The next AWAKE runs: technological advancements, scientific merit, and expected parameter reach

Patric Muggli

MAX-PLANCK-INSTITUT FÜR PHYSIK

Summary & Conclusions

- **AWAKE is on schedule and achieved all milestones**
  - Run 1 - Run 2a programs complete
  - + many additional physics/technology studies performed
  - First promising results on Run 2b

- **AWAKE scientific results**
  - Impact the wakefield community
  - Lead to many publications in high impact journals
  - Almost all of them have early-career researchers as first authors

- **Self-modulator demonstrated** after Run 2b (2024)

Wakefield physics questions specific to the resonant excitation scheme

- **Driver preparation** → Self-modulation ✓
- **Wakefield control** → Seeding ✓
- **Witness acceleration** → External injection ✓
- **Maintain wakefields** → Density step

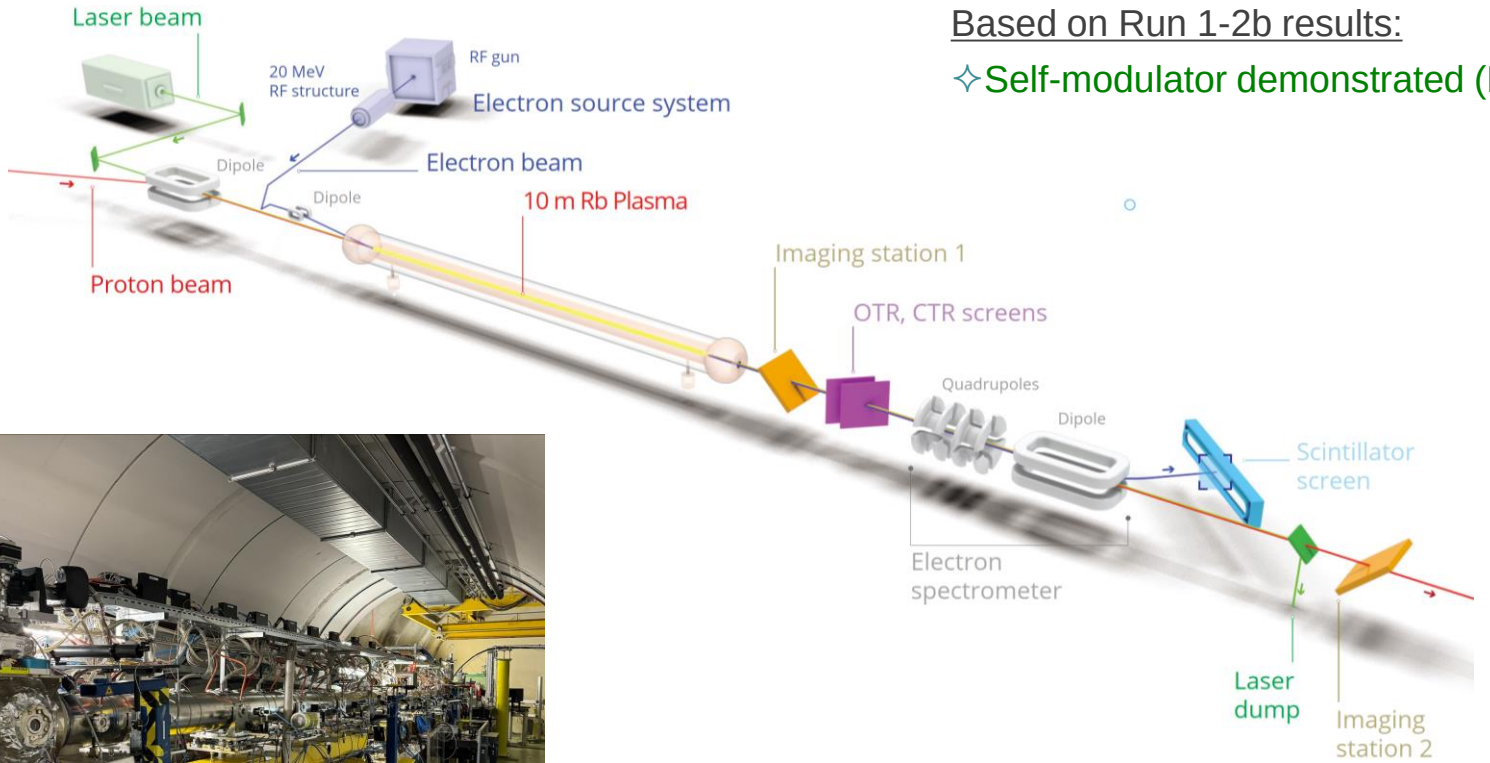
- **Quality** → can the quality of the accelerated bunch be controlled? → Run 2c
- **Scalability** → can the acceleration be scaled? → Run 2d

PLAN

- Plan for Run 2c,d based on successful Run 1,2a,b results (Edda, Marlene)
- Clear and solid plan towards a scalable acceleration system
  - develop all technical components required
- Identify challenges:
  - baseline plan for Run 2c
  - explore options for Run 2d
- Plan:
  - ambitious and challenging, but no showstopper identified
  - includes numerous topics relevant to all plasma-based accelerators (HEP)
  - Includes technological developments
  - aim at parameters for fixed target experiments with e^-

- Goal: propose particle physics experiments in 2030's

RUN 1,2a,b: SELF-MODULATOR FOR RUN 2c,d

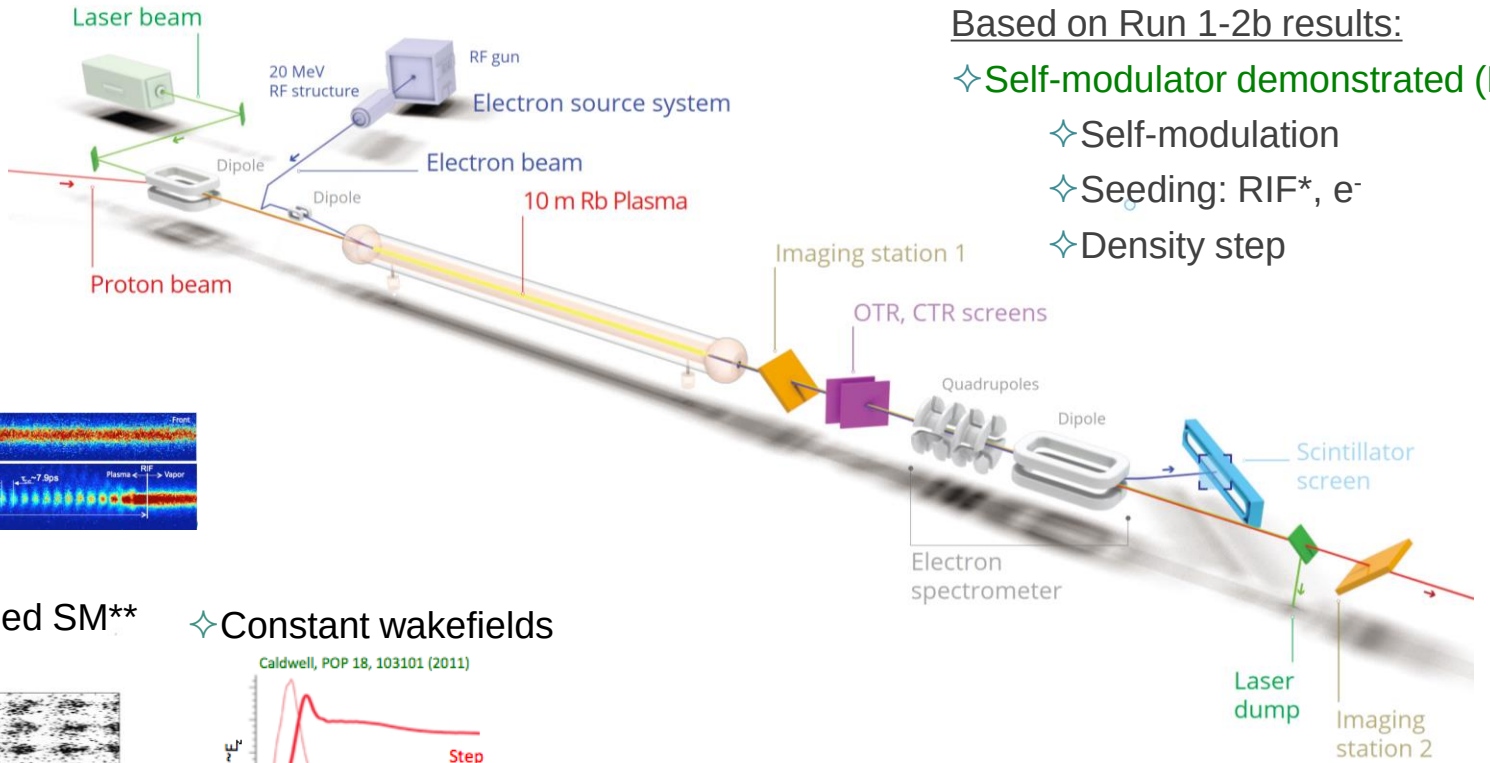


Based on Run 1-2b results:

✧Self-modulator demonstrated (Marlene)

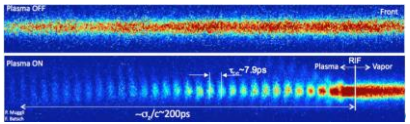
*RIF: Relativistic Ionization Front

RUN 1,2a,b: SELF-MODULATOR FOR RUN 2c,d

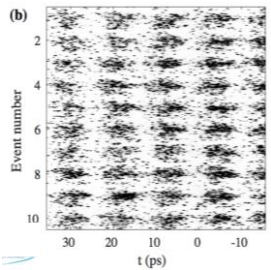


Based on Run 1-2b results:

- ✧Self-modulator demonstrated (Marlene)
  - ✧Self-modulation
  - ✧Seeding: RIF*, e^-
  - ✧Density step

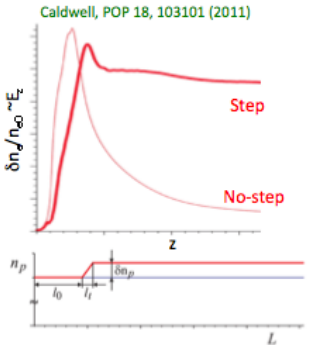


✧Seeded SM**



+

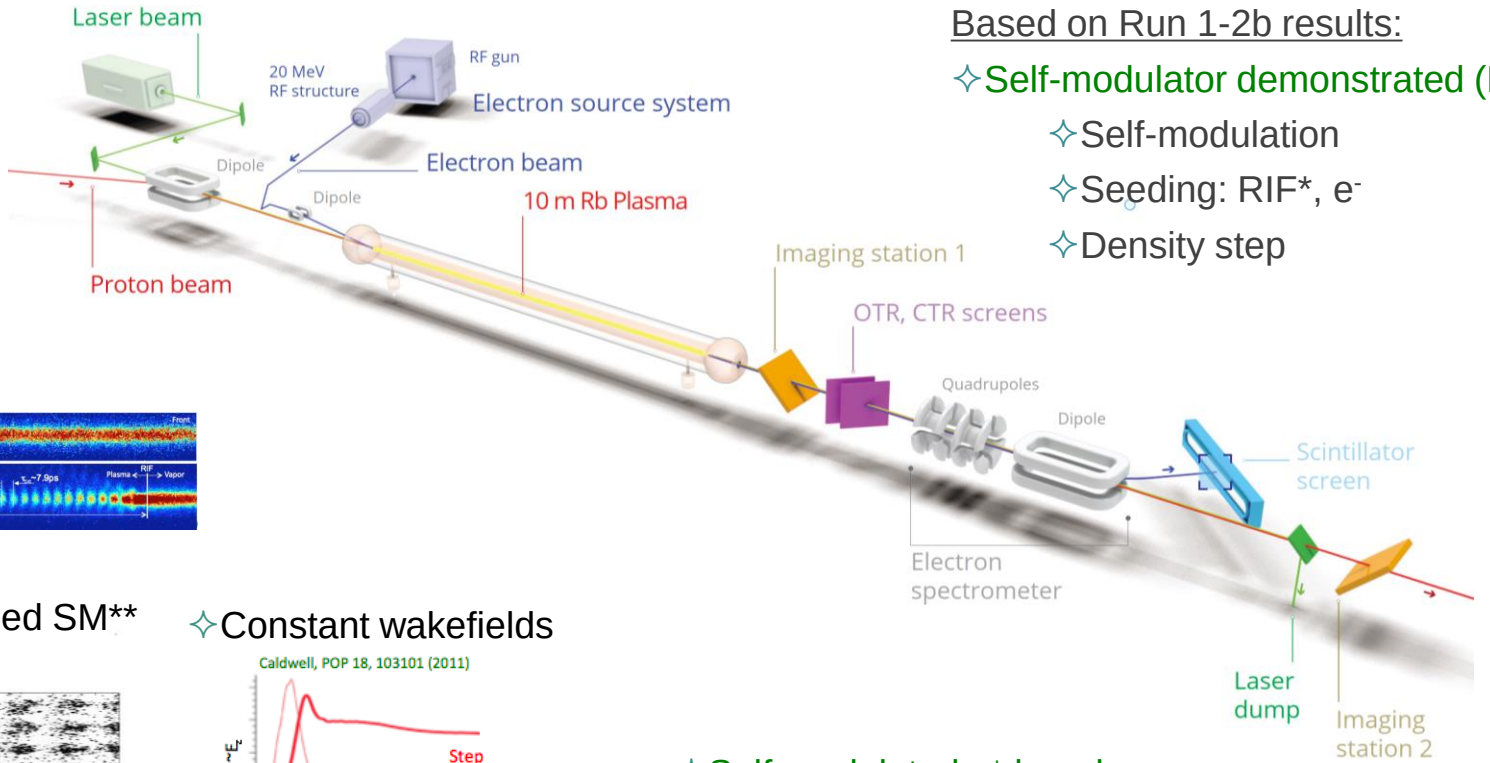
✧Constant wakefields



*RIF: Relativistic Ionization Front

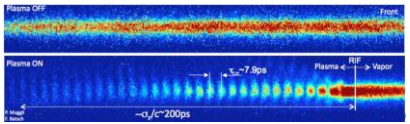
**SM: Self-Modulation

RUN 1,2a,b: SELF-MODULATOR FOR RUN 2c,d

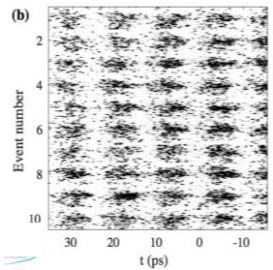


Based on Run 1-2b results:

- ✧Self-modulator demonstrated (Marlene)
  - ✧Self-modulation
  - ✧Seeding: RIF*, e^-
  - ✧Density step

