Medical Cyclotron and Development in China

Two directions:

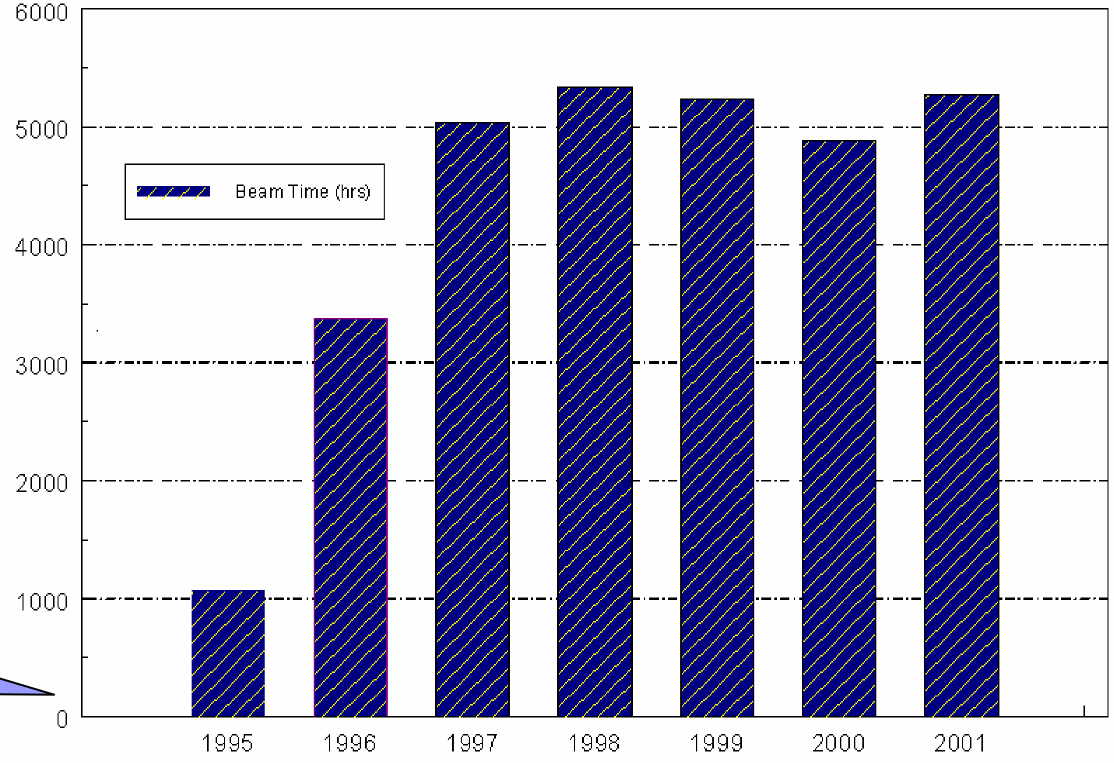
Lower ennergy machine: isotope production

Higher energy machine: tumour therapy

The First Medical Cyclotron in China (CYCIAE-30)

Constructed by China Institute of Atomic Energy (CIAE) in 1995

Used for accelerated Mass production of isotope



Beam time of theCYCIAE-30

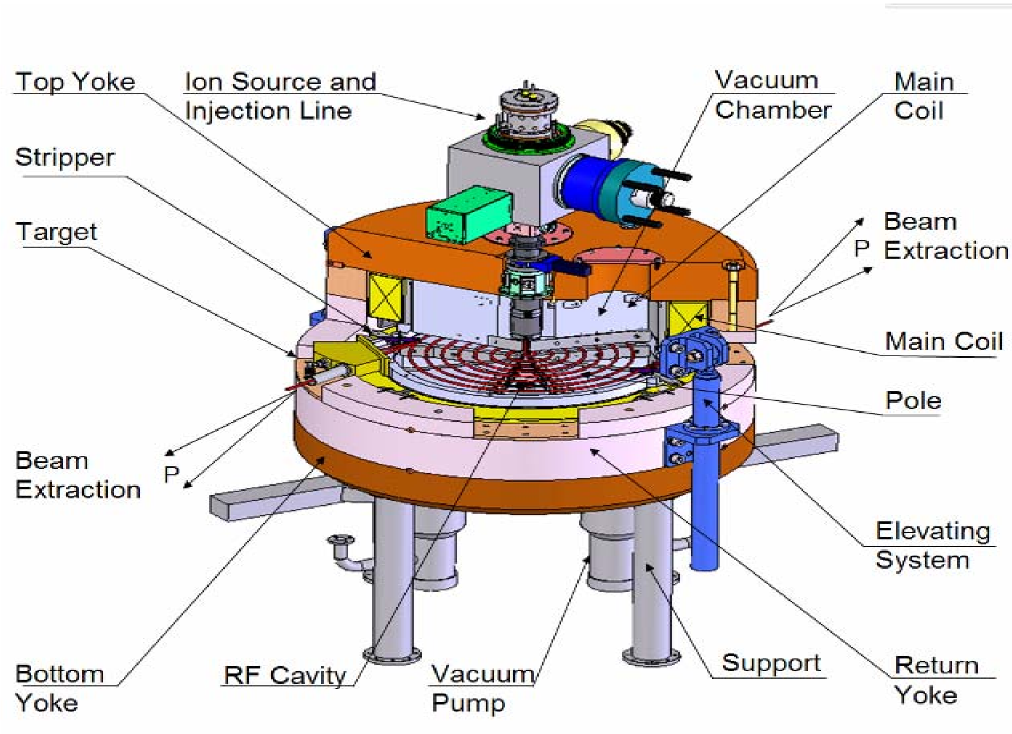
CYCIAE-CRM cyclotron

This is the main part of a high intensity cyclotron experimental platform (CYCIAE-CRM)

It can be used for the developing of PET-cyclotrons which be used for diagnose of cancer and other diseases.

Parameters	Value
Accelerated particle	H^-
Extraction energy	10Mev
Internal beam intensity	430μA

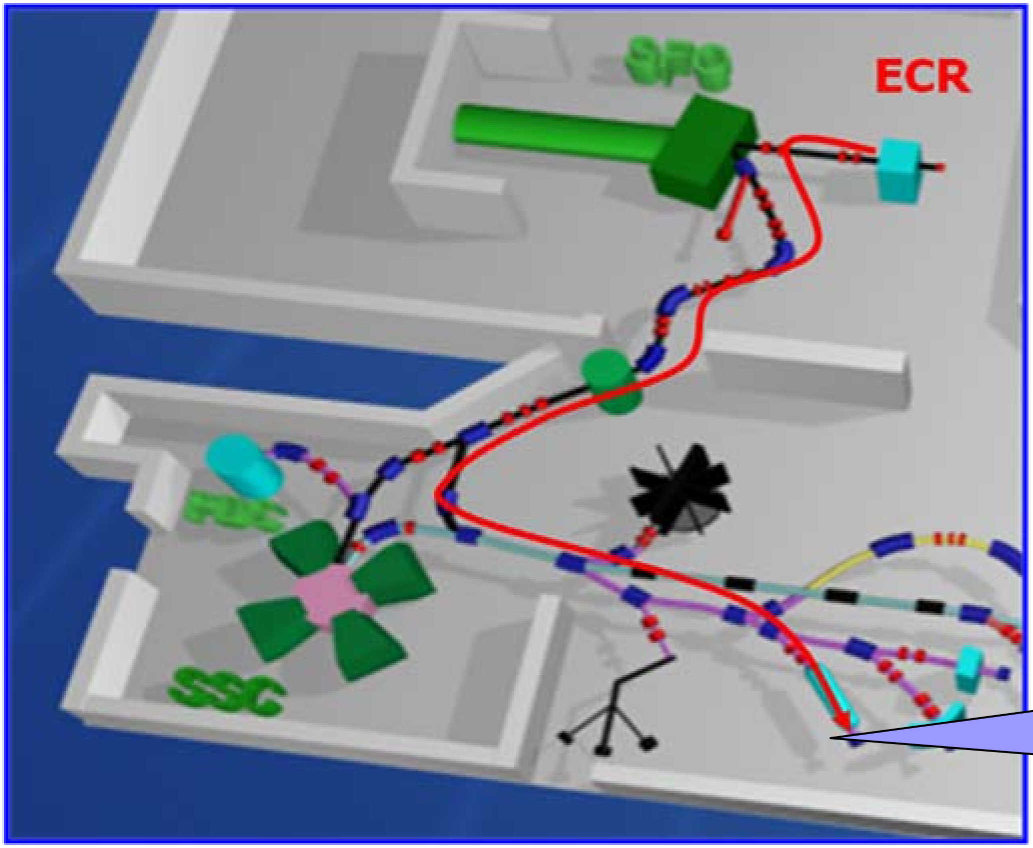
CYCIAE-14



Parameter	value
Particle accelerated	H-
Final energy	14.6MeV
Bmin/Bmax	2.0kGs/18.5kGs
Radius of sector magnet	500mm
Sector angle	52o
Hill gap	23-26mm
Valley gap	318mm
Outer radius of magnet	880mm
Height of Magnet	1066mm
Dee Voltage	50kV
RF frequency	73.02MHz
Harmonic mode	4
Extracted particle	Proton

It can product not only the normal PET particles 11C、15O、13N、18F but also the isotopes 64Cu、124I、99mTc

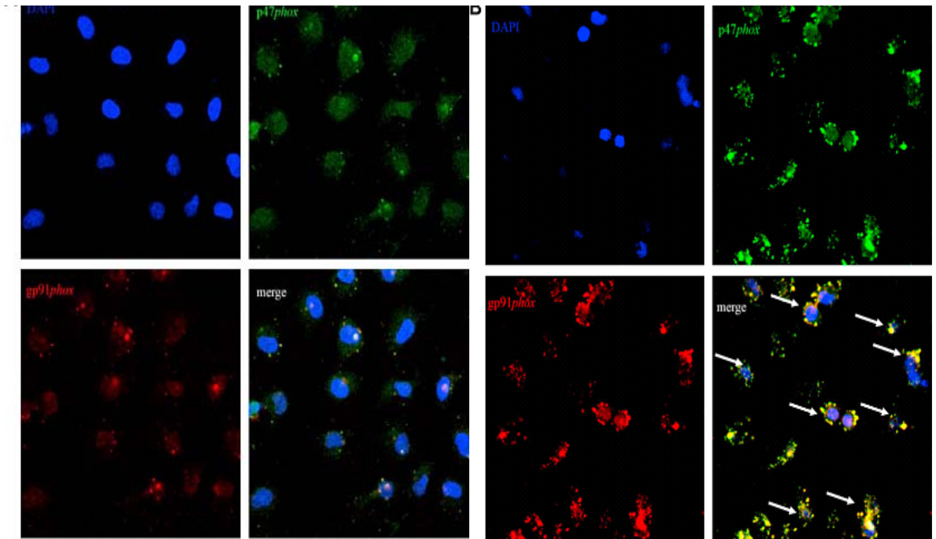
Layout of HIRFL



This is the surface tumor therapy terminal

Basic researches on biomedical related to heavy ion irradiation（1）

The cell injure induced by heavy-ions and their corresponding mechanisms



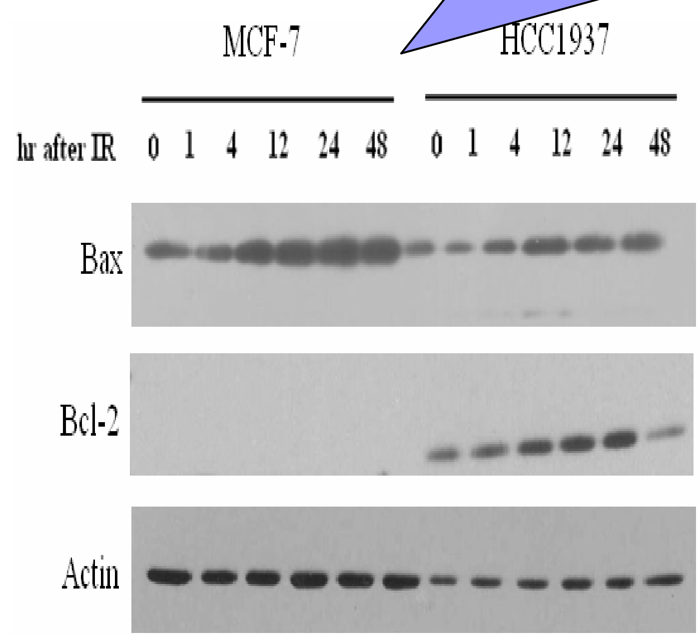
Hela Control gp91*phox*/p47 *phox*

Hela 4Gy HI gp91*phox*/p47 *phox*

The effect of NADPH oxidise-mediated generation of reactive oxygen species on cancer cell

DNA injure induced by heavy-ions

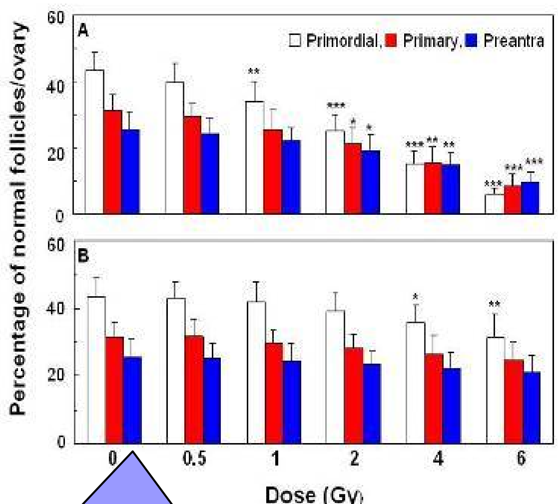
BRCA1 answers for the cancer cell death induced by heavy-ion irradiation by adjusting Bcl-2 protein

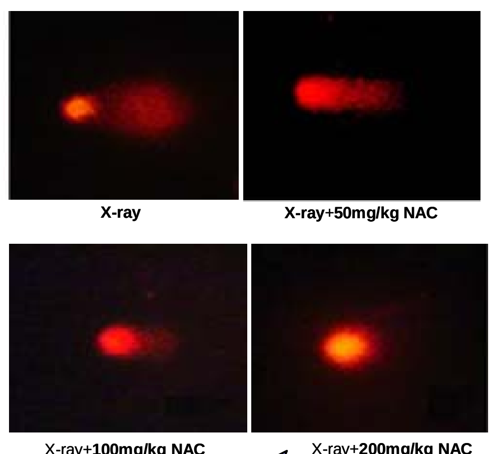


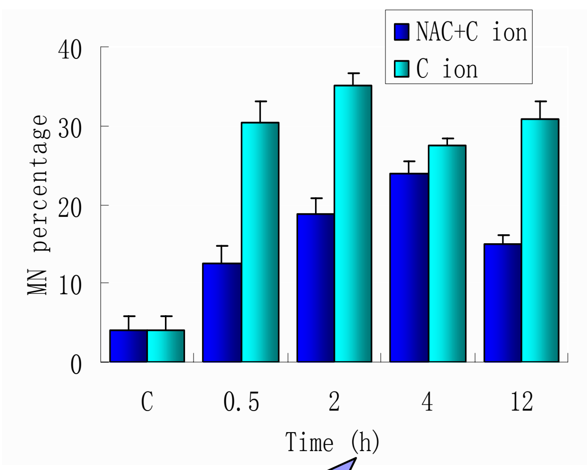
Basic researches on biomedical related to heavy ion irradiation(2)

The affections of heavy-ion irradiations on procreating cells and genetics.

