HALHF WORKSHOP SUMMARY

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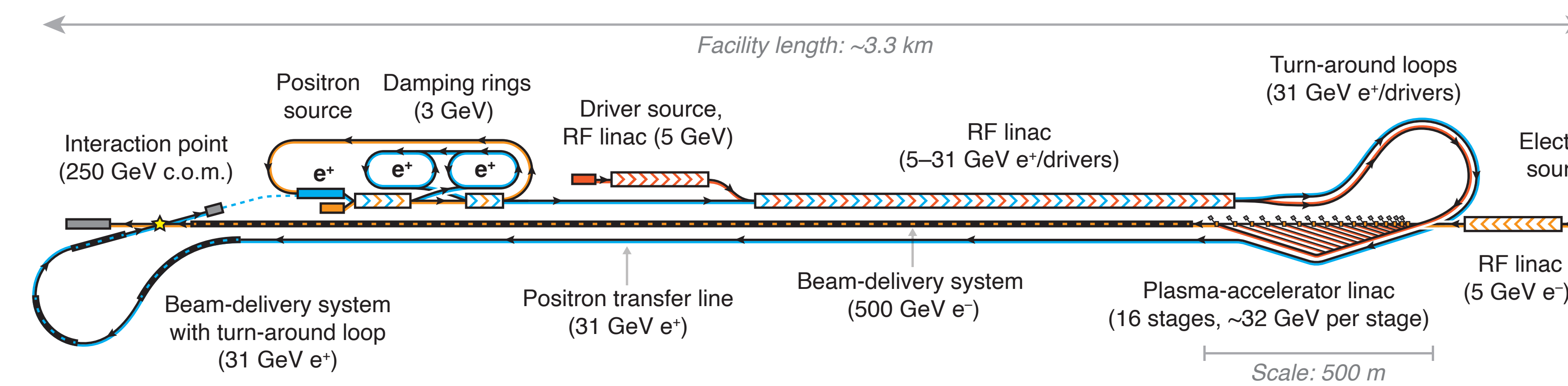
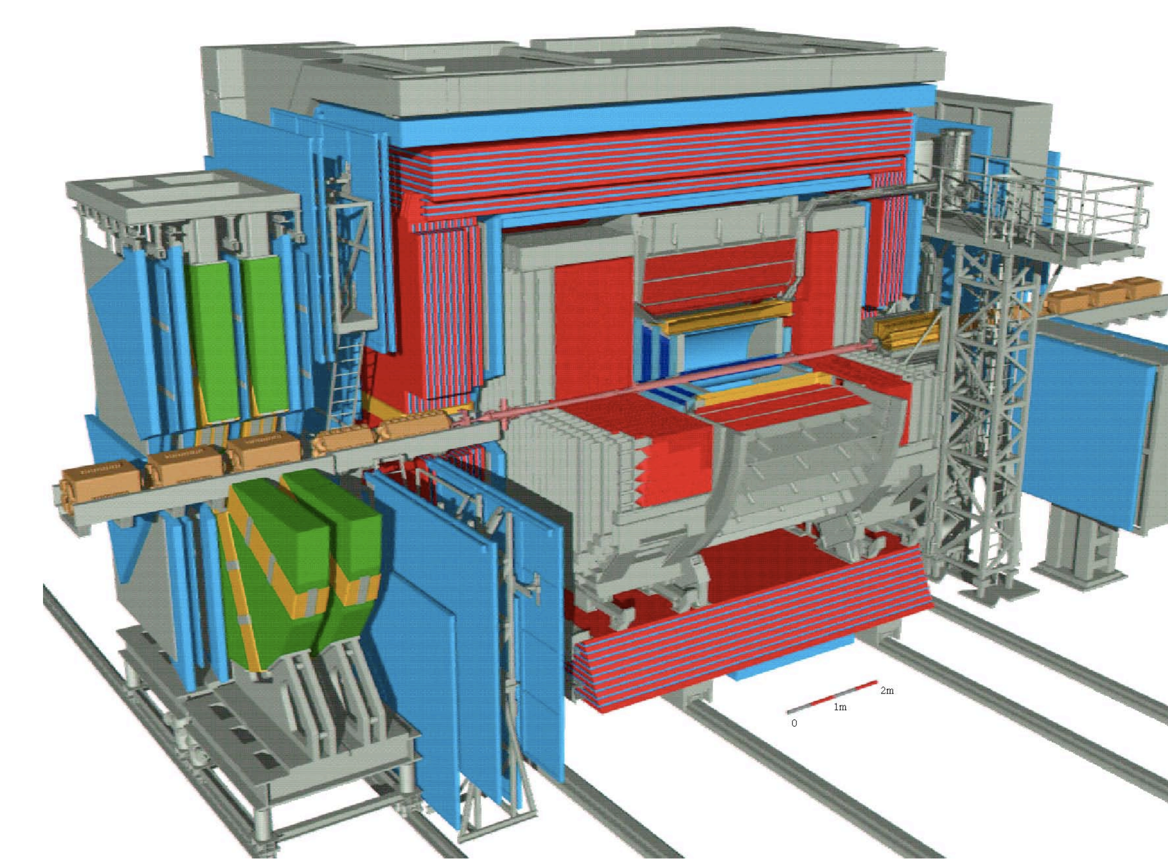
Brief review of HALHF

Reminder of the core principles



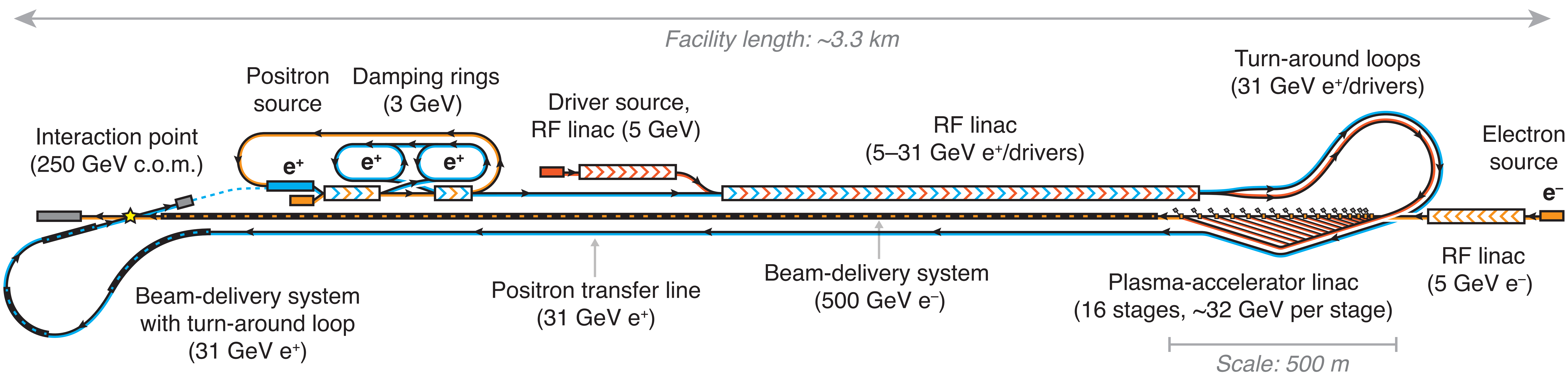
Foster, D'Arcy and Lindstrøm, New J. Phys. 25, 093037 (2023)

- Plasma accelerators have the potential to produce more compact/cheaper colliders
  - GV/m gradients demonstrated
  - Potential for high luminosity (100% charge coupling, beam-quality preservation, in-principle 10 MHz rates, etc.)
- Plasmas are not ideal for accelerating positrons due to the charge asymmetry of plasma ions and electrons
  - Currently no good regime known for accelerating positrons known (although some promising routes proposed)
- HALHF sidesteps this problem by avoiding positron acceleration in plasma
  - Use RF acceleration for (lower-energy) positrons
  - Use plasma accelerator for (higher-energy) electrons:
    - Currently best power efficiency: to use electron-beam-driven plasma acceleration
- Asymmetric beam energies minimise the footprint and cost (e.g., 32 GeV e^+ + 500 GeV e^- = 250 GeV CoM)
  - However, need an asymmetric/forward detector: new advantages, new challenges
  - *Finding*: The more asymmetries (charge, emittance, energy), the better!



Original baseline design

HALHF 1.0



HALHF was well received in general!

HALHF was well received in general!

… but *many* detailed issues were pointed out…

Problems with the original design

The laundry list

- **Transverse instability, tolerances** are too tight.
- **Beam ionisation** of the higher-order ionisation levels for argon (chosen to avoid ion motion).
- **Cross-plane emittance mixing** (Diederichs *et al.*): large horizontal emittance leaks into vertical emittance.
- **Plasma-cell cooling**: too much cooling required per length (~90 kW/m).
- **Radiation reaction** at high energy: large induced energy spread (%-level).
- **Bunch pattern** may not be compatible with PWFA: too much temperature increase? Effect on wakefields? Confinement?
- Exceeded the **Oide limit** in the final focusing magnets.
- **High-energy turn-arounds**: too much energy loss to synchrotron radiation.
- The required **delay chicanes** are (transversely) large and costly. Strong bending magnets (SR is problematic).
- **Combined RF accelerator** has too high gradient given its high power.
- Required **driver bunch length** is too short: problematic beam loading in the RF linac (beam current too high).
- The **instantaneous luminosity is too low**
- **High positron bunch charge**: problematic for production and for collisions.
- Need **polarised beams** for physics.
- Unknown if we can **preserve spin polarization** of electrons in plasma stages and interstages.

