# Towards an Ampere-class deuteron CARA: Beam simulation and machine design

# アンペア級重陽子CARAの実現に向けて: ビームシミュレーションと加速器設計

**CUVELIER Matis**
RIKEN Nishina Center, Université Paris-Saclay

# 自己紹介

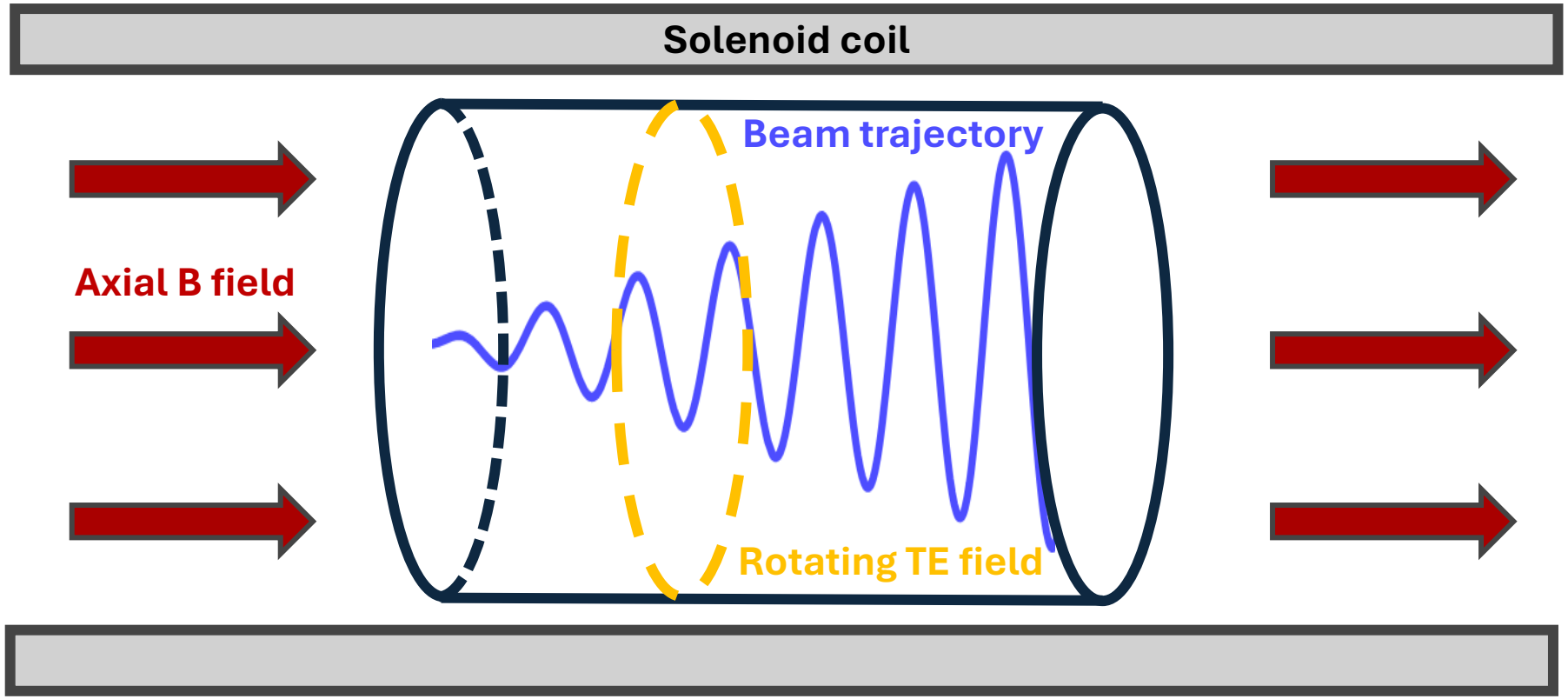
- パリ・サクレー大学からの大学院２年生(物理学専攻)。
- M2のタイトルは「プラズマ、レーザー、加速器、トカマク」
  …特に専門は加速器物理。
- 電子シンクロトロン、CERNの陽子シンクロトロン（PSとSPS)、
  去年からCARAの研究に取り組む。
- 理研は二回目の実習中、奥野さんの指導でCARAについて研究、修士論文執筆中。

これから英語でお話しします。

# CARA – What, Why, How ?

**C**yclotron **A**uto-**R**esonance **A**ccelerator

**Axial magnetic field** + synchronized **rotating RF field** provides **continuous energy gain** in the transverse plane ($q\vec{E} \parallel \vec{v}_\perp$)




$$f_c = \frac{qB}{2\pi m} = f_{RF}$$

« Cyclotron seen from the top with continuous energy gain »

# CARA – What, Why, How ?

**Benefits and demerits :**

☺ **Continuous acceleration** (no gaps) = **compact**

☺ No need for longitudinal matching : can **accelerate DC beams** !

☺ No bore diameter restriction : supports **very high intensity beams** (Ampere-class)

☹ Requires very **large solenoid** with **high magnetic field**

| Applications covered here | Ion | Energy (MeV) | Current (A) | Simulation method |
|---|---|---|---|---|
| **DT fusion for 14 MeV neutron source** | D | 0.4 | 1 | Python code (ideal CARA) |
| **D breakup for fast neutron source (IFMIF-type)** | D | 40 | 0.1 | CST |
| **Test bench** | P | < 1 (radiation safety) | From 1 mA | CST |

# General beam dynamics in ideal CARA configuration

**« Ideal » CARA ?**

Pure fields (no spatial distribution)

$$\vec{E}_{RF} = \begin{cases} E_x = E_0 \cos(\omega_c t) \\ E_y = E_0 \sin(\omega_c t) \\ E_z = 0 \end{cases} \quad \vec{B}_{RF} = \begin{cases} B_x = -E_y/c \\ B_y = E_x/c \\ B_z = 0 \end{cases} \quad \vec{B}_{sol} = B_0 \cdot \vec{e_z}$$

**Equations of motion:**

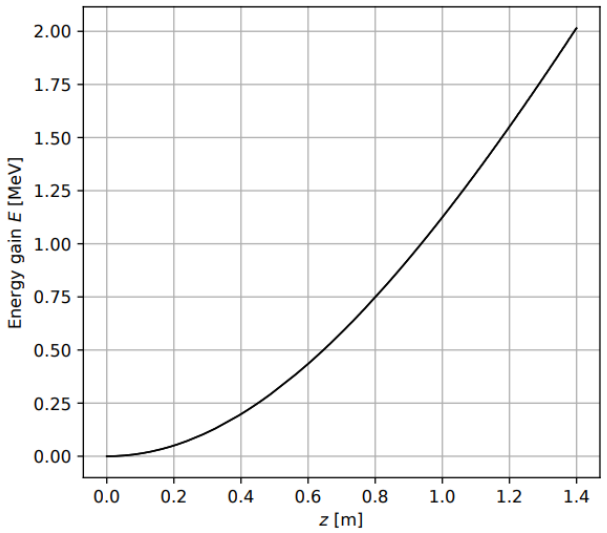
$$\begin{cases} \ddot{x} = \frac{q}{m}\left(E_x + \frac{1}{c}(-\dot{z}E_x) + \dot{y}B_0\right) \\ \ddot{y} = \frac{q}{m}\left(E_y + \frac{1}{c}(-\dot{z}E_y) - \dot{x}B_0\right) \\ \ddot{z} = \frac{q}{mc}\left(\dot{x}E_x + \dot{y}E_y\right) \end{cases}$$

→ **Numerical integration** (RK45, Boris leapfrog…)

