RACCAM

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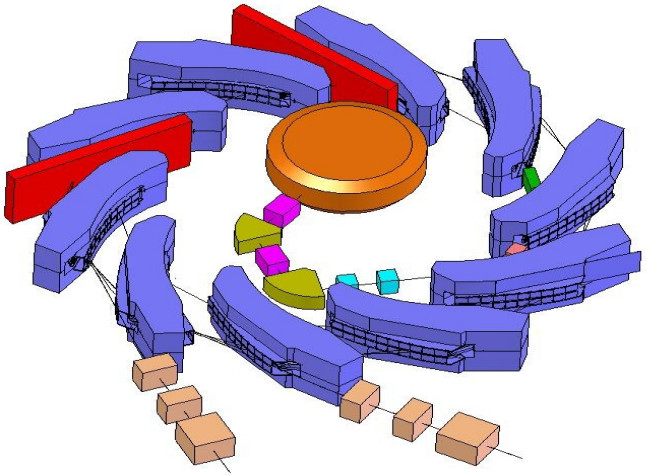


An ANR contract, Feb. 2006 – Feb. 2009

A status, including :
- Magnet prototyping
- Magnetic measurements

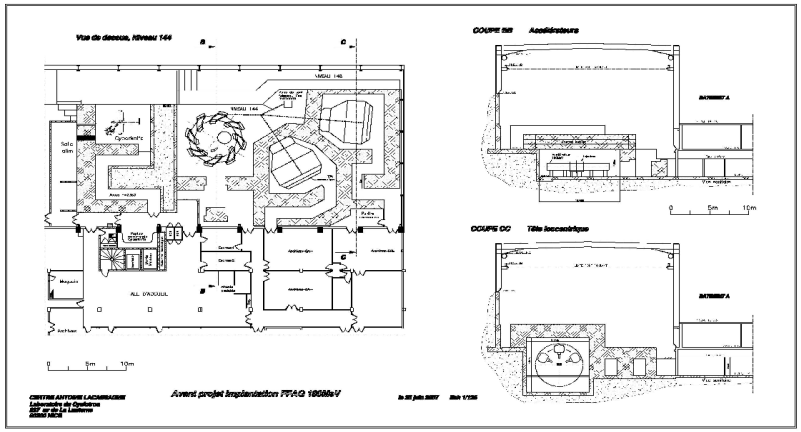
Motivations for a project of a protontherapy FFAG

(i) Hadrontherapy is considered to be more effective for cancer treatment comparing to photons

(ii) FFAGs appear to have various advantages in medical applications:

- Potential for variable energy operation (→ no need of degrader, ESS)
- High dose delivery, potentially >> Gy/min (←high rep rate, potentially 100s Hz)
- Potential for reasonably compact size (if needed...) and low cost
- Flexibility : synchrotron-like manipulattion of beams
  (injection, extraction, multi-particle)
- Stable and easy operation (← fixed magnetic field)
- Potential for multiple extraction ports
- Natural scanning method : bunch-to-voxel

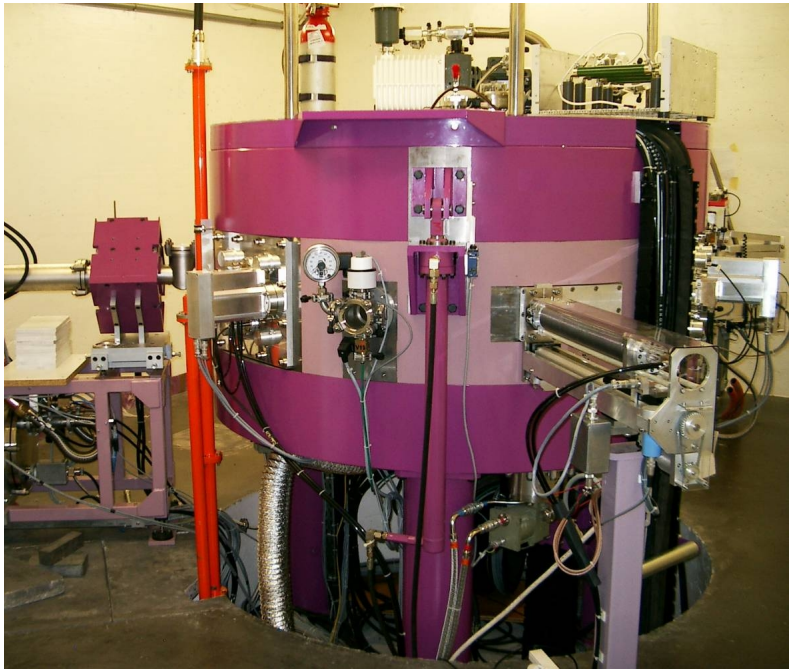
(iii) Possible implementation of a demonstration machine at the Nice anti-cancer clinic (MEDICYC)

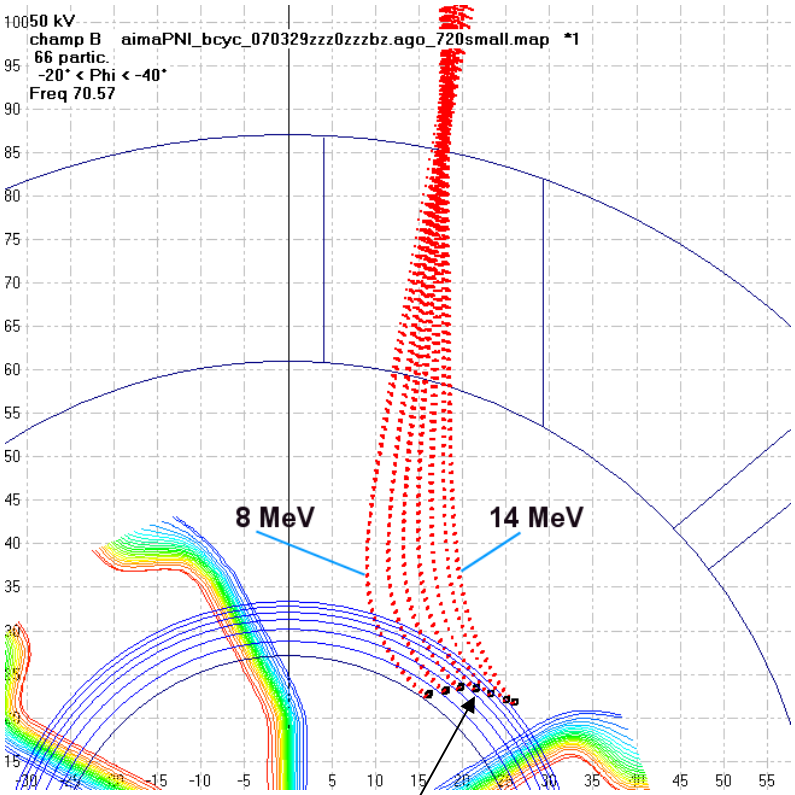


Principle of RACCAM injector : Tunable energy proton beam

Involves using a H- cyclotron injector

AIMA H^- cyclotron – our injector for FFAG





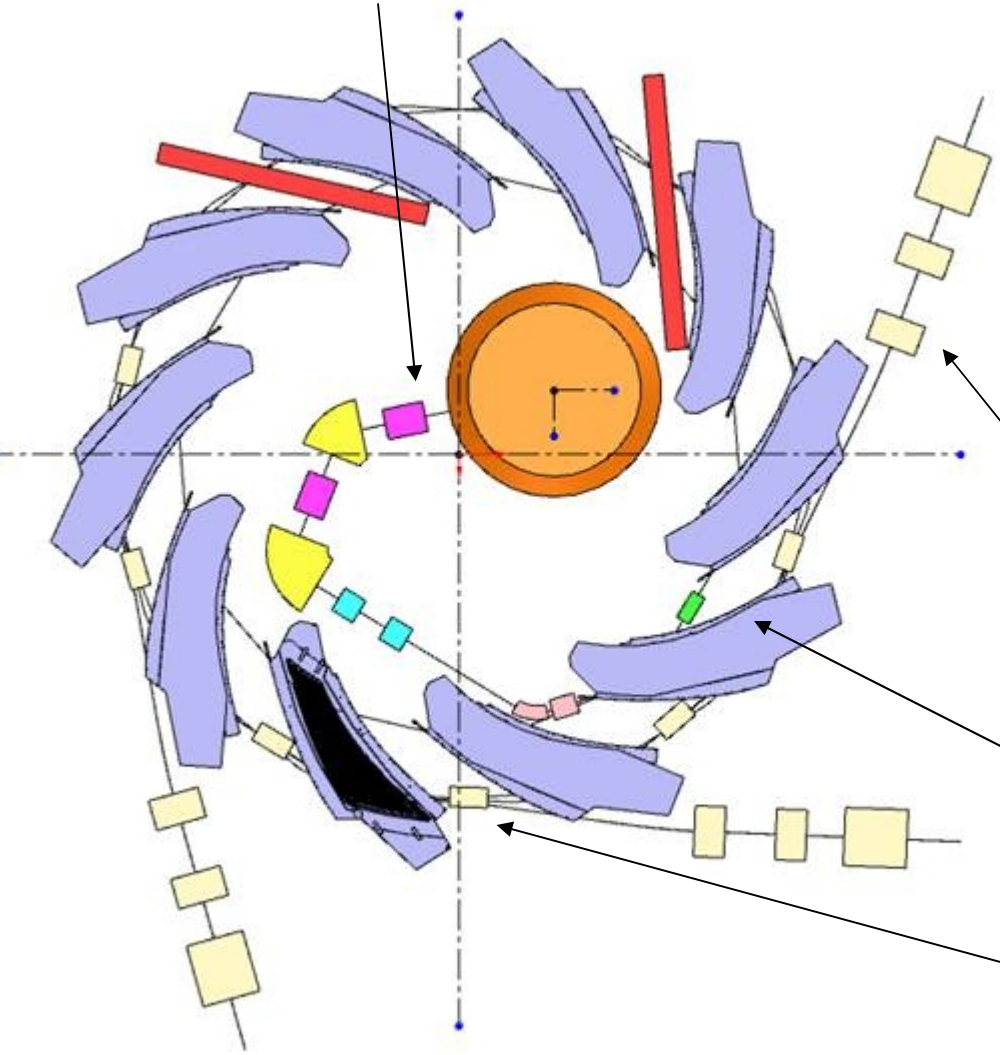
variable stripper position

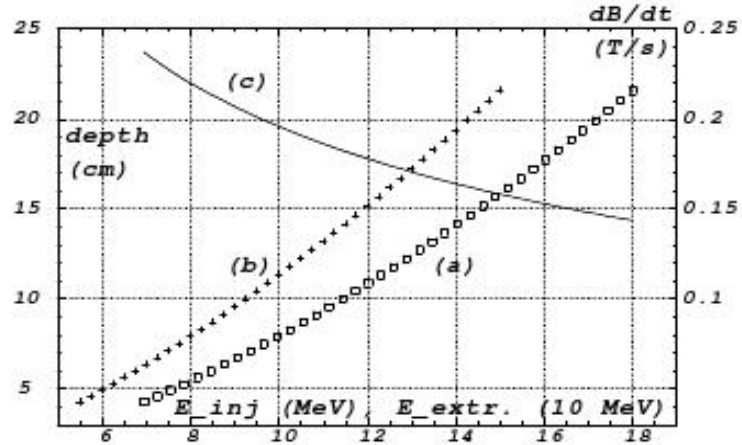
Studies made by AIMA-Development team, MEDICYC, Nice, as part of RACCAM collaboration

Principles of energy variation :

Variable extraction energy from

H^- cyclotron injector





(a) : Bragg pic depth as a function of FFAGextraction energy
(b) : correlated cyclotron energy with 250kV steps
(c) : dB/dt

allows variable extraction energy from FFAG

by varying FFAG rigidity
and / or
by extraction kick
synchronised on turn #

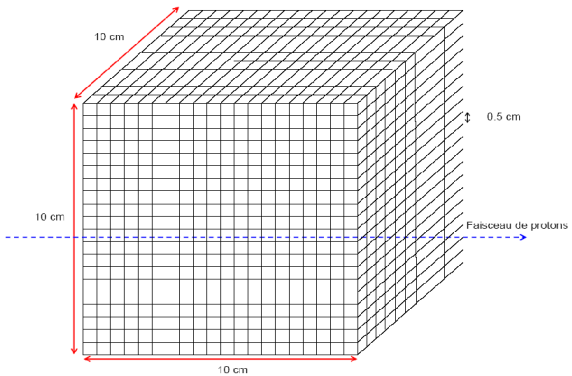
Beam delivery hypothesis

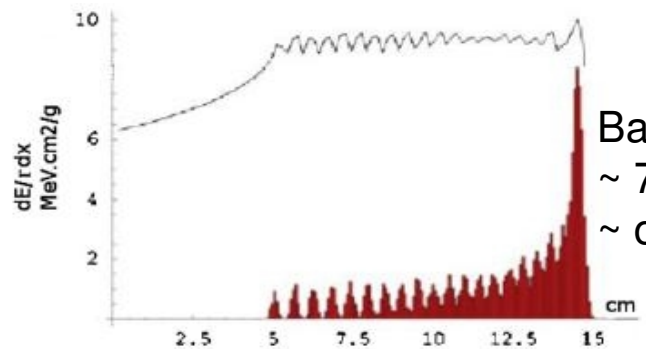
(ii) Spread out Bragg pic (SOBP) :

$$\left|-\frac{dE}{dx}\right| = 2\pi N_a r_e^2 m_0 c^2 \rho \frac{Z}{A}\frac{z^2}{\beta^2}\left[\ln\left(\frac{2m_0\gamma^2 v^2 W_{max}}{I^2}\right) - 2\beta^2 - \delta - 2\frac{C_S}{Z}\right]$$

(i) Reference volume :

- 1 liter cube, 10x10x10cm^3
- Voxel size : 5x5x5 mm^3





Basic results :
~ 7 10^{11} proton/Gy in a liter
~ only weak dependence on E

(iii) Bunch filling for bunch-to-pixel scanning :

