EuPRAXIA@SPARC_LAB
Start to end Simulations

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on behalf of WA1- Beam Physics & collaboration team

OUTLINE

- Recommendations from TDR-RC report Nov 2023
- TDR Chapter 6:
  - Document and technical readiness
- S2E simulations status
- S2E simulations details on:
  - Plasma Acceleration based on Velocity Bunching
  - Plasma Acceleration based on Magnetic Compression and Mask selection
- Conclusions and To-do list

Review Committee Recommendations

- -we would like to hear about the current baseline, in particular about the minimum to make the project successful already on day one (without all bells and whistles)

  -it would be good to hear about a status of each of the WPs of the TDR, in particular about where they are today and how far they are from "completion'

  -we would like to hear about the current schedule and understand reasons for differences between the previous and the current one.

  In summary, we would like to hear about the differences between the state of the TDR now and its (baseline) completion.

1.4 Beam Dynamics

The assumption for the simulations of RF jitter parameters close to the state of the art (SwissFEL measurements), is giving encouraging results, but still too large for plasma acceleration, when using velocity bunching. In order to reduce the jitter between drive and witness bunch and improve the beam parameters (time separation, relative energy spread, ...), the team started studying a masking technique within the dispersive section of the compression chicane as alternative to a laser driven generation of the two bunche. The first simulation results are encouraging, indicating lower energy spread and jitter. The study has not yet produced a value for the emittance of the bunches. Using the masking technique rather than the velocity bunching one does not require changes to the machine layout, only the addition of the mask system. **The RC recommends pursuing the comparison between the two techniques as soon as computing resources will become available. The RC also recommends that optimization of the new scheme in S2E simulations be started as soon as possible. Since the masking technique requires absorption/scattering of electrons, an evaluation of the dose rate increase due to the utilization of a mask is required if pursuing this avenue. The RC notes that several the parameters of many beam line elements are not yet final: design of magnets, apertures, final optics, laser heater, . . .** Beam dynamics is so central to the project that the RC recommends that it be reviewed and frozen (what needs to be) very soon.

TDR – Chapter 6

- **Writing readiness: 10%**
- **Technical Readiness: 70 %**

- The **Writing readiness** stands at **10%** since the activity of the group has been more recently devoted to the study of the Witness-Driver separation and transport after the plasma module, aiming to finalize the separation and transport lattice now based on a system of collimator/scrapers as much as possible realistic. This required a long iterative simulation work now 90% completed.Moreover, a more realistic/constructive definition of the machine layout in terms of magnets, diagnostic systems and vacuum components has started in the past few months, implying again an iterative check of the Beam Dynamics performance of the machine at each significant step forward of the elements definition.
- The **Technical readiness** at **70%** means that:

1. The start to end simulation of the Plasma Acceleration working point based on the velocity bunching scheme is now at the level of jitter evaluation with the realistic driver-witness separation and with jitters considered up to undulator exit.
2. The start to end simulation for the Plasma Acceleration working point based on the magnetic compression and mask selection of the comb beam is now at the level of the Geant evaluation of the mask insertion on the beam quality. Taken for granted all the rest of the lattice optimized for the VB option downstream the magnetic chicane up to the undulator exit.
3. The start to end simulation of the all-RF accelerated 250 pC single bunch is periodically checked and updated with the overall layout changes and has to be finalized with last layout version.

S2E Simulations Status

Plasma Acceleration

- **Velocity Bunching Scheme**
  90%
- **Magnetic Compression&Mask**
  60 %

RF Acceleration

- **Magnetic Compression**
  50 %

Machine and CAD layout merging

- **30%**

Microbunching Instability

- **5%**

- Reference working point:
  Plasma acceleration w comb
  $E = 1\ GeV,$
  $\lambda_r = 4nm,$
  $Q = 30\ pC$
- All RF working point
  Single bunch
  $E = 1\ GeV,$
  $\lambda_r = 4nm,$
  $Q = 250\ pC$

S2E Simulation in Details:

Velocity Bunching for Plasma (90%)

Reference point: Plasma Acceleration w COMB beam
1. Velocity Bunching scheme-Machine Parameters

Cathode Laser System			
	Witness	Driver	
Charge [Q]	30	200	pC
Time delay [Δt]	- 4.8	0	ps
Laser Spot size [σ_r]	175	300	µm
Laser Pulse length [σ_t]	0.30	0.30	ps

RF Gun		
RF Peak Voltage [V]	120	MV
RF Phase [ϕ]	-30	*Deg*
S-band Accelerating Sections		
RF Voltage (on average) [V]	20,19,20,35	MV
RF Phase [ϕ]	-92,-84,-25,-10	*deg*
X-band Accelerating Sections		
RF Voltage (on average) [V]	24	MV
RF Phase [ϕ]	-10	*deg*

Magnets			
S-band Photoinjector - Peak Field			
Type	B_{max} (T)	Length (m)	Energy (MeV)
Gun Solenoid	0.3	2 coils (SABINA like)	-
Acc. Structures solenoids	0.035, 0.075	*4triplets,3 triplets (SABINA like),0,0*	-
X-band Linac			
Type	g_{max} (T/m)	Length (m)	Energy (MeV)
Type A	10	0.010	100 - 350
Type B	13	0.015	330 - 550
Type C	16	0.020	550
PMQ in	280	0.005,0.009,0.005	550

Beam parameters from jitter studies (w/o X-band cavity) at the capillary entrance

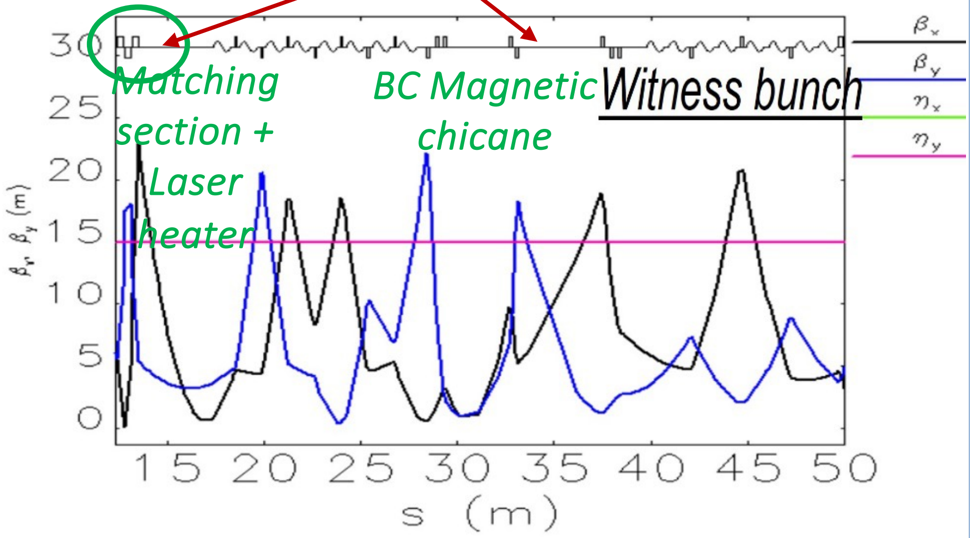
RF Gun (rms)		
RF Voltage [ΔV]	± 0.02	%
RF Phase [Δϕ]	± 0.02	*deg*
S-band Accelerating Sections (rms)		
RF Voltage [ΔV]	± 0.02	%
RF Phase [Δϕ]	± 0.02	*deg*
X-band Accelerating Sections (rms)		
RF Voltage [ΔV]	± 0.02	%
RF Phase [Δϕ]	± 0.10	*deg*
Cathode Laser System (max)		
Charge [ΔQ]	± 1	%
Laser time of arrival [Δ*t*]	± 0.02	fs
Laser Spot size [Δσ]	± 1	%

	Witness		Driver		
	Without errors	With errors	Without errors	With errors	
Charge	30.00	30.00 ± 0.33	200.00	200.00 ± 2.00	pC
Energy	537.18	537.19 ± 0.31	539.29	539.29 ± 0.30	MeV
Energy spread	0.712	0.711 ± 0.003	0.92	0.92 ± 0.001	‰
Bunch length	19.88	19.97 ± 0.32	205.87	205.55 ± 0.87	fs
I_{peak}	1873	1643 ± 99	-	-	kA
Δt	0.494	0.494 ± 0.044	-	-	fs
$\varepsilon_{n_{x,y}}$	0.562	0.562 ± 0.007	4.18	4.22 ± 0.15	mm mrad
$\sigma_{x,y}$	1.5	1.52 ± 0.18	5.85	5.89 ± 1.07	μm
$\beta_{x,y}$	4.3	4.5 ± 1.1	8.8	9.1 ± 3.3	mm
$\alpha_{x,y}$	1.2	1.2 ± 0.25	1.65	1.65 ± 0.30	

