"Control of Intense Charged Particle Beams"

Simon Yu

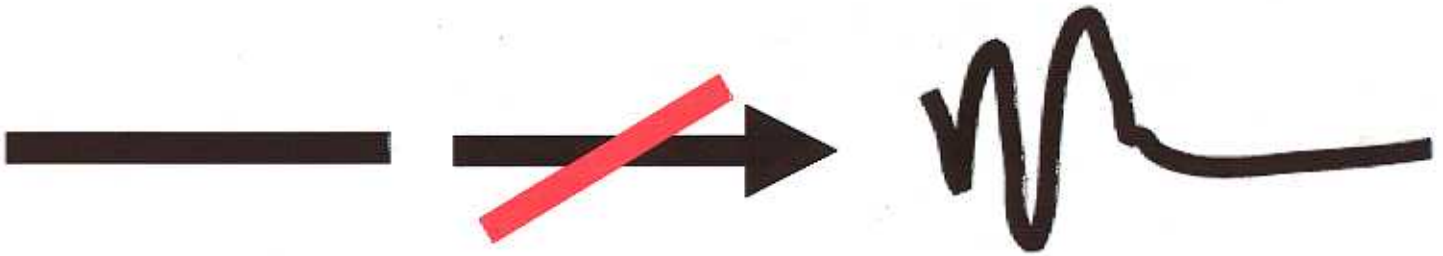
LBNL

March 15, 2003

In honor of Andy Sessler's 75th Birthday Celebration

- Many modern applications of large accelerators require
  - long distance **TRANSPORT** of intense beams
  - and final **FOCUSING** to very tight spots

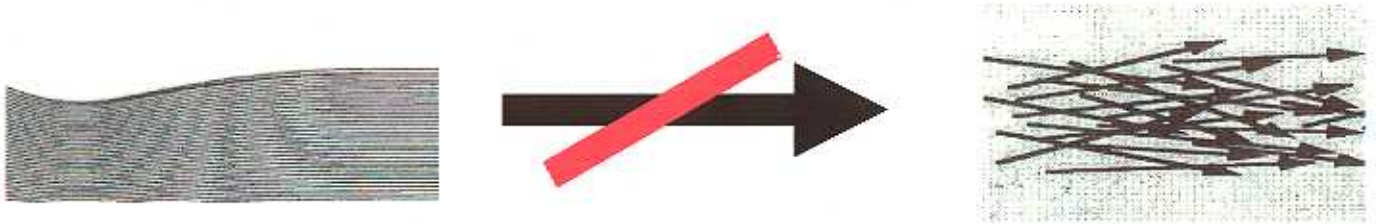
- To achieve the goals of transport and focusing, we must
  - control the growth of beam **INSTABILITIES**



Stable beam

Unstable beam

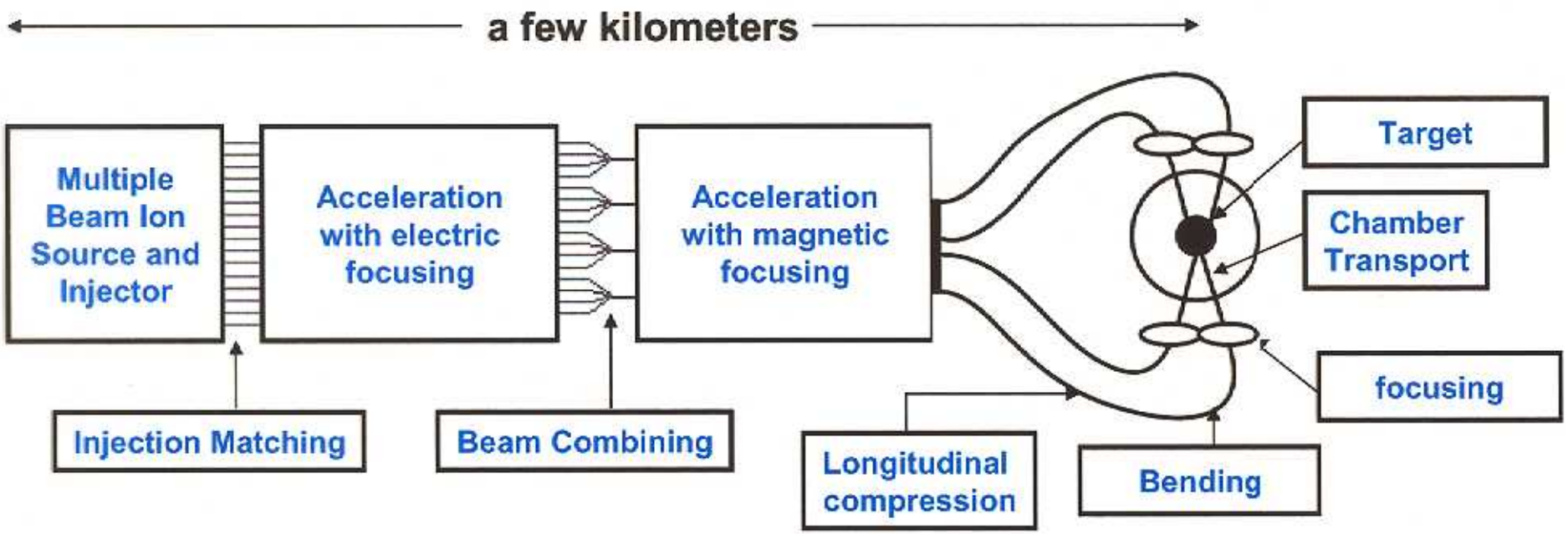
-control the increase of **EMITTANCE** (transverse beam temperature)



Low emittance

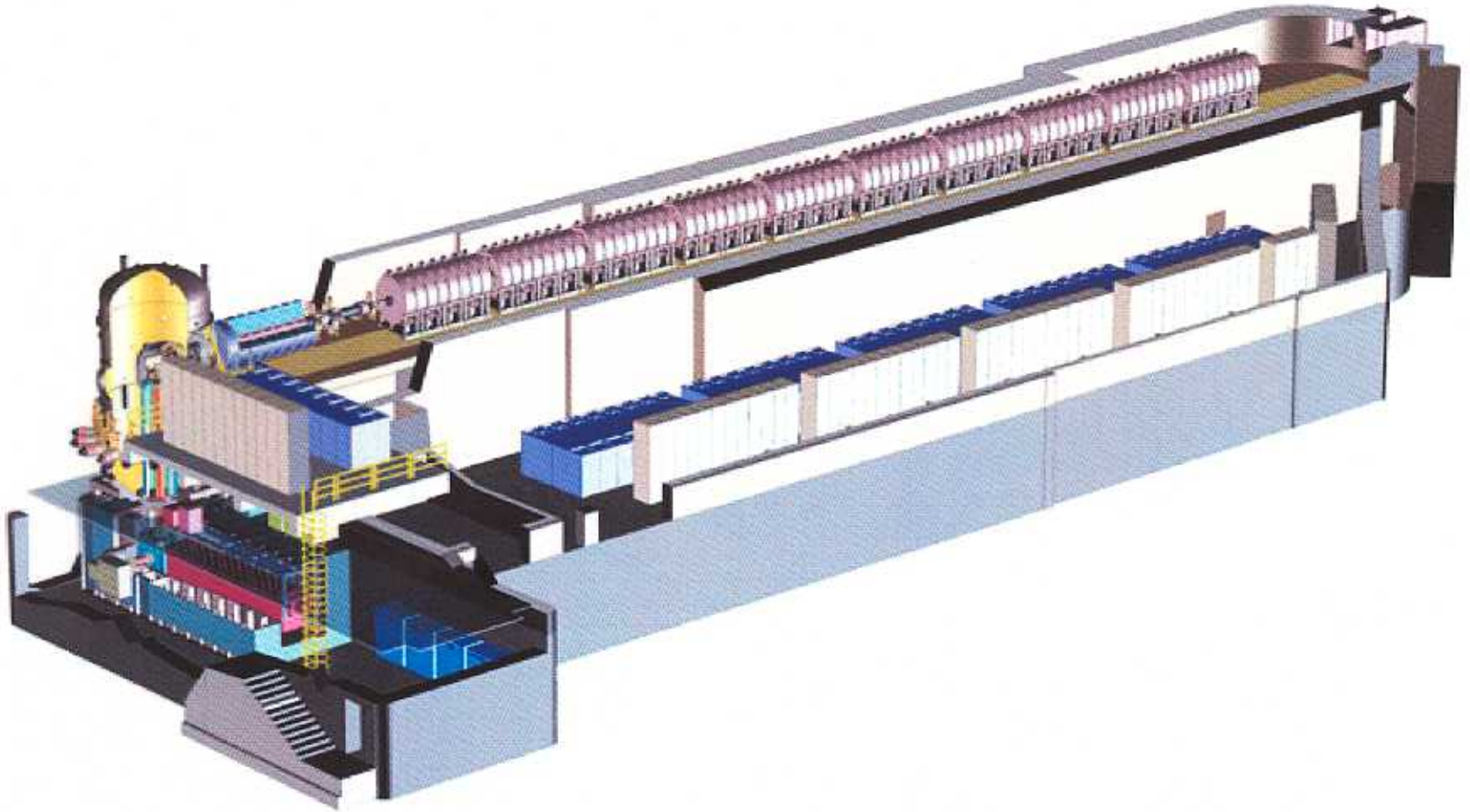
High emittance

An Induction Linear Accelerator for Heavy Ion Fusion



- **Power amplification to the required 10^{14} to 10^{15} W is achieved by beam combining, acceleration and longitudinal bunching.**

DARHT-II - A HIGH CURRENT ACCELERATOR FOR RADIOGRAPHY



Los Alamos
NATIONAL LABORATORY

BERKELEY LAB

Aerial View of DARHT Complex

Los Alamos
NATIONAL LABORATORY

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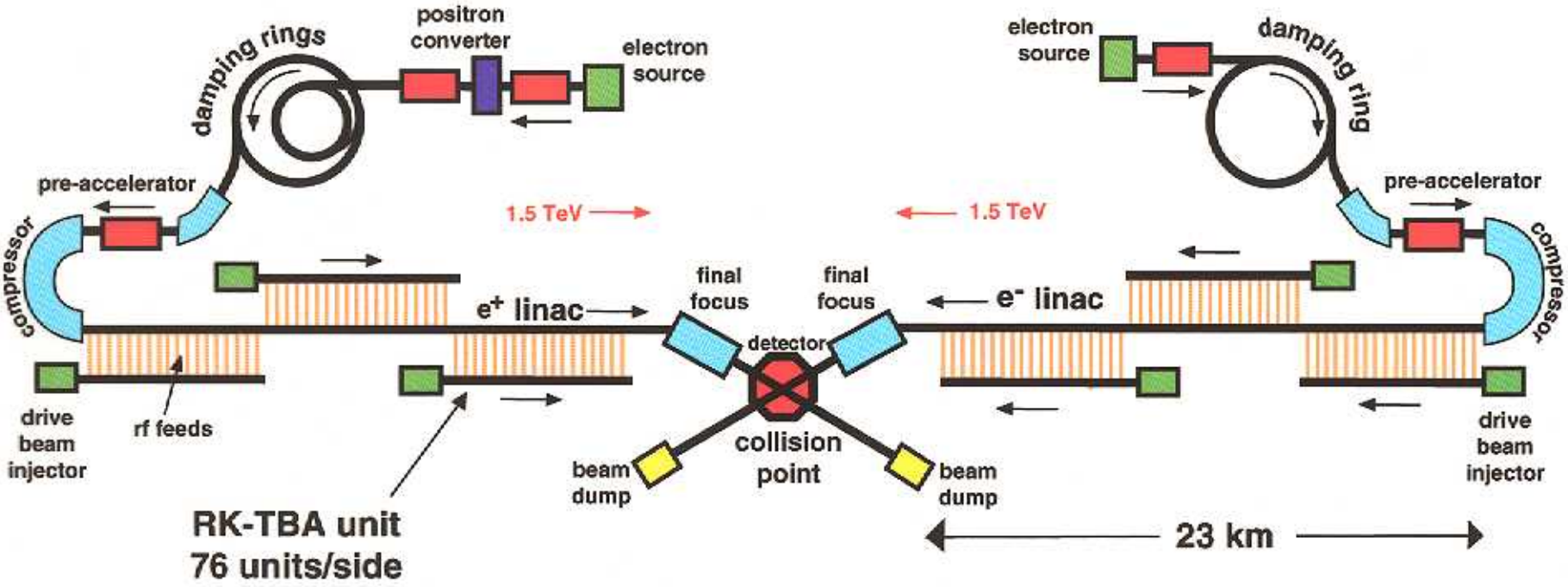
Relativistic Klystron Two-Beam Accelerator concept to provide the rf power for a 3-TeV e^+e^- linear collider

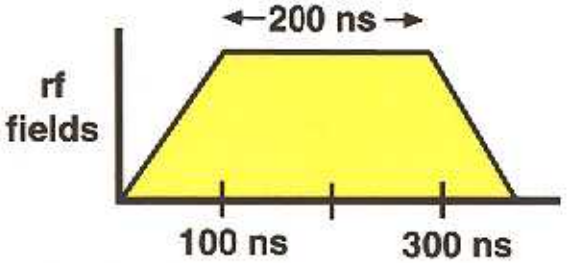
RK-TBA
LBNL – LLNL



Each RK-TBA unit would:

- power a 300-m section of the main linac at 100 MV/m (74 MV/m loaded)
- have 150 rf output structures which each provide 360 MW of rf power

Accelerating fields in main linac



BEAM INSTABILITIES – A NEW INDUSTRY !

