Small Isochronous Ring (SIR) project at NSCL, MSU

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Talk Outline

- Isochronous regime in accelerators, application to Isochronous Cyclotrons
- Space charge effects in the isochronous regime
- Code CYCO: simulation of SC effects in isochronous cyclotrons
- Small Isochronous Ring for experimental studies of space charge effects

Isochronous regime in accelerators

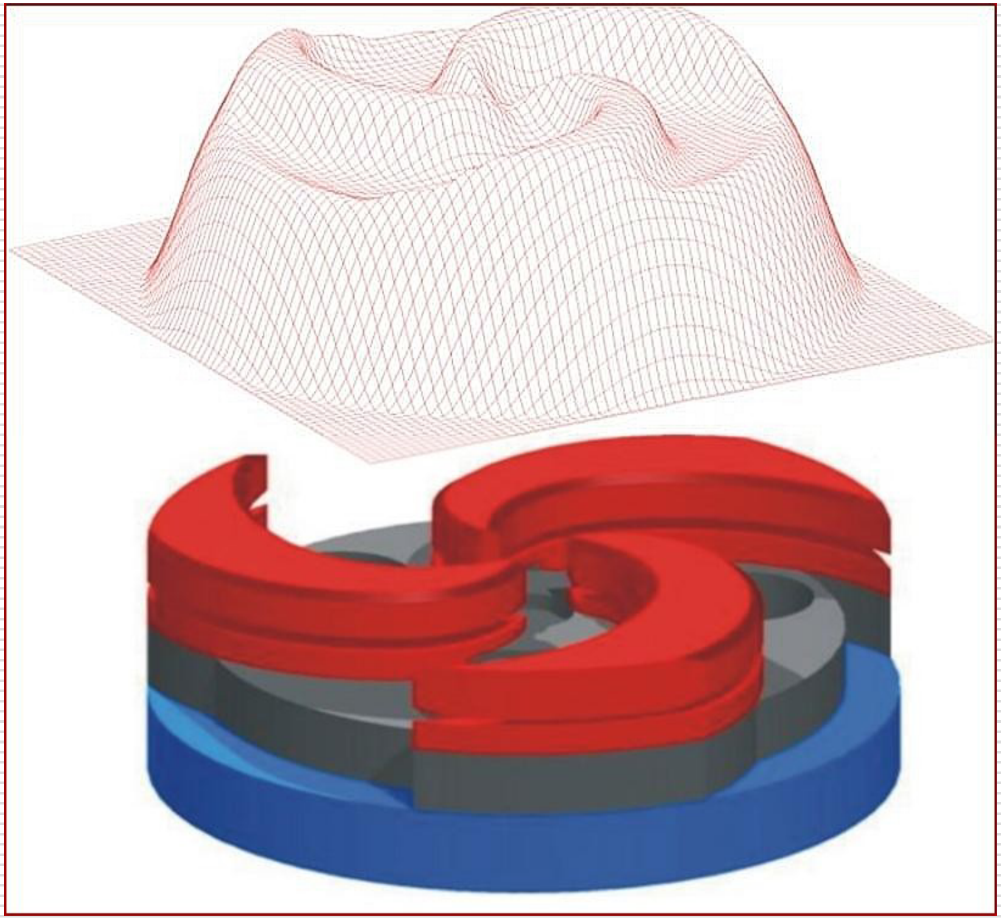
$$\boxed{\frac{\partial \omega}{\partial E} = 0} \quad \text{<=>} \quad \boxed{\frac{p}{T}\frac{dT}{dp} = \alpha_p - \frac{1}{\gamma^2} = 0}$$

No synchronous phase, No longitudinal focusing

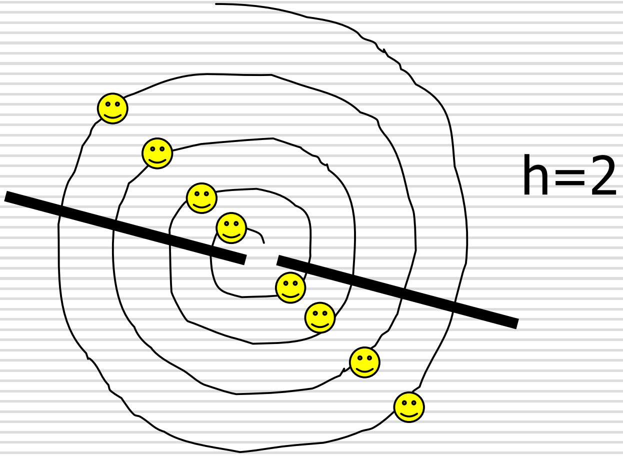
Applications:

- Synchrotrons at γ_{tr}
- Isochronous Cyclotrons

Isochronous cyclotrons



$$\partial B / \partial t = 0$$
$$\partial w_{cyc} / \partial E = 0$$
$$w_{RF} = w_{cyc} h$$
$$\partial w_{RF} / \partial t = 0$$



Isochronous cyclotrons, Cont'd

PSI Main Ring Cyclotron:

E = 600 MeV
I = 2 mA
P = 1.2 MW

1 GeV, 10 mA (10 MW) cyclotron was proposed for:

- Waste transmutation
- Accelerator-driven nuclear reactors
- Neutron and other particle production

Specifics of Space Charge effects in isochronous regime

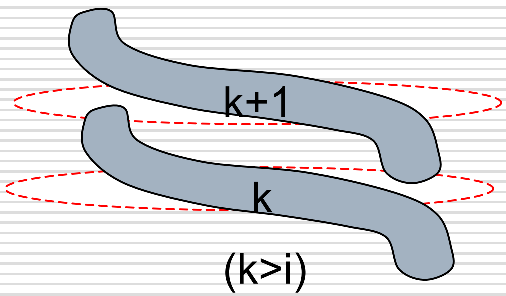


Fig.3
The vortex motion deforms bunches into a galaxy-like shape. The separation between bunches completely disappears. This leads to beam losses at a deflector.

