Possible Experiments With A High-Energy Proton Bunch And A Plasma

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ABSTRACT

We explore possible experiments that could be performed with a CERN-SPS, 400GeV/c, proton bunch with up to $3x10^{11}$ particles traveling in a plasma. Planned experiments include driving wakefields. However other topics could include resonantly driving wakefields a harmonic frequencies, looking for current filamentation instability and possibly driving a shock, as well as using the self-modulation instability to both defocus and slow down the proton bunch.

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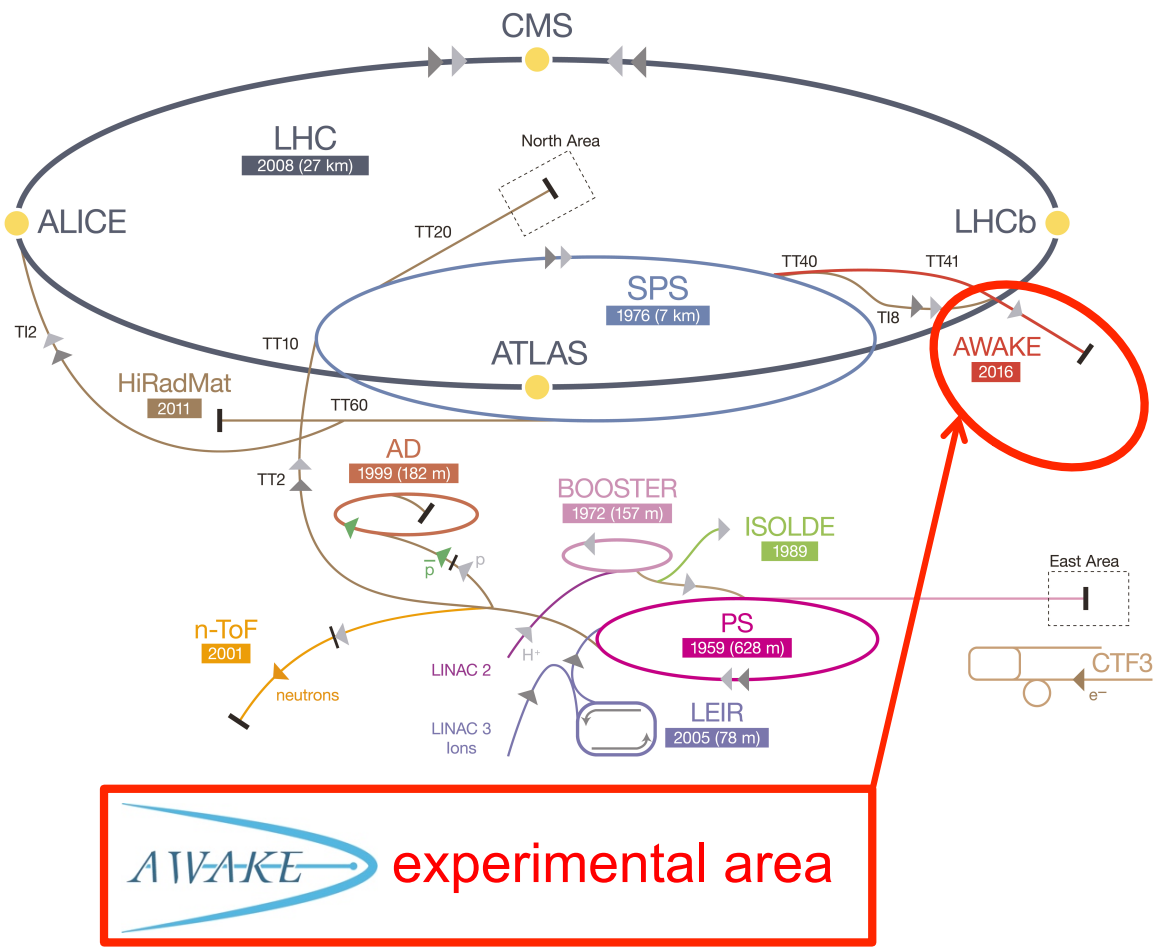
PROTON BEAMS @ CERN

CERN's Accelerator Complex



Parameter	PS	SPS	SPS Opt
E_0 (GeV)	24	400	400
N_p (10^{10})	13	10.5	30
$\Delta E/E_0$ (%)	0.05	0.03	0.03
σ_z (cm)	20	12	12
ε_N (mm-mrad)	2.4	3.6	3.6
σ_r^* (μm)	400	200	200
β^* (m)	1.6	5	5

$n_e \sim 7 \times 10^{14} cm^{-3}$ for $k_p \sigma_r \approx 1$
$\lambda_{pe} \sim 1.2mm << \sigma_z$
$f_{pe} \sim 240GHz$
$L_p \sim 10m \sim 2\beta^*$

✧SPS beam: high energy, small σ_r^*, long β^*

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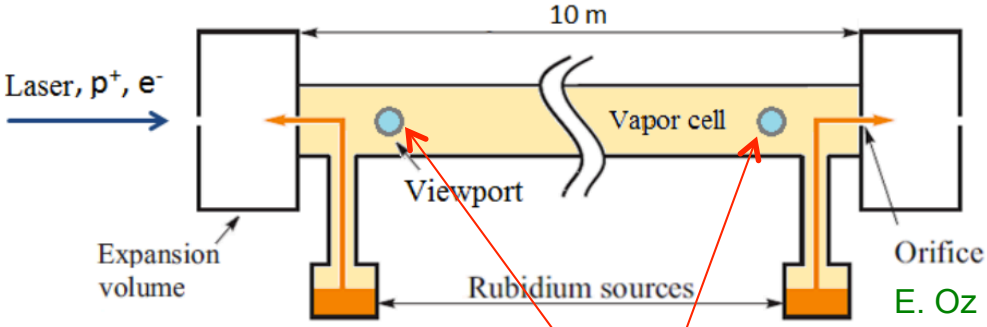
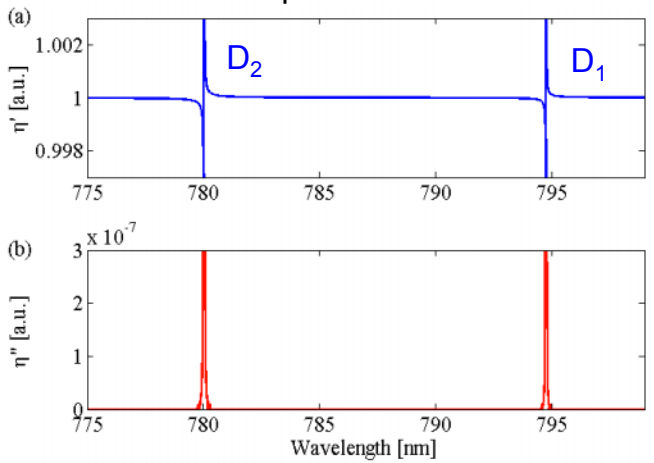
Rb VAPOR/PLASMA SOURCE



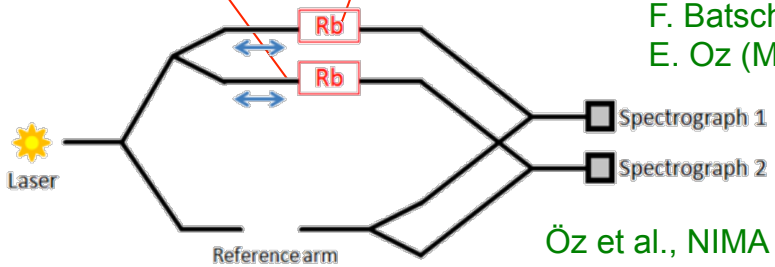
R. Kersevan (CERN)
G. Plyushchev (CERN/MPP/EPFL)

