EUROPEAN
PLASMA RESEARCH ACCELERATOR
WITH EXCELLENCE IN APPLICATIONS

EuPRAXIA

WP2 et al. - Beam Physics studies
Results and next steps
Nov 2017- Nov 2018

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EuPRAXIA Yearly Meeting
& 4th Collaboration Week
Frascati, November 19-23, 2018

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 653782.

The analysis of the **high energy 5 GeV** beam is **not yet finished** and the general impression is that this WP is exploring a field that has **not yet reached its final maturity**.

Rec5. SAC recommends to define a time-line for starting this **down selection process** that should lead to a CDR with identified solutions for the low energy case (1 GeV) and the high-energy case (5 GeV) in one year from now.

OUTLINE

1. Results obtained at each plasma stage
   and selection of the schemes

2. Start-to-End simulations
   Issues
   Results

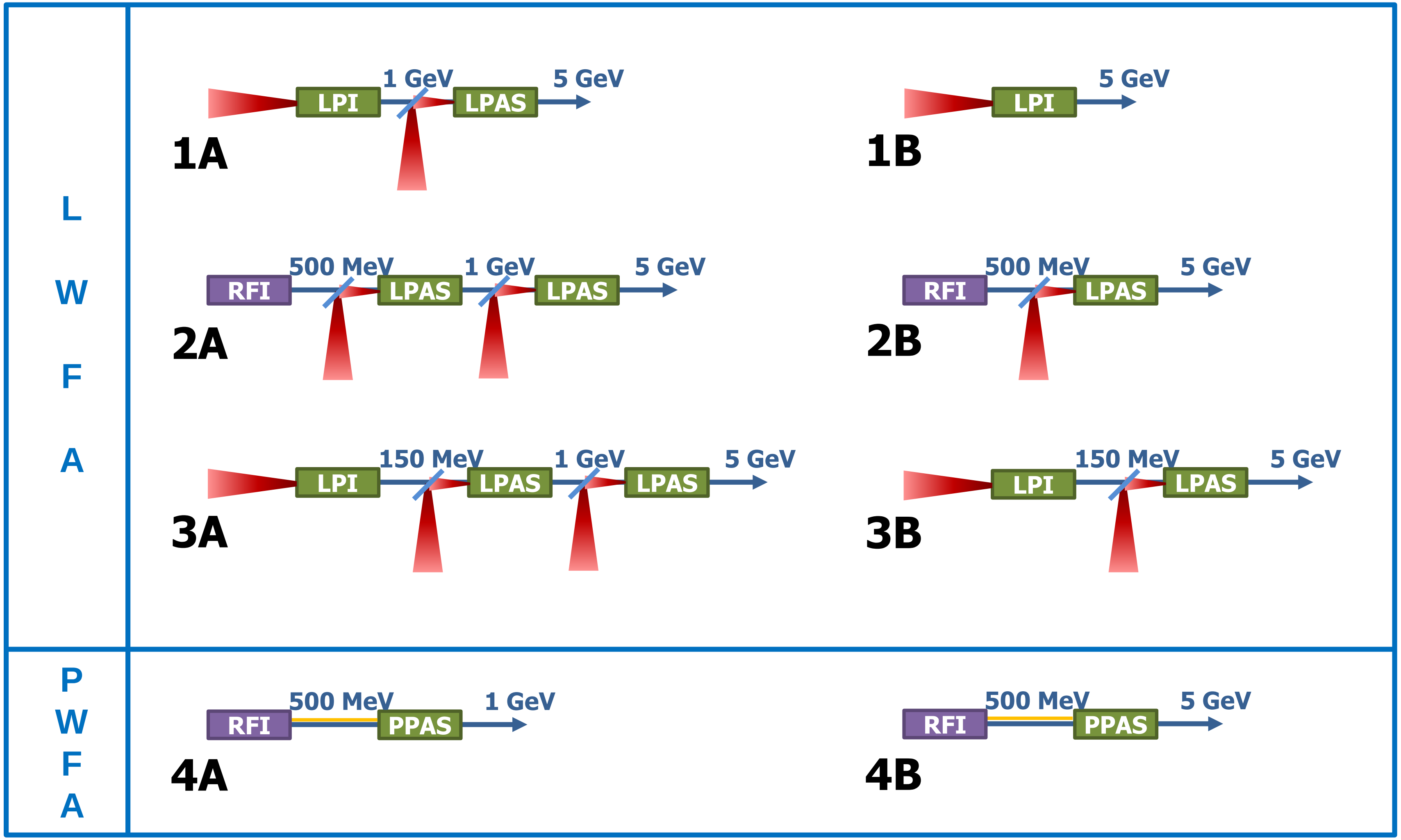
3. Next step
   Study of errors and tolerances

Rec6. SAC recommends reinforcing the **coordination with the above WP** [3, 4, 5, 6, 7] and considering opening up the design space if showstoppers are identified by any of the WPs …

SAC learns from the WP2 leader that the different **codes used were benchmarked** one another on similar physical situations leading to compatible results. Despite this, it was pointed out a poor stability of the solutions analysed leading to a high sensitivity to the input parameters.

Rec7. SAC recommends carrying on an analysis of the stability of the solutions under investigation and including the **stability parameter** as an element in the down selection process; deepening the **analysis of the effects associated to non-ideal conditions**, such as density fluctuations in the plasma target, quality of transverse laser mode, and, ….

EuPRAXIA acceleration schemes



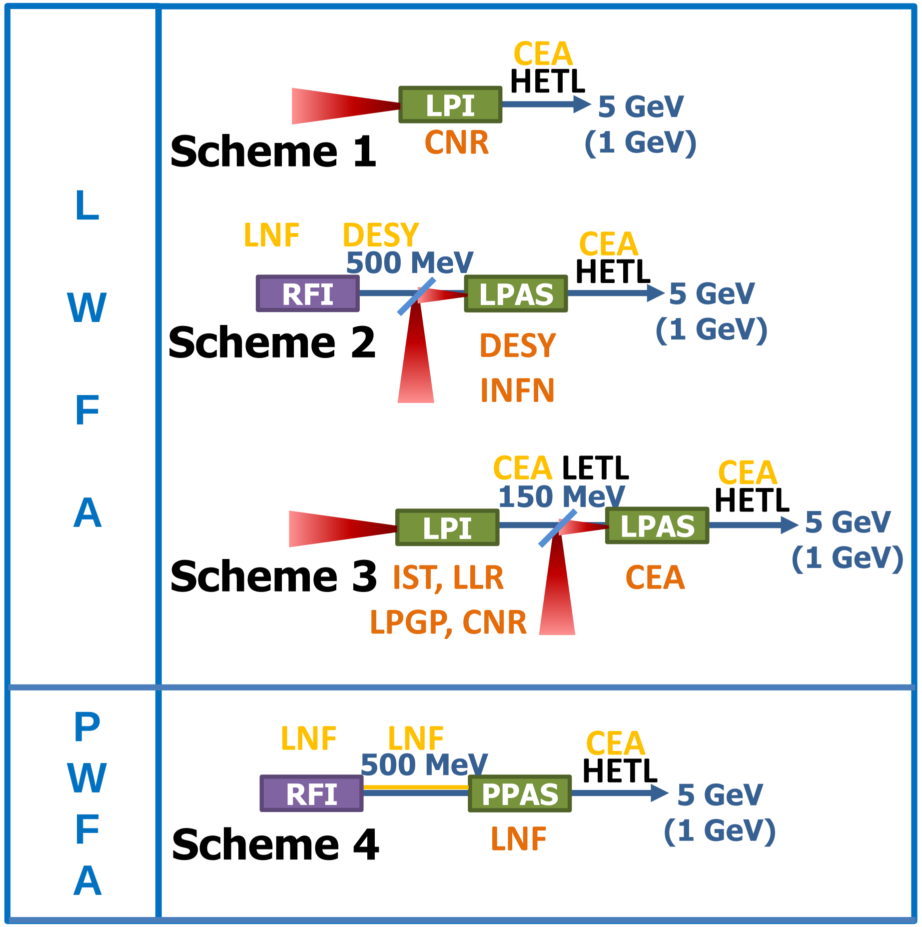
Restricted acceleration schemes

At Yearly meeting in Lisbone (2017)

STRATEGIC Objective:

- Providing beam at **5 GeV** meeting 'perfectly' FEL and HEPO requirements

- Providing as well beam at **1 GeV** 'usable' for FEL and HEPO, as a 'commissioning' step



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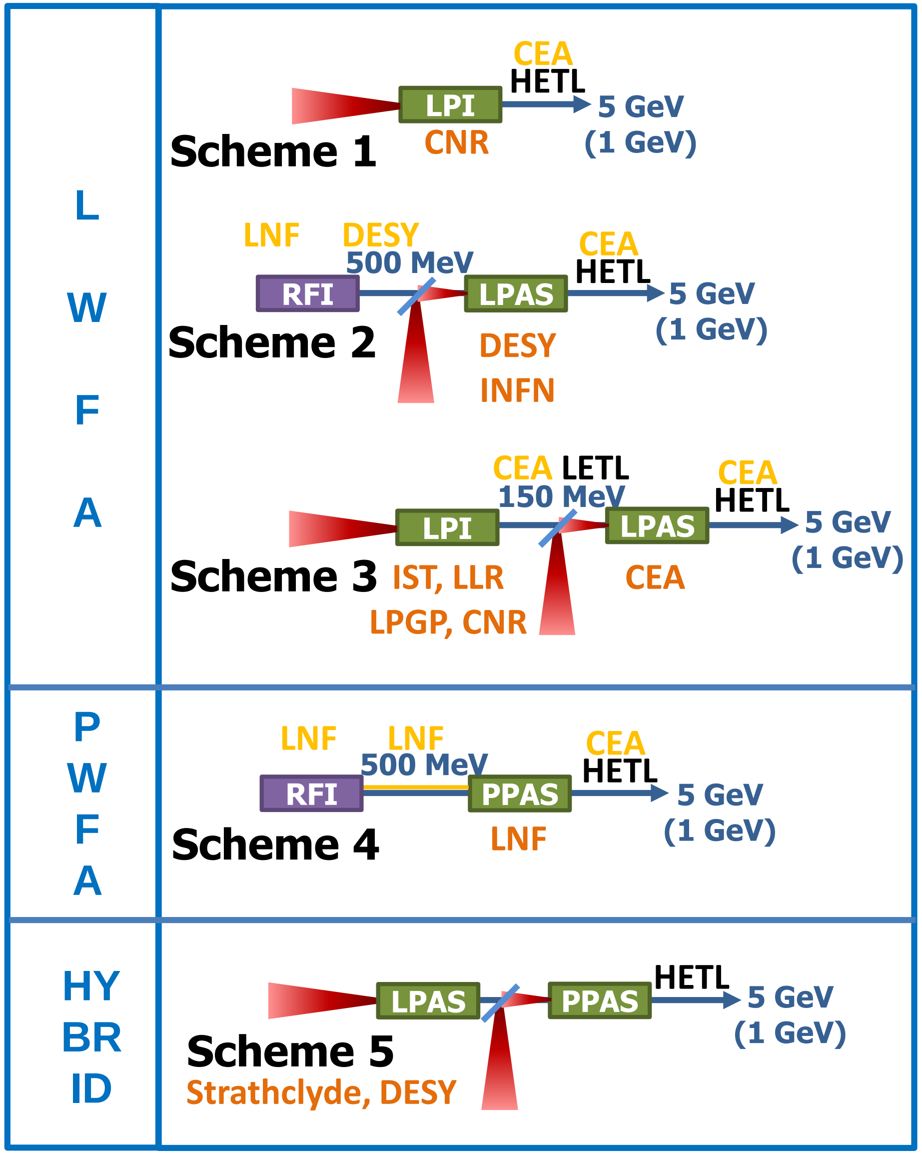
Additionally : Scheme 2A and Hybrid schemes



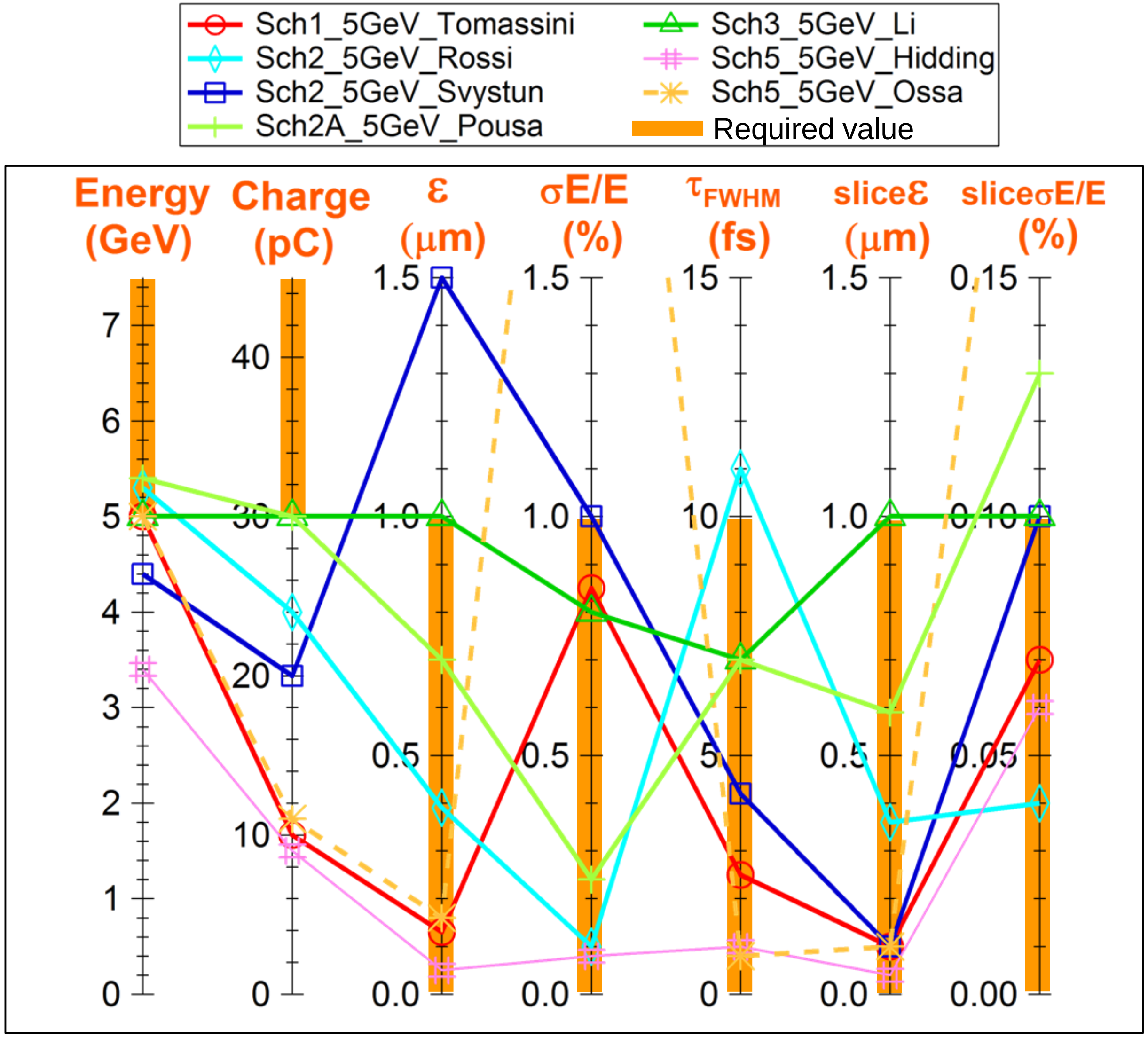
EuPRAXIA requirements

Critical parameters of the electron beam
required at Injection or Acceleration stages

Parameter	LP Injector exit	RF Injector exit	Accelerator exit
E	150 MeV	250-500 MeV	5 GeV (1 GeV)
Q	30 pC	30 pC	30 pC
τ (FWHM)	10 fs	10 fs	10 fs
σ_E/E	5%	0.2 %	1%
$\sigma_{E,s}/E$	t.b.d.	t.b.d.	0.1 %
ε_n	1 mm.mrad	1 mm.mrad	1 mm.mrad
$\varepsilon_{n,s}$	t.b.d.	t.b.d.	1 mm.mrad

