Beam breakup and high order modes instabilities studies for energy recovery linear accelerators (ERLs)

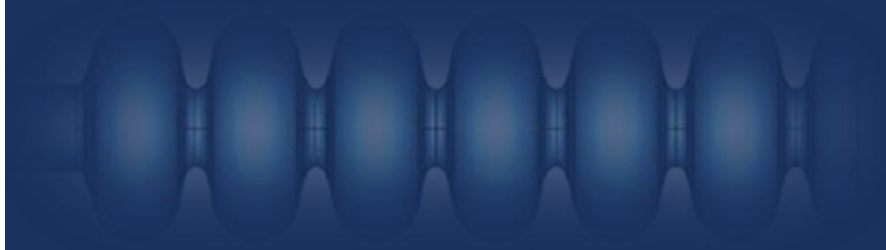
Sanae Samsam (INFN-Milano)

Sapienza Università di Roma

Department of Physics

Accelerator Physics

PhD school Seminar



Supervisor:
Luca Serafini

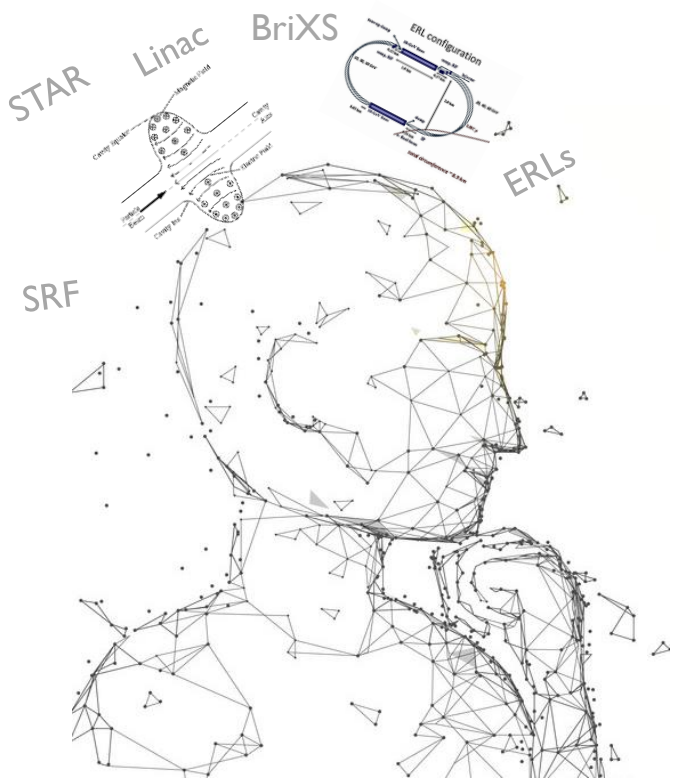
Outline

I. Objectives and Introduction

II. Theory and HOM evolution over very long time-scales

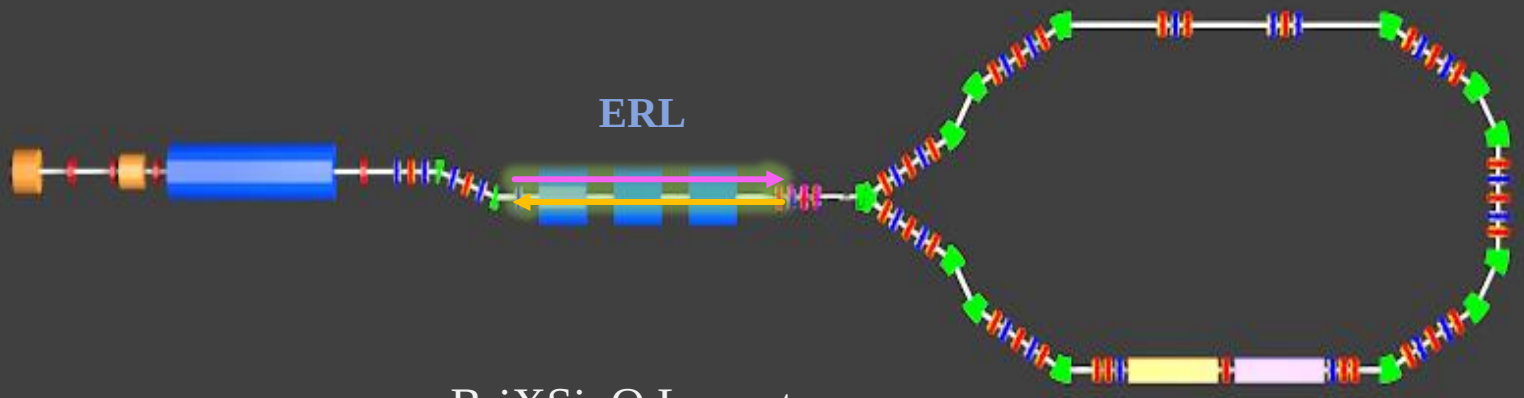
III. Summary and outlook

OBJECTIVES



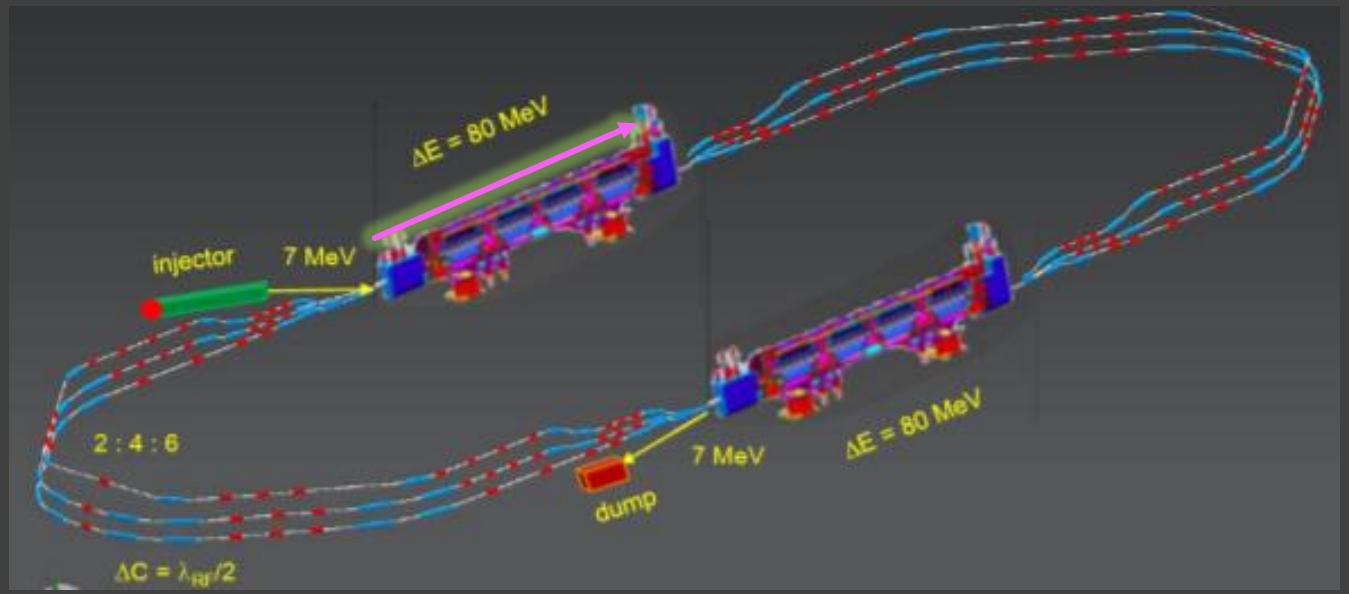
- Electron beams with large average current (mA) and high repetition rate (GHz-class)
