Space-charge compensation for high-intensity linear and circular accelerators at Fermilab

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October 1, 2013

NAPAC ’13, Pasadena, CA

Many valuable inputs from

Qing Ji / Dave Grote (WARP simulation), Sasha Shemyakin / Bruce Hanna / Dmitry Bazyl / Vic Scarpine (PXIE LEBT), Vadim Dudnikov (e-p suppression), Alexander Valishev / Eric Prebys / Viatcheslav Danilov / Giulio Stancari / Sergei Nagaitsev / Victor Vorobjov (IOTA)

U.S. DEPARTMENT OF ENERGY

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Beam Space-Charge: A fundamental intensity limitation in high-intensity accelerators

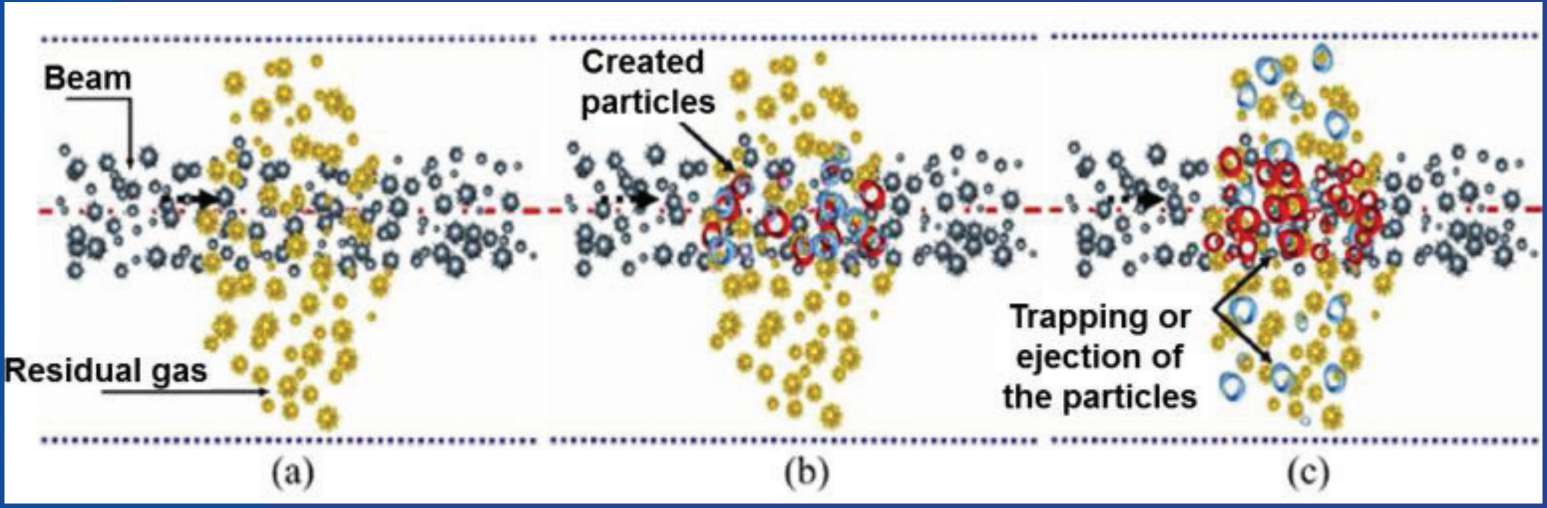
$$s_b = \frac{\hat{\omega}_{pb}^2 / 2\gamma_b^2}{\omega_{\beta\perp}^2} < 1$$

[R.C. Davidson, Physics of nonneutral plasmas (1990)]

$$|\Delta \nu_{sc}| = \frac{N_{b,tot} r_{cb}}{2\pi\beta_b^2\gamma_b^3\varepsilon} \frac{\hat{I}}{\bar{I}} < 0.25$$

[M. Reiser, Theory and design of charged particle beams (1994)]

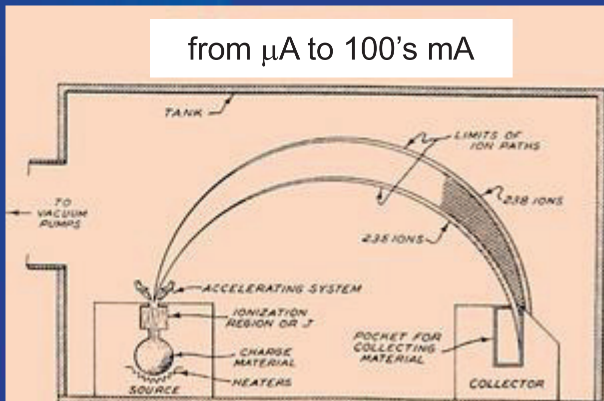
Space-Charge Compensation: Based on neutralization by oppositely charged particles (gas ionization / plasma source)



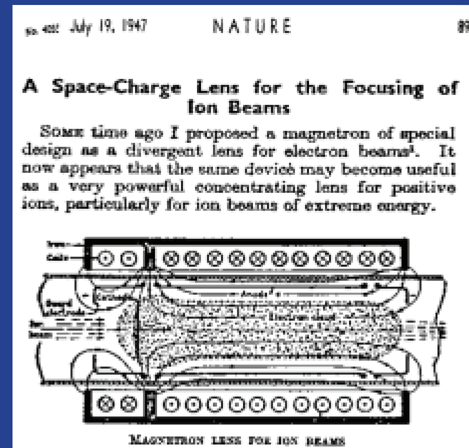
[Courtesy of N. Chauvin, ICIS'11]