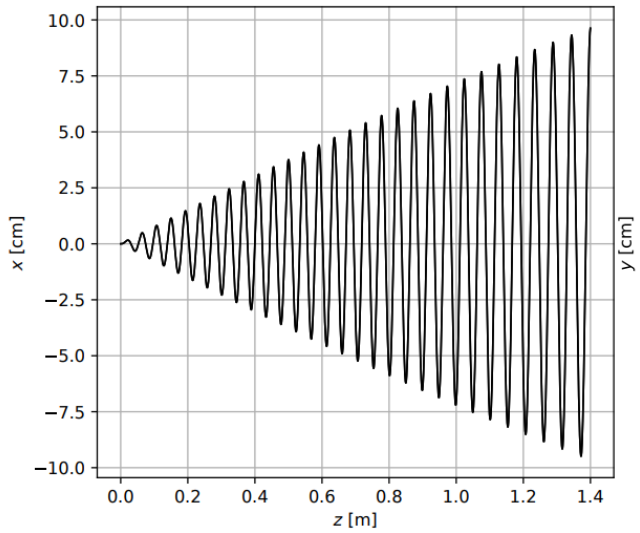
General example (2 MeV) :

For a 10 keV deuteron, $E_0$ = 225 kV/m, $B_0$ = 3 T (f ≈ 23 MHz) :

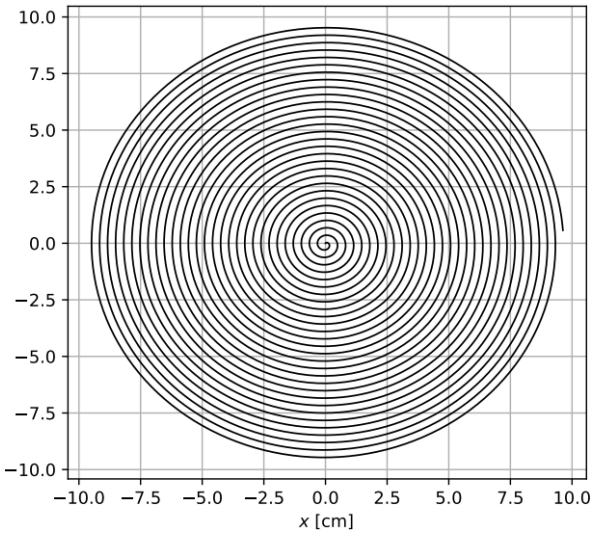
**Energy gain w.r.t. z**




**(x,z) trajectory**




**(x,y) spiral**




Particle **accelerated continuously** through time (z), perfect spiral in transverse plane

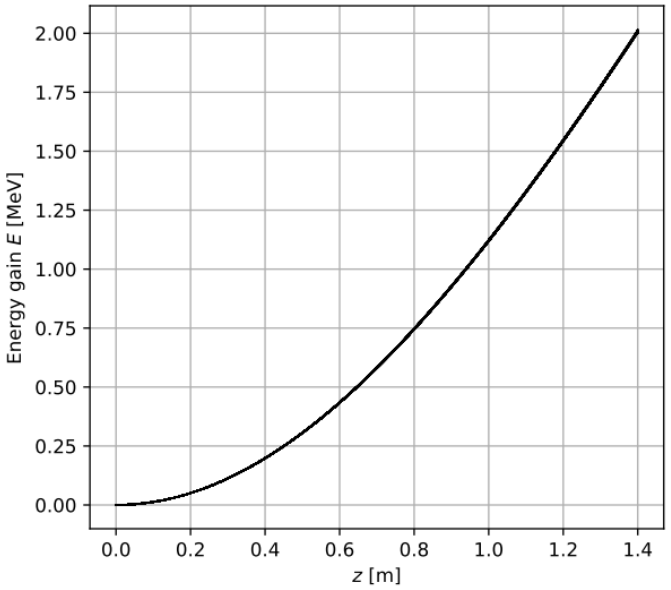
**2 MeV gain with 225 kV/m on 1.4m !**

# General beam dynamics in ideal CARA configuration

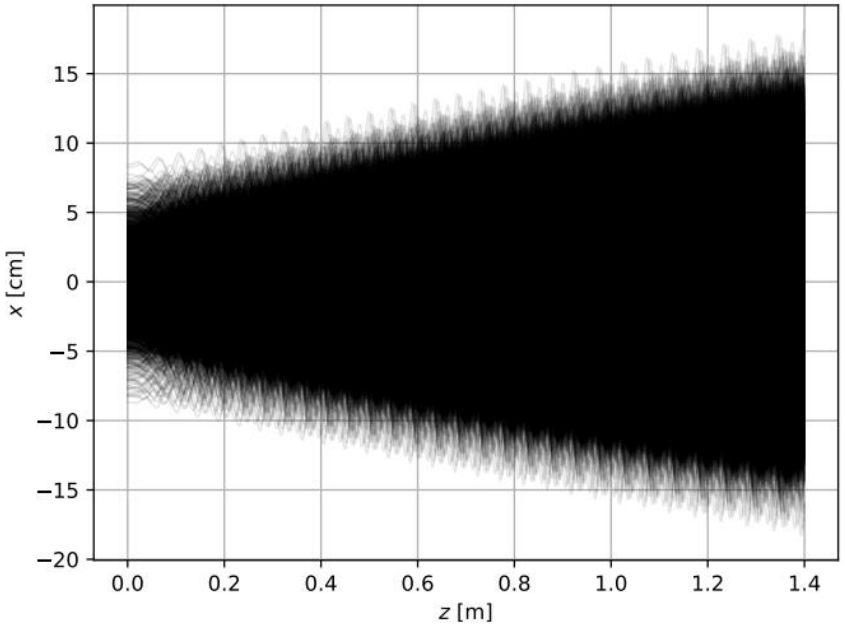
**For a DC beam distribution**

Case of large bore beam (10cmϕ at injection), 5000 particles, ΔE/E = 0.1%

**Energy gain w.r.t. z (all particles)**




**(x,z) trajectory (all particles)**




**Same energy gain for all particles: DC acceleration ☺**

→ Beam envelope ?

$$\begin{cases} \ddot{x} = \frac{q}{m}\left(E_x + \frac{1}{c}\left(-\dot{z}E_x\right) + \dot{y}B_0\right) \\ \ddot{y} = \frac{q}{m}\left(E_y + \frac{1}{c}\left(-\dot{z}E_y\right) - \dot{x}B_0\right) \\ \ddot{z} = \frac{q}{mc}\left(\dot{x}E_x + \dot{y}E_y\right) \end{cases}$$

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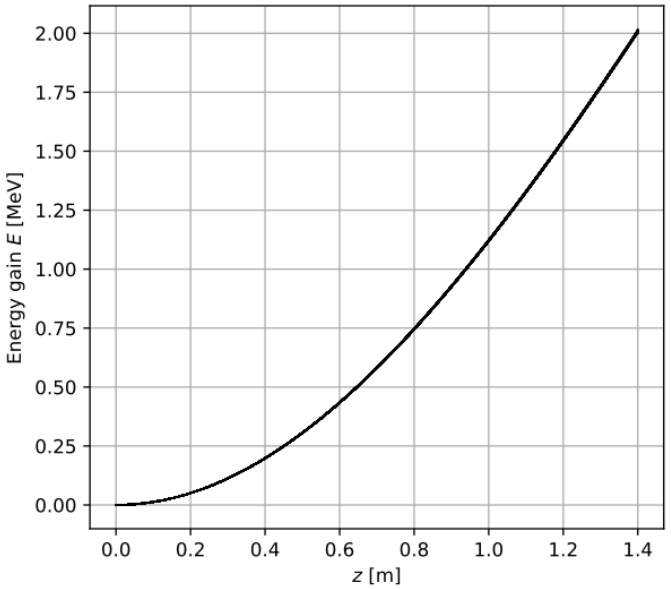


