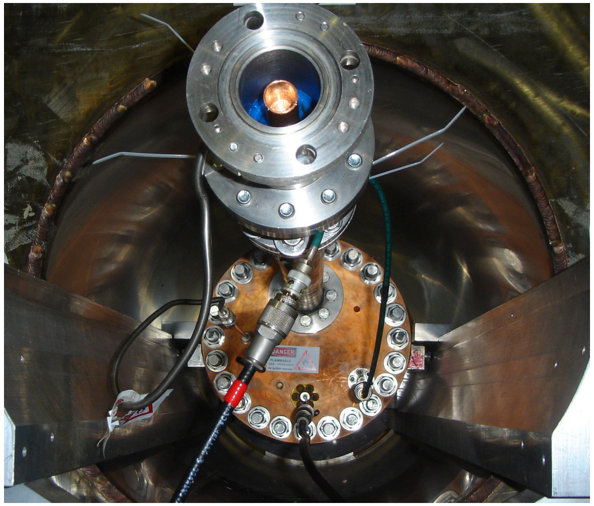
Plasma Lens in Parametric Resonance Ionization Cooling

Katsuya Yonehara

COOL 2021

November 04, 2021



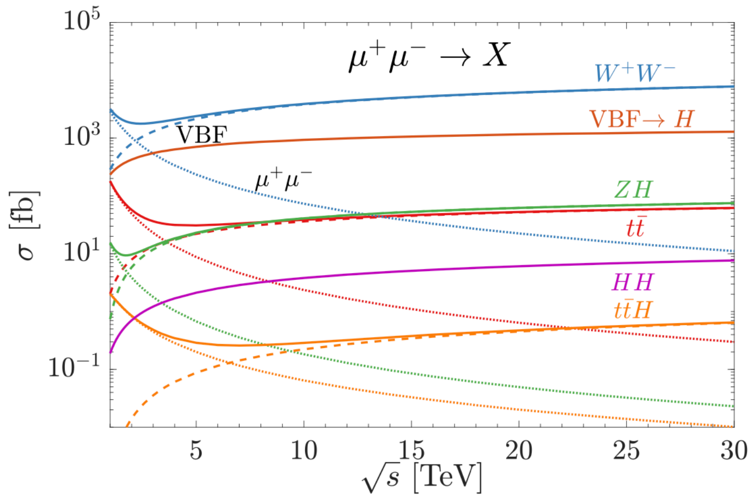
Gas-filled RF test cell

Overview

- Demand exceptional cooling for muon colliders
- Parametric Resonance Ionization Cooling
  – Progress and issue
- Beam-plasma interaction (Plasma lens)
  – Characterize gas plasma
  – Extend plasma parameter for applying cooling channels

Muon Colliders in High Energy Physics

- Beyond Standard Model (BSM) machine



- Vector-boson fusion rate ramps up as COM increase (will be a primary channel to produce Higgs bosons)
- Achieve unprecedented accuracy of electroweak Higgs couplings

The Muon Smasher's Guide arXiv:2103.14043

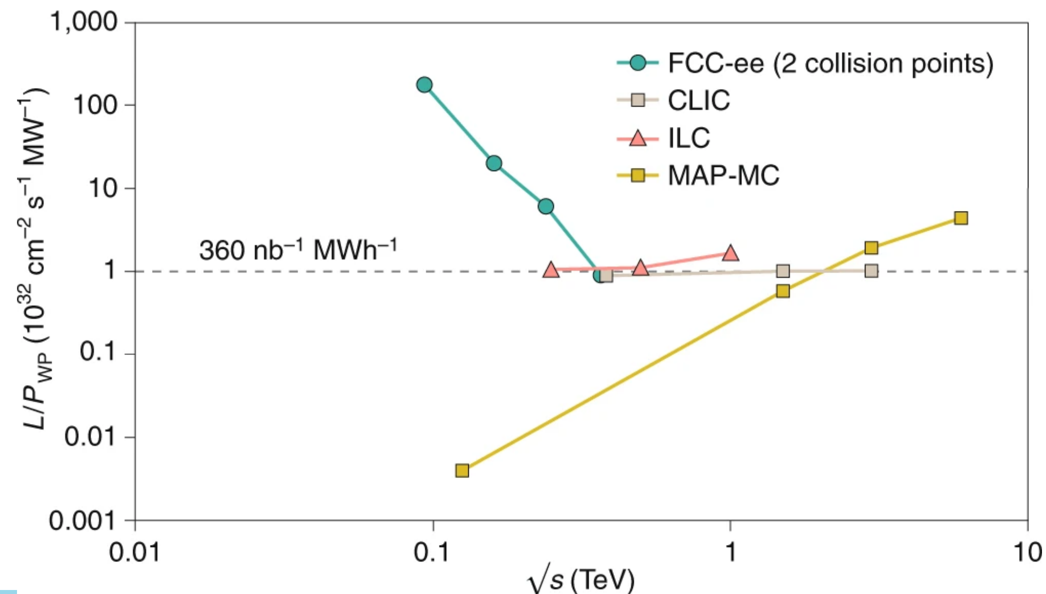
- Energy efficient

CLIC is at the limit of what one can do (decades of R&D)

- No obvious way to improve

Luminosity per beam power increases with energy in muon collider

- **power efficient**



Luminosity goal

Tentative target parameters
Scaled from MAP parameters

Comparison:
CLIC at 3 TeV: 28 MW

Target integrated luminosities

$\sqrt{s}$	$\int \mathcal{L}dt$
3 TeV	1 ab^{-1}
10 TeV	10 ab^{-1}
14 TeV	20 ab^{-1}

Note: currently consider 3 TeV and either 10 or 14 TeV

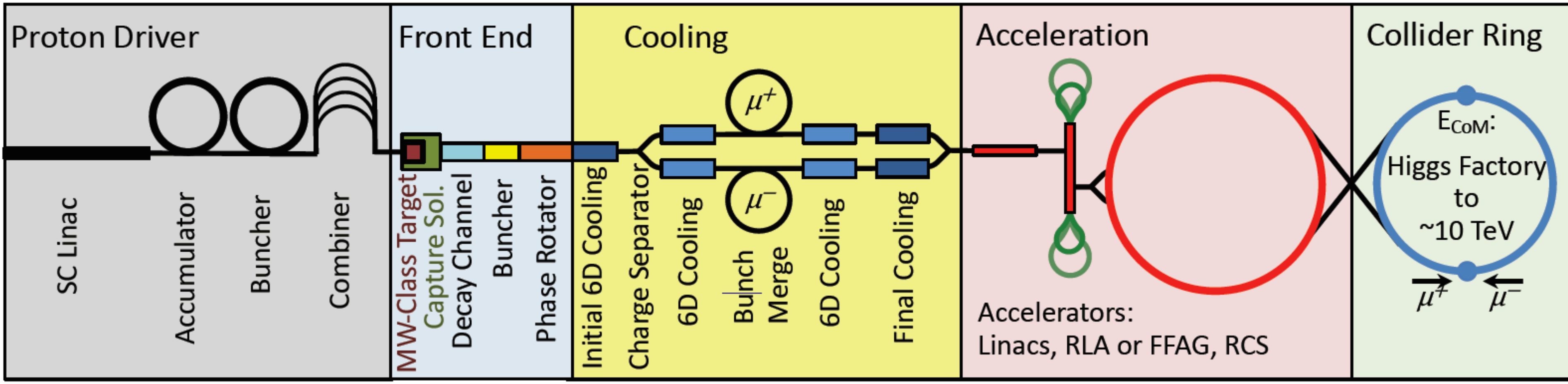
- Tentative parameters achieve goal in 5 years
- FCC-hh to operate for 25 years
- Might integrate some margins
- Aim to have two detectors

