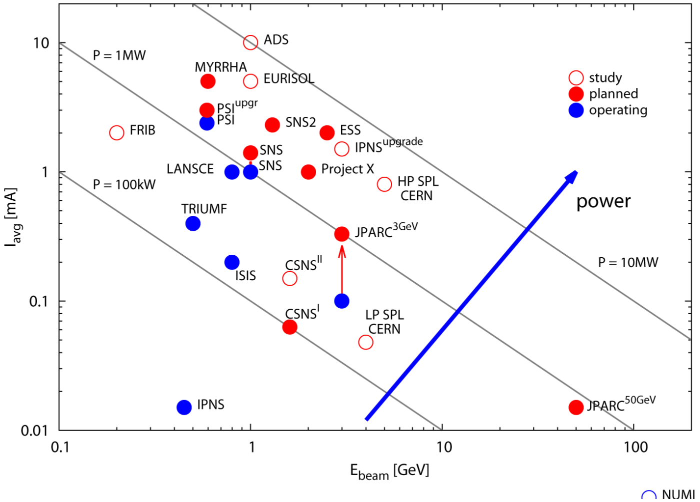
OPAL & FFAGs

A. Adelmann (PSI-AMAS), S. Sheehy & C. Rogers (STFC)

FFAG workshop September 2013

Outline

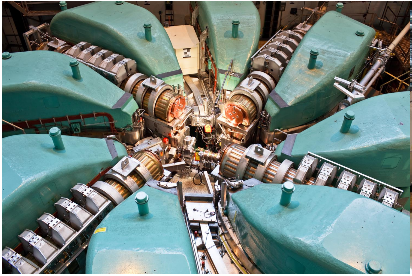
High Power is needed

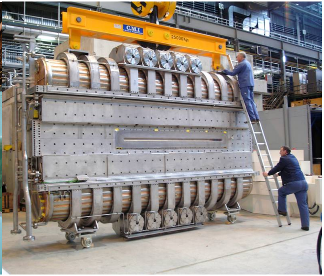


Modeling Challenges

Consider a 0.59 GeV, 2.3 mA (CW) Proton Cyclotron facility

- uncontrolled & controlled beam loss $\mathcal{O}(2\mu A = const)$ in large and complex structures
- PSI Ring: 99.98% transmission $\rightarrow \mathcal{O}(10^{-4}) \rightarrow 4\sigma$
- small changes at injection affects extraction





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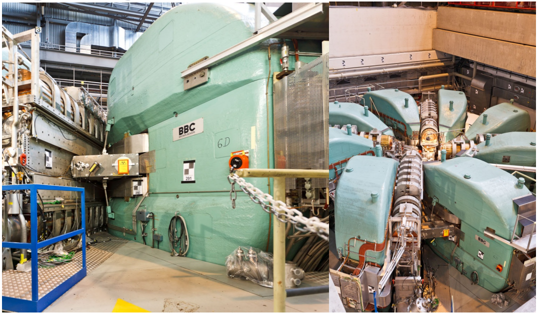

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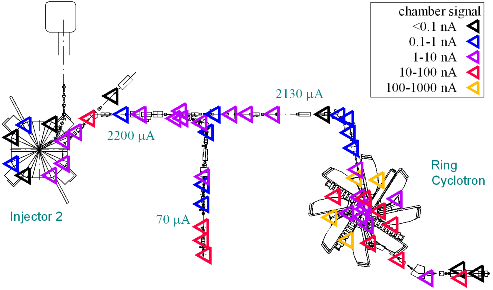

Modeling Challenges

- Multiscale / Multiresolution
  - Maxwell's equations or reduced set combined with particles
  - N-body problem $n \sim 10^9$ per bunch in case of PSI
  - Spatial scales: $10^{-4} \ldots 10^4$ (m) $\rightarrow \mathcal{O}(1e5)$ integration steps
  - $v \ll c \ldots v \sim c$
  - Large (complicated structures)
  - Neighboring bunches
- Multiphysics
  - Particle mater interaction: monte carlo
  - Secondary particles i.e. multi specis
- Large Parameter Space to Optimize
  - Multi Objective Optimization in a Pareto optimale sense

