Beam Halo Formation in High-Current Mismatched Proton Beams/ Theory and Experiment

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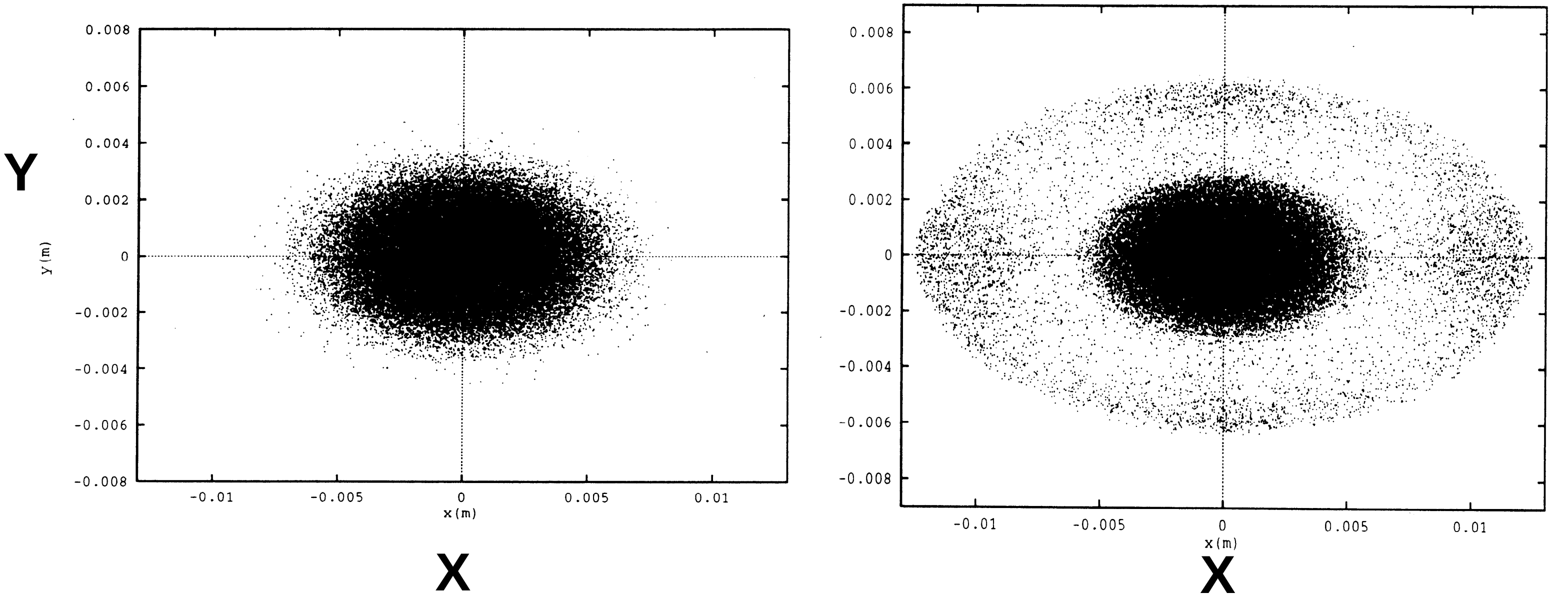
What is Beam Halo?

X-Y cross sections of beams from simulations in quadrupole-focusing channel

Without Halo on the Left--With Halo on the right.



Early History of Beam Halo in Proton Linacs

- Beam loss was associated with presence of beam halo in LANSCE (formerly LAMPF) linac in 1970s.
- Causes of beam halo remained a mystery for almost 2 more decades.
- 100-mA CW Accelerator Production of Tritium (APT) project in 1990s provided motivation to understand beam halo and beam losses. (The reactor approach was selected in 1998.)

Why understanding beam halo is important.