A brief history of Space-Charge Compensation

Isotope separation in the Manhattan project (Lawrence,1941)



Gabor lens (1947)



July 19, 1947 NATURE 89

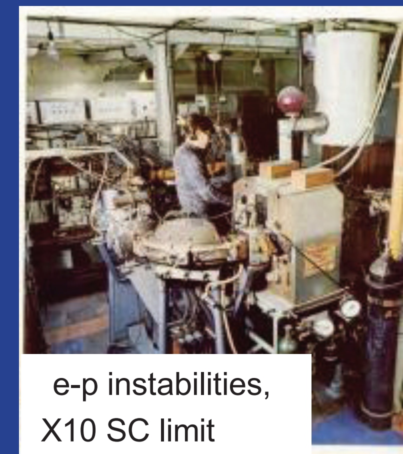
A Space-Charge Lens for the Focusing of Ion Beams

Some time ago I proposed a magnetron of special design as a divergent lens for electron beams[1]. It now appears that the same device may become useful as a very powerful concentrating lens for positive ions, particularly for ion beams of extreme energy.

MAGNETRON LENS FOR ION BEAMS

PSR at INP (1967)

[Budker, Dudnikov et al.]



LEBT after the invention of RFQ by Kapchinsky and Teplyakov (1970)

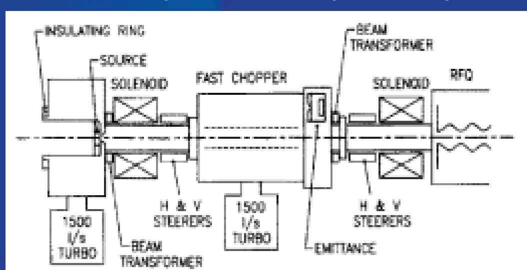
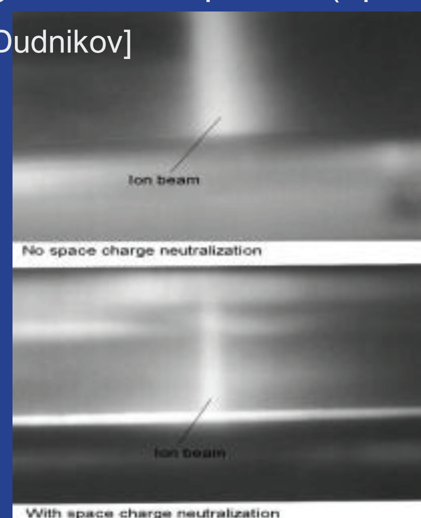


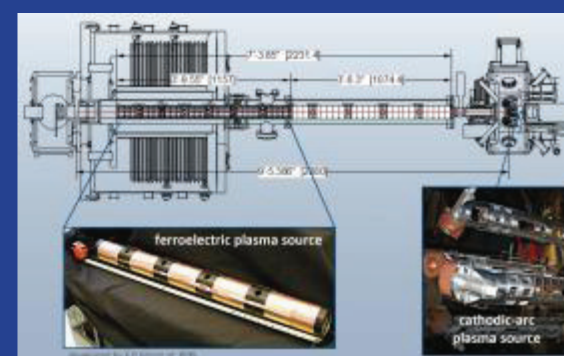
Fig. 1. Layout of the new 35 keV LEBT system for injection into the 200 MHz RFQ at Brookhaven National Laboratory.

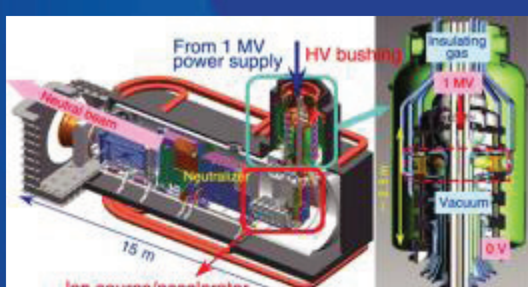
High current implanter (~present)

[A. Dudnikov]



NTX/NDCX-I,II (~ present)





Neutral beam heating (>1970)

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Let’s revisit SCC for the next-generation accelerators

- Mission of the US HEP program in the Intensity Frontier

- New dedicated accelerator R&D facilites
  - Project-X Injector Experiment (PXIE)
  - Integrable Optics Test Accelerator (IOTA)

- Powerful simulation tools with plasma processes
  - WARP 3D [Dave Grote et al, LBNL]
  - VORPAL [Dan T. Abell et al, Tech-X Corp]

- Advanced beam, plasma, and gas diagnostics & controls
  - DCCT, Allison emittance scanner, Faraday cup, scrapers
  - Plasma density/temperature measurements, rotating wall technique
  - Residual gas ion analyzer, controlled leak

Basic definitions and processes:

Neutralization time

$$\tau_n = \frac{1}{n_g \sigma_i v_b}$$

Fractional neutralization

$$f_n = \frac{n_p}{n_b}$$

Voltage difference

$$V_s = \phi(0) - \phi(r_b) = \frac{I_b(1 - f_n)}{4\pi\varepsilon_0 v_b}$$

Critical density

$$n_{g,cr} = \frac{1/\tau_{p,exit}}{v_b \sigma_i}$$

Negative Hydrogen Beam

$$\mathrm{H^-} + \mathrm{H_2} \rightarrow \mathrm{H} + \mathrm{H_2} + e$$ ← Stripping

