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Modeling of Intense Ion Beam Transport and Focusing for High Energy Density Physics Applications

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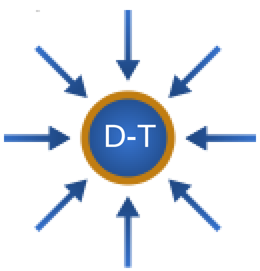
Ion-Beam-Driven High Energy Density Physics

Why ion beams?

- *High production efficiency and repetition rate*
- *High efficiency of energy delivery and deposition*

Heavy Ion Fusion (Future)



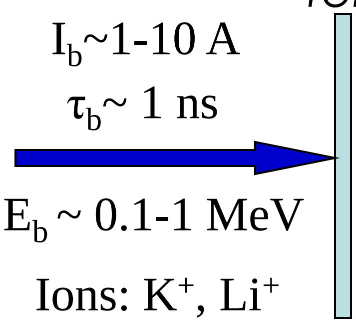
I_{total}~100 kA

τ_b~ 10 ns

E_b ~ 10 GeV

Atomic mass ~ 200

Warm Dense Matter Physics (Present)



I_b~1-10 A

τ_b~ 1 ns

E_b ~ 0.1-1 MeV

Ions: K^+, Li^+

Presently accessible ρ-T regime

ρ~1 g/cm³, T~1 eV

corresponds to the interiors of giant planets and low-mass stars

Outline

Ion driver

ion source → *Modeling of gas-dynamic ECR plasma ion source*

- *Ion beam extraction*
- *Emittance measurements*

acceleration and transport → *Studies of nonlinear dynamics and collective processes in intense ion beams in periodic focusing accelerators and transport systems*

- *Equilibrium (matched) beam distributions*
- *Halo production by a beam mismatch*

neutralized compression → *Studies of neutralized ion beam transport along a weak solenoidal magnetic field*

- *Enhanced self-focusing*
- *Electromagnetic wave excitation*

final focusing → *Studies of collective ion beam focusing by a weak solenoidal magnetic field*

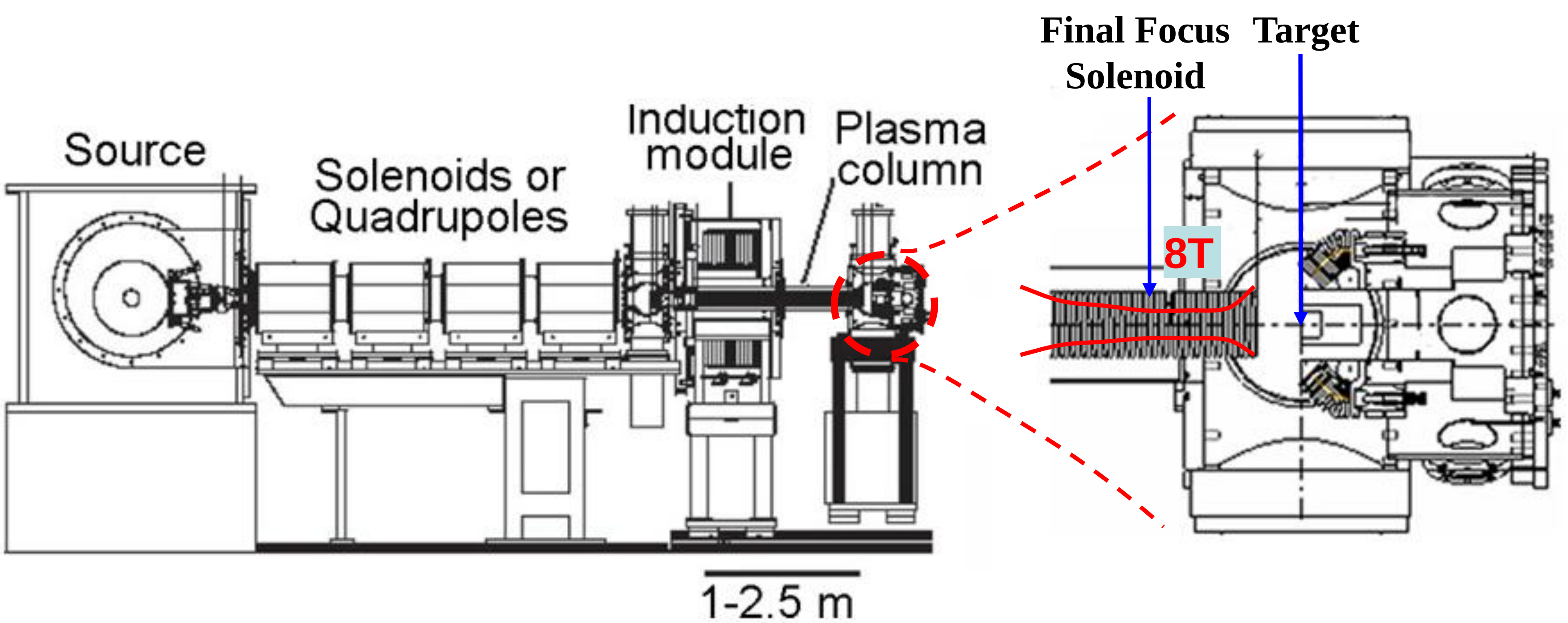
- *Collective focusing magnetic lens*
- *Collective focusing for NDCX final focus*

target

This presentation reviews studies of transport properties of an intense ion beam propagating in an ion driver

Neutralized Drift Compression Experiment (NDCX)

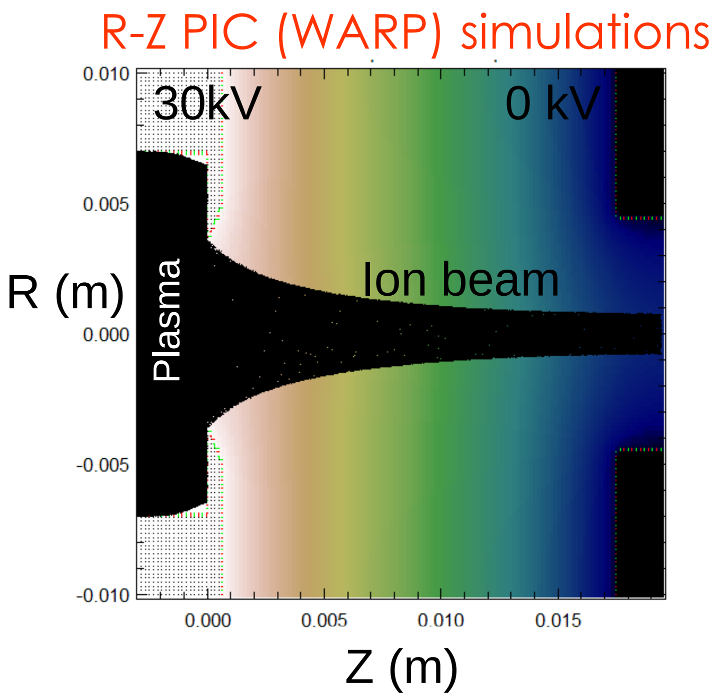
Schematic of the NDCX-I experimental setup (LBNL)
The heavy ion driver for Warm Dense Matter Experiments



Beam parameters at the target plane

K^+ @ 300 keV (β_b=0.004)	*upgrade* →	Li^+ @ 3MeV (β_b=0.03)
I_b~2 A , r_b < 5 mm (n_b~10^{11} cm^{-3})	*NDCX-II*	I_b~30 A , r_b~1 mm (n_b~$6\cdot10^{12}$ cm^{-3})
T_{target} ~0.1 eV		T_{target} ~1 eV

I. Modeling of the ion beam extraction from a gas-dynamic ECR plasma ion source



References
[1] M. Dorf *et al.,* J. Appl. Phys. **102**, 054504 (2007).
[2] M. Dorf *et al.*, Phys. Plasmas, **15**, 093501 (2008).
[3] M. Dorf *et al.*, submitted to Nucl. Instr. Meth. Res. A (2012).
[4] A. Sidorov, M. Dorf, *et al*., Rev. Sci. Instrum. 79, 02A317 (2008).

Gas-Dynamic ECR Ion Source (SMIS 37)

High current / Low Charge State ion sources

Vacuum arc sources (MEVVA), RF (multicusp)

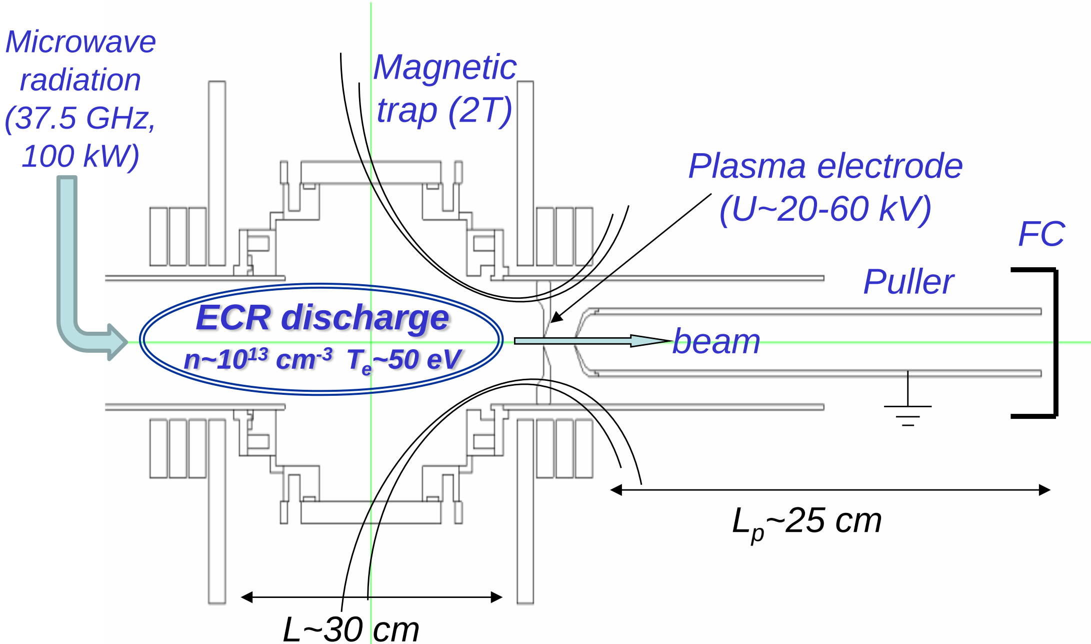
Multi-charged / Low current ion sources

ECR ion sources (classical) $Z_i >> 1$

Gas-dynamic ECR ion source

High beam current *Moderate charge-state* (Z_i>1)

SMIS 37
Build and operated
IAP RAS (Russia)