Parameter	Unit	3 TeV	10 TeV	14 TeV
L	10^{34} $cm^{-2}s^{-1}$	1.8	20	40
N	10^{12}	2.2	1.8	1.8
f_r	Hz	5	5	5
P_{beam}	MW	5.3	14.4	20
C	km	4.5	10	14
<B>	T	7	10.5	10.5
ε_L	MeV m	7.5	7.5	7.5
σ_E / E	%	0.1	0.1	0.1
σ_z	mm	5	1.5	1.07
β	mm	5	1.5	1.07
ε	µm	25	25	25
$\sigma_{x,y}$	µm	3.0	0.9	0.63

NuFACT 2021, D. Schulte

Higher COM gives us advantage for higher luminosity because muons can live longer

Key component in Proton-driven Muon Collider (MC)



Short bunched (1-2 ns) **Multi-Mega Watt proton beam**

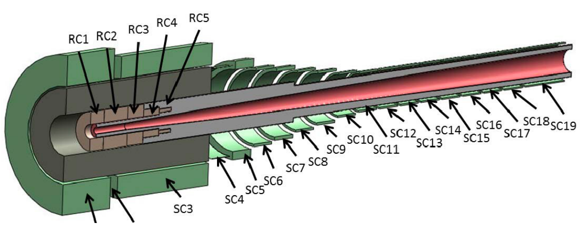
Multi-Mega Watt target system

Shrink muon phase space volume (foot-long to sub-mm)

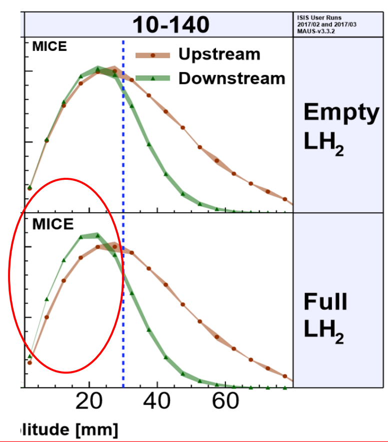
Quick acceleration (MeV to TeV)

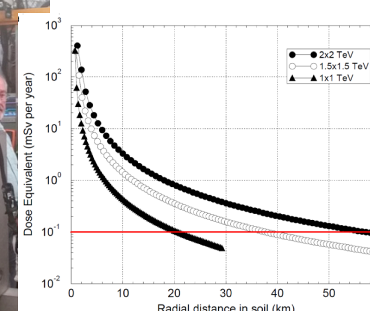
Fast detector (low BG and rad hazard)

Selected recent achievements



Design large bore high field target solenoid





Neutrino radiation

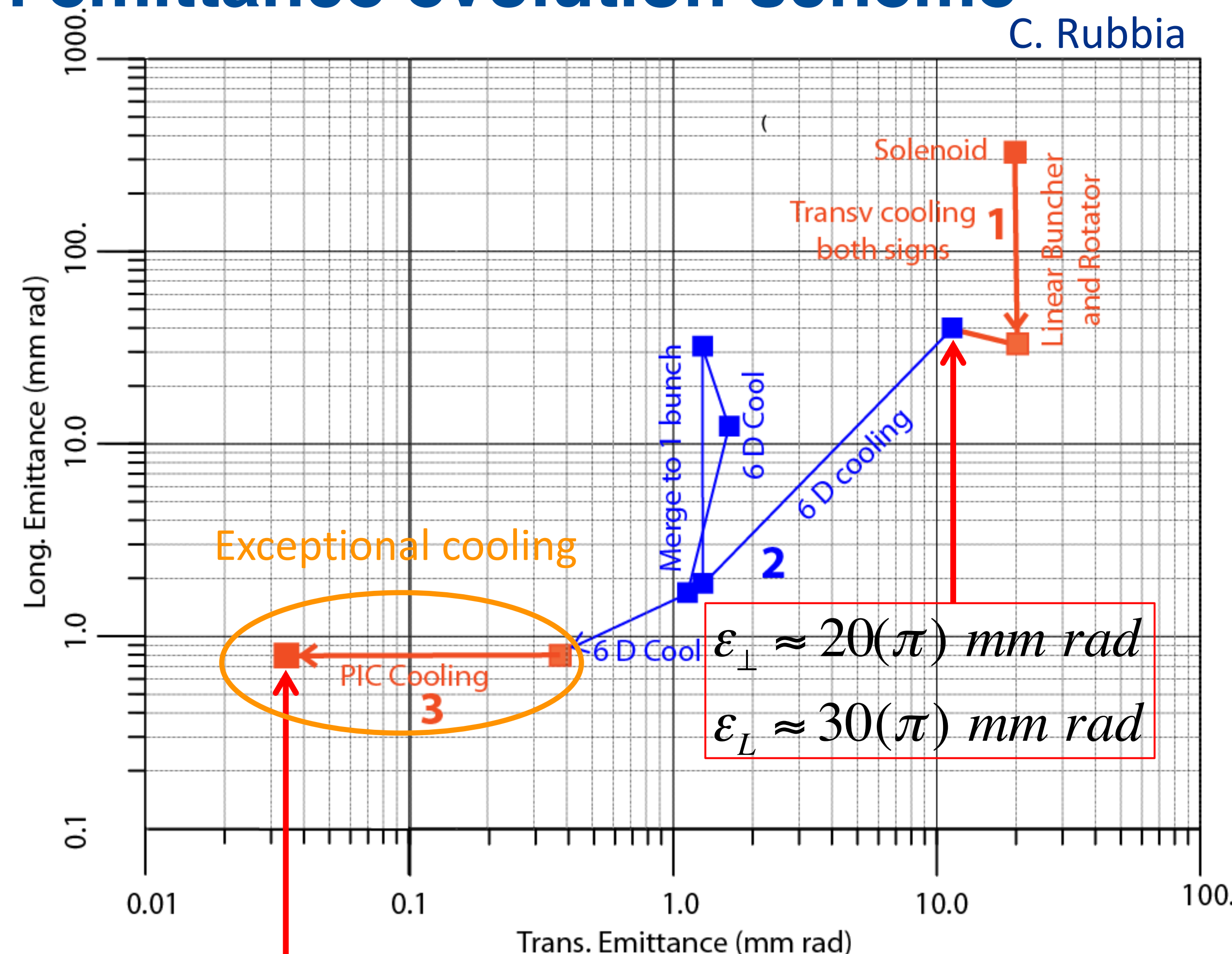
Challenges: Collective (space charge) effect, Radiations at target, Neutrino radiation

Parametric-resonance Ionization Cooling (PIC) in present muon emittance evolution scheme

Maximum achievable cooling is a key to design MC beam parameter

PIC has a potential to additionally reduce the transverse phase space by factor 10