- Linacs with energy recovery → ERL
- Interaction of electron beams with accelerator cavities (HOM induced fluctuations and instabilities…)
- BriXSinO

I. Introduction/ERLs



BriXSinO Layout

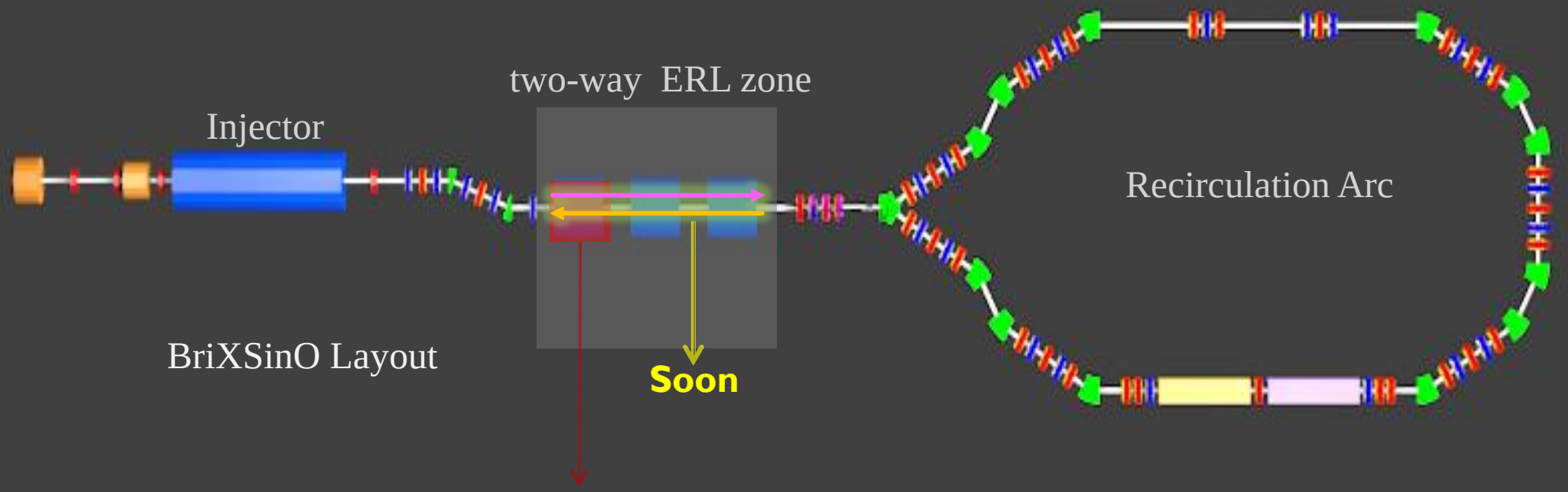
- Operating mode: **CW**
- High average current 5mA
- High repetition rate 100 MHz
- Two-pass two-way acceleration mode

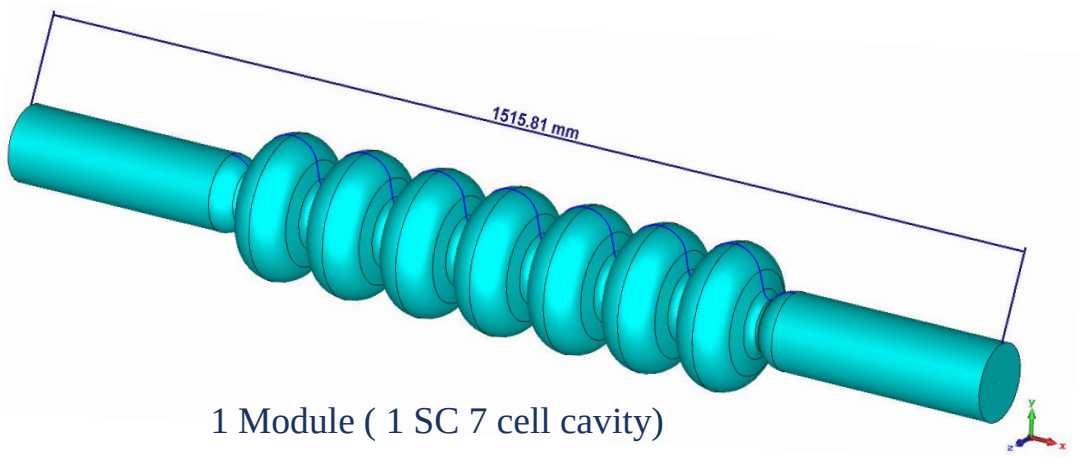


PERLE layout

- One way ERL

I. Introduction/ERLs





1 Module (1 SC 7 cell cavity)

HOMEN main parameters

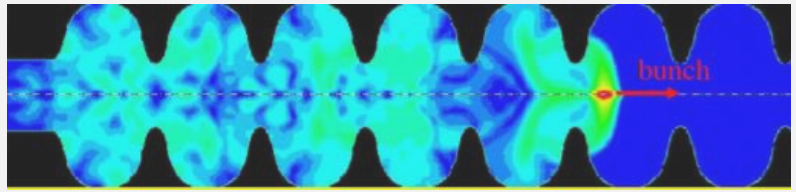
*(**H**igh **O**rder **M**ode Evolution based on **En**ergy badget)*