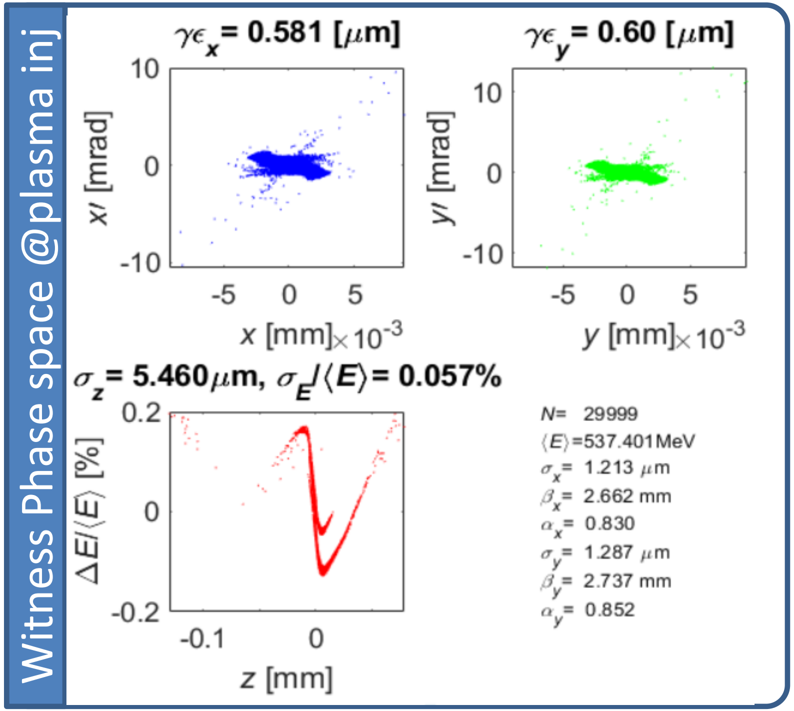
- Errors are intended as rms quantities
- Driver & Witness numerically separated on the longitudinal axes

Twiss parameters for Velocity Bunching scheme

Magnetic Chicanes OFF

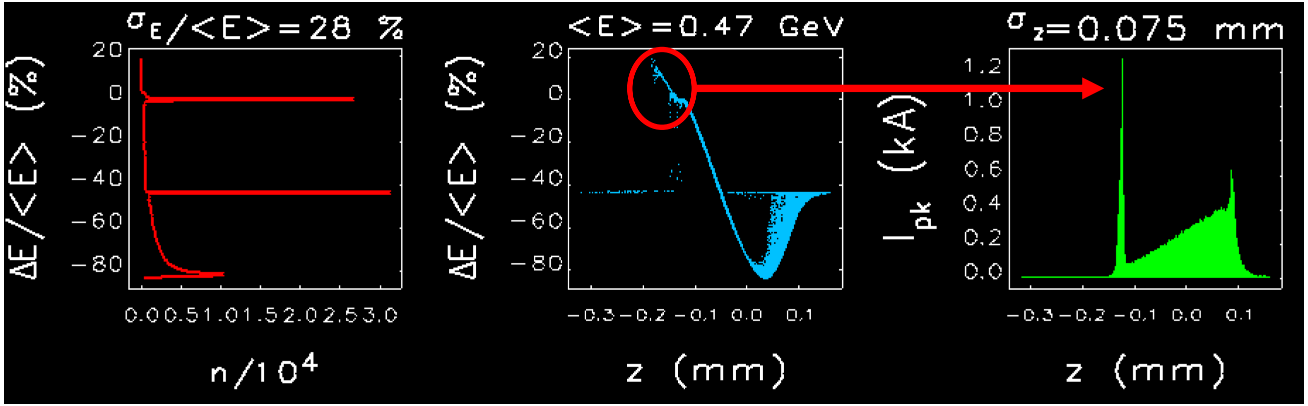


Twiss parameters along the linac for the witness bunch.

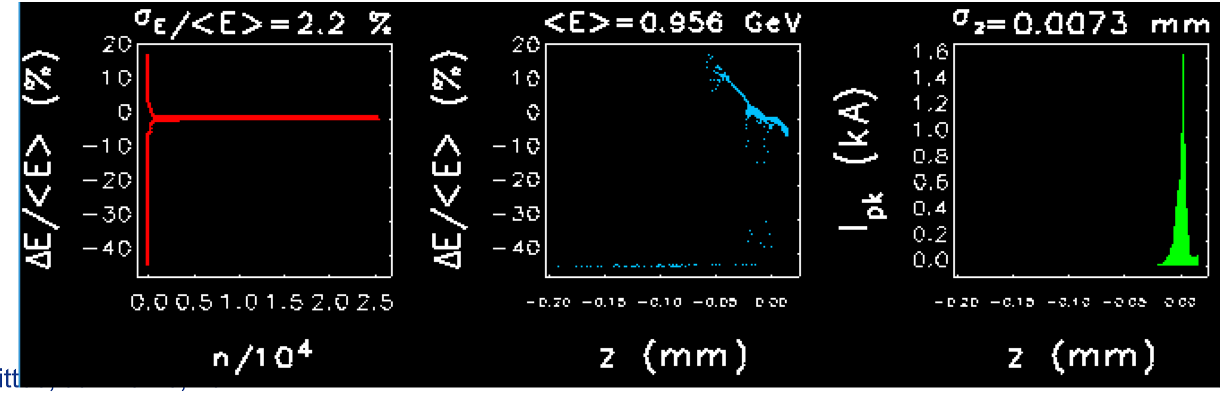


Longitudinal Distribution of the VB Comb beam at the Plasma exit for the reference beam

