Optics Improvements of the K500 Axial Injection Line

M. Doleans
NSCL/MSU
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Overview

MICHIGAN STATE UNIVERSITY

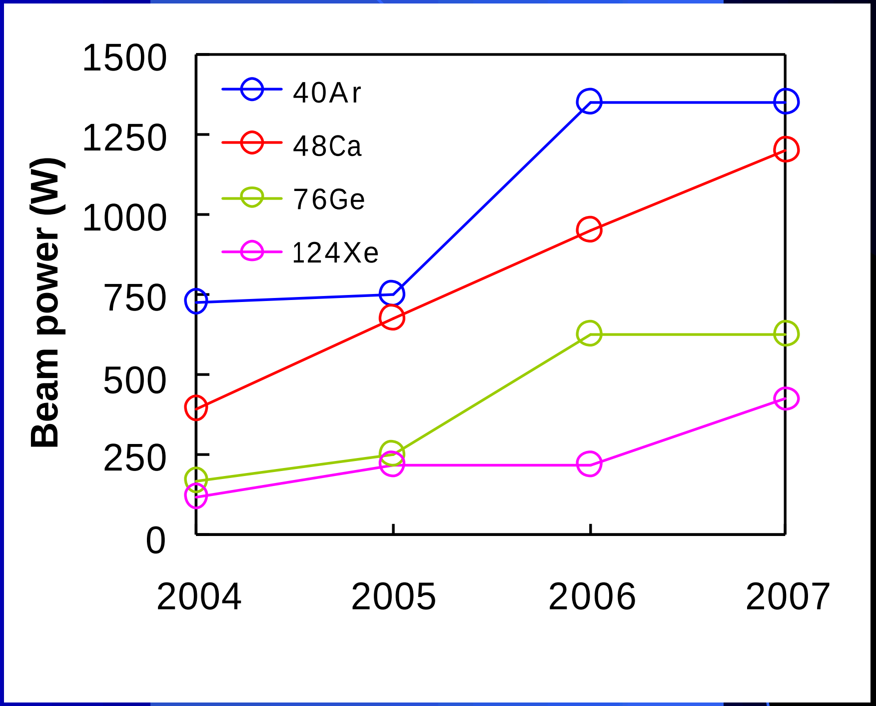
- Improve Primary Beam Power from CCF
  - Improve beam brightness
  - Improve beam matching into K500
  - Minimize beam losses on deflectors
  - Improve stripper foil lifetime

- R&D effort
  - SuSI
  - Artemis-B
  - Emittance scanner
  - Beam collimation
  - Electrostatic focusing below ECR
  - Beam chopper
  - Automatic tuning algorithm …

Beam power on target

- Significant progress since 2004
- Next challenges
  - Deflectors
  - Stripper foils
  - Beam tuning time

	^{40}Ar	^{48}Ca	^{76}Ge	^{124}Xe
2007	1350	1200	625	425
2006	1350	950	625	225
2005	750	675	250	225
2004	725	400	175	125

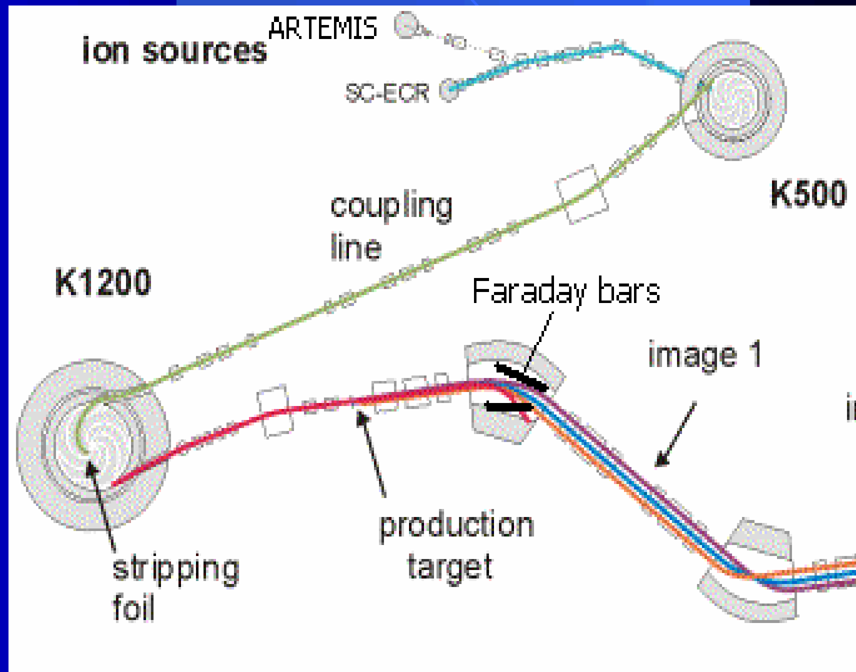


Coupled Cyclotron Facility - CCF

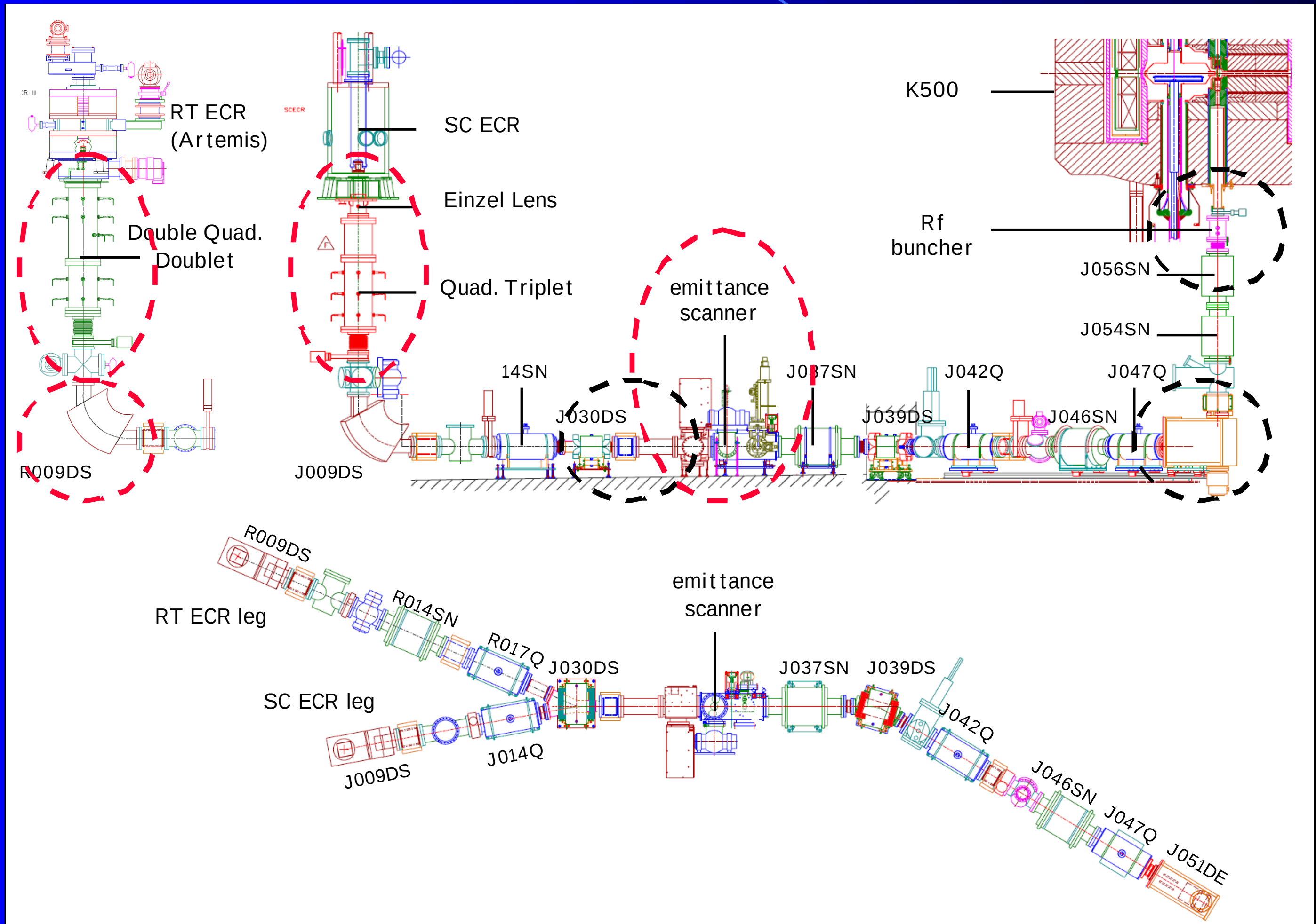
ECR → $^{48}Ca^{8+}$, 5 keV/u → K500 → $^{48}Ca^{8+}$, 12 MeV/u → K1200 → $^{48}Ca^{20+}$, 140 MeV/u → Target

K 500 Injection

Ion	Charge State	Current (euA)
^{18}O	3+	35
^{40}Ar	7+	40
^{58}Ni	11+	8
^{76}Ge	12+	5
^{78}Kr	14+	15
^{48}Ca	8+	10
^{136}Xe	21+	11



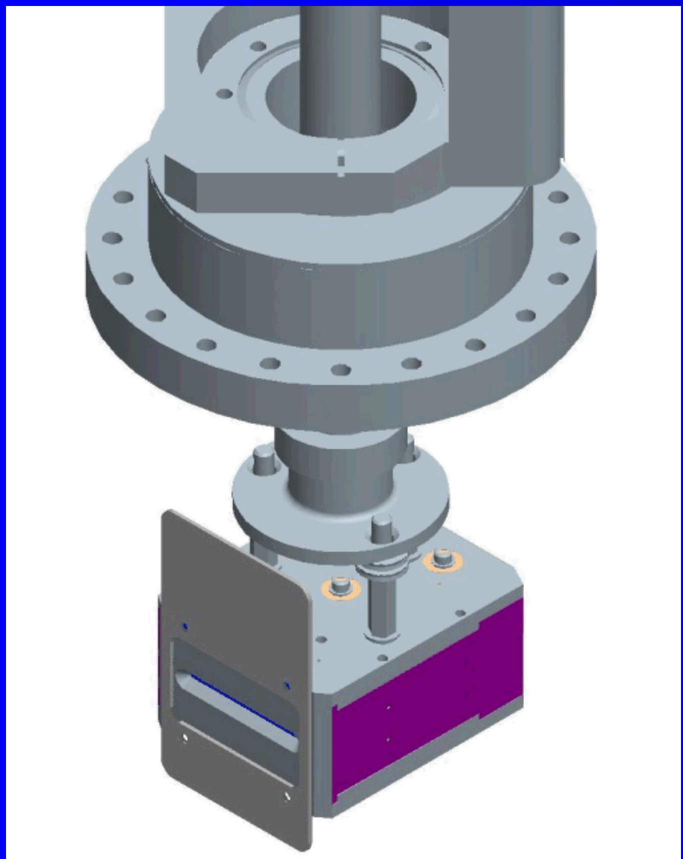
Injection line layout

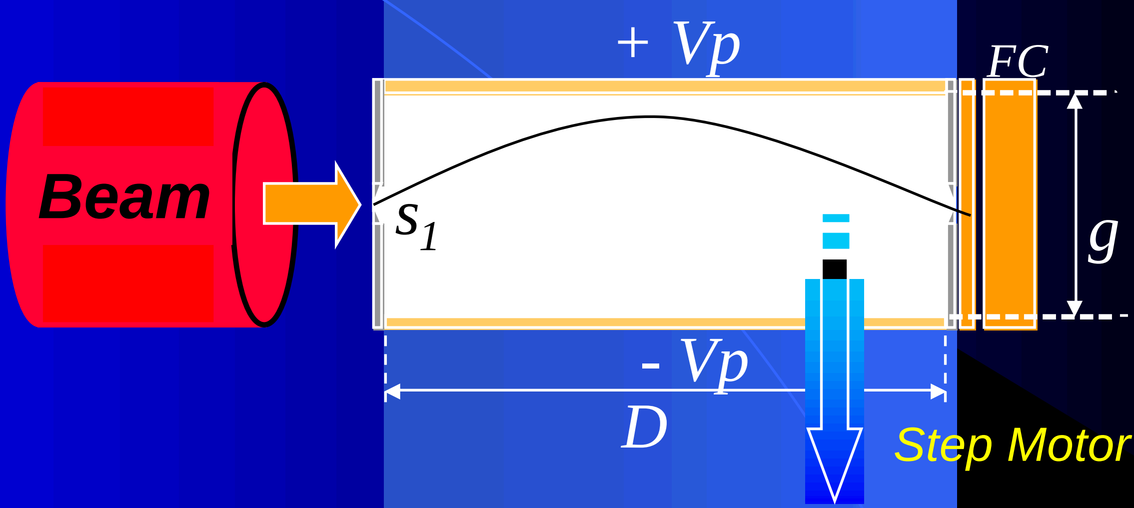


Offline ECR source Artemis-B

- Artemis-B test stand
  - Finished August 2005
  - Room temperature ECR
  - Beam line
  - Beam diagnostics
- R&D for CCF
  - ECR
  - Beam dynamics
  - Beam diagnostics
  - Hardware test
  - Software test

NSCL Allison emittance scanner





Slits: S_1=S_2= 60 mm x 0.5 mm
g=12mm ; D= 7.5 cm ;