- ✓ Dissipation Power (on the cavity walls) : $\frac{\omega_n U_n}{Q_{L_n}}$ = 0.2822 kW
- ✓ Klystron Power : P_{kly} = 11.896 kW
- ✓ Average Power transferred to bunch acceleration $\frac{q_i V_{acc_{i,n}}}{\tau_{cav_i}} \approx$ 11.618 kW

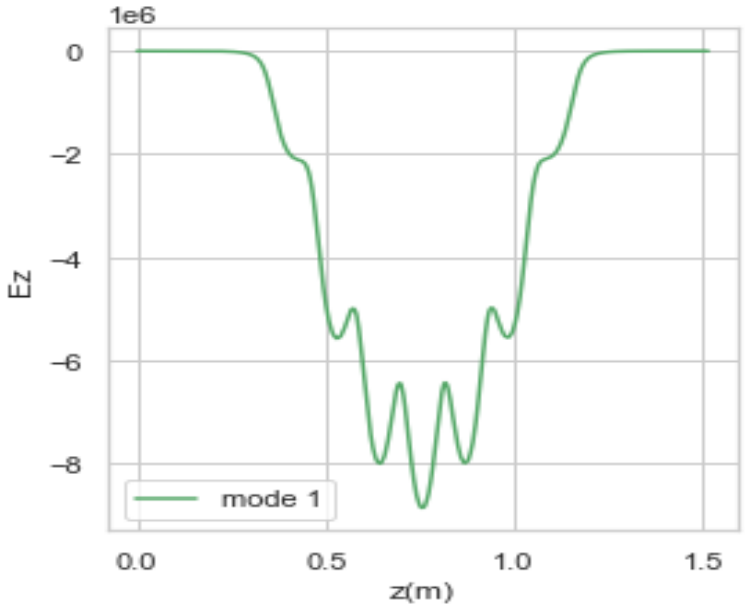
Fundamental mode (n=1)

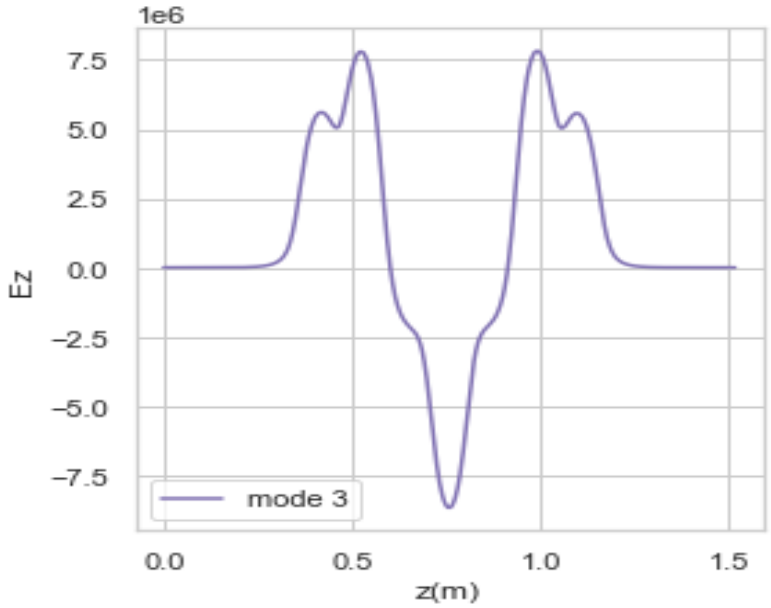
- ✓ Power lost by the beam (wake−field) to the the HOM according to the proper $k_{loss,n}$: $\frac{q_i^2 k_{loss,n}}{\tau_{cav_i}}$