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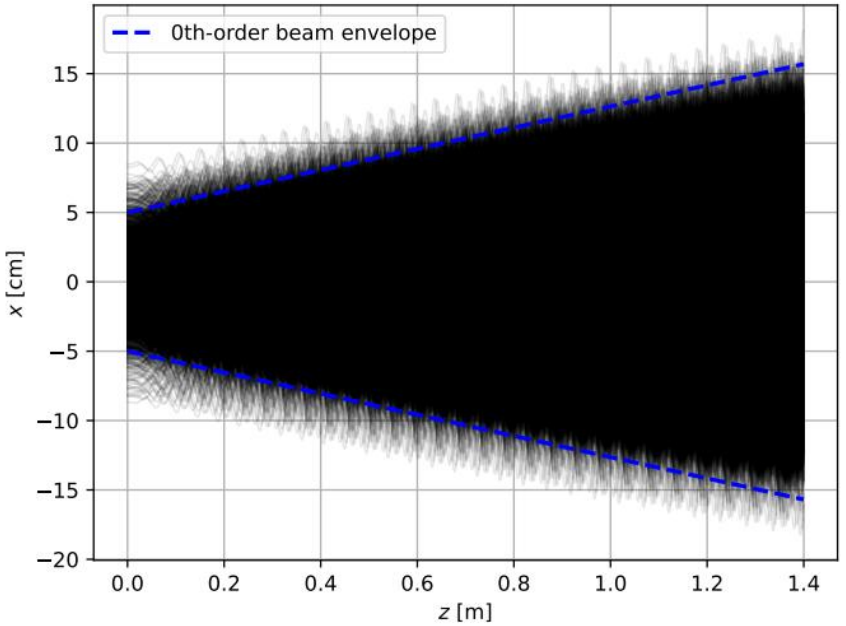


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$$R(z) = R_0 + z\frac{E_0}{B_0}\left(\frac{1}{v_z} - \frac{1}{c}\right)$$

**0th order envelope (constant $v_z$ )**

# General beam dynamics in ideal CARA configuration

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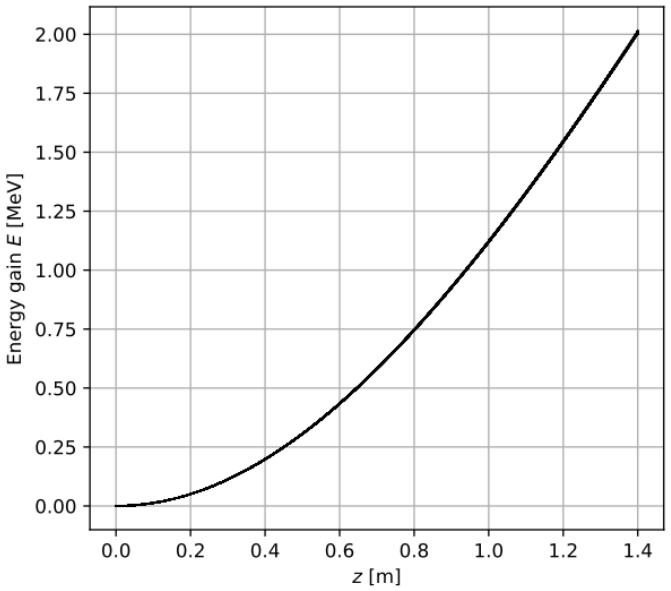


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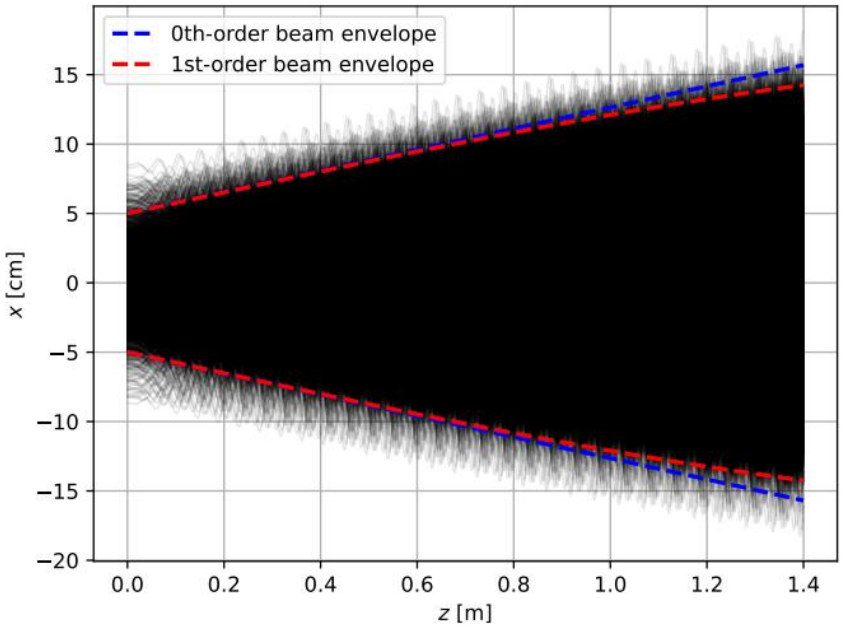


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0th order (constant $v_z$)

$$R(z) = R_0 + z\frac{E_0}{B_0}\left(\frac{1}{v_z} - \frac{1}{c}\right)\left(1 - \frac{Az^2}{v_{z0}^3}\right) \qquad A = \frac{q^2E_0^2}{6m^2c}$$

**1st order envelope ($At^2/v_{z0} \ll 1$)**

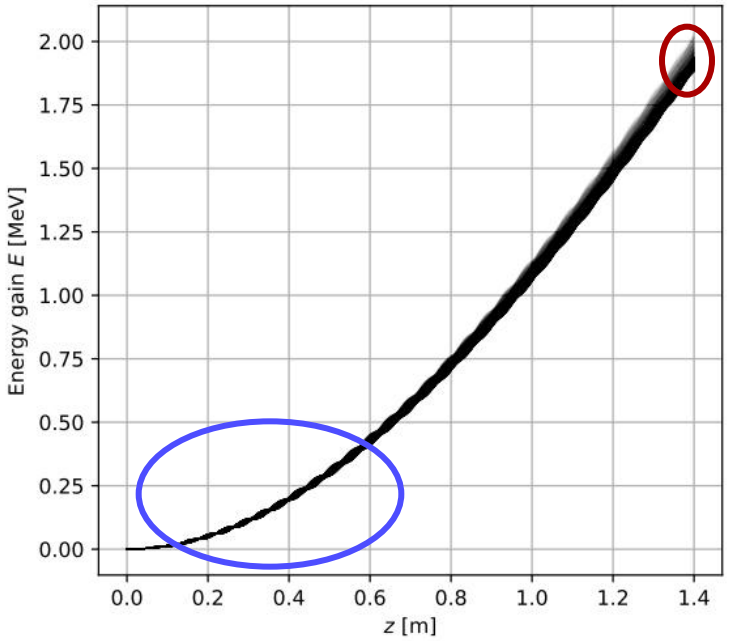
# Study of space charge forces (1A deuteron beam)

**Space charge effects simulation**

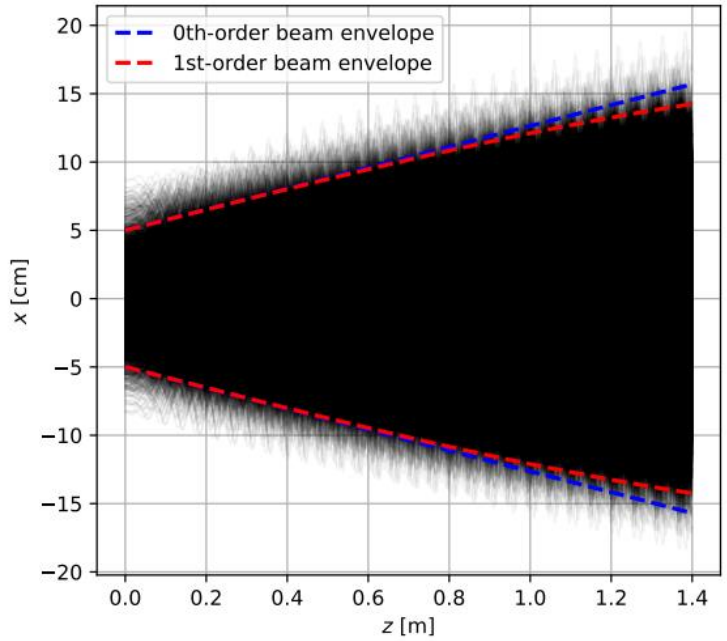
Space charge fields calculated with **cylindrical beam asumption**