Extracted beam

I~150 mA

ε_N~0.9 π·mm·mrad

j~1A/cm^2

N^+ N^{++} N^{+++}

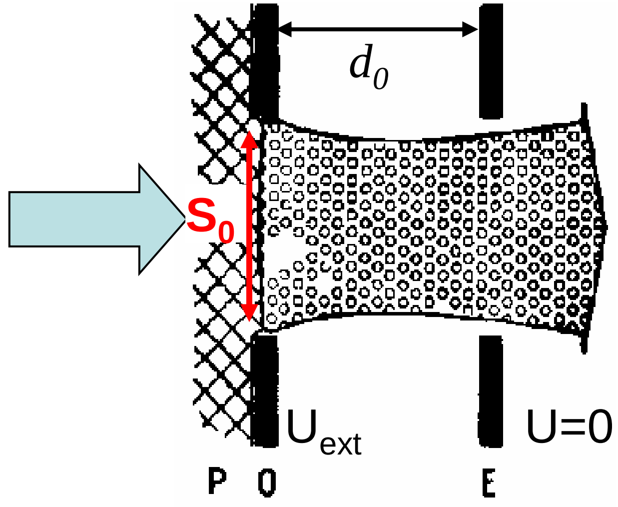
$\langle Z_i \rangle$~2

Gas-dynamic ECR source looks promising as a source for HIF driver

Principles of the Ion Beam Extraction from Plasma

Bohm current

$$j_B = 0.61 \cdot Z_{eff}\, n_0 e \sqrt{\frac{Z_{eff} T_e}{M_i}}$$

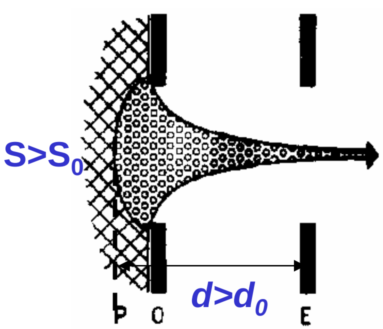


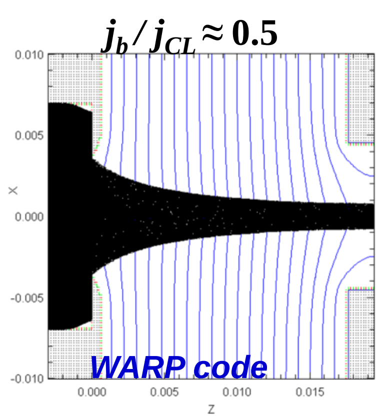
Child-Langmuir current

$$j_{CL}^{0} = 1.72 \left(\frac{Z_{eff}}{A_i}\right) \frac{U^{3/2}}{d_0^2}$$

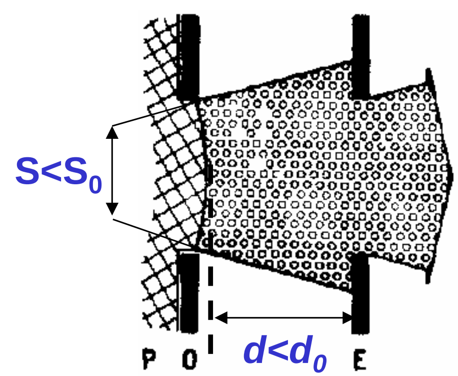
Plasma-vacuum surface (meniscus) evolves in order to match $j_B \approx j_{CL}$

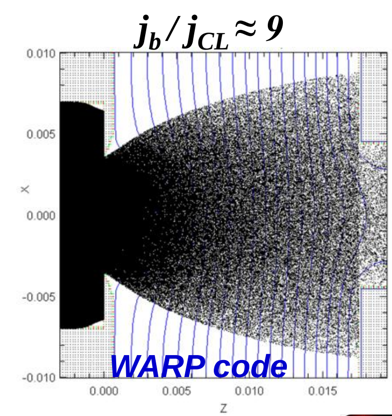
Low-density plasma ($j_B < j^0_{CL}$)





Overdense plasma ($j_B > j^0_{CL}$)





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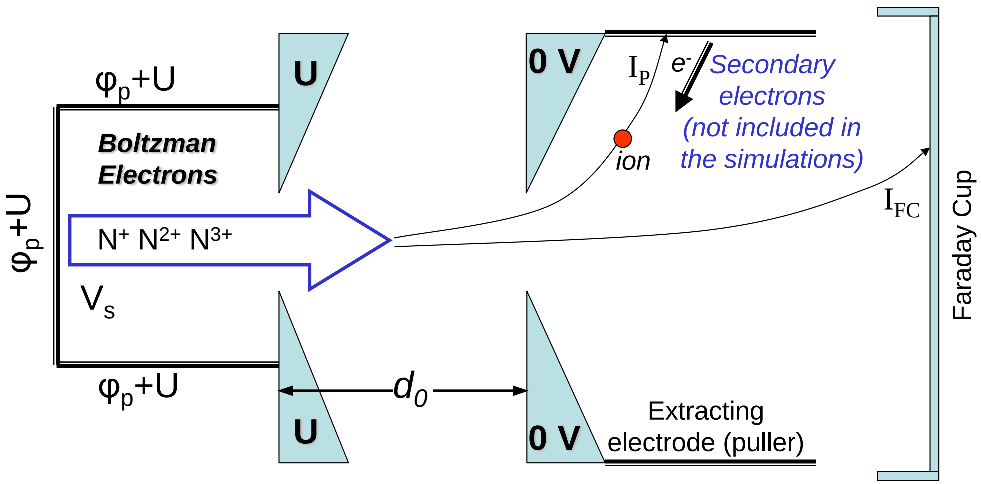
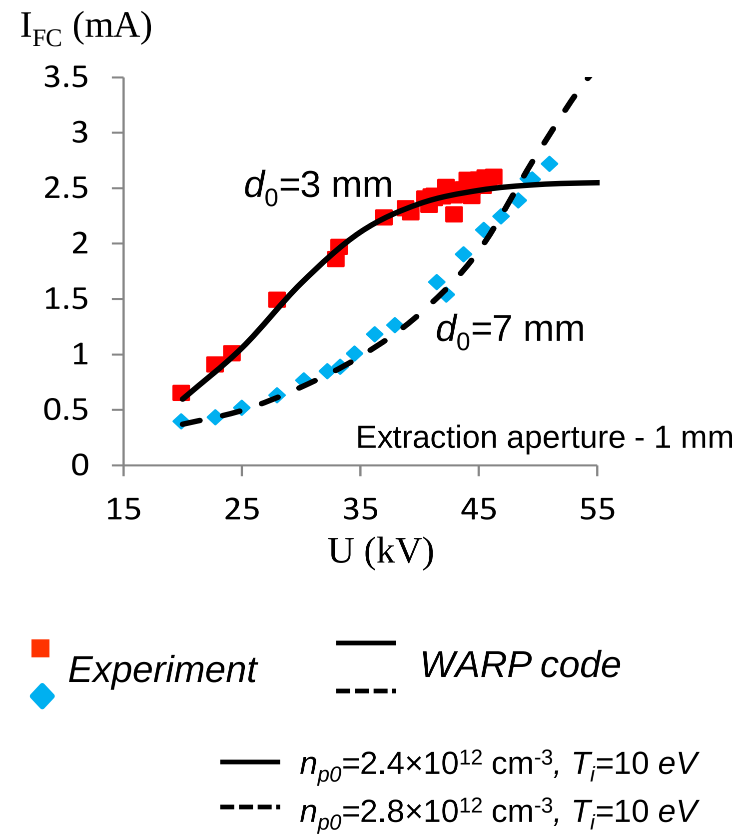
Single-aperture extraction: Experiment and Simulations

Schematic of WARP simulations



Extracted beam current



M. Dorf *et al*. submitted to NIMA (2012)

Plasma sheath model

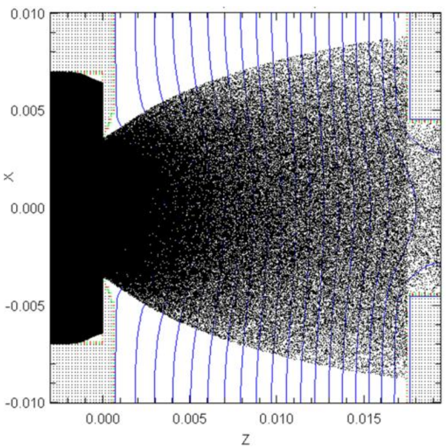
- Ions are injected with the Bohm velocity
- Boltzman electrons with T_e= 50 eV are assumed
- Possion equation is used for potential variations
- N^+:N^{++}:N^{+++} obtained from measurments
- n_{p0} and T_i are chosen to match the measurements

The results of the numerical simulations are in very good agreement with the experimental measurements

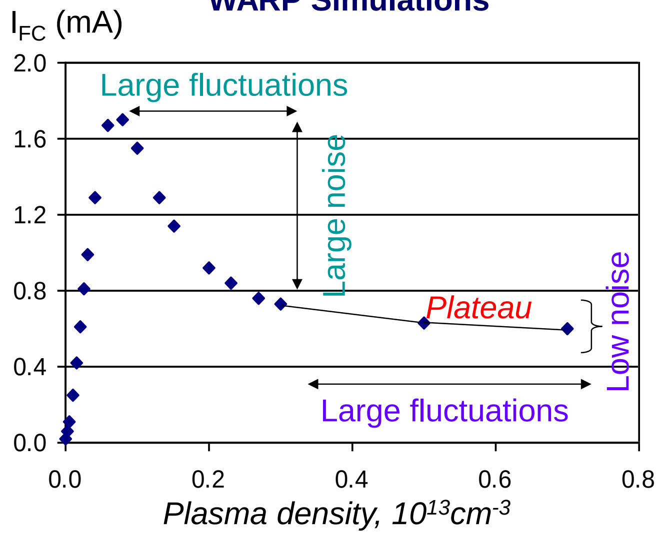
Noise Suppression and Stabilization of an Ion Beam Extracted from Overdense Plasma

It is of particular practical importance to suppress noise in the extracted beam current provided by fluctuations in the plasma density

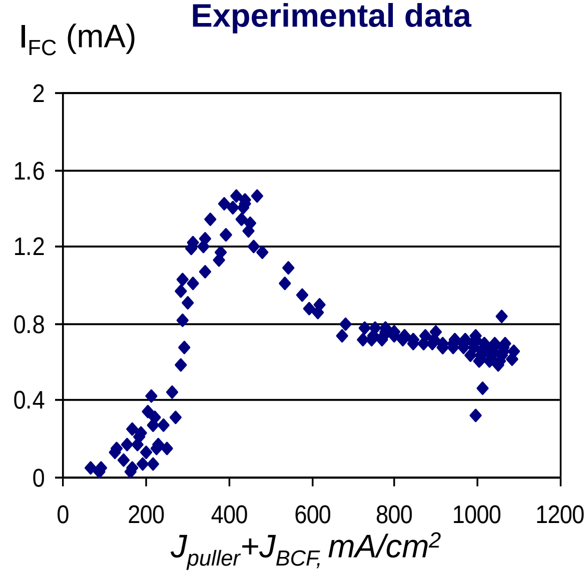
Illustrative cartoon



WARP Simulations



Experimental data



Beam formation in the plateau regime

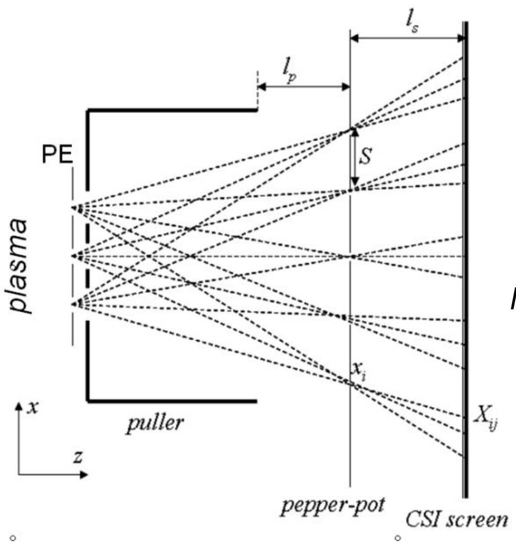
- *provides stable extraction despite large plasma fluctuations*
- *significantly enhances the brightness ($B_{Plateau}$~$16B_{regime\ of\ maximum\ extracted\ current}$)*

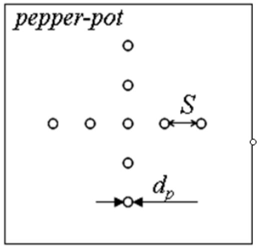
M. Dorf *et al*., J. Appl. Phys., **102**, 054504 (2007).