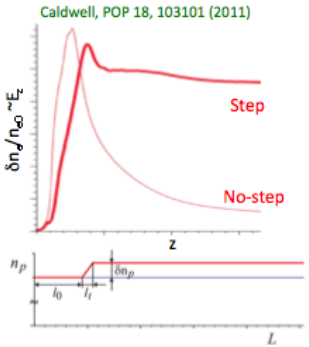


✧Seeded SM**



+

✧Constant wakefields

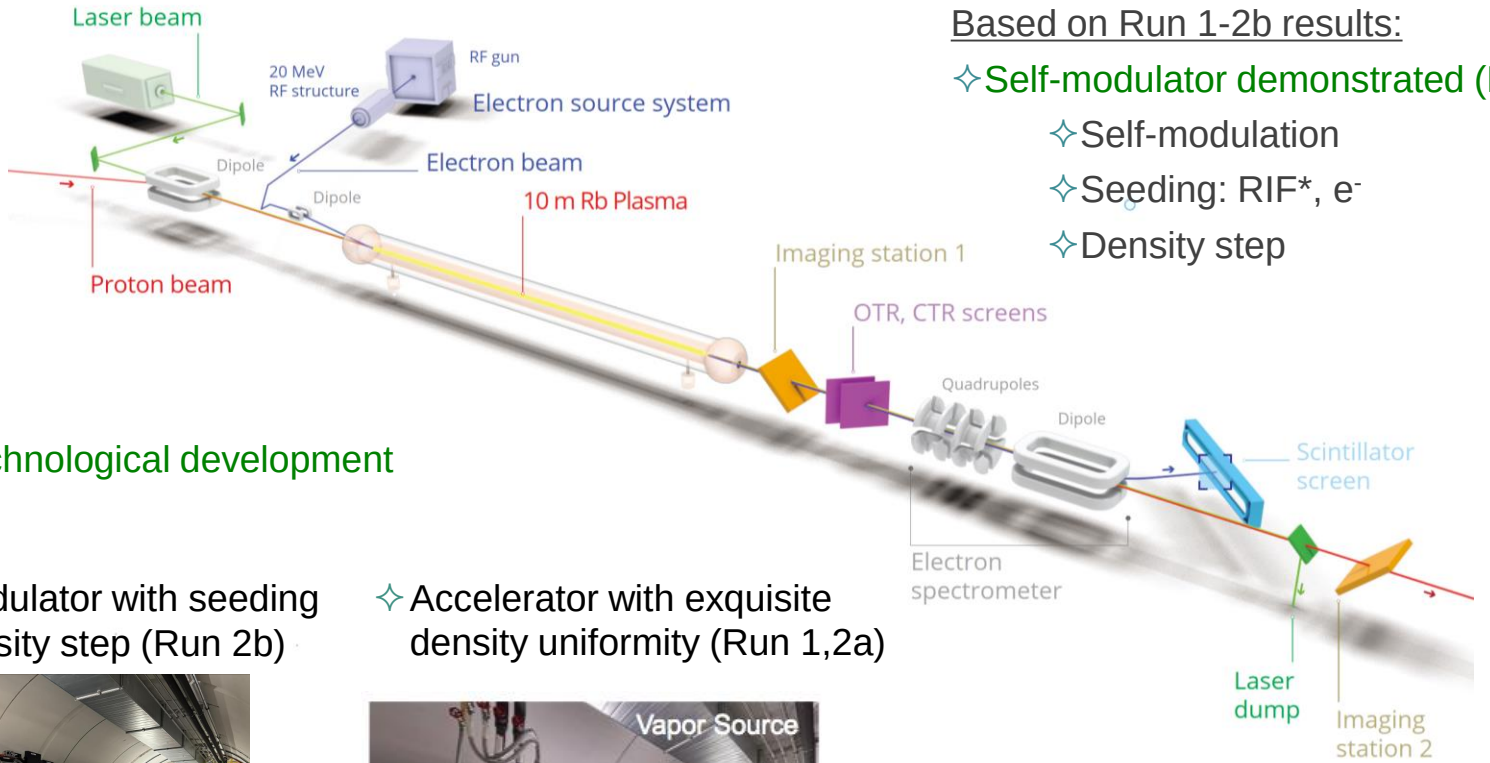


✧Self-modulated p^+ bunch
✧Driver for long accelerator
✧Run 2c,d, applications

*RIF: Relativistic Ionization Front

**SM: Self-Modulation

RUN 1,2a,b: SELF-MODULATOR FOR RUN 2c,d

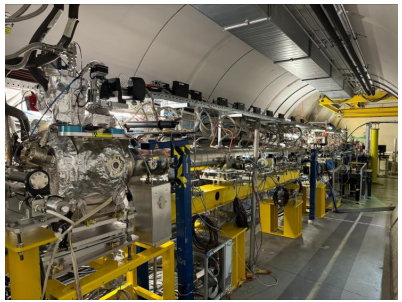


Based on Run 1-2b results:

- ✧Self-modulator demonstrated (Marlene)
  - ✧Self-modulation
  - ✧Seeding: RIF*, e^-
  - ✧Density step

✧Major technological development

✧Self-modulator with seeding and density step (Run 2b)



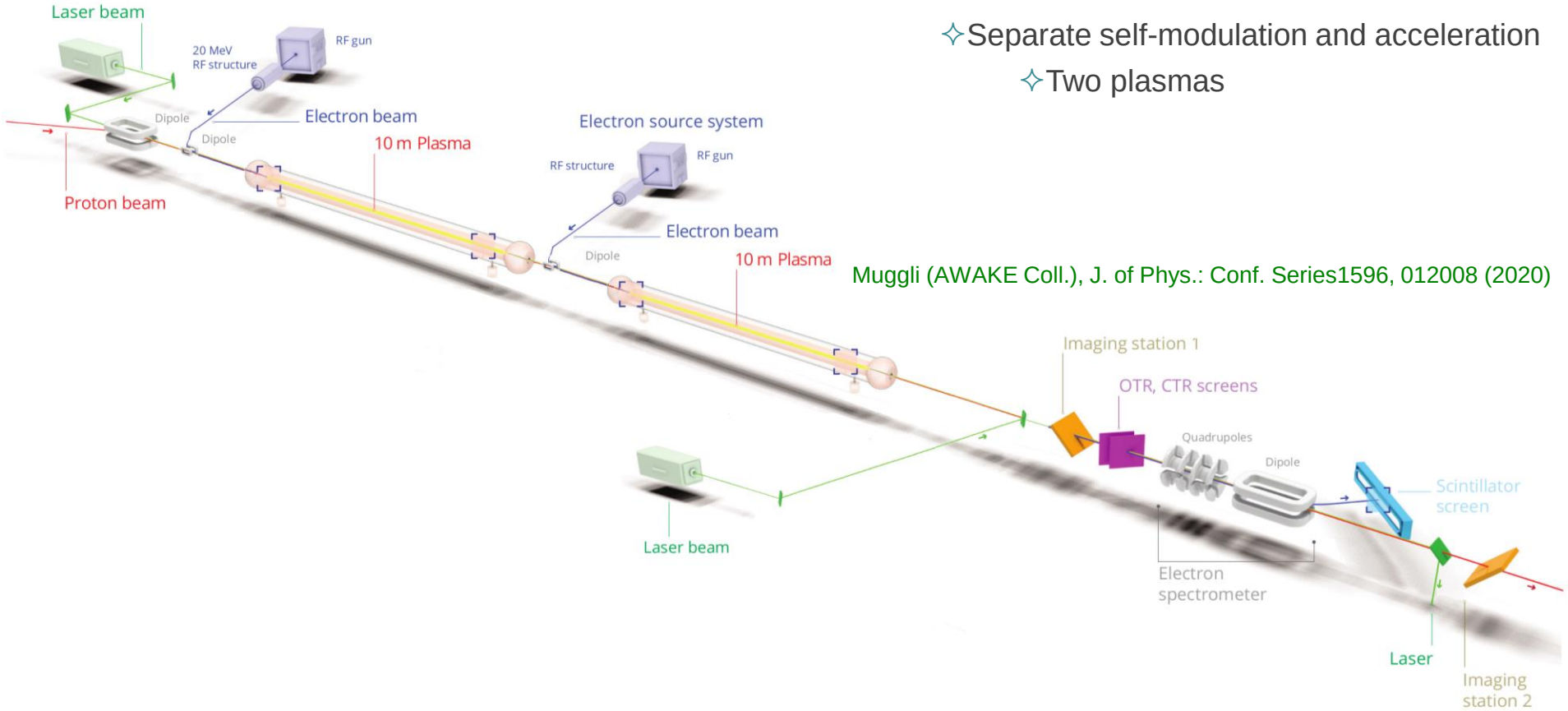
✧Accelerator with exquisite density uniformity (Run 1,2a)

*RIF: Relativistic Ionization Front

**SM: Self-Modulation

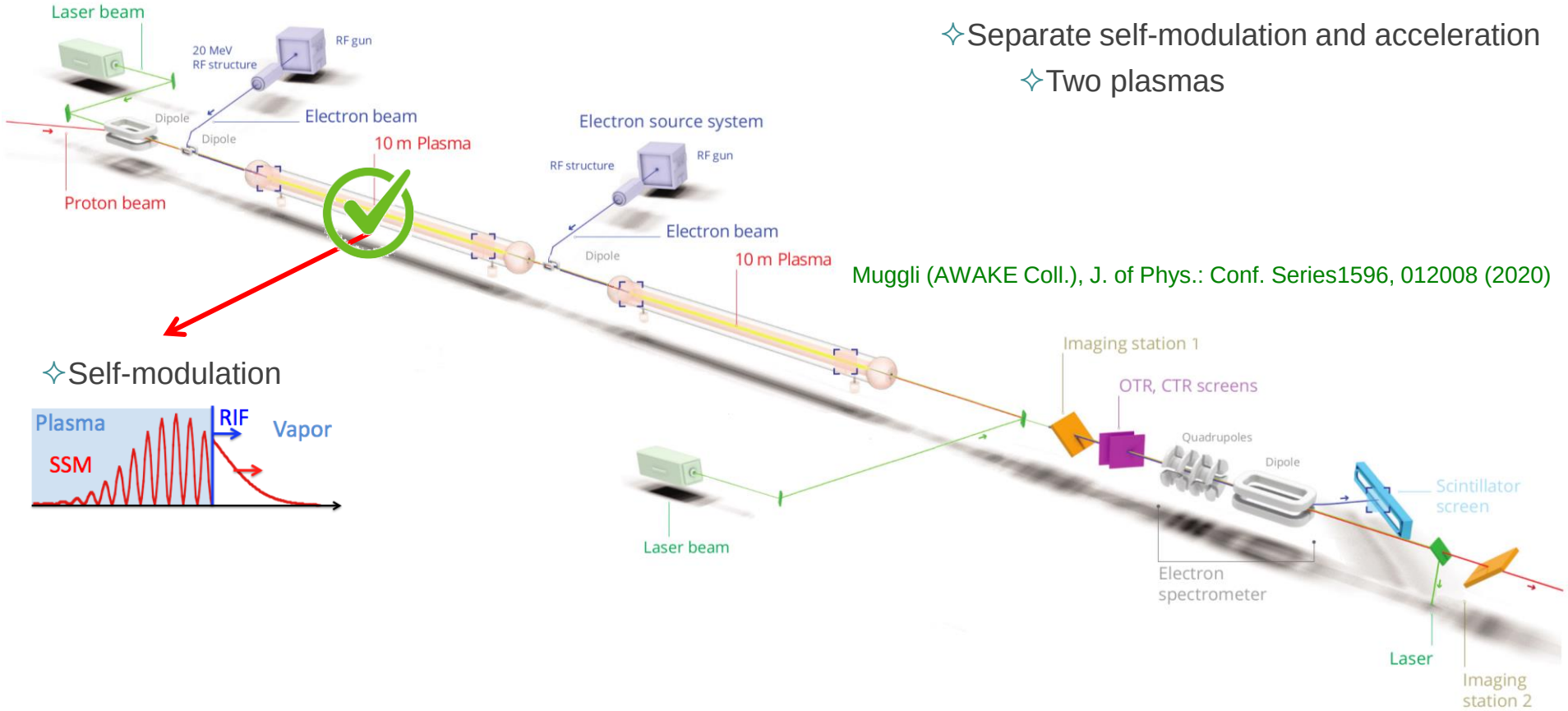
RUN 2c,d: ACCELERATE AN e^- BUNCH, QUALITY

- Separate self-modulation and acceleration
  - Two plasmas



Muggli (AWAKE Coll.), J. of Phys.: Conf. Series1596, 012008 (2020)

RUN 2c,d: ACCELERATE AN e^- BUNCH, QUALITY



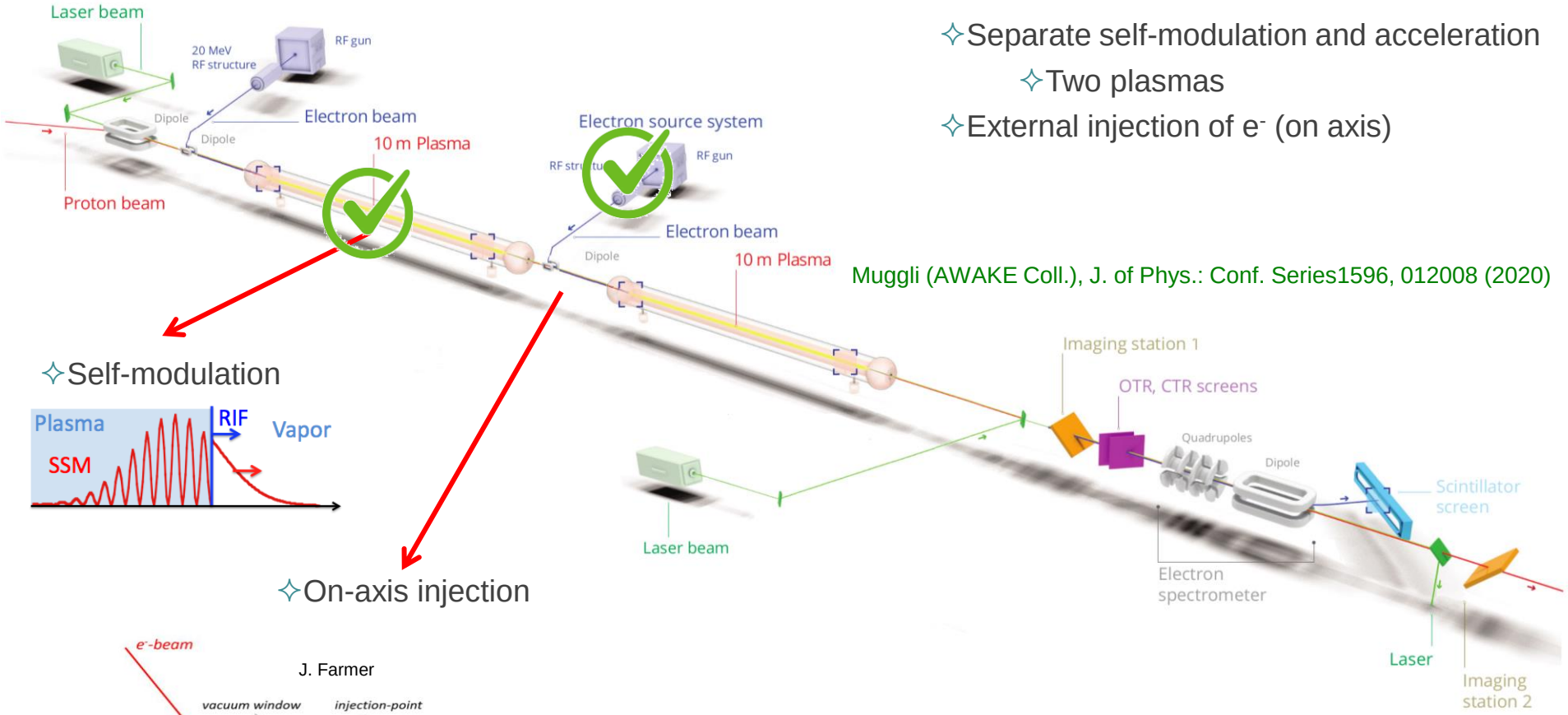
✧Separate self-modulation and acceleration

✧Two plasmas

Muggli (AWAKE Coll.), J. of Phys.: Conf. Series1596, 012008 (2020)

✧Self-modulation

RUN 2c,d: ACCELERATE AN e⁻ BUNCH, QUALITY

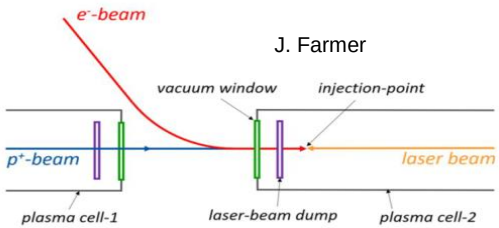


- Separate self-modulation and acceleration
  - Two plasmas
- External injection of e⁻ (on axis)

Muggli (AWAKE Coll.), J. of Phys.: Conf. Series1596, 012008 (2020)