Design MC with lower proton beam power, lower neutrino radiation

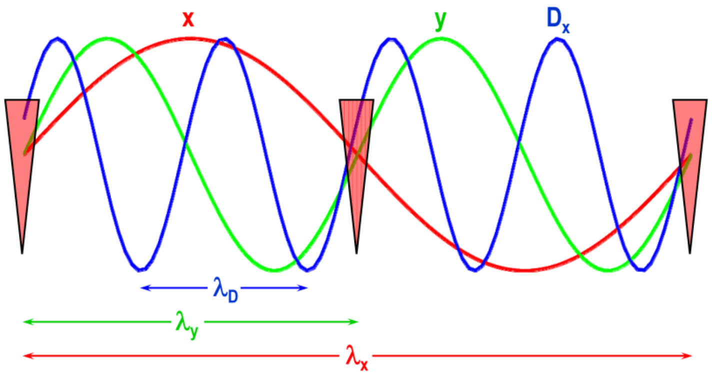


$\varepsilon_\perp = 0.04(\pi)\, mm\, rad \quad \varepsilon_L = 1.0(\pi)\ mm\ rad$

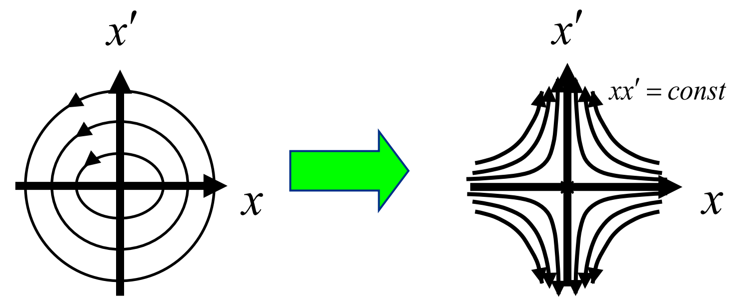
Parametric-resonance ionization cooling (PIC)

Y. Derbenev, R. Johnson

- Half-integer parametric resonances induced in cooling channel
- Enables order of magnitude equilibrium emittance reduction

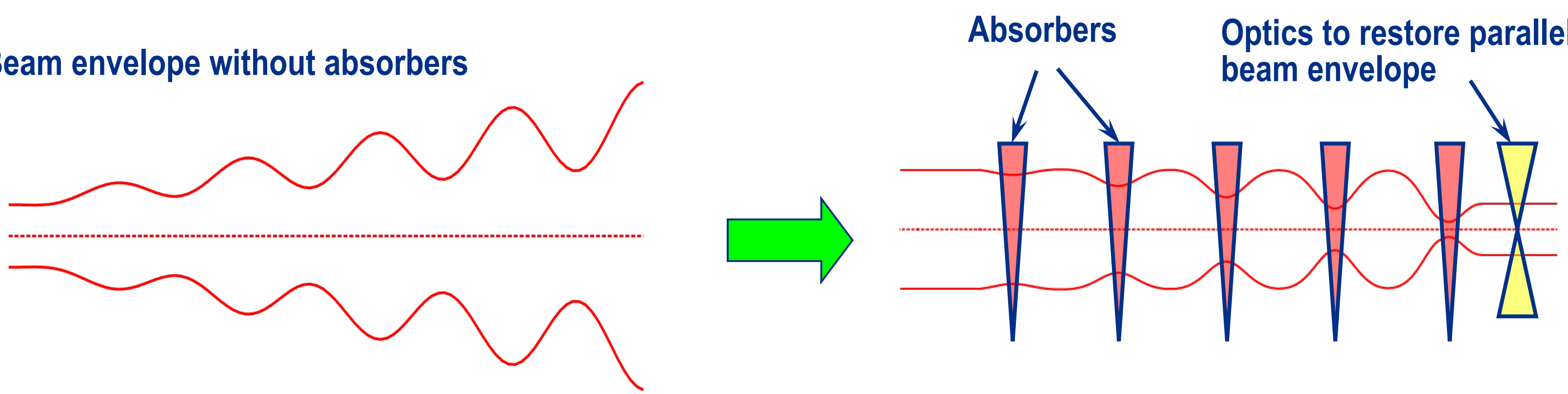


Correlated optics for periodic focusing at absorber positions $\lambda_D = \lambda \;\Rightarrow\; \lambda_x = 2\lambda_y = 4\lambda$



Half-integer resonance at absorber positions drives reduction in x, growth in x'

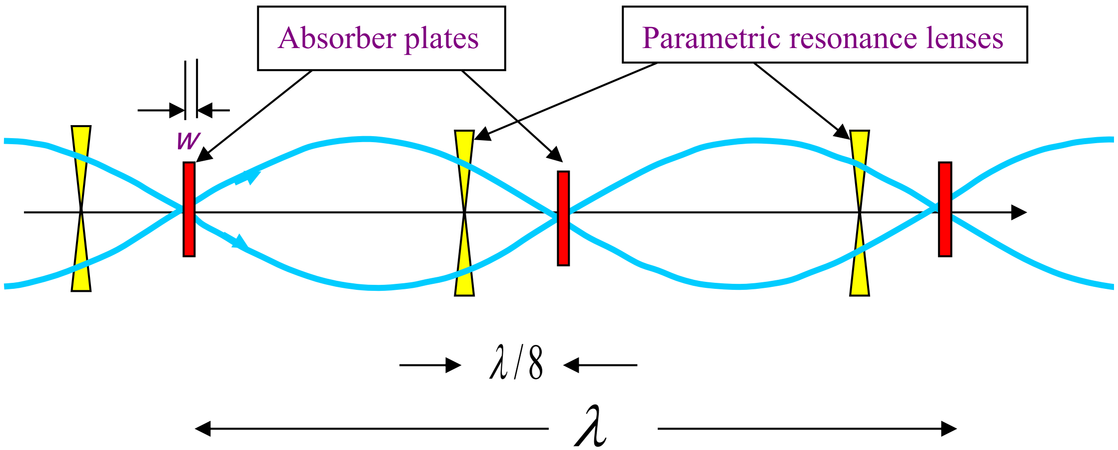
Beam envelope without absorbers



Ionization cooling occurs at absorber plates, and RF cavities restore longitudinal momentum

PIC possible parameters

Y. Derbenev, R. Johnson



Design field

Dipole: 6 Tesla

Quadrupole: 40 T/m

Skew quadrupole: 5 T/m

- **Equilibrium angular spread and beam size at absorber**

$$\theta_a^2 = \frac{3}{2}\frac{(Z+1)}{\gamma\beta^2}\frac{m_e}{m_\mu}, \quad \sigma_a = \frac{1}{2\sqrt{3}}\theta_a w$$

- **Equilibrium emittance (no beta function dependence)**

$$\varepsilon_n = \frac{\sqrt{3}}{4\beta}(Z+1)\frac{m_e}{m_\mu}w$$

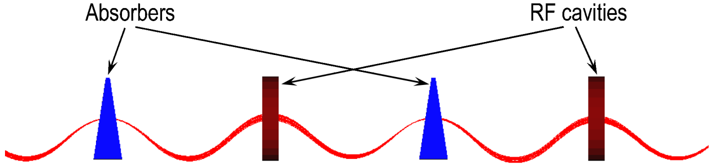
- **improvement by a factor of**

$$\frac{\pi}{\sqrt{3}}\frac{w}{\lambda} = \frac{\pi}{2\sqrt{3}}\frac{\gamma'_{acc}}{\gamma'_{abs}}$$

