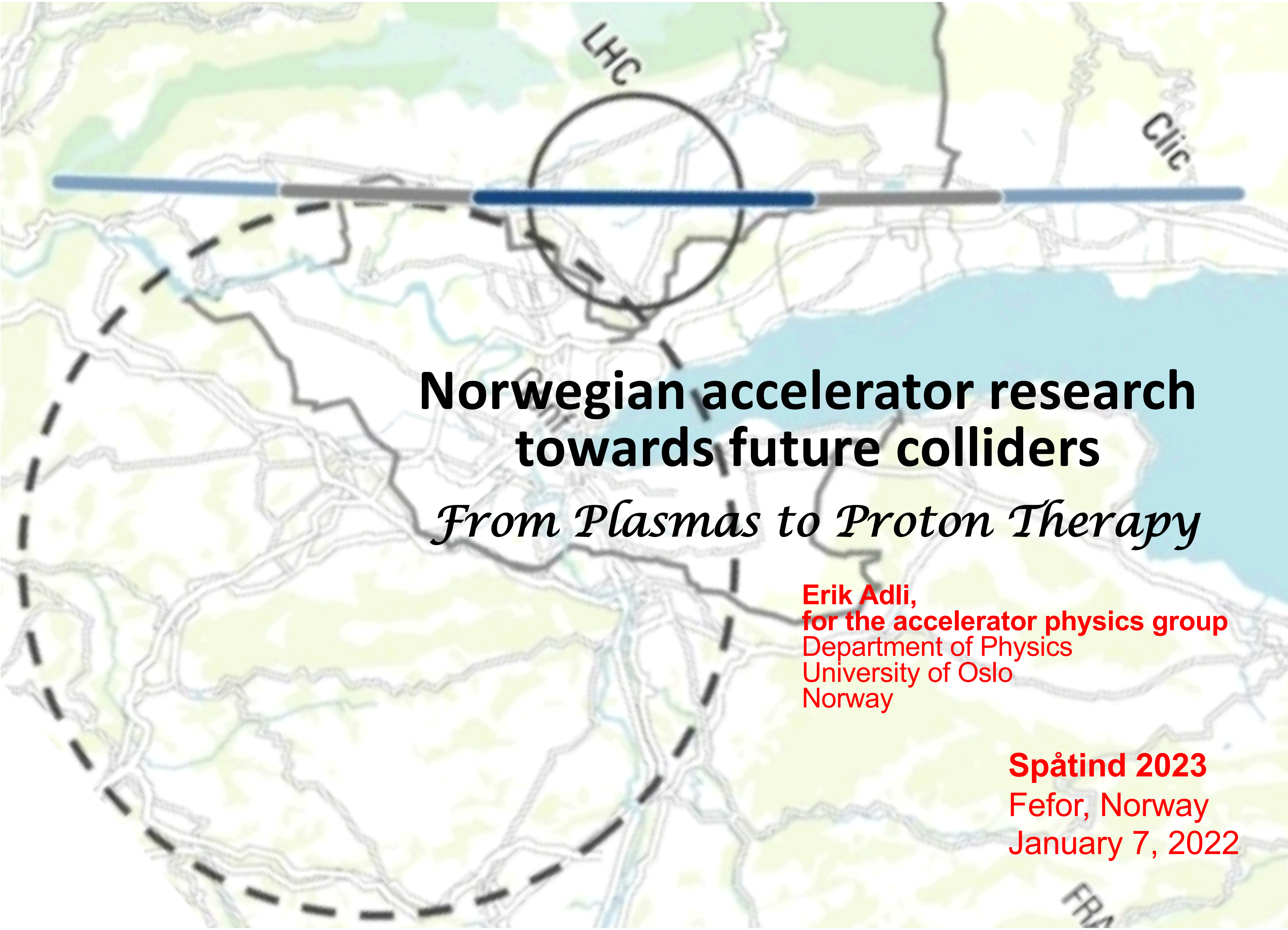


Norwegian accelerator research towards future colliders

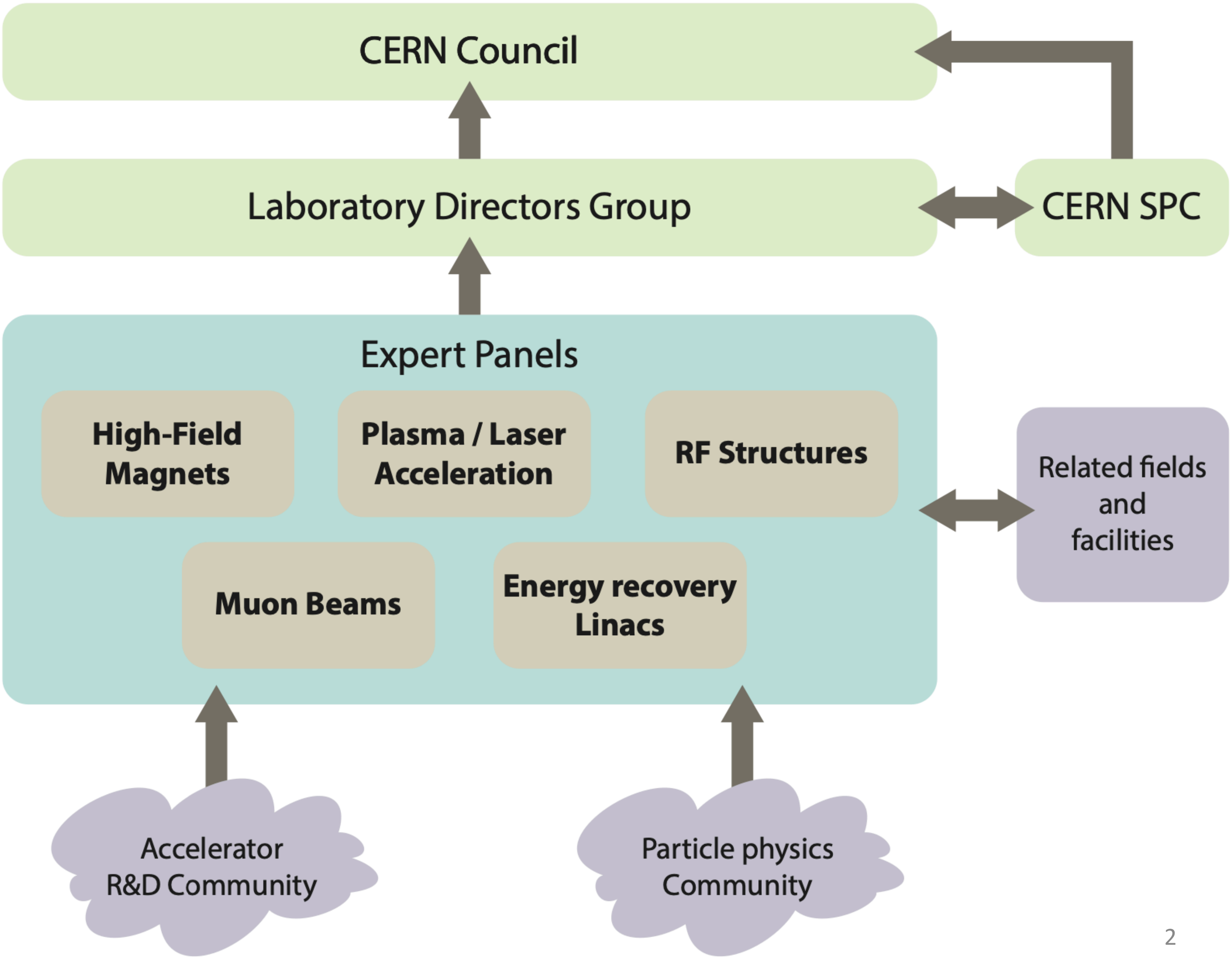
From Plasmas to Proton Therapy

Erik Adli,
for the accelerator physics group
Department of Physics
University of Oslo
Norway

Spåtind 2023
Fefor, Norway
January 7, 2022

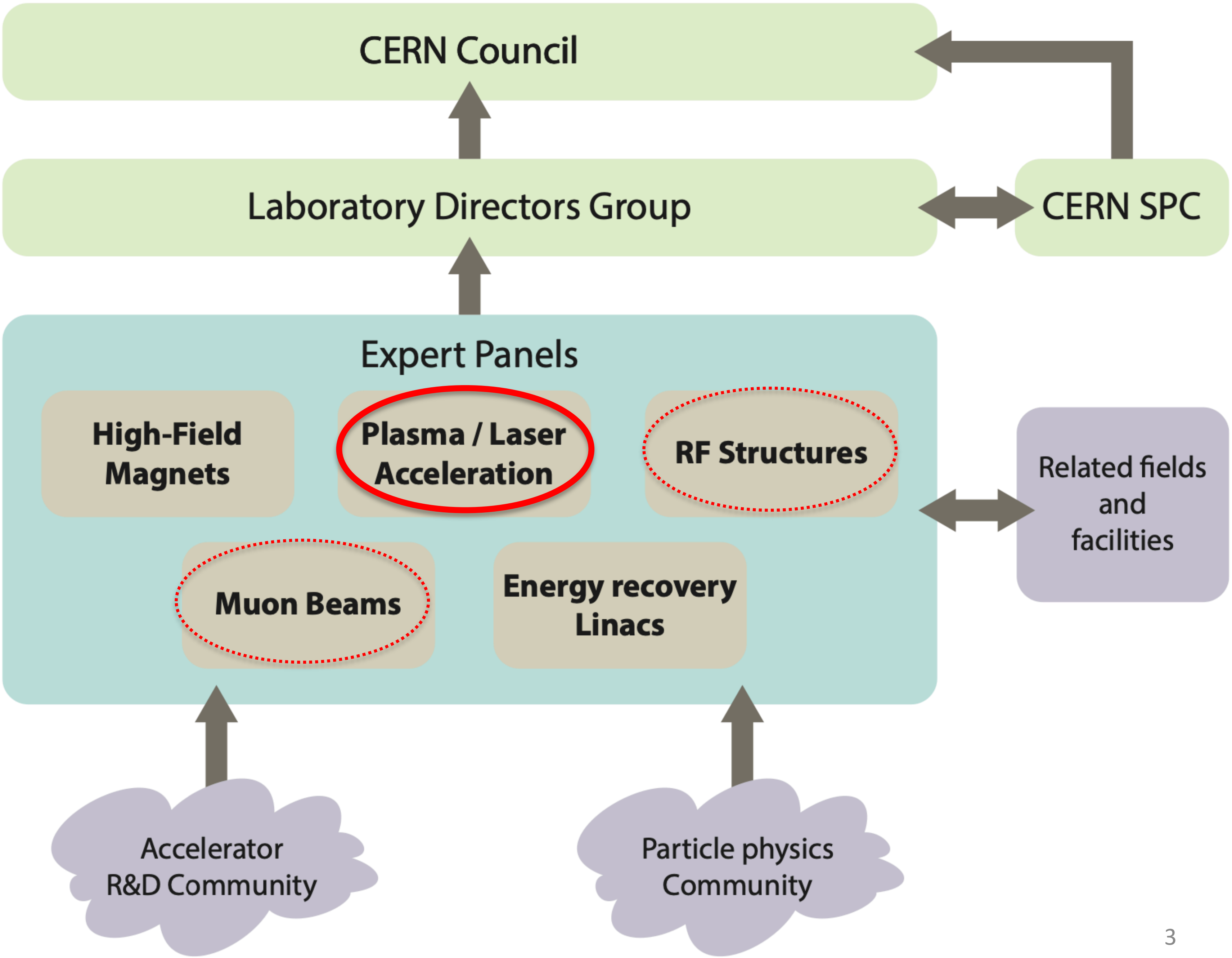
European HEP Accelerator R&D Roadmap (2022)

111th Plenary ECFA Meeting, CERN, Nov 17, 2022



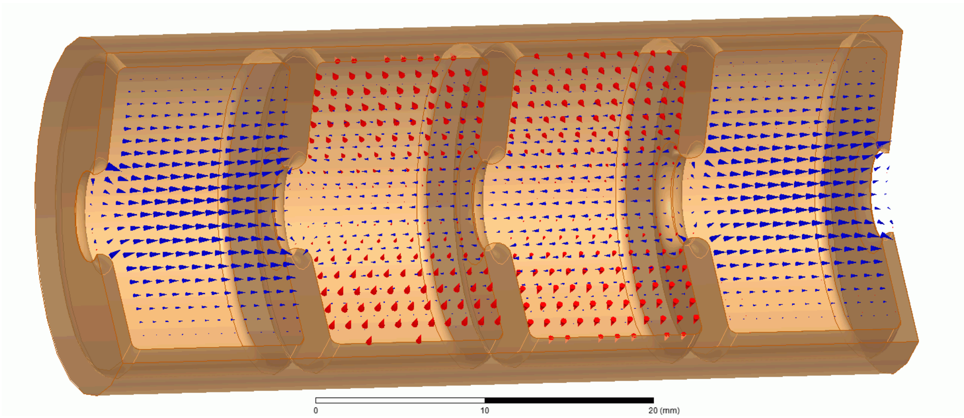
European HEP Accelerator R&D Roadmap (2022)

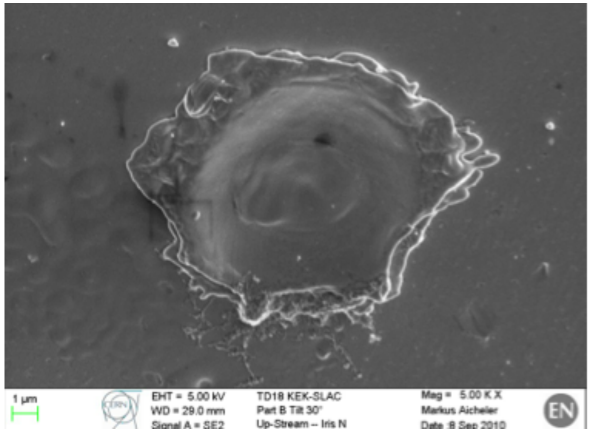
[111th Plenary ECFA Meeting, CERN, Nov 17, 2022]



Why plasma accelerators?

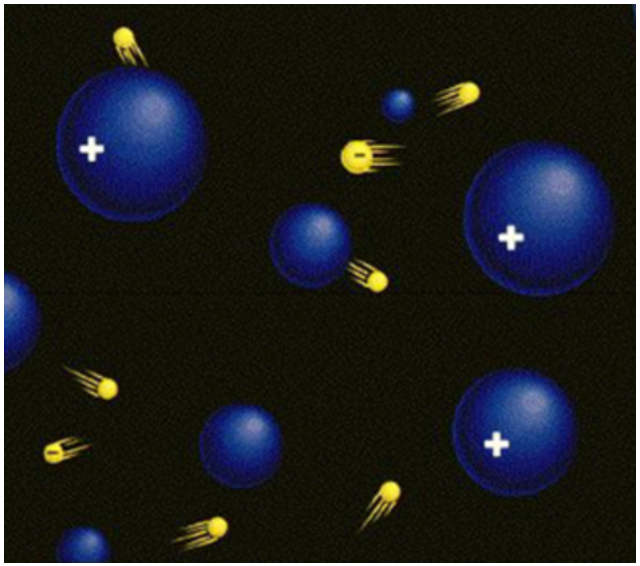
In **metallic structures** too high field amplitudes lead to vacuum arcs, break down of the field. **Current practical limit (CLIC): order of 100 MV/m gradients**.