E. Oz & P. Muggli., NMA 740(11), 197 (2014).

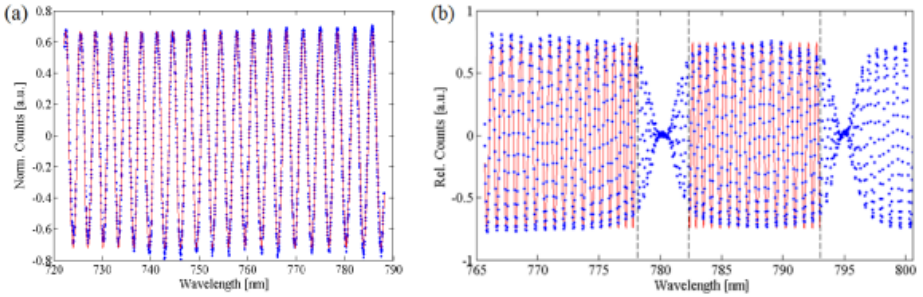
Rb anomalous dispersion at 780 and 794nm



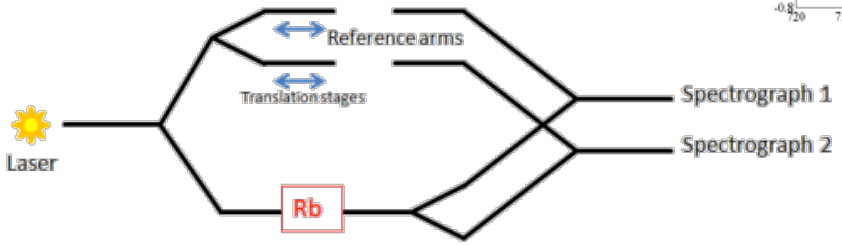
F. Batsch (MPP)
E. Oz (MPP)



Öz et al., NIMA 829, 321 (2016)



Test relative accuracy



$$S(\lambda) = \tilde{A} \cdot \cos\left(\frac{2\pi}{\lambda} \cdot \left[\frac{\tilde{n}l \cdot r_0 f_1 \lambda_1^3}{4\pi(\lambda - \lambda_1)} + \frac{\tilde{n}l \cdot r_0 f_2 \lambda_2^3}{4\pi(\lambda - \lambda_2)} + \tilde{\xi} \right] \right)$$

- n_{Rb}: $10^{14} < n_{Rb,e} < 10^{15}$ cm^{-3}, $\Delta n_{Rb,e}/n_{Rb,e} < 0.2\%$, few cm $n_{Rb,e}$ ramp
- Impose temperature $\Delta T < 0.3$K @500K ($\Delta T/T = \Delta n_{Rb}/n_{Rb} < 0.2\%$) + free expansion at ends
- Anomalous dispersion for n_{Rb} measurement: <0.3% accuracy!

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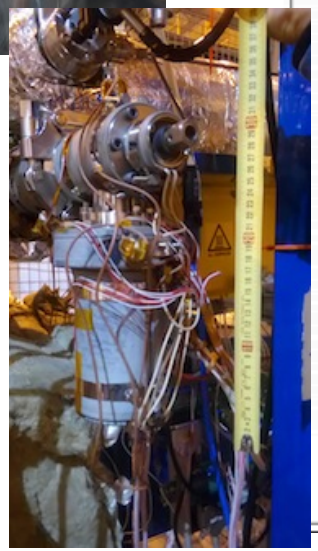
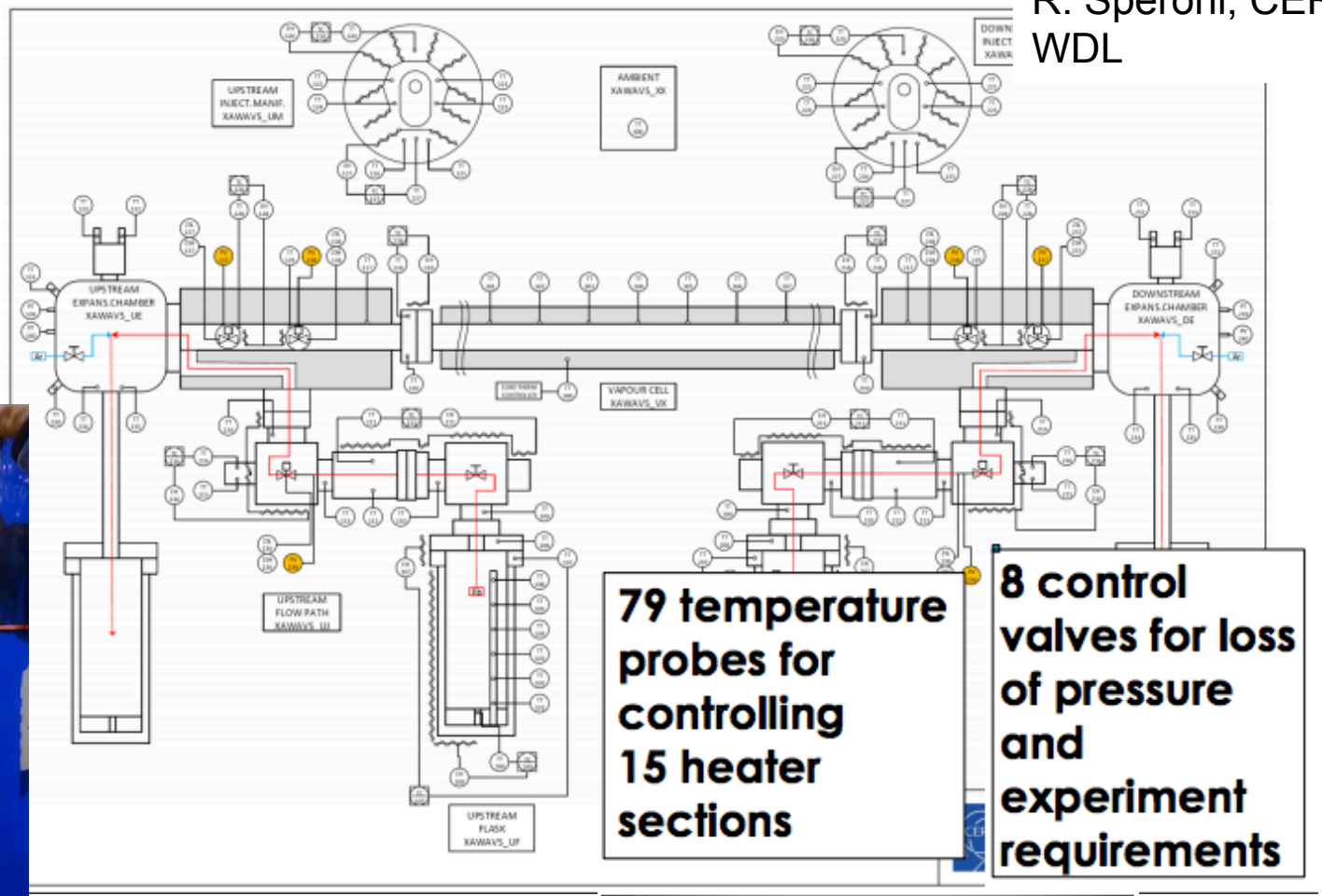
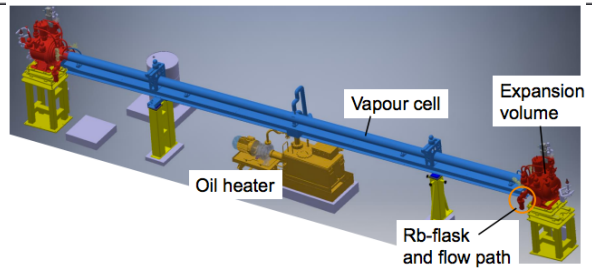
Rb VAPOR/PLASMA SOURCE