Ionization → $$\mathrm{H^-} + \mathrm{H_2} \rightarrow \mathrm{H^-} + \mathrm{H_2^+} + e$$

Ionization → $$e + \mathrm{H_2} \rightarrow \mathrm{H_2^+} + 2e$$

$$\mathrm{H^-} + \mathrm{H} \rightarrow \mathrm{H} + \mathrm{H^-}$$

$$\mathrm{H^-} + \mathrm{H} \rightarrow 2\mathrm{H} + e$$

$$e + \mathrm{H} \rightarrow \mathrm{H^-} + 2e$$

Proton Beam

$$p + \mathrm{H_2} \rightarrow \mathrm{H} + \mathrm{H_2^+}$$

$$p + \mathrm{H_2} \rightarrow p + 2\mathrm{H}$$

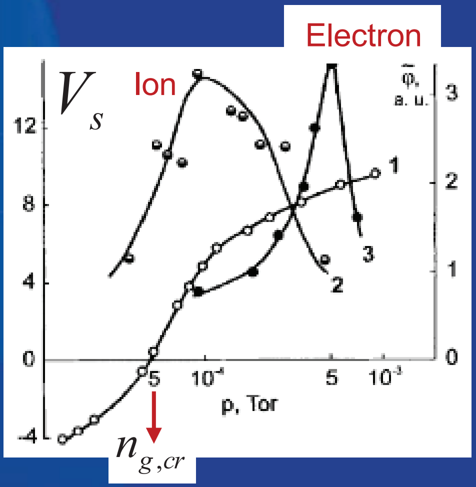
Ionization → $$p + \mathrm{H_2} \rightarrow p + \mathrm{H_2^+} + e$$

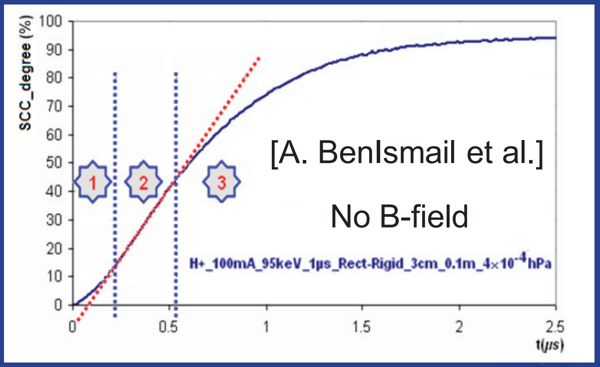
Ionization → $$e + \mathrm{H_2} \rightarrow \mathrm{H_2^+} + 2e$$

$$p + \mathrm{H} \rightarrow \mathrm{H} + p$$

$$e + \mathrm{H} \rightarrow \mathrm{H^-} + 2e$$

[I. A. Soloshenko]