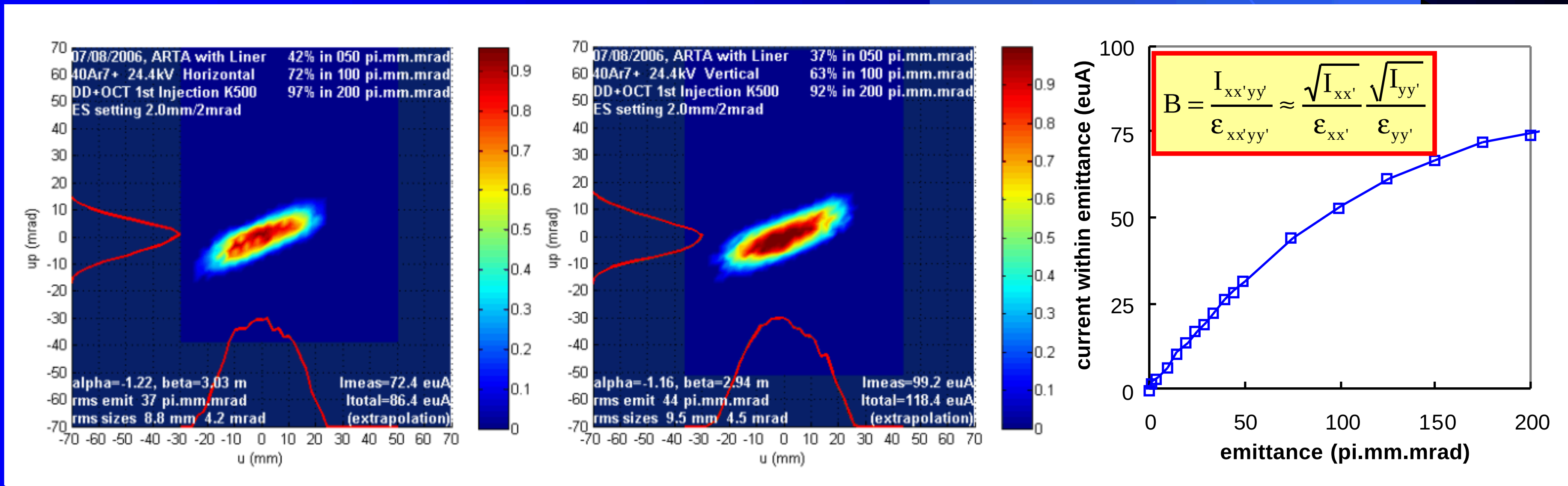
Dx_{int} = s = 0.5 mm

Dx'_{int}=+/- s/D= +/-6.7 mrad

x'_{Max}= 2g/D @ 300 mrad

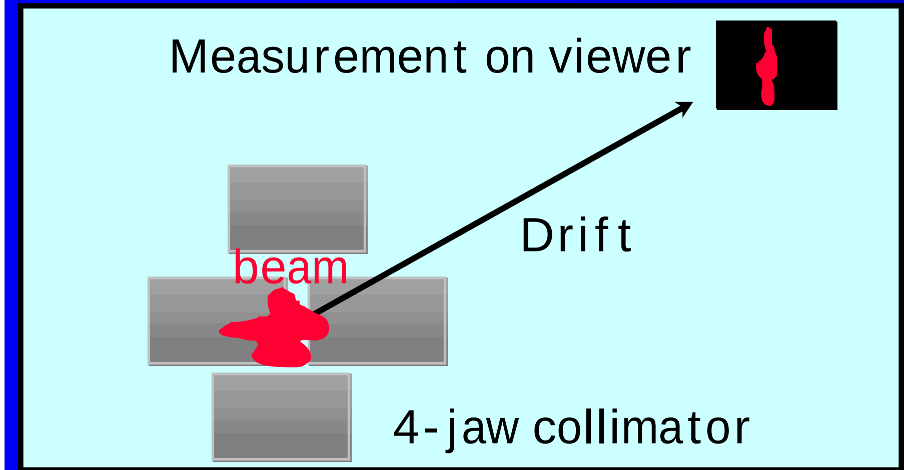
Beam brightness

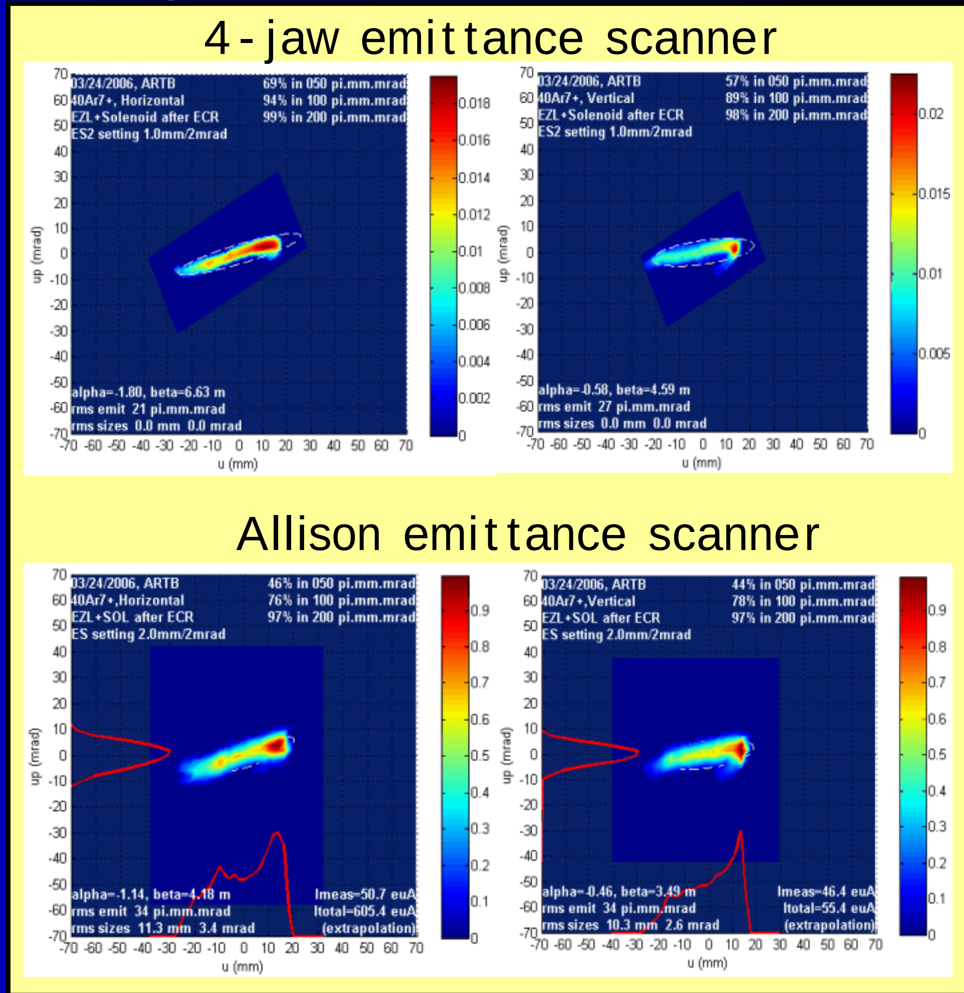
- K500 has limited Beam Acceptance
  - ~75 π.mm.mrad (Snyder's Ph.D. thesis)
- Need
  - Increase current within 75 π.mm.mrad
  - Collimate beam above 75 π.mm.mrad



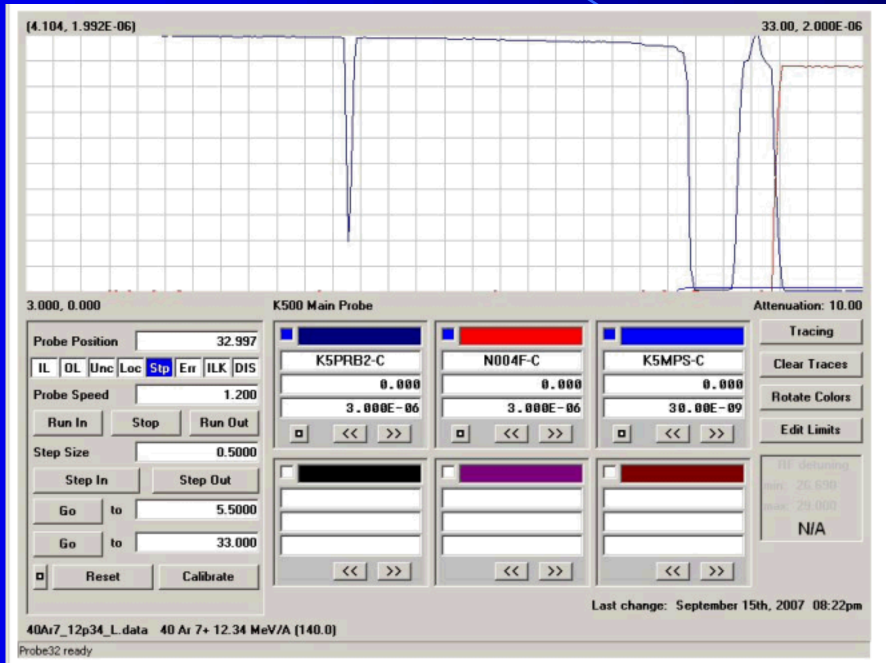
Other emittance scanner

- 4-jaw collimator defines position
- Beam on viewer defines angle
- 2-D scan fast (~1-2min)
- 4-D scan possible
- Benchmarked with Allison scanner
- Usable in coupling line





Collimation benefit



- 93% extraction efficiency reached in K500 !
- Motivation for
  - better brightness
  - Emittance < acceptance

Initial focusing

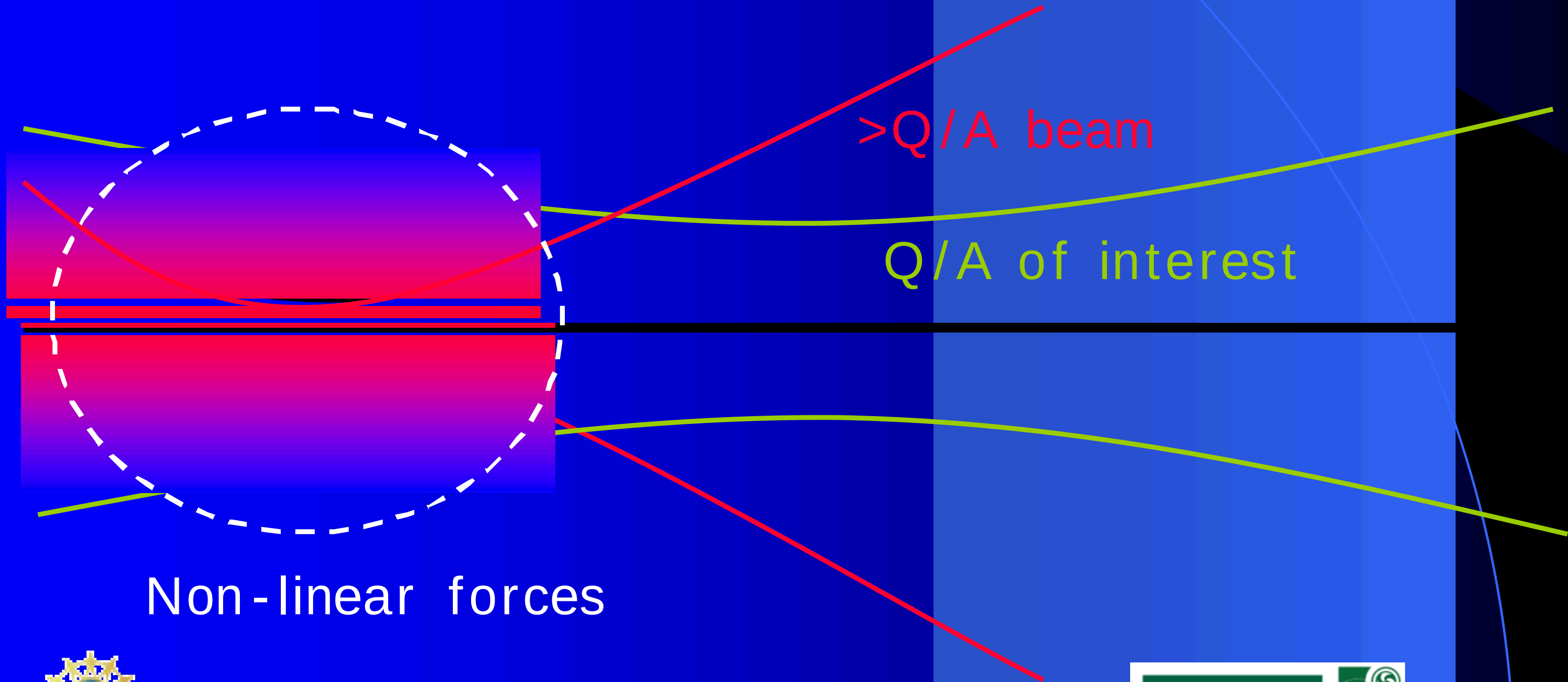
- Electrostatic or Magnetic focusing below ECR ?
- Efficiencies
  - Similar at β~0.003
  - Both options possible
- Electrostatic
  - Focusing independent of Q and A
  - Similar envelopes
- Magnetic
  - Focusing depends of A/Q
  - Larger Q/A beams short foci
  - Non-linear space charge effects

$$E\rho = 2V_{ECR}$$

$$B\rho \cong 4.55.10^{-3}\sqrt{\frac{A}{Q}V_{ECR}}$$

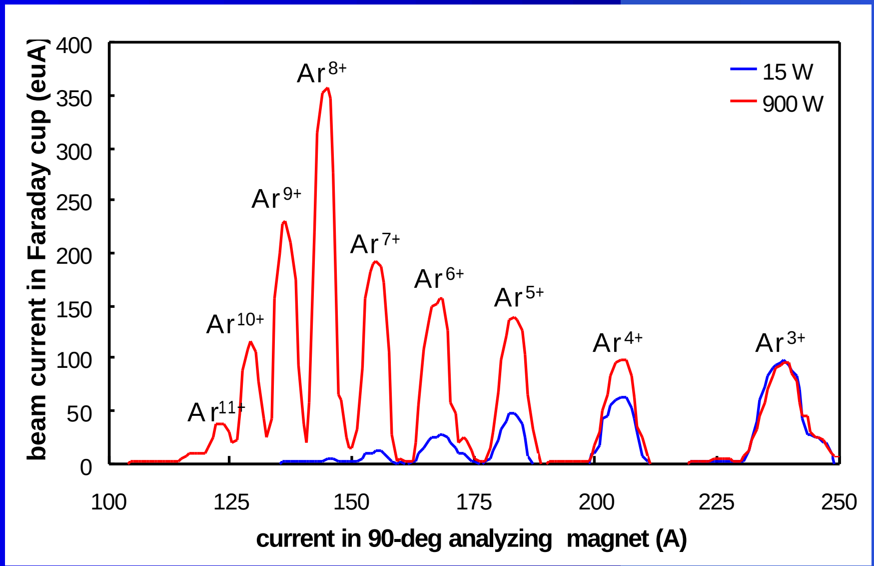
Space charge issue

- Larger Q/A over-focused
- Non-linear space charge forces on beam of interest
- Beam emittance degradation