Andrew Sessler

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Printed in U. S. A.

Transverse Resistive Instabilities of Intense Coasting Beams in Particle Accelerators*

L. JACKSON LASLETT, V. KELVIN NEIL, AND ANDREW M. SESSLER
Lawrence Radiation Laboratory, University of California, Berkeley and Livermore, California

(Received 7 December 1964)

Reprinted from THE REVIEW OF SCIENTIFIC INSTRUMENTS, Vol. 37, No. 11, 1579–1588, November, 1966
Printed in U. S. A.

Transverse Coherent Resistive Instabilities of Azimuthally Bunched Beams in Particle Accelerators*

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(Received 31 May 1966; and in final form, 15 July 1966)

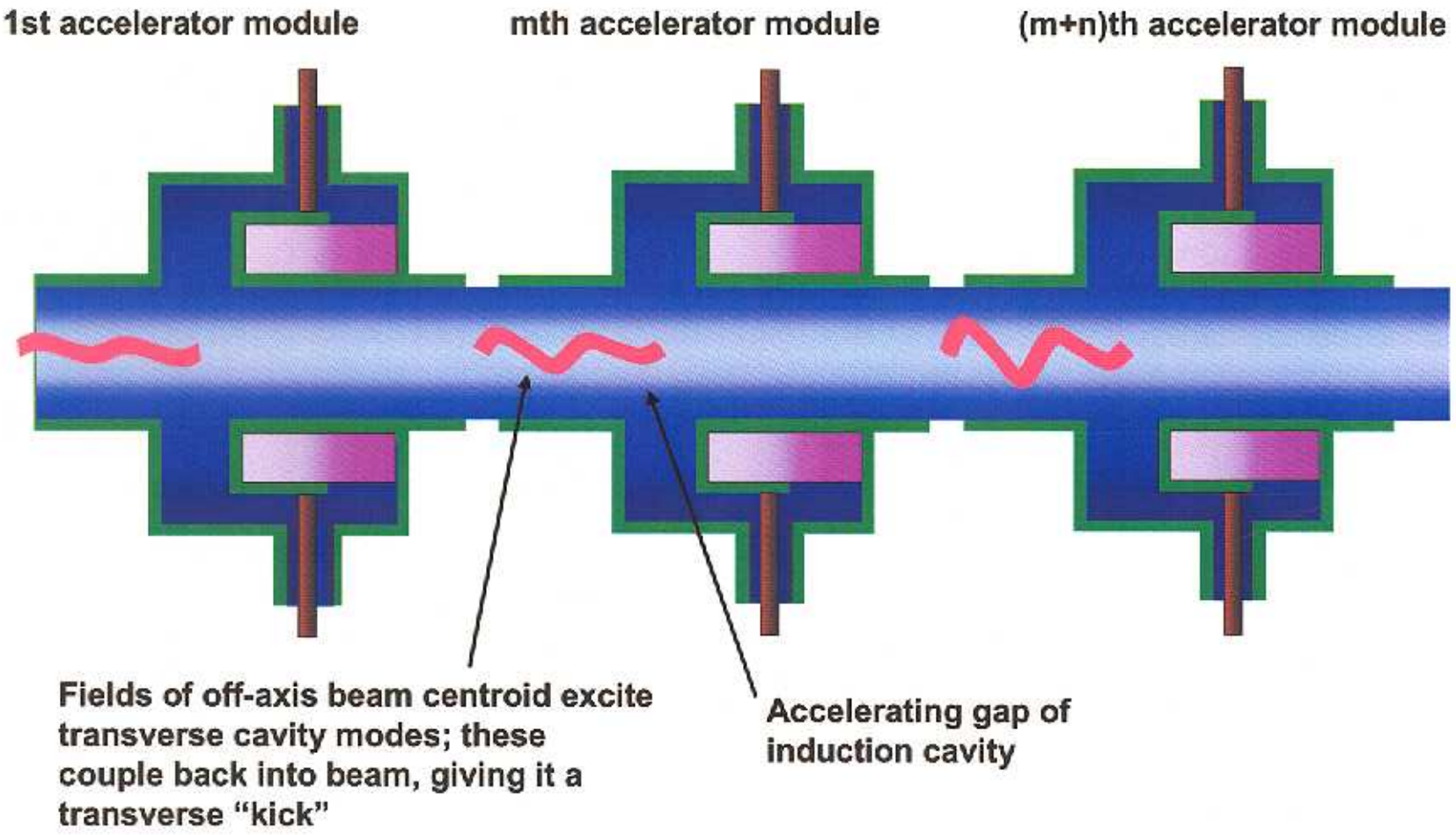
Reprinted from THE REVIEW OF SCIENTIFIC INSTRUMENTS, Vol. 36, No. 4, 429–436, April 1965
Printed in U. S. A.

Longitudinal Resistive Instabilities of Intense Coasting Beams in Particle Accelerators*

V. KELVIN NEIL AND ANDREW M. SESSLER
Lawrence Radiation Laboratory, University of California, Livermore and Berkeley, California

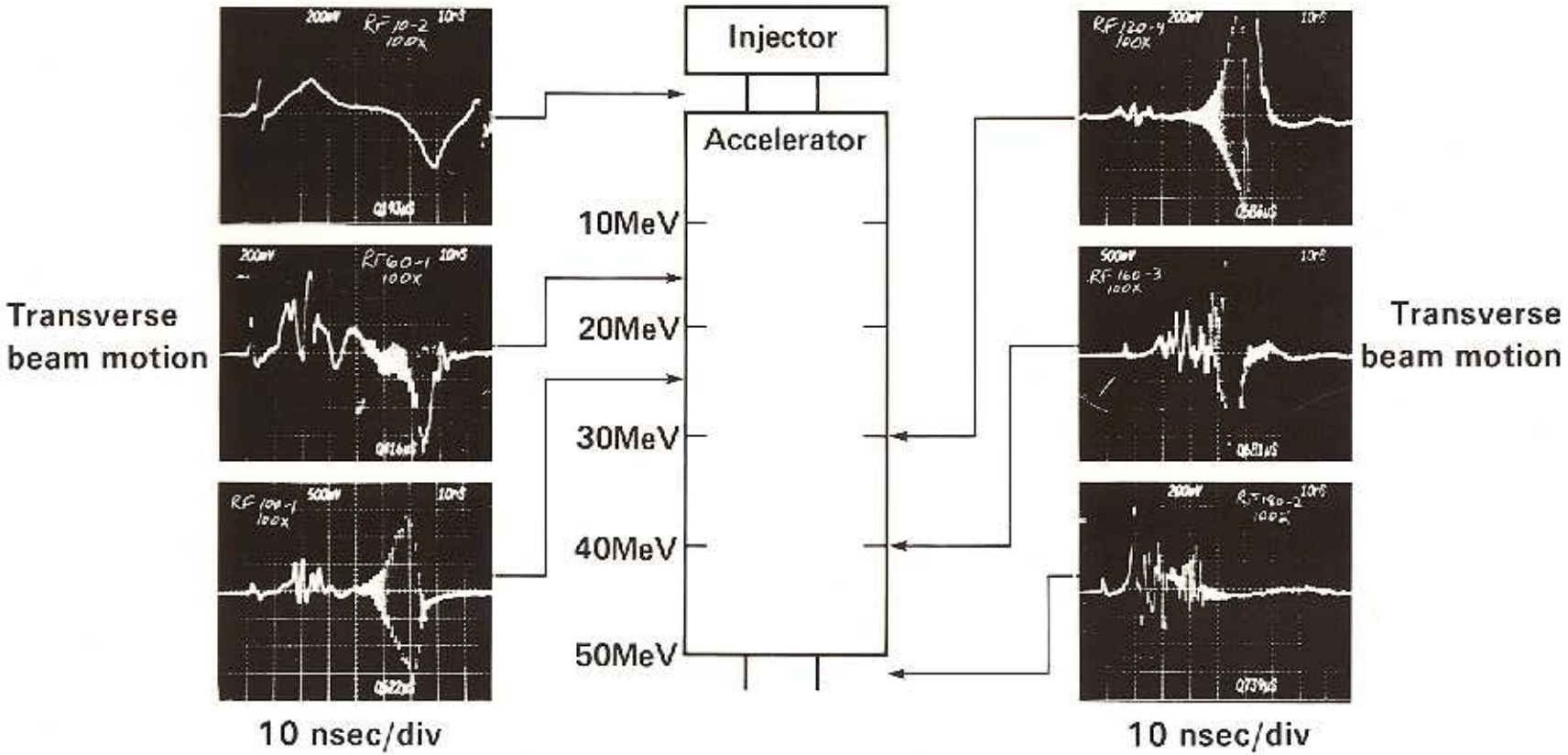
(Received 7 December 1964; and in final form, 6 January 1965)

The beam breakup instability



Without laser guiding (using conventional magnetic solenoids) growth of transverse beam motion degrades ATA beam

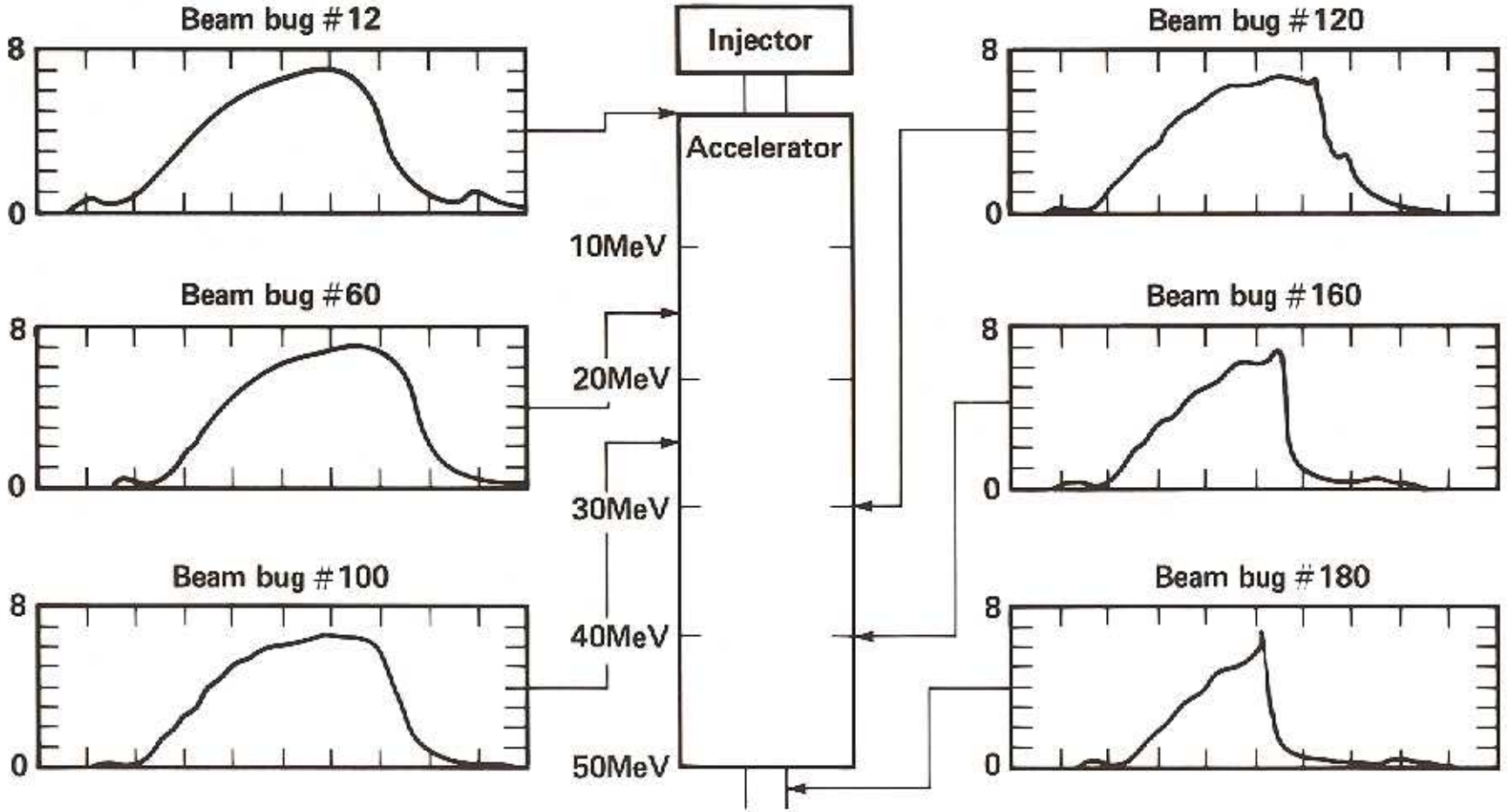
- Oscilloscope traces show growth of transverse beam motion along accelerator length



60-B-1284-22A

Without laser guiding (using conventional magnetic solenoids) transverse beam motion degrades the ATA beam

- Computer plots of ATA beam current as measured by diagnostics located along the accelerator (all traces 1KA/div, 10nS/div.)