- **High power proton linacs are being designed and built for future applications including:**
  -accelerator-driven subcritical reactors for nuclear-waste transmutation **(ATW, ADS, KEK/JAERI, KOMAC),**
  -neutrino factory **(FNAL, CERN SPL),**
  -fusion-materials studies **(IFMIF),**
  -injectors for spallation-neutron sources **(SNS, ESS).**

- **Beam loss produces activation that makes maintenance difficult and time-consuming.**

- **Control of beam halo formation and beam loss is a fundamental requirement for high beam availability in high-power proton linacs.**

Progress in understanding beam halo during past decade

- Theoretical understanding of halo was developed from:
  - computer simulation.
  - Particle-Core Model.

- No experiments had been done until the halo experiment on LEDA was carried out last year.

- Experiment goals were to measure the halo and test:
  - our understanding of the physics mechanism.
  - the predictive capability of simulation codes.

Computer simulations (1991) showed substantial halo is formed in mismatched beams.

A. Cucchetti, M. Reiser, and T. Wangler, Proc. IEEE 1991 Part. Accel. Conf., p.251.

- **Beams are mismatched when focusing and defocusing forces (space charge and emittance) are unbalanced, resulting in coherent rms oscillations.**

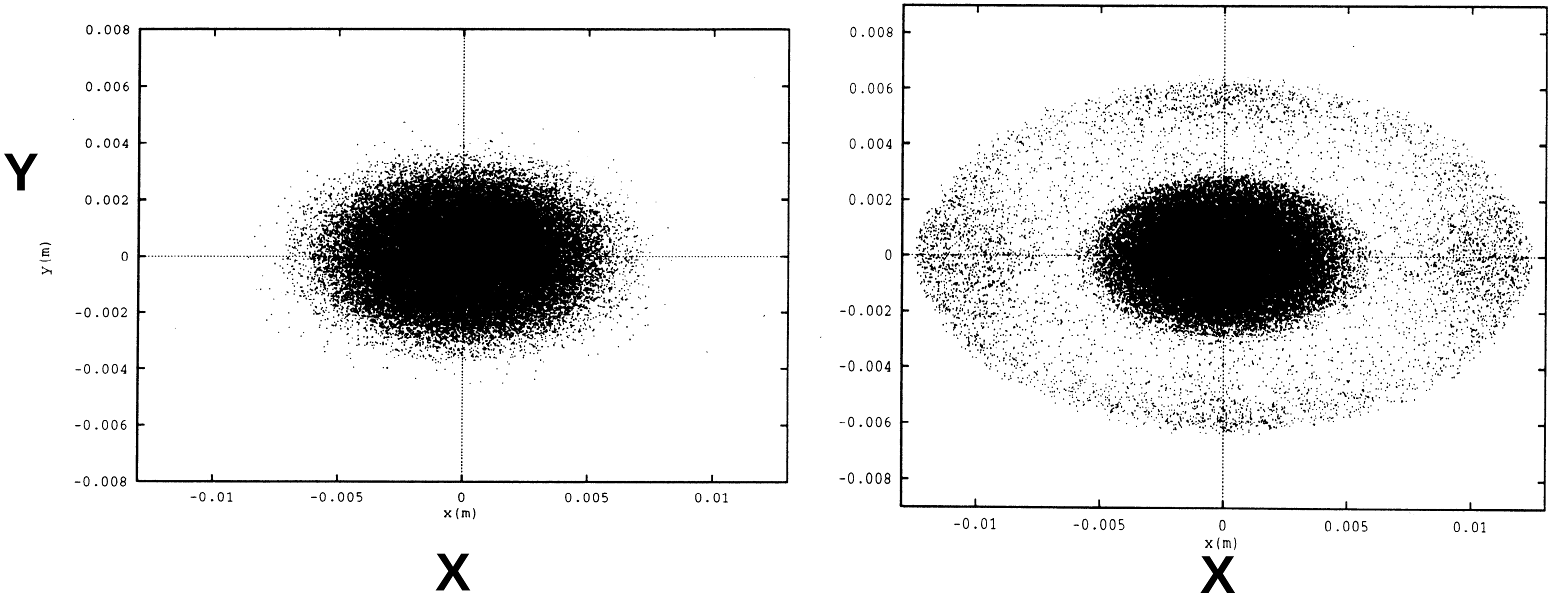
- **Simulations showed beam mismatch is a major source of halo.**