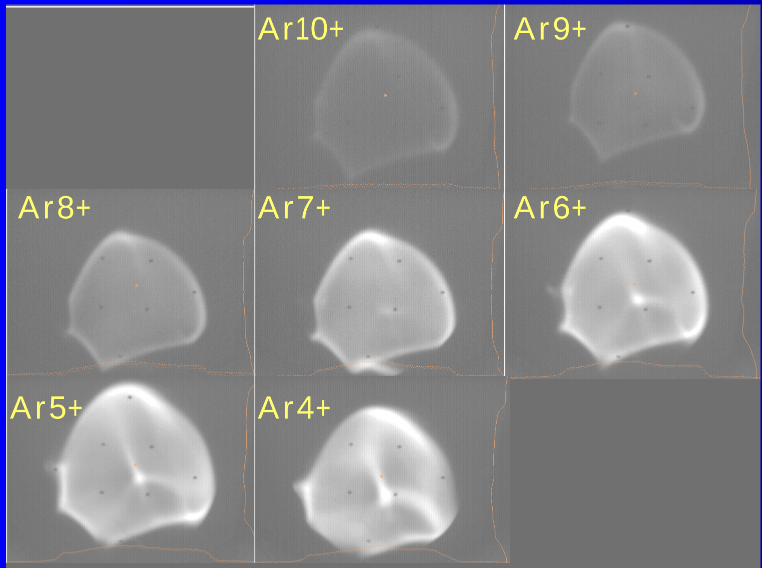
Space charge experiment

- Artemis-B produce argon beam
- Run in 2 modes
  - Low space charge beam (15W rf microwave power)
  - High space charge beam (900W rf microwave power)

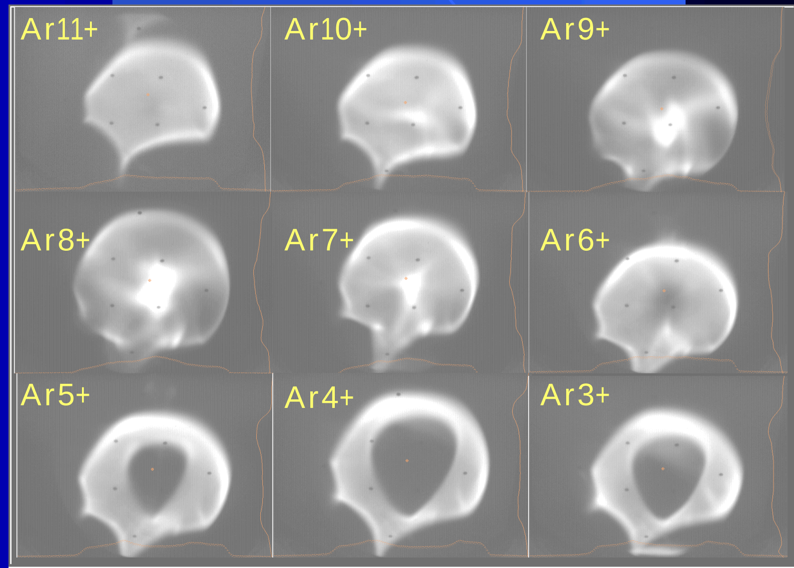


Analyzed beam imaging

- ECR – solenoid – magnet - beam viewer
  - Viewer ~1.5 m after analyzing magnet
  - Line scaled with Bρ to image all Ar^{q+}

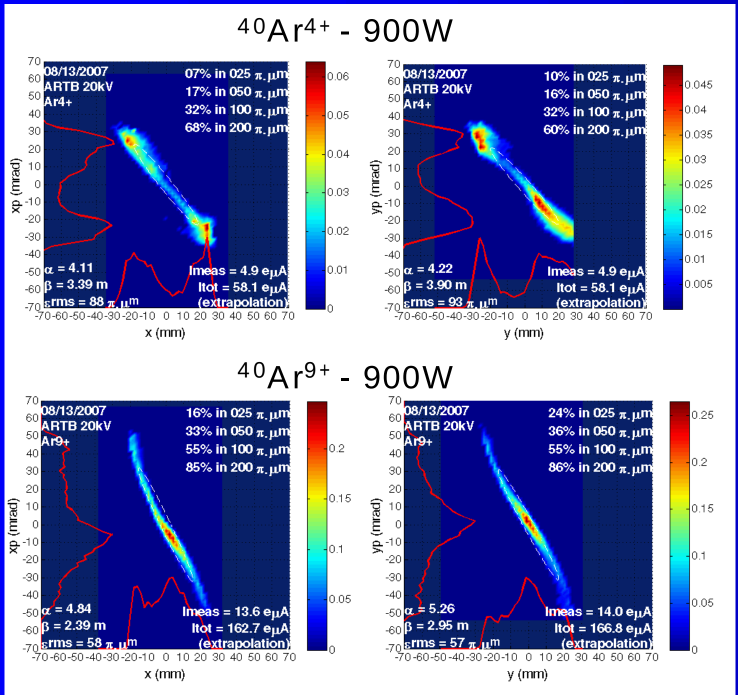


15 W

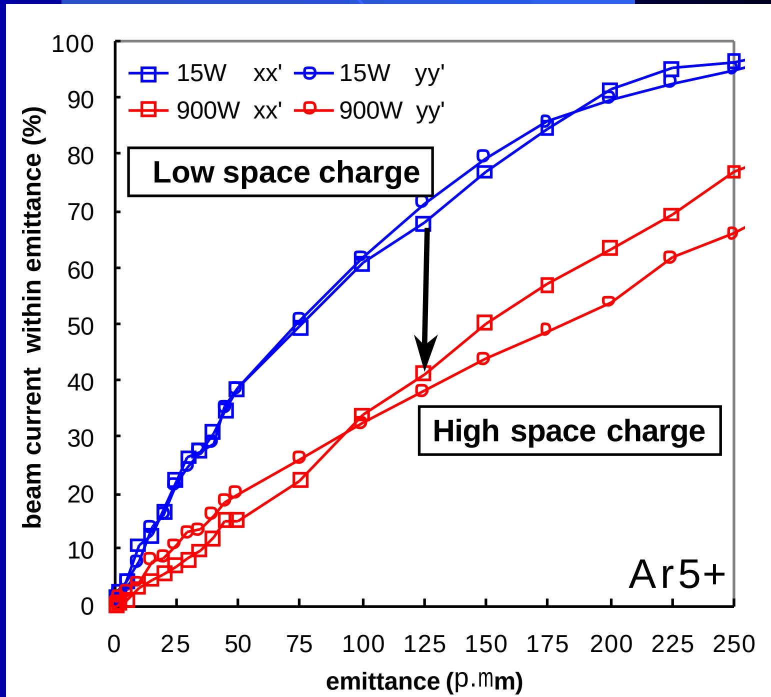


900 W

Analyzed beam brightness



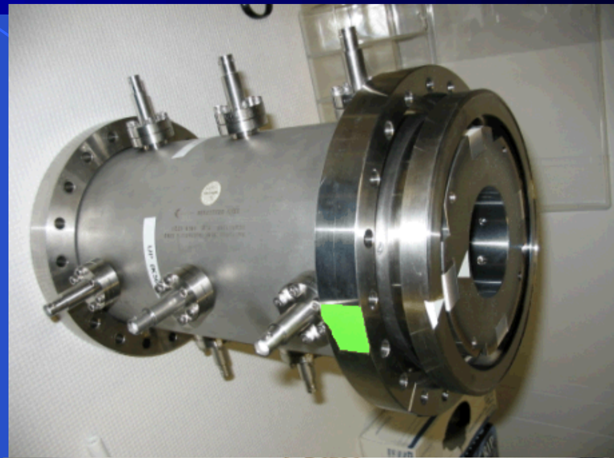
- Ar^{5+} at 15 W and 900 W
- Emittance degradation from non-linear space charge forces

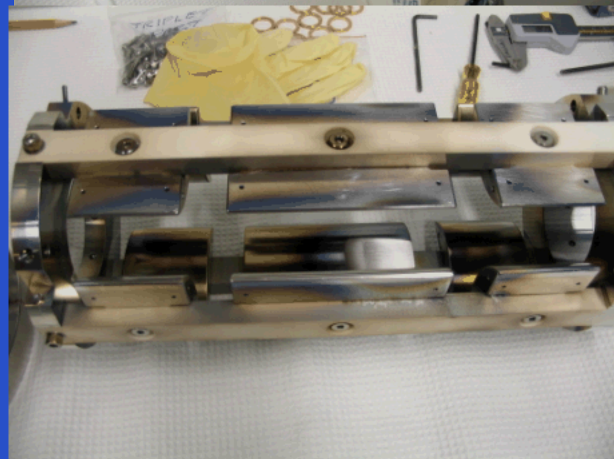


- Ar^{4+} vs Ar^{9+}
- Hollow phase spaces for low Q

Small Bore Elec. Triplet (SBT)

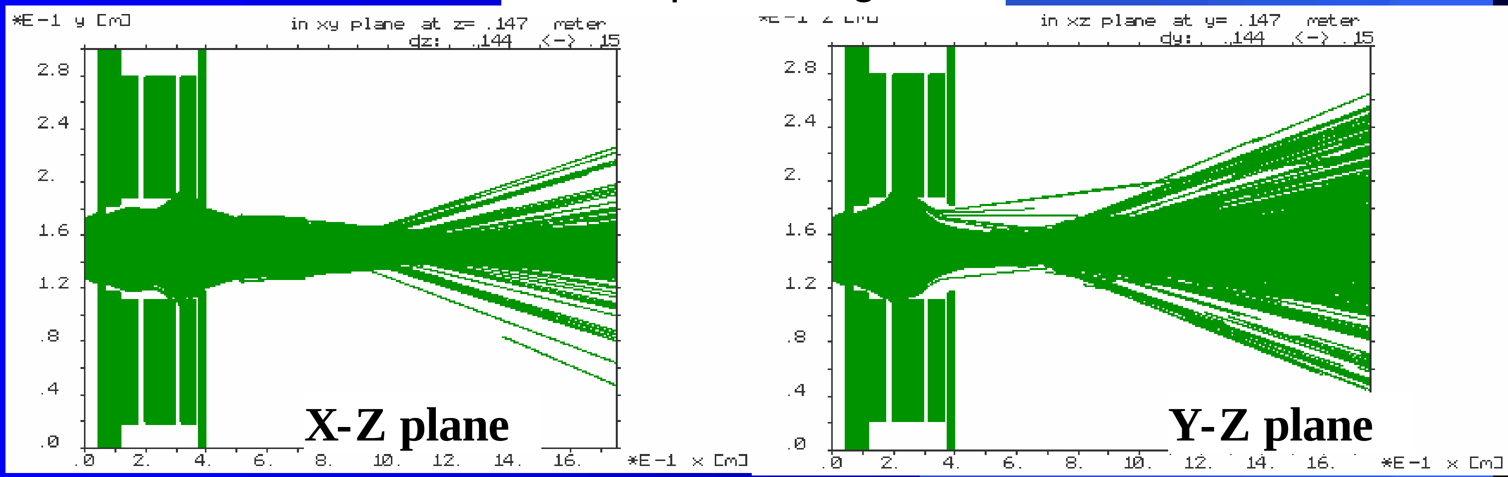
- Benefits:
  - Reduce space charge effects below ECR
- Main dimensions
  - Aperture: 76.2 mm
  - Quads length: 50, 100 mm
  - Collimator aperture: 50 mm



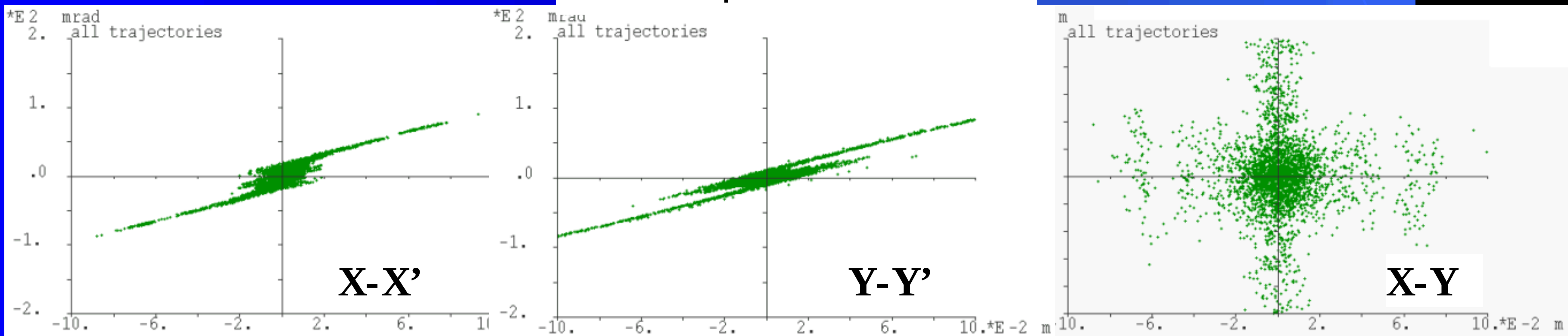


SBT (2)