An updated baseline
based on 10+1 changes

- Reduce plasma density
- Introduce controlled ion motion
- Separate the driver and positron linacs
- Reduce energy asymmetry
- More stages in plasma linac
- Higher transformer ratio
- Longer bunch trains
- Reduce driver separation
- Undulating delay chicanes
- Fewer, but polarised positrons

… which fixed quite a few issues, but caused also new ones…


HALHF Workshop
Ettore Majorana Centre, Erice, Sicily
3–8 October 2024

Workshop aimed to converge on a self-consistent design

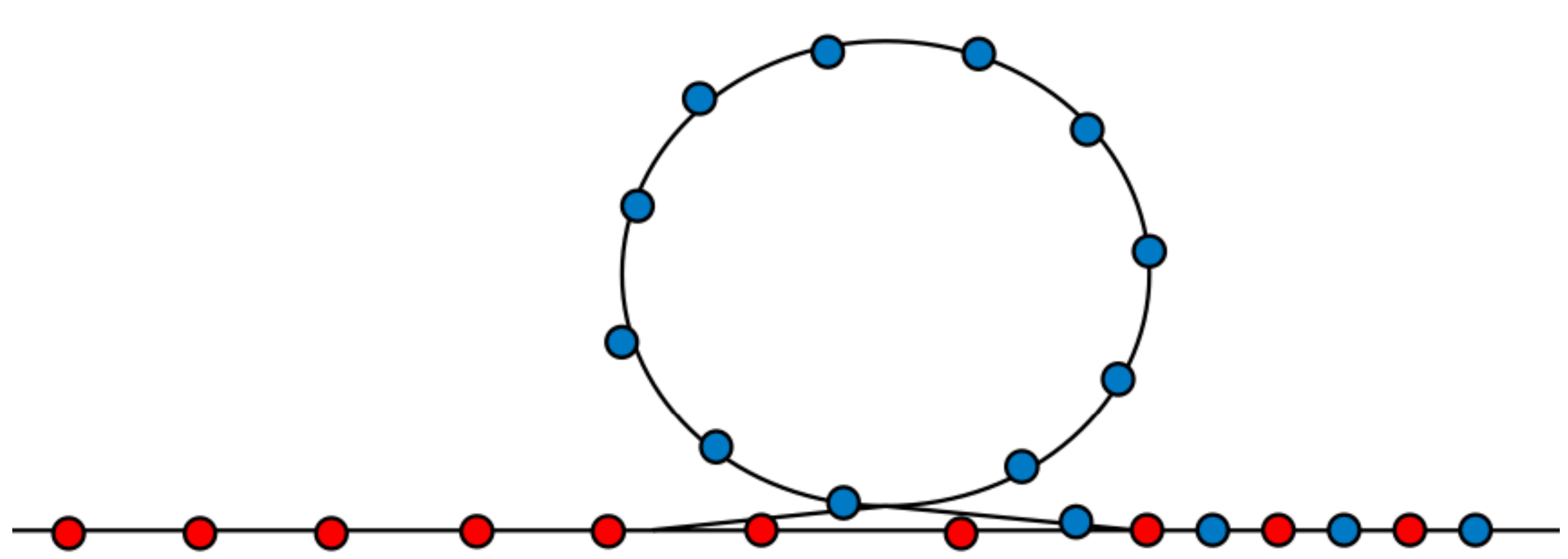
Most work done in parallel groups, working on 8 ‘questions’

- **Question 1**
  RF linac designs: constraints and costs of drive-beam linac and positron linac. (B. List, S. Gessner)
- **Question 2**
  Beam-driven RF/SWFA cost-effective alternative for the positron linac (X. Lu, K. Sjøbæk)
- **Question 3**
  BDS: shorten, collimation, include positron source; positron/electron damping rings design, (A. Seryi, G. Moortgat-Pick)
- **Question 4**
  The upgrade ladder: demonstrators, default energy, XCC, 10 TeV path (T. Barklow, M. Hogan)
- **Question 5**
  Plasma-linac design: staging, driver distribution (C. A. Lindstrøm, M. Thévenet)
- **Question 6**
  Plasma-linac design: polarisation, beam-quality preservation, tolerances (K. Põder, E. Adli)
- **Question 7**
  Plasma generation, heating, cooling and power flow, efficiency (R. D'Arcy, J. Wood)
- **Question 8**
  Physics/detector constraints, including coherent pairs (J. List, S. Farrington)

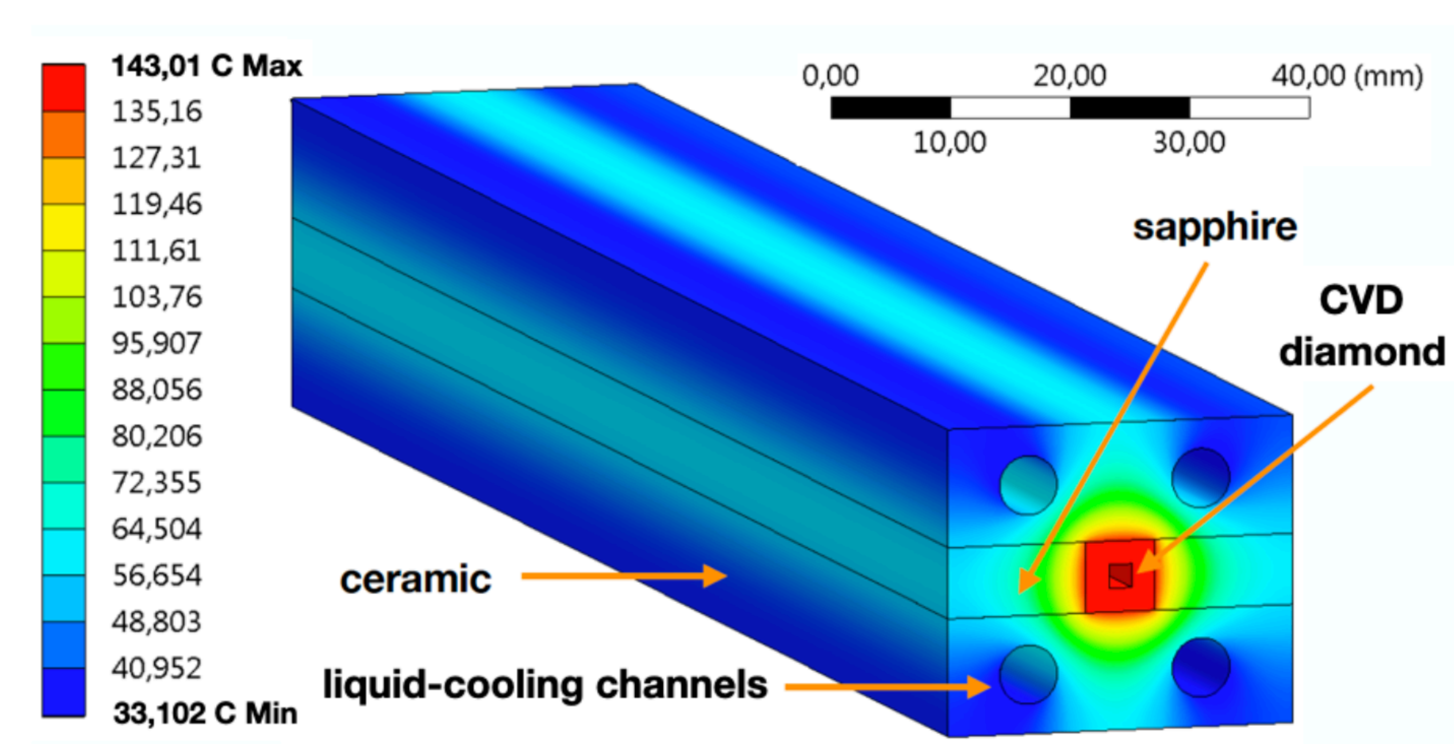
To pulse or not to pulse?

Pulsed and CW modes have benefits and challenges for both plasma and RF

- Small bunch separation of HALHF2.0 very problematic…
  - Could be solved by pulse stacking
  - Still, leads to a lot of peak power -> *many* klystrons
- CW SRF could be a nice solution
  - But CW positron acceleration, requiring high gradient, would be expensive



- Plasma seems to like pulsed mode
  - Enough material still in plasma source
  - MHz discharge tech exists
  - BUT leads to *very* hot plasma (>100keV)
  - Extreme cooling needed (~200MW/m)
- CW mode is *terra incognita* for plasmas
  - Gas flows out on 100us timescales, unless it is somehow confined
  - Heat has time to radiate away
  - But no experimental facilities to test…



Physics & Detectors

Bread and butter stuff - all ticks, apart from the idea of 'more plasma'

