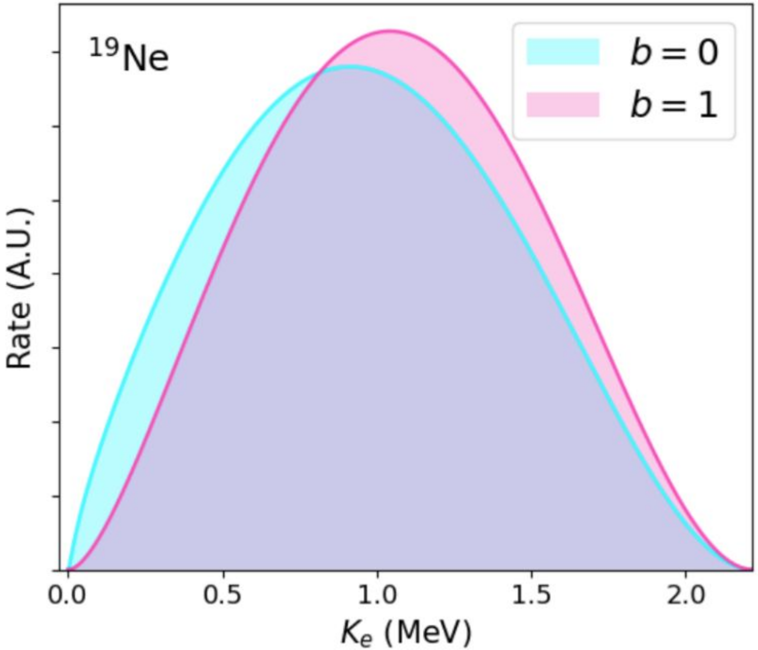
Beta decay: new physics?

$$^6\text{He} \rightarrow ^6\text{Li}^+ + e^- + \bar{\nu}_e$$



$$\frac{dN_{obs}}{dE} \approx \frac{dN}{dE}\left(1 + b_{Fierz}\frac{m_e}{E_e}\right)$$

$$^{19}\text{Ne} \rightarrow ^{19}\text{F}^- + e^+ + \nu_e$$

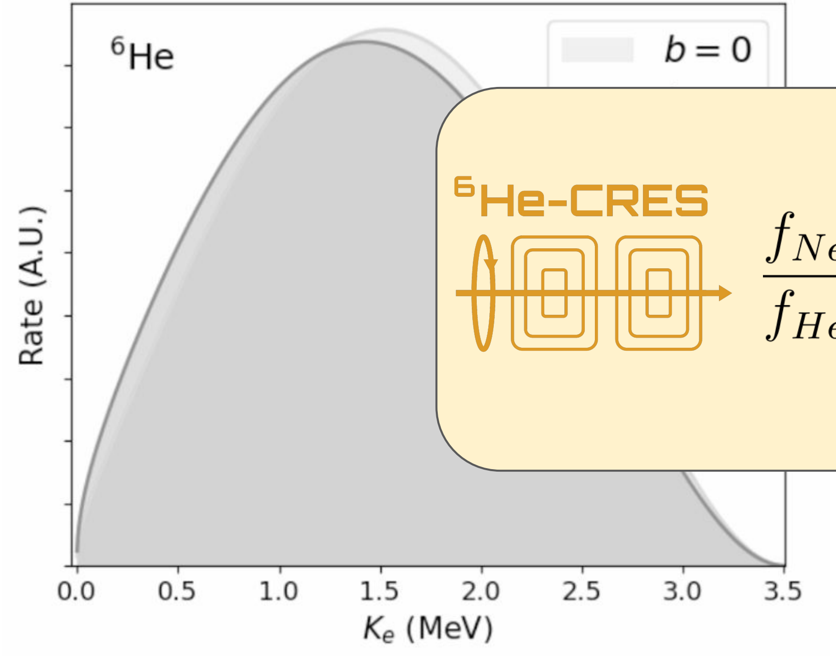


$$\frac{dN_{obs}}{dE} \approx \frac{dN}{dE}\left(1 - b_{Fierz}\frac{m_e}{E_e}\right)$$

(b_{Fierz} exaggerated)

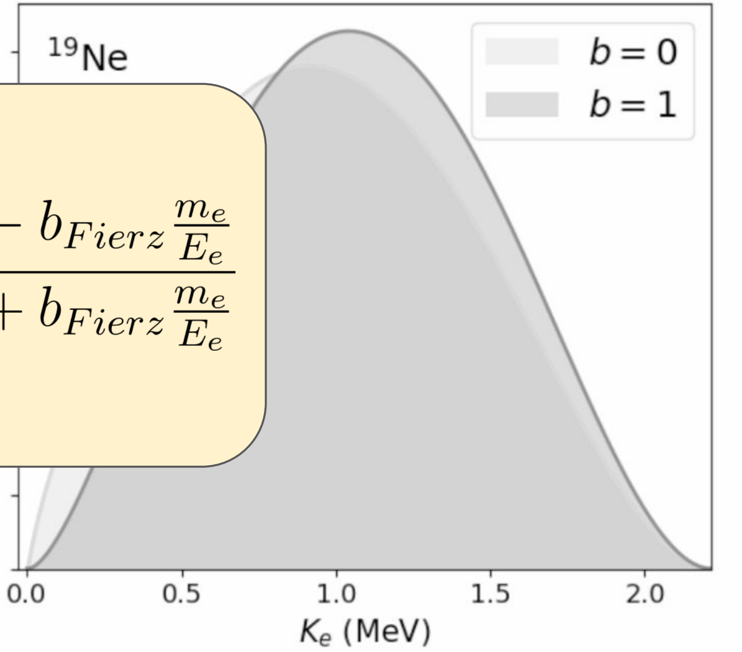
Beta decay: new physics?

$$^{6}\mathrm{He} \rightarrow {}^{6}\mathrm{Li}^{+} + e^{-} + \bar{\nu}_e$$



$$\frac{dN_{obs}}{dE} \approx \frac{dN}{dE}\left(1 + b_{Fierz}\frac{m_e}{E_e}\right)$$

$$^{19}\mathrm{Ne} \rightarrow {}^{19}\mathrm{F}^{-} + e^{+} + \nu_e$$



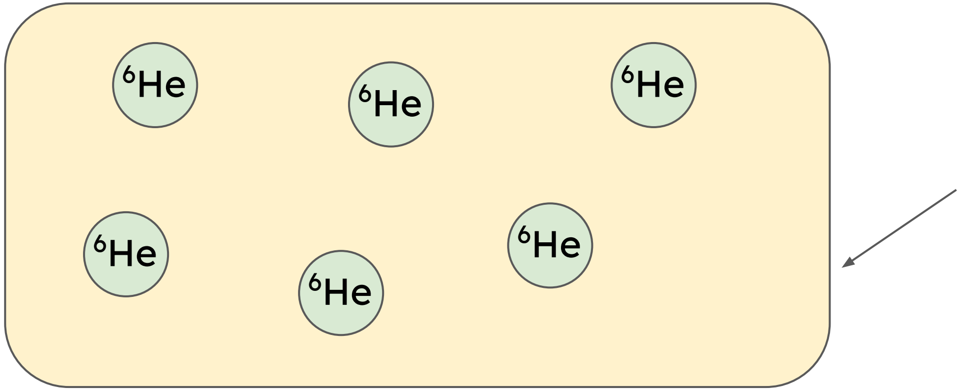
$$\frac{dN_{obs}}{dE} \approx \frac{dN}{dE}\left(1 - b_{Fierz}\frac{m_e}{E_e}\right)$$

^{6}He-CRES

$$\frac{f_{Ne}}{f_{He}} \approx \frac{1 - b_{Fierz}\frac{m_e}{E_e}}{1 + b_{Fierz}\frac{m_e}{E_e}}$$

CRES: a new way to measure β energy

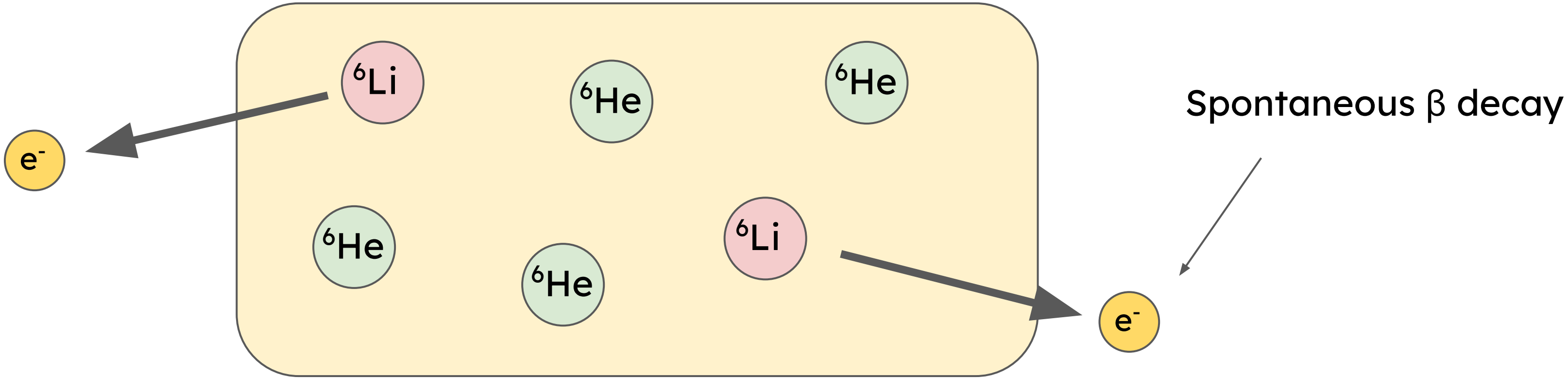
Cyclotron **R**adiation **E**mission **S**pectroscopy



Decay cell
Filled with beta emitting isotope gas (from CENPA accelerator)