- Self-modulation

- On-axis injection

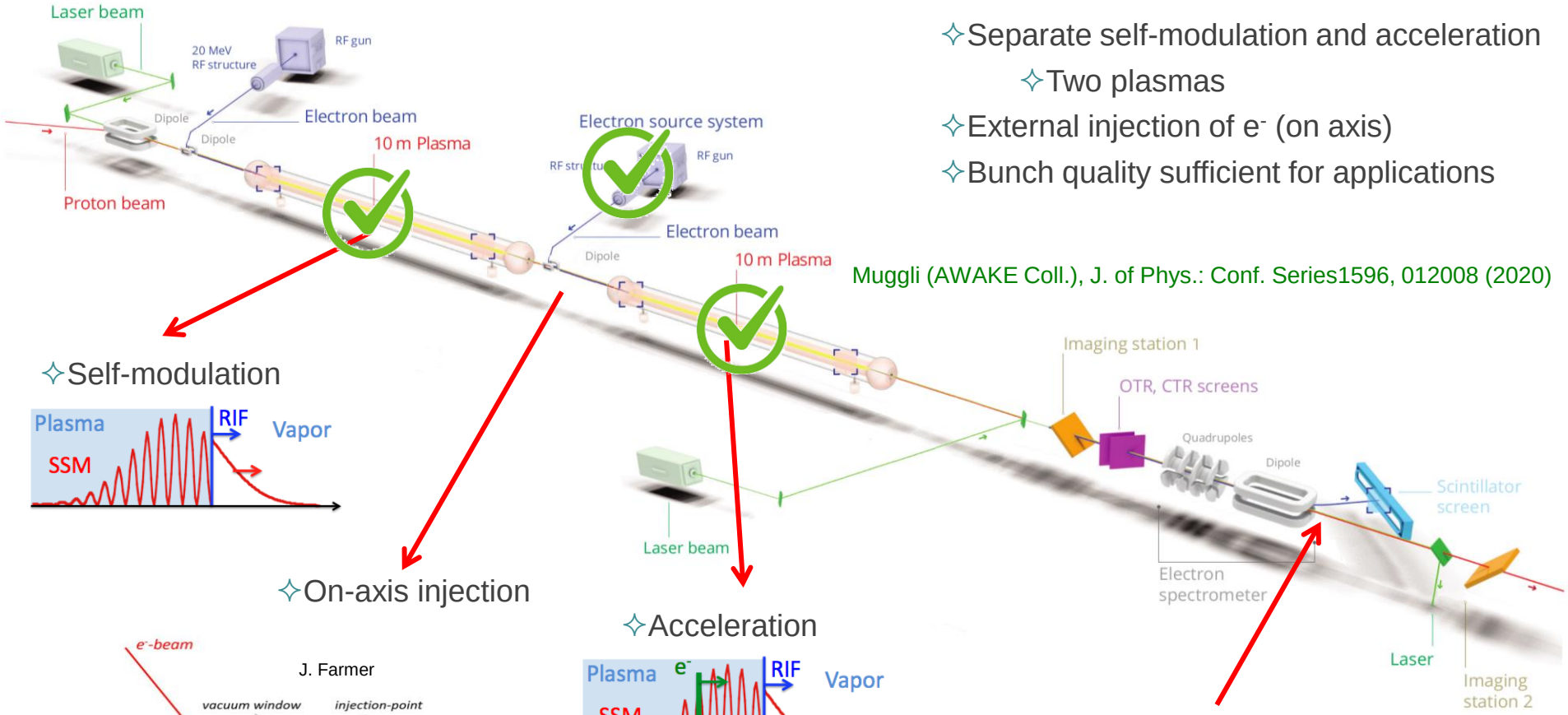


J. Farmer

RUN 2c,d: ACCELERATE AN e⁻ BUNCH, QUALiTY

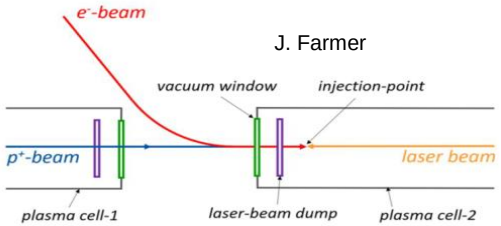
- Separate self-modulation and acceleration
  - Two plasmas
- External injection of e⁻ (on axis)
- Bunch quality sufficient for applications

Muggli (AWAKE Coll.), J. of Phys.: Conf. Series1596, 012008 (2020)



- Self-modulation

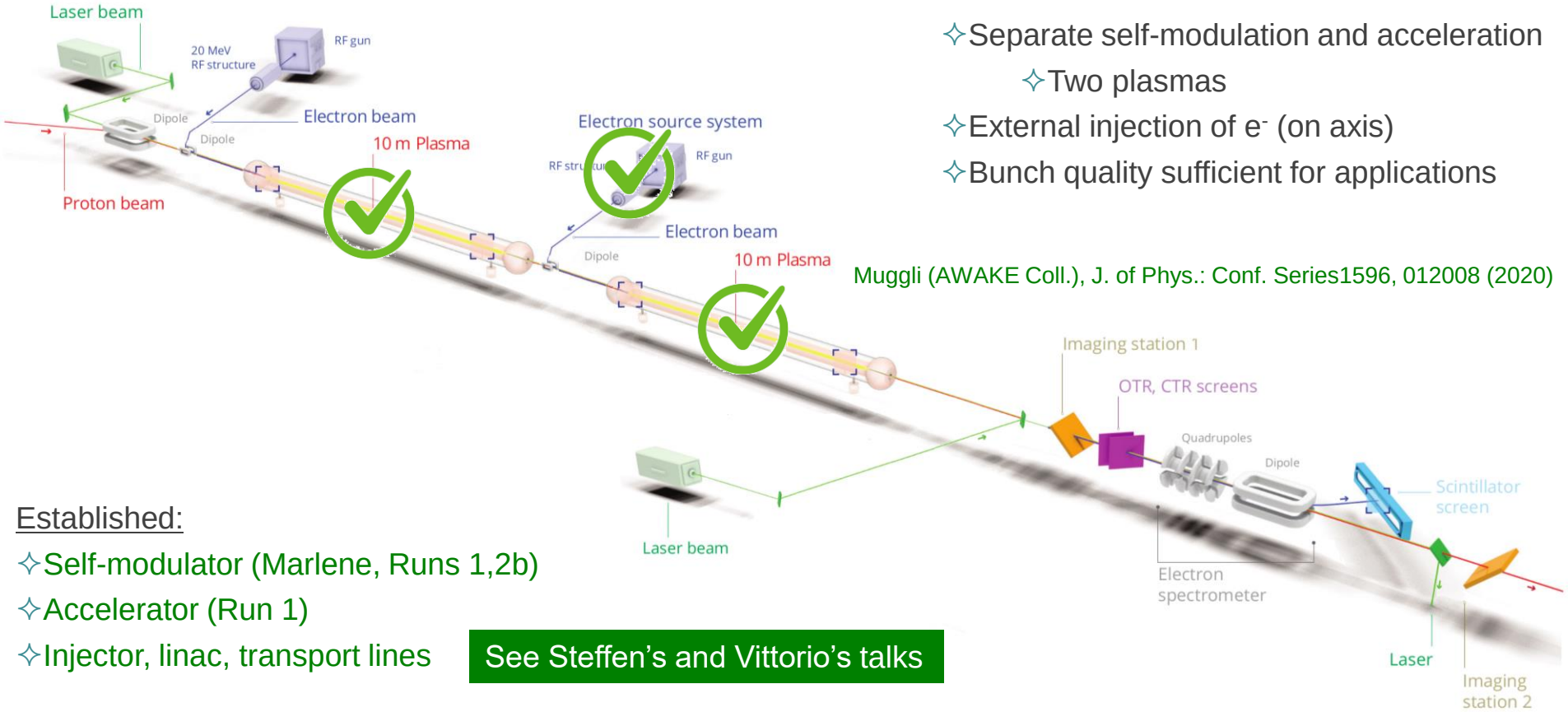
- On-axis injection



- Acceleration

- Quality

RUN 2c: e⁻-EXTERNAL INJECTiON EXPERiMENT



- ✧Separate self-modulation and acceleration
  - ✧Two plasmas
- ✧External injection of e⁻ (on axis)
- ✧Bunch quality sufficient for applications

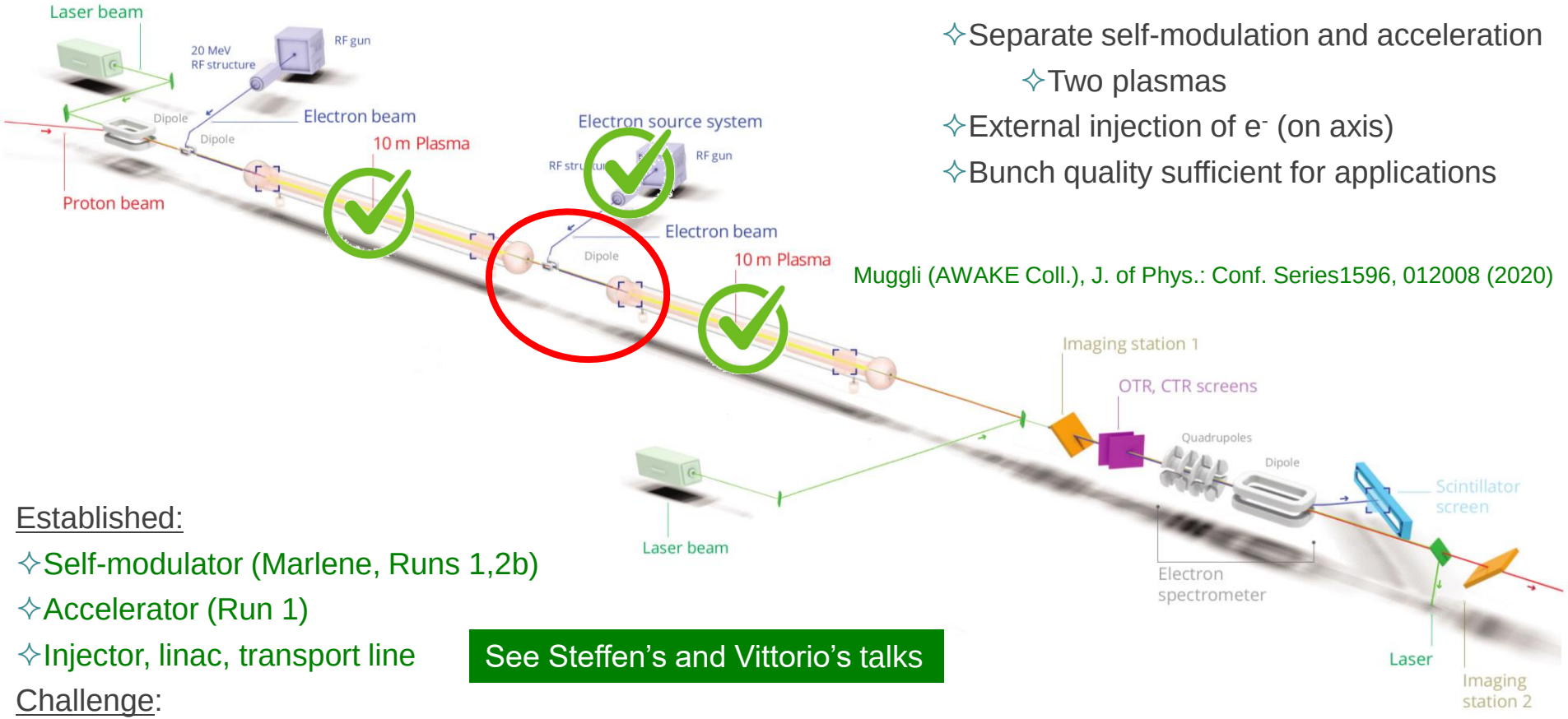
Muggli (AWAKE Coll.), J. of Phys.: Conf. Series1596, 012008 (2020)

Established:

- ✧Self-modulator (Marlene, Runs 1,2b)
- ✧Accelerator (Run 1)
- ✧Injector, linac, transport lines

See Steffen's and Vittorio's talks

RUN 2c: e⁻-EXTERNAL INJECTiON EXPERiMENT



- ✧Separate self-modulation and acceleration
  - ✧Two plasmas
- ✧External injection of e⁻ (on axis)
- ✧Bunch quality sufficient for applications

Muggli (AWAKE Coll.), J. of Phys.: Conf. Series1596, 012008 (2020)

Established:

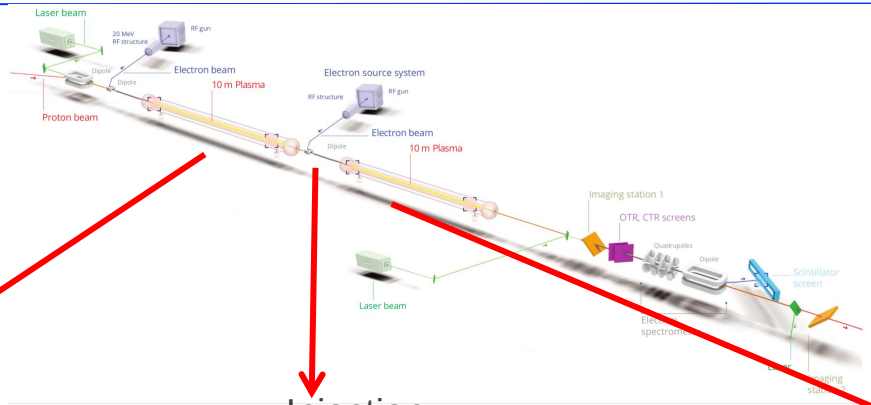
- ✧Self-modulator (Marlene, Runs 1,2b)
- ✧Accelerator (Run 1)
- ✧Injector, linac, transport line

See Steffen's and Vittorio's talks

Challenge:

- ✧Injection region
  - ✧alignment, p^+ and e^- beams

FUNCTiONS



Self-modulator:

- Seeding of SM, reproducible
- Density step: $E_z(z)$=constant

Injection:

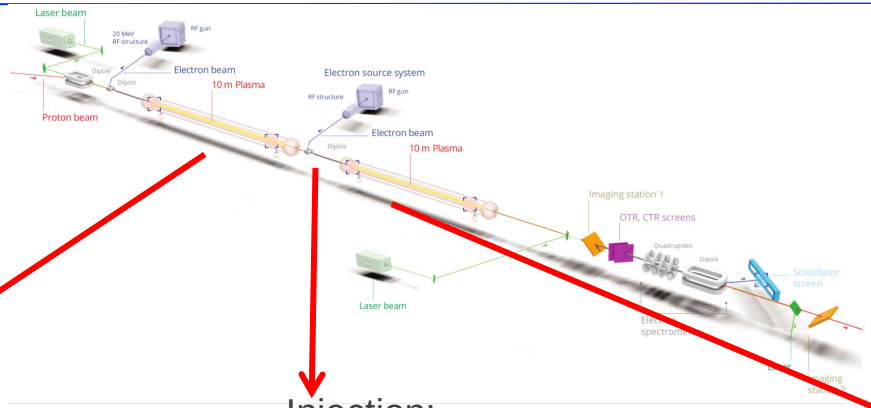
- Matching e-bunch to plasma focusing
  - Blow-out or quasi-linear
- Alignment e^-/p^+ beams

Accelerator:

- Density uniformity
  - $\Delta n_e/n_{e0}<0.25\%$

Density tuning

RUN 2c BASELINE



Self-modulator:

- ✧Seeding of SM, reproducible
- ✧Density step: $E_z(z)$=constant

Injection:

- ✧Matching e-bunch to plasma focusing
  - ✧Blow-out or quasi-linear
- ✧Alignment e^-/p^+ beams

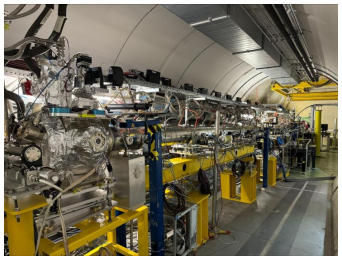
Accelerator:

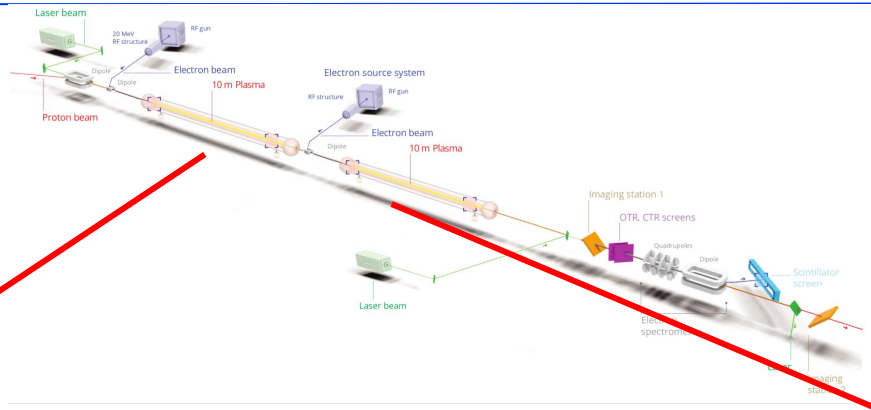
- ✧Density uniformity
  - ✧$\Delta n_e/n_{e0}$<0.25%