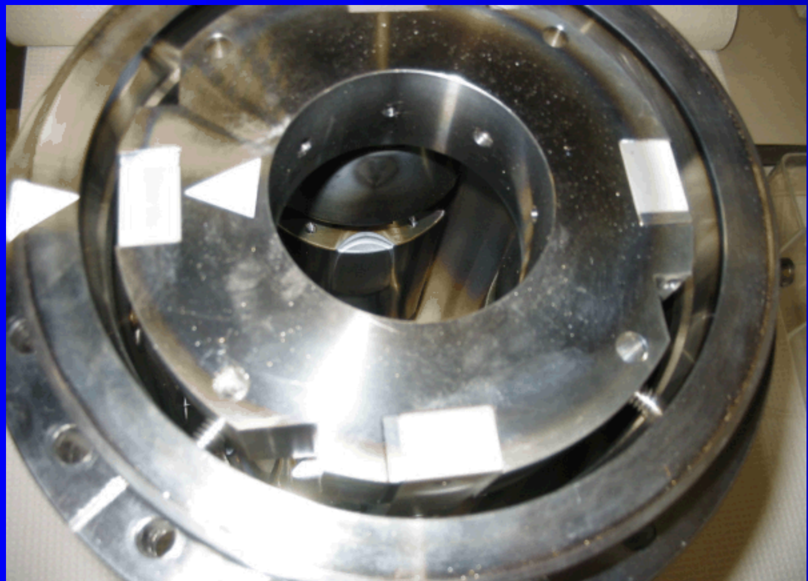
Envelopes along SBT

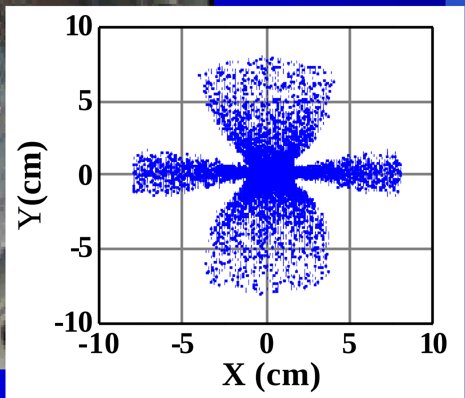


Phase spaces after SBT



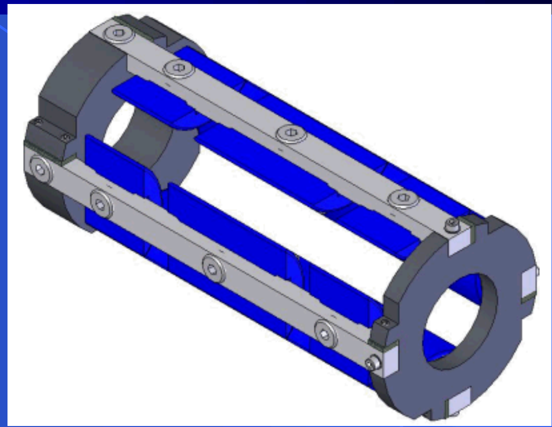
SBT (3)





- Result of SBT
  - Beam current injected into K500 increased
- Possible improvements
  - Better beam transmission
  - Reduce aberrations

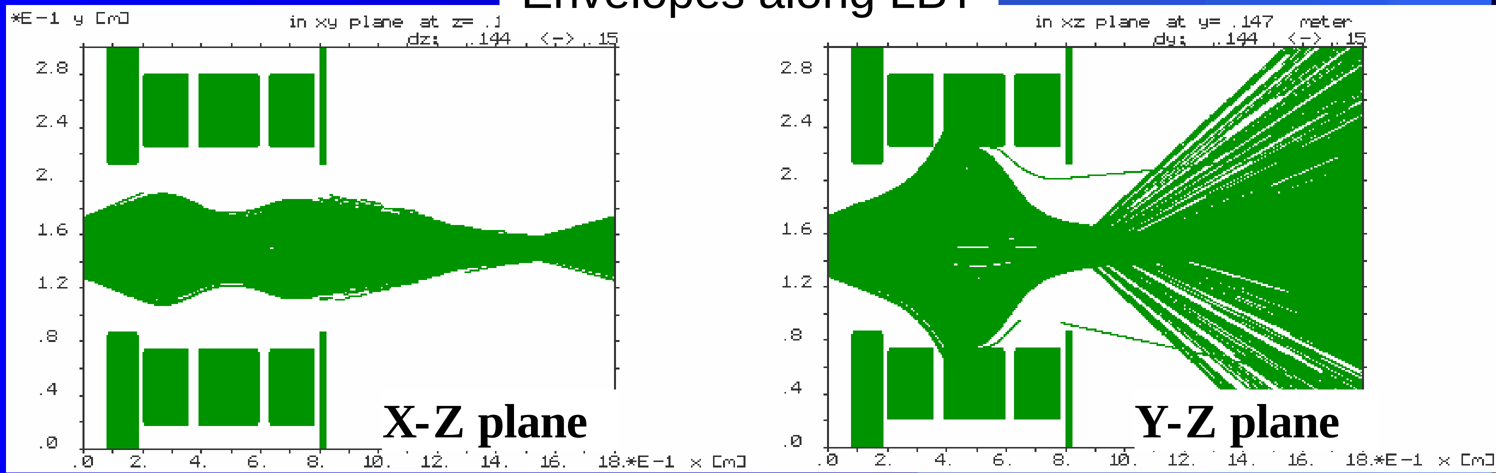
Large Bore Triplet (LBT)



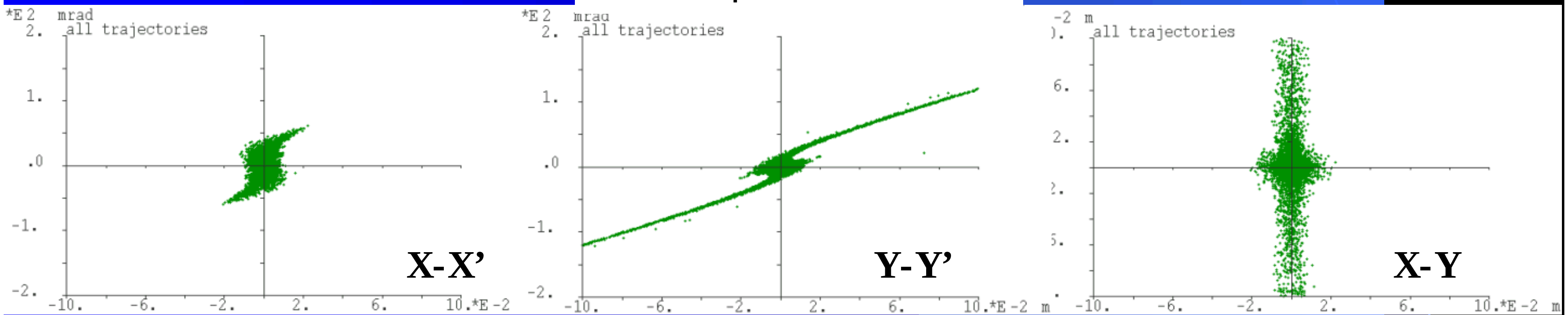
- Benefits:
  - Improves beam transmission
- Main dimensions
  - Aperture: 152.4 mm
  - Quads length: 150, 200 mm
  - Collimator aperture: 100 mm

LBT (2)

Envelopes along LBT



Phase spaces after LBT



LBT(3)

- Result of LBT
  - Beam current injected into K500 increased
- Possible improvements
  - Reduce aberrations further

R. Baartman
TRI-DN-95-21

Design criteria

$$\beta << f\sqrt{L_E/\varepsilon}$$

Small beam size,
Small emittance
Long focal length
Long quadrupole

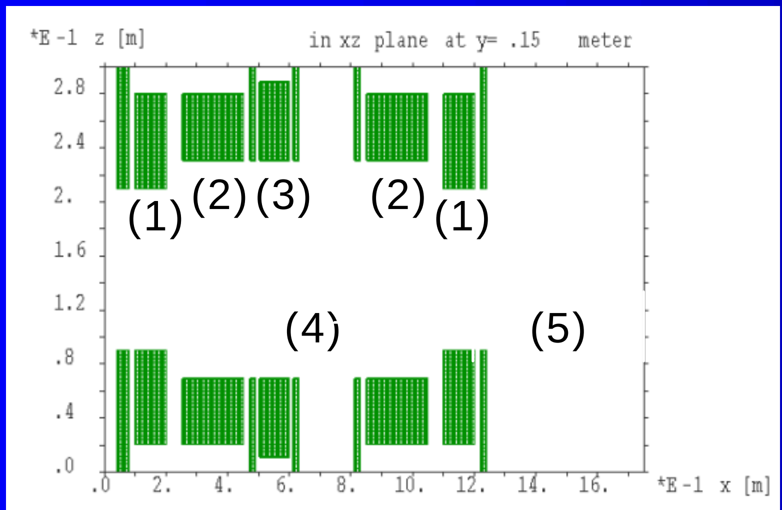
→ design knob

- Reduce aberrations
  - Increase L_E
  - Octupole compensation
  - Increase a doesn't help
  - Increase L_E/a doesn't help
- Other design considerations
  - Good transmission : Increase a
  - Avoid large V_E: Increase L_E
    decrease a

$x = \sqrt{\beta\varepsilon}$	beam size
a	aperture
L_E	length
V_E	quad. voltage
V_{ECR}	ECR Voltage
$f = \dfrac{V_{ECR} a^2}{V_E L_E}$	focal length

Design recipe

- At large beam size use longer quadrupole
- Octupole where aberrations are large
– p phase advance for sextupole compensation



(1) Short quadrupole
- small beam size and aberrations
- reduce aperture to limit the quad voltage.

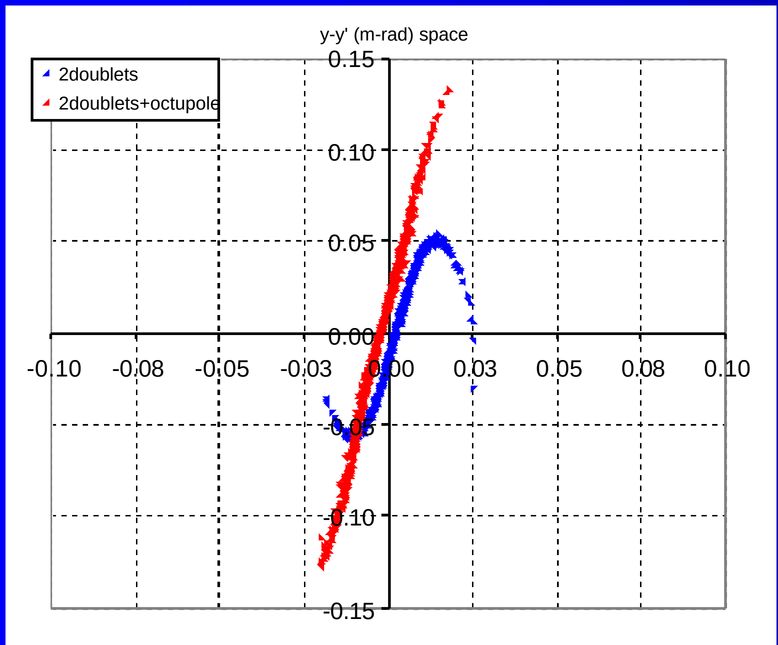
(2) Long quadrupole
- large beam size and aberrations

(3) Octupole
- near the quad with large aberration

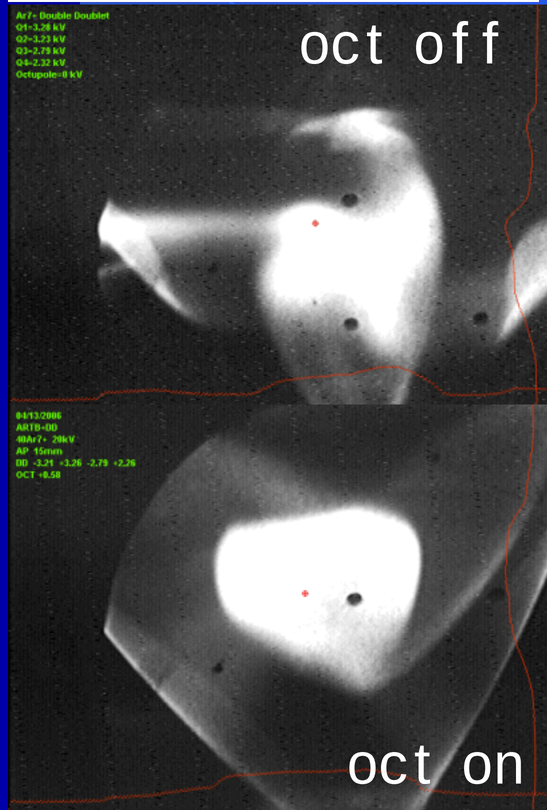
(4,5) Drifts.
- lengths for π phase advance