Instrumentation

F. Braunmueller, MPP
R. Speroni, CERN
WDL







- ✧Somewhat complex control system
- ✧Worked well
- ✧Produced expected Rb vapor density
- ✧No safety incident with Rb

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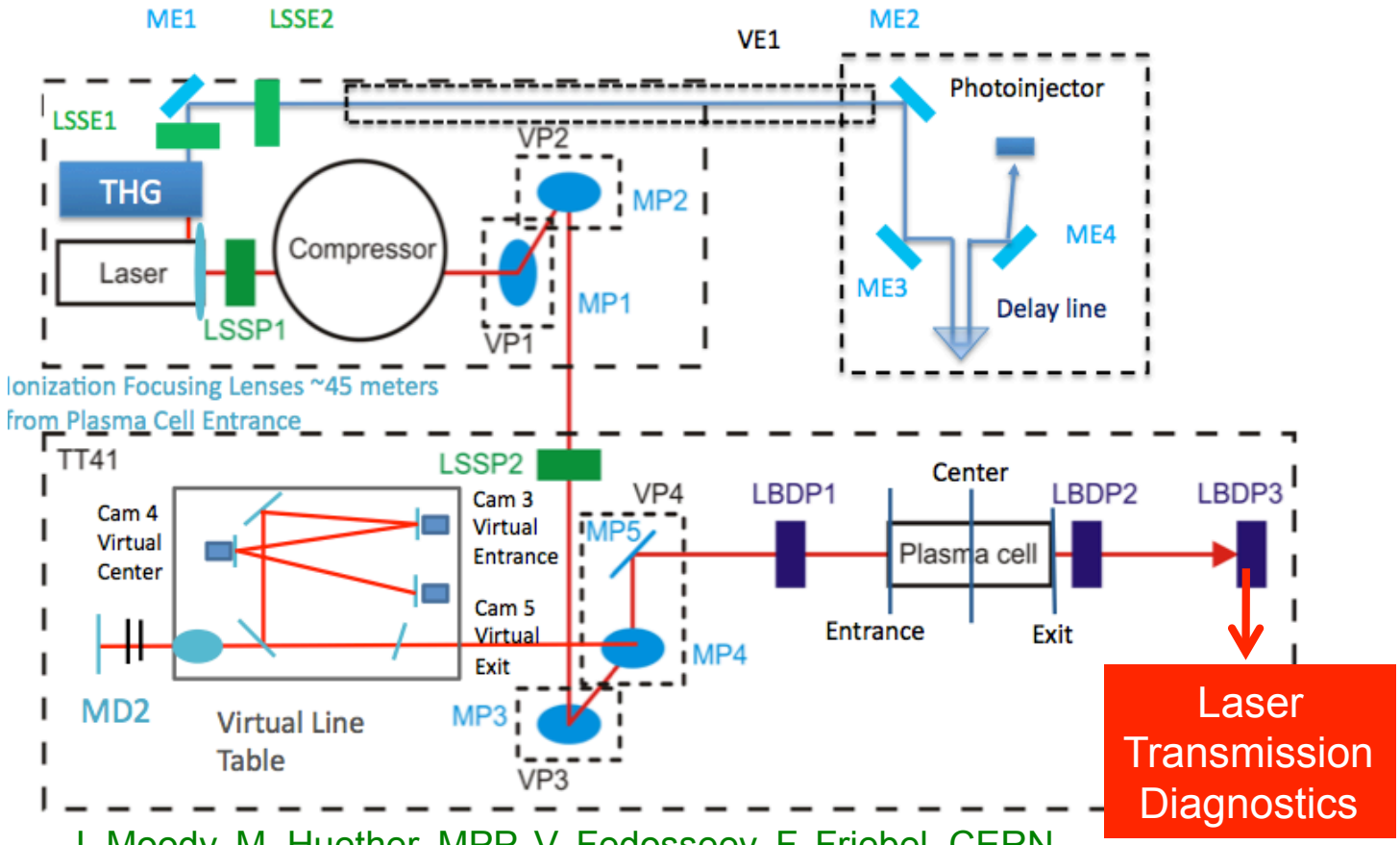
LASER & PLASMA



J. Moody, M. Huether, MPP, V. Fedosseev, F. Friebel, CERN

- ✧Fiber/Ti-Sapphire laser: ~100fs, E_{max}=450mJ
- ✧Rb: ϕ_{IP}=4.177eV, I_{app}~1.7x10^{12}Wcm^{-2},
- ✧r_0~1mm, Z_R~5m, I_{max}>10x10^{12}Wcm^{-2}
- ✧Field ionization => n_e=n_{Rb}, uniformity and ramps
- ✧Virtual plasma for alignment

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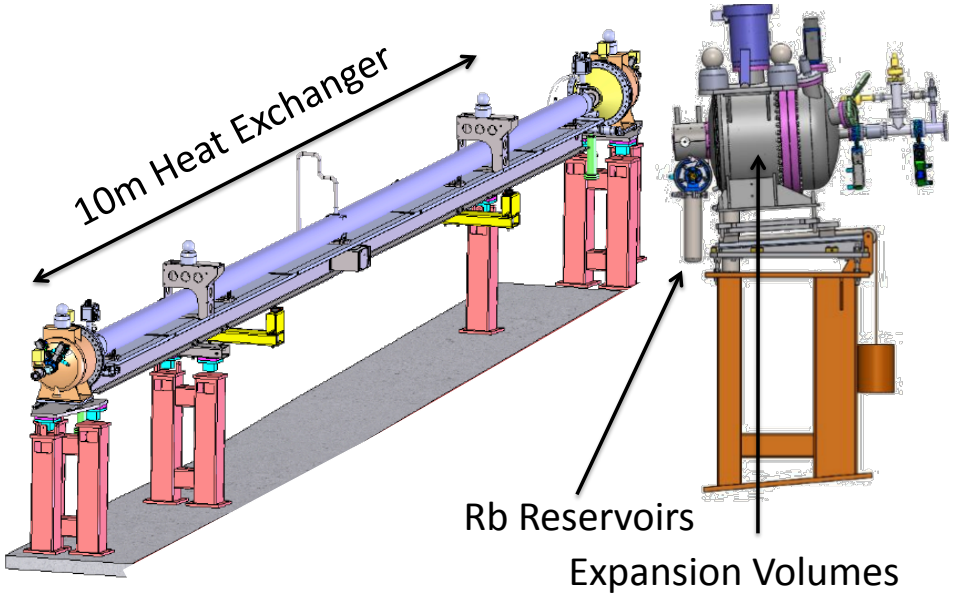
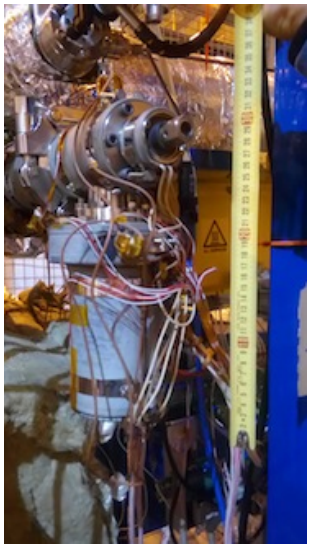
Rb VAPOR SOURCE (heat exchanger)