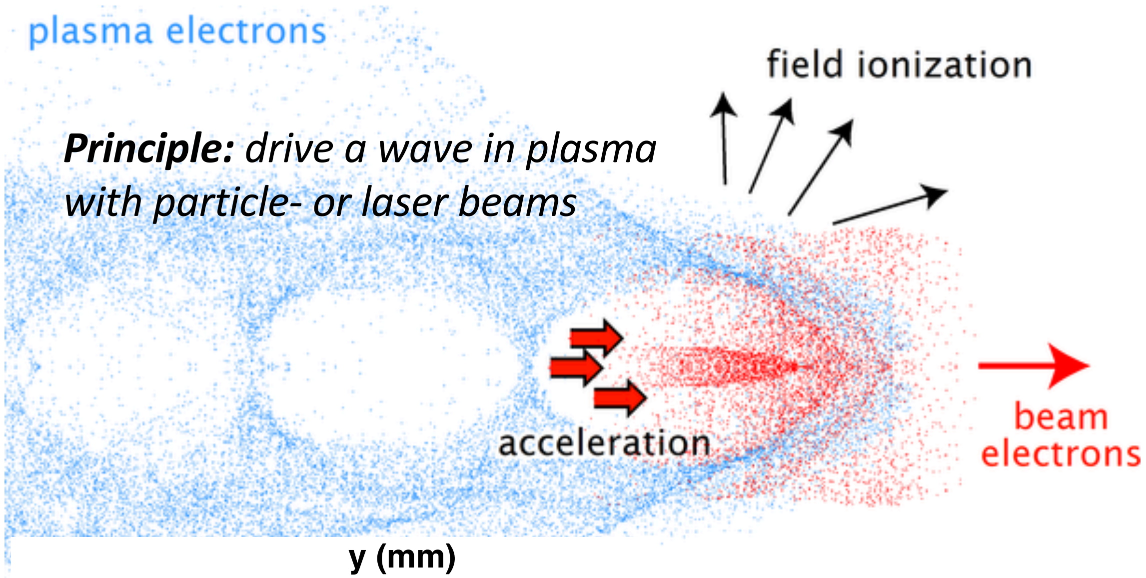
A plasma:

- ions and ionized electrons
- material is **already broken down**
- plasma waves can therefore **sustain very high fields**



Plasma wakefield accelertion

Principle: *drive a wave in plasma with particle- or laser beams*



$$E_z[\mathrm{GV/m}] \approx 9.6\sqrt{n_e[10^{16}\mathrm{cm}^{-3}]}$$

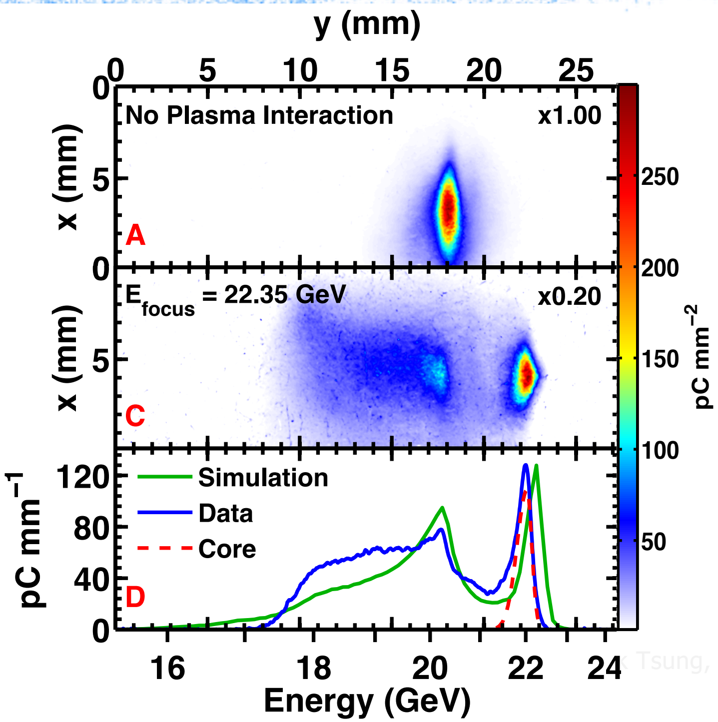
$$\frac{1}{k_p}[\mu\mathrm{m}] \approx 53\sqrt{\frac{1}{n_e[10^{16}\mathrm{cm}^{-3}]}}$$

Typical numbers :

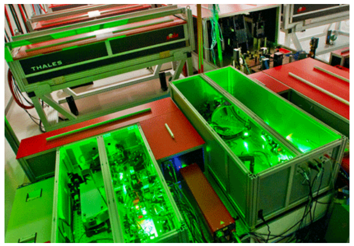
Plasma density ~ $10^{16\text{-}18}/\mathrm{cm}^3$

Field scale: 10-100 GV/m

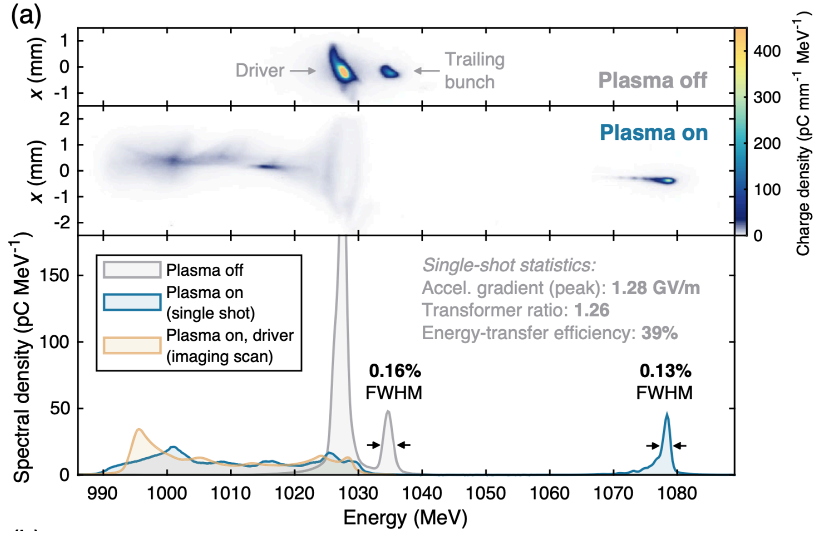
Length scale : $k_p = \lambda_p/2\pi$ **= 10-100 μm**



*M. Litos, E. Adli et al., Nature **515**, 92 (2014)*



W-PW laser technology



C. Lindstrøm et al., PRL **126**, 014801 (2021

Great experimental progress recent years : 10 GV/m accelerating fields **well established,** two-beam acceleration, positron acceleration, high-efficiency, high rep-rate...

So, can we build a collider using plasma acceleration?

So, can we build a collider using plasma acceleration?

RE

Can you build a particle collider using plasma wake field accelerators?

https://chat.openai.com/chat

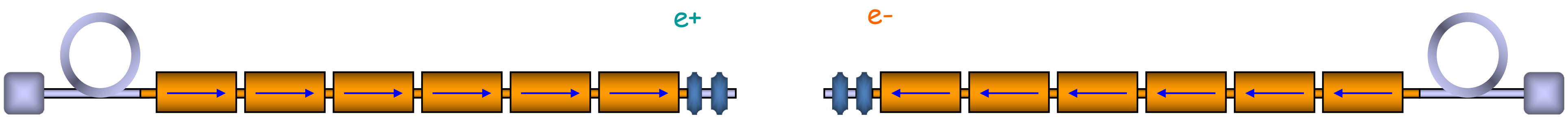
Yes, it is possible to build a particle collider using plasma wake field accelerators. Plasma wake field accelerators use a plasma, or ionized gas, to accelerate charged particles to very high energies over a very short distance. They have the potential to be much more compact and efficient than traditional particle accelerators, which makes them a promising technology for building smaller, more cost-effective particle colliders.

RE

Can you build a particle collider using plasma wake field accelerators?

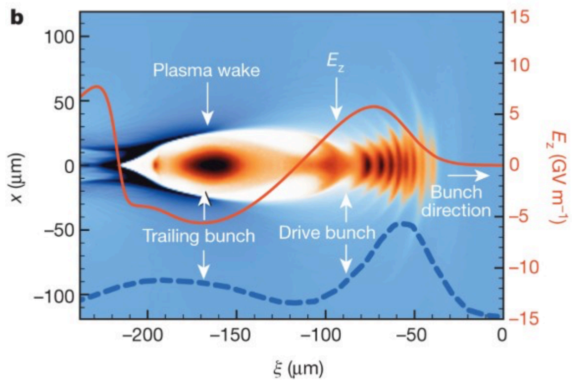
Plasma wakefield accelerators have been suggested as a potential alternative to traditional particle colliders, but they have not yet been demonstrated as a viable technology for building a large-scale particle collider. In a plasma wakefield accelerator, a beam of particles (called a "driver") is sent through a plasma, creating a wave that can be used to

So, can we build a collider using plasma acceleration?



ILC: 31.5 MV/m, 20 km@$\sqrt{s}$=250 GeV, 31 km@$\sqrt{s}$= 500 GeV, $\mathcal{L} \sim 10^{34} cm^{-2}s^{-1}$
CLIC: 100 MV/m, 11 km@$\sqrt{s}$= 380 GeV, 50 km@$\sqrt{s}$= 3 TeV, $\mathcal{L} \sim 10^{34} cm^{-2}s^{-1}$

So, can we build a collider using plasma acceleration?



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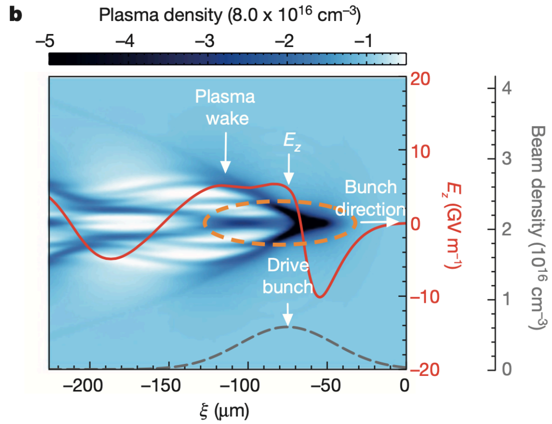
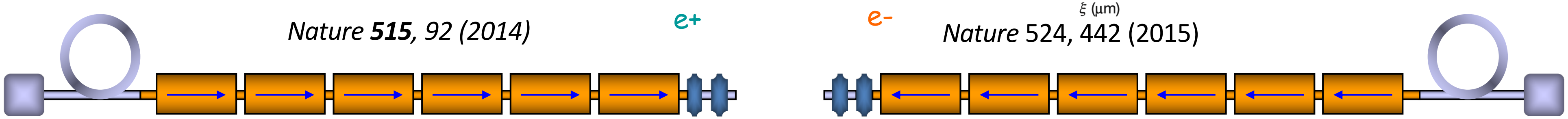


Nature 524, 442 (2015)



ILC: 31.5 MV/m, 20 km@$\sqrt{s}$=250 GeV, 31 km@$\sqrt{s}$= 500 GeV, $\mathcal{L}$ ~10^{34}cm^{-2}s^{-1}
CLIC: 100 MV/m, 11 km@$\sqrt{s}$= 380 GeV, 50 km@$\sqrt{s}$= 3 TeV, $\mathcal{L}$ ~10^{34}cm^{-2}s^{-1}
Plasma: 10 GV/m .... **?** km, $\sqrt{s}$ = **?**, $\mathcal{L}$ = **?**

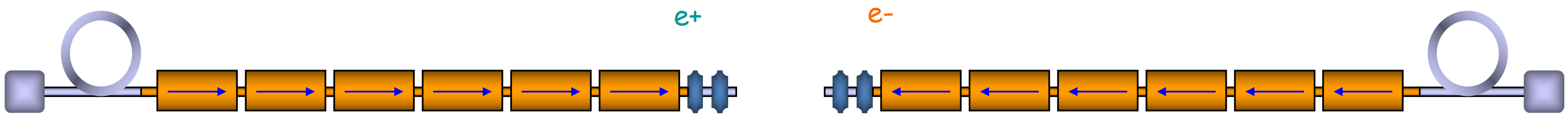
Major challenges to be addressed before the questions can be answered :

1) asymmetry of **positron acceleration**
2) staging of plasmas
3) Beam quality vs power efficiency questions

In addition: need conceptual design of all collider sub-systems

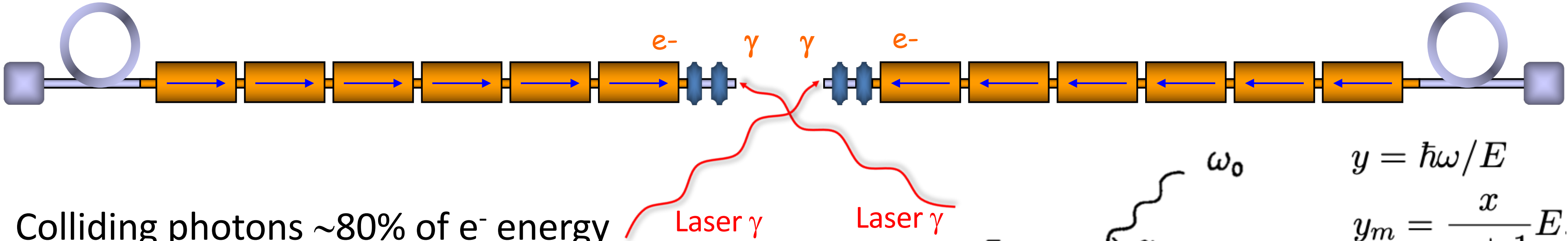
Challenge 1: positron acceleration

Proposed solution: using inverse compton scattering to build a $\gamma\gamma$ (photon-photon) collider

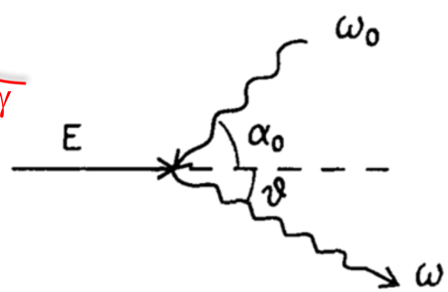


Challenge 1: positron acceleration

Proposed solution: using inverse compton scattering to build a $\gamma\gamma$ (photon-photon) collider
- no more need for positron acceleration