Conclusion & Outlook

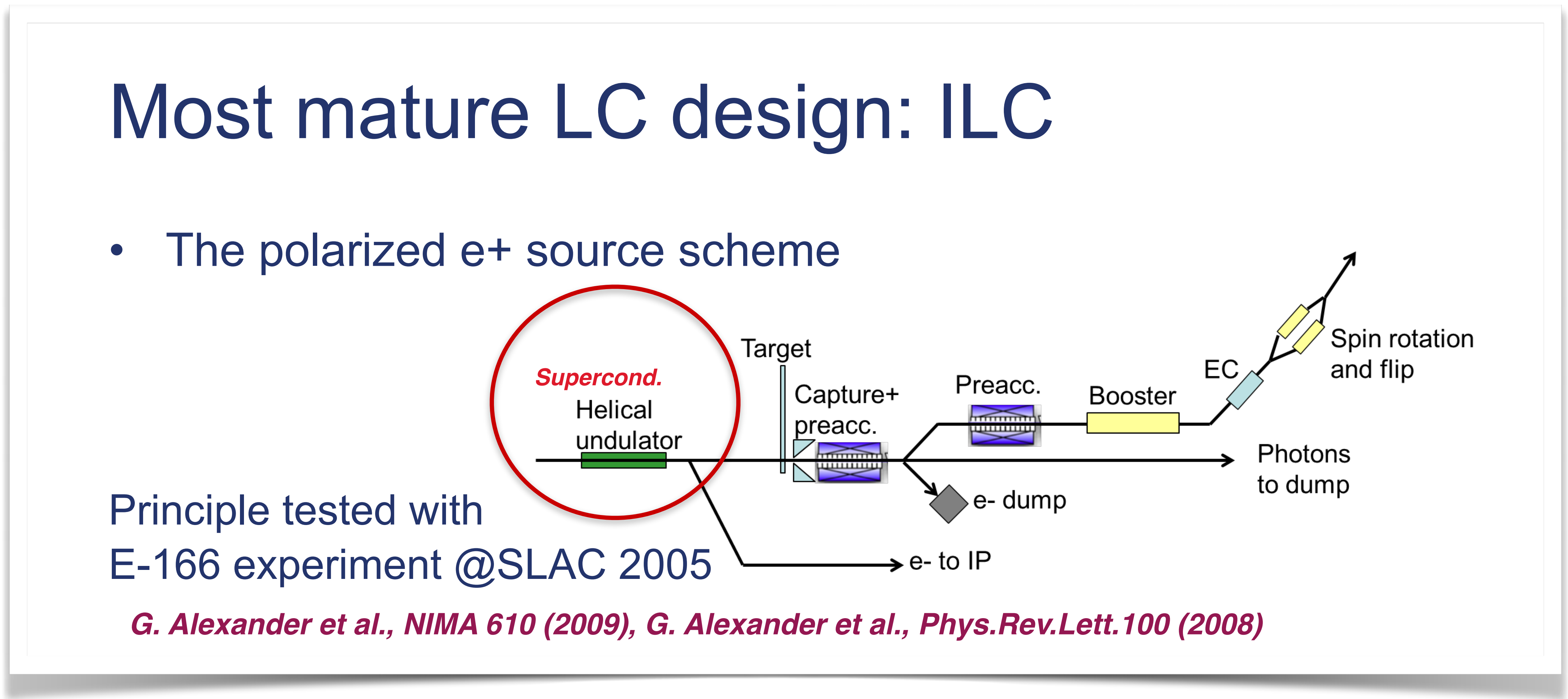
Where we are

- **Fix beam parameter assumptions for detector design (for now)**
  => go with 1.33 : 3 bunch charge & 75 : 300 um bunch length ✔
- **Luminosity measurement**
  => no show-stopper identified, try to get I.Bosovic to take a closer look ✔
- **Tagging heavy quark jets**
  => no show-stopper identified, try to find person power for quantitative studies ✔
- **Momentum measurement in the forward direction**
  => can be solved "the ugly way" => work towards finding more elegant solutions ✔
- **Final Focus**
  => APL at IP = BIG no-no! ✘
- **Status of tools** ✔
  => MC events & fast sim
  => Full simulation: WIP

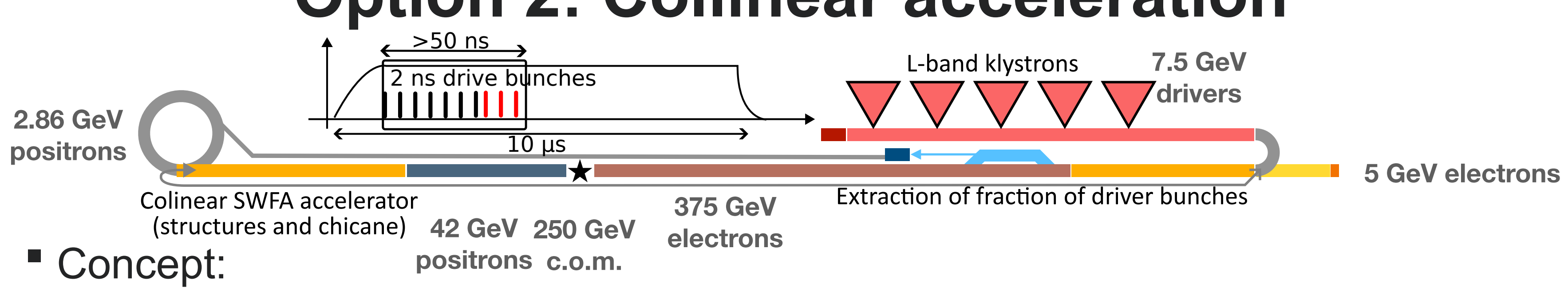
on a good way…

Positrons

Implement the ILC design for generation; SWFA *could* be interesting for acceleration



Option 2: Collinear acceleration



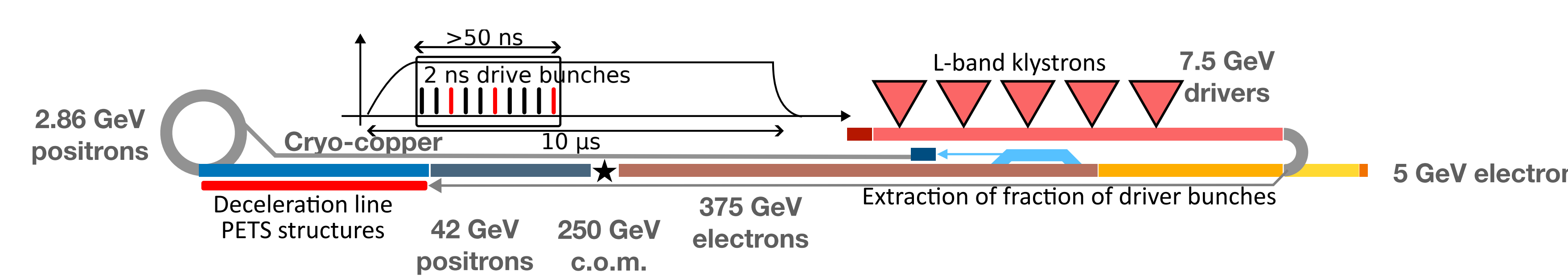
- Concept:
  - Introduce arbitrary time-multiplexing of drive beam i.e. X bunches to X SWFA positron stages, then Y bunches to Y PWFA stages, where Y > X.

Option 3: single-bunch TBA

- Concept: Design PETS and accelerator pairs to work with single drive bunches
- Layout similar to colinear