Same distribution as earlier but with 1A current now gives **oscillation** + **energy spread**

**Energy gain w.r.t. z (all particles)**




**(x,z) trajectory (all particles)**




Despite energy spread, **beam envelope remains the same**

Space charge $E_{SC}$ field ($B_{SC}$ negligible) is **radial** → check **particle position**

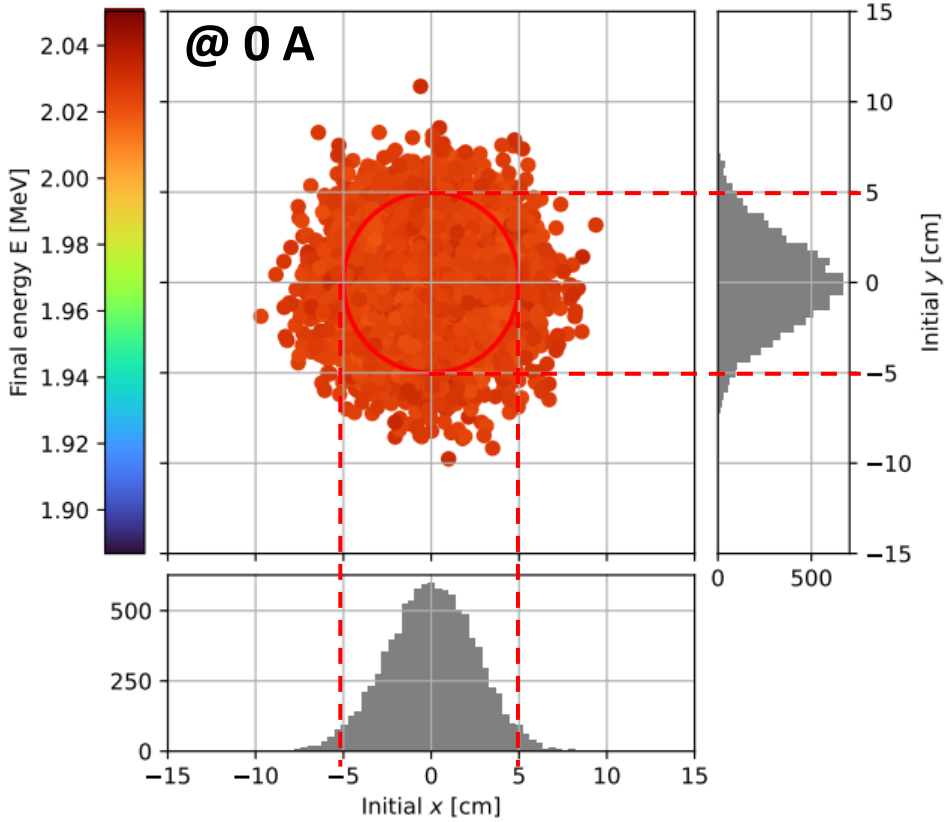
# Study of space charge forces (1A deuteron beam)

**Space charge effects simulation**

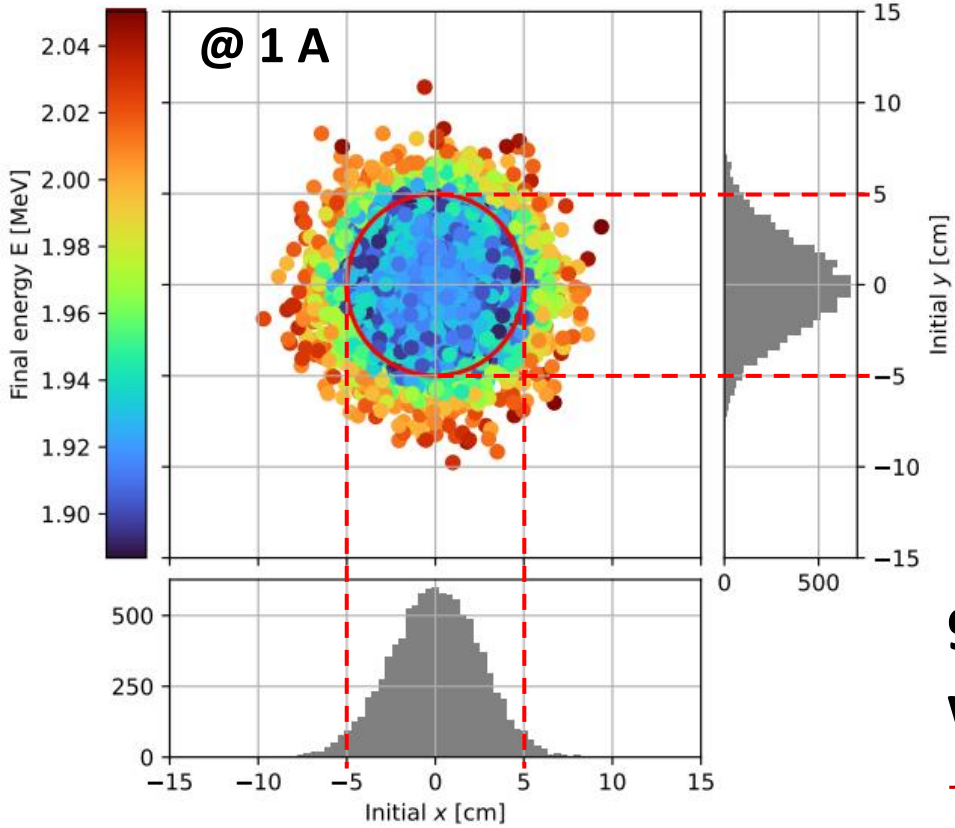
**Initial particle position** (~ gyrocenter !) determines **final energy**

◯ : analytical beam envelope ($R_0$)

**Final energy w.r.t initial (x,y) (all particles)**




**Final energy w.r.t initial (x,y) (all particles)**




**2 regions :**

**$r < R_0$ :**
**Uniform « low » E**

**$r > R_0$ :**
**Increasing E** (until 0 A value)

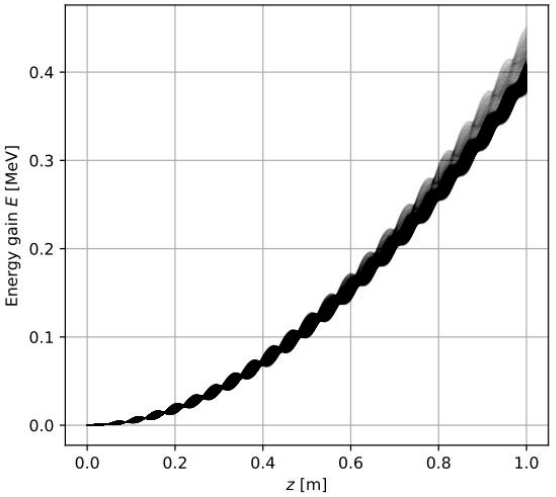
**95% of particles within ~1.9 MeV**
**→ adapt $E_0$ / d**

# Application example – DT for 14 MeV neutron source

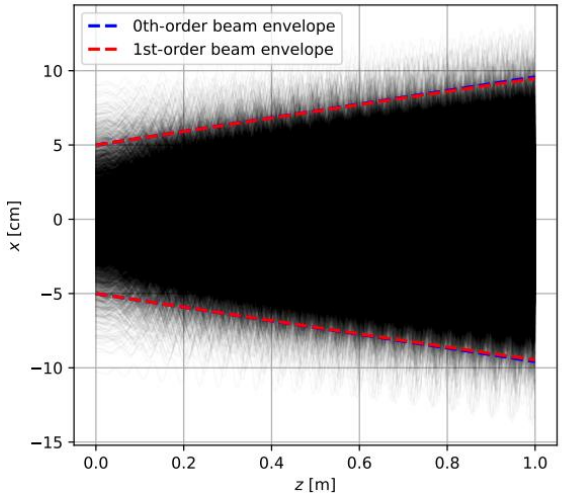
**Beam requirements : 0.4 MeV deuterons @ 1 A**