The affections of heavy-ion irradiations on the immunity system of mice, conservation of antioxidant of injure induced by heavy ions.







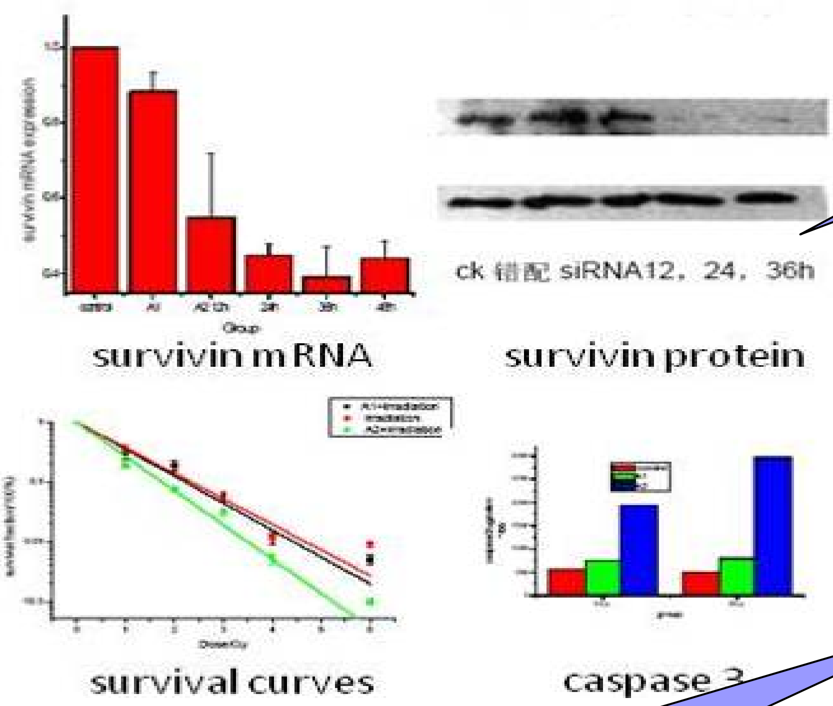
Affections of heavy-ion irradiations on procreating cells and genetics

Affections of heavy-ion irradiations on the immunity system of mice

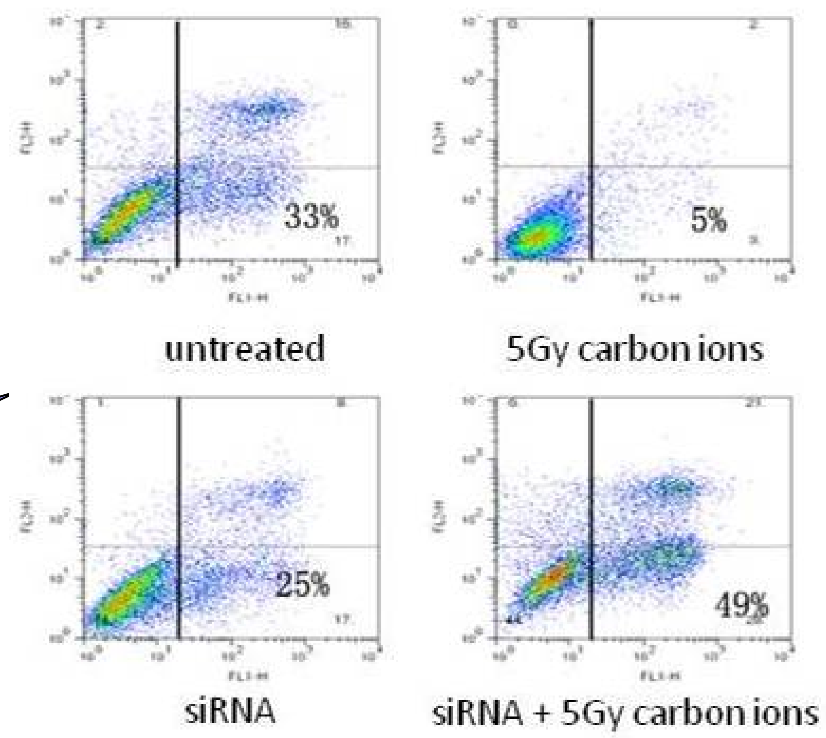
Conservation of antioxidant of injure induced by heavy ions

Basic researches on heavy-ion tumour therapy(1)

siRNA techniques adopted in heavy-ion tumour therapy researches



siRNA restraints the answer of surviving protein

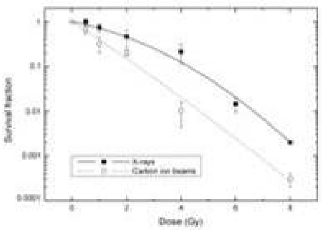


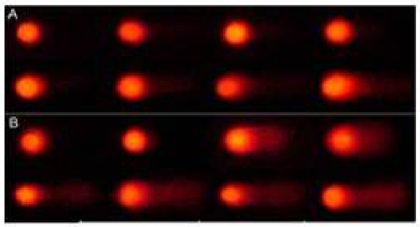
siRNA increase sensitivity of tumor cell to heavy-ion irradiaton

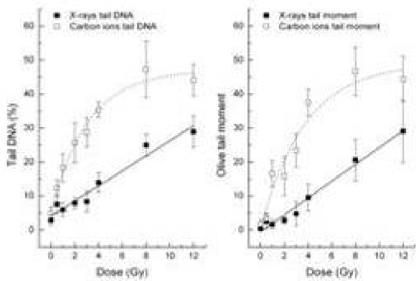
Basic researches on heavy-ion tumour therapy(2)

The protein group method adopted in heavy-ion tumour therapy researches

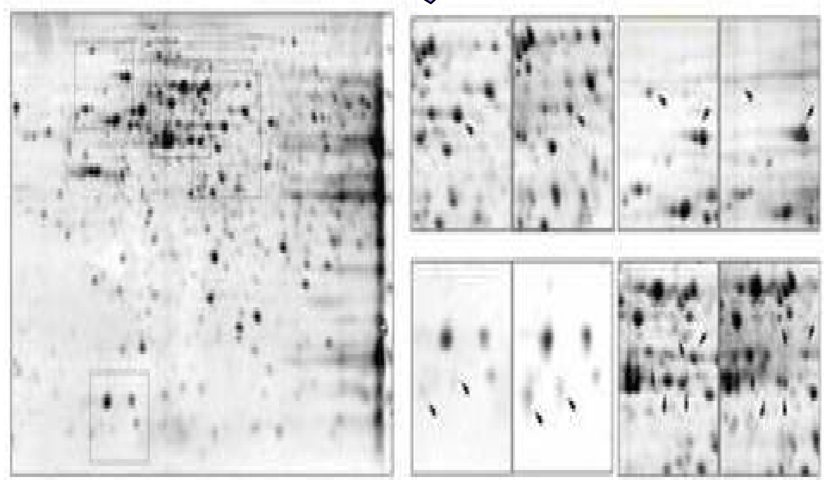
The affection of heavy ion irradiation in mammal cell DNA repair



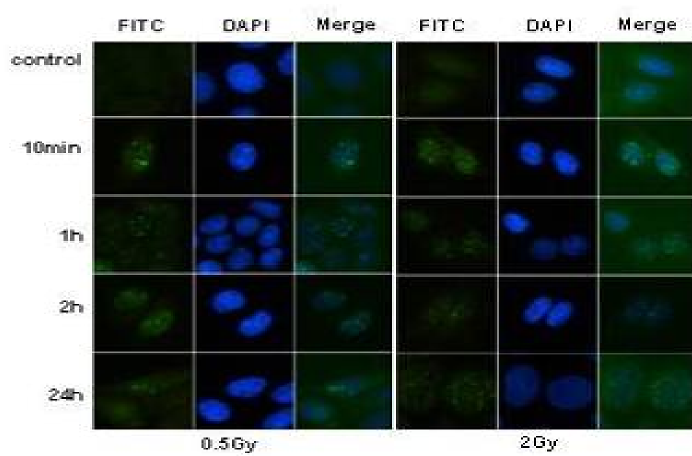




radiation	SF2	OTM2
X-ray	0.463 ± 0.181	2.867 ± 0.492
carbon ion beam	0.174 ± 0.032	15.833 ± 3.826
f-test	p<0.05	p<0.01



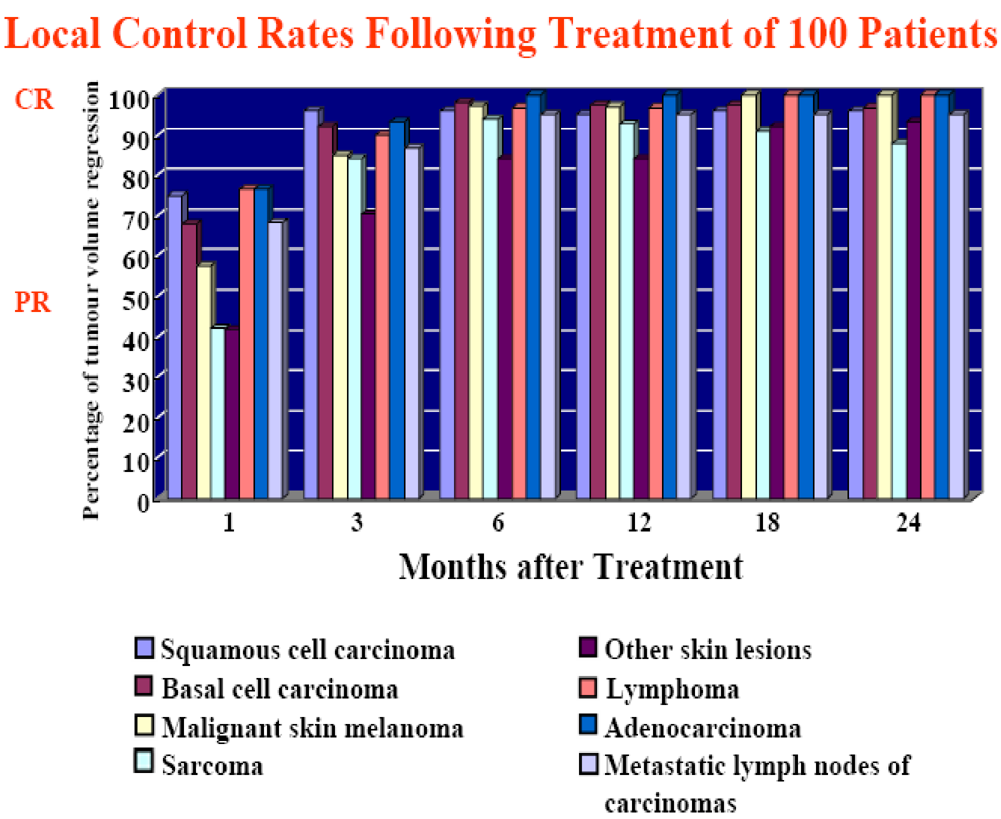
The affection of heavy ion irradiation in mammal cell DNA injure



The protein group method in ion irradiation cancer biomedical

Practice of tumour therapy at IMP

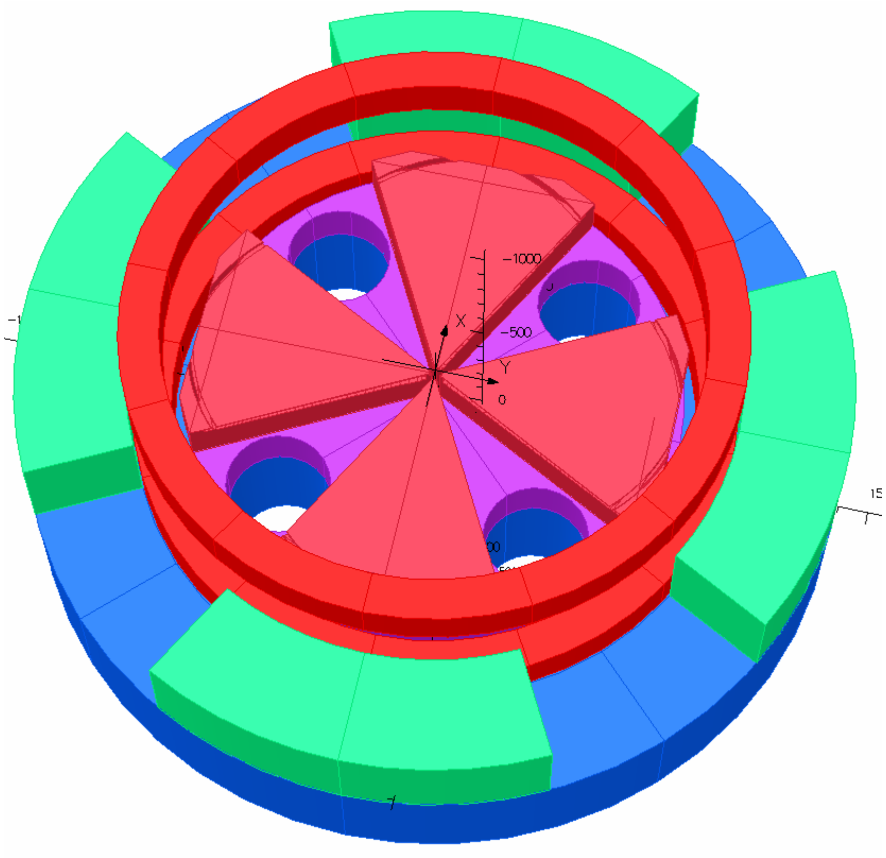
Up to now, there are 103 patients who has a superficial tumour had been treated at IMP