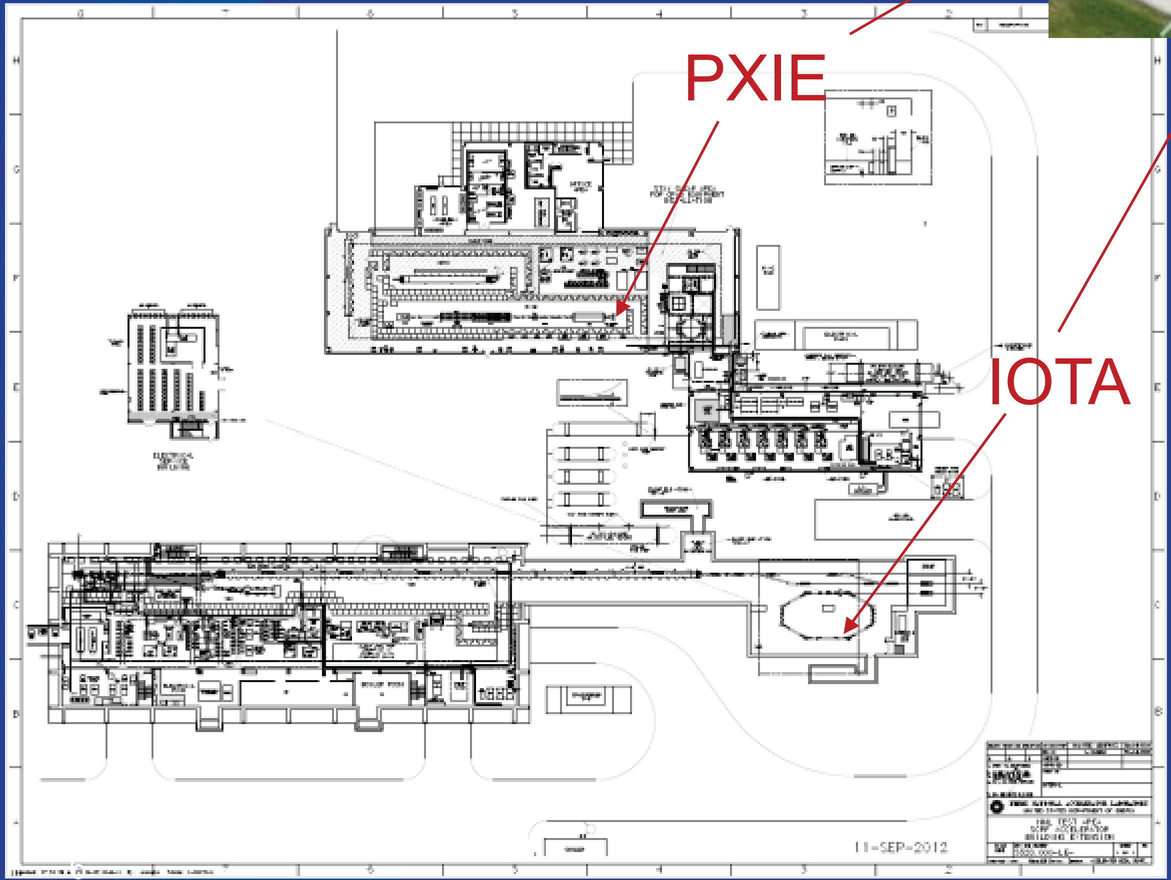




PXIE: An R&D program to address accelerator physics and technology issues of Project-X

Ion source + LEBT + RFQ + MEBT + HWR + SSR1

$H^- + H_2 \rightarrow H^- + H_2^+ + e$



IOTA: A small storage ring to test nonlinear integrable optics

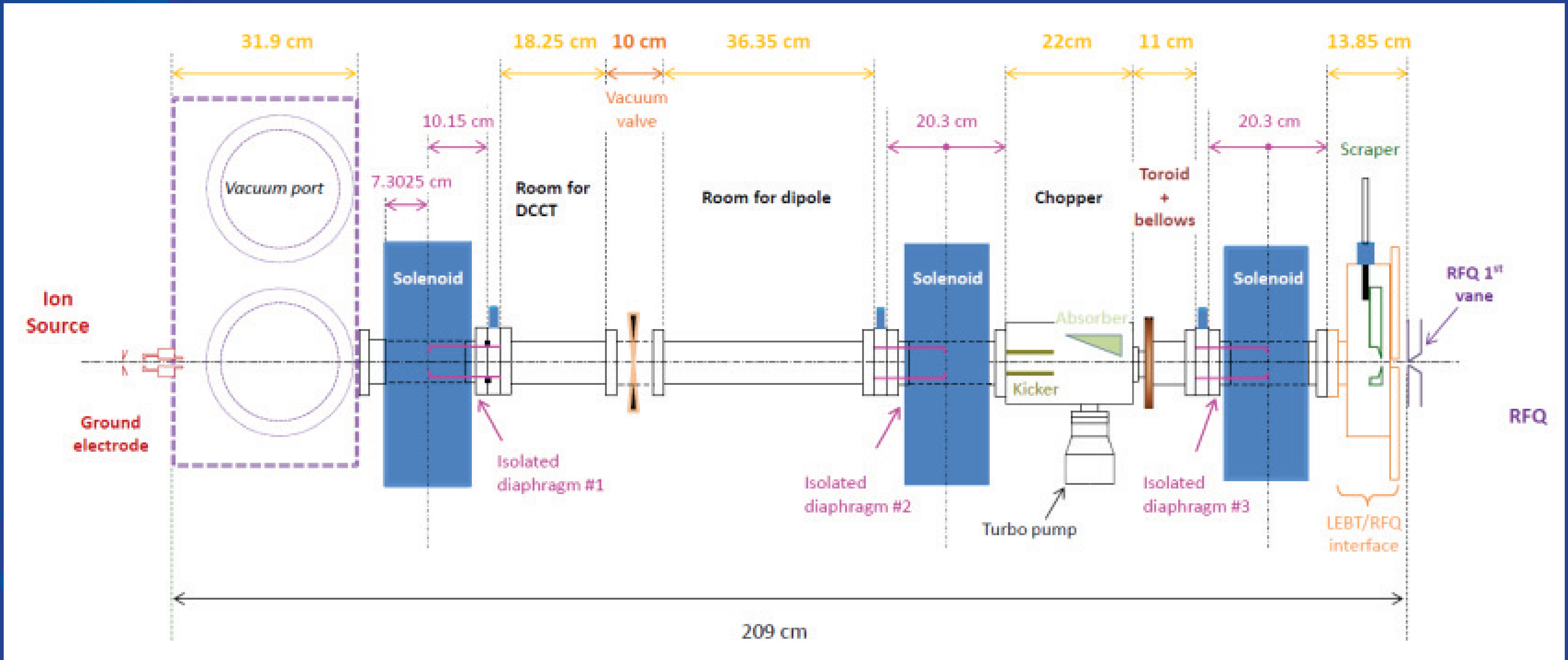
e-beam → single-particle
Proton-beam → space-charge

symmetric lens +
drift with equal β-functions with nonlinear elements +
e-column or e-lens

$p + H_2 \rightarrow p + H_2^+ + e$

1. PXIE: LEBT Functions

- Transports and matches the beam to the RFQ optical functions
- Acts as the first layer of the machine protection system (MPS)
- Provides pulsed (chopped) beam for commissioning of the beam line downstream