Q: How do we obtain a precise beam dynamics simulation model:

- for large structures
- to enable S2E simulations

Modeling Challenges

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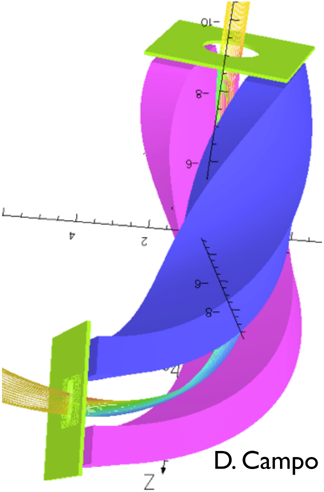
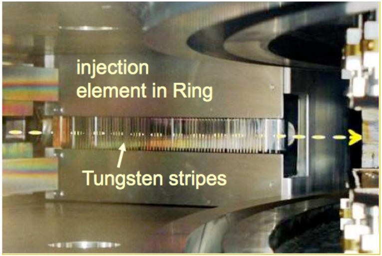
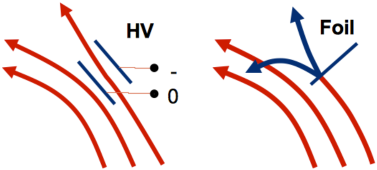
Injection & Extraction

Challenge







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Outline

OPAL in a Nutshell

OPAL is an open-source tool for charged-particle optics in large accelerator structures and beam lines including 3D space charge, particle matter interaction and multi-objective optimisation.

- OPAL is built from the ground up as a parallel application exemplifying the fact that HPC (High Performance Computing) is the third leg of science, complementing theory and the experiment
- OPAL runs on your laptop as well as on the largest HPC clusters
- OPAL uses the MAD language with extensions
- OPAL (and all other used frameworks) are written in C++ using OO-techniques, hence OPAL is easy to extend.
- Documentation is taken very seriously at both levels: source code and user manual (`http://amas.web.psi.ch`)
- International team of (10) developers from US, UK, China, Germany & Switzerland

OPAL and its Flavours

4 OPAL flavours exist:

- OPAL-T
  - OPAL-T tracks particles which 3D space charge uses time as the independent variable, and can be used to model beamlines, guns, injectors and complete FEL's but without the undulator.
  - Field emission (dark current studies)
  - many more linac features ...
- OPAL-ENVELOPE
  - OPAL-ENVELOPE is based on the 3D-envelope equation (à la HOMDYN) and can be used to design FEL's.
  - OPAL-ENVELOPE could also be used for an on-line model (incl. space charge)
  - same lattice than OPAL-T
- OPAL-MAP (not yet released)
  - OPAL-MAP tracks particles with 3D space charge using split operator techniques.
  - $\mathcal{M}(s) = \mathcal{M}_{\text{ext}}(s/2) \otimes \mathcal{M}_{\text{sc}}(s) \otimes \mathcal{M}_{\text{ext}}(s/2) + \mathcal{O}(s^3)$

OPAL and its Flavours cont.

- OPAL-CYCL
  - 3D space charge
  - neighboring turns
  - time is the independent variable.
  - from p to Uranium (q/m is a parameter)
  - Solve Poisson equation with spectral methods
  - Use 4th-order RK, Leap Frog or adaptive schemes [?]
  - Single particle tracking mode & tune calculation
  - Particle Matter Interaction
  - Multipacting capabilities