- **Mismatched beams evolve to a final equilibrium state with accompanying growth of halo and emittance.**

- **Emittance growth is associated with conversion of free energy from the initial mismatch oscillations into thermal energy of the beam.**

Example of Halo From Mismatched Beam in Quadrupole Focusing Channel

Mismatched beam (on right) develops larger amplitudes than matched beam (on left).



Particle-Core Model incorporates the physical mechanism of halo growth.

- **Core dynamics:** Mismatch excites collective beam modes (breathing and quadrupole) of a beam core.

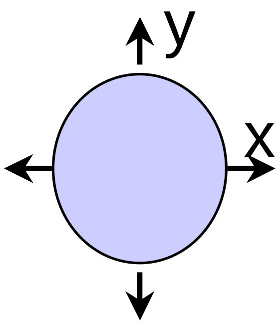
- **Particle dynamics:** Space-charge of oscillating core drives individual particles in nonlinear parametric resonance when $f_{particle} = f_{mode}/2$. [*R. Gluckstern, Phys. Rev. Lett. 73, 1247 (1994)*].

- **Model predicts maximum particle amplitudes.**
  - particle frequency depends on amplitude.
  - dependence of maximum amplitude on mismatch.
  - insensitivity to beam current and core-density distribution.

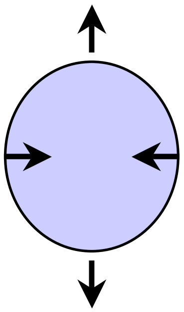
- **Computer simulation is required to predict halo and emittance growth rates.**

Collective Modes of Mismatched Continuous Beams

Symmetric
(Breathing)
Mode



Antisymmetric
(Quadrupole)
Mode



PARTICLE-CORE MODEL

Breathing Mode of Round Continuous Beam Core

T.P.Wangler, K.R.Crandall, R.Ryne, and T.S.Wang, Phys.Rev.Special Topics-Accelerators and Beams , 1, 084201 (1998).

$$R'' + k_0^2 R - \frac{(4\varepsilon_{rms})^2}{R^3} - \frac{K}{R} = 0, \quad \text{envelope equation for core radius } R.$$

$$where\ \ K = \frac{qI}{2\pi\varepsilon_0 mc^3\gamma^3\beta^3}. \qquad \text{Matched case : R = R}_0 = \text{constant.}$$

