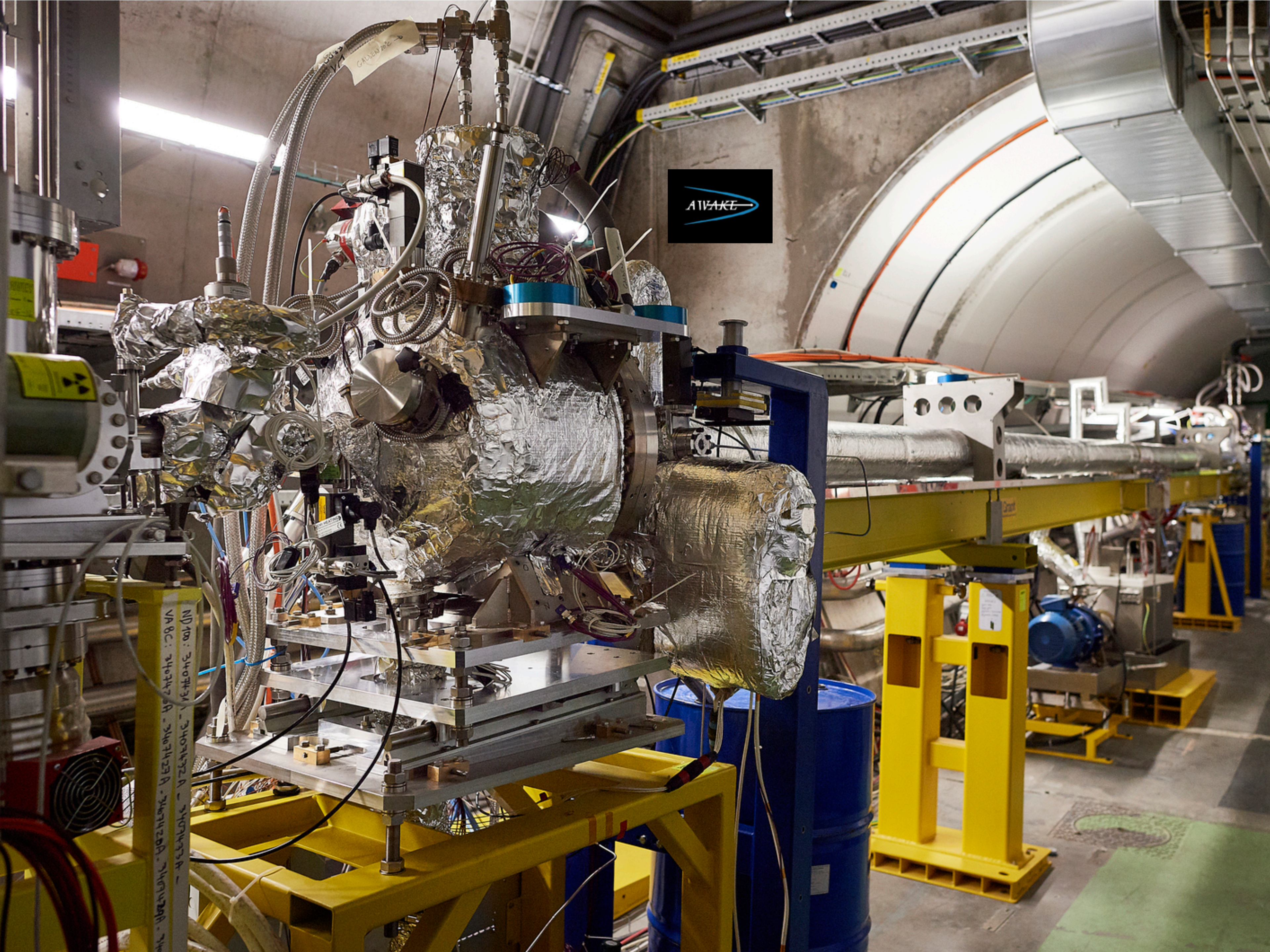
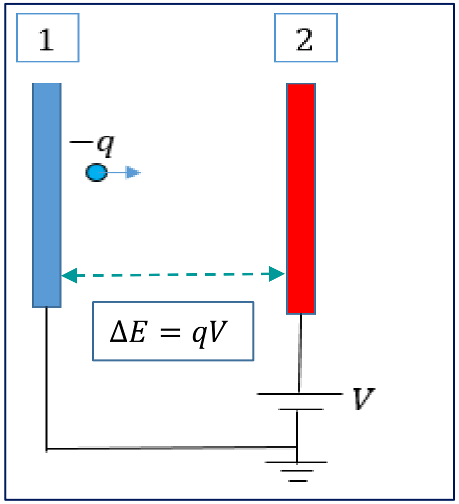
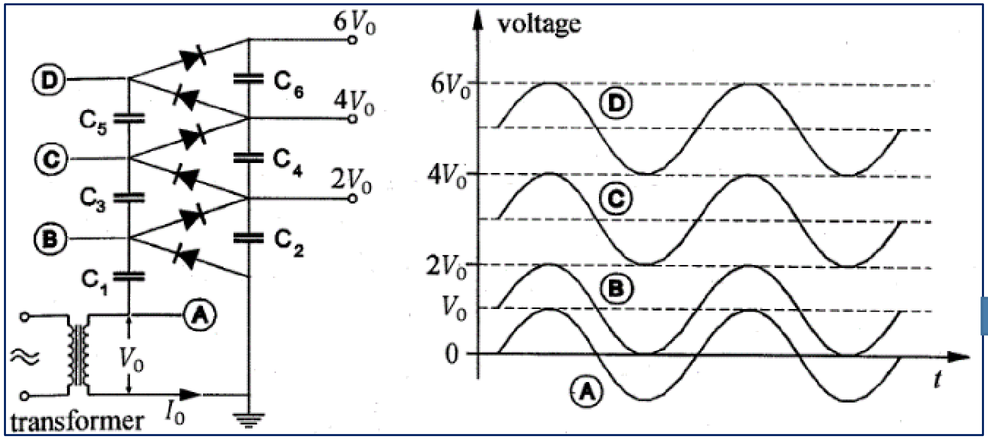

AWAKE

Contents

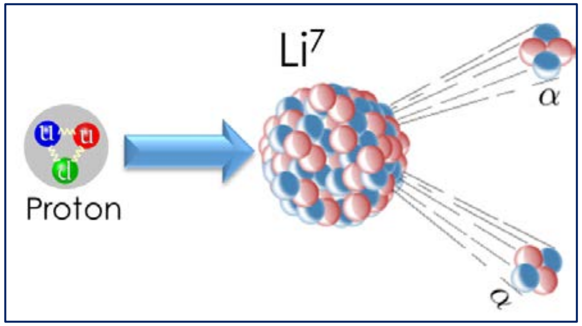
1.1 Electrostatic Accelerators



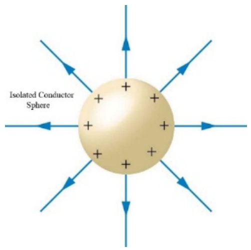


Cockcroft-Walton Accelerator-1928

1932-400 keV

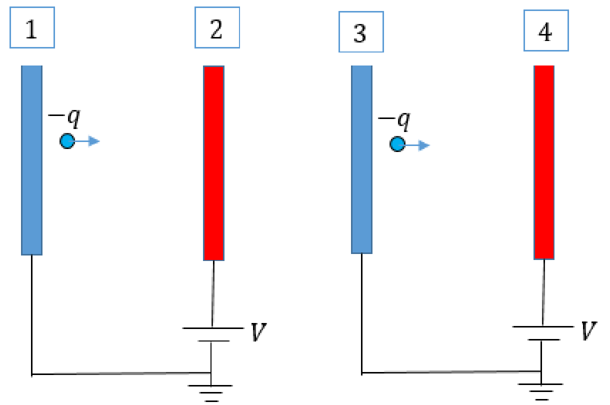


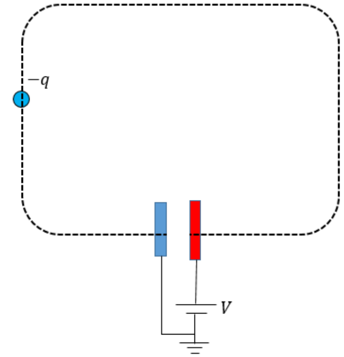
1.1 Electrostatic Accelerators



$$\begin{cases} V = \dfrac{q}{4\pi\varepsilon_0 r} \\ E = \dfrac{q}{4\pi\varepsilon_0 r^2} \end{cases} \Rightarrow E = \frac{V}{r}$$

$E_{max} \approx 2.5\ MV/m$ → To provide higher voltage the structure becomes very bulky → Maximum energy gain $20MeV$





$$\vec{\nabla} \times \vec{E} = 0$$
$$\vec{E} = -\vec{\nabla}\Phi$$

$$\Delta E_k = -\int_a^b q\vec{E} \cdot dl = q \times (\Phi_b - \Phi_a)$$

→ Conservative nature of the electrostatic fields makes it impossible to have a successive acceleration

1.2 RF Accelerators

To provide a successive acceleration → Non-Conservative Fields $\vec{\nabla} \times \vec{E} \neq 0$ → $\vec{\nabla} \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$ → Time dependent fields

Time dependent fields → Alternative electromagnetic fields

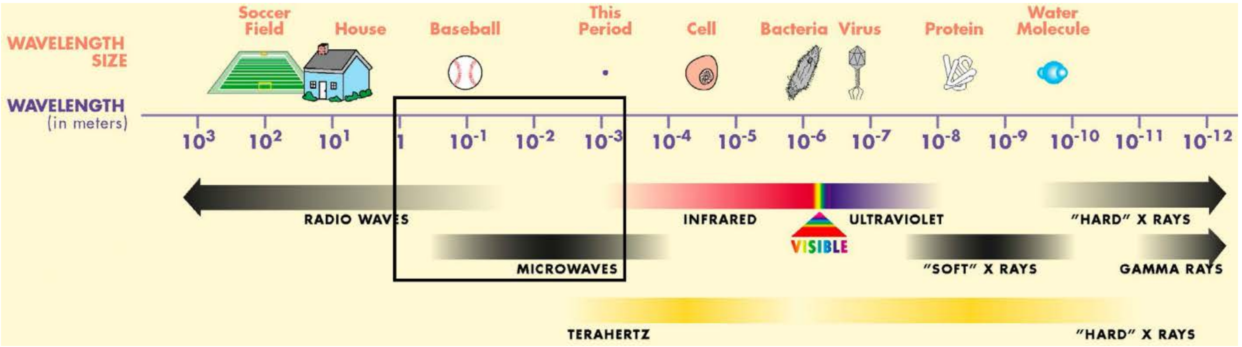
Repeatable acceleration → Alternative electromagnetic fields

Alternative electromagnetic fields ↓

$\vec{E} = \vec{E}_0 \, \mathrm{Sin}(\omega t + \theta_0)$

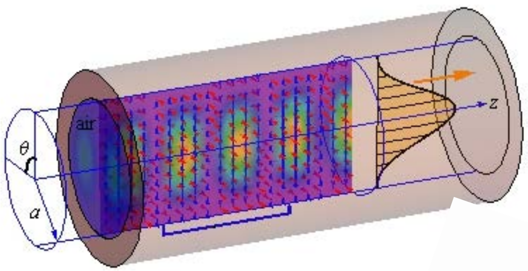
↓

The structural dimensions of the accelerator should be reasonable in ranging from mm to m → electromagnetic fields with wave lengths ranging from mm to m or frequencies between several MHz to several GHz → RF Fields



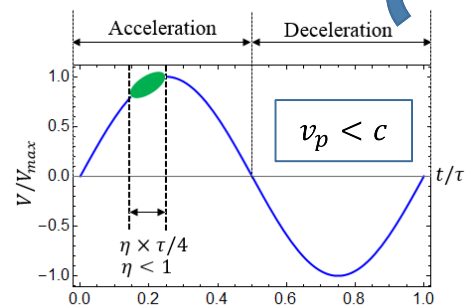
1.2 RF Accelerators

RF waves in a metallic cylinder



$$\vec{E}(\vec{\mathbf{r}},t) = \vec{E}_0(r,\emptyset)e^{i(kz-\omega t)}$$

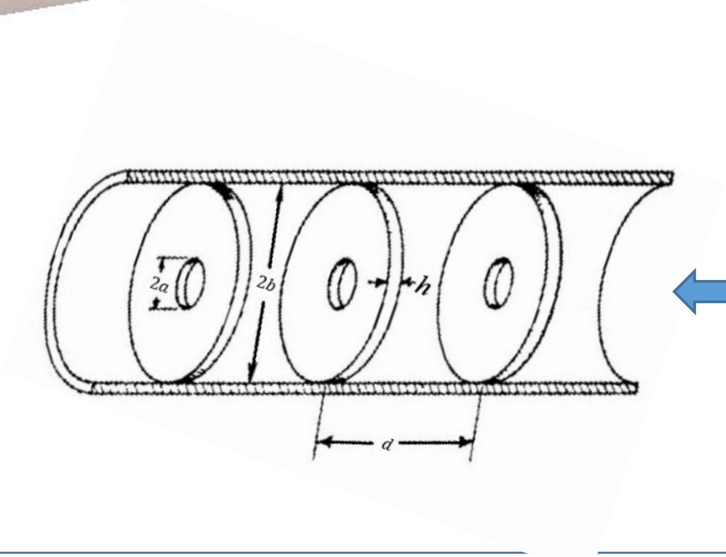
$$v_{ph} \times v_g = c^2$$



Phase Slippage and no net acceleration

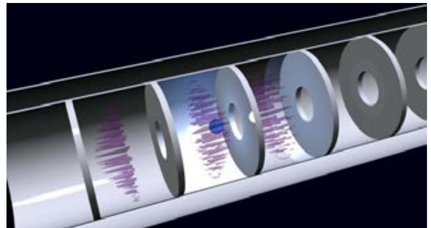
For acceleration we have to decrease v_{ph}

Disk-Loaded Structure



In the same years, Hansen at MIT built the first electron Linac (1947, 4.5 MeV, 3 GHz disk-loaded structure).