Measurements of the Transverse Beam Emittance

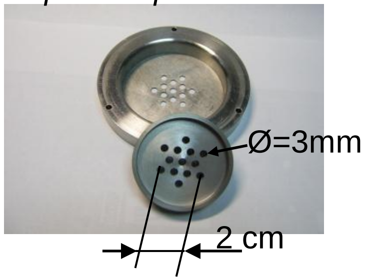
Beam phase-space measurements using the pepper-pot method

Schematic of the diagnostics setup

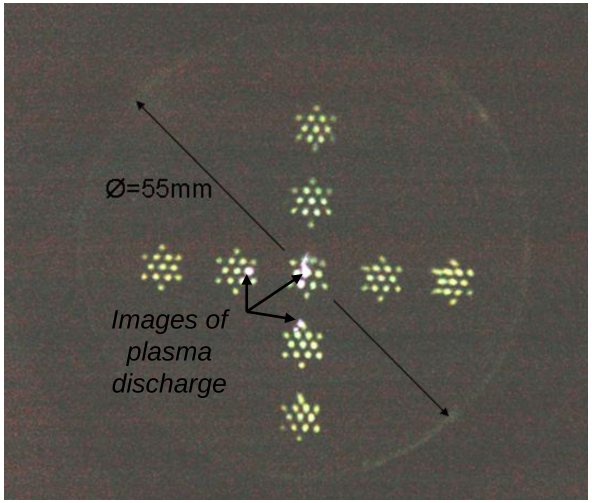




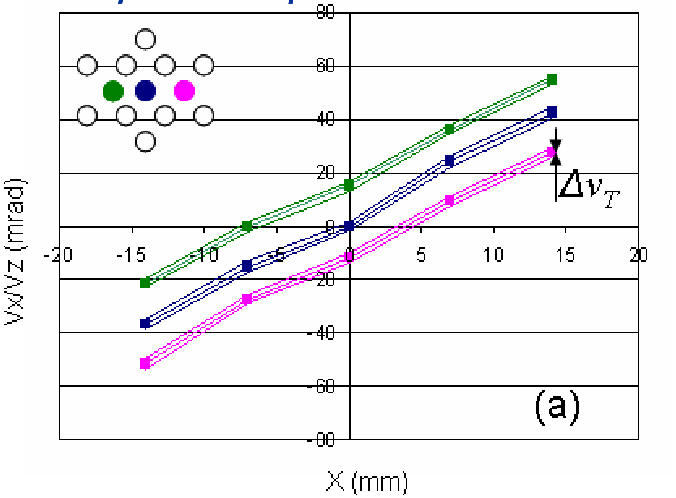
Multiaperture plasma electrode



Scintillator plate image



Beam phase-space reconstruction

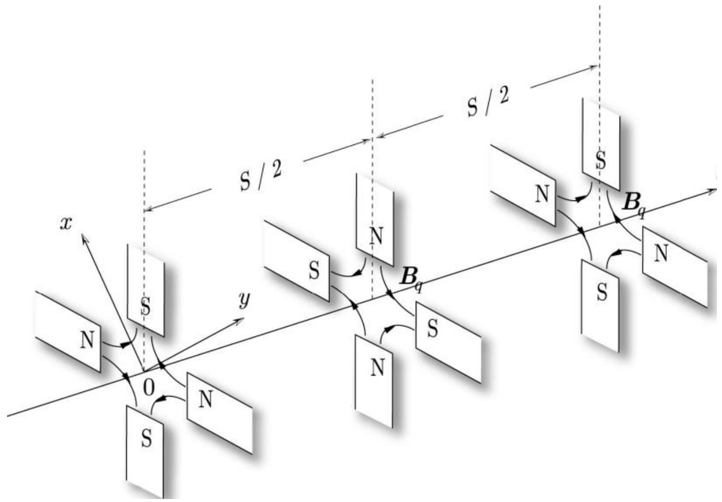


- ***The diagnostics demonstrates high values of the ion beam transverse temperature (~10 eV)***
- ***Similar assumption of high ion temperature (~10 eV) was required in numerical modeling to match the experiments***
- ***A reduced analytical model was developed to explain such high ion temperatures*** M. Dorf *et al*, Phys. Plasmas, **15**, 093501 (2008).

A. Sidorov, M. Dorf, V. Zorin, *et al*., Rev. Sci. Instrum. **79**, 02A317 (2008).

Fusion Energy Sciences

II. Studies of nonlinear transverse beam dynamics in periodic focusing transport systems



References

[1] M. Dorf *et al.,* Phys. Plasmas, **18**, 043109 (2011).

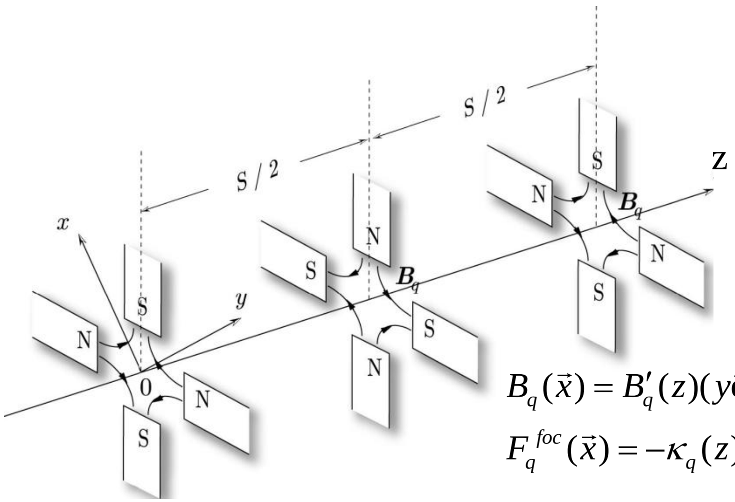
[2] M. Dorf *et al.*, Phys. Plasmas, **16**, 123107 (2009).

[3] M. Dorf *et al.*, Phys. Rev. ST AB **9**, 034202 (2006).

[4] M. Dorf *et al*., PAC Proceeding 2007; 2009.

Periodic Focusing Lattices

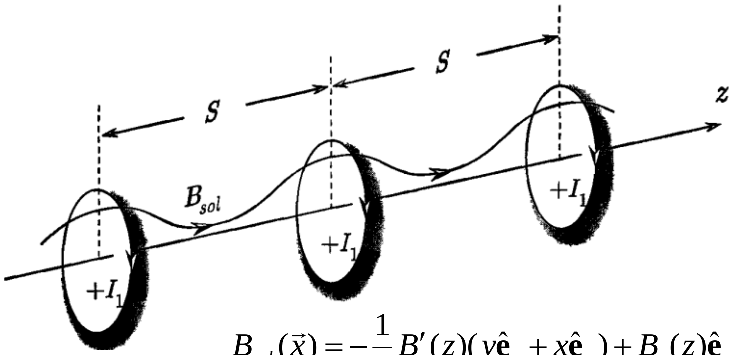
Alternating-gradient quadrupole lattice



$$B_q(\vec{x}) = B'_q(z)(y\hat{\mathbf{e}}_x + x\hat{\mathbf{e}}_y)$$

$$F_q^{foc}(\vec{x}) = -\kappa_q(z)(x\hat{e}_x - y\hat{e}_y)$$

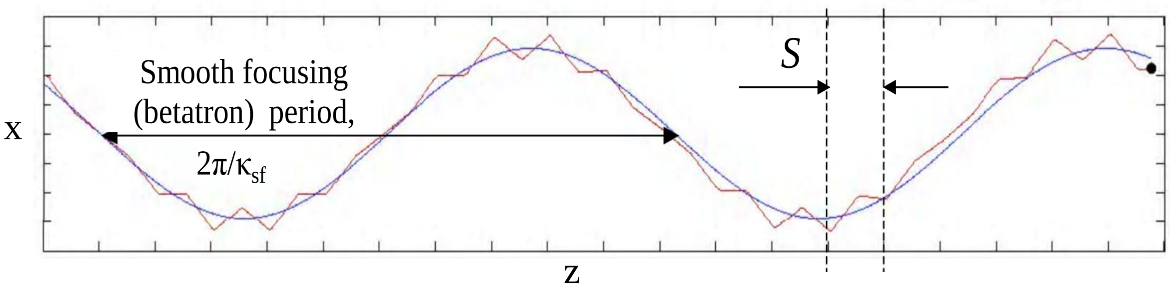
Periodic-focusing solenoidal lattice



$$B_{sol}(\vec{x}) = -\frac{1}{2}B'_z(z)(y\hat{\mathbf{e}}_x + x\hat{\mathbf{e}}_y) + B_z(z)\hat{\mathbf{e}}_z$$

$$F_{sol}^{foc}(\vec{x}) = -\kappa_s(z)(x\hat{e}_x + y\hat{e}_y)$$

Single-particle motion (no space-charge forces)



Smooth-focusing approximation $F_{foc} = -\kappa_{sf} r\hat{\mathbf{e}}_r$

Vacuum phase advance
$\sigma_{vac} = \kappa_{sf}S/2\pi$

In the presence of space charge, the phase advance, σ, is depressed, $\sigma < \sigma_{vac}$

$\sigma/\sigma_{vac} \to 1$ emittance dominated beam

$\sigma/\sigma_{vac} \to 0$ space-charge dominated beam

Equilibrium (Matched) Beam Distribution

Smooth-focusing approximation

$$F_{sf}^{foc} = -\kappa_{sf}\left(x\hat{\mathbf{e}}_x + y\hat{\mathbf{e}}_y\right)$$

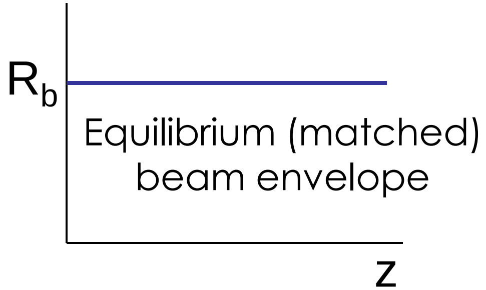
The transverse Hamiltonian is an invariant of beam particles motion

$$H_{\perp}^{0} = \frac{1}{2}\left(x'^2 + y'^2\right) + \frac{1}{2}\kappa_{sf} r^2 + \psi(r)$$