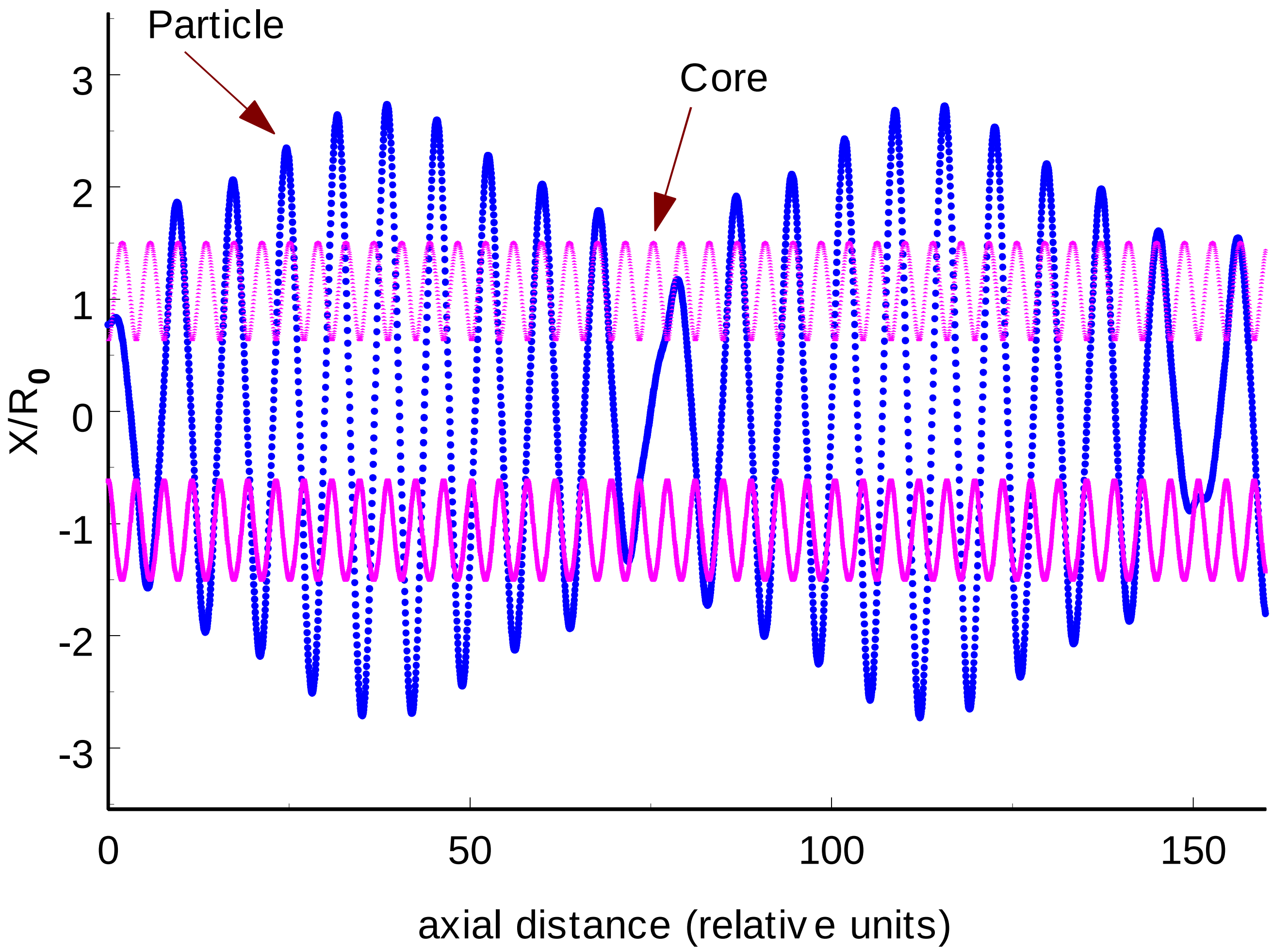
$$x'' + k_0^2 x - F_{SC} = 0, \qquad \text{particle equation of motion,}$$

$$where\ \ F_{SC} = \begin{Bmatrix} \frac{Kx}{R^2}, |x| < R, \\ \frac{K}{x}, |x| \ge R. \end{Bmatrix}. \quad \text{R variation drives parametric resonance.}$$

$$\frac{k}{k_0} = \sqrt{1 - \frac{K}{k_0^2 R^2}}, \text{ tune depression . Mismatch parameter } \mu = \frac{\text{R}_{\text{initial}}}{\text{R}_0}.$$

Example: Displacement versus distance for oscillating uniform-density core and a resonant particle.