Density tuning

✧Rubidium plasma source → ✧RF injector → ✧Rubidium plasma source

PARAMETERS RUN 2c: RUBiDiUM PLASMA





Self-modulator:

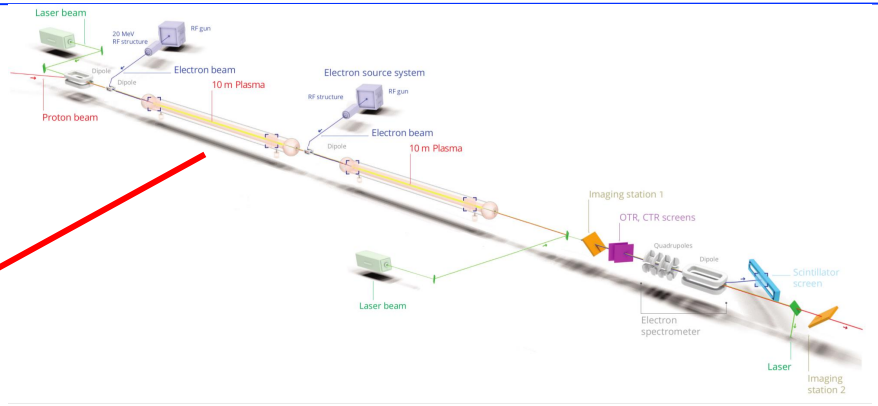
- Rubidium
- L=10m
- n_{e0}=7x10^{14}cm^{-3} (σ_{r0}=200µm)
- Seeding
- Adjustable density step z, $\Delta n_e/n_{e0}$
- Technological advancement

Accelerator:

- Rubidium
- L=10m
- n_{e0}=7x10^{14}cm^{-3}, adjustable
- Uniform ($\Delta n_e/n_{e0}$<0.25%)
- Backward ionization

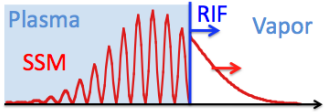
- Similar to Run 1,2b
- Thermal systems for rubidium vapor n_{Rb}
  - ΔT_{source}(0.1-0.5)^{o}C @230^{o}C or 500K
  - Laser ionization (100% RbI→RbII)
  - $n_{e0}=n_{Rb}(T_{source})$
  - $\Delta n_{e0}/n_{e0}$~0.1% (tunability)

PARAMETERS RUN 2c: SEEDING



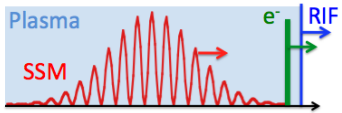
Self-modulator:

- RIF* seeding

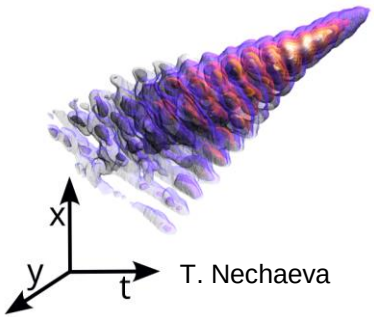


  - simple
  - leaves head of the bunch un-modulated → unstable in ACC'or?
    - Run 2 a,b: NO L. Verra et al., (AWAKE Collab.) Phys. Plasmas 30, 083104 (2023)

- e-bunch seeding

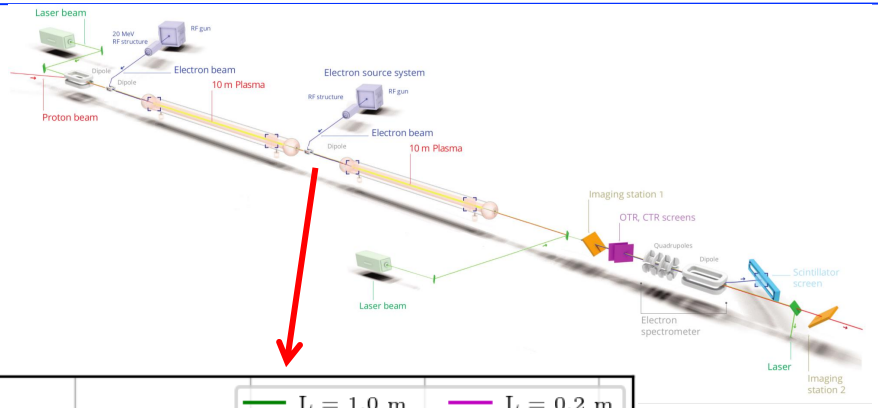


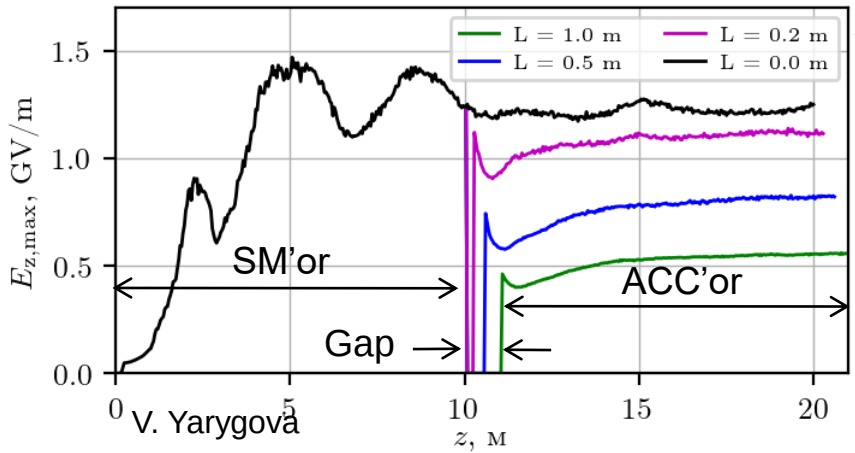
  - entire p^+ bunch self-modulated
  - induces hosing when misalignment T. Nechaeva et al., (AWAKE Collab.) accepted, Phys. Rev. Lett.



*RIF: Relativistic Ionization Front

PARAMETERS RUN 2c: GAP BETWEEN PLASMAS

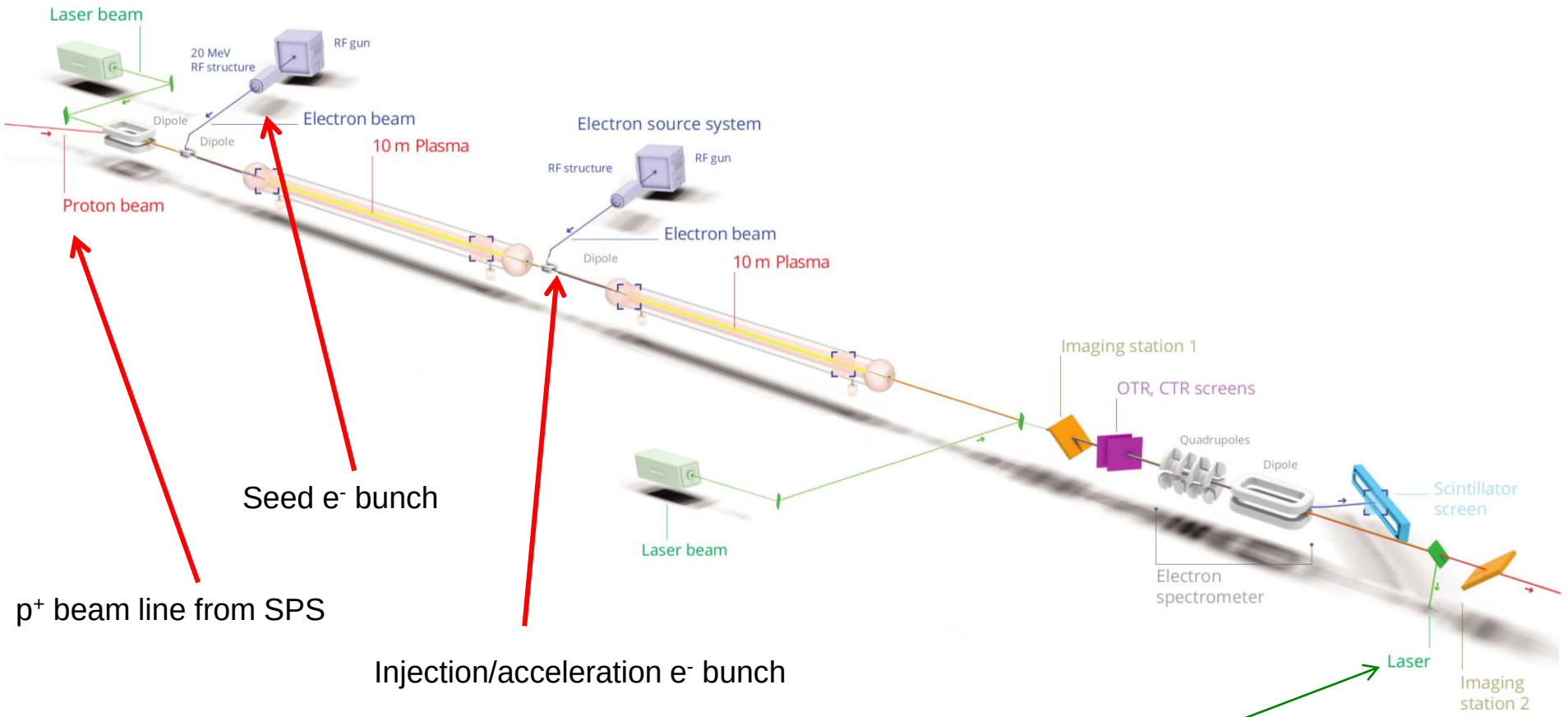




See John's talk

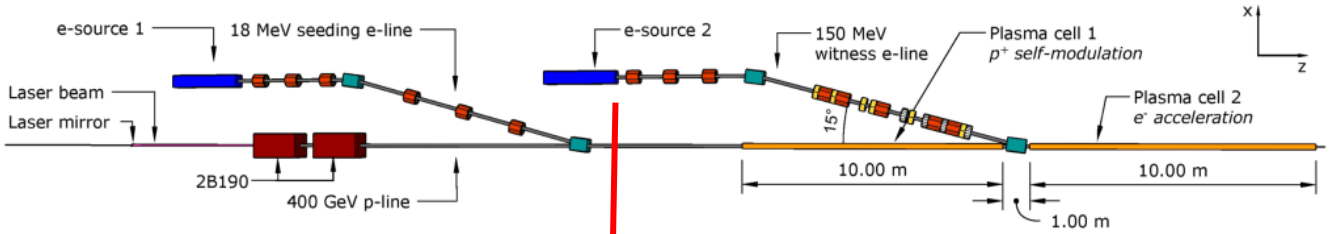
- ✧Continuous transverse evolution of the p+ bunch in the (no plasma, vacuum) gap
- ✧Must minimize gap length to maximize wakefields
  - ✧Integration

BASE LINE, RUN 2c: INJECTOR(S)



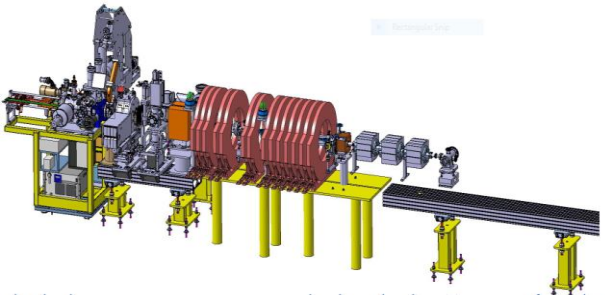
- ✧ All designed
- ✧ … and laser beam lines …E. Granados

BASE LINE, RUN 2c: INJECTOR(S), DESIGNED

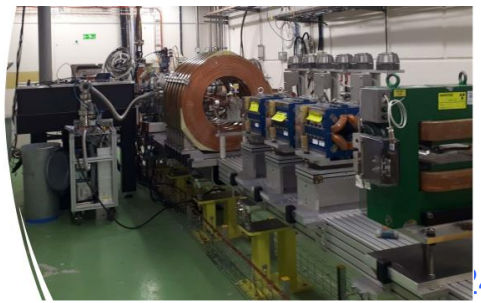


Injector:

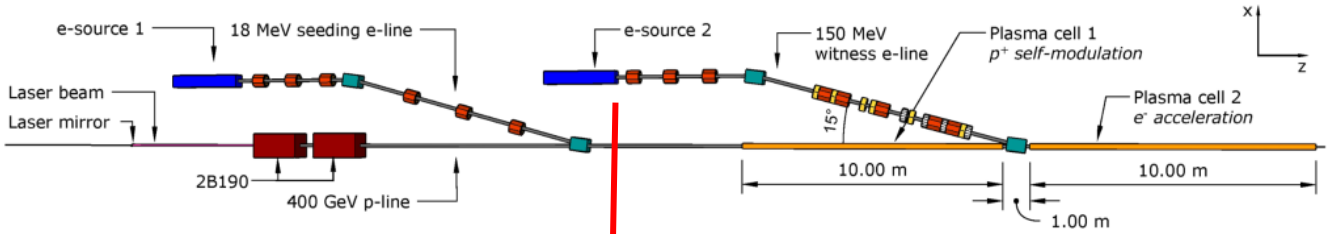
- ✧RF-Injector + Transfer line
- ✧Reproducibility
- ✧Tunability
- ✧Expertise at CERN
- ✧Technological advancement
  - ✧compact
  - ✧high-gradient
  - ✧other applications …



In the lab!

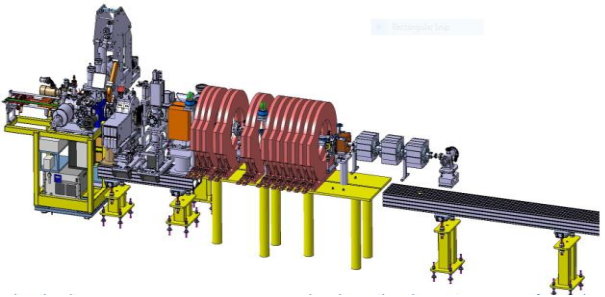


BASE LINE, RUN 2c: INJECTOR(S), DESIGNED



✧Bunch parameters:

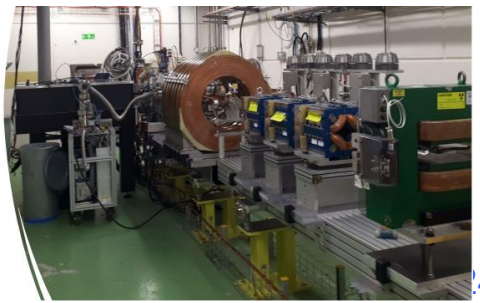
- ✧E=150MeV
- ✧Q=100pC
- ✧ε_N=2mm-mrad
- ✧σ_z=60µm



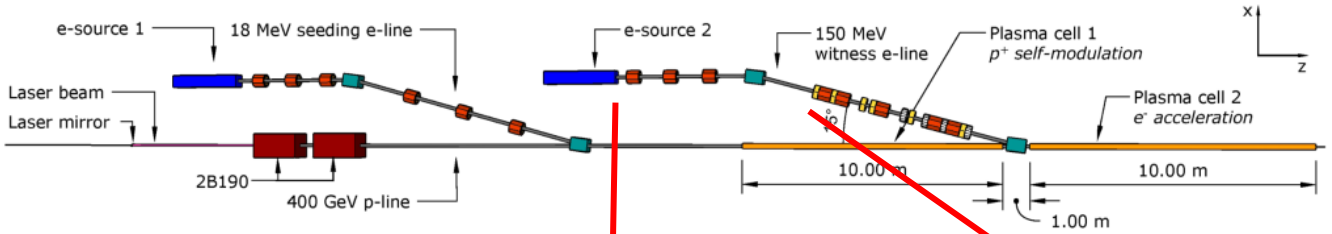
Injector:

- ✧RF-Injector + Transfer line
- ✧Reproducibility
- ✧Tunability
- ✧Expertise at CERN
- ✧Technological advancement
  - ✧compact
  - ✧high-gradient
  - ✧other applications …

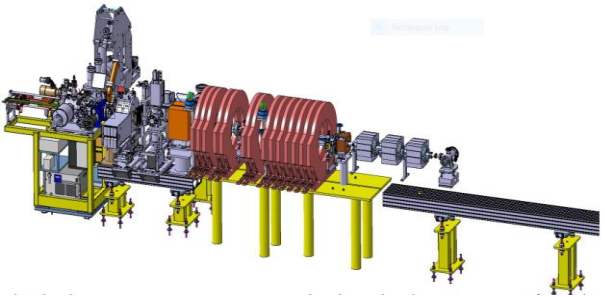
In the lab!