Some typical patient

Cyclotron as a synchrotron injector

Now IMP is designing a cancer therapy machine, it consists a injector cyclotron and a main accelerator synchrotron



Accelerated Ion Species	$^{12}C^{6+}$
Extraction Energy	7Mev/u
Ex-Beam Intensity (C)	10euA
Energy Spread	±1%
Emittance	20-25 π mm.mrad
Frequency	31.02MHz
Accelerating Voltage	70KV
Degree of Dees	30°
Dee Number	2
Stability of Phase	±1°
Stability of Voltage	±5×10-4/24hour
Stability of Frequency	±1×10-6/24hour
Power Source Number	2
Power	50KW

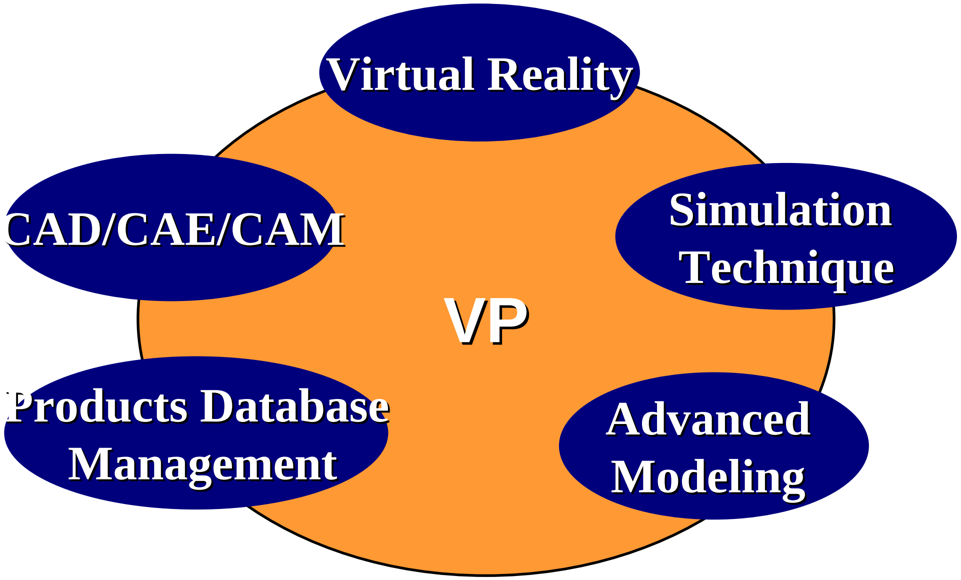
Application
of Virtual Prototyping
in Cyclotron Engineering

Virtual Prototyping (VP)

A digital design method based on computer models of the product

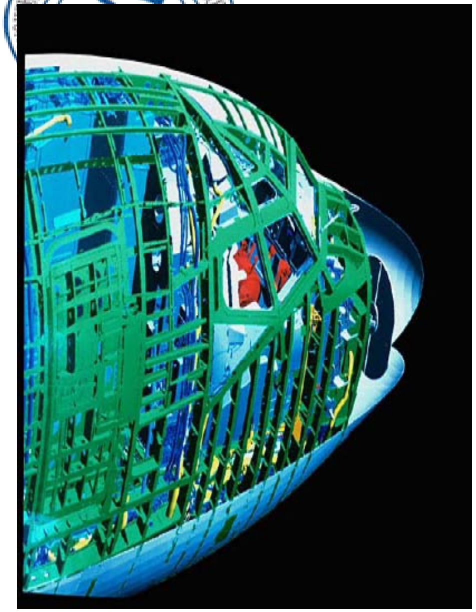
Combines different development models in various engineering area

Simulates the real product from the structures, functionalities and behaviors.

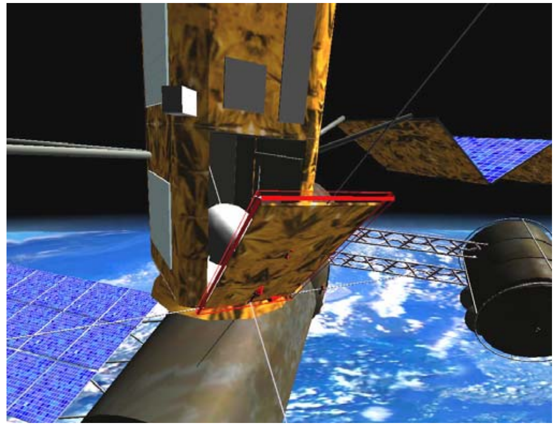


Answer fundamental engineering questions:

- What is the best design?
- How safe is it?
- How much confidence in my answer?

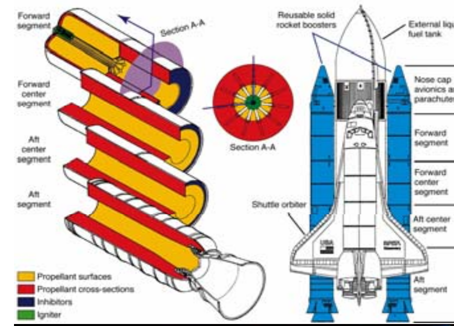


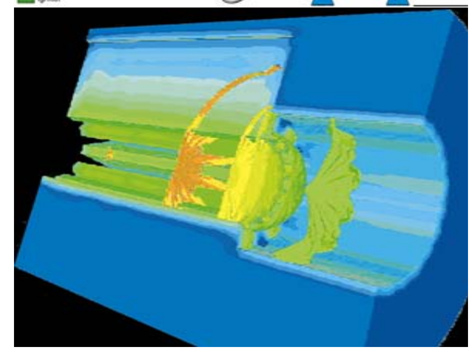
Boeing 777
“the first airplane to be 100% digitally designed and preassembled on computer.”



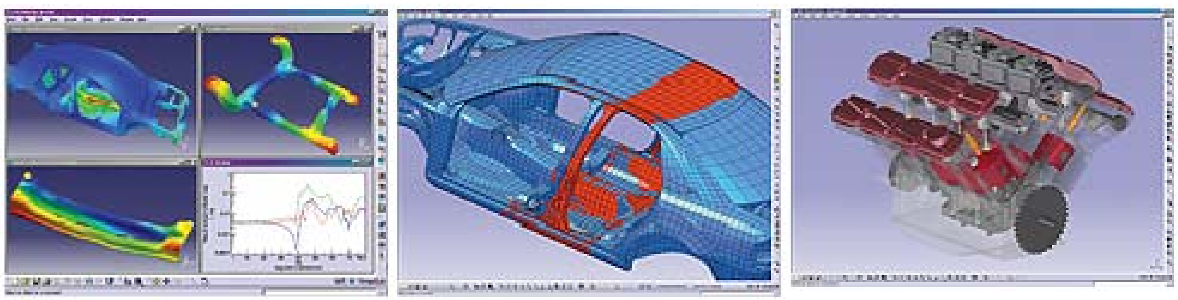
Nanosatellites
(*New Mexico State Univ. & NASA***)**

Applications of Virtual Prototyping





Solid propellant rockets
-Gas temperature & pressure
(*CSAR,USA*)

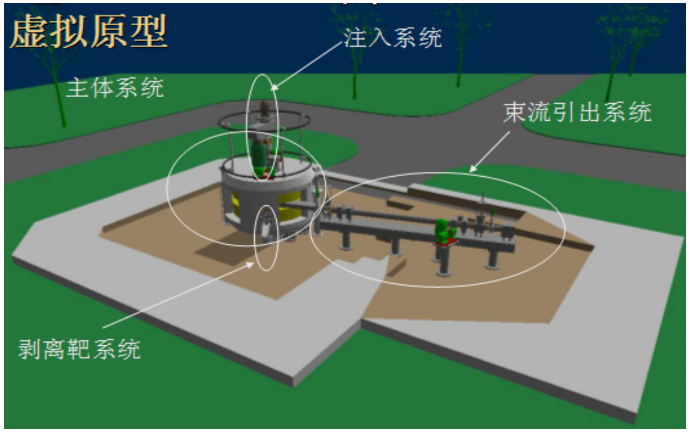


Vehicles design: Structure, Motion, Engine

Applying VP to the Innovative Design of Compact Cyclotrons

Motivations…

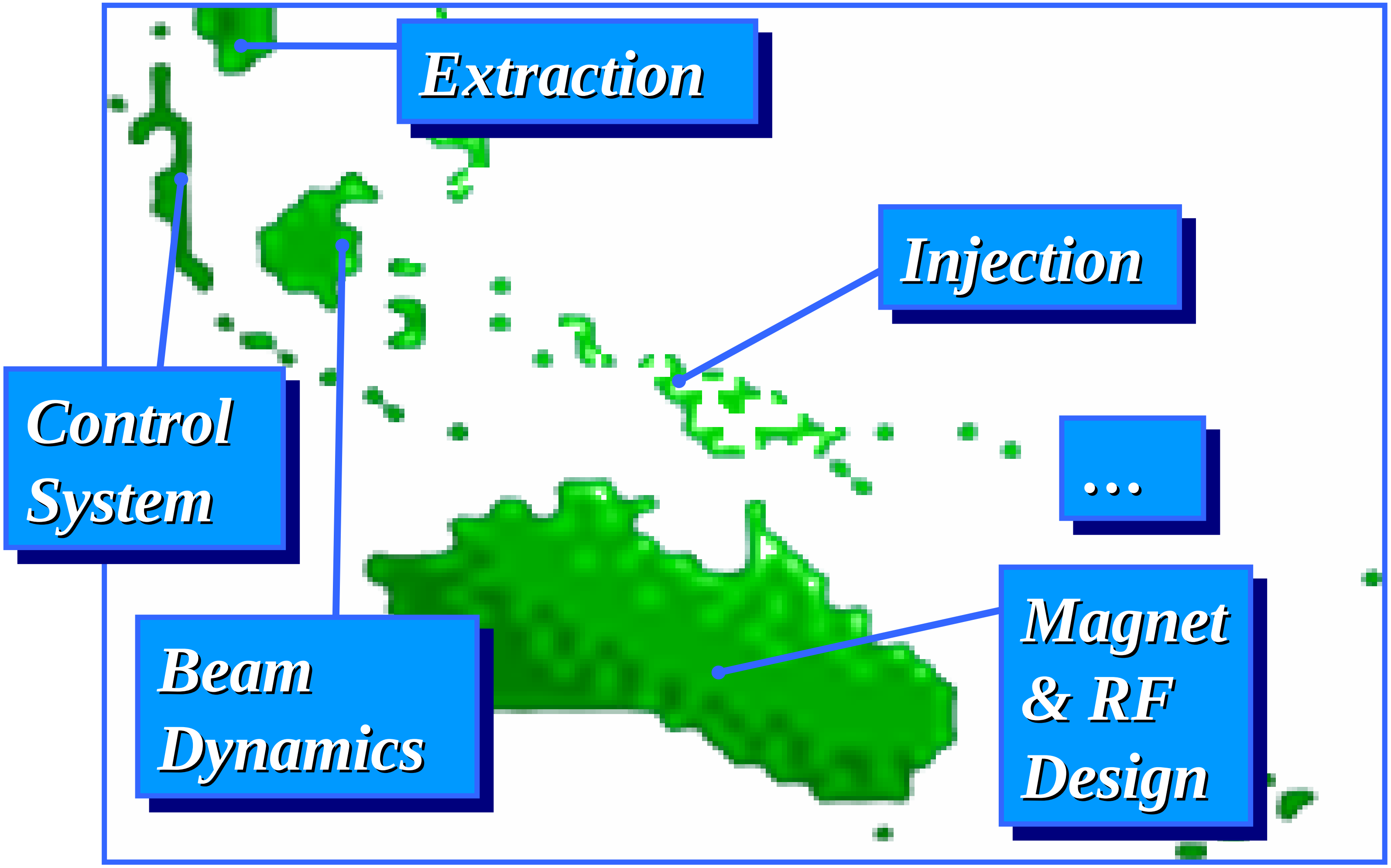
- Decrease the use of physical prototypes
- Reduce time, cost and risk during R&D of cyclotrons
- Promote innovative design