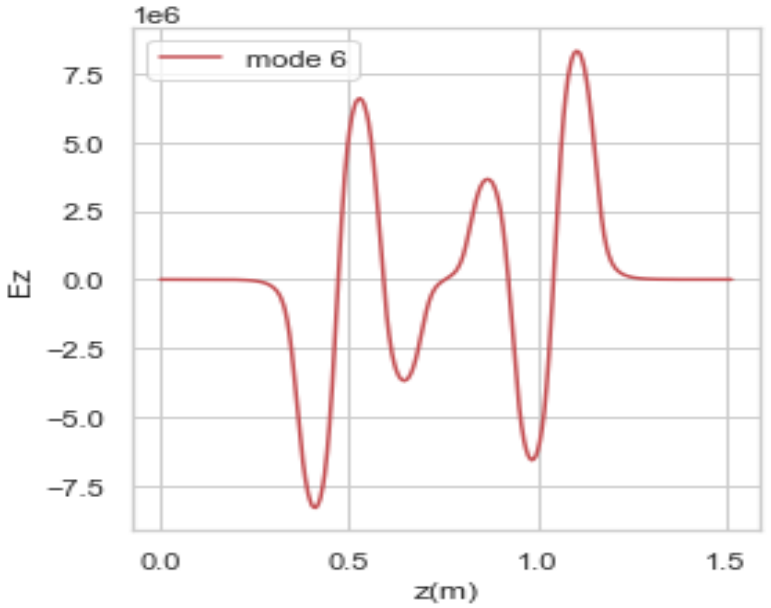
The beam drives HOMs in the cavity

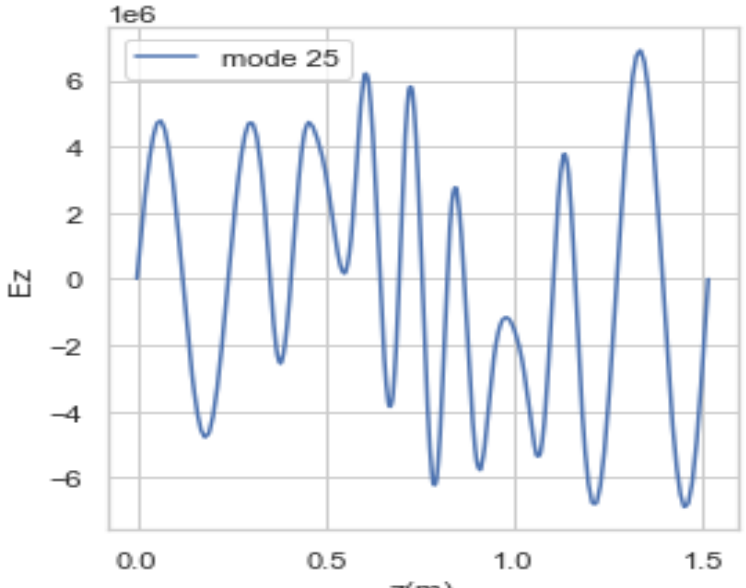


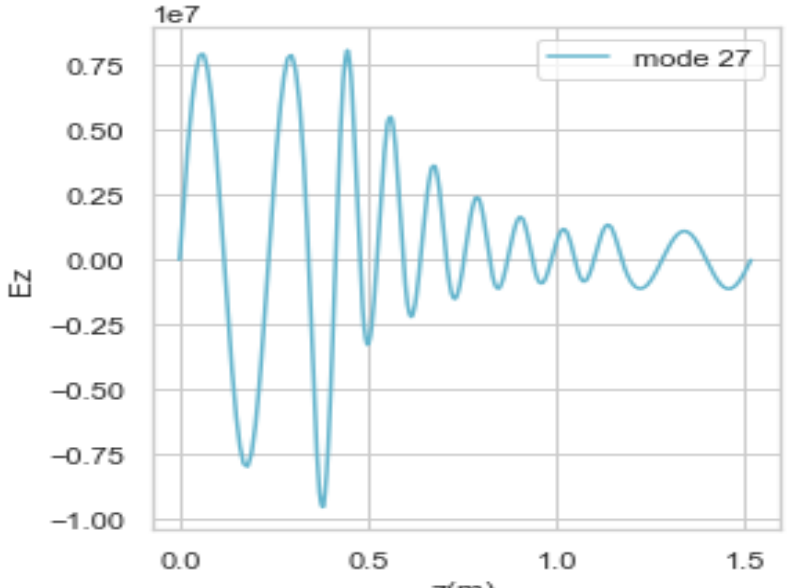
II. Theory and HOM evolution over very long time-scales

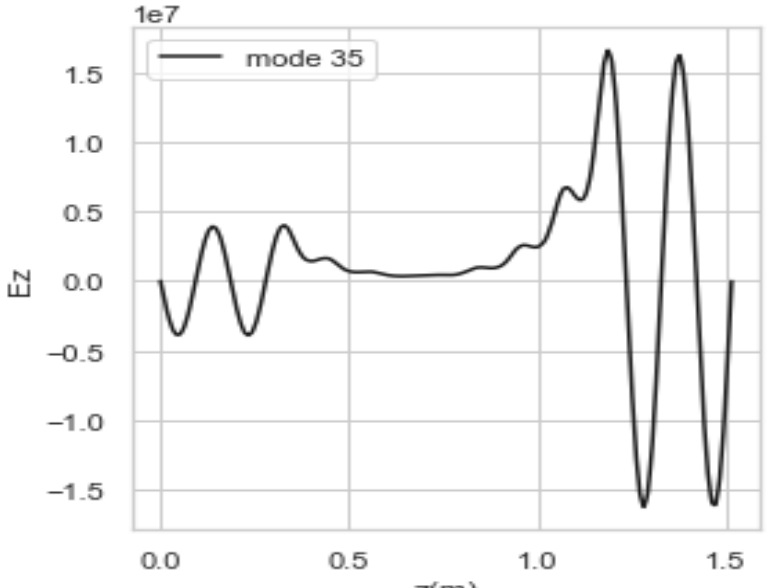












HOMEN's set of equations

The electric field along the cavity axis :

SVEA* approximation for RF modes and beam

$$E_n(z,t) = A_n(t)e_n(z)\sin\left(\omega_n t + \phi_{n,i}\right)$$

n: mode number
i: bunch number

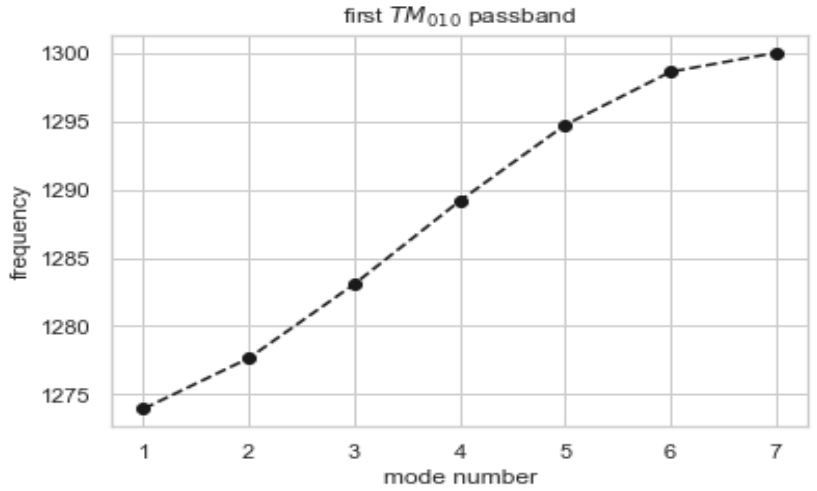
$$\begin{cases} \dfrac{dU_n}{dt} = -\dfrac{\omega_n U_n}{Q_{L_n}} + \delta_{1,n}\left|P_{\text{kly}}\right| - \dfrac{q_i V_{acc_{i,n}}}{\tau_{cav_i}} + \dfrac{q_i^2 k_{loss,n}}{\tau_{cav_i}} & (1) \\ \dfrac{dA_n}{dt} = \dfrac{A_n}{2U_n}\dfrac{dU_n}{dt} & (2) \\ \dfrac{d\gamma_i}{dt} = \dfrac{e}{m_0 c^2 \tau_{cav_i}} \sum_{n=1}^{N_{RF}} V_{acc_{i,n}} & (3) \end{cases}$$

M.Ferrario: Multi-bunch Energy Spread induced by Beam Loading in a Standing Wave Structure