- **400 pixels/slice**, about 20% of the dose in the distal layer, yields a maximum
  5Gy x 7.10^{11} p/Gy x 20% / 400pixel ~ **2x10^9 p/pixel in the distal layer**
- Cyclotron produces 1.5x10^7 ppb, hence need ~**130 cyclotron bunches**
- Cyclotron RF 70MHz (h=3) and FFAG 3MHz @ injection,

i.e. 70MHz/3MHz*h3 = **70 cyclotron bunches in one FFAG turn.**

Hence, for distal pixels,

either (i) 5-turn injection at 50% efficiency

or (ii) single-turn injection and a minimum of 4 paintings

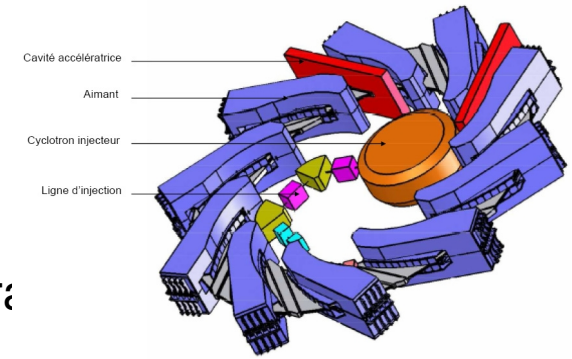
(iv) Repetition rate needed :

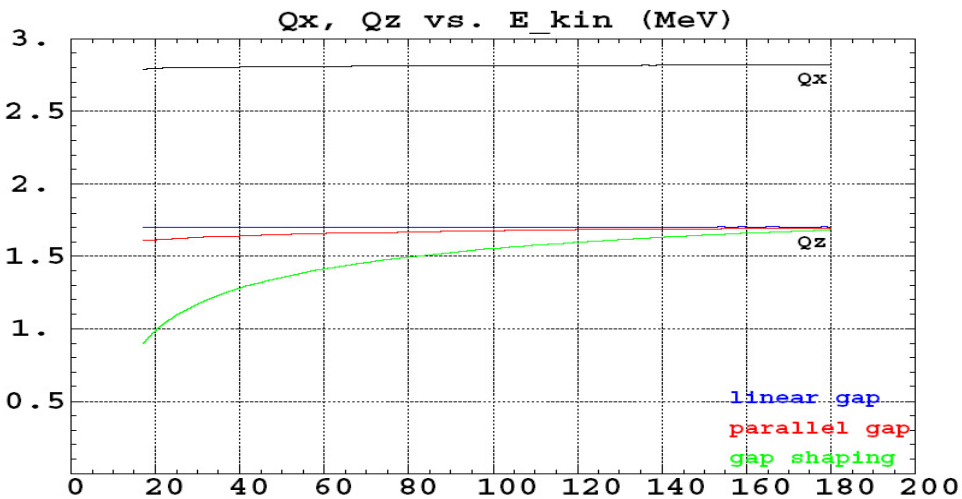
20x20x20 pixels in a minute, hence, ~**130Hz**

Scaling magnet – a delicate problem to deal with :

Vertical focusing:

- strongly influenced by fringe fields
- difficult to obtain constant Q_V
- especially when planning varying field for variable energy
- yet, the theory is well known, confirmed by stepwise ray-tra

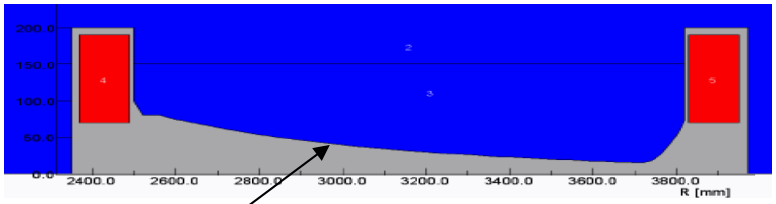




$$M_z = \begin{pmatrix} 1 & 0 & 0 \\ -\frac{\tan(\delta-\psi)}{\rho} & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$\psi = I_1 \frac{\lambda}{\rho} \frac{1+\sin^2(\delta)}{\cos(\delta)} \qquad r = \rho x \frac{\sin\left(\frac{\pi}{N}\right)}{\sin\left(p_f \frac{\pi}{N}\right)}$$

$$I_1 = \int_{-\infty}^{\infty} \frac{B_z(s)\left[B_{z0} - B_z(s)\right]}{\lambda\ B_{z0}^2} ds$$



Scaling, requires $\psi = Cst$ → λ~r

Magnetic field B~r^k requires λ ~ gap ~ $1/r^k$

Conflict!

We have used 2 different tools to simulate the field :

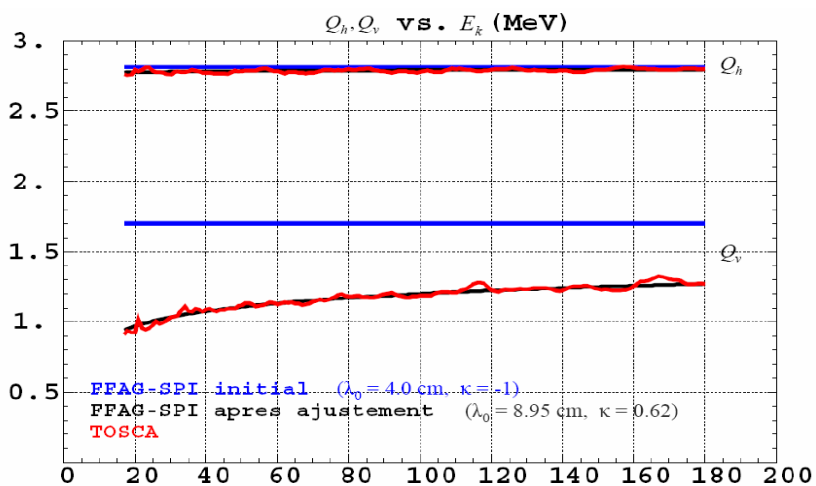
- Either TOSCA that generates field maps,
  yet too slow for beam dynamics optimization method
- Or "FFAG-SPI/Zgoubi" based on analytical model of the spiral field,
  very fast

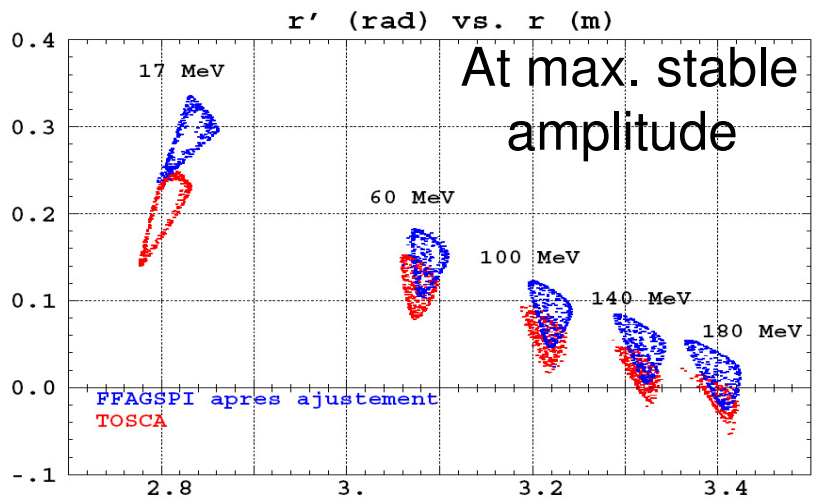
• Magnet prototype design and ring design have been a permanent feedback between the two methods :

- TOSCA field maps when precision is needed
- "FFAG-SPI" when optimization speed is needed

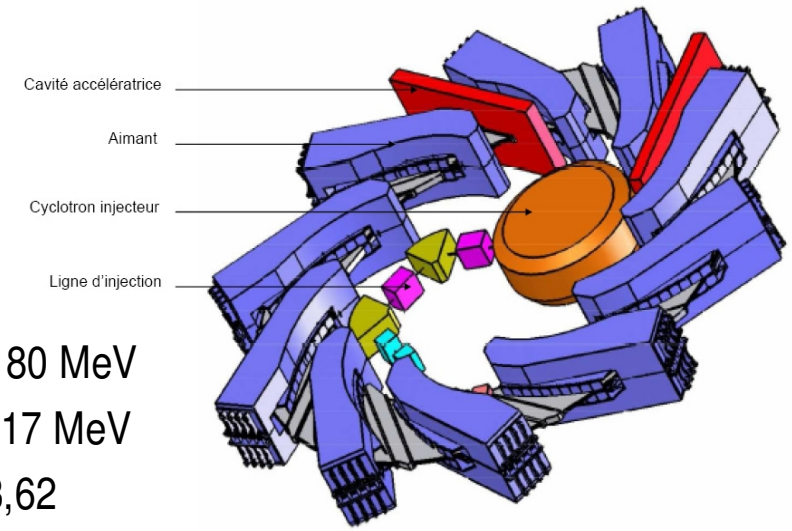
• A sample of the agreement between both :

→ main knob for good match : fringe field extent, λ





We end up with a set of optimized parameters of the RACCAM 10 cell ring and magnet :



Extracion energy, variable (MEDiCYC specs.)	70 – 180 MeV
Injection energy	5.5 – 17 MeV
Nomentum ratio	3,62
Number of cells	10
Packing factor	0,34
Field index, k	5
Spiral angle	53.7 deg.
Qh / Qv	2.76 / 1.55~1.60
Radius on extraction/injection orbit : dR	3.46 m / 2.78 m / 0.67 m
Drift length, extraction/injection orbit	1.42 m / 1.15 m
Frev, 15->180 MeV	3.03 -> 7.54 MHz
Frev, 5.5->70 MeV	1.86 -> 5.07 MHz

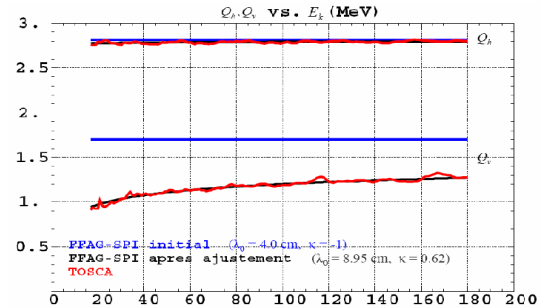
MAGNET PROTOTYPING

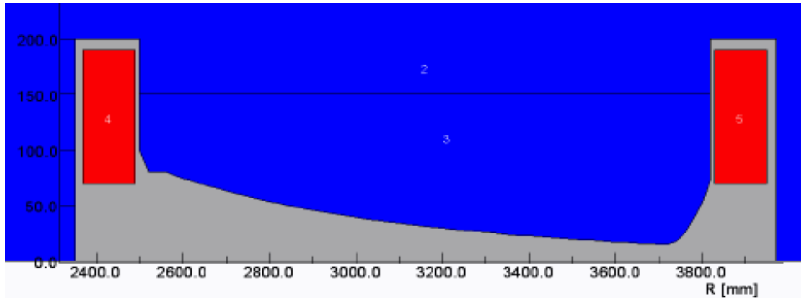
DESIGN STAGE

RACCAM has studied two types of magnets and constructed and tested a prototype

Issues :

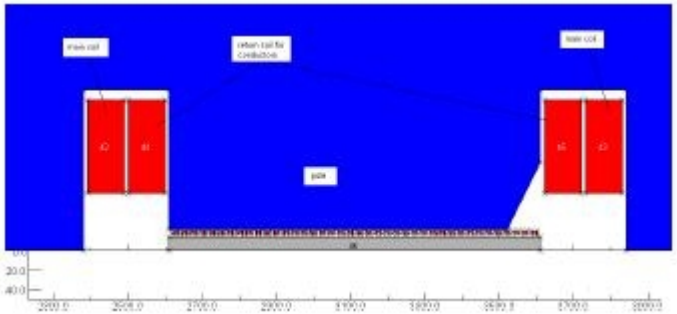
- Need vertical tune constant, whatever the radius
- Good to have a knob for adjusting **k**





Gap shaping magnet:

- Less consuming
- Rather straightforward technology
- Selected for prototyping
- Designed, constructed, measured by SigmaPhi

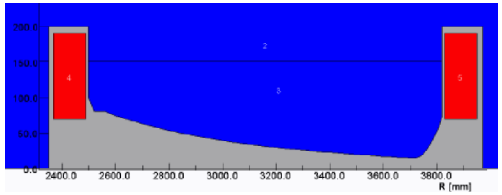


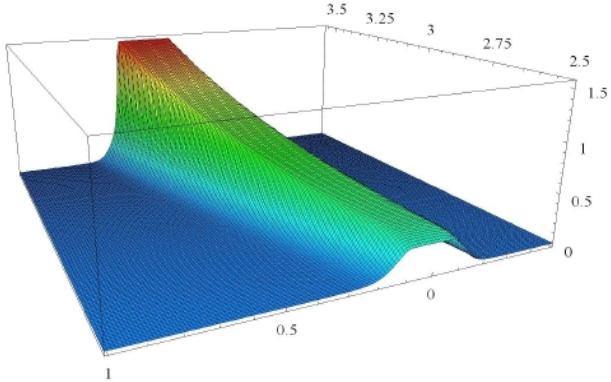
Parallel gap magnet with distributed pole conductors that generate the $B \sim r^k$ law :

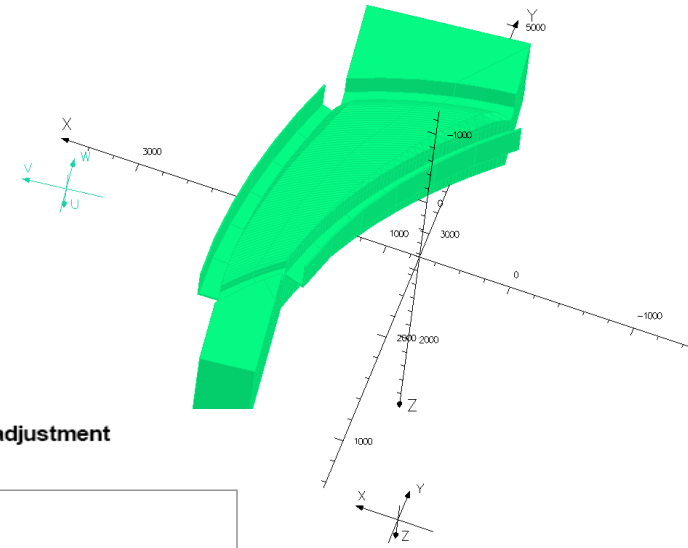
- Would provide knob for k
- Expected to yield lower Qz variation with radius
- Design principles studied by SIGMAPHI/InfinitesiMag

- **Gap shaping magnet prototype. The design stage**

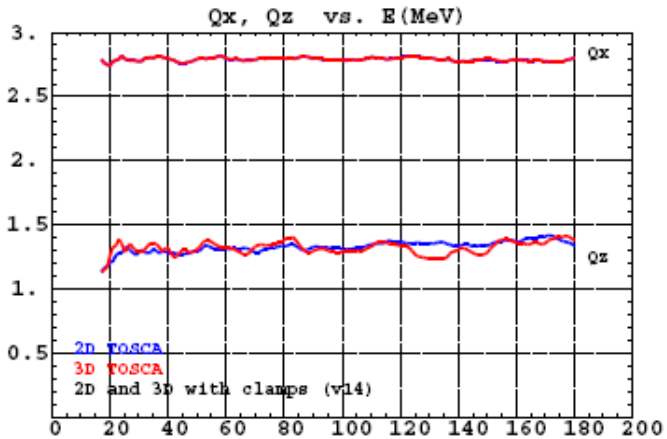
using TOSCA 2D and 3D, showed that stabilization of vertical tune can be achieve by combination of *variable chamfer and field clamp.*