Beam parameters obtained at 5 GeV

All the schemes



Beam parameters obtained at 5 GeV

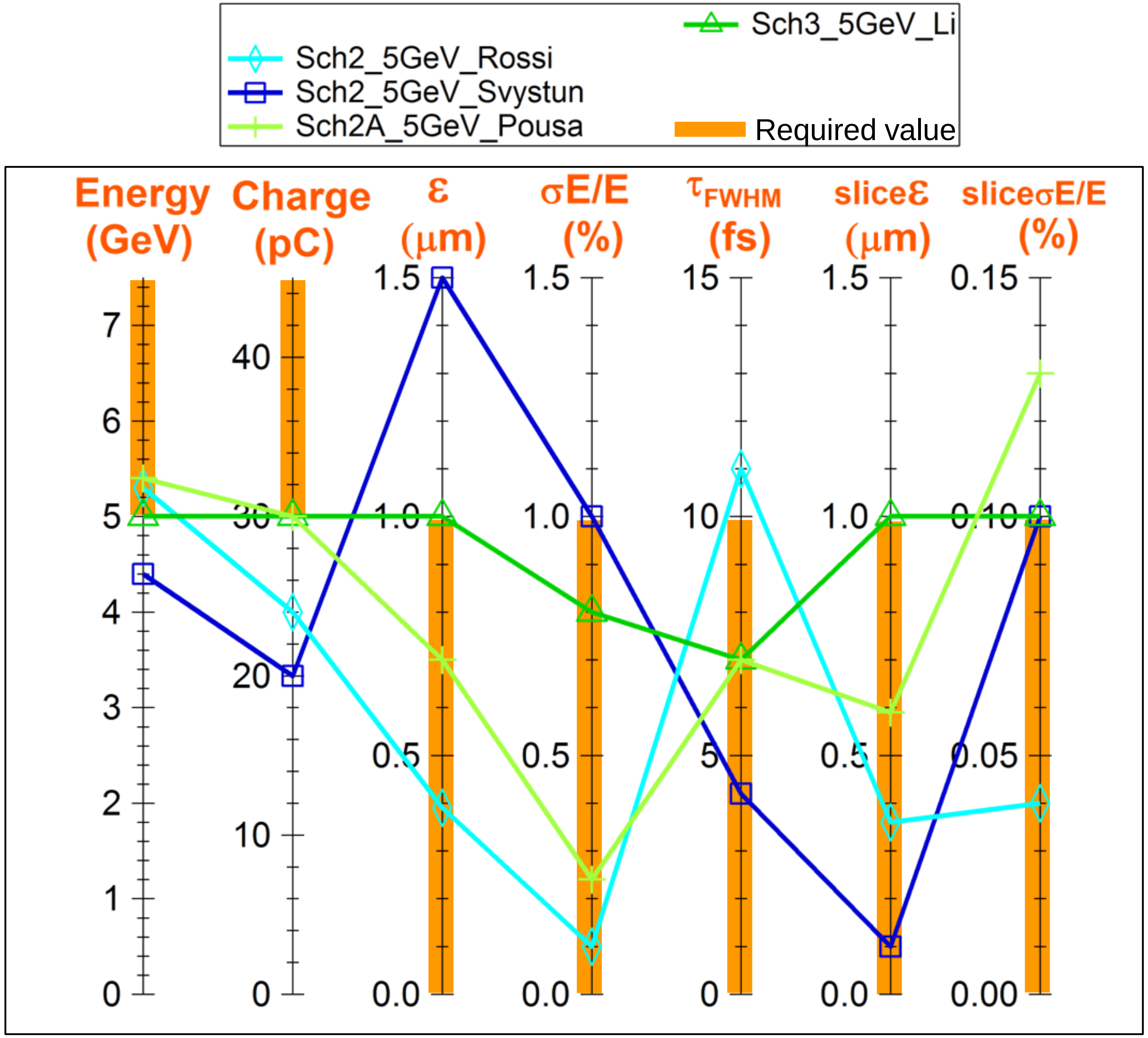
Schemes the closest to the requirements

Four experts
Three institutes

Three codes used:
- Warp 3D
- QFluid ~3D
- FBPIC 3D

Three injectors:
LPI 150 MeV
RFI 240 MeV
RFI 540 MeV

Close plasma,
laser parameters
Quasi linear regime
⇒
Close results



Robustness of the results !!!