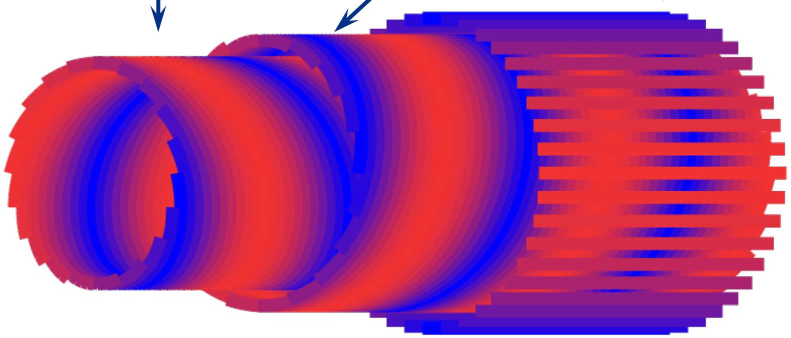
Parameter	Unit	Initial	Final
Muon beam momentum, p	MeV/c	250	250
Number of particles per bunch, N_b	10^{10}	1	1
Be (Z = 4) absorber thickness, w	mm	20	2
Normalized transverse emittance (rms), $\varepsilon_x = \varepsilon_y$	µm	230	23
Beam size at absorbers (rms), $\sigma_a = \sigma_x = \sigma_y$	mm	0.7	0.1
Angular spread at absorbers (rms), $\theta_a = \theta_x = \theta_y$	mrad	130	130
Momentum spread (rms), $\Delta p/p$	%	2	2
Bunch length (rms), σ_z	mm	10	10

Twin helix implementation

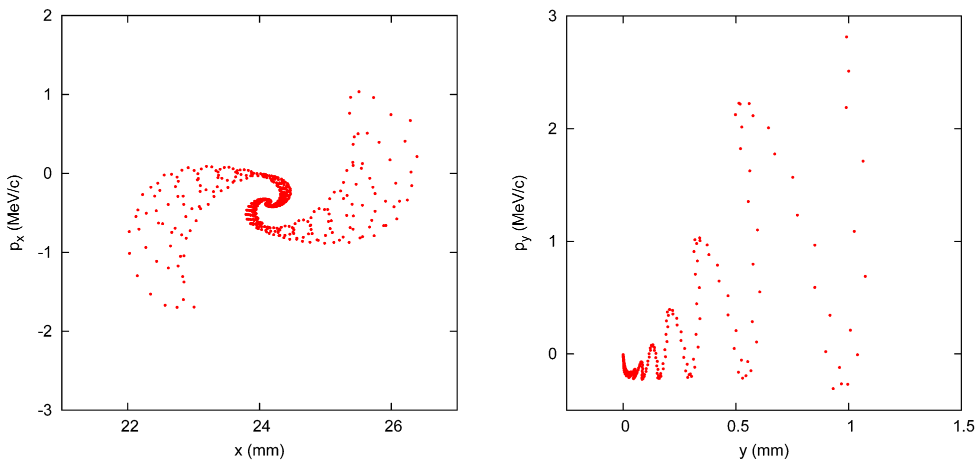
- Two equal-strength opposite-helicity helical dipole harmonics + Straight quad to redistribute horizontal and vertical focusing
- Orbit in horizontal plane + uncoupled horizontal, vertical motion
- $\lambda_D = \lambda \Rightarrow \lambda_x = 2\lambda_y = 4\lambda \Rightarrow \nu_x = 0.25,\ \nu_y = 0.5$