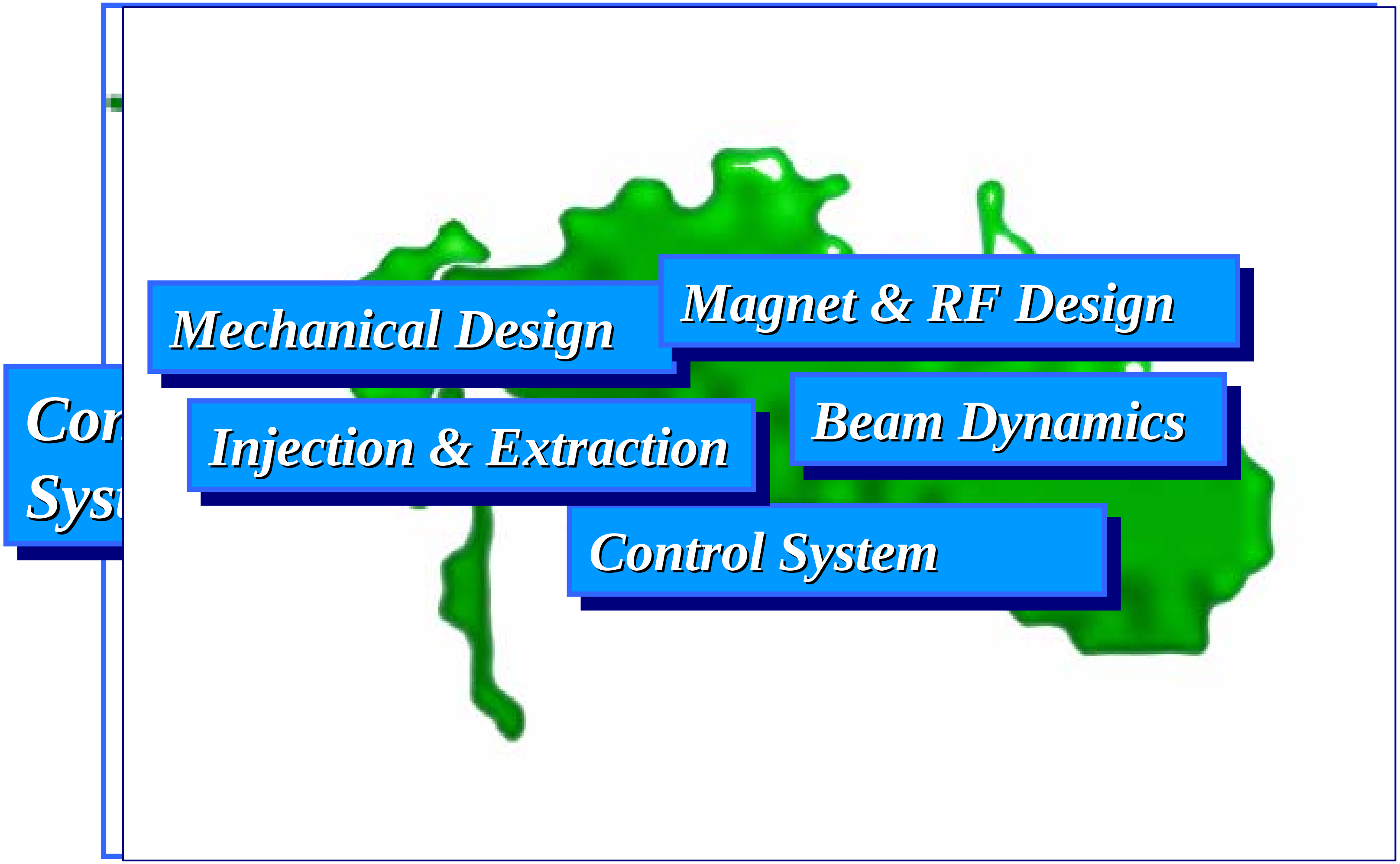
Enables…

- Fit & Assembly
- Finite element analysis (electro-magnetic field, stress, thermal etc.)
- Beam dynamics analysis
- Style & form
- Manufacturability
- Optimization

Collaborative Design in VP

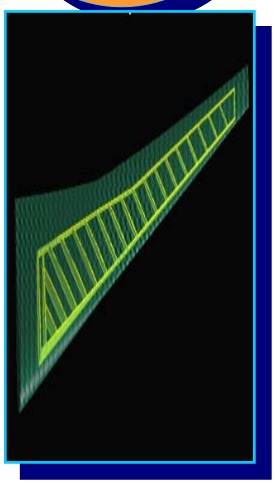


Collaborative Design in VP

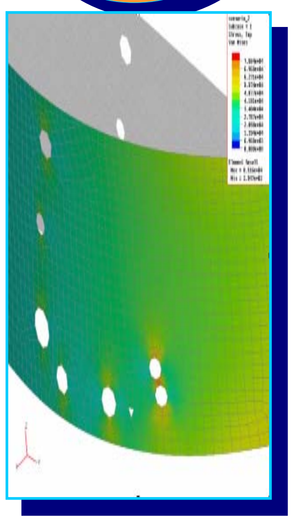


Continuous Development During Product Lift Cycle in VP

Concept Development



Product Development

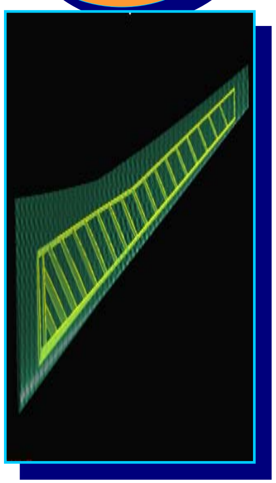


Manufacturing Planning

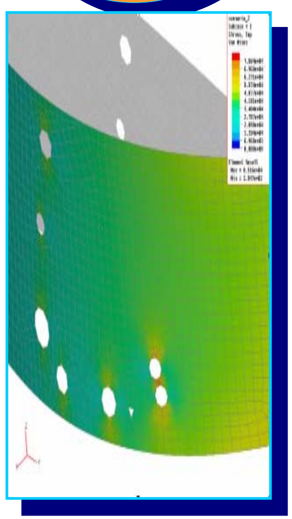
Maintenance & Service

Continuous Development During Product Lift Cycle in VP

Concept Development



Product Development

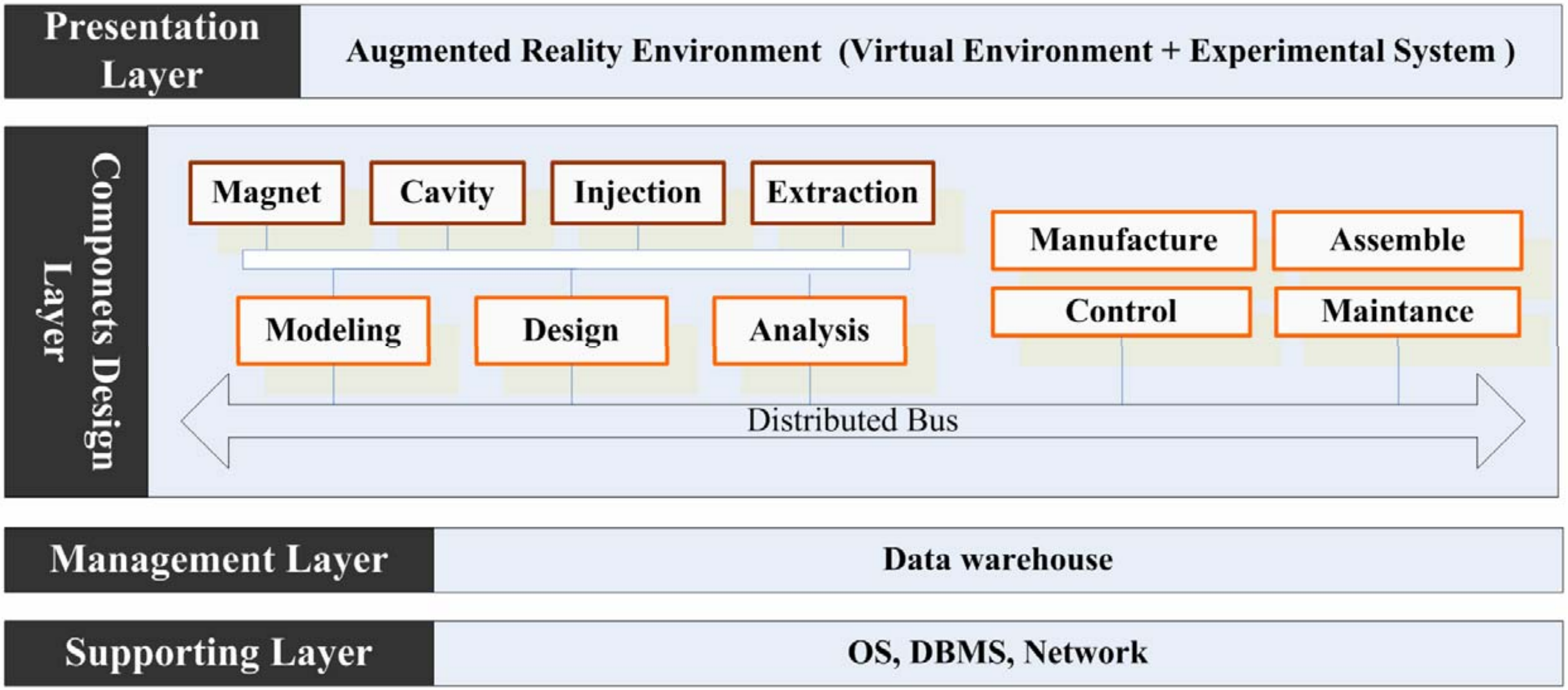


Manufacturing Planning

Maintenance & Service

Cyclotron VP Platform (CVPP)

System Architecture

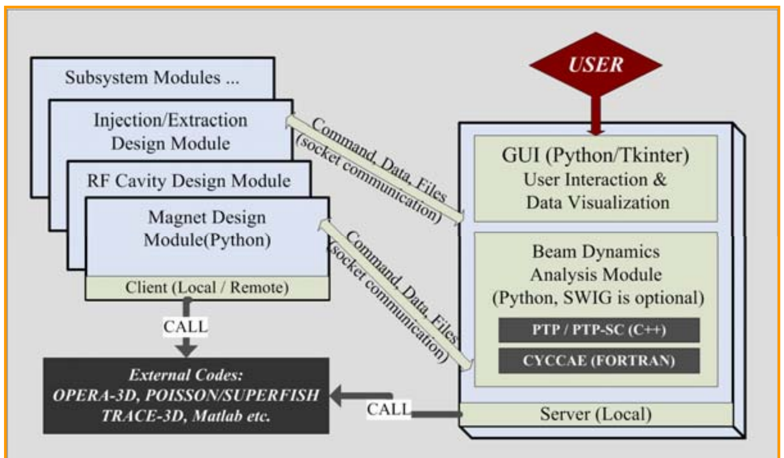


Supporting & Management Layer: Share models & database
Component Design Layer: Collaborative design with distributed computing
Presentation: Augmented reality

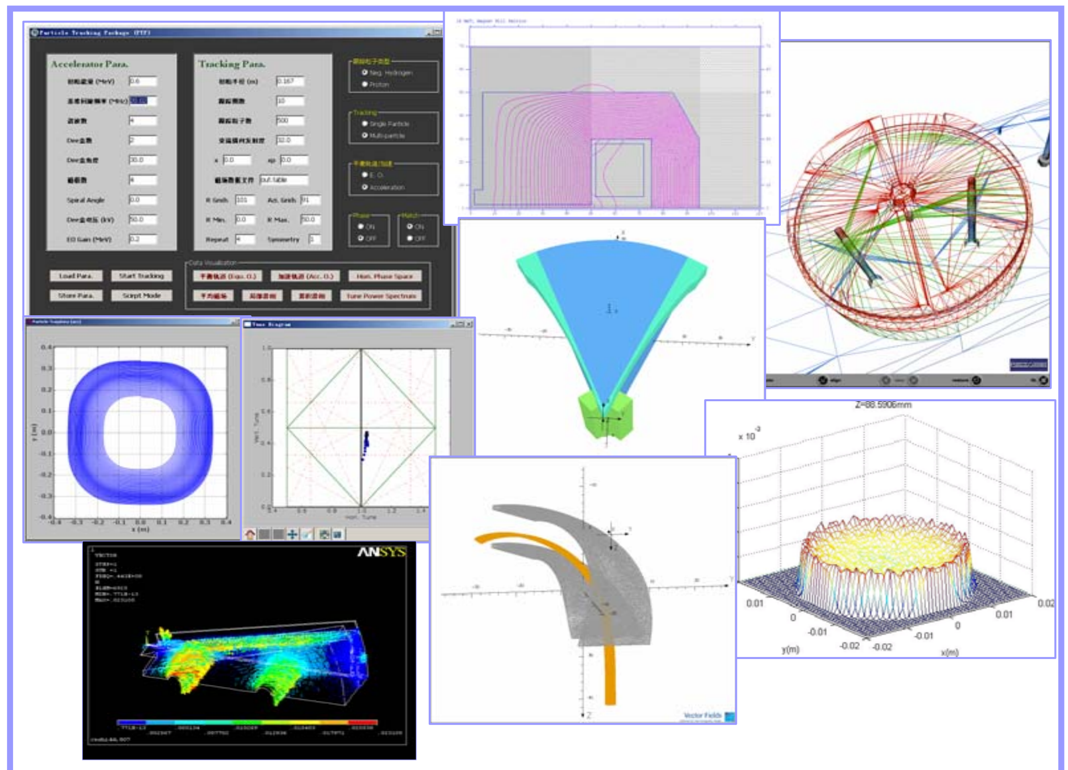
Pythonic Implementation of CVPP

Python: a powerful high-level scripting language; very popular in scientific computing

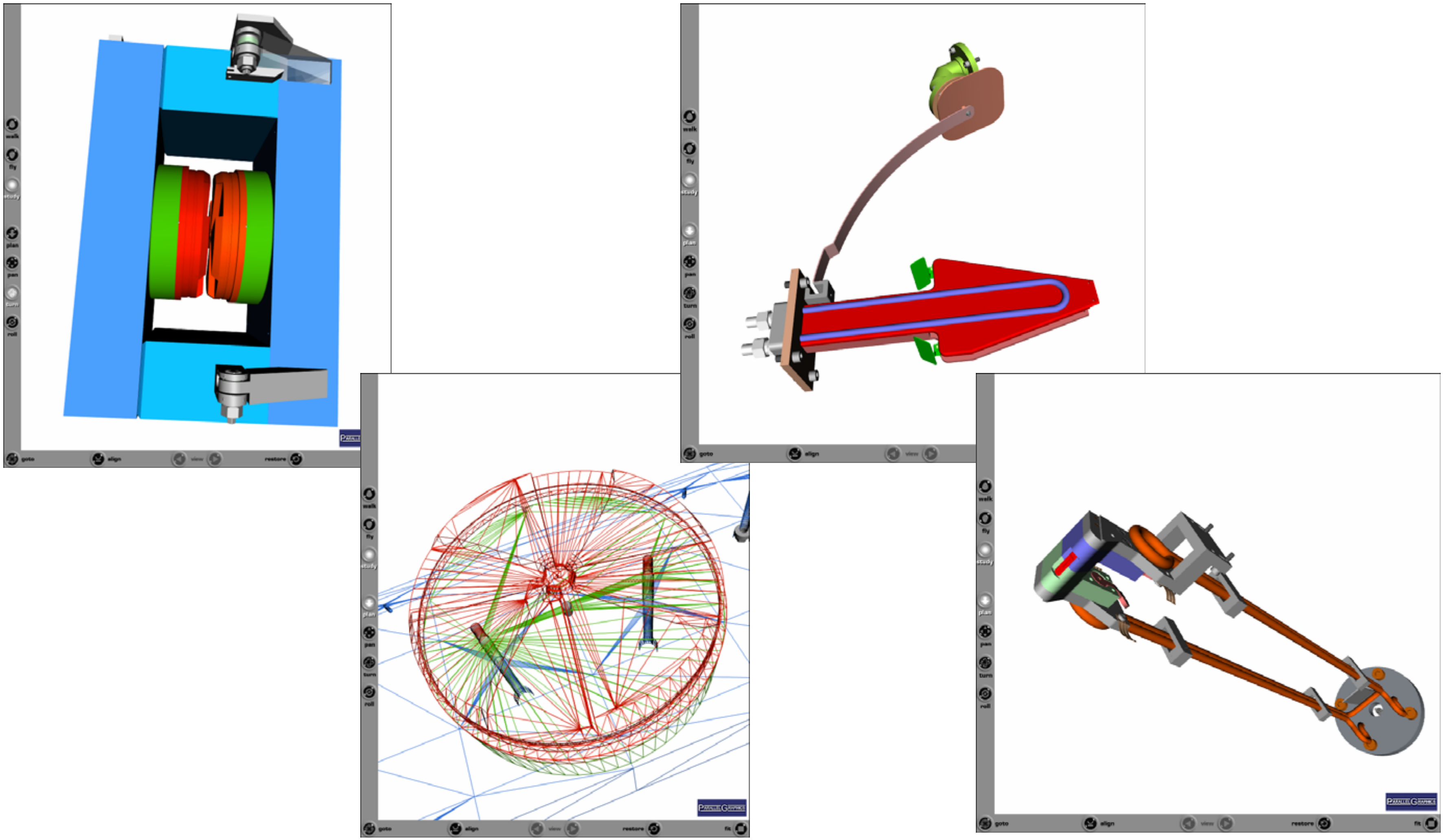
Mixed-programming: integrates heterogeneous design codes written with Fortran/C/C++