Option 4: TBA with interleaved drive bunches

- Concept: use part of the drive beam for PWFA and the rest for SWFA

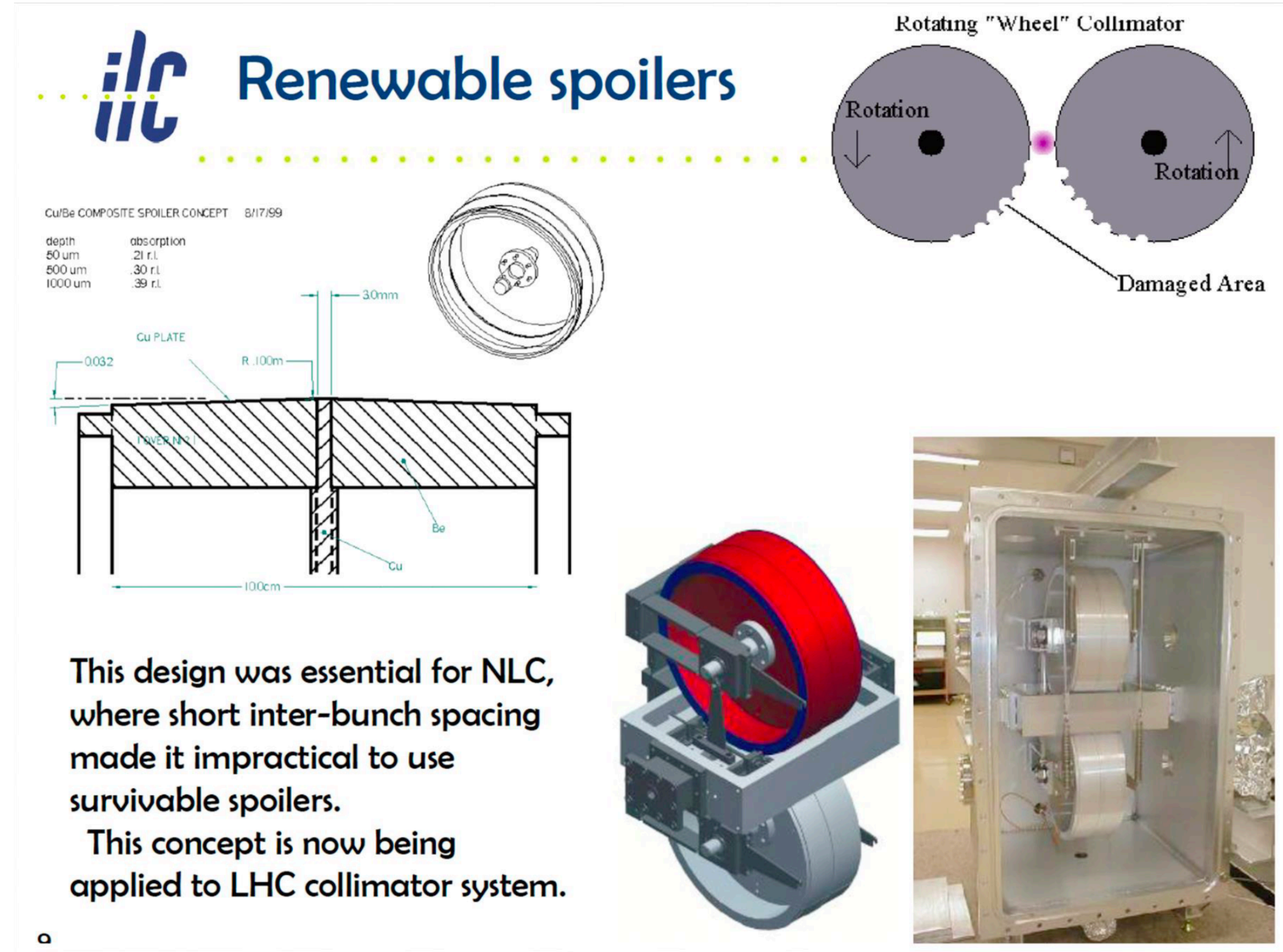


Beam Delivery System

More bread, more butter

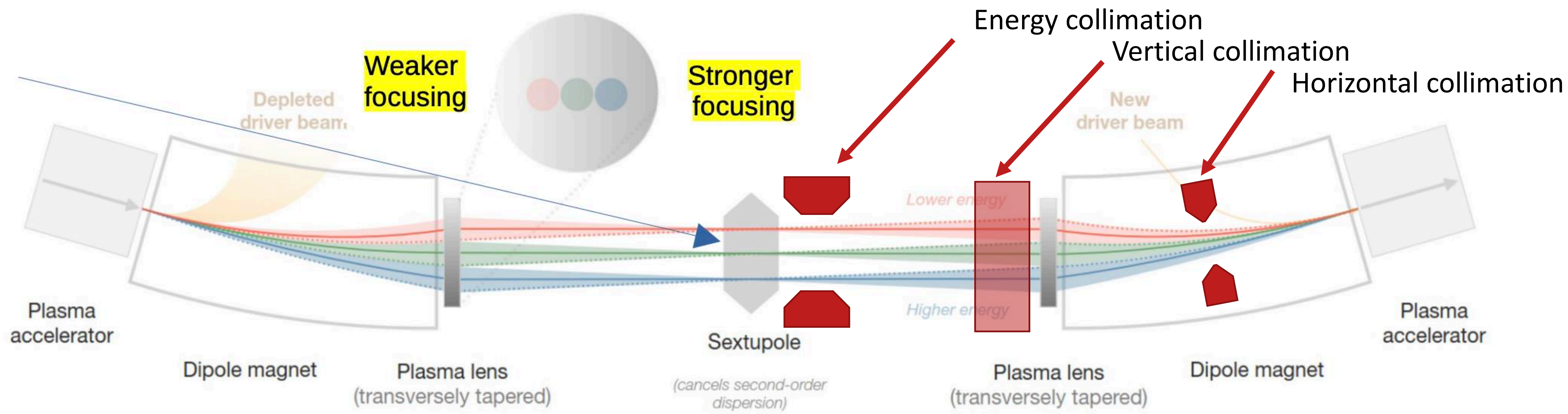
Reiterating the summary – key points on HALHF BDS for CERN strategy contribution

- HALHF BDS design strongly benefits from ILC & NLC BDS designs
  - NLC BDS with renewable spoilers, integrated with ILC BDS design (polarimeters, spectrometers, etc.), is the most close design meeting HALHF parameters
    - Engineering design of renewable spoilers is to be further advanced
  - ATF@KEK Final Focus test is the most essential demonstration – no other demonstrations are needed
- Optional design improvements for HALHF BDS are possible
  - Distributed collimation inside and in between of plasma sections will help
  - This distributed collimation will also ease assumptions for renewable BDS collimators
- Discussion of HALHF upgrades to TeV and multi-TeV opened plethora of ideas
  - Final Focus is scaling nicely to multi-TeV energies
  - The most unfavorable scaling is for energy collimation, but novel ideas such as distributed collimation in plasma sections and nonlinear energy collimation will likely revert the scaling and allow to design a compact BDS for multi-TeV advanced collider



Distributed collimation in plasma sections – for HALHF design

HALHF Workshop 2024, A. Seryi



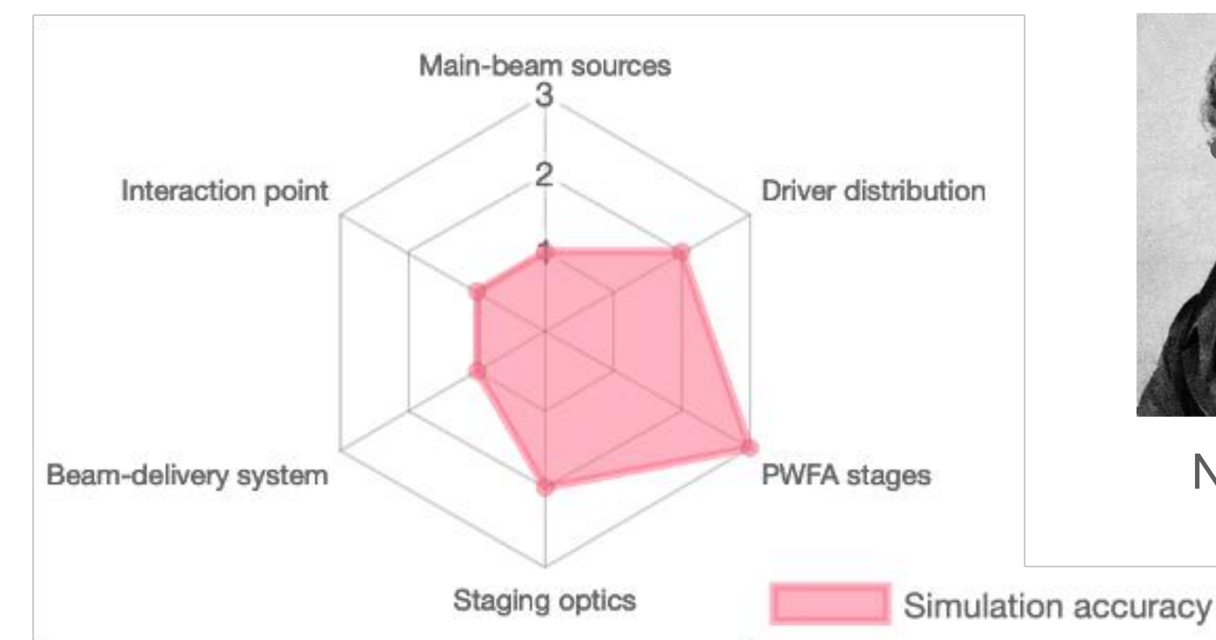
Plasma linac

Fast simulations tools developed to study multi-stage effects

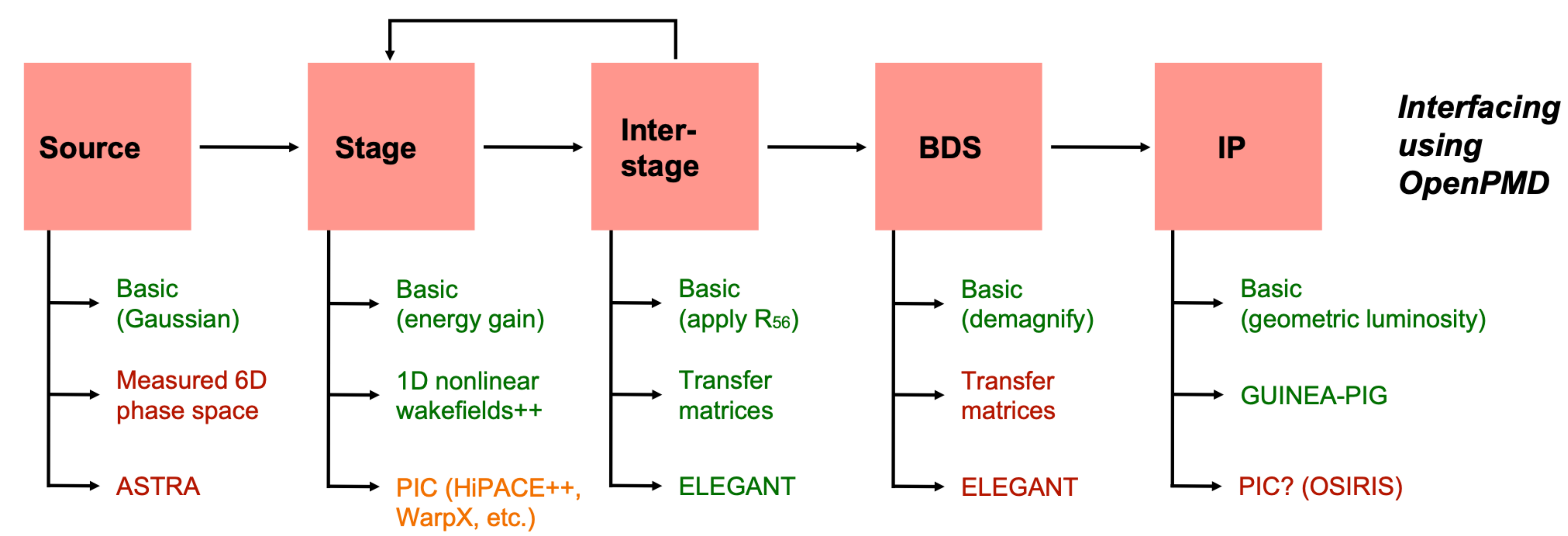
The Adaptable Beginning-to-End Linac simulation framework

Enabling agile design studies of plasma-based linacs/colliders

- Start broad and inaccurately, add details gradually.
- Modular setup, can switch between various codes/models for the machine components.
  - E.g. generate beam from source, track through stages and interstages to IP.
  - Requires many codes! Interfacing using OpenPMD.
  - Currently supports HiPACE++, Wake-T, ELEGANT, GUINEA-PIG, RF-Track.
  - Also built-in simplified models.
  - User-adjusted speed/precision.
  - Easy to isolate effects.
  - Can perform multiple shots in parellel.
  - Driver angular offset and plasma density ramp not implemented yet.
- Support for RF linac (CLICopti) almost ready (Kyrre & Carl).
- Not ready for release. Showcase some features today.