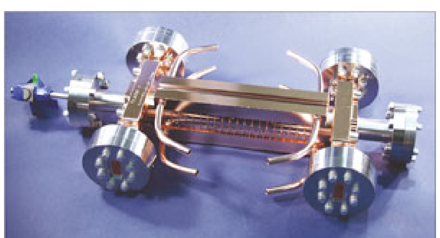
1.2 RF Accelerators



TW

$\vec{E} = \vec{E}_0 Sin(kz - \omega t)$

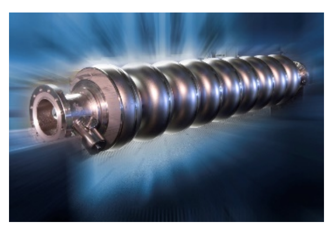
Normal Conducting RF Cavity (12 GHz-100 MV/m)



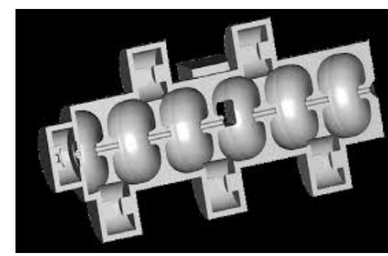
SW

$\vec{E} = \vec{E}_0 Sin(\omega t)$

Niobium super Conductor RF Cavity (1.3 GHz-31.5 MV/m)



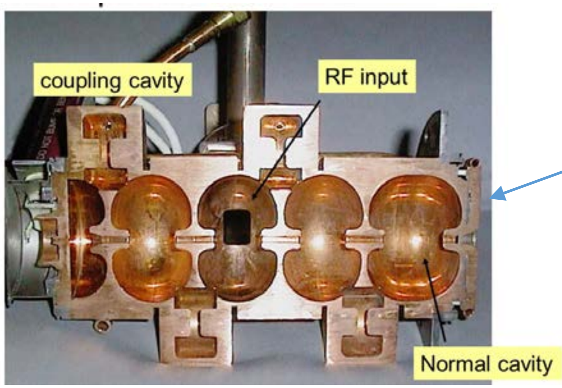
Side Coupled RF Cavity



1.2 RF Accelerators

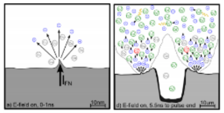
RF Acc. Material

Copper+Aluminum+Steel



Loss ↑ Time ↓ Cost ↓

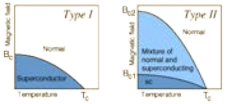
$100\frac{MeV}{m}$



Niobium+Titanium+Tin

Loss ↓ Time ↑ Cost ↑

$35\frac{MeV}{m}$



SCRF — Meissner break down

NCRF — RF breakdown

Maximum gradient of today's accelerators is limited to about $100\frac{MeV}{m}$.

RF Acc. Geometry

Linear Acc.

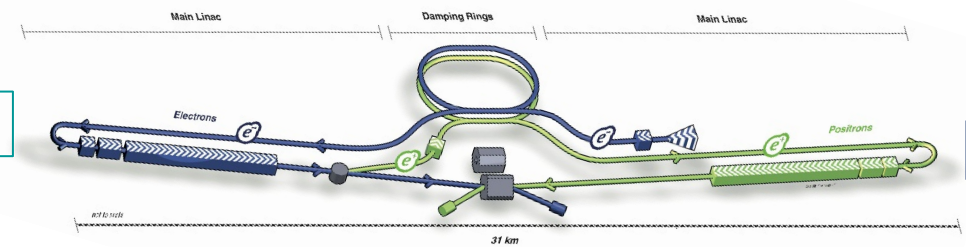
Circular Acc.

1.3 Necessity for a Novel Technology

E_k	$\frac{dE_k}{dz}$	$\left(\frac{dE_{rad}}{dz}\right)_{el}$	$\left(\frac{dE_{rad}}{dz}\right)_{ec}$
$1\ [\boldsymbol{TeV}]$	$100\ [\boldsymbol{MeV/m}]$	$3.8 \times 10^{-5}\ eV/m$	$1.4\ \mathrm{GeV}/m$

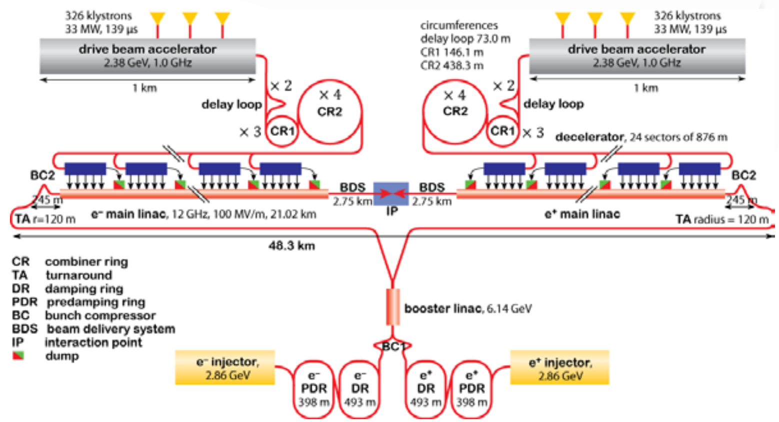
Lepton Collider in TeV Frontier

ILC 1TeV-50 km



60kS,20Bn

CLIC 3TeV-48 km

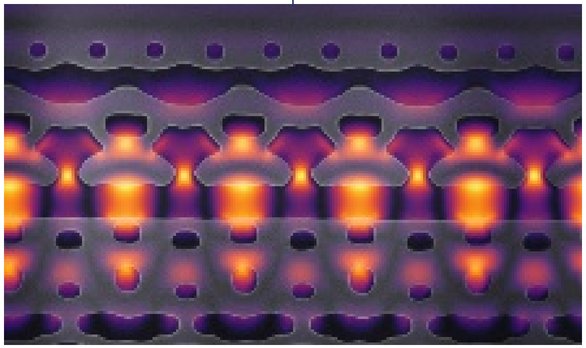


30kS,10Bn

A new high-gradient accelerator technology is mandatory to ensure TeV scale in reasonable cost and space. GeV/m

1.3 Necessity for a Novel Technology

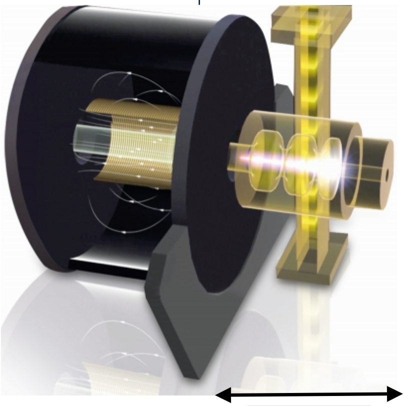
Dielectric Wall Acc.



μm

E_k>GeV/m

Terahertz Acc.

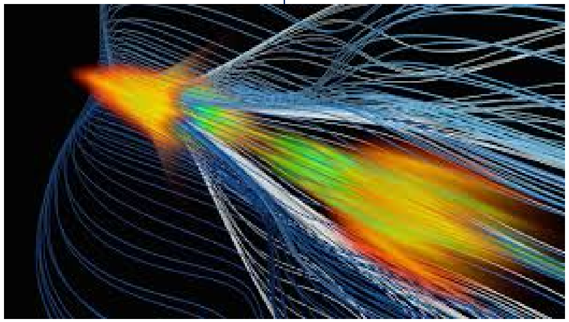


mm

$E \propto \sqrt{\omega}$

E_k >GeV/m

Plasma Wake-Field Acc.



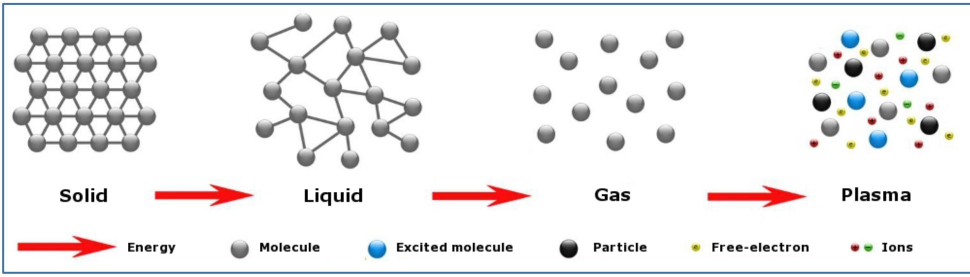
μm

$\nu_p[kHz] \approx 9.0\sqrt{n_0[1/cm3]}$

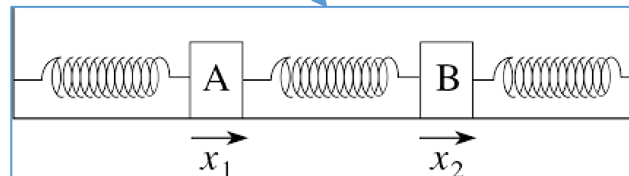
E_k >GeV/m ✓

2. Plasma Wakefield Acceleration

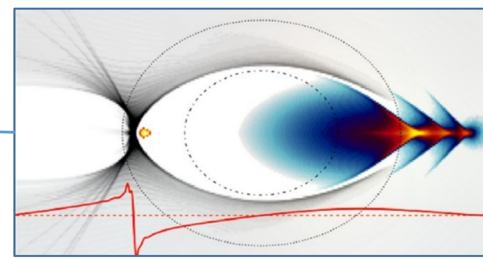
2.1 Plasma and Wakes



An ensemble of coupled oscillators



Separation between ions and electrons leads to charge density oscillation



Plasma wake fields excitation

A beam injected to plasma in right position and time can be accelerated significantly

Maximum field gradient can be excited in a plasma cell

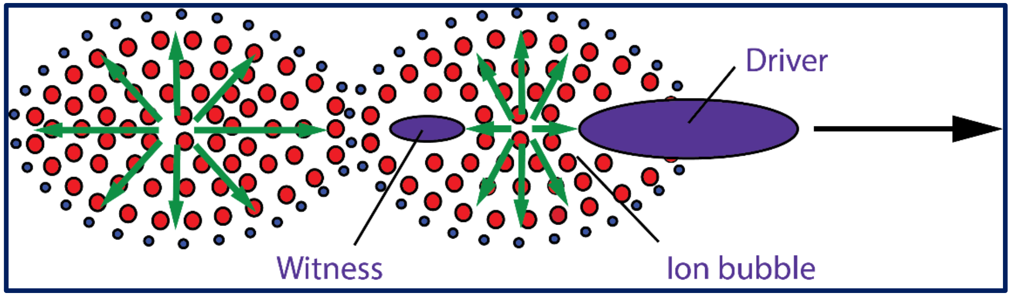
$$E_p \approx \sqrt{\frac{n_e[cm^{-3}]}{10^{14}}}\ GV/m$$

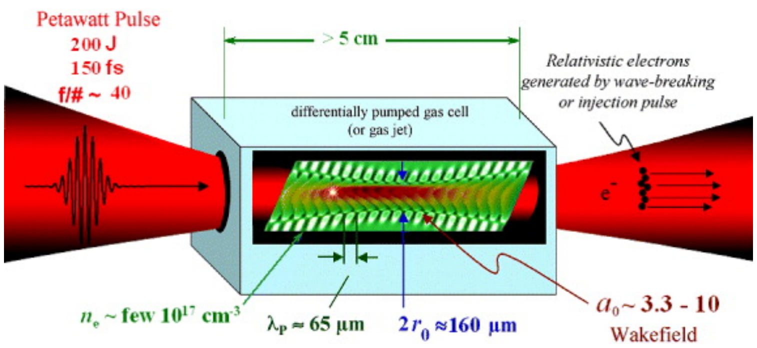
$n_e \geq 10^{14} cm^{-3}$ is required to provide 1 GeV/m