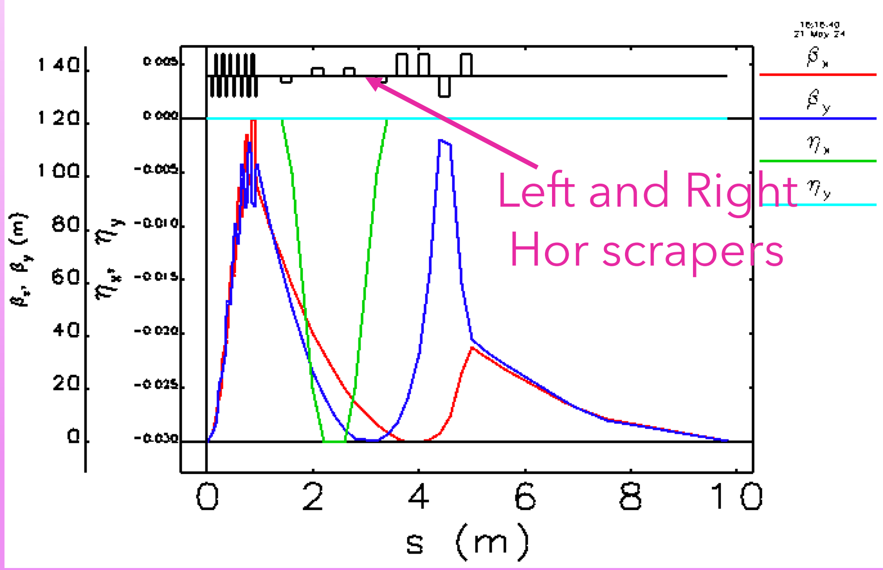
Whole beam

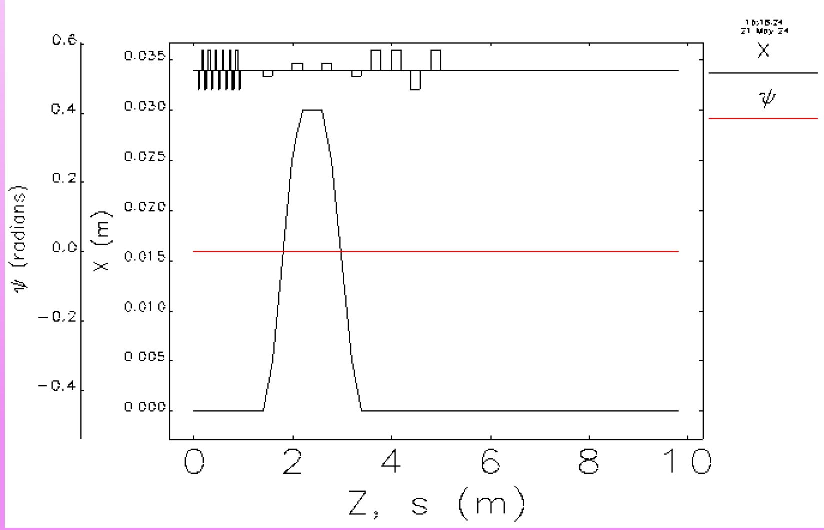


Matlab cut
Witness

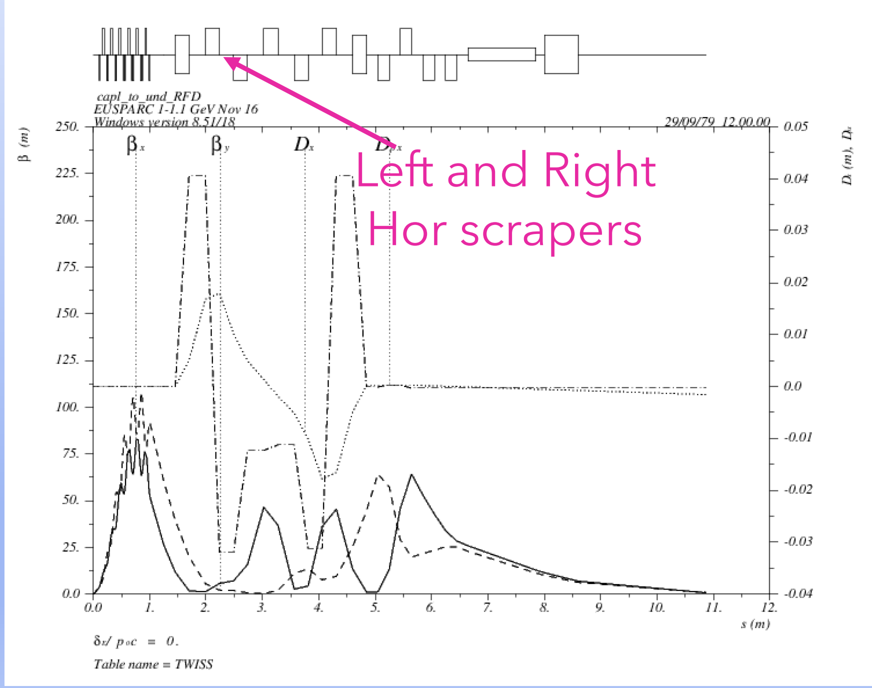


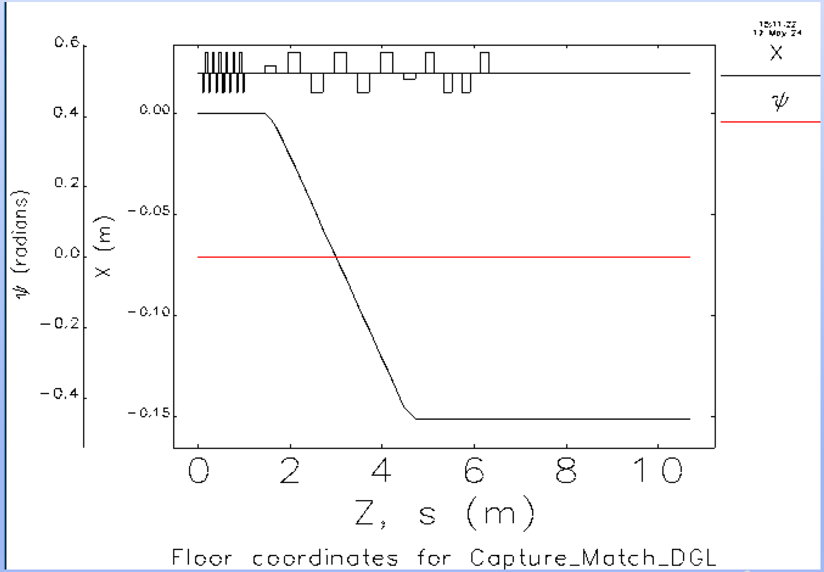
Capture and separation w Chicane (R_{56}=1.46E-03 mm-41 mrad)



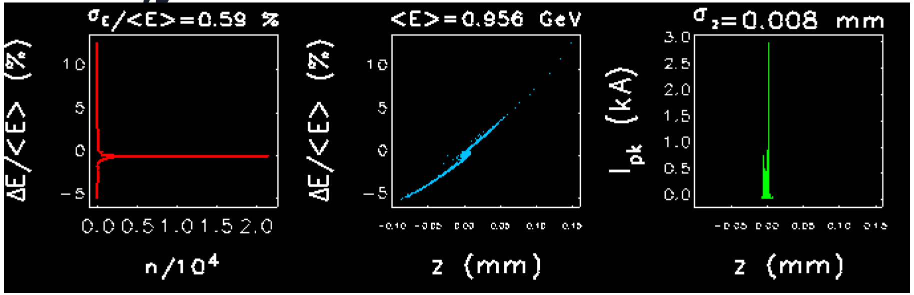


Capture and Separation w Nearly isochronous Dogleg (R_{56}=-2.7 E-05, 40.6 mrad)

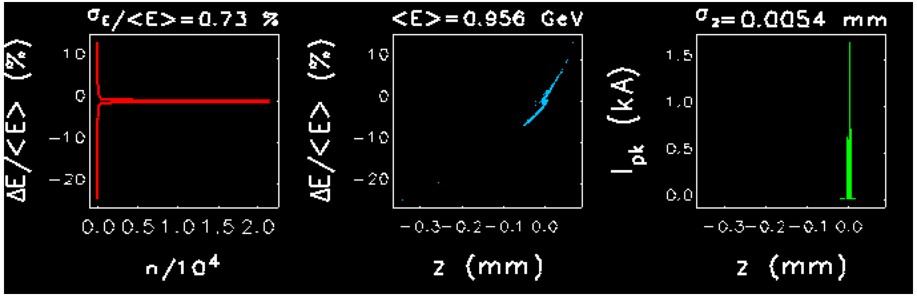




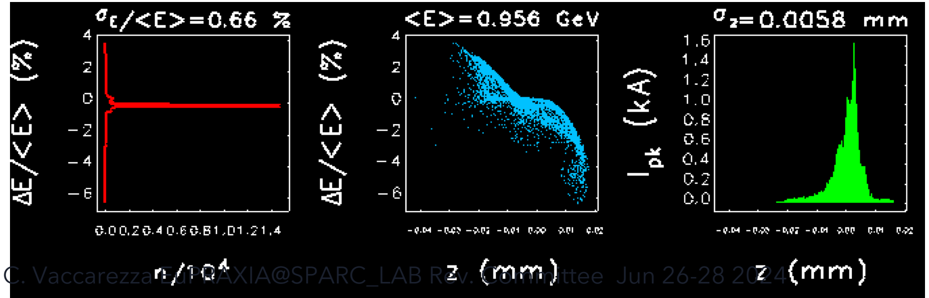
Longitudinal distribution (reference points):



Chicane Angle = 41 mrad



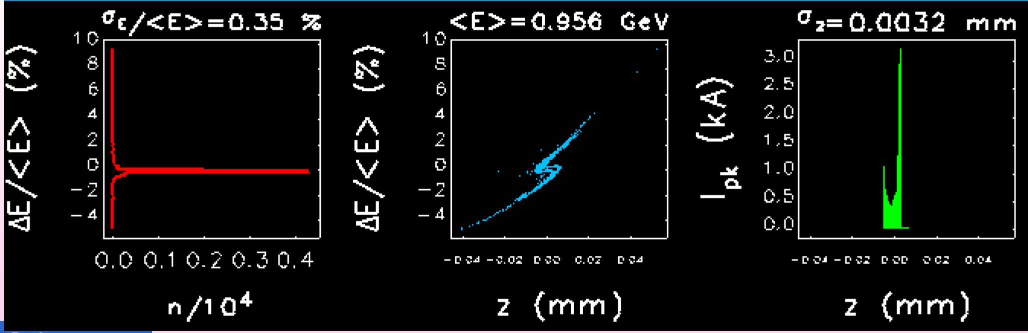
Chicane Angle = 31 mrad



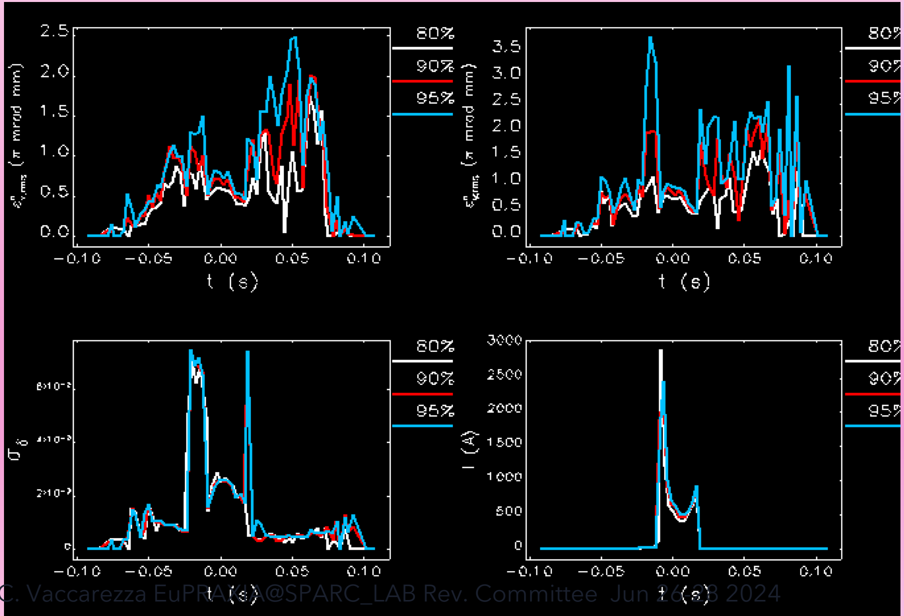
Dogleg DX =15 cm

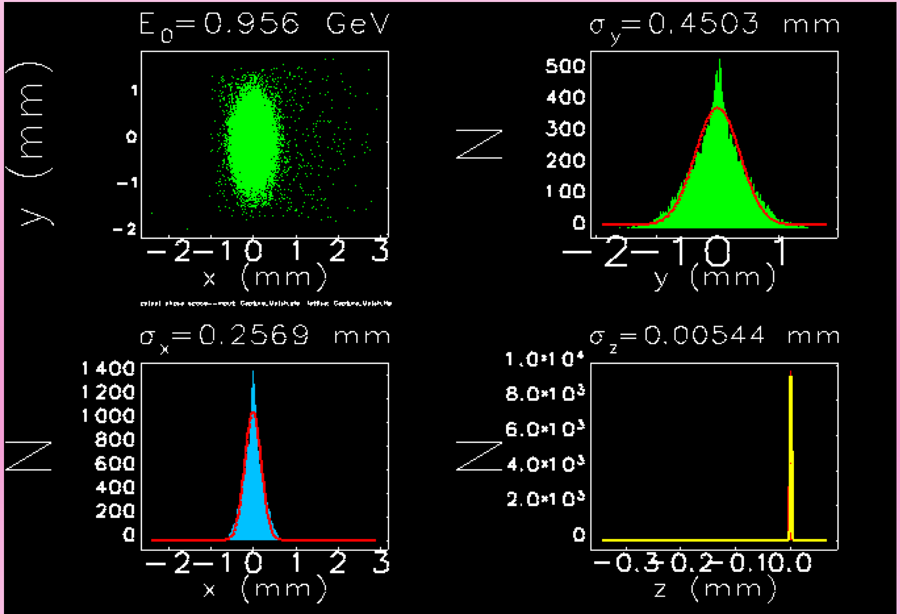
Slit= 800 μm centered

Witness at Chicane exit (41mrad):