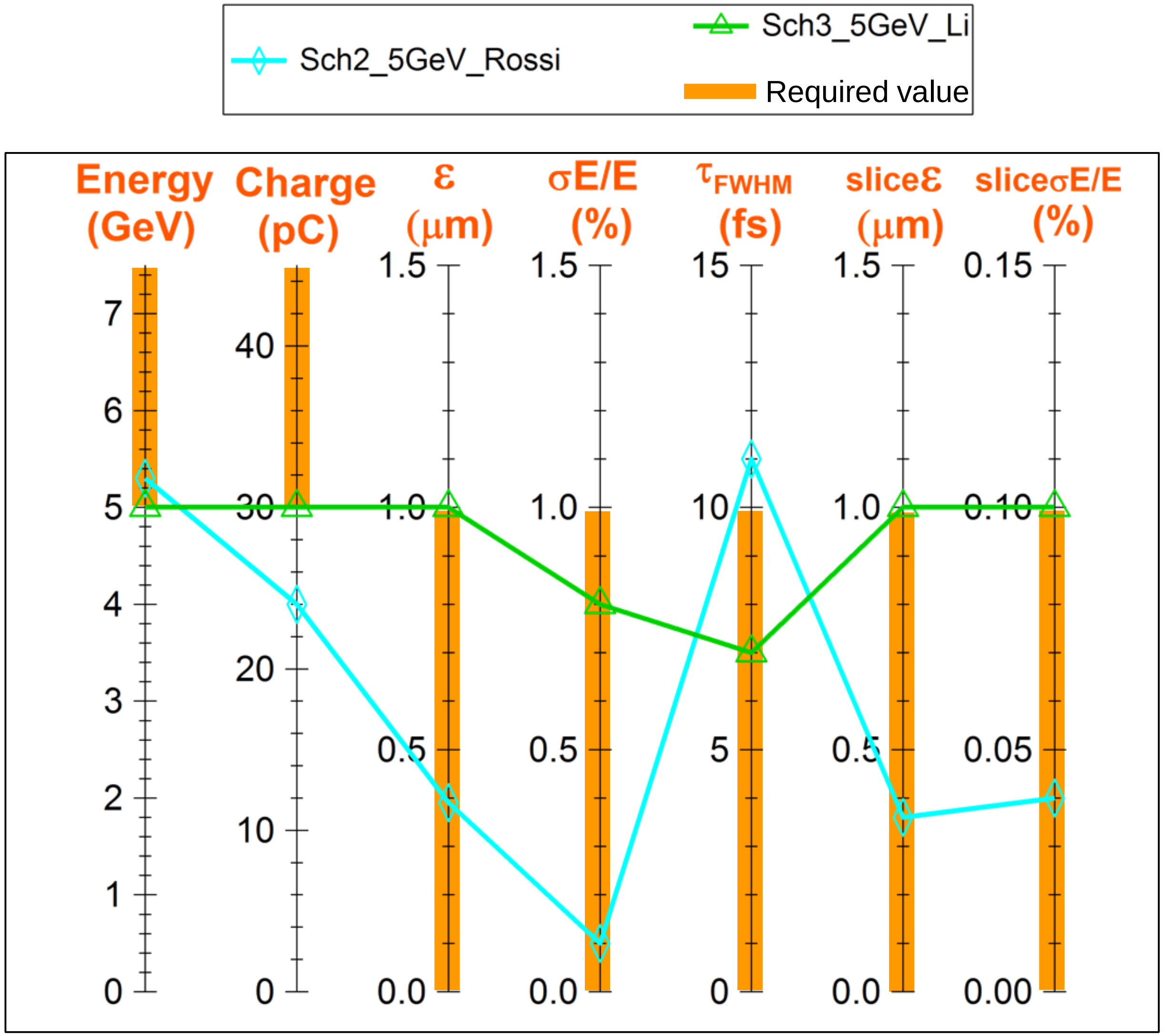
Beam parameters obtained at 5 GeV

Horizon 2020

Schemes selected for Start-to-End simulations

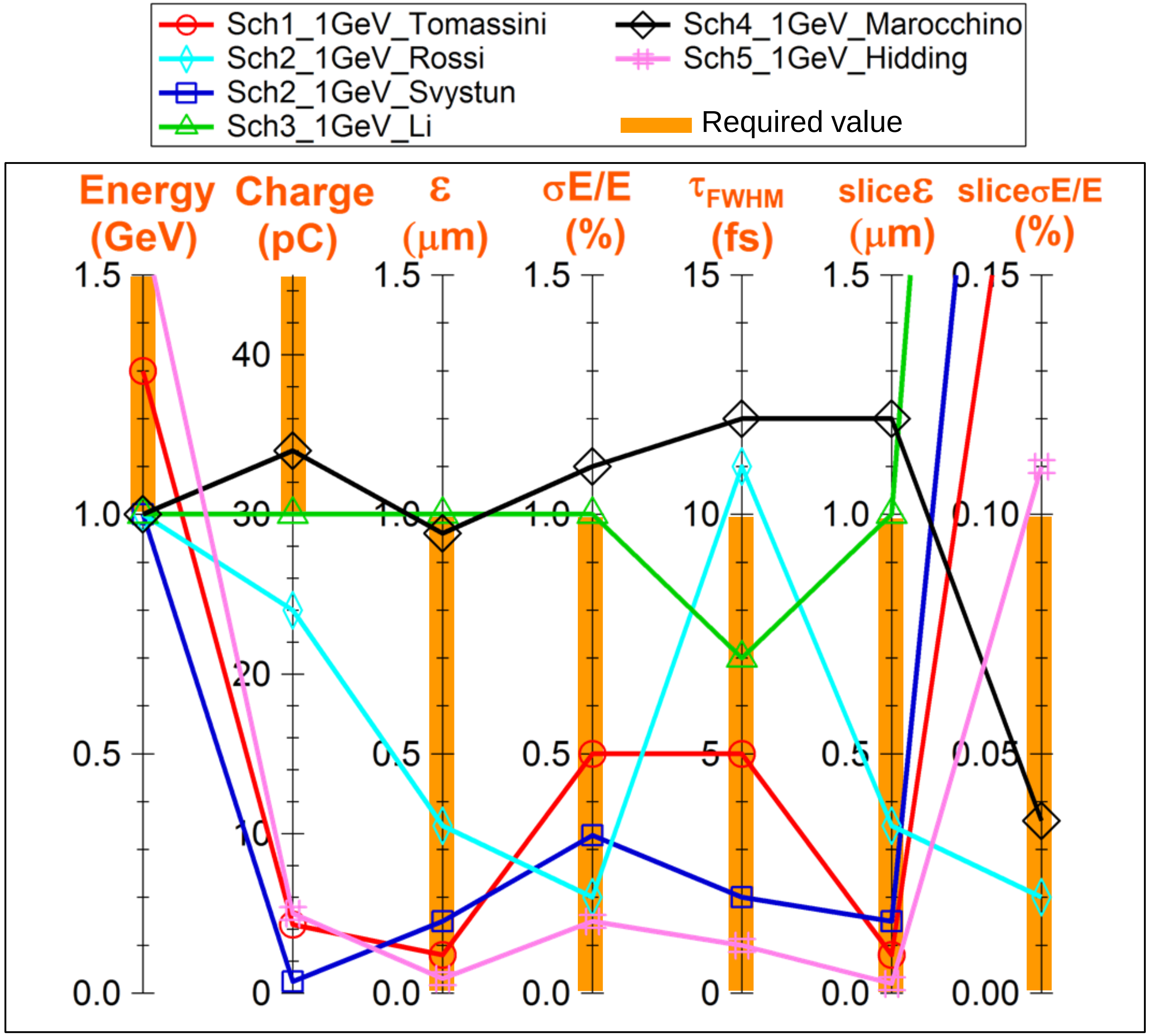
LPI 150 MeV
RFI 540 MeV

Quasi linear regime



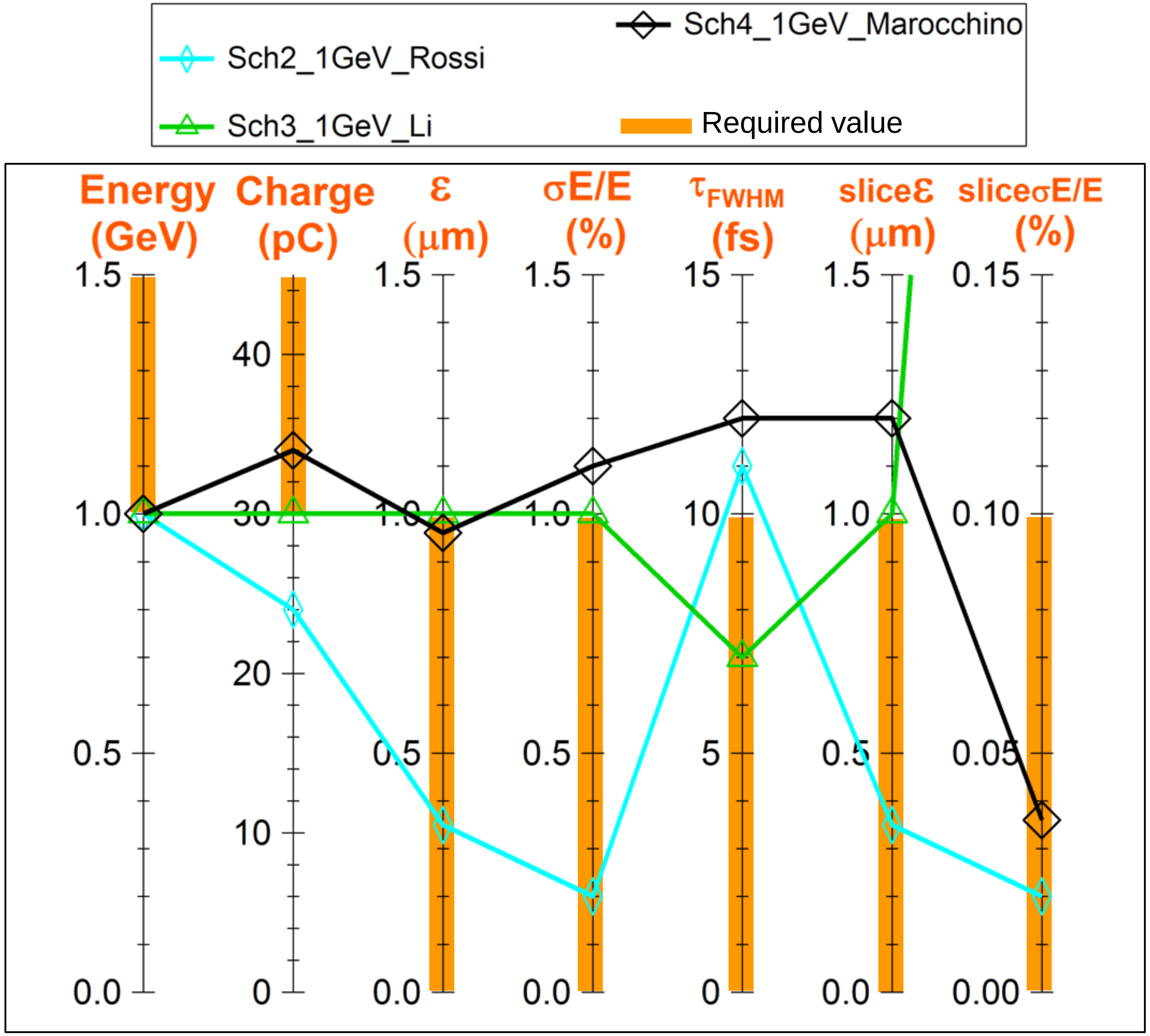
Beam parameters obtained at 1 GeV

All the schemes



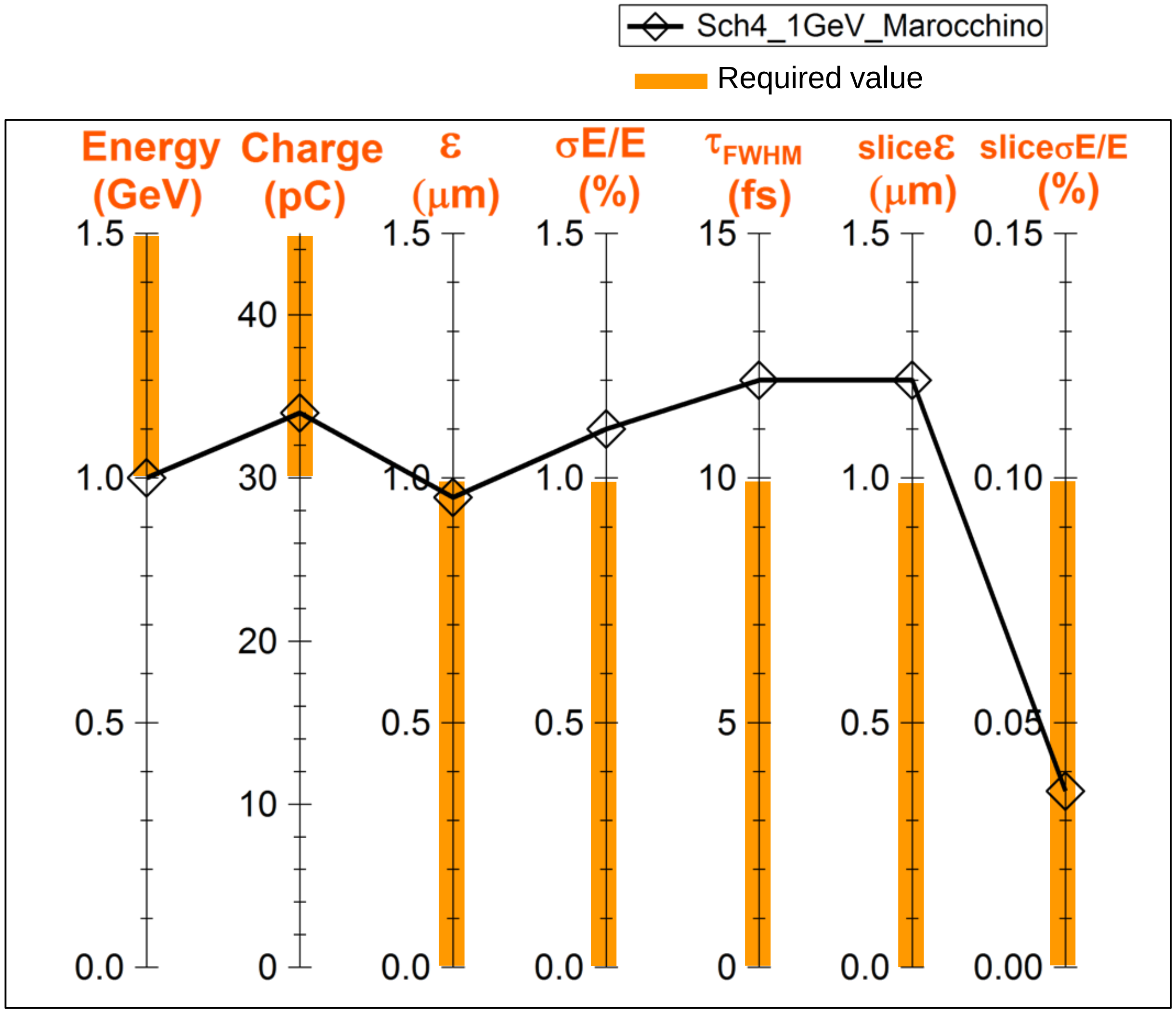
Beam parameters obtained at 1 GeV

Schemes the closest to the requirements