10 times more than maximum gradient in today's accelerators

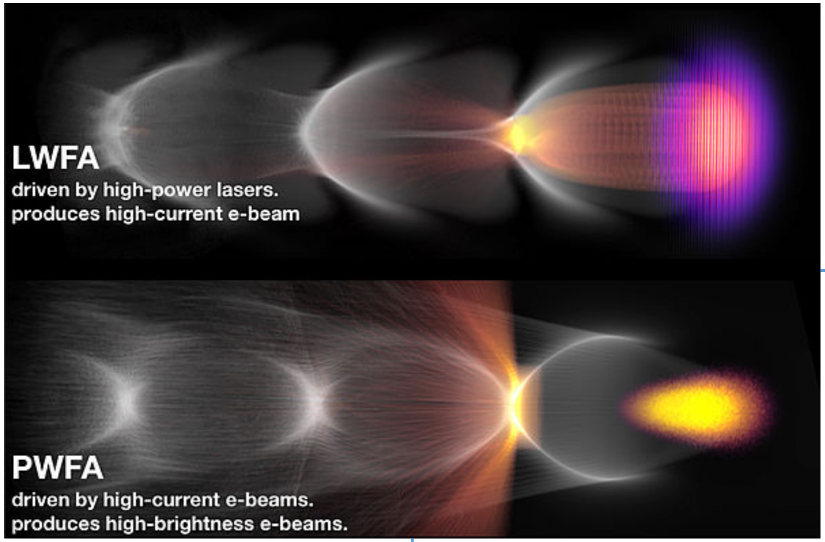
2.2 Wake Excitation

Metal vapor plasma sources (like rubidium), ionized with lasers, routinely (500cc-1at) reach plasma densities of this order and even more





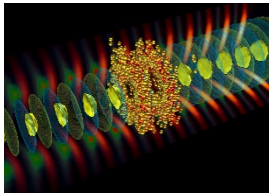
2.2 Wake Excitation



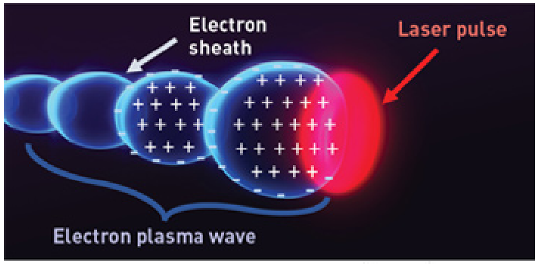
PWFA

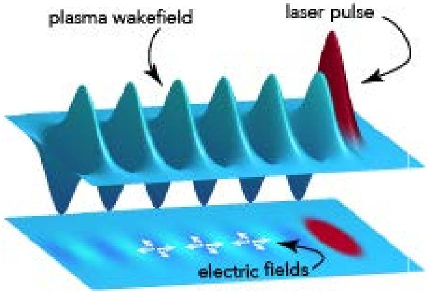
Propagation length of e^- drivers about $1\ m$.

Propagation length of p^+ drivers about $10\ m$.



LWFA

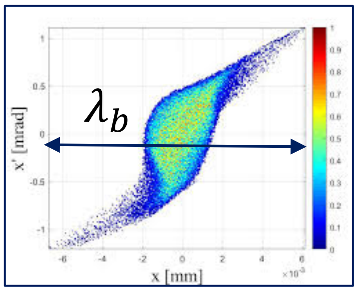




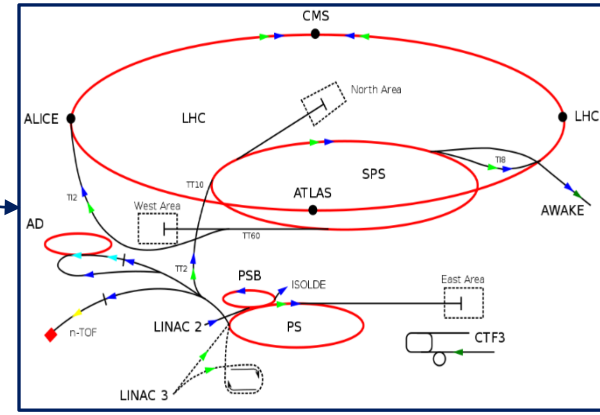
Propagation length about $1cm$

2.2 Wake Excitation

Proton Beams of 100A and Hundreds GeV are Required



CERN SPS : 400 GeV protons with 3×10^{11} particle , 19 kJ energy and 120A.



In order to derive the plasma wake fields efficiently.

$\lambda_p \cong \lambda_b$

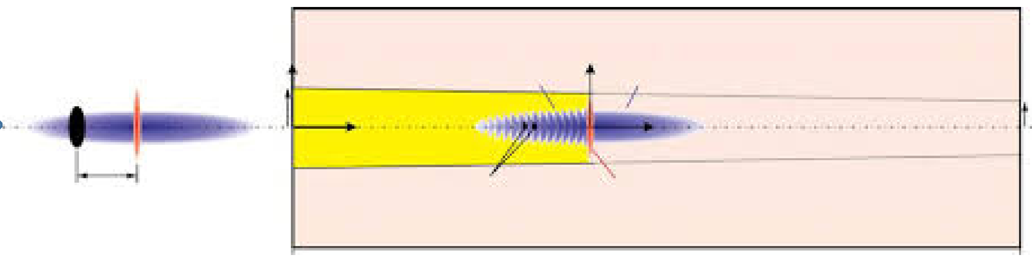
Plasma wavelength

$$\lambda_p \approx \sqrt{\frac{10^{15}}{n_e[cm^{-3}]}}\ mm$$

$\lambda_p \approx 1\ mm$ while SPS proton bunches are about 12cm long.

2.3 Self Modulation Instability

Discovery of self-modulation instability (SMI) (2010).



A long proton bunch in a plasma can generate a low amplitude transverse wake fields within its body.

The excited wakes can modulate periodically bunch radius with the period of λ_p.

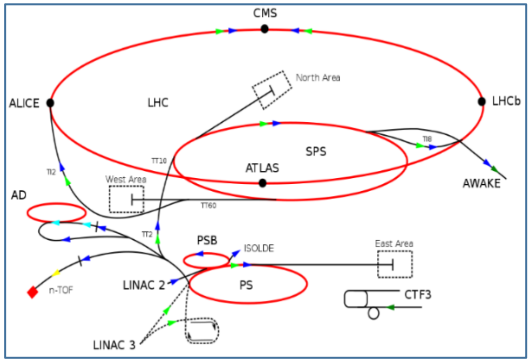
SMI splits the long proton beam into several ultrashort bunches of length λ_p, which can resonantly drive the plasma wake efficiently.

This ability launches the AWAKE (2013).

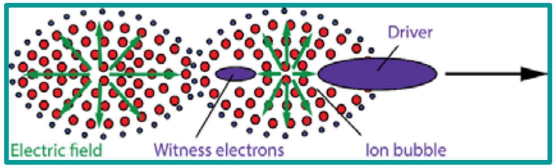
- Demonstration of the proton-driven plasma wake field acceleration power
- Develop necessary technologies for the long-term application.

Advanced Proton Driven Plasma Wakefield Acceleration Experiment (AWAKE)

3.1 AWAKE Experiment



CERN SPS : 400 GeV protons with 3×10^{11} particle , 19 kJ energy and 12 cm bunch length.

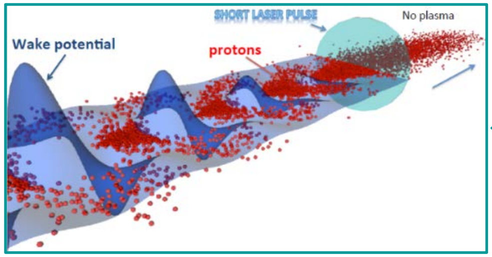


13 Inst.

AWAKE

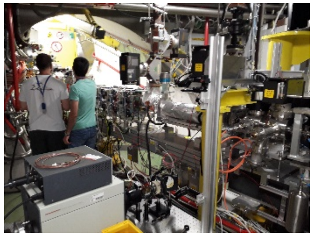
AWAKE: Advanced proton driven plasma wake-field acceleration experiment