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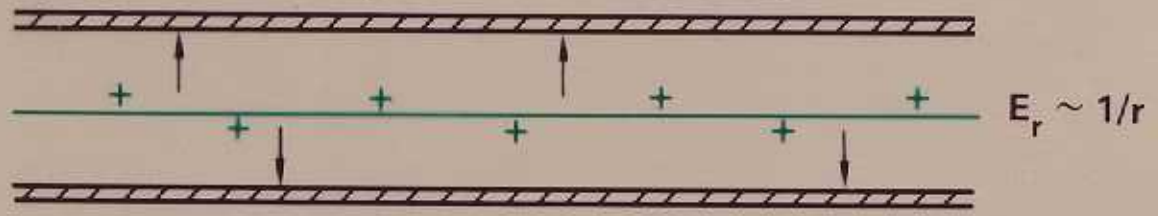
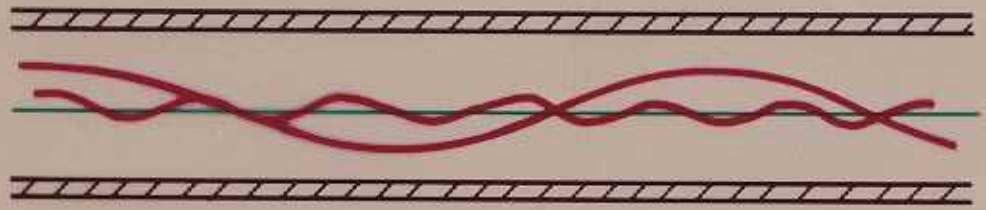
PHASE MIX DAMPING OF BEAM OFF-AXIS DISPLACEMENTS

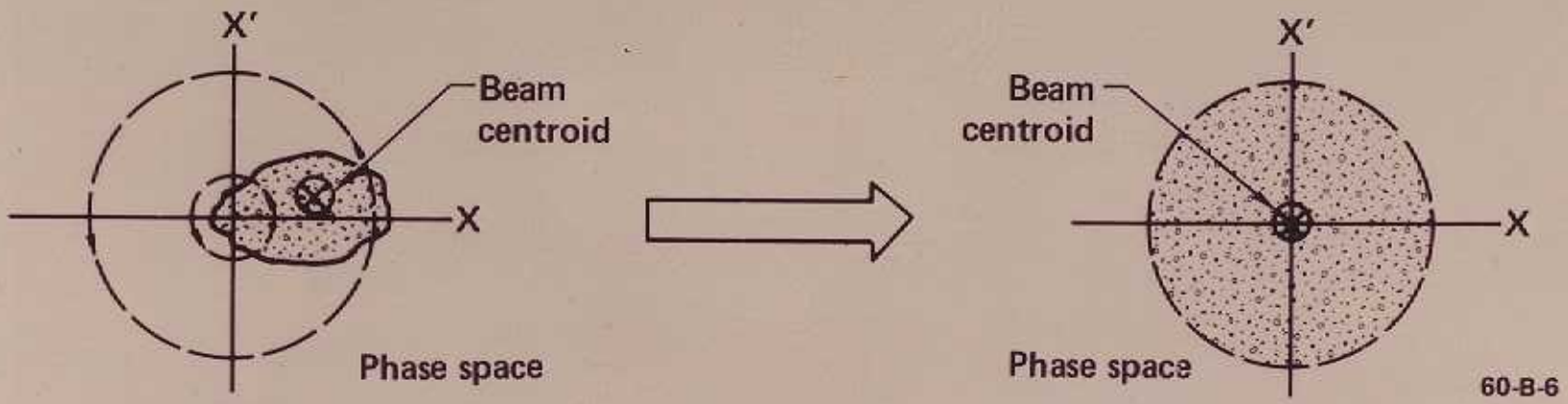
- Consider a line charge as the focusing field for beam electrons



- Beam electrons far off axis will oscillate slower than electrons near axis



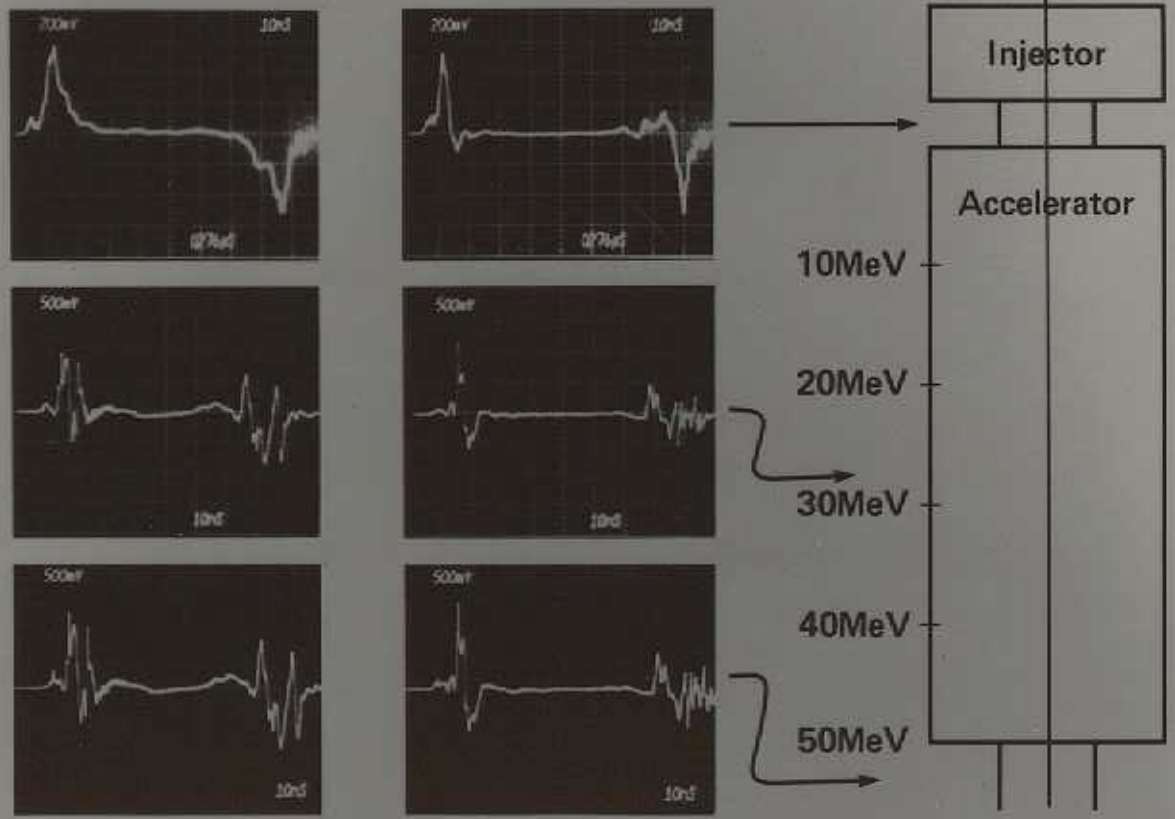
- This "orbital phase mixing" changes coherent displacements into random motion (entropy), or increased emittance



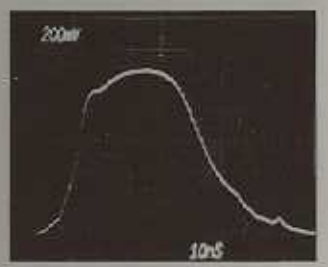
60-B-6

With laser guiding transverse beam motion within ATA is stabilized and suppressed

- Oscilloscope traces on left are from magnetic induction loops at different accelerator locations. Data from one beam pulse is shown in each column. The two columns indicate reproducibility. The oscilloscope trace in the bottom right is accelerator output current (2kA/div. 10 nS/div.).



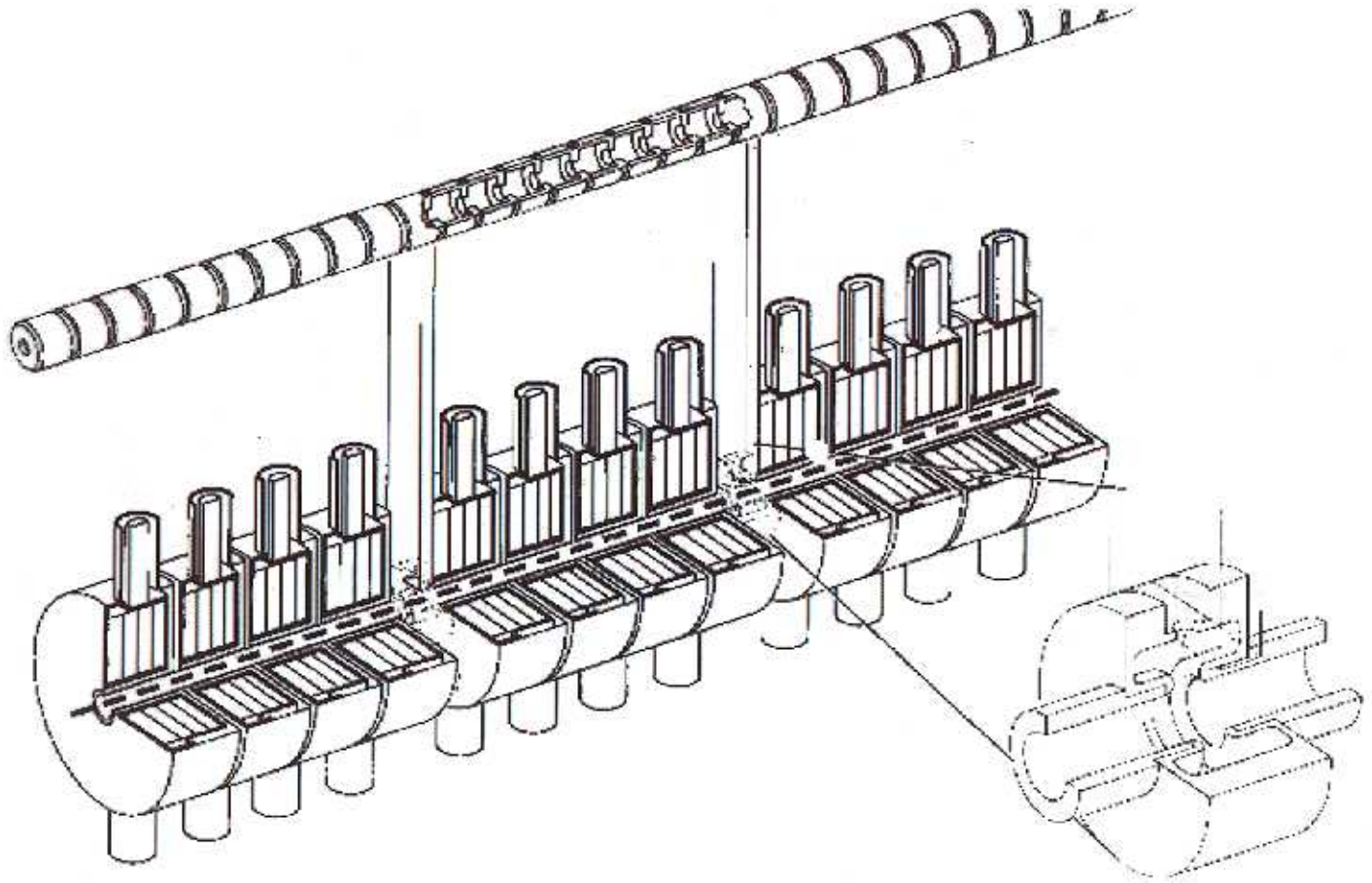
Accelerator output current
2 kA/div, 10nS/div.



60-B-1284-23A

RK-TBA is a concept to improve klystron efficiency by electron beam recycling.