Octupole correction

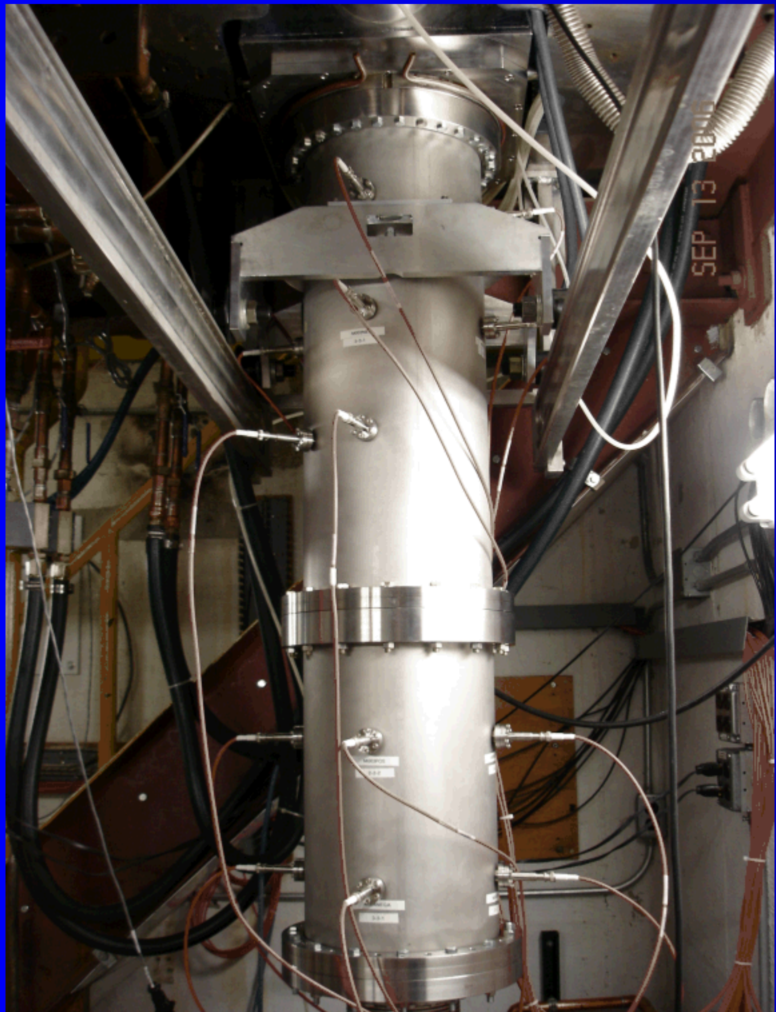
Correct S-shape (3rd order) aberrations in phase space

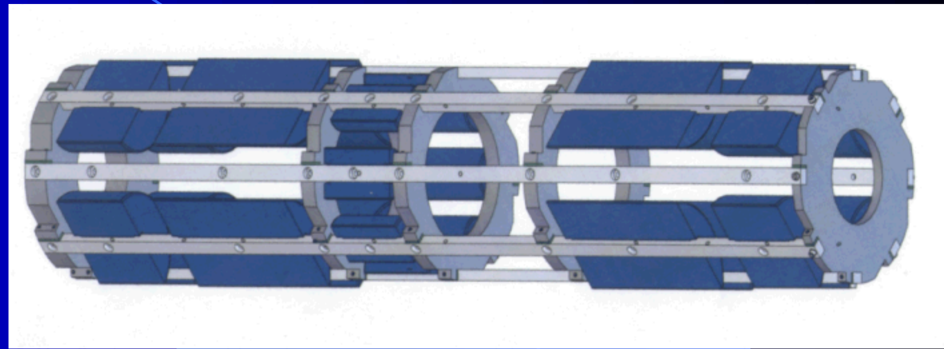


Beam viewer



DD (1)

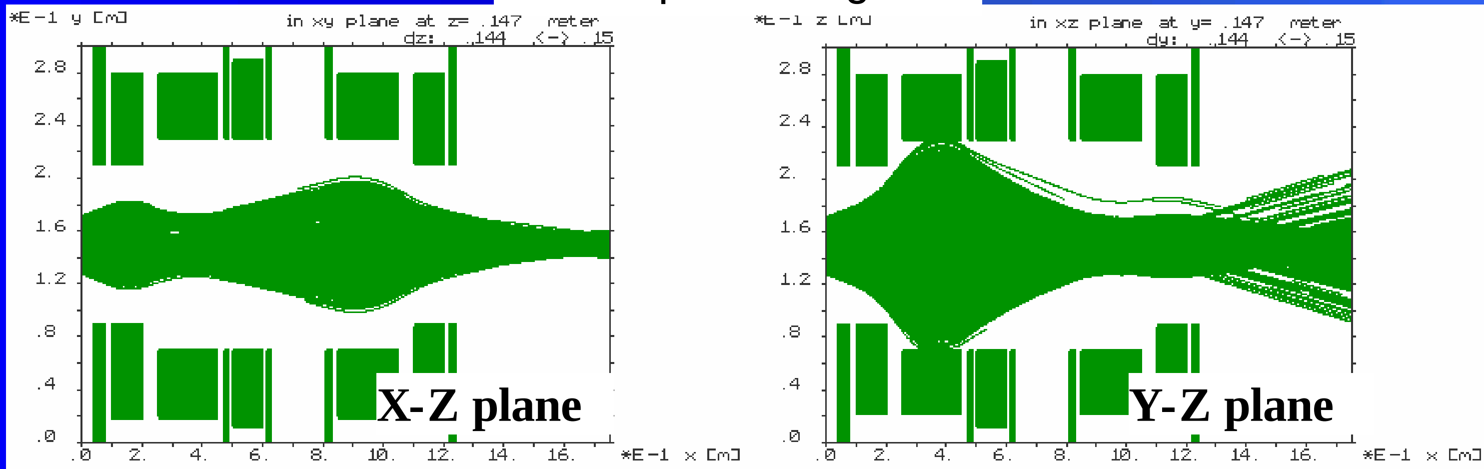




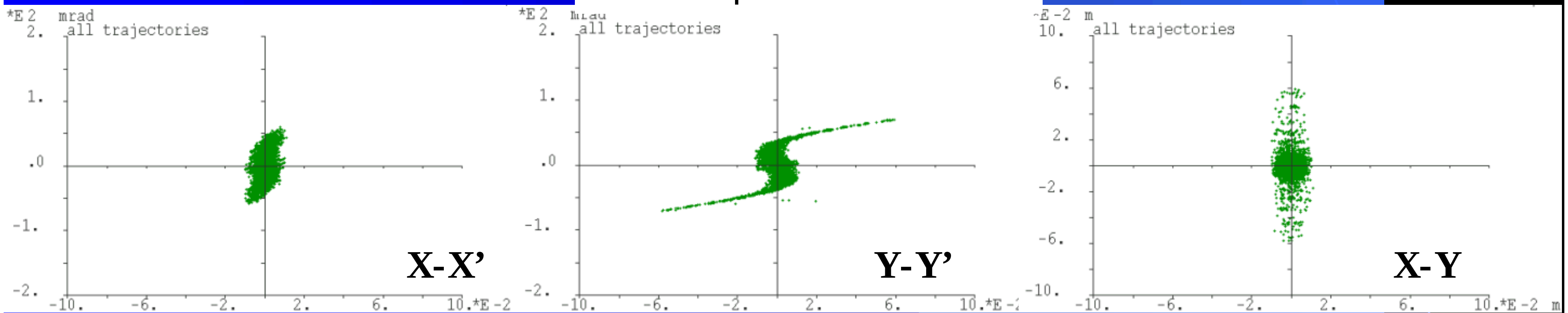
- Benefits:
  - Reduces aberrations
- Main dimensions
  - Aperture: 120, 160 mm
  - Quads length: 100, 200 mm
  - Collimator aperture: 100 mm

DD (2)