OPAL Object Oriented Parallel Accelerator Library

Field Maps & Analytic Models

$$\nabla \cdot \boldsymbol{E}_{sc} = -\rho/\varepsilon_0 = \nabla \cdot \nabla \phi_{sc}$$

$$\Delta \phi_{sc} = -\frac{\rho}{\varepsilon_0}$$

& BC's

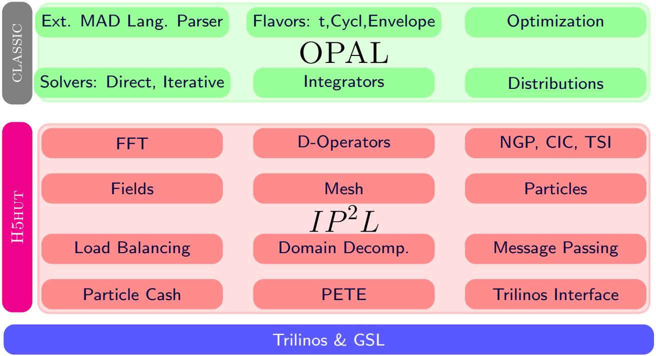
Electro Magneto Optics

$$\boldsymbol{H} = \boldsymbol{H}_{\text{ext}} + \boldsymbol{H}_{\text{sc}}$$

N-Body Dynamics

- Energy loss $-dE/dx$ (Bethe-Bloch)
- Coulomb scattering is treated as two independent events:
  - multiple Coulomb scattering
  - large angle Rutherford scattering
- Field Emission Model (Fowler-Nordheim)
- Secondary Emission Model ([Furman & Pivi] & [Vaughan])

OPAL Architecture



- **OPAL Object Oriented Parallel Accelerator Library**
- IP^2L **Independent Parallel Particle Layer**
- **Class Library for Accelerator Simulation System and Control**
- **H5hut for parallel particle and field I/O (HDF5)**
- **Trilinos http://trilinos.sandia.gov/**

Iterative Poisson Solver SAAMG-PCG

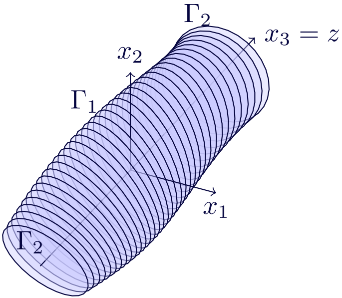
Boundary Problem

$$\Delta\phi = -\frac{\rho}{\varepsilon_0}, \text{ in } \Omega \subset \mathbb{R}^3,$$

$$\phi = 0, \text{ on } \Gamma_1$$

$$\frac{\partial\phi}{\partial\mathbf{n}} + \frac{1}{d}\phi = 0, \text{ on } \Gamma_2$$

- $\Omega \subset \mathbb{R}^3$: simply connected computational domain
- ε_0: the dielectric constant
- $\Gamma = \Gamma_1 \cup \Gamma_2$: boundary of Ω
- d: distance of bunch centroid to the boundary



Γ_1 is the surface of an

1. elliptic beam-pipe
2. arbitrary beam-pipe element

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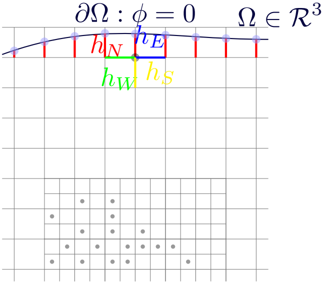
Iterative Poisson Solver SAAMG-PCG cont.

We apply a second order finite difference scheme which leads to a set of linear equations

$$\mathbf{A}\mathbf{x} = \mathbf{b},$$

where **b** denotes the charge densities on the mesh.