CRES: a new way to measure β energy

Cyclotron **R**adiation **E**mission **S**pectroscopy



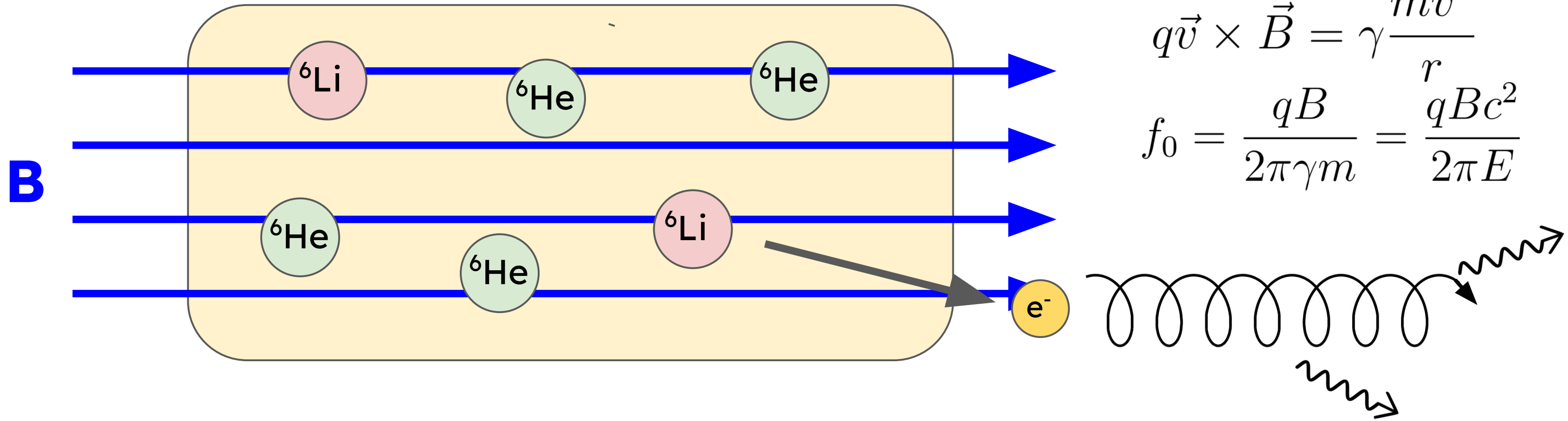
CRES: a new way to measure β energy

Cyclotron **R**adiation **E**mission **S**pectroscopy

Cyclotron motion

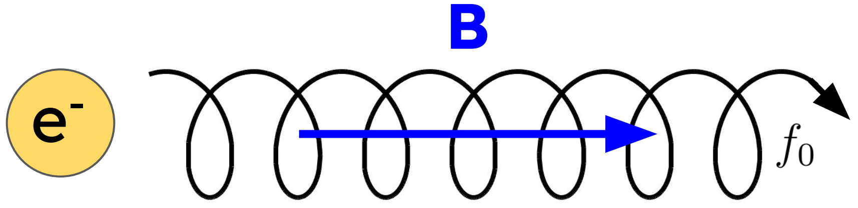
$$q\vec{v} \times \vec{B} = \gamma \frac{mv^2}{r}$$

$$f_0 = \frac{qB}{2\pi\gamma m} = \frac{qBc^2}{2\pi E}$$



CRES: a new way to measure β energy

PROJECT 8



"Never measure anything but frequency!"
- Arthur Schawlow

Measuring neutrino mass!

narrow-band

↓

broad-band

$$f_0 = \frac{qBc^2}{2\pi E} \approx 18\text{-}20 \text{ GHz (RF)}$$

β energy measurement from frequency!

Advantages:

- Avoid material losses (backscattering, bremsstrahlung)
- Resolution determined by FFT

Disadvantages:

Low power

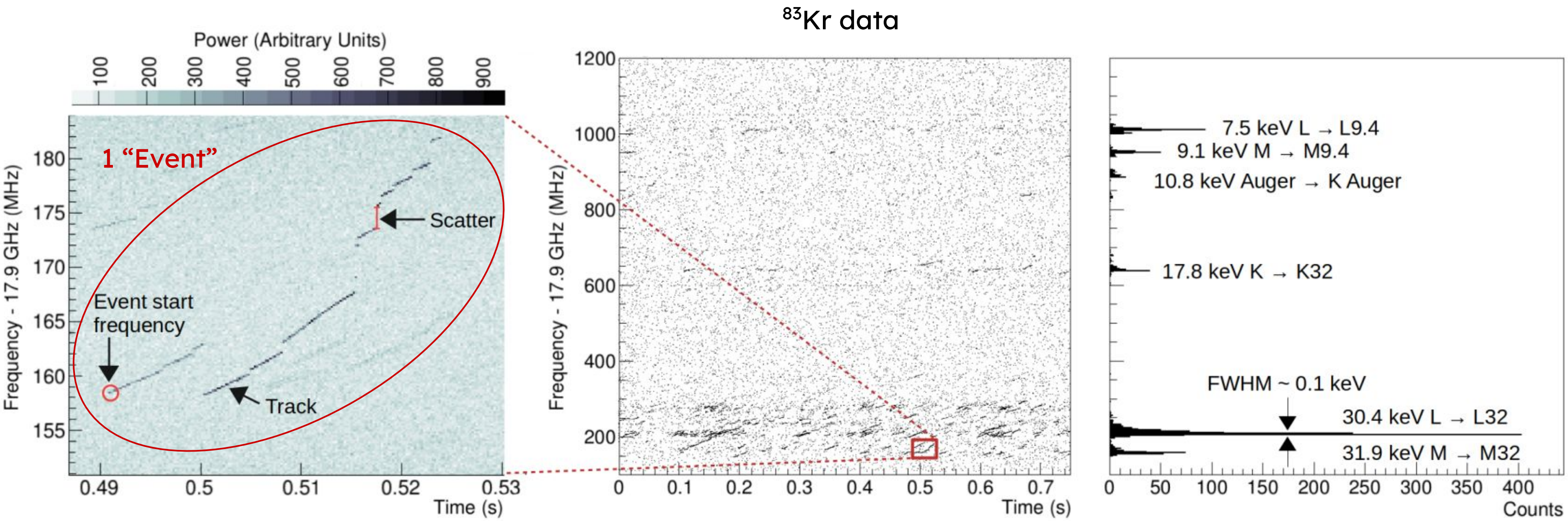
$$P \propto \frac{2}{3}\frac{e^2\omega_c^2 p_\perp^2}{m_e^2 c^3}$$

$$\sim \mathcal{O}(10 \text{ fW})$$

^{6}He-CRES

Probing fundamental symmetries!

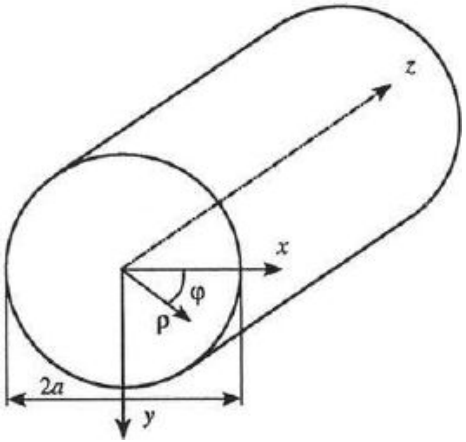
CRES events look like frequency sweeps in time

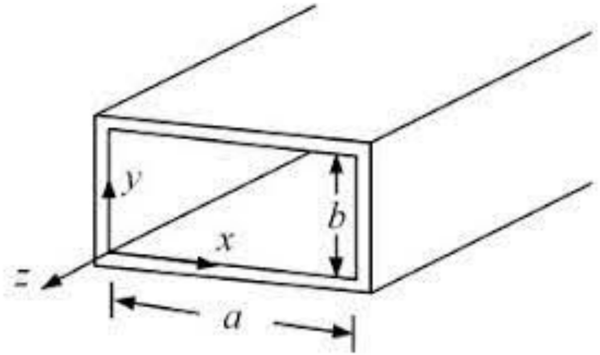


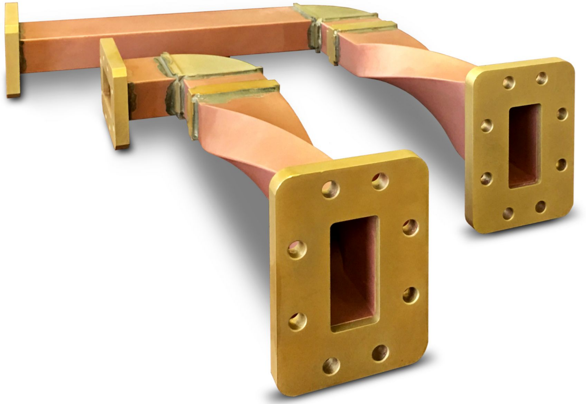
Byron et al. (2023)