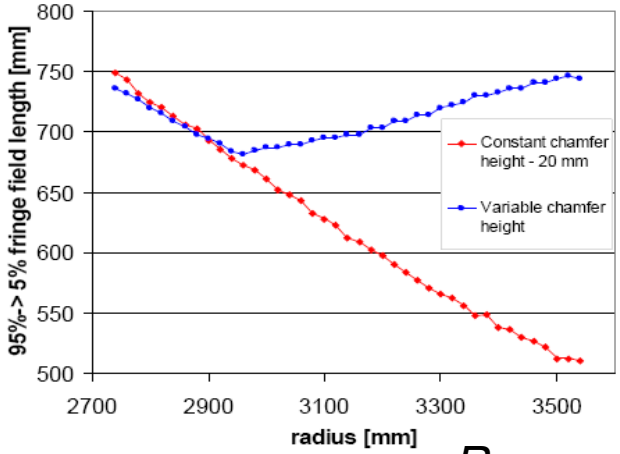






Fringe field length adjustment

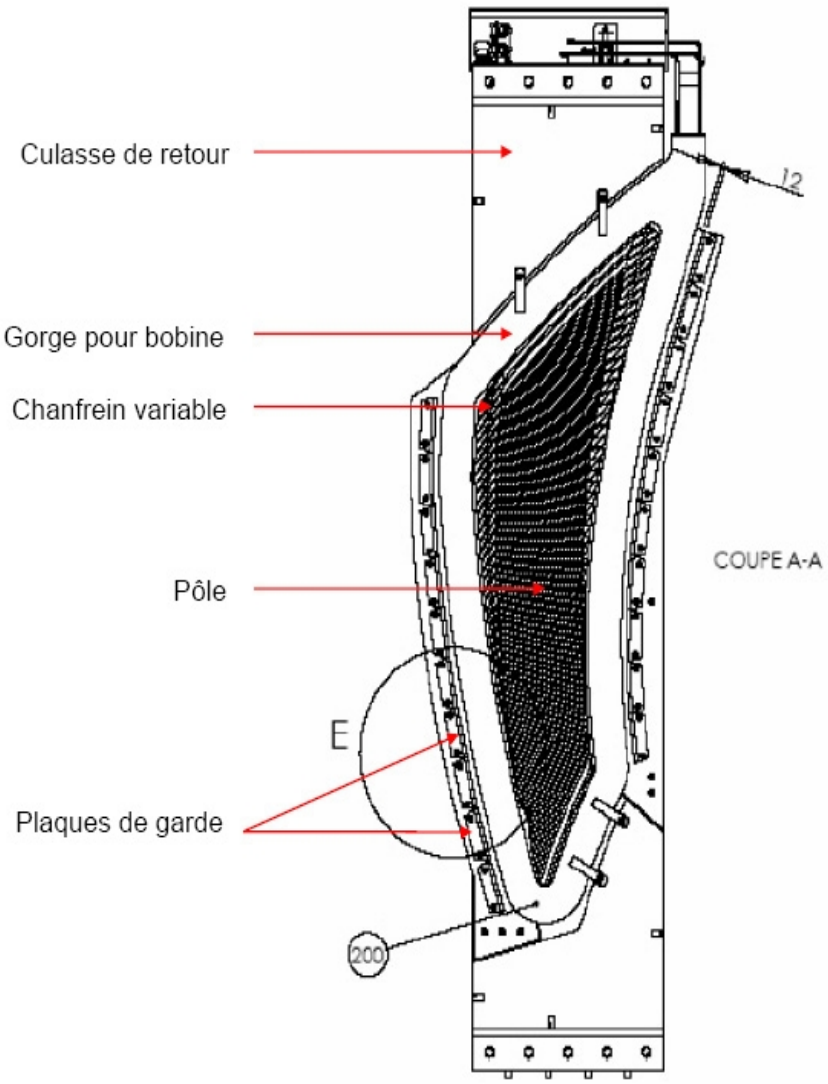


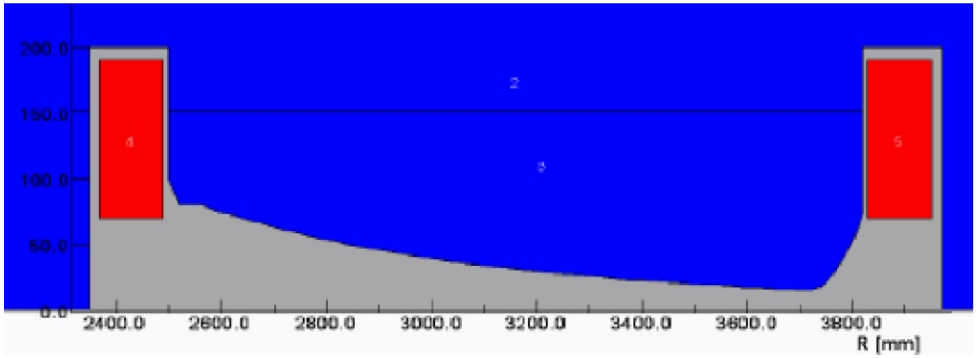


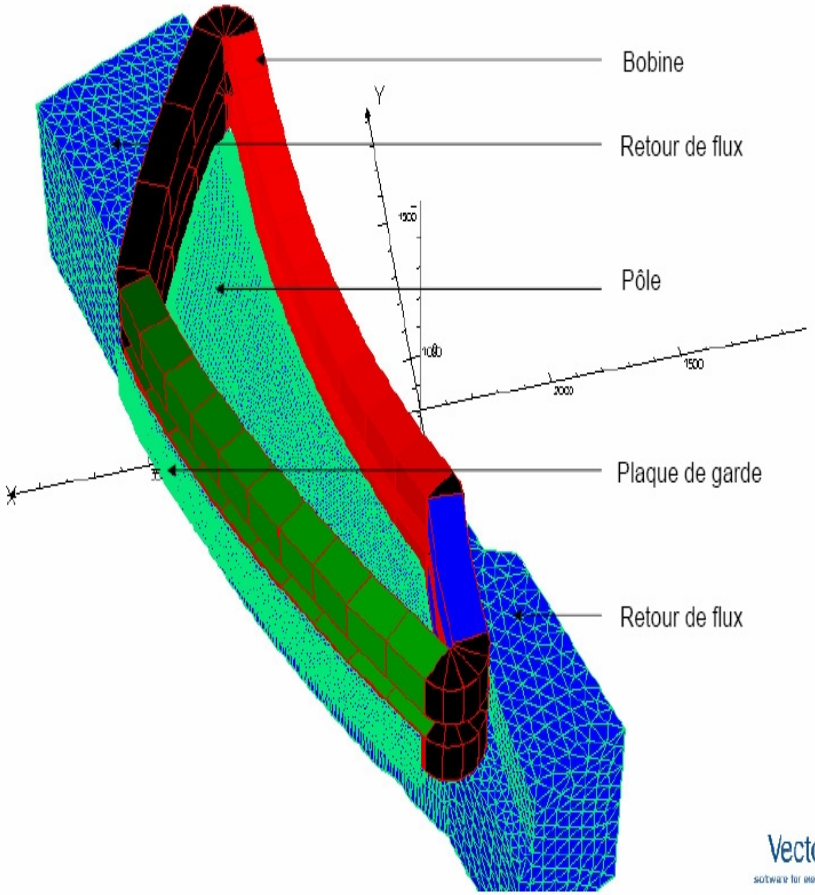
Remember :

$$\psi = I_1 \frac{\lambda}{\rho} \frac{1+\sin^2(\delta)}{\cos(\delta)}$$ requires $\lambda \sim r$

Sample results from TOSCA modelling



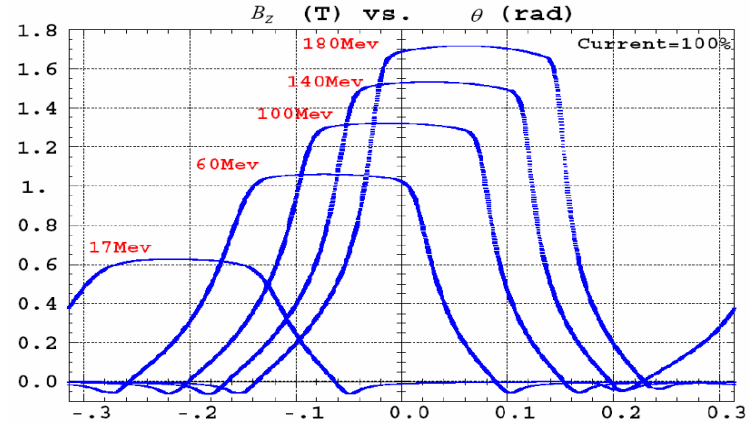


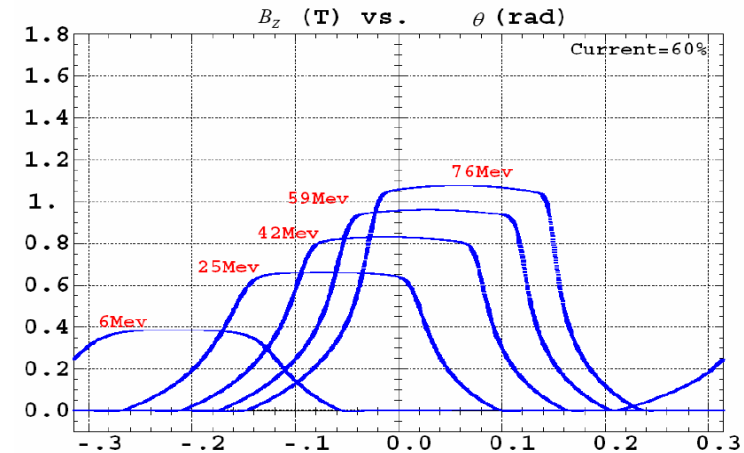


Vector Fields
software for electromagnetic design

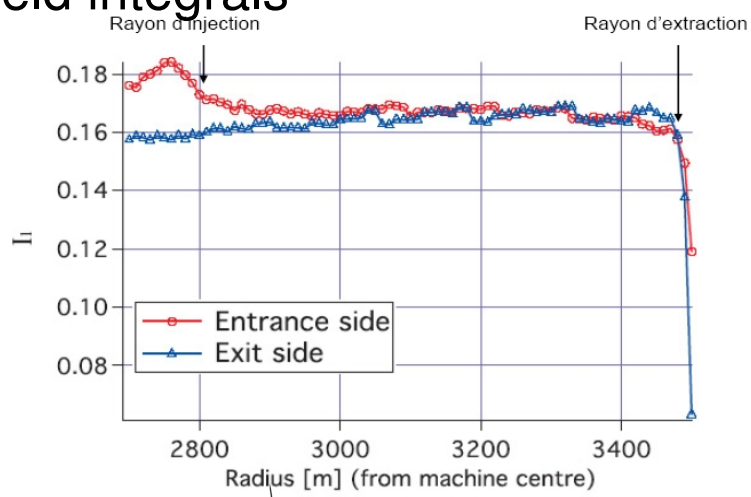
- **Prototype gap shaping magnet :**
  design field on closed orbits

Mode	Energie d'injection / extraction	B_{z0}
100%	17 – 180 MeV	1.71 T
90%	13 – 157 MeV	1.59 T
80%	11 – 130 MeV	1.43 T
70%	9 – 102 MeV	1.25 T





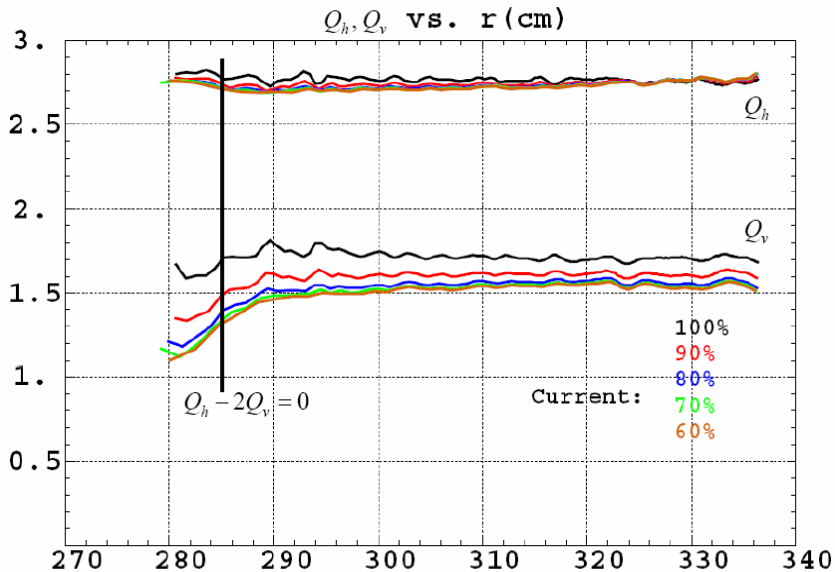
Field integrals

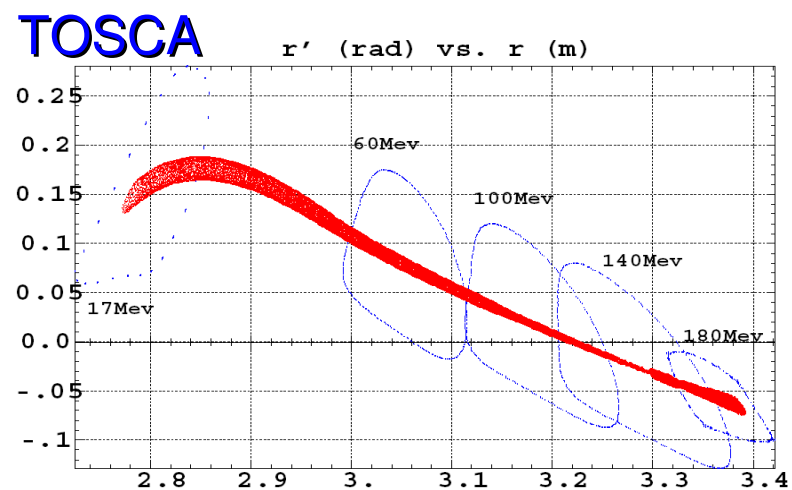


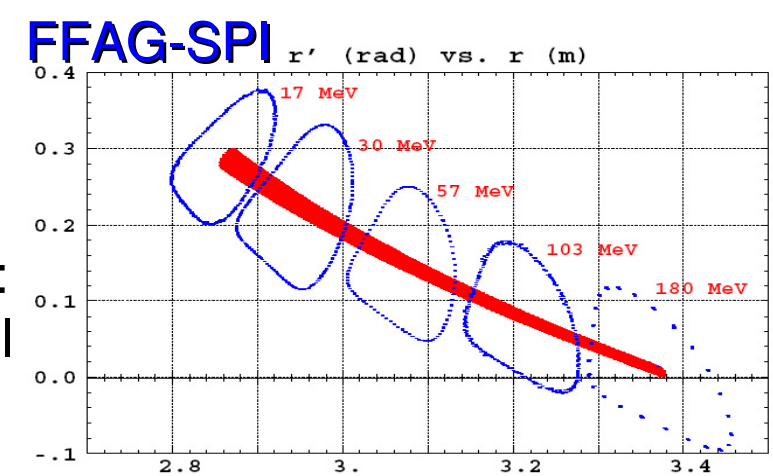
$$M_z = \begin{pmatrix} 1 & 0 & 0 \\ -\frac{\tan(\delta-\psi)}{\rho} & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \qquad \psi = I_1 \frac{\lambda}{\rho} \frac{1+\sin^2(\delta)}{\cos(\delta)} \qquad I_1 = \int_{-\infty}^{\infty} \frac{B_z(s)\left[B_{z0} - B_z(s)\right]}{\lambda\, B_{z0}^2} ds$$