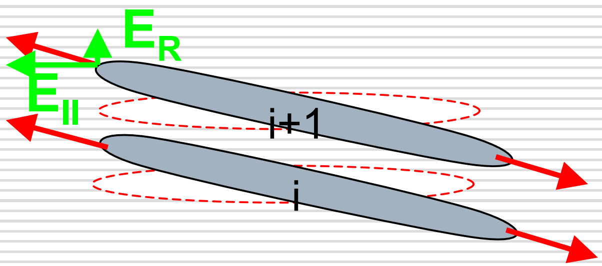


Fig.2
The radial component of the force changes the radius of the equilibrium orbit and brakes isochronism. This induces a vortex motion within bunches.

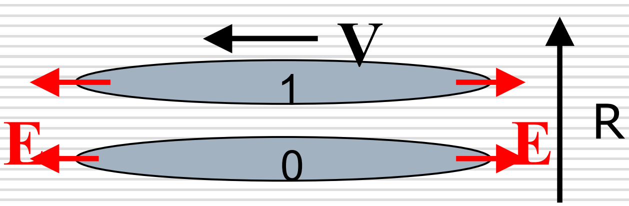


Fig.1
The electric field accelerates head particles and decelerates tail particles that causes the nergy spread to grow and bunches to tilt

CYCO: PIC code for simulation of space charge effects in isochronous cyclotrons

REQUIREMENTS:

- $N_p = 10^5$-10^6
- Realistic 3D treatment of the beam dynamics (both particle motion and SC)
- Must be able to simulate 500 turns in a cyclotron in a day using a regular PC

CYCO: Tracking particles

- Complete system of 6 equations of motion
- 3D measured or calculated field map
- 4^{th}-order RK method (fast and accurate)
- Thin accelerating gaps, any function $\theta(R)$
- Simultaneously tracks several neighboring turns (self-consistent solution)

CYCO: Field solver

- Does not make any assumption on the beam shape
- Uses Particle-Mesh method (PIC)
- Linear charge-assignment scheme
- Based on the convolution method, uses FFT
- Includes image charges on vacuum chamber (infinitely conducting planes, top and bottom)
- Includes field of neighboring turns

Field of 10^5 particles on 64x64x64 mesh in less than **1 sec** (1 GHz Pentium III)

Small Isochronous Ring project at NSCL

MOTIVATION: strong demand for experimental data in the isochronous regime

- Validation of Space Charge codes

- The data can be extrapolated to predict beam dynamics in large-scale accelerators

  - High intensity cyclotrons
  - Synchrotrons at γ_{tr}

SIR: Requirements and choice of main parameters

REQUIREMENTS:

- Small-scale, inexpensive experiment
- Good longitudinal resolution

BEAM PARAMETERS:

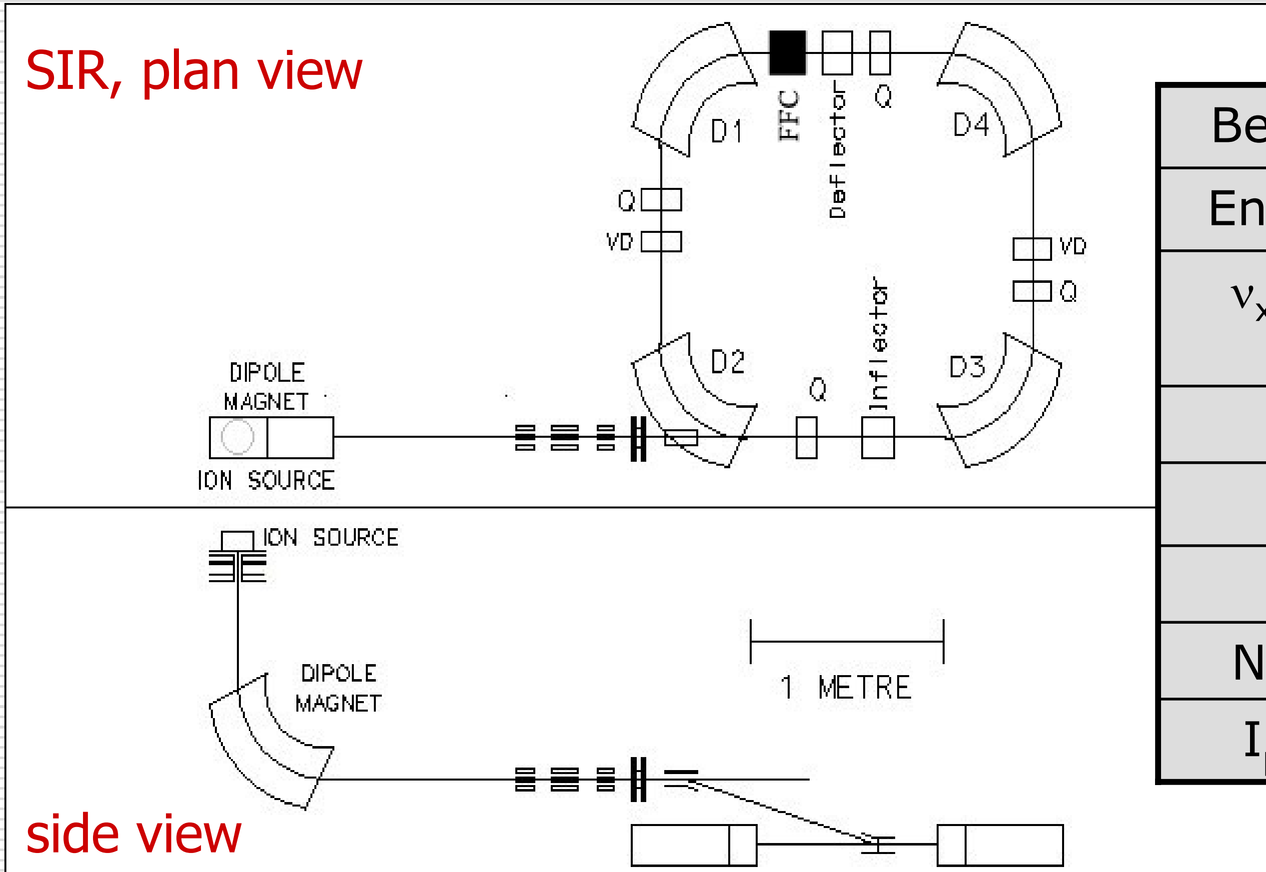
- Low energy
- H_2^+ or D beam

Why low beam energy and high rest mass?

Slow beam

- Low intensity beam
- Relieved requirements on diagnostics and Inj./Extr.
- Simple, low-field magnets
- Magnetic Field is strong enough to avoid stray field problem
- Opportunity to do precise experiments

SIR: Schematic view and main parameters



Beams	H_2^+ or D
Energy	0-30 keV
ν_x, ν_y	1.15, 1.11
α_p	1.0
T	4.5 μsec
C	6.57 m
N_{turns}	30
I_{peak}	0-100 μA

Comparison to large-scale accelerators

SIR: I_{peak}=100 μA, E=20 keV

Transverse

SIR $\delta\nu$=0.2 ($\delta\nu/\nu$=0.18)

SNS $\delta\nu$=0.15 ($\delta\nu/\nu$=0.03)

PSI Inj.2, 0.87 MeV 2mA
$\delta\nu$=0.05 ($\delta\nu/\nu$=0.04)

Longitudinal-Radial

$\boxed{\frac{Q}{A}\frac{I}{\gamma^5 h\omega^3}}$ – IMPORTANT

Equivalent current:

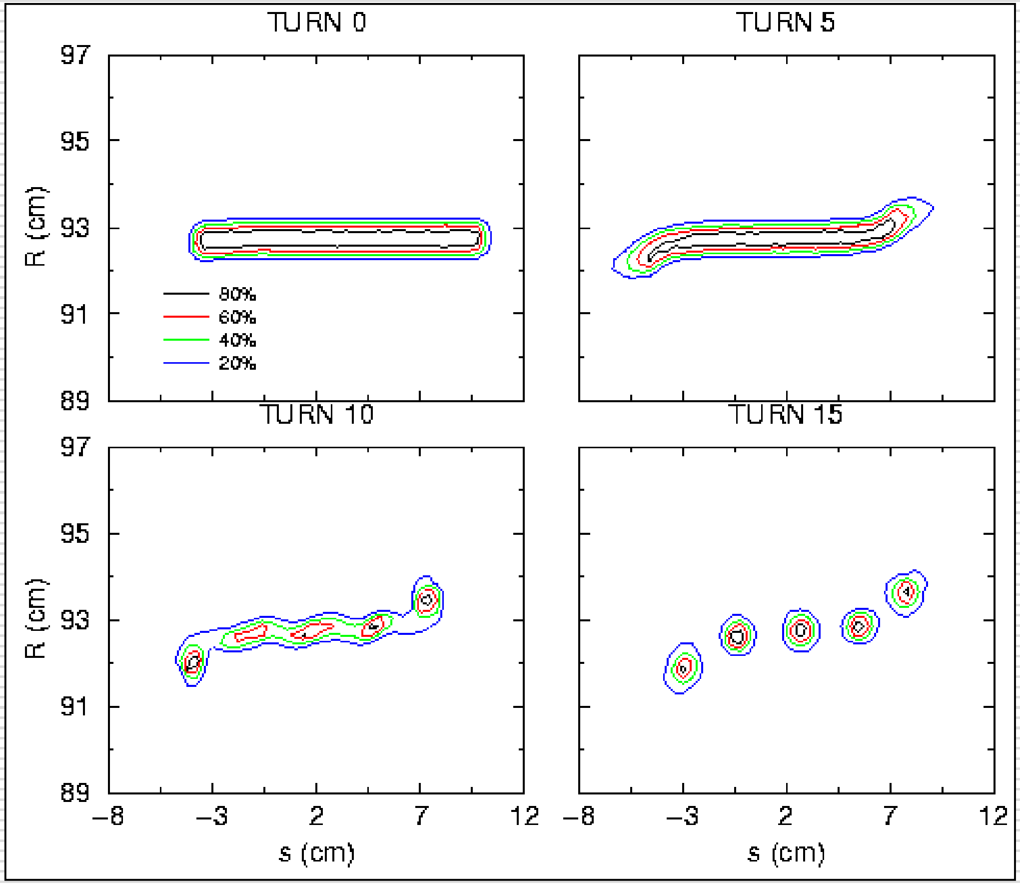
PSI Inj.2: 12 mA

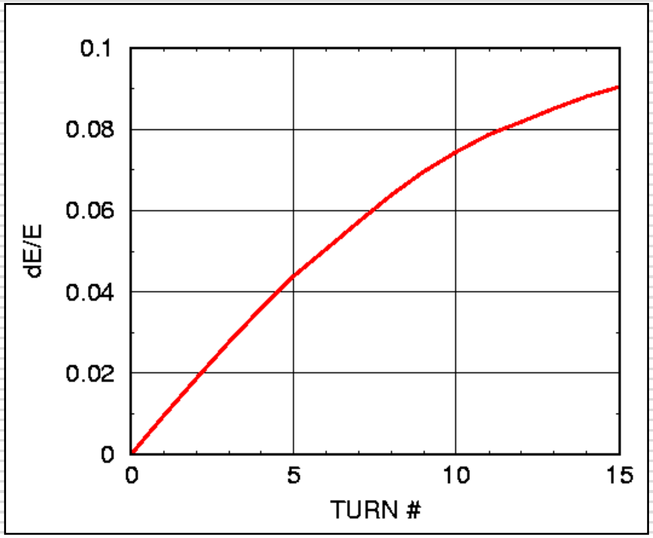
PSI RingCyc: 12 mA

Experimental issues addressed by SIR

- space charge induced vortex motion specific to the isochronous regime
- longitudinal break-up of long bunches
- formation of the self-consistent stable charge distribution by short bunches
- formation of weak beam tails and beam halo.

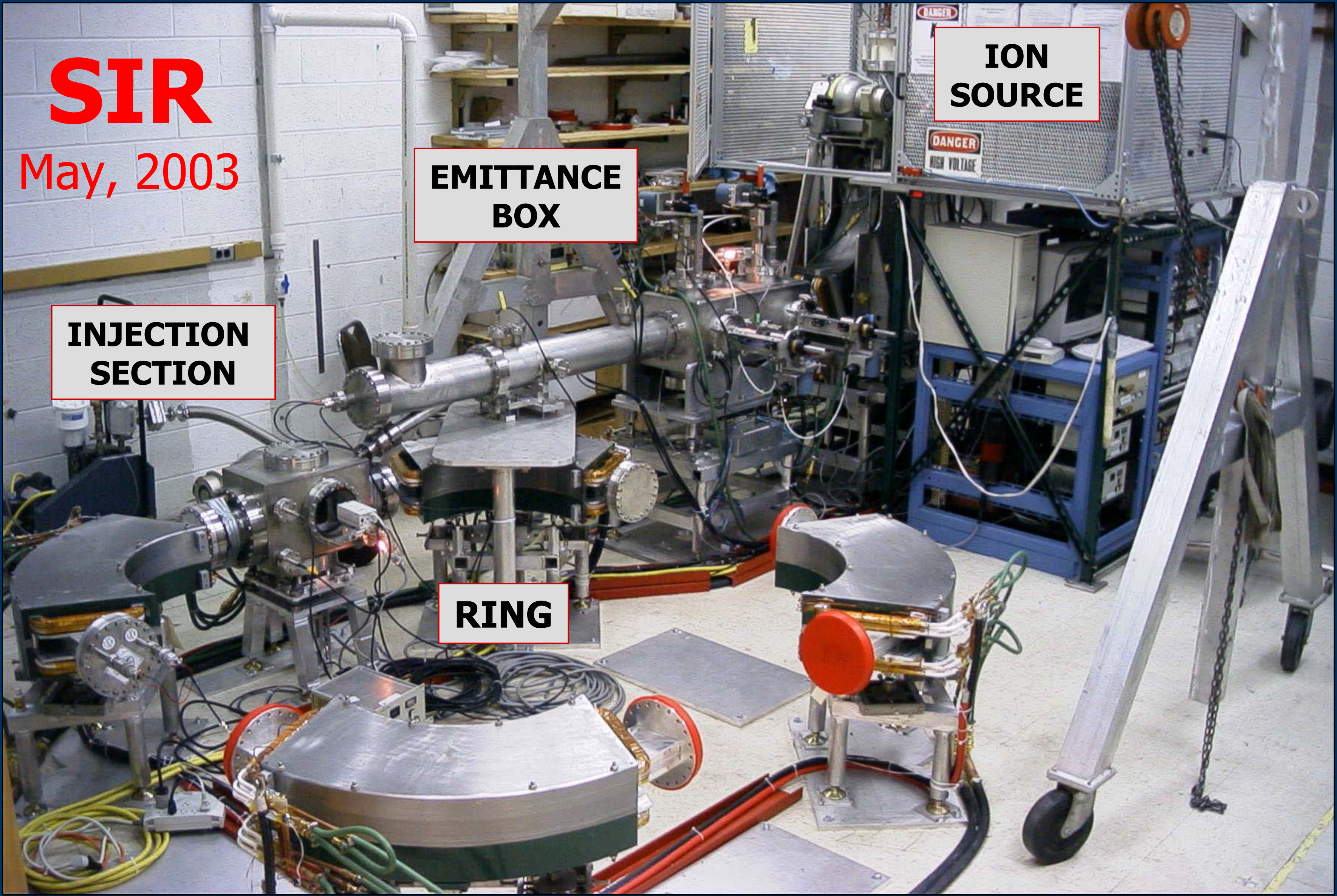
Break up of a “long” bunch in SIR (simulation)