Envelopes along DD



Phase spaces after DD

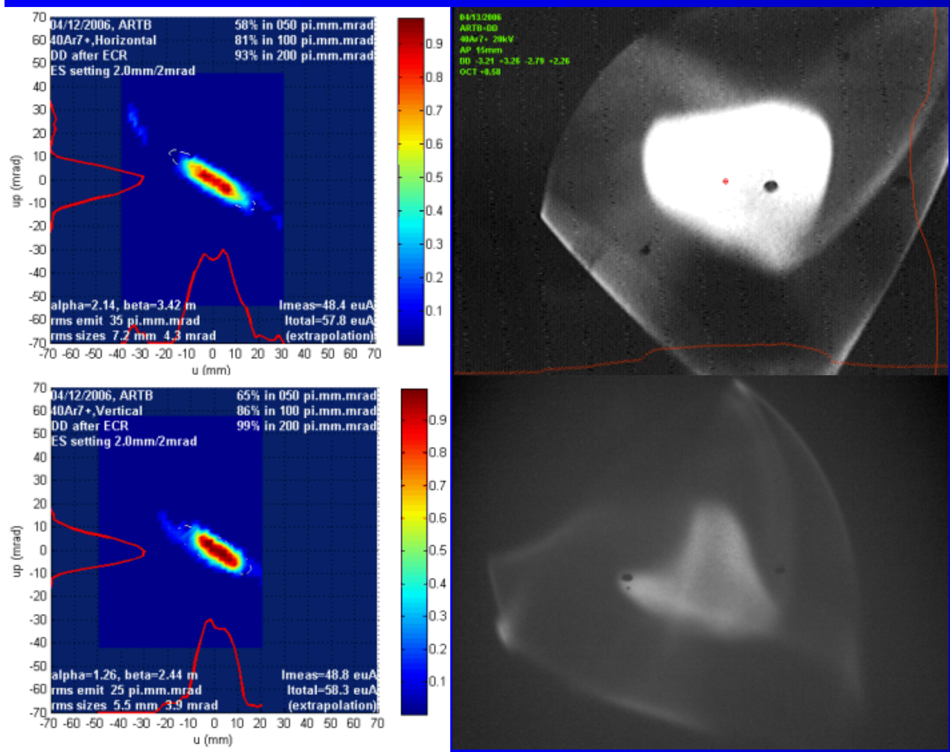


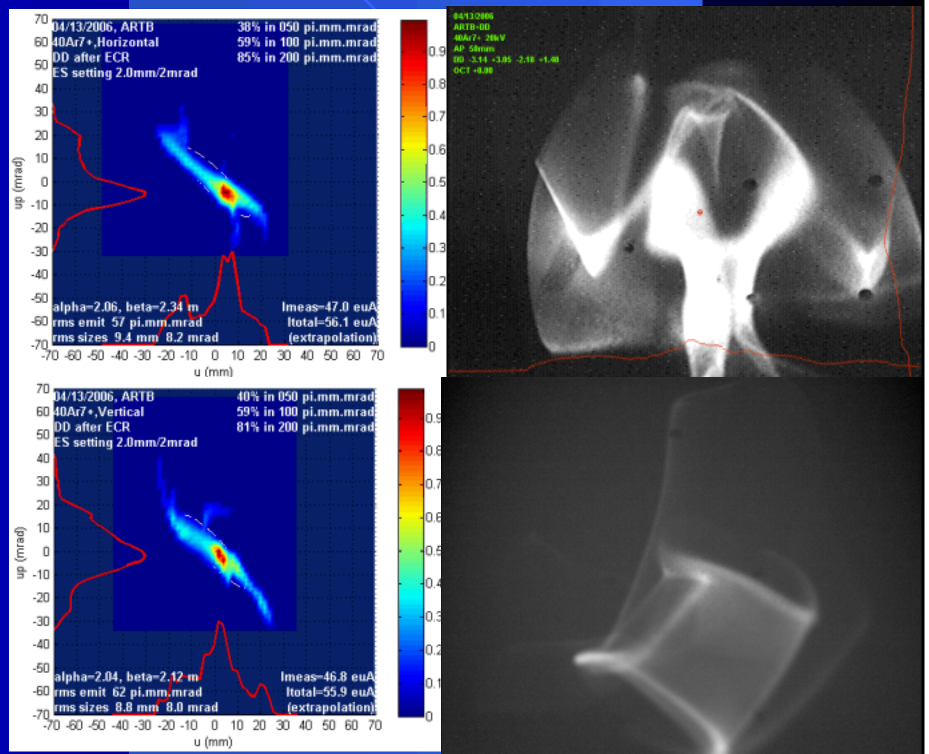
Impact of bad tuning

- Same hardware in both cases : DD + Dipole + Solenoid

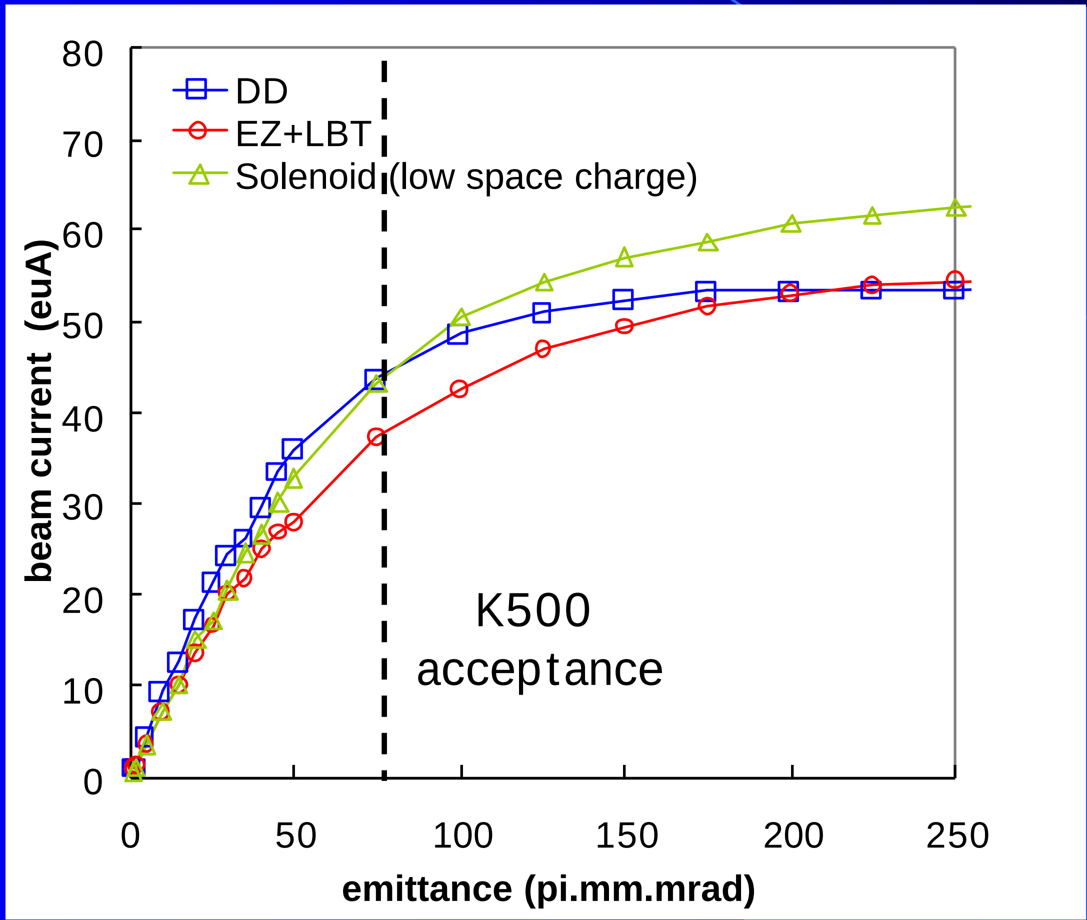
GOOD TUNE

BAD TUNE





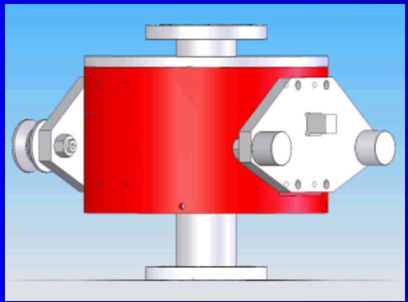
Brightness comparison



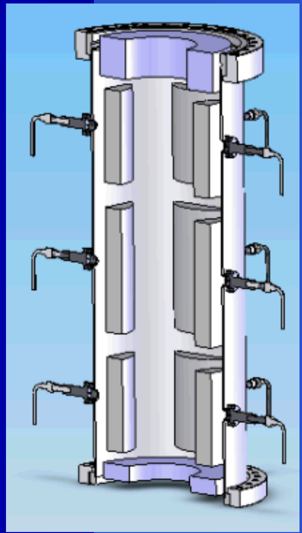
Focusing after ECR

Focusing Device

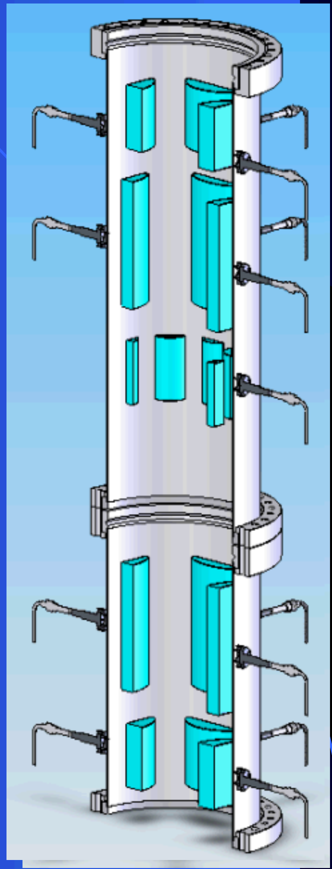
Solenoid



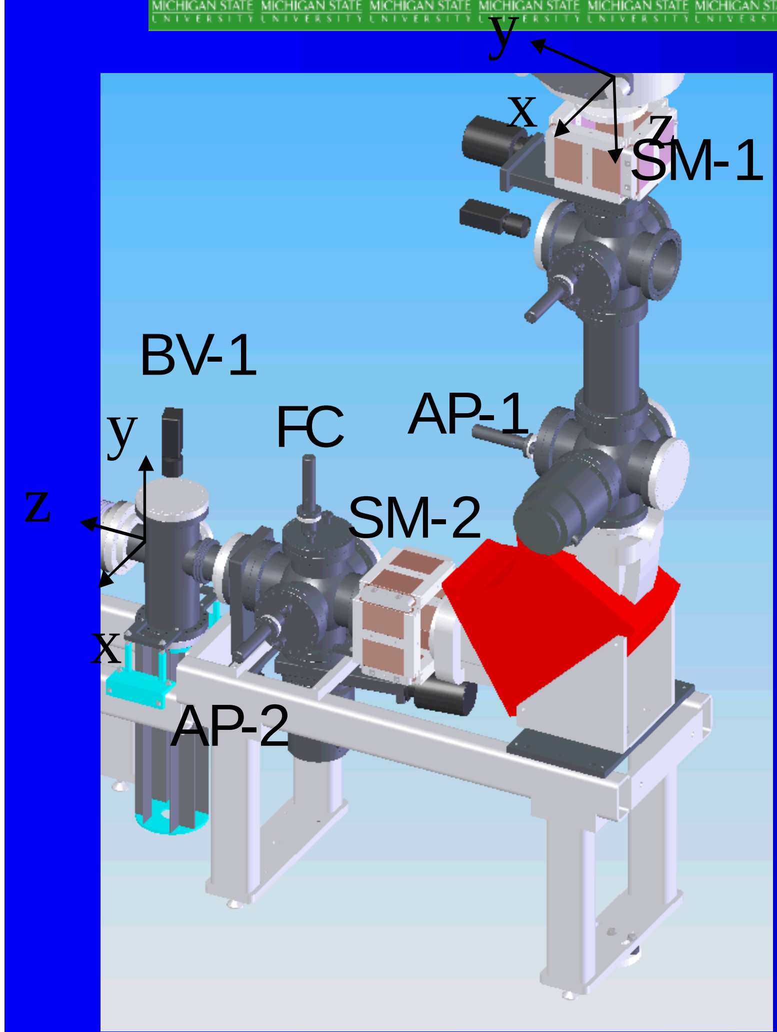
Large Bore Triplet

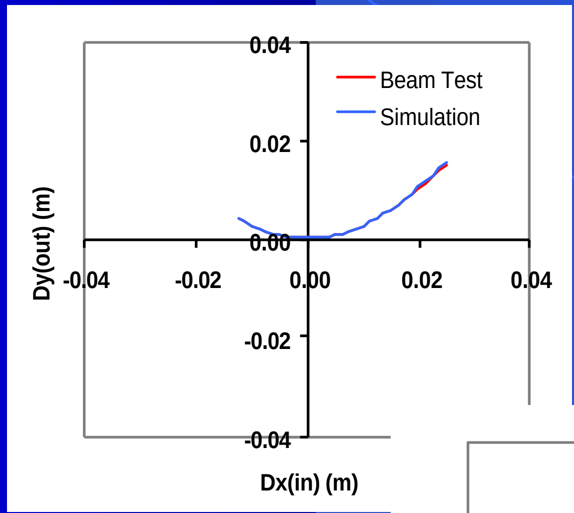


Double Quadrupole Doublet

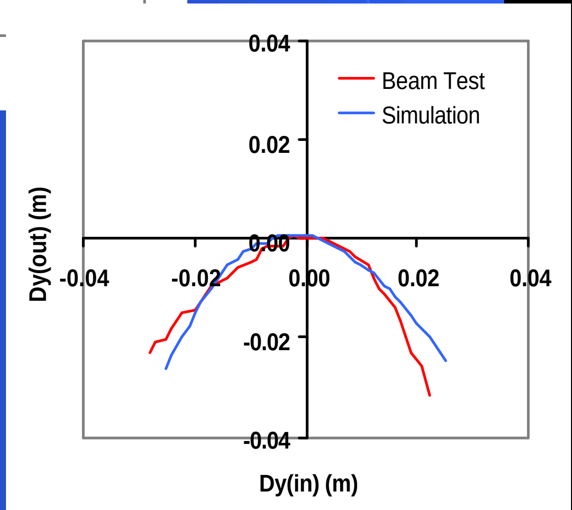


90-degree analyzing dipole





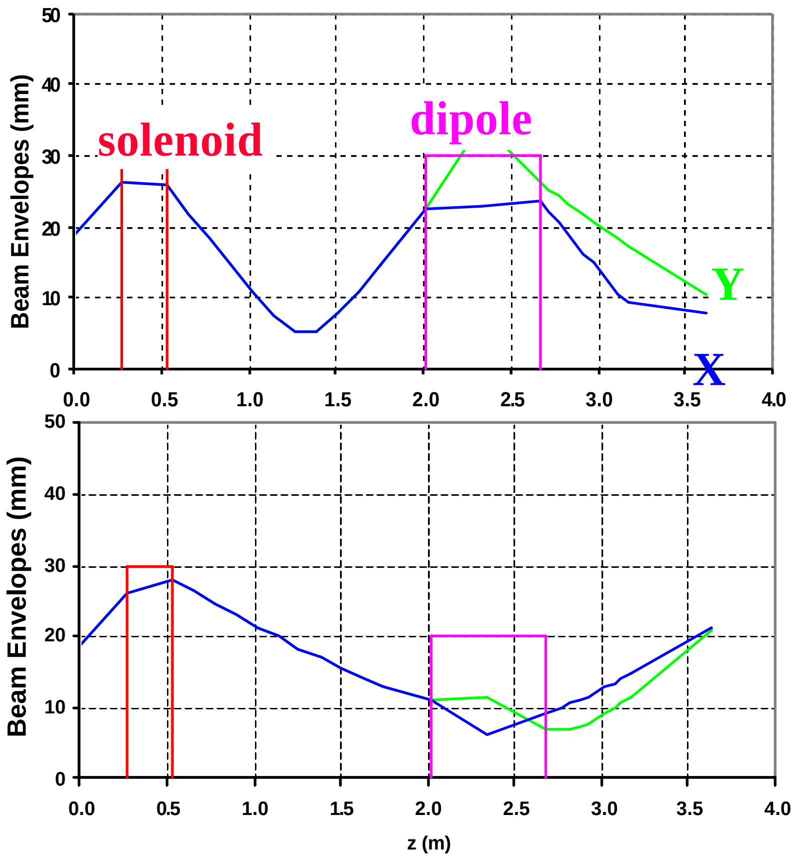
Beam position out v.s. in



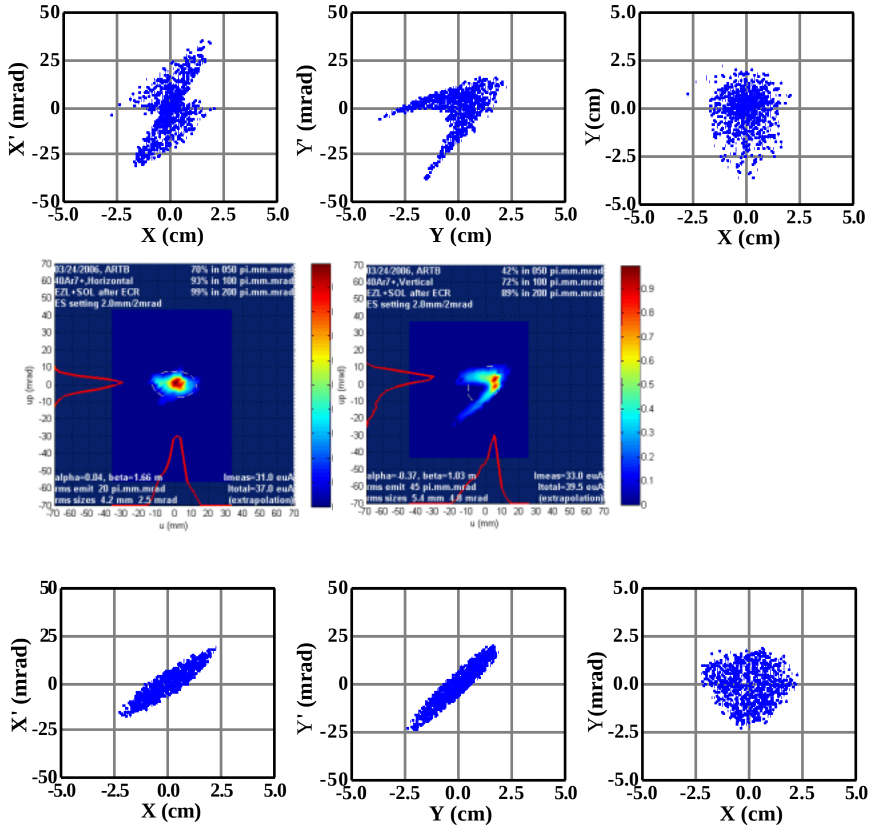
Sextupole Aberrations

90-degree dipole aberrations

Beam Envelopes

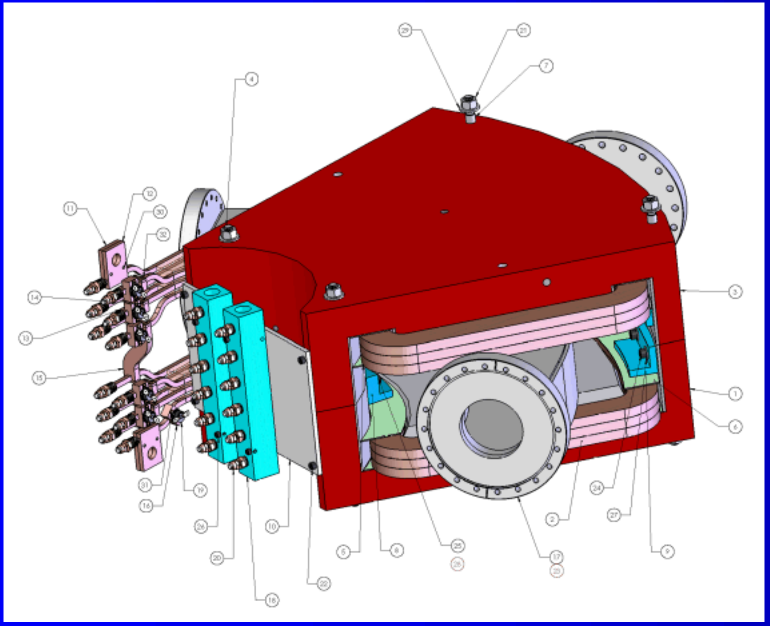


Final Phase Spaces



New analyzing magnet design

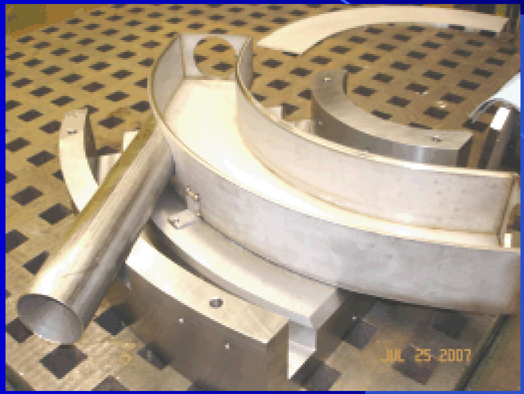
- Reduce 90-degree dipole aberrations
- Yokes and beam chambers done at NSCL
- Coils done at TAMU-CI