FFT amplitude of 6.8 μs "slices" of digitized data vs. time

Interlude I: Important waveguide concepts







$$E, B \propto e^{i(\omega t - \beta z)}$$

Propagation constant $\beta = \frac{\omega}{v_p}$

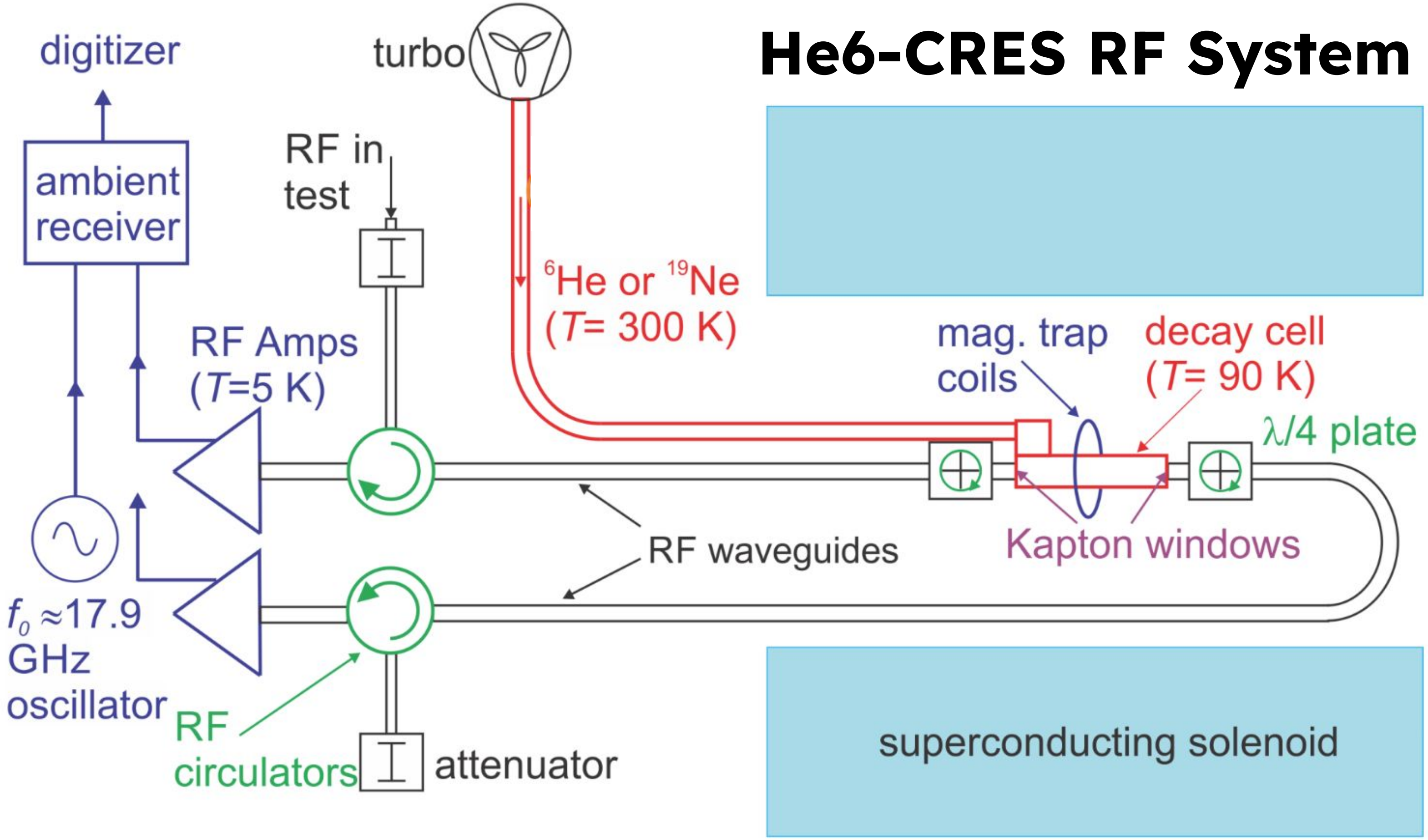
$$\beta = \sqrt{k^2 - k_c^2}$$

TE and TM waves, modes

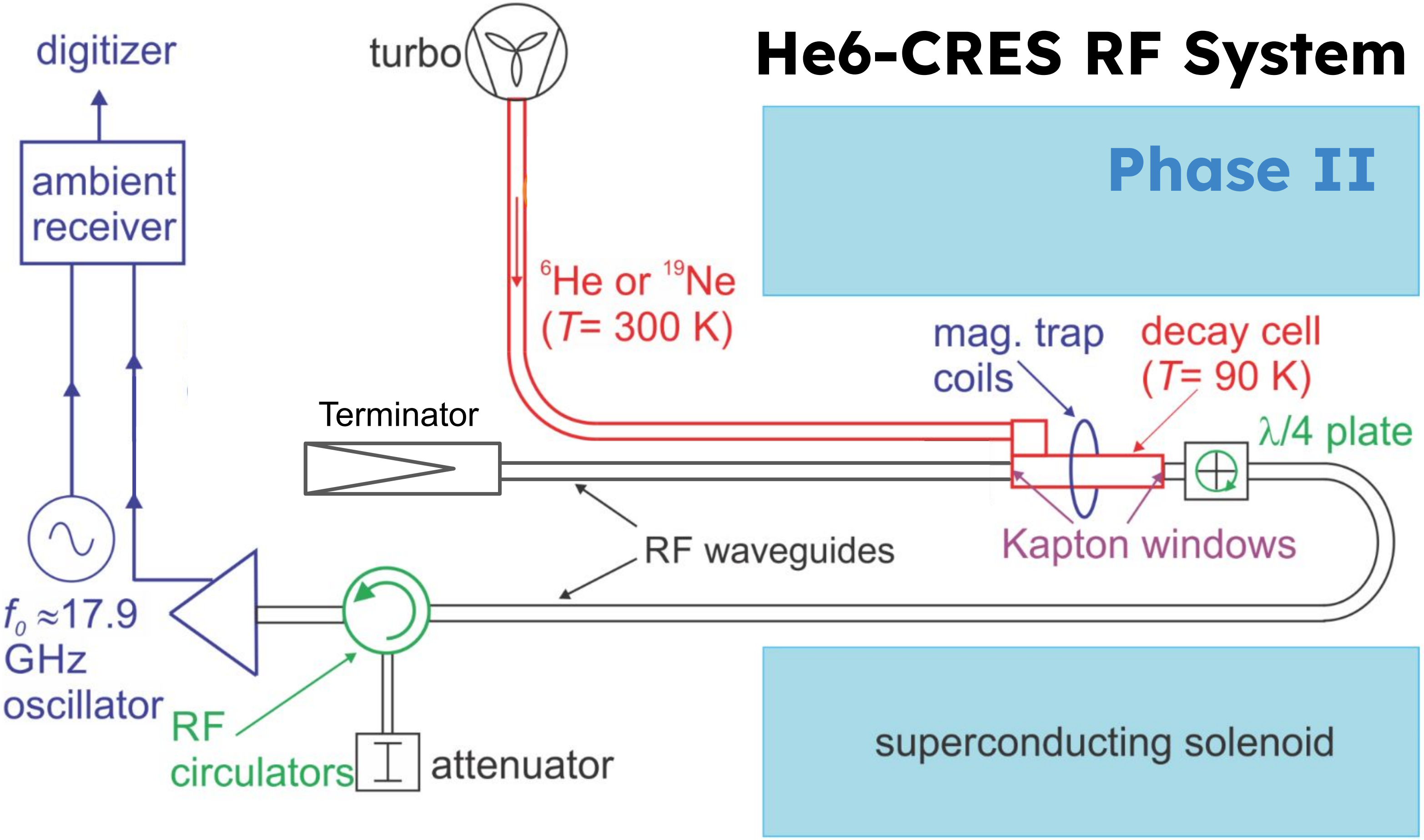
Wave number $k = \frac{\omega}{c}$

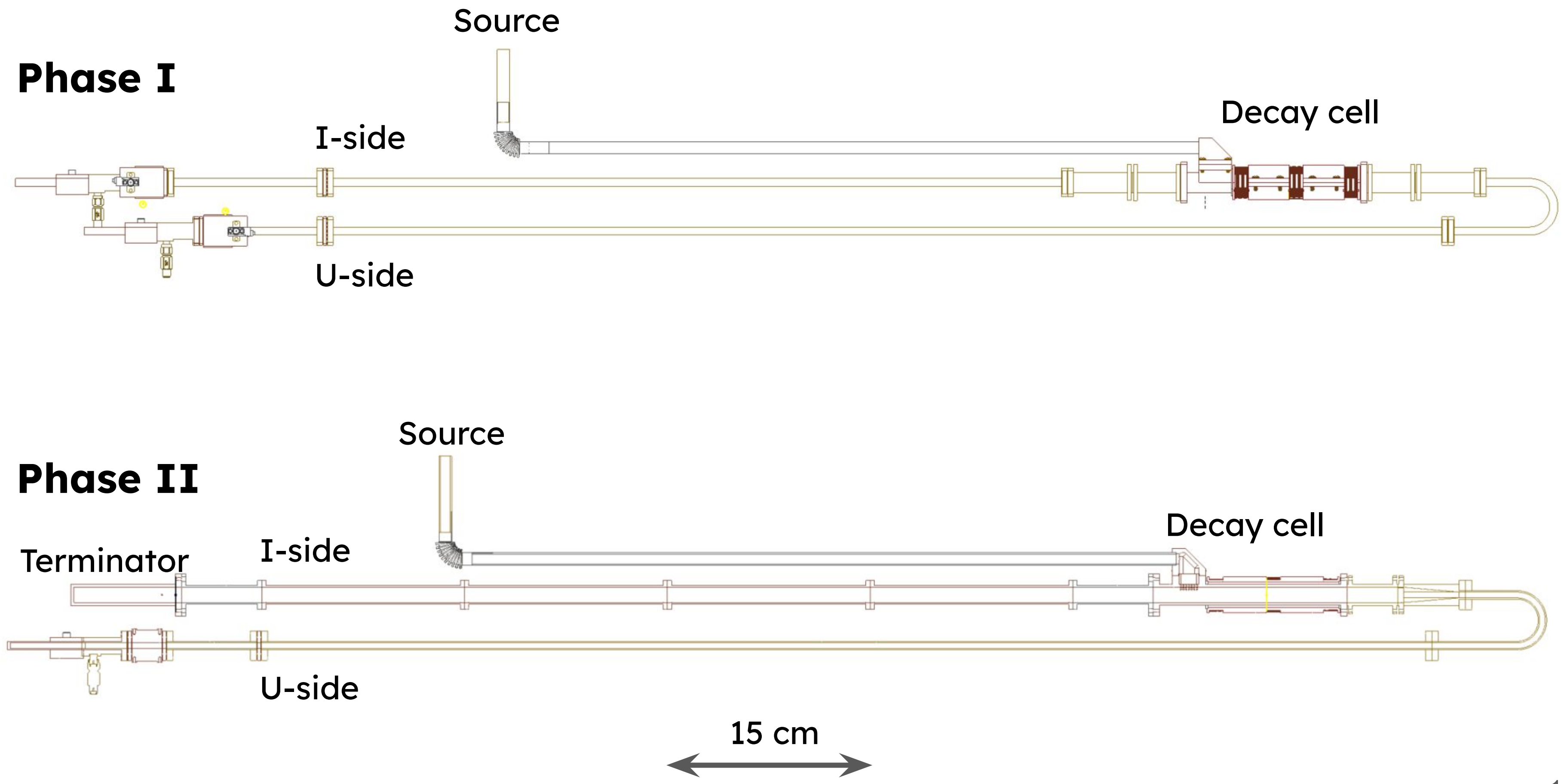
$$f_c = \frac{k_c c}{2\pi}$$

He6-CRES RF System



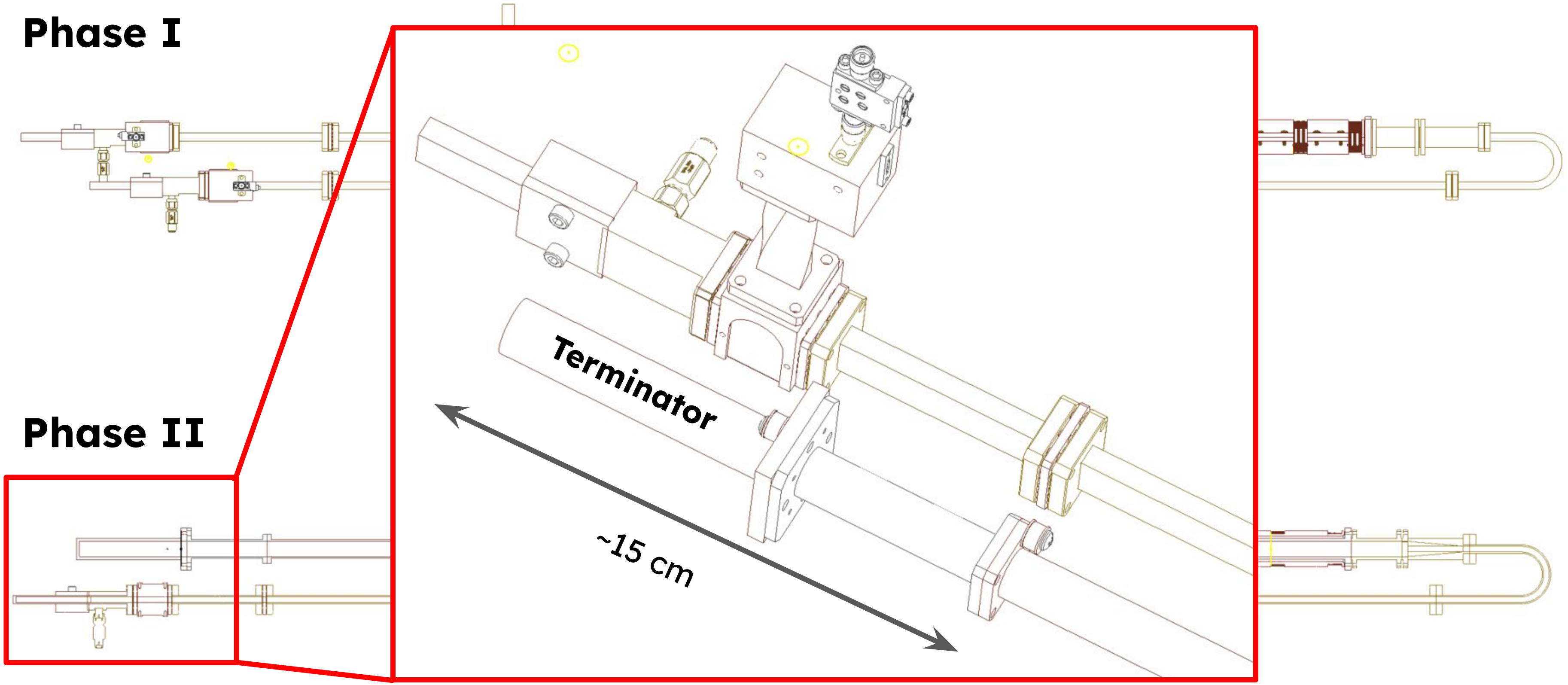
He6-CRES RF System



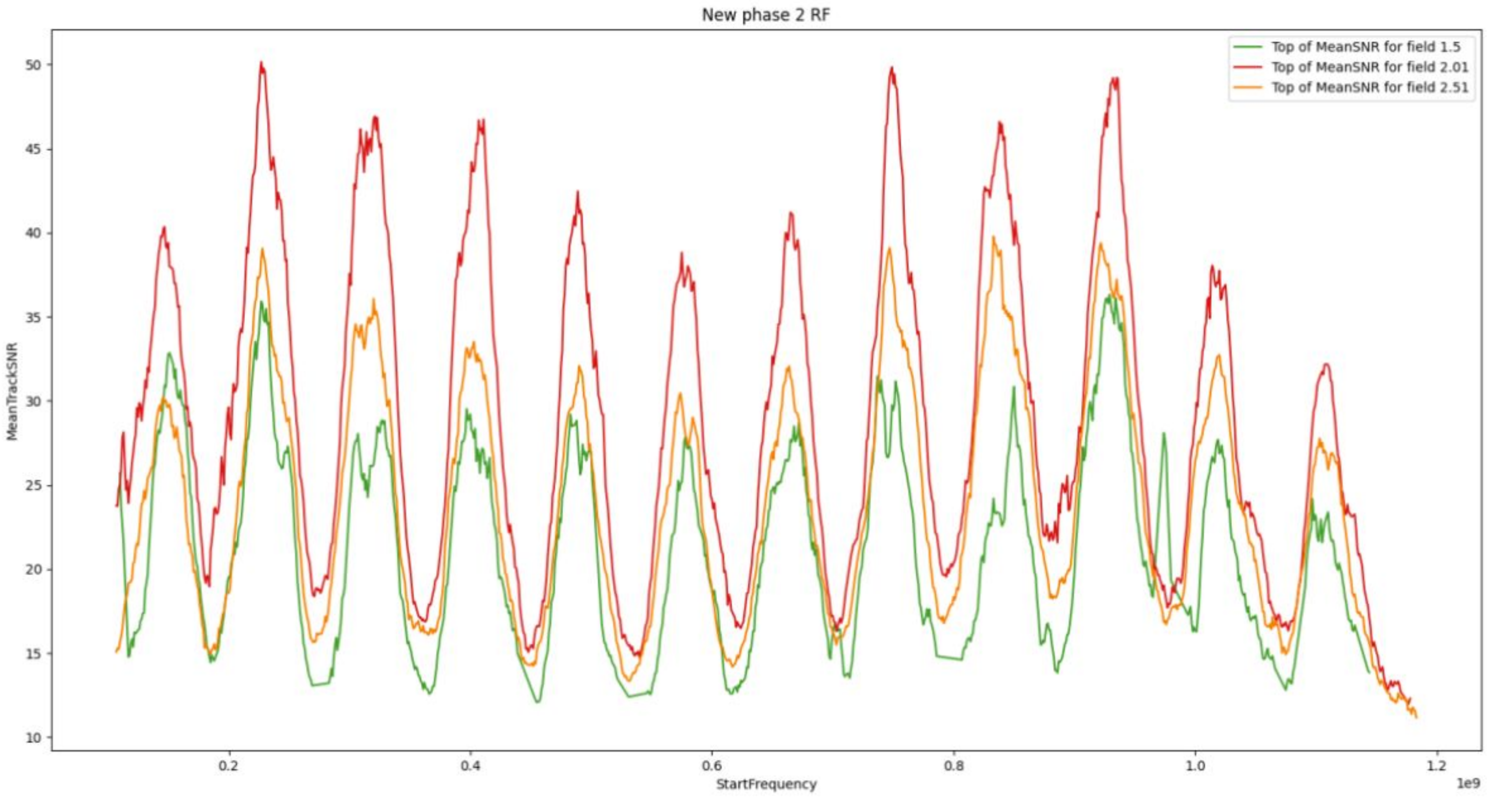

Source
Phase I
I-side
Decay cell
U-side