Colliding photons ~80% of e⁻ energy



$$y = \hbar\omega/E$$

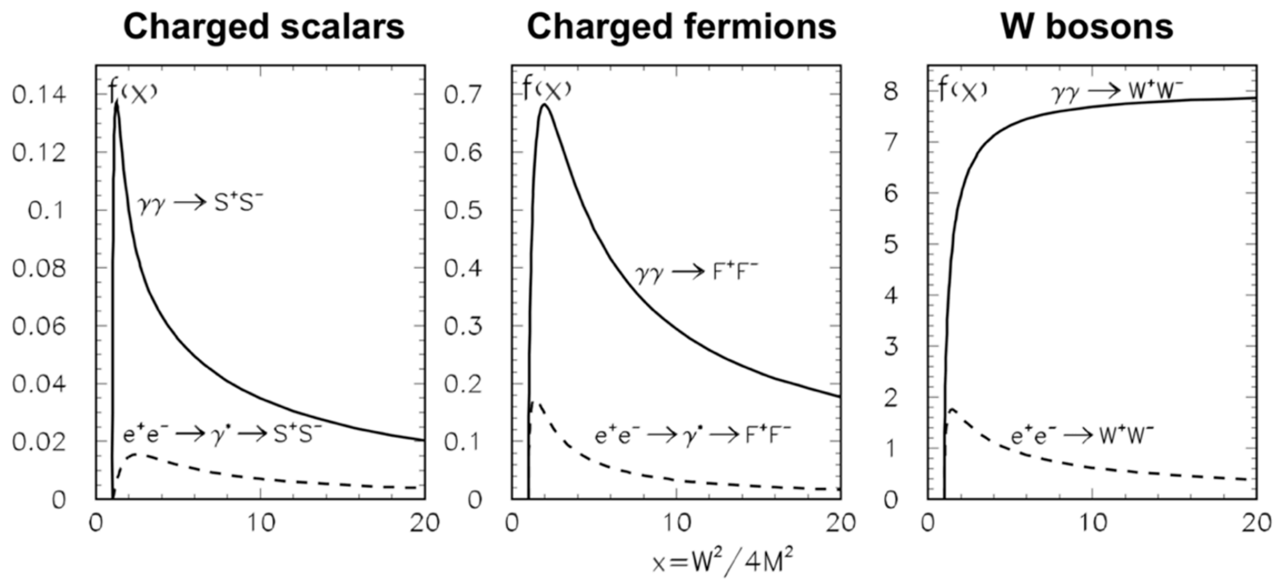
$$y_m = \frac{x}{x+1}E$$

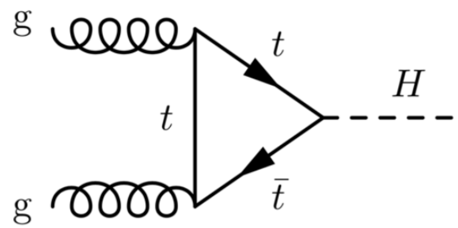
$$x < 2(1+\sqrt{2}) = 4.8$$

$$\lambda_L[\mu\text{m}] \approx 4\,\text{E[TeV]}$$

$\gamma\gamma$ collider: **good physics case**

V. Telnov (Ed.), TESLA TDR, Part VI, Ch 1 arXiv:hep-ex/0108012 (2001)



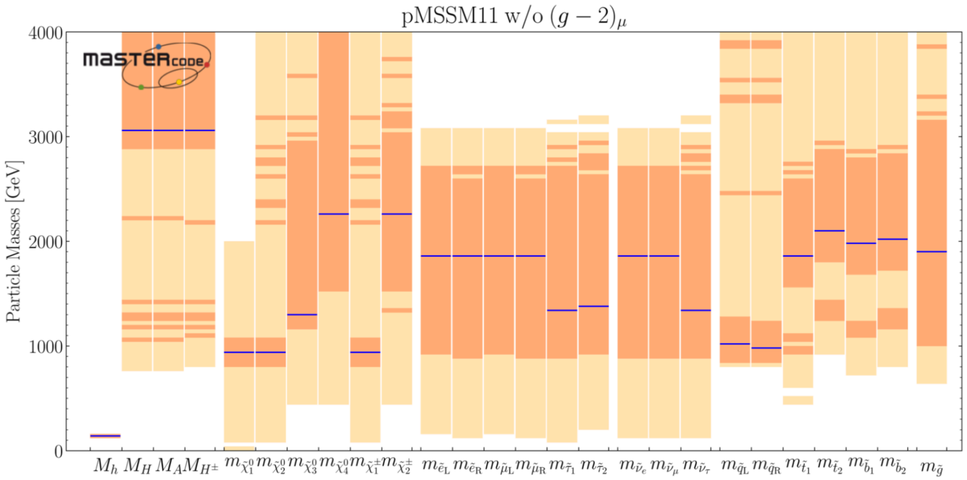


Direct discovery in pair production of charged particles: requirements on integrated luminosity same order of magnitude as for electron-positron collisions. Tested on a SUSY scenario (P. Roloff).

See also CLIC physics studies for a $\gamma\gamma$ collider : *P. Roloff, https://indico.cern.ch/event/778083/*

Multi-TeV $\gamma\gamma$ collider performance example:

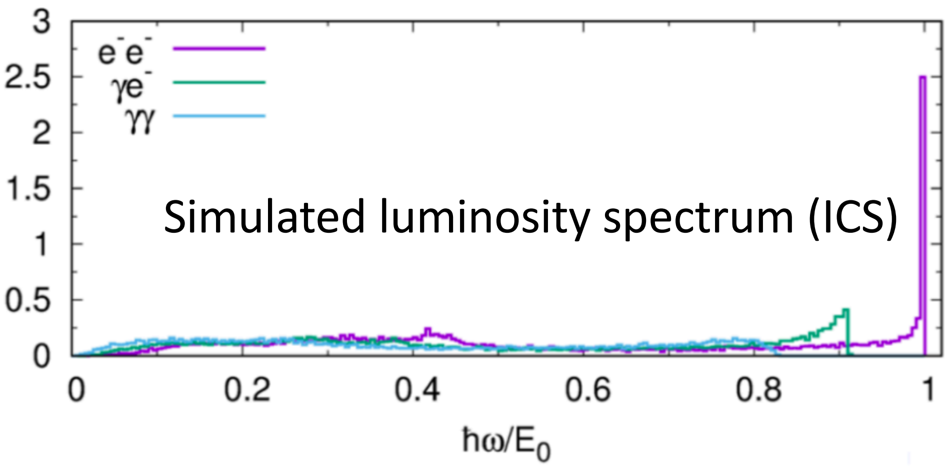
MSSM SUSY model



Blue lines: best fit values

Orange bands: 68% & 95% CL ranges

E. Bagnaschi, arXiv:1710.11091



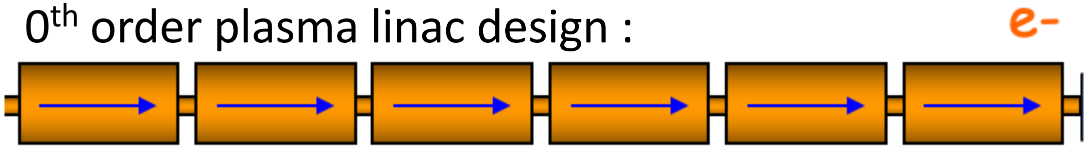
From CLIC WG on Novel Accelerator Technologies,
P. Roloff (CERN), 2019, *https://indico.cern.ch/event/778083/*

Comparison 10 TeV e-e+ vs 10 TeV $\gamma\gamma$

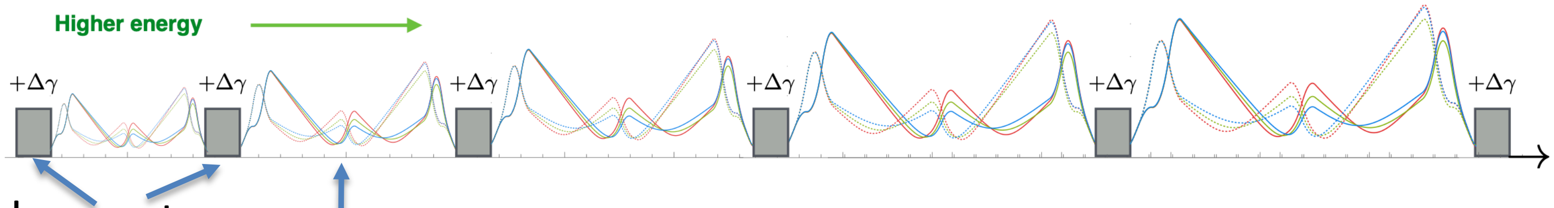
Particle pair	Mass [GeV]	$\sigma(e^+e^- \to XX)$ [fb] Circe2 + ISR, unpol.	$\sigma(\gamma\gamma \to XX)$ [fb] Circe2, unpol.
$\tilde{d}_L\tilde{d}_L$	1009	0.61	0.07
$\tilde{u}_L\tilde{u}_L$	1006	0.89	1.2
$\tilde{s}_L\tilde{s}_L$	1009	0.61	0.07
$\tilde{c}_L\tilde{c}_L$	1006	0.89	1.2
$\tilde{b}_1\tilde{b}_1$	1997	0.19	0.01
$\tilde{t}_1\tilde{t}_1$	1866	0.28	0.22
$\tilde{e}_L\tilde{e}_L$	1869	0.95	0.37
$\tilde{\nu}_{eL}\tilde{\nu}_{eL}$	1867	4.6	/
$\tilde{\mu}_L\tilde{\mu}_L$	1869	0.25	0.37
$\tilde{\nu}_{\mu L}\tilde{\nu}_{\mu L}$	1867	0.11	/
$\tilde{\tau}_1\tilde{\tau}_1$	1328	0.30	0.93
$\tilde{\nu}_\tau\tilde{\nu}_\tau$	1364	0.15	/
$\tilde{d}_R\tilde{d}_R$	988	0.13	0.08
$\tilde{u}_R\tilde{u}_R$	989	0.53	1.2
$\tilde{s}_R\tilde{s}_R$	988	0.13	0.08
$\tilde{c}_R\tilde{c}_R$	989	0.53	1.2
$\tilde{b}_2\tilde{b}_2$	2032	0.07	0.01
$\tilde{t}_2\tilde{t}_2$	2108	0.26	0.16
$\tilde{e}_R\tilde{e}_R$	1856	1.4	0.38
$\tilde{\nu}_{\mu R}\tilde{\nu}_{\mu R}$	1856	0.21	0.38
$\tilde{\tau}_2\tilde{\tau}_2$	1365	0.31	0.86
$\tilde{\chi}^0_1\tilde{\chi}^0_1$	954	≈ 0	/
$\tilde{\chi}^0_2\tilde{\chi}^0_2$	954	≈ 0	/
$\tilde{\chi}^+_1\tilde{\chi}^-_1$	955	2.7	1.4
$\tilde{\chi}^0_3\tilde{\chi}^0_3$	1294	1.1	/
$\tilde{\chi}^0_4\tilde{\chi}^0_4$	2262	0.53	/
$\tilde{\chi}^+_2\tilde{\chi}^-_2$	2262	1.3	1.3
H^0A^0	3046	0.04	/
H^+H^-	3046	0.10	0.08

Challenge 2: staging

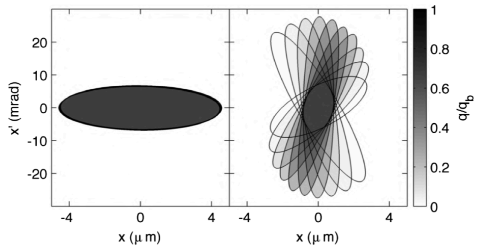
0th order plasma linac design :



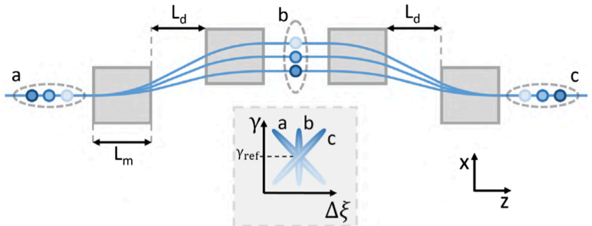
0.1^{th} order plasma linac design :



The interstage optics must perform many tasks to preserve the beam quality :