Kinetic energy — *Applied focusing potential* — *Self-potential*

Beam Equilibrium

$$f_b^0 = f_b^0\left(H_\perp^0\right) \qquad \Delta_\perp \psi(r) \propto \iint f_b \, dx' dy'$$



Oscillating focusing field

$$\kappa_{lattice}(z) = \kappa_{lattice}(z+S)$$

The transverse Hamiltonian (particle energy) is not conserved

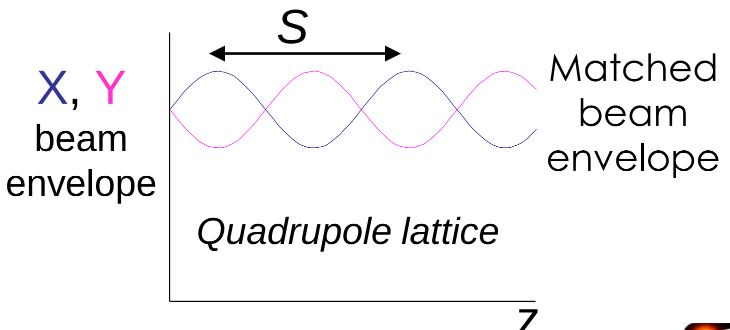
↓

Nonlinear effects of the intense beam self-fields provide a significant challenge for analytical studies

↓

How to find (or load) a matched-beam quasi-equilibrium?

$$f_b(z) = f_b(z+S)$$



Adiabatic Formation of a Matched Beam Distribution

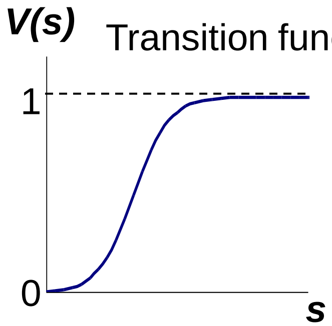
Quadrupole lattice (WARP simulations)

Adiabatic turn-off of the uniform focusing field

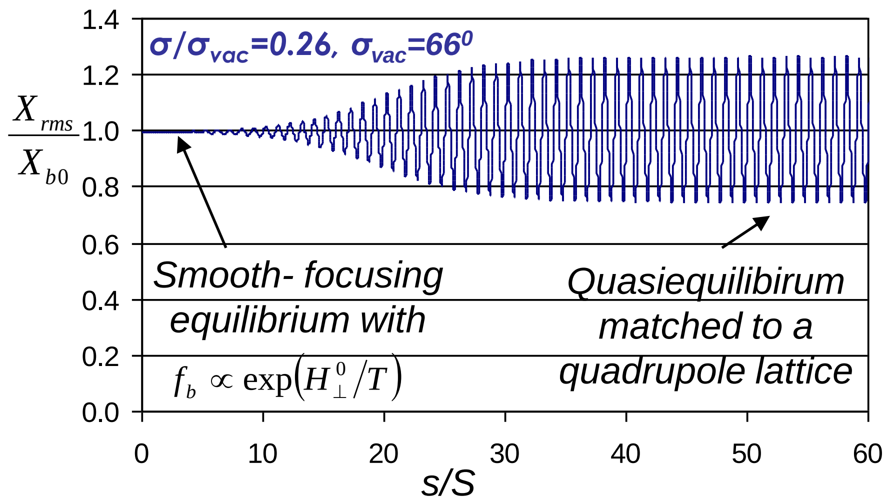
Adiabatic turn-on of the oscillating focusing field

$$F_q = \underbrace{\left[V^2(s)-1\right]\kappa_{sf}^q\left(x\mathbf{e}_x + y\mathbf{e}_y\right) - V(s)\kappa_q(s)\left(x\mathbf{e}_x - y\mathbf{e}_y\right)}$$

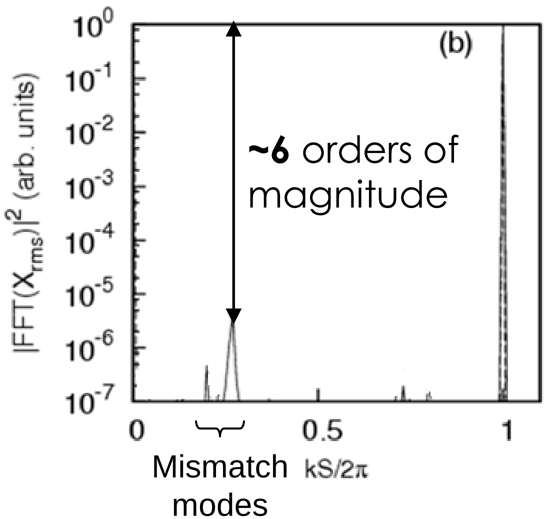
The average (smooth-focusing) effects of the total focusing field is maintained fixed



Evolution of the beam envelope



FFT of the beam envelope time evolution



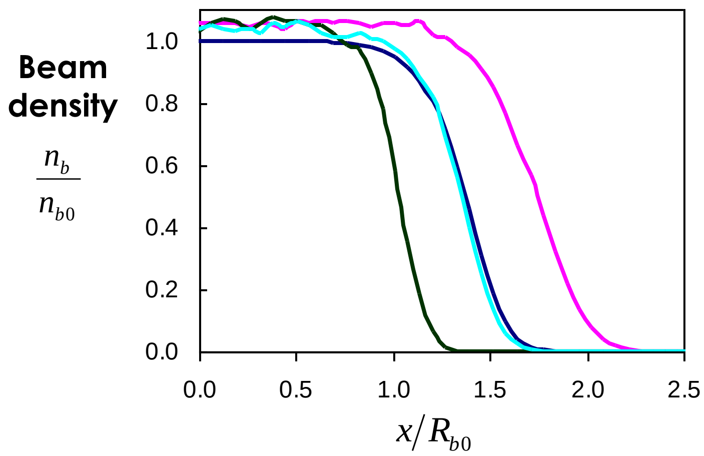
Quiescent beam propagation over several hundred lattice periods has been demonstrated for a broad range of beam intensities and vacuum phase advances

Dorf *et al.*, Phys. Plasmas **16**, 123107 (2009)

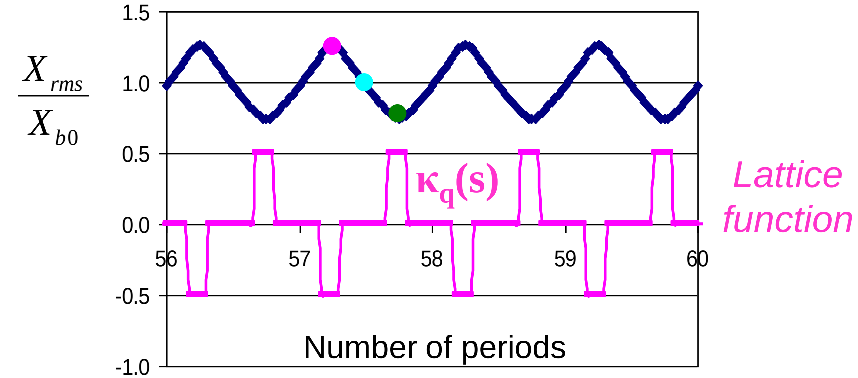
Self-Similar Beam Density Evolution

Quadrupole lattice σ/σ_{vac}=0.26, σ_{vac}=66^0 (WARP simulations)

Regularly normalized coordinates



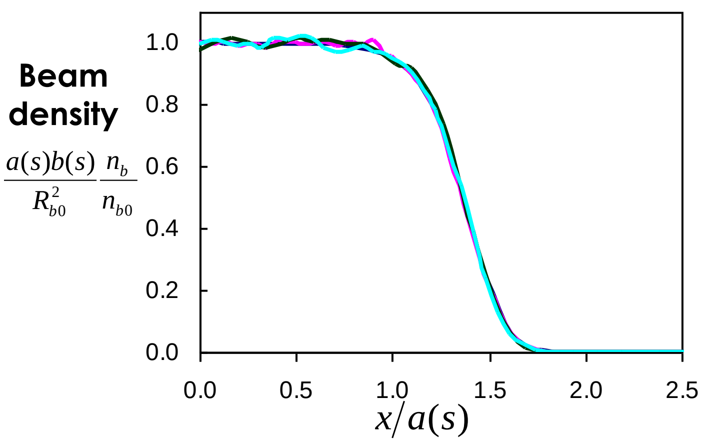
Evolution of the beam envelope



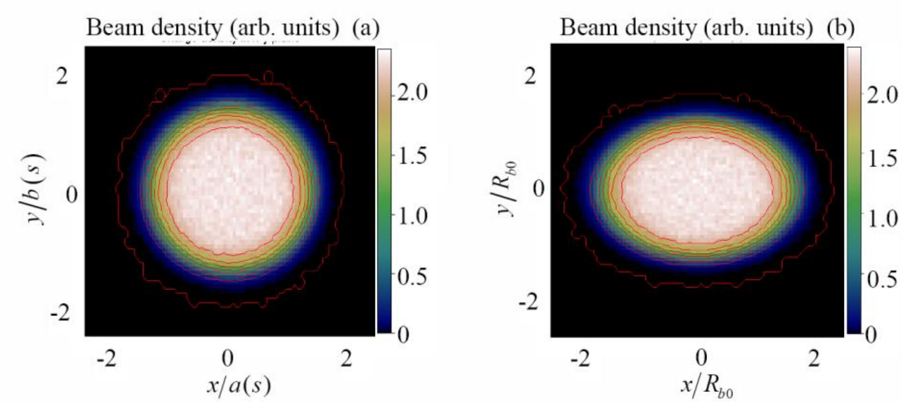
Scaled coordinates

$$a(s) = \sqrt{2}X_{rms}(s)$$

$$b(s) = \sqrt{2}Y_{rms}(s)$$



Contour plots of the beam density (σ_{vac}=45^0)



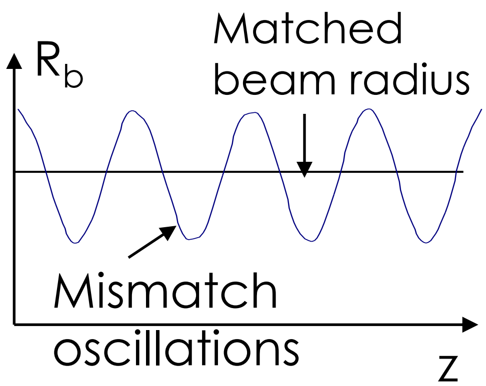
Self-similar beam density evolution has been demonstrated for a broad range of beam intensities. The self-similarity feature becomes less accurate for σ_{vac}~80^0.