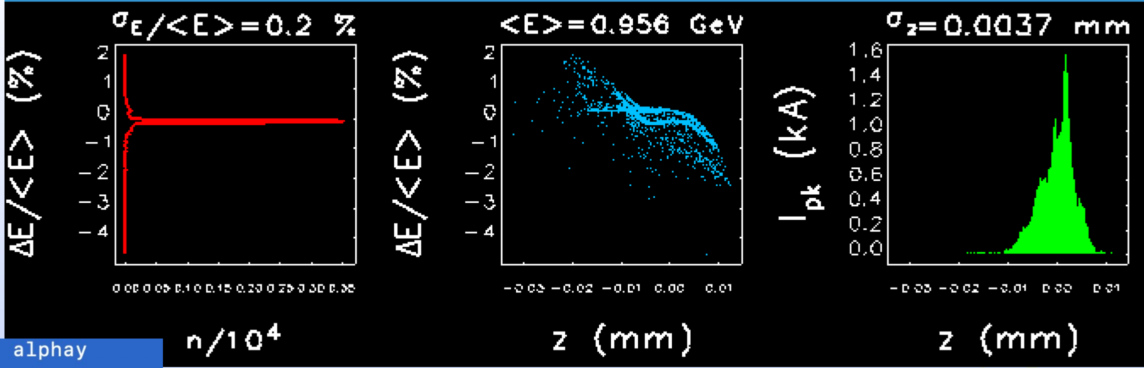


Particles	Sx m	Sy m	alphax	alphay
24367	1.663635e-04	4.357647e-04	-7.216009e+00	-5.646485e+01

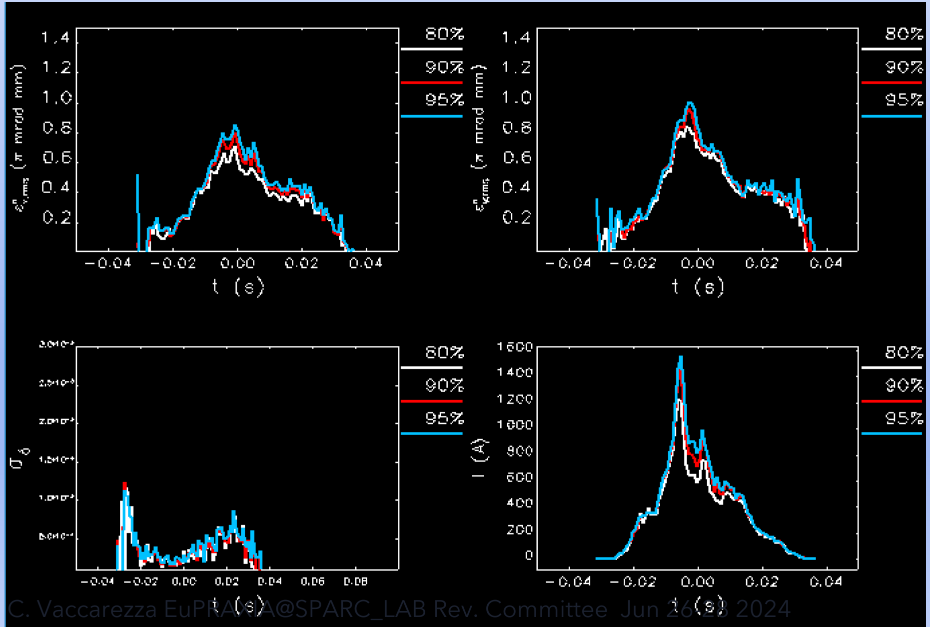


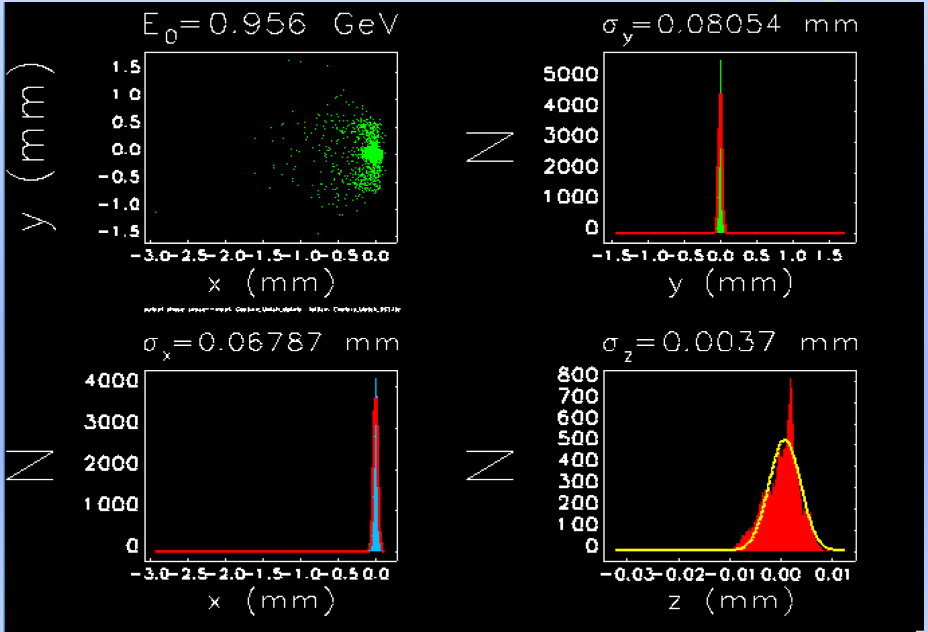


Witness at Dogleg exit:

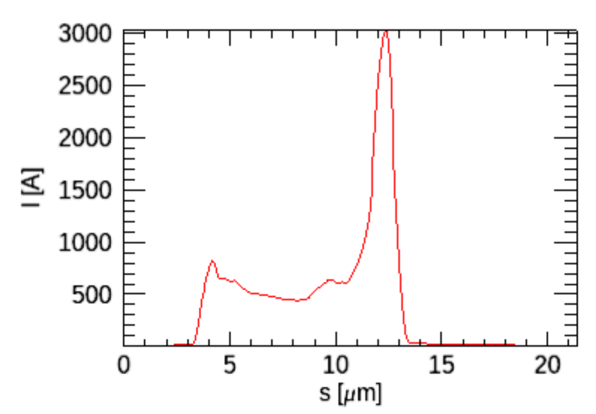


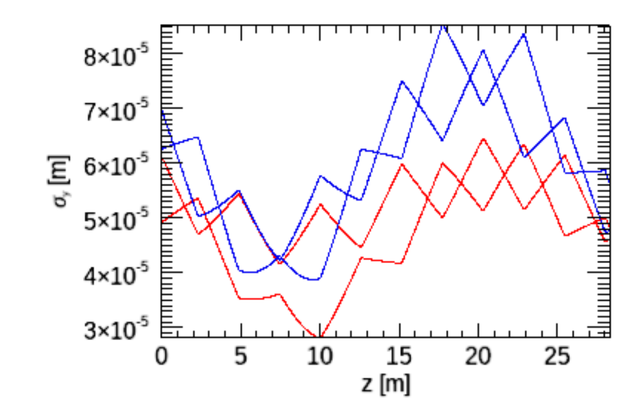
Particles	Sx m	Sy m	alphax	alphay
28537	6.786640e-05	8.053483e-05	-2.894766e-01	2.634596e-01

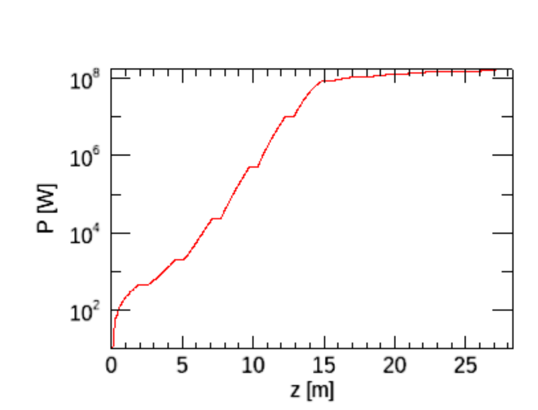


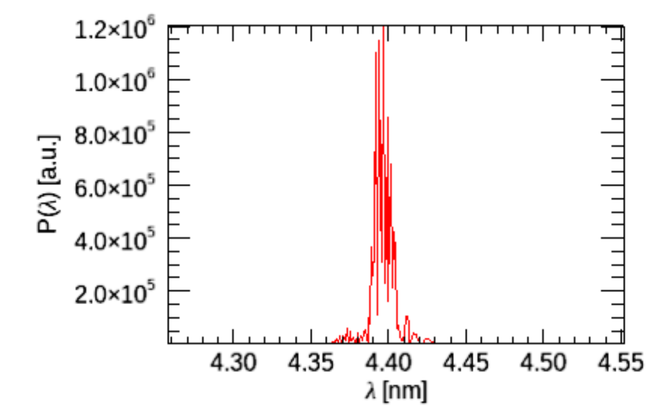


Chicane: Beam after applying a rotation/focusing matrix (evaluated on the projected values)