- solve anisotropic electrostatic Poisson PDE with an iterative solver
- reuse information available from previous time steps
- achieving good parallel efficiency
- irregular domain with "exact" boundary conditions
- easy to specify boundary surface

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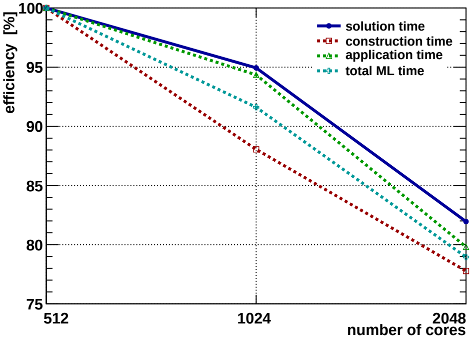
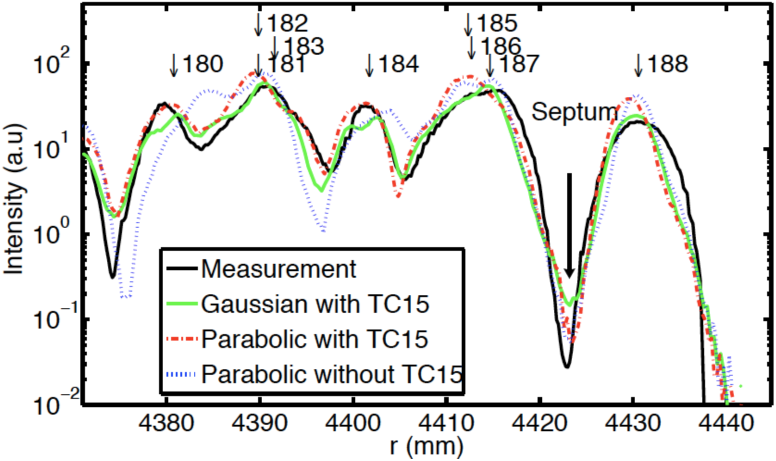
SAAMG-PCG Parallel Efficiency



[A. Adelmann, P. Arbenz, et al., JCP, **229** 12 (2010)]

- obtained for a tube embedded in a $1024 \times 1024 \times 1024$ grid
- construction phase is performing the worst with an efficiency of 73%
- influence of problem size on the low performance of the aggregation in ML

PSI 590 MeV Ring - last 8 turns @ 2.2 mA

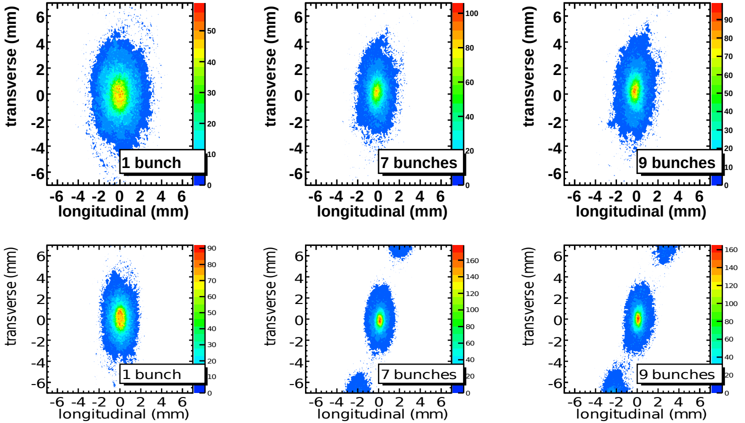


[Y. Bi, A. Adelmann, et al., PR-STAB **14**(5) (2011)]

Neighboring Bunch Effects- Multi Bunch Model

Single bunch and multiple bunches at turn 80 and 130

PSI 590MeV Ring



[J. Yang, A. Adelmann, et al., PR-STAB **13**(6) (2010)]

PSI 590MeV Ring

OPAL-CYCL Multiple bunches simulation of the Ring Cyclotron

(Ring Cyclotron)