Source
Phase II
Decay cell
Terminator
I-side
U-side
15 cm

Phase I

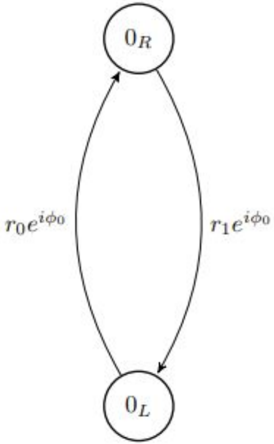
Phase II



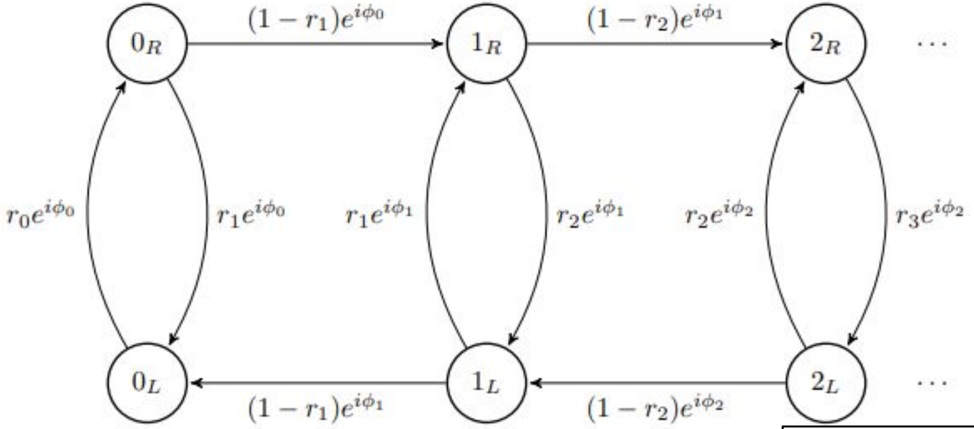
The issue: frequency dependent SNR oscillations



Modeling reflections with Markov chains



2-mirror
Fabry-Perot



N-mirror
Fabry-Perot

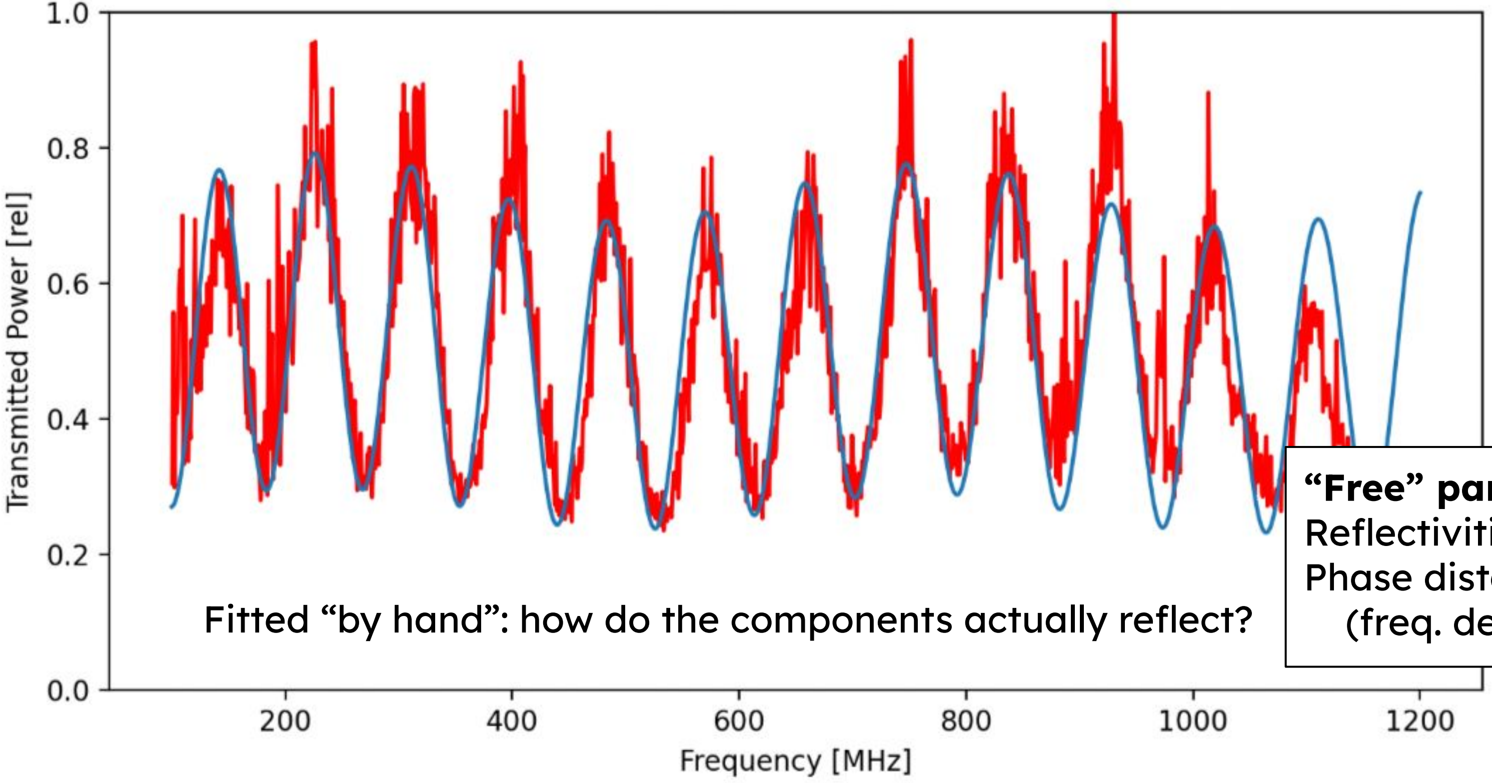
"Free" parameters:
Reflectivities r_n
Phase distances φ_n
(freq. dependence)

$R^k_{i,j}$ is the transition probability between states i and j after k steps

Overall transition probability from geometric series: $\sum_{k=0}^{\infty} \mathbf{R}^k = (\mathbf{I} - \mathbf{R})^{-1}$