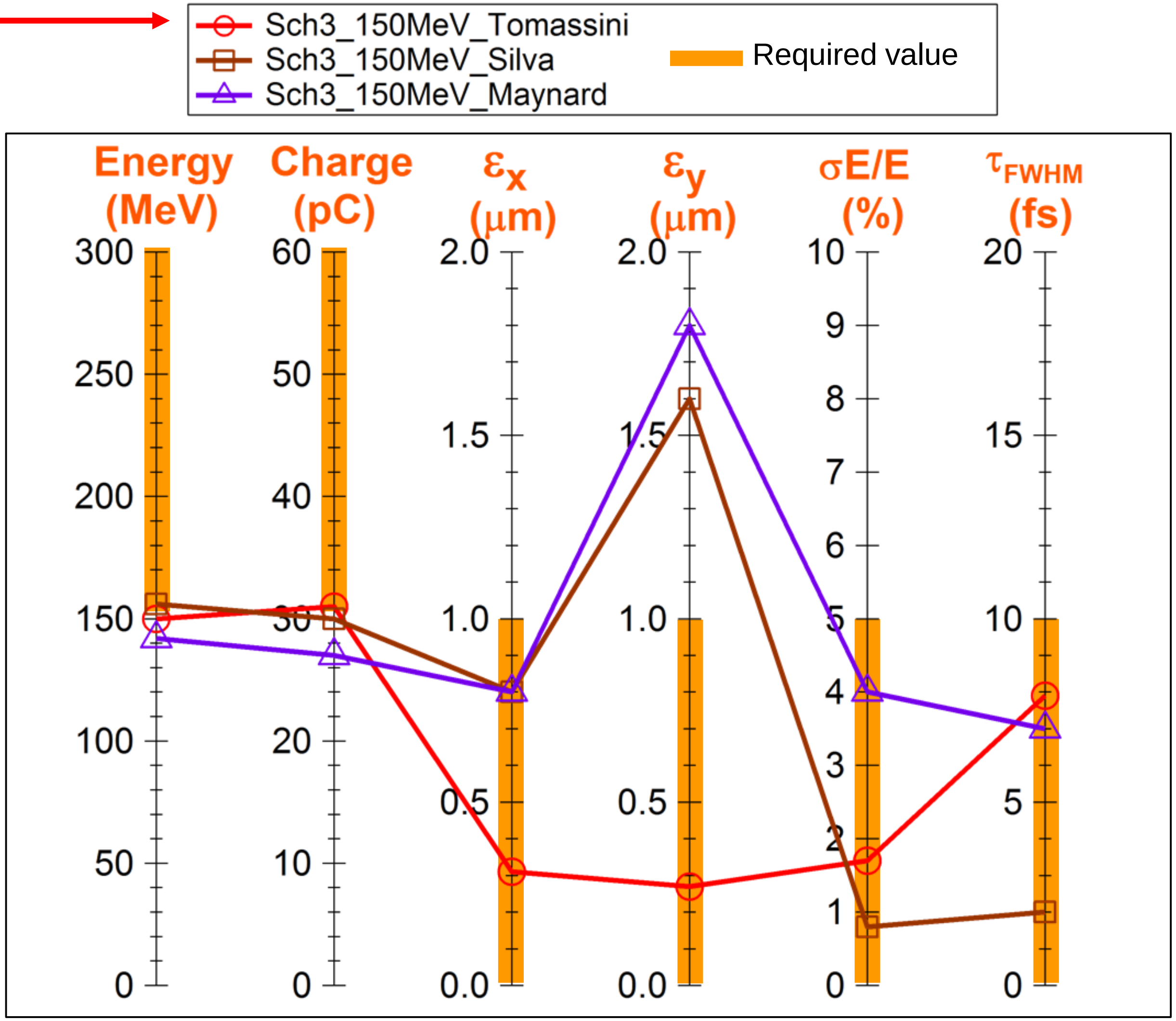
Beam parameters obtained at 1 GeV

Scheme Selected for Start-to-End simulations



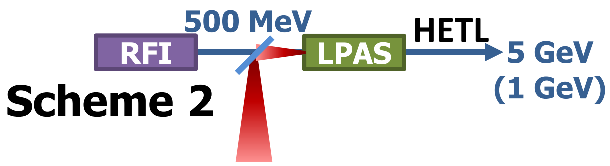
Beam parameters obtained at 150 MeV

Scheme selected for start-to-end simulations

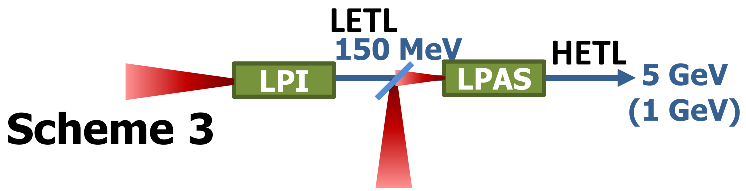


Schemes selected for S2E simulations

Scheme 2 : RFI + LPAS (quasilinear regime)



Scheme 3: LPI (REMPI) + LPAS (quasilinear regime)



Scheme 4: RFI + PPAS (bubble regime)