30 keV, up to 10 mA DC

shutting the beam off in < 1 μs

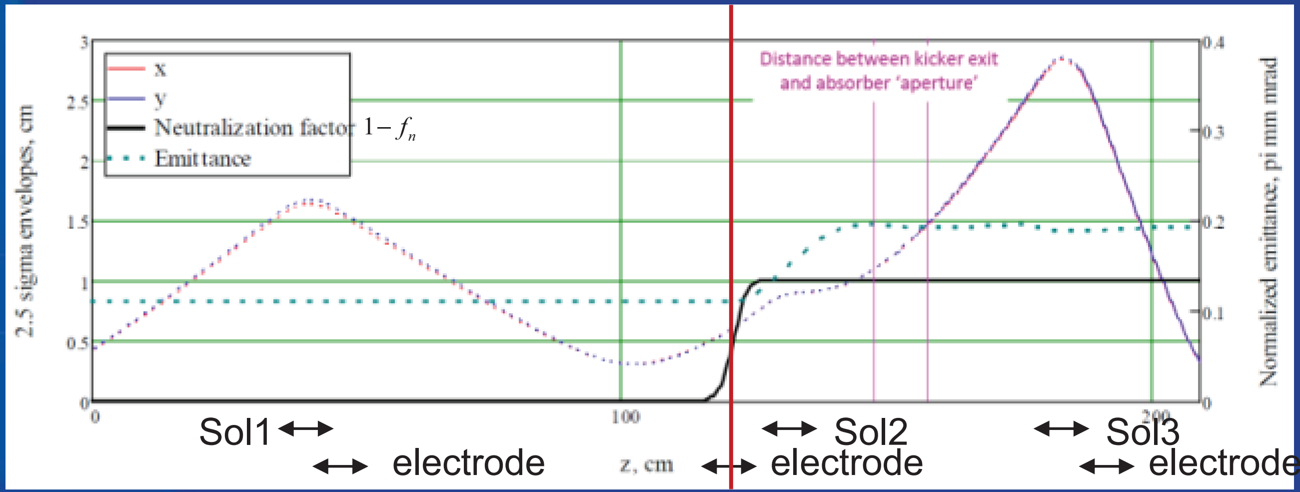
μs to ms pulses at tens of Hz

1. PXIE: Transport Schemes

- Un-neutralized transport
  - ✓ Emittance growth / More stringent vacuum requirement
  - ○ Reduced transition effects
- Neutralized transport
  - ✓ Transition effects for pulsed beam / Gas load to RFQ
  - ○ Low emittance growth

→ Combination of neutralized/un-neutralized transports to minimize beam parameter changes between commissioning (*pulsed/chopped beam*) and normal operation (*DC beam*)

[L. Prost, V. Lebedev]



Neutralized transport ← → Un-neutralized transport

1. PXIE: Beam physics to be tested

Transient effects: after the solenoid 2

- To investigate whether the emittance growth during the transition from neutralized to un-neutralized transports is acceptable
- To investigate whether the beam parameters at the entrance of the RFQ are indeed same for commissioning (pulsed/chopped beam) and normal operation (DC beam)

Collective processes: before the solenoid 2

- To study the stability of the beam-plasma system during the CW operation of the negative hydrogen beam

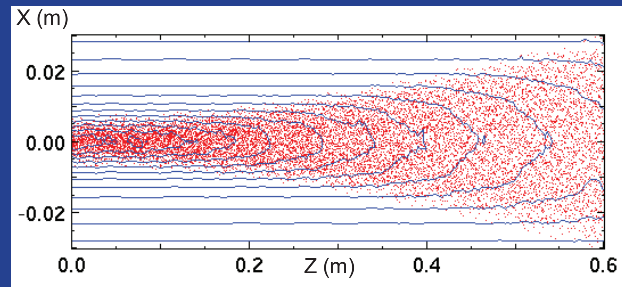
Ready for commissioning in early December.

1. PXIE: WARP 3D simulations with multispecies

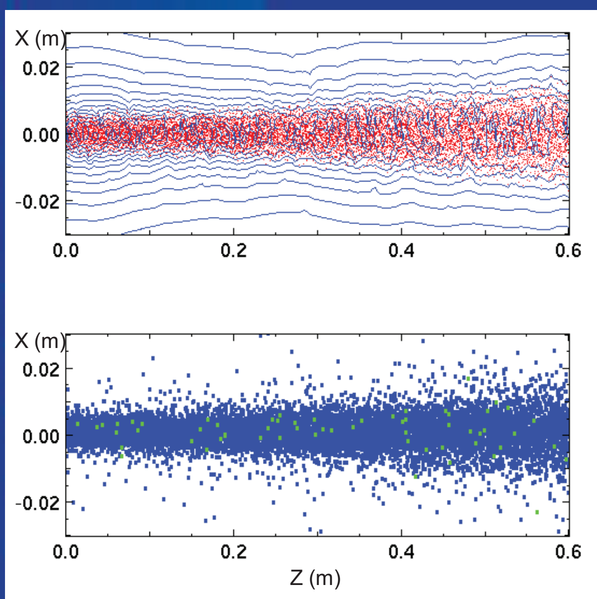
[with D. Grote and Q. Ji]