From Nick Buzinsky

Modeling reflections with Markov chains

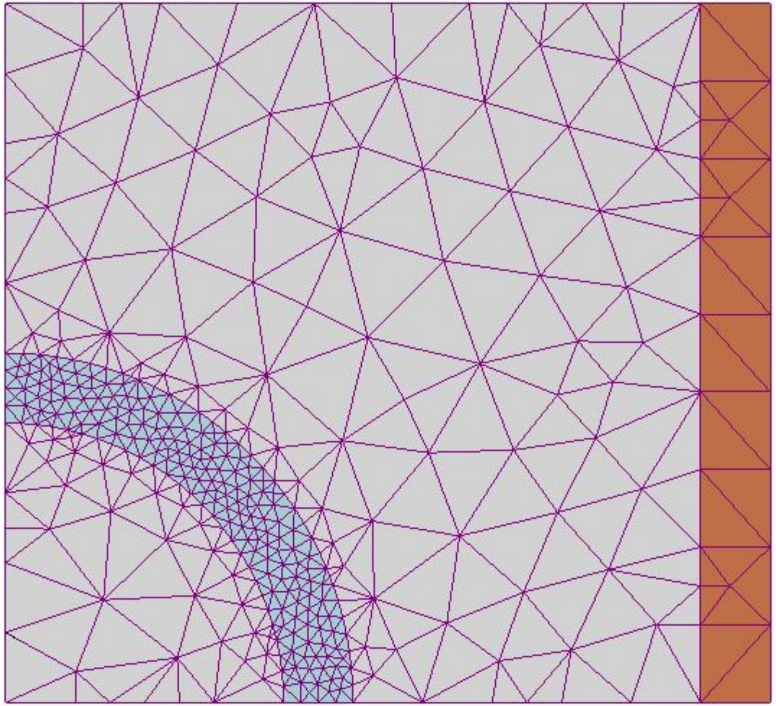


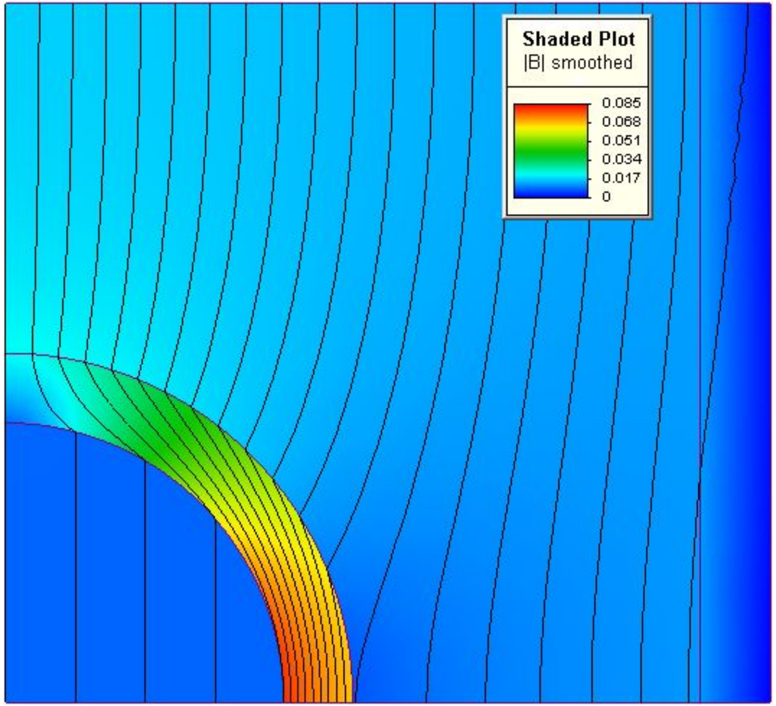
Fitted "by hand": how do the components actually reflect?

"Free" parameters:
Reflectivities r_n
Phase distances φ_n
(freq. dependence)