Note: This is only the present snapshot. Not definitive
Other schemes and other regimes remain to be very precious alternatives !!!
They may be found to be equally or even more appropriate later on

Plasma configurations used in simulations

Interactions with WP3

Brigitte Cros, T. Audet

- Plasma H, Ar, N^{5+}, N2 impurity, …
- Longitudinal: uniform plateau with ramps at entrance and exit
  Radial: parabolic
- Longitudinal: downramp for auto injection
- Gas jet, or capillary, or cell
- Length and density:
  LPAS 5 GeV: 17-28 cm, 0.1-2.5 10^{17} cm^{-3}
  LPAS 1 GeV: 3-7 cm, 1-5 cm^{-3}
  LPI 150 MeV: 0.6-4 mm, 7-80 10^{17} cm^{-3}

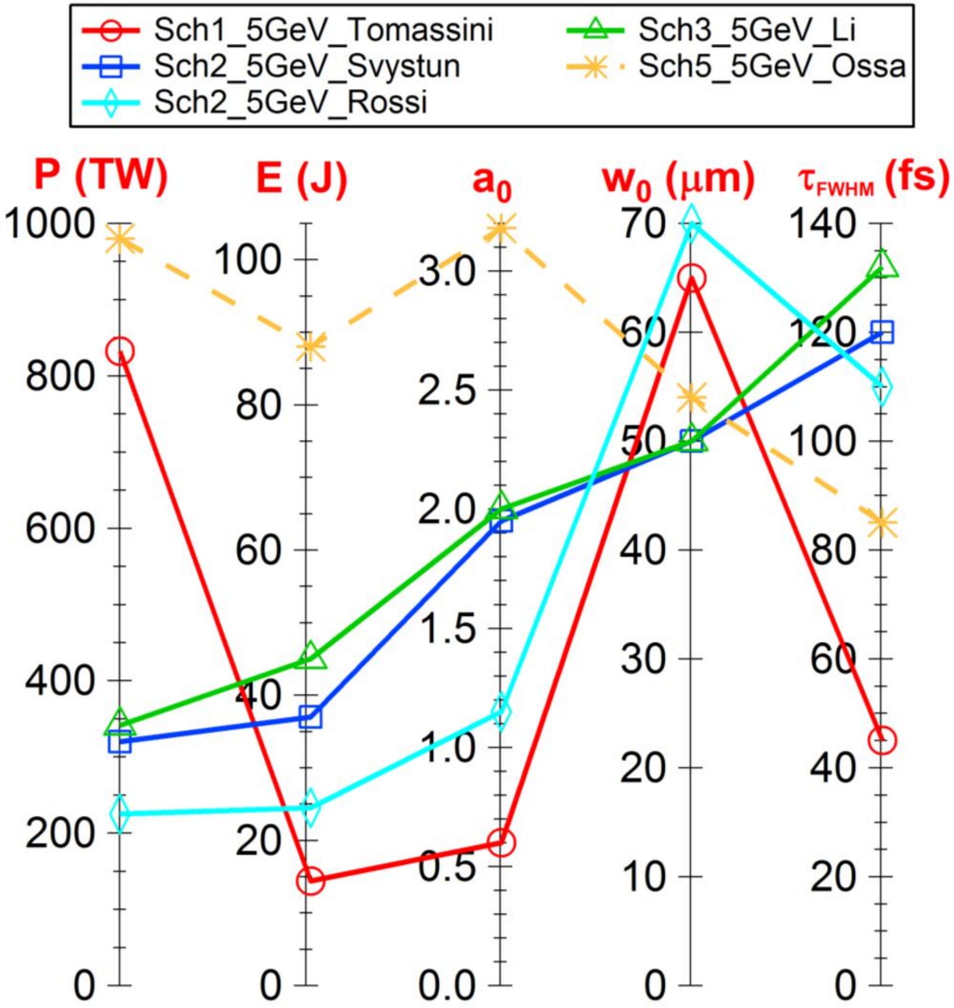
A first estimate is given:
- Realism level
- How to achieve
- Potential imperfections
- Suggestion of alternative

Scheme ID	Realistic?	How to achieve	Imperfections	Alternative
Scheme1B P. Tomassini	No (revised)	? more details on requirements are necessary	Described gradient at entrance too sharp	are smoother gradient and transitions acceptable for the scheme?
Scheme 2B E Svystun et al	Yes	Capillary, ramps given by fluid simuls	Low density challenging for parabolic profile, reproducibility to be tested	Gas cell also an option for parabolic profile (OFI plasma) and length smaller than 20 cm
Scheme 2B A Rossi	No	? details on requirements are necessary	Uniformity over 50cm to be determined for a discharge	Promising option: laser created plasma
Scheme 3B T Silva et al	No	Upramp gradient too sharp; Shock for downramp gradient	Gradient fluctuations	Shock injection with a smooth gradient at entrance
Scheme 3B A Beck	No	? beyond state-of-the-art gas jet	Gradients are linear and too sharp	Gas jets with longer, exponential ramps
Scheme 3B G Maynard	yes	Gas cell	Density controlled better than 10%	Double gas jet
Scheme 3B P Tomassini A	Yes	Gas jet far from the nozzle, smooth gradients	Pure nitrogen may induce non uniform distribution: ionization level?	Gas cell, required profile needs to be specified
Scheme 3B P Tomassini B	No (revised)	Separation of areas with "pure" gas difficult inside gas jets	Ramps need to be determined	Two-stage gas cell
Scheme 3B X Li	Yes	Low density channel may be achieved with OFI in gas capillary	Plasma uniformity needs to be specified Delta n is of the order of fluctuations, 10%	Promising option: laser created plasma
Scheme 4B A Marocchino	? yes if uniform plasma	Depends on transverse profile, uniform ok in capillary tube with OFI	Plasma uniformity needs to be specified	-

Laser parameters used in beam simulations

for 5 GeV

Interactions with WP4



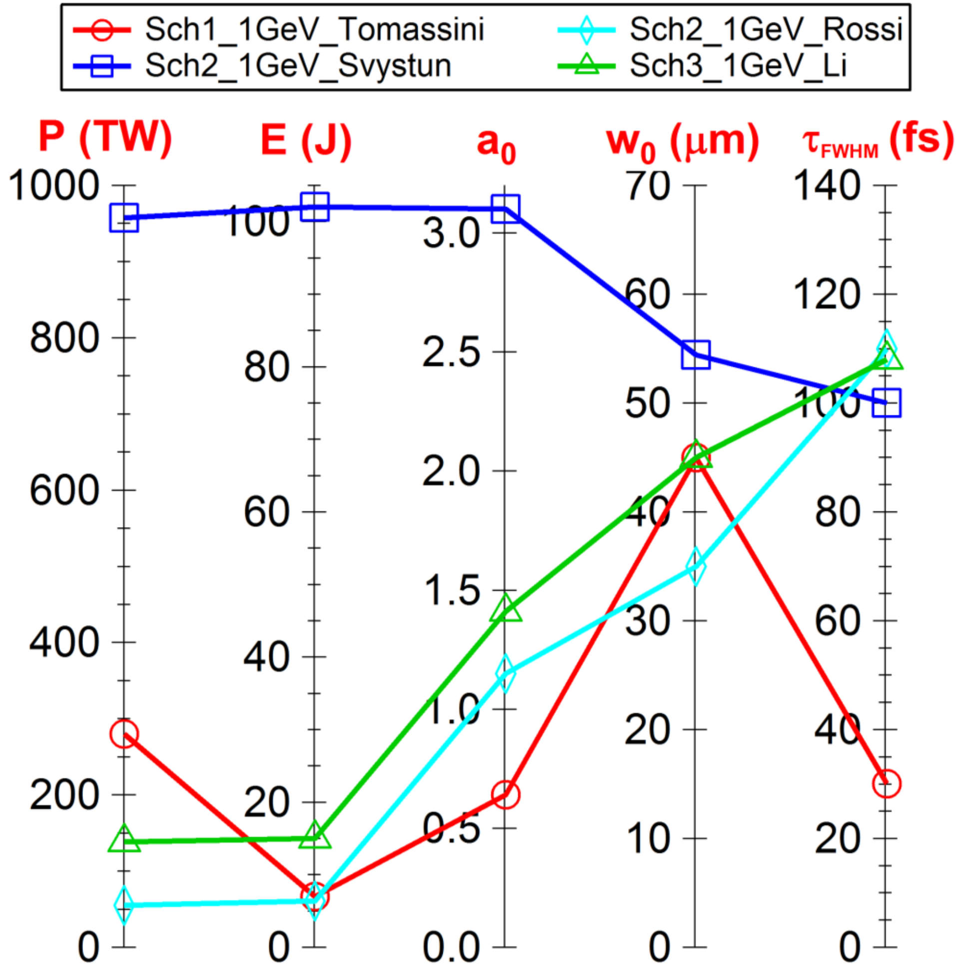
Bi-Gaussian pulse
λ = 800 nm

➡ Required laser parameters: P = 400 TW, E = 60 J, w_0 = 45 μm (a_0 = 2.42, τ_{FWHM} = 141 fs)