Parameter	Value	Unit
Bending angle	90	degrees
Bending radius	40.6	cm
Gap	10	cm
Pole face angles	28.5	degrees
# of coils per magnet # of turns per coil	2 36	- -
Magnetic field	1.64	kG
Current	200	A
Voltage	16	V
Power	3.2	kW

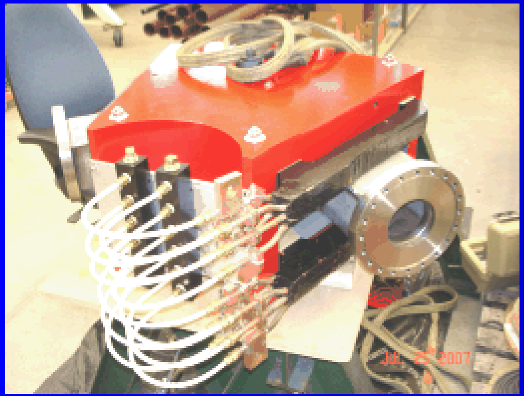
The life of a magnet

birth



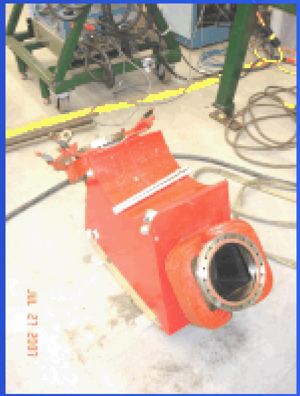
Growing pains

learning



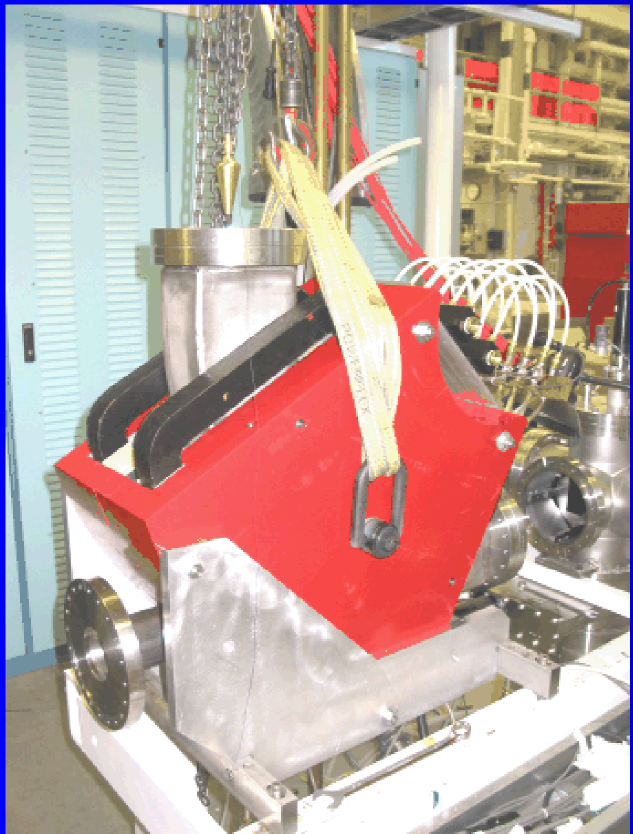
Early 20's

She's a looker !

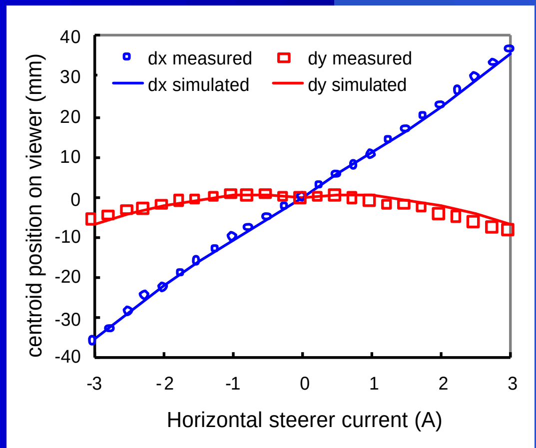


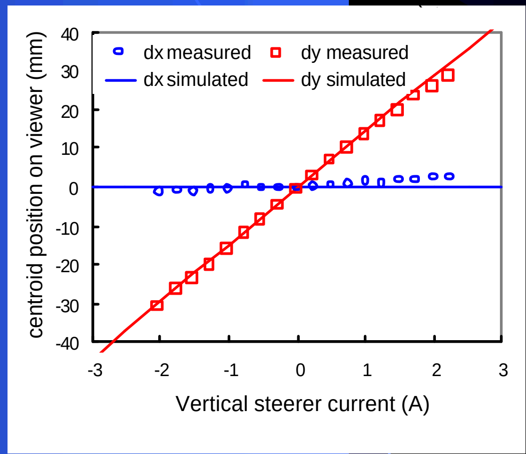
Old age…

Test with beam



- Magnet meets design goals
- Installed under Artemis in CCF August 2007





Automatic tuning algorithm

- MATLAB-EPICS program
- Hybrid optimizer
  - Hill climbing algorithm
  - Genetic algorithm
- Optimize on faraday cup so far

- Genetic Algorithm
  - Large non-linear systems
  - Can start at noise level
  - Population of tunes
  - Random starting tunes
  - Population of tune evolves through
    - Selection
    - Crossover
    - Mutation

Chromosome 1	11011 | 00100110110
Chromosome 2	11011 | 11000011110
Offspring 1	11011 | 11000011110
Offspring 2	11011 | 00100110110

Original offspring 1	1101111000011110
Original offspring 2	1101100100110110
Mutated offspring 1	1100111000011110
Mutated offspring 2	1101101100110110

Automatic tuning

Genetic Algorithm

iteration#	12FC (euA)	Q1(kV)	Q2(kV)	Q3(kV)	Q4(kV)	12FC (euA)
1	76.579	3.690	3.693	2.379	2.013	76.579
2	82.803	3.915	3.767	2.953	2.453	82.803
3	92.760	3.690	3.693	2.079	1.319	92.760
7	93.264	3.690	3.693	2.080	1.319	93.264

Simplex Algortihm

Iteration	Func-count	min	f(x)
0	1	-93.9162	
1	5	-93.9162	initial
2	7	-93.9162	contract
.			
98	231	-97.5317	reflect
99	237	-97.5317	shrink
100	238	-97.5317	reflect

Tuning of DD
40Ar7+ from Artemis

Benchmark of algorithm
- Manually tuning 90 euA
- Automatic tuning 97 euA

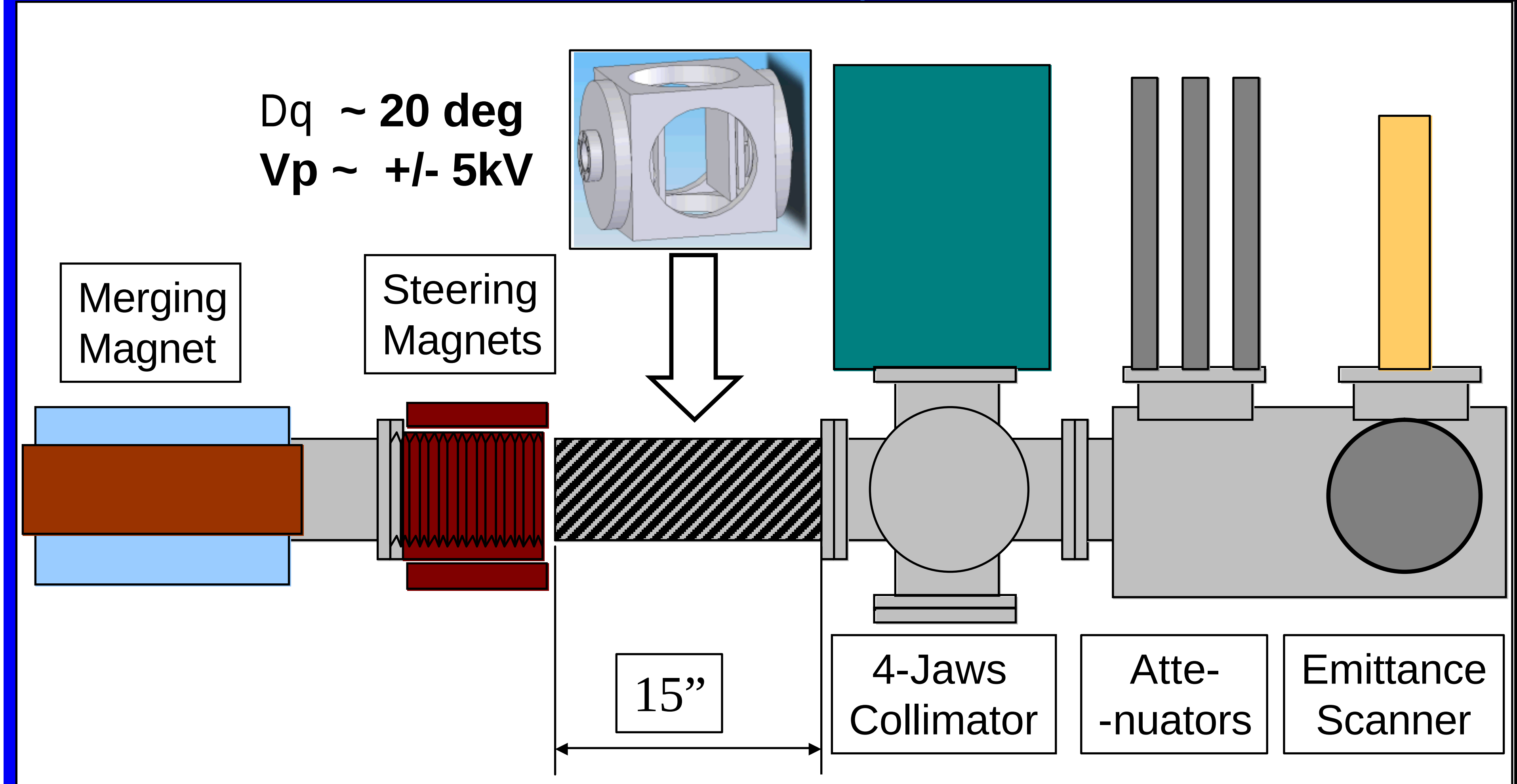
Result satisfactory

Chopper vs Attenuator

- Attenuator
  - Reduce average beam power
  - Protect CCF hardware
  - Large attenuation possible

- Chopper
  - Reduce average beam power (down to 1%)
  - Protect CCF hardware
  - Keep same peak intensity
  - Tuning independent of chopper setting
  - Commissioning on Artemis-B in October
  - Move to CCF before end 2007

Chopper installation



Broad effort

- Accelerator
  - F. Marti, X. Wu, R. York, Q. Zhao
- Computer
  - K. Eason, E. Kasten, B. Pollack
- Fabrication and assembly
  - J. Pline, J. Wagner
- Electronics
  - K. Davidson, K. Kranz, G. Mujtaba, J. Priller, D. Scott, C. Supangco
- Facilities
  - S. Chouhan, S. Hitchcock, J. Yurkon, A. Zeller
- Mechanical Design
  - B. Arend, R. Fontus, P. Glennon, D. Lawton, L. Morris, J. Moskalik, J. Ottarson
- Nuclear
  - T. Glasmacher
- Operation
  - All operators, D. Cole, G. Humenik, G. Machicoane, P. Miller, D. Poe, M. Portillo, M. Steiner, J. Stetson, L. Tobos, P. Zavodsky

Conclusions

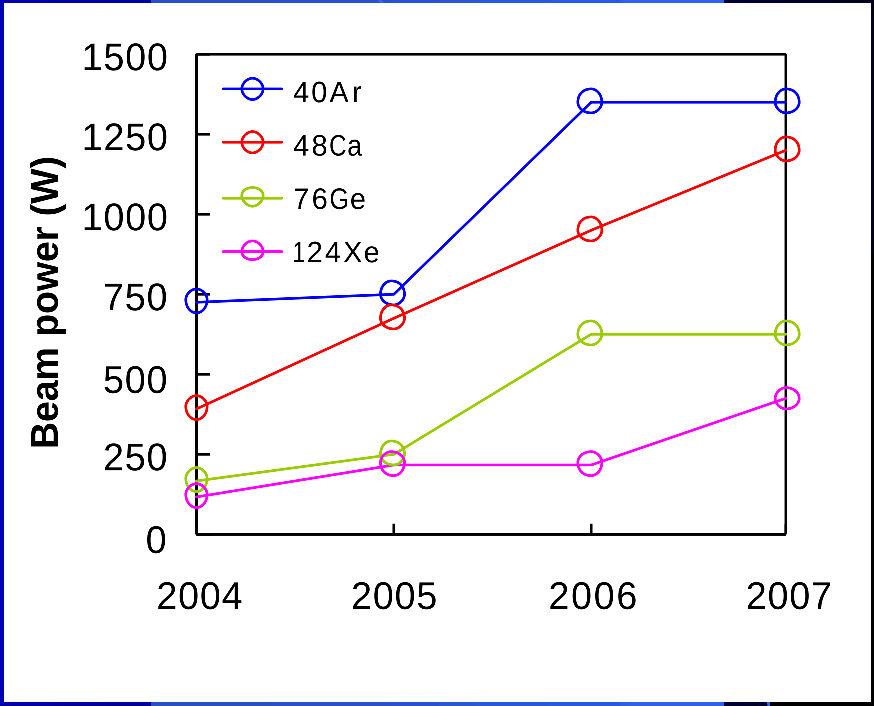
- Beam Power for CCF primary beams increased
  - K500 injection beamline improved
  - Many other improvements (extraction collimators, phase slits…)
  - Artemis-B is very helpful for R&D and Hardware test
  - New hardware
    - Chopper
    - 2^{nd} harmonic for rf buncher
    - Spherical bender below K500
  - New Software
    - Automatic tuning