Pythonic Framework

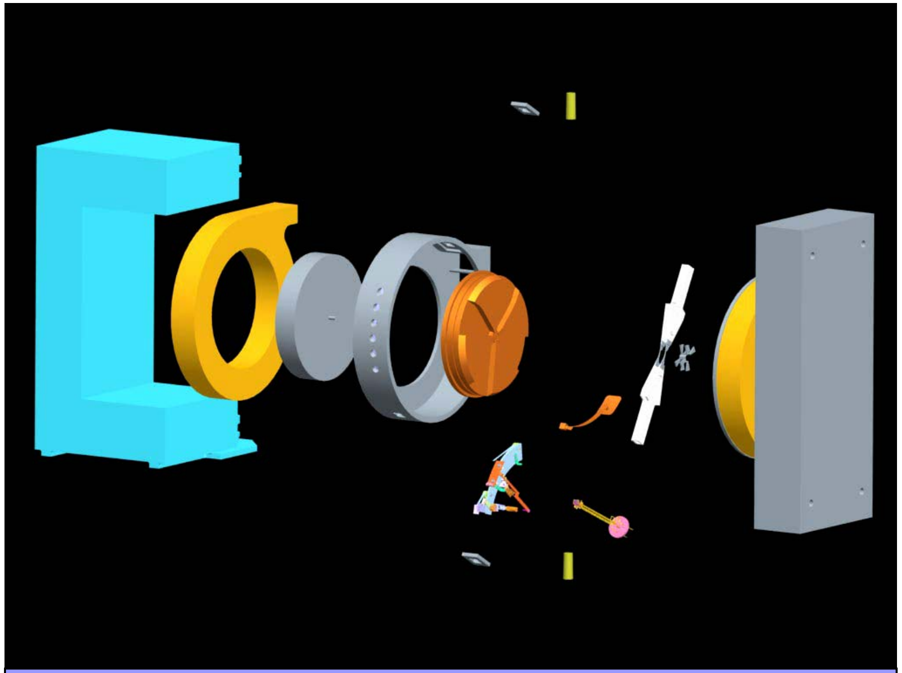


VRML Environment for Model Observation



Virtual Assembling

- ***Digital map for real assemble/disassemble process***
- ***Optimize assemble/disassemble path by collision detection***
- ***Training propose***



Dynamic Assembling Process

Magnet Design

Considerations during magnet design:

Field isochronisms condition during particle acceleration;

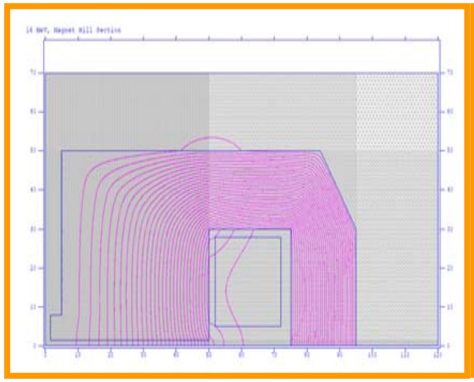
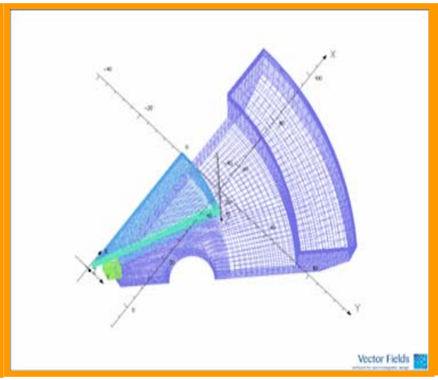
$$B_{iso}(r) = \gamma(r) \cdot B_c = (1 + T / E_0) \cdot B_c$$

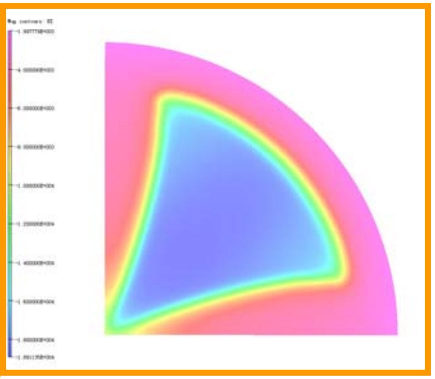
Enough radial and axial focusing of the beam;

Avoid dangerous resonance crossing.

Magnetic field calculation

2D: Poisson/Superfish, OPERA2D   3D: OPERA3D/TOSCA, ANSYS

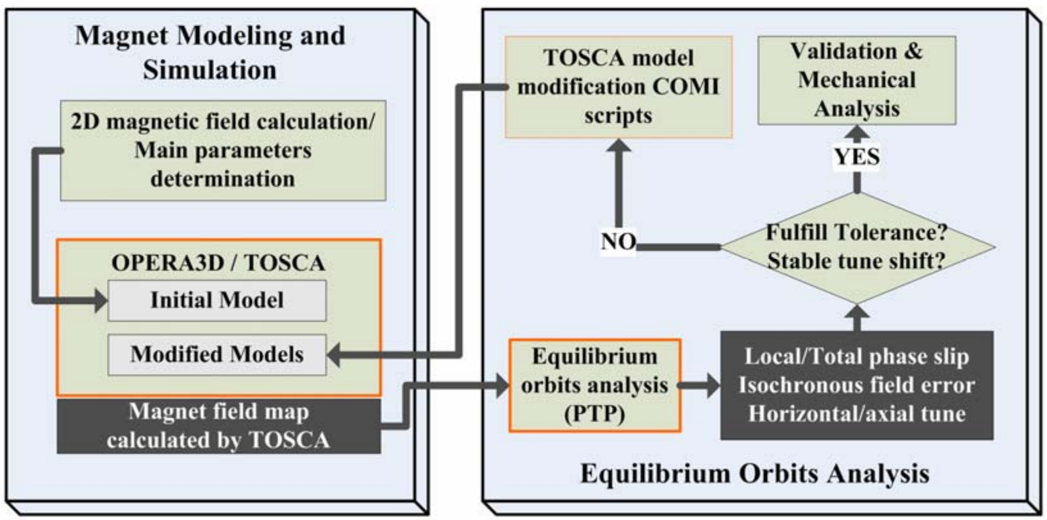


Iterative Magnet Optimization

3D magnet field calculation is close to the reality with the field error less than 2%.

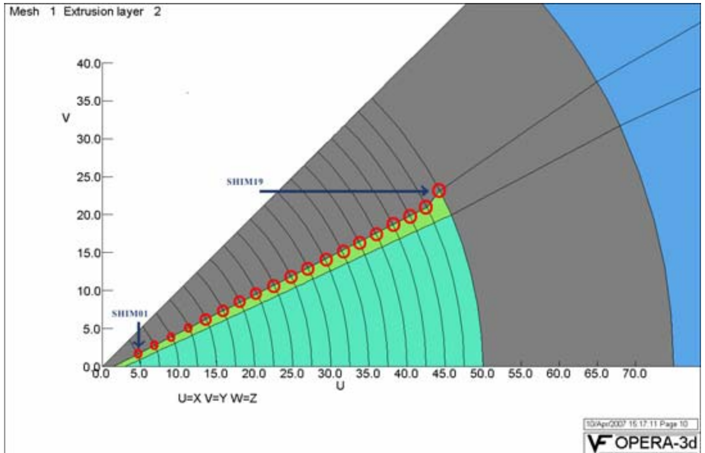
The isochronous field error can be estimated by equilibrium orbit analysis. And the required geometry change of the magnet model is calculated by linear hard edge model.

We developed an automated tool to implement this iterative optimization process of the magnet, with the aid of OPERA-3D and PTP