• **Prototype gap shaping magnet,**
design orbits, including,

- tune behavior
- horizontal DA
- possible emittance increase upon resonance Xing





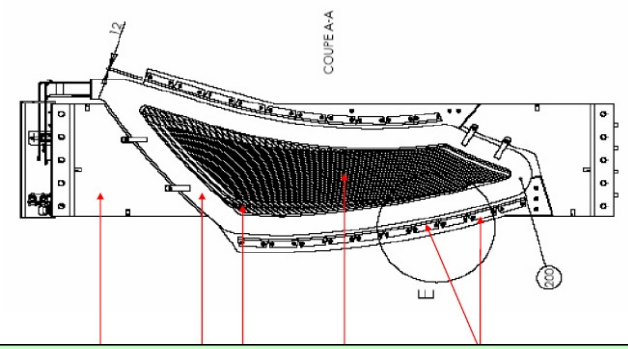


For comparison :
FFAG-SPI model

PROTOTYPE MAGNET : FABRICATION

Mechanical and electrotechnical specifications, according to magnet design

yoke shape		parallelepipedic	to minimize magnet weight
		laminated	to allow for $dB/dt \approx 0.1$ T/s
gap shape		shaping	Fig. 1, $g(r) \approx g_0(r/r_0)^{-k}$
gap at r_{xtr} (g_0)	cm	4	determined by beam size
gap at r_{inj}	cm	~ 11.6	determined by gap law
pole extent, $r_{min} - r_{max}$	m	$2.61 - 3.61$	
chamfers		variable	so to ensure scaling field law
field clamps		spiral	follow $r = r_0 e^{\theta/\tan\zeta}$ line ?
			contribute to scaling field
lamination thickness	mm	1.5	
overall magnet dimensions, $L \times W \times H$	mm	$2913 \times 579 \times 1230$	
total weight of magnet	t	18	
coil			
cross section	mm	113.6x115.6	
average winding length	m	5.157	
weight	kG	271	
resistance, 20 ^0C	Ω	0.335	
voltage	V	79.43	
current	A	225	
dissipated power, per coil	kW	17.873	
number of cooling circuits		6	
total water flow	l/min	12.13	
water temperature, in / out	^{0}C	25 / 44	



Values met by the constructor

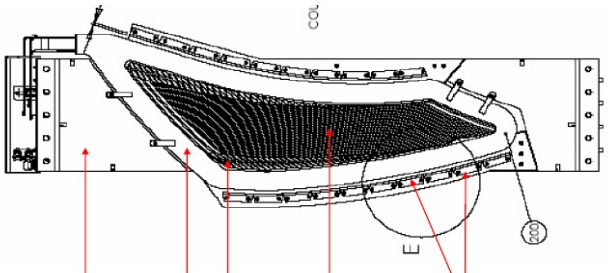
CARACTERISTIQUES ELECTRIQUES (AIMANT) / ELECTRICAL PARAMETERS (MAGNET)	
Courant / Current	**225 A**
Mode d'alimentation / Supply mode	**Autre / Other**
Resistance à 20°C / Resistance at 20°C	**647.40 mΩ**
Tension à chaud / Voltage drop at warm	**153.30 V**
Electrical power	**34.477 KW**
Amperes.tour / Amperes.turn	**64800 A.t**
Inductance	**Not calculed**
Densité de courant dans le conducteur□Current density in the conductor	**A/mm²**
Autre / Other	
CARACTERISTIQUES THERMIQUES / THERMAL PARAMETERS	
Type de refroidissement / Cooling type	**Par eau / Water cooling**
Echauffement / Temperature rise	**18°C**
CARACTERISTIQUES HYDRAULIQUES (AIMANT) / HYDRAULIC PARAMETERS (MAGNET)	
Perte de charge / Pressure drop	**4 Bar**
Débit / Water flow	**24.7 Liter / Minute**
Pression de service / Operating pressure	**10 Bar**
CARACTERISTIQUES MAGNETIQUES / MAGNETIC PARAMETERS	
Champ / Field	**1.7T**

Beam related specifications, from magnet design

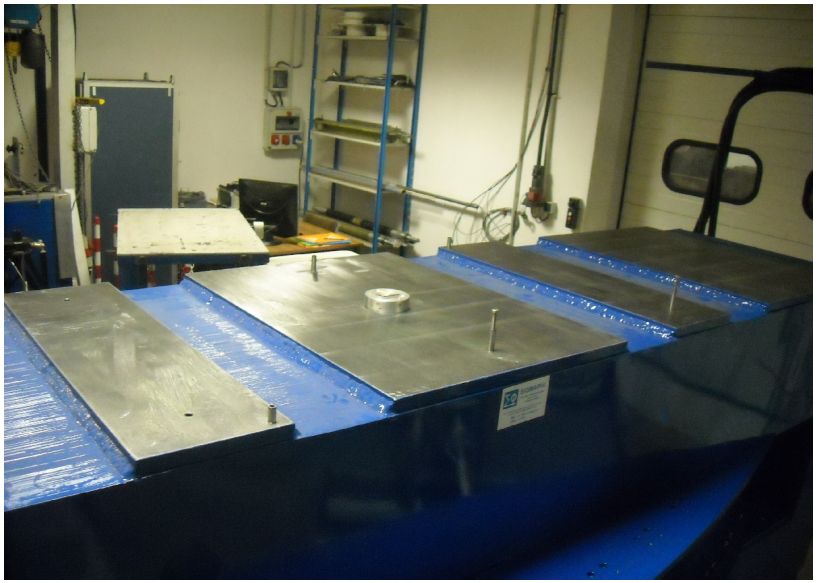
Table 3: Specifications to be met by the RACCAM magnet prototype.

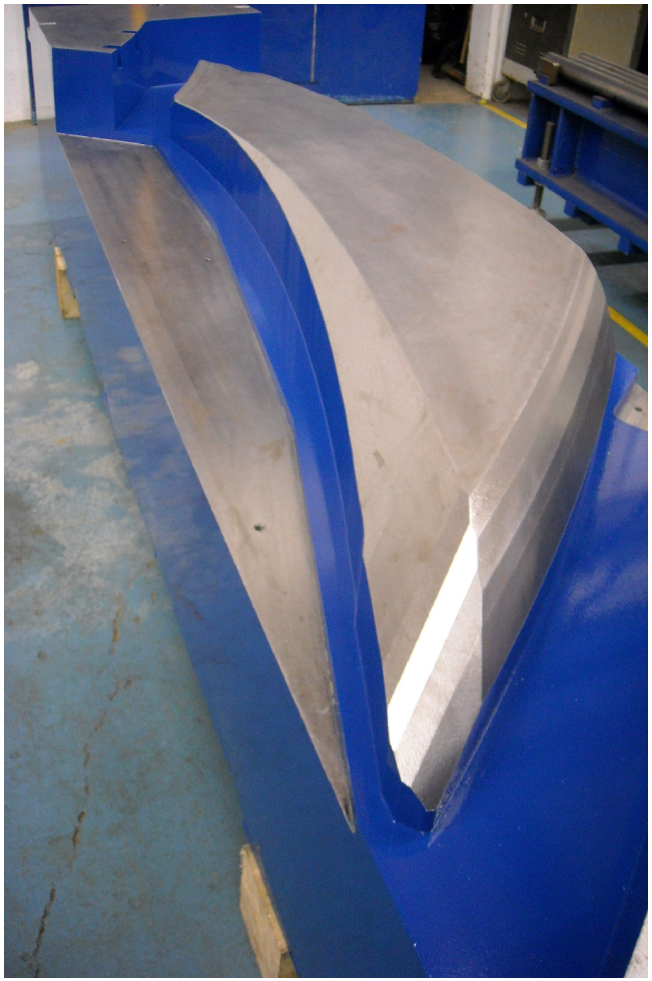
			Comments
magnet shape		spiral	EFB$^{(*)}$ defined by $r = r_0 e^{\theta/\tan\zeta}$
field shape		scaling	$B(r) = B_0 B_r(r) B_\theta(r,\theta)$
radial field dependence		scaling	$B_r(r) = (r/r_0)^k$
axial field dependence		spiral	$B_\theta(r,\theta) = \mathcal{F}(r,\theta)$
field index (k)		5.00	
spiral angle (ζ)	deg.	53.7	
sector angle (A)	deg.	12.24	
bending angle (β)	deg.	36	$2\pi/N$
packing factor		0.34	β/A
energy range, high	MeV	17 $\longrightarrow$ 180	
energy range, low	MeV	6.3 $\longrightarrow$ 70	
$B\rho_{xtr}/B\rho_{inj}$		3.391	
max. radius of GFR$^{(*)}$ ($r_{GFR,max}$)	m	3.4	$E \approx 150$ MeV
min. radius of GFR$^{(*)}$ ($r_{GFR,min}$)	m	2.9	$E \approx 25$ MeV
max. field on $r_{GFR,max}$	T	1.5576	
max. field on $r_{GFR,min}$)	T	0.7032	
fringe field extent (λ)	m	prop. r ?	$\lambda(r)$
I_1 integral		1/6	
horizontal good field region	m	2.9 — 3.4	E : 20 $\longrightarrow$ 150 MeV
orbit excursion	m	0.5	
vertical good field region	m	$\approx$gap/2	
horizontal tune ν_x		2.76	
vertical tune ν_z		1.56 — 1.59	
dB/dt	T/s	0.3	stabilized in less than 100 ms

(*) Good field region



- **The magnet has been built by SIGMAPHI**

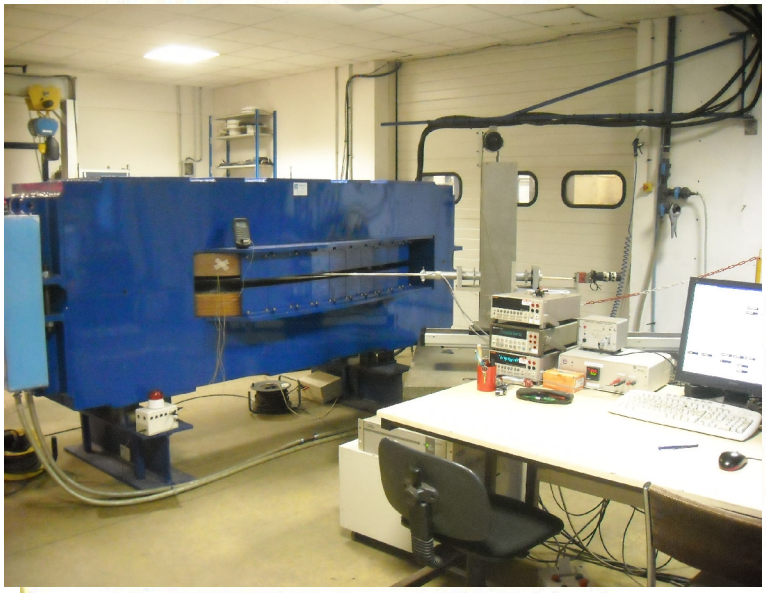




PROTOTYPE MAGNET :
MAGNETIC FIELD MEASUREMENTS

• Magnetic measurements

MEASUREMENT SYSTEM AND ACCURACY

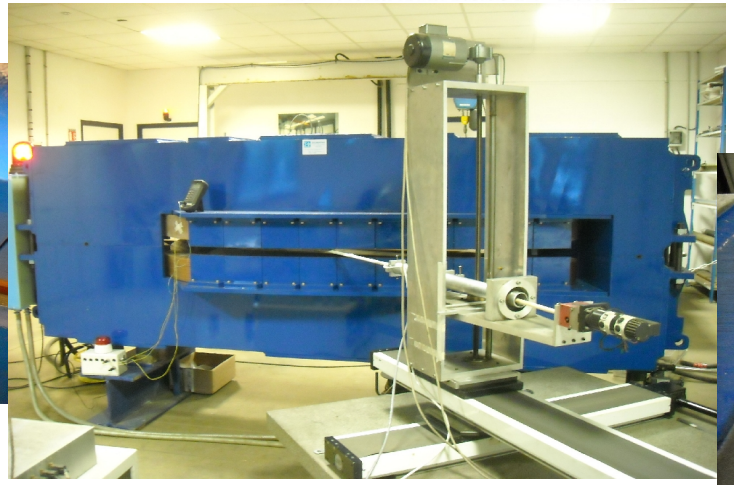


MAPPING system

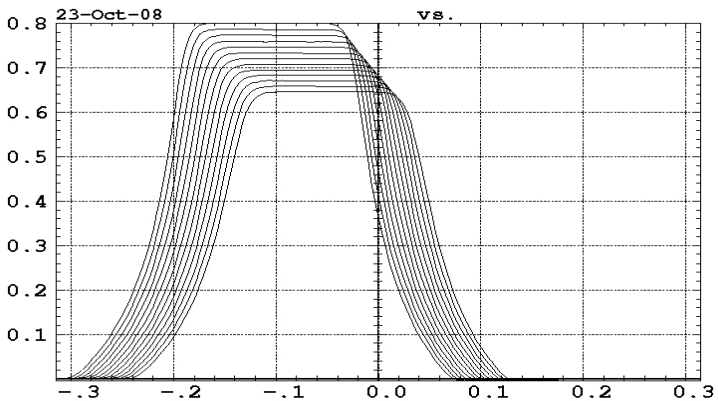
- 3 axis Hall probe Bell BH703, temperature regulated 30°C+/-0.1°C
- Air-conditioned laboratory (20.C+/-1°C)
- Field acquire in 3D with a 20 channels multimeter
- Automated Mapping table 1600*600*800