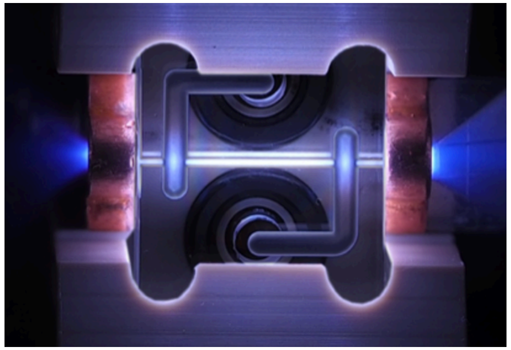


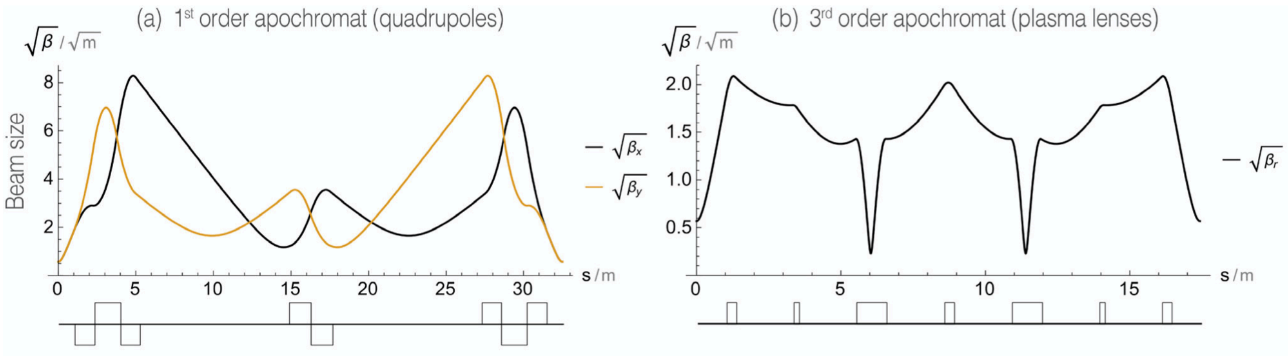
Ensure longitudinal stability



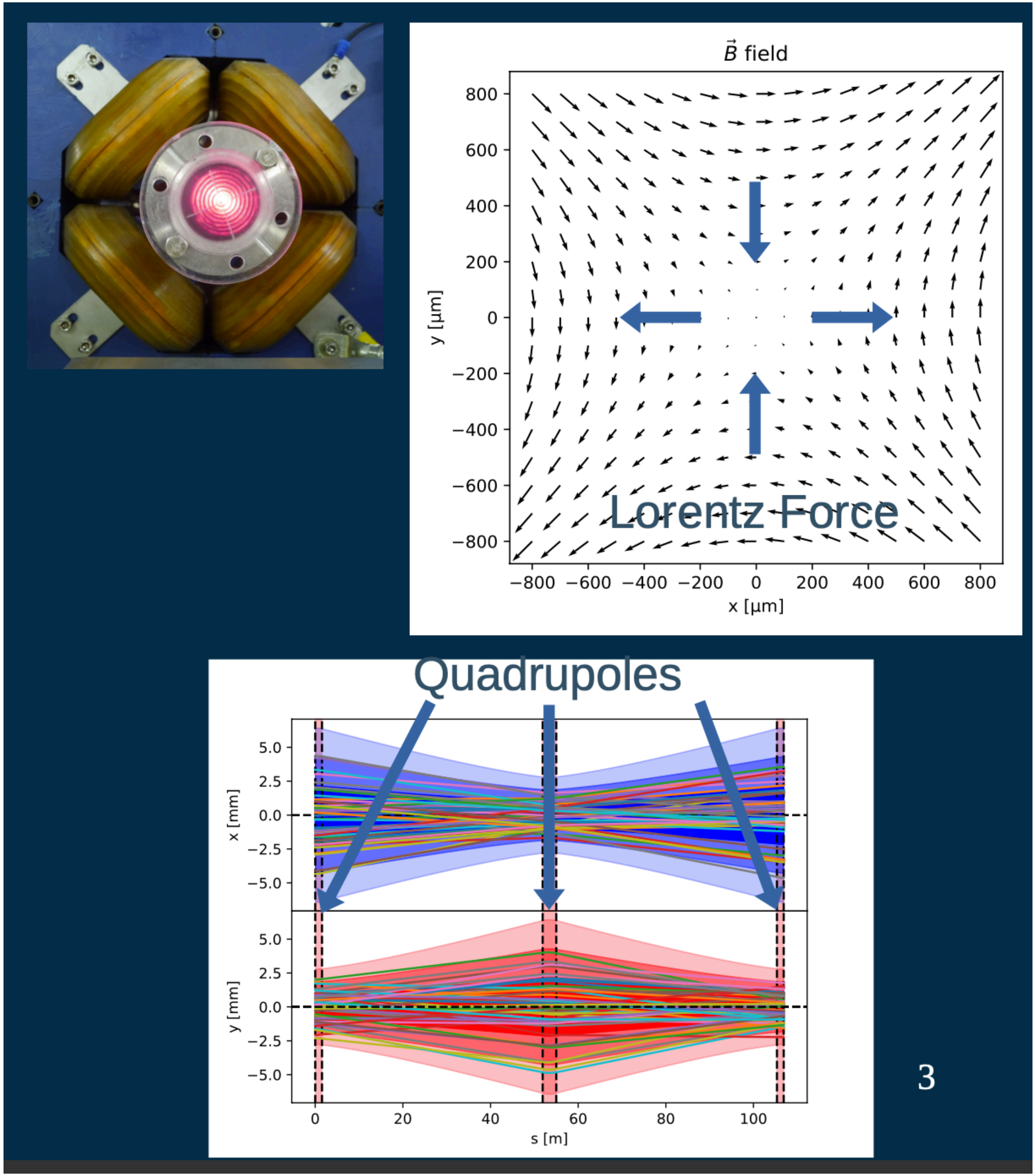
Avoiding chromaticity and emittance growth

Proposed solution: the interstage optics may be greatly simplifed and shortenered by using **plasma lenses** with azimutically symmetric focusing fields.

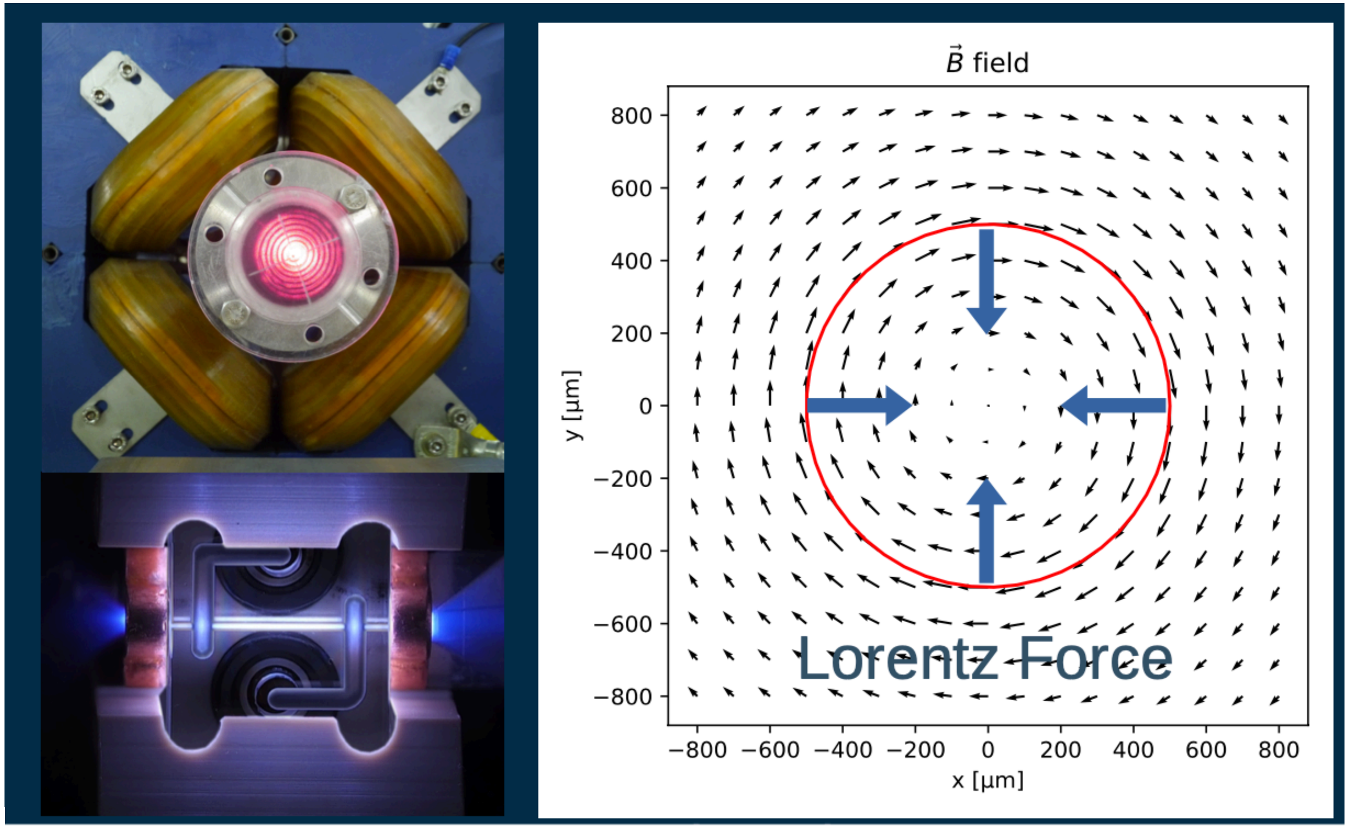


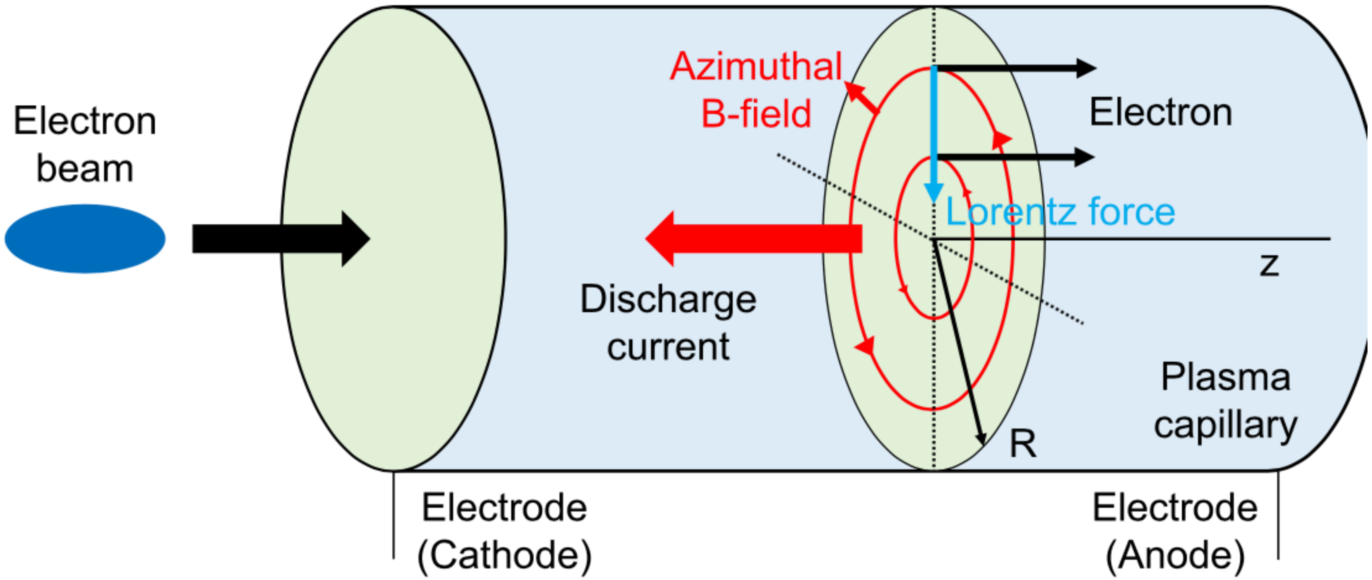


C. A. Lindstrøm and E. Adli, Phys. Rev. Accel. Beams **19** 072001 (2016)



Slide by K. N. Sjobak

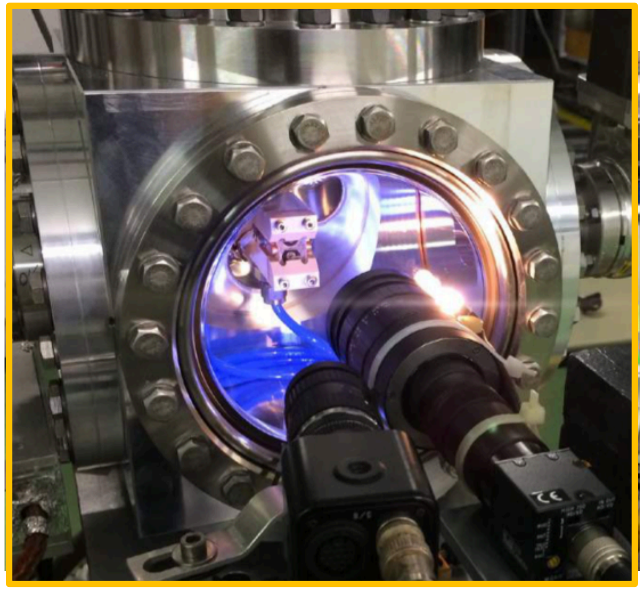


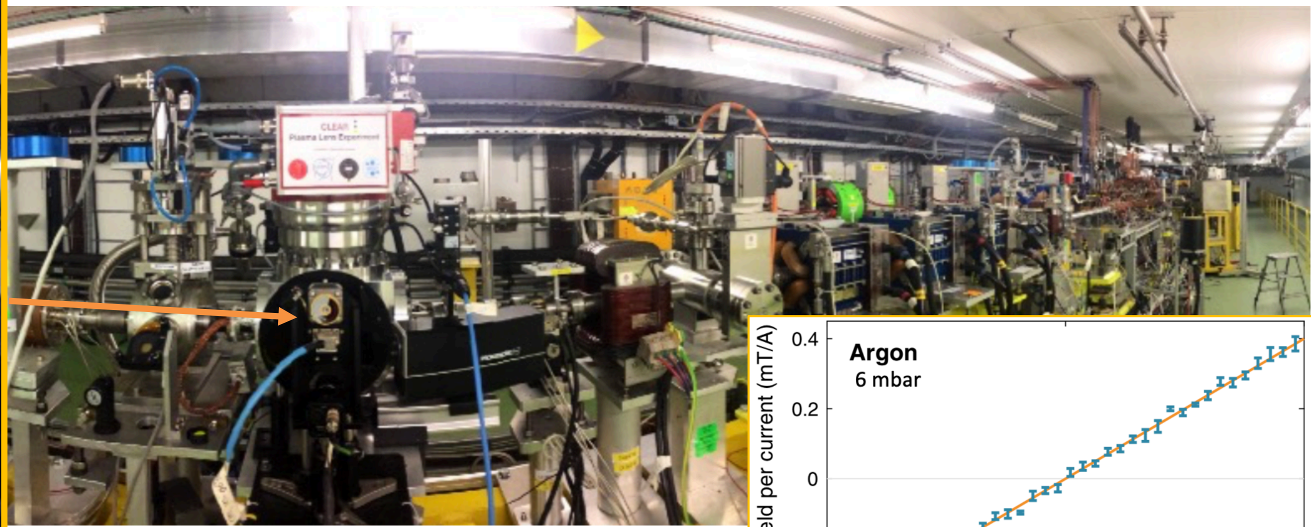


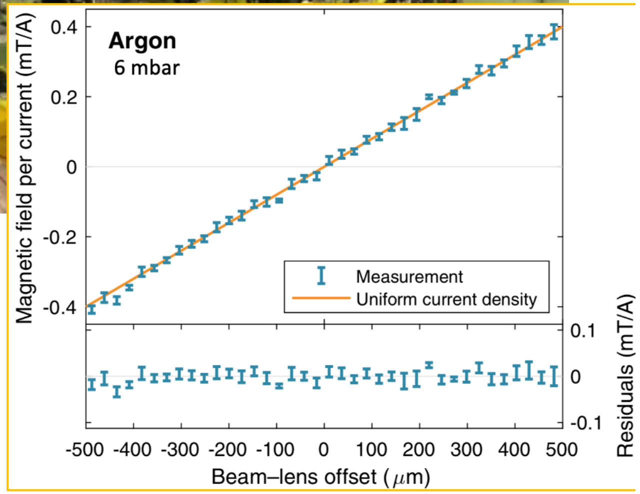
Slide by K. N. Sjobak

Oslo plasmas lenes at CERN:

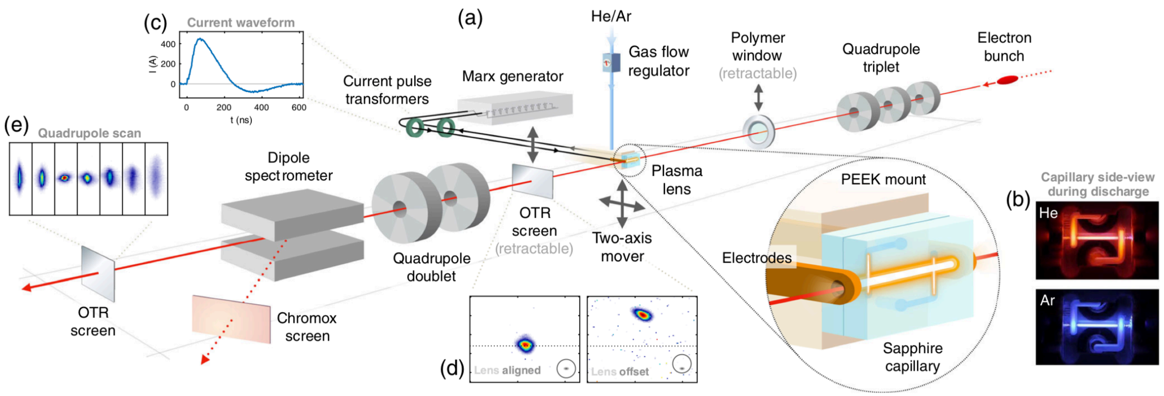
- demonstration of ultra high focusing fields (> 5 kT/m !)
- beam quality preservation in a linear plasma lens