Outline

New OPAL Element **Ring**

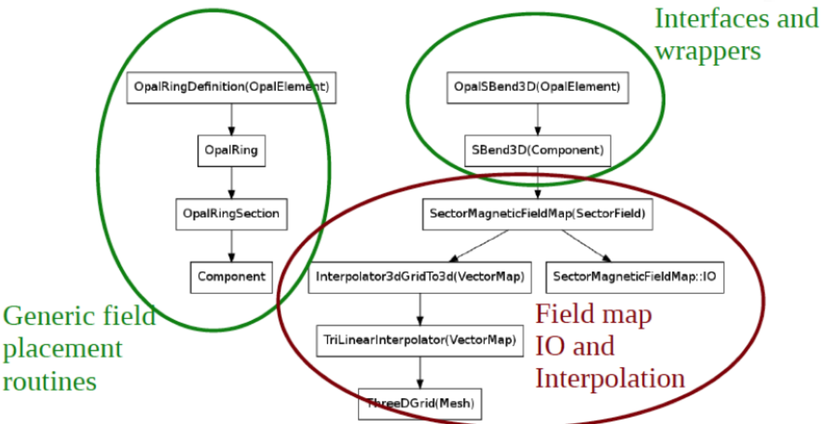
mostly contributed by C. Rogers

OPAL requires modification to adequately track FFAG field maps

- OPAL-t allows tracking through a set of beam elements in linac-type geometry
- OPAL-cycl previously hard coded to use 2D mid plane field map + single RF cavity
- Aim to introduce the capability to track through a set of **arbitrary** beam elements in ring-type geometry
- Additionally introduce specific capability to track through a 3D field map in a sector-type geometry

Use ERIT ring as test-bed for this development

Implementation in OPAL

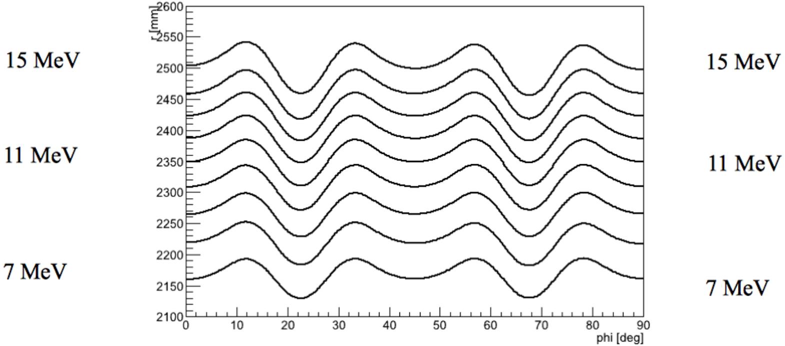


Class diagram for OpalRing and SBend3D: boxes represent classes with arrows representing ownership - owning class points to owned class. Parent classes are shown in brackets. Note that the OpalRingSection is related to the SBend3D through the Component inheritance relationship.

Outline

Getting closed orbit through OPAL

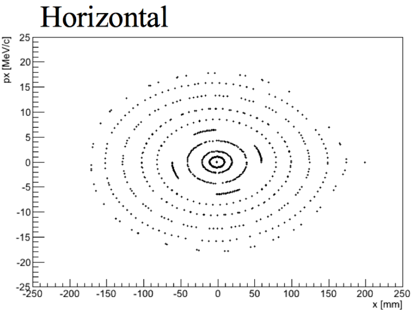
All ERIT simulations are curtesy of C. Rogers

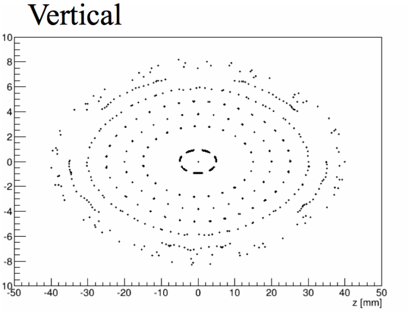


Dynamic Apperture

$\Delta t = 0.1$ ns

- After 100 turns aperture looks okay in OPAL
- Is this dynamic aperture or field map aperture?
- Field map extent is $\pm$ 250 mm in x
- Particles outside aperture are lost after $<$ 1 turn