Red dots : H- (10 mA)
Blue dots: H2+
Green dots: e
Blue curves: e-s potential

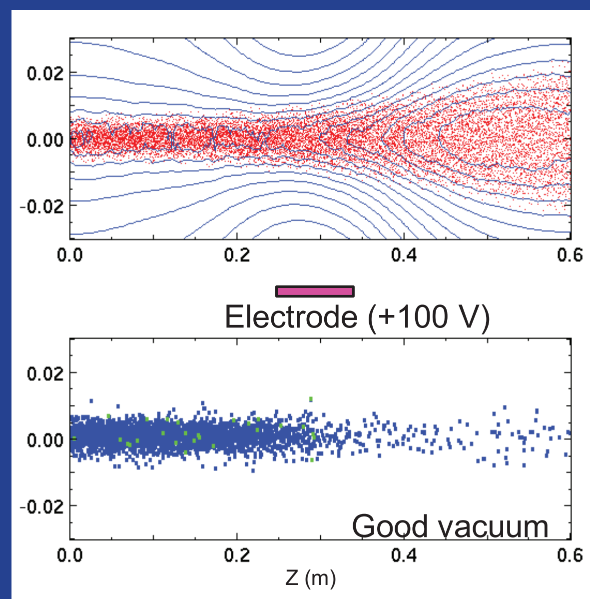
w/o SCC and Bsol=0



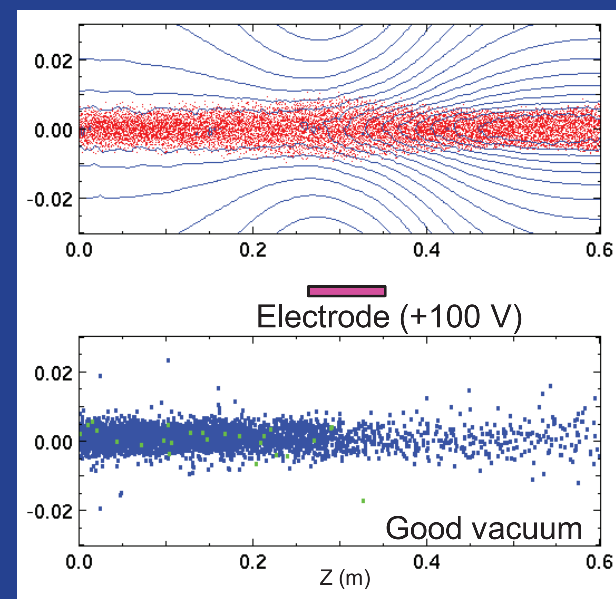
with SCC and Bsol=0



with half-SCC and Bsol=0



with half-SCC and Bsol=4 kG



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2. IOTA: Motivation

- To test a novel solution for nonlinear integrable accelerator lattice that can be practically implemented with special magnets [V. Danilov et al.]

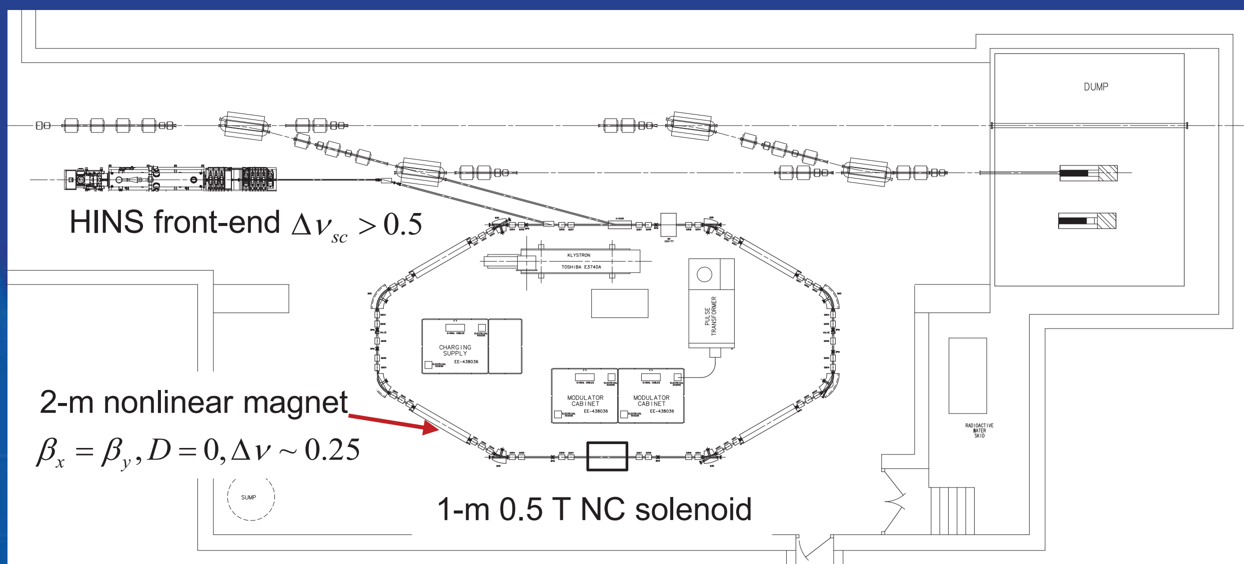
$$\vec{F}_{NL} = q_b\left[-\nabla_\perp \phi + \vec{v}_b \times (\nabla_\perp \times A_s \hat{s})\right] = -q_b \nabla_\perp V$$

$$V(x,y,s) = \frac{E_b \beta_b^2}{q_b} \frac{U_n}{\beta(s)}$$

$$U_n = -\frac{t}{c^2}\mathrm{Re}\left[(x_n + iy_n)^2 + \frac{2}{3c^2}(x_n + iy_n)^4 + \frac{8}{15c^4}(x_n + iy_n)^6 + \cdots\right]$$

- To demonstrate the possibility to achieve very large nonlinear tune spread in a realistic accelerator design using electron beam (~FY15)