RK-TBA
LBNL – LLNL



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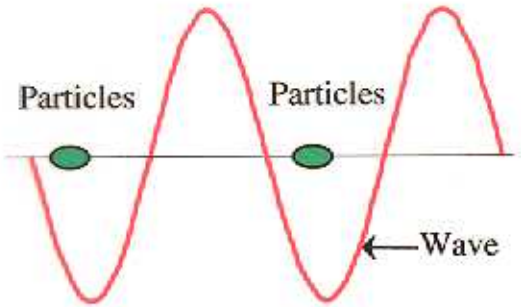
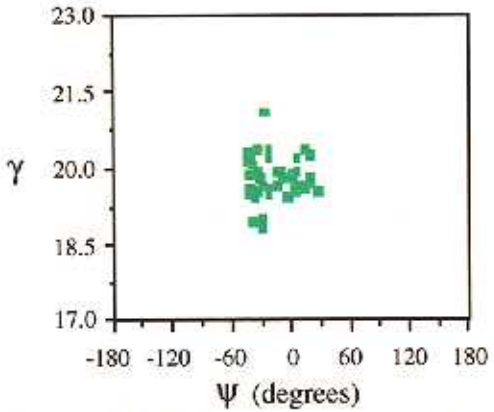
Control of Beam Instabilities in the RK-TBA

RK-TBA
LBNL – LLNL

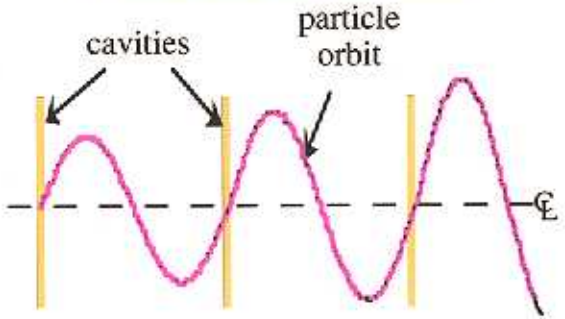
Longitudinal debunching



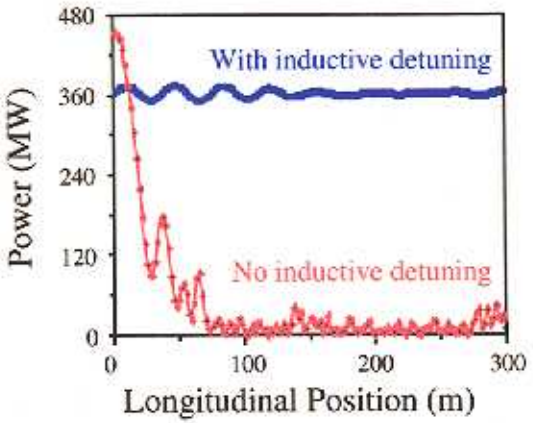
Low frequency BBU from induction cavities



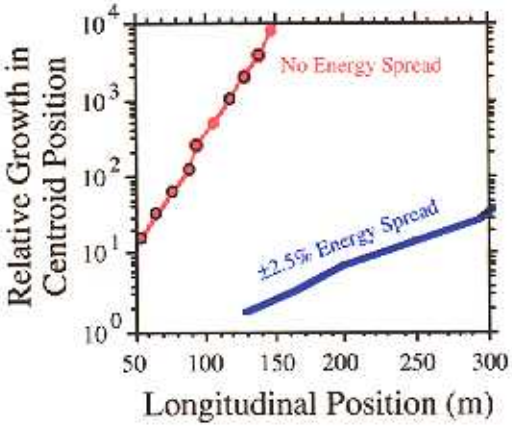
High frequency BBU from transfer cavities



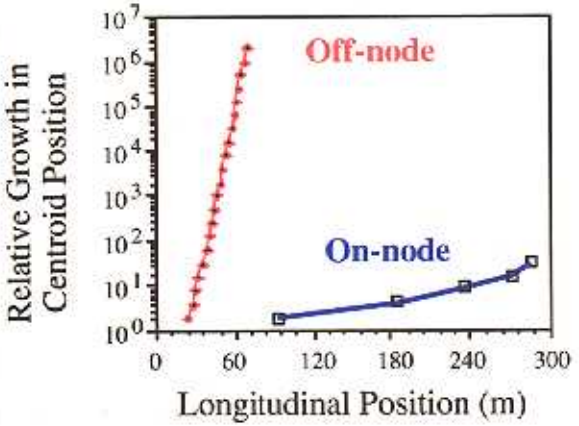
Solution: inductive detuning



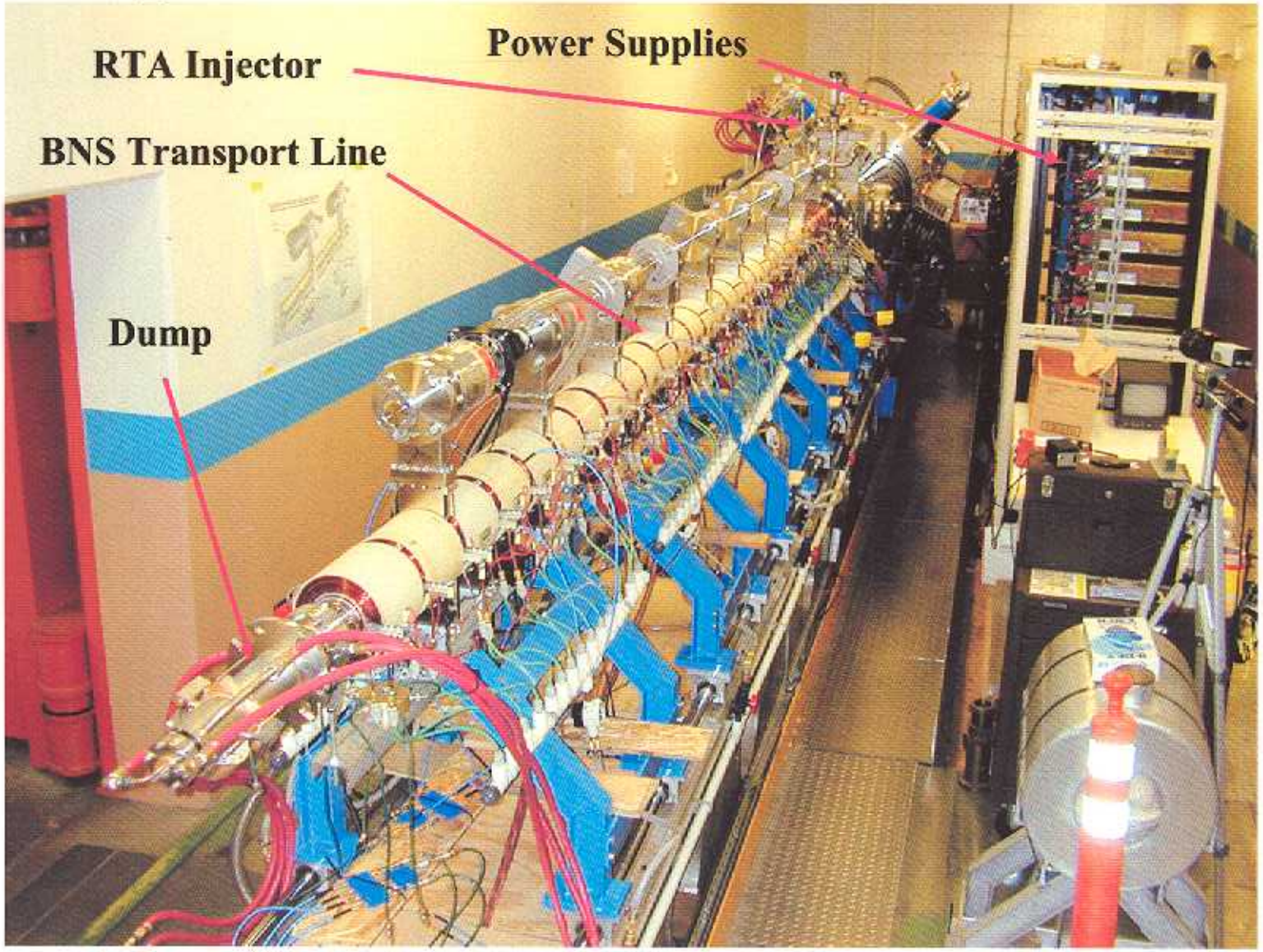
Solution: phase mix damping



Solution: betatron node scheme



The RTA injector and beam line for final experiment.

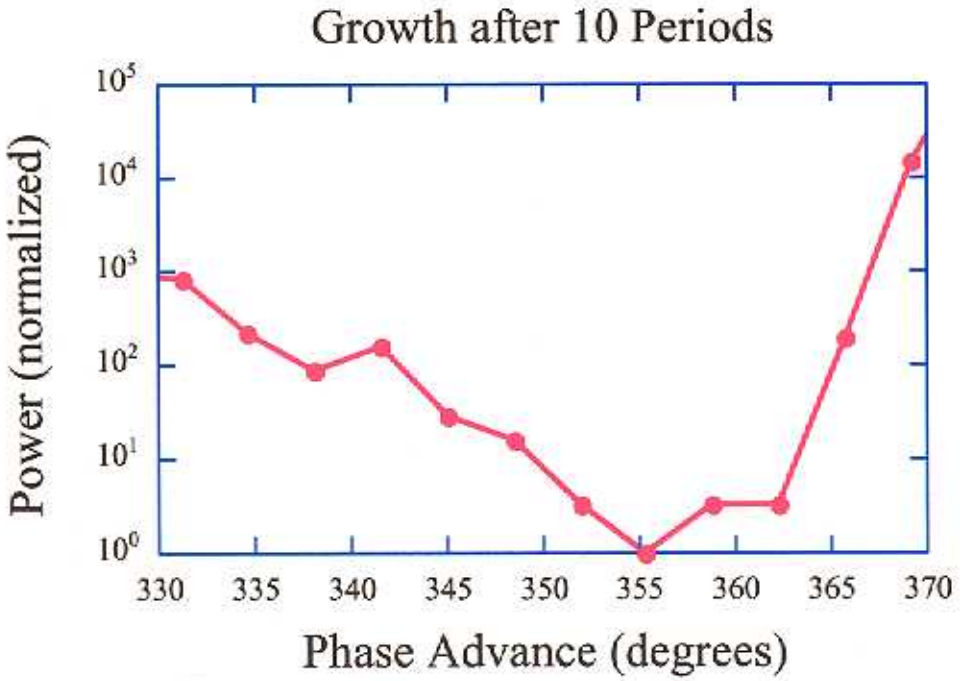


Simulation of BNS scheme used in design of experiment.

Two characteristics of simulations:

1) Significant dip in transverse mode power approaching 360° phase advance between cavities (~1.04 kG),

2) Asymmetry in growth shape about minimum.



Simulation Parameters:

Excitation: $x(0,t) = \sin(\omega t)$

Cavity Characteristics:

$Z_\perp/Q = 13\ \Omega/m$

$Q = 120$

Freq =3.75 GHz (dipole)

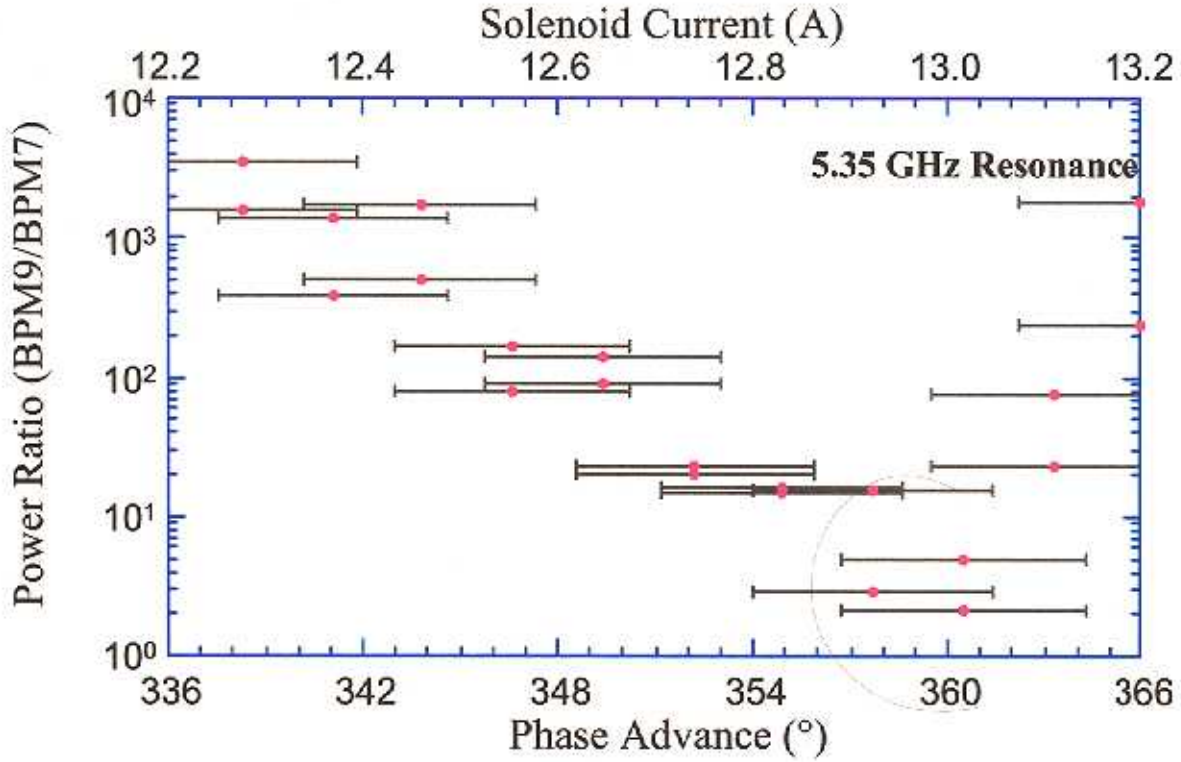
Beam Characteristics:

E = 1.0 MeV

I = 600 A

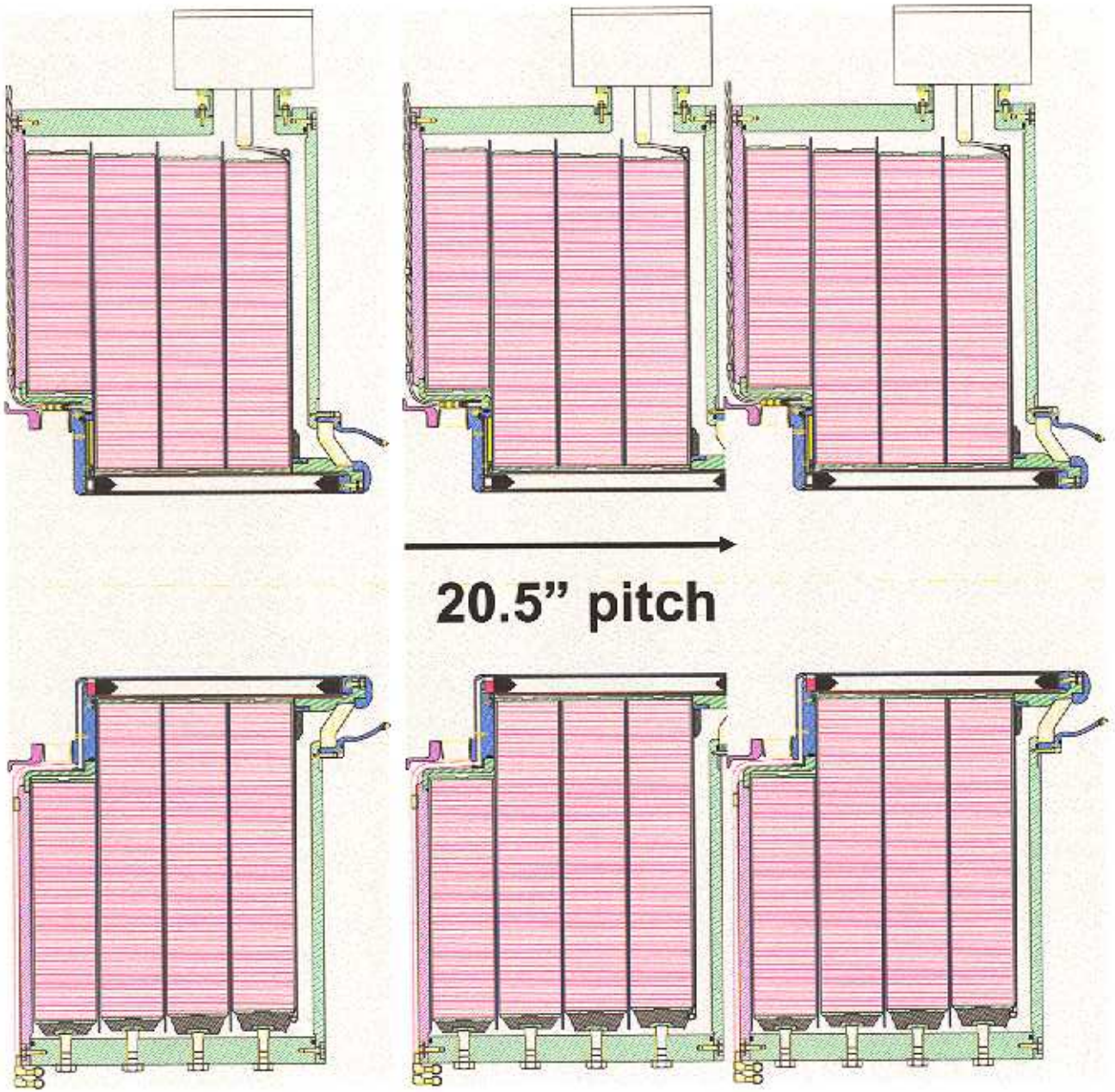
50 ns Rise Time

Experimental Data:
Transverse instability is suppressed by BNS scheme.

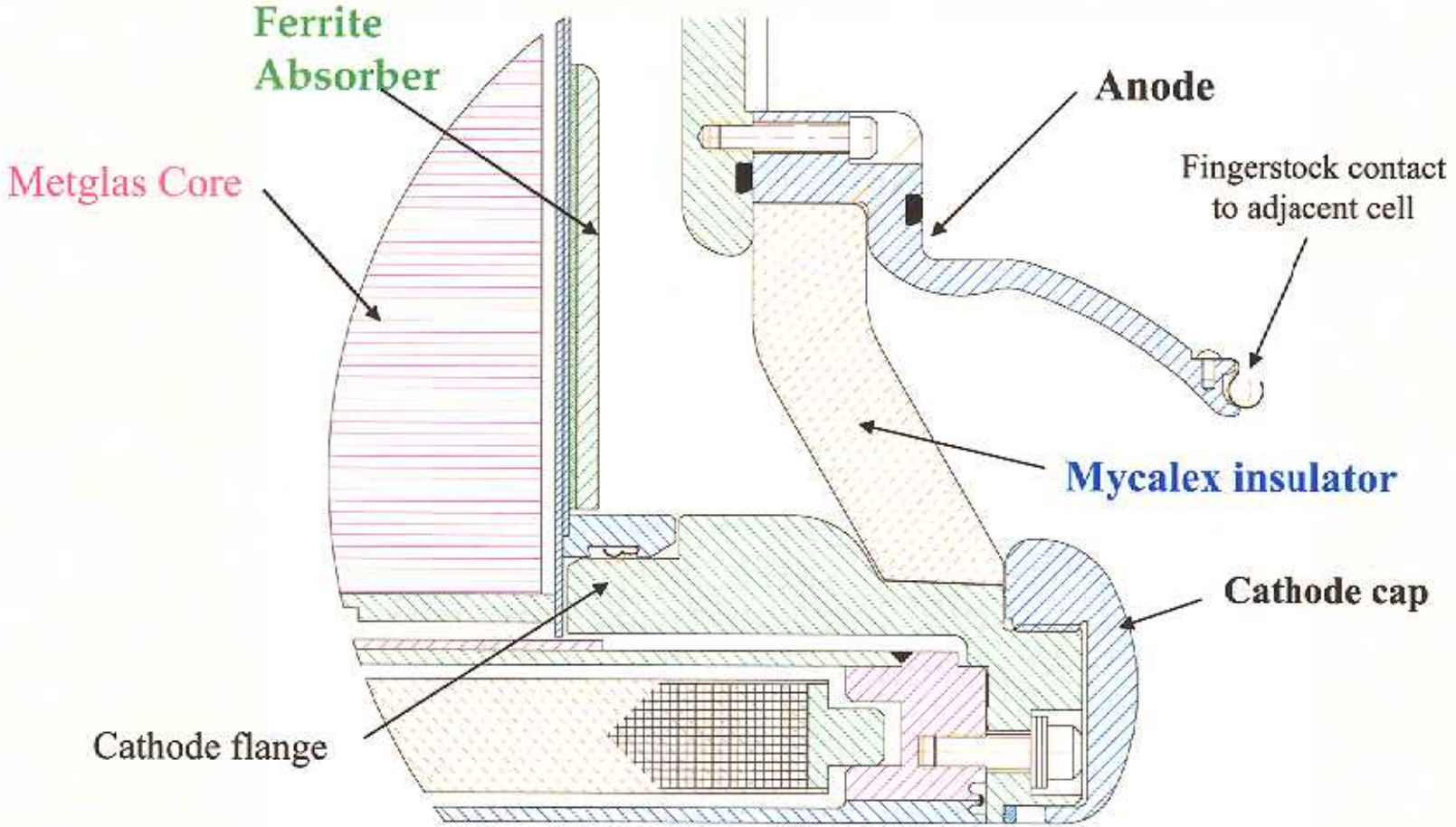


- Graph shows increase in spectral power between periods 6 and 8
- Indicates total growth over 8 periods of more than 13 e-foldings at scan limit
  - Scan limited by beam scraping wall between BPM-7 and BPM-9
- Beam energy 930 kV ± 1.4% for 130 ns for data shown
- Beam current at dump 400 A

DARHT-II Accelerator Cells

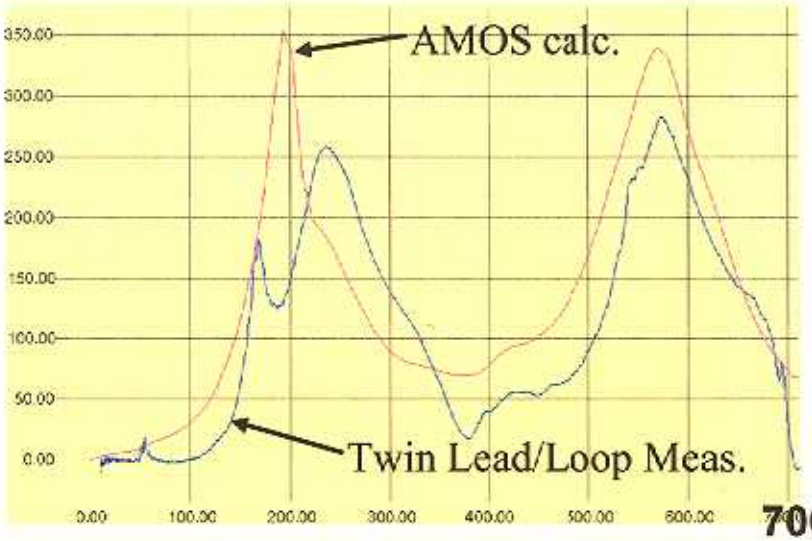


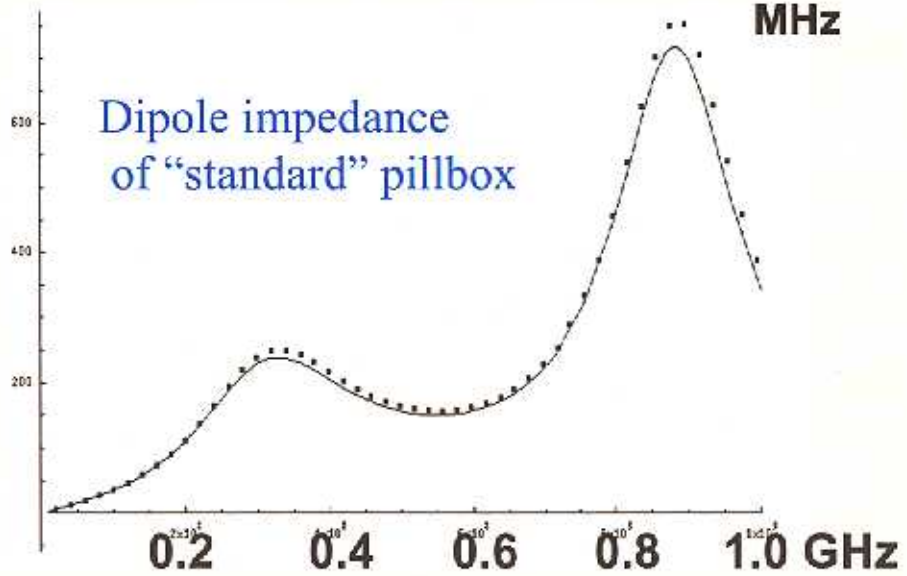
Insulator Cartridge for DARHT II cells



AMOS Code/Expt. Measurement Comparison

- AMOS shows single peak @190 MHz for 10" cell;
  expt => 236 MHz
- Extensive tests by S. Nelson to determine cause of freq. shift
- Standard pillbox modeled; results essentially identical to analytical solution
- Many items examined for frequency sensitivity:
  - gridding resolution
  - insulator dielectric
  - BC at outer radii
- No obvious answer – perhaps associated with double peak of expt. data





700 MHz

Beam Breakup Instability Growth Predictions

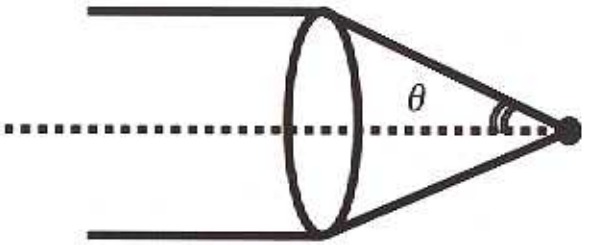
- Injector and standard cell impedance results from twin lead/quad loop measurements & analysis by Briggs-Nelson-Vella-Birx fed into BREAKUP code with 100μm excitation at resonant frequencies