Laser parameters used in beam simulations

for 1 GeV

Interactions with WP4



Bi-Gaussian pulse

λ = 800 nm

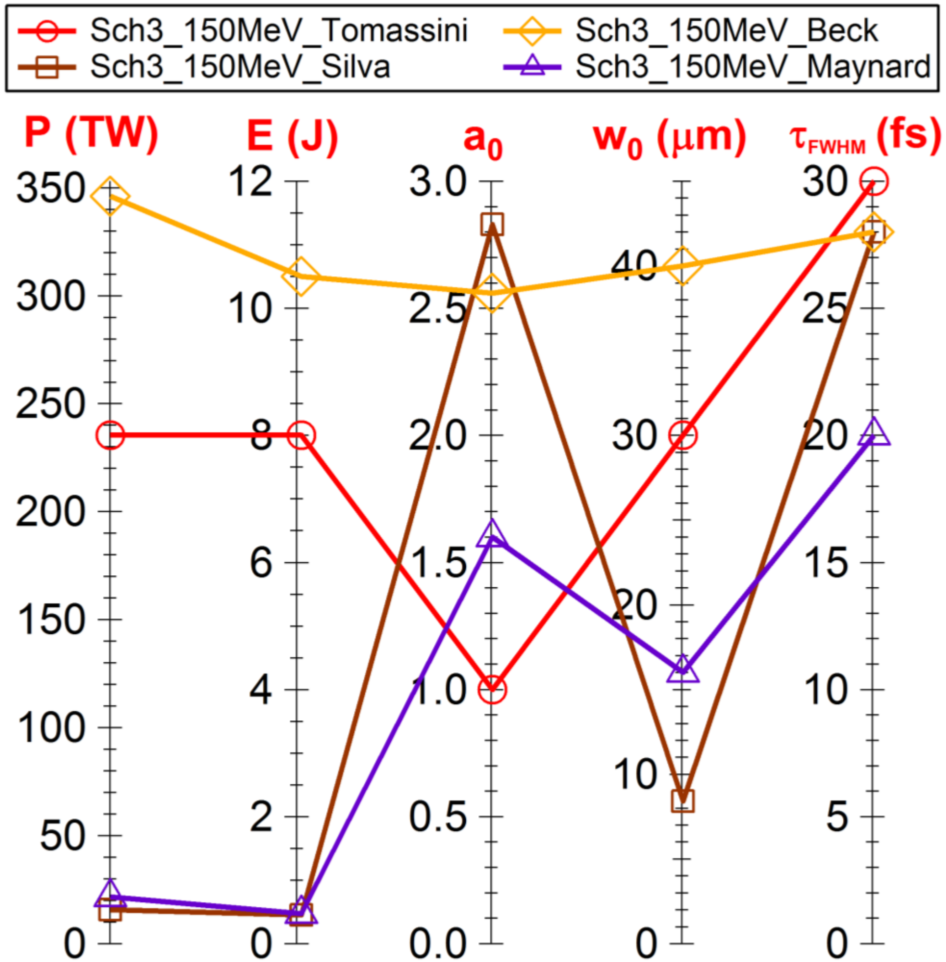
(cosine squared in longitudinal for Sch2_1 GeV_Rossi)

Required laser parameters: P = 200 TW, E = 30 J, w_0 = 30 μm (a_0 = 2.57, τ_{FWHM} = 141 fs)

Laser parameters used in beam simulations

Interactions with WP4

for 150 MeV



Bi-Gaussian pulse
λ = 800 nm

➡ Required laser parameters: P = 250 TW, E = 10 J, w_0 = 30 μm (a_0 = 2.87, τ_{FWHM} = 38 fs)

Start-to-End simulations

Issue: preserving emittance
when extracting the beam from the plasma and transporting it
- Parameters governing emittance growth not clear
- No solution for avoiding emittance growth in case of high charge beam

Thorough study shows that ALL the parameters governing emittance growth are:

$$\varepsilon_{ph,n}^2 - \varepsilon_{ph0,n}^2 = \varepsilon_{tr0,n}^2 \left(\frac{\sigma_p}{p_0}\right)^2 \gamma_0 l(\gamma_0 l - 2\alpha_0)$$ through a drift of length l

$$\varepsilon_{tr,n}^2 - \varepsilon_{tr0,n}^2 = \varepsilon_{tr0,n}^2 \beta_0^2 k^2 \left(\frac{\sigma_p}{p_0}\right)^2$$ through a thin lens of strength k

Recommended strategy:

1. Minimize emittance ε and energy spread $\frac{\sigma_p}{p_0}$ in the acceleration part

2. Minimize the Twiss parameter γ_0 in the plasma ramp

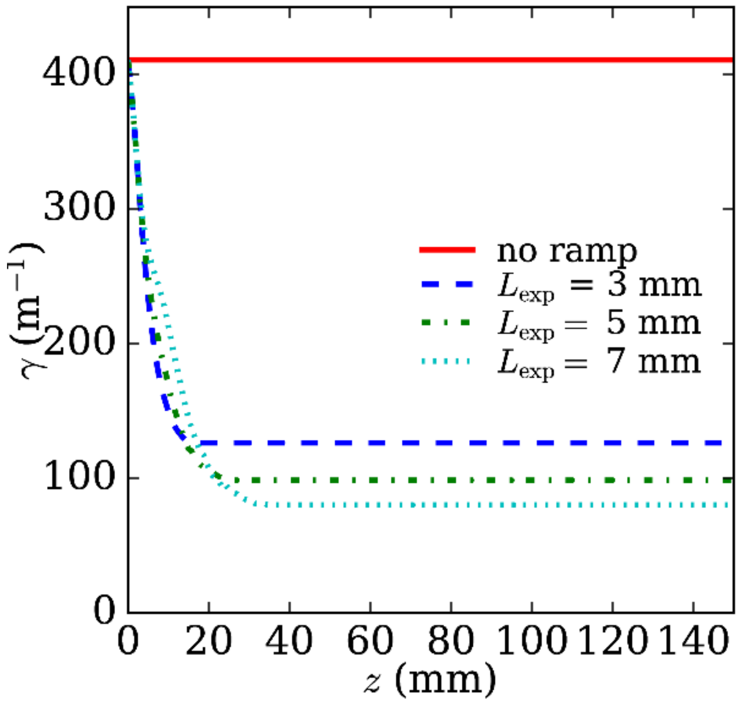
3. Minimize the integrated focusing strength k in the transfer line

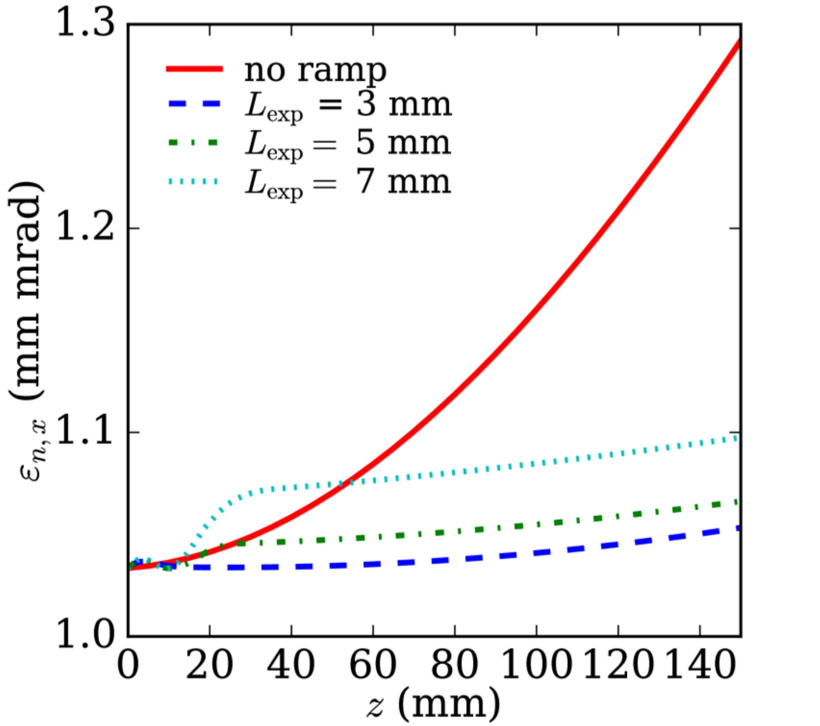
Start-to-End simulations

1 **Up- and Downramp** with Linear or Exponential density profiles have been checked