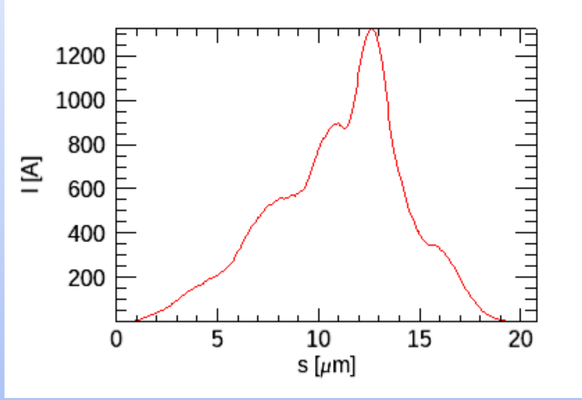


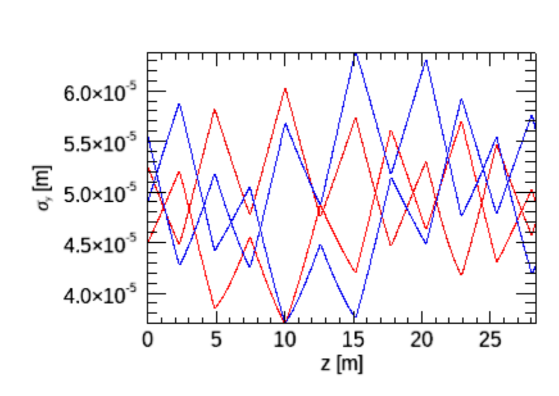


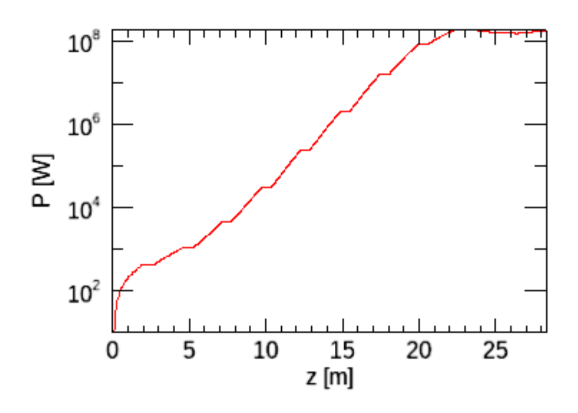
Dogleg: Applying to the whole beam a rotation/focusing matrix (evaluated on the projected values)

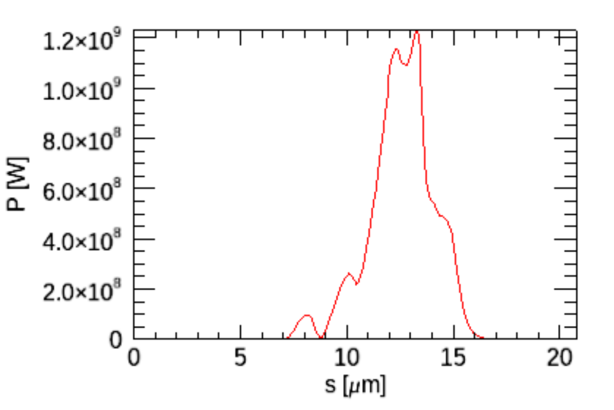
Red: average

Blue: on the current peak









Summary table for Velocity Bunching Reference Point at the undulator exit

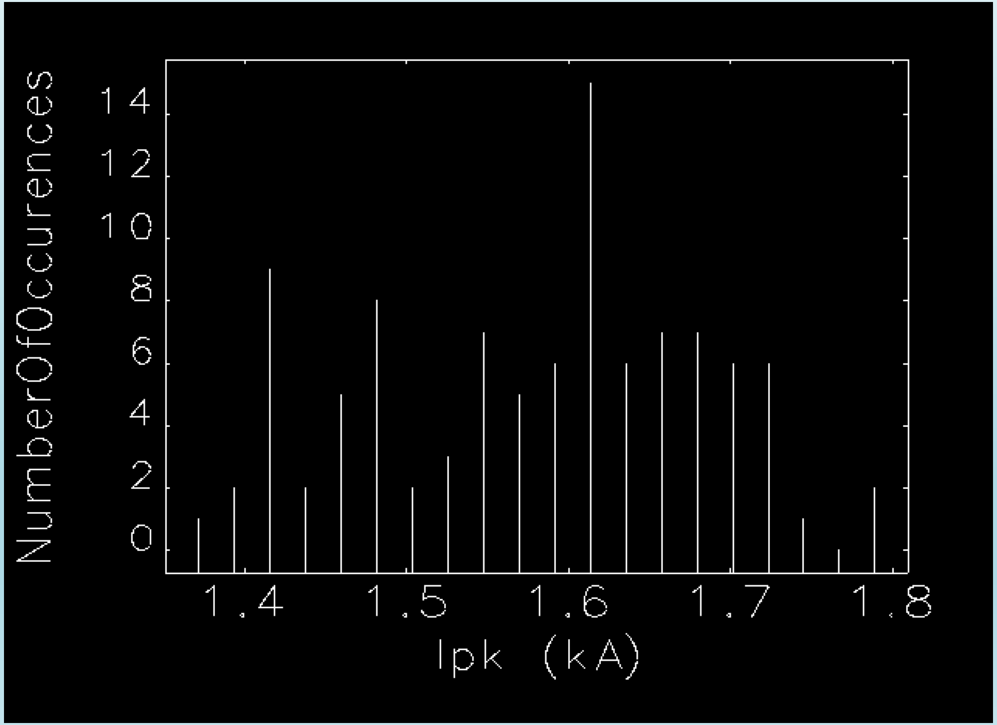
		chicane
Charge before cut	pC	28.3
Charge after cut (a.c.)	pC	26.5
Peak current (a.c.)	kA	3.19
Emittance projected a.c. (x,y)	mm mrad	0.63, 0.73
Emittance slice a.c. (x,y)	mm mrad	0.66, 0.856
Energy spread a.c (relative)		1.7x10^-3
Energy spread slice a.c.		2.88x10^-4
Rho	X10^-3	1.6
Rho_3d	X 10^-3	1.5
Energy emitted (25 m)	microJ	13.2
Photon emitted (25 m)	X 10^11	2.5
Saturation length	m	20
Wavelength	nm	4.4
Bandwidth (25 m)	%	0.2
Size	micron	120
Divergence	microrad	19

		dogleg
Charge before cut	pC	28.5
Charge after cut (a.c.)	pC	27.2
Peak current (a.c.)	kA	1.5
Emittance projected a.c. (x,y)	mm mrad	0.62, 0.72
Emittance slice a.c. (x,y)	mm mrad	0.71, 0.92
Energy spread a.c (relative)		1x10^-3
Energy spread slice a.c.		2 x10^-4
Rho	X10^-3	1.3
Rho_3d	X 10^-3	1.1
Energy emitted (25 m)	microJ	**13.3**
Photon emitted (25 m)	X 10^11	**2.65**
Saturation length	m	**23**
Wavelength	nm	4.4
Bandwidth (25 m)	%	0.12
Size	micron	100
Divergence	microrad	18

Jitter Analysis for Velocity Bunching reference point

VB Comb beam:

Ipeak Current Distribution w all Jitters at the plasma exit

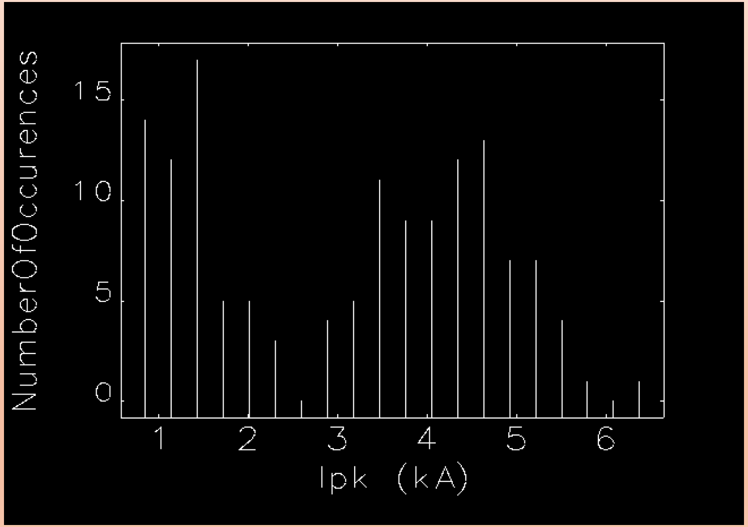


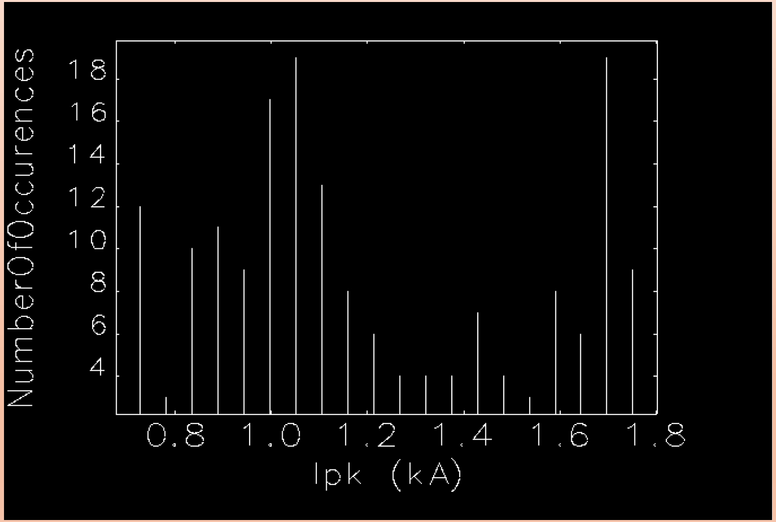
Jitter analysis out of Chicane/Dogleg-800μm slit:

Peak Current:

Chicane: $\theta = 41.0\ mrad$

Dogleg: $\theta = 40.6\ mrad, \Delta x = 15cm$

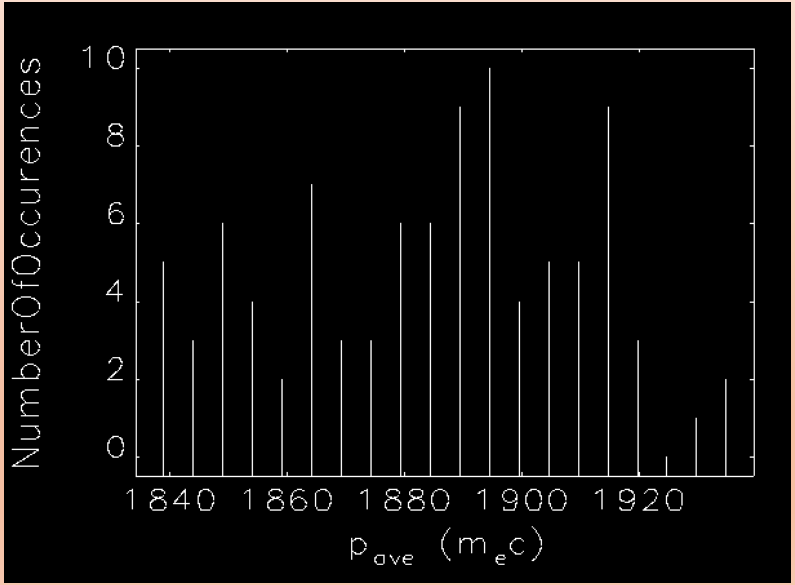




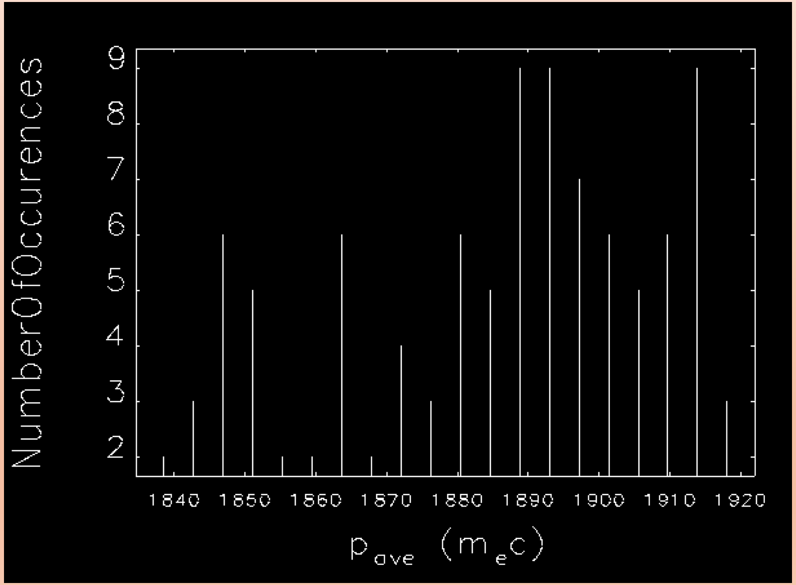
Jitter analysis out of Chicane/Dogleg-800μm slit:

Energy:

Chicane: $\theta = 41.0\ mrad$

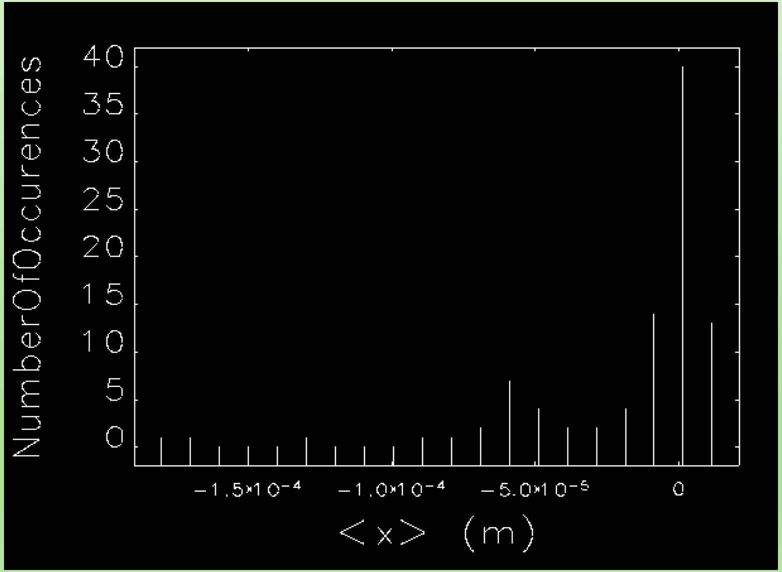


Dogleg: $\theta = 40.6\ mrad, \Delta x = 15cm$

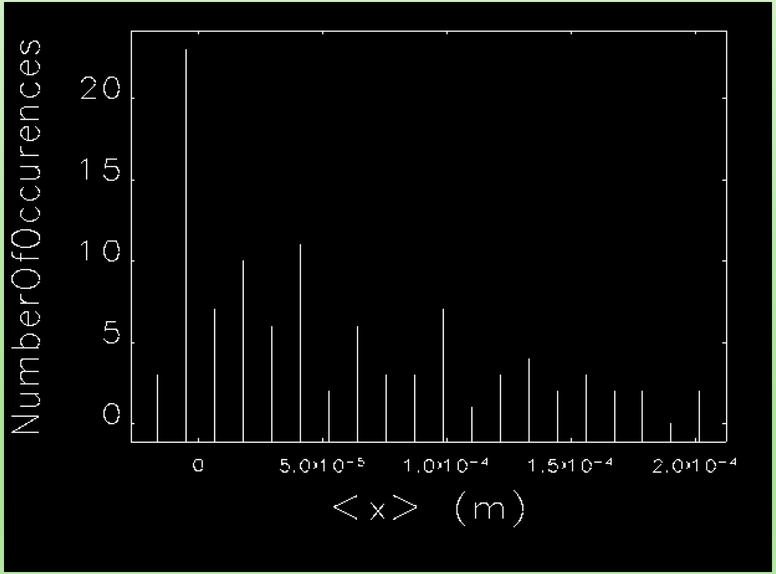


Jitter analysis out of Chicane/Dogleg:
Pointing Stability HOR:

Chicane: $\theta = 41.0\ mrad$

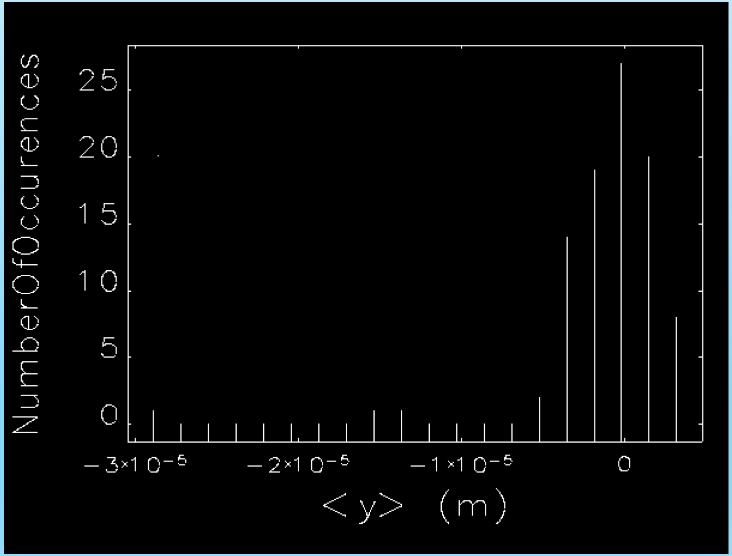


Dogleg: $\theta = 40.6\ mrad, \Delta x = 15cm$

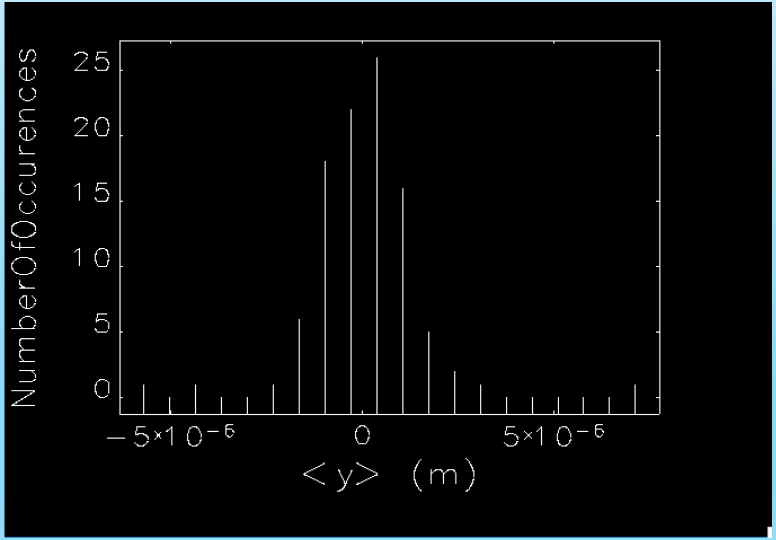


Jitter analysis out of Chicane/Dogleg:
Pointing Stability VER:

Chicane: $\theta = 41.0\,mrad$



Dogleg: $\theta = 40.6\,mrad, \Delta x = 15cm$



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Summary Table of Jitter Analysis for Velocity Bunching reference point