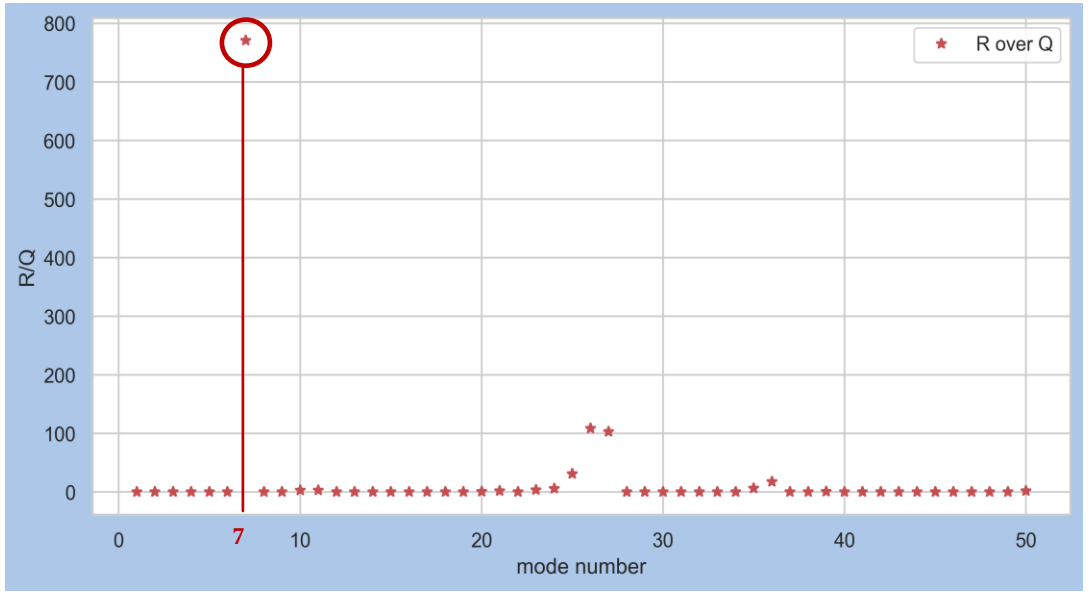
$$V_{acc_{i,n}} = A_n(t_{0,i}) \int_0^{L_{cav}} e_n(z)\sin\left(\frac{\omega_n z}{\beta(t_{0,i})c} + \phi_{n,i}\right) dz, \qquad (4) \quad \tau_{cav_i} = \frac{L_{cav}}{\beta(t_{0,i})c} \;\&\; \beta_i = \sqrt{1 - \frac{1}{\gamma_i^2}}$$

*S.V.E.A. = Slowly Varying Envelope Approximation

First Monopole passband TM010



First passband frequencies

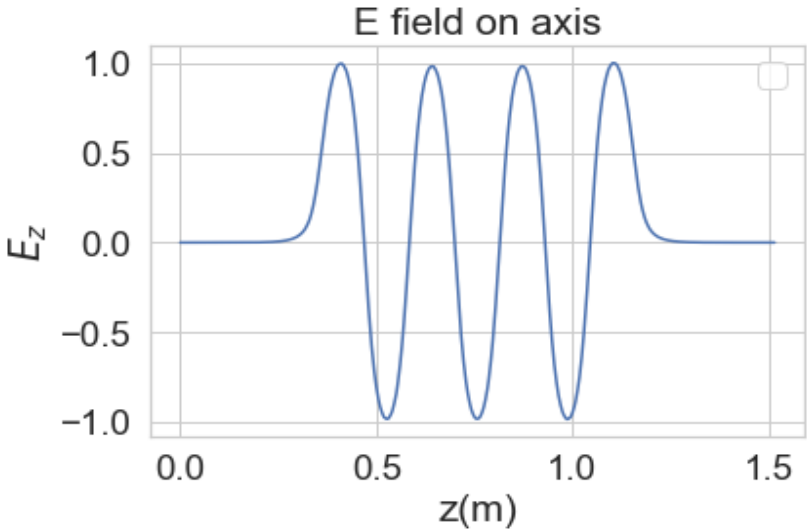


R/Q parameter

Data provided by D.Sertore & A.Bosotti (LASA)

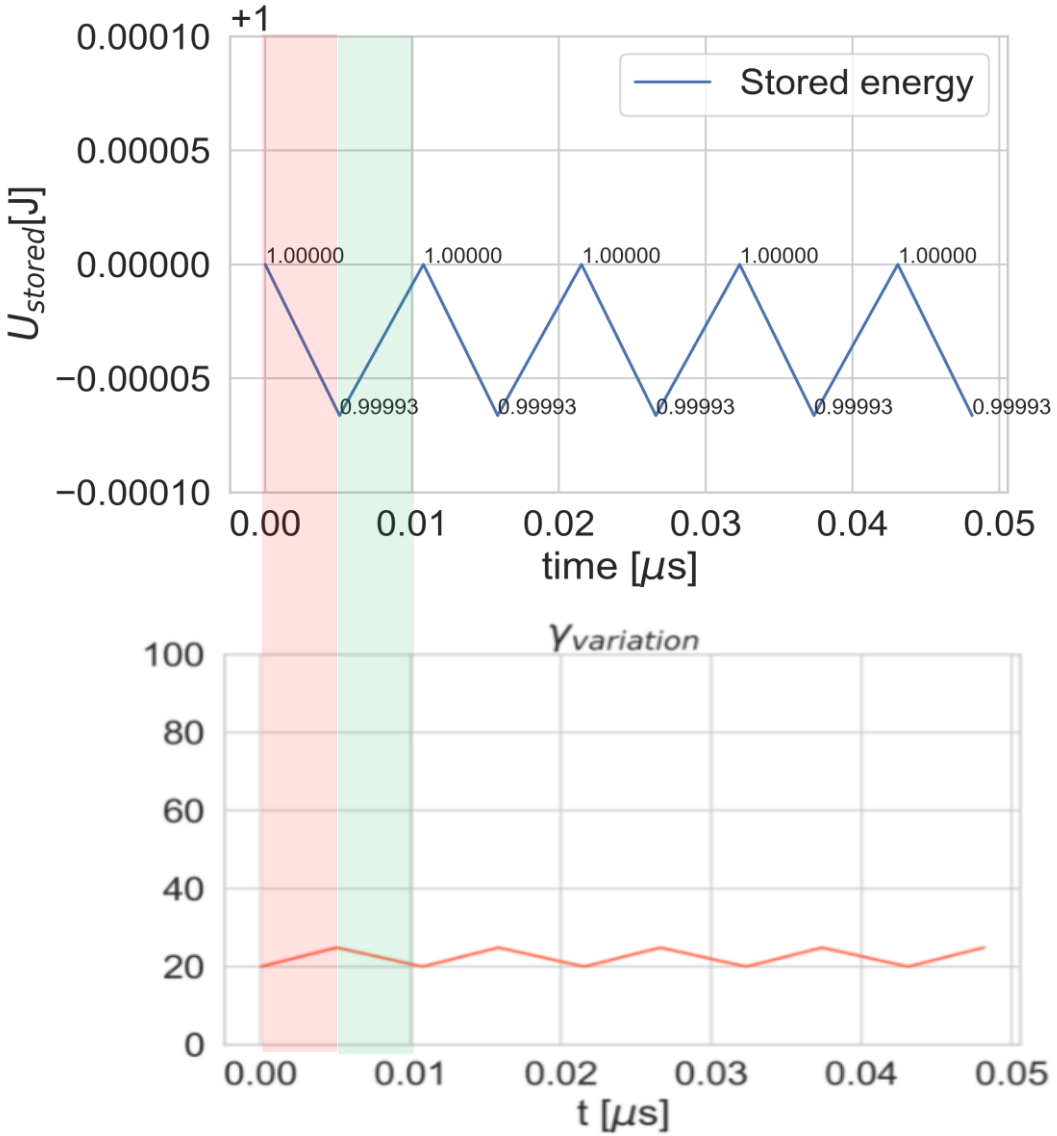
Frequency [MHz]	Q-Factor	*Mode number*
1273.9472	2.8959396e+10	1 (π/7 mode)
1277.6519	2.8957212e+10	2
1283.0615	2.8954195e+10	3
1289.1452	2.8950851e+10	4
1294.7012	2.8946409e+10	5
1298.5887	2.8942676e+10	6
1299.9838	2.8944223e+10	7(π mode)