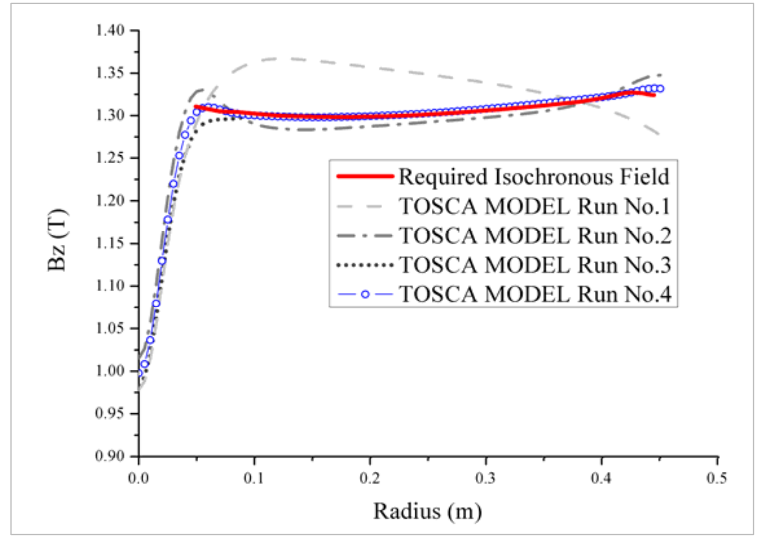


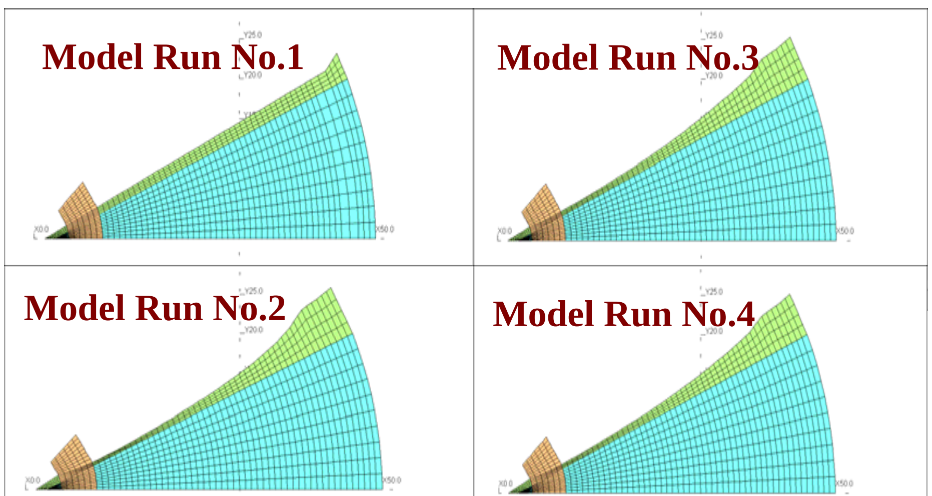
Magnet design and optimization process

Isochronous Field Optimization

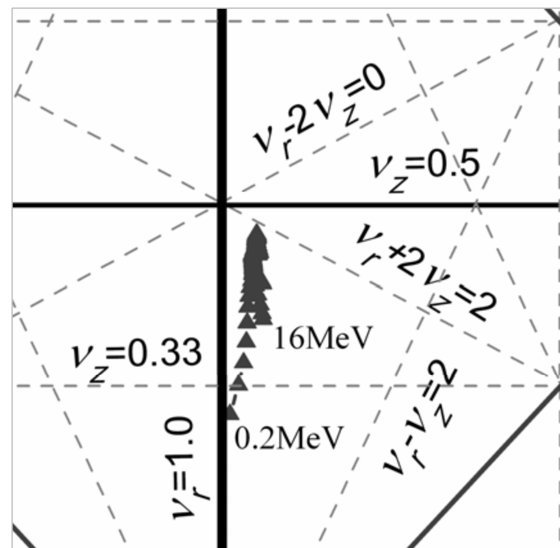


Parametric TOSCA Model



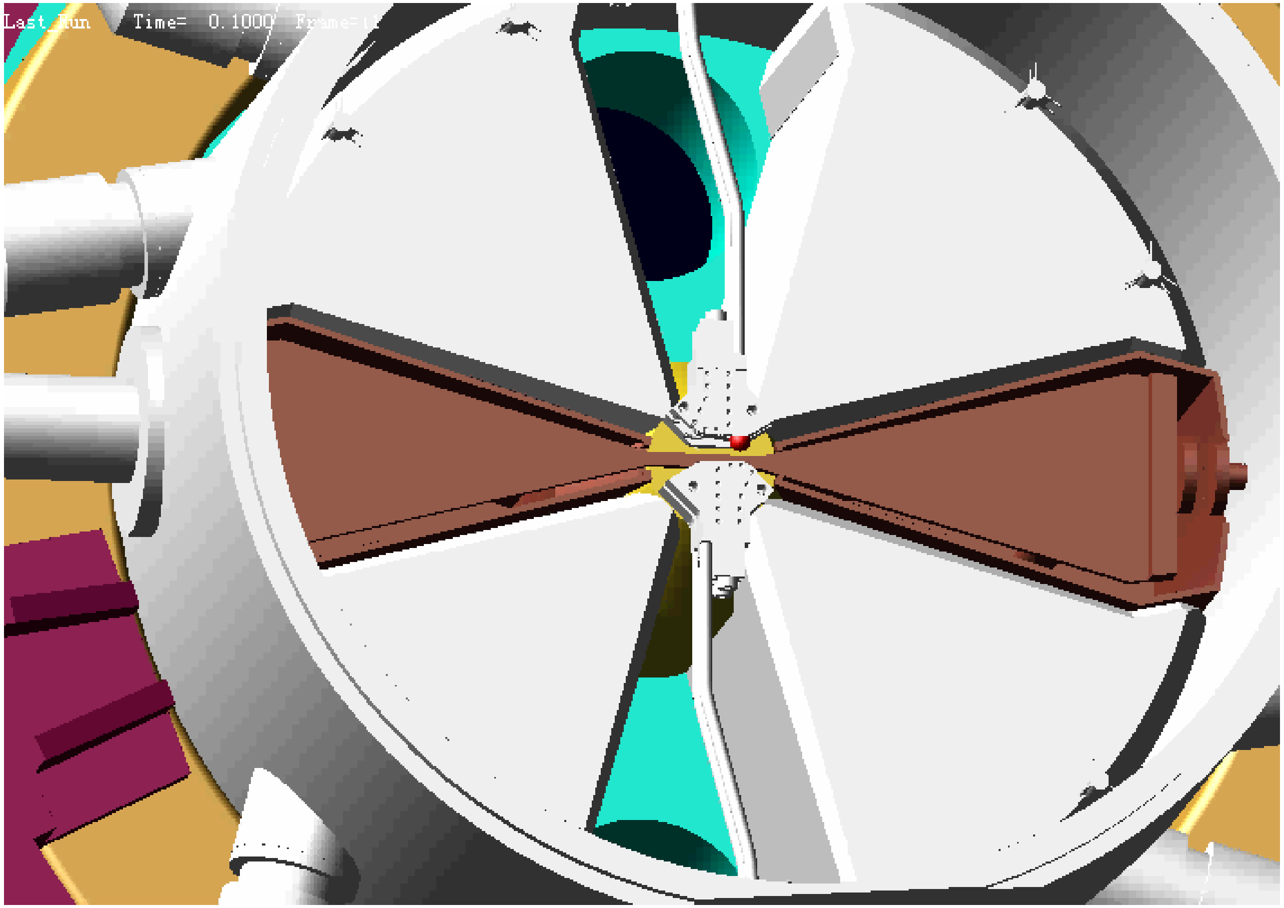


Iterative optimization of pole shape



Tune diagram

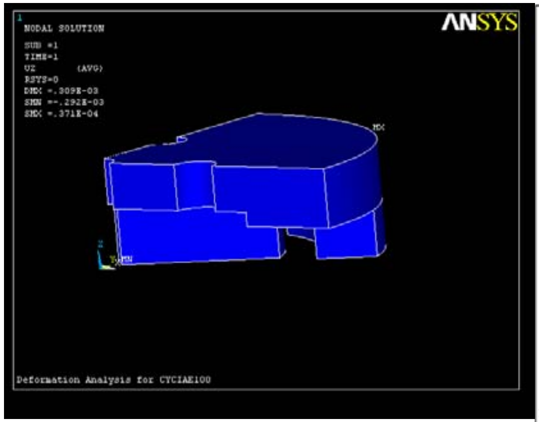
Isochronous Field Optimization

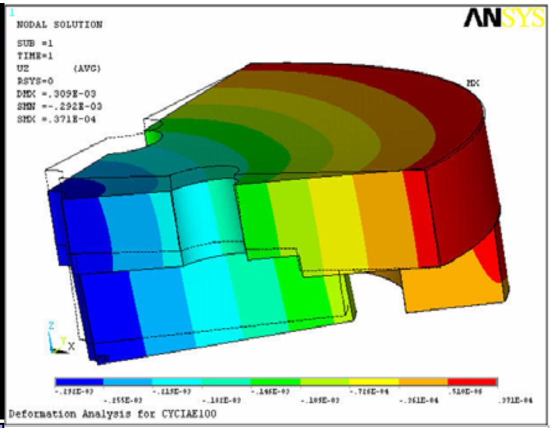


Magnet Structure Analysis

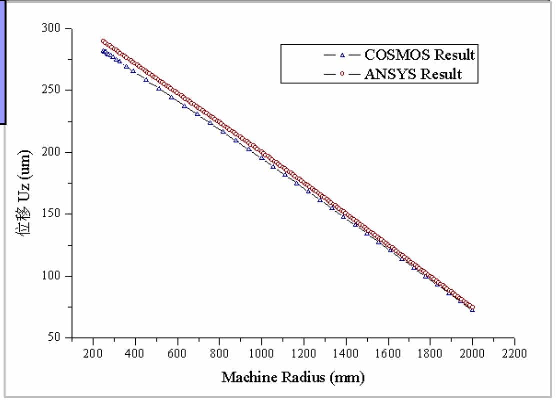
Magnet deformation due to atmosphere pressure, gravity and magnetic force;

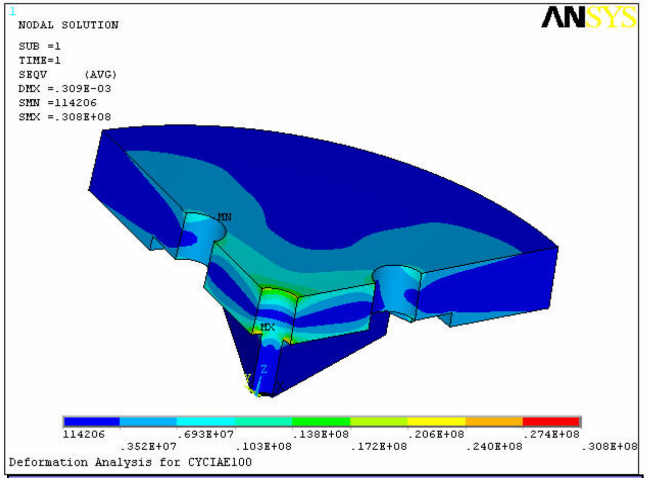
Von Mises stress analysis





Deformation of the magnet pole



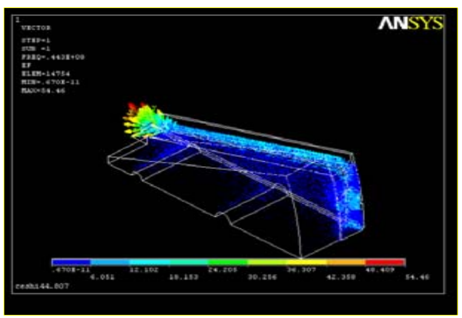


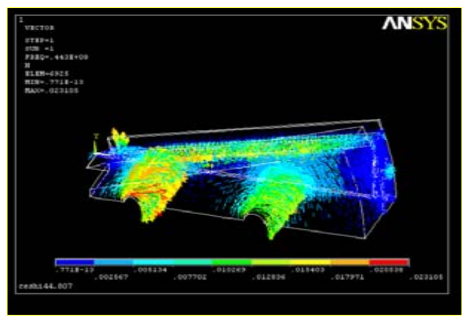
Von Mises stress distribution

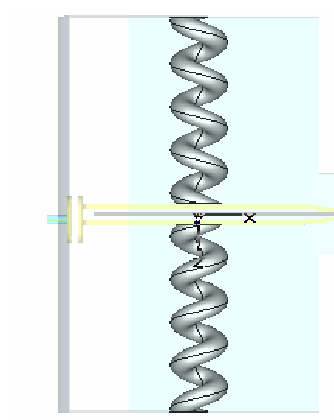
RF Cavity Modeling & Calculation

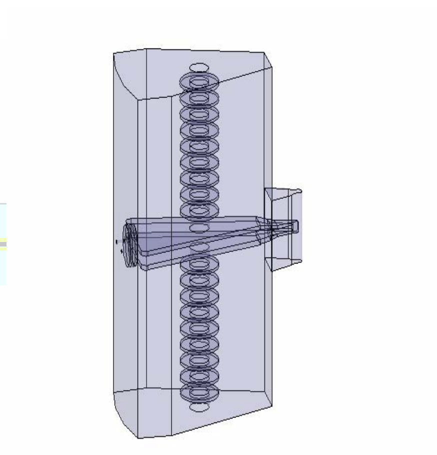
Stable resonance frequency determined by isochronous magnetic field
Relative high quality factor (Q value)
Reasonable distribution of Dee voltage

Other problems to be considered:
Frequency compensation
Effective coupling









- Calculation of resonance frequency, Q-value, electric field distribution with FEM code ANSYS & FIT code CST Microwave Studio

Spiral Inflector Design

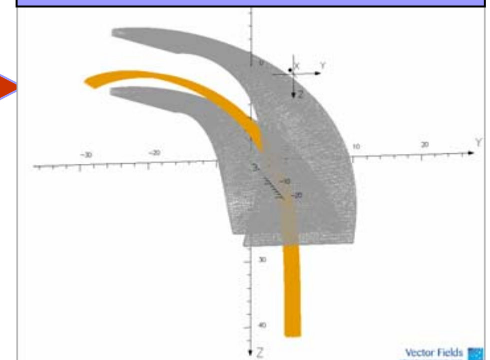
$$x(b) = \frac{A}{2}\left[\frac{2}{1-4K^2} + \frac{\cos[(2K-1)b]}{2K-1} - \frac{\cos(2K+1)b}{2K+1}\right]$$

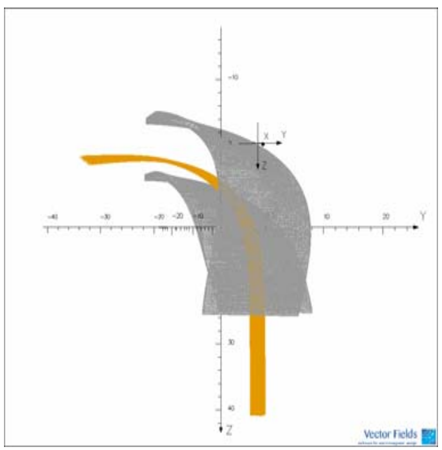
$$y(b) = \frac{A}{2}\left[\frac{\sin[(2K+1)b]}{2K+1} - \frac{\sin[(2K-1)b]}{2K-1}\right]$$

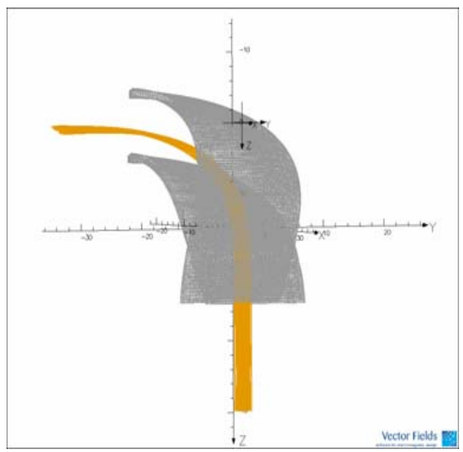
$$z(b) = A[1-\sin(b)], \qquad 0 \le b \le \pi/2$$

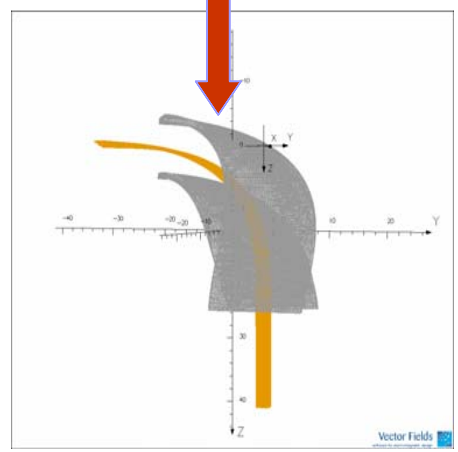
Auto-generated VRML model

Import into OPERA3D & Simulation





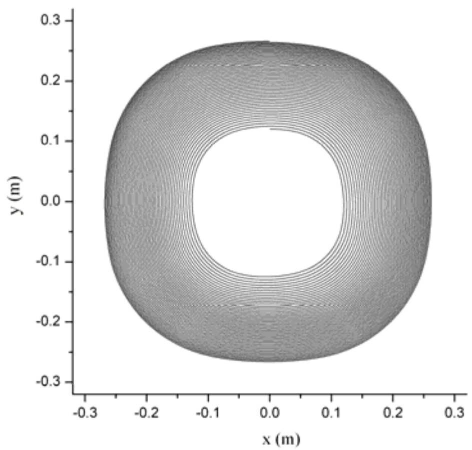


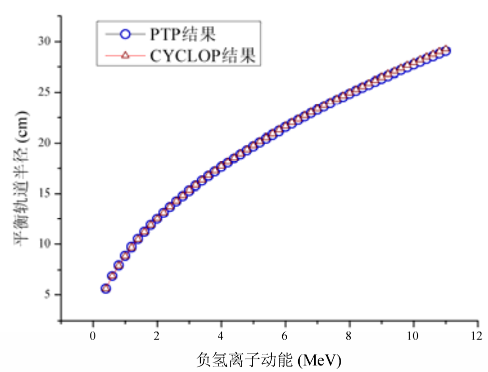


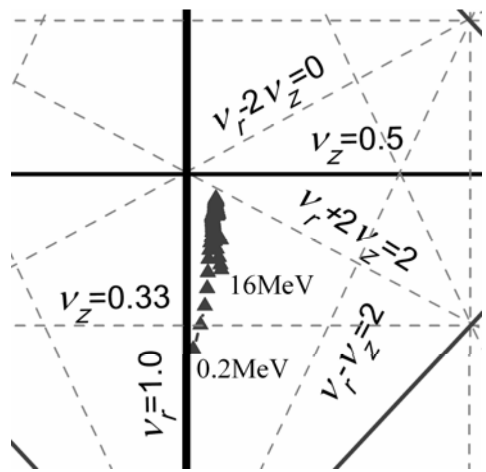
Fringe electric field compensation, $\chi = 0\%$, $\chi = 5\%$, $\chi = 8\%$