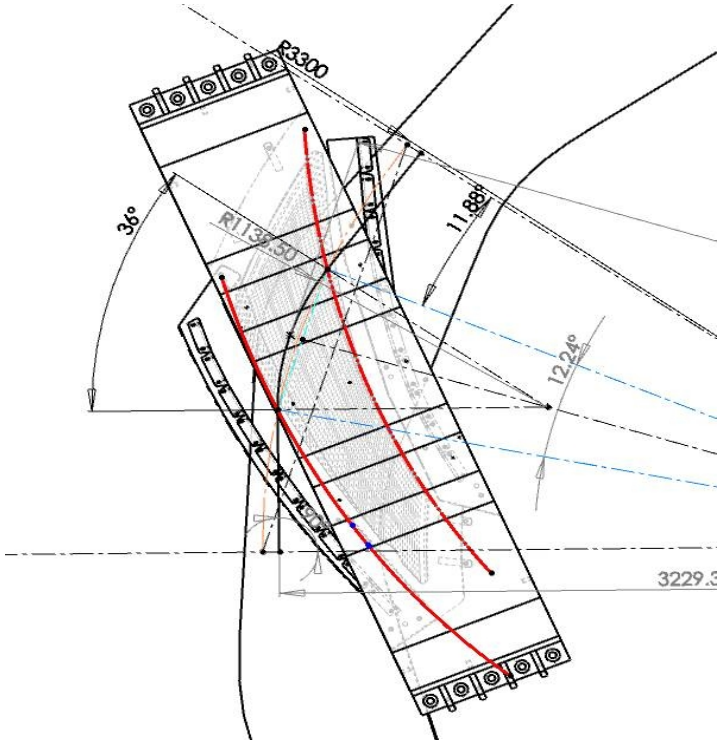
- Hall probe calibration until 1.8T, accuracy 3.10^{-5}
- Current stability < 5.10^{-5}
- Hall tension stability < 0.2 Gauss

3 AXIS HALL PROBE



- **Magnetic measurements**

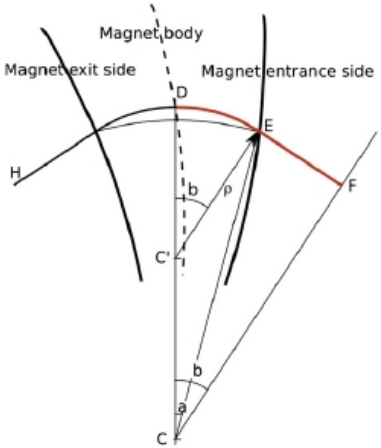




The bulk of the measurements : field on 11 arcs around given R :
R=2750, 2900, 3125, 3300, 3450mm, +/-55mm, step 11mm.

Done for current in coil of

225 Amp	→ 1.93 T at 3.46 m	(227MeV)
80%	→ 1.61 T	(162 MeV)
60%	→ 1.23 T	(98 MeV)



• Magnetic measurements

Typical result data sheet, at given range R_i +/-55mm

product number	RACCAM
magnet number	proto
date and time	16:05 Oct. 20 2008
operator	BD MJL
power supply	Teckelec
current	134.54
calibration	sept 2008
alignment	1
plane	0
Bo ref (T)	-0.000202
Io ref (A)	134.5424
dBo' (Gauss)	0.169053821846605
dIo' (mA)	2.45292000005293
trajectory number	1
radius (mm)	3125
average current (A)	134.542235299468
dI/I	3.548533E-05
Bo' (T)	-0.000200247120160589
Io' (A)	134.544428895
BL (T.mm)	505.885212406895
Leff (mm)	-802992.400645865
BL' (T.mm)	505.892841139384
Leff ' (mm)	-803004.509745054

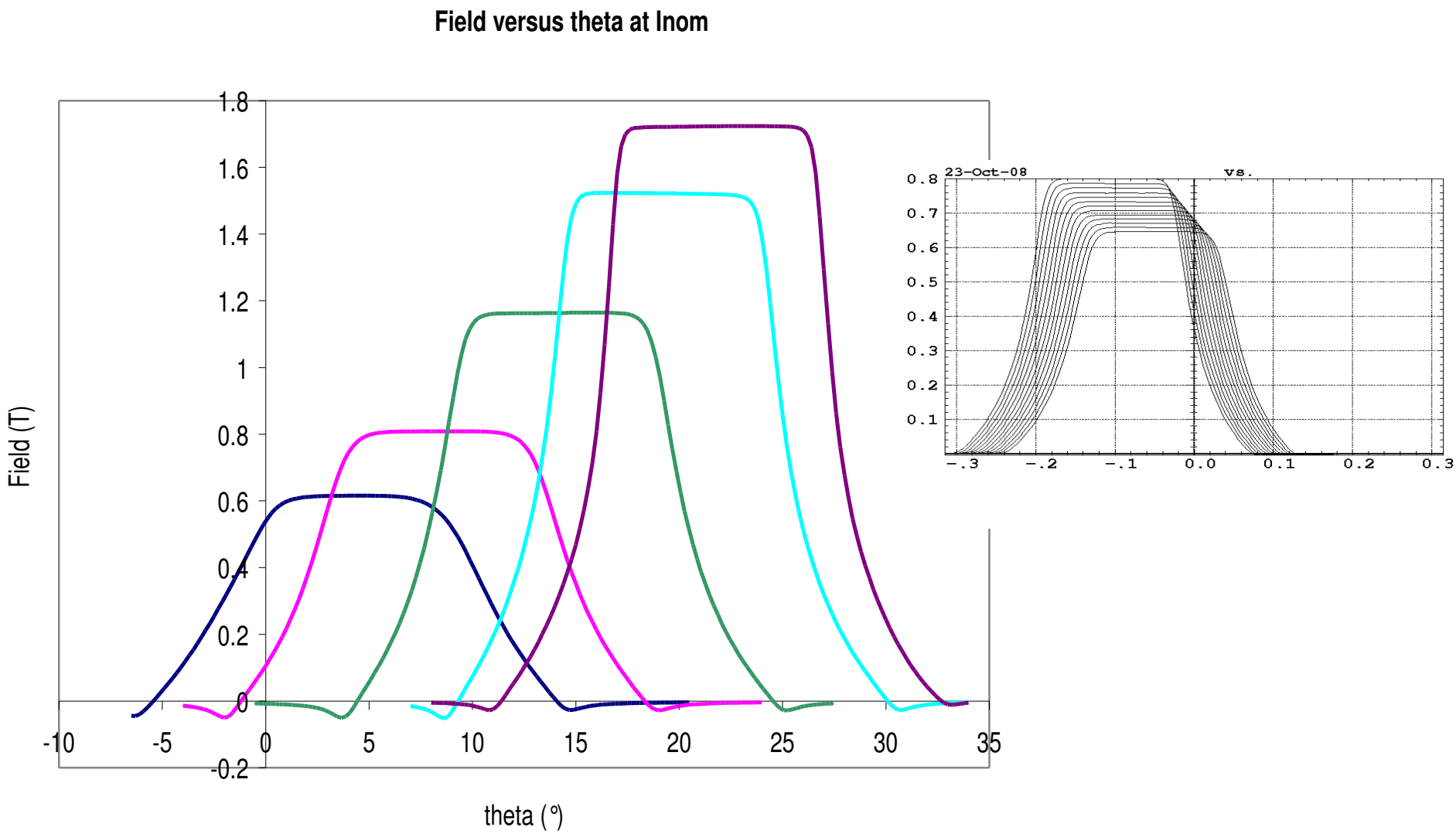
I(A)	S (mm)	Bx' (T)	By' (T)	Bz' (T)
134.54279601	0	-4.40555886854806E-06	-0.00020178076496973	-5.13163278608349E-06
134.54318139	10.9083022868645	-6.71516828434976E-06	-0.000173860930283967	-2.81547410028881E-06
134.543874225	21.8166045737289	-1.5083741228815E-05	-0.00014450812779144	1.825869774473E-06
134.543386845	32.7249068605931	-2.31711875462776E-05	-0.000110181750828479	1.04986204858515E-05
134.5425936	43.6332091474577	-3.66599568322746E-05	-6.44735929806508E-05	1.64599055918868E-05
134.54265273	54.5415114343223	-5.41474621126063E-05	-1.11150090658309E-05	2.91068921850812E-05
134.54396997	65.4498137211867	-8.11101358072387E-05	6.16329994040072E-05	4.35289268704956E-05
134.5436901	76.358116008051	-0.000119002478299474	0.000153409929871422	7.49343162681751E-05
134.54213934	87.2664182949157	-0.000180007120272256	0.000283658936709981	0.000115037695365823
134.542668135	98.1747205817799	-0.000288781087814502	0.000470136526019504	0.000184966572401949
134.54307276	109.083022868644	-0.000489362703287365	0.000747077905775863	0.000312082102654512
134.54286615	119.991325155509	-0.000886865983967809	0.00124443548650822	0.000572616925150128
134.54313933	130.899627442373	-0.00171134879284399	0.00225260648318265	0.00108023746889217
134.54336622	141.807929729238	-0.00312856876128646	0.00443311405817762	0.00197751956588934
134.542886145	152.716232016102	-0.00474535988718232	0.00844660434350137	0.00309922279276627
134.541251925	163.624534302967	-0.00584485101822694	0.0141376656356812	0.00398318418995119
134.541315855	174.532836589831	-0.00640055964991634	0.0208894717430771	0.00449966269162818
134.54202519	185.441138876695	-0.00666163887333702	0.0284339396929519	0.00478987689528881
134.542559085	196.34944116356	-0.00678134961692702	0.0365558843055311	0.00497910690572788
134.542708455	207.257743450424	-0.00683175801275004	0.0453150813202366	0.00511415619153322
134.543050815	218.166045737289	-0.0068268832403686	0.0545747904389083	0.00522319262827881
134.54266305	229.074348024153	-0.00682403652947264	0.0644727521440337	0.00533216276476242
134.54110908	239.982650311018	-0.00678678420120075	0.0749895849925962	0.00542258744061969
134.54265918	250.890952597882	-0.00676963856803778	0.0860332982175262	0.00552160827087861

trajectory number	
radius (mm)	
average current (A	
dI/I	
Bo' (T)	
Io' (A)	
BL (T.mm)	
Leff (mm)	
BL' (T.mm)	
Leff ' (mm)	

I(A)
134.542194045
134.54203248
134.54362353
134.54197182
134.541337335
134.54243883
134.542343775
134.542178835
134.54230155
134.54184606
134.5422003
134.541751725
134.542336245
134.54217753
134.542081635
134.542037595
134.54317419
134.541902205
134.54235837
134.542520895
134.542789275
134.541978405
134.542201725
134.54236056

- **Magnetic measurements**

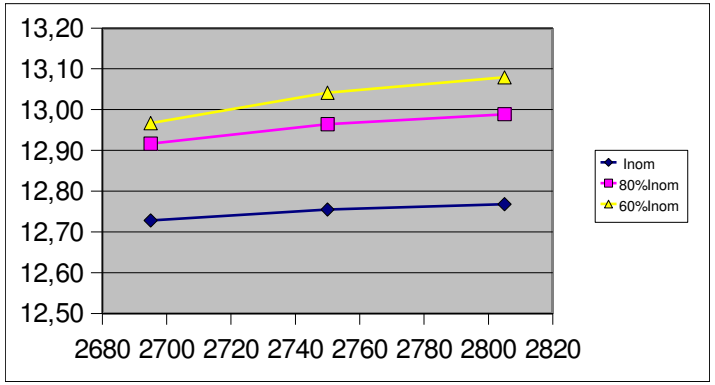
Typical result data sheet, at given range R_i +/-55mm

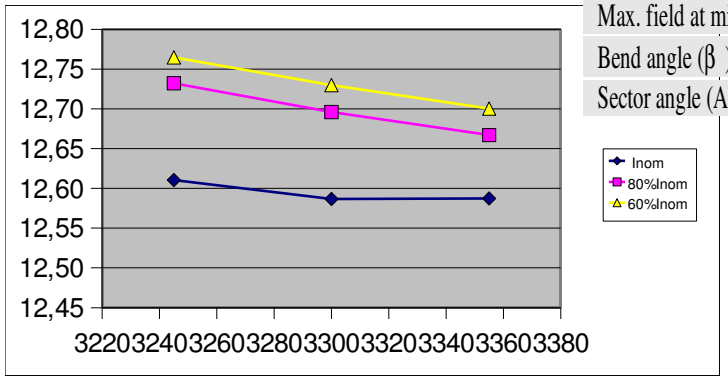


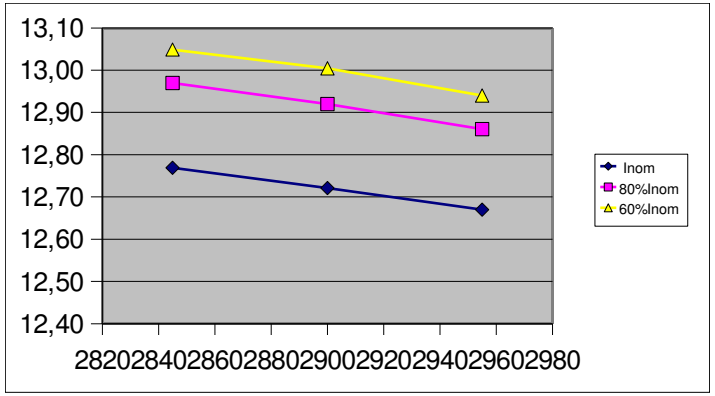
- **Magnetic measurements**

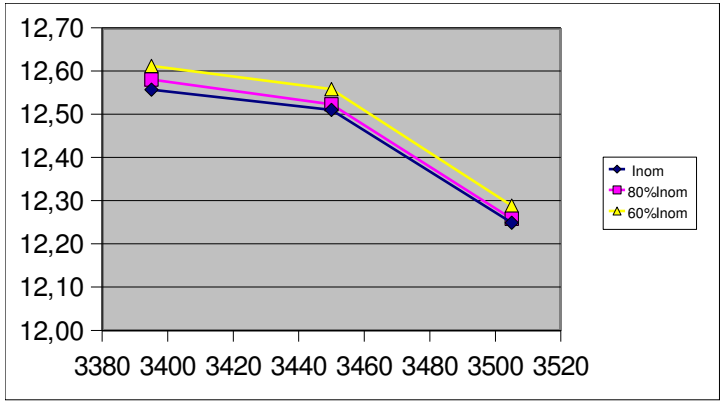
Sector angle, A. Theoretical : 12.24 deg