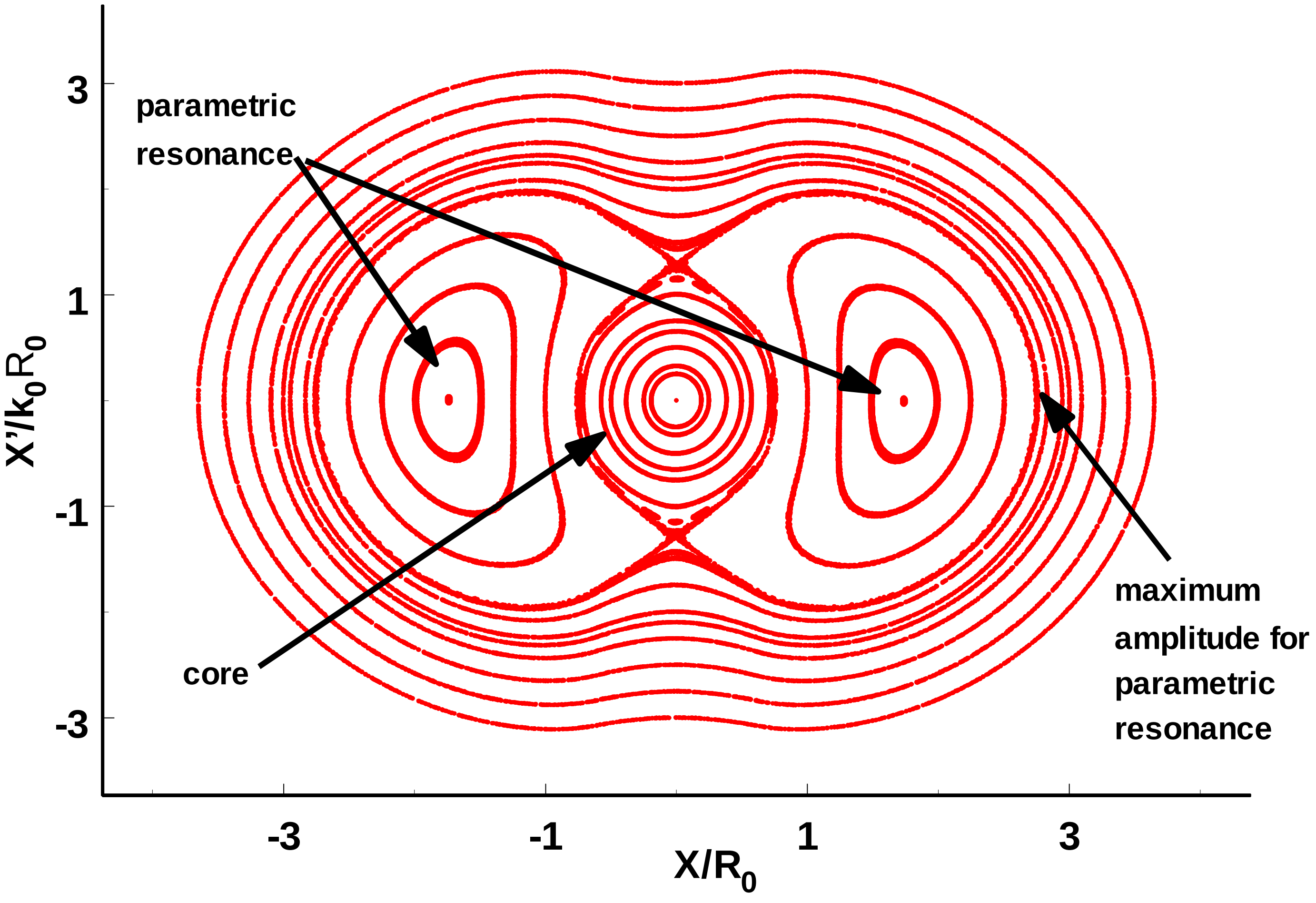
(uniform core, mismatch parameter μ=1.5, tune depression=0.5)



Stroboscopic phase-space plot

Particle-Core Model - breathing mode excitation of uniform core.