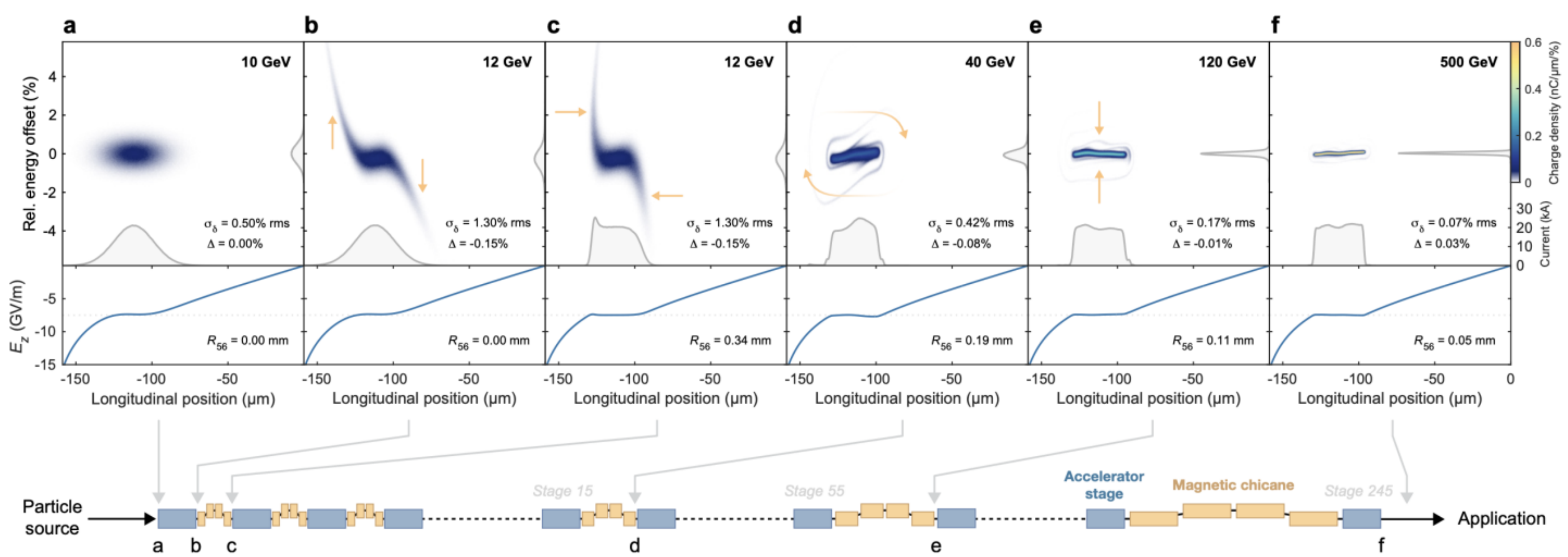
N. H. Abel



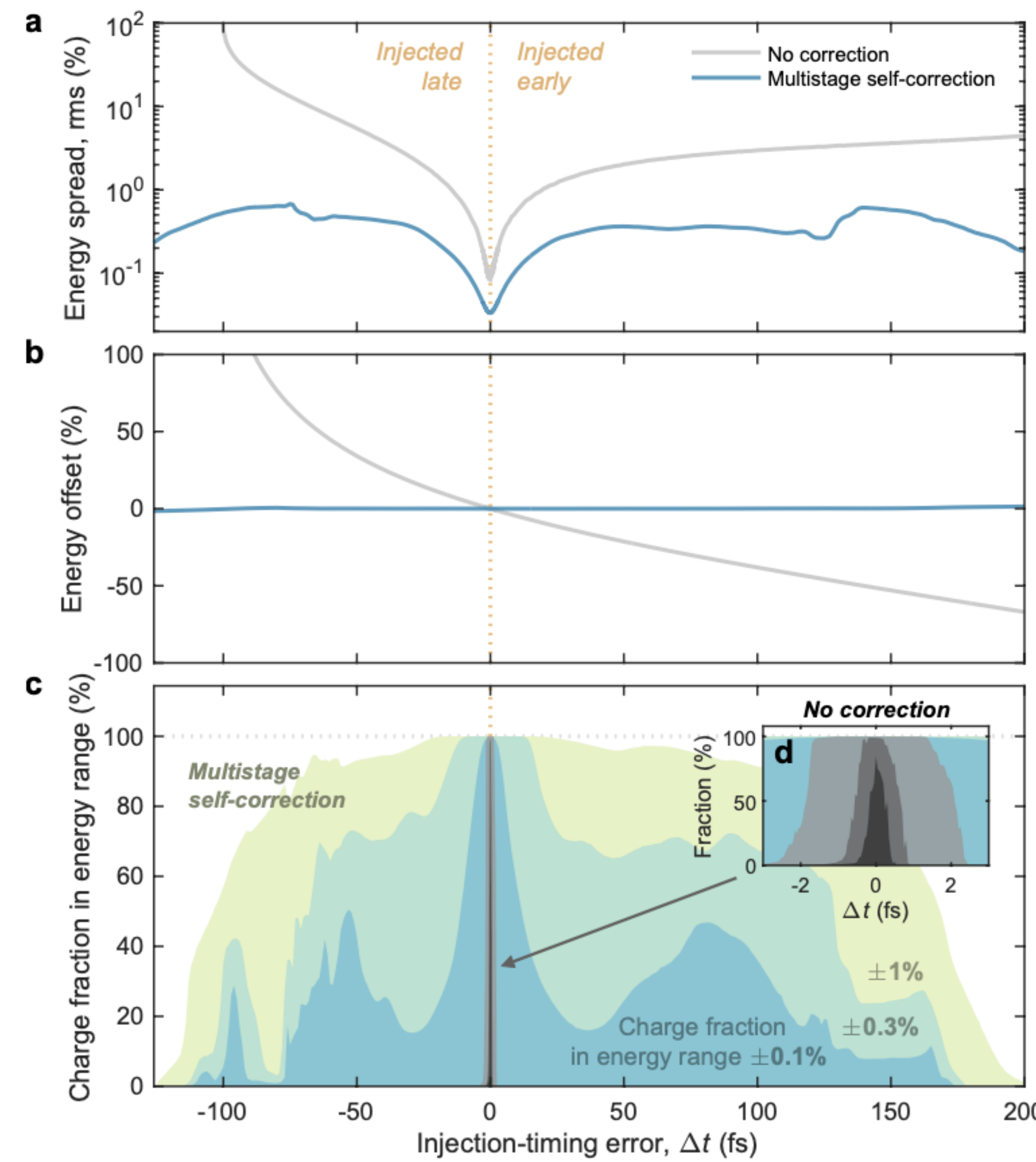
Plasma linac

Self-correction in achromatic interstage design also greatly relaxes timing requirements

Longitudinal tolerances



Carl A. Lindstrøm, arXiv:2104.14460
[Self-correcting longitudinal phase space in a multistage plasma accelerator]



Expected to greatly mitigate initial tight phase tolerances.
To be studied: tolerances with full interstage