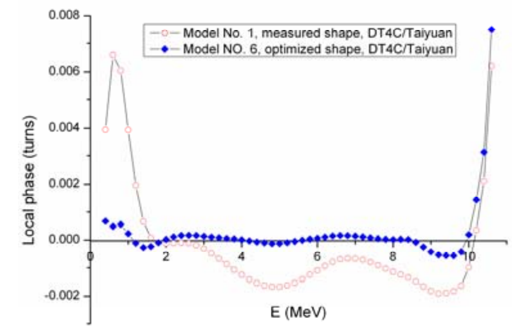
Beam Dynamics – Single Particle

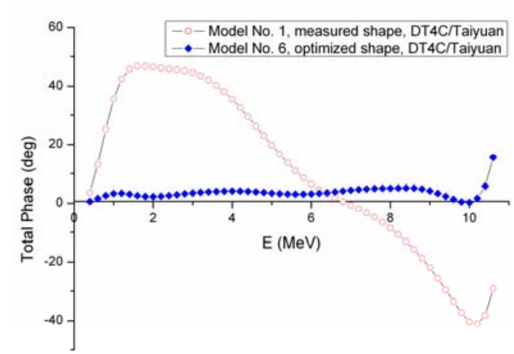
- Equilibrium orbit analysis: field error, transversal betatron frequency, local/total phase slip, etc.
- Particle tracing for injection/extraction/acceleration
- PTP, CYCCAE, CYCLOP, CYCLONE codes











Space Charge Effect Simulation based on PIC Numerical Method

Using BEM as Poisson solver

Object oriented C++ code : PTP-SC

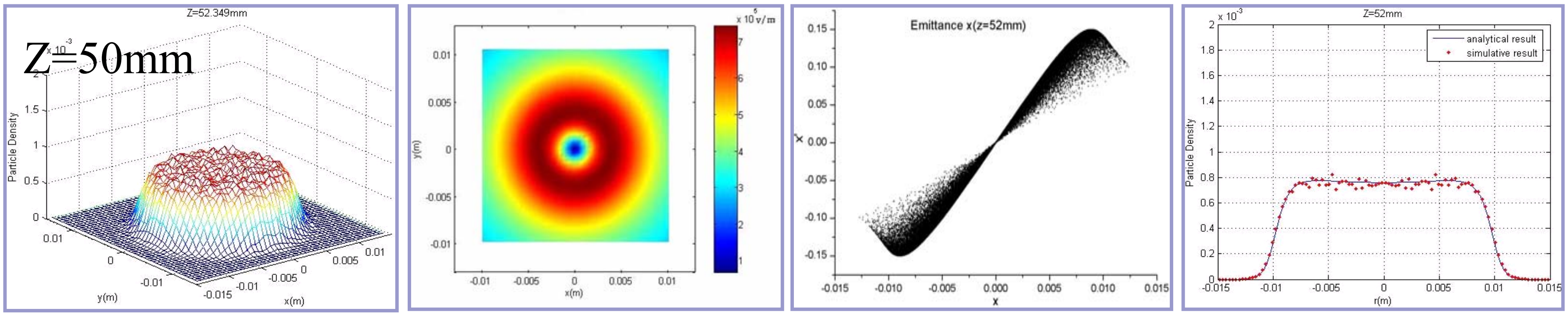
$$\begin{cases} \nabla^2 u + p = 0 & (in\ \Omega) \\ u = \bar{u} & (on\ S_1) \\ \dfrac{\partial u}{\partial n} = q & (on\ S_2) \end{cases}$$

$$E_x(x,y) = \frac{1}{2\pi\varepsilon} \iint_s \frac{(x_i - x)\rho(x_i, y_i)}{(x-x_i)^2 + (y-y_i)^2} dS(x,y)$$

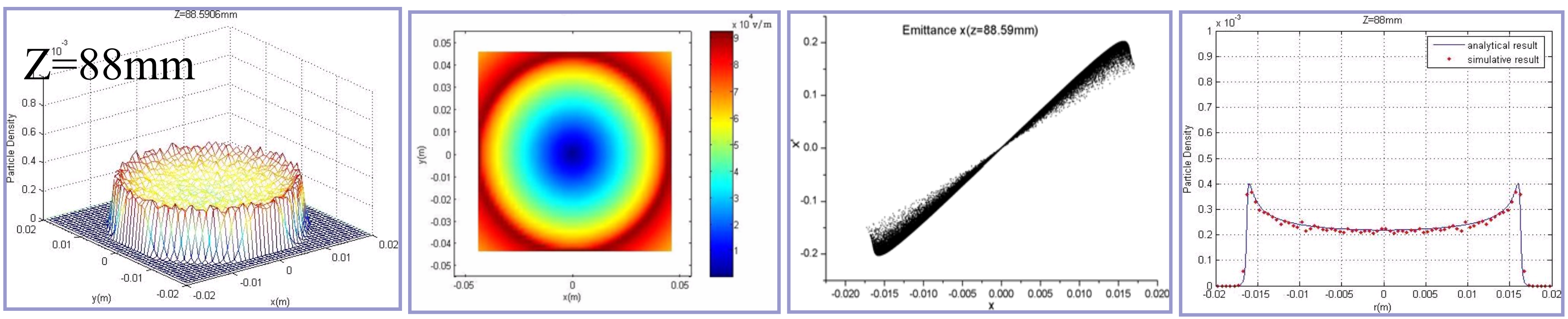
$$E_x(x,y,z) = \frac{1}{4\pi\varepsilon} \iiint_v \frac{(x_i - x)\rho(x_i, y_i, z_i)}{\left[(x-x_i)^2 + (y-y_i)^2 + (z-z_i)^2\right]^{\frac{3}{2}}} dv(x,y,z)$$

Simulation in Drift Space due to Nonlinear Space Charge Effect

Extreme case for comparison with theoretical result:
parallel proton beam with 1A, 100keV, *Rrms*=5mm, in 200mm drift space.



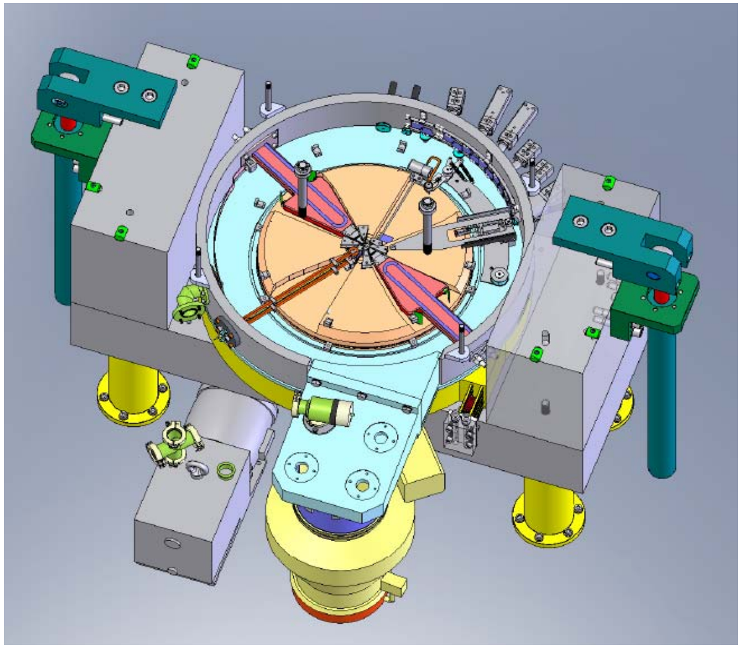
Beam density **Space charge** **Emmitance** **Beam profile**



Specifications of CYCHU-10

Adopt internal PIG ion source for compactness and reducing cost
Small Valley Gap (SVG) magnet

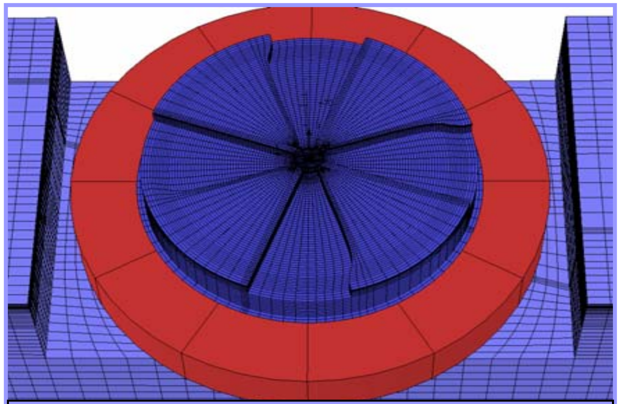
Magnet		**Ion source**	
Sector numbers	4	**Type**	H^- internal PIG
Hill angle	32~54 degree	**Arc voltage**	2~3kV
Hill/valley gap	2.5 / 10.0 cm	**RF**	
Pole radius	33 cm	**Frequency**	101 MHz
Average field	1.65 T	**Dee Number**	2
Maximum energy	10 MeV	**Dee Angle**	31 degree
Extraction radius	27.2 cm	**Dee Voltage**	35 kV
Acceleration turns	83 turns	**Magnet coils**	
Weight	11 ton	**Ampere-turns**	38000 AT
Power supply	14 kW	**Current density**	2.2 A/mm^2



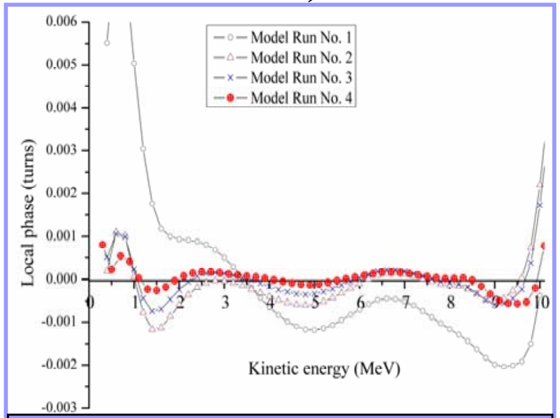
Magnet

High average magnetic field (>1.6T) due to SVG

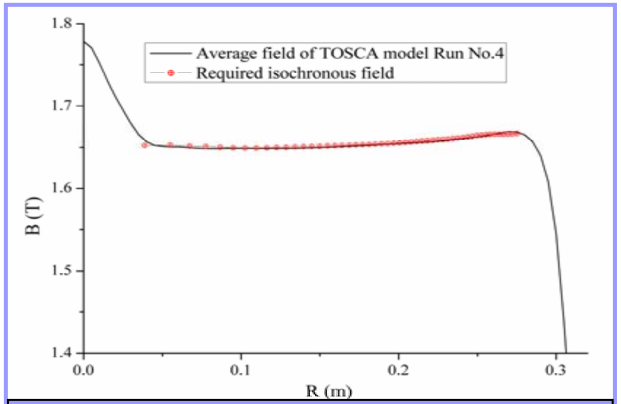
Compactness (about 11tons including yoke & coils)



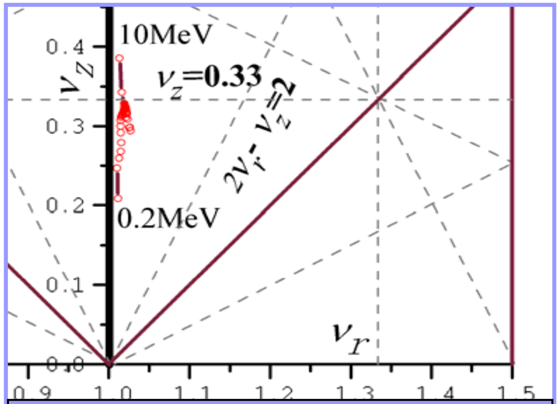
Magnet model in OPERA3D



Local phase



Average magnetic field

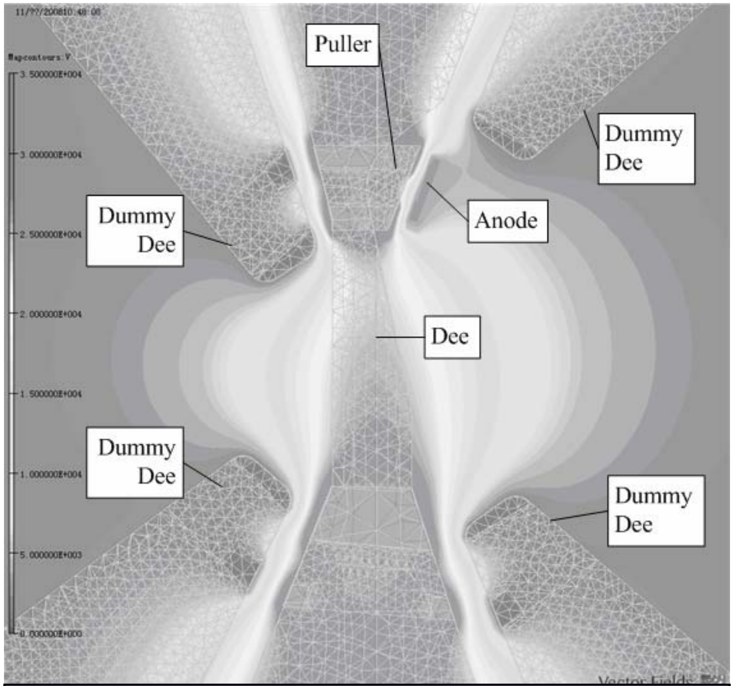


Tune shift

Central Region Considerations

Relative low beam intensity (about 60uA) suitable for short-lived isotopes production such as ^{18}F, ^{15}O

Internal PIG ion source: without beam manipulation by external injection line, the CR should be carefully designed.