150 MeV e
2.5 MeV p

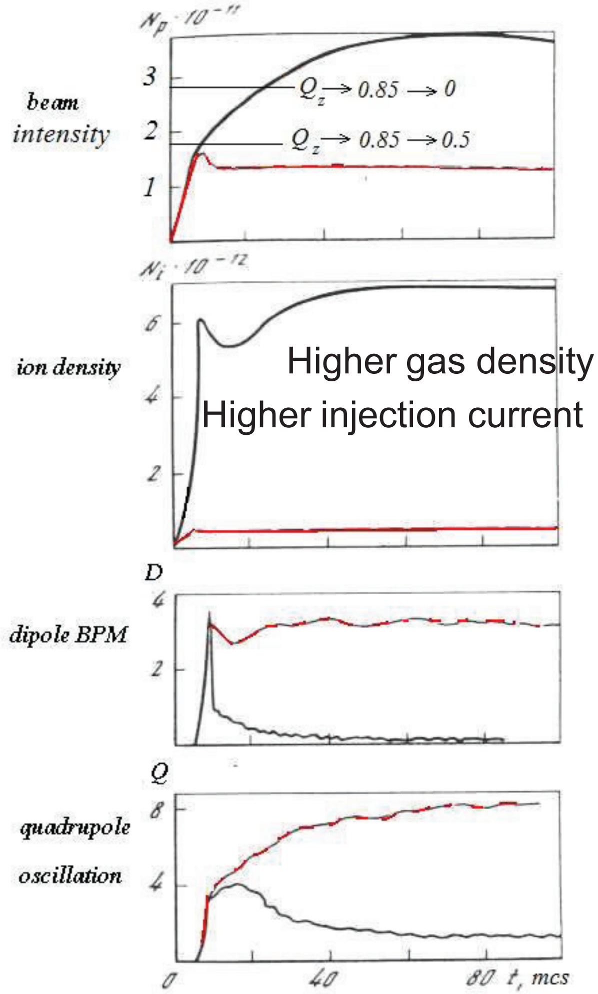


- To demonstrate performance in the space-charge dominated regime using proton beam (large tune spread ? → e-p suppression ?)

2. IOTA: Is SCC possible in rings ?

INP PSR (1967)

$$n_e \approx (n_b + n_i) > \frac{\beta_b^2}{2\pi r_{ce} r_b^2} \longrightarrow \lambda < r_b$$



[Courtesy of V. Dudnikov]

Fermilab's tradition: manipulating beams by well-controlled electrons

- Relativistic e-cooling
- Beam-Beam compensation
- Controlled halo removal

New ideas:

e-lens (e-gun + optics + solenoid)

Space-Charge Compensation in High-Intensity Proton Rings

A.V. Burov, G.W. Foster, V.D. Shiltsev

Fermi National Accelerator Laboratory

P.O. Box 500, Batavia, Illinois 60510

e-column (solenoid)

The Use of Ionization Electron Columns for Space-Charge Compensation in High Intensity Proton Accelerators

V.Shiltsev[a], Y.Alexahin[a], V.Kamerdzhiev[a], V.Kapin[a], G.Kuznetsov[a]

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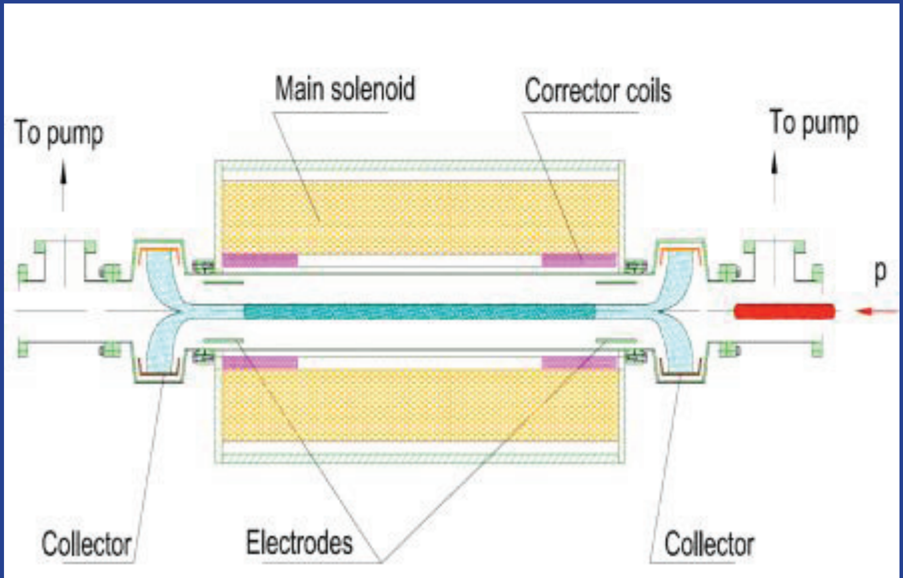
2. IOTA: E-column concept



1. The impact of electrons is equal to the total impact of space-charge over the ring

$$\left|\Delta\nu_{sc}\right| = \frac{N_{b,tot} r_{cb}}{2\pi\beta_b^2\gamma_b^3\varepsilon}\frac{\hat{I}}{\bar{I}} = \Delta\nu_e = \frac{N_e r_{cb}}{2\pi\beta_b^2\gamma\varepsilon}$$

$$\frac{N_e}{N_{b,tot}(\hat{I}/\bar{I})} = \frac{1}{\gamma_b^2} = \eta_0\frac{N_{ec}L_{ec}}{C}$$