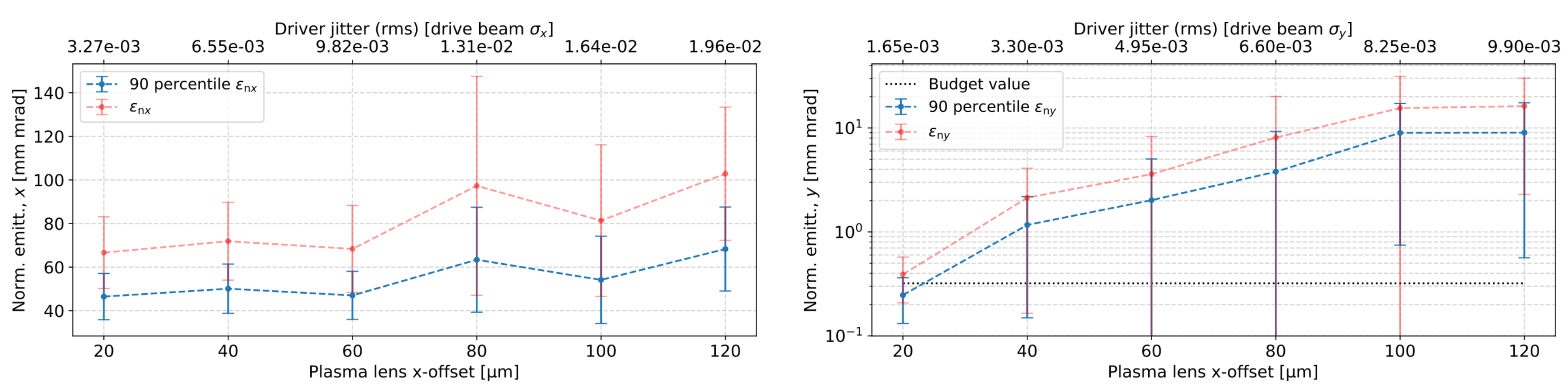
Plasma linac

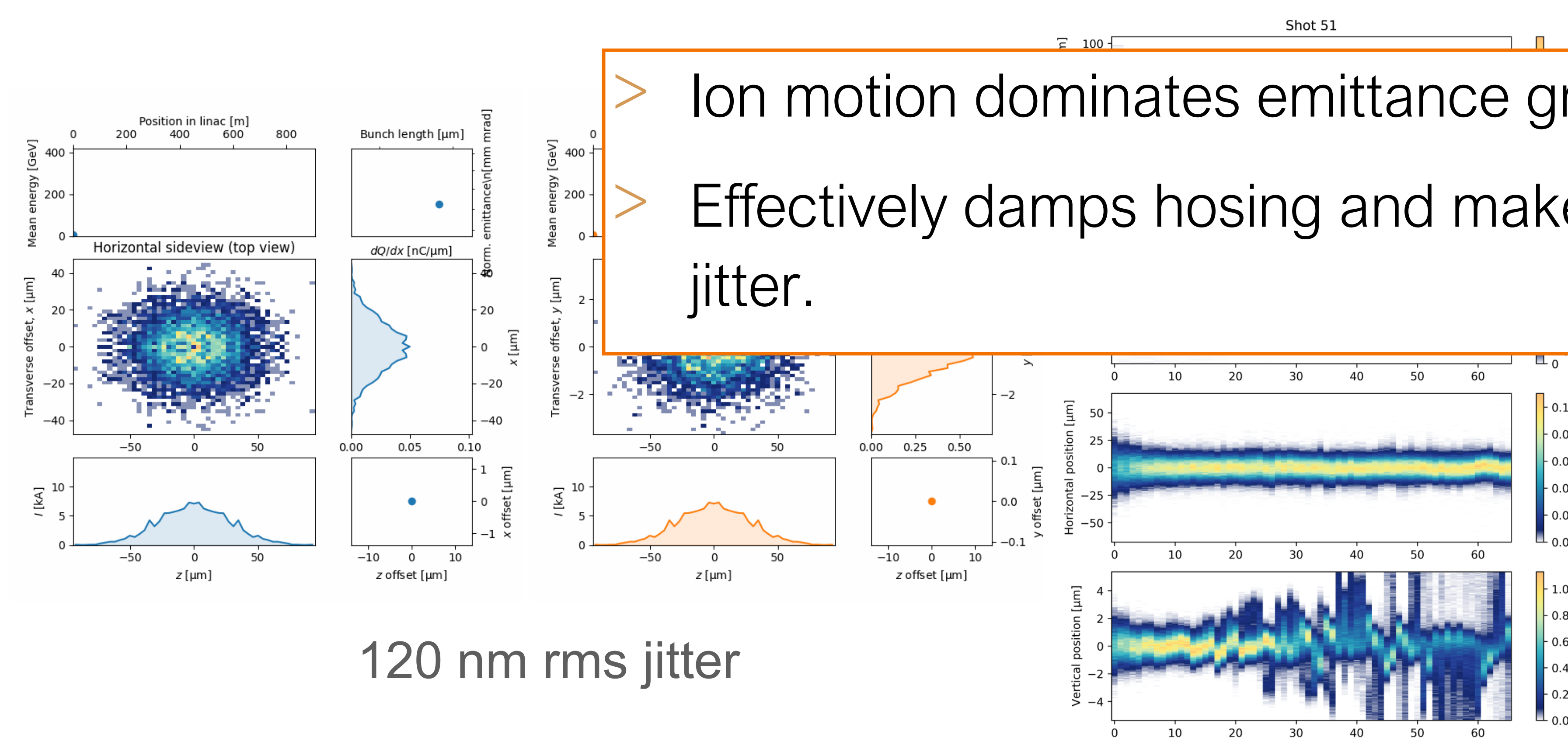
Understanding effects of drive beam jitter: plasma ion motion acts as damper

Updated drive beam jitter scan

Initial emittances 15 / 0.1 mm mrad

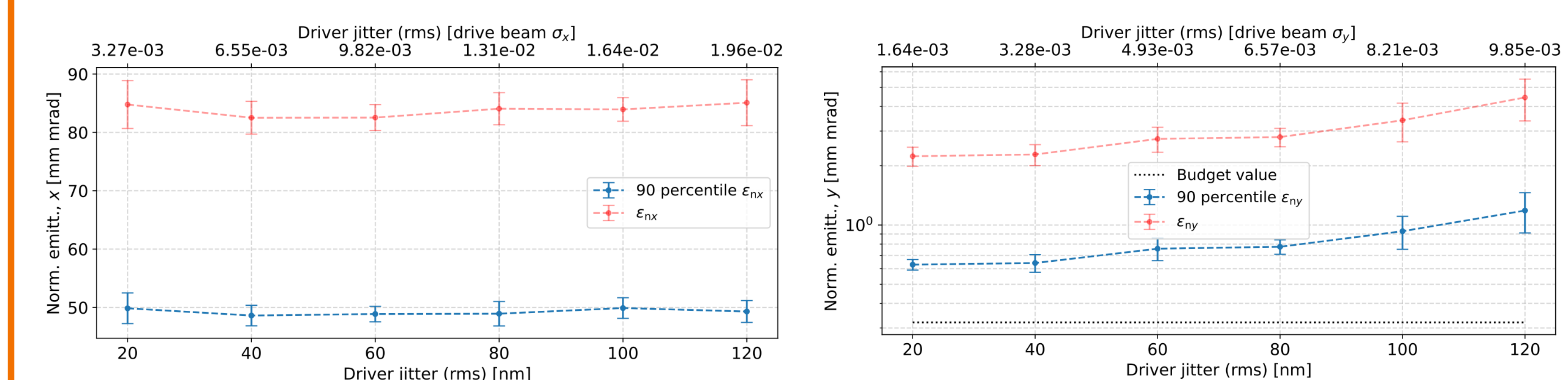
Transverse wake enabled, ion motion disabled

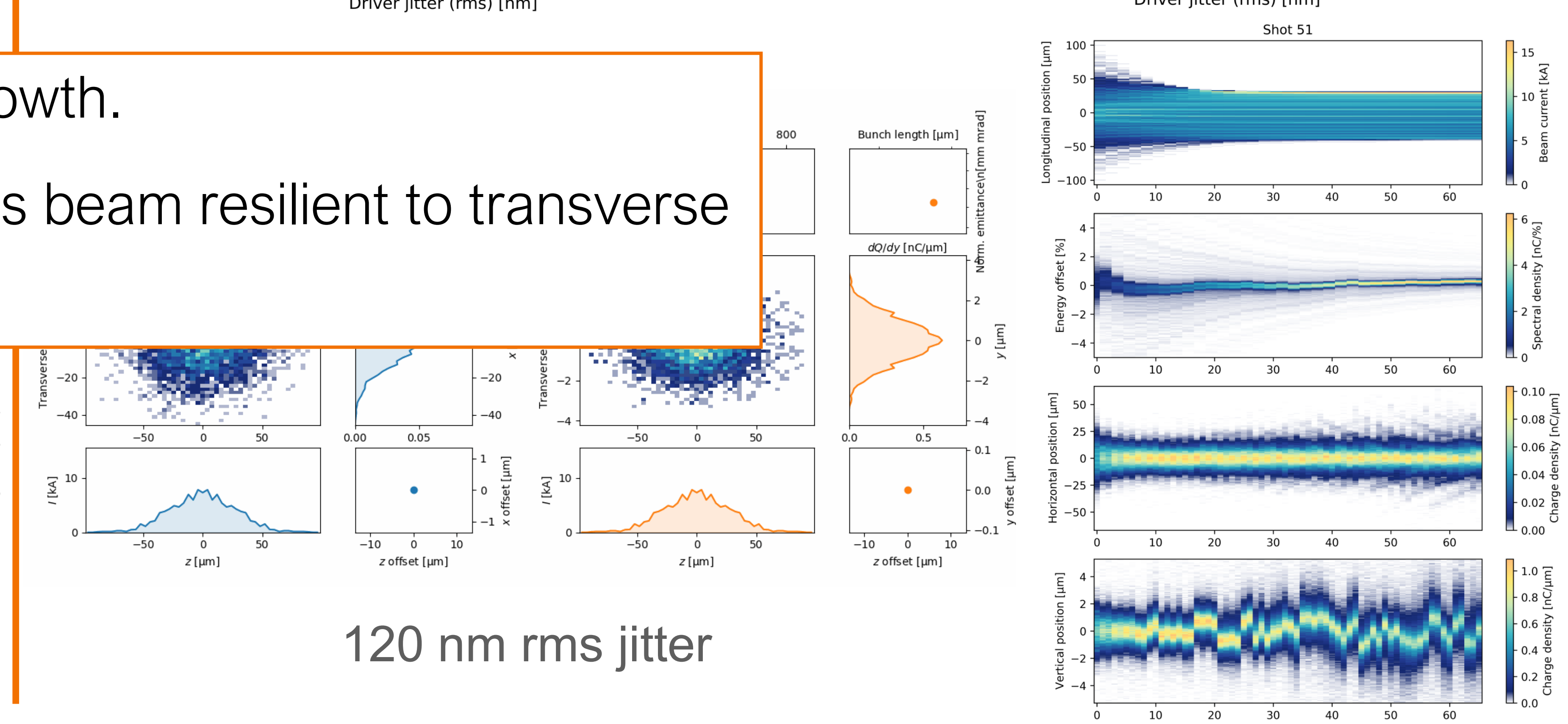




120 nm rms jitter

All physics effect enabled





120 nm rms jitter

- Ion motion dominates emittance growth.
- Effectively damps hosing and makes beam resilient to transverse jitter.