Excitation Frequency (MHz)	$Z_\perp$ (ohm/m)	Q	Amplitude (mm) @ cell 44	Amplitude (mm) @cell 88
146	106	4.0	0.125	0.11
200	120	2.75	0.14	0.16
500	500	2.0	0.125	0.115
168	93	15	0.145	0.155
236	251	2.5	0.16	0.225
572	278	5.9	0.17	0.26
ALL – full $Z_\perp$ (50um excitation)			0.145	0.18
ALL – no $Z_\perp$ (50um excitation)			0.13	0.105

Requirements for small final spots

-low emittance
-strong final focus magnet

$$r = \frac{\in}{\theta}$$



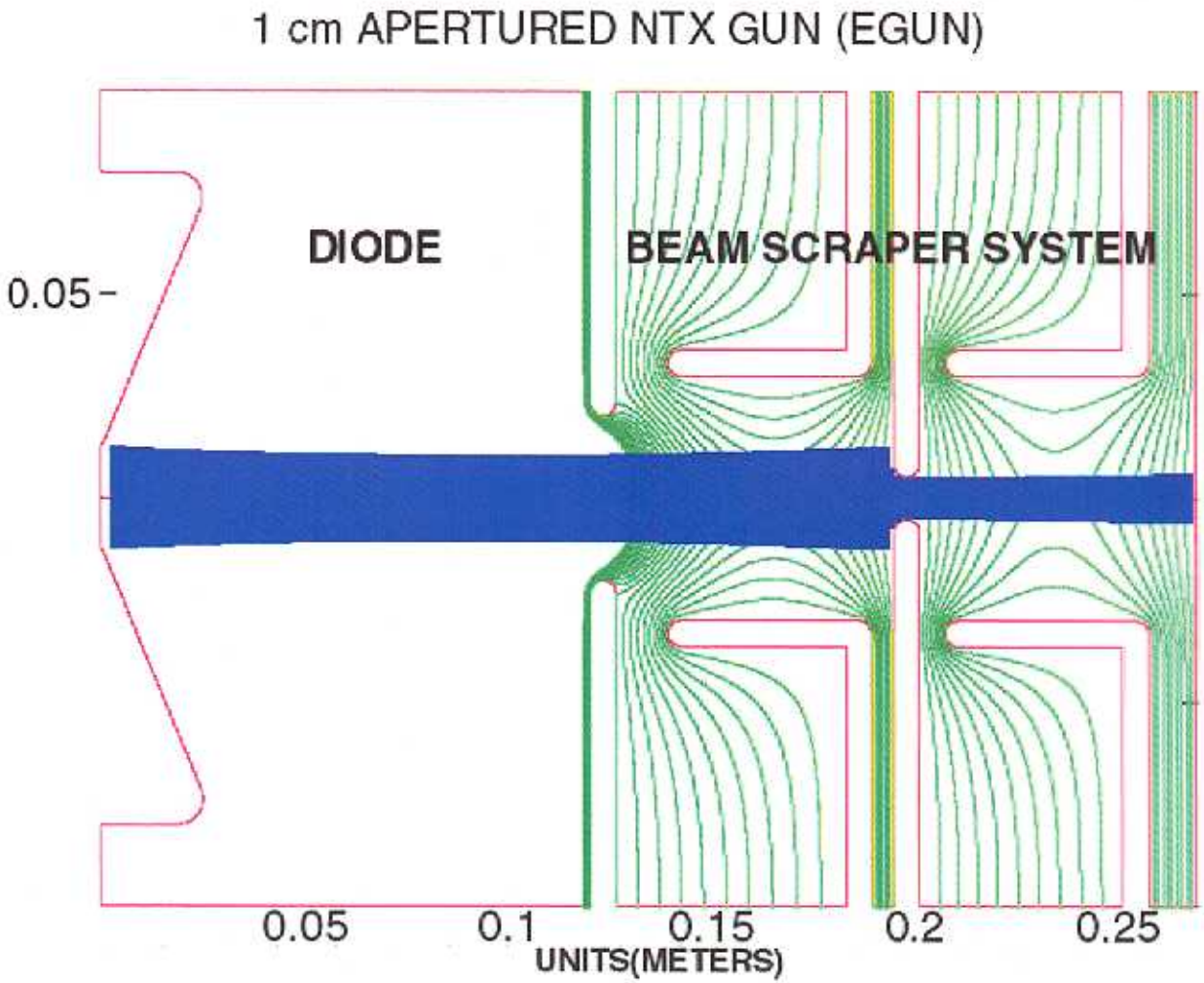
r = spot radius

$\in$ = emittance

For space-charge-dominated beams, emittance increases if the transverse beam profile is nonuniform (nonlinear forces)

Beam Aperturing Experiment to obtain variable perveance beams

EGUN simulation of beam aperturing

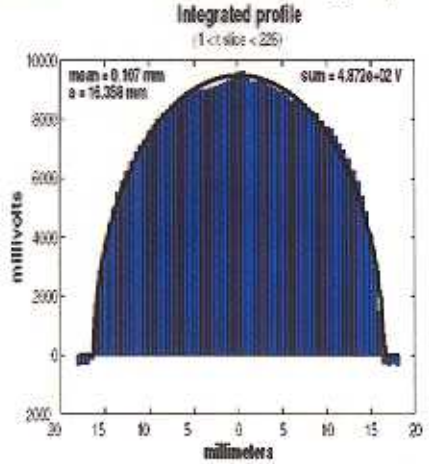


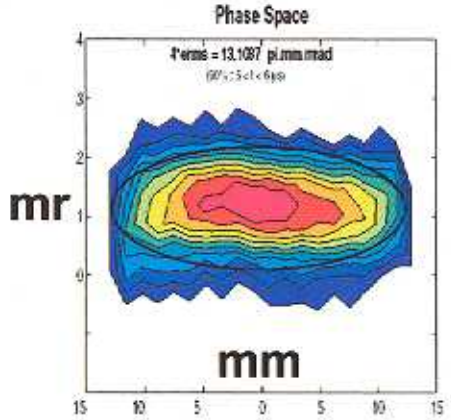
A High Brightness Apertured Beam (300kV, 25 mA)

Slit-integrated density profile

Phase Space Diagram

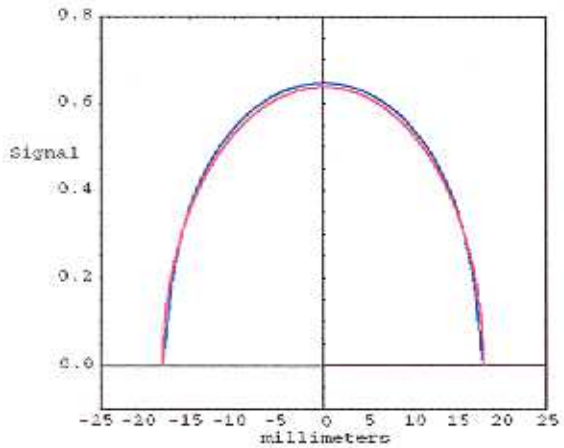
Experiment

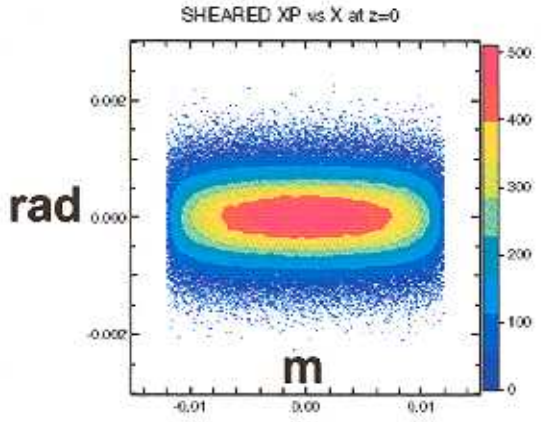




Measured $\varepsilon_N = 0.050\ \pi$ *mm-mr*

Calculated (EGUN)



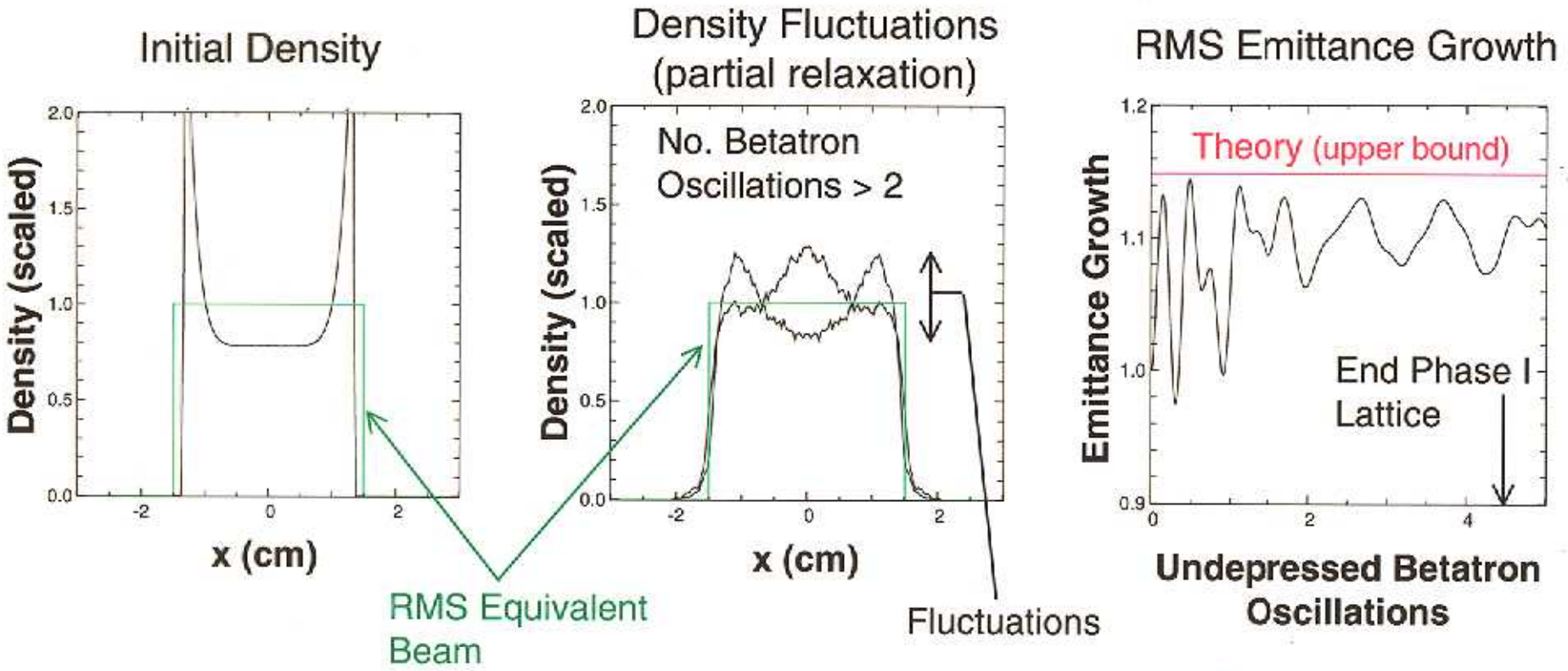


(ε_N from source temperature alone = 0.03π mm-mr)

Perturbations launched by initial distribution nonuniformities can phase-mix to a more uniform profile with increased emittance

Mode spectrum launched can undergo a rapid cascade, settling to a smaller amplitude and lower order distortion

- Approximate conservation constraints employed to bound emittance increases resulting from full relaxation to a uniform profile [Lund, Lee, and Barnard, Proc. Linac 2000, pg. 290]
- How will such evolutions influence the range and interpretation of measurements

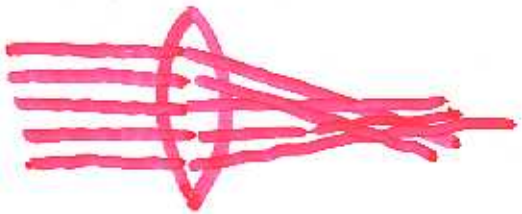


Emittance Growth at Final Focus (Limit on multi-TeV e^+e^- colliders)

(1) Small spots ($\sim$ nm) at TeV collider final focus require very strong magnets

(2) Synchrotron radiation at final magnet introduces large energy spread $\Rightarrow$ large emittance increase

(3) This effect sets a limit on how small spots can be for very high energy e^+e^- colliders (Oide limit)