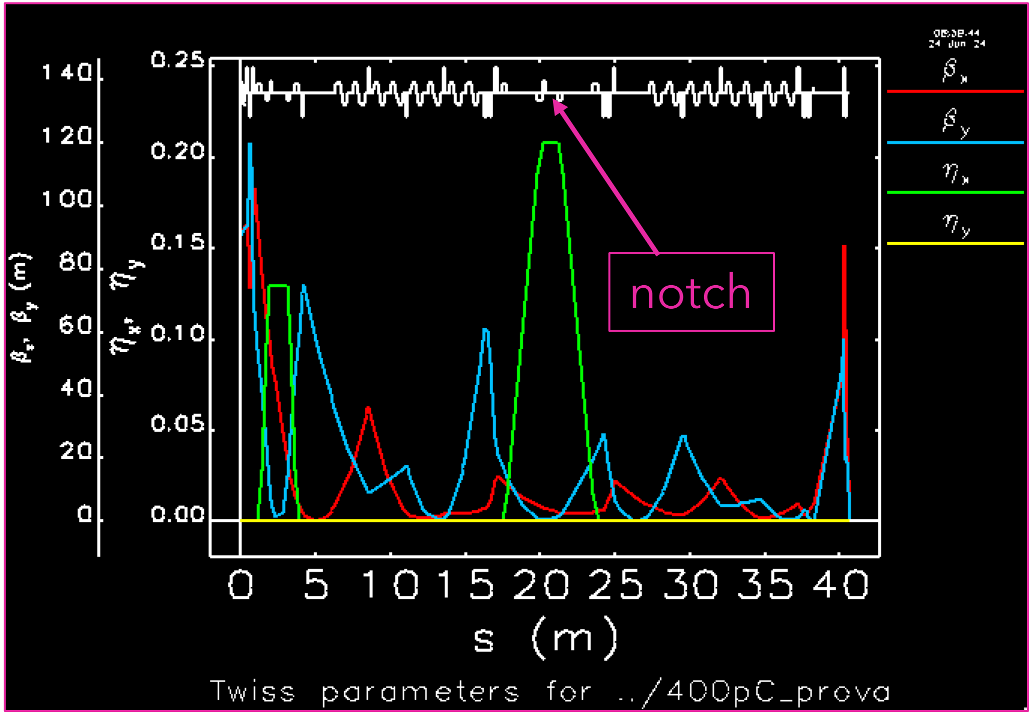
	Out of Plasma	Out of Separation Chicane	Out of Separation Dogleg
Cx (m)	-1.2e-08	-1.62 e-05	5.23e-05
Cx std (m)	4.2e-08	3.7e-05	5.87e-05
Cy (m)	3.2e-07	-1.11e-06	2.62e-08
Cy std (m)	7.20e-08	4.2e-06	1.4e-06
Charge (C)	2.30e-10	2.92e-11	3.24e-11
Charge std (C)	3.6e-25	4.2e-12	4.5e-12
Ipk (kA)	1.6	3.6	1.2
Ipk std (kA)	1.3e-01	1.7	3.2e-01
pAverage (BetaGamma)	9.11e+02*	1.88e+03	1.88e+03
pAverage std (BetaGamma)	5.5e+00*	2.5±e+01	2.3e+01

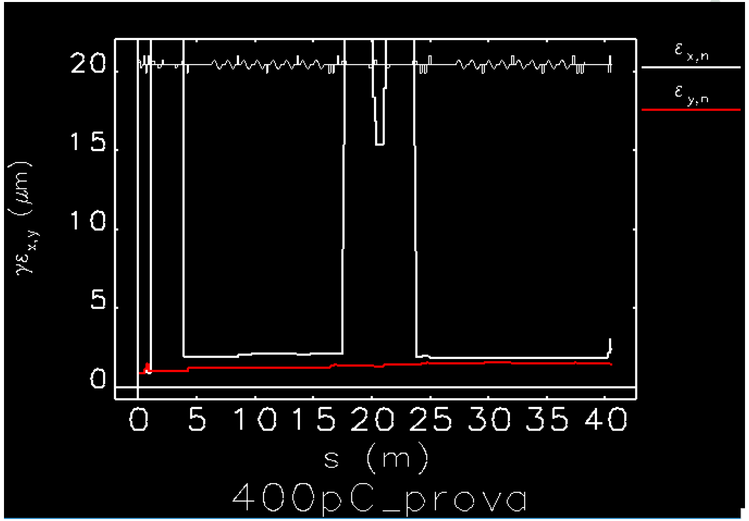
S2E Simulation in Details:

BC&Mask optimization

Twiss Parameters & normalized transverse emittance for BC&Mask operation : 400 pC bunch from Injector

LH chicane: R_{56}=-52.7 mm, T_{566} =45.2 mm
BC chicane: R_{56}=-34.6 mm, T_{566} =52.5 mm

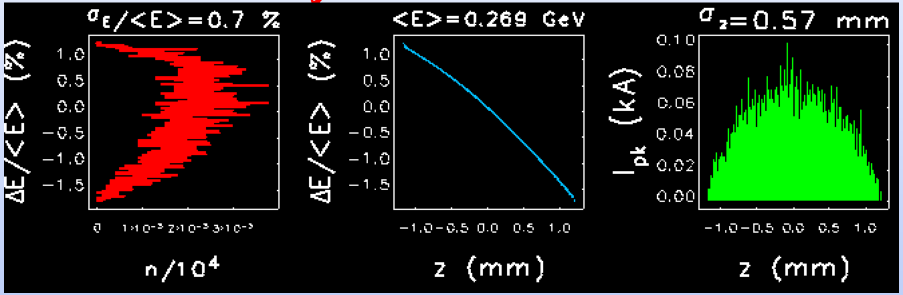




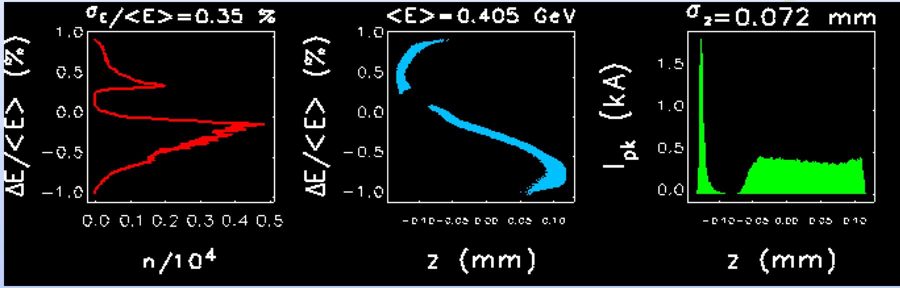
T.K. Charles *et al.*, «Current-horn suppression for reduced coherent-synchrotron-radiation-induced emittance growth in strong bunch compression», *Phys.Rev.Accel.Beams* 20 (2017) 3, 030705

Beam Longitudinal distribution trough the Linac

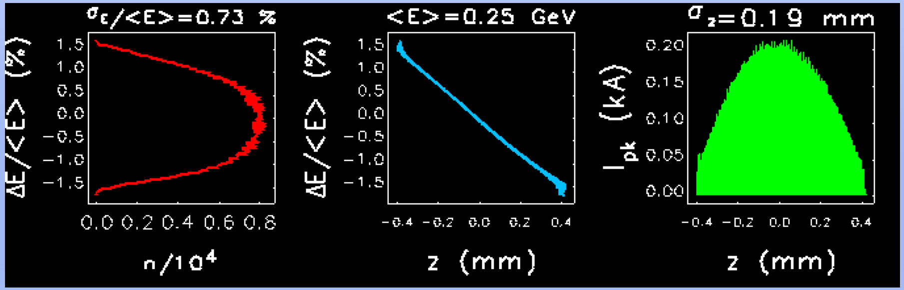
From Photoinjector (on crest)