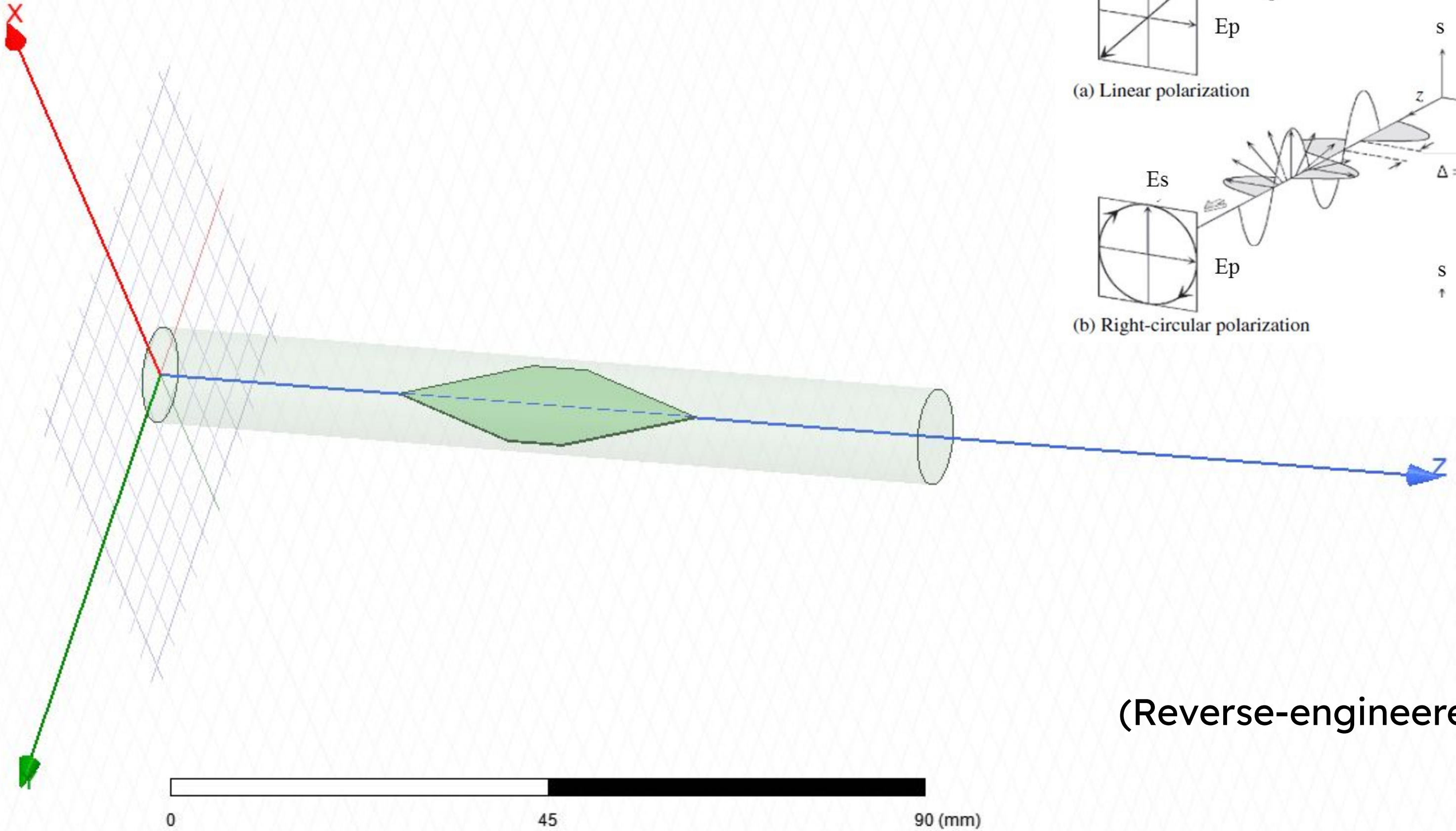
From Nick Buzinsky

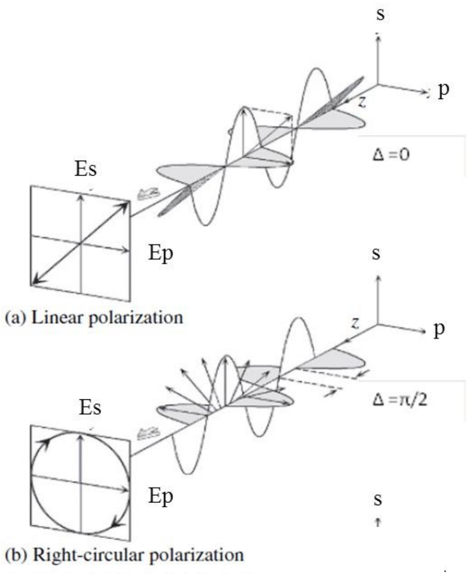
Finite Element Analysis





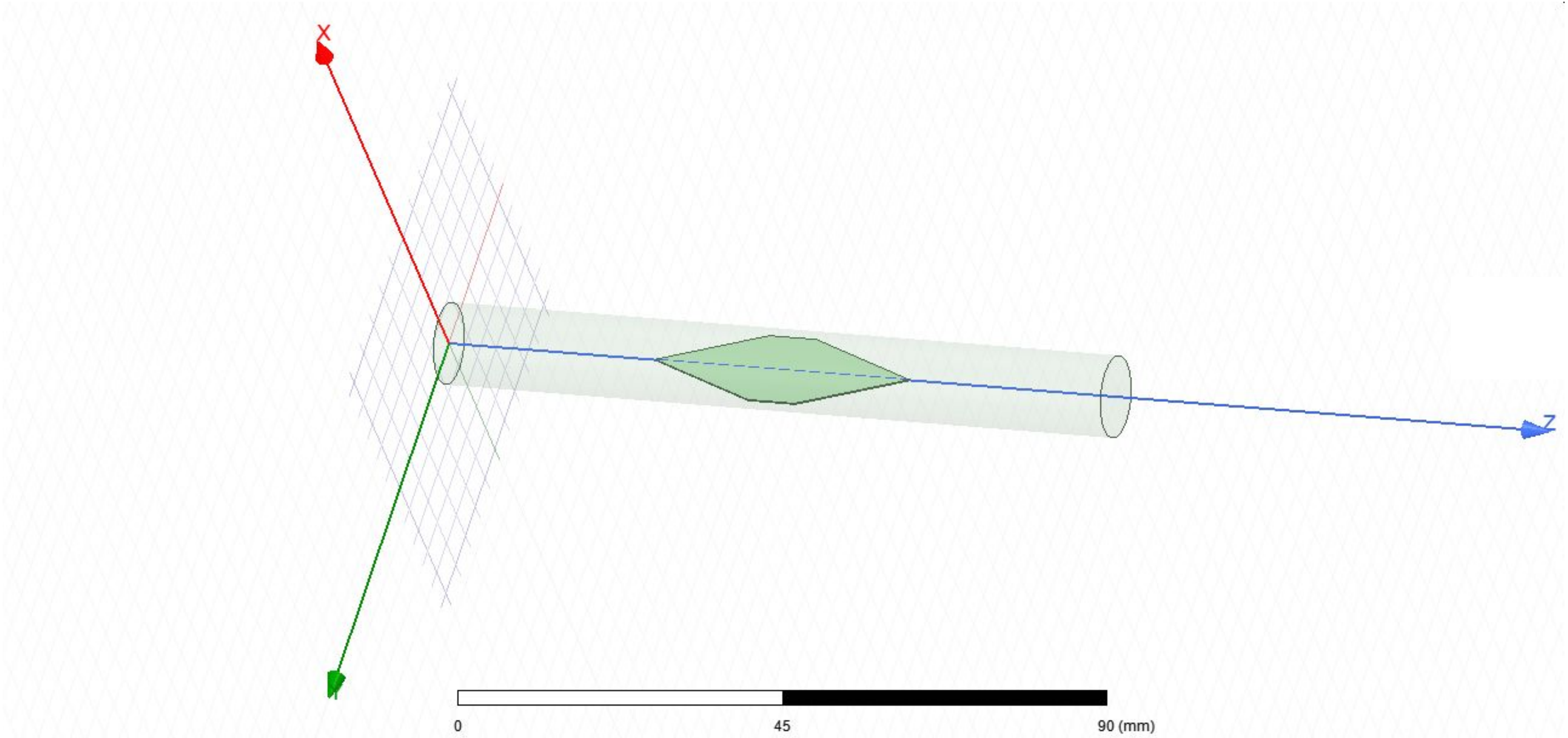
Circular-to-linear polarizer



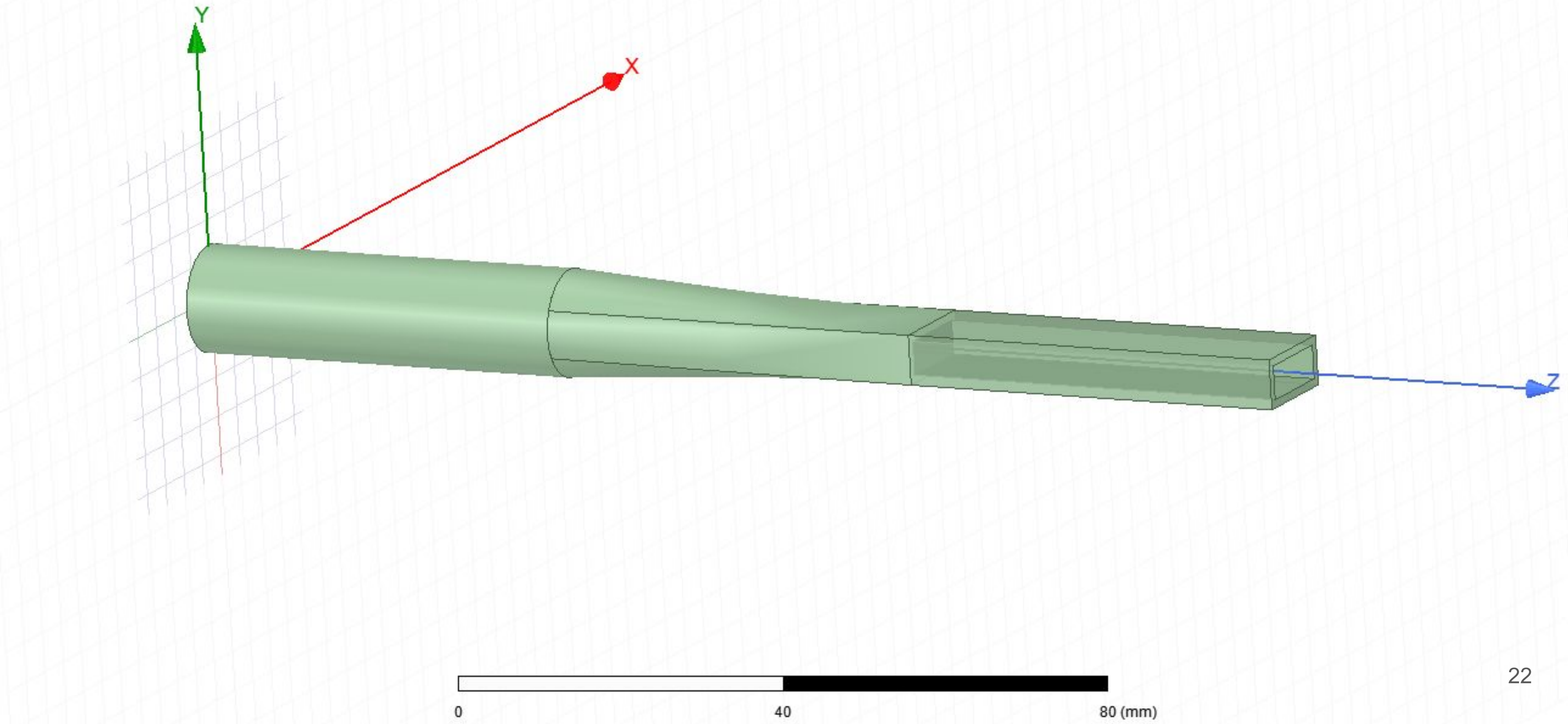


(Reverse-engineered)

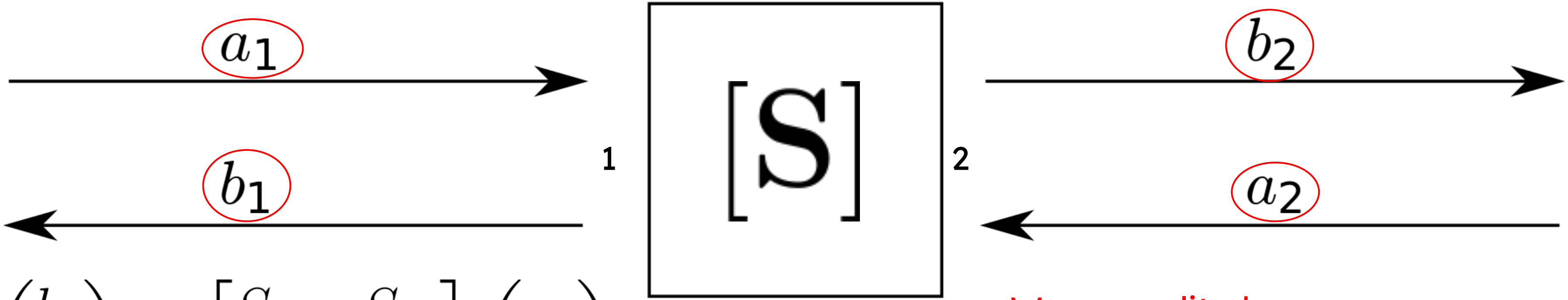
Circular-to-linear polarizer



Circular to rectangular waveguide adapter



Interlude II: S-parameters



$$\begin{pmatrix} b_1 \\ b_2 \end{pmatrix} = \begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} \begin{pmatrix} a_1 \\ a_2 \end{pmatrix}$$

Wave amplitudes
a_n: incident on port n
b_n: reflected from port n

S_{ij}: how much an incident wave at port *j* contributes to a wave leaving port *i*
Used to measure reflections **and** transmissions

S_{11}: **reflection at port 1** when $a_2 = 0$
S_{21}: **transmission from 1 to 2**, $a_2 = 0$

S_{12}: **transmission from 2 to 1**, $a_1 = 0$
S_{22}: **reflection at port 2** when $a_2 = 0$

Interlude II: n-port S-parameter generalization

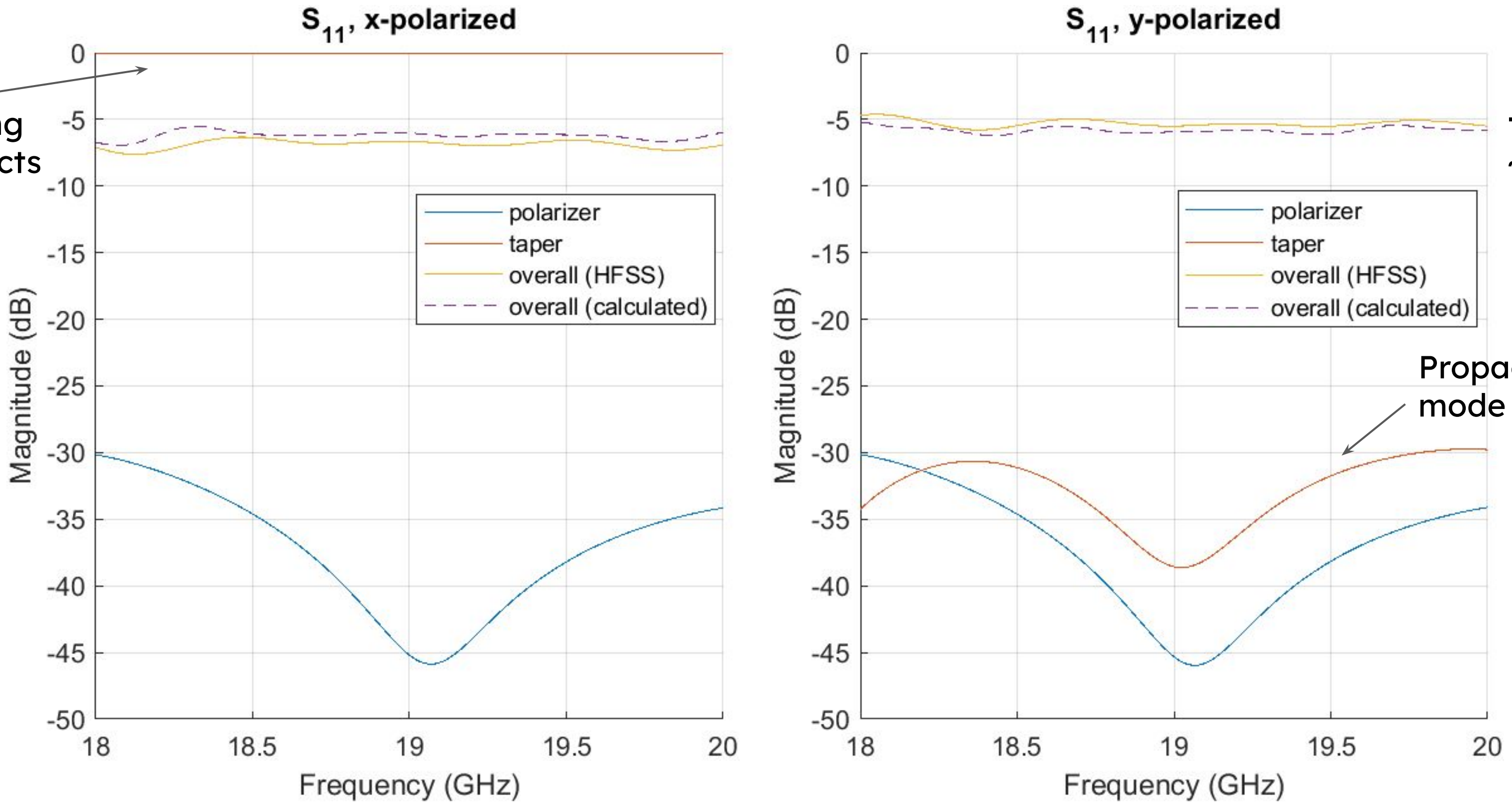
$$\begin{pmatrix} b_1 \\ \vdots \\ b_n \end{pmatrix} = \begin{pmatrix} S_{11} & \cdots & S_{1n} \\ \vdots & \ddots & \vdots \\ S_{n1} & \cdots & S_{nn} \end{pmatrix} \begin{pmatrix} a_1 \\ \vdots \\ a_n \end{pmatrix}$$

S_{ij} : how much an incident wave at port *j* contributes to a wave leaving port *i*
Used to measure reflections **and** transmissions

S_{ii}: **reflection at port i** (all $a_{k \neq i} = 0$)
S_{ij}: **transmission from j to i,** (all $a_{k \neq j} = 0$)