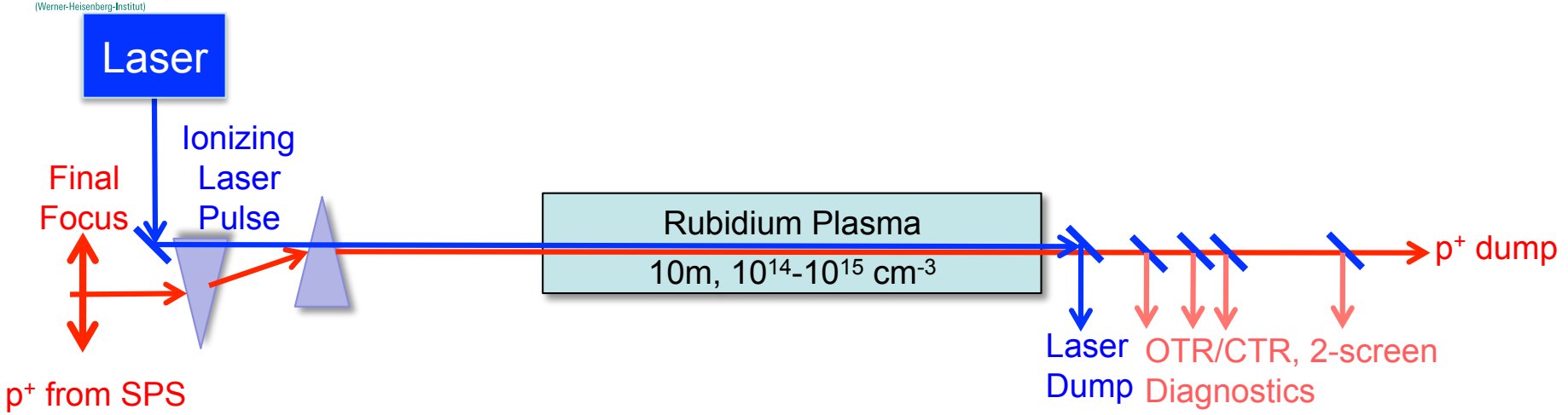
Development of the ends

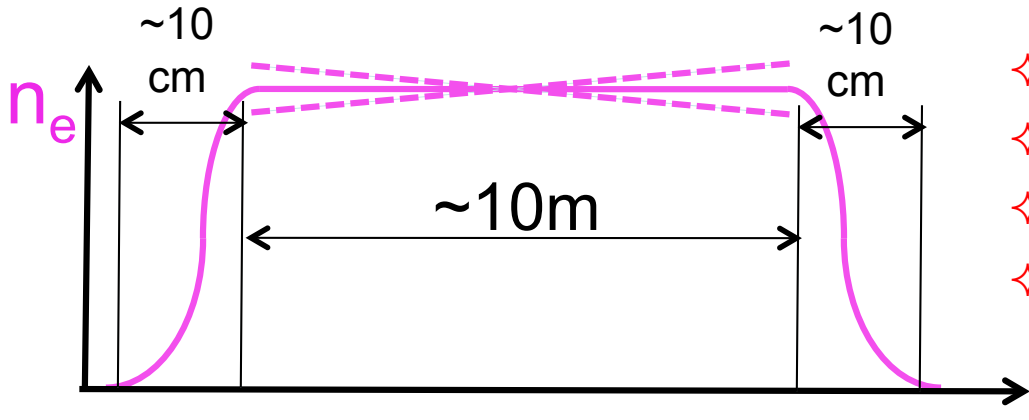


Installed in AWAKE!

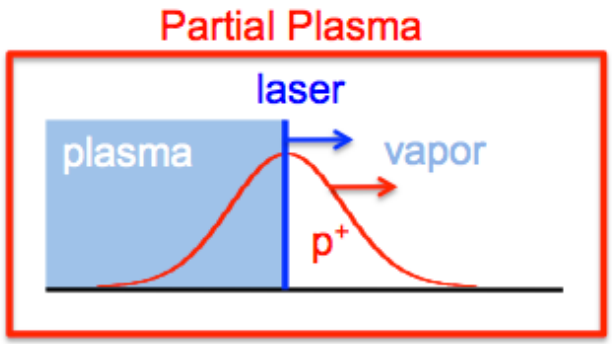


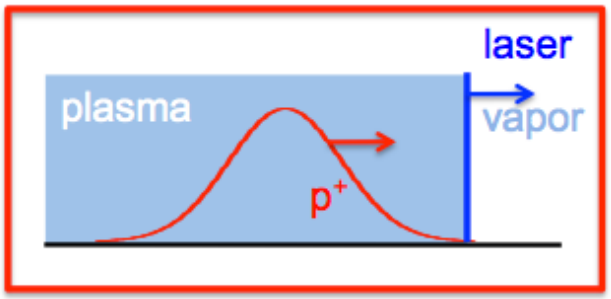
EXPERIMENTAL APPARATUS



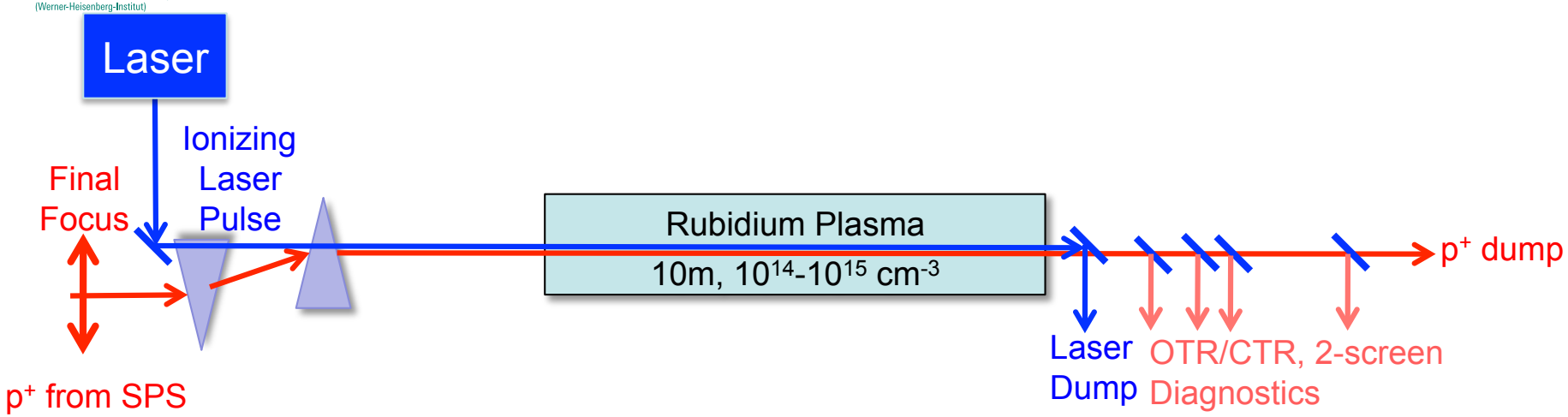


- Laser field-ionization
- $n_e=n_{Rb}$, $\Delta n_e/n_e<0.2\%$
- Few cm n_e ramp
- ±10% density gradient





DIAGNOSTICS



- Chromox screens => beam evolution: x(z), y(z)
- Optical transition radiation (OTR) => time integrated transverse image (x,y)
- OTR + streak camera => time resolved (ns, ps) image (x,t)
- Microwave diagnostics: Schottky diodes, heterodyne system