2013 CDR



2018 ACHV

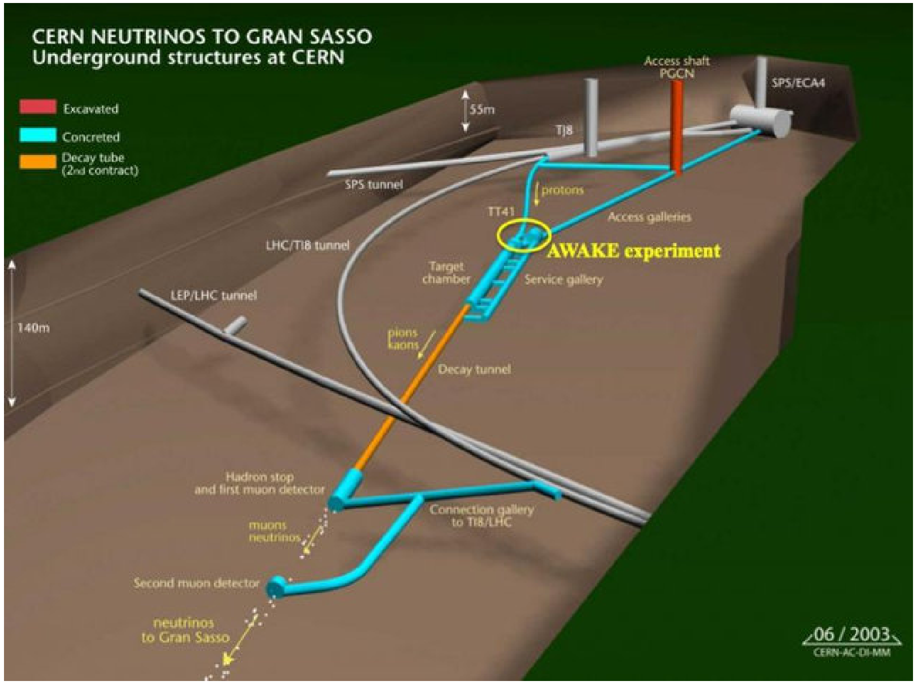
200 MeV/m



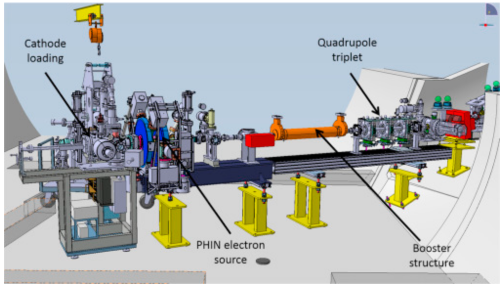
Edda Gschwendtner

3.1 AWAKE Experiment

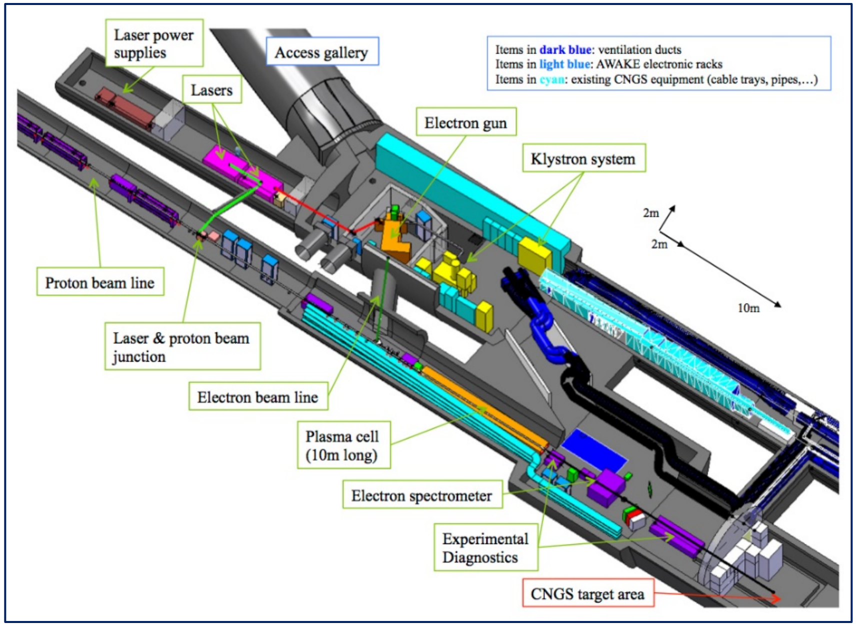
Awake underground



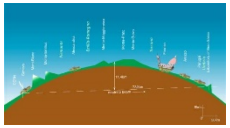
Awake e source



Awake Area

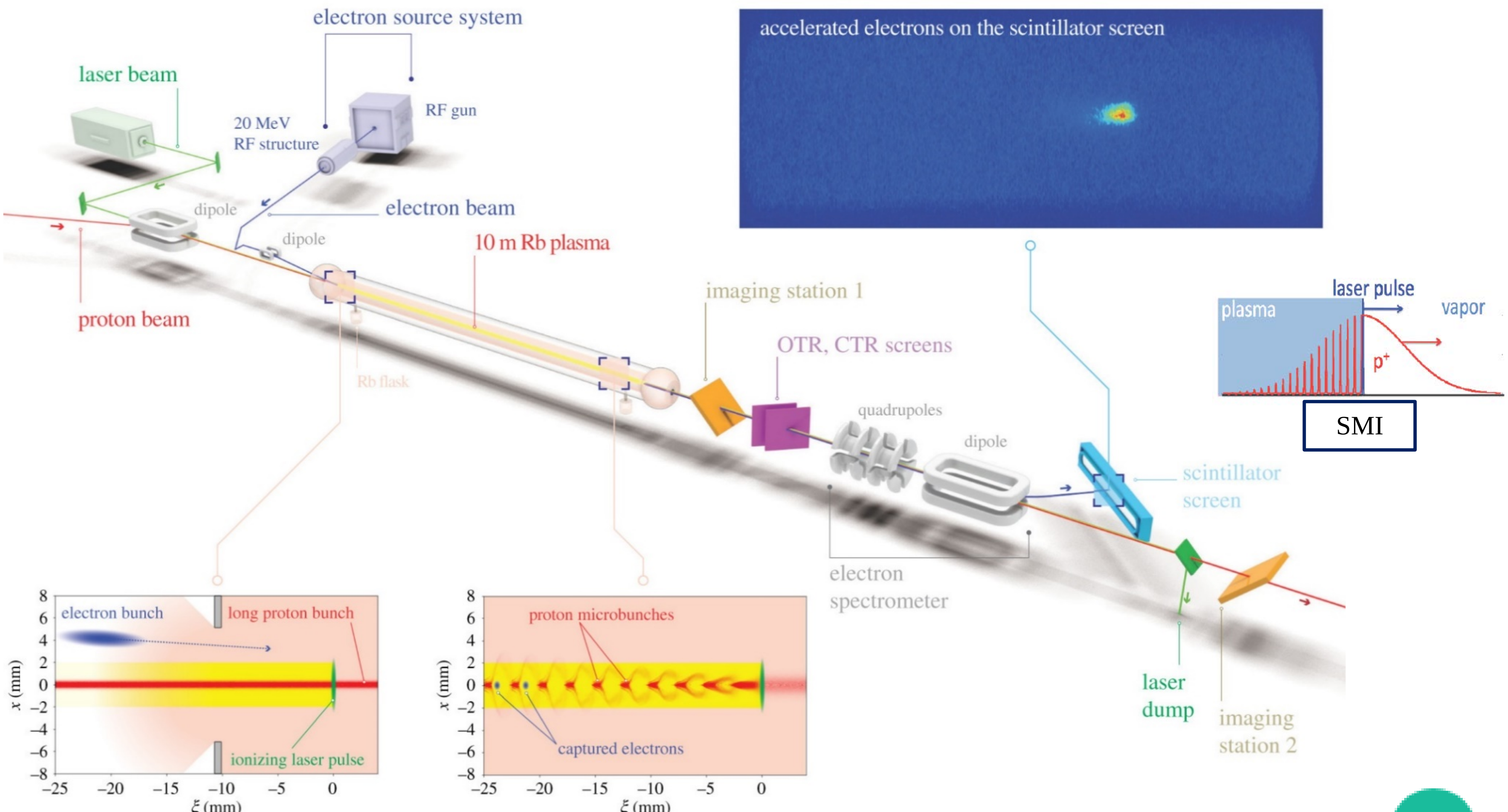


CNGS: CERN Neutrinos to Gran Sasso



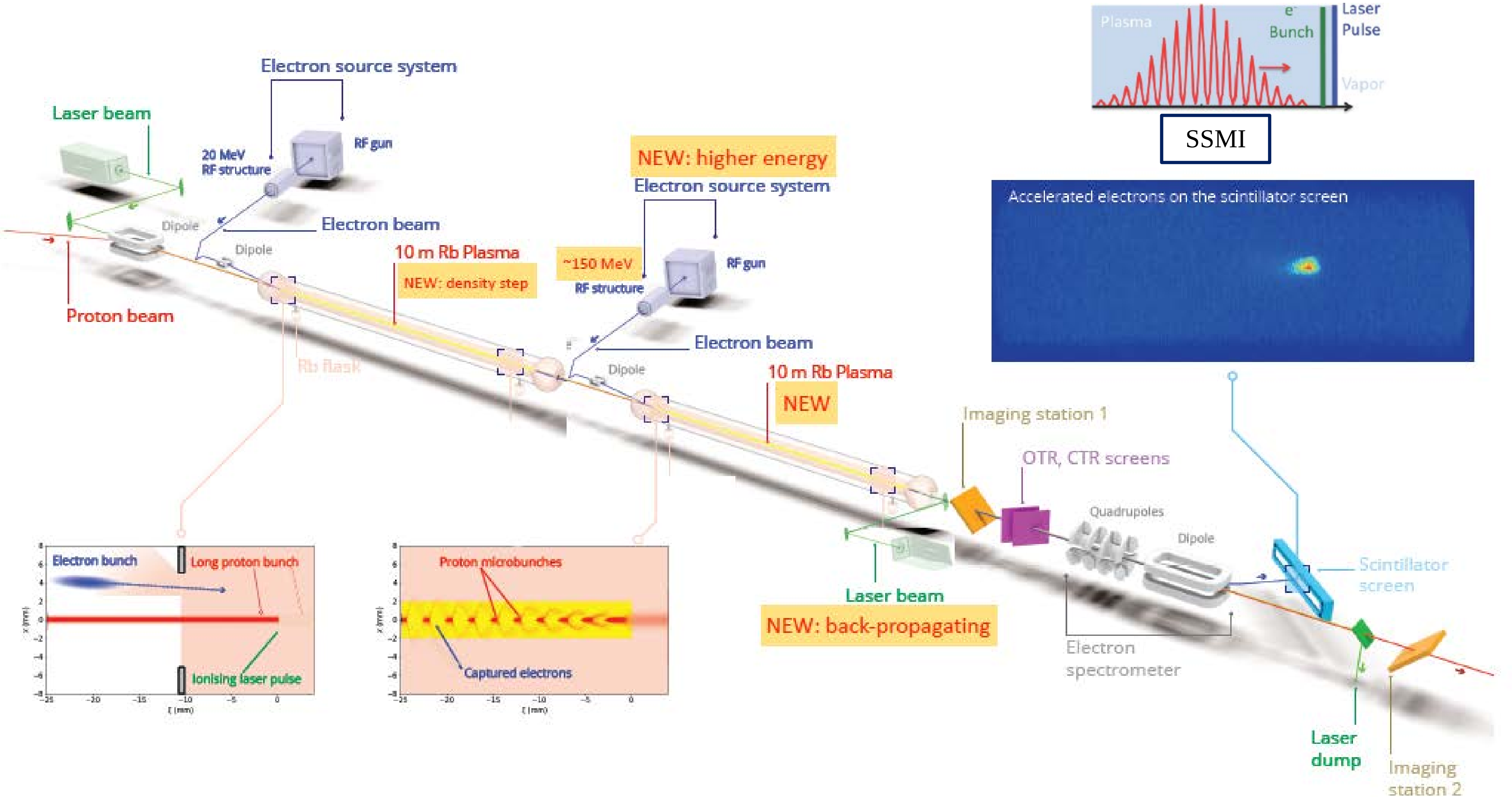
3.2 AWAKE Run I

RUN 1: 2016-2018: Proof-of-concept experiment. Successful electron acceleration in wakefield driven by a self-modulated proton beam.



3.3 AWAKE Run II

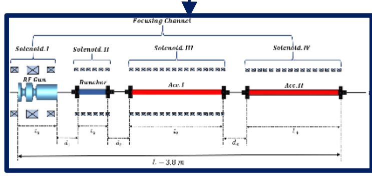
RUN 2: 2021 : Accelerate electrons to high energies (~10GeV) while preserving the beam quality and demonstrate the scalability in order to have first high energy physics applications.



3.4 IPM Collaboration

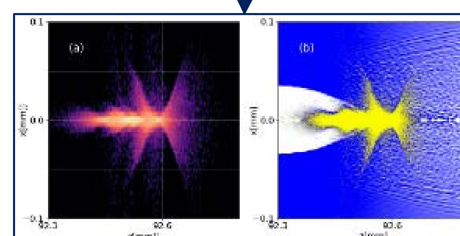
IPM Contribution
Since 2017

Electron Source, Design,
Simulation and Optimization



- Ultra Short
- High Current
- High Quality
- In Compact Structure

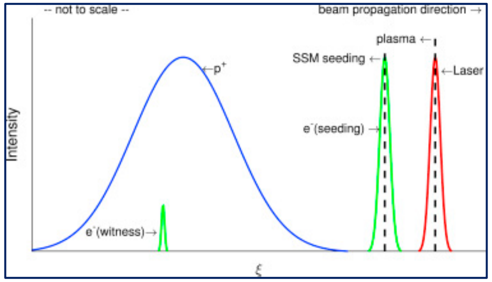
Simulation of the Plasma
Wake field Acceleration

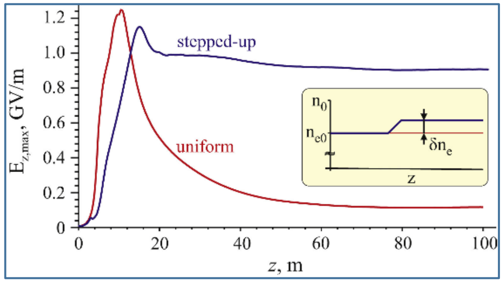


3.4 AWAKE Phases

AWAKE Run 2 Phases

- **A** → Demonstrate electron SSMI in first plasma cell
  - Predicted by simulations, but not yet fully explored in data
  - Find the best parameters to work reliably and phase-stable
- **C**
- **D**
- **B** → Demonstrate the stabilization of the micro-bunches with a density step
  - Design and install new plasma cell (SSMI source)
  - Show levelling of strong acceleration field