BASE LINE, RUN 2c: INJECTOR(S), DESIGNED



✧Bunch parameters:
- ✧E=150MeV
- ✧Q=100pC
- ✧ε_N=2mm-mrad
- ✧σ_z=60µm

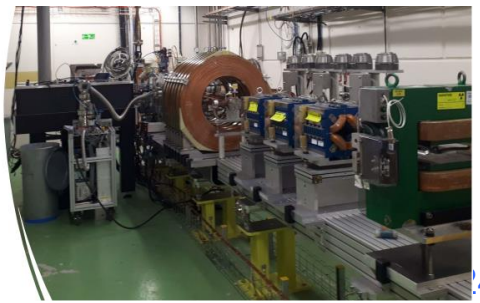


Injector:
- ✧RF-Injector + Transfer line
- ✧Reproducibility
- ✧Tunability
- ✧Expertise at CERN
- ✧Technological advancement
  - ✧compact
  - ✧high-gradient
  - ✧other applications …

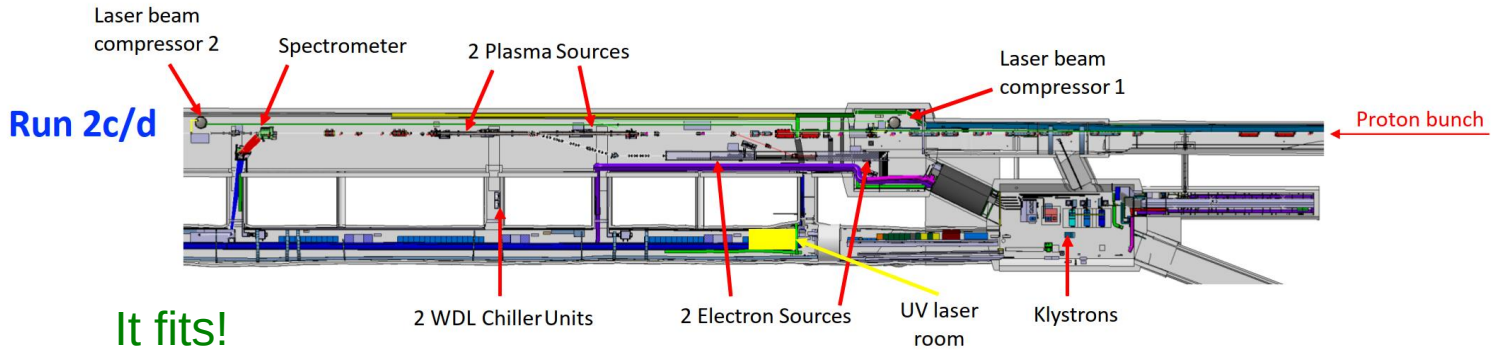
See Steffen's and Vittorio's talks

Transport lines:
- ✧p^+, e-seed, e-injection
  - ✧Designed

In the lab!



BASE LINE, RUN 2c: INJECTOR(S), DESIGNED

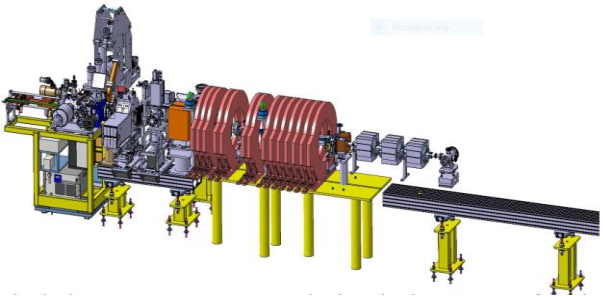


Injector:

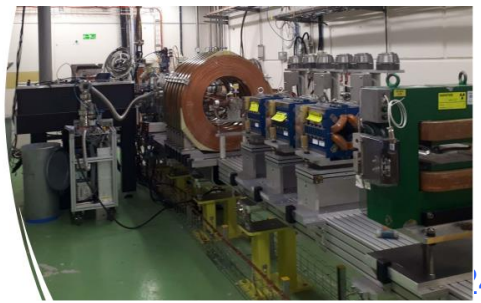
- ✧RF-Injector + Transfer Line
- ✧Reproducibility
- ✧Tunability
- ✧Expertise at CERN
- ✧Technological advancement
  - ✧compact
  - ✧high-gradient
  - ✧other applications …

Transport lines:

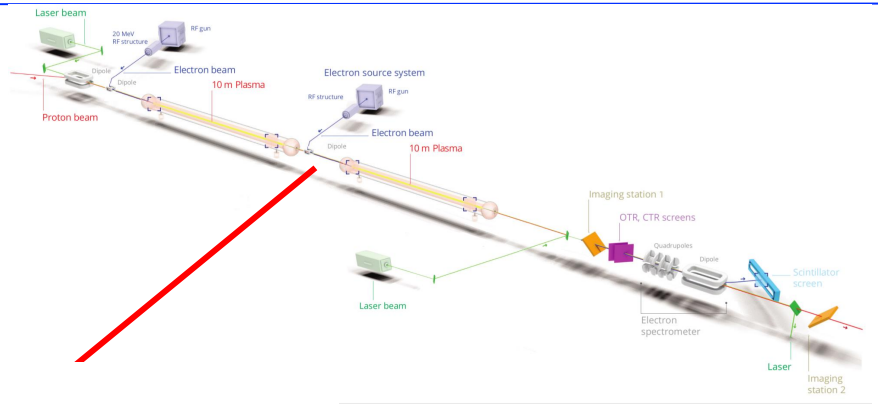
- ✧p^+, e-seed, e-injection
  - ✧Designed

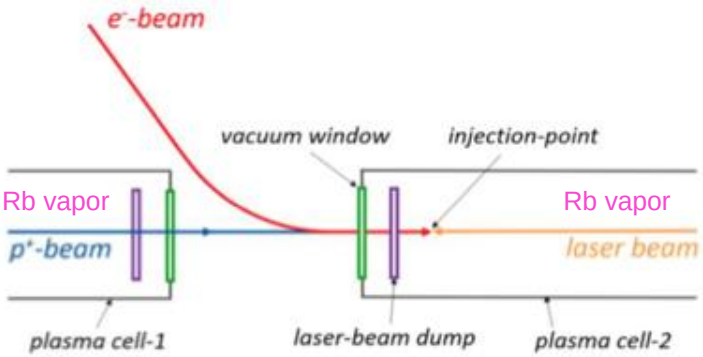


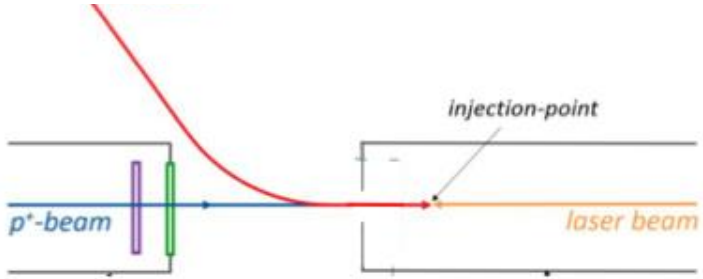
In the lab!



RUN 2c: INJECTiON REGiON

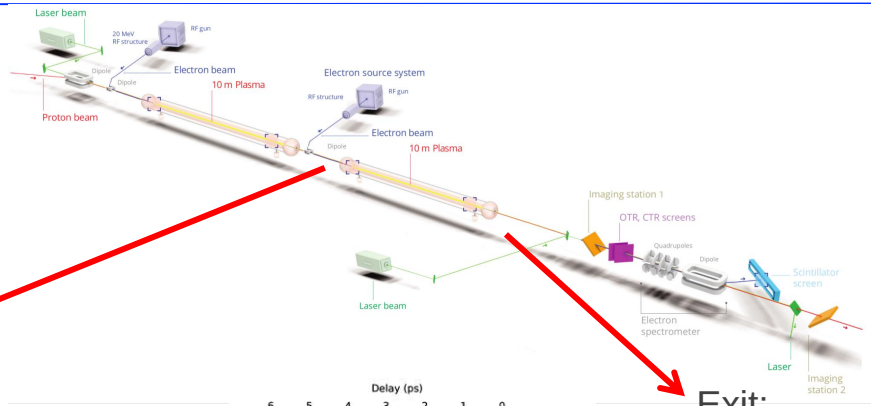






- Foils
  - emittance growth, ε_N=2→16mm-mrad
- No foil
  - expansion volume
  - no emittance growth, ε_N=2mm-mrad

PARAMETERS RUN 2c: INJECTiON/ACCELERATiON



Entrance:

✧E=150MeV, σ_z=60µm, Q=100pC

✧"High emittance", foils

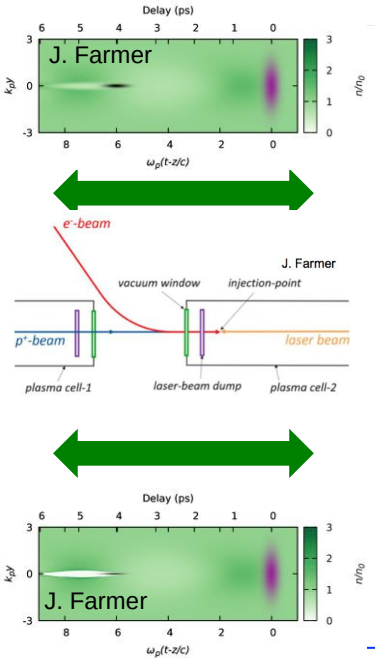
✧ε_N=16mm-mrad

✧$\sigma_{r,matched}$=26µm

✧"Low emittance", no foil

✧ε_N=2mm-mrad

✧$\sigma_{r,matched}$=6µm



Exit:

✧L=10m, 1m gap

✧ε_N=17mm-mrad ⇔ quasi-linear

✧E=4GeV

✧ΔE/E=8%

✧Q=100pC

Farmer, arXiv:2203.11622 (2022)

✧ε_N=2mm-mrad ⇔ blow-out

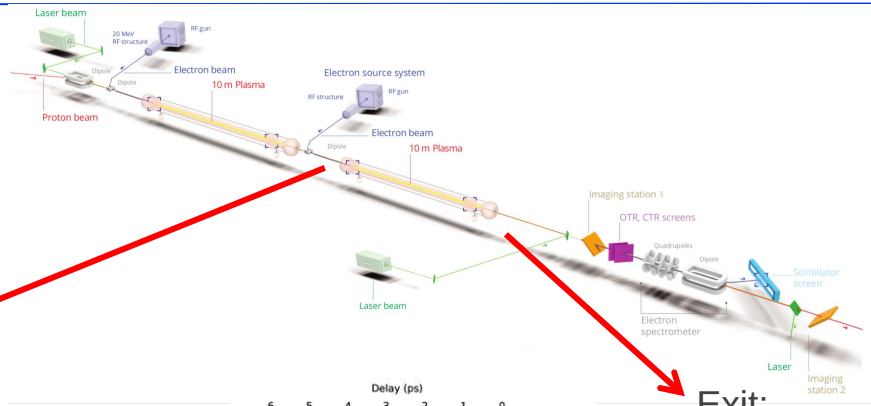
✧E=4GeV

✧ΔE/E=5%

✧Q=100pC

V. K. Berglyd Olsen
PR- AB 21, 011301 (2018)

PARAMETERS RUN 2c: INJECTiON/ACCELERATiON



Entrance:

✧E=150MeV, σ_z=60µm, Q=100pC

✧"High emittance", foils

✧ε_N=16mm-mrad

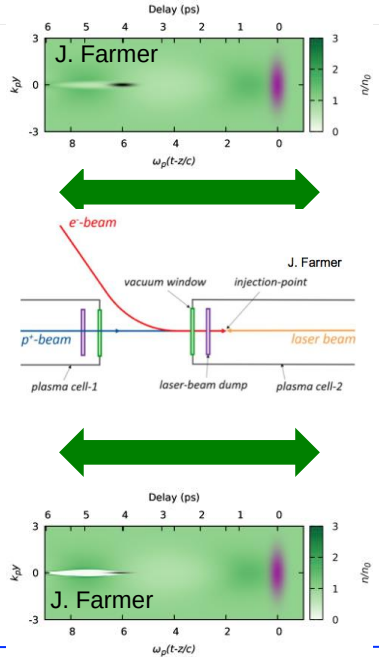
✧$\sigma_{r,matched}$=26µm

✧"Low emittance", no foil

✧ε_N=2mm-mrad

✧$\sigma_{r,matched}$=6µm

See John's talk



Exit:

✧L=10m, 1m gap

✧ε_N=17mm-mrad ⇔ quasi-linear

✧E=4GeV

✧ΔE/E=8%

✧Q=100pC

Farmer, arXiv:2203.11622 (2022)

Emittance Control!

✧ε_N=2mm-mrad ⇔ blow-out

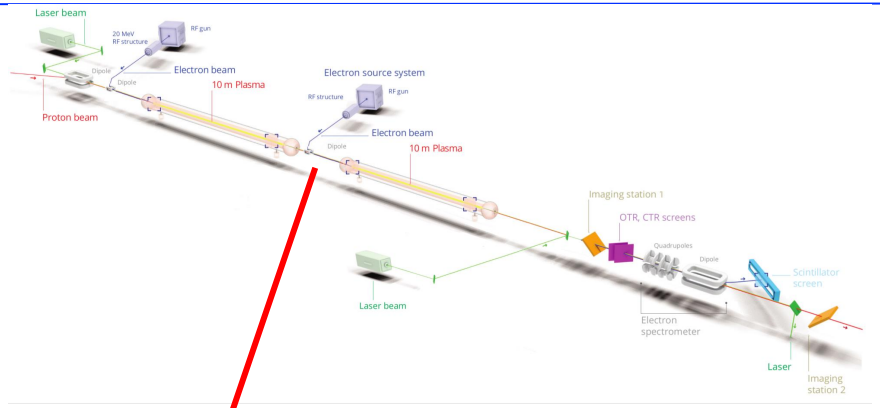
✧E=4GeV

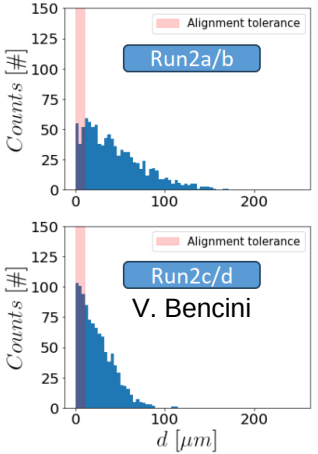
✧ΔE/E=5%

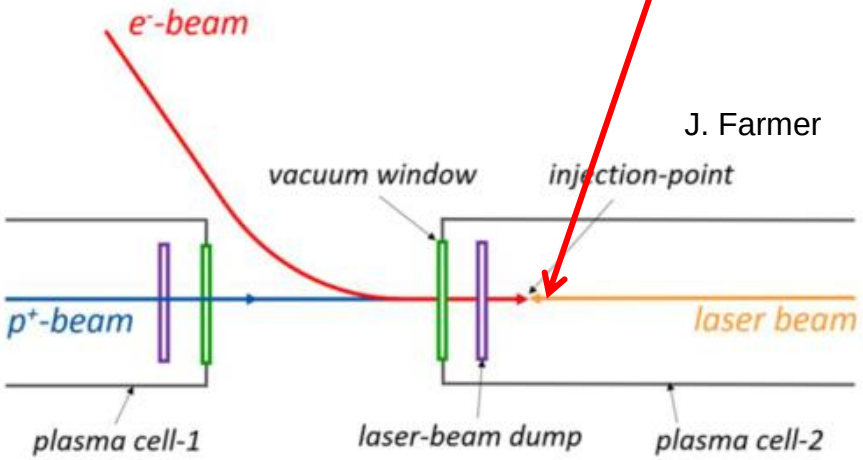
✧Q=100pC

V. K. Berglyd Olsen
PR- AB 21, 011301 (2018)

RUN 2c: INJECTiON DiAGNOSTiCS



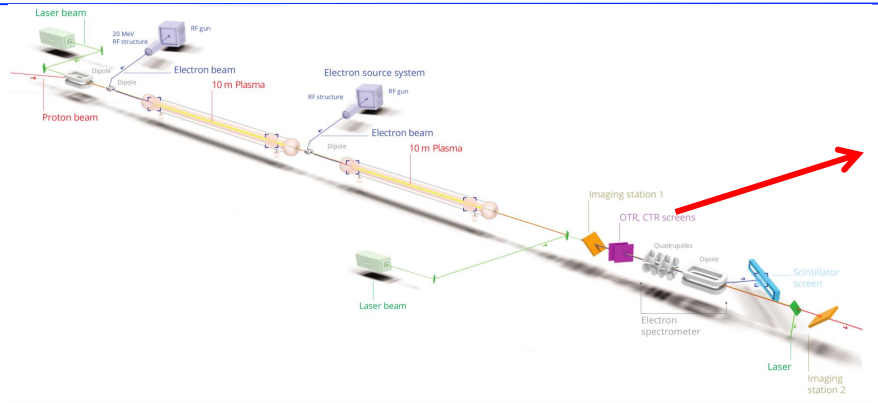




J. Farmer

- Align (position, pointing) two beams with:
  - β_{p+}~m, σ_r>200μm
  - β_{e-}~mm, σ_r~5-20μm
  - include relative jitter — Vittorio's talk
  - Timing synchronization e-laser pulse <100fs
    - $<T_{pe}$=4.3ps (n_{eo}=7x10^{14}cm^{-3})
- TBD
- Tested screen @ 200°C @ CLEAR
- Tested screen in rubidium