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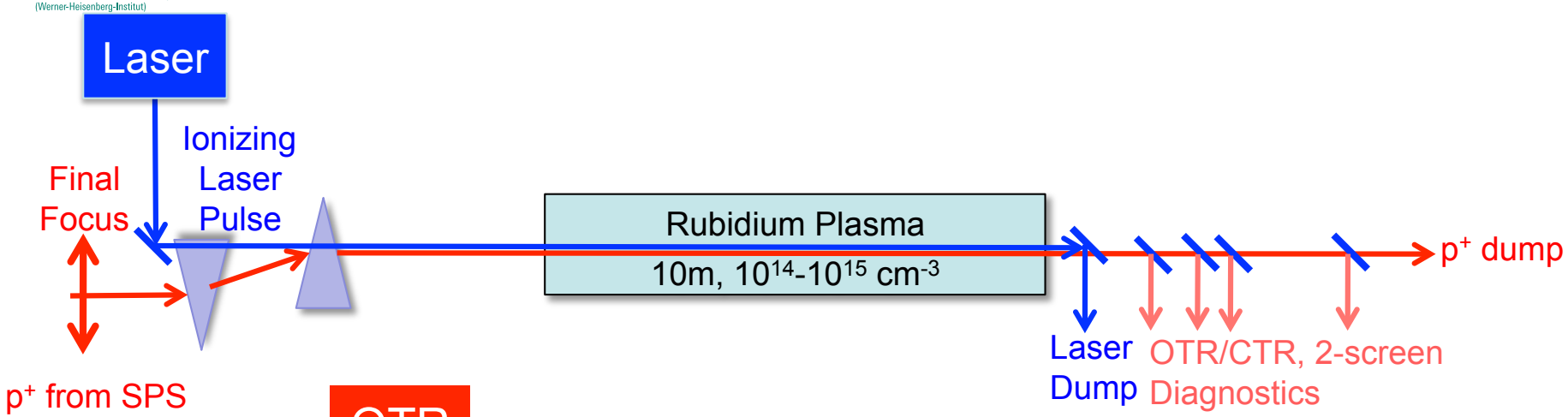
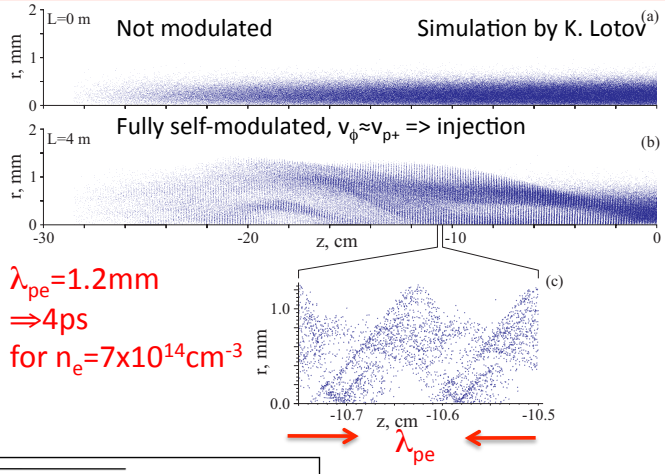
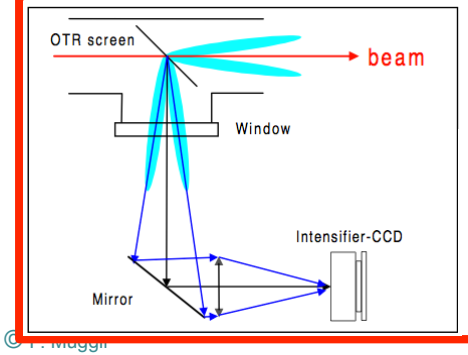
DIAGNOSTICS