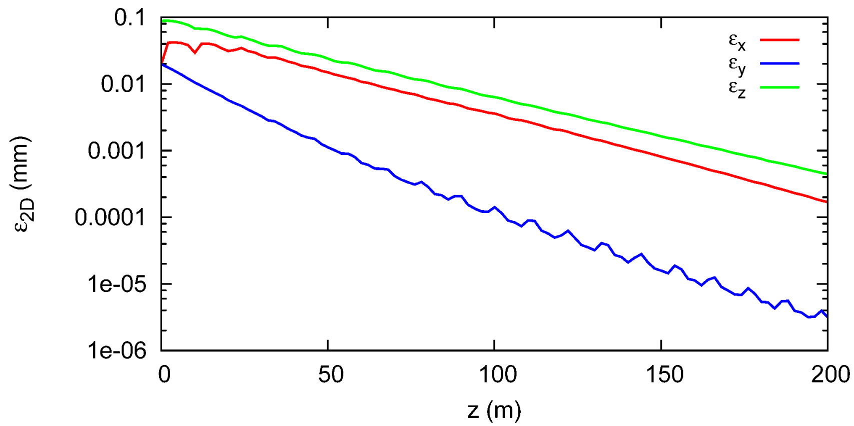
V. Morozov



"Twisted" Meyer magnet



Phase space behavior with induced parametric resonance

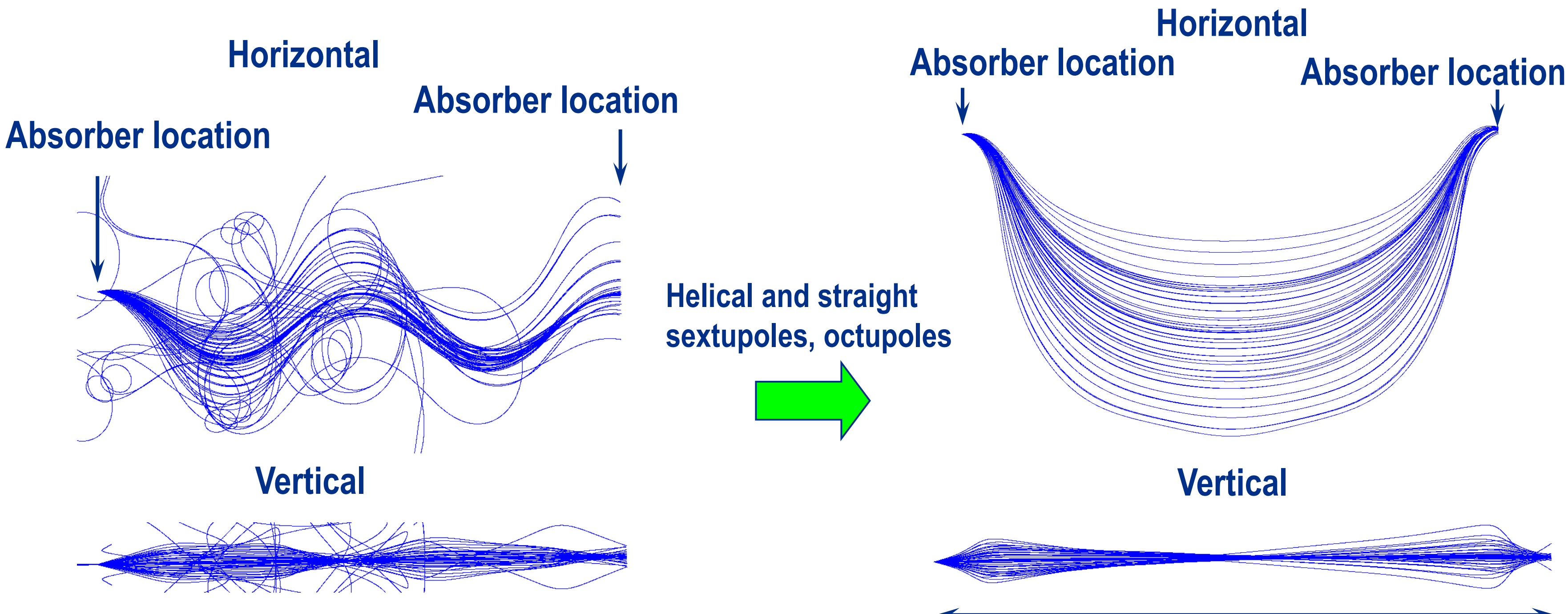


Emittance evolution, no stochastics or energy straggling

Twin helix challenges

V. Morozov

- Beam aberrations cause beam blowup at focal points

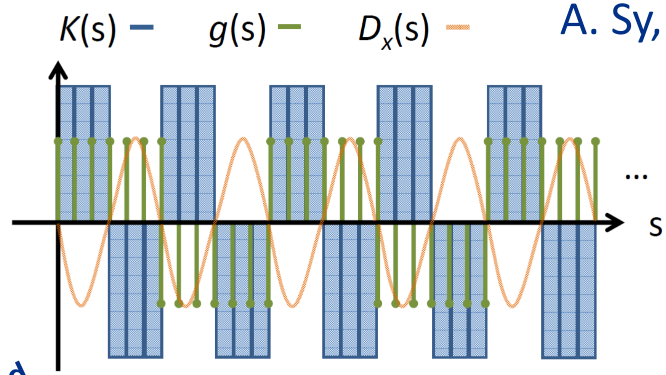


- Under correlated optics conditions, continuous harmonically-varying multipoles excite nonlinear resonances
- Aberration compensation is difficult with limited multipole choices

Skew PIC implementation

- Skew quads in PIC channel for strong x-y coupling → correlated optics for radial motion
- Betatron tunes shifted away from resonant values → easier aberration compensation

A. Sy, V. Morozov



uncoupled $\lambda_{Dx} = \lambda \;\Rightarrow\; \lambda_x = 2\lambda_y = 2\lambda \;\Rightarrow\; \nu_x = 1.0,\ \nu_y = 2.0$

Skew PIC theory

$$x'' + [K^2(s) - n]x + g(s)y = K(s)\delta$$

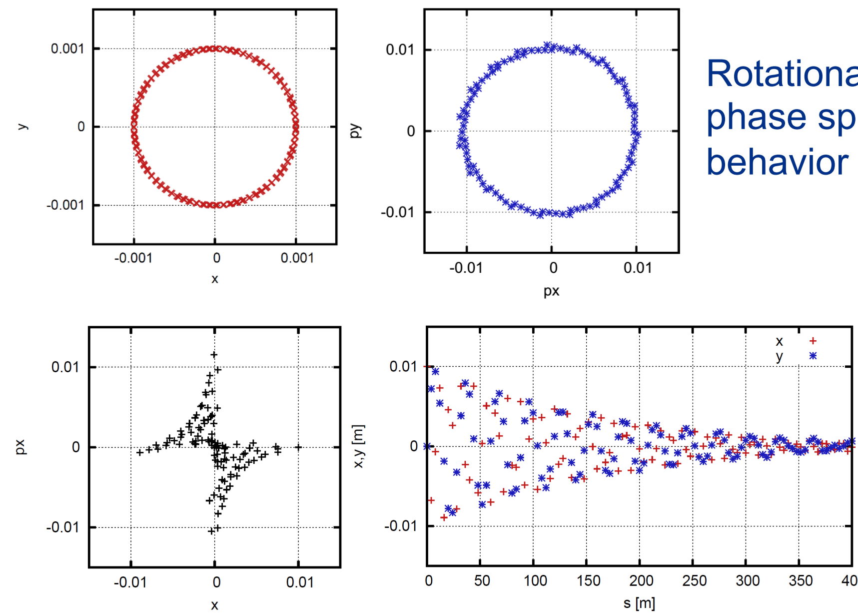
$$y'' + ny + g(s)x = 0$$

$$\begin{pmatrix} x_f \\ y_f \\ x'_f \\ y'_f \end{pmatrix} = \mathrm{M} \begin{pmatrix} x_i \\ y_i \\ x'_i \\ y'_i \end{pmatrix}, \quad \mathrm{M} = \begin{pmatrix} M & 0 \\ L & N \end{pmatrix}, \quad \det(\mathrm{M}) = \det(M)\cdot\det(N) = 1$$

$\det(M) = \det(N) = 1$ **for stability of linear motion**

$$\mathrm{M} = \begin{pmatrix} M & 0 \\ 0 & N \end{pmatrix}, \quad M = N = \begin{pmatrix} \cos(4\theta) & -\sin(4\theta) \\ \sin(4\theta) & \cos(4\theta) \end{pmatrix}$$

$$\tan\theta = \frac{K^2 - 2n - \sqrt{(K^2 - 2n)^2 + 4g^2}}{2g}$$



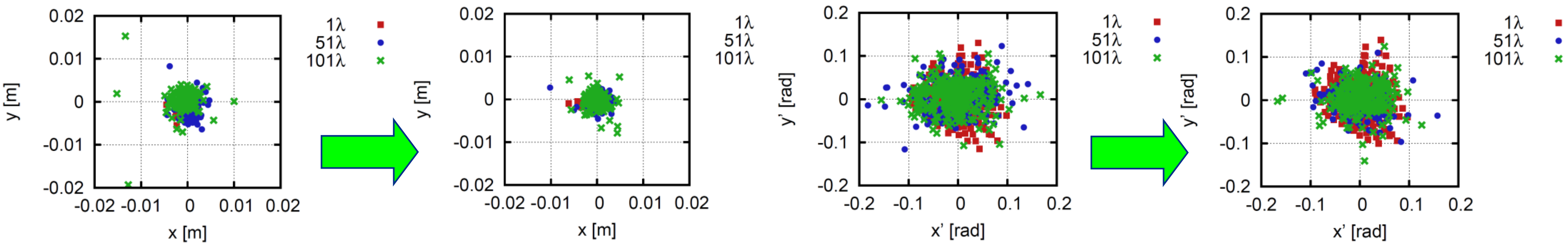
Rotational phase space behavior

Simultaneous x, y focusing with induced parametric resonance

Skew PIC challenges

A. Sy, V. Morozov

- Dynamic aperture optimization easier than in normal PIC, but still challenging



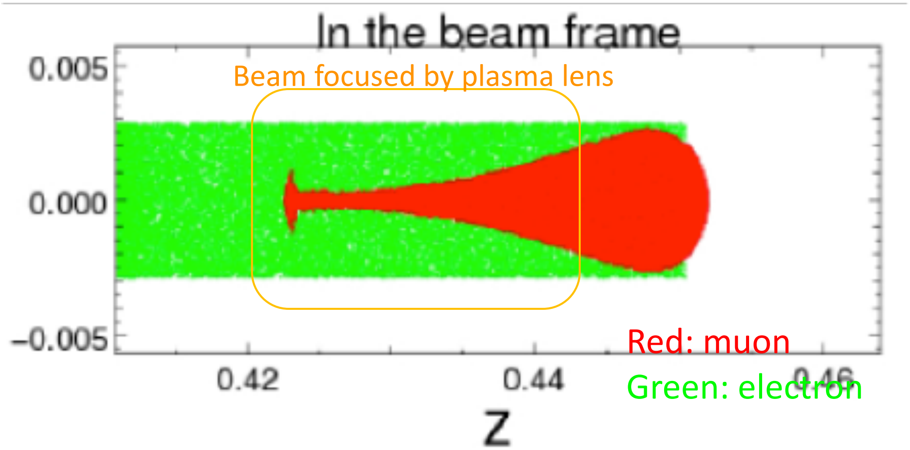
x,y and x',y' phase space including sextupole, octupole, decapole harmonics