(mismatch parameter μ = 1.5, tune depression=0.5)

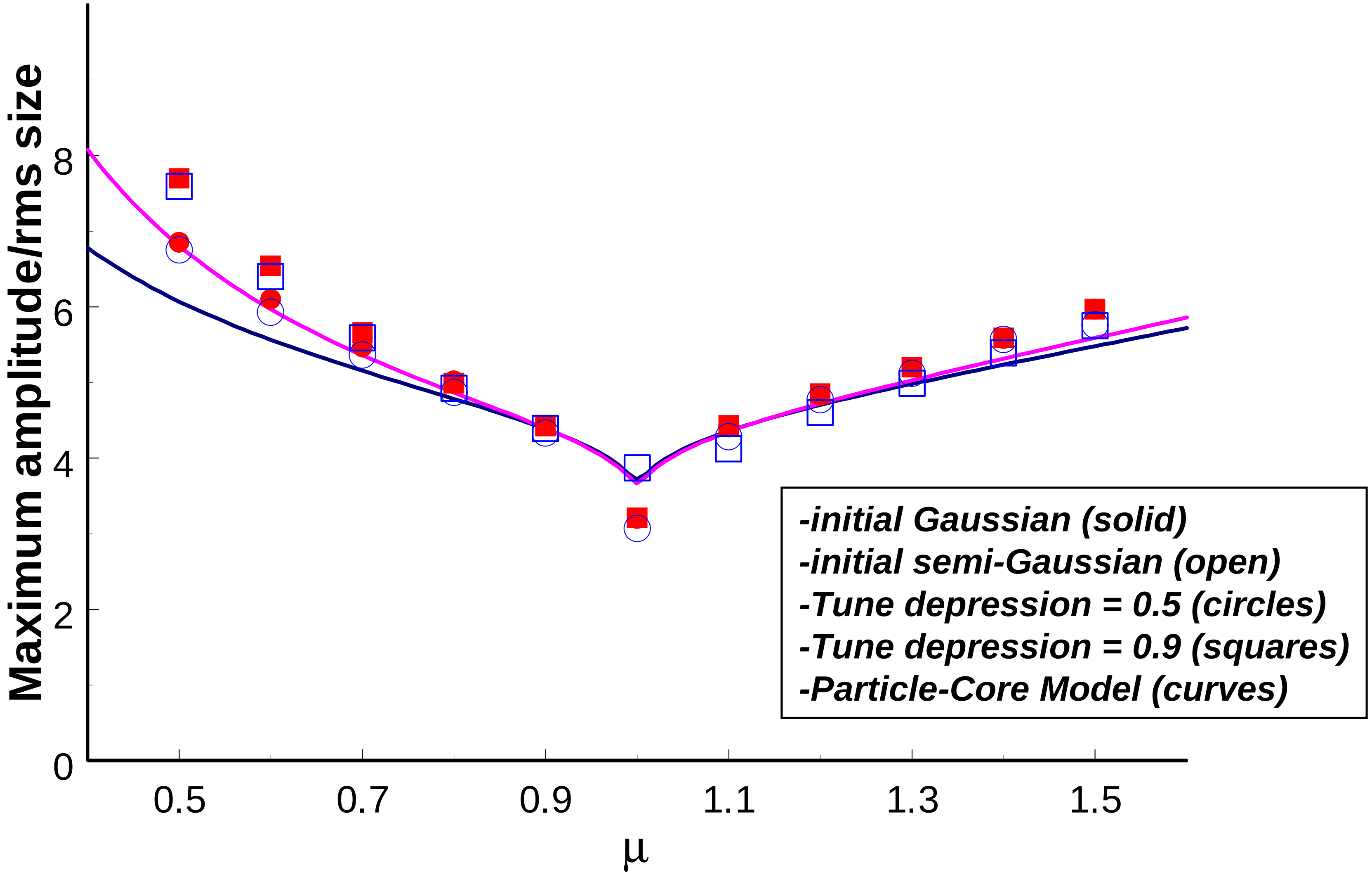


parametric resonance

core

maximum amplitude for parametric resonance

Particle-Core Model Predictions of Maximum Particle Amplitudes Agree Well With Numerical Simulations.



Conception of Halo Experiment

- **Objective: a relatively simple and affordable experiment to detect halo and test basic physics understanding.**

- **Halo experiment a challenge for beam diagnostics** because of high peak beam flux (6.7 MeV, 0.1 A, 0.67 MW, rms beam size~1 mm) and short stopping range (0.1 g/cm^2).