- THANKS FOR YOUR ATTENTION

Beam power on target

- Significant progress since 2004
- Next challenges
  - Deflectors
  - Stripper foils
  - Beam tuning time

	^{40}Ar	^{48}Ca	^{76}Ge	^{124}Xe
2007	1350	1200	625	425
2006	1350	950	625	225
2005	750	675	250	225
2004	725	400	175	125



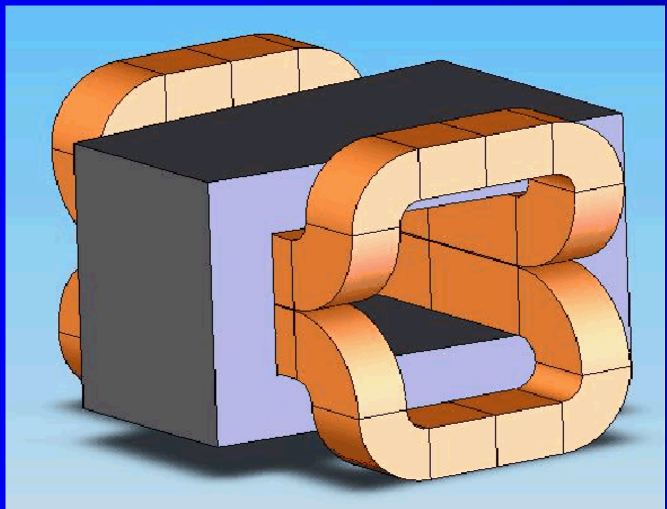
Back-up slides

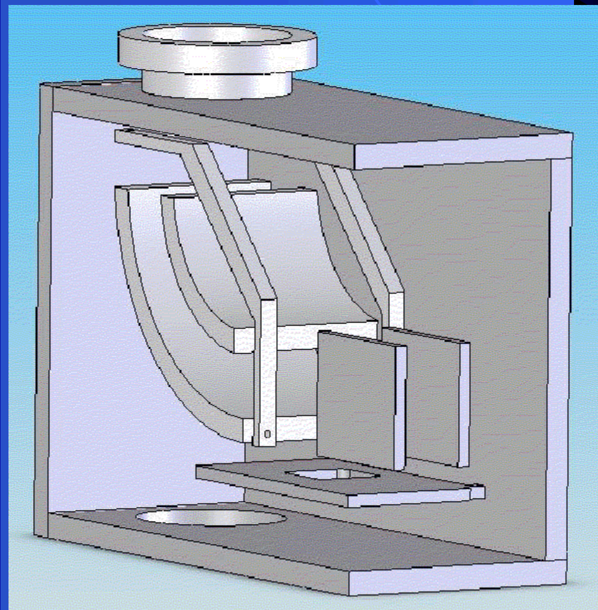
Solenoid test in CCF

	2SOL	EZ+LBT	
16O3+	3.0	4.5	euA at N004FC
	x3	x3	Attenuator
	25%	31%	N004/INF
	70%	82%	N004/K526"
40Ar7+	3.1	2.2	euA at N004FC
	x3	x3	Attenuator
	28%	33%	N004/INF
	73%	82%	N004/K526"
78Kr14+	6.2	3.6	euA at N004FC
	x1	x1	Attenuator
	31%	42%	N004/INF
	65%	81%	N004/K526"
124Xe20+	3.7	3.2	euA at N004FC
	x1	x1	Attenuator
	29%	22%	N004/INF
	57%	52%	N004/K526"

Matching into K500

- Find matching parameters for best injection efficiency
- 3D model to get accurate injection beamline model
- Use data from Allison emittance scanner for input conditions





Automatic tuning

Genetic Algorithm										1200 probe
1	0.048584	3.795256	-3.09757	22.43303	143.9479	27.90232	-114.844	1.757575	-2.49963	0.048584
3	0.225023	3.795256	-3.09757	22.43303	143.9479	27.90232	-114.844	1.2	-2.49963	0.225023
4	1.171141	3.795256	-3.21665	22.43303	143.9479	27.90232	-114.844	1.757575	-2.49963	1.171141
6	1.299634	3.795256	-3.21497	22.43303	143.9479	27.90232	-114.844	1.751604	-2.49963	1.299634
8	1.333168	3.795256	-3.21497	22.43303	143.9479	27.90232	-114.844	1.757575	-2.49963	1.333168

Simplex Algortihm

Iteration	Func-count	min f(x)	Procedure	
0	1	-1.59423		
1	9	-1.59423	initial	simplex
2	11	-1.59423	contract	inside
.				
48	83	-1.95624	reflect	
49	85	-1.9632	contract	inside
50	87	-1.9632	contract	inside

Coupling line (K500-K1200)

Automatic program achieved ~ 2euA (~75% injection efficiency)

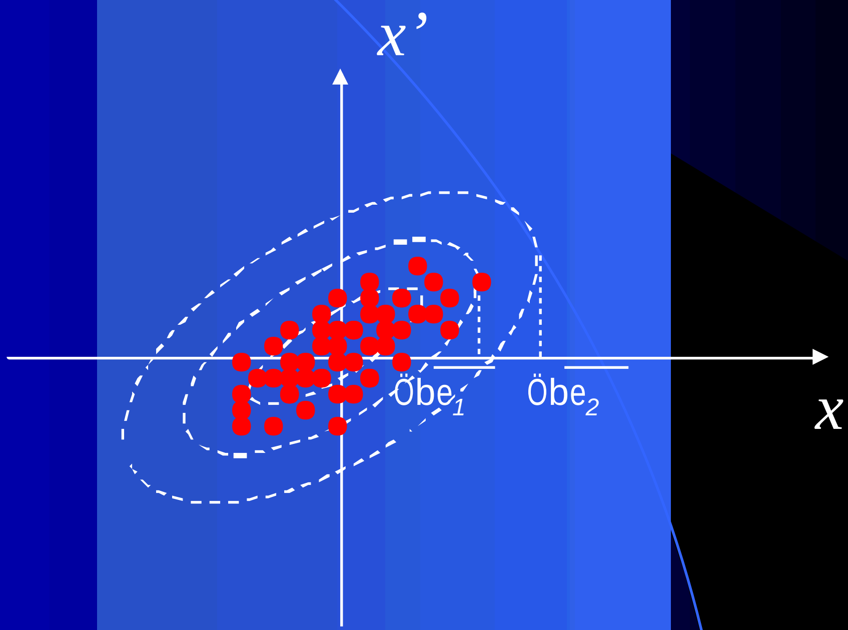
Preliminary results satisfactory

Solenoid VS El. Quad

- SOLENOID
  - Efficient focusing +
  - Spherical aberrations -
  - Aberrations from leads -
  - Space charge issue -
- ELECTROSTATIC QUADRUPOLE
  - Motion in the transverse dimensions decoupled +
  - Reduces space-charge issue +
  - Large beam envelope and field aberrations -
  - Octupole correction +

RMS Parameters – Brightness

- RMS Emittance (2D)
  - $\varepsilon_{rms} = \sqrt{<x^2><x'^2>-<xx'>^2}$
  - ellipse area = $\pi\varepsilon$
- RMS Twiss Parameters
  - $\alpha = - <x.x'> / \varepsilon_{rms}$
  - $\beta = <x^2> / \varepsilon_{rms}$
  - $\beta\gamma - \alpha^2 = 1$
- **Brightness**
  - % beam in (α, β, ε) ellipse



Elect. Quad aberrations **TRI-DN-95-21**

Eq. motion

$$\beta'_x = -\frac{q}{A}\frac{1}{W_0}\frac{1}{\beta_z}\frac{\partial\Phi}{\partial x}$$

Hamiltonian of the system

$$\frac{1}{2}AW_0(\beta_x{}^2+\beta_y{}^2+\beta_z{}^2)+q\Phi = qV_{ECR} \approx \frac{1}{2}AW_0\beta_{z_0}{}^2$$

with normalization

$$\tilde{x}=x/a \quad \tilde{y}=y/a \quad \tilde{z}=z/a$$

$$\tilde{\beta}_i=\beta_i/\beta_{z_0}$$

$$\tilde{\Phi}=\Phi/V_{ECR}$$

rewrite

$$\tilde{\beta}'_x = -\frac{1}{2}\frac{1}{\tilde{\beta}_z}\frac{\partial\tilde{\Phi}}{\partial\tilde{x}}$$

$$\tilde{\beta}_x^2+\tilde{\beta}_y^2+\tilde{\beta}_z^2 = 1-\tilde{\Phi}$$

integrated effects

$$\Delta\tilde{\beta}_{x\,\mathrm{NLtr}} \approx -\frac{\tilde{x}}{\tilde{f}}$$

$$\Delta\tilde{\beta}_{x\,\mathrm{NLtr}} \approx -\frac{\tilde{x}}{\tilde{f}}\left(\frac{\tilde{x}^2}{2\tilde{f}\tilde{L}_E}\right)$$

$$\Delta\tilde{\beta}_{x\,\mathrm{NLlg}} \approx -\frac{\tilde{x}}{\tilde{f}}\left(\frac{\tilde{x}^2-\tilde{y}^2}{2\tilde{f}\tilde{L}_E}\right)$$

quadrupole potential

$$\tilde{\Phi}=\tilde{V}(\tilde{z})\times(\tilde{x}^2-\tilde{y}^2)-\tilde{V}''(\tilde{z})\times(\tilde{x}^4-\tilde{y}^4)/12+\ldots$$

$$\tilde{\beta}'_x = -\tilde{V}\tilde{x} \quad + \quad \frac{1}{6}\tilde{V}''\tilde{x}^3 \quad - \quad \frac{1}{2}\tilde{V}\tilde{x}\left(\tilde{V}(\tilde{x}^2-\tilde{y}^2)+\tilde{\beta}_x^2+\tilde{\beta}_y^2\right)$$

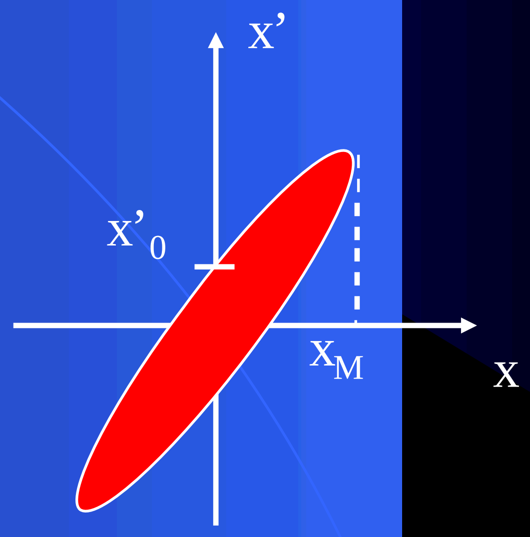
Elect. Quad aberrations (2)

Elliptic beam $\gamma x^2 + 2\alpha x x' + \beta x'^2 = \varepsilon$

with $x_M = \sqrt{\beta\varepsilon} \qquad x'_0 = \varepsilon / x_M = \sqrt{\varepsilon/\beta}$

small effect on emittance $\Delta x'_{NL} << x'_0$

For focal length $f = \dfrac{V_{ECR} a^2}{V_E L_E}$



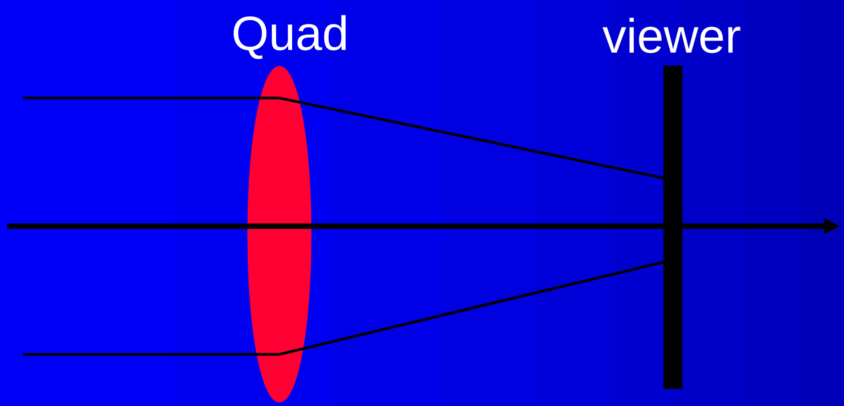
Condition for small aberrations $\beta << f\sqrt{L_E / \varepsilon}$

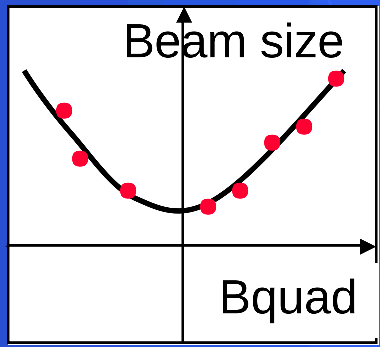
Below ECR : f~0.5m Le~15cm ε~160π.mm.mrad à β << 15 m

Envelope ~ 7.5cm gives β=35 m à significant aberrations in quad

CCF - Beam Diagnostics (3)

- Measure response beam size response matrix to variation of beam optics upstream
  - Injection beamline
  - Coupling line between K500 and K1200
  - High energy beamlines





Deflector losses