- Able to stabilize particle motion within ±90 mrad without damping and ±120 mrad with damping
- However, ±120 mrad is ~$1\sigma_\theta$
- Serious problem with amplitude-dependent time of flight for large θ when longitudinal motion is included

Fermilab

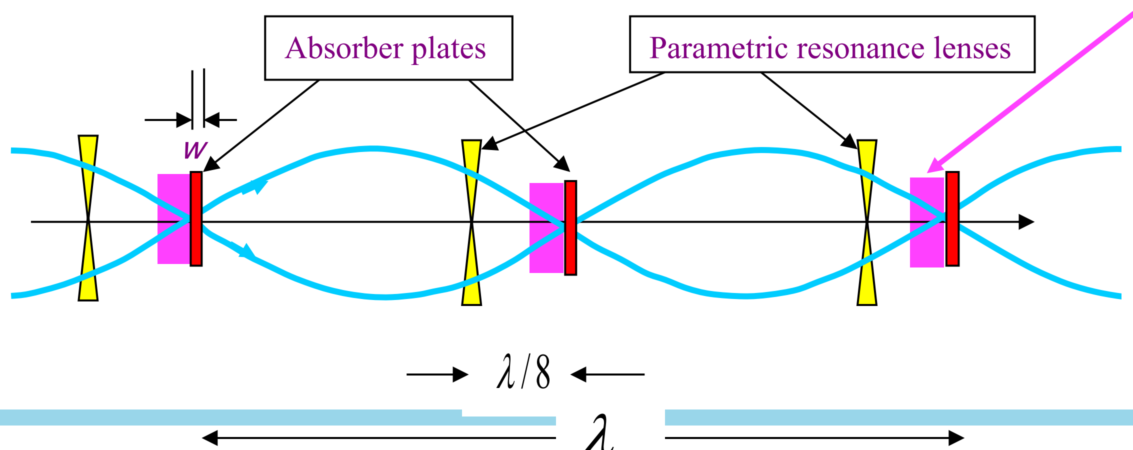
Plasma channel with PIC

- Strong focusing would help alleviate many of the problems
- Consider plasma focusing in gas-filled RF cavities
- Idea supported by initial simulations



- Bunch length ~ 100 ps
- σx ~ σy ~ 2 mm
- $n_\mu = 10^{12}$ μs/bunch
- β = 0.88 (200 MeV/c)
- Gas pressure 200 atm

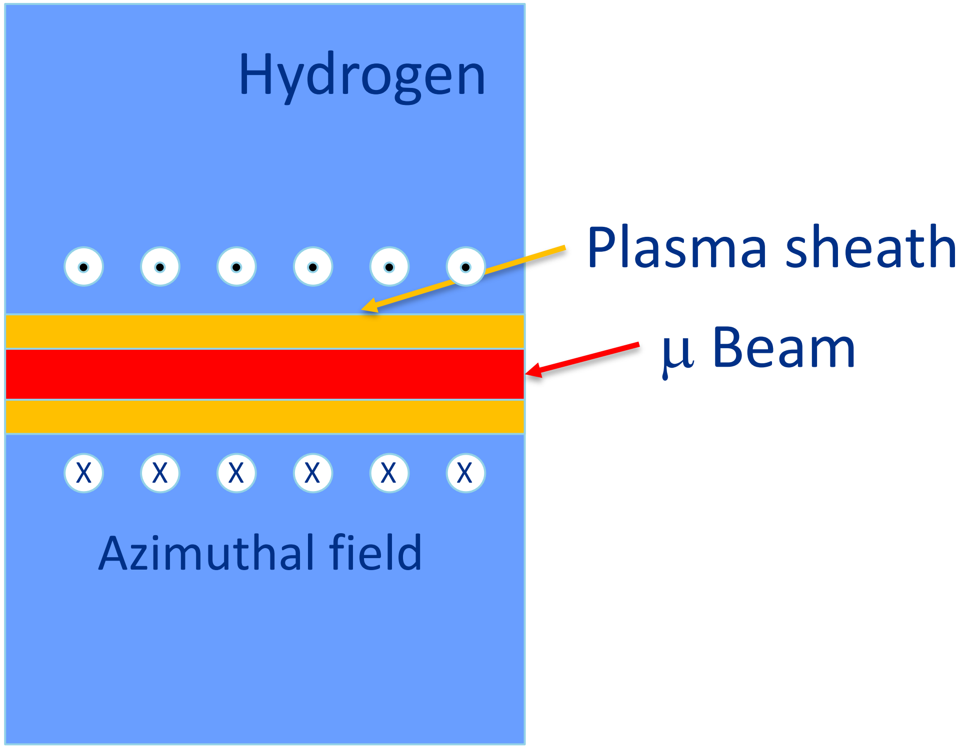
- Proposal submitted on this topic



- Short length high gradient focusing field to mitigate heating due to multiple scattering
- Add high gradient RF field to compensate energy loss
- Or, equally-spaced gas-filled RF cavities acting as radially focusing lens

Concept of plasma lens for PIC

Gas-plasma volume



Side view

- Plasma sheath is formed by either incident beam or pre-formed
- Approximately 1,000 electron ion pairs per unit length created by single muon
- Ionization electrons are quickly thermalized by neutral gas and polarized by space charge of the beam
- Total charge in the beam is neutralized by polarization
- Vector potential from beam current induces an azimuthal self-focusing field
- RF will be applied (gas-filled RF cavity) to compensate ionization energy loss

Charge neutralization for both signs

- μ-/μ+ beam incidents in gas and negatively/positively charged plasma sheath is formed by the Coulomb potential in beam