Plasma linac

Good progress in understanding what limits the feasibility of a staged plasma linac

HALHF, PWFA LINAC ONLY

Feasibility issues, open questions, plans (v0.3)

System	Issues to demonstrate	Simulation and design studies **Time scale for progress:** **Few months to few years. Possibly in time for ESU/pre-CDR.**	Experiments and test-facilities Time scale: **Few- to several years.**
Single stage	Gradient, energy gain, length, efficiency, rep. rate, (see HALHF linac table)	• High-res, full PIC simulations of first and last plasma stage, all relevant physics included **Progress:ion motion shown to mitigate wake**	• Demonstrate 2B PWFA with simultaneous HALHF parameters • Demonstrate high-rep rate, long lifetime plasma sources • Demonstrate cooling of plasma stage, energy recovery? • Precise Instrumentation
Interstage	Optics performance, non-linear lenses	• Lattice design • Component design **Progress:** component tolerances studies performed (Ben)	• Any LWFA/PWFA staging preservering charge! • Demonstrate novel components (non-linear pl… • D… stage design, and HALHF-like beam parameters **Progress:** first texperiments in APL@CELAR (Pierre)
Multi-stage effects	Wakefields/ transverse instabilities, Radiation reaction, Beam and component jitter, Scattering, Ion motion, Spin-transport	• Multi-stage beam dynamics (self-correction) • S… i… **Progress betatron: simulations of HALHF and scaling laws** (Daniel) • Show acceptable radiation reaction effect • **Progress wakefield:** ion motion (Ben) • … .. **Jitter tolerances:** offet tolerances studied (Ben)	• Demonstrate stability/jitter of acceleration process in single stage • Benchmark physics models with single stage
Drive-beam distribution	TBD	• Invent appropriate concept • Lattice design	• Demonstrate specialized components, e.g. magnets/kickers • Staging including drive beam injection

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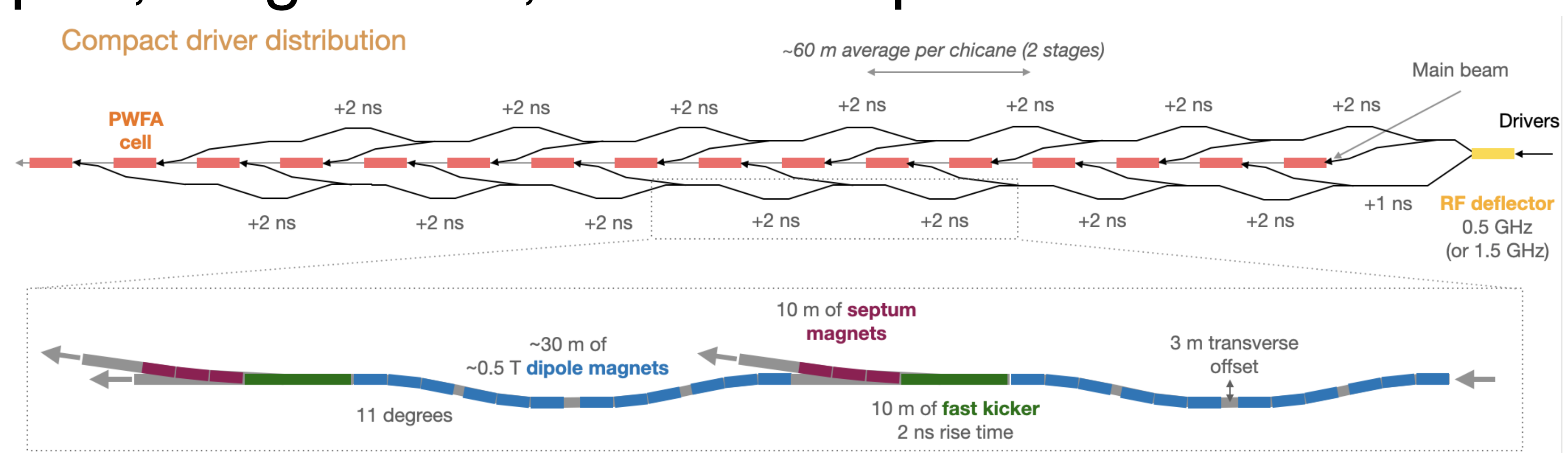
Plasma linac

Practicalities, eg driver distribution, diagnostics, beam dumps etc discussed

Q5 – Driver transport, diagnostics, beam dump



- **Delay chicanes**
  - Could be vertical or horizontal while injecting horizontal.
  - Driver jitters important to monitor/control.
- **Fast kickers**
  - Ramp-up time < 1 ns, ramp-down < 80 ns: challenging in particular for stability.
  - Harmonic kickers could be a solution?
  - CW makes it easier?
- **Combiner ring**
  - Seems necessary, more time for ramp-down for the kickers.
- **Beam dumps**
  - Large average power, accept 10-100% initial driver energy.
  - Conventional diagnostics.

→ ***No show-stopper. CW or not hugely important (except for***
→ ***Jitters in the vertical direction need careful monitoring.***

Q5 – Beam diagnostics and dump

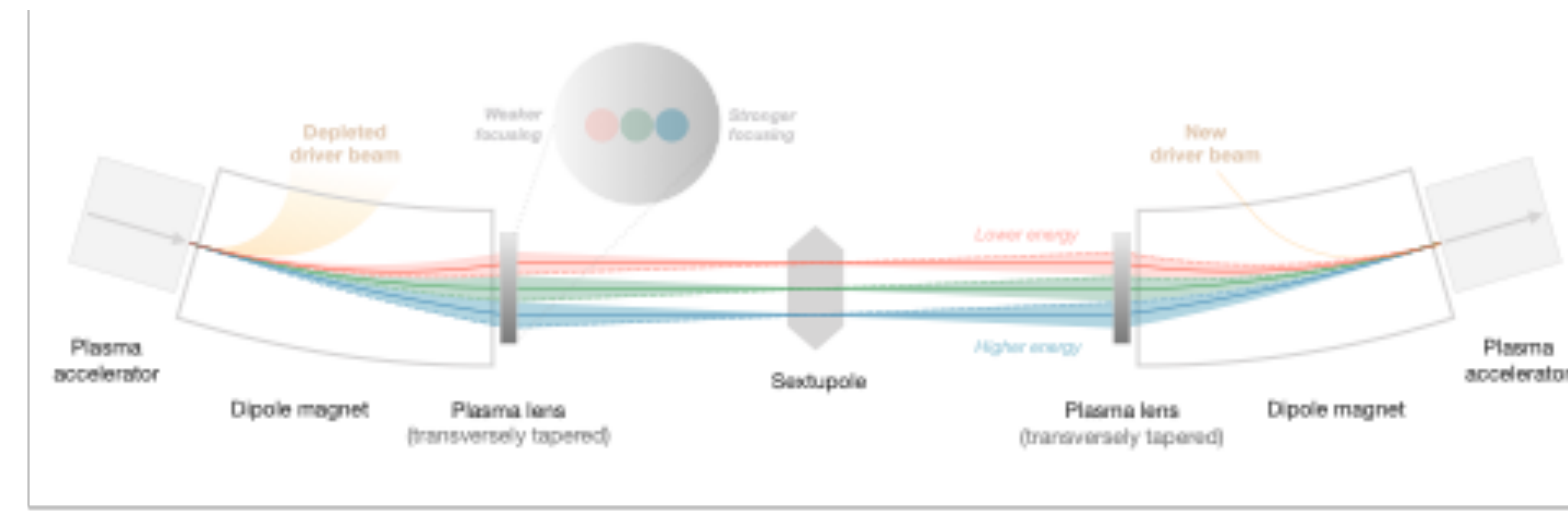


Figure 4: **Proposed optics using transversely tapered plasma lenses.** From Lindstrøm, to be published (2021).

Commissioning day 1: stage by stage, with diagnostics in each section

- Could **flip some dipole**
- **BPMs probably before and after every stage**; pointing needs to be monitored.
- **Online spectrometer around the sextupole** in the coupling section?
- **Betatron radiation as diagnostics** after each stage?
- It's a **high-radiation environment**, a concern for later.
- Selective beamline, **collimation** clarified by Andrei