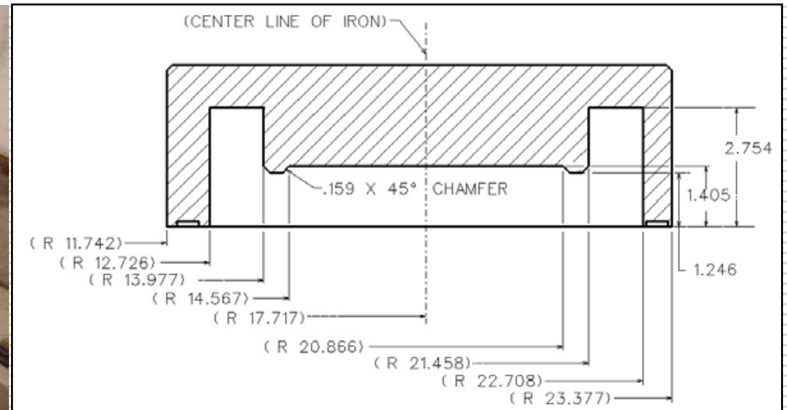
PIC code CYCO, $N_p = 10^5$

Magnetic field generated by TOSCA (OPERA 3D)

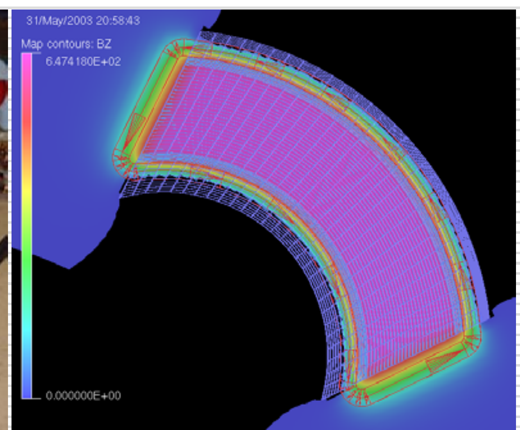


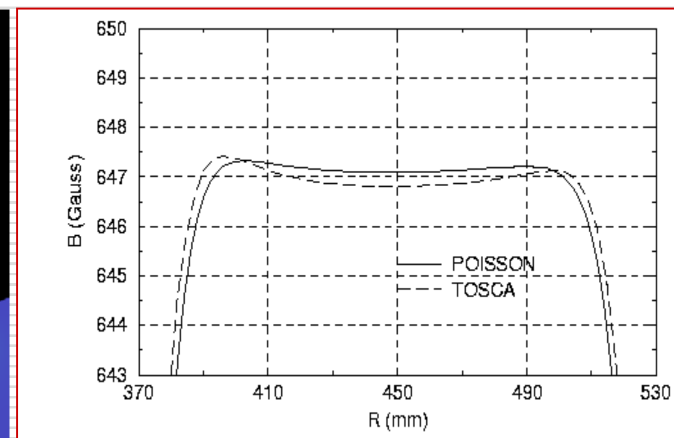
SIR
May, 2003
ION SOURCE
EMITTANCE BOX
INJECTION SECTION
RING
DANGER
DANGER
HIGH VOLTAGE

SIR subsystems: Dipole magnets

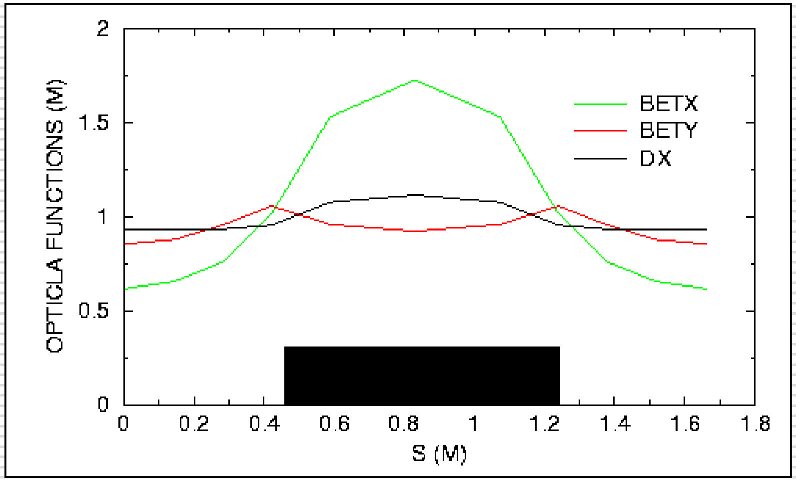


B	1000 G
R	450mm
Bend	90deg
Edge	26deg
Gap	71mm
Weight	250kg
Power	750W





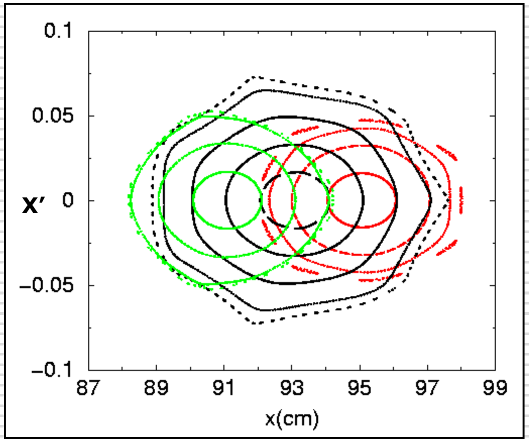
SIR: Single-Particle beam dynamics in TOSCA field (simulations)