Mode frequencies of the 1° passband and their associeted Quality factor



Injection of 100 bunches

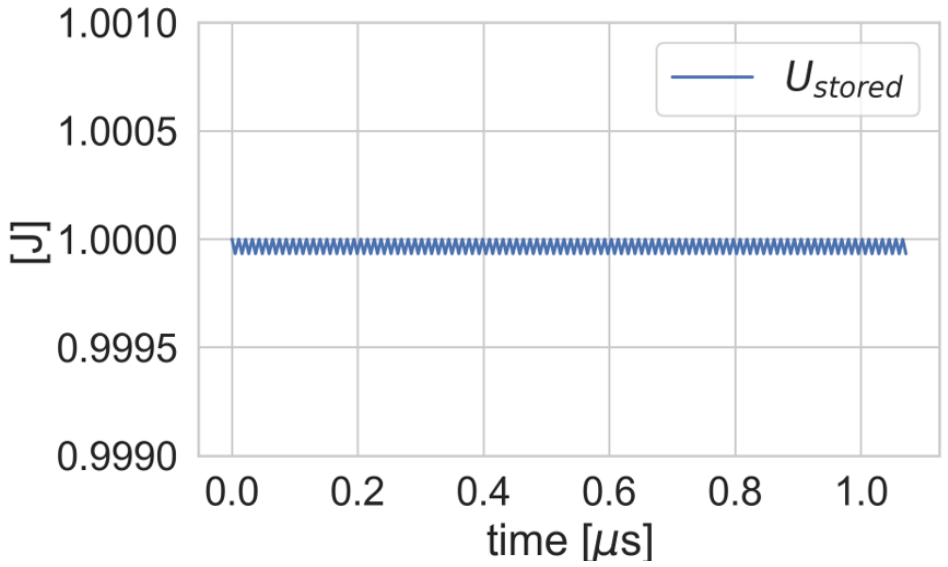
✓ TM010 results

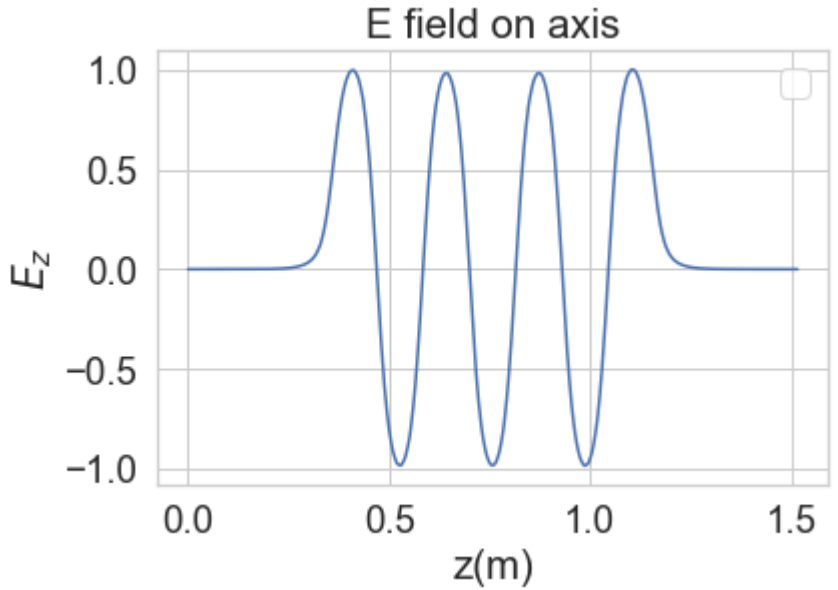


τcav(flight time) ≈ 5.06 ns
Time between bunches = 10.8 ns
Empty cavity time = 5.7 ns