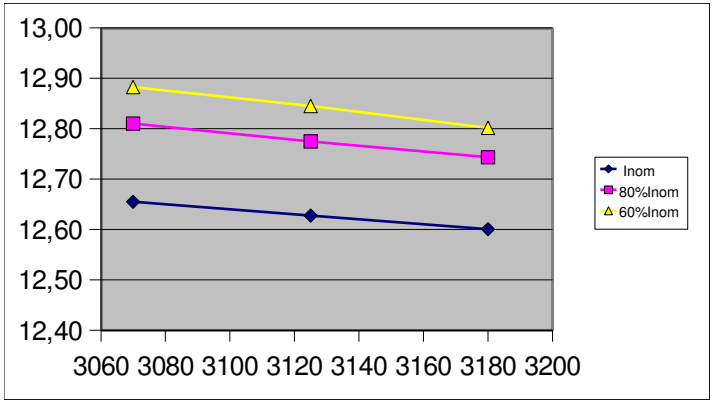
Type	Gap shaping
Packing factor (pf)	0.34
Field index (k)	5
Spiral Angle (ζ) (deg)	53.7
Min./Max. radius of good field region (m)	2.9/3.3
Max. field at min./max. radius (T)	0.58/1.7
Bend angle (β) (deg)	36
Sector angle (A) (deg)	12.24

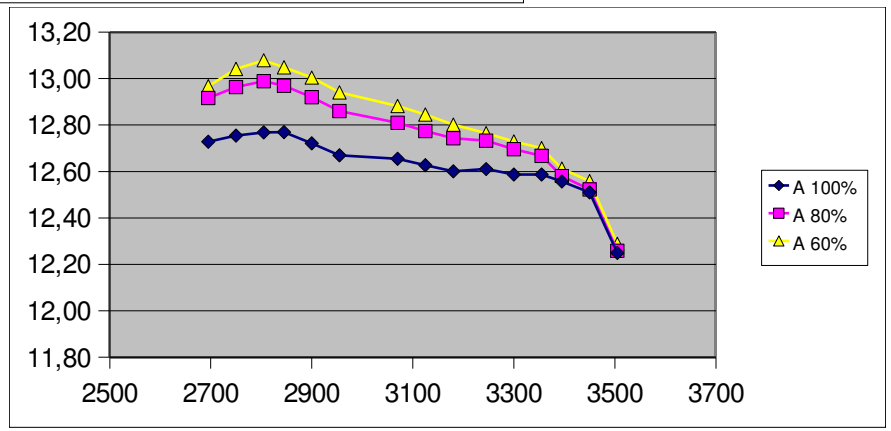








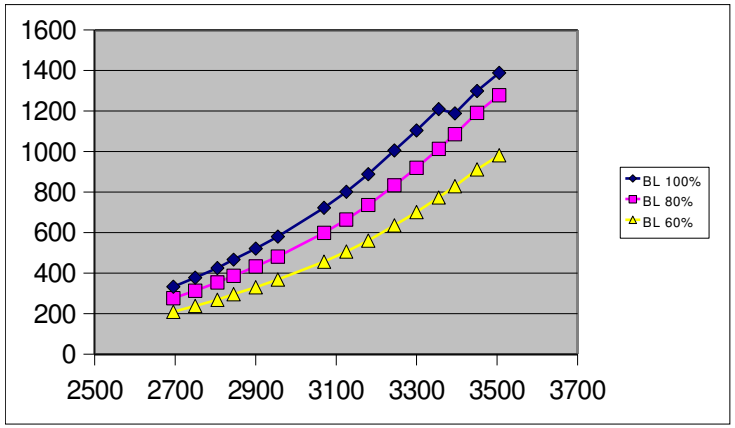


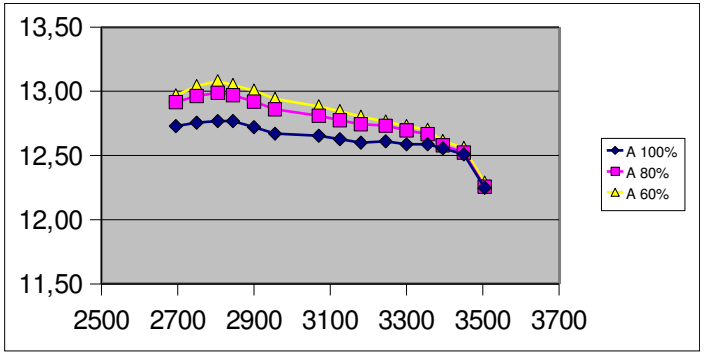


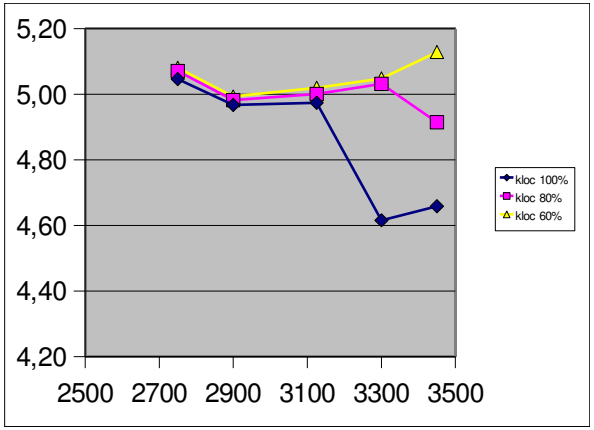
- **Magnetic measurements**

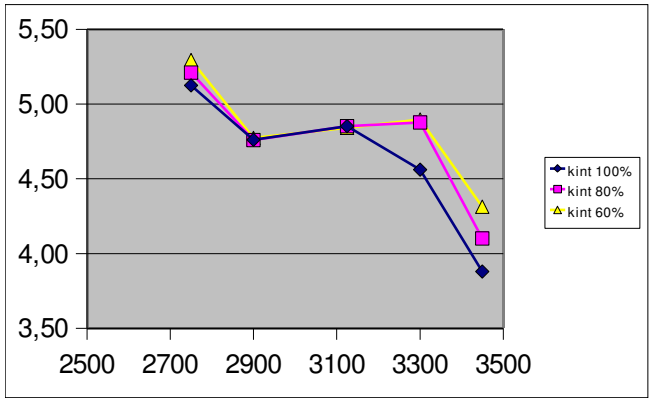
Synthesis : field integrals (th. 36deg, normalized), sector angle A (th. 12.24 deg) local k from B (taken at A/2), average k from BL (th. 5.00), spiral angle at entrance/exit

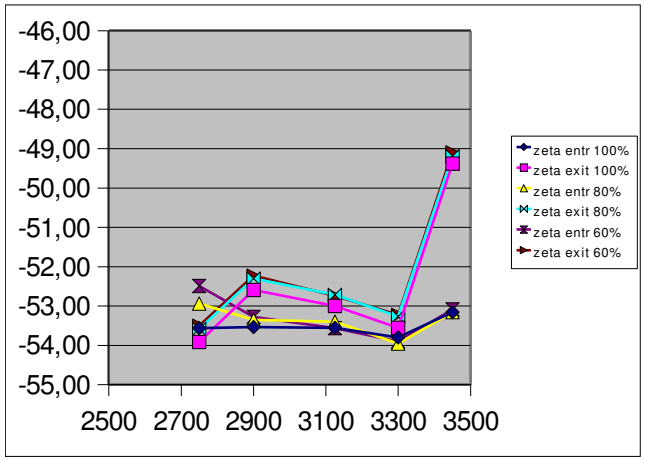
Packing factor (pf)	0.34
Field index (k)	5
Spiral Angle (ζ) (deg)	53.7
Min./Max. radius of good field region (m)	2.9/3.3
Max. field at min./max. radius (T)	0.58/1.7
Bend angle (β) (deg)	36
Sector angle (A) (deg)	12.24