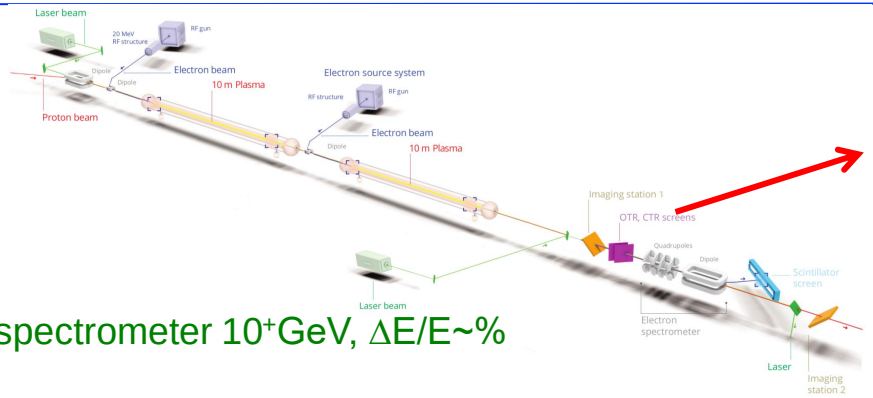
DiAGNOSTiCS: e^- BUNCH



Typical parameters

- ε_N=(2-30)mm-mrad
- Q=100pC, N_{e^-}~6x$10^9 e^-$
- $\Delta E/E$=5-8%
- E~4-10^+GeV

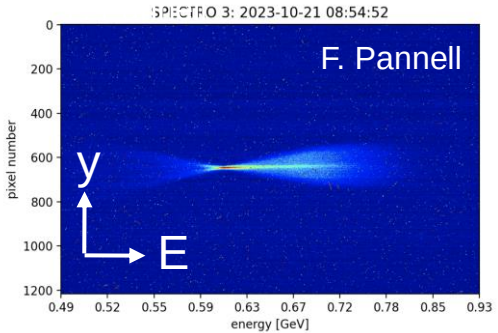
DiAGNOSTiCS: e^- BUNCH

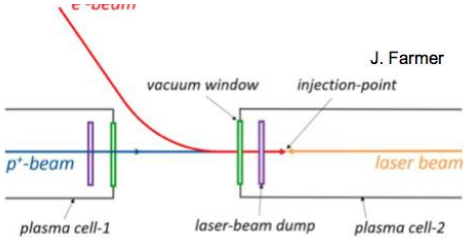


Typical parameters

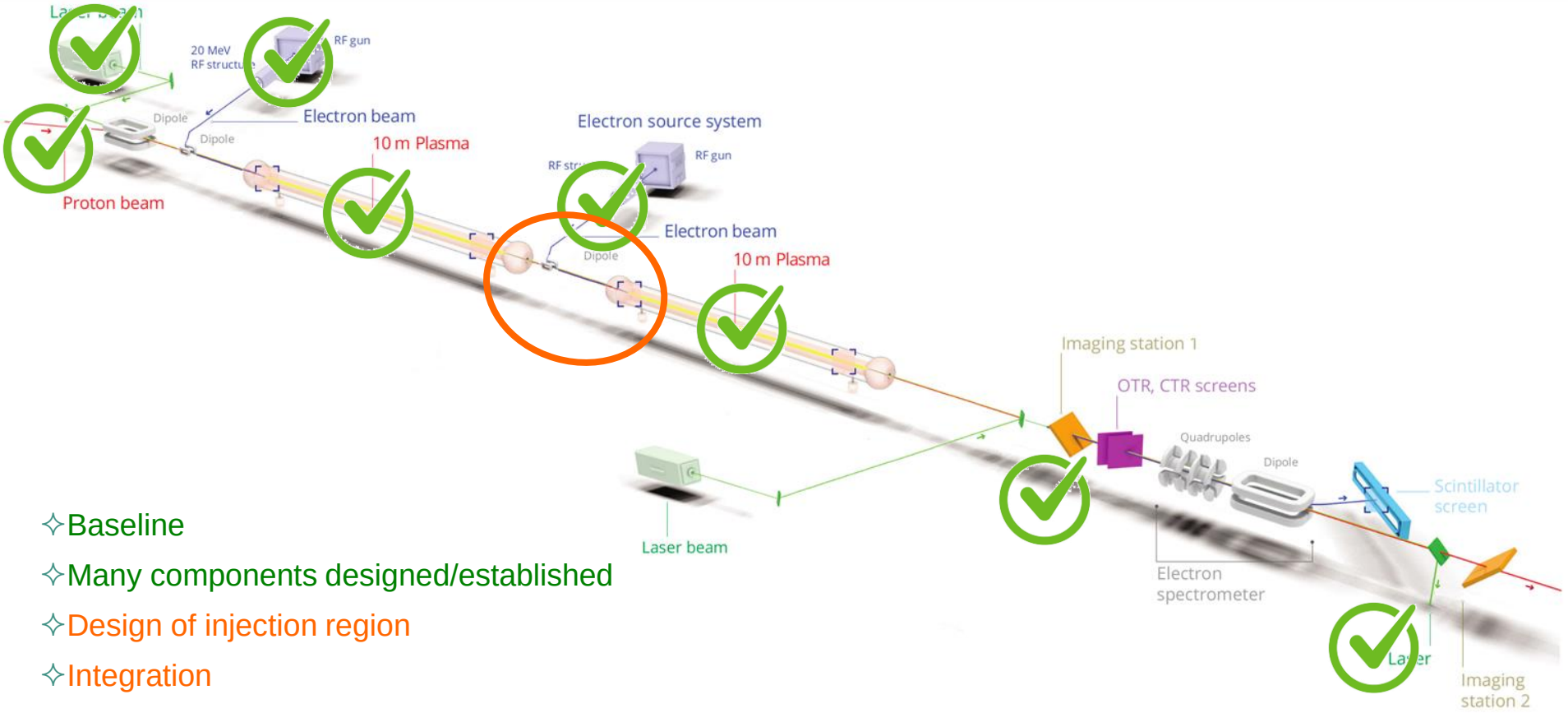
- ✧ε_N=(2-30)mm-mrad
- ✧Q=100pC, N_{e^-}~6x10$^9e^-$
- ✧ΔE/E=5-8%%
- ✧E~4-10$^+$GeV

- ✧Energy:
  - ✧Imaging magnetic spectrometer 10$^+$GeV, ΔE/E~%
- ✧Emittance (ε_N=2-30µm)
  - ✧butterfly method
  - ✧micro-lens array (optical pepper-pot)
- ✧Bunch length (σ_z=60µm)
  - ✧OTR + streak camera (200fs)
  - ✧electro-optical sampling (EOS)
  - ✧time-deflecting cavity (TDC)
  - ✧coherent emission (relative)
- ✧Focal size, alignment, position&pointing
  - ✧Imaging, YAG screen
  - ✧synchrotron radiation (relative)





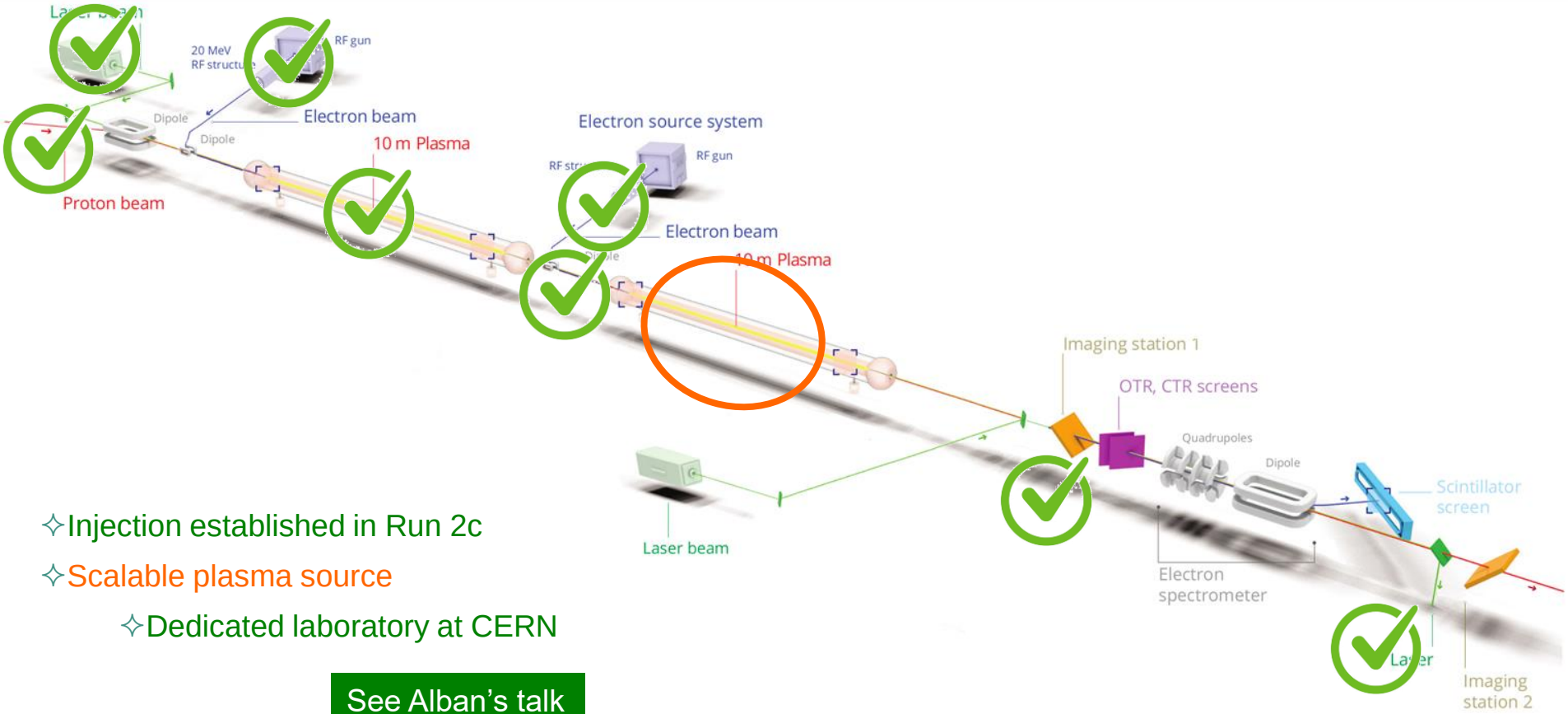
RUN 2c: DESiGN



- ✧Baseline
- ✧Many components designed/established
- ✧Design of injection region
- ✧Integration

Muggli (AWAKE Coll.), J. of Phys.: Conf. Series1596, 012008 (2020)

RUN 2d: DESiGN

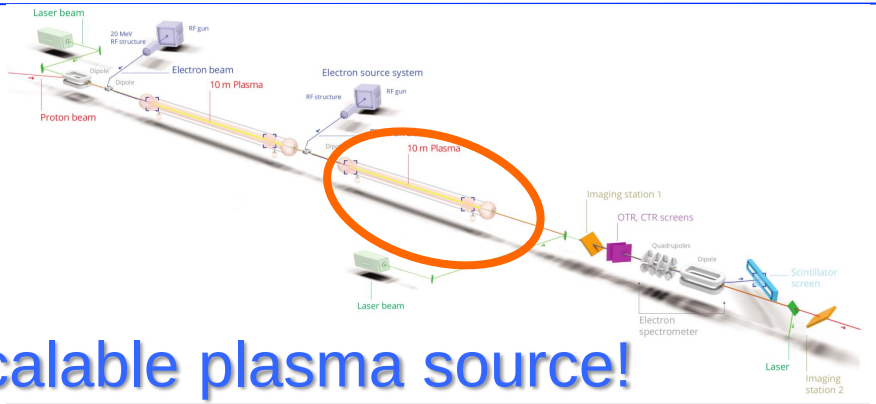


- ✧Injection established in Run 2c
- ✧Scalable plasma source
  - ✧Dedicated laboratory at CERN

See Alban's talk

Muggli (AWAKE Coll.), J. of Phys.: Conf. Series1596, 012008 (2020)

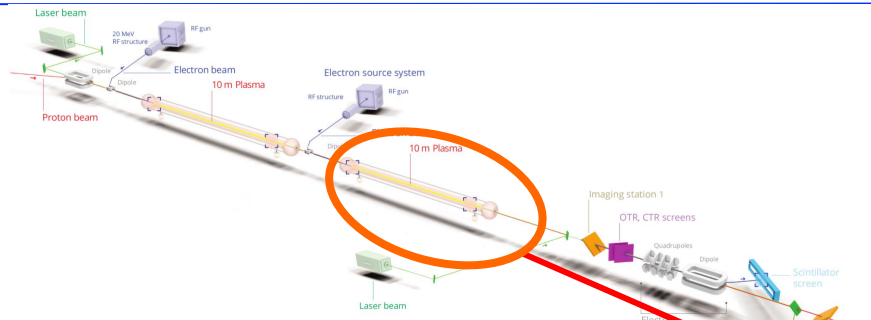
CHOiCE FOR RUN 2d



Accelerator: scalable plasma source!

*DPS: Discharge Plasma Source

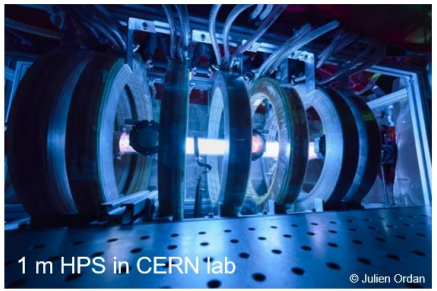
CHOiCE FOR RUN 2d



Accelerator: scalable plasma source!