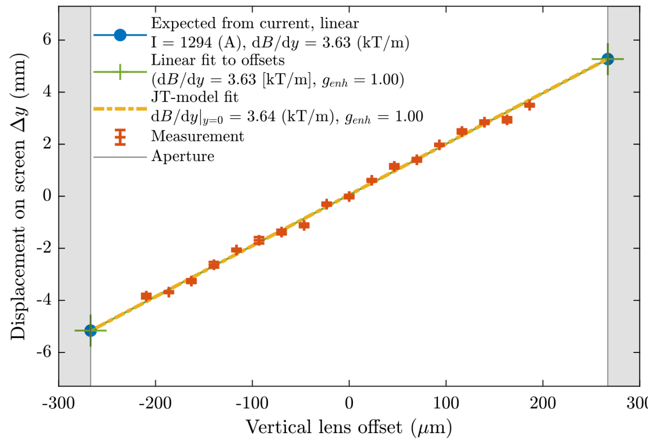




Experimental setup



C. A. Lindstrøm, K. Sjobak, E. Adli et al., PRL ***121****, 194801 (2018)*



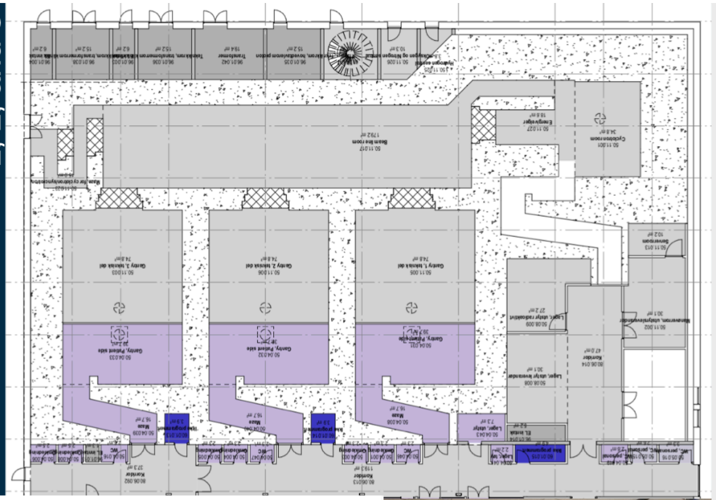
K. Sjobak, C. A. Lindstrøm, E. Adli et al., Phys. Rev. AB **24**, 121306 (2021)

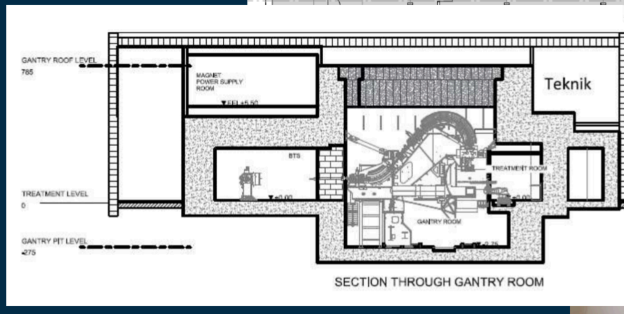
Other applications for strong focusing?

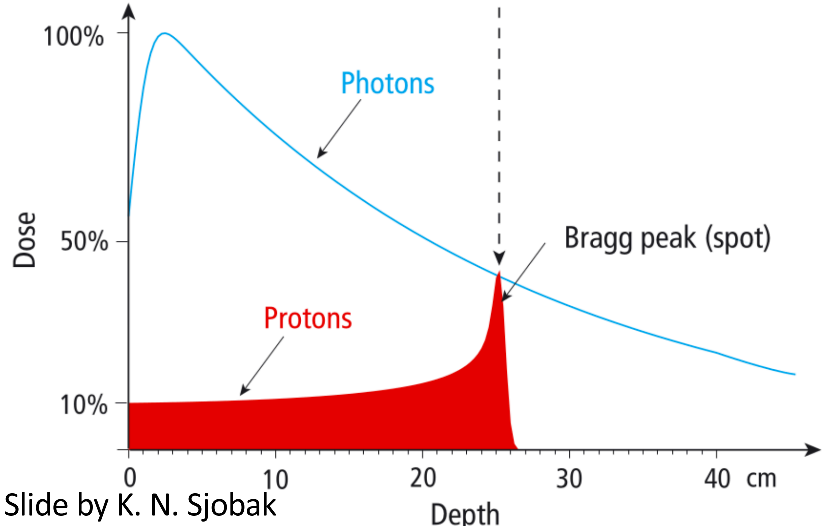
Proton therapy in Norway

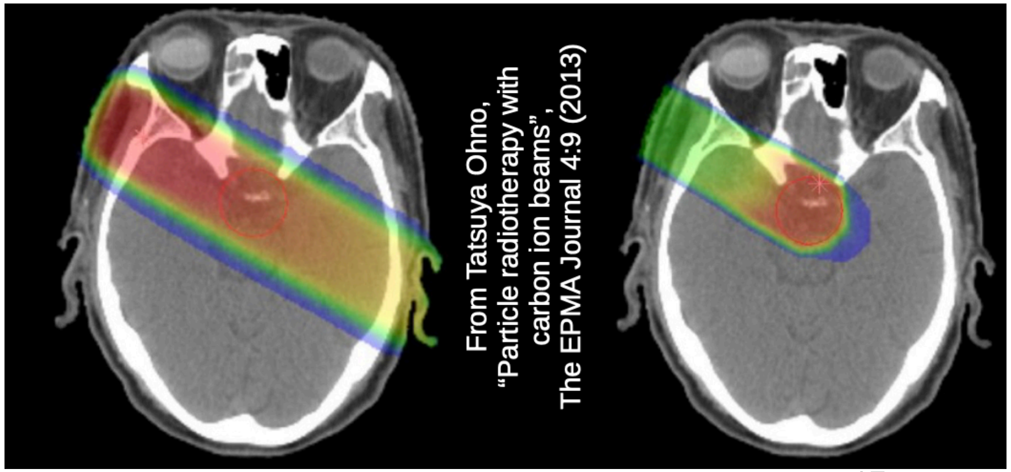
From refs. 1, 2, and 3

- Two centers under construction: Oslo (Radiumhospitalet) and Bergen (Haukland)
- First patient planned in 2024
- Oslo: 3 gantries, 2 for patients and 1 for research
- Bergen: 2 gantries, 1 for patients and 1 for research





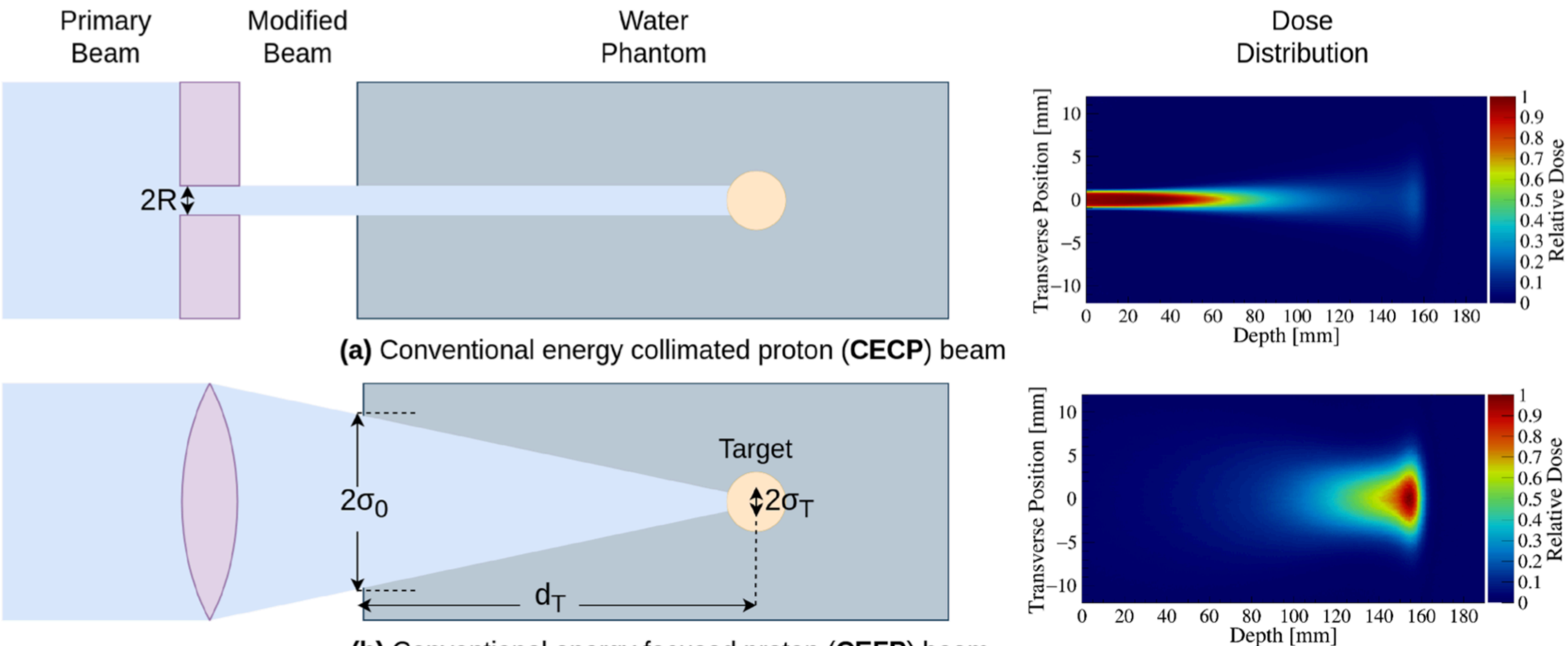




Slide by K. N. Sjobak

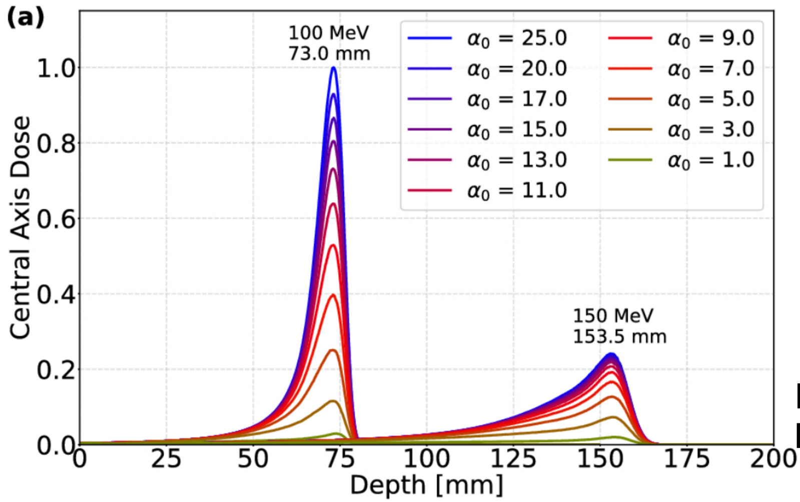
Other applications for strong focusing?

(Surprisingly) little work done on beam shaping and strong focusing for proton therapy.



(a) Conventional energy collimated proton (**CECP**) beam

(b) Conventional energy focused proton (**CEFP**) beam



$$\sigma_{u'} = \frac{\sigma_0}{d_T}\sqrt{\frac{\alpha_0^2}{1+\alpha_0^2}}$$

F. Reaz, K. Sjobak, E. Adli et al., *Sci. Rep.* **12** 18919 (2022)

Inspired by work for FLASH very high energy electron therapy:
K. Kokurewicz, K Sjobak et al., Commun. Phys **4**, 33 *(2021)*

So, can we build a collider using plasma technology?

- We cannot yet answer the question above, but, by bypassing the positron problem, developing plasma lenses and finding compact staging solution, we (the Oslo group) hope to understand *how compactly and efficiently* we can make electron plasma linacs.

- As part of this, we develop novel, strong focusing technology.

- In the process, we also attempt to improve fields relevant for society; proton therapy.

- Conceptual design for all collider parts must be done before the potential of plasma colliders can be properly assessed.

Extra

Cross sections for 10 TeV colliders

- Direct discovery in pair production of charged particles, requirements on integrated luminosity same order of magnitude as for electron-positron collisions

- Promising opportunities for precision measurements in multi-boson production (will be explored further)

- $\gamma\gamma$ ideal to study light-by-light scattering

- Some unique opportunities in electron-photon interactions

Particle pair	Mass [GeV]	$\sigma(e^+e^- \to XX)$ [fb] Circe2 + ISR, unpol.	$\sigma(\gamma\gamma \to XX)$ [fb] Circe2, unpol.
$\tilde{d}_L\tilde{d}_L$	1009	0.61	0.07
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$\tilde{\chi}_2^0\tilde{\chi}_2^0$	954	≈ 0	/
$\tilde{\chi}_1^+\tilde{\chi}_1^-$	955	2.7	1.4
$\tilde{\chi}_3^0\tilde{\chi}_3^0$	1294	1.1	/
$\tilde{\chi}_4^0\tilde{\chi}_4^0$	2262	0.53	/
$\tilde{\chi}_2^+\tilde{\chi}_2^-$	2262	1.3	1.3
H^0A^0	3046	0.04	/
H^+H^-	3046	0.10	0.08