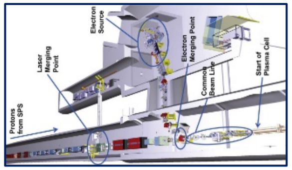
3.4 AWAKE Phases

AWAKE Run 2 Phases

C

Demonstrate electron acceleration and emittance preservation

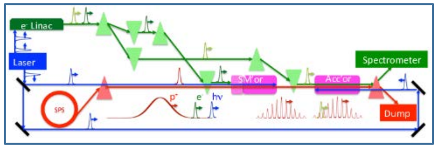
Expand the experimental area



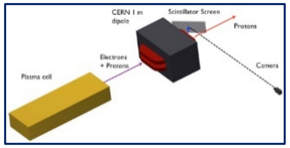
New electron source and beam line

New plasma cell

New laser to 2nd plasma cell



New diagnostics



Experimental program to demonstrate simultaneous energy gain and good emittance

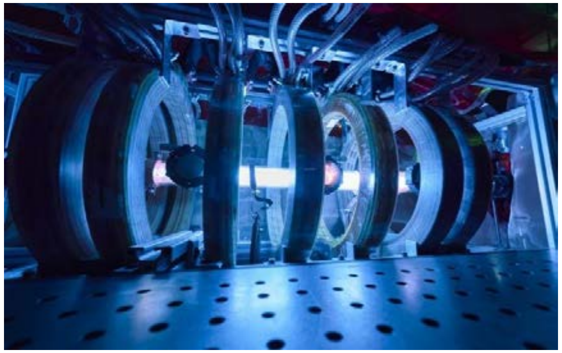
3.4 AWAKE Phases

AWAKE Run 2 Phases

D

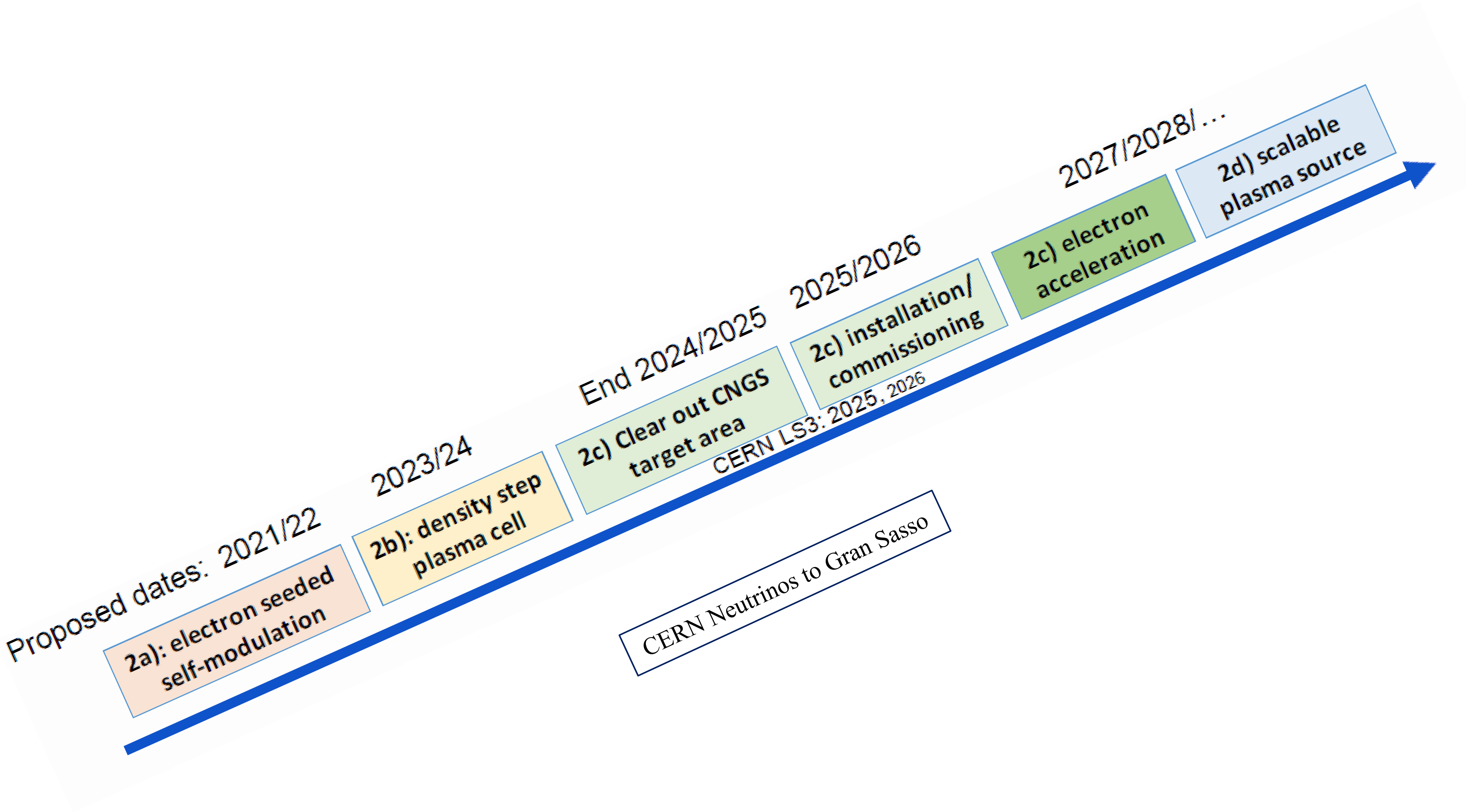
Demonstrate scalable plasma sources

Laboratory developments in dedicated plasma labs



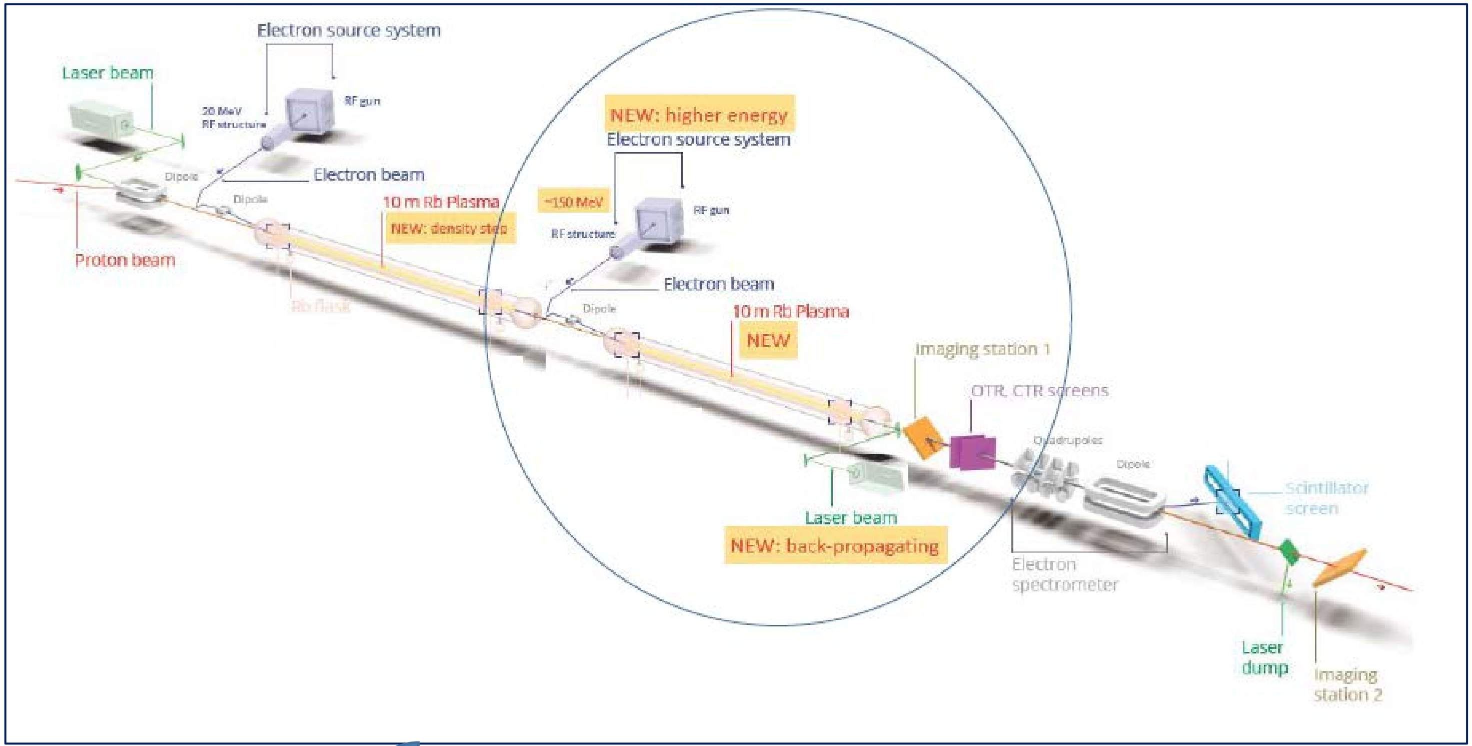
Proof-of concept in AWAKE experiment

3.4 AWAKE Phases



3.5 AWAKE Phases C

Run 2c: Demonstrate Electron Acceleration and Emittance Preservation

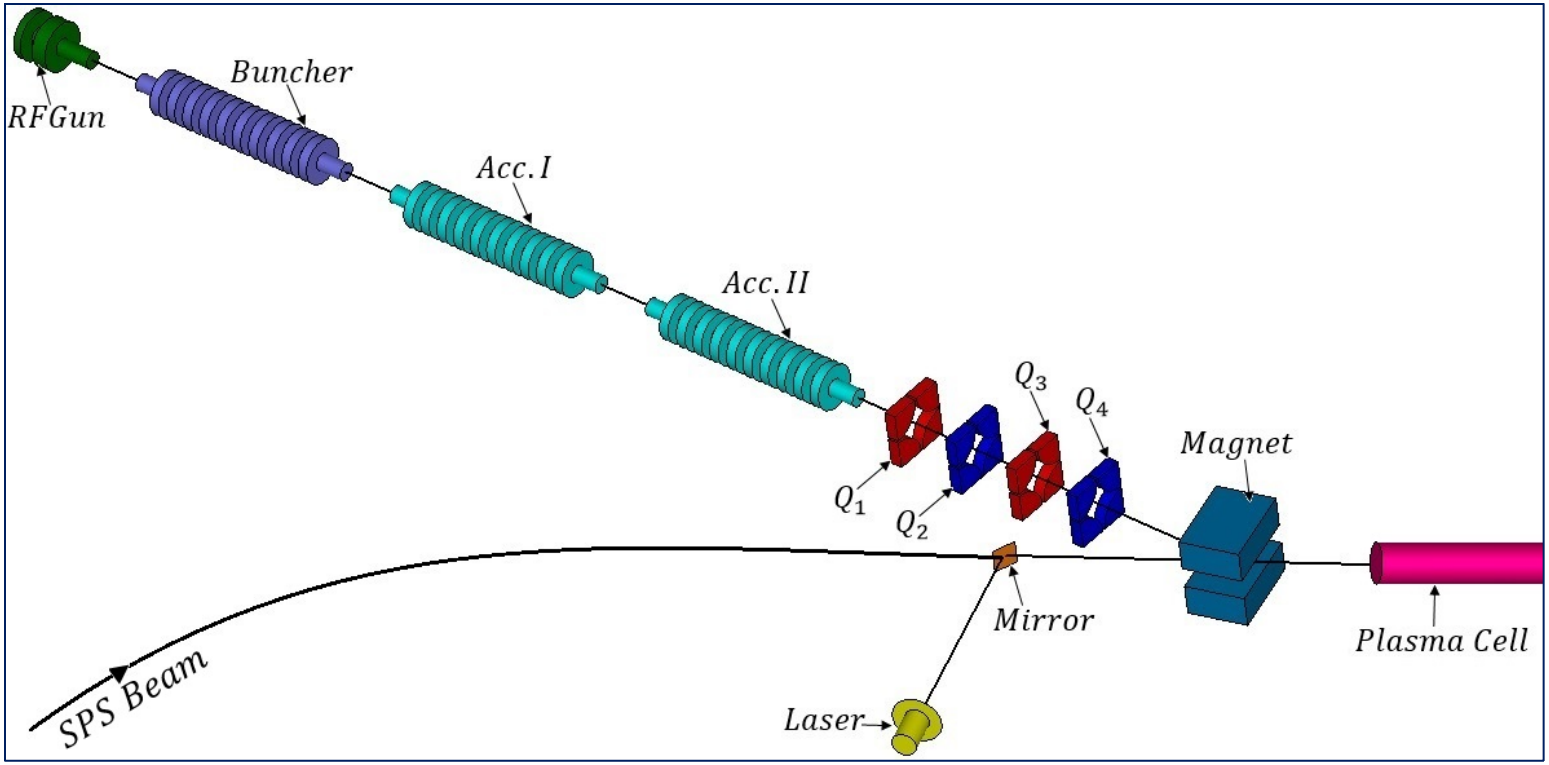


Detailed studies of the electron acceleration need to be done now to be ready for Run 2

2024-2025

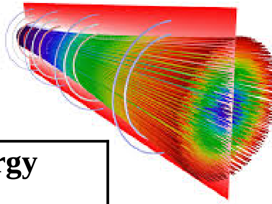
4.1 E-Source Layout

Injection of a compact and high-quality electron bunch at a right phase allows for a propagation over long distances with no emittance growth (apart from the head of the bunch)



4.2 E-Source Requirements

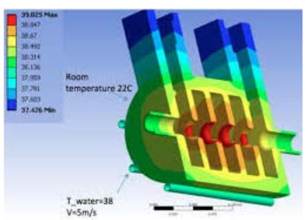
Beam Characteristics



Type	Bunch Charge	Bunch Length	Energy Spread	Emittance	Beam Size	Energy
1st	$100-600\ pC$	$2-3ps$	$<1\%$	$<5\ \mu m$	$<190\mu m$	$15-20MeV$
2nd	$100\ pC$	$50-300fs$	$<1\%$	$<2\ \mu m$	$<5.75\mu m$	$80\ -160MeV$

RF Characteristics

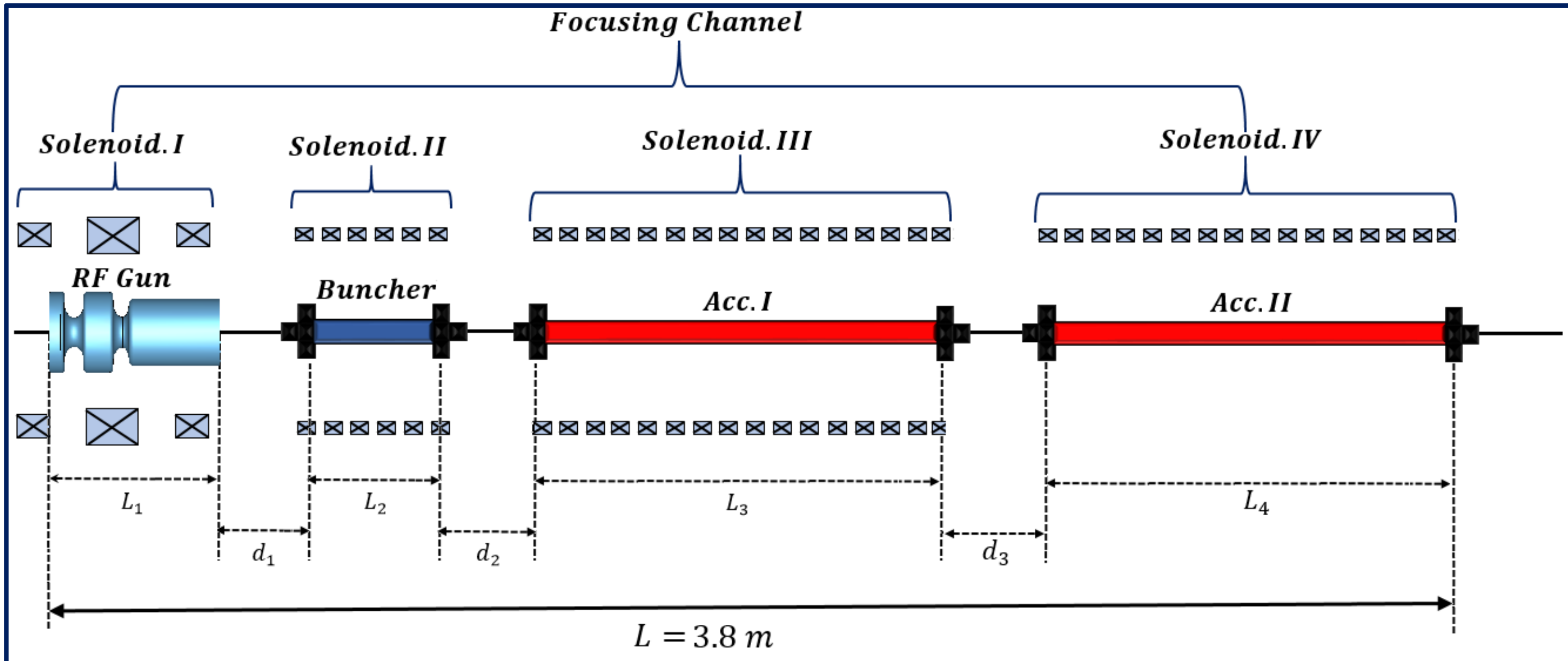
Parameter	RF Gun	Buncher	Acc. I	Acc. II
Frequency	3.0	$3-12.0$	$3-12.0$	$3-12.0$
Gradient	$120MV/m$	$20-50MV/m$	$20-80MV/m$	$20-80MV/m$
N. Cell	1.5	30	120	120