Dorf *et al.*, Phys. Plasmas **16**, 123107 (2009)

Halo Production by a Beam Mismatch

Smooth-focusing approximation

Collective motion

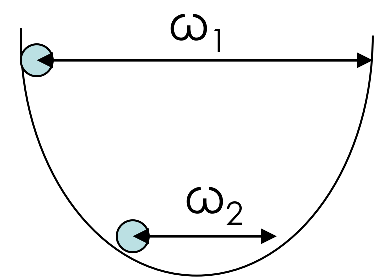


Energy transfer

$$\omega_{part} \sim \omega_{mis}/2$$

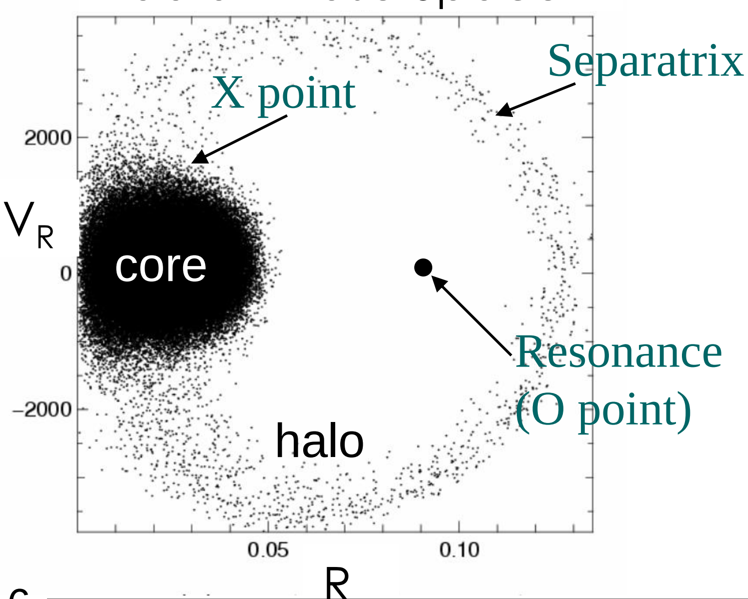
Parametric resonant interaction

Individual motion (each particle is an oscillator)



Due to the nonlinear effects of the beam self-fields particles with higher energy move with higher frequency

Radial Phase Space



Beam Halo

- Cause degradation of the beam quality
- Can provide activation of the chamber wall

One of the important problems:

How to quantitatively define beam halo?

Fusion Energy Sciences

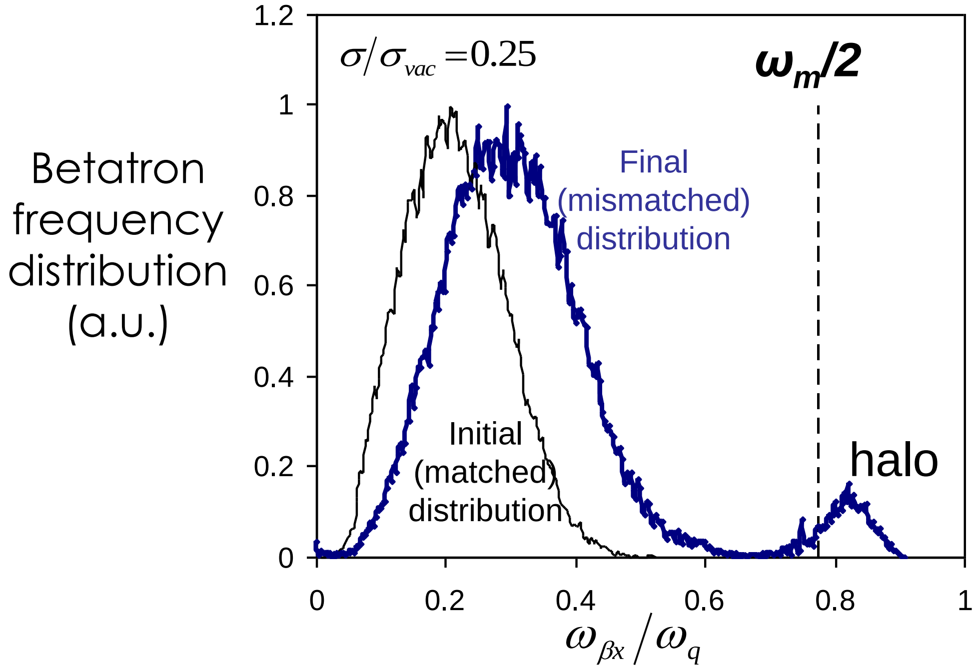
Spectral Method for Halo Particle Definition

Smooth-focusing model (WARP simulations)

Consider a mismatched intense beam with $\delta R_b/R_b=0.12$

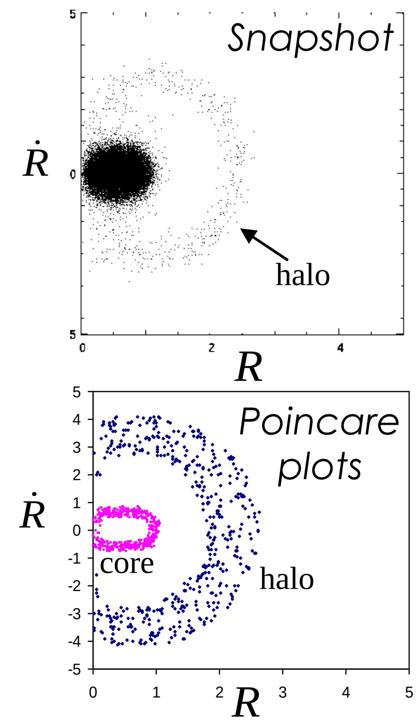
Beam frame:
- $\omega_q=\kappa_{sf}V_b$ smooth-focusing frequency
- ω_m frequency of mismatch oscillations

Beam is an ensemble of betatron oscillators

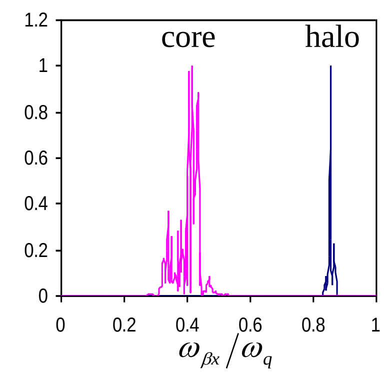


Bump-on-tail structure for $\omega_\beta>\omega_m/2$ can be attributed to beam halo particles

Radial phase-space



FFT of a particle trajectory

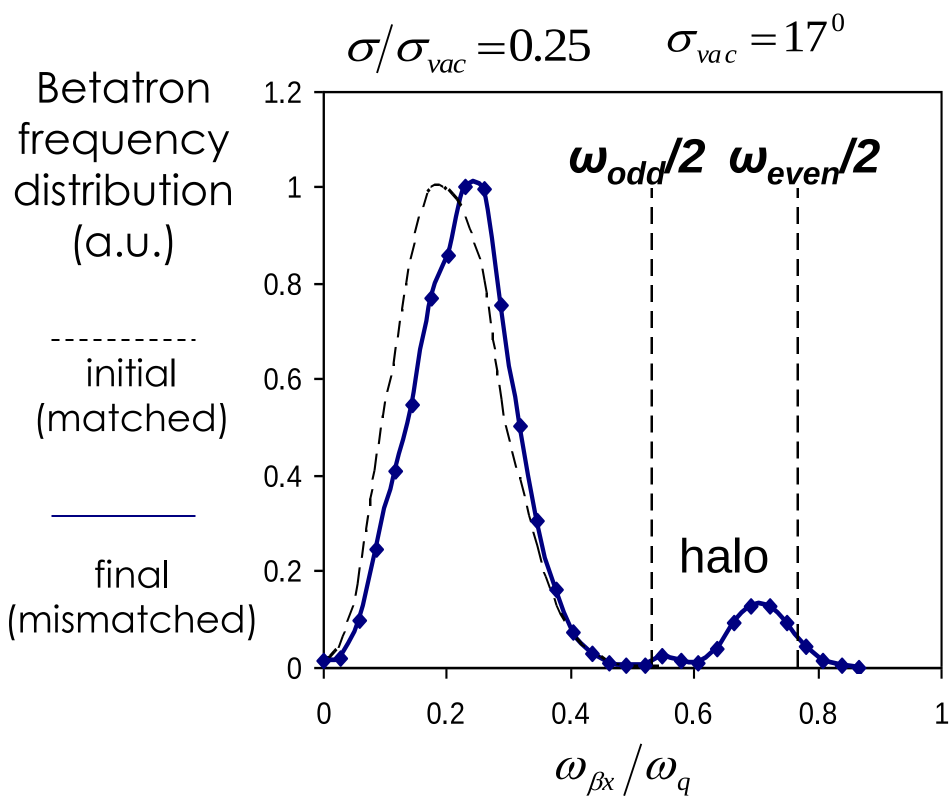


M. Dorf *et al* Phys. Plasmas, **18**, 043109 (2011).

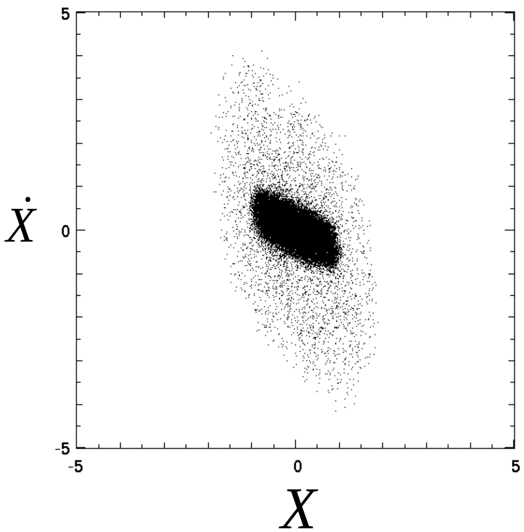
Extension of the Spectral Method to the Case of a Quadrupole Lattice

Quadrupole lattice (WARP simulations)

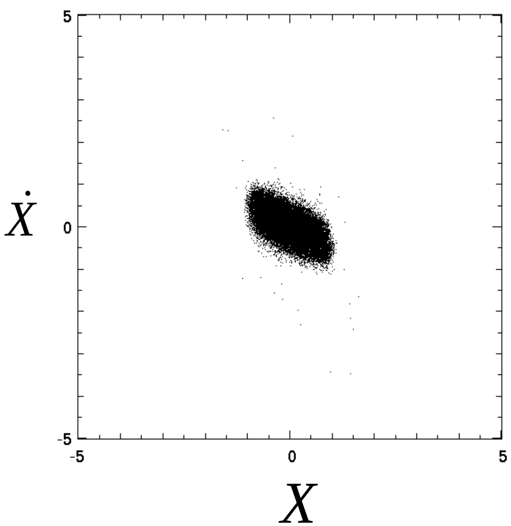
Symmetric (even) and quadrupole (odd) modes are simultaneously excited



Transverse phase-space



Halo removal



Bump-on-tail structure for $\omega_\beta > \omega_{odd}/2$ can be attributed to beam halo particles

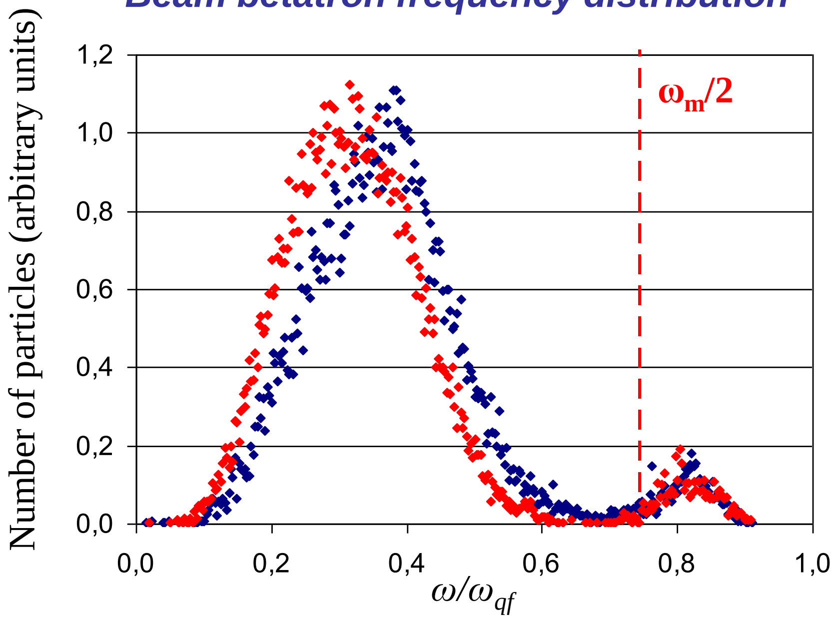
M. Dorf *et al* Phys. Plasmas, **18**, 043109 (2011).