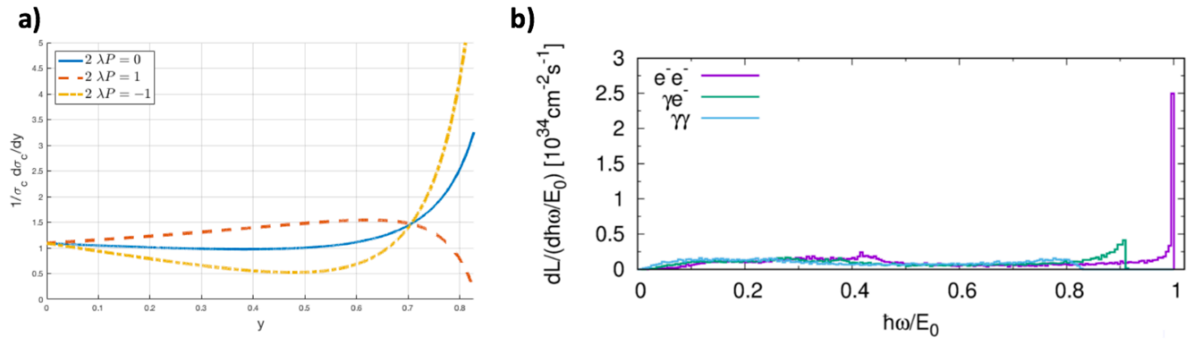
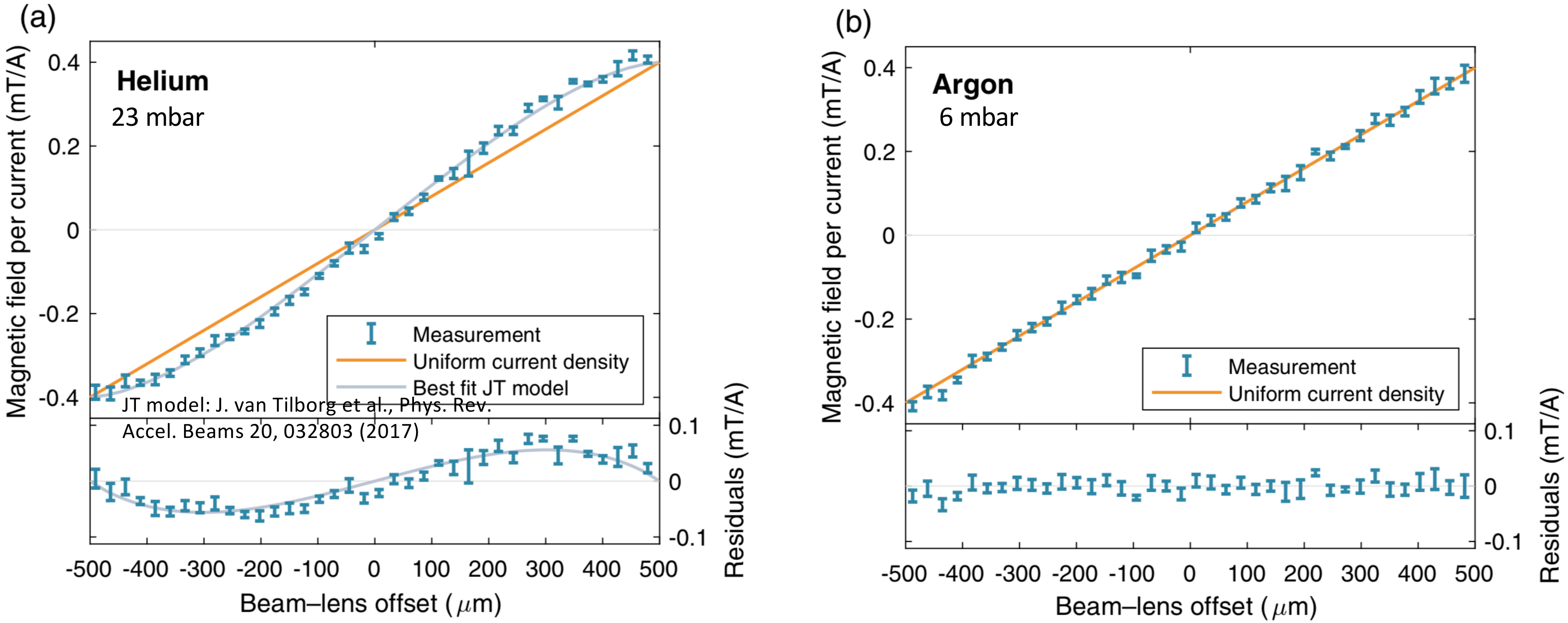
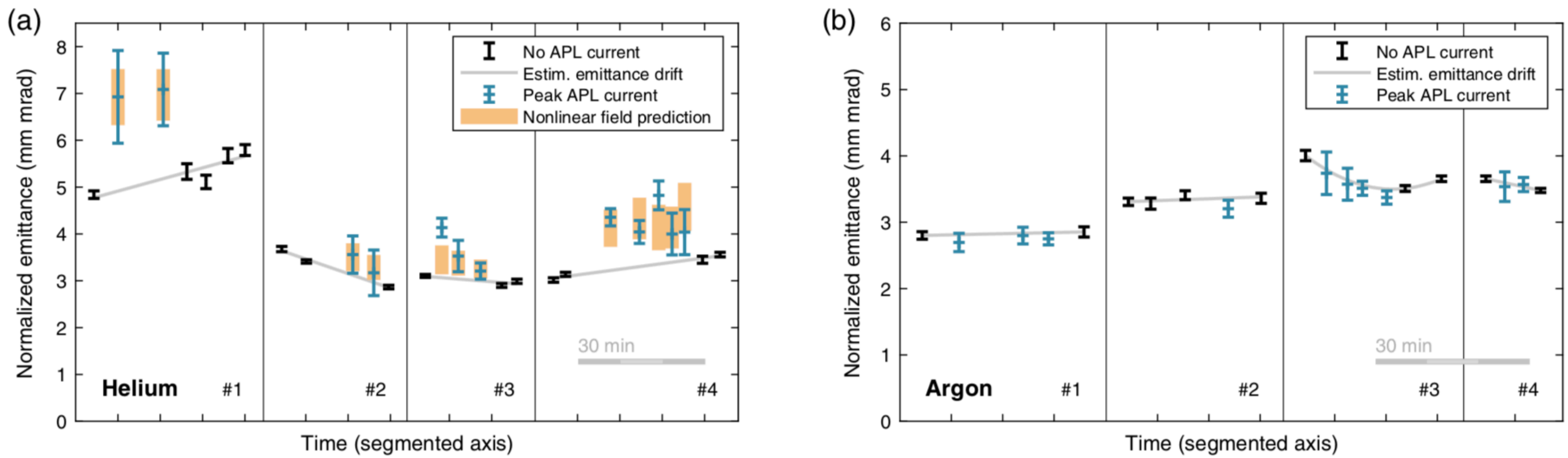


Figure 6: a) The energy spectrum from ICS, for different combinations of electron beam (λ) *and laser (P) polarization. b) The luminosity spectrum for a* E_0*=10 TeV* $\gamma\gamma$ *collider, assuming a laser with the optimal wavelength (x=4.8) and energy. The incoming electron and laser beams are assumed unpolarized. The electrons are not separated from the photons, giving luminosity for* e^-e^- *,* γe^- *and* $\gamma\gamma$ *collisions.*

Aberrations from plasma temperature gradients

C. A. Lindstrøm et al., PRL ***121****, 194801 (2018)*





Emittance of about 3 um norm **preserved** while focusing. Bunch charges about 20 pC.

V. Telnov (Ed.), TESLA TDR, Part VI, Ch 1 arXiv:hep-ex/0108012 (2001)
https://arxiv.org/pdf/hep-ex/0108012v1.pdf

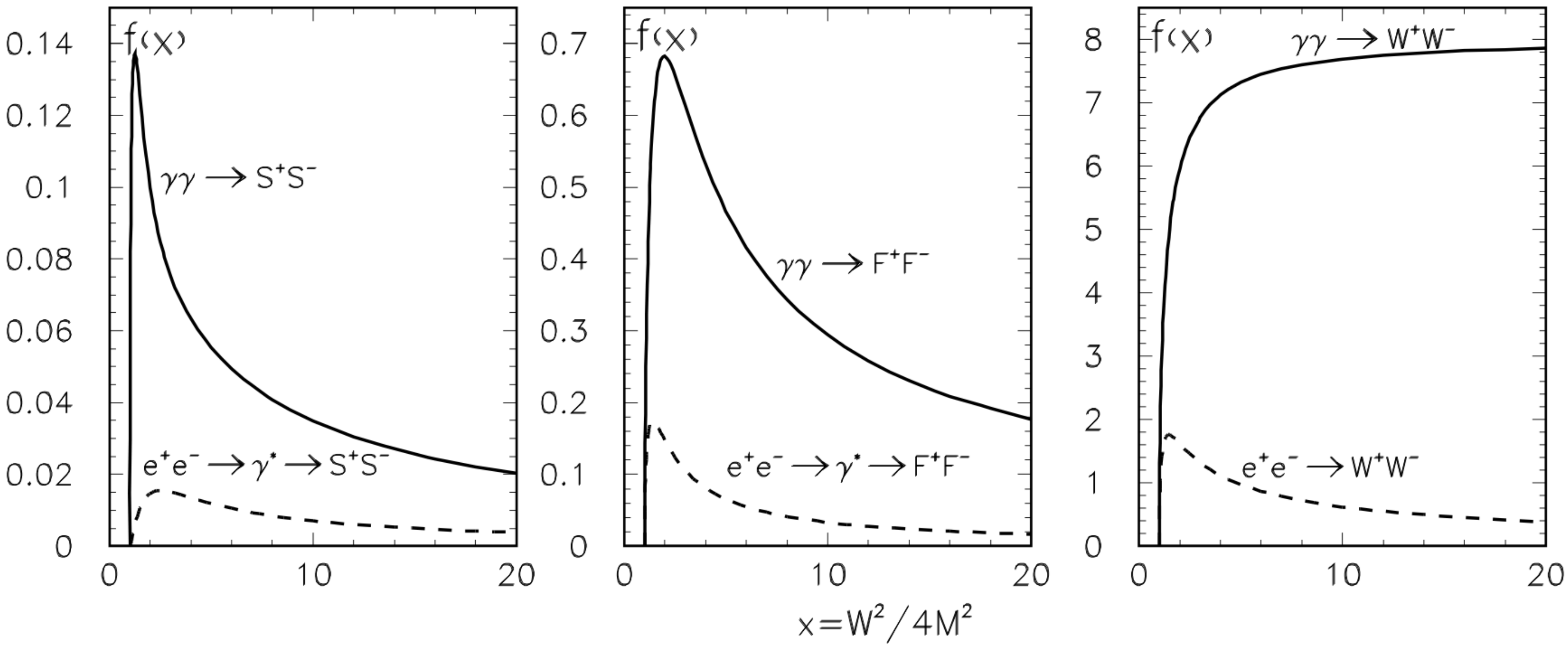
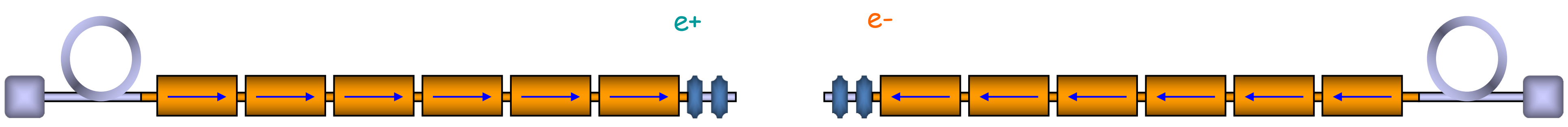
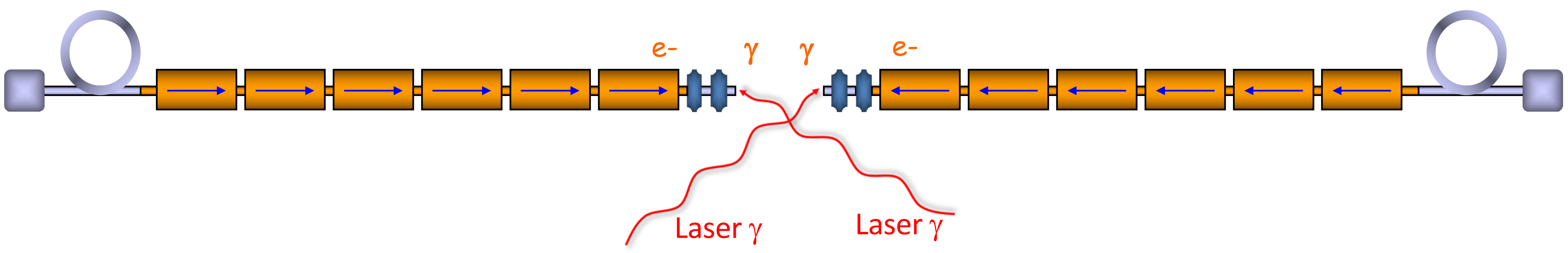


Figure 1.1.3: *Comparison between cross sections for charged pair production in unpolarised e^+e^- and $\gamma\gamma$ collisions. S (scalars), F (fermions), W (W bosons); $\sigma = (\pi\alpha^2/M^2)f(x)$, M is the particle mass, W is the invariant mass (c.m.s. energy of colliding beams), $f(x)$ are shown. Contribution of Z boson for production of S and F in e^+e^- collisions was not taken into account, it is less than 10%*

Challenge 1: positron acceleration

Proposed solution: using inverse compton scattering to build a photon-photon collider





RE

Can you build a particle collider using plasma wake field accelerators?

Yes, it is possible to build a particle collider using plasma wake field accelerators. Plasma wake field accelerators use a plasma, or ionized gas, to accelerate charged particles to very high energies over a very short distance. They have the potential to be much more compact and efficient than traditional particle accelerators, which makes them a promising technology for building smaller, more cost-effective particle colliders.

One of the key challenges in building a particle collider using plasma wake field accelerators is creating and maintaining a stable plasma wake over the required distance. This can be difficult because the plasma wake can be disrupted by various factors, such as instabilities or the presence of other charged particles. Researchers are working on various techniques to overcome these challenges and make plasma wake field accelerators a viable option for building particle colliders.

RE

Can you build a particle collider using plasma wake field accelerators?