✧Discharge Plasma Source (DPS)

✧Helicon Plasma Source (HPS)



Accelerator:

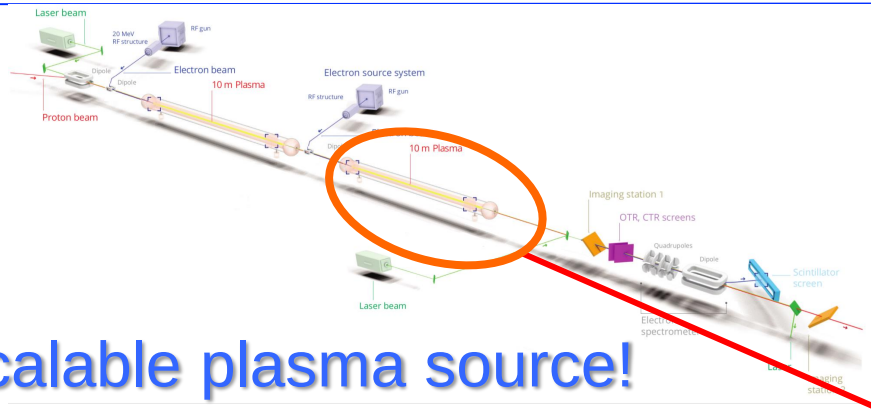
✧DPS*, HPS**

- ✧Density uniformity
- ✧Tunability
- ✧Reproducibility

*DPS: Discharge Plasma Source

*HPS: Helicon Plasma Source

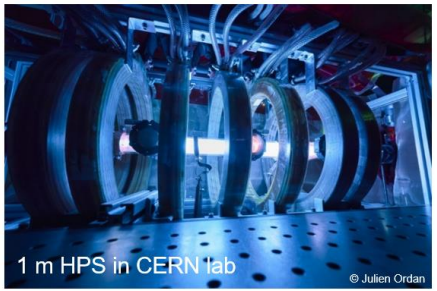
CHOiCE FOR RUN 2d



Accelerator: scalable plasma source!

✧Discharge Plasma Source (DPS)

✧Helicon Plasma Source (HPS)



Accelerator:

✧DPS*, HPS**

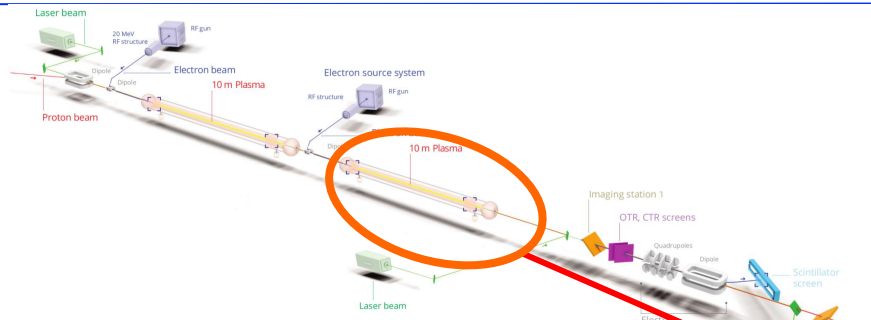
- ✧Density uniformity
- ✧Tunability
- ✧Reproducibility

- ✧Dedicated laboratory plasma source at CERN
- ✧ESSENTIAL for the success of Run 2d and for applications
- ✧Development that applies to other accelerators (parameters)

*DPS: Discharge Plasma Source

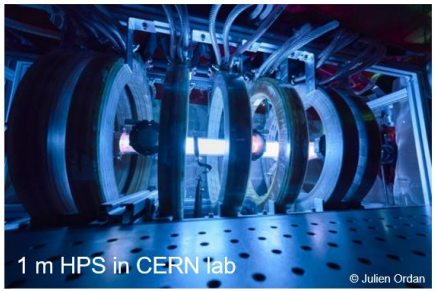
*HPS: Helicon Plasma Source

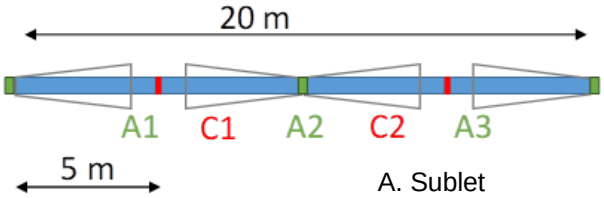
CHOiCE FOR RUN 2d



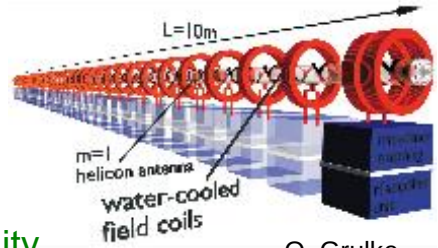
Accelerator: scalable plasma source!

✧Discharge Plasma Source (DPS) ✧Helicon Plasma Source (HPS)





A. Sublet



O. Grulke

✧Scalability …

Accelerator:

✧DPS*, HPS**

- ✧Density uniformity
- ✧Tunability
- ✧Reproducibility

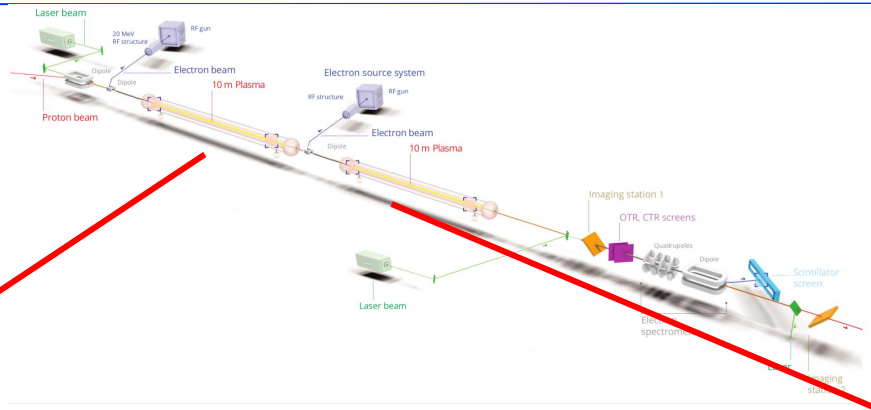
See Alban's talk

- ✧Dedicated laboratory plasma source at CERN
- ✧ESSENTIAL for the success of Run 2d and for applications
- ✧Development that applies to other accelerators (parameters)

*DPS: Discharge Plasma Source

*HPS: Helicon Plasma Source

OPTiONS FOR RUN 2d



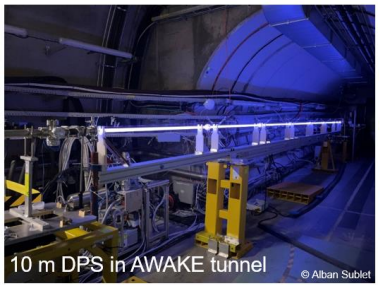
Self-modulator:

- ✧DPS*, Argon
  - ✧Simplicity
  - ✧e-seeding
  - ✧Density step
- ✧e^- bunch seeding

✧Plasma sources: major technological development that applies to other accelerators (parameters)

Accelerator:

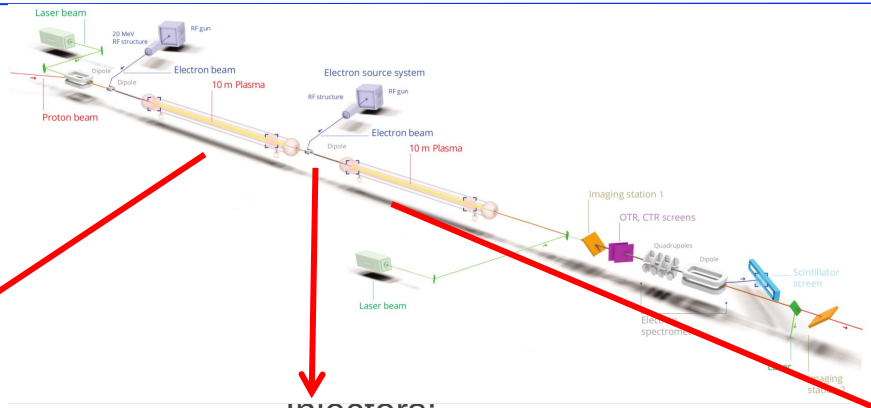
- ✧DPS*, HPS**
  - ✧Density uniformity
  - ✧Tunability
  - ✧Reproducibility



*DPS: Discharge Plasma Source

*HPS: Helicon Plasma Source

OPTIONS FOR RUN 2d



Self-modulator:

- ✧DPS*, Argon
  - ✧Simplicity
  - ✧e-seeding
  - ✧Density step
- ✧e^- bunch seeding

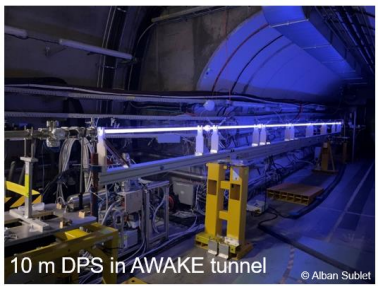
Injectors:

- ✧LWFA (EARLI Project)
  - ✧Novelty
  - ✧Reproducibility
  - ✧Tunability
- ✧Foil injection
  - ✧no gap

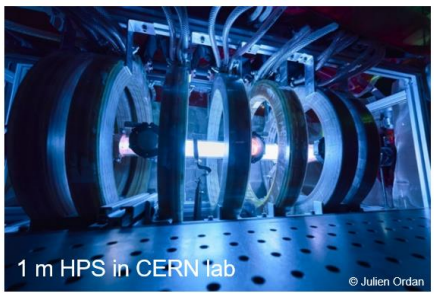
See John's talk

Accelerator:

- ✧DPS*, HPS**
  - ✧Density uniformity
  - ✧Tunability
  - ✧Reproducibility



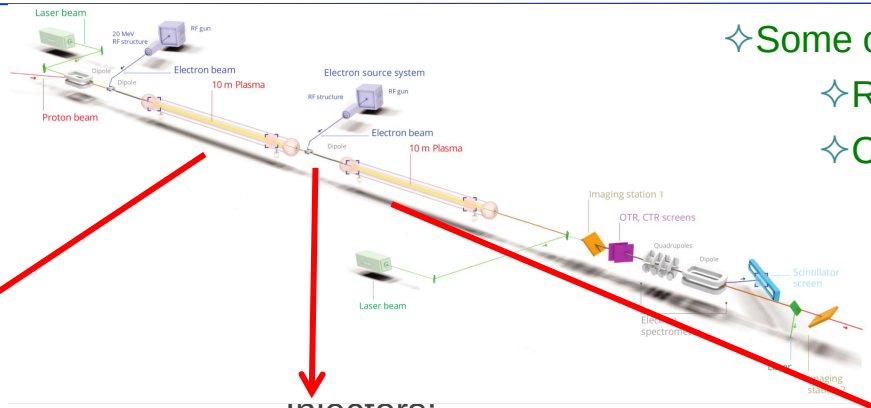
✧LWFA injector: technological development that applies to other accelerators (parameters)



*DPS: Discharge Plasma Source

*HPS: Helicon Plasma Source

OPTIONS FOR RUN 2d



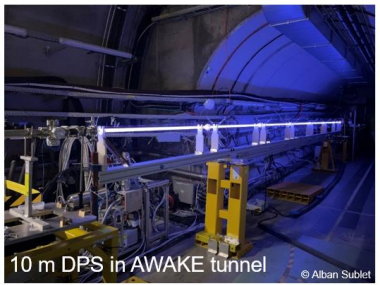
✧Some options for Run 2c?
- ✧Ready
- ✧Cheaper, easier

Self-modulator:
- ✧DPS*, Argon
  - ✧Simplicity
  - ✧e-seeding
  - ✧Density step
- ✧e^- bunch seeding

Injectors:
- ✧LWFA (EARLI Project)
  - ✧Novelty
  - ✧Reproducibility
  - ✧Tunability
- ✧Foil injection
  - ✧no gap

Accelerator:
- ✧DPS*, HPS**
  - ✧Density uniformity
  - ✧Tunability
  - ✧Reproducibility

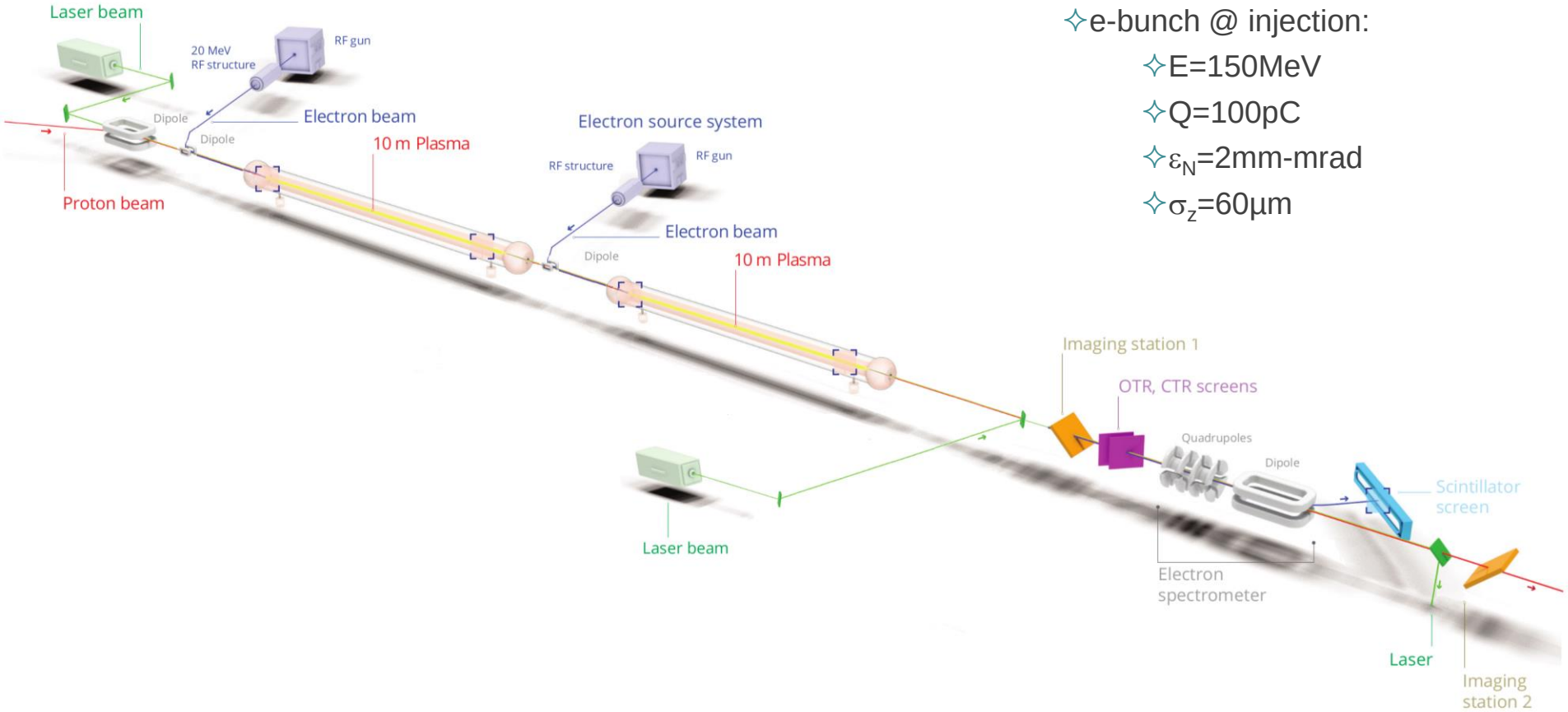
✧LWFA injector: technological development that applies to other accelerators (parameters)