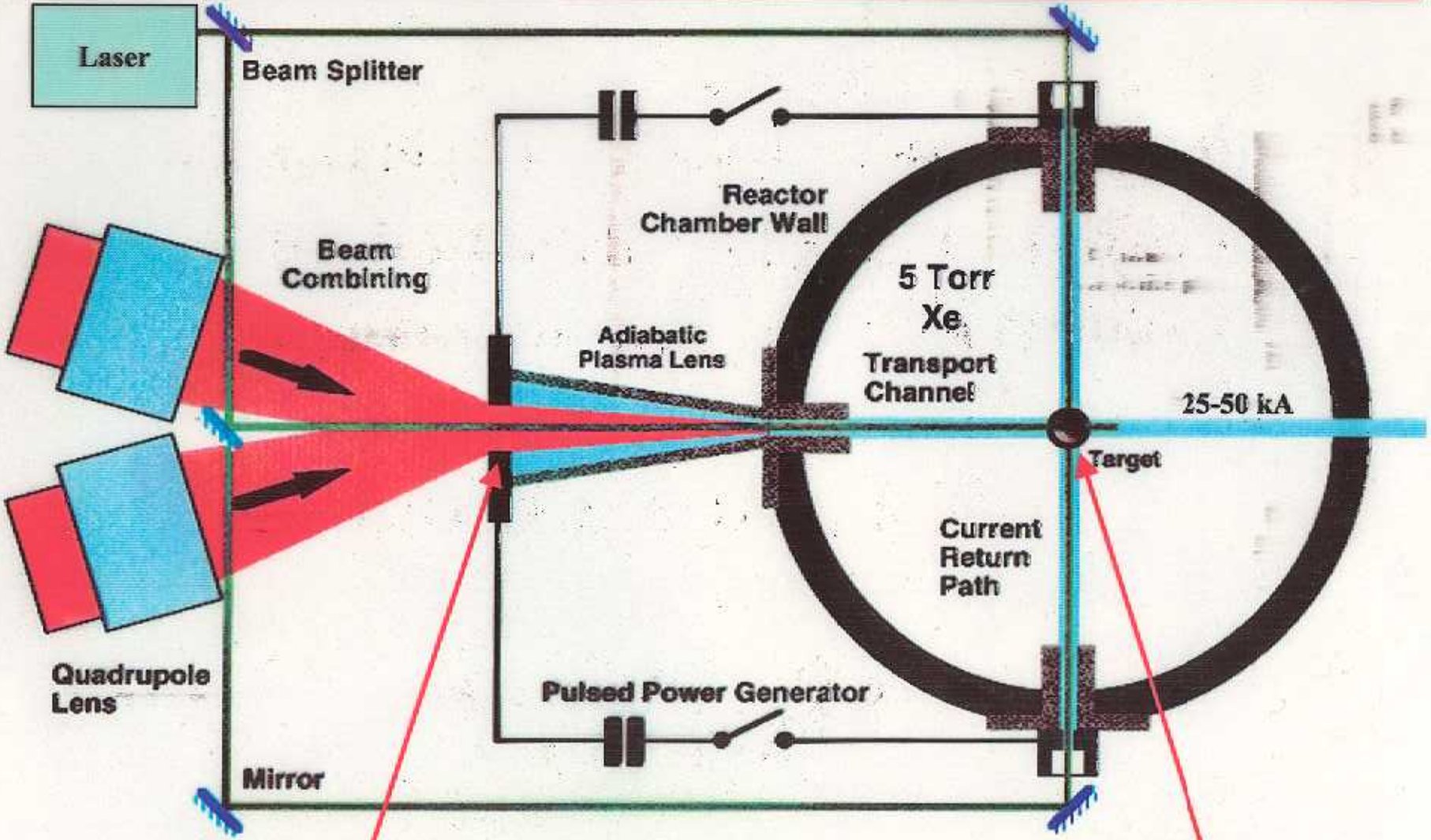
One possible solution: Plasma-Based Adiabatic Focuser
- Chen, Oide, Seryi & Yu Phys Rev Lett 64 1231 (1990)

Strong, and increasing plasma focusing all the way to the target

Postulate :

$$M_{kl} \equiv V_{kl} \frac{1}{R^k}$$

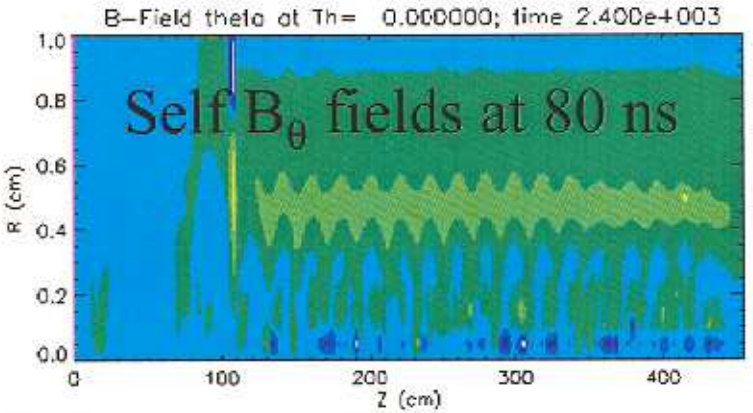
Z Pinched Transport can reduce chamber focus requirements and reduce driver costs.

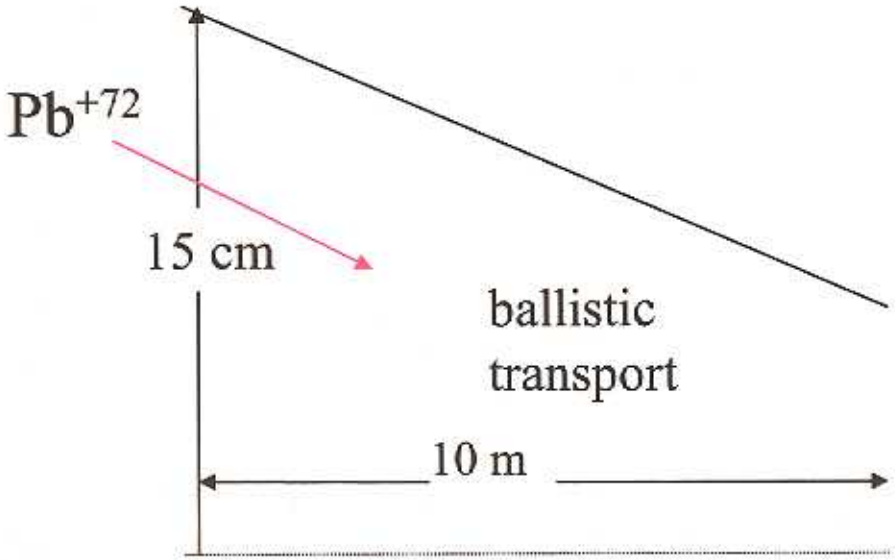


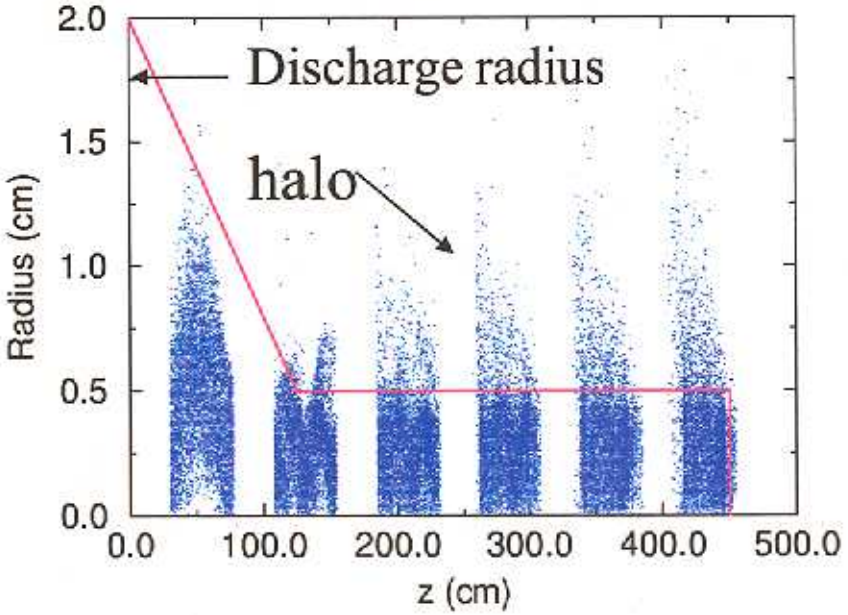
87% energy transport, 3.5-mm RMS radius calculated for APT

- 4-GeV, 6 MA Pb^{+72} ions, 1-mrad divergence

-Beam, ohmic heating produce $T_e > 100$ eV
-Calculated $\tau_d = 5$ μs limits net current growth to 30 kA over 8-ns pulse
-Halo grows from self-field interaction
-Difficult to hit annular target

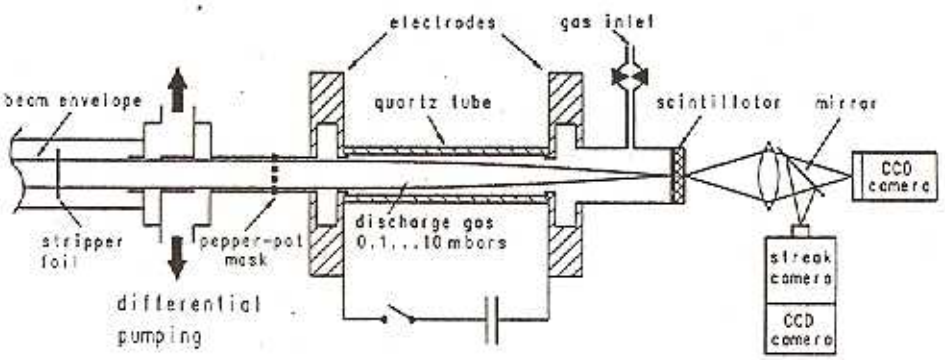






Experiments Addressing Plasma Lens Focusing

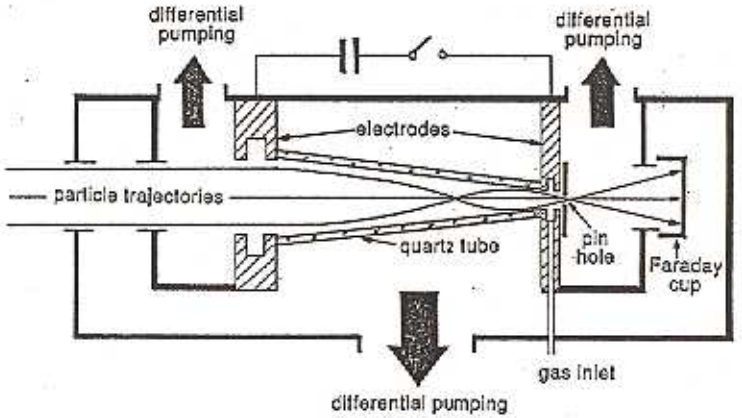
Final Focus Experiments at GSI
(thin lens)



I=20 kA, length: 10 cm, beam: Au^{60+} 2.2 GeV

Results:
- emittance limited focusing
- nonlinearities <1%
- scattering and energy loss are negligible at 10 MeV/u

Focusing Experiments with the ESQ Injector Beam
(adiabatic focusing)

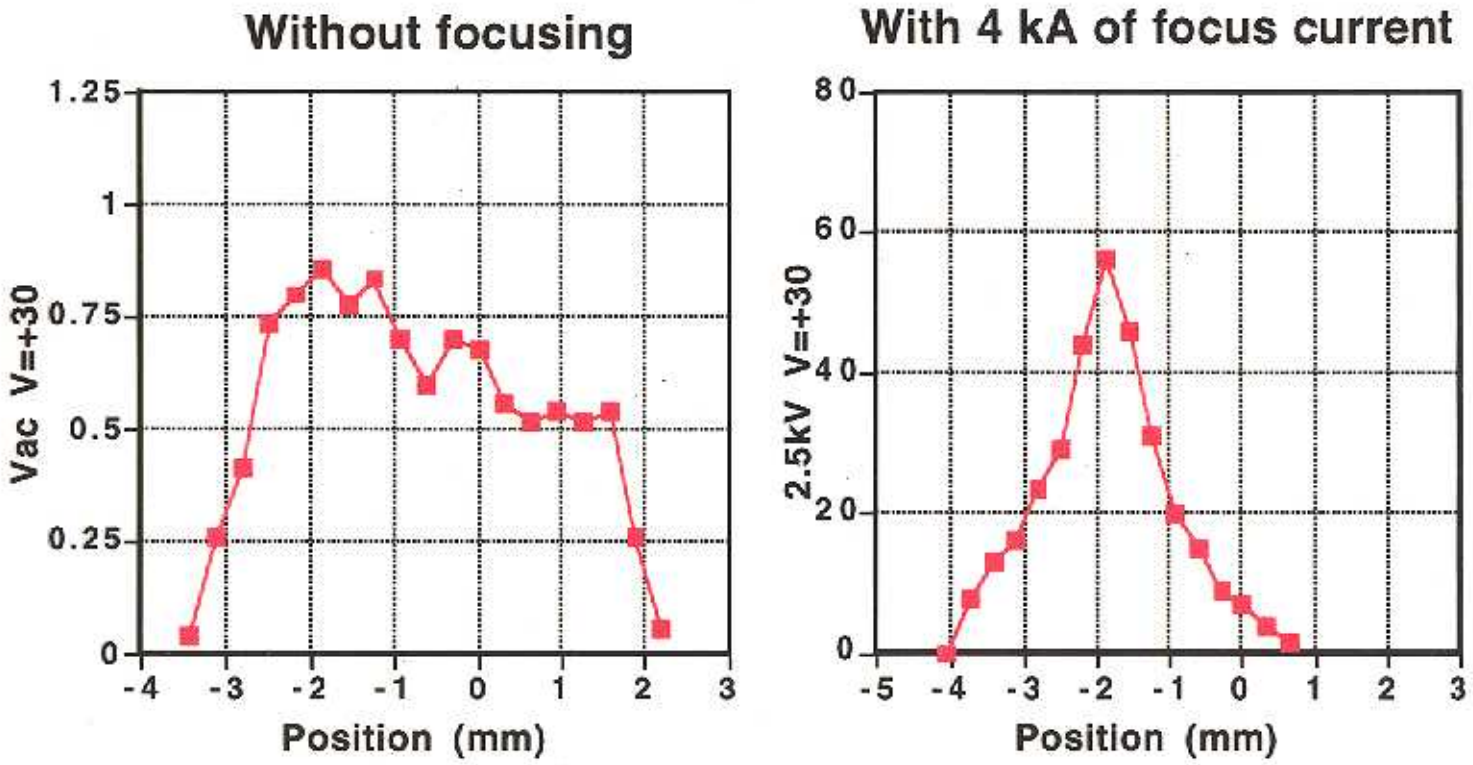


I=30kA, length: 35 cm, beam: K^+ 2 MeV

Objectives:
- test of adiabatic focusing
- test of space charge and current neutralization
- loss of beam particles