Polarizer and taper reflections

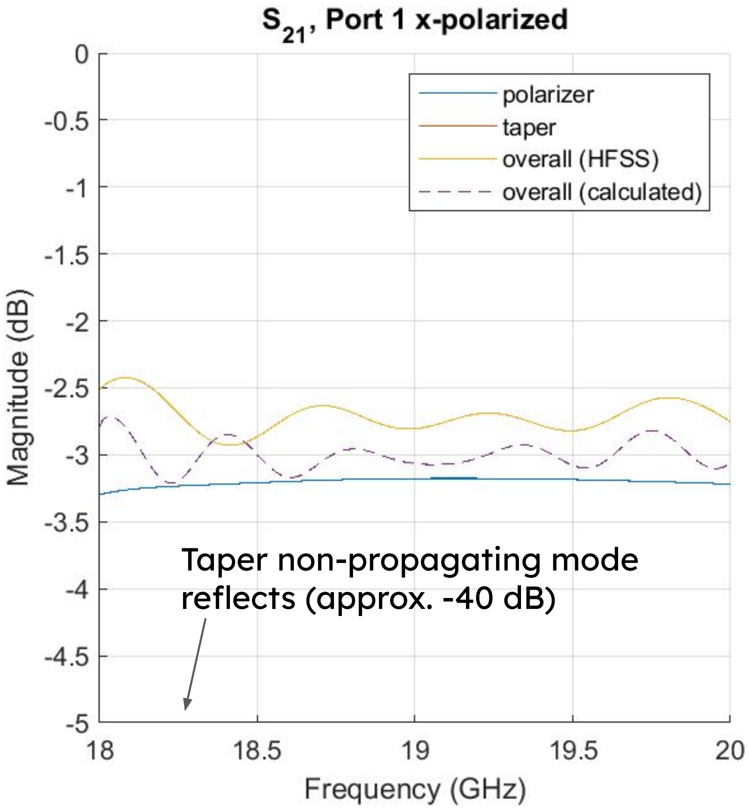
Non-propagating mode reflects

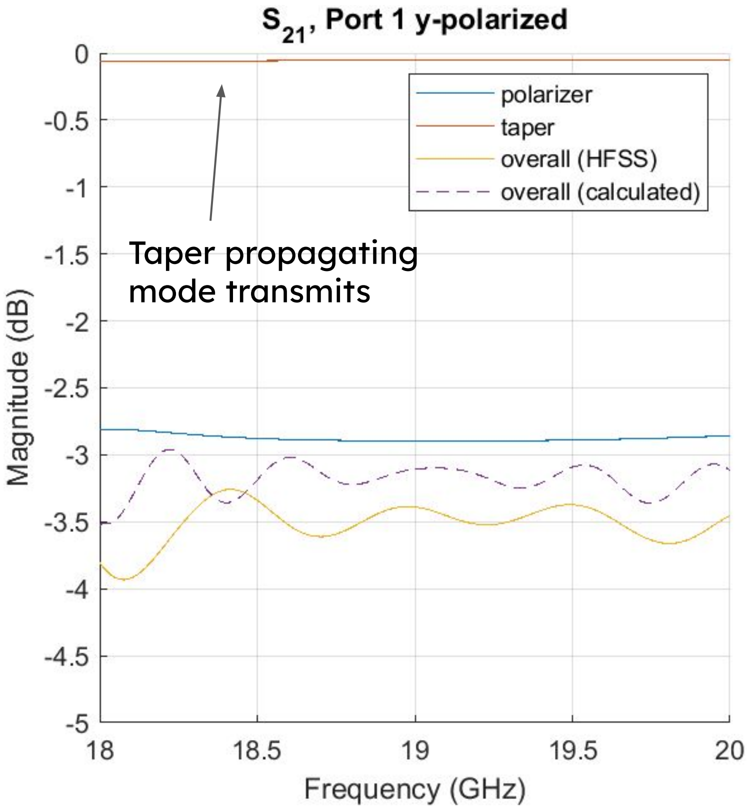


-6 dB is ~¼ power

Propagating mode transmits

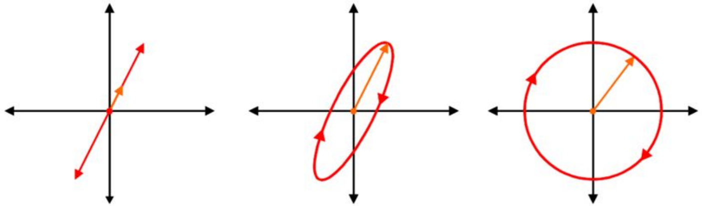
Polarizer and taper transmission

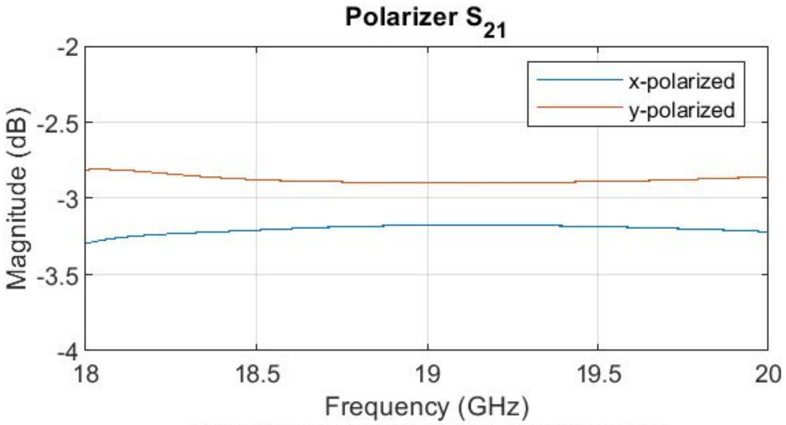


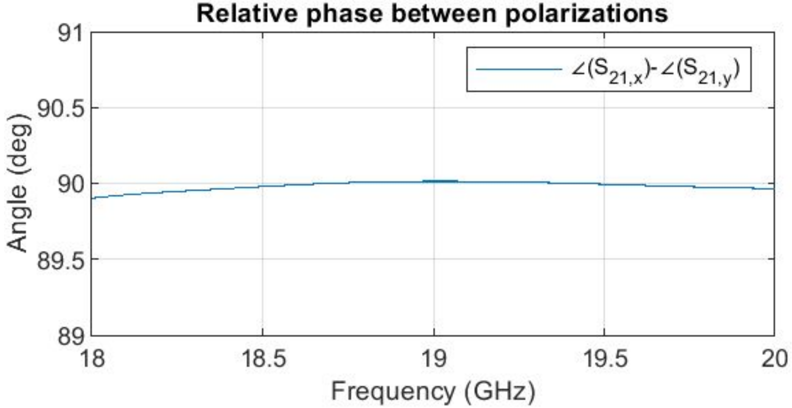


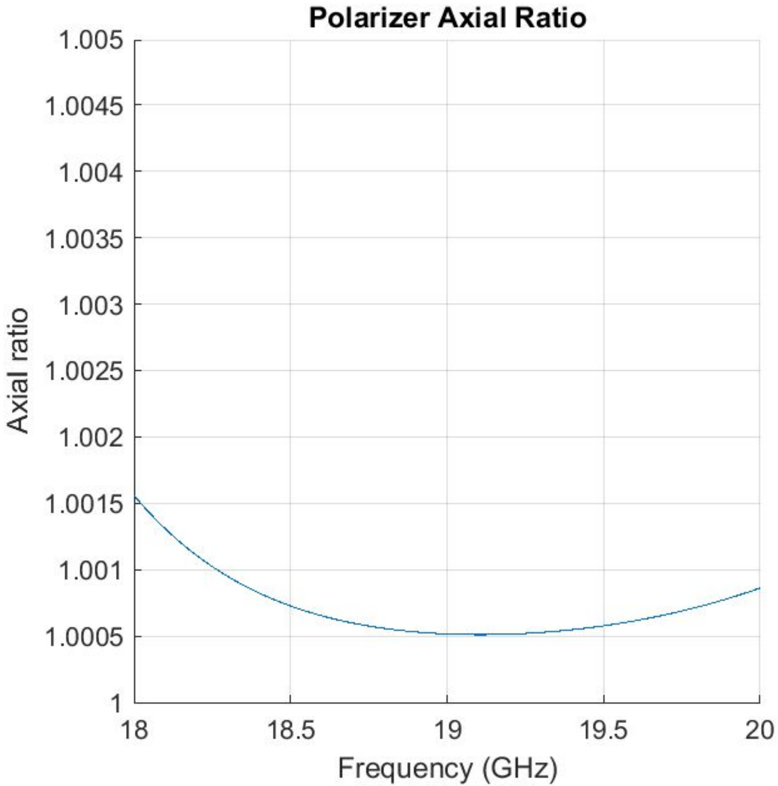
-3 dB is ~½ power

Polarization quality

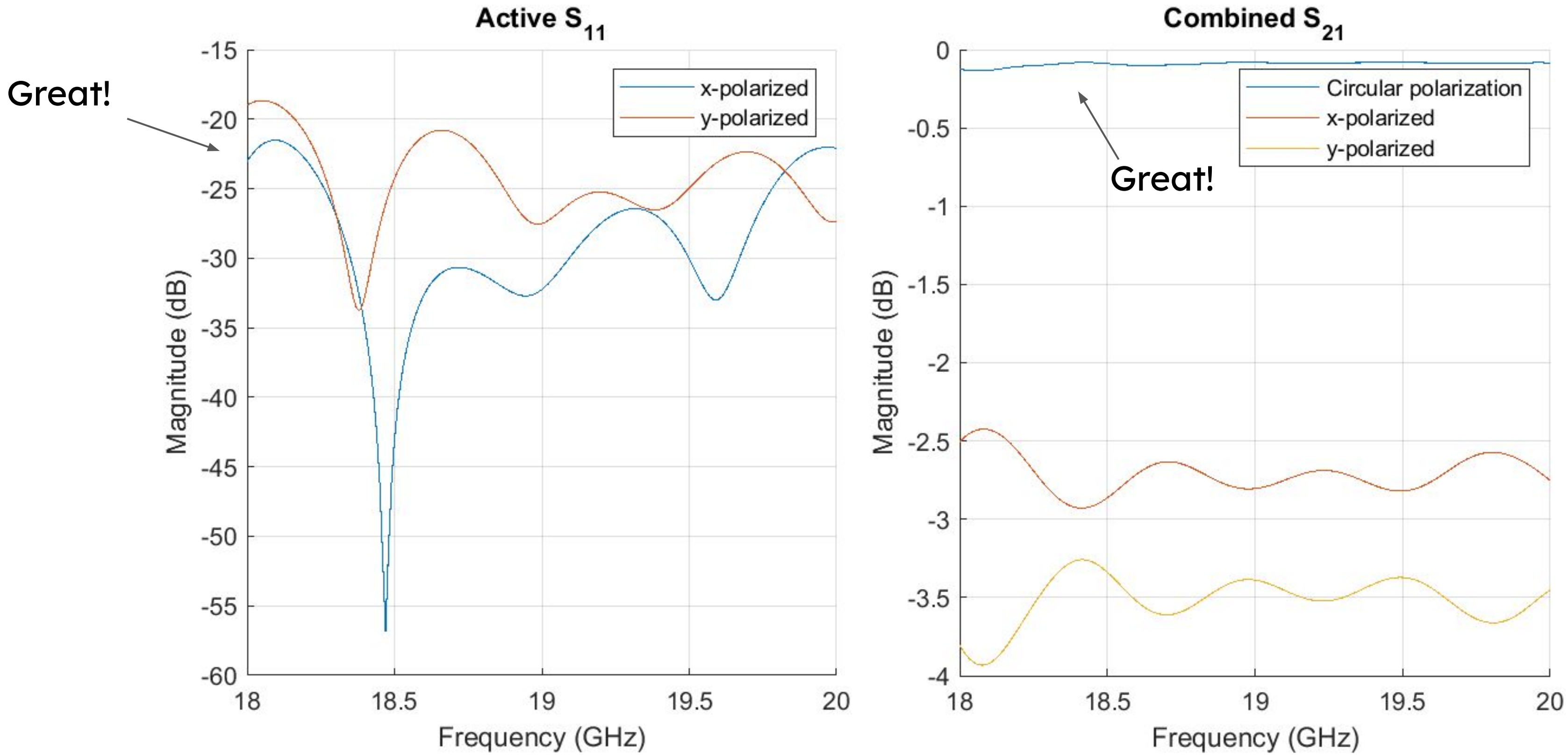




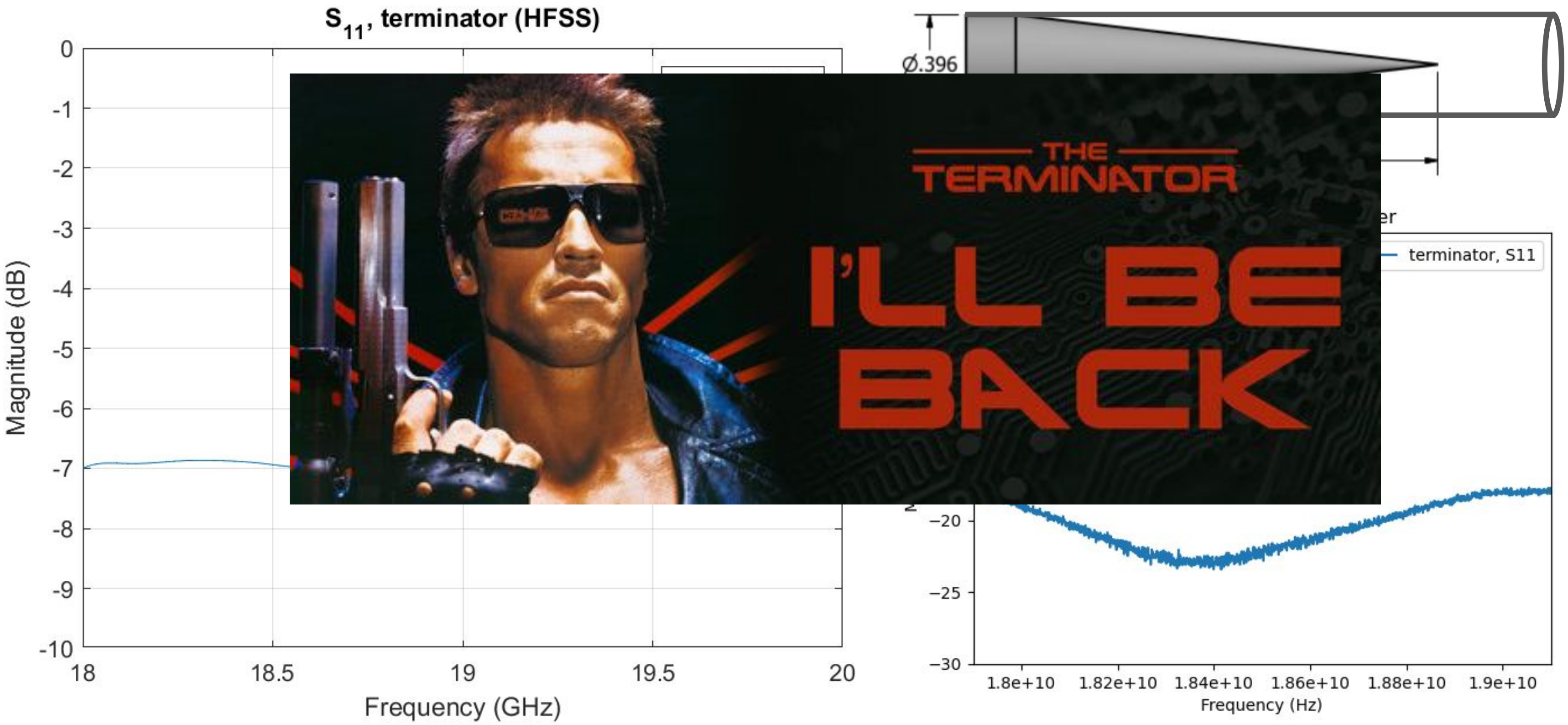




Transmitting/reflecting circularly polarized waves



Terminator that doesn't terminate in simulation



Project summary

- ★ Big picture: explain observed SNR oscillations in CRES data
- ★ Smaller goal: FEM simulation of waveguide components in RF system
- ★ Developed parametrized & tunable models of polarizer, circular-to-rectangular transition, kapton windows
- ★ Explored chaining S-parameters of individual components and compared to numerical results, reducing simulation load
- ★ Future work: simulating terminator and comparing to measurements

Acknowledgements

Dr. Alejandro Garcia, PI

He6-CRES collaboration members