- **Broad support for the LEDA halo experiment.**

- **Experiment funding from APT project closeout funds.**

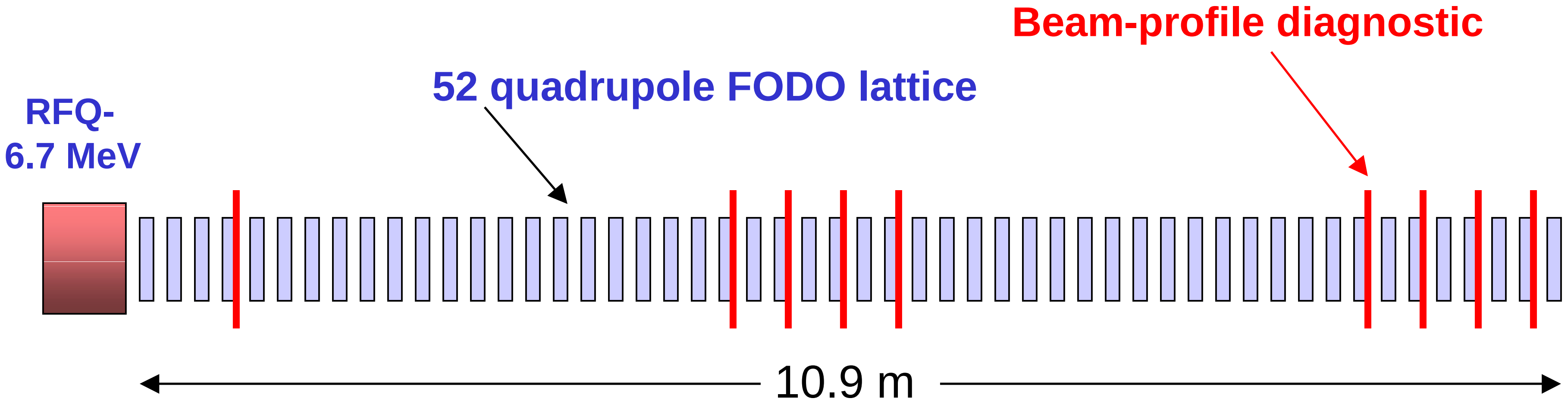
- **Halo Experiment Scientific Team**: C.K.Allen, K.C.D.Chan, P.Colestock, K.R.Crandall, R.W.Garnett, J.D.Gilpatrick, W.Lysenko, J.Qiang, J.D.Schneider, M.E.Schulze, R.Sheffield, H.V.Smith, T.P.Wangler.

Beam-halo experiment designed to investigate our understanding of halo formation from mismatch.

- **Pulsed beam from 6.7-MeV RFQ into 52 quadrupole transport line. First four quadrupoles create mismatches.**
- **10 breathing-mode oscillations, enough to see initial stages of emittance growth and resonant halo-formation.**
- **Beam debunches longitudinally.**
- **Vary mismatch and current. Six mismatch settings at 15, 50, 75, and 100 mA.**
- **Measure beam profiles to obtain:** 1) **rms emittances,** 2) **maximum detectable amplitudes, 3) beam widths at different intensity contours**.

52 quad -11m beam channel after 6.7-MeV LEDA RFQ

Beam-halo experiment showing locations of beam-profile diagnostics.



New state-of-the-art beam-profile diagnostics were designed and built for the halo experiment.

(J.D.Gilpatrick, et al.)

- **Components mounted on common movable frame.**
  - 33μ carbon wire to measure beam core. Detect secondary electron emission induced by beam.
  - Pair of 1.5-mm-thick graphite scraper plates for outer halo. Detect charge deposited by stopped proton beam.

- **Data from wire and scraper plates combined in computer software to produce single distribution with 10^5:1 dynamic intensity range.**

- **9 measurement stations at which both horizontal and vertical profiles were measured.**