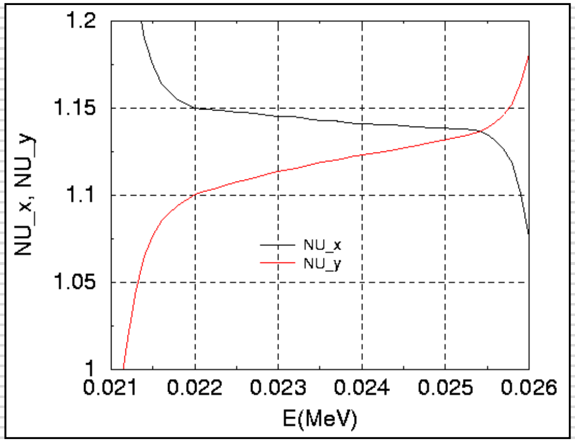


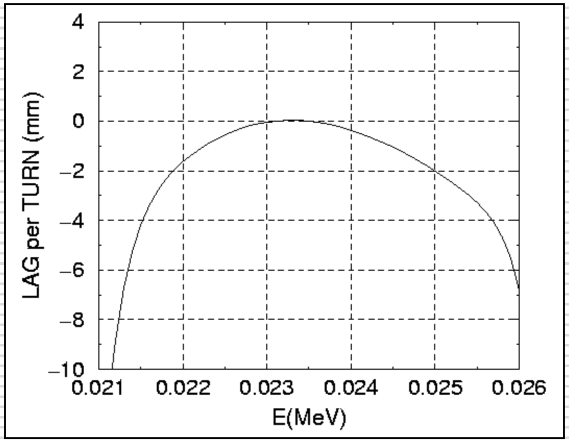
B 647G

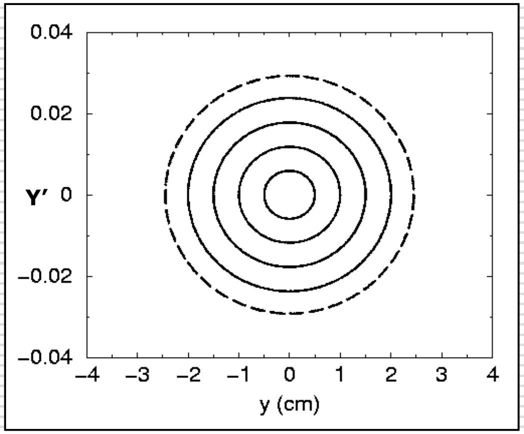
Beam H_2^+

E_{inj} 23.5keV

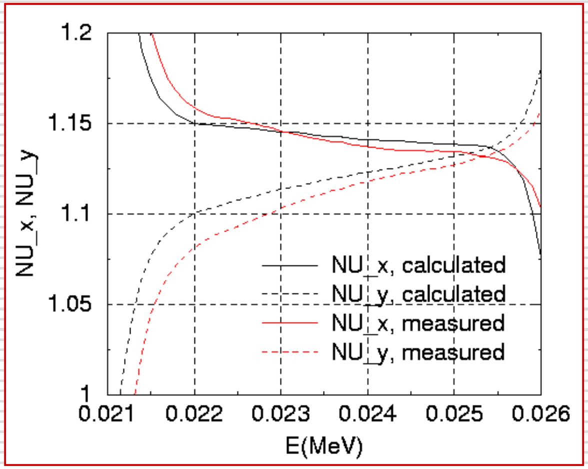