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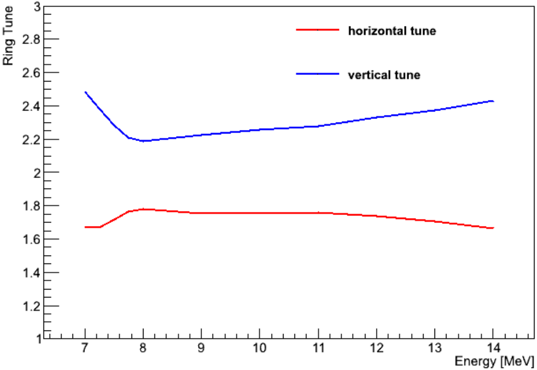
Tune Variation with Energy

$\Delta t = 0.1$ ns & 100 turns

- Calculated by method of FFT



Outline

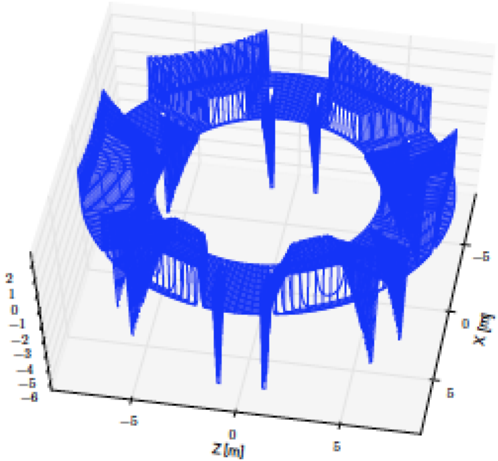
Lattice design & tracking with OPAL

S. L. Sheehy, C. Johnstone, *A 1 GeV CW FFAG High Intensity Proton Driver*, IPAC2012

- 300 MeV to 1 GeV ring
- 4-cell quasi-isochronous non-scaling FFAG design
- short (1cm long) 1 π mm mrad proton bunch
- acceleration is achieved with 3 cavities with an energy gain of 22 MV per turn, which is sufficient to open the serpentine channel
- the beam exhibits expected phase space distortion and filamentation even in the 0 mA

Lattice design & tracking with OPAL cont.

S. L. Sheehy, C. Johnstone, *A 1 GeV CW FFAG High Intensity Proton Driver*, IPAC2012



Lattice design & tracking with OPAL cont.

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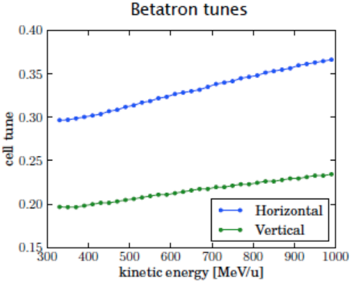

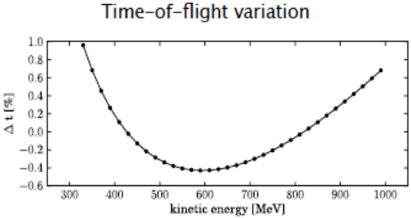

Lattice design & tracking with OPAL cont.

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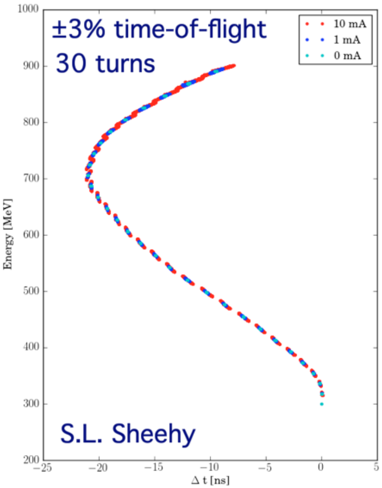