Laser Characteristics

$\lambda[nm]$	$w[ev]$	$r[mm]$	$t[ps]$	$q[pc]$
262	4.31	1.0-2.0	1.0	100-600

4.3 E-Source Structure



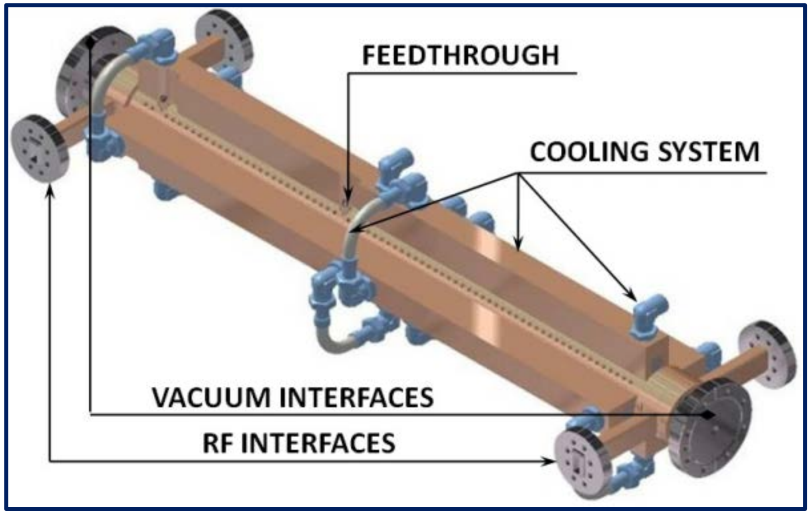
S Band RF Gun Very High Quality EBeam Generation

X Band Buncher for Very Strong Bunching

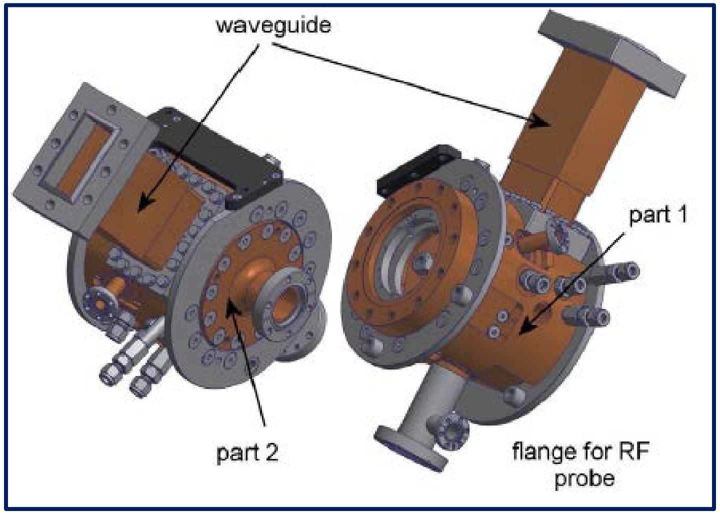
X Band Acc for Very Compact Acceleration

4.3 E-Source Structure

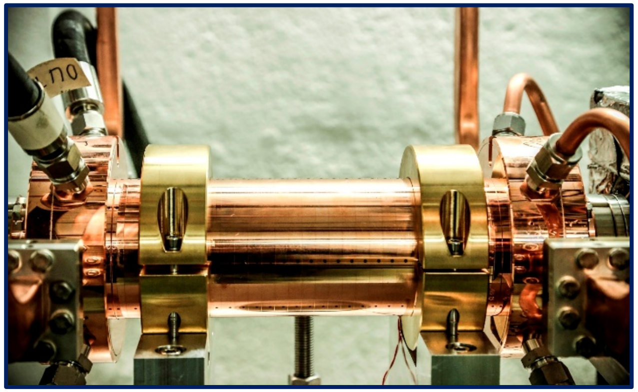
120 cell, X-Band, Swiss FEL Str.



1.6 cell, S-Band, LNF-INFN Str.



30 cell, X-Band, CLIC Str.



5.1 Ray Equations

Lorentz's Force Equation: $\frac{d\vec{p}}{dt} = q\vec{\boldsymbol{E}} + q\vec{v} \times \vec{\boldsymbol{B}}$

$p_z \gg p_\perp$

$\frac{d}{dt} \cong \beta c \frac{d}{dz}$

$r \ll d_{ex}$

Dimensions of the External Apparatus

$$\vec{E} \cong E_z^s \hat{z} + E_r^s \hat{r} + \left(\hat{z} - \frac{r\hat{r}}{2}\frac{\partial}{\partial z}\right) E_z^e$$

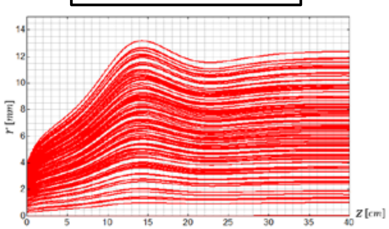
$$\vec{B} \cong \frac{\beta_0}{c} E_r^s \hat{\emptyset} + \left(\hat{z} - \frac{r\hat{r}}{2}\frac{\partial}{\partial z}\right) B_z^e + \left(\frac{r\hat{\emptyset}}{2c^2}\frac{\partial}{\partial t}\right) E_z^e$$

Energy Terms

External Terms

Space Charge Terms

Ray Equations



$$\left\{\frac{d^2}{d{z_0}^2} + \frac{{\gamma_0}'}{\gamma_0(\gamma_0\beta_0)^2}\frac{d}{dz_0} + \left[\frac{\eta}{2\gamma{\beta_0}^2}\left(\frac{\partial E_z^e}{\partial z} + \frac{\beta_0}{c}\frac{\partial E_z^e}{\partial t}\right) + \left(\frac{\eta c B_z^e}{2\gamma_0\beta_0}\right)^2\right] - \frac{\eta E_r^s}{r\gamma_0(\gamma_0\beta_0)^2}\right\}(\Delta x + i\Delta y) \cong 0$$

$$\left\{\frac{d^2}{d{z_0}^2} + \frac{{\gamma_0}'}{\gamma_0(\gamma_0\beta_0)^2}\frac{d}{dz_0}\right\}\Delta z + \frac{{\gamma_0}'}{\gamma_0(\gamma_0\beta_0)^2} \cong \frac{\eta E_z^e}{\gamma_0(\gamma_0\beta_0)^2} + \frac{\eta E_z^s}{\gamma_0(\gamma_0\beta_0)^2}$$

50k Particles

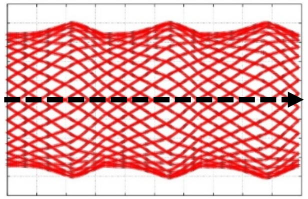
5.2 Envelope Equations

Beam Envelops

$$\sigma_r = \sqrt{\langle r^2 \rangle}$$

$$\sigma_z = \sqrt{\langle \Delta z^2 \rangle}$$

Particle Trajectories



z

Take an Average over Whole Particles

$$\sigma_r'' + \frac{\gamma_0'}{\gamma_0 {\beta_0}^2}\sigma_r' = -\frac{\eta \sigma_r}{2{\beta_0}^2\gamma_0}\langle \frac{\partial E_z^e}{\partial z} + \frac{\beta_0}{c}\frac{\partial E_z^e}{\partial t}\rangle - \frac{\eta^2 c^2 \sigma_r}{4{\gamma_0}^2{\beta_0}^2}\langle {B_z^e}^2 \rangle + \frac{\eta}{{\beta_0}^2{\gamma_0}^3\sigma_r}\langle E_r^s r\rangle + \frac{(\varepsilon_x + \varepsilon_y)^2}{{\beta_0}^2{\gamma_0}^2{\sigma_r}^3}$$

$$\sigma_z'' + \frac{\gamma_0'}{\gamma_0 {\beta_0}^2}\sigma_z' = +\frac{\eta}{{\beta_0}^2{\gamma_0}^3\sigma_z}\langle E_z^e\, \Delta z\rangle + \frac{\eta}{{\beta_0}^2{\gamma_0}^3\sigma_z}\langle E_z^s \Delta z\rangle + \frac{(\varepsilon_z)^2}{{\beta_0}^2{\gamma_0}^2{\sigma_z}^3}$$

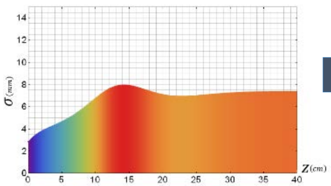
External Forces

Space charge Forces

Emittance Forces

5.3 Space Charge Forces

Envelope Equations



Full/Semi-Analytical Model for E-Source Design

Fast Design Tool Vs Trks

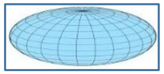
Most problematic issue is Space charge forces

Radial reduction factor

Radial perveance

$$\frac{\eta}{{\beta_0}^2{\gamma_0}^3\sigma_r}\langle E_r^s r\rangle = \frac{K_r}{\sigma_r}\times\left(1-\frac{I_c\eta\beta_0}{2\langle I(r,z)\rangle}\langle\int_0^r \frac{\partial E_z^s(r',z)}{\partial z}r'dr'\rangle\right)=\alpha_r\times\frac{K_r}{\sigma_r}$$

$$K_r = \frac{\eta}{2\pi\varepsilon_0{\beta_0}^2{\gamma_0}^3}\langle\int_0^r \rho(r',z)2\pi r'dr'\rangle$$

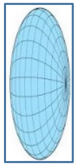


longitudinal perveance

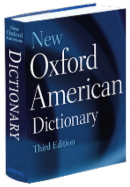
$$\frac{\eta}{{\beta_0}^2{\gamma_0}^3\sigma_z}\langle E_z^s\Delta z\rangle = \alpha_z\times\frac{K_z}{\sigma_z}$$

Longitudinal enhancement factor

$$K_z = \frac{\eta}{\varepsilon_0{\beta_0}^2{\gamma_0}^3}\langle z\int_{-\infty}^{z}\rho(r,z')dz'\rangle$$



Space Charge Dictionary



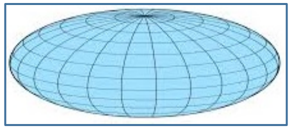
5.3 Space Charge Forces

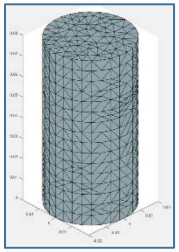
From Physics point of view We expect that

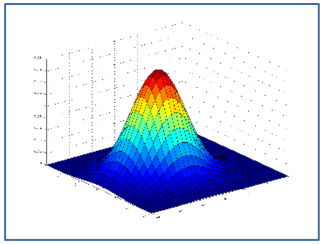
- These coefficients should be largely independent of the details of bunch structure
- They should greatly depend on the general bunch characteristics and be determined functionally from the bunch dimensions σ_r and σ_z.

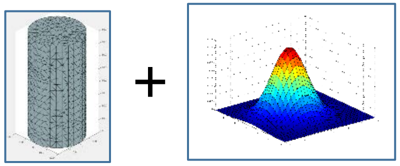
We can consider a few simple cases where their calculations are more straightforward and fully analytic

Type	$\rho(r, z, \sigma_r, \sigma_z)$
GG	$\dfrac{q_b e^{-\left(\frac{z}{\sqrt{2}\sigma_z}\right)^2} e^{-\left(\frac{r}{\sigma_r}\right)^2}}{\pi\sqrt{2\pi}{\sigma_r}^2\sigma_z}$
GU	$\dfrac{q_b e^{-\left(\frac{r}{\sigma_r}\right)^2}}{2\sqrt{3}\pi{\sigma_r}^2\sigma_z} \times \begin{cases} 0 & Else \\ 1 & \lvert z\rvert \leq \sqrt{3}\sigma_z \end{cases}$
US	$\dfrac{3q_b}{10\sqrt{5}\pi{\sigma_r}^2\sigma_z} \times \begin{cases} 0 & Else \\ 1 & \left(\frac{\sqrt{2}r}{\sqrt{5}\sigma_r}\right)^2 + \left(\frac{z}{\sqrt{5}\sigma_z}\right)^2 \leq 1 \end{cases}$
UG	$\dfrac{q_b e^{-\left(\frac{z}{\sqrt{2}\sigma_z}\right)^2}}{2\pi\sqrt{2\pi}{\sigma_r}^2\sigma_z} \times \begin{cases} 0 & Else \\ 1 & r \leq \sqrt{2}a \end{cases}$
UC	$\dfrac{q_b}{4\sqrt{3}\pi{\sigma_r}^2\sigma_z} \times \begin{cases} 0 & Else \\ 1 & \lvert z\rvert \leq \sqrt{3}\sigma_z \;,\; r \leq \sqrt{2}\sigma_r \end{cases}$









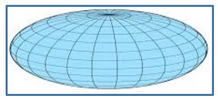
5.3 Space Charge Forces

$$K_r = \alpha_0 \times \frac{\eta q_b}{8\pi\varepsilon_0 {\beta_0}^2 {\gamma_0}^3 \sigma_z}$$

$$K_z = \alpha_0 \times \frac{\eta q_b \sigma_z}{4\pi\varepsilon_0 {\beta_0}^2 {\gamma_0}^3 {\sigma_r}^2}$$

Type	GG	GU	US	UG	UC
α_0	$1/\sqrt{\pi}$	$1/\sqrt{3}$	$1.2/\sqrt{5}$	$1/\sqrt{\pi}$	$1/\sqrt{3}$