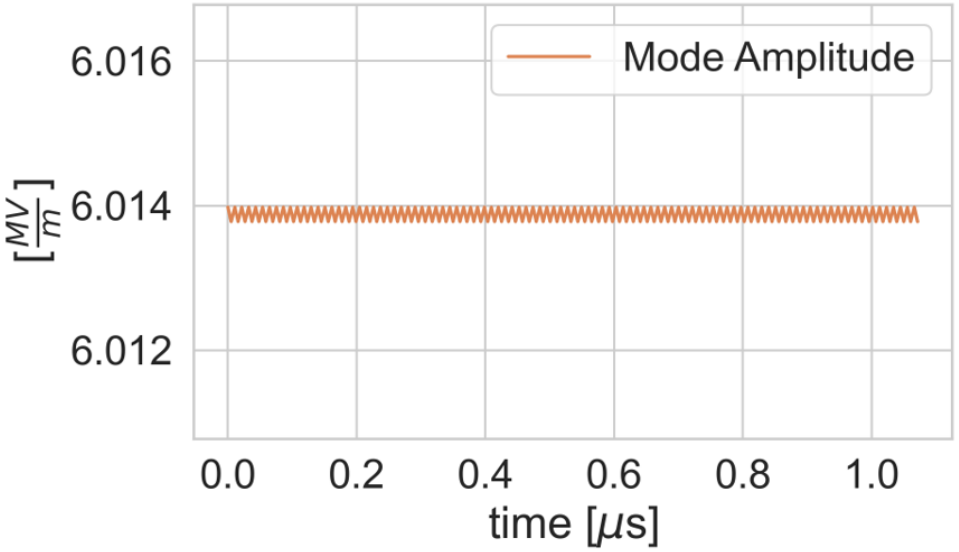
Injection of 100 bunches

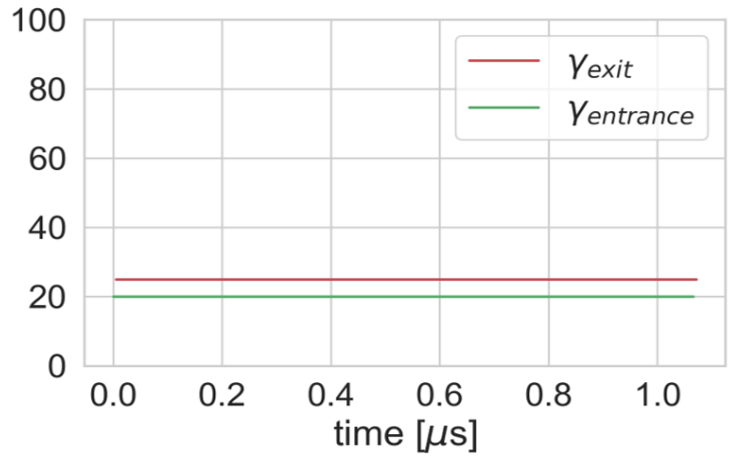
✓ TM010 results





Normalized on axis electric field of the accelerating mode



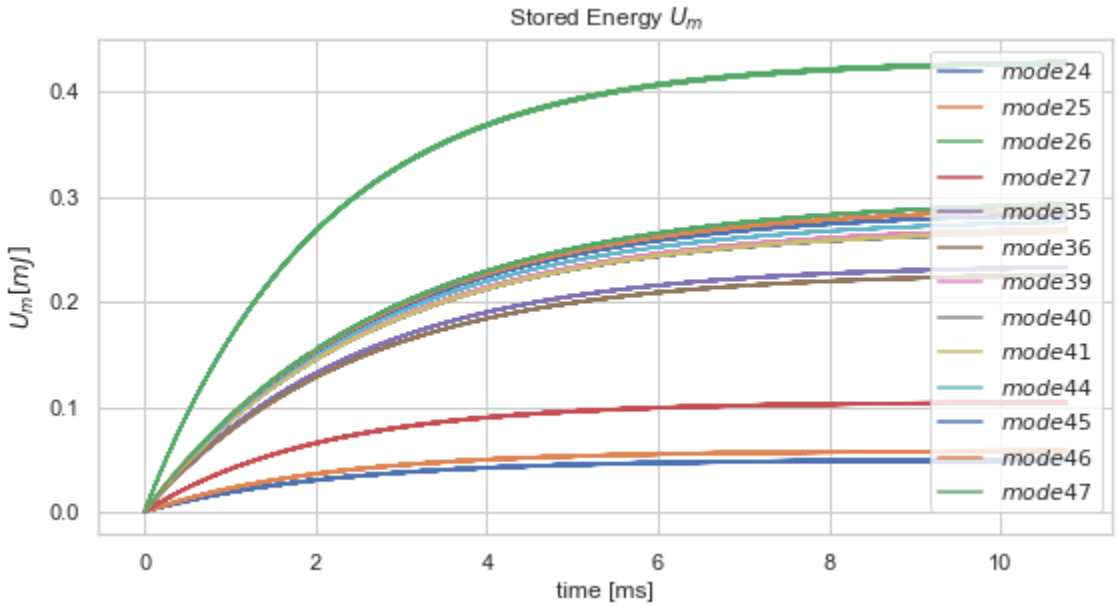


Energy at the entrance & exit of the cavity

HOMs Contribution

- Injecting **one million** bunches using estimated loss factors

$$\frac{dU_n}{dt} = -\frac{\omega_n U_n}{Q_{L_n}} + \delta_{1,n}\left|P_{\text{kly}}\right| - \frac{q_i V_{acc_{i,n}}}{\tau_{cav_i}} + \frac{q_i^2 \boldsymbol{k_{loss,n}}}{\tau_{cav_i}}$$