Plasma wakefield accelerators have been suggested as a potential alternative to traditional particle colliders, but they have not yet been demonstrated as a viable technology for building a large-scale particle collider. In a plasma wakefield accelerator, a beam of particles (called a "driver") is sent through a plasma, creating a wave that can be used to accelerate other particles (called "witness" particles). This process is much more efficient than traditional methods of particle acceleration, and it has the potential to accelerate particles to much higher energies in a shorter distance. However, there are still many technical challenges that must be overcome before plasma wakefield accelerators can be used to build a particle collider.

https://chat.openai.com/chat

RE

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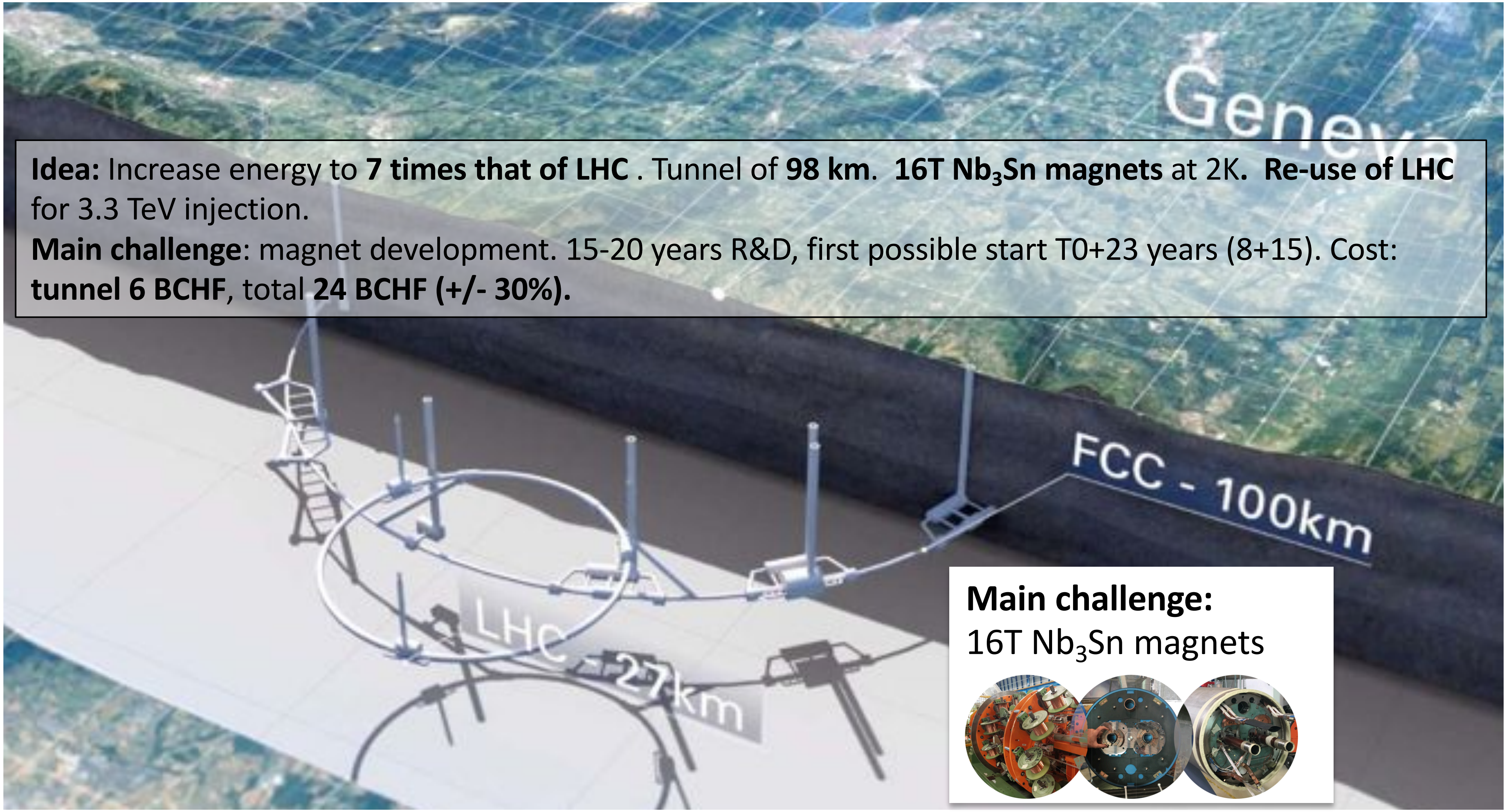
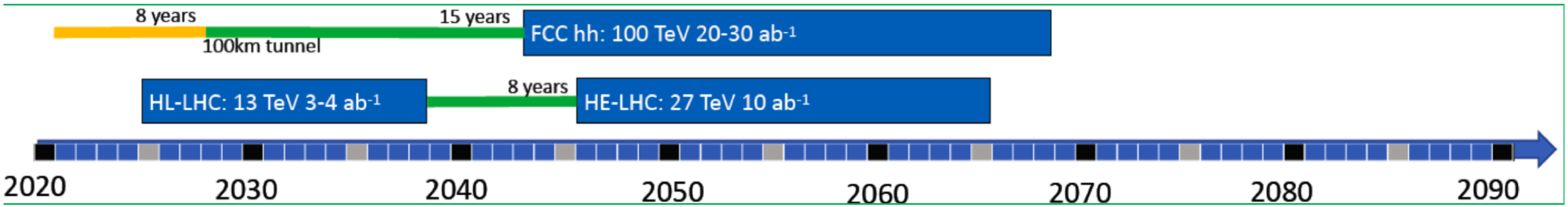
The Future Circular Collider - **FCC-hh**

Idea: Increase energy to **7 times that of LHC** . Tunnel of **98 km**. **16T Nb_3Sn magnets** at 2K. **Re-use of LHC** for 3.3 TeV injection.
Main challenge: magnet development. 15-20 years R&D, first possible start T0+23 years (8+15). Cost: **tunnel 6 BCHF**, total **24 BCHF (+/- 30%).**



Main challenge:
16T Nb_3Sn magnets

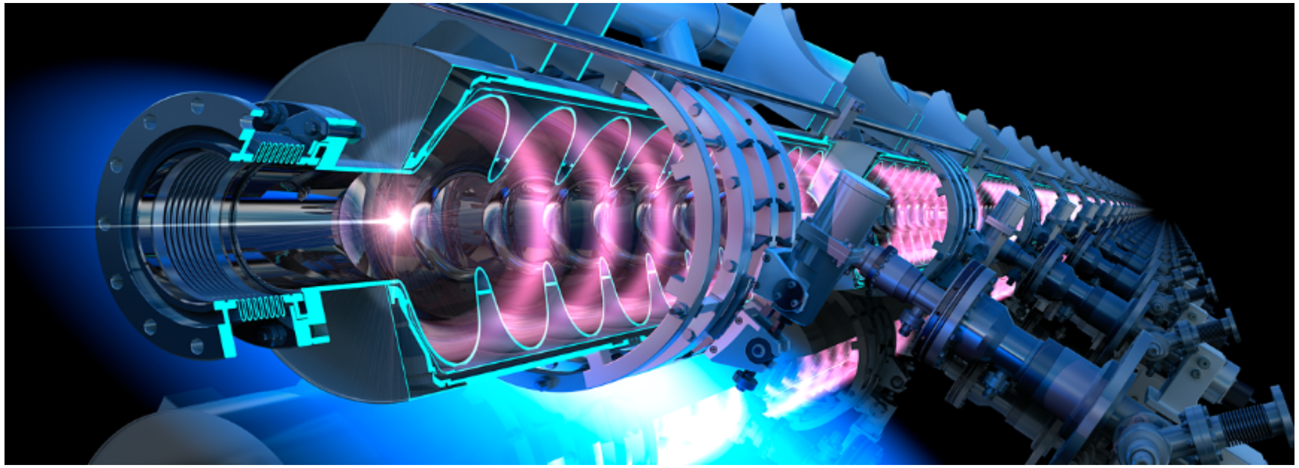


Linear Electron Positron Colliders: **ILC**

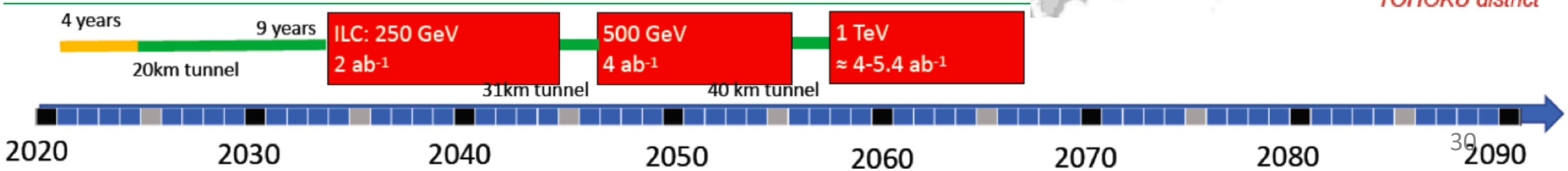
The International Linear Collider, ILC - Japan potential host

Superconducting 1.3 GHz cavities, 31.5 MV/m,

First stage 250 GeV, 20 km. Upgradable to 1 TeV, ~50 km.



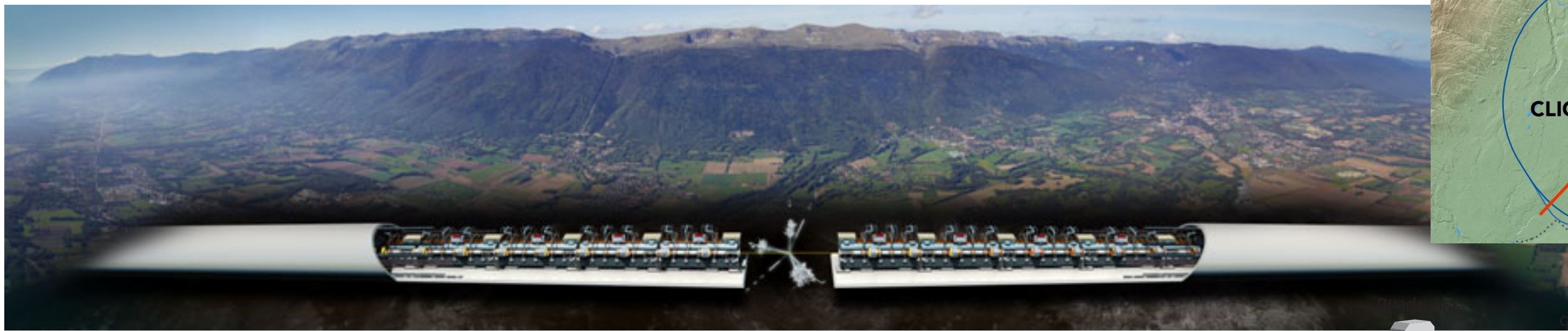
- Development of SCRF cavities with 31.5 MV/m, mostly done. Technology proven (XFEL).
- Technical Design done – almost ready for construction
- Cost: **4.8-6.3B 2012$** (250 GeV)
- May go forward if the Japanese government agrees to pay the bulk, and with sufficient support from Europe and USA. decision process has taken a long time

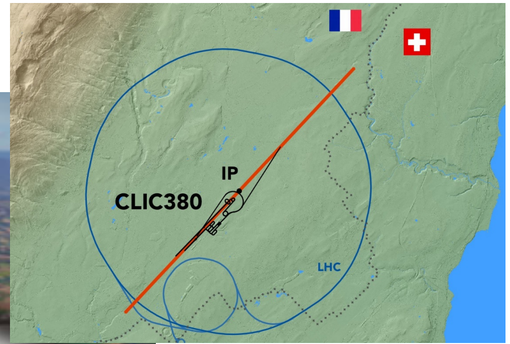


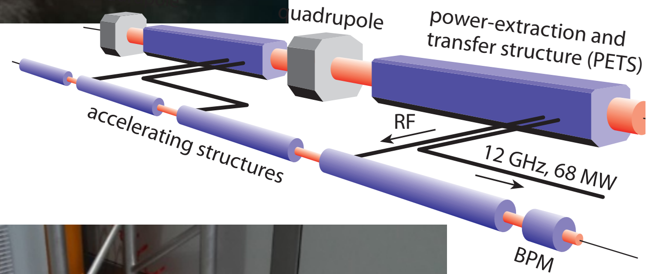
Linear Electron Positron Colliders: **CLIC**

The Compact Linear Collider, CLIC - CERN potential host

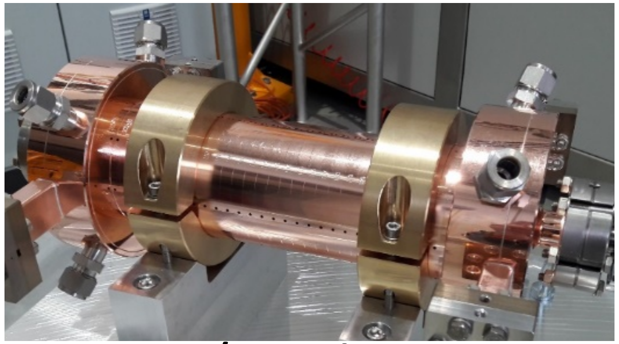
Normal conducting 12 GHz, two-beam acceleration, 100 MV/m.
First stage 380 GeV, 11 km. Upgradable to 3 TeV, 50 km.