CENPA faculty, students, and staff

Dr. Gray Rybka and Dr. Arthur Barnard, REU Co-directors

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My fellow 2023 Physics REU participants!

NSF

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Center for Experimental
Nuclear Physics and Astrophysics
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^{6}He-CRES

Extra slides

Other open questions in He6-CRES

Tracks from below

Sidebands

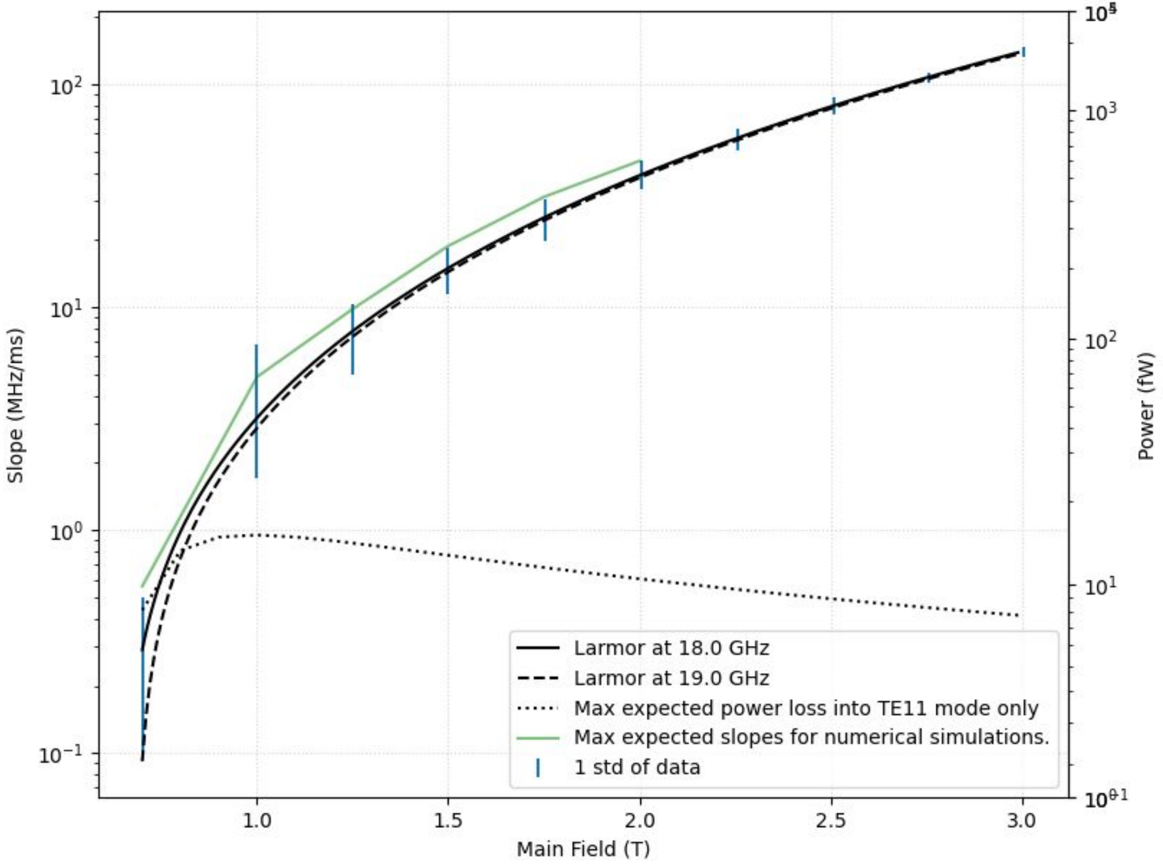
Scattering and vacuum quality

Event reconstruction algorithms

Beta monitor stability

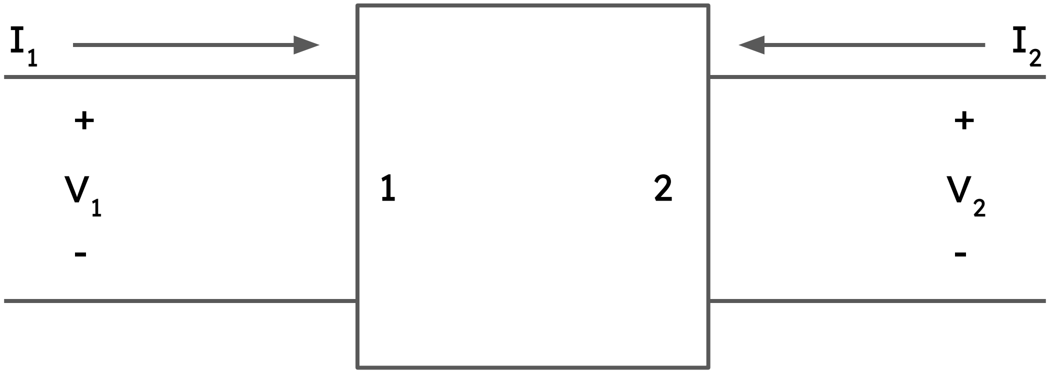
Unknown mass 19 signature

Discrepancy between run 1 and 2 data



Slope (MHz/ms)
Power (fW)
Main Field (T)
Larmor at 18.0 GHz
Larmor at 19.0 GHz
Max expected power loss into TE11 mode only
Max expected slopes for numerical simulations.
1 std of data

Interlude II: 2-port networks, z-parameters



General two-port network

$$\begin{pmatrix} V_1 \\ V_2 \end{pmatrix} = \begin{bmatrix} Z_{11} & Z_{12} \\ Z_{21} & Z_{22} \end{bmatrix} \begin{pmatrix} I_1 \\ I_2 \end{pmatrix} = \mathbf{Z} \begin{pmatrix} I_1 \\ I_2 \end{pmatrix}$$