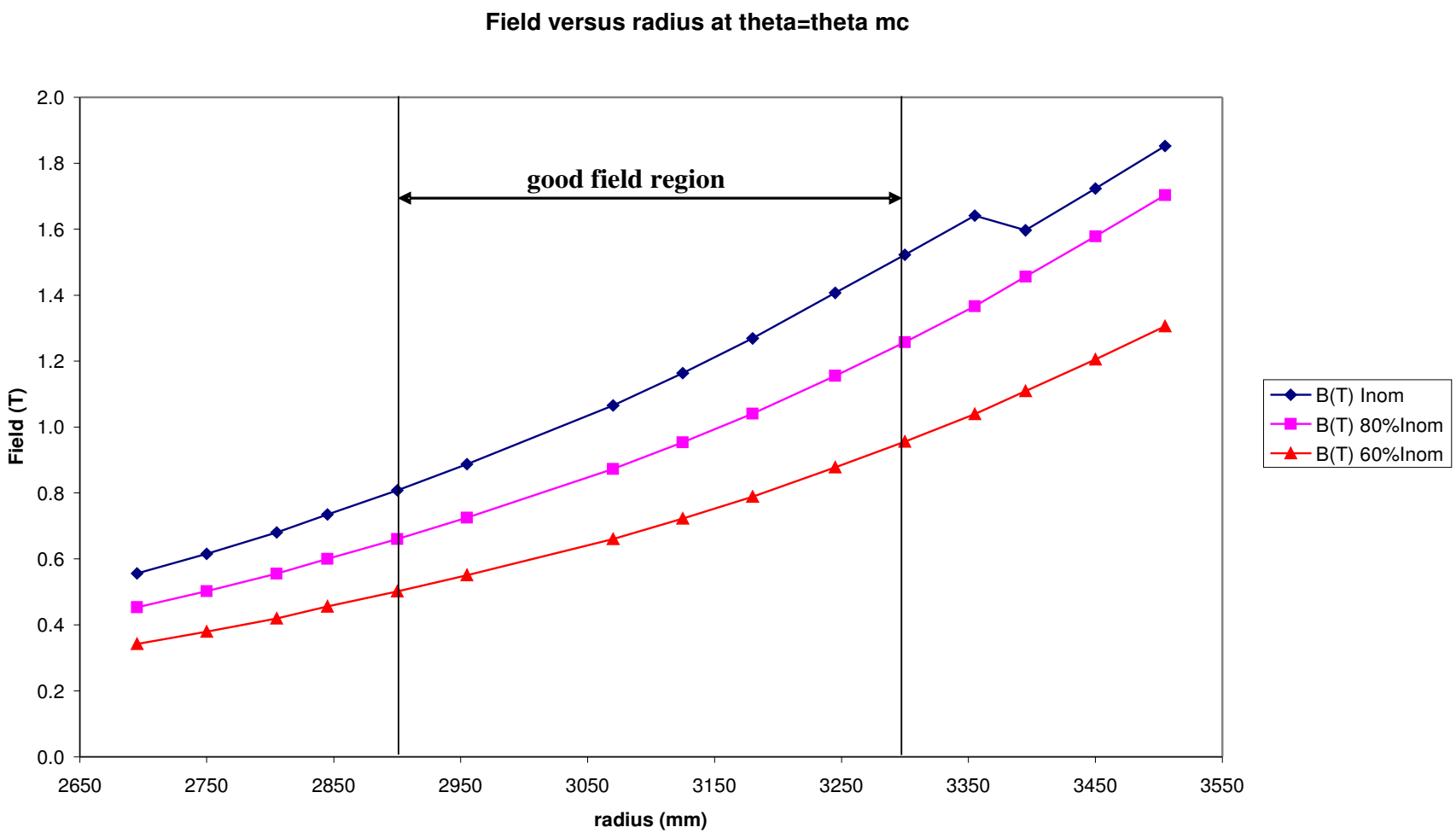




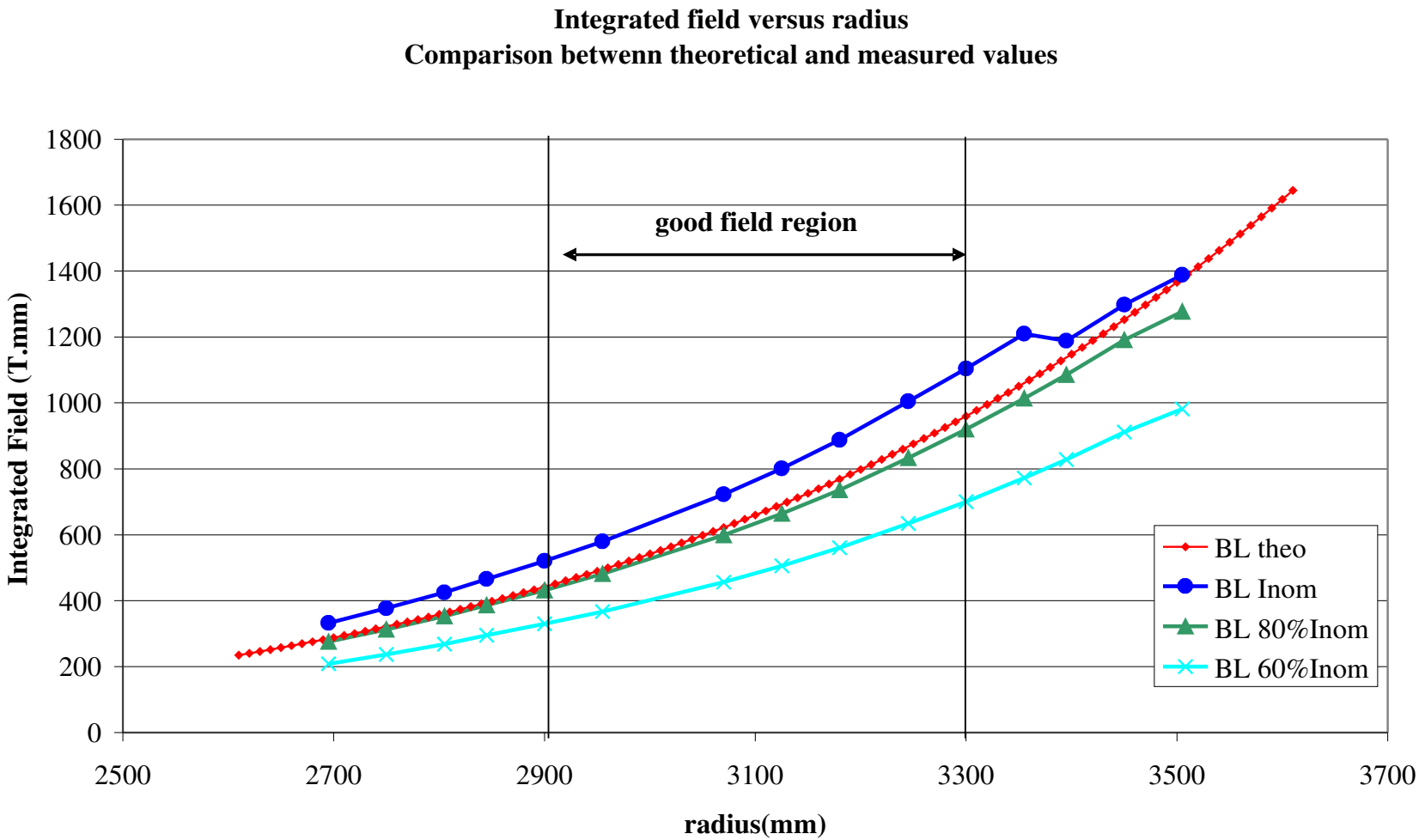




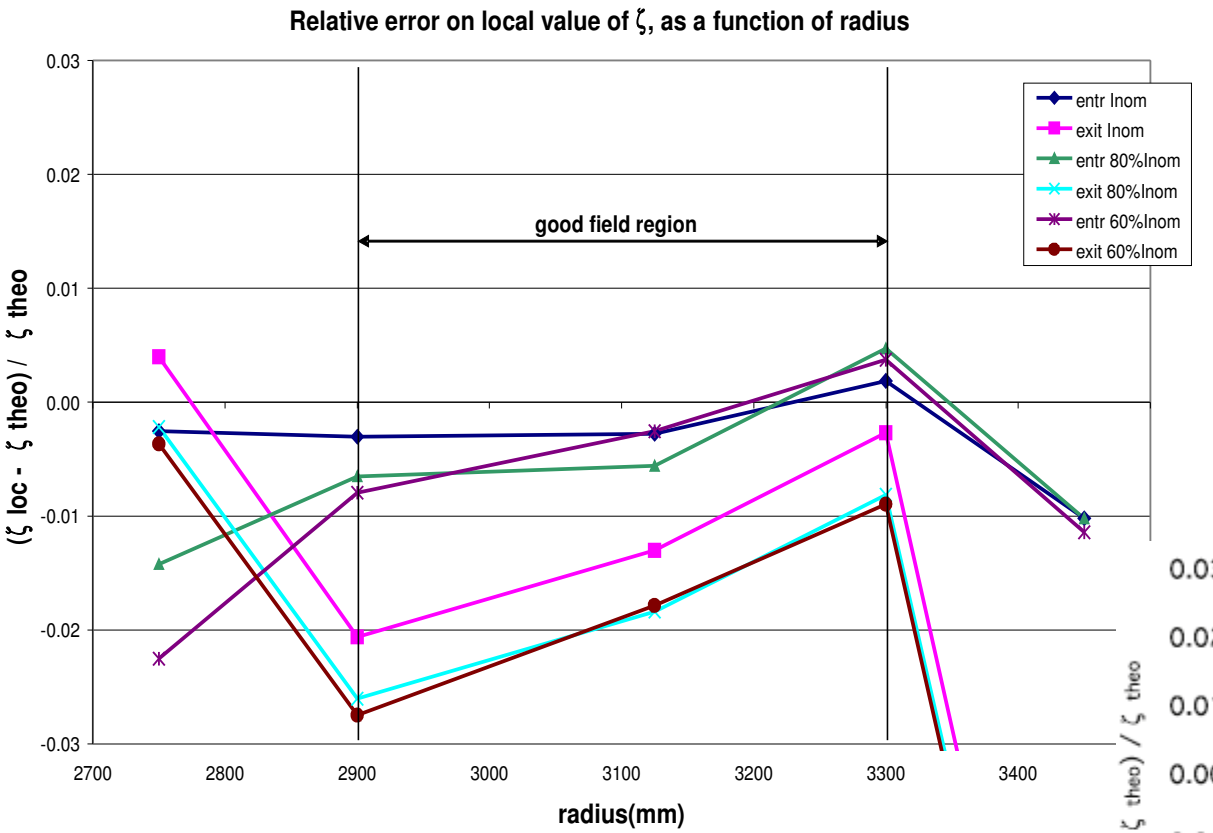
• Magnetic measurements



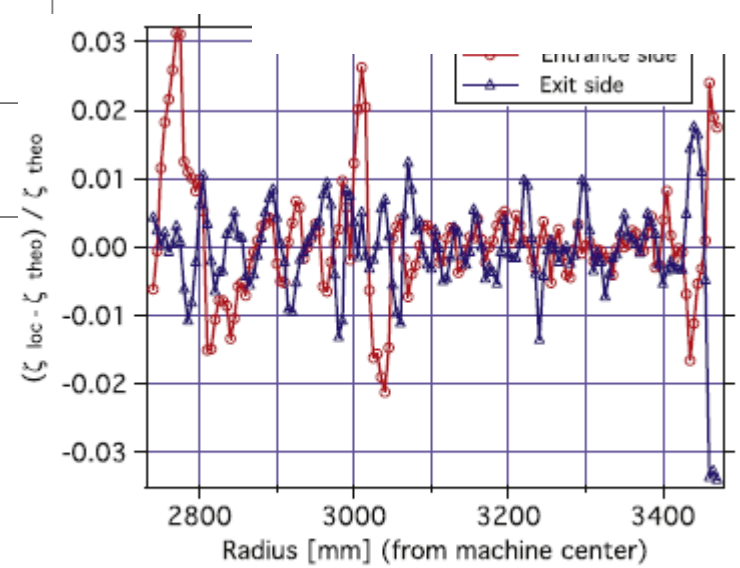
• Magnetic measurements



• Magnetic measurements

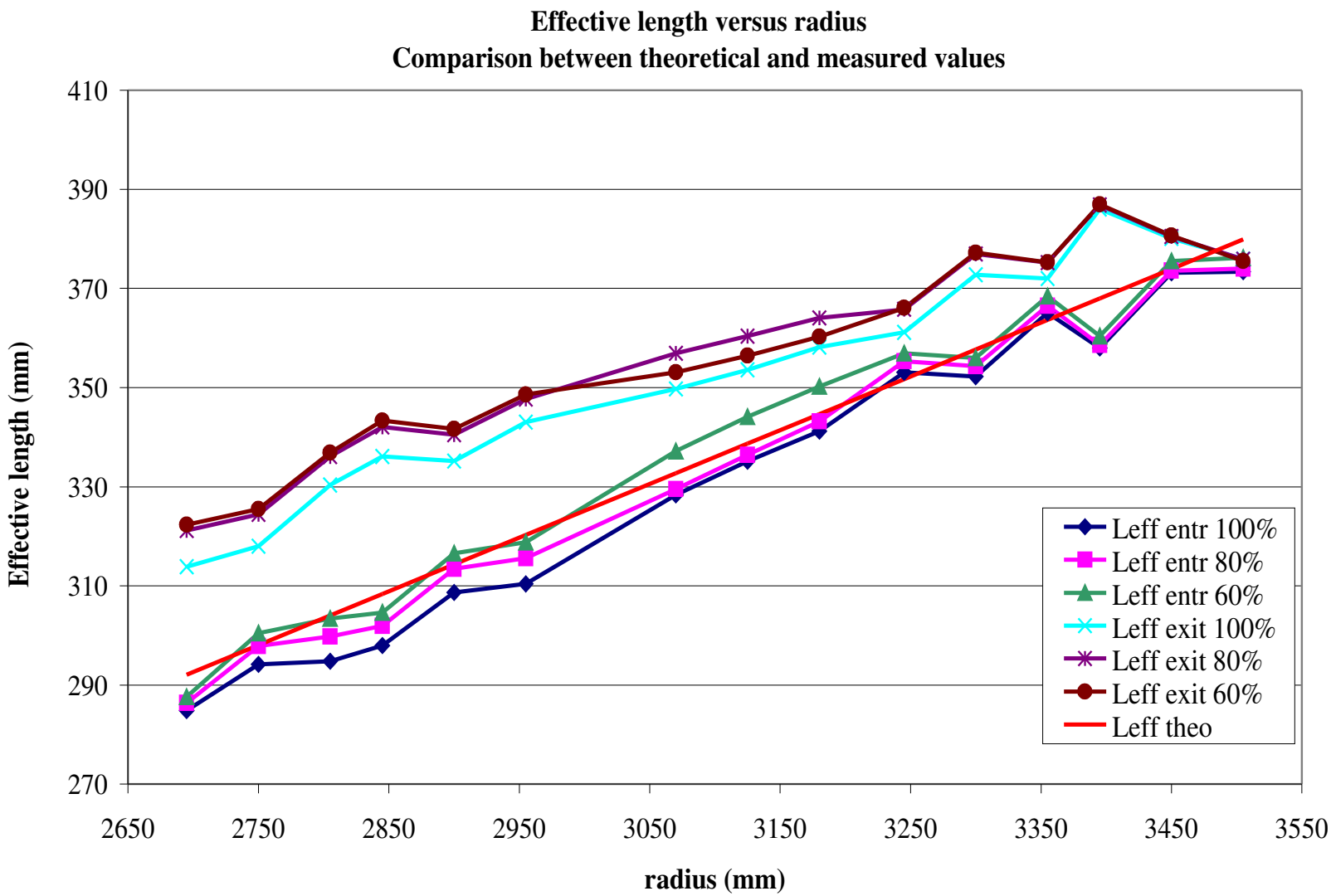


Comparison with TOSCA results

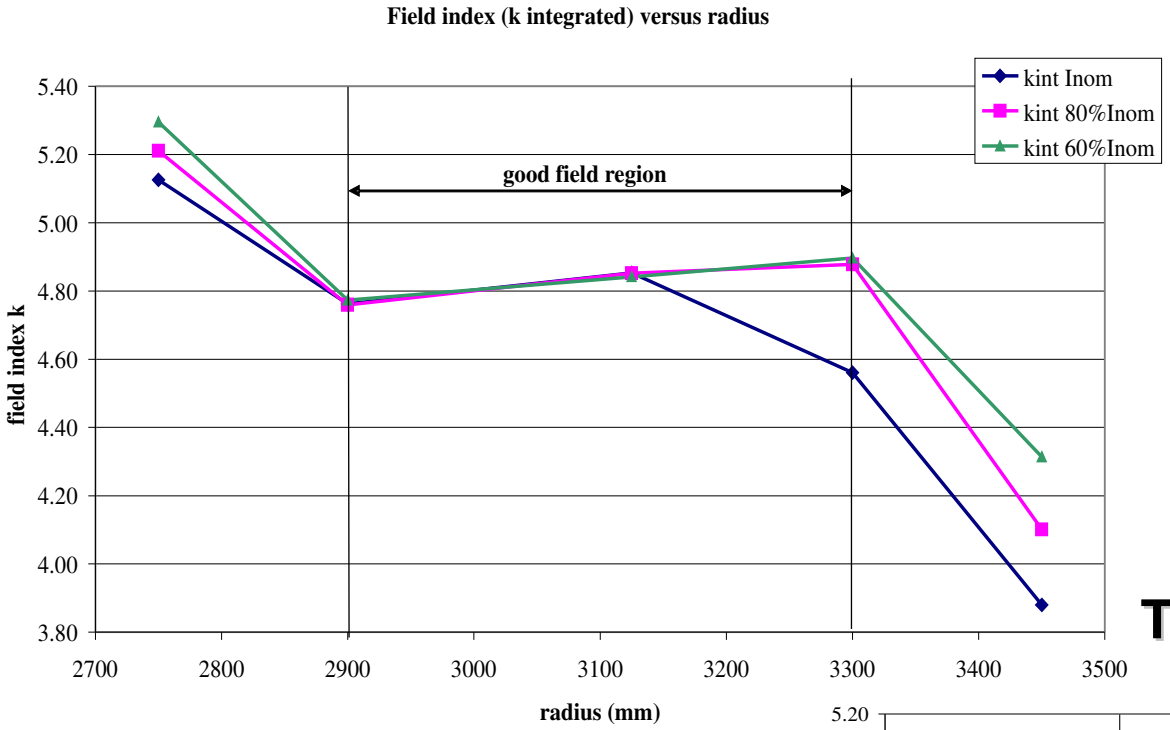


Relative error on local value of ζ, as a function of radius.

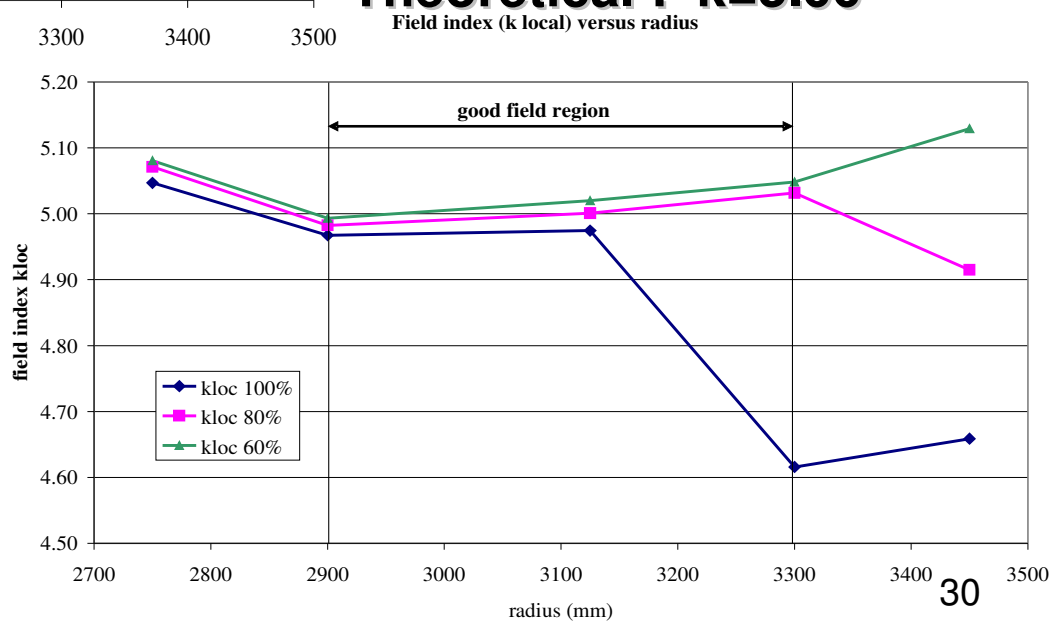
- **Magnetic measurements**



• Magnetic measurements



Theoretical : k=5.00



• Prototype gap shaping magnet : tracking in the measured field maps, Zero-th order (3/5) → see PAC 09 Proceedings

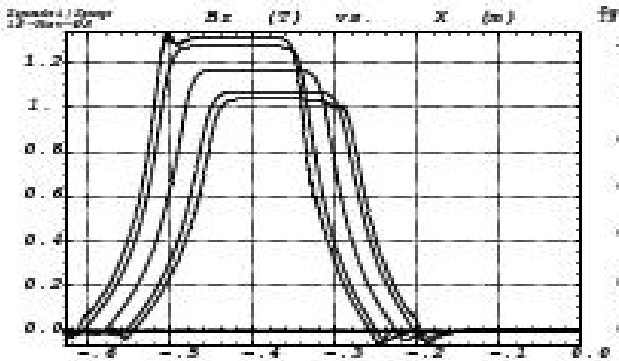


Figure 3: Magnetic field along 5 arcs of circles.