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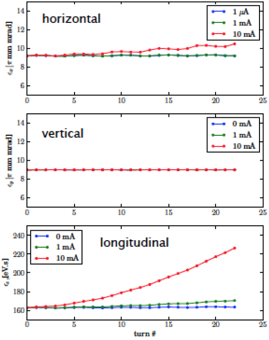
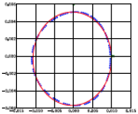
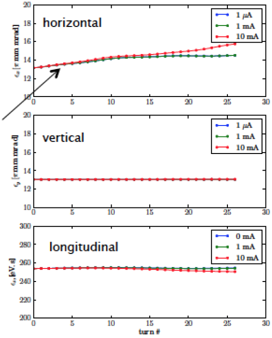
Coasting Beam @ 330 & 610 MeV

Tracked with unnormalised 10π mm mrad, shown are ε normalised





Strong non-linearities mean even 10mm single-particle tracking does not quite produce an ellipse.

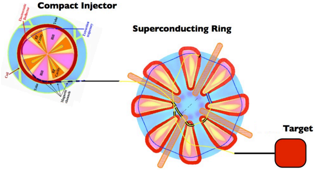


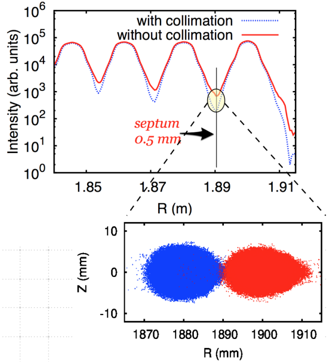
Outline

The DAEδALUS Injector Cyclotron → a FFAG ??

60 MeV/n, 10 mA/CW [J. Yang, A. Adelmann, et al., NIM-A **704**(11) (2013)]

	type	orbit radius (cm)	kin. energy (MeV/amu)	avg. power (MW)	avg. field (T)	sector no.	cavity no.	cavity type	turn no.
DIC	normal	5. . . 200	0.035. . . 60	0.12	0.95. . . 1.17	4	double-gap	4	107
DSRC	SC	190. . . 480	60. . . 800	1.6	1.06. . . 1.88	8	single-gap	4	401





OPAL . . .

- OPAL is augmented with FFAG (Ring) design capabilities
- We are ready to study FFAG's with space charge as we have done for Cyclotrons
- Work on ERIT and a 1 GeV high power nsFFAG has just begun

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Lets find out the high intensity limits of FFAG's!

References

- A. Adelmann, P. Arbenz, et al., J. Comp. Phys, 229 (12): 4554 (2010)
- M. A. Furman and M. Pivi, Phys. Rev. STAB **5**, 124404 (2002)
- Y. Bi, A. Adelmann et al., Phys. Rev. STAB **14**(5) 054402 (2011)
- J. Yang, Adelmann et al., Phys. Rev. STAB **13**(6) 064201 (2010)
- J. Yang, Adelmann et al., NIM-A **704**(11) 84-91 (2013)
- J. R. M. Vaughan, IEEE Transactions on Electron Devices 40, 830 (1993)

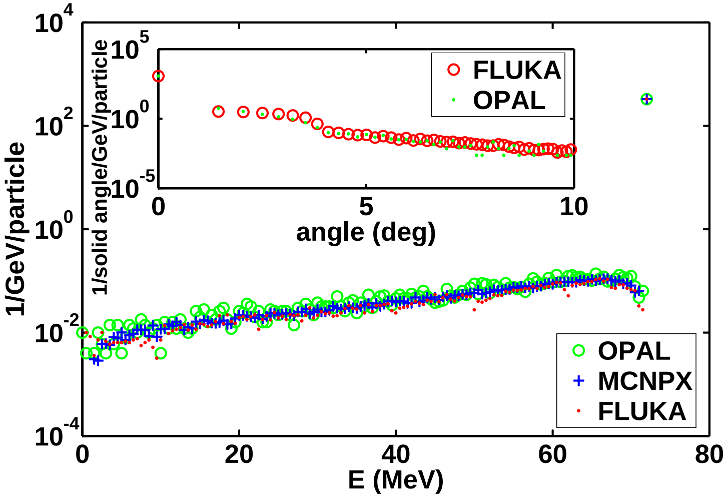
Backup

Particle Matter Interaction

- Energy loss $-dE/dx$ (Bethe-Bloch)
- Coulomb scattering is treated as two independent events: the multiple Coulomb scattering and the large angle Rutherford scattering
- Space charge & halo generated by the obstacle

A 72 MeV cold Gaussian beam with $\sigma_x = \sigma_y = 5$ mm passing a copper slit with the half aperture of 3 mm from 0.01 m to 0.1 m.