→ ***No show-stopper***

Plasma linac

Spin polarisation preservation in plasma linacs seems possible

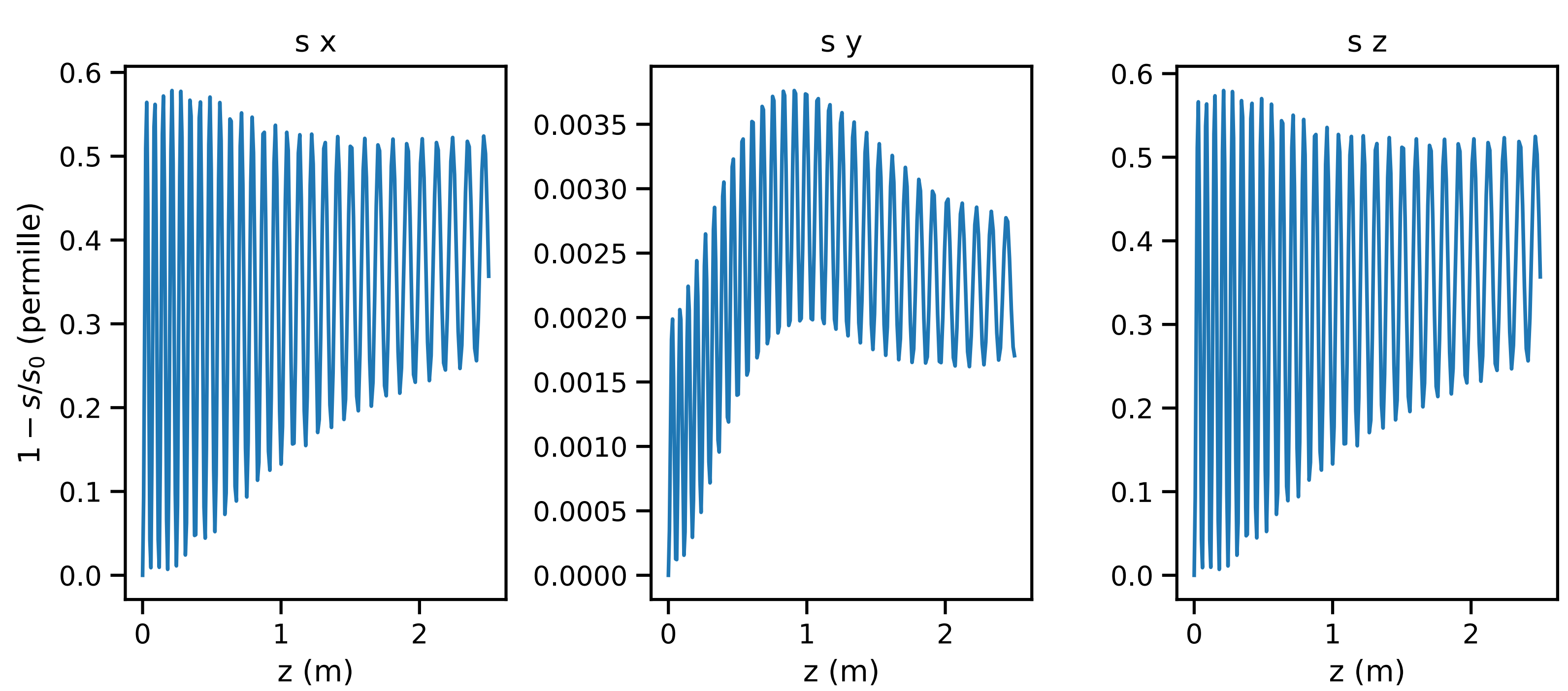
Polarisation preservation for HALHF 1.0 seems possible (?!?)

Stage 1 of seems promising, with sub-permille polarisation change

TBMT

$$\frac{\mathrm{d}s_x}{\mathrm{d}t} = a_e F_r s_z$$
$$\frac{\mathrm{d}s_z}{\mathrm{d}t} = -a_e F_r s_x$$

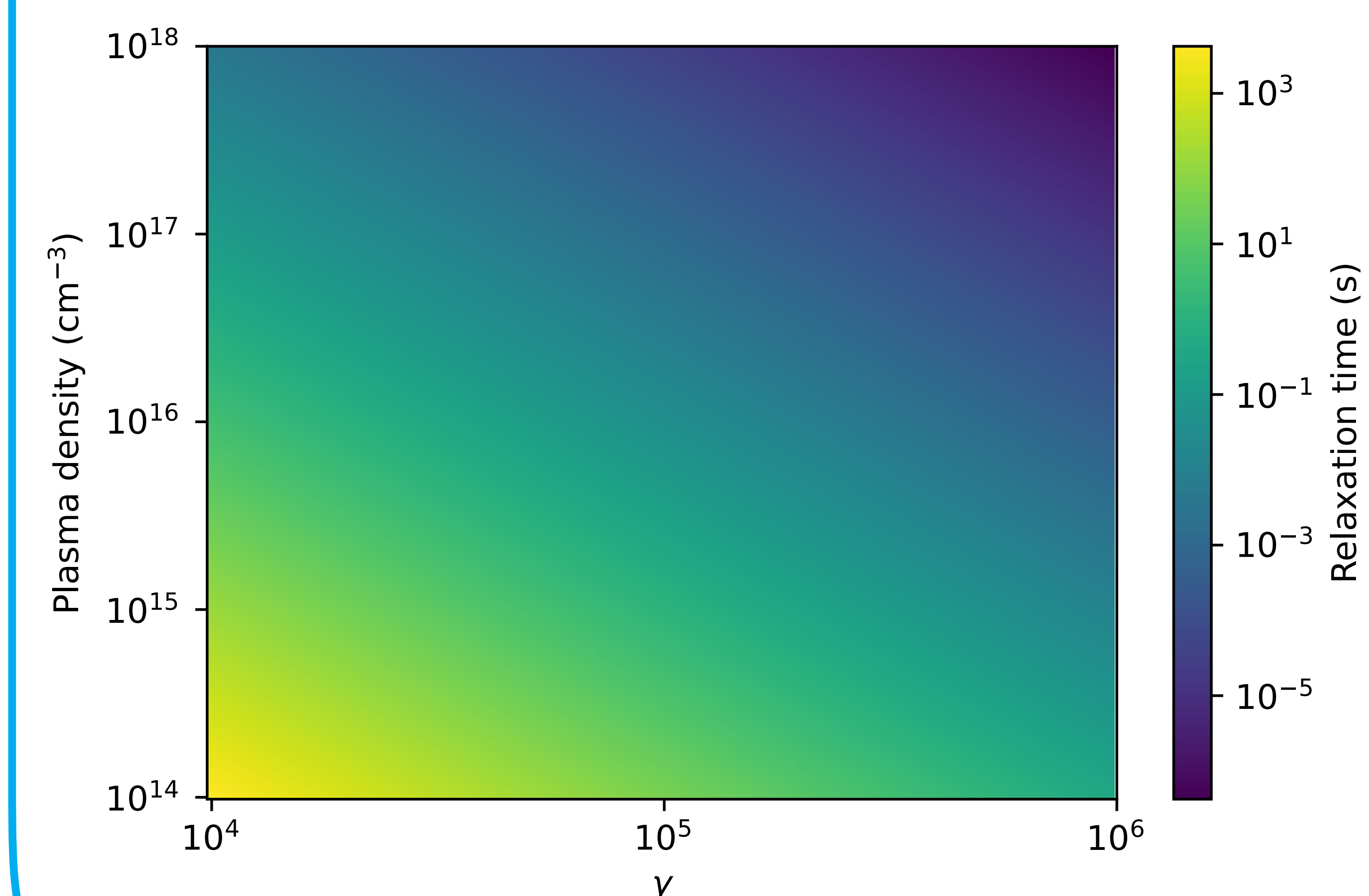
Flat beams @HALHF: s_y ~ *const*



All spins uniform -> need to create a realistic beam

Sokolov-Ternov

Timescales >> ms



Upgrade ladder

Discussions on upcoming test facilities and physics programme to demonstrate relevant technologies

Facilities/Demonstrators vs Physics Opportunities

Future facilities that can support R&D while providing unique physics opportunities.

	R&D Opportunities	Physics Opportunities	Energy Scale
O(100) MeV multi-stage demo	Staging		100 MeV
FlashForward with undulator	Beam quality	UV FEL	2 GeV
EuPRAXIA	Beam quality	XFEL	5 GeV
XFEL Energy Doubler	Beam quality	XFEL	10-20 GeV
SPARTA	Staging, Compton IP	NLQED, Muons for imaging, Dump physics?	50 GeV
SPARTA-XCC	HALHF rep rate, multi-bunch, ε,...	Higgs Factory	60+60 GeV
High-rep rate facility	Plasma stage power handling	e^-p^+ collisions, beam dump physics, detector test beams	10-100 GeV

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High-rep rate facility	Plasma stage power handling	e^-p^+ collisions, beam dump physics, detector test beams	10-100 GeV

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Milestones, Energy Scales and Timelines

Energy (GeV) Tech/Concept	1-10	10-100	100-1000	1000-3000	3000-10000
FELs and single stage tech	FACET-II AWAKE EUPraxia				
NLQED and multi-stage demo		SPARTA			
XFEL R&D for γγ					
Higgs Factory			HALHF 250 XCC-plasma		
EW-scale collider			HALHF 380-500		
TeV-scale collider				Plasma e^+e^- Plasma γγ	
Multi-TeV collider					Plasma e^+e^- Plasma γγ
Timeline	2024-2039	2030-2039	2040-2055	2050-2059	2060–

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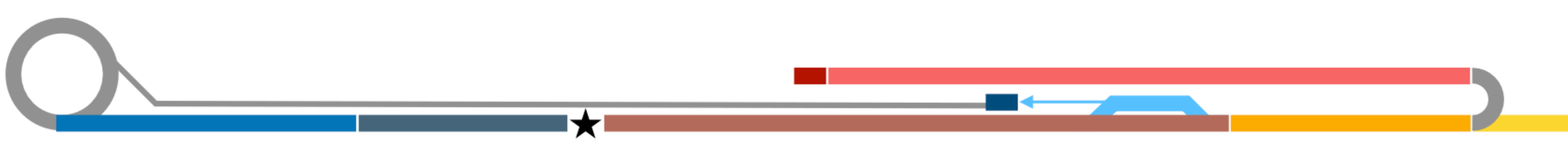
Summary

HALHF is evolving more and more towards a realistic, self-consistent design

- Despite almost no funding, the design is evolving and solutions are actively identified
  - Monthly online meetings to keep the momentum
  - For plasma linac, many interesting questions are being investigated
  - Proof-of-principle experiments of achromatic interstage coupling within SPARTA
- Potential synergies with other projects popping up
- Aim to write input for ESPPU in 2025
  - Next workshop planned at DESY end of Feb 2025 to



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