$E_0$ = 135 kV/m over 1m (same other parameters)

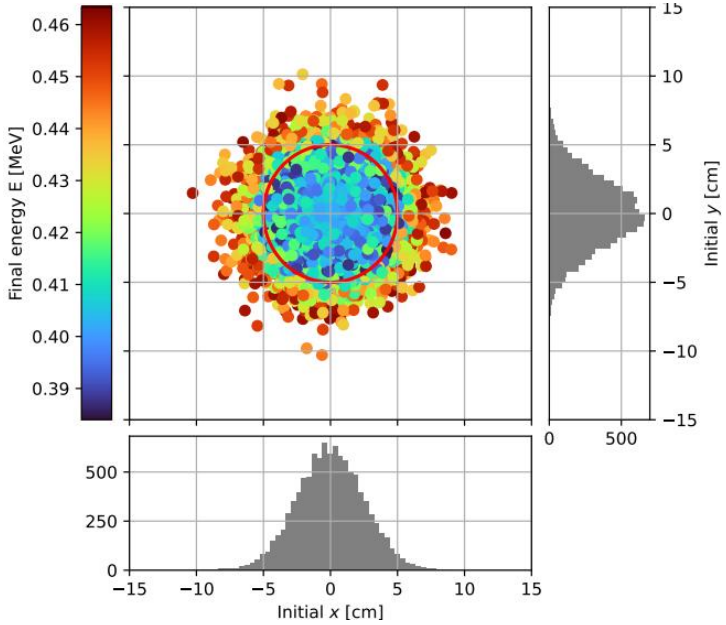
**Energy gain w.r.t. z (all particles)**



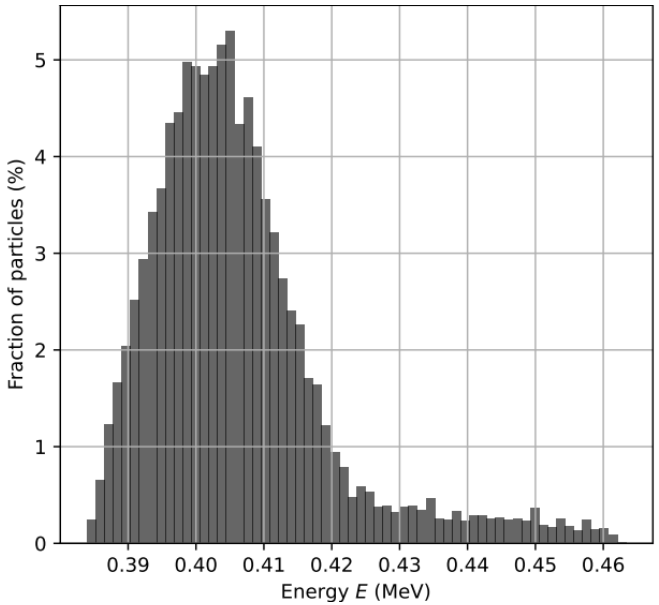

**(x,z) trajectory (all particles)**




**Final energy w.r.t initial (x,y) (all particles)**




**Final beam energy distribution (all particles)**




Despite high current, **majority** of beam within **0.4 MeV target energy**

# Practical difficulties in deuteron CARA design

**How to make a CARA cavity ?**

$TE_{111}$ mode : **cylindrical cavity** required

Rotating field : **perpendicular** $TE_{111}$ polarization + **90° phase** difference

**For deuterons ?**

Even for high B fields, **low frequency** (53 MHz at 7 T)

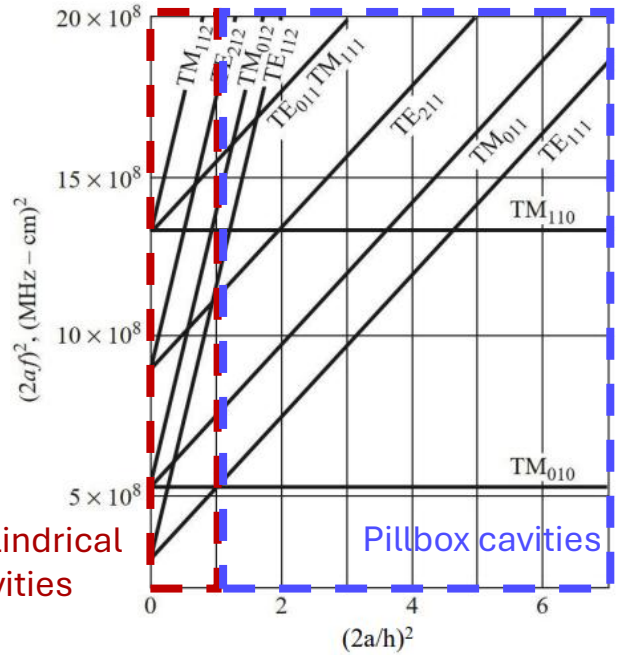
⟶ Need **big cavity** : **how to make it compact** ?

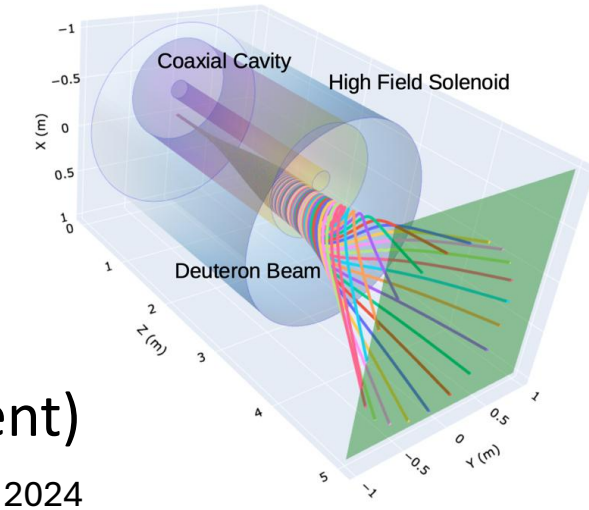
Jiang et al.[1] proposed coaxial TEM deuteron cavity for 7 T solenoid with $r_{inner}$ = 0.1 m, $r_{outer}$ = 0.6 m, L = 2.83 m

**Problems :**

- TEM electric field is **radial**, not rotating ⟶ not exactly a CARA
- Quite **long cavity** (2.83 m for HWR)
- Designed for 80 mA : **suitable for 1 A** ? (assymetric beam environnement)

Source : Pozar, Microwave engineering, 4th ed., Wiley




[1] Jiang et al., *High-current deuteron accelerator for neutron production*, Proceedings IPAC' 2024