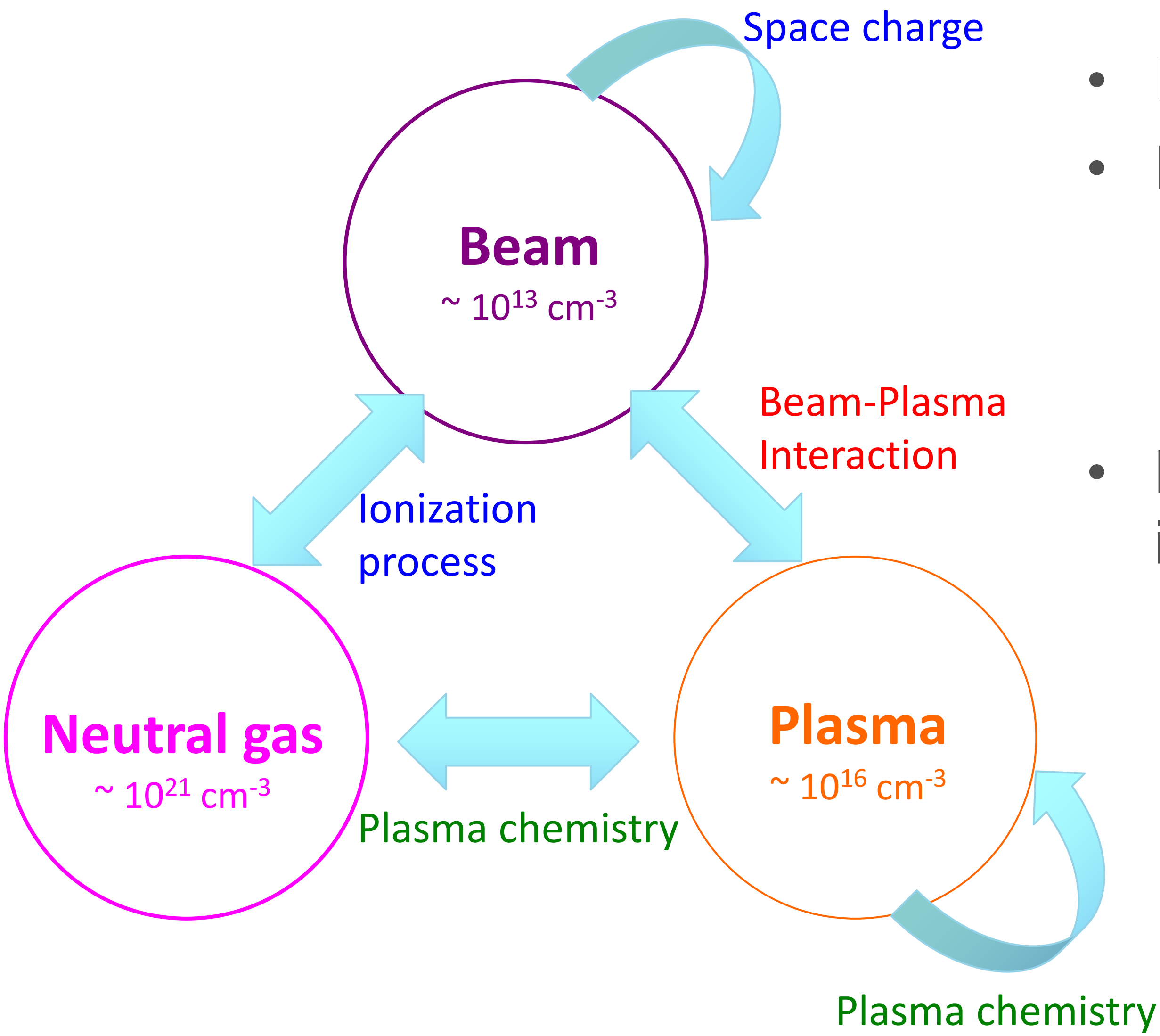
Negatively charged plasma sheathe

Positively charged plasma sheathe

Front view of plasma sheath (beam direct from back to front)

- Arrow is an electron motion; force is repulsive (attractive) when μ^- (μ^+) incident
- Cross-point is the beam center
- # of electron/ion pairs are 1,000 times larger than the number of beam particles; thus, a small displacement of polarization is sufficient to neutralize space charge

Beam-gas-plasma interactions

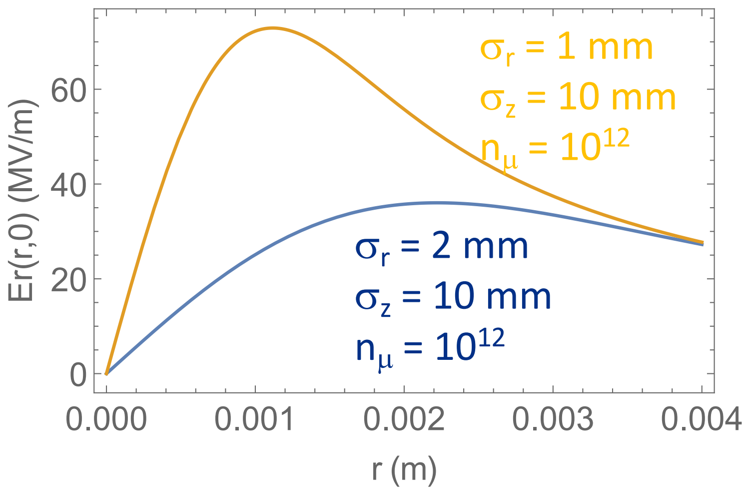


- Ionization process
- Plasma chemistry
  - Recombination
  - Electron attachment
  - Cluster
- Beam-plasma interaction
  - Collective motion in extreme plasma affects beam dynamics

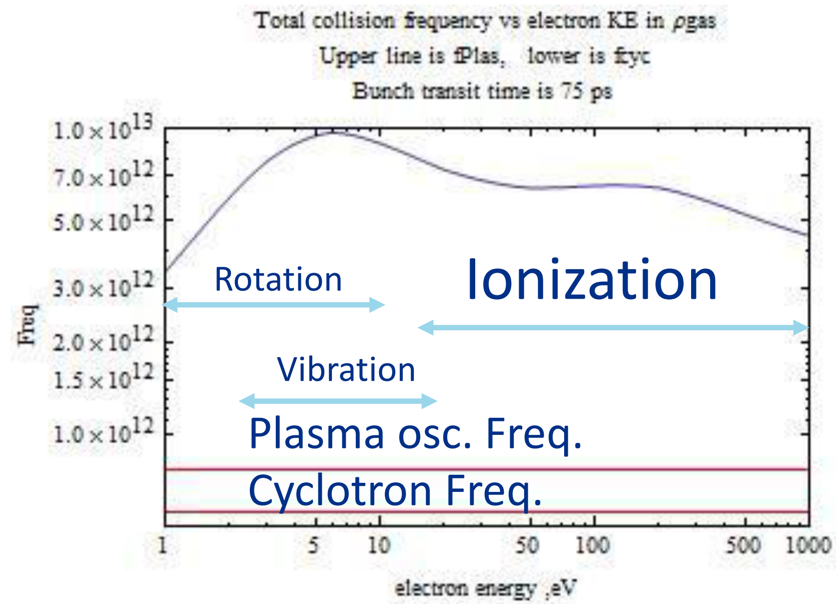
Observed plasma density in RF breakdown is ~10^{19} cm^{-3} & electron temperature ~20,000 K for pre-formed plasma sheath?

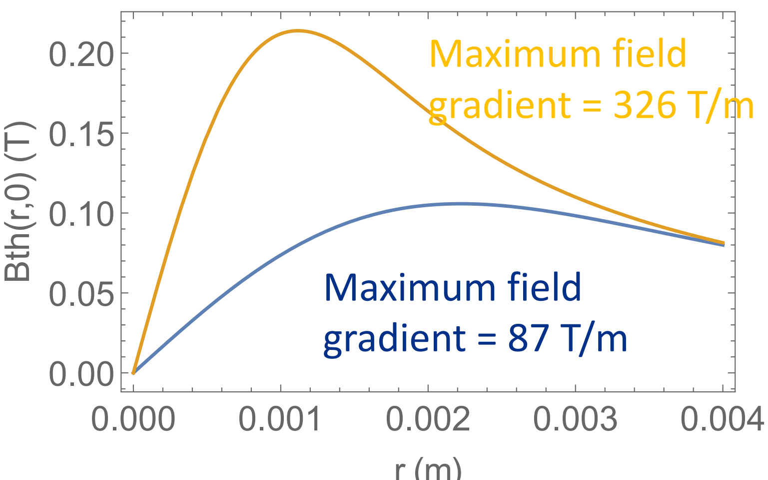
Space charge potential vs Thermalization