Focusing increases beam current density by ≥70

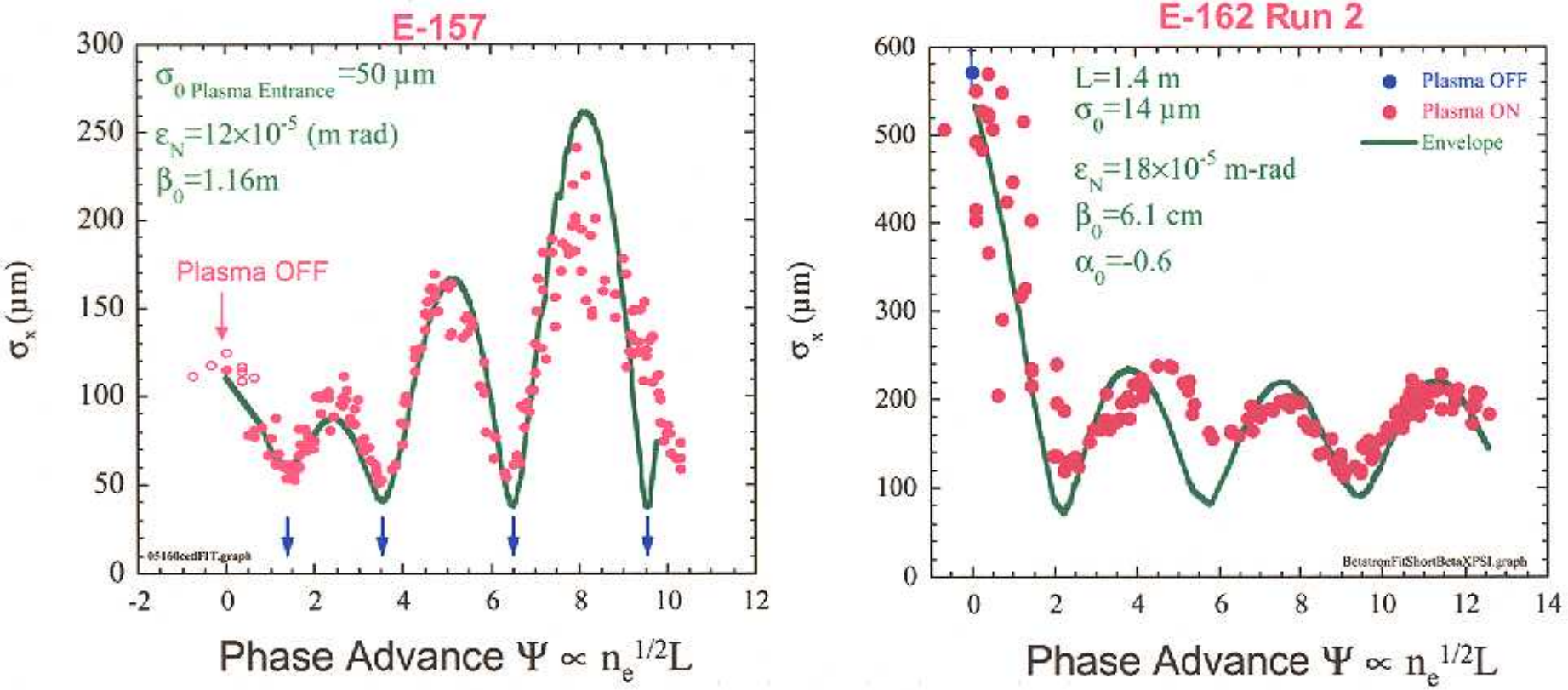
- Pinhole scans of the exit beam



- Without focusing the beam fills the tube exit (≈ 5mm dia.)
- The beam is smaller than the pinhole (1 mm dia.) with focusing.

Matched Beam Propagation Through A Long Plasma

- Smaller "matched" beam size at the plasma entrance reduces amplitude of the betatron oscillations measured at the OTR downstream of the plasma
- Matched beam propagation => pre-cursor to adiabatic plasma lens



C. E. Clayton et al., PRL Vol. 88, 154801/1-4 (15 April 2002)

Stanford Linear Accelerator Center

Happy Birthday Andy!

UCLA USC

From the
E-162 & E-164 Collaborations

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Emittance Growth at Final Focus (limit on multi-TeV $e^+ e^-$ colliders)

1. **Small spots (~nm) at TeV collider final focus require very strong magnets**
2. **Synchrotron radiation at final magnet introducer larger energy spread => large emittance increase**
3. **This effect sets a limit on how small spots can be for very high energy $e^+ e^-$ colliders (Oide limit)**

One possible solution: Plasma-Based Adiabatic Focuser

- Chen, Oide, Sessler & Yu Phys Rev Lett 64 1231 (1990)

Strong, and increasing plasma focusing all the way to the target

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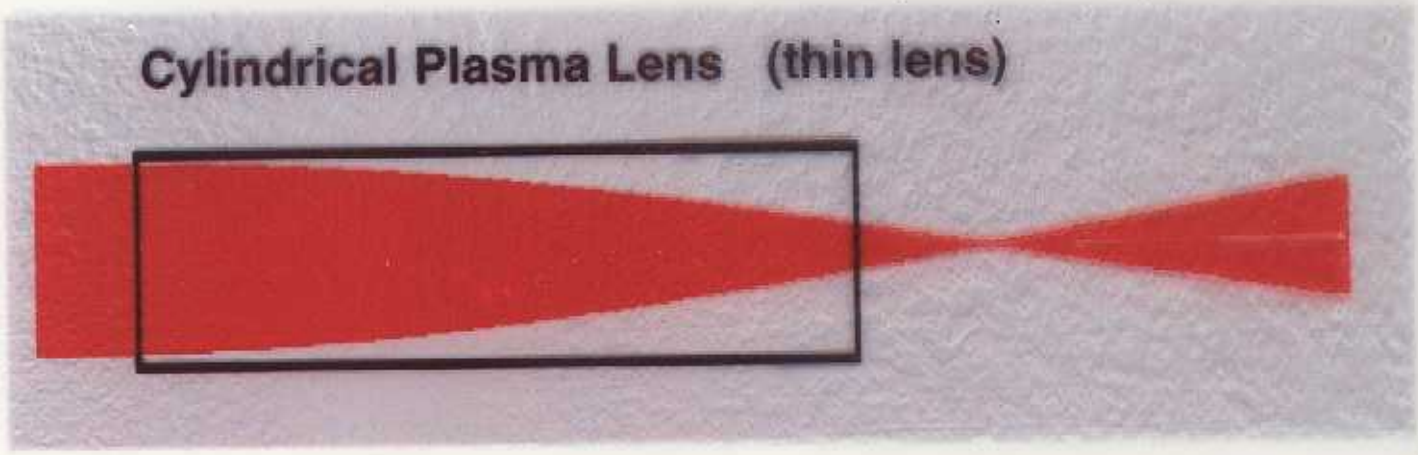
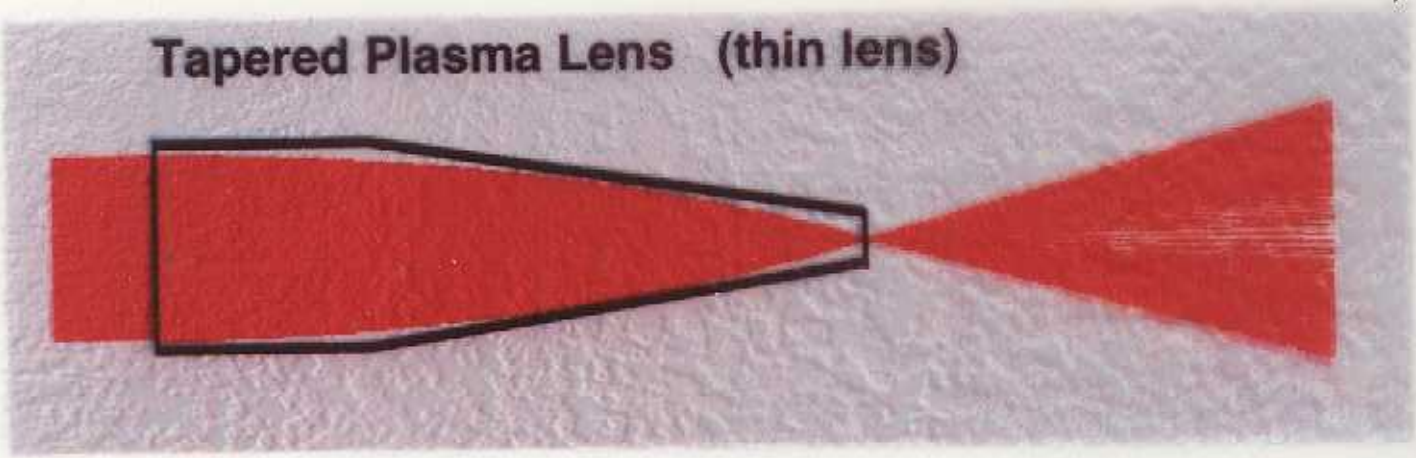
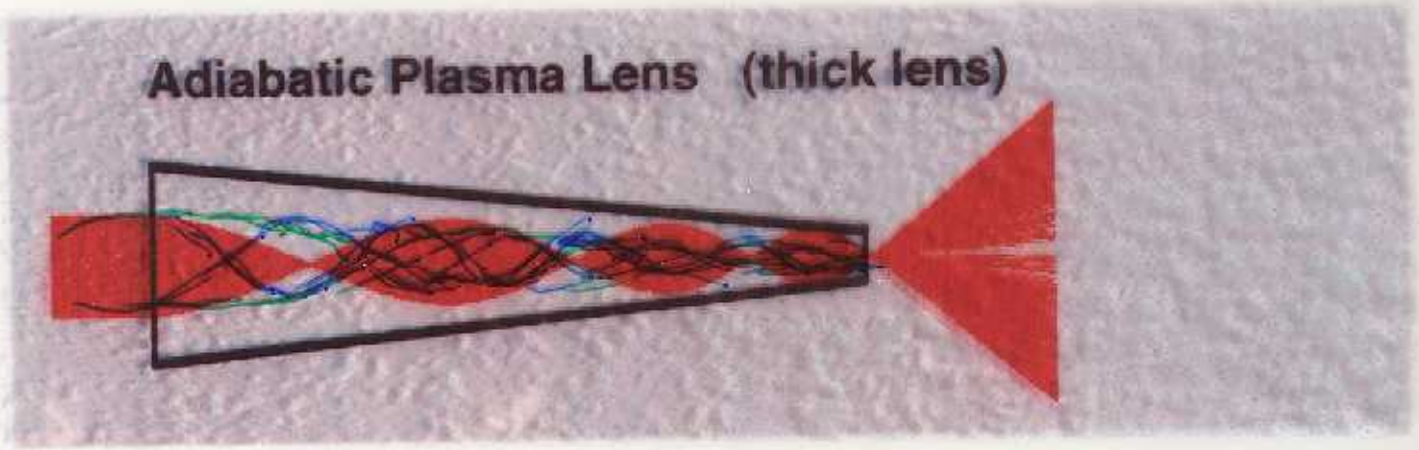

Cylindrical Plasma Lens (thin lens)


Tapered Plasma Lens (thin lens)


Adiabatic Plasma Lens (thick lens)