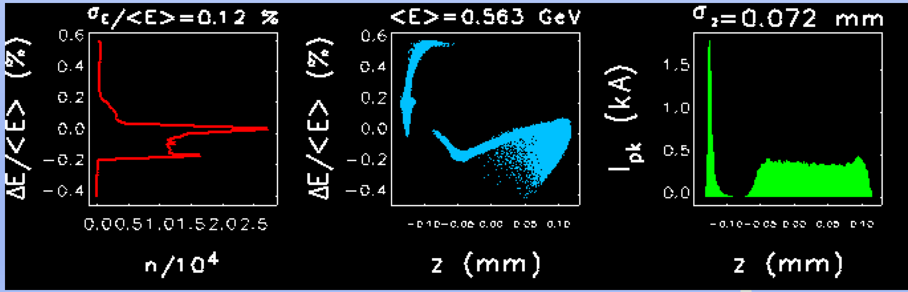
BC exit



LH chicane exit

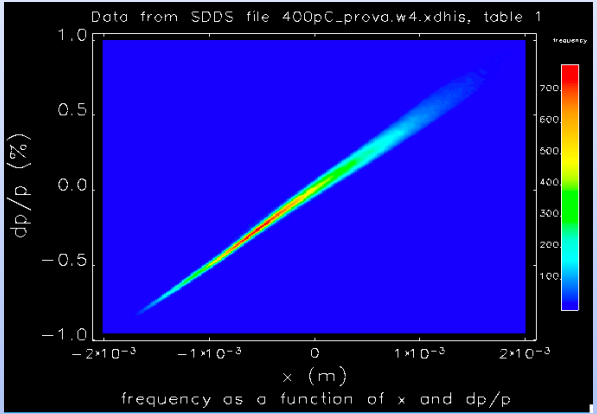


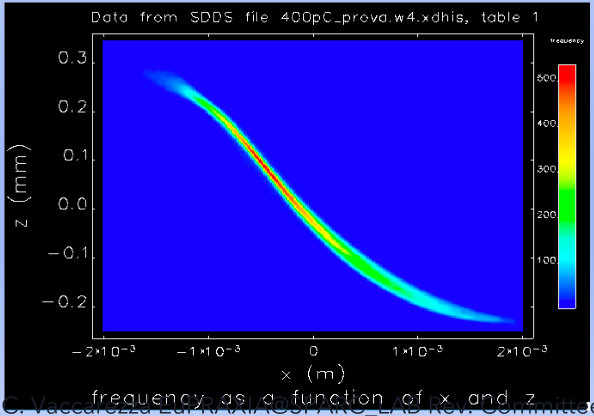
Plasma capillary entrance



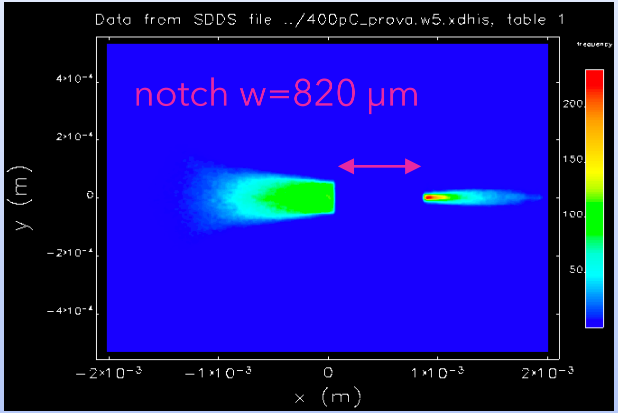
Inside the BC Chicane

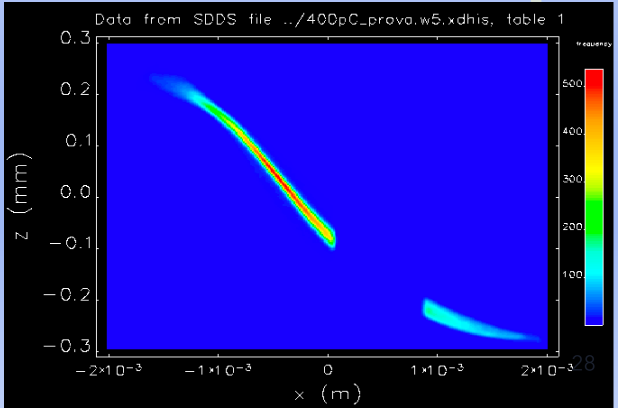
Before cut





After cut





400 pC beam,800kp

theta= 22.8 e 88. mrad

Phi RFX1=83.3,

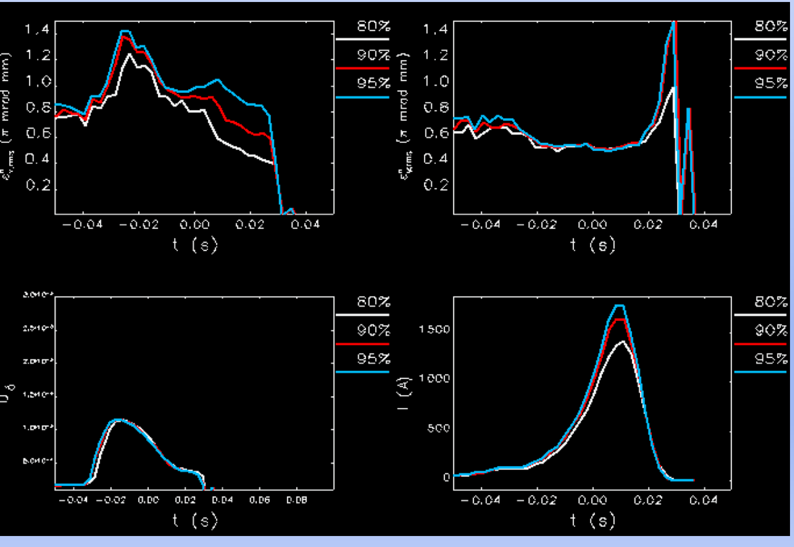
Phi RFX0=270, V RFX0=19 MV

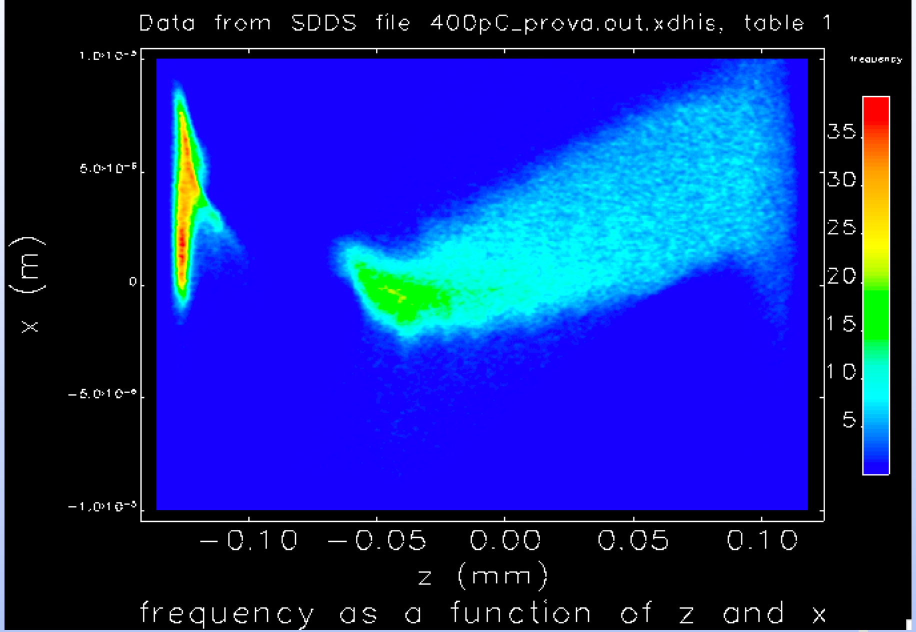
LH_sext: L=10 cm, K2=-190

BC_sext: L=20 cm, K2= 160.1

Transverse-Longitudinal correlation

Beam slice analysis






```
Printout for SDDS file Wit_w0.out

Particles =      95269

Printout for SDDS file Wit_w0.out.ana

     enx            eny           Sx            Sy            St            Sdelta         Cx            Cxp
     Cy             pCentral
     m              m             m             m             s                            m
     m              m$be$nc
--------------------------------------------------------------------------------------------------------------
  1.799461e-06   7.704585e-07  2.443715e-06  2.383371e-06  2.152147e-14  1.511137e-03  3.420929e-06  -7.211326e-06
 -1.732878e-09   1.147225e+03
Printout for SDDS file Dri_w0.out

Particles =     458933

Printout for SDDS file Dri_w0.out.ana

     enx            eny           Sx            Sy            St            Sdelta         Cx            Cxp
     Cy             pCentral
     m              m             m             m             s                            m
     m              m$be$nc
--------------------------------------------------------------------------------------------------------------
  2.169978e-06   1.326597e-06  4.425059e-06  1.242000e-06  1.650286e-13  6.615917e-04  2.330755e-06  1.907985e-06
 -1.927676e-09   1.148276e+03
```

Driver-Witness divergence: Betatron oscillations

$$F_x = \frac{e^2 n_p}{2\epsilon_0} x$$

$$F_x = \frac{d}{dt}(\gamma m_e \dot{x})$$

$$F_x = \dot{\gamma} m_e \dot{x} + \gamma m_e \ddot{x}$$

$$\gamma m_e \ddot{x} + \frac{e^2 n_p}{2\epsilon_0} x = 0$$

$$x'' + \left(\frac{e^2 n_p}{2\epsilon_0 \gamma m_e c^2}\right) x = 0$$

$$k_p^2 = \frac{e^2 n_p}{\epsilon_0 m_e c^2}$$

$$k^2 = \frac{k_p^2}{2\gamma}$$

$$x(z) = x_1 \cos kz + x_2 \sin kz$$

$$x'(z) = -k x_1 \sin kz + k x_2 \cos kz$$

$$x(0) = x_1$$

$$x'(0) = k x_2$$

$$x_2 = \frac{x'(0)}{k}$$

$$x_2 = \frac{x'(0)\sqrt{2\gamma}}{k_p}$$

For EuPRAXIA parameters assume

$$n_p = 10^{16}\ [\mathrm{cm}^{-3}]$$

$$1000 \leq \gamma \leq 2000$$

Simulation results give a value for driver-witness misalignment at plasma injection

$$x'(0) \approx 10^{-5}\ \mathrm{rad}$$

$$0.023\mu\mathrm{m} \leq x_2 \leq 0.033\mu\mathrm{m}$$

Conclusions

- The VB scheme for plasma is almost completed and can be transferred to TDR. Nevertheless, the completion of the Machine model with CAD is propaedeutic for the finalization of the S2E simulations. (Small changes to be checked)
- The BC&Mask scheme for plasma is close to completion.
- The All-RF 250 pC SB has to be checked trough the final layout
- The Microbunching Instability also has to be performed on the basis of the final layout

To do list (in parallel)

- VB scheme:
  - Repeat Jitter analysis w smaller offset for dogleg separation towards 30% of current pointing instability
  - Rise the current & separation from PhInj (beam already optimized, tracking in the Linac is ongoing)
- Reference Point and Jitter analysis for BC mask scheme with GEANT notch simulation
  - Experimental campaign at Fermi facility in Nov 2024.
- Machine-Model-CAD Layout Merging (Magnets-Diagnostics)
- Provide beam data for Radioprotection Analysis
- Trajectory correction w Diagnostic setup (40 % already done)
- Check All-RF - 250 pC Working Point with the final layout
- Complete Microbunching instability Analysis ➜ Laser parameters
- **Our goal is to almost complete TDR by end of 2024**

Thanks for yor attention