M. Chung



A. Tollestrup

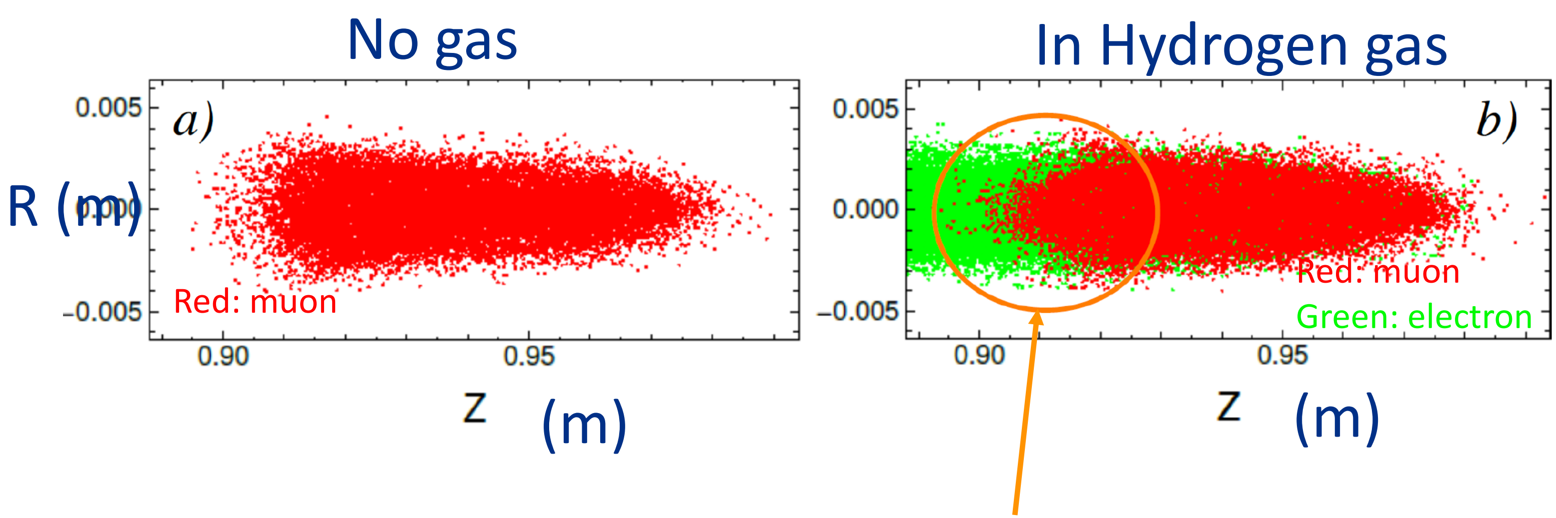




- Electron temperature is a function of E/p
- Bunch length is 40-100 ps
- Electron-Hydrogen collision frequency 10^{12}-10^{13} Hz
- What is a time constant of thermalization of ionization electrons? (Past measurement shows $\tau \ll 50$ ps)

Demonstrate plasma lens in WARP

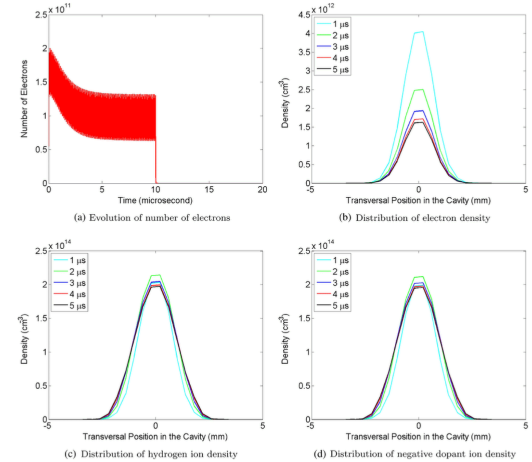
- Demonstrate 2D (r-t) plasma lens simulation in WARP
  - Ionization process is included, but no energy loss nor multiple scattering are taken into account
  - Ionized electron immediately thermalized
  - A straight solenoidal field is applied to hold beam in a volume



Beam tail is focused by a self-induced azimuthal field

Future work

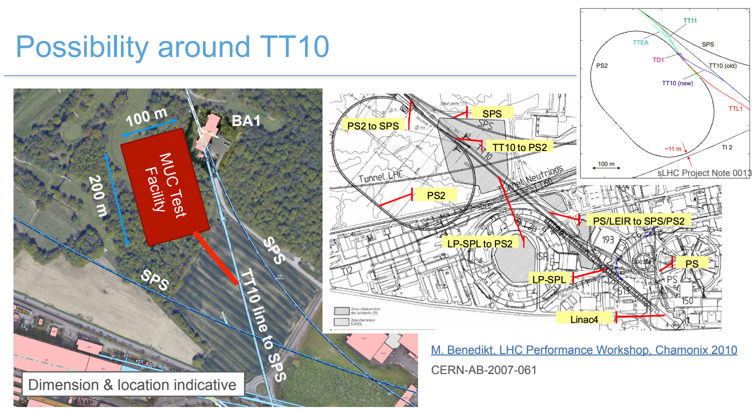
4D simulation of plasma dynamics in **SPACE** code (K. Yu)



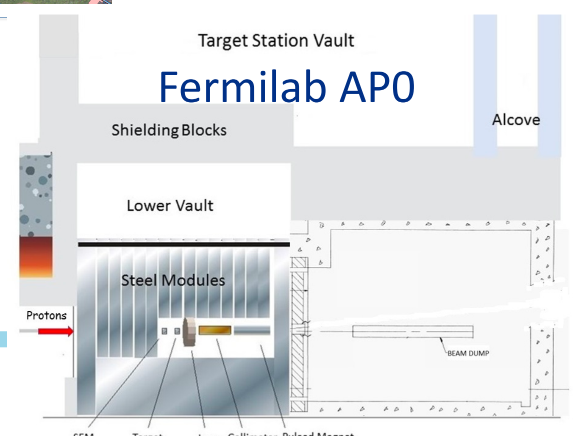
(a) Evolution of number of electrons
(b) Distribution of electron density
(c) Distribution of hydrogen ion density
(d) Distribution of negative dopant ion density

- Plasma simulation study
  - Time domain plasma dynamics
    - Beam-induced plasma vs pre-formed plasma
  - Control plasma dynamics with plasma chemistry
    - Electronegative dopant to adjust electron/plasma temperatures
  - Beam-plasma interactions
    - Space charge field
    - Self-focusing field
- Cooling simulation
  - Define plasma parameter for cooling
- Design for demonstration test
  - Muon cooling test facility
    - CERN, Fermilab, etc
- Timeline
  - R&D may start after SNOWMASS 2022 & P5 2023

Possibility around TT10



M. Benedikt, LHC Performance Workshop, Chamonix 2010
CERN-AB-2007-061



Conclusion

- Exceptional cooling is a key to realize muon colliders
- Parametric resonance Ionization Cooling is proposed
  - No beta function dependence on the equilibrium emittance
  - Lattice is relatively simple
  - Larger angular momentum acceptance is required
- Plasma lens is proposed
  - Fundamental part of plasma dynamics has been understood from experimental and analytical investigations
  - Demonstration test is considered to study the beam-gas-plasma interactions
  - Plasma lens will be applied for other cooling schemes