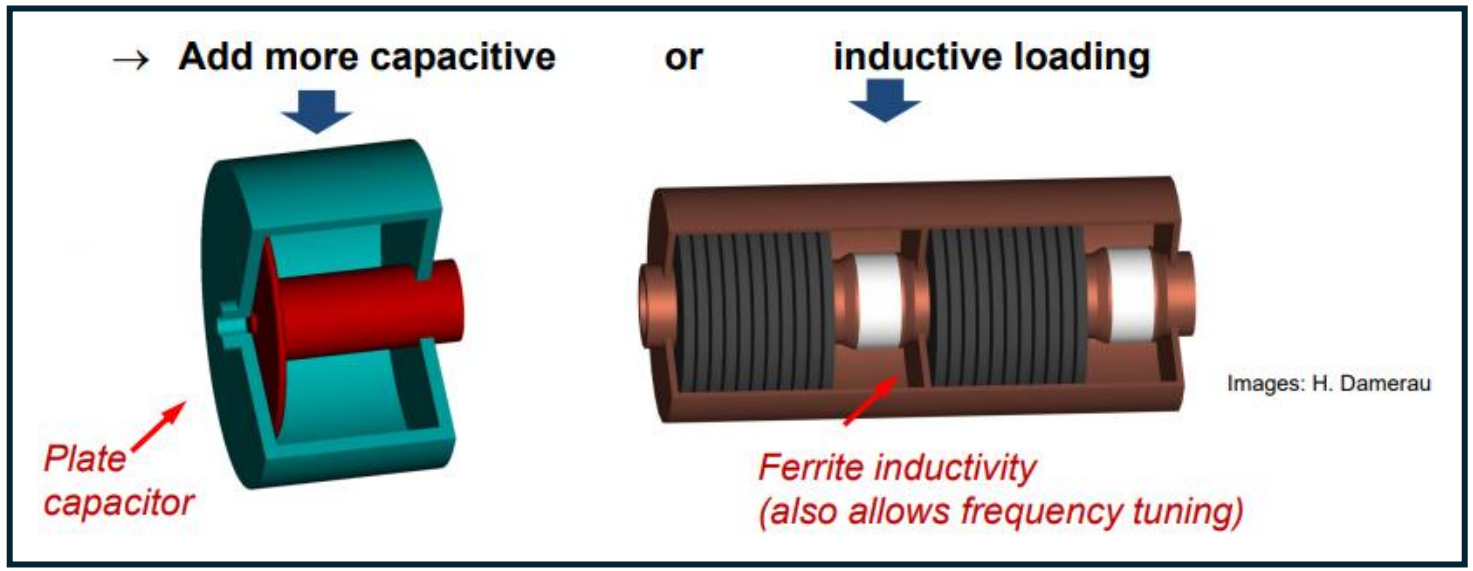
# Proposal of capacitive loading for deuteron cavities

**The idea**

Cavity size is **not** the only way to **change resonant frequency** !

→ Increase cavity capacitance/inductance by **dielectric loading**

$$f = \frac{1}{2\pi\sqrt{LC}}$$




Source : C. Völlinger (CERN), M. Wendt (BNL), *Beyond Pillbox Resonators*, in RF Engineering Course, Joint Universities Accelerator School (JUAS) 2025

But CARA = **high magnetic field** : **inductive loading difficult**

→ **capacitive loading** only

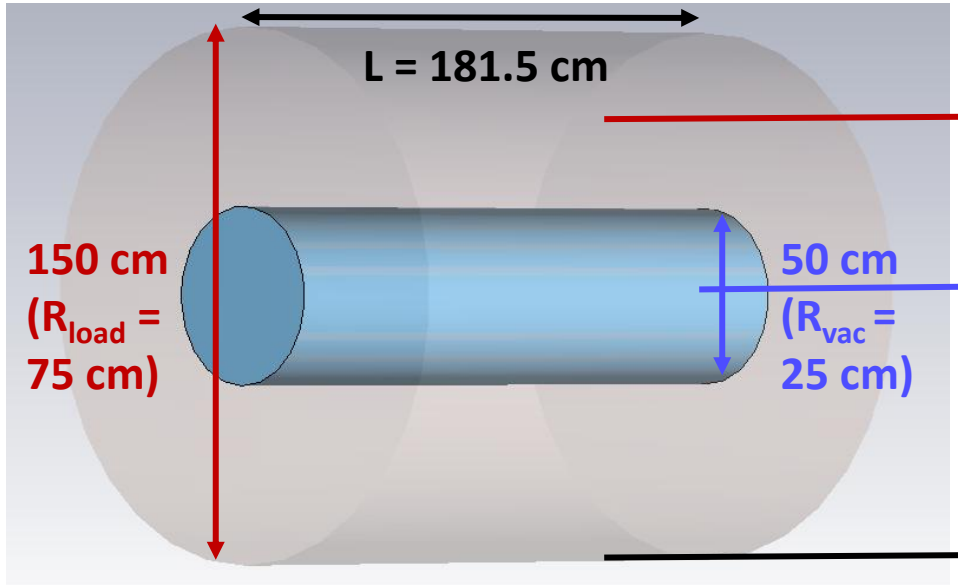
At CERN, use of **ceramics** (high ε, relatively cheap and convenient)

→ Ceramic-loaded cavity design on CST Studio Suite

# Proposal of capacitive loading for deuteron cavities

## Cavity design

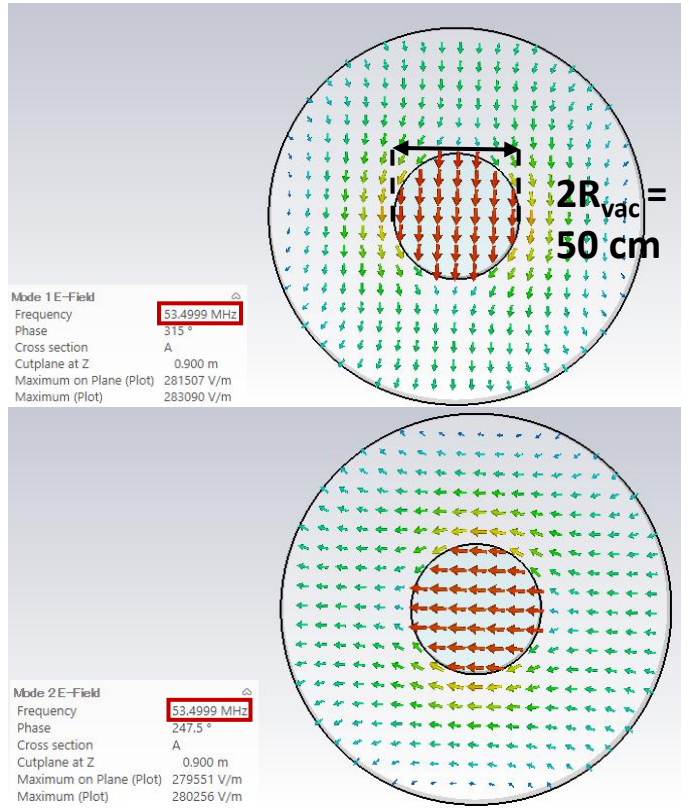
Assuming a 7 T magnetic field (53.4 MHz)