2. The transverse profile of the electron is the same as that of the proton beam

→ use of solenoid

3. The system of electrons and protons is dynamically stable

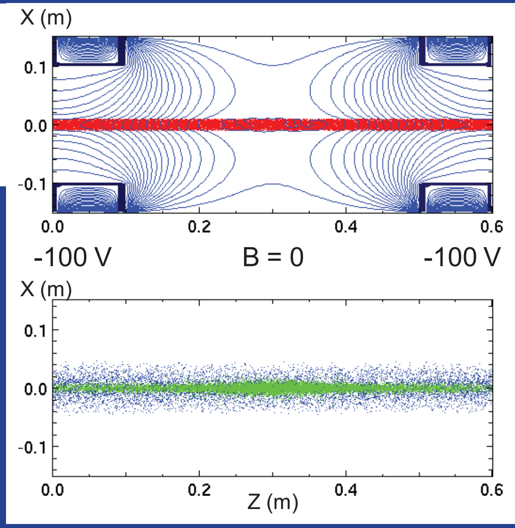
→ two-stream instability suppression (nonlinear magnet) /

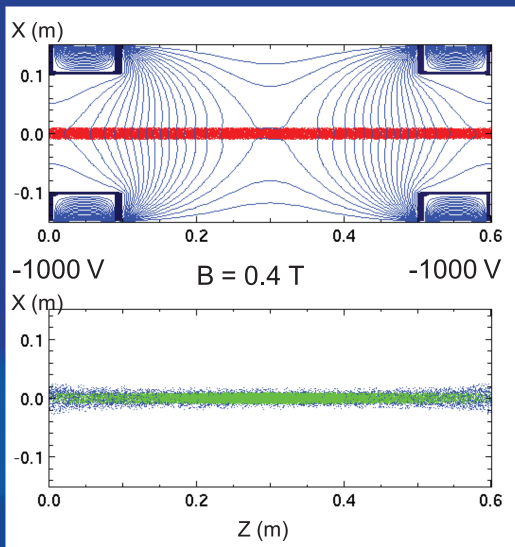
ion accumulation (electrode/vacuum) / stable electron trapping (rotating wall)

2. IOTA: Plasma and beam simulations

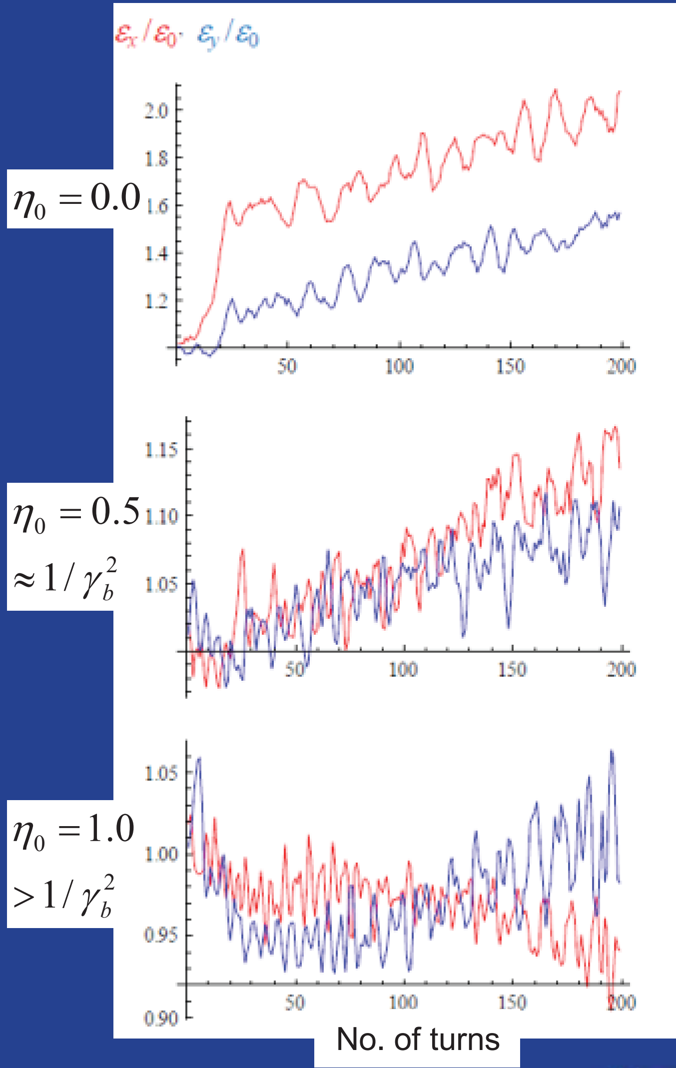
[WARP 3D]

Red dots : p (10 mA)
Blue dots: H2+
Green dots: e
Blue curves: e-s potential





[MAD: Y. Alexahin, V. Kapin]



$N_{ec} = 24$
$L_{ec} = 1$ m
$C = 474$ m

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Conclusion

- As the accelerators for Intensity Frontier face formidable challenges, it is timely to revisit novel compensation methods to overcome space-charge limit
- Two unique experiments on space-charge compensation (one in a linac, and the other in a ring) are planned at Fermilab
- Advanced simulation tools, and dedicated diagnostics and controls could enable detailed understanding of the space-charge compensation processes, and eventually allow to achieve intense beams with improved stability and quality