Mismatch Relaxation in Intense Beams

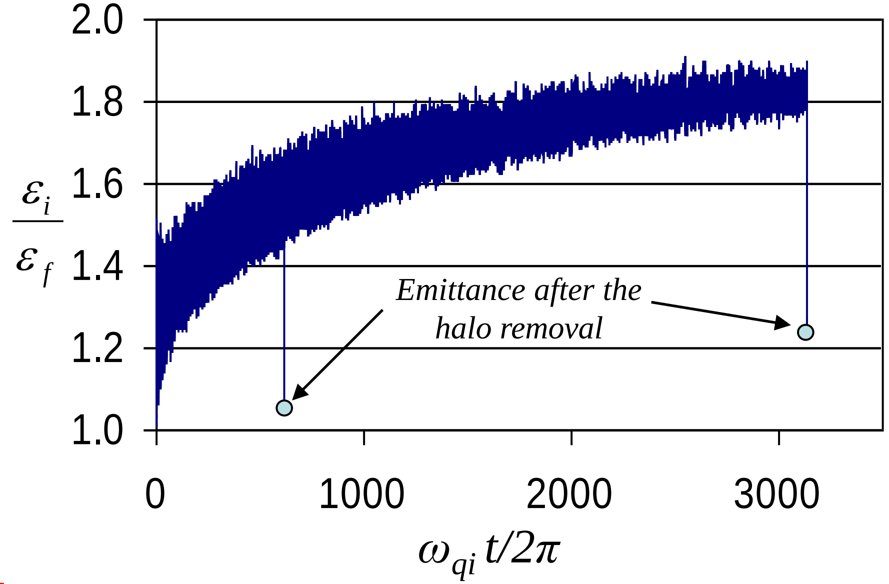
Smooth-focusing approximation. Intense beam with σ/σ_{vac}=0.25 (WARP simulations)

We introduce a mismatch by an instantaneous increase in the smooth-focusing frequency $\omega_{qf}=1.4\omega_{qi}$

Beam betatron frequency distribution



Normalized emittance

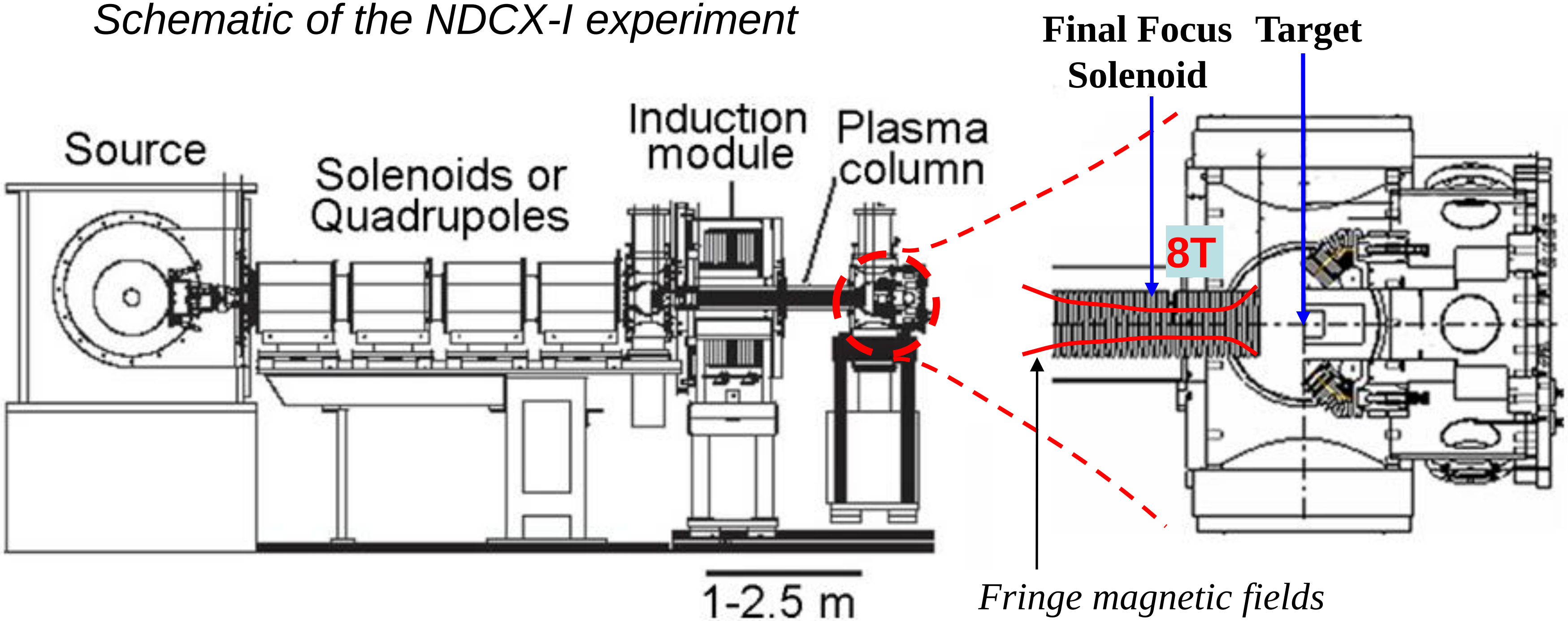


Frequency distribution @
- $t=617*2\pi/\omega_{qi}$ (red)
- $t=3140*2\pi/\omega_{qi}$ (blue)

- *Most of the halo is generated relatively fast*
- *Core relaxation process takes much more time*
- *Core relaxation process also leads to emittace growth*

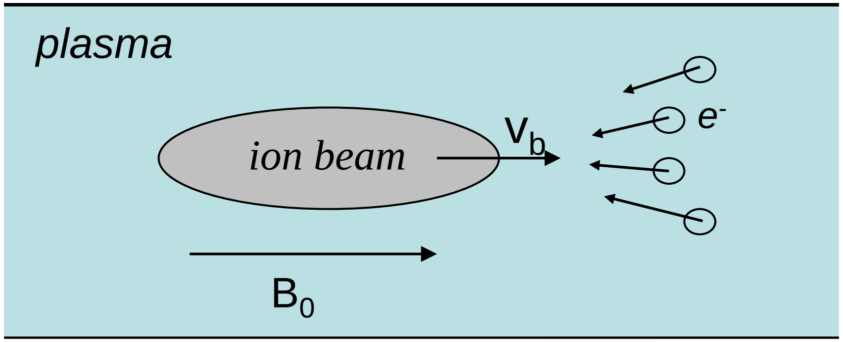
III. Intense Ion Beam Transport through a Background Plasma

Schematic of the NDCX-I experiment



- **Weak fringe magnetic fields (~100 G) penetrate deep into background plasma.**
- **Can a weak solenoidal magnetic field has a significant influence on intense ion propagation through a background plasma?**

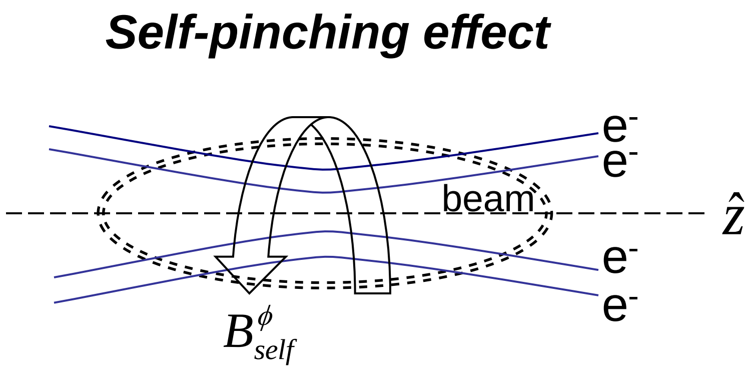
III. Ion Beam Propagation through a Neutralizing Background Plasma Along a Solenoidal Magnetic Field



References
[1] M. Dorf *et al.,* Phys. Plasmas, **19**, 056704 (2012) .
[2] M. Dorf *et al.*, Phys. Plasmas, **17**, 023103 (2010).
[3] M. Dorf *et al.*, Phys. Rev. Lett., **103**, 075003 (2009).