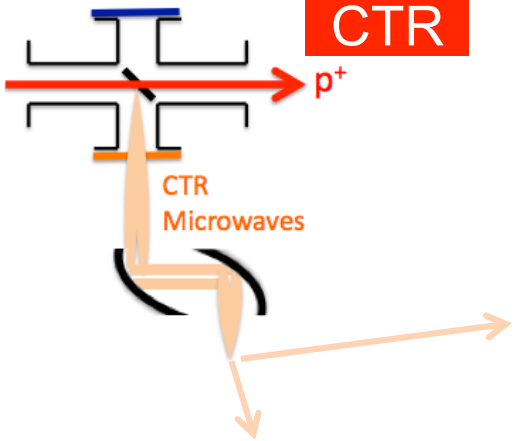
OTR



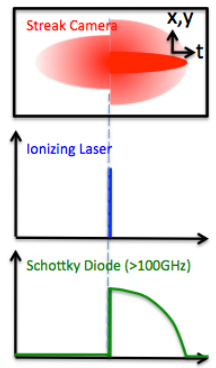


Streak Camera
≤1ps resolution

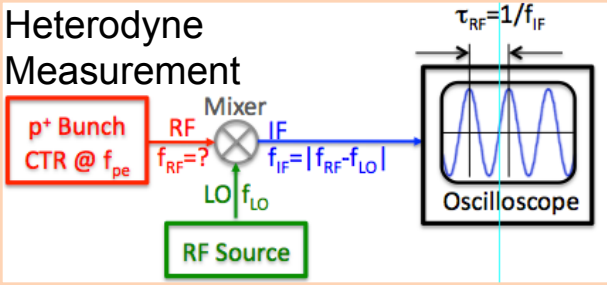
CTR



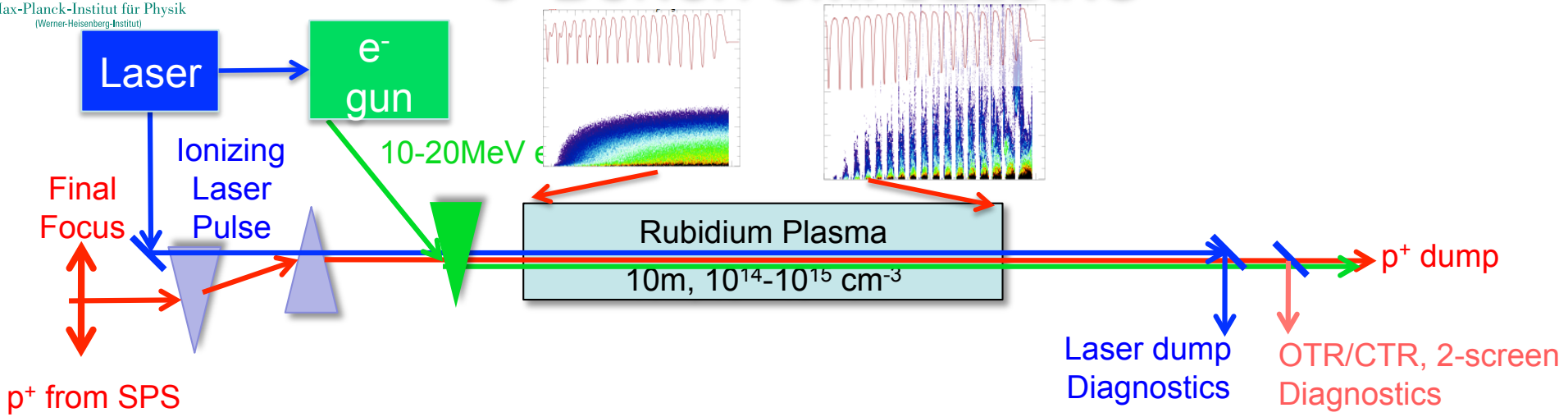
Schottky Diode



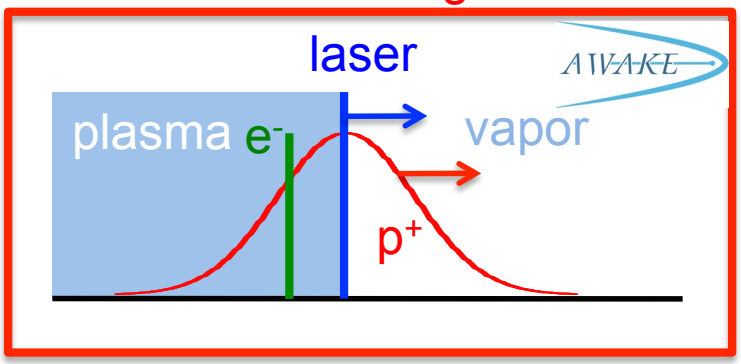
Heterodyne Measurement



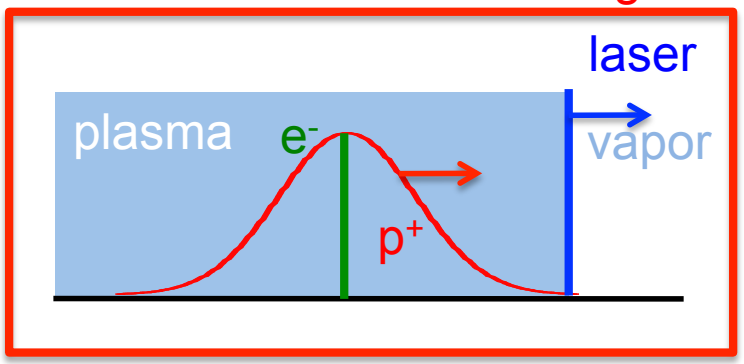
e⁻ BUNCH SMi SEEDiNG



SMI Ionization Seeding/e⁻ Acceleration

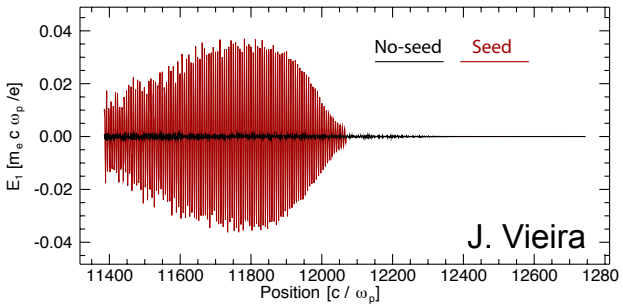


SMI e⁻ Bunch Seeding



- Seed SMI with ionization front (AWAKE)
- Seed SMI with e⁻ bunch (20MeV)
- Can use preformed plasma
- Simpler, cheaper plasma source

- No seed no SMI (over 10m)



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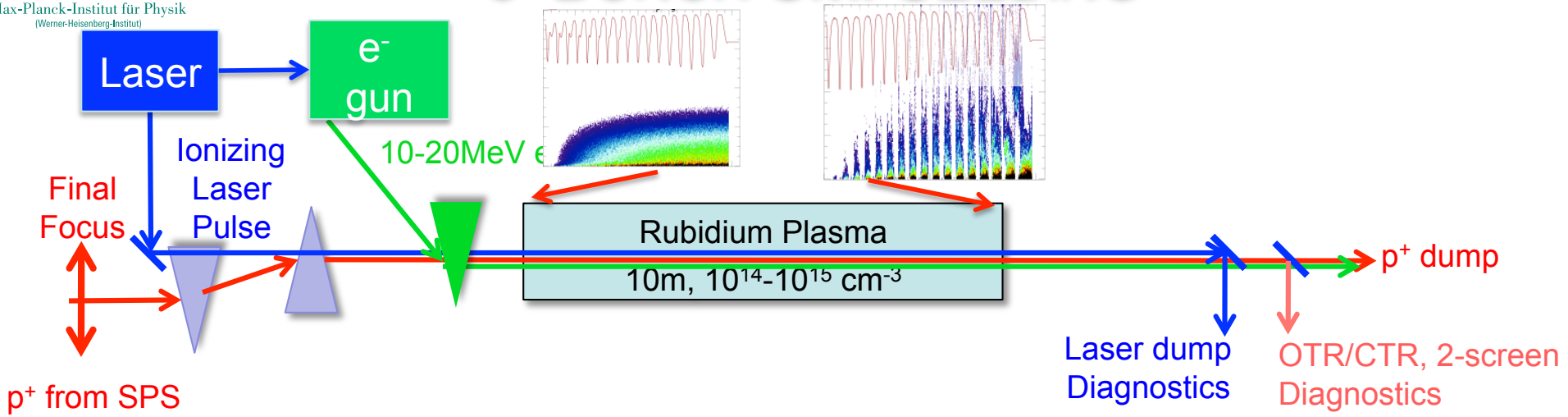
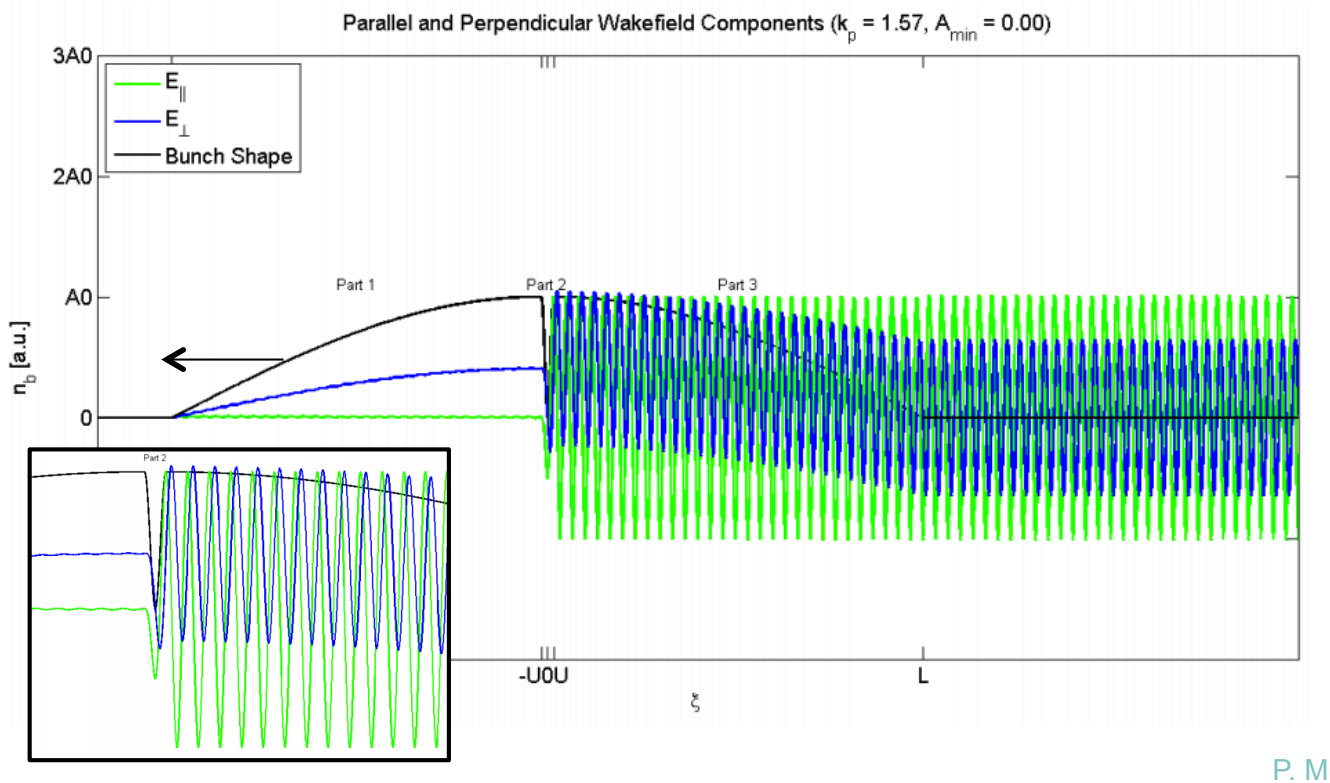
e⁻ BUNCH SMi SEEDiNG