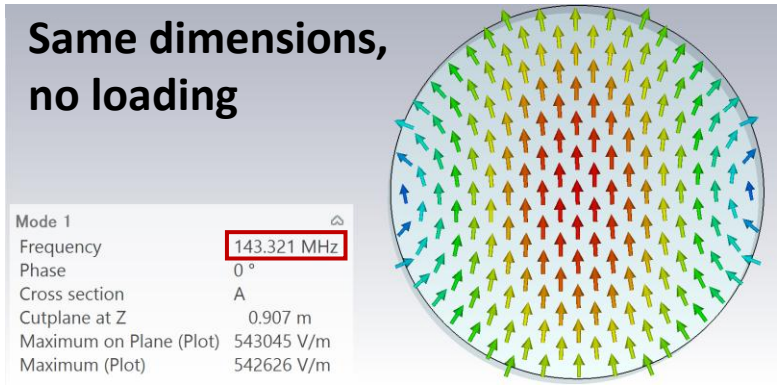

**Ceramic load (Al 99.5%)**

**Vacuum (beam path)**

**Cavity metallic walls**




$Q_{CST}$ = 8.7e+03

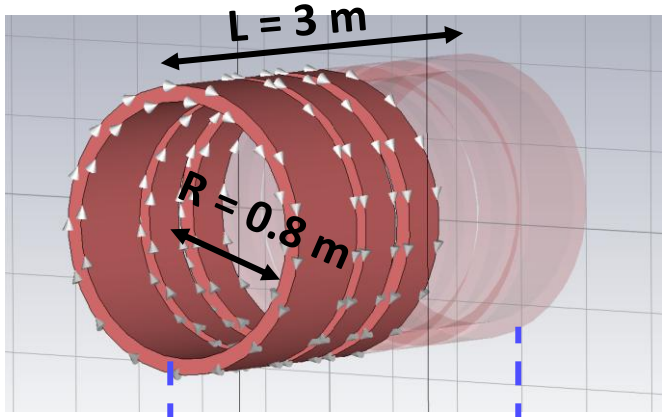


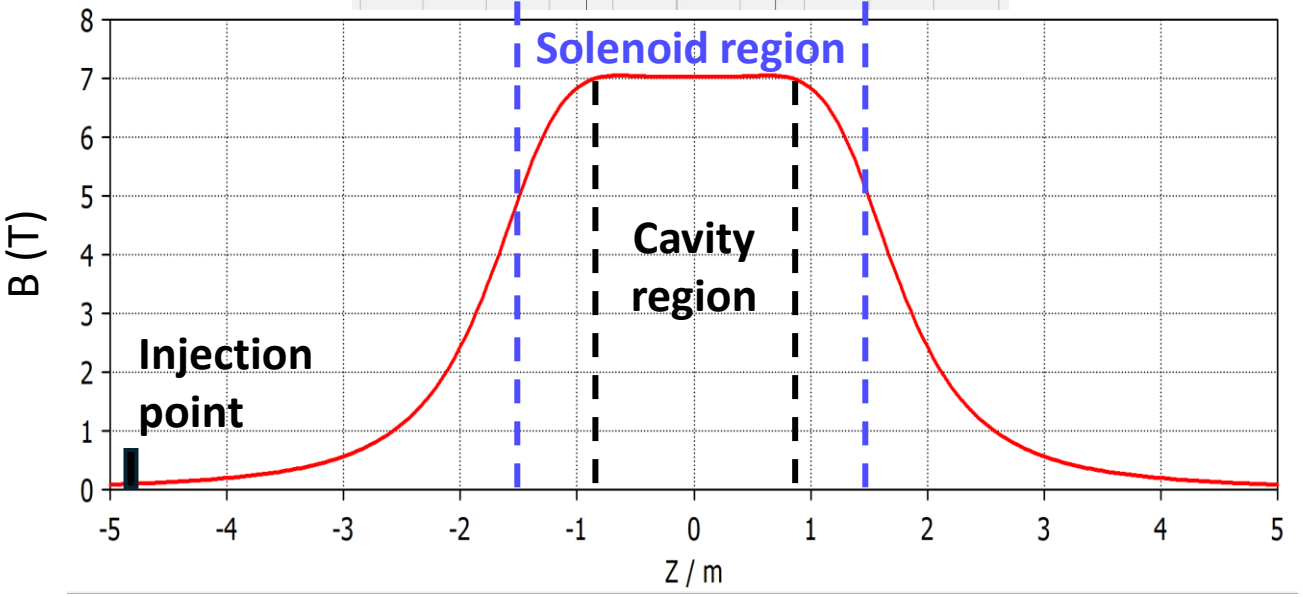

- Reached **target frequency** ☺
- E field <u>inside vacuum</u> completely **uniform** ☺
- (Surprisingly) **high Q-factor** ☺

# Particle tracking on CST Studio Suite

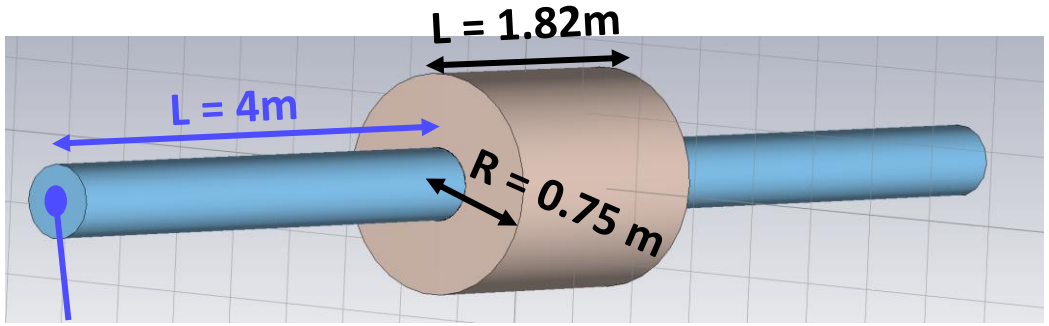
**Overall transport line design**

Simple **7T solenoid** magnet (2x3 main coils) @ 1kA




**Beamline = vacuum extension:**



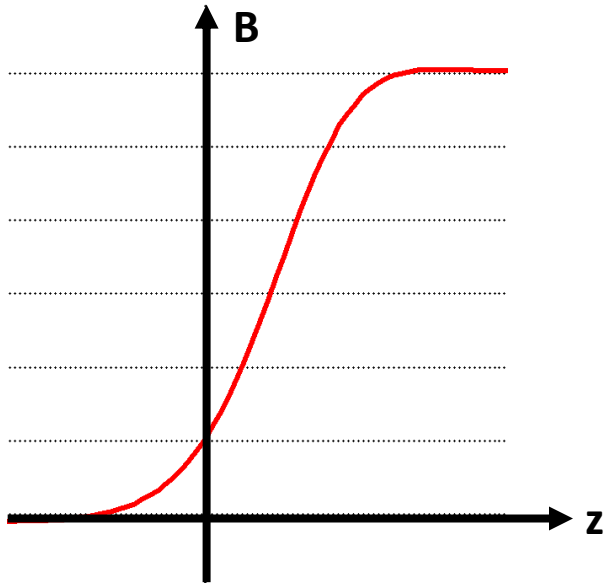

Particle source (injection)

# Particle tracking on CST Studio Suite

**Pre-requisite : Charged particle motion through magnetic gradients**

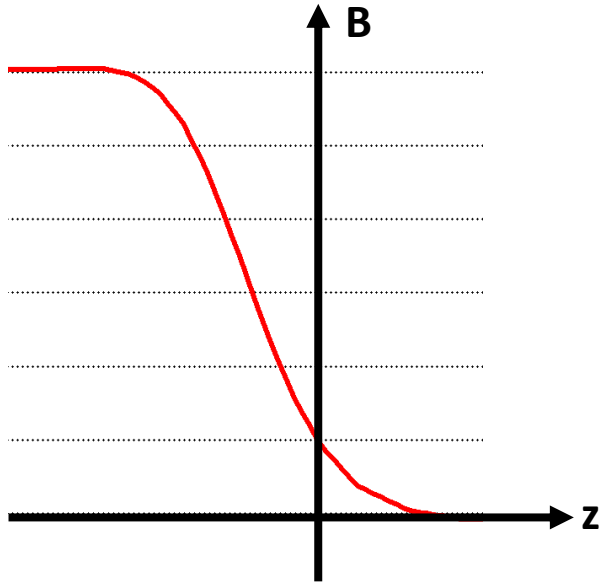
Derived from **magnetic moment adiabatic invariance** + **total energy conservation**