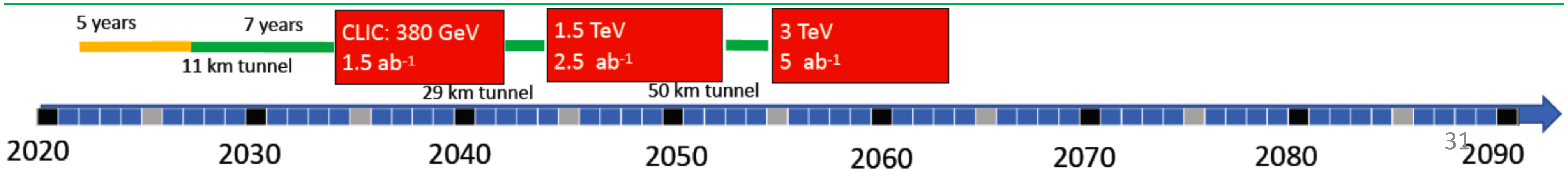


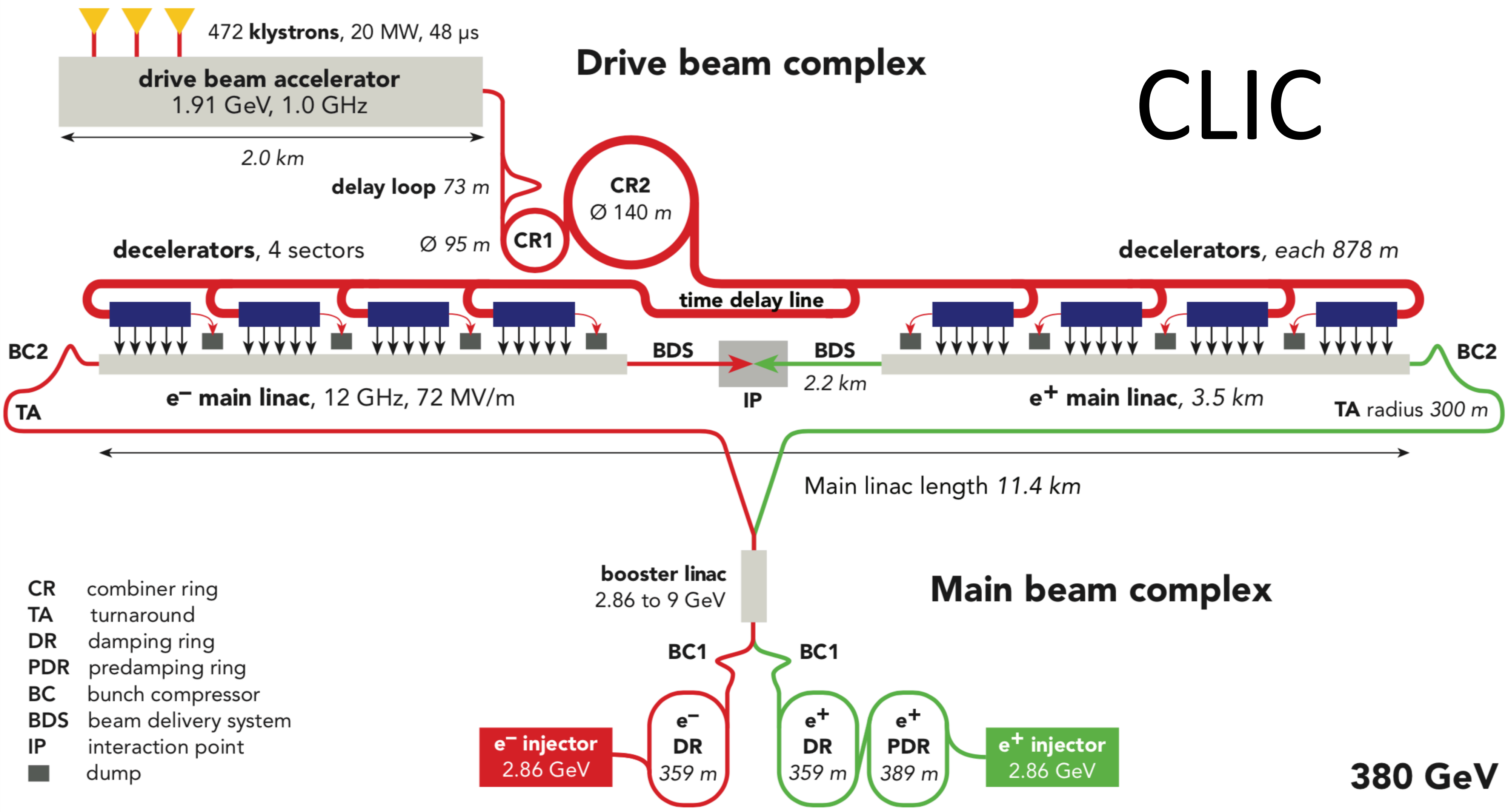


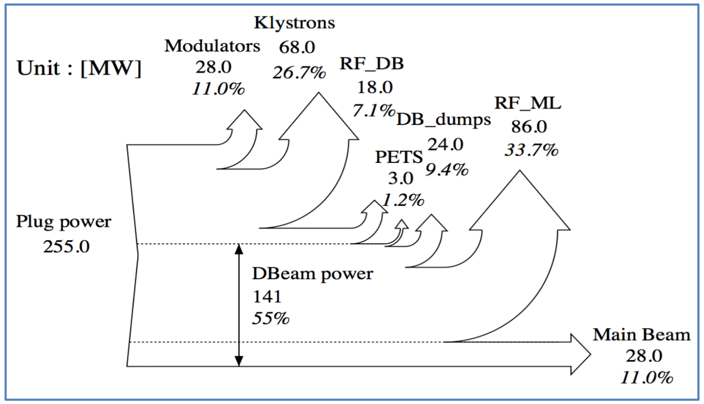
- Two-beam acceleration with **100 MV/m demonstrated** at CERN
- **Conceptual Design done** – about 5 years of technical design required before construction
- Cost: **5.9 BCHF** (380 GeV) + 5.1 BCHF (1.5 TeV) + 7.3 BCHF (3 TeV) = **18.3 BCHF total**



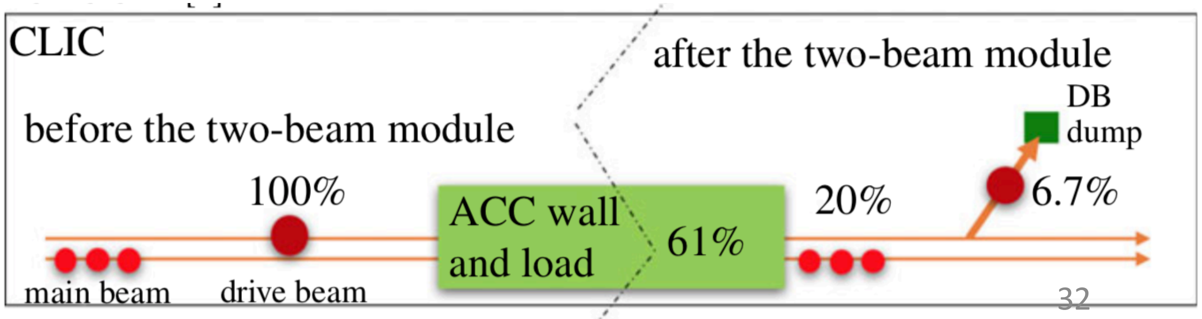
CLIC 100 MV/m accelerating structure







CLIC drive- to main beam power efficiency



Novel accelerator concepts: **muon collider**

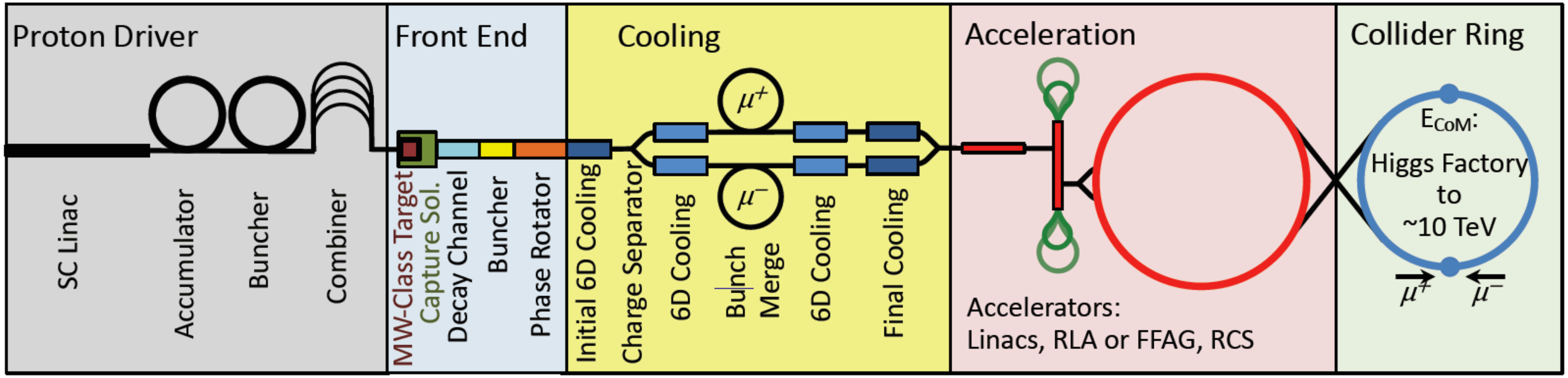
Novel concepts: boost accelerator performance with **radical change in technology**
Very promising and interesting research, many hurdles to overcome before use in a collider.

Muon collider pros and cons

Negligible synchrotron radiation

Main challenge: τ_μ = 2.2 μs

- Produce sufficiently dense muon beams
- Rapid acceleration
- Mitigate radiation hazards



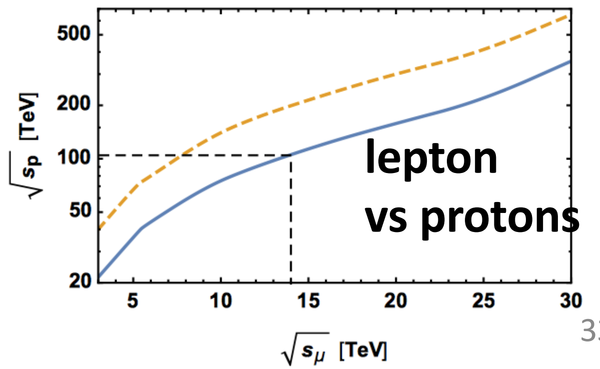
Protons on target hadronic showers, Pions decay into muons

Muon are captured, bunched and then cooled.

Rapid acceleration to collision energy

Collision

Precision, plus discovery potential!
3 TeV ~ LHC
14 TeV ~ FCC-hh;
30 TeV ~ "amazing"



Plasma collider: the luminosity challenge

The luminosity requirements for linear colliders are of order 10^{34} cm^{-2} s^{-1} (a few ab^{-1} integrated luminosity in the machine lifetime). Luminosity targets is **equally important** as energy targets.

General formula:

$$\mathscr{L} = f_{rep} \frac{N^2 n_b}{4\pi\sigma_x\sigma_y} H_b$$

CLIC 3 TeV:P_{AC} = 500+ MW

Rewrite in terms of power :

$$\mathscr{L}/P_{AC} \propto \frac{\eta_{\mathrm{AC}\rightarrow\mathrm{beam}}}{mc^2} \frac{N}{\sigma_x\sigma_y}$$

Taking into account beam strahlung :

$$\mathscr{L}/P_{AC} \propto \frac{\eta_{\mathrm{AC}\rightarrow\mathrm{beam}}}{mc^2} \frac{1}{\sqrt{\sigma_z}\sigma_y}$$

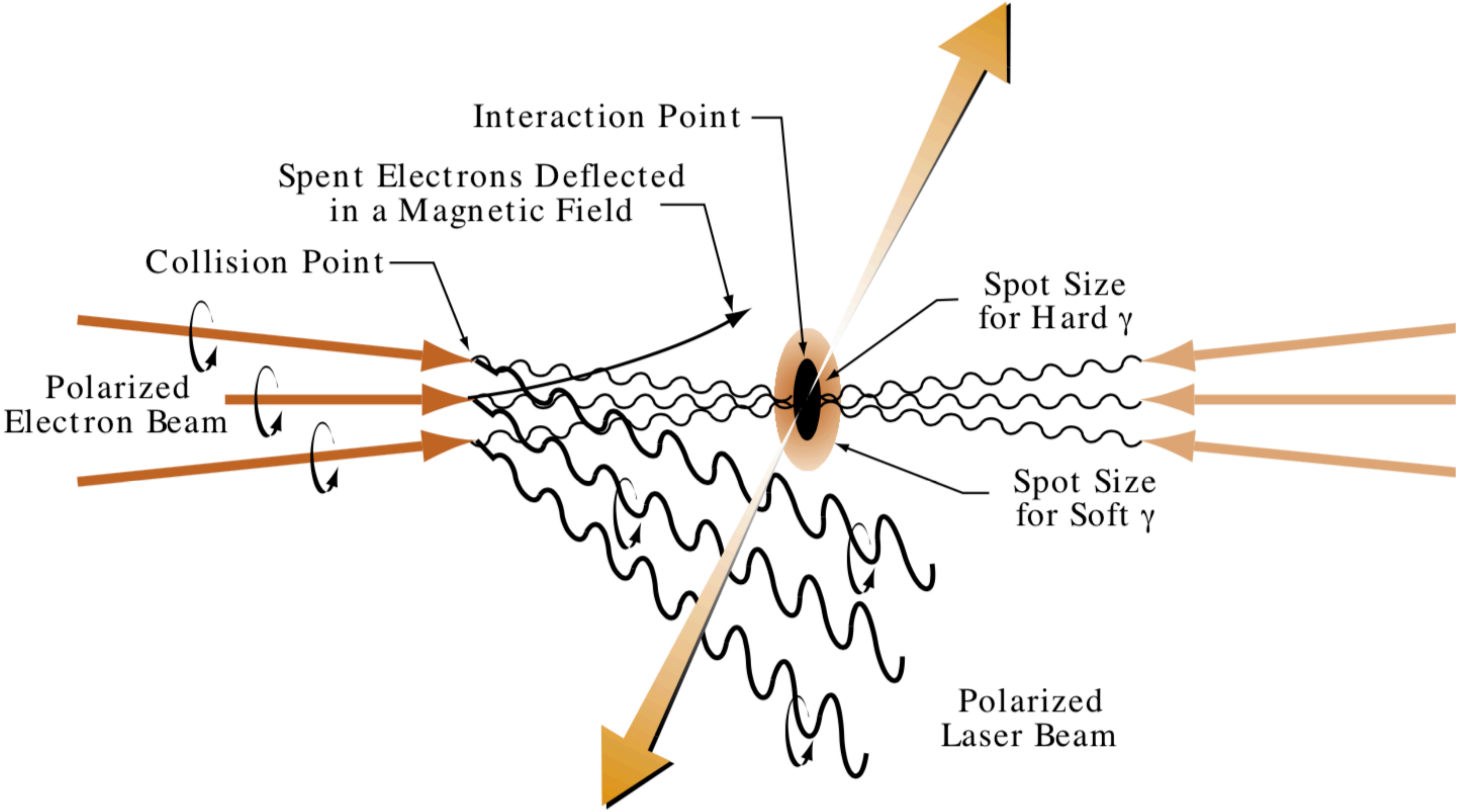
$\sigma_y^2 = \beta_y \varepsilon_y$

Implications :

- **Minimize vertical emittance**
- Minimize vertical focusing function
- **Short bunches**
- Low energy spread
- **Maximize wall-plug-to-beam efficiency**

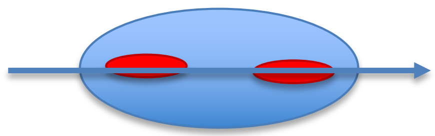
D. Schulte, IPAC 2002
K. Yokoya, P. Chen, KEK, 1991
CLIC CDR, 2012

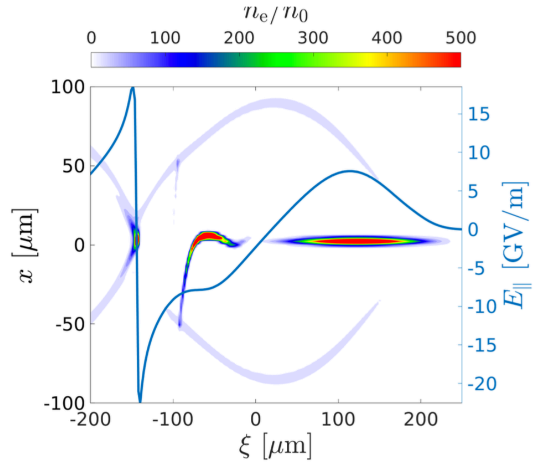
Gamma-gamma collider

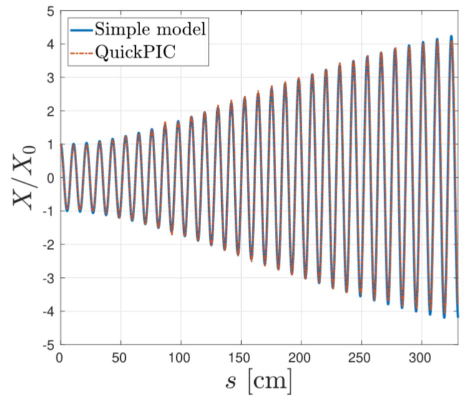


Transverse instabilities: RF colliders vs plasma colliders

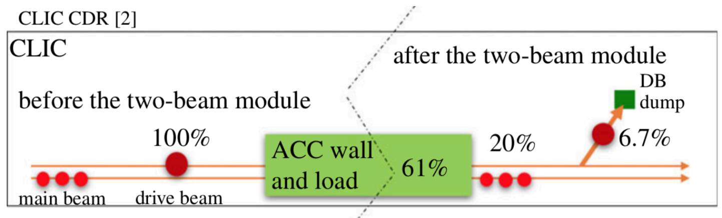
Focus lately: witness beam intra-beam wake :







Why are the linear community scrutinizing the main beam single bunch wake?
The single-bunch wake decides how much charge can be loaded into CLIC.



CLIC:
Limit for transverse single bunch wake: **100 kV/pC/m/m**
Goal attained by spreading pulse charge into multi-bunch trains. **Limits** the CLIC wake to RF efficiency to ~25%.

Current plasma collider concepts: **single bunch acceleration**
- may also lose on efficiency if charge needs to be reduced

Open questions:
- sufficient mitigation of the instability for efficient PWFA single bunch acceleration?
- further benchmarking with PIC simulations and experiment needed