Linear PWFA Theory calculation by M. Huether, MPP



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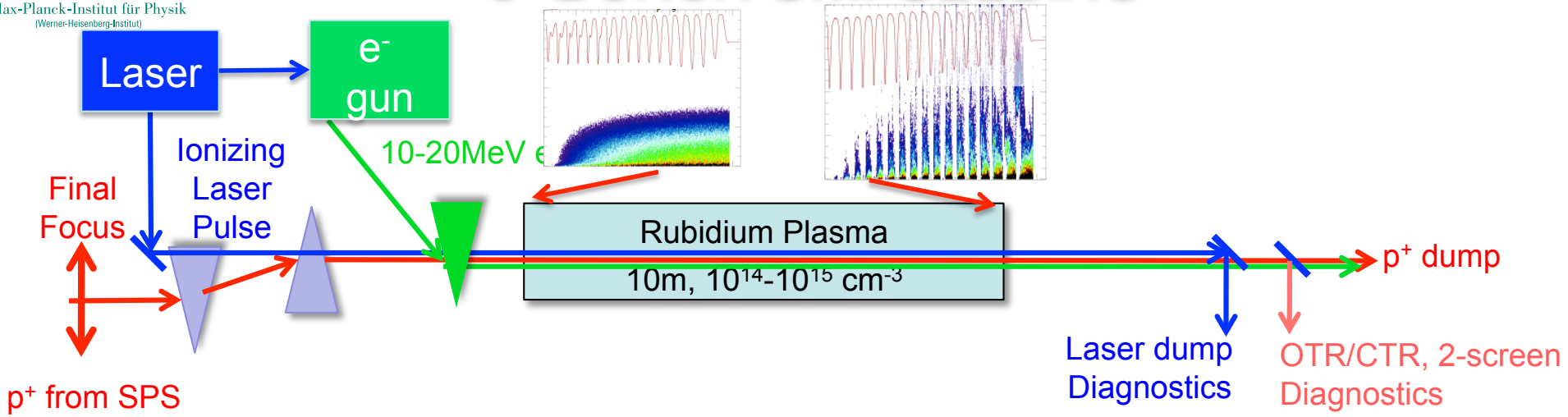
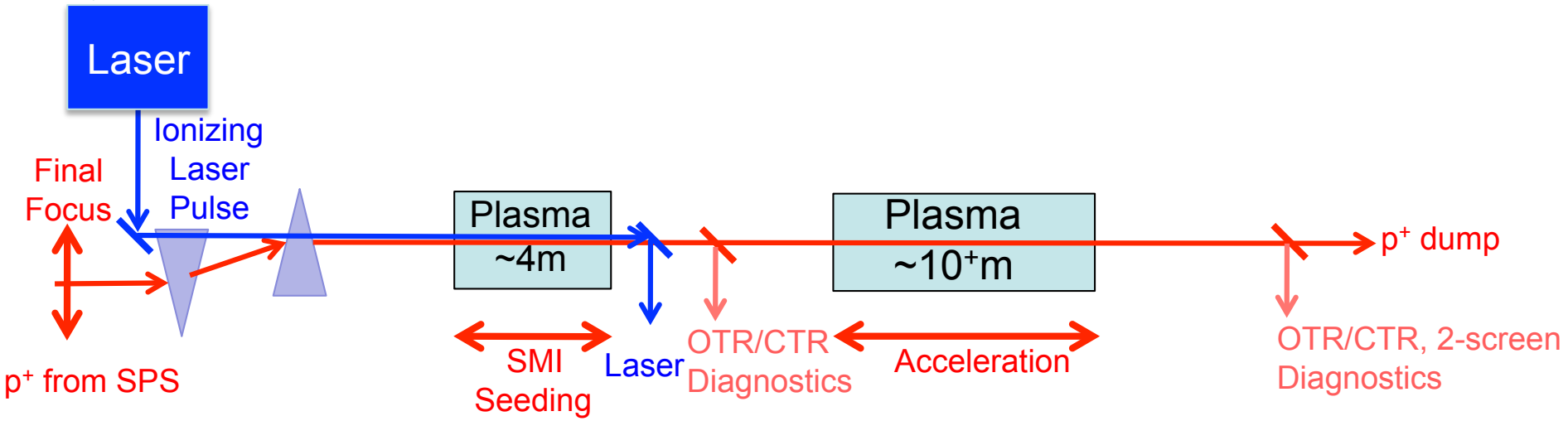
e⁻ BUNCH SMi SEEDiNG

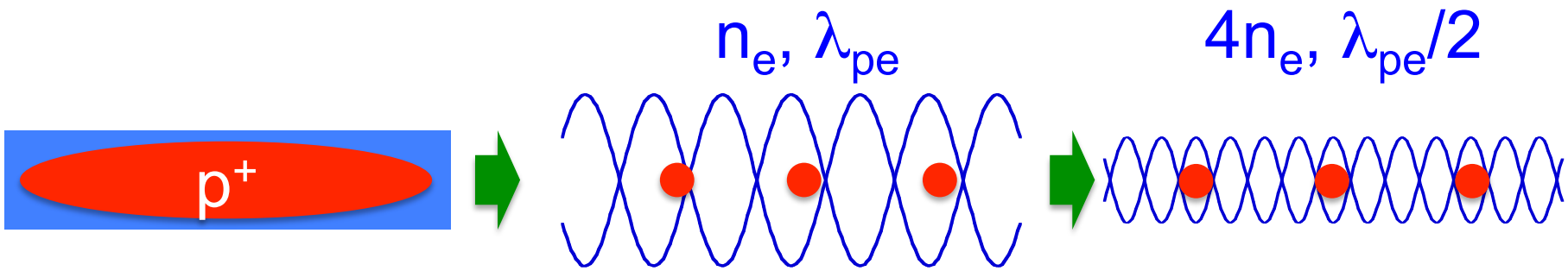


Challenges:

- e^- bunch: $\sigma_z < \lambda_{pe}$
- $E_{z,\,seed} \sim 10$MeV/m → energy loss
- p^+ bunch transverse field defocusing for e^-
- Need $I_{e^-} > I_{p^+}$?

2nd HARMONIC WAKEFIELDS

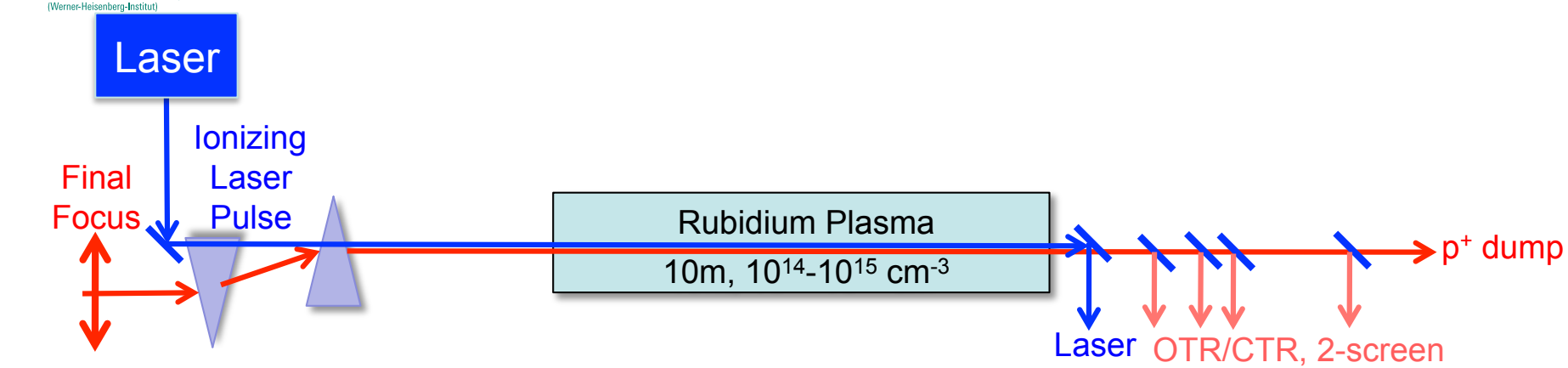




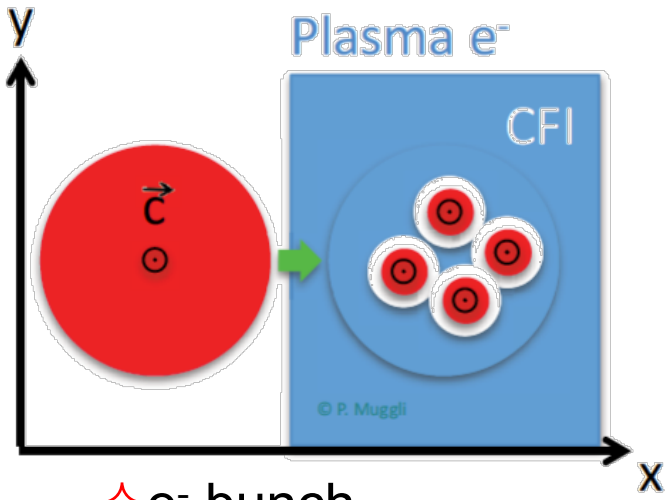
- 1^{st}: n_{e1}, $\lambda_{pe1} \sim n_{e1}^{-1/2}$
- Seed SMI: $k_{pe1}\sigma_{r1} \sim 1 \Rightarrow k_{pe}\sigma_r < 1$
- $\sigma_z \Rightarrow \sim \lambda_{pe1}/4$ bunches, every λ_{pe1}
- n_{b1} increases
- $E_{z1} \sim E_{WB1} \sim n_{e1}^{1/2}$