Optimized length → Minimum emittance growth

Efficient and easy to implement



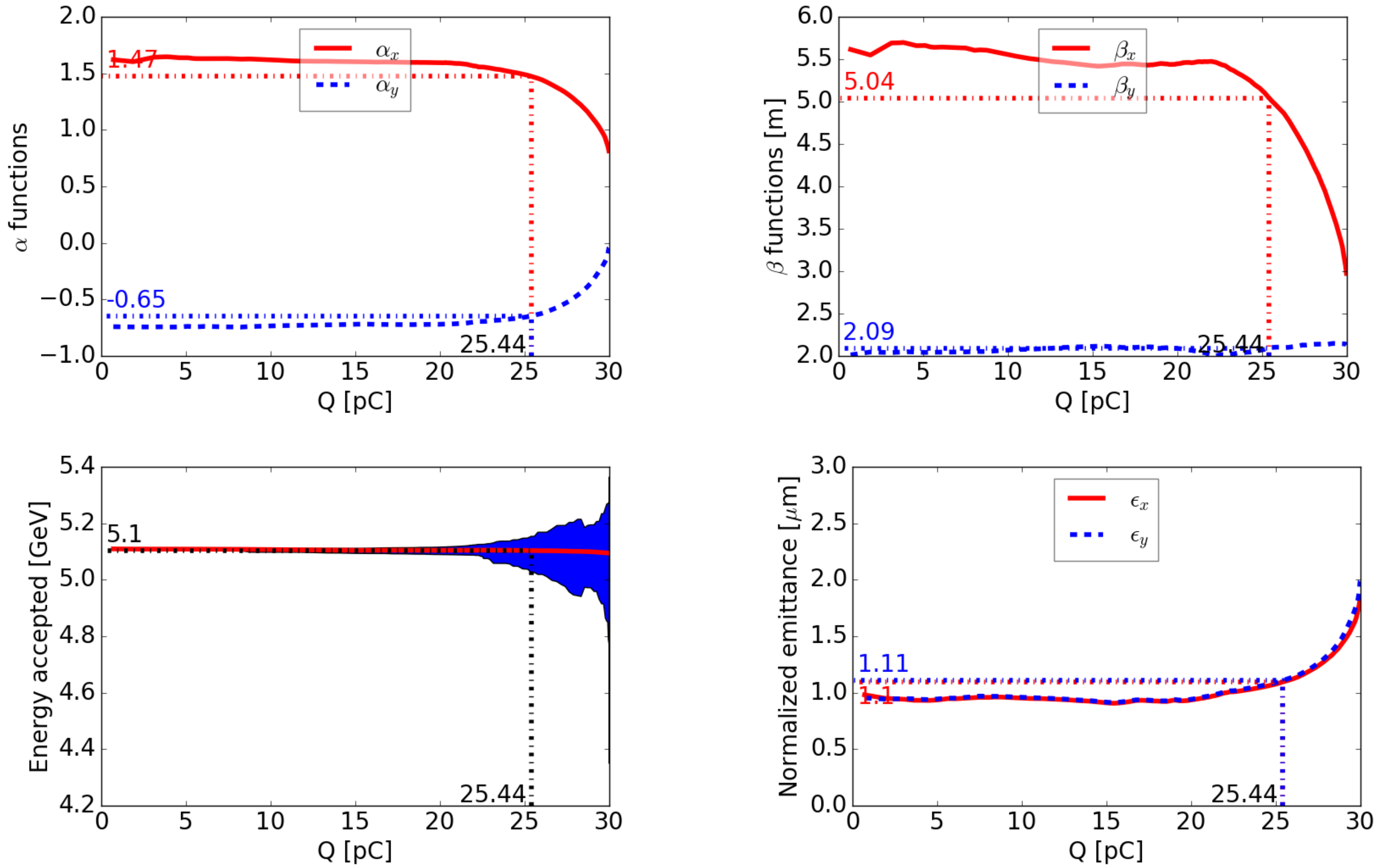


2 **Transfer line**: number of quadrupoles = number of constraints

6 quadrupoles → emittance growth of only 10% at FEL entrance

Start-to-End simulations

At the entrance of user's applications,
when keeping only the "core" part where rms values are in the "plateau"

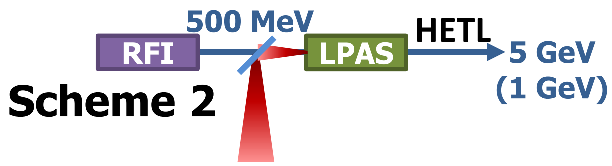


Start-to-End simulations

At the entrance of user's applications,
when keeping only the "core" part where rms values are in the "plateau"

Scheme 2 : RFI + LPAS (quasilinear regime)

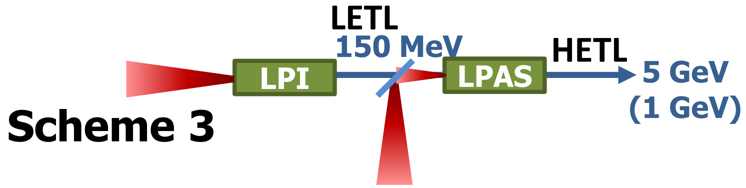
$$Q = 24\ \text{pC},\ \varepsilon_{tr,n} = 0.32\ \text{mm mrad}$$



Scheme 3: LPI (REMPI) + LPAS (quasilinear regime)

$$Q = 25\ \text{pC},\ \varepsilon_{tr,n} = 1.1\ \text{mm mrad}$$

(actual beam distribution from LPI to LPA remaining to be done)



Scheme 4: RFI + PPAS (bubble regime)

$$Q = 28\ \text{pC},\ \varepsilon_{tr,n} = 1.8\ \text{mm mrad}$$

(γ_0 can be furthermore decrased)

every other beam parameters remaining unchanged by the transfer lines

Further progress are still possible…

Next step: Error and Tolerance studies

Deliverable Report in Spring 2019: "Final tolerance analysis"

Issue: very time consuming simulations

→ Strategy of error studies to be defined

→ Sharing of works to be coordinated

→ Prerequisite: Top Level Tolerances to be defined

} At this meeting!

For the moment:
- Pre-discussions on these subjects have been launched
- A preliminary list of Errors/Requirements is circulating for collecting comments

Preliminary list of Errors/Requirements

Tolerance on Requirements

Energy Charge	Emittance Twiss α, β Slice emittance	Energy spread Slice energy spread Bunch length	Alignment, position Alignment, angle

Errors on Plasma

- Plasma density
- Plateau long. profile
- Plateau trans. profile
- Ramp long. profile
- Input beam energy
- Input beam position
- Input beam angle
- Input beam emittance
- Input beam Twiss α, β
- ...

Errors on Laser

- Power
- Energy
- w0
- Transv. profile
- Longit. profile
- Focal plane position
- Alignment, angle
- Time shift
- ...

Errors on Transfer Line

- Quadrupole position
- Quadrupole strength
- Input beam energy
- Input beam position
- Input beam angle
- Input beam emittance
- Input beam Twiss α, β
- ...

Conclusions

Tremendous simulations and optimizations have been performed by many contributors

→ Many results obtained on different injection/acceleration schemes and techniques

→ First down selection performed for S2E simulations

→ Issues of S2E simulations studied and solved

→ Beam parameters at user's door very close to requirements
Other schemes or techniques remain very promising
Further progress still possible
Robust results (see also presentation tomorrow afternoon)

Next step: Errors and Tolerances studies