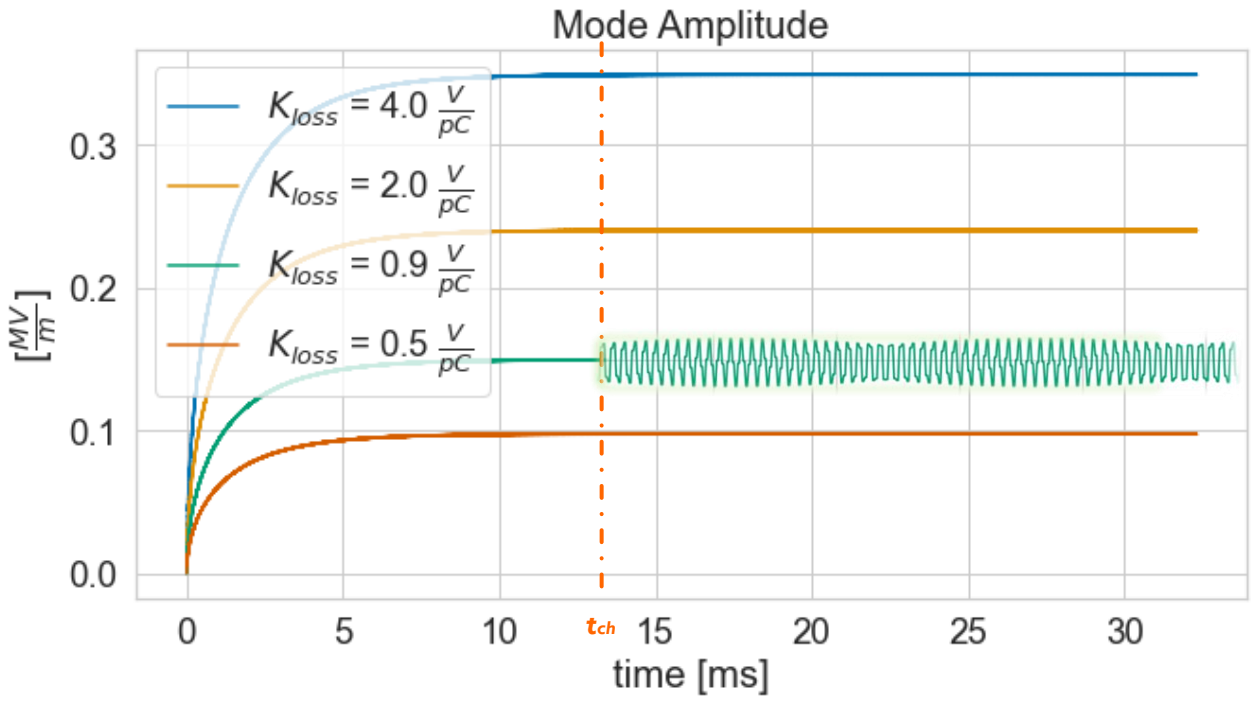
Data provided by D.Sertore & A.Bosotti

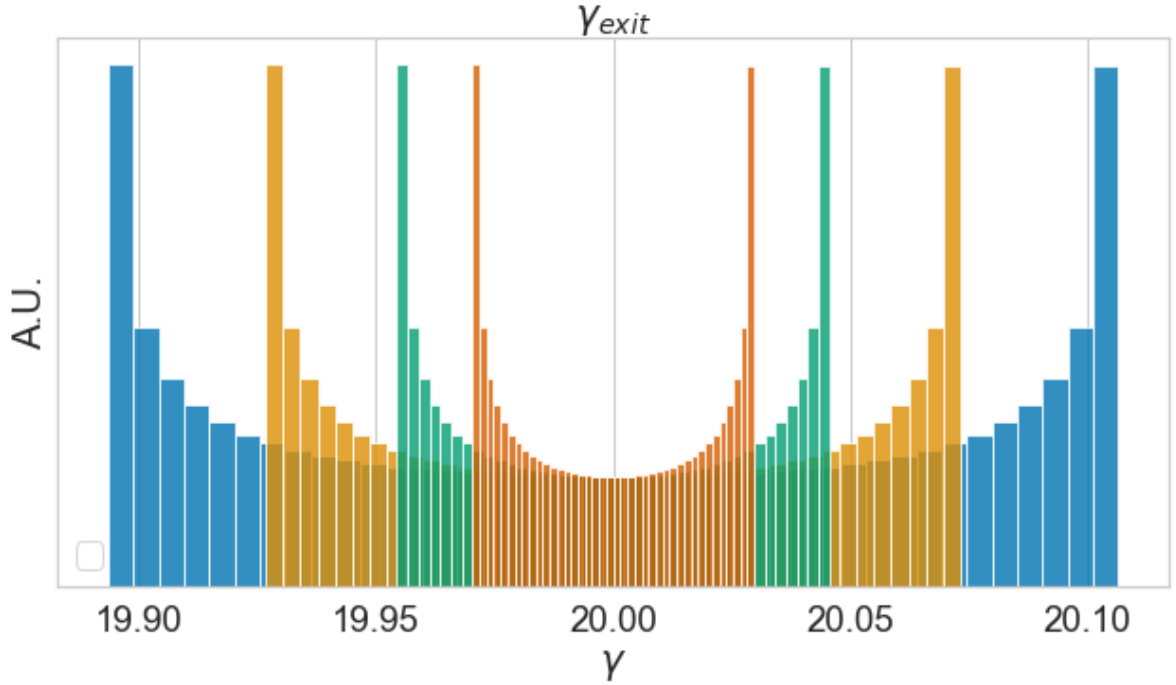
Frequency [MHz]	Q-Factor	Mode number
2409.9849	3.2347463e+10	24
2425.2874	3.1373833e+10	25
2437.268	3.147119e+10	26
2443.2179	3.1232002e+10	27
2633.807	4.0346052e+10	35
2633.8968	4.026427e+10	36
2680.5603	4.4368181e+10	39
2694.9205	4.4335046e+10	40
2714.0437	4.4612449e+10	41
2735.3095	4.5169996e+10	44
2756.1057	4.6008084e+10	45
2773.5275	4.7057488e+10	46
2785.0463	4.8021573e+10	47

Monopole HOM

Loss factor (kloss) contribution

- The total loss factor of our model (7-cell cavity) $k_{loss,tot} = 3.5$ V/pC
- $k_{loss,26} = 0.9$ V/pC (ν_{26} = 2.437268 GHz), $t_{ch,26} = \frac{Q_{26}}{\omega_{26}} = 12.91$ ms
- Relative Energy spread of the bunch about 2.5×10^{-3}
  - **Injecting 3 million bunches :**





Energy distribution of the bunch at the cavity exit

III. Summary & Outlook

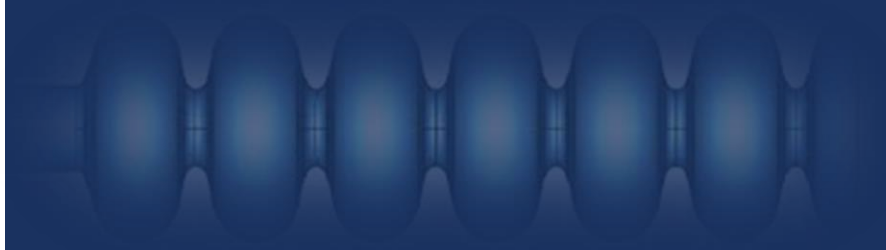
The data obtained are intended to be used in further beam dynamics.

- Longer simulations
- Use 3 SRF
- Counter propagation in ERL

Further development (beyond PhD): Transverse Dynamics

Beam breakup and high order modes instabilities studies for energy recovery linear accelerators (ERLs)

Thank you for your attention!



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