Enhanced Self-Focusing of an Intense Ion Beam Pulse

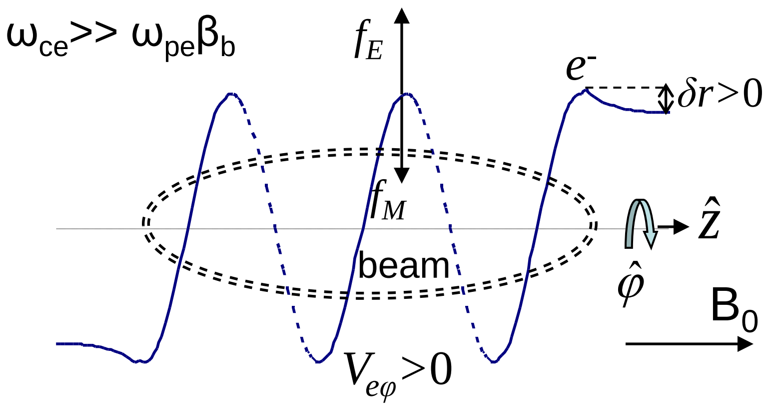
Magnetic field is not applied
$B_0=0$



- The ion beam space-charge is typically better compensated than the beam current
- Net self-pinching force is produced due to the self-magnetic field
- The effects of self-pinching is maximum for $r_b \ll c/\omega_{pe}$, and the focusing force is given by

$$F_{sp} = Z_b^2 \frac{\omega_{pe}^2}{c^2} m_e V_b^2 \frac{1}{r n_p} \int r n_b dr$$

Weak magnetic field is applied
$B_0 \sim 100$ G



- Radial displacement of background electrons is accompanied by an azimuthal rotation
- Strong radial electric field is produced to balance the magnetic V×B force acting on the electrons
- The total self-focusing force is given by

$$F_{sf} = Z_b^2 m_e V_b^2 \frac{1}{n_p} \frac{dn_b}{dr} \quad \text{for} \quad \frac{V_b}{\omega_{ce}} \sqrt{1 + \frac{\omega_{ce}^2}{\omega_{pe}^2}} \ll r_b \ll \frac{c}{\omega_{pe}}$$

$$F_{sf}/F_{sp} \sim (c/\omega_{pe} r_b)^2 \gg 1$$

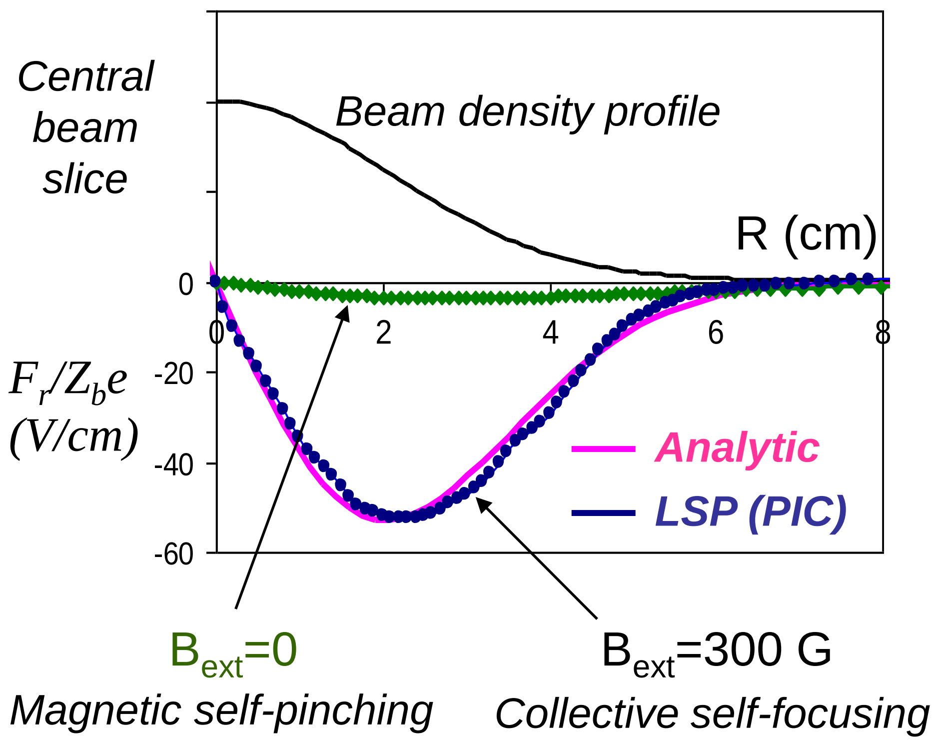
There is a significant enhancement of the ion beam self-focusing effect in the presence of a weak solenoidal magnetic field.

M. Dorf *et al.*, *PRL* **103**, 075003 (2009)

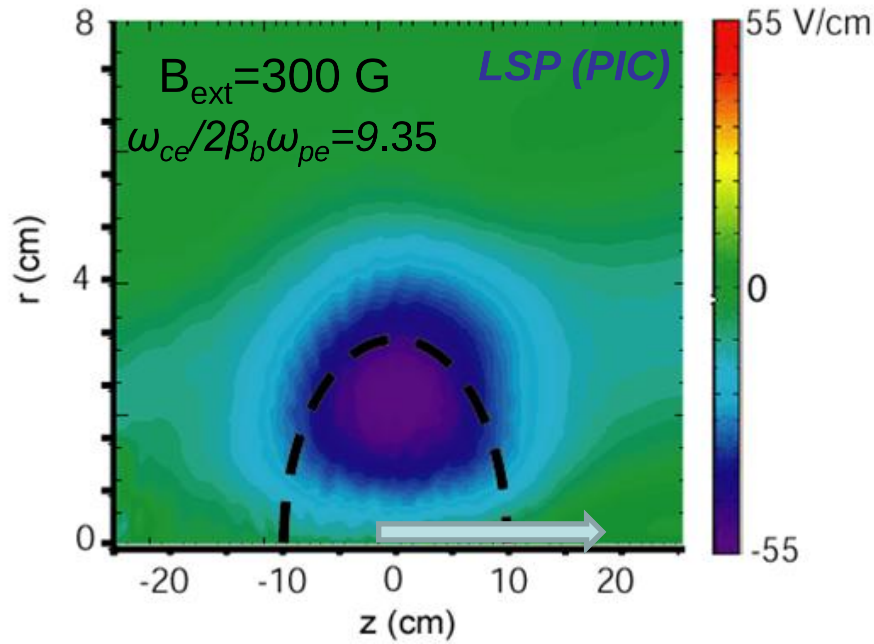
Enhanced Self-Focusing is Demonstrated in Simulations

Gaussian beam: $\mathbf{r_b=0.55c/\omega_{pe}}$, $L_b=3.4r_b$, $\beta=0.05$, $n_b=0.14n_p$, $n_p=10^{10}\ cm^{-3}$

Radial focusing force



Radial electric field



The enhanced focusing is provided by a strong radial self-electric field

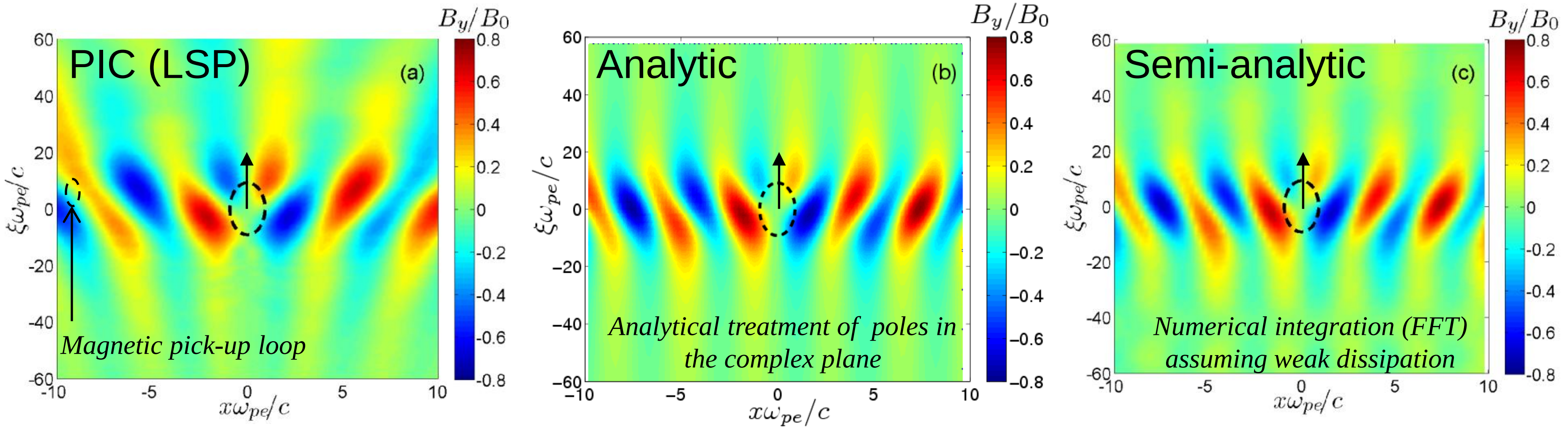
Influence of the plasma-induced collective focusing on the ion beam dynamics in

- *NDCX-I is negligible*
- *NDCX-II is comparable to the final focusing of an 8 T short solenoid*

M. Dorf *et al*, PRL **103**, 075003 (2009).

Electromagnetic Wave Excitation

Transverse magnetic field (Whistler waves)



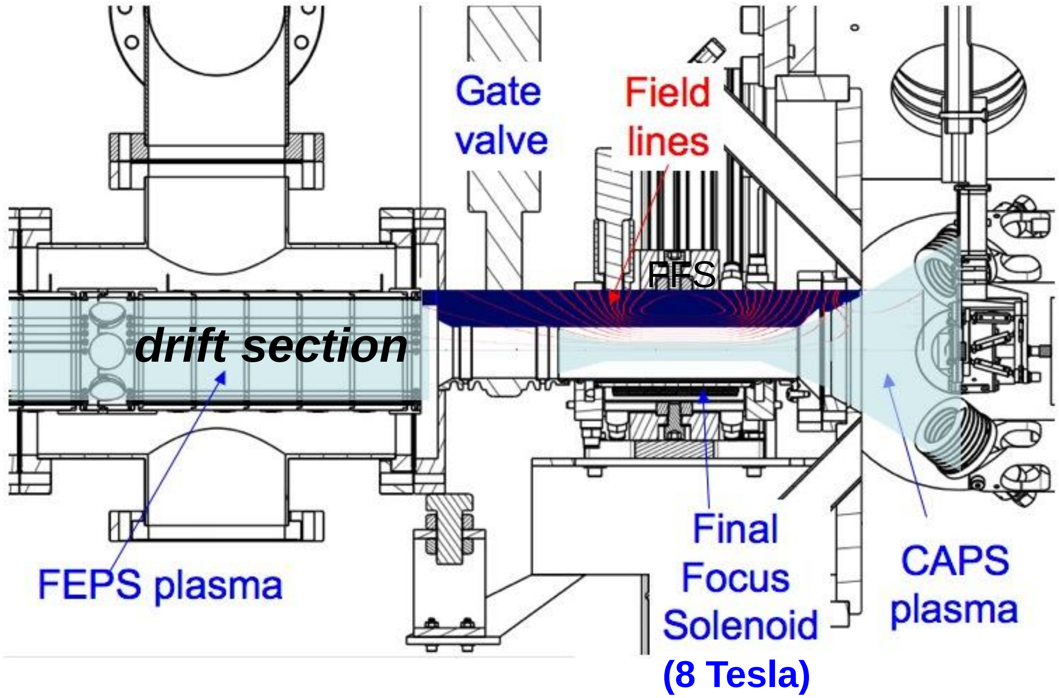
β_b=0.33, l_b=10r_b, r_b=0.9·c/ω_{pe}, n_b=0.05n_p, B_{ext}=1600G, n_p=2.4·10^{11}cm^{-3}

- ***Analytic theory is in very good agreement with the PIC simulations***
- ***Strong wave excitation occurs at $\omega_{ce}/2\beta_b\omega_{pe}$ (supported by PIC simulations)***
- ***Wave-field excitations can be used for diagnostic purposes***