*DPS: Discharge Plasma Source

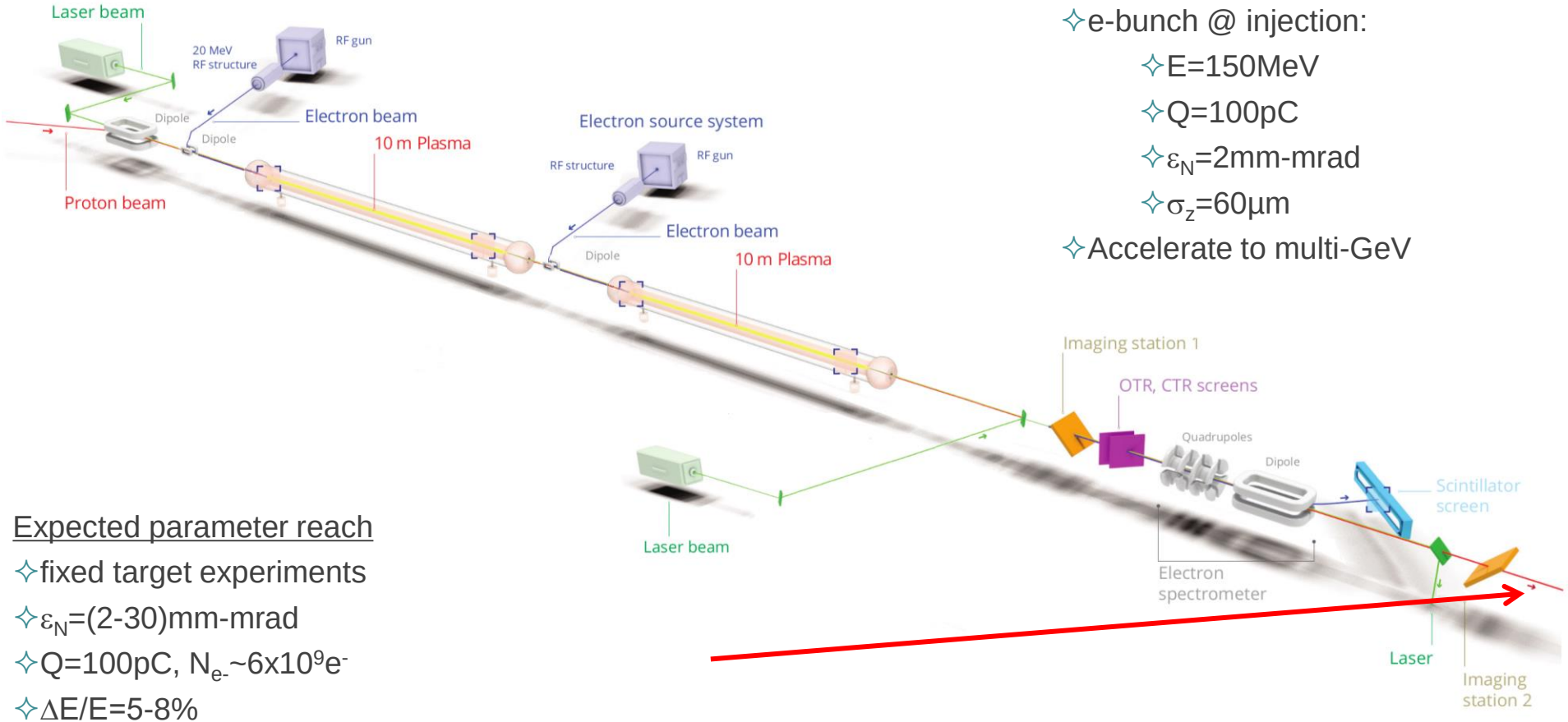
*HPS: Helicon Plasma Source

RUN 2c,d: EXPECTED PARAMETER REACH



- e-bunch @ injection:
  - E=150MeV
  - Q=100pC
  - ε_N=2mm-mrad
  - σ_z=60µm

RUN 2c,d: EXPECTED PARAMETER REACH



- ✧e-bunch @ injection:
  - ✧E=150MeV
  - ✧Q=100pC
  - ✧ε_N=2mm-mrad
  - ✧σ_z=60µm
- ✧Accelerate to multi-GeV

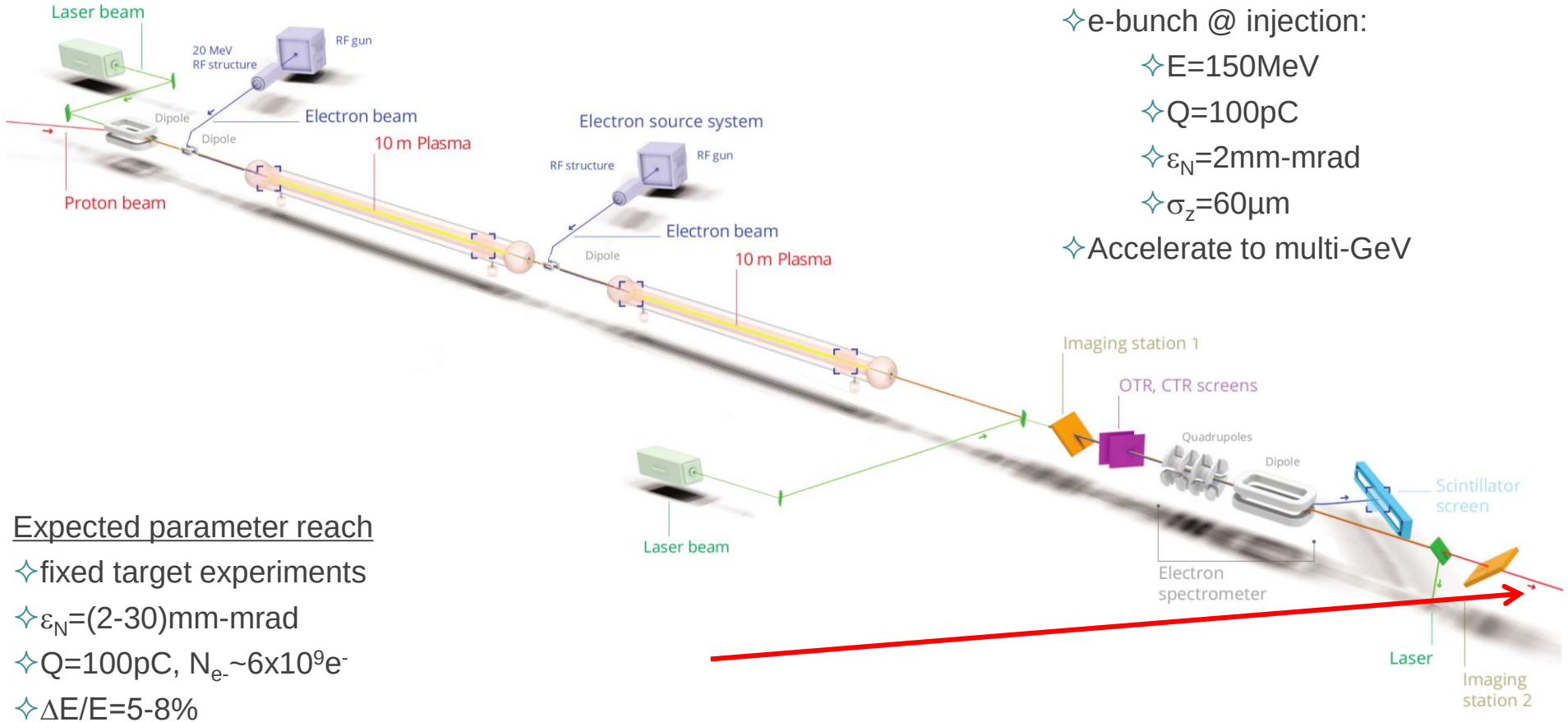
Expected parameter reach

- ✧fixed target experiments
- ✧ε_N=(2-30)mm-mrad
- ✧Q=100pC, N_{e^-}~6x10^{9}e$^-$
- ✧$\Delta E/E$=5-8%
  - ✧Run 2c: E~4-10GeV, 10m
  - ✧Run 2d: E>10GeV, 10$^+$m, scalable

See John's talk

Wing, Phil. Trans. Royal Soc., 377, 20180185 (2019)

RUN 2c,d: EXPECTED PARAMETER REACH



- ✧e-bunch @ injection:
  - ✧E=150MeV
  - ✧Q=100pC
  - ✧ε_N=2mm-mrad
  - ✧σ_z=60µm
- ✧Accelerate to multi-GeV

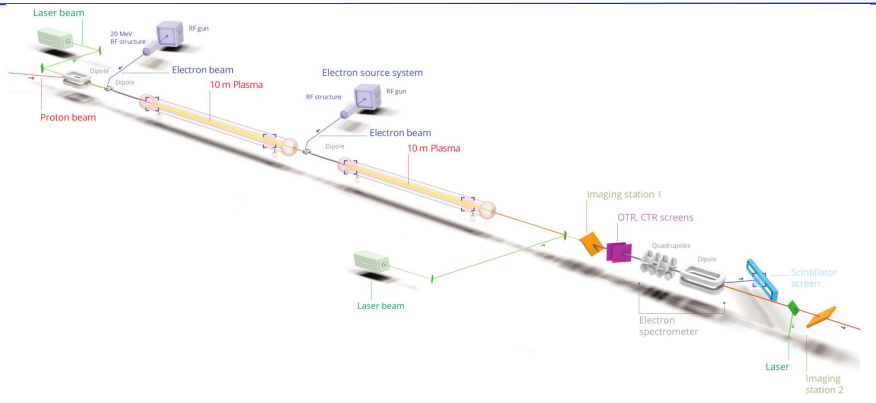
<u>Expected parameter reach</u>

- ✧fixed target experiments
- ✧ε_N=(2-30)mm-mrad
- ✧Q=100pC, N_{e^-}~6x10^{9}e$^-$
- ✧$\Delta E/E$=5-8%
  - ✧Run 2c: E~4-10GeV, 10m
  - ✧Run 2d: E>10GeV, 10$^+$m, scalable

➡ ✧Application: ~50GeV

Wing, Phil. Trans. Royal Soc., 377, 20180185 (2019)

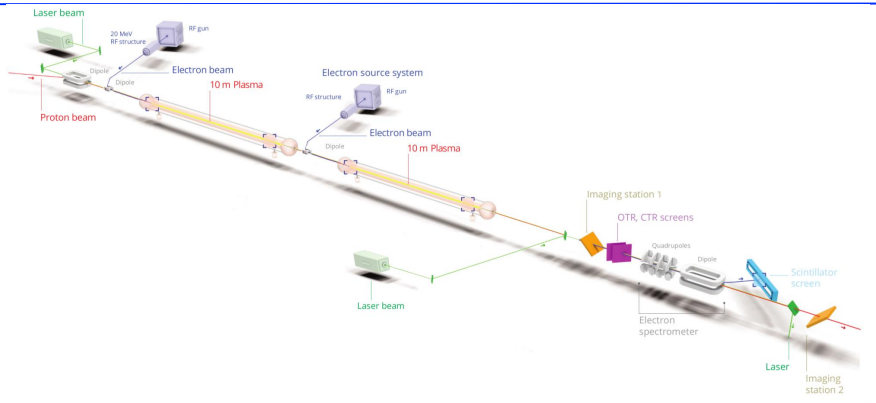
RELEVANCE TO OTHER ADVANCED ACCELERATORS



Developments shared with other plasma-based accelerators:

- ✧Externally inject an e^- bunch ⇔ injection, staging
- ✧Acceleration to multi GeV level ⇔ large energy gain
- ✧Control e-bunch quality: E, $\Delta E/E$, Q, ε_N ⇔ quality!!
- ✧Plasma source: length, density uniformity, reproducibility, tunability ⇔ staging, >1 plasma
- ✧Development of diagnostics: plasma density, bunch parameters (ε_N) ⇔ quality

RELEVANCE



Technological developments

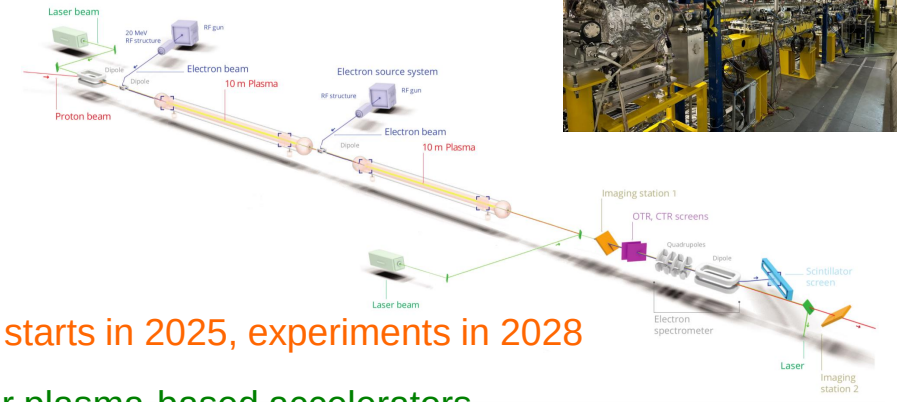
- Plasma sources
  - rubidium, discharge, helicon
  - parameters
  - reproducibility, tunability, uniformity, etc.
- Injectors/injection
  - RF-based, LWFA, …
  - parameters
  - reproducibility, tunability, uniformity, etc
- Diagnostics

Scientific merit

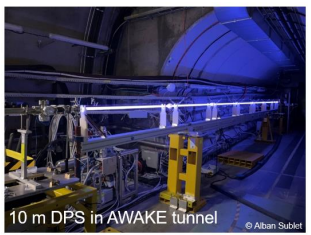
- Edda's, Marlene's talk
  - publications
  - education, prizes
- Understanding plasma-based accelerators
  - and more …

SUMMARY

- Solid plan based on results of successful Run 1,2a,b
  - Demonstrated baseline self-modulator for Run 2c,d
- **Baseline for Run 2c: external injection experiment**
  - Rb self-modulator plasma
  - Rb accelerator plasma
  - RF-based e-bunch injector (CERN)

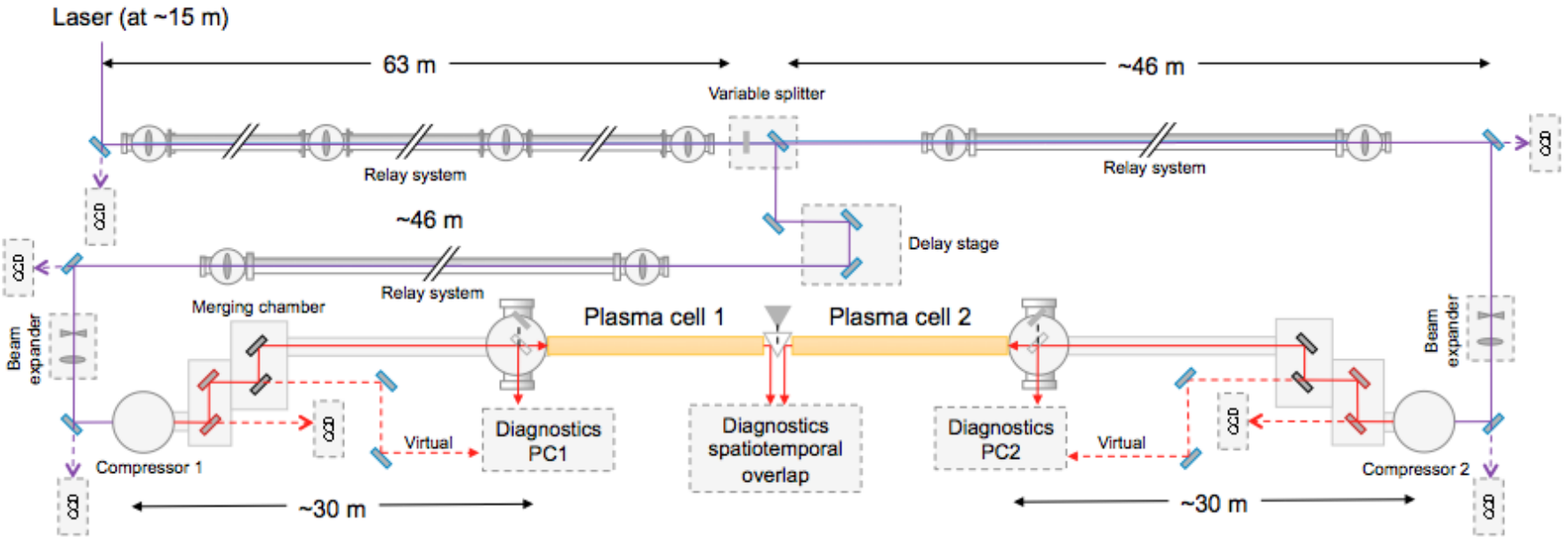


- Design/construction has started, design of injection zone starts in 2025, experiments in 2028
- Most topics addressed for Run 2 c,d are relevant for other plasma-based accelerators
- Technological developments: plasma source, injector, …
- Scientific merit: publications, invited presentations, PhDs, Masters, prizes, …
- **Run 2d: acceleration experiment in scalable plasma source**
  - Preparation has started, plasma source lab at CERN
- No showstoppers identified
- Can produce parameters for first particle physics applications in early 2030's



IONIZING LASER: LAYOUT

IR beams delivery to plasma cells, relays



- Relay imaging systems require only low-level primary vacuum, blue mirrors are "in air"
- Focusing on plasma cell attained by mismatching beam expanders
- Content of diagnostics sets still to be determined, location of safety devices, etc…

E. Granados