**Positive gradient :**




$$\mu = \frac{mv_\perp^2}{2B} = \text{const.}$$

**Negative gradient :**




- **Longitudinal → Transverse** momentum conversion
- **$v_z$ decrease**

- **Transverse → Longitudinal** momentum conversion
- **$v_z$ increase**

**CARA = High B field = high gradients !**

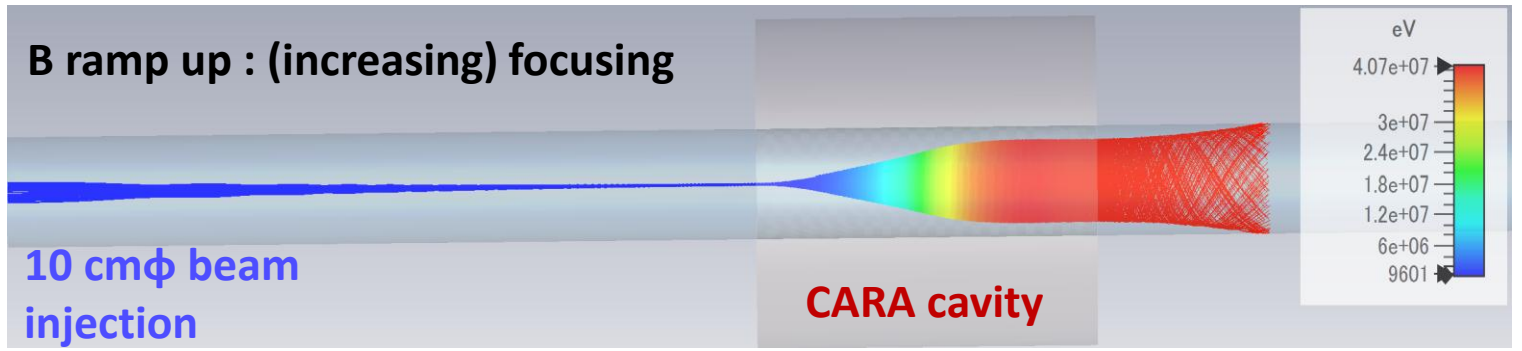
# Particle tracking on CST Studio Suite

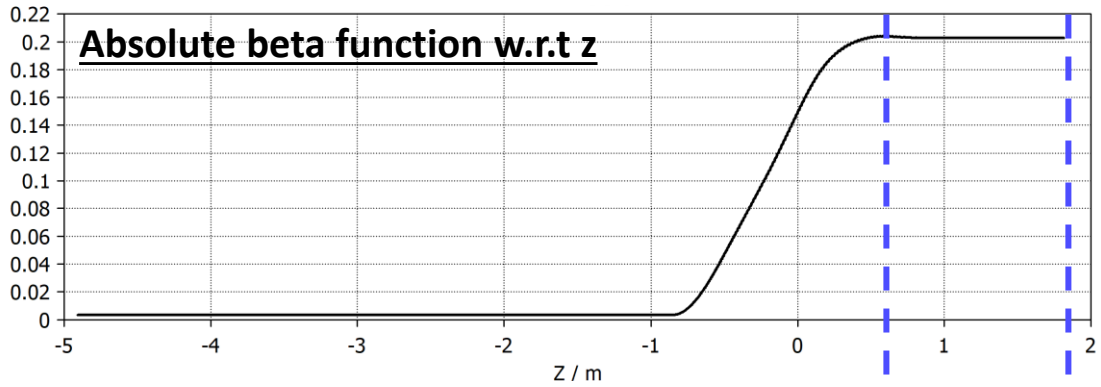
**CARA transport dynamics**

**40 MeV energy gain !**

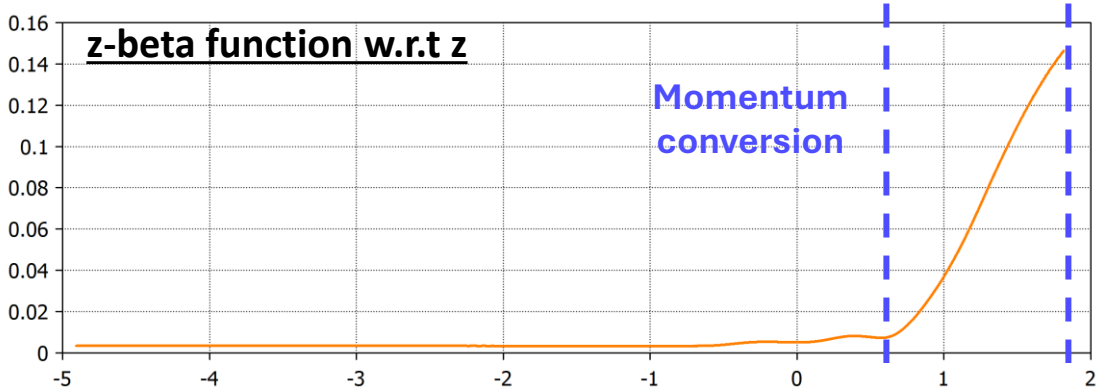
$P_{RF}$ = 5.2 MW

$E_{in}$ = 10 keV, ΔE/E = 0.1%




~40 MeV




~20 MeV

> **40 MeV target energy reached !**
(deuteron breakup)

> **Natural transverse → longitudinal**
momentum conversion (**50%**).
Further conversion = magnetic cusp

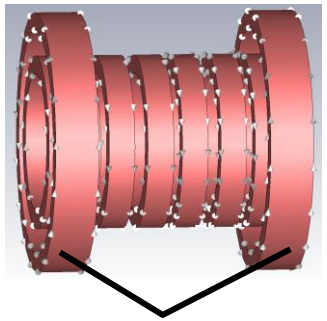
→ **Custom magnet design**.
Test bench = real MRI magnet **: feasible ?**

# Preliminary study of proton CARA testbench

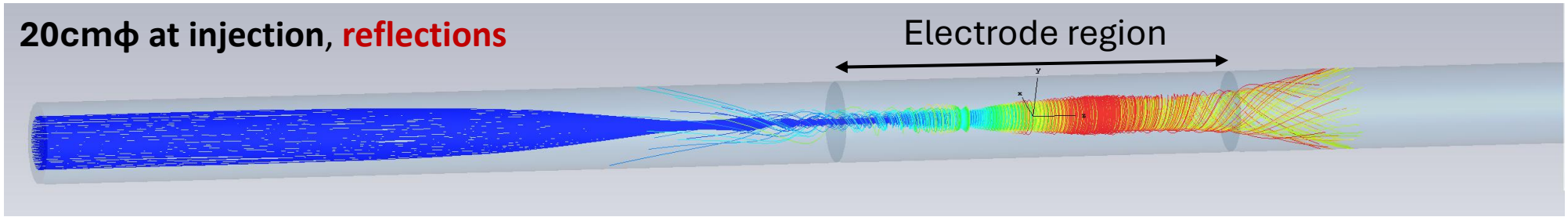
**Approaching « realistic » testbench conditions**

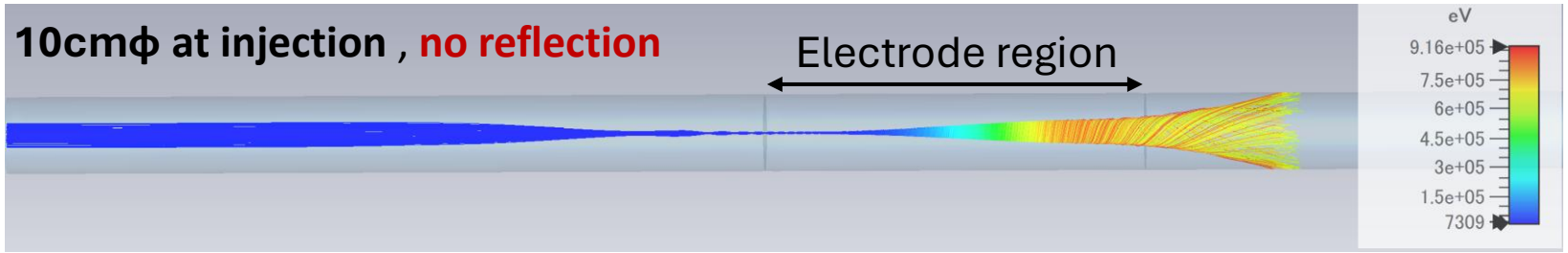
**Real MRI magnet** = ~1.5m length, inner diameter 80 cmϕ : 30 cmϕ beam pipe

Testbench : 1 m electrode oscillating field = one polarization



**Shielding coils**
**= higher gradient..**




**Initial beam size affect reflections :**
smaller beam, **less reflections**

But testbench will be done at low currents : **diameter << 10 cmϕ** !!

Magnet gradient (w/ shielding coils) might **not be a problem** in **testbench conditions** ☺

# Recap and perspectives

**What has been done so far**

Ideal simulations : **Target energy** despite **space charge**-induced **energy spread** ✓

Deuteron CARA : Design of **capactive-loaded cavities** for **compact low frequency** RF ✓

CST tracking : **5 MW cavity** for **compact IFMIF-type beam** + natural **momentum conversion** ✓

Testbench : **Low-currents** (= small bore) allow use of **commercial MRI magnet** ✓

**Next steps**

Capacitive loading (ceramics) : **losses, heating, practical feasibility** ?

CST simulations: **Space charge : PIC** simulations under 1A (ongoing)

# Thank you for your attention !
# ご清聴ありがとうございました！

**CUVELIER Matis**
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