Particle Matter Interaction cont.



OPAL

Sketch of an inputfile

```
ffag: Cyclotron, TYPE="FFAG", CYHARMON=1, PHIINIT=phi0,
PRINIT=pr0, RINIT=r0 , SYMMETRY=1.0,
RFFREQ=200.0, BSCALE=10.0,
FMAPFN="NSFFAGfieldPSI.dat";

rf0: RFCavity, VOLT=cavvol1, FMAPFN="Cav1.dat",
TYPE="SINGLEGAP", FREQ=200.0,
RMIN = 2100.0, RMAX = 4000.0,
ANGLE=45.0, GAPWIDTH = 300.0,
PHI0=ph;

Dist1:DISTRIBUTION, DISTRIBUTION=GAUSS,
SIGMAX=  1.0e-03, SIGMAPX=1.0e-4, CORRX=0.5,
SIGMAY=  2.0e-03, SIGMAPY=1.0e-4, CORRY=-0.5,
SIGMAT=  3.0e-03, SIGMAPT=1.0e-4, CORRT=0.0;
l1: Line = (ffag,rf0);
```

OPAL

Sketch of an inputfile

```
Fs1:FIELDSOLVER, FSTYPE=FFT, MX=64, MY=64, MT=64,
                 PARFFTX=true, PARFFTY=true, PARFFTT=false,
                 BCFFTX=open, BCFFTY=open, BCFFTT=open;

beam1: BEAM, PARTICLE=PROTON, pc=P0, SPACECHARGE=false,
               NPART=1E6, BCURRENT=1.0E-9, BFREQ= 200.0;

track,line=l1, beam=beam1,MAXSTEPS=turns,STEPSPERTURN=180;
 run, method = "CYCLOTRON-T", beam=beam1,
 fieldsolver=Fs1, distribution=Dist1;
endtrack;
```

Collision-less (non relativistic) Vlasov-Maxwell equation

$f_s \subset (\mathbb{R}^3 \times \mathbb{R}^3), \mathbb{R}^3 :\rightarrow \mathbb{R}^3$ and s are the species.

$$\frac{\partial f_s}{\partial t} + \mathbf{v} \cdot \nabla_x f_s + \frac{q_s}{m_s}(\mathbf{E} + \mathbf{v} \times \mathbf{B}) \cdot \nabla_v f_s = 0,$$

$$\left.\begin{aligned} \partial_t \mathbf{E} - c^2 \nabla \times \mathbf{B} = \frac{\mathbf{J}}{\varepsilon_0}, \qquad & \nabla \cdot \mathbf{E} = \frac{\rho}{\varepsilon_0}, \\ \partial_t \mathbf{B} + \nabla \times \mathbf{E} = 0, \qquad & \nabla \cdot \mathbf{B} = 0, \end{aligned}\right\} \qquad \text{Maxwell's equations}$$

where the source terms are computed by

$$\rho = \sum_s q_s \int f_s \, d\mathbf{v}, \qquad \mathbf{J} = \sum_s q_s \int f_s \mathbf{v} \, d\mathbf{v}.$$

The electric and magnetic fields $\mathbf{E}$ and $\mathbf{B}$ are superpositions of external fields and self-fields (space charge),

$$\mathbf{E} = \mathbf{E}_{\text{ext}} + \mathbf{E}_{\text{sc}}, \quad \mathbf{B} = \mathbf{B}_{\text{ext}} + \mathbf{B}_{\text{sc}}.$$