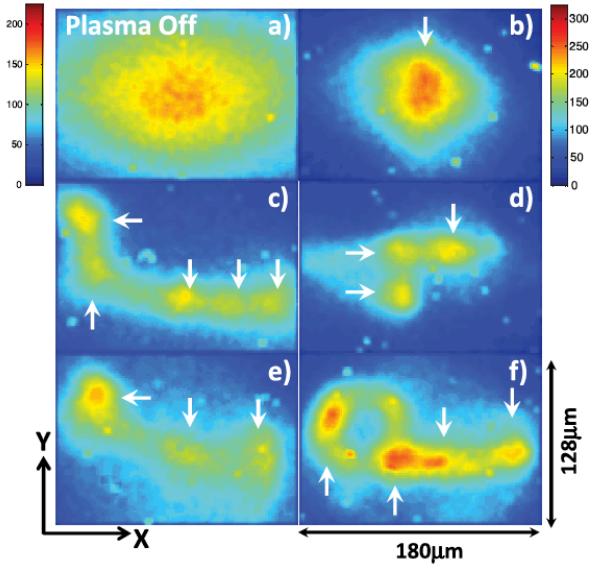
- 2^{nd} plasma: $n_{e2}=4n_{e1}$, $\lambda_{pe2}=\lambda_{pe1}/2$
- $k_{pe2}\sigma_r \sim 1$
- Bunches every $2\lambda_{pe2}$
- $n_{b2} > n_{b1}$
- $E_{z2} \sim E_{WB2} \sim n_{e2}^{1/2} \sim 2E_{z1}$

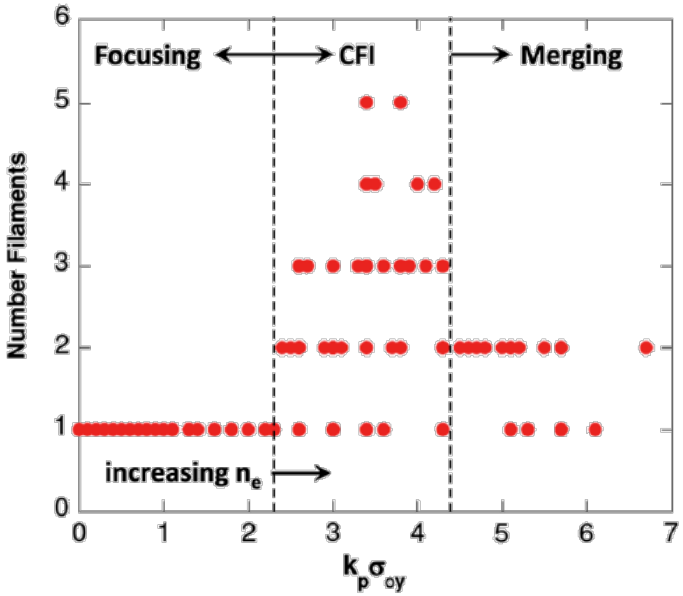
CURRENT FILAMENTATION INSTABILITY (CFI)



$$\Gamma = \beta_0 \sqrt{\frac{\alpha}{\gamma_0}}\omega_{pe} = \beta_0 \sqrt{\frac{n_b e^2}{\gamma_0 m_e \varepsilon_0}}, \qquad \alpha = n_b/n_e$$



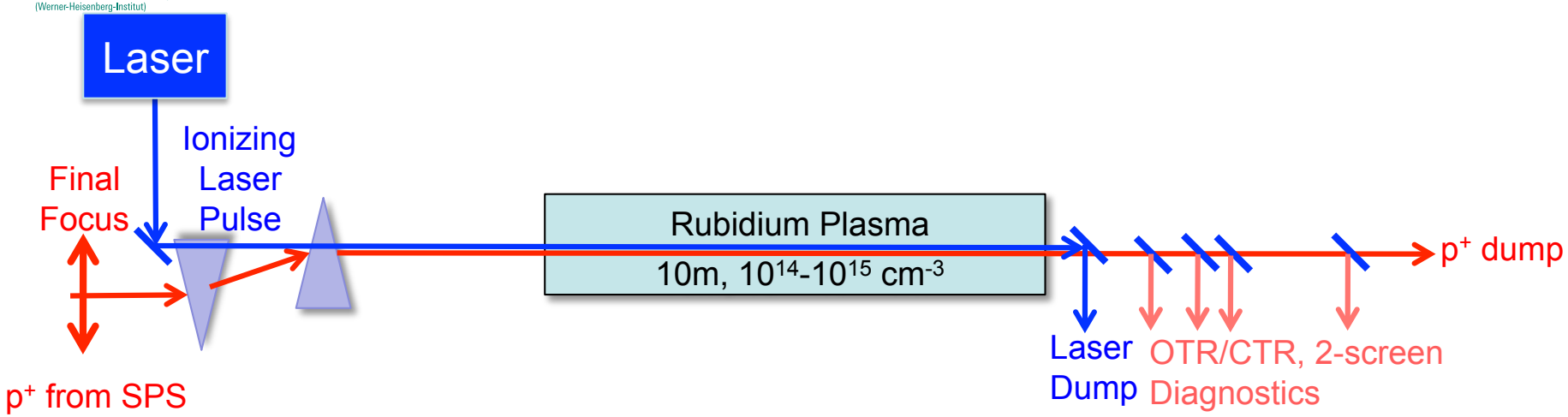




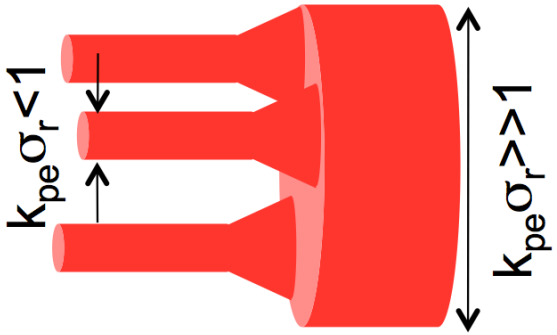
- e^- bunch
- 60MeV
- n_e=10^{16}-$10^{19}$$cm^{-3}$

Allen, PRL109, 185007 (2012).

CURRENT FILAMENTATION INSTABILITY (CFI)



- CFI of p^+ bunch?
- $n_e = 10^{15} cm^{-3}$
- σ_r=1mm → $k_{pe}\sigma_r \sim 6$ → CFI
- σ_z=12cm → $k_{pe}\sigma_z \sim 714$ → Dissipation, shock?
- L_p=10m → $k_{pe}L_p \sim 60'000$ → Dissipation, shock?



SUMMARY

- Fully equipped facility: 400GeV p^+ bunch, 10m plasma, diagnostics
- AWAKE plasma wakefield acceleration experiment
- e^- beam SMI seeding
- Wakefields at second harmonic
- Transverse current filamentation instability (CFI, Weibel) of p^+ bunch
- Drive shocks with p^+ bunch CFI?