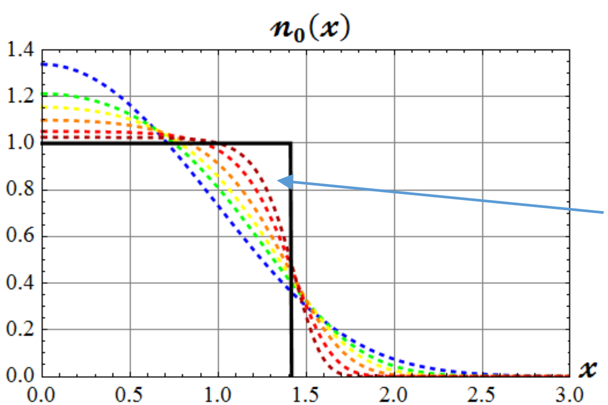
Deviation



Without US 4.8 %

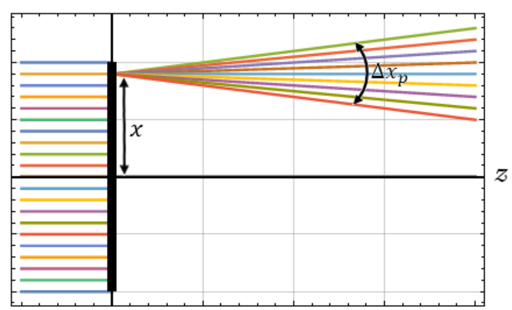
With US 1.2 %

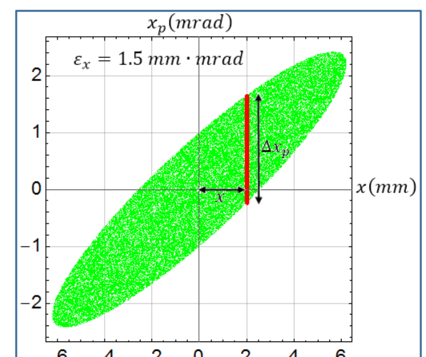
US bunch → zero-temperature Maxwell–Boltzmann distribution. → A bunch with vanishing emittance



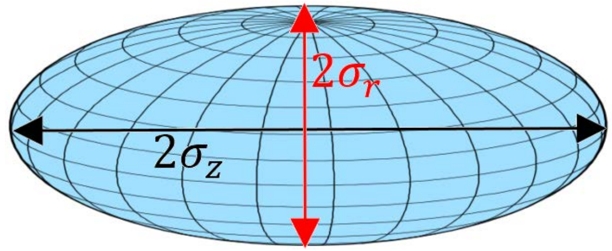
$\varepsilon = 0$

$$\varepsilon_x = \sqrt{\langle x^2\rangle\langle {p_x}^2\rangle - \langle x p_x\rangle^2}$$





5.3 Space Charge Forces



Space-Charge Potential

CMF

$$\psi^s(r,z,\sigma_r,\sigma_z) = \frac{1}{4\pi\epsilon_0}\int_{-\infty}^{+\infty}\int_0^{\infty}\int_0^{2\pi}\frac{\rho(r',z',\sigma_r,\sigma_z)r'dr'd\emptyset'dz'}{\left((z-z')^2+r^2+r'^2-2rr'Cos(\emptyset')\right)^{1/2}}$$

Space-Charge Field

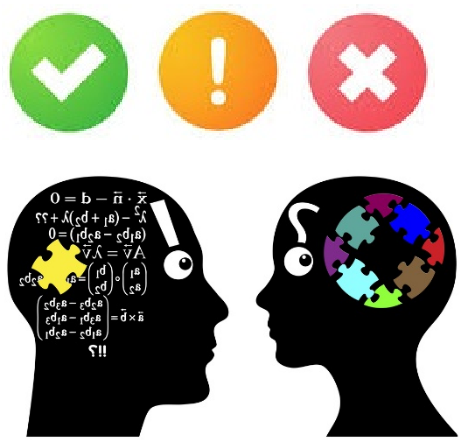
LF

$$\overrightarrow{E^s}(r,z) \cong -\lim_{\substack{z\to\gamma_0\delta_z\\ \sigma_z\to\gamma_0\sigma_z}}\left(\hat{z}\frac{\partial}{\partial z}+\gamma_0\hat{r}\frac{\partial}{\partial r}\right)\psi(r,z,\sigma_r,\sigma_z)$$

5.3 Space Charge Forces

$$\langle E_z^s z\hat{z} + E_z^s r\hat{r}\rangle = -\frac{1}{4\pi\epsilon_0 q_b}\int_{-\infty}^{+\infty}\int_0^{\infty}\int_0^{2\pi}\rho(r,z,\sigma_r,\sigma_z)\,r\,dr\,d\emptyset\,dz$$

$$\times \lim_{\substack{z\to\gamma_0\delta_z \\ \sigma_z\to\gamma_0\sigma_z}}\left(\hat{z}\frac{\partial}{\partial z} + \gamma_0\hat{r}\frac{\partial}{\partial r}\right)\int_{-\infty}^{+\infty}\int_0^{\infty}\int_0^{2\pi}\frac{\rho(r',z',\sigma_r,\sigma_z)\,r'\,dr'\,d\emptyset'\,dz'}{\left((z-z')^2 + r^2 + r'^2 - 2rr'Cos(\emptyset')\right)^{1/2}}$$



5.3 Space Charge Forces

$$\langle E_z^s z\rangle = \frac{q_b\sqrt{3}\sigma_z}{2\pi\epsilon_0{\sigma_r}^2}\int_0^\infty \frac{J_1\left(\sqrt{\frac{2}{3}}\mu u\right)^2 e^{-u}\left(uCosh(u) - Sinh(u)\right)}{u^4}du$$

$$\langle E_r^s r\rangle = \frac{q_b}{8\pi\sqrt{3}\epsilon_0\sigma_z}\left(1 - \frac{4\sqrt{6}}{\mu}\int_0^\infty \frac{J_1\left(\sqrt{\frac{2}{3}}\mu u\right)J_2\left(\sqrt{\frac{2}{3}}\mu u\right)e^{-u}Sinh(u)}{u^3}du\right)$$

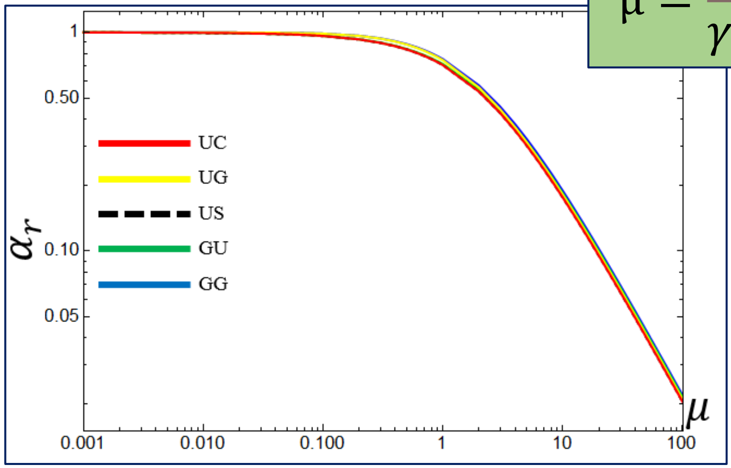
$$\mu = \frac{\sigma_r}{\gamma_0\sigma_z}$$

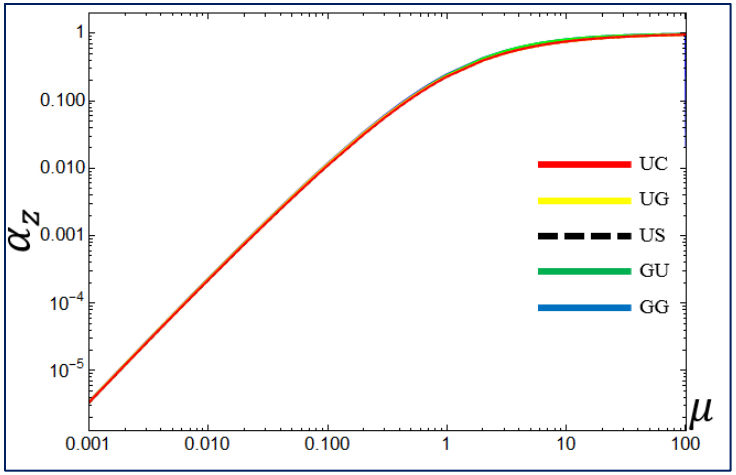
5.3 Space Charge Forces

Type	$\alpha_r(\mu)$
GG	$\sqrt{\pi}\mu^2\int_0^\infty u^2 e^{u^2} e^{-\left(\frac{\mu u}{\sqrt{2}}\right)^2} Erfc(u)du$
GU	$\frac{\mu^2}{3}\int_0^\infty e^{-\left(\frac{\mu u}{\sqrt{6}}\right)^2}\left(u-e^{-u}sinh(u)\right)du$
US	$2A_r\left(\frac{1}{2}\mu^2-1\right)$
UG	$\frac{16}{\sqrt{2\pi}\mu}\int_0^\infty \frac{e^{-\left(\frac{u}{\sqrt{2}}\right)^2} K_1(\mu u)I_2(\mu u)}{u}du$
UC	$1-\frac{4\sqrt{6}}{\mu}\int_0^\infty \frac{J_1(\sqrt{2/3}\mu u)J_2(\sqrt{2/3}\mu u)e^{-u}sinh(u)}{u^3}du$

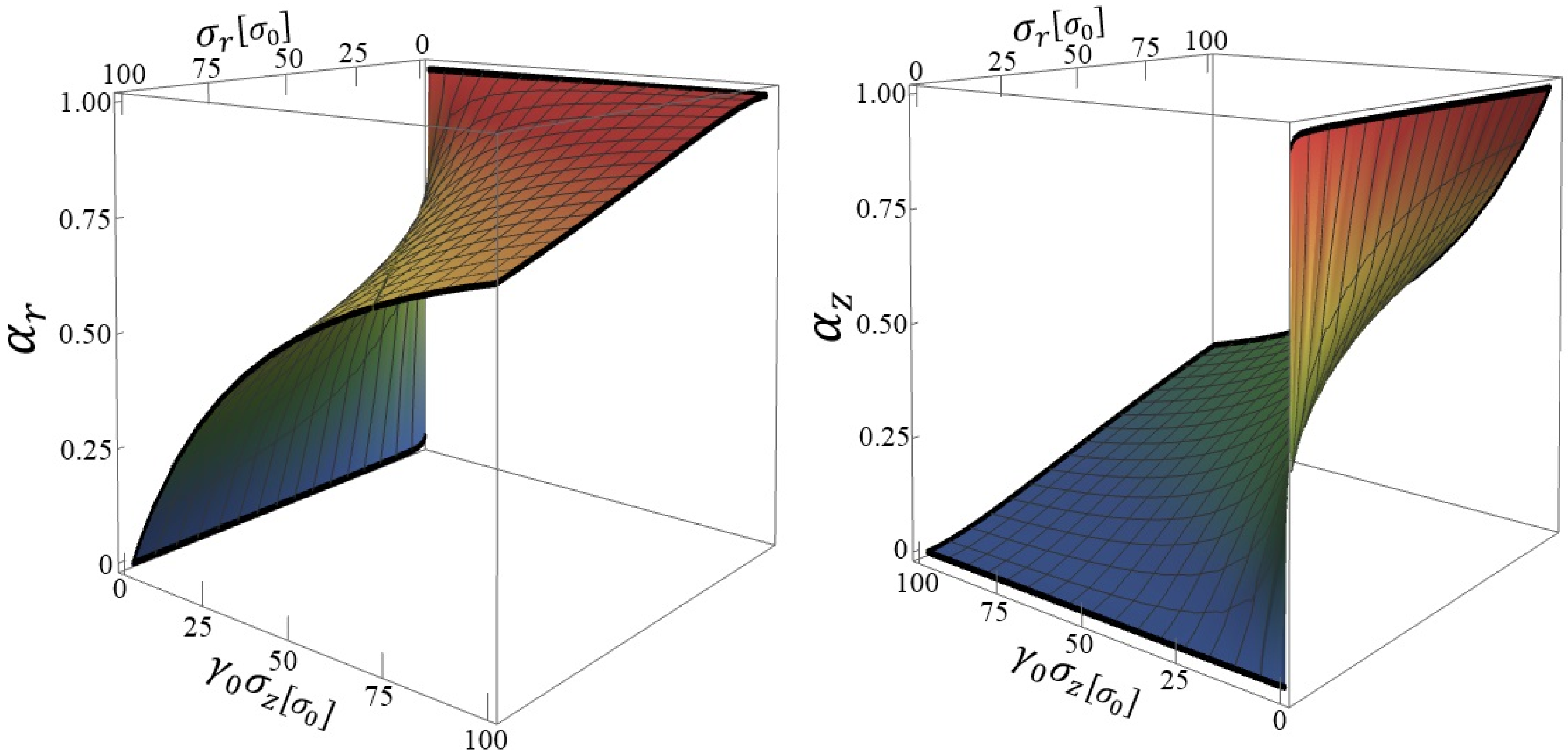
Type	$\alpha_z(\mu)$
GG	$\mu^2\int_0^\infty u\left(1-\sqrt{\pi}ue^{u^2}Erfc(u)\right)e^{-\left(\frac{\mu u}{\sqrt{2}}\right)^2}du$
GU	$\mu^2\int_0^\infty \frac{e^{-\left(\frac{\mu u}{\sqrt{6}}\right)^2}\left(e^{-u}[ucosh(u)-sinh(u)]\right)}{u^2}du$
US	$A_z\left(\frac{1}{2}\mu^2-1\right)$
UG	$1-\frac{4}{\sqrt{2\pi}}\int_0^\infty e^{-\left(\frac{u}{\sqrt{2}}\right)^2} I_1(\mu u)K_1(\mu u)du$
UC	$6\int_0^\infty \frac{J_1\left(\sqrt{\frac{2}{3}}\mu u\right)J_1\left(\sqrt{\frac{2}{3}}\mu u\right)}{u^4}e^{-u}\left(ucosh(u)-sinh(u)\right)du$