M. Dorf *et al,* Phys. Plasmas, **17**, 023103 (2010).

IV. Collective Focusing Lens for Final Beam Focusing

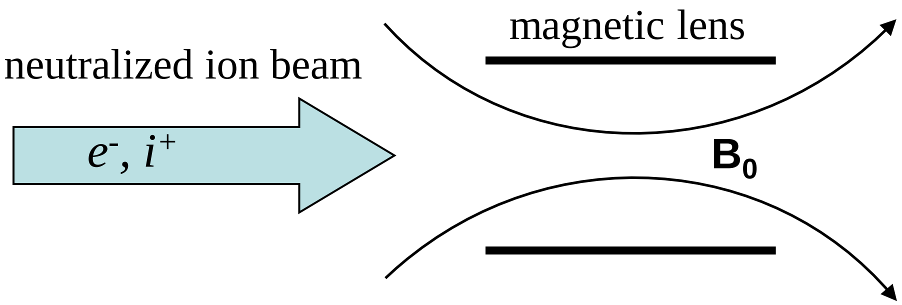
Schematic of the present NDCX-I final focus section



- **Challenges:**
  - *Operate 8 T final focus solenoid*
  - *Fill 8 T solenoid with a background plasma*

- **Can a weak magnetic lens be used for tight final beam focusing?**

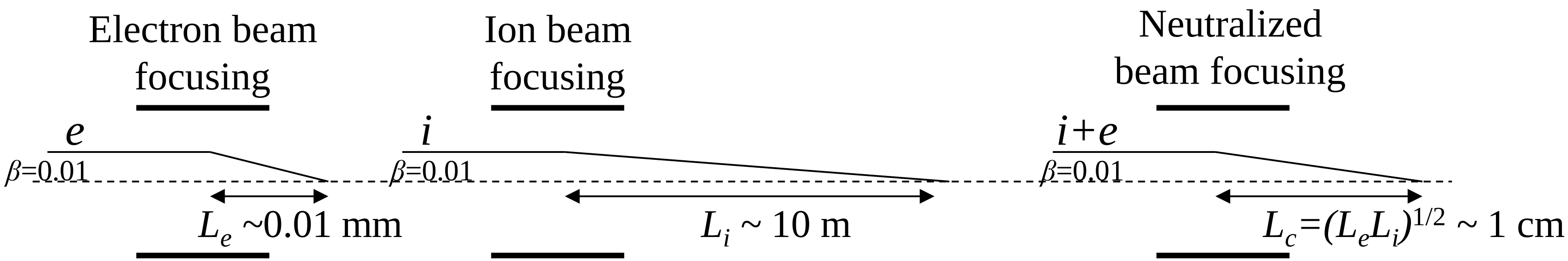
IV. Collective Focusing of an Intense Neutralized Ion Beam Pulse



References
[1] M. Dorf *et al.,* Phys. Plasmas, **18**, 033106 (2011).
[2] M. Dorf *et al.,* PAC Proceeding 2011.

Collective Focusing Lens

Collective Focusing Concept (S. Robertson 1982, R. Kraft 1987)



Electron beam focusing	Ion beam focusing	Neutralized beam focusing
B=500 G L=10 cm	B=500 G L=10 cm	B=500 G L=10 cm

The use of a collective focusing lens allows for decrease in the magnetic field by $(m_i/m_e)^{1/2}$

- Strong ambipolar electric field is produced to balance the magnetic V×B force acting on the co-moving electrons

$$eE_r = \frac{e}{c}V_{e\phi}B_0 - m_e\frac{V_{e\phi}^2}{r}$$

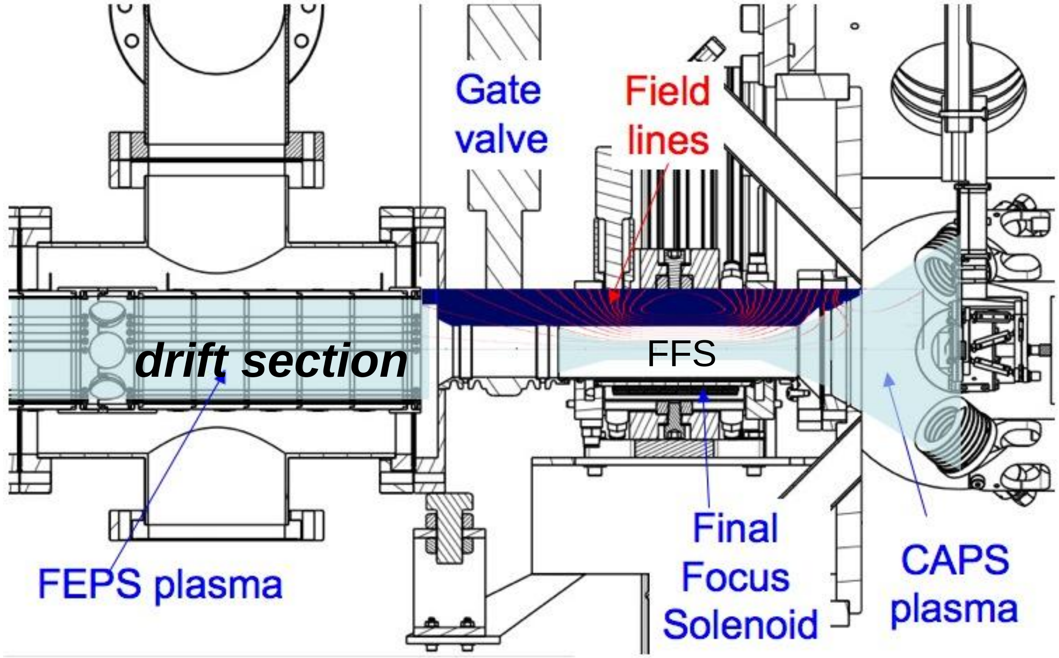
Electric force — V×B magnetic force — Centrifugal force

- From conservation of canonical angular momentum $\quad V_{e\varphi} = -\omega_{ce}\frac{r}{2}$
- The radial electric field is given by $\quad E_r = -m_e\Omega_e^2\frac{r}{4e}$

- **Conditions for collective focusing**
  - *To maintain quasi-neutrality* $\quad \omega_{pe} \ge \Omega_e/\sqrt{2}$
  - *To assure small magnetic field perturbations (due to the beam)* $\quad r_b \le 2c/\omega_{pe}$

Collective Focusing Lens for a Heavy Ion Driver Final Focus

Schematic of the present NDCX-I final focus section



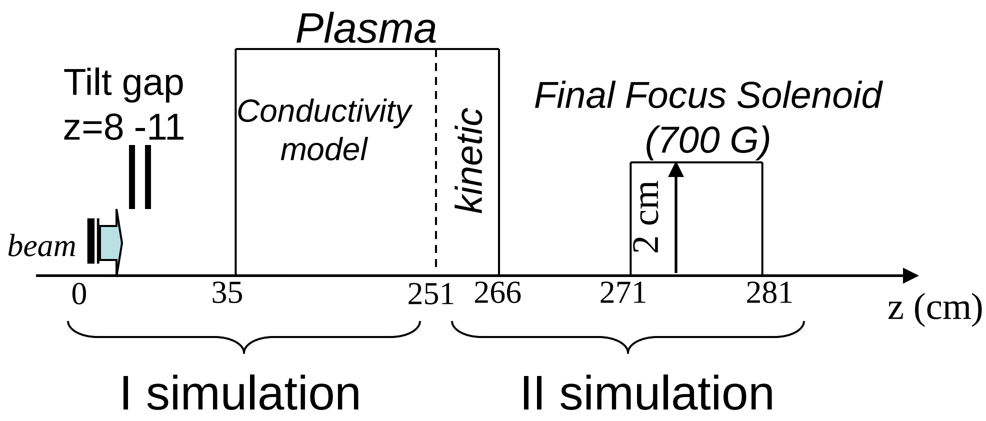
Beam can drag neutralizing electrons from the drift section filled with plasma.

⇨ ***The collective focusing concept can be utilized for final ion beam focusing in NDCX.***

- ***No need to fill the final focus solenoid (FFS) with a neutralizing plasma***
- ***Magnetic field of the FFS can be decreased from 8 T to ~700 G***

Numerical Simulations Demonstrate Tight Collective Final Focus for NDCX-I

Schematic of the NDCX-I simulation R-Z PIC (LSP)



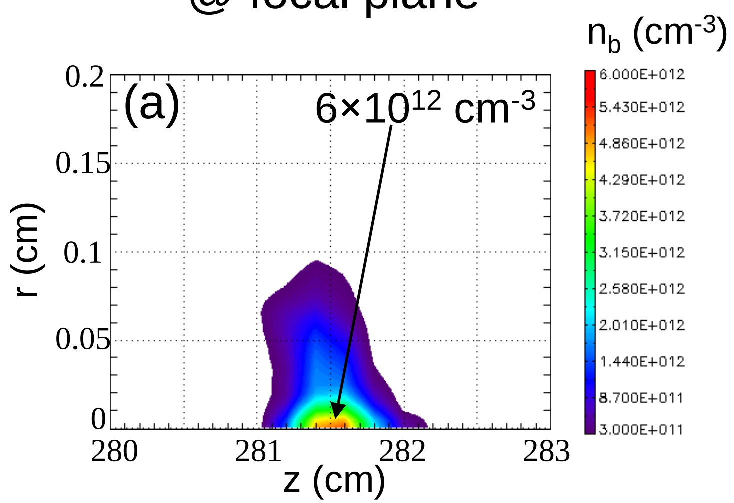
Beam injection parameters:

K^+ @ 320 keV, r_b=1.6 cm,
I_b=27 mA T_b=0.094 eV,

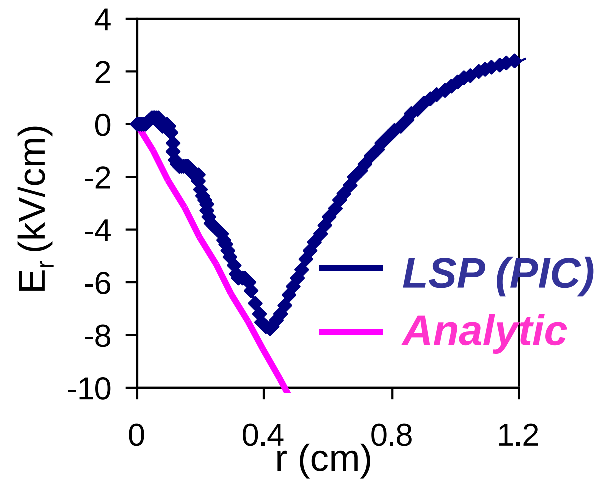
Plasma parameters (for the simulation II)

$n_p=10^{11}$ cm^{-3}, T_e=3 eV

Beam density @ focal plane



Radial electric field inside the solenoid



M. Dorf *et al.*, Phys. Plasmas, **18**, 033106 (2011).

Conclusions

Transport properties of intense ion beam pulse propagating in an ion driver have been investigated, in particular:

ion source →

- Modeling of the ion beam extraction from the SMIS-37 ion source was performed
- Low-noise extraction regimes were identified
- Ion beam transverse emittance was analyzed

acceleration and transport →

- A numerical method for the adiabatic formation of a quasi-equilibrium beam distribution matched to a periodic focusing lattice was developed
- A spectral method for beam halo definition was proposed

neutralized compression →

- Enhanced self-focusing of an intense ion beam pulse propagating through a magnetized plasma background was found
- Electromagnetic (whistler) wave excitation was analyzed

final focusing →

- The feasibility of tight collective focusing of intense ion beams for NDCX was demonstrated