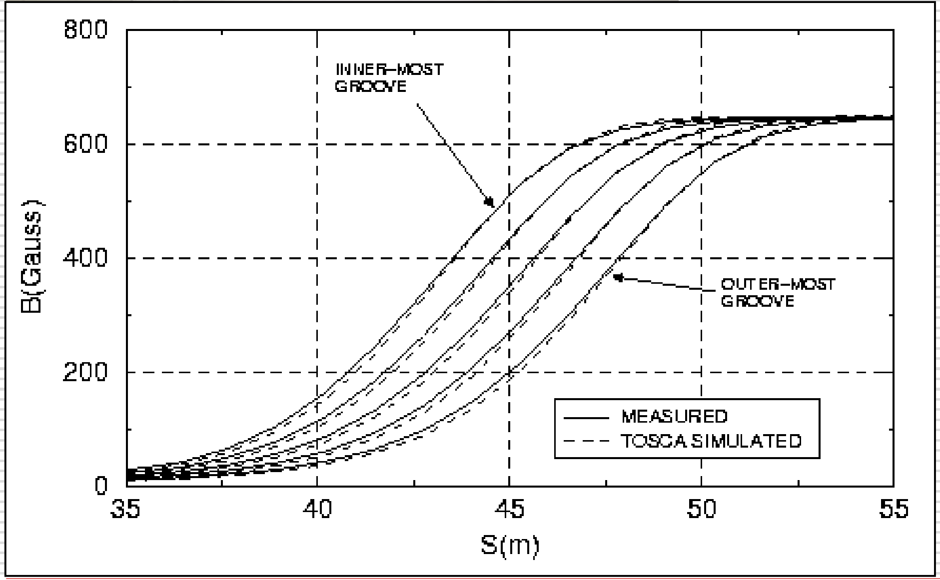


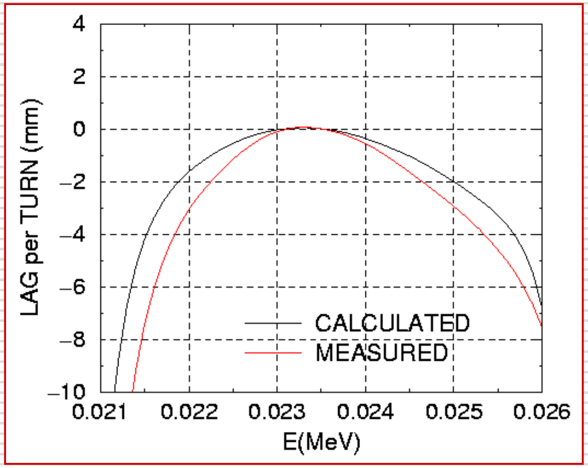




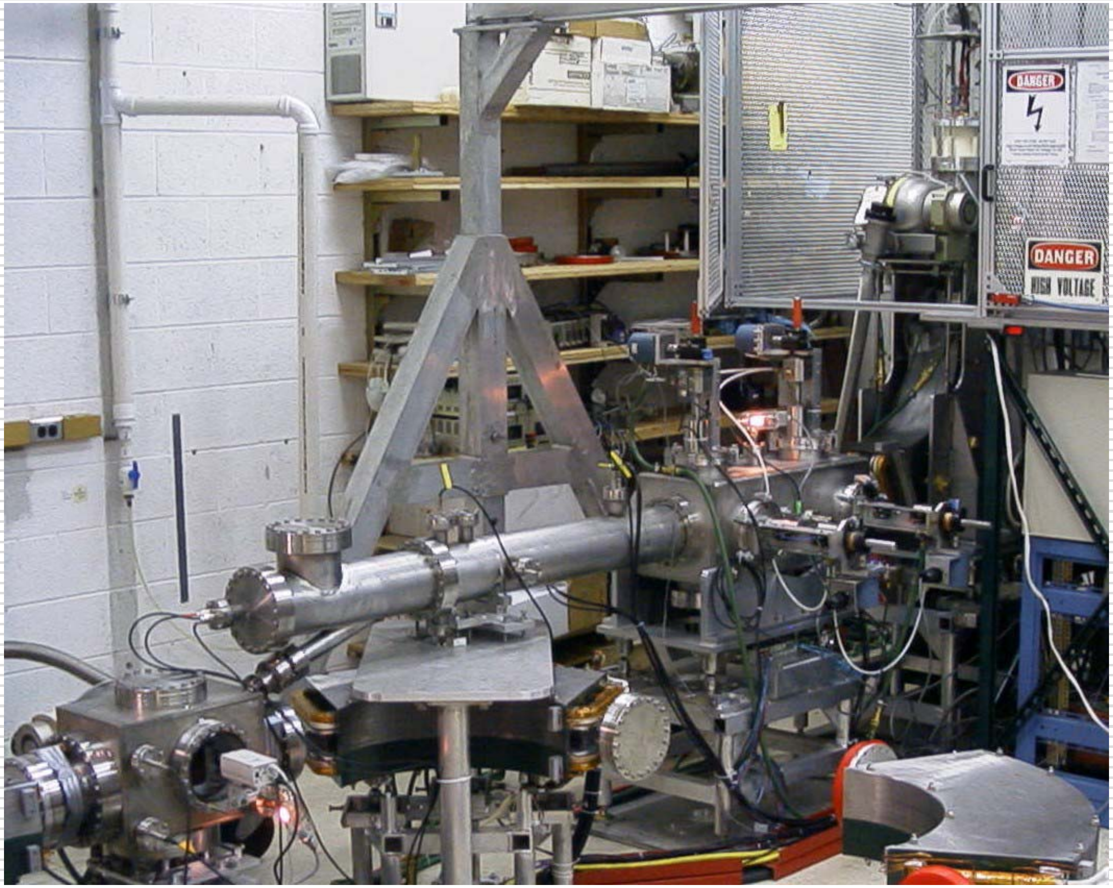
SIR: Field measurement and single-particle dynamics in measured field (simulation)