$$\mu = \frac{\sigma_r}{\gamma_0\sigma_z}$$





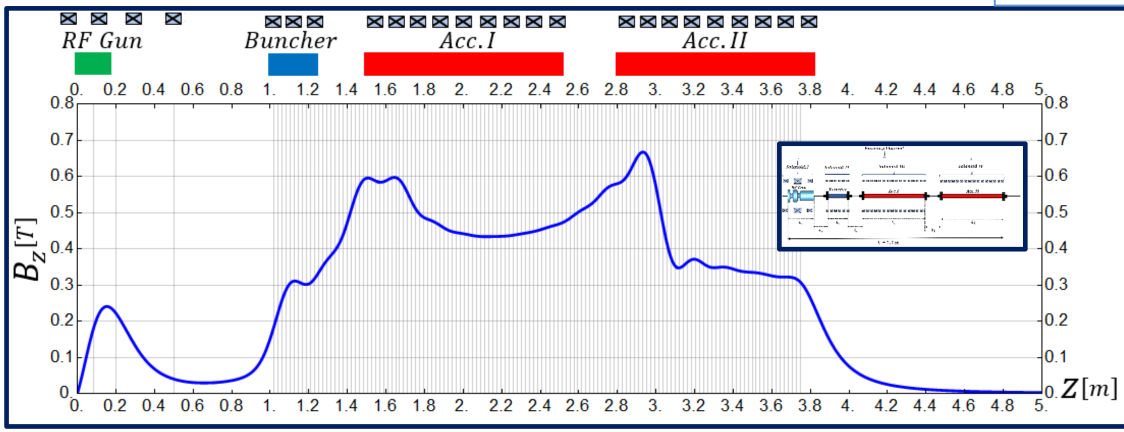
5.3 Space Charge Forces

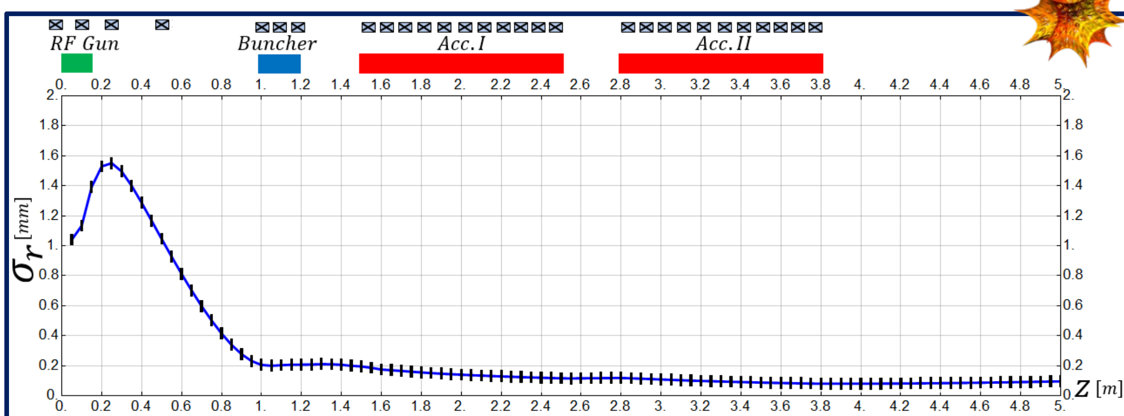


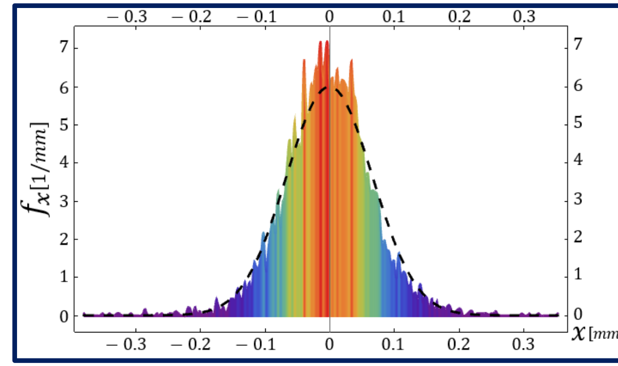
6.1 Design

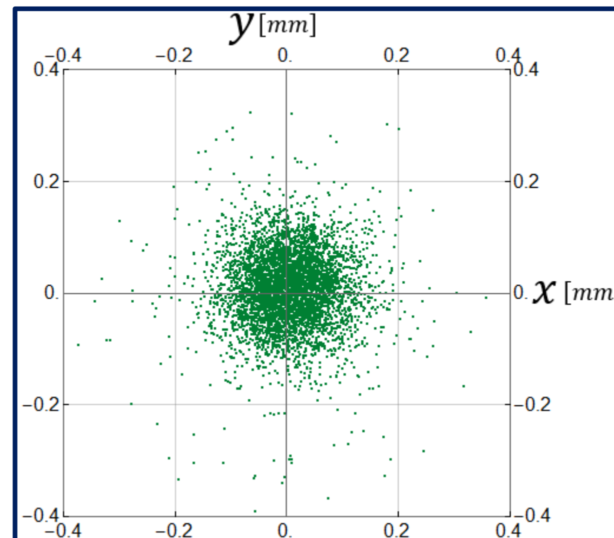
15 sec vs 45min

ASTRA

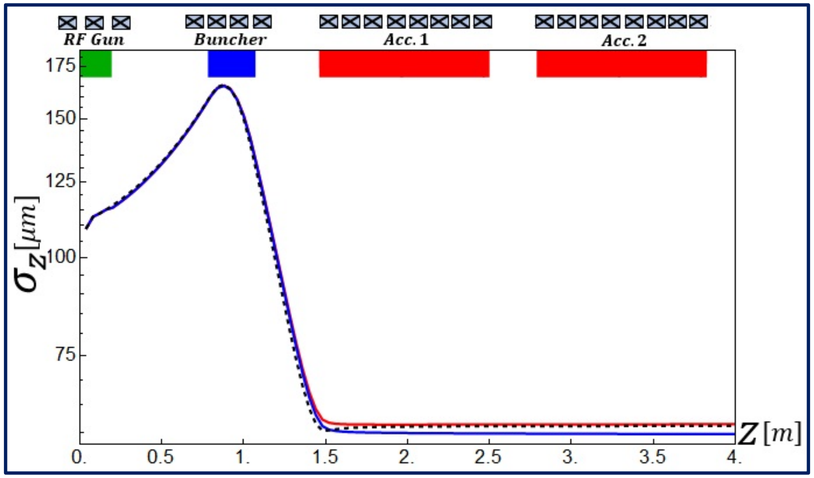


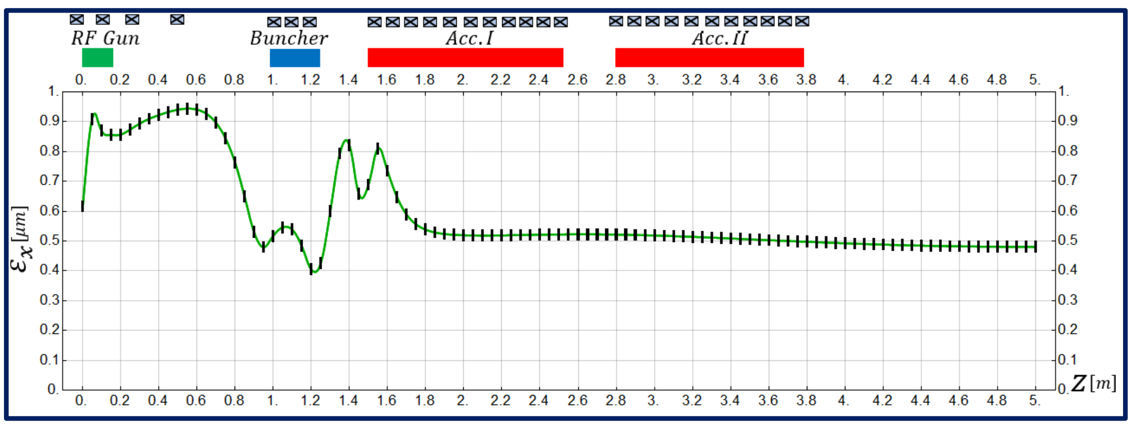






6.1 Design





$\varepsilon_x[\mu m]$	$\sigma_E[\%]$	$\sigma_z[\mu m]$
0.48	0.24	30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ELSEVIER

Evolution of bunch envelope and emittance in photo-injectors with application to the AWAKE experiment

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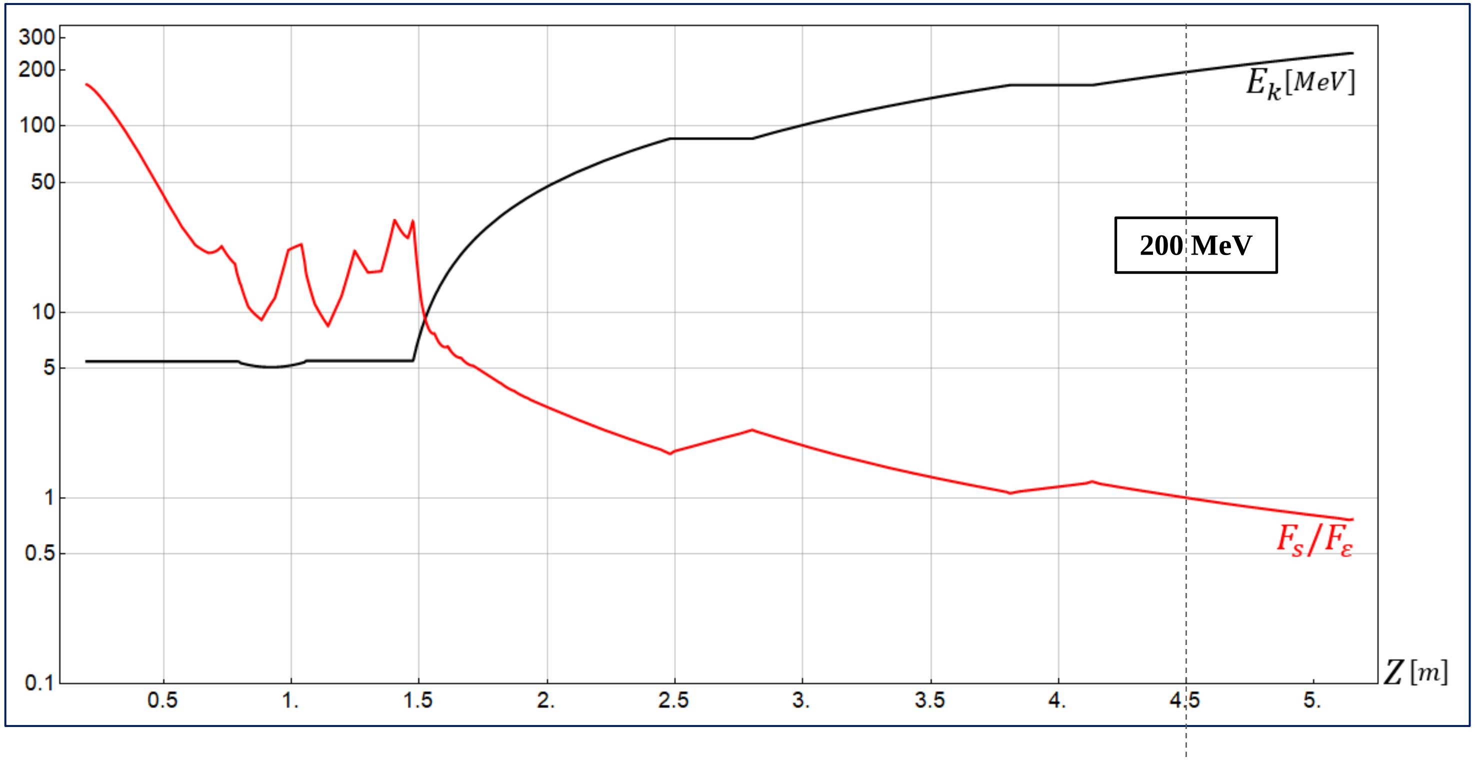
6.3 More Considerations



e beam	$\mathbf{166\ MeV} \rightarrow \boldsymbol{\beta}$=0.999995
	$\mathbf{247\ MeV} \rightarrow \boldsymbol{\beta}$=0.999998

p beam	$\mathbf{400\ GeV} \rightarrow \boldsymbol{\beta}$=0.999997

Thanks for Attention