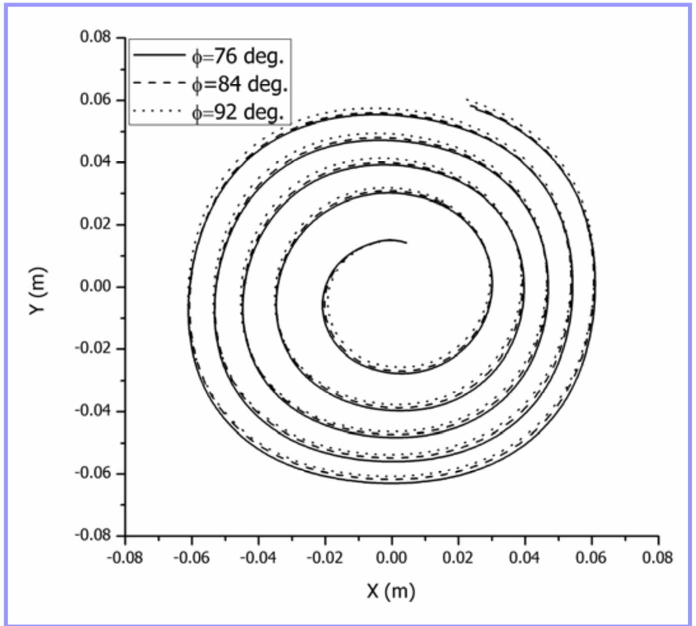


CR Structure

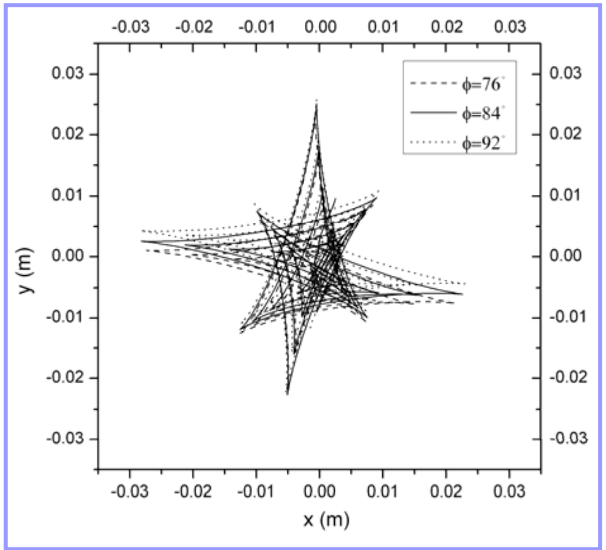
Basic parameters

Parameters	Value
Dee width	31deg.
Dee voltage	35 kV
Harmonic mode	4
RF frequency	101MHz
Injection radius	1.6 cm
Central magnetic field	1.68T

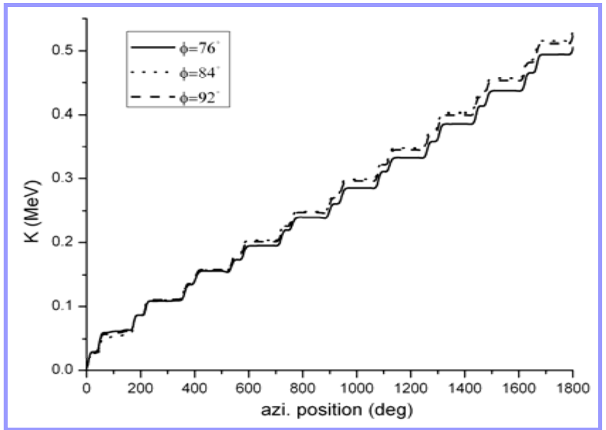
CR – Horizontal Motion



Particle trajectories for the first 5 turns, start RF phase 76° ~ 92°



The motion of orbit centers



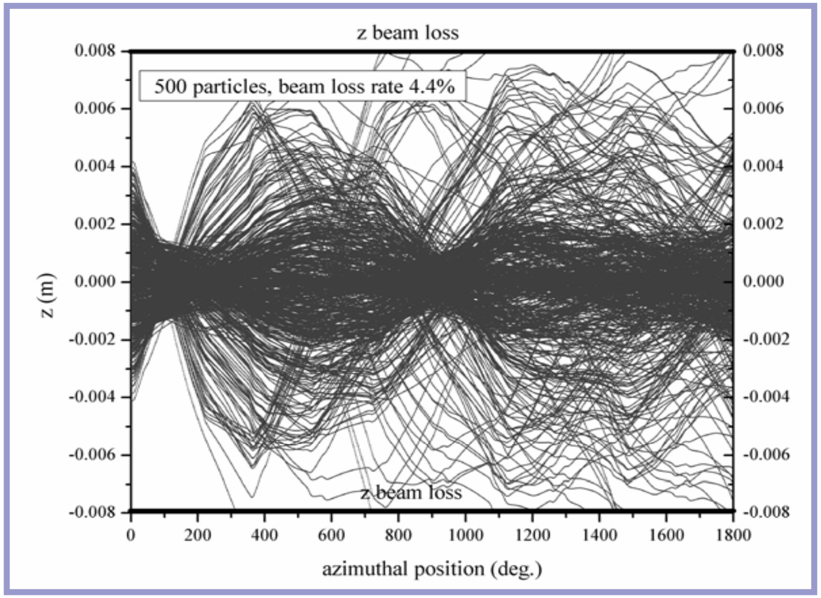
The energy gain of the first 5 turns

The horizontal RF phase acceptance is about 25 deg., and should be optimized larger than 30 deg.

CR - Vertical Beam Loss

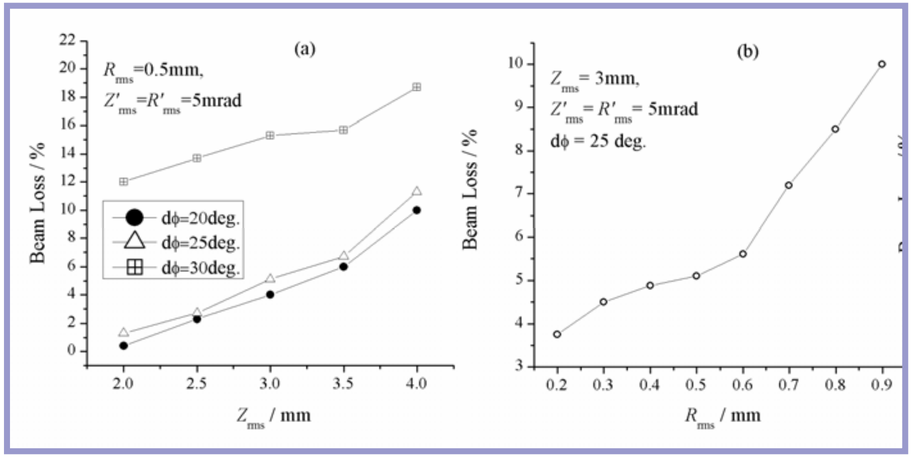
Multi-particle tracing with 4D Gaussian phase space distribution and a KV start RF phase distribution

5% beam loss with the condition: slit size dR=0.8mm, dZ=6mm, $R'_{rms}, Z'_{rms} \le 10\text{mrad}$, RF phase width 25 deg.



Vertical beam motion in the first 5 turns with

$R_{rms} = 0.4\text{mm}, Z_{rms} = 3\text{mm}, R'_{rms} = Z'_{rms} = 5\text{mrad}, \Delta\phi = 20^{\circ}$

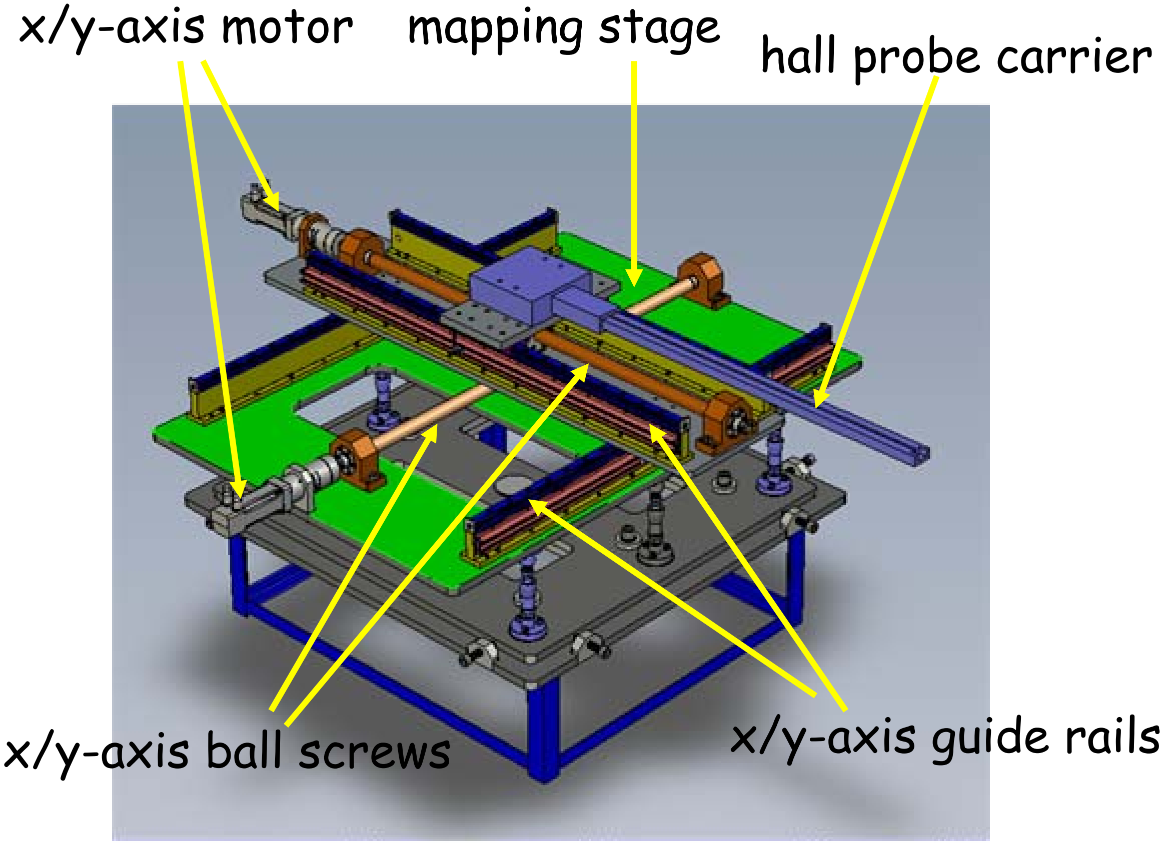


Beam loss rate with different slip aperture size

Magnet Mapping System

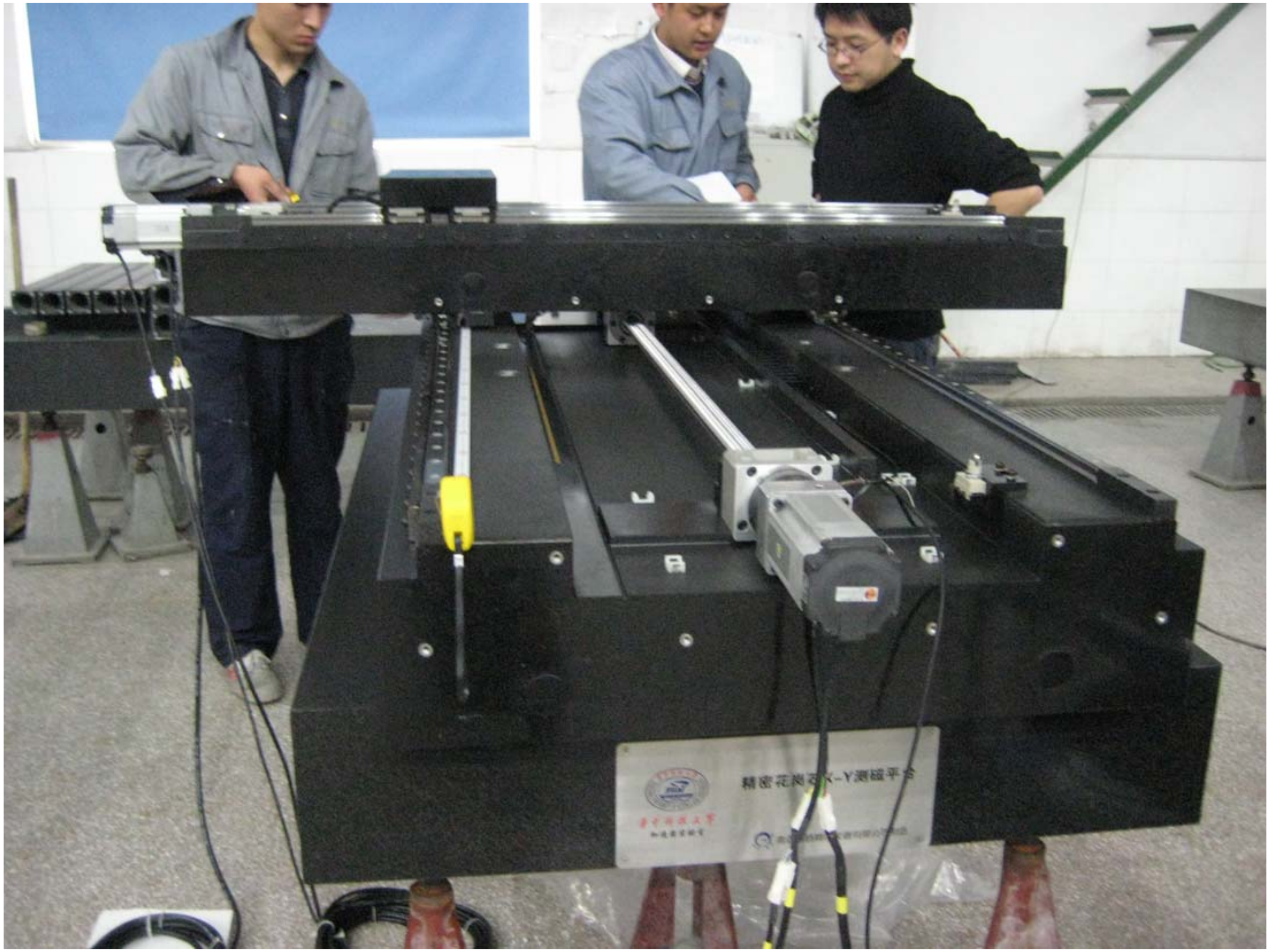
Specifications

System specification	*Value*
X scan capability	1100mm
Y scan capability	1100mm
Mechanical resolution	5 μm
Range of magnetic field	2.5T
Relative random fluctuation error	0.01%



Hall Probe Mapping System

- Cartesian mapping system
- Automatic measurement with fly mode



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Conclusion

- Medical cyclotron has developed in China for 15 years
- Several cyclotrons are used in medical research and technology
- Many peoples are involved in medical cyclotron accelerator physics and technology
- Medical cyclotron may be developed faster in China in the coming future


Thanks for attention!