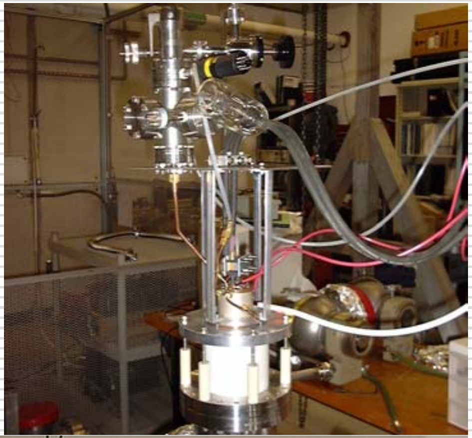


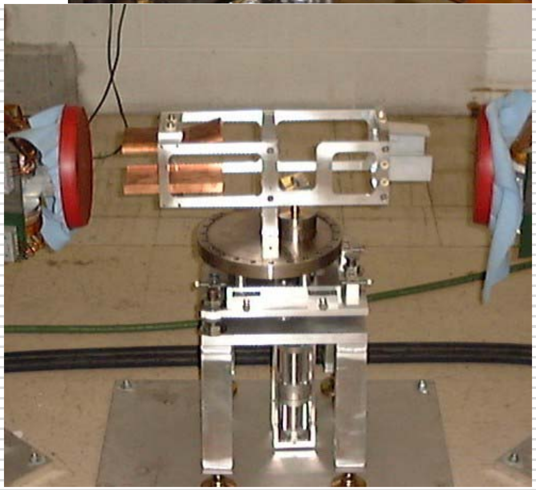




SIR subsystems: Ion source, Injection line, Injection system







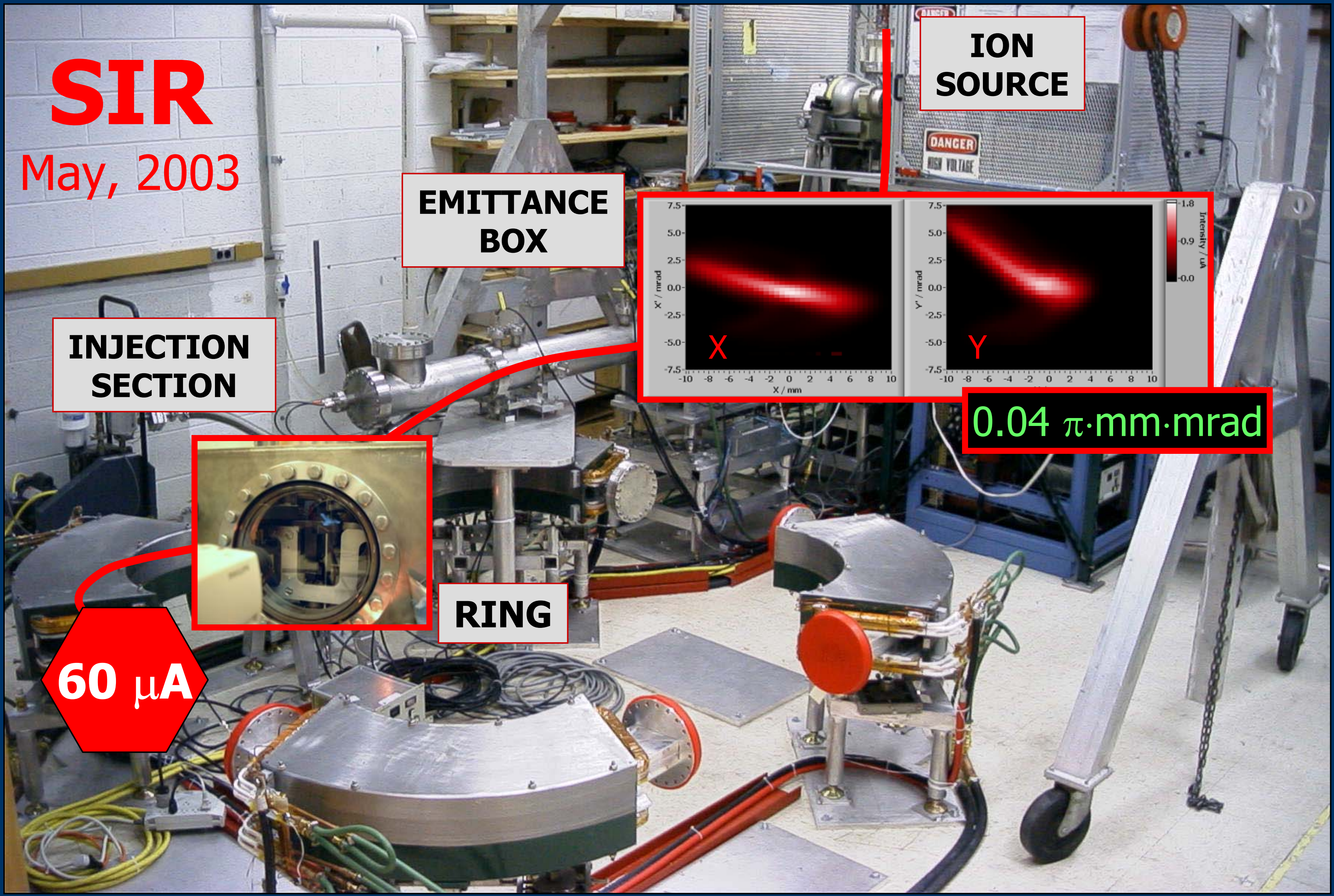
SIR subsystems: Vacuum system

- Gas sources:
  Outgassing + Ion source
- Pumping:
  3-4 500l/s Turbo-pumps
- Expected vacuum:
  $>10^{-7}$ Torr
- Expected life time:
  200 Turns

Vacuum chamber in dipoles made of aluminum with 8″ Al-SS flanges

SIR subsystems: Diagnostics

- Inj.Line: Emittance measurement system, Faraday Cup
- SIR: Phosphor screens, 2X+2Y Scanning Wire monitors, X+Y Capacitive BPMs
- Experiment Diagnostics: Movable Fast Faraday Cup, Z=50 Ohm, Rise/Decay time of 10^{-9} sec (equivalent to 1.5 mm)



SIR
May, 2003
ION SOURCE
EMITTANCE BOX
INJECTION SECTION
RING
60 μA
0.04 π·mm·mrad
X
Y
X / mm

Time Line

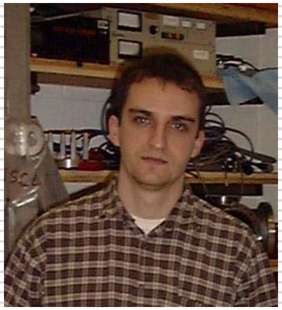
- Fall 2000 - Proposal to build SIR
- Sep 2001 - Ion source tested
- Nov 2002 - First magnet assembled, mapped
- Apr 2003 - Ion source + Inj.Line + Magnets
- April 30, 2003 – Faraday cup after a quarter of the ring registered 60 μA beam.

Future Plans

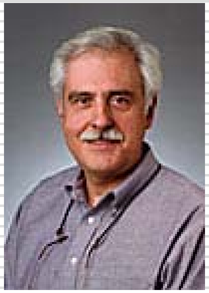
- Construction completion, Fall 2003
- Commissioning, Fall 2003
- Experiment, Phase I, Fall 2003–Winter 2004
  Isochronous regime, longitudinal beam dynamics,
  $\delta\nu_{SC} = 0.03 - 0.05$
- Experiment, Phase II, (?)
  Non-isochronous regime, transverse and longitudinal beam dynamics, $\delta\nu_{SC} = 0.2$, will include RF system

Acknowledgment

J.A. Rodriguez, Grad Student



F. Marti, Supervisor



R.C. York, Associate Director for Accelerators

R. Fontus, D. Lawton, D. Sanderson, A. Zeller, R. Zink