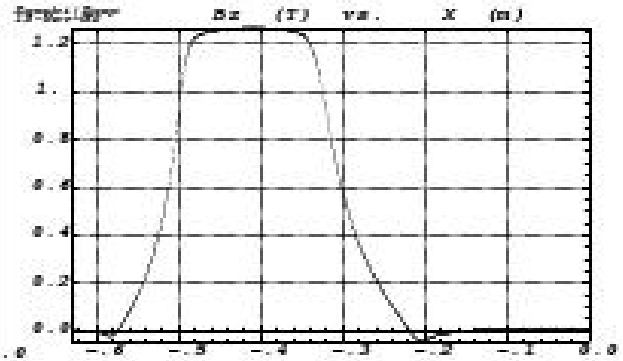


Figure 4: Field on closed orbit in the $R = 3125$ mm region.

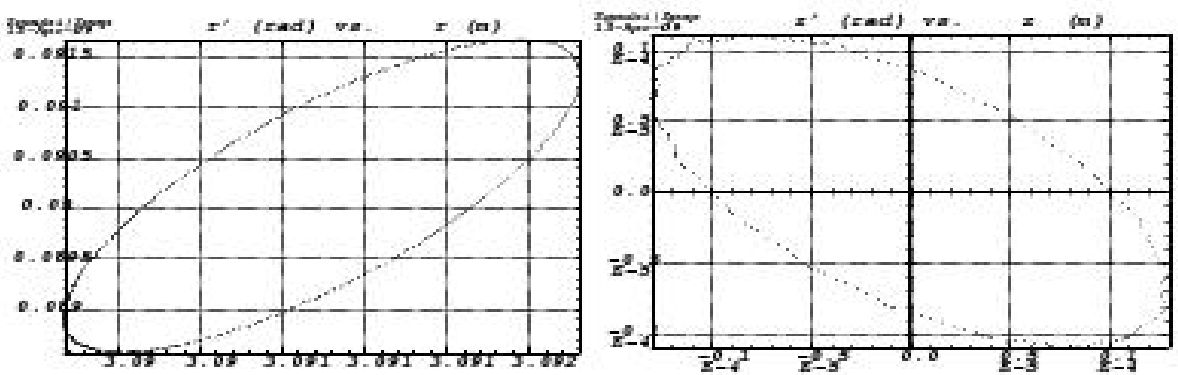


Figure 5: Typical paraxial motion used for tune computation, horizontal (left), vertical (right).

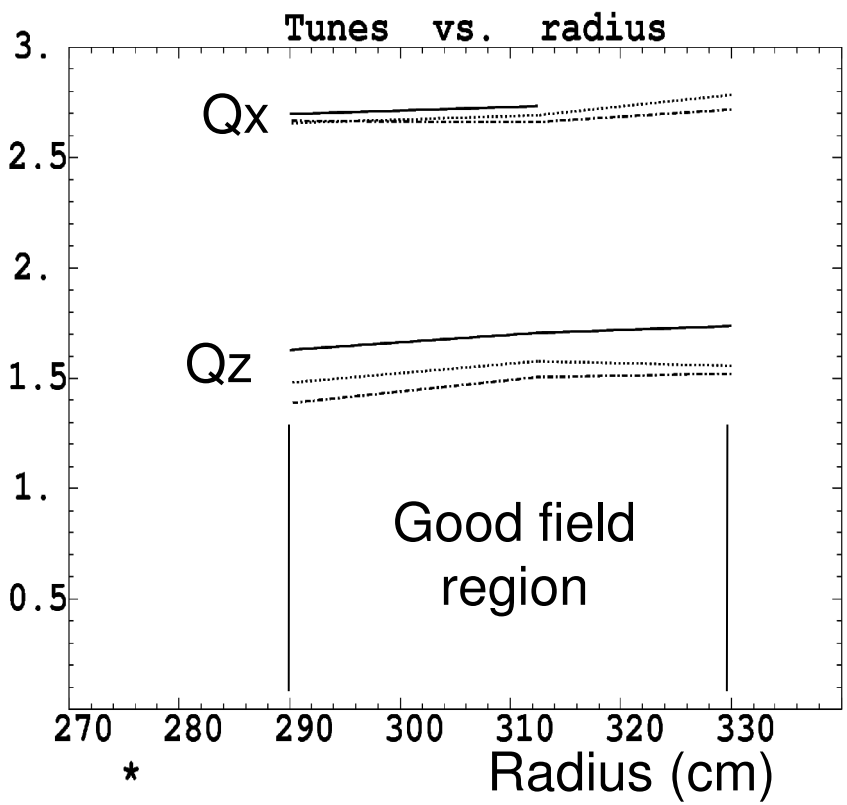
Zero-th order :

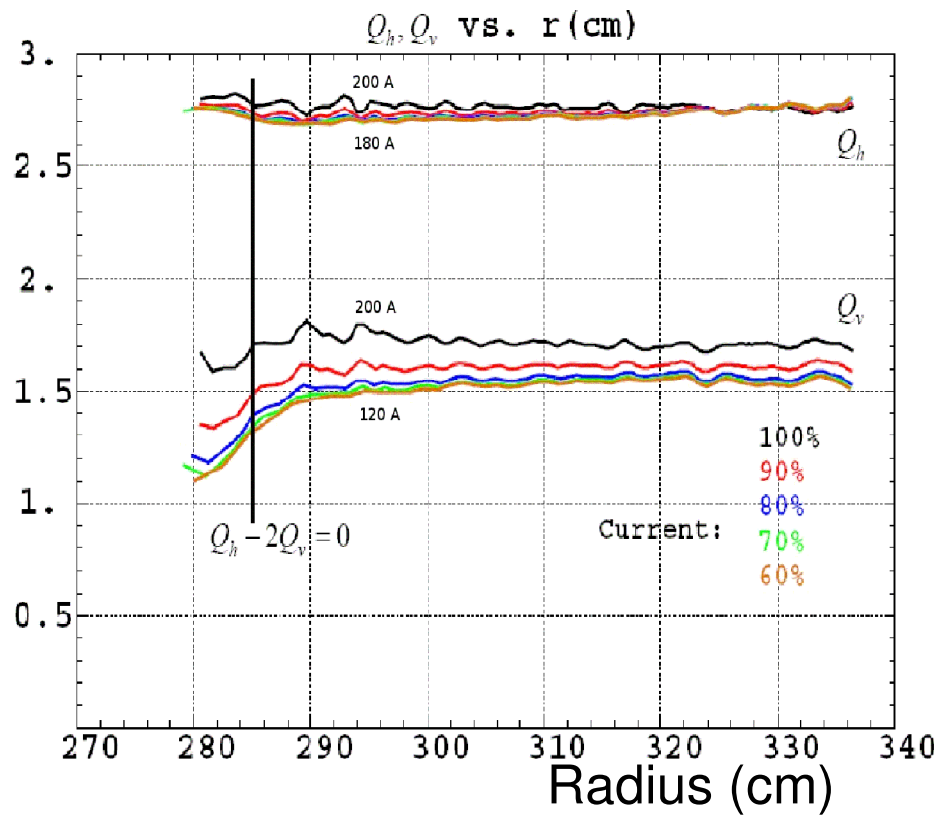
R (mm)	$E_{c.o.}$ (MeV)	$\hat{r}$ (mm)	$\hat{B}$ (T)
Maximal current			
2900	38.0	2950	0.880
3125	86.5	3175	1.259
3300	156.0	3350	1.631
$80\% I_{max}$			
2900	26.2	2950	0.719
3125	60.8	3175	1.032
3300	112.7	3350	1.356
$60\% I_{max}$			
2900	15	2950	0.546
3125	35.9	3175	0.782
3300	67.3	3350	1.031

• Correlation between E and r agrees with theory within a few per-mil

• Prototype gap shaping magnet : tracking in magnetic field maps, First order (4/5)

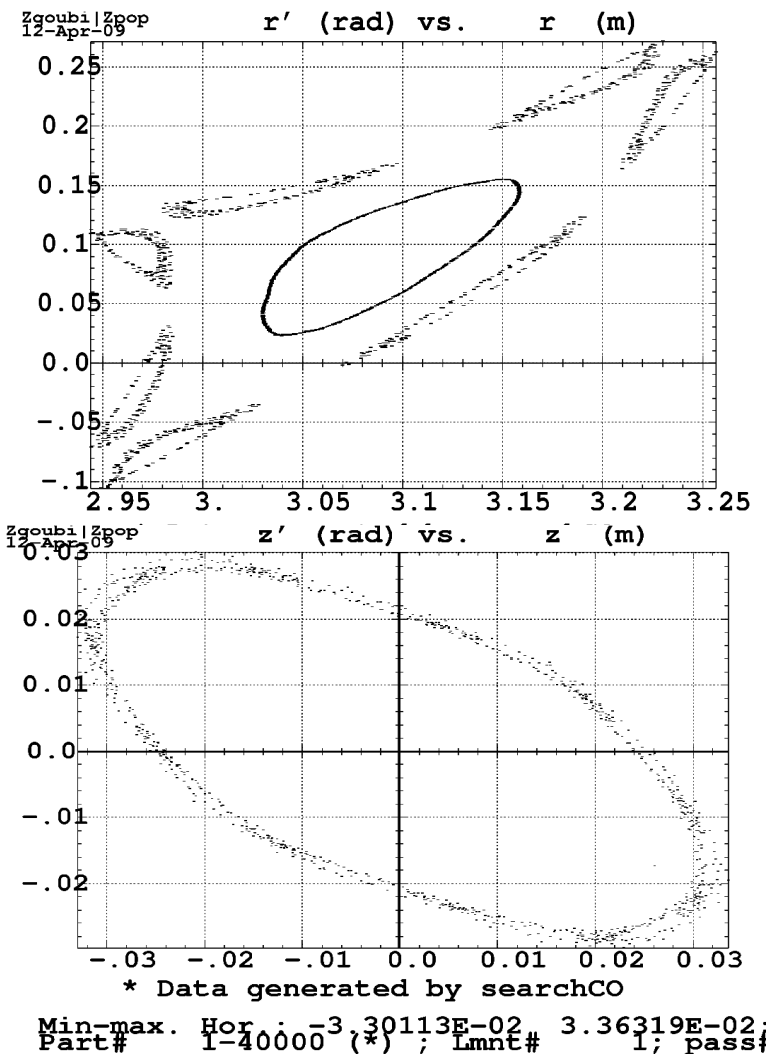
• Tunes, from magnetic measurements (left) and from design simulations using TOSCA (right)





<X>, Sig X, X min, max : 308.4

• Prototype gap shaping magnet : tracking in magnetic field maps, Dynamic acceptance (5/5) → see PAC 09 Proceedings



• Large DA's are obtained, consistent with design specifications

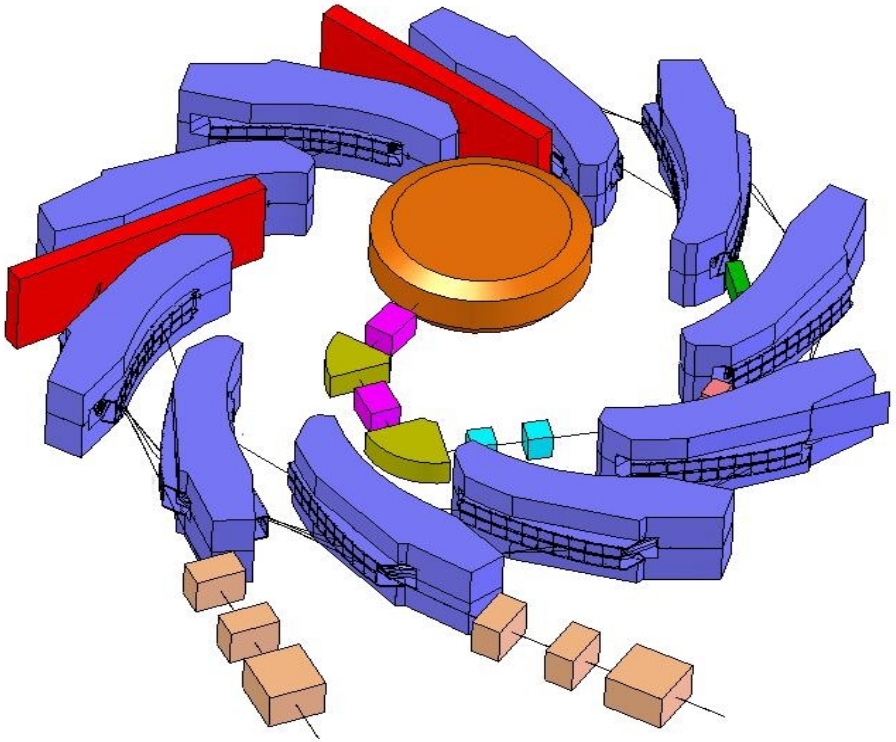
Table 4: Dynamic apertures.

R region (mm)	E (MeV)	From measured field maps Ax	Az	From OPERA 3D field maps Ax	Az
		(πmm.mrad)			
Maximal current		($B_0 = 1.933\,T$)		($B_0 = 1.7\,T$)	
2900	38.0	1800	900	2500	900
3125	86.5	2600	800	2900	1000
3300	156	5500	1500	3500	950
$80\%I_{max}$		($B_0 = 1.606\,T$)			
2900	15	4000	1500		
3125	35.9	1500	1200		
3300	67.3	1700	1400		
$60\%I_{max}$		($B_0 = 1.227\,T$)			
2900	15	1200	900		
3125	35.9	1200	900		
3300	67.3	2200	900		

CONCLUSION

A lot can still be done using measurement data :

- *Difference* with TOSCA simulated field, including
  - Best fit of mutual relative positionning
  - With possible benefits as,
    - removing the r-dependence of Leff ? slide 29
- In general, analyse these data in detail, including
  - Systematic comparisons with TOSCA simulations
  - Understanding effects as
    - The local value of k, the integral value of k
    - The offset in the spiral angle
- The magnet is still there, it can be thought of experimenting further :
  - Moving the clamps
  - Presence of magnetic (RF) material in the drift region
  - Response to dB/dt

    etc...

THANK YOU FOR YOUR ATTENTION